The Flavorful Road to New Physics

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Why flavor matters in the LHC era?

- Directly relates to two outstanding HEP issues: SM & NP flavor puzzles
- Indirectly probes NP scales up to 10^5 TeV through virtual effects
- Can help shed light / constrain the nature of the EWSB & the Higgs sector
- Can help reduce fine-tuning in models addressing the EW hierarchy in light of null LHC NP search results
- In case of observed deviations from SM, can point towards experimental targets both at high-p_T and at other venues

Why flavor matters in the LHC era?

SM phenomenologically very successful

Most likely just (experimentally accessible) effective theory

Unification of interactions

$$\mathcal{L}_{\nu\mathrm{SM}} = \boxed{\mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i)} + D_\mu \phi^\dagger D^\mu \phi - V_{\mathrm{eff}}(\phi, A_a, \psi_i)$$

$$V_{\mathrm{eff}} = \boxed{-\mu^2} \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + \boxed{Y^{ij}} \psi_L^i \psi_R^j \phi + \frac{\boxed{y^{ij}}}{\Lambda} \psi_L^{iT} \psi_L^j \phi^T \phi + \ldots$$

EW scale stabilization

Origin of flavor

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Baryogenesis

Unification of interactions

Dark matter?

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EW scale stabilization

Origin of flavor

m_ν

Need to understand/constrain size of <u>additional terms in series</u>

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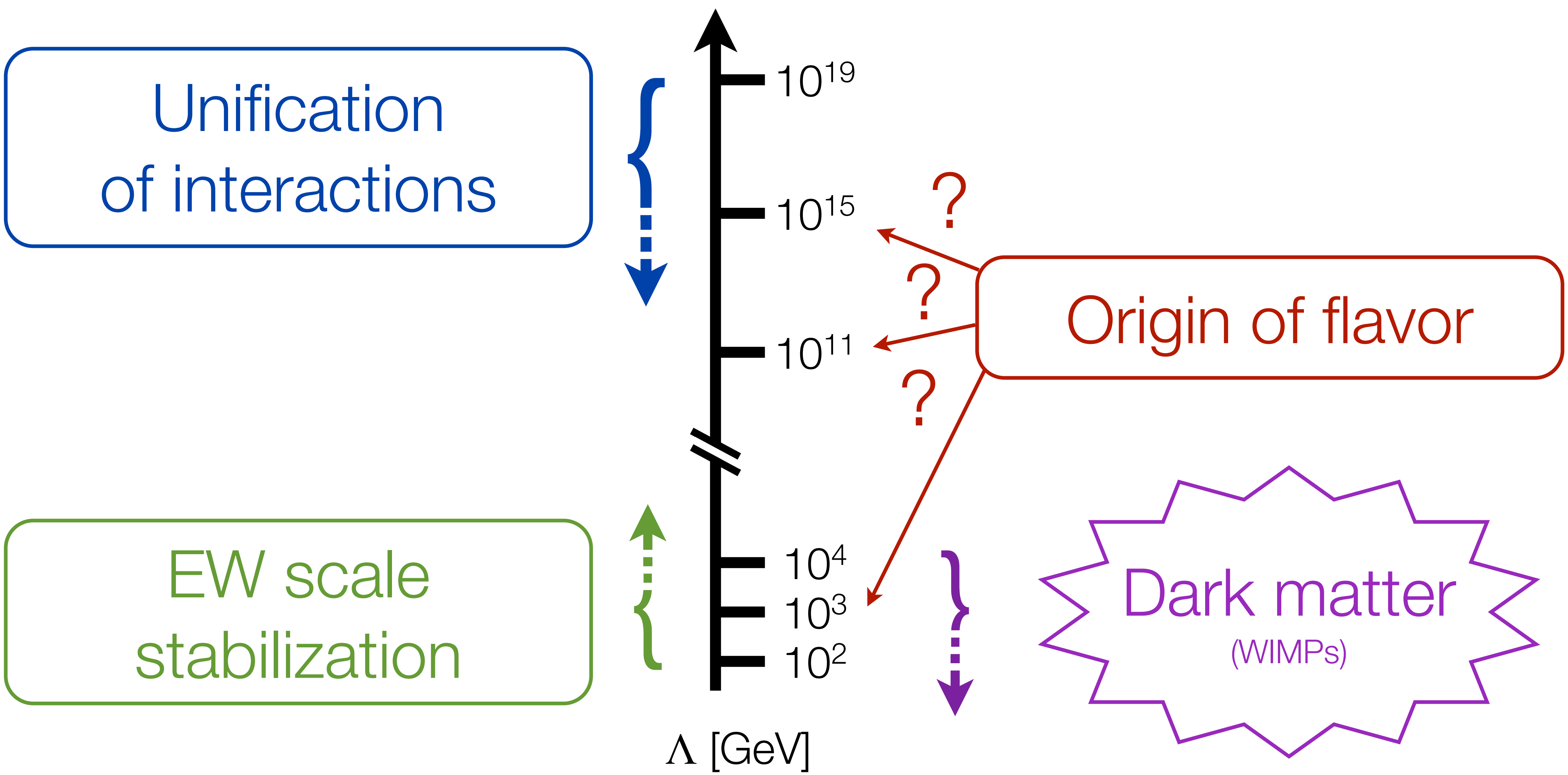
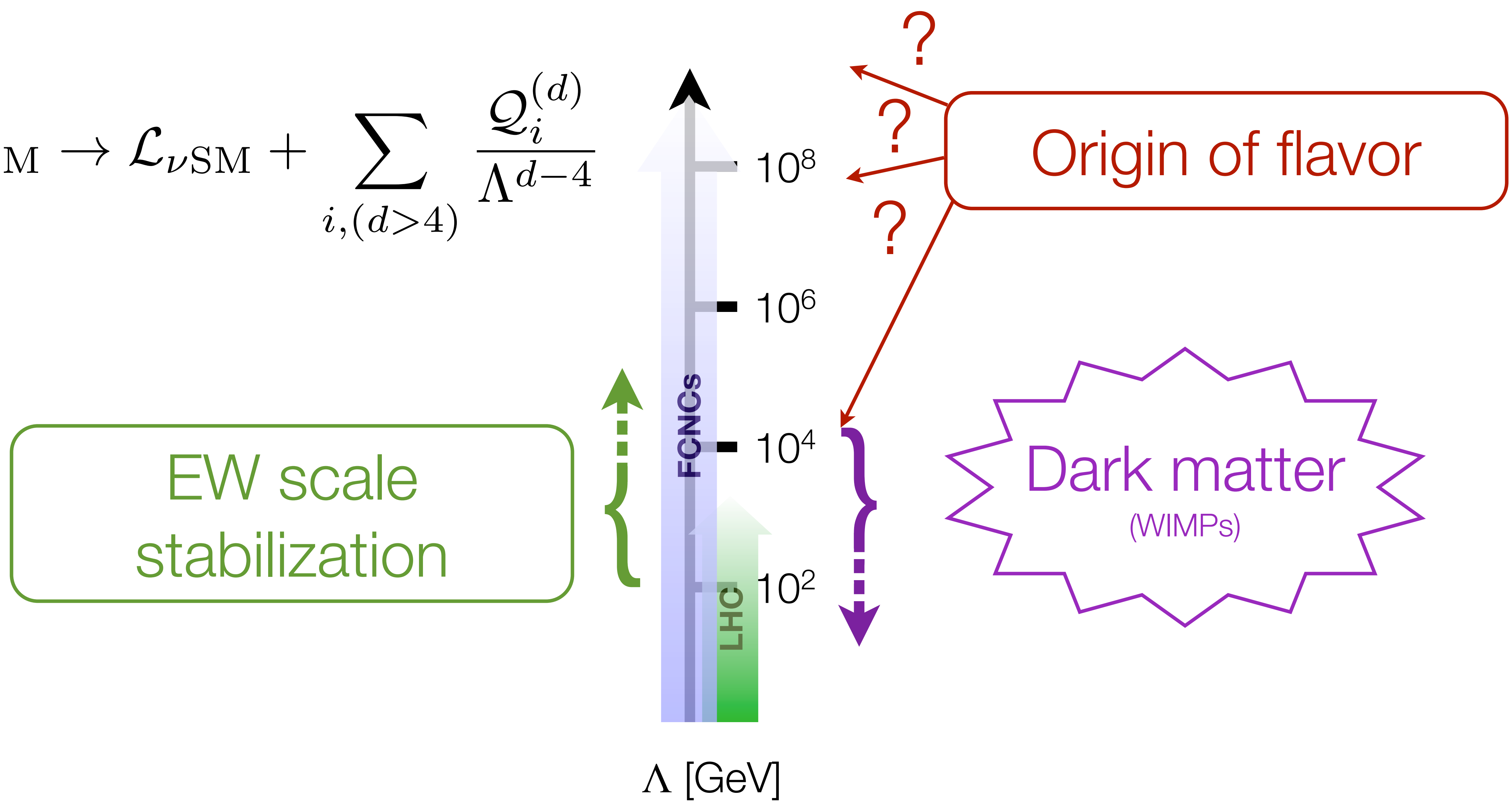


Why flavor matters in the LHC era?

Twofold role of flavor physics

(1) Indirect probe of BSM physics beyond direct reach

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



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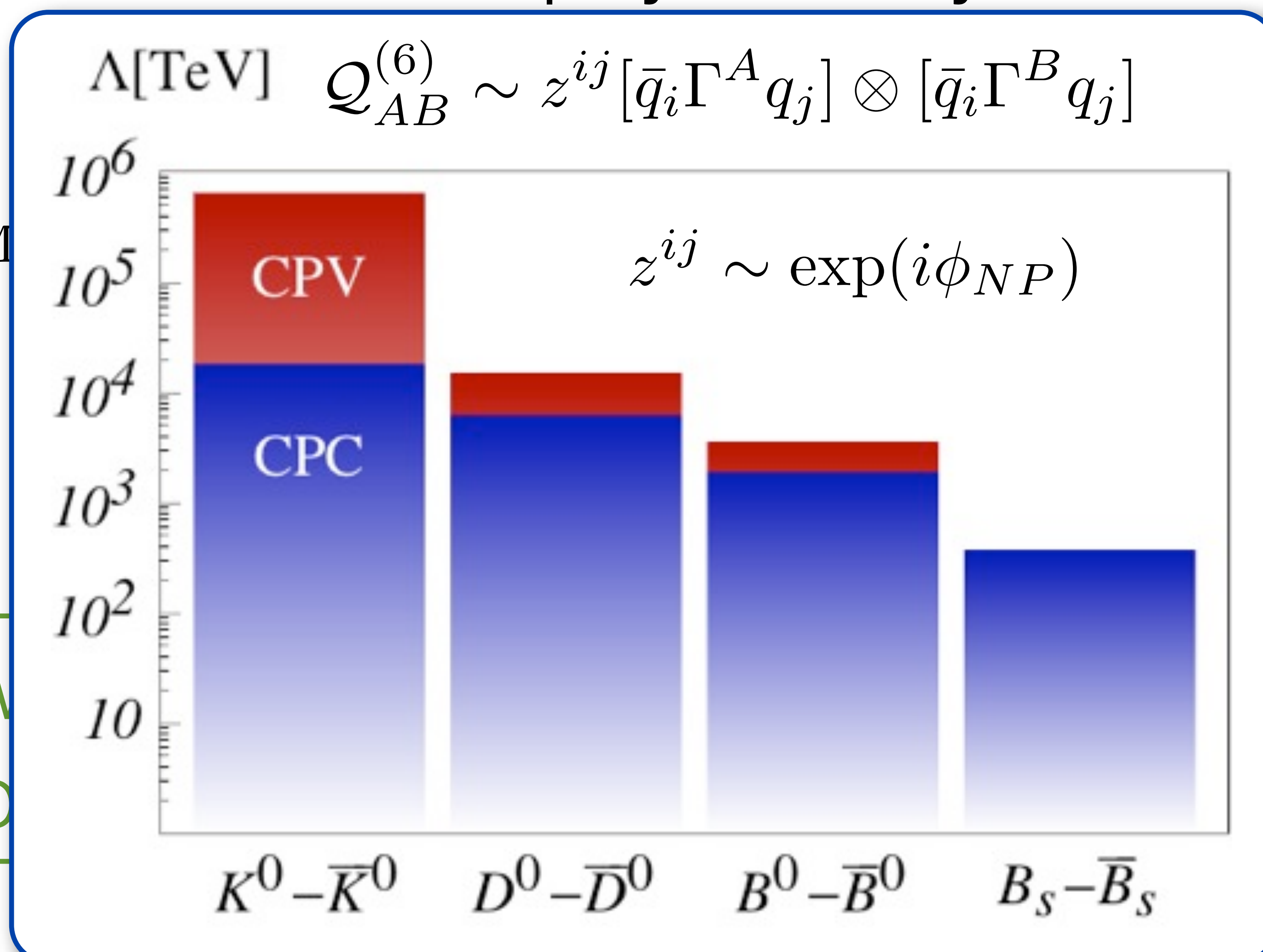

EW
stab

matter
WIMPs)

UTFit, 0707.0636
Isidori, Nir & Perez, 1002.0900
Lenz et al., 1203.0238
ETMC, 1207.1287

Crucial input from Lattice QCD &
measurements of SM flavor parameters!

