THE STANDARD MODEL AND BEYOND'19

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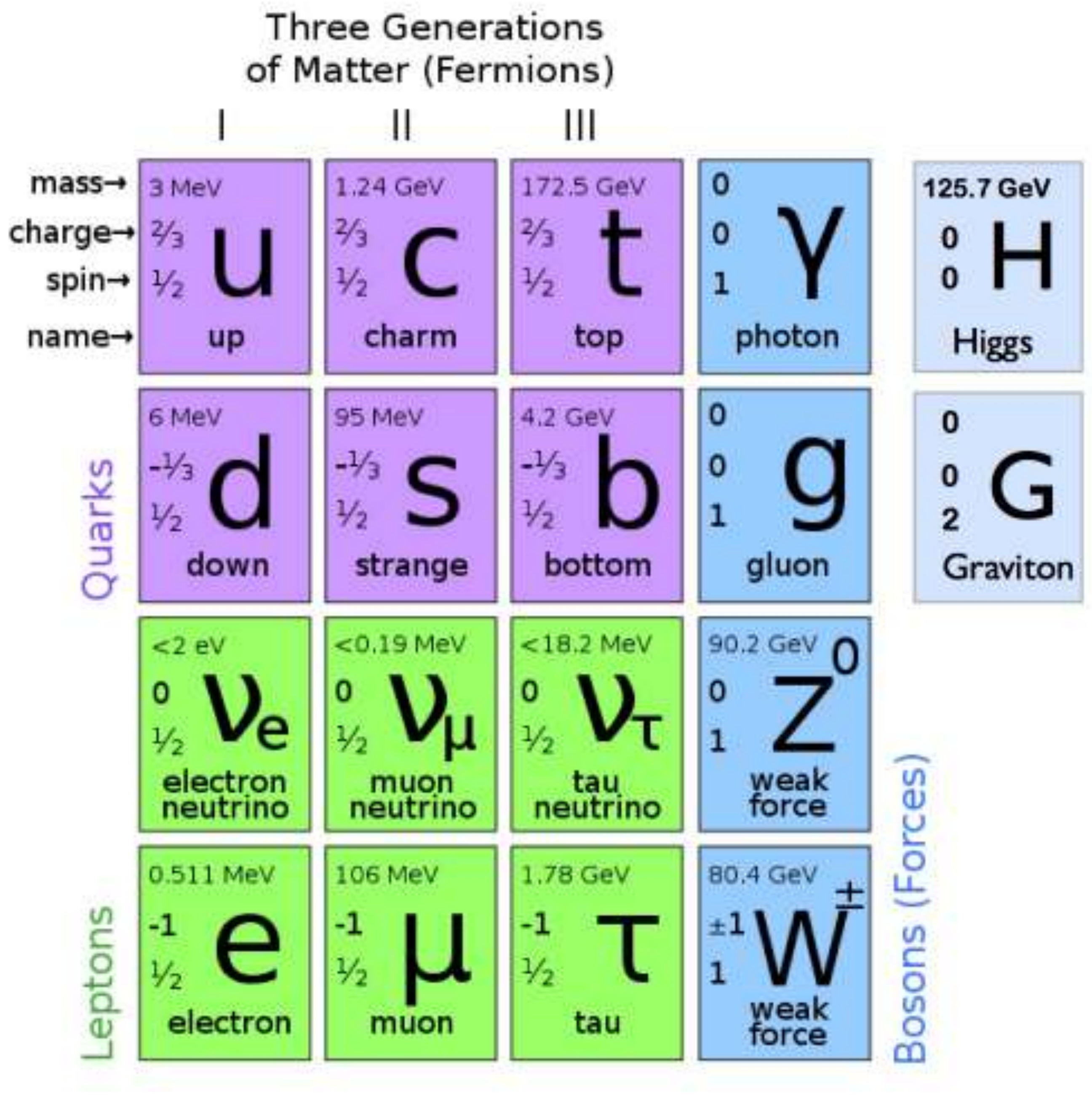
THE STANDARD MODEL OF FUNDAMENTAL INTERACTIONS

SU(3)

SU(2)

U(1)

Частицы



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
Quarks		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	
Leptons		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	

Силы

Электромагнитные

Сильные

Слабые

Gravity

THE PRINCIPLES

- Three gauged symmetries SU(3)xSU(2)xU(1)
- Three families of quarks and leptons $(\underline{3}x\underline{2}, \underline{3}x\underline{1}, \underline{1}x\underline{2}, \underline{1}x\underline{1})$
- 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

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 LAGRANGIAN

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

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

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

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

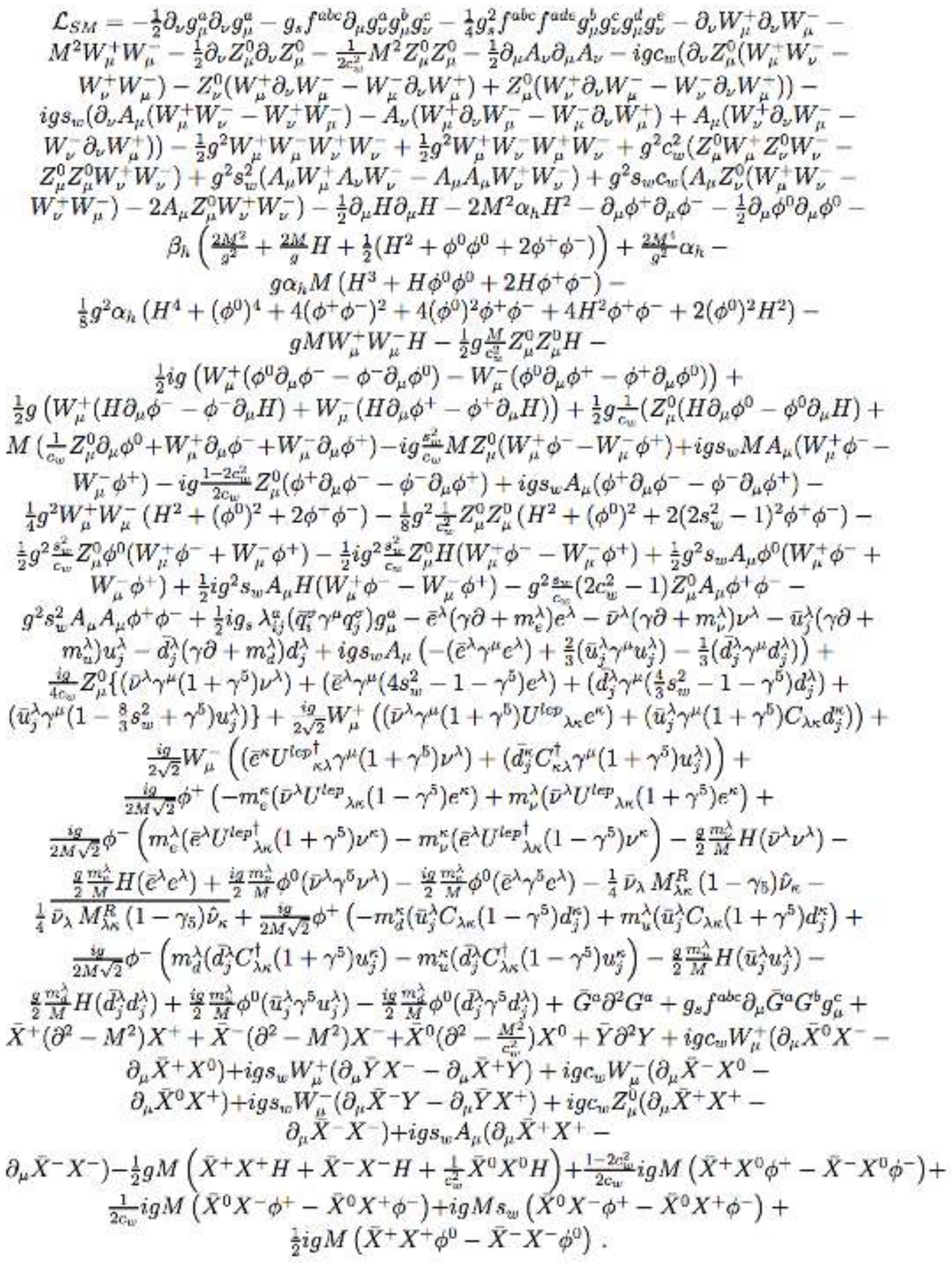
$$\boxed{+i\overline{N}_\alpha\gamma^\mu\partial}$$

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

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

$$\mathcal{L}_{Higgs} = -V =$$

All these parameters are not predicte



$$\begin{gathered}
\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^2c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s^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_wMA_\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_wA_\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^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\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_wA_\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_wA_\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(\frac{4}{3}s^2_w-1-\gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1-\frac{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) - \\
\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^5e^\lambda) - \frac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\overline{\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^5u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^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^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \\
\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) + igs_wA_\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).
\end{gathered}$$

Quantum Numbers of Matter

- Quarks

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

$$U_R = up_R$$

$$D_R = down_R$$

	SU(3)$_c$	SU(2)$_L$	U$_Y$(1)
Q_L	3	2	$1/3$
U_R	3	1	$4/3$
D_R	3	1	$-2/3$

triplets

doublets

singlets

V-A currents in weak interactions

- Leptons

$$L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

$$N_R = \nu_R \ ?$$

$$E_R = e_R$$

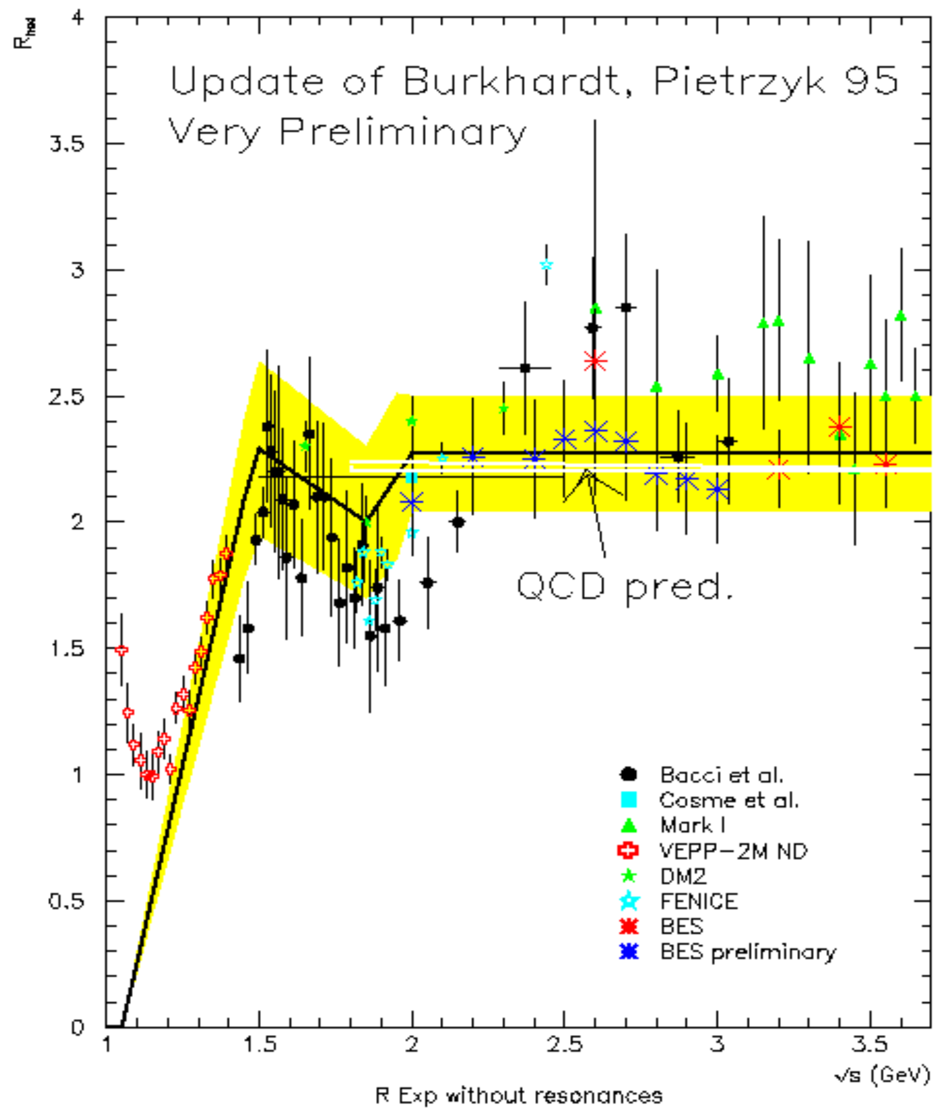
$$\begin{matrix} \frac{1}{2} \\ -\frac{1}{2} \end{matrix} \Big\} T_3 \qquad \begin{matrix} 0 \\ 0 \end{matrix} \Big\} T_3$$

L_L	1	2	-1
N_R	1	1	0
E_R	1	1	-2

Electric charge

$$Q = T_3 + Y/2$$

The Number of Colours



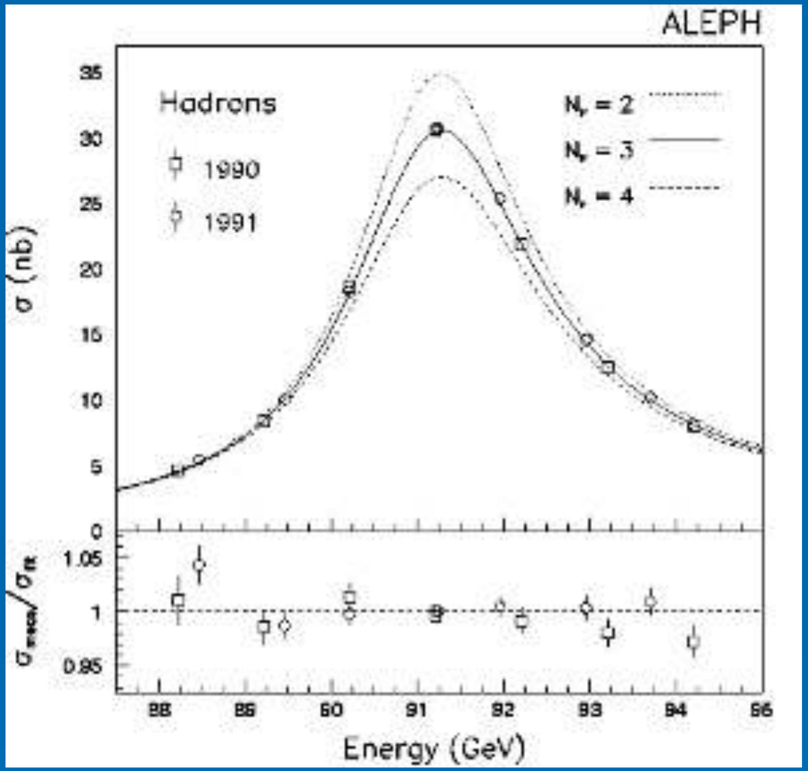
- The x-section of electron-positron annihilation into hadrons is proportional to the number of quark colours. The fit to experimental data at various colliders at different energies gives

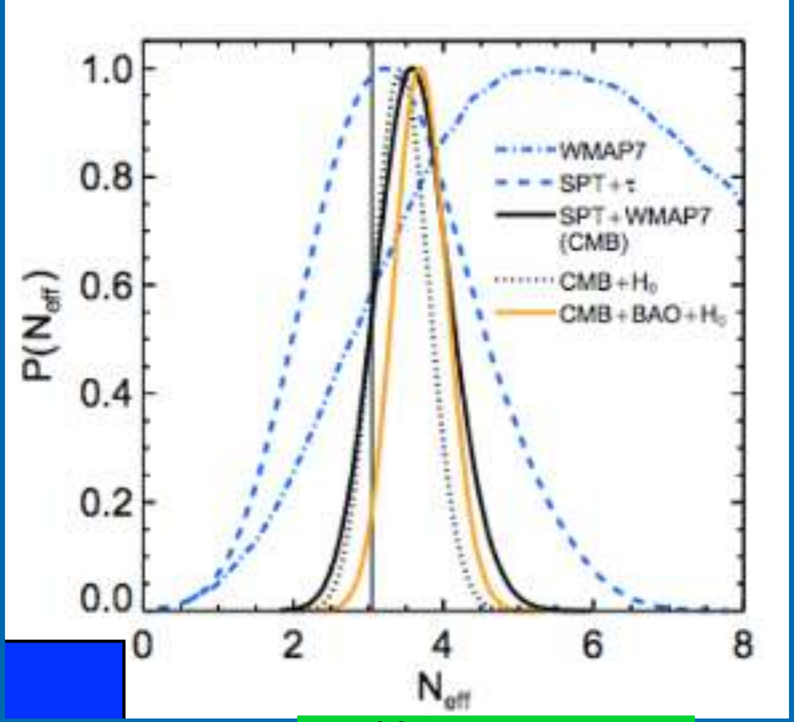
$$N_c = 3.06 \pm 0.10$$

The Number of Generations

- The width of the Z-boson (LEP)

- The CMB spectrum (Planck)





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

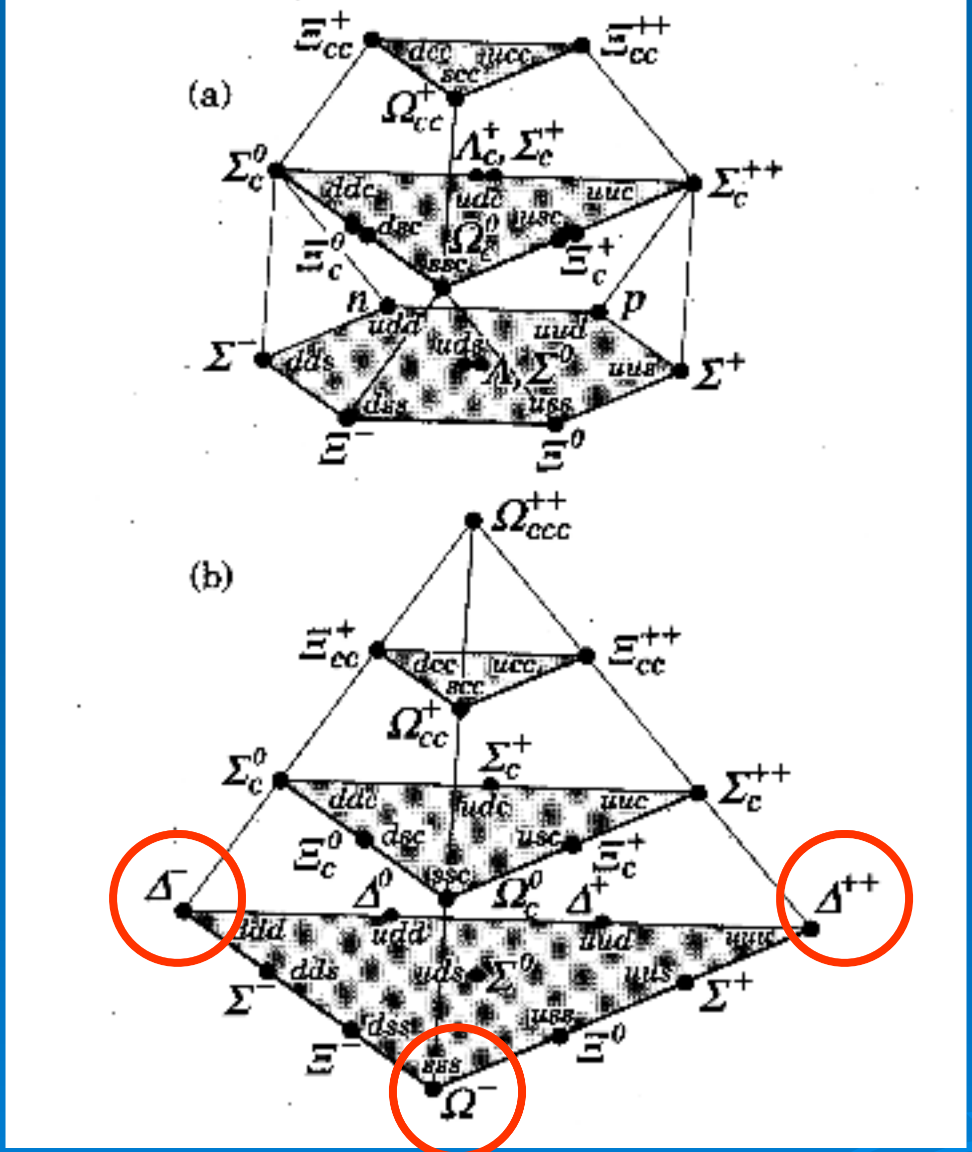
- ➢ Z-line shape obtained at LEP depends on the number of flavours and gives the number of (light) neutrinos or (generations) of the Standard Model

- ➢ The shape of the CMB temperature fluctuations give the number of active neutrinos or generations of the Standard Model assuming the quark-lepton symmetry

$N_g = 2.982 \pm 0.013$

Quark’s Colour

Baryons are “made” of quarks



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

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

?

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

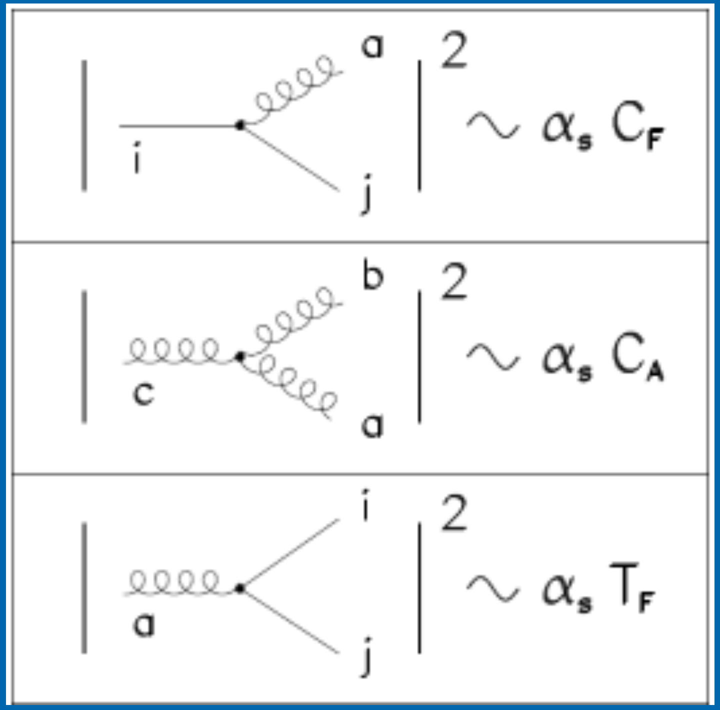
To avoid Pauli principle veto one can antisymmetrize the wave function introducing a new quantum number - “colour”, so that

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

The group structure of the SM

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

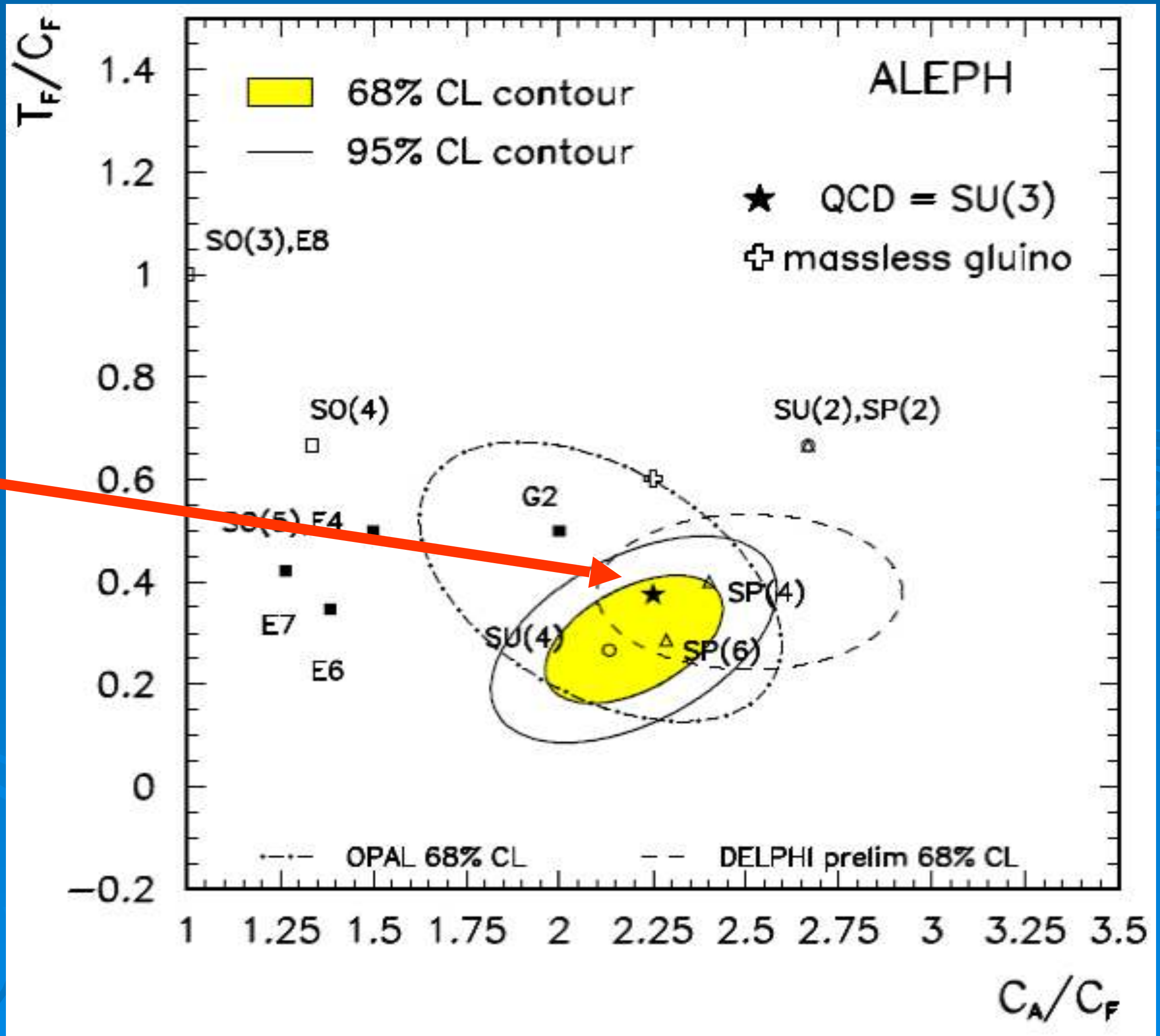
Casimir Operators



For SU(N)

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

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



Electro-weak sector of the SM

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

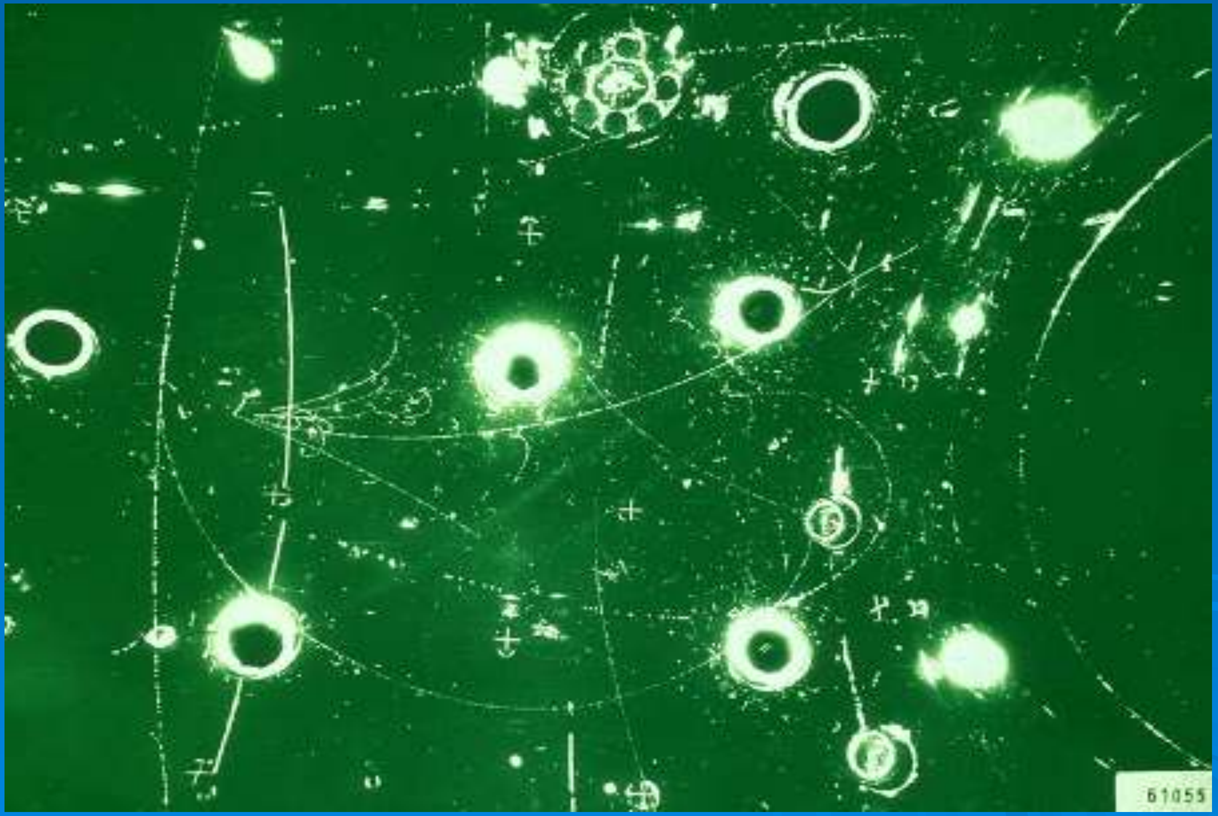
3 gauge bosons 1 gauge boson 3 gauge bosons

After spontaneous symmetry breaking one has

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

⟺

2 massive gauge bosons
(W^+ , W^-) and 1 massless (γ)



- 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

Flavour Sector

Electromagnetic Interactions

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

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

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

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

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

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

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

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

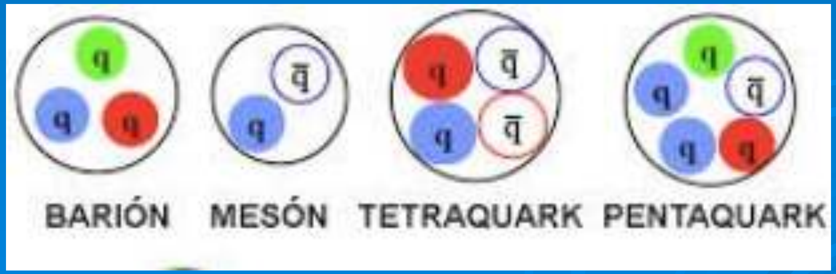
3. Charged particles (quarks and leptons) obey Dirac equation

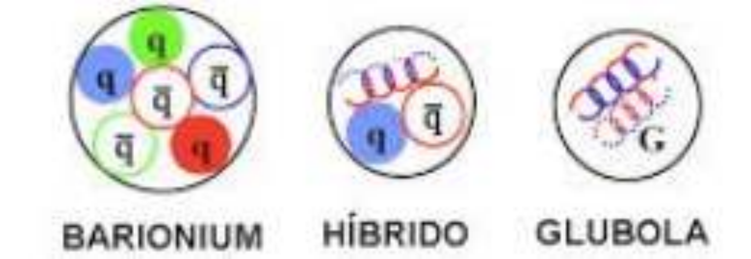
$$(\hat{\partial} - m - e\hat{A})\psi = 0 \qquad \hat{\partial} = \gamma^\mu \partial_\mu$$

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)
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:

   mesons $M = \bar{q}q$ and baryons $B = qqq$
6. However, exotic hadrons are proved to exist



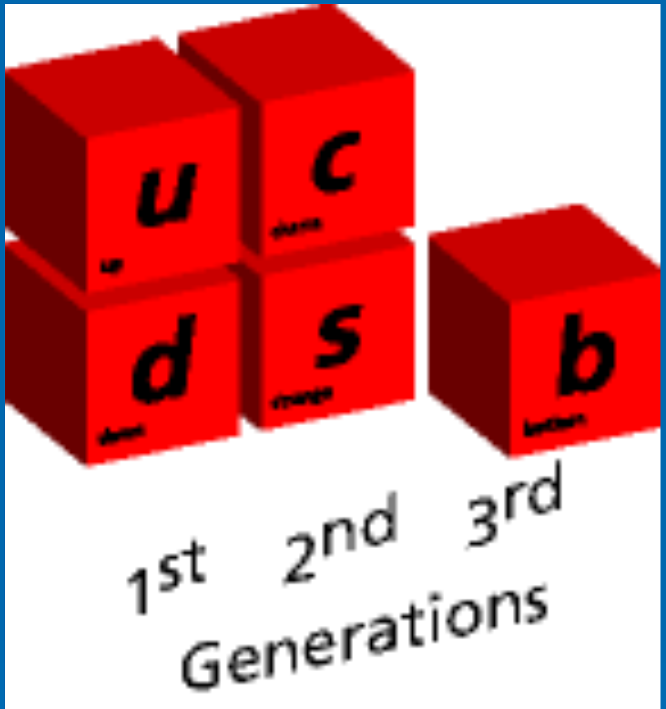


Weak Interactions

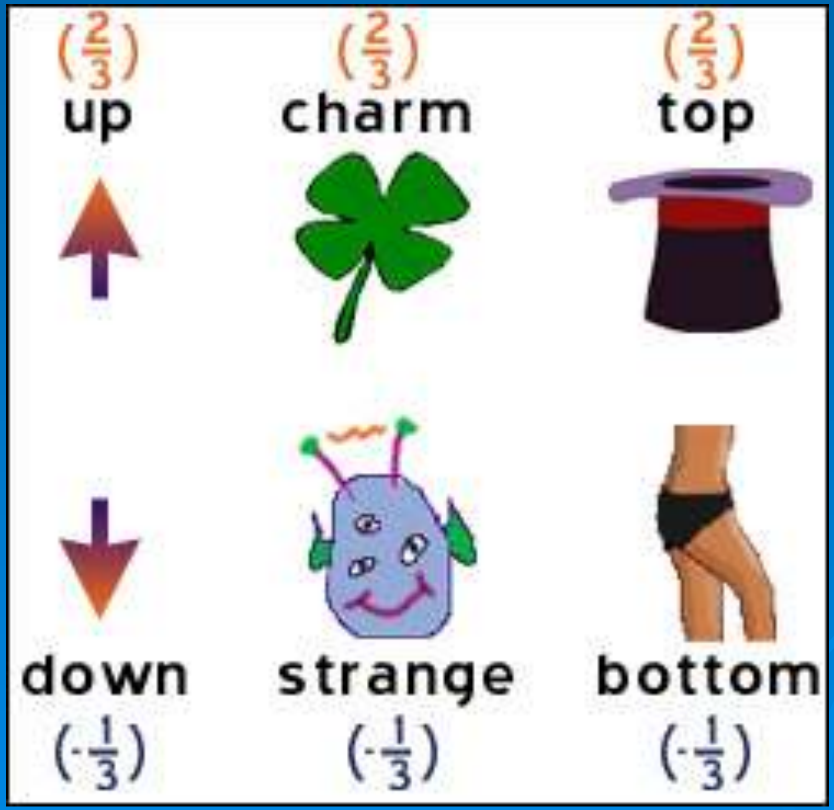
1. Performed via exchange of intermediate weak bosons W, Z
2. The fields W and Z are described by Yang-Mills eqs (generalization of Maxwell eqs)
3. The fields W, Z carry weak charge (isospin) and interact with each other
4. W, Z can be observed in free state and are massive
5. Weak interactions involve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

Quarks – “the building blocks of the Universe”

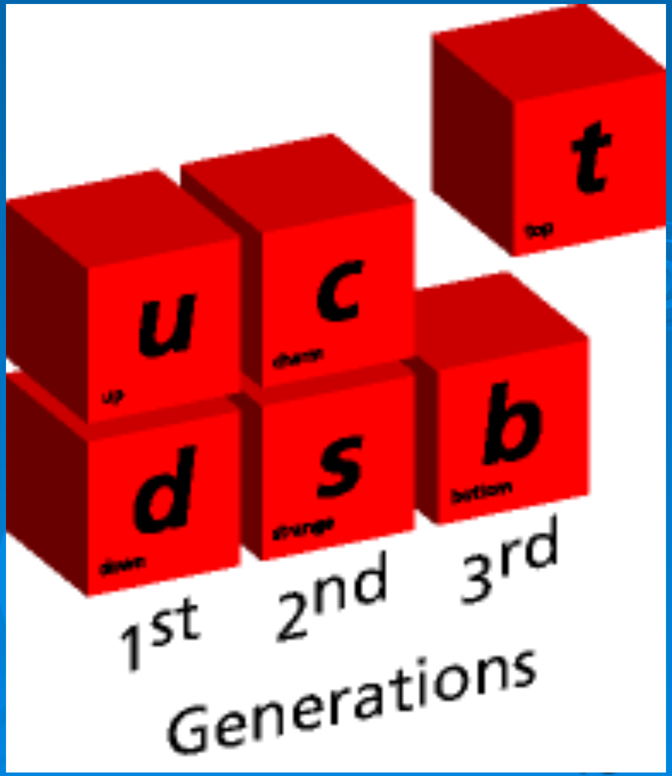
Charm came as surprise but completed the picture



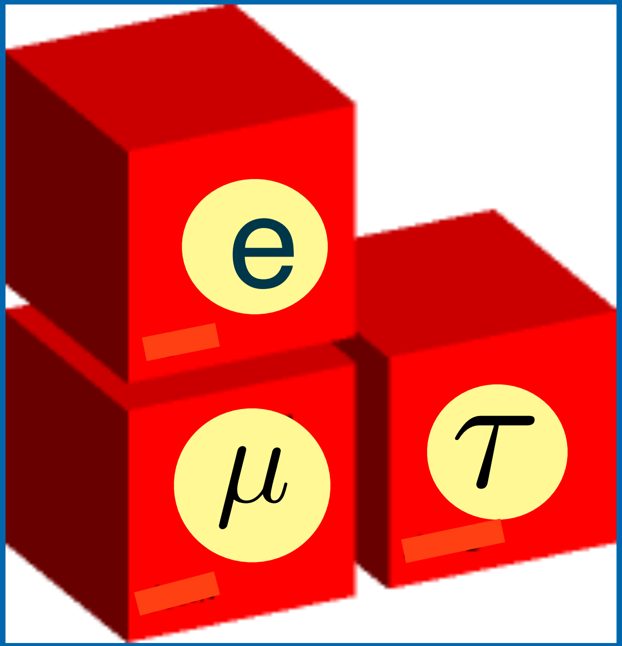
The number of quarks increased with discoveries of new particles and have reached 6

