11th International Workshop on the CKM Unitarity Triangle (CKM 2021)

Progress in theory on new physics and flavor-high p_T interplay

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Zoomverse
22/11/2021

Introduction

(almost...) all microscopic phenomena we observe in terrestrial experiments well described by SM

However: SM not complete theory of Nature

theoretical puzzles (values of SM parameters):

➡ charge quantization

➡ flavor - patterns of (charged) fermion masses & mixing

➡ (absence of) strong CP

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missing dynamics (degrees of freedom):

➡ (particle) DM?

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theoretical puzzles (values of SM parameters):

- ➡ charge quantization
- ➡ flavor - patterns of (charged) fermion masses & mixing
- ➡ (absence of) strong CP
- ➡ hierarchy problem - existence of quantum gravity
- ➡ neutrino masses - fate of Lepton number

missing dynamics (degrees of freedom):

- ➡ (particle) DM?

Introduction

Emerging (and fading) experimental hints of NP?

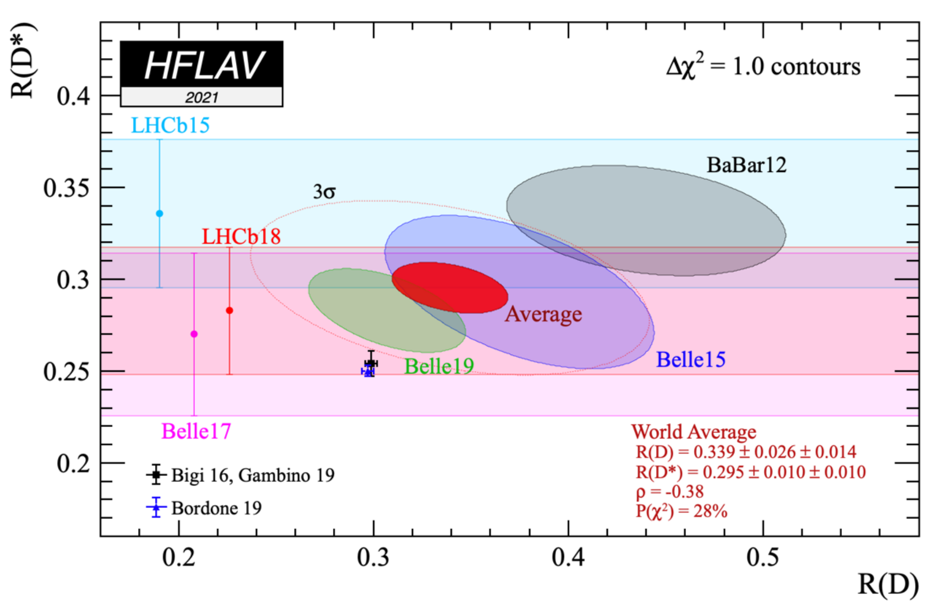
Flavor anomalies

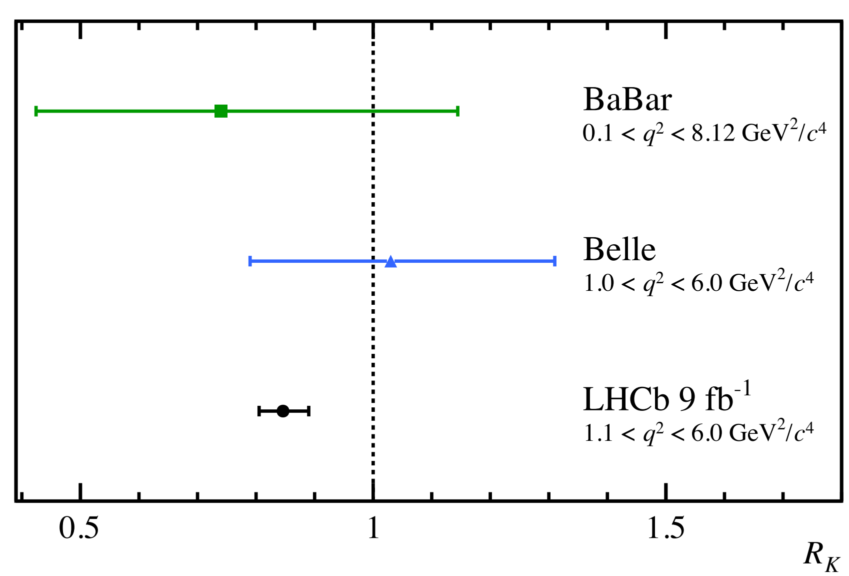
- ➡ ε'/ε, Δa$_{CP}$, $K_L \to \pi^0 \nu\bar{\nu}$ … — see talks by Buras et al.… Paul et al.…
- ➡ Cabibbo angle - CKM unitarity — see talks in WG1
- ➡ semitauonic b-decays
- ➡ rare semileptonic b-decays — see talk by Altmannshofer

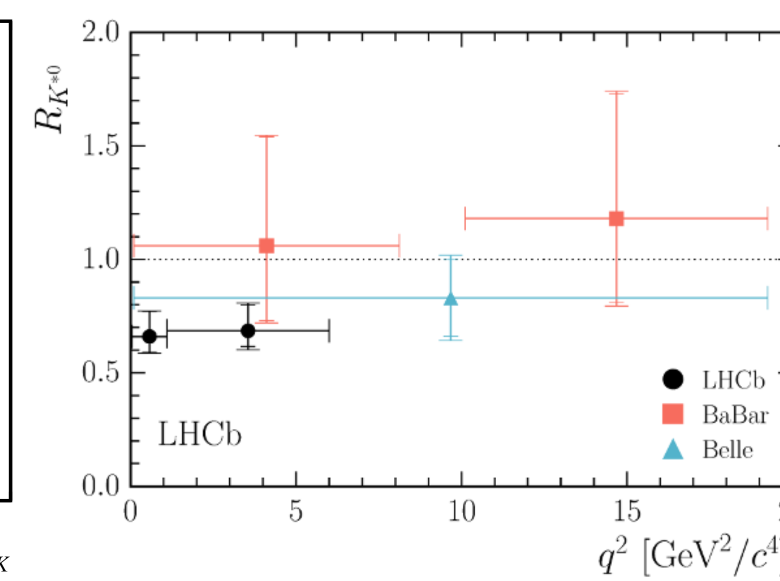
$$\mathcal{R}(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

$$R_H \equiv \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\mathcal{B}(B\to H\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\mathcal{B}(B\to He^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}\,.$$

+ angular observables and BRs
see e.g.
Alguero et al., 2104.08921







largest “coherent” set of deviations

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- rare semileptonic b-decays

Neutrino anomalies

- reactor spectra
- neutrino capture rates in gallium
- LSND, MiniBooNE

see e.g. Kopp @ IJS, 2021,
https://indico.ijs.si/event/1364/

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- anomalous magnetic moment of muon

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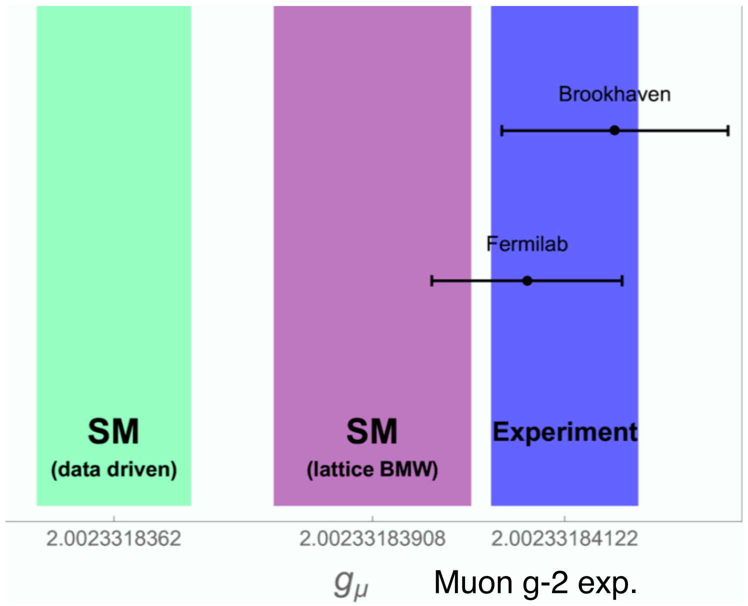
Aoyama et al., 2006.04822

Borsanyi et al., Nature 593, 51–55 (2021)



Muon g-2 exp.
hep-ex/0602035
2104.03247

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Challenge LFU

see also
Crivellin & Hoferichter, 2002.07184
Bryman et al., 2111.05338

Neutrino anomalies

- reactor spectra
- neutrino capture rates in gallium
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Flavor in SM

In SM: Higgs Yukawas unique source of both flavor and LFU breaking

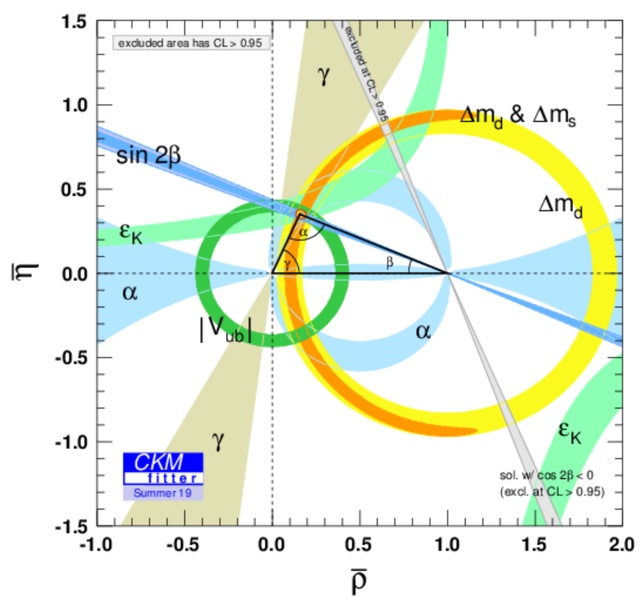
$$\mathcal{L}_{\rm SM} \ni Y_f^{ij}\, \bar{f}_L^i H f_R^j + \text{h.c.}$$

see talk by K. Vos

see talks in Soreq et al.…

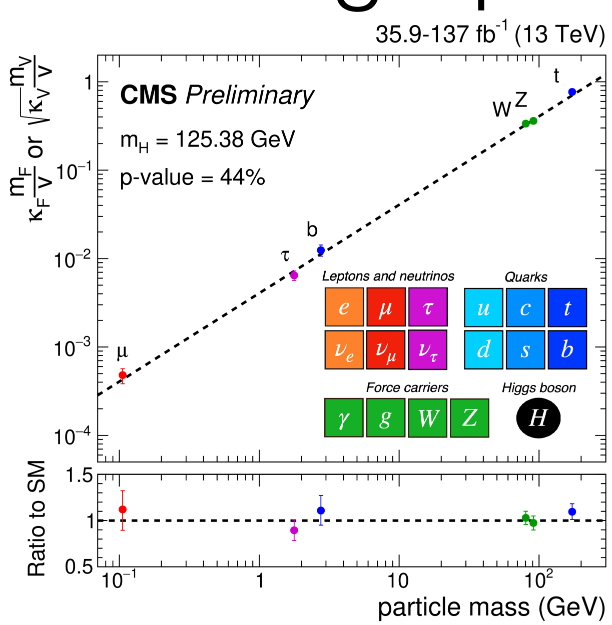
$$V_{CKM}^{ij}\, \bar{u}_L^i \not{W} d_L^j$$

