Workshop on high-energy implications of flavor anomalies

# Who ordered that, again?


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# Why are the LFU B anomalies interesting

Indications of non-universal behavior of different lepton generations

$e$ vs. $\mu$ $\qquad$ $e,\mu$ vs. $\tau$

In both charged and neutral current mediated b-decays

$b \to s$ $\qquad$ $b \to c$

Probably the largest “coherent” set of non-standard results in present data

several modes, measurements, different experiments

see next talks by Koppenburg
Pierini

and also by Jaeger
Ligeti

# Why are the LFU B anomalies interesting

SM gauge sector respects accidental flavor symmetry

$$G_F^{\mathrm{SM}} = U(3)_Q \times U(3)_U \times U(3)_D \times \underbrace{\boxed{U(3)_L \times U(3)_E}}_{\text{LFU}}$$

*neutrino masses

Broken only by Higgs Yukawas

$$G_{\mathrm{acc.}}^{\mathrm{SM}} = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

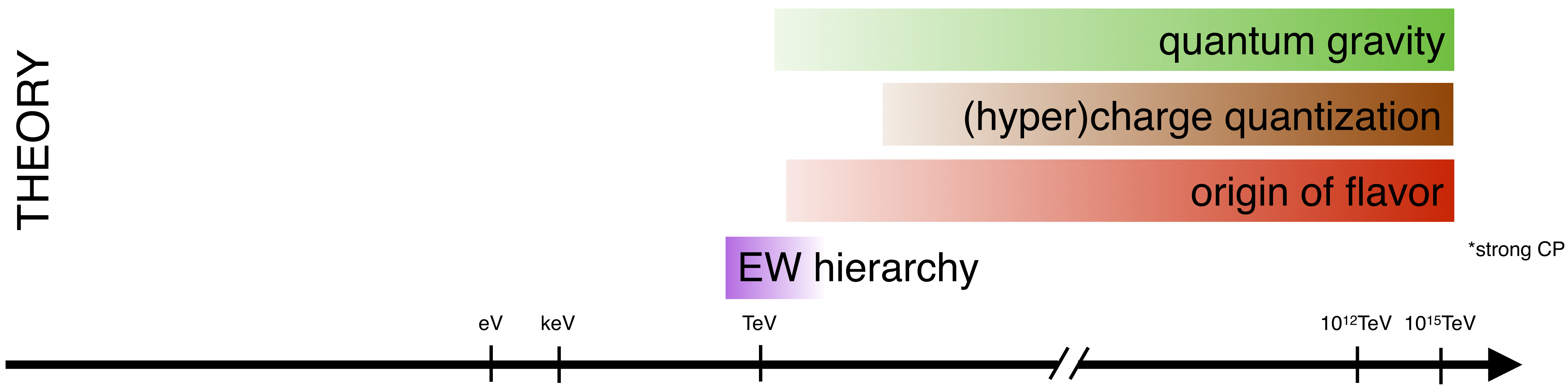
⇒ Unique source of LFU breaking: $m_e \neq m_\mu \neq m_\tau$

Any LFU violation beyond lepton mass effects sign of NP!

*Higgs boson processes

# Why the LFU anomalies surprise us

## Theory guidance (prejudice?) based on SM shortcomings



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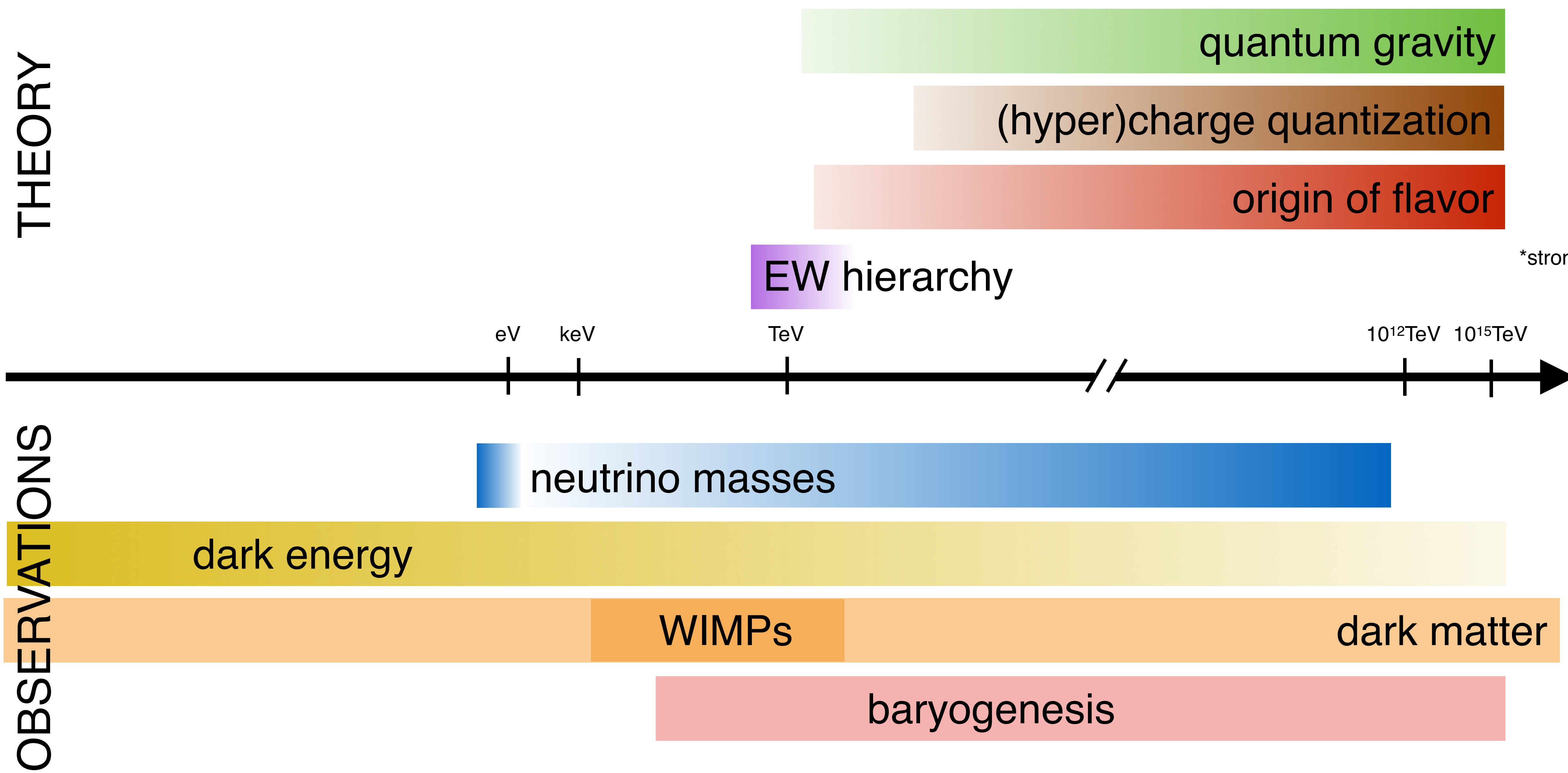