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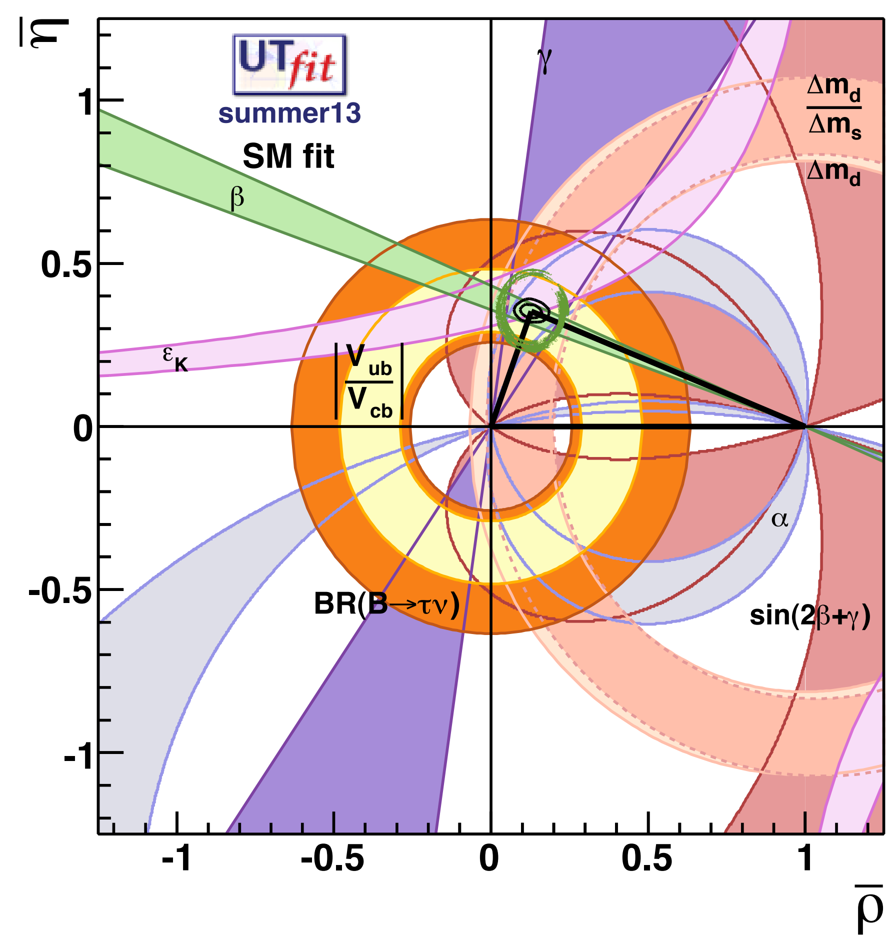
$\mathcal{L}_{\rm BSM} \to \mathcal{L}$

Excellent overall consistency



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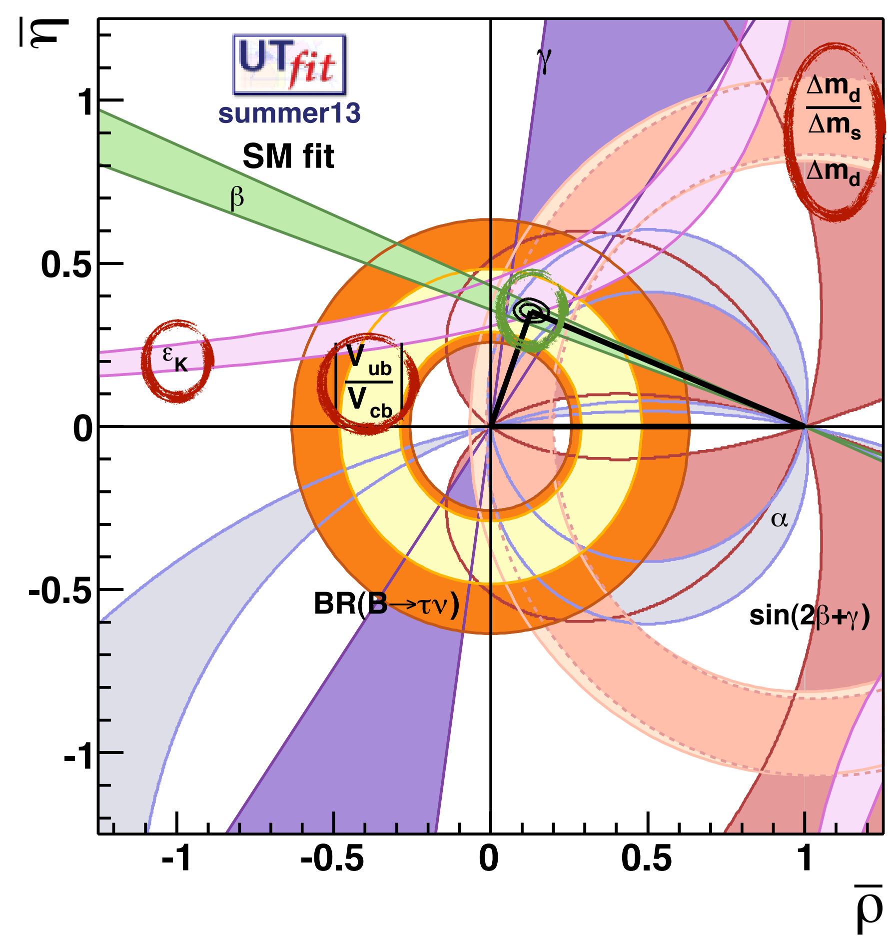
Future progress by Lattice QCD



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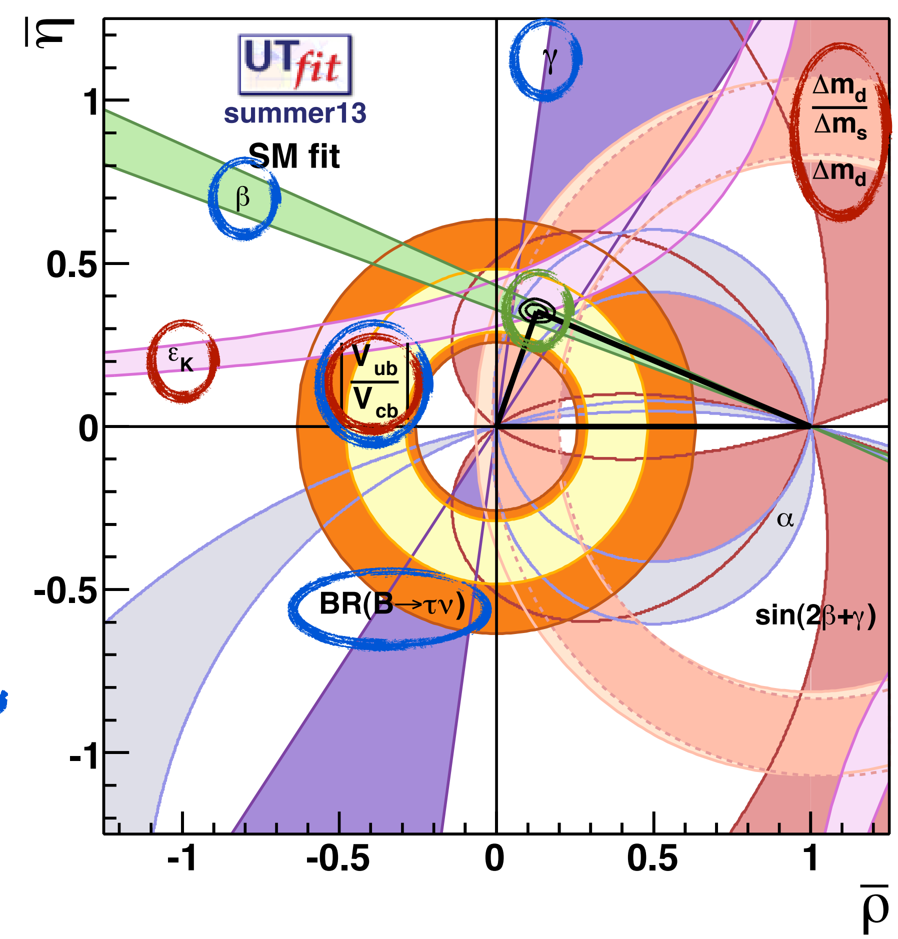
Interplay of LHCb, BelleII



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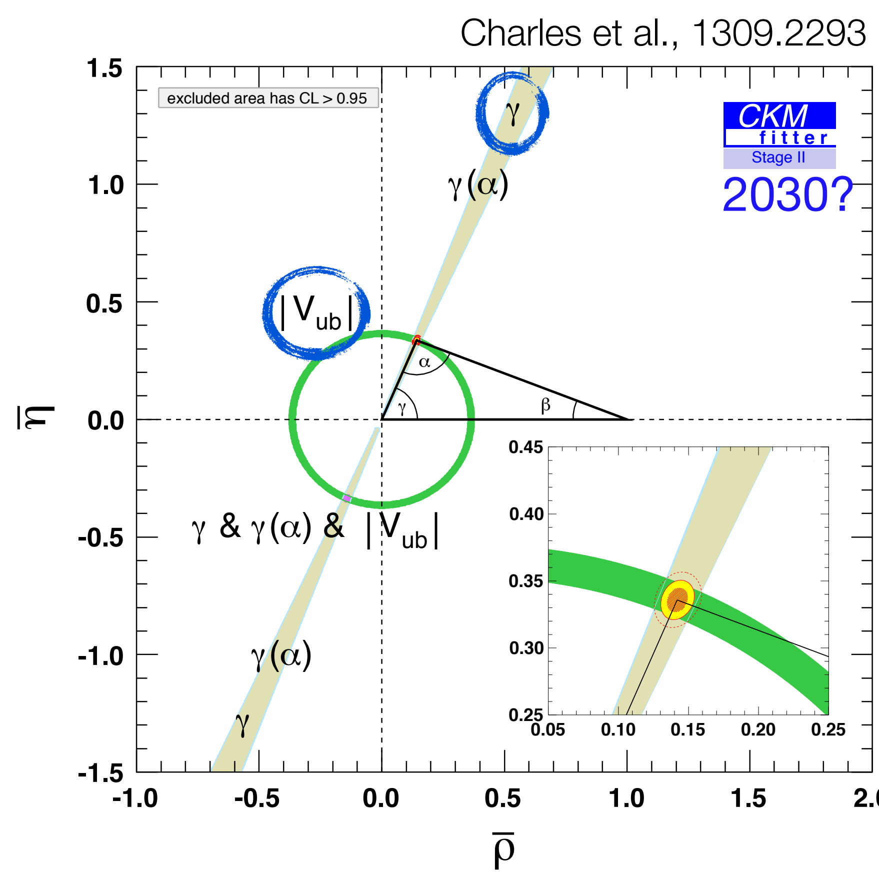

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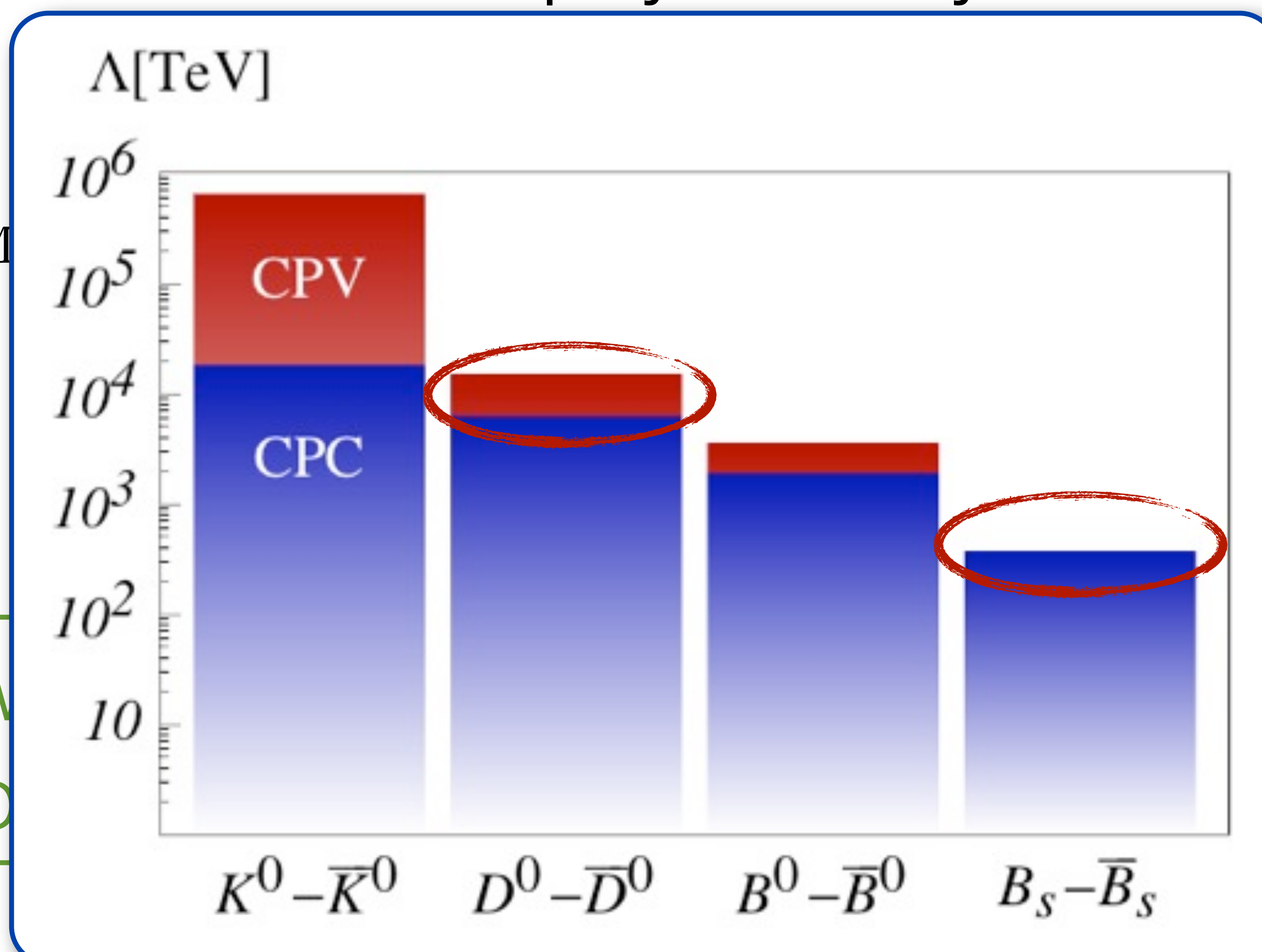

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WIMPs)

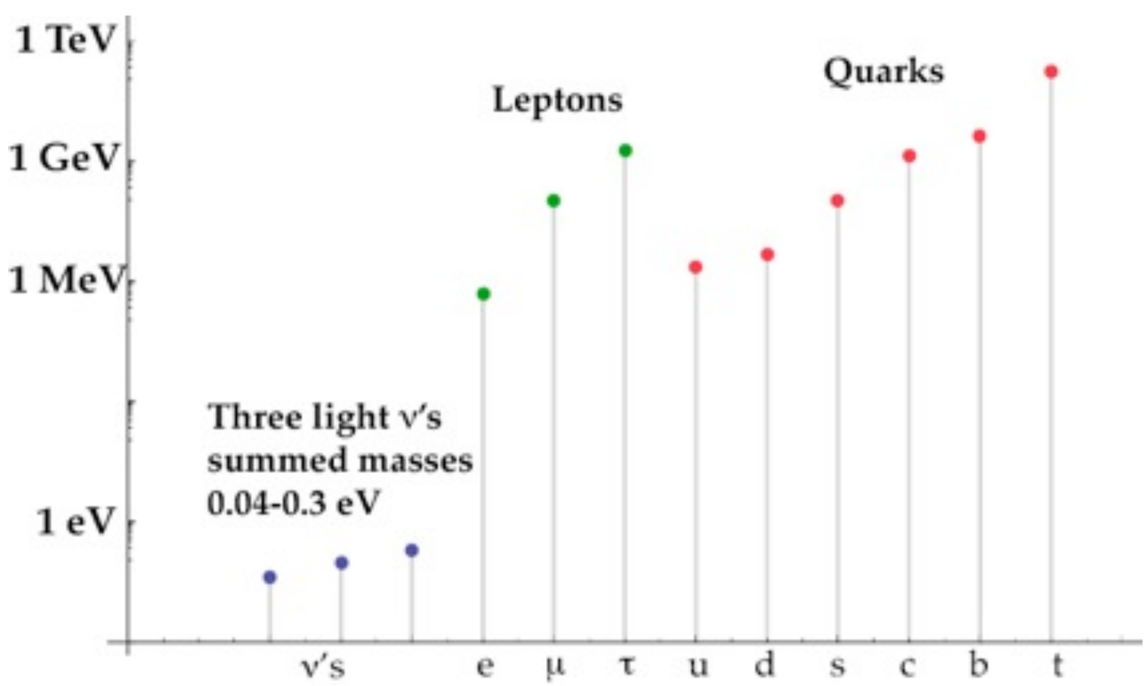
CPV in D, B_s only constraints not (yet) theory limited
⇒ effective null-tests within SM

Why flavor matters in the LHC era?

