Xth Rencontres du Vietnam

Flavour Physics Conference

BSM physics driven by a possible solution of hierarchy problem at the electroweak scale

Jernej F. Kamenik

Univerza *v Ljubljani*

Institut “Jožef Stefan”

01/08/2014, Quy Nhon

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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

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Why flavor matters in the LHC era?

SM phenomenologically very successful

Most likely just (experimentally accessible) effective theory

Unification of interactions

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

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

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 additional terms in series

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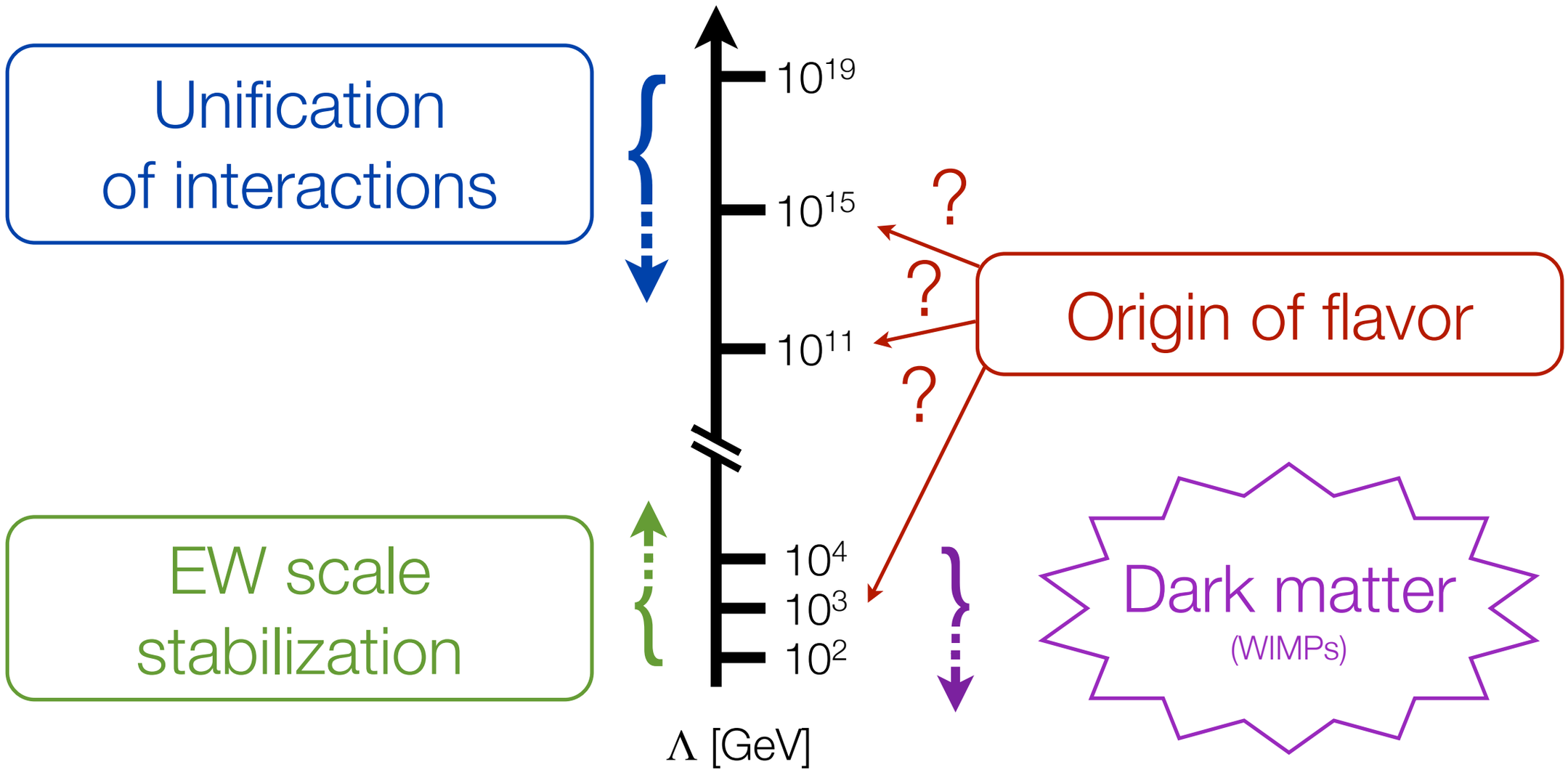
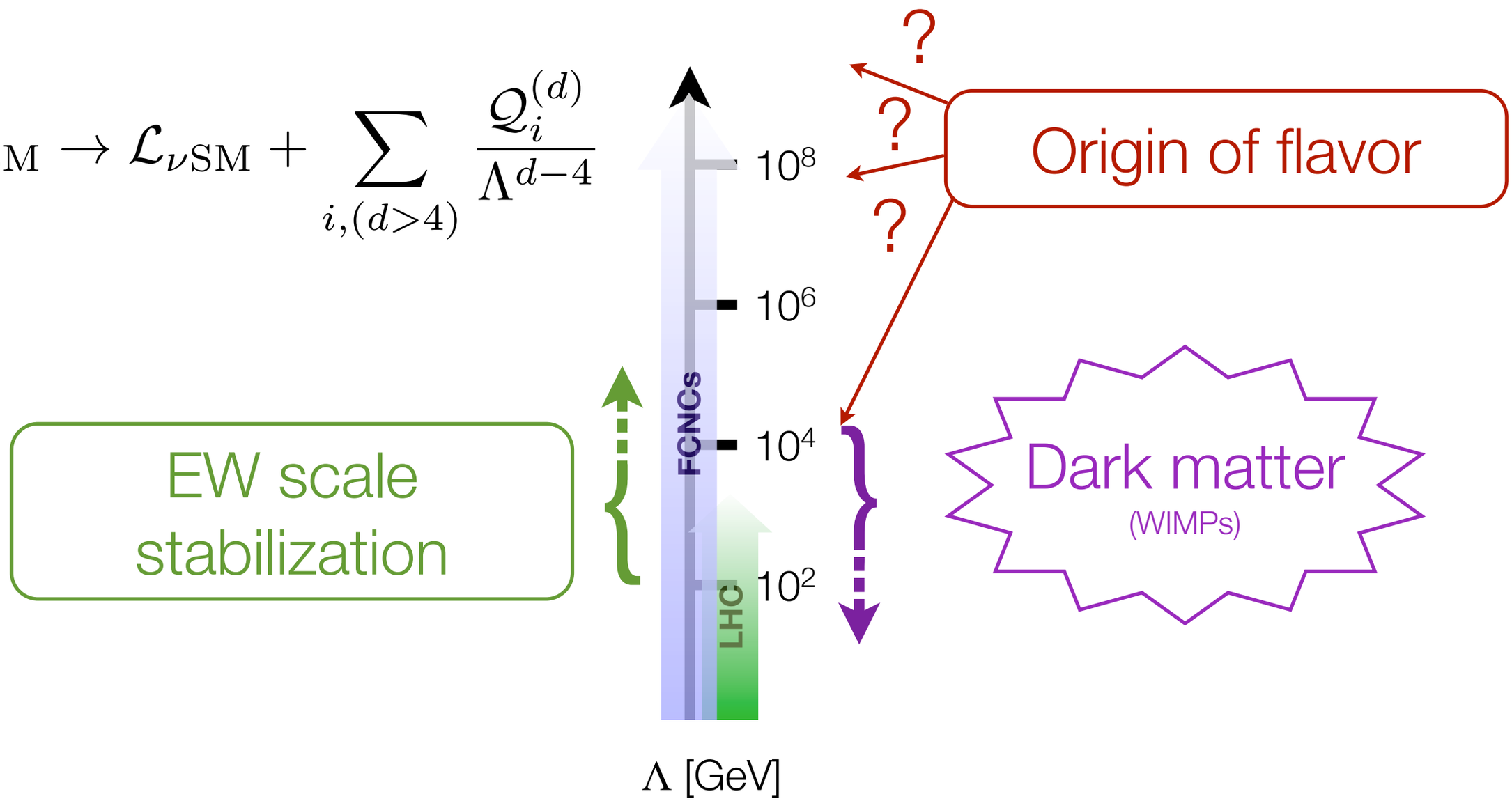


Why flavor matters in the LHC era?

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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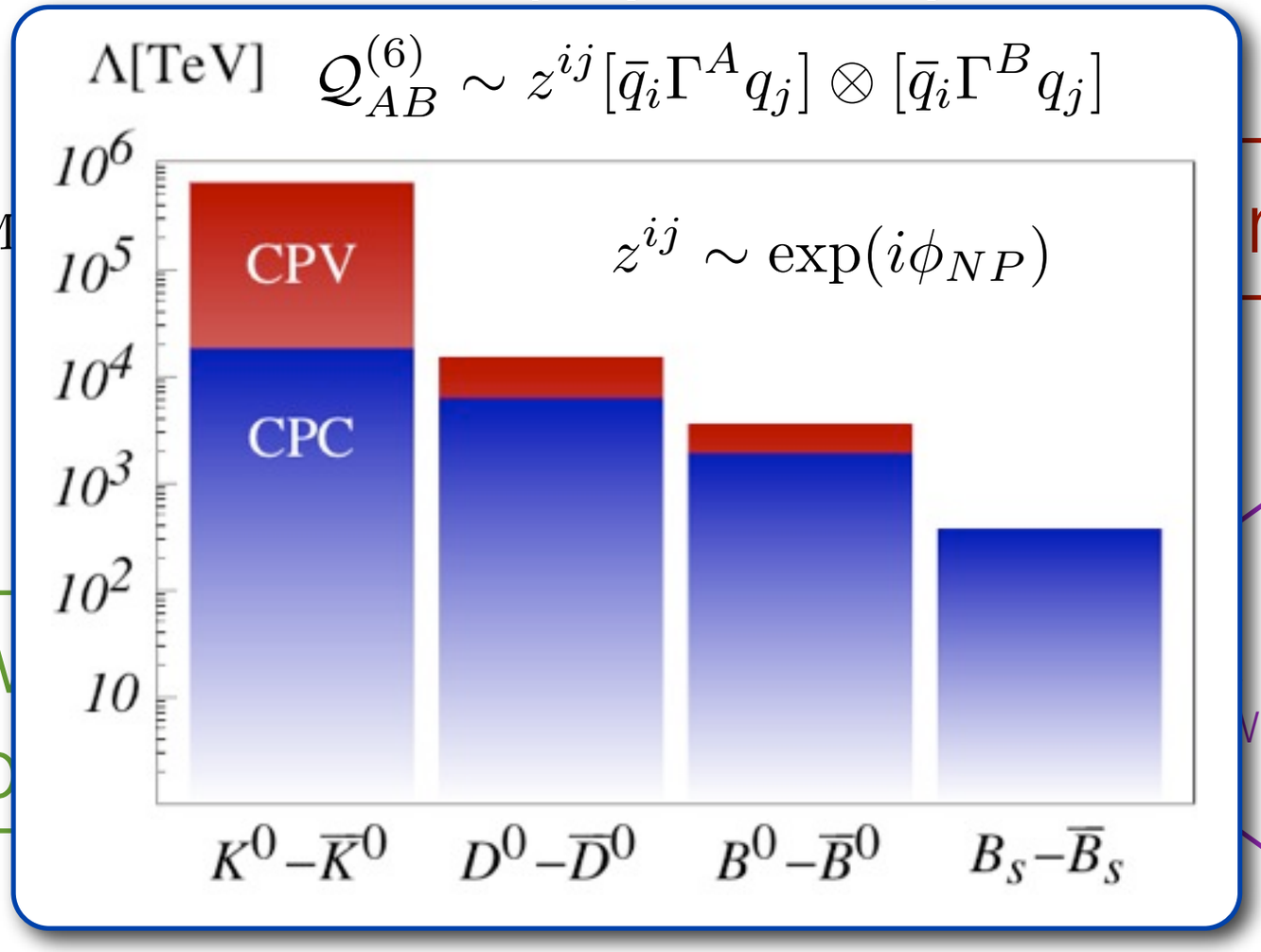


n of flavor

EW
stab

matter
VIMPs)

