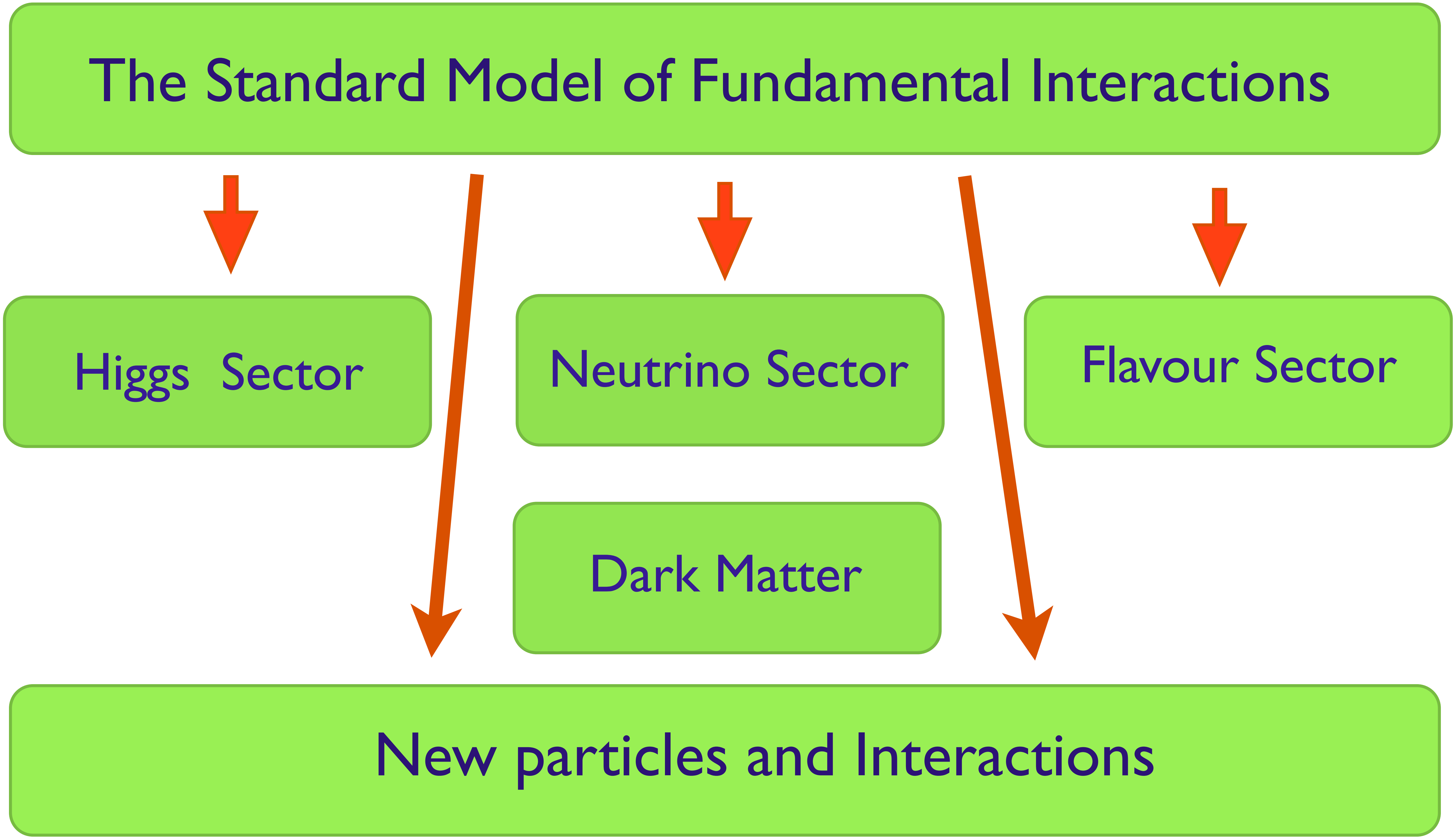
WHAT MAKES US THINK THAT THERE IS PHYSICS BEYOND THE STANDARD MODEL?

Dmitry Kazakov

BLTP JINR

THE STANDARD MODEL: THE WAYS BEYOND



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 ?

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

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

←

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

THE LAGRANGIAN

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

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

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

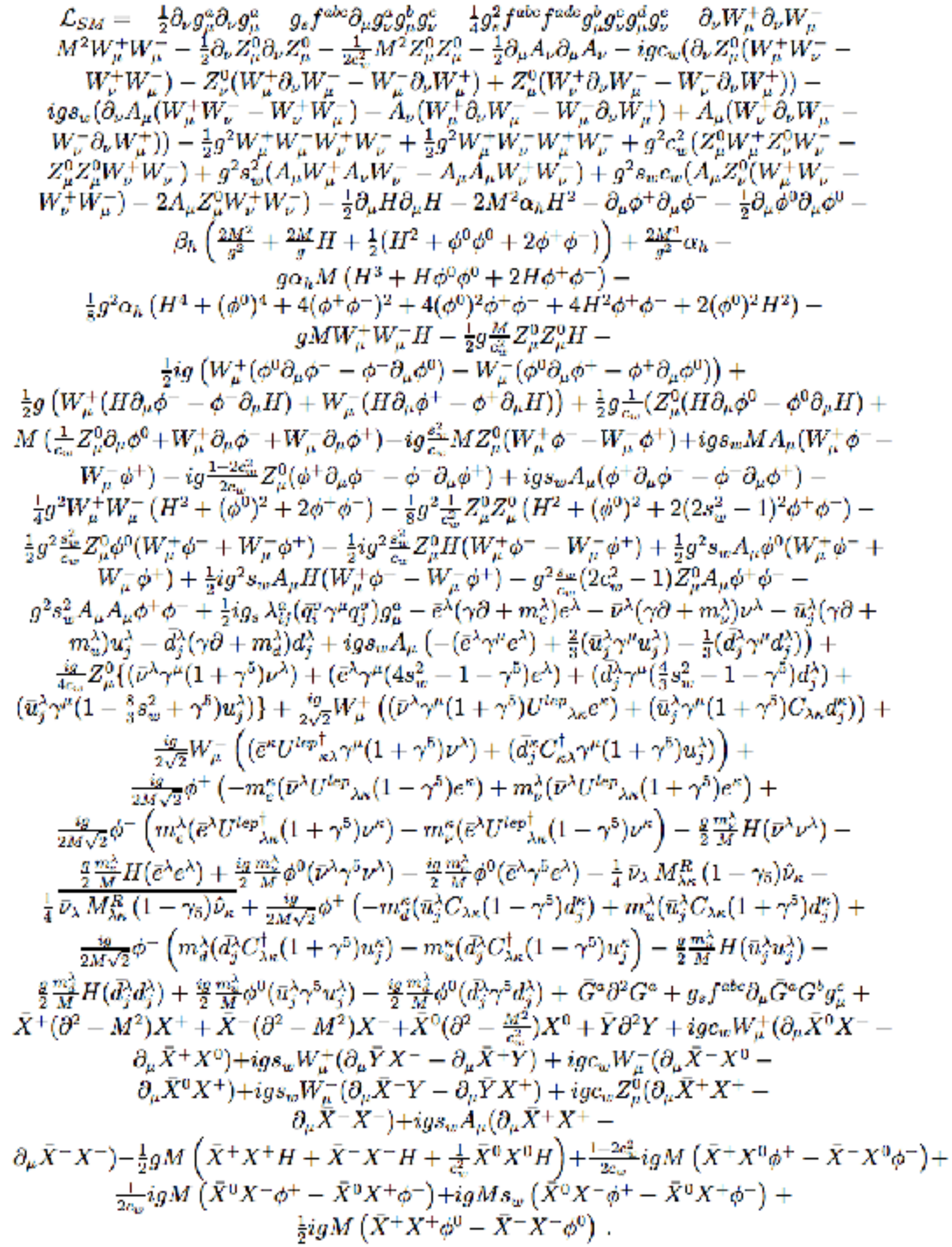
$$+i\overline{U}_\alpha\gamma^\mu D_\mu U_\alpha +$$

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

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

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

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



$$\begin{aligned}
\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_s^2 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^2W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2Z^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^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
& Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_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_w^2}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_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
& W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
& \tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
& \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
& W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
& g^2s_w^2A_\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_wA_\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_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
& (\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \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^5e^\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^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{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 - \tfrac{M^2}{c_w^2})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^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
& \tfrac{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) + \\
& \tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).
\end{aligned}$$

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

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

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

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

Three gauge couplings

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

possible right handed neutrino ?

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Three or four Yukawa matrices

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Two parameters

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possible right handed neutrino ?

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

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

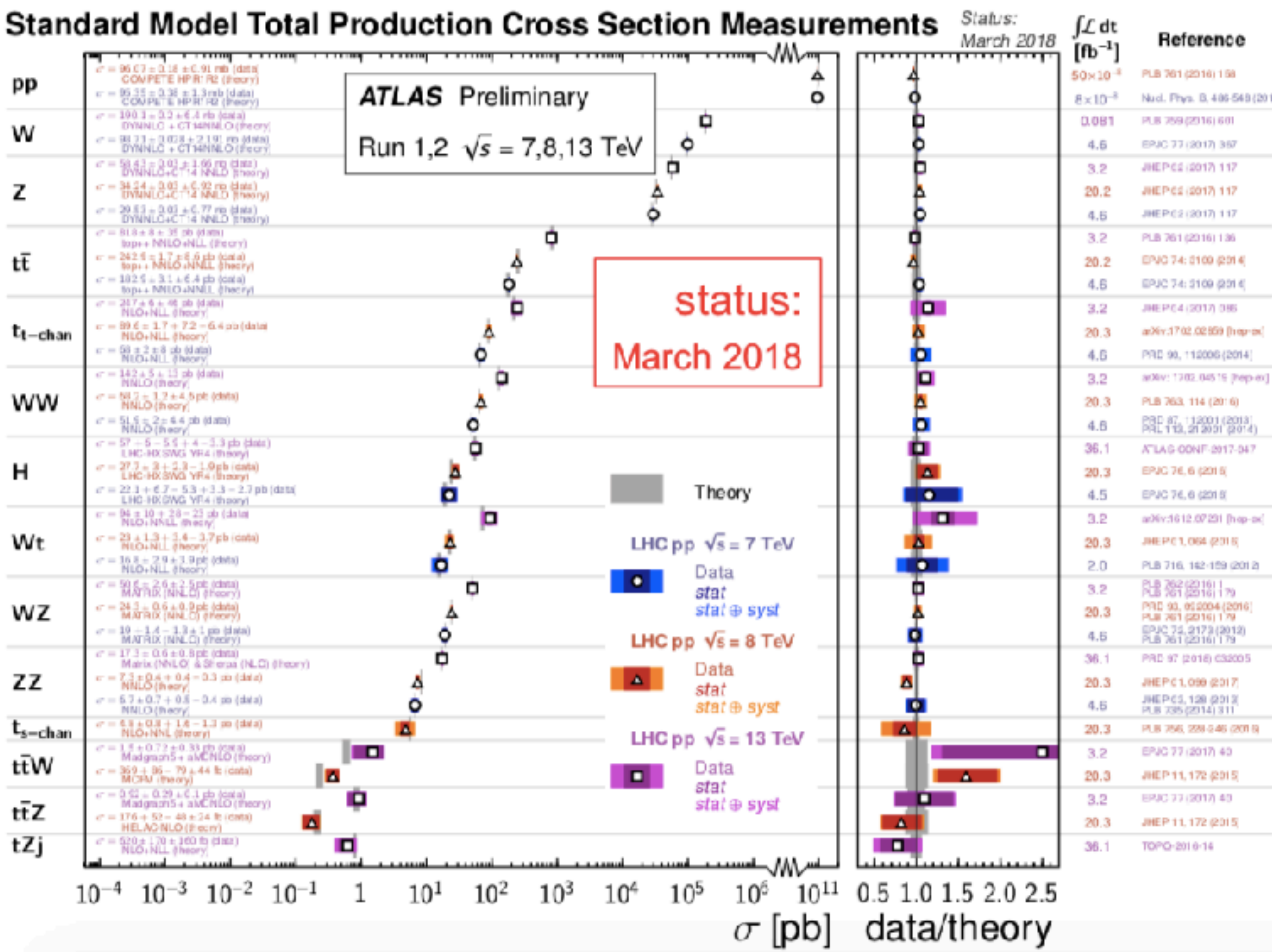
All these parameters are not predicted by the SM and determined experimentally