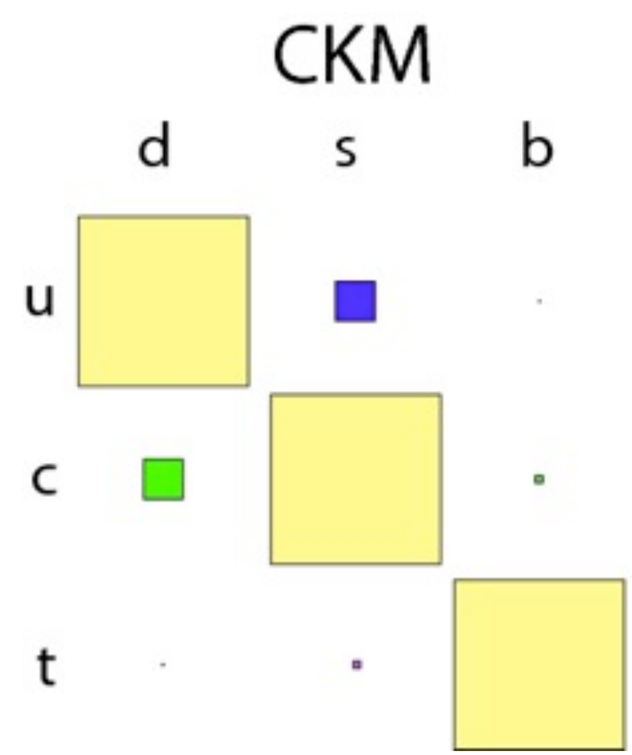
Twofold role of flavor physics

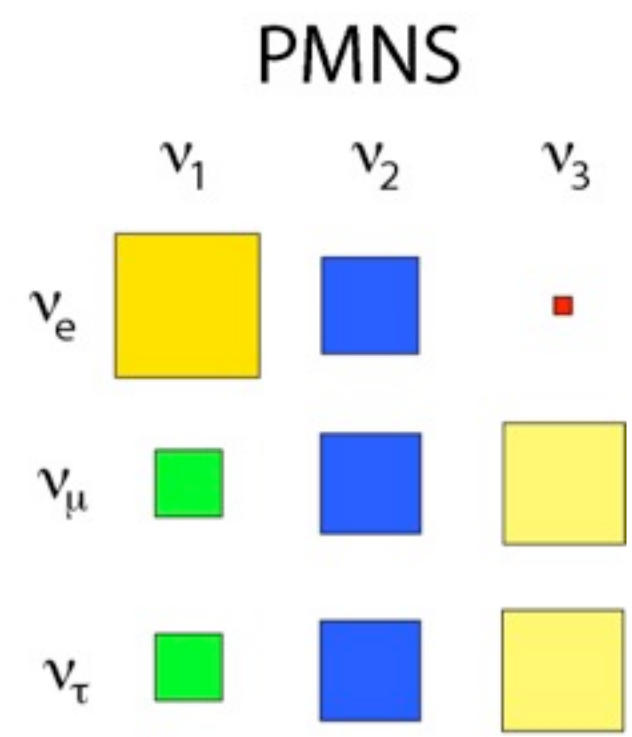
(2) Test sources of flavor symmetries & their violation

Suggestive pattern of masses and mixings



S. Stone, 1212.6374





Accidental? Dynamics? Symmetries?

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(2) Test sources of flavor symmetries & their violation

In SM flavor only broken by Higgs interactions

$$V_{\text{eff}} = \underbrace{\boxed{-\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2}}_{\text{EW breaking}} + \underbrace{\boxed{Y^{ij}\psi_L^i\psi_R^j\phi + \frac{y^{ij}}{\Lambda}\psi_L^{iT}\psi_L^j\phi^T\phi}}_{\text{Flavor breaking}} + \ldots$$

BSM sources of flavor breaking may or may not be related to EW scale generation

Why flavor matters in the LHC era?

Twofold role of flavor physics

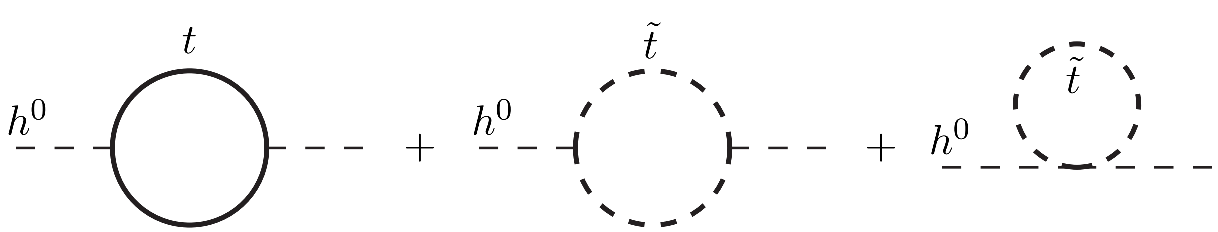
Example 1: MSSM

New flavor sources from SUSY breaking

- squark, slepton masses & trilinear terms

Radiative EWSB from flavor effects

- Higgs mass term driven negative by top Yukawa RGE



tries & their violation

gs interactions

$$\psi_L^i \psi_R^j \phi + \frac{y^{ij}}{\Lambda} \psi_L^{iT} \psi_L^j \phi^T \phi + \dots$$

Flavor breaking

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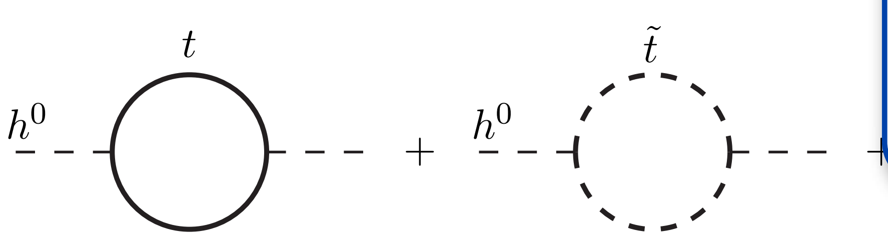

Example 2: composite pseudo-Goldstone Higgs

New flavor sources from partial compositeness

- mixing with heavy vector-like fermions

Radiative EWSB from flavor effects

- Goldstone shift symmetry broken by top Yukawa

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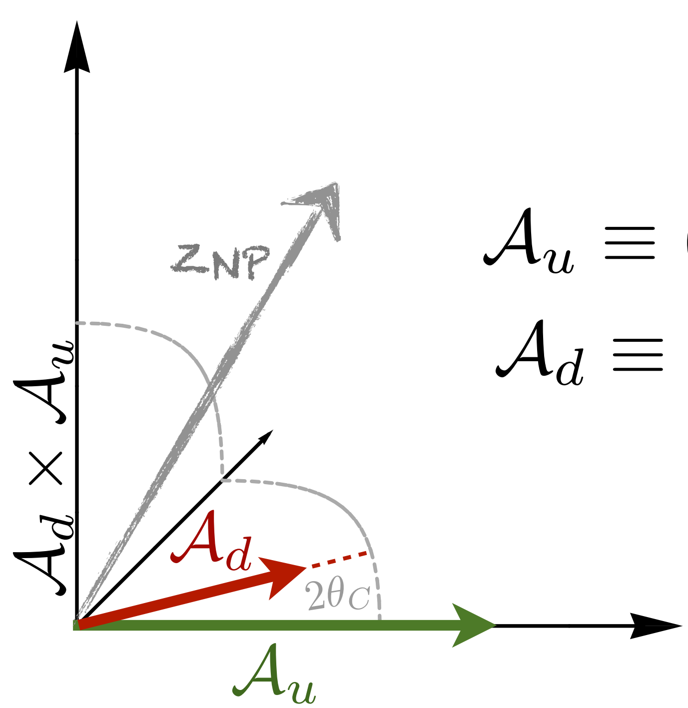
(2) Test sources of flavor symmetries & their violation

Global flavor symmetry of SM broken by Yukawas:

$$G_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$



$$\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{t\!\!/r}\,,$$
$$\mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{t\!\!/r}$$

SM contributions highly hierarchical & aligned

$\Downarrow$

Severe constraints on generic BSM sources

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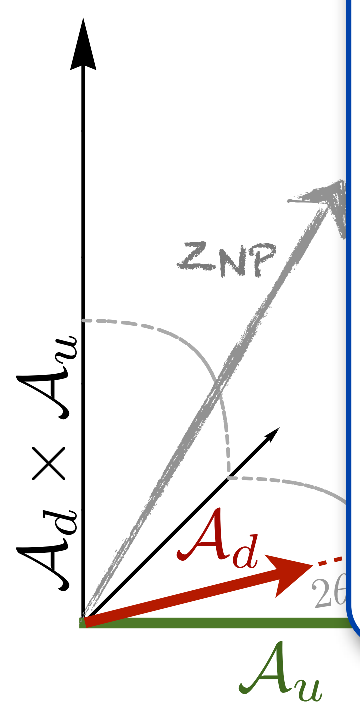
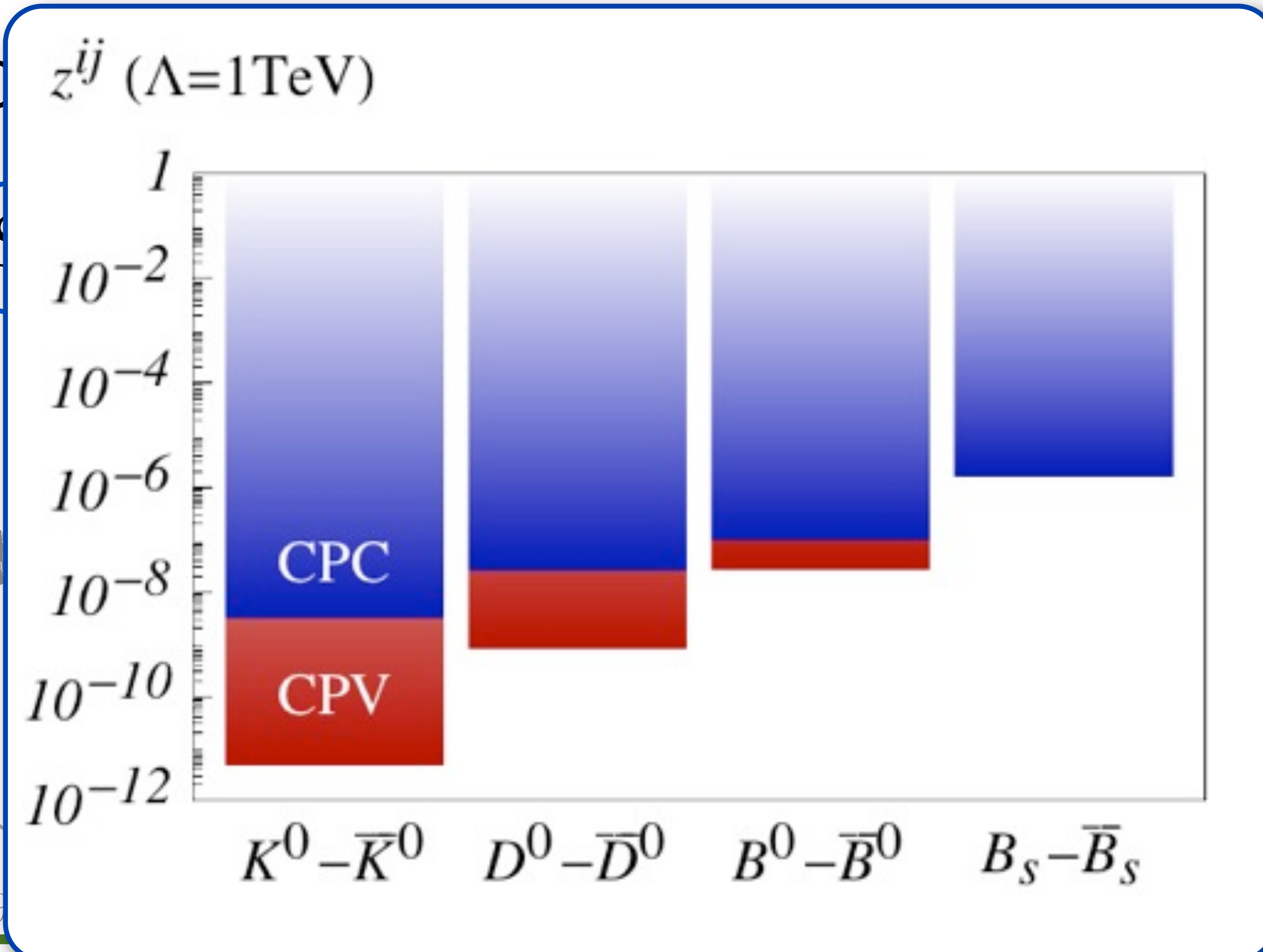
Global flavo awas:

$$G_F = \ldots \times SU(3)_E$$





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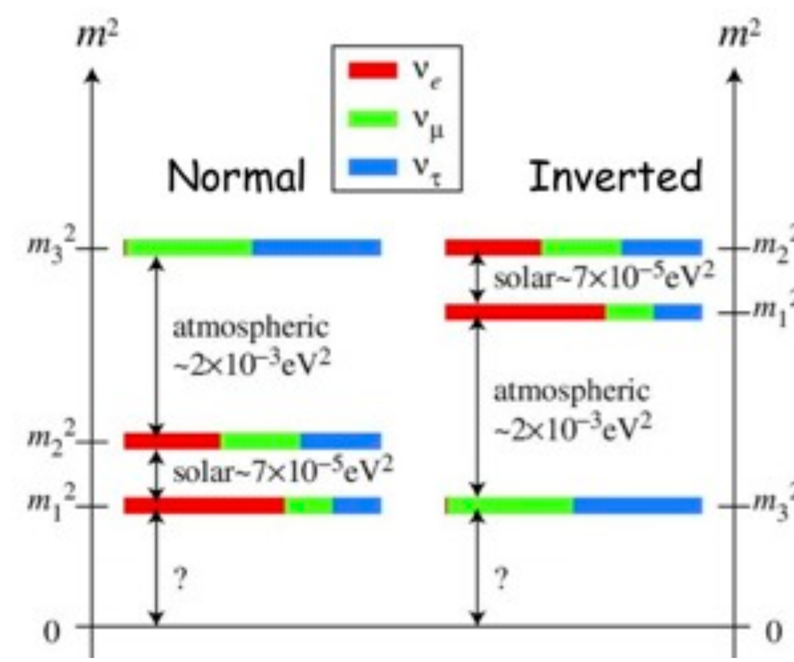
Flavor mixing in lepton sector is large

Tied to chiral symmetry (for Dirac ν's) or lepton number breaking (for Majorana ν's)

⇒ observables generically suppressed by m_ν



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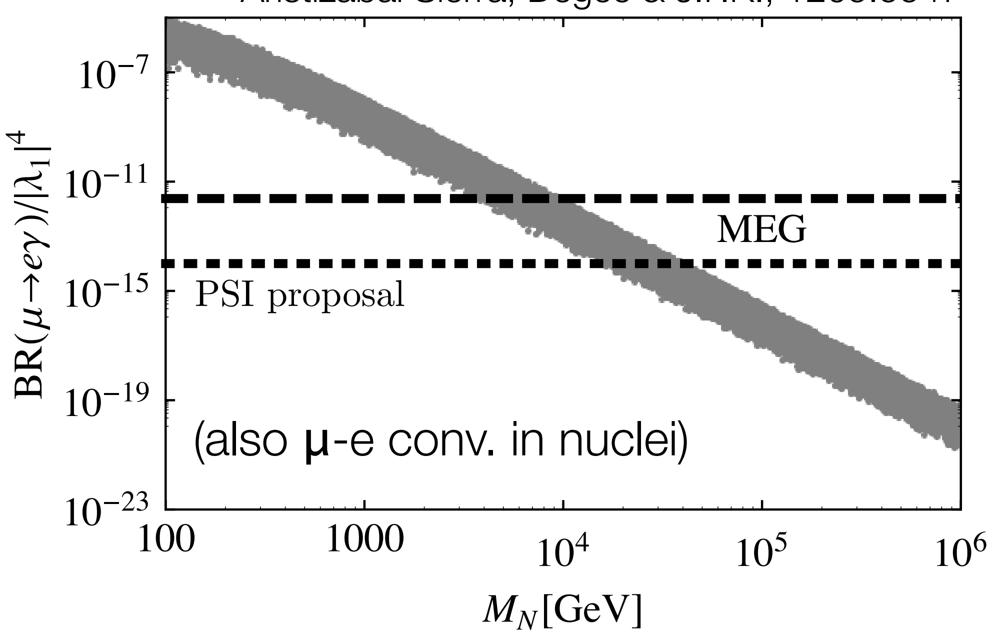
A (minimal) case for LFV:

