Flavor Physics at the LHC

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LHC as a flavor factory

What are the unique capabilities of LHC for flavor studies?
(energy, luminosity)

Which observables are most promising?
(Higgs, top, CPV in charm & B_s, rare decays with di-leptons)

What have we learned already?
(implications for SM hierarchy, flavor, DM puzzles, hints of NP?)

Disclamer: personal selection of topics

Introduction

SM phenomenologically very successful theory

Strong theoretical arguments to consider it as 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

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

Introduction

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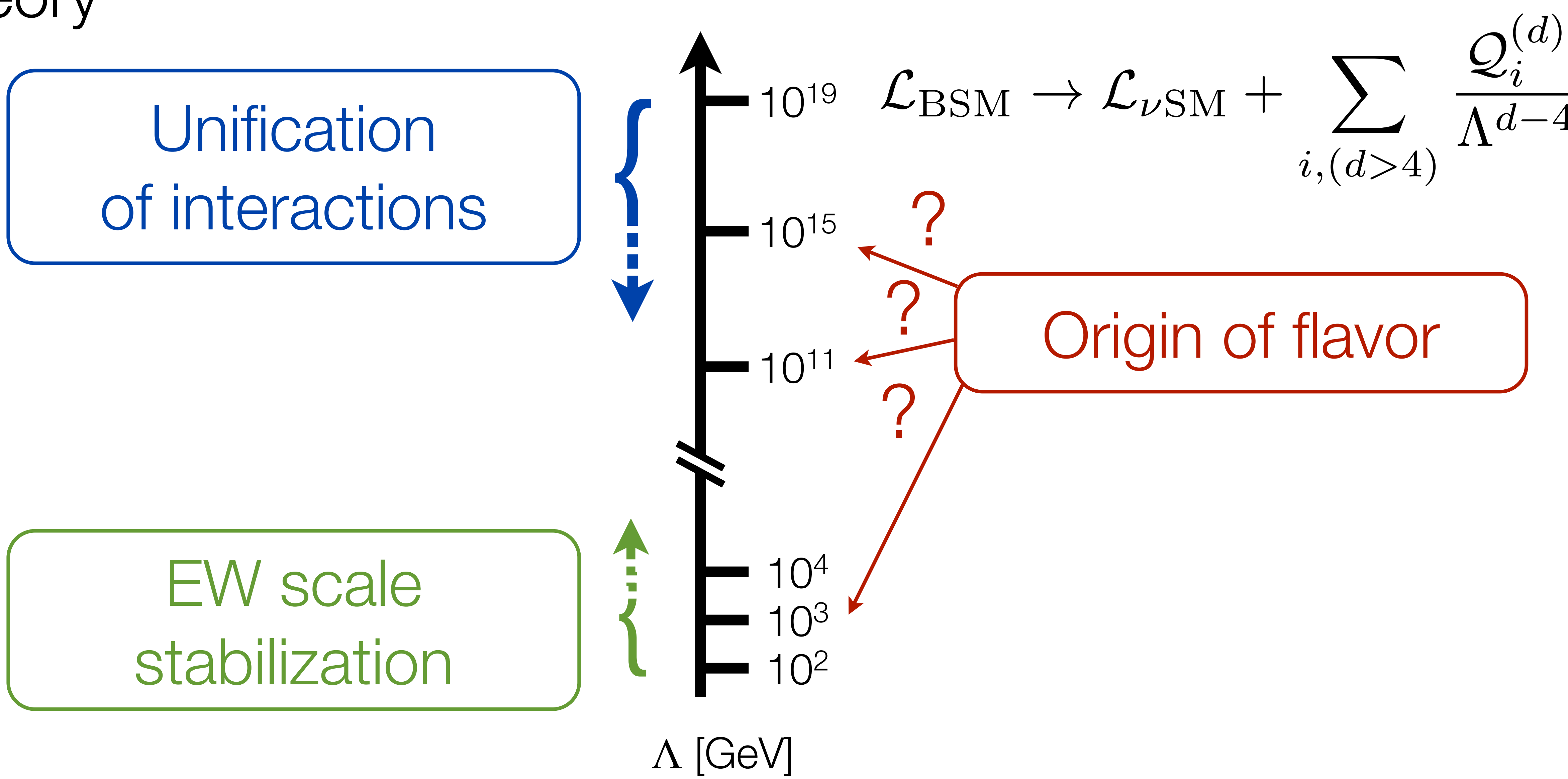
Strong theoretical arguments to consider it as effective theory



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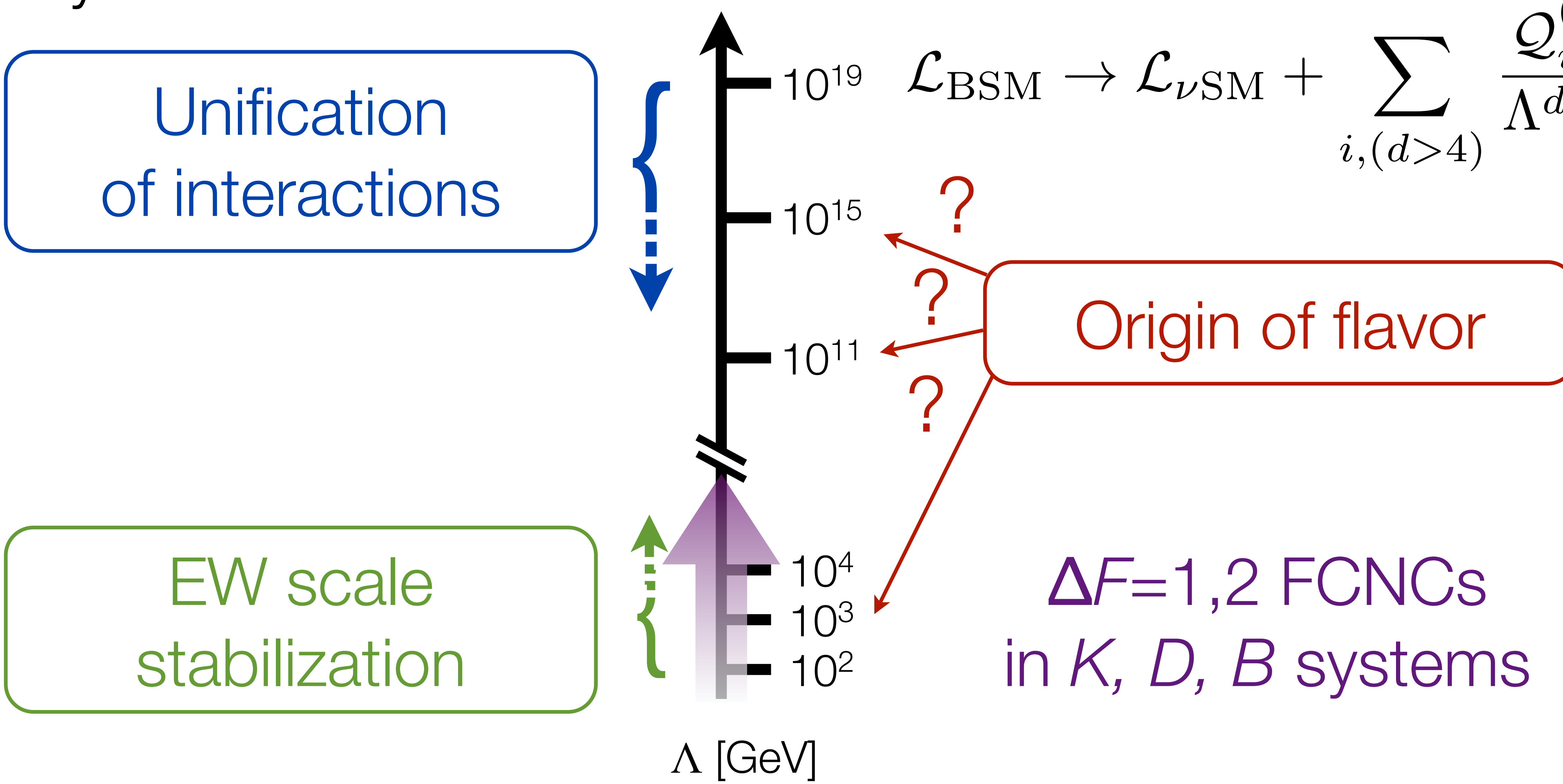

$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\nu\rm SM} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

Introduction

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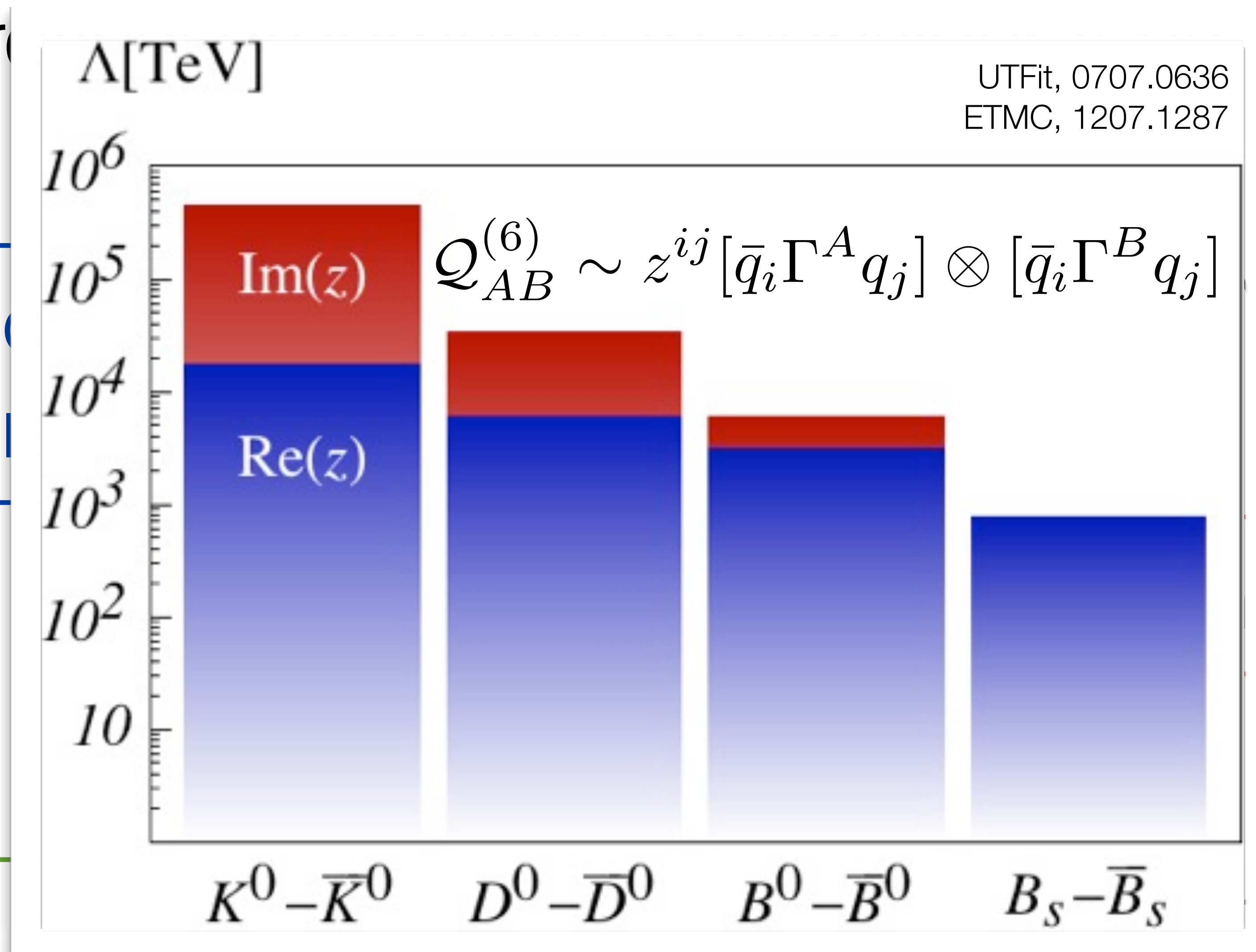
Strong theor… effective theory

$$+ \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

Unifi… of inte…



…of flavor

EW… stabilization

10^3
10^2

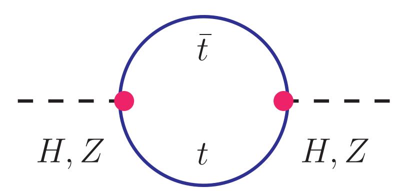
FCNCs in *K*, *D*, *B* systems

Λ [GeV]

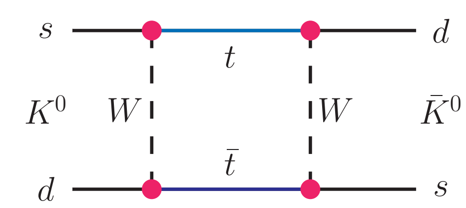
Unique LHC probes of flavor

Top quark - heaviest point-like particle known to exist

⇒ O(1) coupling to the Higgs $y_t \equiv \sqrt{2} m_t / v_{\rm EW} \simeq 1$



⇒ Profound effects on EW and flavor physics



Higgs boson interactions with fermions of special interest

⇒ probe existence of new flavor dynamics not too far above the electroweak scale

⇒ suppressed contributions to low energy observables lead to weak indirect constraints

Testing flavor through Higgs observables

Testing flavor through Higgs observables

Giudice, Lebedev, 0804.1753
Agashe, Contino, 0906.1542
Goudelis, Lebedev, Park, 1111.1715
Arhrib, Cheng, Kong, 1208.4669
Alonso et al., 1212.3307
Dery et al., 1302.3229, 1304.6727
...

