BEAUTY 2019

18th INTERNATIONAL CONFERENCE ON B-PHYSICS AT FRONTIER MACHINES

Flavor at low and high p_T

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Outline

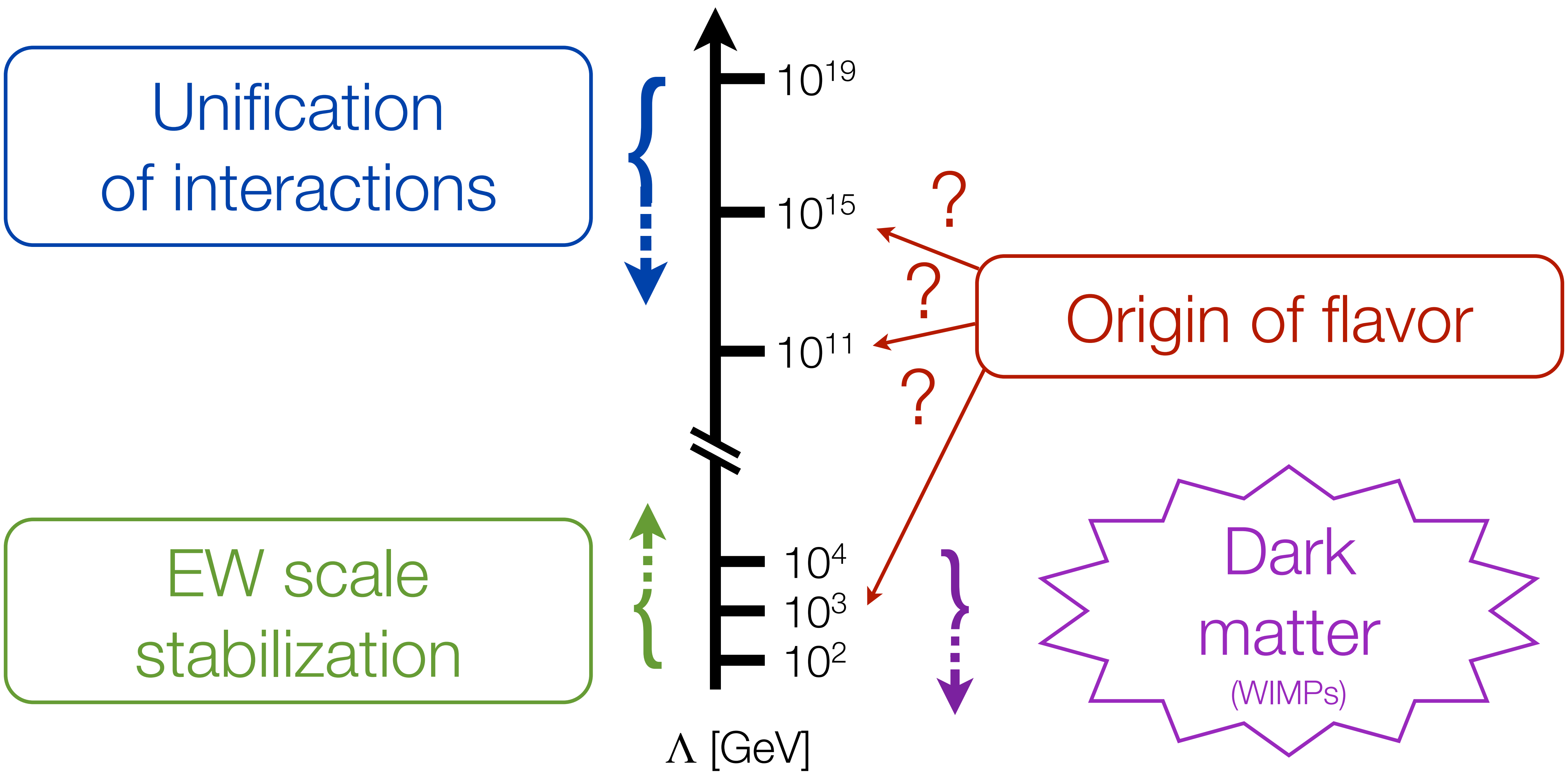
Flavor & high p_T physics interplay in several ways

- Complementary constraints on NP models from low energy precision observables vs. high p_T searches
- Nontrivial flavor structure affects collider signatures & reach
- Anomalies in *B*/*D*/*K* physics motivate NP searches at high p_T

Flavor bounds on NP vs. LHC reach

SM as EFT:

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



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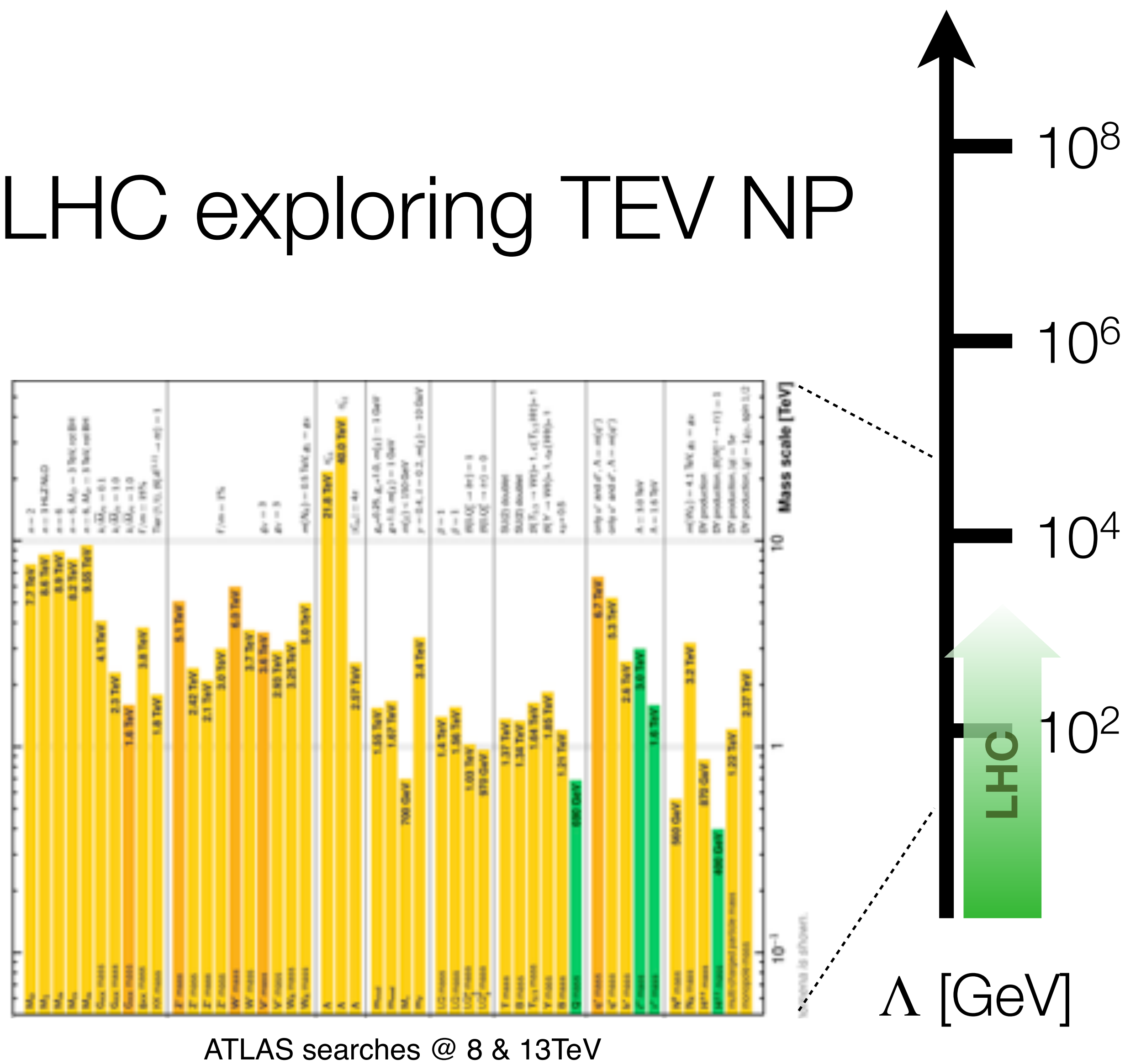
- LHC exploring TEV NP