Most sensitive low energy flavor observables



$$\frac{m_i}{v} h \bar{f}_i f_i$$

Can only be observed at high-p_T



Beyond SM

In absence of new (light) d.o.f.s can regard SM as EFT

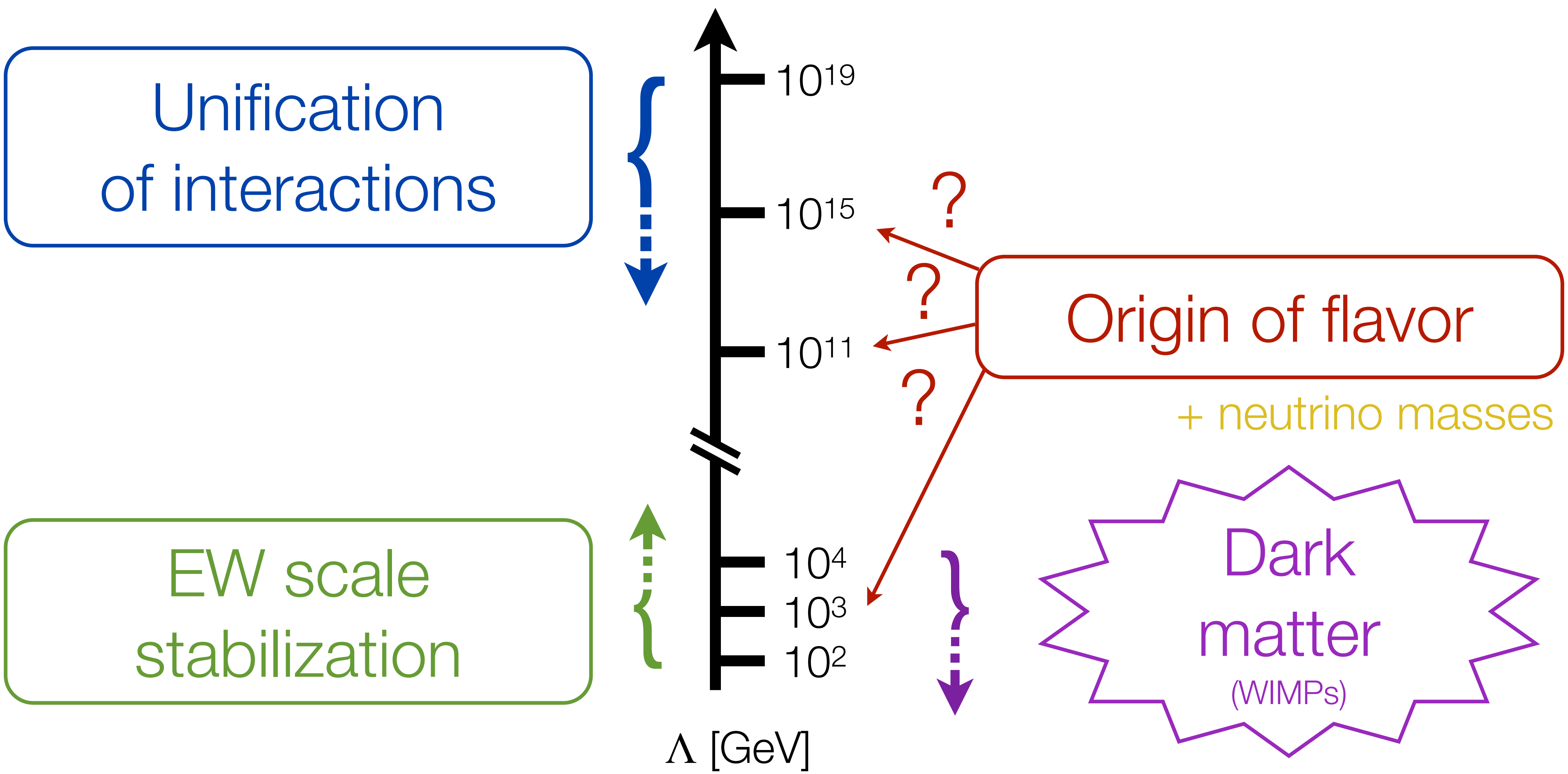
$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\nu{\rm SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

$\Lambda \sim 1/L$ parametrizes "size" of NP effects

indirectly related to new mass thresholds $\Lambda \sim \dfrac{g_{\rm NP}}{M_{\rm NP}}$

SM puzzles imply NP at different scales

BSM scales - theory expectations



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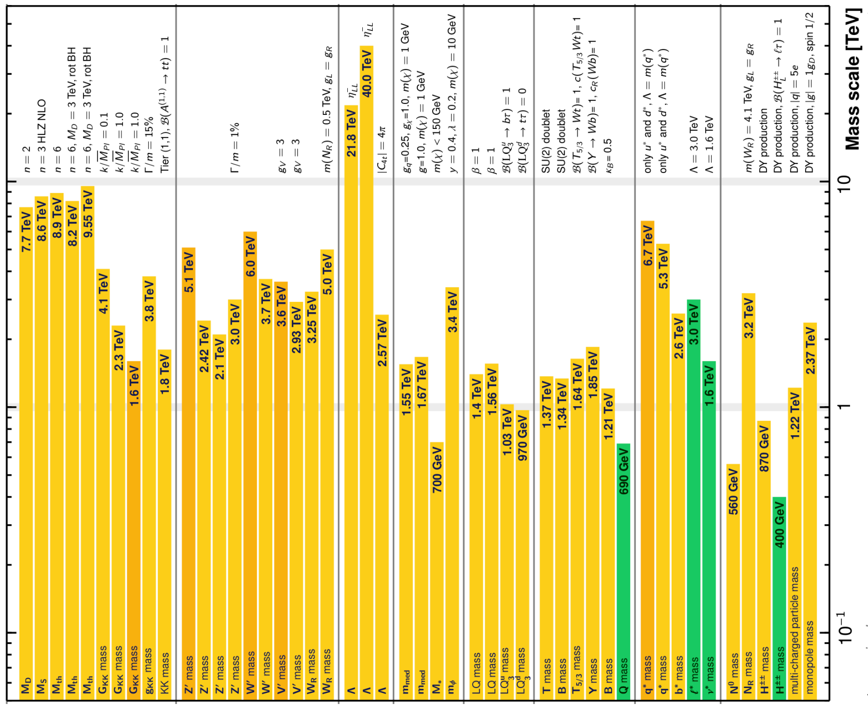
SM puzzles imply NP at different scales

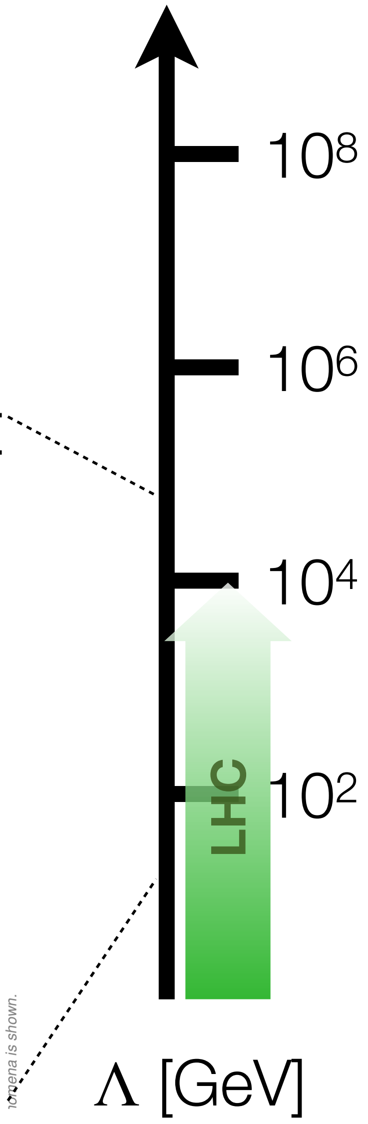
exp. searches for NP $\Rightarrow$ upper reach on mass-scale of (perturbative) NP

