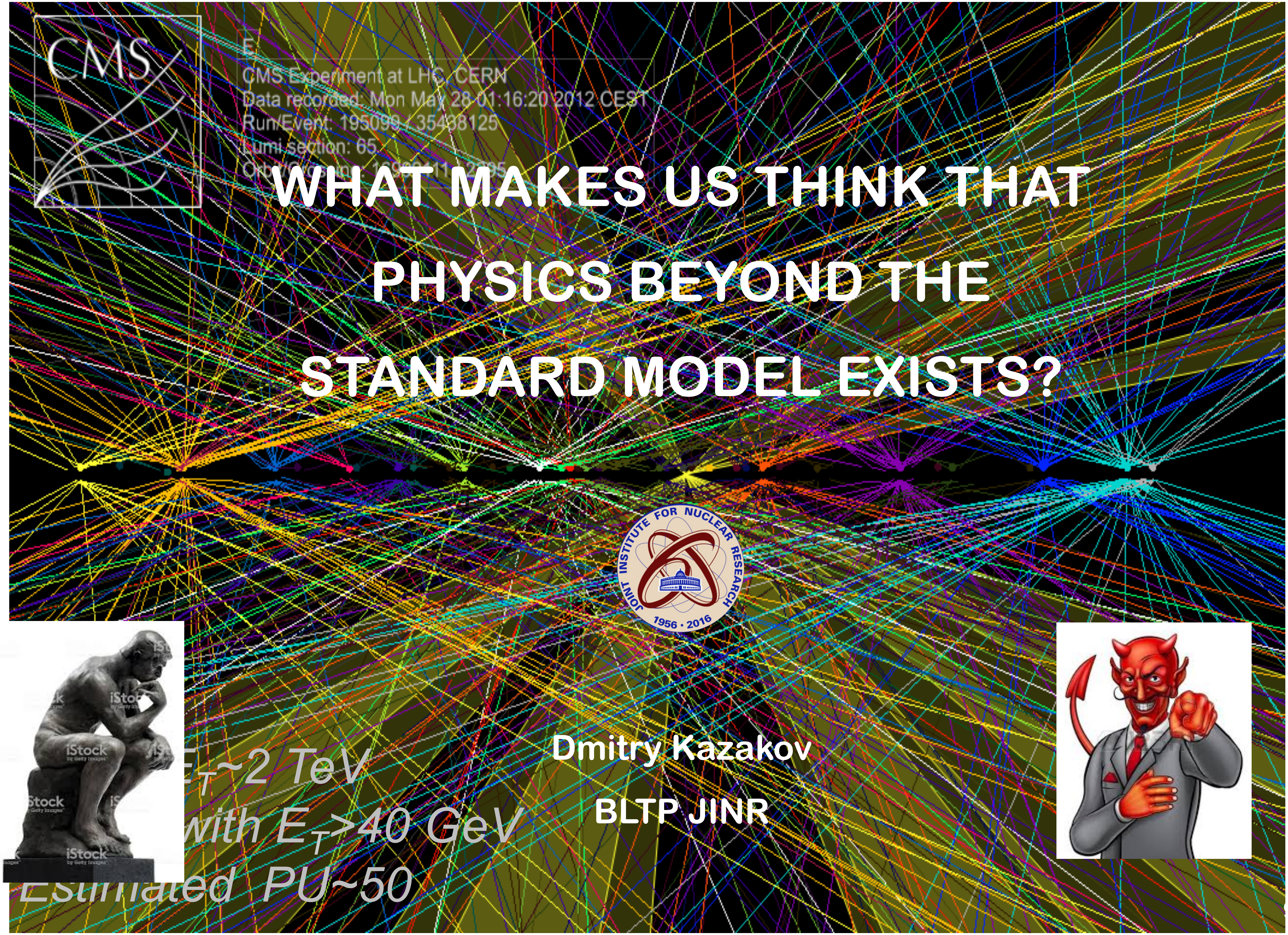
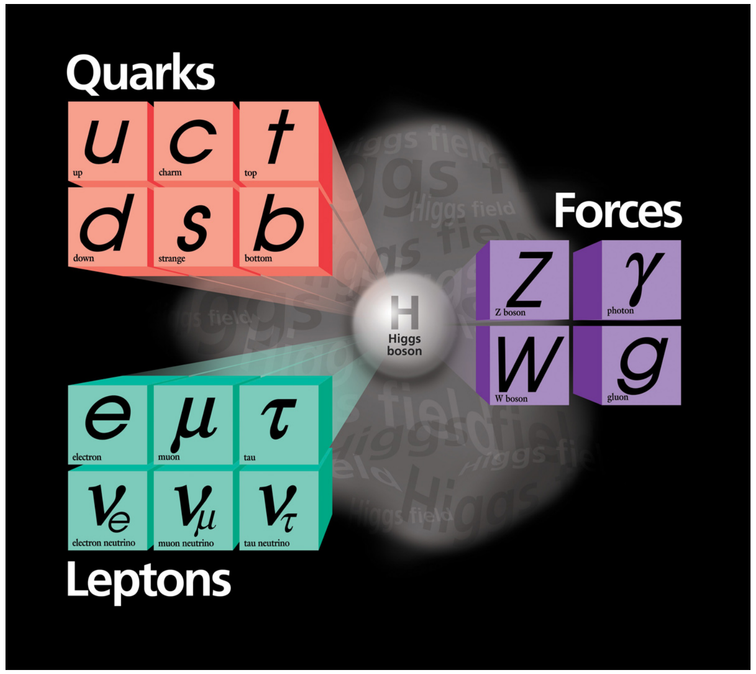


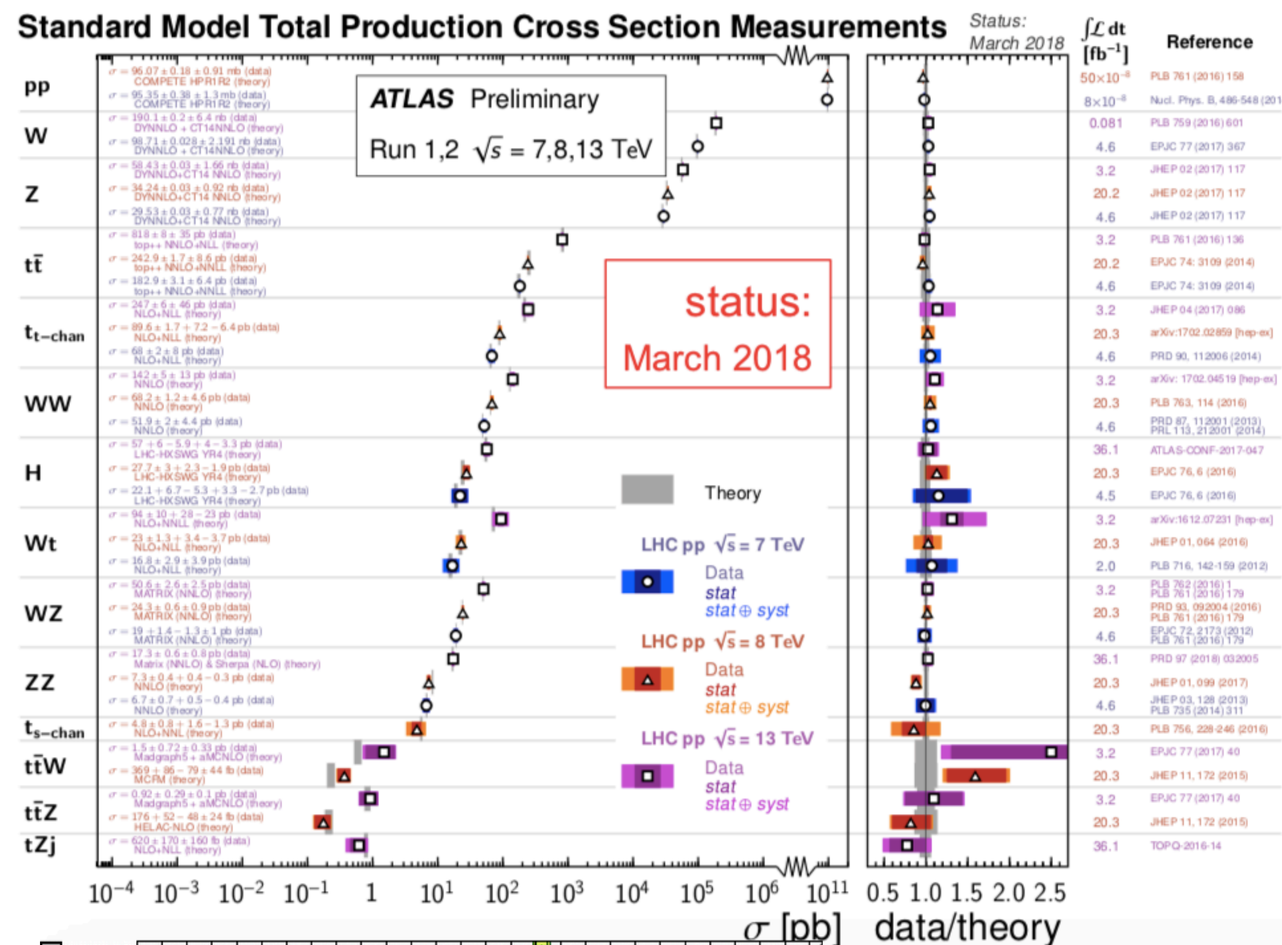
WHAT MAKES US THINK THAT PHYSICS BEYOND THE STANDARD MODEL EXISTS?

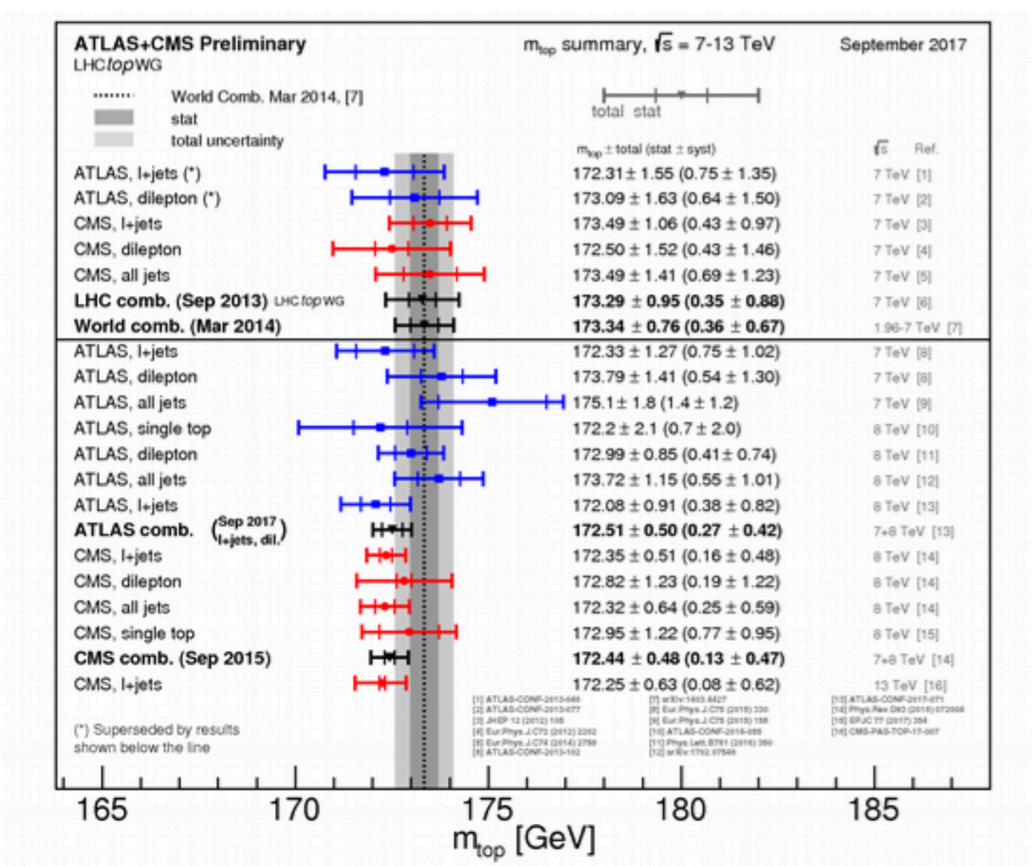
Dmitry Kazakov

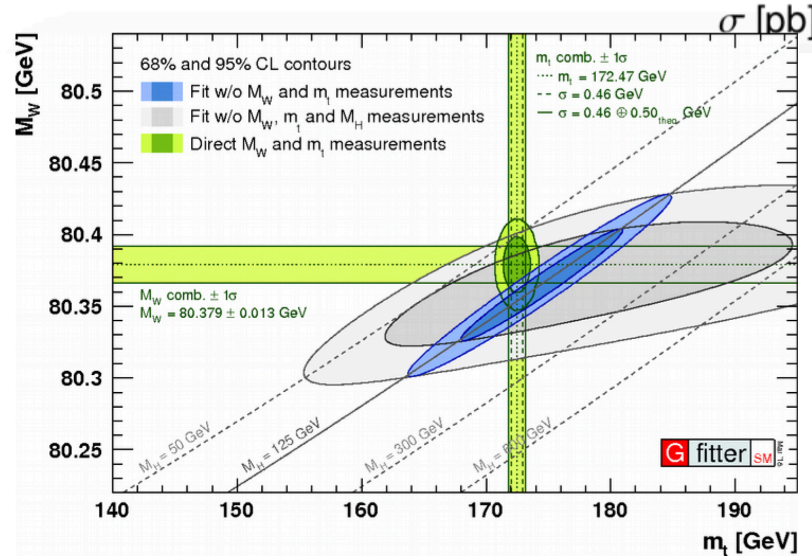
BLTP JINR

The Standard Model



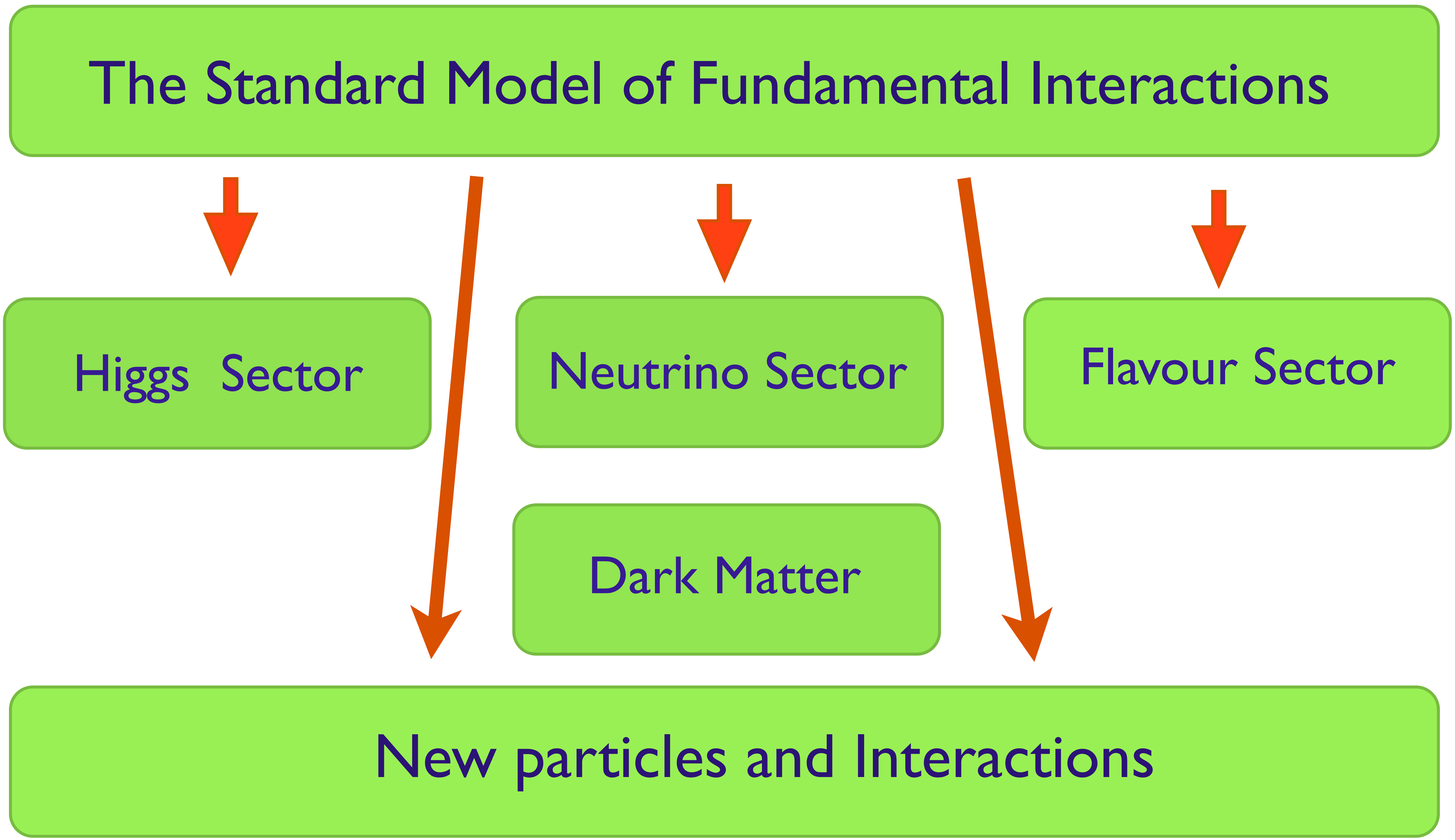






Extraordinary agreement between measurements and SM predictions

THE STANDARD MODEL: THE WAYS BEYOND



THE PRINCIPLES

- Three gauged symmetries SU(3)xSU(2)xU(1)
- Three families of quarks and leptons (3x2, 3x1, 1x2, 1x1)
- 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 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?

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

- 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?

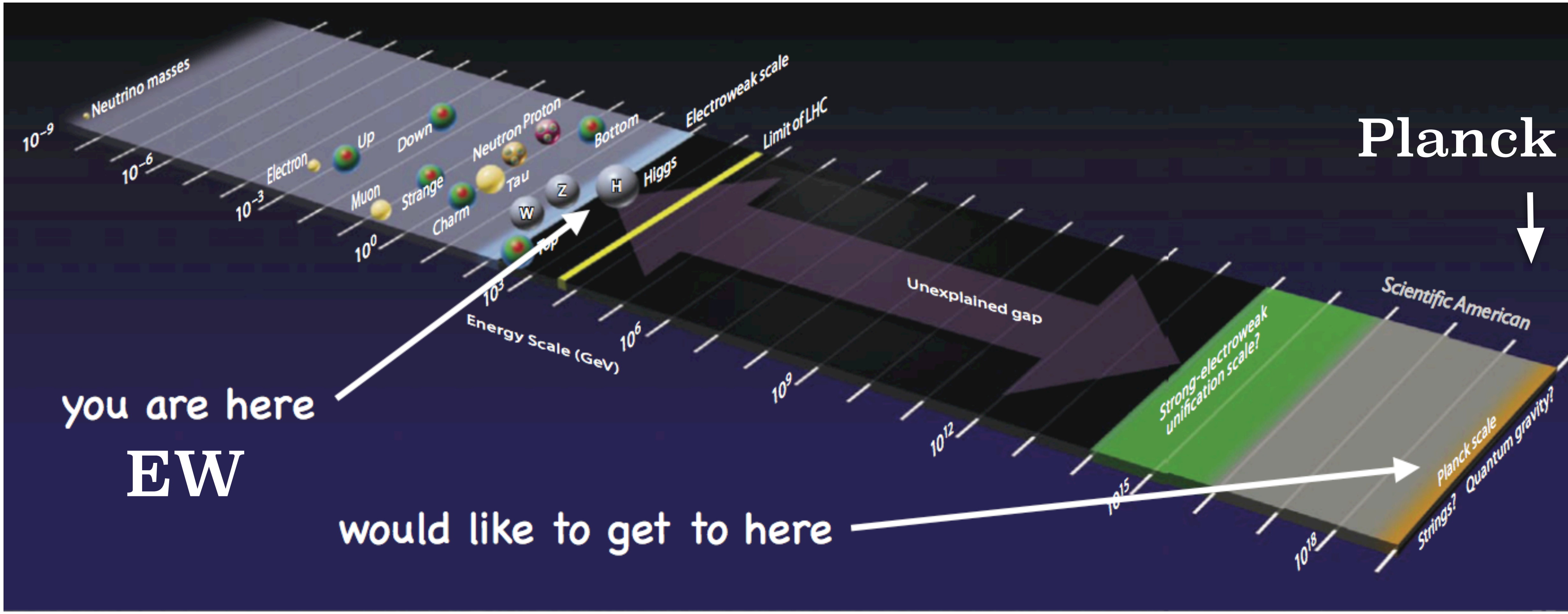
- With the Higgs Boson discovery the Standard Model is completed !
- Why are we not satisfied and think that new physics exists and new discoveries will come?

- 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

ACTUAL QUESTIONS

- What the dark matter is made of?
- Nature of neutrino: Dirac or Majorana ?
- The Higgs sector: one or many?
- CP violation and baryon asymmetry of the Universe?
- Is there and what kind of confinenent-deconfinement phrase transition?
- Lepton nonuniversality: fiction or real?
- How are hadrons build: spin, multi quark states, gluebols?
- (Non)stability of electroweak vacuum?
- Is there any deviations from the Standard model ?

