Kobayashi-Maskawa Institute for
the Origin of Particles and the Universe

Interplay Between LHC and Flavor Physics

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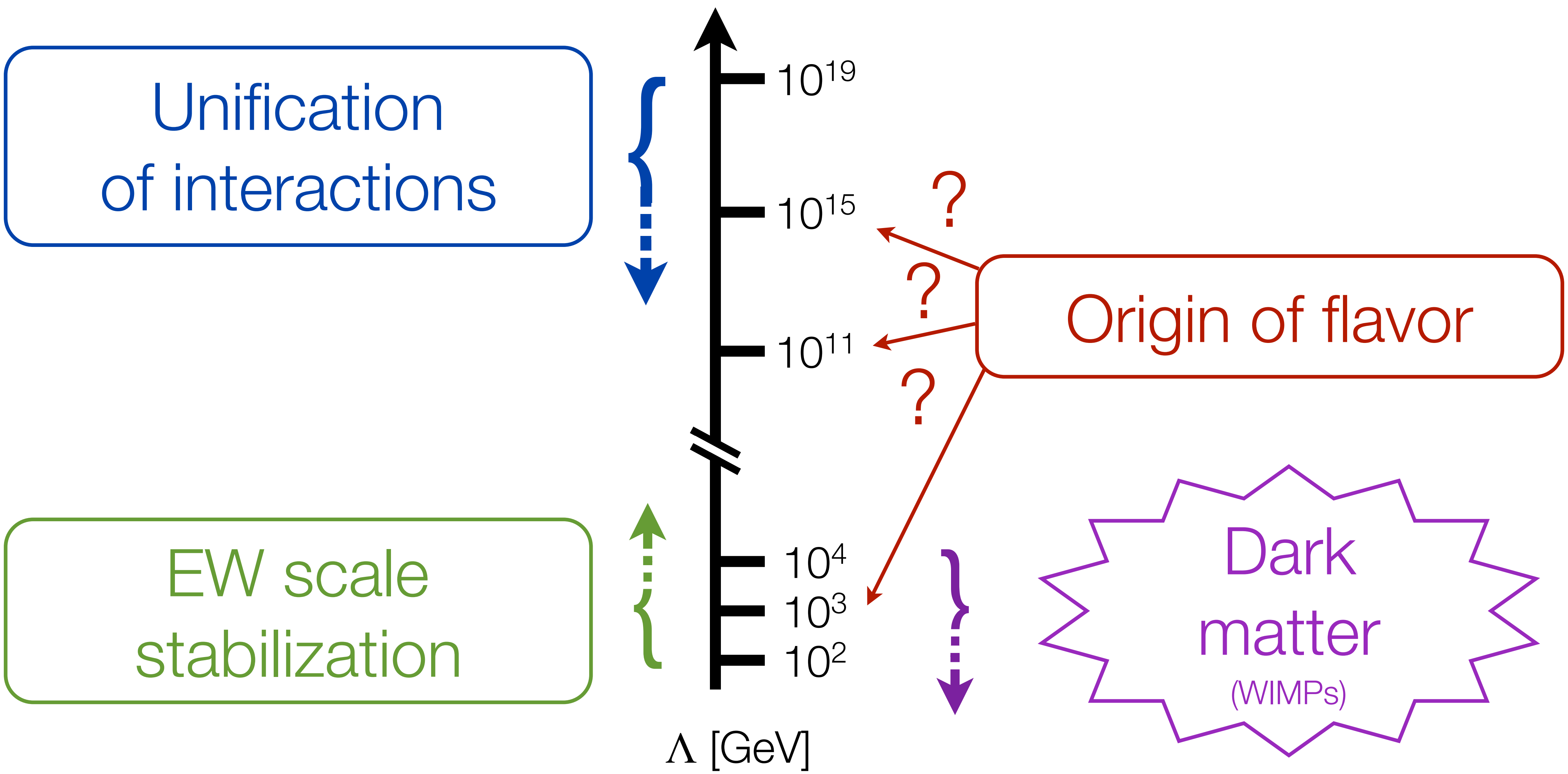
Outline

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 modifies signatures at LHC
- Anomalies in *B*/*D*/*K* physics motivate NP searches at high p_T
  - goes also the other way (e.g., $h \to \tau\mu$)

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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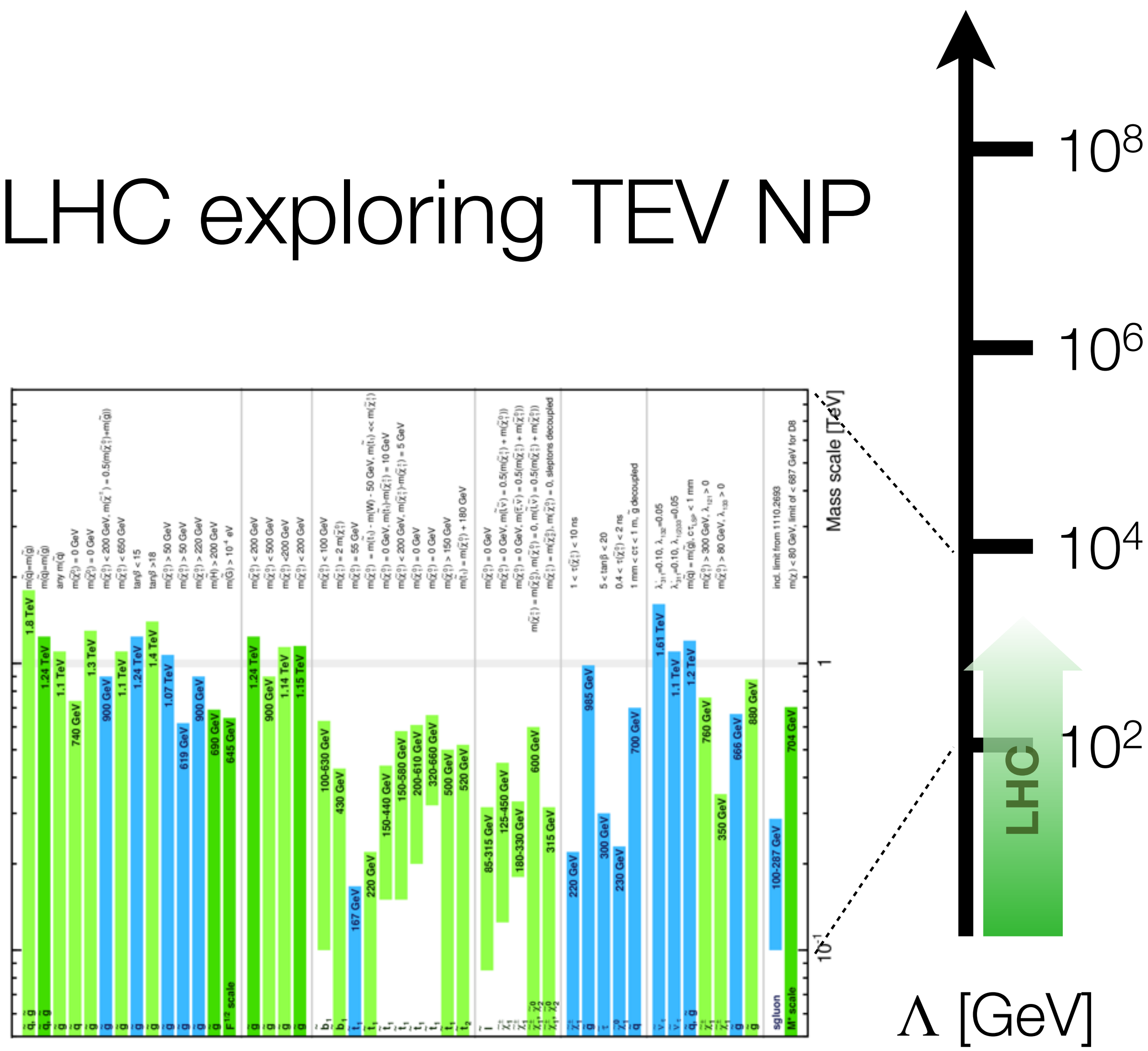
- LHC exploring TEV NP