- assume L breaking at high scale as suggested by small m_ν
- decouple flavor & L breaking scales

  ⇒ pseudo-Dirac neutrinos with sizable LFV (fixed by neutrino data up to overall Yukawa normalization λ_1)

Aristizabal Sierra, Degee & J.F.K., 1205.5547



<u>Example</u>: Type-I see-saw (2 fermionic EW singlets N_i)

c.f. Gavela et al., 0906.1461

Reclaiming flavorful NP at EW scale

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Global flavor symmetry of SM broken by Yukawas:

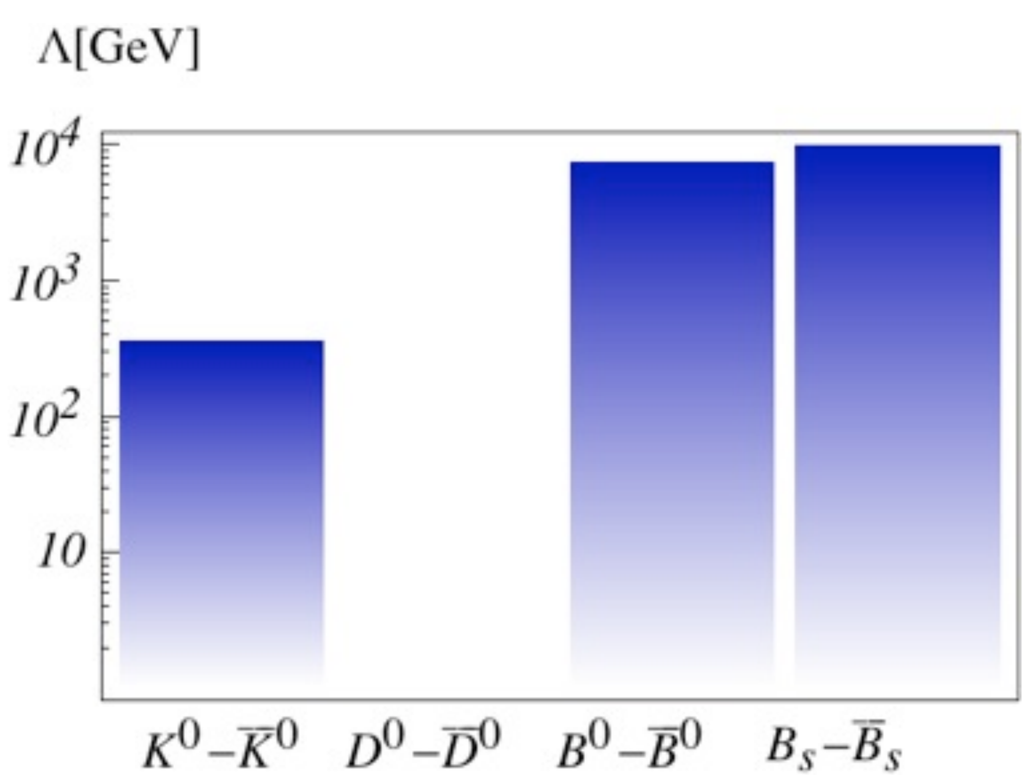
$$G_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$

Formally, <u>NP flavor cannot be completely trivial</u> $\int d^4x\, T\{\mathcal{Q}_{\rm NP}\, \mathcal{H}_{\rm SM}\}$

$$\mathbf{z} = \mathbf{1} + a_1 \mathcal{A}_u + a_2 \mathcal{A}_d + \ldots$$

$a_{i>2} \lesssim a_{1,2}$ “Minimal Flavor Violation”

d’Ambrosio et al., hep-ph/0207036
Colangelo et al., 0807.0801
...



$$\mathcal{Q}^{(6)} \sim [\mathcal{A}_u^{ij} (\bar{Q}_i \gamma_\mu Q_j)]^2$$

NP in loops

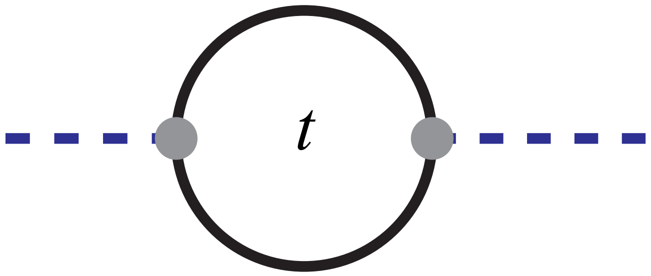
$\Downarrow$

<u>probe EW scale masses</u>

Reclaiming flavorful NP at EW scale

Flavor triviality imposes degeneracy in NP spectra - problematic for naturalness@LHC

In SM, top Yukawa imposes largest fine-tuning in Higgs potential ⇒



$$\delta m_h^2 \sim \frac{m_t^2}{v^2}\Lambda^2$$

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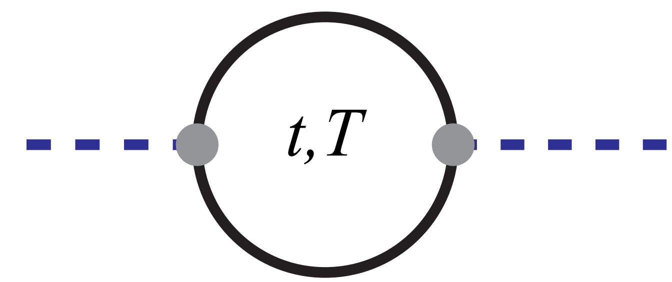
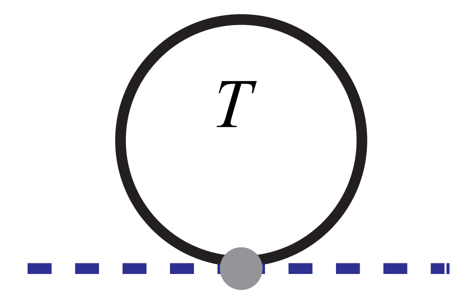
$$\delta m_h^2 \sim \cancel{\frac{m_t^2}{v^2}\Lambda^2} + \frac{m_t^2}{v^2} m_T^2 \log\frac{\Lambda^2}{m_T^2} + \dots$$

prefer light top partners ($m_T < 1\,\mathrm{TeV}$)





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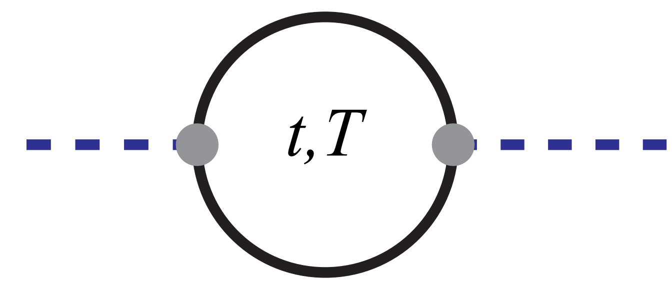
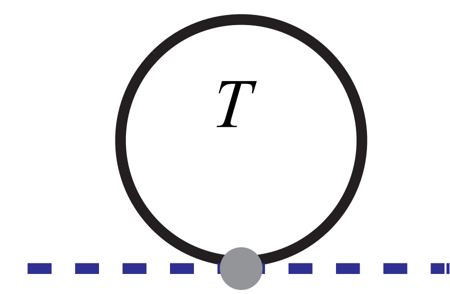
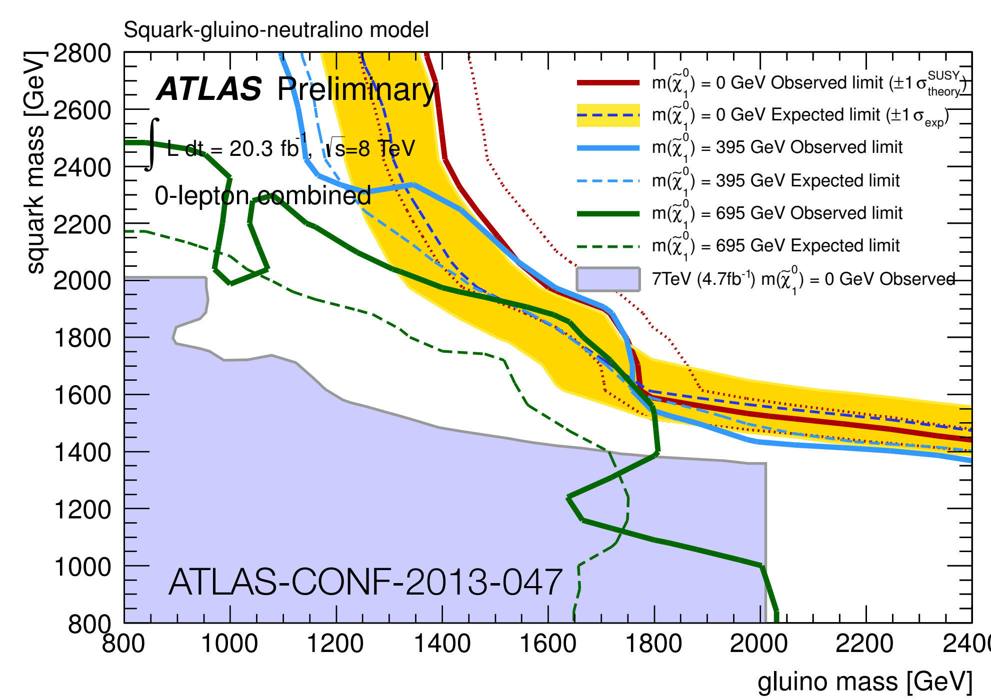




avoiding flavor bounds though triviality ⇒ presence of u,d,... partners ($m_U \sim m_T$)



Strong LHC direct search constraints (MSSM example)

Reclaiming flavorful NP at EW scale

EW hierarchy stabilization only requires light 3rd generation partners ⇒ LHC bounds then imply flavor nontrivial spectra

Possible in flavor models mimicking the SM SU(3)/SU(2) flavor breaking pattern (i.e. $U(2)^3$)

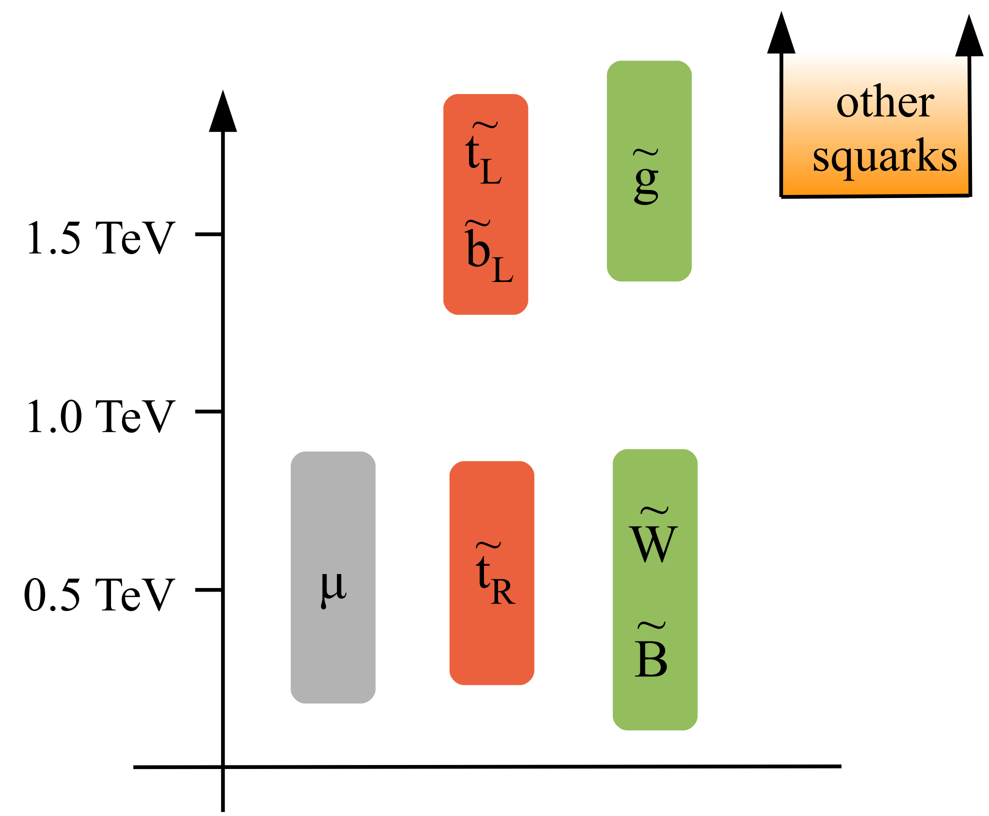
Kagan et al., 0903.1794
Buras & Girrbach, 1206.3878
Barbieri et al., 1105.2296
1108.5125
1203.4218
1206.1327
1211.5085

Example: natural SUSY

BSM flavor effects mediated by 3rd generation squarks (& sleptons)

Key observables:

- (CPV) in K(ε_K), B mixing (Δm_q, ϕ_q)
- Rare B decays ($B \to (X) l^+ l^-, \nu\nu$)
- LFV & EDMs