Three gauge couplings

Three or four Yukawa matrices

Two parameters

C. Gwenlan
ICHEP2018

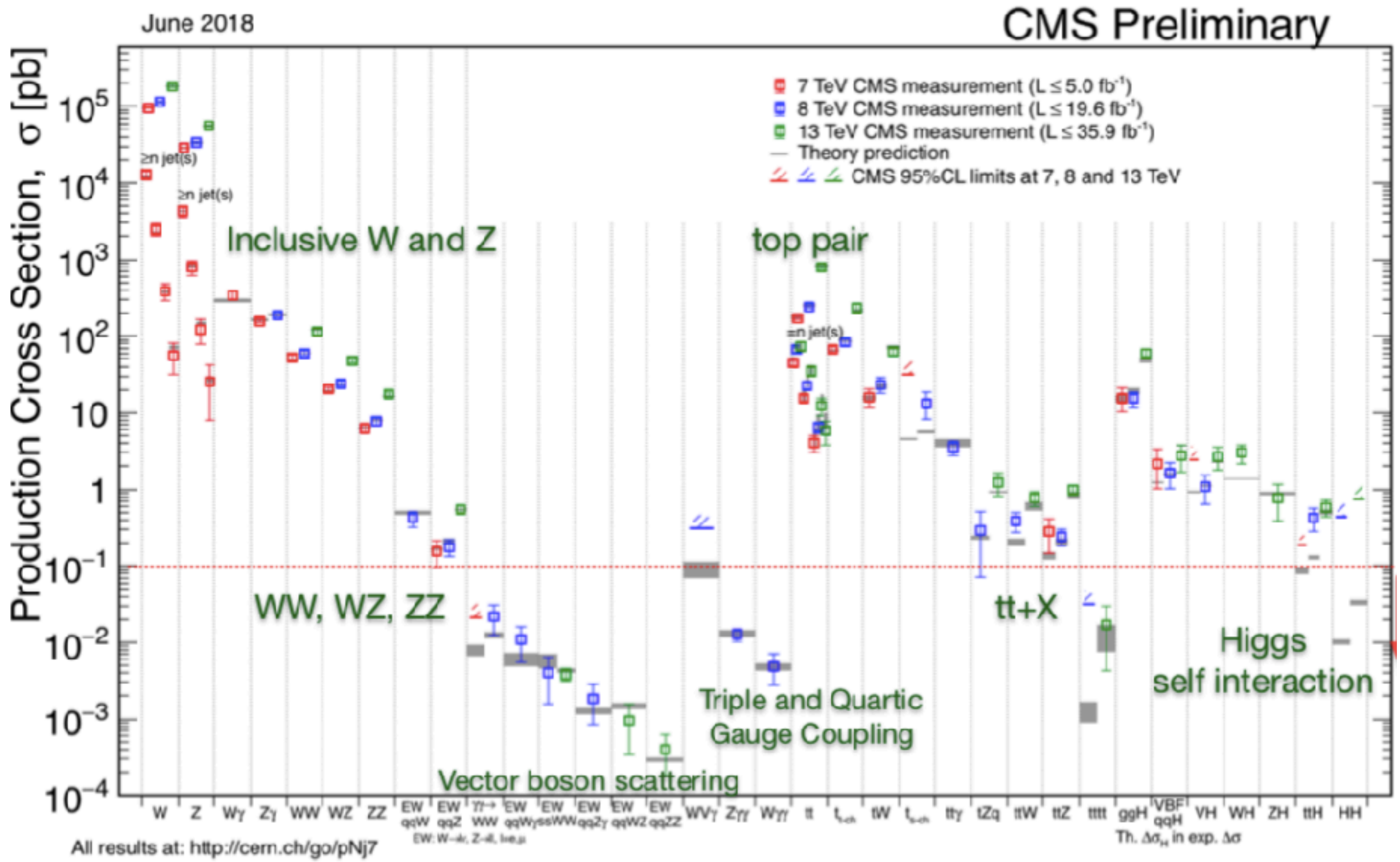


Extraordinary agreement between measurements and SM predictions

New physics through precision

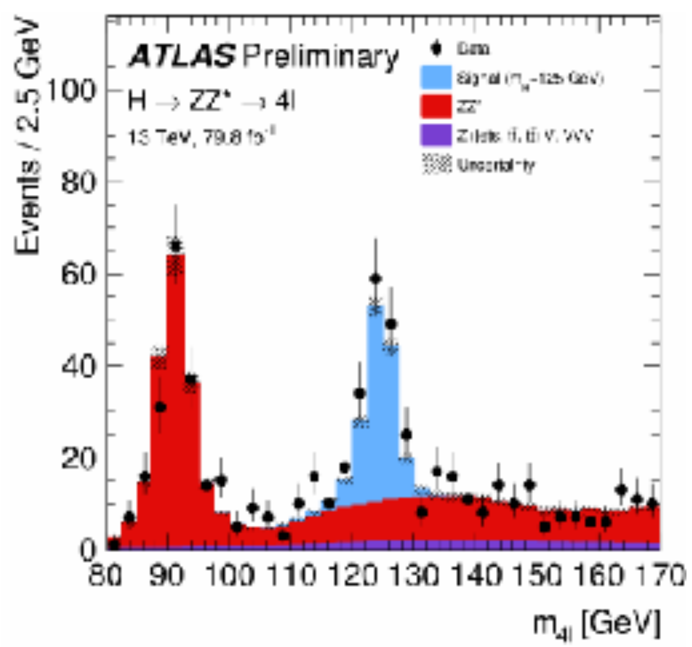
S. Rathatlou

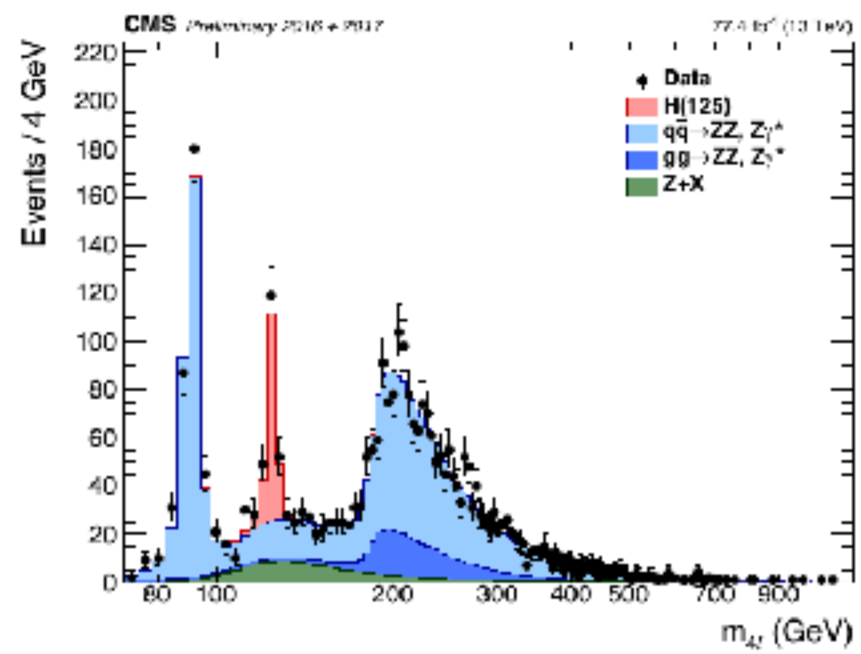
ICHEP2018



Higgs bosons - entering precision era

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





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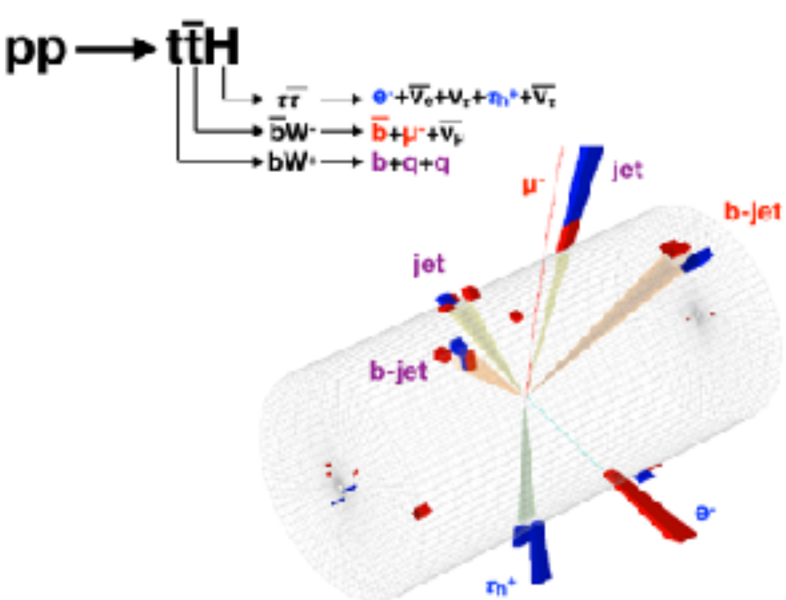
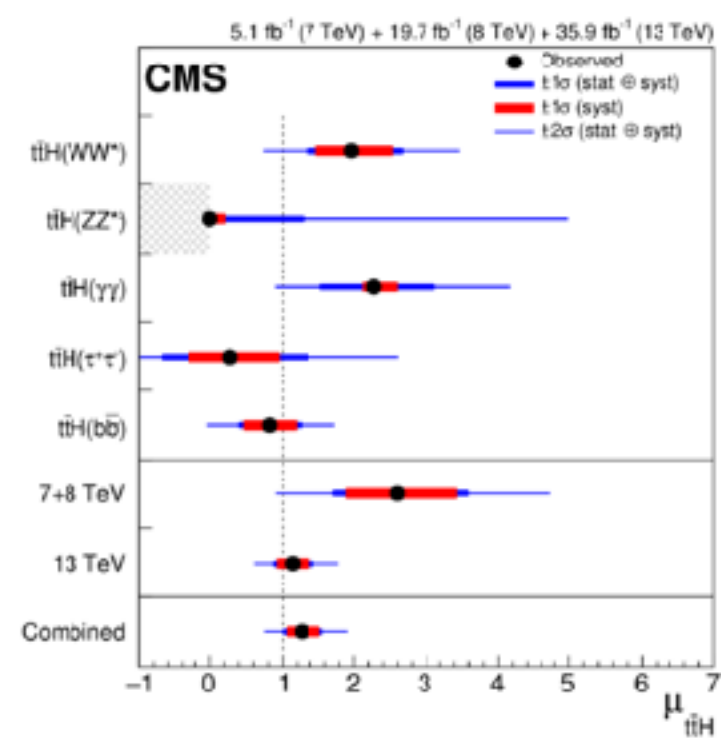
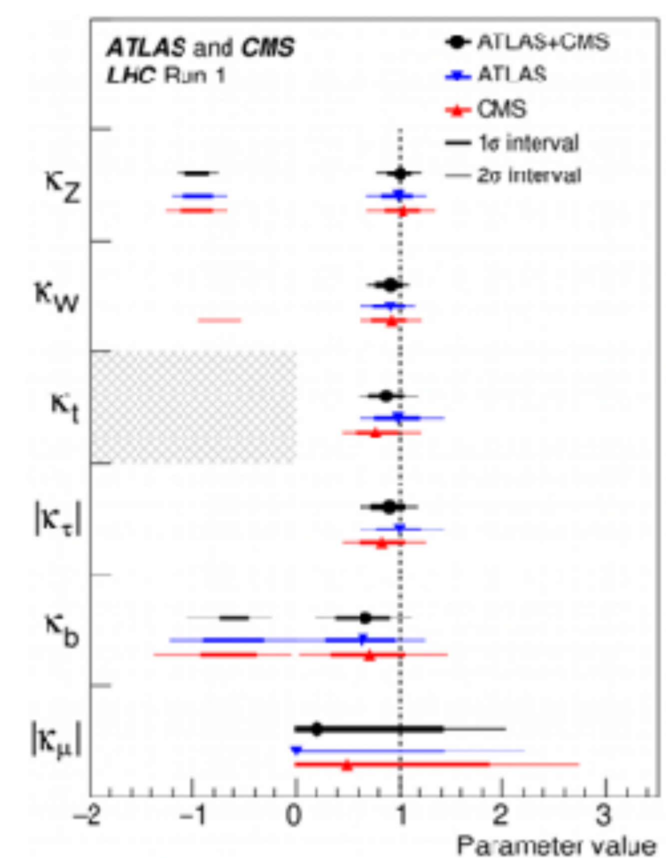
LHCp2018

ttH observation







Precision EW mass measurements

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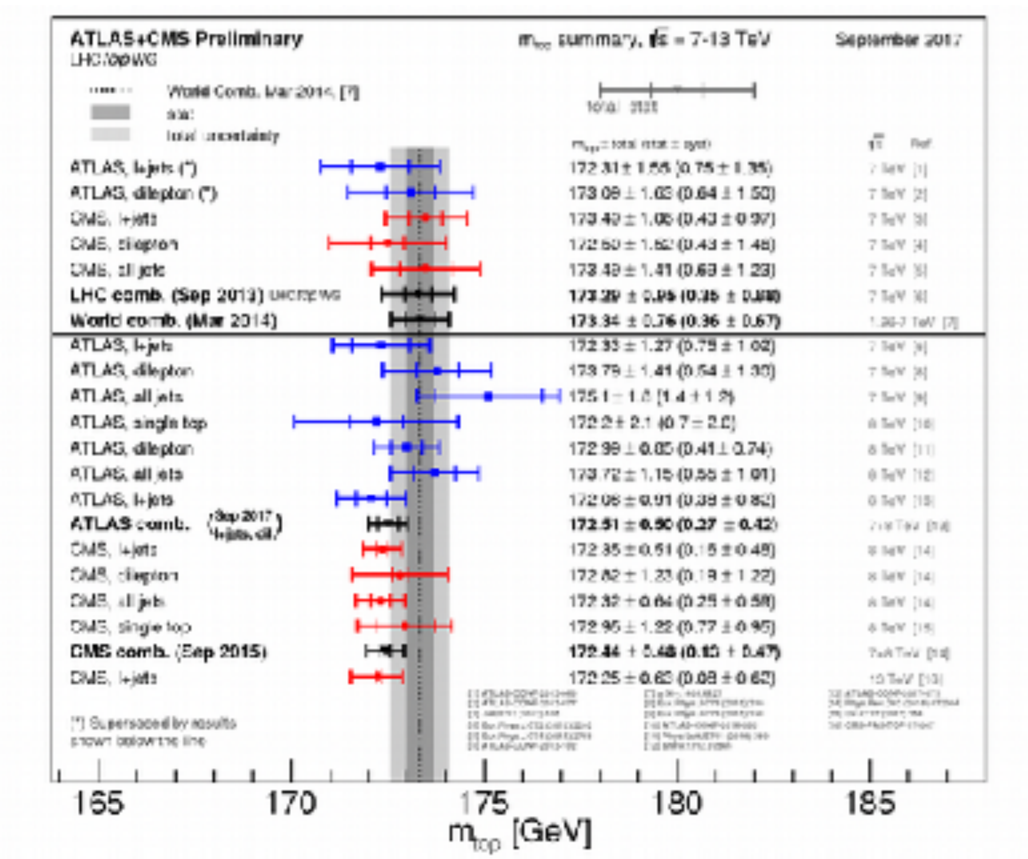
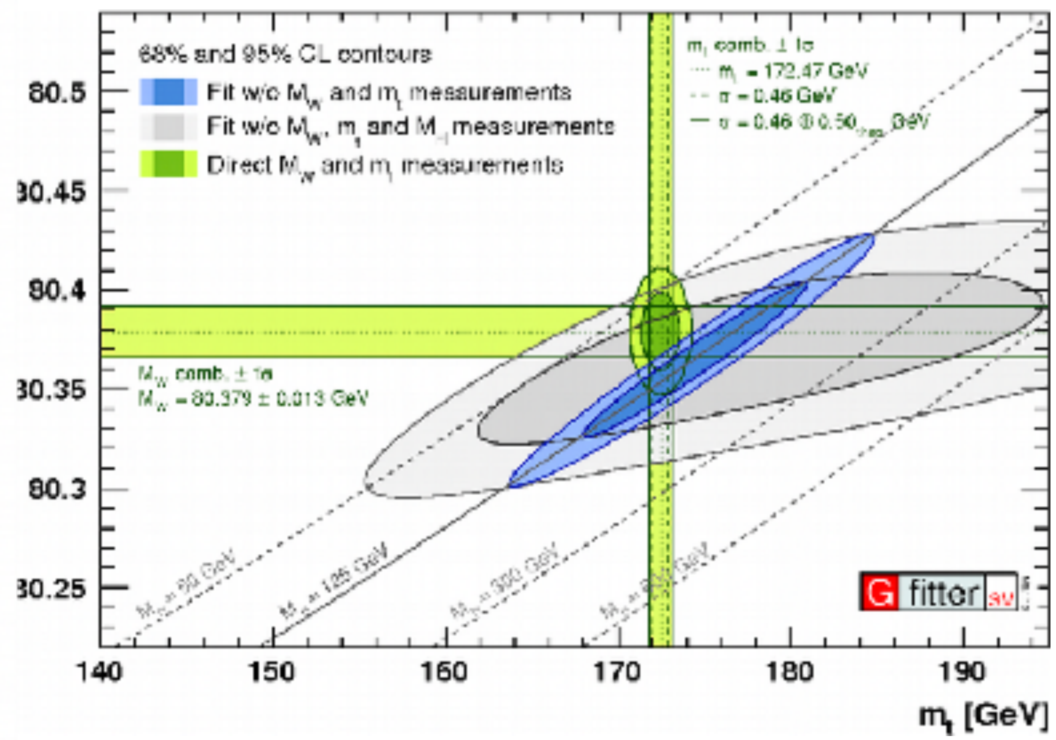
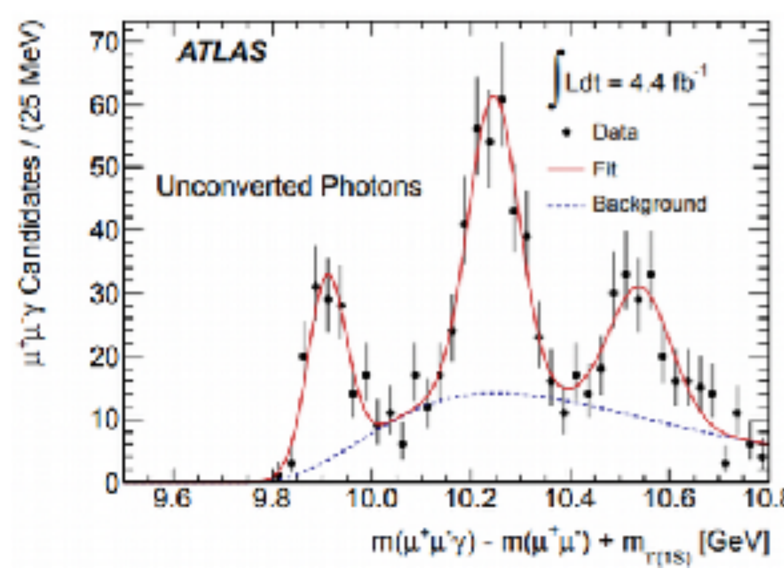
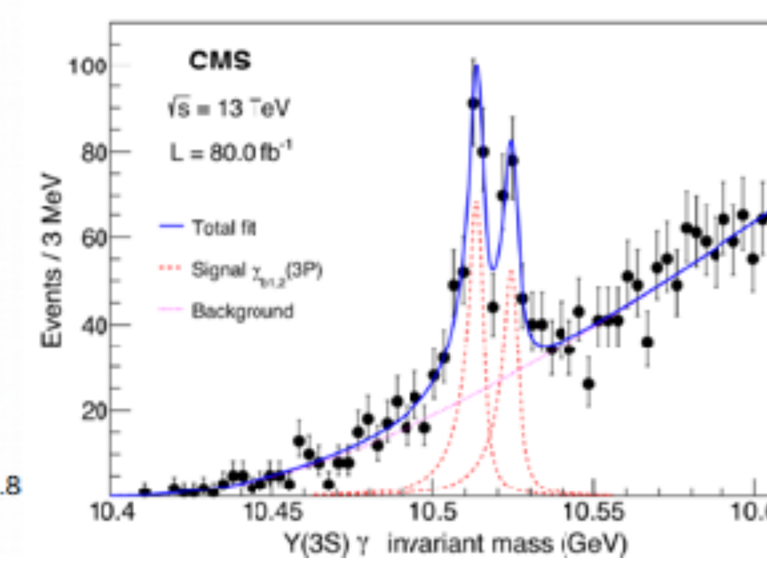