ATLAS SUSY searches @ 8TeV

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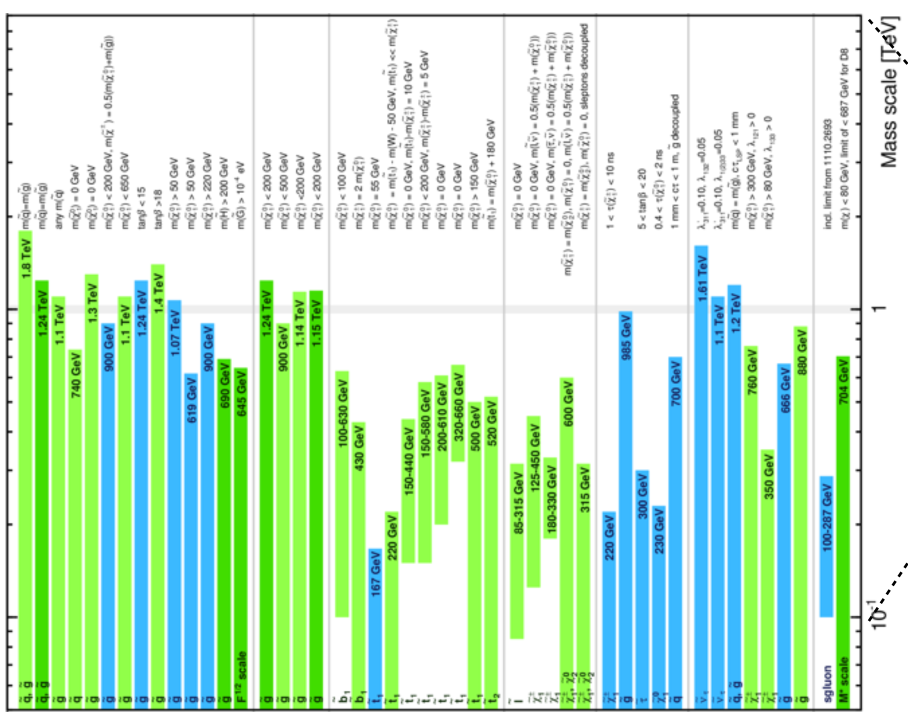
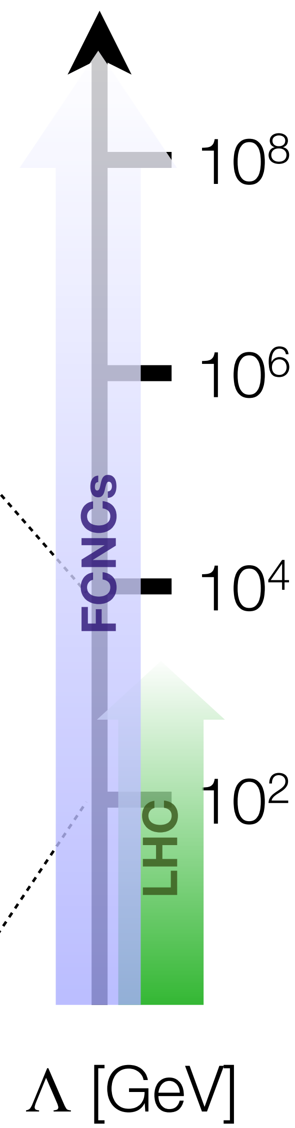
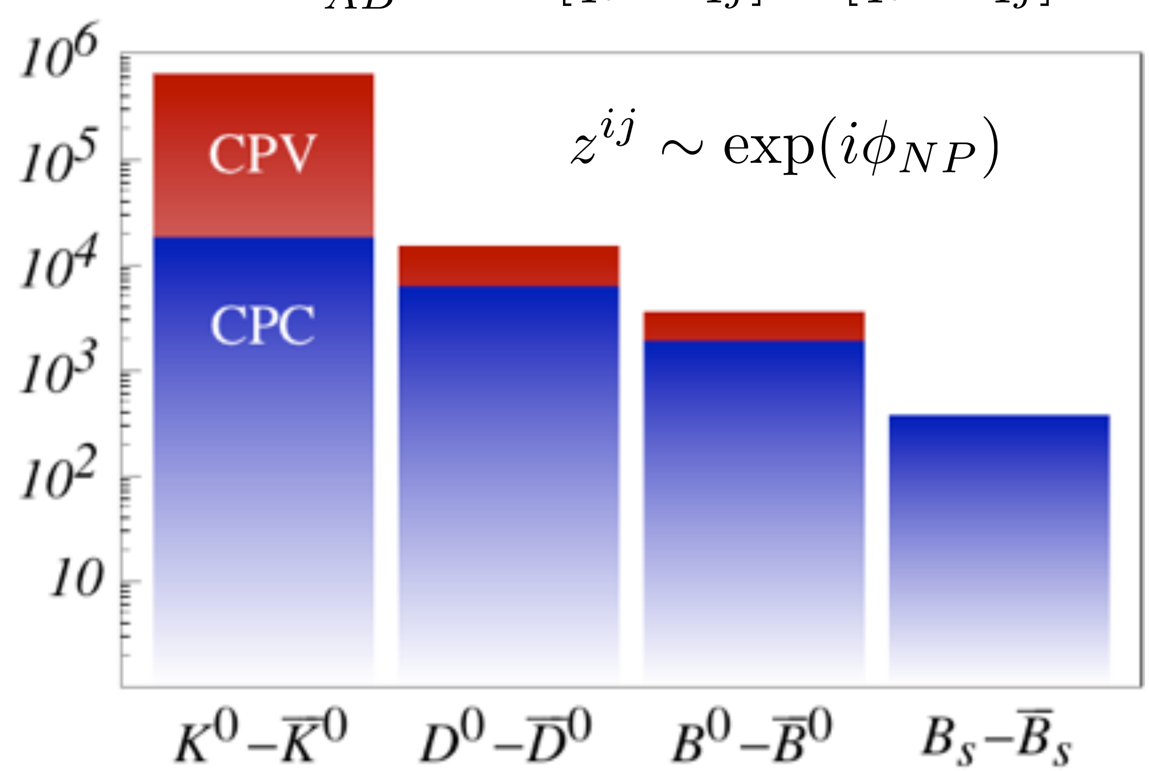