Is there another scale except for EW and Planck?



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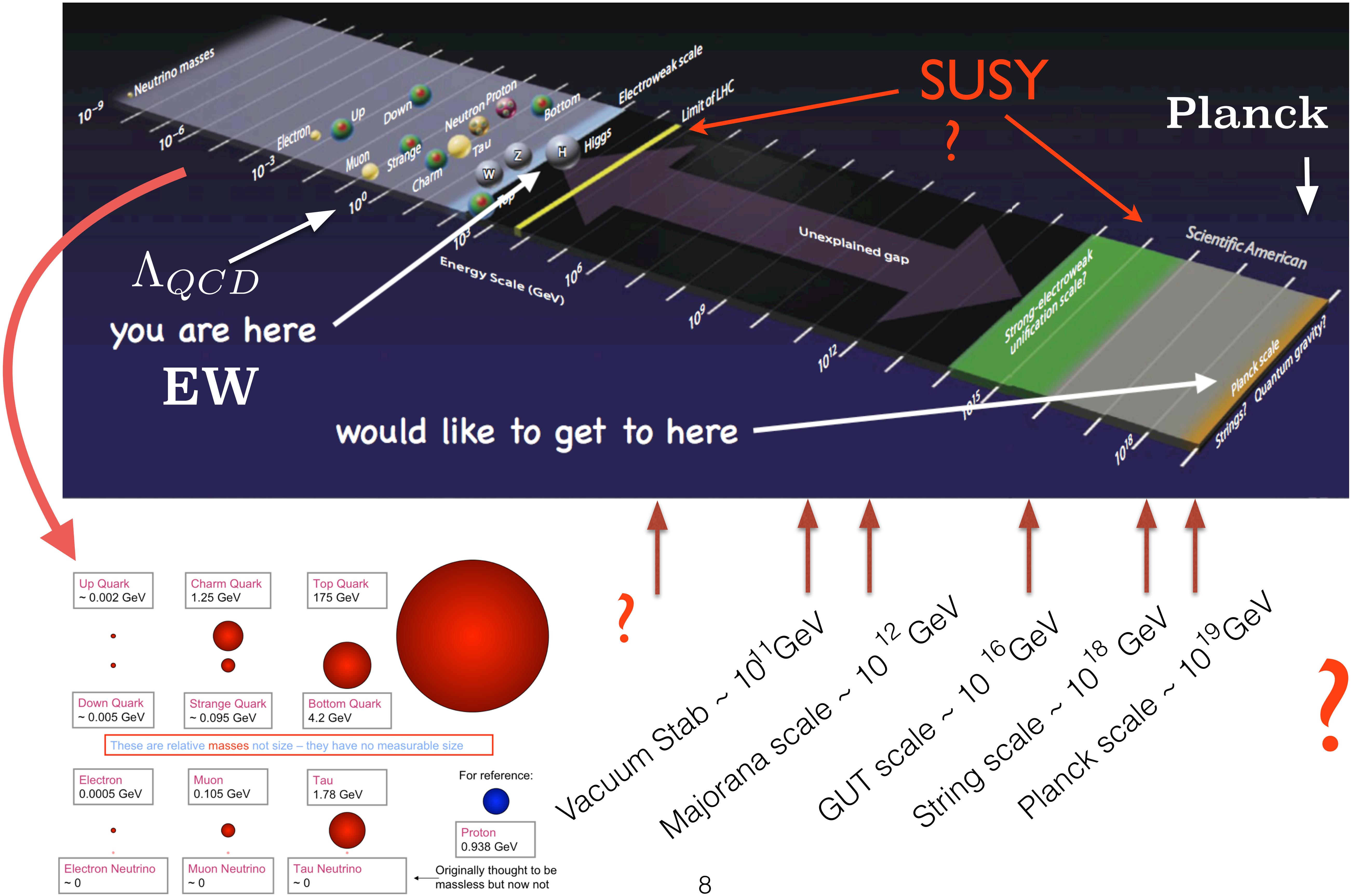

THE LAGRANGIAN

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

$$\mathcal{L}_{gauge} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W^i_{\mu\nu} - \frac{1}{4} B_{\mu\nu} B_{\mu\nu}$$
$$+ i\overline{L}_\alpha \gamma^\mu D_\mu L_\alpha + i\overline{Q}_\alpha \gamma^\mu D_\mu Q_\alpha + i\overline{E}_\alpha \gamma^\mu D_\mu E_\alpha$$
$$+ i\overline{U}_\alpha \gamma^\mu D_\mu U_\alpha + i\overline{D}_\alpha \gamma^\mu D_\mu D_\alpha + (D_\mu H)^\dagger (D_\mu H),$$

$$+ i\overline{N}_\alpha \gamma^\mu \partial_\mu N_\alpha$$ ← possible right handed neutrino ?

$$\mathcal{L}_{Yukawa} = y^L_{\alpha\beta} \overline{L}_\alpha E_\beta H + y^D_{\alpha\beta} \overline{Q}_\alpha D_\beta H + y^U_{\alpha\beta} \overline{Q}_\alpha U_\beta \tilde{H} + h.c.,$$

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

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

THE LAGRANGIAN

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

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

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

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

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

$$\mathcal{L}_{Yukawa} = y^L_{\alpha\beta}\overline{L}_\alpha E_\beta H$$

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

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

$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 -$$
$$\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$
$$\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c^2_w}Z^0_\mu Z^0_\mu H -$$
$$\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\tfrac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c^2_w}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-\right) -$$
$$\tfrac{1}{2}g^2\tfrac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2 s^2_w A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial +$$
$$m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w - 1 - \gamma^5)d^\lambda_j) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s^2_w + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa -$$
$$\tfrac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$
$$\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 -$$
$$\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w}\bar{X}^0 X^0 H\right) + \tfrac{1-2c^2_w}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) +$$
$$\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) +$$
$$\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).$$

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possible right handed neutrino ?

$$\mathcal{L}_{Yukawa} = y^L_{\alpha\beta}\overline{L}_\alpha E_\beta H + y^D_{\alpha\beta}\overline{Q}_\alpha D_\beta H + y^U_{\alpha\beta}\overline{Q}_\alpha U_\beta \tilde{H} + h.c.,$$

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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

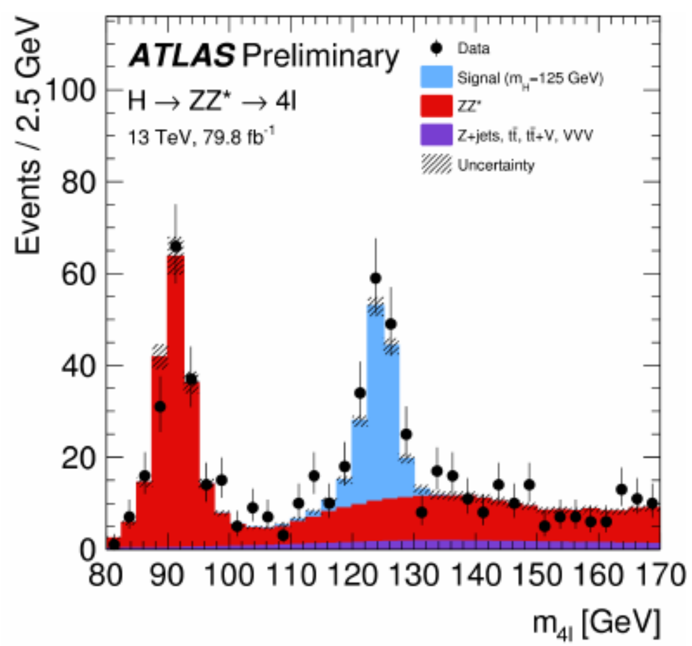
Three or four Yukawa matrices

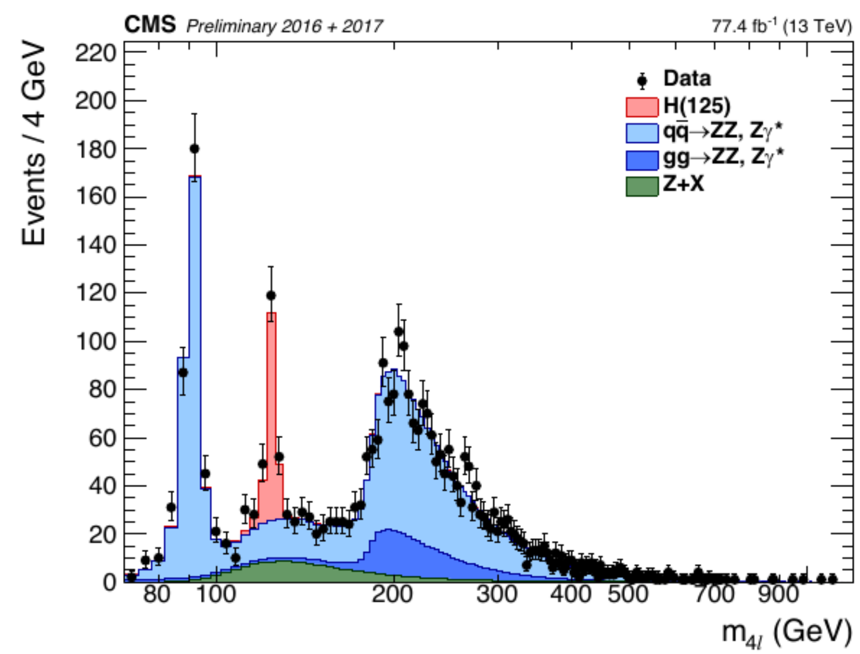
Two parameters

Higgs sector

Higgs bosons - entering precision era

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

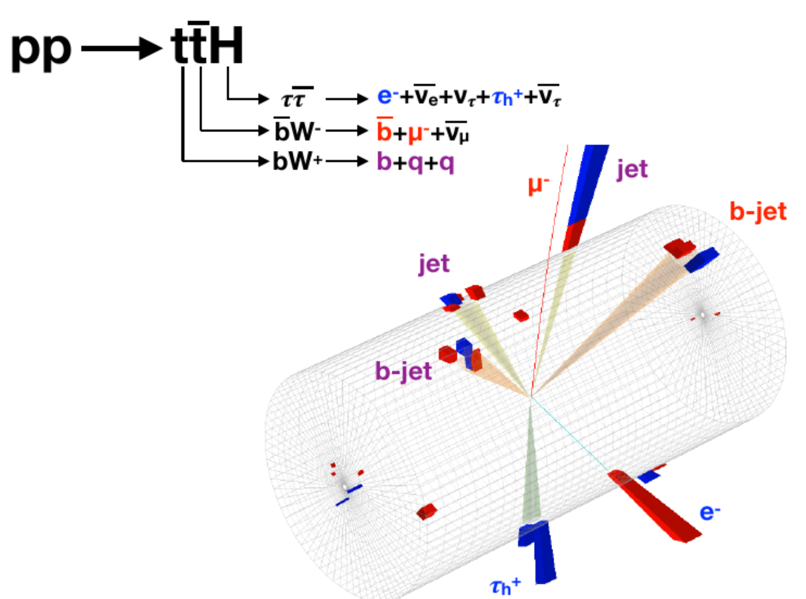


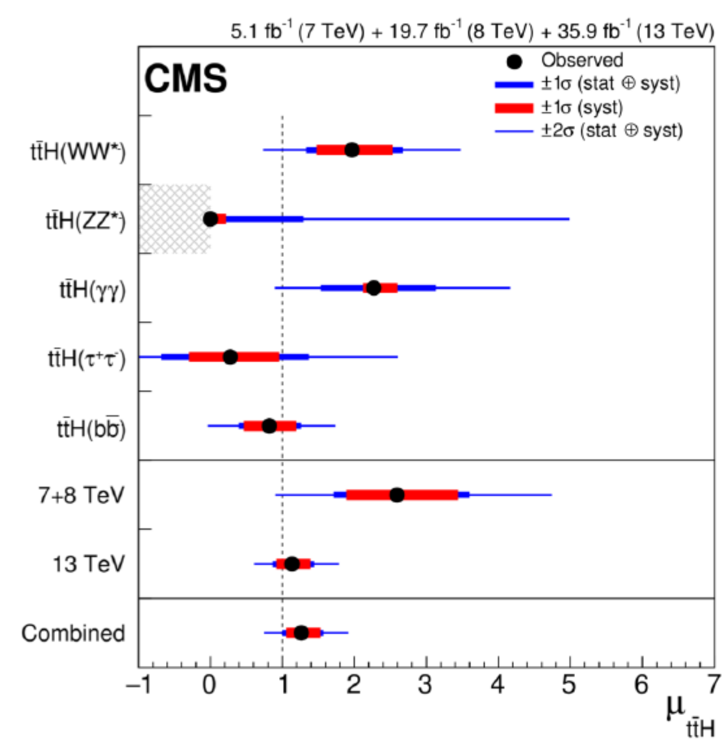


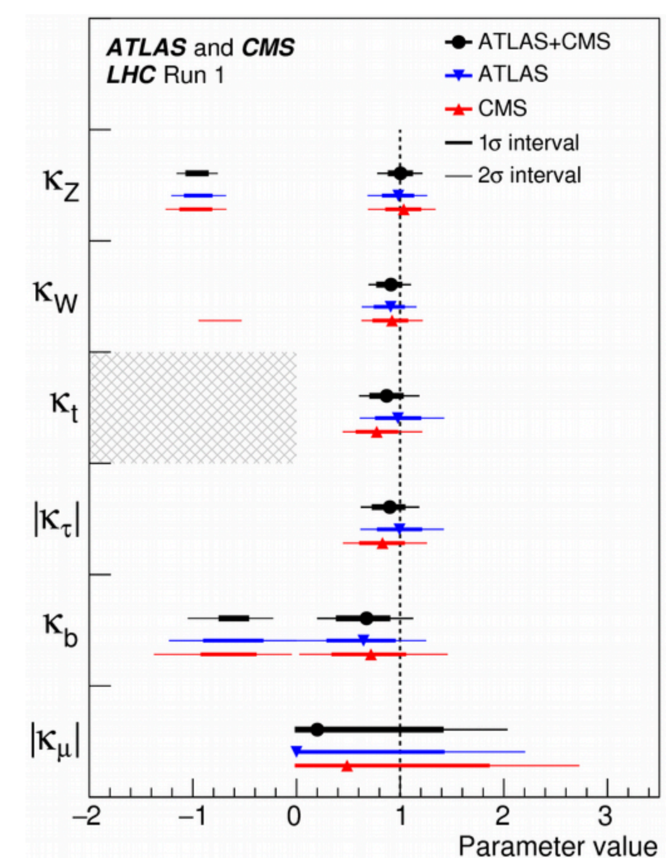
D. Charlton

LHCp2018

ttH observation

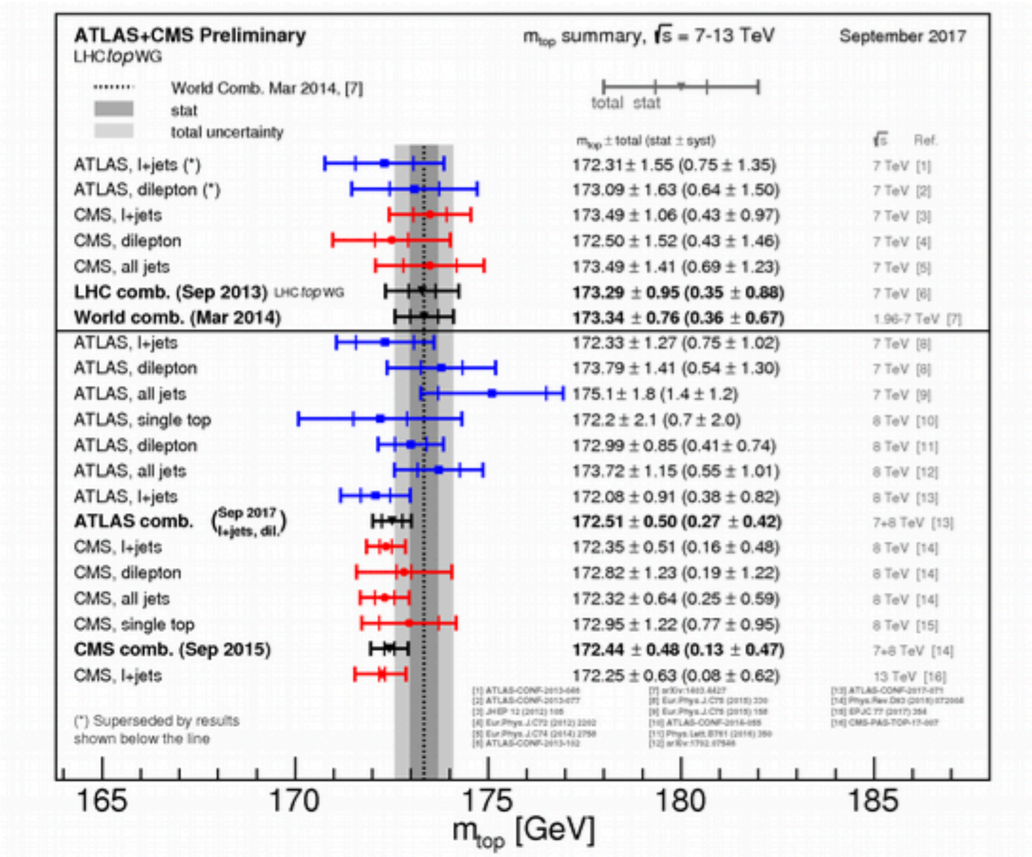


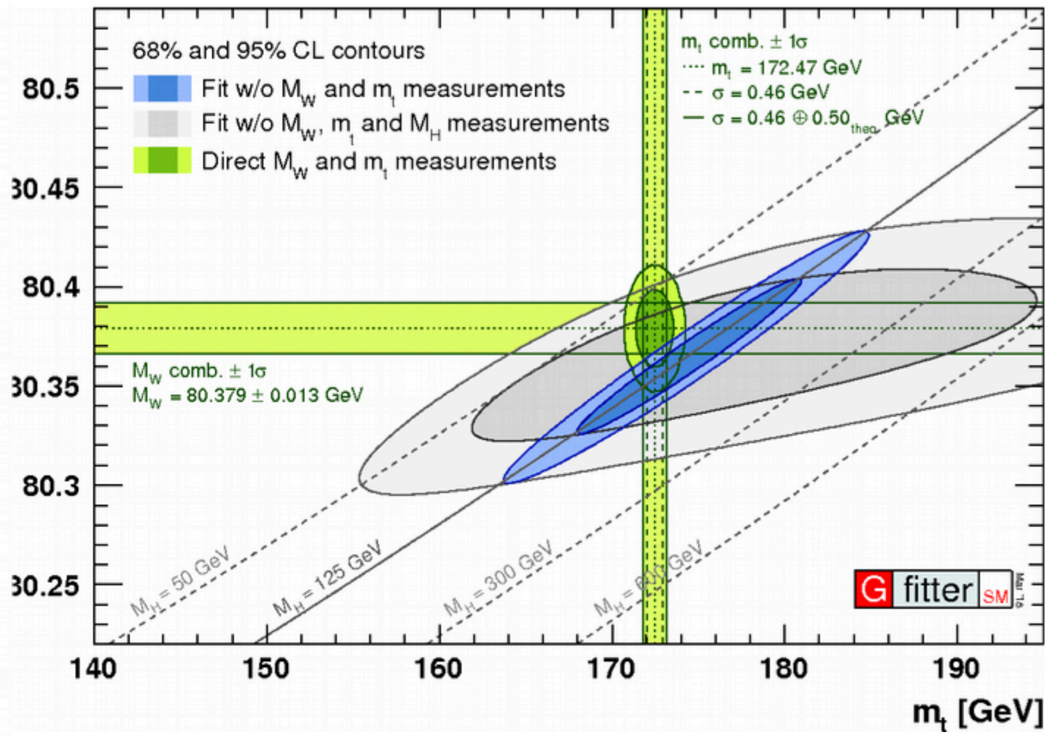




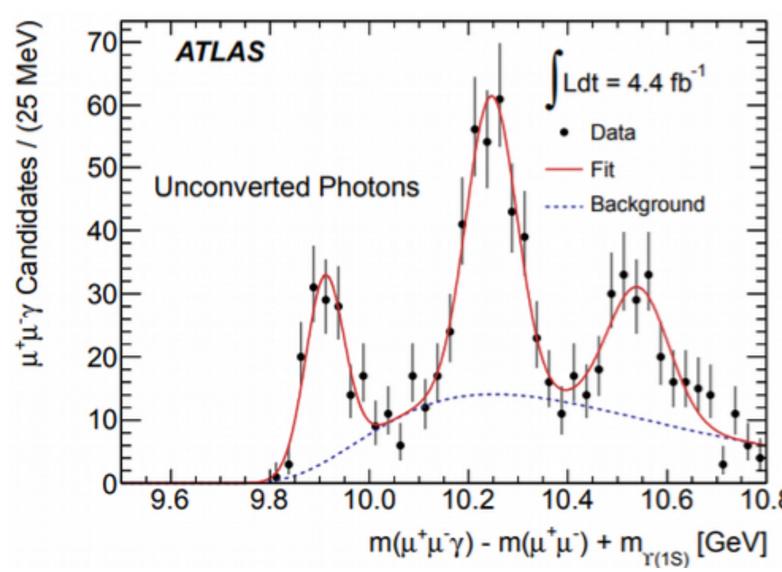
Precision EW mass measurements

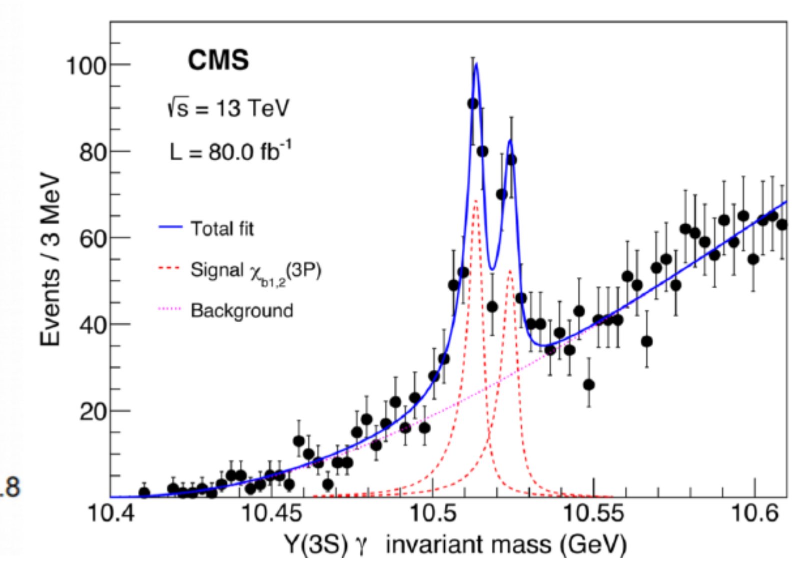
D. Charlton
LHCp2018





Precision spectroscopy!