Precision spectroscopy!



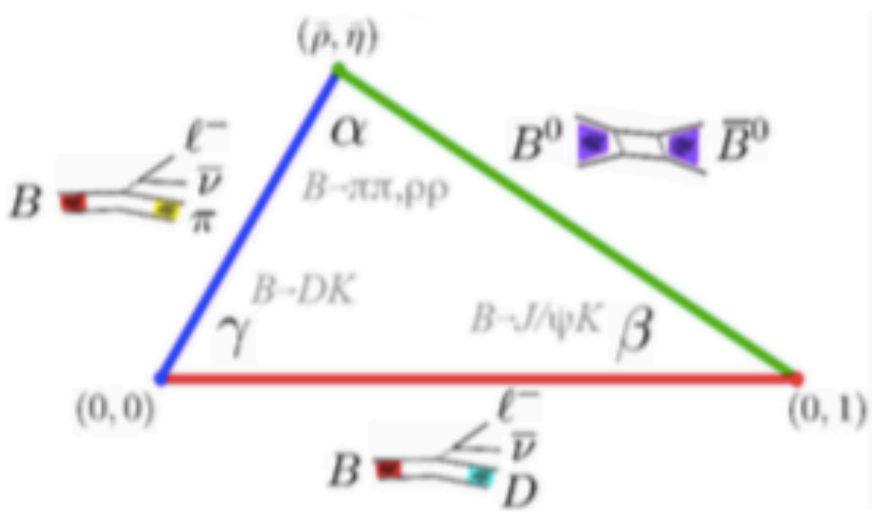


$m(\chi_{b2}(3P)) - m(\chi_{b2}(3P))$ =

10.60 ± 0.64(stat) ± 0.17 (syst) MeV

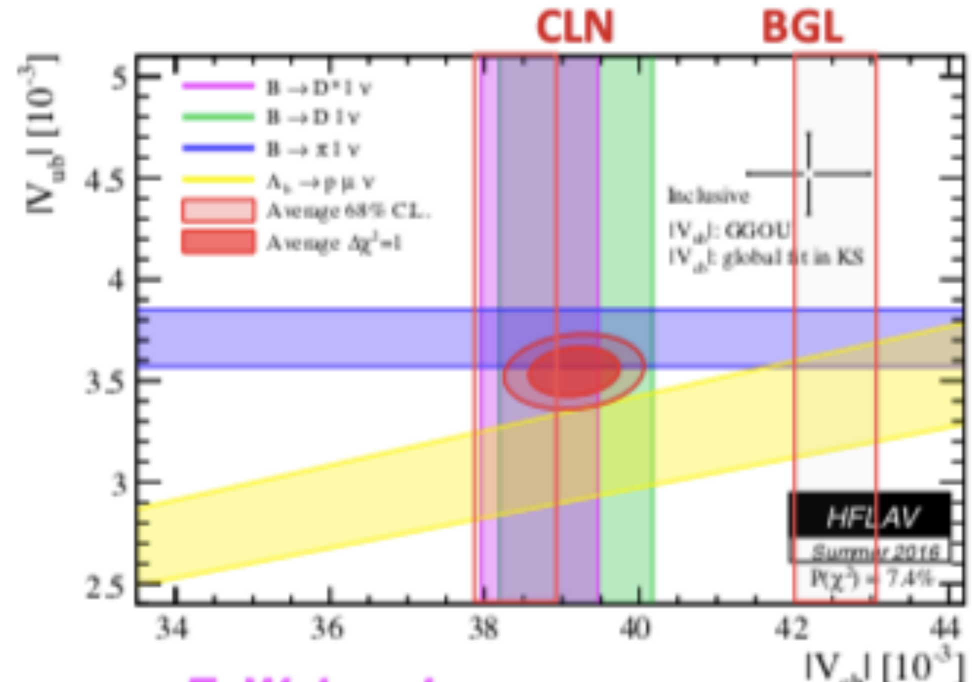
Flavor Physics

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

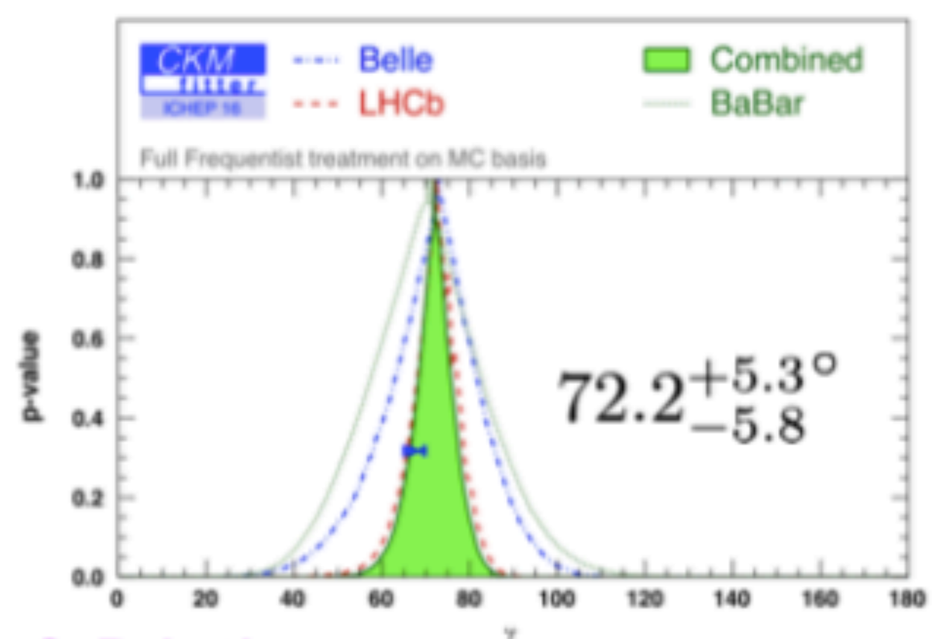


P. Urquijo

$B \to \pi\pi, \rho\rho$	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



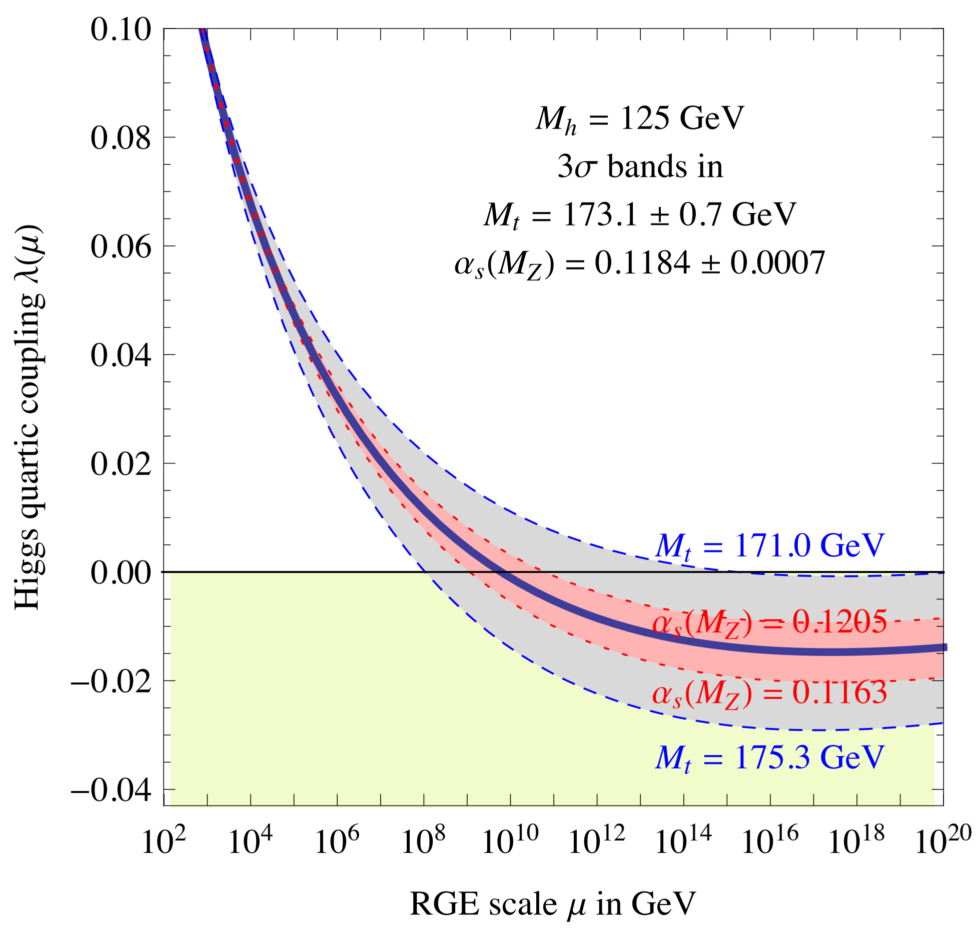
E. Waheed

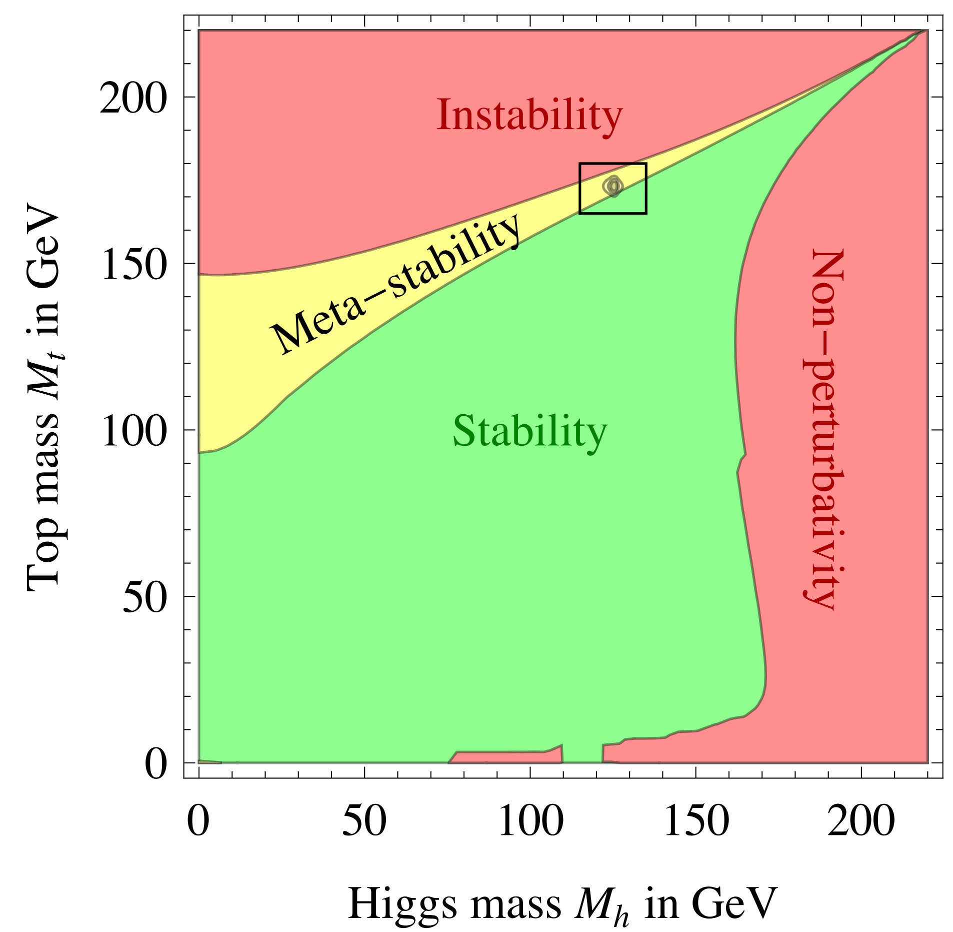


S. Rahatlou

- The electroweak vacuum is unstable under radiative corrections

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



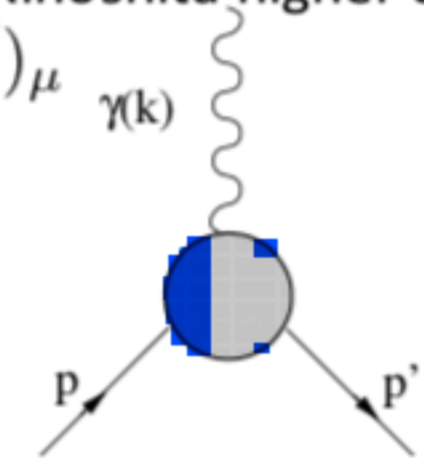


- the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and high accuracy of calculations (3 loops)

Muon anomalous magnetic moment

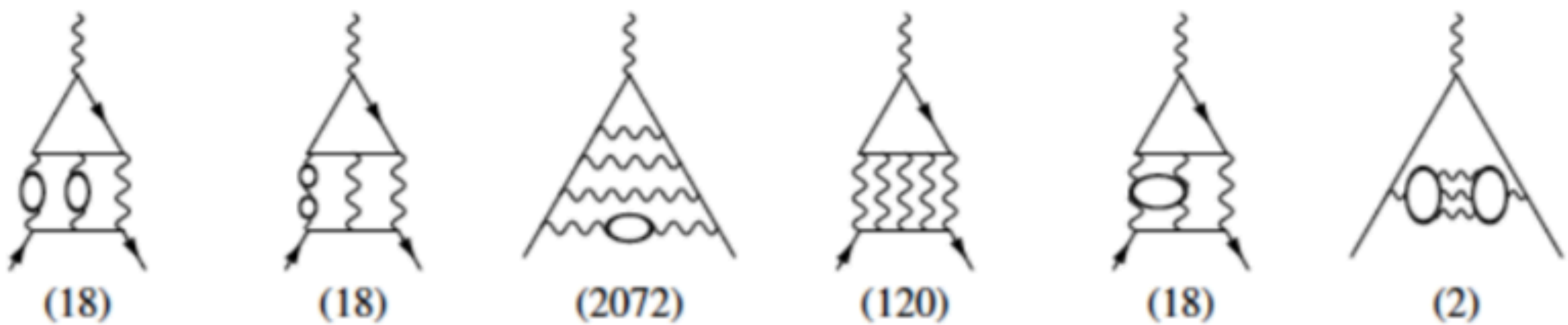
(Schwinger α/π, Kinoshita higher orders in α)

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



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

For electron a_e theory and experiment agrees!