ATLAS SUSY searches @ 8TeV



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



- For generic NP flavor severe indirect bounds

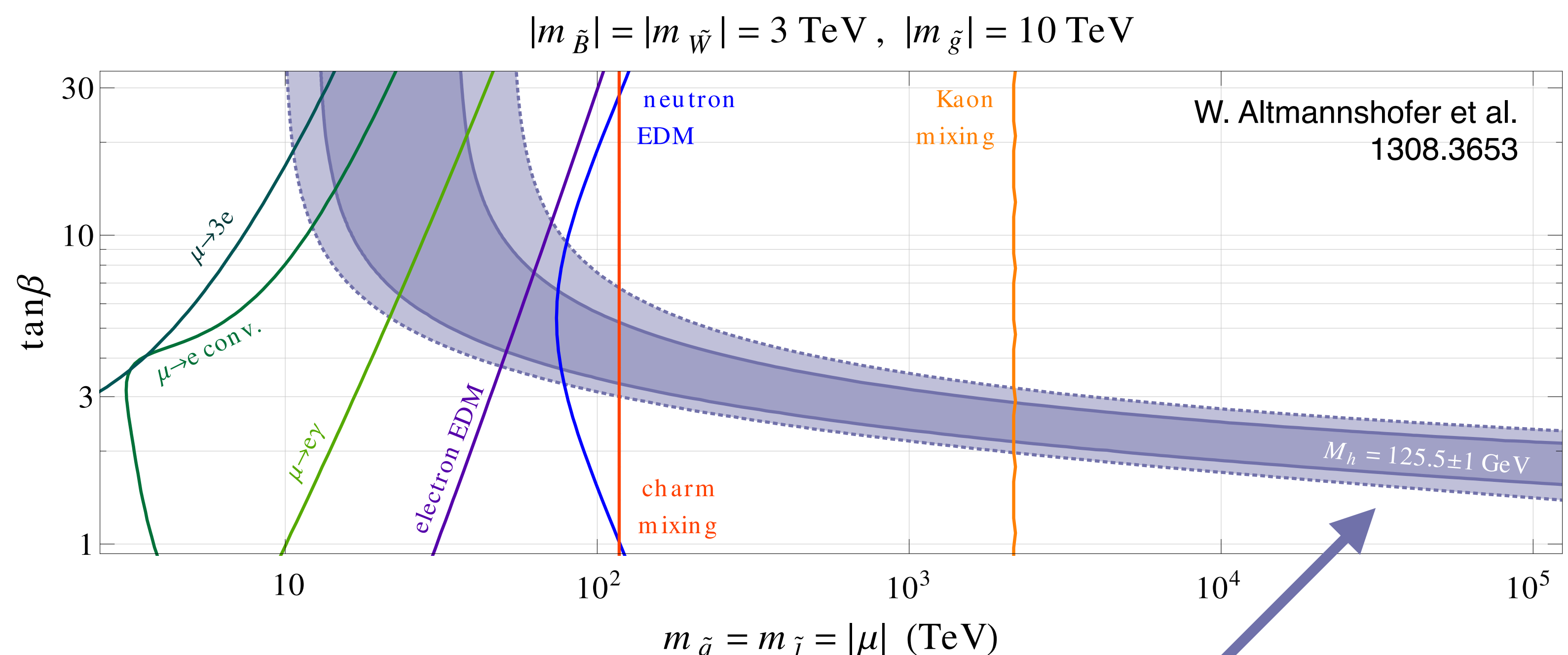
see e.g. UTFit 1411.7233
ETM 1505.06639

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

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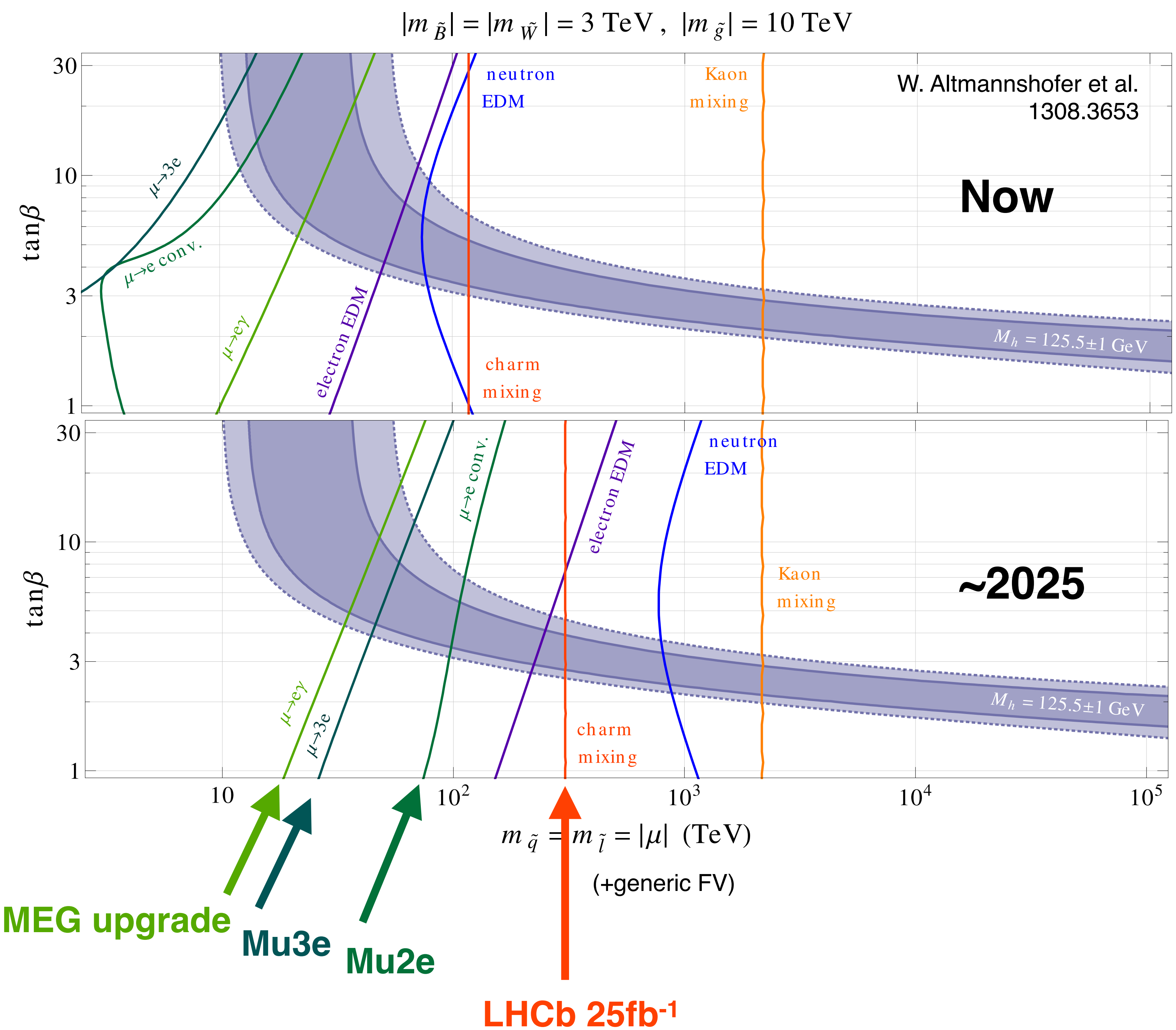
Flavor (& CPV) powerful probes of PeV sfermions

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

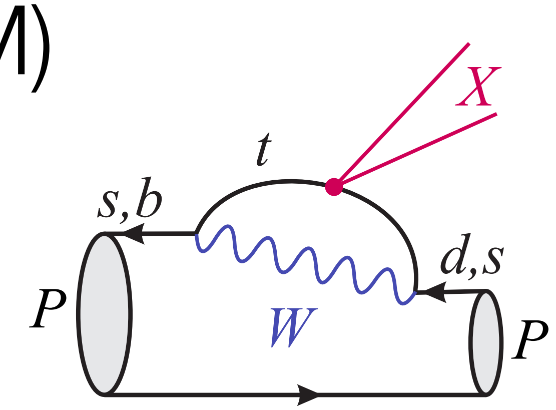
$\Rightarrow$ FCNCs loop & GIM suppressed (as in SM)

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

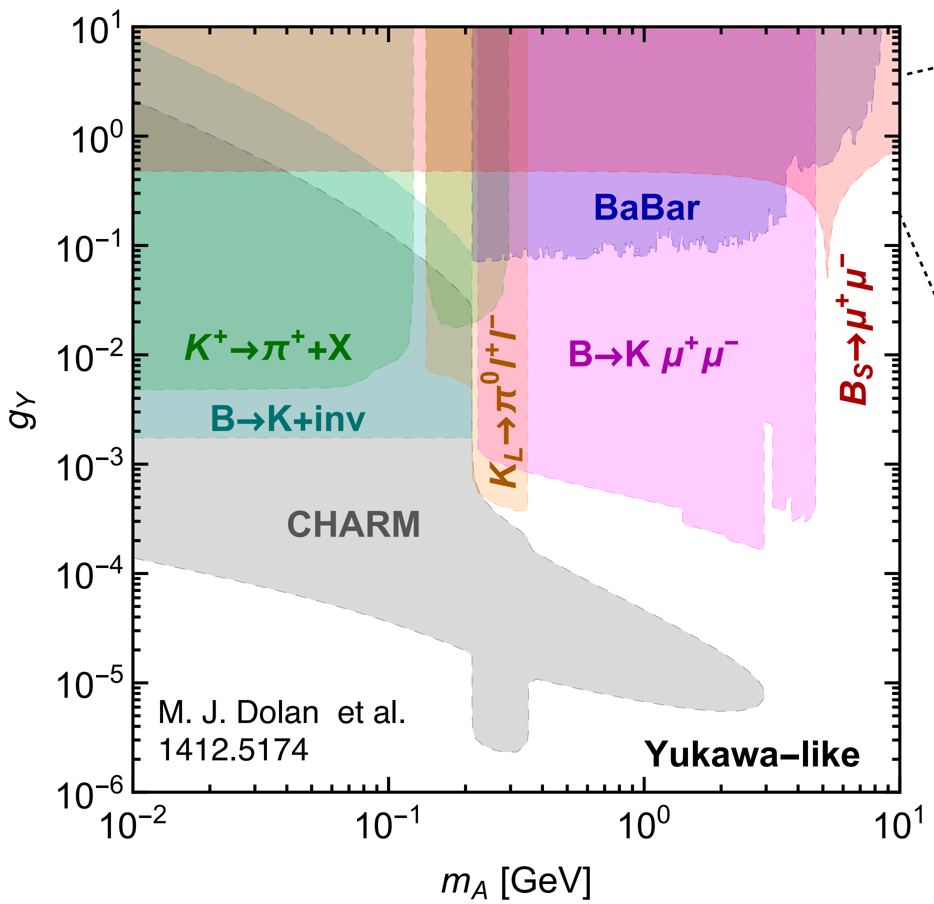
Example: simplified DM models with (pseudo)scalar mediators

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

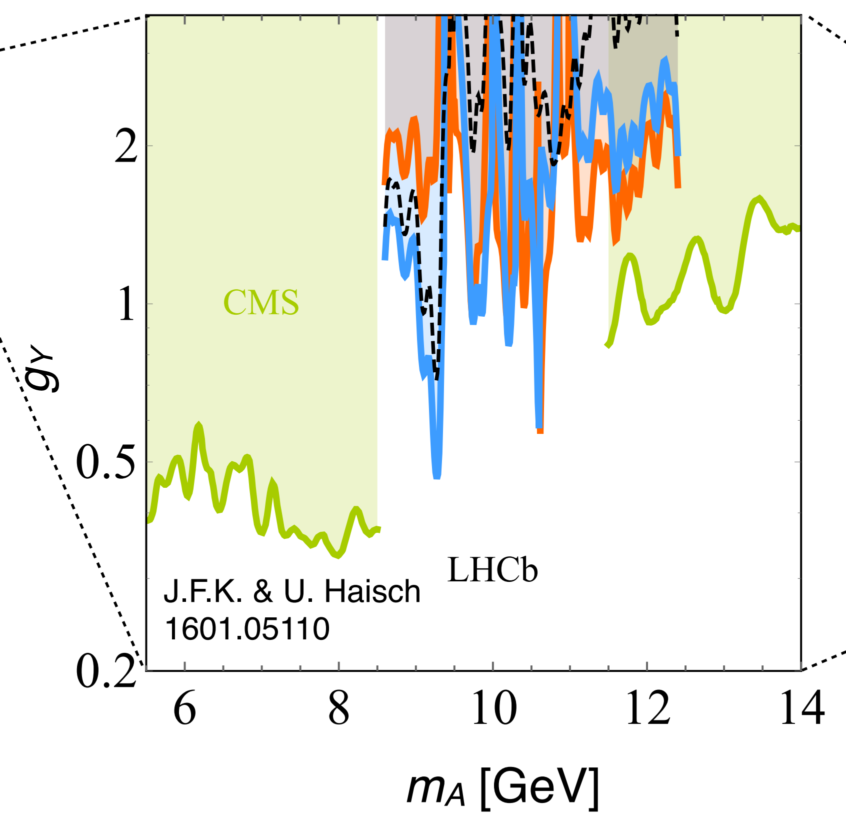
- Direct DM detection suppressed
- SM Yukawa-like couplings: $g_f = \sqrt{2}\, g_Y\, m_f/v$
- No missing E_T signals for $m_\chi > m_A/2$