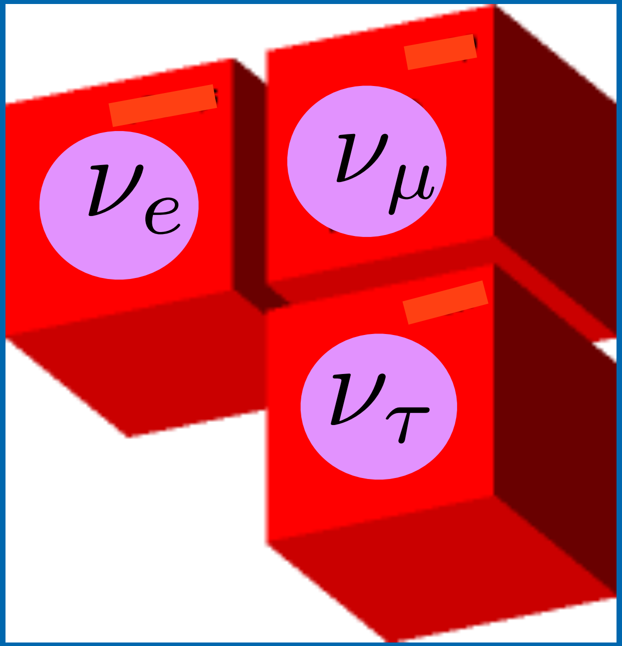


For unknown reasons Nature created 3 copies (generations) of quarks and leptons

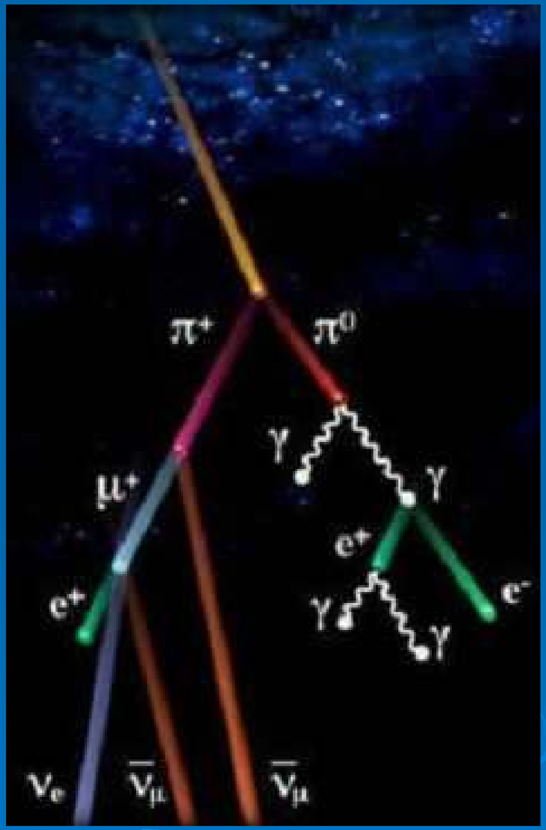


Leptons are from λεπτόσ - light





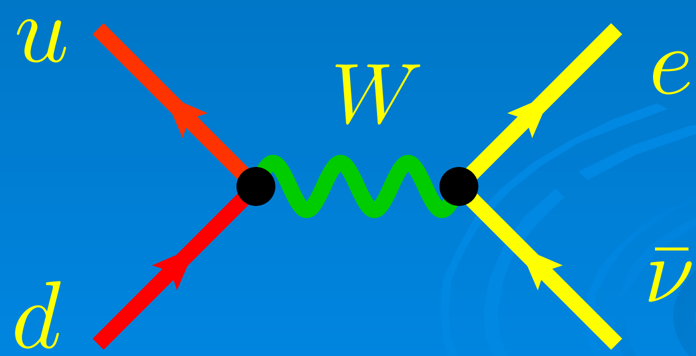
Muons are created from π-mesons decay in cosmic rays and decay into electrons and two neutrinos

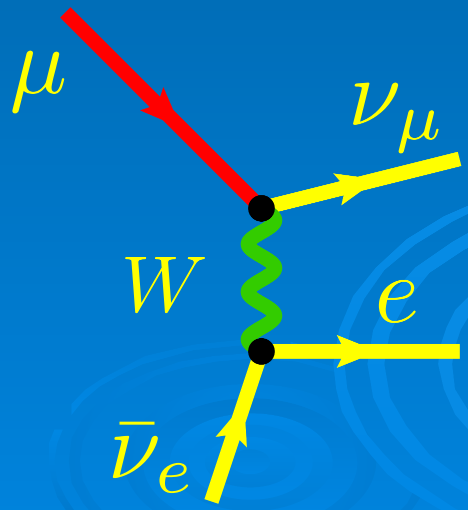


Electrons form atomic shells and define all chemistry of animated and unanimated nature

Neutrino are produced in hadron decay

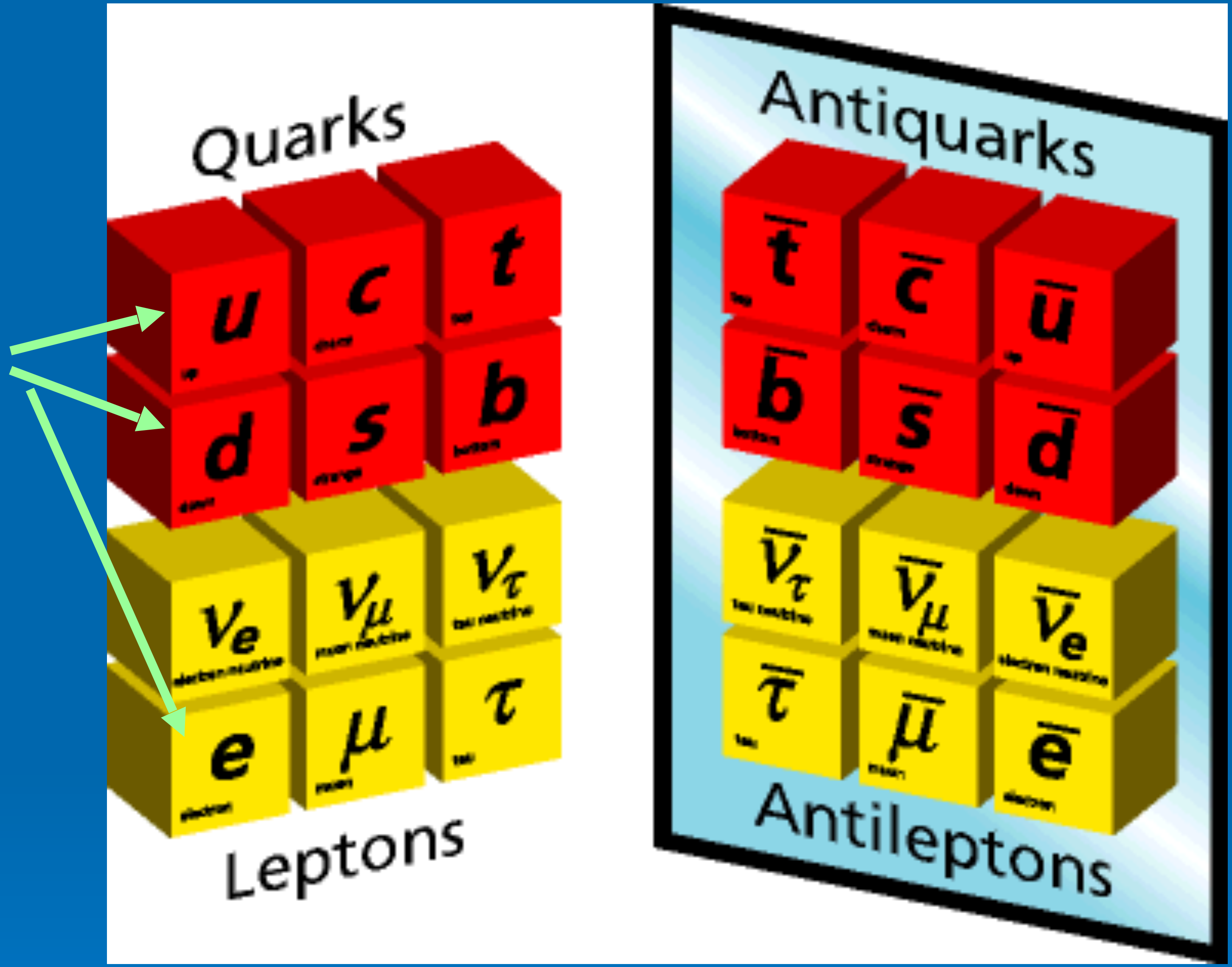
$$n(udd) \rightarrow p(uud) + e + \bar{\nu}$$





Matter and Antimatter

The first generation is what we are made of

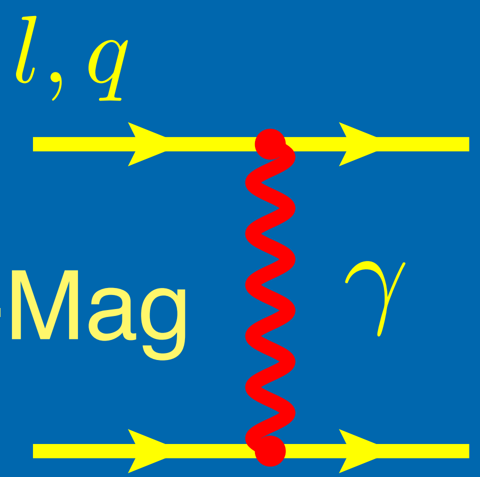


Antimatter was created together with matter during the “Big bang”

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

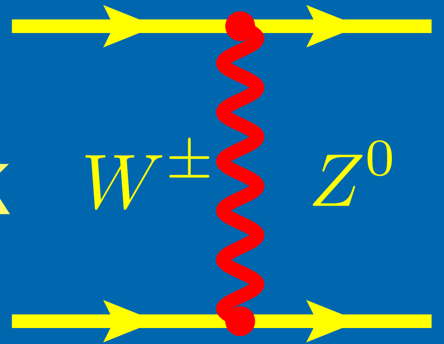
Five fundamental forces of Nature

El-Mag



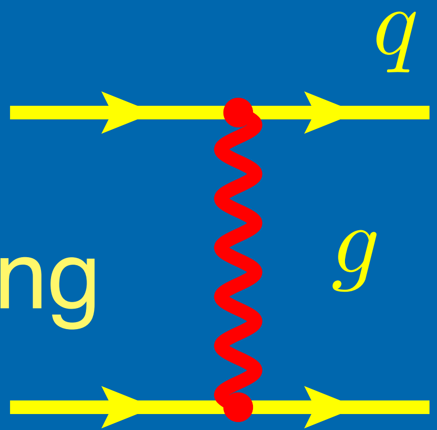
$$V(r) = -\frac{e_1 e_2}{r}$$

Weak



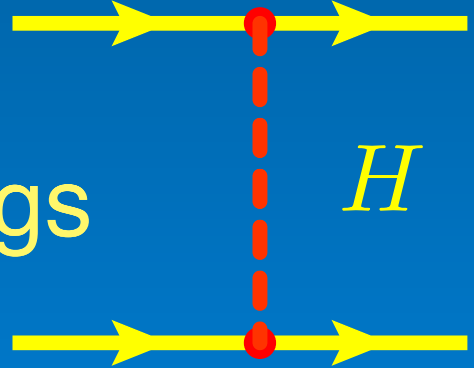
$$V(r) = -\frac{g^2}{r} e^{-M_W r}$$

Strong



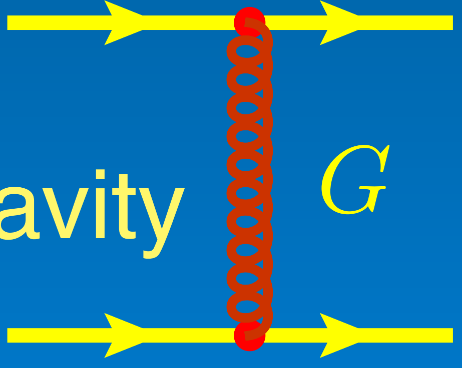
$$V(r) = -\frac{g_s^2}{r} + br$$

Higgs



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

Gravity



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

Spin

$\gamma \; W^\pm Z^0 \; g$ =1
H =0
G =2

Gauge Invariance

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

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

matrix $\quad U^+U = 1 \quad$ parameter $\quad$ matrix

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

Fermion Kinetic term

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

Covariant derivative $$\partial_\mu \to D_\mu = \partial_\mu I + g\boxed{A^a_\mu}T^a \equiv \partial_\mu I + gA_\mu$$

Gauge field

Gauge invariant kinetic term ⟶ $$\boxed{i\bar{\psi}(x)\gamma^\mu D_\mu\psi(x)}$$

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

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

Field strength tensor

Gauge field kinetic term $$\boxed{-\frac{1}{4}TrG_{\mu\nu}G^{\mu\nu}}$$

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

$SU_L(2)$

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

SU(2) doublet SU(2) singlet

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

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

$$\cancel{\bar{\psi}^{c}_L\psi_L + \bar{\psi}_L\psi^{c}_L}$$

$U_Y(1)$

$$\cancel{\bar{\psi}^{c}_R\psi_R + \bar{\psi}_R\psi^{c}_R}$$

Unless Q=0, Y=0

$$\bar{\nu}^{c}_R\nu_R$$

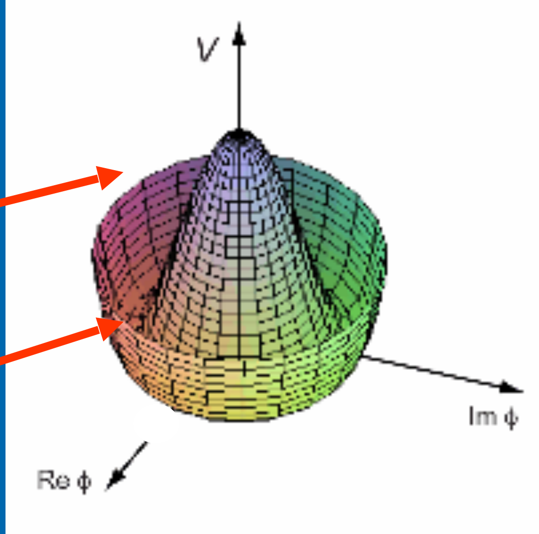
Majorana mass term

Spontaneous Symmetry Breaking

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

Introduce a scalar field with quantum numbers: (1,2,1) $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

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



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

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

The Higgs Mechanism

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_μ^i, i=1,2,3

Gauge transformation $$\widehat{W}_\mu \rightarrow e^{i\alpha^a\sigma^a}\,\widehat{W}_\mu\, e^{-i\alpha^a\sigma^a} - \tfrac{1}{g}\partial_\mu \underline{\left(e^{i\alpha^a\sigma^a}\right) e^{-i\alpha^a\sigma^a}}$$

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

Longitudinal components

Higgs field kinetic term $$\left|D_\mu H\right|^2 = \left|\partial_\mu H - \tfrac{g}{2}\widehat{W}_\mu H - \tfrac{g'}{2}\widehat{B}_\mu H\right|^2 \longleftarrow H = \begin{pmatrix} 0 \\ \mathrm{v} \end{pmatrix}$$

$$\rightarrow \tfrac{1}{4}(0\ \mathrm{v}) \begin{pmatrix} \mathrm{g}W_\mu^3 + g'B_\mu & \sqrt{2}\mathrm{g}W_\mu^- \\ \sqrt{2}\mathrm{g}W_\mu^+ & -\mathrm{g}W_\mu^3 + g'B_\mu \end{pmatrix} \begin{pmatrix} \mathrm{g}W_\mu^3 + g'B_\mu & \sqrt{2}\mathrm{g}W_\mu^- \\ \sqrt{2}\mathrm{g}W_\mu^+ & -\mathrm{g}W_\mu^3 + g'B_\mu \end{pmatrix} \begin{pmatrix} 0 \\ \mathrm{v} \end{pmatrix}$$

$$\Rightarrow \frac{g^2}{2}\mathrm{v}^2 W_\mu^+ W_\mu^- + \frac{1}{4}\mathrm{v}^2(-gW_\mu^3 + g'B_\mu)^2$$

$$M_W^2 = \tfrac{1}{2}g^2\mathrm{v}^2$$
$$M_Z^2 = \tfrac{1}{2}(g^2 + g'^2)\mathrm{v}^2$$

$$\tan\theta_W = g'/g$$
$$M_\gamma = 0$$

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

The Higgs Boson and Fermion Masses

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

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

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

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

α, β =1,2,3 - generation index

Dirac fermion mass

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

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

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

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

Cabibbo-Kobayashi-Maskawa mixing matrix

$$K = V_U^+ V_D$$

The (only) source of flavour mixing in the SM

Unitarity: $K^+K=1$

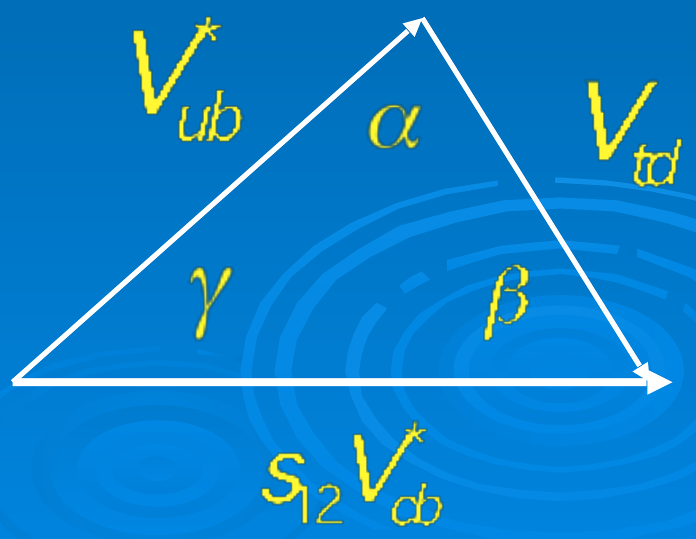
CKM Matrix and Unitarity Triangle

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

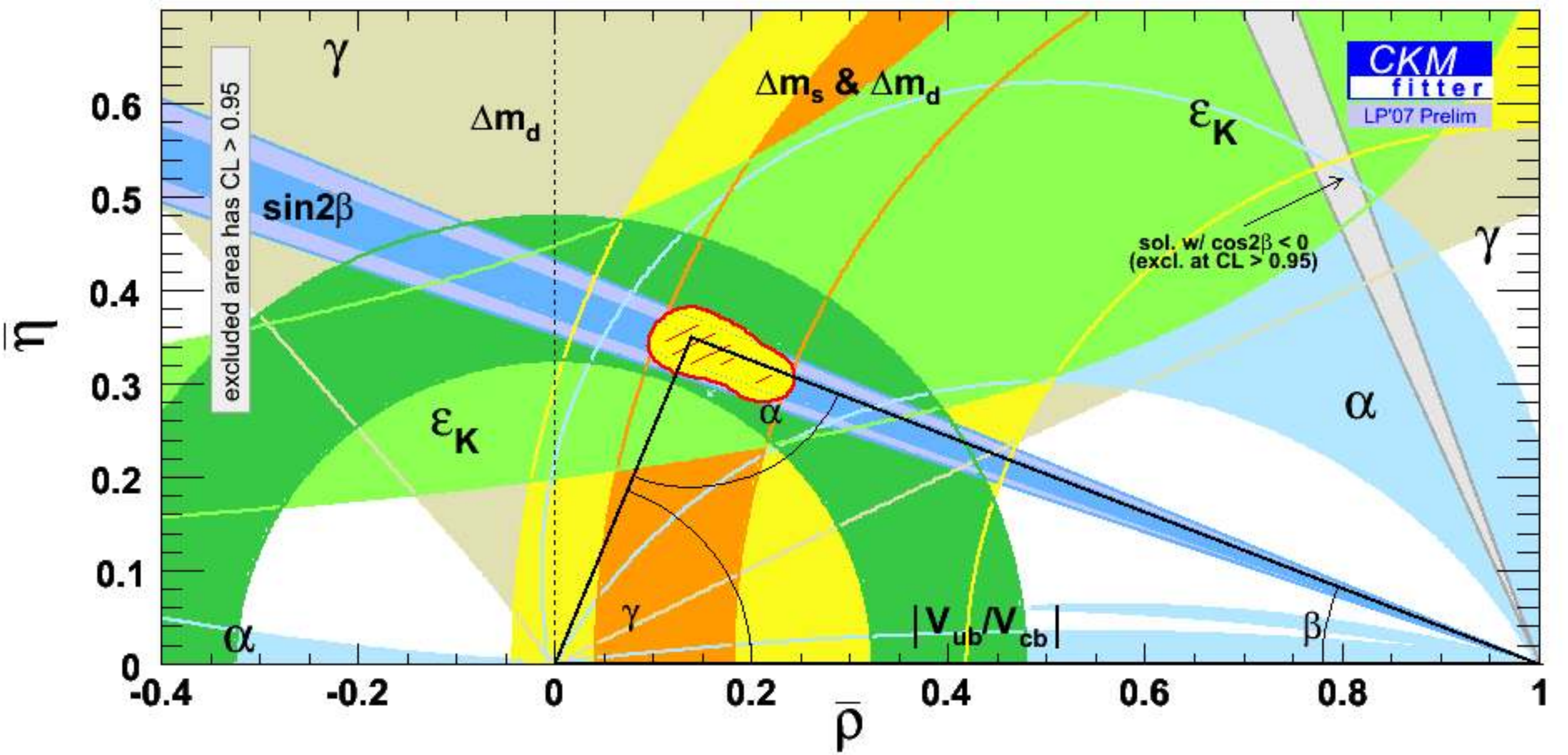
Two important properties

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

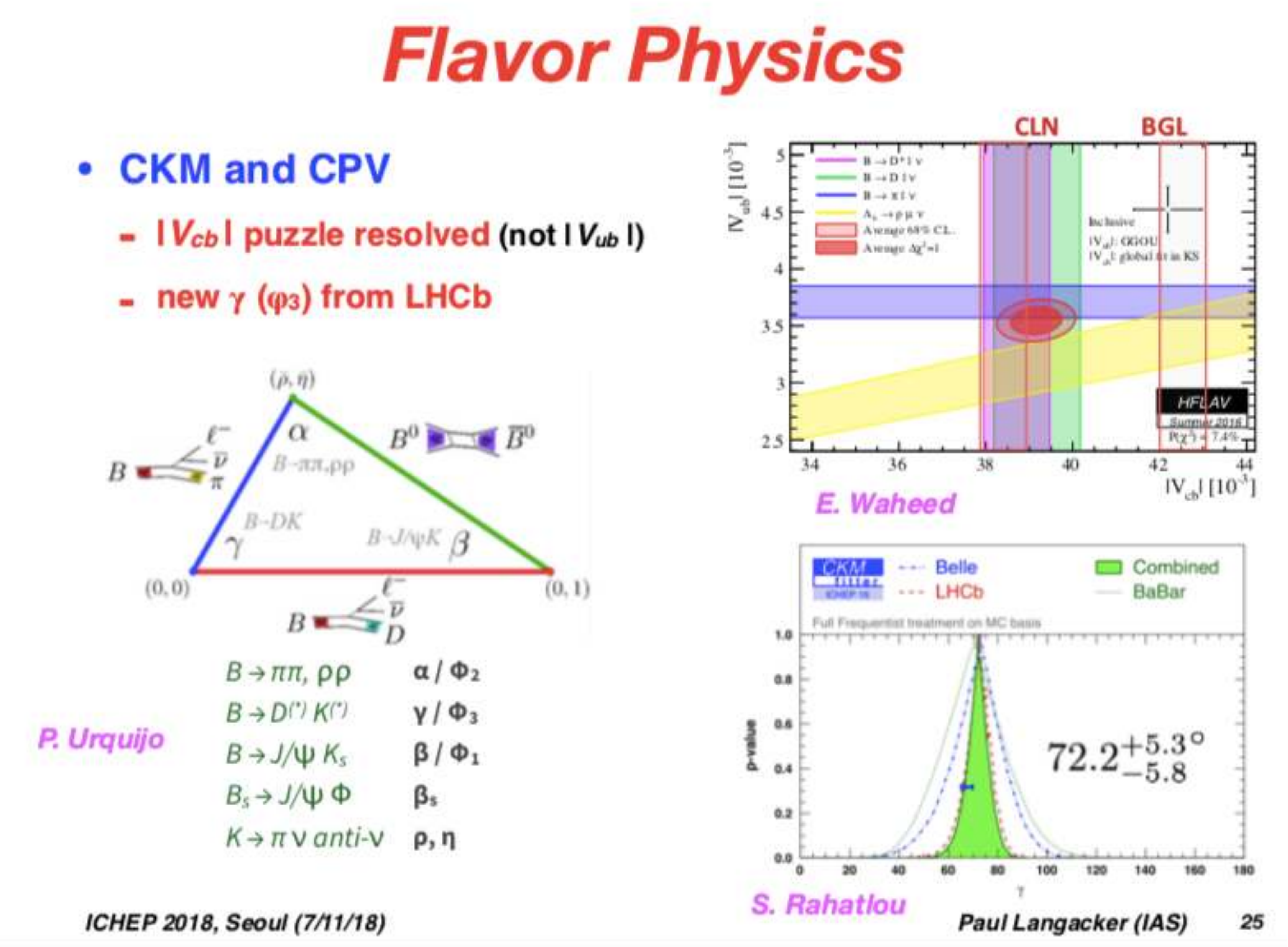
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$
$$\Rightarrow \quad V_{ub}^{*} + V_{td} = s_{12}V_{cb}^{*}$$



The Unitarity Triangle: all constraints



A consistent picture across a huge array of measurements



Flavor Physics

- **CKM and CPV**
  - $|V_{cb}|$ puzzle resolved (not $|V_{ub}|$)
  - new γ (φ_3) from LHCb

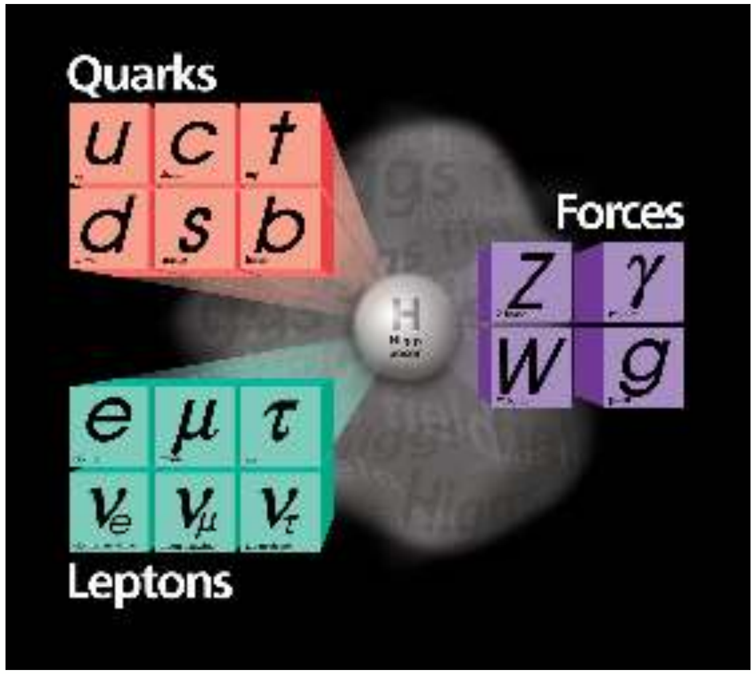
$B \to \pi\pi, \rho\rho$	α / Φ_2
$B \to D^{(*)} K^{(*)}$	γ / Φ_3
$B \to J/\psi K_S$	β / Φ_1
$B_s \to J/\psi \Phi$	β_s
$K \to \pi \nu$ anti-ν	ρ, η

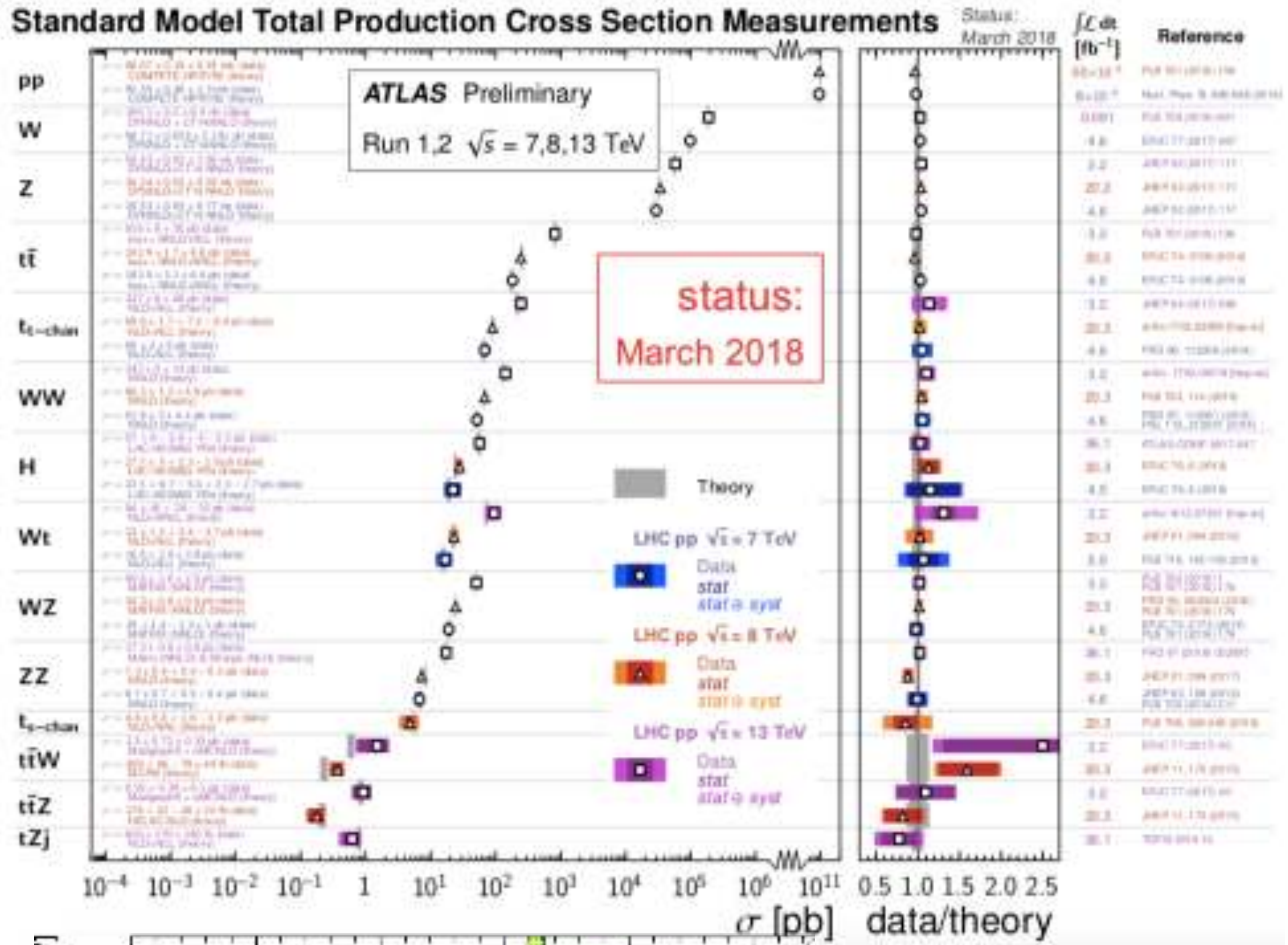
P. Urquijo

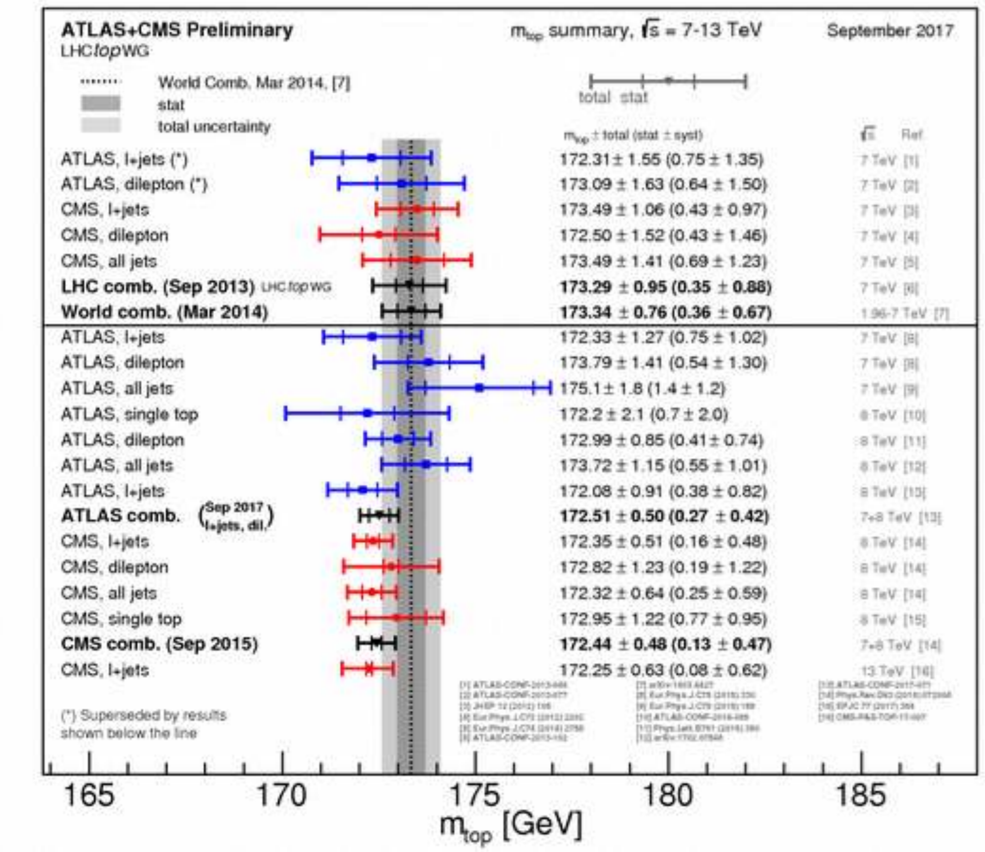
E. Waheed

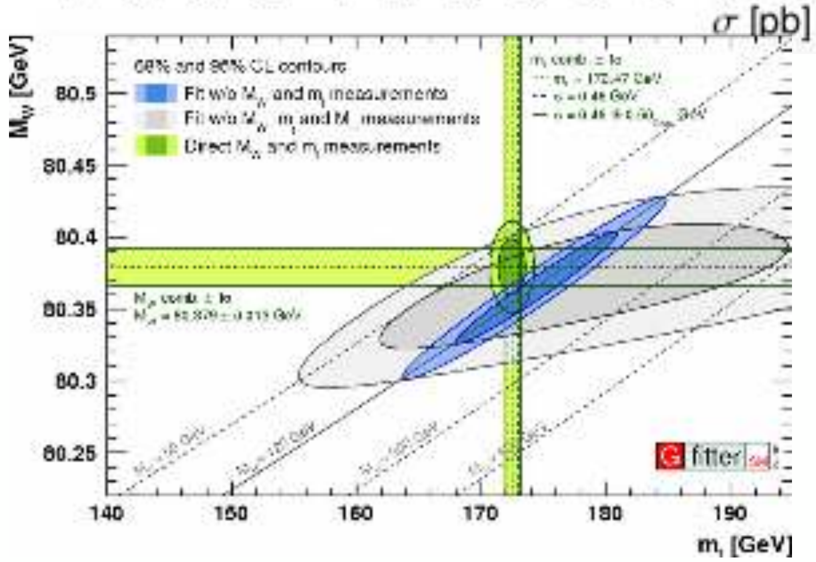
S. Rahatlou

The Standard Model









Extraordinary agreement between measurements and SM predictions

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 OPEN QUESTIONS

Why's?

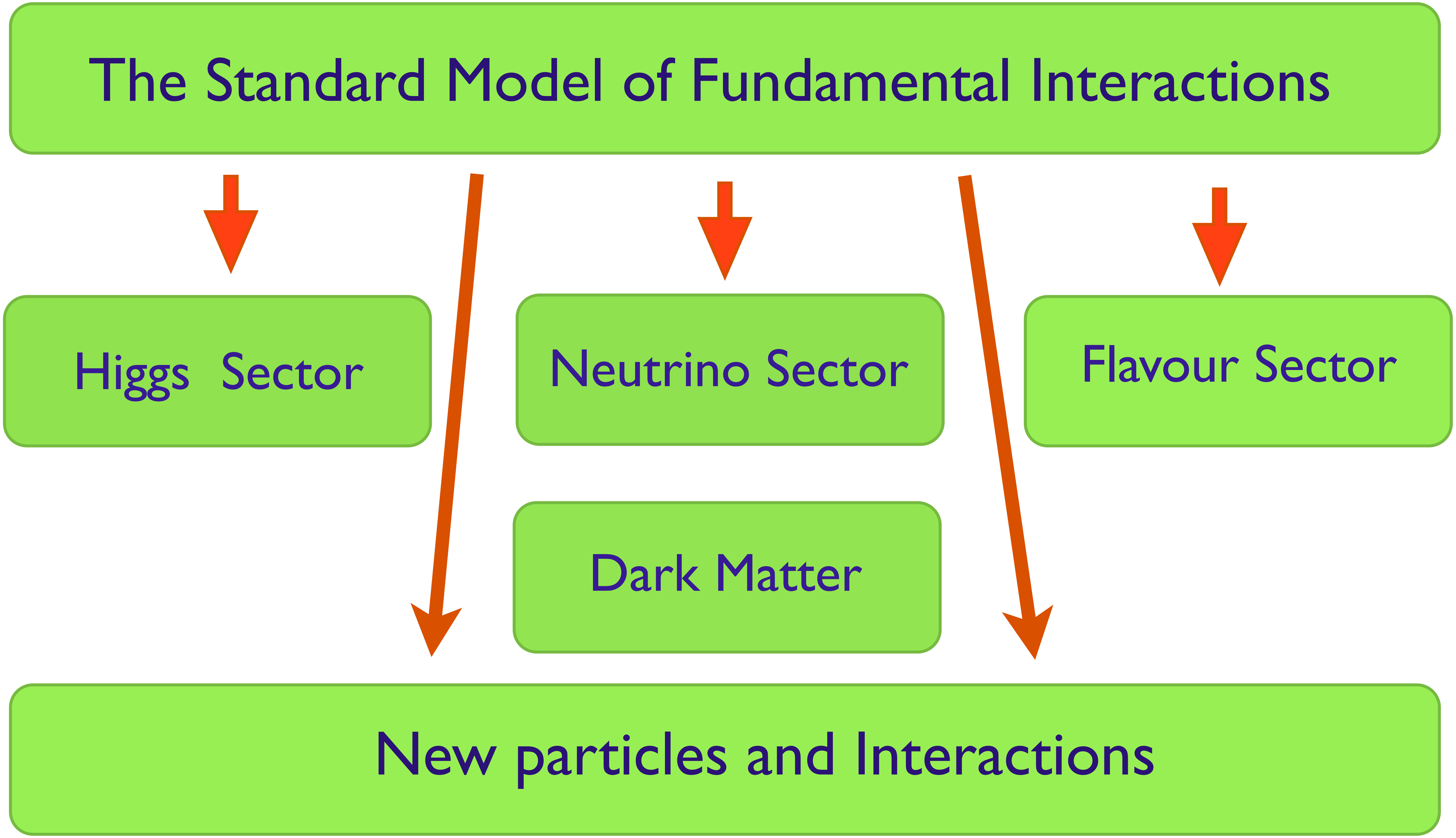
- why the SU(3)xSU(2)xU(1) ?
- why 3 generations ?
- why quark-lepton symmetry?
- why V-A weak interaction?
- why L-R asymmetry?
- why B & L conservation?
- etc

How's?

- how confinement actually works ?
- how the quark-hadron phase transition happens?
- how neutrinos get a mass?
- how CP violation occurs in the Universe?
- how to protect the SM from would be heavy scale physics?

- Is it self consistent ?
- Does it describe <u>all</u> experimental data?
- Are there <u>any</u> indications for physics beyond the SM?
- Is there another scale except for EW and Planck?
- Is it compatible with Cosmology? Where is dark matter?