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

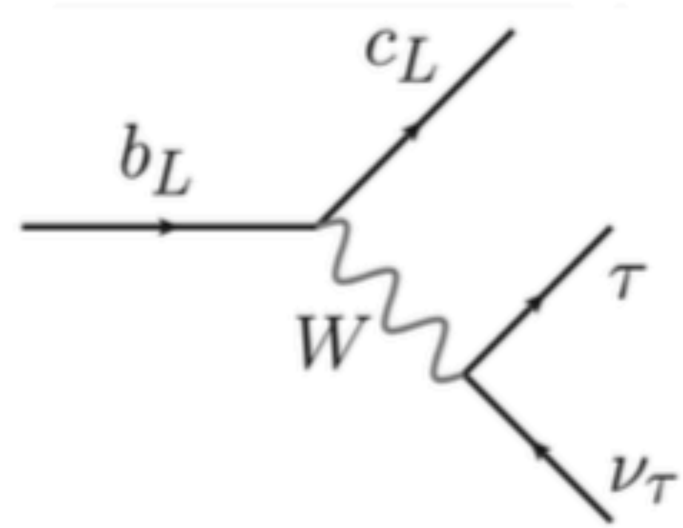
Fermilab and J-Park experiments are expected to clarify existing discrepancy!

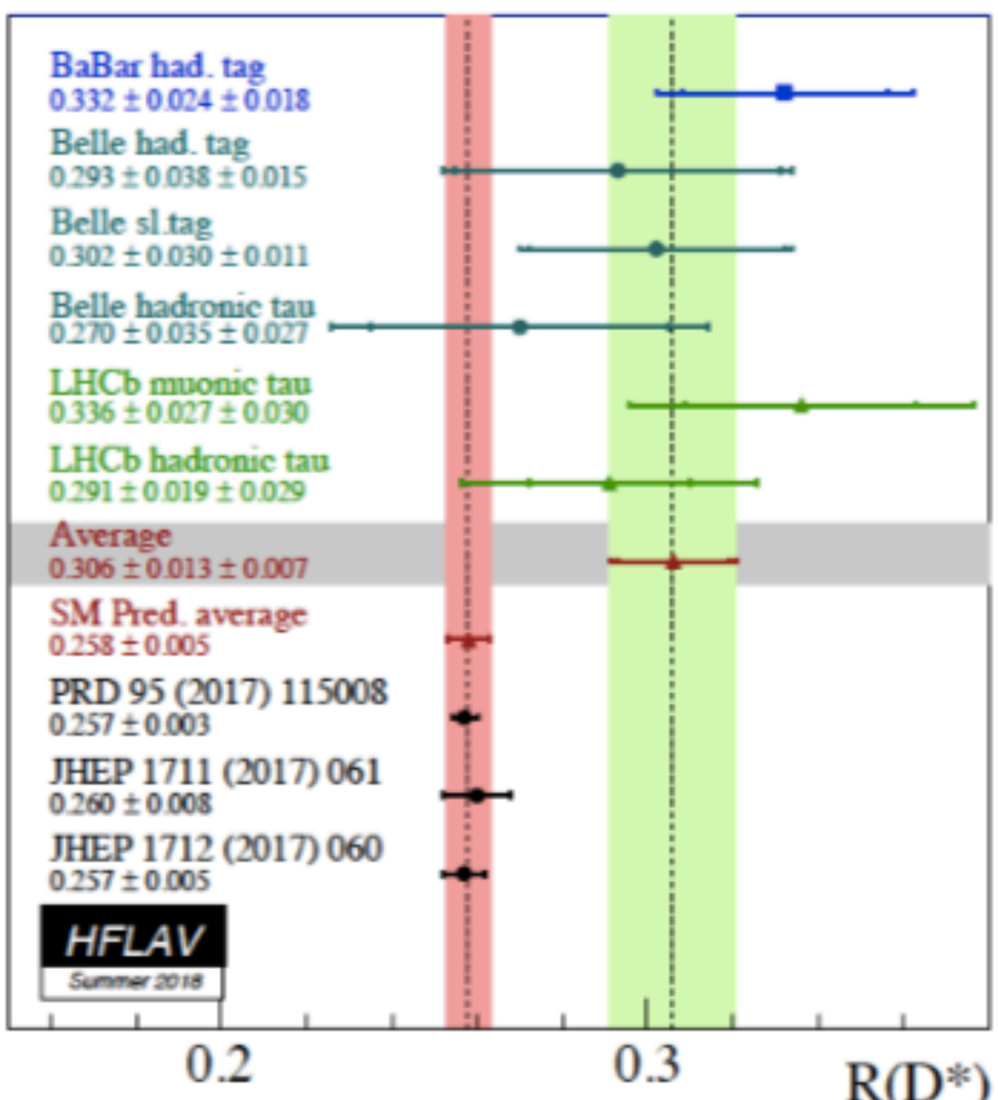
B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)

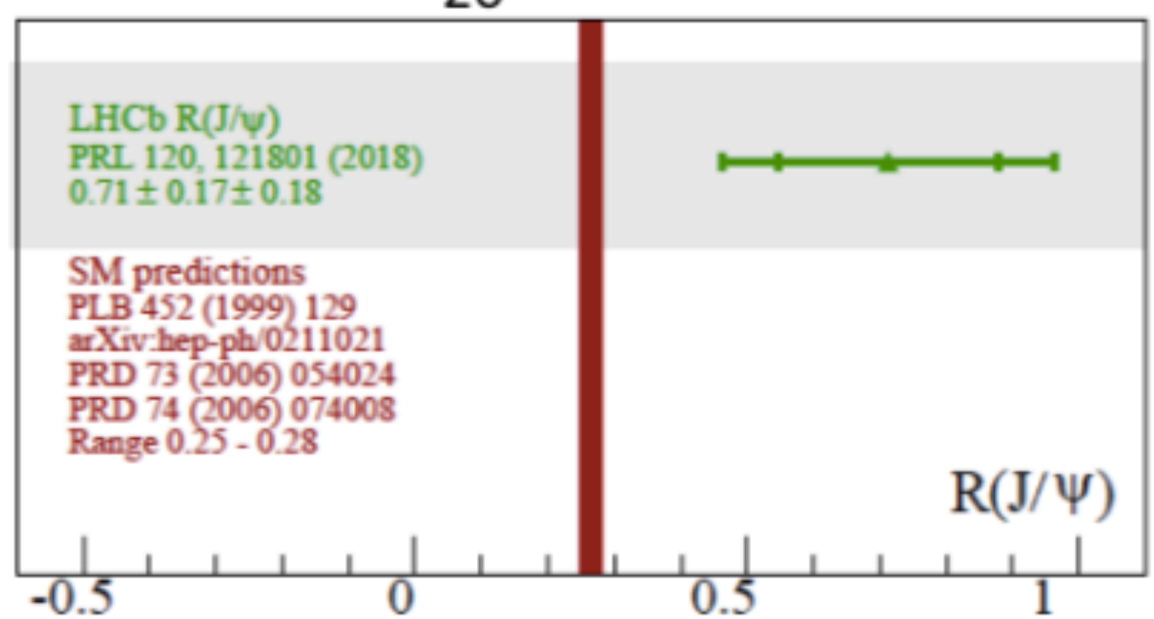
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$

3.8σ





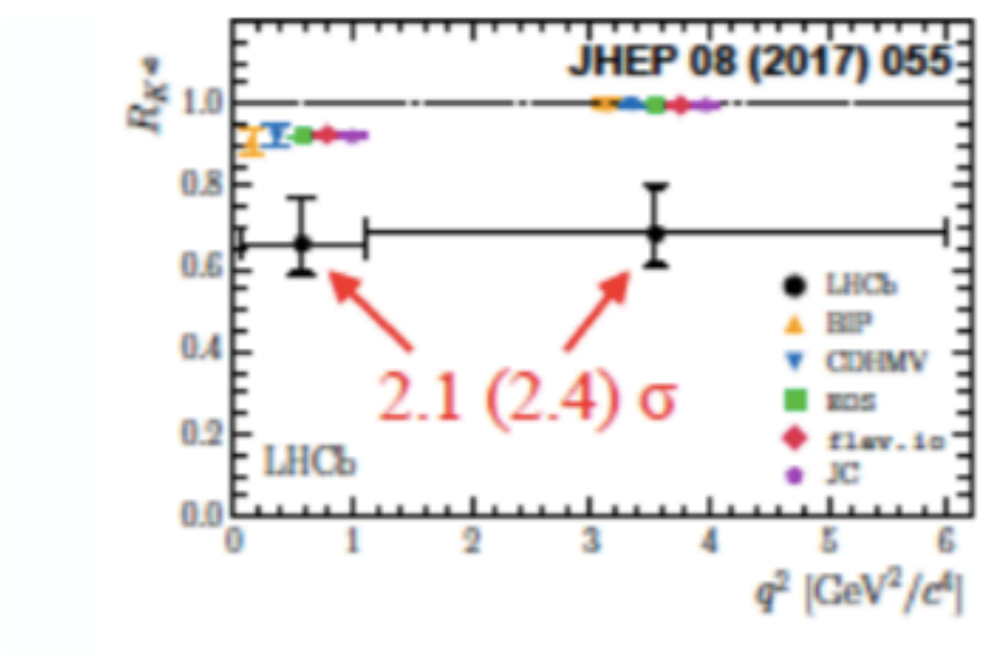
2σ

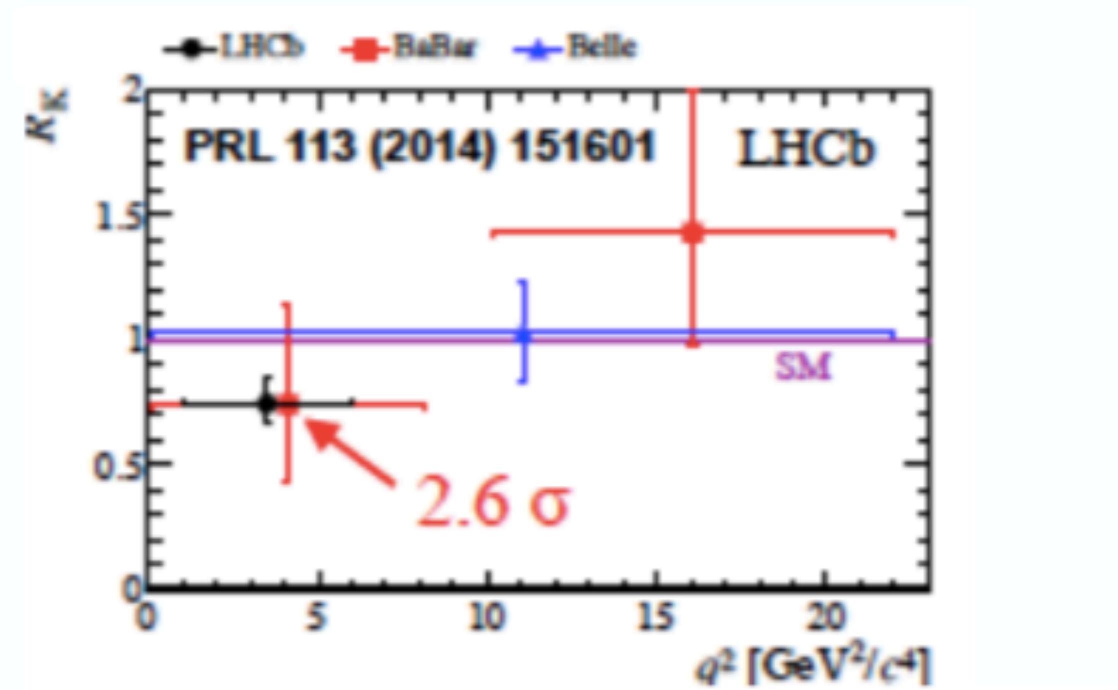


See Leroy's talk at ICHEP2018

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

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



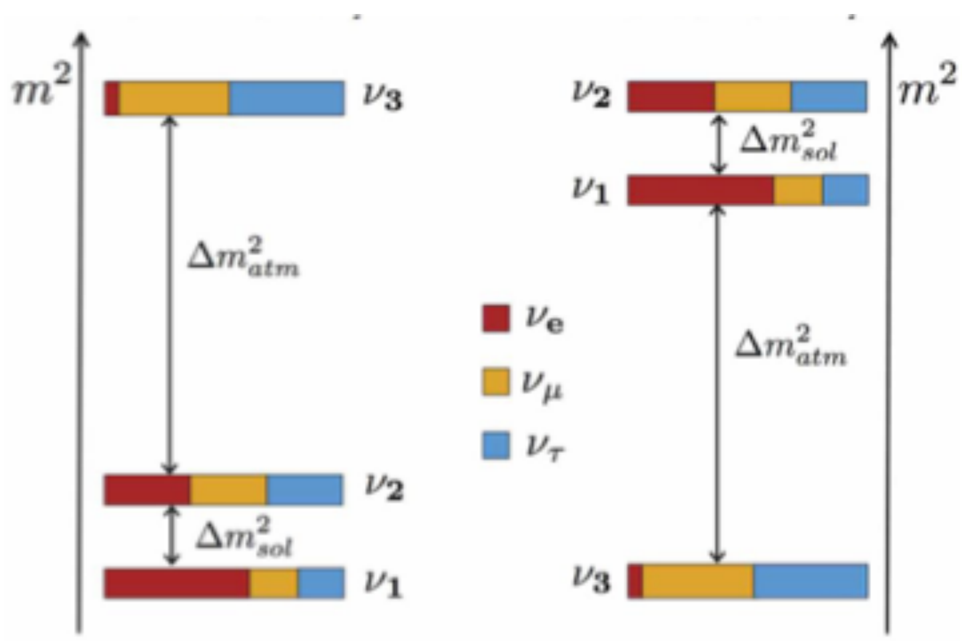


P_5' in $B \to K^*\mu^+\mu^-$ (angular distribution functions) 3σ

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

(see Capriotti talk at ICHEP2018)