BSM modifications of Yukawa sector

$$\mathcal{Q}_Y^{(6)} \sim Y'_{ij} \psi_L^i \psi_R^j \phi (\phi^\dagger \phi)$$

In EW vacuum: $\mathcal{L}_Y = -m_i \psi_L^i \psi_R^i - \bar{Y}_{ij} (\psi_L^i \psi_R^j) h + \text{h.c.} + \ldots$

Generally present if more than one source of fermion masses

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Simplest model examples:

(1) THDM III $\mathcal{L}_{\text{THDMIII}} \ni -Y_{ij}^{(1)} \psi_L^i \psi_R^j \phi^{(1)} - Y_{ij}^{(2)} \psi_L^i \psi_R^j \phi^{(2)} + \text{h.c.}$

$\rightarrow \mathcal{L}_Y +$ couplings to heavier Higgs bosons

c.f. Davidson & Greiner, 1001.0434

(2) Partial compositeness $\mathcal{L}_{\text{PC}} \ni - y_{ij} D_L^i S_R^j \phi - \bar{y}_{ij} D_R^i S_L^j \phi$

$- M_D^i D_R^i D_L^i - M_S^i S_R^i S_L^i$

$- m_D^{ij} D_R^i \psi_L^j - m_S^{ij} S_L^i \psi_R^j + \text{h.c.}$

(D,S - vector-like fermionic doublets, singlets)

$\rightarrow \mathcal{L}_Y +$ couplings of heavier fermions

c.f. Delaunay, Grojean & Perez, 1303.5701

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Stability of fermionic mass hierarchies: $|\bar{Y}_{ij} \bar{Y}_{ji}| \lesssim \frac{m_i m_j}{v^2}$

Cheng & Sher,
Phys.Rev. D35, 3484 (1987)

New neutral currents

- flavor diagonal (LHC)
- flavor violating (flavor factories, LHC)

+ EDMs if CPV

Brod, Haisch & Zupan, 1310.1385
Gorban & Haisch, 1404.4873

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Are Higgs couplings to light flavors SM-like?

Current Higgs data exhibit poor sensitivity to first two generation quark Yukawas

Fajfer, Greljo, J.F.K. & Mustac, 1304.4219
Delaunay, Golling, Perez & Soreq, 1310.7029

⇒ in production

1 loop contributions to $gg \to h$ suppressed by small loop function

$$\mathcal{A}_{1/2} \sim r_q \log r_q \,, \quad r_q \equiv (m_q/m_h)^2 \ll 1$$

direct $q\bar{q} \to h$ suppressed by small parton luminosity functions

$$\mathcal{L}_{u\bar{u}}(m_h)/\mathcal{L}_{gg}(m_h) \sim 4\%(2\%) \,@\, 7\,\mathrm{TeV}(14\,\mathrm{TeV})\ \mathrm{LHC}$$

⇒ in decay:

need to compete against dominant $h \to b\bar{b}$ mode

$$|\bar{Y}_{qq}|^2 \simeq 10^{-3} \Gamma_{h\to q\bar{q}}/\Gamma_h^{\mathrm{SM}} \qquad \bar{Y}_{bb}^{\mathrm{SM}} \equiv \frac{m_b}{v} \simeq 0.02$$

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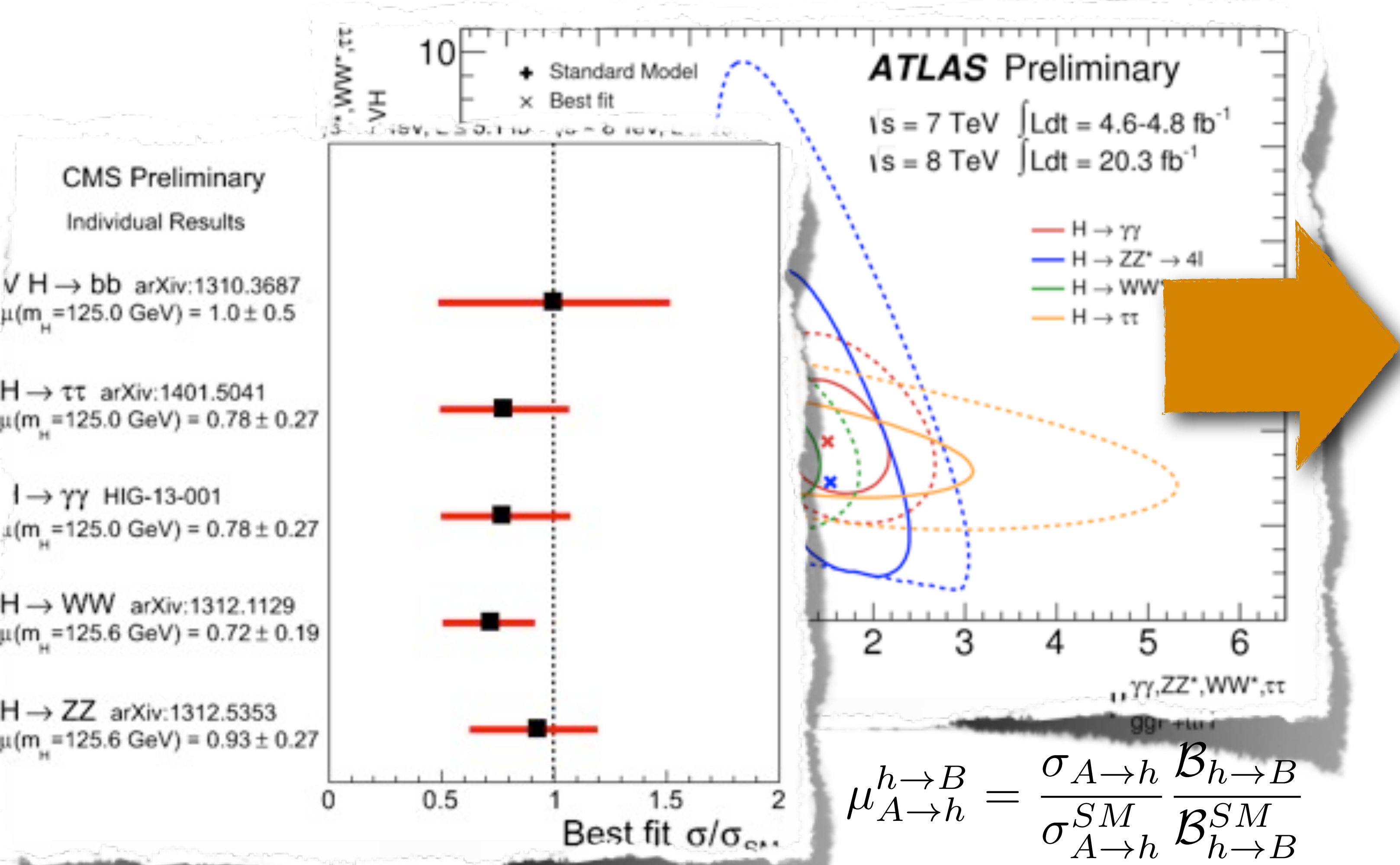
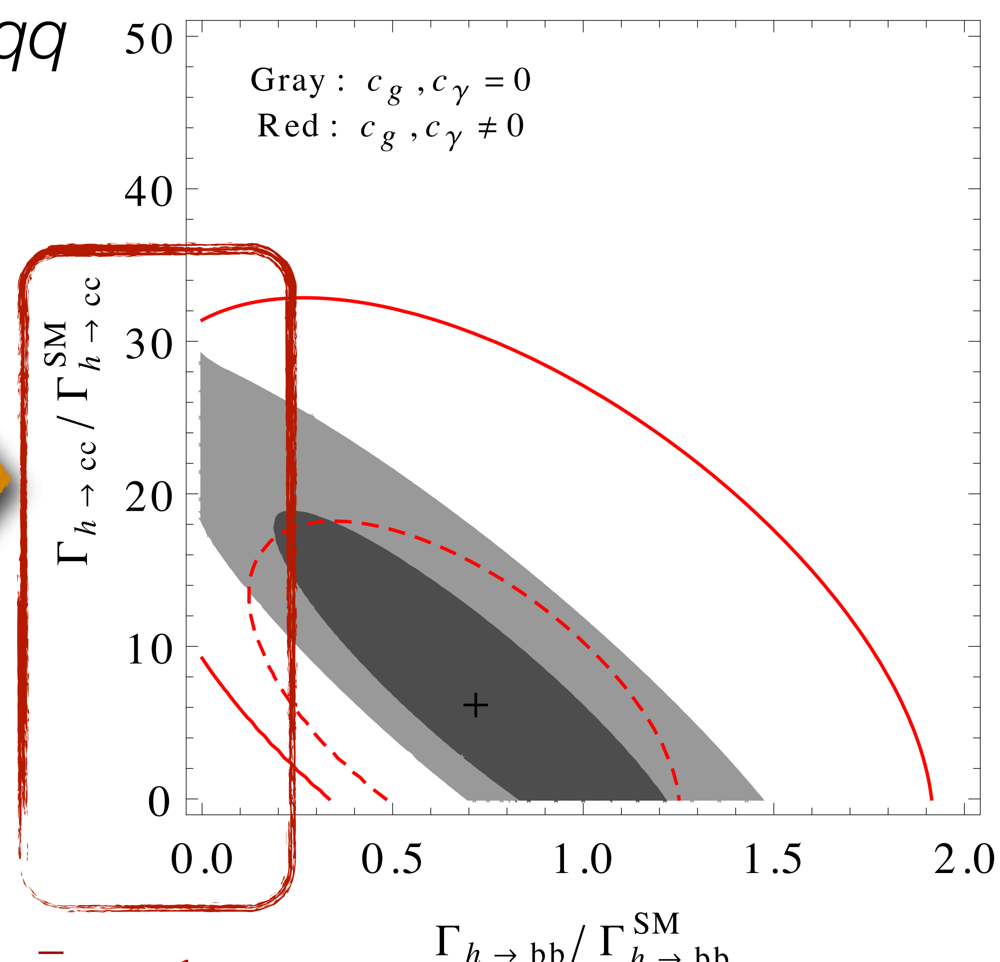
⇒ Global fit to LHC Higgs signal strenghts