Flavor & high-p_T as complementary NP probes

Example: simplified DM models with (pseudo)scalar mediators



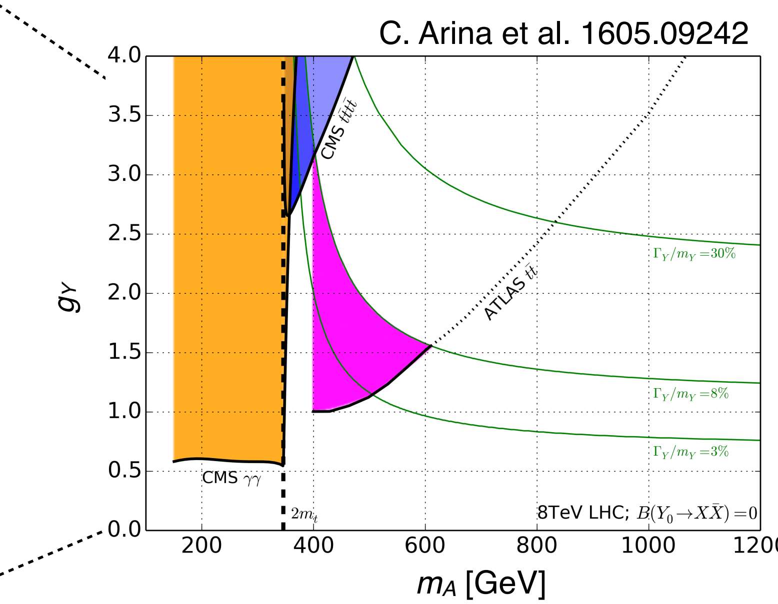
FCNCs dominate bounds at low m_A



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

(also possible at LHCb)

see also P. Ilten et al. 1603.08926



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

Flavor probes of the Higgs sector

generation of masses in SM through Higgs mechanism

⇒ Higgs has hierarchical couplings to fermions

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

How well have we tested this?

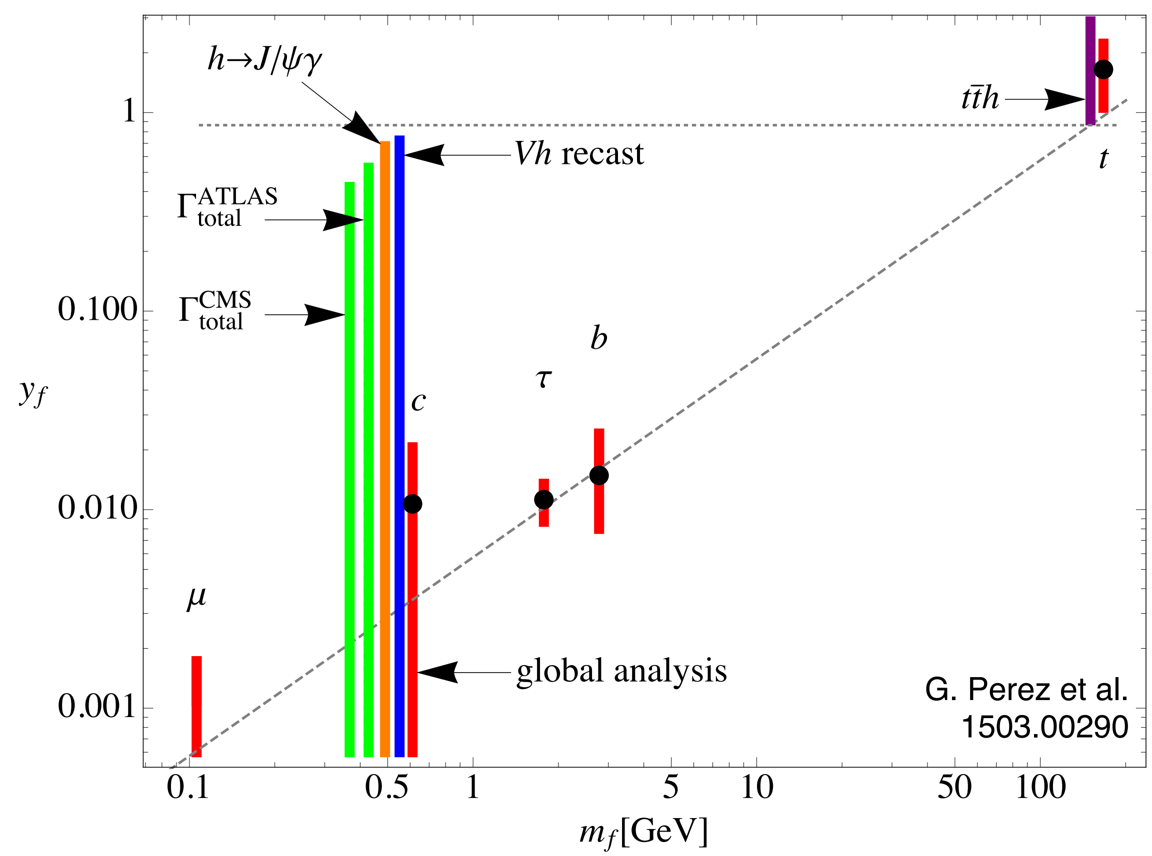
A. Dery et al., 1302.3229

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

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

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

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



Many recent proposals… 1306.5770, 1406.1722, 1503.04830, 1505.03870, 1606.09621

Lepton Flavor violating Higgs decays?

CMS @ 8 TeV observed a slight hint of an excess for

$$\mathrm{BR}(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\,\%$$ 1502.07400

ATLAS @ 8TeV & early CMS @ 13TeV have neither confirmed not excluded this excess.

1508.03372 CMS-PAS-HIG-16-005

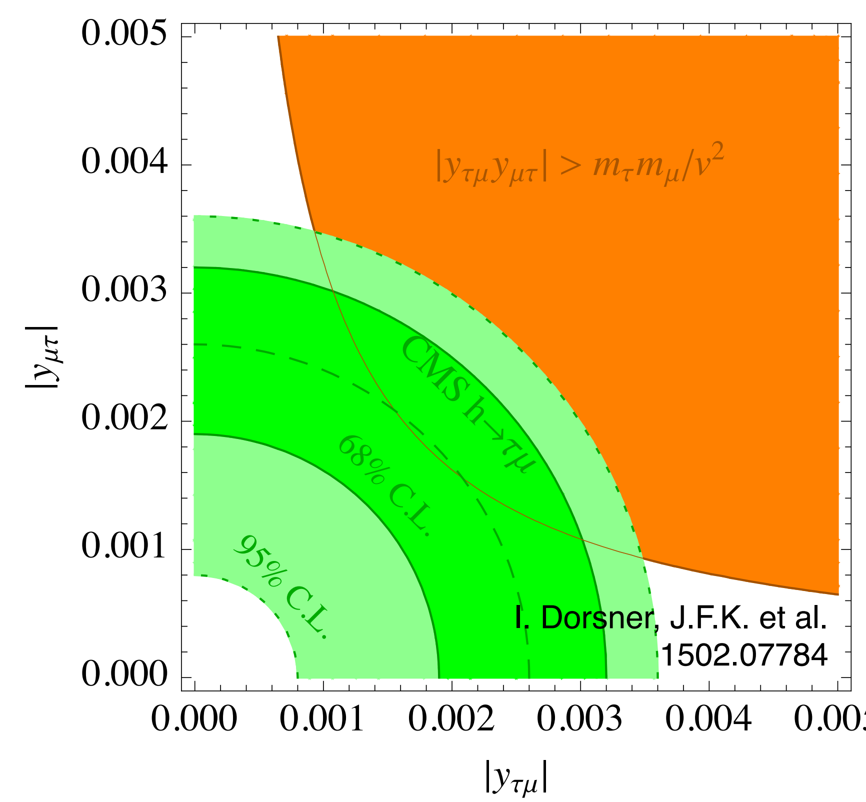
Can one have lepton flavor violating Higgs decays at ~1% level in reasonable NP models?

$$\mathcal{L}^{\mathrm{eff.}}_{Y_\ell} = -m_i \delta_{ij} \bar{\ell}^i_L \ell^j_R - y_{ij} \left(\bar{\ell}^i_L \ell^j_R\right) h + \ldots + \mathrm{h.c.}\,,$$

radiative stability of Yukawas

Ceng & Sher, PhysRevD.35.3484,
Branco et al., 1106.0034

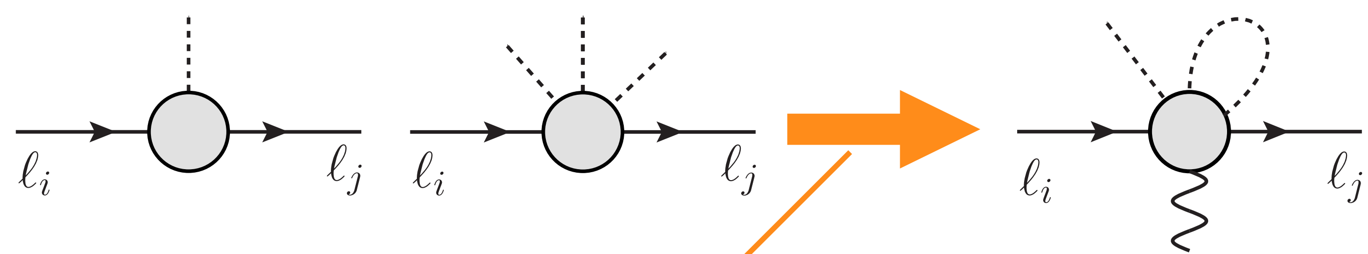
$$\sqrt{|y_{\tau\mu} y_{\mu\tau}|} \lesssim \frac{\sqrt{m_\mu m_\tau}}{v} = 0.0018$$



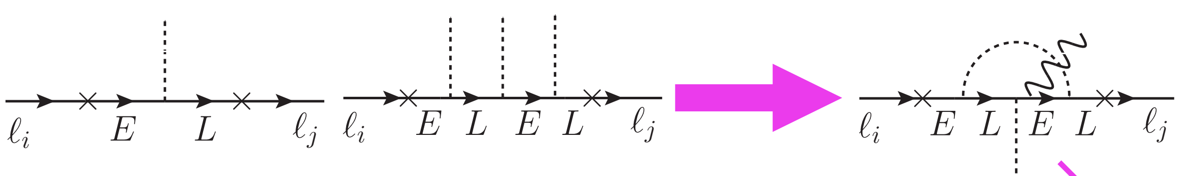
Lepton Flavor violating Higgs decays?