Isidory @ ICHEP’14

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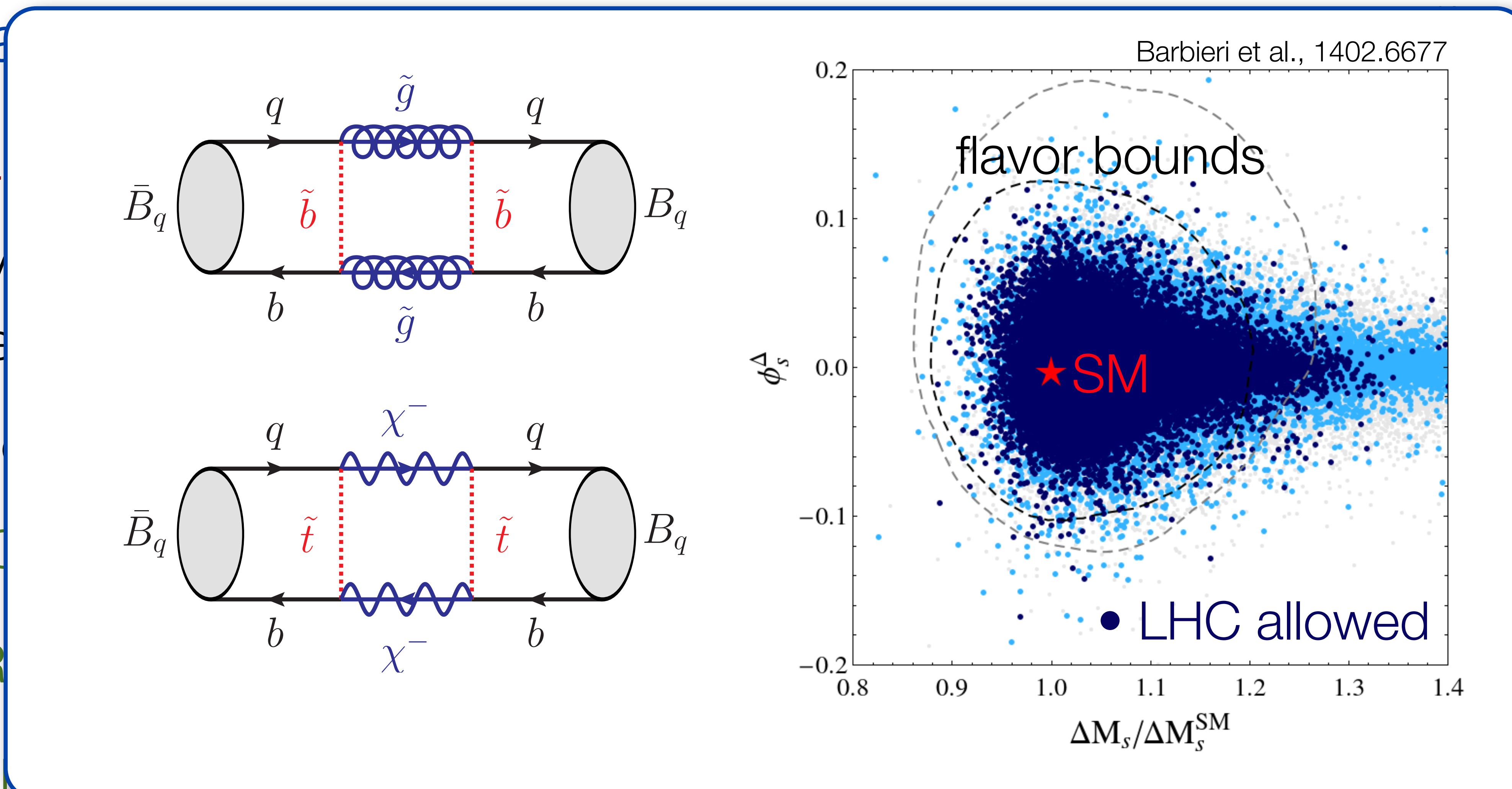

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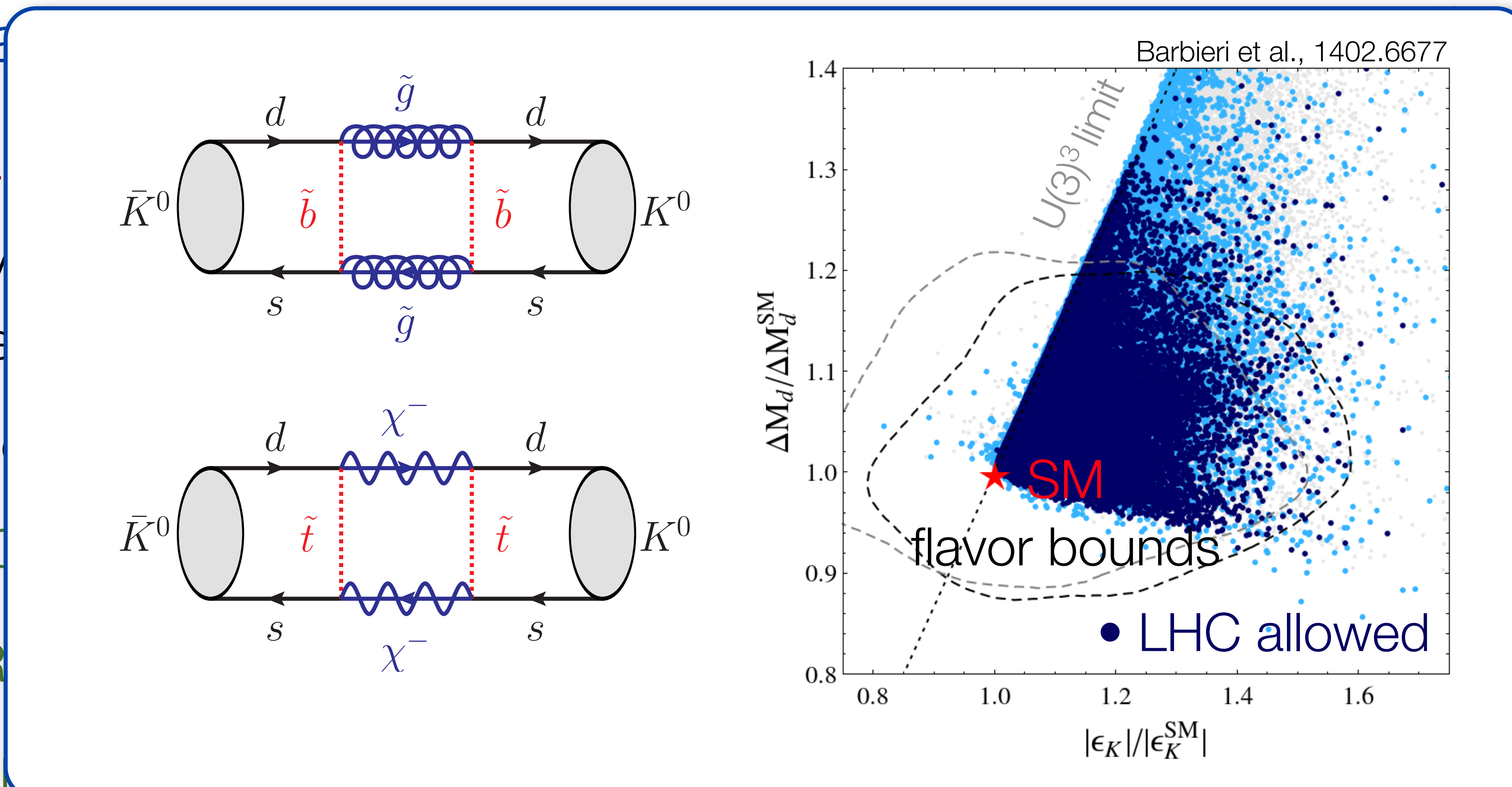

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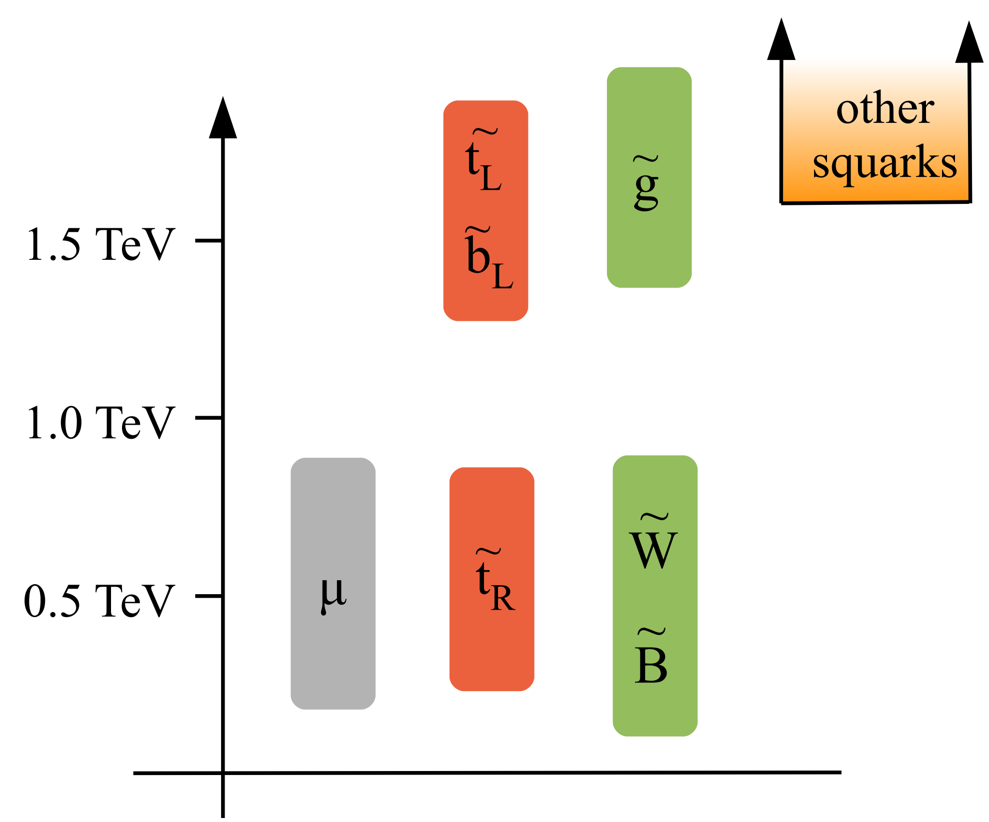

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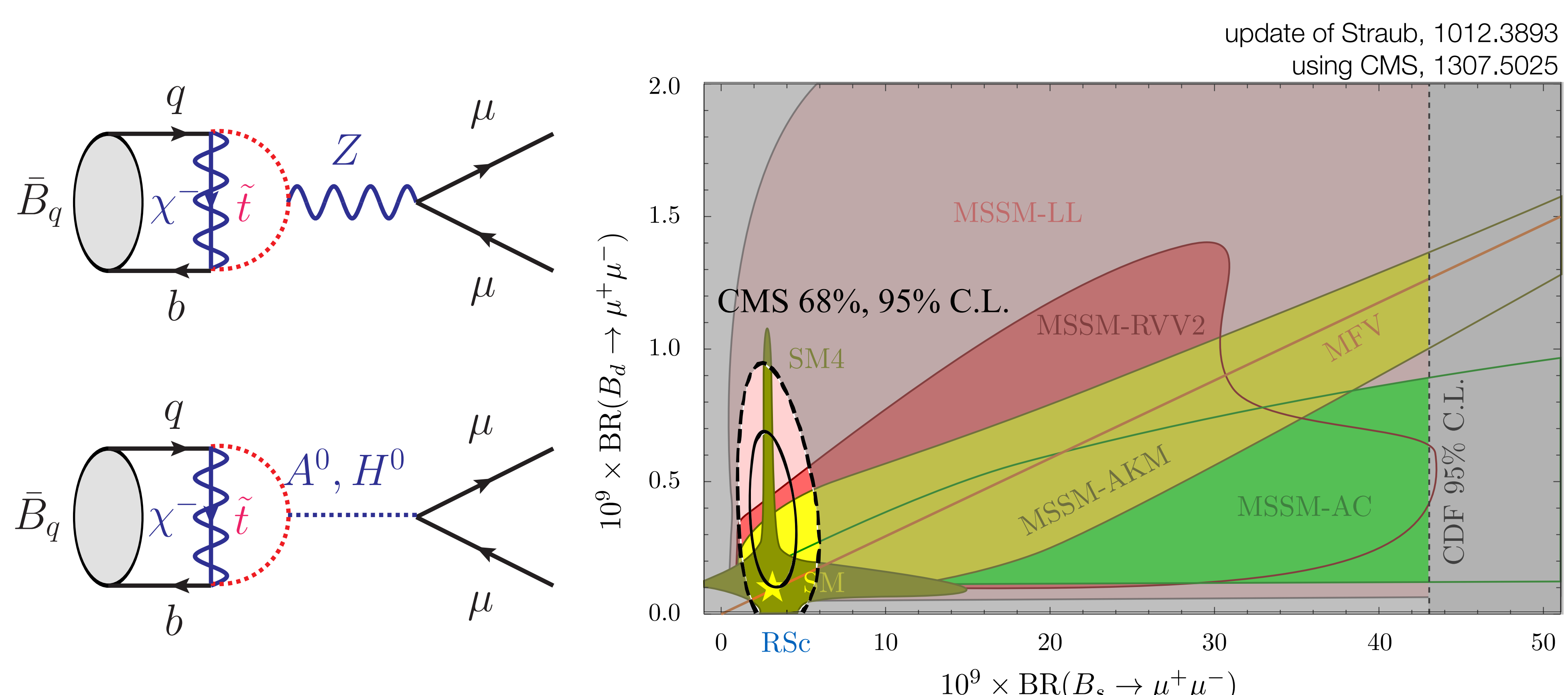

Nontrivial test of MFV.

Hurth et al., 0807.5039

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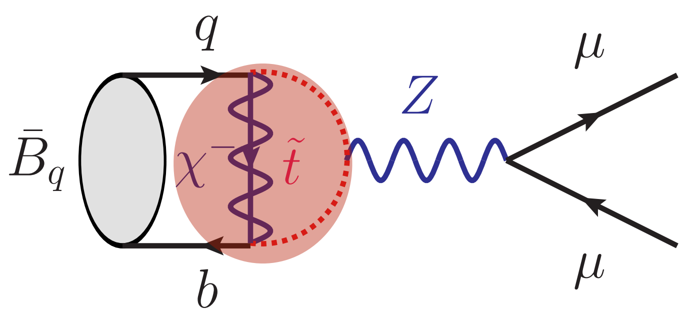
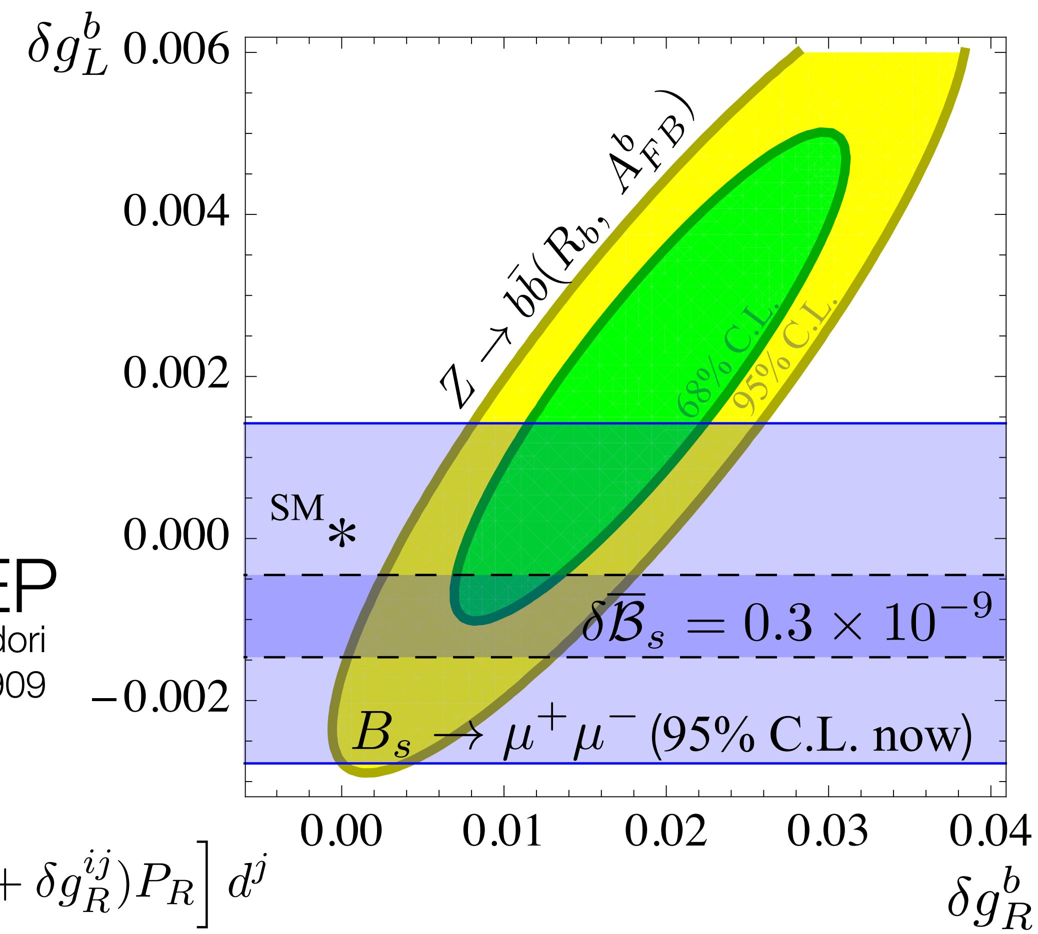