BSM scales - experimental reach

- LHC exploring TEV NP

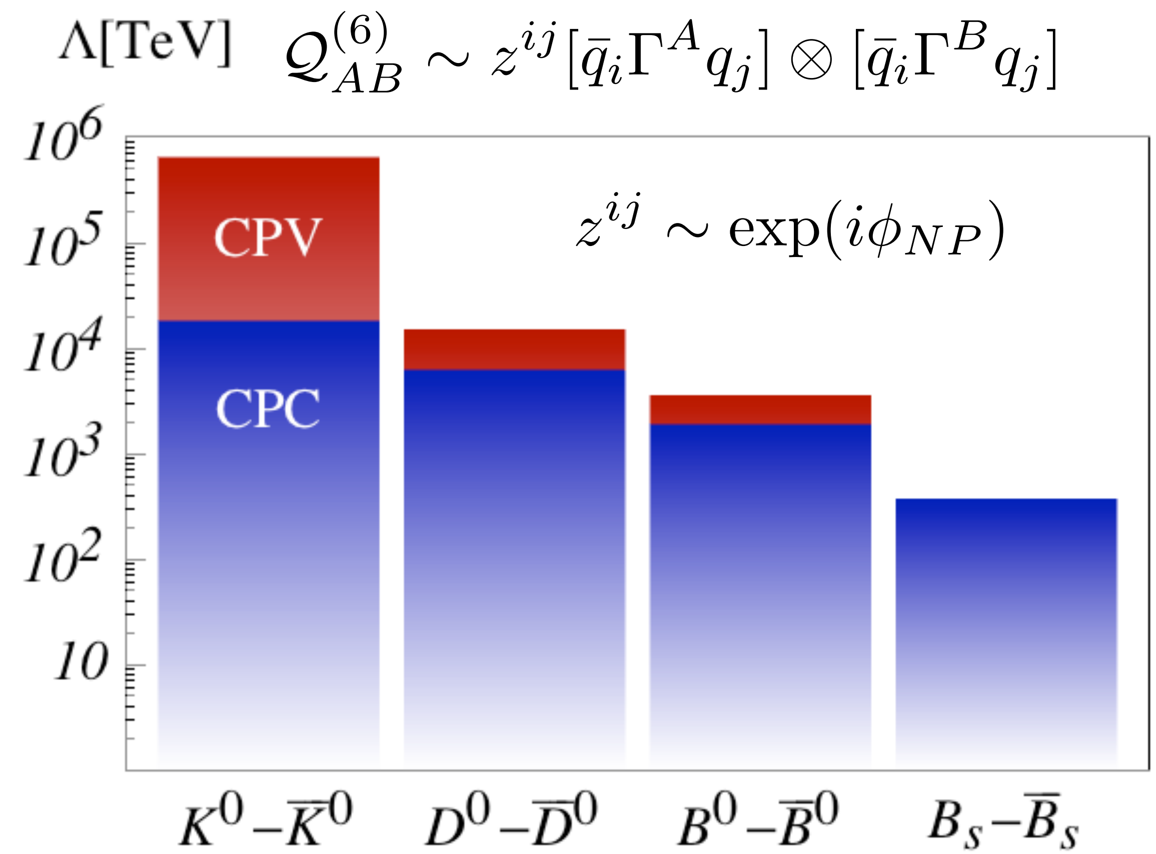


ATLAS searches @ 8 & 13TeV

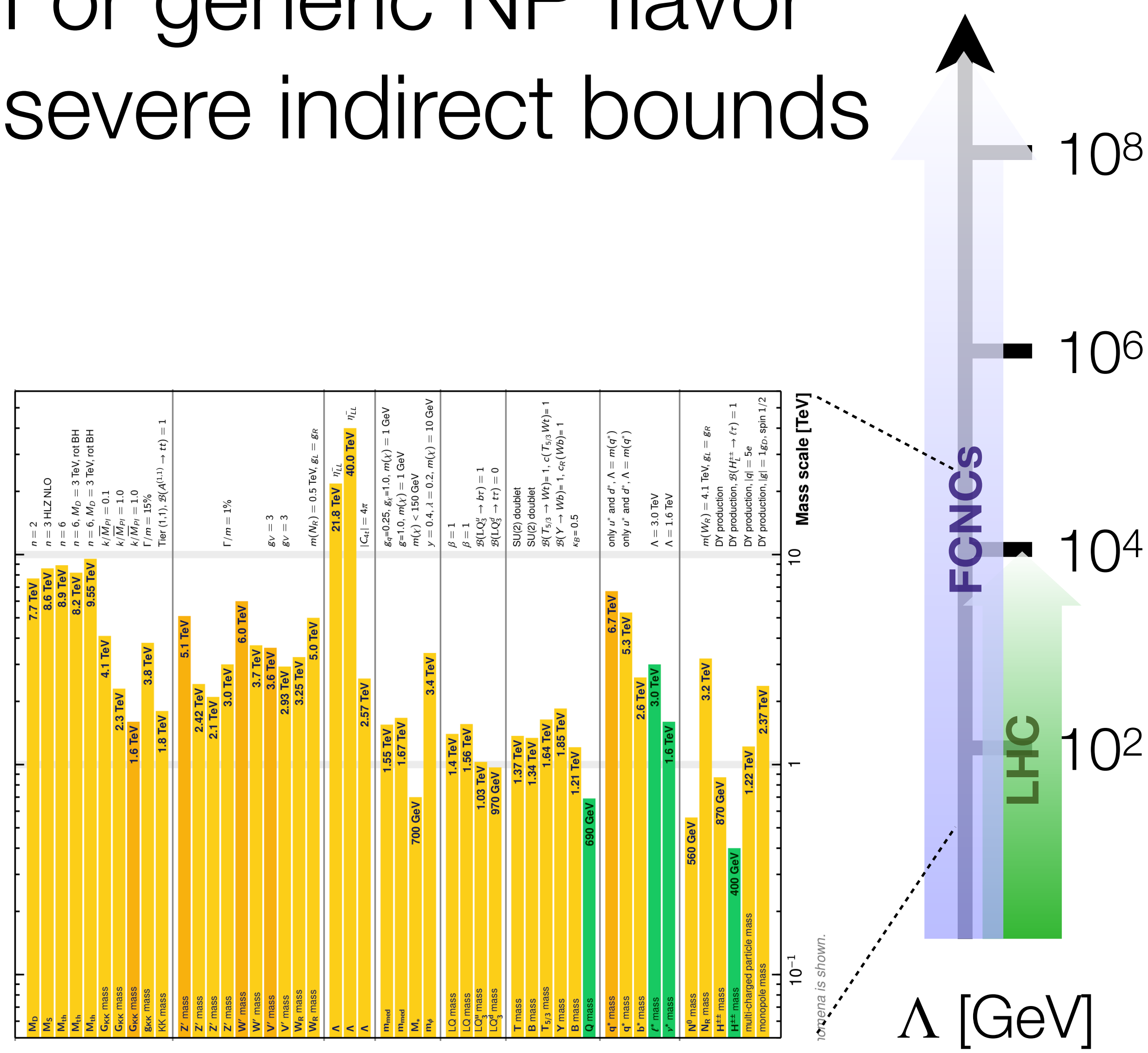


BSM scales - experimental reach

- LHC exploring TEV NP
- For generic NP flavor severe indirect bounds



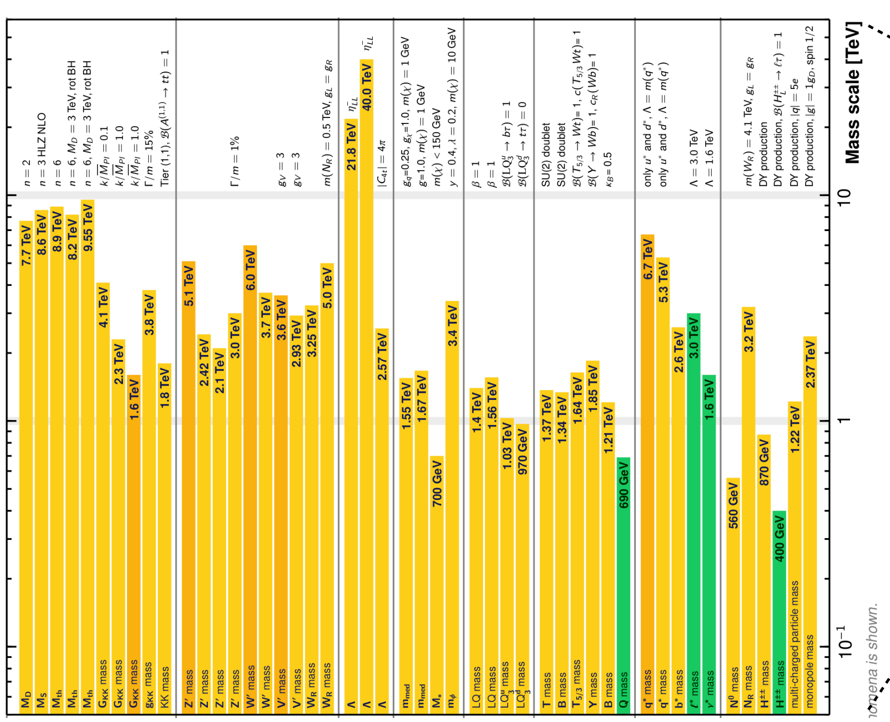
see e.g. UTFit 1411.7233
ETM 1505.06639
Fermilab Lattice & MILC, 1706.04622
Aebischer et al., 2009.07276



ATLAS searches @ 8 & 13TeV

BSM scales - experimental reach

- LHC exploring TEV NP
- For generic NP flavor and/or CPV severe indirect bounds



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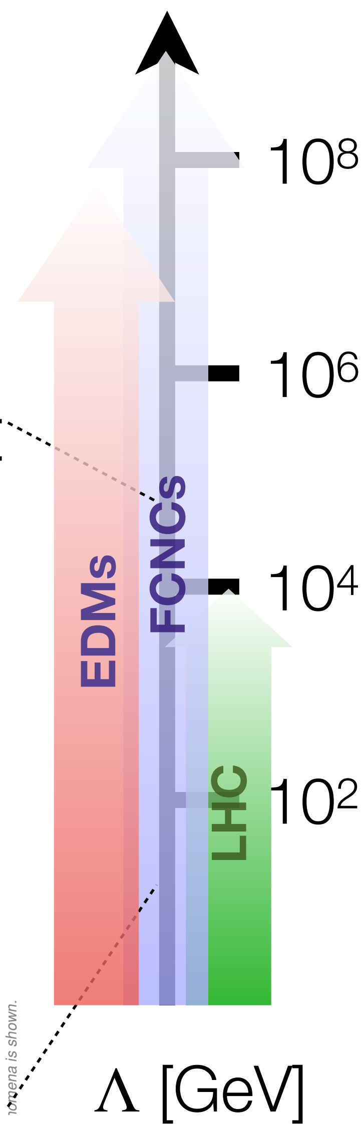

