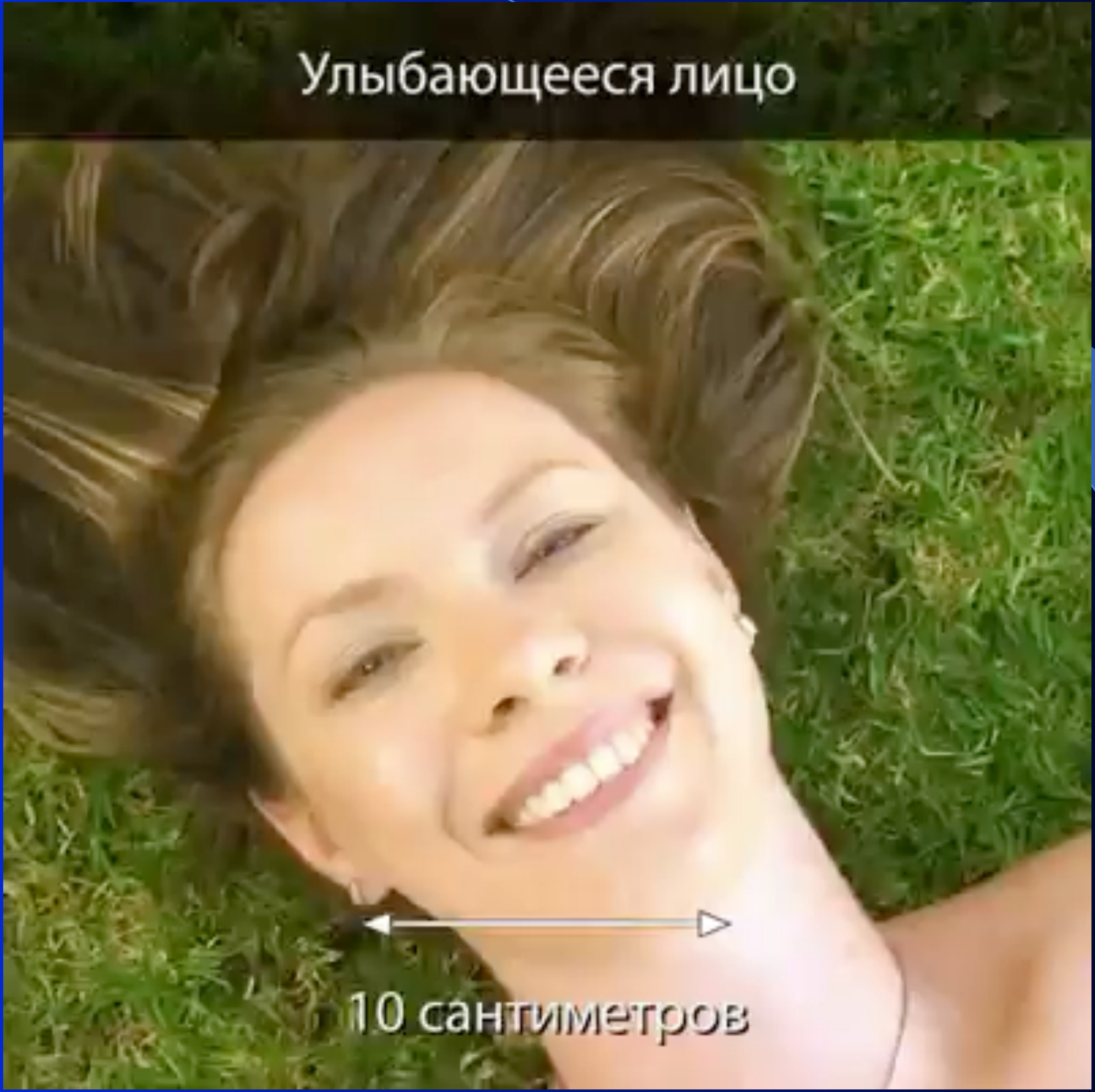
THE STANDARD MODEL AND BEYOND'24

DMITRY KAZAKOV

JINR(DUBNA)

The Universe



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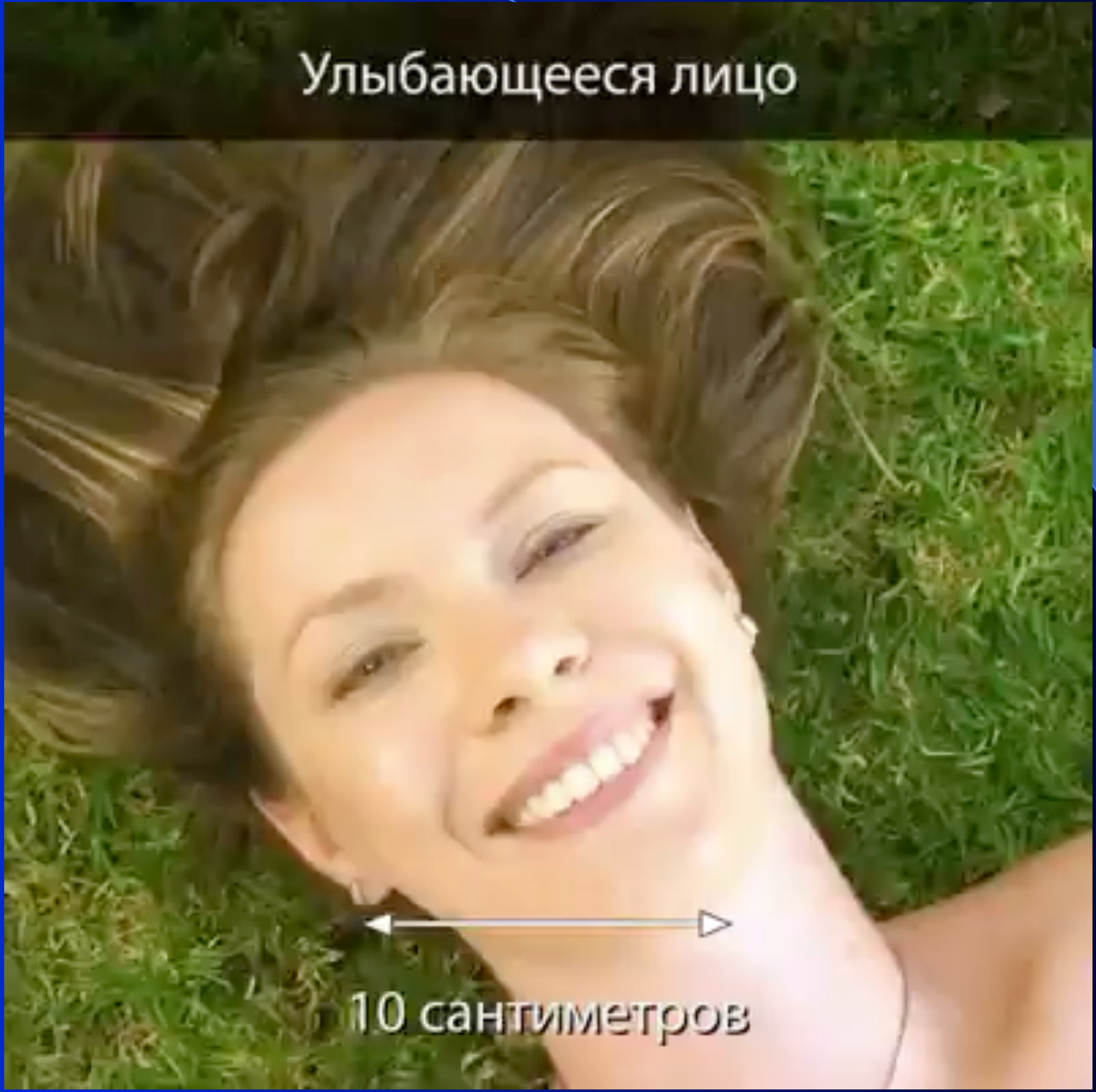


Улыбающееся лицо

10 сантиметров

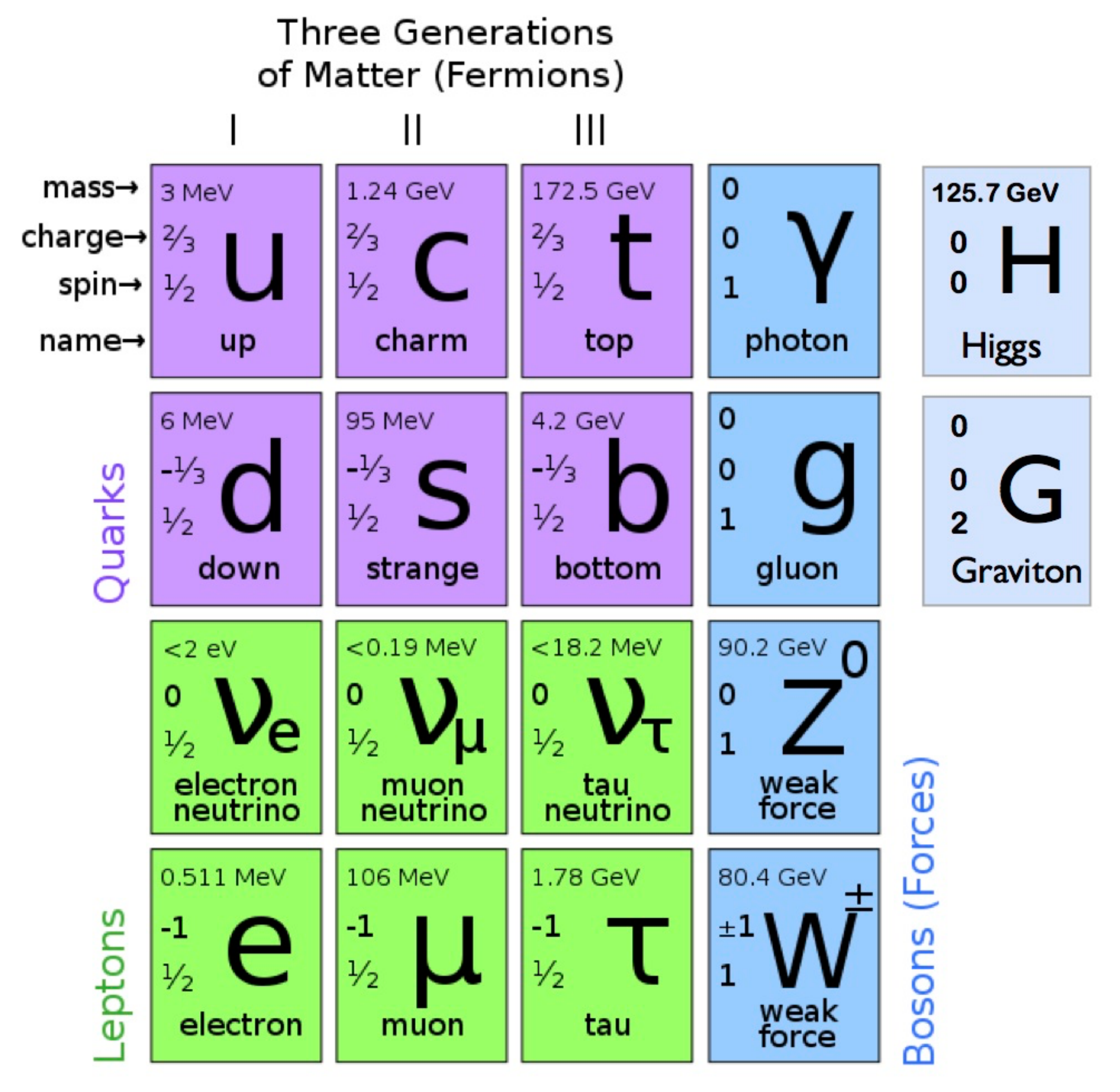
The Standard Model

SU(3)

SU(2)

U(1)

Particles



Three Generations of Matter (Fermions)

		I	II	III	Bosons (Forces)	
Quarks	mass→ charge→ spin→ name→	3 MeV ⅔ ½ u up	1.24 GeV ⅔ ½ c charm	172.5 GeV ⅔ ½ t top	0 0 1 γ photon	125.7 GeV 0 0 H Higgs
		6 MeV -⅓ ½ d down	95 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon	0 0 2 G Graviton
Leptons		<2 eV 0 ½ ν_e electron neutrino	<0.19 MeV 0 ½ ν_μ muon neutrino	<18.2 MeV 0 ½ ν_τ tau neutrino	90.2 GeV 0 1 Z^0 weak force	
		0.511 MeV -1 ½ e electron	106 MeV -1 ½ μ muon	1.78 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force	

Forces

Electromagnetic

Strong

Weak

Гравитация

THE STANDARD MODEL OF FUNDAMENTAL INTERACTIONS

THE PRINCIPLES

- Three gauged symmetries SU(3)xSU(2)xU(1)
- Three families of quarks and leptons $(\underline{3}\mathrm{x}\underline{2}, \underline{3}\mathrm{x}\underline{1}, \underline{1}\mathrm{x}\underline{2}, \underline{1}\mathrm{x}\underline{1})$
- Brout-Englert-Higgs mechanism of spontaneous EW symmetry breaking -> Higgs boson
- CKM and PMNS mixing of flavours
- CP violation via phase factors
- Confinement of quarks and gluons inside hadrons
- Baryon and lepton number conservation
- CPT invariance -> existence of antimatter

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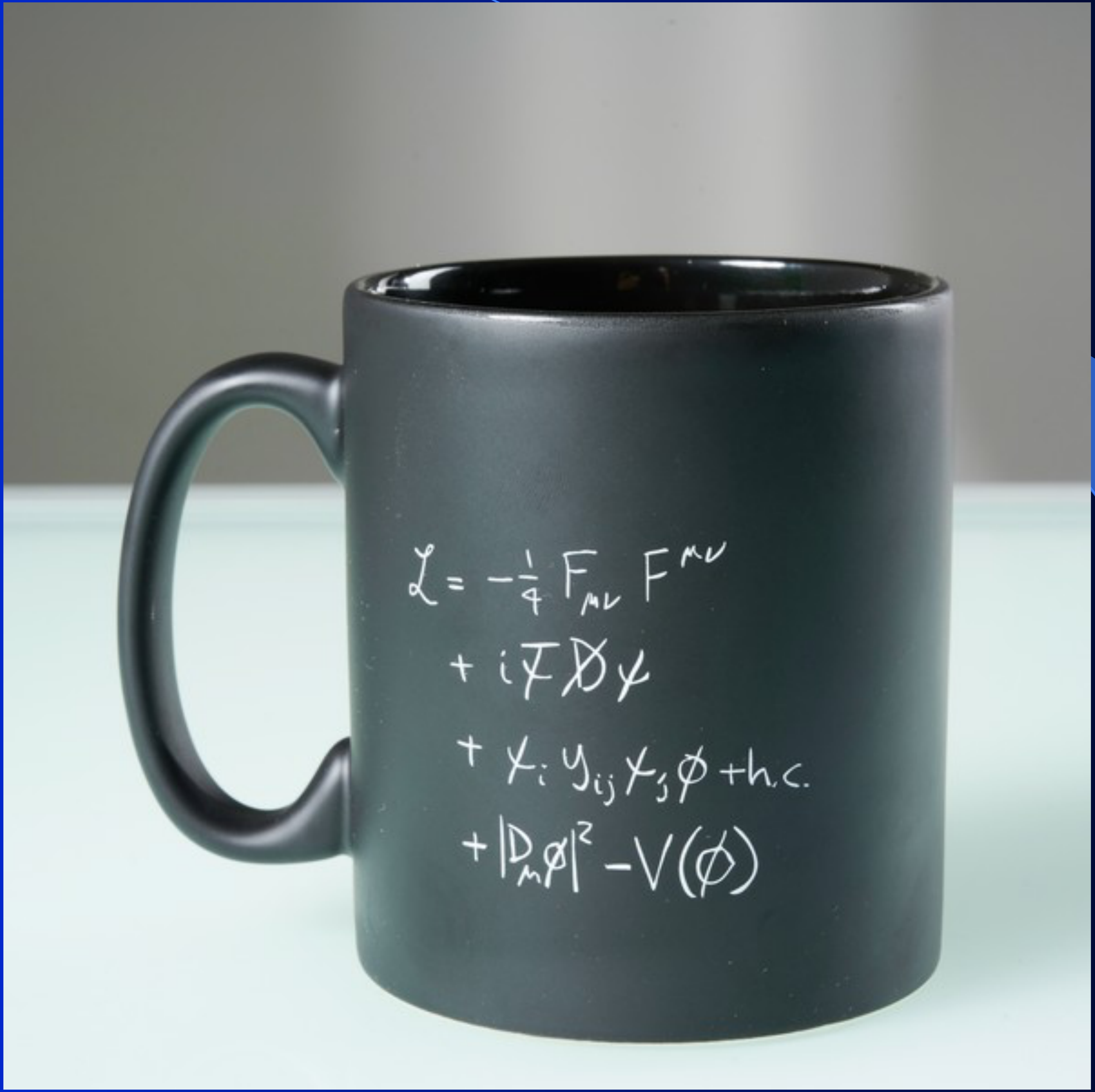
The ST principles allow:

- Extra families of quarks and leptons
- Presence or absence of right-handed neutrino
- Majorana or Dirac nature of neutrino
- Extra Higgs bosons

The Standard Model



THE LAGRANGIAN

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Higgs},$$

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$$\boxed{+i\overline{N}_\alpha\gamma^\mu\partial_\mu N_\alpha} \longleftarrow$$

possible right handed neutrino ?

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Three gauge couplings

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Three or four Yukawa matrices

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Two parameters

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All these parameters are **not** predicted by the **SM** and determined experimentally

Three gauge couplings

Three or four Yukawa matrices

Two parameters

THE LAGRANGIAN

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}$$

$$\mathcal{L}_{gauge} = -\frac{1}{4}G^a_\mu$$

$$+i\overline{L}_\alpha\gamma^\mu D_\mu L$$

$$+i\overline{U}_\alpha\gamma^\mu D_\mu U_\alpha +$$

$$\boxed{+i\overline{N}_\alpha\gamma^\mu\partial}$$

$$\mathcal{L}_{Yuk} \quad y^L_{\alpha\beta}\overline{L}_\alpha E_\beta H$$

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$$\boxed{+y^N_{\alpha\beta}\overline{L}_\alpha N}$$

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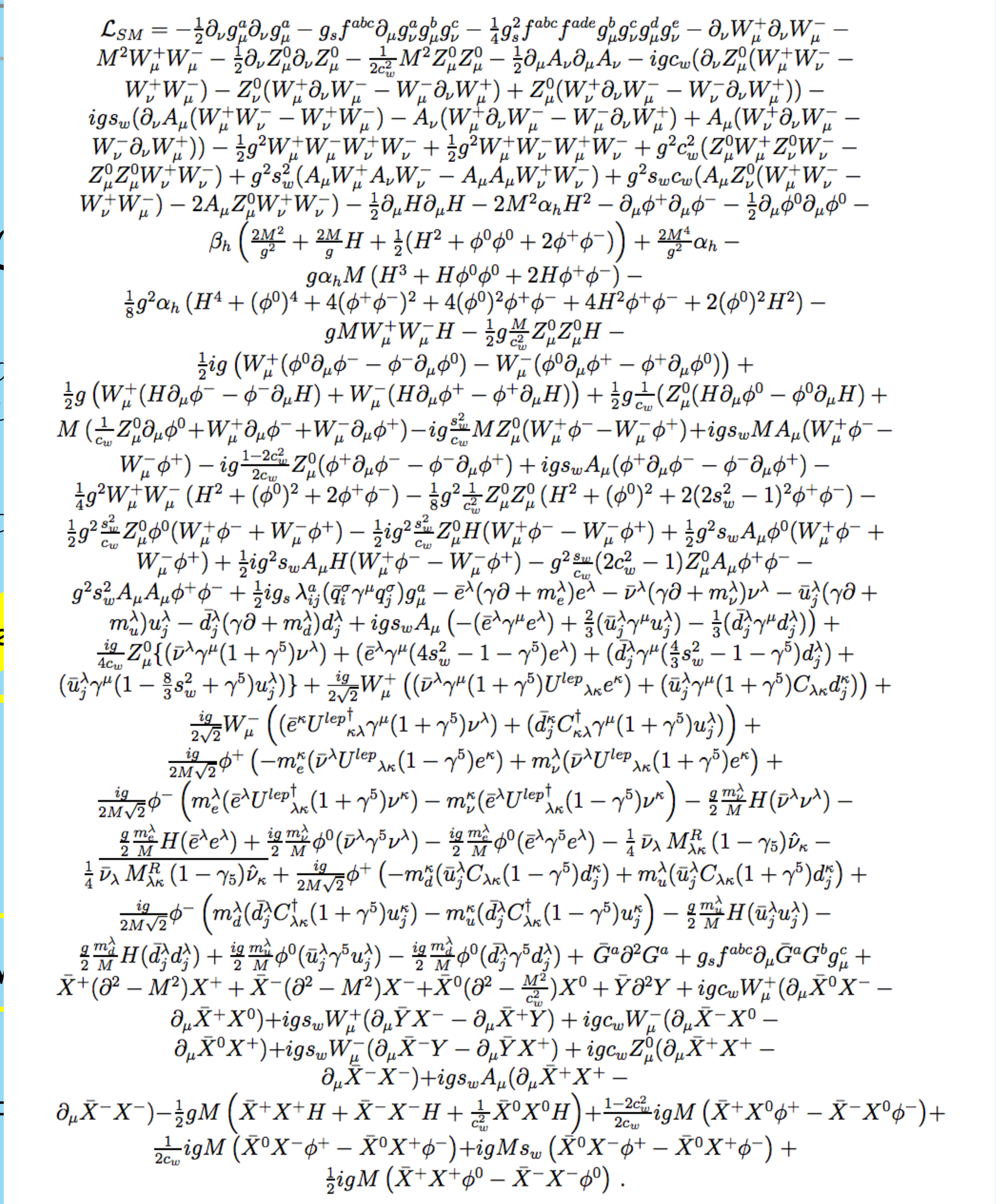

$$\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) -$$

$$igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu -$$

$$W^-_\nu\partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$

$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 -$$

$$\beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h -$$

$$g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$

$$\frac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$

$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H -$$

$$\frac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$

$$\frac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$

$$M\left(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- -$$

$$W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$

$$\frac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \frac{1}{8}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s^2_w-1)^2\phi^+\phi^-\right) -$$

$$\frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w-1)Z^0_\mu A_\mu\phi^+\phi^- -$$

$$g^2s^2_w A_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial +$$

$$m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$

$$\frac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w - 1 - \gamma^5)d^\lambda_j) +$$

$$(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s^2_w + \gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$

$$\frac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep}{}^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$

$$\frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) +$$

$$\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep}{}^\dagger_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep}{}^\dagger_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \frac{g}{2}\frac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) -$$

$$\underline{\frac{g}{2}\frac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) +} \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \frac{1}{4}\,\bar{\nu}_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa -$$

$$\frac{1}{4}\,\bar{\nu}_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) +$$

$$\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) -$$

$$\frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu +$$

$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$

$$\partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 -$$

$$\partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ -$$

$$\partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ -$$

$$\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c^2_w}\bar{X}^0X^0H\right) + \frac{1-2c^2_w}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) +$$

$$\frac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) +$$

$$\frac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right) .$$

THE LAGRANGIAN

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Higgs},$$

$$\mathcal{L}_{gauge} = -\frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^i \quad - \quad B_{\mu\nu}B$$

$$+i\overline{L}_\alpha\gamma^\mu D_\mu L_\alpha + i\overline{Q} \quad D_\mu Q_\alpha + i\overline{E} \quad D_\mu E_\alpha$$

$$+i\overline{U}_\alpha\gamma^\mu D_\mu U_\alpha + \quad \gamma^\mu D_\mu D_\alpha + (D_\mu H)^\dagger(D_\mu H),$$

Three gauge couplings

$$\boxed{+i\overline{N}_\alpha\gamma^\mu\partial}$$

possible right handed neutrino ?

All these parameters are **not** predicted by the **SM** and determined experimentally

$$\mathcal{L}_{Yuk} \quad y^L_{\alpha\beta}\overline{L}_\alpha E_\beta H + y^D_{\alpha\beta}\overline{Q}_\alpha D_\beta H + y^U_{\alpha\beta}\overline{Q}_\alpha U \quad h.c.,$$

$$\boxed{+y^N_{\alpha\beta}\overline{L}_\alpha N_\beta\tilde{H}}$$

Three or four Yukawa matrices

$$\mathcal{L}_{Higgs} = -V = m^2H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

Two parameters

Quantum Numbers of Matter

	$SU(3)_c$	$SU(2)_L$	$U_Y(1)$
Quarks			
$Q_L = \begin{pmatrix} up \\ down \end{pmatrix}_L$	3	2	$1/3$
$U_R = up_R$	3	1	$4/3$
$D_R = down_R$	3	1	$-2/3$
Leptons			
$L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$	1	2	-1
$N_R = \nu_R$?	1	1	0
$E_R = e_R$	1	1	-2

Quantum Numbers of Matter

- Quarks

triplets

$$Q_L = \begin{pmatrix} up \\ down \end{pmatrix}_L$$

$$U_R = up_R$$

$$D_R = down_R$$

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Quantum Numbers of Matter

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doublets

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doublets

singlets

V-A currents in weak interactions

- Leptons

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singlets

- Leptons

$$L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \begin{matrix} \frac{1}{2} \\ -\frac{1}{2} \end{matrix} \; T_3$$

$$N_R = \nu_R \;? \quad 0 \; T_3$$

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1	2	-1
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Quantum Numbers of Matter

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- Leptons

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$$N_R = \nu_R \ ?$$

$$E_R = e_R$$

$\frac{1}{2}$, $-\frac{1}{2}$: T_3

0, 0 : T_3

L_L	1	2	-1
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Electric charge

$$Q = T_3 + Y/2$$

Quarks – "the building blocks of the Universe"

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Charm came as surprise but completed the picture

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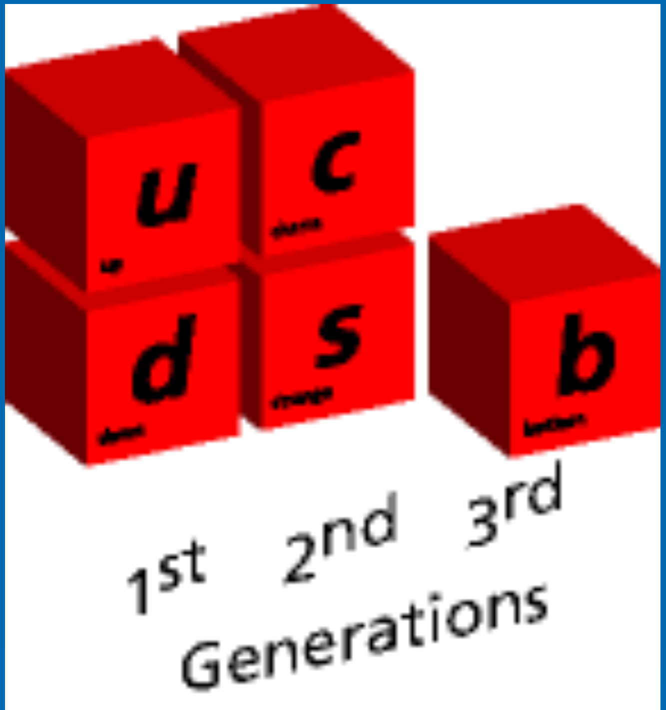

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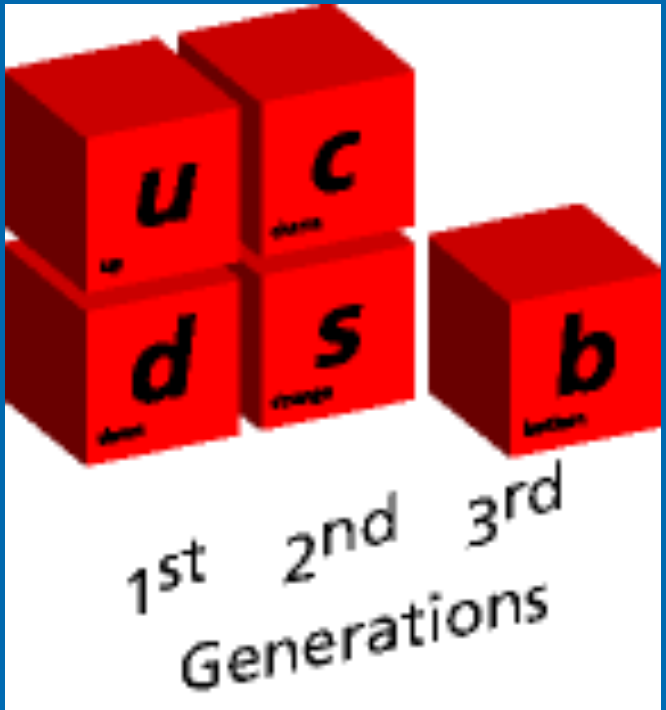
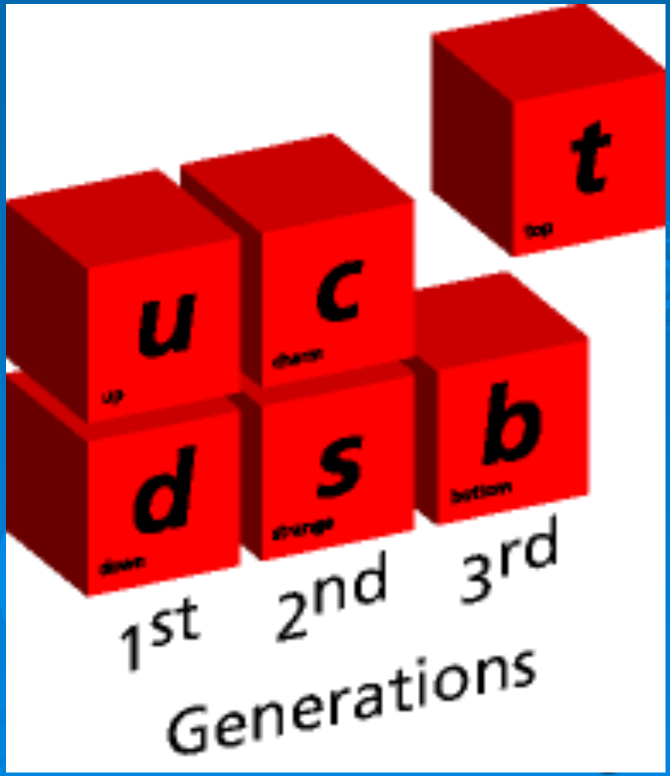


The number of quarks increased with discoveries of new particles and have reached 6



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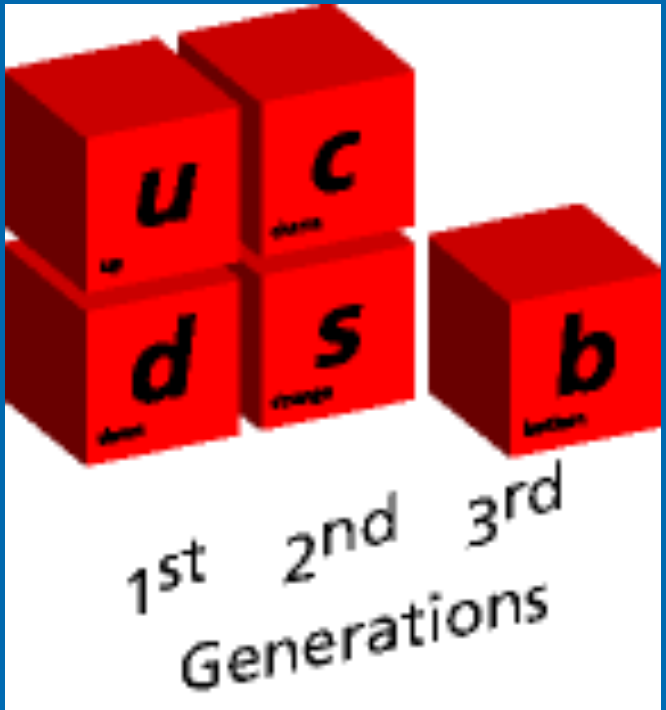

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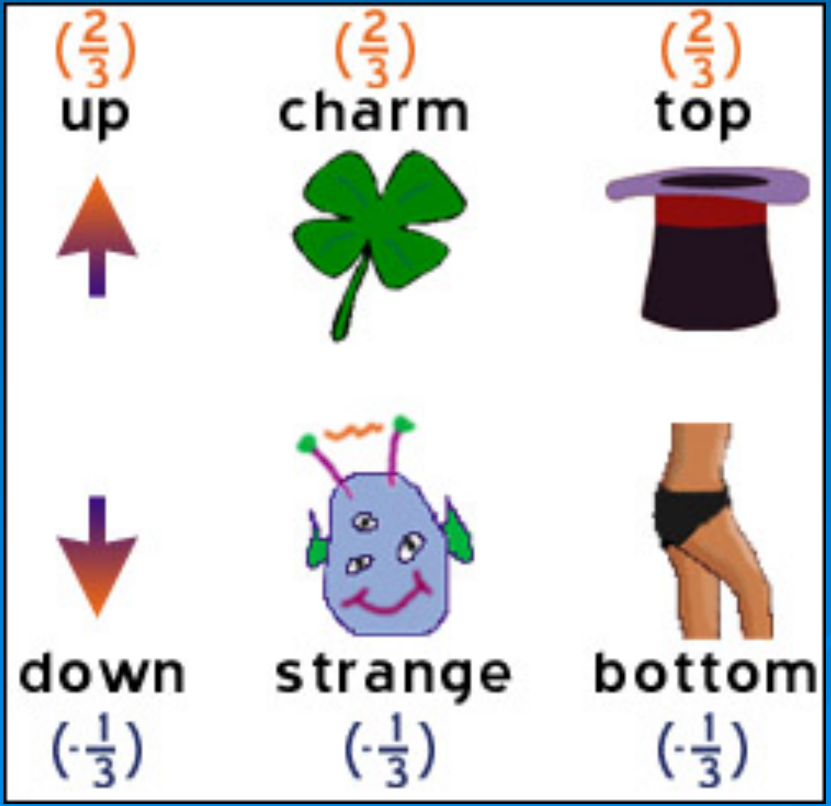
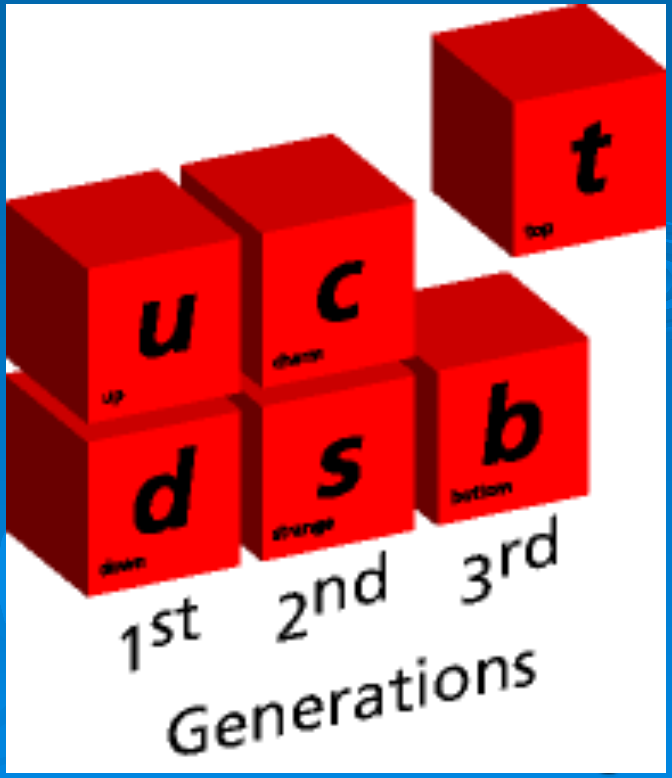
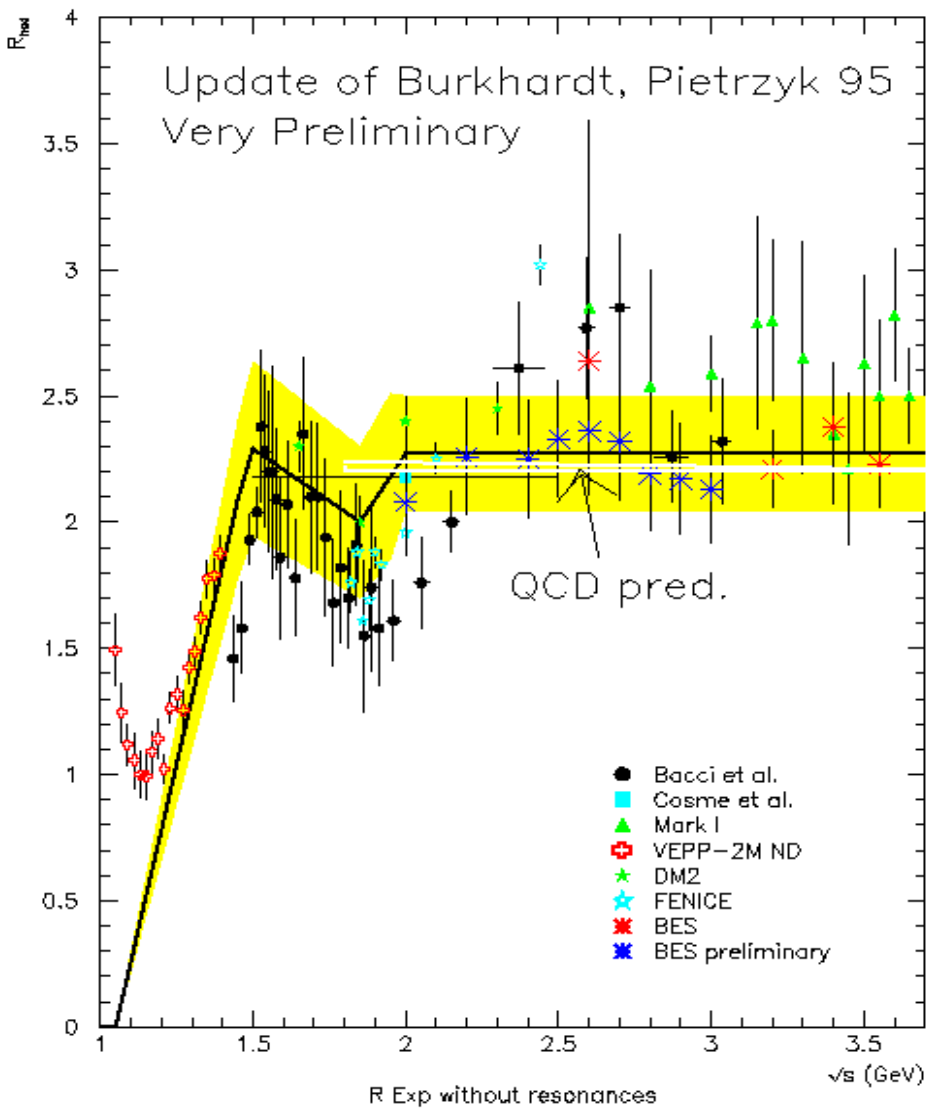


For unknown reasons Nature created 3 copies (generations) of quarks and leptons



The Number of Colours

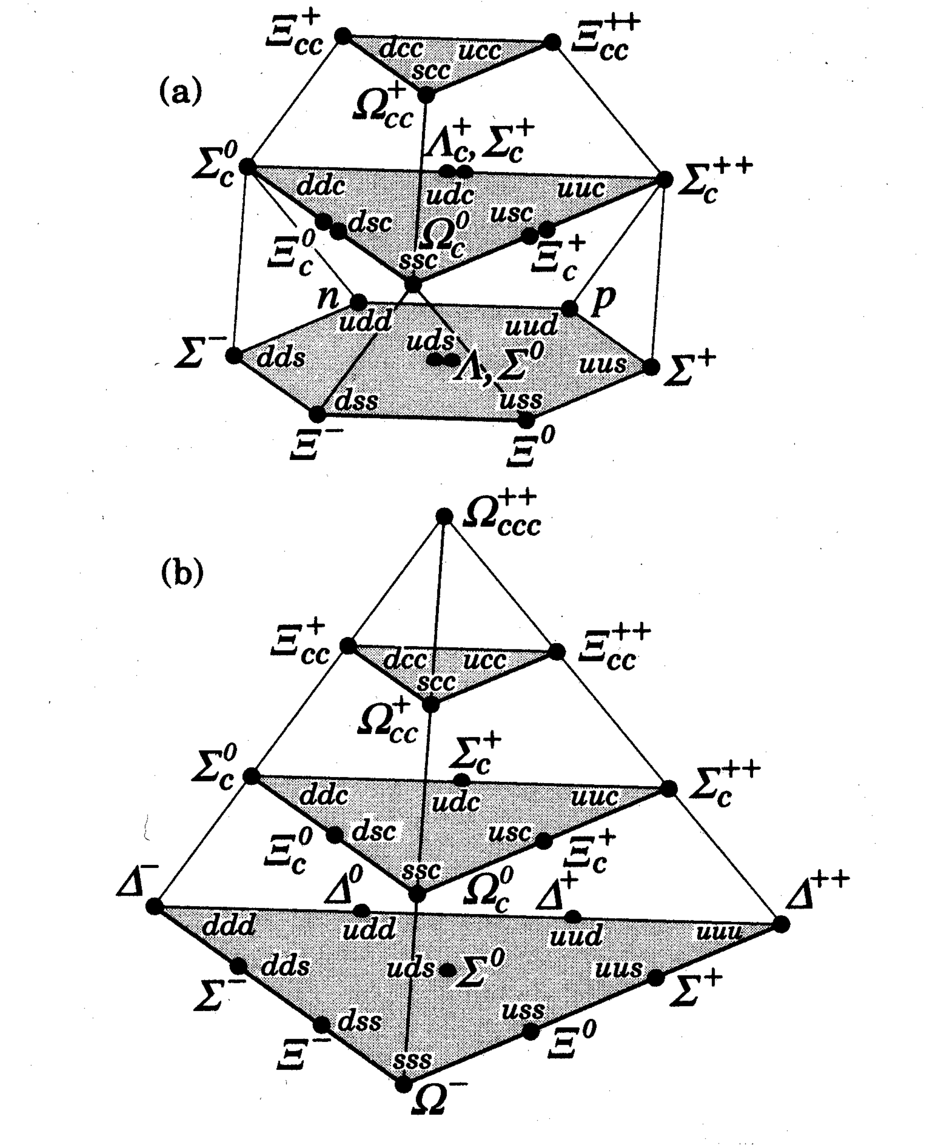


- The x-section of electron-positron annihilation into hadrons is proportional to the number of quark colours. The fit to experimental data at various colliders at different energies gives

$$N_c = 3.06 \pm 0.10$$

Quark's Colour

Baryons are "made" of quarks



$$\Delta^-(d\uparrow d\uparrow d\uparrow)$$

$$\Omega^-(s\uparrow s\uparrow s\uparrow)$$

$$\Delta^{++}(u\uparrow u\uparrow u\uparrow)$$

Quark's Colour

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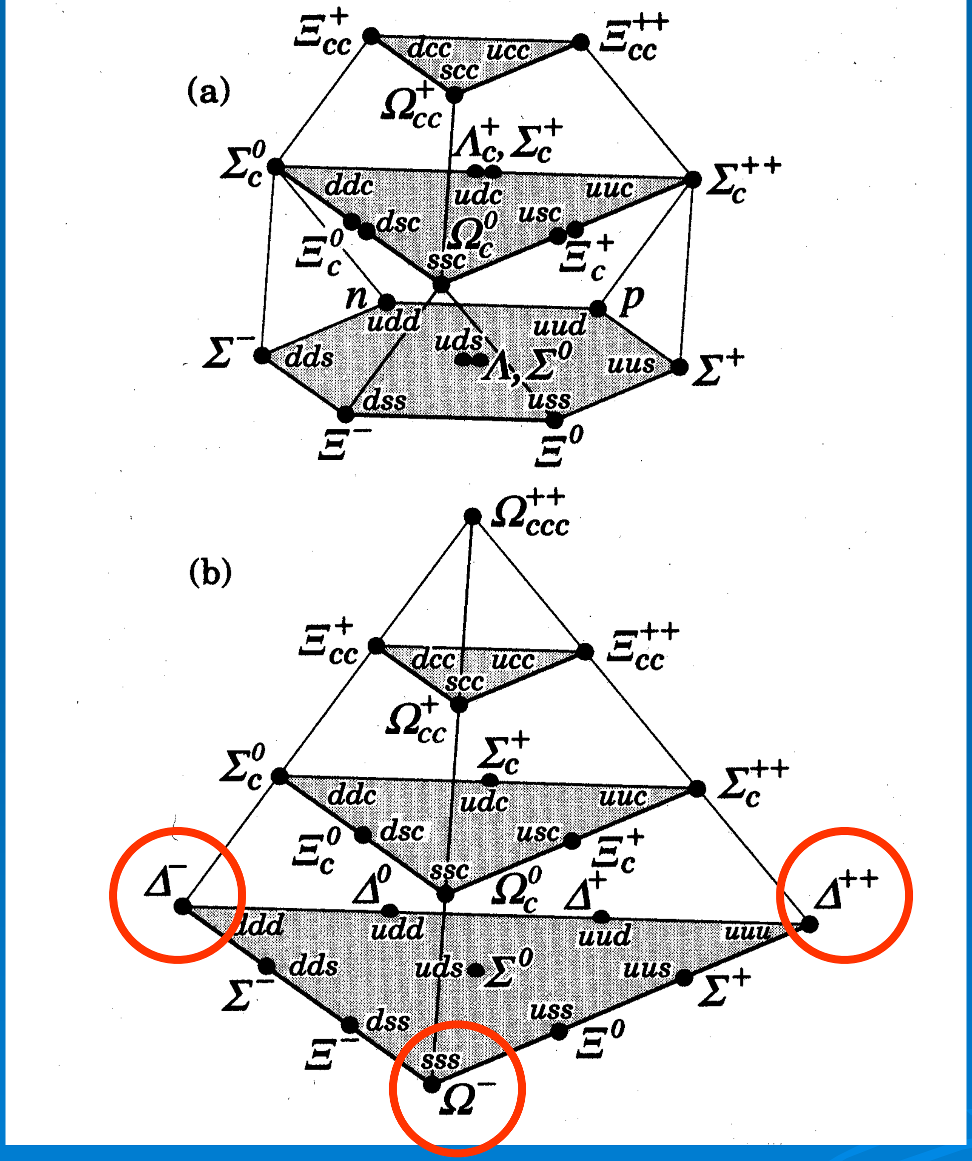

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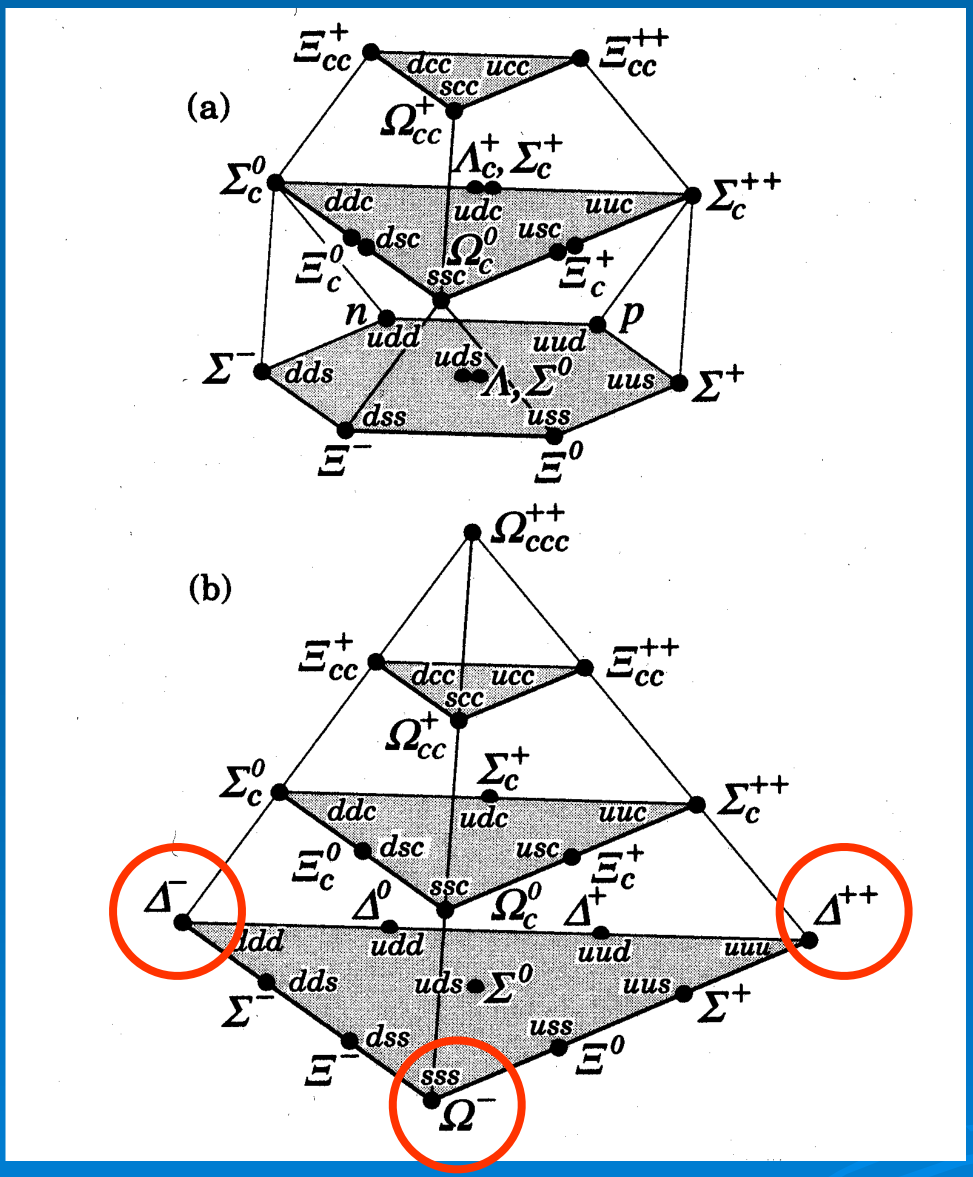

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To avoid Pauli principle veto one can antisymmetrize the wave function introducing a new quantum number - “colour”, so that

Quark’s Colour

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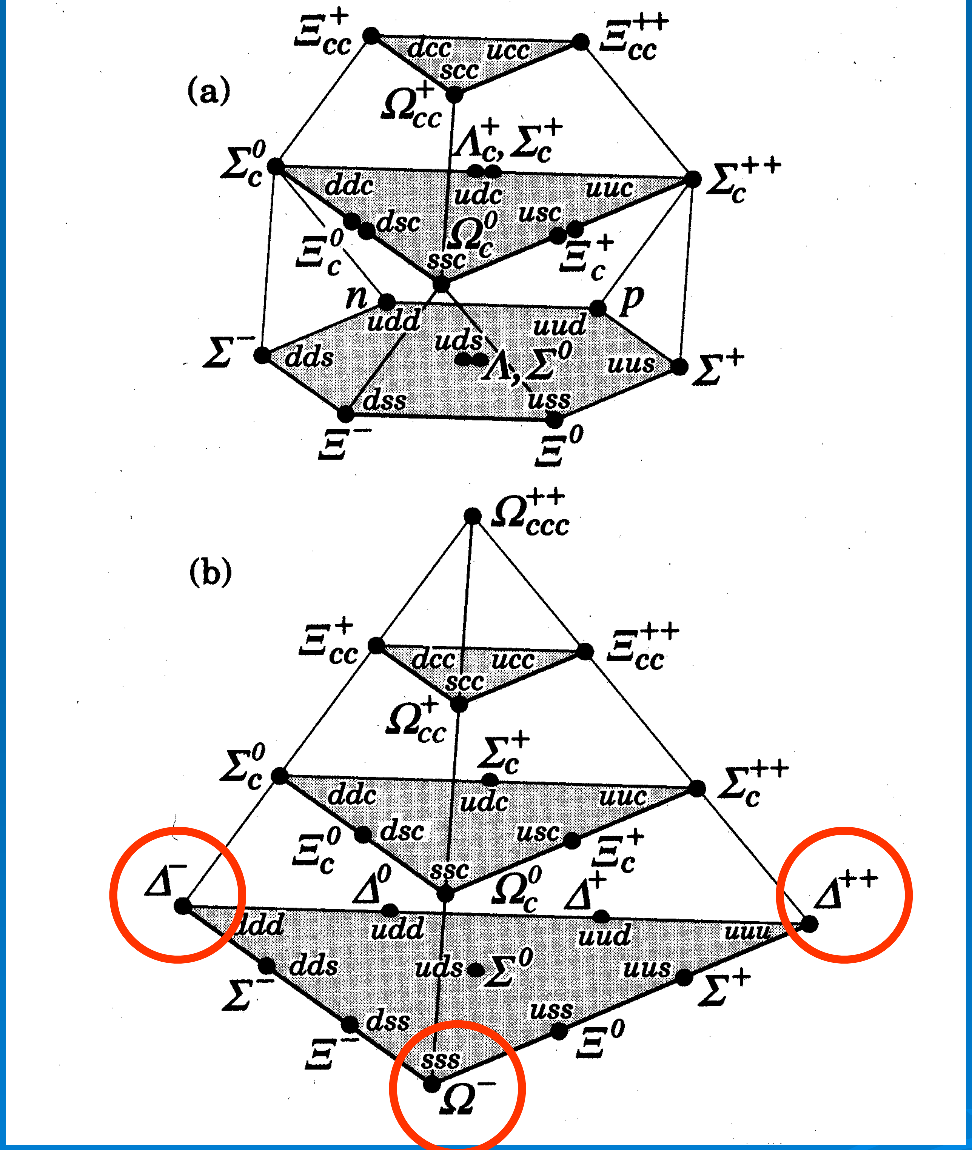

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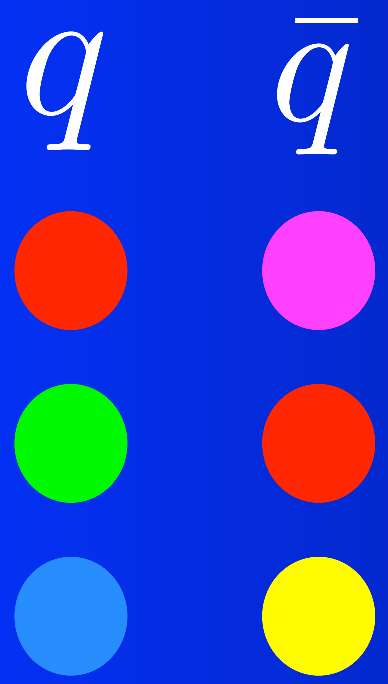
?

To avoid Pauli principle veto one can antisymmetrize the wave function introducing a new quantum number - “colour”, so that

$$\Delta^- = \epsilon^{ijk}(d_i\uparrow d_j\uparrow d_k\uparrow)$$

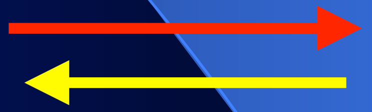
Colored quarks



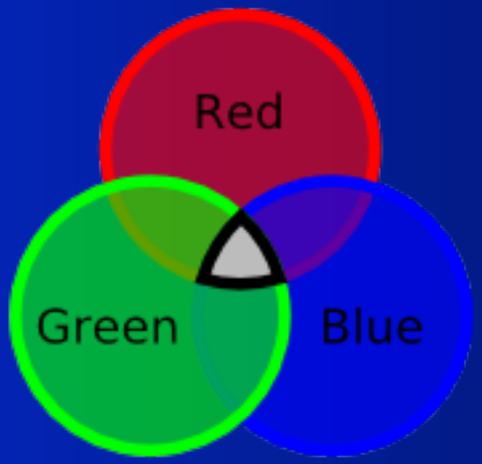
Each flavour of quarks can have three color charges: red, green, blue

Antiquarks have three anticolors: antipred - violet, antigreen - red, antiblue - yellow

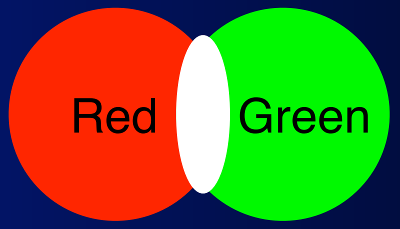
Gluons have eight colors:
red-antiblue, green-antired, …



All bound states of quqrks, baryons and mesons - colorless!



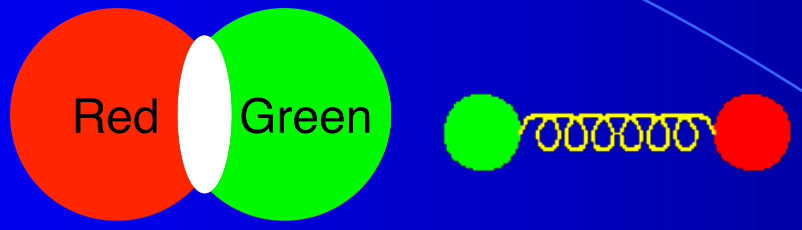
baryon



meson

Hypothesis of quark confinement

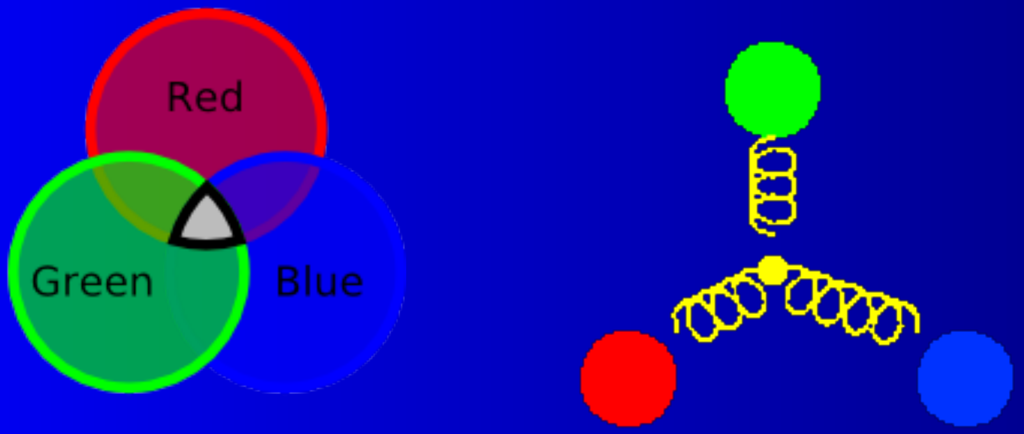
Quarks are confined inside hadrons due to interactions with gluons, which form strings stretched between quarks



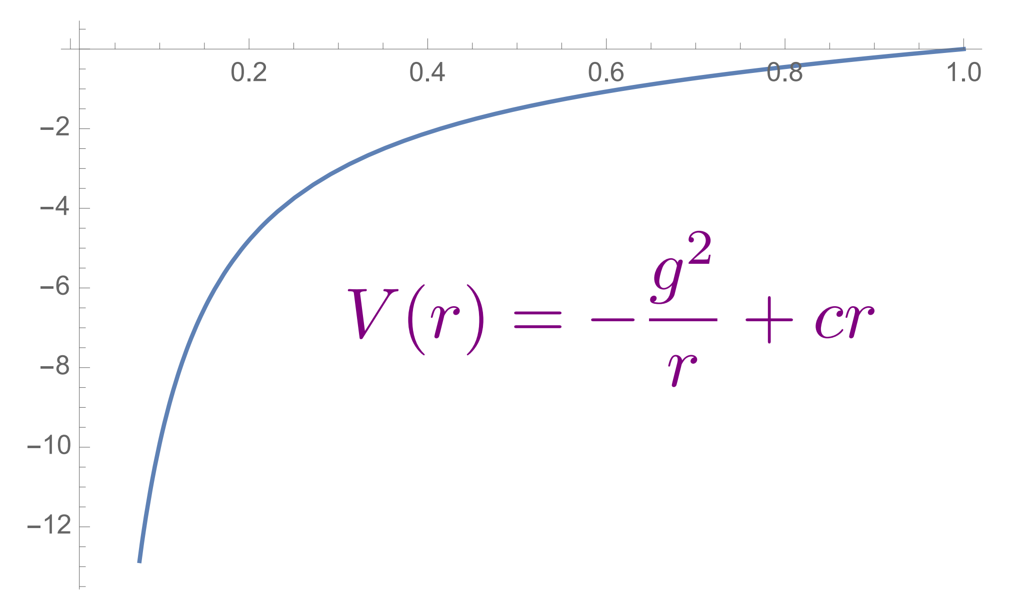
Meson

Break of a string

Creation of new quarks

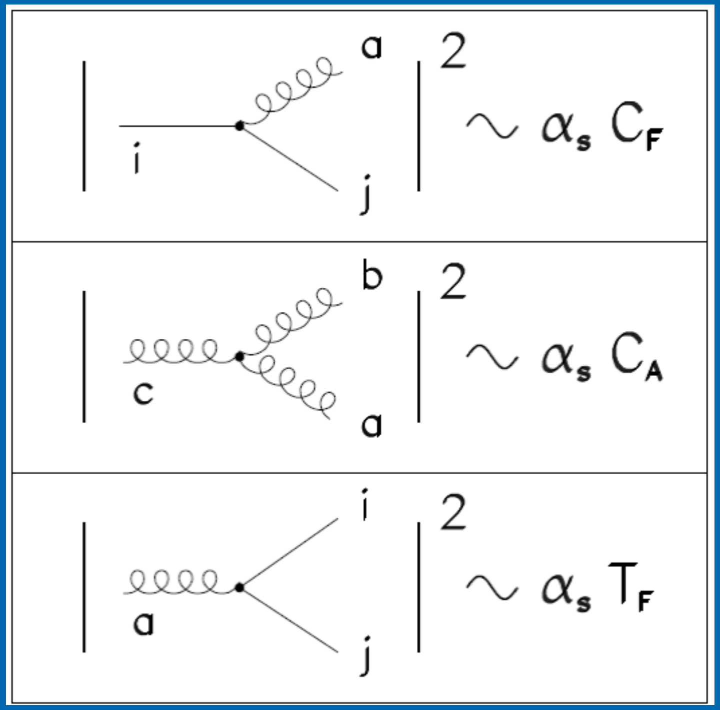


baryon



$$V(r) = -\frac{g^2}{r} + cr$$

The group structure of the SM



$$\sum_{a=1}^{N_A} \left(T^a T^{\dagger a}\right)_{ij} = \delta_{ij} C_F \quad , \quad \sum_{i,j=1}^{N_F} T^a_{ij} T^{\dagger b}_{ji} = \delta^{ab} T_F \quad , \quad \sum_{a,b=1}^{N_A} f^{abc} f^{*abd} = \delta^{cd} C_A$$

Casimir Operators

For SU(N)

$$C_A = N_C \quad , \quad C_F = \frac{N_C^2 - 1}{2N_C} \quad , \quad T_F = 1/2$$

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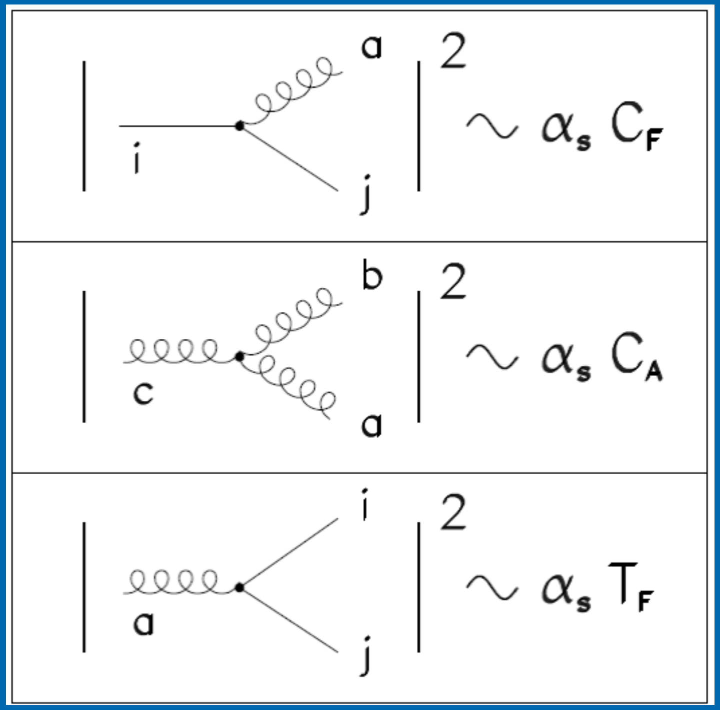

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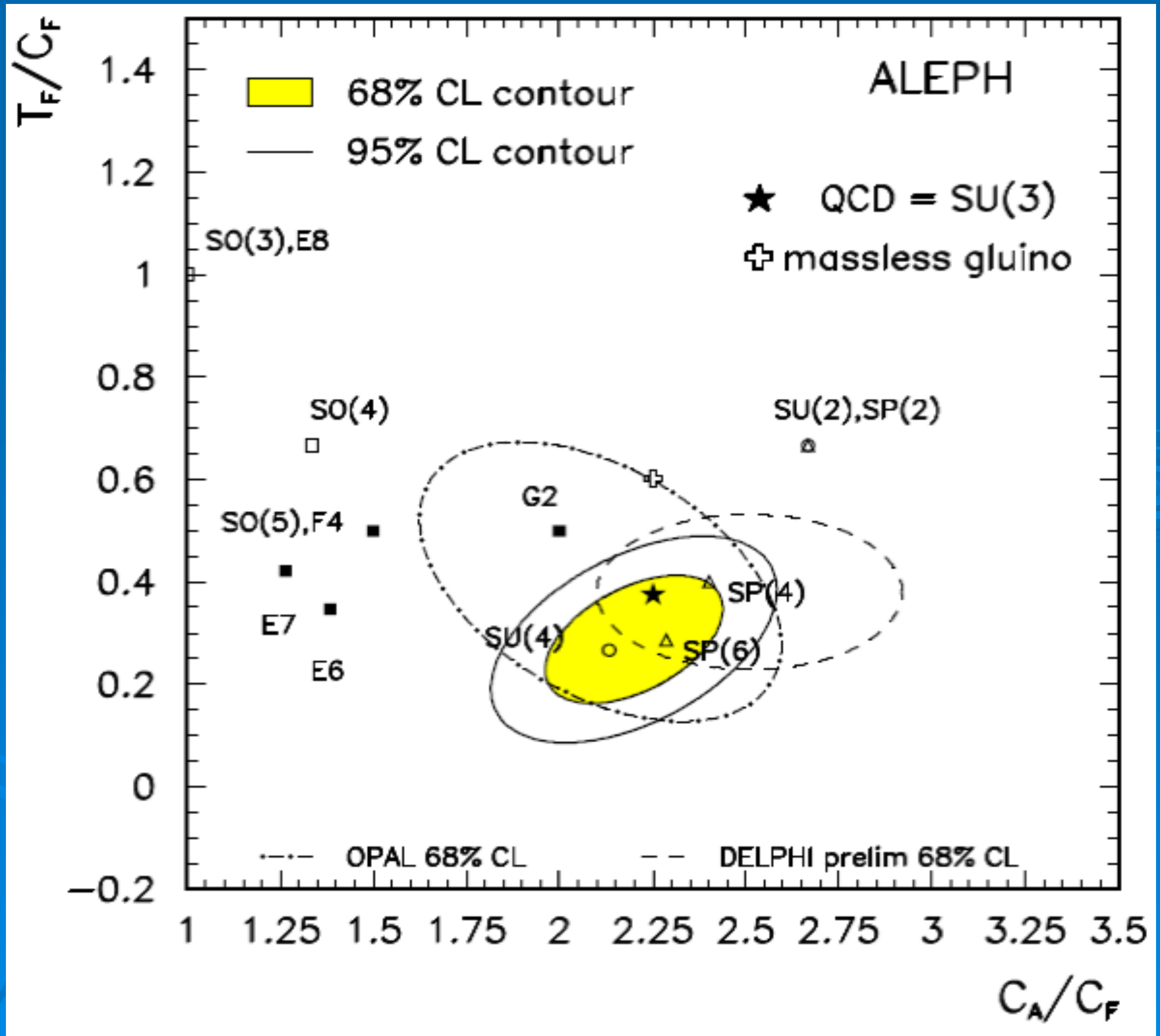
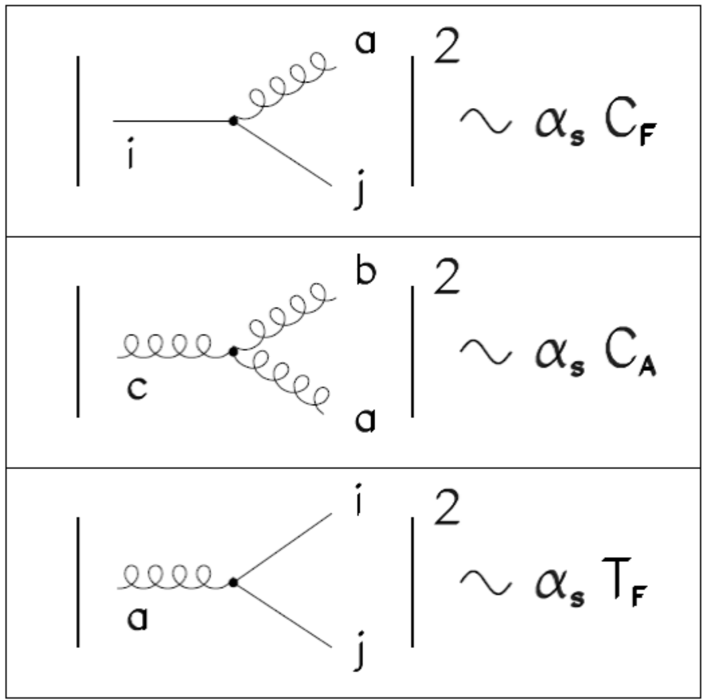


The group structure of the SM



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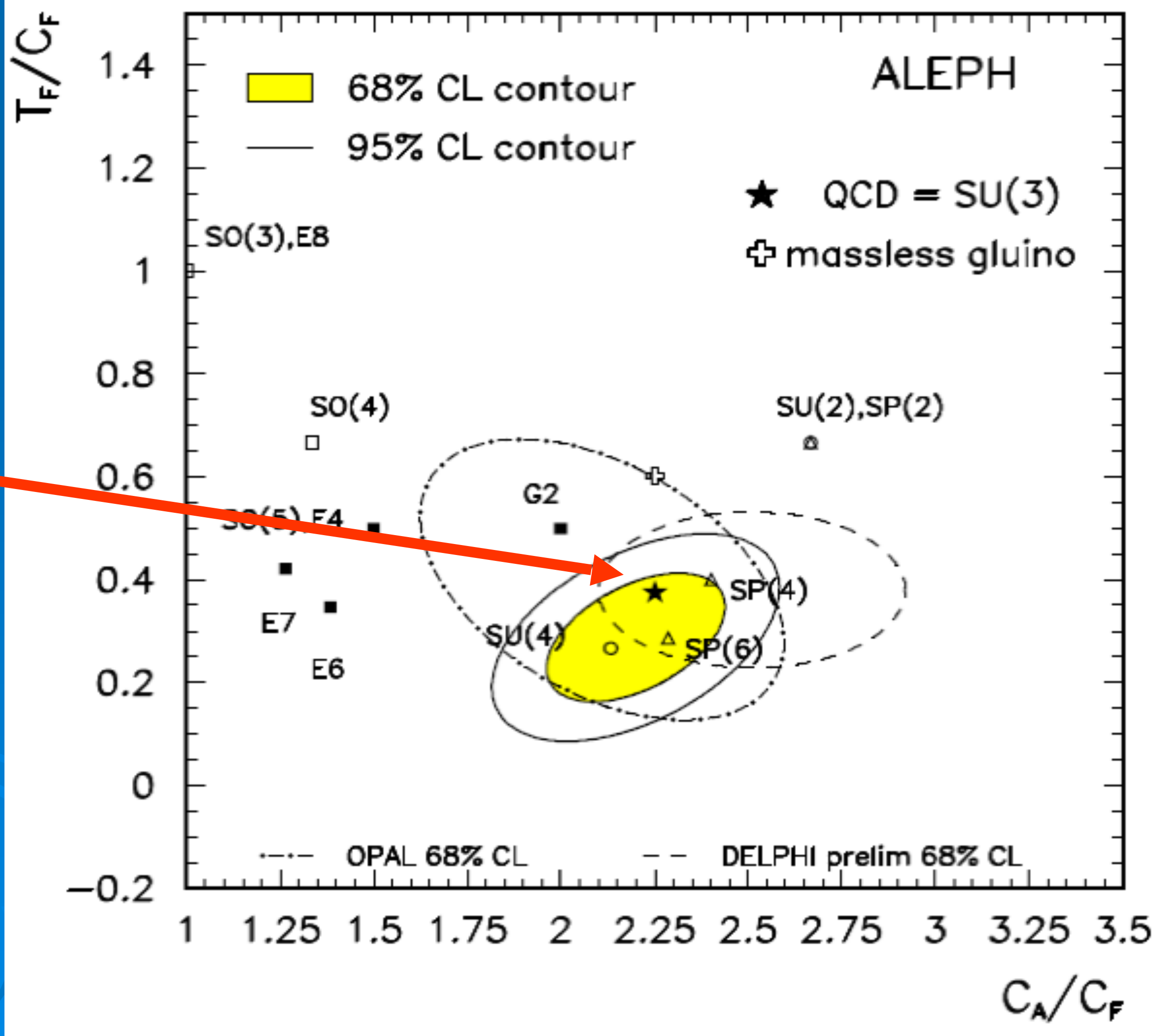
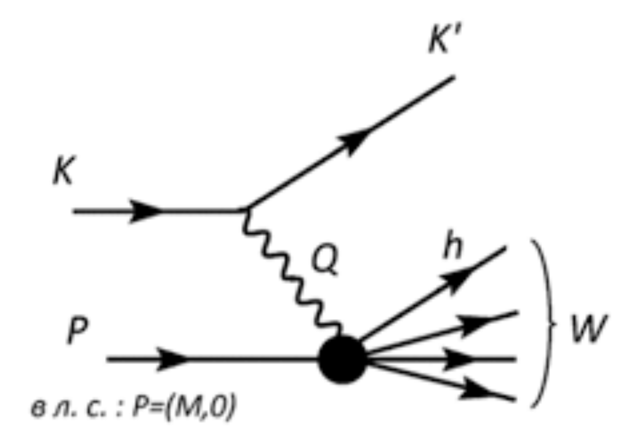
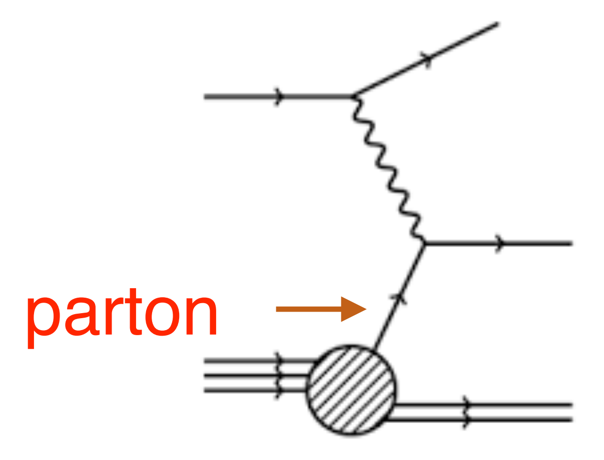
QCD analysis definitely singles out the SU(3) group as the symmetry group of strong interactions

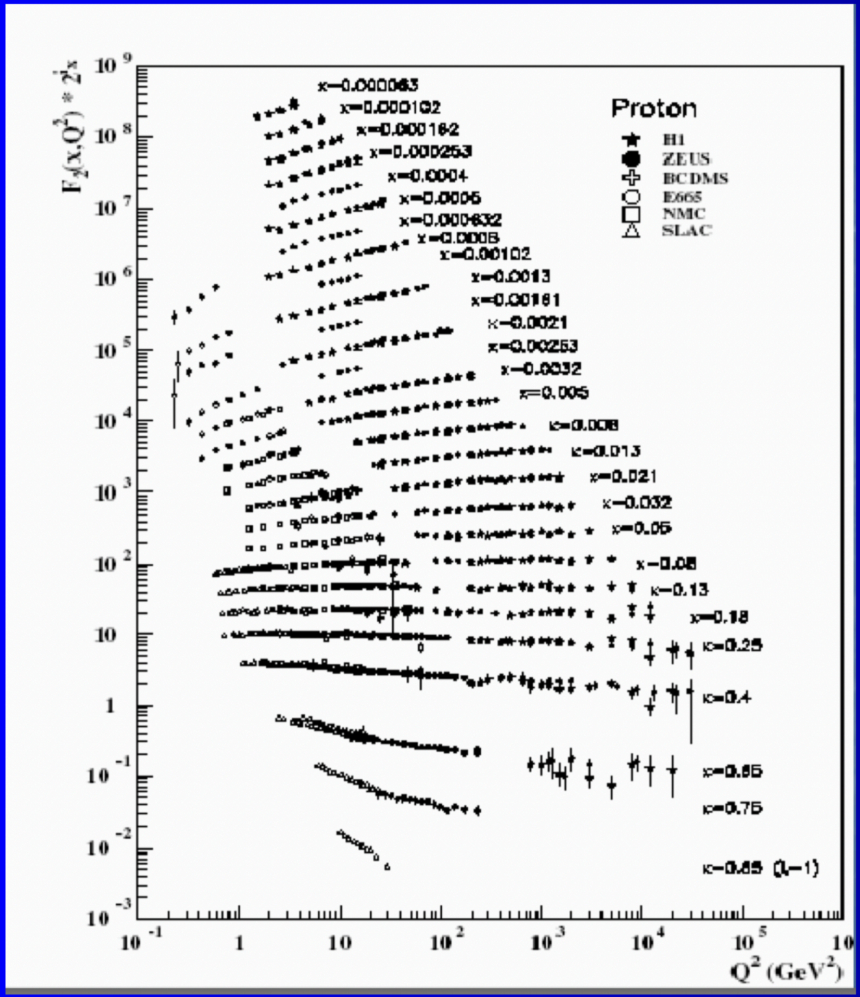


Scattering of electrons on protons
Parton Model



Q - transfer momentum from electron to proton



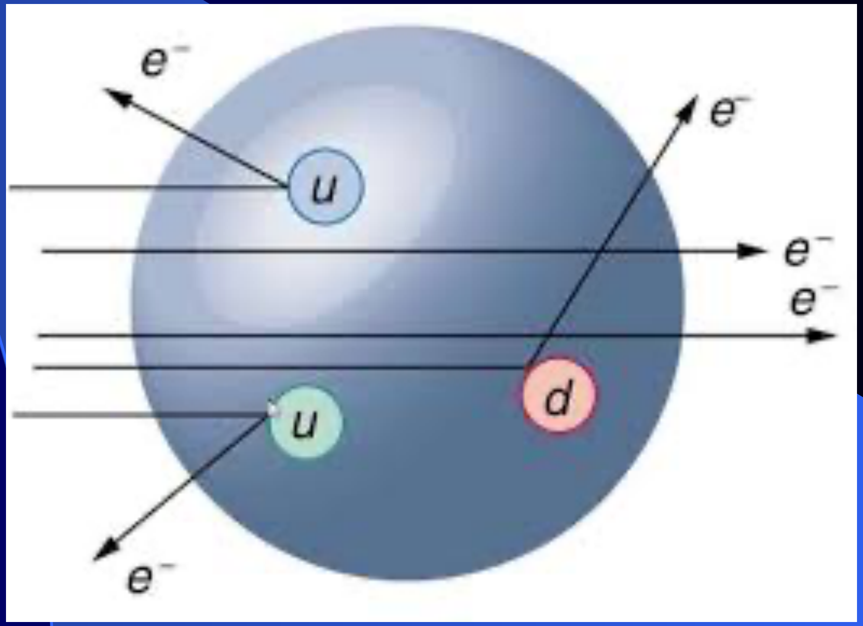


W - total energy of created hadrons

Indetification of partons as quarks

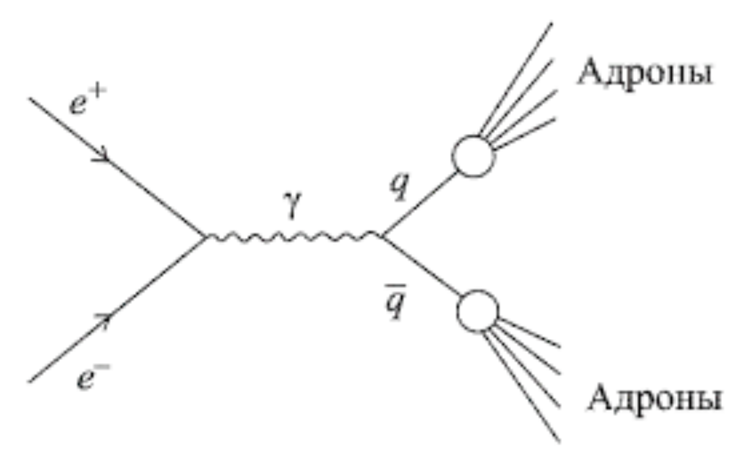
$$x = \frac{Q^2}{W^2}$$

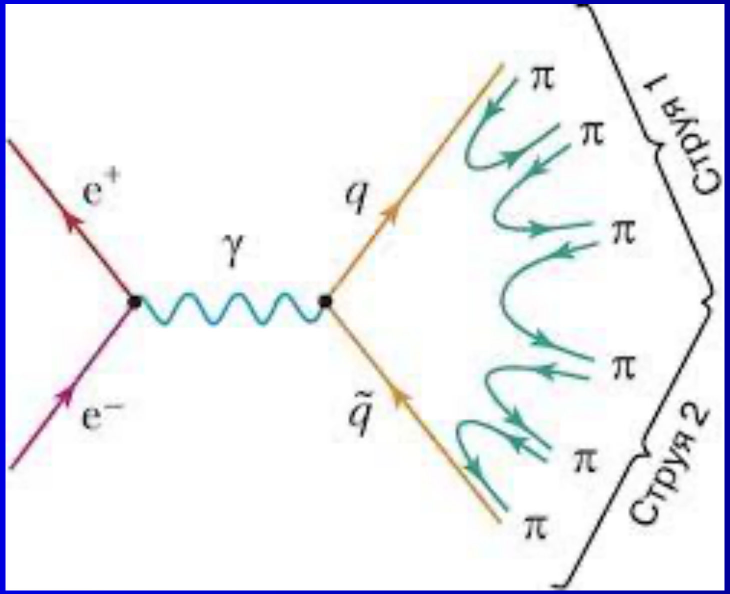
scaling



Creation of hadrons at colliders

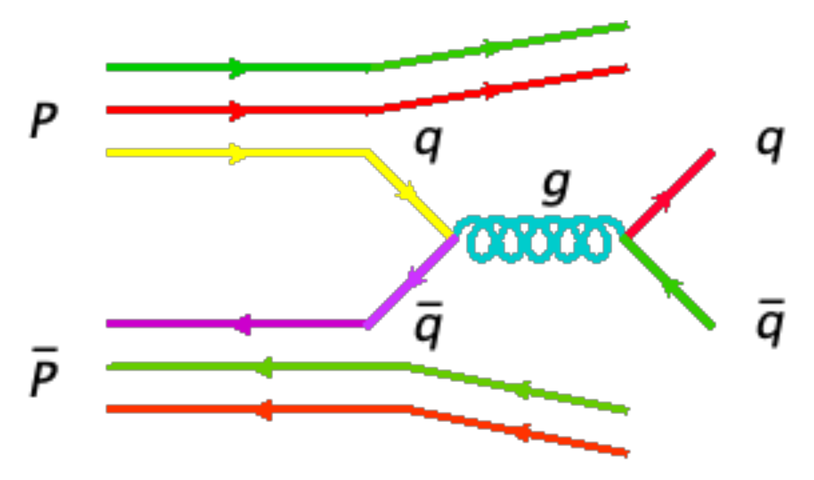
Electron-positron collider

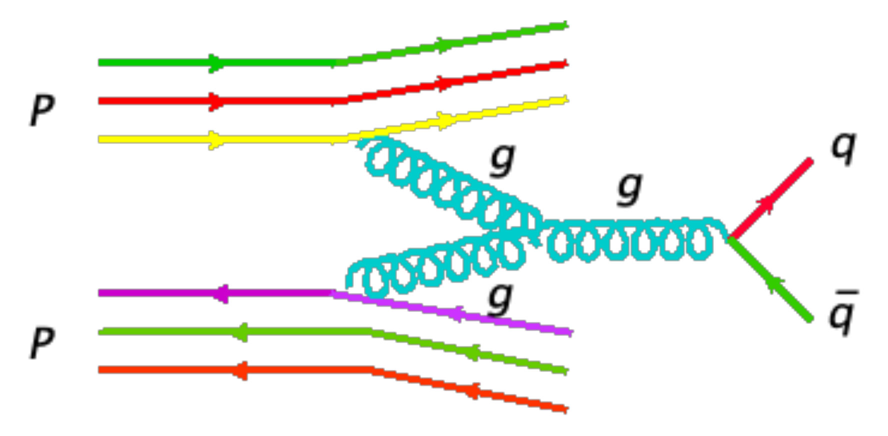




Hadrons form jets along the line of created quarks

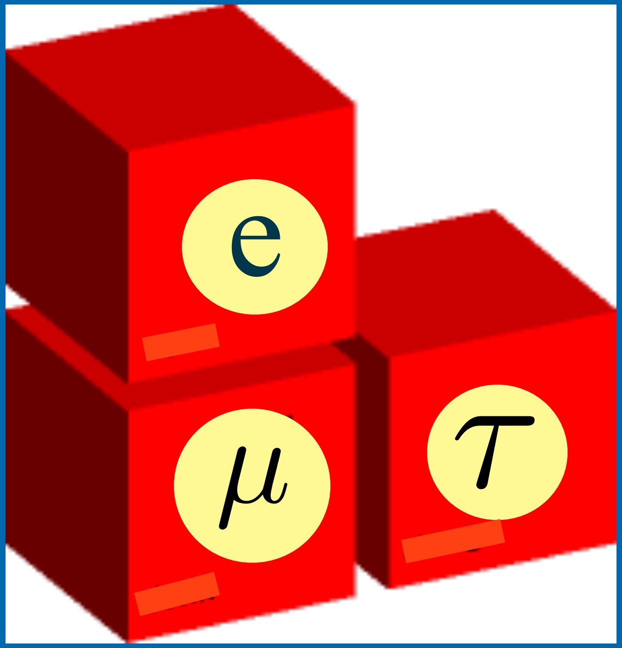
Proton collider

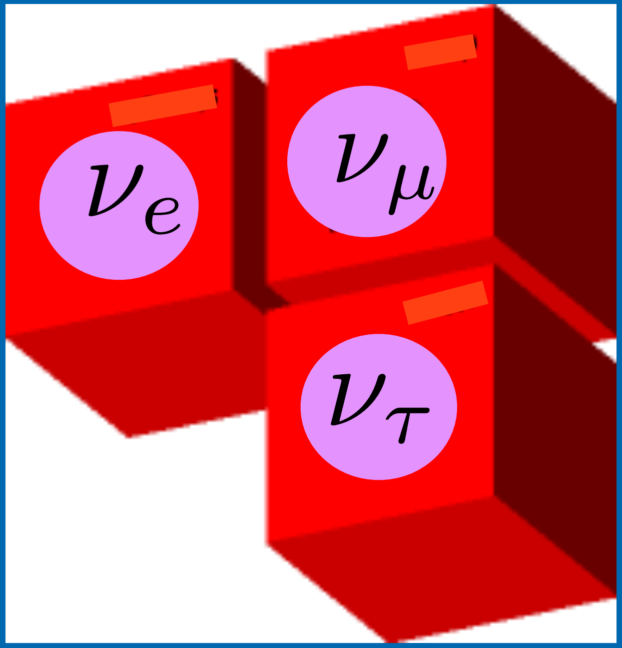




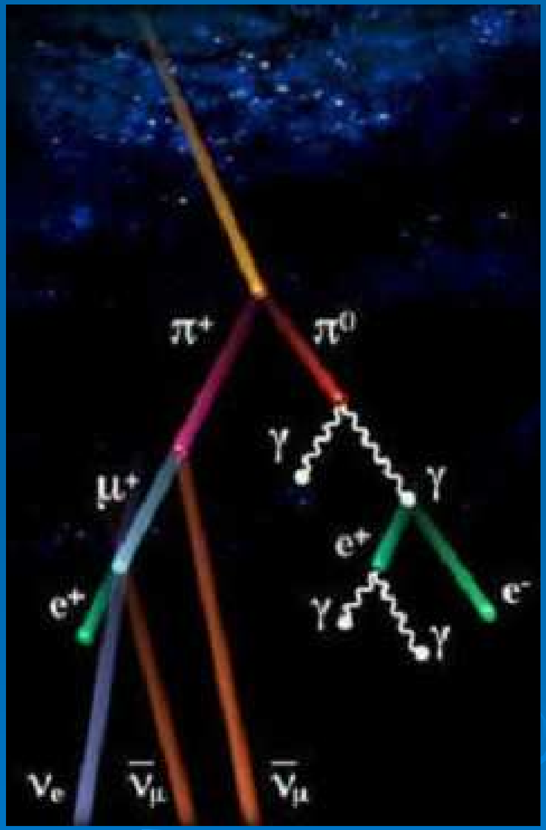
Quark subprocesses

Leptons are from λεπτόσ - light





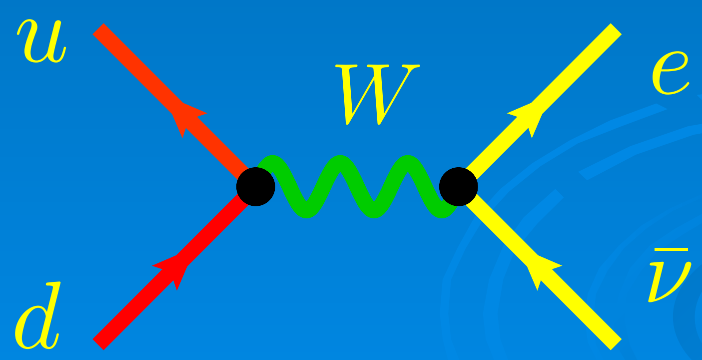
Muons are created from π-mesons decay in cosmic rays and decay into electrons and two neutrinos