Generic obstacle to large $h \to \tau\mu$ is the bound on $\tau \to \mu\gamma$ R. Harnik et al. 1209.1397

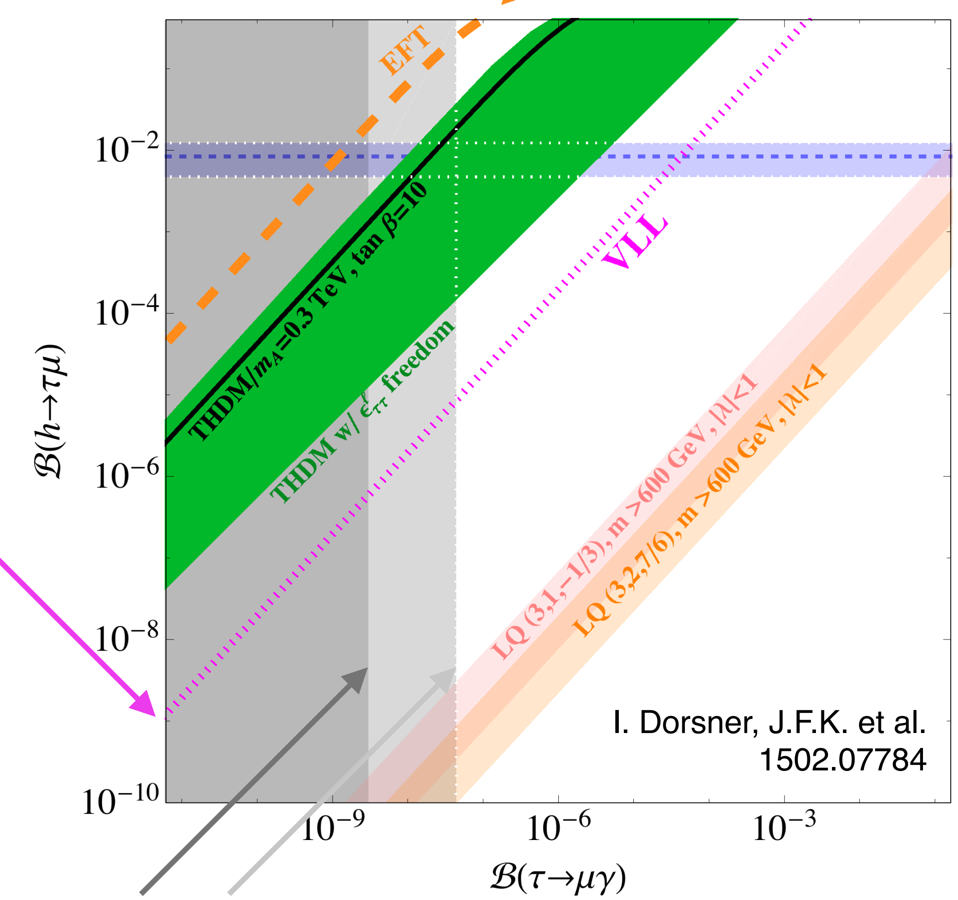
$\Rightarrow$ two observables share identical flavor structure



Example: Mixing with VL leptons



$\Rightarrow$ Belle II improvement on Br($\tau \to \mu\gamma$) can have big impact



Belle II projection Current bound

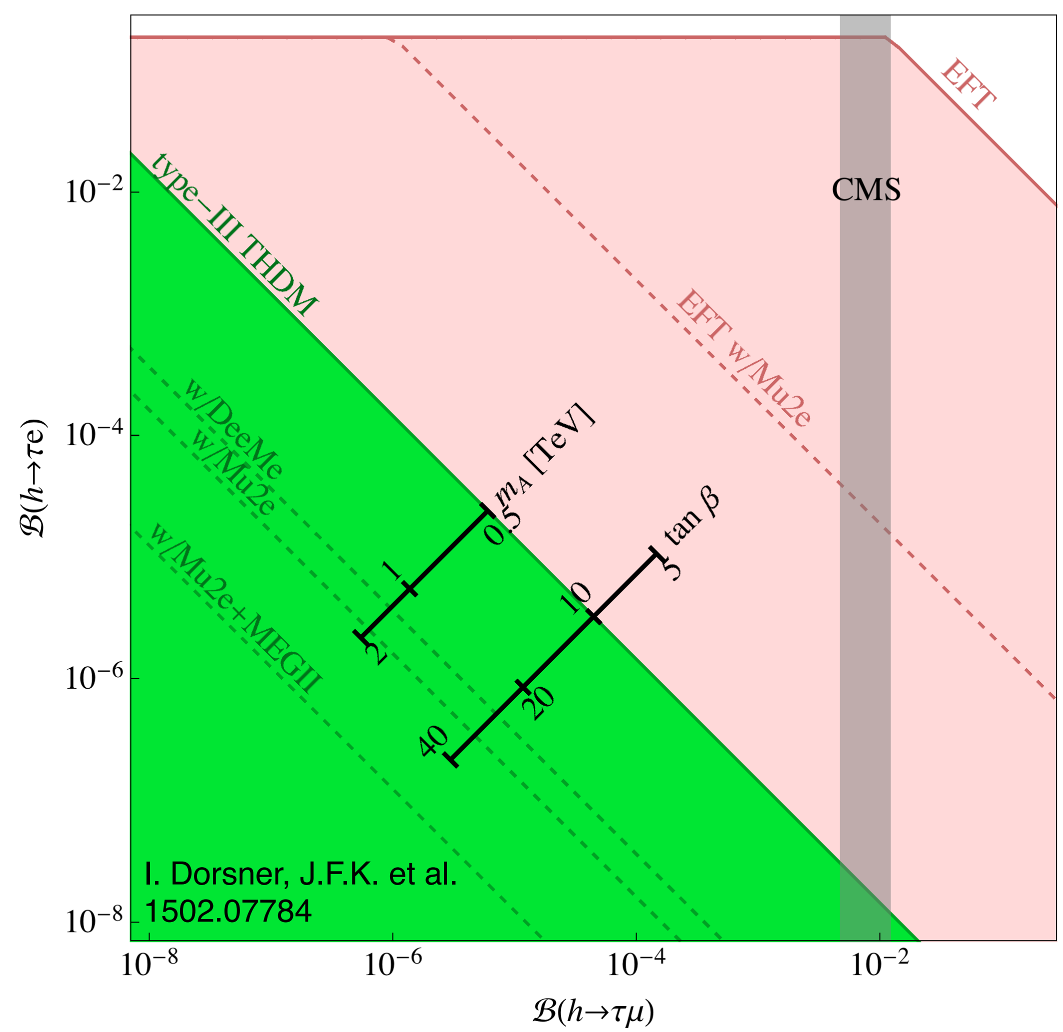
Lepton Flavor violating Higgs decays?

Solution: decouple fermion mass generation from $\tau \to \mu\gamma$

- possible if new source of EWSB (strong dynamics, multi-Higgs doublet models) W. Altmannshofer et al. 1507.07927 see also A. Crivellin et al. 1611.02703

Generic implications:

- LFV tau decays close to present bounds
- New d.o.f.s within LHC energy reach
- $h \to \tau e$ constrained by $\mu \to e$ conversions