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
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60
$\|\Delta m^2_{31}\|$ [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

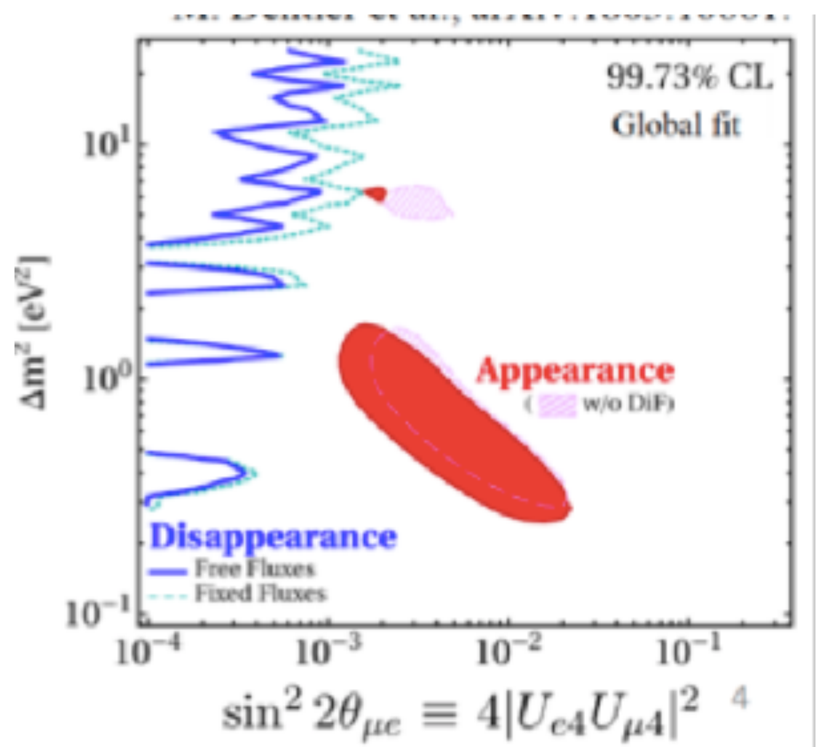
Type I seesaw mechanism: ν_{lR} - RH νs' (heavy).

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.

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



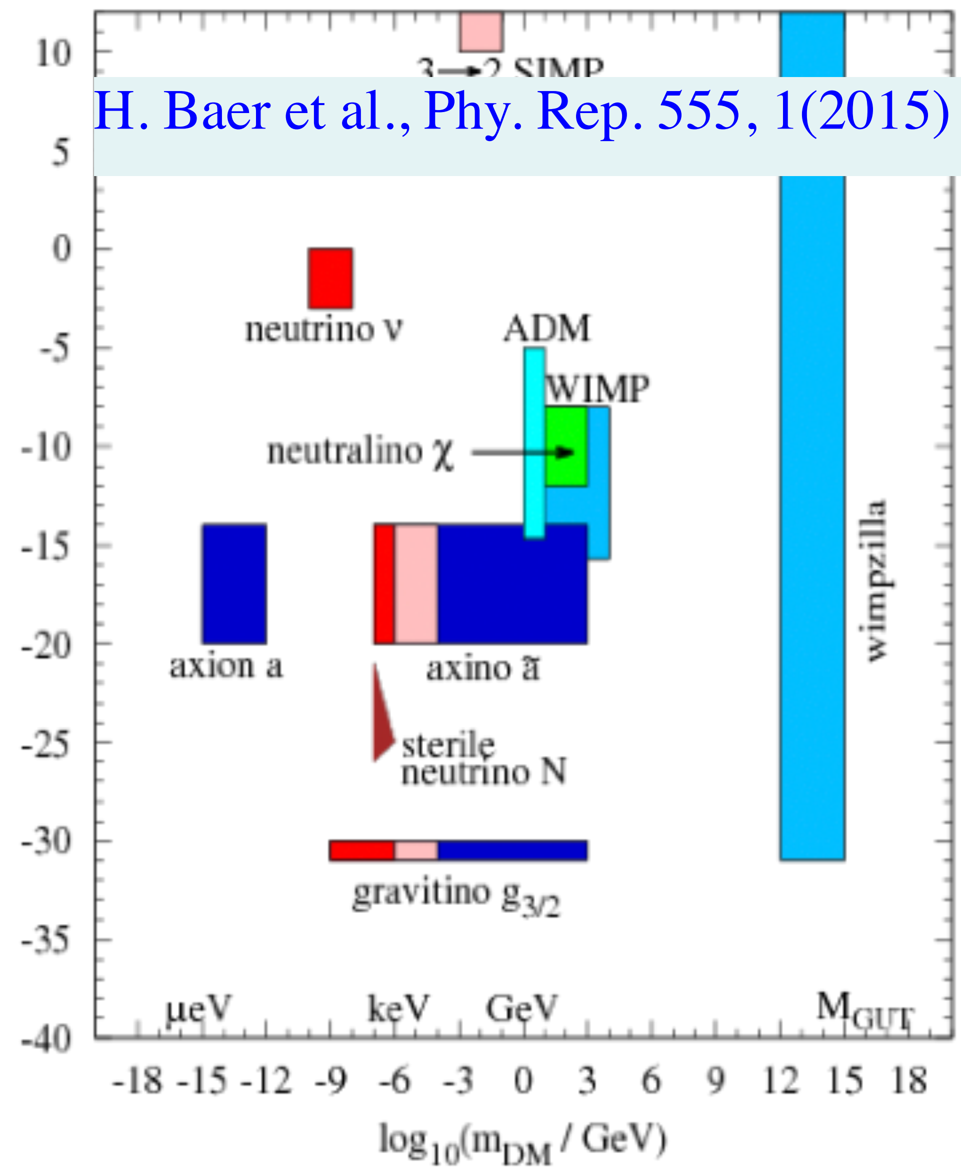
Major problem: 85% of matter is dark and remains invisible!