Sensitivity to Z-penguins already competitive with LEP

Guadagnoli & Isidori
1302.3909



Example: MFV EFT

$$\mathscr{L}_{\rm eff}^Z = \frac{g}{c_W} Z_\mu \bar{d}^i \gamma^\mu \left[(g_L^{ij} + \delta g_L^{ij}) P_L + (g_R^{ij} + \delta g_R^{ij}) P_R \right] d^j$$

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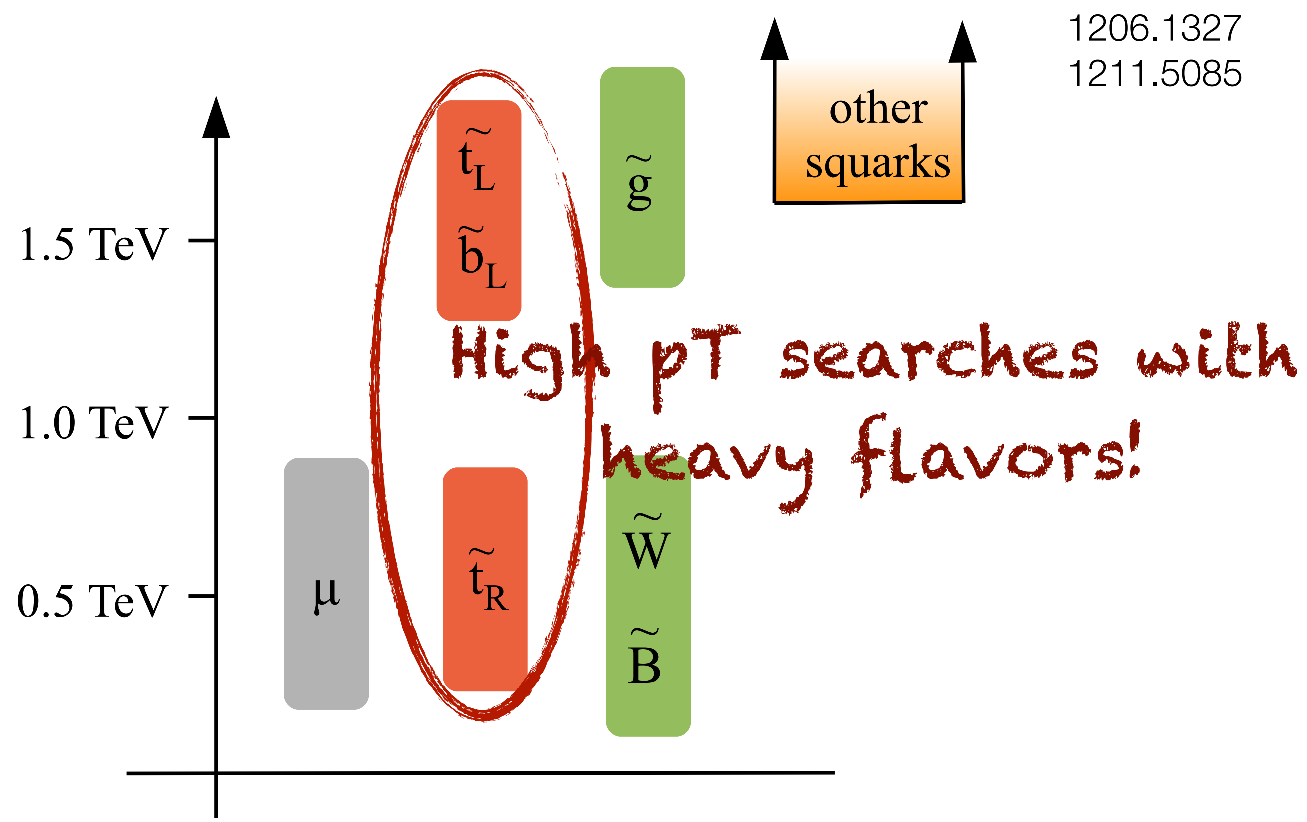

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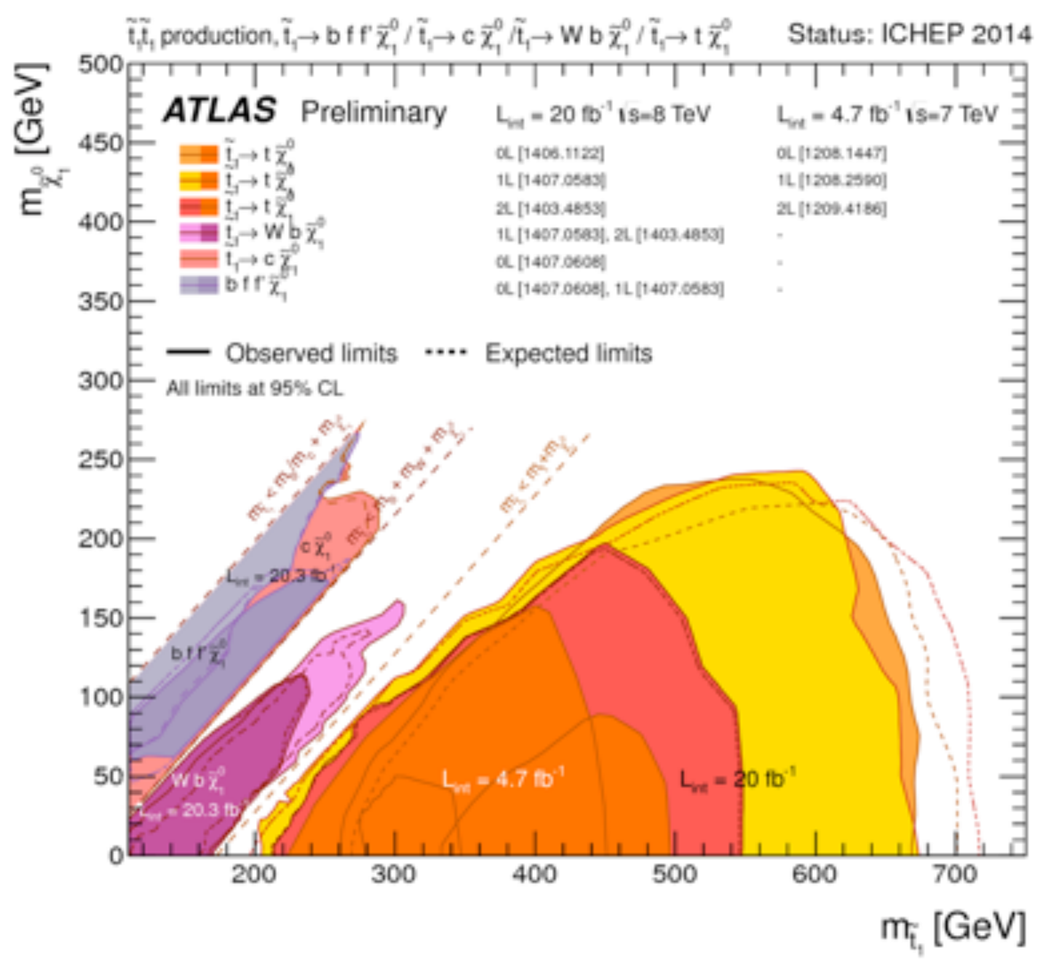
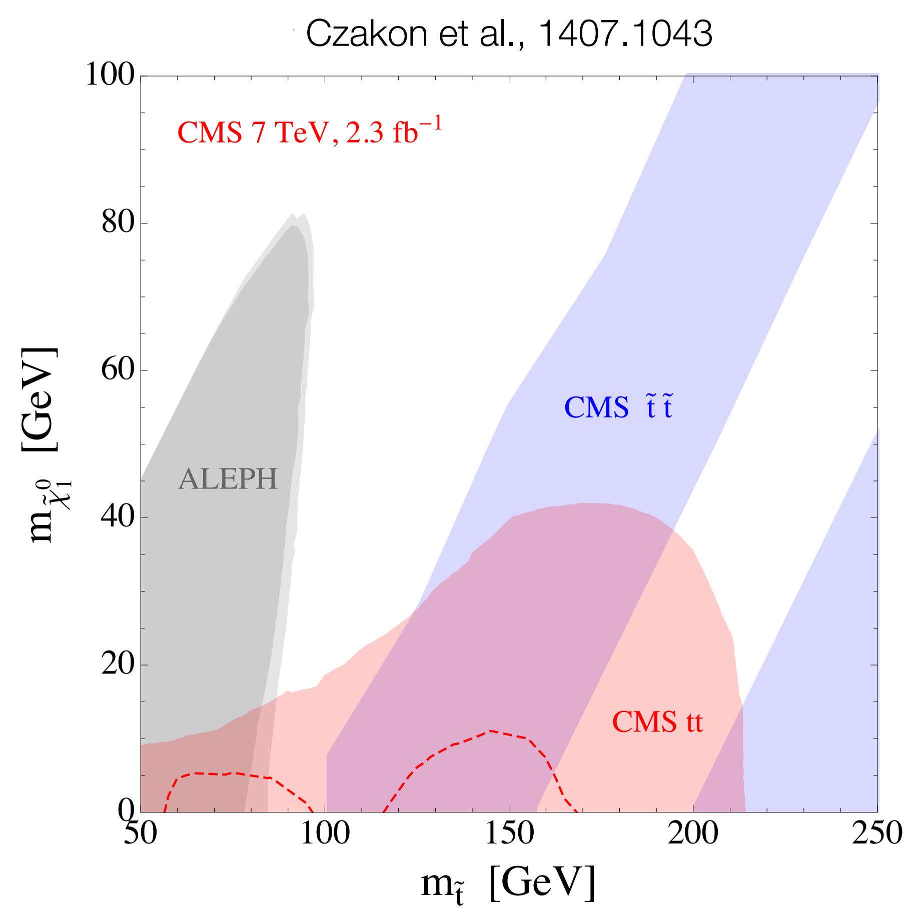




Note: sizable top-charm partner mixing allowed!
⇒ flavor violating high-pT signatures

Gedalia et al., 1202.5038
Mahbubani et al., 1212.3328
Blanke et al., 1302.7232
Delaunay et al., 1311.2072

Reclaiming flavorful NP at EW scale

EW hierarchy stabilization only requires light 3rd generation partners ⇒ LHC bounds then imply flavor nontrivial spectra

ACME, 1310.7534

Possible in flavor models mimicking the SM SU(3)/SU(2) flavor breaking pattern (i.e. U(2)^3)

Kagan et al., 0903.1794
Buras & Girrbach, 1206.3878
Barbieri et al., 1105.2296
1108.5125
1203.4218
1206.1327
1211.5085

Example: natural SUSY

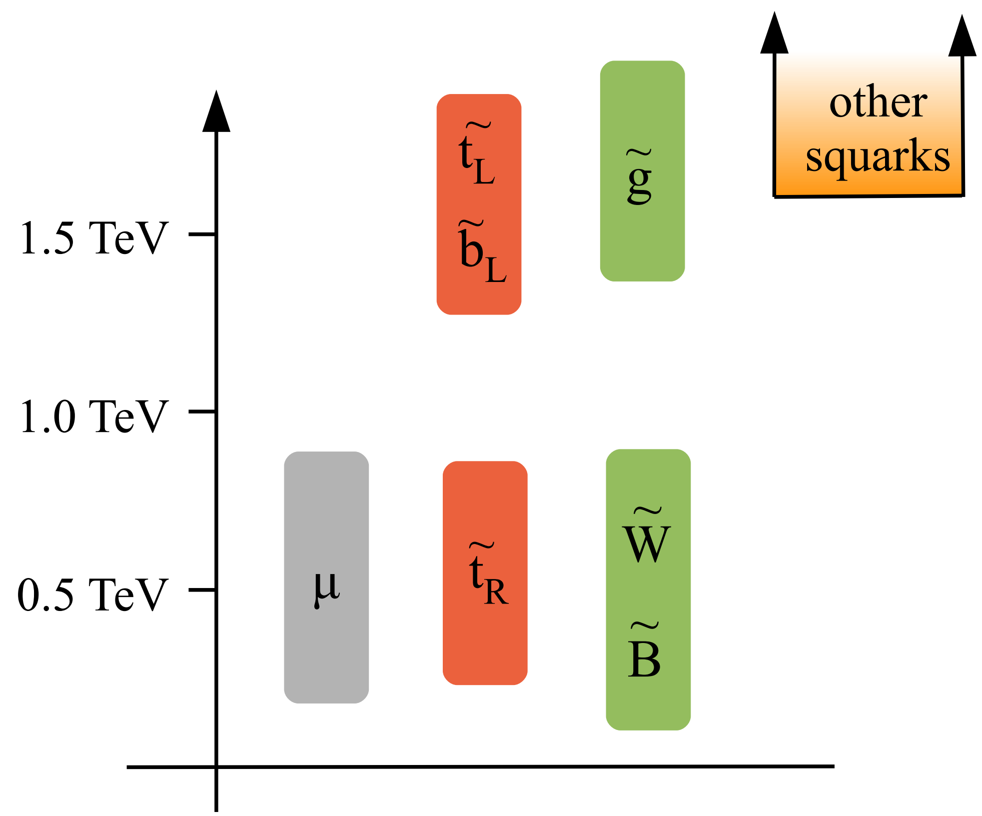
BSM flavor effects mediated by 3rd generation squarks (& sleptons)

Key observables:

- (CPV) in K(ε_K), B mixing (Δm_q, ϕ_q)
- Rare B decays ($B \to (X) l^+ l^-, \nu\nu$)

Barbieri et al., 1402.6677

- LFV & EDMs



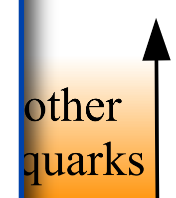
Isidory @ ICHEP'14

Reclaiming flavorful NP at EW scale

EW hierarchy stabilization only requires light 3rd generation partners ⇒ LHC bounds then imply flavor nontrivial spectra

Possible in flav… 2) flavor breaking patter…

Kagan et al., 0903.1794
…as & Girrbach, 1206.3878
Barbieri et al., 1105.2296
1108.5125
1203.4218
1206.1327
1211.5085



Example: natur…

BSM flavor effects … generation squark…

Key observables:

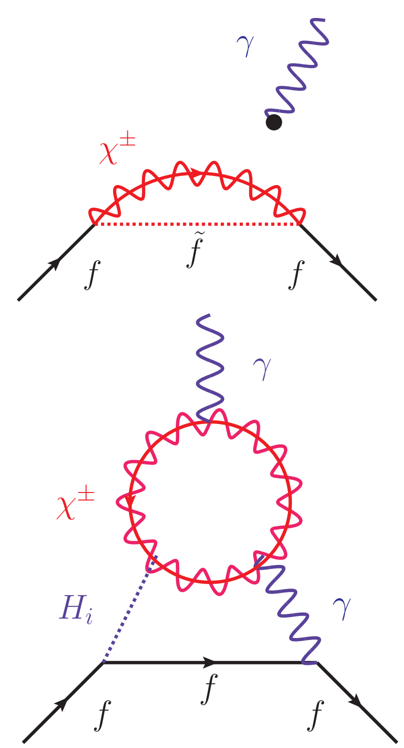
- (CPV) in K(ε_K), E…
- Rare B decays
- LFV & EDMs