Admir Greljo
private communication
see also talk by Y. Soreq

allowing modifications in *hgg* (c_g), *hγγ* (c_γ), *hqq*



$$\mu_{A\to h}^{h\to B} = \frac{\sigma_{A\to h}}{\sigma_{A\to h}^{SM}} \frac{\mathcal{B}_{h\to B}}{\mathcal{B}_{h\to B}^{SM}}$$



$\bar{Y}_{qq} \lesssim 0.01$

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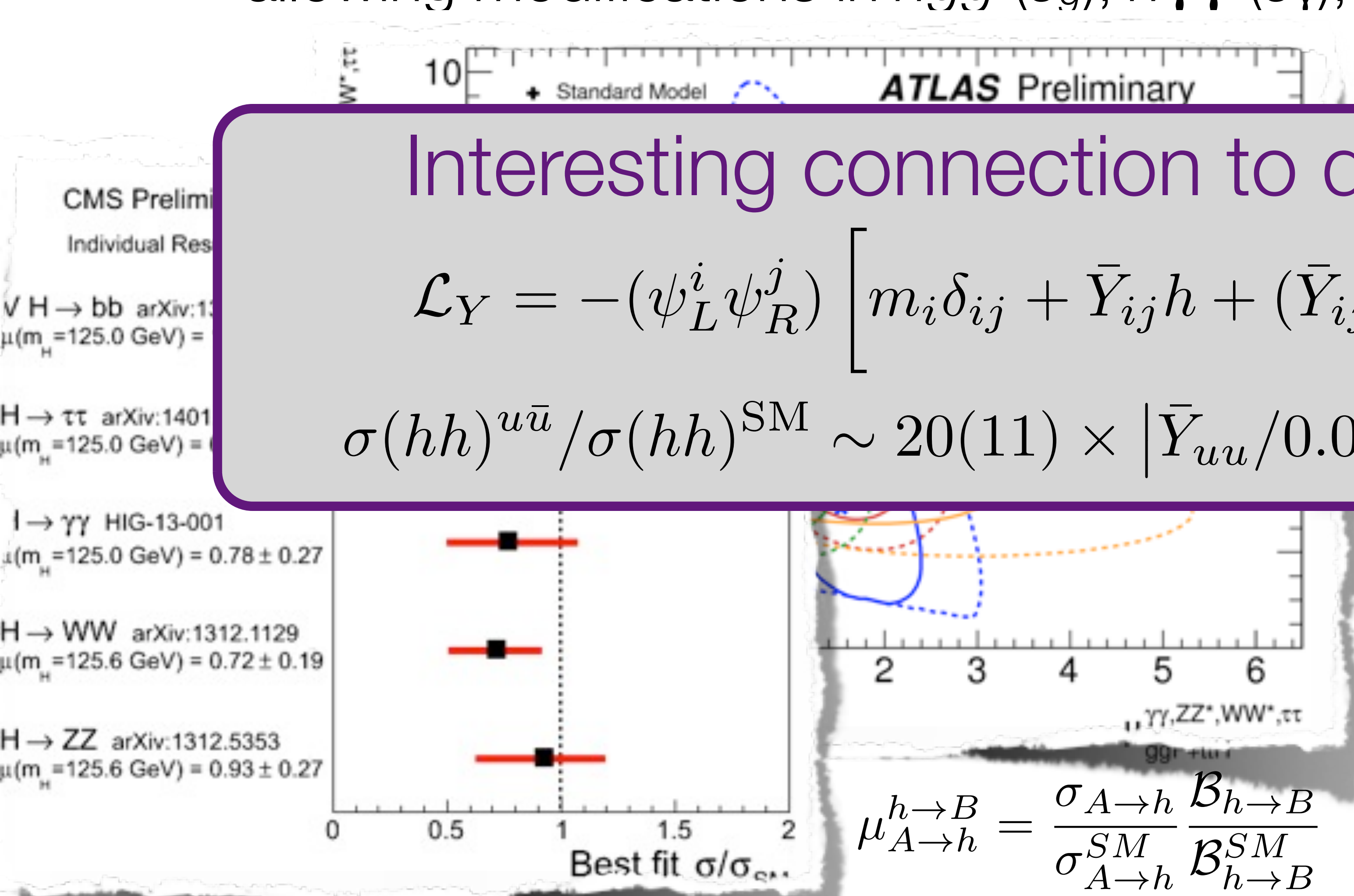

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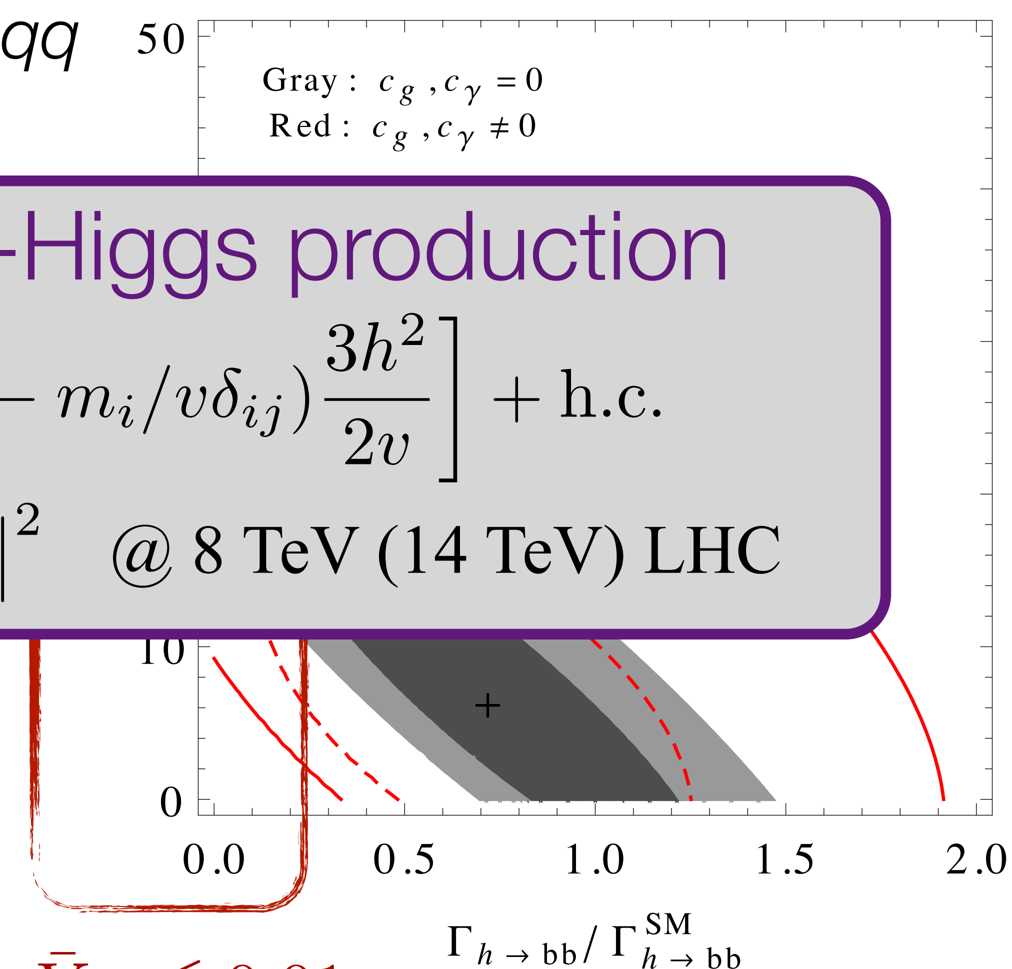

$\bar{Y}_{qq} \lesssim 0.01$

Interesting connection to di-Higgs production

$$\mathcal{L}_Y = -(\psi_L^i \psi_R^j)\left[m_i \delta_{ij} + \bar{Y}_{ij} h + (\bar{Y}_{ij} - m_i/v\,\delta_{ij})\frac{3h^2}{2v}\right] + \text{h.c.}$$

$$\sigma(hh)^{u\bar{u}}/\sigma(hh)^{\text{SM}} \sim 20(11) \times \left|\bar{Y}_{uu}/0.01\right|^2 \quad @\ 8\ \text{TeV}\ (14\ \text{TeV})\ \text{LHC}$$

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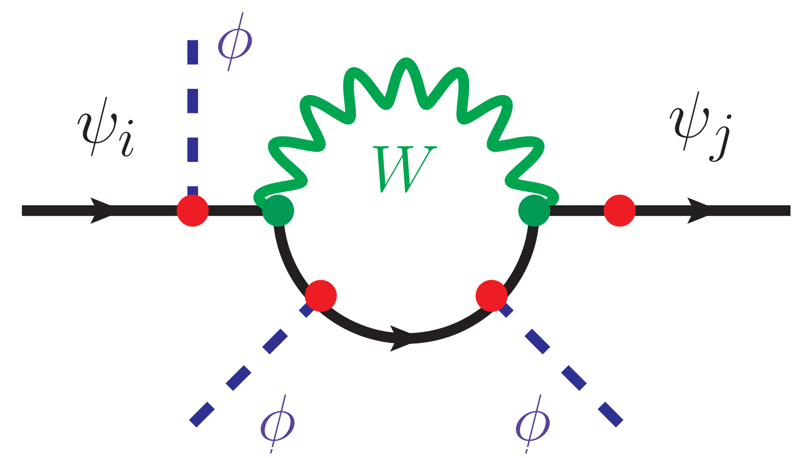
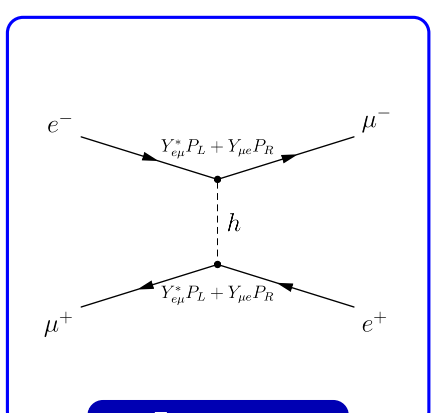
Testing flavor through Higgs observables

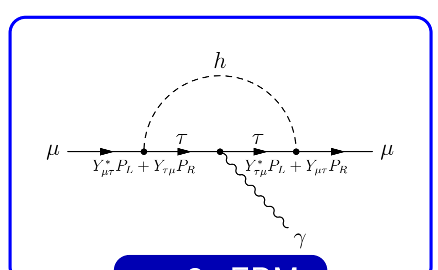
Within SM effective $Y_{i\neq j}$ extremely suppressed (GIM+CKM/m_ν & chirality)



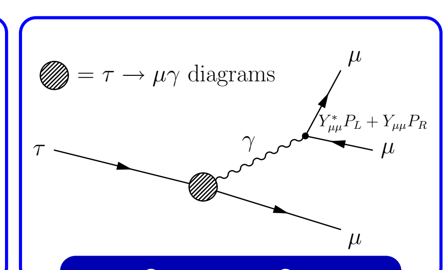
Constraints on first two generation $Y_{i\neq j}$ dominated by precision low energy observables



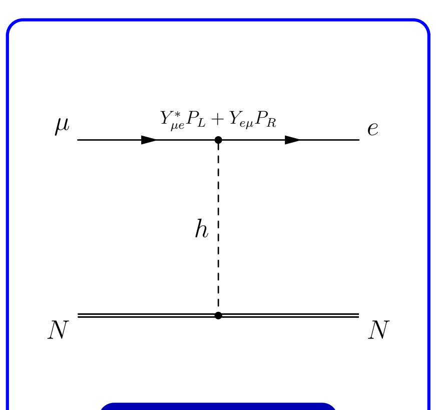
M–$\bar{M}$ oscillations



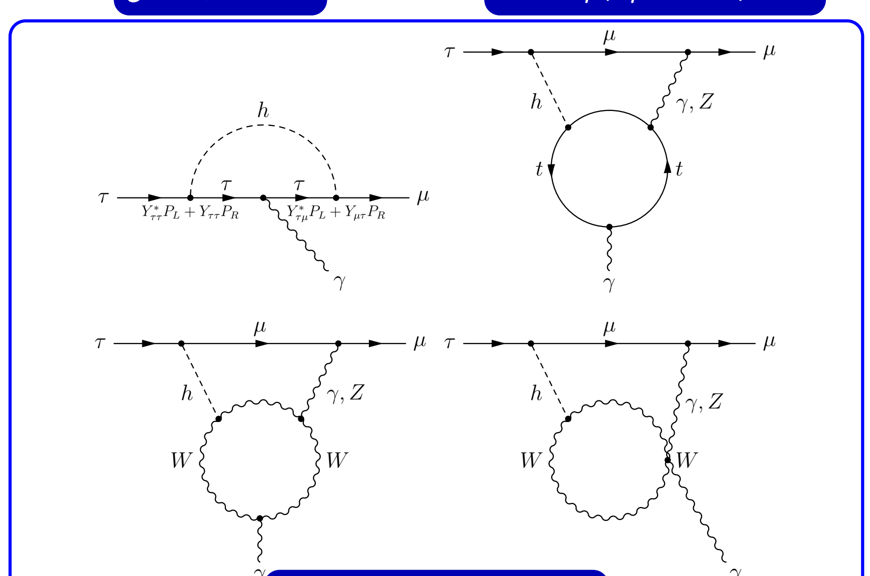
$g-2$, EDMs



$\tau\to 3\mu$, $\mu\to 3e$, etc.