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

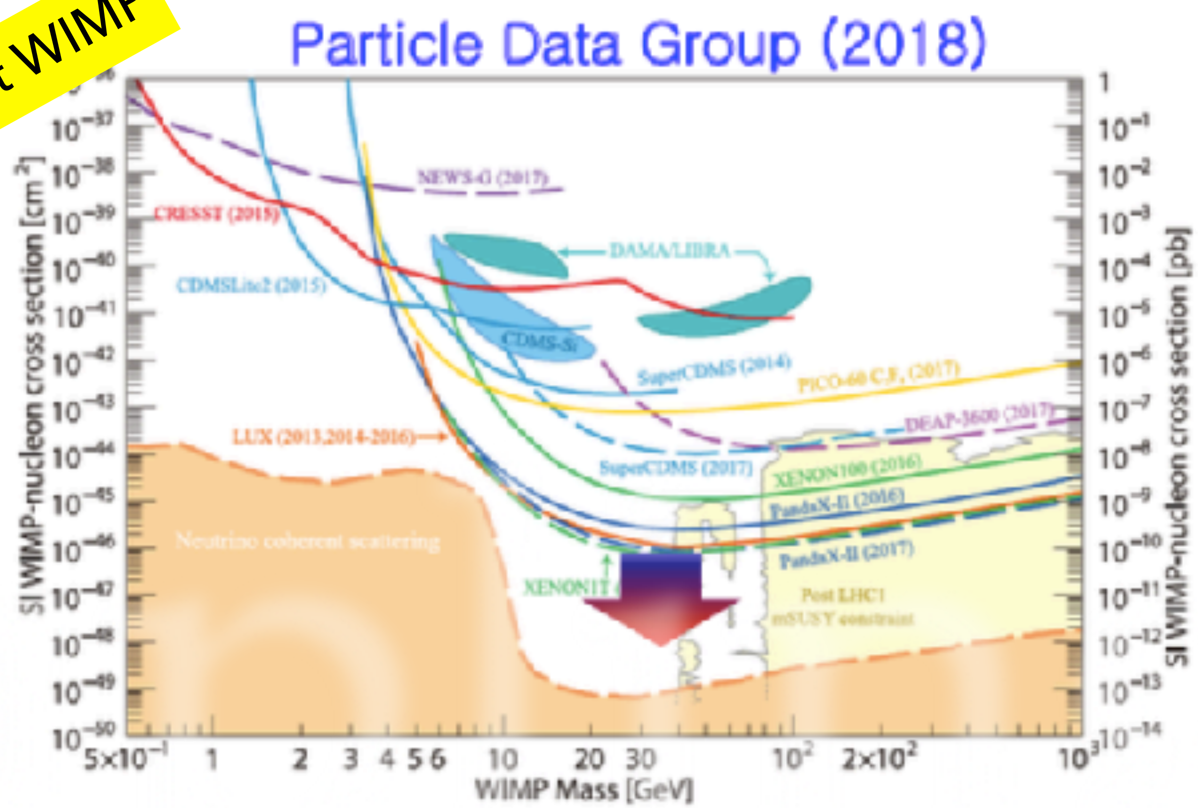
M. Drees

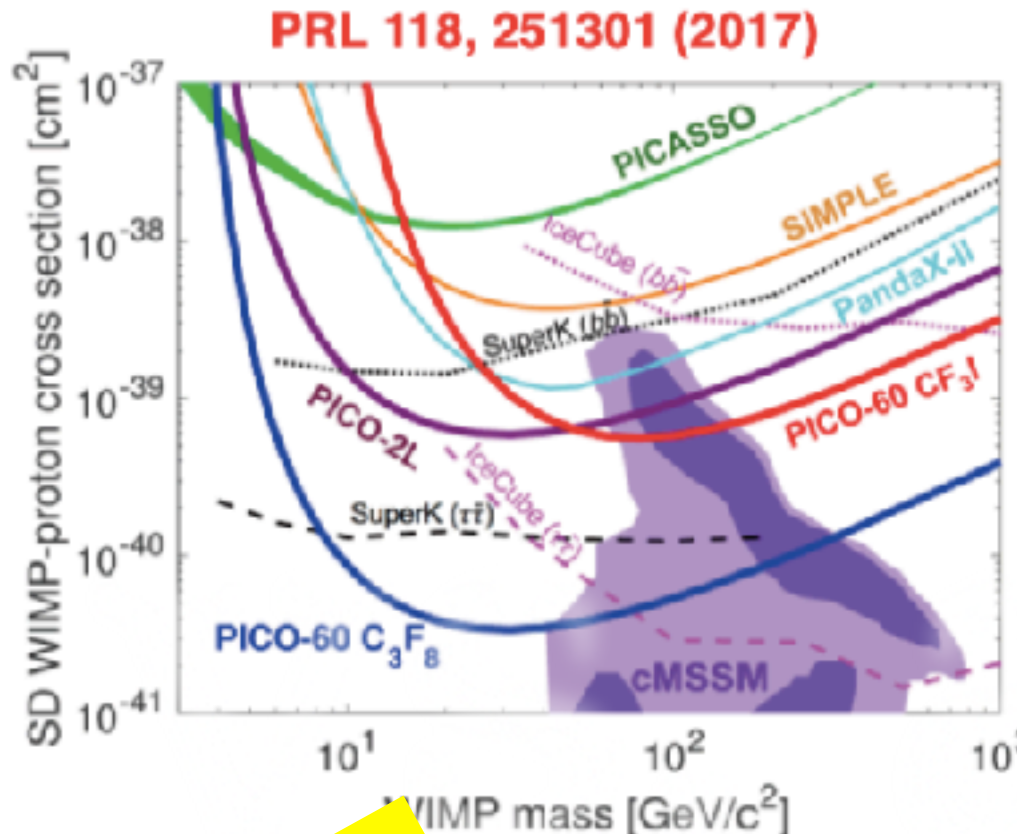


H. Baer et al., Phy. Rep. 555, 1(2015)

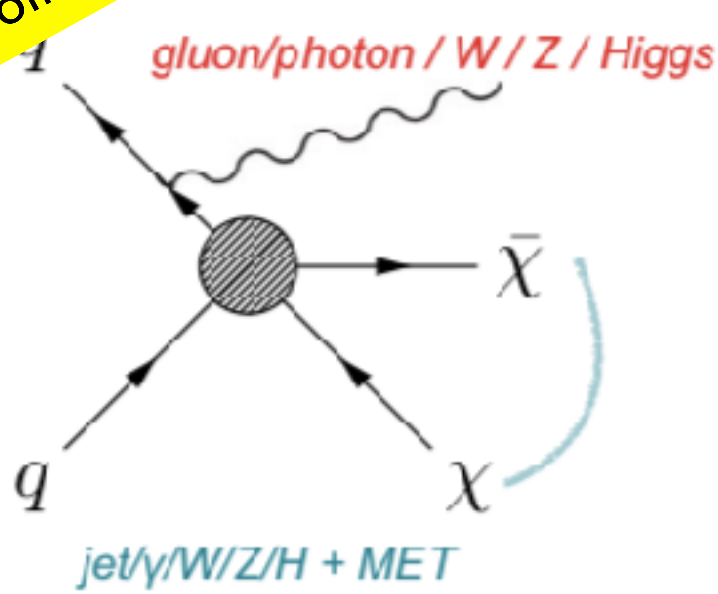
- Direct, indirect, collider

Direct WIMP





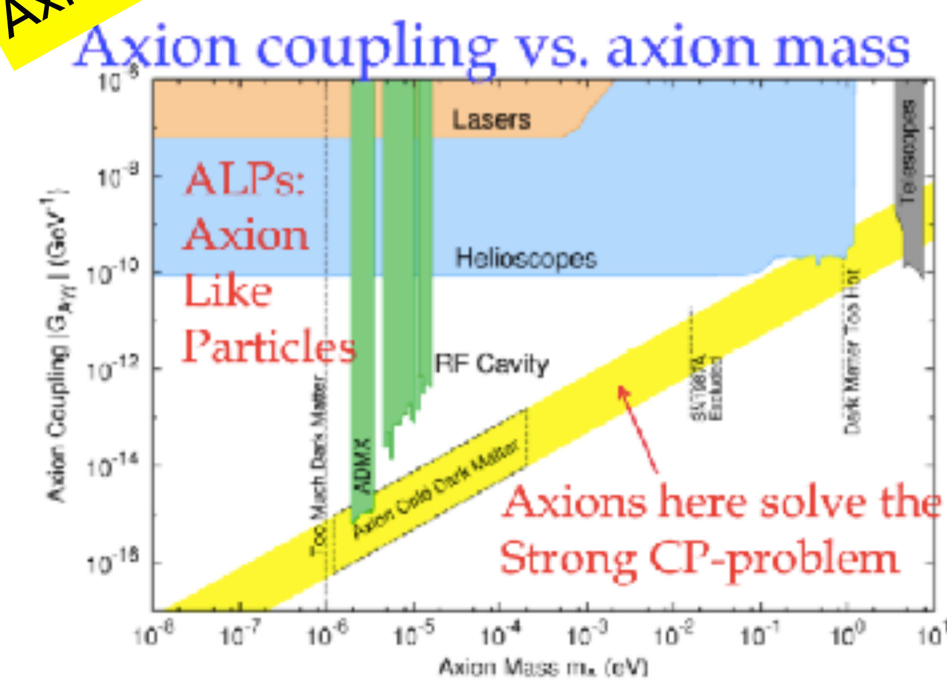
Colliders WIMP



- **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

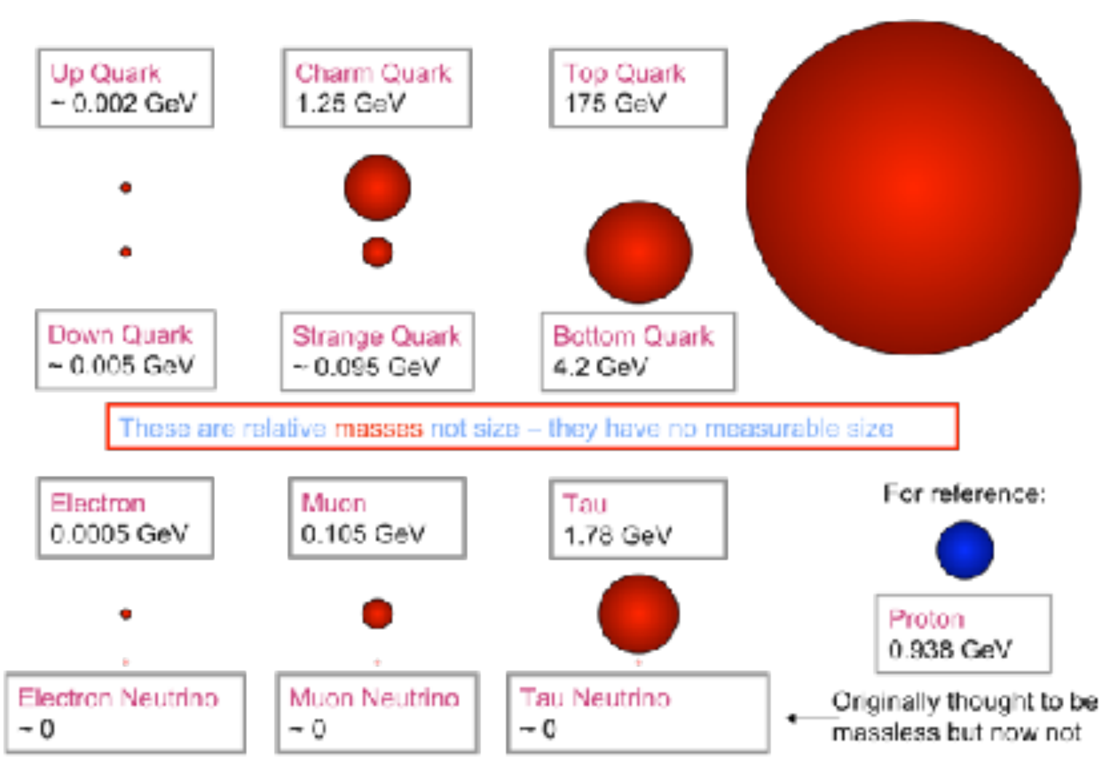


Y. Semertzidis

- Mass spectrum?

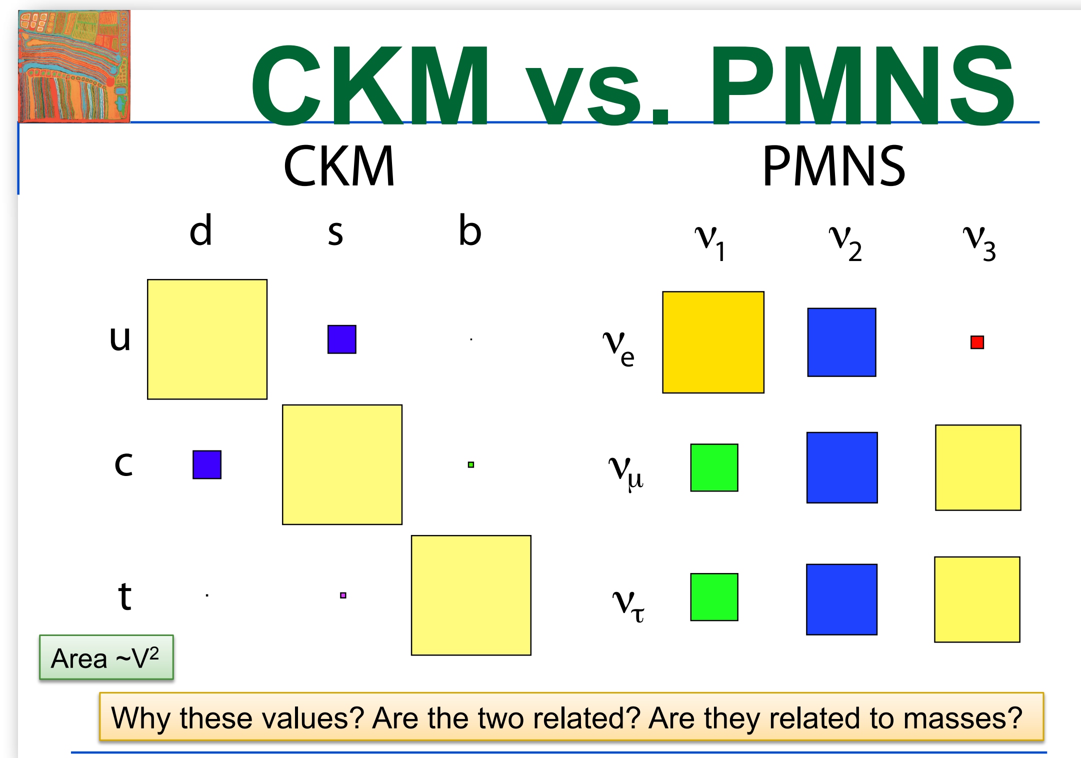
$$m_{quark} = y_{quark} \cdot v$$
$$m_{lepton} = y_{lepton} \cdot v$$
$$m_W = g/\sqrt{2} \cdot v$$
$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$
$$m_H = \sqrt{\lambda} \cdot v$$
$$m_\gamma = 0$$
$$m_{gluon} = 0$$

SM



- 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?

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

$$U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}; \quad U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \pm\frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \pm\frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \mp\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}. \quad U_{HGM} = \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

BEYOND THE STANDARD MODEL: QUEST FOR SYMMETRY

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

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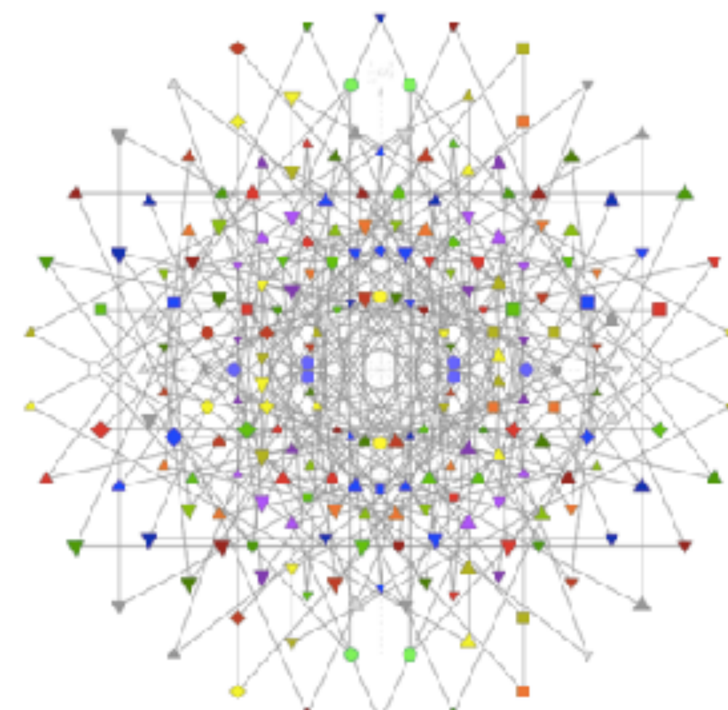

E8 roots

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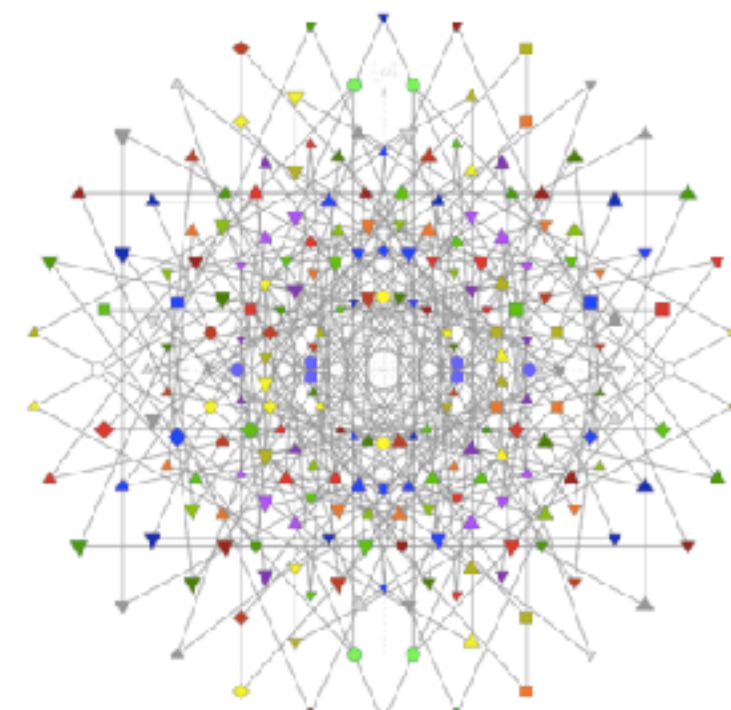
Symmetry might be tricky



E8 roots

- Baryon asymmetry of the Universe

$$\frac{N(B)-N(\bar{B})}{N_\gamma} \sim (6.19 \pm 0.14) \times 10^{-10}$$

- still not explained
- three conditions (A.D.Sakharov)

1. Violation of a thermal equilibrium in early Universe

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

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

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

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) ⟷ $\not{CP}$

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

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

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- 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

Physics with a single generation

Back to the middle of the XX century





Physics with a single generation

Back to the middle of the XX century





All the world around us is made of the 1st generation

Physics with a single generation

Back to the middle of the XX century





All the world around us is made of the 1st generation

p 1919

n 1932

e 1897

Physics with a single generation

Back to the middle of the XX century





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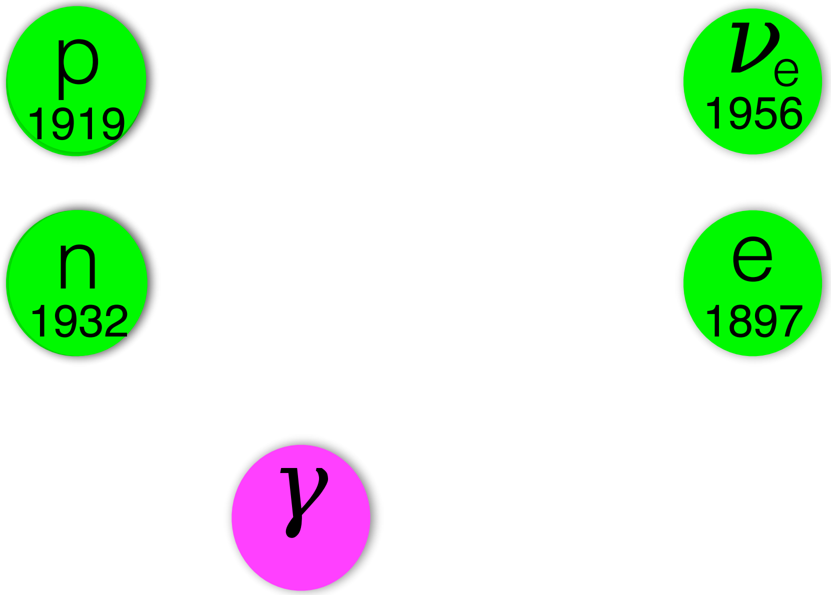

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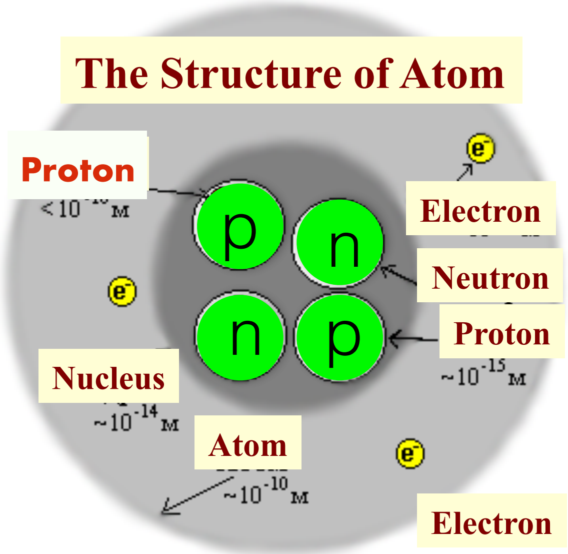

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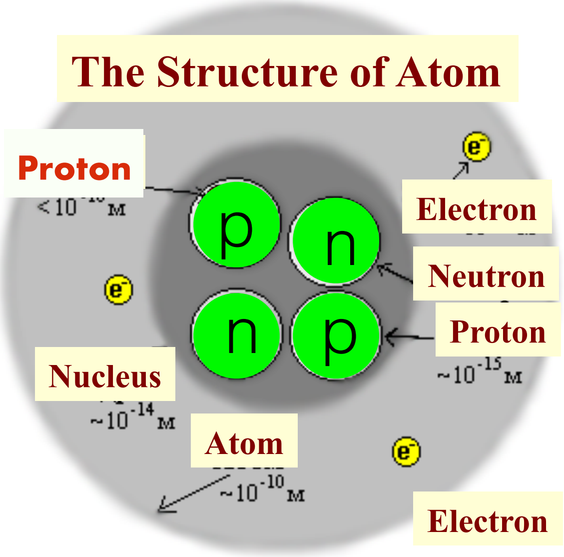

- Who expected new physics to come?

