

# XXVI INTERNATIONAL SYMPOSIUM ON LEPTON PHOTON INTERACTIONS AT HIGH ENERGIES

## Flavor constraints on New Physics

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# Why flavor matters in the LHC era?

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- Indirectly probes NP scales up to  $10^8$  GeV 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

# Introduction

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SM phenomenologically very successful theory

Strong theoretical arguments to consider it as effective theory

Unification  
of interactions

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

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

EW scale  
stabilization

Origin of flavor

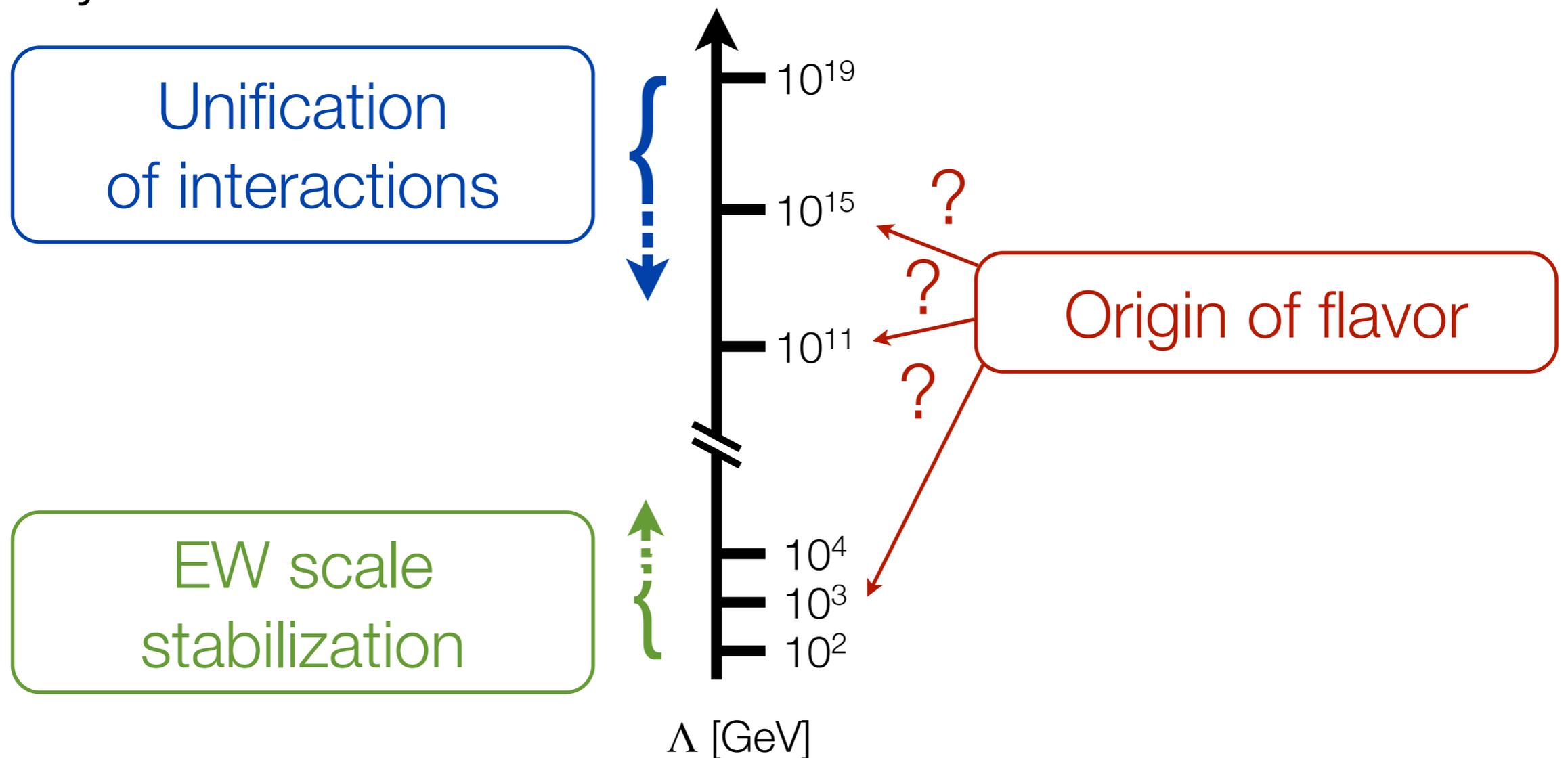
Need to understand/constrain size of additional terms in series

# Introduction

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Strong theoretical arguments to consider it as effective theory



# (Over)constraining the SM flavor sector

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In SM quark sector  $Y_u, Y_d$  only source of global flavor symmetry breaking:

10 physical parameters:

6 quark masses

3 CKM mixing angles

1 CP odd phase

$$m_u = v V_L^u Y^u V_R^{u\dagger}$$

$$m_d = v V_L^d Y^d V_R^{d\dagger}$$

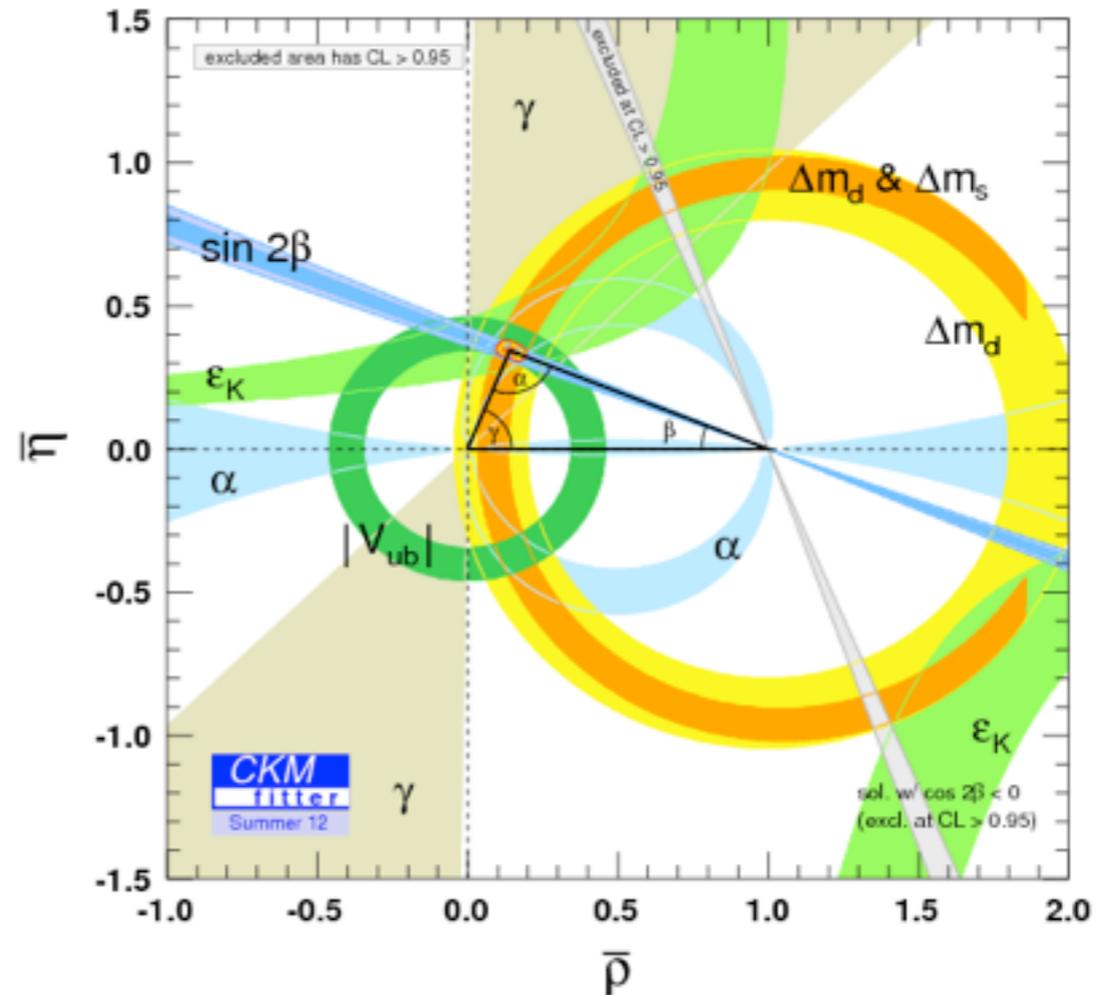
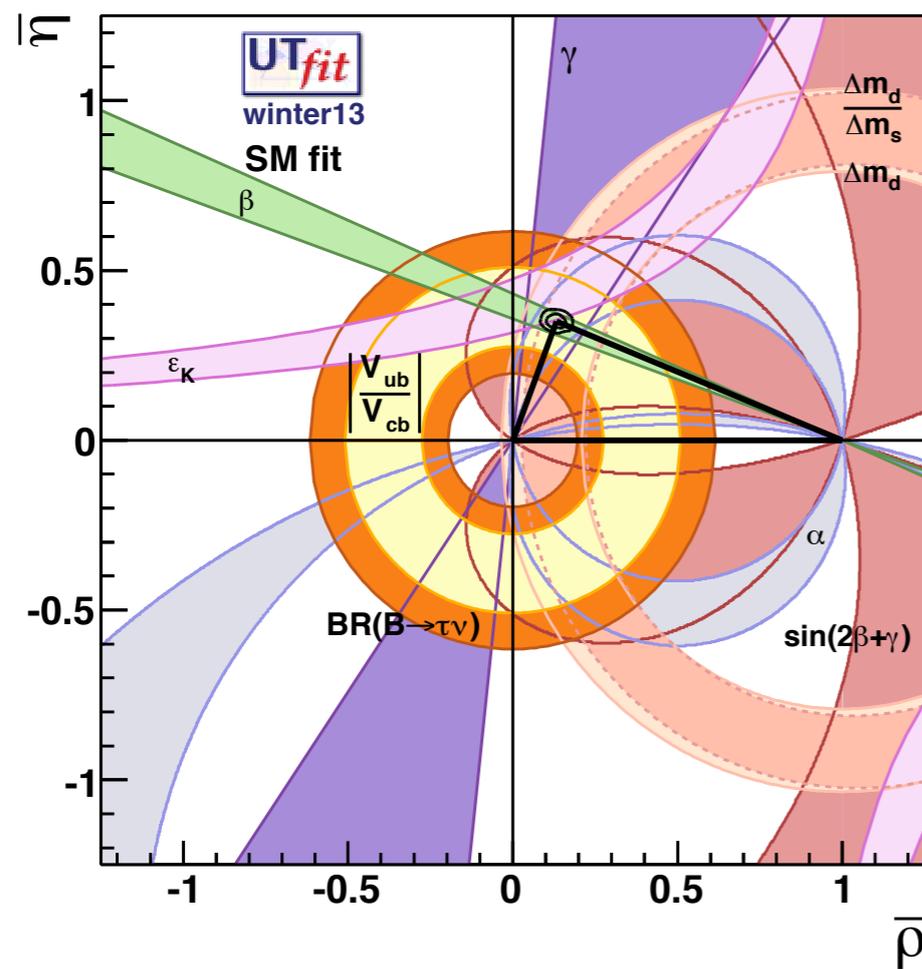
$$V = V_L^u V_L^{d\dagger}$$

Determine all flavor phenomena in quark sector!