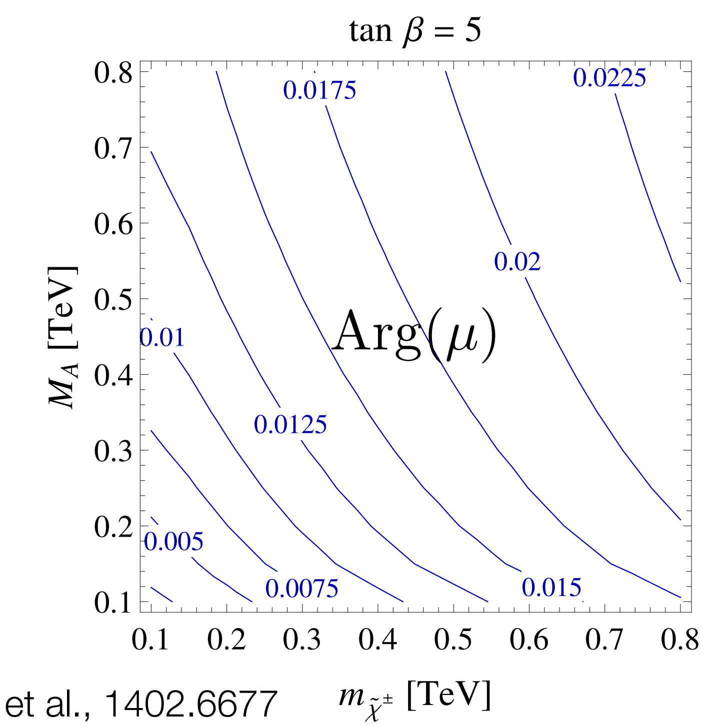
ACME, 1310.7534

Improved constraint on $|d_e| < 8.7 \times 10^{-29}\, e\,\mathrm{cm}$

⇒ Bounds Higgsino & sneutrino parameters

$$m_{\tilde{\nu}_1} > 17\,\mathrm{TeV} \times \sqrt{\mathrm{Im}(\mu)\tan\beta}$$





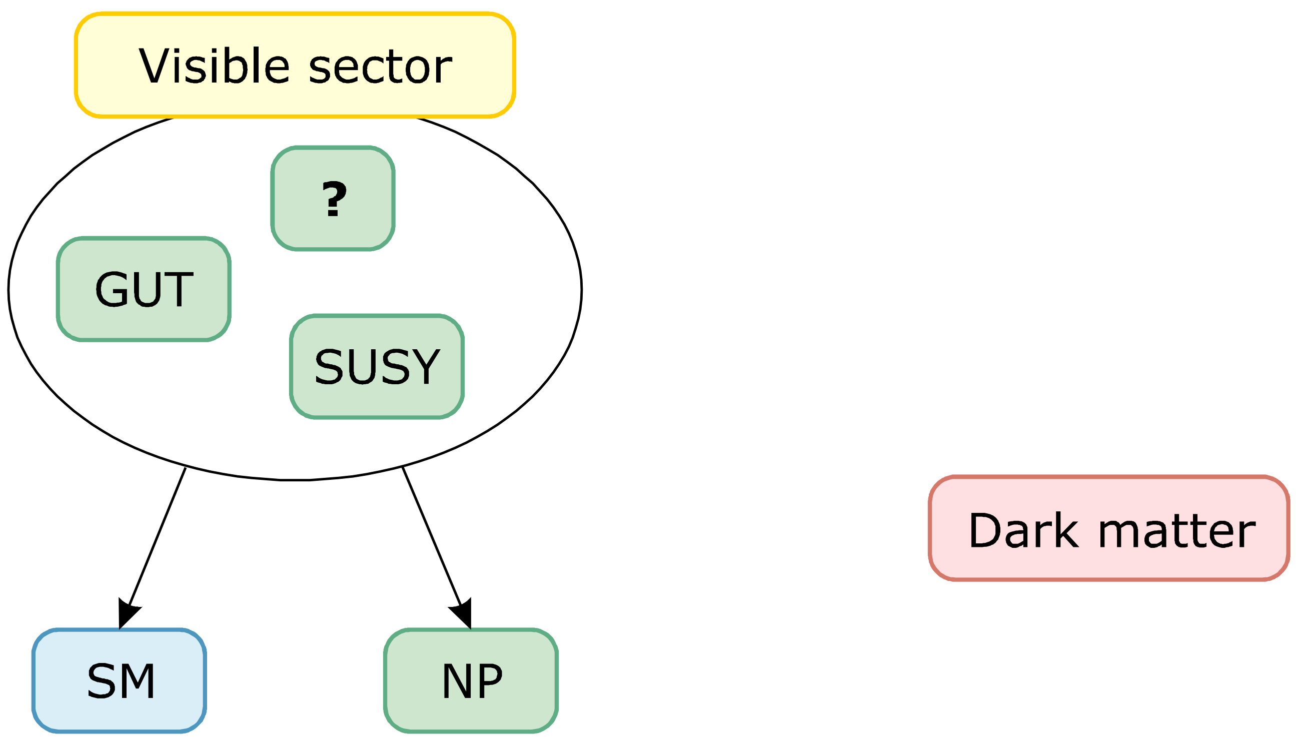
Barbieri et al., 1402.6677

Flavor portals to dark sector

Are there only SM particles at low-energy?

- **Experimentally:**
  - Even very light states could be missed if very weakly interacting,
  - There is dark matter in the Universe; it could be relatively light.
- **Theoretically:** Plenty of models predict new light particles
  - Pseudo-Goldstone scalars (axion, familon,...),
  - U(1) vectors (string, ED,...),
  - Hidden sectors & messengers (SUSY, mirror worlds,...)
  - Many others: millicharged fermions, dilaton, majoron, neutralino, sterile neutrino, gravitino,...

How to probe low-energy particle content?



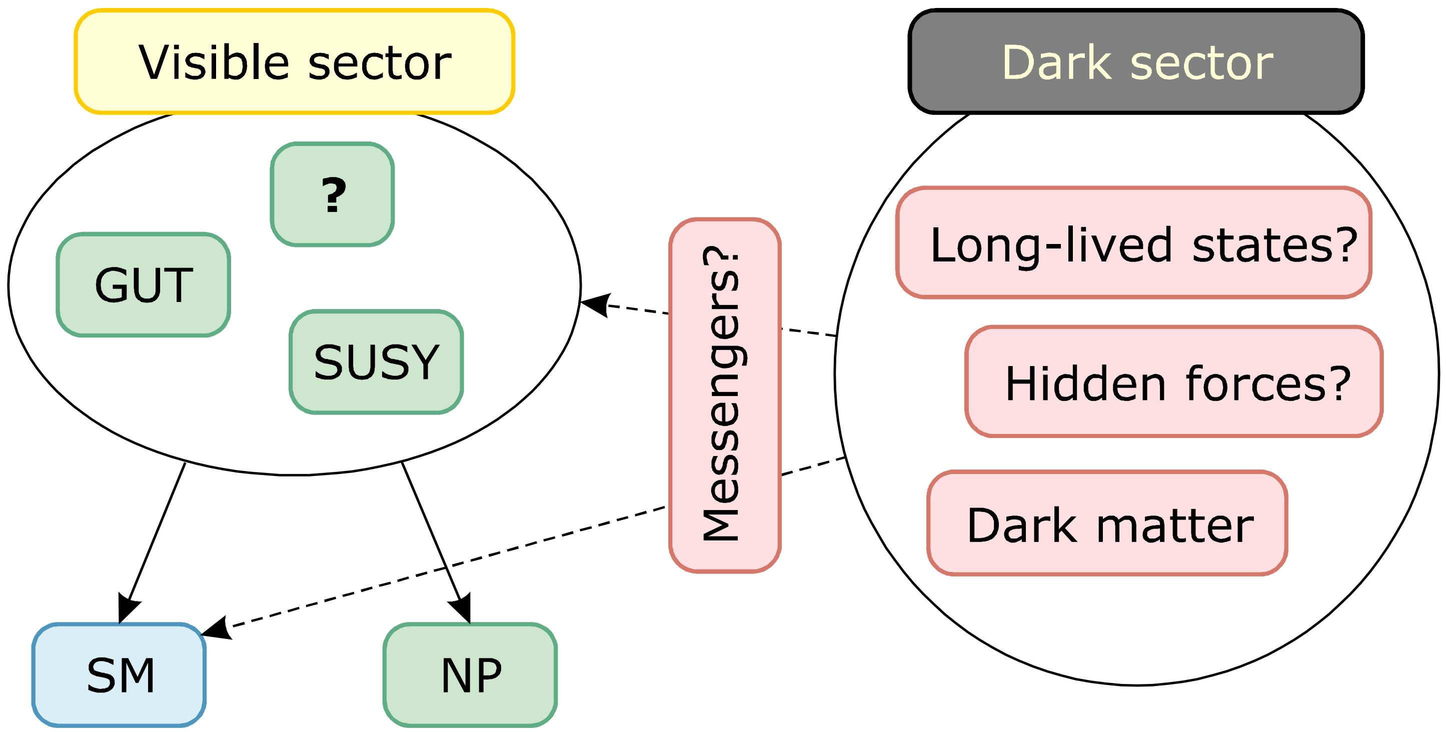
taken from C. Smith @ LPC - Clermont-Ferrand, 4/2012

- Heavy NP can be projected onto effective gauge-invariant operators built in terms of SM fields.

Buchmuller & Wyler, Nucl.Phys. B268 (1986) 621
Grzadkowski et al., arXiv:1008.4884

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i + \ldots$$

How to probe low-energy particle content?



X = dark sector state connected to the SM, or a light messenger.

taken from C. Smith @ LPC - Clermont-Ferrand, 4/2012

- Take X as neutral, but include all possible interactions as SM gauge-invariant effective operators.

J. F. K. & C. Smith, 1111.6402

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2}Q_i + \ldots \qquad + \sum_{d\geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}}Q_i' + \ldots$$

How to probe low-energy particle content?

Assumptions about the dark state X :

- Not stable ⇒ No DM constraints.
- Long-lived ⇒ Escapes as missing energy.
- Weakly coupled ⇒ Does not affect SM processes.

⇒ Main impact is then to open new decay and production channels.

How to probe low-energy particle content?

Assumptions about the dark state X :

- Not
- Lor
- We

⇒ Ma

chann

m_X [GeV]	(decay probes)	(SM width suppression)
100	Higgs boson	loop, helicity, phase-space
10	Quarkonium	Zweig rule
	K & B FCNCs	loop, CKM
1	LFV	neutrino mass
0.1	Light mesons	loop, helicity
0.001	Orthopositronium	phase-space

How to probe low-energy particle content?

Assumptions about the dark state X :

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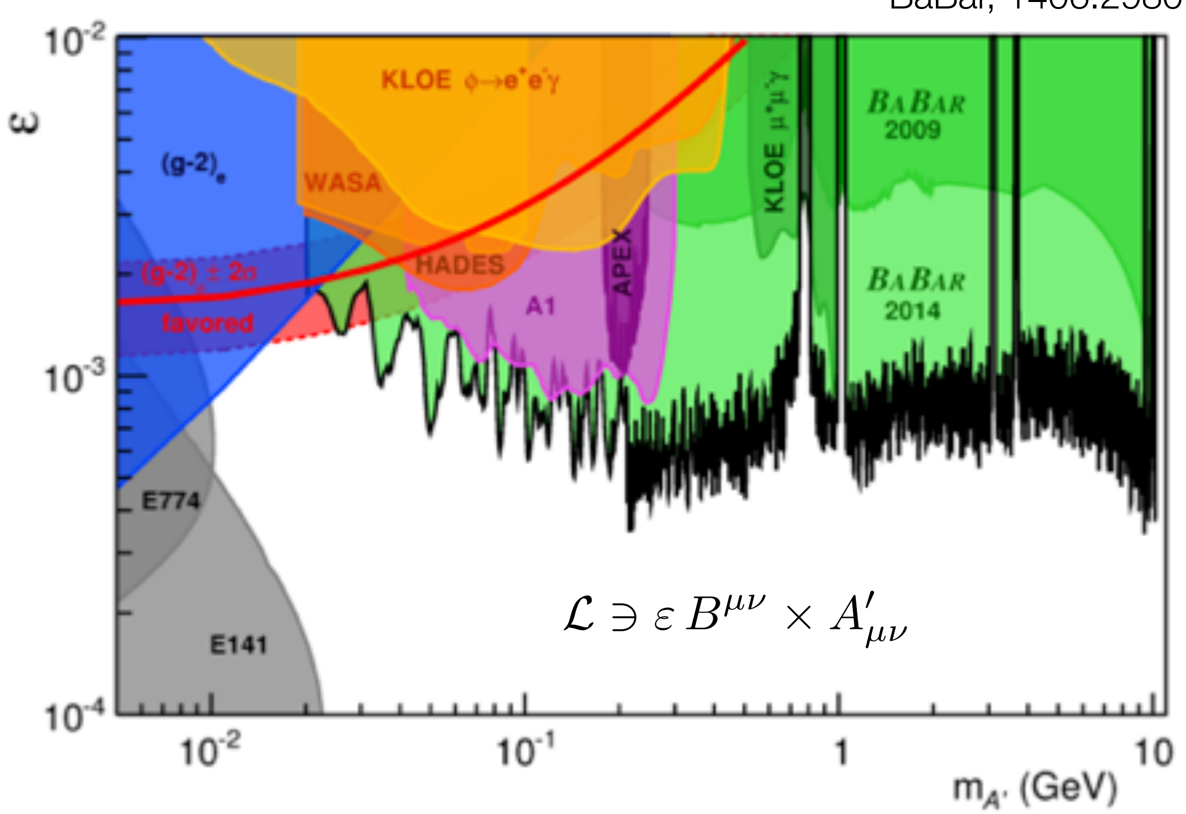
⇒ Ma

chann

m_X[GeV]	(decay probes)	(SM width suppression)
100	Higgs boson	loop, helicity, phase-space
10	Quarkonium	Zweig rule
1		
0.1		
0.001		

BaBar, 1406.2980



Recent example:
hidden photons
& $(g-2)_\mu$

How to probe low-energy particle content?

Assumptions about the dark state X :

- Not
- Lon
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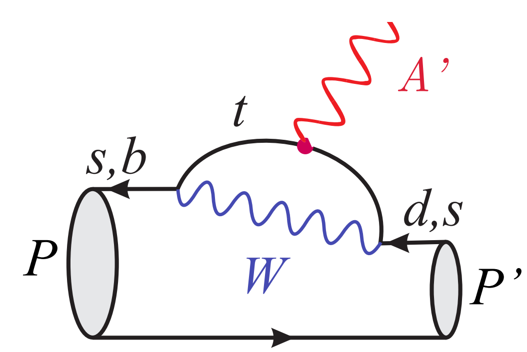
⇒ Ma

chann

m_X[GeV]	(decay probes)	(SM width suppression)
100	Higgs boson	loop, helicity, phase-space
10	Quarkonium	Zweig rule
1	K & B FCNCs	loop, CKM
0.1		
0.001		

Contributions to rare decays via heavy quark loops suppressed



$$\mathcal{B}(b \to sA') \simeq |\varepsilon|^2 \mathcal{B}(b \to s\gamma)^{\rm SM}$$

Recent example:
hidden photons
& $(g-2)_\mu$

How to probe low-energy particle content?