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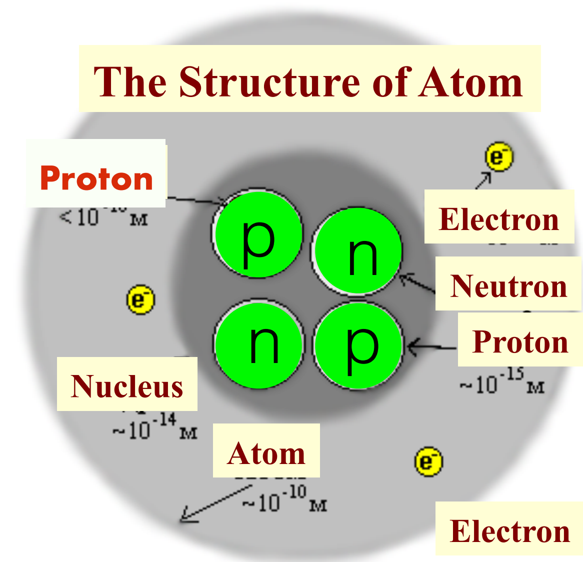

- Who expected new physics to come?
- What scale of NP?

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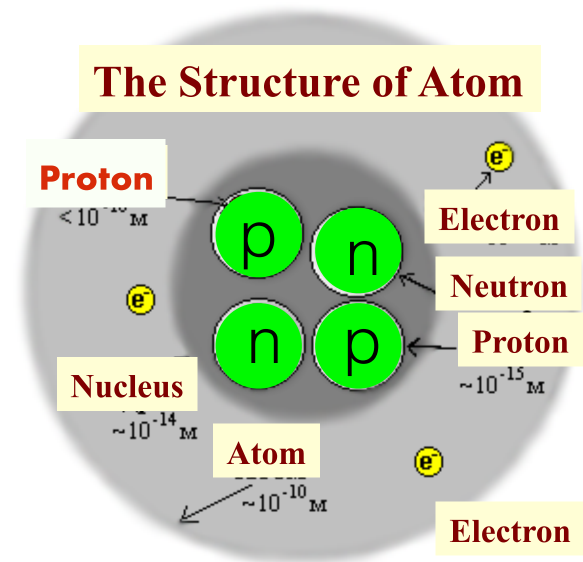
ν_μ 1963

μ 1936

γ



- Muon - heavy electron - 2nd generation ?

- Who expected new physics to come?
- What scale of NP?

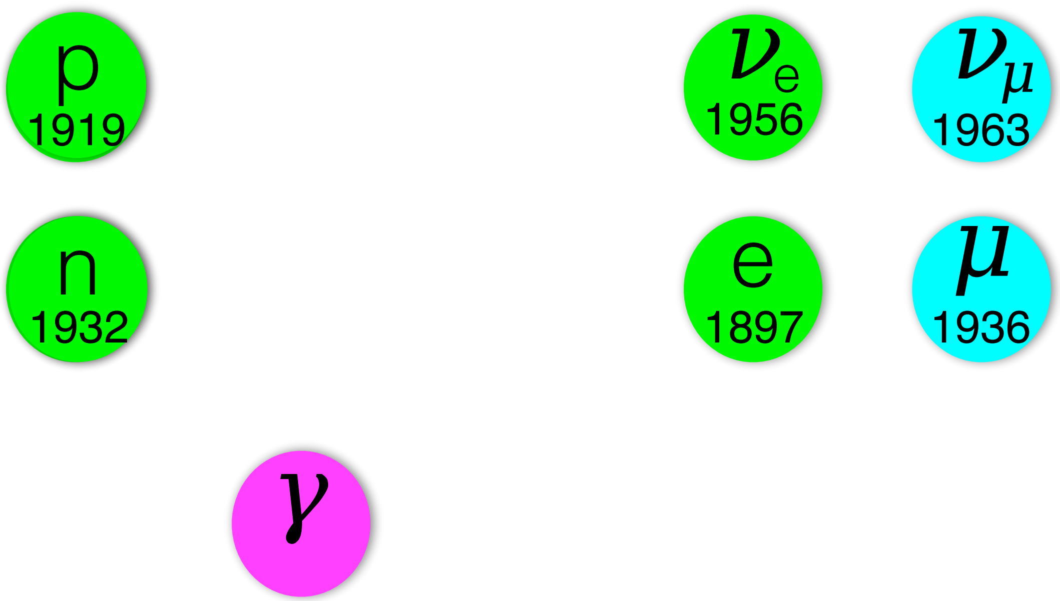
Physics with a single generation

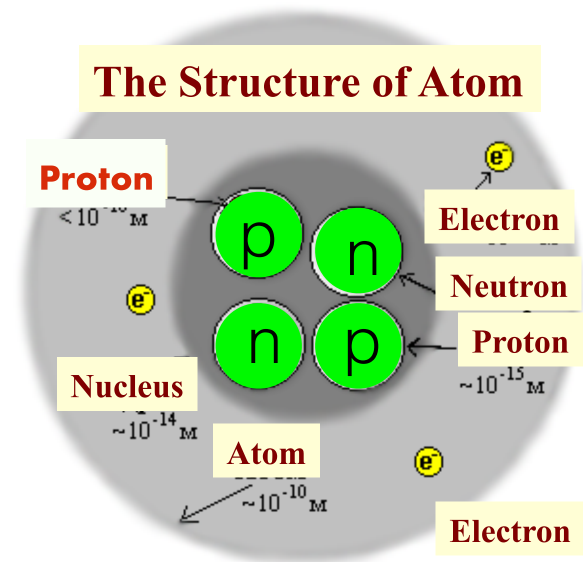
Back to the middle of the XX century





All the world around us is made of the 1st generation





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- Who expected new physics to come?
- What scale of NP?

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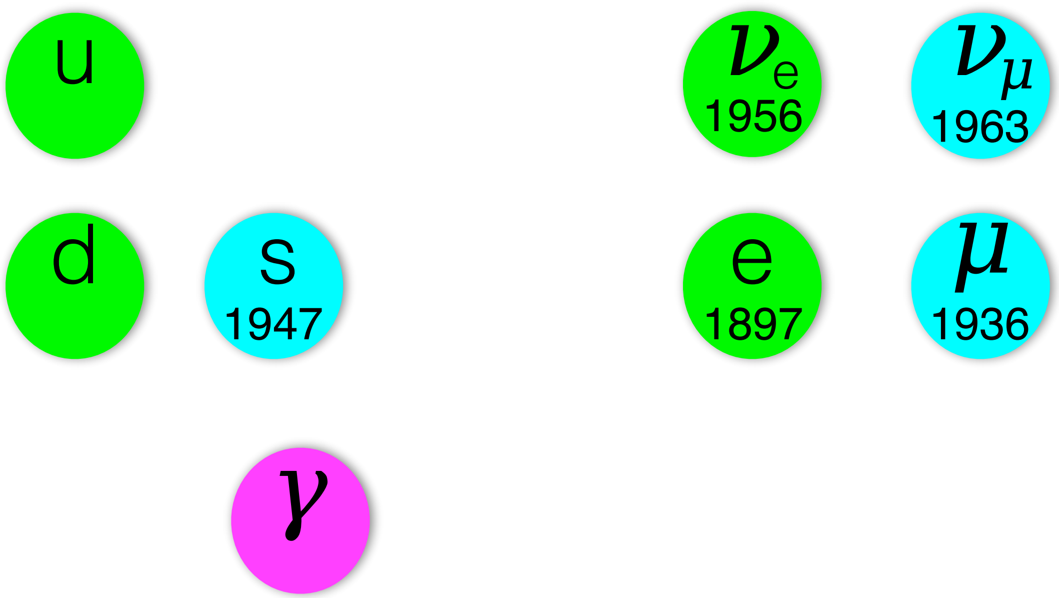

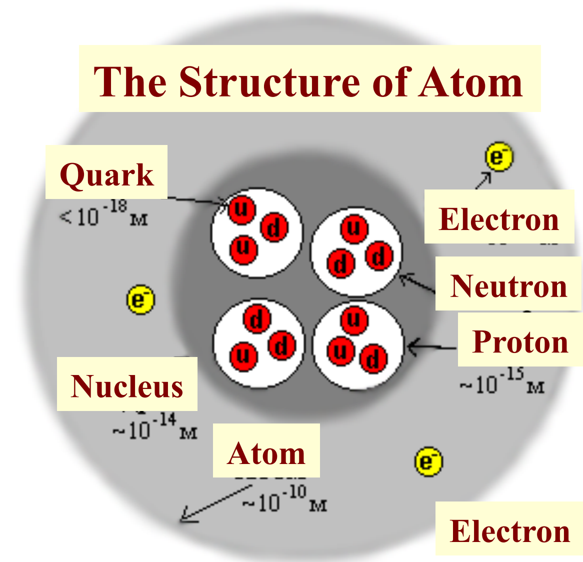

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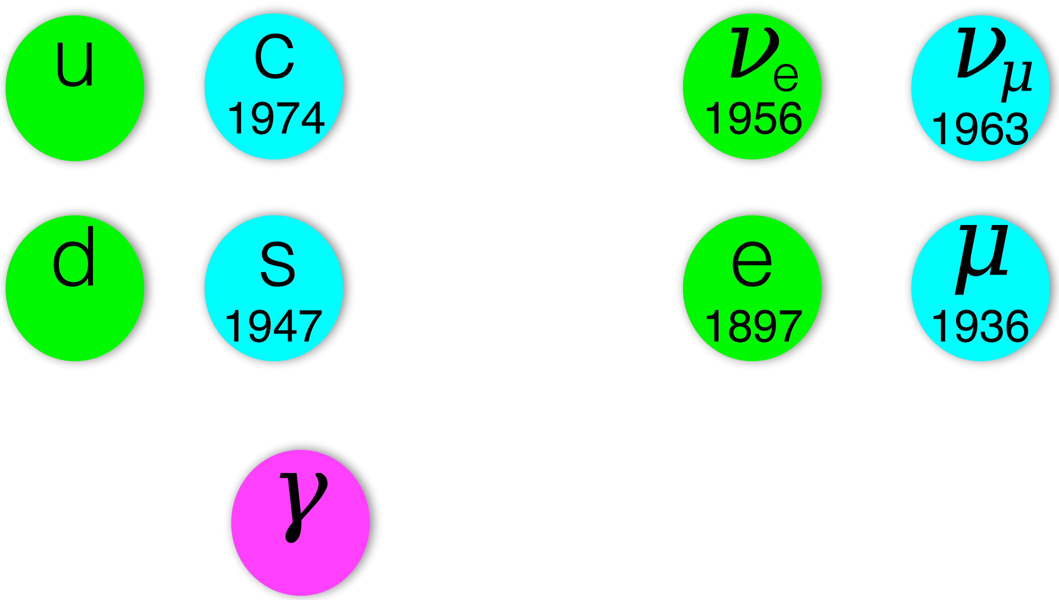

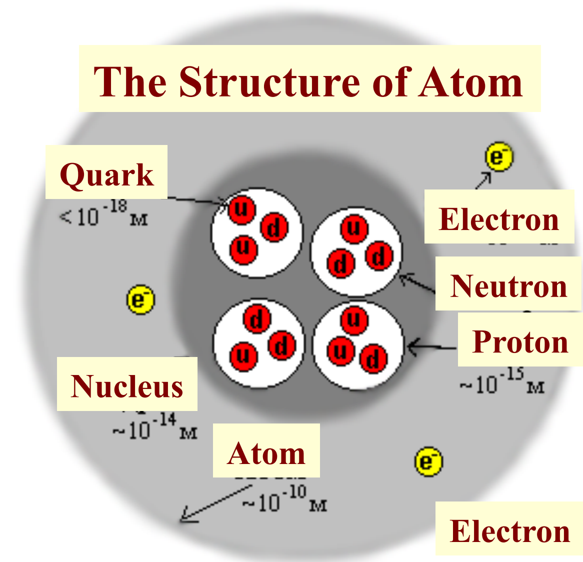

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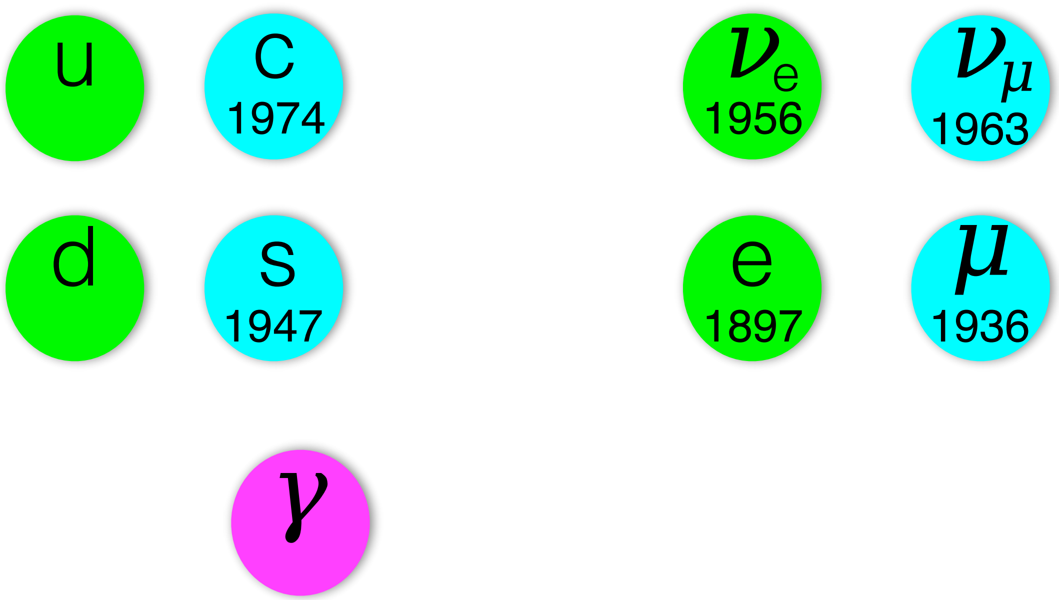

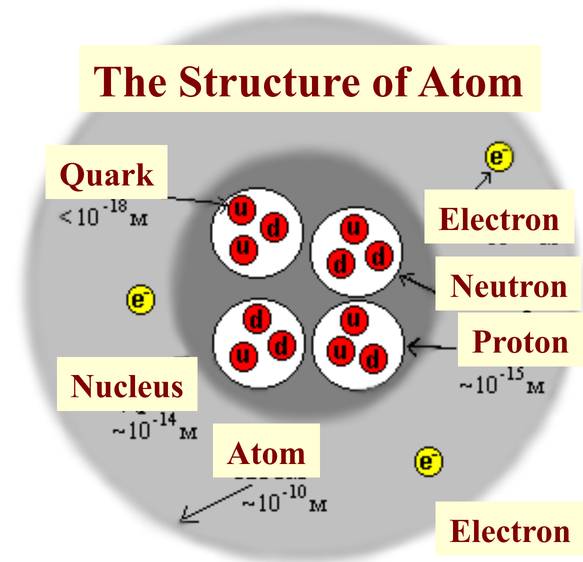

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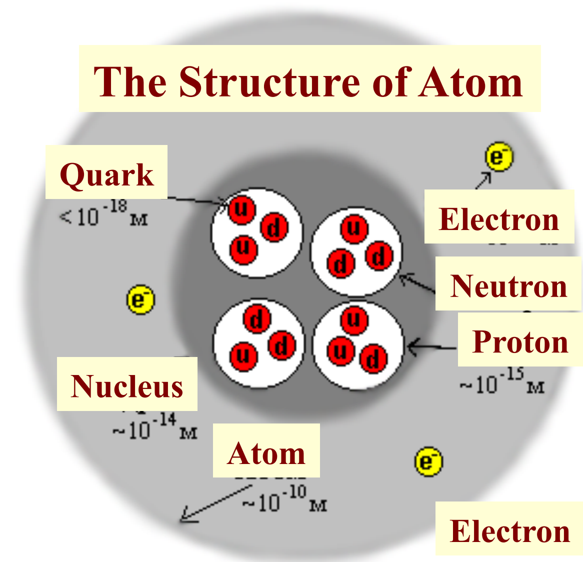
γ