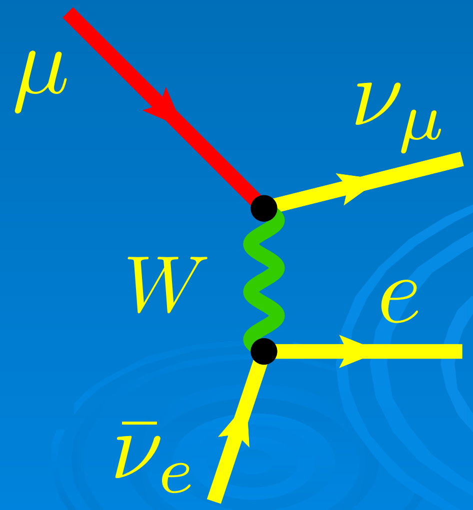


Electrons form atomic shells and define all chemistry of animated and unanimated nature

Neutrino are produced in hadron decay

$$n(udd) \to p(uud) + e + \bar{\nu}$$





Electro-weak sector of the SM

SU(2) x U(1)   versus   O(3)

3 gauge bosons   1 gauge boson   3 gauge bosons

Electro-weak sector of the SM

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After spontaneous symmetry breaking one has

Electro-weak sector of the SM

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After spontaneous symmetry breaking one has

3 massive gauge bosons
(W^+ , W^- , Z^0) and 1 massless (γ)

Electro-weak sector of the SM

SU(2) x U(1) versus O(3)

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⟺

2 massive gauge bosons
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3 gauge bosons

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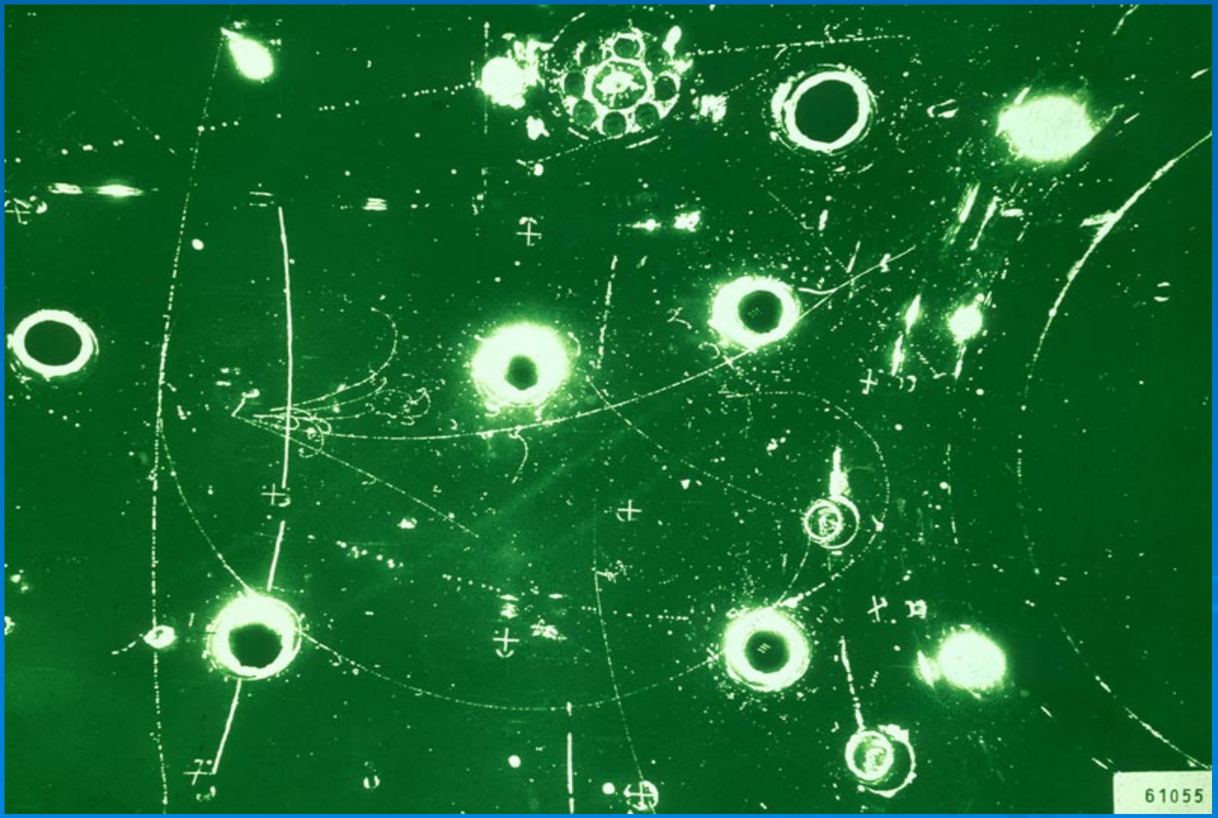
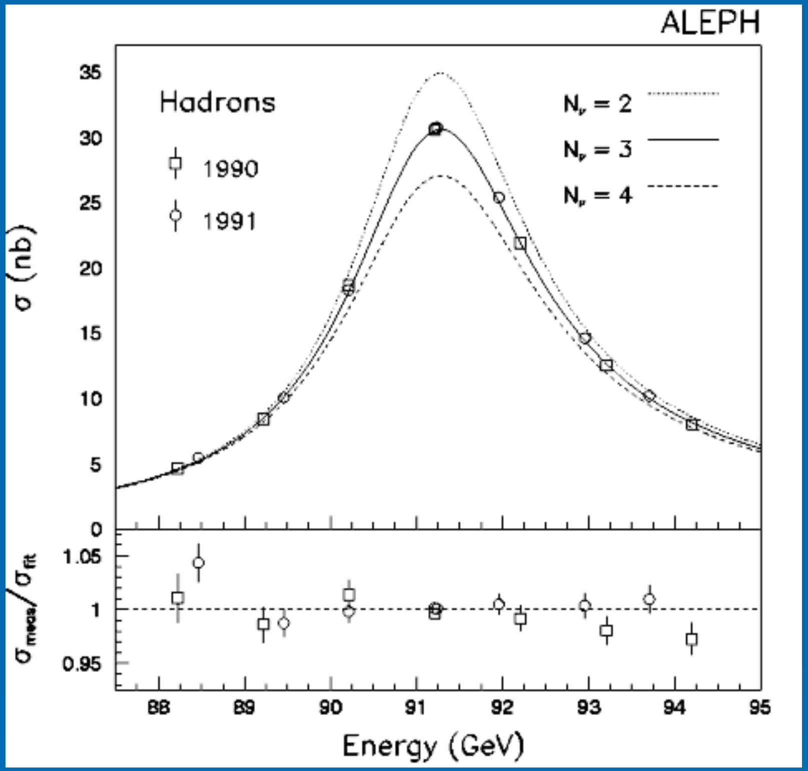


- Discovery of neutral currents was a crucial test of the gauge model of weak interactions at CERN in 1973

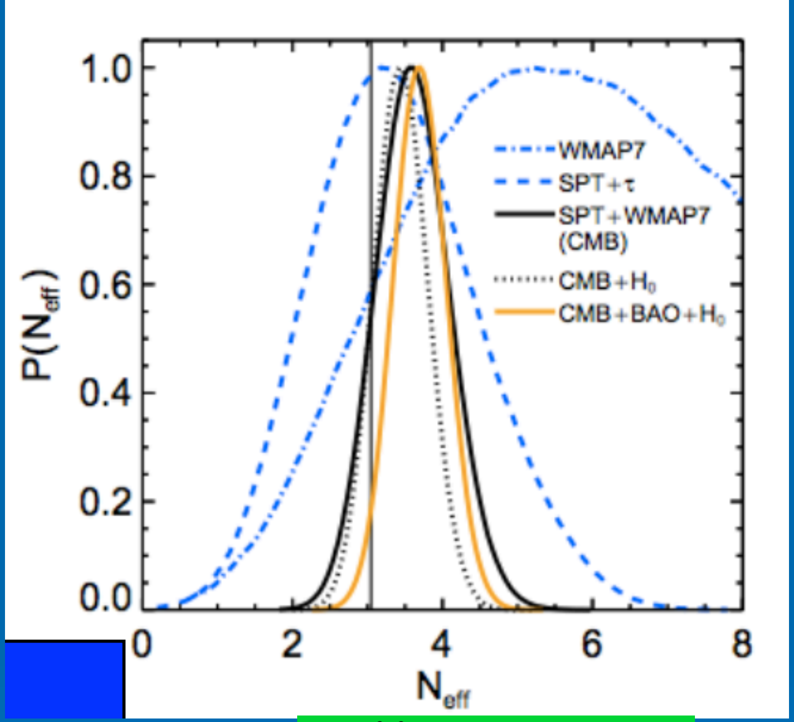
- The heavy photon gives the neutral current without flavour violation

The Number of Generations

- The width of the Z-boson (LEP)



- The CMB spectrum (Planck)



$N_\nu^{eff} < 3.30 \pm 0.27$

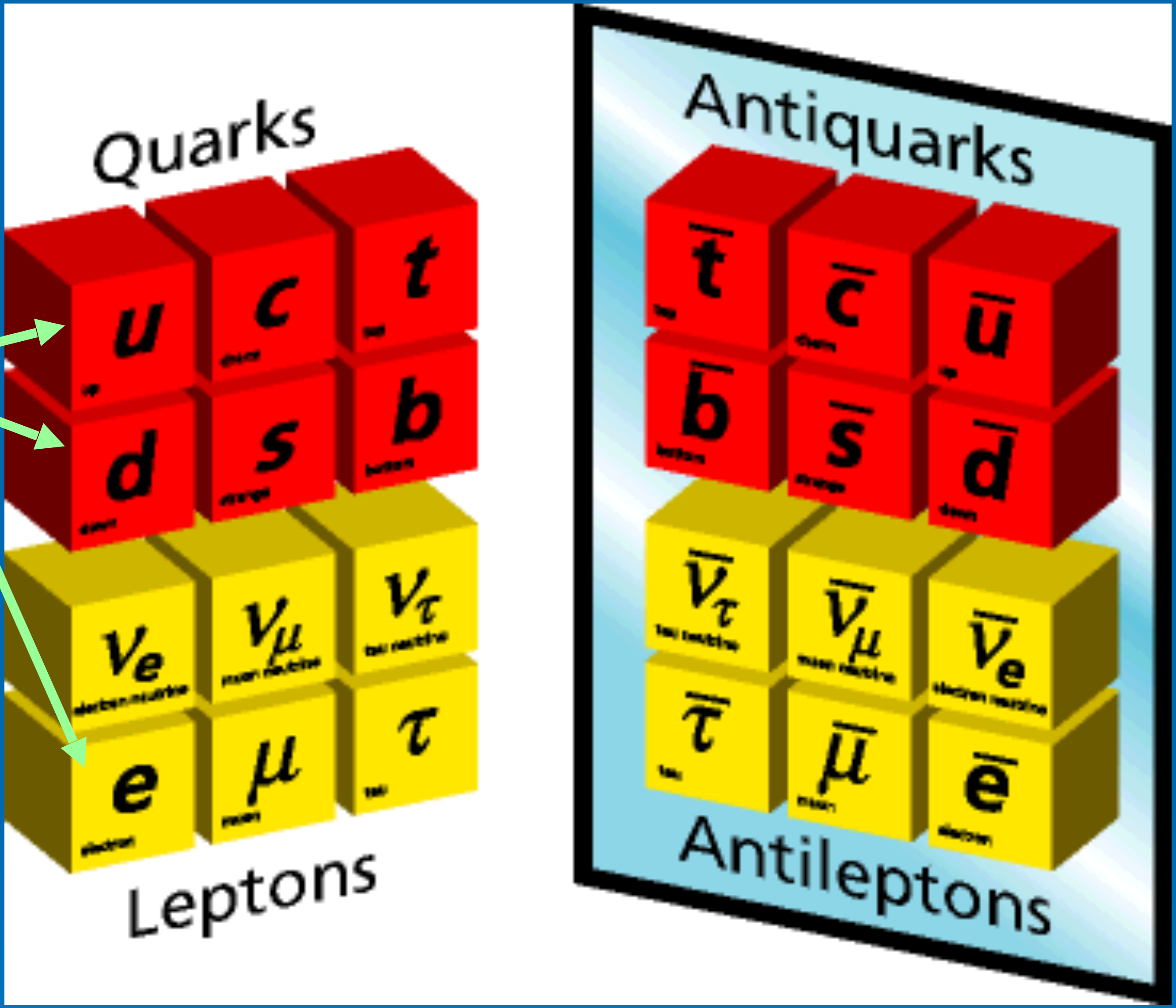
- ➢ Z-line shape obtained at LEP depends on the number of flavours and gives the number of (light) neutrinos or (generations) of the Standard Model
- ➢ The shape of the CMB temperature fluctuations give the number of active neutrinos or generations of the Standard Model assuming the quark-lepton symmetry

$$N_g = 2.982 \pm 0.013$$

Flavour Sector

Matter and Antimatter

The first generation is what we are made of



Antimatter was created together with matter during the “Big bang”

Antiparticles are created at accelerators in ensemble with particles but the visible Universe does not contain antimatter

Interactions in the SM (Forces)

SU(3)

SU(2)

U(1)

The Higgs boson

Interactions in the SM (Forces)

SU(3)

- Strong Interactioins between quarks via gluons exchange
  Bound hadrons together, lead to nuclear forces inside the nucleus

SU(2)

- Weak Interactioins between quarks and leptons
  via W and Z exchage
  Responsible for decays of hadrons and leptons

U(1)

- Electromagnetic Interactioins between quarks and leptons via photon exchange
  Responsible for all macro forcers in Nature

H

The Higgs boson

- Yukawa Interactioins between quarks and leptons and the Higgs boson
  Responsible for creation of masses of quarks and leptons

Electromagnetic Interactions

1. Performed via exchange of quanta of electromagnetic field - photon
2. Electromagnetic field is described by Maxwell equations

$$\partial_\mu F_{\mu\nu} + j_\mu = 0$$

$$\partial_\mu \tilde{F}_{\mu\nu} = 0$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\partial_t \vec{E} - \vec{\nabla} \times \vec{B} = -\vec{j}$$

$$\vec{\nabla}\vec{E} = \rho$$

$$\partial_t \vec{B} + \vec{\nabla} \times \vec{E} = 0$$

$$\vec{\nabla}\vec{B} = 0$$

3. Charged particles (quarks and leptons) obey Dirac equation

$$(\hat{\partial} - m - e\hat{A})\psi = 0 \qquad \hat{\partial} = \gamma^\mu \partial_\mu$$

Strong Interactions

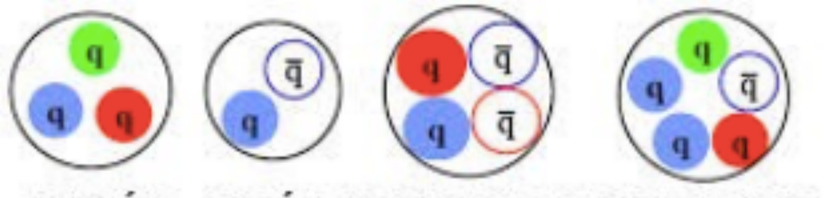
1. Performed via exchange of quanta of gluon (color) field -gluon
2. Gluon field is described by Yang-Mills equations (generalization of Maxwell eqs)

$$D_\mu F_{\mu\nu} + j_\mu = 0$$

$$D_\mu = \partial_\mu + gA_\mu$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu]$$

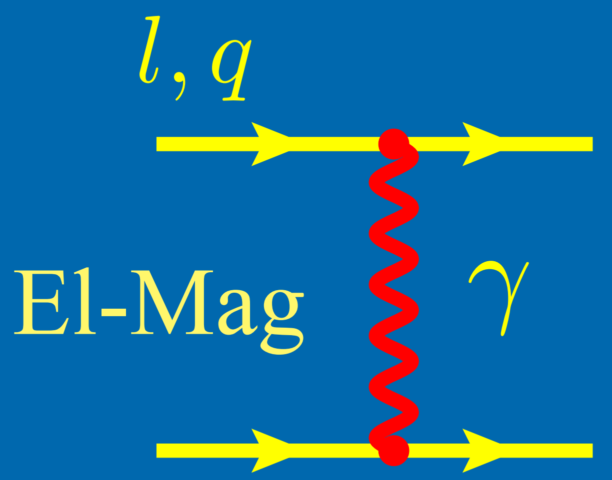
3. The main difference from Electrodynamics is that gluons carry color charge and interact with each other
4. Postulate of confinement: quarks and gluons cannot be observed in free state, only «colorless» objects are observed
5. Colorless objects appear in two combinations: $M = \bar{q}q$ mesons and baryons $B = qqq$
6. However, exotic hadrons are proved to exist

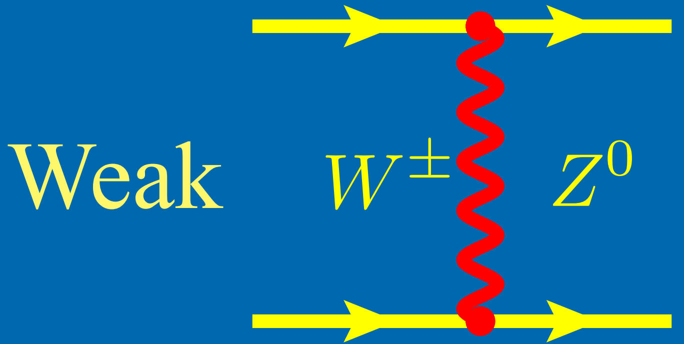


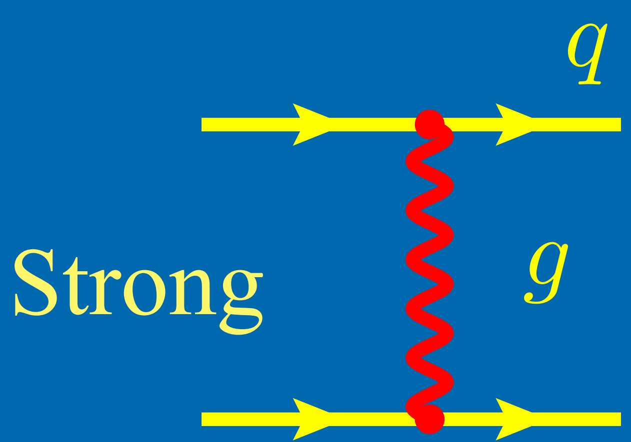
Weak Interactions

1. Performed via exchange of intermediate weak bosons W, Z
2. The fields W and Z are described by Yang-Mills eqs (generalization of Maxwell eqs)
3. The fields W, Z carry weak charge (isospin) and interact with each other
4. W, Z can be observed in free state and are massive
5. Weak interactions involve quarks and leptons
6. Weak interactions are short-range $R \sim 1/M_W$
7. Weak interactions describe decay of particles

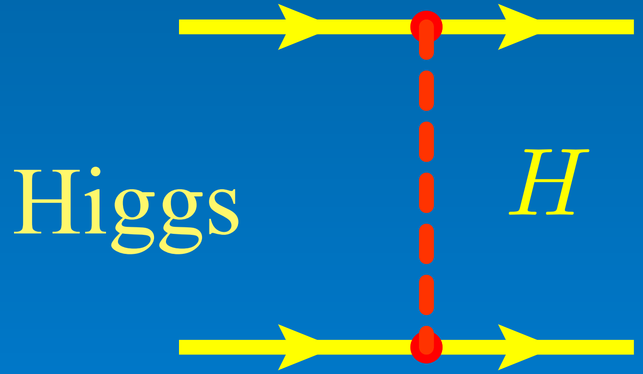
Five fundamental forces of Nature

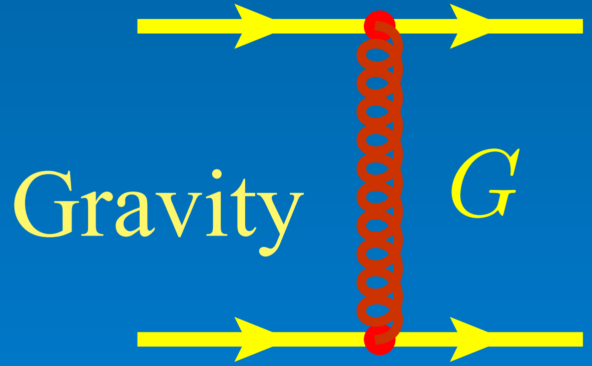






$$V(r) = -\frac{e_1 e_2}{r} \qquad V(r) = -\frac{g^2}{r} e^{-M_W r} \qquad V(r) = -\frac{g_s^2}{r} + br$$





Spin

$\gamma \; W^\pm Z^0 \; g$ =1

H =0

G =2

$$V(r) = -\frac{m_1 m_2}{v_H^2 r} e^{-M_H r} \qquad V(r) = -\frac{m_1 m_2}{M_{PL}^2 r}$$

Gauge Invariance

Gauge transformation $\psi_i(x) \rightarrow U_{ij}(x)\psi_j(x) = exp[i\alpha^a(x)T^a_{ij}]\psi_j(x)$

$\uparrow$ $\uparrow$ $\uparrow$

$\bar{\psi}_i(x) \rightarrow \bar{\psi}_j U^+_{j1}(x)$ matrix $U^+U = 1$ parameter matrix

$a = 1, 2, ..., N$

Gauge Invariance

Gauge transformation $\psi_i(x) \rightarrow \underset{\uparrow}{U_{ij}}(x)\psi_j(x) = exp[i\underset{\uparrow}{\alpha^a}(x)\underset{\uparrow}{T^a_{ij}}]\psi_j(x)$

$\bar{\psi}_i(x) \rightarrow \bar{\psi}_j U^+_{j1}(x)$ matrix $U^+U = 1$ parameter matrix

$a = 1, 2, ..., N$

Fermion Kinetic term

$$i\bar{\psi}(x)\gamma^\mu\partial_\mu\psi(x) \rightarrow i\bar{\psi}(x)U^+(x)\gamma^\mu\partial_\mu(U(x)\psi(x))$$

$$= i\bar{\psi}(x)\gamma^\mu\partial_\mu\psi(x) + i\bar{\psi}(x)\gamma^\mu U^+(x)\partial_\mu U(x)\psi(x)$$

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Covariant derivative $\partial_\mu \rightarrow D_\mu = \partial_\mu I + gA^a_\mu T^a \equiv \partial_\mu I + gA_\mu$

Gauge field

Gauge Invariance

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$$\bar{\psi}_i(x) \rightarrow \bar{\psi}_j U^+_{j1}(x)$$

matrix $U^+U = 1$

parameter matrix

$a = 1, 2, \ldots, N$

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Gauge field

Gauge invariant kinetic term →

$$\boxed{i\bar{\psi}(x)\gamma^\mu D_\mu\psi(x)}$$

Gauge Invariance

$$\hat{A}_\mu \to U^+(x)\hat{A}_\mu U(x) + gU^+(x)\partial_\mu U(x)$$

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$$\hat{A}_\mu \to U^+(x)\hat{A}_\mu U(x) + gU^+(x)\partial_\mu U(x)$$

$$[D_\mu, D_\nu] = G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu A_\nu]$$

$$G_{\mu\nu} \to U^+(x)G_{\mu\nu}U(x)$$

Gauge Invariance

Gauge field transformation

$$\hat{A}_\mu \to U^+(x)\hat{A}_\mu U(x) + gU^+(x)\partial_\mu U(x)$$

Field strength tenzor

$$[D_\mu, D_\nu] = G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu A_\nu]$$

$$G_{\mu\nu} \to U^+(x)G_{\mu\nu}U(x)$$

Gauge field kinetic term

$$\boxed{-\frac{1}{4}TrG_{\mu\nu}G^{\mu\nu}}$$

Contains self interaction of the gauge fields!

Fermion Masses in the SM

Direct mass terms are forbidden due to SU(2)$_L$ invariance !

Dirac Spinors left right Dirac conjugated Charge conjugated

$$\psi \, , \; \psi_L = \frac{1-\gamma^5}{2}\psi \, , \; \psi_R = \frac{1+\gamma^5}{2}\psi \;, \overline{\psi} = \psi^+\gamma^0, \; \psi^c = C\gamma^0\psi = i\gamma^2\psi^*$$

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Lorenz invariant Mass terms

$$\bar{\psi}_L\psi_R \quad + \quad \bar{\psi}_R\psi_L$$

SU(2) doublet SU(2) singlet

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Lorenz invariant Mass terms

SU$_L$(2)

$$\cancel{\bar{\psi}_L\psi_R} + \cancel{\bar{\psi}_R\psi_L}$$

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Lorenz invariant Mass terms

SU$_L$(2)

$$\cancel{\bar{\psi}_L\psi_R} + \cancel{\bar{\psi}_R\psi_L} \qquad \bar{\psi}_L\psi_L = \bar{\psi}_R\psi_R = 0$$

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SU(2) doublet SU(2) singlet

$$\bar{\psi}^c_L\psi_L + \bar{\psi}_L\psi^c_L \qquad \bar{\psi}^c_R\psi_R + \bar{\psi}_R\psi^c_R$$

Fermion Masses in the SM

Direct mass terms are forbidden due to $SU(2)_L$ invariance !

Dirac Spinors

left

right

Dirac conjugated

Charge conjugated

$$\psi,\ \psi_L = \frac{1-\gamma^5}{2}\psi,\ \psi_R = \frac{1+\gamma^5}{2}\psi\ ,\bar{\psi} = \psi^+\gamma^0,\ \psi^c = C\gamma^0\psi = i\gamma^2\psi^*$$

Lorenz invariant Mass terms

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SU(2) doublet

SU(2) singlet

$SU_L(2)$ & $U_Y(1)$

$U_Y(1)$

$$\cancel{\bar{\psi}^c_L\psi_L + \bar{\psi}_L\psi^c_L} \qquad \cancel{\bar{\psi}^c_R\psi_R + \bar{\psi}_R\psi^c_R}$$

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Direct mass terms are forbidden due to $SU(2)_L$ invariance !

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$SU_L(2)$ & $U_Y(1)$

$$\cancel{\overline{\psi}^c_L\psi_L + \overline{\psi}_L\psi^c_L}$$

$U_Y(1)$

$$\cancel{\overline{\psi}^c_R\psi_R + \overline{\psi}_R\psi^c_R}$$

Unless Q=0, Y=0

$$\overline{\nu}^c_R\nu_R$$

Majorana mass term

Spontaneous Symmetry Breaking

$$SU_c(3) \otimes SU_L(2) \otimes U_Y(1) \rightarrow SU_c(3) \otimes U_{EM}(1)$$

Spontaneous Symmetry Breaking

$$SU_c(3) \otimes SU_L(2) \otimes U_Y(1) \rightarrow SU_c(3) \otimes U_{EM}(1)$$

Introduce a scalar field with quantum numbers: (1,2,1)

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

With potential

$$V = -m^2 H^\dagger H + \tfrac{\lambda}{2}(H^\dagger H)^2$$

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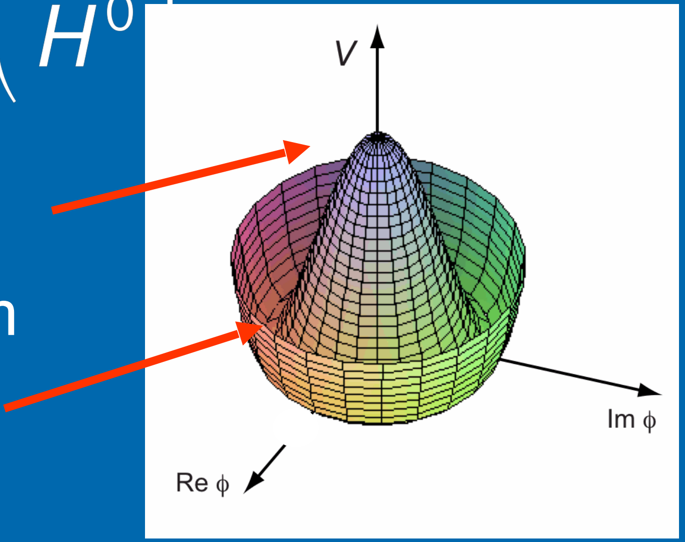

Unstable maximum

Stable minimum

Spontaneous Symmetry Breaking

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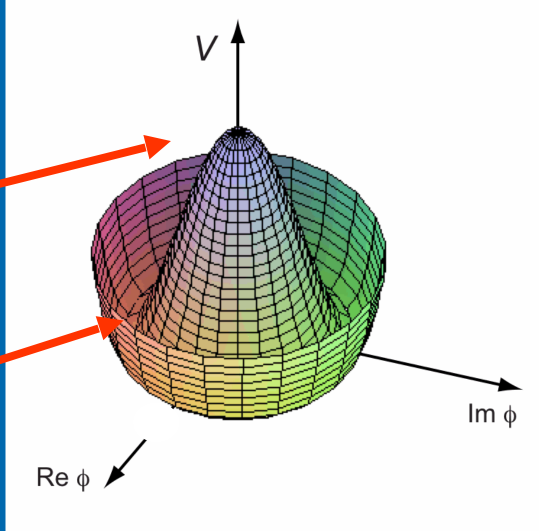

Unstable maximum

Stable minimum

At the minimum

v.e.v.

$$H=\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}=\begin{pmatrix} H^+ \\ v+\frac{S+iP}{\sqrt{2}} \end{pmatrix}=exp(i\frac{\xi^a\sigma^a}{2})\begin{pmatrix} 0 \\ \frac{S}{\sqrt{2}} \end{pmatrix}$$

scalar

pseudoscalar

Spontaneous Symmetry Breaking

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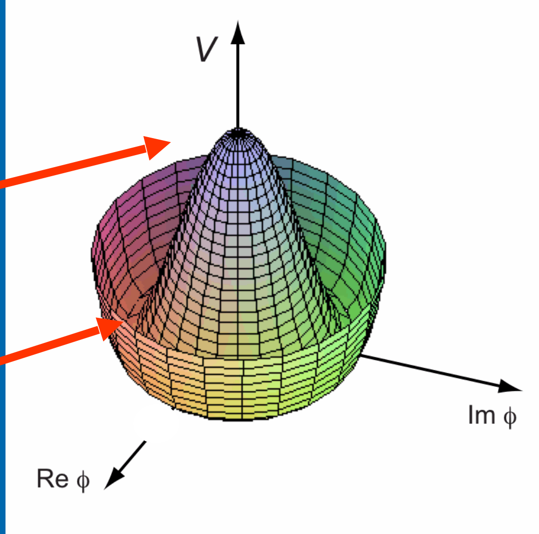

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scalar

pseudoscalar

Gauge transformation

$$H\rightarrow H'=exp(i\frac{\alpha^a\sigma^a}{2})H\quad\xrightarrow{\alpha^a=-\xi^a}\quad H'=\begin{pmatrix}0\\\frac{h}{\sqrt{2}}\end{pmatrix}$$

Higgs boson

Mechanism of Spontaneous Symmetry breaking (Brout-Englert-Higgs)

Q: what happens with missing d.o.f (massless Goldstone bosons P, H^+ or $\vec{\xi}$)?

A: they become longitudinal d.o.f of the gauge bosons $W^i_\mu, \ i = 1, 2, 3$

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Gauge transformation

$$\hat{W}_\mu \to e^{i\alpha^a\sigma^a}\hat{W}_\mu e^{-i\alpha^a\sigma^a} - \frac{1}{g}\partial_\mu(e^{i\alpha^a\sigma^a})e^{-i\alpha^a\sigma^a}$$

$\alpha^a = -\xi^a$

Longitudinal components

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Longitudinal components

Higgs field kinetic term

$$|D_\mu H|^2 = |\partial_\mu H - \frac{g}{2}\hat{W}_\mu H - \frac{g'}{2}\hat{B}_\mu H|^2$$

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$\alpha^a = -\xi^a$

Longitudinal components

Higgs field kinetic term

$$|D_\mu H|^2 = |\partial_\mu H - \frac{g}{2}\hat{W}_\mu H - \frac{g'}{2}\hat{B}_\mu H|^2 \qquad \leftarrow H = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\to \frac{1}{4}(0v)\begin{pmatrix} gW^3_\mu + g'B_\mu & \sqrt{2}W^-_\mu \\ \sqrt{2}W^+_\mu & -gW^3_\mu + g'B_\mu \end{pmatrix}^2 \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\to \frac{g^2}{2}v^2 W^+_\mu W^-_\mu + \frac{1}{4}(-gW^3_\mu + g'B_\mu)^2$$

Gauge Bosons Masses

$$\Delta L_{mass} \to \frac{g^2}{2} v^2 W^+_\mu W^-_\mu + \frac{1}{4}(-gW^3_\mu + g' B_\mu)^2 \quad + \frac{1}{4}(\cancel{gW^3_\mu + g'} B_\mu)^2$$

$$W^\pm_\mu = \frac{W^1_\mu \mp W^2_\mu}{\sqrt{2}}$$

$$Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W^3_\mu \qquad \tan\theta_W = g'/g$$

$$\gamma_\mu = \cos\theta_W B_\mu + \sin\theta_W W^3_\mu$$

$$\boxed{\begin{aligned} M^2_W &= \tfrac{1}{2} g^2 v^2 \\ M^2_Z &= \tfrac{1}{2}(g^2 + g'^2) v^2 \\ M_\gamma &= 0 \end{aligned}}$$

$$M^2_W = \frac{g^2}{g^2 + g'^2} M^2_Z = \cos^2\theta_W M^2_Z$$

Gauge Bosons Masses

The mass terms

$$\Delta L_{mass} \rightarrow \frac{g^2}{2} v^2 W_\mu^+ W_\mu^- + \frac{1}{4}(-gW_\mu^3 + g' B_\mu)^2 \quad + \frac{1}{4}\cancel{(gW_\mu^3 + g' B_\mu)^2}$$

$$W_\mu^\pm = \frac{W_\mu^1 \mp W_\mu^2}{\sqrt{2}}$$
$$Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W_\mu^3 \qquad \tan\theta_W = g'/g$$
$$\gamma_\mu = \cos\theta_W B_\mu + \sin\theta_W W_\mu^3$$

$$\boxed{\begin{aligned} M_W^2 &= \tfrac{1}{2} g^2 v^2 \\ M_Z^2 &= \tfrac{1}{2}(g^2 + g'^2) v^2 \\ M_\gamma &= 0 \end{aligned}}$$

$$M_W^2 = \frac{g^2}{g^2 + g'^2} M_Z^2 = \cos^2\theta_W M_Z^2$$

The Higgs Boson and Fermion Masses

$$H = \begin{pmatrix} 0 \\ \mathrm{v} + \frac{h}{\sqrt{2}} \end{pmatrix} \Rightarrow \quad V = -m^2 H^\dagger H + \tfrac{\lambda}{2}(H^\dagger H)^2$$

$$\Rightarrow \quad V = -\frac{\lambda \mathrm{v}^4}{2} + \boxed{\lambda \mathrm{v}^2 h^2} + \frac{\lambda \mathrm{v}}{\sqrt{2}} h^3 + \frac{\lambda}{8} h^4 \qquad \mathrm{v}^2 = m^2 / \lambda$$

$$\boxed{m_h = \sqrt{2}m = \sqrt{2\lambda}\,\mathrm{v}}$$

$$L_{Yukawa} = y^E_{\alpha\beta} \overline{L}_\alpha E_\beta H + y^D_{\alpha\beta} \overline{Q}_\alpha D_\beta H + y^U_{\alpha\beta} \overline{Q}_\alpha U_\beta \widetilde{H}$$

α, β =1,2,3 - generation index

Dirac fermion mass

$$\boxed{M^u_i = Diag(y^u_{\alpha\beta})\mathrm{v}, \quad M^d_i = Diag(y^d_{\alpha\beta})\mathrm{v}, \quad M^l_i = Diag(y^l_{\alpha\beta})\mathrm{v}}$$

$$y^N_{\alpha\beta} \overline{L}_\alpha N_\beta \widetilde{H} \rightarrow M^\nu_i = Diag(y^N_{\alpha\beta})\mathrm{v}$$

Dirac neutrino mass

Quark/Lepton Mixing

- The mass matrix is non-diagonal in generation space
- It can be diagonalized by field rotation Q -> Q'= V Q

$$\bar{U} M_U U -> \bar{U}' V_U^{+} M_U V_U U' = \bar{U}' M_U^{Diag} U'$$

$$\bar{D} M_D D -> \bar{D}' V_D^{+} M_D V_D D' = \bar{D}' M_D^{Diag} D'$$

- Neutral Current:

$$\bar{U} Z_\mu U -> \bar{U}' V_U^{+} Z_\mu V_U U' = \bar{U}' Z_\mu U' \quad V_U^{+} V_U = \bar{U}' Z_\mu U'$$

- Charged Current

$$\bar{U} W_\mu D -> \bar{U}' V_U^{+} W_\mu V_D D = \bar{U}' W_\mu V_U^{+} V_D D'$$

$$K = V_U^{+} V_D$$

Cabibbo-Kobayashi-Maskawa mixing matrix (quarks)

Pontecorvo-Maki-Nakagava-Sakato mixing matrix (leptons)

The (only) source of flavour mixing in the SM

Unitarity: $K^{\dagger} K=1$

Mixing Matrix and Unitarity Triangle

Quarks and leptons of different generations can mix interacting with W-boson

Two generations

$$(\bar{u}\ \bar{c})\begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix} W \begin{pmatrix} d\\ s\end{pmatrix}$$

Mixing matrix

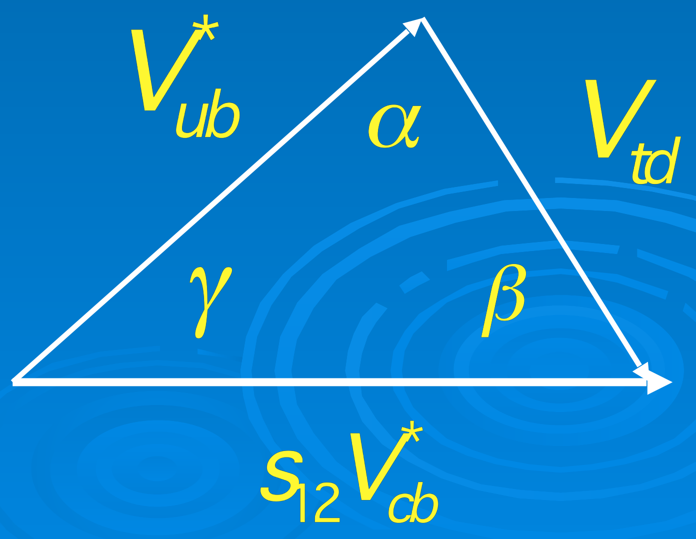
Three generations

$$K = \begin{pmatrix} V_{ud} & V_{us} & V_{ub}\\ V_{cd} & V_{cs} & V_{cb}\\ V_{td} & V_{ts} & V_{tb}\end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{pmatrix}$$

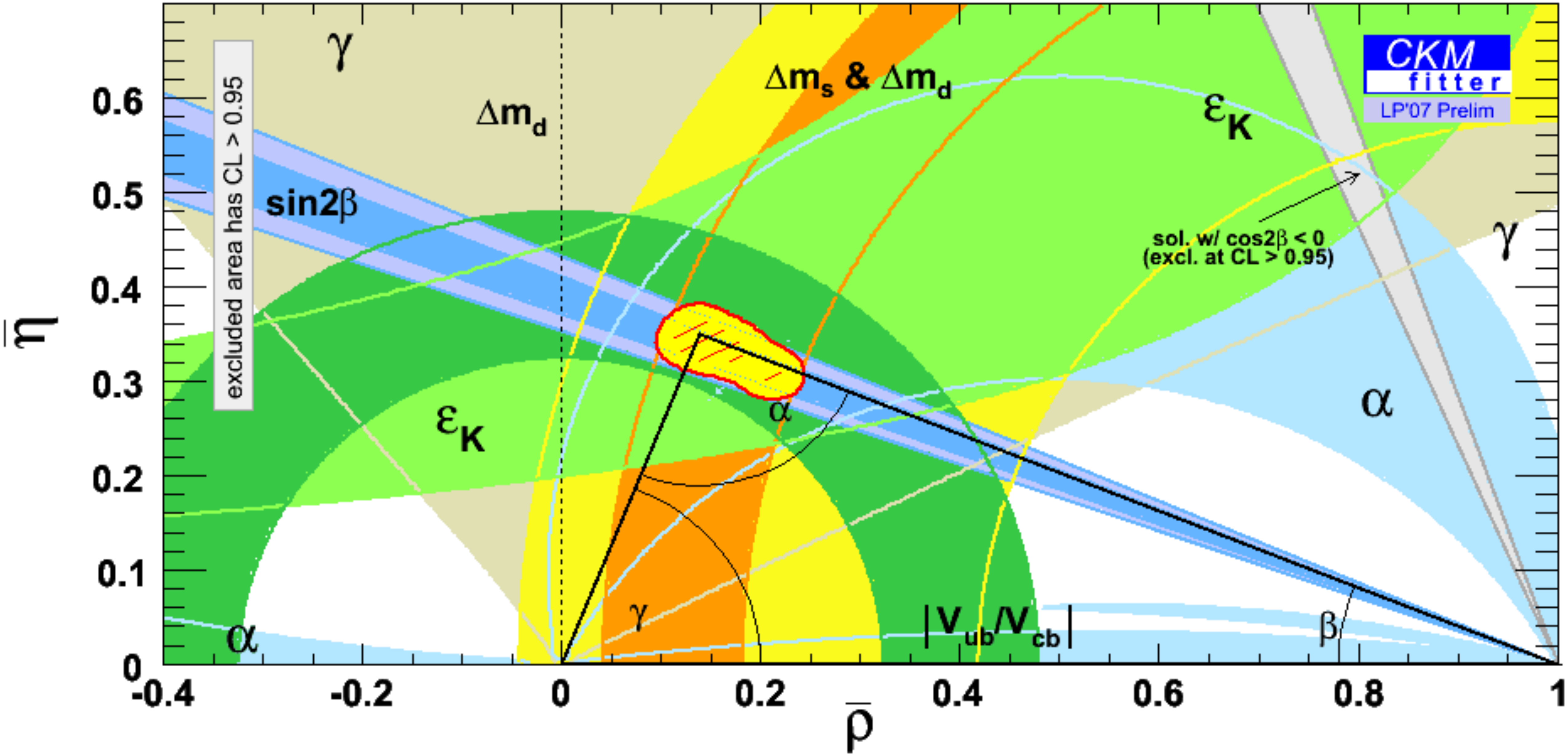
Two important properties

1. CP-violation due to a complex phase δ !
2. Unitarity triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
$$\Rightarrow \quad V_{ub}^* + V_{td} = s_{12}V_{cb}^*$$



The Unitarity Triangle: all constraints

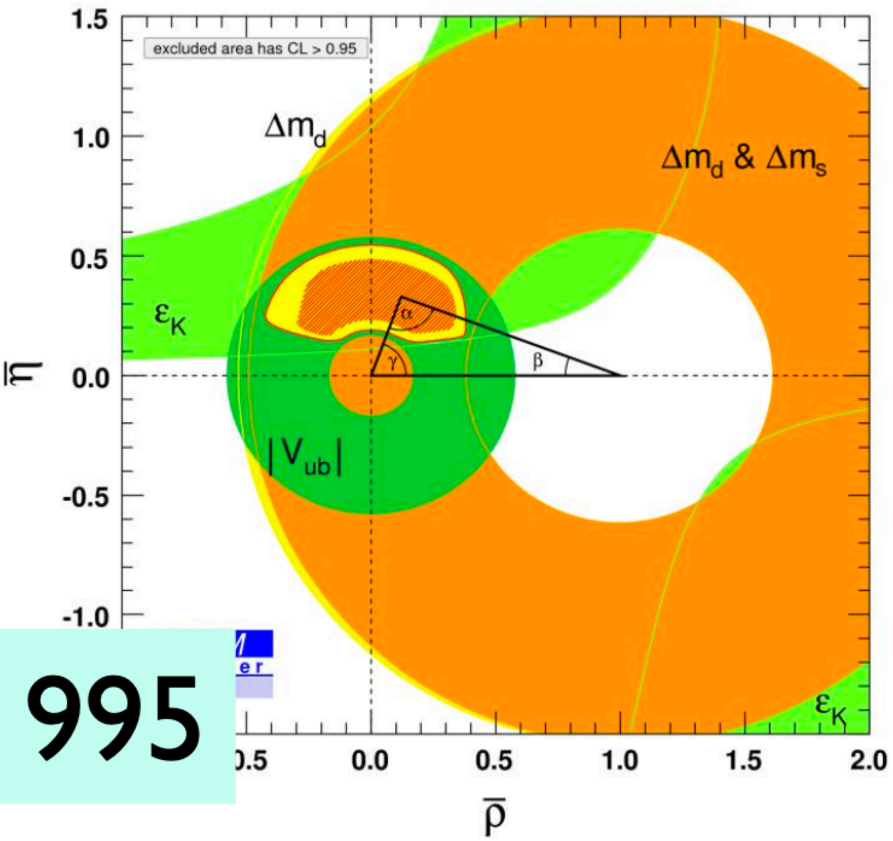


A consistent picture across a huge array of measurements

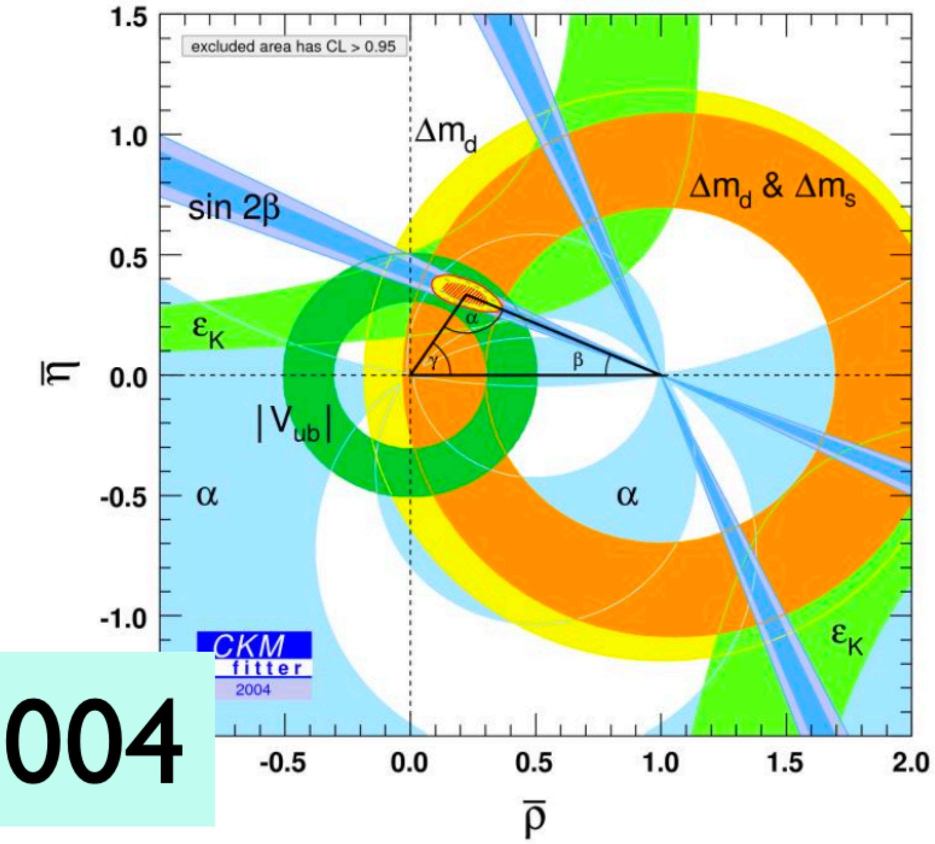
Unitarity Triangle measurements

- Amazing progress in the last 27 years; the SM remains intact, but a whole lot still to learn

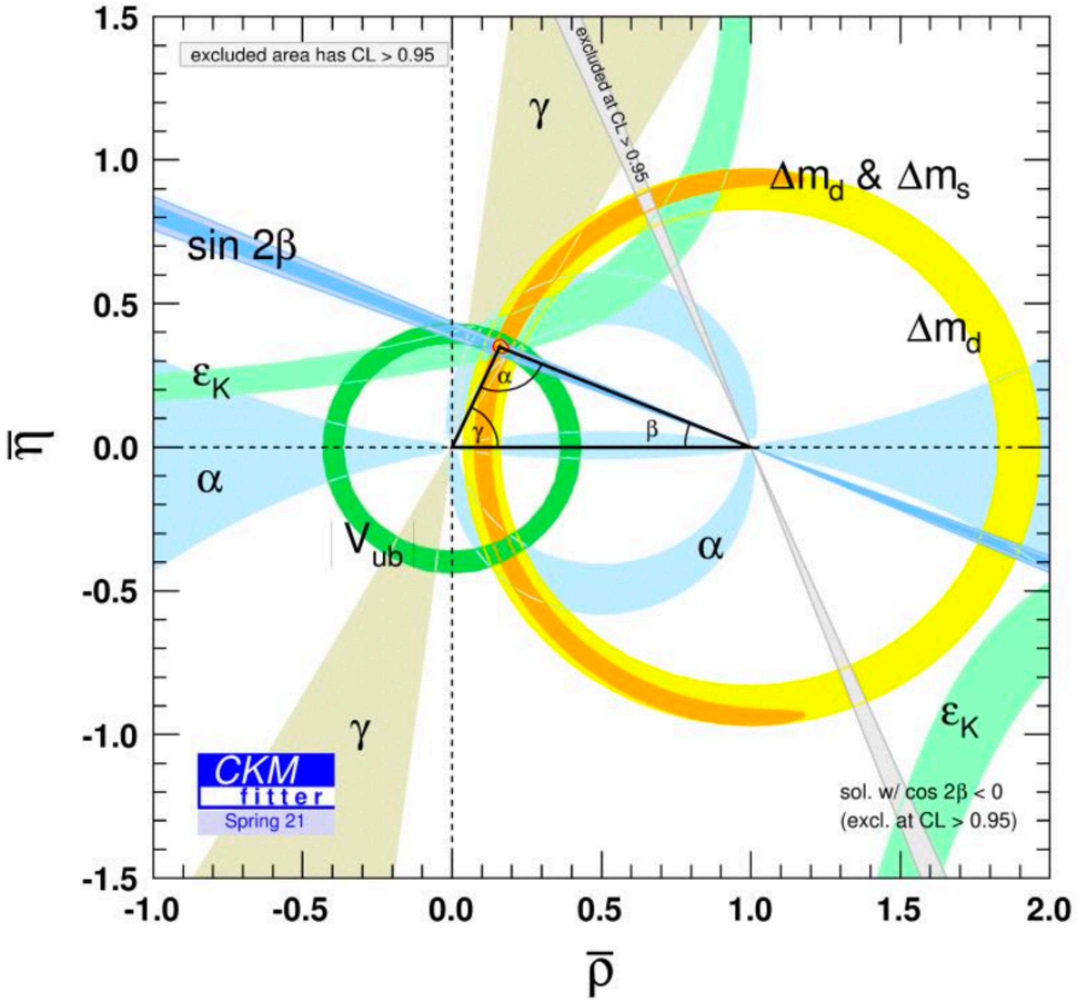
http://ckmfitter.in2p3.fr



1995



2004



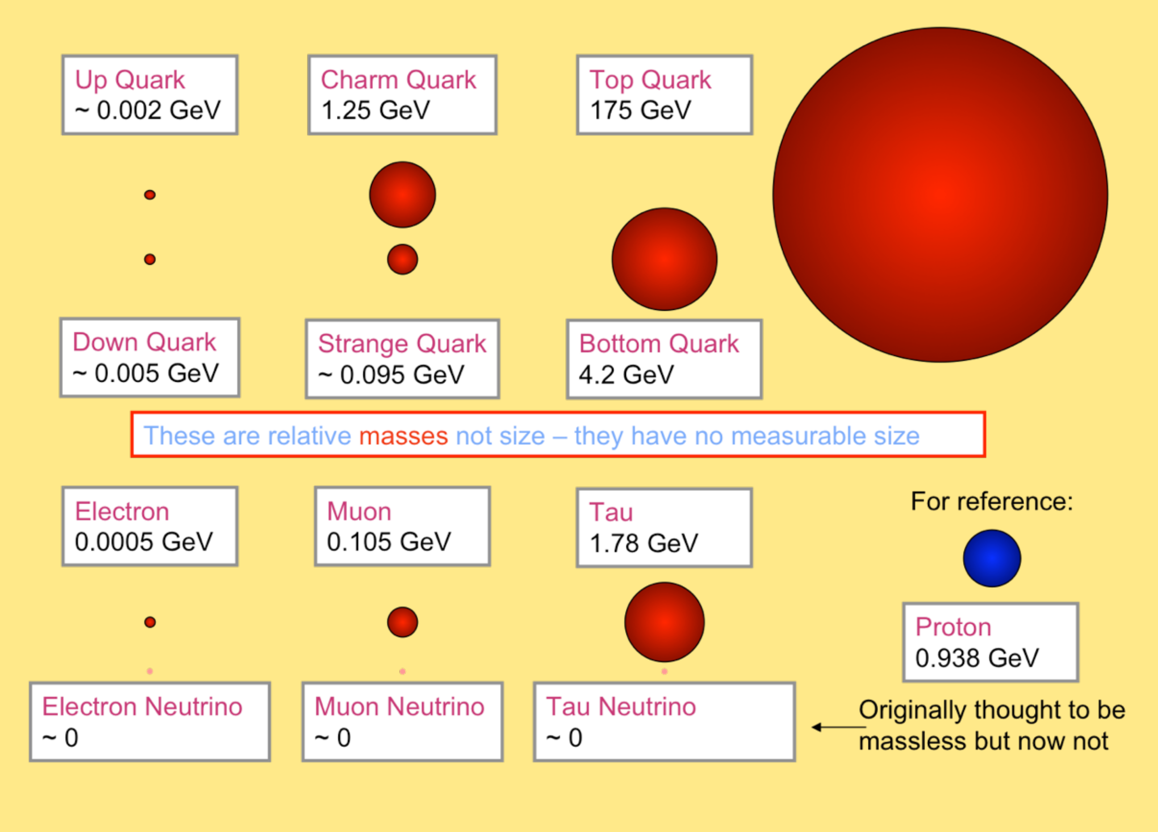
Now (dominated by LHCb)

Mass spectrum and Mixing angles

- Mass spectrum?

$$m_{quark} = y_{quark} \cdot v$$
$$m_{lepton} = y_{lepton} \cdot v$$
$$m_W = g/\sqrt{2} \cdot v$$
$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$
$$m_H = \sqrt{\lambda} \cdot v$$
$$m_\gamma = 0$$
$$m_{gluon} = 0$$

SM

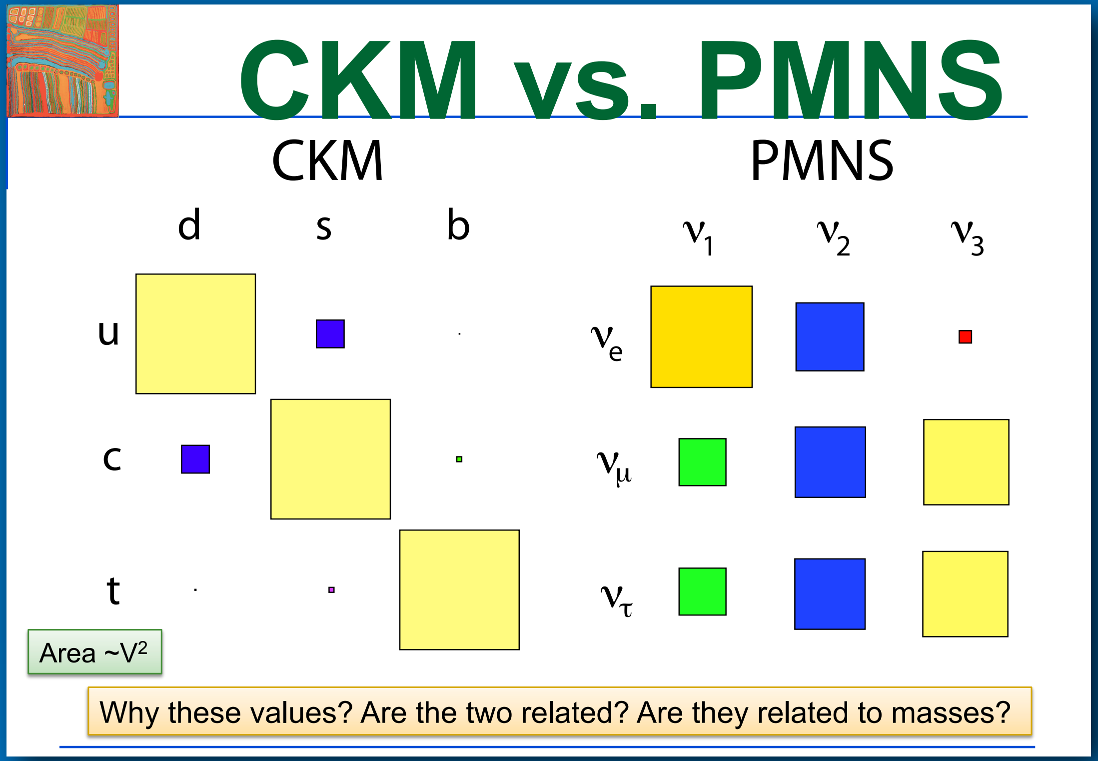


These are relative masses not size – they have no measurable size

Originally thought to be massless but now not

- Mixing Matrices?

- Quark-Lepton Symmetry
- Strong difference in parameters



Why these values? Are the two related? Are they related to masses?

Mass spectrum and Mixing angles

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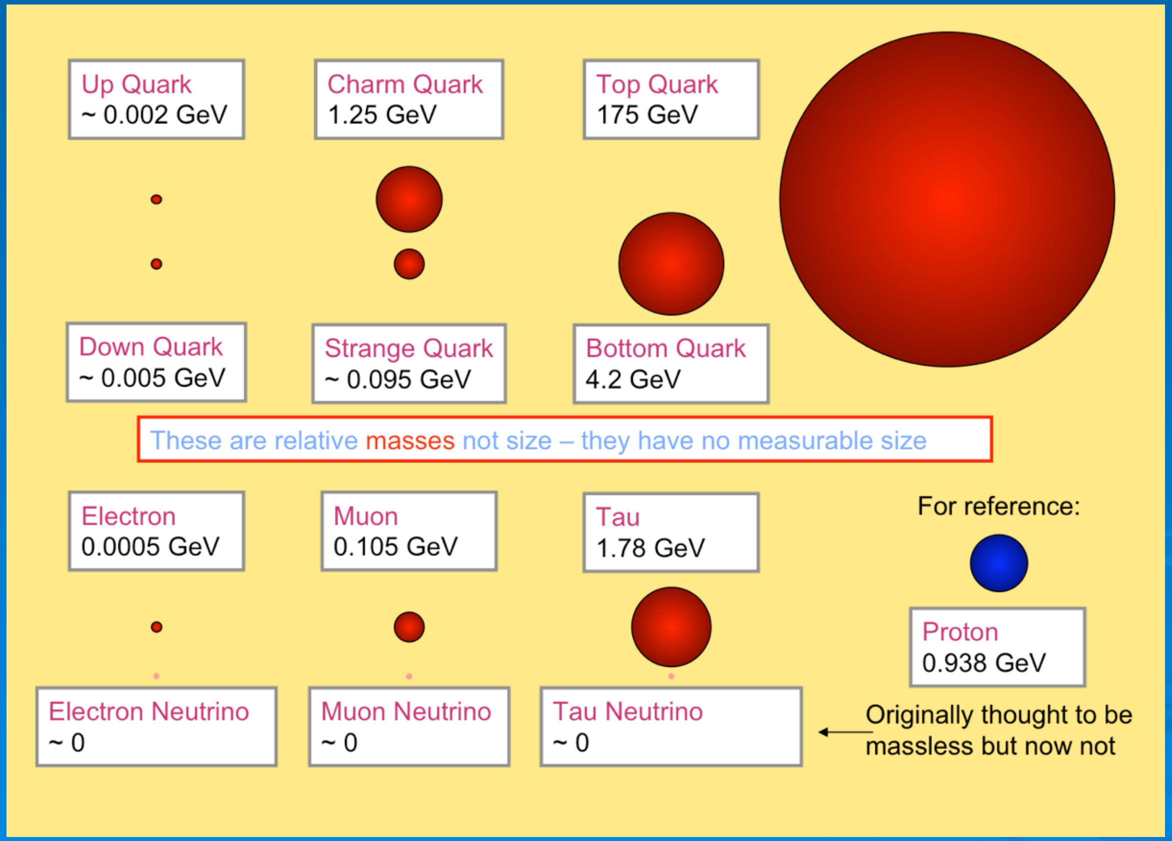
Up Quark
~ 0.002 GeV

Charm Quark
1.25 GeV

Top Quark
175 GeV

Down Quark
~ 0.005 GeV

Strange Quark
~ 0.095 GeV

Bottom Quark
4.2 GeV

These are relative **masses** not size – they have no measurable size

Electron
0.0005 GeV

Muon
0.105 GeV

Tau
1.78 GeV

For reference:

Proton
0.938 GeV

Electron Neutrino
~ 0

Muon Neutrino
~ 0

Tau Neutrino
~ 0

Originally thought to be massless but now not

- Mixing Matrices?

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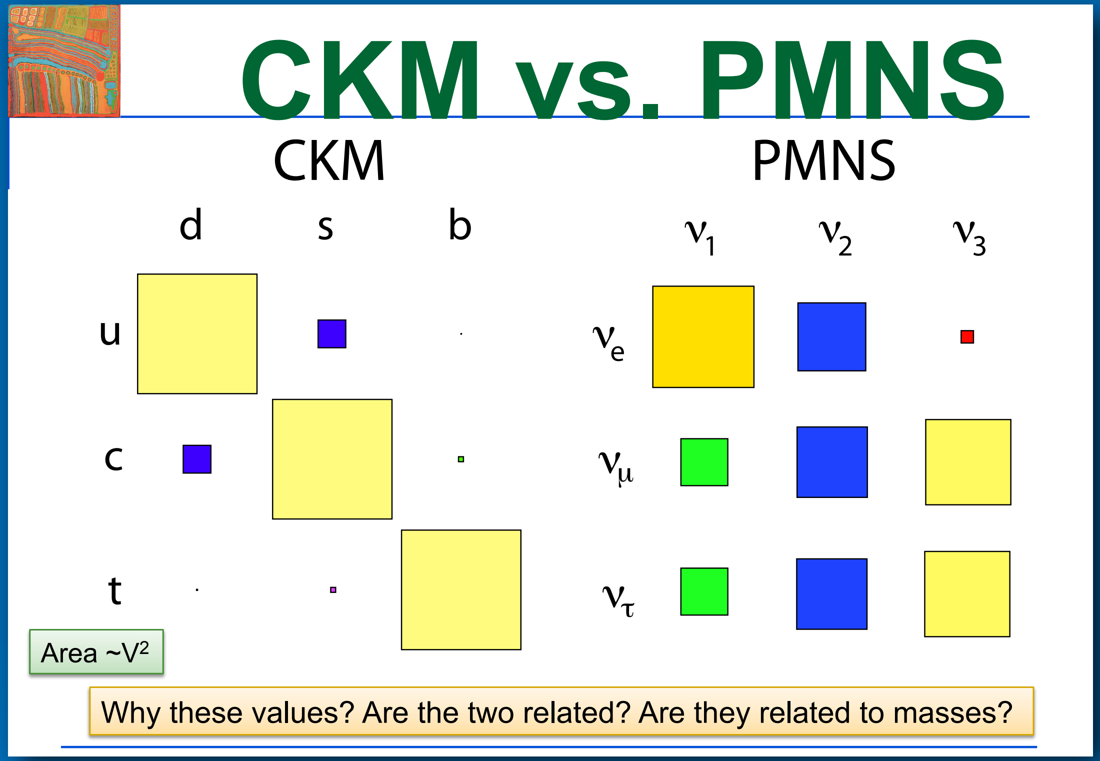
CKM vs. PMNS

Why these values? Are the two related? Are they related to masses?

- What are the CKM and PMNS phases?
- Where lies the source of CP violation: in quark or lepton sector?

Mass spectrum and Mixing angles

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SM

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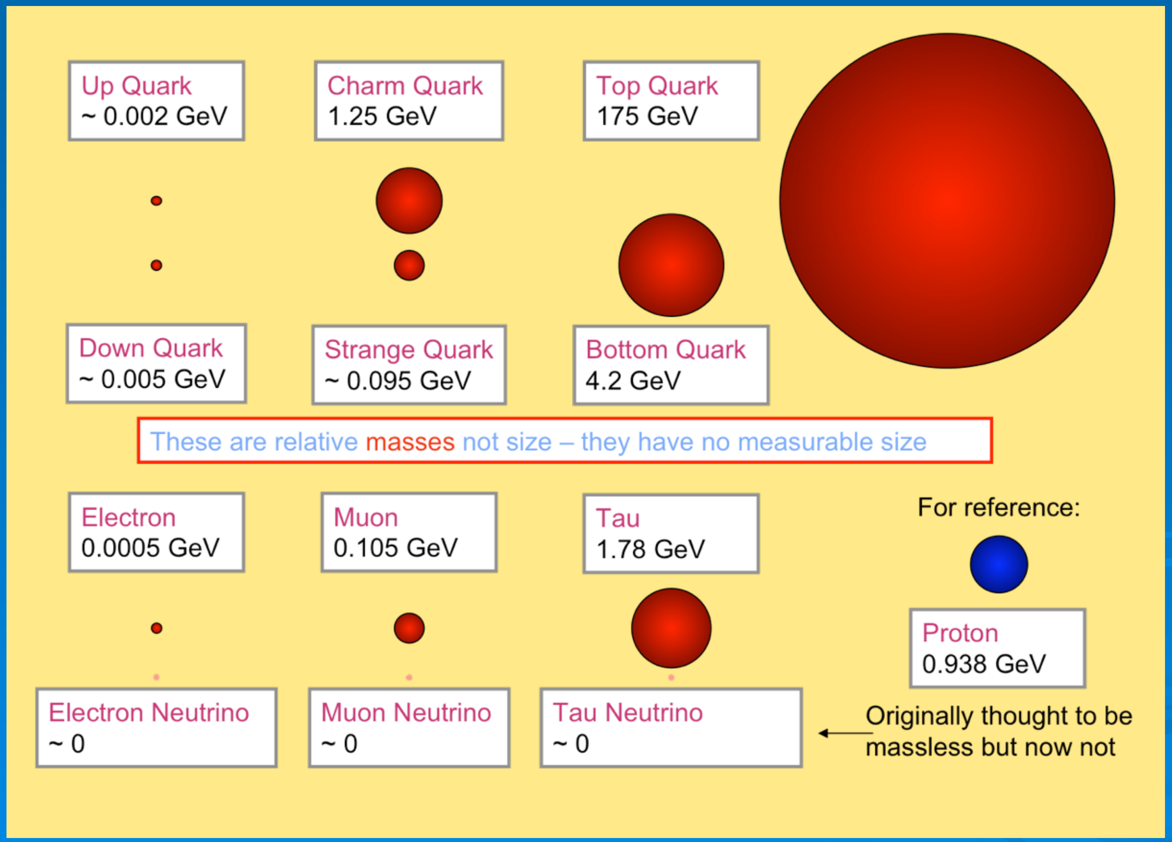

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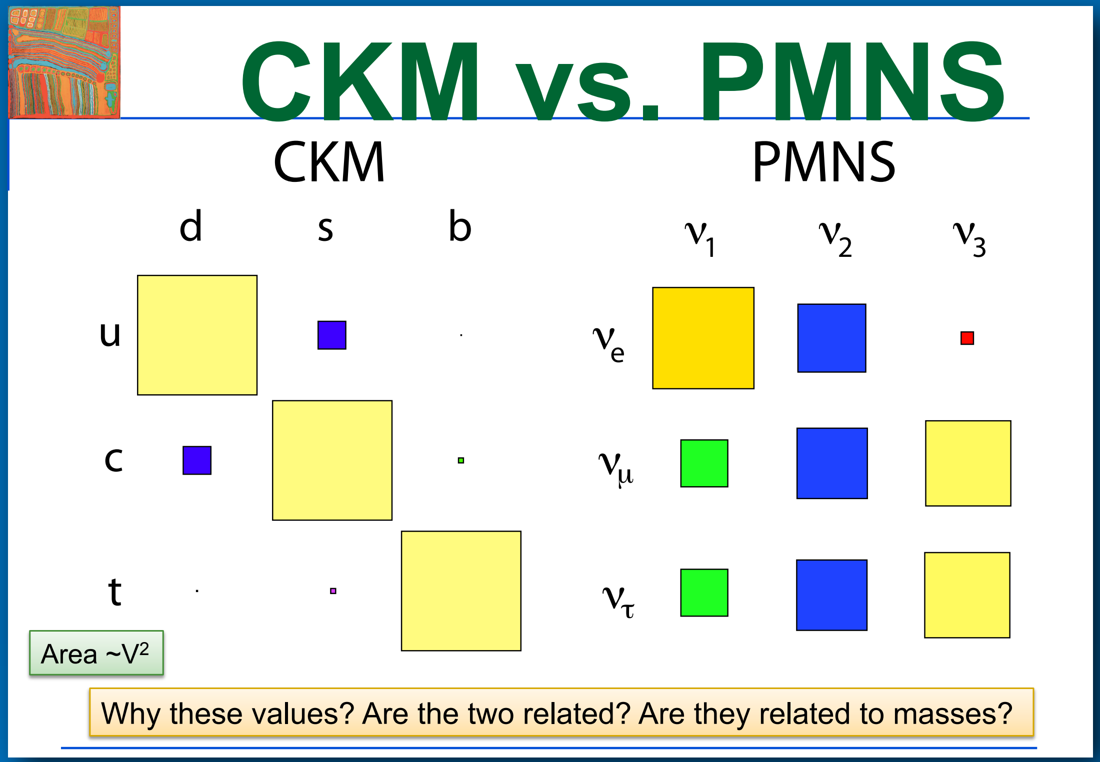


CKM vs. PMNS

CKM

PMNS

Area ~V²

Why these values? Are the two related? Are they related to masses?

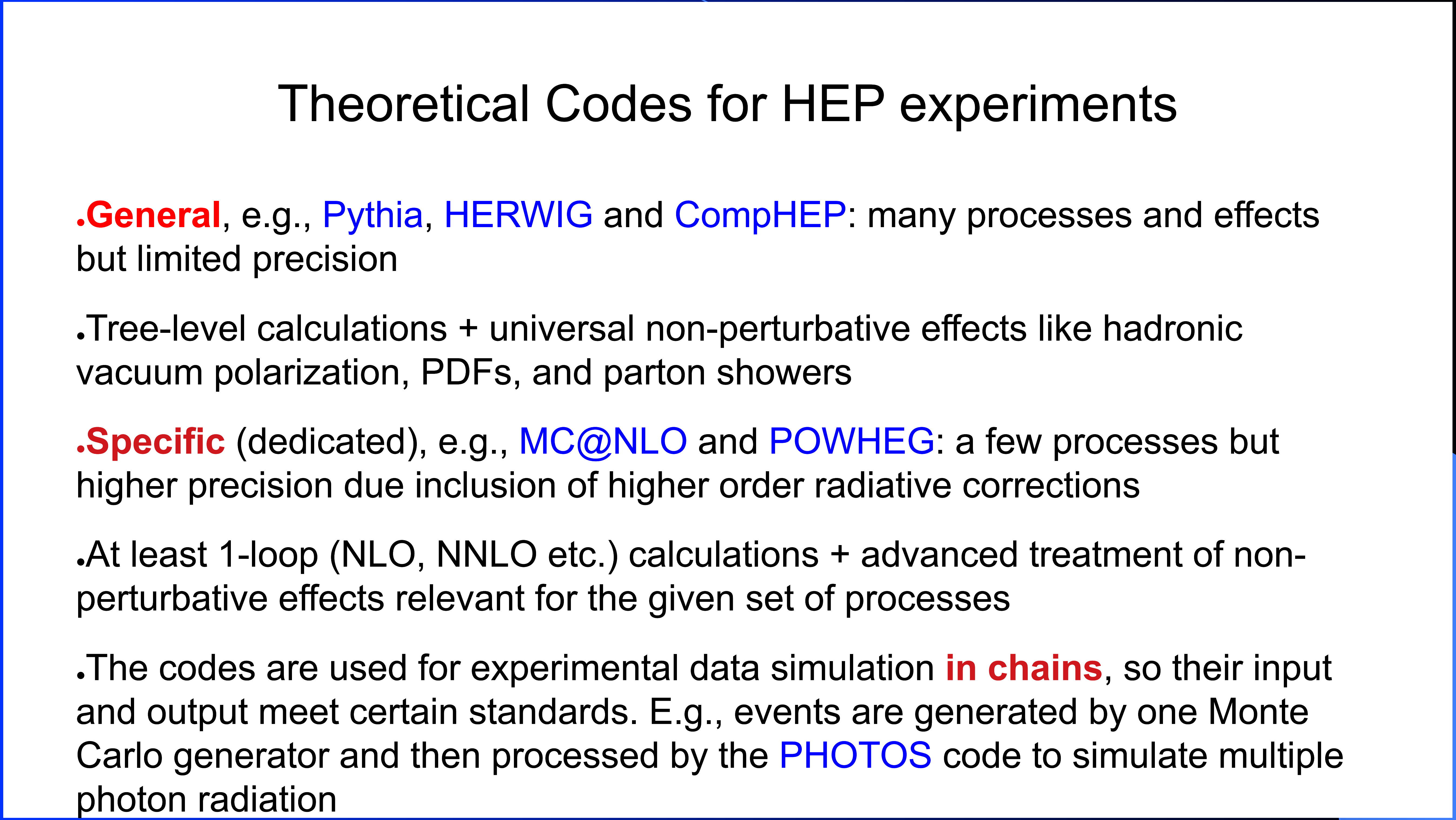
- What are the CKM and PMNS phases?
- Where lies the source of CP violation: in quark or lepton sector?

$$J_{CP} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Calcultion of Theoretical Predictions in HEP

- Choose a process and estimate the required precision => number of loops and legs
- Generate (or draw) Feynman diagrams: from a few to many thousands
- E.g., Mathematica package FeynArts is widely used
- Perform algebraic evaluation and reduce the problem to calculation of so-called master integrals, e.g., by LiteRed package.
- Compute those master integrals either analytically or numerically. There are many advanced methods...
- Perform renormalization, take care on infrared singularities and matching to non-perturbative effects
- Collect all components and get the analytic result for completely differential cross section, e.g., distribution of the reaction products in energy, momenta, and spin.
- Create a Monte Carlo event generator to simulate the distribution. Pass it to the colleagues from an experiment

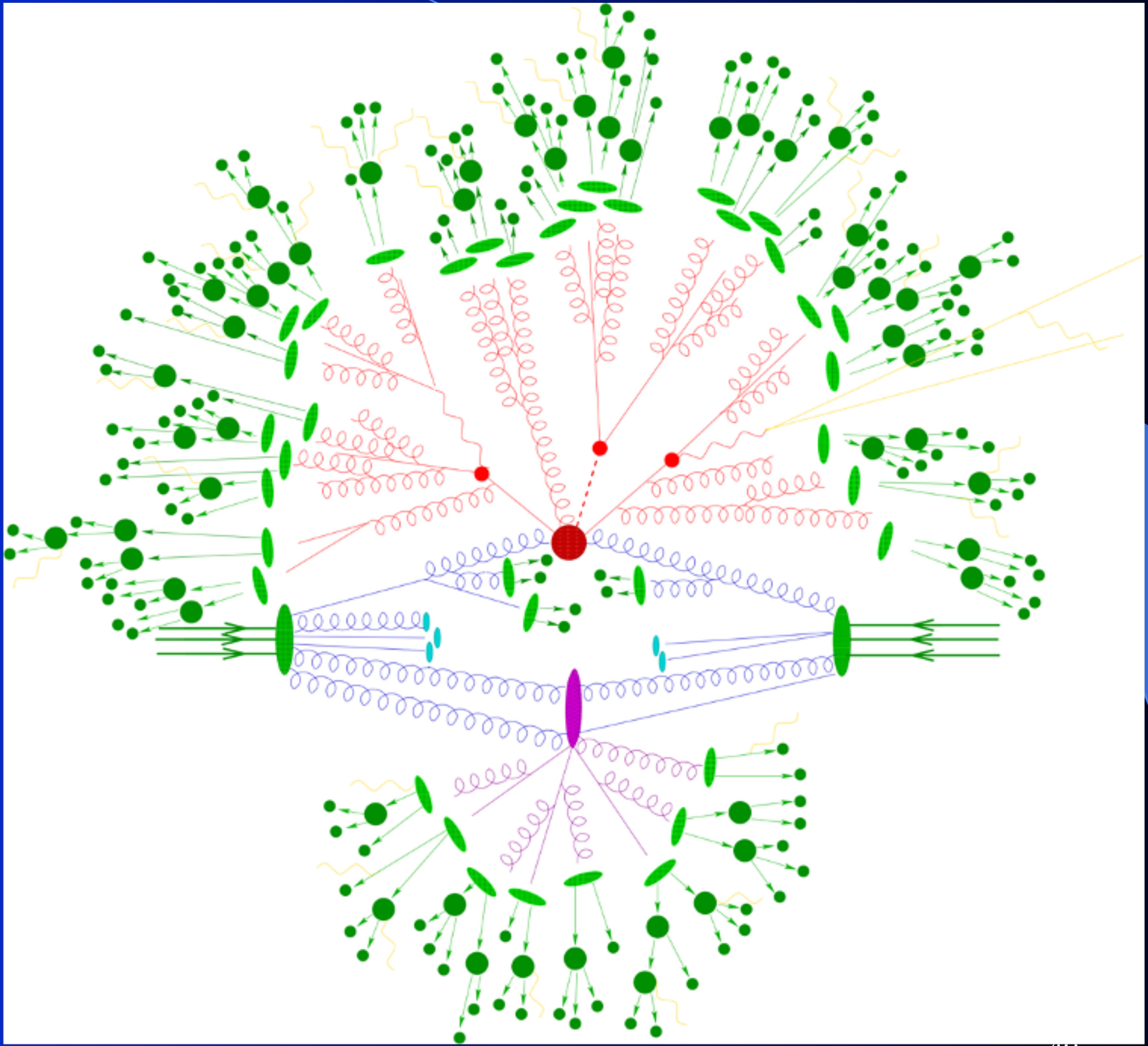
Theoretical Codes for HEP Experiments



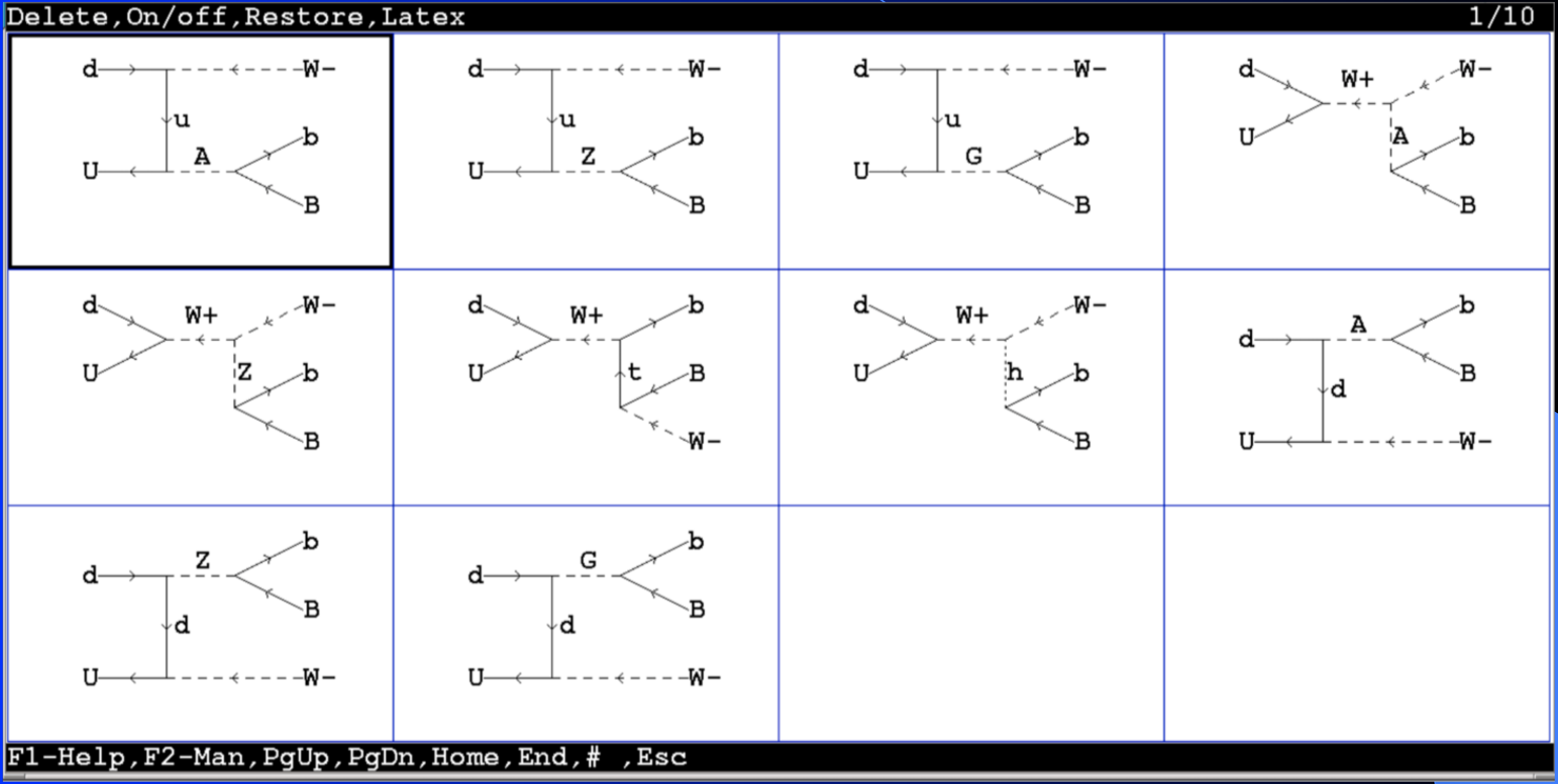
Theoretical Codes for HEP experiments

- **General**, e.g., Pythia, HERWIG and CompHEP: many processes and effects but limited precision
- Tree-level calculations + universal non-perturbative effects like hadronic vacuum polarization, PDFs, and parton showers
- **Specific** (dedicated), e.g., MC@NLO and POWHEG: a few processes but higher precision due inclusion of higher order radiative corrections
- At least 1-loop (NLO, NNLO etc.) calculations + advanced treatment of non-perturbative effects relevant for the given set of processes
- The codes are used for experimental data simulation **in chains**, so their input and output meet certain standards. E.g., events are generated by one Monte Carlo generator and then processed by the PHOTOS code to simulate multiple photon radiation

Progress of Theoretical Calculations

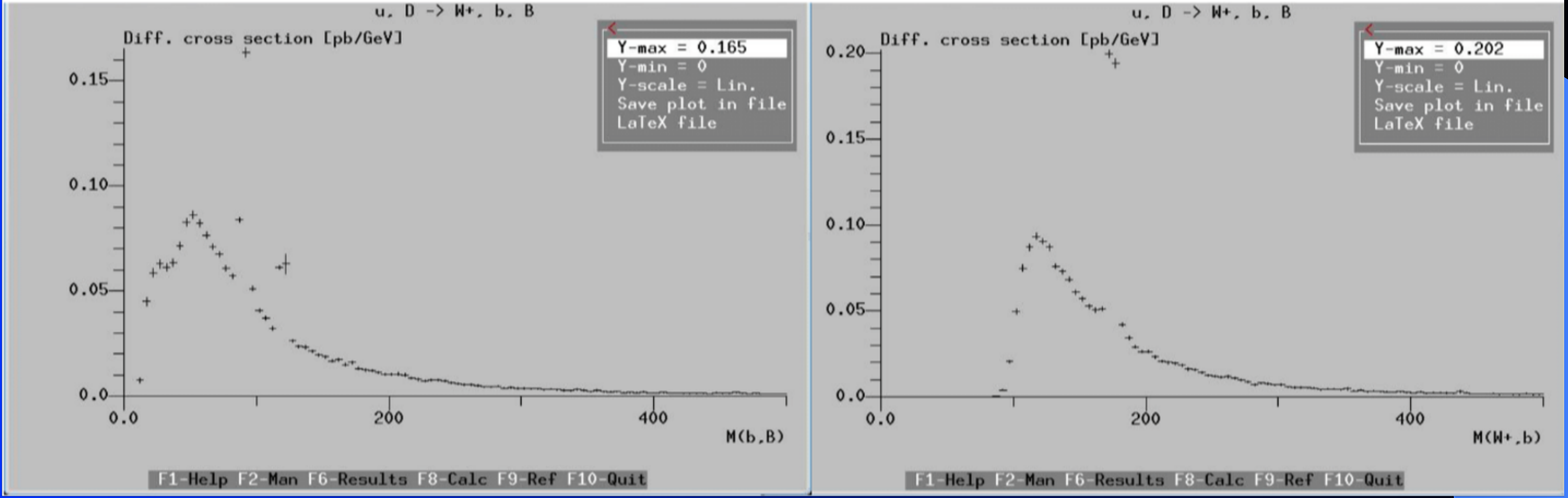


Example: diagrams generated by CalcHEP



CalcHEP: from Feynman rules to distributions

Resulting M_{bb} and M_{Wtb} kinematical distributions



Y-max = 0.165
Y-min = 0
Y-scale = Lin.
Save plot in file
LaTeX file

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Y-max = 0.202
Y-min = 0
Y-scale = Lin.
Save plot in file
LaTeX file

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Using a chain of Programs

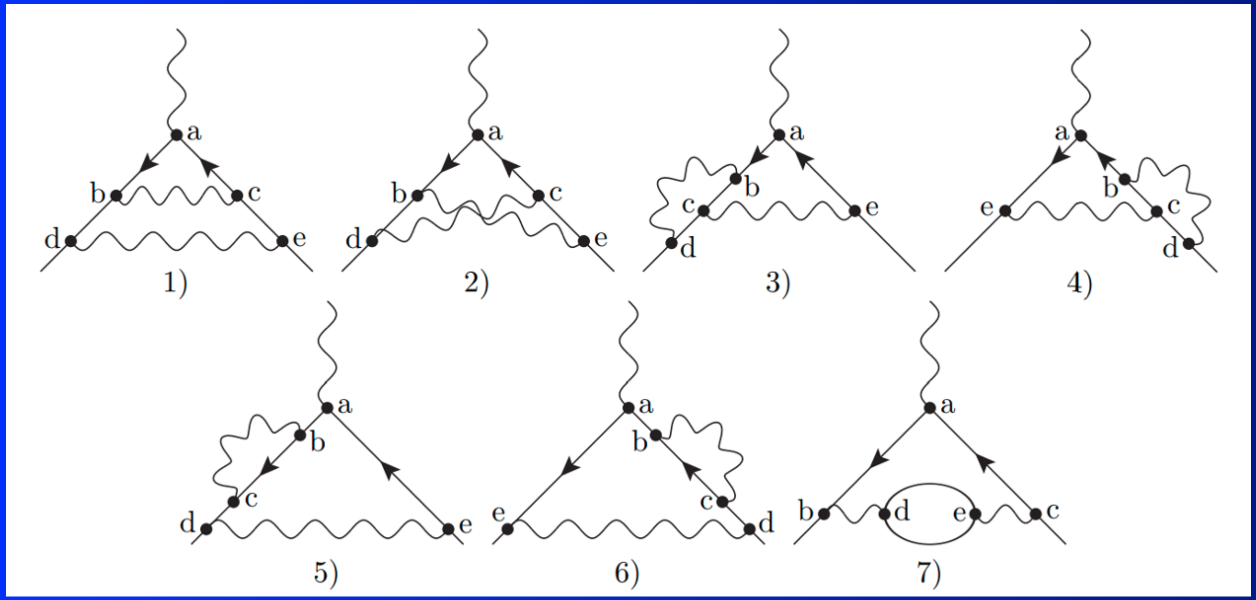
Using a chain of programs:
an example on electron loop contributions to g-2 of muon

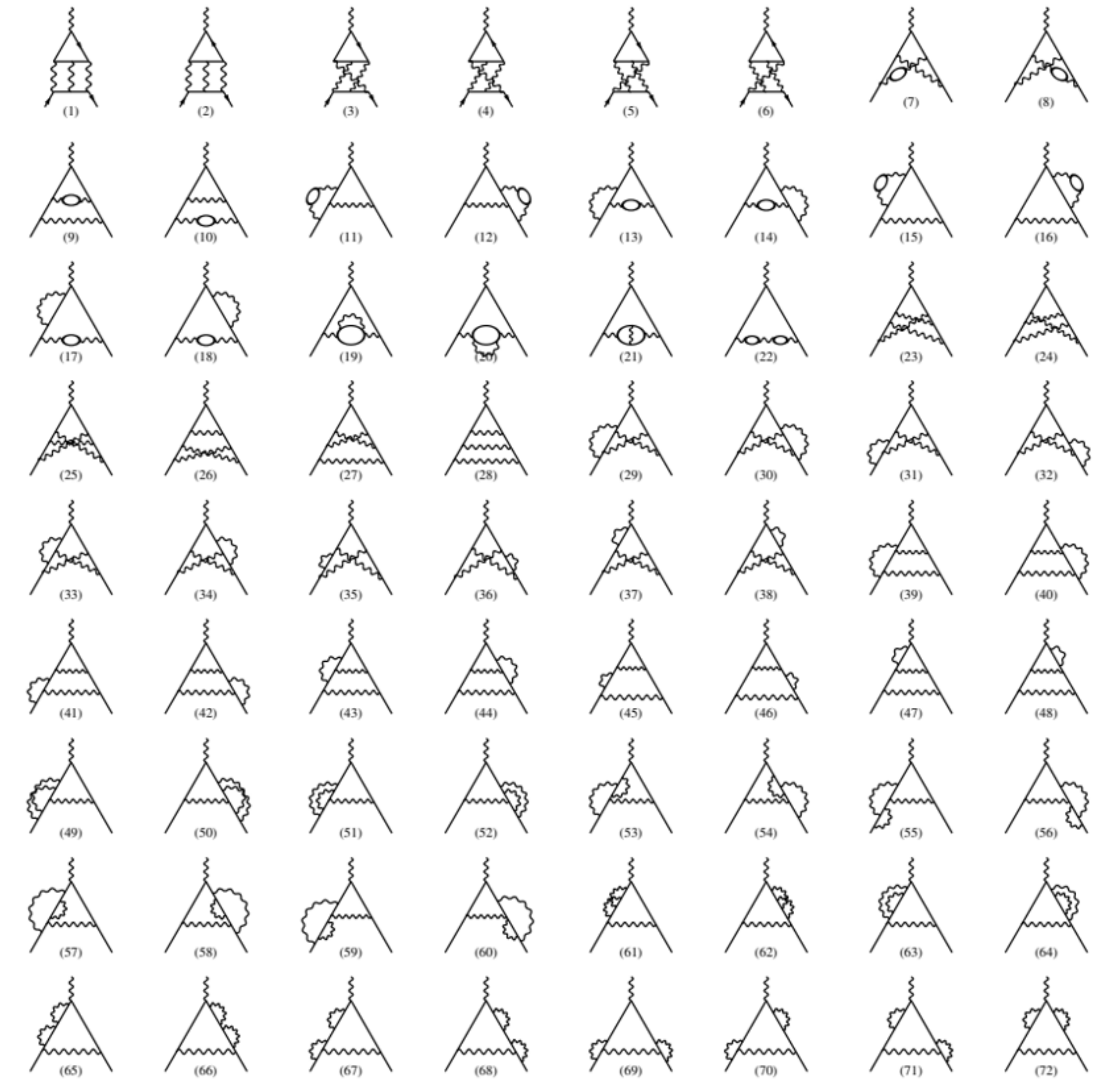
Step 1. Generate 4-loop QED Feynman diagrams by QGRAF code [Nogueira]
Step 2. Read the diagrams: a bridge between QGRAF and exp [Harlander, Seidensticker, Steinhauser]
Step 3. exp/asy/in hause: asymptotic expansion with mass hierarchy m_e << m_\mu [Harlander, Seidensticker, Steinhauser]/ [Pak, Smirnov; Jantzen, Smirnov, Smirnov]
Step 4. FORM: calculations of diagrams [Vermaseren]
Step 5. FIRE/Crusher: reduction to master integrals [Smirnov]/[Marquard, Seidel]
Step 6. FIESTA: evaluation of master integrals [Smirnov]
Step 7. See a numerical agreement with Kinoshita's results.