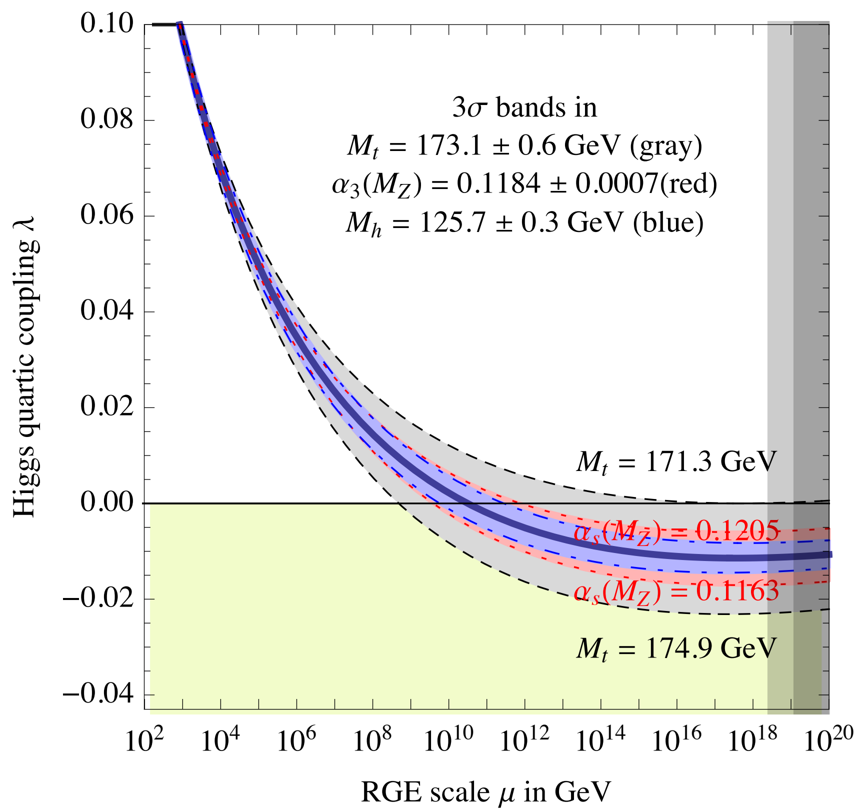


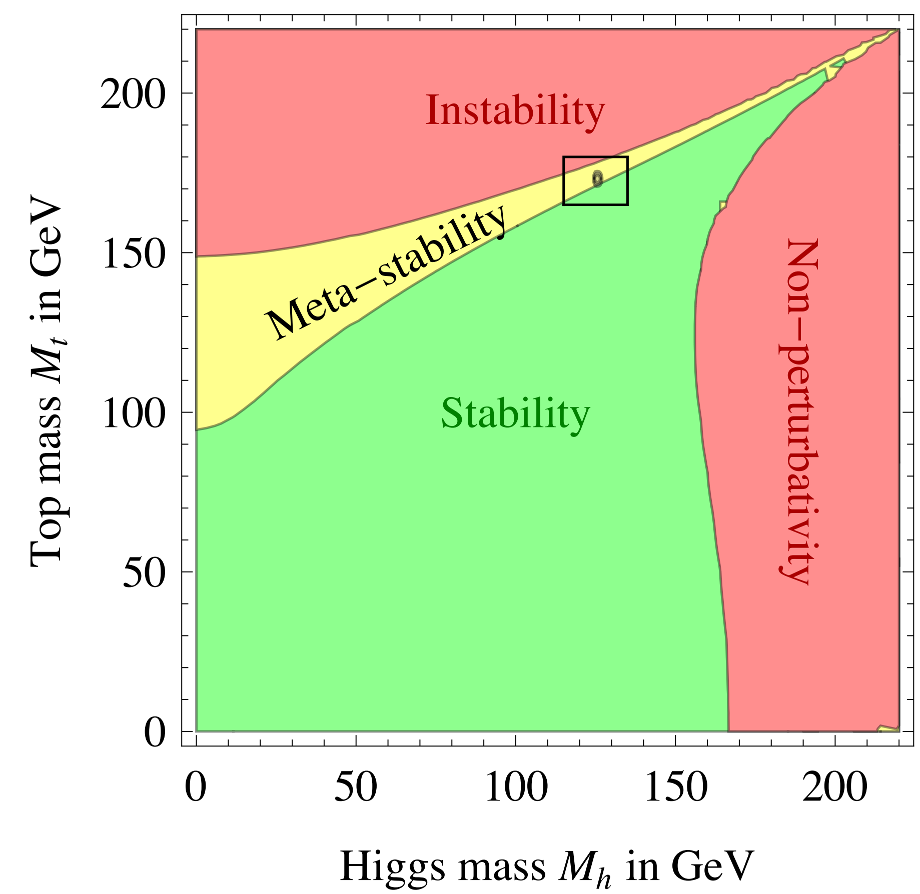
$m(\chi_{b2}(3P)) - m(\chi_{b2}(3P))$ =

10.60 ± 0.64(stat) ± 0.17 (syst) MeV

- The electroweak vacuum is unstable under radiative corrections

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





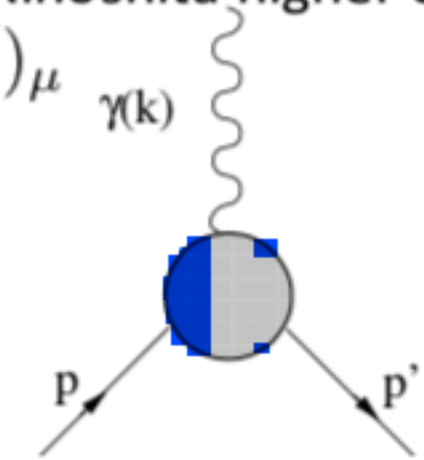
- the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and high accuracy of calculations (3 loops)

g-2

Muon anomalous magnetic moment

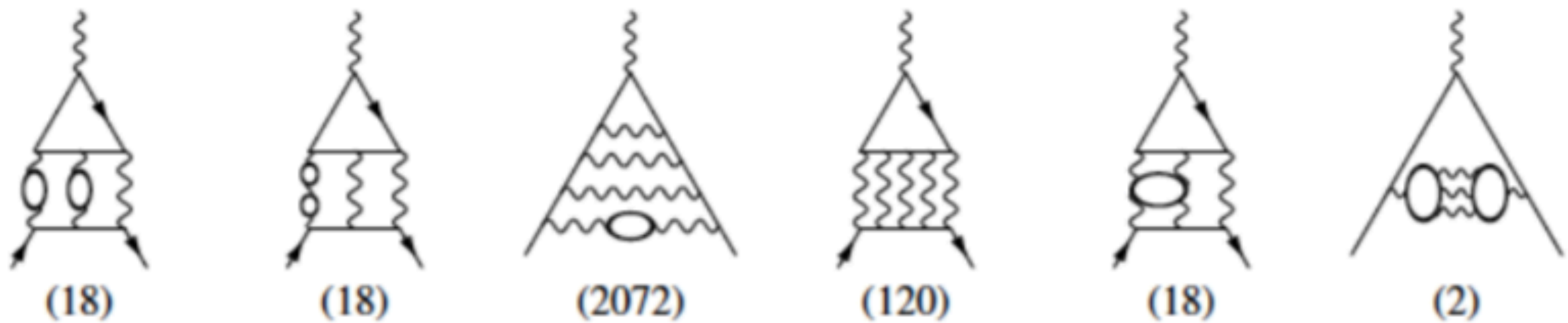
(Schwinger α/π,
Kinoshita higher orders in α)

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



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

For electron a_e theory and experiment agrees!



$$a_\mu^{th} - a_\mu^{exp} = -(3.06 \pm 0.76) \times 10^{-8}$$ 3,7 σ

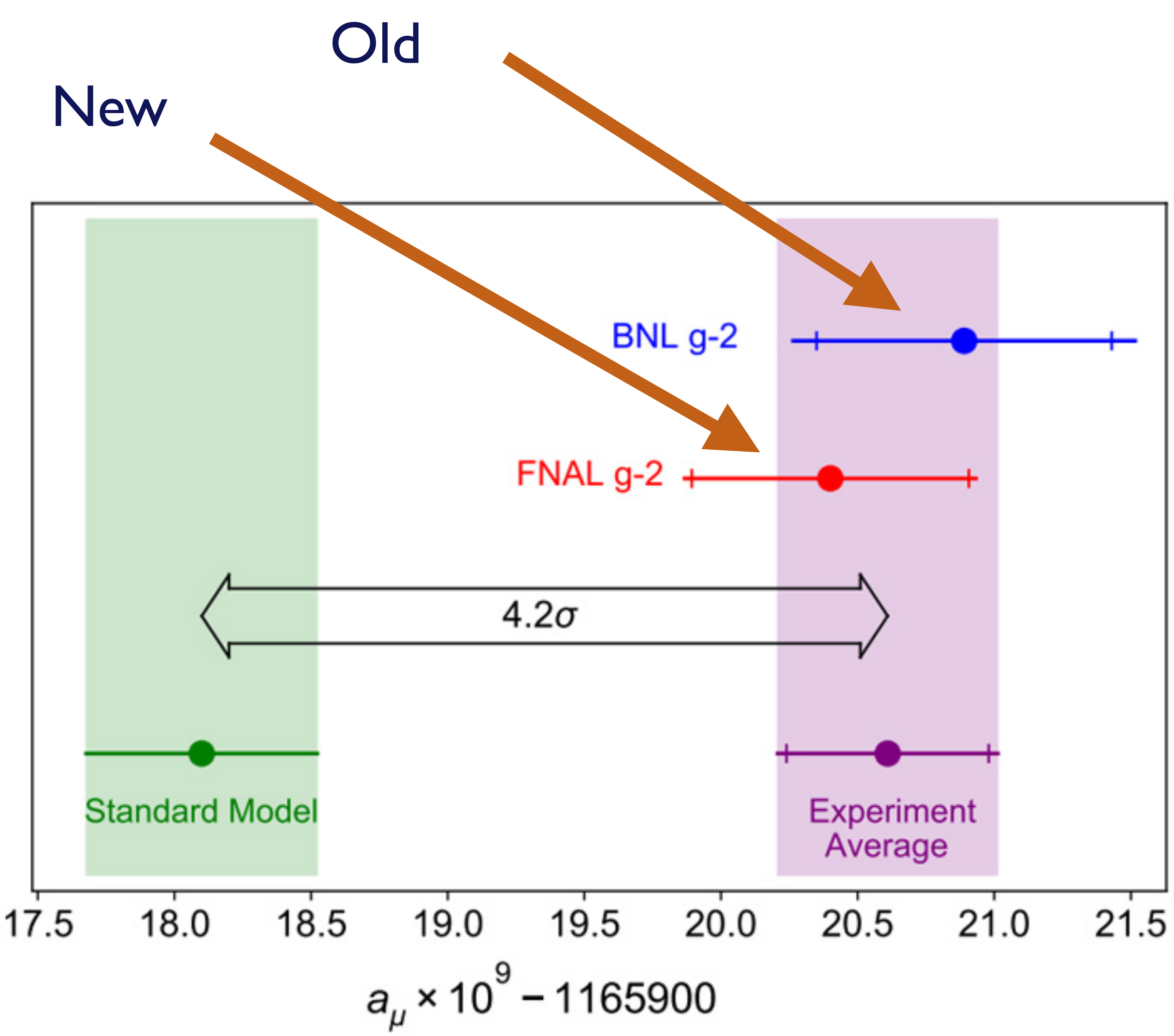
Theory: uncertainty in hadronic contributions to the muon g – 2, (Jägerlehner, 1802.08019).
Lattice QCD great progress light-by-light study (RBC & UKQCD, 1801.07224).

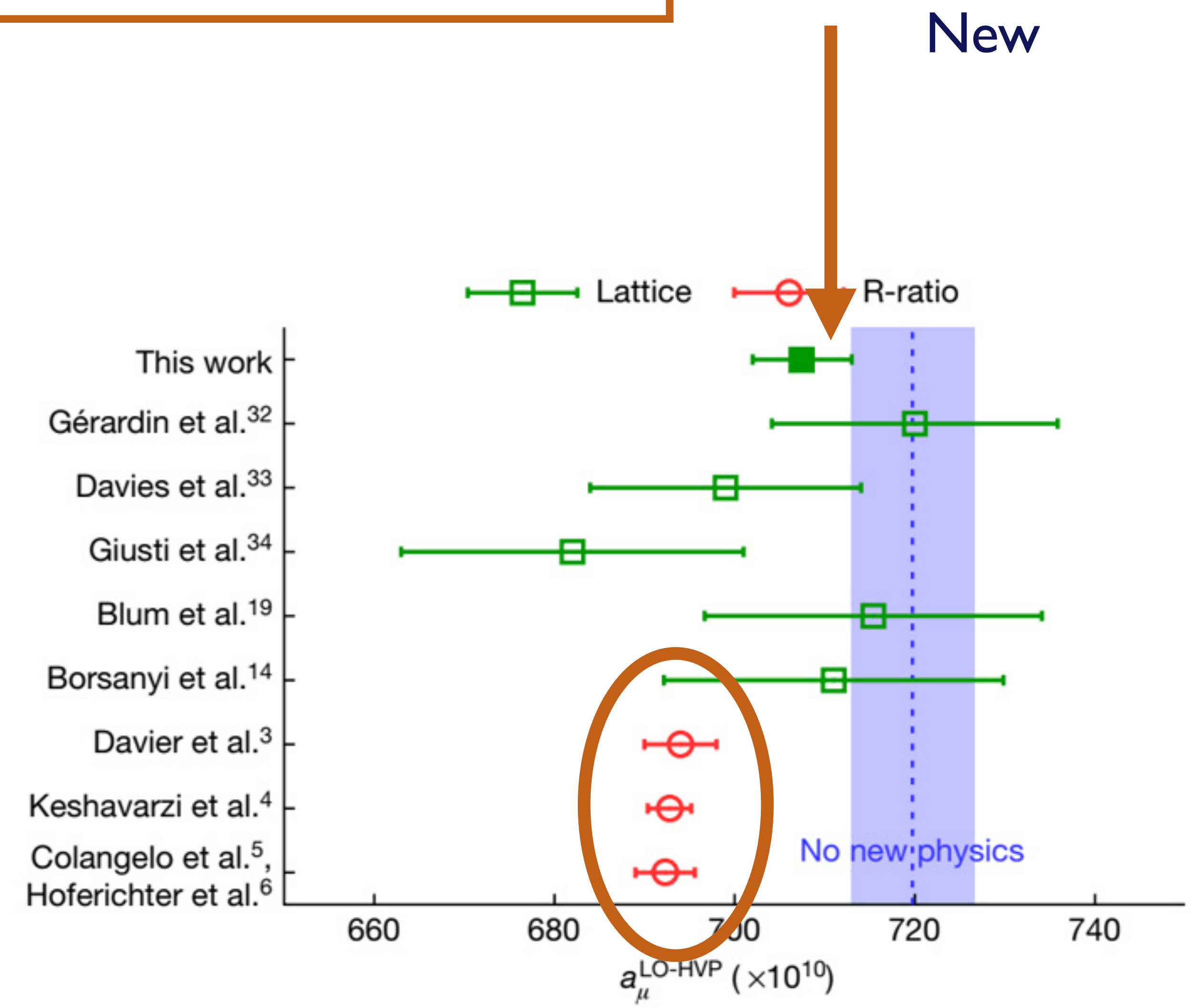
Fermilab and J-Park experiments are expected to clarify existing discrepancy!

THE STANDARD MODEL: THE STATUS AND OPEN QUESTIONS

FermiLab April 2021

$a_\mu(\mathrm{E821}) = (116\ 592\ 089 \pm 63)\times 10^{-11}$.





The problem remained

May be not!

Conclusion: it is important to take into account the strong interactions contribution correctly!

$\Lambda \approx v$: SUSY and the muon $(g-2)$

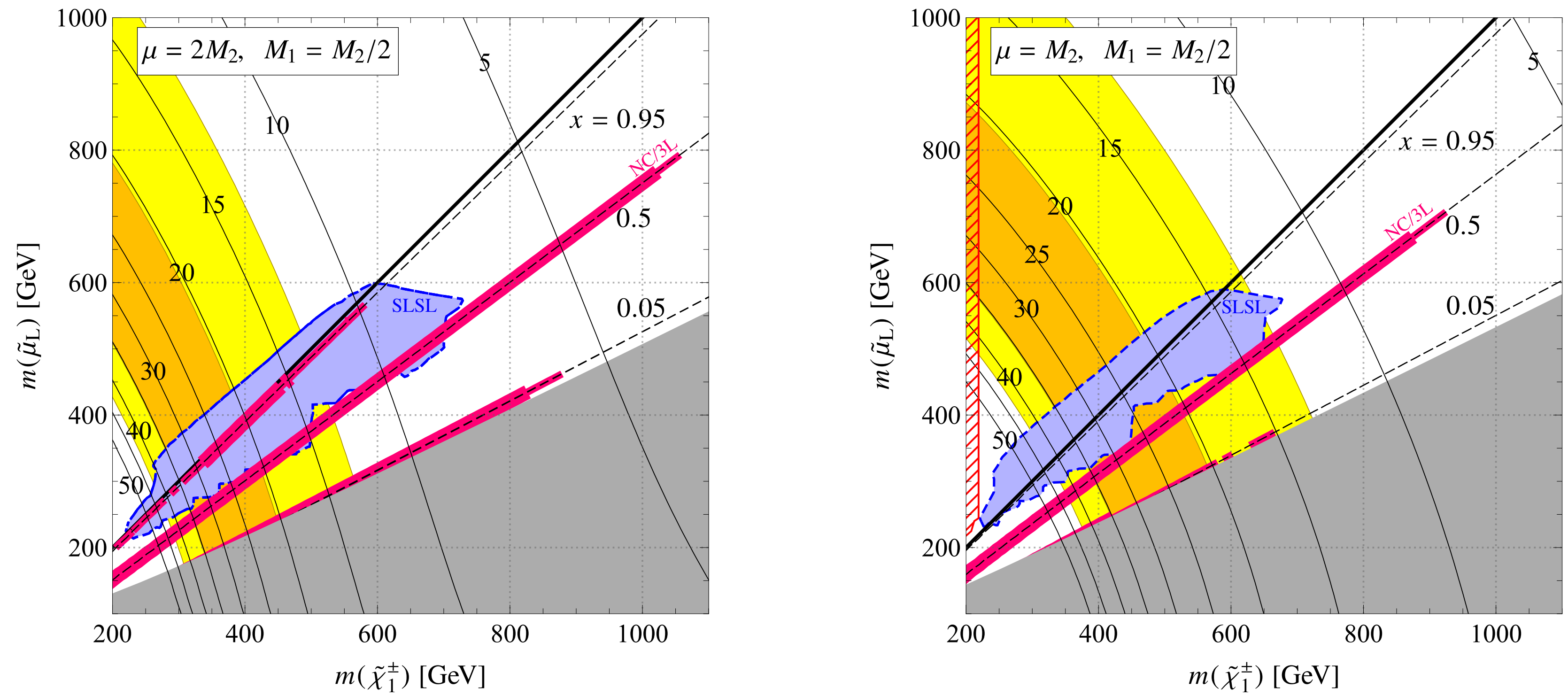
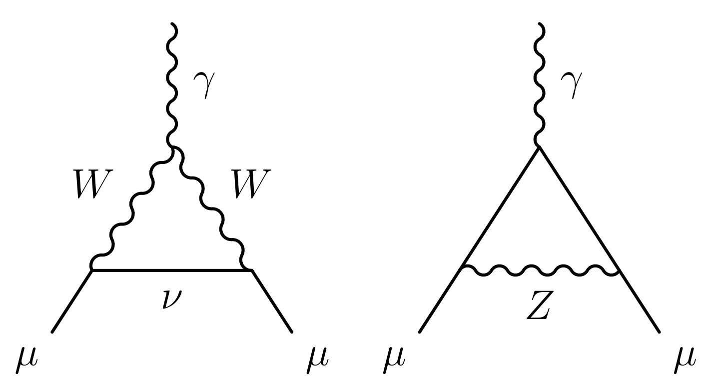
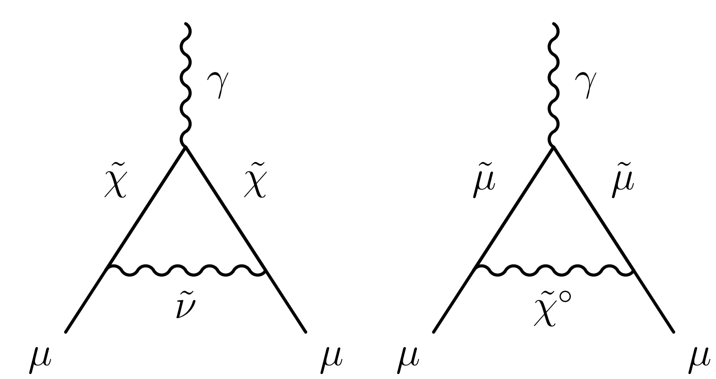