# (Over)constraining the SM flavor sector

In SM quark sector  $Y_u, Y_d$  only source of global flavor symmetry breaking:

$$\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$$

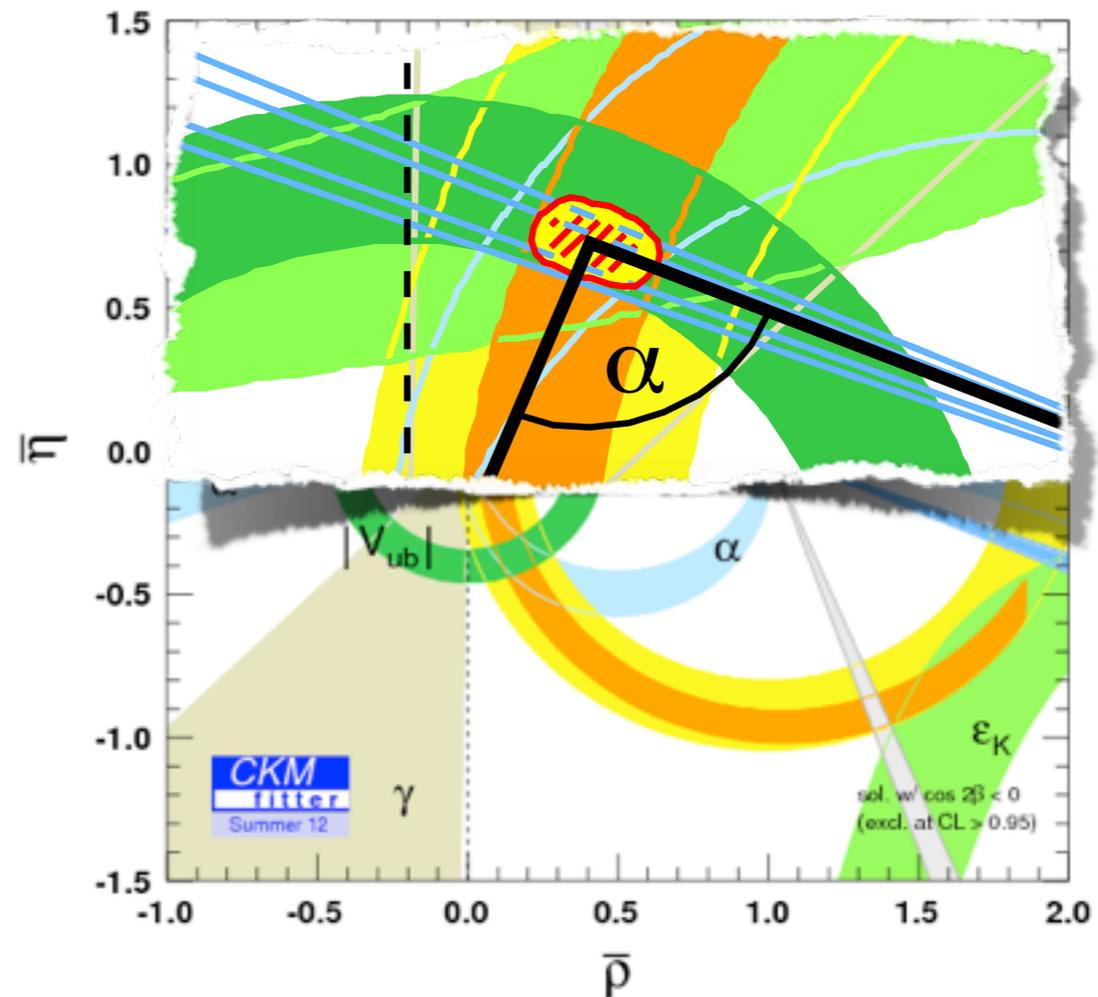
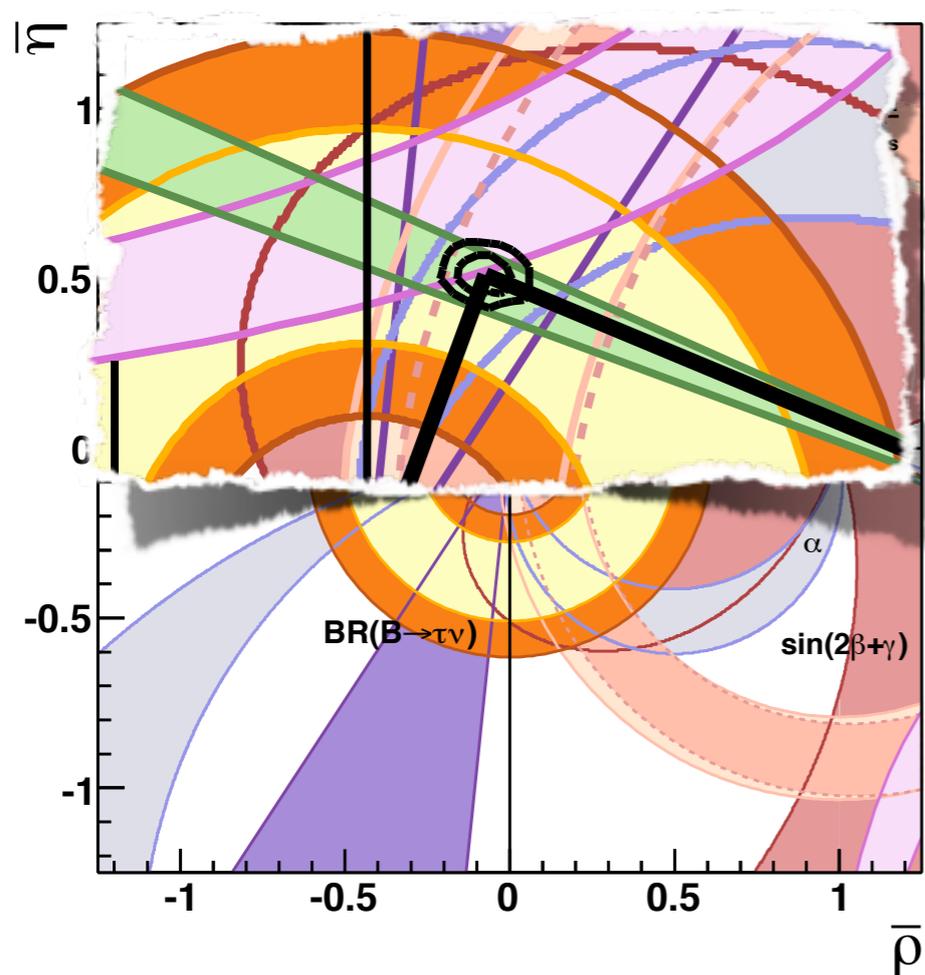


Generally excellent consistency!

# (Over)constraining the SM flavor sector

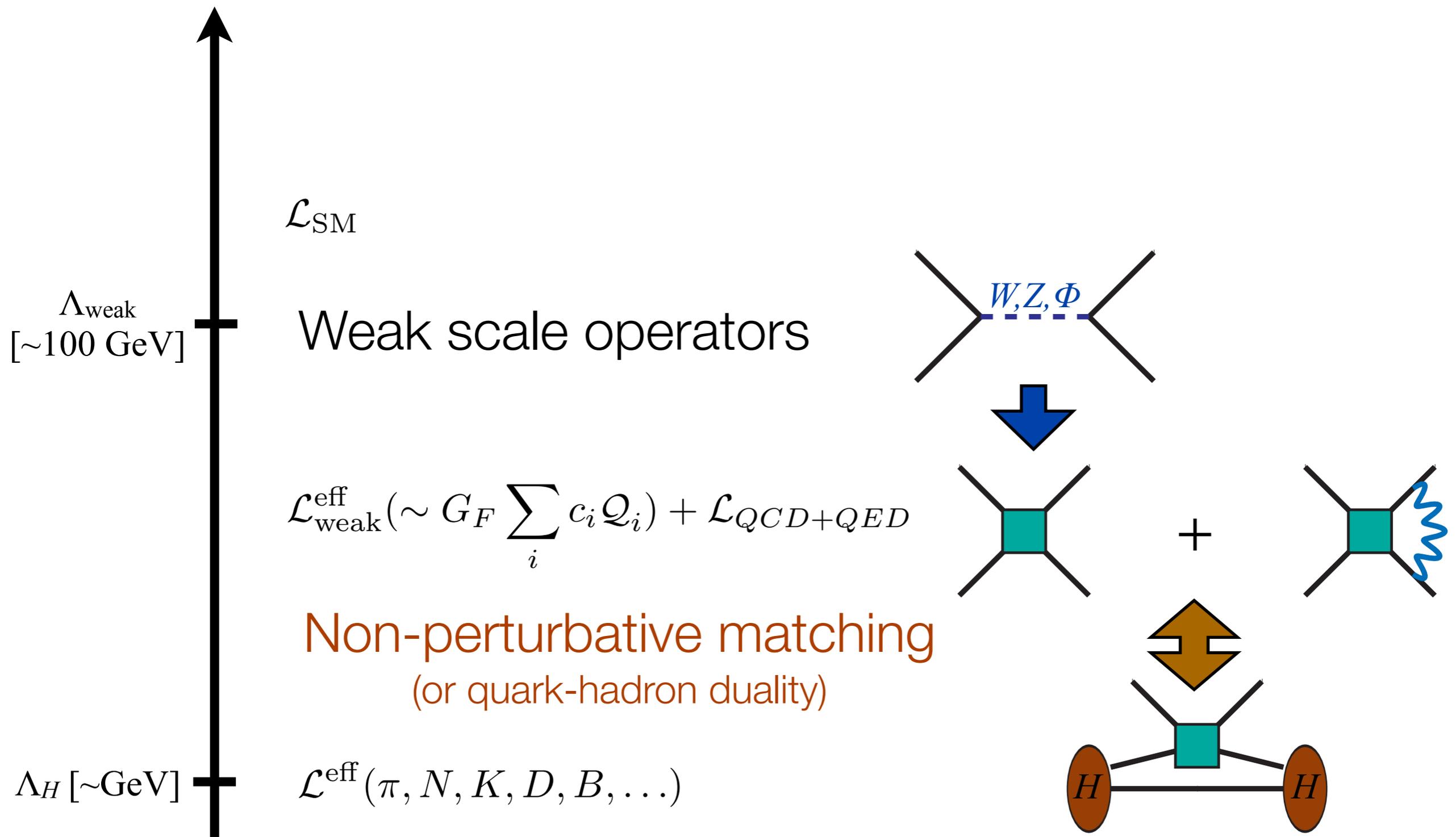
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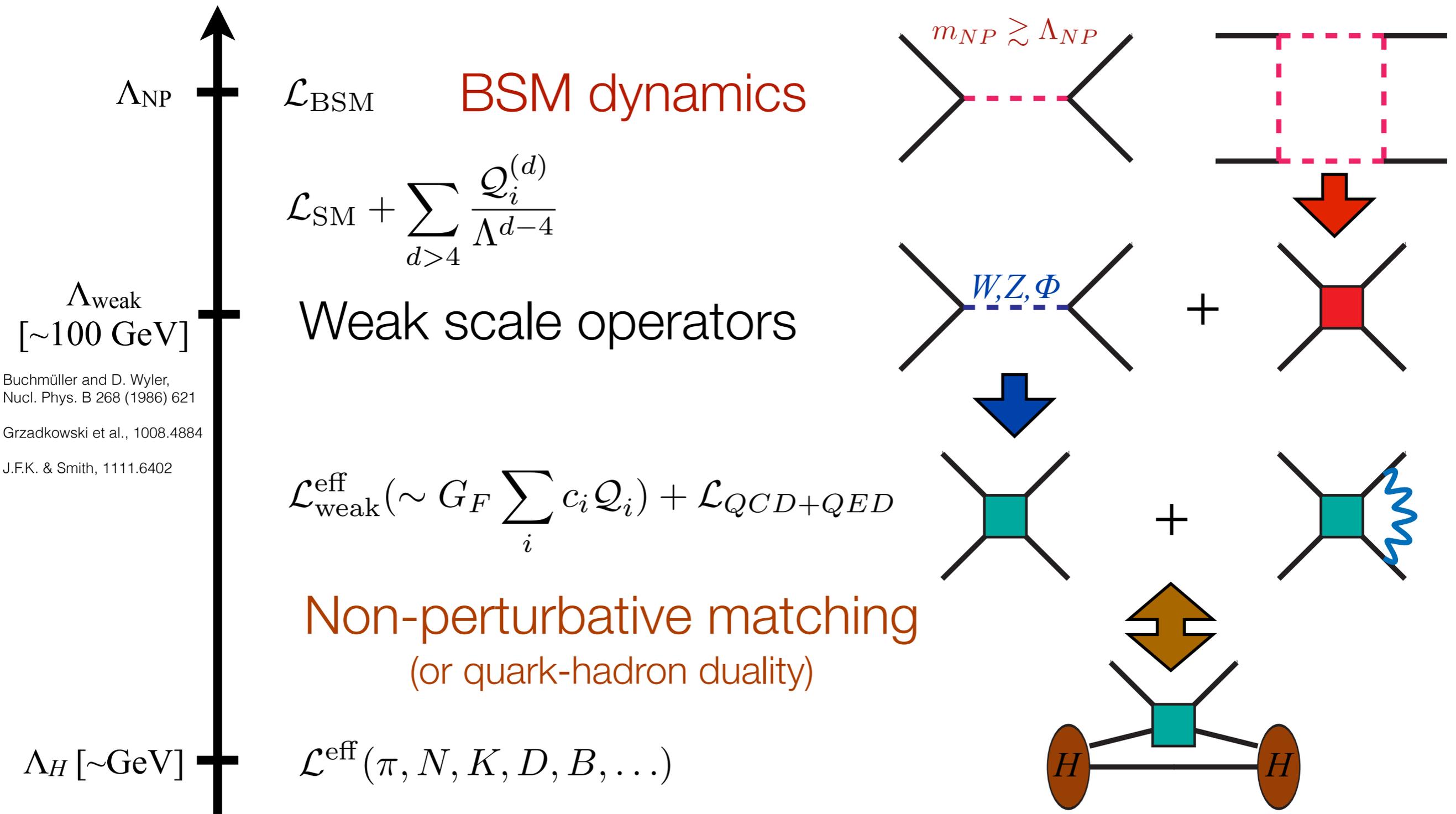