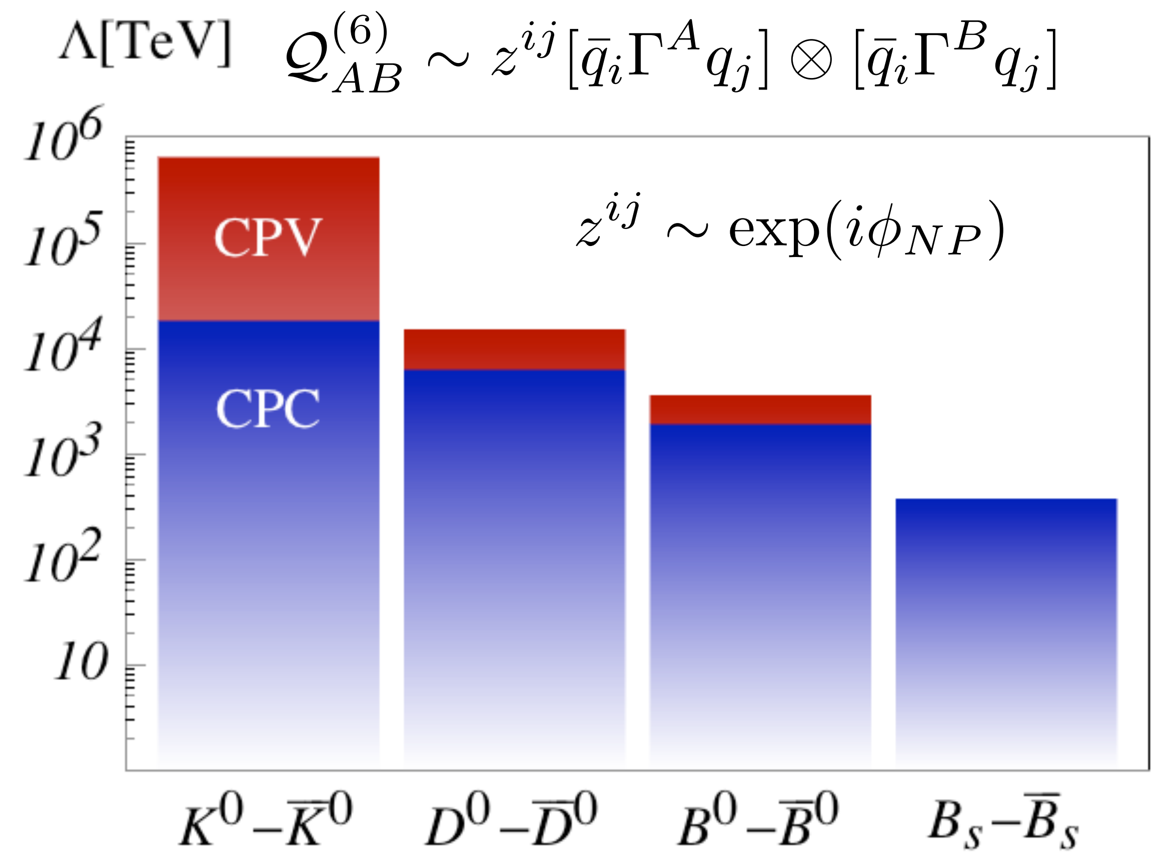

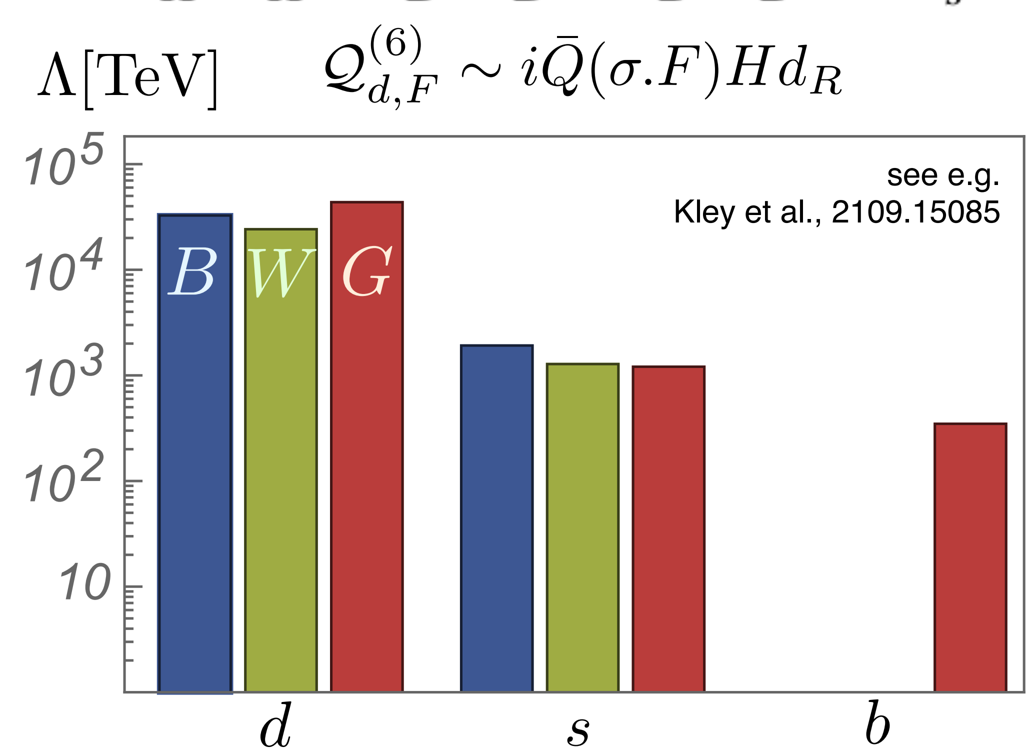

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indirectly related to new mass thresholds $\Lambda \sim \dfrac{g_{\rm NP}}{M_{\rm NP}}$

SM puzzles imply NP at different scales

$$\frac{\text{exp. searches for NP}}{\text{low energy hints of NP}} \Rightarrow \frac{\text{upper reach}}{\text{upper bounds}}$$ on mass-scale of (perturbative) NP

see e.g.
Di Luzio, JFK & Nardecchia, 1604.05746
Di Luzio & Nardecchia, 1706.01868

BSM scales - B anomalies

LFUV in $R(D^{(*)})$: $\Lambda \simeq 2.5\,\mathrm{TeV}$

e.g. $\mathcal{Q} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu)$

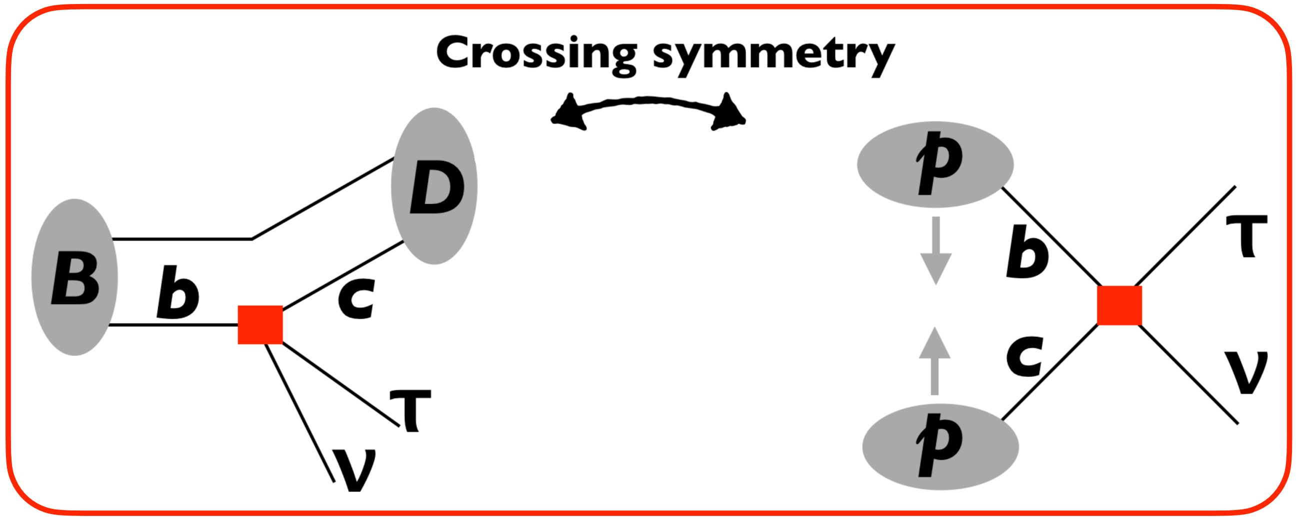
$\Rightarrow$ tree-unitarity $M_{\mathrm{NP}} \lesssim 6.5\mathrm{TeV}$

up to the edge of LHC kinematical reach

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

<u>Example</u>: mono-tau production @ LHC

Greljo et al., 1811.07920



see also
Angelescu, Faroughy & Sumensari, 2002.05684
Fuentes-Martin et al., 2003.12421
Bordone, Greljo & Marzocca, 2103.10332

$$\sigma \sim \mathcal{L} \times \hat{\sigma}$$

✗ heavy flavour pdf. suppression

$$\mathcal{L}_{ij} \propto \int f_i(x) f_j(\hat{s}/sx) dx$$

✔ compensated by high partonic energy

$$\hat{\sigma} \propto \left(\hat{s}/M^2\right)^2$$

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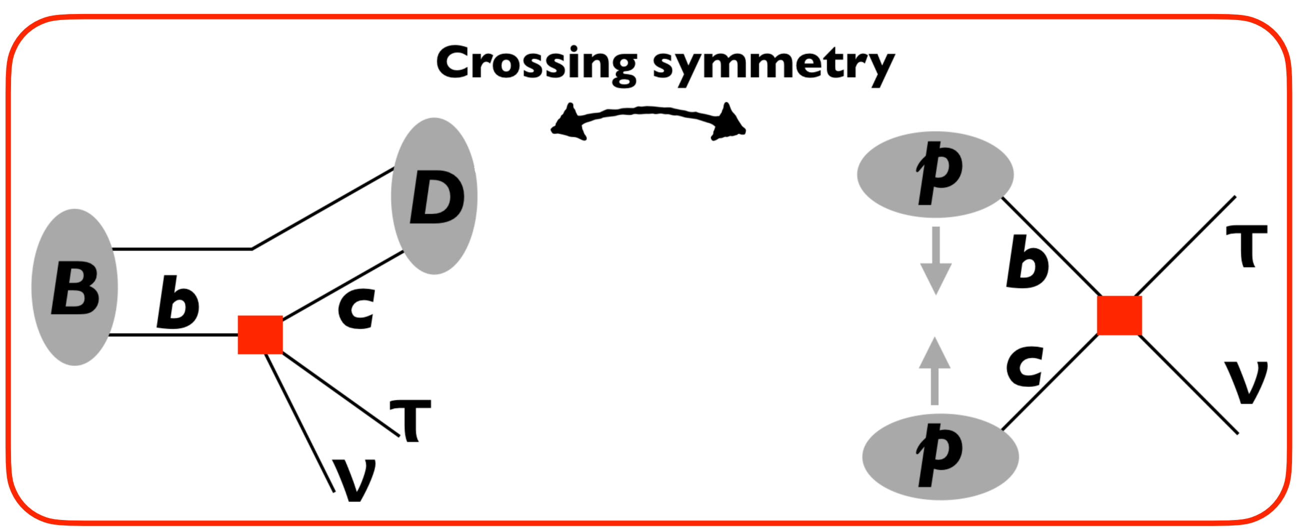

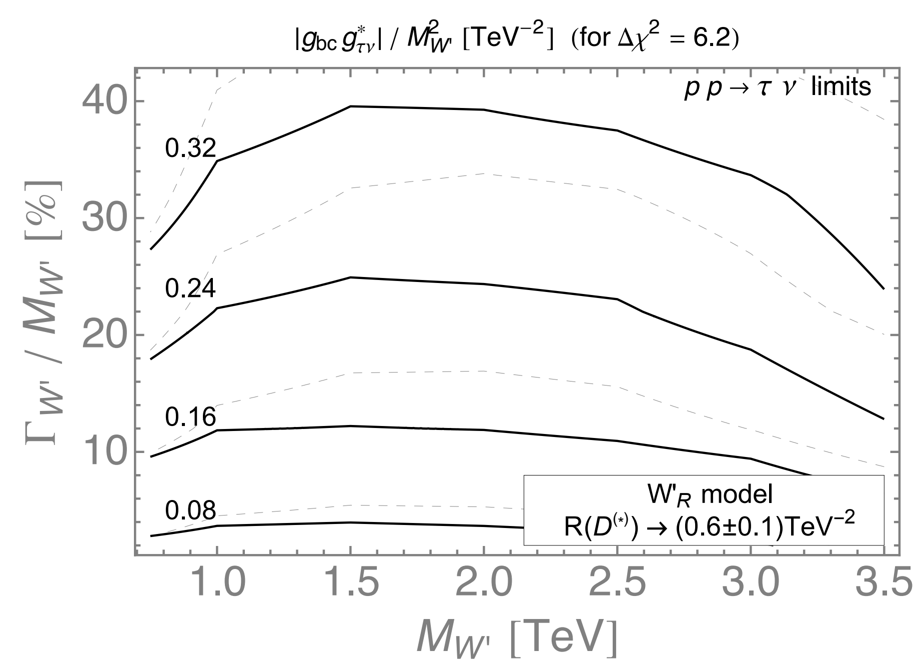

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⇒ tree-unitarity $M_{\mathrm{NP}} \lesssim 6.5\mathrm{TeV}$