THE STANDARD MODEL: THE WAYS BEYOND



The Standard Model of Fundamental Interactions

Higgs Sector

Neutrino Sector

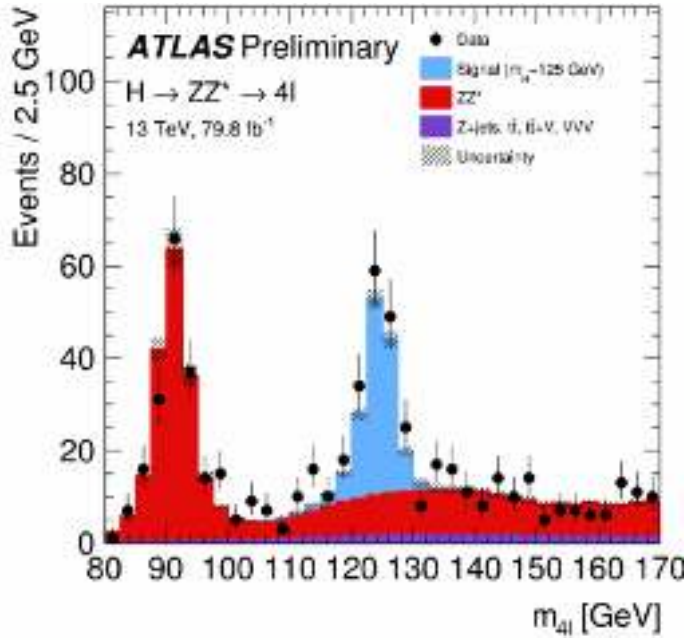
Flavour Sector

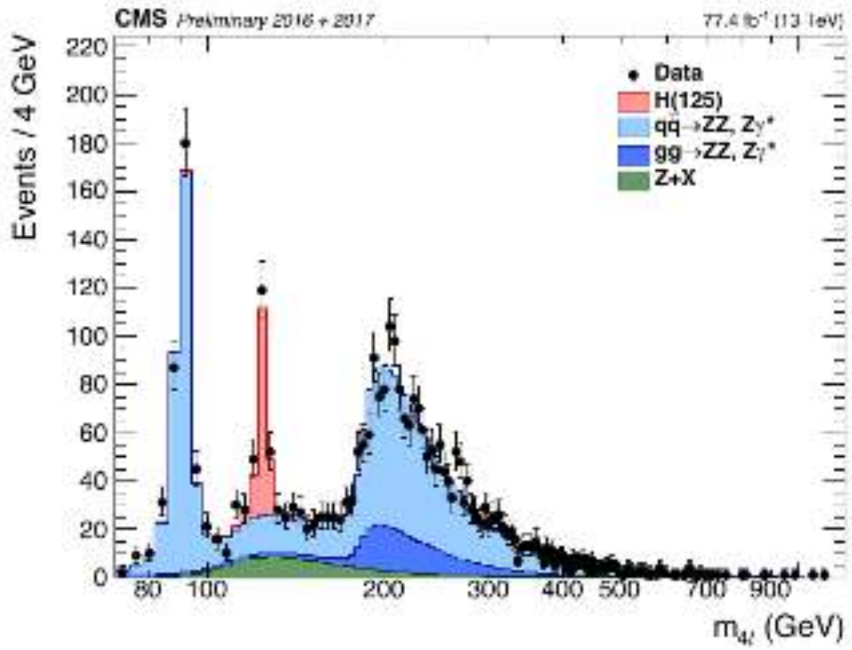
Dark Matter

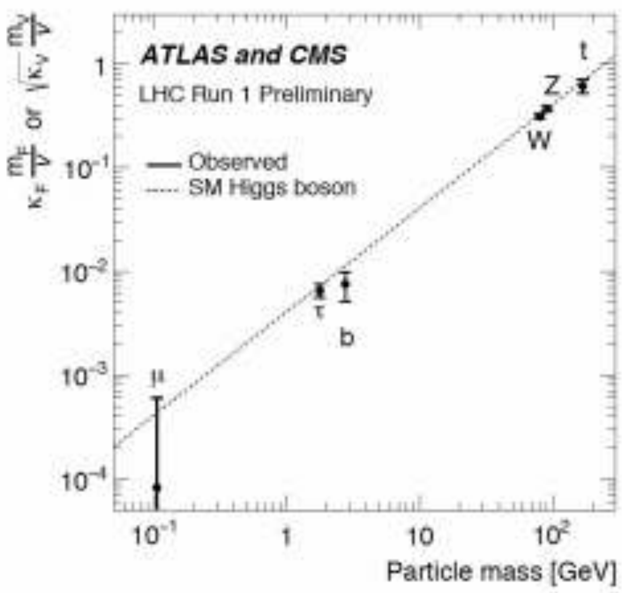
New particles and Interactions

Higgs bosons - entering precision era

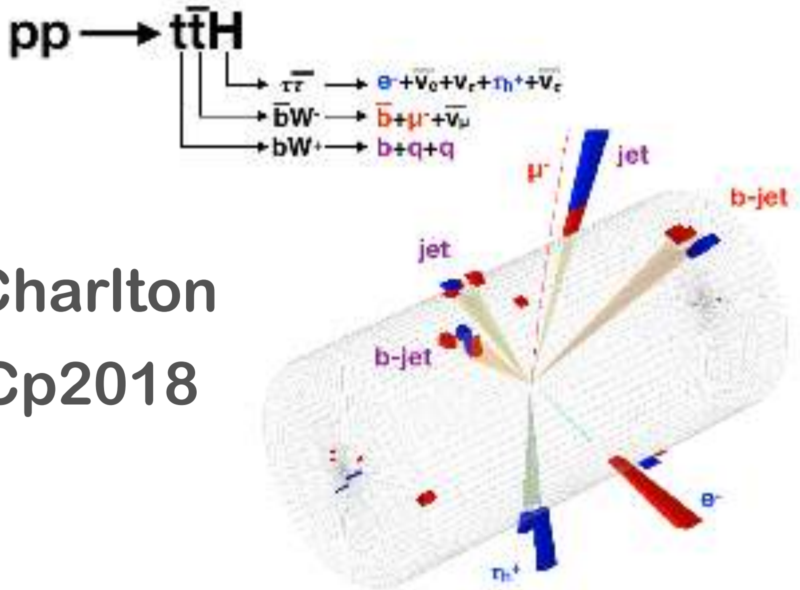
Run-2 analyses with 80 fb^{-1} for the first time – higher precision is coming!

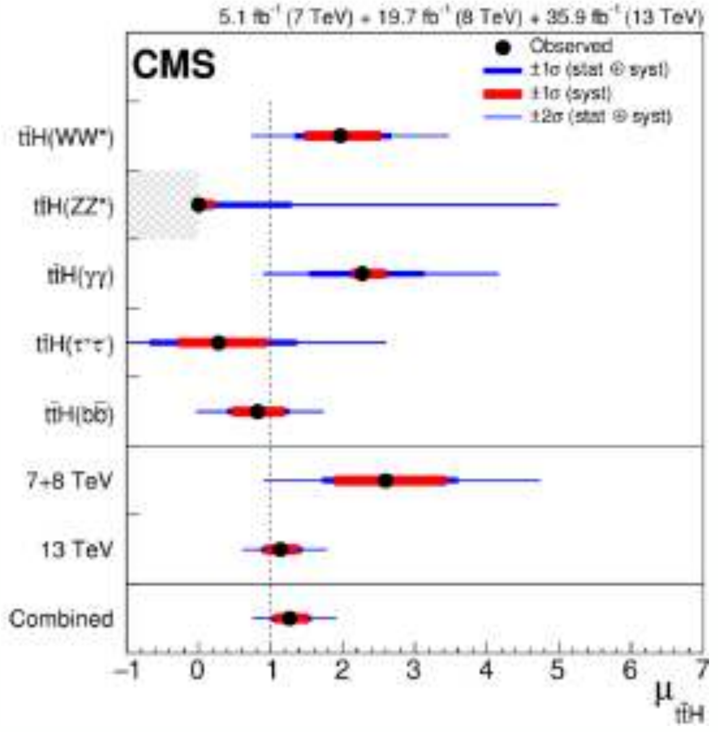


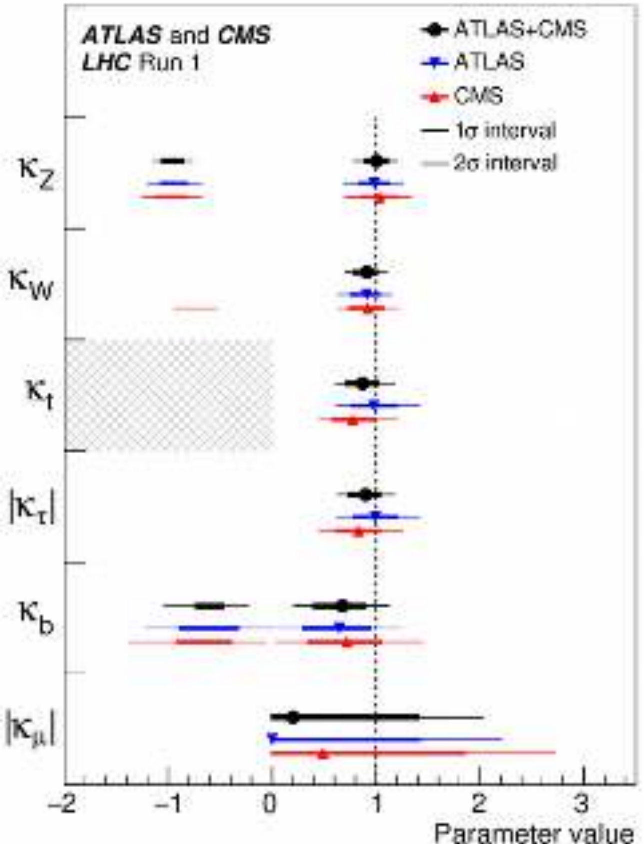




ttH observation





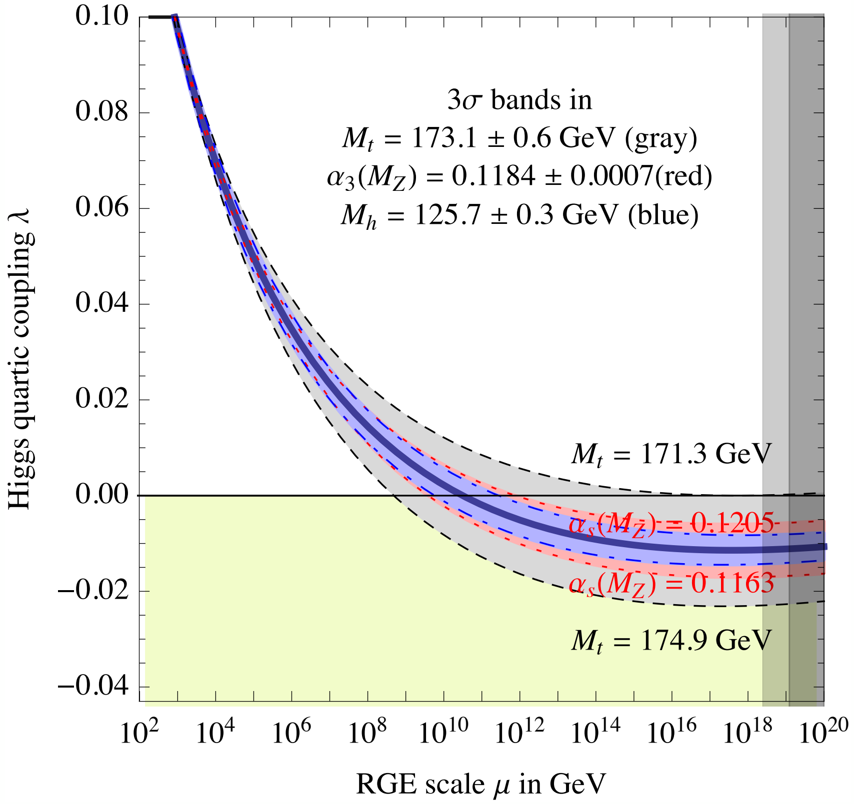


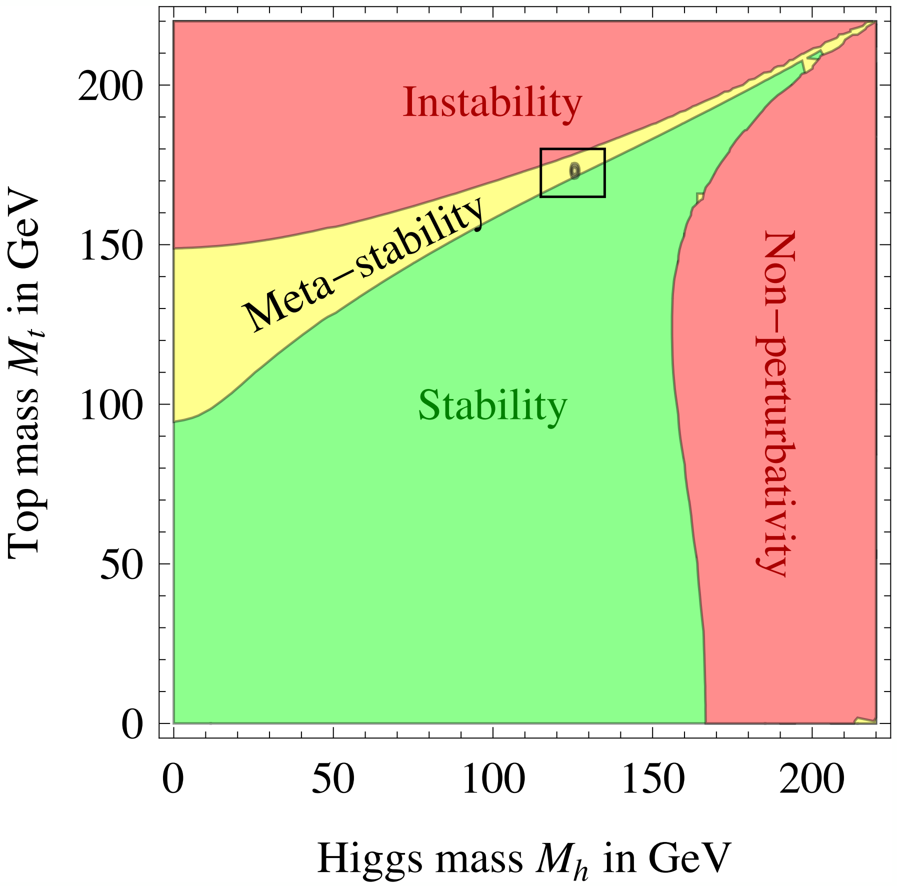
D. Charlton
LHCp2018

THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

- The electroweak vacuum is unstable under radiative corrections

- The whole construction of the SM may be in trouble being metastable or even unstable

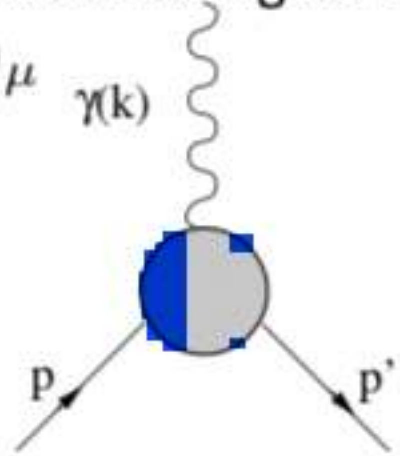




- the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and high accuracy of calculations (3 loops)

Muon anomalous magnetic moment

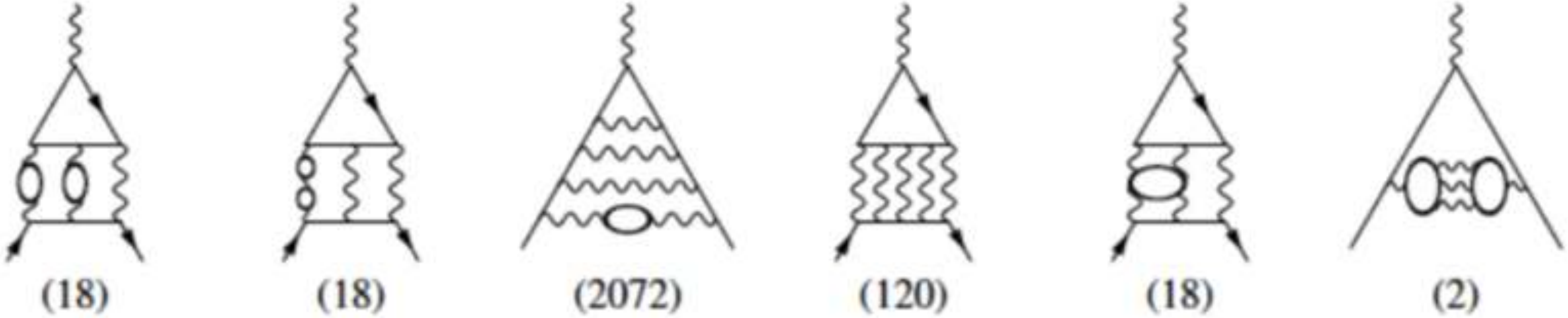
(Schwinger α/π,
Kinoshita higher orders in α)



$$ie\bar{u}_\ell(p')\left[\gamma^\mu - \frac{a_\ell}{2m_\ell}i\sigma^{\mu\nu}q_\nu\right]u_\ell(p)\epsilon^*_\mu, \qquad q_\mu = (p-p')_\mu$$

Dirac equation predicts g=2 $a = (g-2)/2$

For electron a_e theory and experiment agrees!



$$\boxed{a_\mu^{th} - a_\mu^{exp} = -(3.06 \pm 0.76) \times 10^{-8}}$$ 4 σ

Theory: uncertainty in hadronic contributions to the muon g – 2, (Jägerlehner, 1802.08019).
Lattice QCD great progress light-by-light study (RBC & UKQCD, 1801.07224).

Fermilab and J-Park experiments are expected to clarify existing discrepancy!

THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)

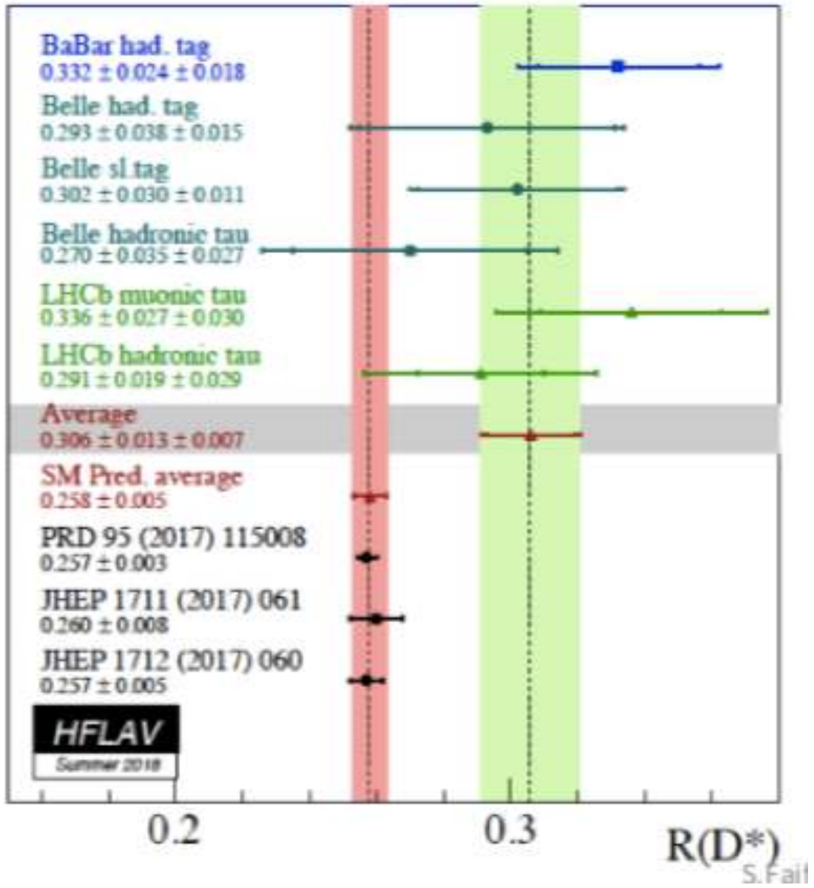
FCNC - SM loop process: $R_{K(*)}$ anomaly

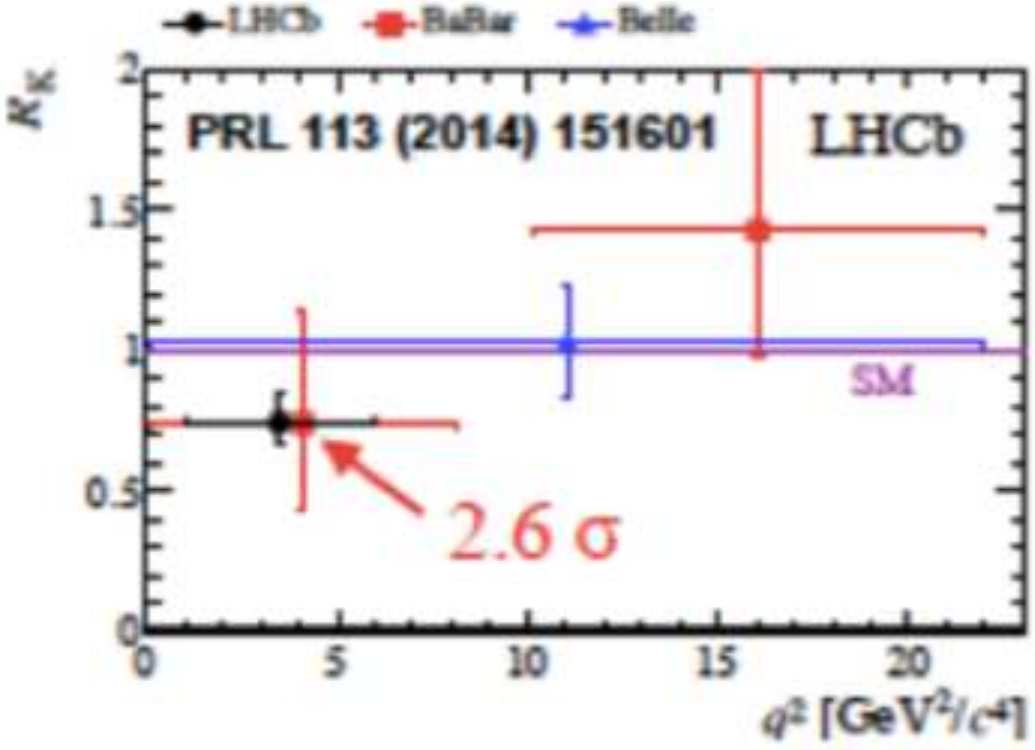
$$R_{D(*)} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$

3.8σ

$$R_{K(*)} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

3σ

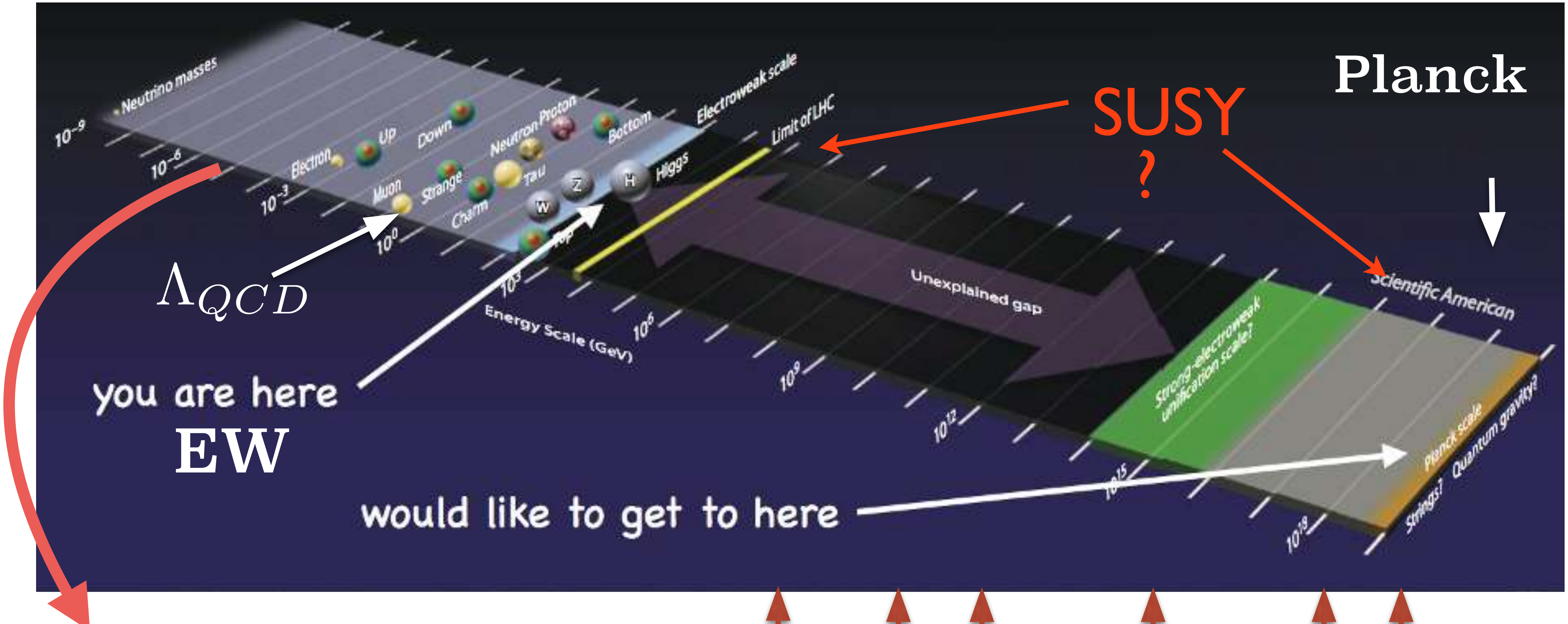




LHCb: the discrepancy present in $B_s \to \phi\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$

Discrepancy might dissolve and might as well grow up

IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANK?



Planck

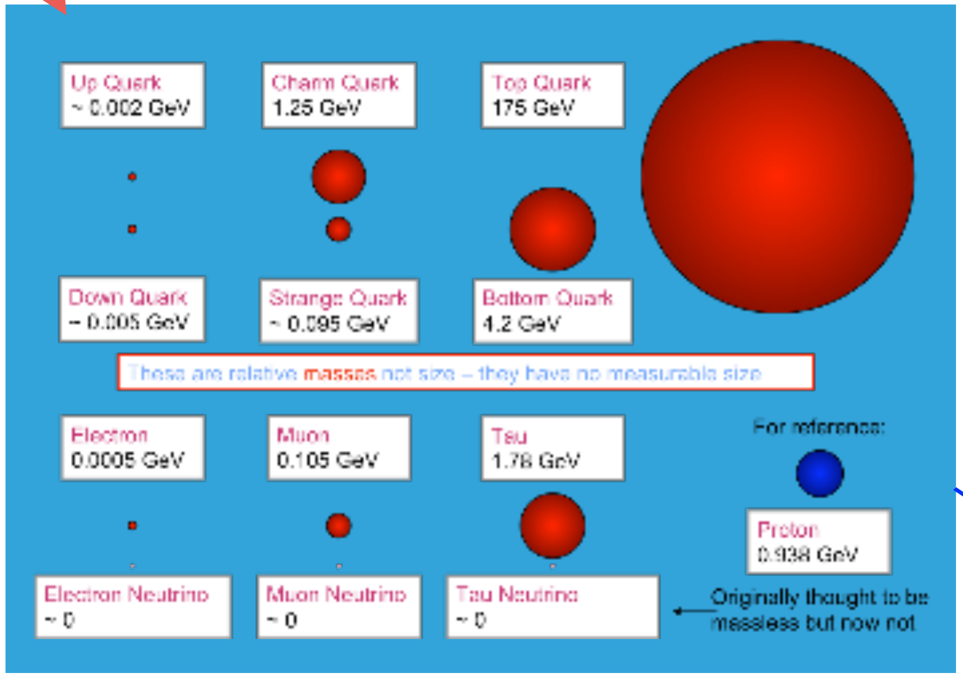
SUSY
?

Λ_{QCD}

you are here

EW

would like to get to here



?

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

?

THE WAYS BEYOND

- 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

- Additional particles: Extra generations, extra gauge bosons, extra Higgs bosons, extra neutrinos, etc

  -> may solve the problem of stability, DM

- Extra dimensions: Compact or flat extra dim

  -> Opens a whole new world of possibilities, may solve the problem of stability and the hierarchy problem, gives new insight into gravity

- 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

$$
\begin{aligned}
&[P_\mu, P_\nu] = 0,\\
&[P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),\\
&[M_{\mu\nu}, M_{\rho\sigma}] = i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho})
\end{aligned}
$$

Super Poincare Algebra $Q_i, \ \bar{Q}_i$

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0,$$

$$[Q^i_\alpha, M_{\mu\nu}] = \tfrac{1}{2}(\sigma_{\mu\nu})_\alpha^\beta Q^i_\beta, \qquad [\bar{Q}^i_{\dot\alpha}, M_{\mu\nu}] = -\tfrac{1}{2}\bar{Q}^i_{\dot\beta}(\bar{\sigma}_{\mu\nu})^{\dot\beta}_{\dot\alpha},$$

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

$$\{Q^i_\alpha, Q^j_\beta\} = 2\epsilon_{\alpha\beta}Z^{ij}, \qquad Z^{ij} = Z^+_{ij},$$

$$\{\bar{Q}^i_{\dot\alpha}, \bar{Q}^j_{\dot\beta}\} = -2\epsilon_{\dot\alpha\dot\beta}Z^{ij}, \qquad [Z_{ij}, anything] = 0,$$

$$\alpha, \dot\alpha = 1, 2 \qquad i, j = 1, 2, \ldots, N.$$

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
# of states	1	1	1	1

(λ, A_μ)

spinor vector

Members of a supermultiplet are called **superpartners**

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

$$\boxed{N \le 4S} \leftarrow \text{spin}$$

$N \le 4$ For renormalizable theories (YM)

$N \le 8$ 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

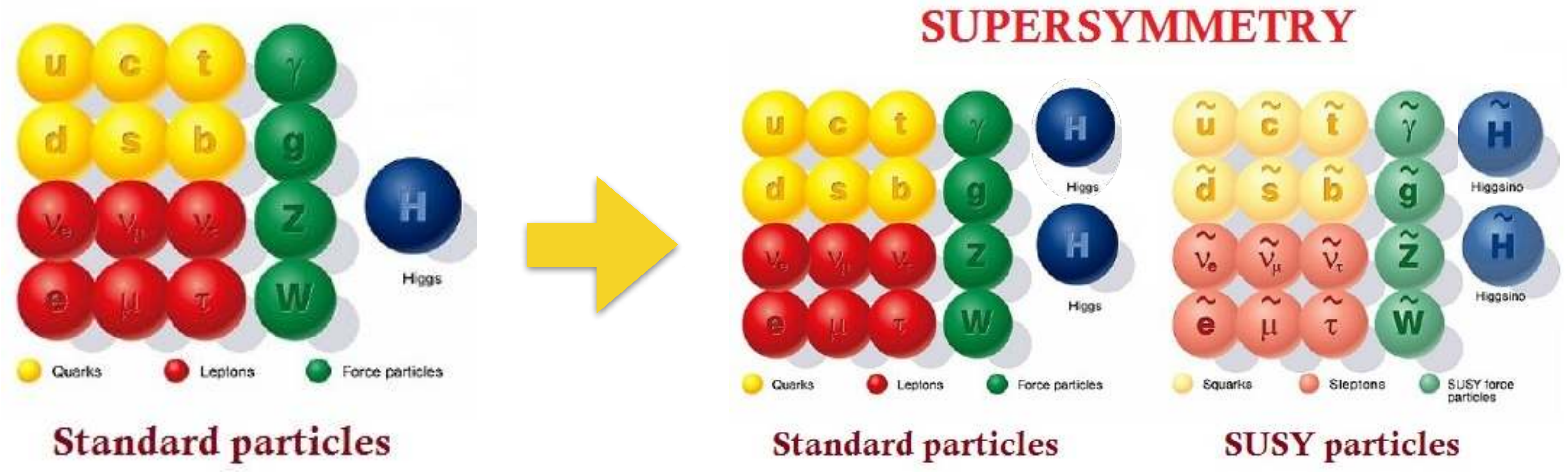
vector

gravitino

graviton

MOTIVATION FOR SUSY IN PARTICLE PHYSICS

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



Why SUSY?

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

- Unification with gravity!

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

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

Local supersymmetry = general relativity !

THE R-PARITY

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

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

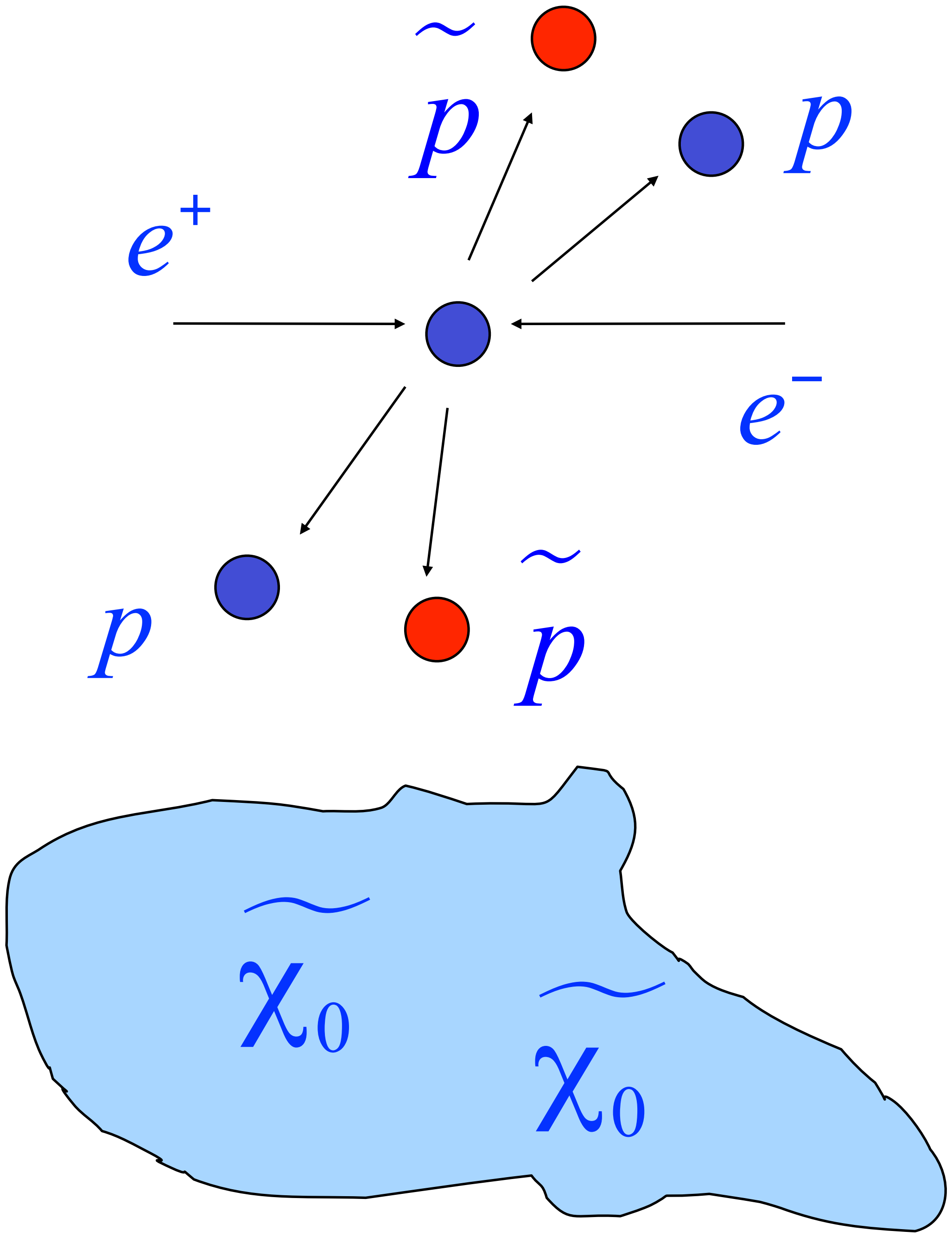
B - Baryon Number
L - Lepton Number
S - Spin

The consequences:

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

⇓

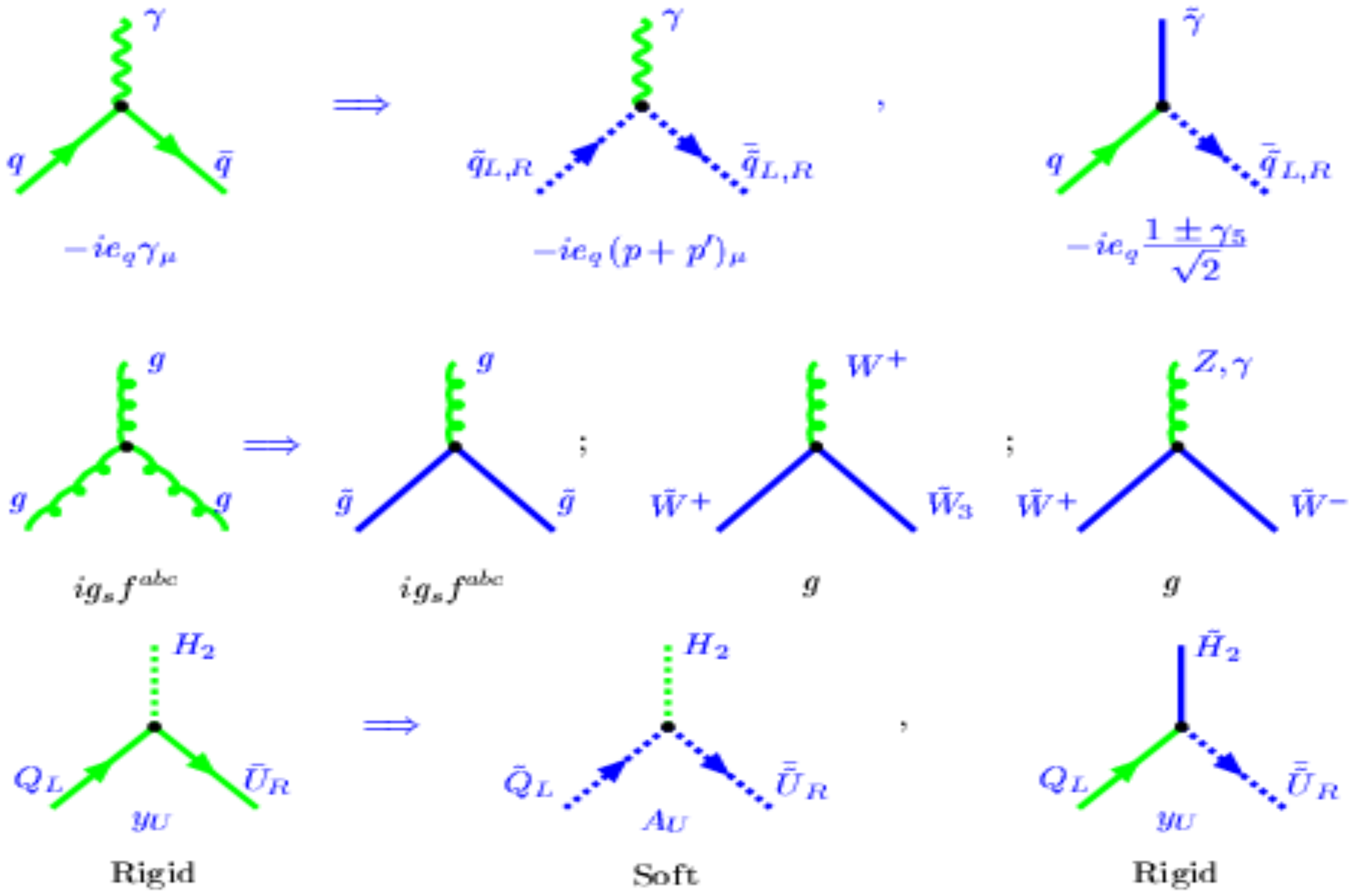
- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\tilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe