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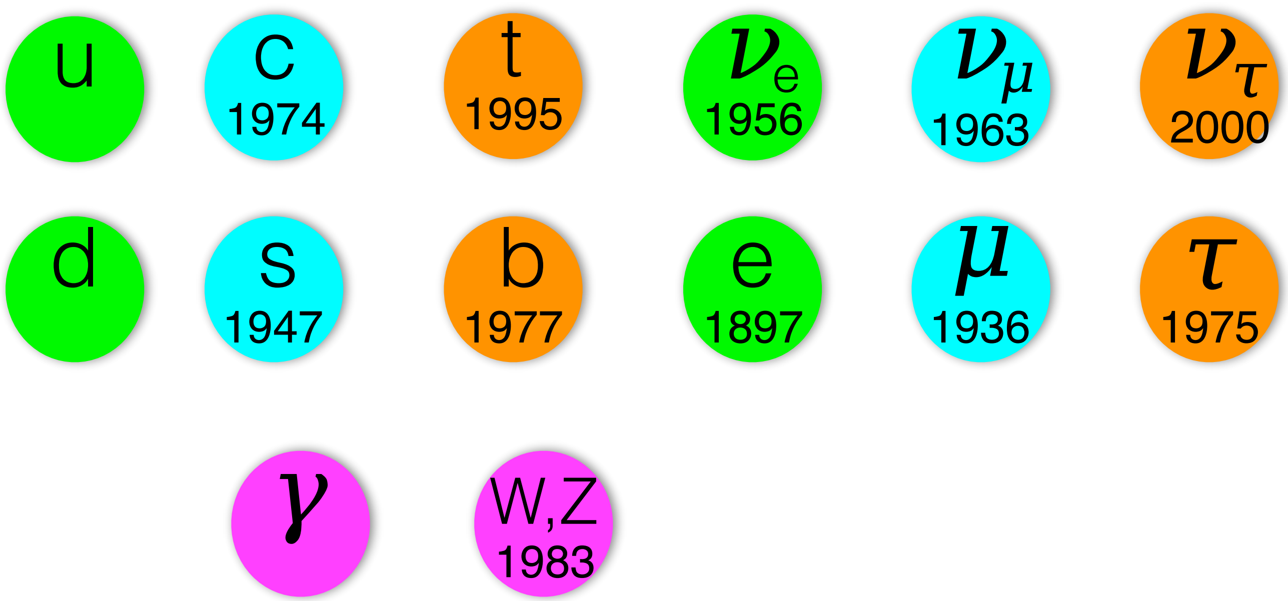

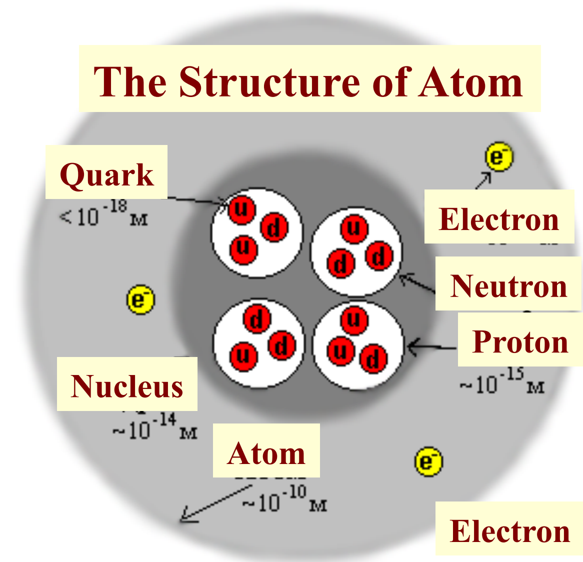

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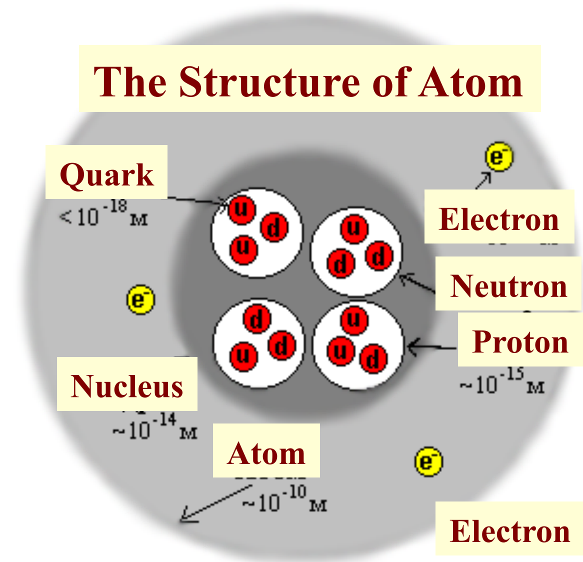

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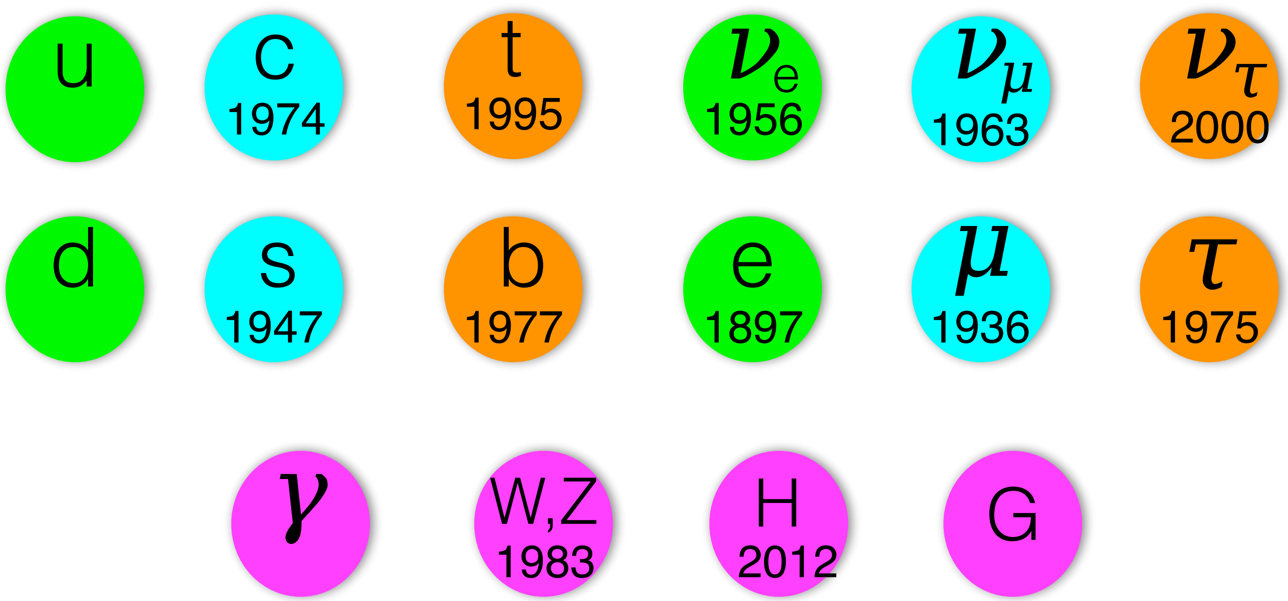

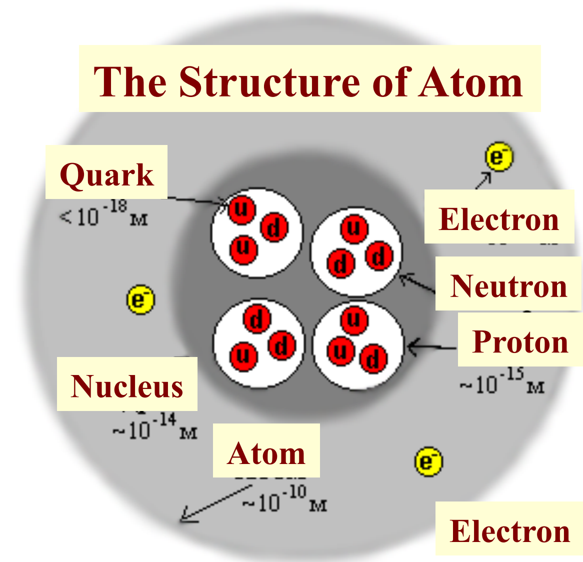

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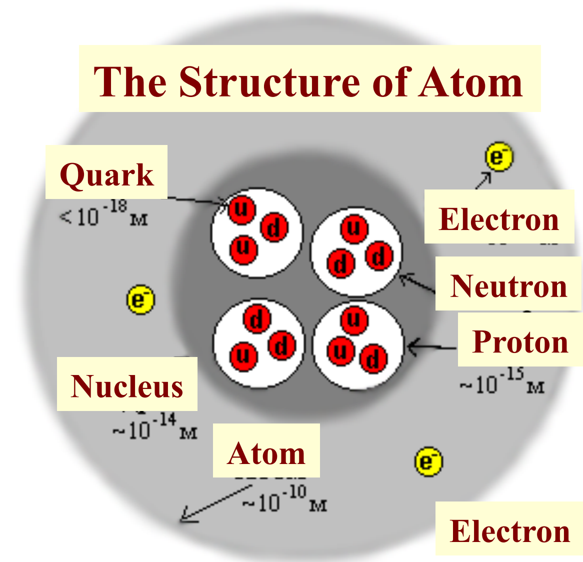

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Astrophysics & Cosmology challenge

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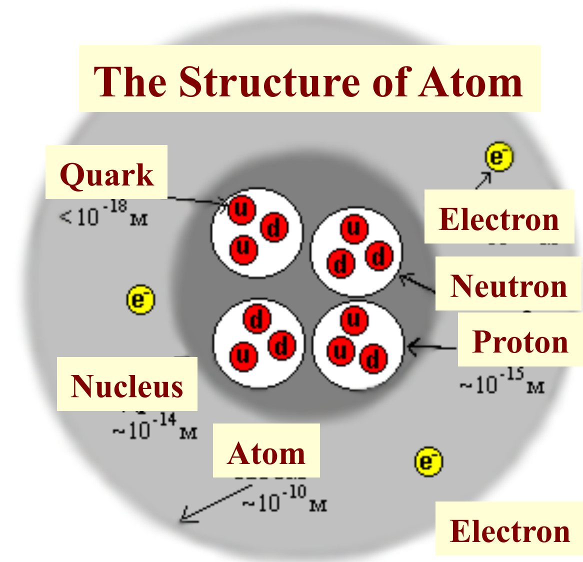

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<u>Astrophysics & Cosmology challenge</u>

- Baryon asymmetry of the Universe
- Description of the Dark Matter

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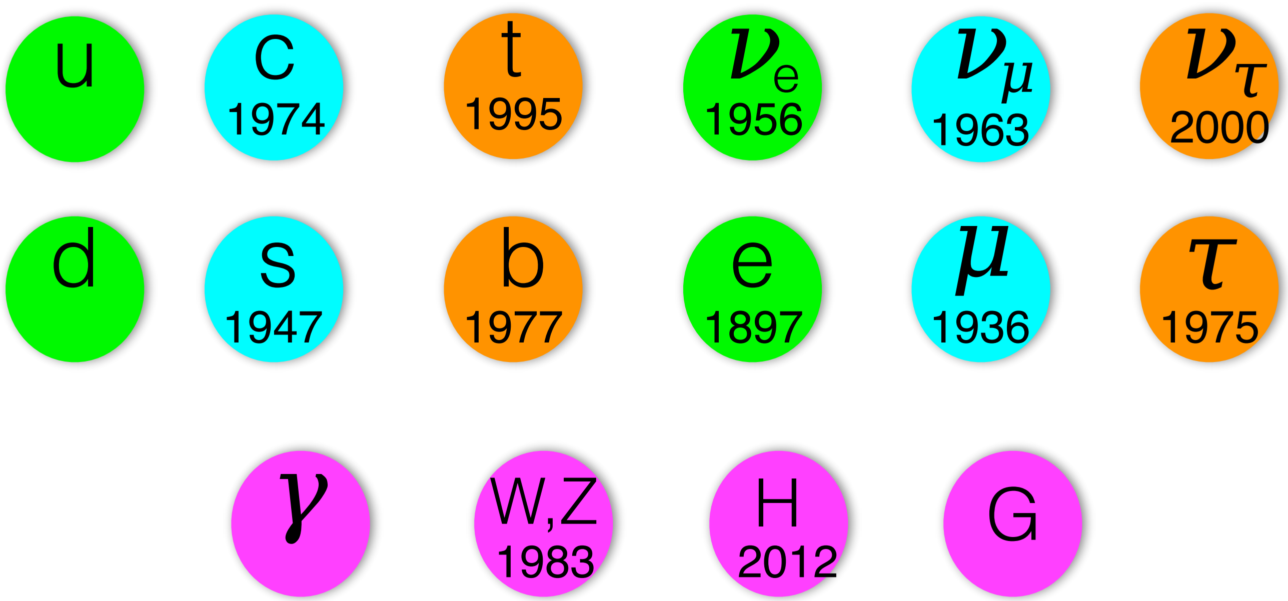

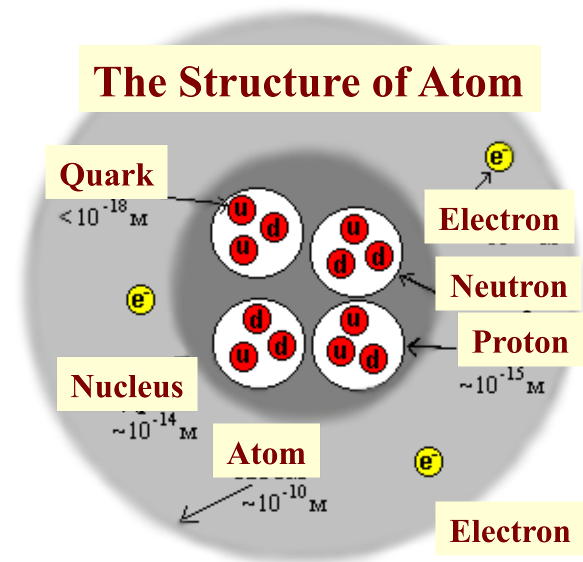

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Ideas (conventional and not)

- 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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How Will We Make Progress?

• • •

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• • •

The energy frontier

The precision frontier and neutrinos

Cosmology and astrophysics

Paul Langacker (IAS)