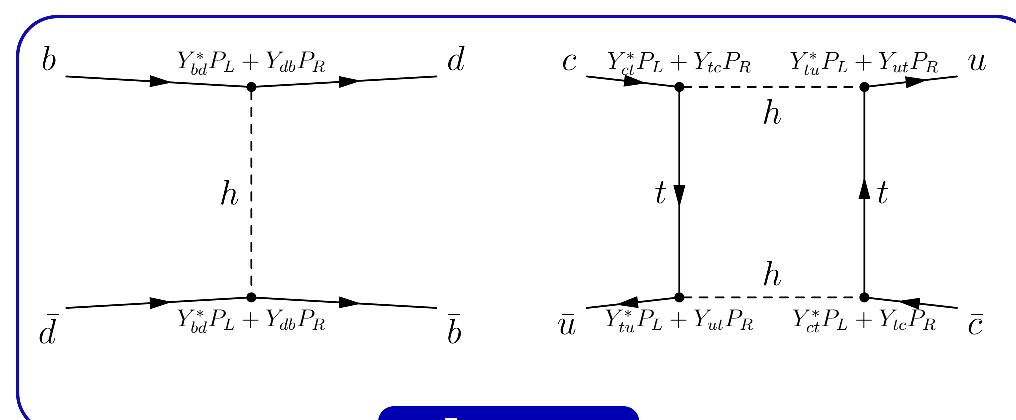


μ–e conversion



$\tau\to\mu\gamma$, $\mu\to e\gamma$, etc.

taken from Joachim Kopp's slides
on LHC Results Forum (@UTexas)



M–$\bar{M}$ oscillations

Harnik, Kopp, Zupan, 1209.1397
McKeen, Pospelov, Ritz, 1208.4597
Blankenburg, Ellis, Isidori, 1202.5704

Probing Flavor Violation in Top - Higgs Sector

Top-Higgs FV interactions only enter low energy observables at loop level

⇒ EDMs still severily constrain CPV contributions — Gorban & Haisch, 1404.4873

⇒ Sensitive only to certain products of couplings

Direct LHC probes

⇒ Higgs decays $BR(h \to t^* q) \simeq \frac{\Gamma(h \to t^* q)}{\Gamma_h^{SM}} \simeq 0.12(0.27|y_{tq}|^2 + |y_{qt}|^2)$

⇒ Top Decays $\mathcal{B}(t \to hq) \simeq \frac{\Gamma(t \to hq)}{\Gamma(t \to W^+ b)} \simeq 0.29(|y_{tq}|^2 + |y_{qt}|^2)$

⇒ Associated top-Higgs production (relevant for y_{tu}, y_{ut})

$$\sigma(pp \to th) \simeq 74\ (180)\ \text{pb} \times \left(|y_{tu}|^2 + |y_{ut}|^2\right)$$ @ 8TeV (14TeV) LHC

+ several other, less sensitive signatures

Greljo, J.F.K. & Kopp, 1404.1278
Atwood, Gupta & Soni, 1305.2427

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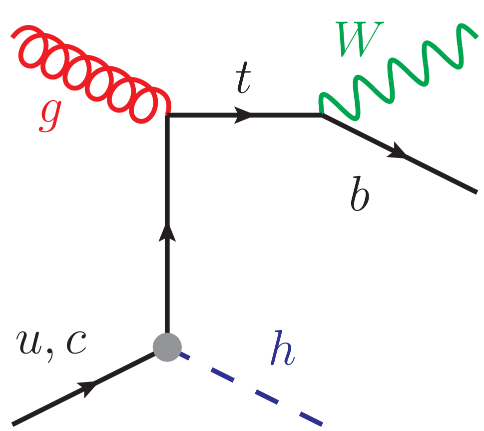
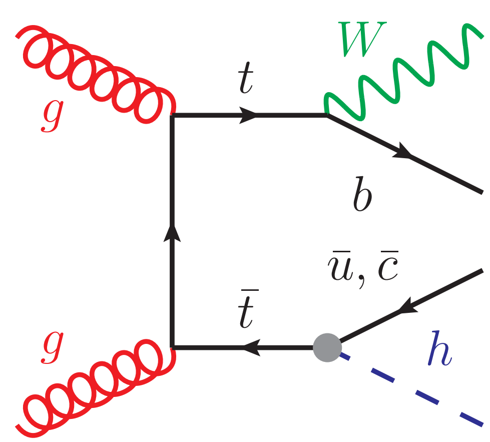
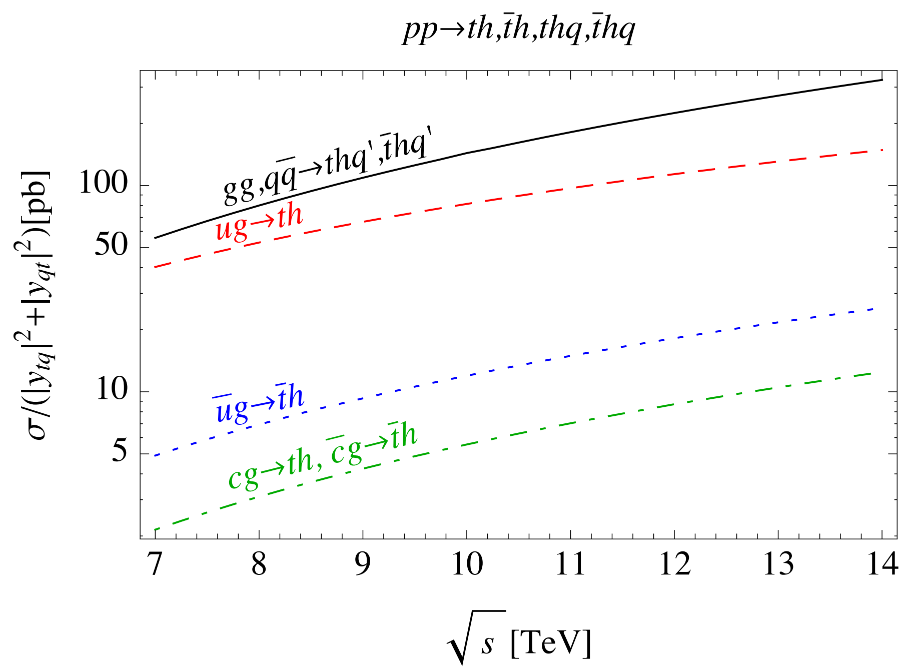
Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

Greljo, J.F.K. & Kopp, 1404.1278

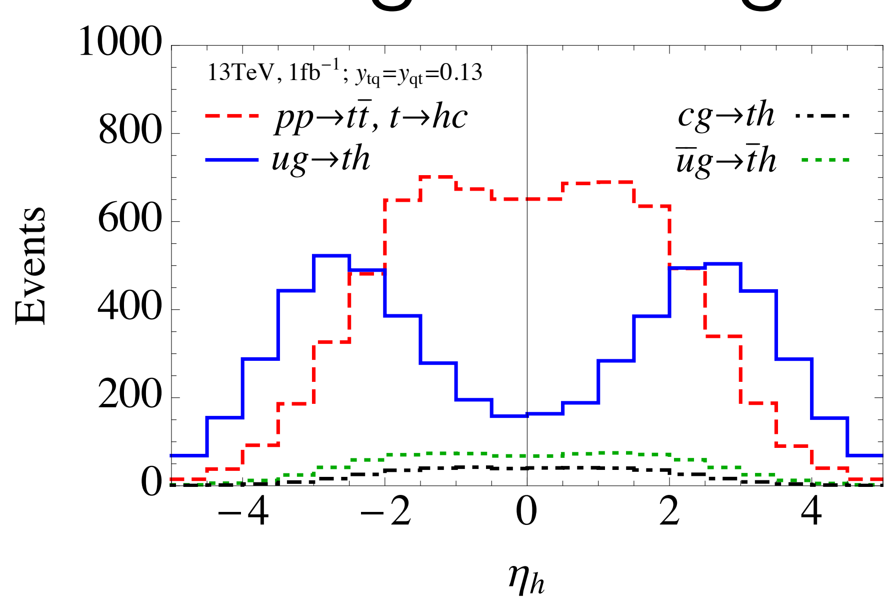
Two complementary production processes (in case of *thu*)







Can be disentangled using Higgs rapidity & total event charge



$$\lim_{m_h, m_t \to 0} \frac{d\hat{\sigma}(ug \to ht)}{d\theta} \propto \frac{(1+\cos\theta)^2}{1-\cos\theta}$$

Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

Greljo, J.F.K. & Kopp, 1404.1278

Several competitive signatures

Multileptons

$$h \to WW^* \to \ell\ell\nu\nu,\ h \to \tau\tau,$$
$$h \to ZZ^* \to \ell\ell jj,\ h \to ZZ^* \to \ell\ell\nu\nu,$$
$$t \to b\ell^+\nu$$

✘ No Higgs/top reconstruction
✔ Many Higgs decay modes

CMS-PAS-HIG-13-034, CMS arXiv:1404.5801; CMS-SUS-13-002
CMS-PAS-HIG-12-053 vector boson plus Higgs recast

Lepton + di-photon

$$t \to b\ell^+\nu \qquad h \to \gamma\gamma$$

✘ Low rate
✔ Exclusive Higgs reconstruction

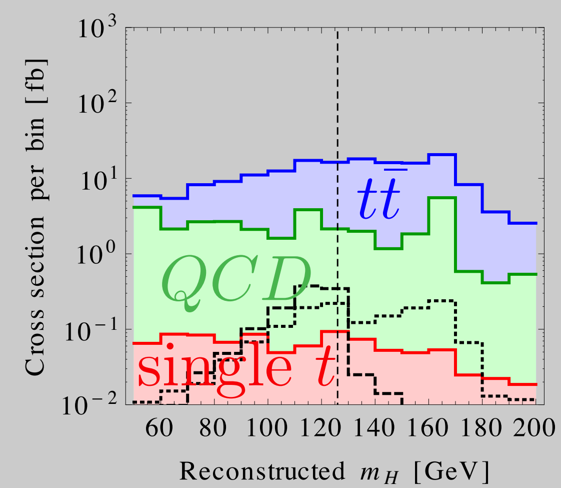
CMS-PAS-HIG-13-025
(also ATLAS, arXiv:1403.6293)

All hadronic (new)

$$h \to b\bar{b}, h \to gg, h \to \tau\bar{\tau}, h \to c\bar{c}$$
$$t \to bu\bar{d}$$