THE INTERACTIONS IN THE MSSM

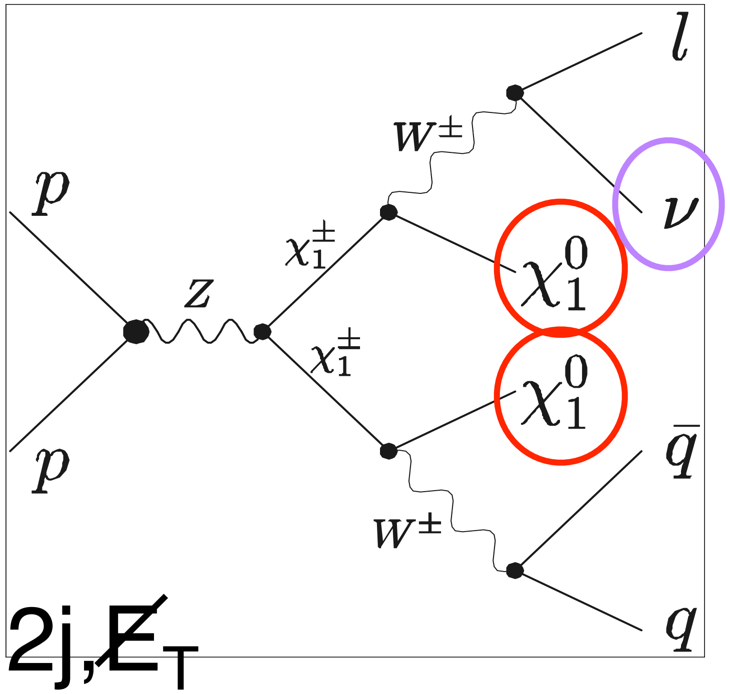
SM → **MSSM**

Vertices

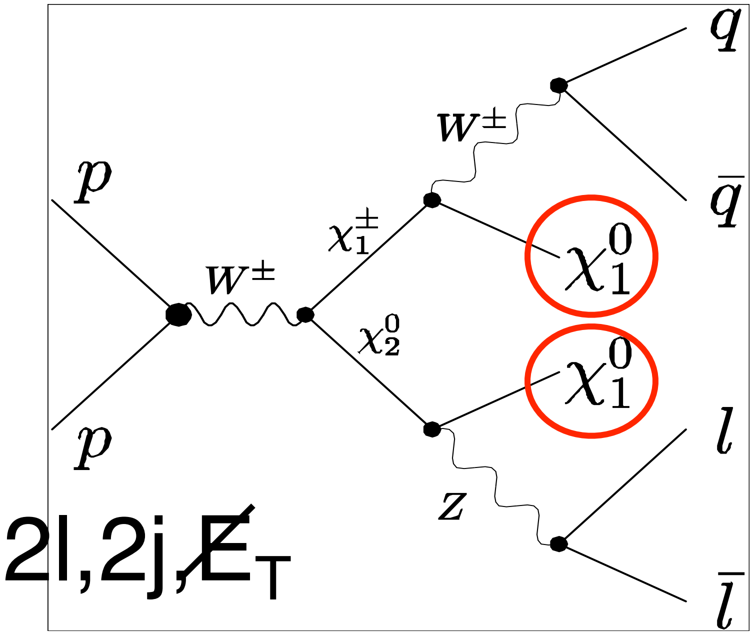


CREATION AND DECAY OF SUPERPARTNERS IN CASCADE PROCESSES @ LHC

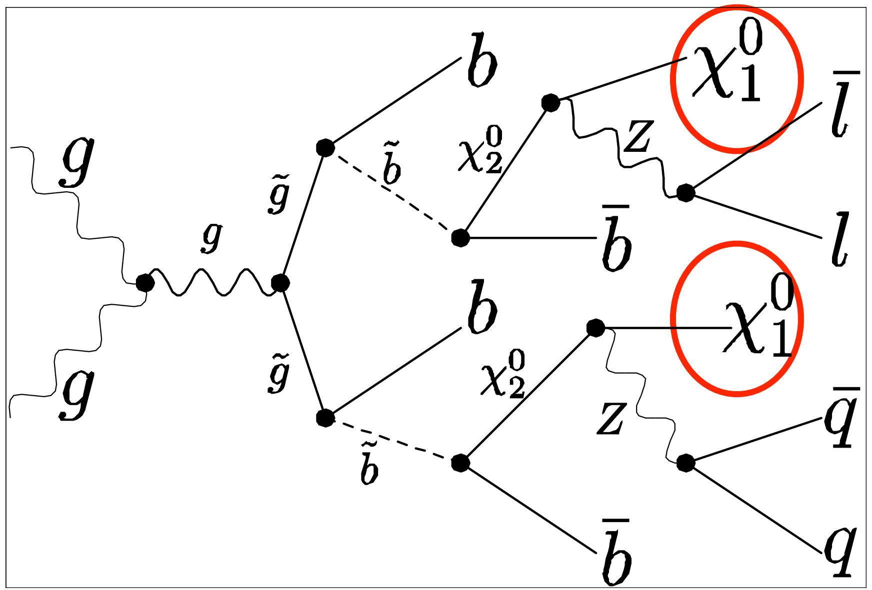
weak int's



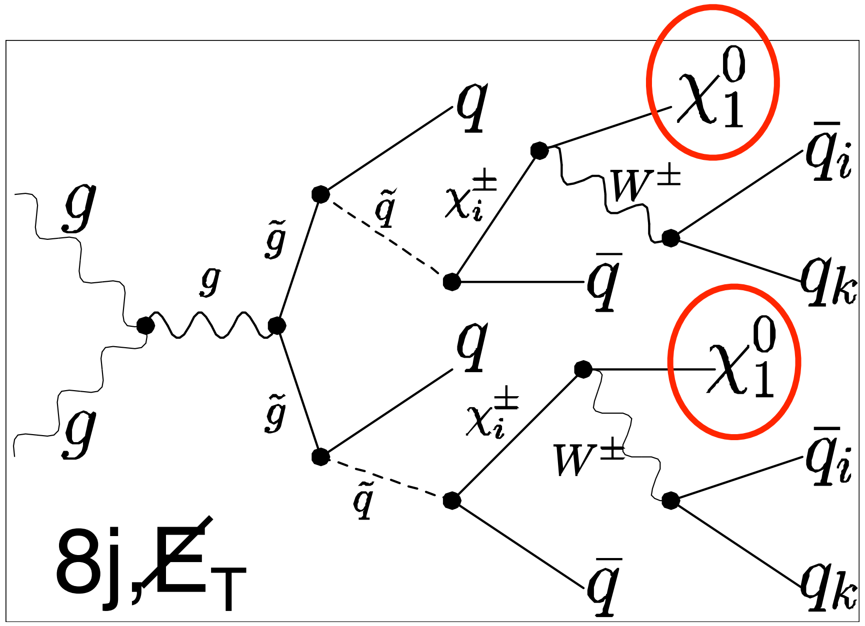
l,2j,$\not{E}_T$



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

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

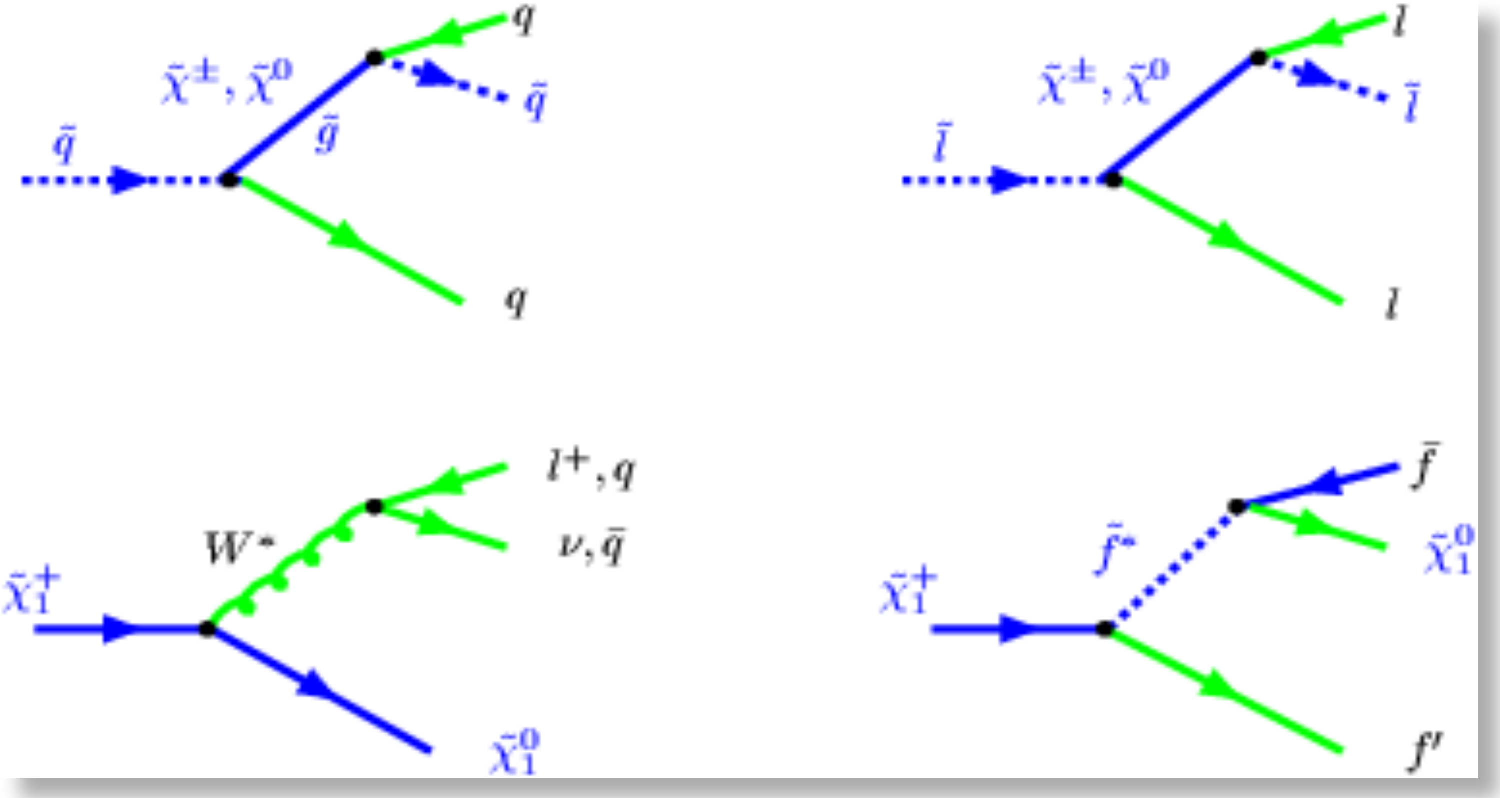
$$\tilde{\chi}_i^\pm \rightarrow e + \nu_e + \tilde{\chi}_i^0$$

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

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

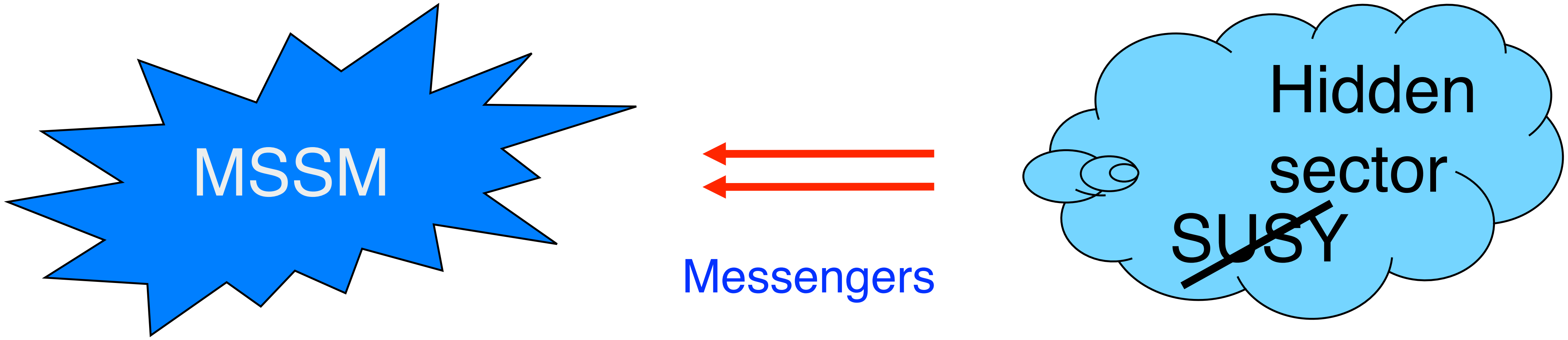
$$l^+ l^- + \not{E}_T$$

$$2 \text{ jets } + \not{E}_T$$

$$\gamma + \not{E}_T$$

$$\not{E}_T$$

SOFT SUSY BREAKING



MSSM

Messengers

Hidden sector ~~SUSY~~

Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

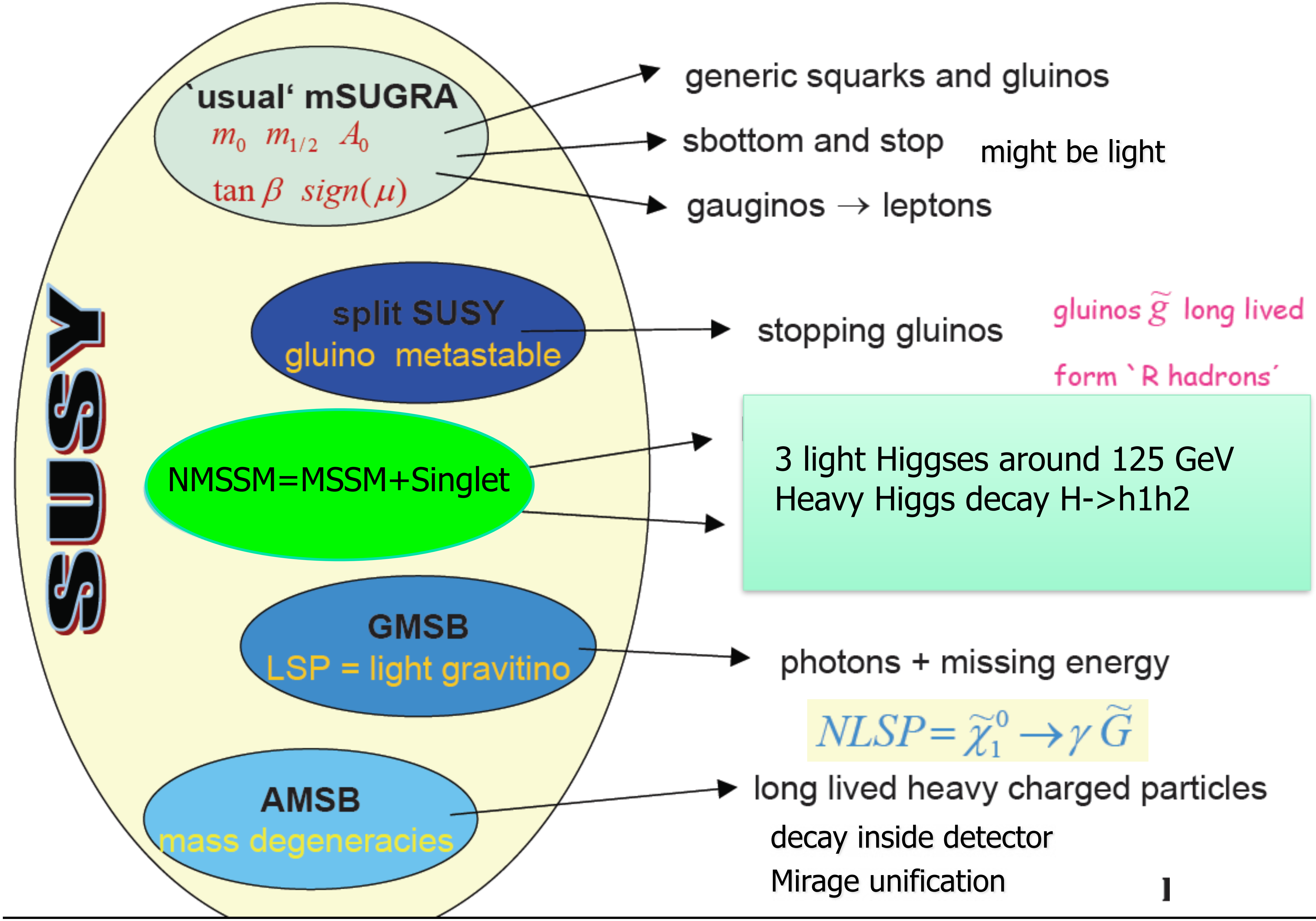
$$-L_{Soft} = \sum_{\alpha} M_i \widetilde{\lambda}_i \widetilde{\lambda}_i + \sum_i m_{0i}^2 \, | A_i |^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{ij} A_i A_j$$

gauginos

scalar fields

Over 100 of free parameters !

SUSY Models and Signatures



SUSY

`usual' mSUGRA

m_0 $m_{1/2}$ A_0

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

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'

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

mass degeneracies

long lived heavy charged particles

decay inside detector

Mirage unification

SEARCH FOR SUSY MANIFESTATION

Particle Phys

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

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

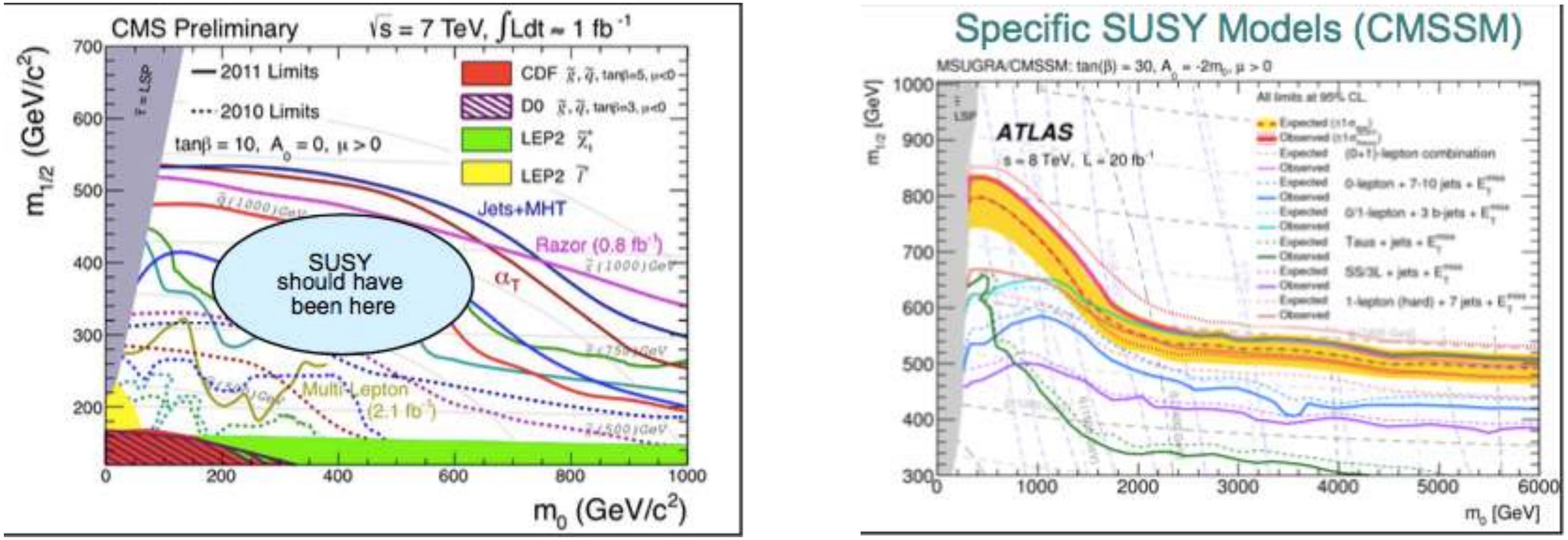
  g-2 of the muon
- Search for long-lived SUSY particles

Astro Phys (if SUSY DM)

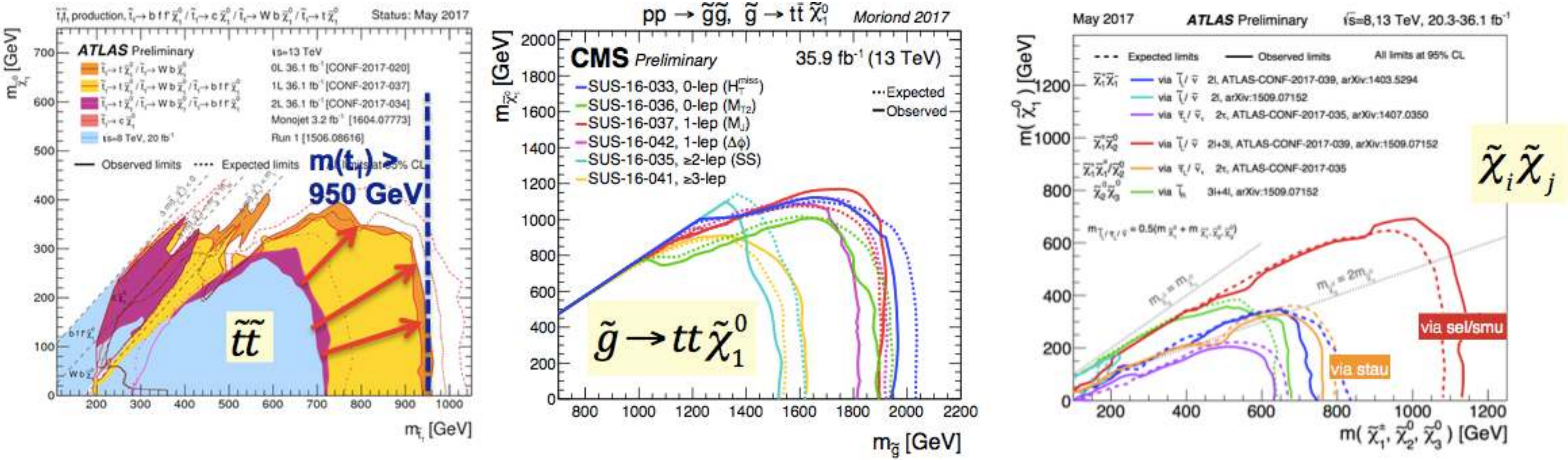
- Relic abundancy of Dark Matter in the Universe
- DM annihilation signal in cosmic rays
- Direct DM interaction with nucleons

Nothing so far ...

WHAT IS THE LHC REACH NOW?



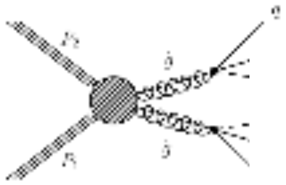
Universal parameters



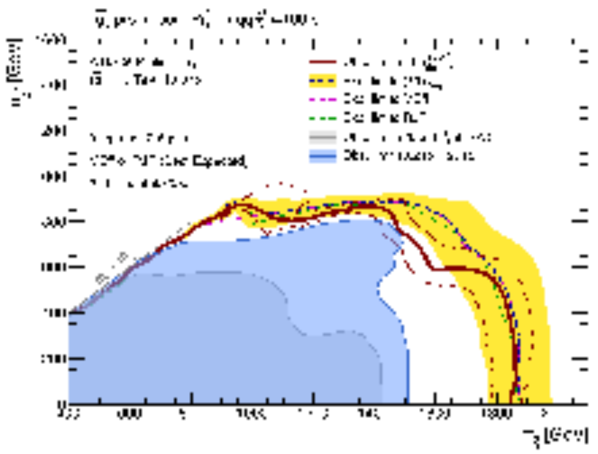
Masses of superpartners

SUPERSYMMETRY @ LHC

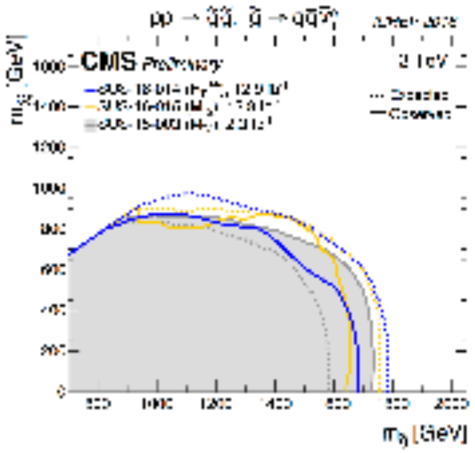
Gluino decays to qq+LSP



Summary of decays to light quarks + LSP

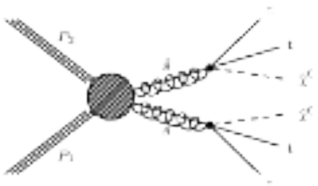


ATLAS-CONF-2016-078



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

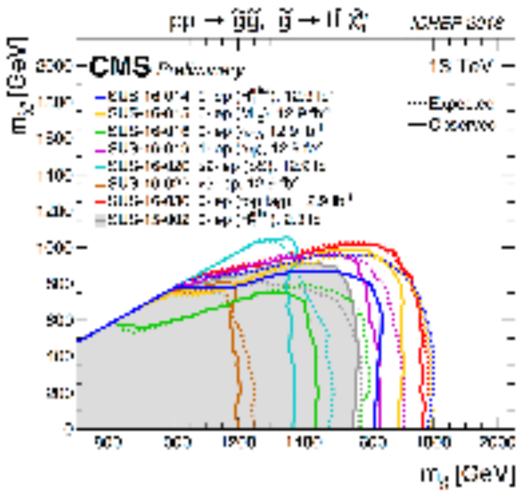
Gluino decays to tt+LSP

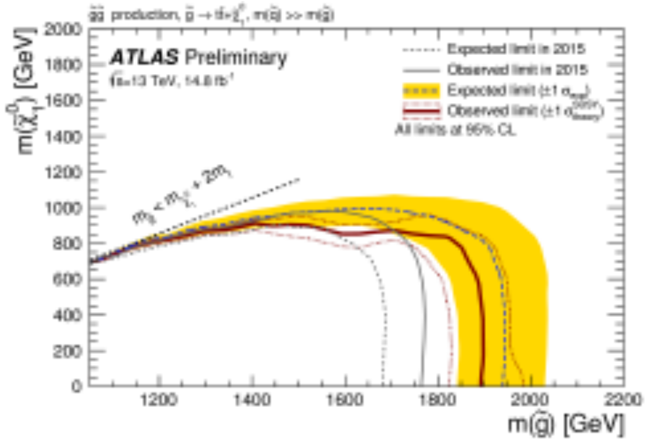


CMS summary

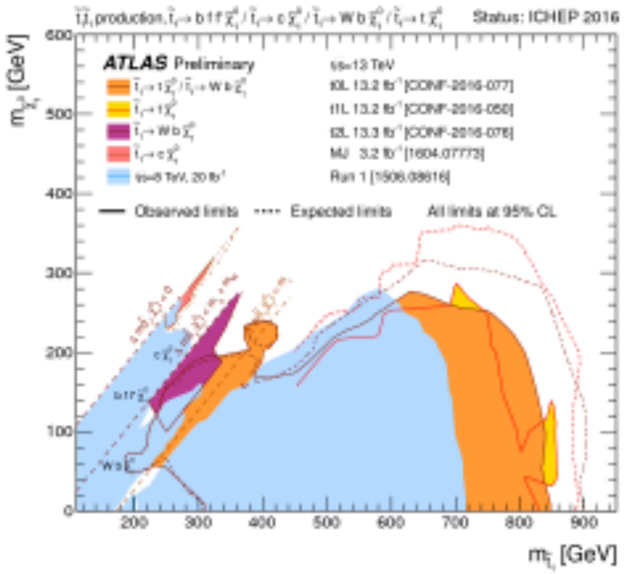
ATLAS multi-b

ATLAS-CONF-2016-052

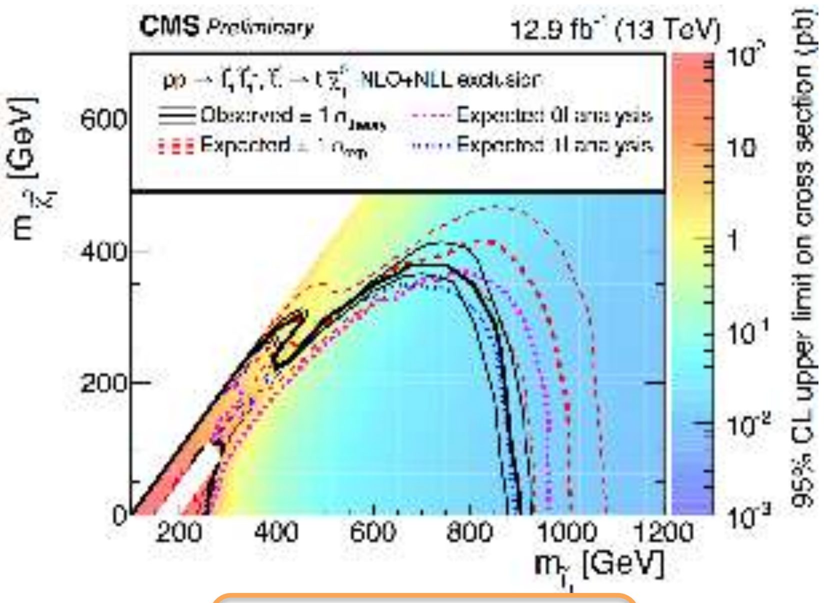




Top squarks - summaries



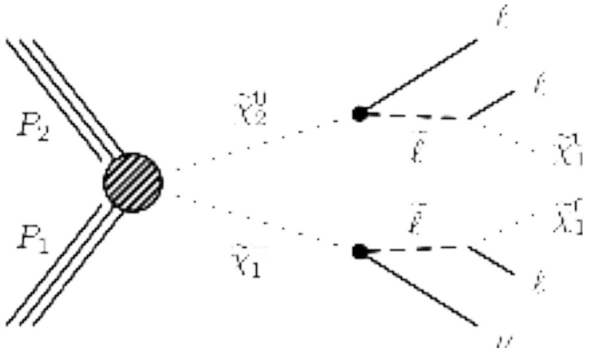
ATLAS summary



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

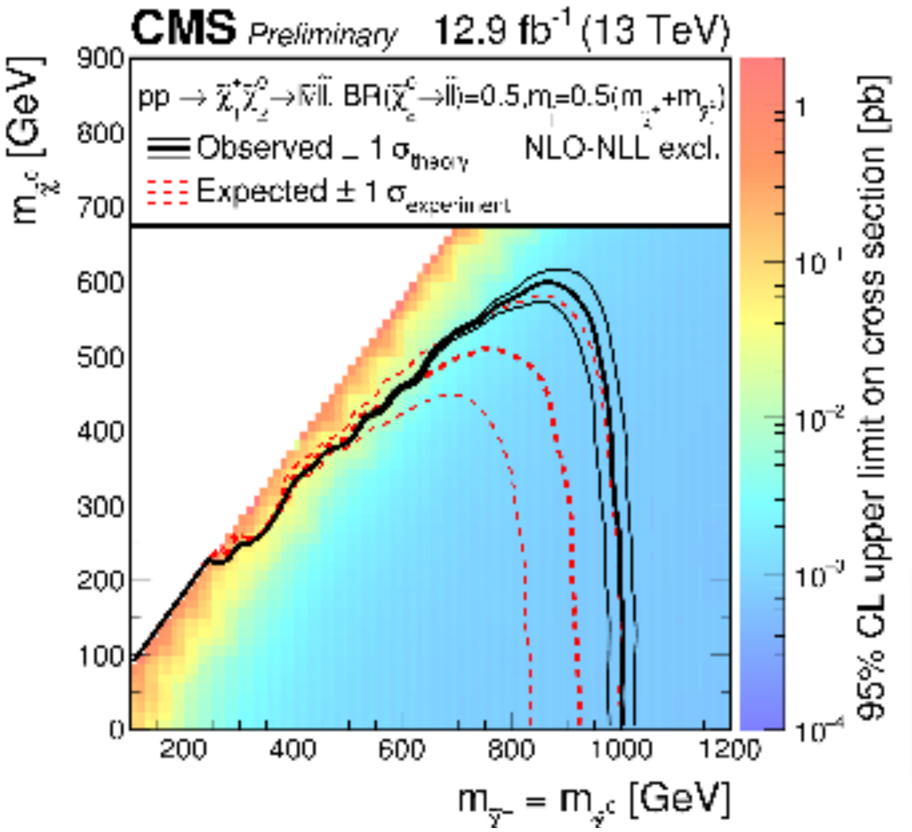
Chargino / neutralino production



Direct production of “electroweakino” pairs

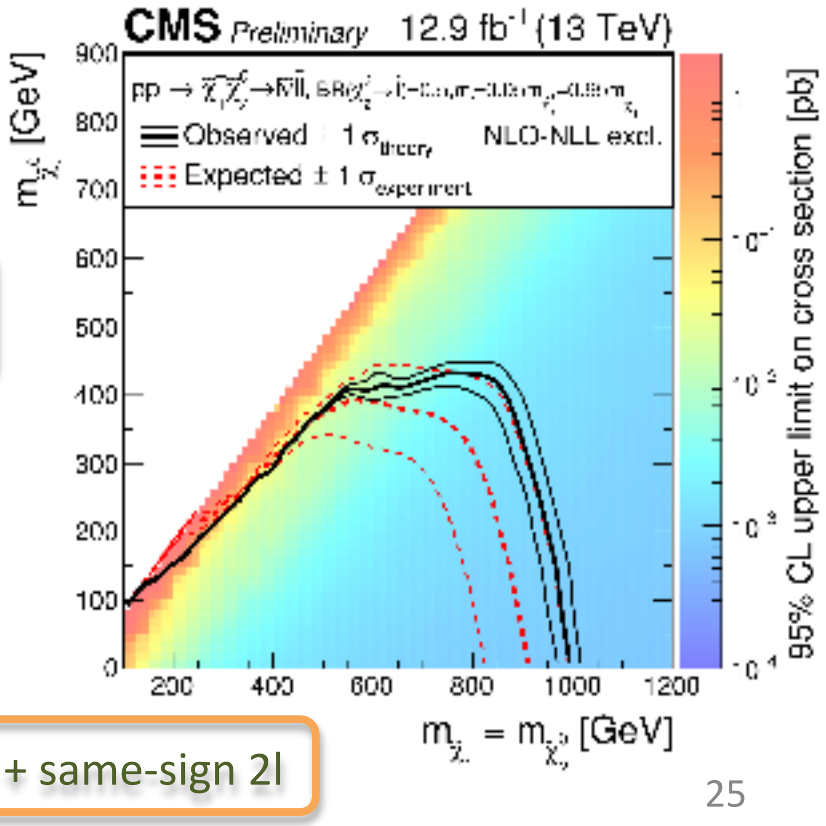
- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

No light EWkinos



Effect of change in intermediate slepton mass

↔

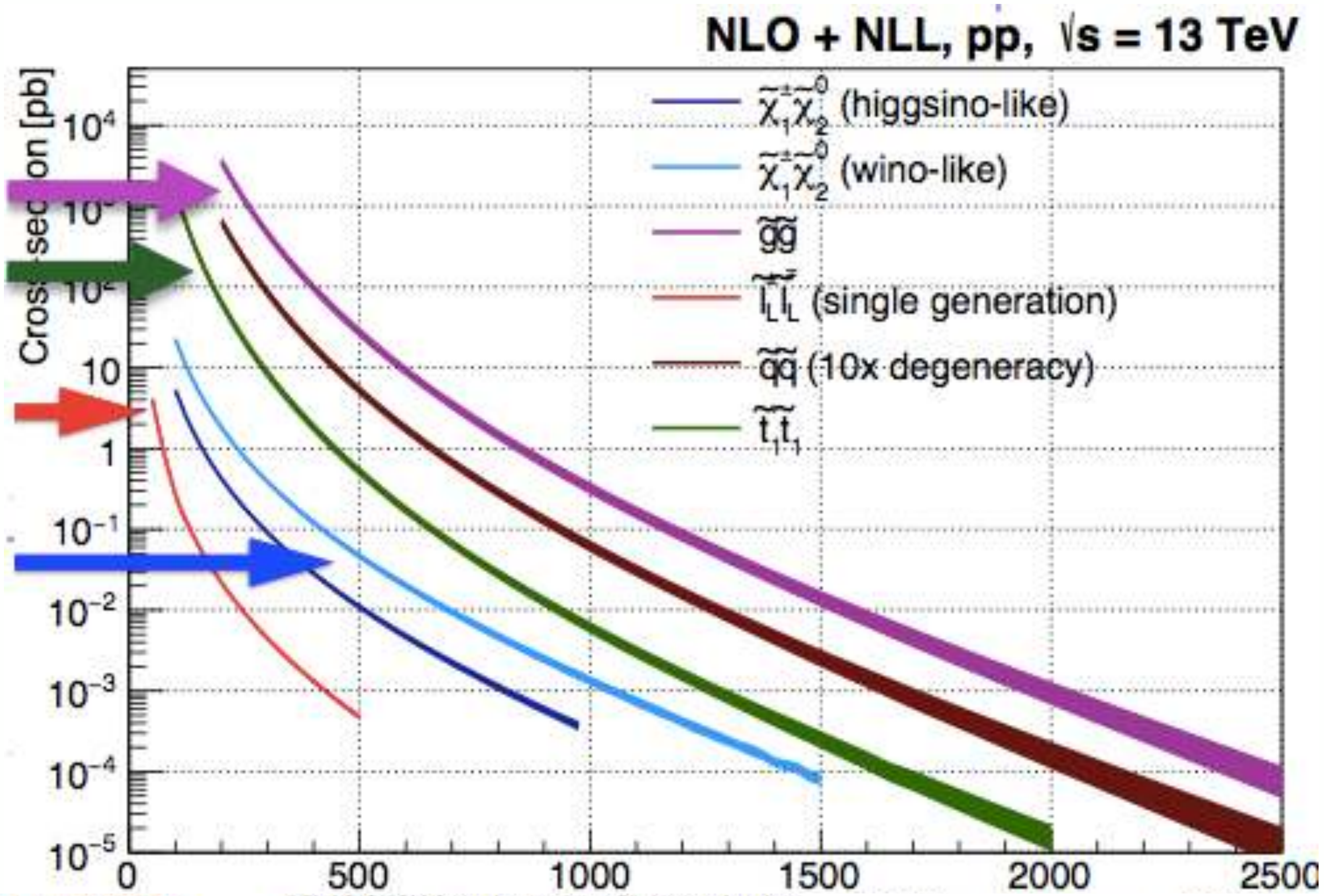


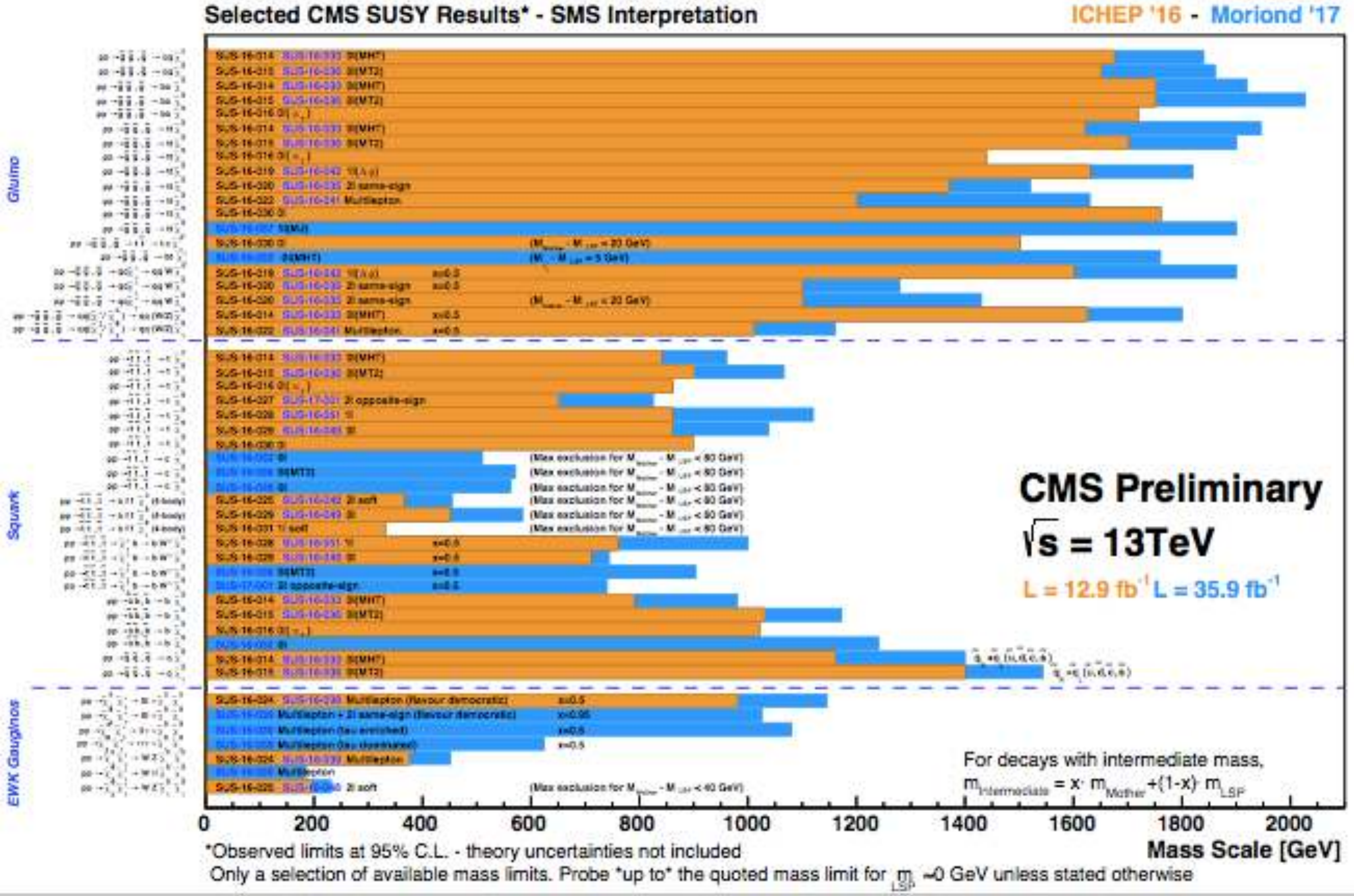
3l + same-sign 2l

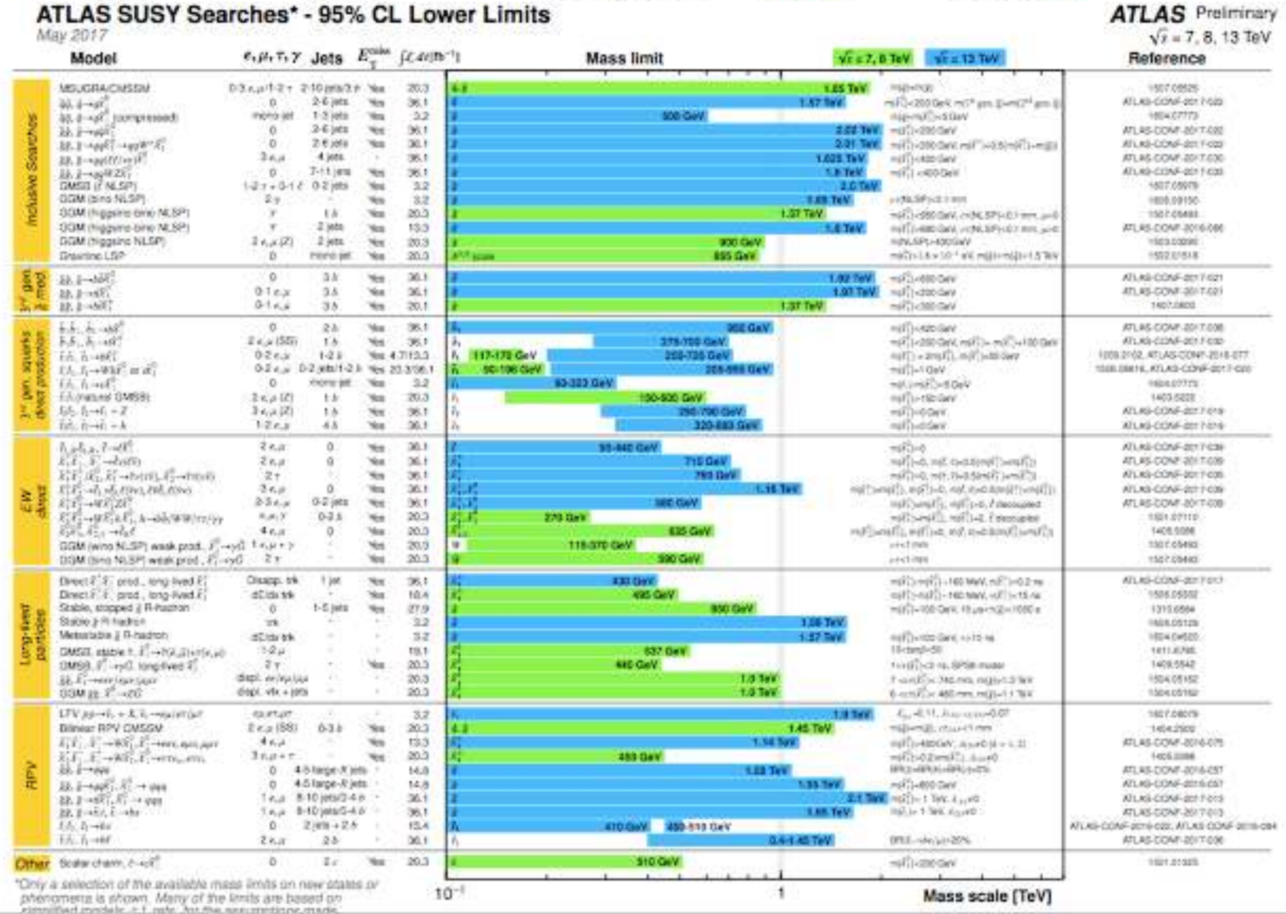
WHERE ARE WE NOW?