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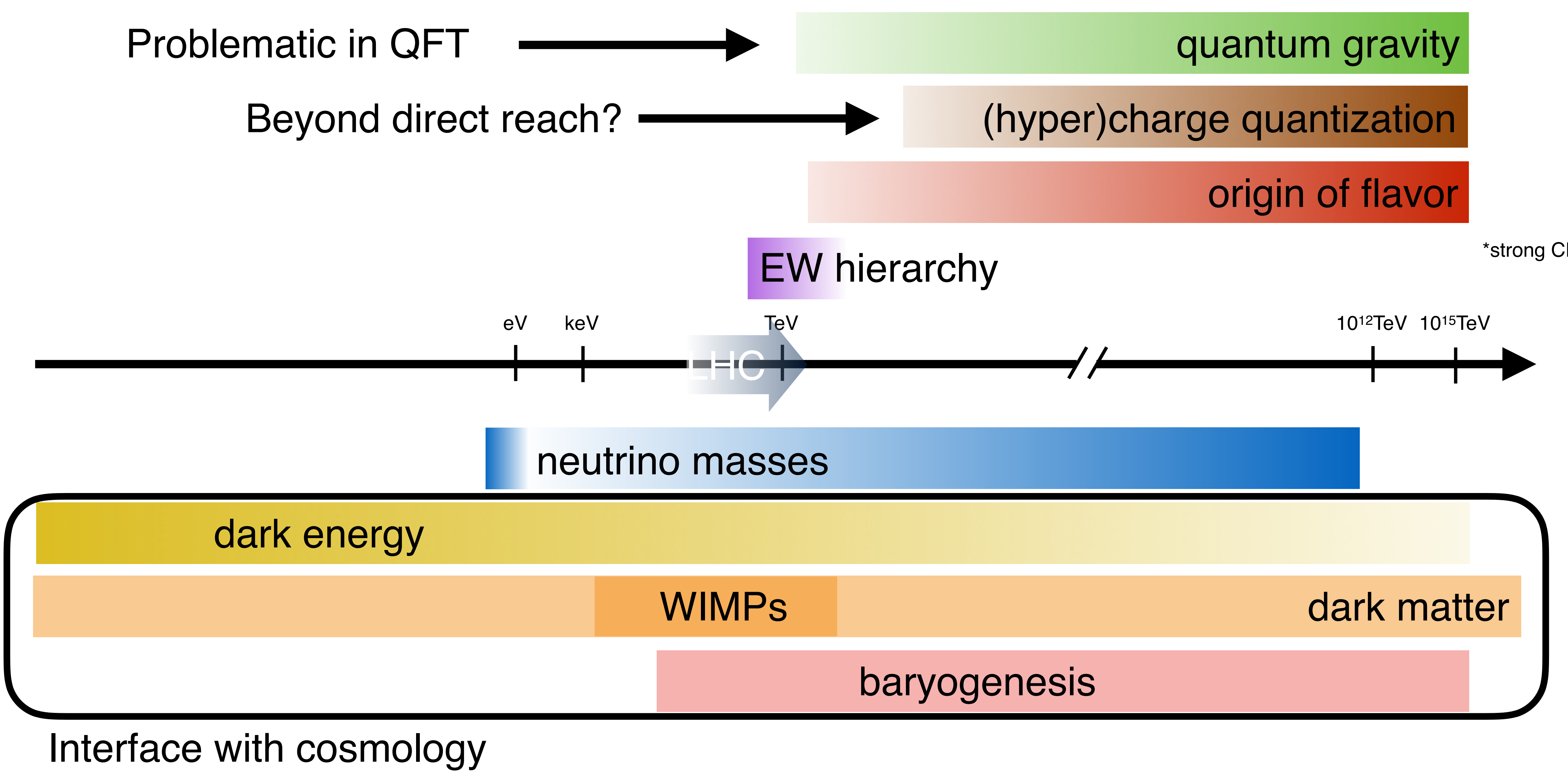