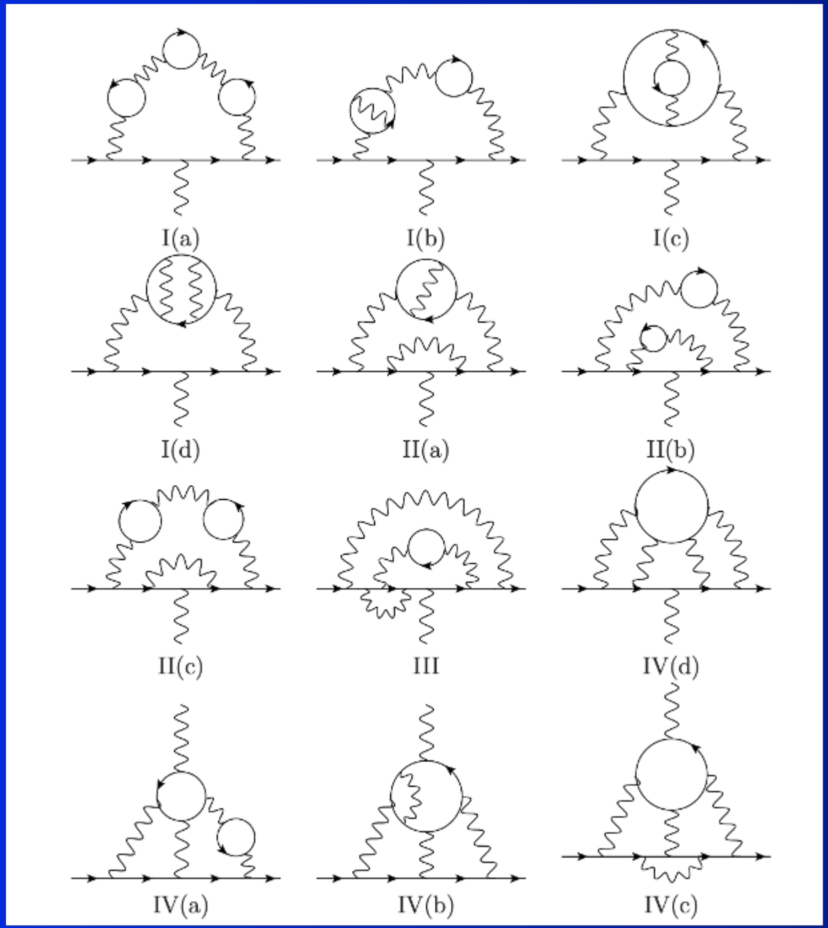
*The names of computer codes are in blue. Their authors are given in square brackets.

[A. Kurz, P. Marquard, A.V. Smirnov , V.A. Smirnov, M. Steinhauser, *Phys.Rev.D* 93 (2016) 5, 053017]

QED Diagrams for g-2 of muon

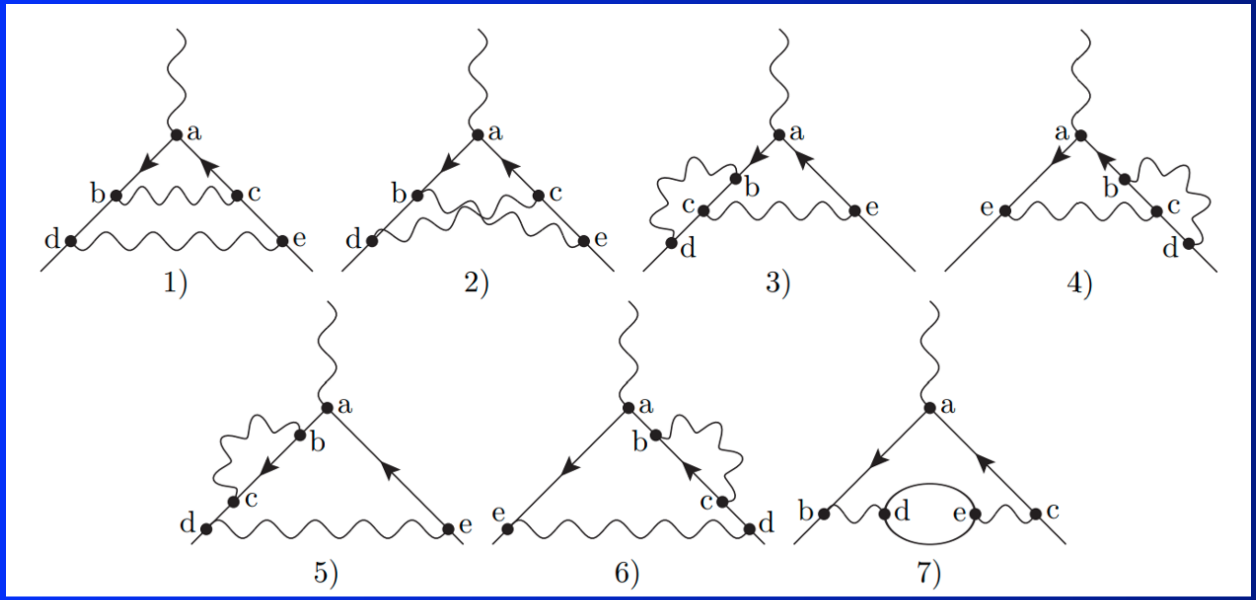




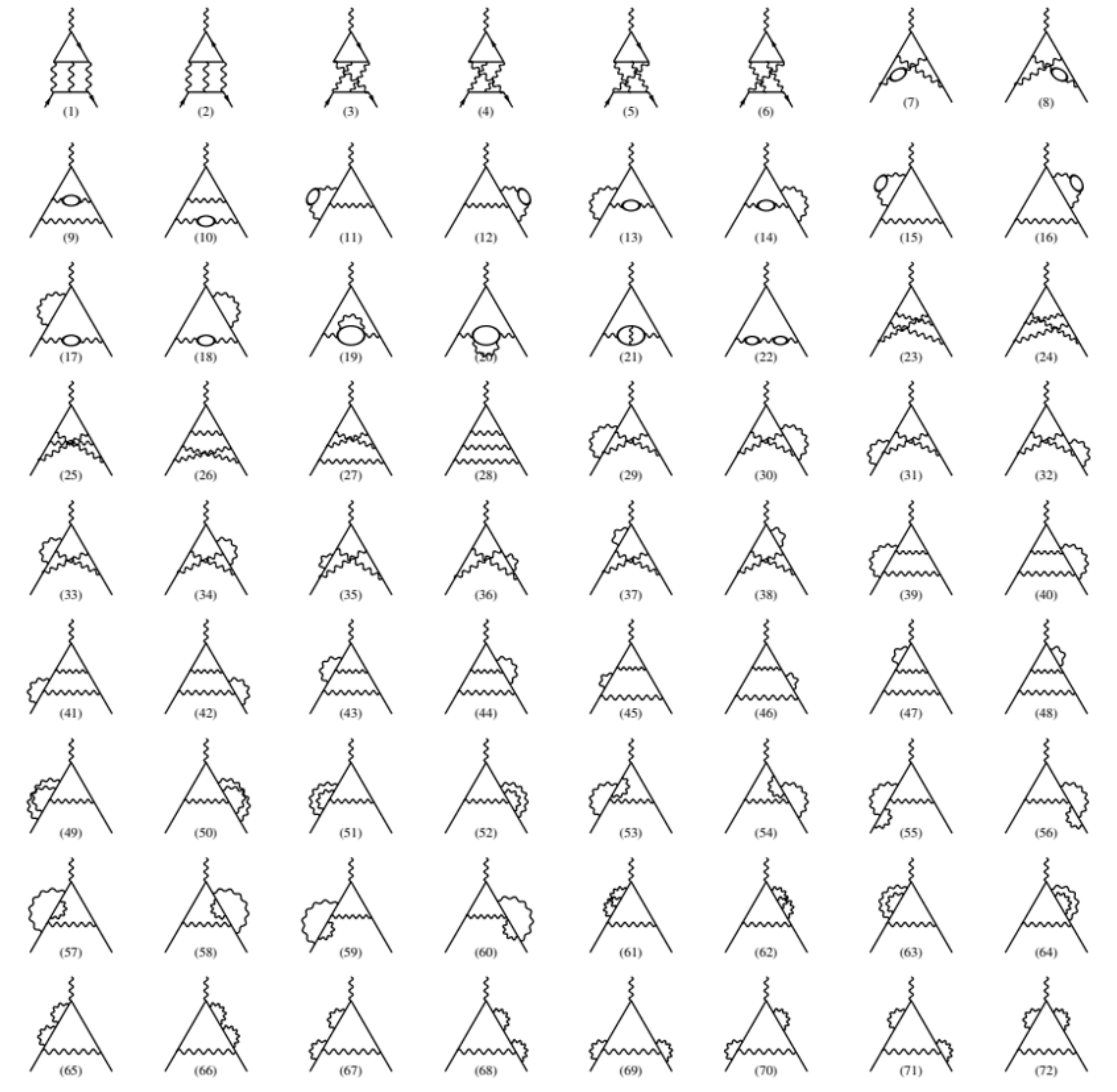


QED Diagrams for g-2 of muon

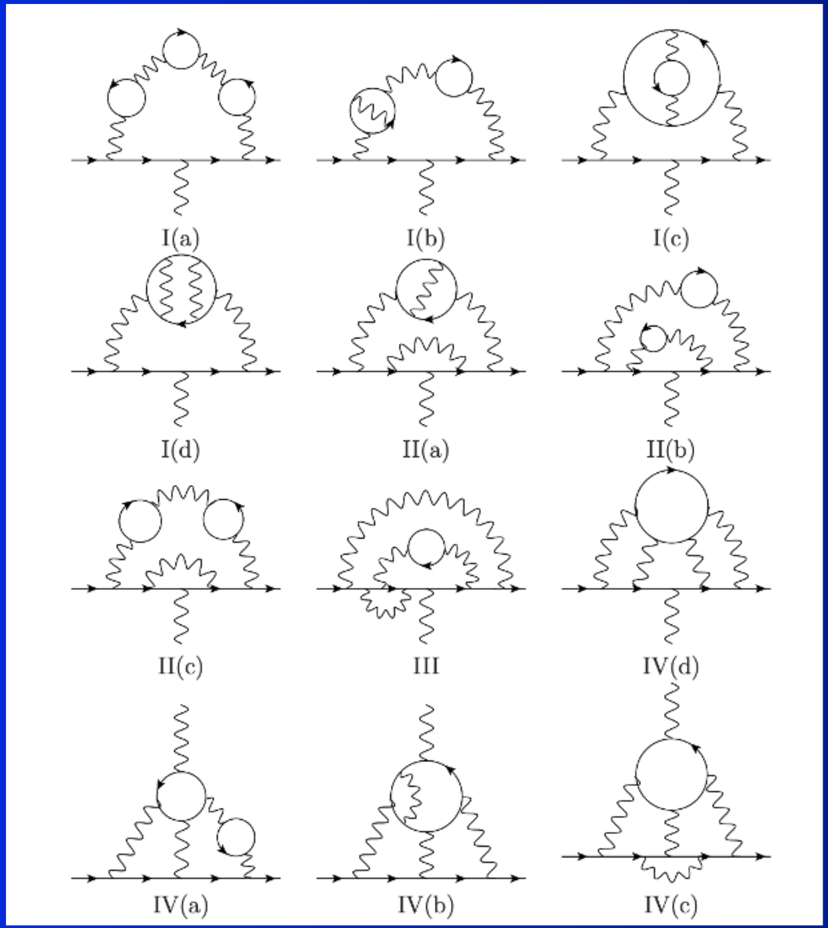
Two-loop diags



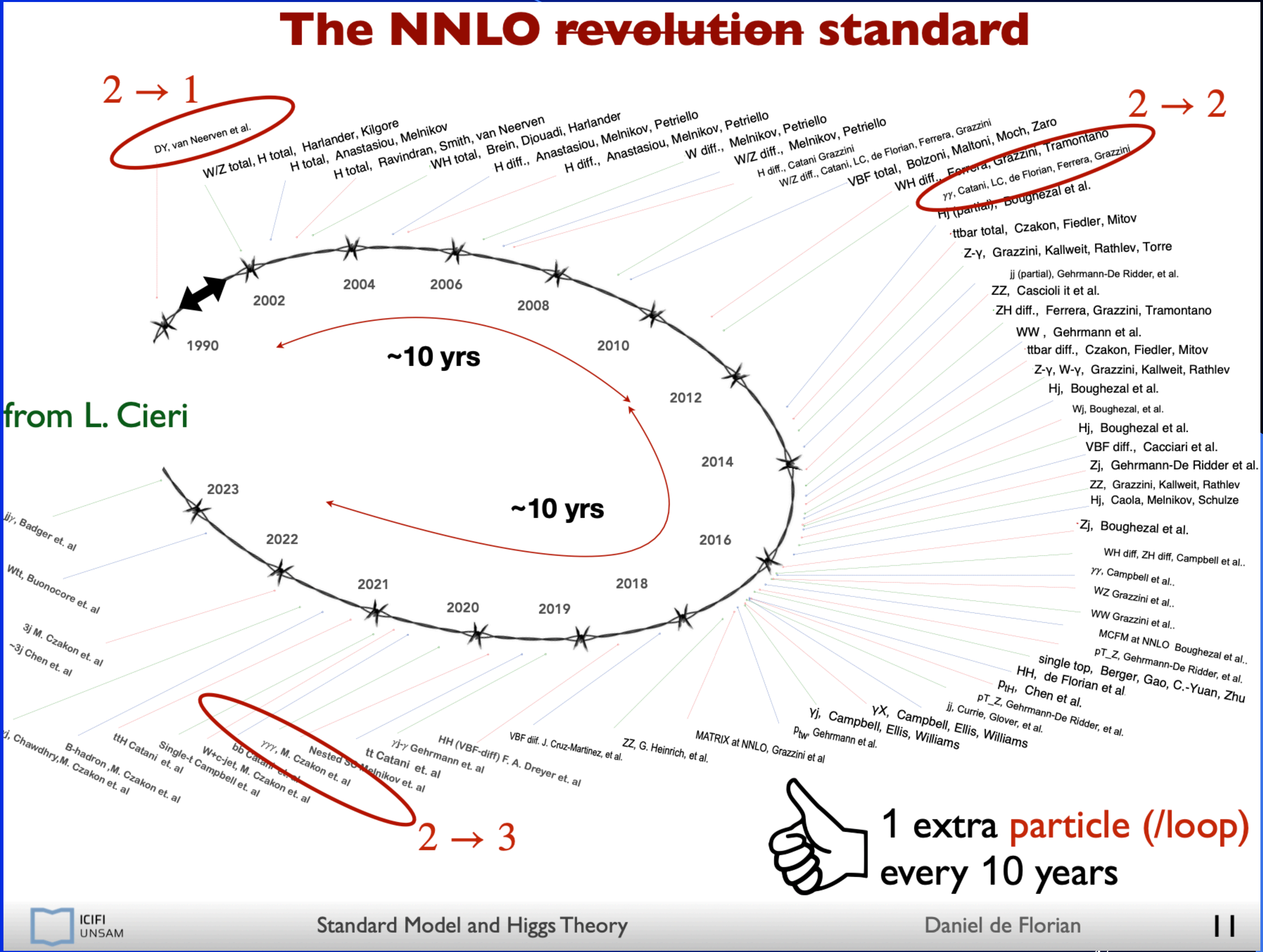
Three-loop diags



Types of frour-loop diags with electron loops



Progress of Theoretical Calculations



The NNLO ~~revolution~~ standard

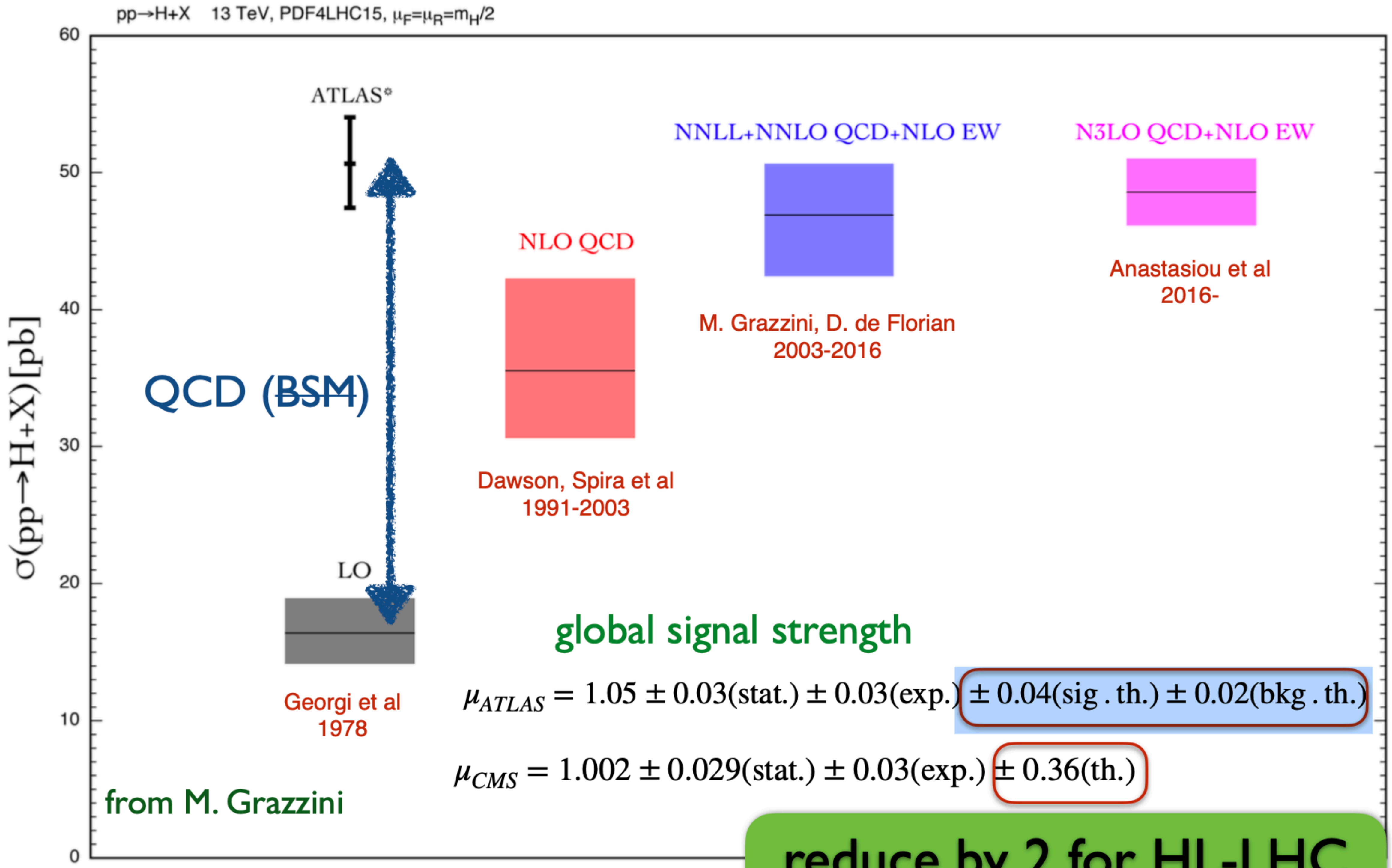
from L. Cieri

1 extra particle (/loop)
every 10 years

Standard Model and Higgs Theory

Daniel de Florian

Inclusive Higgs : an example of precision



global signal strength

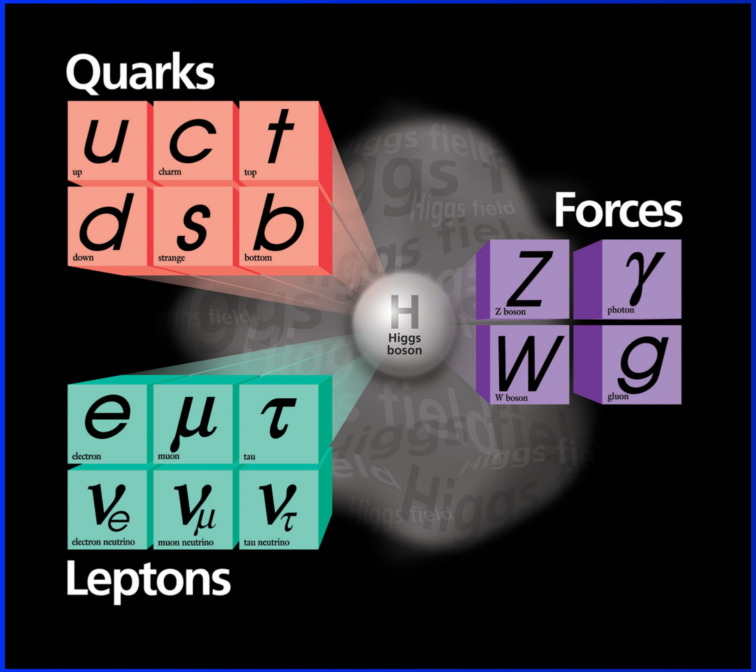
$$\mu_{ATLAS} = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \boxed{\pm 0.04(\text{sig . th.}) \pm 0.02(\text{bkg . th.})}$$

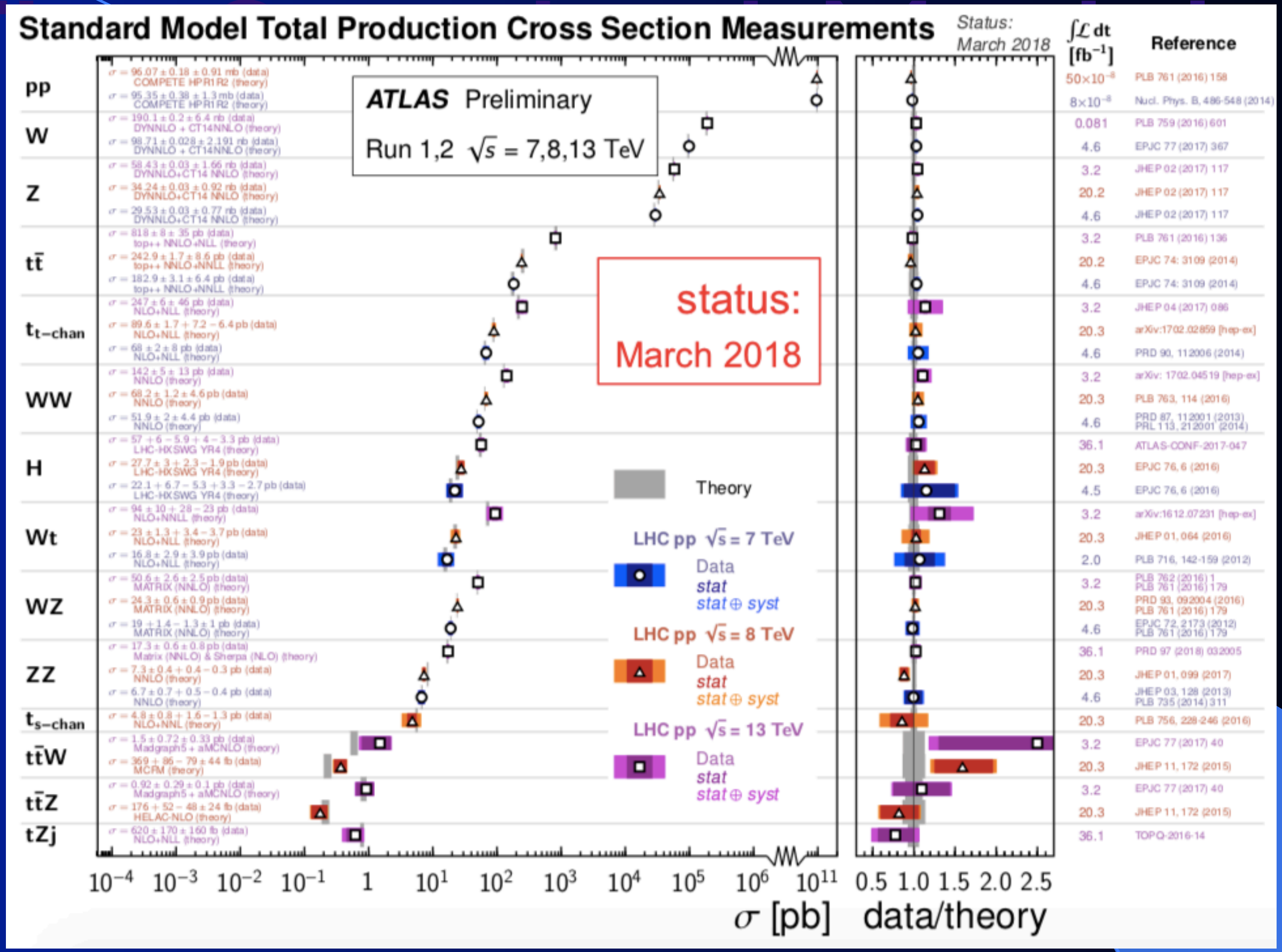
$$\mu_{CMS} = 1.002 \pm 0.029(\text{stat.}) \pm 0.03(\text{exp.}) \boxed{\pm 0.36(\text{th.})}$$

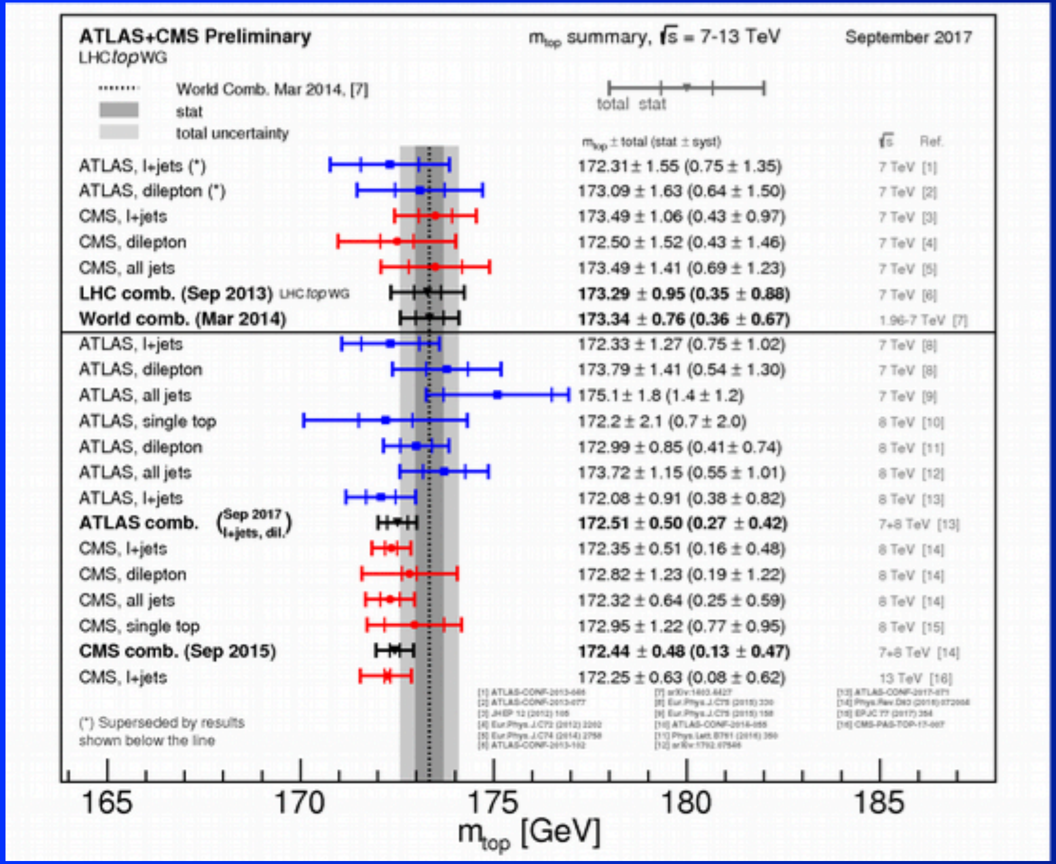
from M. Grazzini

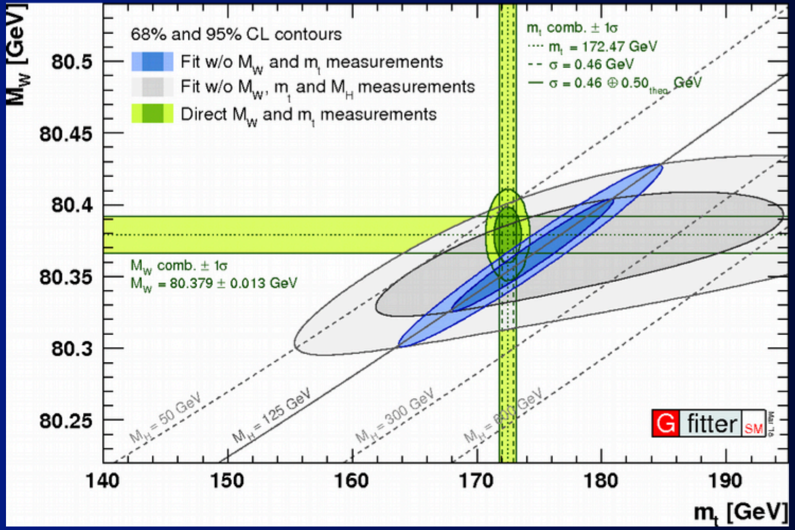
reduce by 2 for HL-LHC

THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS



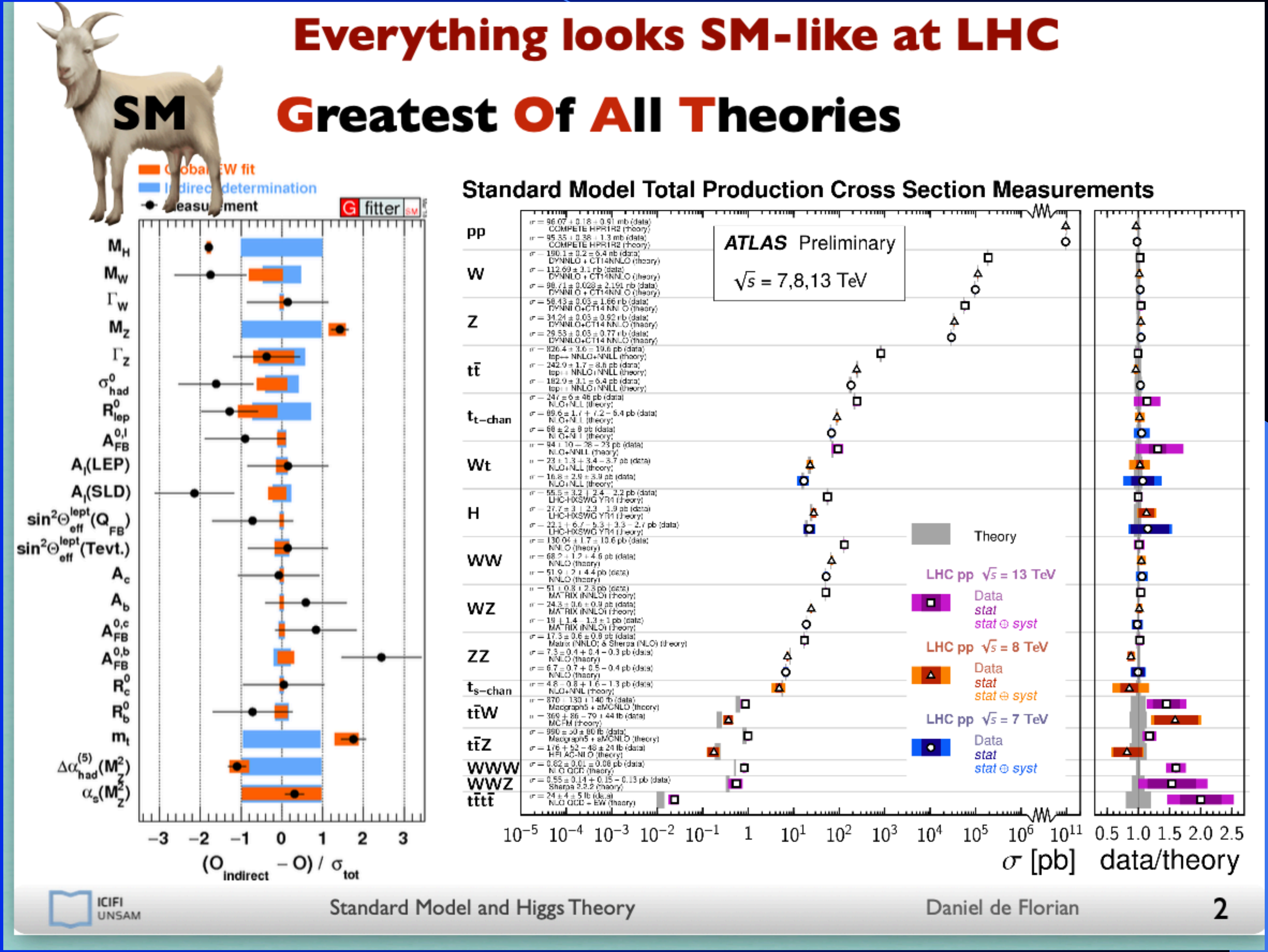






Extraordinary agreement between measurements and SM predictions

The Triumph of the Standard Model



Everything looks SM-like at LHC

SM Greatest Of All Theories

ICIFI UNSAM

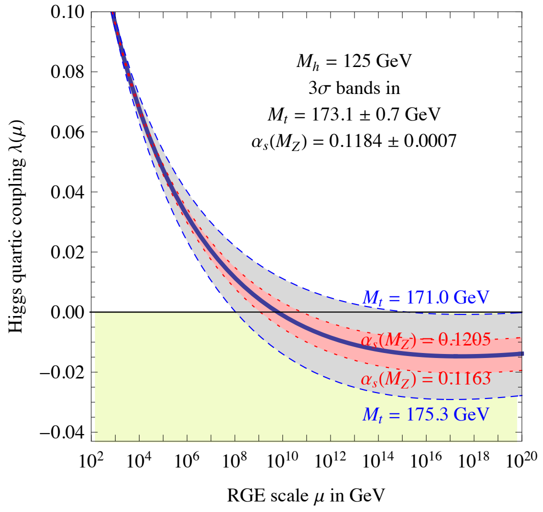
Standard Model and Higgs Theory

Daniel de Florian

THE PROBLEMS

- Quantum corrections can make the vacuum unstable

  - the whole construction of the SM may be in trouble being metastable or even unstable
  - the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and accuracy



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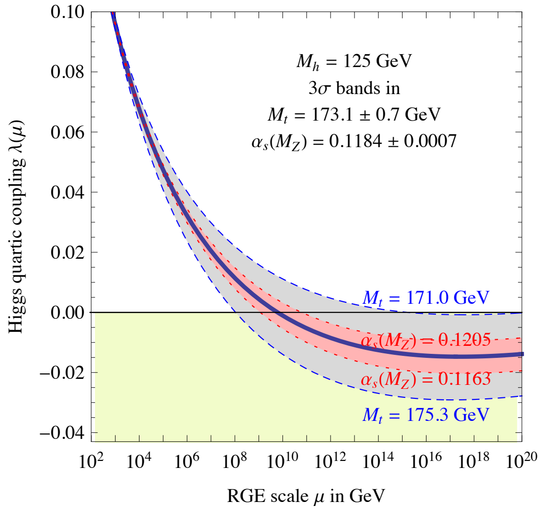

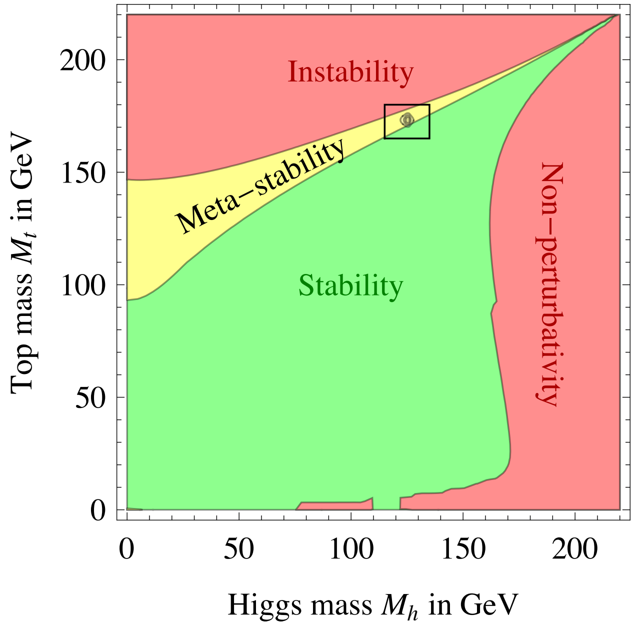

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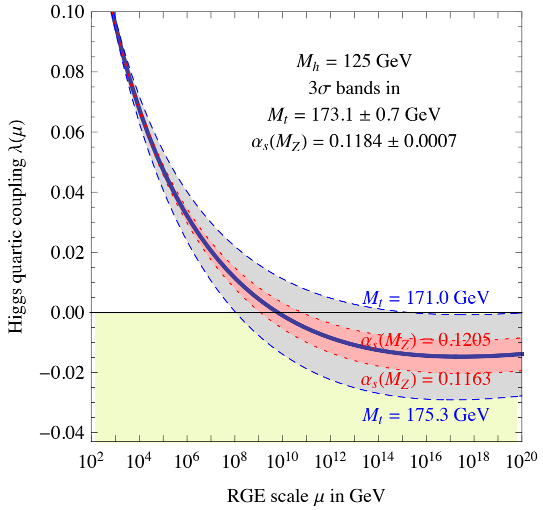

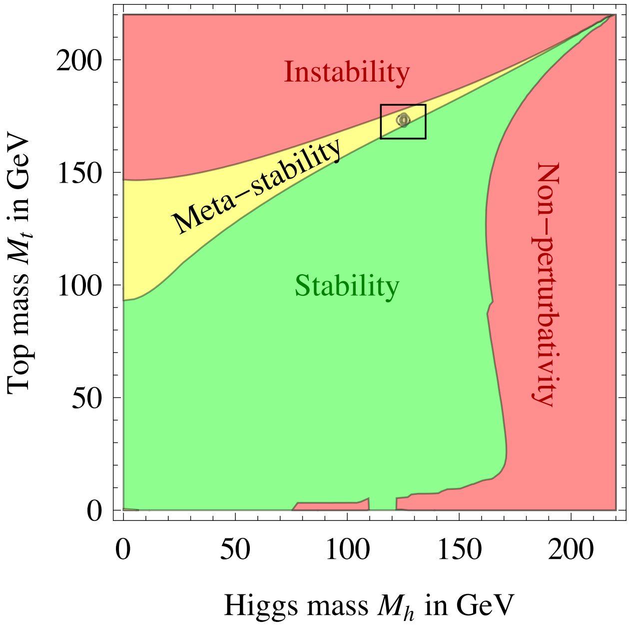

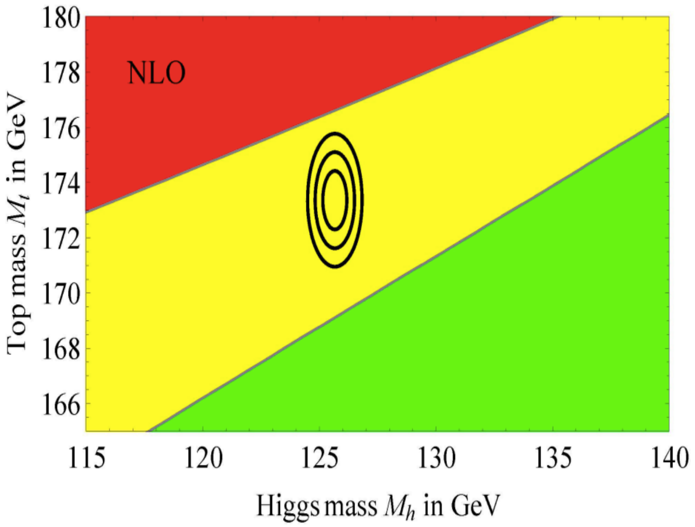

NLO

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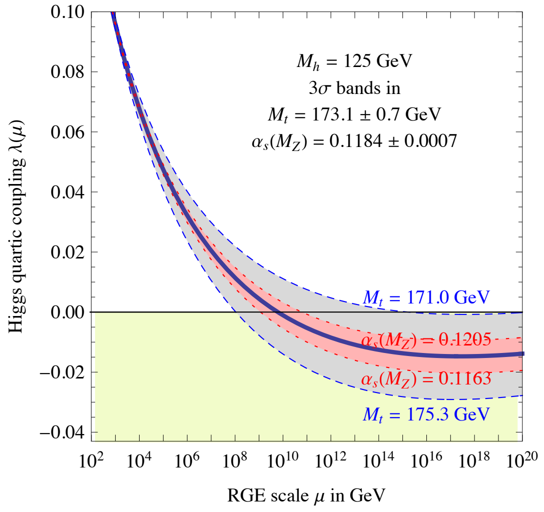
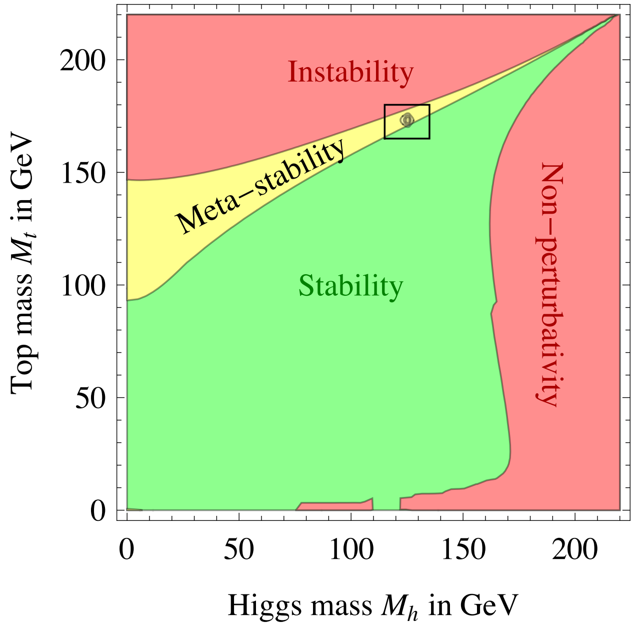
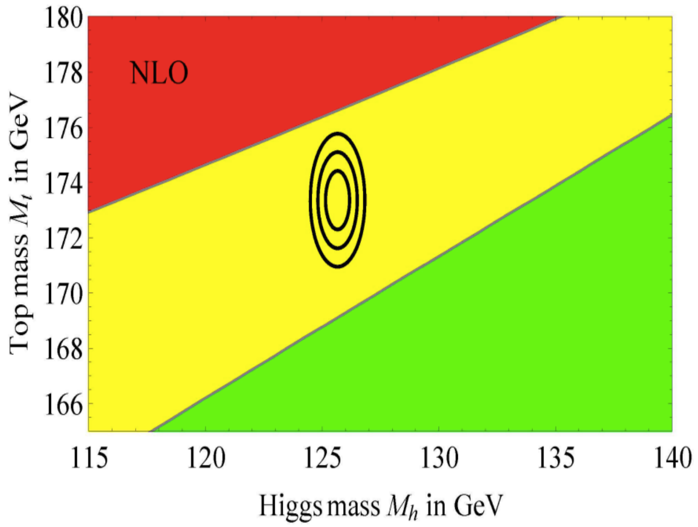
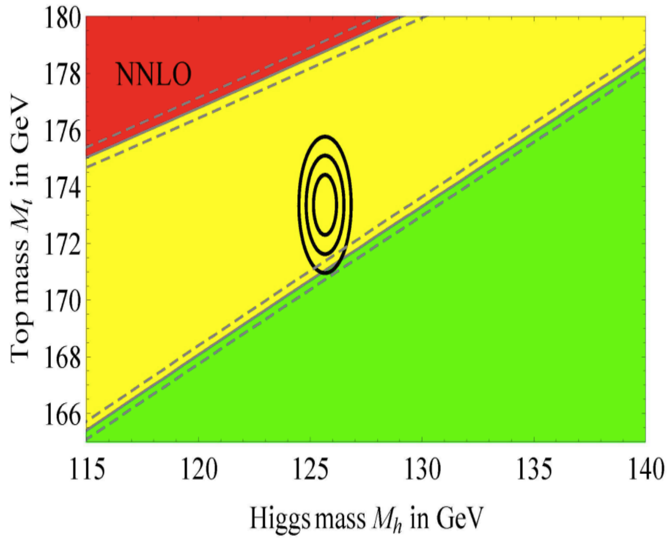






NLO



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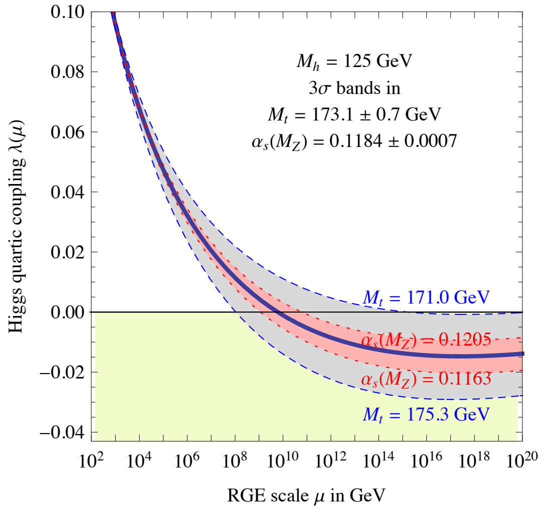
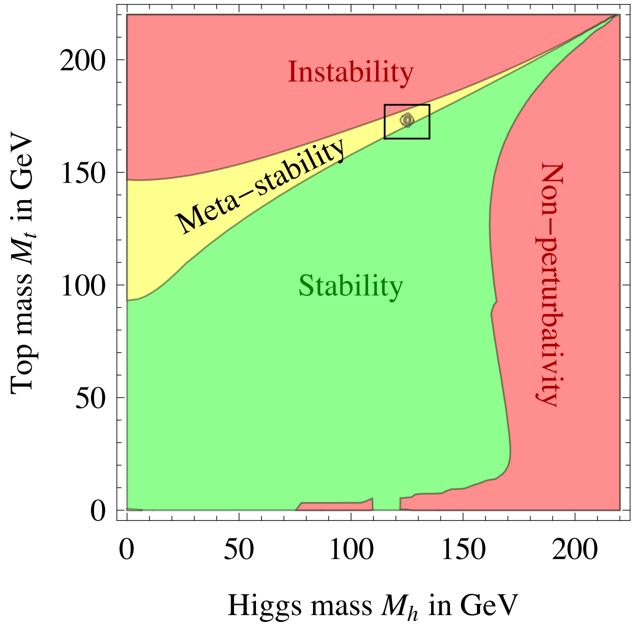
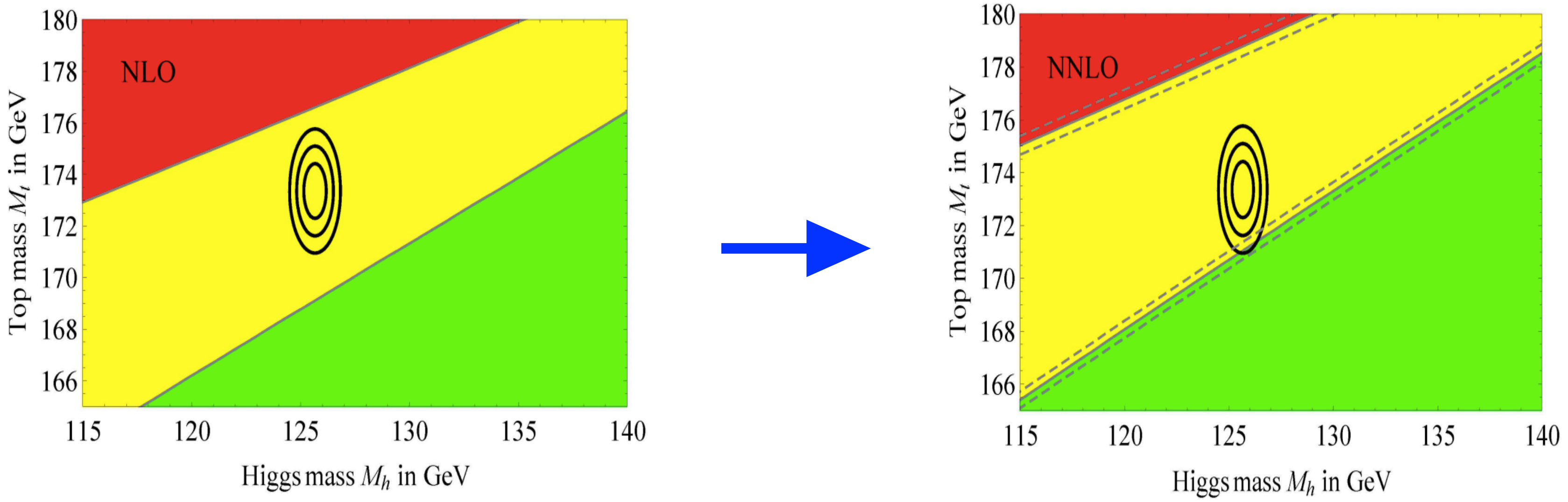






NLO NNLO

The way out might be the new physics at higher scale

THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

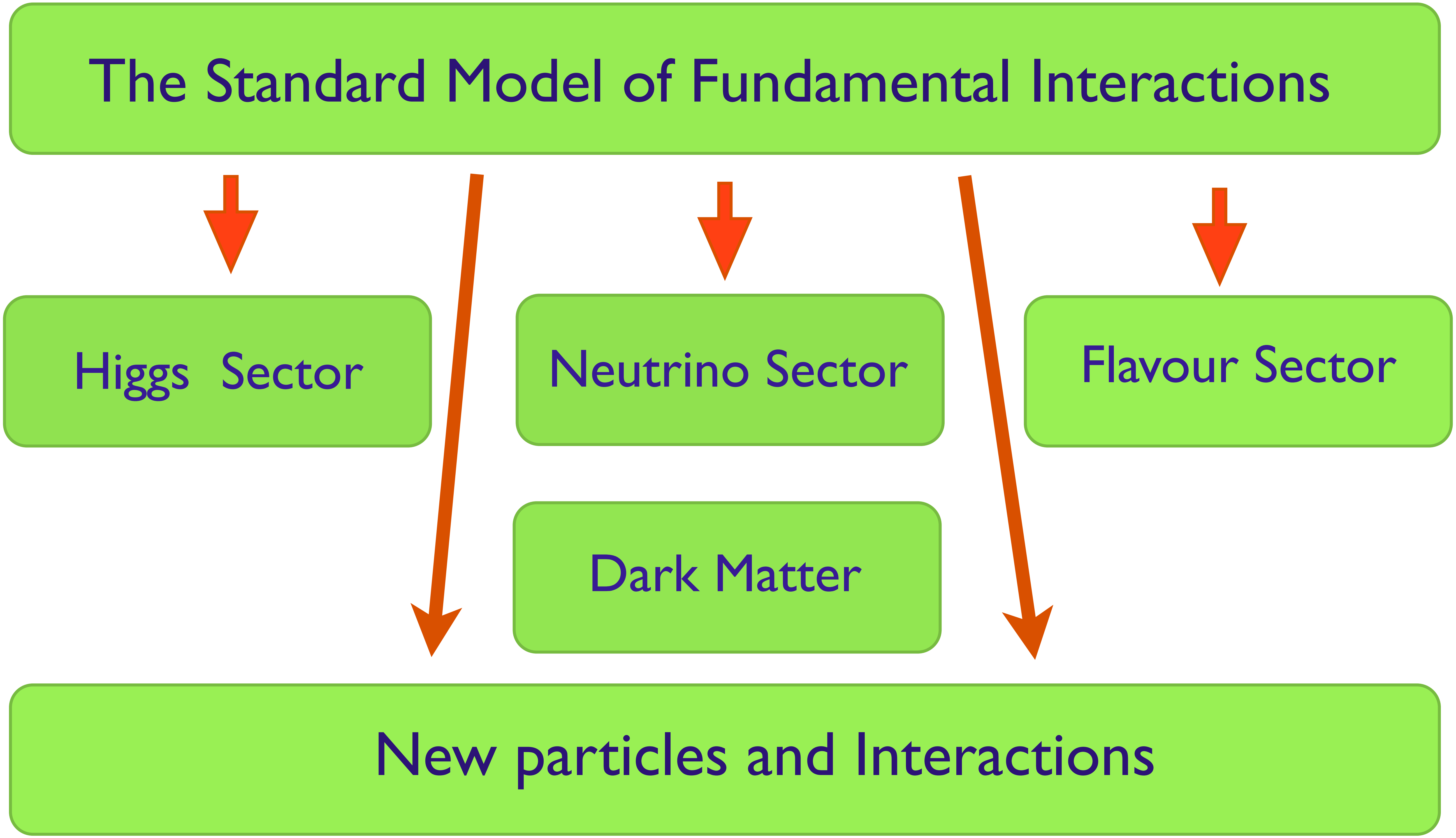
- With the Higgs Boson discovery the Standard Model is completed !
- Why are we not satisfied and think that new physics exists and new discoveries will come?

THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

- With the Higgs Boson discovery the Standard Model is completed !
- Why are we not satisfied and think that new physics exists and new discoveries will come?

- There are conceptional problems which require a critical view beyond the SM
- There are small discrepancies which might grow up to become a problem for the SM
- It is hard to believe that the quest for the miracle of Nature is over

THE STANDARD MODEL: THE WAYS BEYOND



The Standard Model of Fundamental Interactions

Higgs Sector

Neutrino Sector

Flavour Sector

Dark Matter

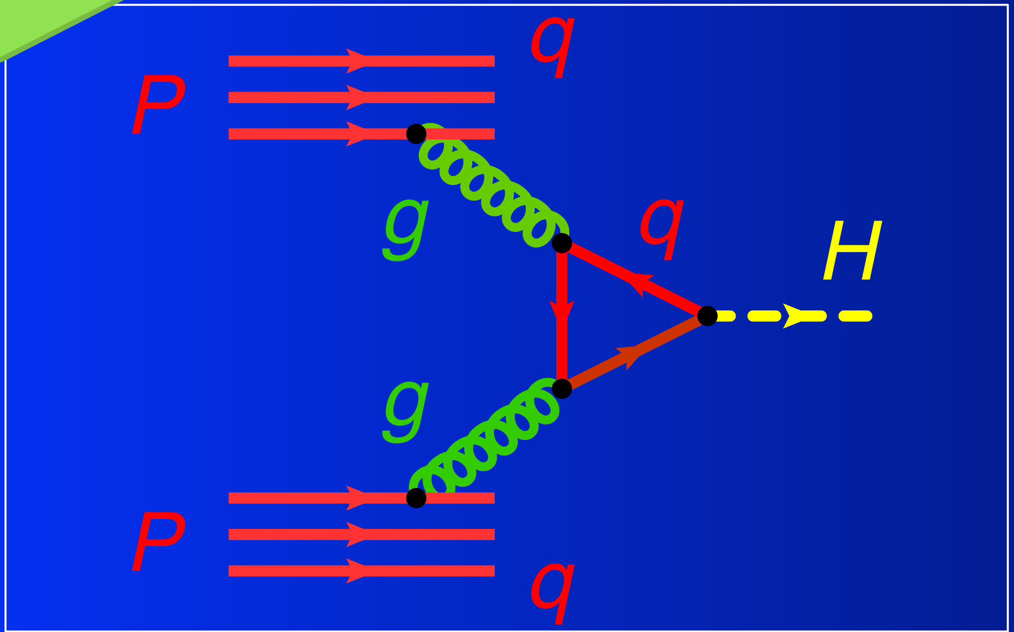
New particles and Interactions

Di very of the Higgs Boson

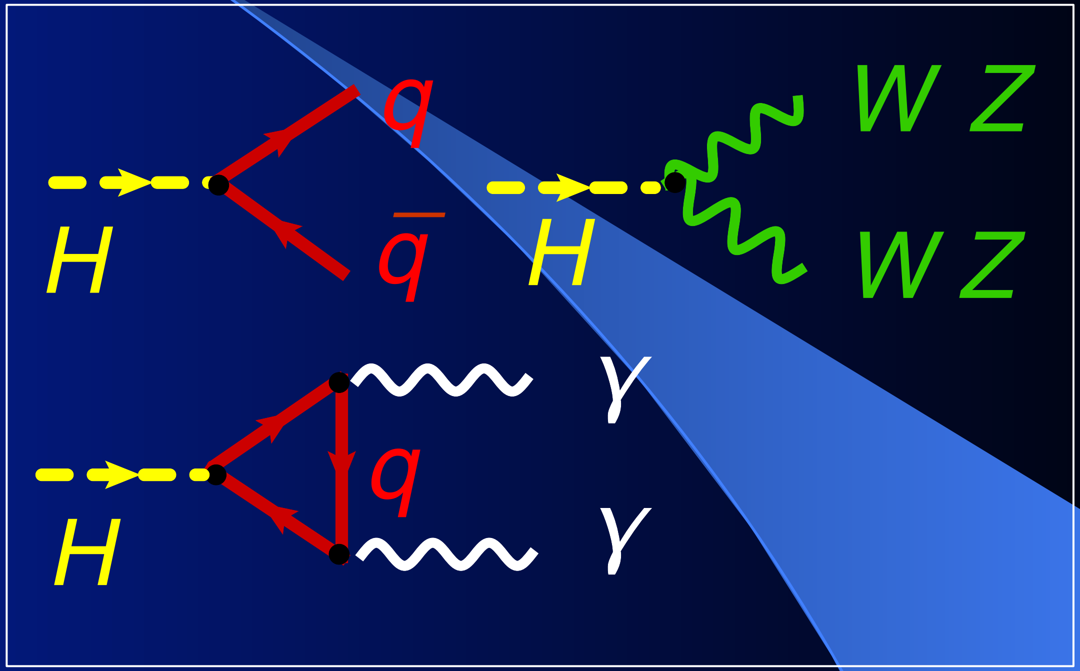
Higgs Sector

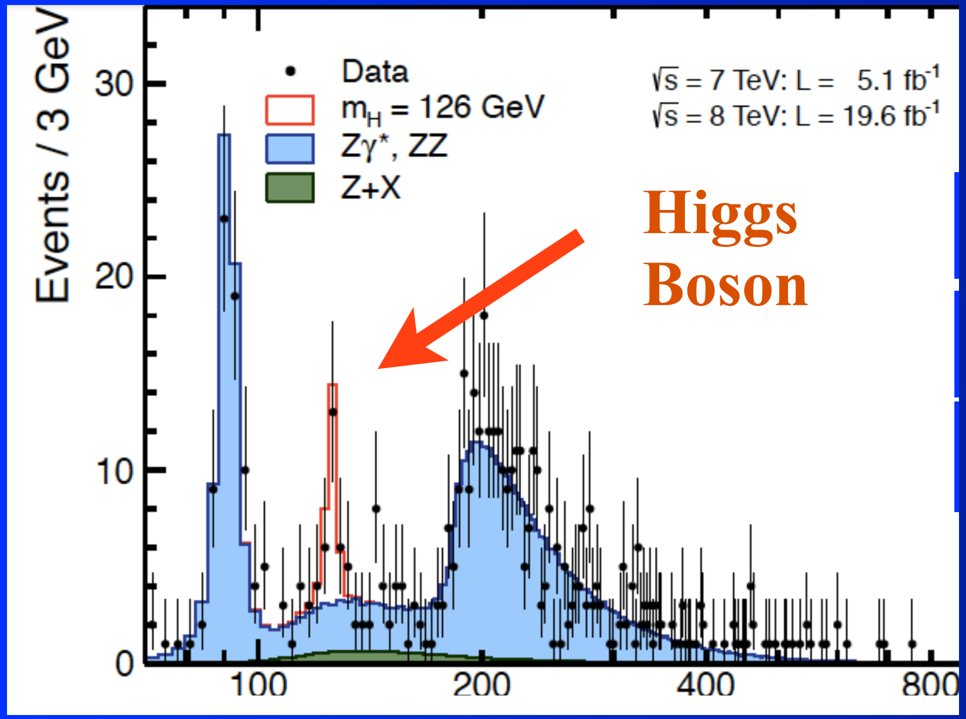
CERN, Large Hadron Collider, 2012

n at Hadron Collider

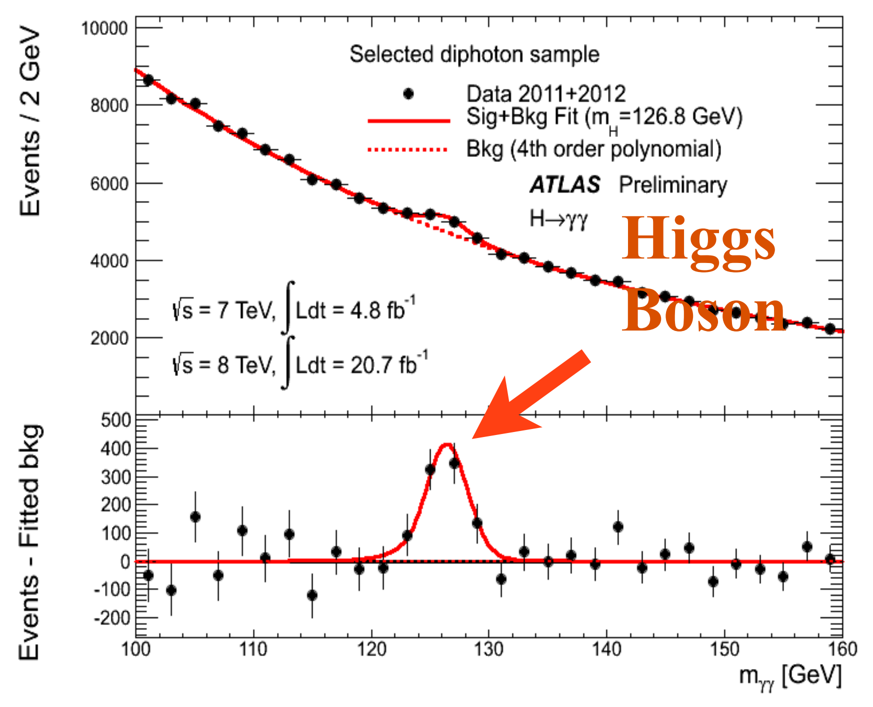


Decay modes

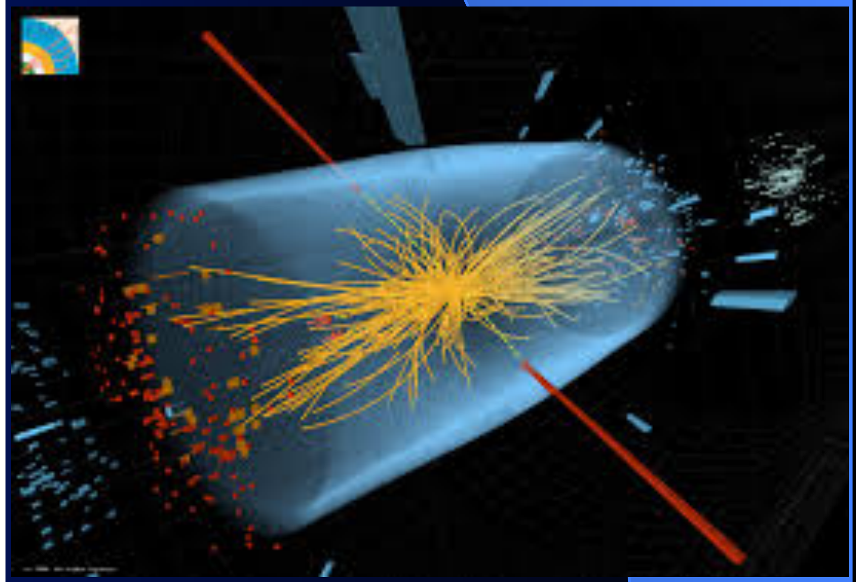




Higgs Boson

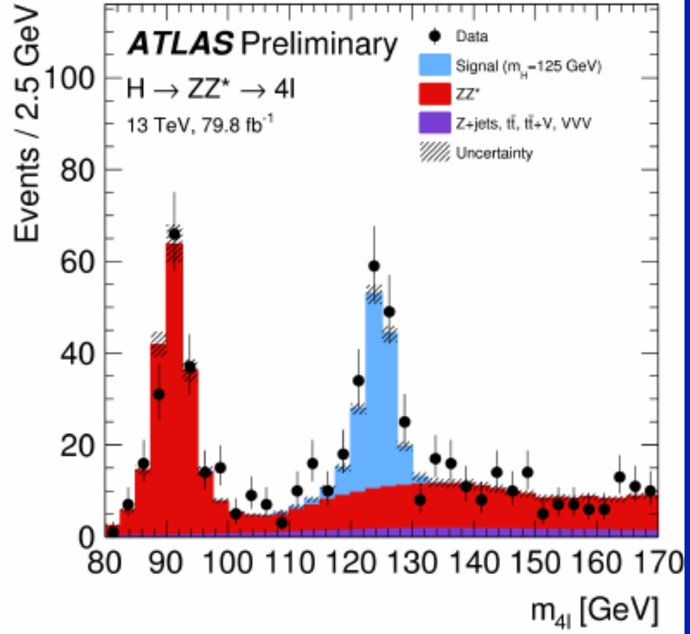


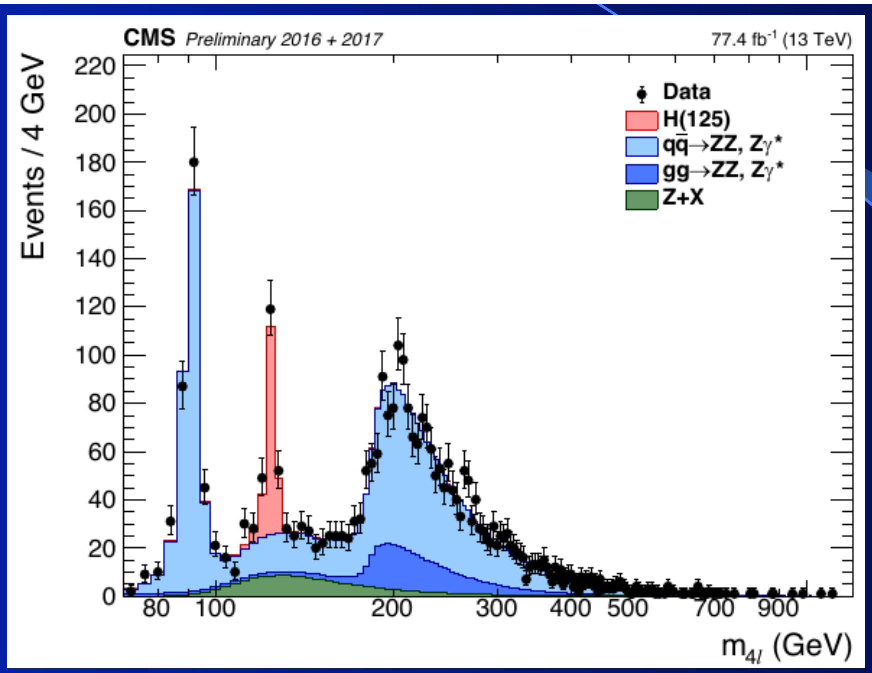
Higgs Boson

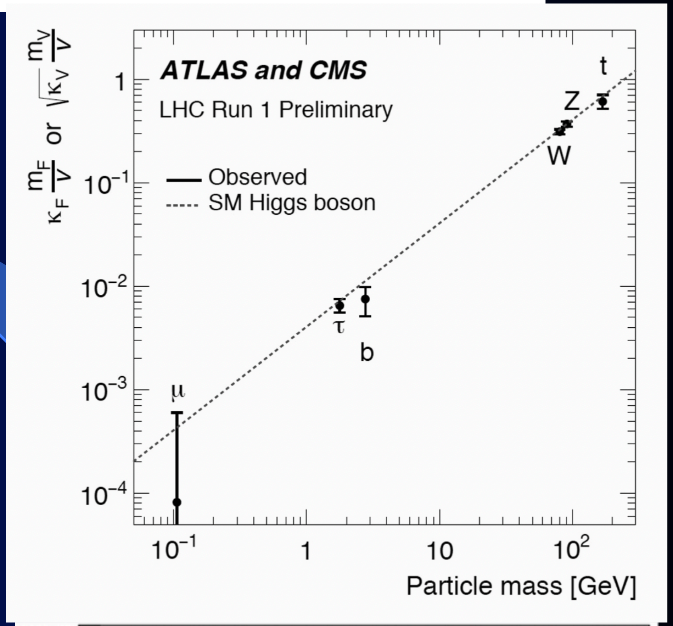


Higgs bosons - entering precision era

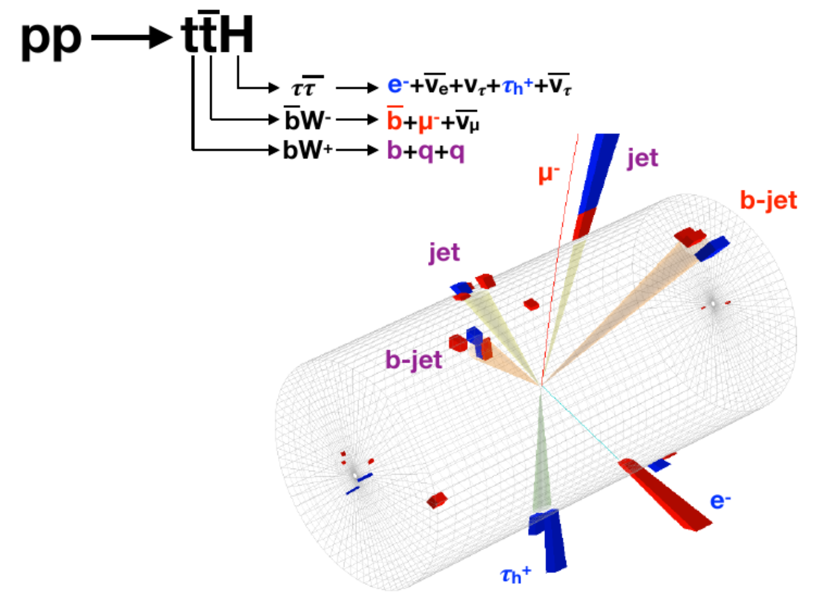
Run-2 analyses with 80 fb^{-1} for the first time – higher precision is coming!

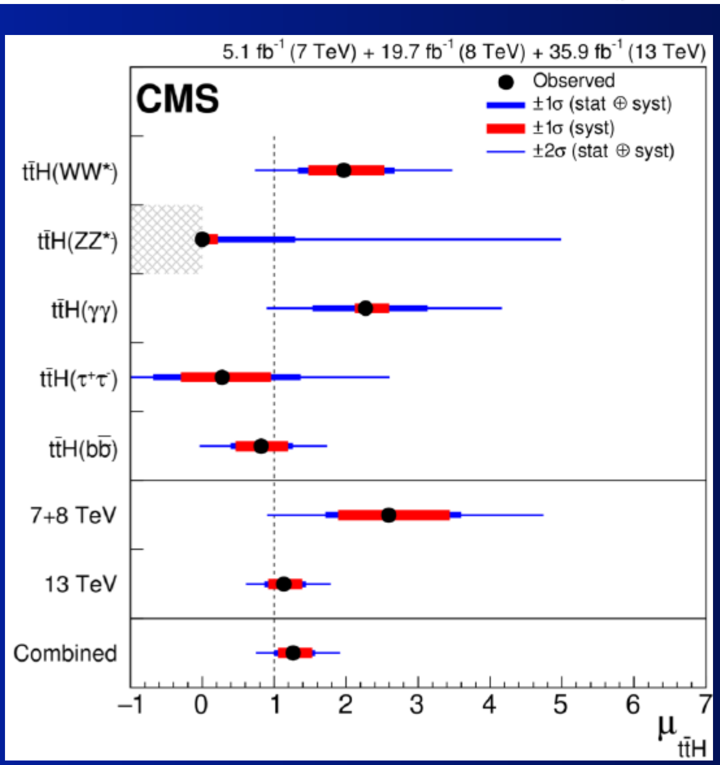


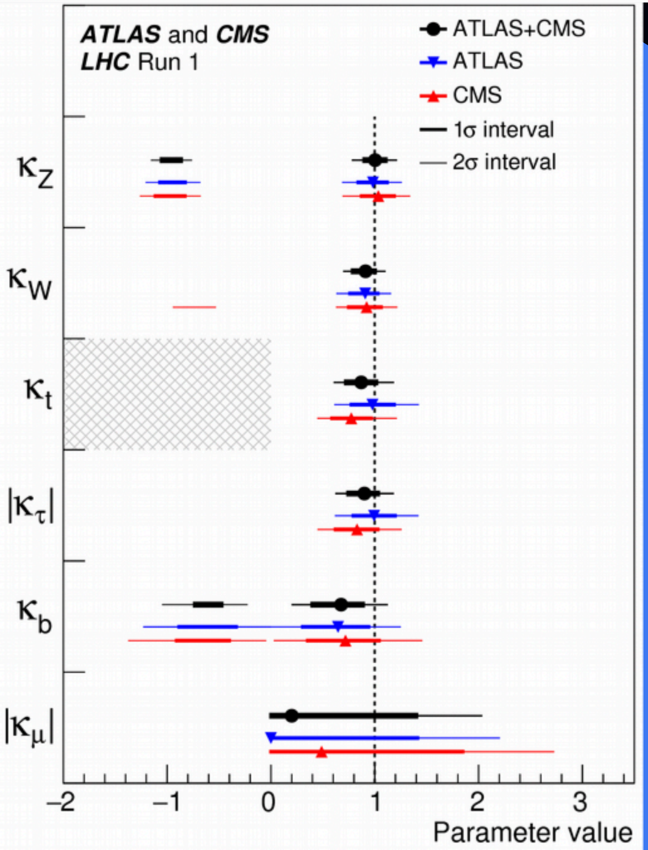




ttH observation







NEW PARTICLES

EXTENDED HIGGS SECTOR

NEW PARTICLES

EXTENDED HIGGS SECTOR

Is it the SM Higgs boson or not?

What are the alternatives?