Strong production
(gluinos, squarks)

EWK production
(charginos, neutralinos, sleptons)







FUTURE SUSY SEARCHES

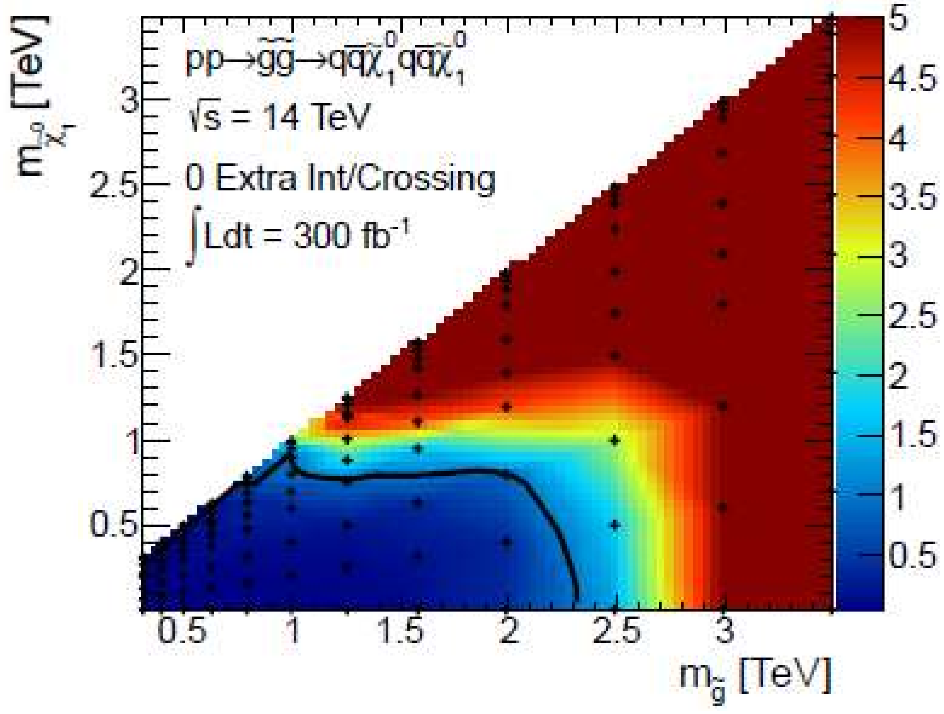
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

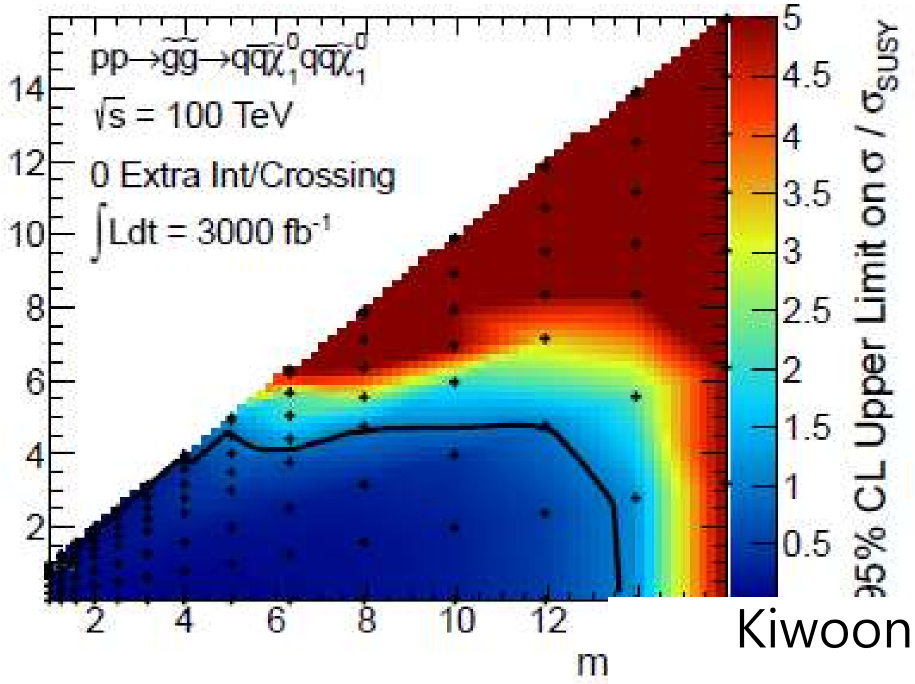
* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, ‘13

100 TeV collider

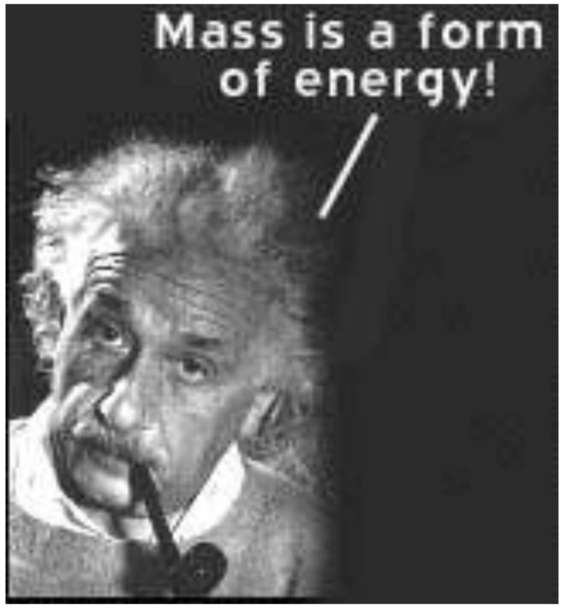


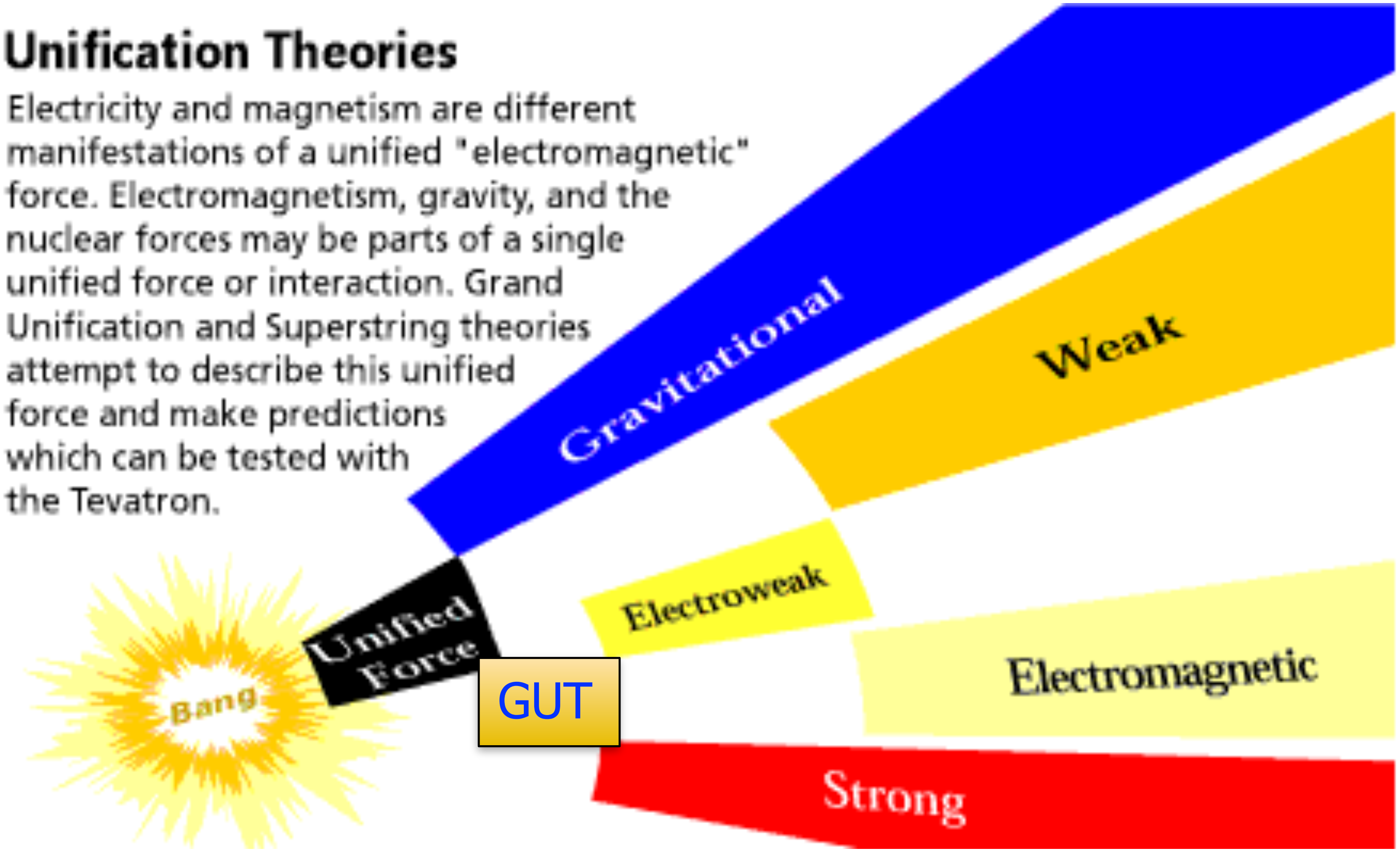


Kiwoon Choi

(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

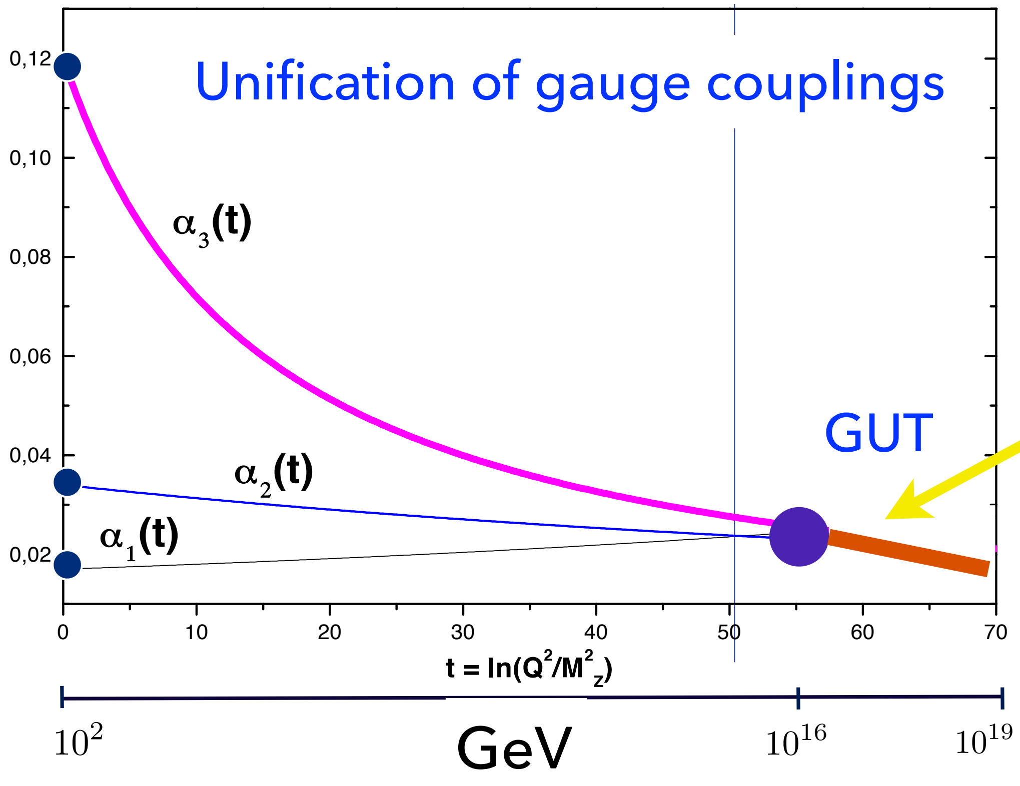
- Unification of strong, weak and electromagnetic interactions within Grand Unified Theories is a new step in unification of all forces of Nature
- Creation of a unified theory of everything based on string paradigm seems to be possible

NEW SYMMETRIES

GRAND UNIFICATION

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

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



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

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

GUT MODELS

SU(5) - Minimal GUT

$$\left(\begin{array}{ccc|cc} & & & X & Y \\ & SU_c(3) & & X & Y \\ & & & X & Y \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ X & X & X & SU_L(2) & \\ Y & Y & Y & & \end{array}\right)$$

Gauge fields

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

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

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

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

SU(5)

Higgs Multiplets

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

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

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

SO(10)

Higgs Multiplets

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

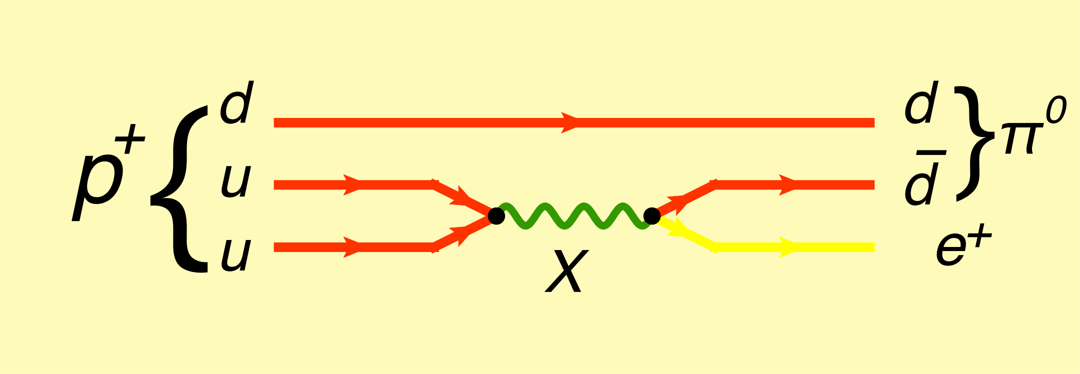
$$\begin{tikzcd}
 & SU(5) \arrow[r, "M_2"] & SU(3) \otimes SU(2) \otimes U(1) \arrow[r, "M_W"] & SU(3) \otimes U(1) \\
SO(10) \arrow[ur] \arrow[dr] \arrow[r, phantom, "M_1"] & & & \\
 & SO(6) \otimes SO(4) \sim SU(4) \otimes SU_L(2) \otimes SU_R(2) & &
\end{tikzcd}$$

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

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



- Unification of the gauge couplings
- stabilization of the hierarchy

Low energy SUSY

Creates new problems:

- Hierarchy of scales $M_W/M_G \sim 10^{-14}$
- Large Higgs sector is needed for GUT symmetry breaking

Crucial predictions:

- Proton decay $P \to e^+\pi, \quad P \to \bar{\nu}K^+$
- Neutron-antineutron oscillations
- $|\Delta(B-L)| = 1 \; (|\Delta(B-L)| = 2)$ processes

Experiment:

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

$$\tau_{proton} \sim 10^{32} years$$

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

SUSY GUT

Crucial points:

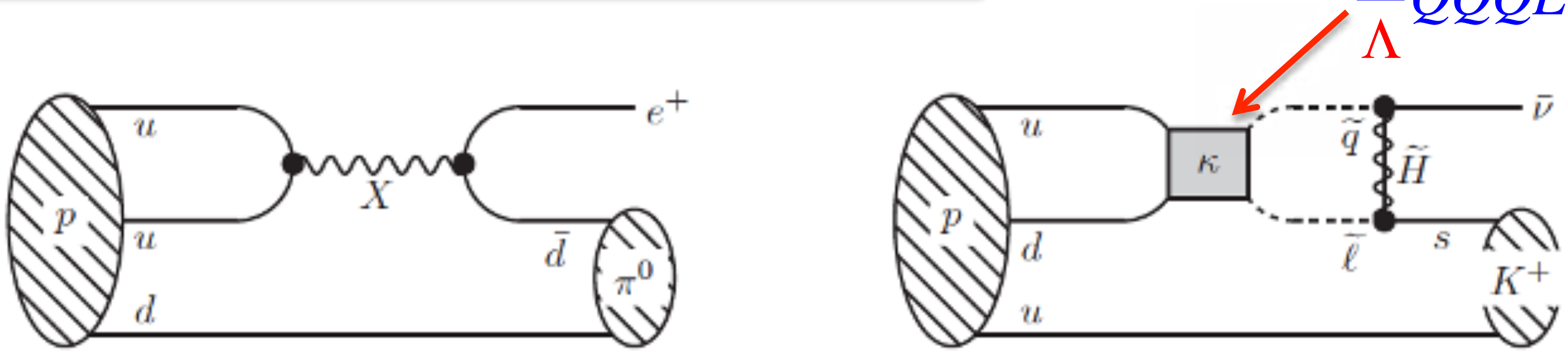
- SUSY leads to unification
- SUSY solves the hierarchy problems for GUTs
- No GUT without SUSY

New properties:

- Later unification - higher GUT scale
- Longer proton life-time $\tau \sim M_{GUT}^4$
- New modes of proton decay

SUSY GUTS – Nucleon decay

$\frac{1}{\Lambda} QQQL|_F$



(a) Dimension 6.

(b) Dimension 5.

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

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

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

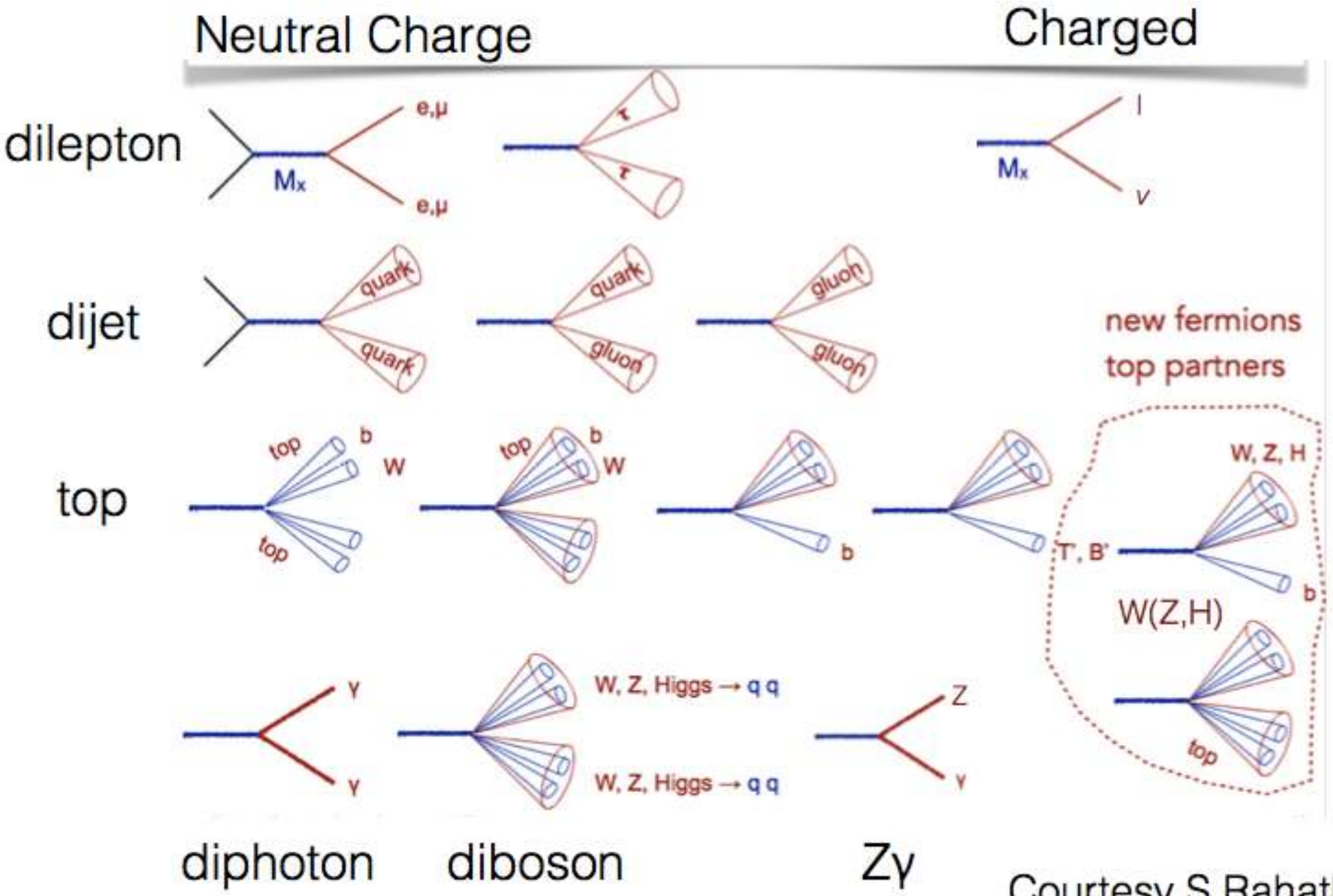
$\tau_{p\to K^+\bar{\nu}} > 3.3\times 10^{33} yrs$

NEW SYMMETRIES

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

- Appear in some GUT models
- Inspired by string models

Used as possible BSM signal with energetic single jet or diet events



Courtesy S.Rahatlou

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

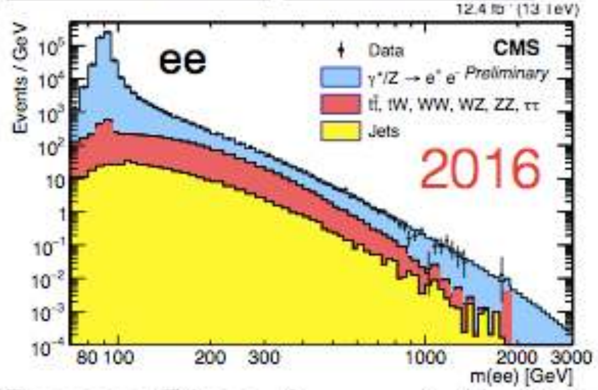
ADDITIONAL GAUGE BOSONS

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

Same Flavor Opposite Sign (ee, μμ, ττ)

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

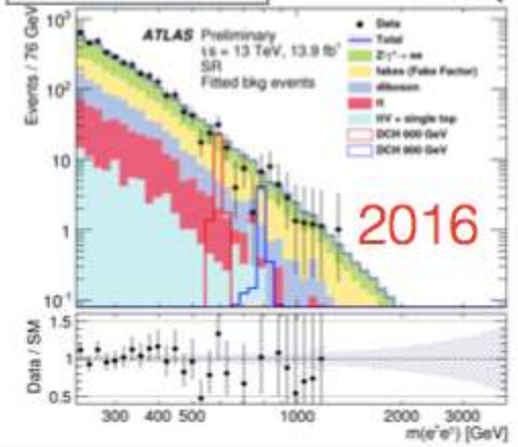


Same Sign (ee, μμ) Z'_{SSM}(3% width) >4 TeV

ATLAS-CONF-2016-051

Z'_{ψ} (0.5% width) >3.36 TeV

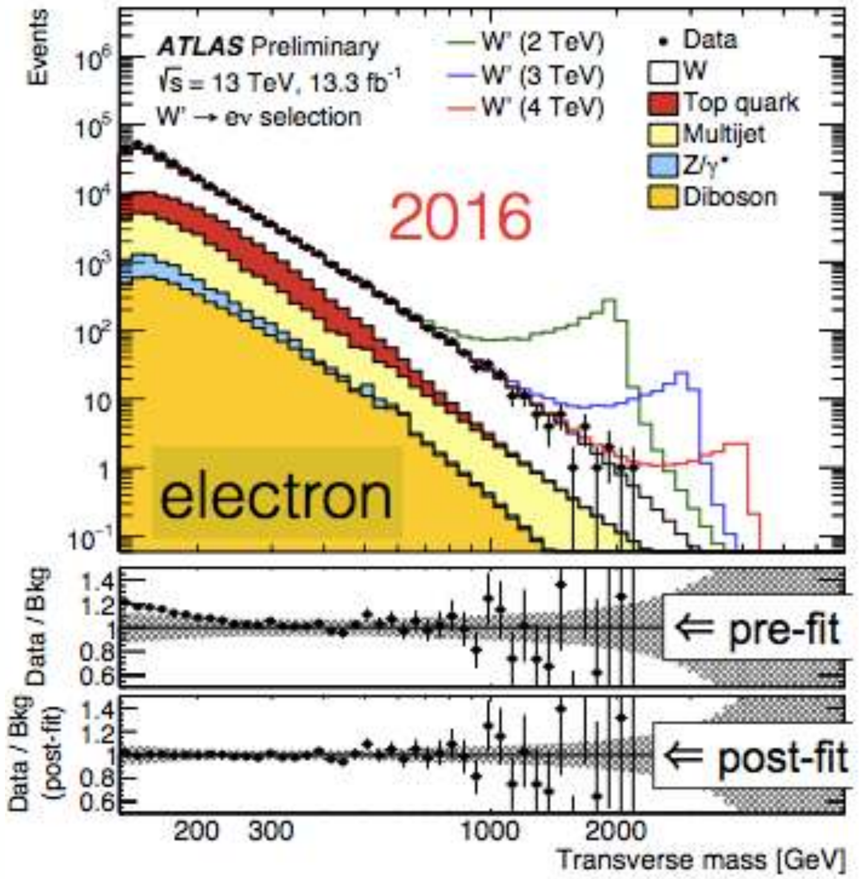
95% CL exclusion limit



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

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

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



SSM W’ >4.74 TeV

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

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

Custodial symmetry as guiding principle for extensions

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

indicates that an approximate global symmetry exists, broken by the vev to the diagonal 'custodial' symmetry group

Thus the Higgs field transforms under

$$SU(2)_L \times SU(2)_R : \quad \Phi \to L\Phi R^\dagger$$

$$\rho = \frac{\sum_{i=1}^{n} [I_i(I_i+1) - \frac{1}{4}Y_i^2]v_i}{\sum_{i=1}^{n} \frac{1}{2}Y_i^2 v_i} \sim 1$$

For both SU(2)-singlet with Y=0

and SU(2) doublet with Y=+-1

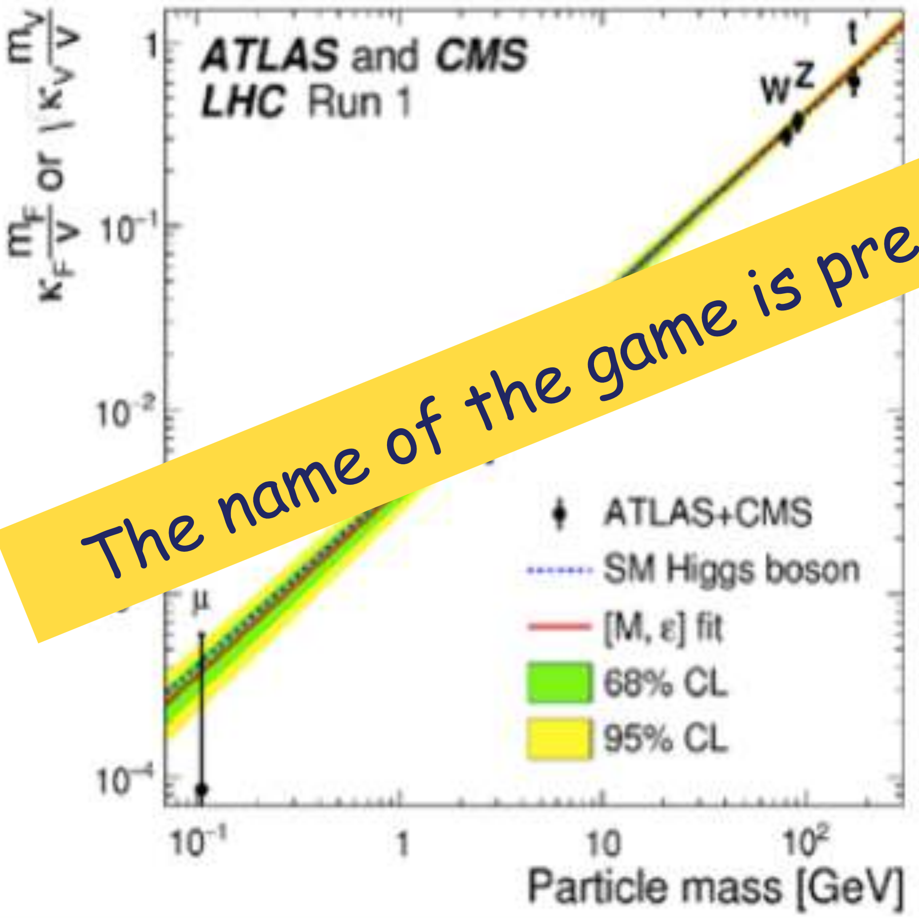
Any number of singlets and doublets respects custodial symmetry at tree level. Not so for arbitrary triplet models …

Model	Particle content
SM	h CP-even
2HDM/ MSSM	h,H CP-even A CP-odd H
NMSSM	H1,H2,H3 CP-even A1,A2 CP-odd
Composite	h CP-even + excited states

EXTENDED HIGGS SECTOR

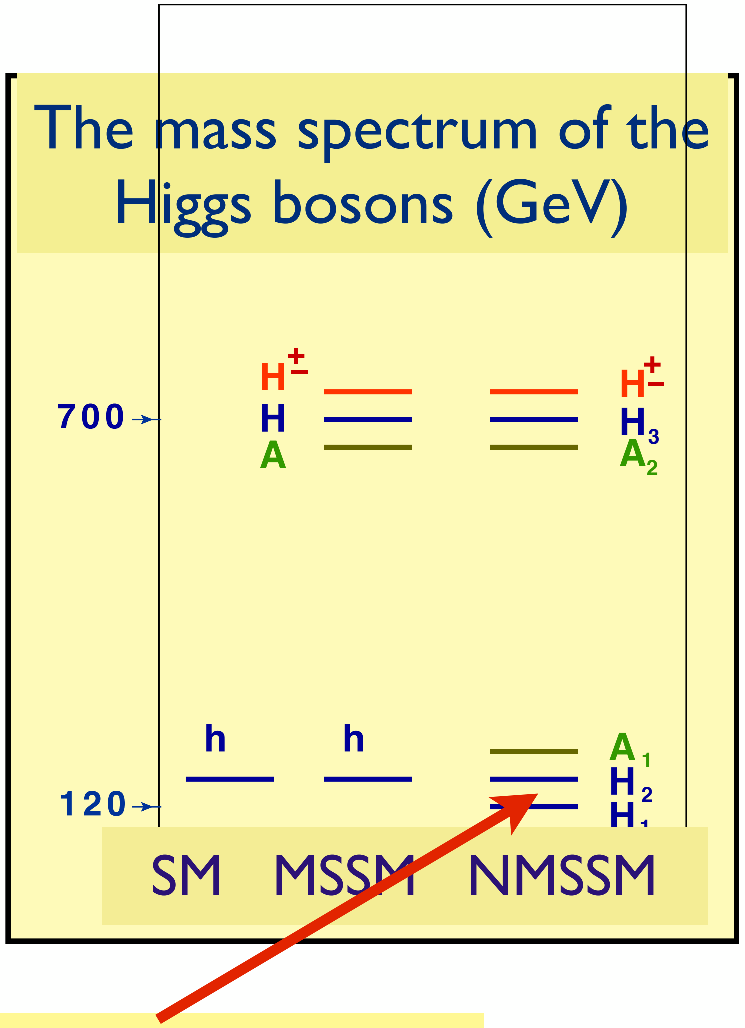
How to probe?