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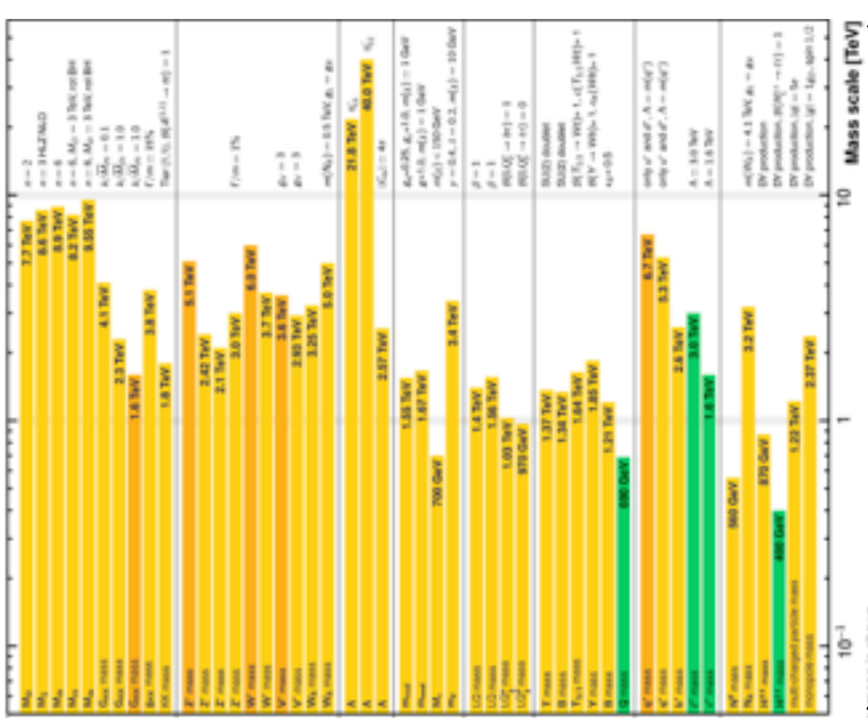
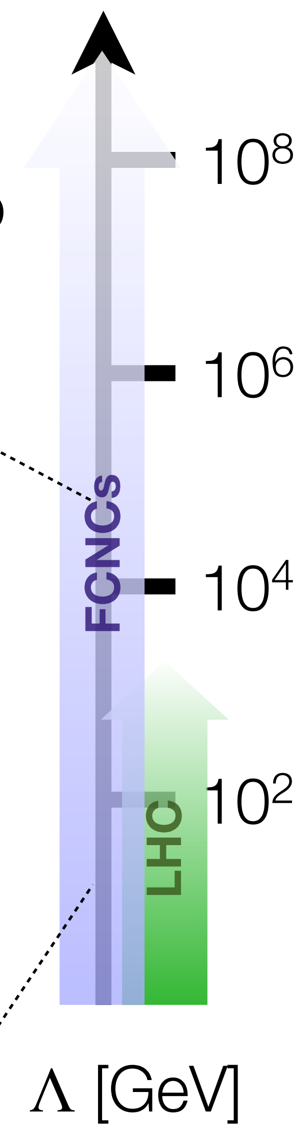
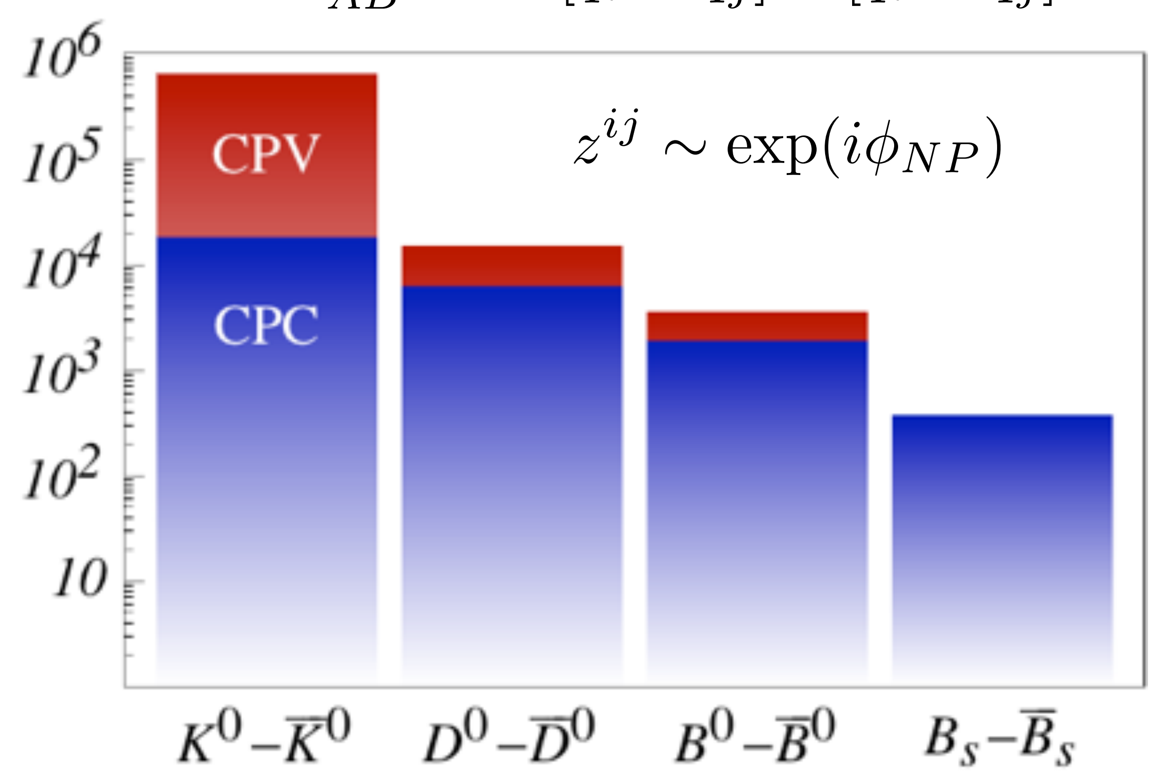


ATLAS searches @ 8 & 13TeV



Λ[TeV] $\mathcal{Q}_{AB}^{(6)} \sim z^{ij}[\bar{q}_i \Gamma^A q_j] \otimes [\bar{q}_i \Gamma^B q_j]$



- For generic NP flavor severe indirect bounds

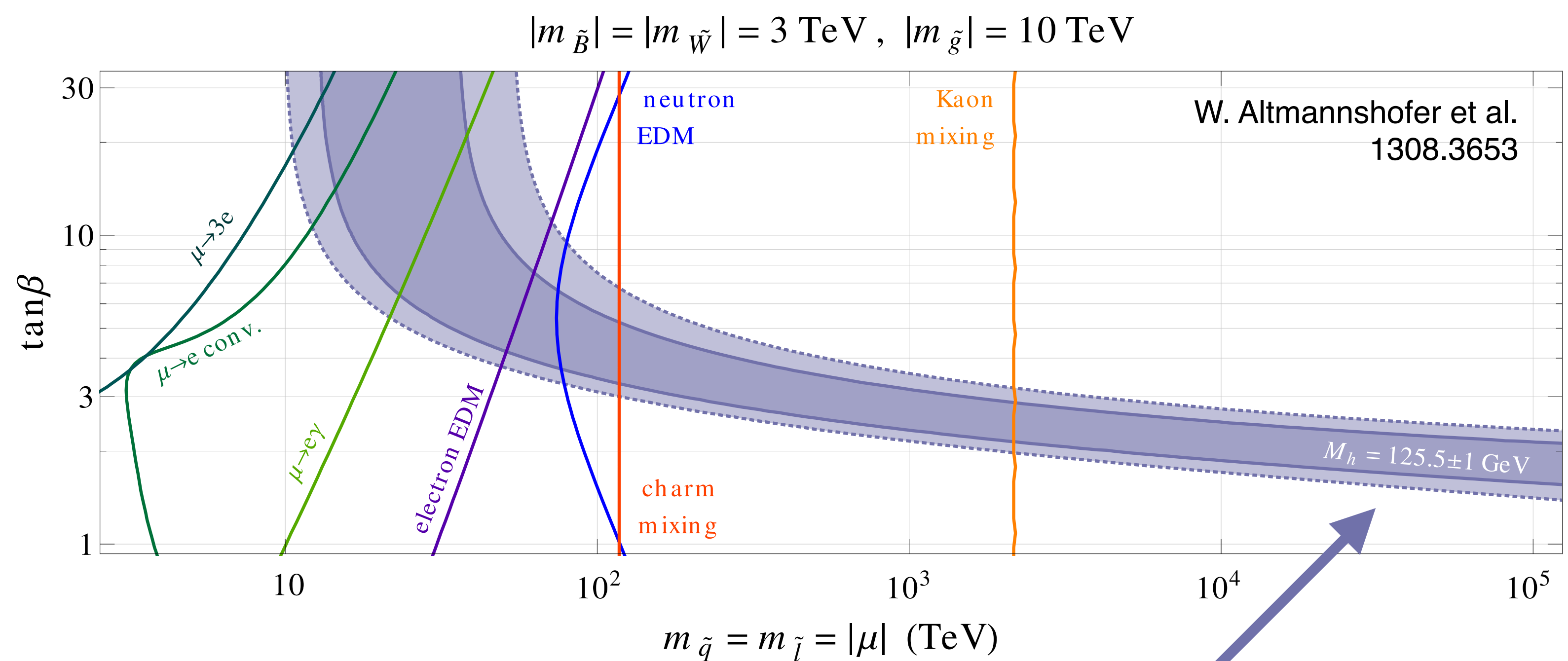
see e.g. UTFit 1411.7233
ETM 1505.06639
Fermilab Lattice & MILC, 1706.04622

LHC bad dream scenario: (mini)split SUSY

NP thresholds beyond direct reach

Flavor (& CPV) powerful probes of PeV sfermions

(motivated by Higgs mass)