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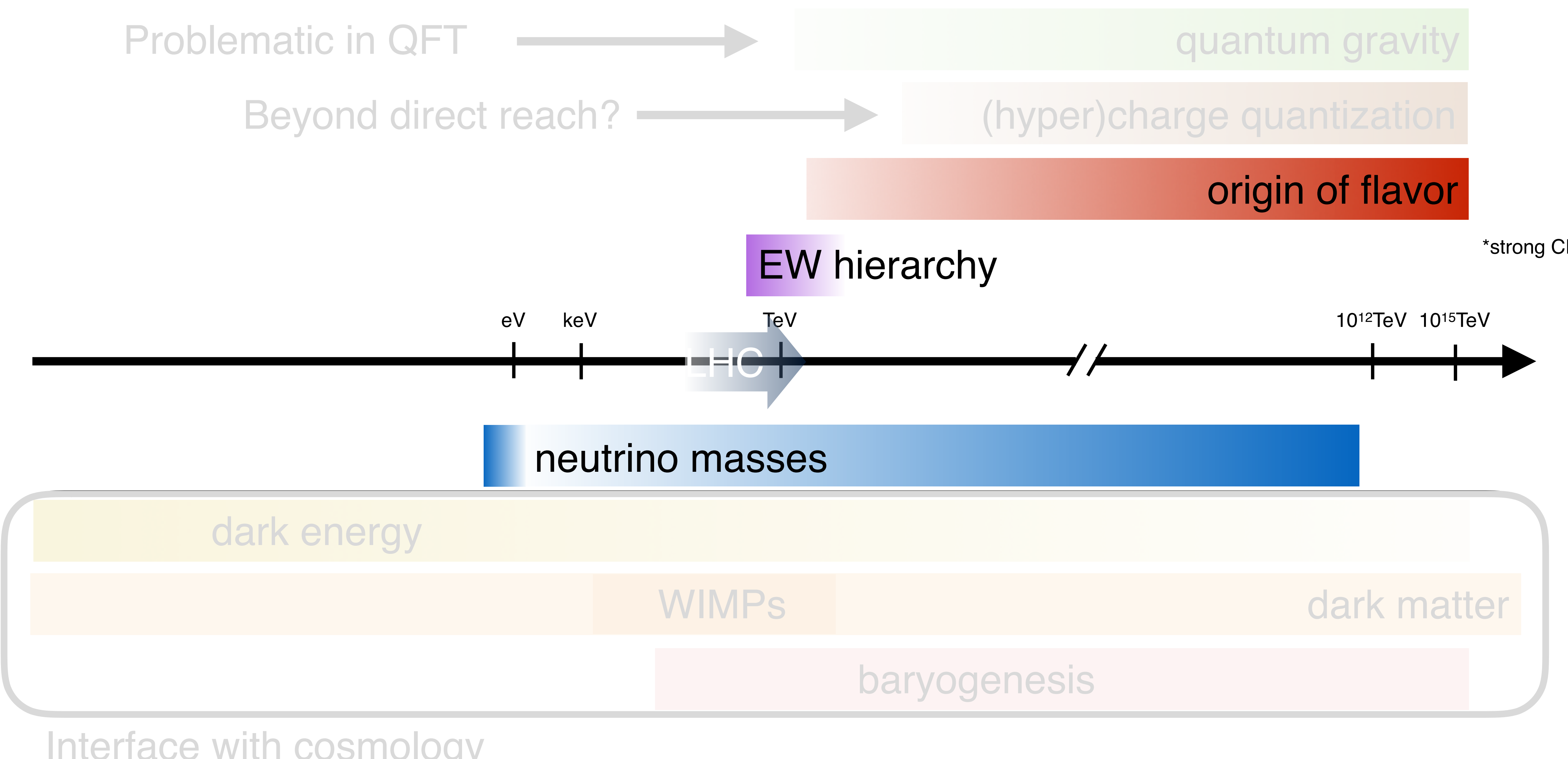