- Probe deviations from the SM Higgs couplings



The name of the game is precision

- Perform direct search for additional scalars

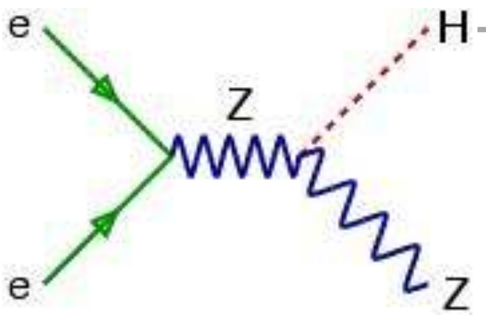


The mass spectrum of the Higgs bosons (GeV)

We may have found one of these states

One has to check the presence or absence of heavy Higgs bosons

PRECISION PHYSICS OF THE HIGGS BOSONS



→ $b\bar{b}q\bar{q}$

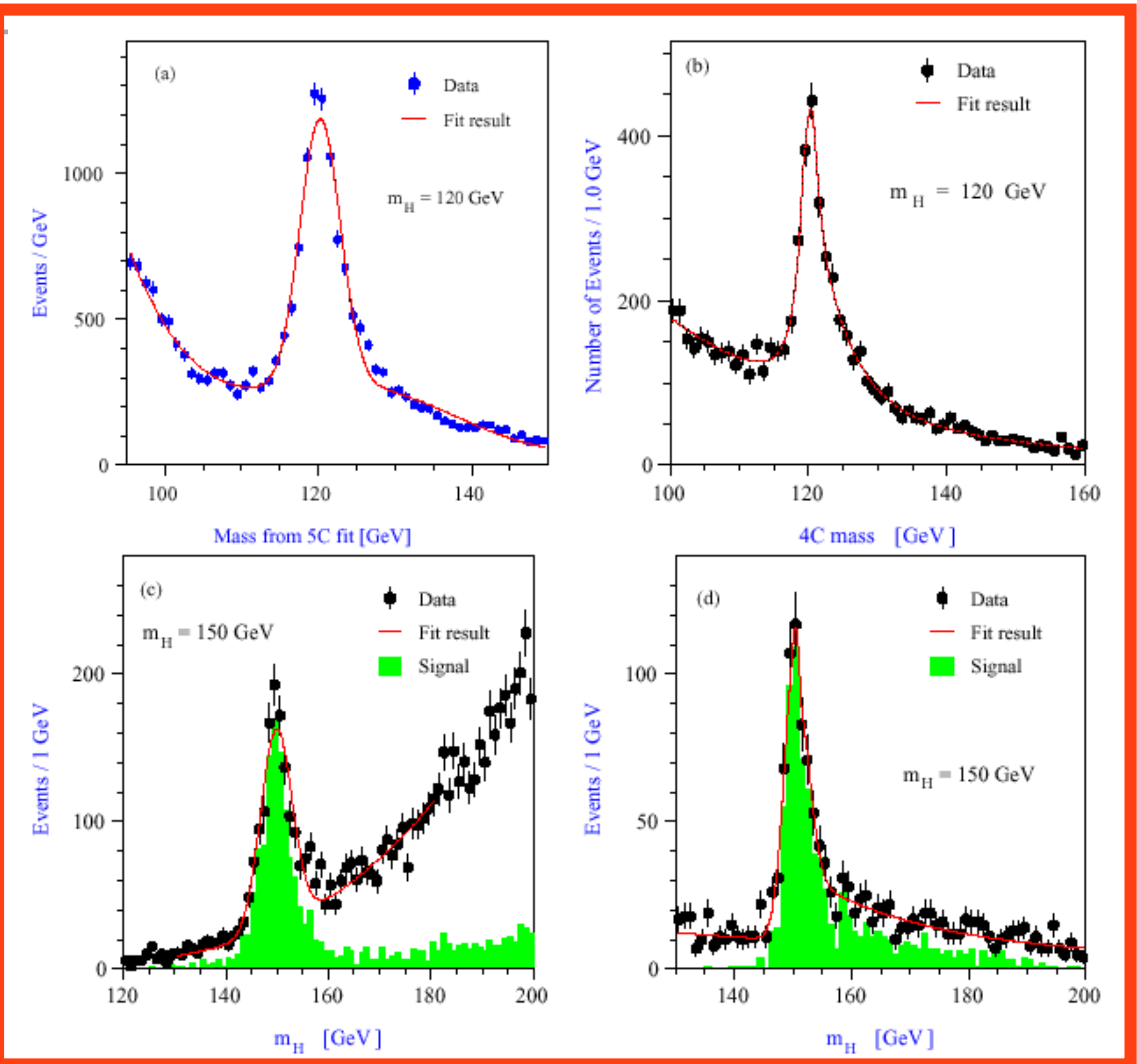
→ $q\bar{q}\ell^+\ell^-$

ee -> HZ diff. decay channels

Int Linear Collider

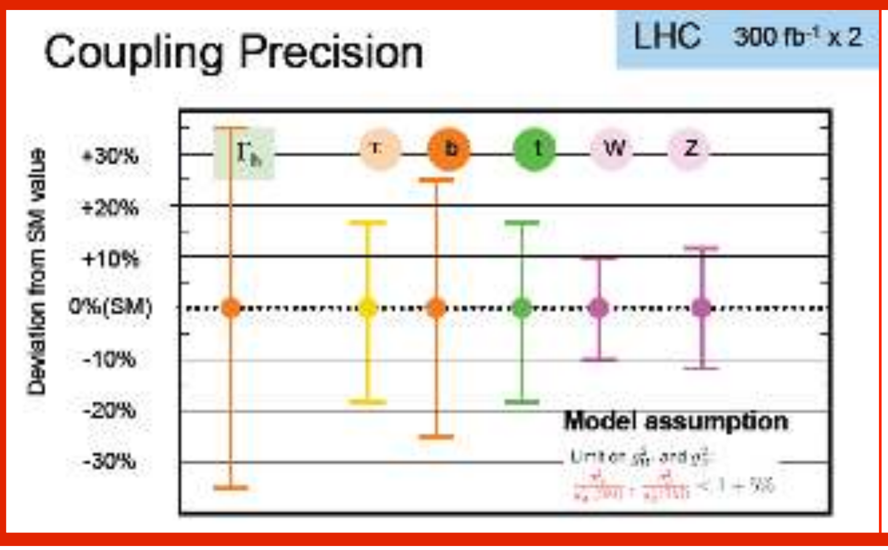
→ $W^+W^-q\bar{q}$

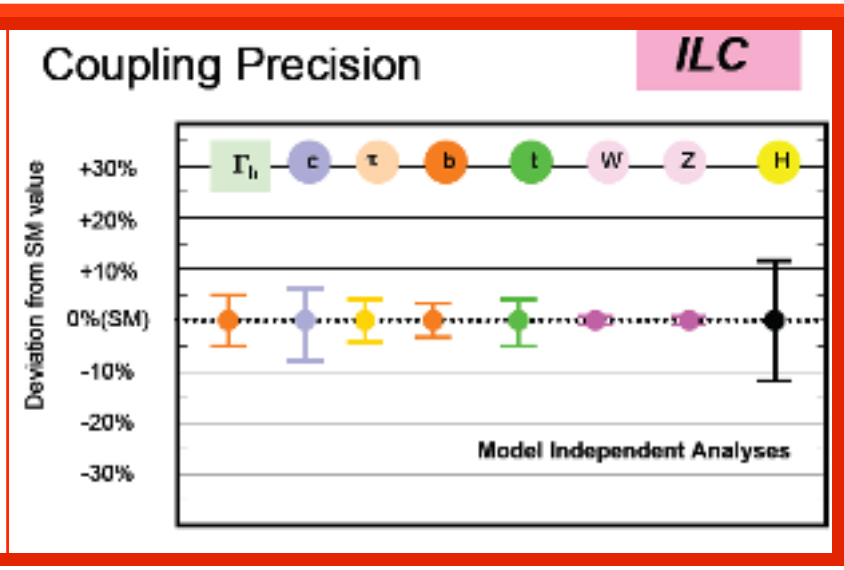
→ $W^+W^-\ell^+\ell^-$

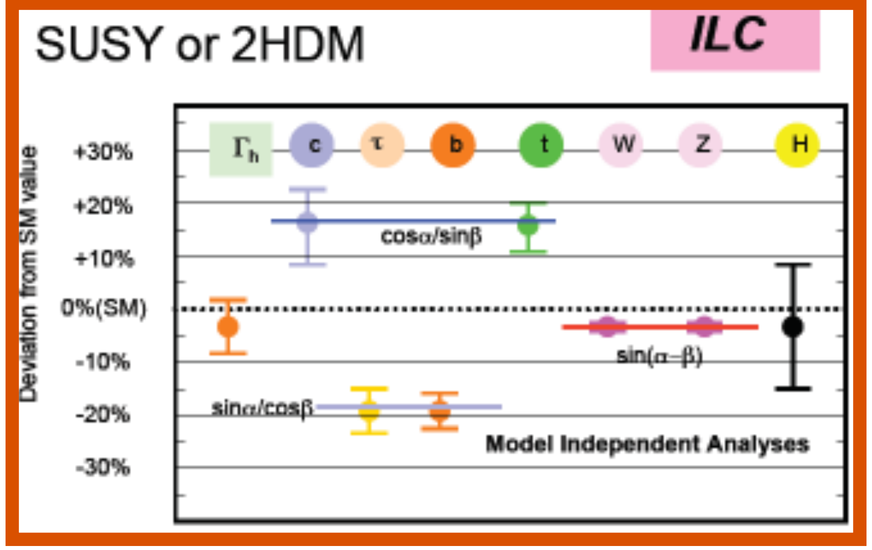


Δm_H = 40 MeV

Δm_H = 70 MeV

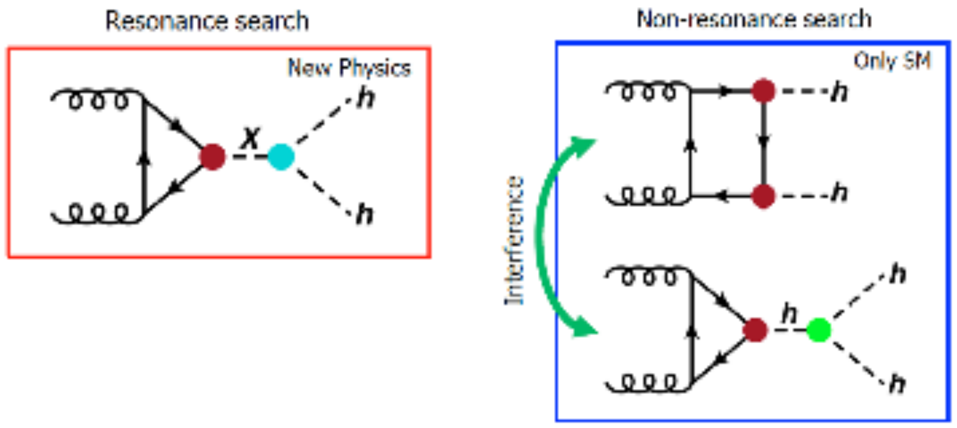




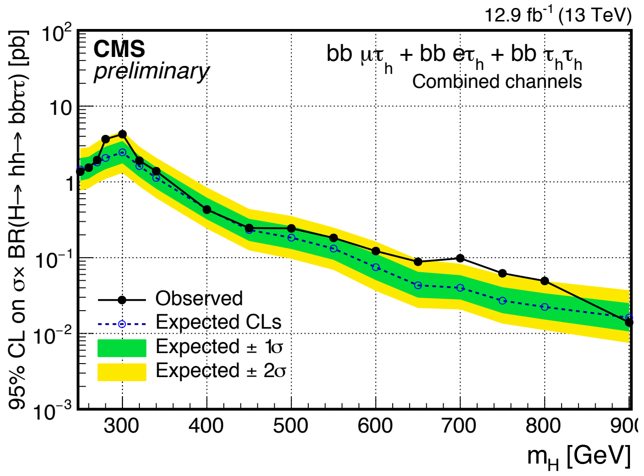


EXTRA HIGGS BOSONS

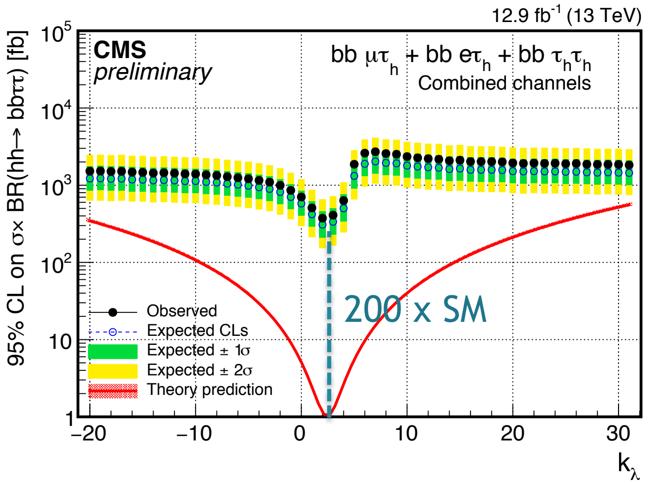
Higgs→hh→bbττ



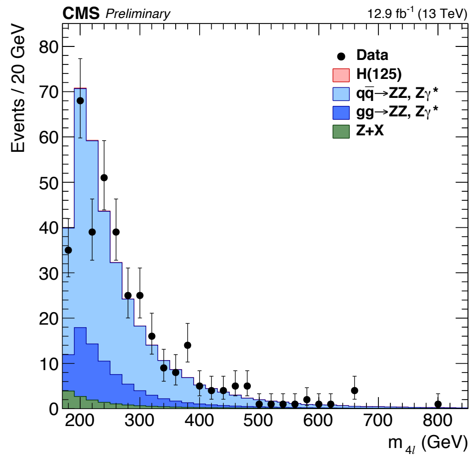
Resonant

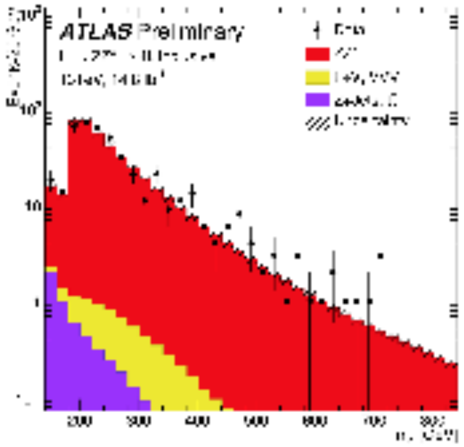


Non-Resonant

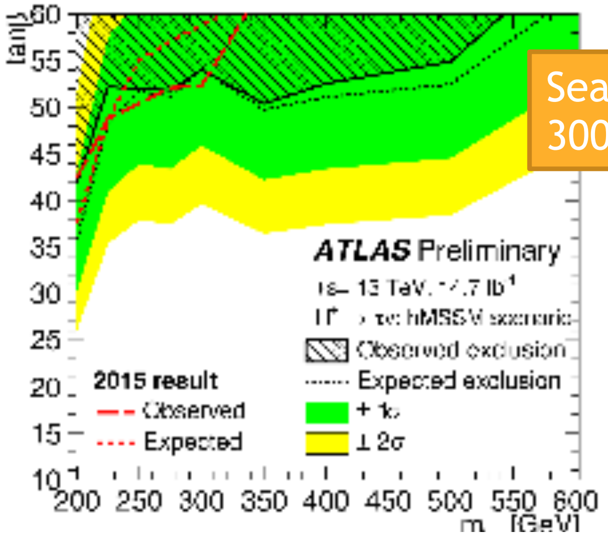


Heavy Higgs→ZZ→4l



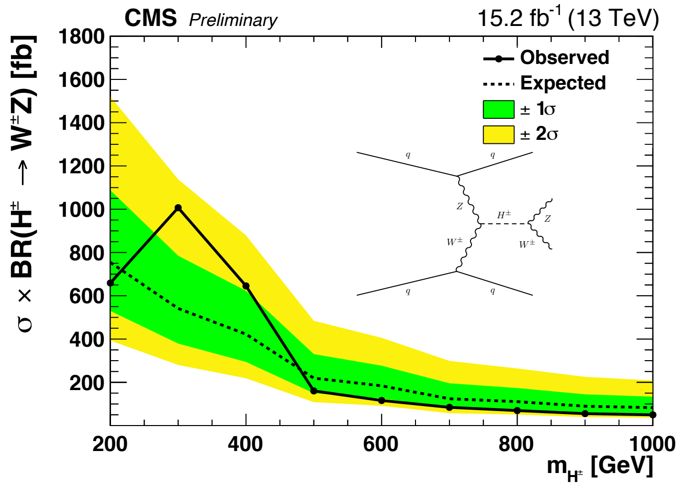


Charged Higgs

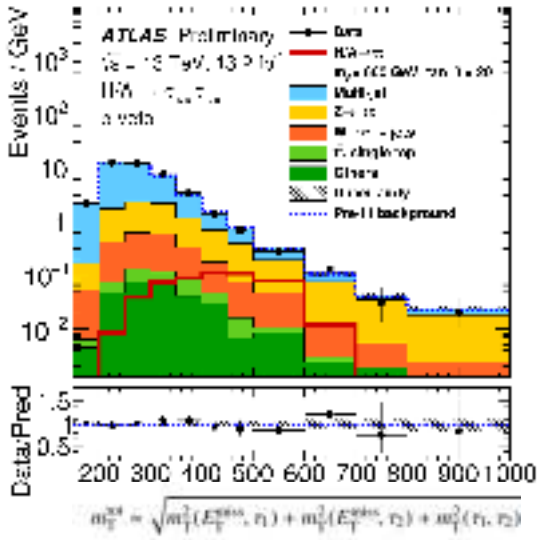


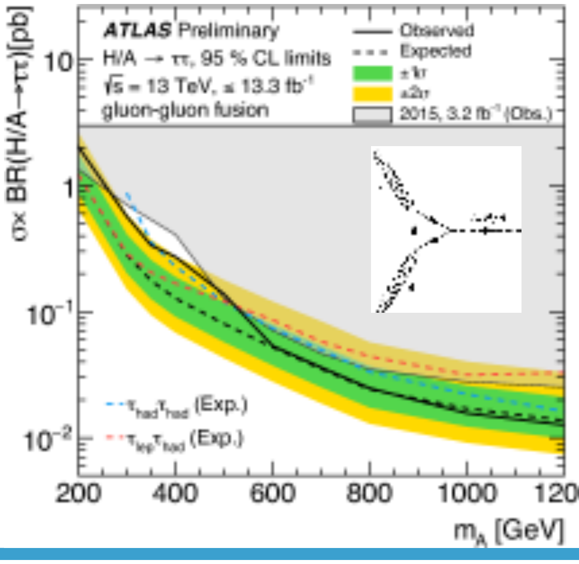
Search for H±→tb
300<$m_{H^\pm}$<1000 GeV

Search for H±WZ



Heavy Higgs→ττ





NEW PARTICLES

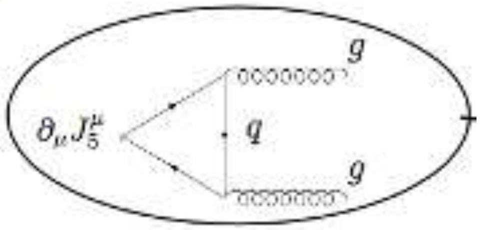
AXION OR AXION-LIKE PARTICLES

Javier Redondo, EPS HEP 2017

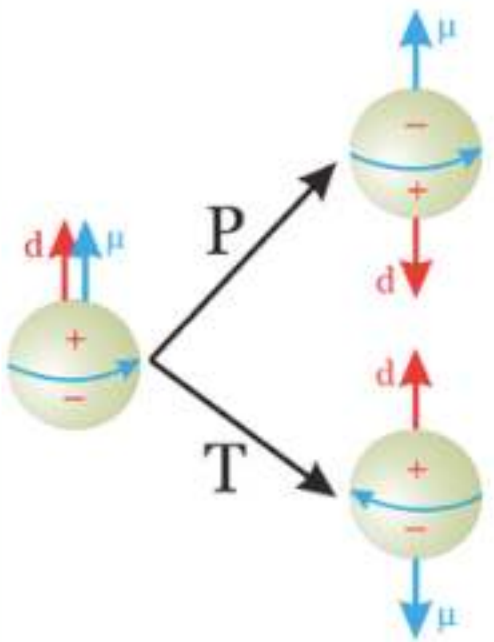
- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\rm QCD} + N_f\delta$

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

Axial anomaly



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)**

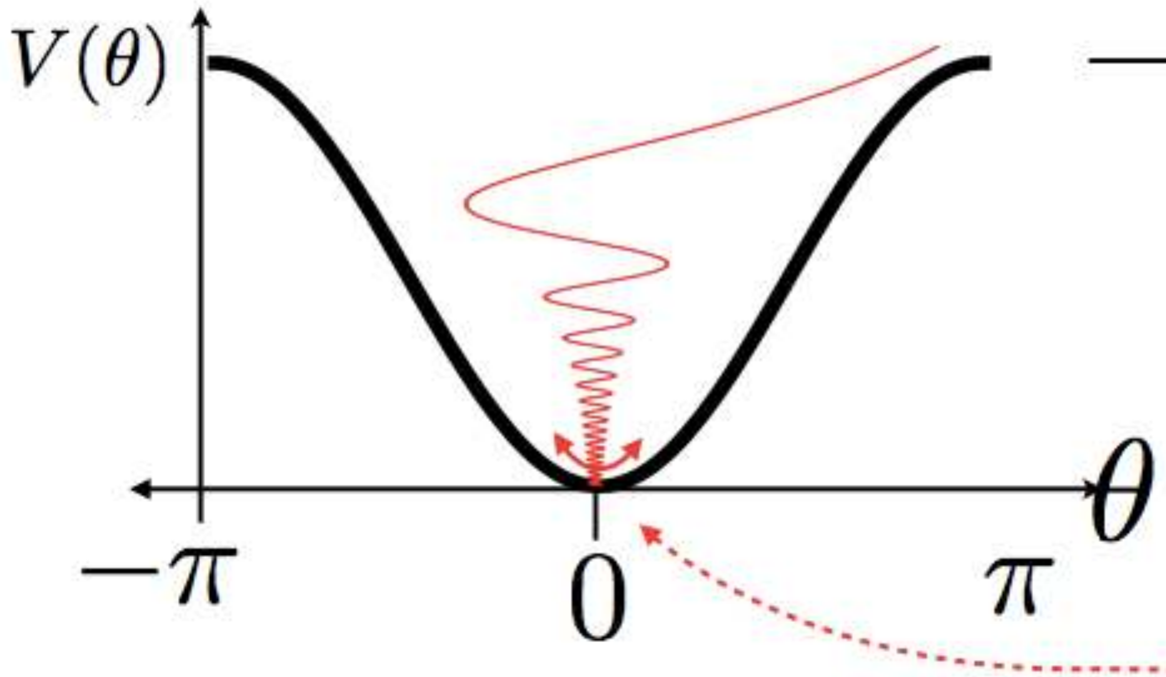
$$|d_n| < 3 \times 10^{-13}\,[\mathrm{e\,fm}]$$

- **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

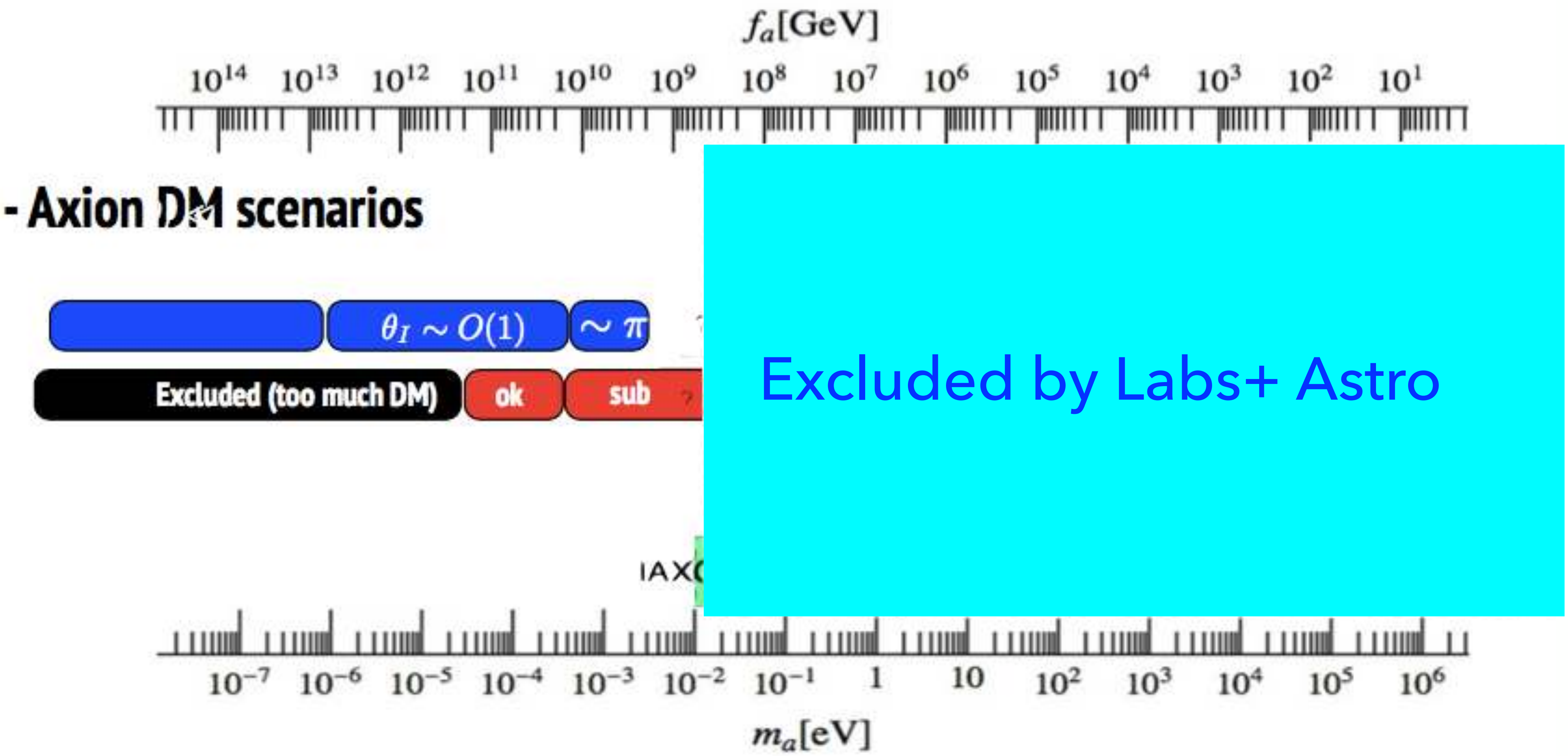
$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta)f_a^2 - \frac{\alpha_s}{8\pi}G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}\theta$$

New Spontaneous symmetry breaking [energy] scale f_a

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

WW Axion

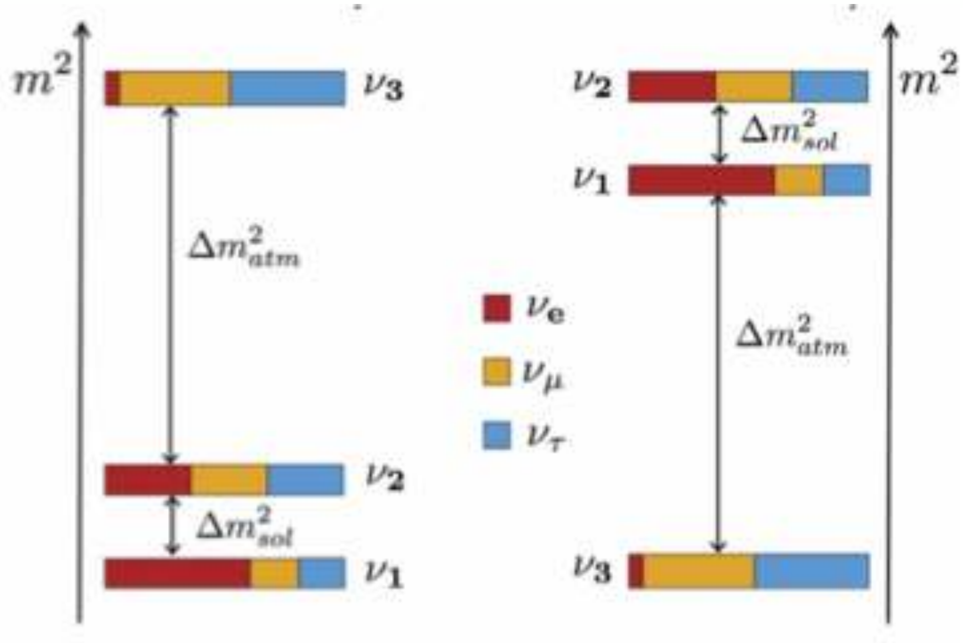
WHAT IS THE MASS TO GET $\Omega_{CDM}h^2 = 0.12$?

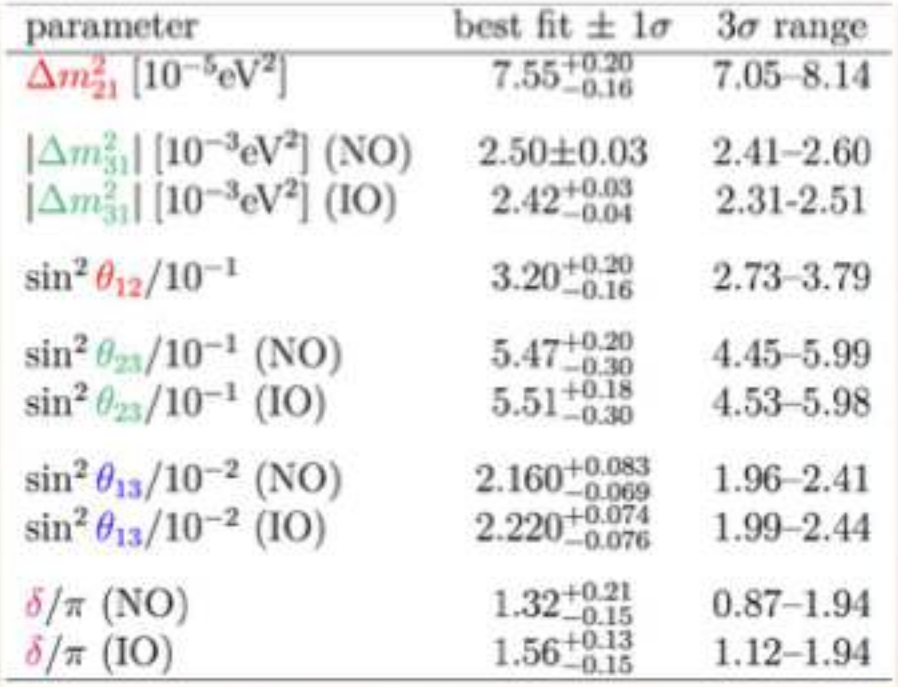


Excluded by Labs+ Astro

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

Neutrino Physics





parameter	best fit ± 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

de Salas et al, 1708.01186

- Absolute value of neutrino masses ?
- Mass hierarchy?
- Dirac or Majorana?
- Fourth sterile neutrino?
- Neutrino dark matter?

$$\boxed{0.06\ eV < \sum m_\nu < 0.12\ eV}$$

ν-osc

CMB

PMNS-matrix parameters are measured with high accuracy of few %

- Normal hierarchy favoured at 3.1 σ
- Nonzero CP phase favoured
- Upper octant favoured

DIRAC OR MAJORANA?

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

Mass martix

$$\mathcal{M} = \begin{array}{cc} L & R & \\ \left(\begin{array}{c} 0 \\ m_D^* \end{array}\right. & \left.\begin{array}{c} m_D \\ M \end{array}\right) & \begin{array}{c} L \\ R \end{array} \end{array}$$

Majorana term

Mass eigenvalues

$$m_1 \approx \frac{m_D^* m_D}{M} \qquad m_2 \approx M$$

Light

Heavy

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

?

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

BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

- Mass spectrum?

$$m_{quark} = y_{quark} \cdot v$$

$$m_{lepton} = y_{lepton} \cdot v$$

$$m_W = g/\sqrt{2} \cdot v$$

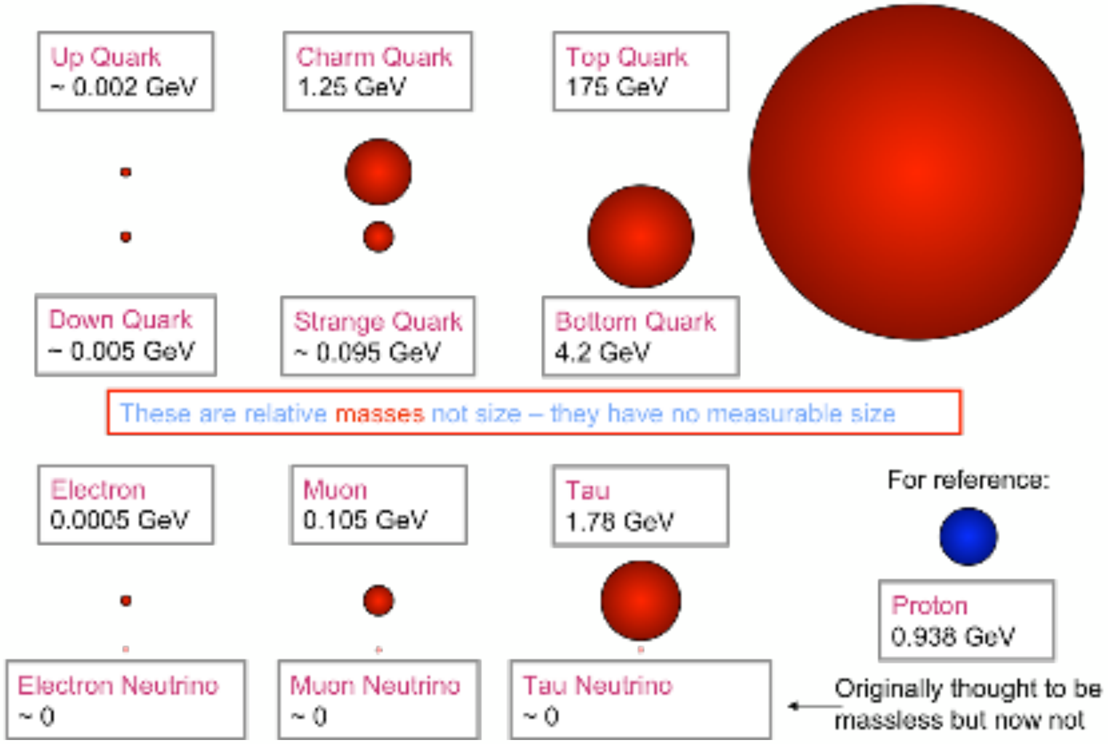
$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$

$$m_H = \sqrt{\lambda} \cdot v$$

SM

$$m_\gamma = 0$$

$$m_{gluon} = 0$$

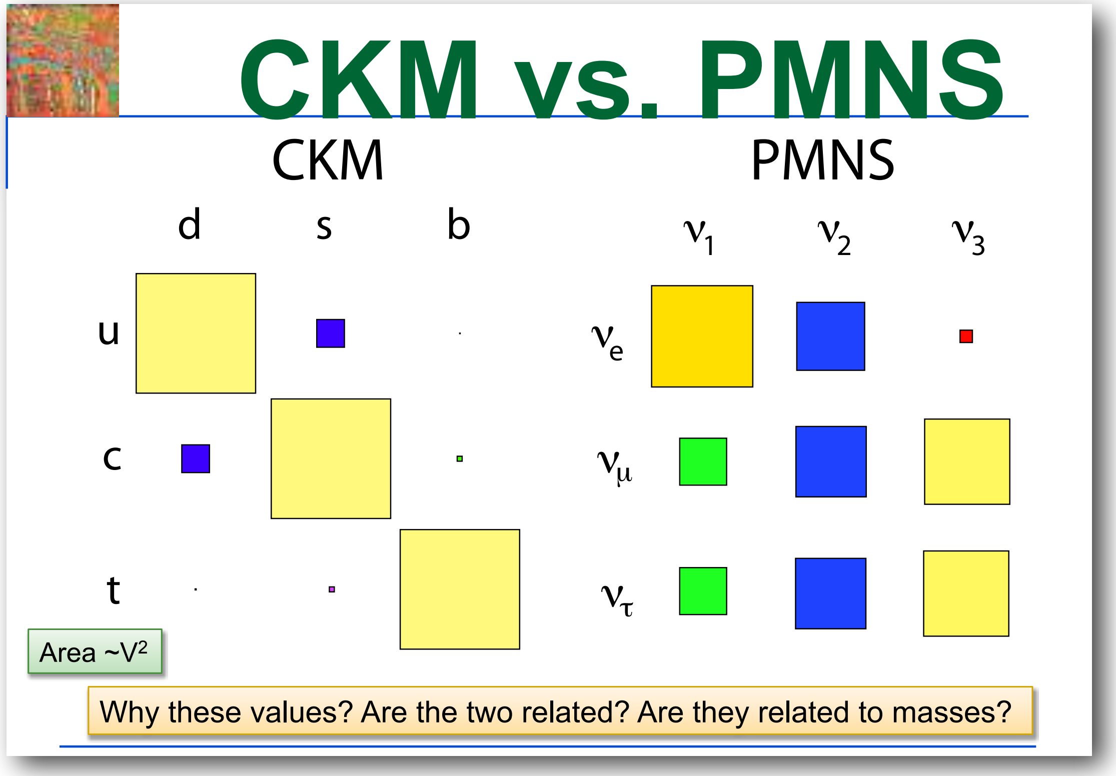


These are relative masses not size – they have no measurable size

Originally thought to be massless but now not

- Mixing Matrices?

- Quark-Lepton Symmetry
- Strong difference in parameters



CKM vs. PMNS

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

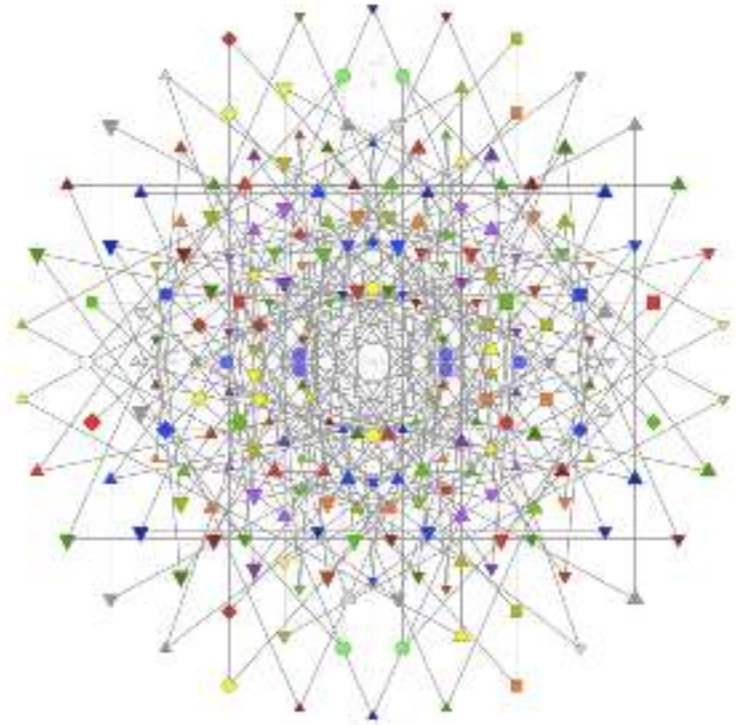
- What are the CKM and PMNS phases?
- Where lies the source of CP violation: in quark or lepton sector?

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

BEYOND THE STANDARD MODEL: QUEST FOR SYMMETRY

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

Symmetry might be tricky



E8 roots

Is it just the SM or requires New physics?

Three Types of Seesaw Mechanisms

Require the existence of new degrees of freedom (particles) beyond those present in the SM

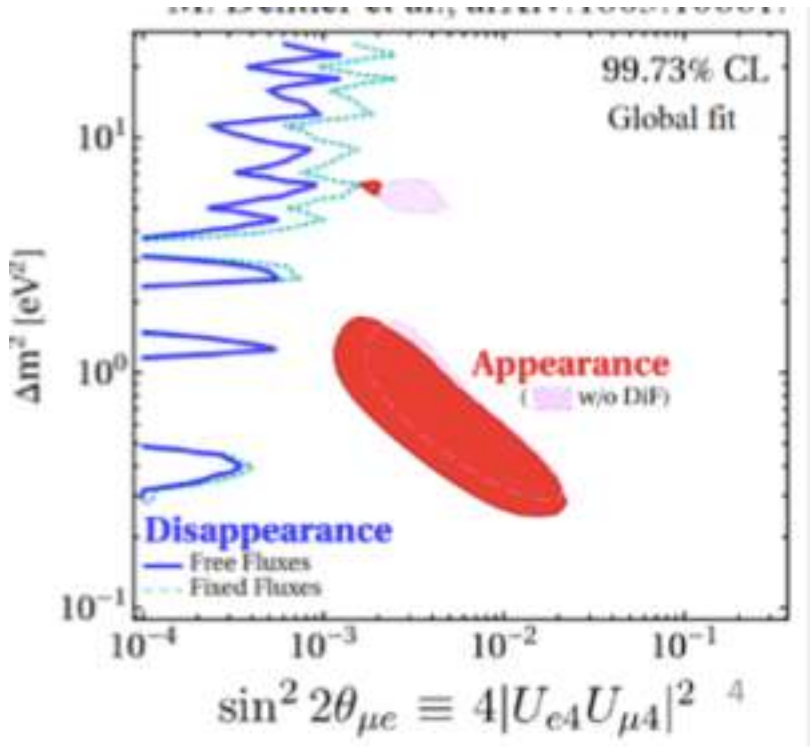
Type I seesaw mechanism: ν_{lR} - RH νs' (heavy).

Type II seesaw mechanism: H(x) - a triplet of H^0,H^-,H^{--} Higgs fields.

Type III seesaw mechanism: T(x) - a triplet of fermion fields.