A. Singlet extension
B. Higgs doublet extension
C. Higgs triplet extension

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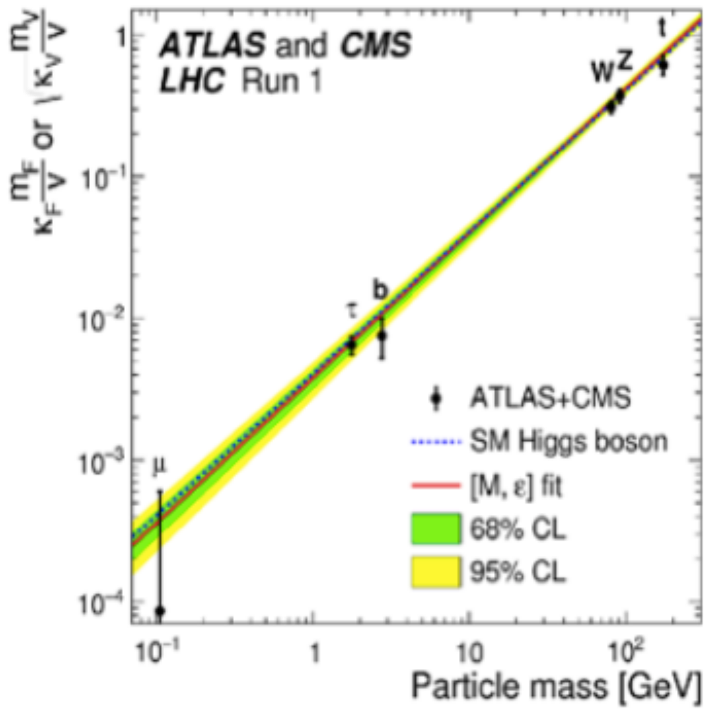
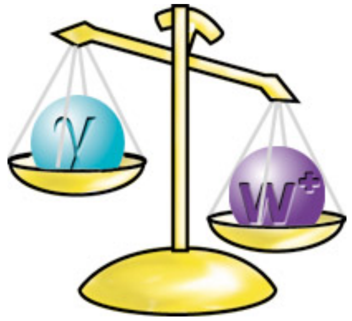
- Probe deviations from the SM Higgs couplings



EXTENDED HIGGS SECTOR



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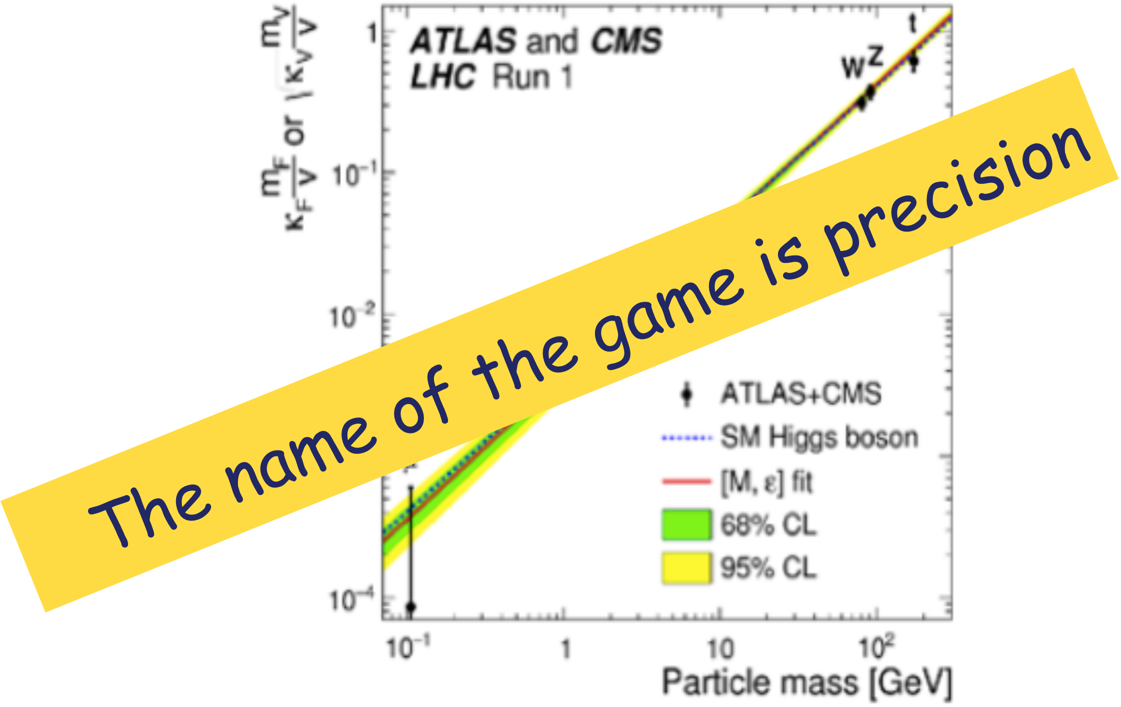

The name of the game is precision

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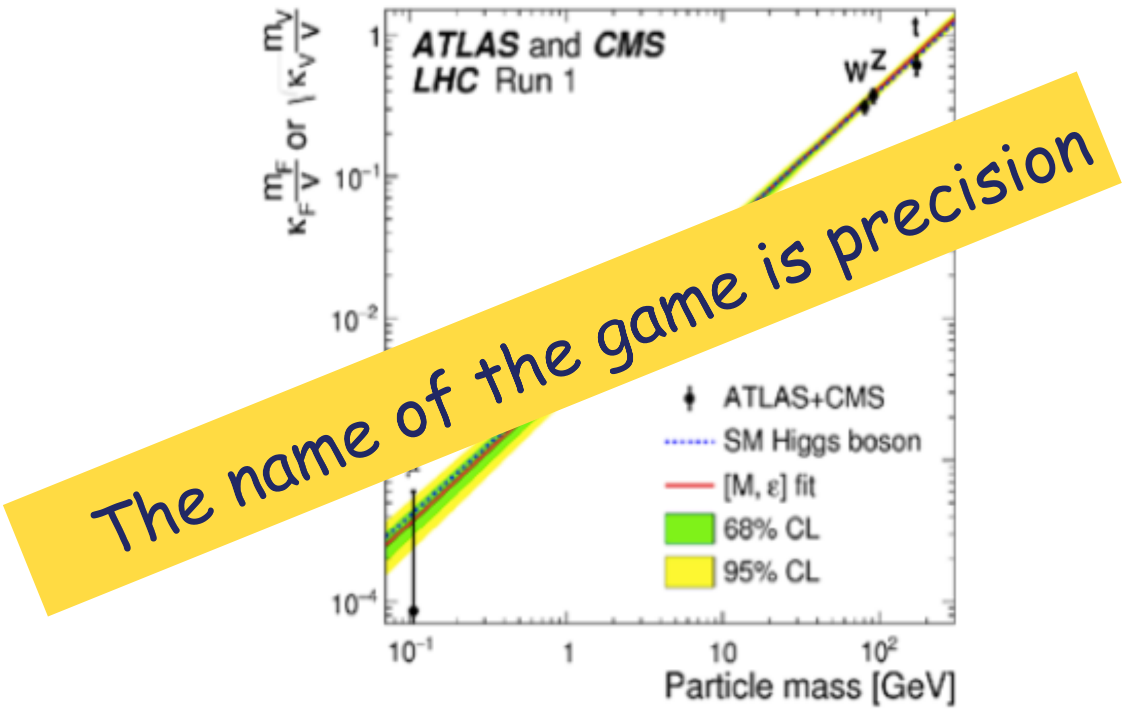

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- Perform direct search for additional scalars

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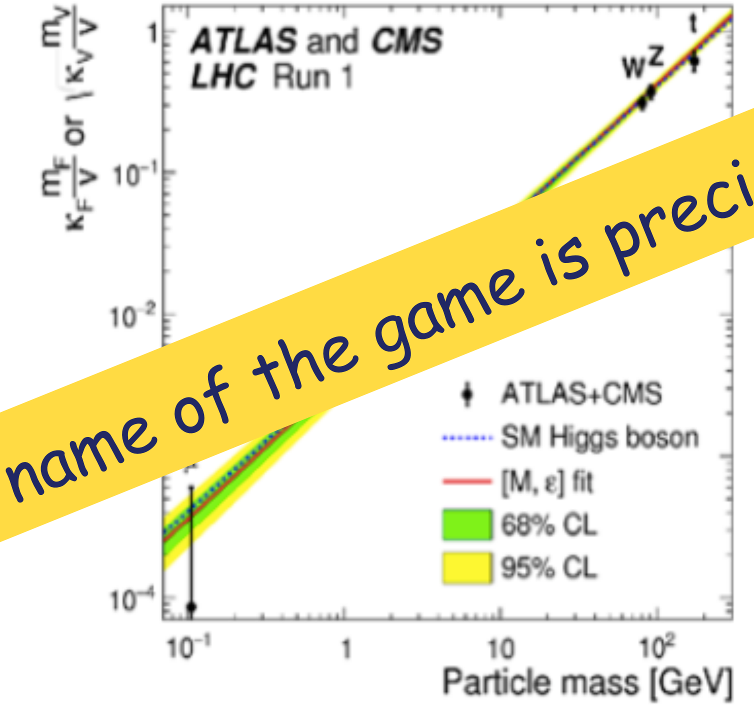

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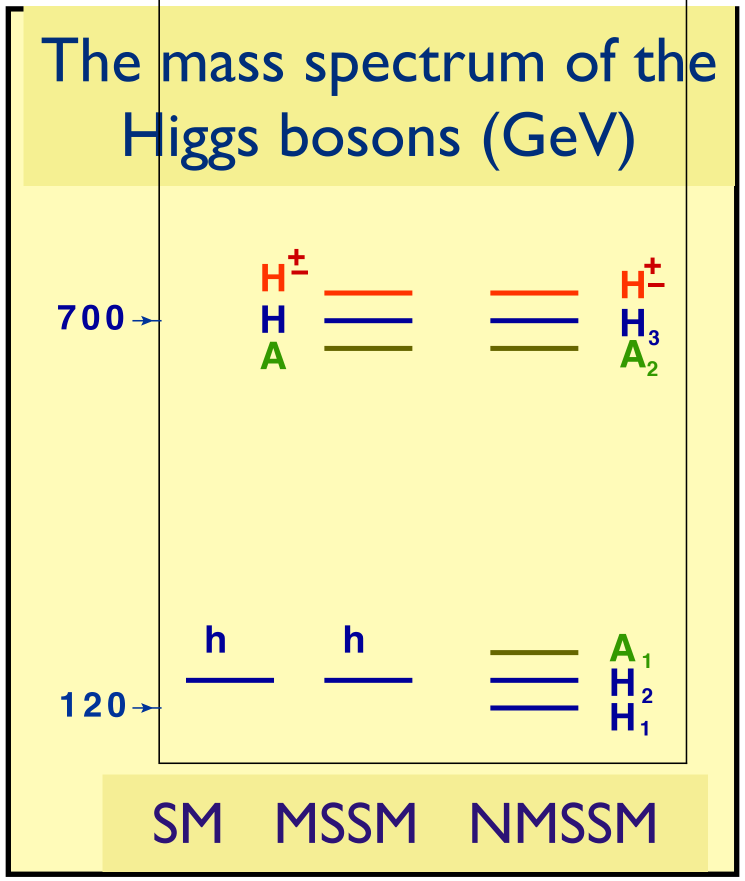

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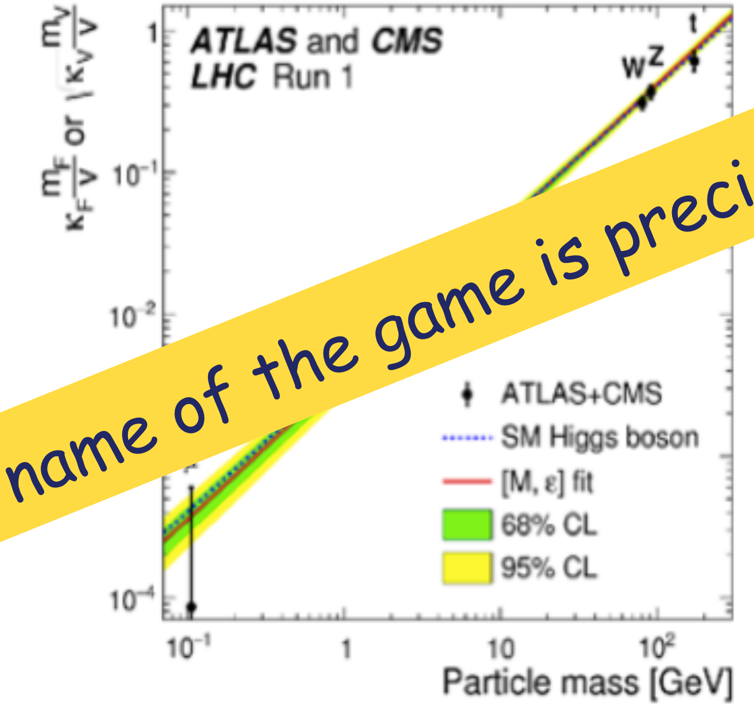


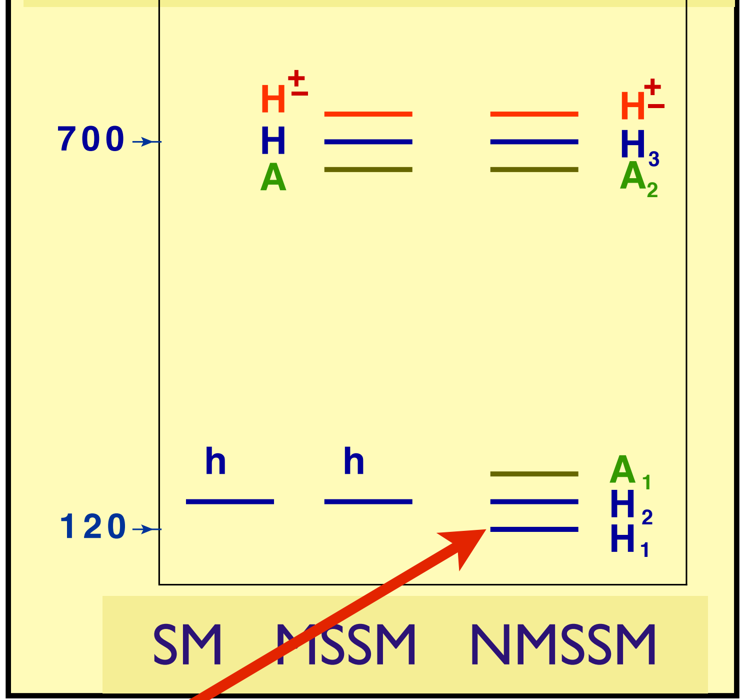
The name of the game is precision

EXTENDED HIGGS SECTOR

A. Singlet extension
B. Higgs doublet extension
C. Higgs triplet extension

- Perform direct search for additional scalars

The mass spectrum of the Higgs bosons (GeV)



We may have found one of these states

NEW PARTICLES

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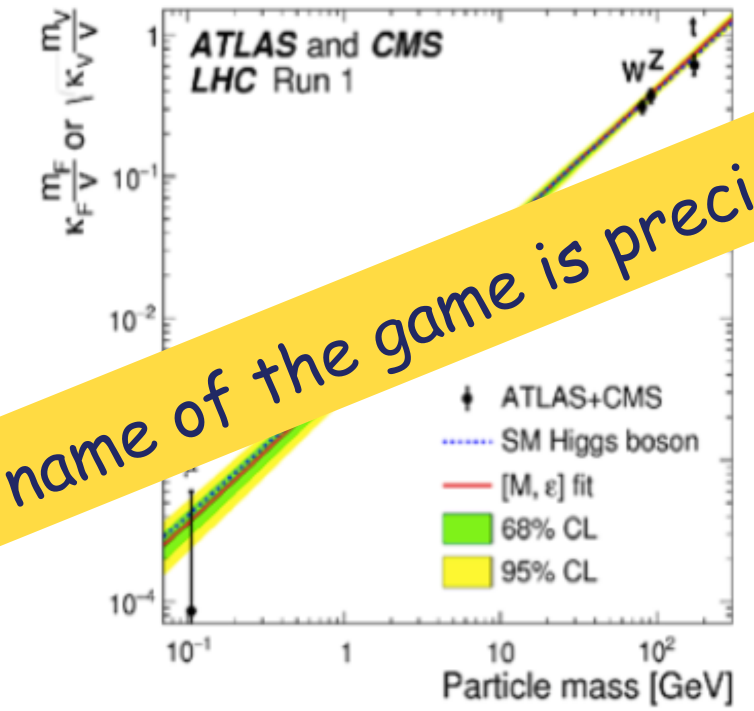


The name of the game is precision

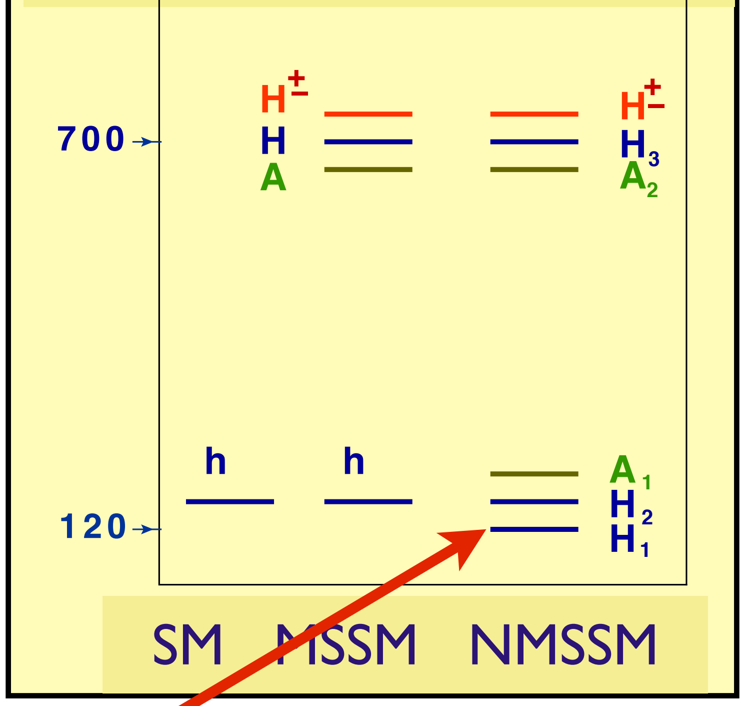
- The Higgs physics has already started
- This is the task of vital importance.
- May require the electron-positron collider

EXTENDED HIGGS SECTOR

A. Singlet extension
B. Higgs doublet extension
C. Higgs triplet extension

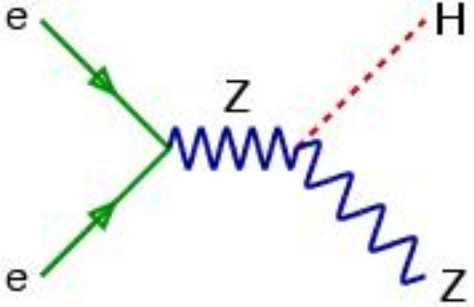
- Perform direct search for additional scalars

The mass spectrum of the Higgs bosons (GeV)



We may have found one of these states

PRECISION PHYSICS OF THE HIGGS BOSONS

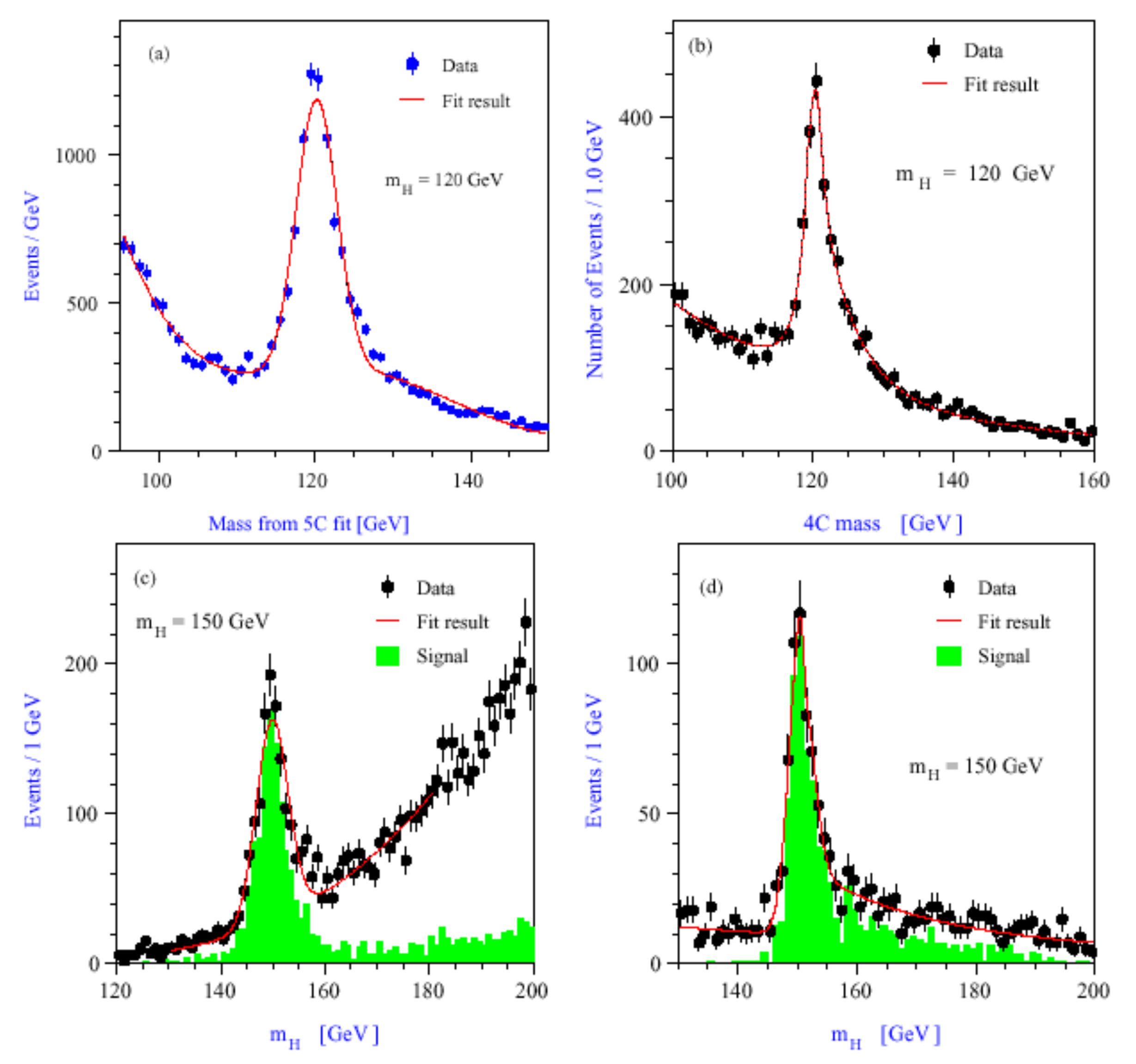


$\rightarrow b\bar{b}q\bar{q}$

ee -> HZ diff. decay channels

Int Linear Collider

$\rightarrow W^+W^-q\bar{q}$

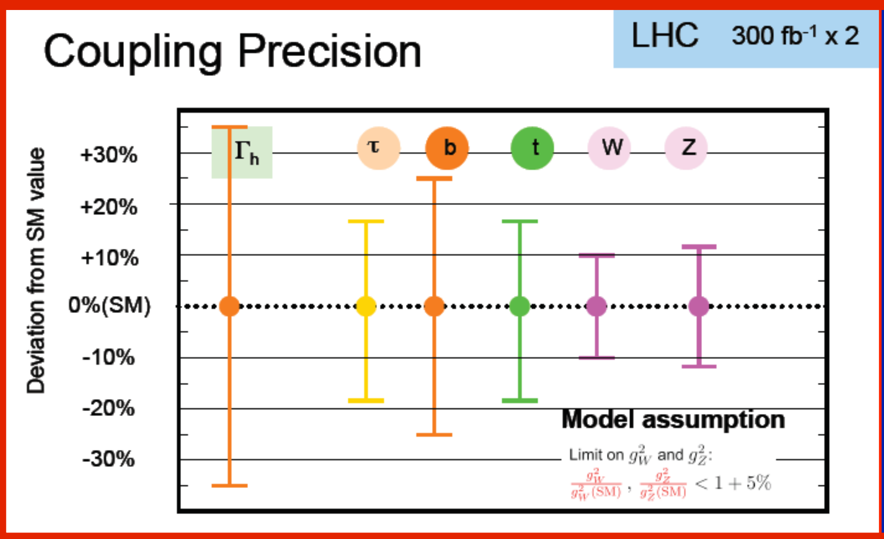


$\rightarrow q\bar{q}\ell^+\ell^-$

$\Delta m_H =$ 40 MeV

$\rightarrow W^+W^-\ell^+\ell^-$

$\Delta m_H =$ 70 MeV



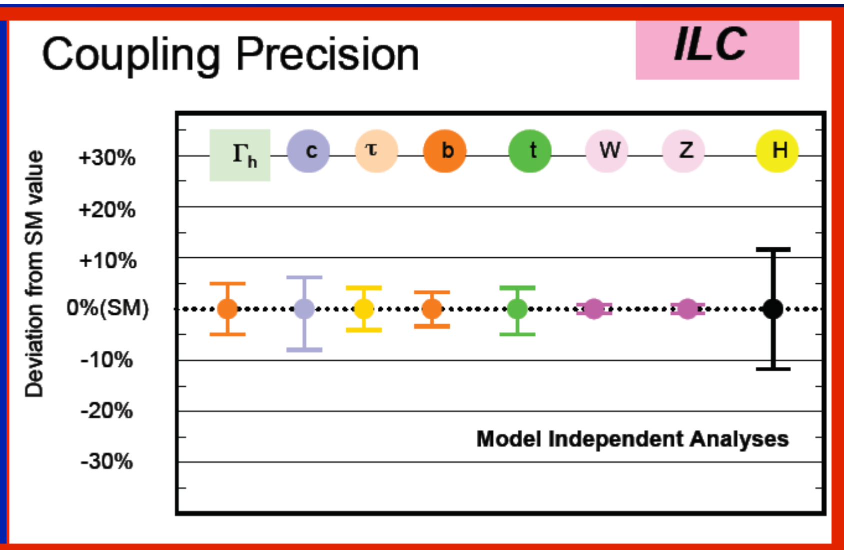
Coupling Precision

LHC 300 fb⁻¹ x 2

Model assumption

Limit on g_W^2 and g_Z^2:

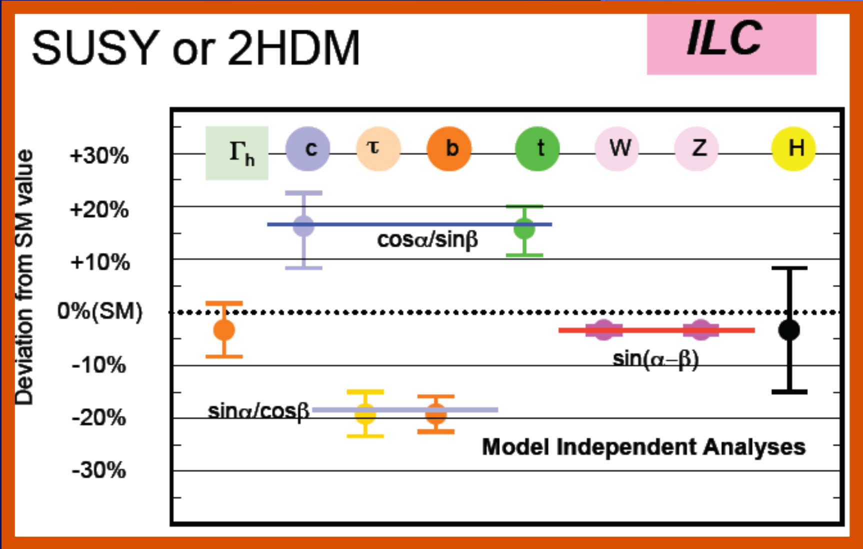
$\frac{g_W^2}{g_W^2(\mathrm{SM})}, \frac{g_Z^2}{g_Z^2(\mathrm{SM})} < 1+5\%$



Coupling Precision

ILC

Model Independent Analyses



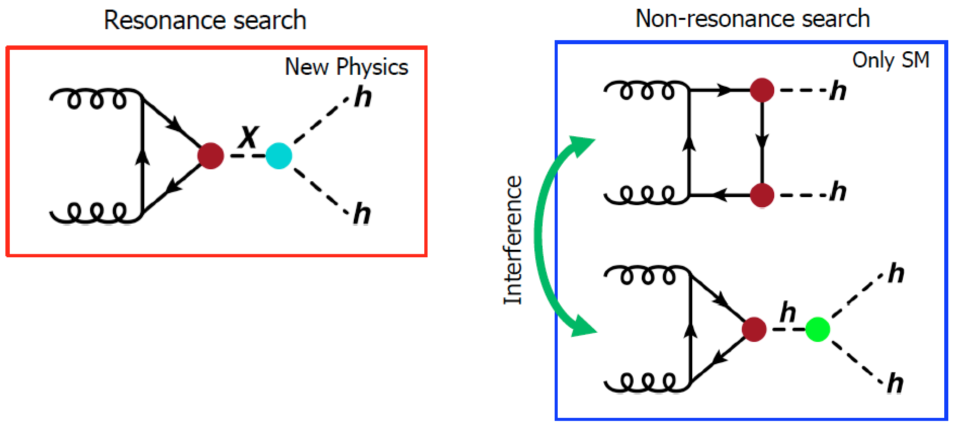
SUSY or 2HDM

ILC

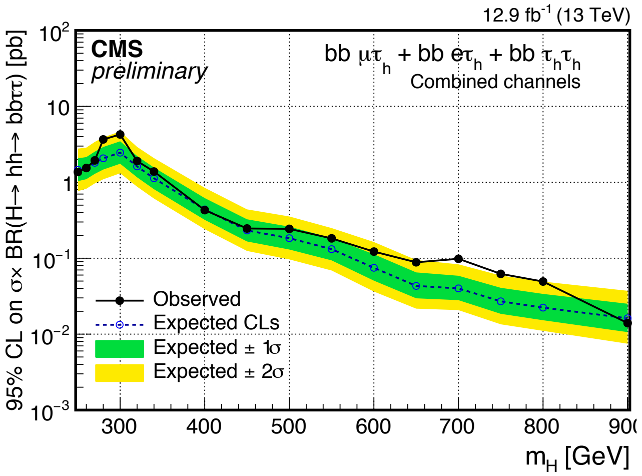
Model Independent Analyses

EXTRA HIGGS BOSONS

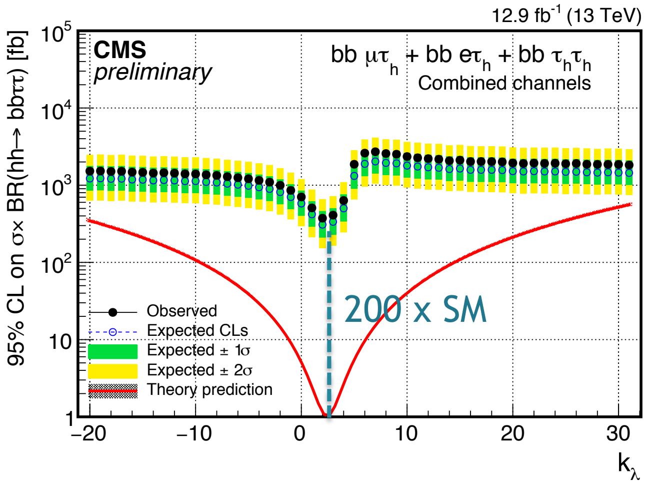
Higgs→hh→bbττ



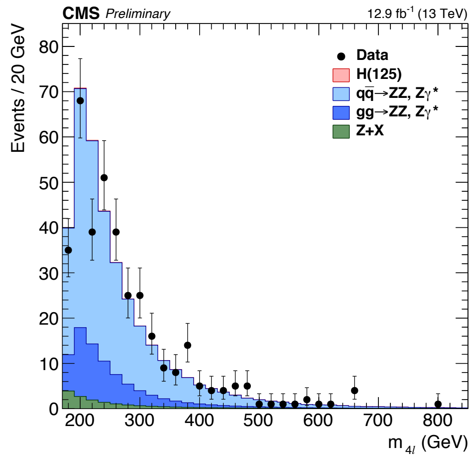
Resonant

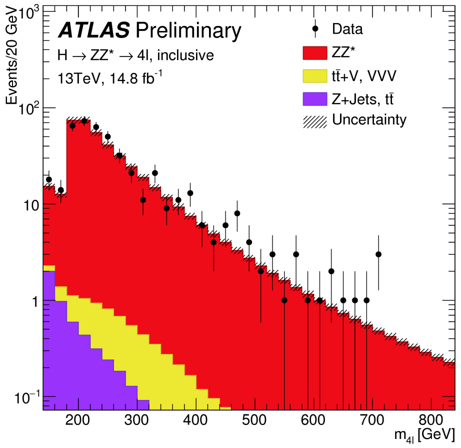


Non-Resonant

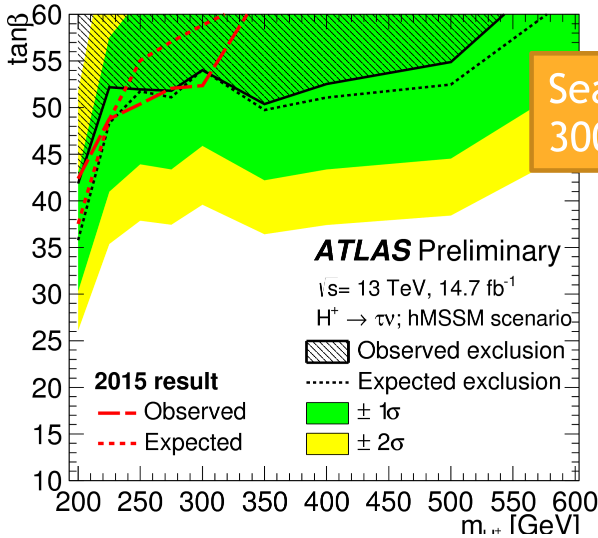


Heavy Higgs→ZZ→4l



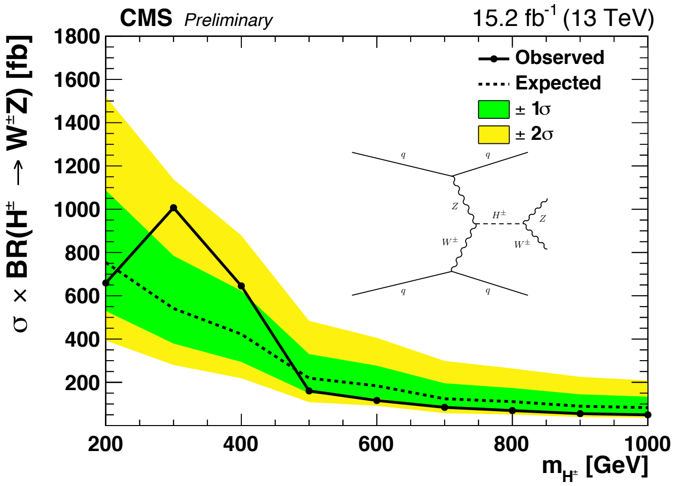


Charged Higgs

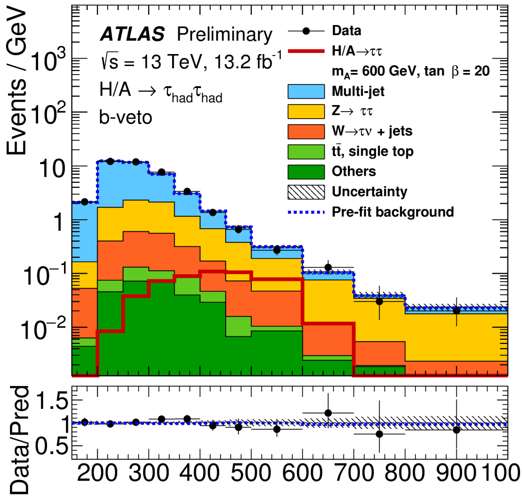


Search for H±→tb
300<m$_{H^\pm}$<1000 GeV

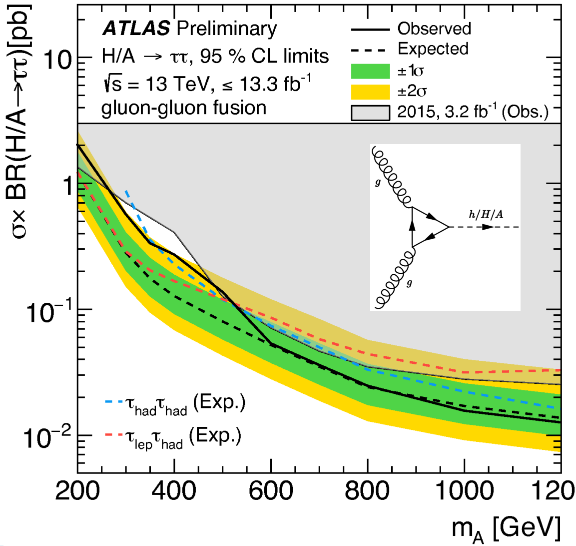
Search for H±WZ



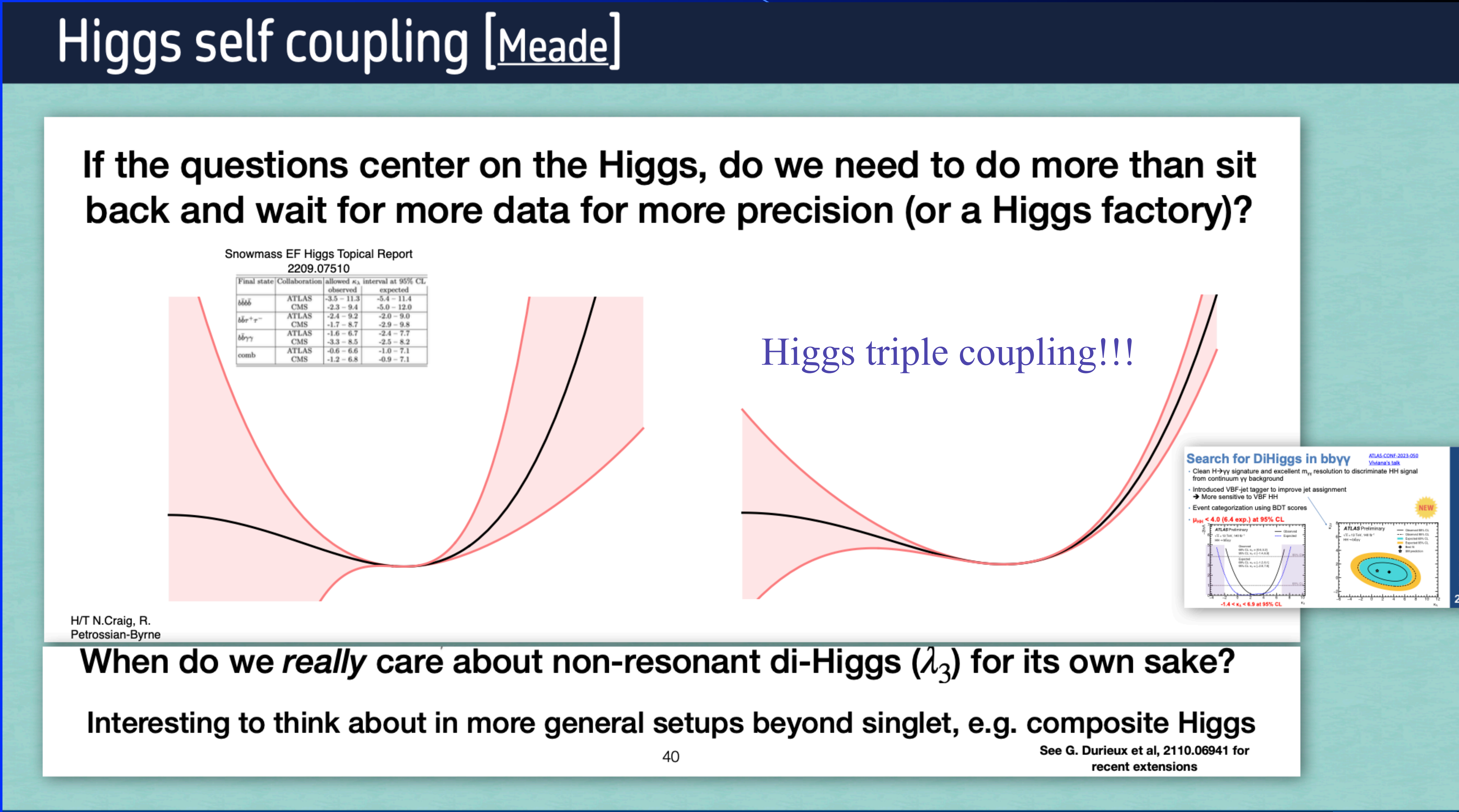
Heavy Higgs→ττ



$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}$$



The Higgs potential - test of the SM



Higgs self coupling [Meade]

If the questions center on the Higgs, do we need to do more than sit back and wait for more data for more precision (or a Higgs factory)?

Snowmass EF Higgs Topical Report
2209.07510

Final state	Collaboration	allowed κ_λ interval at 95% CL	
		observed	expected
$b\bar{b}b\bar{b}$	ATLAS CMS	-3.5 – 11.3 -2.3 – 9.4	-5.4 – 11.4 -5.0 – 12.0
$b\bar{b}\tau^+\tau^-$	ATLAS CMS	-2.4 – 9.2 -1.7 – 8.7	-2.0 – 9.0 -2.9 – 9.8
$b\bar{b}\gamma\gamma$	ATLAS CMS	-1.6 – 6.7 -3.3 – 8.5	-2.4 – 7.7 -2.5 – 8.2
comb	ATLAS CMS	-0.6 – 6.6 -1.2 – 6.8	-1.0 – 7.1 -0.9 – 7.1

Higgs triple coupling!!!

Search for DiHiggs in bbγγ ATLAS-CONF-2023-050 Viviana's talk

- Clean H→γγ signature and excellent $m_{\gamma\gamma}$ resolution to discriminate HH signal from continuum γγ background
- Introduced VBF-jet tagger to improve jet assignment
  ➔ More sensitive to VBF HH
- Event categorization using BDT scores
- μ_{HH} < 4.0 (6.4 exp.) at 95% CL

-1.4 < κ_λ < 6.9 at 95% CL

H/T N.Craig, R. Petrossian-Byrne

When do we *really* care about non-resonant di-Higgs (λ_3) for its own sake?

Interesting to think about in more general setups beyond singlet, e.g. composite Higgs

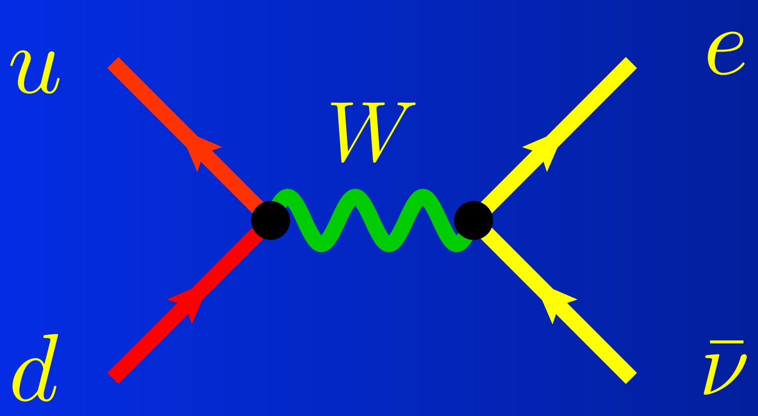
See G. Durieux et al, 2110.06941 for recent extensions

Neutrino Sector

Neutrino-misterious particle

Neutrino is created in the process of weak decays of hadrons

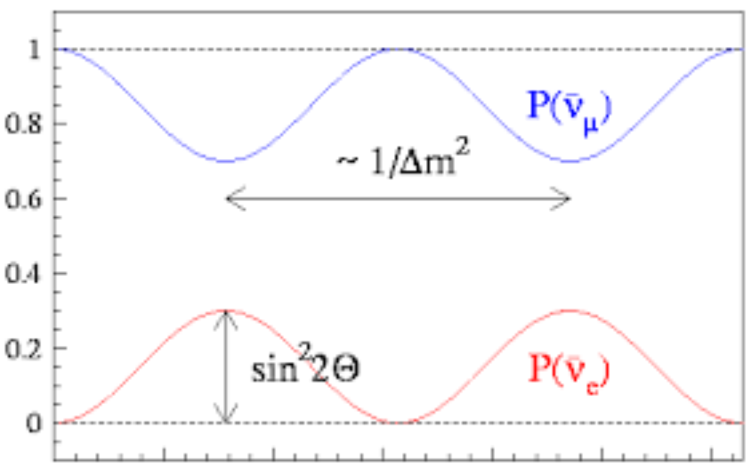
$$n(udd) \rightarrow p(uud) + e + \bar{\nu}$$



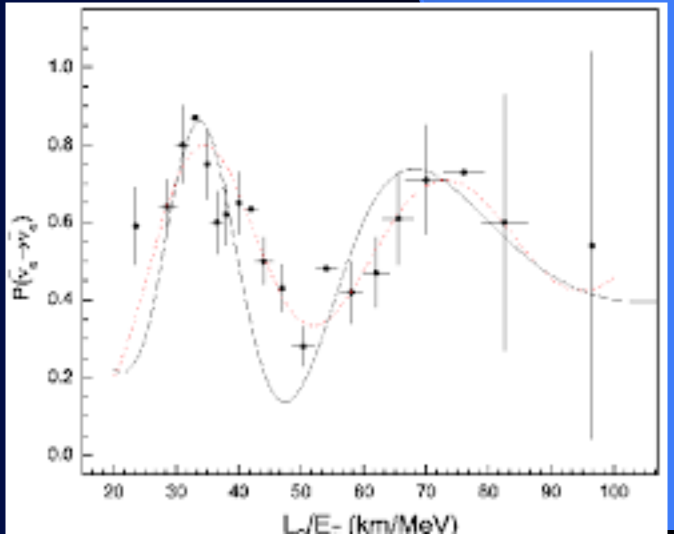
Neutrino

- Has no electric chartge
- Do not participate in electromagnetic interactions
- Do not participate in strong interactions
- Participate in weak interactions
- Interact with the Higggs field
- Has a very small (< 1 ev) mass

Non-zero neutrino mass follows from the observation of neutrino oscillations

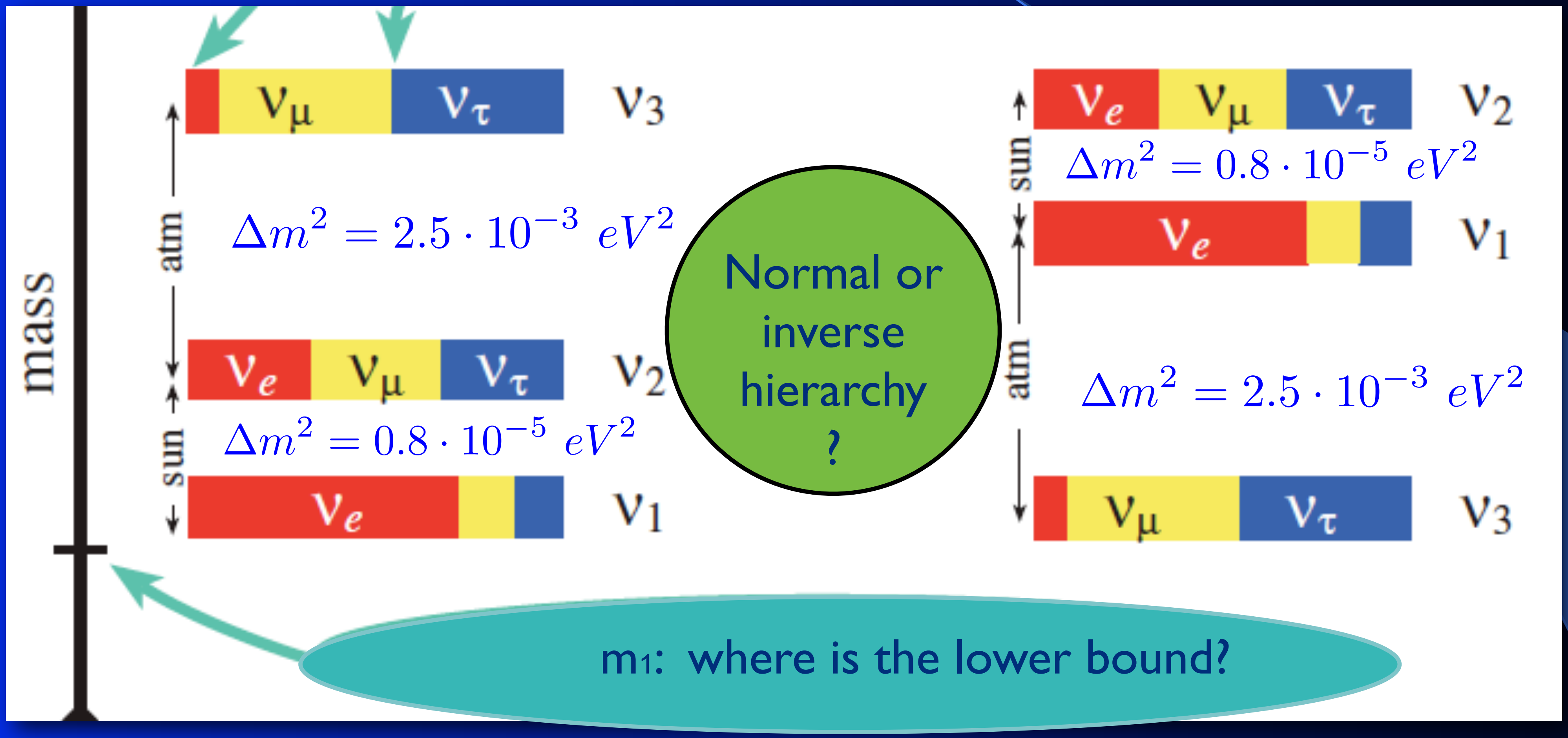


$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2 \left(\frac{\Delta m^2_{\alpha\beta} L}{4E} \right)$$



Neutrino-misterious particle

Neutrino masses



$m_{\nu_e} < 2\ eV$ ➡ $m_{\nu_e} < 0.2\ eV$

Planck

$0.06\ eV < \sum m_\nu\ < \ 0.12\ eV$

β-decay

Troitsk-Mainz

KATRIN

Neutrino oscillations

Spectrum of cosmic microwave background

Is neutrino an antiparticle to itself ?

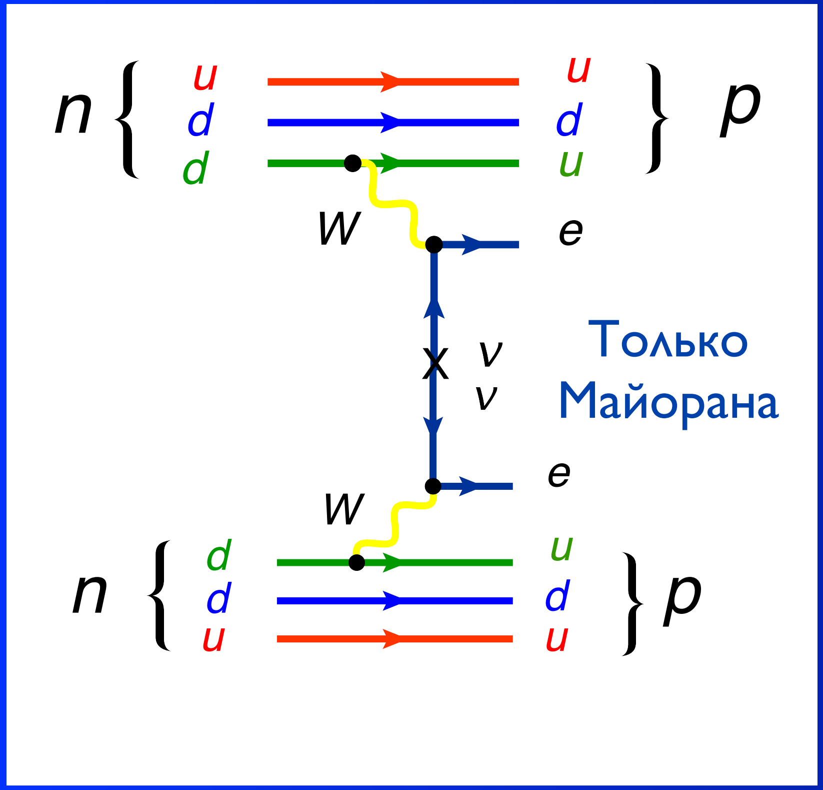
$$\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}$$

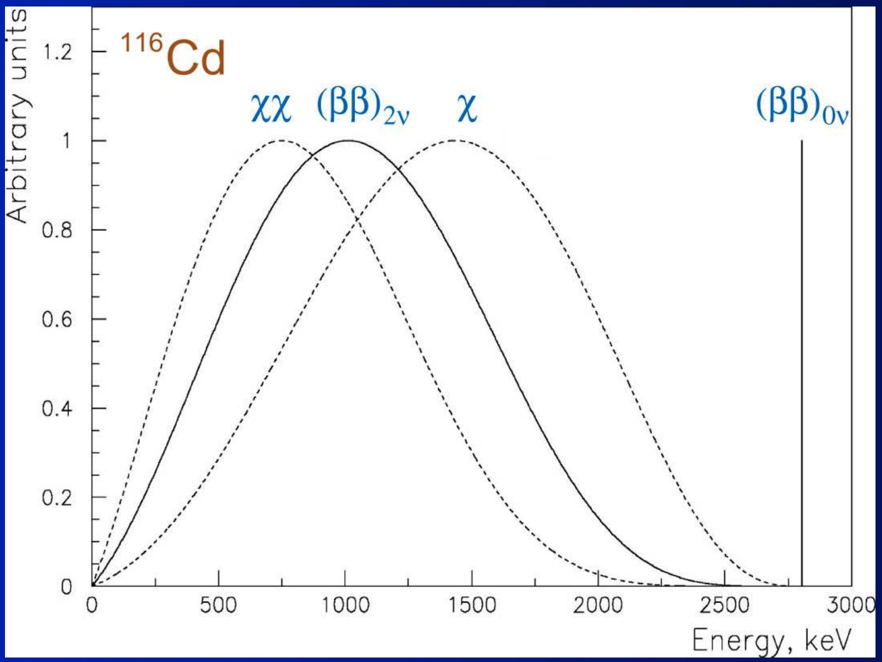
$$\nu_D \neq \nu_D^* \qquad m_{\nu_L} = m_{\nu_R}$$

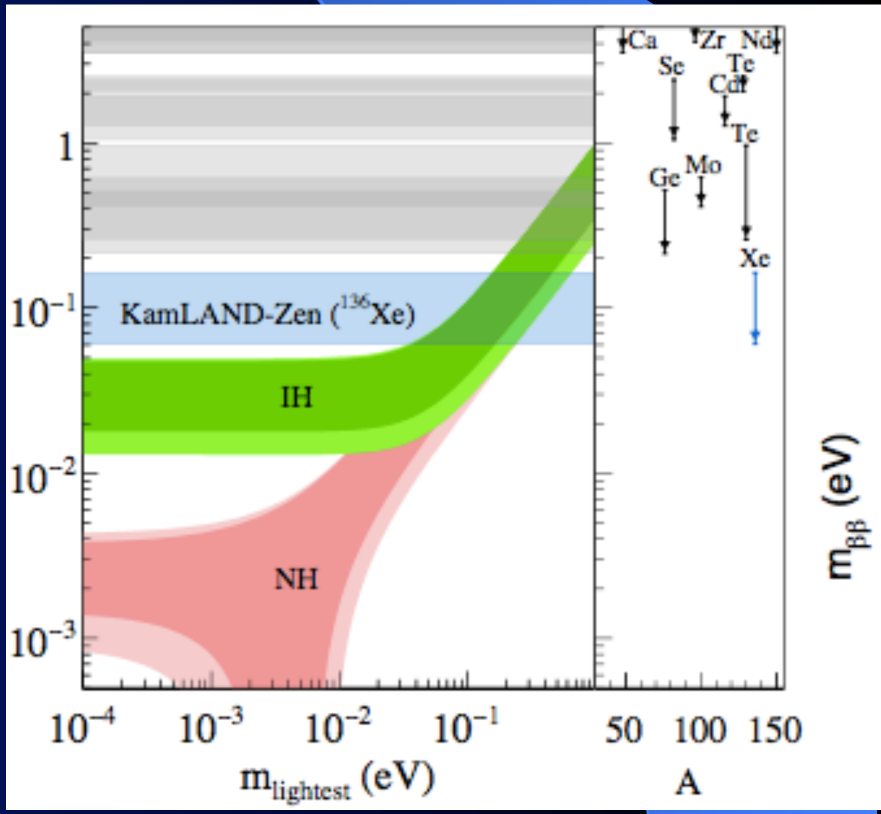
?

$$\nu_M = \nu_M^* \qquad m_{\nu_{M_1}} \neq m_{\nu_{M_2}}$$

0νββ decay







$T_{1/2}0\nu\beta\beta$ (^{136}Xe) x 10^{25} yr > 1.6 (90% CL)

Is neutrino an antiparticle to itself ?

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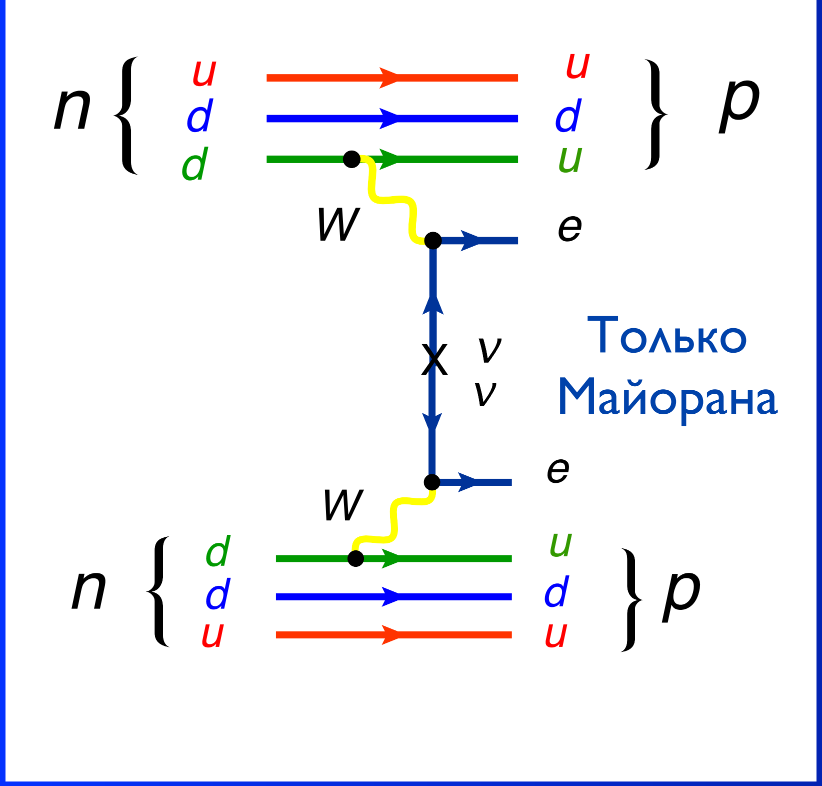
$$\nu_D \neq \nu_D^*$$
$$m_{\nu_L} = m_{\nu_R}$$

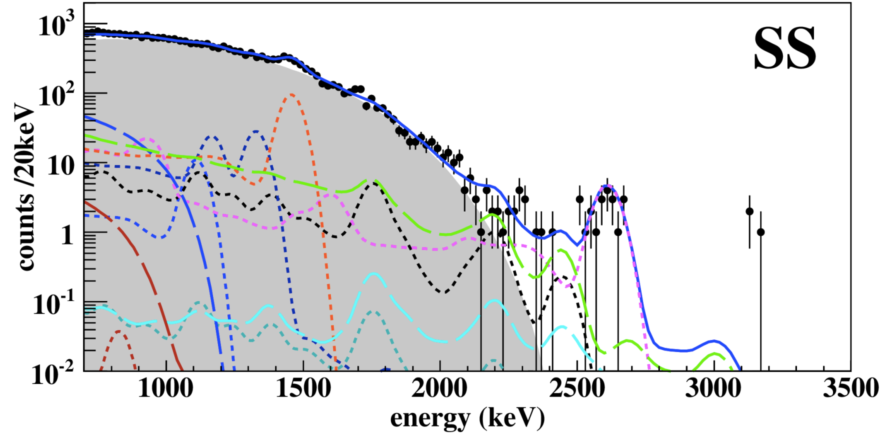
?

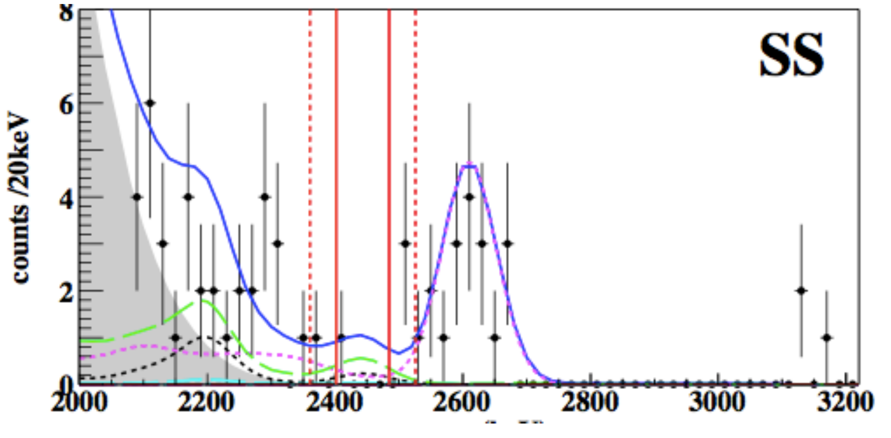
$$\nu_M = \nu_M^*$$
$$m_{\nu_{M_1}} \neq m_{\nu_{M_2}}$$

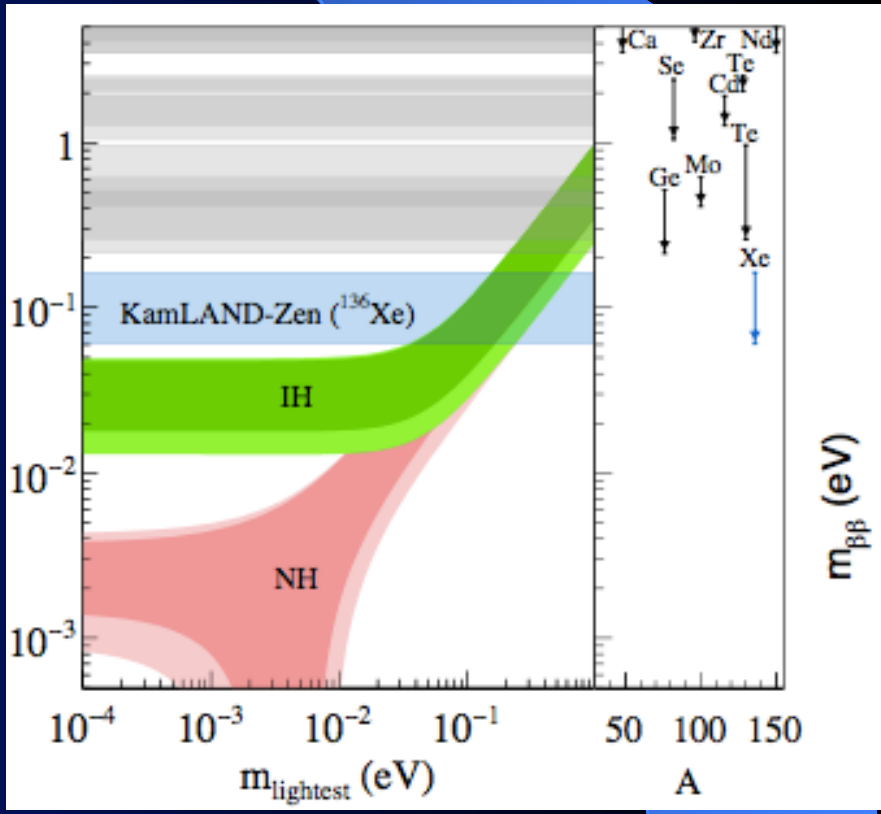
0νββ decay



Только Майорана







$T_{1/2}0\nu\beta\beta$ (^{136}Xe) x 10^{25} yr > 1.6 (90% CL)

Precision Neutrino Physics

Current knowledge and open questions

- precise measurements test the 3-flavor paradigm

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2(\theta_{23}) = \boxed{0.539} \pm 0.022 \quad (S = 1.1) \quad$ (Inverted order)

$\sin^2(\theta_{23}) = \boxed{0.546} \pm 0.021 \quad$ (Normal order)

$\Delta m^2_{32} = (\boxed{-2.536} \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Inverted order)

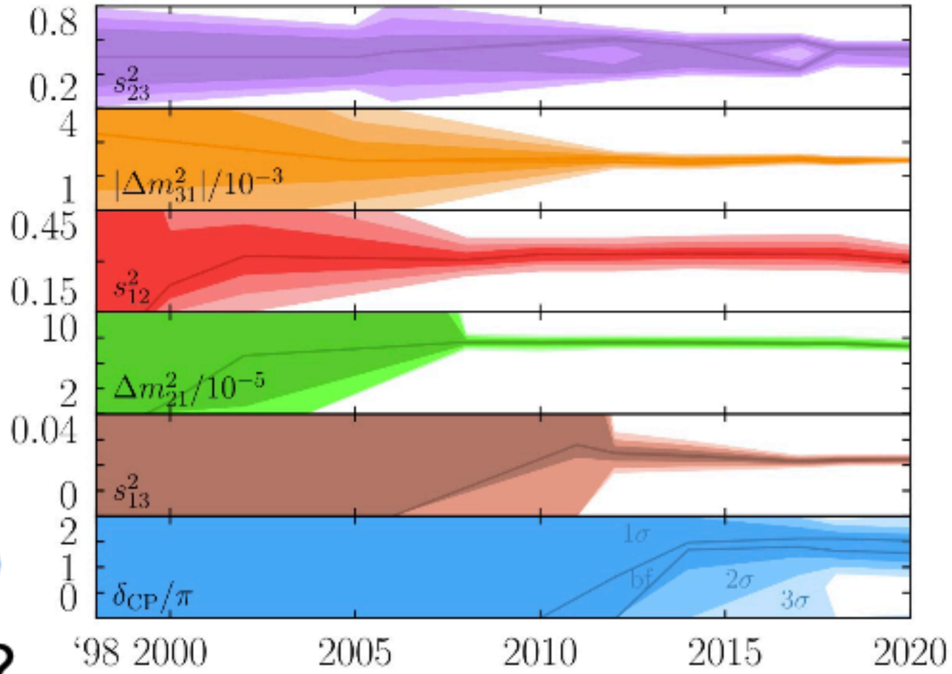
$\Delta m^2_{32} = (\boxed{2.453 \pm} 0.033) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Normal order)

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

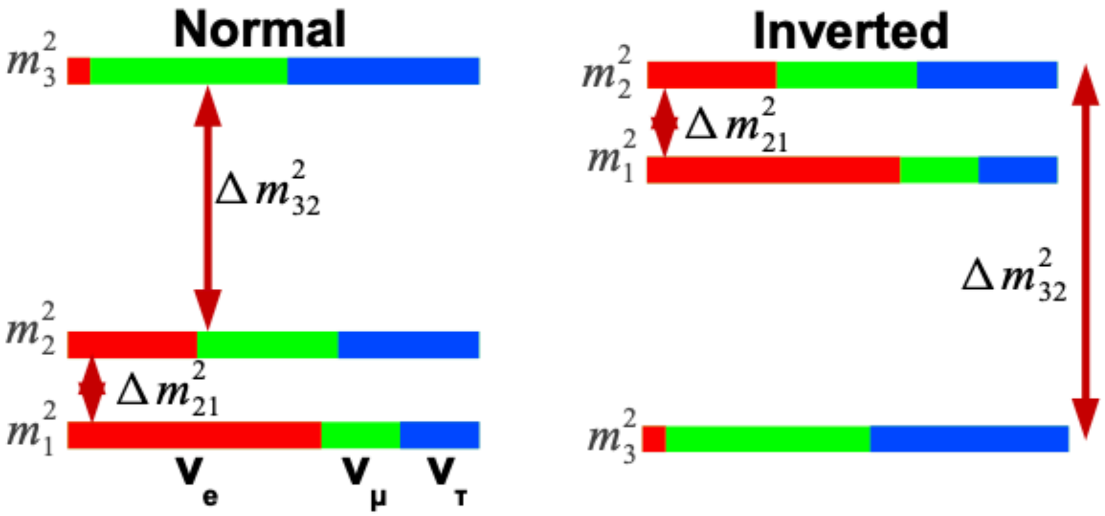
δ, CP violating phase $= \boxed{1.36^{+0.20}_{-0.16}\ \pi}$ rad

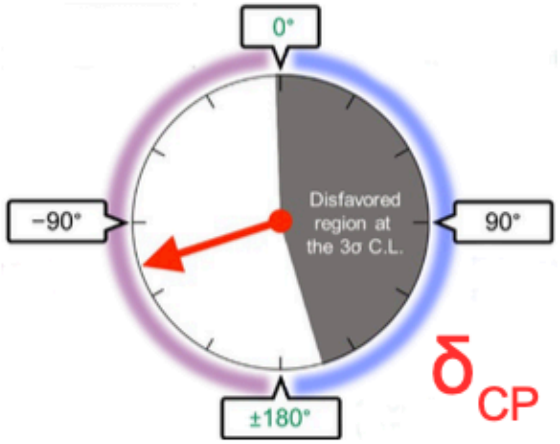
PTEP 2022, 083C01 (2022)

©P.Denton



- θ_{23} octant, mass ordering, CP violation ???





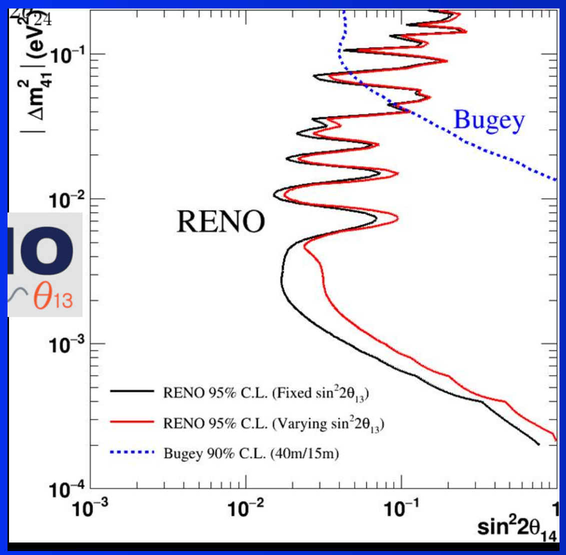
T2K Nature 580, 339 (2020)

Not covered by this talk: direct mass measurements, Dirac/Majorana nature of neutrinos, origin of masses and mixing

STERILE NEUTRINO

No evidence for sterile neutrinos

Various exps interpreted within 4 neutrino framework



Oscillation channels are related:

$$P_{\nu_e \to \nu_e} \approx 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\nu_\mu \to \nu_\mu} \approx 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$
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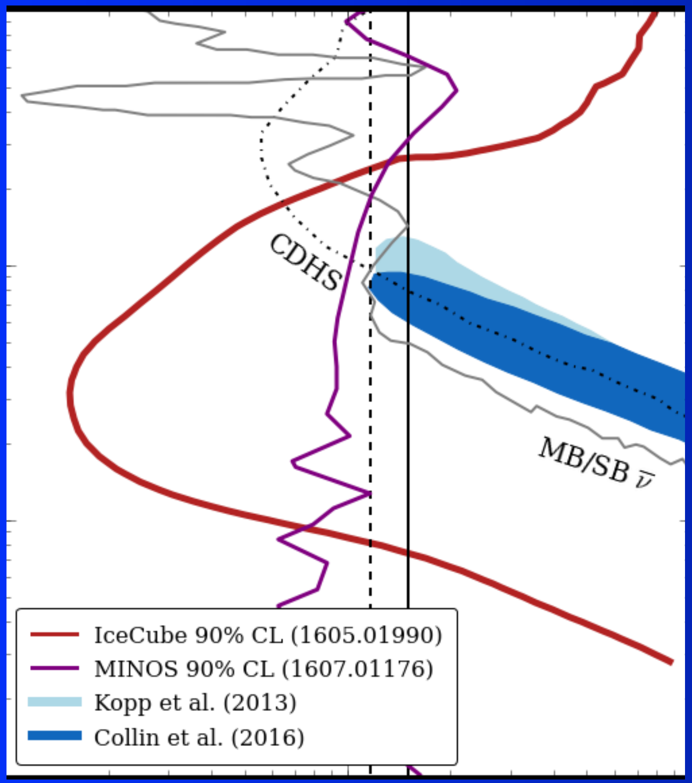
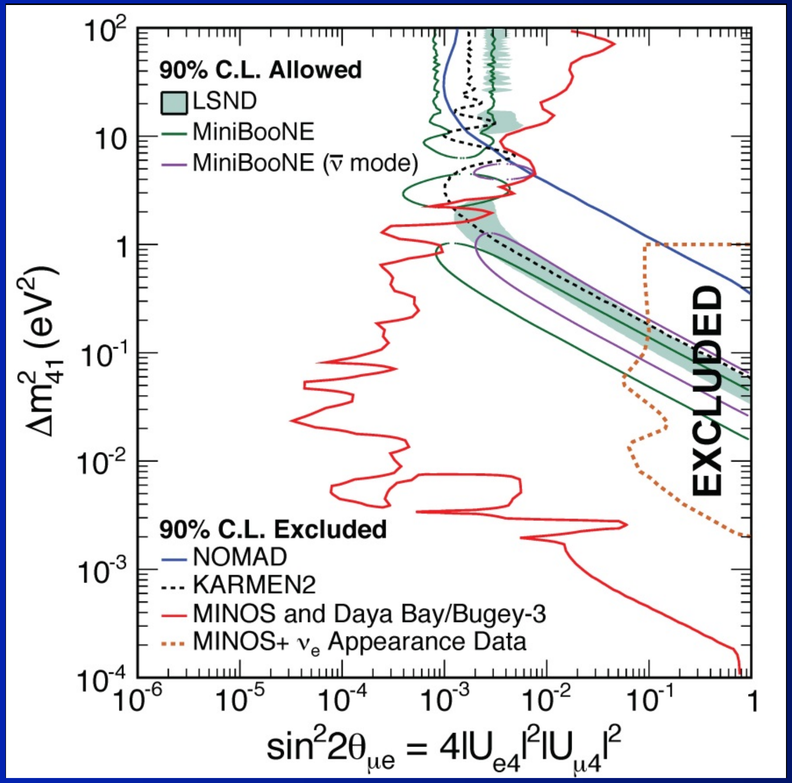
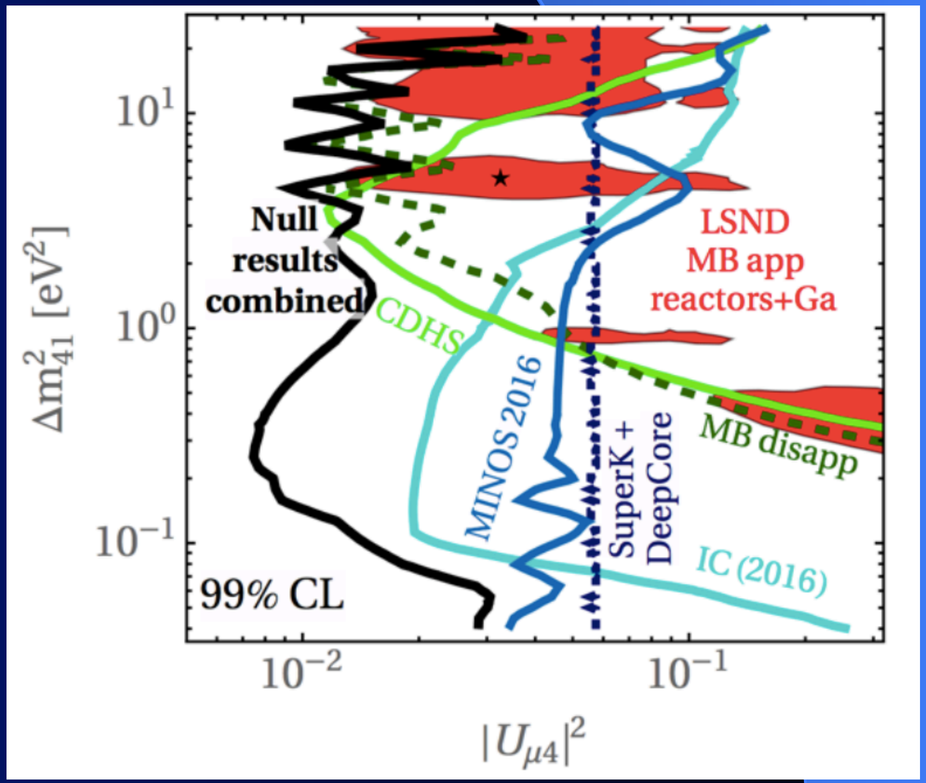
for $4\pi E/\Delta m^2_{41} << L << 4\pi E/\Delta m^2_{31}$

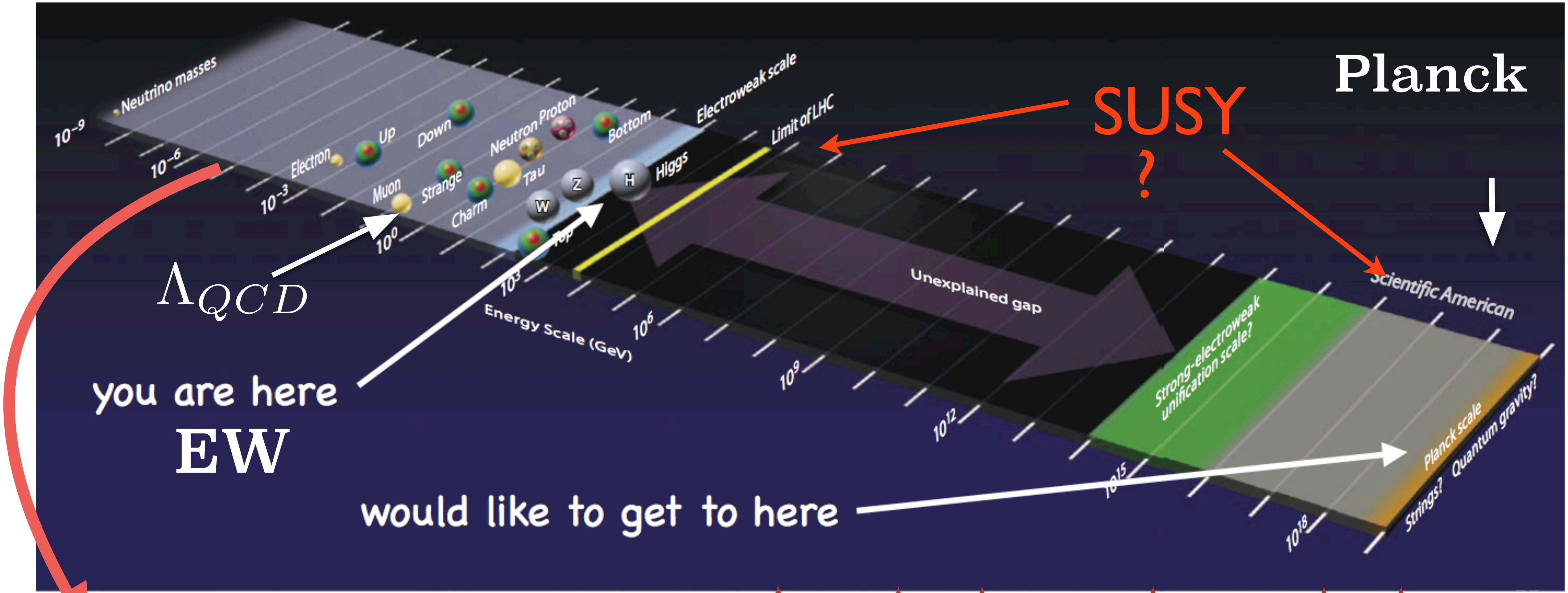


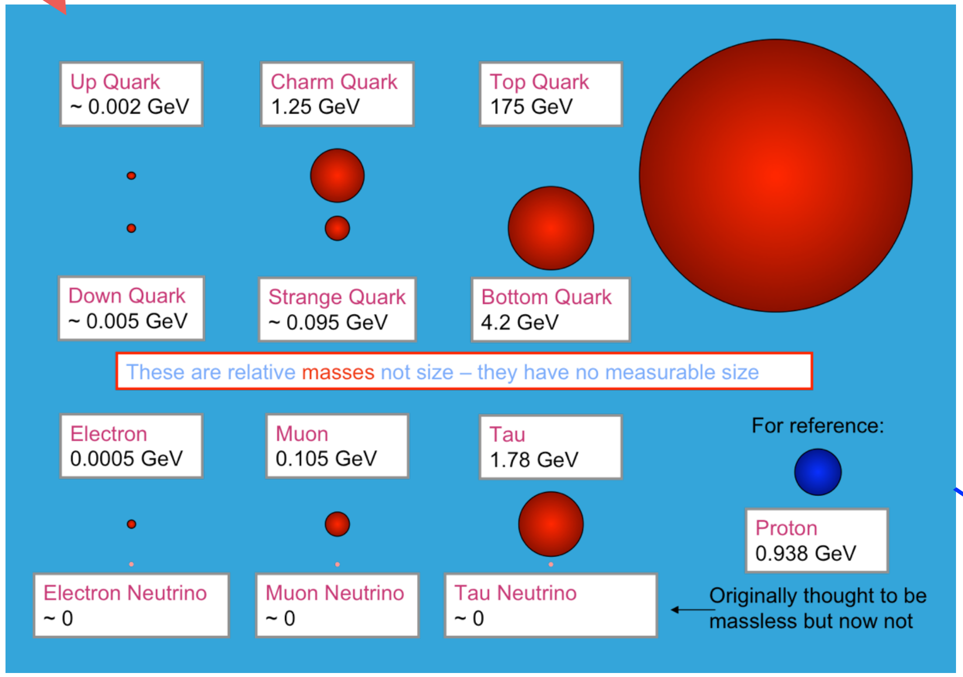




Beyond the Standard Model

IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANK?





?

Vacuum Stab ~ 10^{11} GeV

Majorana scale ~ 10^{12} GeV

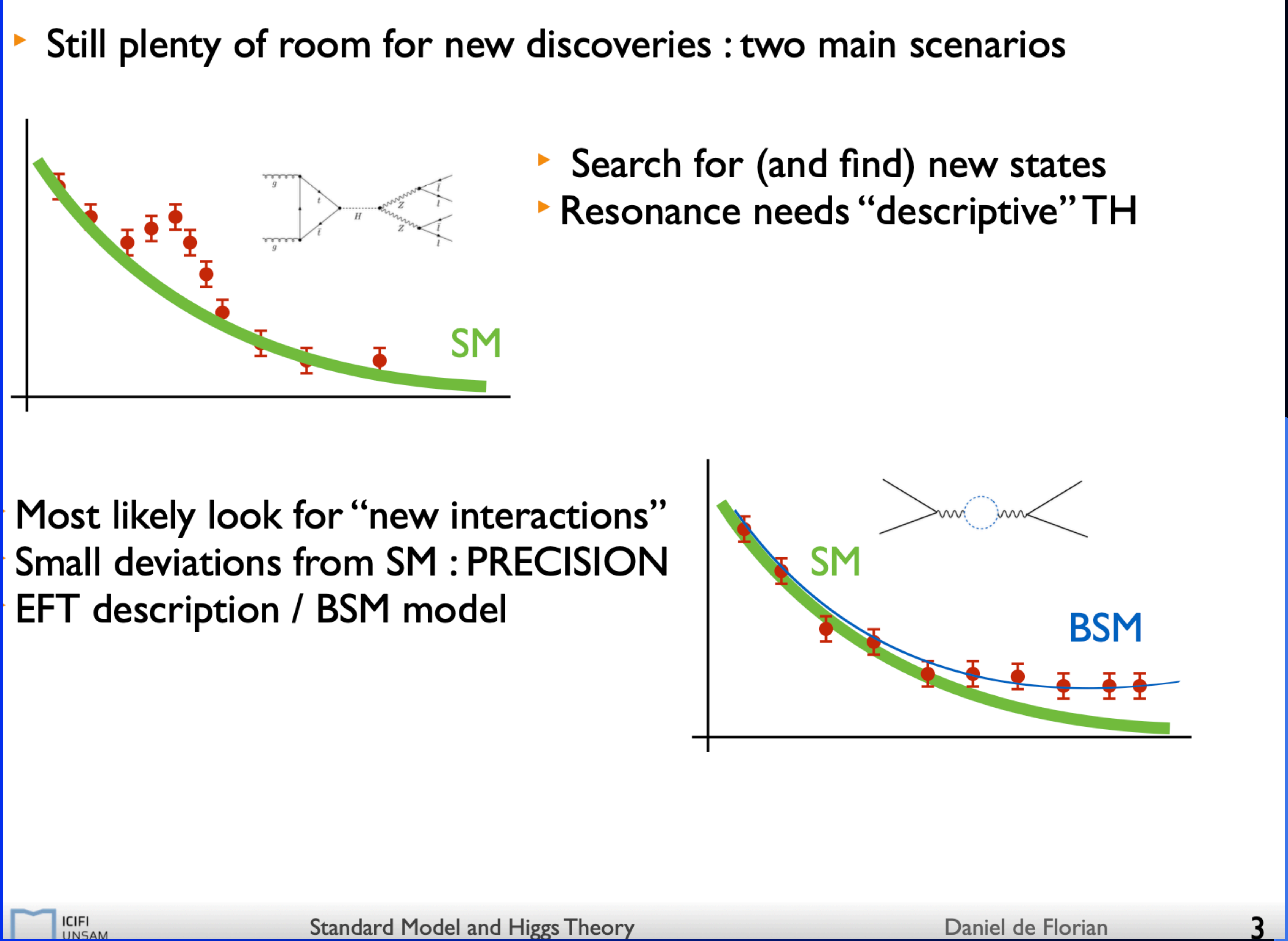
GUT scale ~ 10^{16} GeV

String scale ~ 10^{18} GeV

Planck scale ~ 10^{19} GeV

?