$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3m_t^2}{4\pi^2 v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

$$m_Q^2 = m_{\tilde{q}}^2(\mathbb{1} + \delta_q^L)$$

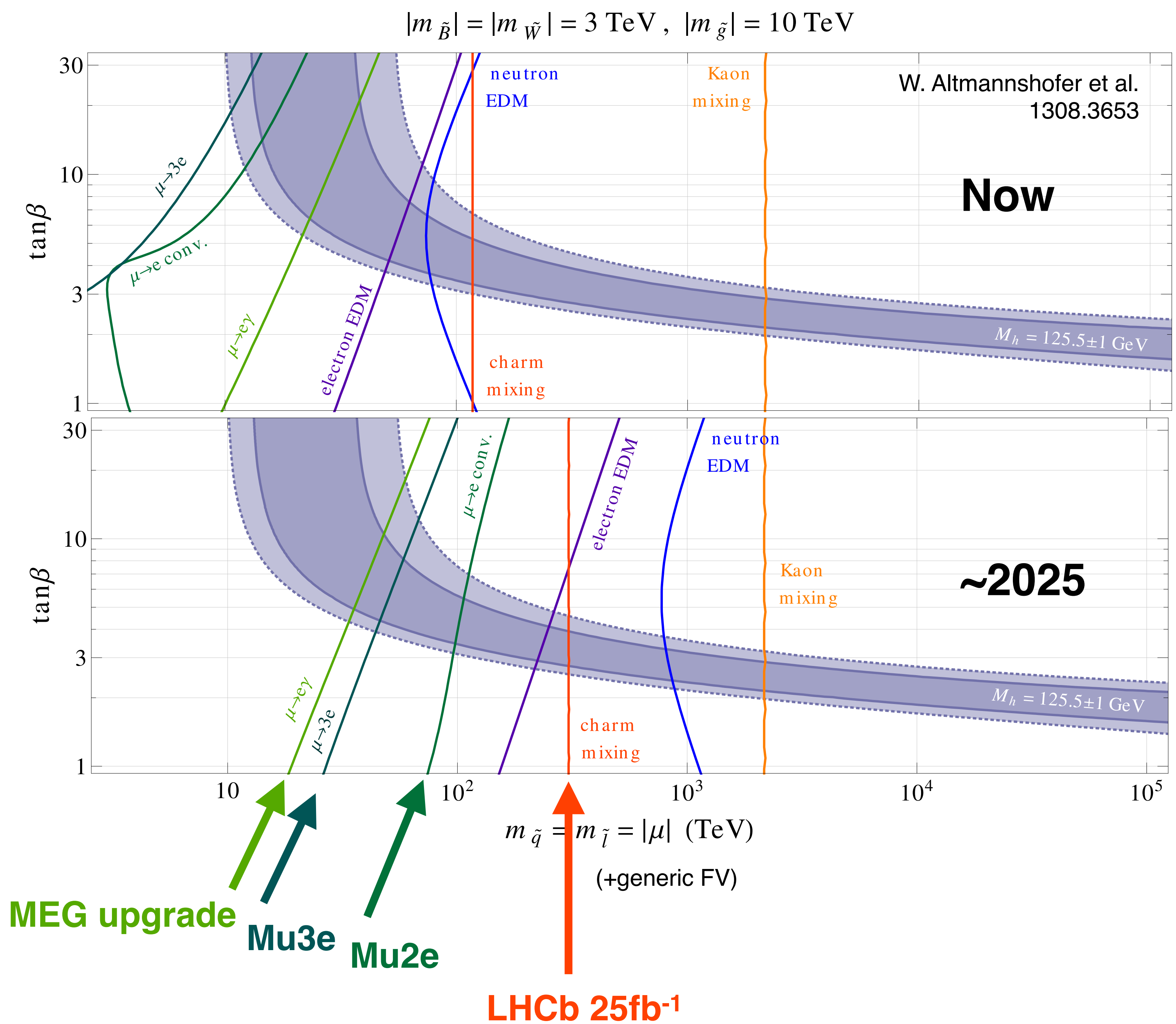
generic FV ~ O(1)

LHC bad dream scenario: (mini)split SUSY

NP thresholds beyond direct reach

Flavor (& CPV) powerful probes of PeV sfermions

Significant improvements expected in next decade



Flavor & high-p_T as complementary NP probes

Flavor safe NP? Flavor already broken in SM (Higgs).

$$\mathcal{H}_{mat} = \boxed{\frac{c^{IJ}_{RL}}{\Lambda^n} H^\dagger \bar{D}^I Q^J \times X + \frac{c^{IJ}_{LR}}{\Lambda^n} H \bar{Q}^I D^J \times X} + \boxed{\frac{c^{IJ}_{LL}}{\Lambda^n} \bar{Q}^I Q^J \times X + \frac{c^{IJ}_{RR}}{\Lambda^n} \bar{D}^I D^J \times X\,.}$$

Any (additional) scalar coupling to SM fermions introduces additional breaking (can be aligned with Higgs)

New (massive) vectors coupling to SM fermionic currents can preserve flavor

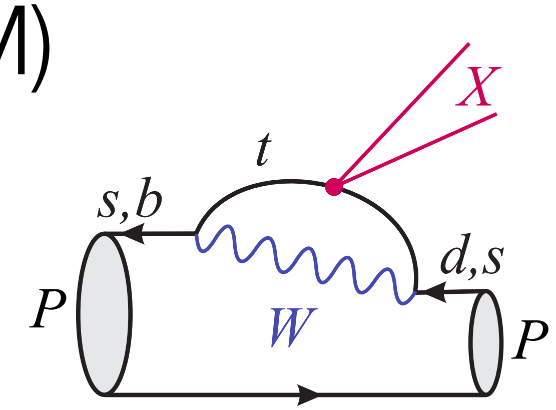
$\Rightarrow$ FCNCs loop & GIM suppressed (as in SM)

see e.g. J.F.K. & C. Smith 1111.6402

'MFV'

D'Ambrosio et al. hep-ph/0207036

$$c^{IJ} \to (g/(4\pi))^2 V^*_{tI} V_{tJ} \times c^{33}$$



Flavor & high-p_T as complementary NP probes

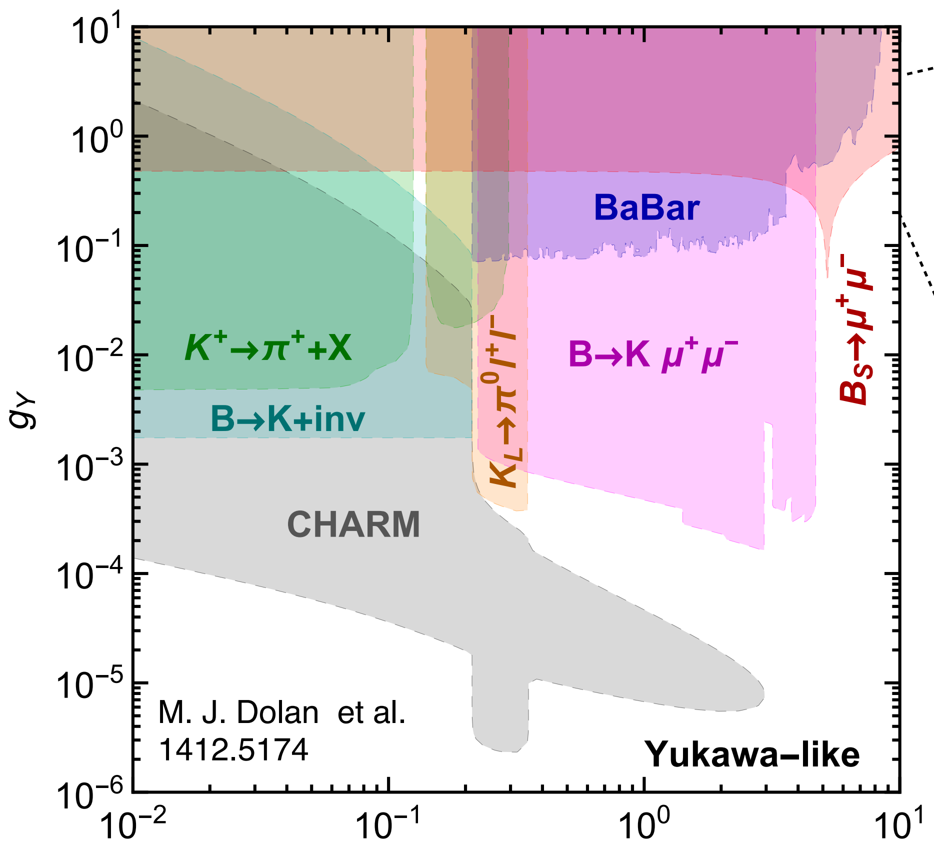
Example: simplified DM models with (pseudo)scalar mediators

$$\mathcal{L}_{\rm DM} = i\, g_\chi\, A\, \bar\chi \gamma^5 \chi + \sum_{f=q,\ell,\nu} i\, g_f\, A\, \bar f \gamma^5 f$$

- Direct DM detection suppressed
- SM Yukawa-like couplings: $g_f = \sqrt{2}\, g_Y\, m_f / v$
- No missing E_T signals for $m_\chi > m_A/2$

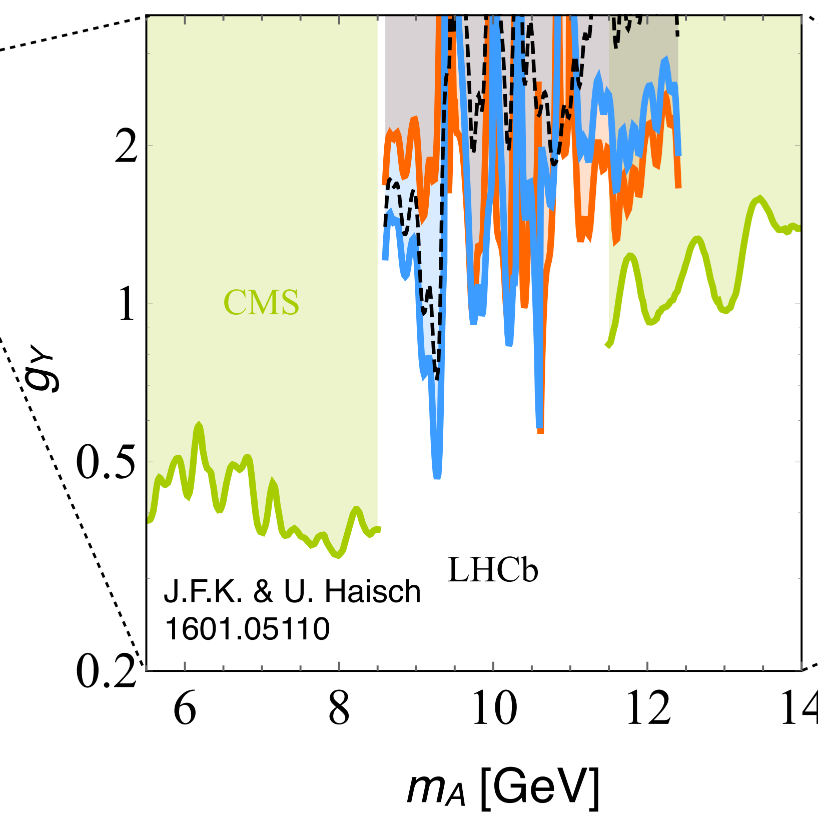
Flavor & high-p_T as complementary NP probes