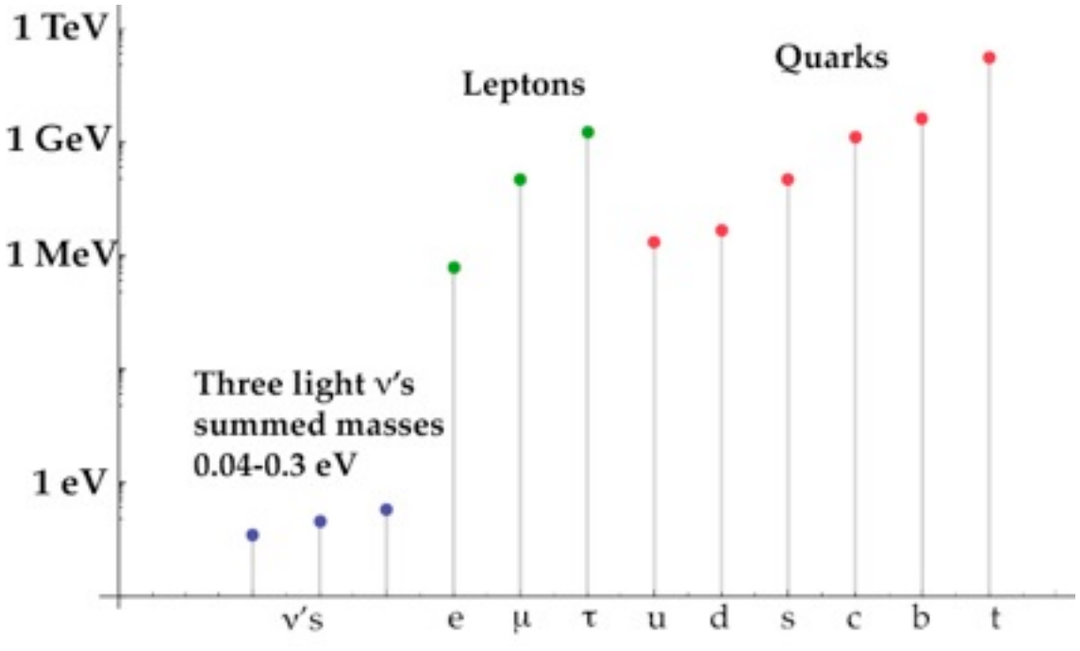
UTFit, 0707.0636
Isidori, Nir & Perez, 1002.0900
Lenz et al., 1203.0238
ETMC, 1207.1287

Why flavor matters in the LHC era?

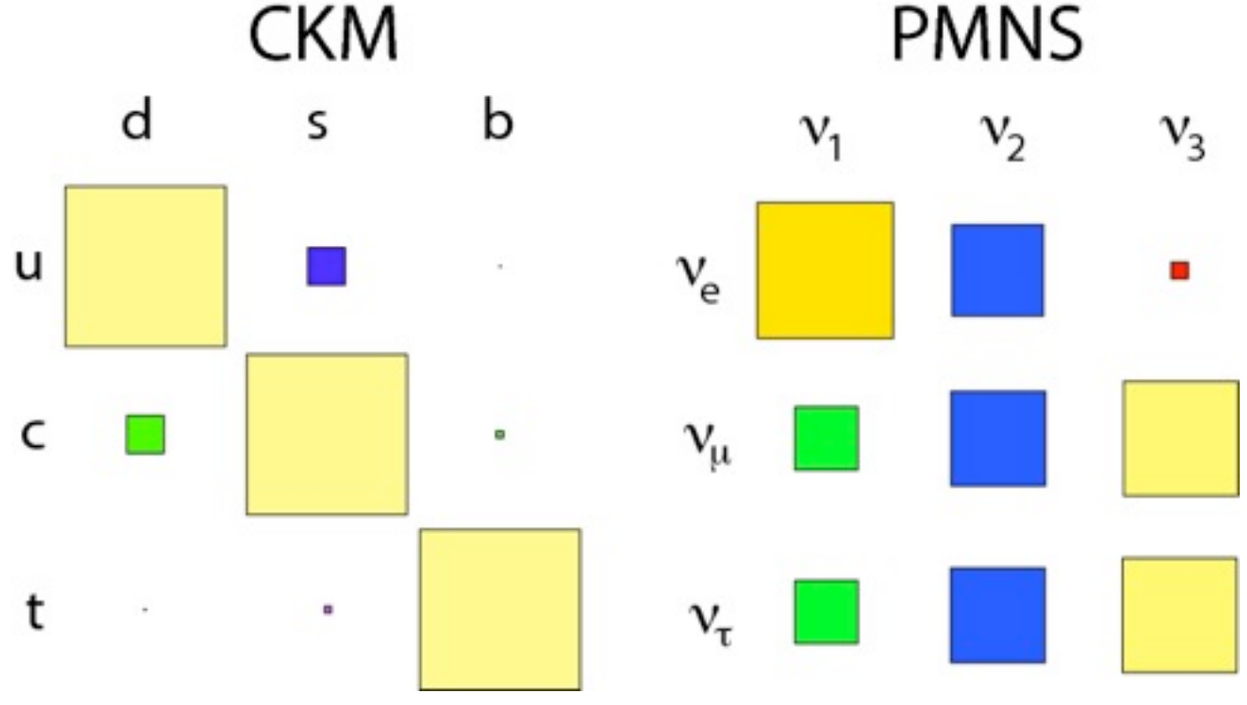
Twofold role of flavor physics

(2) Test sources of flavor symmetries & their violation

Suggestive pattern of masses and mixings



S. Stone, 1212.6374



Accidental? Dynamics? Symmetries?

Why flavor matters in the LHC era?

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(2) Test sources of flavor symmetries & their violation

In SM flavor only broken by Higgs interactions

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

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

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tries & their violation

gs interactions

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

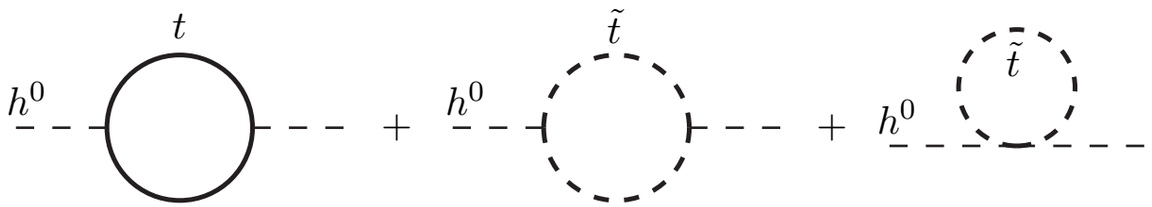
Flavor breaking

may or may not be related to

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



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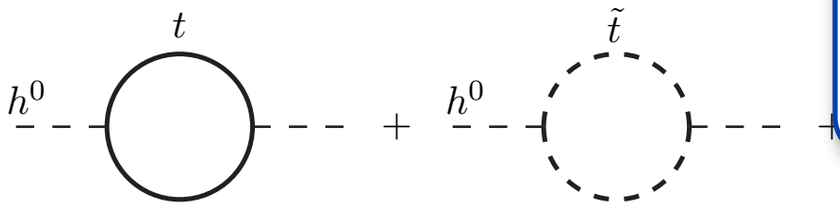
<u>Example 1: MSSM</u>

New flavor sources from SUS
- squark, slepton masses & t

Radiative EWSB from flavor e
- Higgs mass term driven neg
Yukawa RGE



tries & their violation

<u>Example 2: composite pseudo-Goldstone Higgs</u>

New flavor sources from partial compositeness
- mixing with heavy vector-like fermions

Radiative EWSB from flavor effects
- Goldstone shift symmetry broken by top Yukawa

. . .

to

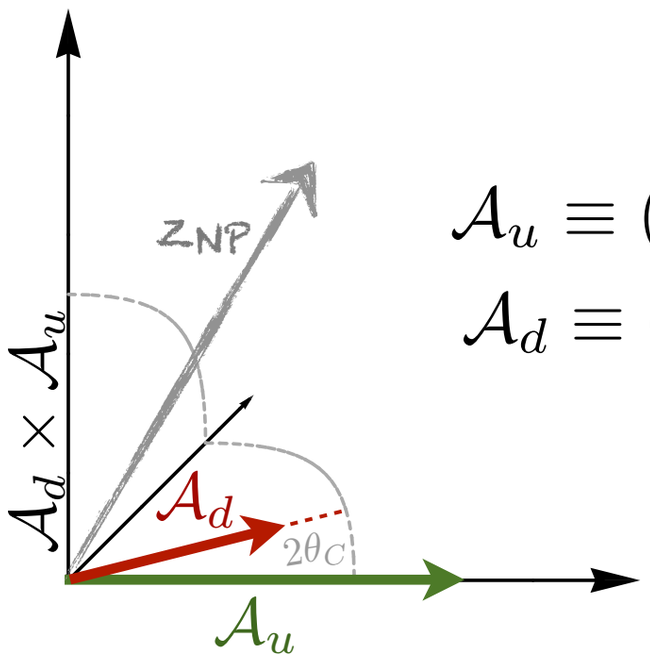
Why flavor matters in the LHC era?

Twofold role of flavor physics

(2) Test sources of flavor symmetries & their violation

Global flavor symmetry of SM broken by Yukawas:

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



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

SM contributions highly hierarchical & aligned

⇓

Severe constraints on generic BSM sources

Why flavor matters in the LHC era?