✘ Horrendous backgrounds
✔ Largest rate

In the boosted regime, can employ jet substructure methods



modified HEPTopTagger of Plehn et al., 0910.5472, 1006.2833

Higgs tagging: Butterworth et al., 0802.2470 Cacciari, Salam & Soyez, 1111.6097

Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

Greljo, J.F.K. & Kopp, 1404.1278

Improving the LHC reach

	$\sqrt{y_{ut}^2 + y_{tu}^2}$	$\mathcal{B}(t \to hu)$	$\sqrt{y_{ct}^2 + y_{tc}^2}$	$\mathcal{B}(t \to hc)$
New limits from existing data				
Sec. III A: Multilepton	< 0.19	$< 1.0\%$	< 0.23	$< 1.5\%$
Sec. III B: Diphoton plus lepton	< 0.12	$< 0.45\%$	< 0.15	$< 0.66\%$
Sec. III C: Vector boson plus Higgs	< 0.16	$< 0.70\%$	< 0.21	$< 1.2\%$
Projected future limits (13 TeV, 100 fb^{-1})				
Sec. III C: Vector boson plus Higgs	< 0.076	$< 0.15\%$	< 0.084	$< 0.19\%$
Sec. IV A: Multilepton	< 0.087	$< 0.22\%$	< 0.11	$< 0.33\%$
Sec. IV B: Fully hadronic	< 0.12	$< 0.36\%$	< 0.13	$< 0.48\%$

⇒ Limits on $B(t \to hu)$ x 1.5 better than on $B(t \to hc)$

⇒ Future LHC searches could test $|y_{tq}| \sim 0.1$

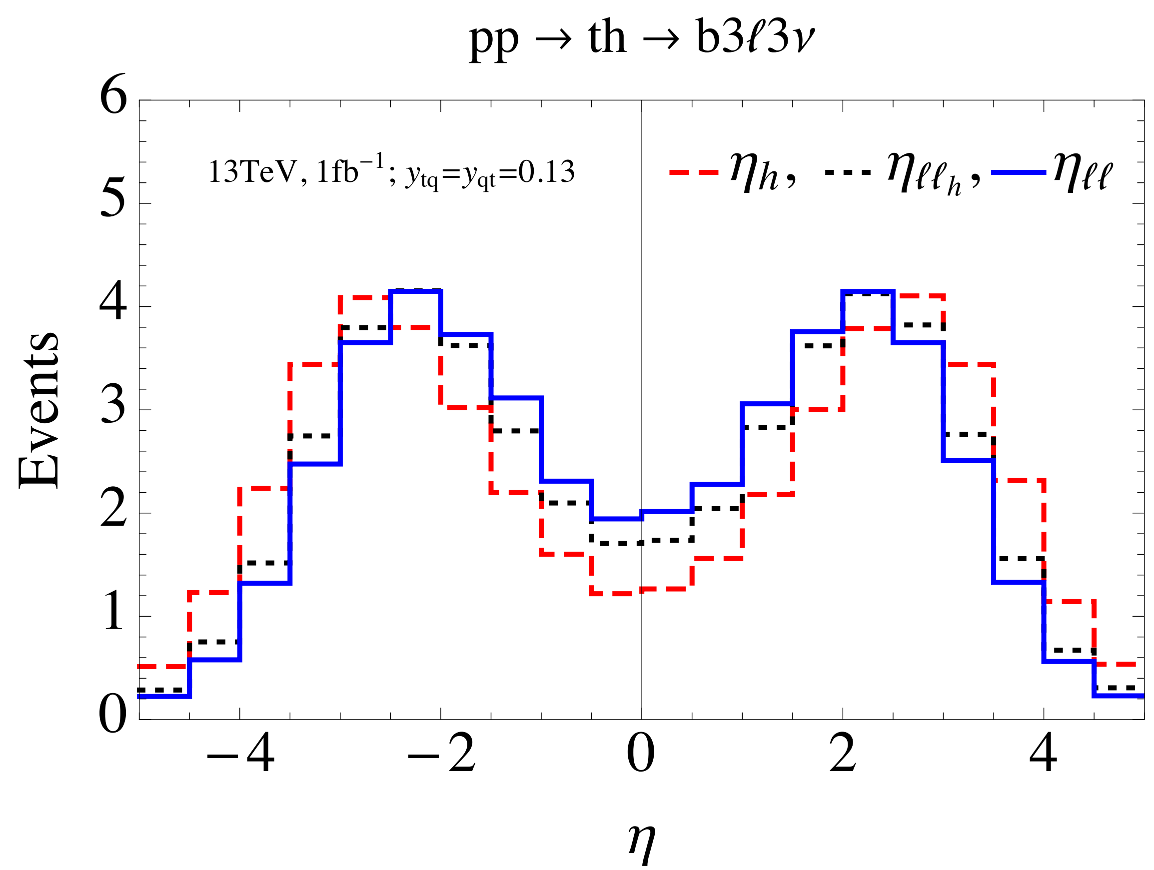
Disentangling Flavor Violation in the Top - Higgs Sector at the LHC

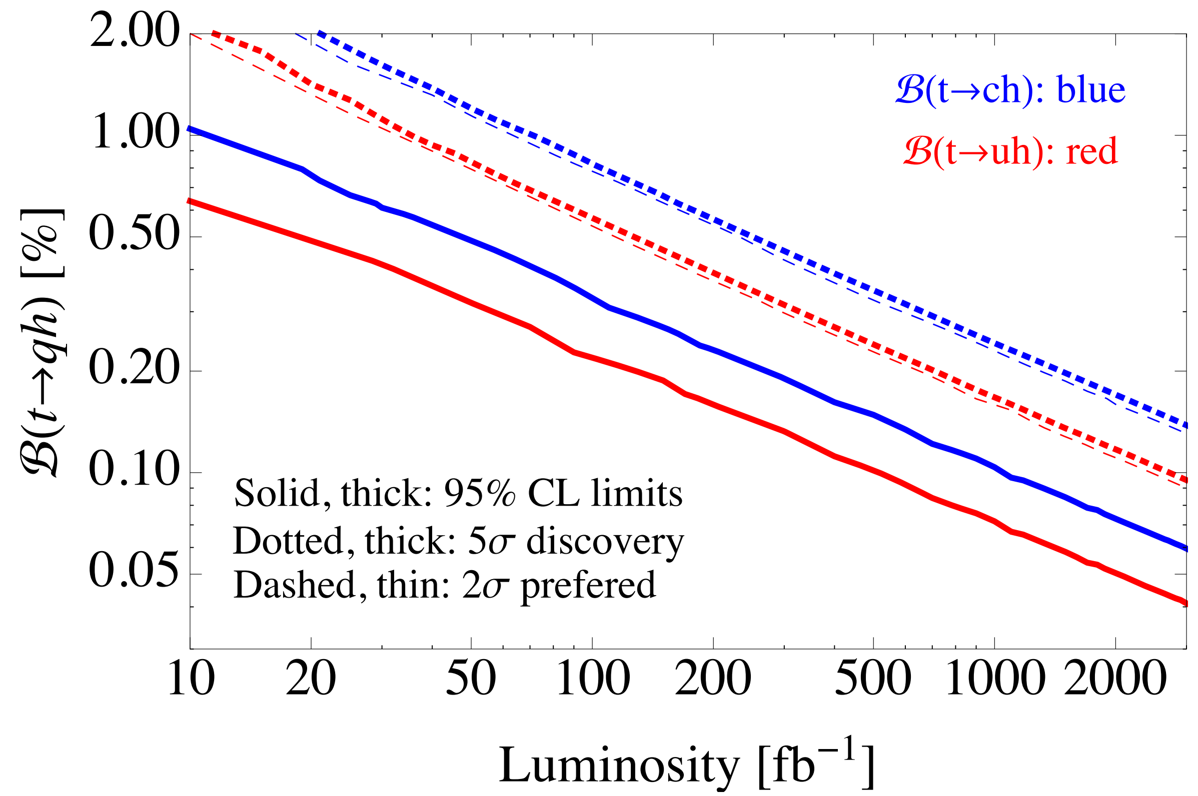
Greljo, J.F.K. & Kopp, 1404.1278

Discrimination between thc & thu couplings

Possible even without explicit Higgs reconstruction (like in multilepton searches)

In $h \rightarrow WW^* \rightarrow ll\nu\nu$ use leptons closest in rapidity as proxy for $\boldsymbol{\eta}_h$





Projection of multilepton search sensitivity (using a η_{ll} cut $|\eta_{ll}|>1$)

Probing the invisible through flavor violation
at LHC

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,...

see
J. F. K. & C. Smith, 1111.6402
and refs. therein

Invisibles Pair Production at Hadron Colliders

General discussion in terms of EFT

J.F.K. & Zupan, 1107.0623

$$\mathcal{L}_{\rm int} = \sum_a \frac{C_a}{\Lambda^{n_a}} \mathcal{O}_a$$

- With B preservation, O_a need to be bilinear in quark fields

$$\mathcal{O}_{1a}^{ij} = (\bar{Q}_L^i \gamma_\mu Q_L^j) \mathcal{J}_a^\mu\,,$$

$$\mathcal{O}_{2a}^{ij} = (\bar{u}_R^i \gamma_\mu u_R^j) \mathcal{J}_a^\mu, \qquad \mathcal{O}_{3a}^{ij} = (\bar{d}_R^i \gamma_\mu d_R^j) \mathcal{J}_a^\mu\,,$$

$$\mathcal{O}_{4a}^{ij} = (\bar{Q}_L^i H u_R^j) \mathcal{J}_a\,, \qquad \mathcal{O}_{5a}^{ij} = (\bar{Q}_L^i \tilde{H} d_R^j) \mathcal{J}_a\,,$$

- coupling to suitable dark sector currents, i.e.

$$\mathcal{J}_{V,A}^\mu = \bar{\chi}\gamma^\mu\{1,\gamma_5\}\chi \quad \mathcal{J}_{S,P} = \bar{\chi}\{1,\gamma_5\}\chi \qquad \mathcal{J} = \chi^\dagger\chi,\ \mathcal{J}^\mu = \chi^\dagger\partial^\mu\chi$$

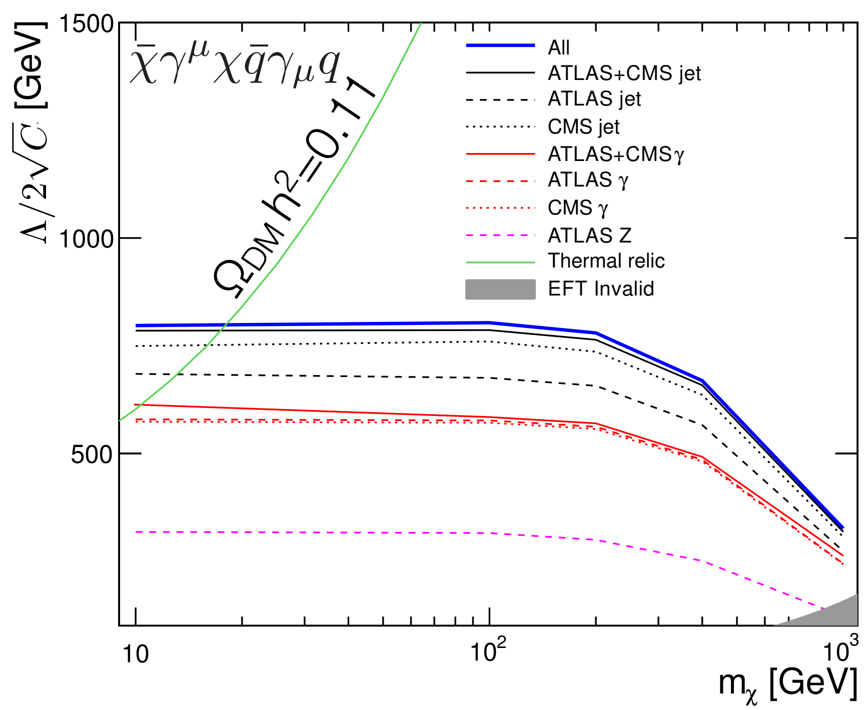
Fermionic

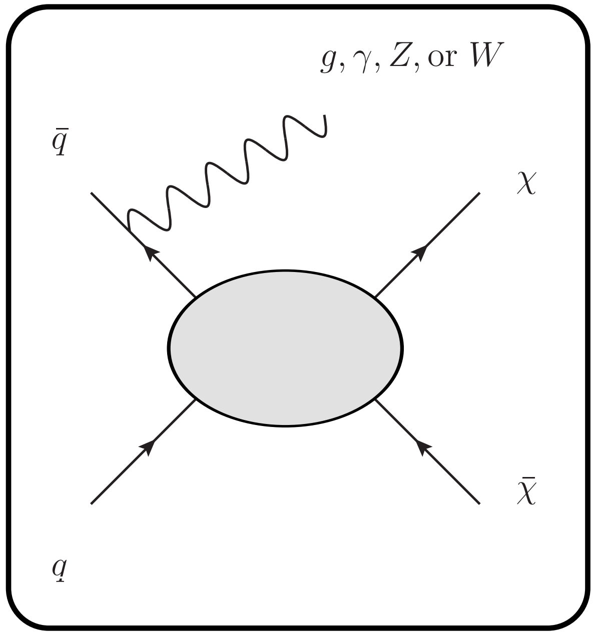
Scalar

Invisibles Pair Production at Hadron Colliders

Flavor universal contributions ($C^{ij} \sim \delta^{ij}$)