Figure: LHC Run 2 bounds on SUSY scenario for the muon $g-2$ anomaly for $\tan\beta = 40$. Orange (yellow) regions satisfy the muon $g-2$ anomaly at the 1σ (2σ) level [Endo et al., '20].





$$(a_\mu^{\rm SM})_{weak} \approx \frac{g^2 m_\mu^2}{32\pi^2 M_W^2} \approx 2 \times 10^{-9}$$

$$a_\mu^{\rm SUSY} \approx \frac{g^2 m_\mu^2 \tan\beta}{32\pi^2 \tilde{m}^2} \quad \underbrace{\approx 2 \times 10^{-9}}_{\tilde{m} = 500\,{\rm GeV}\ \&\ \tan\beta = 40}$$

$\Lambda \lesssim 1$ GeV: Axion-like Particles and the muon $(g-2)$

Axion-like Particle effective Lagrangian

$$\mathcal{L} = e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{c_{\mu\mu}}{2}\frac{\partial^\nu a}{\Lambda}\,\bar{\mu}\gamma_\nu\gamma_5\mu$$

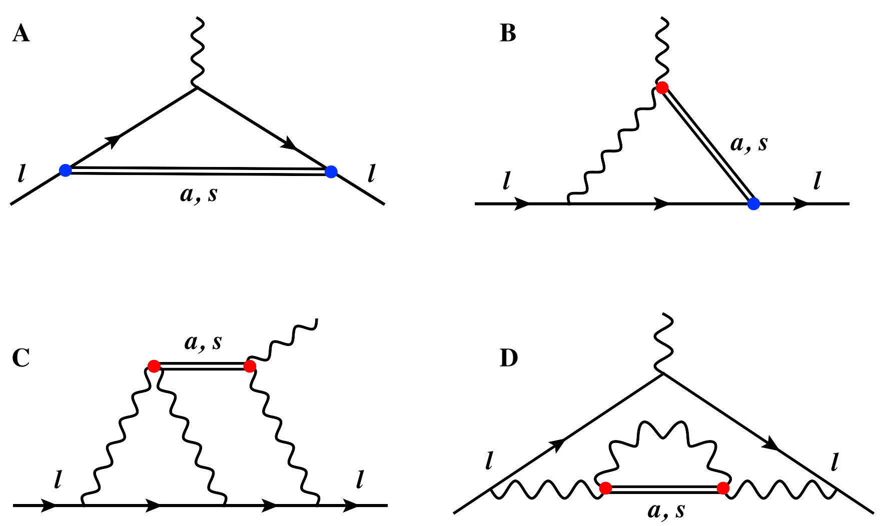


Figure: Contributions of a scalar 's' and a pseudoscalar 'a' ALP to the $(g-2)_\ell$.

[Marciano, Masiero, PP, Passera '16]

[Cornella, P.P., Sumensari '19]

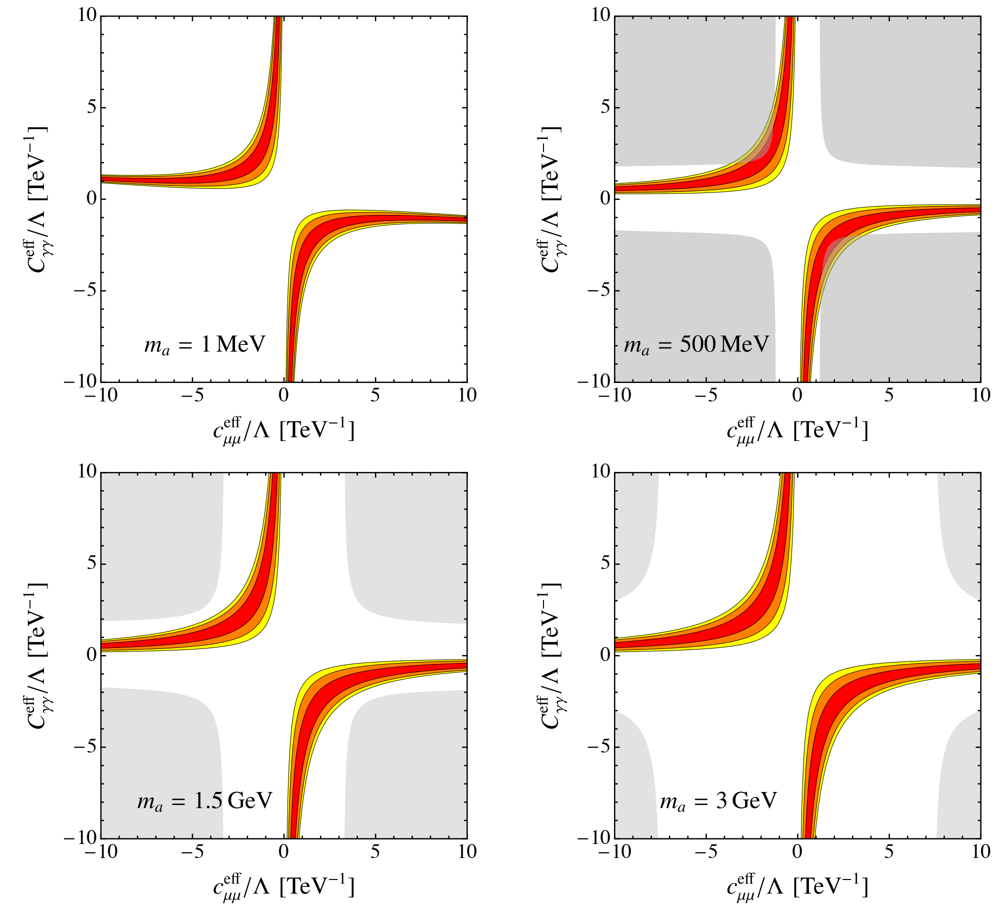
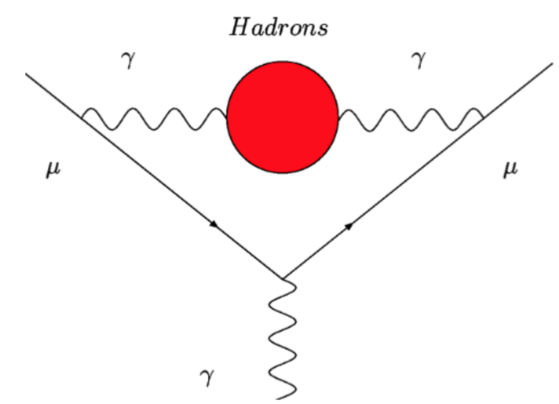


Figure: Δa_μ regions favoured at 68% (red), 95% (orange) and 99% (yellow) CL. Gray regions are excluded by the BaBar search $e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$ [Bauer, Neubert, Thamm, '17]

$$\Delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left[\frac{12\alpha^3}{\pi}\,C_{\gamma\gamma}^2\,\ln^2\frac{\Lambda^2}{m_\mu^2} - \frac{(c_{\mu\mu})^2}{16\pi^2}h_1\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}c_{\mu\mu}C_{\gamma\gamma}\ln\frac{\Lambda^2}{m_\mu^2}\right]$$

HLO contribution from $e^+e^- \to$ *hadrons*

- dominated by $e^+e^- \to \pi^+\pi^-$ channel (70% of the full hadronic)



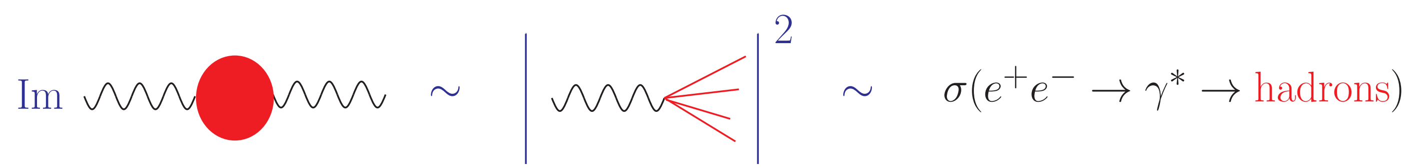
$$(a_\mu^{\rm HVP})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty} \frac{ds}{s} K(s)\,{\rm Im}\,\Pi_{\rm had}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\sigma_{\rm had}(s)$$

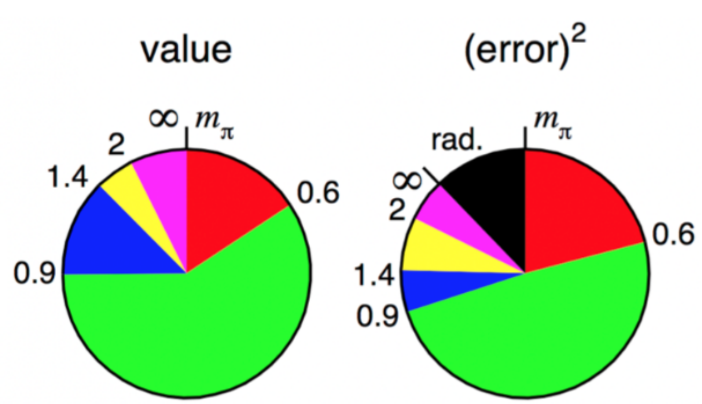
dispersion relations

optical theorem

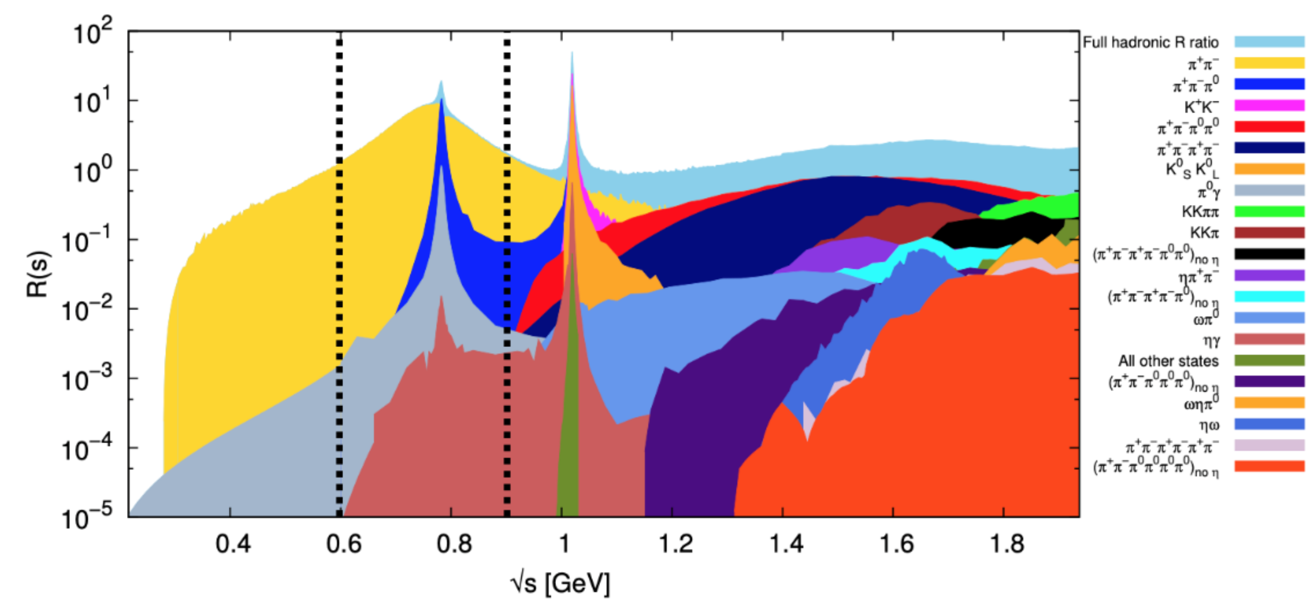
kernel function

$K(s) \approx m_\mu^2/3s$ for $\sqrt{s} \gg m_\mu$





Keshavarzi, Nomura, Teubner 2018

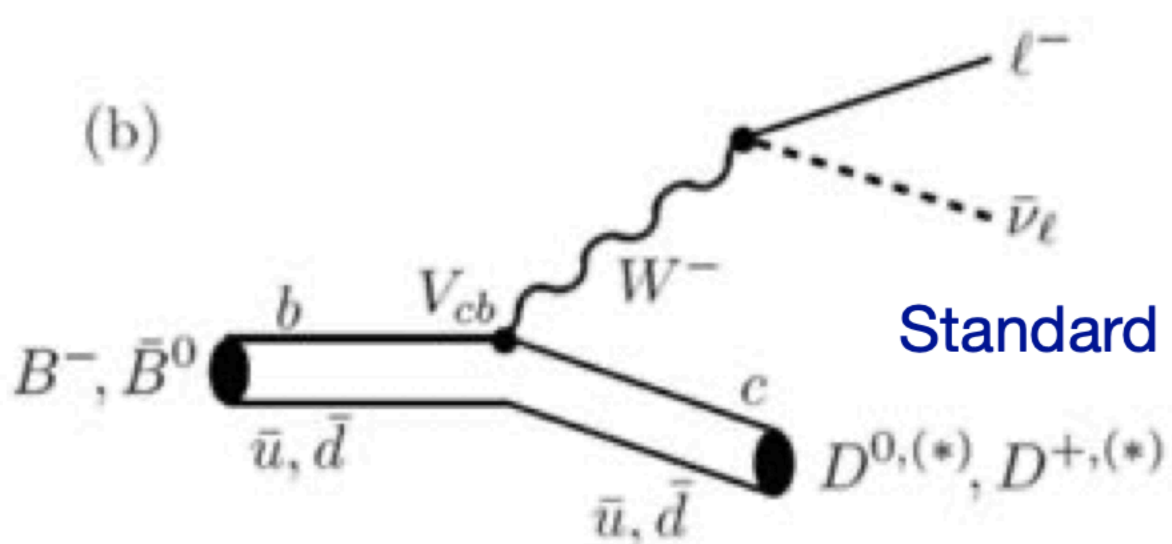


$$a_{\mu,e^+e^-}^{\rm HLO} = 6931(40) \times 10^{-11} (0.6\%)$$ [WP20]

Flavor Anomaly

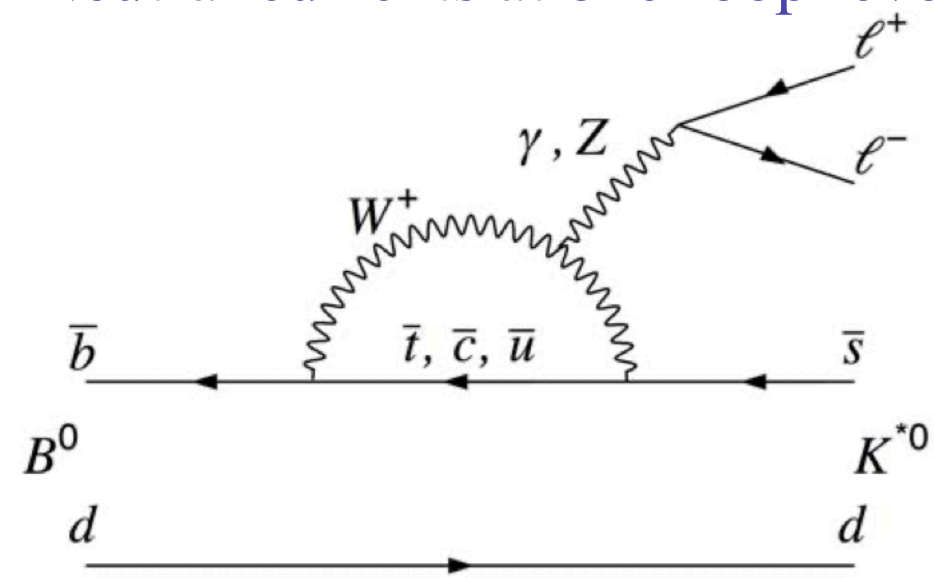
LEPTON (NON) UNIVERSALITY (?!)

Charged currents ot tree level



Standard Model

Neutral currents at one-loop level



$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$ 3.8σ

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$ 2.5σ

$$\mathcal{R}(D)_{SM} = 0.299 \pm 0.003$$

$$\mathcal{R}(D^*)_{SM} = 0.258 \pm 0.005$$

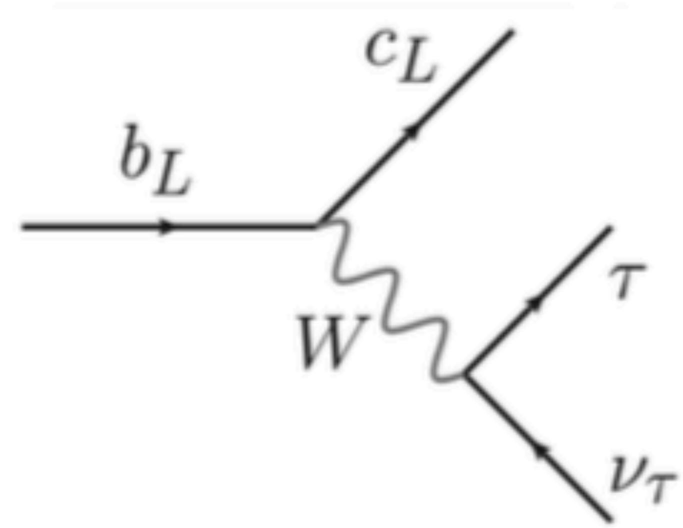
$$\mathcal{R}(K^*)_{SM} = 1.0$$

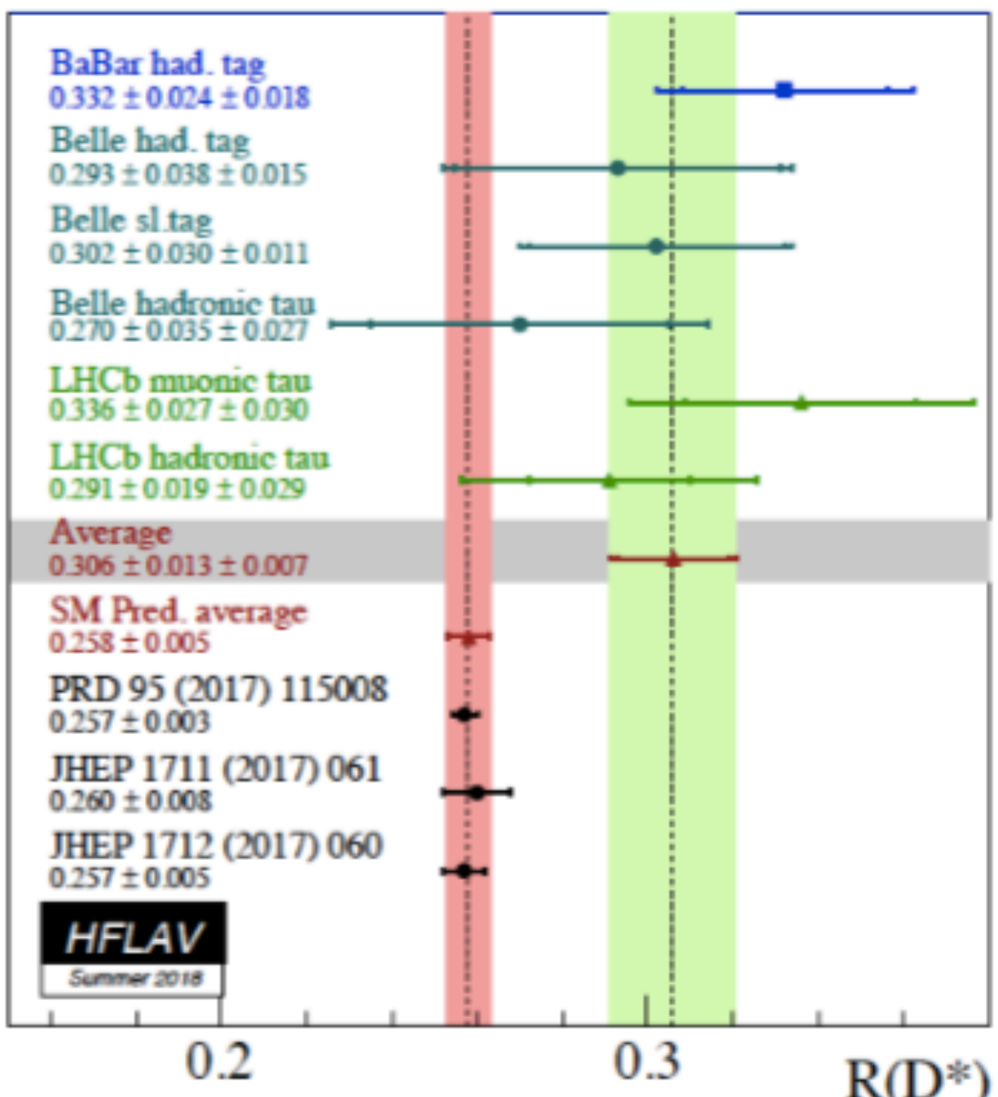
B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)