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Global flavo awas:

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

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aligned

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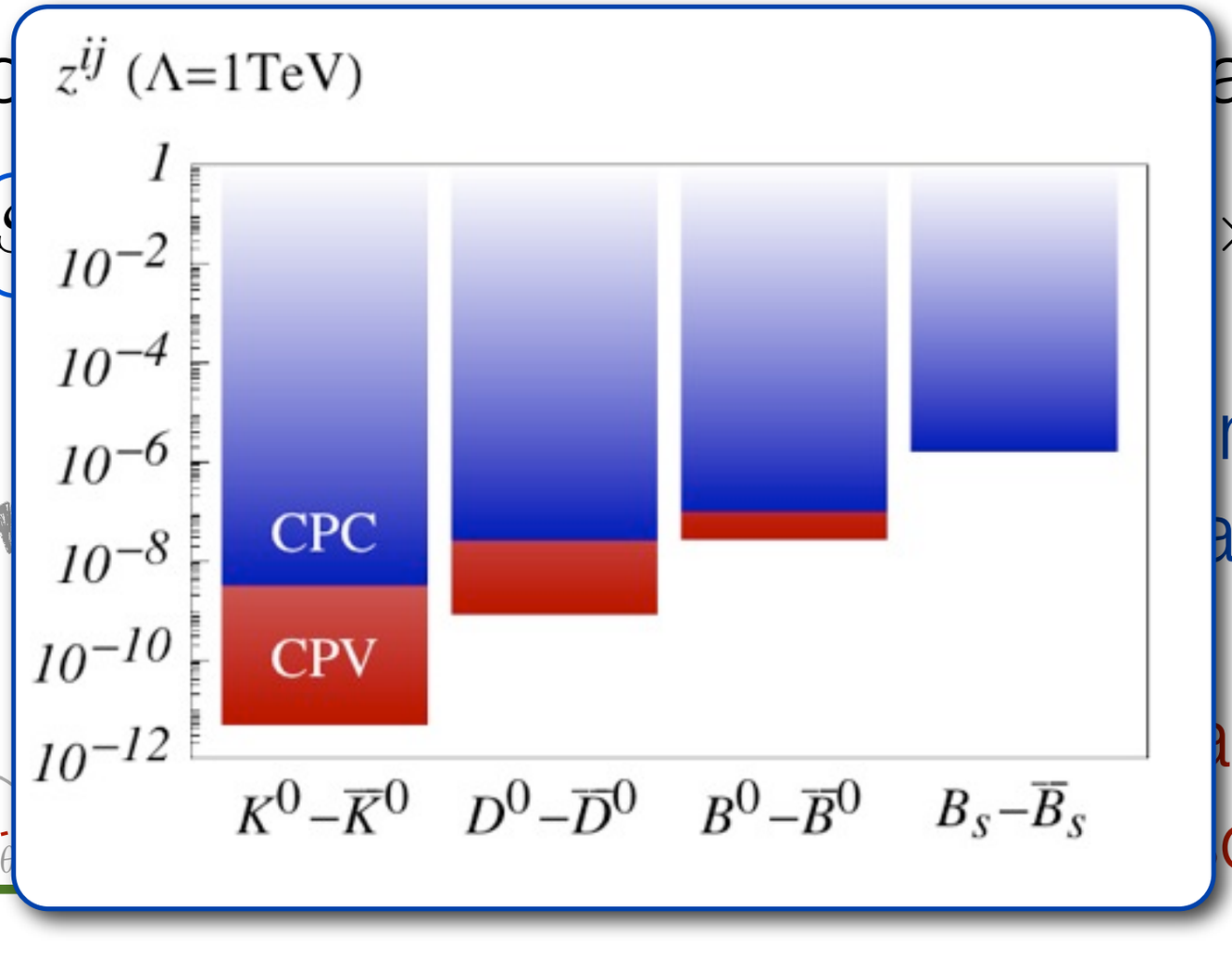

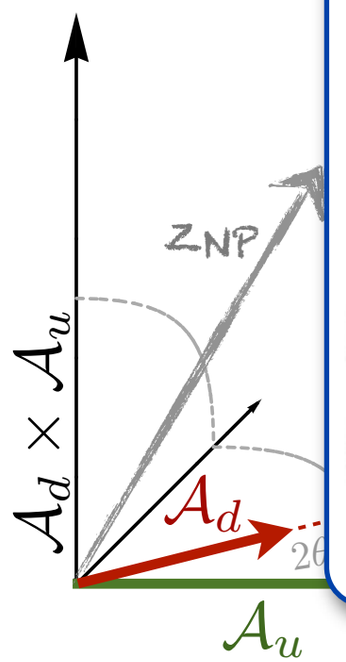

Reclaiming flavorful NP at EW scale

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Global flavor symmetry of SM broken by Yukawas:

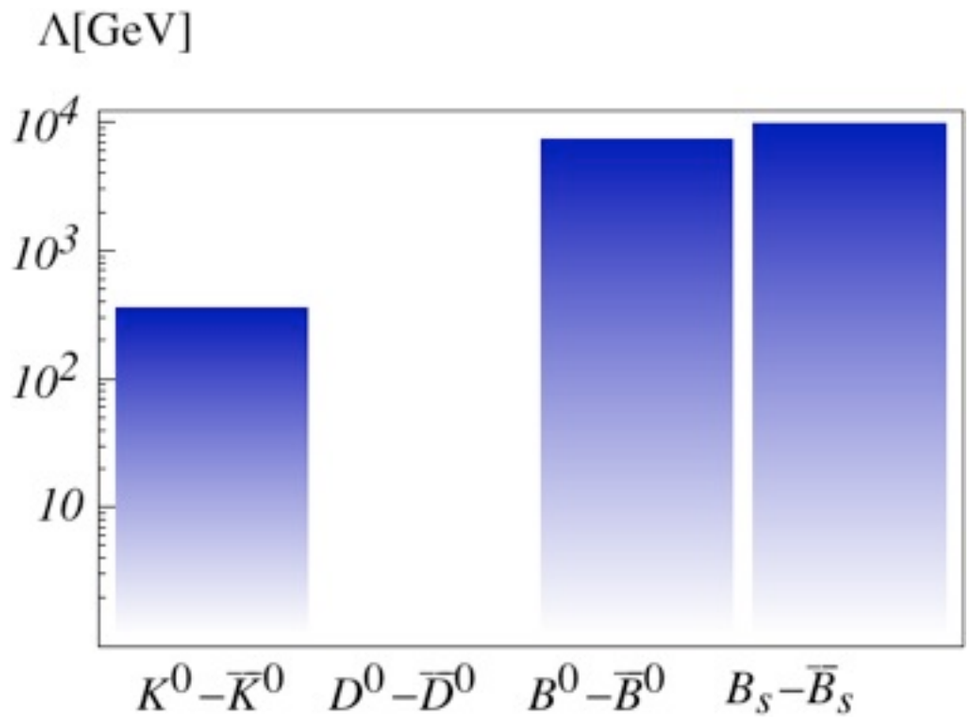
$$G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$

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

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

$a_{i>2} \lesssim a_{1,2}$ "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

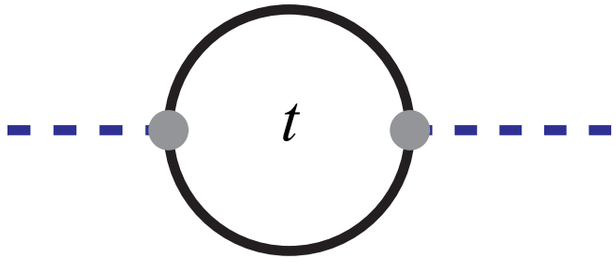
⇓

probe EW scale masses

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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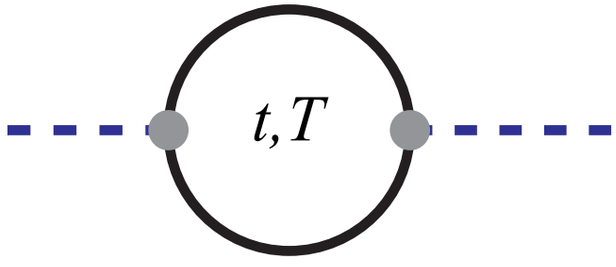
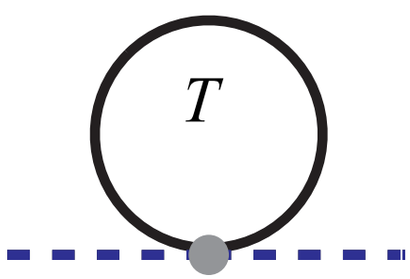


$$\delta m_h^2 \sim \frac{m_t^2}{v^2}\Lambda^2 + \frac{m_t^2}{v^2} m_T^2 \log\frac{\Lambda^2}{m_T^2} + \dots$$



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

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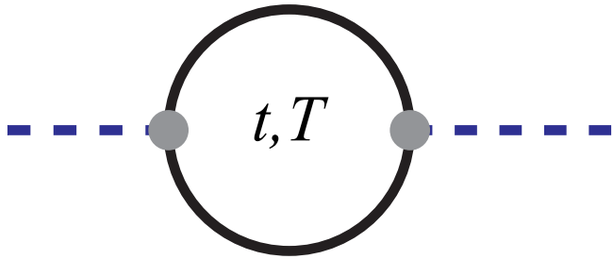

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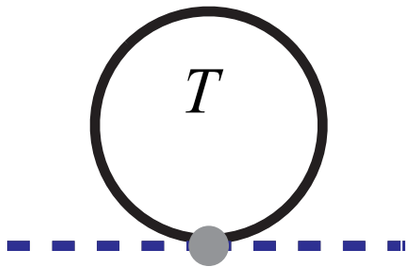
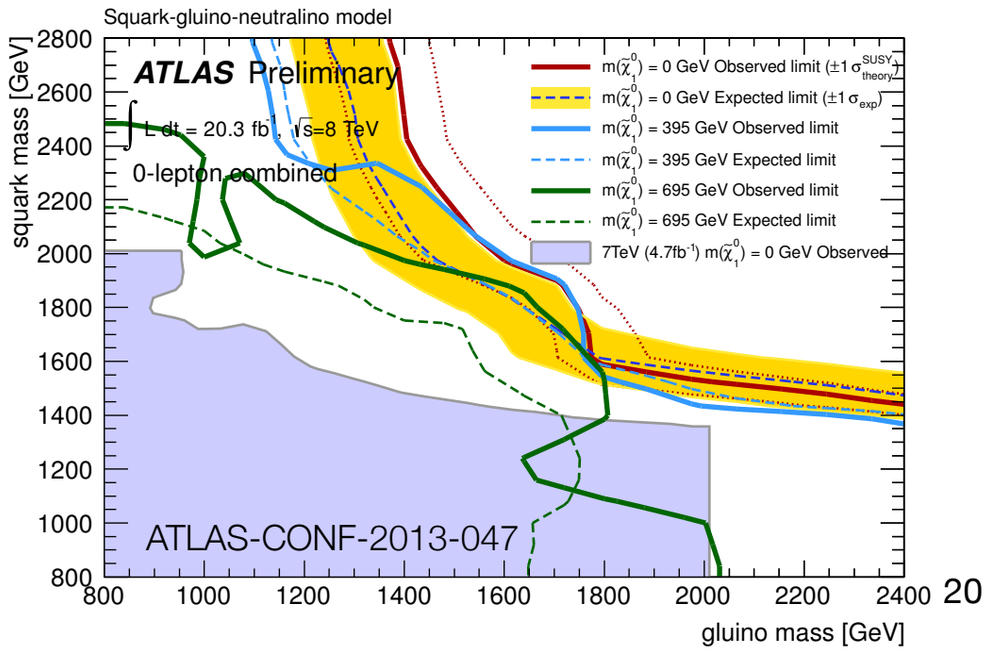


prefer light top partners ($m_T < 1\text{TeV}$)