$\Rightarrow$ mono[jet, γ, Z, W] constraints using initial state radiation for tagging





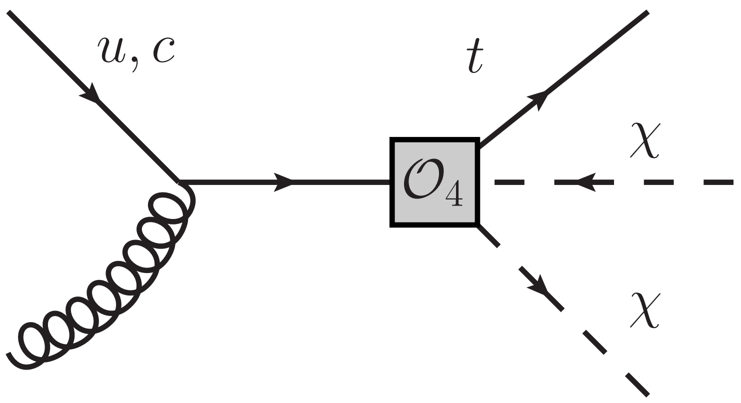
Zhou, Berge & Whiteson, 1302.3619 (see also refs. therein)

Flavor Bounds

Can flavor violating interactions be competitive?

- Constraints from ΔF=2 observables

  Example: $\frac{C_{1a}^{13}}{\Lambda} \lesssim \frac{1}{2\ \mathrm{TeV}}, \quad \frac{C_{1a}^{23}}{\Lambda} \lesssim \frac{1}{0.3\ \mathrm{TeV}},$

  - effectively no bounds on $C_{2a,4a}^{13,23}$

- Large monotop ($t+E_{\mathrm{miss}}$) signals possible due to chirality flipping operators

  (also $b+E_{\mathrm{miss}}$, but can be due to flavor conserving ops.)

  - reconstruction using $j_{(b)}jj+E_{\mathrm{miss}}$, or $j_{(b)}l+E_{\mathrm{miss}}$ (~ 1% signal eff.)

Andrea, Fuks & Maltoni, 1106.6199
Alvarez, Coluccio Leskow, Drobnak & J.F.K., 1310.7600
Agram et al., 1311.6478

Expectations in Models of Flavor

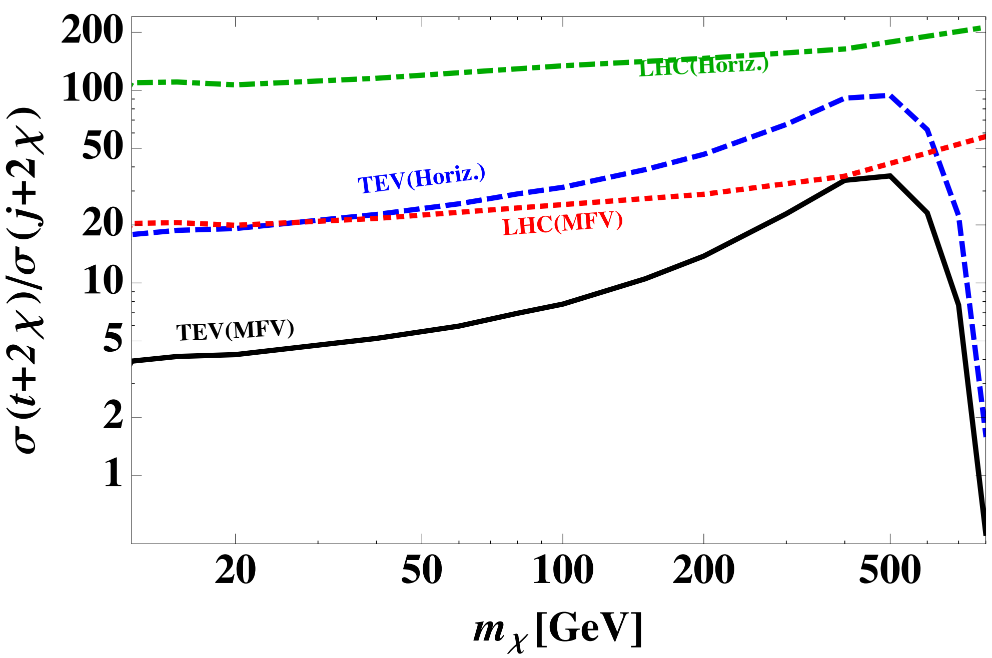
d'Ambrosio et al., hep-ph/0207036
...

Minimal Flavor Violation

$$C_{2a} = b_1^{(2a)} + b_2^{(2a)} Y_u^\dagger Y_u + b_3^{(2a)} Y_u^\dagger Y_d Y_d^\dagger Y_u + \cdots ,$$
$$C_{4a} = \left(b_1^{(4a)} + b_2^{(4a)} Y_d Y_d^\dagger + \cdots\right) Y_u .$$

- For $b_1^a \sim b_2^a \sim b_3^a$ C_{2a} almost flavor diagonal and universal
- C_{4a} is highly hierarchical, can have large flavor violation if $y_b \sim 1$

$$\frac{\hat\sigma(ug \to t + 2\chi)}{\hat\sigma(ug \to u + 2\chi)} \sim \left(\frac{y_t |V_{ub}| y_b^2}{y_u}\right)^2 \sim 5 \cdot 10^5 \, y_b^4 ,$$
$$\frac{\hat\sigma(cg \to t + 2\chi)}{\hat\sigma(cg \to c + 2\chi)} \sim \left(\frac{y_t |V_{cb}| y_b^2}{y_c}\right)^2 \sim 50 \, y_b^4 .$$



Larger effects expected with horizontal symmetries

Single invisible + t Production

Corresponds to production of neutral mediators in DM models

- Example: Scalar DM (S) via (heavy h_2) Higgs portal in THDMIII

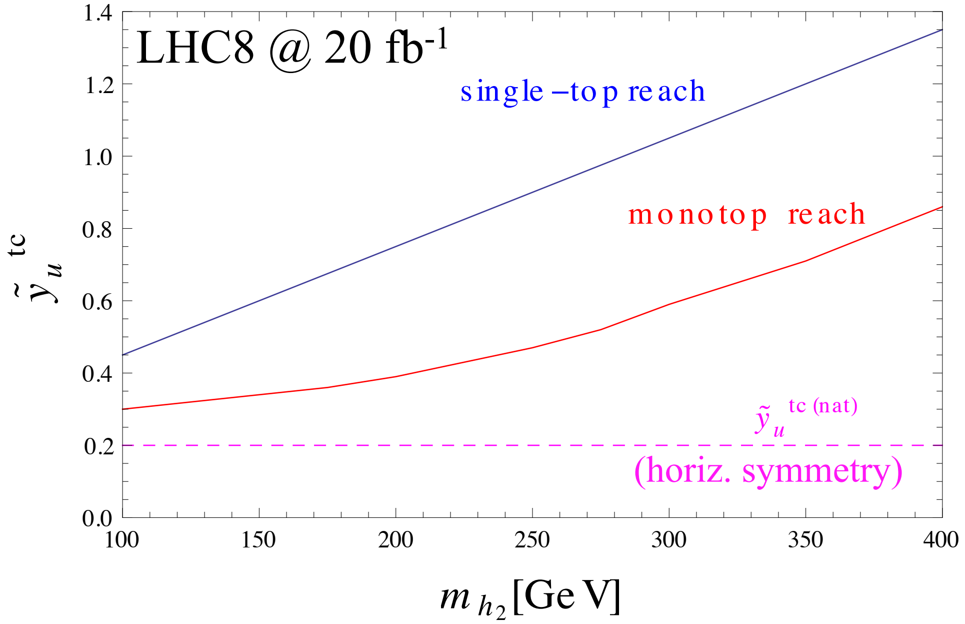
$$\mathcal{L}_{h_2}^{\tilde{y}} = \sum_{ij} \left(\tilde{y}_u^{ij} \bar{u}^i P_R u^j h_2 + \tilde{y}_d^{ij} \bar{d}^i P_R d^j h_2 \right) + \text{h.c.} + \lambda v_{\text{EW}} h_2 S S,$$

- D-$\underline{D}$ mixing constraints

$$|\tilde{y}_u^{ut} \tilde{y}_u^{ct}|, |\tilde{y}_u^{tu} \tilde{y}_u^{tc}| < 0.030 \times \left(\frac{m_{h_2}}{250\text{GeV}} \right)^2 ,$$

$$|\tilde{y}_u^{tu} \tilde{y}_u^{ct}|, |\tilde{y}_u^{ut} \tilde{y}_u^{tc}| < 0.0088 \times \left(\frac{m_{h_2}}{250\text{GeV}} \right)^2 ,$$

$$\sqrt{|\tilde{y}_u^{ut} \tilde{y}_u^{tu} \tilde{y}_u^{ct} \tilde{y}_u^{tc}|} < 0.0036 \times \left(\frac{m_{h_2}}{250\text{GeV}} \right)^2 ,$$



Recently first experimental LHC search using hadronic final states by CMS (CMS-PAS-B2G-12-022)

Flavor probes of EW and Higgs sectors

$B_{s,d} \to \mu^+\mu^-$

Theoretically very clean (virtually no long-distance contributions)

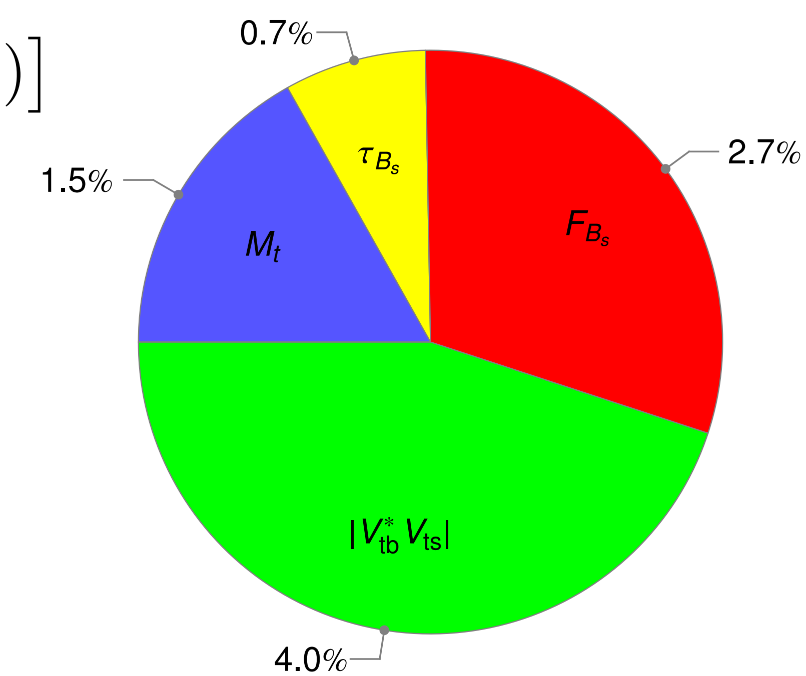
$$\mathcal{B}_{d,SM} = (1.07 \pm 0.10) \times 10^{-10} \qquad \overline{\mathcal{B}}_{s,SM} = (3.56 \pm 0.18) \times 10^{-9}$$