Generally excellent consistency!

# (Over)constraining the SM flavor sector



# (Over)constraining the SM flavor sector (and NP)

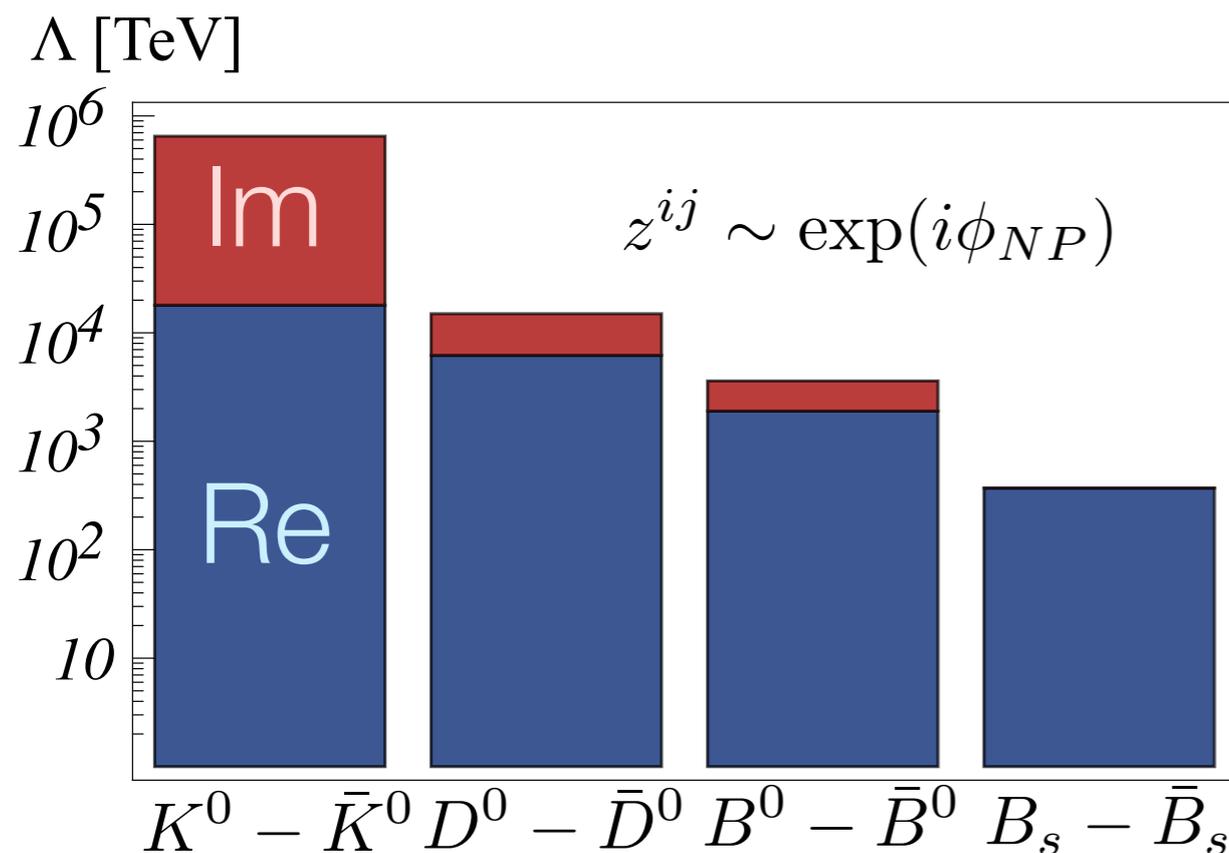


# (Over)constraining the SM flavor sector (and NP)

## Canonical example: NP in $\Delta F=2$ processes

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

$$Q_{AB}^{(6)} \sim z^{ij} [\bar{q}_i \Gamma^A q_j] \otimes [\bar{q}_i \Gamma^B q_j]$$



- Most constraints now limited by theory uncertainties (both SM & NP) c.f. Buras & Gorbach, 1201.1302  
Mescia & Virto, 1208.0534

Need NLO QCD matching

- Crucial non-pert. QCD input

see talk by Davies

Large NP mass gap / flavor symmetry-structure

(Over)constraining the SM flavor sector (and NP)

---

Is flavor trivial NP safe from flavor constraints?

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0008 \left( {}^{+7}_{-6} \right)$$

RBC/UKQCD Collaboration, 1305.7217

$$Q_{\phi Q}^{(6)} \sim z^{ij} \bar{Q}_L^i \tau^a \gamma^\mu Q_L^j \phi^\dagger \tau_a \overleftrightarrow{D}_\mu \phi$$

$$z^{ij} = \delta^{ij} : G_F^{(sl)} = G_F^{(\mu)} \left[ 1 + \frac{v^2}{2\Lambda^2} \right] \longrightarrow \Lambda > 5.5 \text{ TeV}$$

Competitive EW precision constraints?  
Is flavor trivial NP realistic?



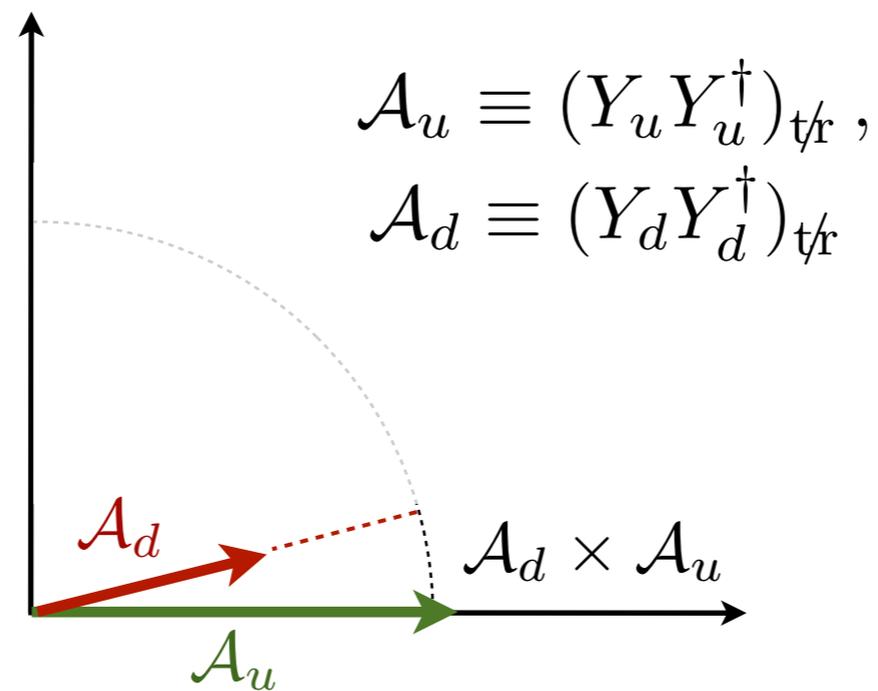
Reclaiming flavorful NP at EW scale

# Reclaiming flavorful NP at EW scale

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Global flavor symmetry of SM broken by Yukawas:

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



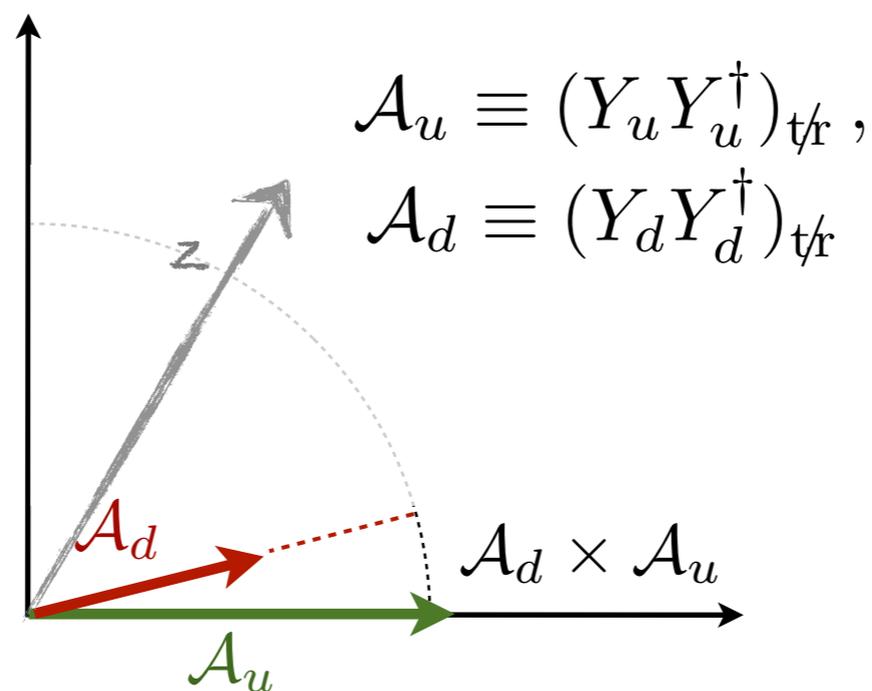
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Formally, NP flavor cannot be completely trivial



$$\int d^4x T\{Q_{\text{NP}} \mathcal{H}_{\text{SM}}\}$$

# Reclaiming flavorful NP at EW scale

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Global flavor symmetry of SM broken by Yukawas:

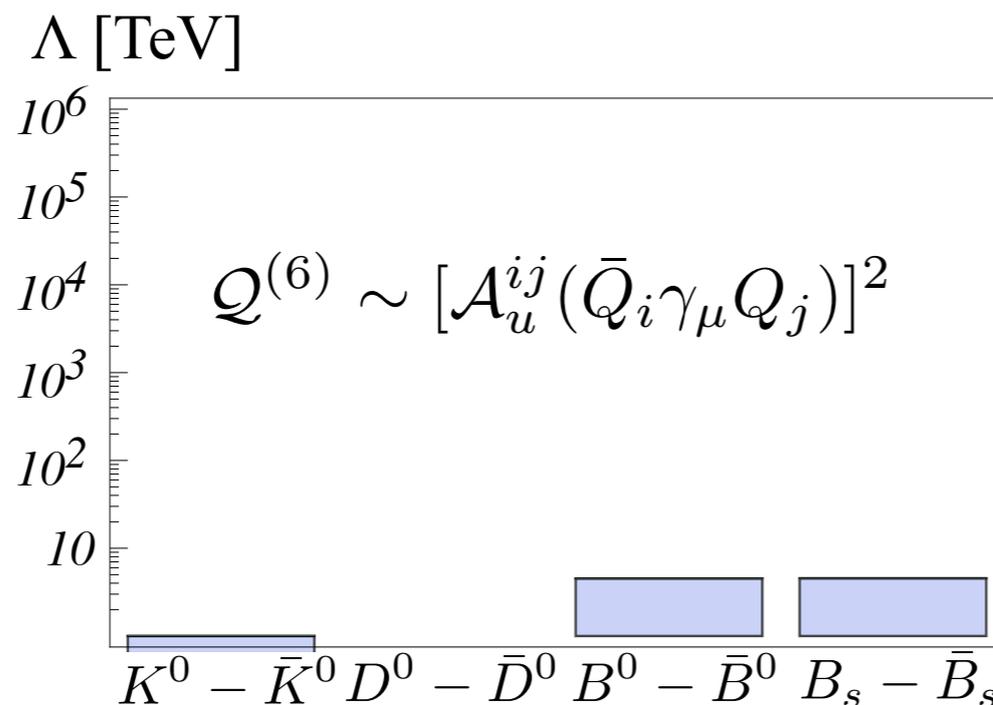
$$G_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D$$

Formally, NP flavor cannot be completely trivial

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

$a_{i>2} \lesssim a_{1,2}$  “Minimal Flavor Violation”

d'Ambrosio et al., hep-ph/0207036  
Colangelo et al., 0807.0801



NP in loops  
 $\Downarrow$   
probe EW scale masses

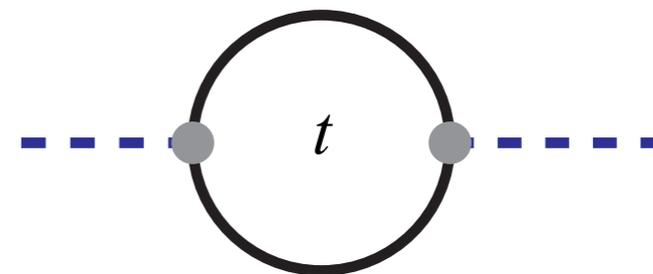
# Reclaiming flavorful NP at EW scale

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Flavor triviality imposes degeneracy in NP spectra -  
**problematic for naturalness@LHC**

In SM, top Yukawa imposes largest fine-tuning in Higgs potential  $\Rightarrow$

$$\delta m_h^2 \sim \frac{m_t^2}{v^2} \Lambda^2$$



# Reclaiming flavorful NP at EW scale

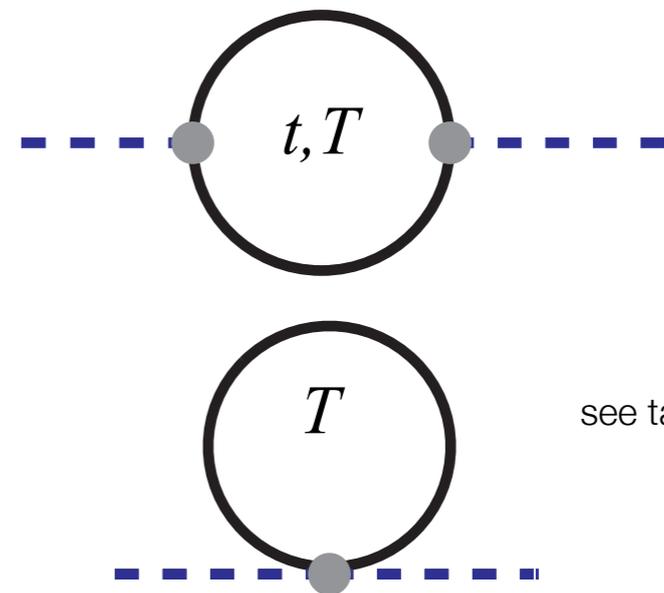
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Flavor triviality imposes degeneracy in NP spectra -  
**problematic for naturalness@LHC**

In SM, top Yukawa imposes largest fine-tuning in Higgs potential  $\Rightarrow$

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

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



see talk by Han

# Reclaiming flavorful NP at EW scale

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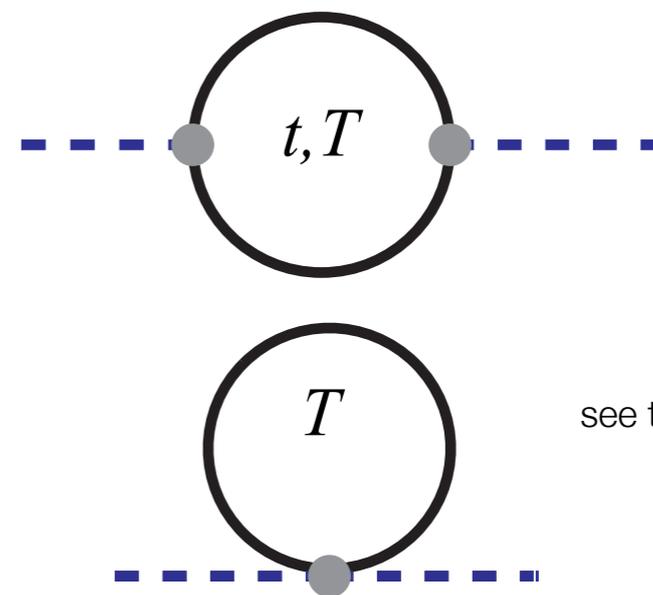
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prefer light top partners ( $m_T < 1\text{TeV}$ )

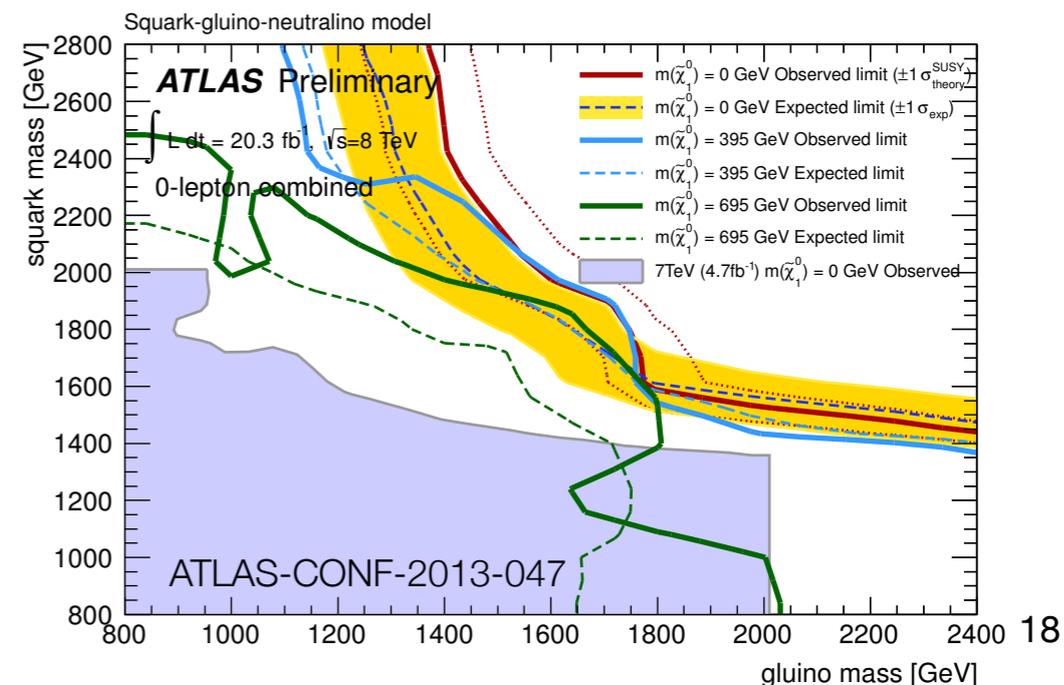
avoiding flavor bounds through triviality  
 $\Rightarrow$  presence of u,d,... partners ( $m_U \sim m_T$ )

**Strong LHC direct search constraints  
 (MSSM example)**

see talk by Hoecker



see talk by Han



# Reclaiming flavorful NP at EW scale

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Flavor triviality imposes degeneracy in NP spectra -  
**problematic for naturalness@LHC**

Dominant SM flavor breaking characterized by  $SU(3)/SU(2)$

NP respecting such pattern can avoid stringent FCNC constraints in  $K$  and  $D$  sectors - GMFV, horizontal  $U(2)^3$

Kagan et al., 0903.1794

- new (CPV) effects still possible in  $B$  ( $D$ ) processes

Buras & Girschbach, 1206.3878

- examples in MSSM, partial compositeness  
⇒ allow for lighter 3rd generation partners