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:

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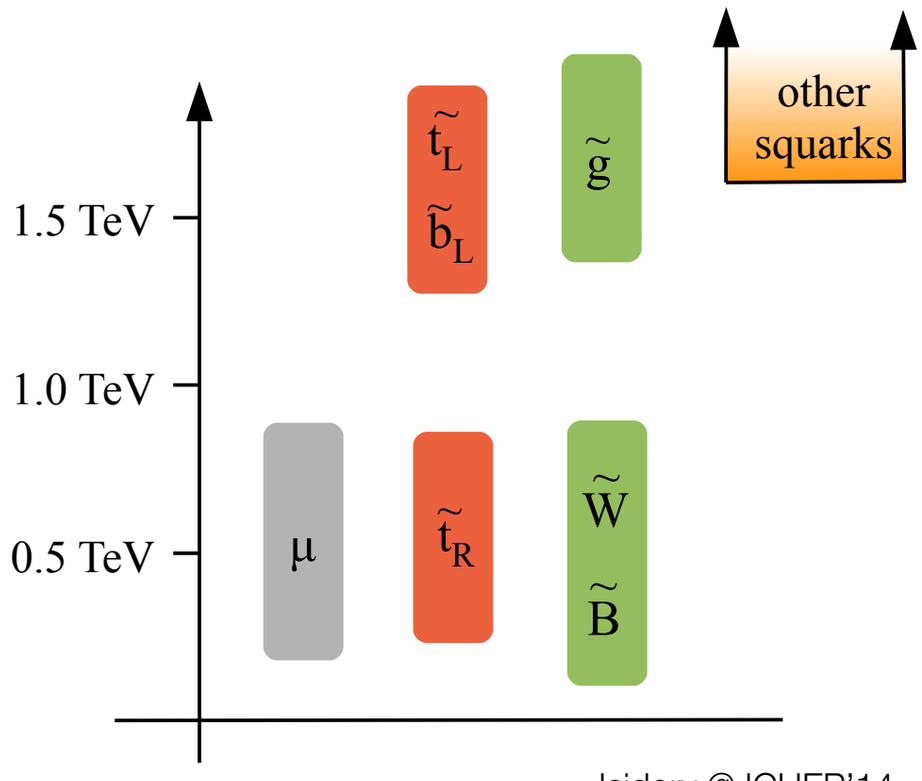

Isidory @ ICHEP'14

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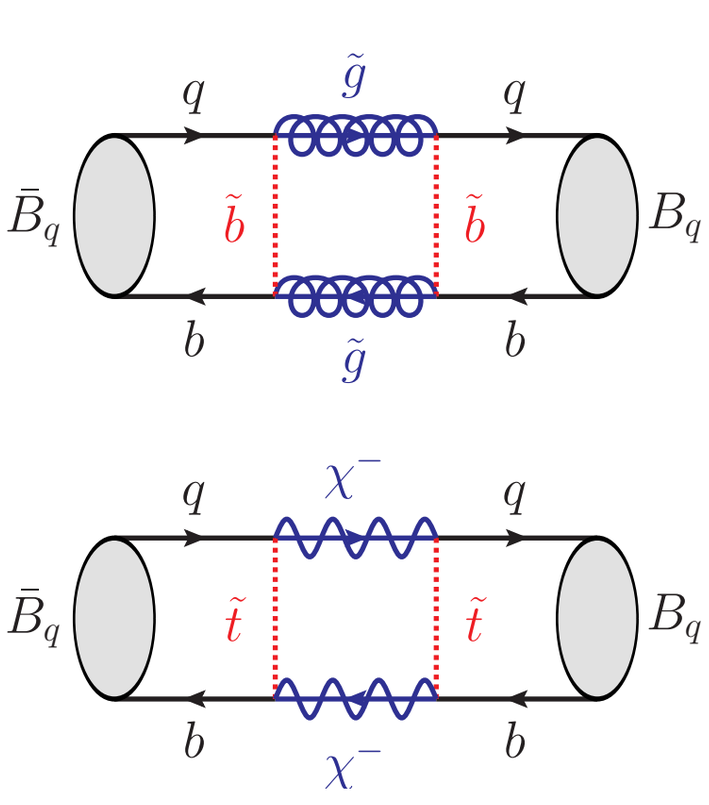
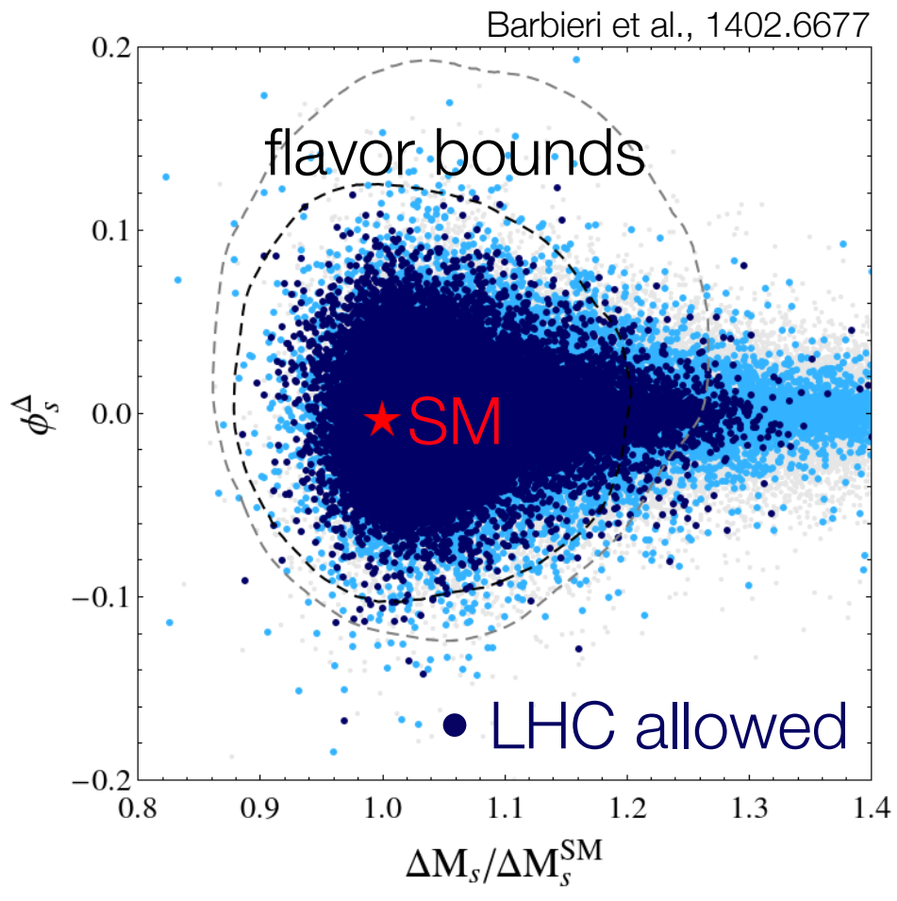
Exa

BSM
gene

Key

- (C
- R
- L





et al., 0903.1794
bach, 1206.3878
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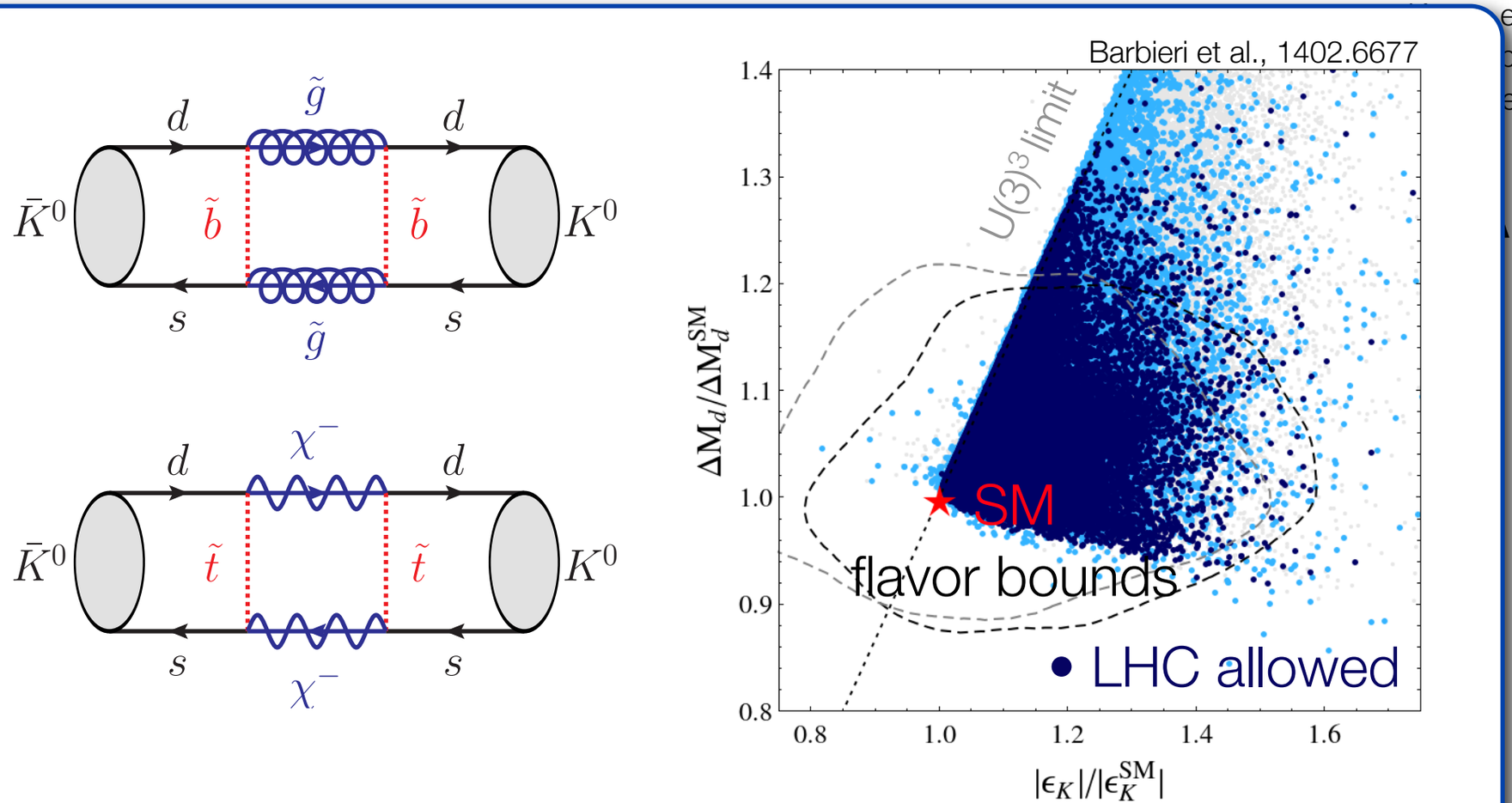