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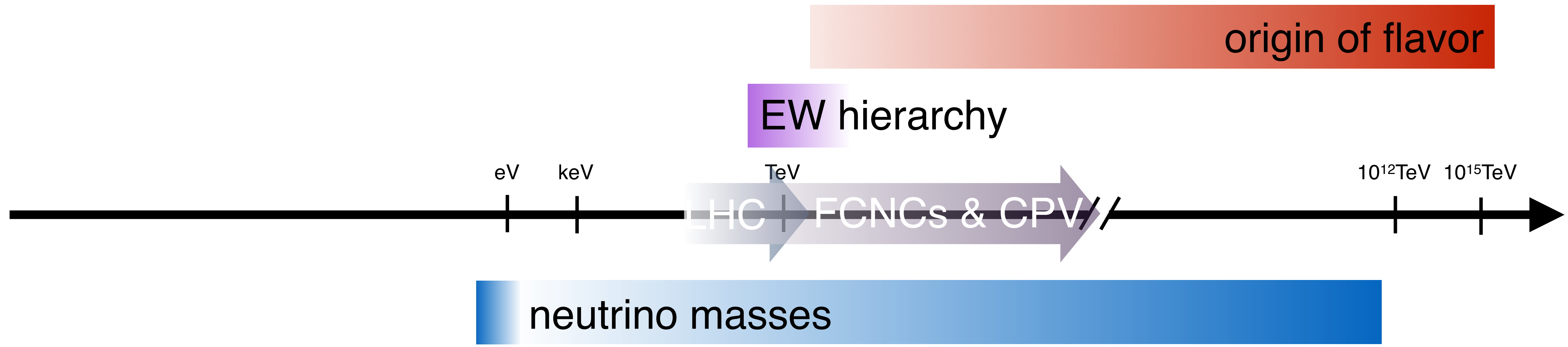
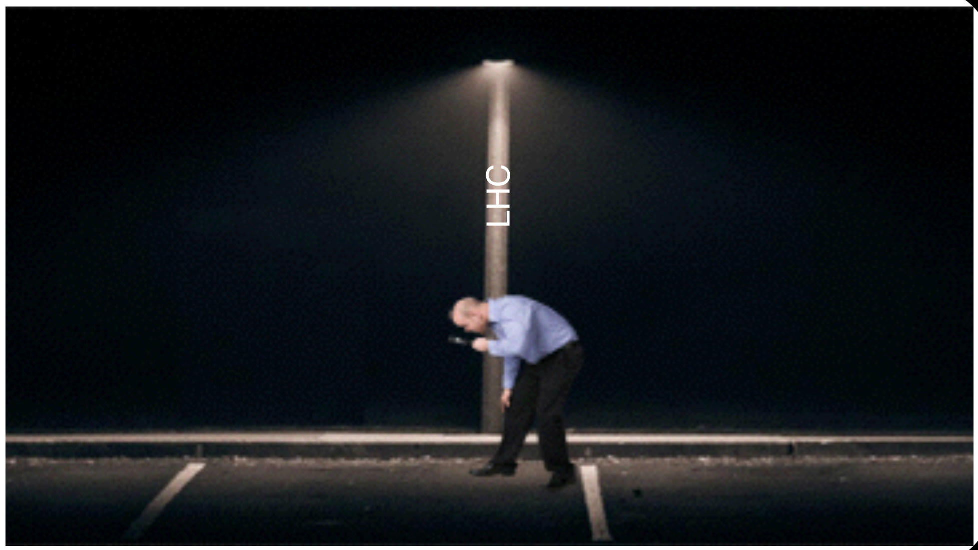



Conventional (practical) approach:

1. focus on EW hierarchy problem
2. postpone flavor problem



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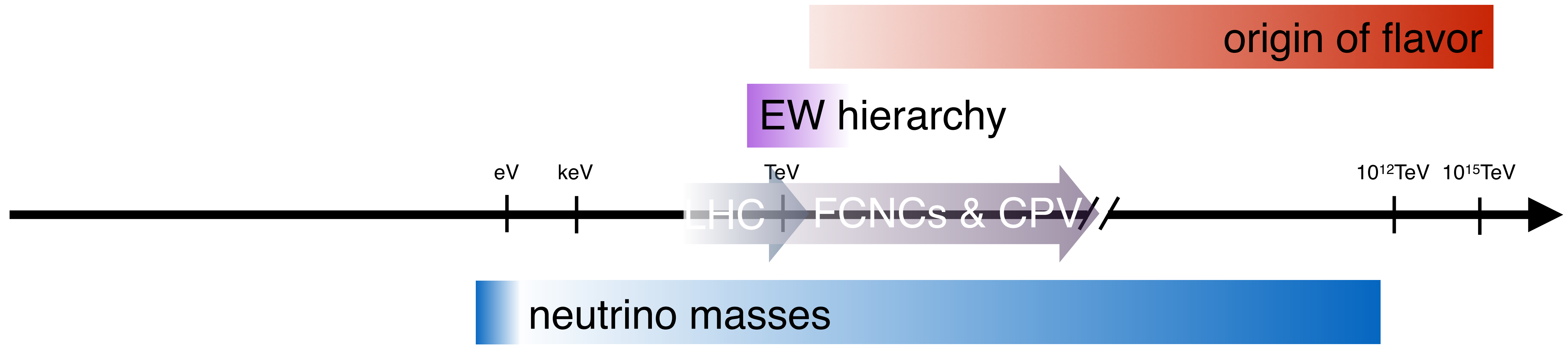


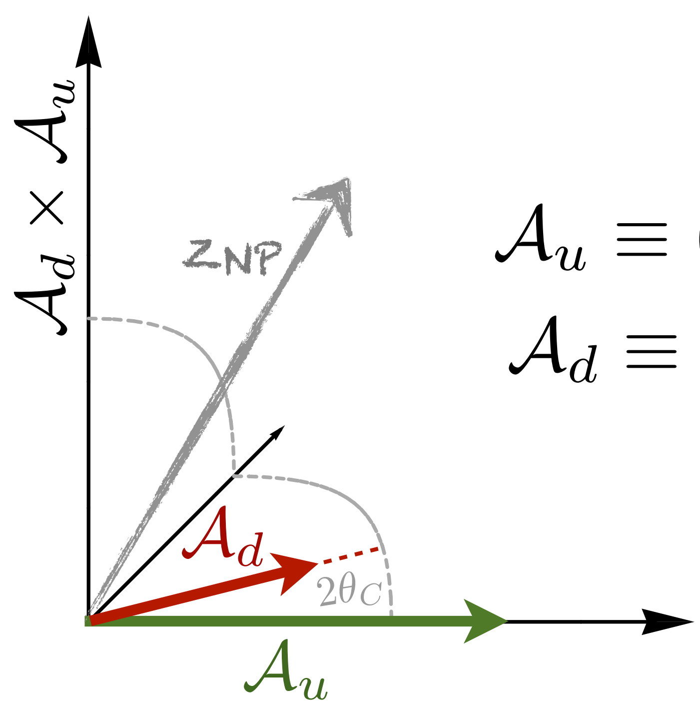

LFU B anomalies challenge several (implicit) assumptions

- ✘ Charged currents NP free - "standard candles"
- ✘ LFU respected by (SM) gauge symmetry - uninteresting