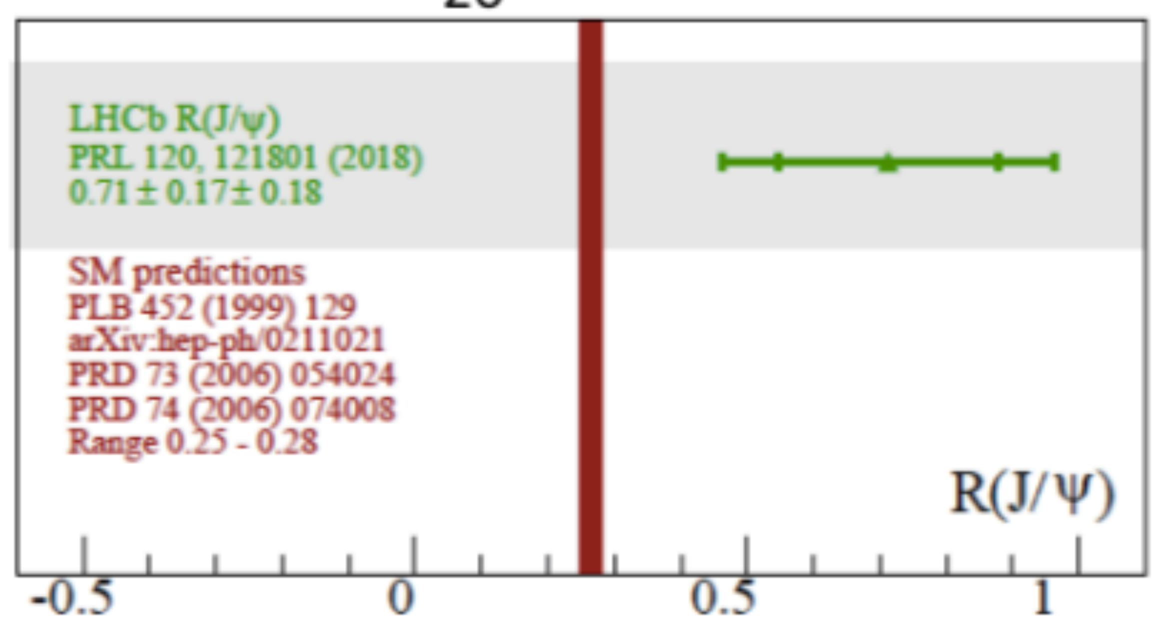
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$

3.8σ





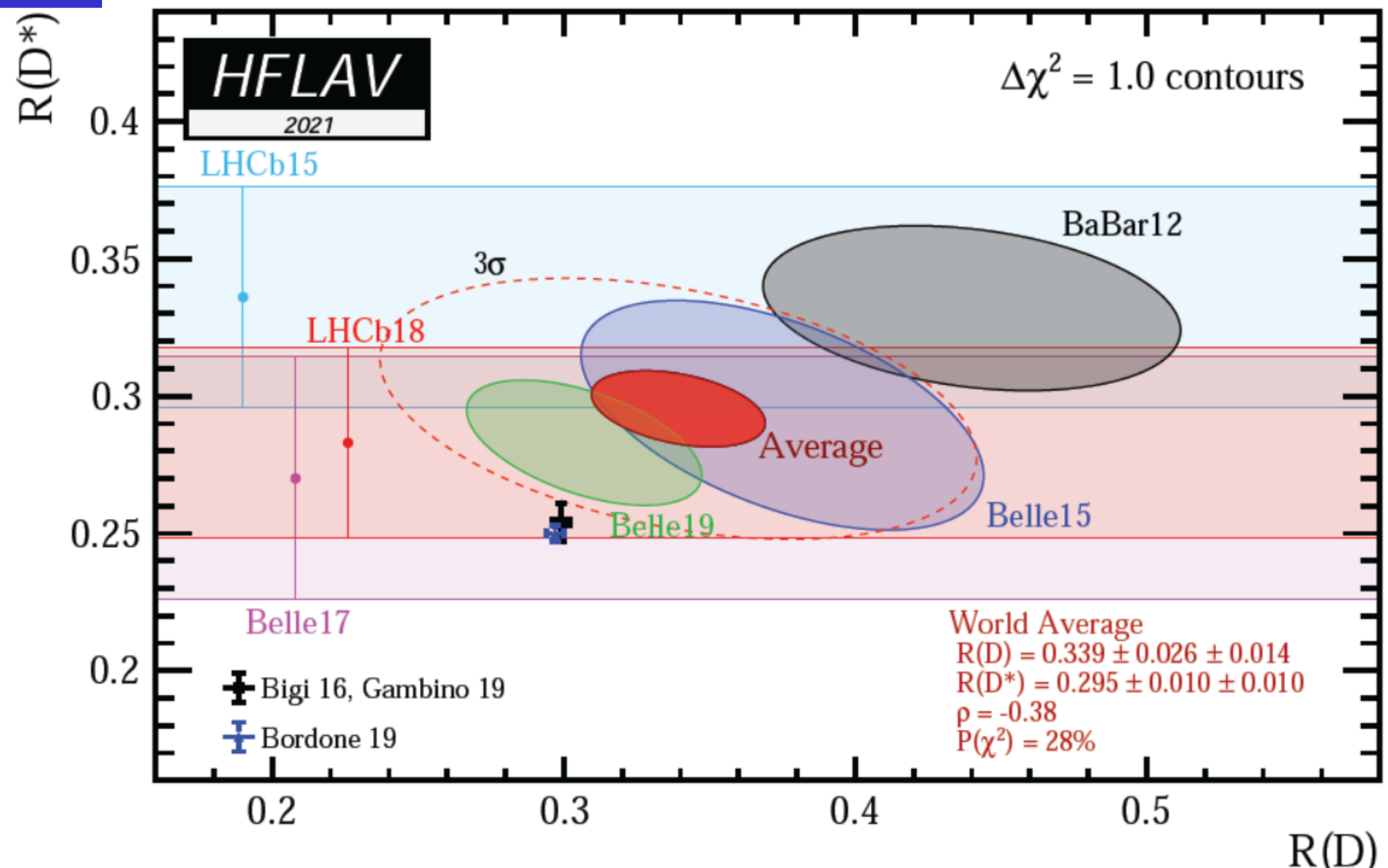
2σ



See Leroy's talk at ICHEP2018

$R(D)$ vs $R(D^*)$

- All experiments see an excess wrt SM predictions
- Combining R(D)/R(D*) average ~3.4 σ tension with SM



- Intriguing as anomaly occurs in a tree-level SM process
- New LHCb result

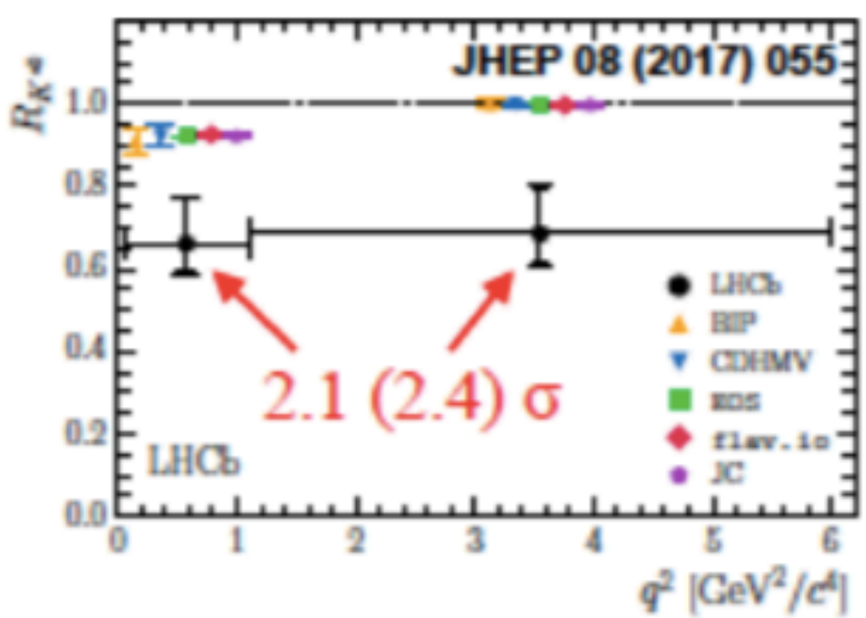
$R(\Lambda_c) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059(\text{ext})$

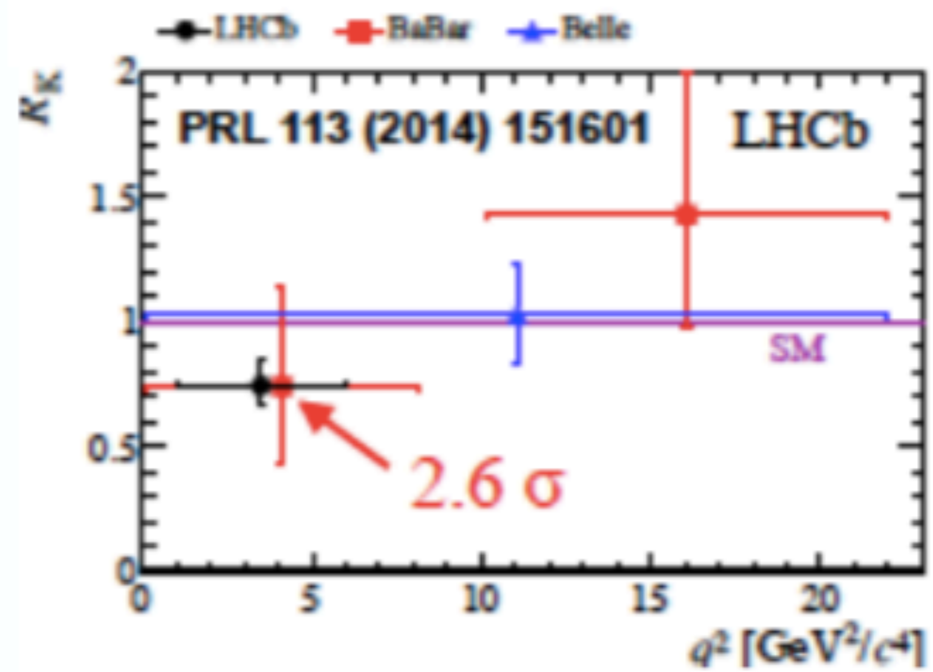
arxiv:2201:03497

Measurement is consistent with SM (~1σ "low") [SM=0.324±0.004].

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

$$R_{K^{(*)}} = \left. \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)} \right|_{q^2 \in [q^2_{min}, q^2_{max}]}$$



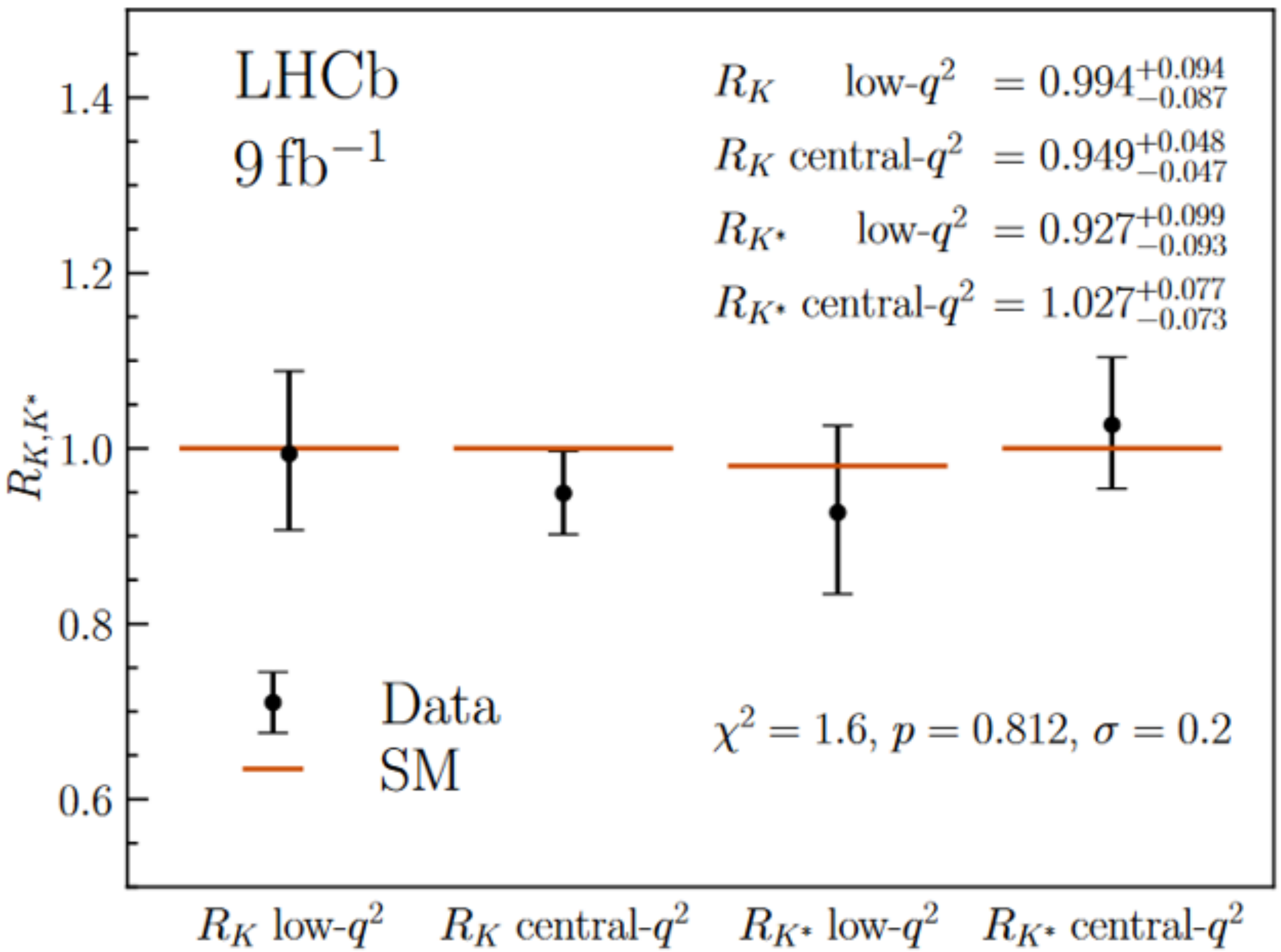


P_5' in $B \to K^* \mu^+ \mu^-$ (angular distribution functions) 3σ

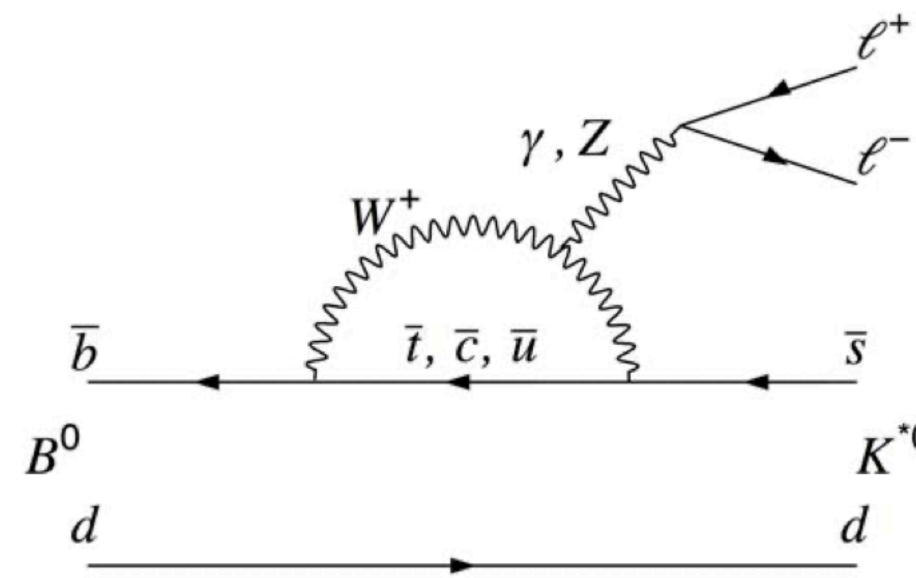
LHCb: the discrepancy present in $B_s \to \phi\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$

(see Capriotti talk at ICHEP2018)

THE LHCB RECENT RESULTS



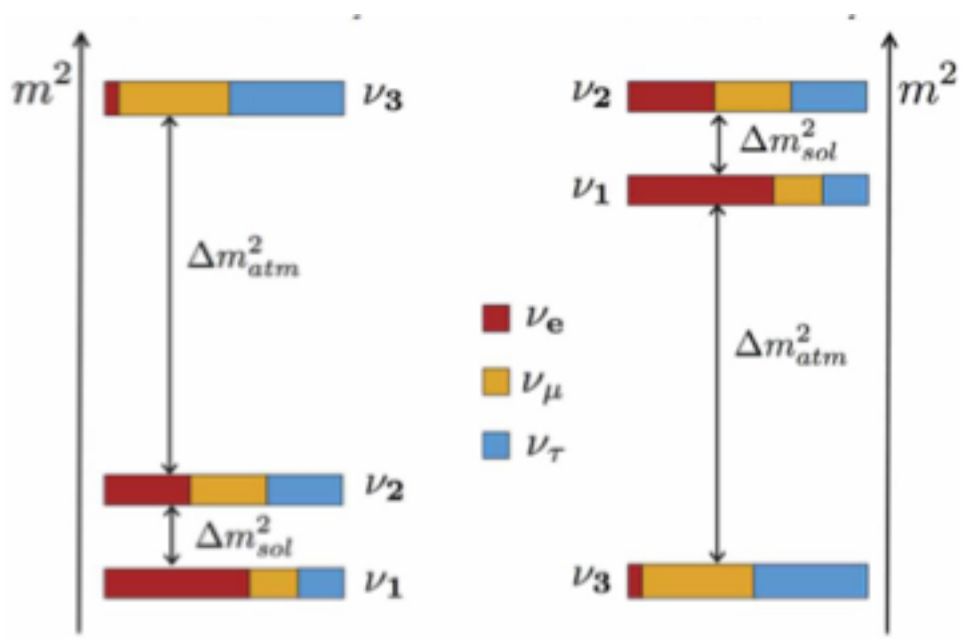
$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$



$$\mathcal{R}(K^*)_{SM} = 1.0$$

Neutrinos

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?

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

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

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.

Is it just the SM or requires New physics?

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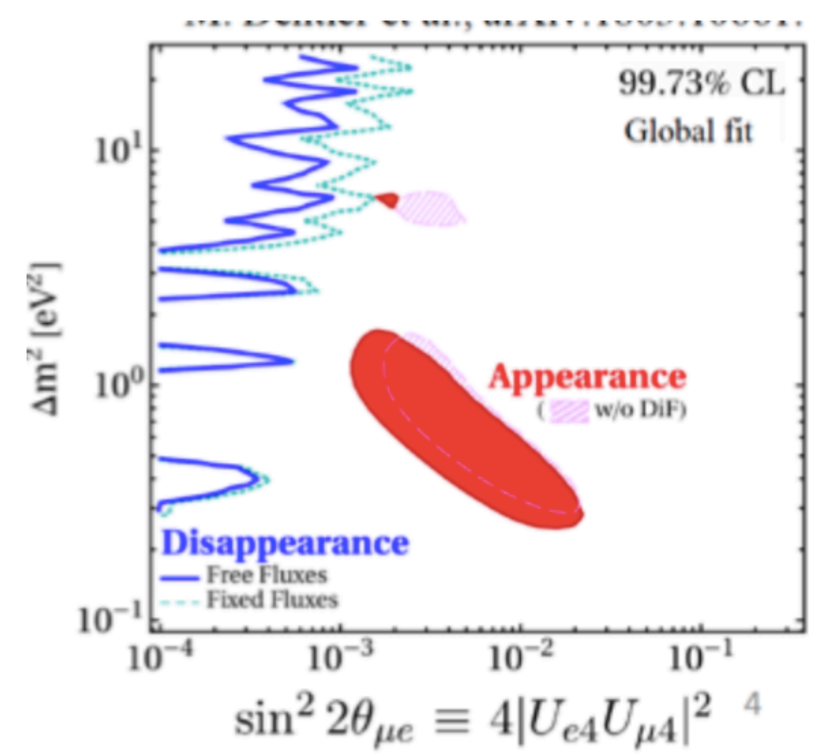
Type III seesaw mechanism: T(x) - a triplet of fermion fields.