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Example: natural SUSY

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

Key observables:

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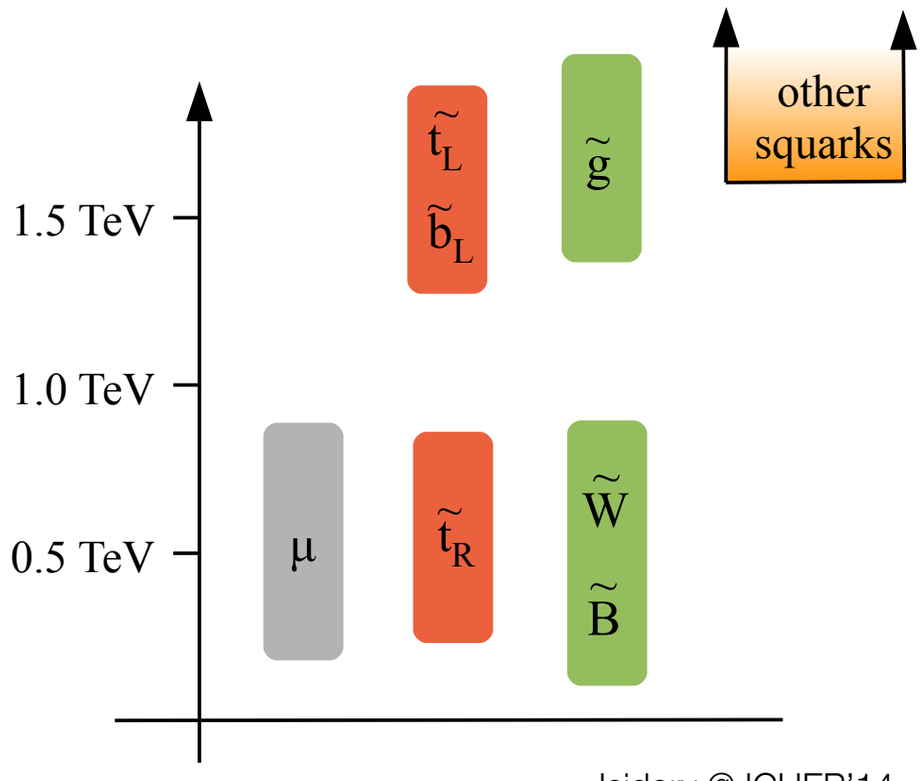

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Key

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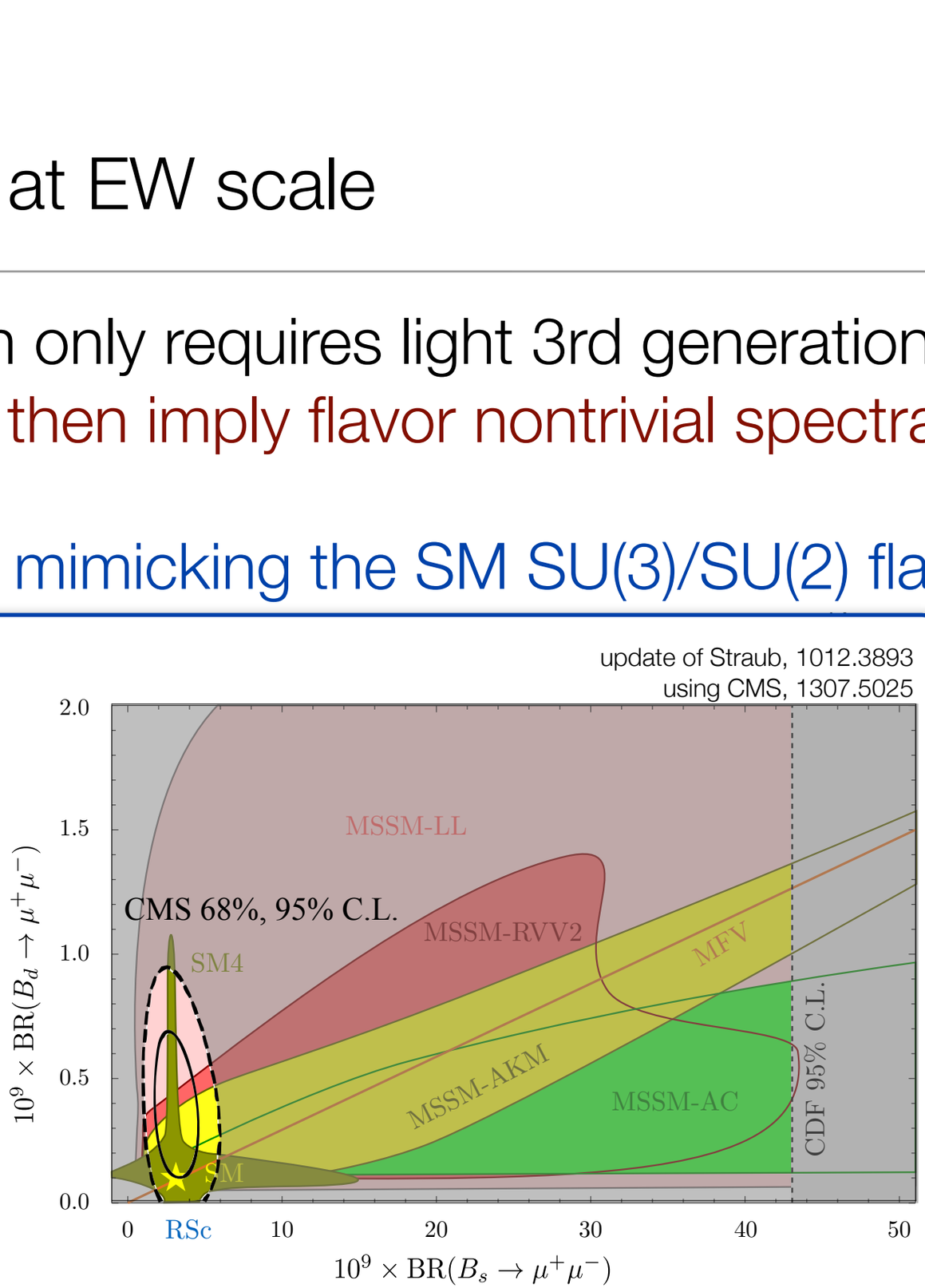
Nontrivial test of MFV.

Hurth et al., 0807.5039

update of Straub, 1012.3893
using CMS, 1307.5025



In the future also with $B \to K\nu\nu$, $K \to \pi\nu\nu$!

al., 0903.1794
ch, 1206.3878
al., 1105.2296
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ACME, 1310.7534

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Barbieri et al., 1402.6677

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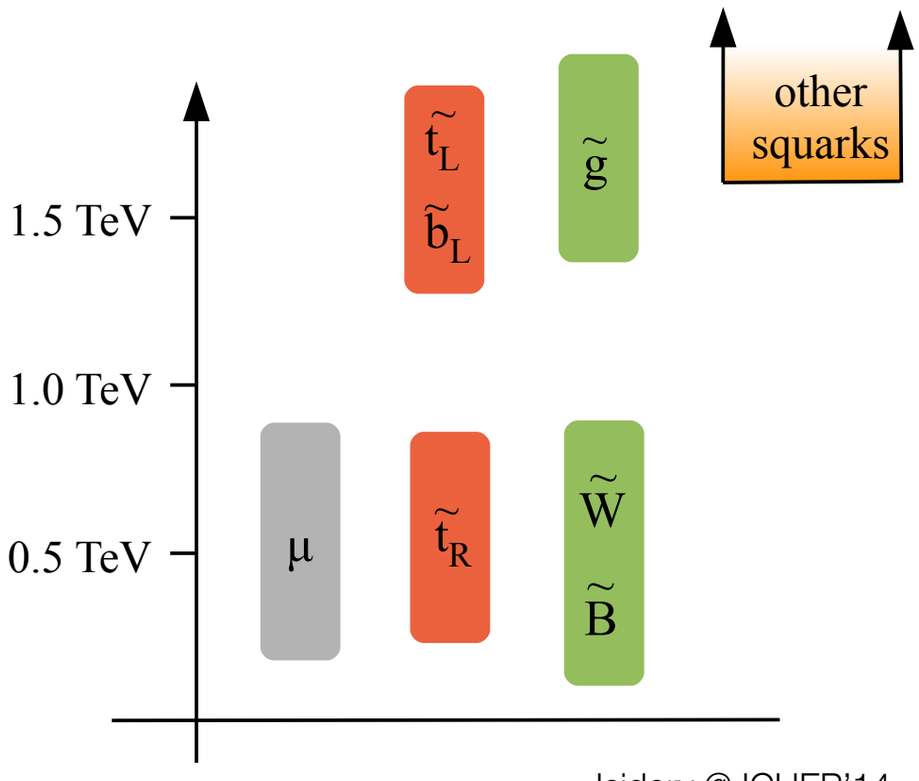

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Possible in flav… 2) flavor breaking patter…

Kagan et al., 0903.1794
…as & Girrbach, 1206.3878
Barbieri et al., 1105.2296
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other quarks

Example: natur…

BSM flavor effects … generation squark…

Key observables:

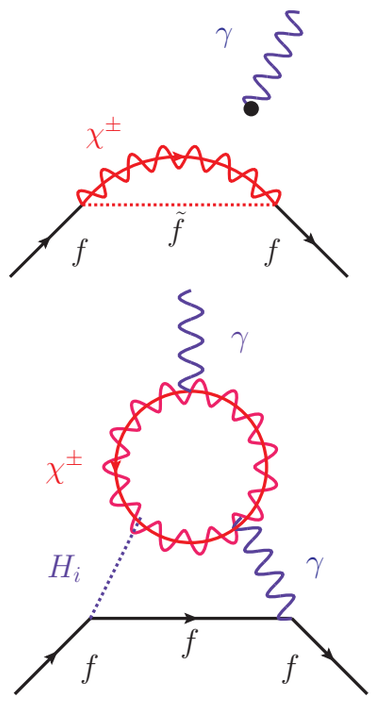
- (CPV) in K(ε_K), …
- Rare B decays …
- LFV & EDMs