up to the edge of LHC kinematical reach

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

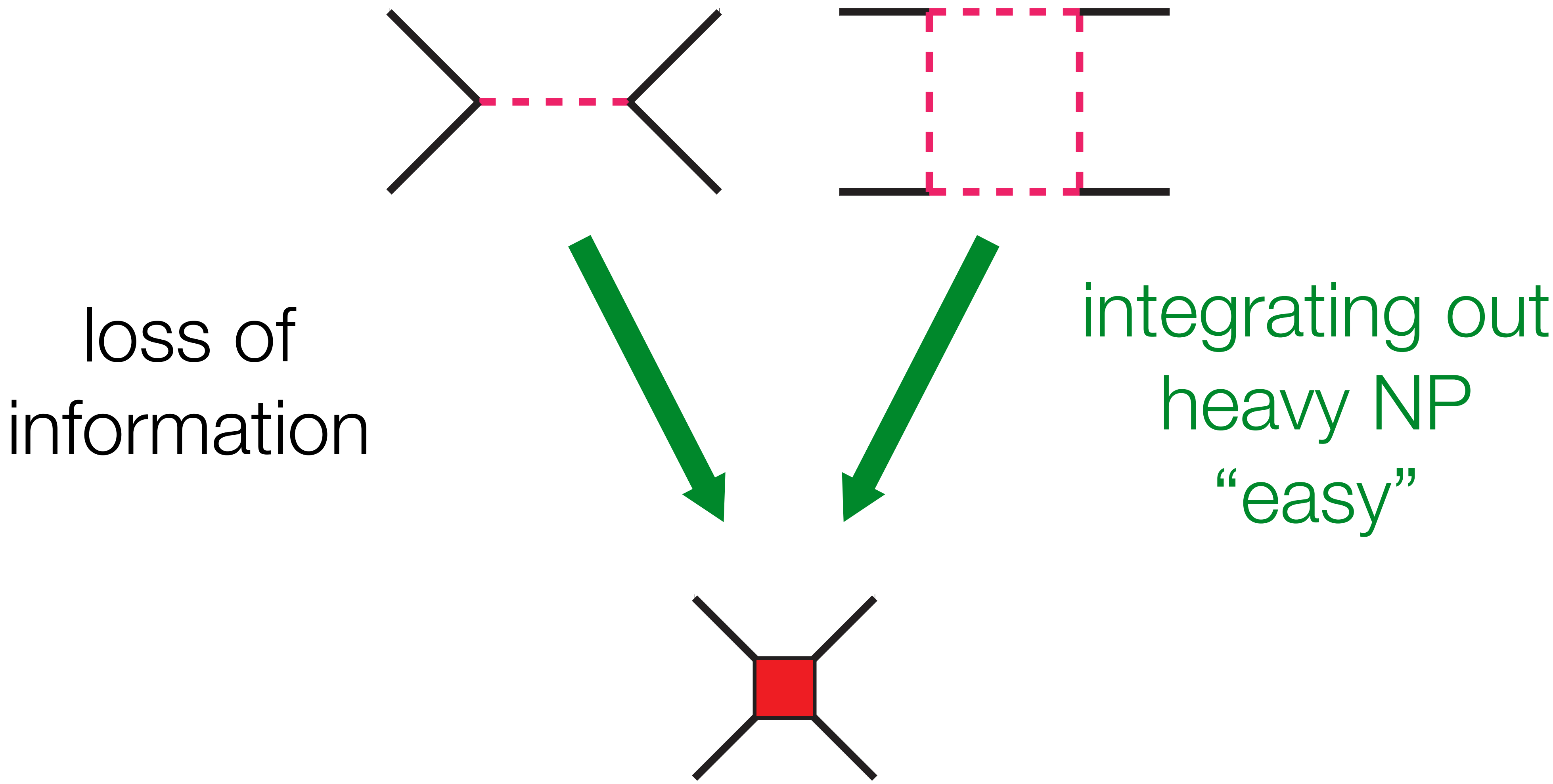
LFUV in $R_{K^{(*)}}$ (& other obs.) : $\Lambda \sim 40\mathrm{TeV}$

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*!

Caveats

1. Low energy measurements can only probe IR properties of heavy NP (its projection to SMEFT)



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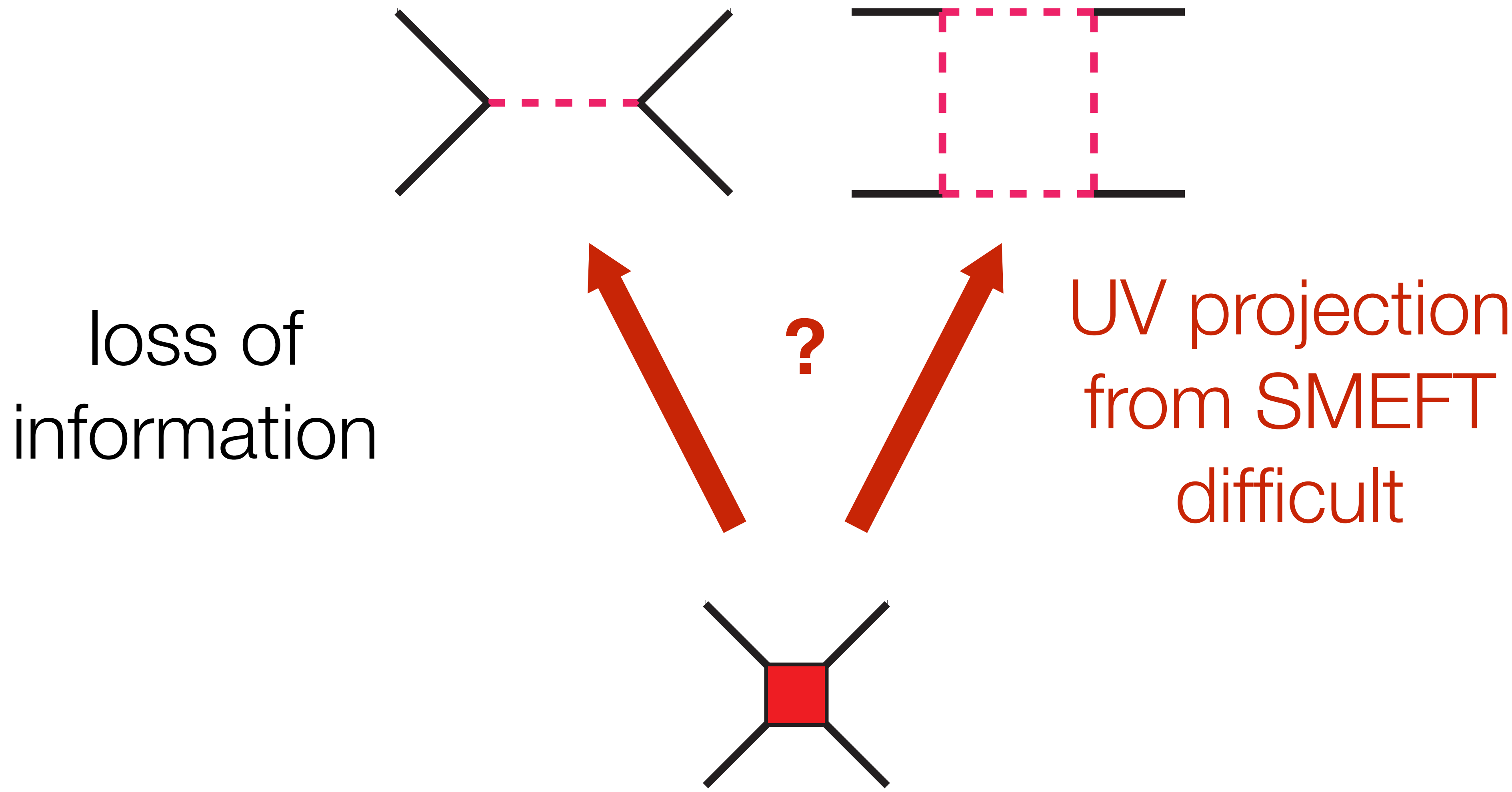

If d.o.f.s within kinematical reach, LHC crucial to disentangle various UV models of NP

Caveats

1. Low energy measurements can only probe IR properties of heavy NP (its projection to SMEFT)

Example: B-anomalies

At EW scale: in terms of four-fermion operators

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

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

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Buttazzo et al., 1706.07808

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

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*B_c lifetime, decays
Alonso et al., 1611.06676
Akeroyd & Chen, 1708.04072
Blanke et al., 1811.09603
…

Buttazzo et al., 1706.07808

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*right-handed currents
Greljo et al., 1804.04642
…

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Example: B-anomalies

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

*right-handed currents
Greljo et al., 1804.04642
...

Simplest UV: Z'/W' $\quad$ $\mathrm{LQ's}$ $\quad$ $H^\pm$ different LHC pheno!