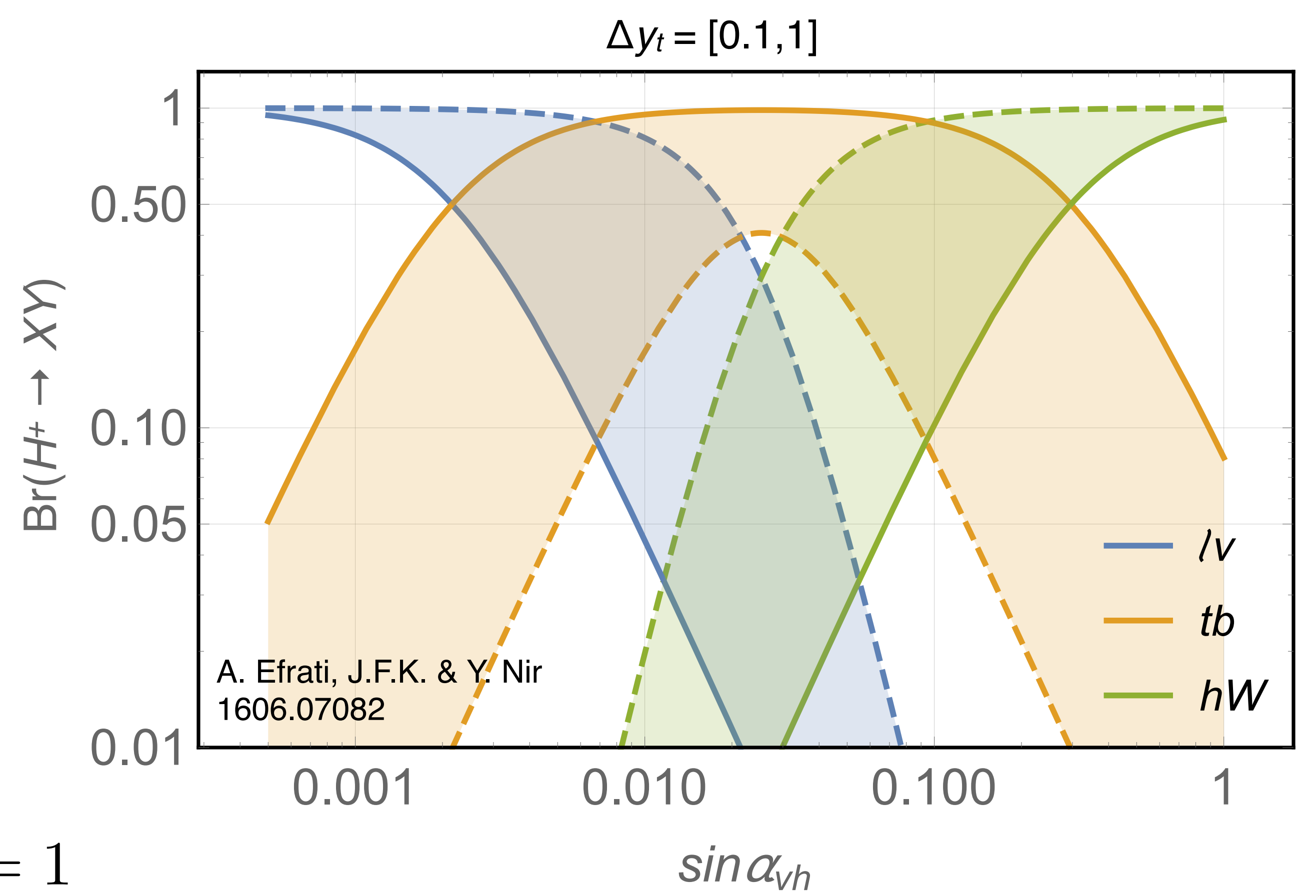


Flavor structure affecting high-p_T searches

Nontrivial flavor structure can have important implications also for on-shell searches

Example: THDM accommodating $h \to \tau\mu$

$\Rightarrow$ Both neutral and charged heavy scalars can dominantly decay to leptons



$\Rightarrow$ By SU(2) invariance:

$$R^{H^+/A}_{hW^+Z} \simeq R^{H^+/A}_{t\bar{b}\bar{t}} = R^{H^+/A}_{\tau^+\nu\mu^-} + R^{H^+/A}_{\mu^+\nu\tau^-} = 1$$

$$R^{H^+/A}_{XYZ} \equiv \frac{\Gamma(H^+ \to XY)}{\Gamma(A \to XZ)}$$

& assuming $m_{H^+} \sim m_A$

↑ *v*-*h* misalignement angle

Flavor anomalies motivate high-p_T searches

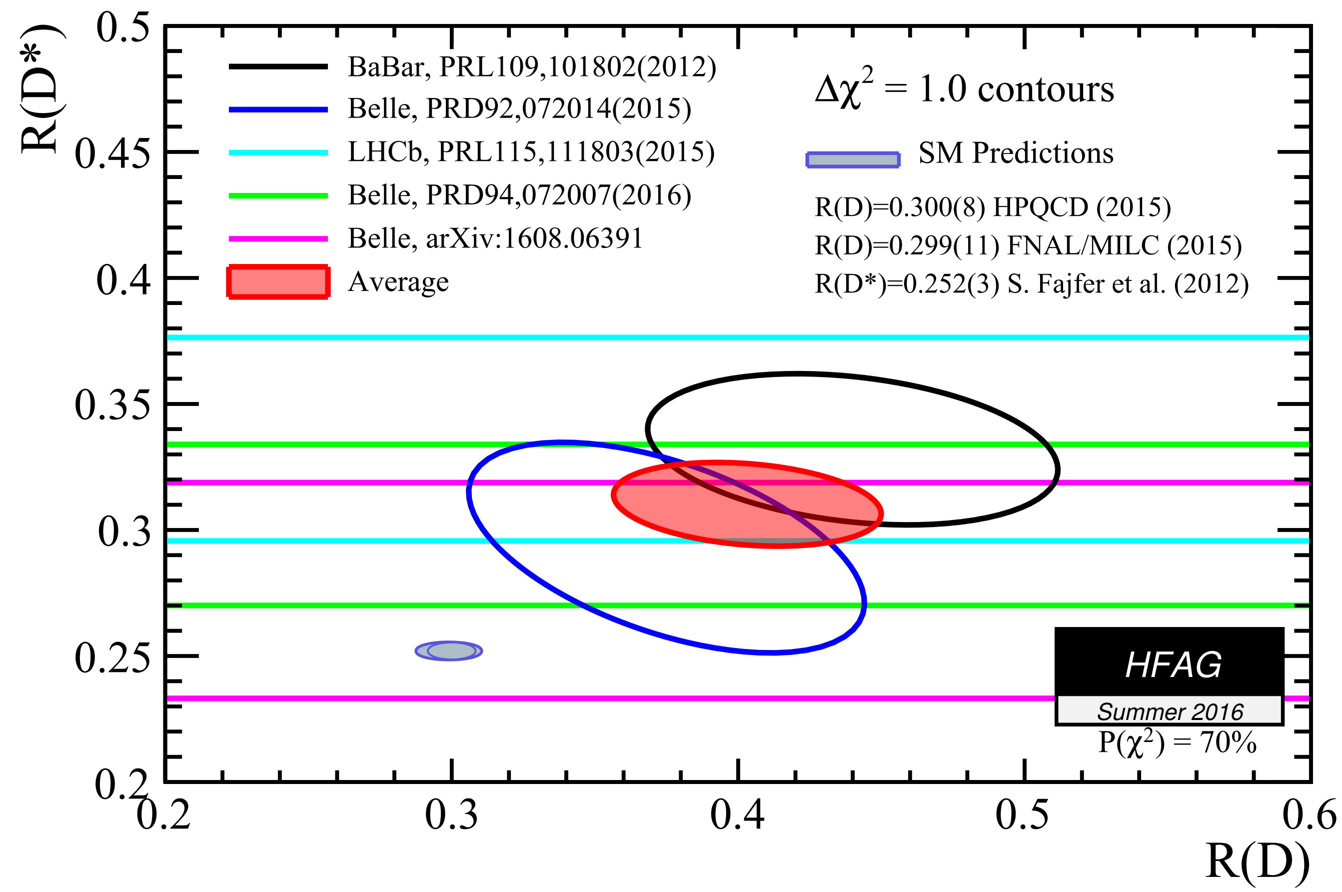
Charged-current decays $B \to D^{(*)} l \nu$:

- with $l = e, \mu$ used to measure CKM element V_{cb}
- $B \to D^{(*)} \tau \nu$ precisely predicted in SM if normalized to $l = e, \mu$ modes - $R(D^{(*)})$.

Intriguing exp. situation:

⇒ 3.9σ combined tension with SM (HFAG)

⇒ SM (FF) uncertainties insignificant at this point



Flavor anomalies motivate high-p_T searches

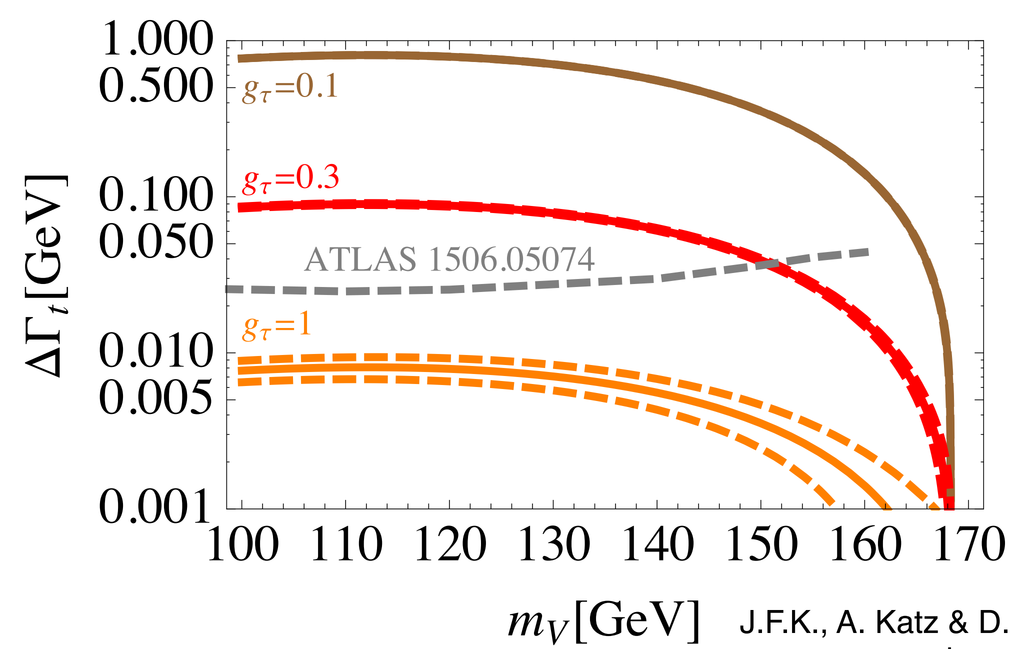
Size of effect calls for tree-level NP, needs to be EM charged.