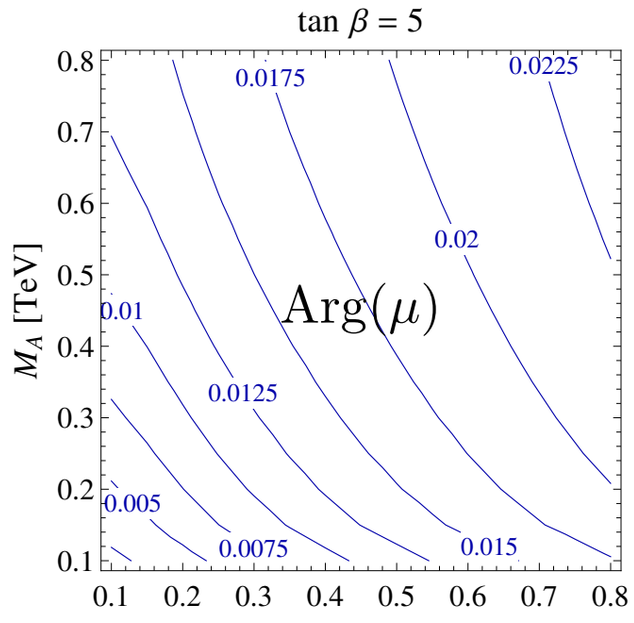
ACME, 1310.7534

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

⇒ Bounds Higgsino & sneutrino parameters

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





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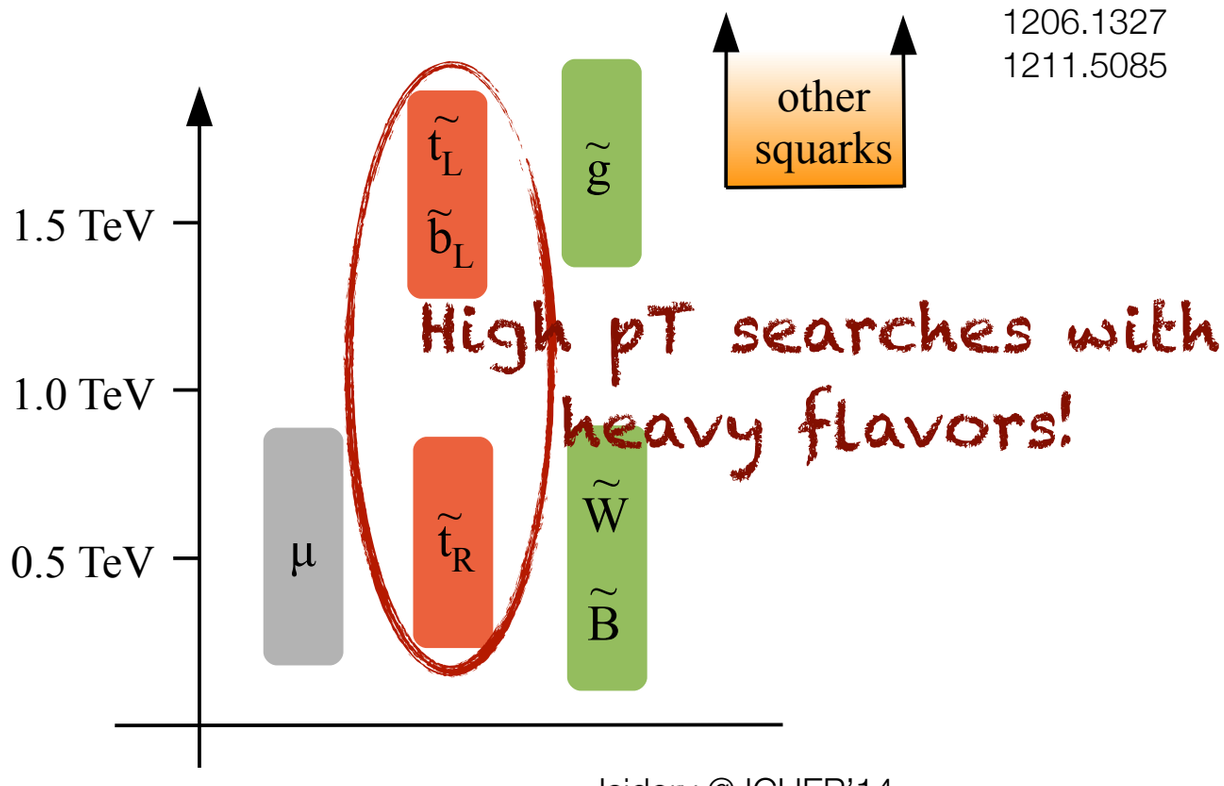

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Reclaiming flavorful NP at EW scale

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

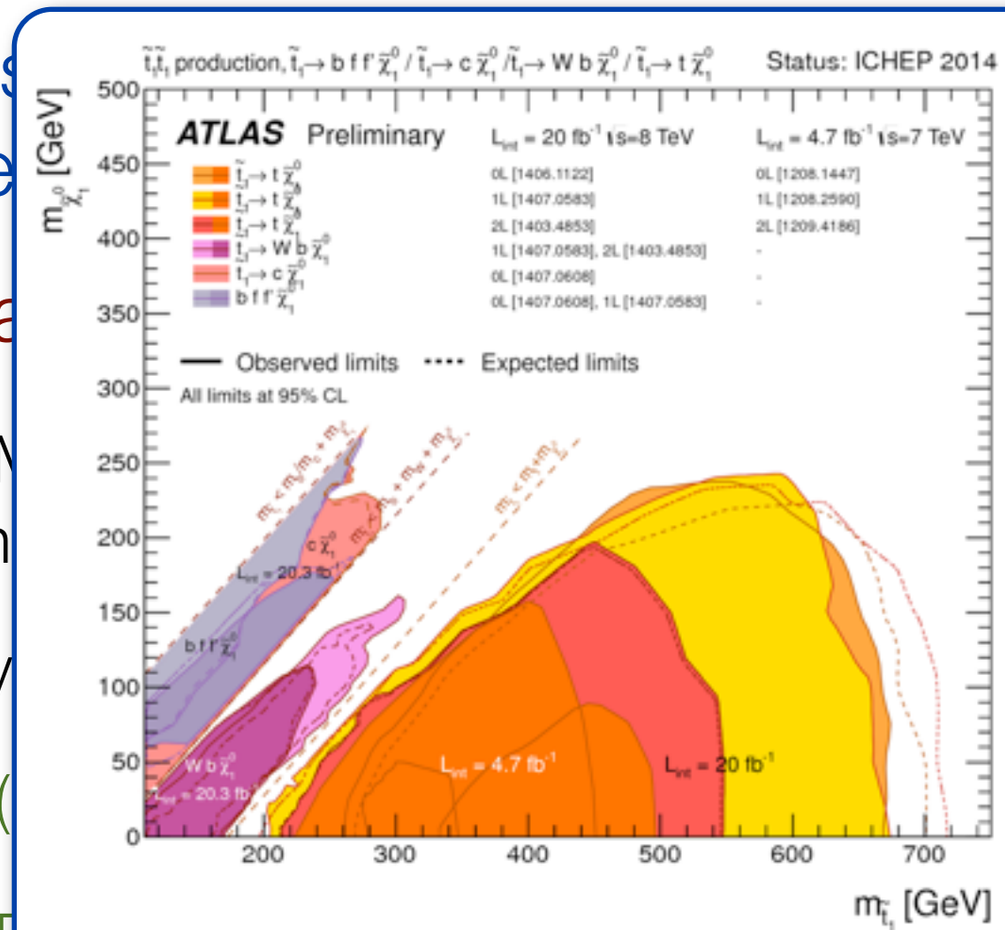
Pos… bre…

Exa…

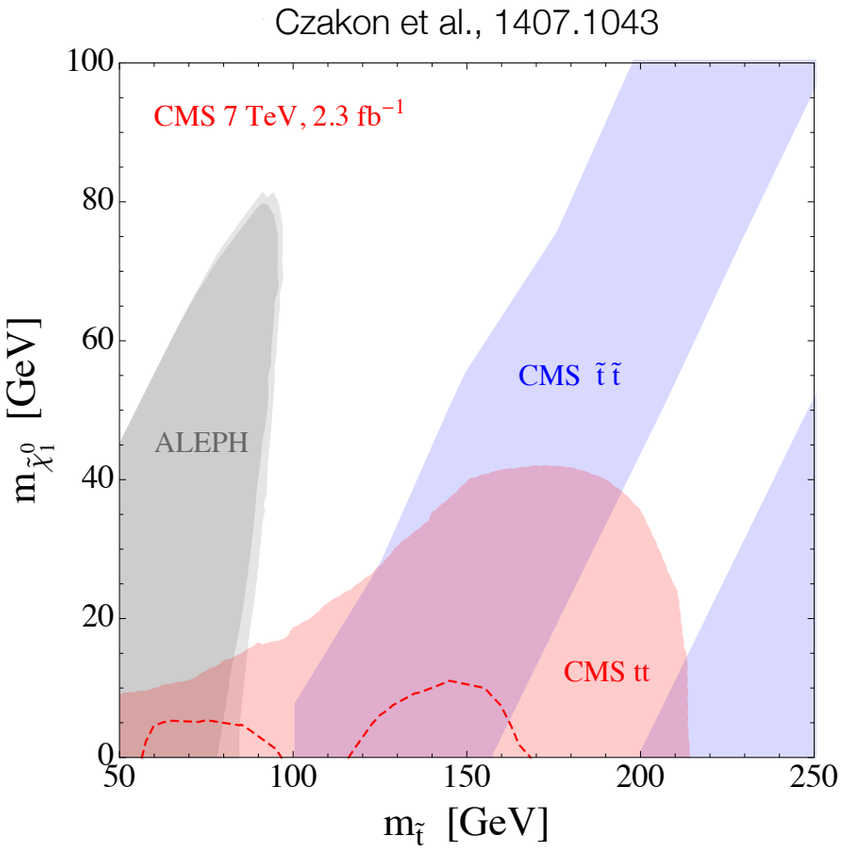
BSM… gen…

Key…

- (…
- F…
- LFV & EDMs



Czakon et al., 1407.1043



see also ATLAS, 1406.5375

…vor
…al., 0903.1794
…ach, 1206.3878
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1206.1327
1211.5085

…nes with …vors!