Example: simplified DM models with (pseudo)scalar mediators



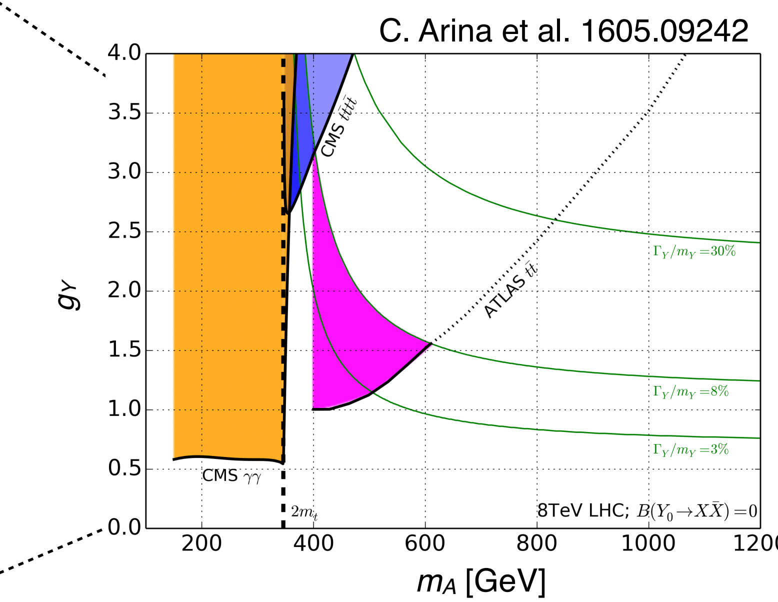
see also
Dobrich et al.,
1810.11336

FCNCs dominate bounds at low m_A



$pp \to A \to \mu^+\mu^-$ search for $m_A \sim (10-50)\,\mathrm{GeV}$

recently improved by LHCb, 1805.09820



High-pT searches for $m_A \gtrsim 50\,\mathrm{GeV}$

see also Banerjee et al., 1705.02327

Flavor probes of the Higgs sector

generation of masses in SM through Higgs mechanism

⇒ Higgs has hierarchical couplings to fermions

$$y_f^{\mathrm{SM}} = \sqrt{2} m_f / v$$

How well have we tested this?

A. Dery et al., 1302.3229

- proportionality $y_{ii} \propto m_i$
- factor of proportionality

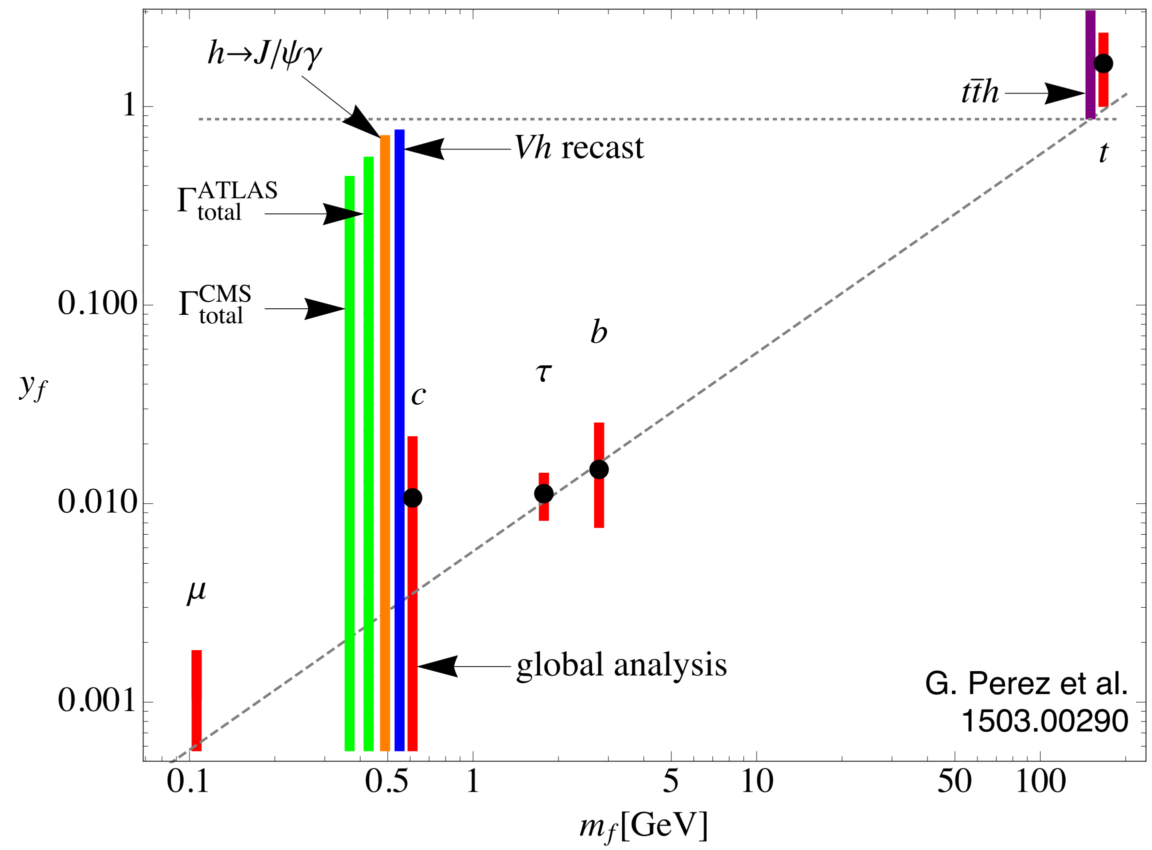
$$y_{ii}/m_i = \sqrt{2}/v$$

- diagonality $y_{ij} = 0, \quad i \neq j$

G. Blankenburg et al., 1202.5704,
R. Harnik et al., 1209.1397, …

- CP nature: $h \bar{f} f$ vs. $h \bar{f} \gamma_5 f$

R. Harnik et al., 1308.1094
J. Brod et al., 1310.1385
J. Ellis et al., 1312.5736 …



Many proposals… 1306.5770, 1406.1722, 1503.04830, 1505.03870, 1505.06689, 1507.02916, 1606.09621, 1611.05463 …

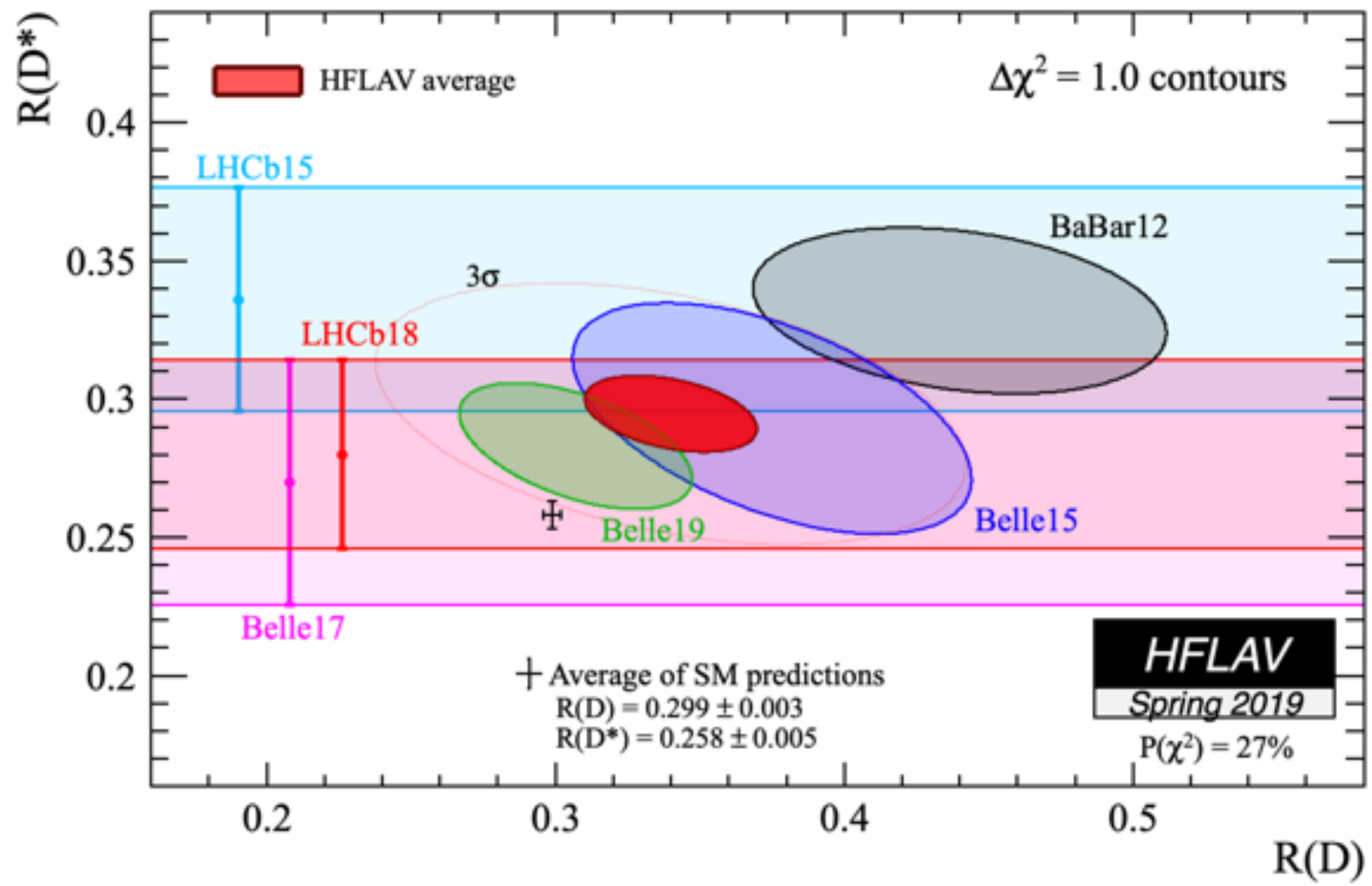
Flavor anomalies motivate high-p_T searches