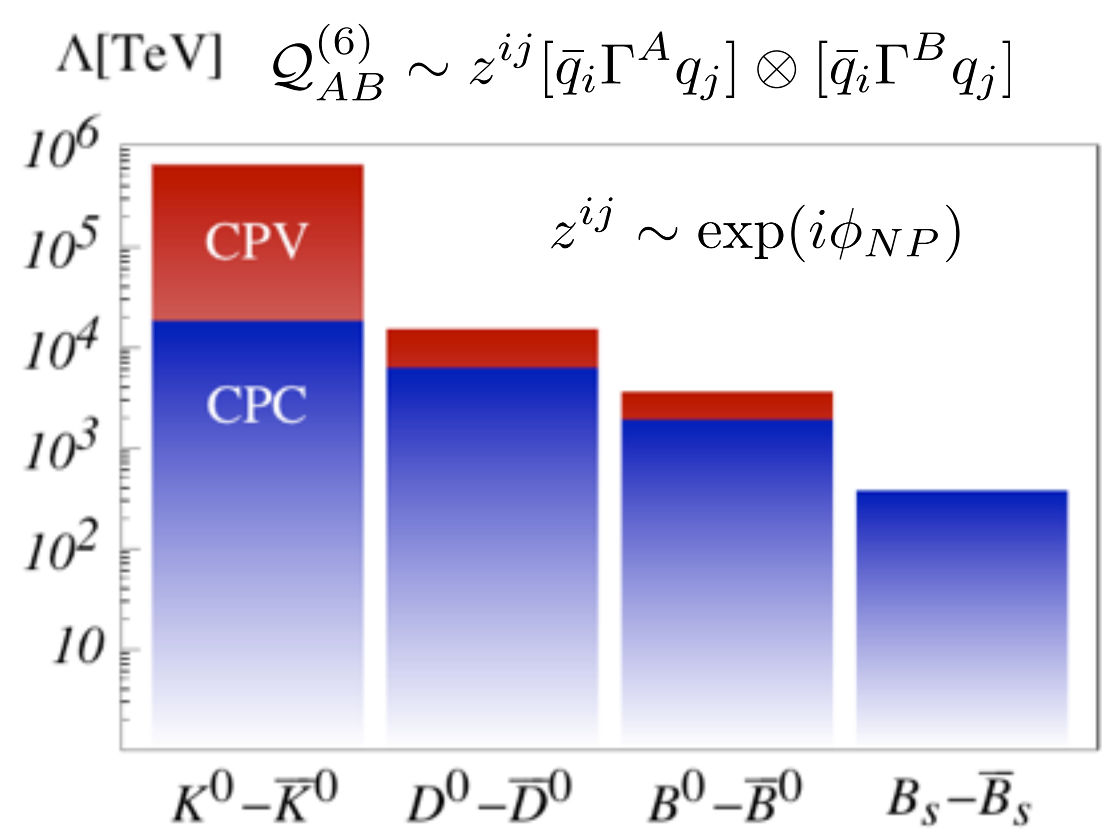
# (Re)interpreting NP flavor problem

SM flavor (Yukawa) sector highly non-generic, exhibits clear patterns - hierarchy & alignment

$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\nu{\rm SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$




$$\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\rm tr}}\,,$$
$$\mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\rm tr}}$$




Severe constraints on generic new (BSM) flavor breaking sources - *(mis)interpreted as indication of high flavor scale*

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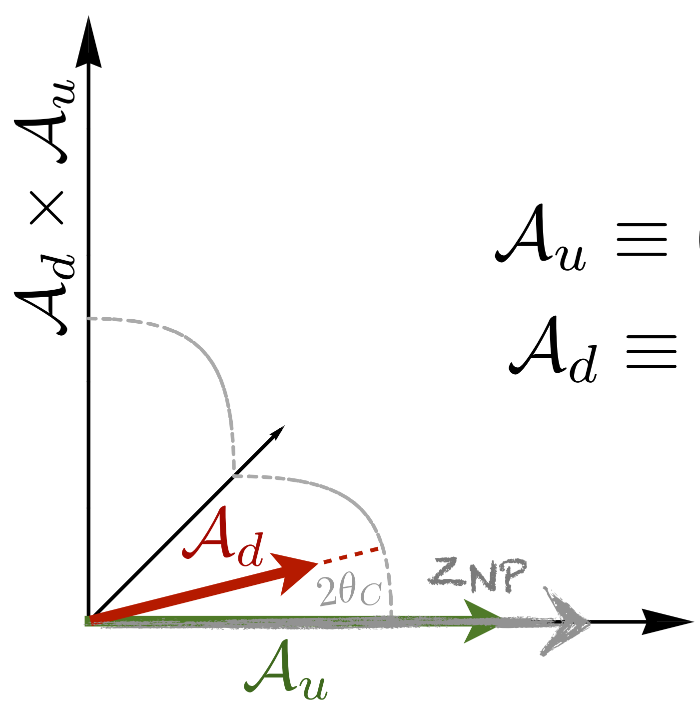