Search for New Physics



- Still plenty of room for new discoveries : two main scenarios

- Search for (and find) new states
- Resonance needs "descriptive" TH

Most likely look for "new interactions"
Small deviations from SM : PRECISION
EFT description / BSM model

THE WAYS BEYOND

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- Extension of symmetry group of the SM : SUSY, GUT, new U(1)’s

-> may solve the problem of Landau pole, the problem of stability, the hierarchy problem, may give the DM particle

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- New paradigm beyond local QFT: string theory, brane world, etc
  -> main task is unification with gravity and construction of quantum gravity

NEW SYMMETRIES

SUPERSYMMETRY

Supersymmetry is an extension of the Poincare symmetry of the SM

Poincare Algebra

$$
\begin{aligned}
&[P_\mu, P_\nu] = 0,\\
&[P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),\\
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\end{aligned}
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Super Poincare Algebra $Q_i, \ \bar{Q}_i$

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&\alpha, \dot\alpha = 1, 2 \qquad i, j = 1, 2, \ldots, N.
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SUSY MULTIPLETS

Chiral multiplet $N = 1, \ \lambda = 0$

helicity	-1/2	0	1/2
# of states	1	2	1

scalar spinor

(φ, ψ)

Vector multiplet $N = 1, \ \lambda = 1/2$

helicity	-1	-1/2	1/2	1
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(λ, A_μ)

spinor vector

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Extended supersymmetry

N=4	SUSY YM	helicity	-1 –1/2 0 1/2 1
	λ = -1	# of states	1 4 6 4 1
N=8	SUGRA	helicity	-2 –3/2 –1 –1/2 0 1/2 1 3/2 2
	λ = -2	# of states	1 8 28 56 70 56 28 8 1

SUSY MULTIPLETS

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$\boxed{N \leq 4S}$ ← **spin**

$N \leq 4$ **For renormalizable theories (YM)**

$N \leq 8$ **For (super)gravity**

THE SIMPLEST (N=1) SUSY MULTIPLETS

Bosons and Fermions come in pairs

$$(\varphi,\psi) \qquad (\tilde{\lambda}, A_\mu) \qquad (\tilde{g}, g)$$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

scalar

chiral fermion

majorana fermion

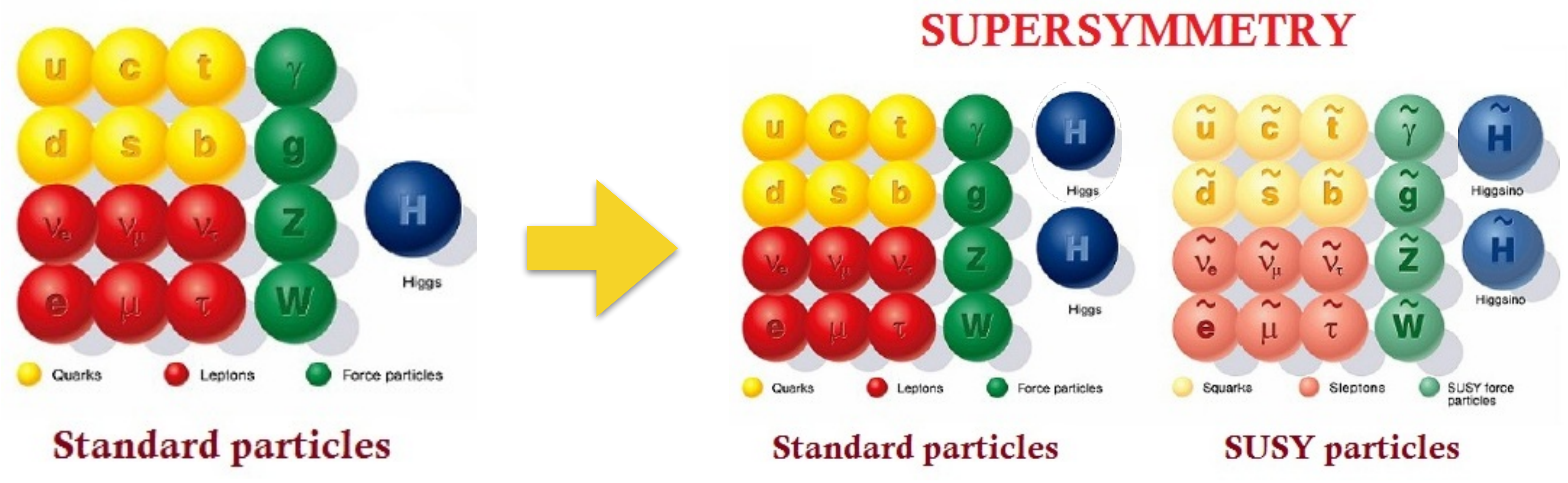
vector

gravitino

graviton

MOTIVATION FOR SUSY IN PARTICLE PHYSICS

Supersymmetry is a dream of a unified theory of all particles and interactions



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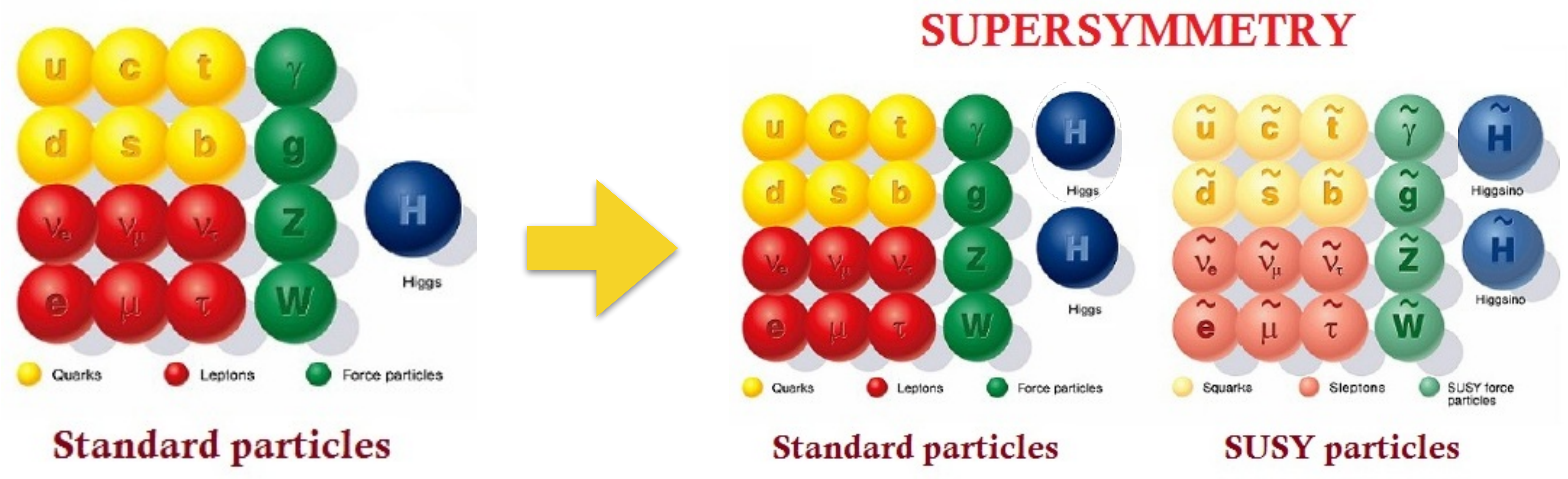

Why SUSY?

- Unification with gravity!
- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
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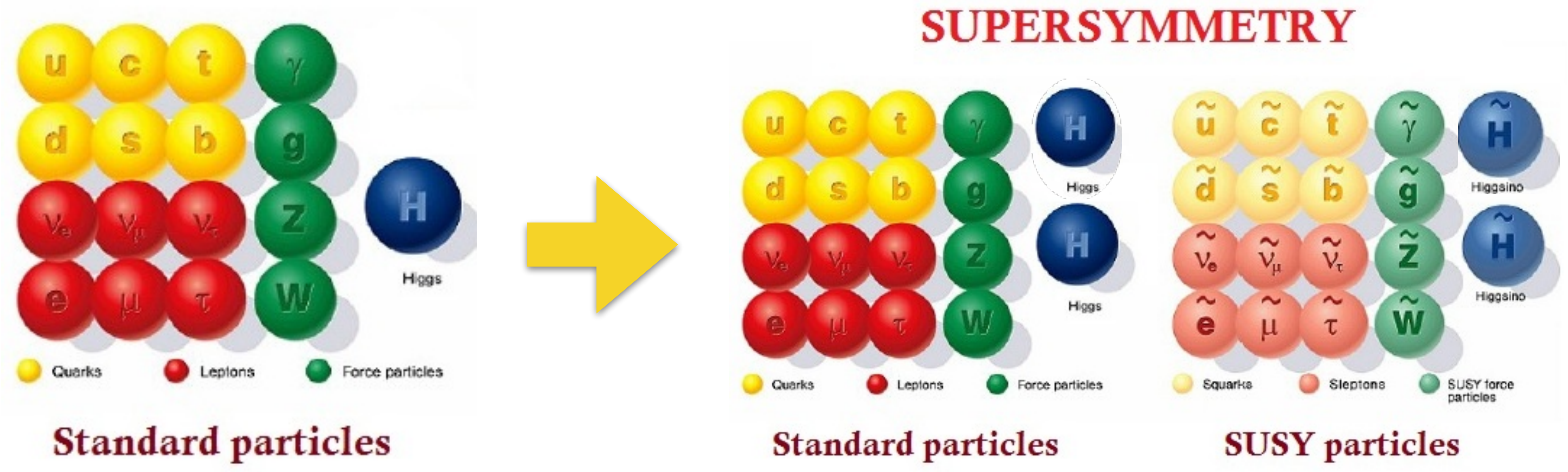

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$$\{Q^i_\alpha,\overline{Q}^j_\beta\}=2\delta^{ij}(\sigma^\mu)_{\alpha\beta}P_\mu \quad\Rightarrow\quad \{\delta_\varepsilon,\overline{\delta}_{\overline{\varepsilon}}\}=2(\varepsilon\sigma^\mu\overline{\varepsilon})P_\mu$$

$$\varepsilon=\varepsilon(x)\ \ \text{local coordinate transf.}\ \Rightarrow\ \text{(super)gravity}$$

Local supersymmetry = general relativity !

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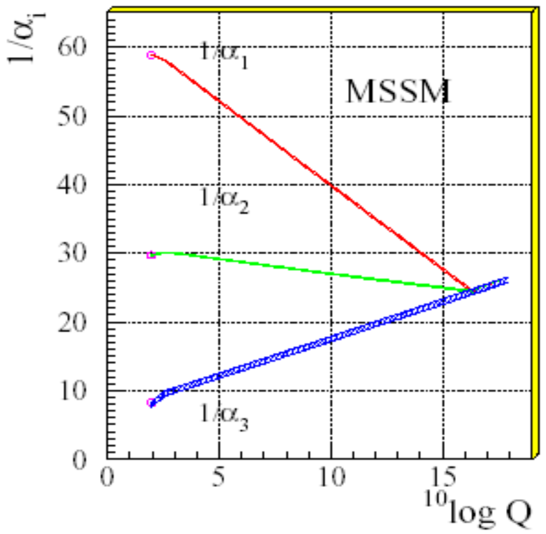

The basis of a grand Unified Theory

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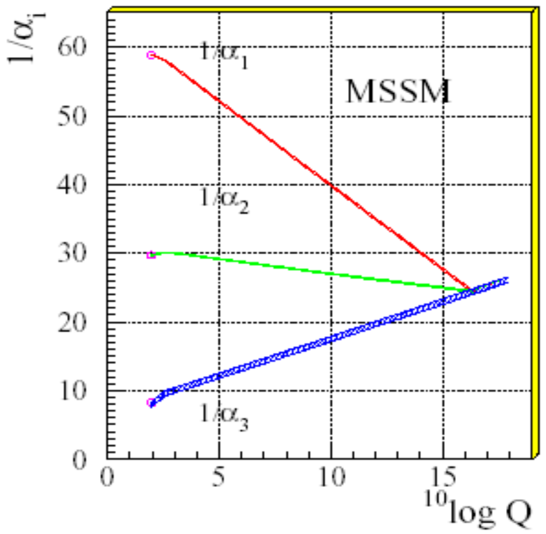
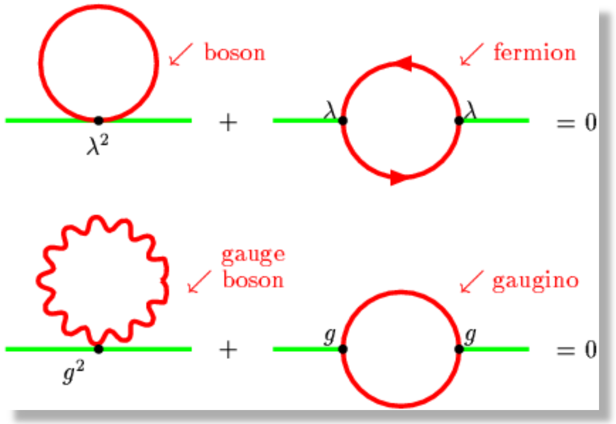


The basis of a grand Unified Theory

Solution of the hierarchy problem



Cancellations of corrections and stabilization of the Higgs potential

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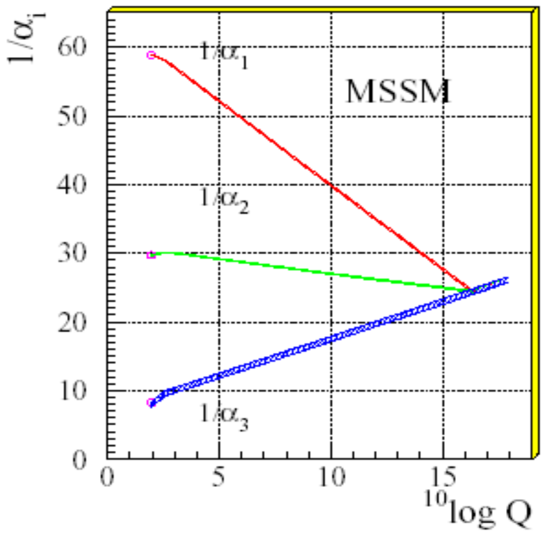

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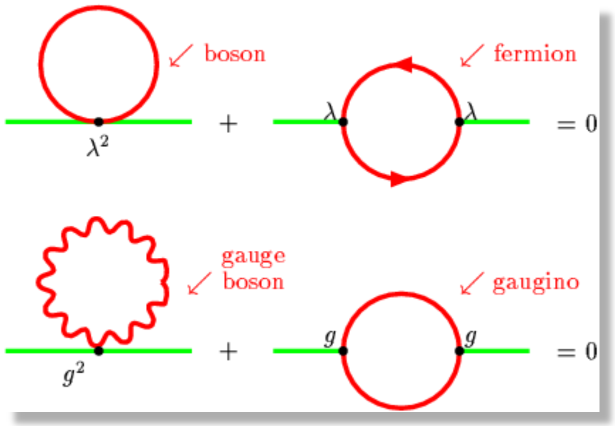

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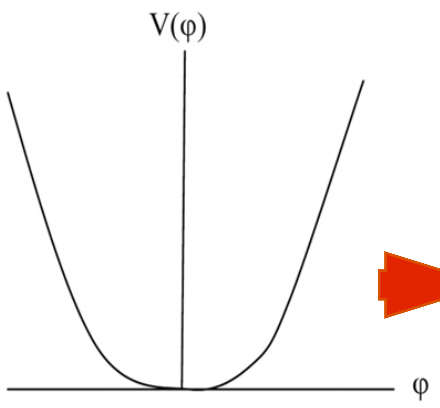
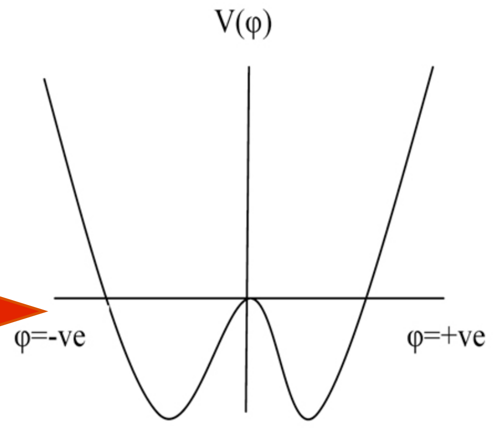


Fig(a): Before symmetry breaking



Fig(b): After symmetry breaking

Violation of symmetry comes from radiative corrections

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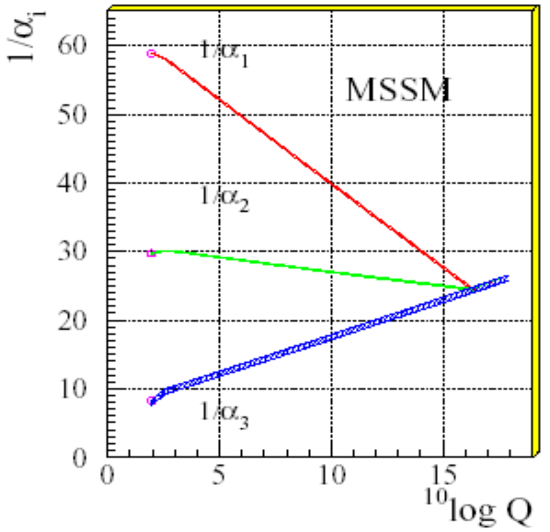

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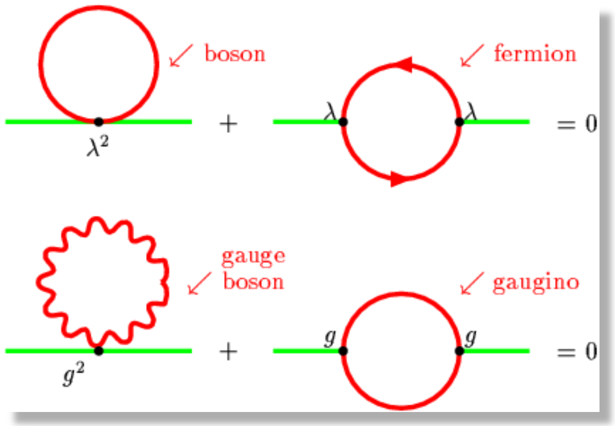

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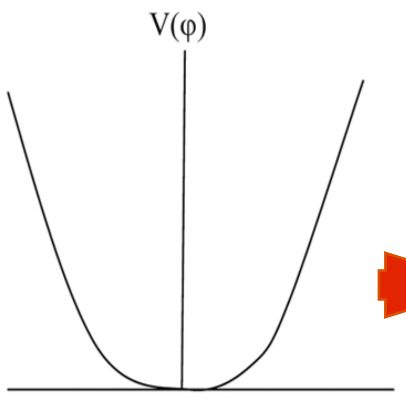

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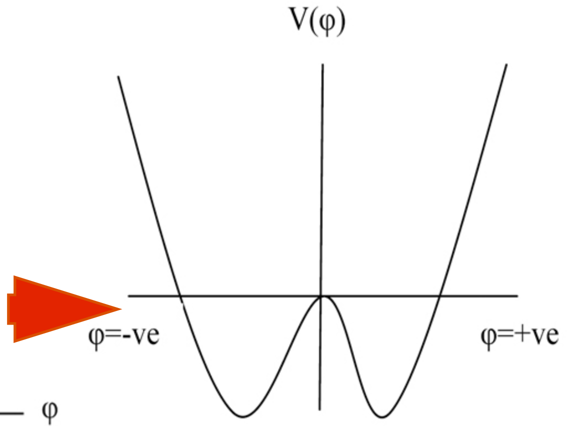

Fig(b): After symmetry breaking

Violation of symmetry comes from radiative corrections

- Provided the DM particle

$$\tilde{\chi}^0 = N_1\tilde{\gamma} + N_2\tilde{z} + N_3\tilde{H}_1^0 + N_4\tilde{H}_2^0$$

Neutralino=DM

THE PARTICLE CONTENT OF THE MSSM

Superfield	Bosons	Fermions	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
$\mathbf{G^a}$	gluon g^a	gluino $\tilde{g}^a$	8	0	0
$\mathbf{V^k}$	Weak W^k $(W^\pm, Z)$	wino, zino $\tilde{w}^k$ $(\tilde{w}^\pm, \tilde{z})$	1	3	0
$\mathbf{V'}$	Hypercharge B (γ)	bino $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
$\mathbf{L_i}$	sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons $L_i = (\nu, e)_L$	1	2	−1
$\mathbf{E_i}$	$\tilde{E}_i = \tilde{e}_R$	$E_i = e_R$	1	1	2
$\mathbf{N_i}$	$\tilde{N}_i = \tilde{\nu}_R$	$N_i = \nu_R$	1	1	0
$\mathbf{Q_i}$	squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks $Q_i = (u, d)_L$	3	2	1/3
$\mathbf{U_i}$	$\tilde{U}_i = \tilde{u}_R$	$U_i = u^c_R$	3*	1	−4/3
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$\mathbf{V'}$	Hypercharge	B (γ)	*bino*	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter							
$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	−1
$\mathbf{E_i}$		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
$\mathbf{N_i}$		$\tilde{N}_i = \tilde{\nu}_R$		$N_i = \nu_R$	1	1	0
$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	1/3
$\mathbf{U_i}$		$\tilde{U}_i = \tilde{u}_R$		$U_i = u_R^c$	3*	1	−4/3
$\mathbf{D_i}$		$\tilde{D}_i = \tilde{d}_R$		$D_i = d_R^c$	3*	1	2/3
Higgs							
$\mathbf{H_1}$	Higgses	H_1	higgsinos	$\tilde{H}_1$	1	2	−1
$\mathbf{H_2}$		H_2		$\tilde{H}_2$	1	2	1
$\mathbf{S}$	Singlet	s	singlino	s	1	1	0

THE PARTICLE CONTENT OF THE MSSM

Superfield	Bosons		Fermions		$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge							
G $\mathbf{G^a}$	gluon	g^a	gluino	$\tilde{g}^a$	8	0	0
$\mathbf{V^k}$	Weak	W^k $(W^\pm, Z)$	wino, zino	$\tilde{w}^k$ $(\tilde{w}^\pm, \tilde{z})$	1	3	0
$\mathbf{V'}$	Hypercharge	B (γ)	bino	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter							
$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1
$\mathbf{E_i}$		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
$\mathbf{N_i}$		$\tilde{N}_i = \tilde{\nu}_R$		$N_i = \nu_R$	1	1	0
$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	$1/3$
$\mathbf{U_i}$		$\tilde{U}_i = \tilde{u}_R$		$U_i = u_R^c$	3^*	1	$-4/3$
$\mathbf{D_i}$		$\tilde{D}_i = \tilde{d}_R$		$D_i = d_R^c$	3^*	1	$2/3$
Higgs							
$\mathbf{H_1}$	Higgses	H_1	higgsinos	$\tilde{H}_1$	1	2	-1
$\mathbf{H_2}$		H_2		$\tilde{H}_2$	1	2	1
$\mathbf{S}$	Singlet	s	singlino	s	1	1	0

NMSSM

THE R-PARITY

$$R = (-)^{3(B-L)+2S}$$

The Usual Particle : R = + 1
SUSY Particle : R = - 1

B - Baryon Number
L - Lepton Number
S - Spin

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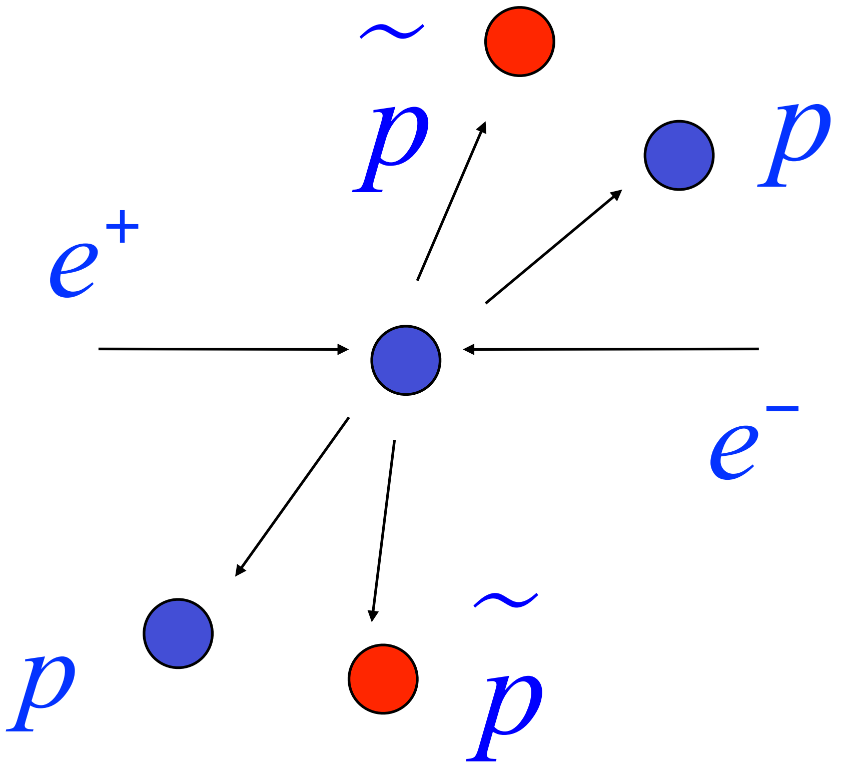
The consequences:

- The superpartners are created in pairs
- The lightest superparticle is stable



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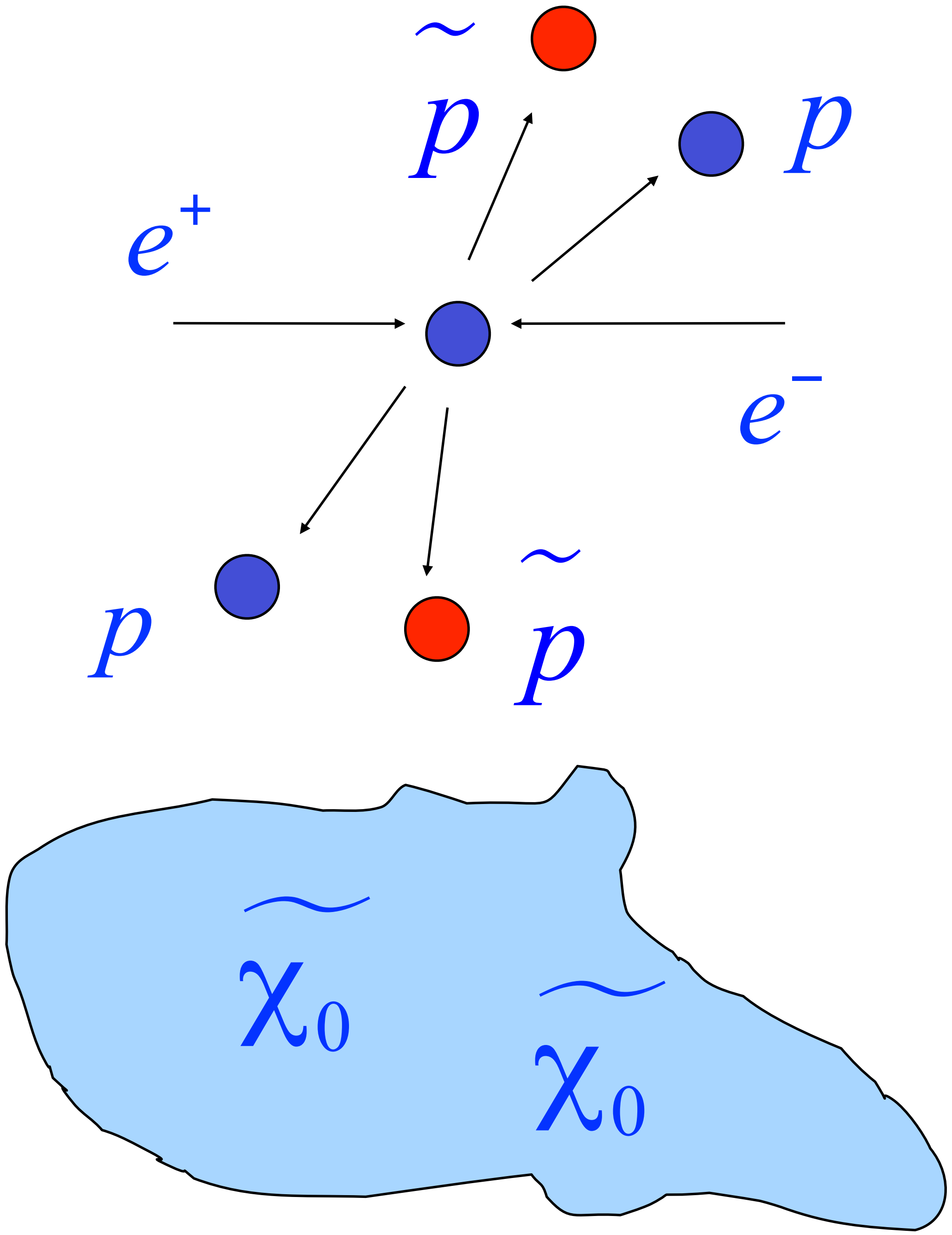
⬇

- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\widetilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe



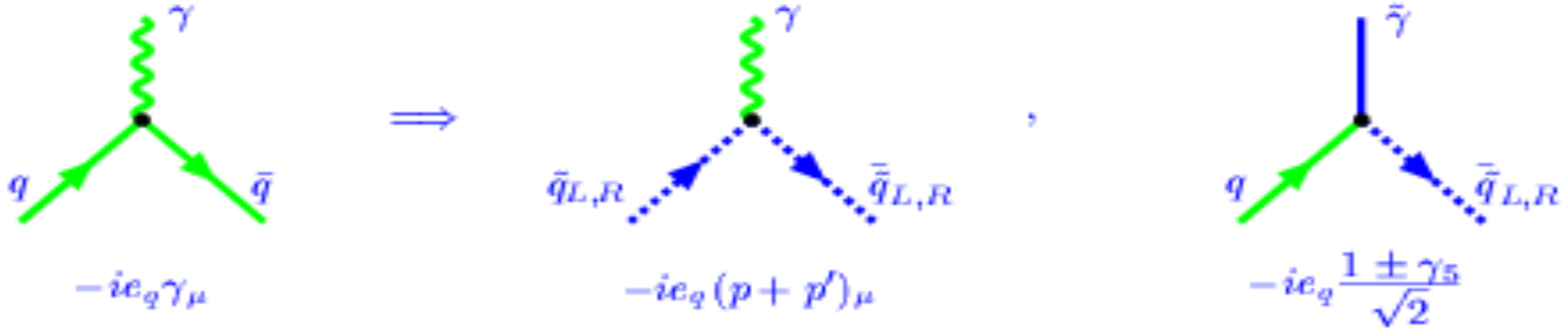
THE INTERACTIONS IN THE MSSM

SM → **MSSM**

THE INTERACTIONS IN THE MSSM

Vertices

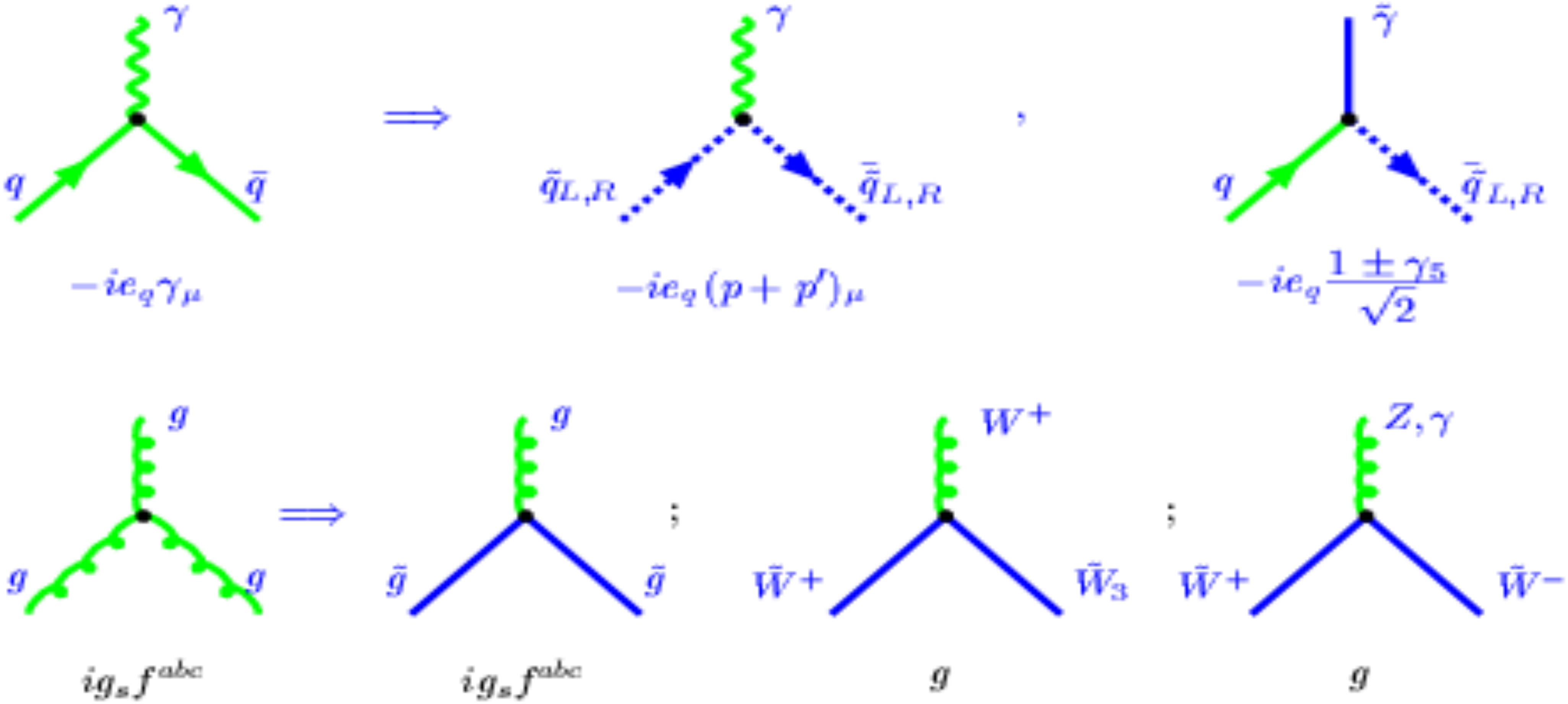
SM → **MSSM**



THE INTERACTIONS IN THE MSSM

Vertices

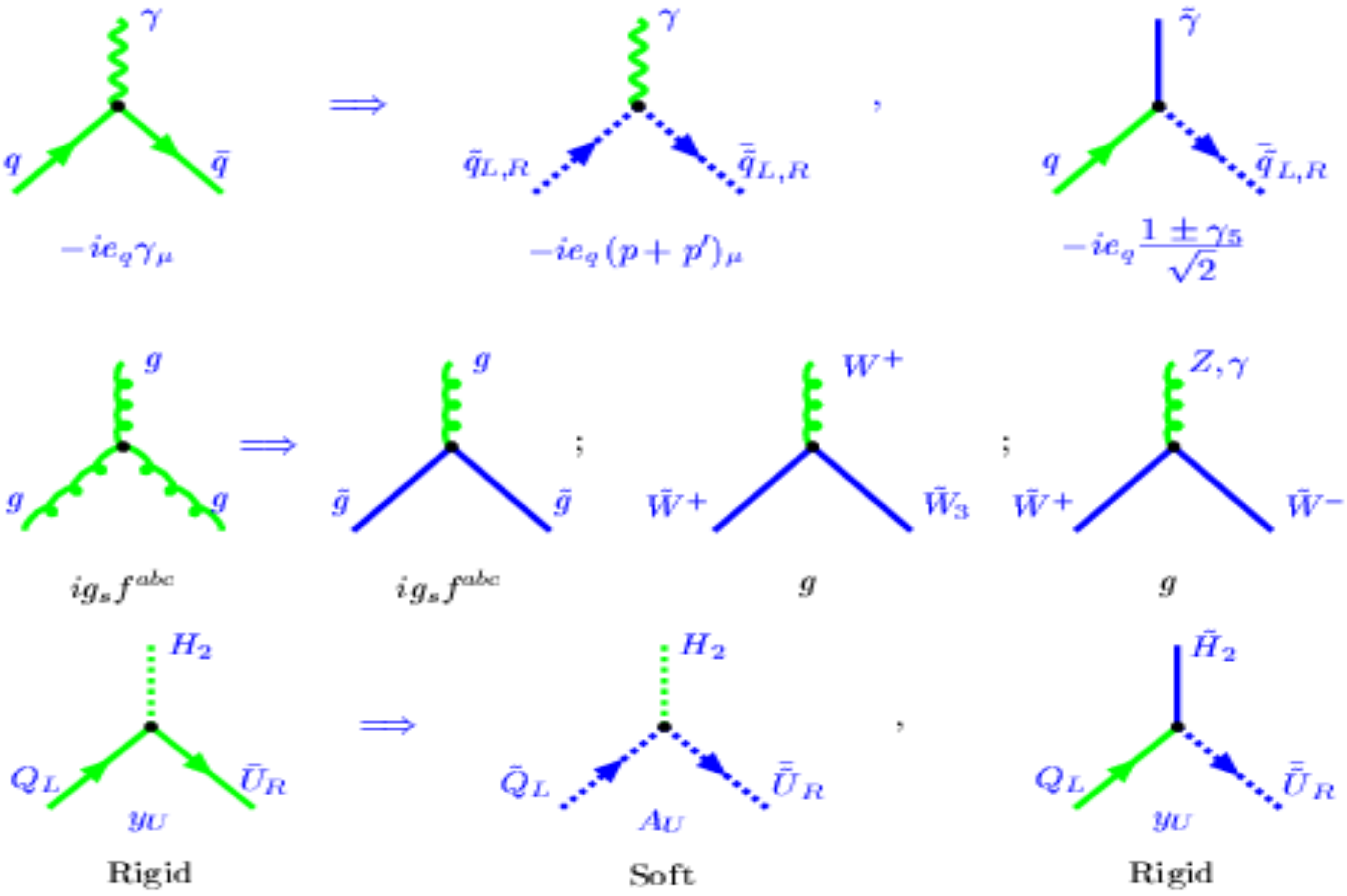
SM → **MSSM**



THE INTERACTIONS IN THE MSSM

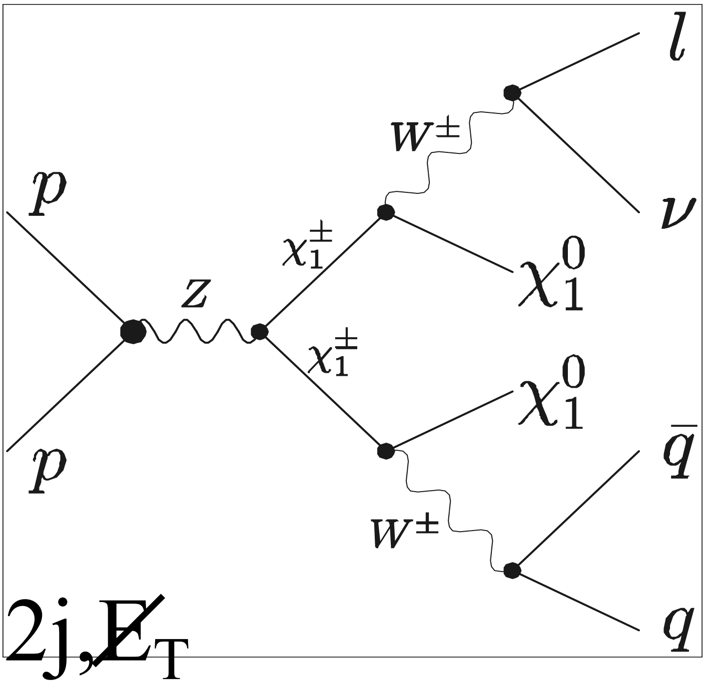
SM → **MSSM**

Vertices

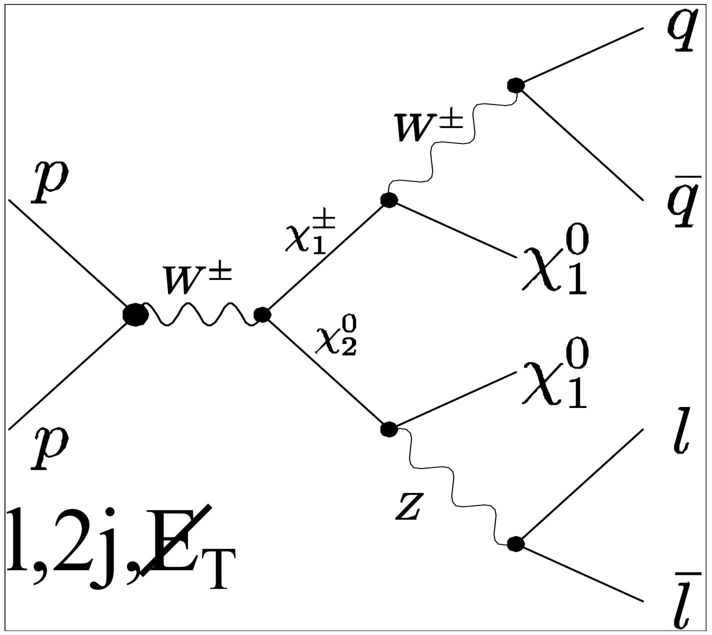


CREATION AND DECAY OF SUPERPARTNERS IN CASCADE PROCESSES @ LHC

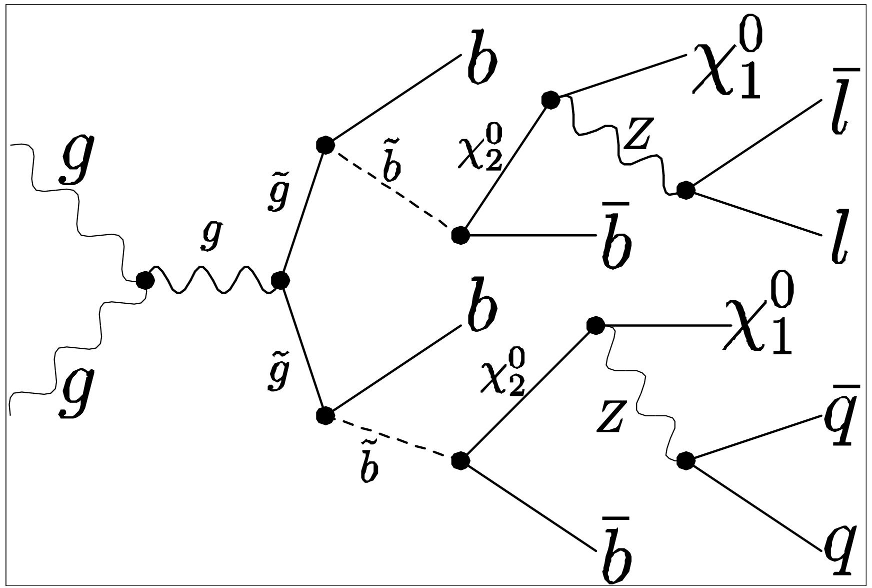
weak int's



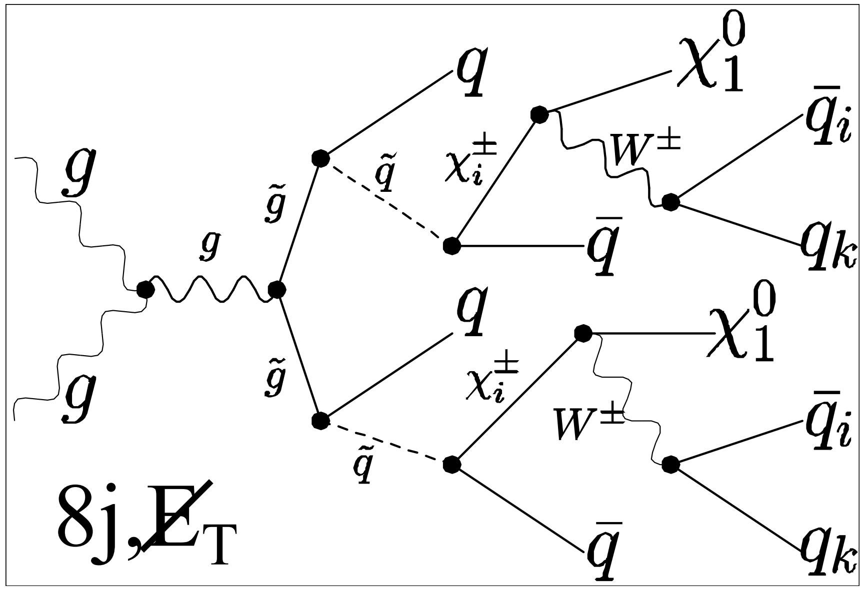
1,2j,$\not{E}_T$



2l,2j,$\not{E}_T$



2l,6j,$\not{E}_T$



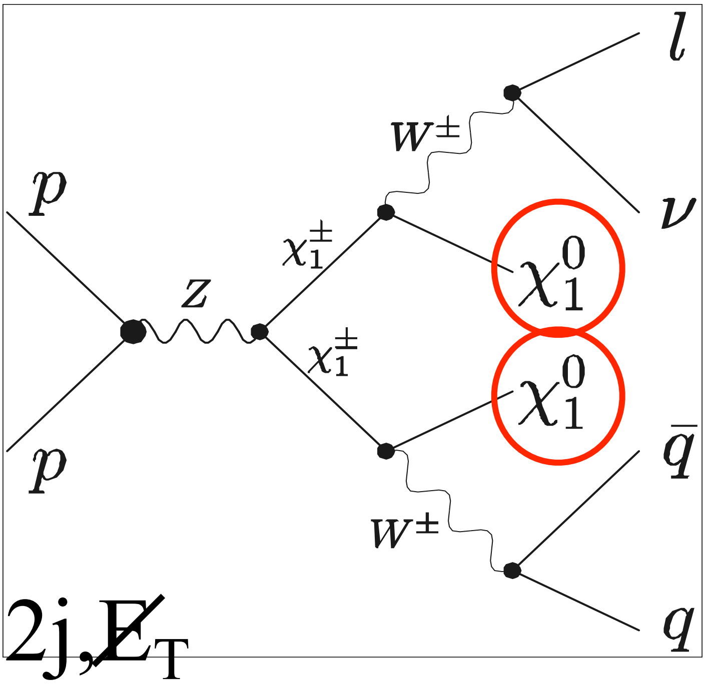
8j,$\not{E}_T$

Strong int's

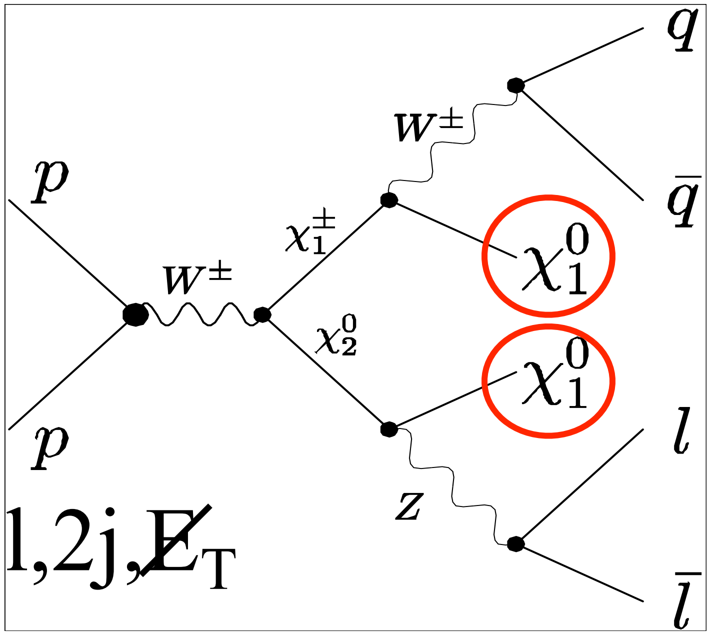
Typical SUSY signature: Missing Energy and Transverse Momentum

CREATION AND DECAY OF SUPERPARTNERS IN CASCADE PROCESSES @ LHC

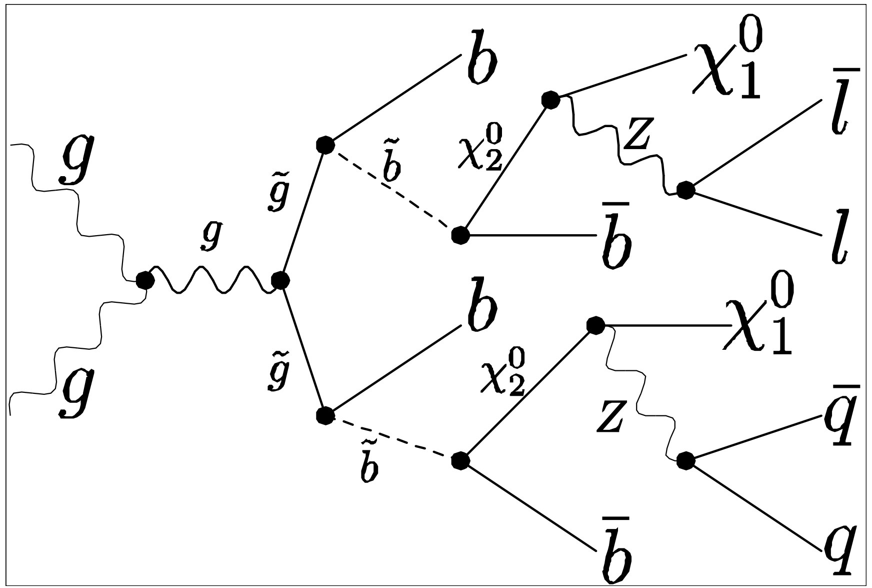
weak int's



$l,2j,\not{E}_T$



$2l,2j,\not{E}_T$



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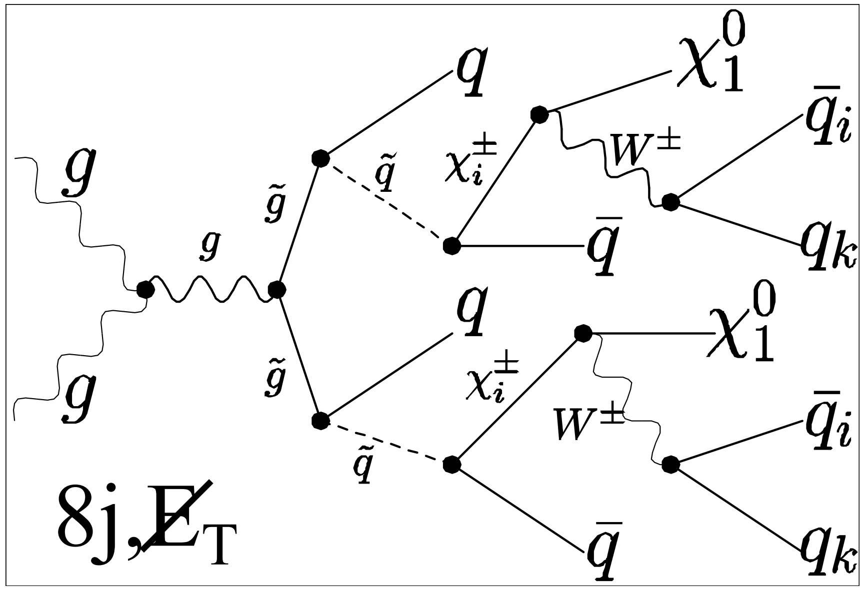

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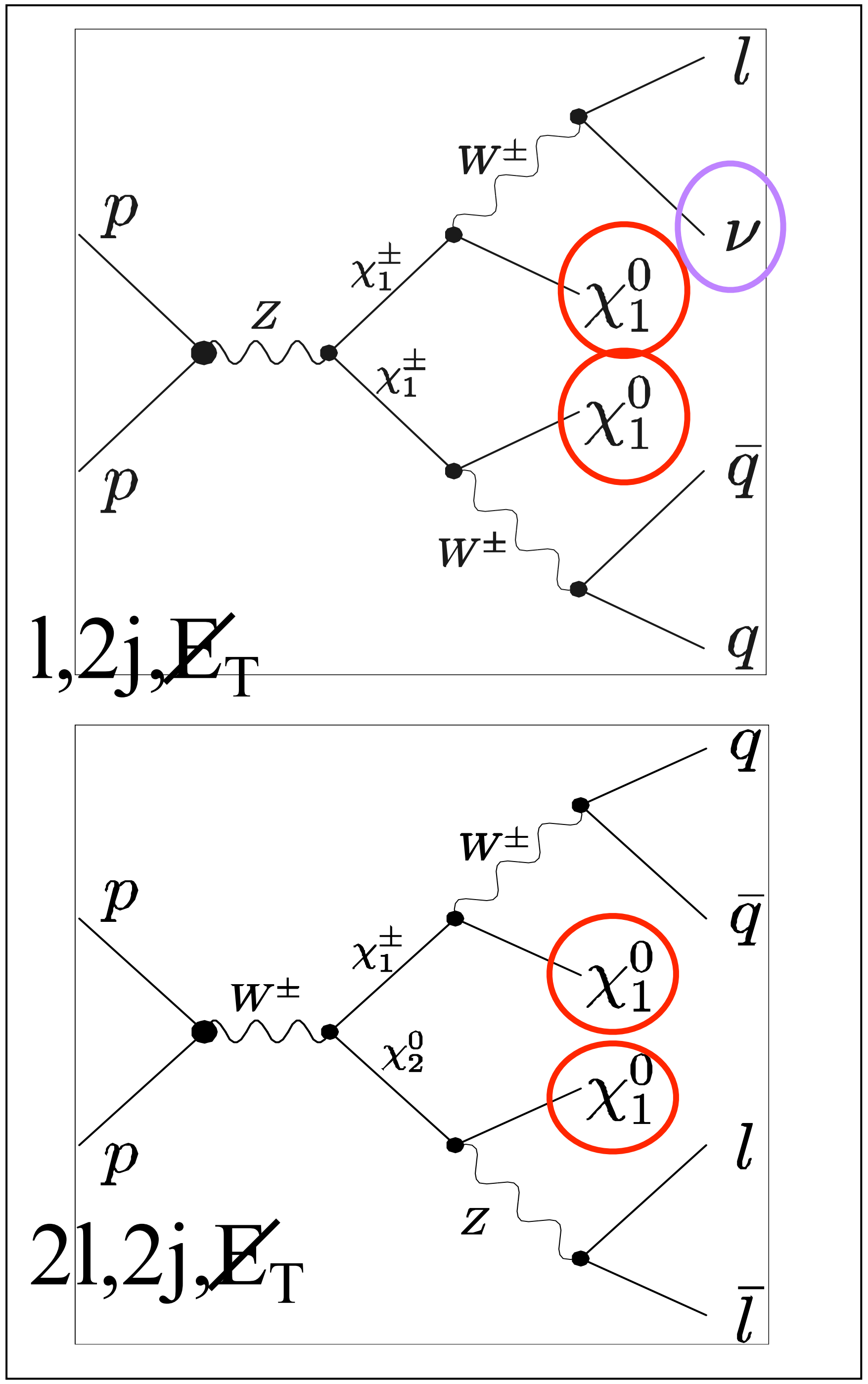

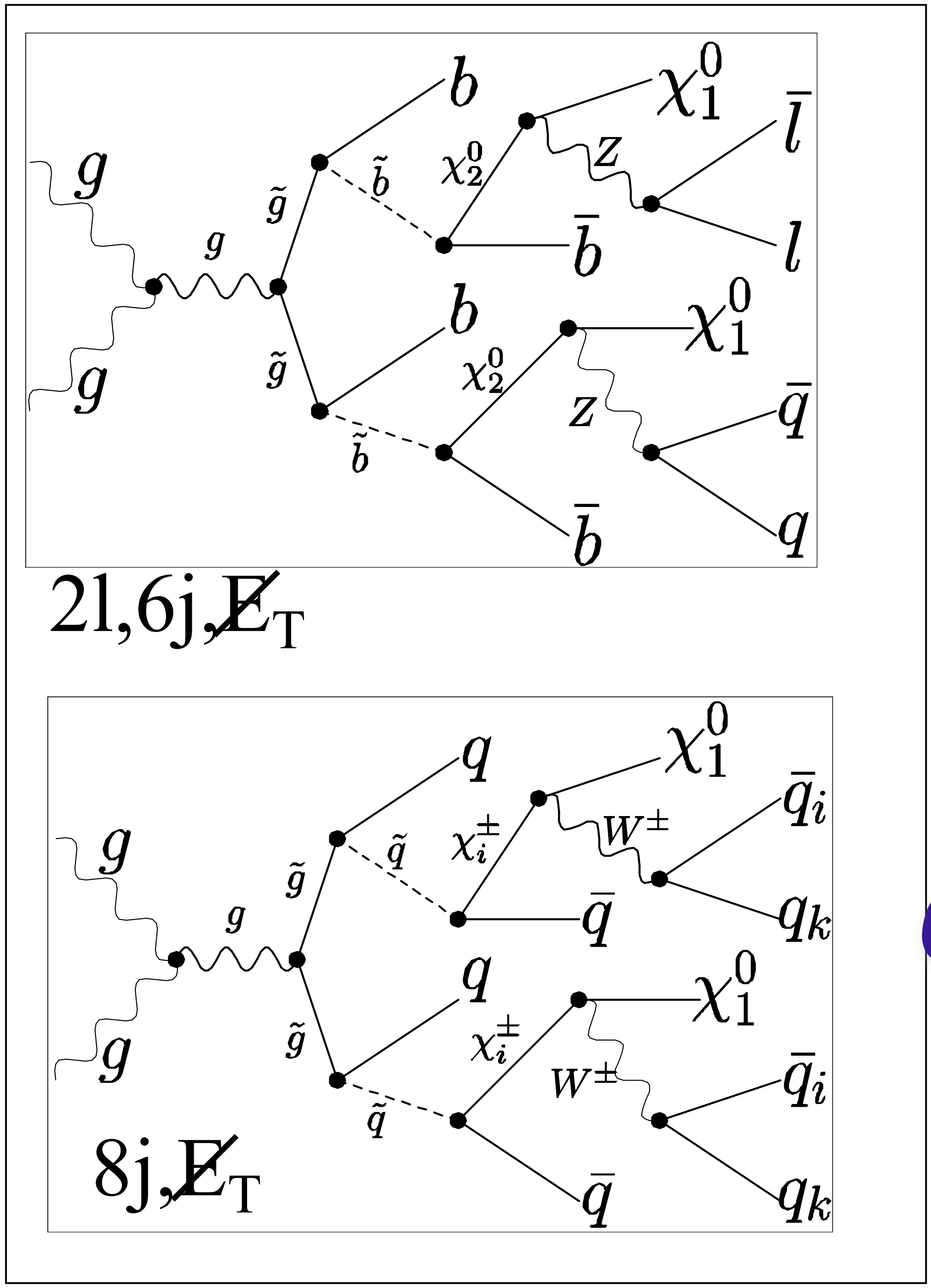

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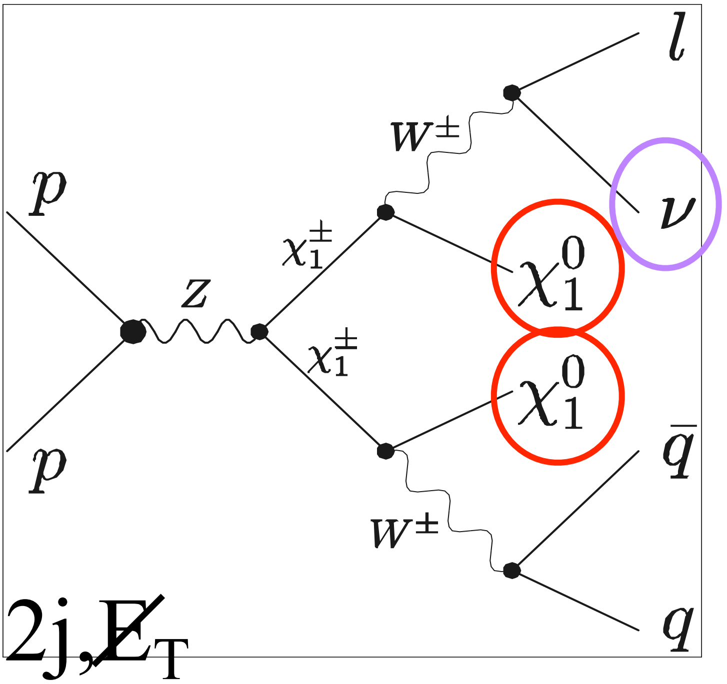

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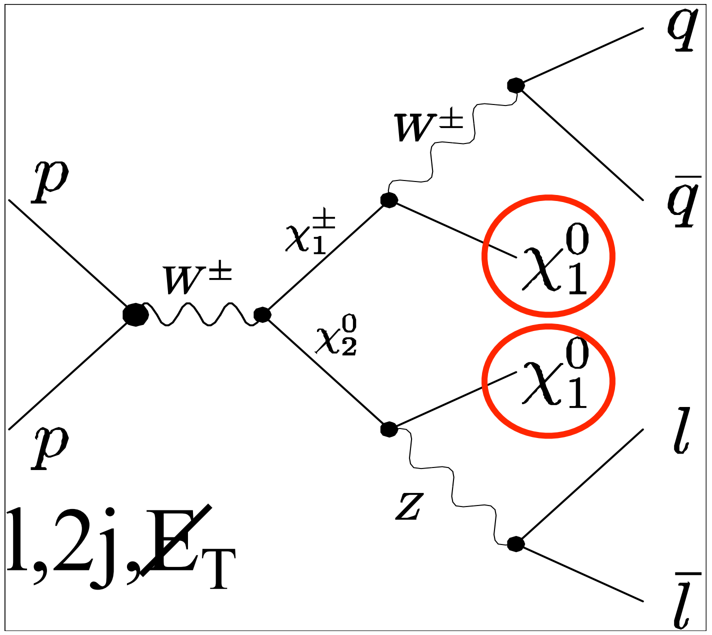

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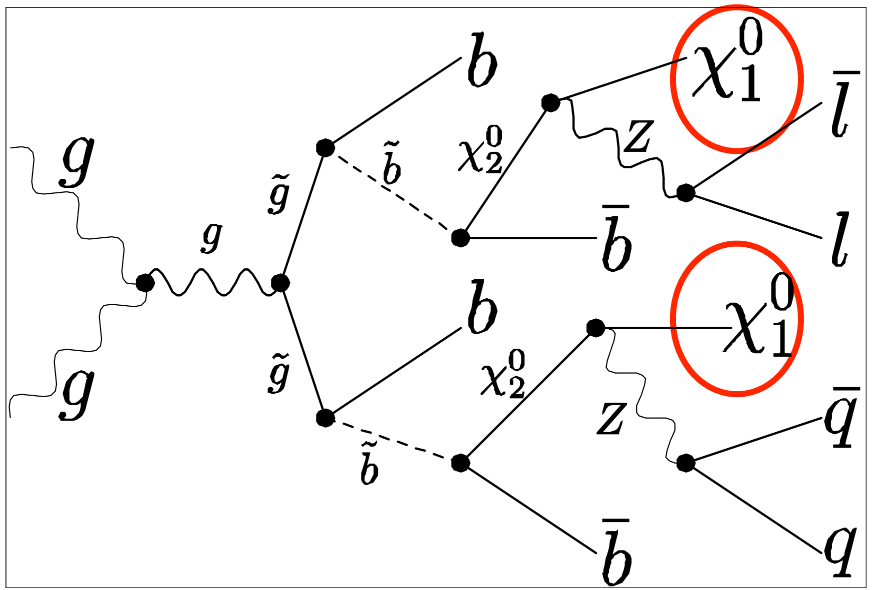

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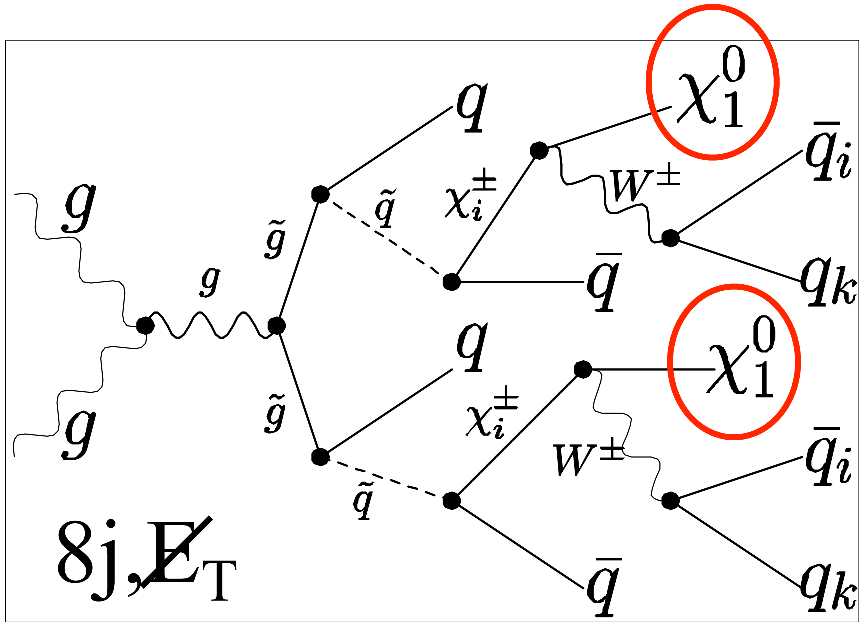

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THE DECAY OF SUPERPARTNERS

squarks

$$\tilde{q}_{L,R} \rightarrow q + \tilde{\chi}_i^0$$

$$\tilde{q}_L \rightarrow q' + \tilde{\chi}_i^\pm$$

$$\tilde{q}_{L,R} \rightarrow q + \tilde{g}$$

sleptons

$$\tilde{l} \rightarrow l + \tilde{\chi}_i^0$$

$$\tilde{l}_L \rightarrow \nu_l + \tilde{\chi}_i^\pm$$

chargino

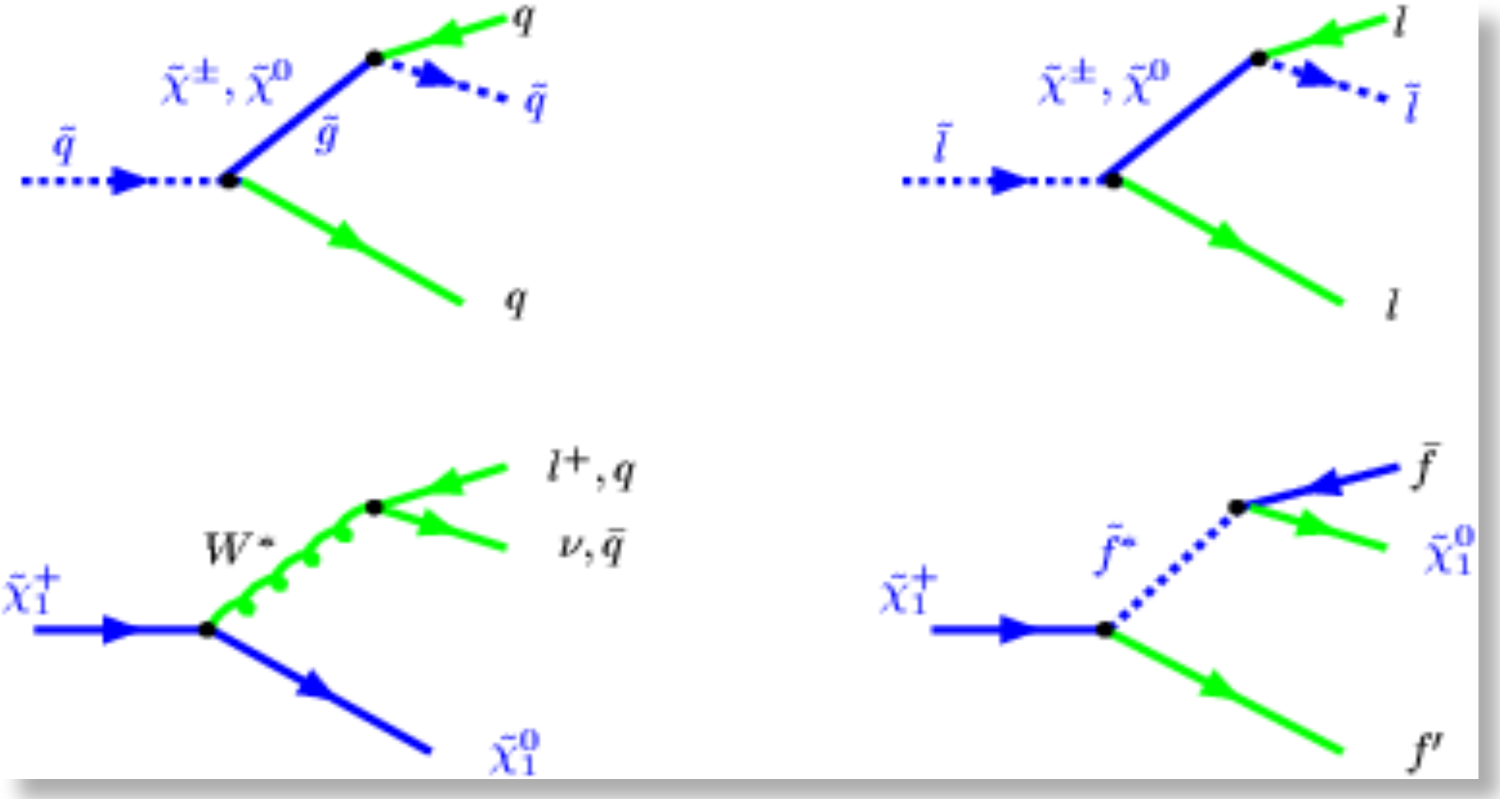
$$\tilde{\chi}_i^\pm \rightarrow e + \nu_e + \tilde{\chi}_i^0$$

$$\tilde{\chi}_i^\pm \rightarrow q + \bar{q}' + \tilde{\chi}_i^0$$

gluino

$$\tilde{g} \rightarrow q + \bar{q} + \tilde{\gamma}$$

$$\tilde{g} \rightarrow g + \tilde{\gamma}$$



neutralino

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + l^+ + l^-$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + q + \bar{q}'$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^\pm + l^\pm + \nu_l$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + \nu_l + \bar{\nu}_l$$

Final states

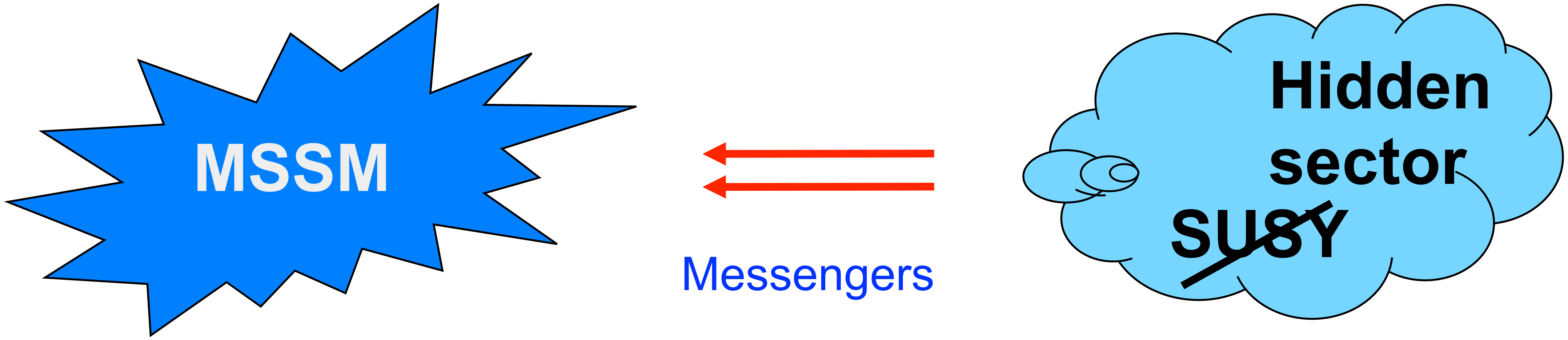
$l^+ l^- + \not{E}_T$

2 jets $+ \not{E}_T$

$\gamma + \not{E}_T$

$\not{E}_T$

SOFT SUSY BREAKING



MSSM

Messengers

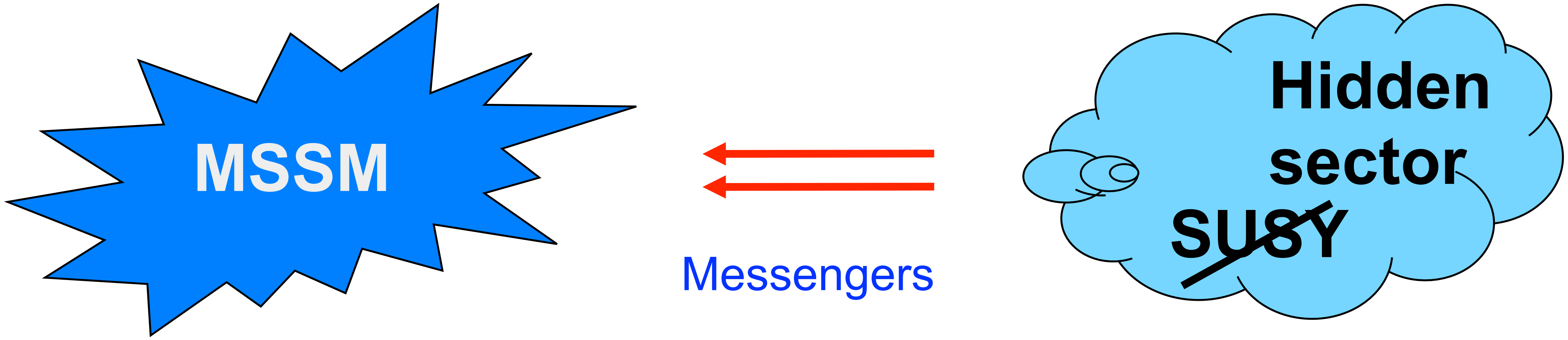
Hidden sector

~~SUSY~~

Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

SOFT SUSY BREAKING



MSSM

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Gravitons, gauge, gauginos, etc

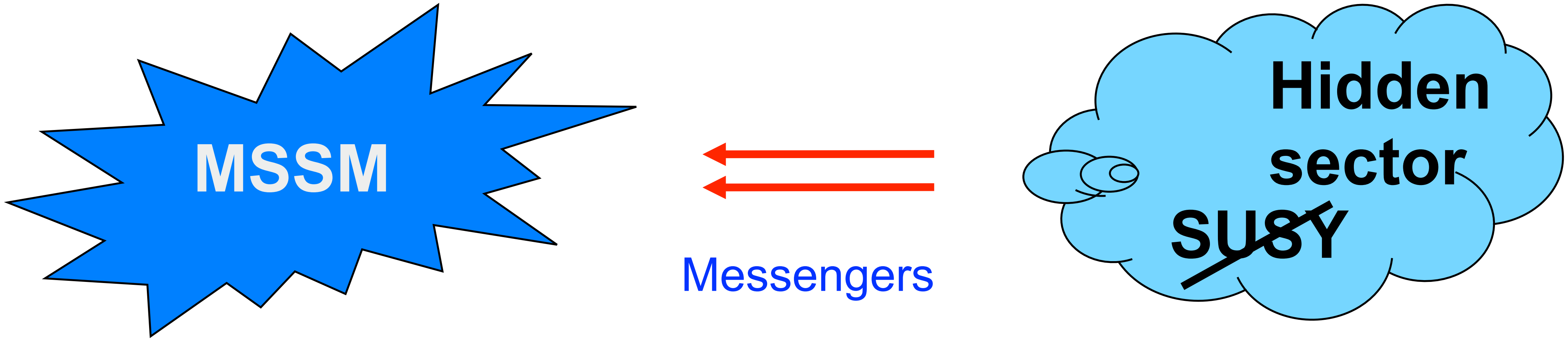
Breaking via F and D terms in a hidden sector

$$-L_{Soft} = \sum_{\alpha} M_i \widetilde{\lambda}_i \widetilde{\lambda}_i + \sum_i m_{0i}^2 \, | A_i |^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{ij} A_i A_j$$

gauginos

scalar fields

SOFT SUSY BREAKING



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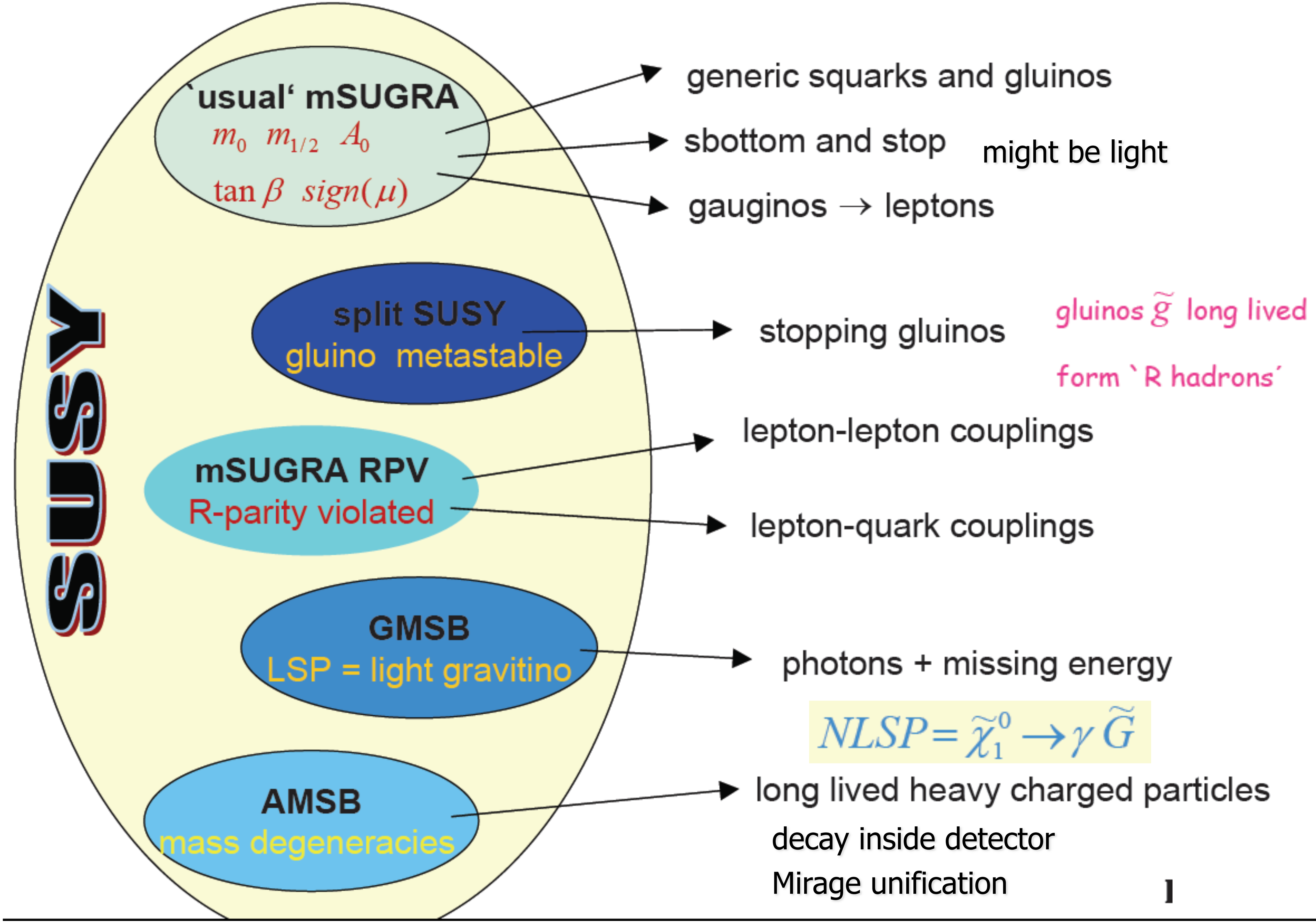
gauginos

scalar fields

Over 100 of free parameters !

SUSY Models and Signatures

T.Hebbeker



SUSY

`usual' mSUGRA

$m_0 \quad m_{1/2} \quad A_0$

$\tan\beta \quad sign(\mu)$

- generic squarks and gluinos
- sbottom and stop — might be light
- gauginos → leptons

split SUSY

gluino metastable

- stopping gluinos

gluinos $\tilde{g}$ long lived

form `R hadrons´

mSUGRA RPV

R-parity violated

- lepton-lepton couplings
- lepton-quark couplings

GMSB

LSP = light gravitino

- photons + missing energy

$$NLSP = \tilde{\chi}_1^0 \rightarrow \gamma\,\tilde{G}$$

AMSB

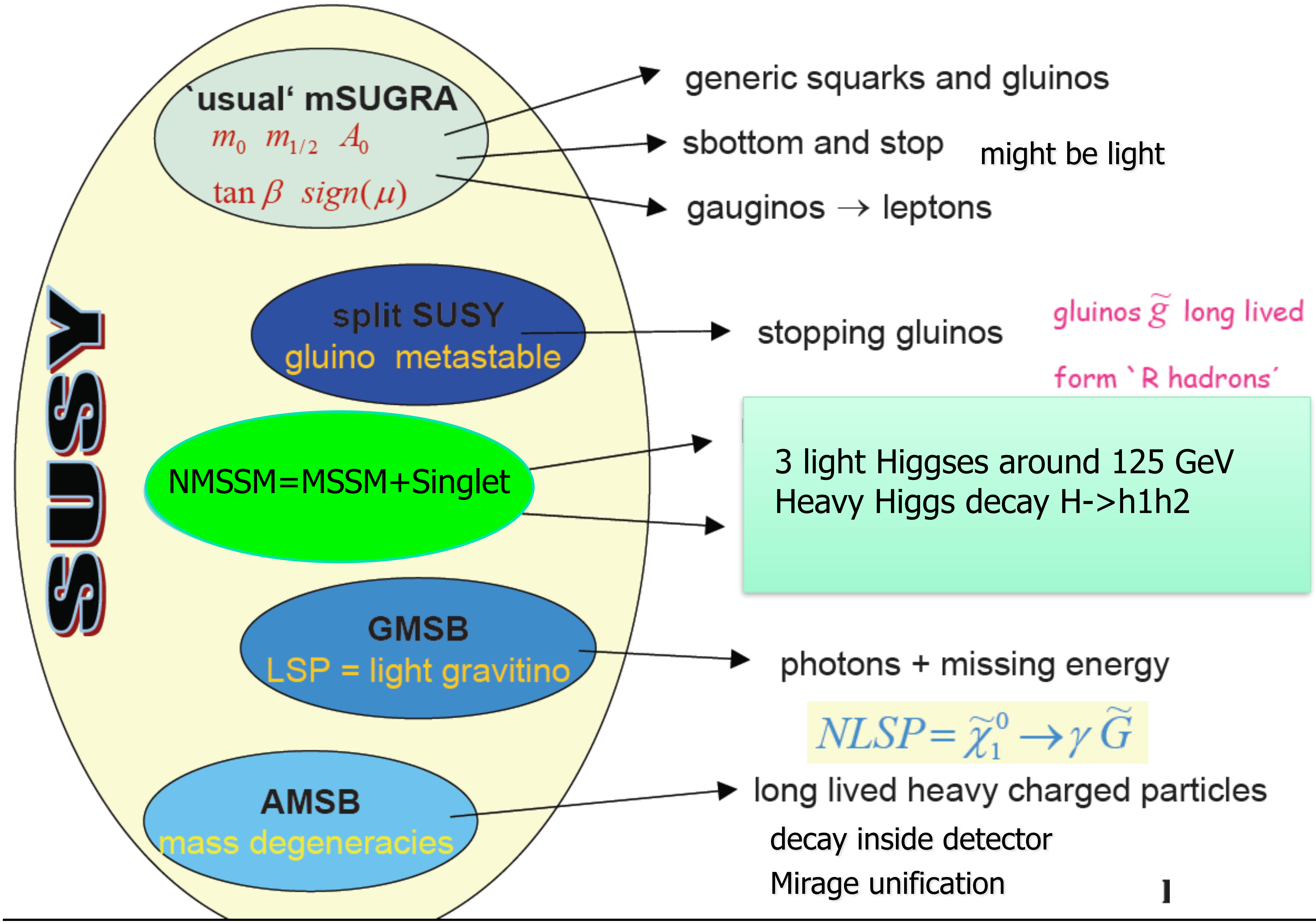
mass degeneracies

- long lived heavy charged particles

decay inside detector

Mirage unification

SUSY Models and Signatures



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NMSSM=MSSM+Singlet

3 light Higgses around 125 GeV
Heavy Higgs decay H->h1h2

GMSB
LSP = light gravitino

photons + missing energy

$$NLSP = \tilde{\chi}_1^0 \rightarrow \gamma\, \tilde{G}$$

AMSB
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SEARCH FOR SUSY MANIFESTATION

Particle Phys

- Direct production at colliders at high energies
- Indirect manifestation at low energies

  Rare decays ($B_s \to s\gamma,\ B_s \to \mu^+\mu^-, B_s \to \tau\nu$)

  g-2 of the muon

- Search for long-lived SUSY particles

Astro Phys (if SUSY DM)

- Relic abundancy of Dark Matter in the Universe
- DM annihilation signal in cosmic rays
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Nothing so far ...

WHAT IS THE LHC REACH NOW?