Semileptonic B anomalies: LFU in charged currents

see talks by Tilley, Hara

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

$^{*}R(B_c \to J/\psi)$
LHCb, 1711.05623



Intriguing exp. situation: O(3σ) combined tension with SM

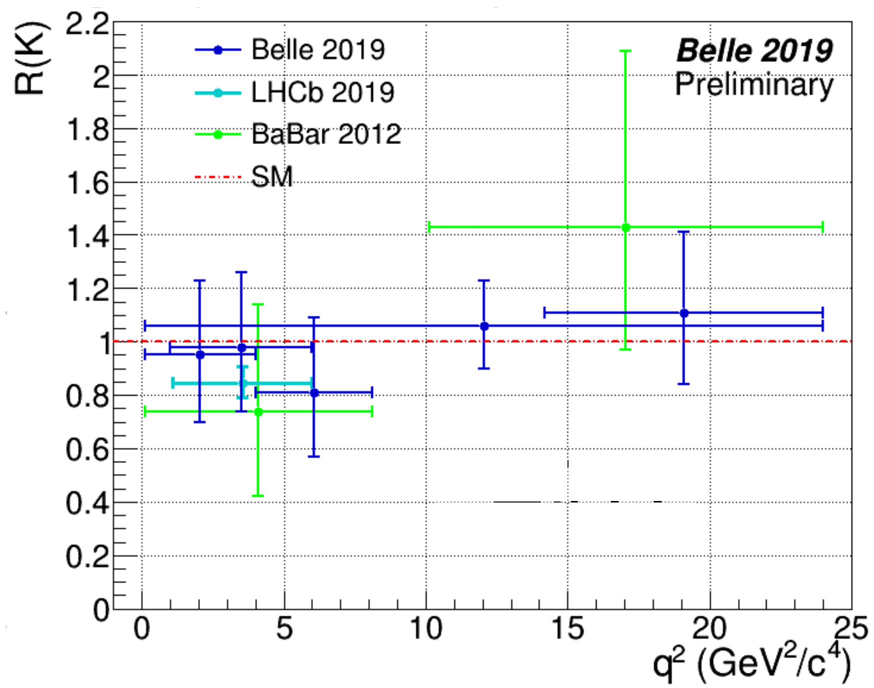
~20% (upwards) deviation!

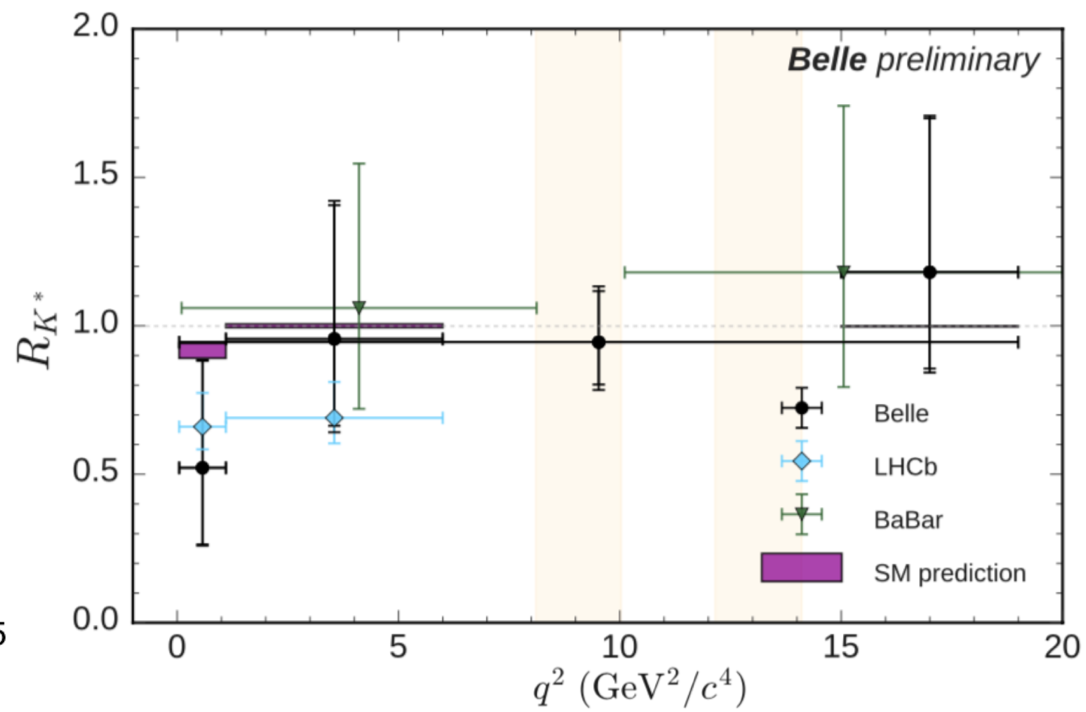
see also talk by Kitahara

Flavor anomalies motivate high-p_T searches

Semileptonic B anomalies: neutral currents

see talks by Langenbruch,Watanuki





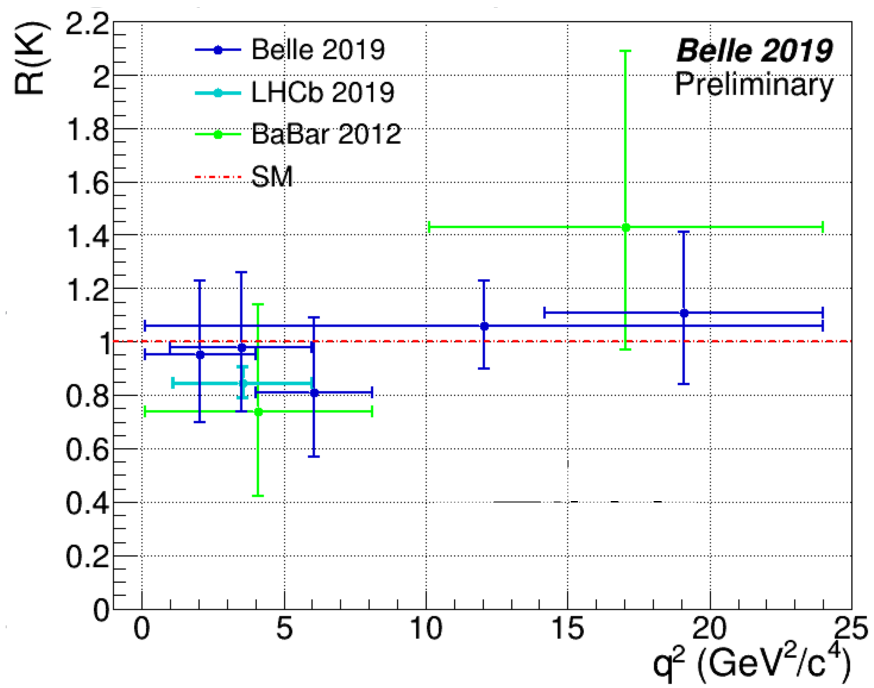
at O(2.5σ), 20% (downwards) deviation!

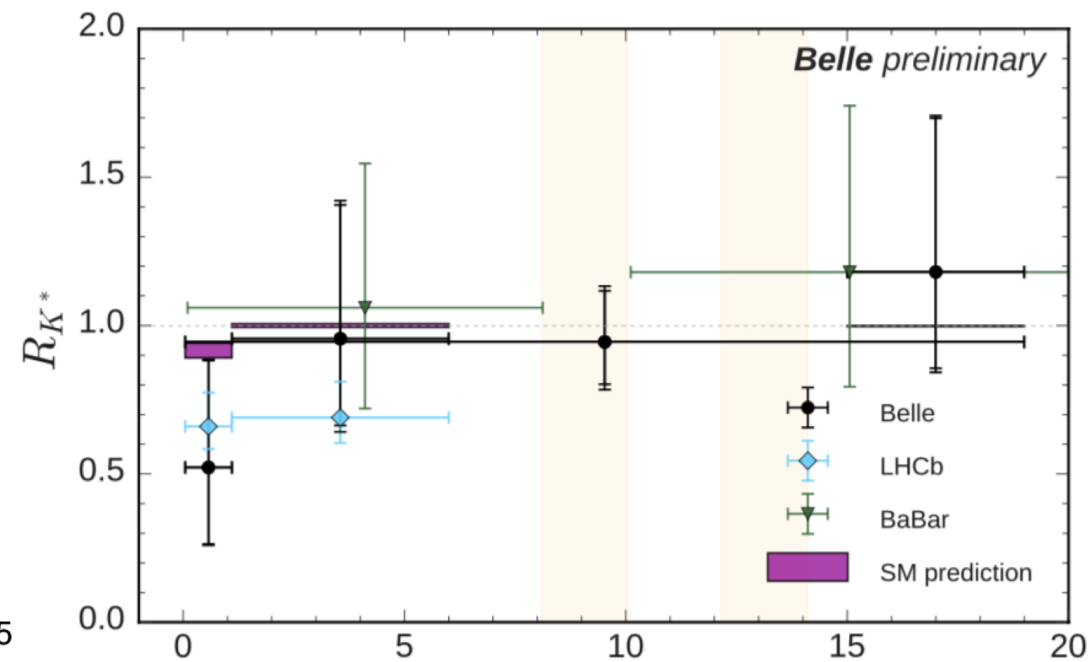
$$R_K = \frac{\int \mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}{\int \mathrm{d}\Gamma[B^+ \to K^+e^+e^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}$$