M. Weber ICHEP2018

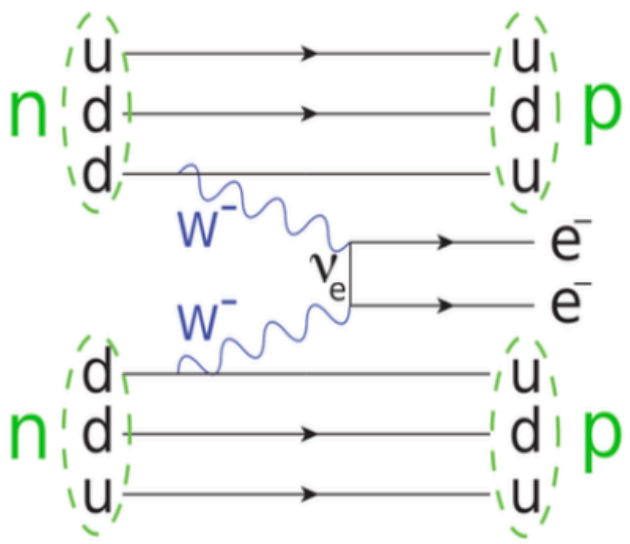
- **Possible Sterile Neutrino?**
  - **New MiniBooNE consistent with LSND** **(but low energy excess?)**
  - **Reactor anomaly questioned by Daya Bay/RENO time dependence**
  - **New SBL and source experiments**
  - **Conflict with ν_μ disappearance**

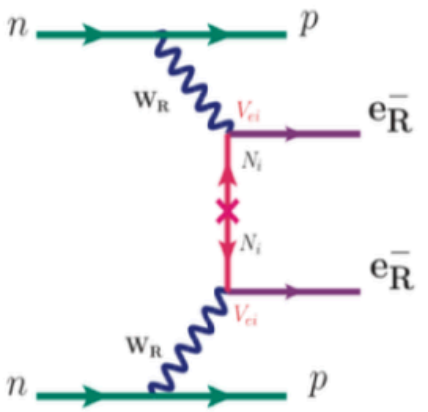


Neutrinoless Double Beta Decay

The question is still unanswered:

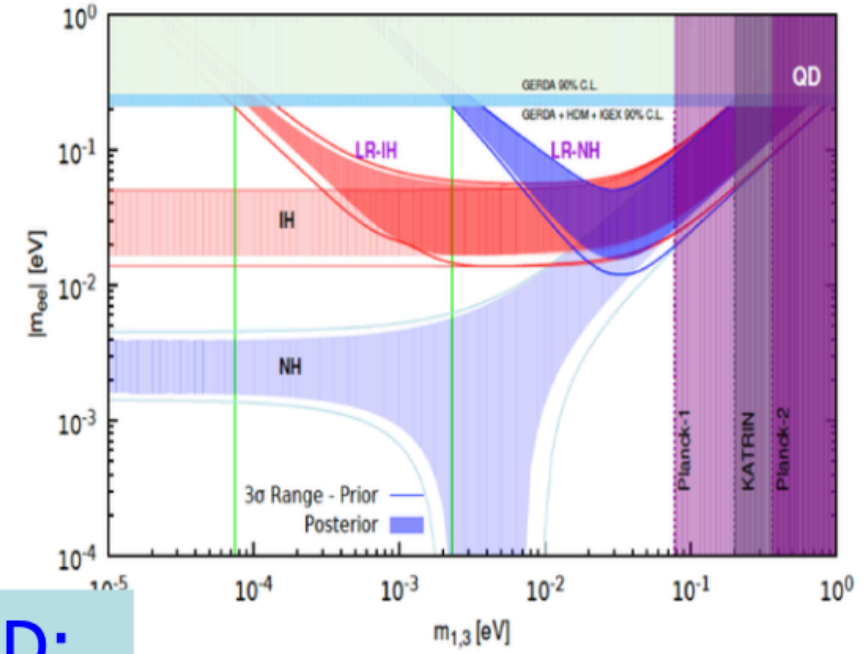
Are neutrinos their own antiparticles?





Left-Right Symmetric Model,
$M_{W_R} \sim 2$ TeV, $M_N = 1$ TeV,
$g_R \sim 2/3\, g_L$

JHEP 10 (2015) 077



Ton scale 0nuBB experiments will cover the inverted hierarchy by 2035

Many experiments operating, planned or in R&D:
LEGEND, SNO+, NEXT, CUPID, THEIA...

Sterile Neutrinos

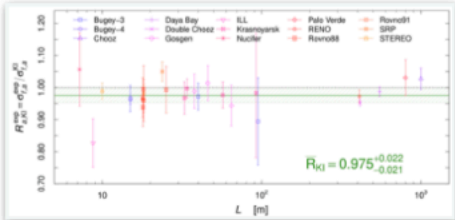
Several anomalies around in the community since some years…
Additional sterile neutrinos as a possible candidate explanation

- ☑ Very generic extension of SM
  - can be leftover of extended gauge multiplet
- ☑ Useful phenomenological tool
  - can explain ν masses (seesaw mechanism, $m \sim$ TeV…M_{Pl})
  - can explain cosmic baryon asymmetry (leptogenesis, $m \gg 100$ GeV)
  - can explain dark matter ($m \sim$ keV)
  - can explain oscillation anomalies ($m \sim$ eV)
    Promote mixing matrix to 4 x 4, oscillation formula unchanged:

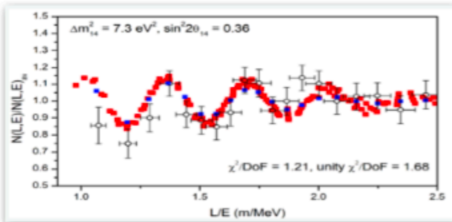
$$P_{\alpha\to\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i(E_j - E_k)T\right]$$

Neutrino Anomalies

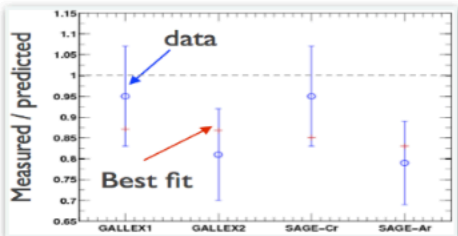
Albert De Roeck



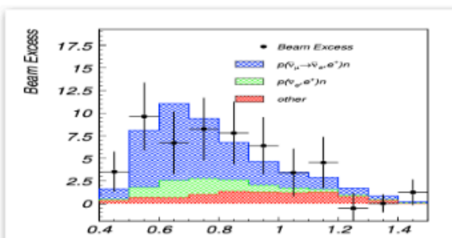
reactor flux anomaly
resolved with new input data
to flux calculation ✓



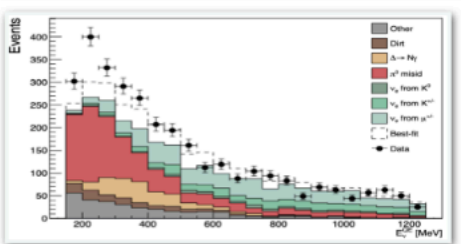
reactor spectra
is there really an anomaly? -> DANSS ?



gallium anomaly
unresolved, recently reinforced BEST ?



LSND
unresolved ?



MiniBooNE
unresolved µBooNe excluded some explanations
resolvable by next-gen. SBL experiments ?

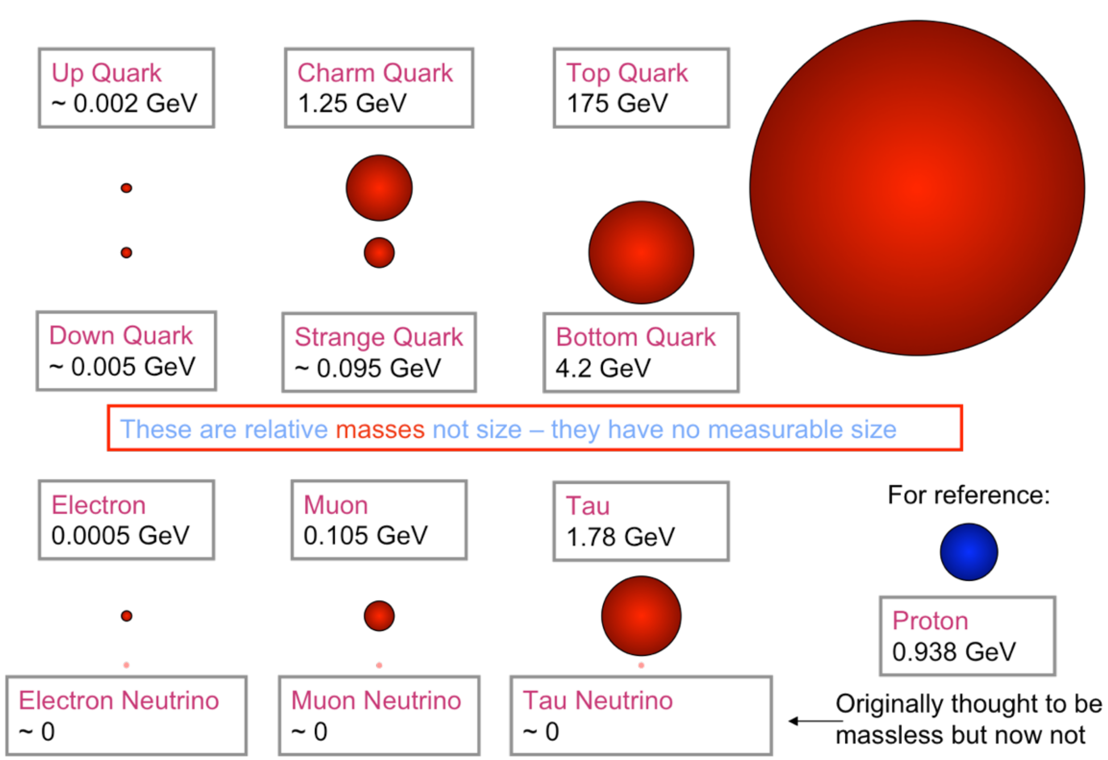
More details in the backup

- Jury still out on many of these anaomalies. No clear picture emerging yet.
- Simple sterile neutrino would not fit all the data. Tensions on all sides…
- Future: Reactor experiments continuing or new ones (eg JSNS^2) or new experiments at the FNAL short neutrino baseline… (ICARUS, SBND)

BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

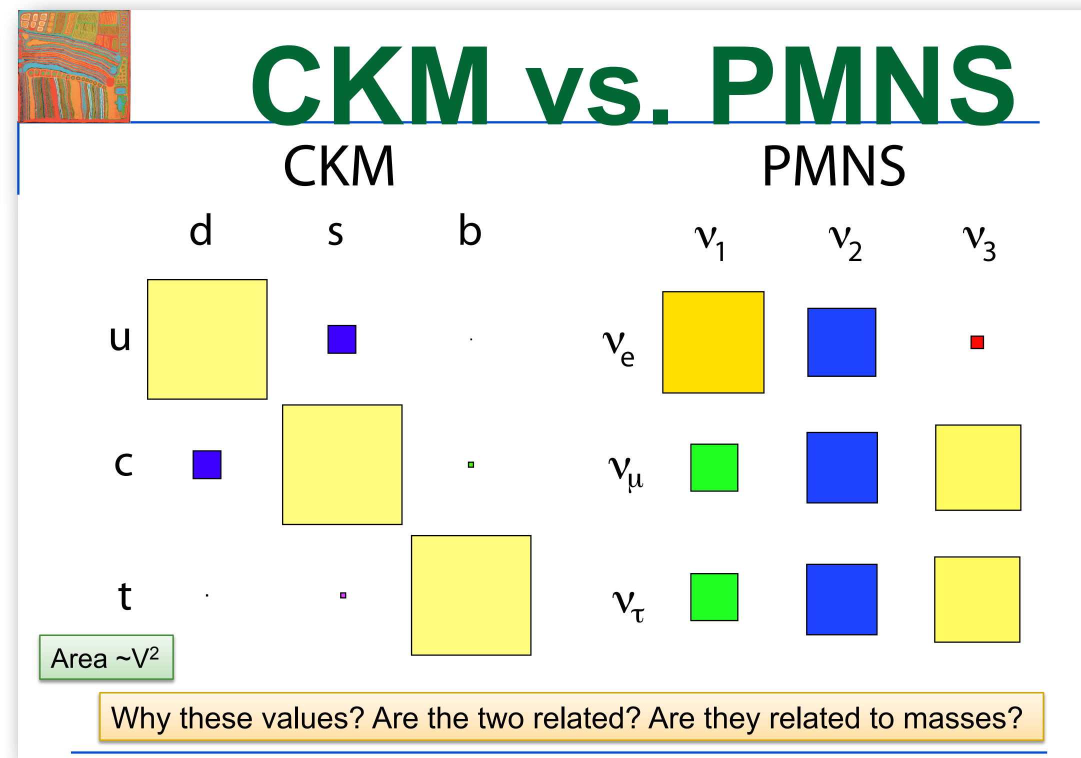
- Mass spectrum?

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



- Mixing Matrices?

- Quark-Lepton Symmetry
- Strong difference in parameters



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

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

Neutrino Mixing: New Symmetry?

- $\theta_{12} = \theta_{\odot} \cong \frac{\pi}{5.4}, \quad \theta_{23} = \theta_{\rm atm} \cong \frac{\pi}{4}(?), \quad \theta_{13} \cong \frac{\pi}{20}$

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Follows the attempts in quark sector with 30 years delay: so far unsuccessful

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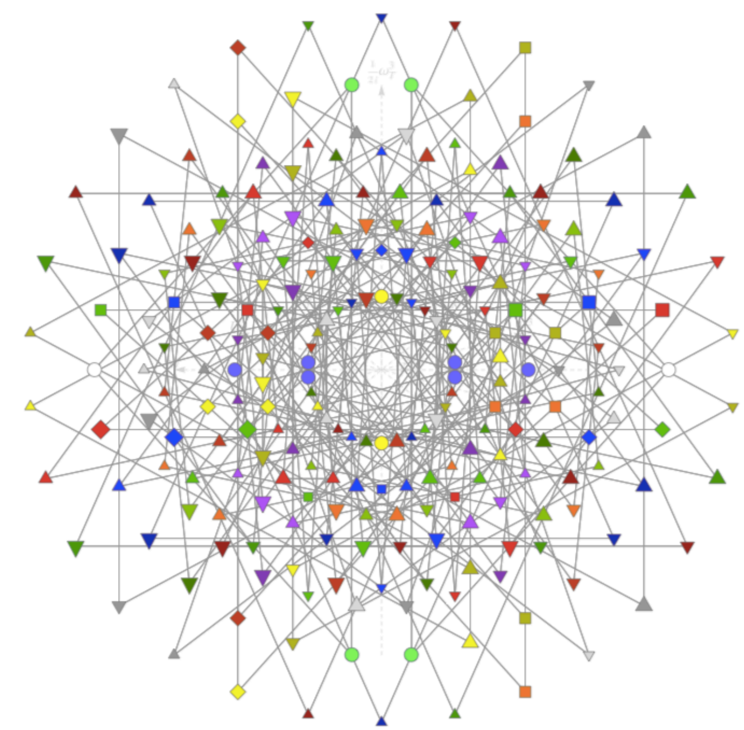

E8 roots

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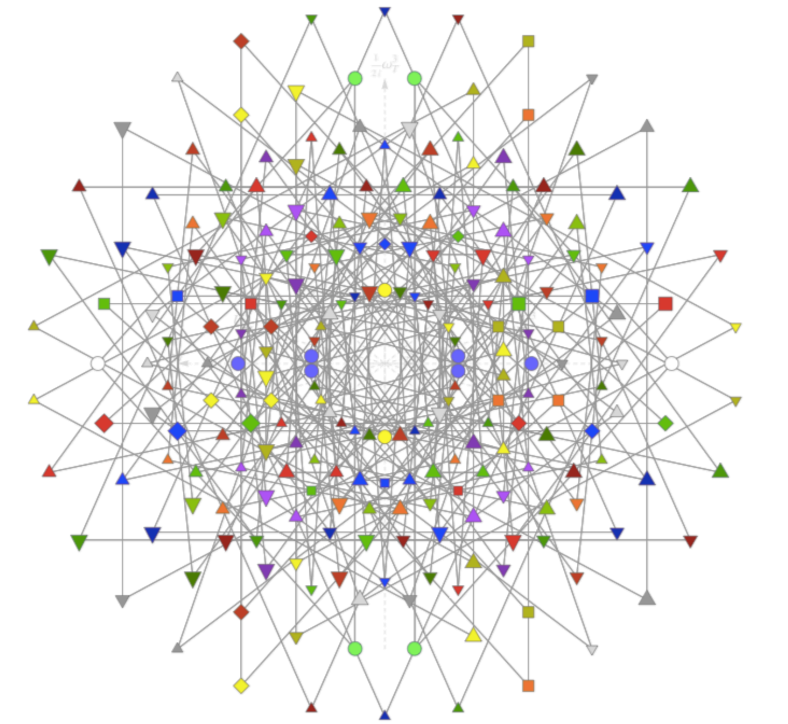
Follows the attempts in quark sector with 30 years delay: so far unsuccessful

Symmetry might be tricky



E8 roots

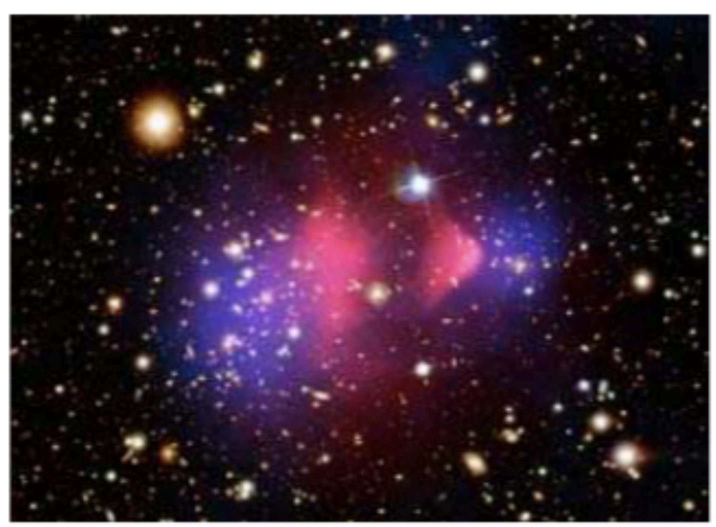
Dark matter

Major problem: 85% of matter is dark and remains invisible!

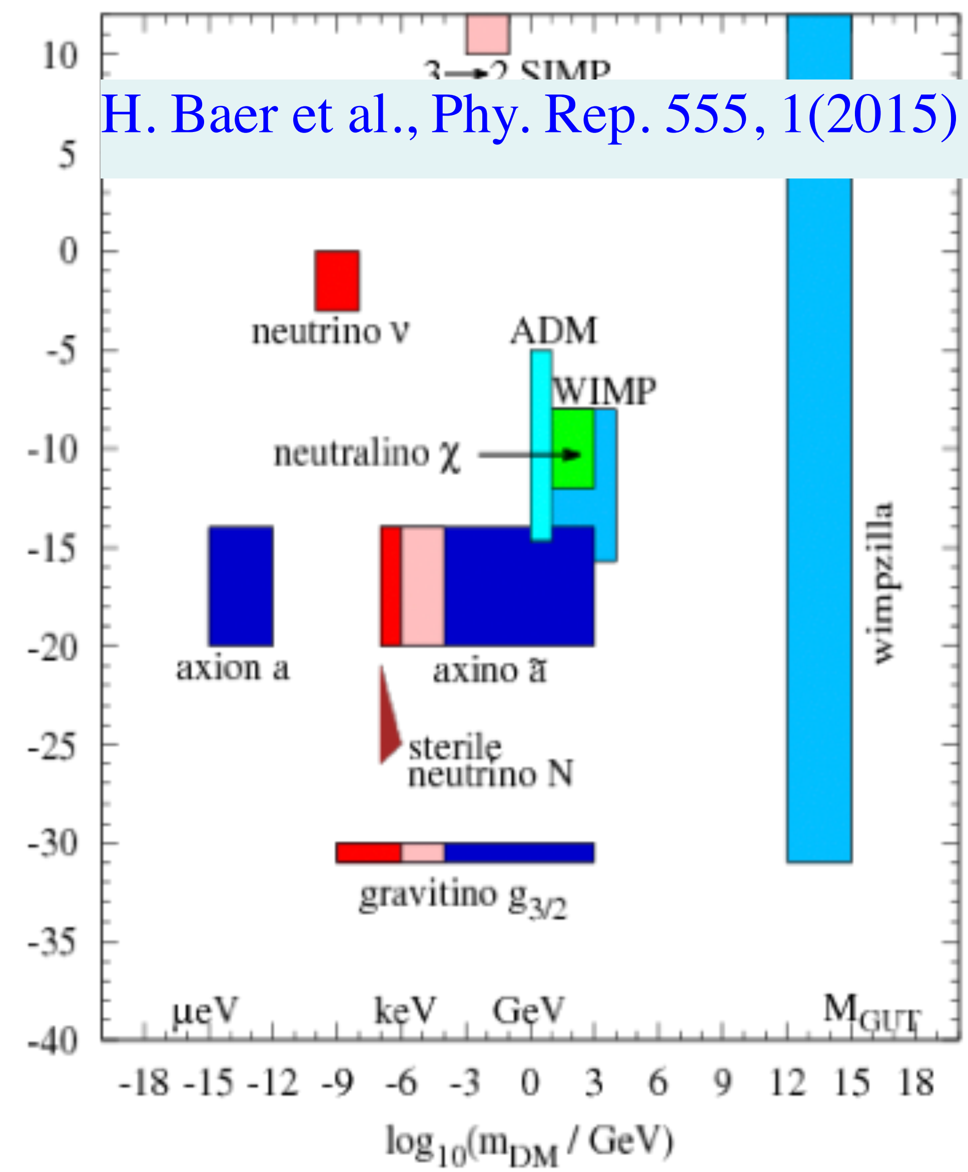
Is this compatible with the SM?