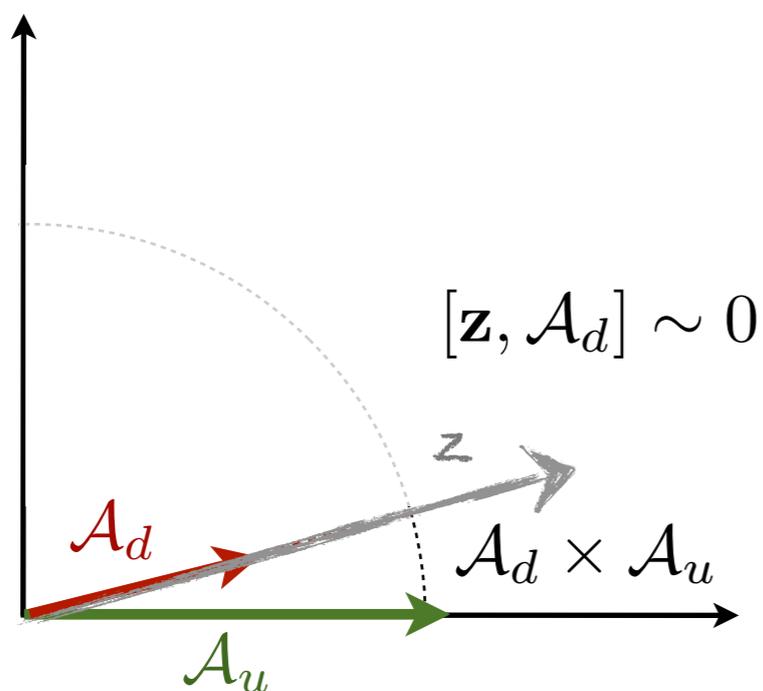
Barbieri et al., 1105.2296  
1108.5125  
1203.4218  
1206.1327  
1211.5085

# Reclaiming flavorful NP at EW scale

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Flavor triviality imposes degeneracy in NP spectra -  
**problematic for naturalness@LHC**

Alternatively, align SM & NP flavor breaking



Can use abelian flavor charges

Nir & Seiberg, hep-ph/9304307

CPV in light quark FCNCs  
automatically suppressed

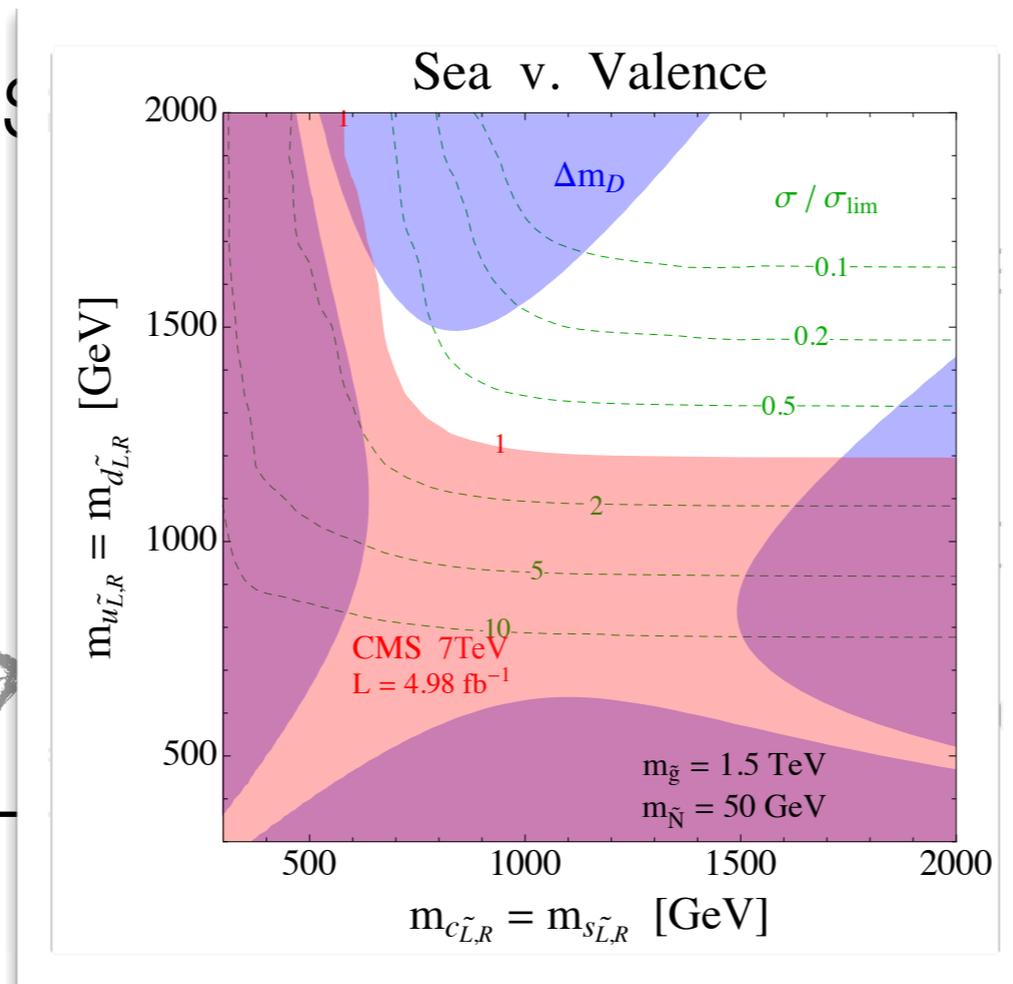
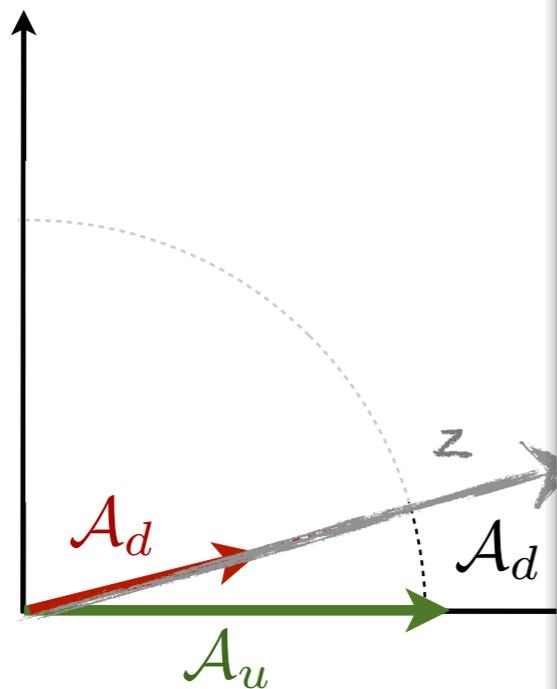
Gedalia et al., 1202.5038

Allows split NP spectrum

# Reclaiming flavorful NP at EW scale

Flavor triviality imposes degeneracy in NP spectra -  
**problematic for naturalness@LHC**

Alternatively, align S



Flavor charges

Nir & Seiberg, hep-ph/9304307

FCNCs

Suppressed

Gedalia et al., 1202.5038

Spectrum

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

Mahbubani et al., 1212.3328

# Reclaiming flavorful NP at EW scale

---

Flavor triviality imposes degeneracy in NP spectra -  
**problematic for naturalness@LHC**

- 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

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

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

# Reclaiming flavorful NP at EW scale

Flavor triviality imposes degeneracy in NP spectra -  
**problematic for naturalness@LHC**

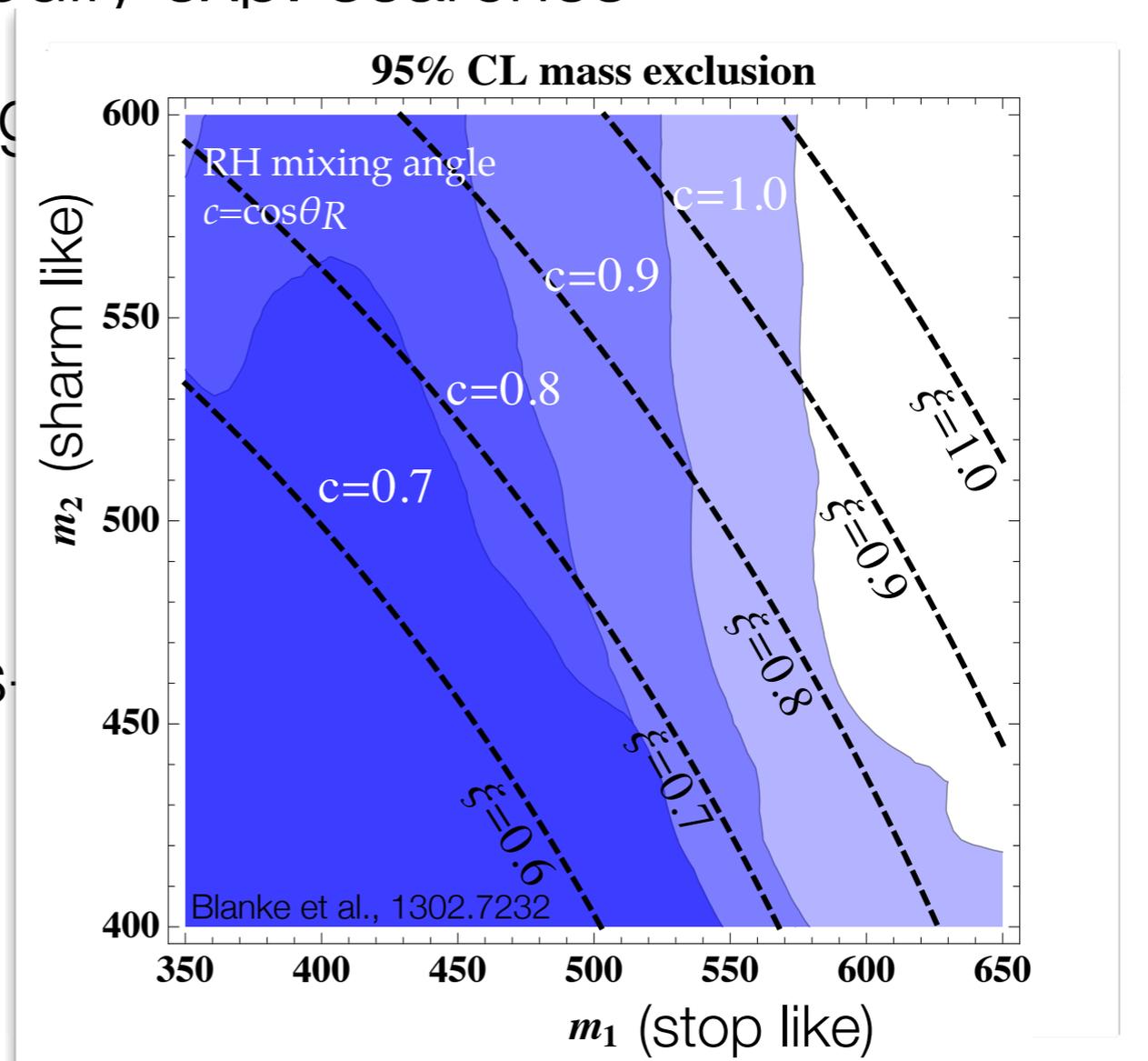
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Example: large  $\tilde{t}_R - \tilde{c}_R$  mixing

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

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

Tuning measure:  $\xi = \frac{c^2 m_1^2 + s^2 m_2^2}{m_0^2}$   
 (compared to pure stop) (shown for  $c=0.7$ )





Higgs as probe of flavor

# Testing flavor through Higgs observables

## BSM modifications of Yukawa sector

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

Giudice, Lebedev, 0804.1753  
Agashe, Contino, 0906.1542  
Goudelis, Lebedev, Park, 1111.1715  
Arhrib, Cheng, Kong, 1208.4669  
McKeen, Pospelov, Ritz, 1208.4597  
Blankenburg, Ellis, Isidori, 1202.5704  
Harnik, Kopp, Zupan, 1209.1397  
Alonso et al., 1212.3307  
Dery et al., 1302.3229, 1304.6727

...