Flavor anomalies motivate high-p_T searches

Semileptonic B anomalies: neutral currents

see talks by Langenbruch,Watanuki

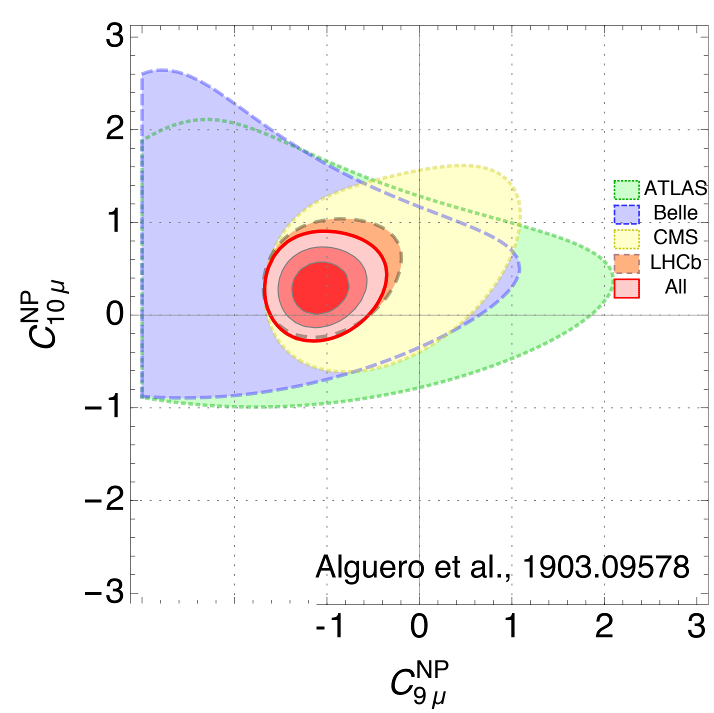




Corroborating evidence from angular analyses, rate measurements:

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i.\ell} (C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell) + \text{h.c.}\,,$$

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$



see talk by Descotes-Genon

Implications for high p_T: general considerations

B-anomalies in presence of (heavy) NP:

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

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

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*!

Implications of LFUV for NP flavor breaking

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
Blanke et al., 1811.09603
...

Buttazzo et al., 1706.07808

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

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

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

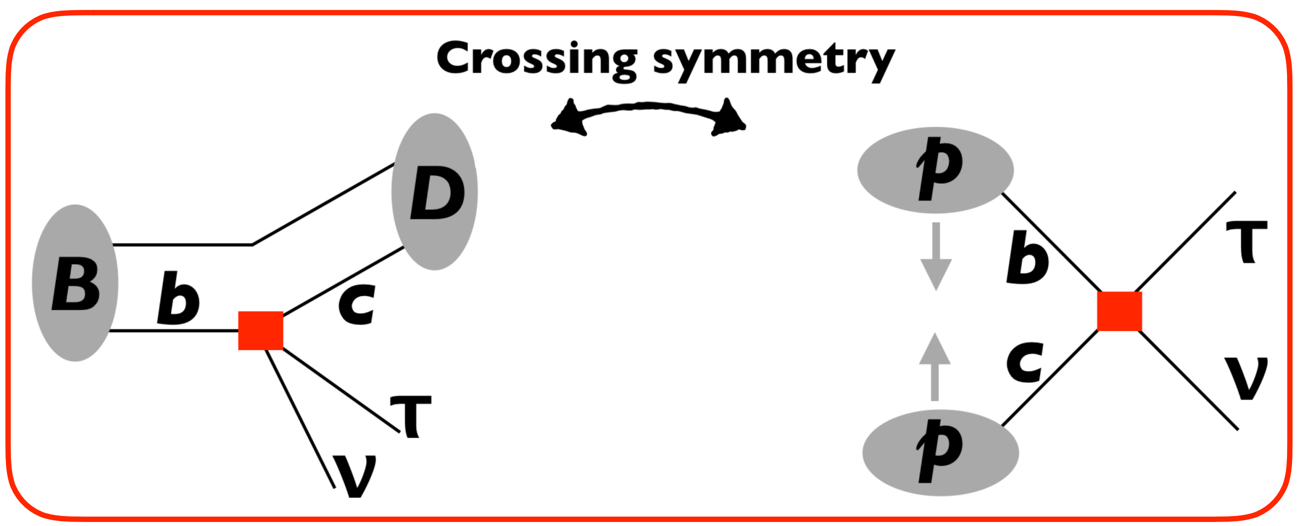
*right-handed currents
Greljo et al., 1804.04642
...

Simplest UV: Z'/W' LQ's $H^\pm$

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

Application of crossing - mono-tau production @ LHC

A. Greljo et al., 1811.07920



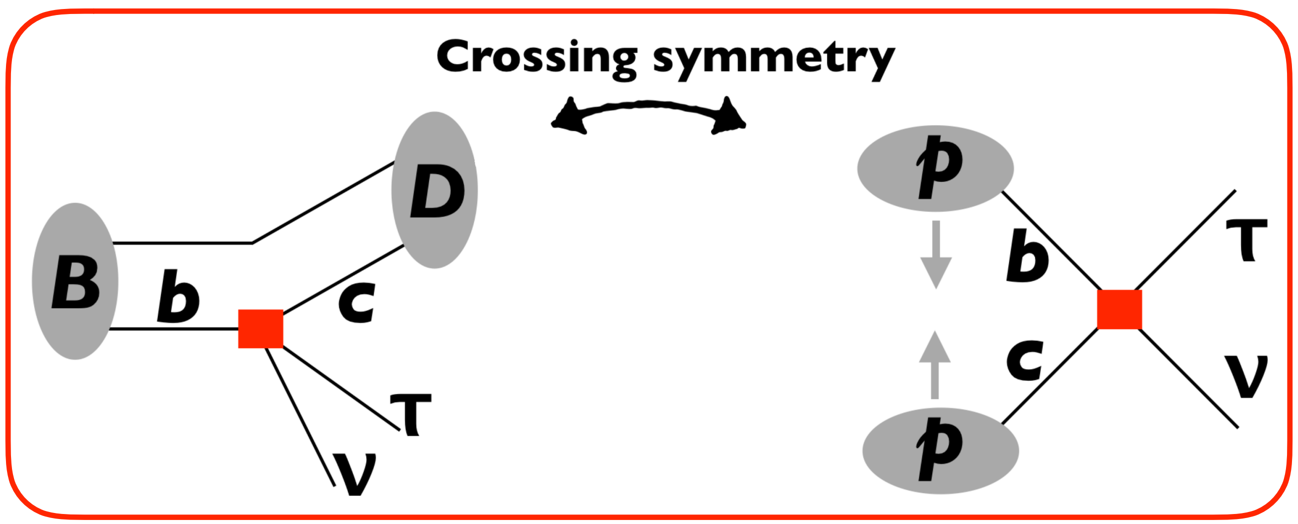
$$\sigma \sim \mathcal{L} \times \hat{\sigma}$$

✗ heavy flavour pdf. suppression $\mathcal{L}_{ij} \propto \int f_i(x) f_j(\hat{s}/sx) dx$

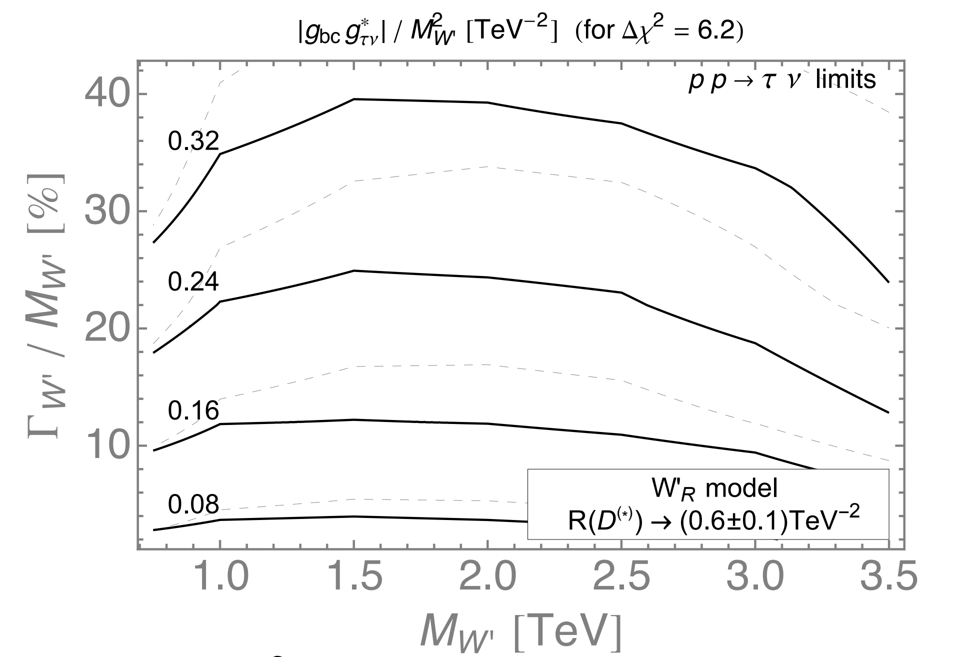
✔ compensated by high partonic energy $\hat{\sigma} \propto \left(\hat{s}/M^2\right)^2$