M. Weber ICHEP2018

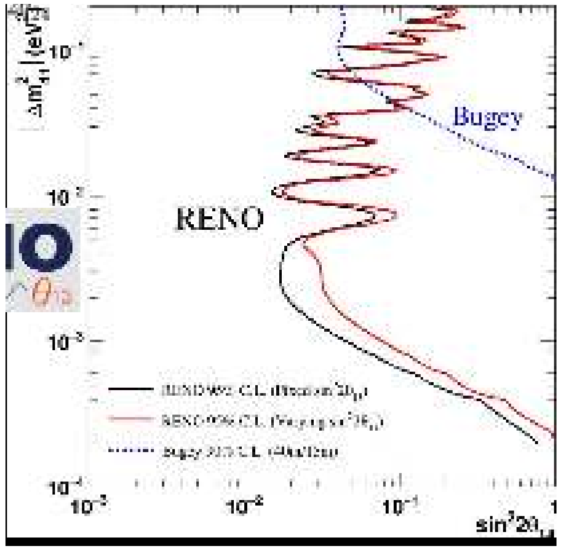
- **Possible Sterile Neutrino?**
  - **New MiniBooNE consistent with LSND** **(but low energy excess?)**
  - **Reactor anomaly questioned by Daya Bay/RENO time dependence**
  - **New SBL and source experiments**
  - **Conflict with ν_μ disappearance**



STERILE NEUTRINO

No evidence for sterile neutrinos

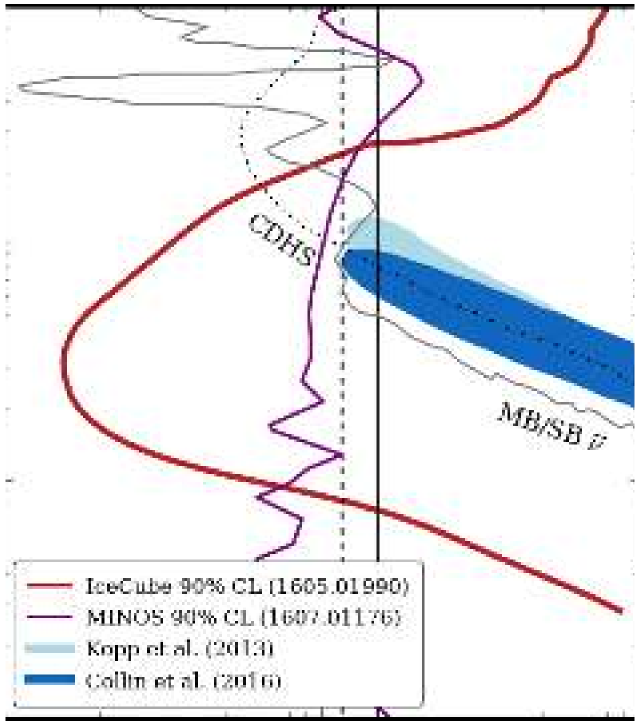
Various exps interpreted within 4 neutrino framework

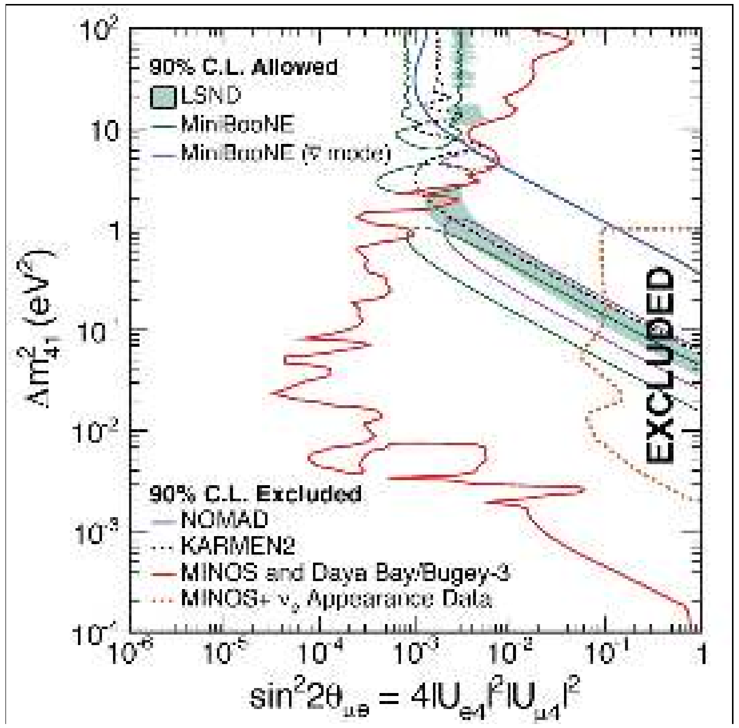


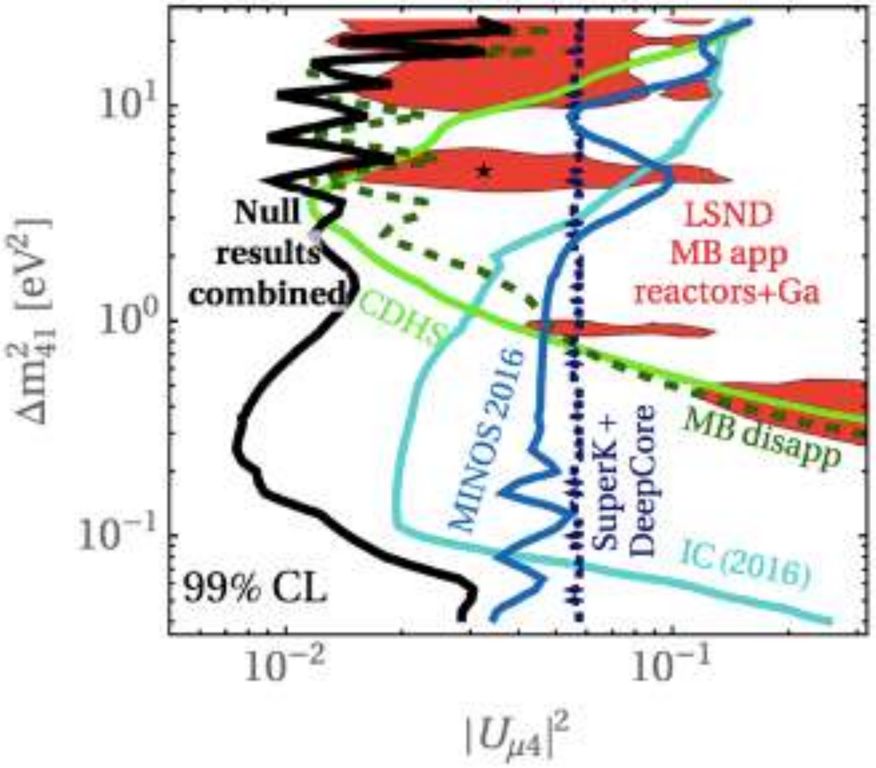
Oscillation channels are related:

$$P_{\nu_e \to \nu_e} \approx 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\nu_\mu \to \nu_\mu} \approx 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$$
$$P_{\nu_\mu \to \nu_e} \approx 2|U_{e4}|^2|U_{\mu4}|^2$$

for $4\pi E/\Delta m^2_{41} << L << 4\pi E/\Delta m^2_{31}$

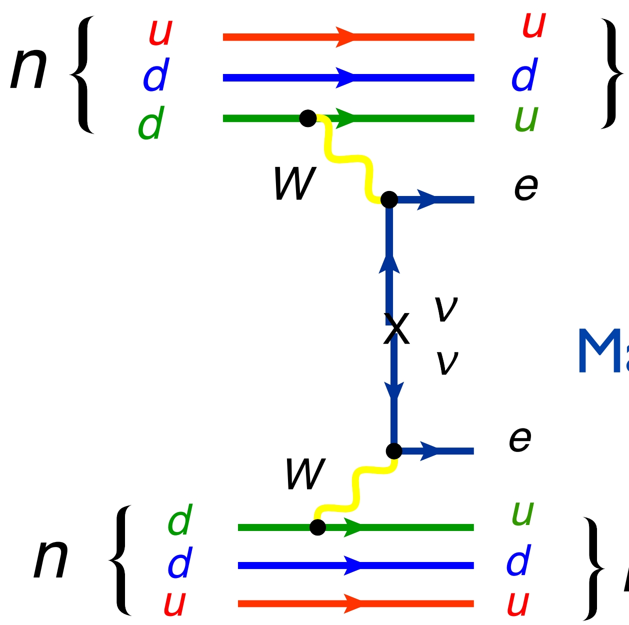




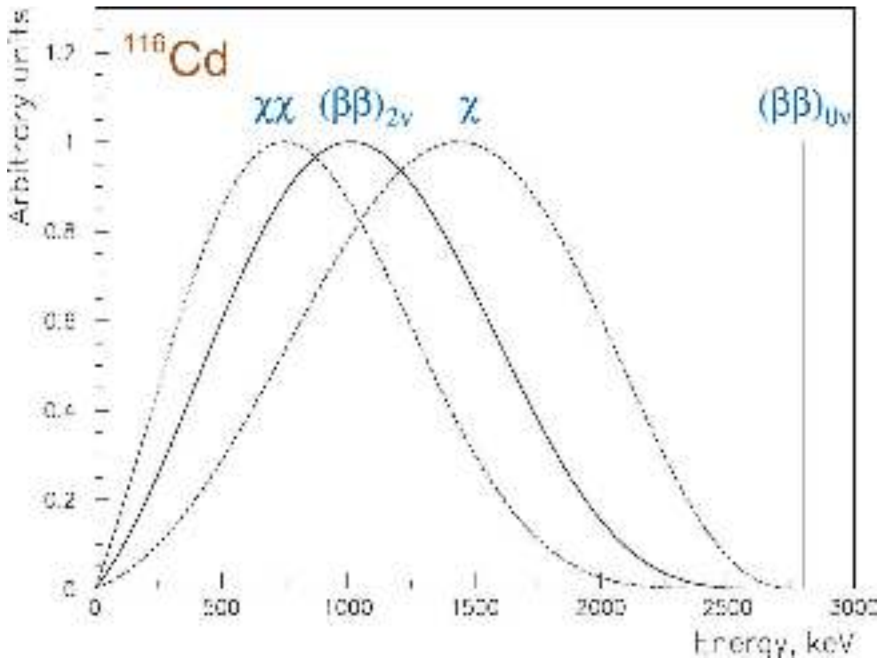


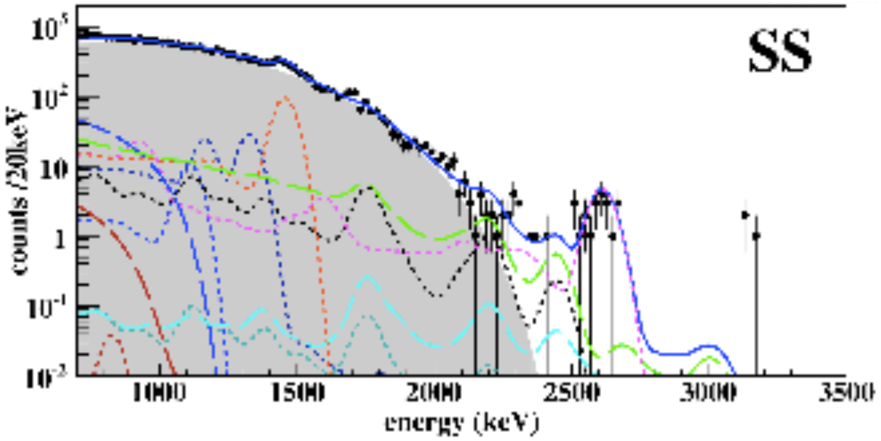
$0\beta\beta\nu$ NEUTRINOLESS DOUBLE BETA DECAY

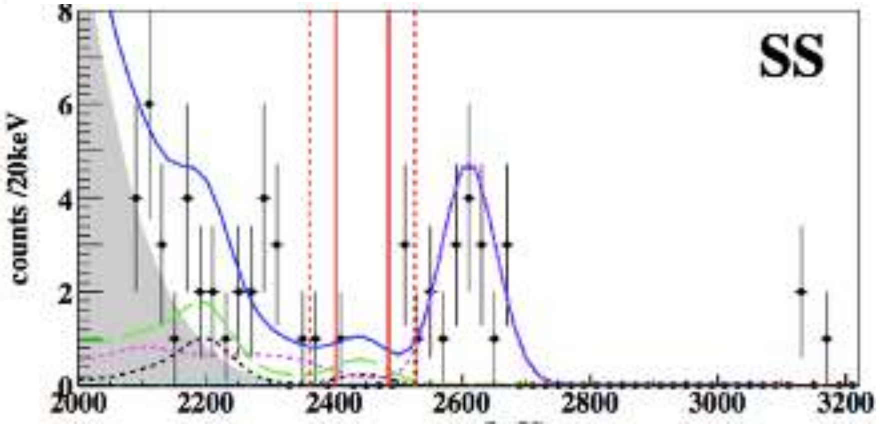
0νββ decay

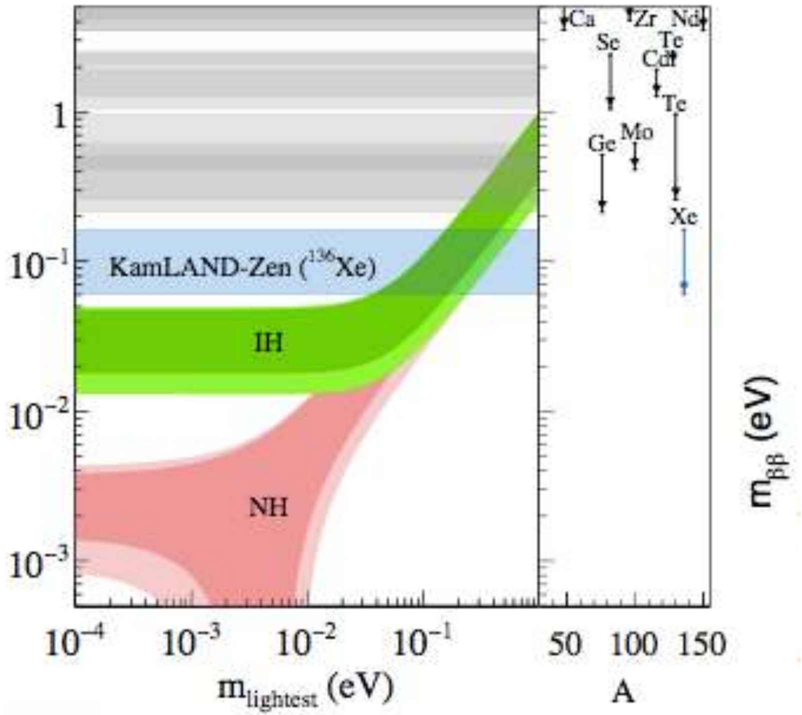


Only Majorana









Candidate Isotope	Experiment
^{48}Ca	Candles
^{76}Ge	**Gerda**, Majorana
^{82}Se	SuperNemo,Lucifer
^{130}Te	**CUORE**
^{136}Xe	**EXO**, NEXT, **KamLAND-Zen**
^{150}Nd	SNO+

$T_{1/2}$2νββ (^{136}Xe) x 10^{21} yr = 2.23 ± 0.017 stat ± 0.22 sys

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

NEW PARTICLES

DARK MATTER

The Dark Matter is made of:

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

Not from the SM

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

mSUGRA

might be invisible (?)

detectable in 3 spheres
less theory favorable

might be undetectable (?)

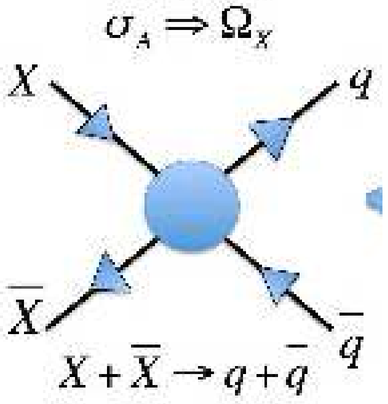
possible, but not
related to the other
models

WIMP is our chance !

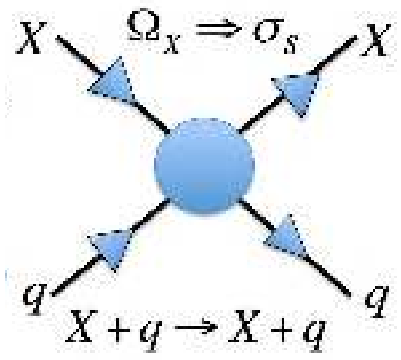
But we have to look elsewhere !

WIMP

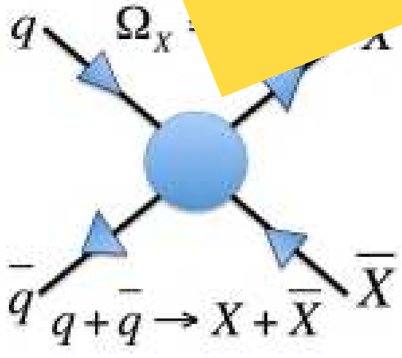
Annihilation
in the halo



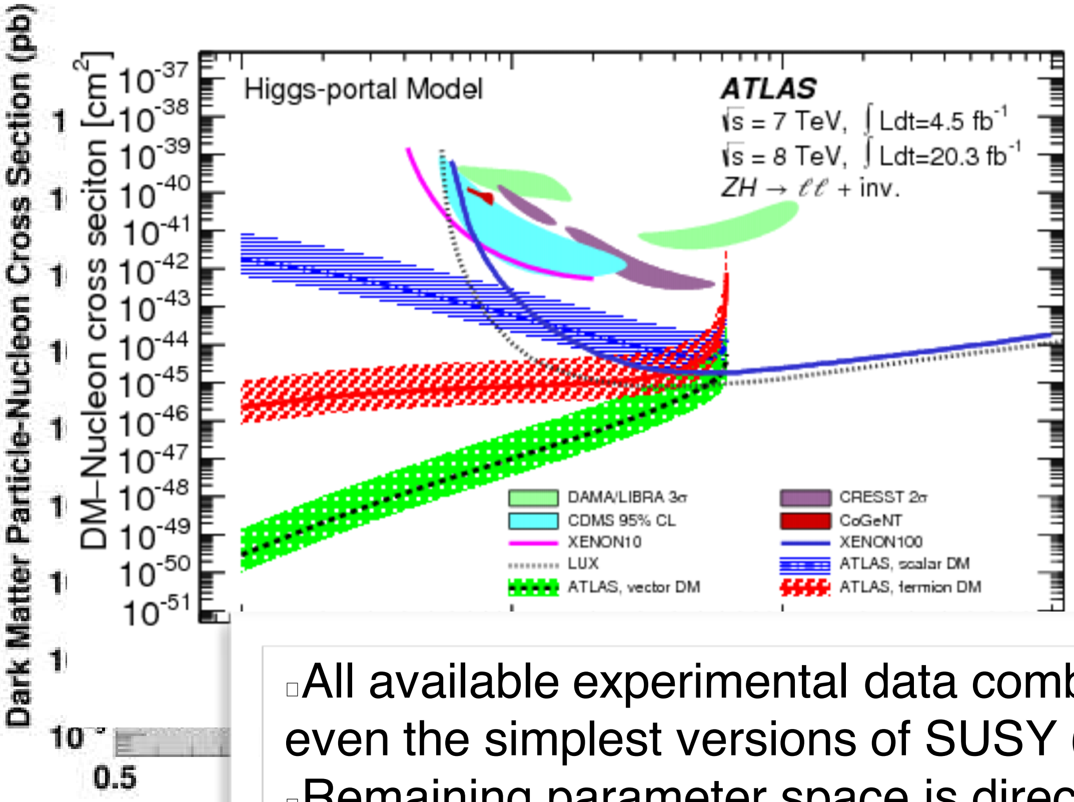
Scattering
on a target

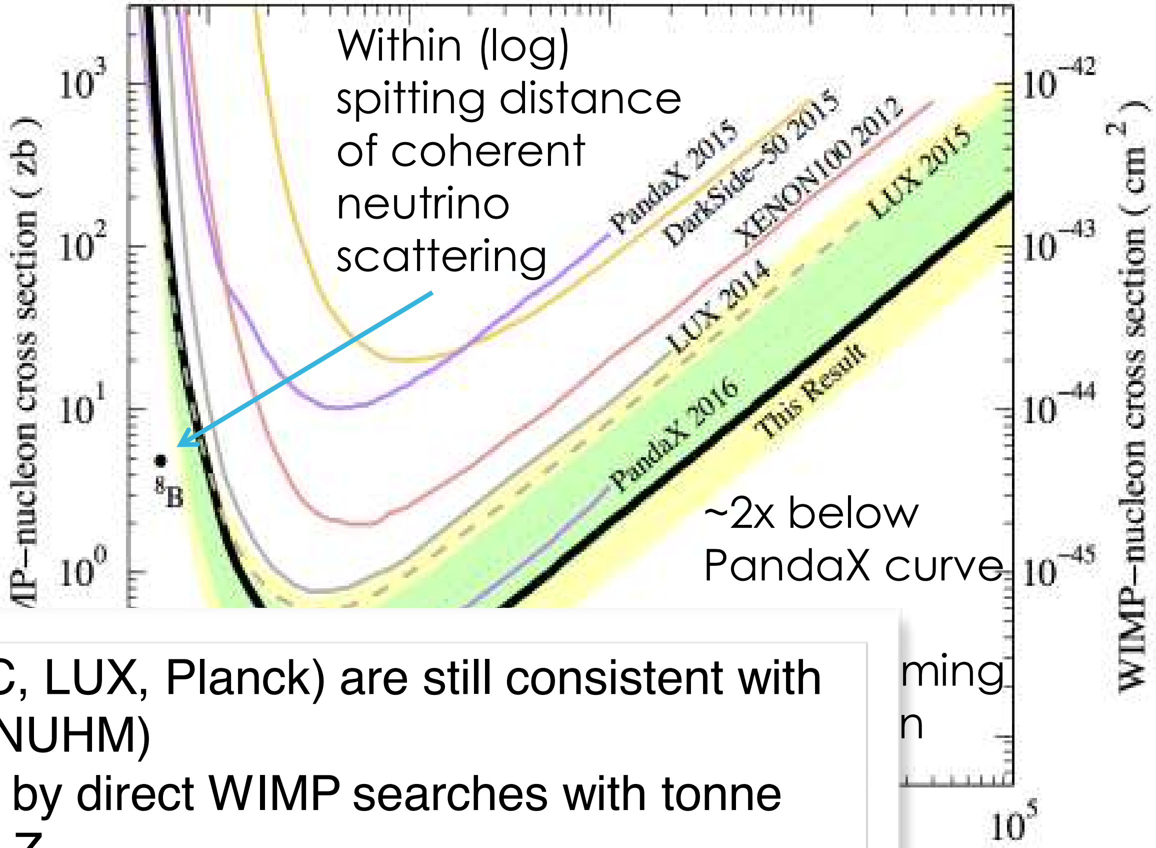


Creation at
the LHC



DARK MATTER: DIRECT DETECTION





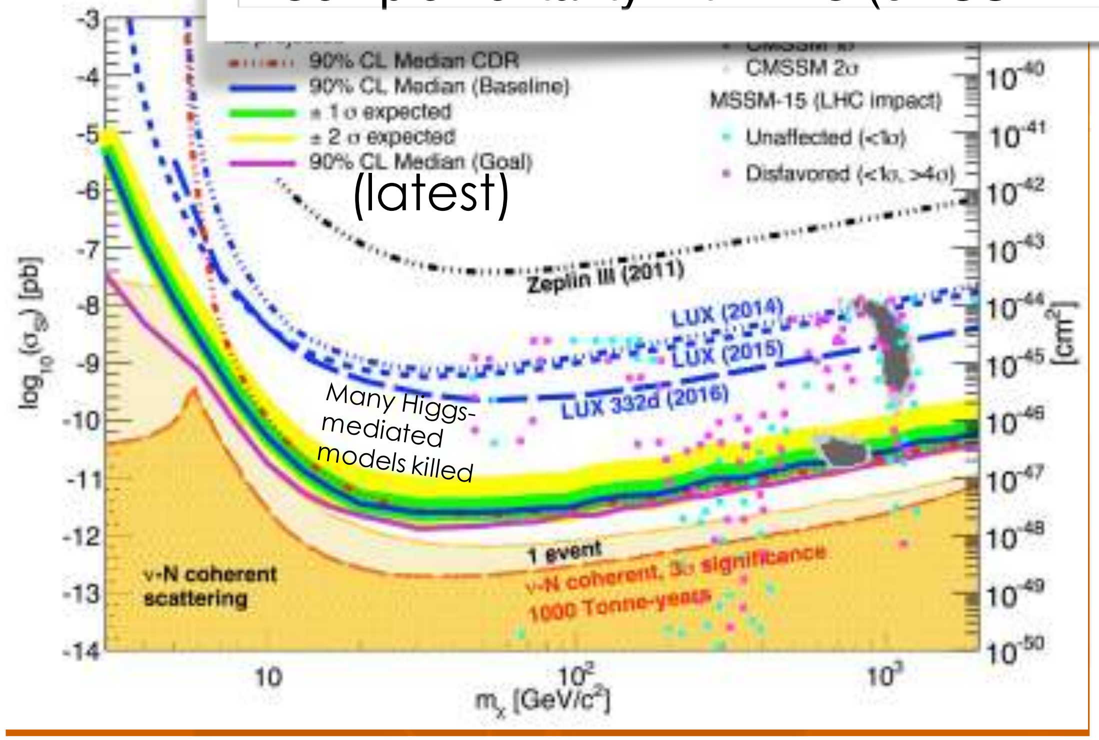
Within (log) spitting distance of coherent neutrino scattering

~2x below PandaX curve

ming

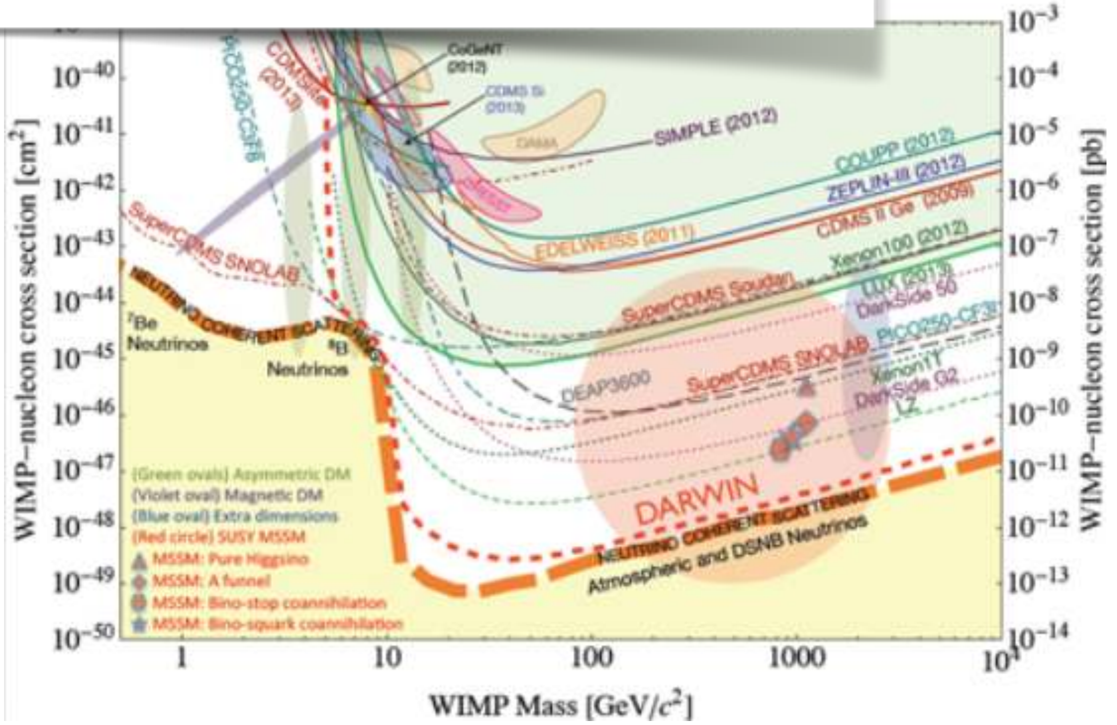
n

- All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM)
- Remaining parameter space is directly probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LUX/LZ
- Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)



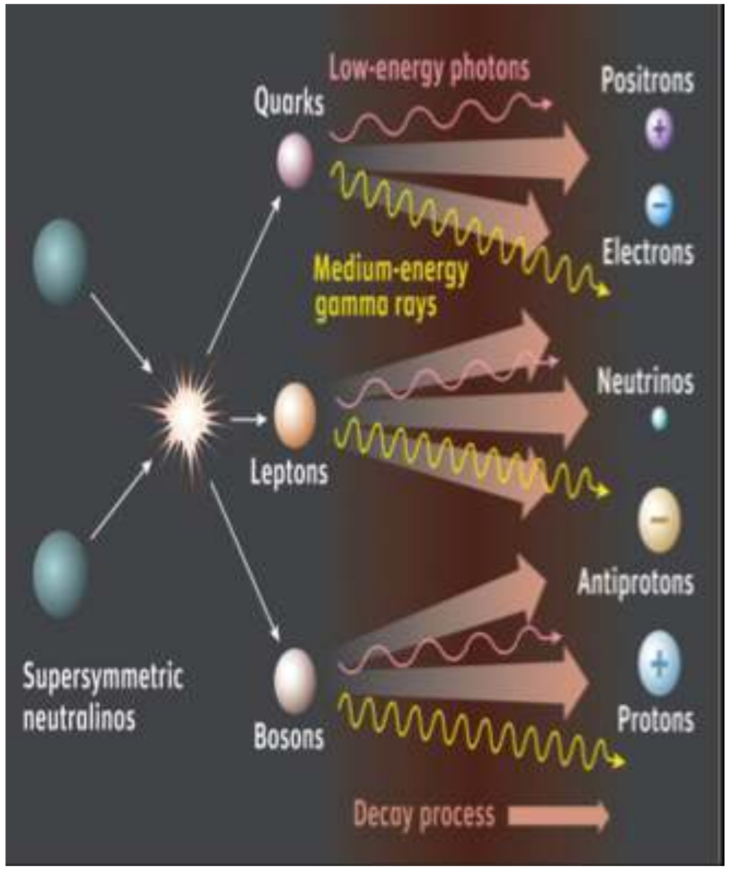
(latest)

Many Higgs-mediated models killed

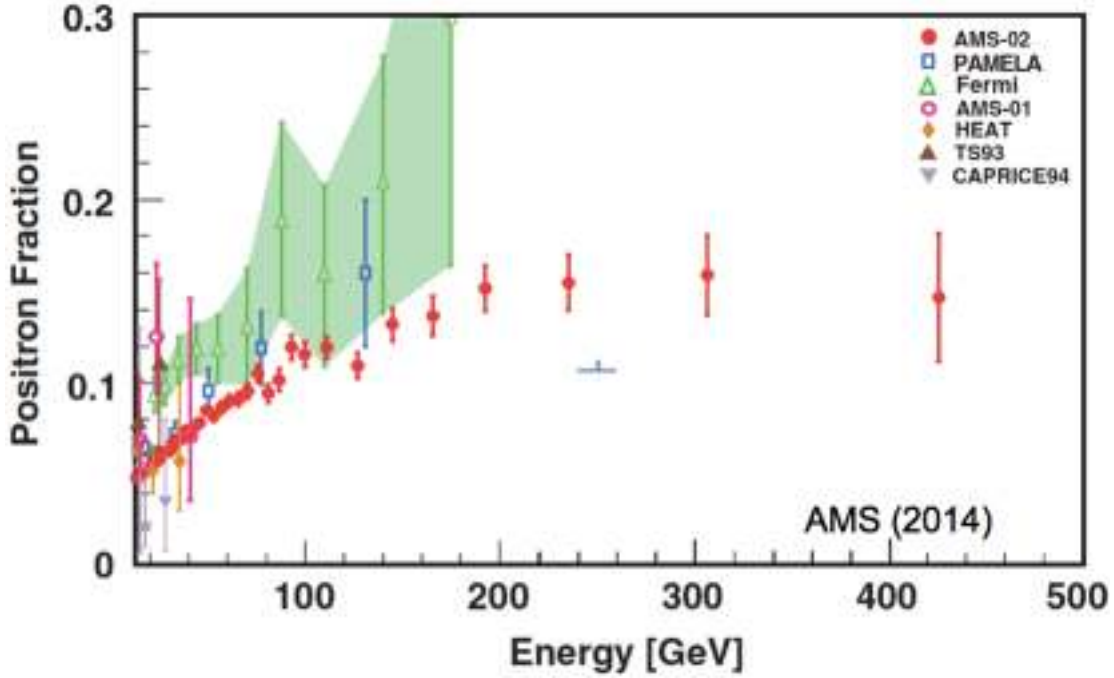


DARK MATTER: INDIRECT DETECTION

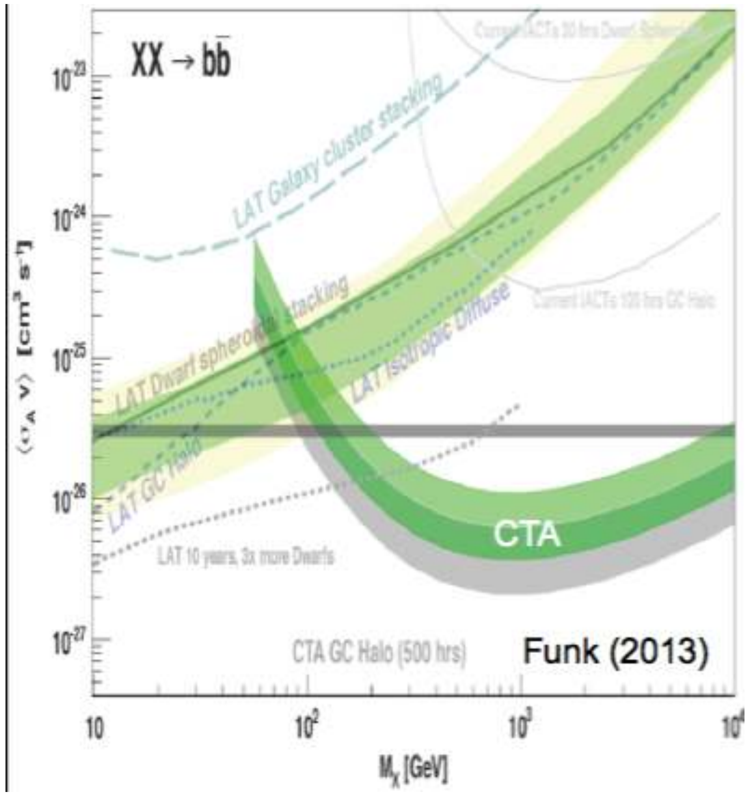
- Dark matter may pair annihilate or decay in our galactic neighborhood to:
- positrons
- high-energy photons
- neutrinos
- antiprotons
- antideutrons

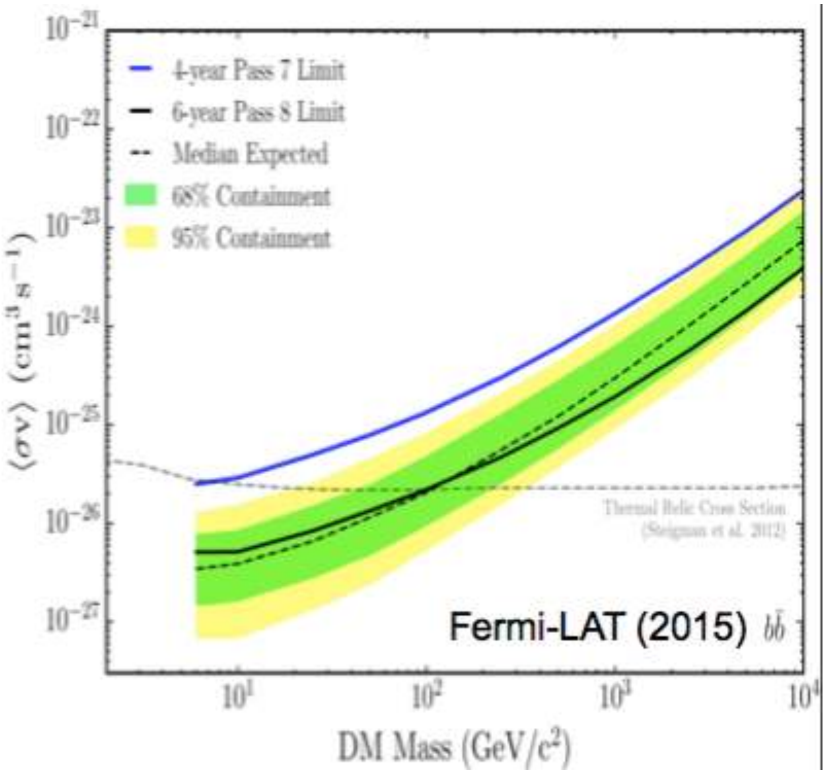


INDIRECT DM: POSITRON RESULTS



INDIRECT DM: PHOTON RESULTS





- Rapid improvements in recent years, Fermi-LAT now excludes WIMP makes up to ~100 GeV for certain annihilation channels

- The future is the Cherenkov Telescope Array, which will extend the reach by two orders in mass up to masses

  ~ 10 TeV

DARK MATTER/NEW PHYSICS

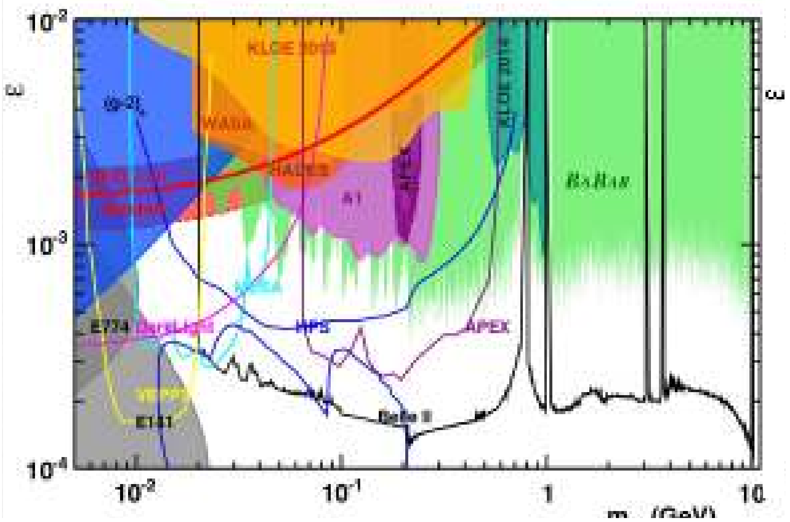
SIMPs(strong interacting massive particle)

- dark matter is strongly interacting under the **other SU(N) gauge interactions.**
- DM may be pion/Baryon/gluball of the new strong interactions or couple to new scalar by large Yukawa coupling

dark photon

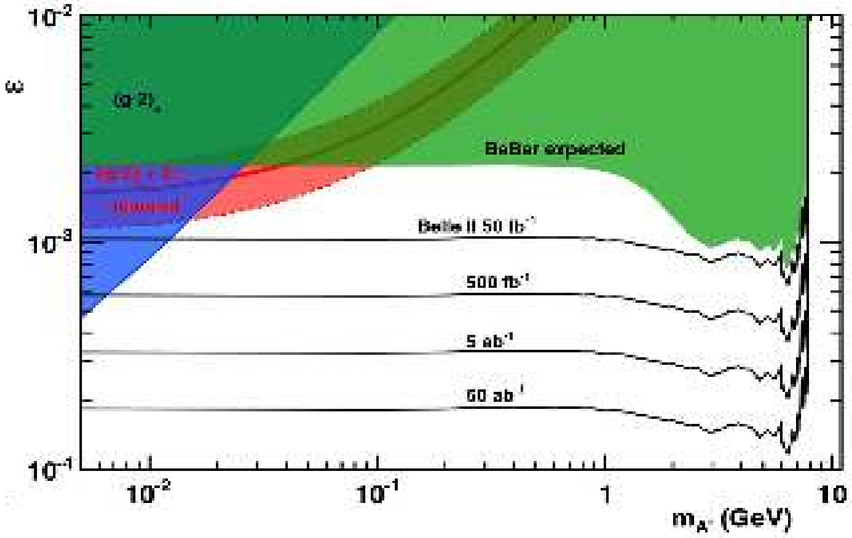
- U(1) gauge boson is relatively easy going object "gauge invariant $F'_{\mu\nu}$"
- sequestering $U(1)_D$ dark sector from SM sector,
- Interaction with SM may arises from kinetic mixing $F_{\mu\nu}F'^{\mu\nu}$
- Dark matter couple to $U(1)_D$ can have very small coupling, and also Very light $U(1)_D$ $a' \rightarrow 3\gamma$ has very long lifetime. Both can be dark matter.