$\Rightarrow$ Mass bounds from LEP M > 100 GeV

FCNC & LFU constraints require flavor alignement with the 3rd generation

$\Rightarrow$ effects in top quark decays

$$\mathcal{L}^{(a)} = \mathcal{L}_{\rm SM} + \frac{1}{4}R^{+}_{\mu\nu}R^{-\mu\nu} - m_\rho^2 \rho^+_\mu \rho^{-\mu} + [g_b \sum_q V_{qb}\bar{q}\not{\rho}^+ P_L b + g_\tau \bar{\tau}\not{\rho}^- P_L \nu_\tau + \text{h.c.}] \,,$$



J.F.K., A. Katz & D. Stolarski in preparation

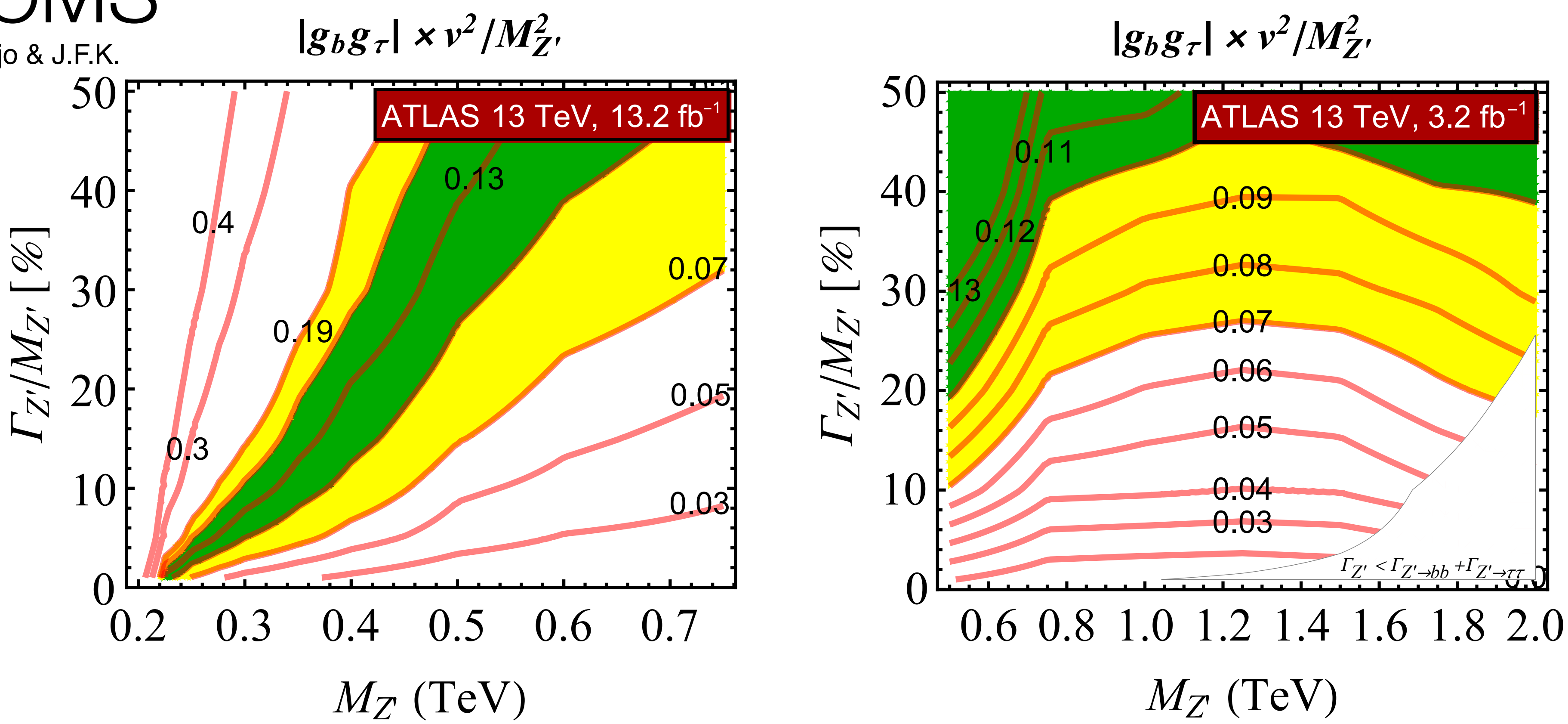
LHC measurements starting to constrain m_V<m_t region.

Flavor anomalies motivate high-p_T searches

In addition SU(2) invariance predict significant tau production at LHC

Strong constraints from existing $pp \to \tau^+\tau^-$ searches at ATLAS/CMS

D. A. Faroughy, A. Greljo & J.F.K.
1609.07138



W′/Z′ explanation only allowed if light (M < 500 GeV) or broad (Γ/M > 30%)

Conclusions

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

- to ensure no stone is left unturned (and that the most interesting stones are turned first)
- in case of significant signals of NP in flavor observables can identify prospective LHC experimental targets

Conclusions

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

Examples: 125GeV Higgs & now defunct 750GeV di-photon resonance

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

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

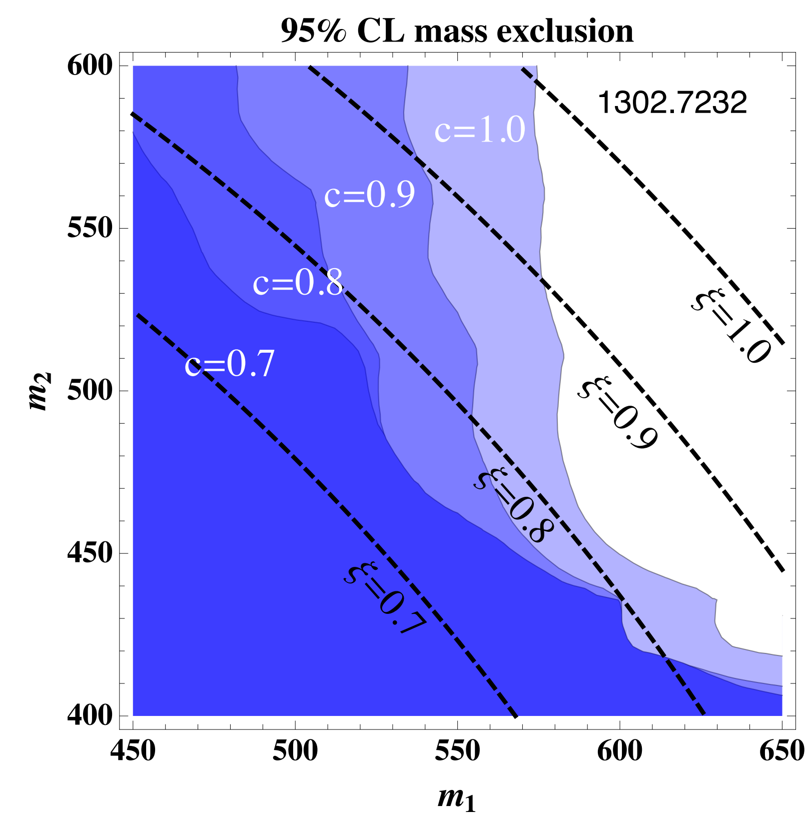
Additional material

Flavor structure affecting high-p_T searches

Top partners - direct test of EW naturalness

- stop in SUSY, custodians in composite Higgs
- large flavor breaking can modify exp. searches

$\Rightarrow$ reduction of fine-tuning

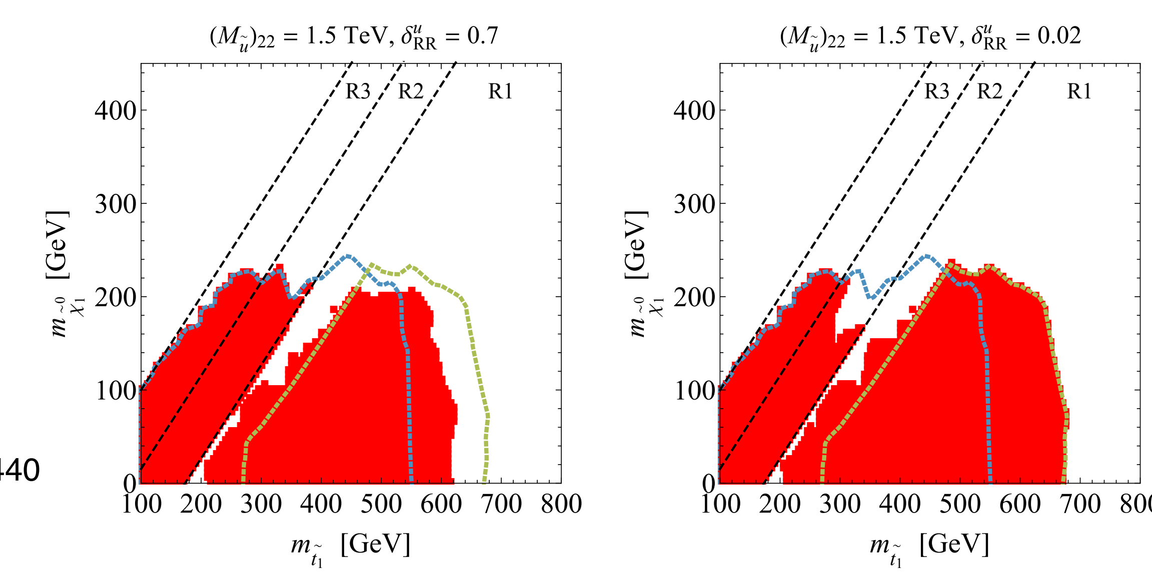


- example: large $\tilde{t}_R$-$\tilde{c}_R$ mixing in MSSM

$$c = \cos\theta_R^{ct} \qquad \xi = \frac{c^2 m_1^2 + s^2 m_2^2}{m_0^2}$$

$\Rightarrow$ new signature t+c-jet+MET

A. Crivellin et al. 1604.00440



Flavor & high-p_T as complementary NP probes

Further examples: modified tbW, ttZ, ttγ, ttg, ttH couplings

$$Q^{(3)}_{\phi q,33} \equiv (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3}),$$