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

Application of crossing - mono-tau production @ LHC



A. Greljo et al., 1811.07920



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Excludes W_R-ν_R explanation, constrains some LQ scenarios

Implications of LFUV for NP flavor breaking

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

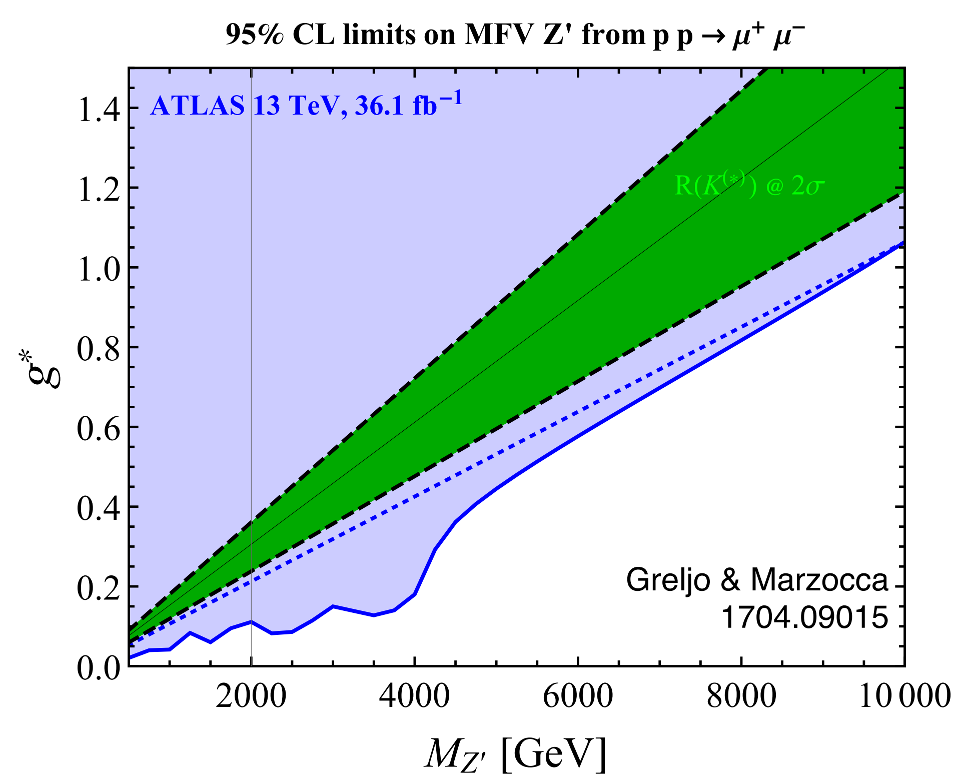
$U(2)_F$, MFV

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

Fajfer et al., 1206.1872
Bordone et al., 1702.07238

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

Not universal! High pT di-muon searches



Immediate implications for LHC

Flavor alignment 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

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

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

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

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

Well within LHC reach!

Still only marginally!

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

Enhanced LFUV in top processes:

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

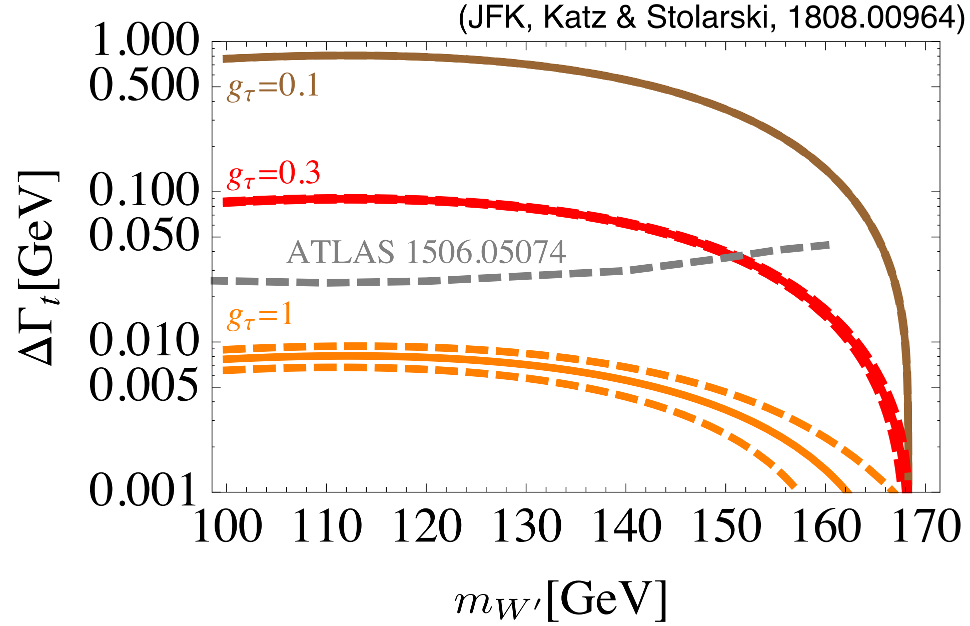
Currently tested to O(10%)

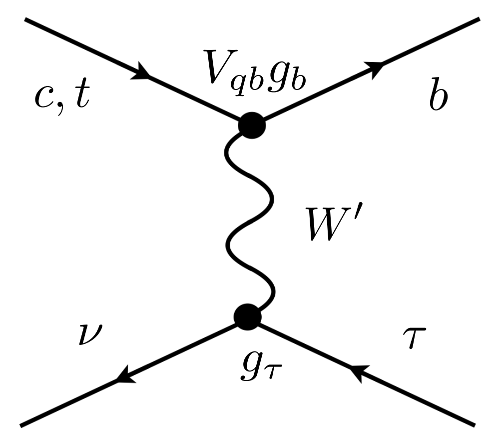
$$\mathcal{B}_e = 13.3(4)(4)\%\,,\ \mathcal{B}_\mu = 13.4(3)(5)\%\,,\ \mathcal{B}_{\tau_h} = 7.0(3)(5)\%\,,$$

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.

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

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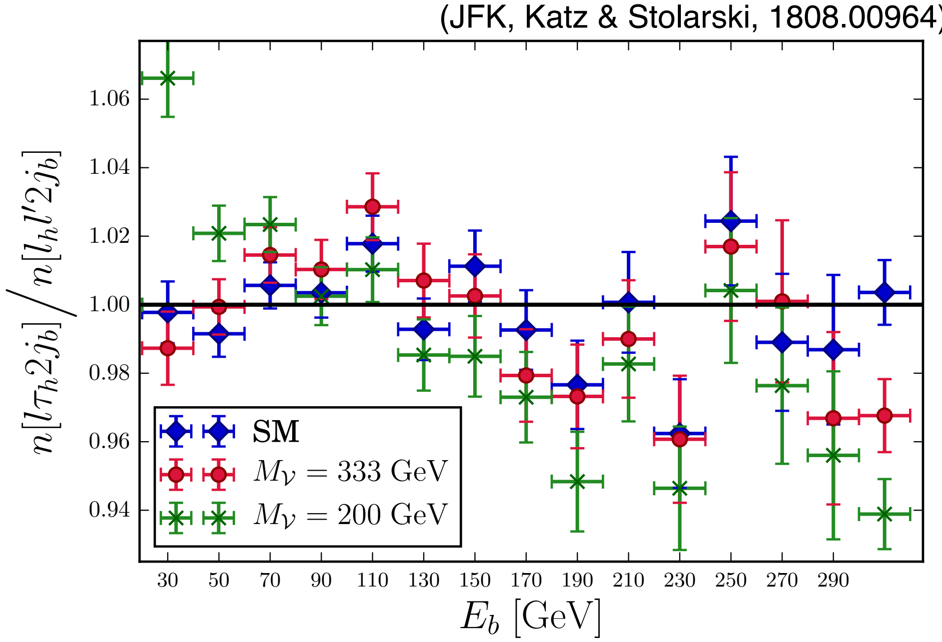