see e.g. Angelescu et al., 2103.12504

Caveats

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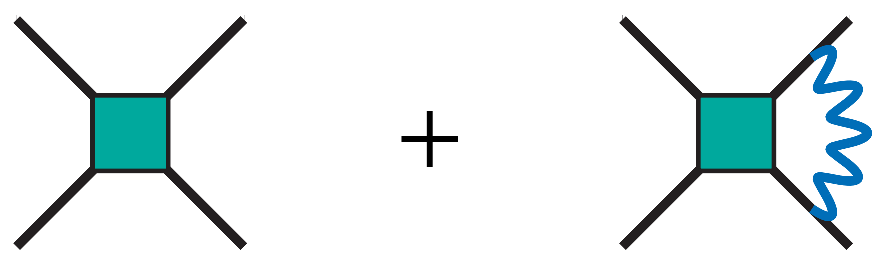
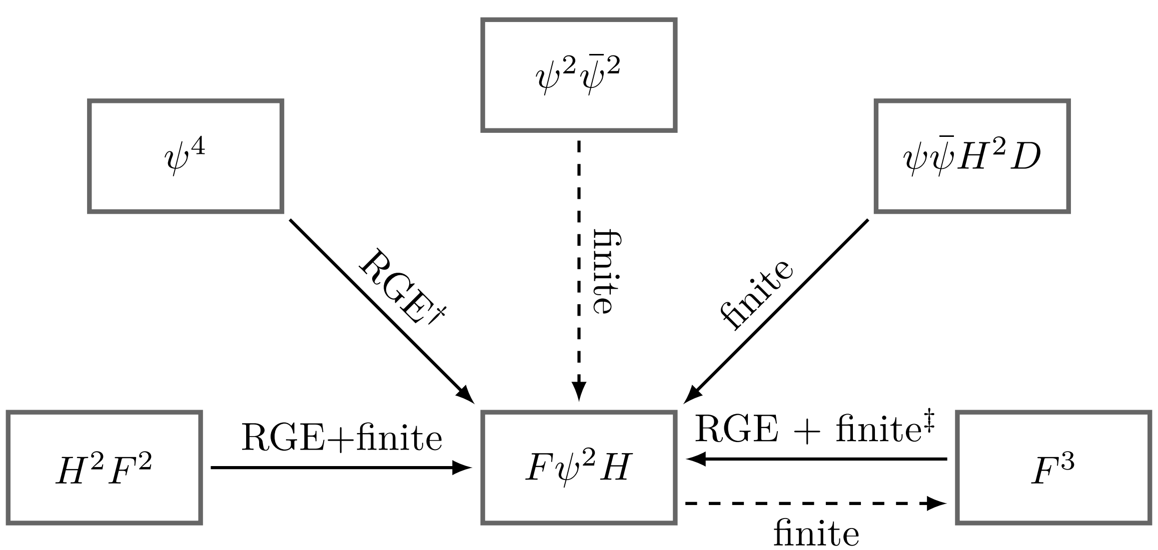
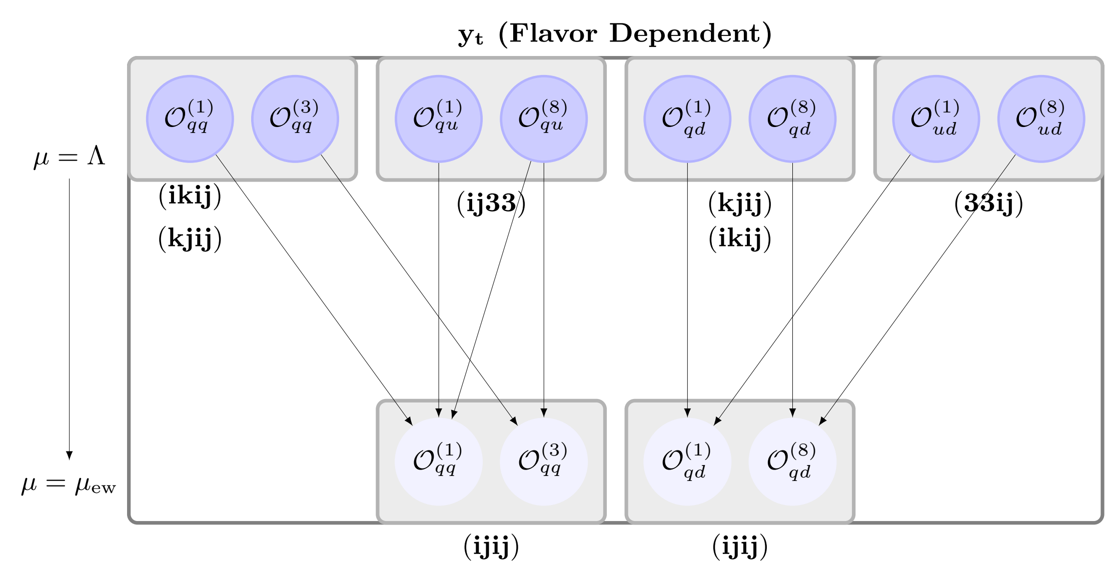
2. Operators in (SM)EFT mix under renormalization





Kley et al., 2109.15085



Aebischer et al., 2009.07276

⇒ IR projection function of (unknown) UV scale!

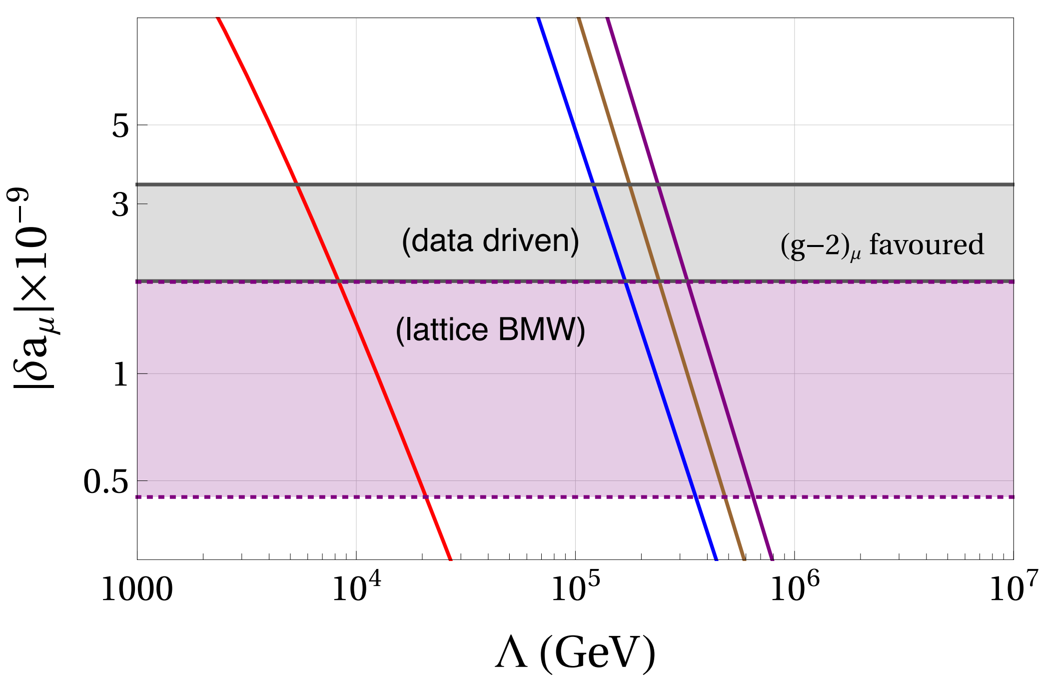
Caveats

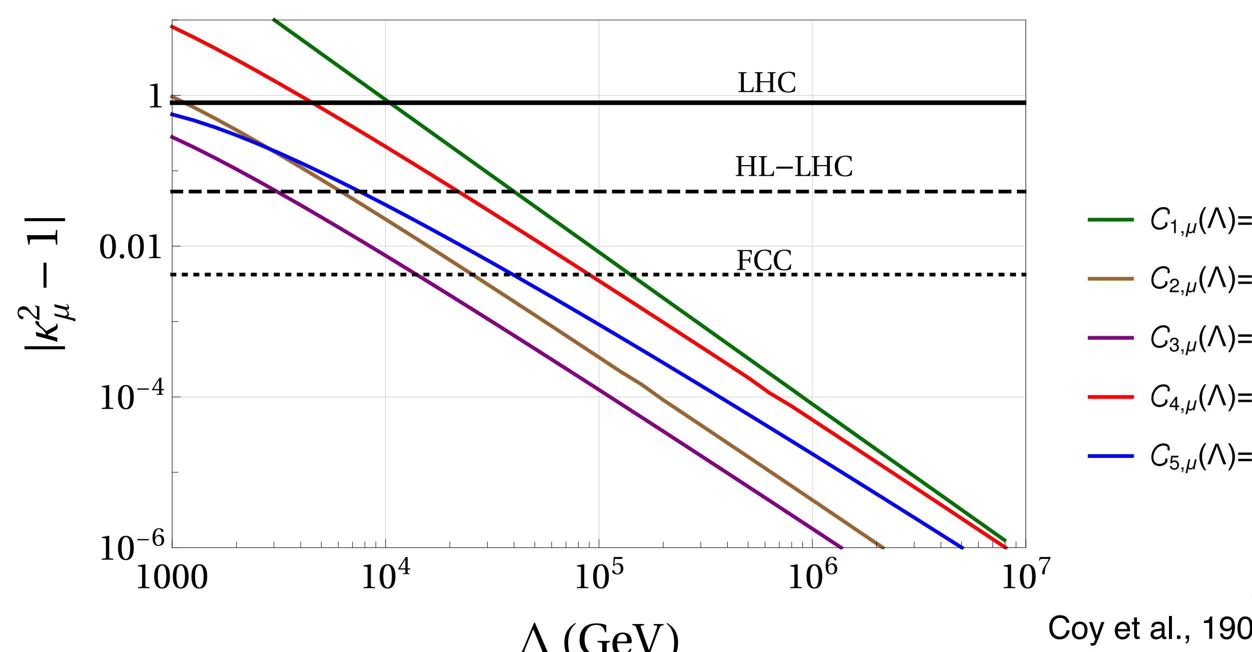
1. Low energy measurements can only probe IR properties of heavy NP (its projection to SMEFT)

2. Operators in (SM)EFT mix under renormalization

<u>Example</u>: muon g-2 & Higgs decays to muons

Fajfer, JFK & Tammaro, 2103.10859





see also
Coy et al., 1909.08567
Crivellin, Muller & Saturnino, 2008.02643

$$\mathcal{O}_{1,pr} = \left(\varphi^\dagger\varphi\right)\left(\bar{\ell}_p e_r \varphi\right)\,,\quad \mathcal{O}_{2,pr} = \left(\bar{\ell}_p \sigma^{\mu\nu} e_r\right)\tau^a \varphi W^a_{\mu\nu}\,,\quad \mathcal{O}_{3,pr} = \left(\bar{\ell}_p \sigma^{\mu\nu} e_r\right)\varphi B_{\mu\nu}\,.$$

$$\mathcal{O}_{4,prst} = \left(\bar{\ell}^j_p e_r\right)\epsilon_{jk}\left(\bar{q}^k_s u_t\right)\,,\quad \mathcal{O}_{5,prst} = \left(\bar{\ell}^j_p \sigma_{\mu\nu} e_r\right)\epsilon_{jk}\left(\bar{q}^k_s \sigma^{\mu\nu} u_t\right)$$

Caveats

1. Low energy measurements can only probe IR properties of heavy NP (its projection to SMEFT)

2. Operators in (SM)EFT mix under renormalization ⇒ IR projection function of (unknown) UV scale!

3. Comparison of high p_T & FCNC/CPV measurements (and their interpretation within SMEFT) depends crucially on assumed (unknown) flavor & CP structure of NP

   the rest of this talk…

see e.g.
Descotes-Genon et al., 1812.08163
Faroughy et al., 2005.05366
Aebischer et al., 2009.07276
Kley et al., 2109.15085
Greljo et al., 2107.07518

Flavor of new physics (pre LHC)