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

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)

# Testing flavor through Higgs observables

Currently LHC most constraining in  $\tau$ - $\mu$ ,  $\tau$ - $e$  sectors (recast of  $h \rightarrow \tau \tau$ )

Target benchmark flavor model predictions

Dery et al., 1302.3229

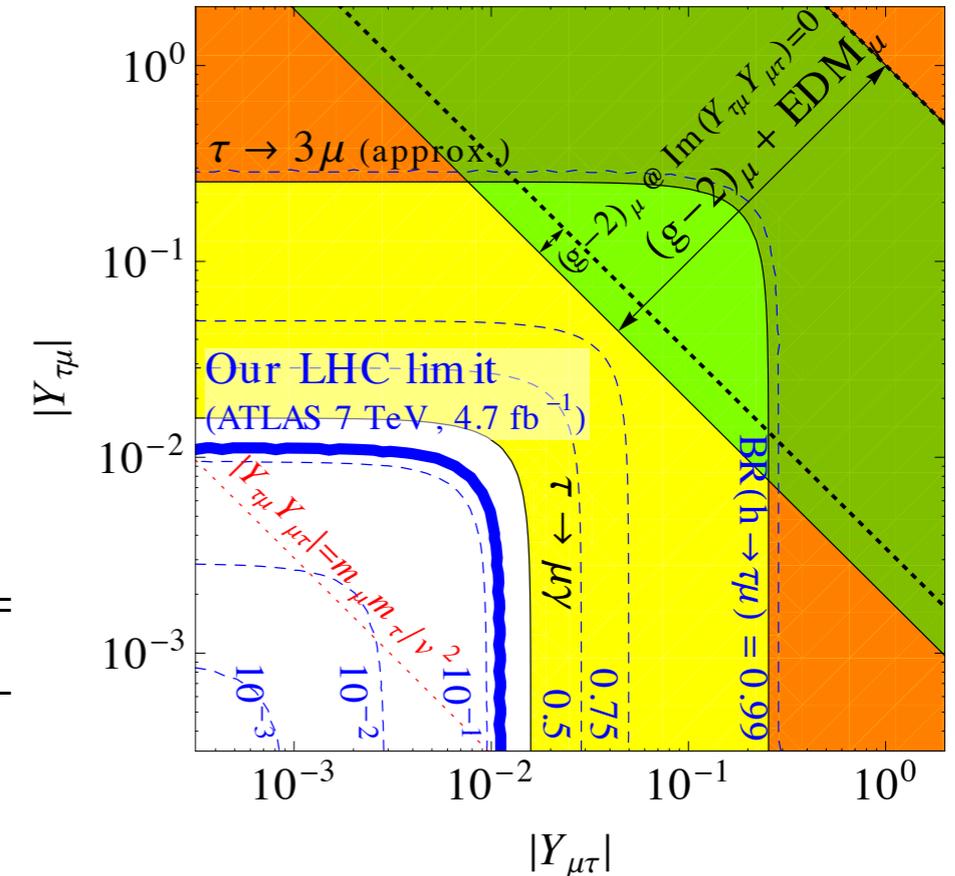
Model	$\left(\frac{\sigma(pp \rightarrow h)^{\text{SM}}}{\sigma(pp \rightarrow h)} \frac{\Gamma_{\text{tot}}}{\Gamma_{\text{tot}}^{\text{SM}}}\right) R_{\tau^+\tau^-}$	$X_{\mu^+\mu^-} / (m_\mu^2/m_\tau^2)$	$\bar{Y}_{\mu\tau}$
SM	1	1	0
NFC	$(V_{h\ell}^* v/v_\ell)^2$	1	0
MSSM	$(\sin \alpha / \cos \beta)^2$	1	0
MFV	$1 + 2av^2/\Lambda^2$	$1 - 4bm_\tau^2/\Lambda^2$	0
FN	$1 + \mathcal{O}(v^2/\Lambda^2)$	$1 + \mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}( U_{23} ^2 v^4/\Lambda^4)$
GL	9	25/9	$\mathcal{O}(X_{\mu^+\mu^-})$

$$R_{\tau^+\tau^-} \equiv \frac{\text{BR}(h \rightarrow \tau^+\tau^-)}{\text{BR}(h \rightarrow \tau^+\tau^-)^{\text{SM}}}$$

$$X_{\mu^+\mu^-} \equiv \frac{\text{BR}(h \rightarrow \mu^+\mu^-)}{\text{BR}(h \rightarrow \tau^+\tau^-)}$$

In quark sector,  $Y_{tc}$ ,  $Y_{qq}$  ( $q \neq b, t$ ) still poorly constrained

Harnik, Kopp, Zupan, 1209.1397





Flavor probes of EW and Higgs sectors

$$B_s \rightarrow \mu^+ \mu^-$$


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Theoretically very clean (virtually no long-distance contributions)

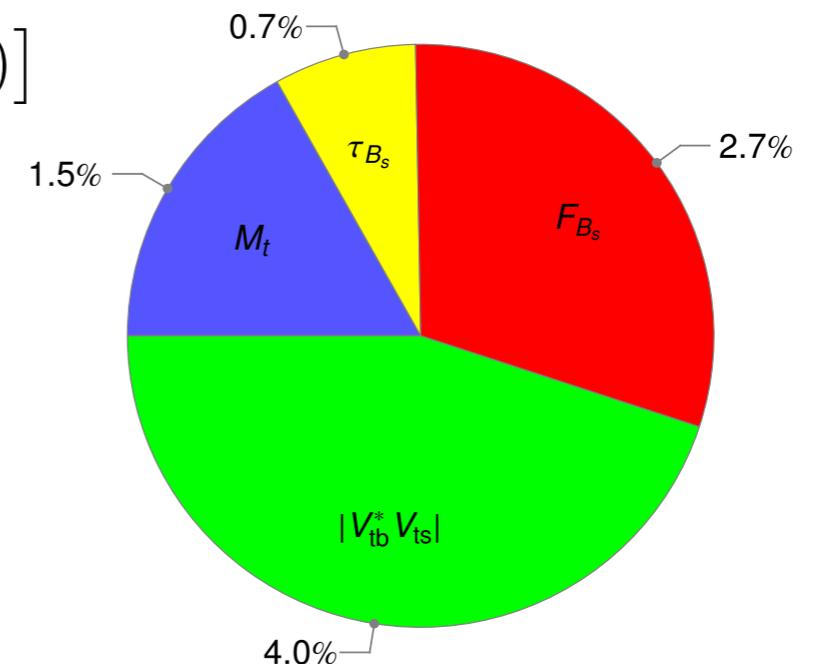
Important effect due to  $\Delta\Gamma_s \neq 0$

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

Buras et al., 1208.0934, 1303.3820

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

Dominant parametric uncertainties



In good agreement with experiment

$$\overline{\mathcal{B}}_s^{(\text{exp})} = (3.2_{-1.2}^{+1.5}) \times 10^{-9}$$

LHCb, 1211.2674

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

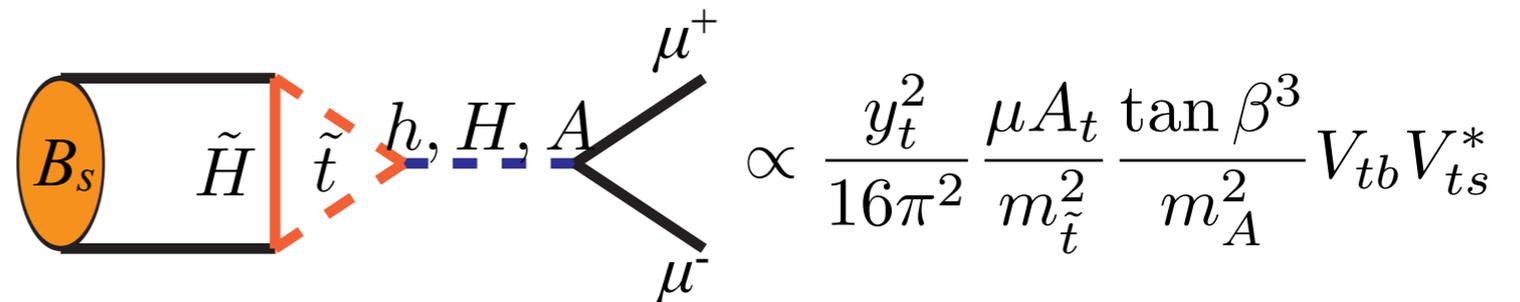
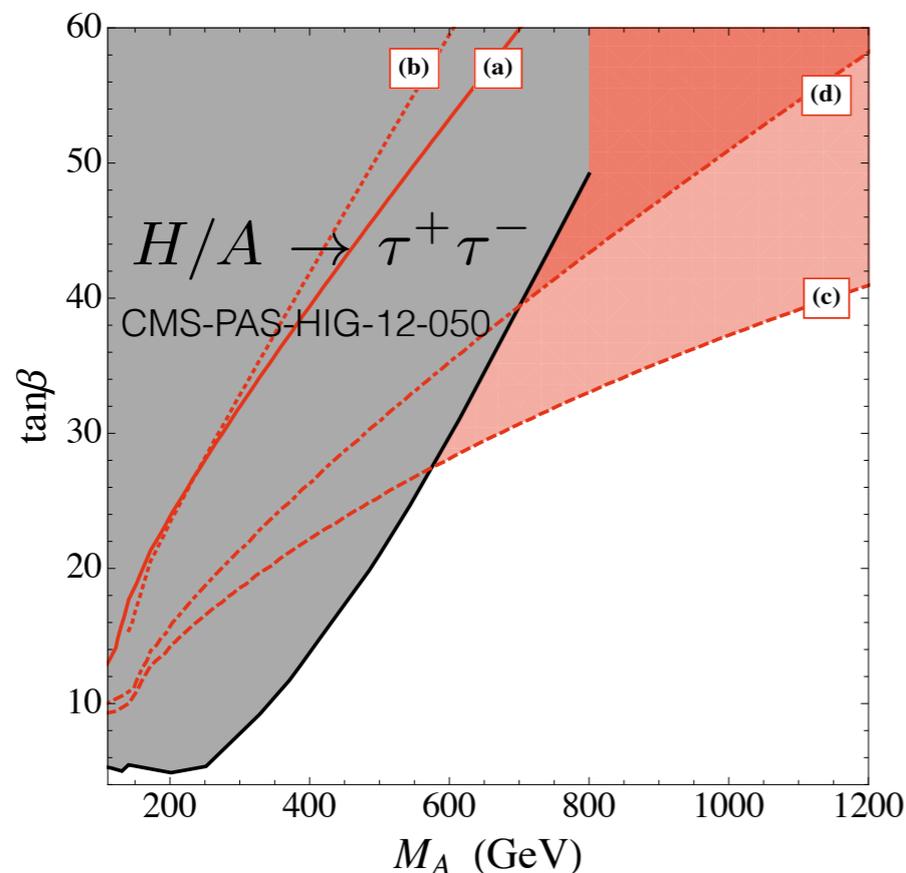
Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction ( $\Rightarrow$  Higgs sector)

beyond tree level

Example: MFV MSSM with large  $\tan\beta$

Altmannshofer et al., 1211.1976



Scenario	(a)	(b)	(c)	(d)	(e)
$\mu$ [TeV]	1	4	-1.5	1	-1.5
sign( $A_t$ )	+	+	+	-	-

$$m_{\tilde{q}} = 2 \text{ TeV}$$

$$6M_1 = 3M_2 = M_3 = 1.5 \text{ TeV}$$

$A_t$  fixed by  $m_h$

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

Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction ( $\Rightarrow$  Higgs sector)