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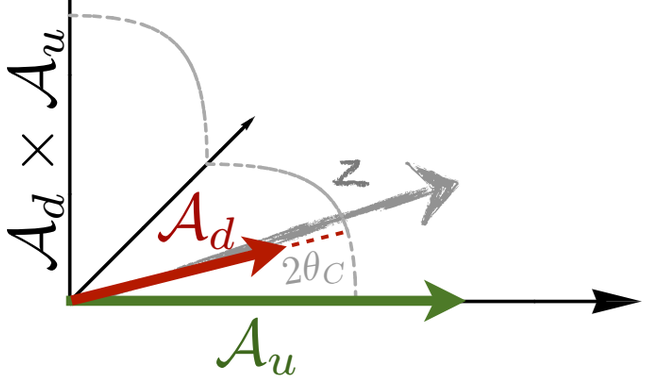
Alternatively, align SM & NP flavor breaking

Can use abelian flavor symmetries

Nir & Seiberg, hep-ph/9304307

$[\mathbf{z}, \mathcal{A}_d] \sim 0$

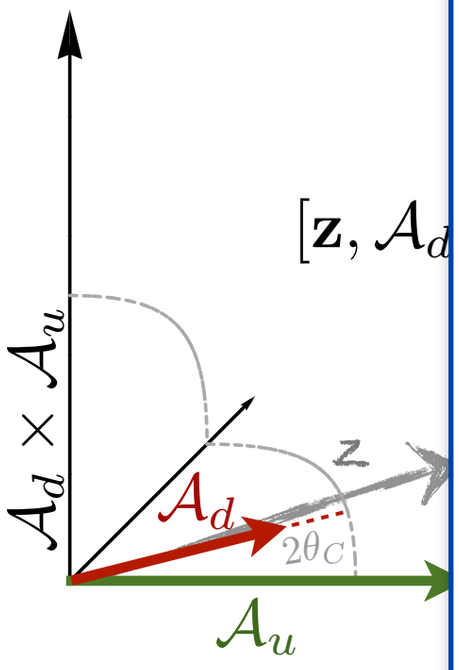


CPV in light quark FCNCs automatically suppressed

Reclaiming flavorful NP at EW scale

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

Alternatively, a



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r & Seiberg, hep-ph/9304307

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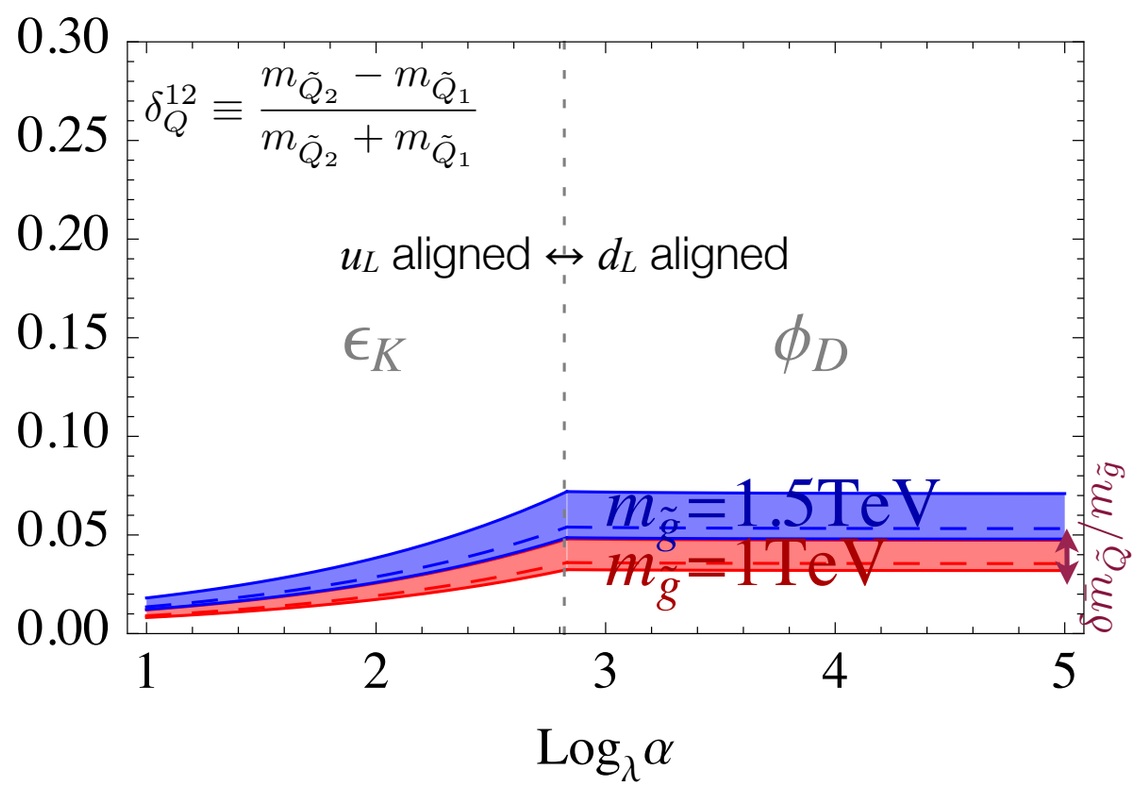

Assuming maximal CPV

Blum et al., 0903.2118

Reclaiming flavorful NP at EW scale

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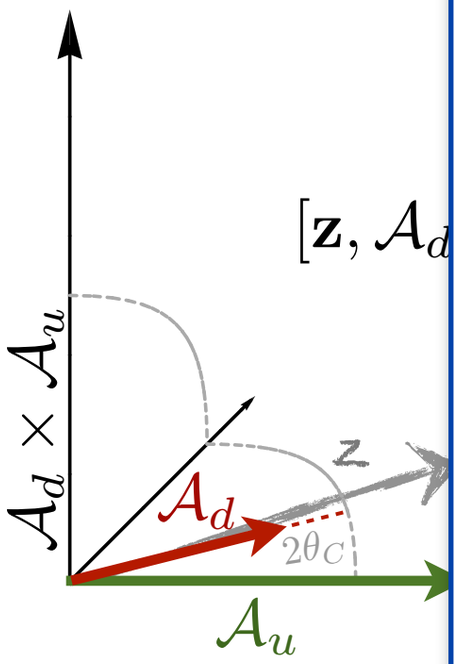
Alternatively, a



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r & Seiberg, hep-ph/9304307

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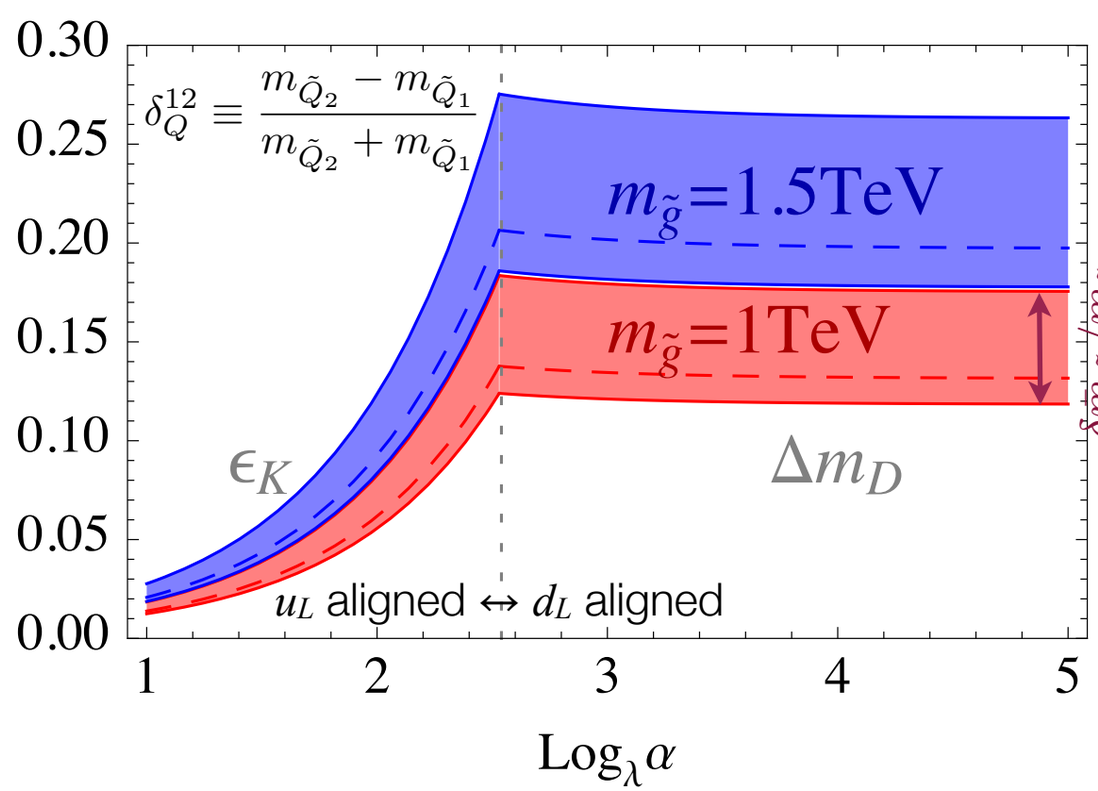