Features around the SM peak of b-jet energy distribution

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

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

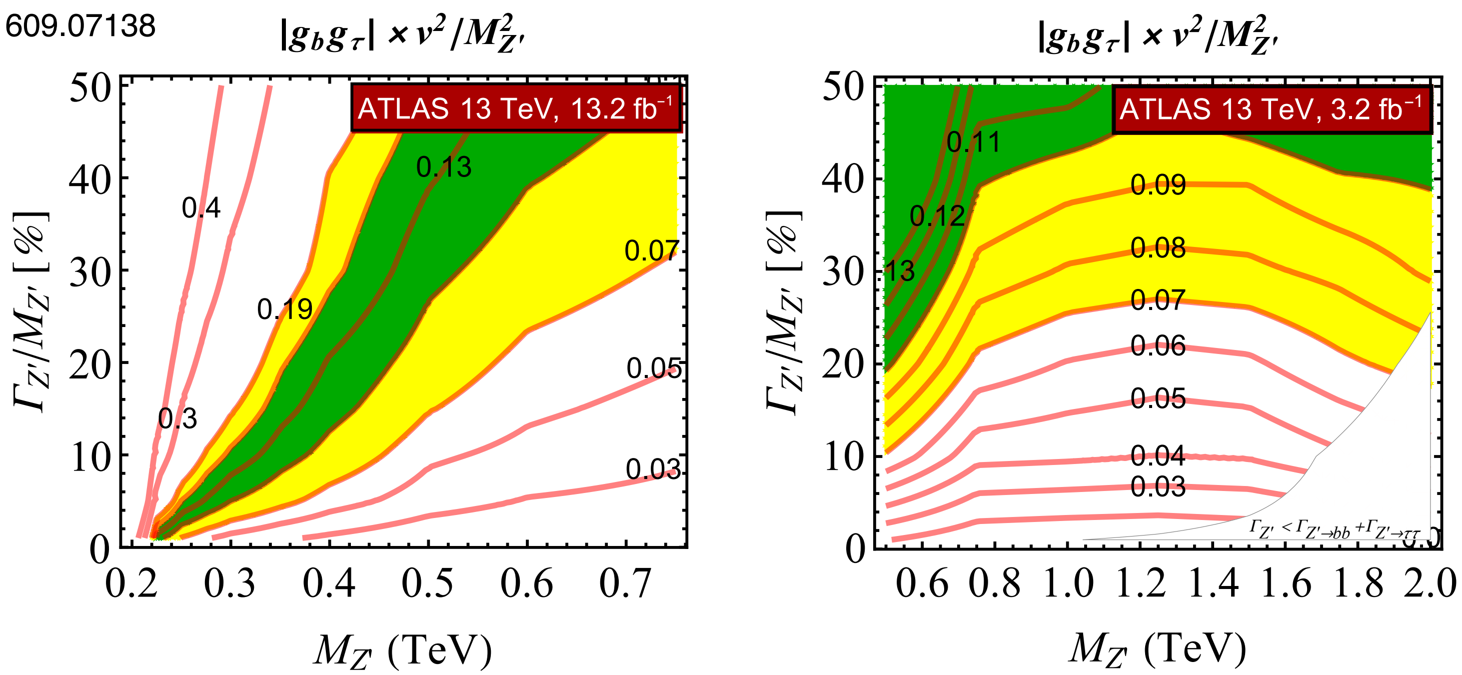
Immediate implications for LHC: $R(D^{(*)})$

Weak gauge invariance ⇒ neutral currents

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

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

Faroughy, Greljo & JFK, 1609.07138



W'/Z' explanation only allowed if light (M < 400 GeV) or broad (Γ/M > 20%)

Leptoquark, charged scalar explanations disfavored

Departures from strict $U(2)_F$ limit can ameliorate the bounds

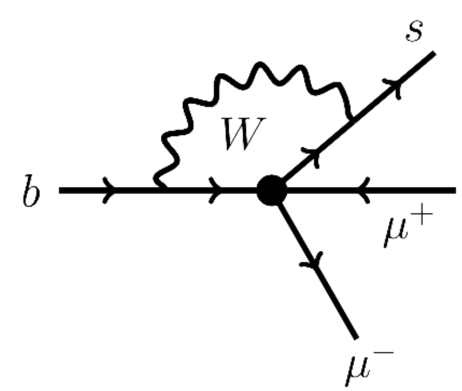
see e.g.
Buttazzo et al., 1706.07808

Importance of EW radiative corrections: B-anomalies without new quark flavor violation

Starting with flavor conserving non-universal operators:

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

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

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

JFK, Soreq & Zupan, 1704.06005

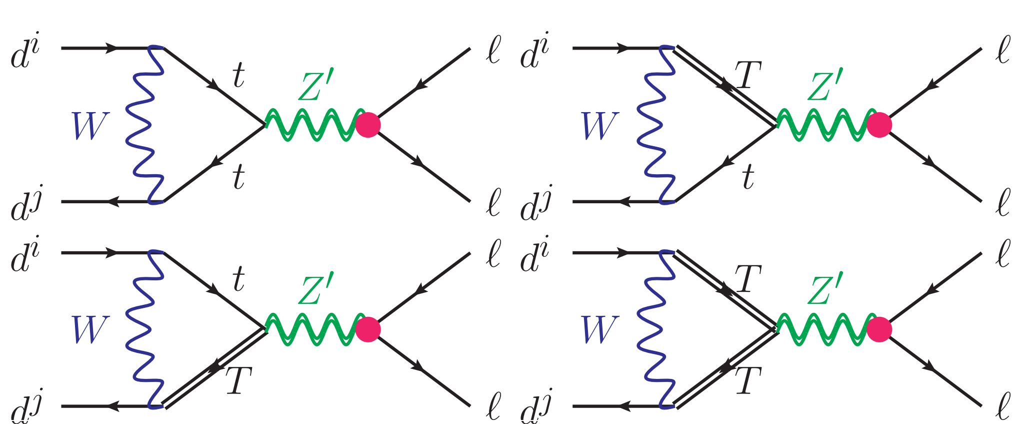
VL quark partner of right-handed top (T),

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

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

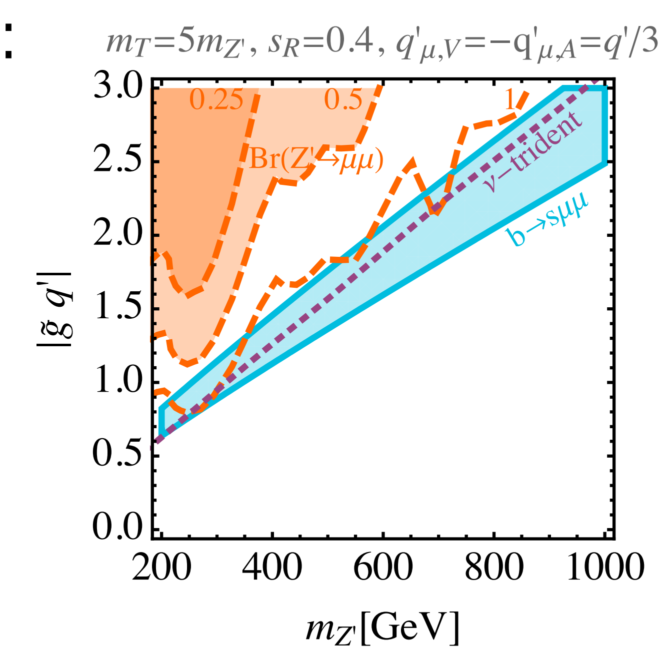
(similar mechanism possible to induce muon $U(1)$' charge)

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



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

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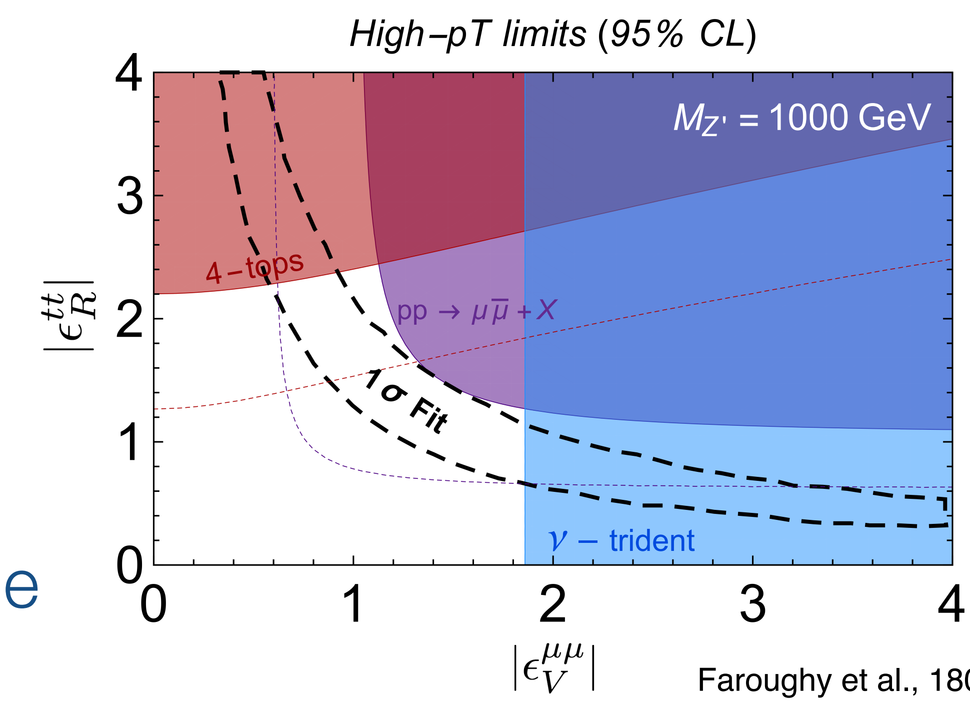
- T-t_R mix after $U(1)'$ breaking - induced $U(1)'$ charge of t_R

(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

Conclusions

Flavor is powerful guide to high-p_T searches at LHC:

- In case new phenomena are discovered at LHC, flavor physics will allow to disentangle different possible interpretations and discriminate between different proposals and scenarios

Example: 125GeV Higgs

- In case no new d.o.f.s are seen at LHC, precision tests of flavor, CP, B & L possibly best probes forward

$\Longrightarrow$ their sensitivity in many cases already (far) exceeds energies/scales attainable in present and planned collider & cosmic ray experiments.

Conclusions

Flavor is powerful guide to high-p_T searches at LHC:

- In case of significant signals of NP in flavor observables can identify prospective LHC experimental targets

Generally, NP d.o.f.'s accommodating tentative B-anomalies could be beyond LHC reach.

Phenomenological and model-building considerations point towards more optimistic scenarios

- Low energy constraints can point to lighter mediators!
- Example of fruitful interplay between NP searches at energy and intensity frontiers