Buras et al., 1208.0934, 1303.3820

Important effect due to $\Delta\Gamma_s \neq 0$

$$\langle \mathcal{B}(B_s \to f) \rangle_{[t]} = \frac{1}{2} \int_0^t dt' \left[\Gamma(B_s(t') \to f) + \Gamma(\bar{B}_s(t') \to f) \right]$$

de Bruyn et al., 1204.1735



Dominant parametric uncertainties

In good agreement with experiment

$$\overline{\mathcal{B}_d}^{(\mathrm{exp})} = (3.6^{+1.9}_{-1.2}) \times 10^{-10} \qquad \overline{\mathcal{B}_s}^{(\mathrm{exp})} = (2.9^{+0.8}_{-0.6}) \times 10^{-9}$$

LHCb,1307.5024
CMS, 1307.5025

$B_{s,d} \to \mu^+\mu^-$

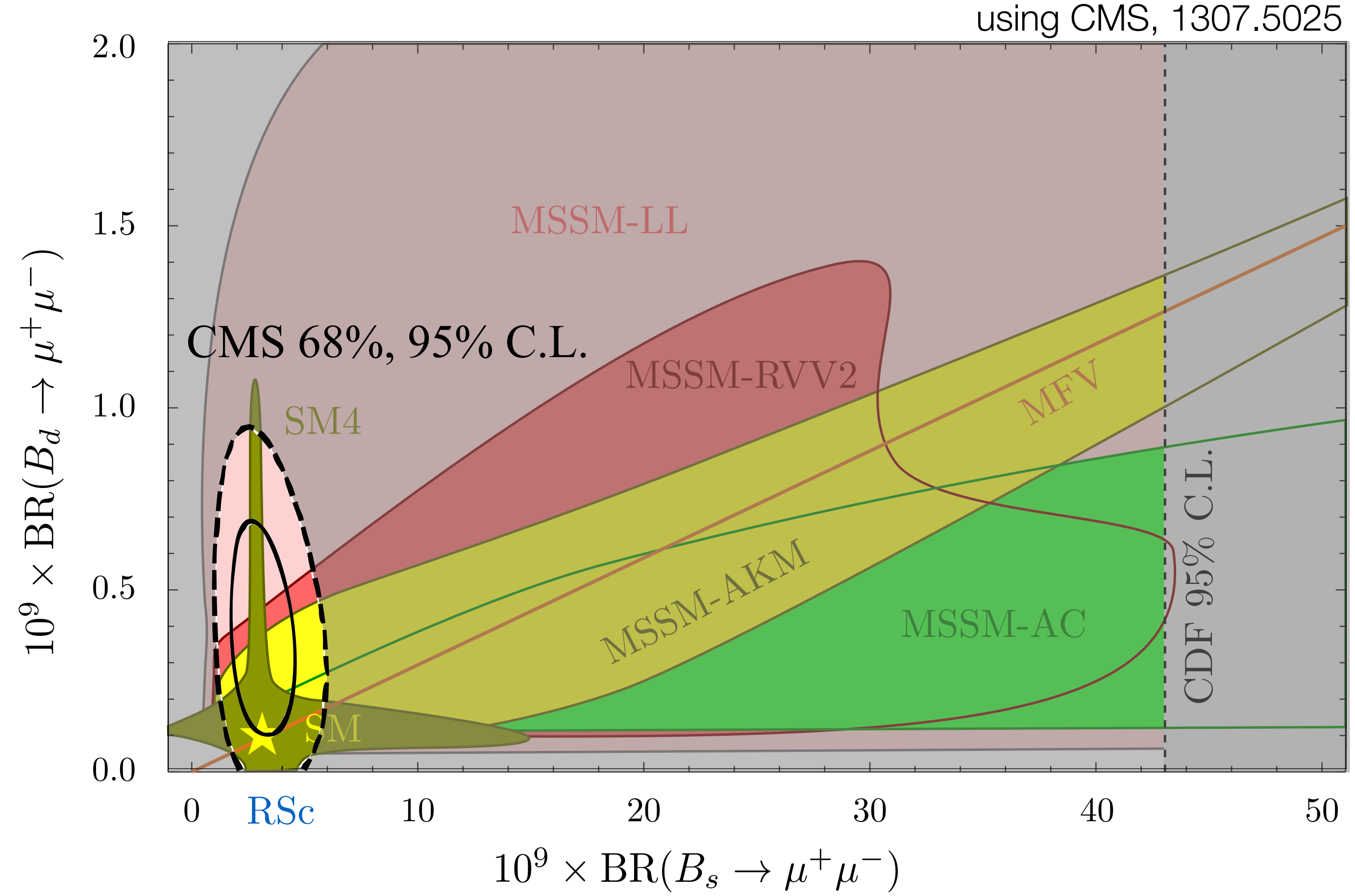
Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction (⇒ Higgs sector)

beyond tree level

update of Straub, 1012.3893
using CMS, 1307.5025

Latest results beginning to test possible $\mathcal{B}_d/\overline{\mathcal{B}}_s$ enhancement



Nontrivial test of MFV

Hurth et al., 0807.5039

Modified Z couplings

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

Fixing flavor model one can compare:

flavor (non)universality (*Zbb/Zqq*) vs. flavor violation (*Zbs*)

Guadagnoli & Isidori
1302.3909

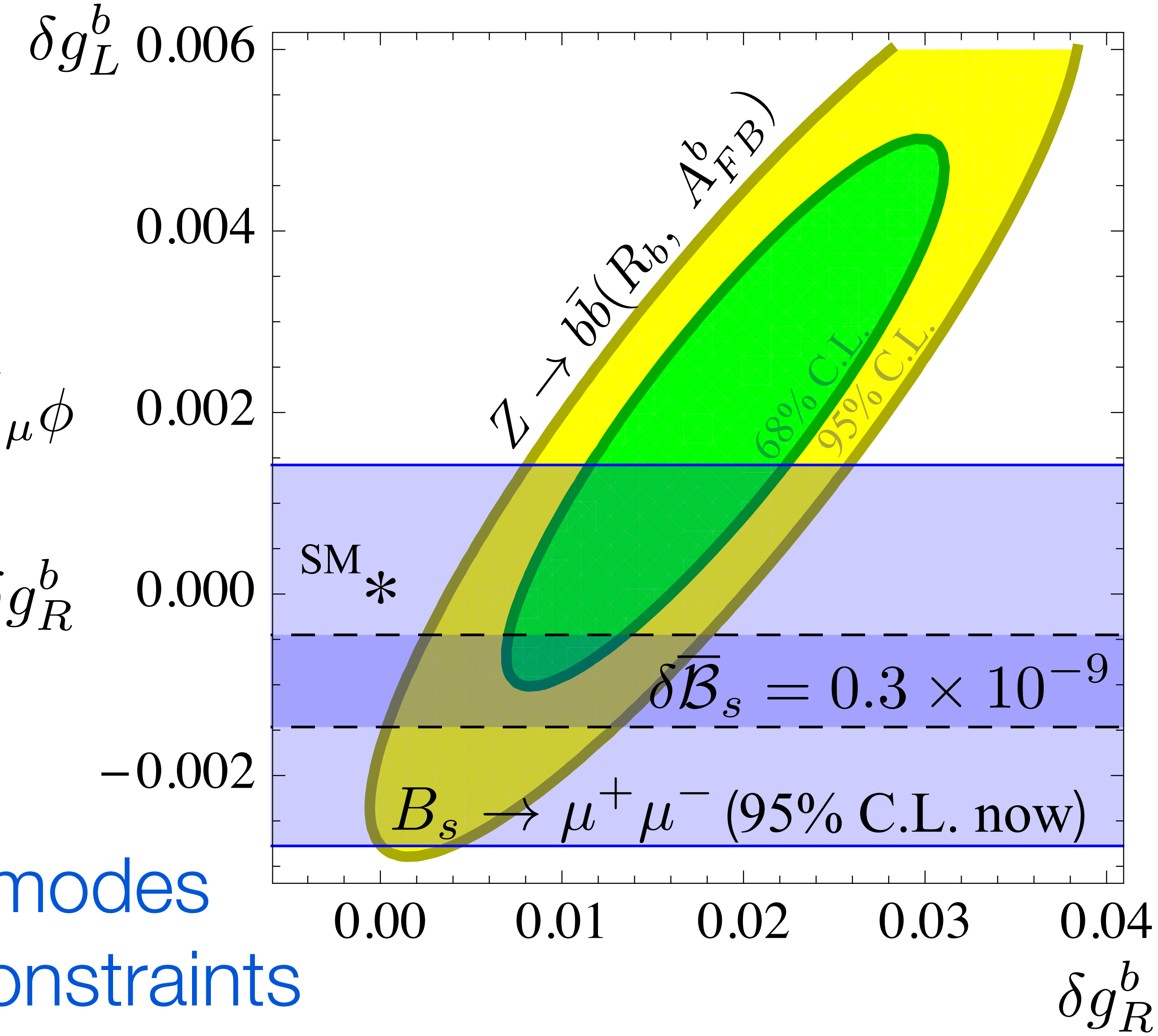
<u>Example</u>: MFV

$$\mathcal{Q}_L^{(6)} \sim c_{1L} (Y_u Y_u^\dagger)^{ij} \bar{Q}_L^i \gamma^\mu Q_L^j \phi^\dagger \overleftrightarrow{D}_\mu \phi$$

$$\mathcal{Q}_R^{(6)} \sim c_{1R} Y_d^i (Y_u Y_u^\dagger)^{ij} Y_d^j \bar{d}_R^i \gamma^\mu d_R^j \phi^\dagger \overleftrightarrow{D}_\mu \phi$$

$$\delta g_L^{bs} = \frac{V_{tb} V_{ts}^*}{|V_{tb}|^2} \delta g_L^b \qquad \delta g_R^{bs} = \frac{m_s V_{tb} V_{ts}^*}{m_b |V_{tb}|^2} \delta g_R^b$$

(update using the latest exp. results)

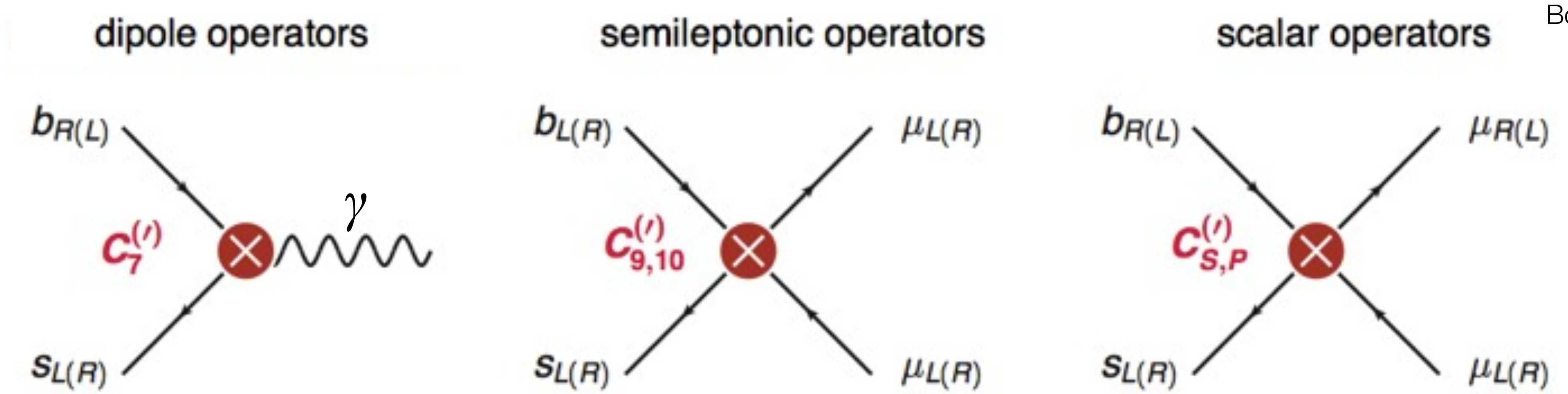


Inclusion of other $b \to s\ \mu^+\mu^-$ modes could further improve these constraints

Deconstructing $b \to s(\gamma, \ell^+\ell^-)$ transitions

Much more information available:

Kruger & Matias, hep-ph/0502060
Buchalla et al., hep-ph/0503151
Bobeth, Hiller & Piranishvili, 0709.4174, 0805.2525
Egede et al., 0807.2589, 1005.0571
Altmannshofer et al., 0811.1214
Alok et al., 0912.1382, 1008.2367, 1103.5344
Bobeth, Hiller & van Dyk, 1006.5013, 1105.0376, 1111.2558, 1212.2321
Descotes-Genon et al., 1104.3342, 1202.4266, 1207.2753, 1303.5794
Becirevic & Schneider, 1106.3283
Altmannshofer, Paradisi & Straub, 1111.1257
Matias et al., 1202.4266
Becirevic et al., 1205.5811, 1206.1502
Beaujean et al., 1205.1838
Altmannshofer & Straub, 1206.0273
...