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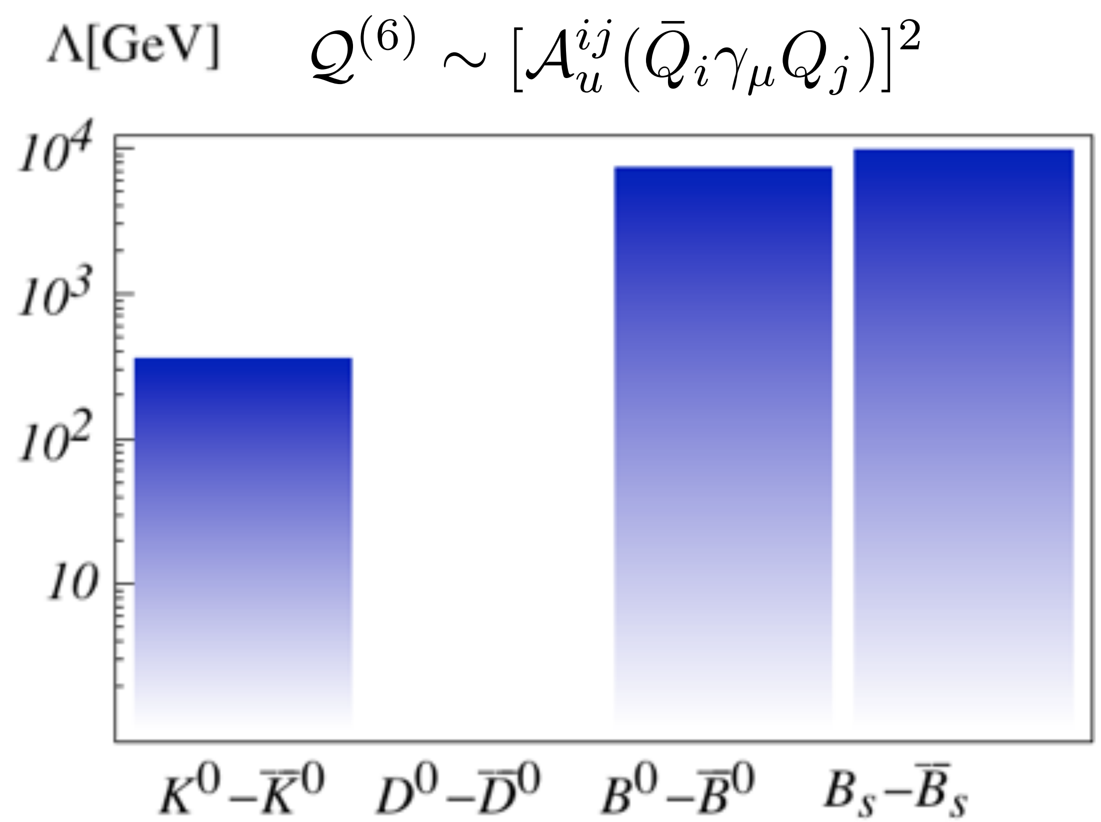



Severe constraints on generic new (BSM) flavor breaking sources ⇔ new d.o.f's within LHC reach if flavor aligned

see e.g. 1009.2049, 1807.09792

# New Flavor BSM Paradigm?

To avoid NP flavor problem & address LFU anomalies need BSM with non-generic (suppressed or vanishing)

see e.g. talks by Silvestrini
Gonzalez-Alonso

- ? new flavor breaking
- ? new CPV
- ? new chiral structures

severely constrained,

*not* required by LFUV hints

in relation to SM flavor sector.

Can keep ignoring SM "origin of flavor" puzzle?

see e.g. talk by Ziegler

# Implications for high $p_T$: general considerations

B-anomalies in presence of (heavy) NP:

$$\mathcal{L}_{\text{BSM}} \to \mathcal{L}_{\nu\text{SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

Deviations in flavor ⇒ indications of NP scale

$$[\text{scale}] = \frac{[\text{mass}]}{[\text{coupling}]}$$

Unitarity/Perturbativity

⇒ upper bound on coupling

Di Luzio & Nardecchia, 1706.01868

⇒ upper bound on NP d.o.f. mass

# Implications for high $p_T$: general considerations

LFUV in $R(D^{(*)})$ : $\Lambda \simeq 2.5\,\mathrm{TeV}$ e.g. $\mathcal{Q} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu)$

⇒ tree-unitarity $M_{\mathrm{NP}} \lesssim 6.5\mathrm{TeV}$

up to the edge of LHC kinematical reach

and e.g.
Altmannshofer et al., 1704.06659
Iguro et al., 1810.05843

LFUV in $R_{K^{(*)}}$ (& other obs.) : $\Lambda \sim 40\mathrm{TeV}$

e.g. $\mathcal{Q} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu P_L \mu)$

⇒ NP d.o.f.s accessible at LHC only if their couplings to *bs* and/or *μμ suppressed*!