UV solutions to EW hierarchy problem require NP @ TeV

Not possible for generic flavor & CP structure

"NP flavor & CP" problem

Minimal flavor violating assumption: all flavor & CP violation (even BSM) proportional to SM Yukawas

$$\mathcal{L}_{\rm SM} \ni Y_f^{ij}\, \bar{f}_L^i H f_R^j + \text{h.c.}$$

Formally: $Y_{u,d,e}$ only (spurionic) sources of SM $U(3)^5$ flavor symmetry (& CP) breaking even BSM

d'Ambrosio et al., hep-ph/0207036

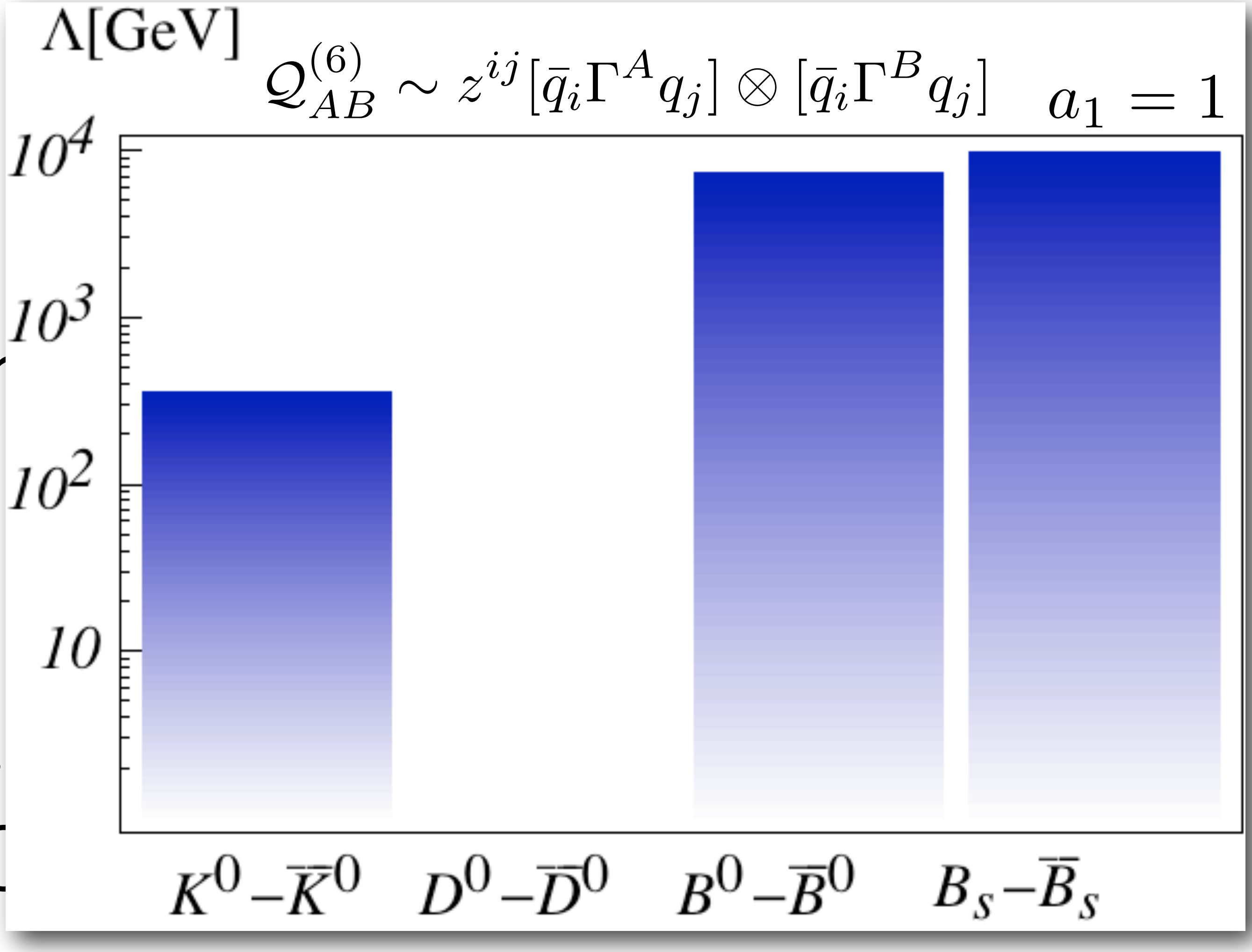
Flavor of new physics (pre LHC)

UV solutions to EW hierarchy problem require NP @ TeV

Not possible for generic flavor & CP structure

Minimal flavor [partly hidden] CP violation

(even BSM) pr[partly hidden]



Formally: $Y_{u,d,}$ [partly hidden] $U(3)^5$ flavor

symmetry (& C[partly hidden]

Example: $z^{ij} = a_0\delta^{ij} + a_1(Y_uY_u^\dagger)^{ij} + \ldots$

Flavor of new physics (mid LHC)

For generic expansion ($a_i \sim 1$) MFV solutions to EW hierarchy & B-anomalies already in tension with direct LHC searches!

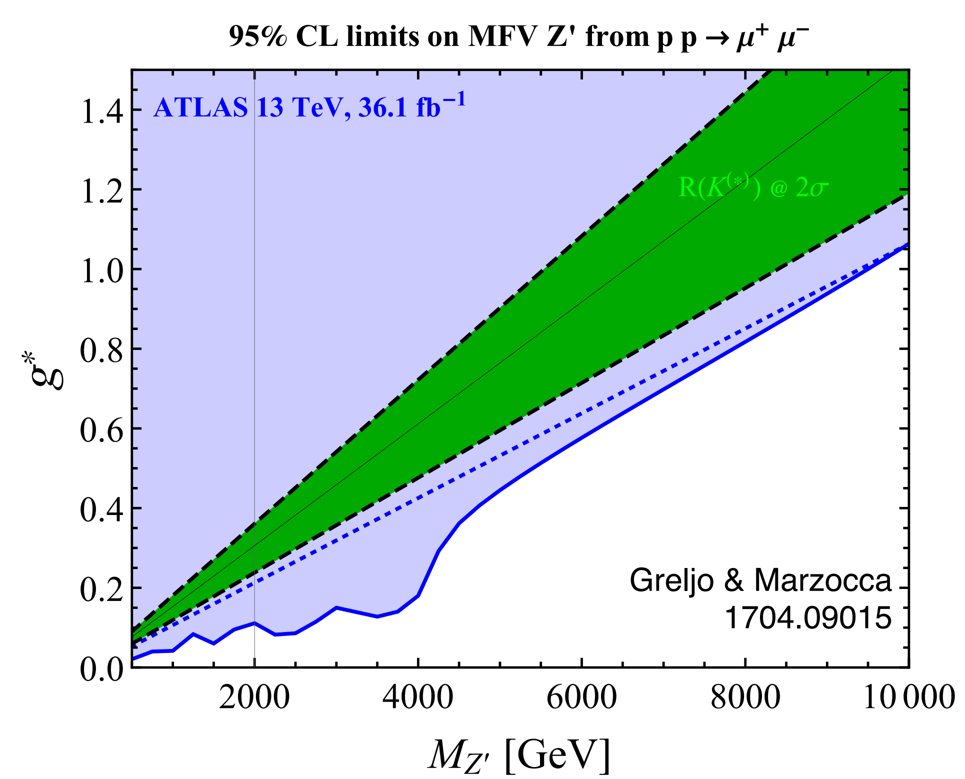
Also: Unless CP conservation assumed in UV in general strong bounds on NP scale from EDMs

Flavor of new physics (mid LHC)

For generic expansion ($a_i \sim 1$) MFV solutions to EW hierarchy & B-anomalies already in tension with direct LHC searches!

Example: R_K $\quad \epsilon^Q_{sb} \propto V_{tb} V_{ts}$

$$\epsilon^Q_{ij} \simeq \mathbf{1} + \mathcal{O}(\mathbf{Y}\mathbf{Y}^\dagger)$$



Flavor of new physics (mid LHC)

For generic expansion ($a_i \sim 1$) MFV solutions to EW hierarchy & B-anomalies already in tension with direct LHC searches!

However: LHC sensitivity dominated by couplings to first generation quarks, while EW fine-tuning (& B-anomalies) dominated by third (& second) generation couplings!

Also: other FCNC & CPV bounds most severe for 1st - 2nd generations (mixing)

Implications for TeV scale NP: coupling (predominantly) to 3rd gen. fermions ⇒ 3rd gen. alignment [GMFV, U(2)]

$$\epsilon_{ij}^{Q} \simeq \cancel{\mathbf{1}} + \mathcal{O}(\mathbf{Y}\mathbf{Y}^{\dagger})$$

see e.g.
Kagan et al., 0903.1794
Barbieri et al., 1105.2296
Fajfer et al., 1206.1872
Bordone et al., 1702.07238

Immediate implications of B-anomalies for LHC

Quark 3rd gen. flavor alignment implies lower NP scale (similar to MFV):

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

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

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

Well within LHC reach!

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

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

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

Still only marginally!

However: Including 3rd gen. alignment in lepton sector (with small breaking): $(\bar{Q}_3 Q_3)(\bar{L}_3 L_3) \to V_{tb}V_{ts}(\bar{s}b)(\bar{\tau}\tau + \epsilon_\ell^2 \bar{\mu}\mu)$

see e.g. Cornella et al., 2103.16558

$\epsilon_\ell \sim m_\mu / m_\tau$

1. can fit both LFU anomalies, d.o.f.s within LHC reach!
2. important implications for $b \to s\tau^+\tau^-$

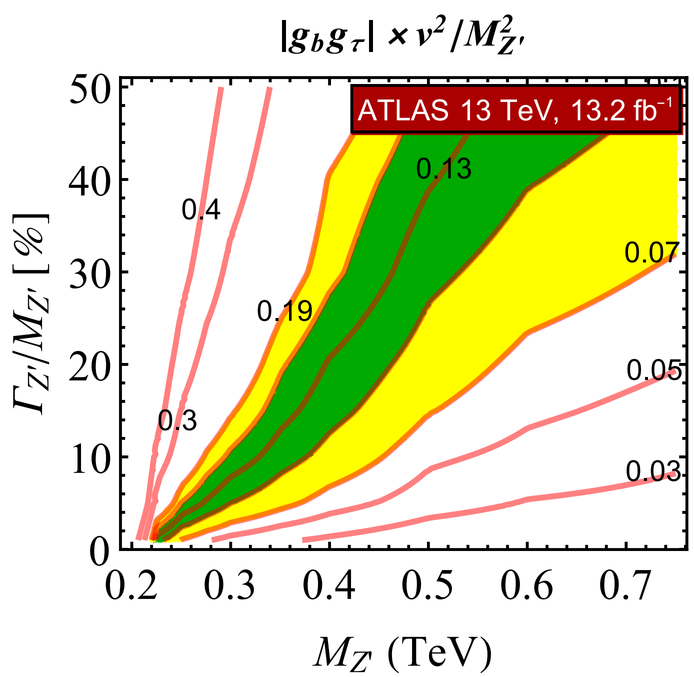
JFK et al., 1705.11106
Capdevila et al., 1712.01919
Cornella et al., 2001.04470