Does it requires modification of the SM or addition of gravity?

- **Many candidates in many orders of magnitude of mass:**
  - **MOND** (Problems: large scales, Bullet cluster)
  - **Primordial black holes** (LIGO, but constraints)
  - **Fuzzy** (very light bosons)
  - **Warm** (KeV sterile)
  - **WIMP**
  - **Axions/ALPs**
  - **Dark sector**
  - **Gravitinos**
  - **Moduli**
  - **Wimpzillas**



M. Drees

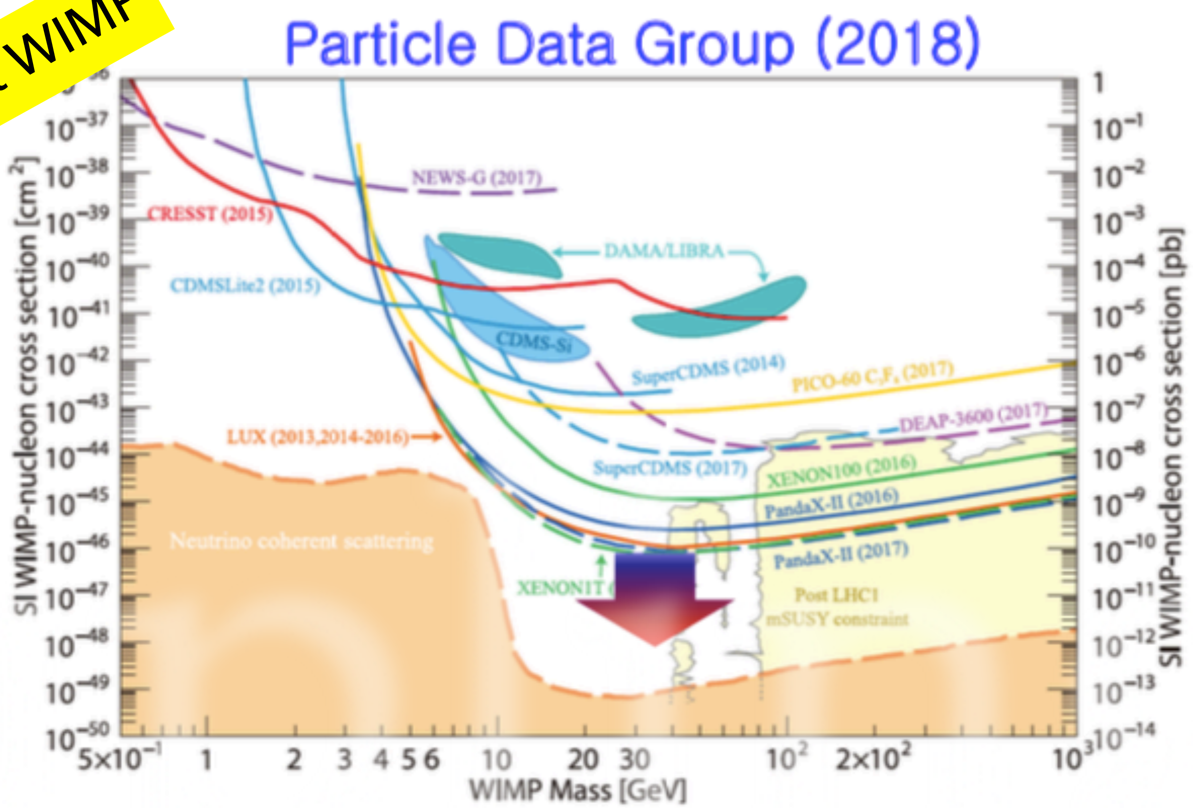


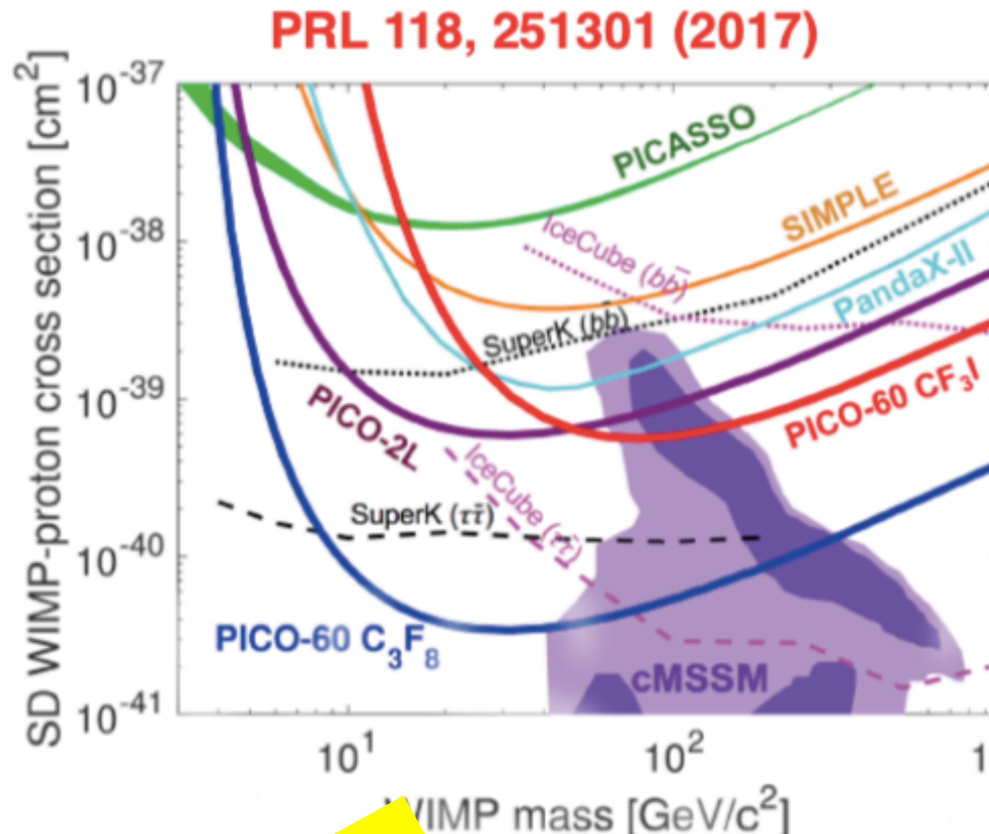
H. Baer et al., Phy. Rep. 555, 1(2015)

- **Direct, indirect, collider**

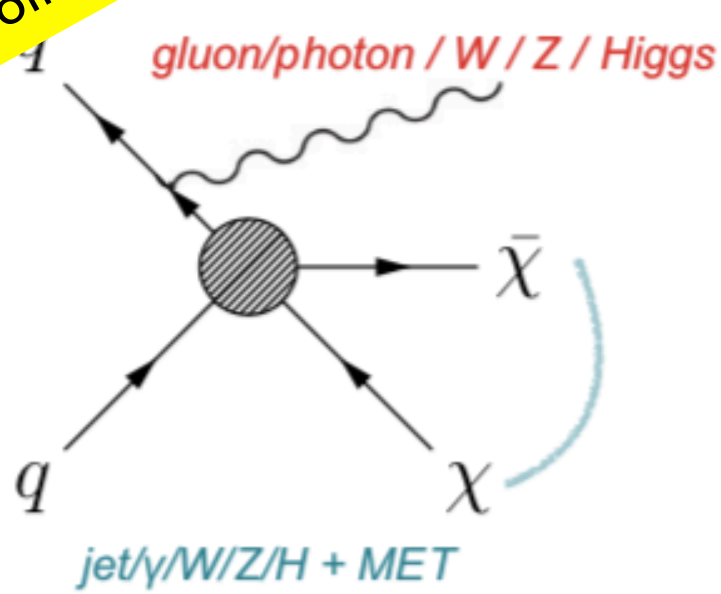
BEYOND THE STANDARD MODEL: DARK MATTER SEARCHES

Direct WIMP





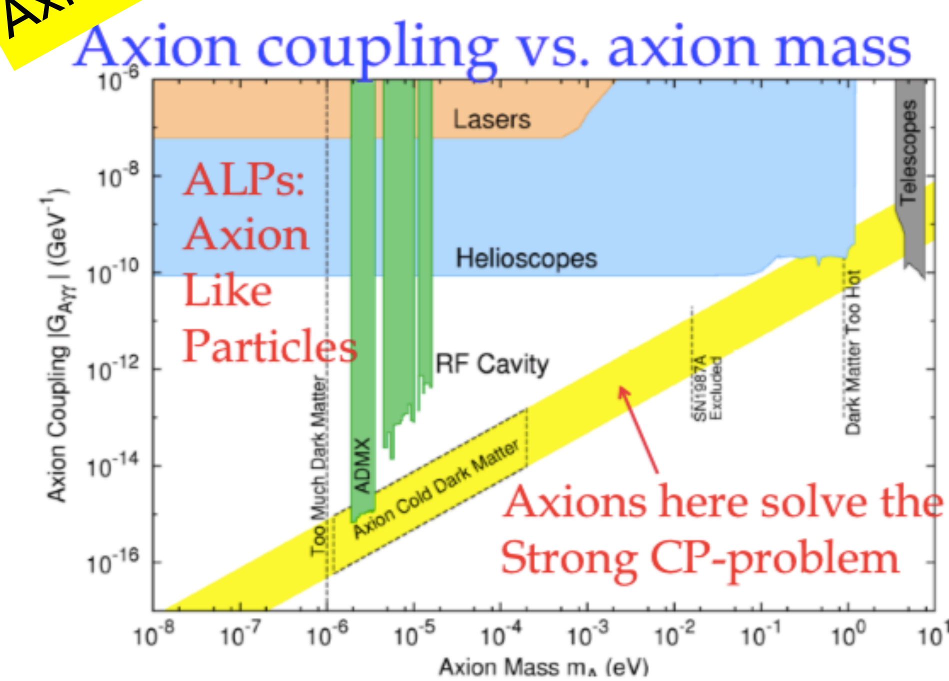
Colliders WIMP



- **mono-jet**
  - most general signature, constraints on many mode
- **mono-photon**
  - more challenging for background estimation
  - less powerful: EW vs. strong interaction
- **mono-W/Z leptonic**
  - clean signature and simple trigger
  - penalized by W/Z branching fraction
- **mono-W/Z hadronic**
  - larger statistics with larger background
- **tt+MET/bb+MET and mono-top**
  - more complicated experimentally
  - powerful in some scenarios
- **mono-Higgs**
  - powerful in some scenarios

D. del Re

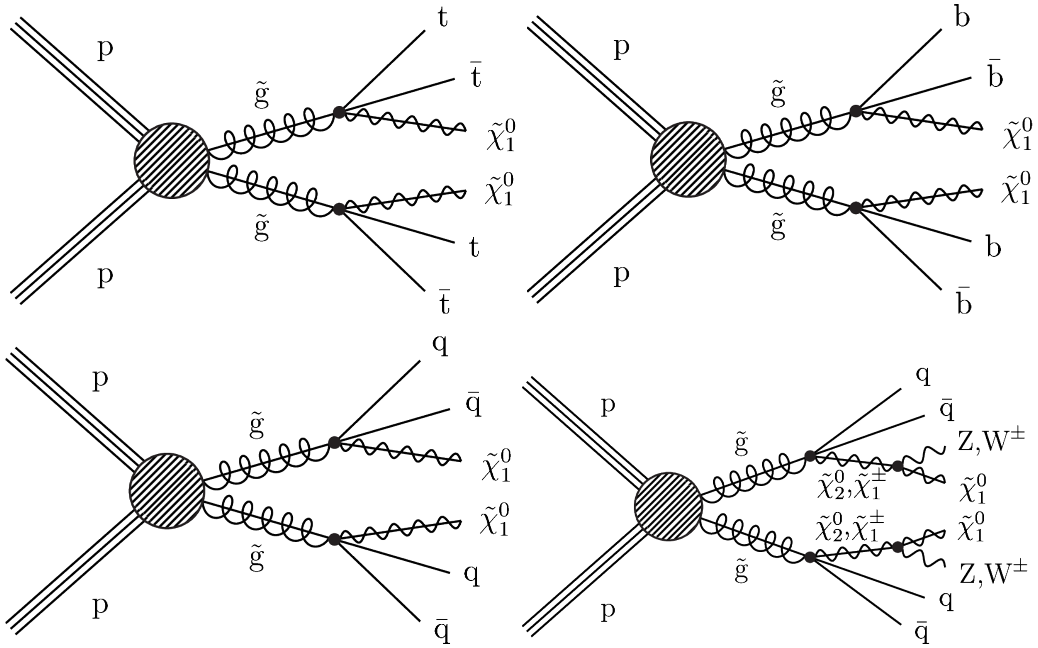
Axion-likes

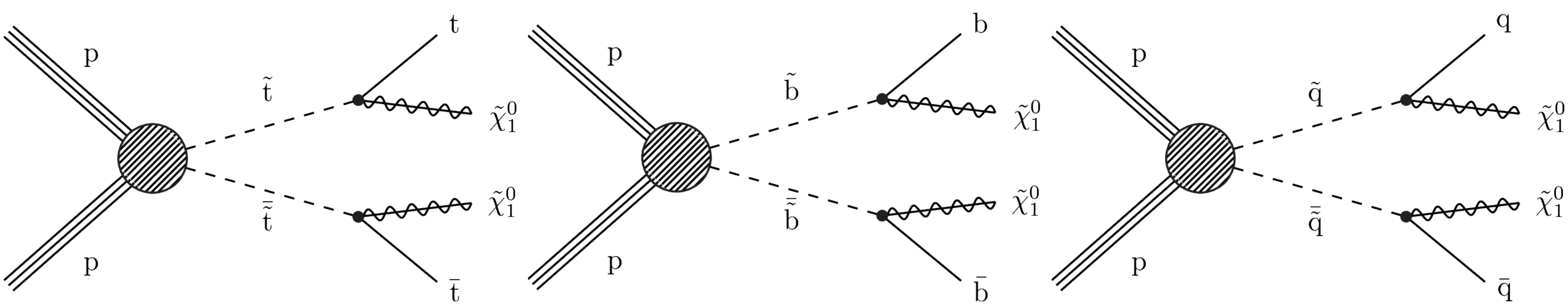


Y. Semertzidis

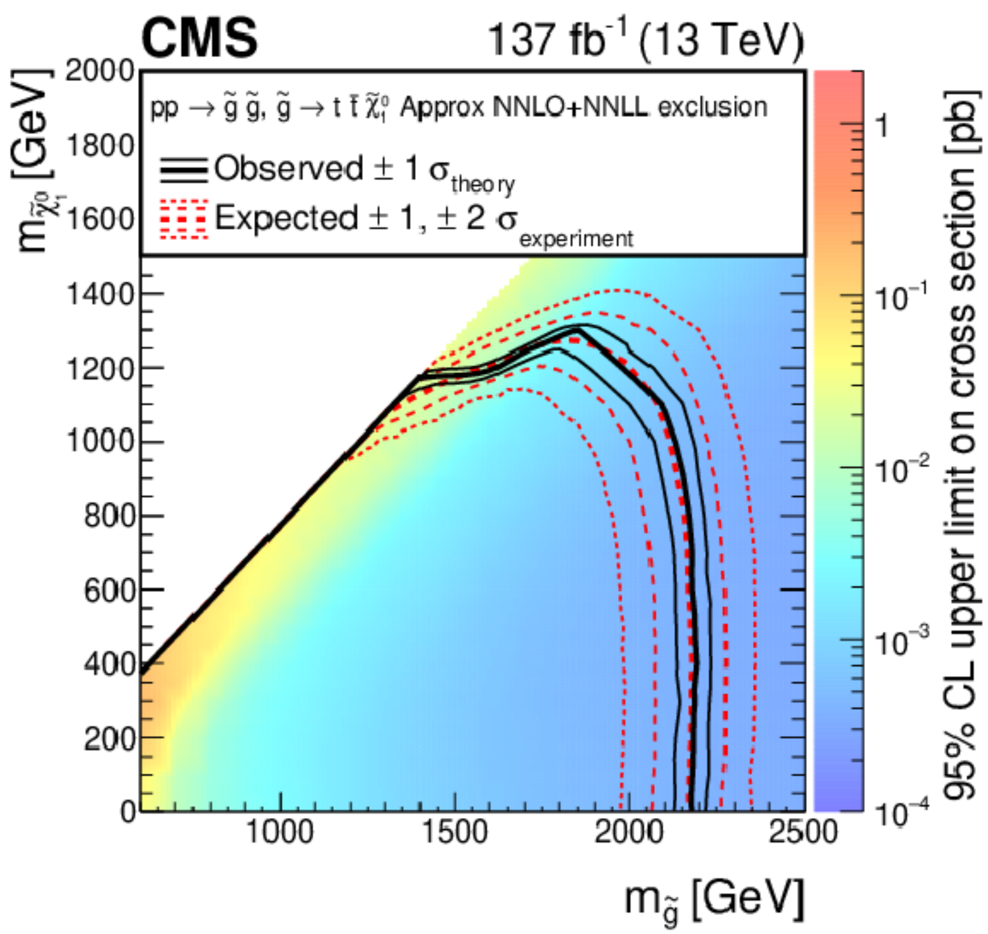
SUSY Searches

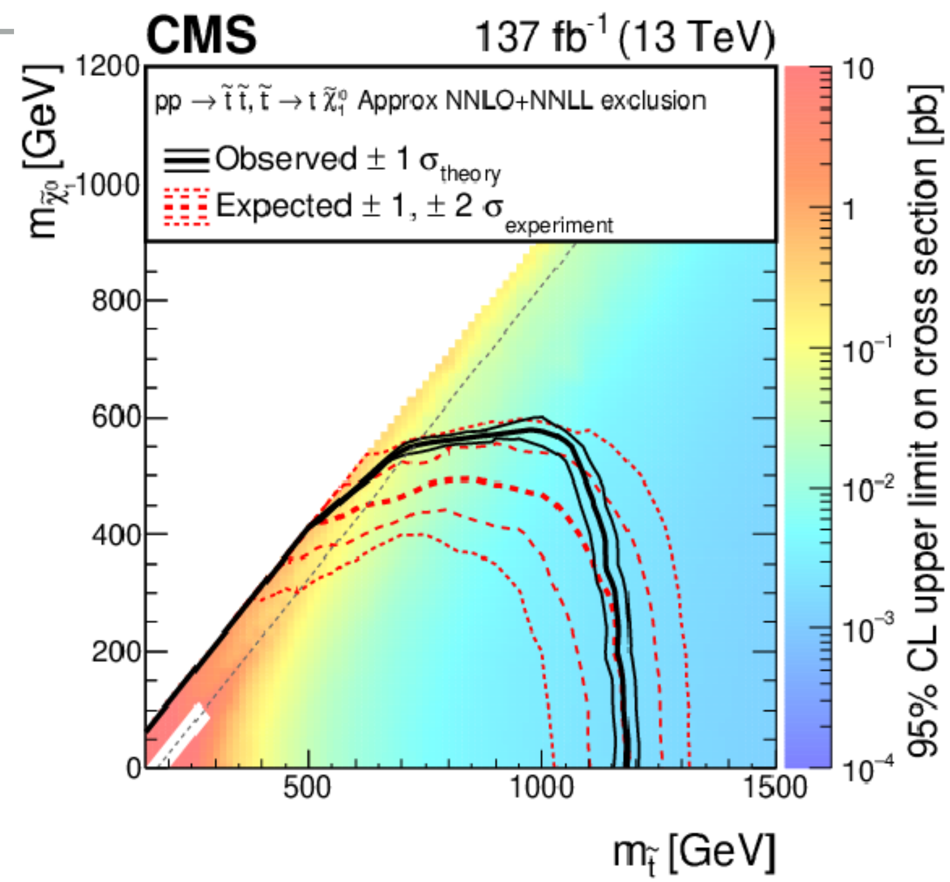
SUSY PRODUCTION





SUSY LIMITS


CMS
137 fb-1 (13 TeV)
pp → g̃ g̃, g̃ → t t̄ χ̃⁰₁ Approx NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1, ± 2 σexperiment
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]
95% CL upper limit on cross section [pb]