# Implications of LFUV for NP model building

## NP needs to respect SM gauge symmetry

$$\mathcal{Q}_i[Q, D, U, L, E]$$

## At EW scale: in terms of four-fermion operators

$R_{K^{(*)}}$

$$\epsilon^{L}_{ij}\epsilon^{Q}_{kl}(\bar{L}_i L_j)(\bar{Q}_k Q_l)$$

$$\epsilon^{E}_{ij}\epsilon^{Q}_{kl}(\bar{E}_i E_j)(\bar{Q}_k Q_l)$$

$$\epsilon^{EL}_{ij}\epsilon^{QD}_{kl}(\bar{E}_i H^\dagger L_j)(\bar{Q}_k H D_l)$$

$$\epsilon^{LE}_{ij}\epsilon^{QU}_{kl}(\bar{L}_i H E_j)(\bar{Q}_k \tilde{H} U_l)$$

$R(D^{(*)})$

*$B_c$ lifetime, decays
Alonso et al., 1611.06676
Akeroyd & Chen, 1708.04072

*right-handed currents
see e.g. talk by Shih

Buttazzo et al., 1706.07808

$$\epsilon^{L,E}_{\mu\mu},\ \epsilon^{Q}_{sb} \neq 0$$

$$\epsilon^{L,EL}_{\tau i},\ \epsilon^{Q,QD}_{cb} \neq 0$$

$$\epsilon^{LE}_{i\tau},\ \epsilon^{QU}_{bc} \neq 0$$

see e.g. talks by Sumensari
D'Ambrosio
Watanabe
Marzocca
Gripaios
Košnik
Jung
Cox

Simplest UV: $Z'/W'$ LQ's $H^{\pm}$ nonpert. composite dynamics?

new gauge interactions? extended scalar sector?

matter unification?

# Immediate implications for LHC

Absence of BSM LFUV, FCNCs in Kaon, Charm, $\tau$ decays requires approximate alignment with the 3rd generation

$\epsilon^Q_{sb} \propto V_{tb}V_{ts}$ $\epsilon^Q_{cb} \propto V_{cb}$

$U(2)_F$, MFV

see also e.g.
Fajfer et al., 1206.1872
Bordone et al., 1702.07238

Implies lower NP scale:

$$(\bar{Q}_3 Q_3)(\bar{L}_3 L_3) \to V_{cb}(\bar{c}b)(\bar{\tau}\nu)$$

$\Rightarrow$ $R(D^{(*)})$ anomaly

$$\Lambda\sqrt{|V_{cb}|} \sim 500\,\mathrm{GeV}$$

Well within LHC reach!

see e.g. Abdullah et al., 1805.01869
Robinson et al., 1807.04753
Implications for top physics: JFK, Katz & Stolarski, 1808.00964

$$(\bar{Q}_3 Q_3)(\bar{L}_2 L_2) \to V_{tb}V_{ts}(\bar{s}b)(\bar{\mu}\mu)$$

$\Rightarrow$ $R_{K^{(*)}}$ anomaly

$$\Lambda\sqrt{|V_{ts}|} \sim 8\,\mathrm{TeV}$$

Still only marginally!

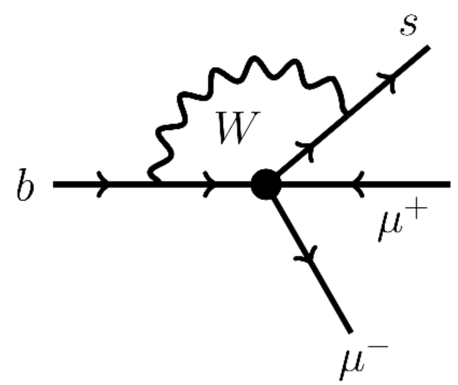
see e.g. talks by Buttazzo
Greljo
Soni

# B-anomalies without new quark flavor violation

Starting with flavor conserving non-universal operators in both quark and lepton sectors:

$$(\bar{L}_2 L_2)(\bar{U}_3 U_3) \qquad\qquad (\bar{E}_2 E_2)(\bar{U}_3 U_3)$$

EW matching & RGE induce LFUV in rare FCNC B decays




see talk by Faroughy

Effective NP scale now loop-suppressed: $\Lambda \frac{\sqrt{|V_{ts}|}}{4\pi} \sim 600\,\mathrm{GeV}$

⇒ automatically respects 3rd gen. alignment

⇒ d.o.f.'s mediating $R_K$ well within LHC kinematical reach

Flavor considerations/constraints lead to lower NP mass scale

# Further directions

NP related to 3rd generation - relation to EW hierarchy?

Potentially challenging signatures in direct LHC searches (multi $\tau$, top, $b$)

see e.g. talks by Kogler
Hryn'ova

NP in lepton flavor - neutrino connection?

see e.g. Altmannshofer et al., 1403.1269
Boucenna et al., 1503.07099

Neutrino masses - first clear BSM indication 20yrs ago

Relations to other SM puzzles: DM

$\nu_R$ solutions to $R_D$ introduce SM gauge singlet…

see e.g. talk by Cline

Many examples of fruitful interplay between NP searches at high energy, intensity and cosmology frontiers

# Additional material

# Immediate implications for LHC: $R(D^{(*)})$

## Enhanced LFUV in top processes:

$$(\bar{Q}_3 Q_3)(\bar{L}_3 L_3) \to V_{cb}(\bar{c}b)(\bar{\tau}\nu) + \boxed{V_{tb}(\bar{t}b)(\bar{\tau}\nu)}$$