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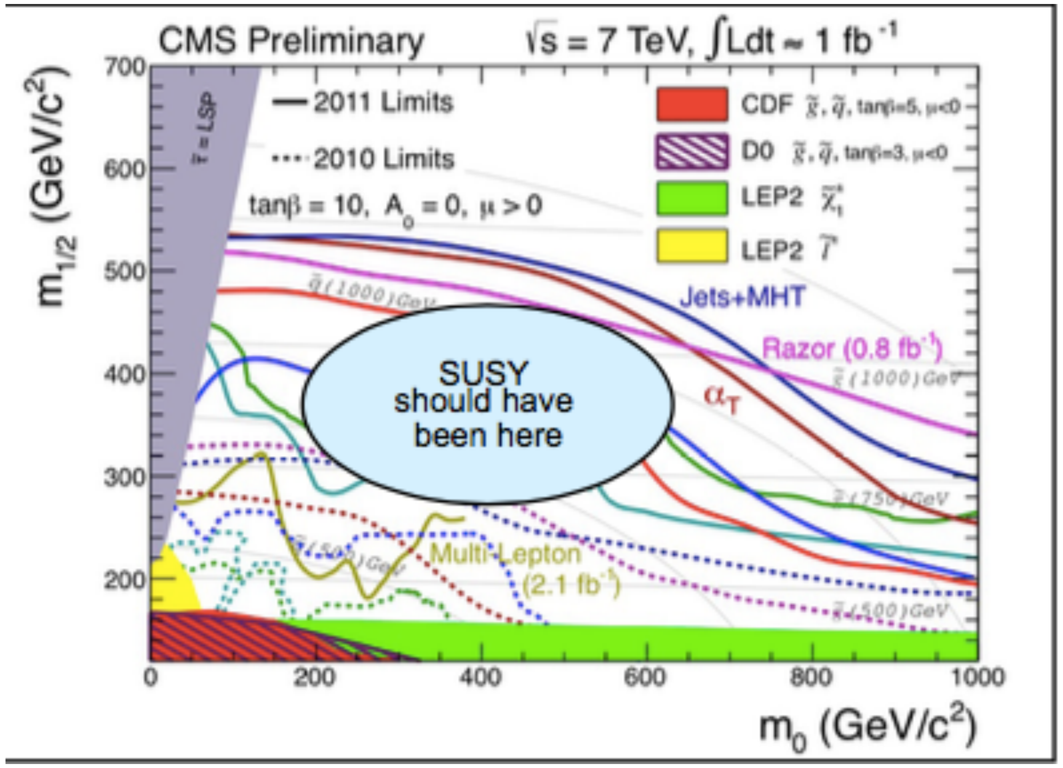
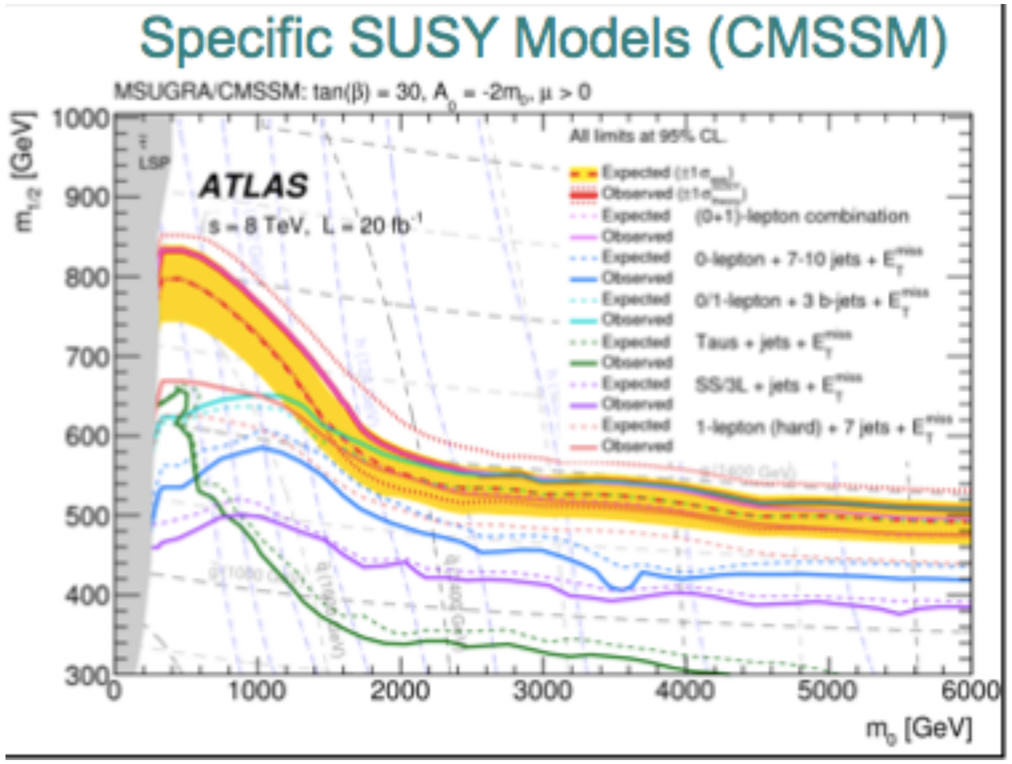
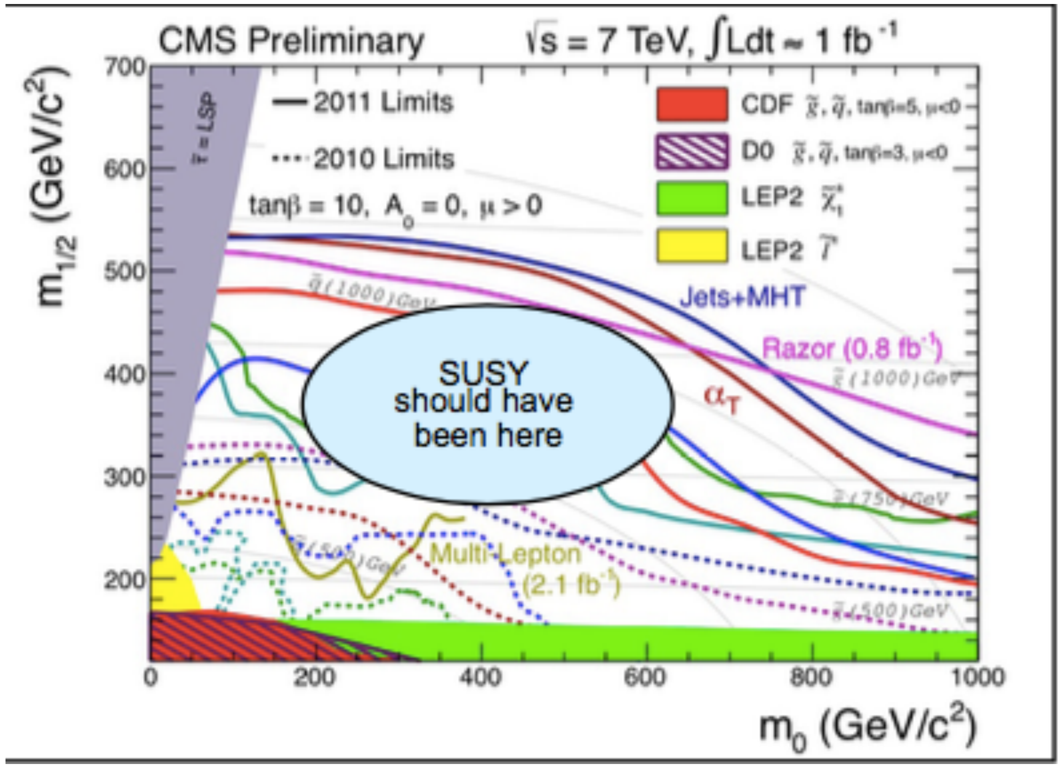
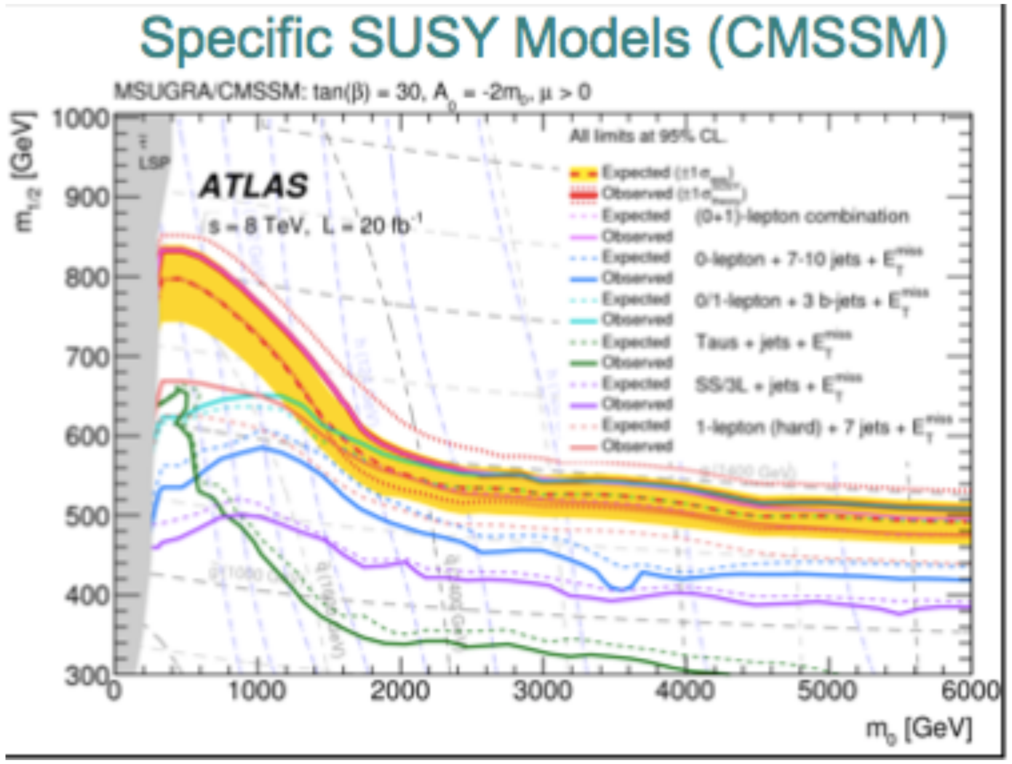




Universal parameters

WHAT IS THE LHC REACH NOW?





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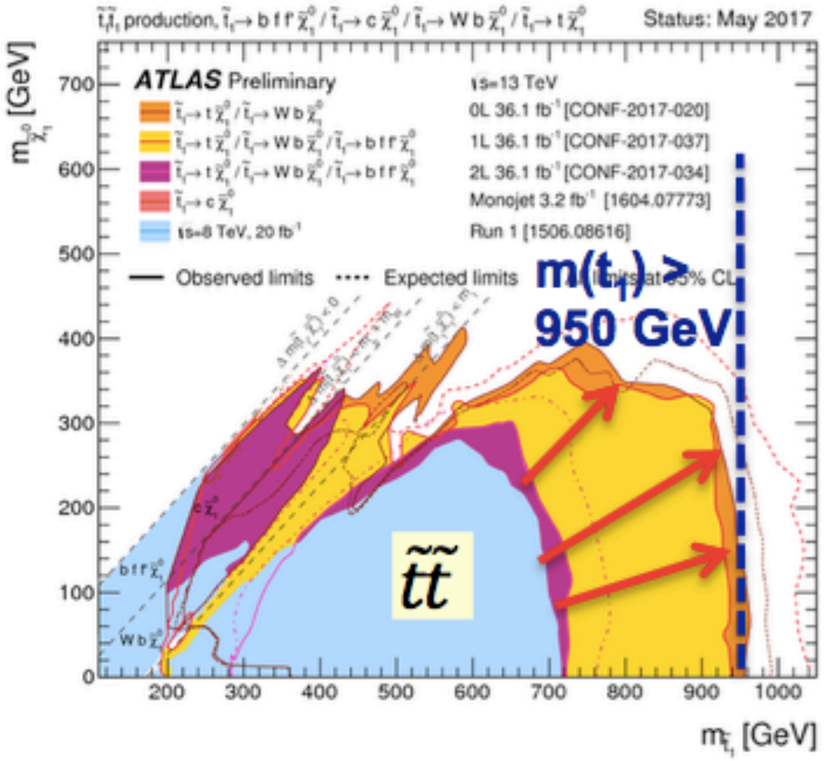
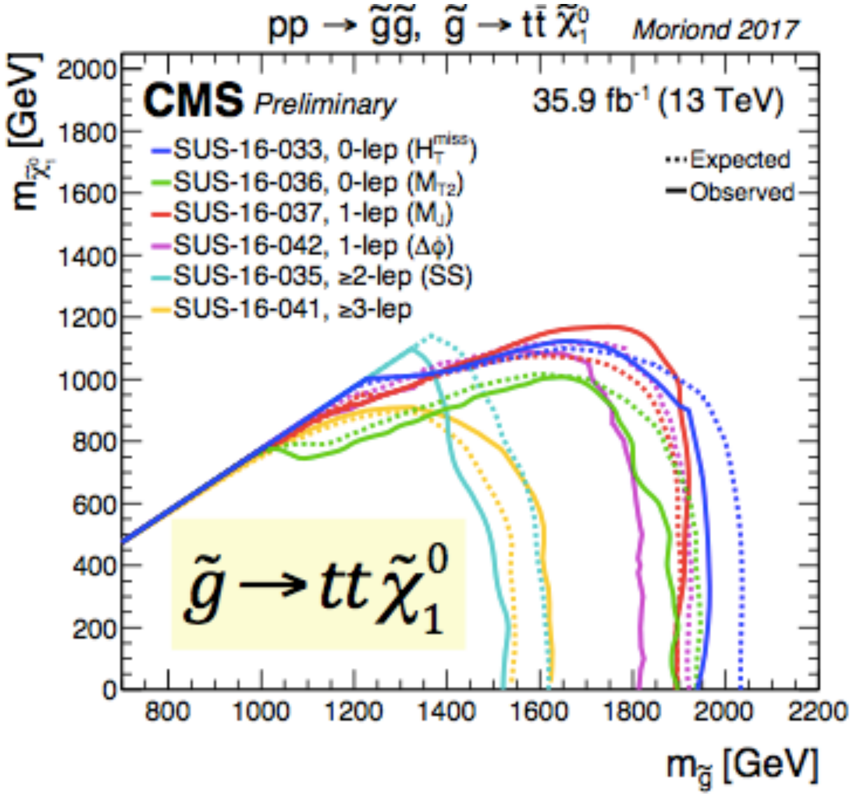
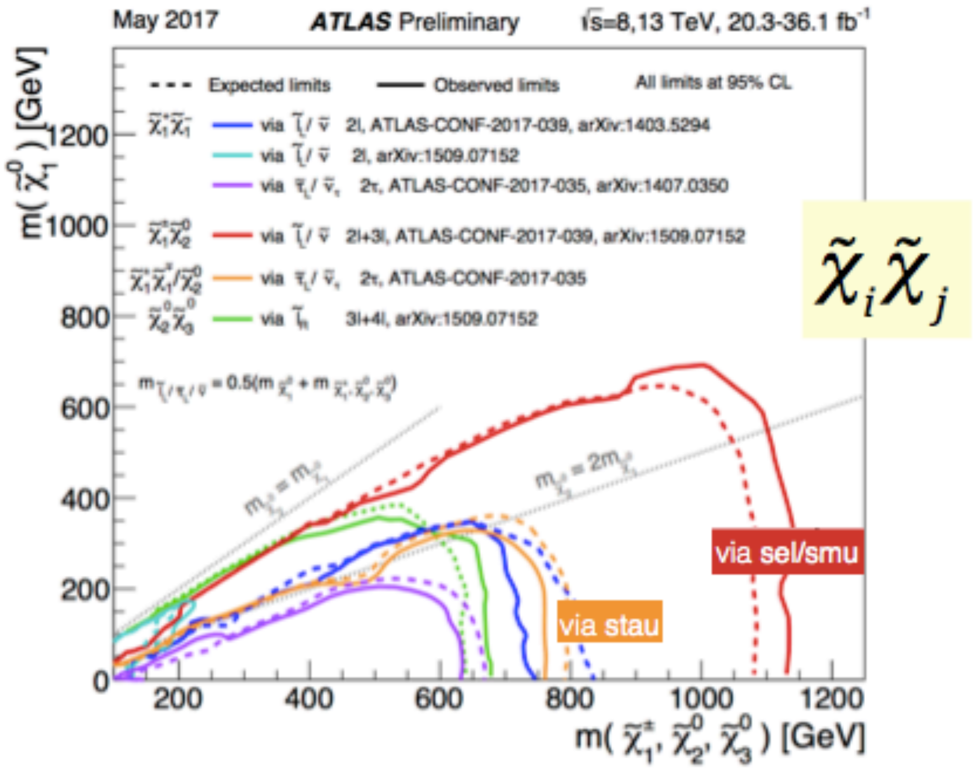


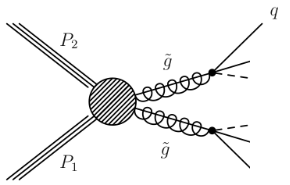




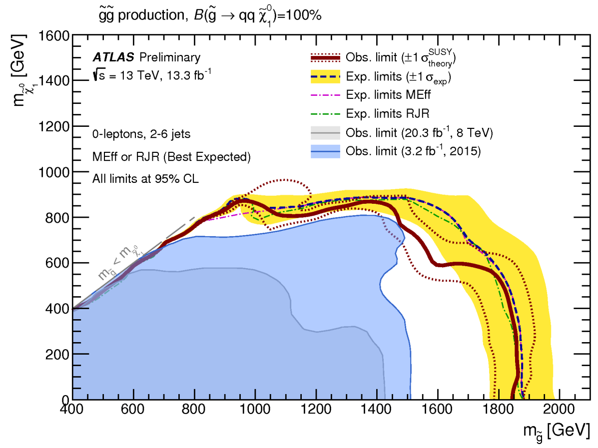
Masses of superpartners

SUPERSYMMETRY @ LHC

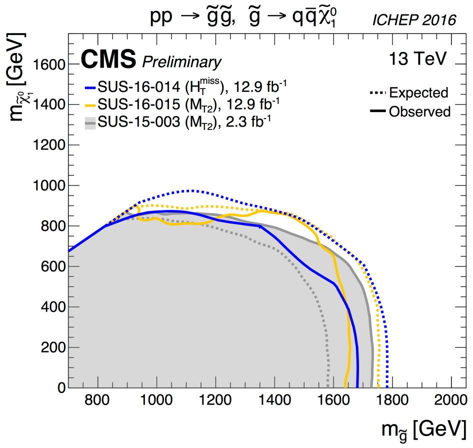
Gluino decays to qq+LSP



Summary of decays to light quarks + LSP

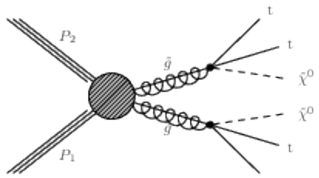


ATLAS-CONF-2016-078



CMS-SUS-16-014
CMS-SUS-16-015

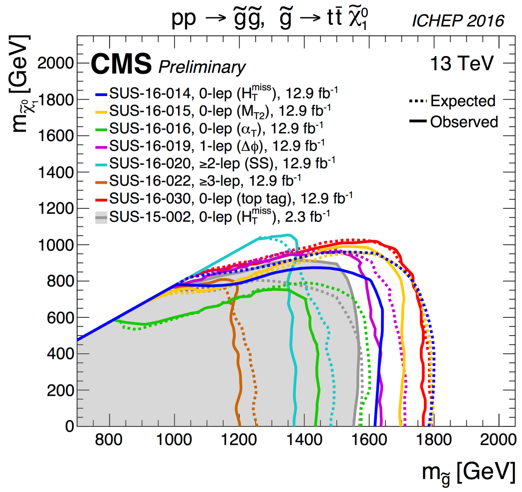
Gluino decays to tt+LSP

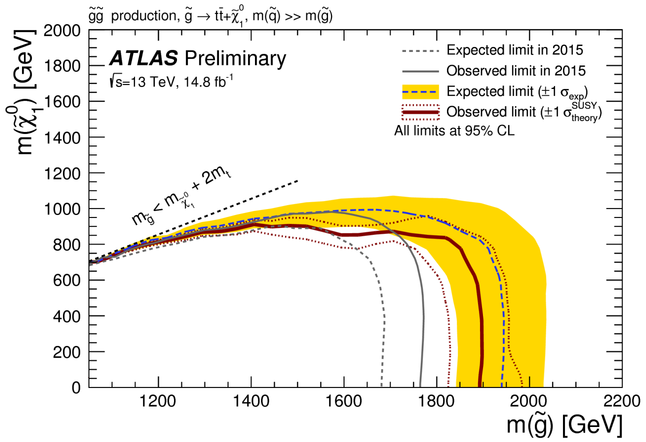


CMS summary

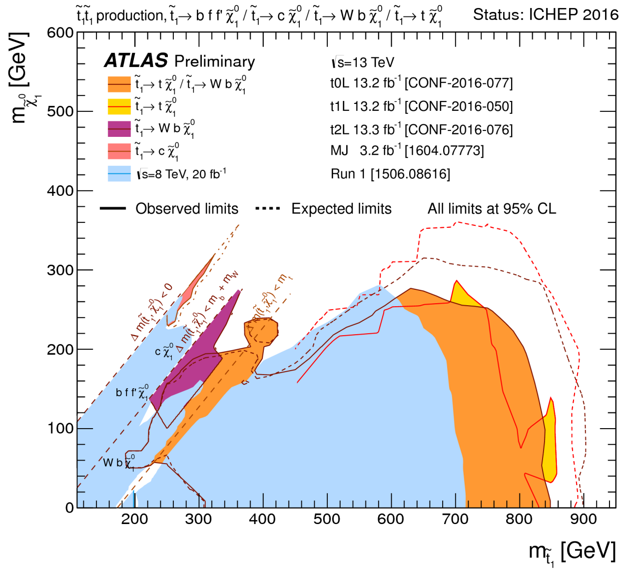
ATLAS multi-b

ATLAS-CONF-2016-052

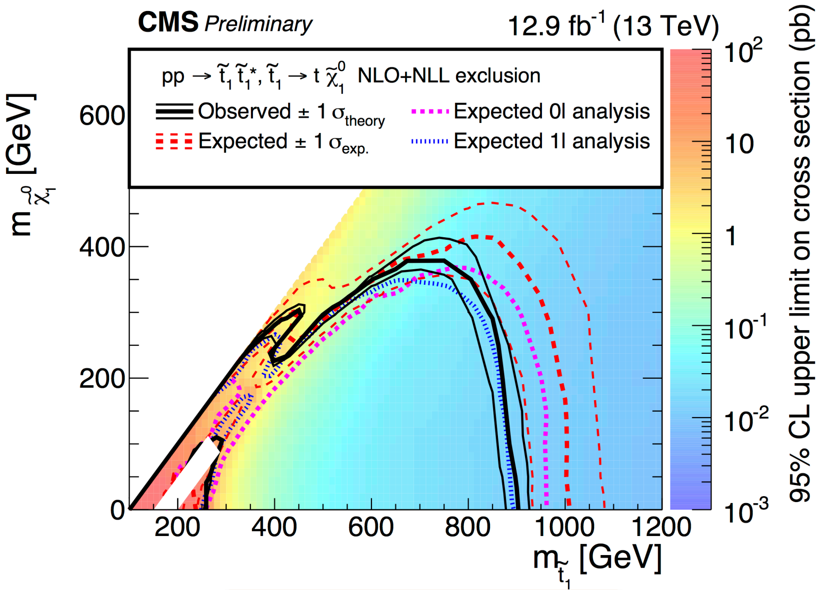




Top squarks - summaries



ATLAS summary

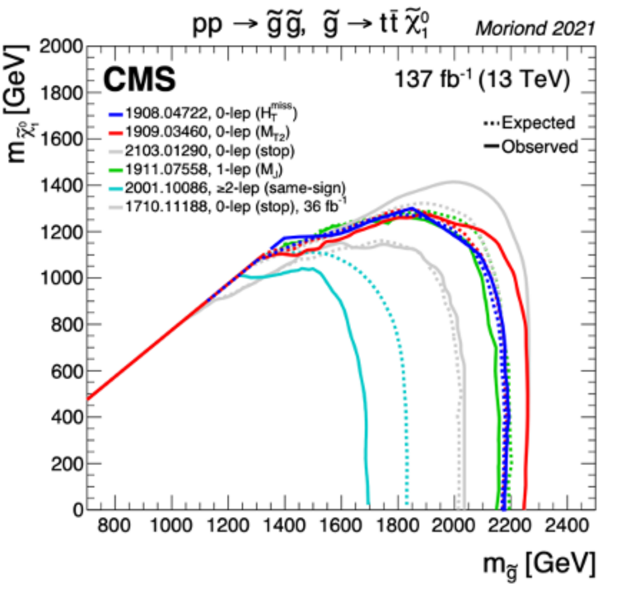


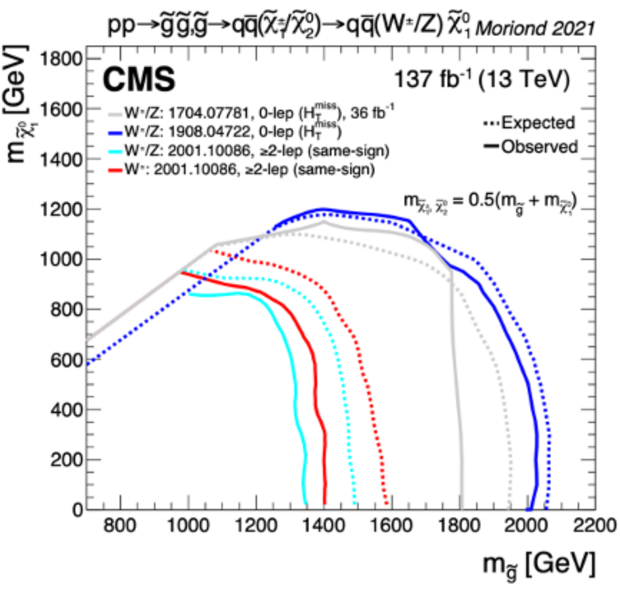
CMS 0l+1l combination
for 2-/3-body decay

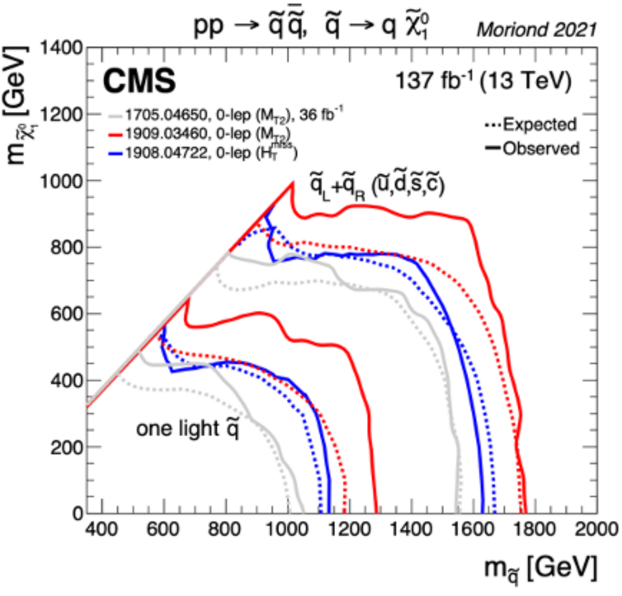
- SUSY limits for strong int's are pushed above 1 TeV
- This already requires fine tuning - little hierarchy prob
- No guiding lines

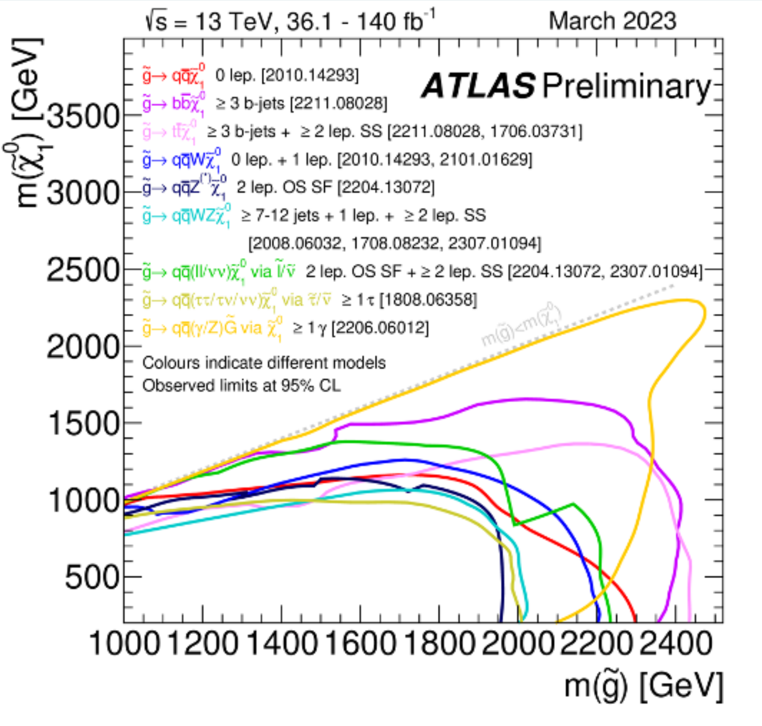
RECENT LHC LIMITS ON MSSM ‘23

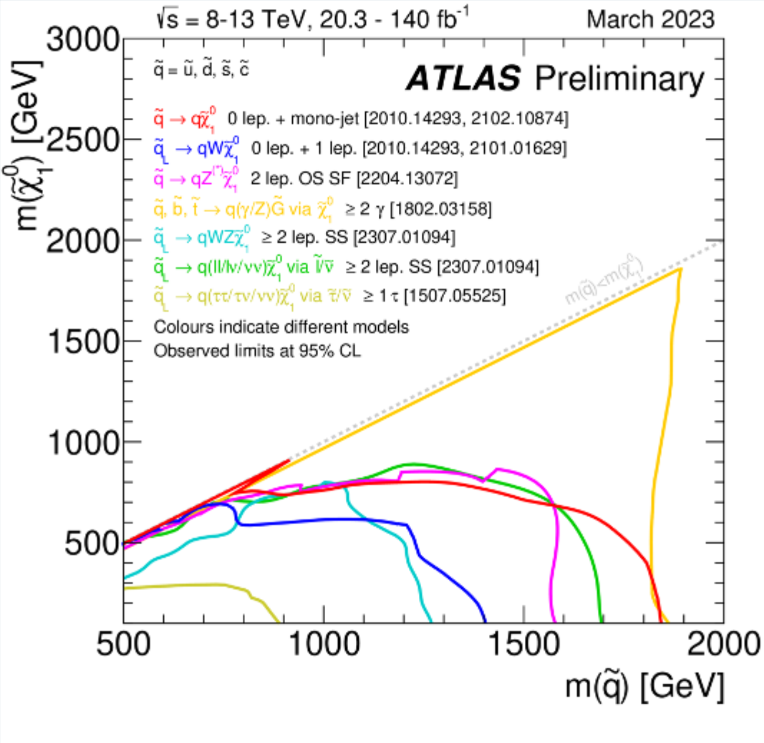
RUN2 LHC limits om MSSM, ATLAS&CMS

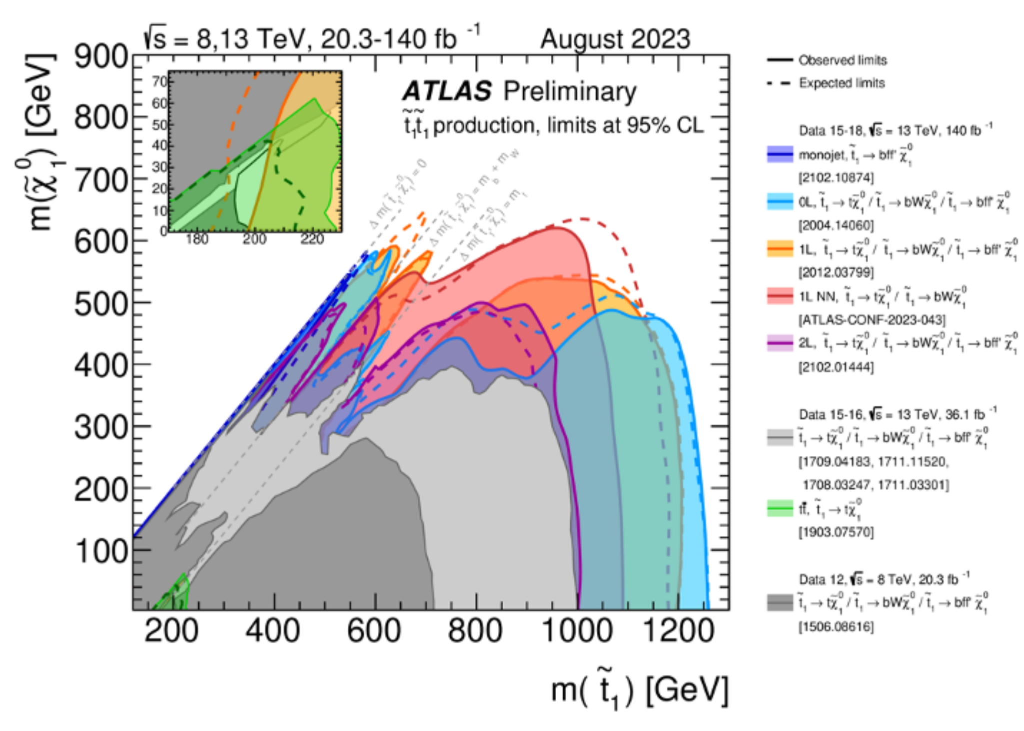




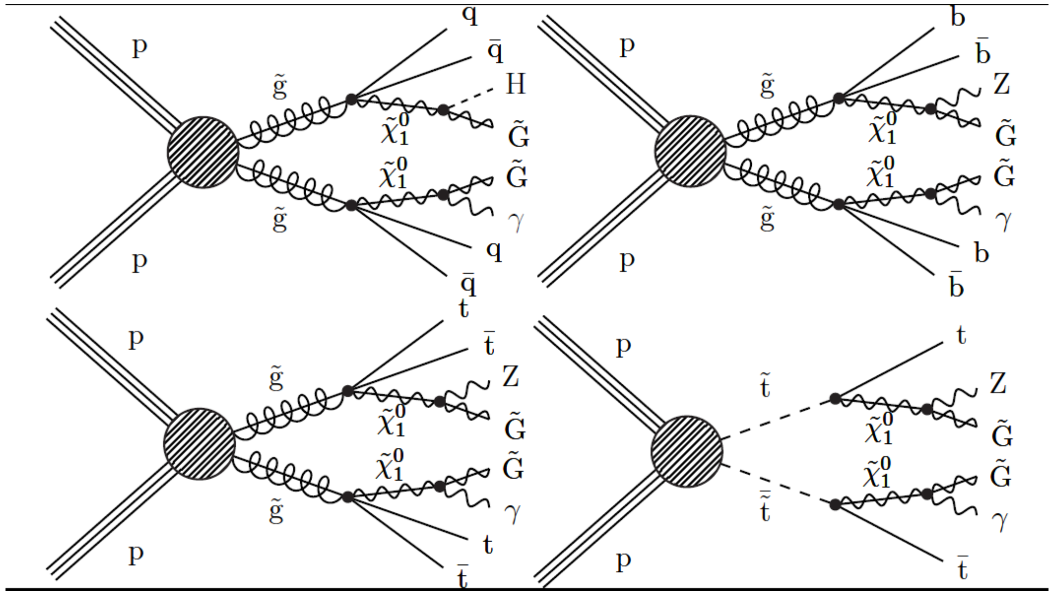


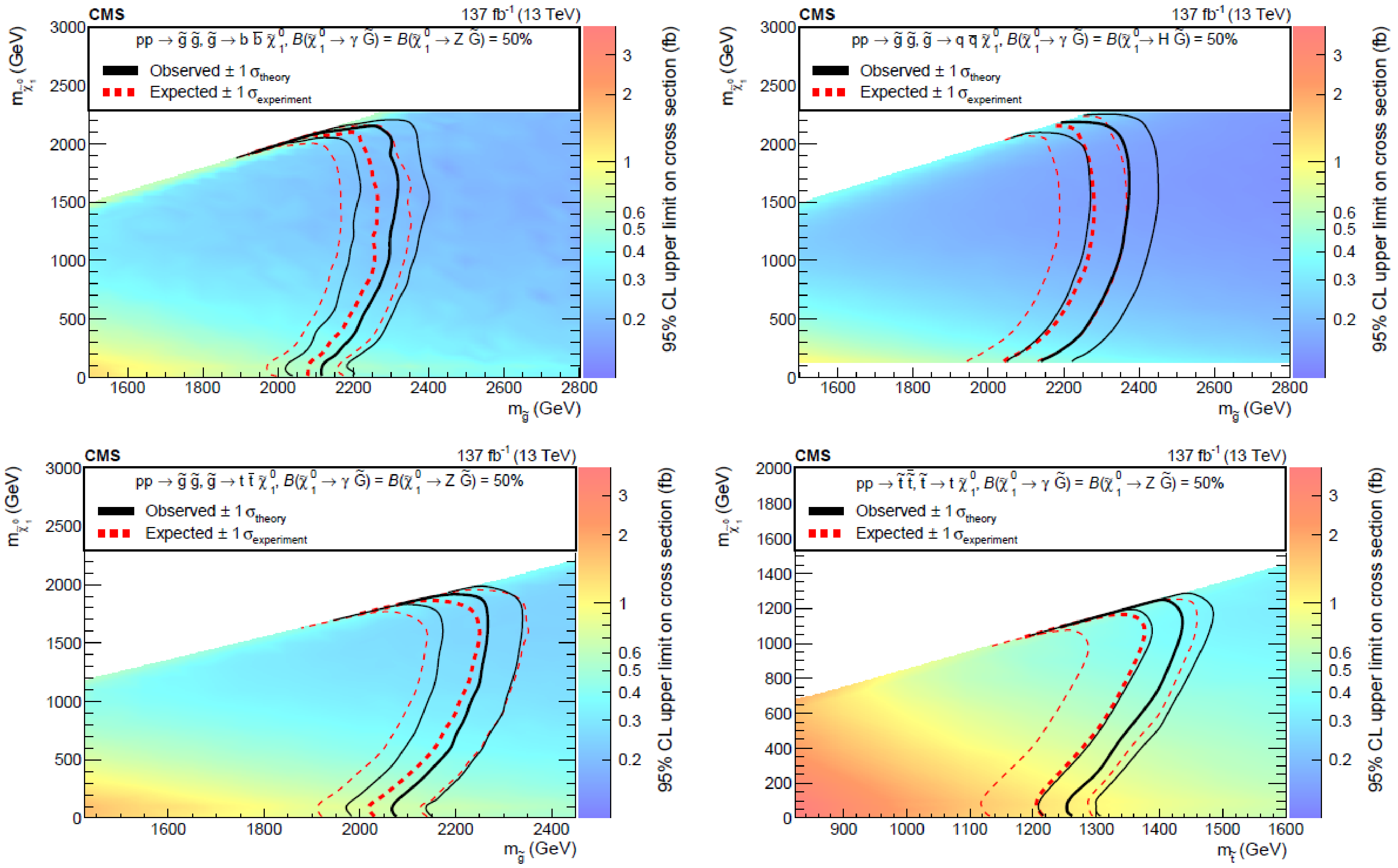




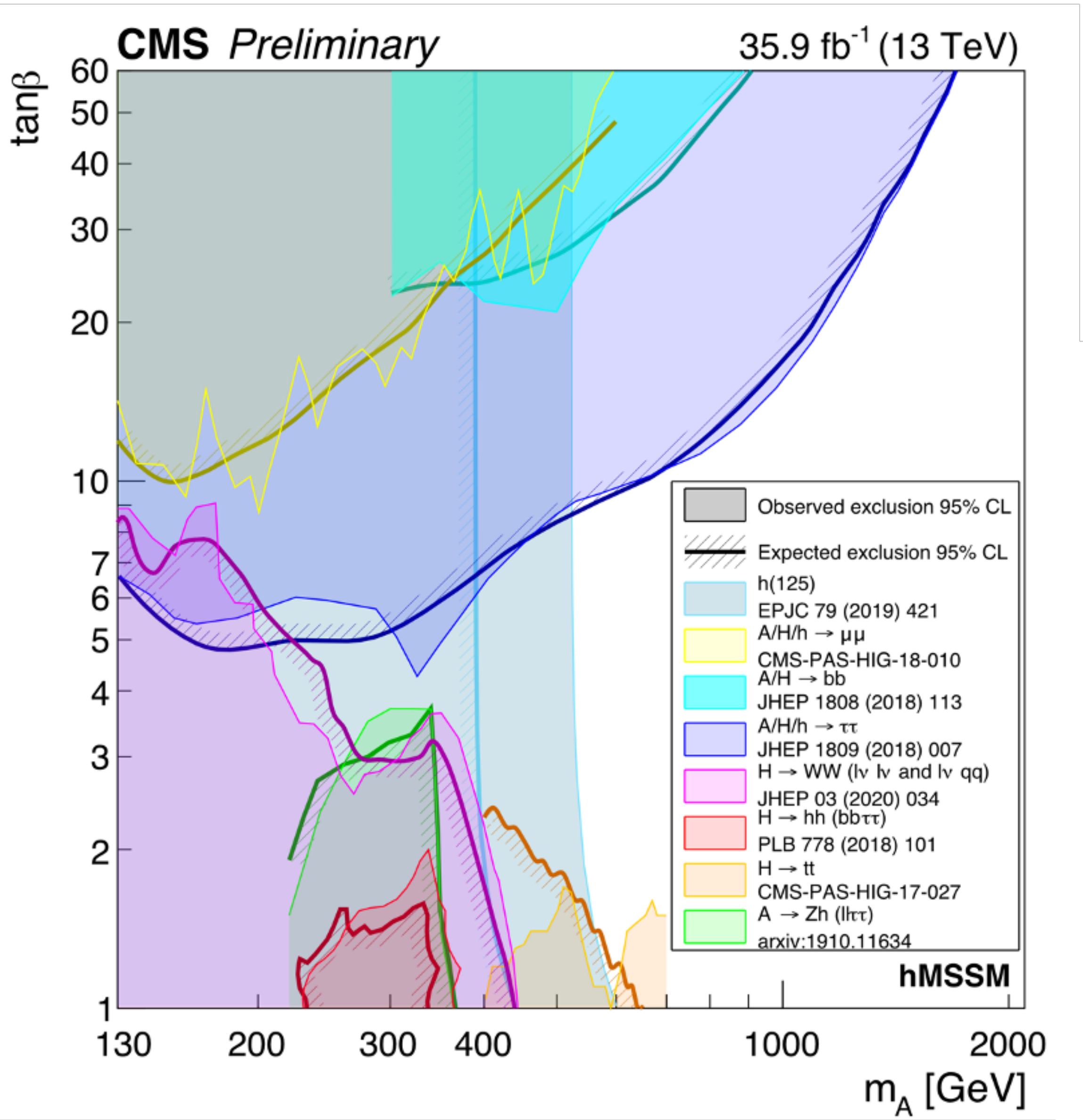


RUN2 LHC LIMITS ON GMSB MSSM, CMS



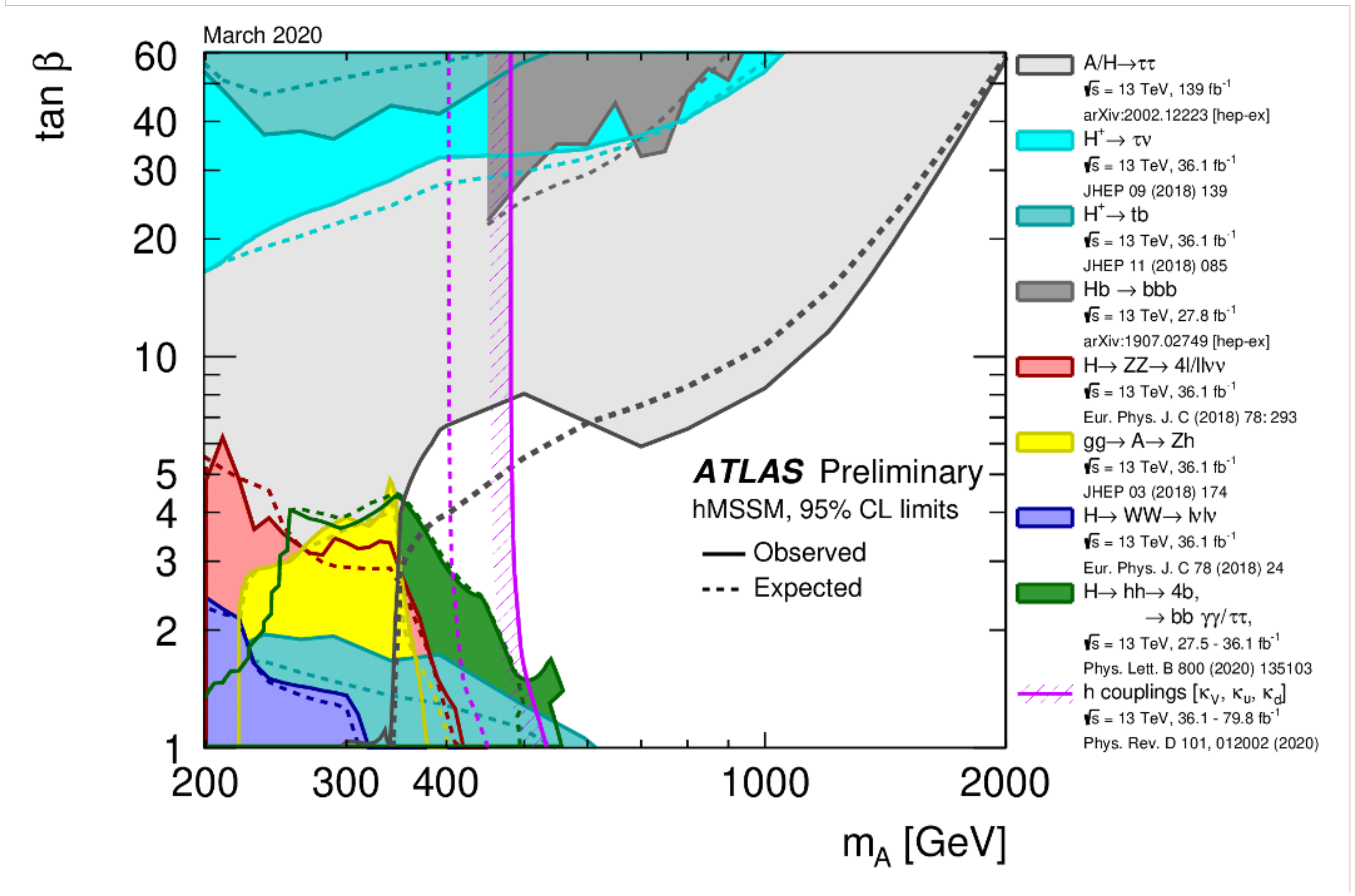


2HDM AND HMSSM LIMITS, RUN2

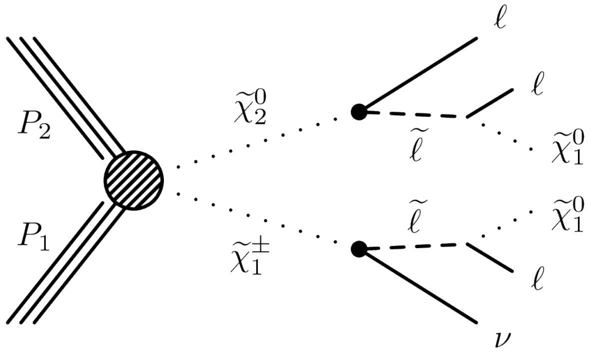


2HDM hMSSM combined results, RUN2

Much more details see in a talk by Adam Bailey
(+ comprehensive list of analyses for ATLAS & CMS)



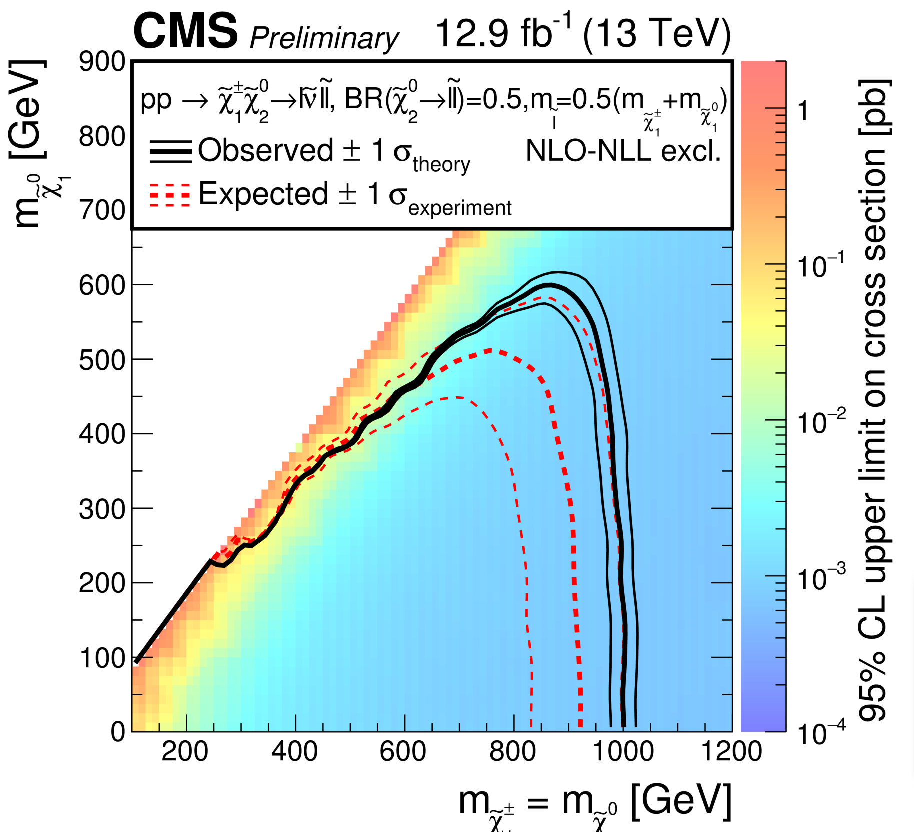
Chargino / neutralino production



Direct production of “electroweakino” pairs

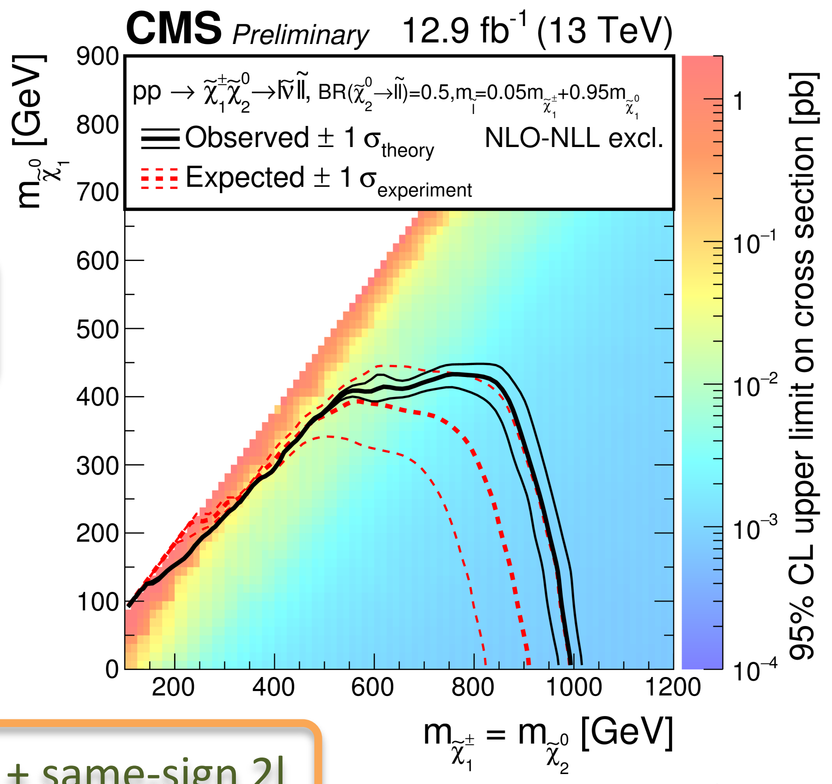
- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

No light EWkinos



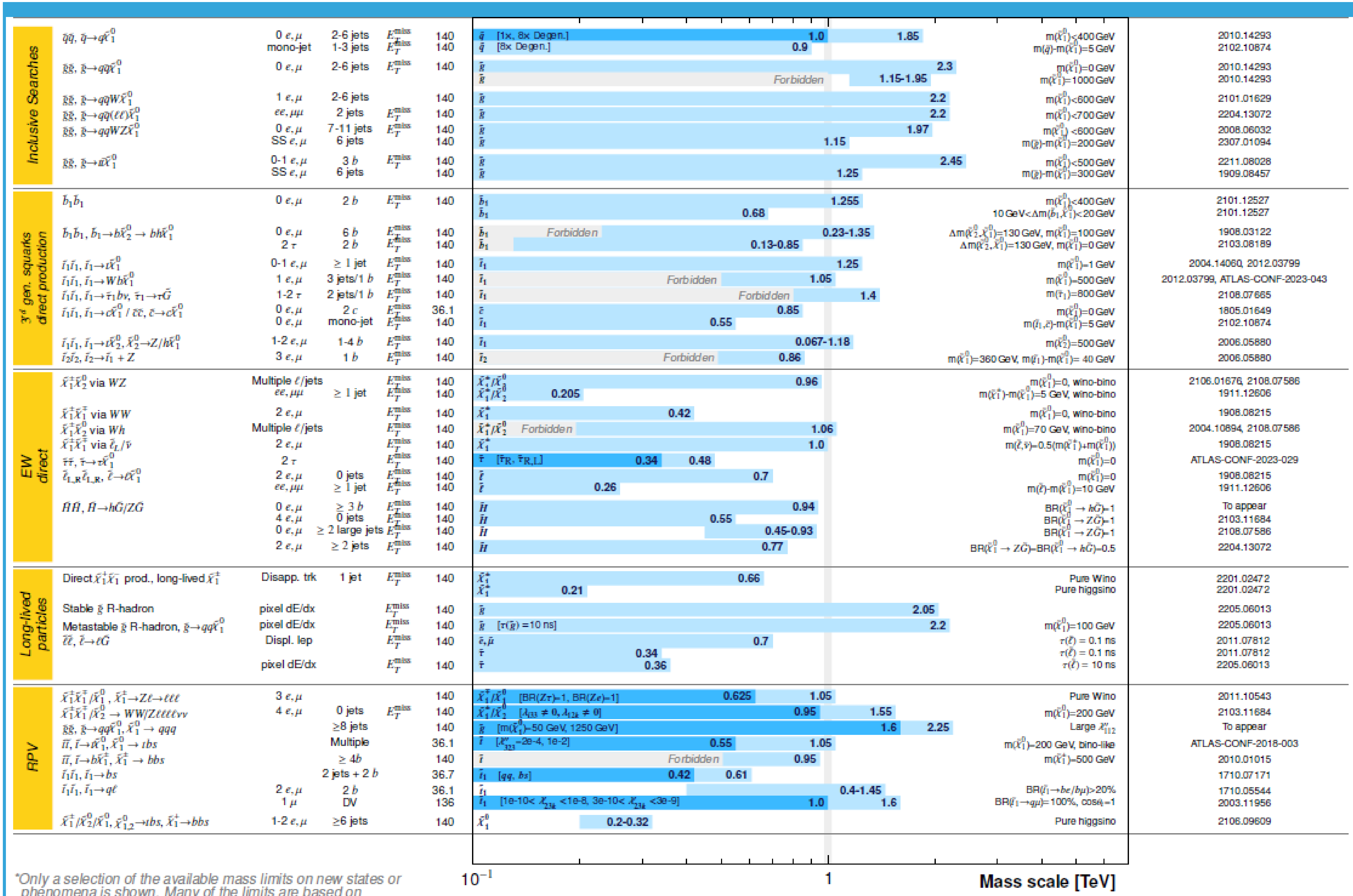
Effect of change in intermediate slepton mass

↔



3l + same-sign 2l

ATLAS AND CMS LIMITS 2023



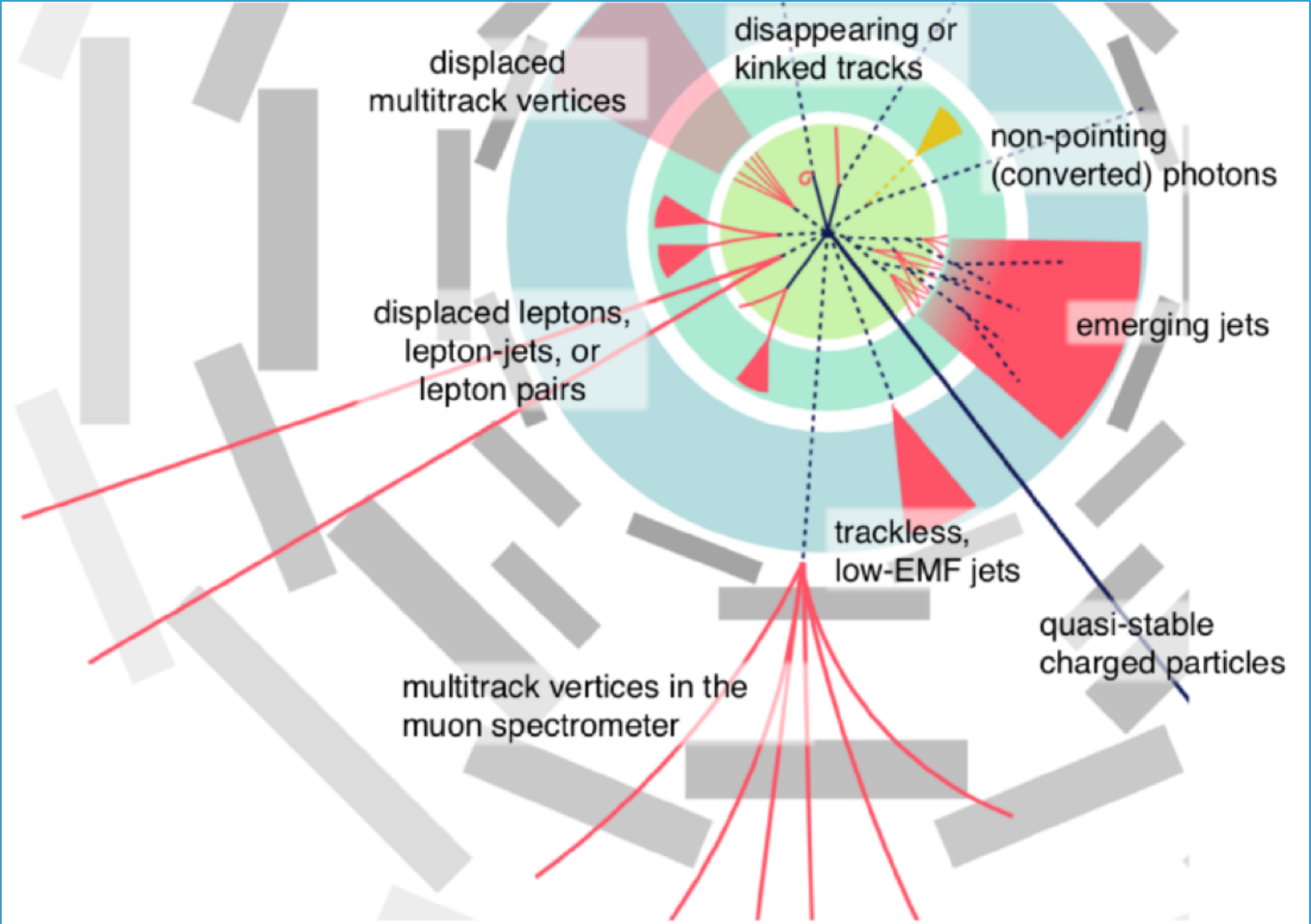
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

LONG LIVED PARTICLES

"The non-standard" (Long-Lived Particle) signatures

LLP:
a proper lifetime $c\tau_0$ is greater than or comparable to the characteristic size of the (sub)detectors

- ✓ small $c\tau_0$ that comparable to the inner tracker size, no displaced tracks → "standard" prompt decay
- ✓ intermediate $c\tau_0$ → LLP
- ✓ very large/infinite large $c\tau_0$ → stable particles, "standard" MET signatures

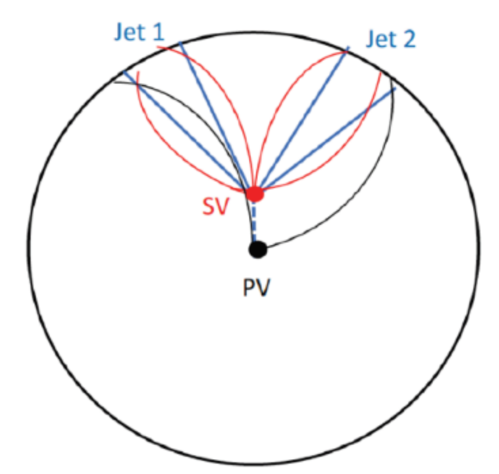


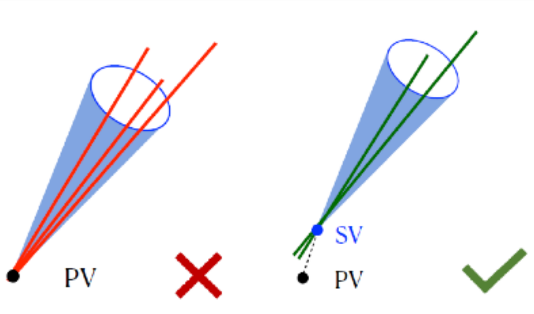
Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP White Paper: arXiv:1903.04497

LLP theory motivations: arXiv:1806.07396

displaced jets/leptons

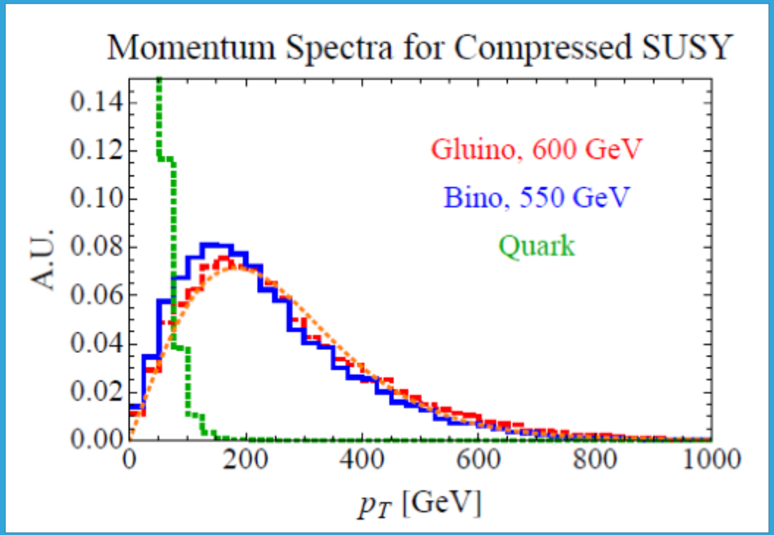


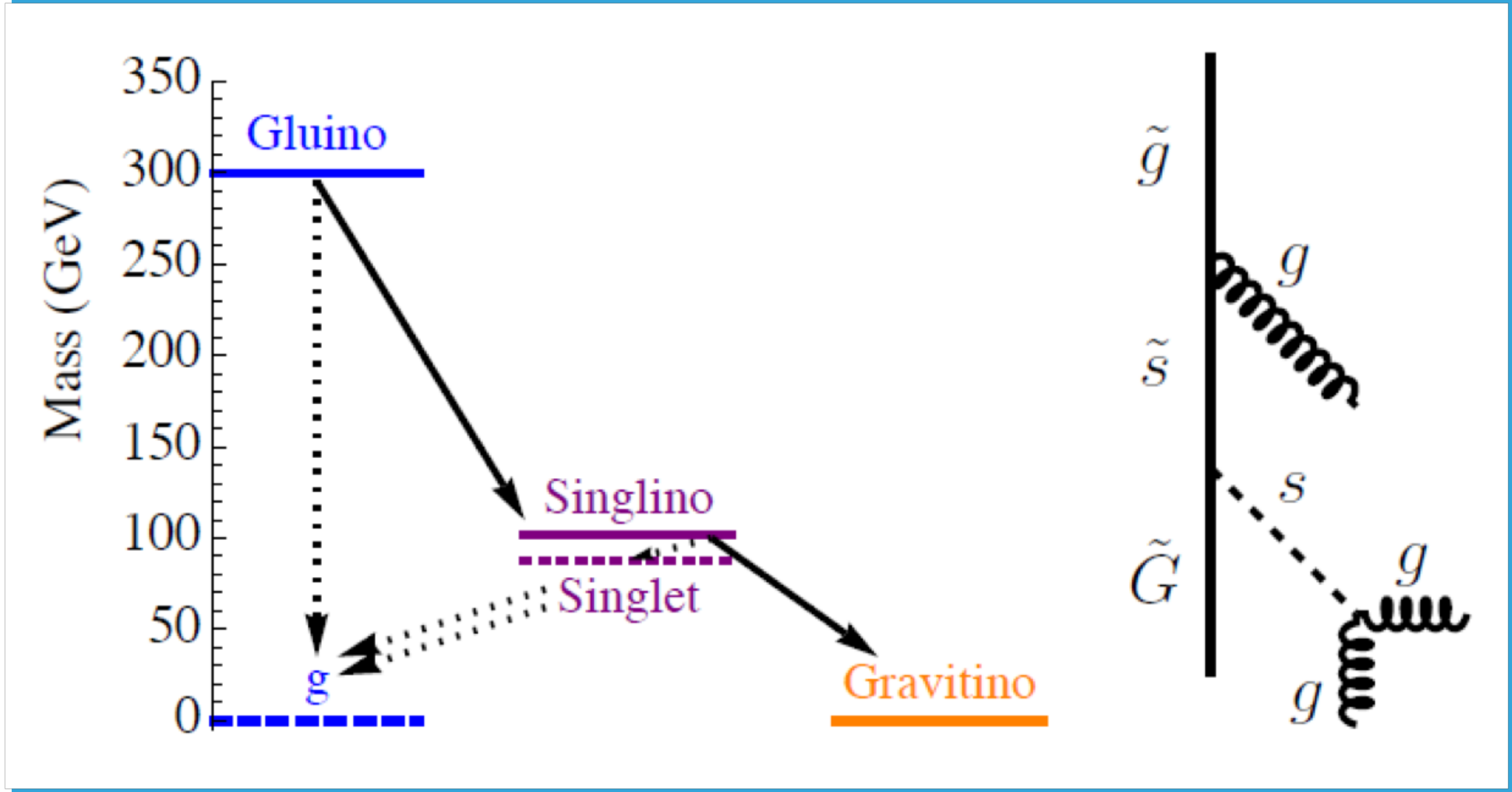


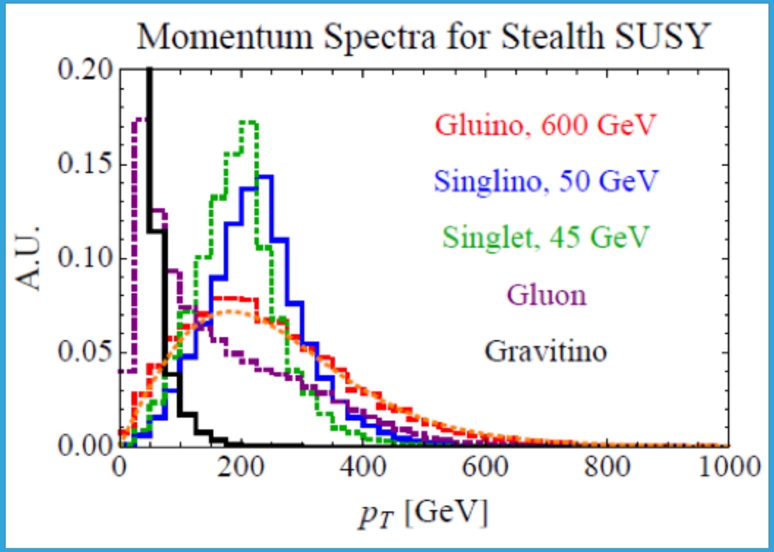
Stealth supersymmetry model

Stealth supersymmetry idea

SUSY is natural, low-scale SUSY breaking, hidden sector with one chiral singlet supefield (singlino/singlet). The lightest supersymmetric particle – gravitino (GMSB), LOSP decay to gravitino through a hidden sector. R-odd singlino, R-even singlet. Masses in a hidden sector of order the EW scale, states approximately supersymmetric – mass splitting is much smaller than masses, states are closely degenerated by masses. Suppression of large missing E_T (connected with gravitino).







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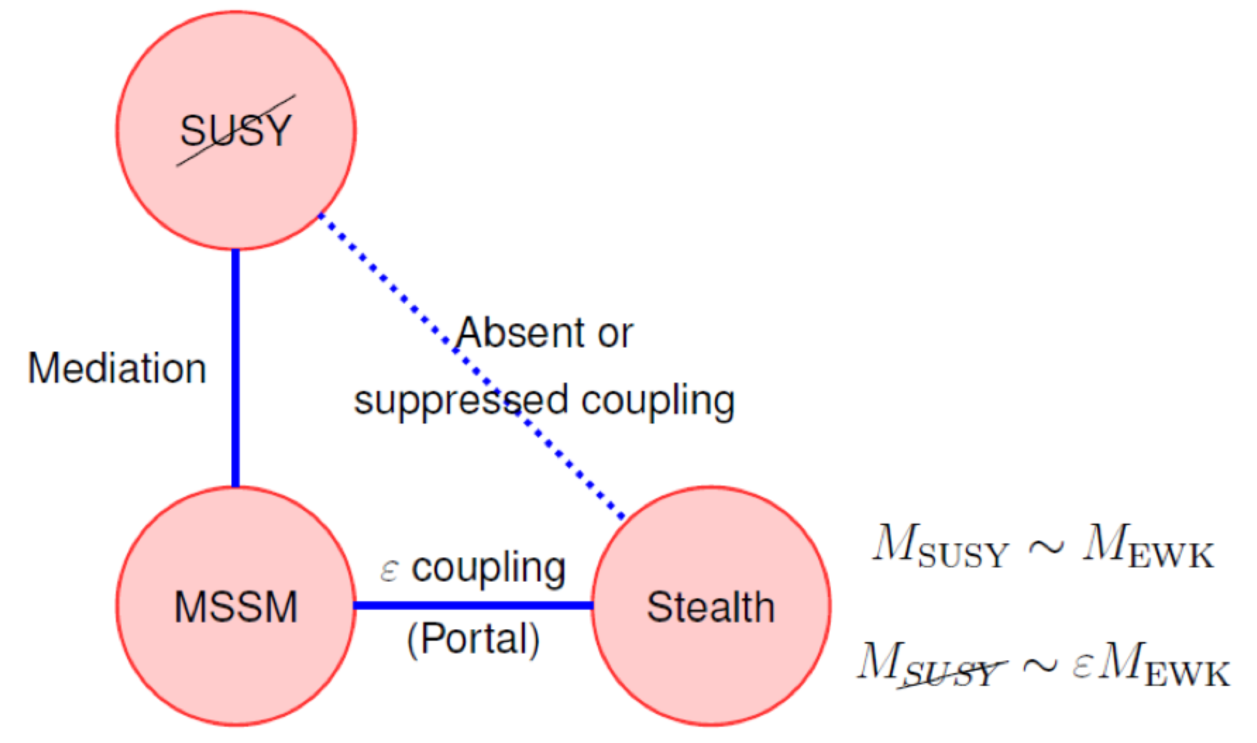


SUSY breaking – low-scale vs high-scale (large soft mass contributions to the stealth sector), mX_1X_2

Soft SUSY_breaking B-term (or M_{Pl} suppression in SUGRA)

$$\mathcal{L} \supset \int d^2\theta \; m \left(1 + \theta^2 m_{3/2}\right) X_1 X_2 \supset m_{3/2} m X_1 X_2$$

$$\delta m = m - \sqrt{m^2 - B} \approx \frac{B}{2m}$$

splitting of about 10 GeV,

$$B = m_{3/2} m \Longrightarrow m_{3/2} \lesssim 2\delta m \lesssim 20 \text{ GeV}$$

Stealth masses of about the EW scale – accident or common underlying physics? Small Bμ/dynamically generated masses

GMSB decay width

$$\Gamma(\tilde{g} \to g\tilde{G}) = \frac{m_{\tilde{g}}^5}{48\pi M^2 m_{\tilde{G}}^2} = 1.1 \times 10^{-9}\,\text{GeV} \left(\frac{m_{\tilde{g}}}{250\,\text{GeV}}\right)^5 \left(\frac{m_{\tilde{G}}}{1\,\text{eV}}\right)^{-2}$$

will be modified by new hidden sector

FUTURE SUSY SEARCHES

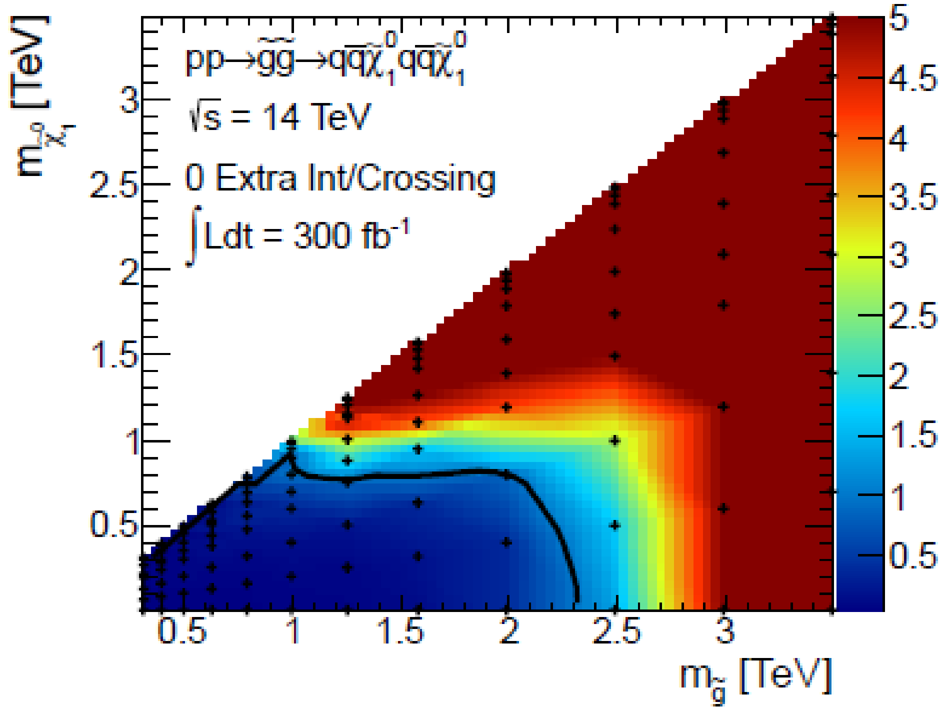
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

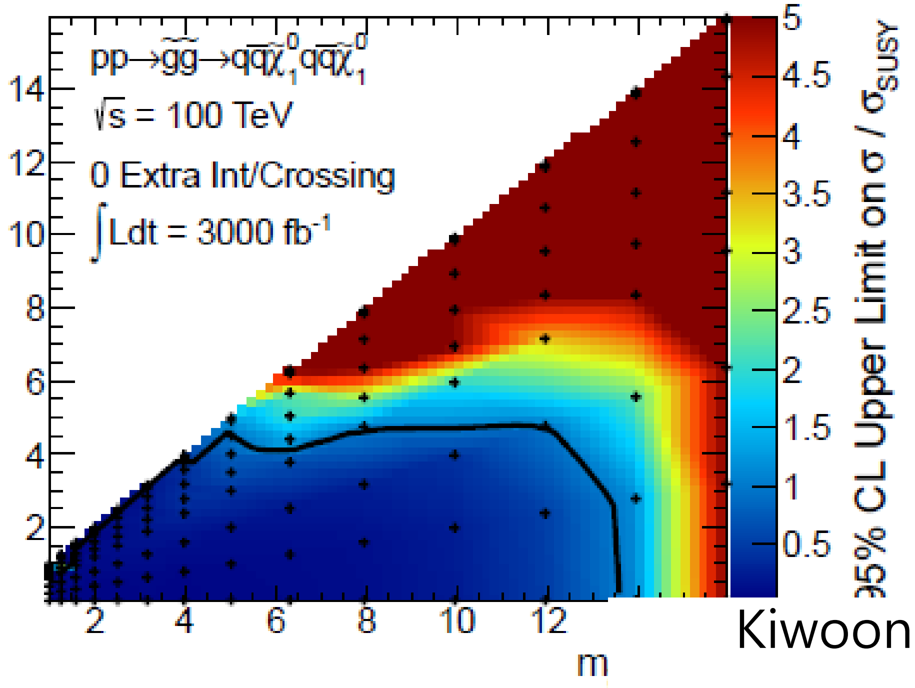
* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, '13

100 TeV collider

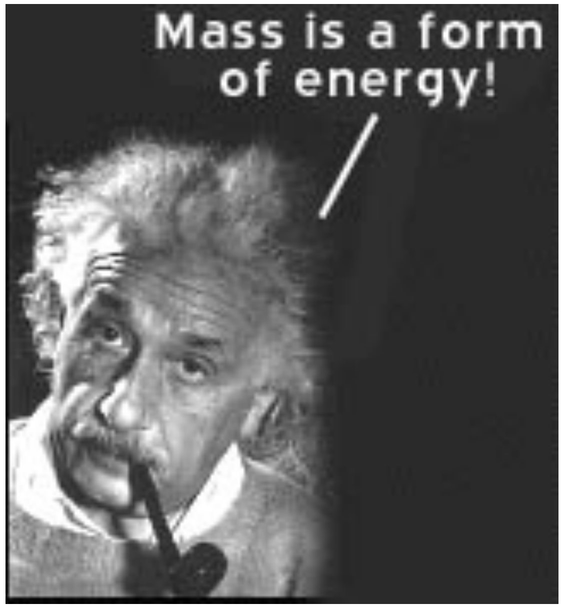


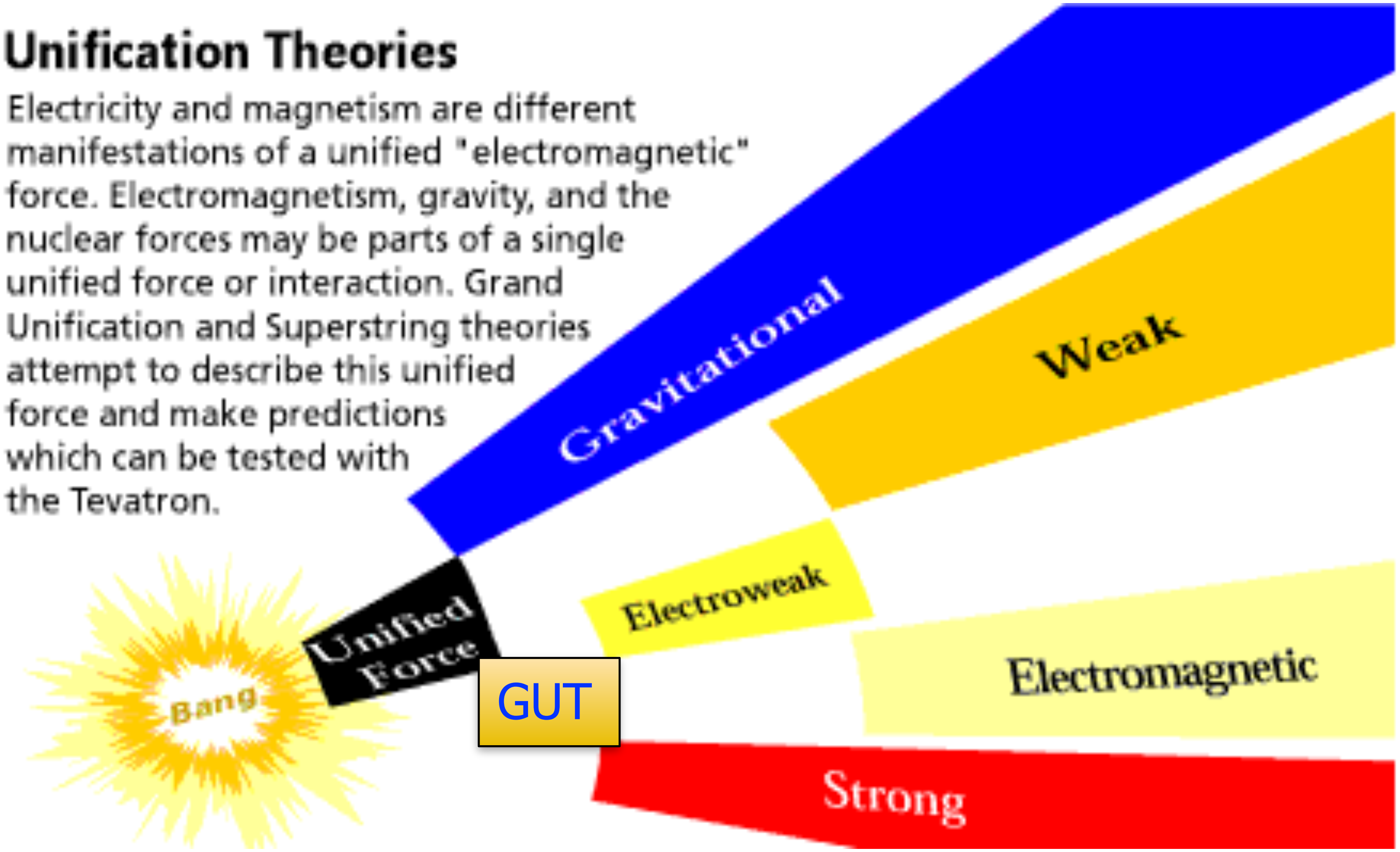


Kiwoon Choi

(ICHEP 2016, Chicago)

THE UNIFICATION PARADIGM





Unification Theories

Electricity and magnetism are different manifestations of a unified "electromagnetic" force. Electromagnetism, gravity, and the nuclear forces may be parts of a single unified force or interaction. Grand Unification and Superstring theories attempt to describe this unified force and make predictions which can be tested with the Tevatron.