Assumptions about the dark state X :

- Not
- Lon
- We

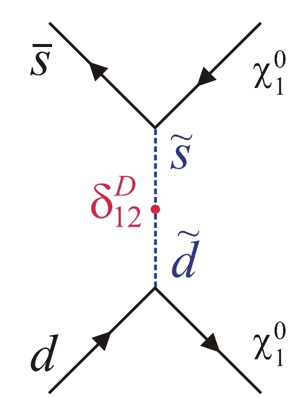
⇒ Ma

chann

	(decay probes)	(SM width suppression)
100	Higgs boson	loop, helicity, phase-space
10	Quarkonium	Zweig rule
1	K & B FCNCs	loop, CKM
0		
0.00		

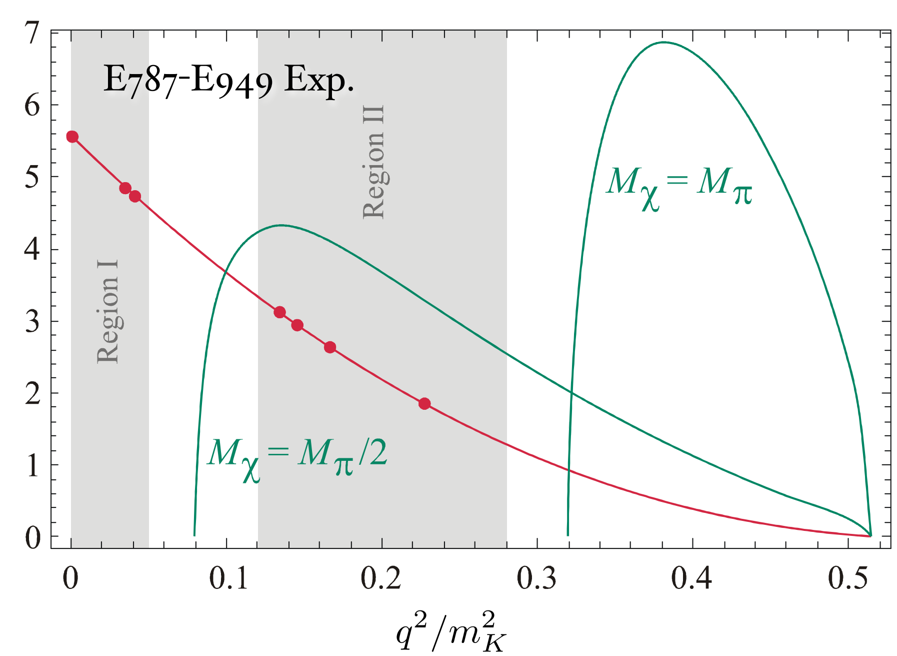
Example: light neutralino & down squark mixing in

$$K^+ \to \pi^+ \; E_{miss} \; (B \to X \; E_{miss}, \; \dots)$$



$[\bar{s}\gamma^\mu(1 \pm \gamma_5)d][\bar{\chi}\gamma_\mu\gamma_5\chi]$

$(\delta^{LL,RR})$



How to probe low-energy particle content?

Assumptions about the dark state X :

- Not
- Lon
- We

⇒ Ma

chann

E_{CMS}[TeV]	(production probes)	(main SM backgrounds)
	...	
0.2	t+E_{miss}	W+jets, $t\bar{t}$
	h+E_{miss}	hZ, ...
0.1	Z,W + E_{miss}	ZZ, ZW, ...
	jet(s)+E_{miss}	Z+jets
0.01	lepton(s)+E_{miss}	W→lν
	γ+E_{miss}	γZ,...

Andrea, Fuks & Maltoni, 1106.6199
J.F.K. & Zupan, 1107.0623
CDF, 1202.5653
Ezequiel et al., 1310.7600
Agram et al., 1311.6478
CMS-PAS-B2G-12-022

New flavor & DM dynamics at high pT

Conclusions

Success of SM in describing flavor-changing processes implies that large new sources of flavor symmetry breaking at TeV scale are mostly excluded.

However, NP at TeV scale need not be flavor trivial!

If (properly aligned) new sources of flavor breaking present

- Precision flavor observables may hide NP signals @10% level in well motivated NP models (natural SUSY)
- can significantly affect & guide NP searches high p_T
- have implications for EW fine-tuning

Worth to invest in searches of exotic flavor-violating effects

- Example: missing energy modes as portals to dark BSM sectors

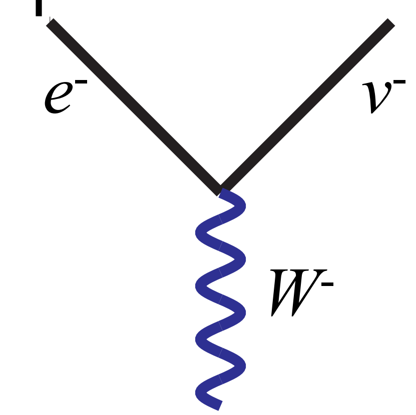
Thank you!

Backup

Flavor as guide to high p_T

LFU in (semi)leptonic B decays

In SM weak charged current interactions are lepton flavor universal



- Tested directly at colliders via *W* decays ~1%

Additional charged (scalar) interactions could induce LFU violation in processes at low energies

Can be predicted accurately even in hadronic processes, since most QCD uncertainties cancel in ratios

- Pion, kaon, *D* processes well consistent with LFU expectations ~(0.1-1)%

c.f. HFAG, 1010.1589

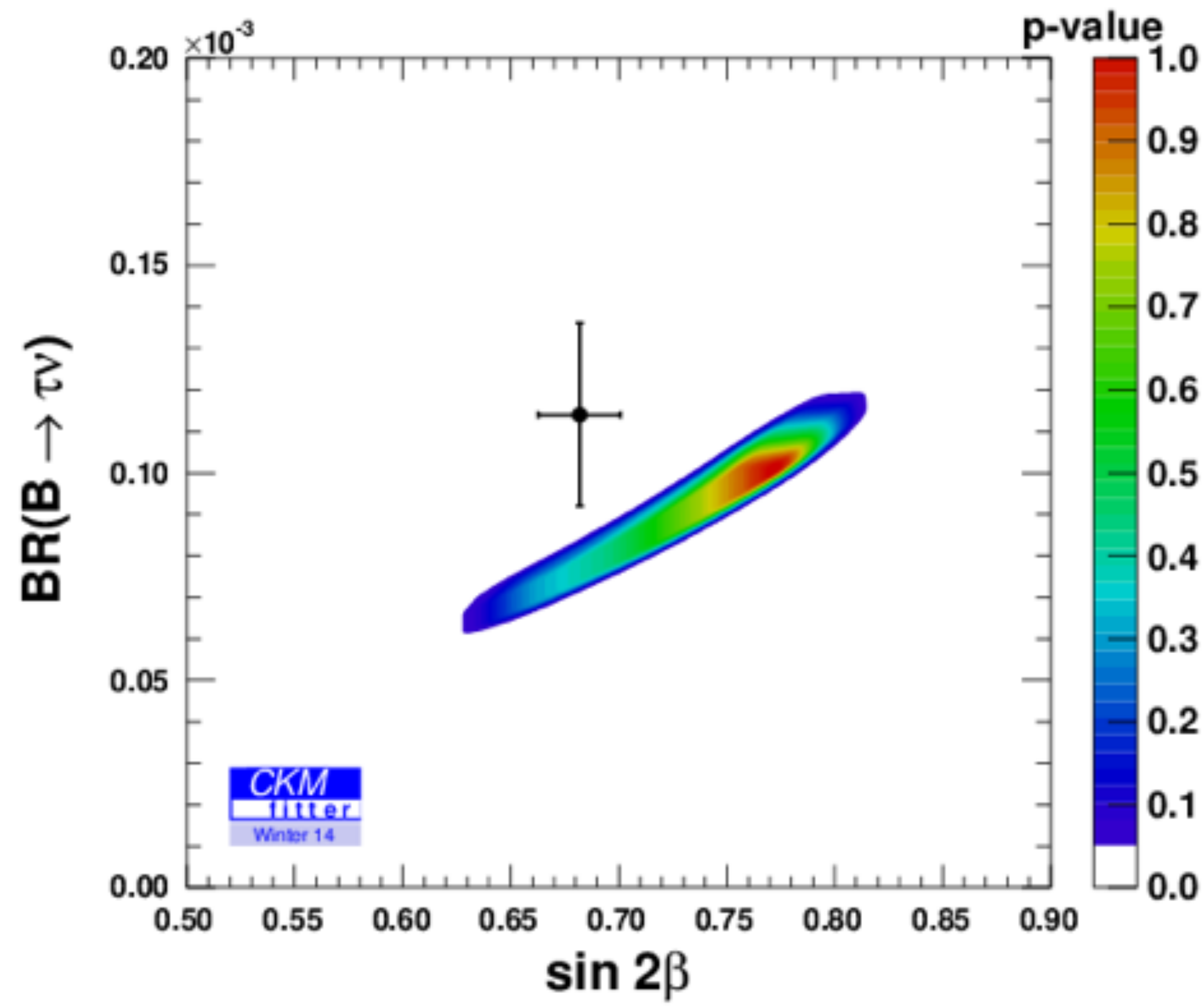
LFU in (semi)leptonic B decays

Apparent tension in global CKM unitarity fits

Discrepancy between $|V_{ub}|$ determinations see talks by Kwon, Bharucha

Most pronounced for taunic B decay

Somewhat reduced with updated Belle result Belle, 1208.4678



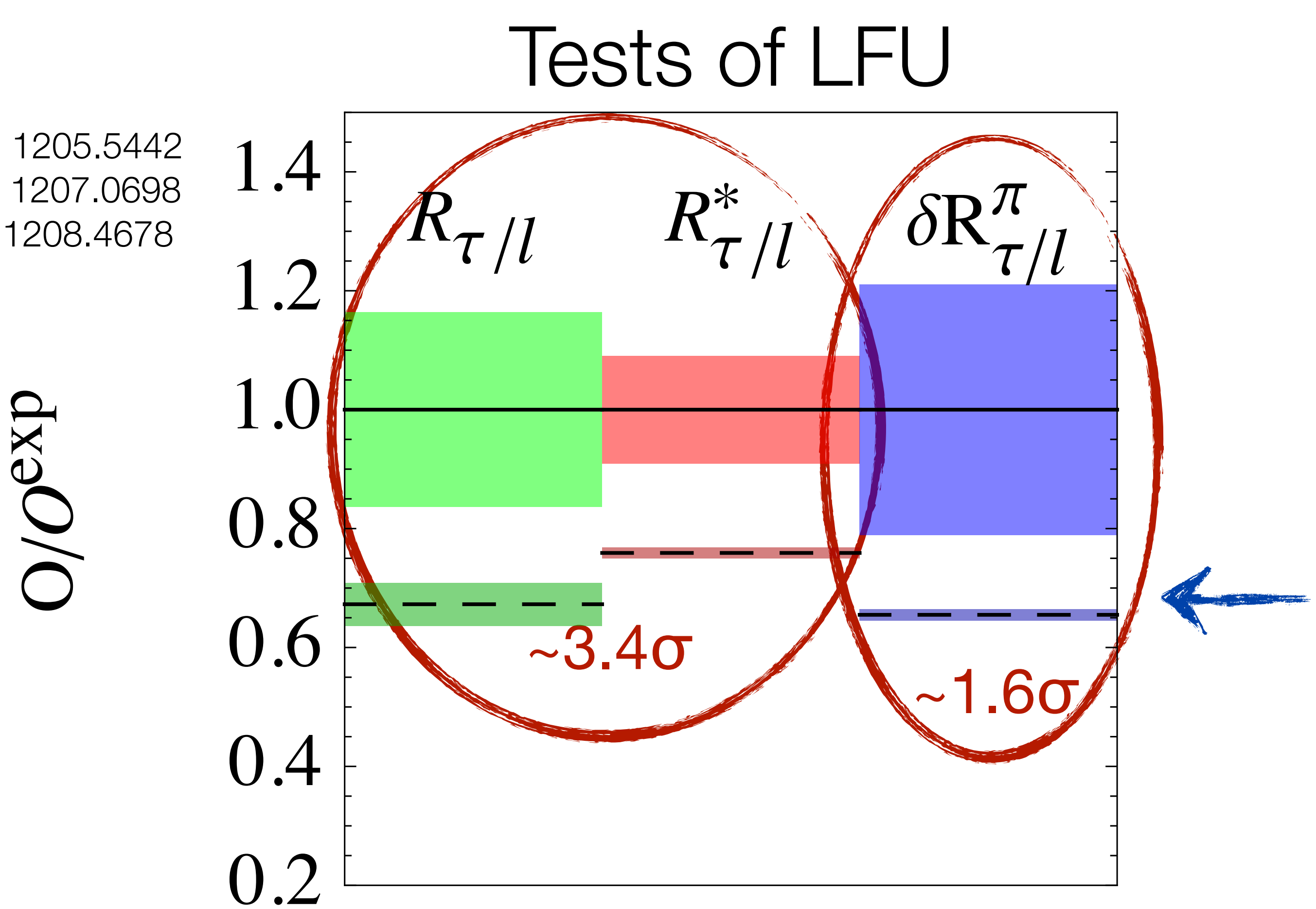
LFU in (semi)leptonic B decays

However, maybe not CKM issue at all

Can eliminate $|V_{ub}|$ in ratio $\Delta\mathcal{R}^{\pi}_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu})}{\Delta\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu})}$

Similarly in semitauonic decays $\mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$ $\mathcal{R}^*_{\tau/\ell} \equiv \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\ell\nu)}$

BaBar, 1205.5442
Babar, 1207.0698
Belle, 1208.4678



SM predictions very robust

Fajfer, J.F.K., Nisandzic,1203.2654
J.F.K. & Mescia, 0802.3790
Nierste, Trine & Westhoff, 0801.4938
Tanaka & Watanabe, 1005.4306
Becirevic, Kosnik, Tayduganov, 1206.4977
Bailey et al., 1206.4992
Khodjamirian et al., 1103.2655
Fajfer, J.F.K., Nisandzic & Zupan, 1206.1872

LFU in (semi)leptonic B decays

Can it be NP? Need to satisfy severe constraints:

- no tree-level down quark / charged lepton FCNCs
- no LFU violations in pion, kaon sectors

} require flavor alignment

Points towards low NP scale: $\Lambda \lesssim 100\,\mathrm{GeV}$ for $\mathcal{Q}_{AB}^{(6)} \sim V_{qb}[\bar{b}\,\Gamma_A q] \otimes [\bar{\nu}\,\Gamma_B \tau]$

Fajfer, J.F.K., Nisandzic & Zupan, 1206.1872

$$\mathcal{Q}_L = (\bar{q}_3 \gamma_\mu \tau^a q_3)\mathcal{J}^\mu_{3,a}\,, \qquad \mathcal{Q}_{LR} = i\partial_\mu(\bar{q}_3 \tau^a H b_R)\textstyle\sum_j \mathcal{J}^\mu_{j,a}\,,$$

$$\mathcal{Q}^i_R = (\bar{u}_{R,i}\gamma_\mu b_R)(H^\dagger \tau^a \tilde{H})\mathcal{J}^\mu_{3,a} \qquad \mathcal{Q}^i_{RL} = i\partial_\mu(\bar{u}_{R,i}\tilde{H}^\dagger \tau^a q_3)\textstyle\sum_j \mathcal{J}^\mu_{j,a}\,,$$

Predict effects in top physics

$$pp \to t E_T^{\mathrm{miss}}$$

Predict effects in Higgs physics

$$pp \to h\tau E_T^{\mathrm{miss}}$$