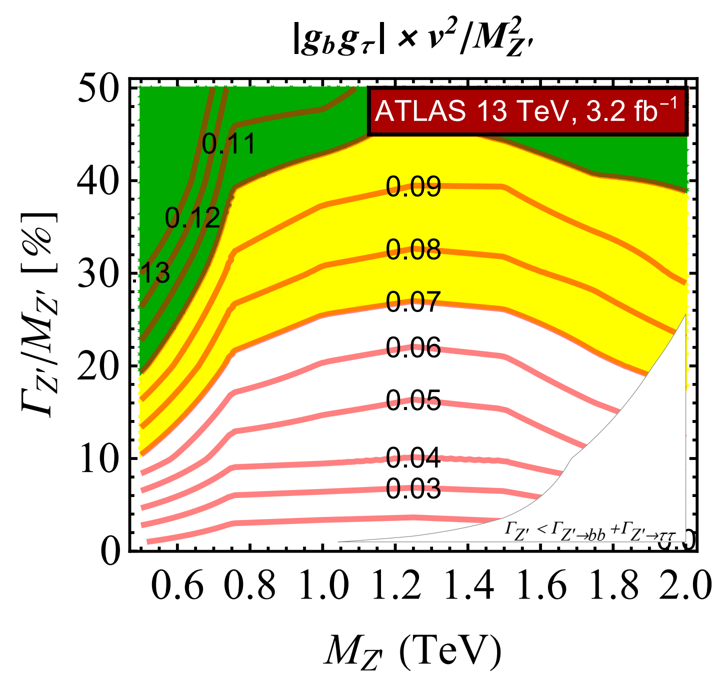
Immediate implications for LHC: $R(D^{(*)})$

Weak gauge invariance ⇒ neutral currents

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

Constraints from existing $pp \to \tau^+\tau^-$ searches at LHC





Faroughy, Greljo & JFK, 1609.07138

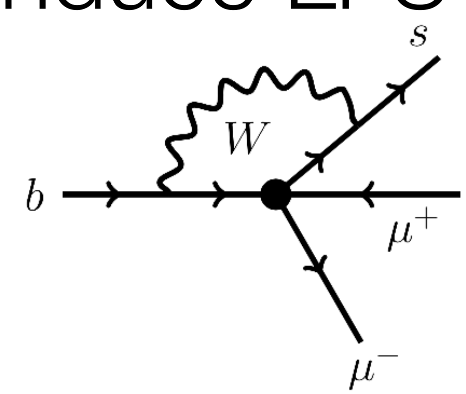
see also
Buttazzo et al., 1706.07808

B-anomalies without new quark flavor violation

Starting with flavor conserving non-universal (3rd gen. aligned) operators:

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

EW matching & RGE induce LFUV in rare FCNC B decays



Aebischer et al., 1512.02830
Faroughy et al., 1805.04917

see also
Blanger, Delaunay, & Westhoff, 1507.06660
Bauer et al., 1511.01900
Becirevic & Sumensari, 1704.05835

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

JFK, Soreq & Zupan, 1704.06005

Conclusions

Low energy flavor & CP probes together with high p_T searches at LHC put strong constraints on TeV scale NP

Interesting case for 3rd generation flavor alignment

➡ Implications for EW hierarchy solutions (don't give up yet!)

➡ Coherent pattern of LFUV observables in b-hadron decays

Crucial to explore related pheno (both at low E and high pT):

➡ $b \to q\tau\nu \; (R_\pi, R_\Upsilon, \ldots)$

➡ $b \to q\nu\nu \; (B \to K^{(*)}\nu\bar{\nu}, \ldots)$

➡ $b \to q\tau\ell \; (B \to K^{(*)}\tau\mu, \ldots)$

see talks in WG3

➡ $pp \to \tau X, \; E_T^{\rm miss} X$

see talks by Greljo et al…

➡ higgs decays

see talks by Soreq et al.…

➡ top quark decays, production

see talks by Worek et al…

see also
Allwicher, Isidori & Selimovic, 2109.03833
Bordone eta l., 2101.11626
Descotes-Genon et al., 2104.06842 , 2005.03734
Angelescu et al., 2103.12504
Cornella et al., 2103.16558
Aloni et al., 1702.07356
JFK, Katz & Stolarski, 1808.00964
…

Essential role of Belle II and future colliders (FCC-ee)

Amhis et al., 2105.13330
Charles et al., 2006.04824
Grossman & Ligeti, 2106.12168

Conclusions

More generally: Flavor studies of NP in the scope of general SMEFT are well under way

see e.g.
Descotes-Genon et al., 1812.08163
Faroughy et al., 2005.05366
Aebischer et al., 2009.07276
Kley et al., 2109.15085

Important implications for measurement interpretations as well as UV NP model building see talks by Hiller et al…

Going beyond SMEFT: NP with light new d.o.f.s (ALPs, dark photons)

see e.g.
Banerjee et al., 1705.02327
Bauer et al., 1908.00008, 2012.12272, 2102.13112
Cornella, Paradisi & Sumensari, 1911.06279
Calibbi et al., 2006.04795, 1612.08040
Galda, Neubert & Renner, 2105.01078

Flavor important/complementary probe also of light (invisible) NP

JFK & Smith 1111.6402
Dolan et al., 1412.5174
JFK & Haisch, 1601.05110
Dobrich et al., 1810.11336

Highlight possible role of Flavor experiments as discovery machines

see e.g.
Ilten et al., 1603.08926
Borsato et al., 2105.12668

Backup

$R_{K^{(*)}}$ without new flavor violation: a UV completion

JFK, Soreq & Zupan, 1704.06005

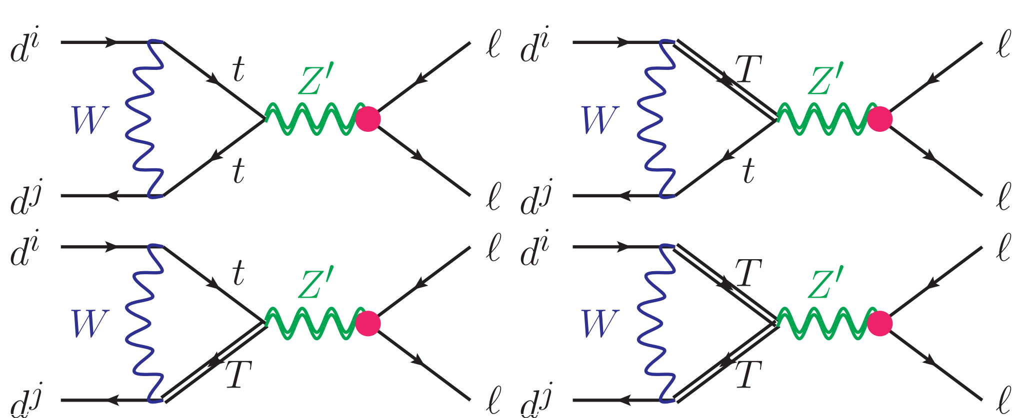
VL quark partner of right-handed top (T),

- charged under gauged $U(1)$' (Z', h')

- T-t_R mix after $U(1)$' breaking - induced $U(1)$' charge of t_R

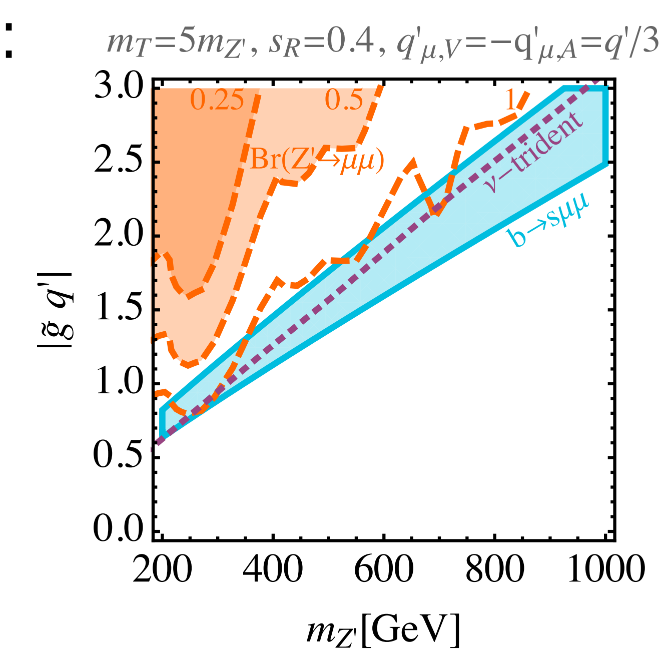
(similar mechanism possible to induce muon $U(1)$' charge)

R$_K$ induced through W loops



Dominant signatures:

- neutrino trident
- $pp \to 4t$
  Alvarez et al., 1611.05032
- $pp \to 2\mu 2t$
  see also
  Fox et al., 1801.03505



$R_{K^{(*)}}$ without new flavor violation: a UV completion

JFK, Soreq & Zupan, 1704.06005

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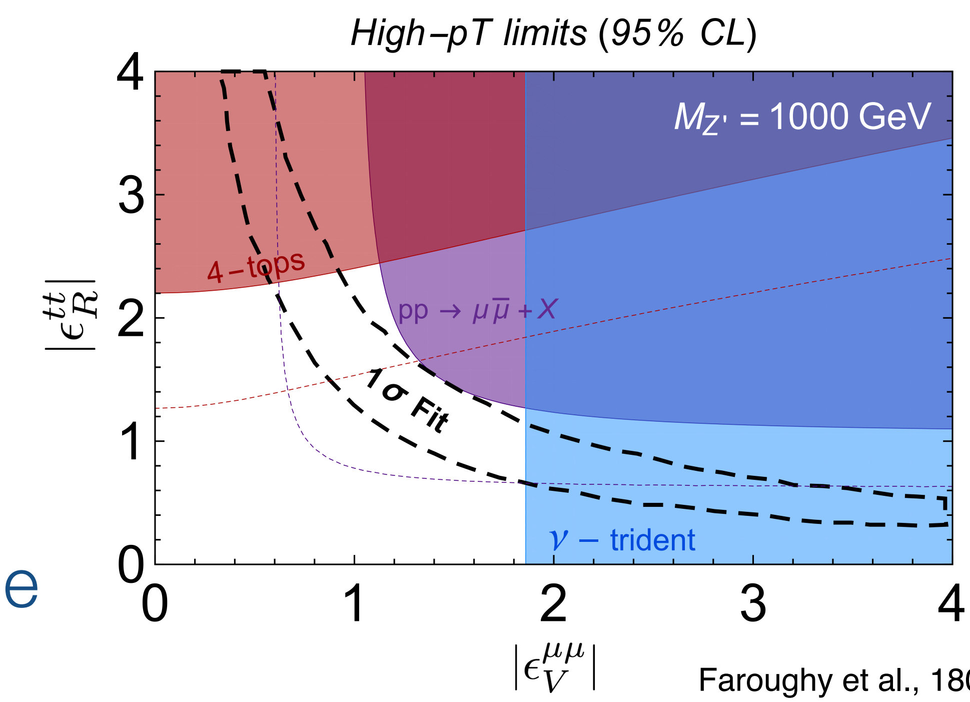
(similar mechanism possible to induce muon $U(1)'$ charge)

Complementary constraints:

- Flavor (LHCb, BelleII)
- LHC top & muon production
- Low energy colliders: neutrino trident

Existing experiments should confirm/exclude



Faroughy et al., 1805.04917