10^{-34} cm

D=10

- Unification of strong, weak and electromagnetic interactions within Grand Unified Theories is a new step in unification of all forces of Nature
- Creation of a unified theory of everything based on string paradigm seems to be possible

NEW SYMMETRIES

GRAND UNIFICATION

Grand Unification is an extension of the Gauge symmetry of the SM

$$
\begin{array}{ccccl}
 & \text{Low energy} & & \Rightarrow & \text{High energy} \\
SU_c(3)\otimes & SU_L(2)\otimes & U_Y(1) & \Rightarrow & G_{GUT} \quad (or\ G^n + \text{discrete symmetry}) \\
\text{gluons} & W, Z & \text{photon} & \Rightarrow & \ \text{gauge bosons} \\
\text{quarks} & \text{leptons} & & \Rightarrow & \text{fermions} \\
g_3 & g_2 & g_1 & \Rightarrow & g_{GUT}
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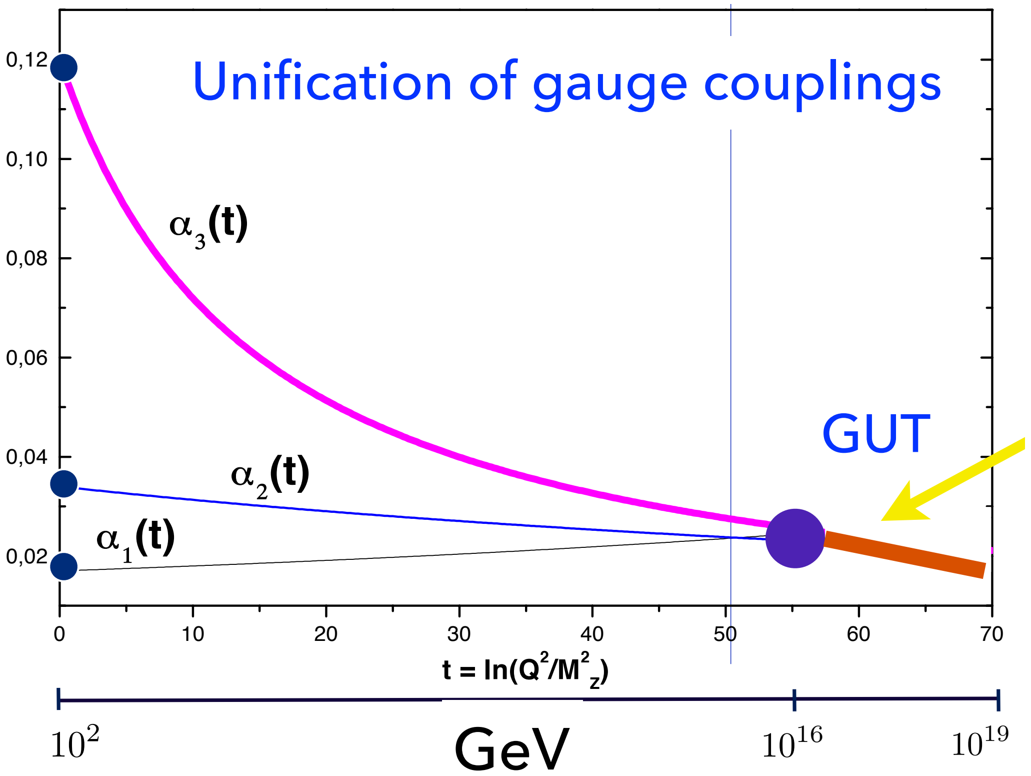

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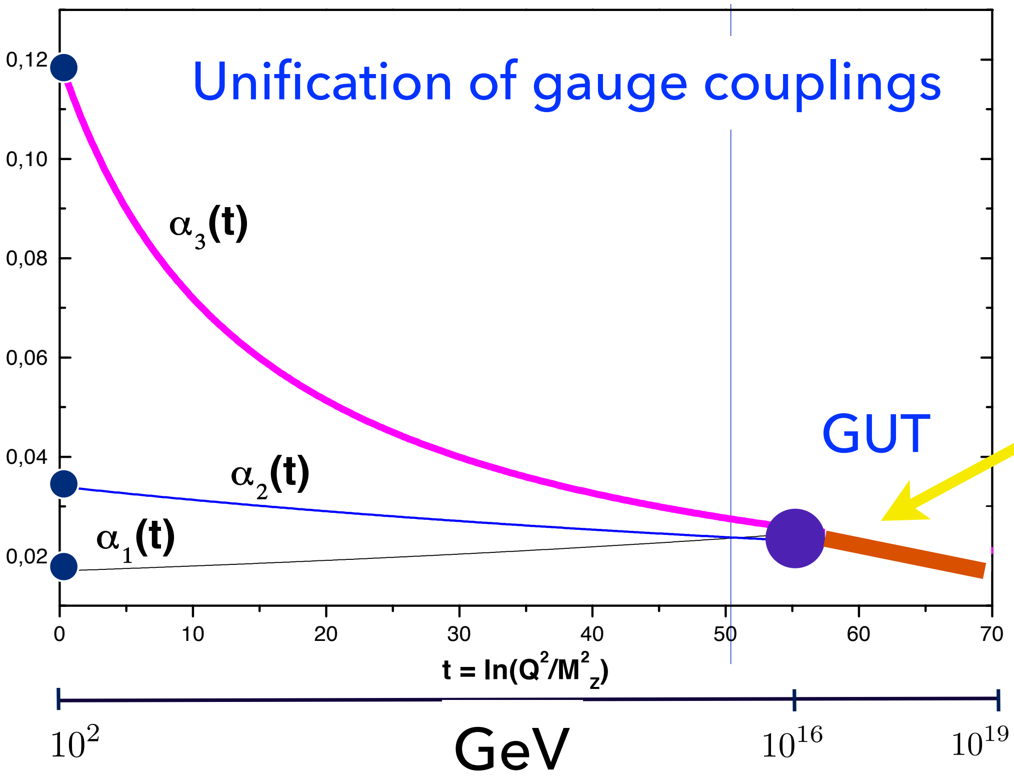

$$SU(3) \times SU(2) \times U(1) \subset G_{GUT}$$

$$Ex : SU(5), SO(10), E(6), SU(5) \times U(1),$$
$$SU(4) \times SU(2) \times SU(2), SO(10) \times U(1)$$

GUT MODELS

SU(5) - Minimal GUT

Gauge fields

$$\underline{24} = \underset{gluons}{(\underline{8},\underline{1})} \quad \underset{W\ and\ Z}{+(\underline{1},\underline{3})} \quad \underset{leptoquarks}{+(\underline{3},\underline{2}) + (\underline{3},\underline{2})}$$

$$\begin{pmatrix} & & & \vdots & X & Y \\ & SU_c(3) & & \vdots & X & Y \\ & & & \vdots & X & Y \\ \cdots & \cdots & \cdots & \vdots & \cdots & \cdots \\ X & X & X & \vdots & SU_L(2) & \\ Y & Y & Y & \vdots & & \end{pmatrix}$$

$$SU(5) : \bar{5} + 10 + 1$$

$$\underline{5}^* = (d_1^c, d_2^c, d_3^c, e^-, \nu_e)_{Left} \qquad \underline{10} = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ & 0 & u_1^c & u_2 & d_2 \\ & & 0 & u_3 & d_3 \\ & & & 0 & e^+ \\ & & & & 0 \end{pmatrix}_{Left} \qquad 1 = \nu_L^c$$

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$$\begin{array}{llll} \underline{24} = & (\underline{8},\underline{1}) & +(\underline{1},\underline{3}) & +(\underline{3},\underline{2})+(\underline{3},\underline{2}) \\ & gluons & W\ and\ Z & leptoquarks \end{array}$$

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SO(10) - Optimal GUT

Matter fields - just one representation

$$\underline{16} = (u_1\ u_2\ u_3\ d_1\ d_2\ d_3\ \nu_e\ e^-\ u_1^c\ u_2^c\ u_3^c\ d_1^c\ d_2^c\ d_3^c\ \nu_e^c\ e^+)_{Left}$$

SU(5) decomposition

$$\underline{16} = \underline{5}^* + \underline{10} + \underline{1} \qquad fermions,$$

$$\underline{45} = \underline{24} + \underline{10} + \underline{10^*} + \underline{1} \qquad gauge\ bosons$$

GUT SYMMETRY BREAKING

GUT symmetry is broken spontaneously by Brout-Englert-Higgs Mechanism

GUT SYMMETRY BREAKING

GUT symmetry is broken spontaneously by Brout-Englert-Higgs Mechanism

SU(5)

Higgs Multiplets $SU(5) \xrightarrow{\Sigma} SU(3) \times SU(2) \times U(1) \xrightarrow{H} SU(3) \times U(1)$

$$< \Sigma_{24} >= \begin{pmatrix} V & & & & \\ & V & & & \\ & & V & & \\ & & & -3/2\ V & \\ & & & & -3/2\ V \end{pmatrix} \qquad < H_5 >= \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$V \sim 10^{15}\ GeV \qquad v \sim 10^{2}\ GeV$$

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SO(10)

Higgs Multiplets

$$16\ or\ 126;\ \ 45\ or\ 54\ or\ 210$$

$$\begin{tikzcd} & SU(5) \arrow[r, "M_2"] & SU(3) \otimes SU(2) \otimes U(1) \arrow[r, "M_W"] & SU(3) \otimes U(1) \\ SO(10) \arrow[ur, "M_1"] \arrow[dr] & & & \\ & SO(6) \otimes SO(4) \sim SU(4) \otimes SU_L(2) \otimes SU_R(2) & & \end{tikzcd}$$

$$M_1 \gg M_2 \gg \cdots M_W$$

GRAND UNIFICATION

Solves many problems of the SM:

- absence of Landau pole
- Decreases the number of parameters
- All particles in a single representation (**16** of SO(10))
- Unifies quarks and leptons -> spectrum and mixings from «textures»
- A way to **B** and **L** violation

Creates new problems:

- Hierarchy of scales $M_W/M_G \sim 10^{-14}$
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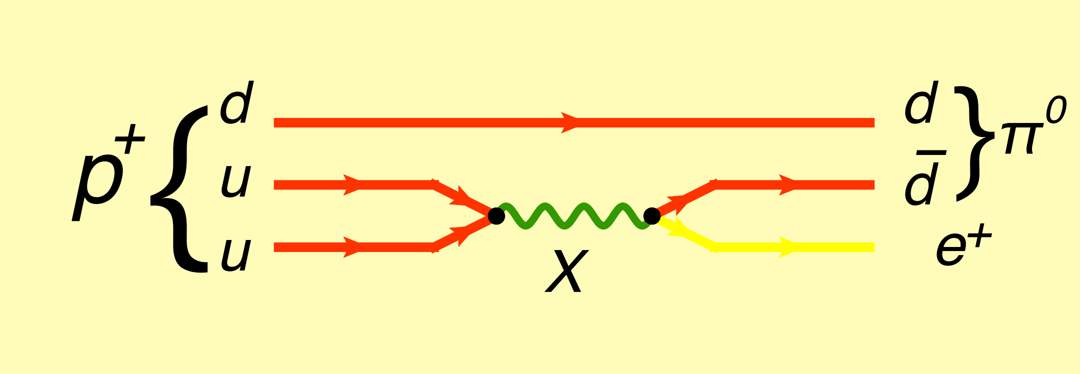

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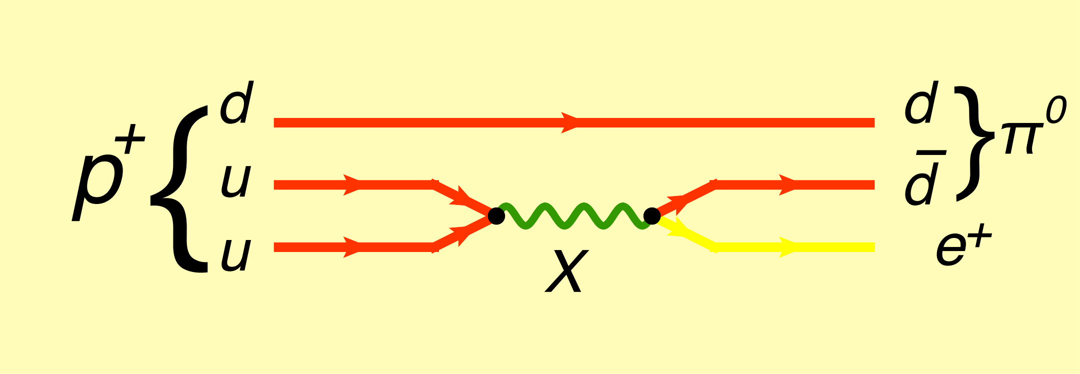

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mean life time > $10^{31} - 10^{33}$ years

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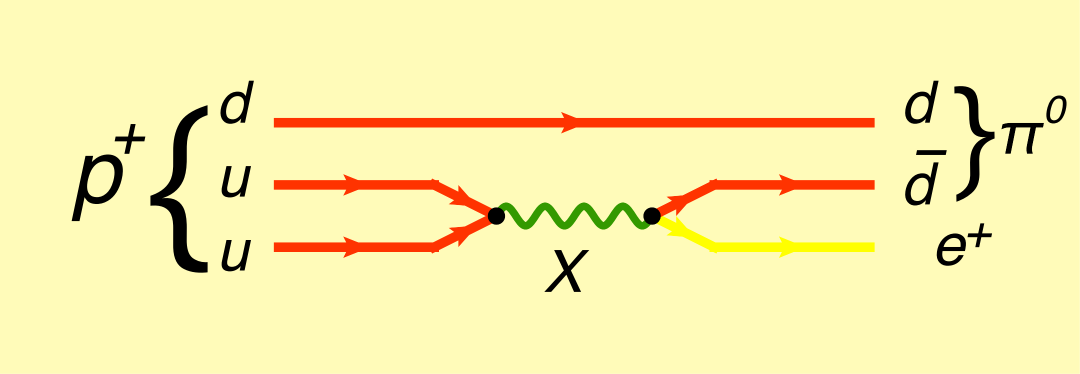

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$$\tau_{Universe} \approx 14 \cdot 10^9 years$$

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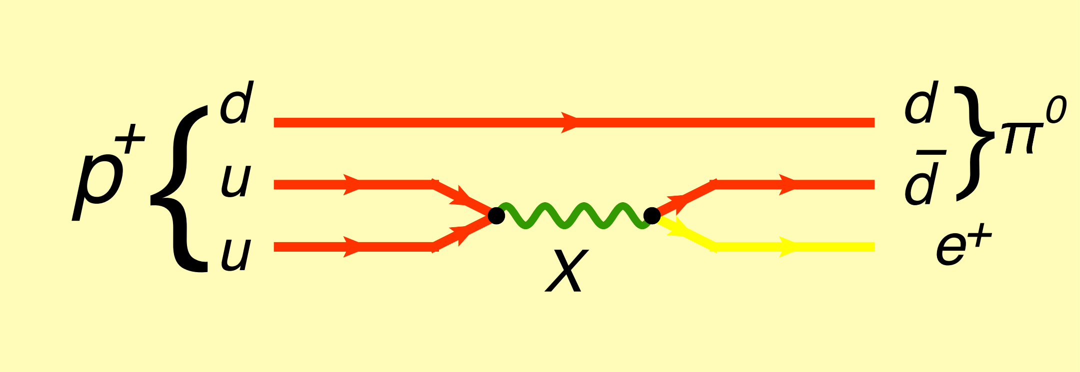

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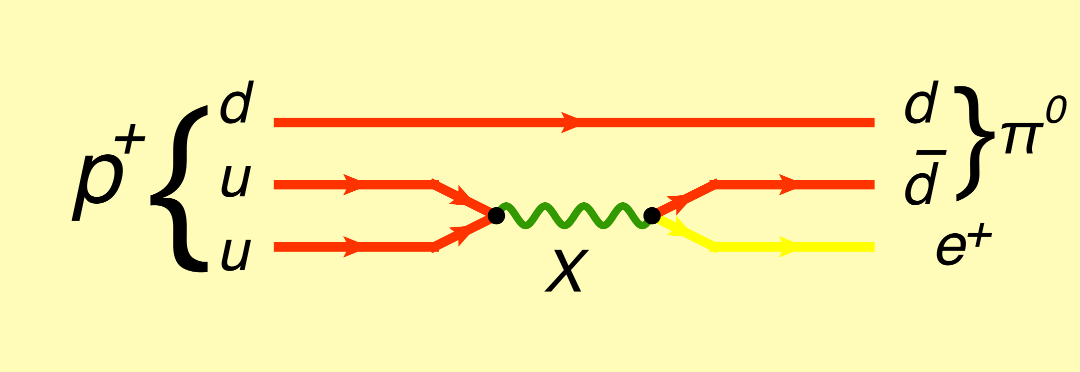

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Low energy SUSY

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SUSY GUT

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- Later unification - higher GUT scale
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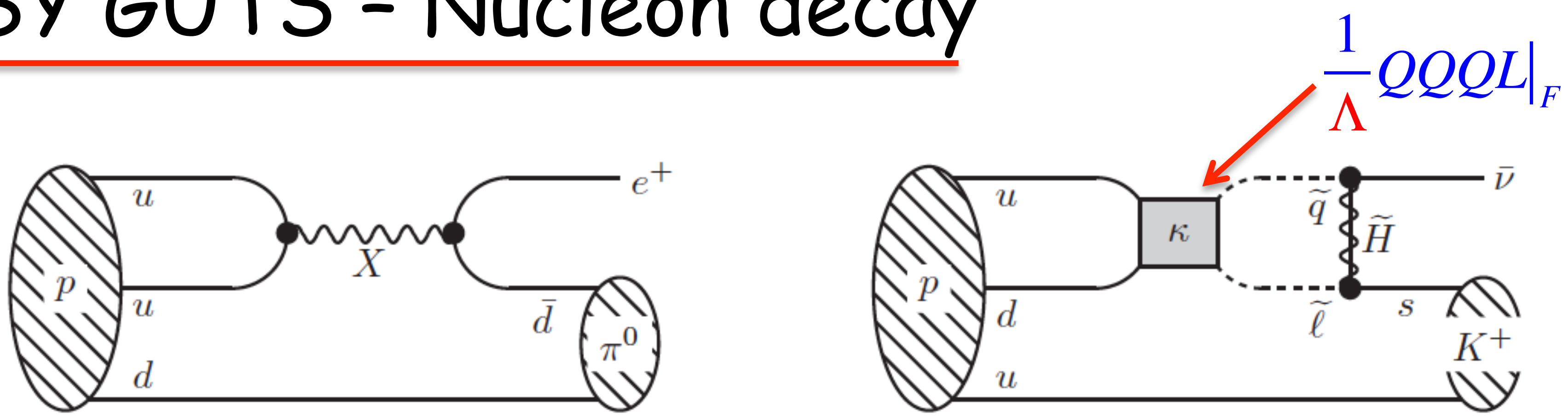
- New modes of proton decay

SUSY GUTS - Nucleon decay



(a) Dimension 6.

(b) Dimension 5.

$p \to \pi^0 + e^+$

$\tau_{p \to e^+ \pi^0} > 1 \times 10^{34}$ yrs, $M_X > 10^{16}\, GeV$

$p \to K^+ + \bar{\nu}$

$\tau_{p \to K^+ \bar{\nu}} > 3.3 \times 10^{33}\, yrs$

NEW SYMMETRIES

EXTRA U(1)', SU(2)'

- Appear in some GUT models
- Inspired by string models

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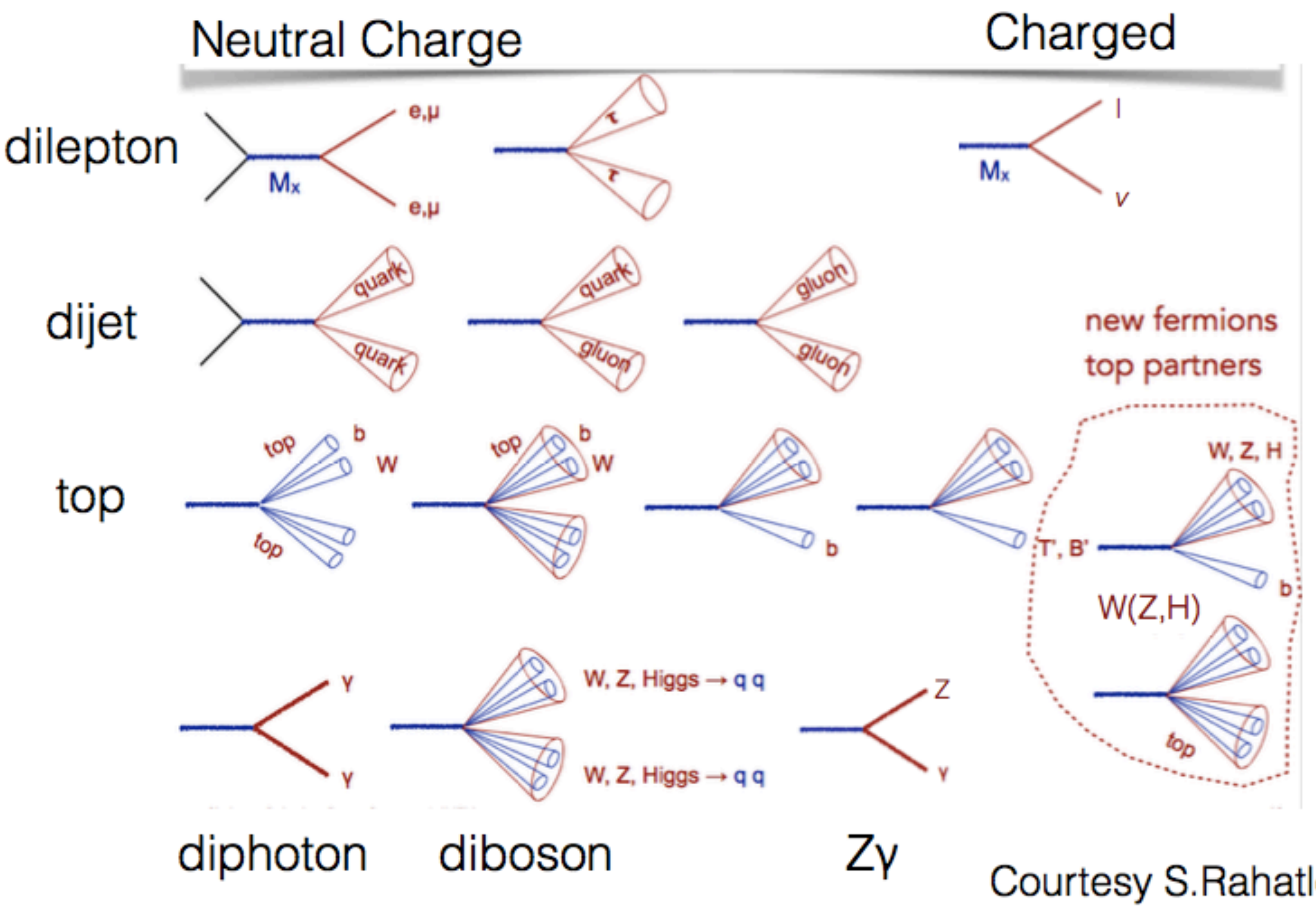

Courtesy S.Rahatlou

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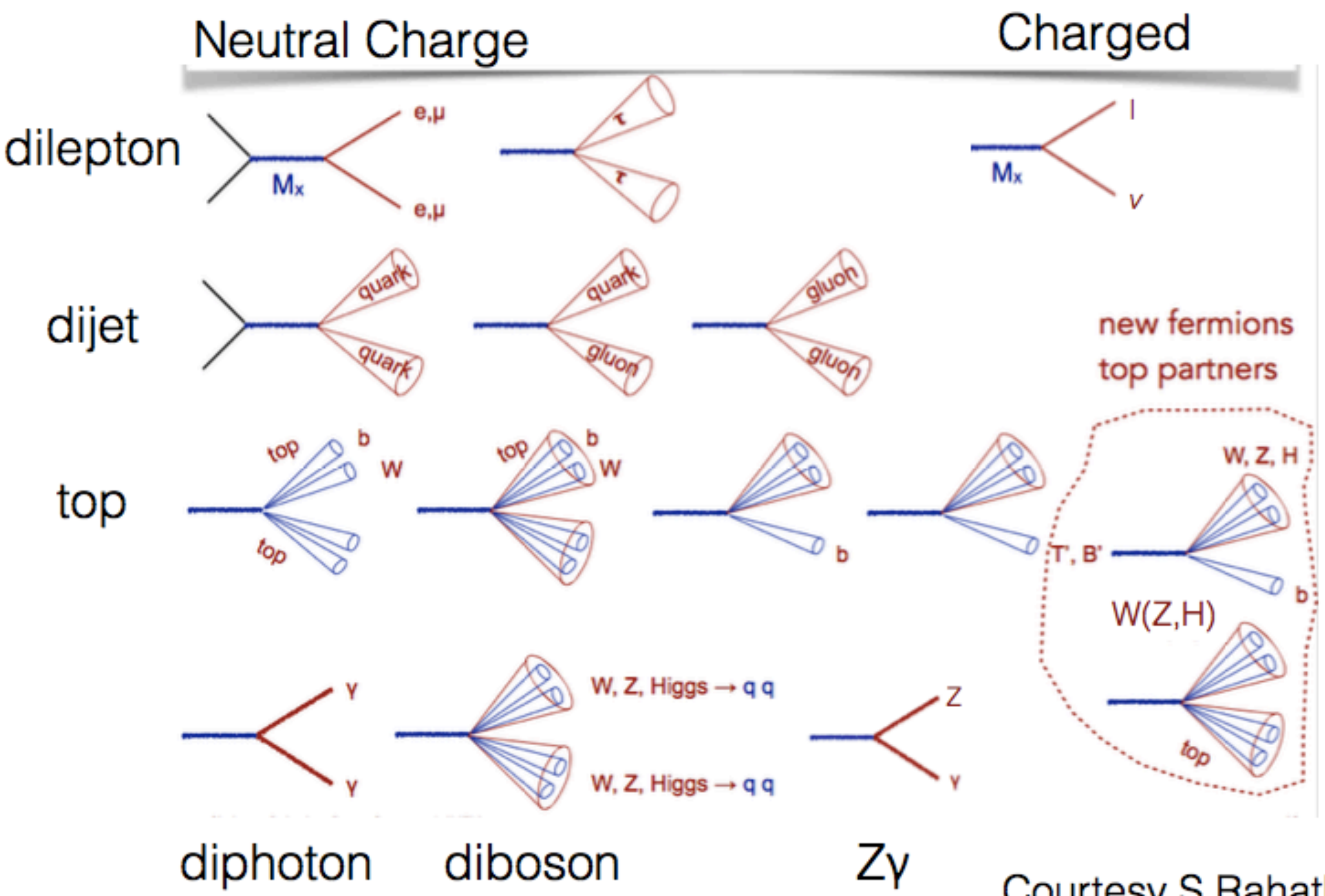

Courtesy S.Rahatlou

EXTRA U(1)', SU(2)'

Used as possible Dark matter candidate - Dark photon

Mixture of a usual EM U(1) photon and a new U(1)' one

$$\mathcal{L} \sim F_{\mu\nu} F^{'\mu\nu}$$

Dedicated experiment to look for conversion of a usual photon into a dark one

NEW SYMMETRIES

ADDITIONAL GAUGE BOSONS

Experiment

- Search for Z’ (Di-muon events)
- Search for W’ (single muon/ jets)
- Search for resonance decaying to t-tbar
- Search for diboson resonances
- Monojets + invisible

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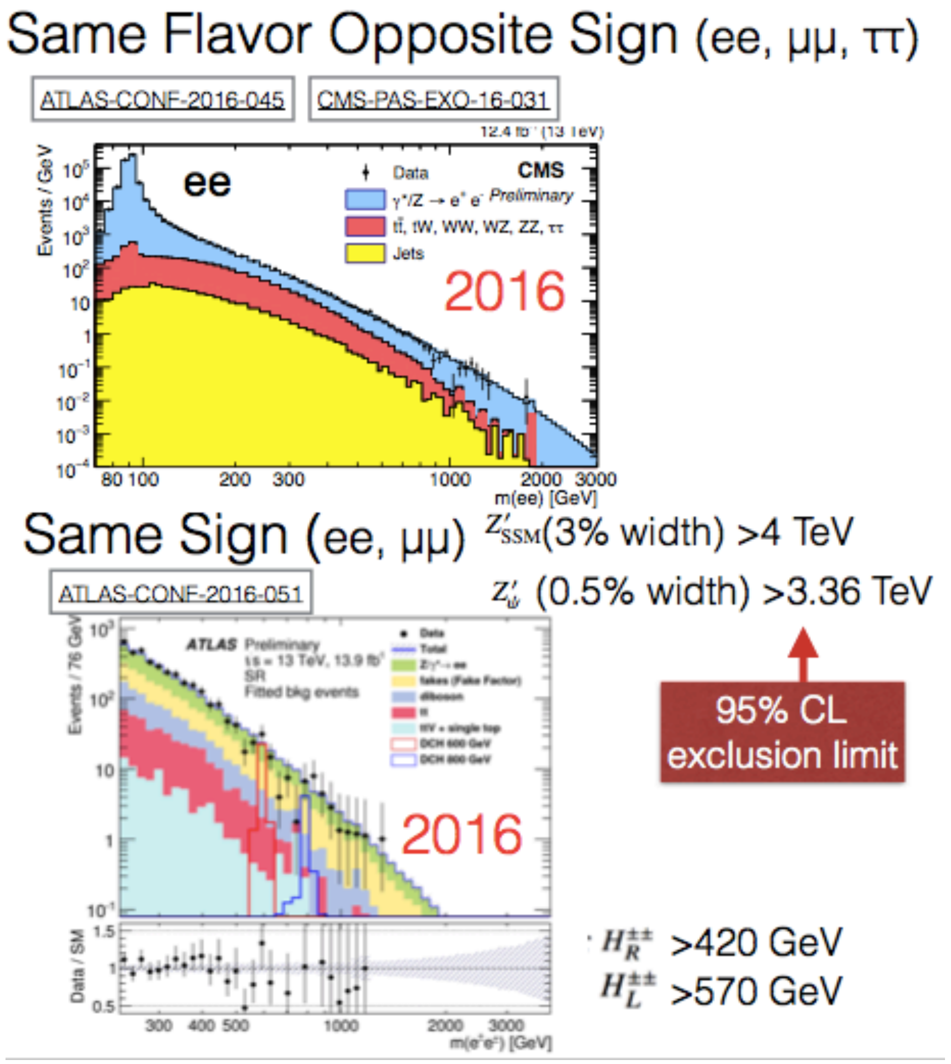

Same Flavor Opposite Sign (ee, μμ, ττ)

ATLAS-CONF-2016-045 CMS-PAS-EXO-16-031

Same Sign (ee, μμ)

ATLAS-CONF-2016-051

Z'_{SSM}(3% width) >4 TeV

Z'_{ψ} (0.5% width) >3.36 TeV

95% CL exclusion limit

$H_R^{\pm\pm}$ >420 GeV

$H_L^{\pm\pm}$ >570 GeV

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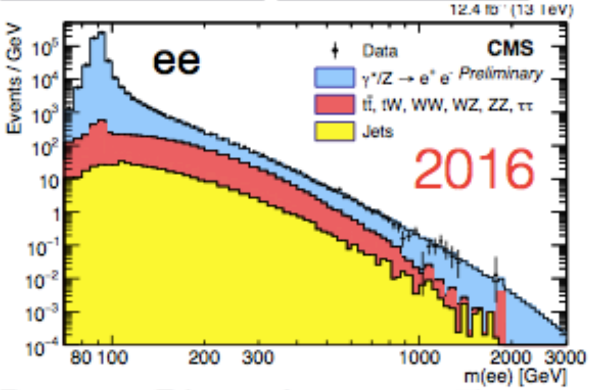

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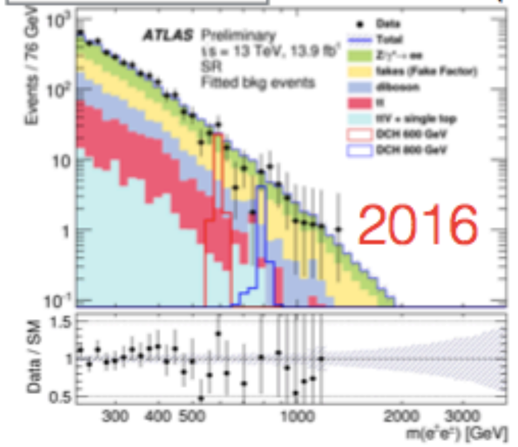

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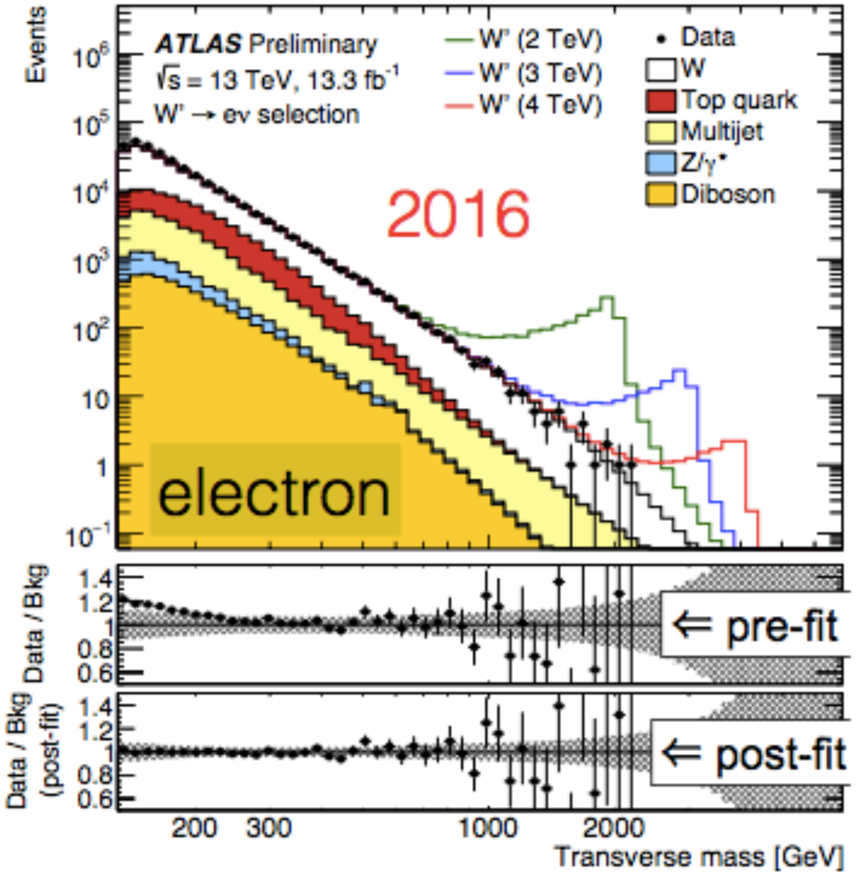
ATLAS-CONF-2016-061 CMS-PAS-EXO-15-006



SSM W’ >4.74 TeV

NEW SYMMETRIES

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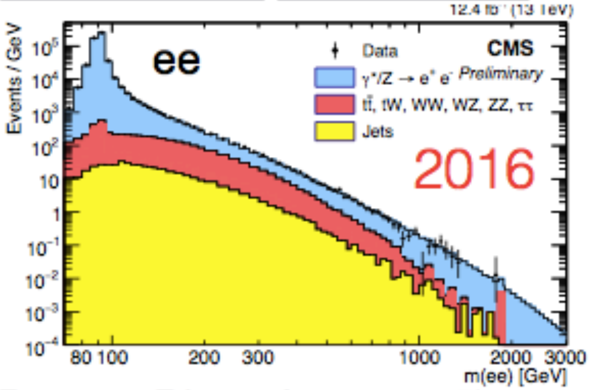

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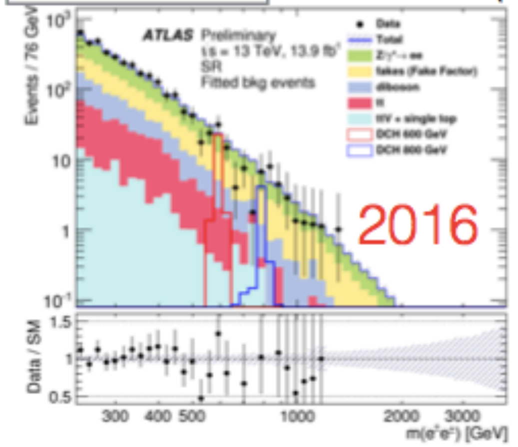

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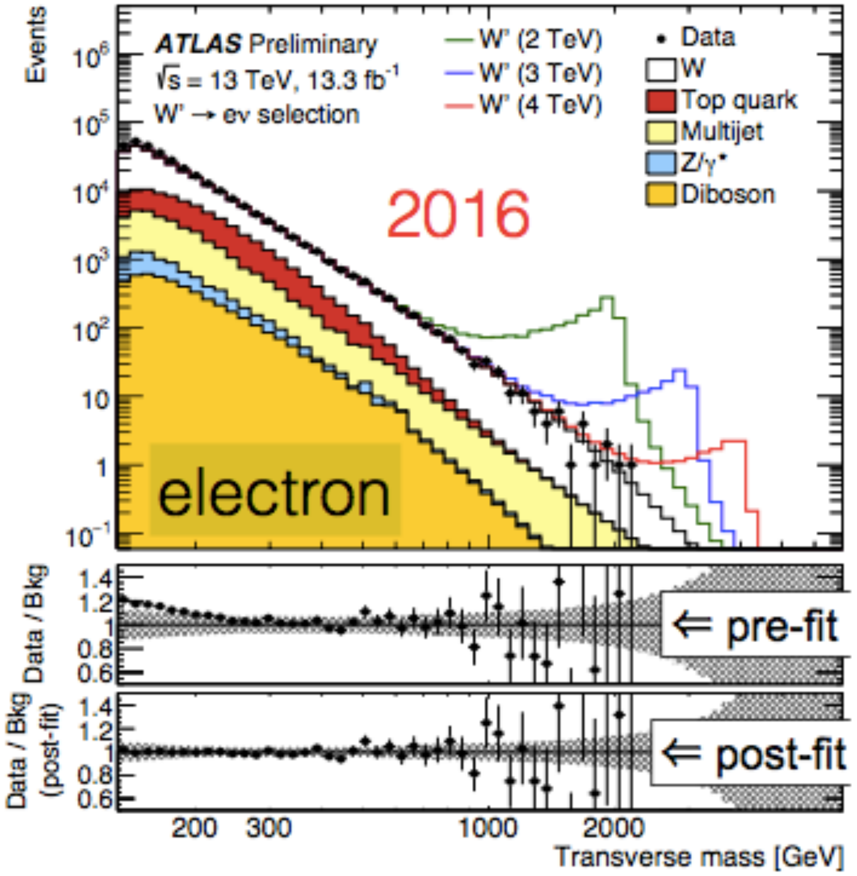


SSM W' >4.74 TeV

No indication so far - experimental limits on Z′ and W′ masses around few TeV

NEW PARTICLES

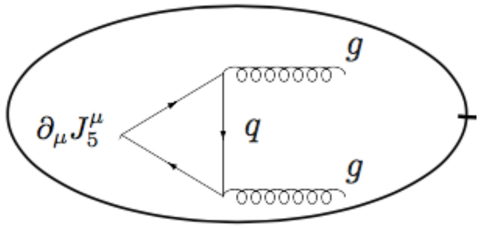
AXION OR AXION-LIKE PARTICLES

Javier Redondo, EPS HEP 2017

- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\mathrm{QCD}} + N_f \delta$

$$\mathcal{L}_{\mathrm{SM}} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \dots \\ 0 & m_d e^{i\delta/2} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\mathrm{QCD}}$$

Axial anomaly



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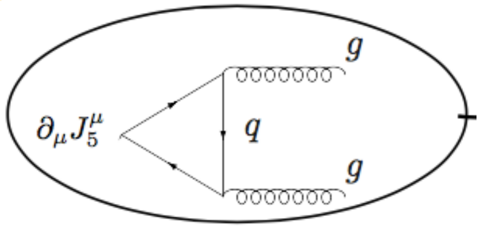
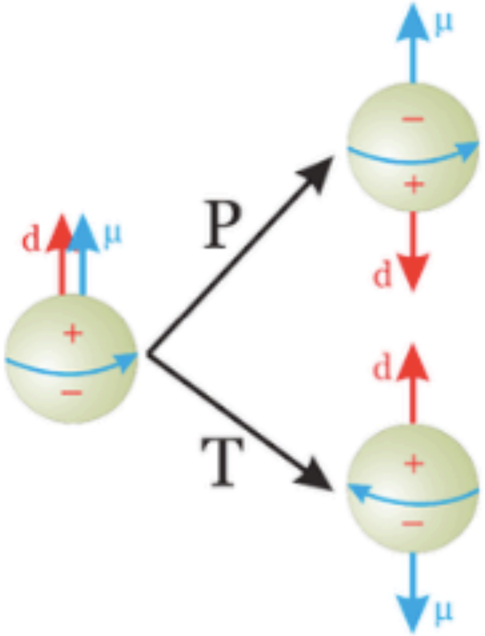


The θ-angle produces flavour-neutral CP violation like Electric Dipole Moments



- Neutron EDM **(Guo 1502.02295)**

$$d_n = -4 \times 10^{-3} \times \theta\,[\mathrm{e\,fm}]$$

- Experimental upper limit **(Grenoble hep-ex/0602020)**

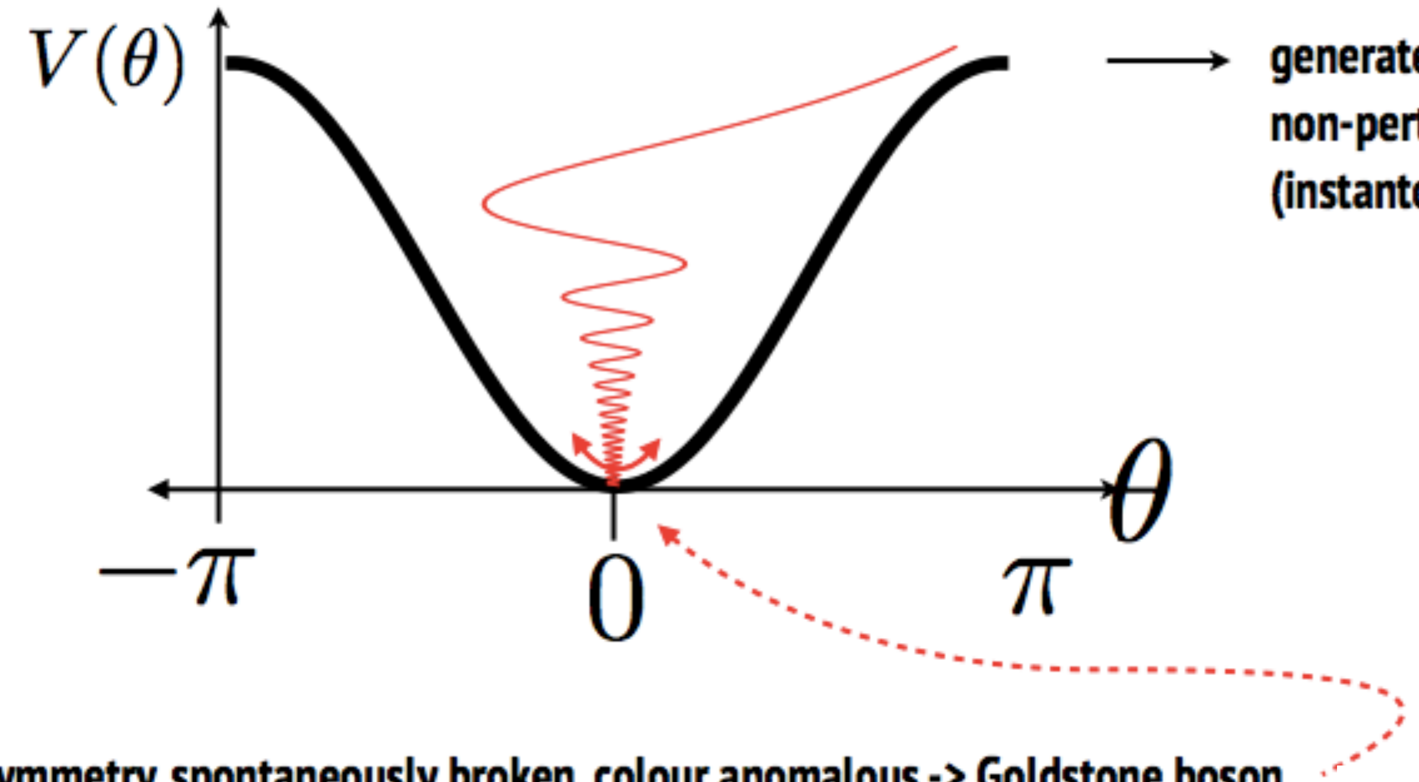
$$|d_n| < 3 \times 10^{-13}\,[\mathrm{e\,fm}]$$

- Why is $\theta < 10^{-10}$?

PECCEI-QUINN MECHANISM - AXION

- Any theory promoting θ to a dynamical field, $\theta(t, \mathbf{x})$,will dynamically set $\theta \to 0$ after some time...

Potential energy density



generated by QCD non-perturbative dynamics (instantons)

- PQ Mechanism: Global U(1) axial symmetry, spontaneously broken, colour anomalous -> Goldstone boson

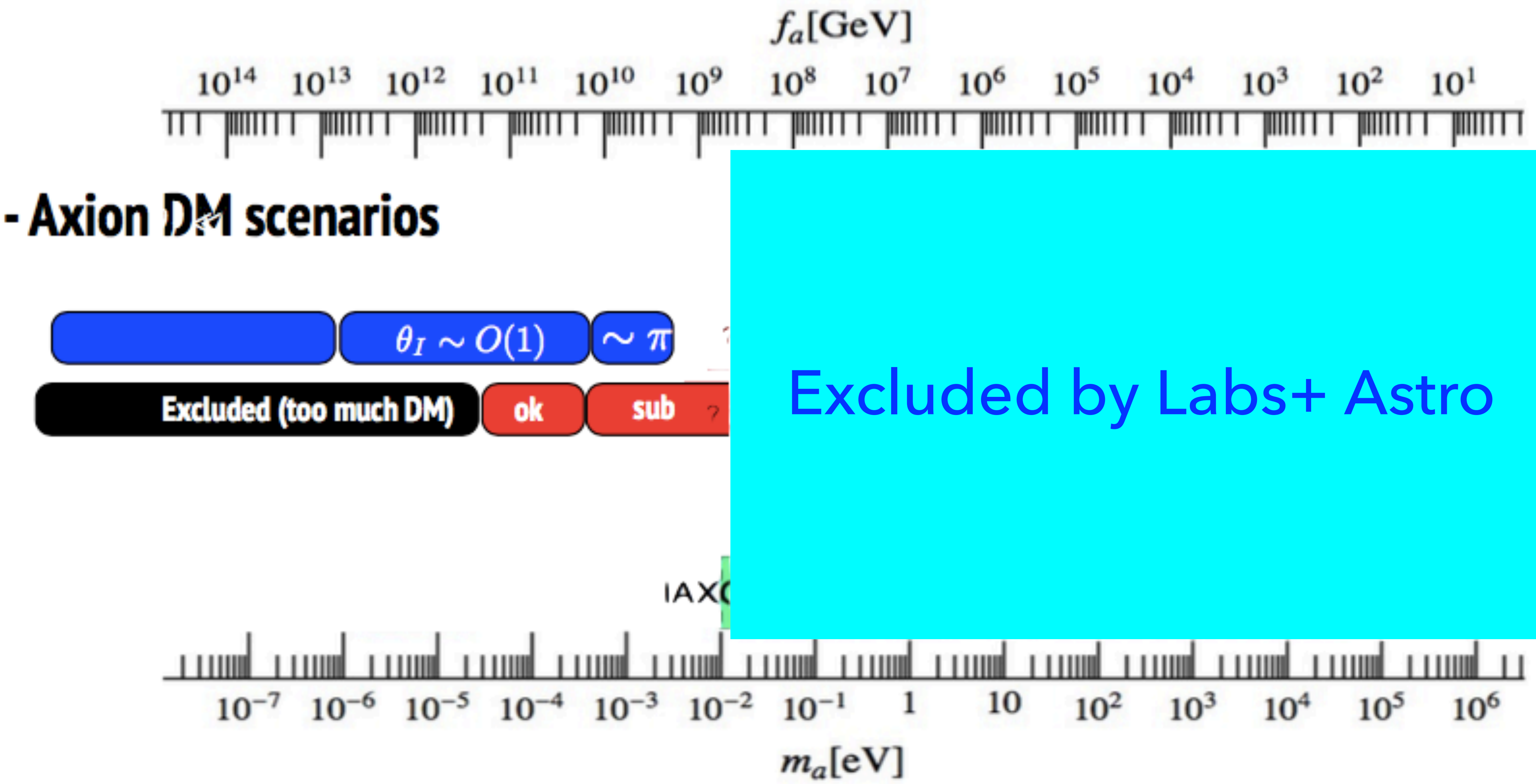
$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta)f_a^2 - \frac{\alpha_s}{8\pi}G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}\theta$$

New Spontaneous symmetry breaking [energy] scale f_a

Canonically normalised θfield is the QCD AXION! $a(x) = \theta(x) f_a$

WW Axion

WHAT IS THE MASS TO GET $\Omega_{CDM} h^2 = 0.12$?



Excluded by Labs+ Astro

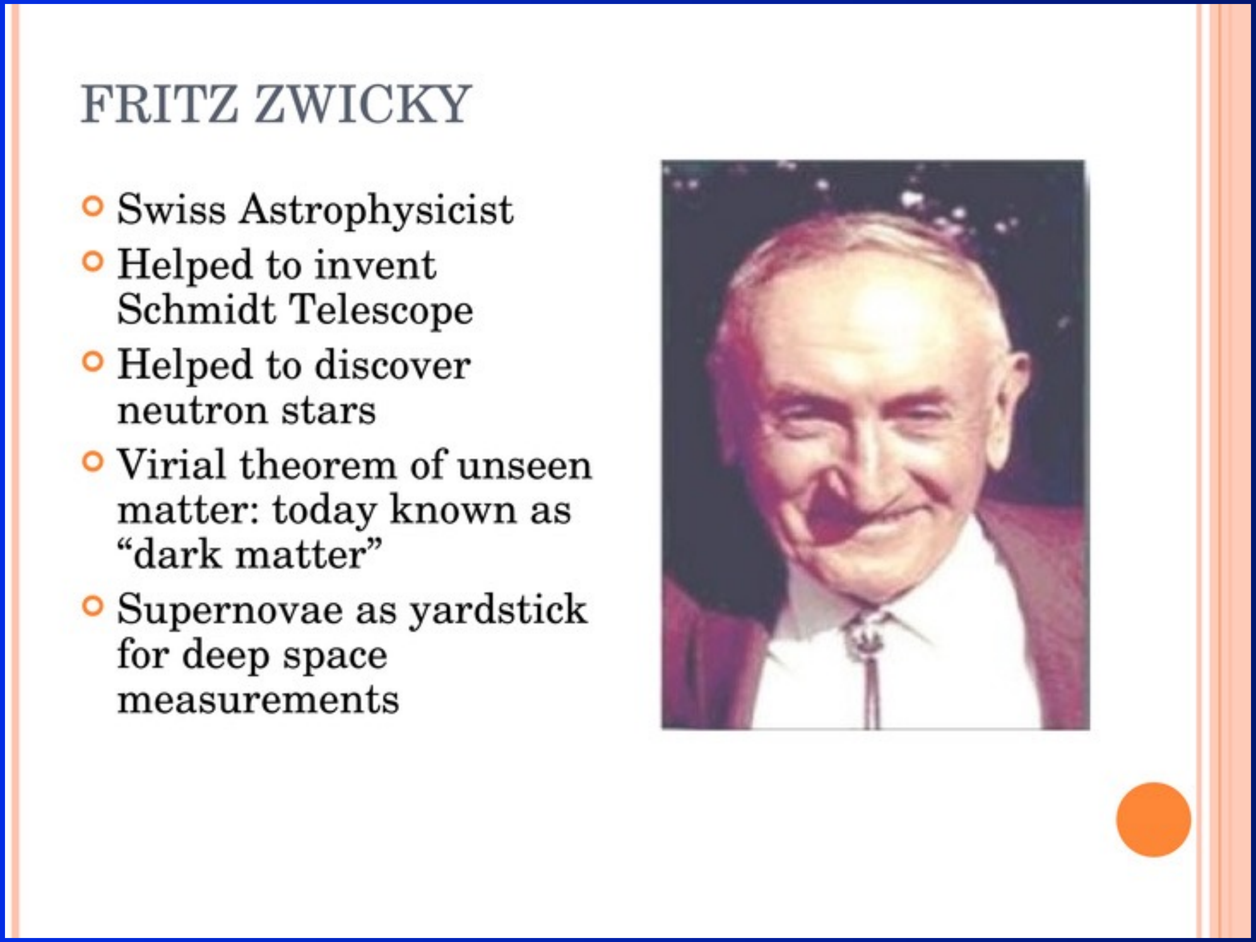
- Less minimal axion models have further possibilities ....

Dark Matter

Three questions

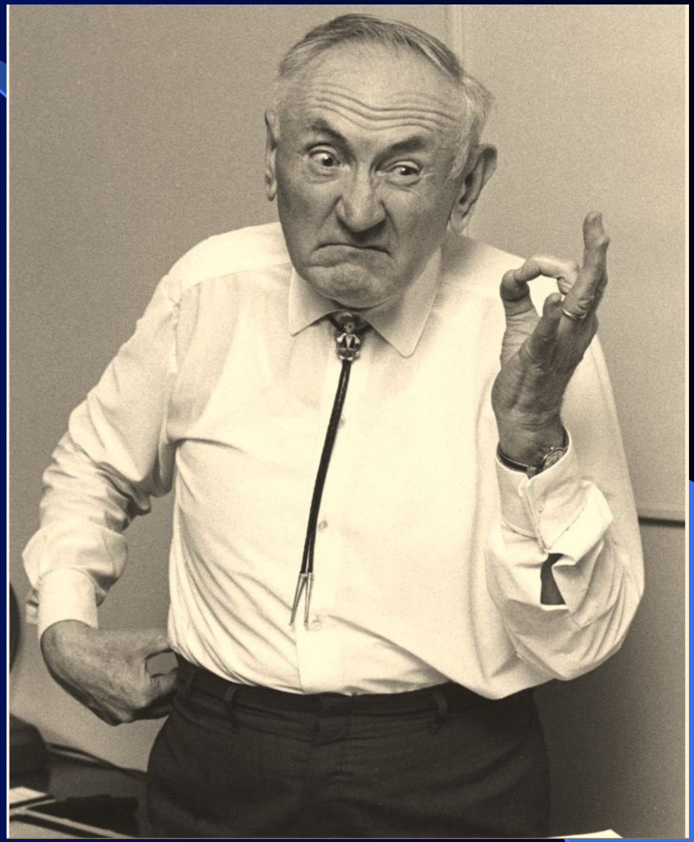
- What is Dark matter and what it is composed of?
- What is the role of Dark matter in the energetic balance of the Universe?
- How to find manifestations of Dark Mater in space, underground and at Large Hadron Collider?

Gravitational manifestation of existence of Dark matter



FRITZ ZWICKY

- Swiss Astrophysicist
- Helped to invent Schmidt Telescope
- Helped to discover neutron stars
- Virial theorem of unseen matter: today known as "dark matter"
- Supernovae as yardstick for deep space measurements



Introduced the notions of

- **Supernova and neutron stars**
- **Gravitational Lensing**
- **Dark matter (hidden mass)**

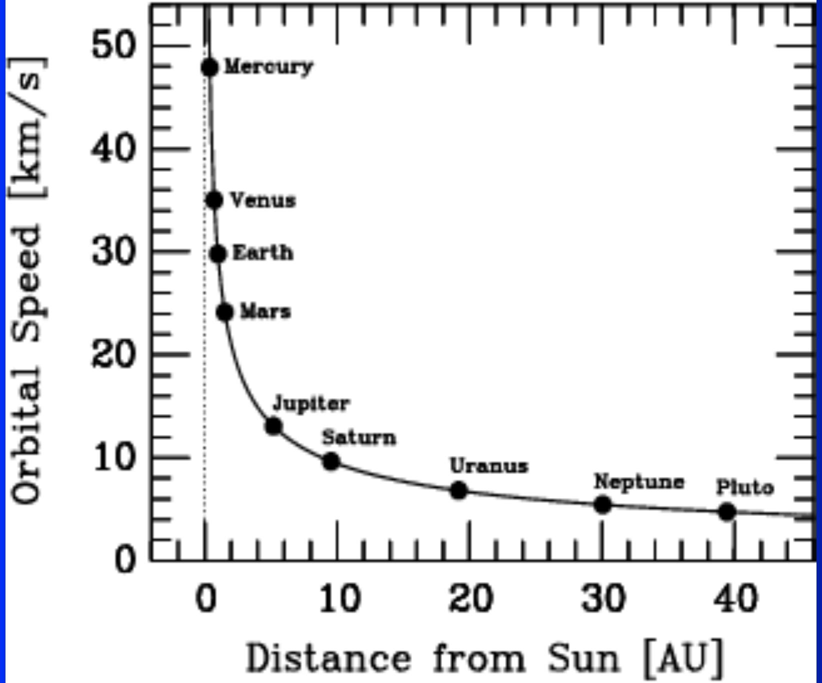
Galactic coaster Coma (1934г.)

Stars rotation curves

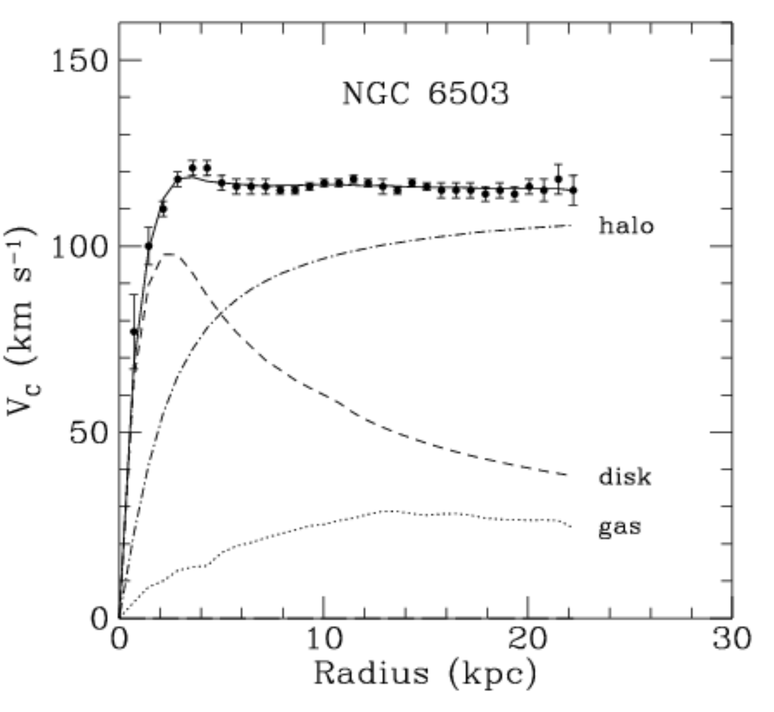
Centrifugal force

$$\frac{mv^2}{r} = G\frac{mM(r)}{r^2}$$

Gravity



Density of dark matter in Solar system is negligibal



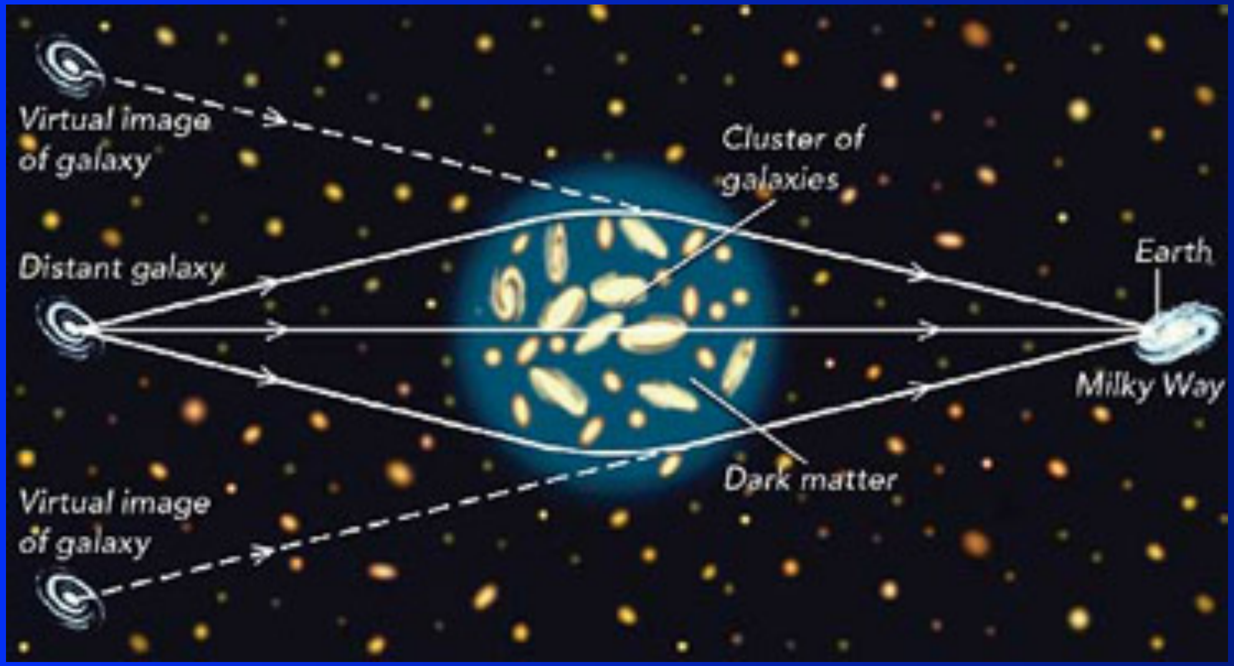
Dark matter is bounded at Galactic scales

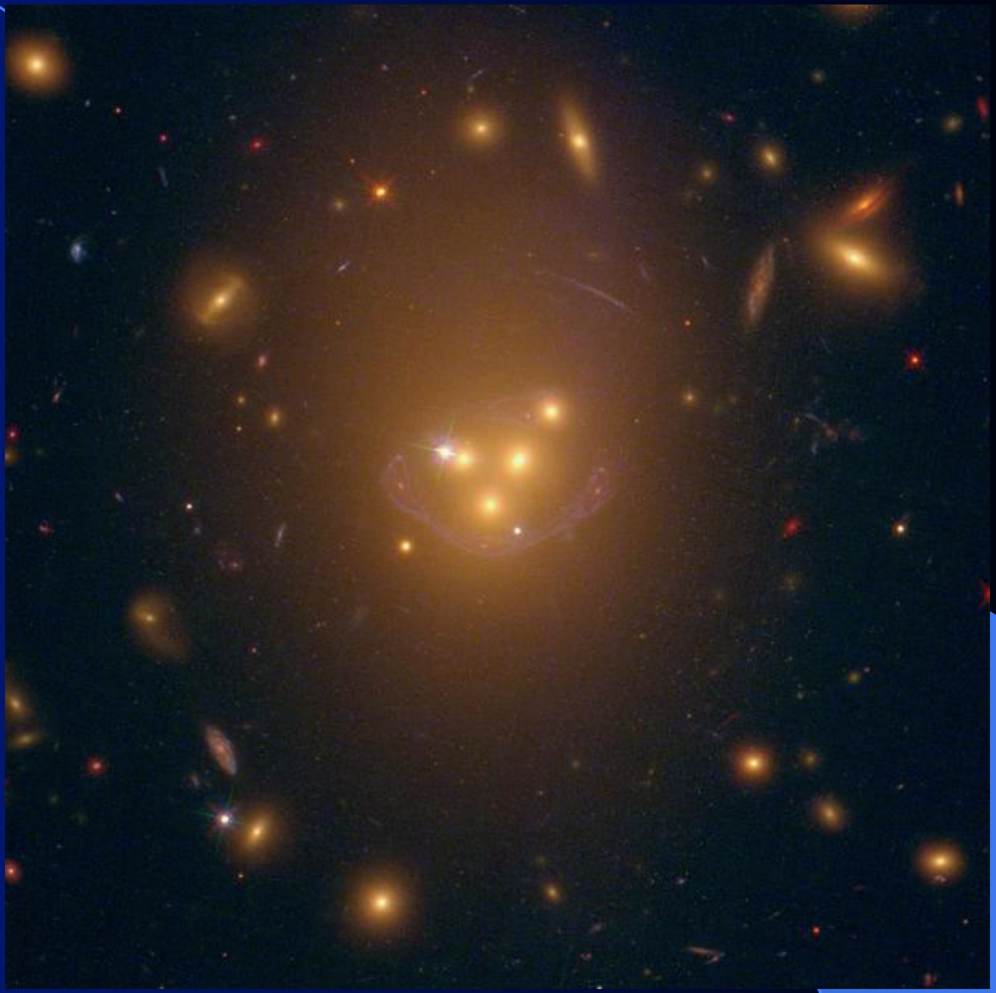
Solar system

Galaxy

- Today we know thousands of rotation curves and all of them indicate in favour of existence of hidden mass in the halo of a Galaxy which is 10 times exceeds the mass of the stars in a disk

Gravitational Lences



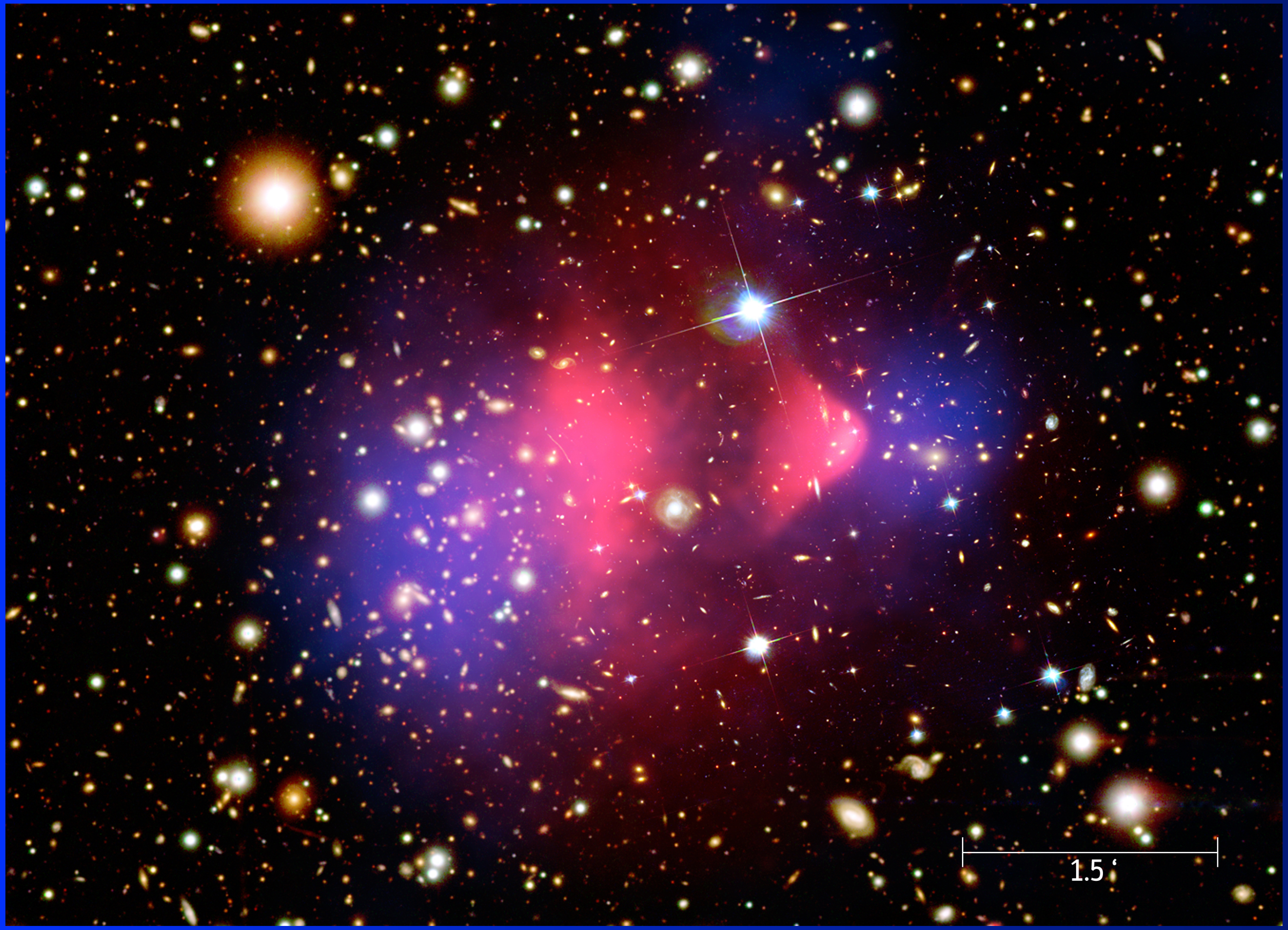


Consequence of GR: deflection of light in gravitational field

The formation of a virtual image of a distant galaxy due to the deflection of light rays by dark matter located between the galaxy and the observer

Observation of Dark Matter

Bullet cluster

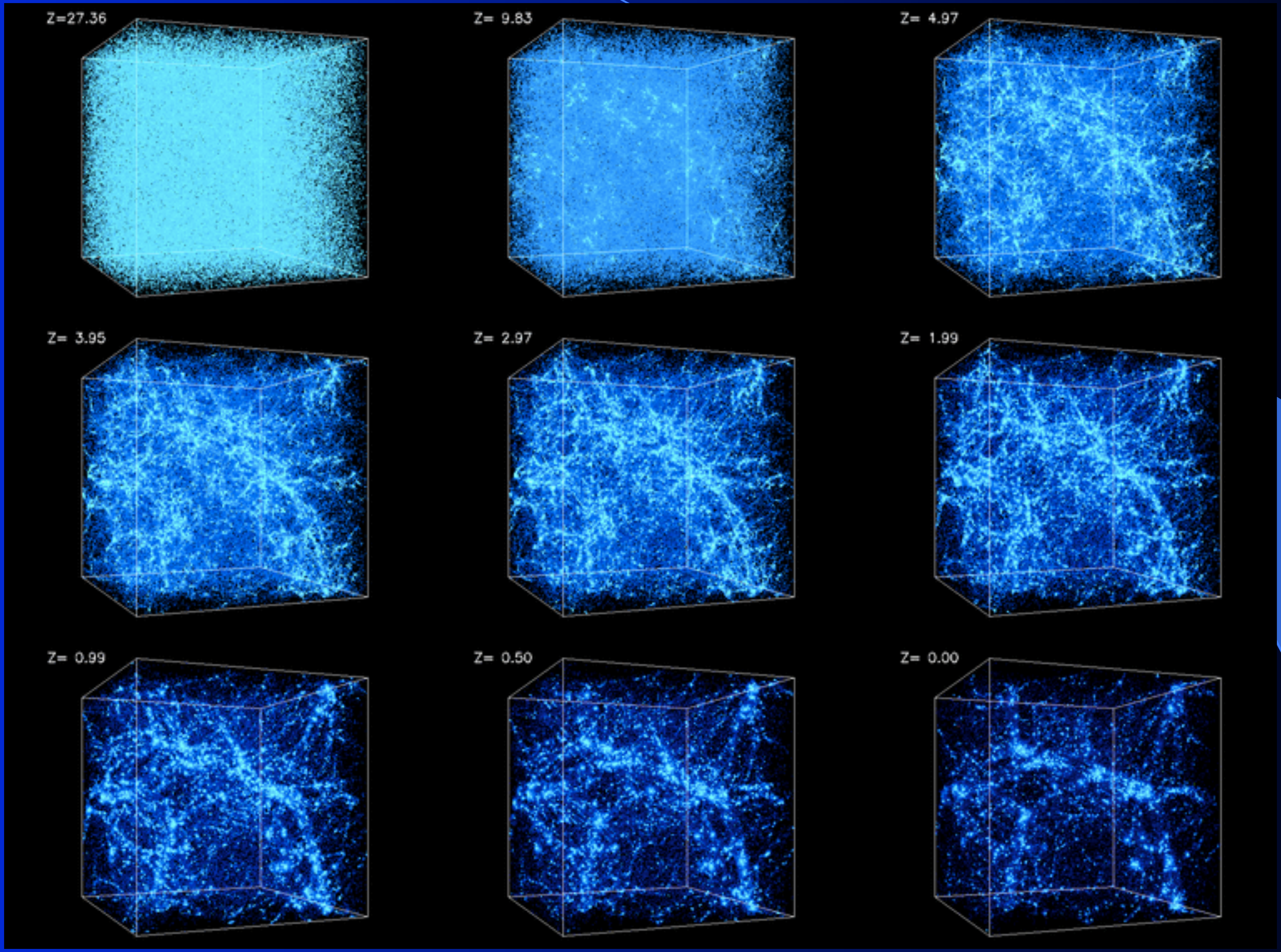


The mass distribution reconstructed from strong and weak gravitational lensing is shown in blue, the X-ray emission of hot gas observed by the Chandra telescope is shown in red.

The most direct observational evidence comes from the Bullet cluster. In most regions, dark and visible matter are found together due to their gravitational pull. In the Bullet cluster, they have diverged due to past collisions between two small clusters. Electromagnetic interactions between the gas particles led to a concentration of gas near the impact site.

X-ray observations show that most of the luminous matter is concentrated in the center of the cluster. Gravitational lensing shows that dark matter is located outside the central region. Unlike galactic rotation curves, these proofs are independent of the details of Newtonian gravity, directly supporting the dark matter hypothesis.

The formation of large-scale structures in the Universe

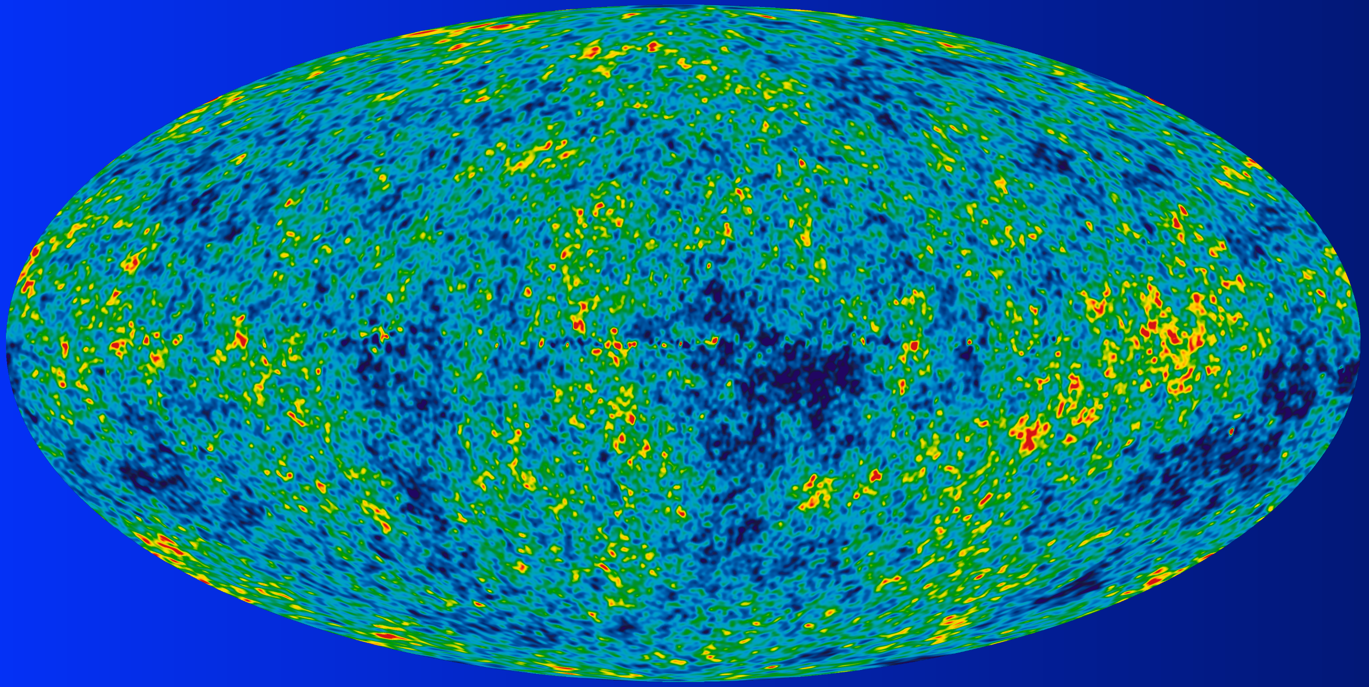


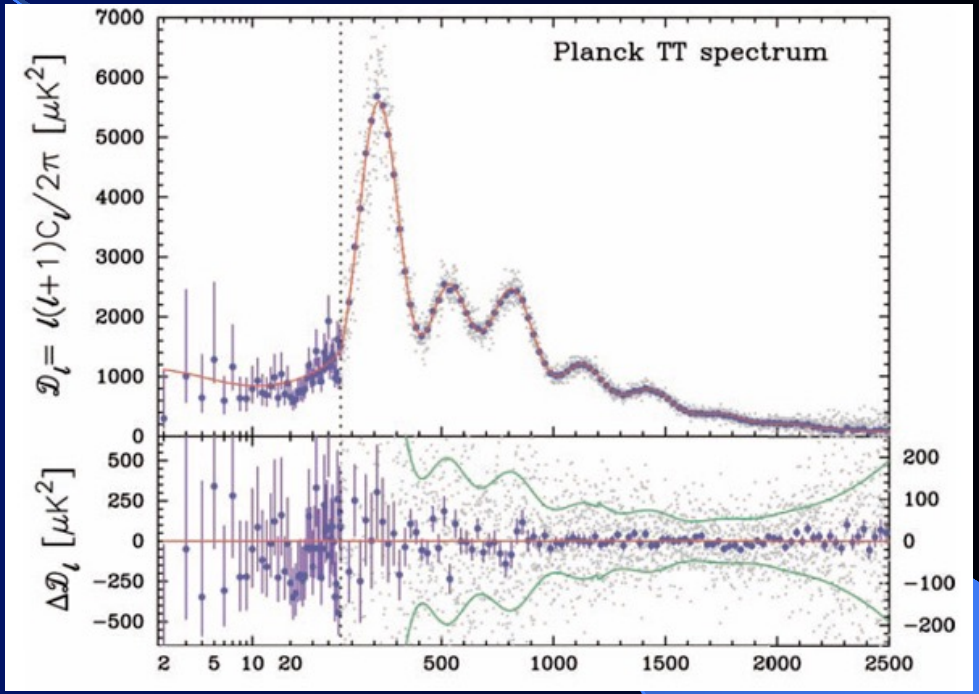
First, the formation of structures from dark matter occurs, and then the concentration of ordinary matter occurs in the gravitational potential formed by dark matter

Cosmic MicrowaveBackground

Map of CMB $T \approx 2.7K^o$

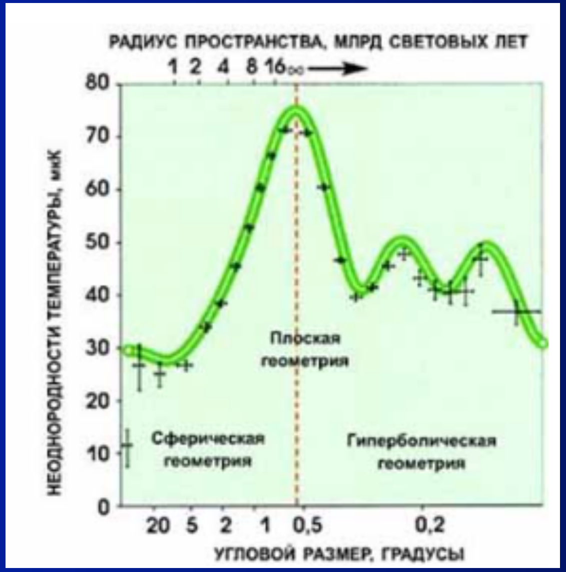
Angular harmonics expansion





Temperature fluctuations of CMB

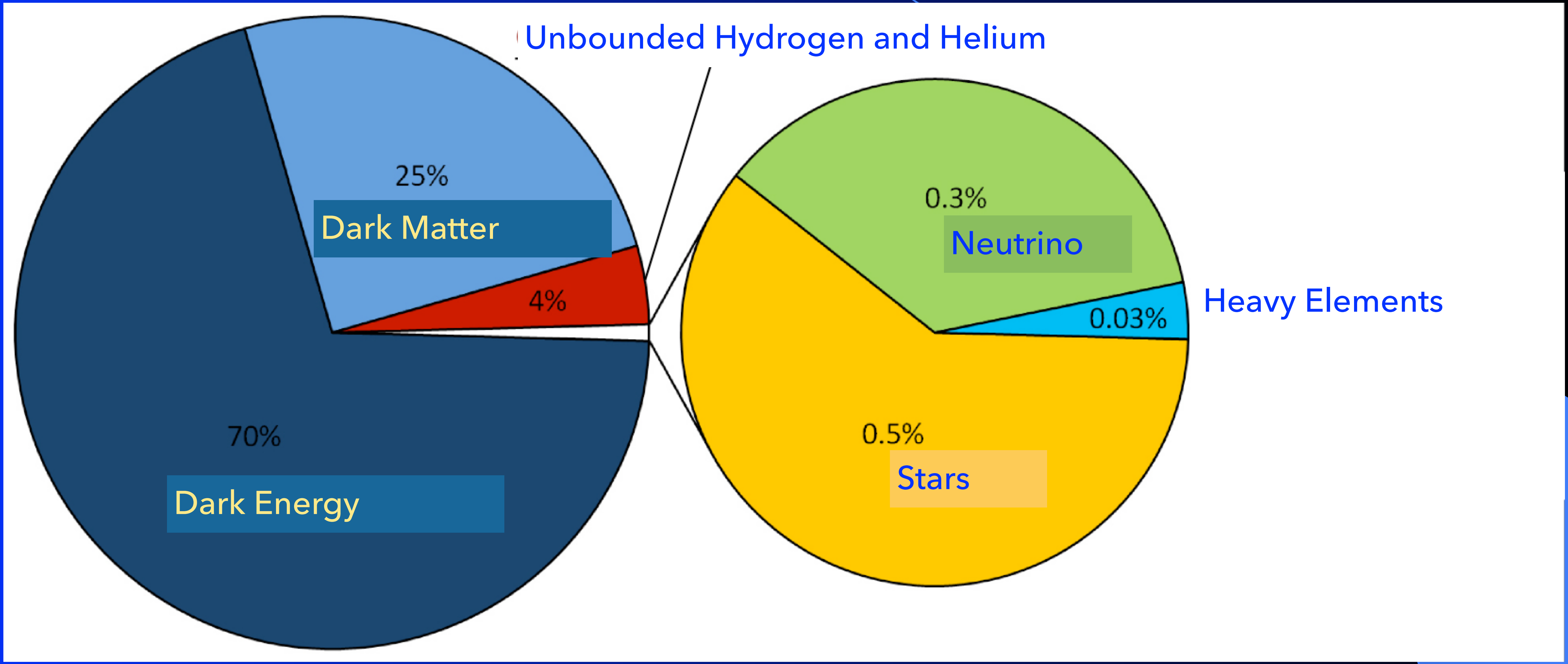
$$\frac{\Delta T}{T} \sim 10^{-5}$$



$$\Omega_{UsualMatter} = 4.9\%$$
$$\Omega_{DarkMatter} = 26.8\%$$
$$\Omega_{DarkEnergy} = 68.3\%$$

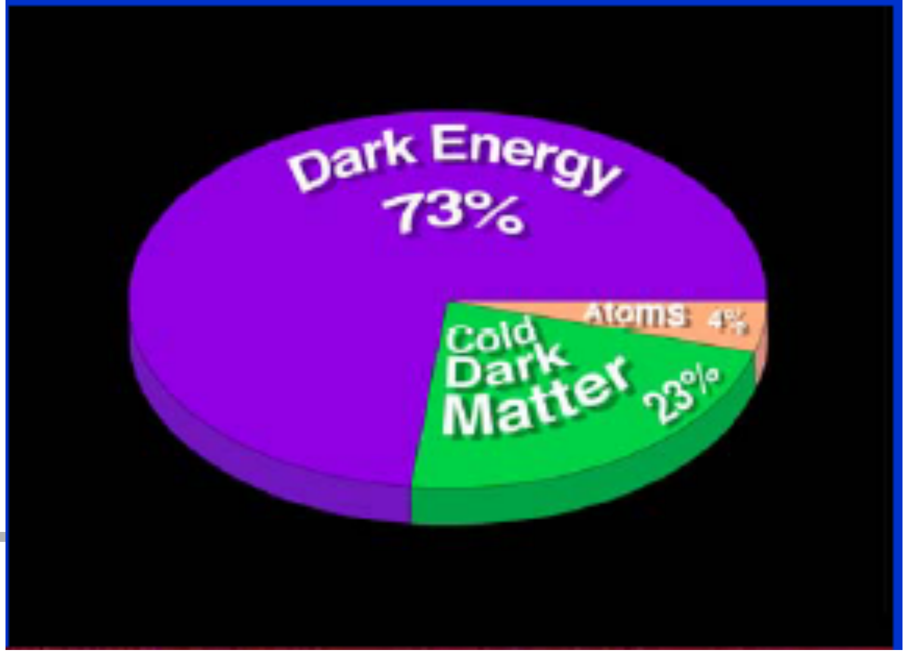
$$\Omega = 1.02 \pm 0.02$$

The Energy Balance of the Universe



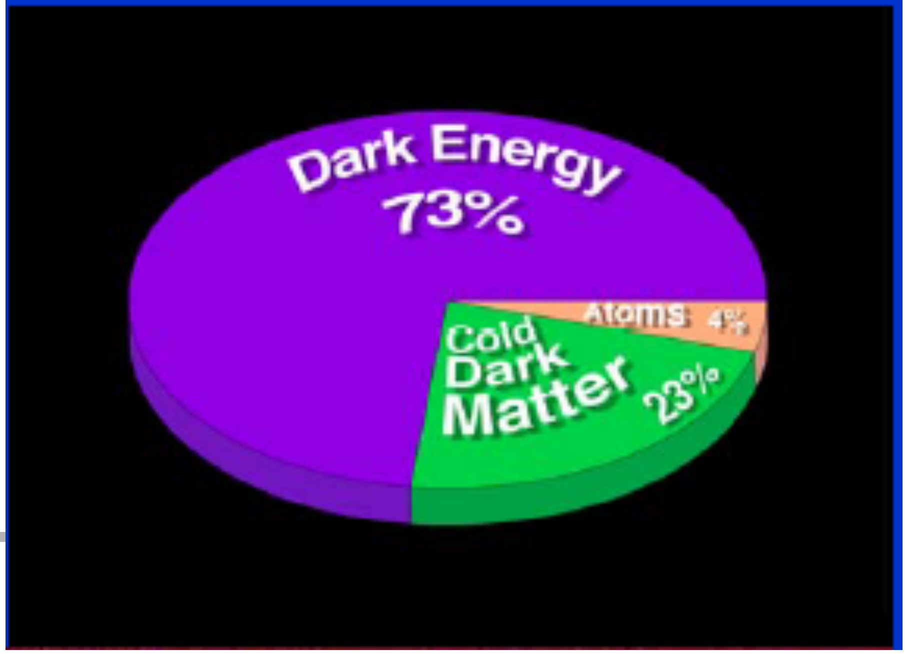
Our knowledge concerns only a small part of the universe, but perhaps we know 90% (50%) of elementary particles

Dark Matter



What is Dark Matter ?