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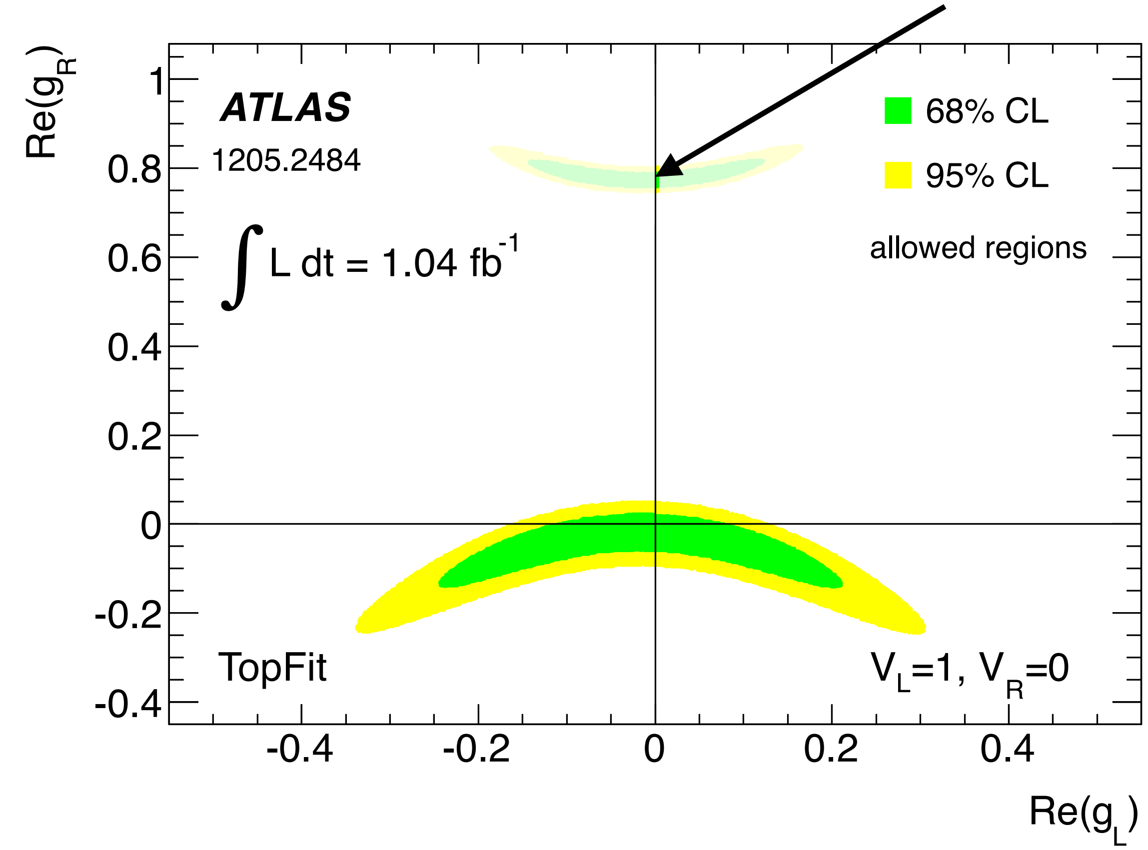
J. Drobnak, S. Fajfer & J.F.K. 1109.2357, 1102.4347
B. Grzadkowski & M. Misiak 0802.1413

- Probed directly through (single, pair, associate) top production and decays at LHC
- Important complementarity with low energy probes

constrained by $b \to s\gamma$



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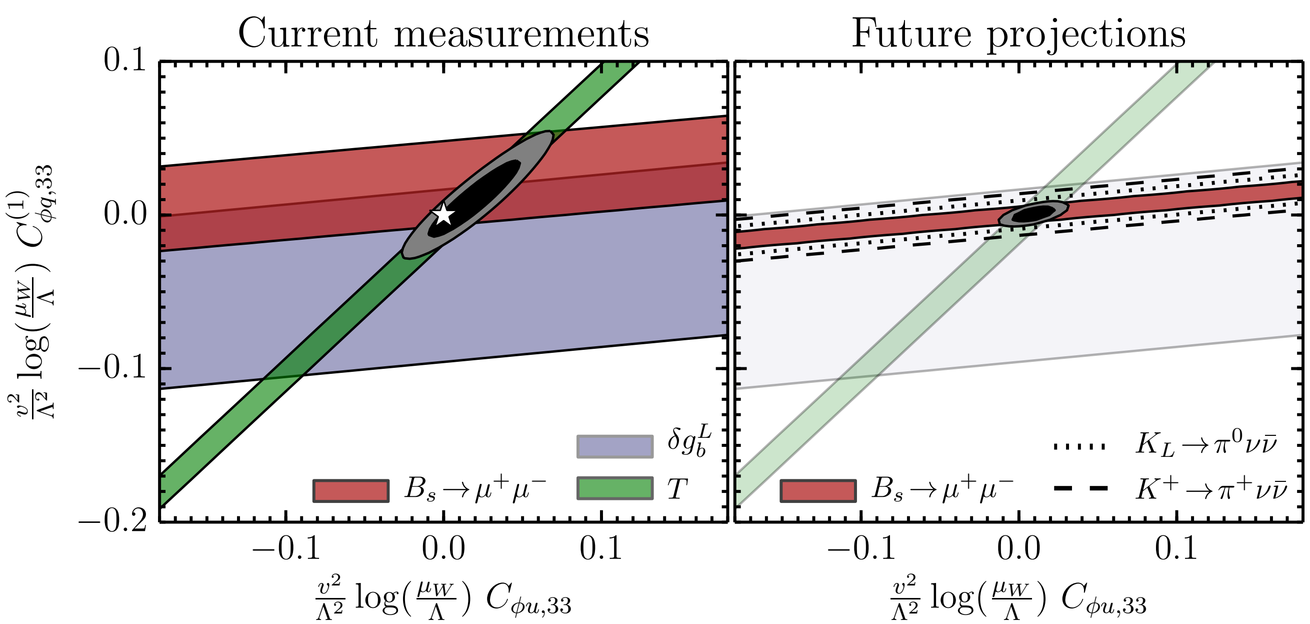

J. Brod et al. 1408.0792

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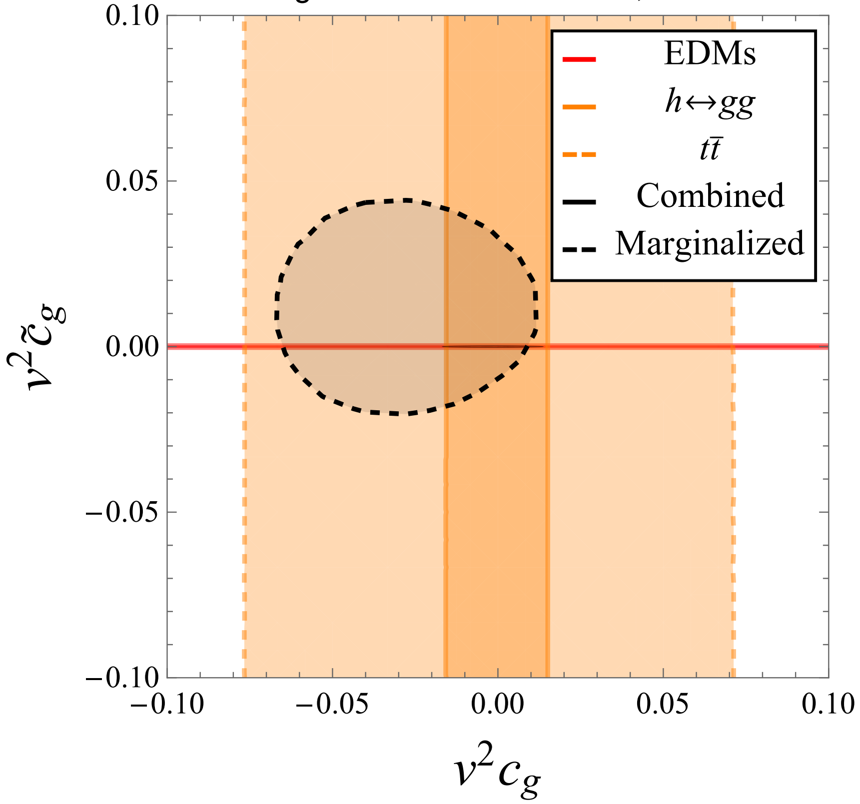
J.F.K. et al. 1107.3143
C. Degrande et al. 1205.1065
Schulze & Soreq 1603.08911
Cirigliano et al. 1603.03049, 1605.04311



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J. Brod et al. 1310.1385