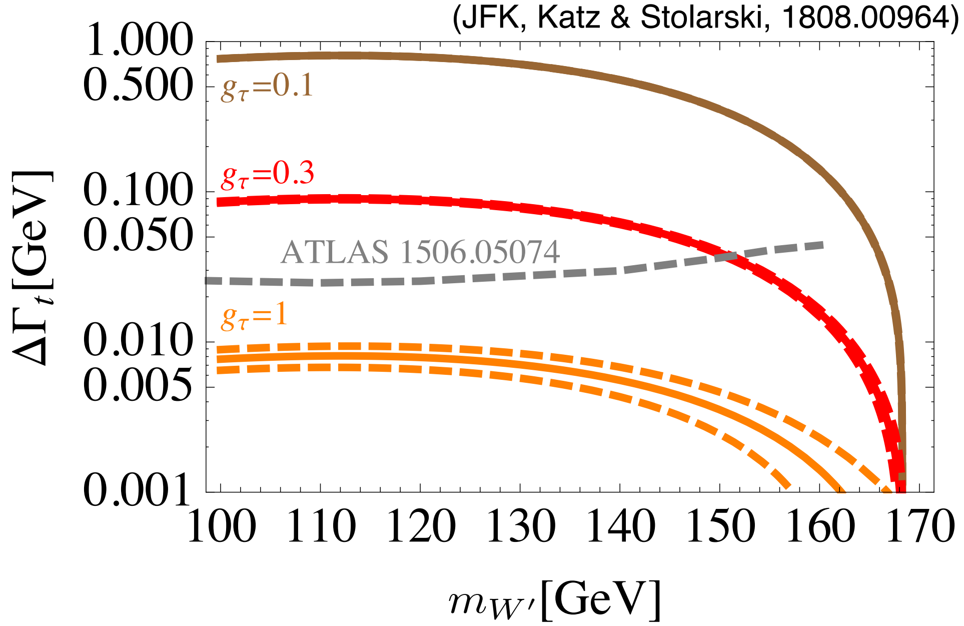
## Currently tested to O(10%)

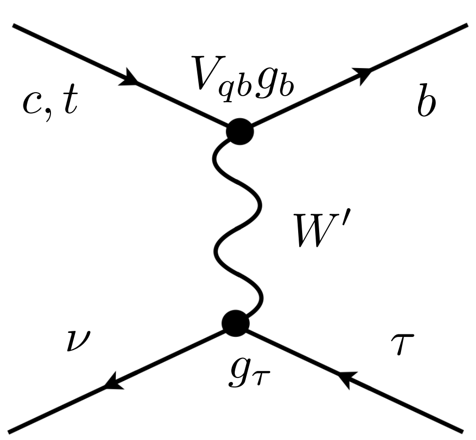
$$\mathcal{B}_e = 13.3(4)(4)\%\,,\ \mathcal{B}_\mu = 13.4(3)(5)\%\,,\ \mathcal{B}_{\tau_h} = 7.0(3)(5)\%\,,$$

ATLAS, 1506.05074

Example simplified model: charged spin-1 boson (W')

(JFK, Katz & Stolarski, 1808.00964)




LHC measurements starting to constrain $m_{W'} < m_t$ region.

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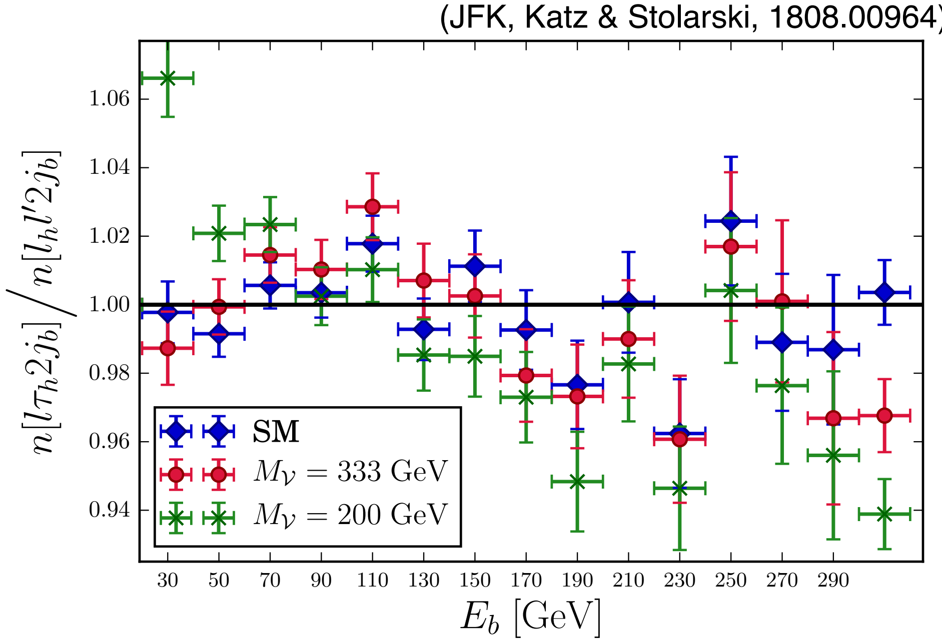


Features around the SM peak of b-jet energy distribution

$$E_b^* = \frac{m_t^2 - m_{l\nu}^2}{2m_t}$$

HL-LHC prospects for testing (sub-)percent level LFU