	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'	C_S, C_S', C_P, C_P'
$B \to (X_s, K^*)\,\gamma$	★			
$B \to (X_s, K, K^*)\,\ell^+\ell^-$	★	★	★	(★)
$B_s \to \mu^+\mu^-$			★	★

adopted from Altmannshofer @ Snowmass Intensity Frontier Workshop 2013, Argonne

$B \to K^* \ell^+ \ell^-$ anomaly

LHCb, 1308.1707

Fit of angular observables (A_{FB}, P_i) binned in low q^2 region

- Mostly sensitive to $\mathcal{Q}_7 \sim C_7\, m_b[\bar{s}\sigma_{\mu\nu}(1+\gamma_5)b]eF^{\mu\nu}$
  $\mathcal{Q}_9 \sim C_9\,[\bar{s}\gamma_\mu(1-\gamma_5)b][\bar{\ell}\gamma^\mu\ell]$ (+chirally flipped ops.)

- In ~3σ tension with SM estimates (dominated by P_5', also A_{FB}, P_2)

- Can be reconciled by ~40% reduction of $\langle \mathcal{Q}_9 \rangle$

c.f.
Descotes-Genon, Matias & Virto, 1307.5683
Altmannshofer & Straub, 1308.1501
Hurth & Mahmoudi, 1312.5267
...

A sign of NP? Recheck SM theory estimates

- Based on QCD factorization at large hadronic recoil

- Form factor reduction - broken by α_s (computed), $1/m_b$ (estimated) corrections

- Underestimated LD contributions? $\int d^4x\, e^{-iq\cdot x} \langle \bar{K}^* | T\{ j_\mu^{\text{em}}(x),\, \mathcal{H}_{\text{eff}}^{\text{had, lq}}(0)\} | \bar{B} \rangle,$

Jager & Camalich, 1212.2263

First-principles QCD estimate possible?

Khodjamirian et al., 1006.4945

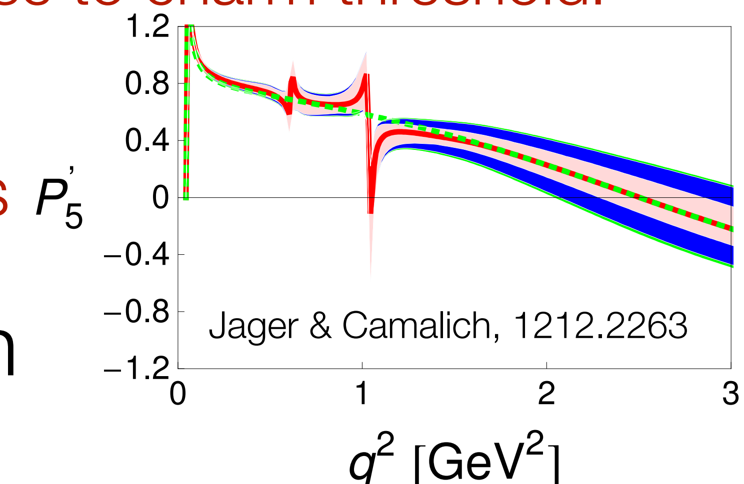
$B \to K^* \ell^+ \ell^-$ anomaly

Possible experimental tests:

- More inclusive observables (integrated over $q^2 = [1, 6]$ GeV^2)

  Not too close to charm threshold!

  - less sensitive to non-local (resonance) contributions
  - fine binning could enhance sensitivity to QCD effects



- Consider high q^2 (low hadronic recoil) region

  - different theory systematics (HQET OPE)

  However, some indications that some of assumptions might be violated

  LHCb, 1307.7595

- Complementary observables in other modes

  $(B_s \to \phi \ell^+ \ell^-, B \to K \ell^+ \ell^-, B \to X_s \ell^+ \ell^-, \ldots)$

  i.e. expect reduced rates compared to SM estimates

  Recent indications?

  Horgan et al., 1310.3722, 1310.3887

  LHCb,1403.8044

  - if due to QCD, don't necessarily expect identical effects

Conclusions

Success of SM (CKM paradigm) in describing (quark) flavor phenomena puzzling in light of EW hierarchy problem

Flavor physics intimately connected to Higgs phenomenology - directions just starting to be explored

Top-flavor processes ideal for LHC studies - interesting links to EW hierarchy, flavor, DM puzzles

see also
Blanke et al., 1302.7232

Puzzling results in rare B decays due to be properly understood

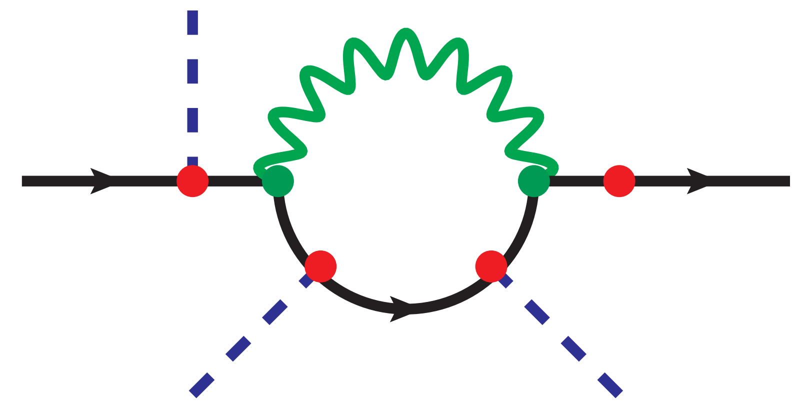
Backup

Testing flavor through Higgs observables (at LHC)

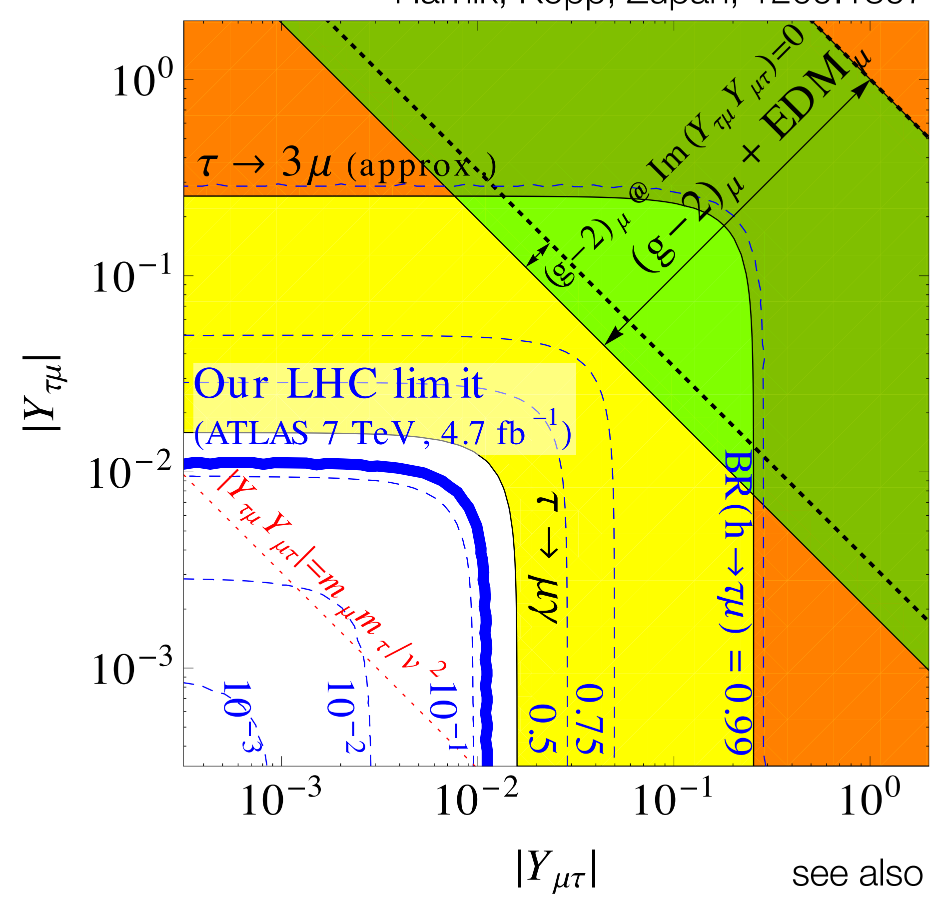
Within SM effective $Y_{i\neq j}$ extremely suppressed (GIM+CKM/m_ν & chirality)

Constraints on first two generation $Y_{i\neq j}$ dominated by precision flavor observables (both lepton and quark)

Currently LHC already most constraining in τ-μ, τ-e sectors (recast of $h\to\tau\tau$)



Harnik, Kopp, Zupan, 1209.1397



see also
McKeen, Pospelov, Ritz, 1208.4597
Blankenburg, Ellis, Isidori, 1202.5704

$B_{s,d} \to \mu^+\mu^-$

Particularly sensitive to FCNC scalar currents and FCNC Z penguins

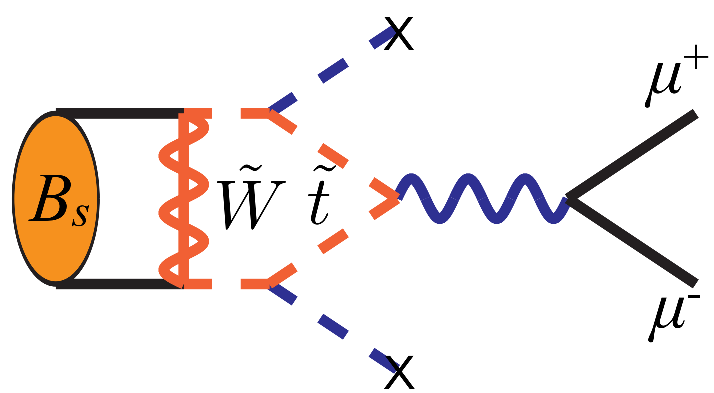
Clean probe of the Yukawa interaction (⇒ Higgs sector)

beyond tree level

Example: general MSSM

c.f. Isidori & Retico, hep-ph/0208159

$$m_h \sim 125\ \text{GeV}$$
$$\Downarrow$$
large A_{33}



$$\propto G_F^2 m_W^2 \frac{y_t^2}{16\pi^2} \frac{A_{23} A_{33}^*}{m_{\tilde{t}_R}^2}$$

Measurement with σ(BR) ~ 30% provides relevant constraint on such couplings below stability bounds

$(|A_{23}A_{33}| < 3m_{\tilde{t}_L}^2)$ for $m_{\tilde{t}_L} < 1\,\text{TeV}$, $m_{\tilde{t}_R} < 0.5\,\text{TeV}$

Isidori @ HCP2012, Kyoto
Behring et al., 1205.1500
Mahmoudi, Neshatpour & Orloff 1205.1845