Dark Matter



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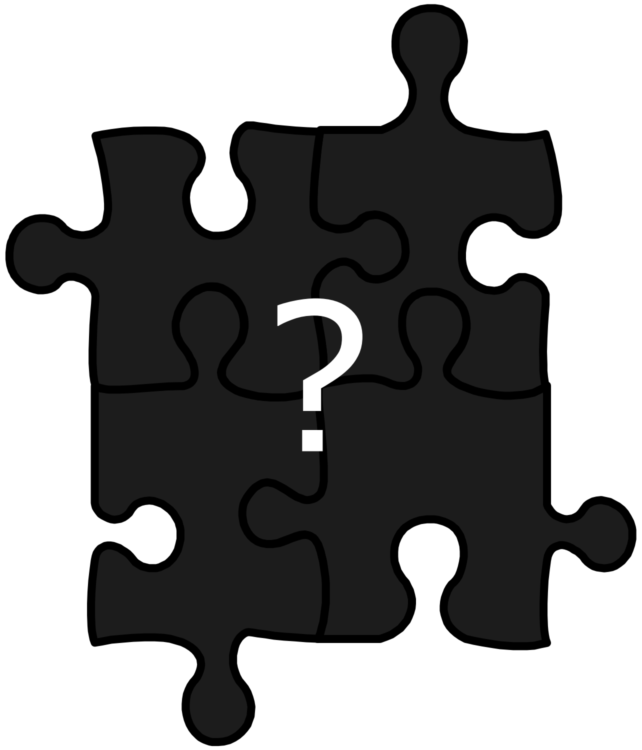
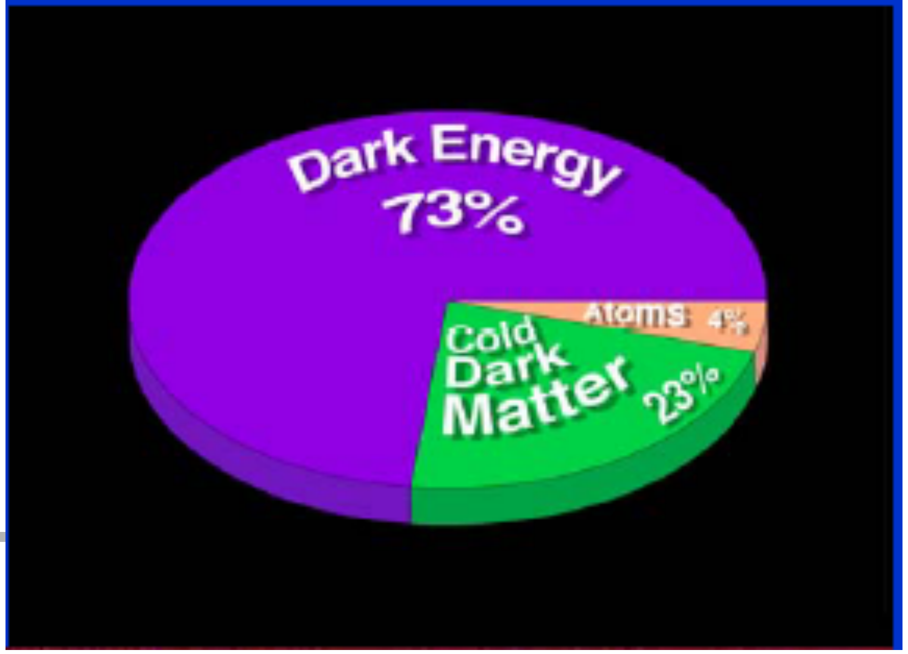


DARK

Dark Matter



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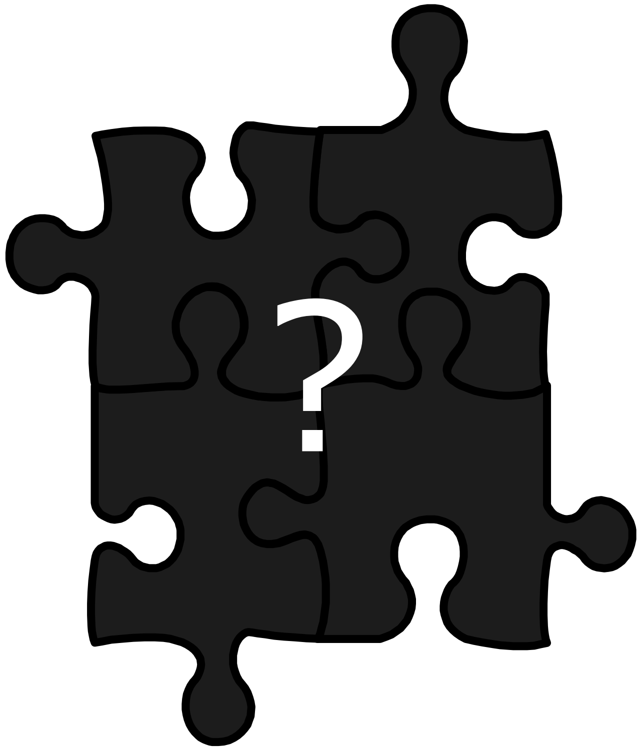
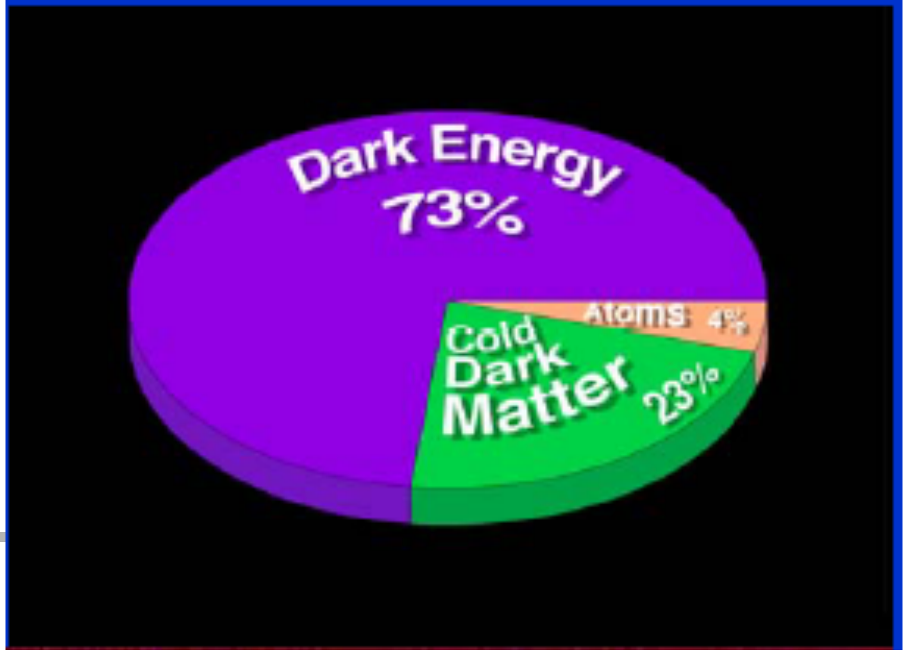


DARK

WIMP

Dark Matter



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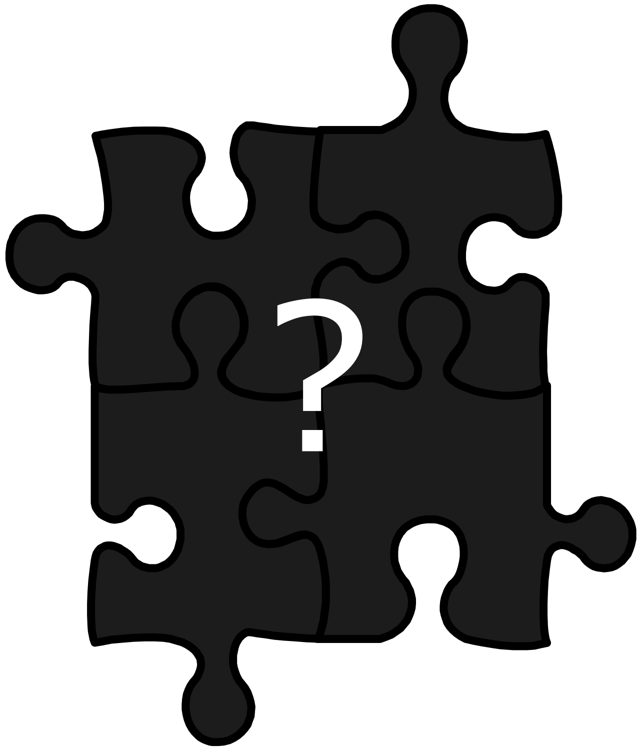

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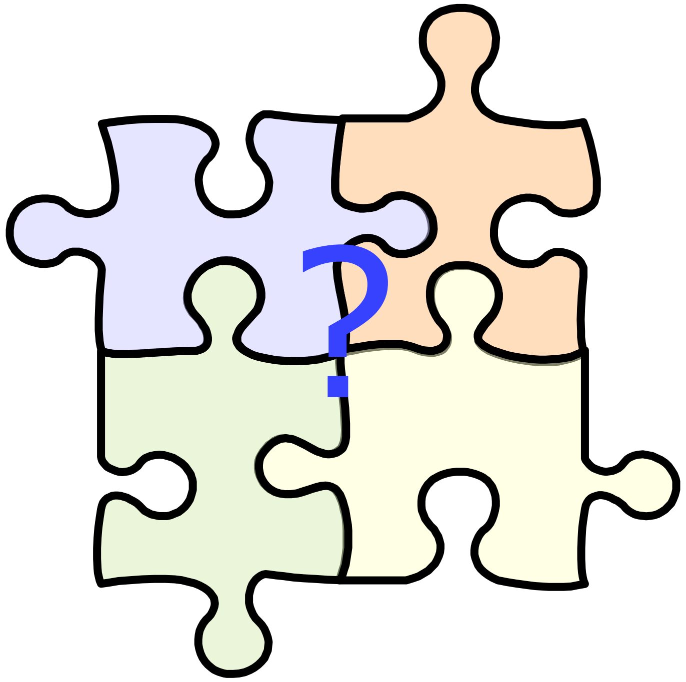
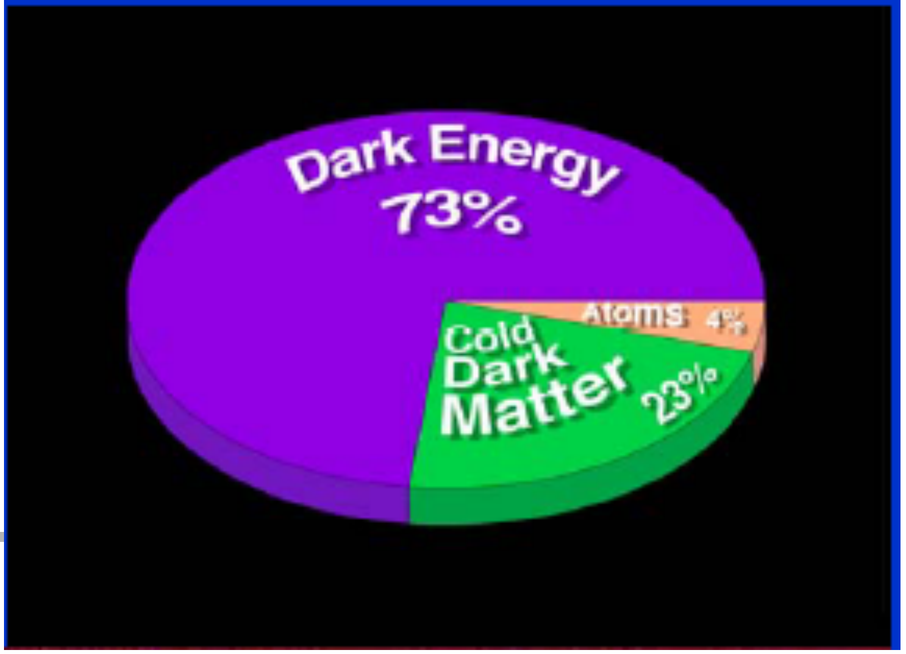


TRANSPARENT

Dark Matter



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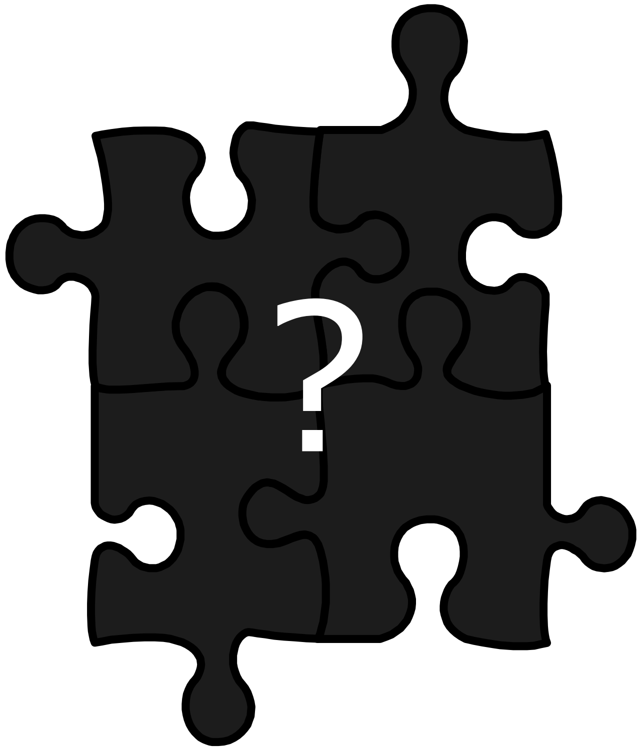
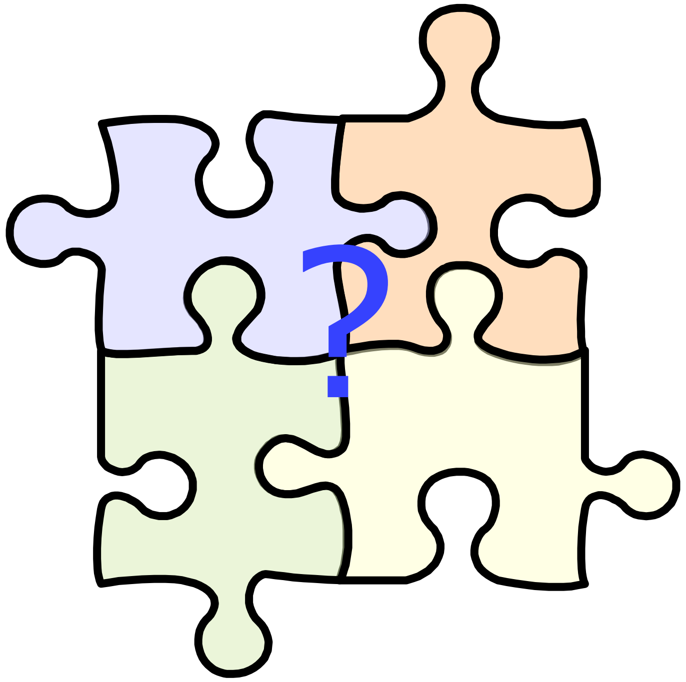




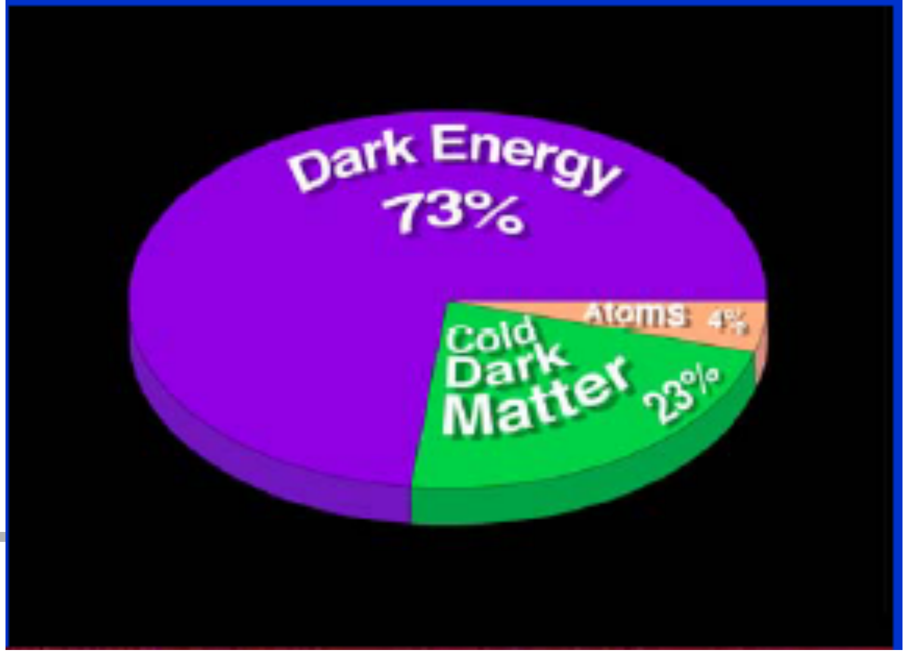
DARK

WIMP

TRANSPARENT

GRAVITINO

Dark Matter



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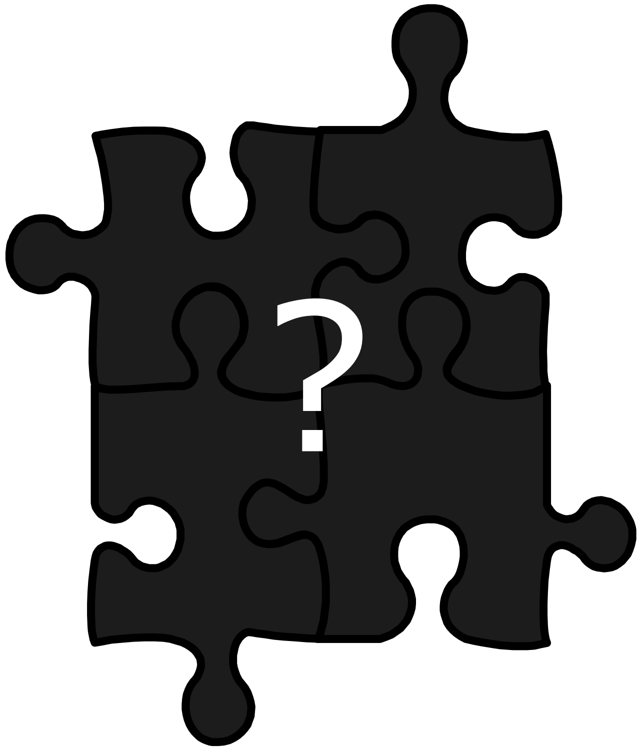

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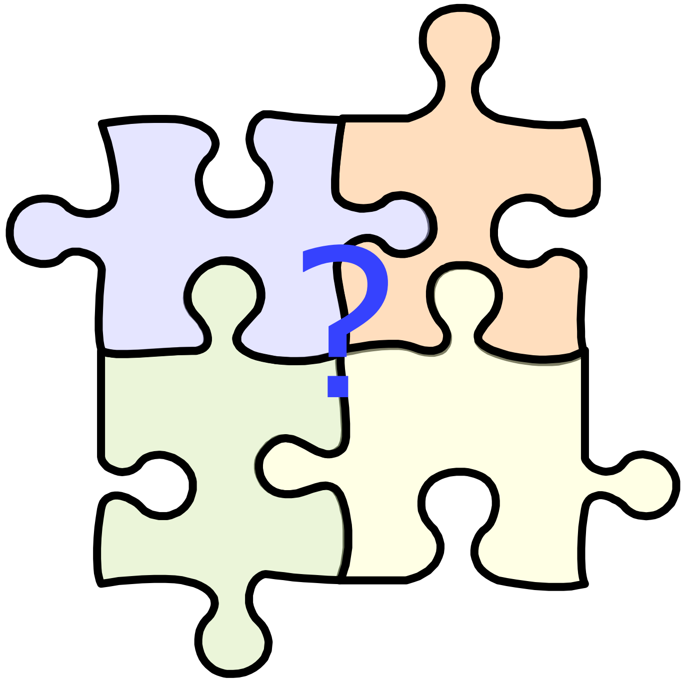


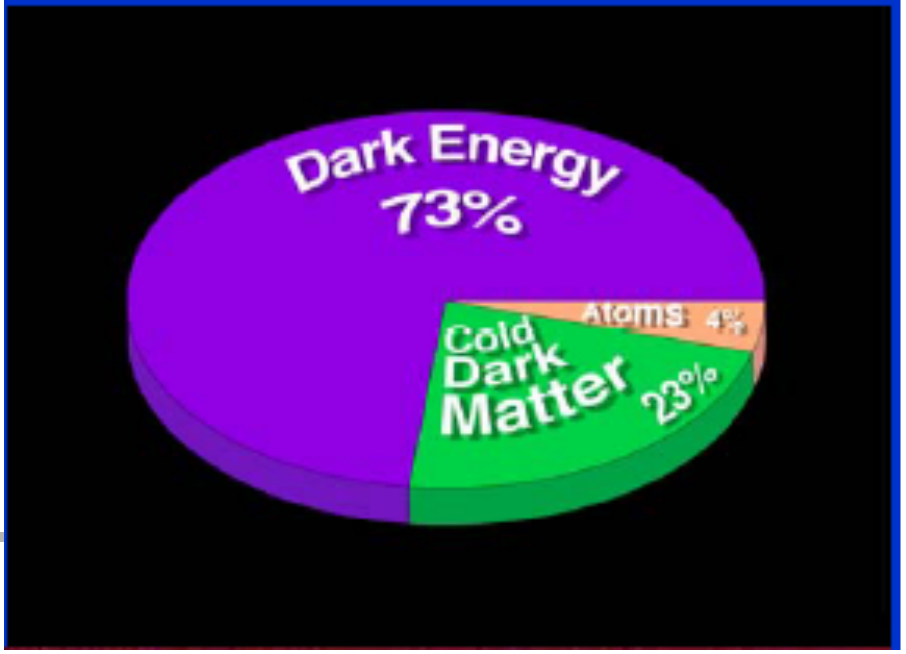
TRANSPARENT

GRAVITINO

?

INVISIBLE

Dark Matter



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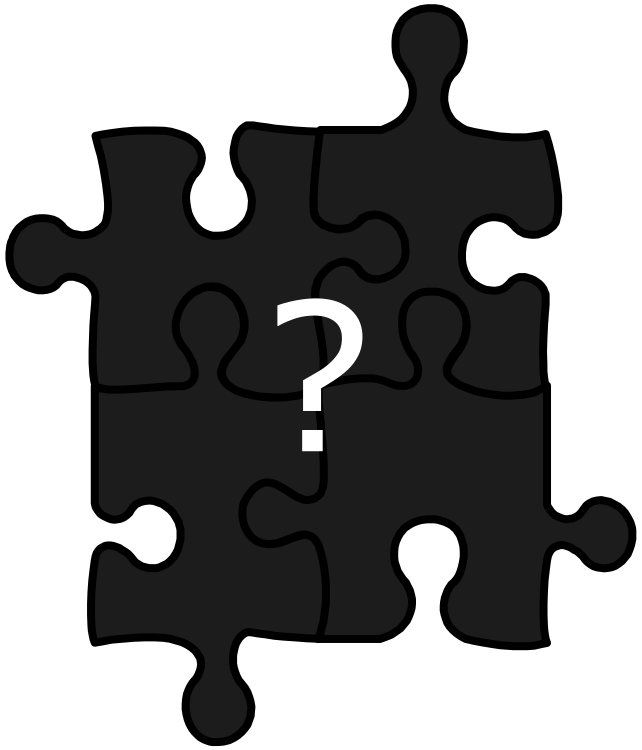
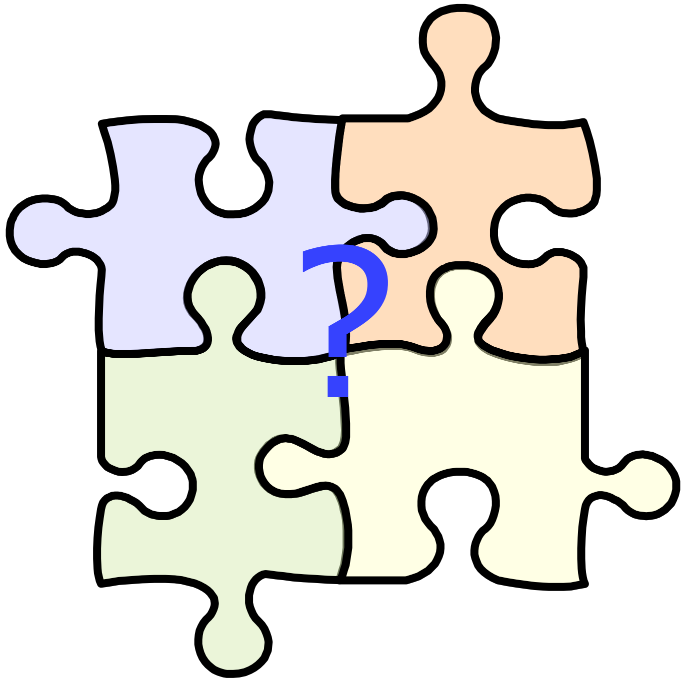
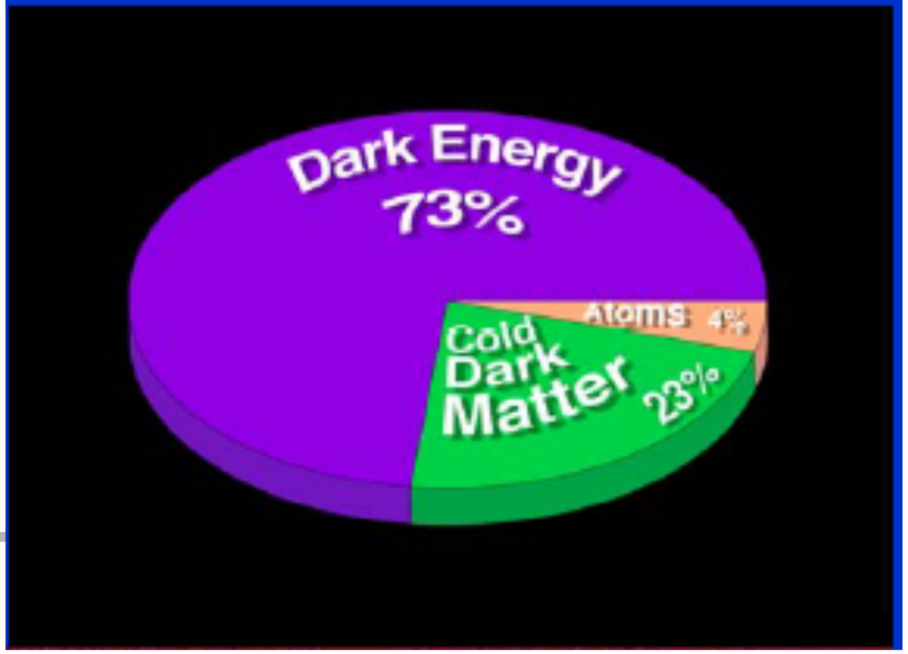




?

DARK	TRANSPARENT	*INVISIBLE*
WIMP	GRAVITINO	*AXION*

Dark Matter



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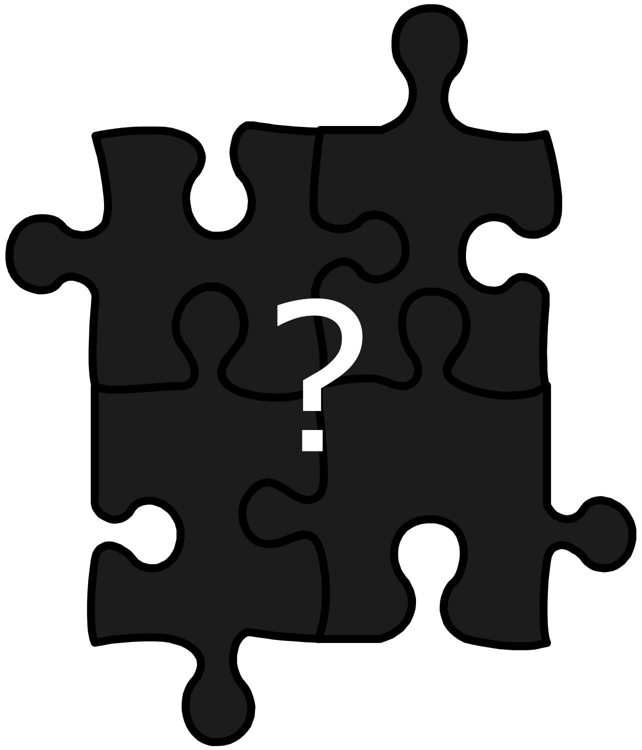

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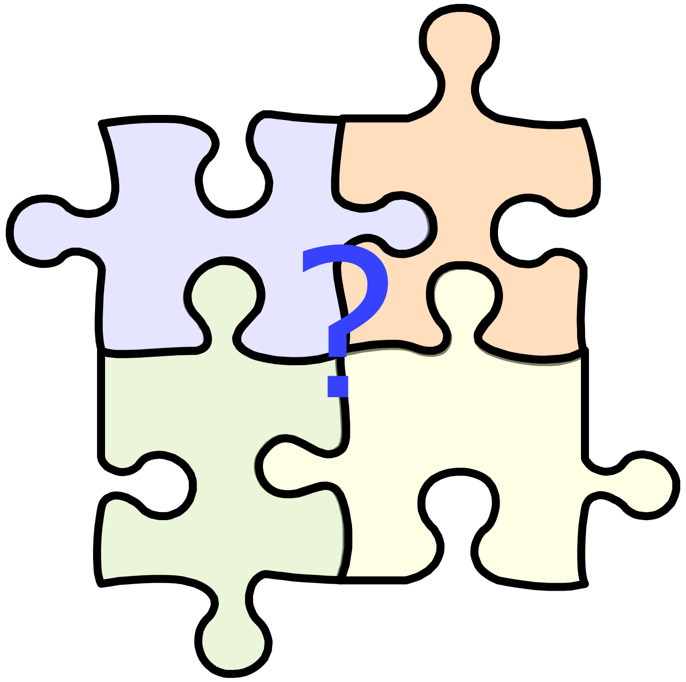


TRANSPARENT

GRAVITINO

?

INVISIBLE

AXION

What is it made of ?

The Origin of Dark Matter

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right neutrino

  - axion (axino)
  - neutralino mSUGRA
  - sneutrino
  - gravitino
  - heavy photon
  - heavy pseudo-goldstone
  - light sterile higgs

Not from the SM

The Origin of Dark Matter

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right neutrino — not favorable but possible

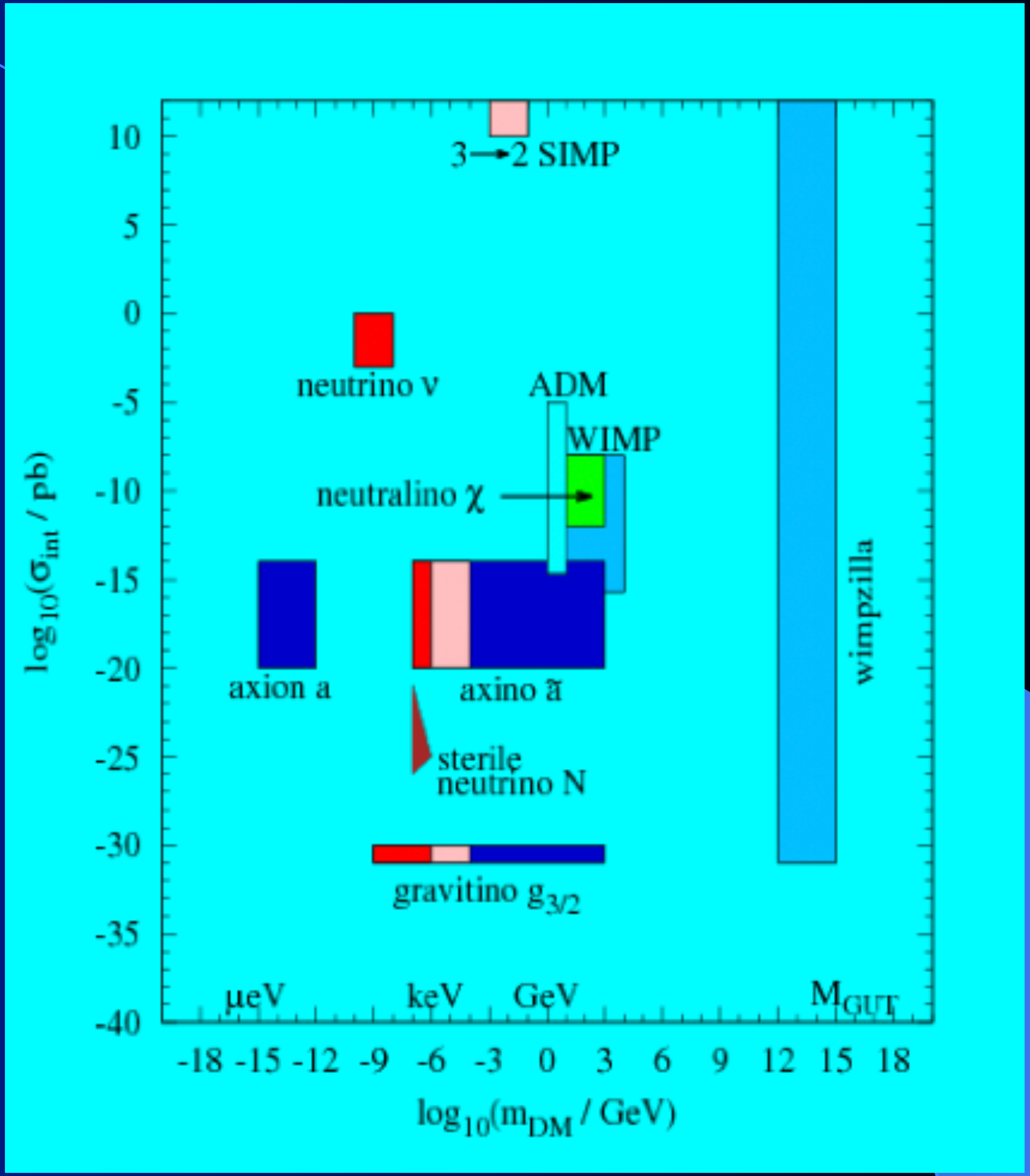
Not from the SM

- axion (axino) — might be invisible (?)
- neutralino — mSUGRA — detectable in 3 spheres
- sneutrino — less theory favorable
- gravitino — might be undetectable (?)
- heavy photon
- heavy pseudo-goldstone
- light sterile higgs

possible, but not related to the other models

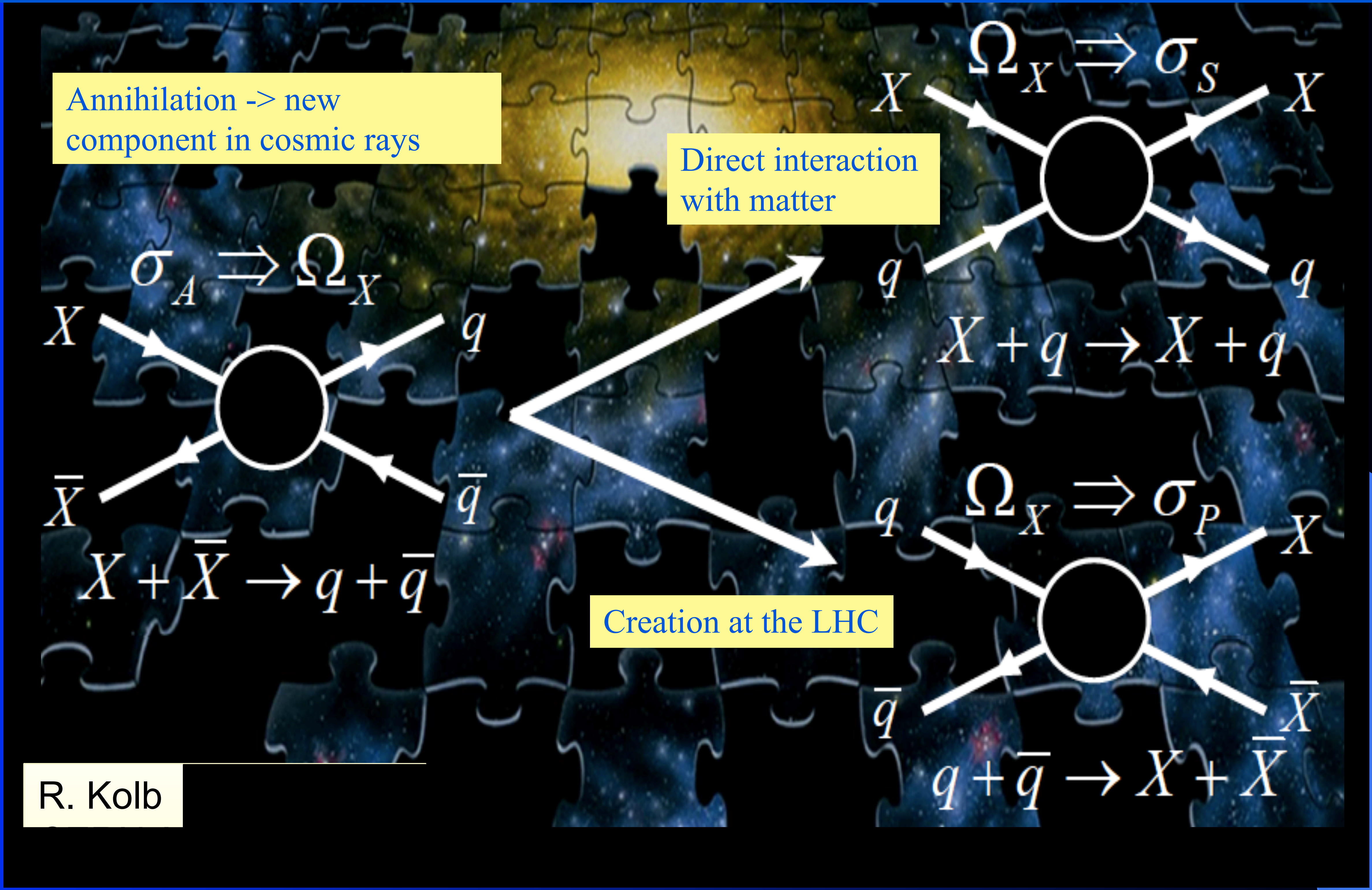
Dark Matter candidates

Can one register the Dark matter particle?



If it is a WIMP, then it can be detected by means of elementary particle physics. If it is only a gravitationally interacting particle, then detection is very difficult.

Search for Dark Matter Particles



Annihilation -> new component in cosmic rays

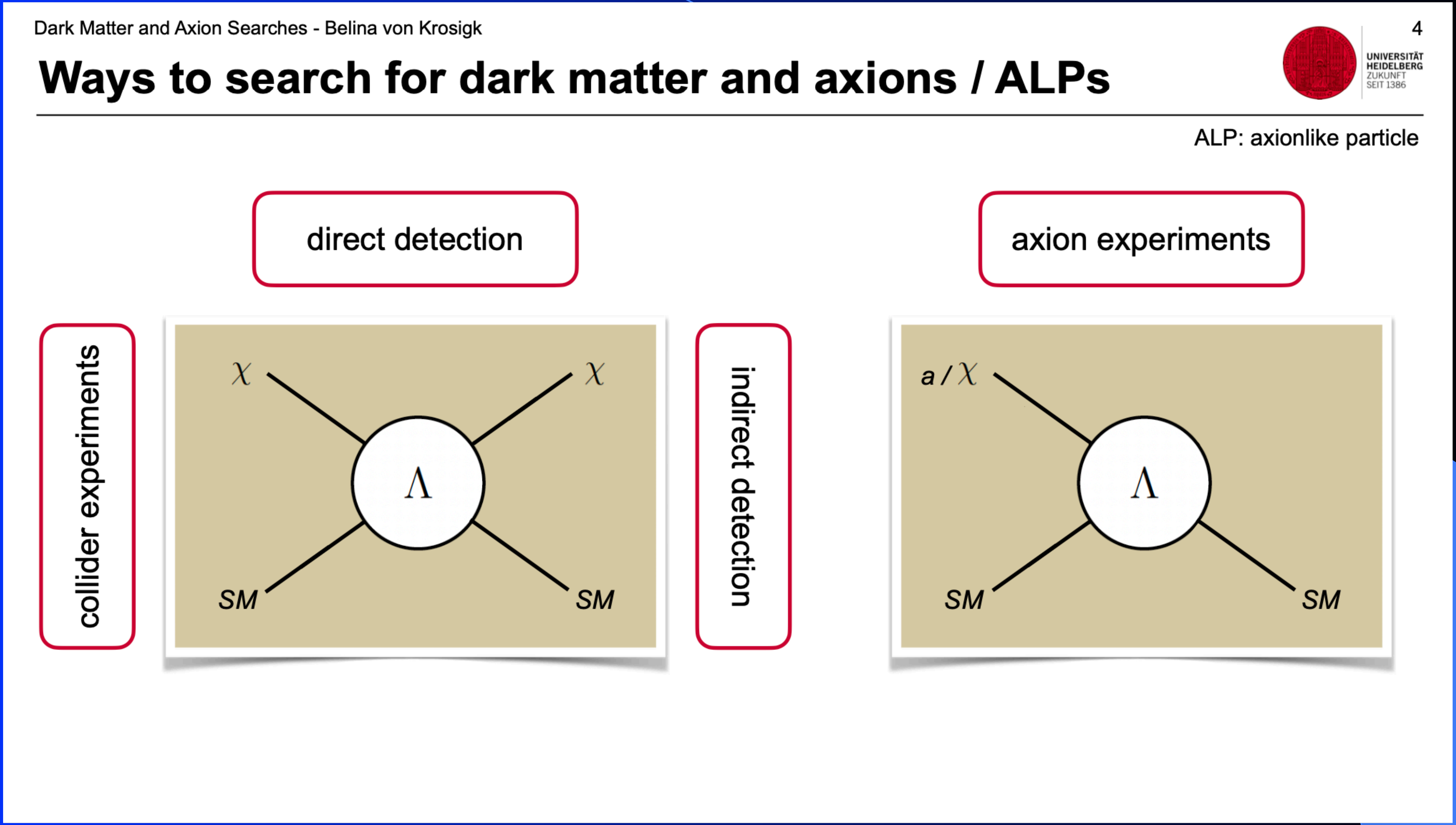
Direct interaction with matter

Creation at the LHC

R. Kolb

The signal is absent so far

Search for Dark Matter Particles



Ways to search for dark matter and axions / ALPs

ALP: axionlike particle

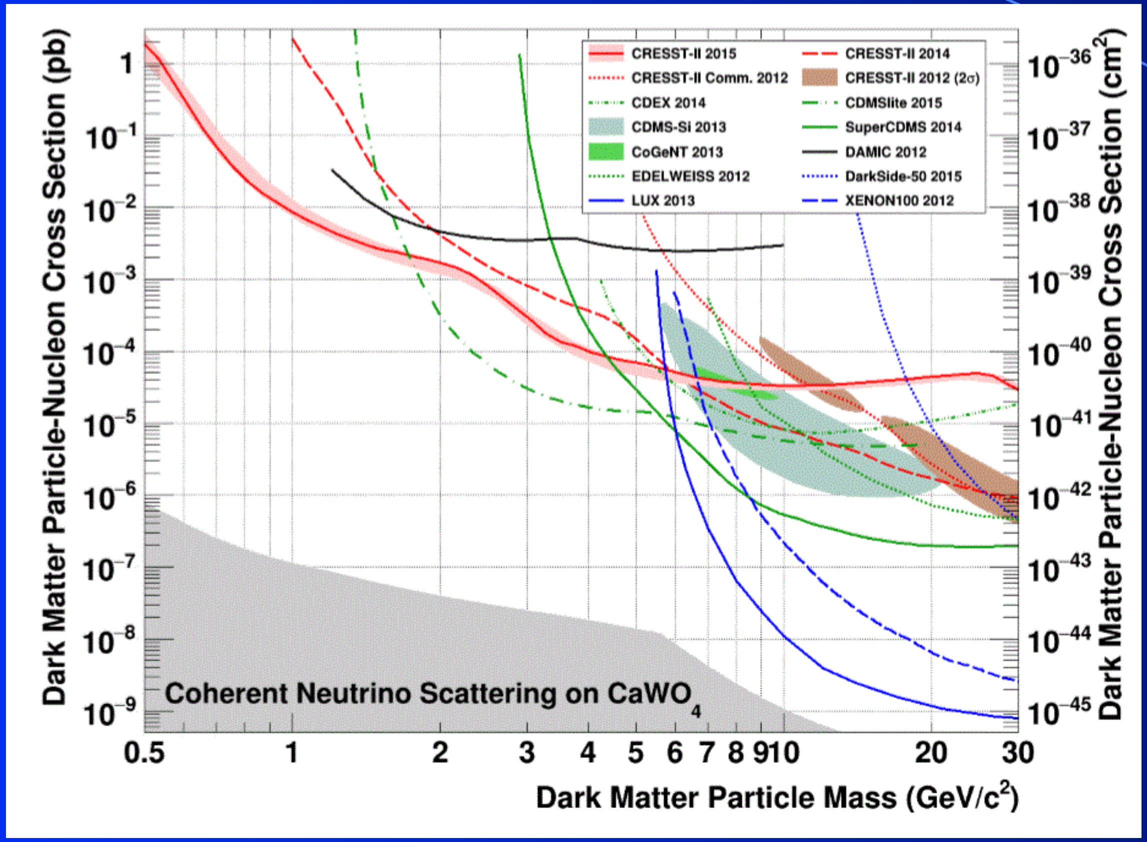
direct detection

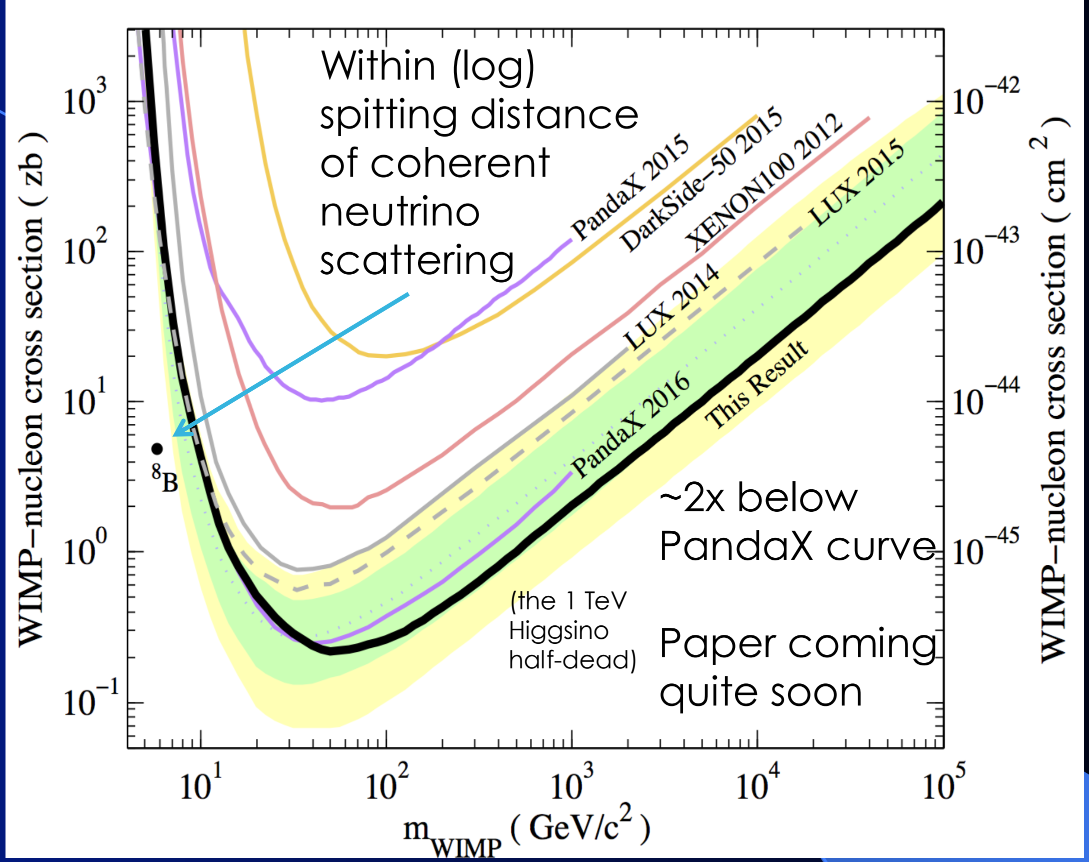
axion experiments

collider experiments

indirect detection

DARK MATTER: DIRECT DETECTION



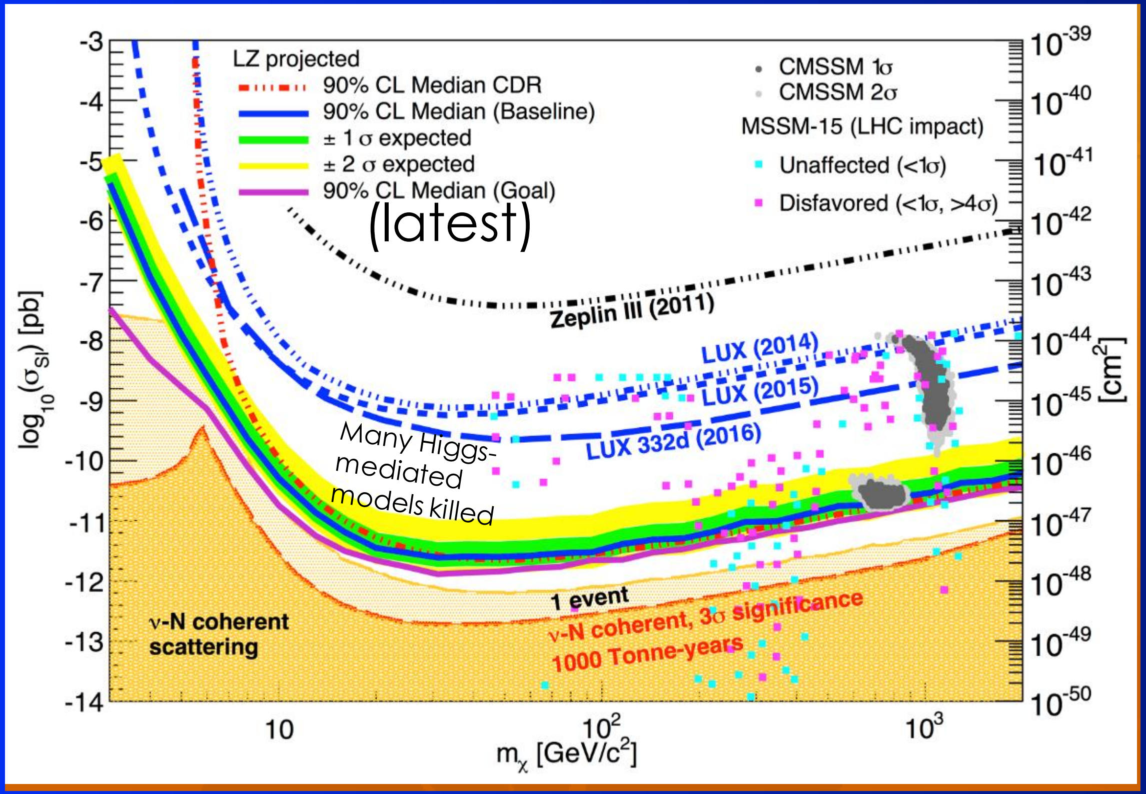


Within (log) spitting distance of coherent neutrino scattering

~2x below PandaX curve

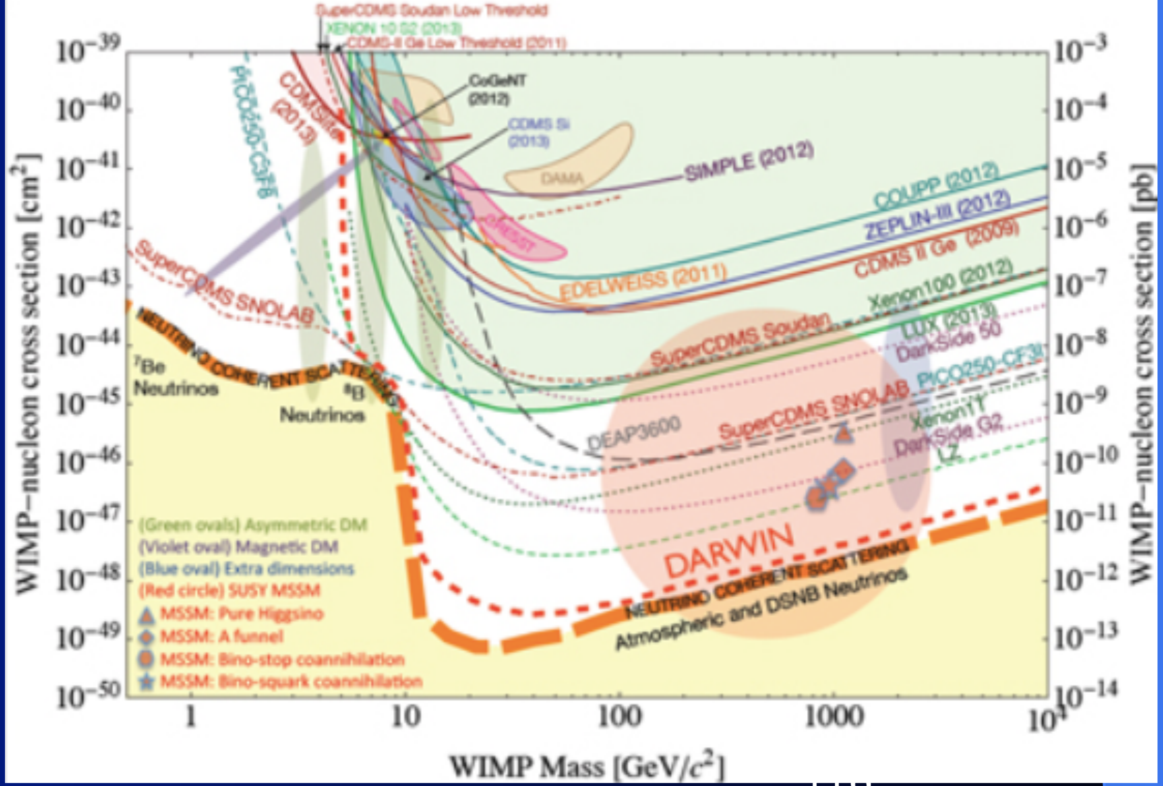
(the 1 TeV Higgsino half-dead)

Paper coming quite soon

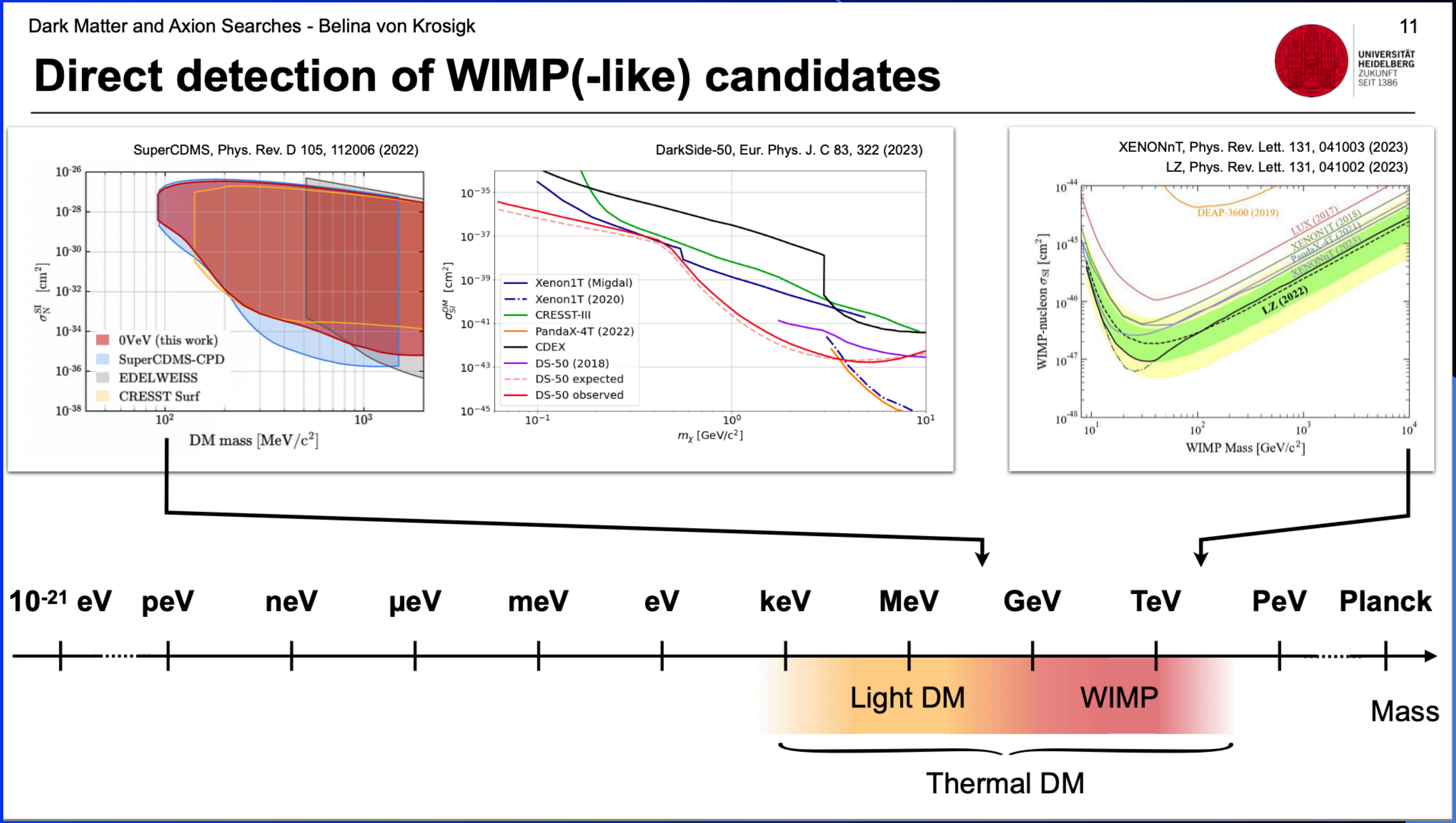


(latest)

Many Higgs-mediated models killed



Direct Detection of WIMPs



Dark Matter and Axion Searches - Belina von Krosigk

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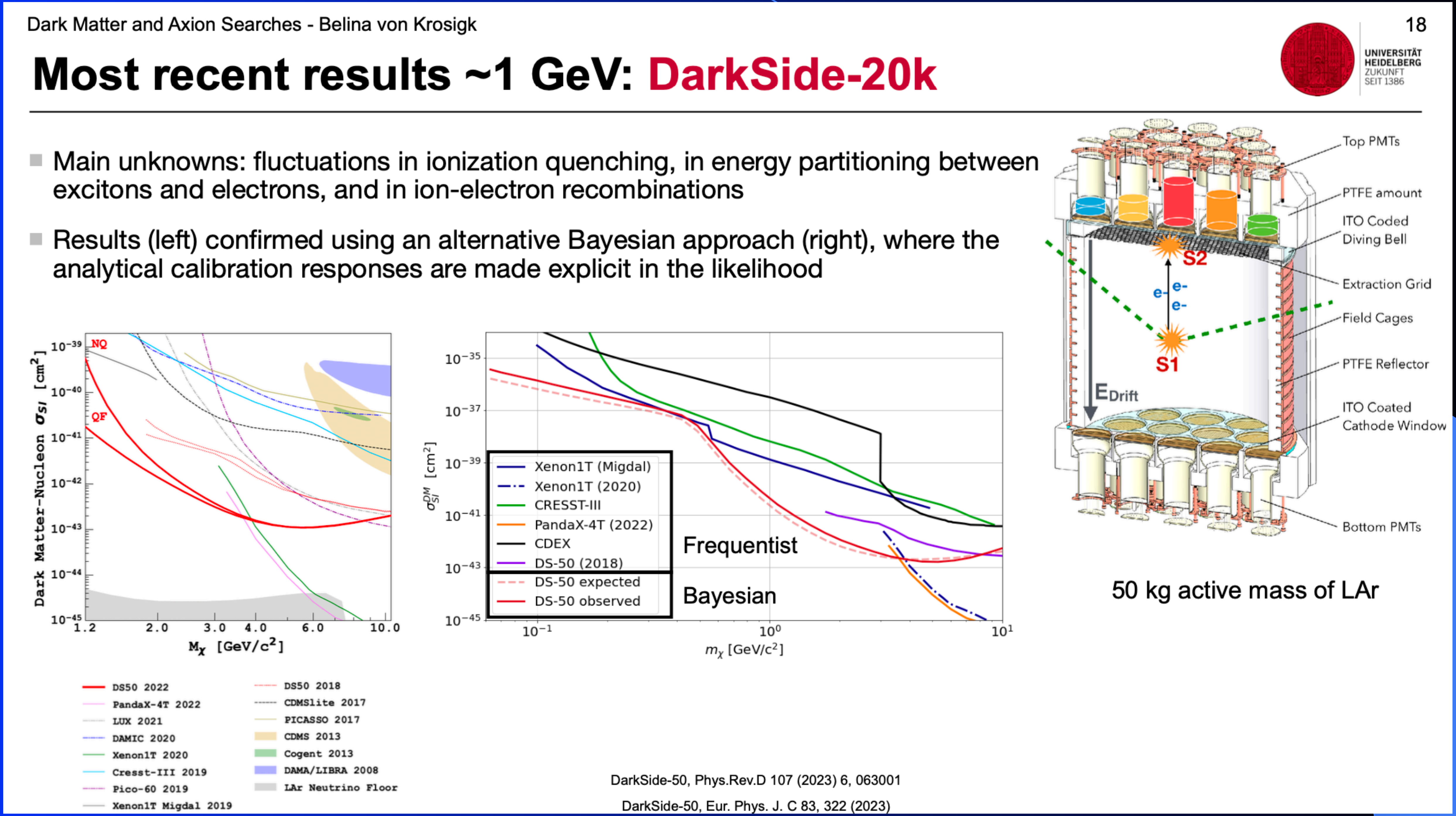
Direct detection of WIMP(-like) candidates

SuperCDMS, Phys. Rev. D 105, 112006 (2022)

DarkSide-50, Eur. Phys. J. C 83, 322 (2023)

XENONnT, Phys. Rev. Lett. 131, 041003 (2023)
LZ, Phys. Rev. Lett. 131, 041002 (2023)

Detection of light WIMPs



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Most recent results ~1 GeV: **DarkSide-20k**

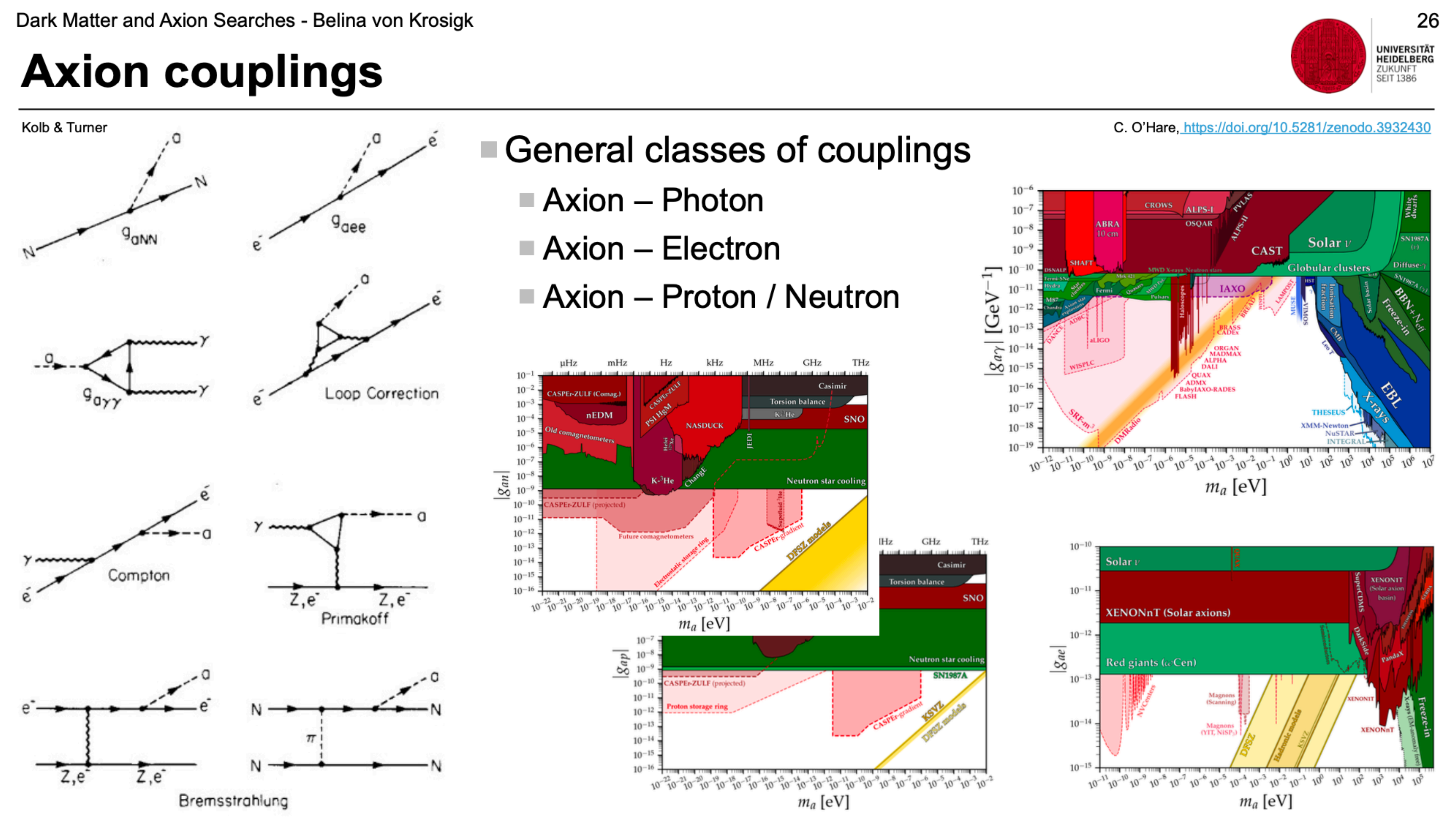
- Main unknowns: fluctuations in ionization quenching, in energy partitioning between excitons and electrons, and in ion-electron recombinations
- Results (left) confirmed using an alternative Bayesian approach (right), where the analytical calibration responses are made explicit in the likelihood

50 kg active mass of LAr

DarkSide-50, Phys.Rev.D 107 (2023) 6, 063001

DarkSide-50, Eur. Phys. J. C 83, 322 (2023)

Search for Axions and Axion-like particles



Dark Matter and Axion Searches - Belina von Krosigk

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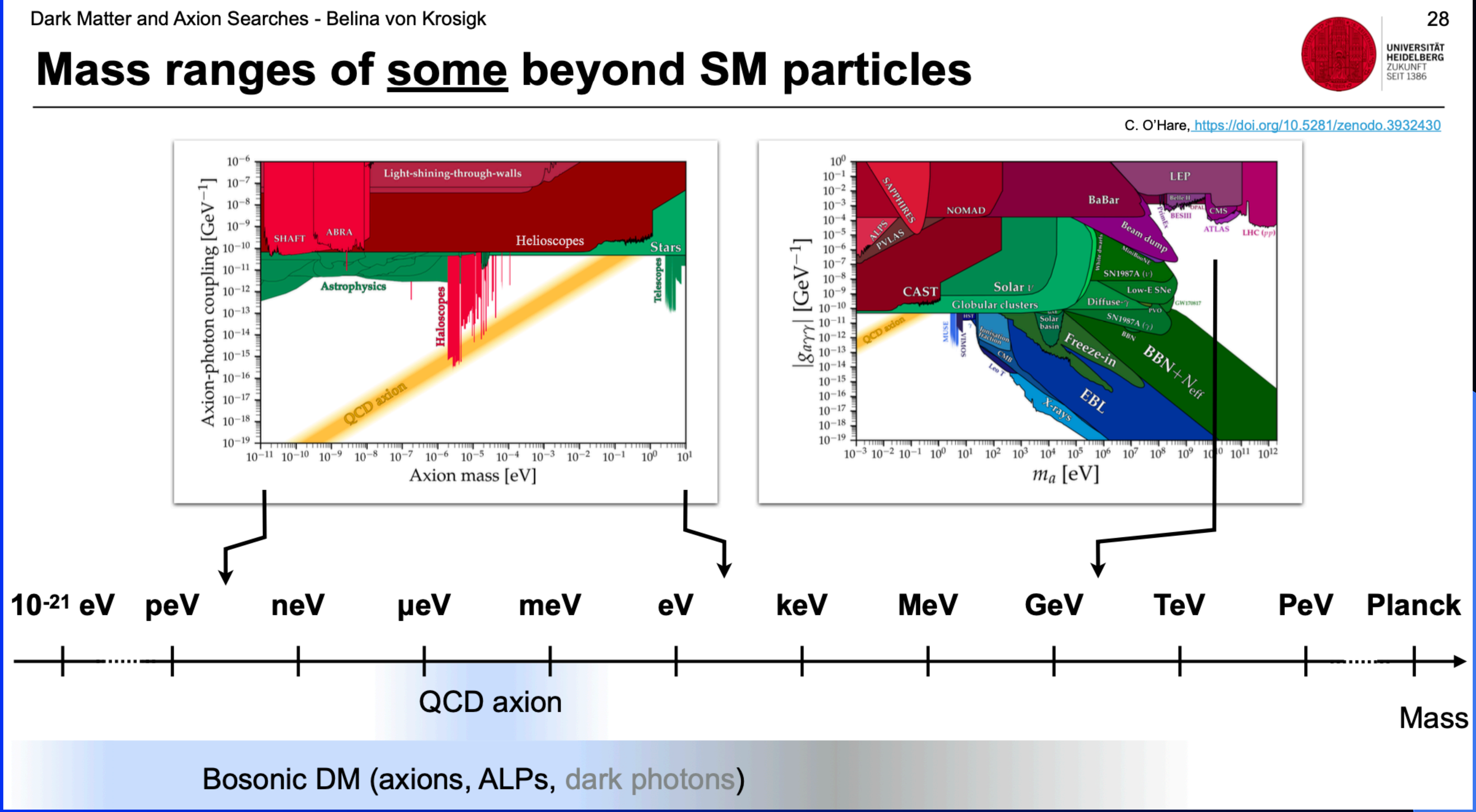
Axion couplings

Kolb & Turner

C. O'Hare, https://doi.org/10.5281/zenodo.3932430

- General classes of couplings
  - Axion – Photon
  - Axion – Electron
  - Axion – Proton / Neutron

Detection of ALPs



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Mass ranges of some beyond SM particles

C. O'Hare, https://doi.org/10.5281/zenodo.3932430

10^{-21} eV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
Planck

QCD axion

Mass

Bosonic DM (axions, ALPs, dark photons)

Baryon asymmetry of the Universe

- If there were no baryon asymmetry, there would be no matter in the universe!
- It indicates the existence of a fundamental symmetry breaking between particles and antiparticles

Average number of photons per unit volume

$$n_\gamma = 410.4 \pm 0.9 \ cm^{-3}$$

Average number of protons per unit volume

$$n_B = 0.25 \cdot 10^{-6} \ cm^{-3}$$

Left after proton-antiproton annihilation

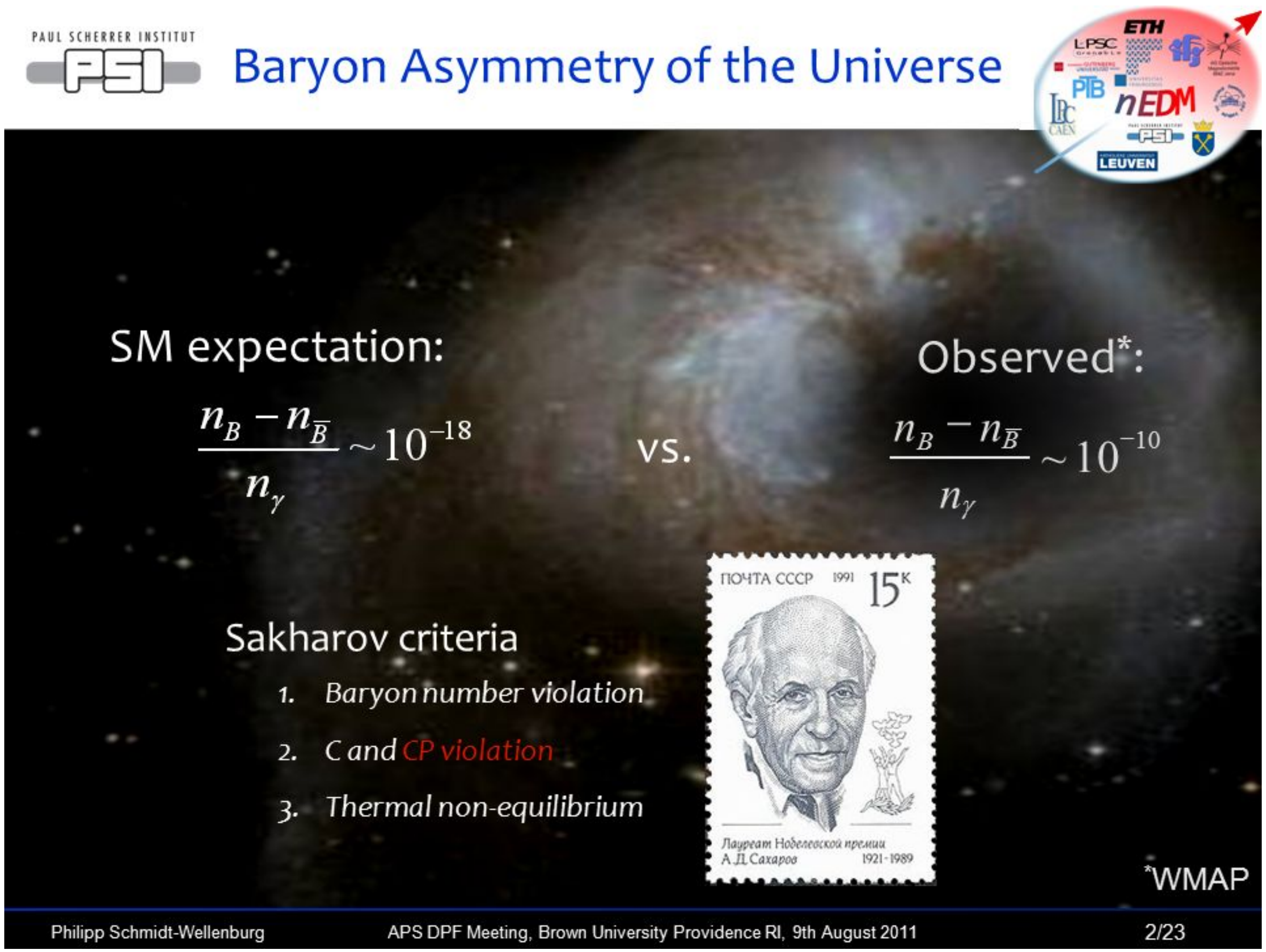
$$\frac{n_B}{n_\gamma} = \frac{0.25 \cdot 10^{-6}}{410.4} = 6.1 \cdot 10^{-10}$$

Three Sakharov's criteria

- Violation of baryon number
- Violation of C and CP invariance
- Violation of яermal equilibrium

- What is the source of baryon asymmetry of the Universe?
- Where the symmetry between particles and antiparticles is violated?

Baryon asymmetry of the Universe



Baryon Asymmetry of the Universe

SM expectation:

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-18}$$

vs.

Observed*:

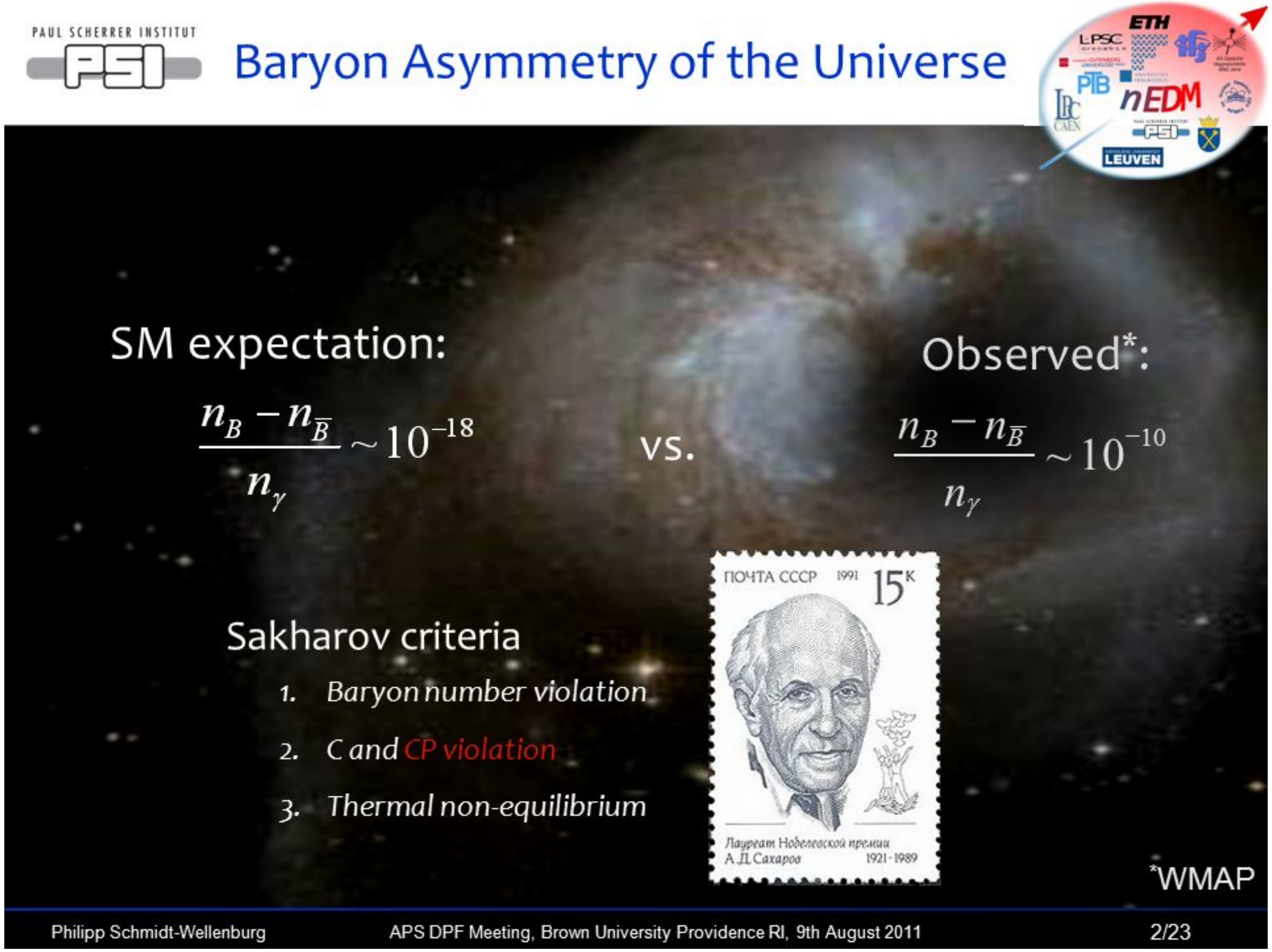
$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-10}$$

Sakharov criteria

1. *Baryon number violation*
2. *C and CP violation*
3. *Thermal non-equilibrium*

*WMAP

Baryon asymmetry of the Universe



PAUL SCHERRER INSTITUT

PSI

Baryon Asymmetry of the Universe

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ПОЧТА СССР 1991 15к

Лауреат Нобелевской премии
А.Д.Сахаров 1921-1989

*WMAP

Philipp Schmidt-Wellenburg APS DPF Meeting, Brown University Providence RI, 9th August 2011 2/23

- Baryon number is conserved in the SM with exponential accuracy

- Violation of baryon number occur in Grand Unified Theories and in Lepton=fourth color models (Pati-Salam model)

New particles = Leptoquarks, Extended Highs sector

$$B = \frac{N_q - N_{\bar{q}}}{3} \qquad \cancel{B}$$

- Violation of CP invariance in the SM achieved via phase factors in the CKM and PMNS mixing matrices ↔ $\cancel{CP}$

BAU requires larger CP than in the SM   Possible Baryogeneses via Leptogeneses

The presence of new phase factors in extended models (2HDM, SUSY, etc)

BEYOND THE STANDARD MODEL: CONCLUSIONS

WHAT MAKES US THINK THAT THERE IS PHYSICS BEYOND THE STANDARD MODEL?

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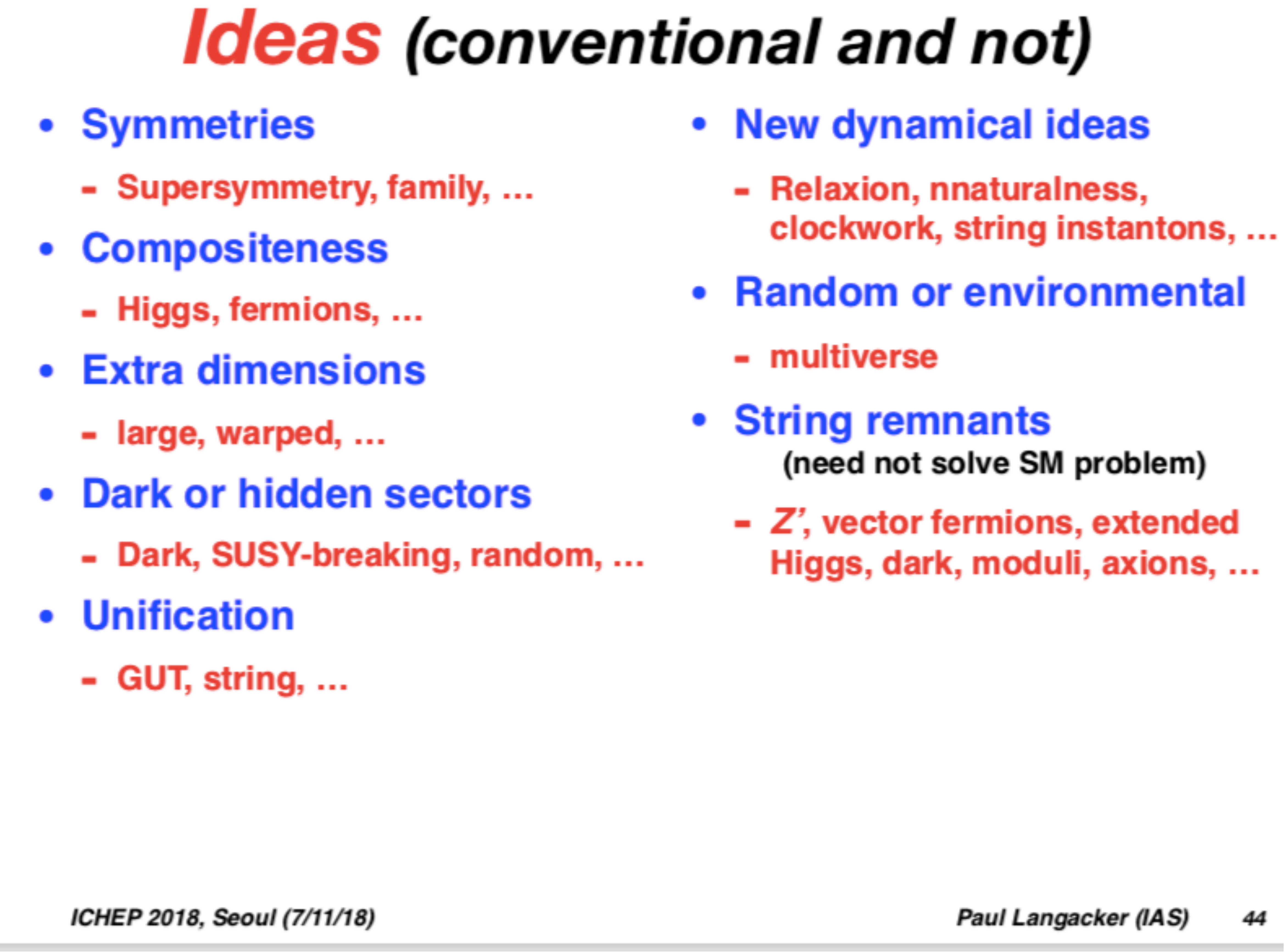
- Lack of understanding of flavor structure of the SM calls for explanation at higher level
- New era in gravity due to discovery of gravitational waves and black holes might change the landscape



Ideas (conventional and not)

- **Symmetries**
  - Supersymmetry, family, …
- **Compositeness**
  - Higgs, fermions, …
- **Extra dimensions**
  - large, warped, …
- **Dark or hidden sectors**
  - Dark, SUSY-breaking, random, …
- **Unification**
  - GUT, string, …
- **New dynamical ideas**
  - Relaxion, nnaturalness, clockwork, string instantons, …
- **Random or environmental**
  - multiverse
- **String remnants**

  (need not solve SM problem)
  - *Z'*, vector fermions, extended Higgs, dark, moduli, axions, …

ICHEP 2018, Seoul (7/11/18) *Paul Langacker (IAS)* 44

BEYOND THE STANDARD MODEL: QUEST FOR SYMMETRY

Looking for new physics we are looking for new Symmetry of Nature!

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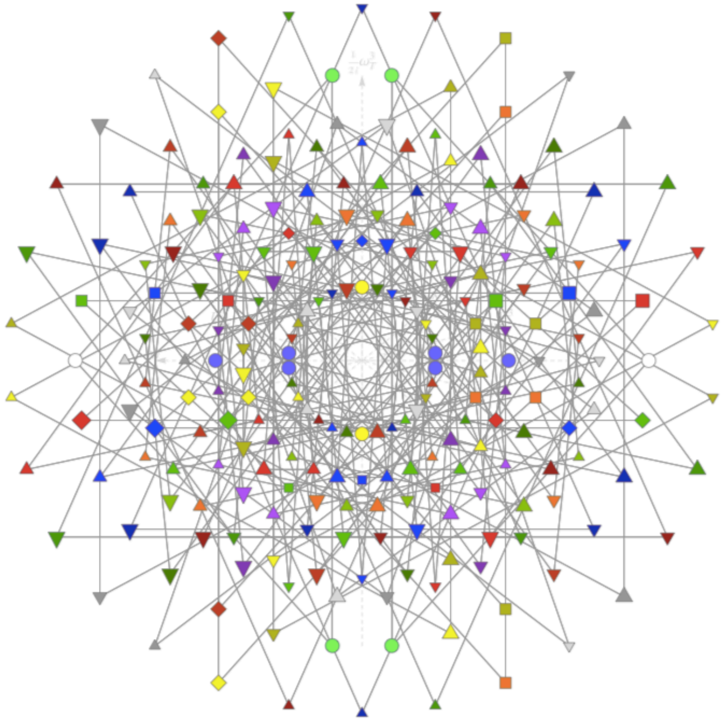

E8 roots

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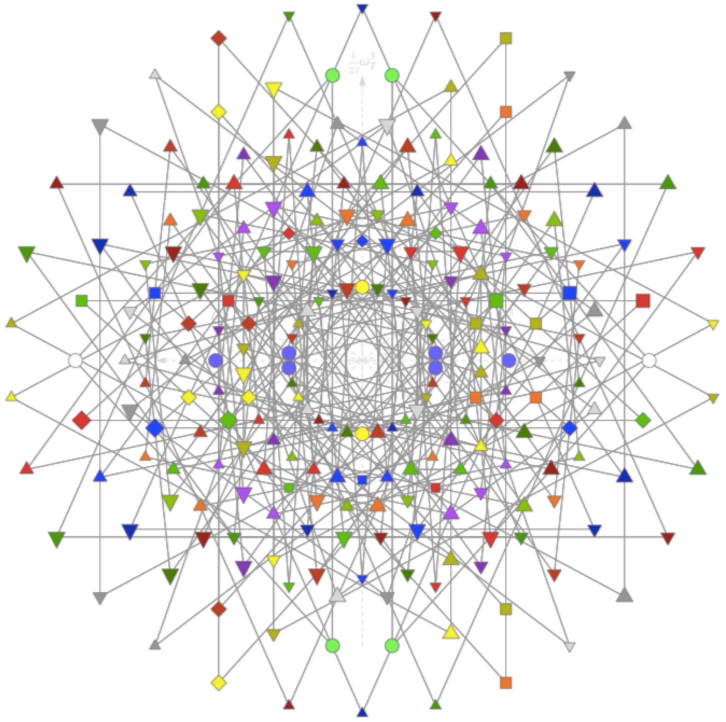
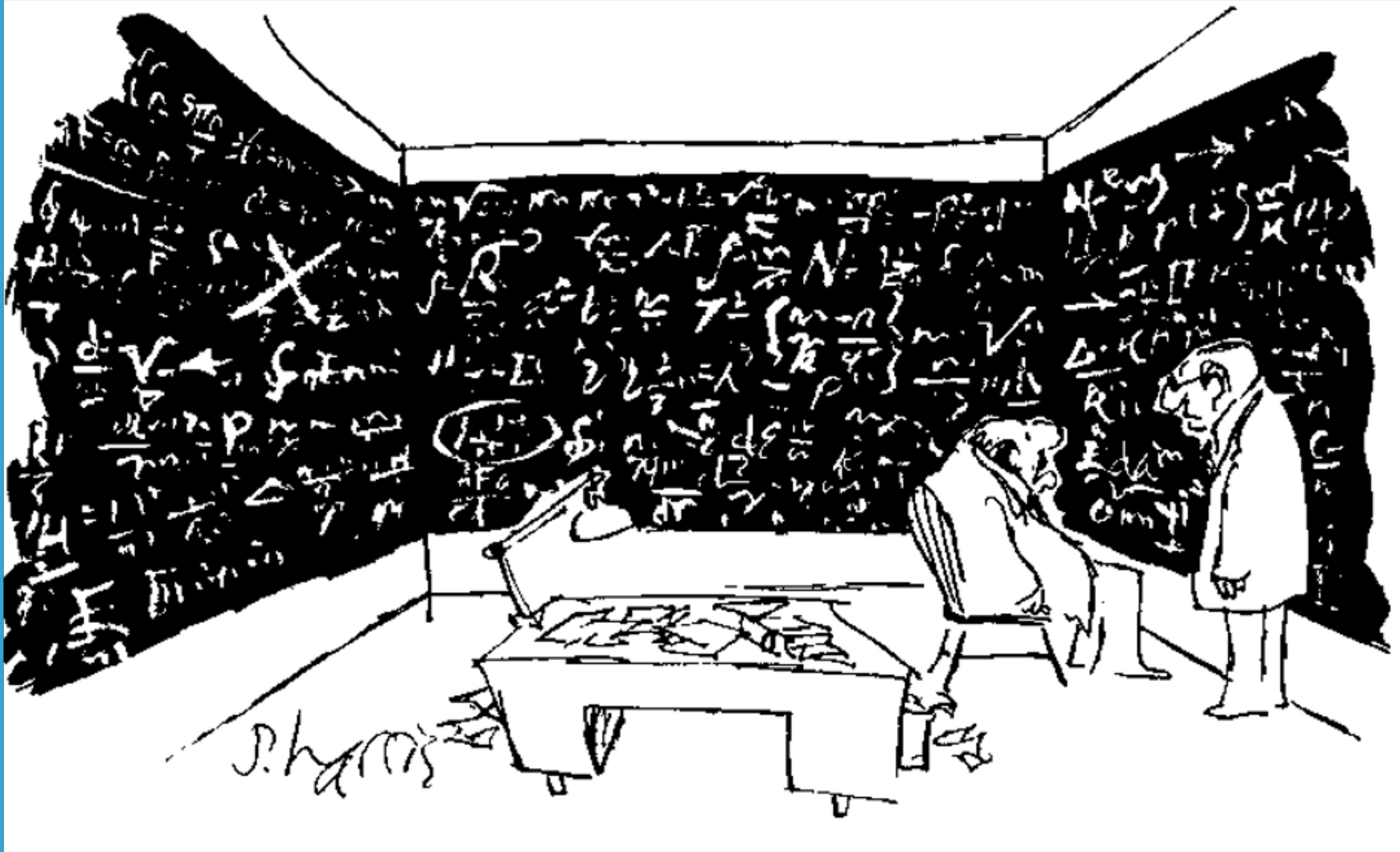


E8 roots

Symmetry might be tricky

We like elegant solutions



“Whatever happened to *elegant* solutions?”

Future Particle Physics

Beyond SM

Energy frontier: HL LHC, FCC e^+e^-mode,
CLIC, China colliders

Intensity Frontier: SuperBelle, BEPCIII, SHiP, NA62, NA64, VEPP, Super c-τ-factory

Precision Frontier: g-2, nEDM

Under –ground, -water, -ice: Icecube, Baikal

Neutrino: JUNO, HyperK, …, DUNE

Cosmic Rays: Pierre Auger,…, satellites

New Dynamics in SM

EIC (electron ion collider) BNL
NICA
FAIR
JLAB
U-76
China electron-ion collider

Experimental Particle Physics

Russia & JINR

Beyond SM

Intensity & Precision Frontier:
VEPP, Super c-τ-factory, nEDM

Under –ground, -water: GVD-Baikal
Neutrino: BEST, NEUTRINO-4, DANSS, …
Cosmic Rays: Pamir, Tian-Shan, satellites …

New Dynamics in SM

NICA: MPD heavy-ion collisions
BM@N short-range nucleon correlations
SPD spin structure, partonic 3D-structure
exotic resonances
electron-ion collider option R&D

U-76 SPASCHARM charm and exotic resonances

Which way to go ?

Which way to go ?

Which way to go ?

Which way to go ?

What the future may bring?