$e^+e^- \rightarrow \gamma A' \rightarrow \gamma e^+e^-, \gamma \mu^+\mu^-$, *prompt*



$e^+e^- \rightarrow \gamma A' \rightarrow \gamma \chi \bar{\chi}$

In



- **Nature of Dark matter** is one of the big questions that particle physics should answer.
- Success of LHC and dark matter searches and we are wondering over next steps to go.

NEW DIMENSIONS

EXTRA SPACE DIM

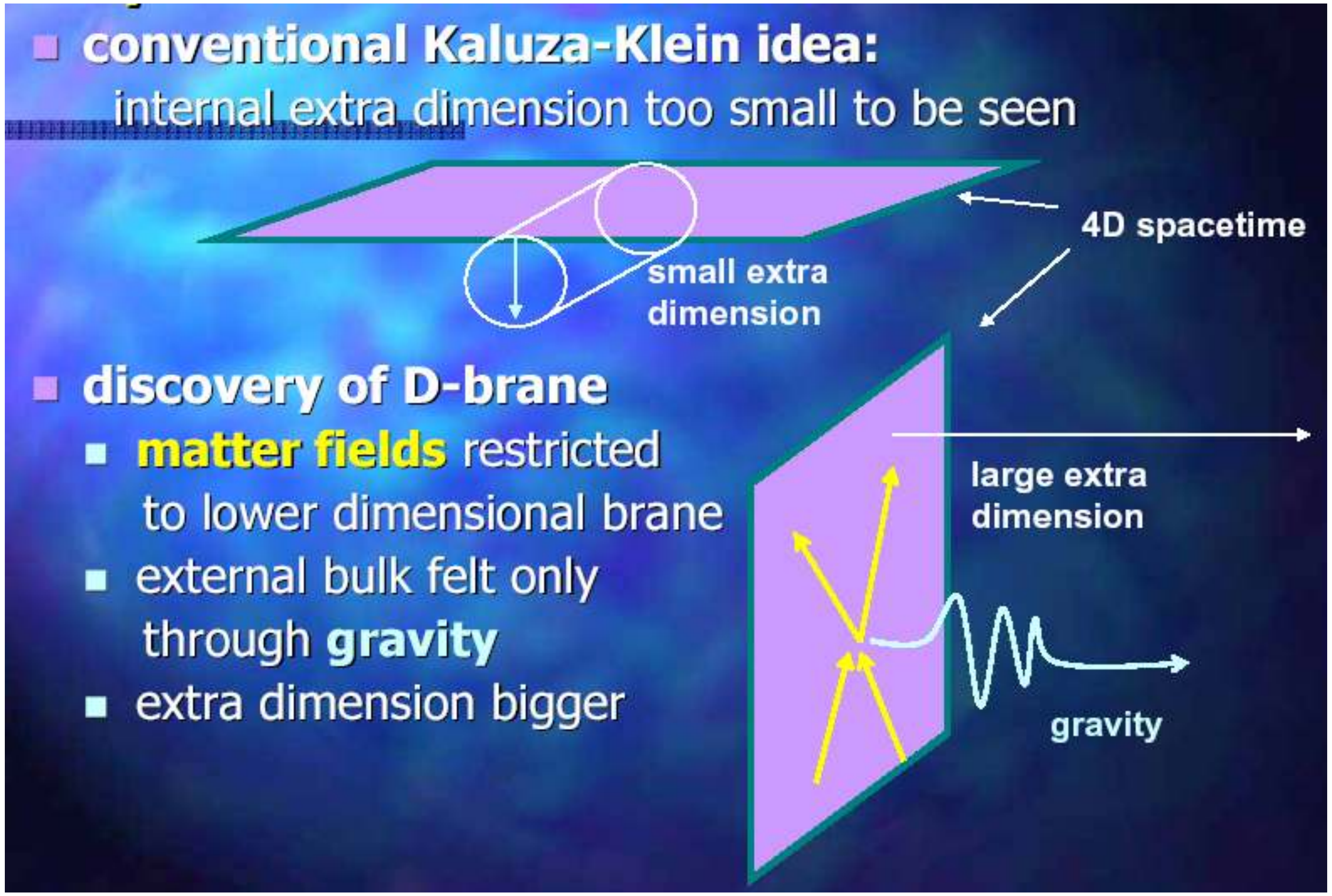
$$1+3 \to 1+n, \;\; n>3$$

Motivations

1. String theory
2. Interesting possibility that opens wide opportunities

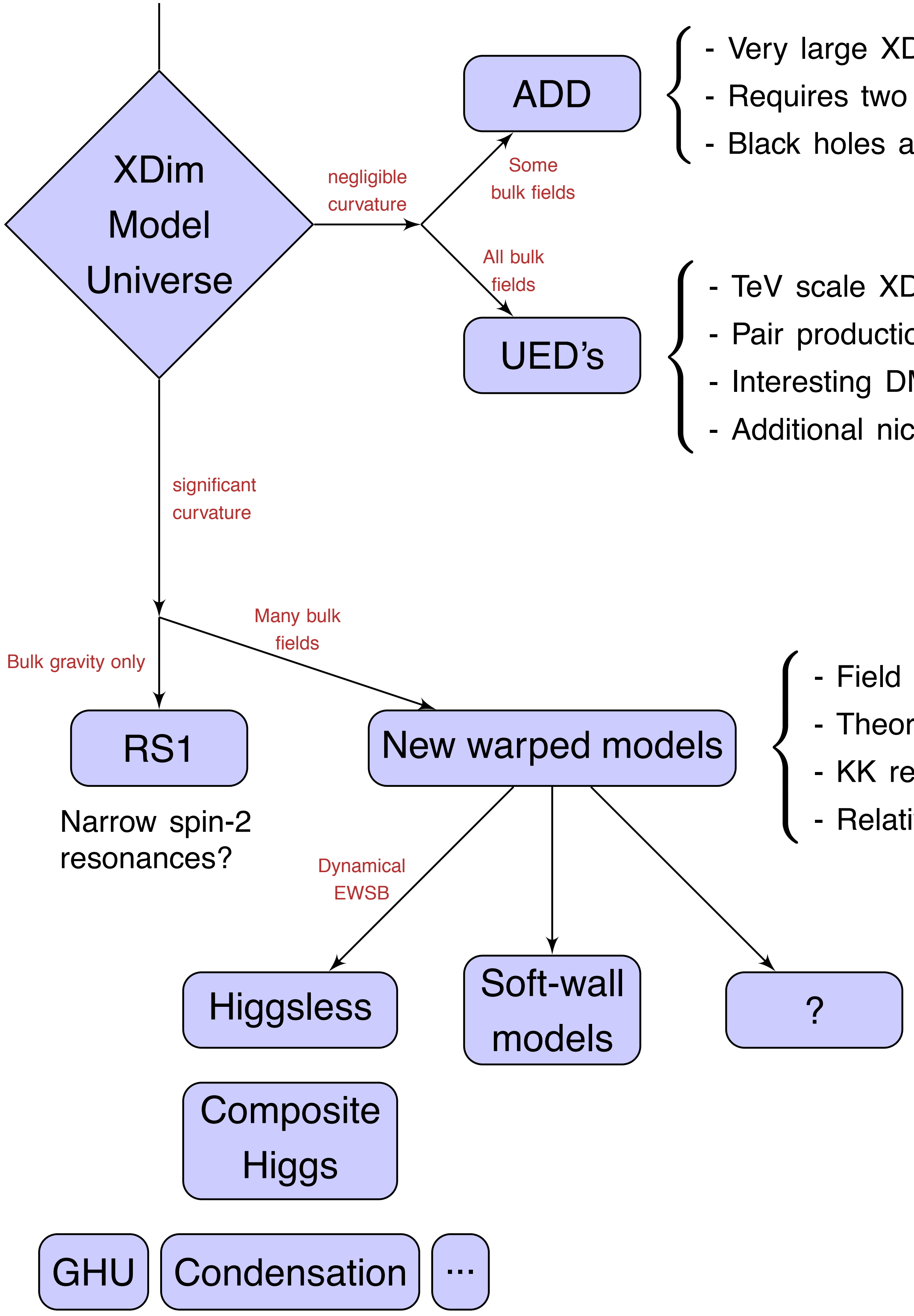
- String theory suffers conformal anomalies that make it inconsistent.
- Conformal anomaly cancels at D=26 for a bosonic string and D=10 for a fermionic string

Why don't we see extra dimensions



- **conventional Kaluza-Klein idea:**
  internal extra dimension too small to be seen
- **discovery of D-brane**
  - **matter fields** restricted to lower dimensional brane
  - external bulk felt only through **gravity**
  - extra dimension bigger

EXTRA SPACE-TIME DIMENSIONS



XDim Model Universe

negligible curvature

Some bulk fields

ADD

- Very large XDim accesible only to gravity
- Requires two or more XDim
- Black holes at colliders?

All bulk fields

UED's

- TeV scale XDim (several hundred GeV?)
- Pair production, $\not{E}_T$ (SUSY-like)
- Interesting DM candidate (non SUSY-like)
- Additional nice features in 6D

significant curvature

Bulk gravity only

RS1

Narrow spin-2 resonances?

Many bulk fields

New warped models

- Field localization
- Theories of flavor?
- KK resonances at few TeV
- Relatively broad resonances

Dynamical EWSB

Higgsless

Composite Higgs

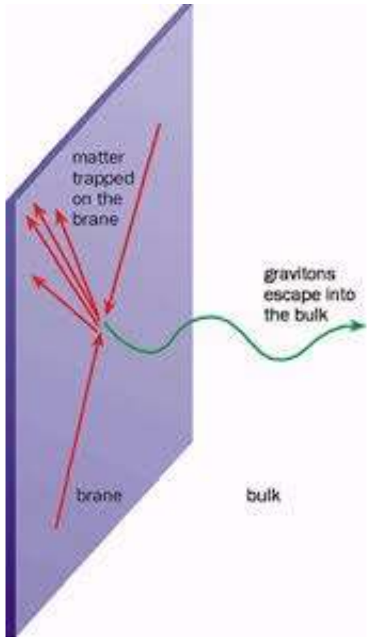
GHU

Condensation

...

Soft-wall models

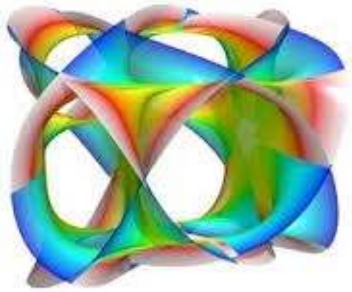
?

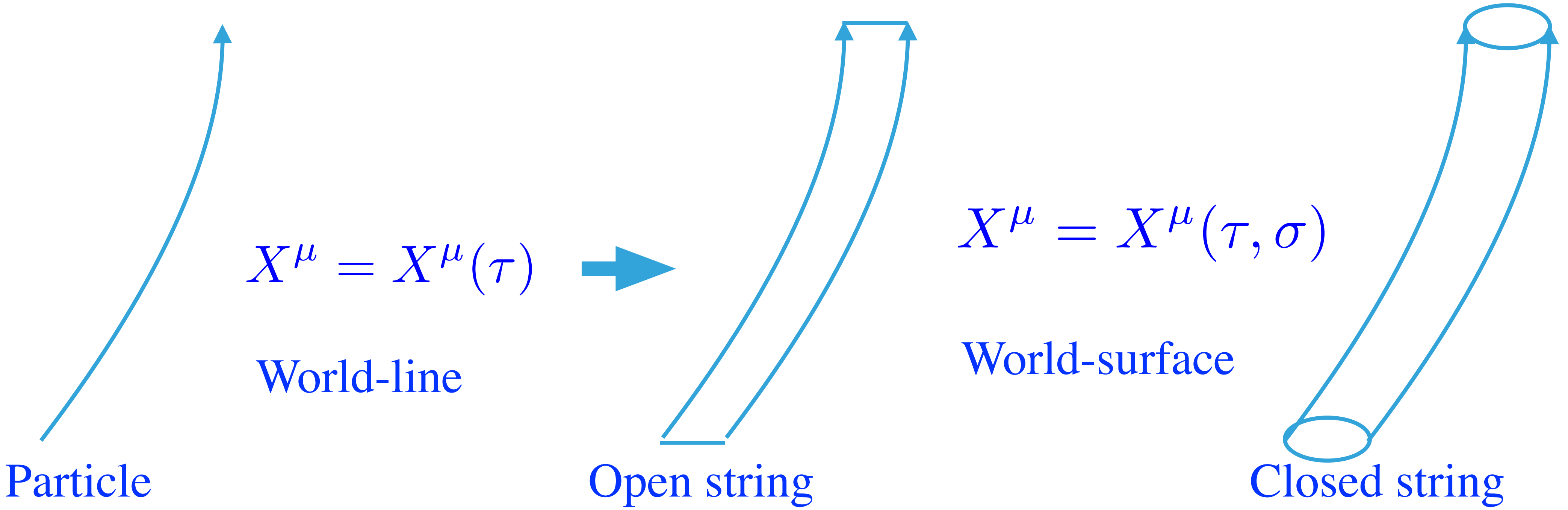


E.Pontón

NEW PARADIGM

STRING THEORY





$X^\mu = X^\mu(\tau)$

World-line

Particle

Open string

$X^\mu = X^\mu(\tau,\sigma)$

World-surface

Closed string

World-line action:

$$S = -m\int d\tau\sqrt{-\frac{dX^\mu}{d\tau}\frac{dX^\nu}{d\tau}\eta_{\mu\nu}} \to \frac{d^2X^\mu}{d\tau^2} = 0$$

World-sheet action:

$$S = -\frac{1}{2\pi l_S^2}\int d^2\sigma\sqrt{-det\left(\frac{dX^\mu}{d\sigma^\alpha}\frac{dX^\nu}{d\sigma^\beta}\eta_{\mu\nu}\right)}$$

string tension

l_S string length

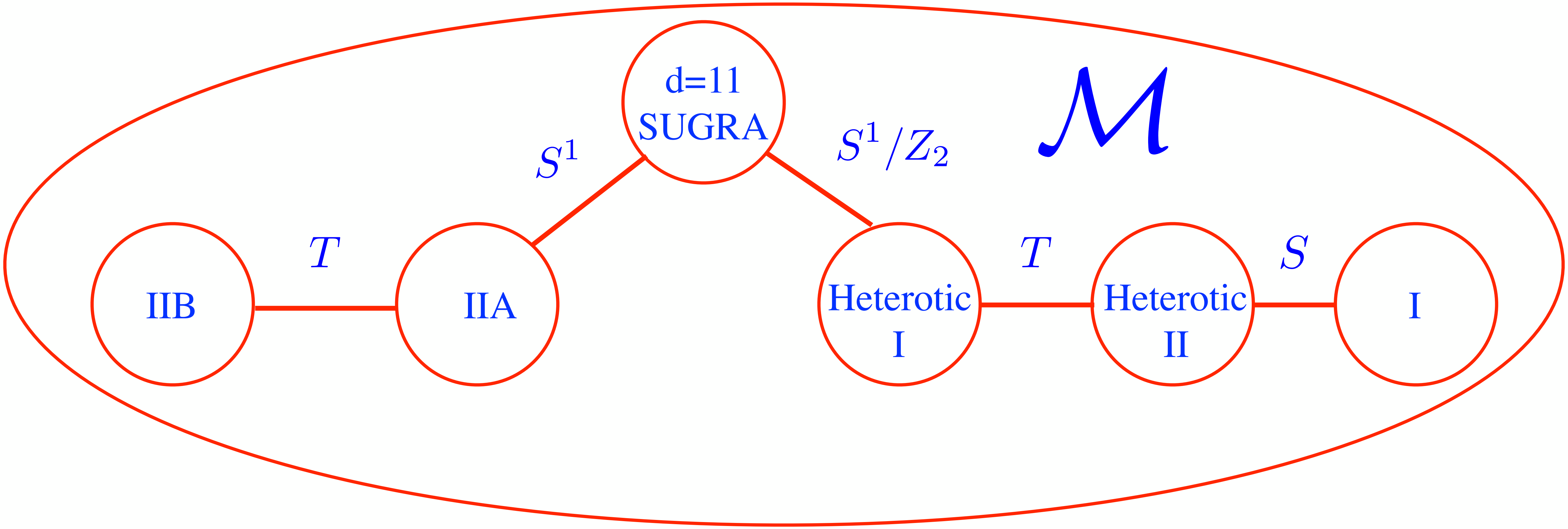
STRING THEORY

✳ There are five types of string theories (IIA, IIB, I, two Heterotic)

✳ All five string theories are only consistent in 10 space-time dimensions

✳ All five string theories have world-sheet supersymmetry and lead to space-time-supersymmetry in 10 dimensions

✳ All five string theories are related and part of a single ‘’theory”: M-theory

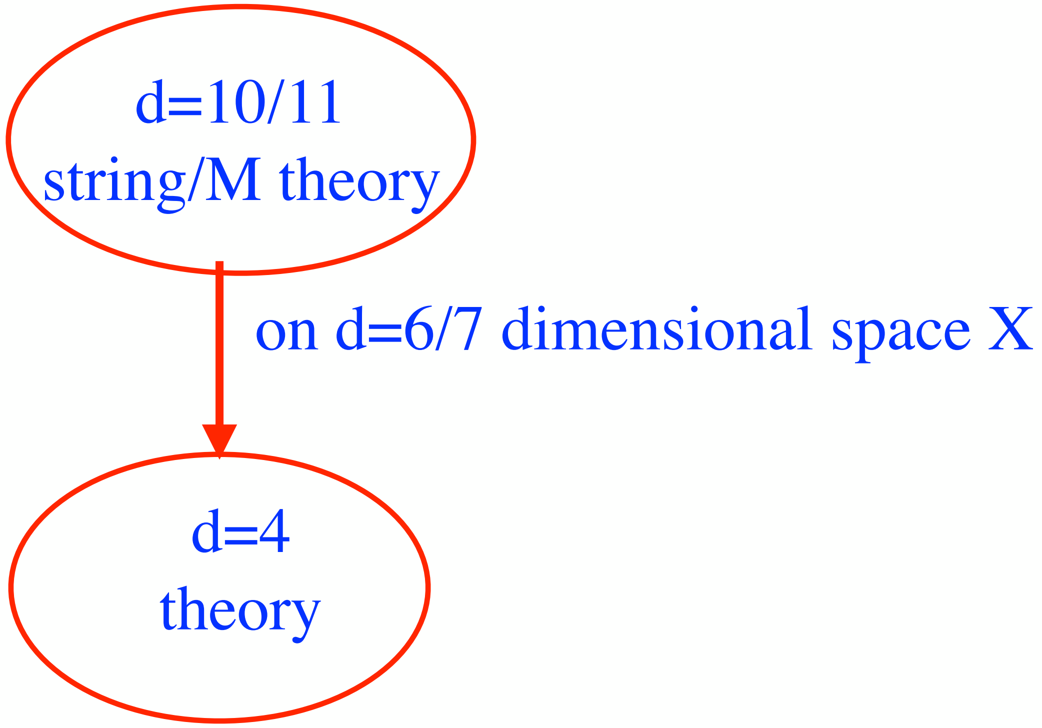


M-theory is a patchwork of the constituent theories plus many “rules”.

It seems unclear, at present, what its fundamental degrees of freedom are.

STRING THEORY AND THE "REAL" WORLD

Need to compactly six or seven dimensions to obtain d=4 theory


d=10/11
string/M theory

on d=6/7 dimensional space X

d=4
theory

Two-fold degeneracy in space X: continuous one in size and shape (moduli) and discrete one topology

Topology determines the structure of d=4 theory

Moduli appearing as scalar fields determine values of couplings in d=4

in D=10/11:

gravity…

… and a p-brane

$$S_D = \frac{1}{l_S^{D-2}} \int d^Dx\sqrt{-g}R + \cdots + \frac{1}{l_S^{p-3}} \int d^{p+1}x\sqrt{-\gamma}\, tr(F_{\alpha\beta}F^{\alpha\beta}) + \cdots$$

in D=4:

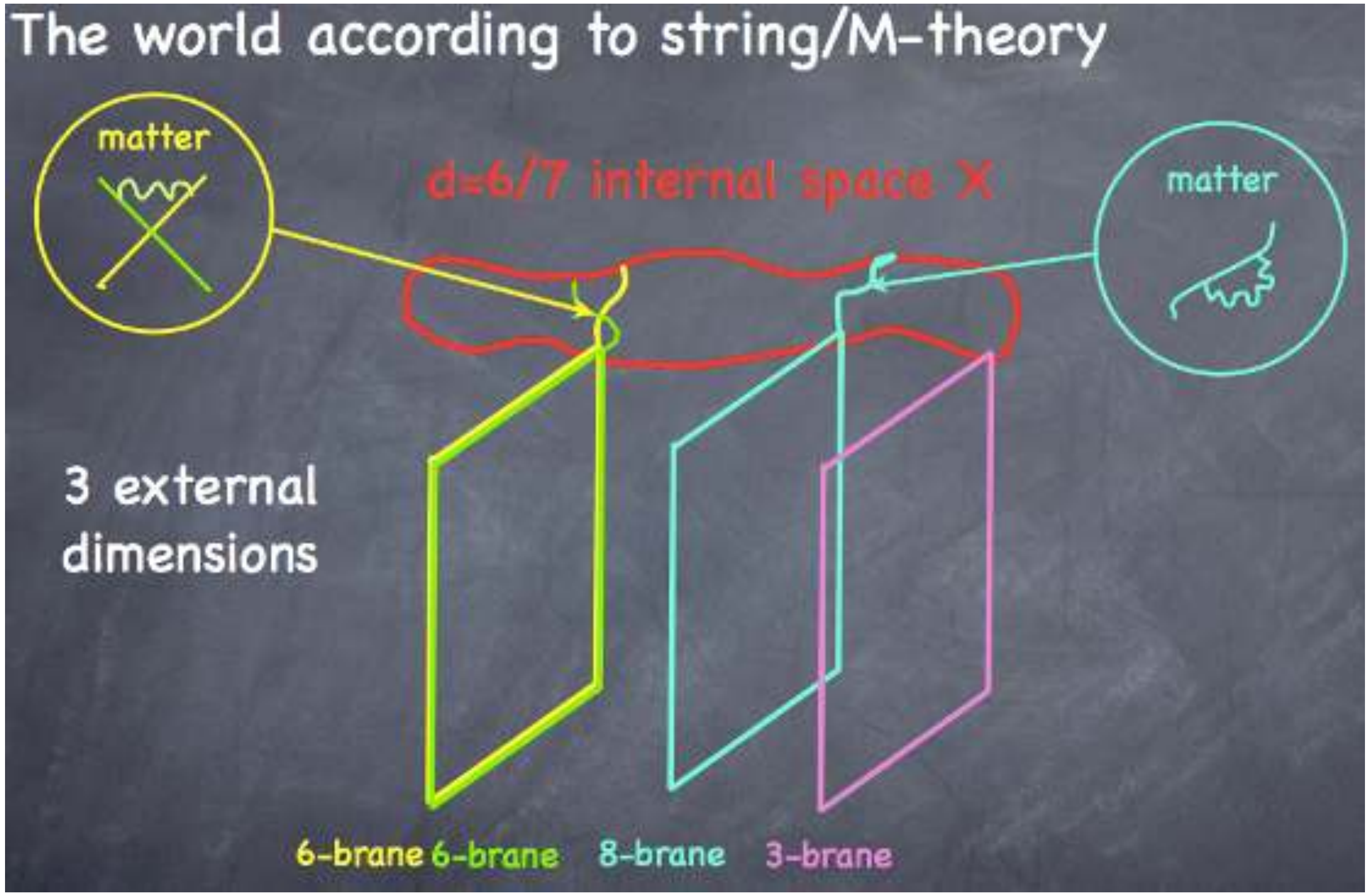
$$S_4 = \underbrace{\frac{V}{l_S^{D-2}}}_{\frac{1}{16\pi G_N}} \int d^Dx\sqrt{-g_4}R_4 + \cdots + \underbrace{\frac{v}{l_S^{p-3}}}_{\frac{1}{16\pi g_{YM}^2}} \int d^{p+1}x\sqrt{-g_4}\, tr(F_{\mu\nu}F^{\mu\nu}) + \cdots$$

NEW PARADIGM

BRAIN WORLD

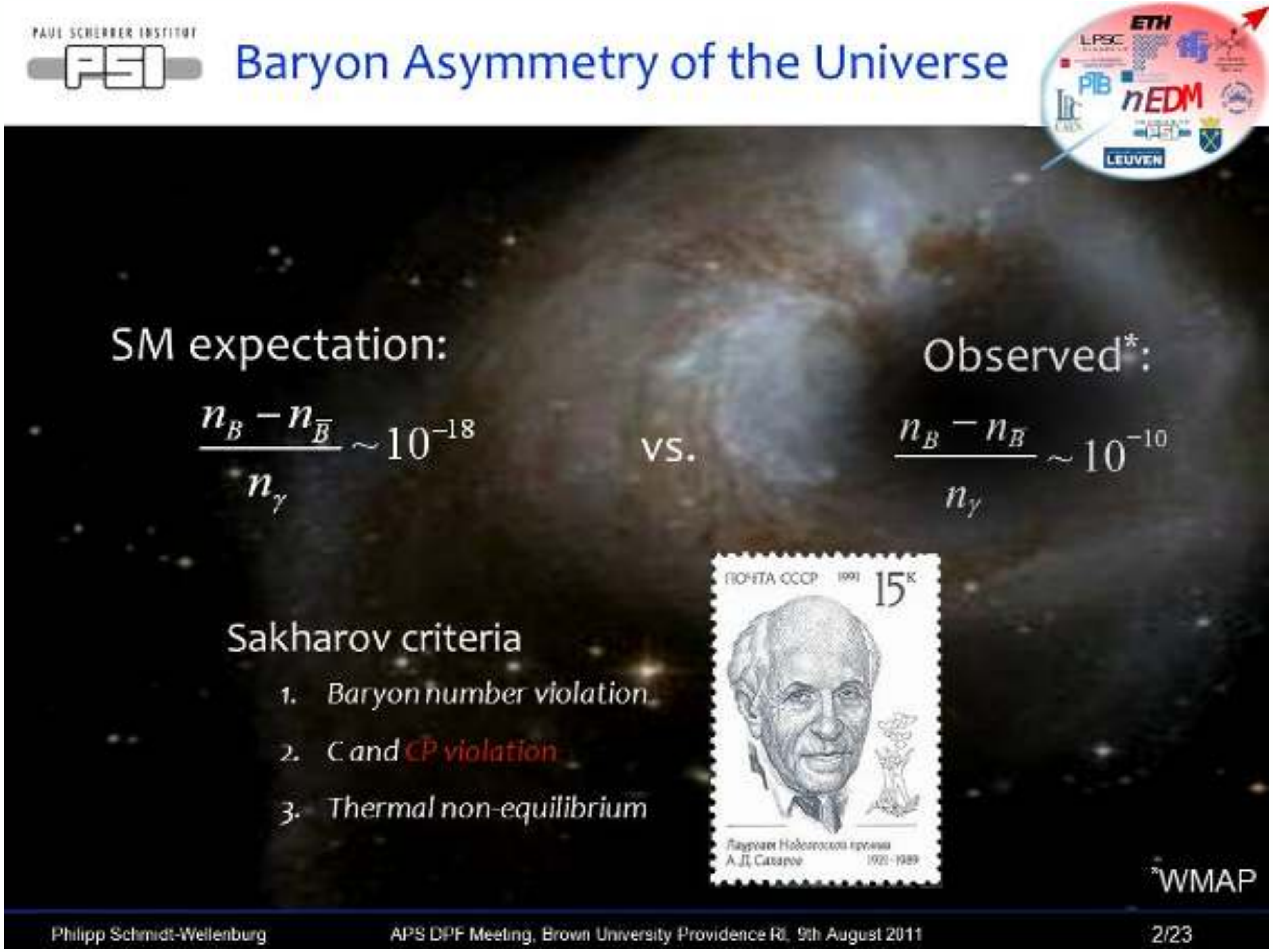
String theory contains not just strings but extended objects

- branes - of all dimensions



Q: Do we really live on a brane?
A: We have to check it
Q: Do we have good reasons to believe in it?
A: No, but it is appealing
Q: Why D>4?
A: String theory loves it
Q: Is it what we believe in?
A: We believe in BIG deal

THE STANDARD MODEL: CONCEPTUAL PROBLEMS



Baryon Asymmetry of the Universe

SM expectation:

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

vs.

Observed*:

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

Sakharov criteria

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

*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

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

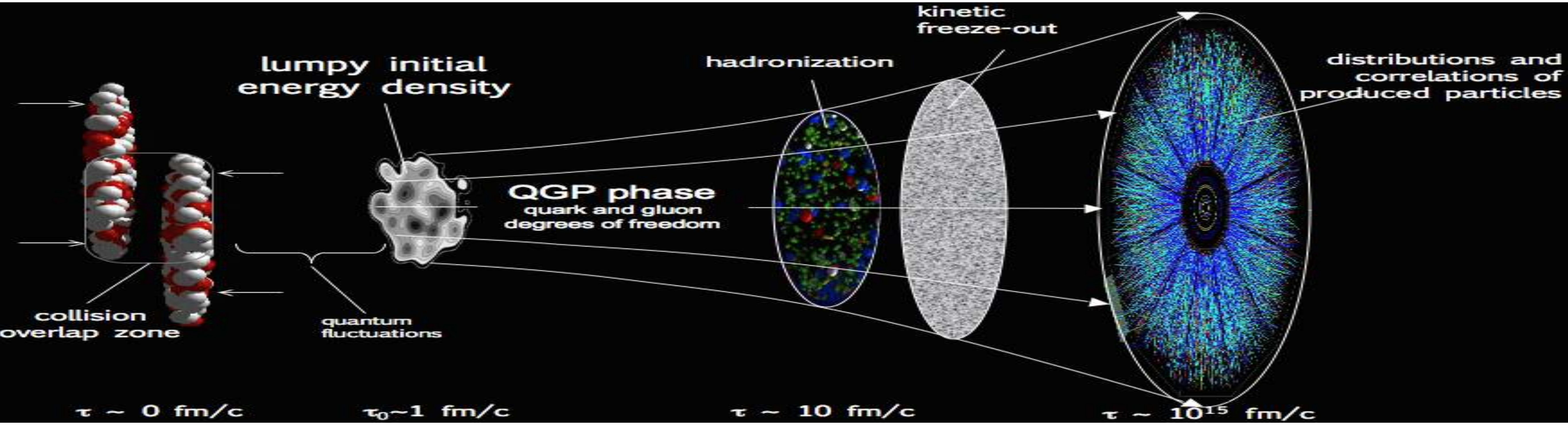
$\cancel{B}$

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

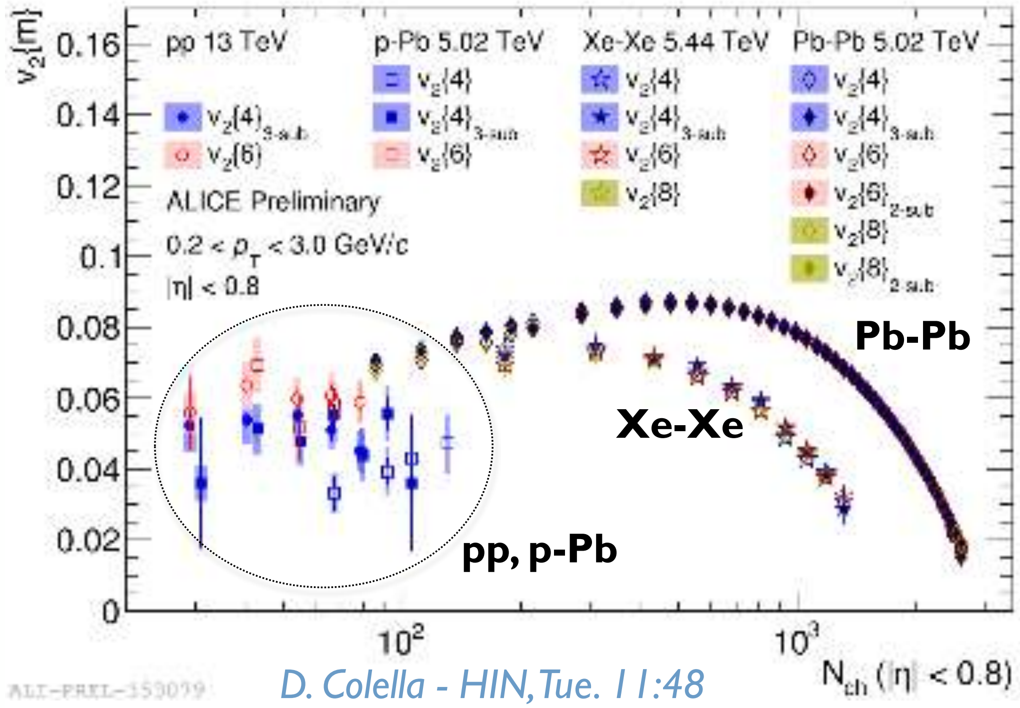
BAU requires larger CP than in the SM Possible Baryogeneses via Leptogeneses

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

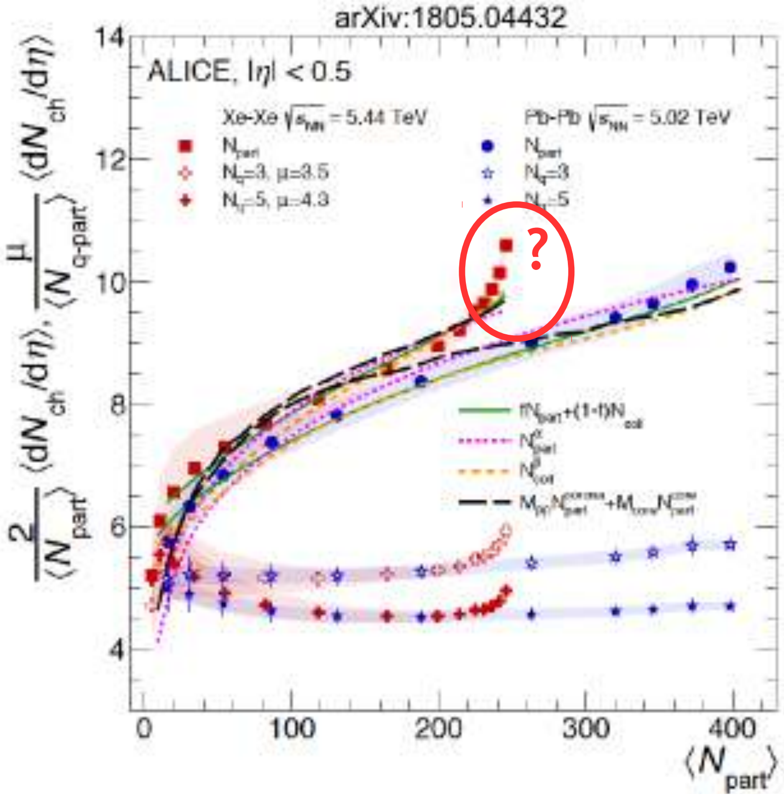
Heavy Ion Collisions: new State of Matter and new Phenomena at Density Frontier



Collectivity in small systems



D. Colella - HIN, Tue. 11:48

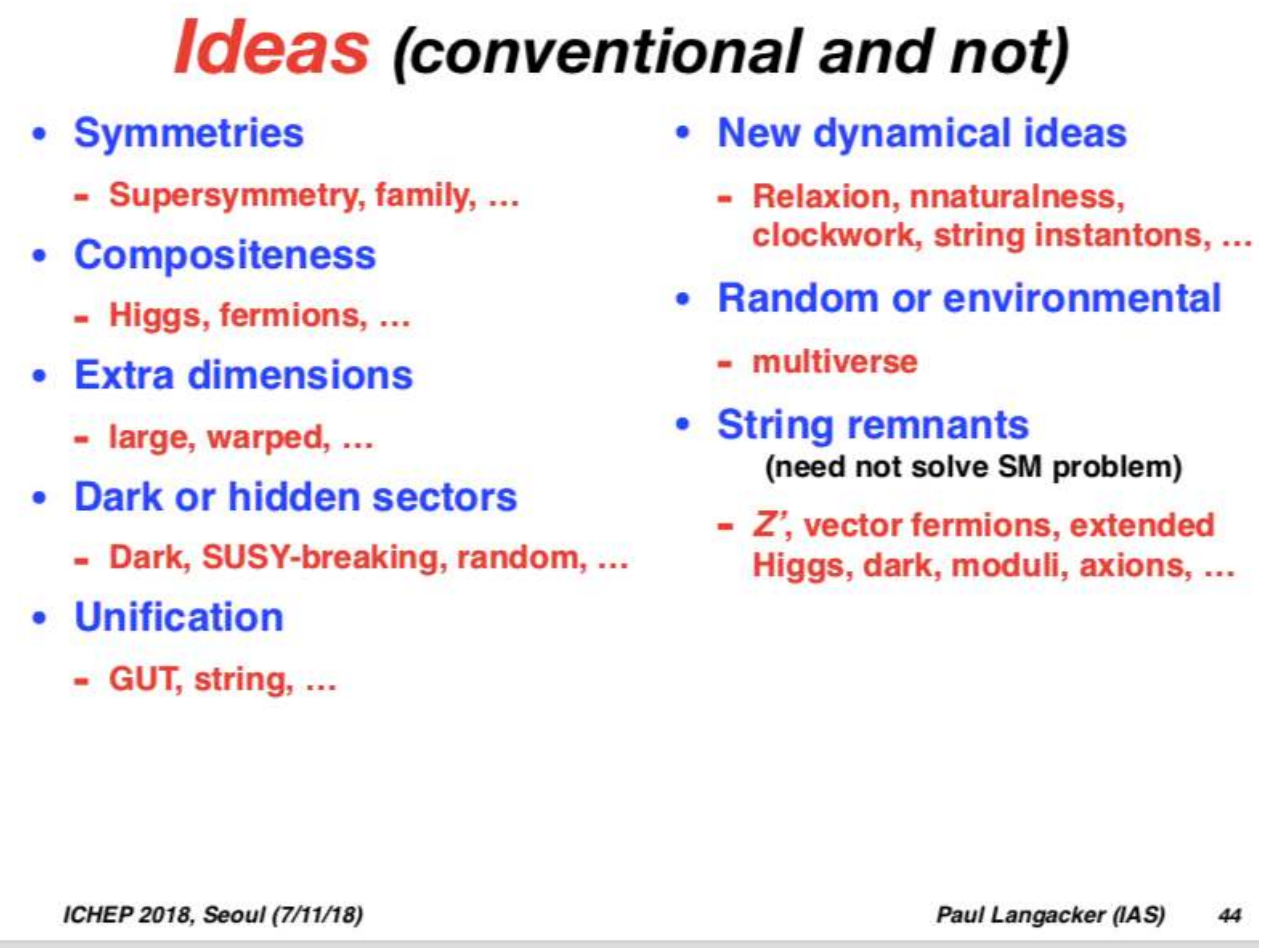


Sharp increase in multiplicity at high centrality in XeXe – not seen in PbPb

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

- Small discrepancy with experimental data
- Possible new ingredients in neutrino sector (majorana neutrino)
- Instability of electroweak vacuum
- Inability to describe the Dark matter (unless it has pure gravitational nature)
- Baryon asymmetry of the Universe is a fundamental problem (Baryon and Lepton genesis might require new ingredients)
- 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

BEYOND THE STANDARD MODEL: CONCLUSIONS



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, …

BEYOND THE STANDARD MODEL: CONCLUSIONS

Which way to go ?

How Will We Make Progress?

- The energy frontier
- The precision frontier and neutrinos
- Cosmology and astrophysics