CMS
137 fb-1 (13 TeV)
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Observed ± 1 σtheory
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m_χ̃⁰₁ [GeV]
m_t̃ [GeV]
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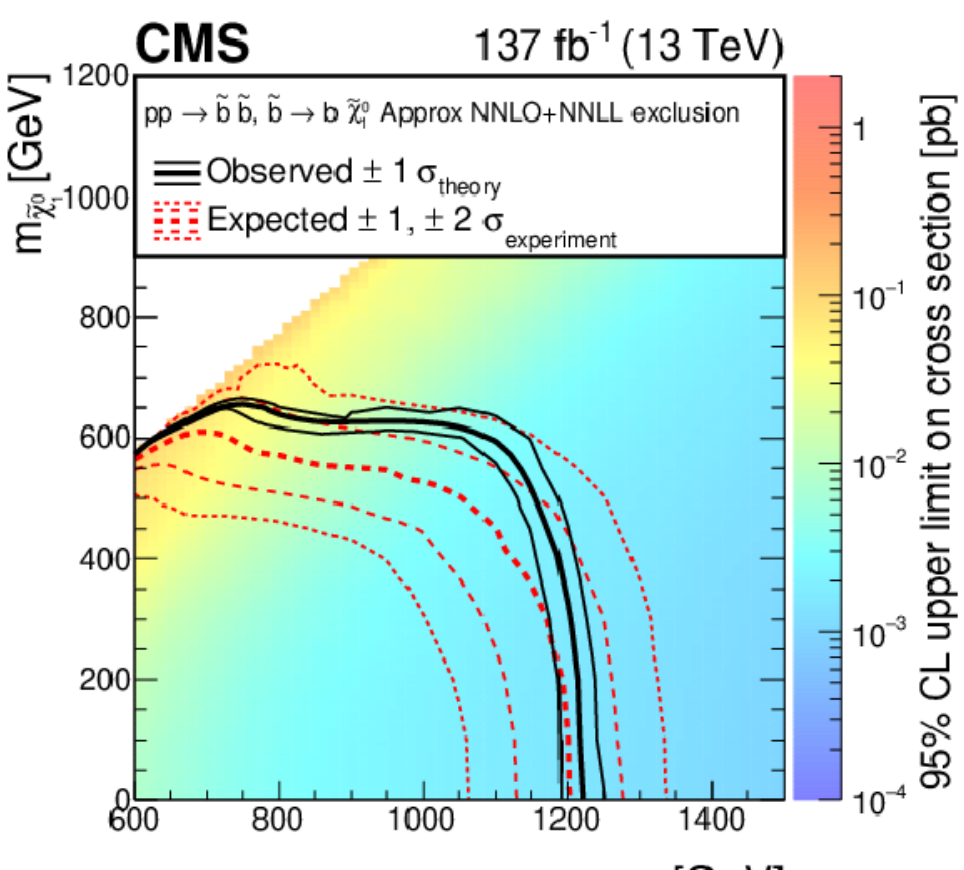
CMS
137 fb-1 (13 TeV)
pp → b̃ b̃, b̃ → b χ̃⁰₁ Approx NNLO+NNLL exclusion
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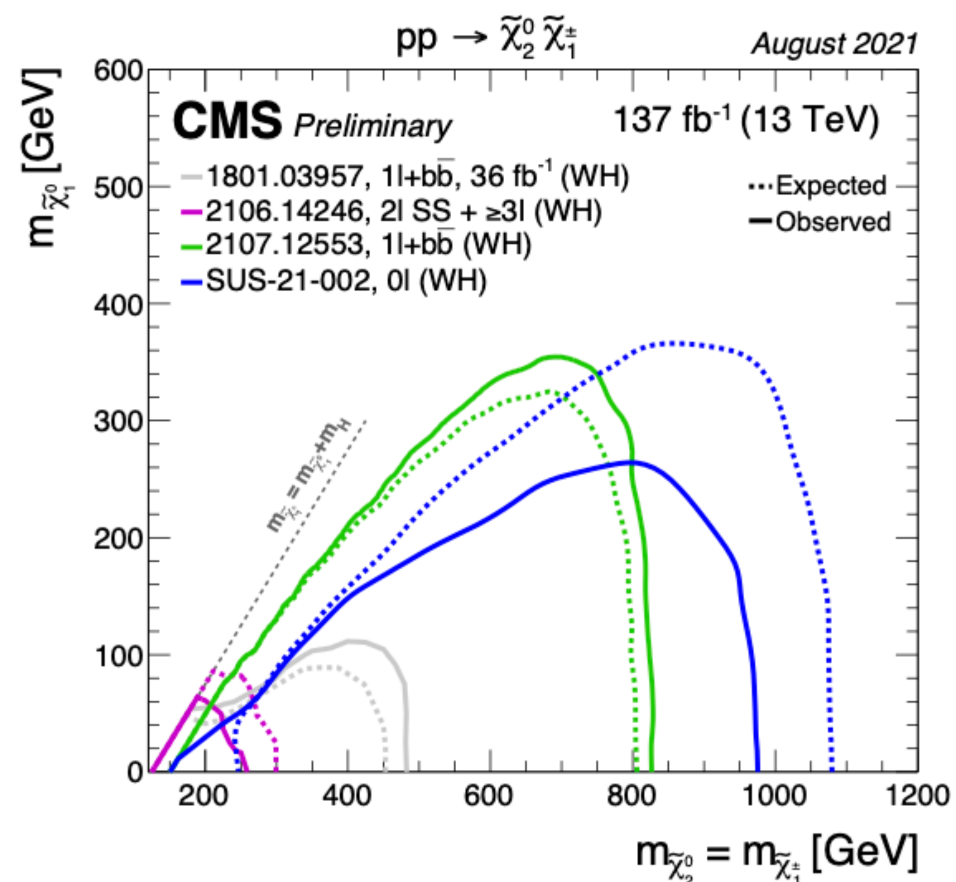
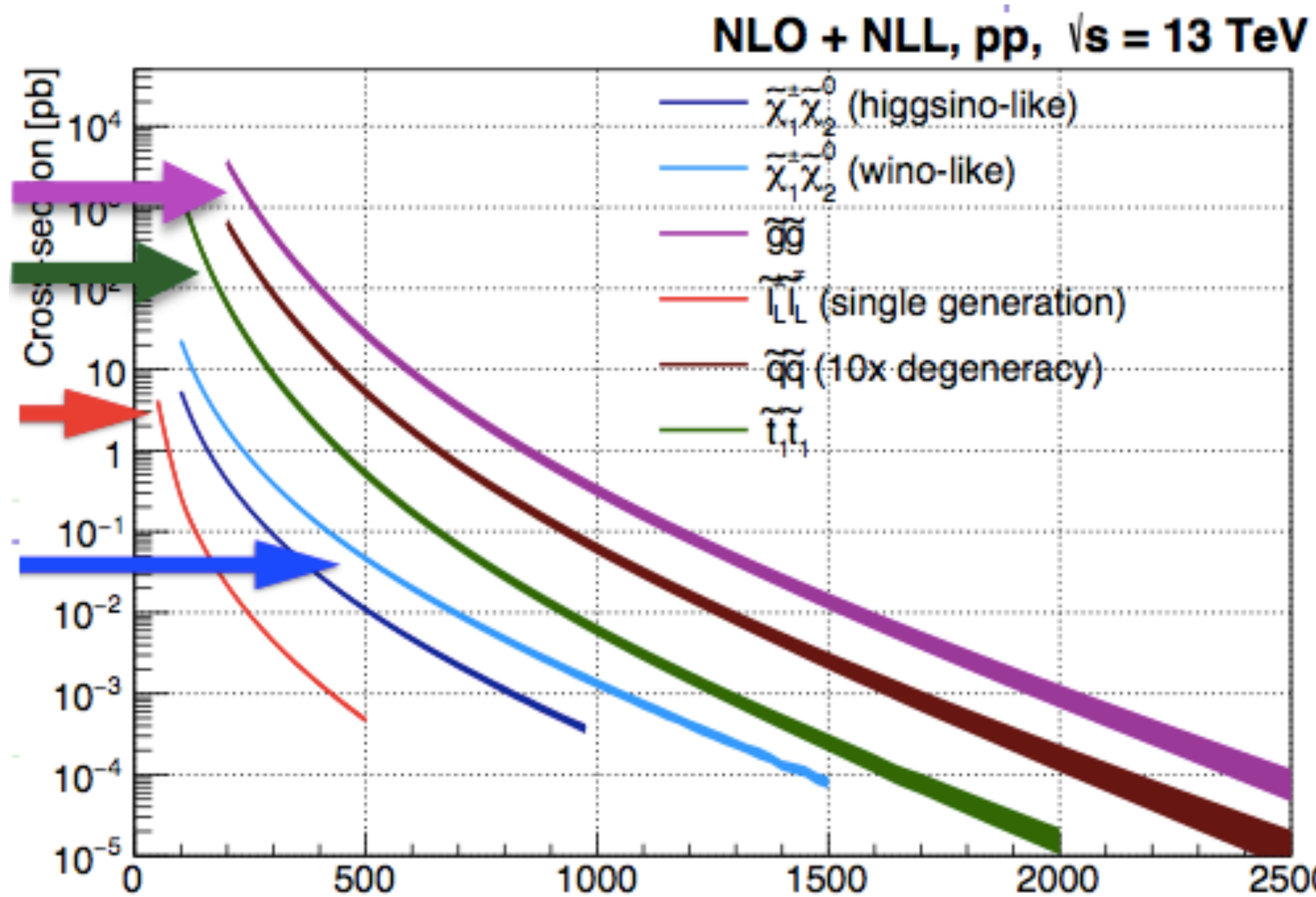
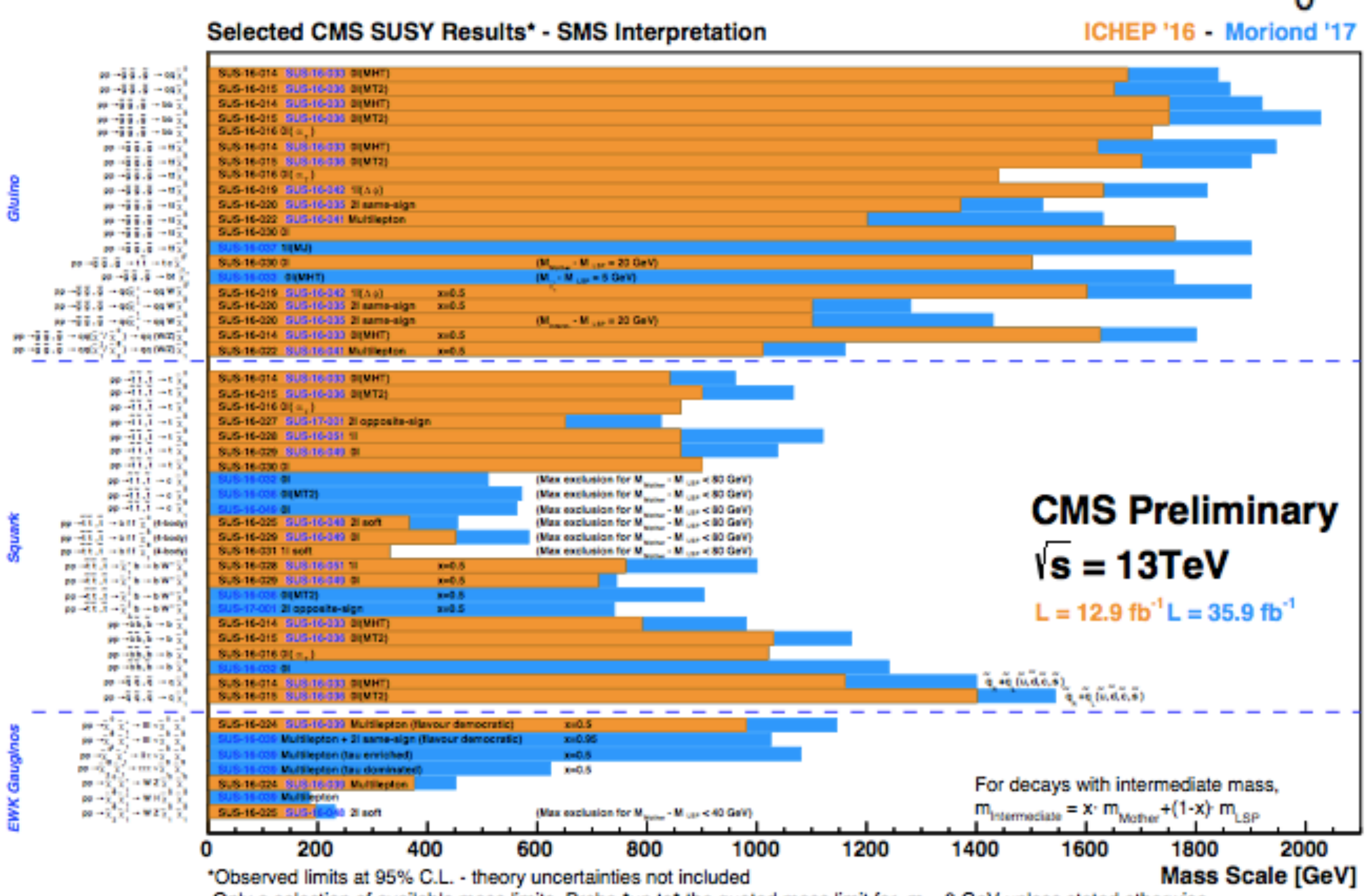

pp → χ̃⁰₂ χ̃±₁
August 2021
CMS Preliminary
137 fb-1 (13 TeV)
1801.03957, 1l+bb̄, 36 fb-1 (WH)
2106.14246, 2l SS + ≥3l (WH)
2107.12553, 1l+bb̄ (WH)
SUS-21-002, 0l (WH)
Expected
Observed
m_χ̃⁰₁ [GeV]
m_χ̃⁰₂ = m_χ̃±₁ [GeV]

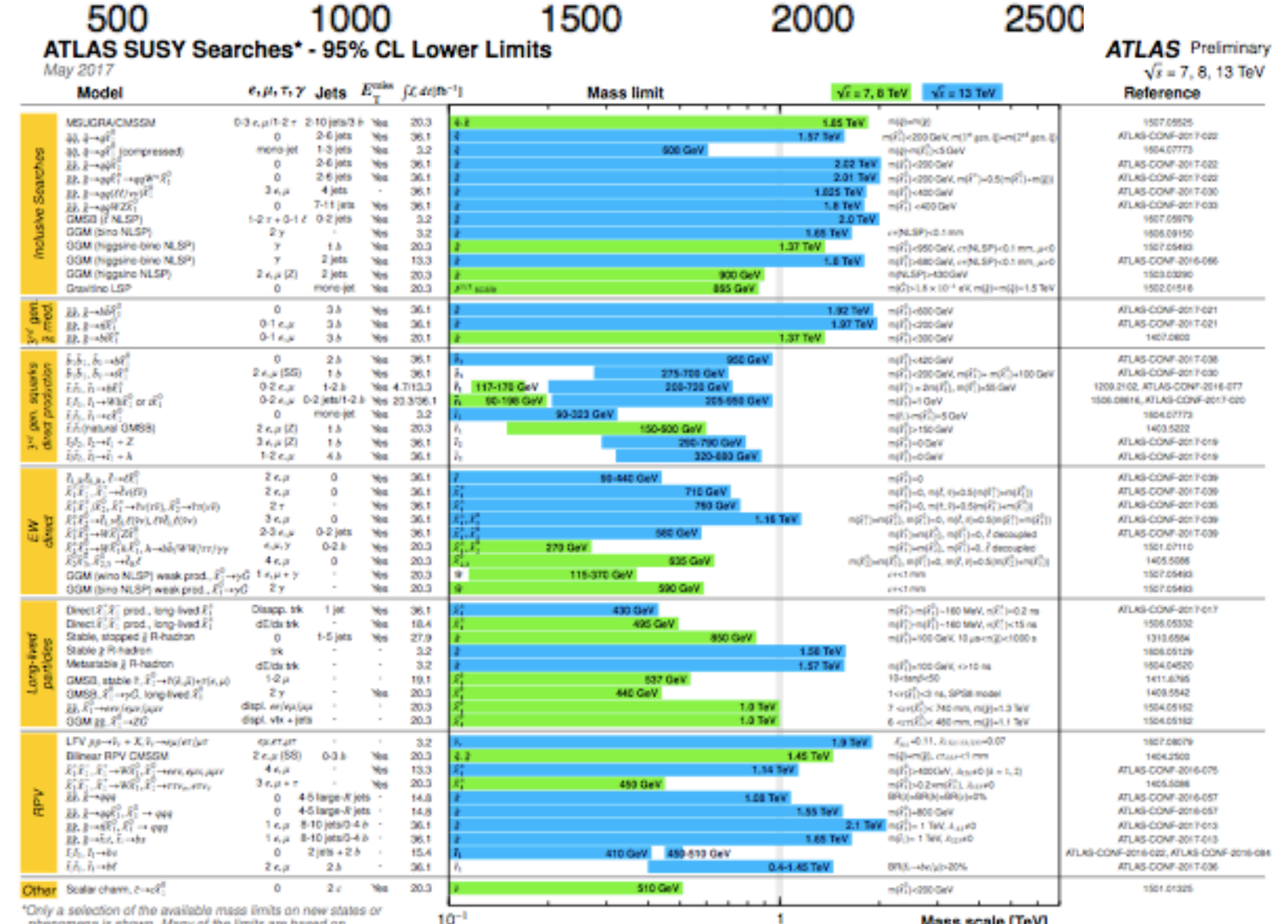
SUSY SEARCHES

Strong production
(gluinos, squarks)

EWK production
(charginos, neutralinos, sleptons)

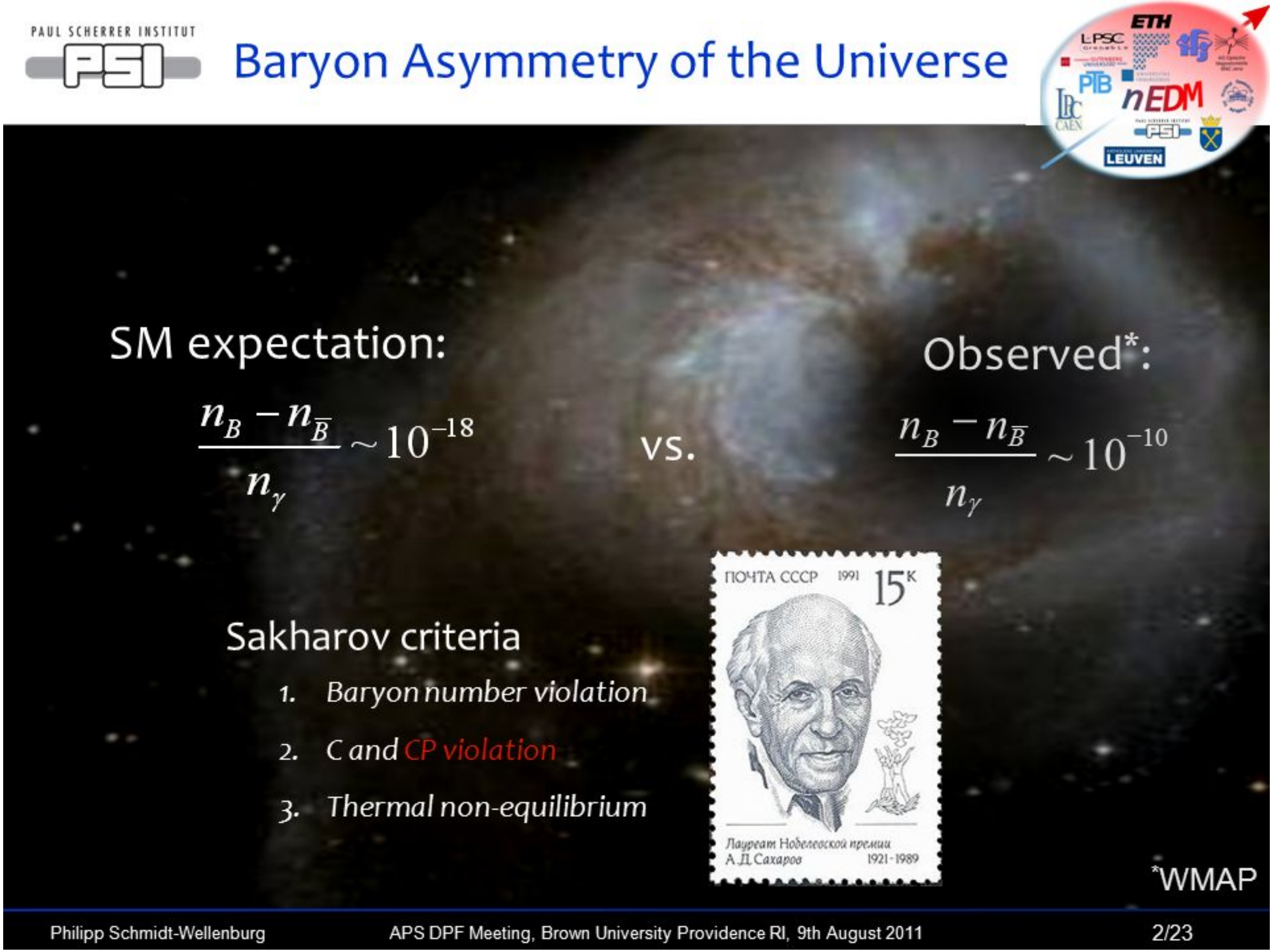






Baryon Asymmetry of the Universe

THE STANDARD MODEL: CONCEPTUAL PROBLEMS



- Baryon asymmetry of the Universe

1. Violation of a thermal equilibrium

A possible scenario in the early Universe when particles drop from thermal equilibrium violations T invariance $\longleftrightarrow$ $\not{T}$

2. Violation of baryon number $\longleftrightarrow$ $\not{B}$

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

Baryon number is conserved in the SM with exponential accuracy

Violation of baryon number occurs in Grand Unified Theories and in Lepton=fourth color models (Pati-Salam model) } New particles = Leptoquarks, Extended Highs sector

3. Violation of CP invariance (requires larger CP than in the SM) $\longleftrightarrow$ $\not{CP}$

In the SM achieved via phase factors in the CKM and PMNS mixing matrices

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

CPT is exact symmetry of Nature

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- 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, ...

BEYOND THE STANDARD MODEL: CONCLUSIONS

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- The intensity frontier
- The precision frontier
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