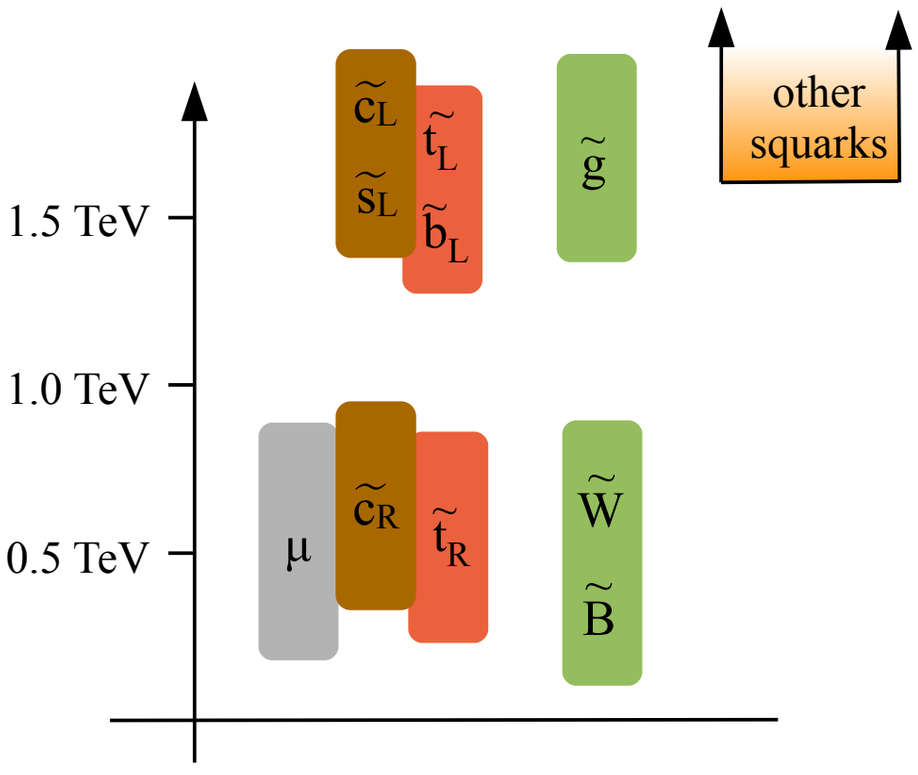
Assuming realistic CPV

Gedalia, J.F.K, Ligeti & Perez 1202.5038

Reclaiming flavorful NP at EW scale

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

Alternatively, align SM & NP flavor breaking



Can use abelian flavor symmetries

Nir & Seiberg, hep-ph/9304307

CPV in light quark FCNCs automatically suppressed

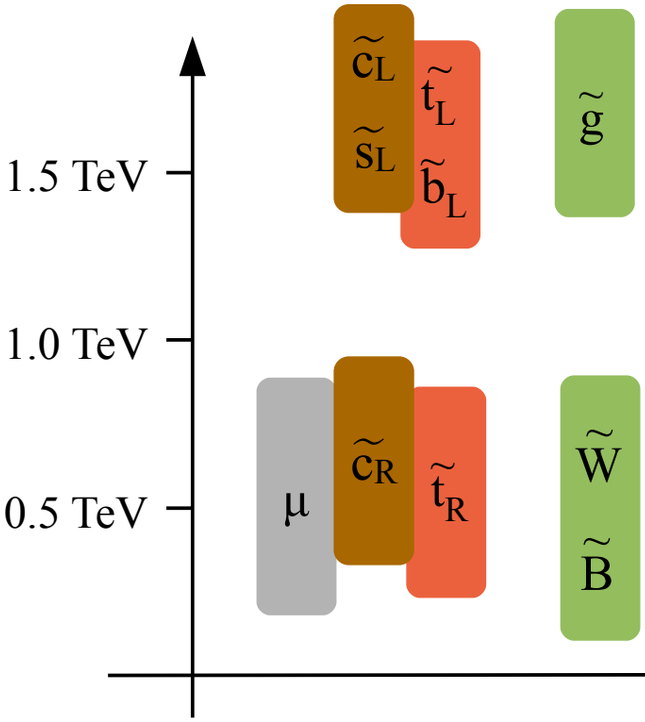
Gedalia, J.F.K, Ligeti & Perez 1202.5038

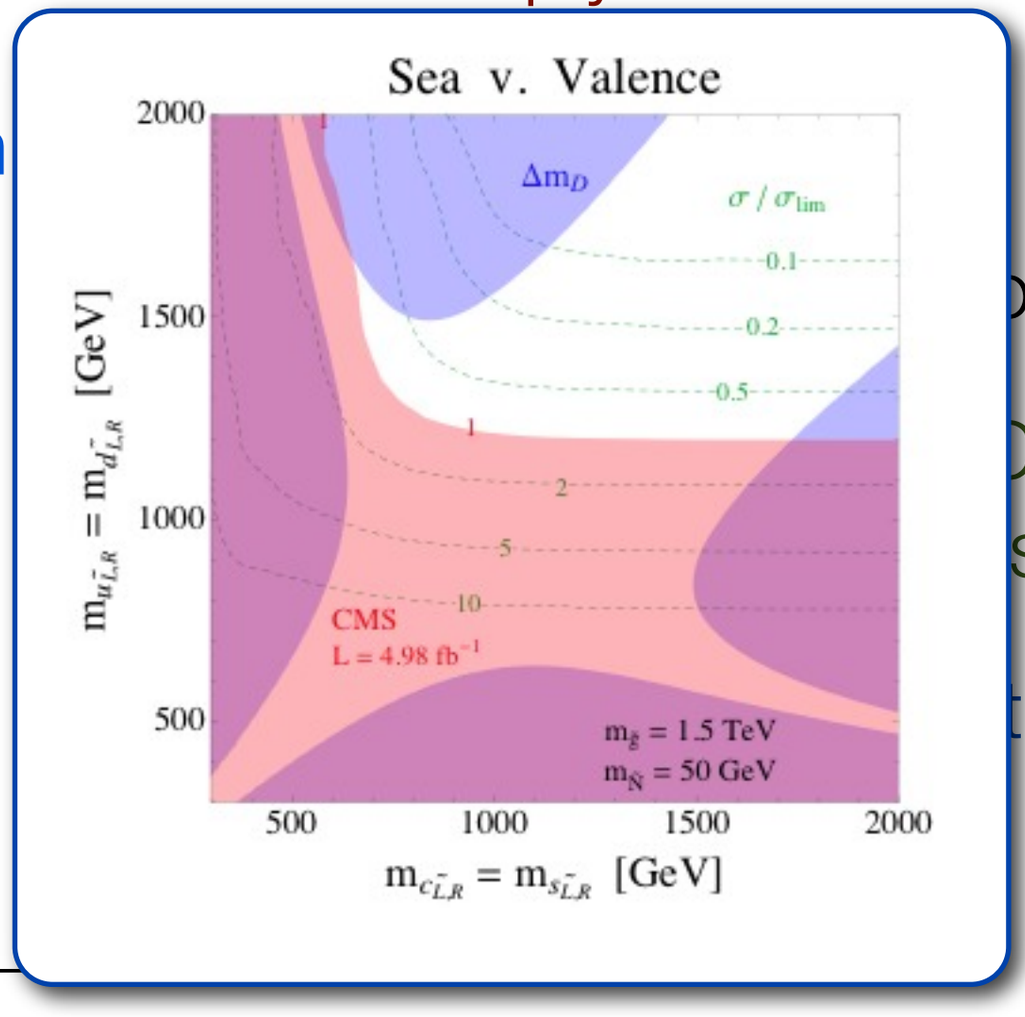
Allows split NP spectrum

Reclaiming flavorful NP at EW scale

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

Alternatively, align





…r symmetries

Nir & Seiberg, hep-ph/9304307

…CNCs

…ssed

Gedalia, J.F.K, Ligeti & Perez 1202.5038

…trum

Example: MSSM with 2nd (& 3rd) gen. squarks below TeV

Mahbubani et al., 1212.3328

Reclaiming flavorful NP at EW scale

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

- Large flavor breaking can modify exp. searches
- Some reduction of fine-tuning

Example: large $\tilde{t}_R - \tilde{c}_R$ mixing in MSSM

Blanke et al., 1302.7232

see also ATLAS-CONF-2013-068
1407.0608

new signature $tj_c E_T^{\rm miss}$

traditional $t\bar{t}E_T^{\rm miss}$ and jets+$E_T^{\rm miss}$ searches not optimized

Reclaiming flavorful NP at EW scale

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

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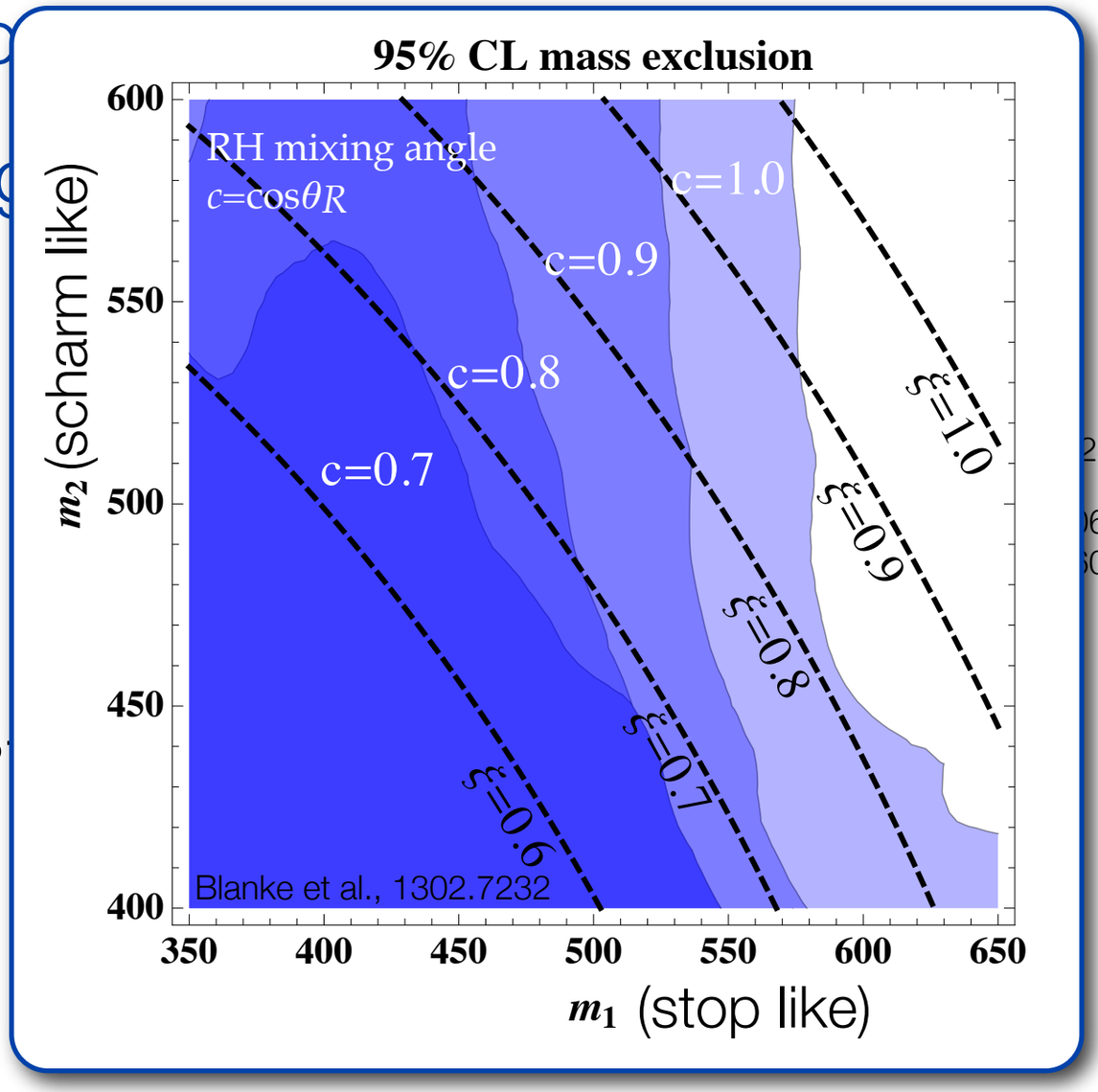
<u>Example</u>: large $\tilde{t}_R - \tilde{c}_R$ mixing

new signature $tj_c E_T^{\rm miss}$

traditional $t\bar{t}E_T^{\rm miss}$ and jets

Tuning measure: $\xi = \dfrac{c^2 m_1^2 + s^2 m_2^2}{m_0^2}$ (shown for c=0.7)

(compared to pure stop)



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068
508

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