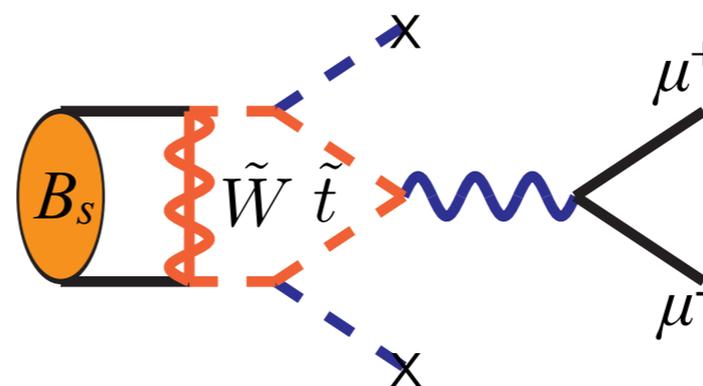
beyond tree level

Example: general MSSM

$$m_h \sim 125 \text{ GeV}$$



large  $A_{33}$



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

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

Measurement with  $\sigma(\text{BR}) \sim 30\%$  provides relevant constraint on such couplings below stability bounds

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

Isidori @ HCP2012, Kyoto  
Behring et al., 1205.1500

Mahmoudi, Neshatpour & Orloff 1205.1845

# Modified Z couplings

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

Fixing flavor model one can compare:

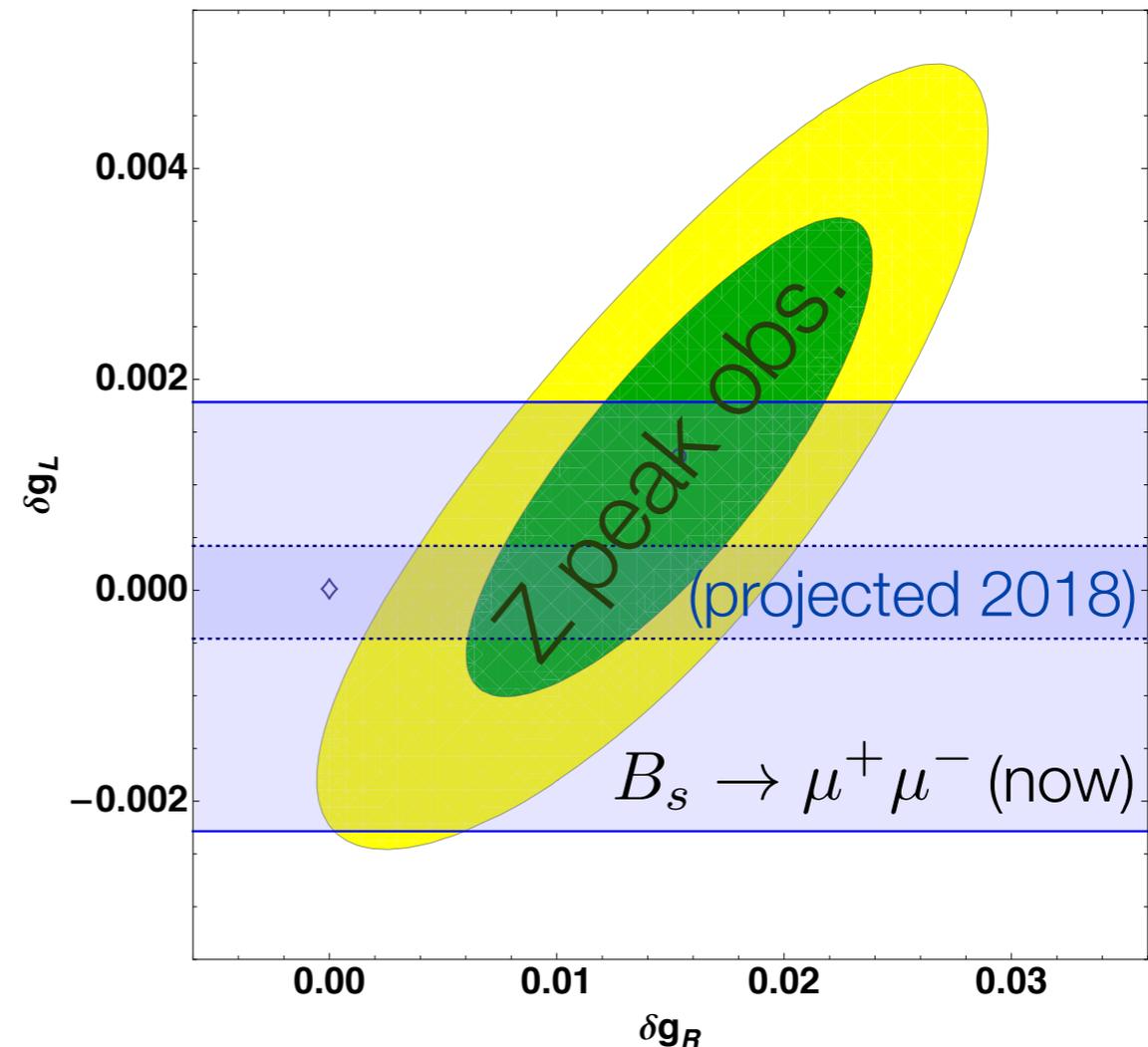
Guadagnoli & Isidori  
1302.3909

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

Example: MFV

$$Q^{(6)} \sim z^{ij} \bar{Q}_L^i \tau^a \gamma^\mu Q_L^j \phi^\dagger \tau_a \overleftrightarrow{D}_\mu \phi$$

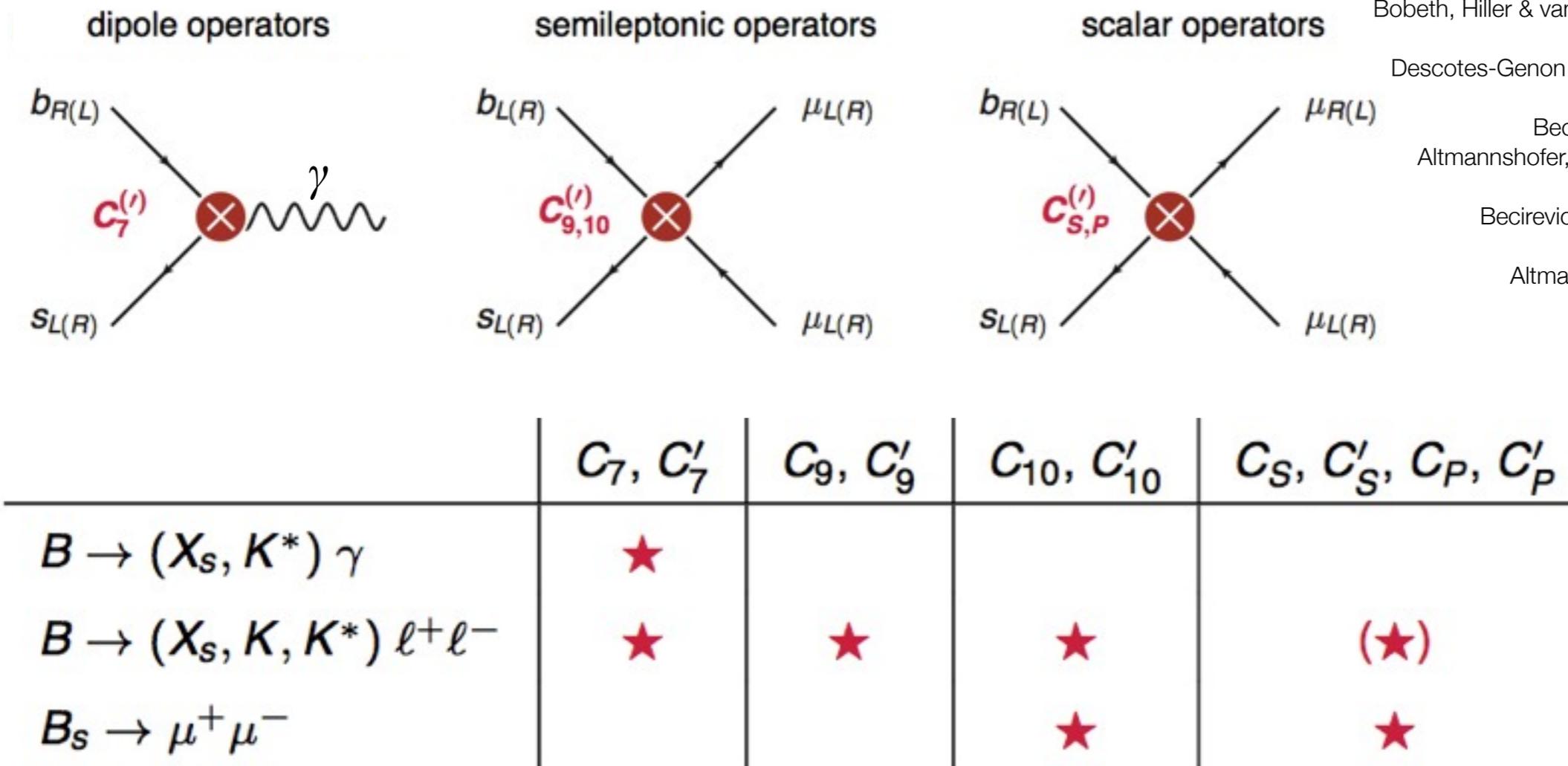
$$z^{ij} = (Y_u Y_u^\dagger)^{ij} \quad \delta g_L^{ij} = \frac{v^2 z^{ij}}{16\Lambda^2}$$



# Deconstructing $b \rightarrow s(\gamma, \ell^+ \ell^-)$ 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  
 ...



adopted from Altmannshofer @ Snowmass Intensity Frontier Workshop 2013, Argonne

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

Much more information available:

Can define theoretically clean complementary observables, sensitive to NP

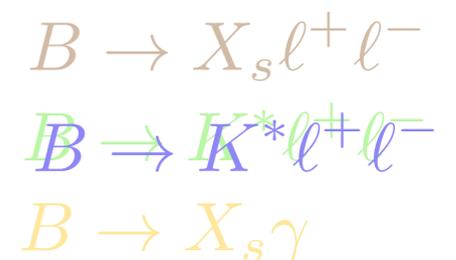
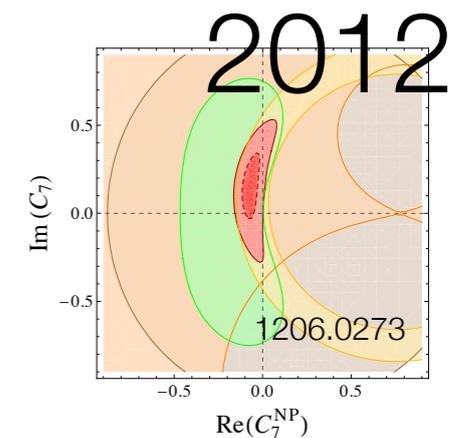
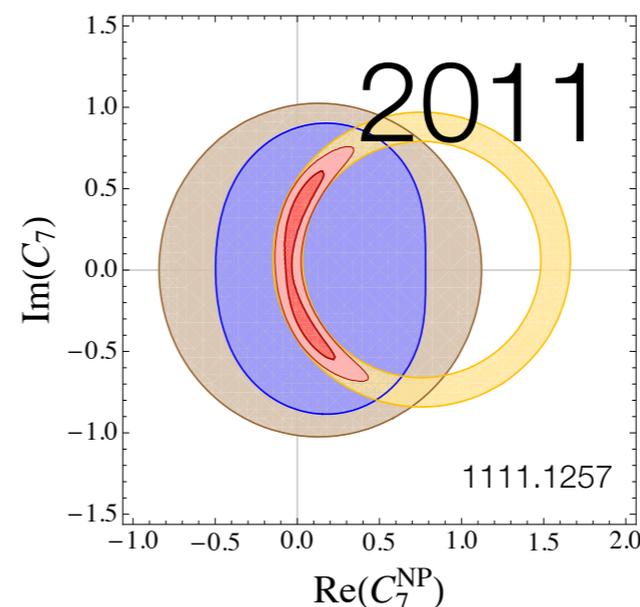
- Transverse asymmetries ( $A_T^{(l)}$ , ...) in  $B \rightarrow K^* \ell^+ \ell^-$
- Time dependent decay observables in  $B_s \rightarrow \mu^+ \mu^-$

Impact of existing LHCb data

Example: NP in dipole operators

Impact of  $A_{FB}$  in  $B \rightarrow K^* \ell^+ \ell^-$

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  
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 Matias et al., 1202.4266  
 Becirevic et al., 1205.5811, 1206.1502  
 Beaujean et al., 1205.1838  
 Altmannshofer & Straub, 1206.0273  
 ...  
 Buras et al., 1303.3820





Signs of NP?

(1) CP violation in charm decays

# CP violation in charm decays

Direct CPV  $a_f \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}$   $\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-}$

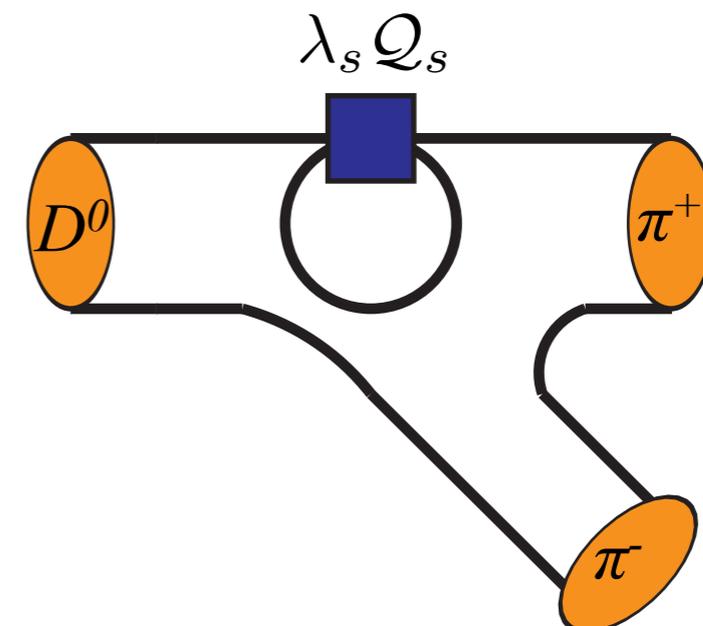
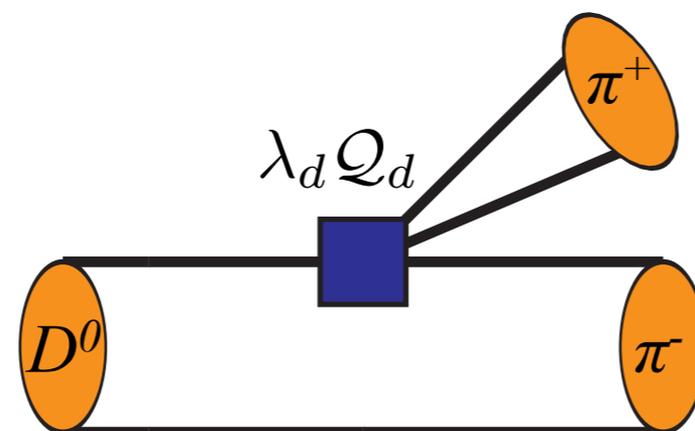
Experiment (WA):  $\Delta a_{CP} = (-0.329 \pm 0.121)\%$

HFAG, March 2013

Larger than naive SM estimates:  $|\Delta a_{CP}| = \left| \text{Im} \left( \frac{\lambda_s}{\lambda_d} \right) \right| \frac{\alpha_s}{\pi} \ll 0.1\%$

c.f. Grossman et al., hep-ph/0609178

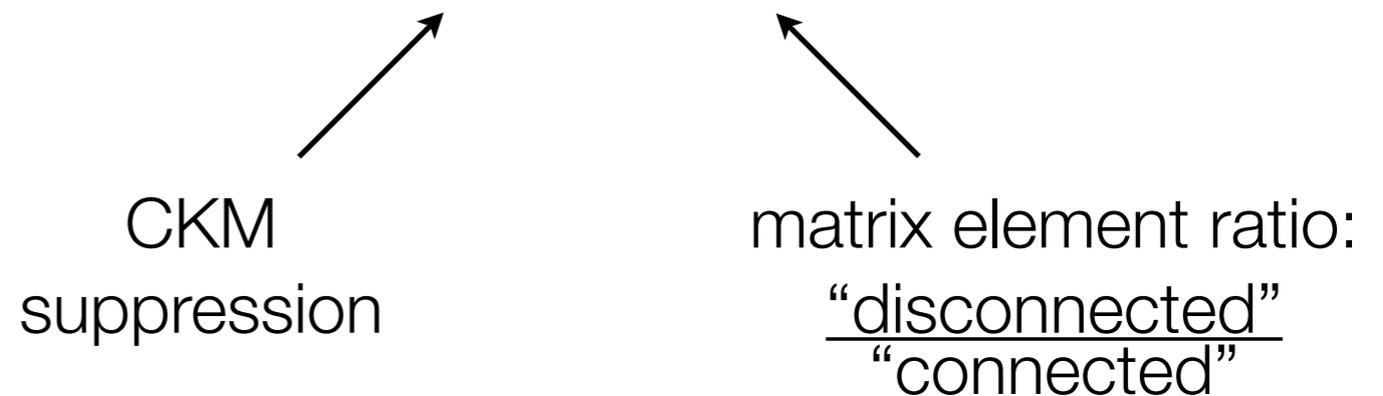
$$\lambda_q \equiv V_{cq}^* V_{uq}$$



# CP violation in charm decays

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Revisiting SM prediction:  $\Delta a_{CP} \approx (0.13\%) \text{Im}(\Delta R^{\text{SM}})$



$\Delta R^{\text{SM}} > 1$  is not what we expect for  $m_c \gg \Lambda_{QCD}$ , but is not impossible treating charm quark as light:

- possible connection with the  $\Delta I=1/2$  rule in  $K \rightarrow \pi\pi$

Golden & Grinstein Phys. Lett. B 222 (1989)

- could also address apparent sizable light flavor  $SU(3)$  violation in  $D$  decay rates

Brod, Kagan & Zupan 1111.5000  
Feldmann, Nandi & Soni, 1202.3795  
Brod, Grossman, Kagan & Zupan 1203.6659  
Franco, Mishima & Silverstrini, 1203.3131  
Hiller, Jung & Schacht, 1211.3734

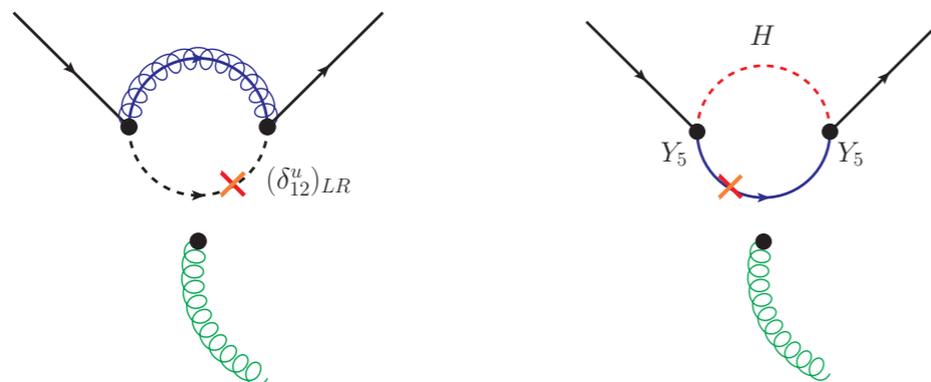
# CP violation in charm decays

## Could it be NP?

Isidori, J.F.K, Ligeti & Perez  
1111.4987

- typical scales probed for  $\mathcal{Q}^{(6)} \sim [\bar{c}\Gamma_A u] \otimes [\bar{q}\Gamma_B q] : \Lambda \sim 15 \text{ TeV}$
- important constraints from  $D$  oscillations, CPV in  $K$  decays, EDMs, ...
- needs to involve new  $SU(3)_U$  flavor breaking
- can be generated in well-motivated models (SUSY, warped extra-dim. / composite Higgs,....)

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



Giudice, Isidori & Paradisi, 1201.6204  
Chang et al., 1201.2565  
Hiller, Hochberg & Nir, 1201.6204  
Keren-Zur et al., 1205.5803  
Delaunay, J.F.K., Perez & Randall, 1207.0474

...

# CP violation in charm decays

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Key question: how to distinguish NP vs. SM explanations?

In NP models: search for other signatures (collider, EDMs,...)

Hochberg & Nir, 1112.5268  
Altmannshofer et al., 1202.2866  
Da Rold, 1208.1499

Using charm data:

- **isospin sum rules** violated if NP ( $a_{CP}(D^+ \rightarrow \pi^+ \pi^0) = 0, \dots$ )  
Grossman, Kagan & Zupan, 1204.3557
- **CPV in radiative  $D$  decays** ( $D \rightarrow (P^+ P^-)_V \gamma$ ; also  $D \rightarrow (P^+ P^-)_V l^+ l^-$ )  
Isidori & J.F.K., 1205.3164  
Lyon & Zwicky, 1210.6546  
Fajfer & Kosnik, 1208.0759  
Cappiello, Cata & D'Ambrosio, 1209.4235
- CPV in other non-leptonic  $D$  decays  
Bhattacharya, Gronau & Rosner, 1201.2351



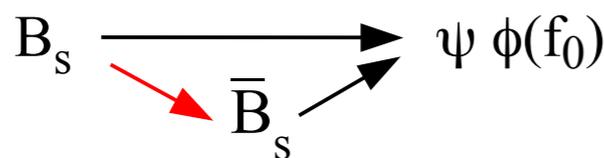
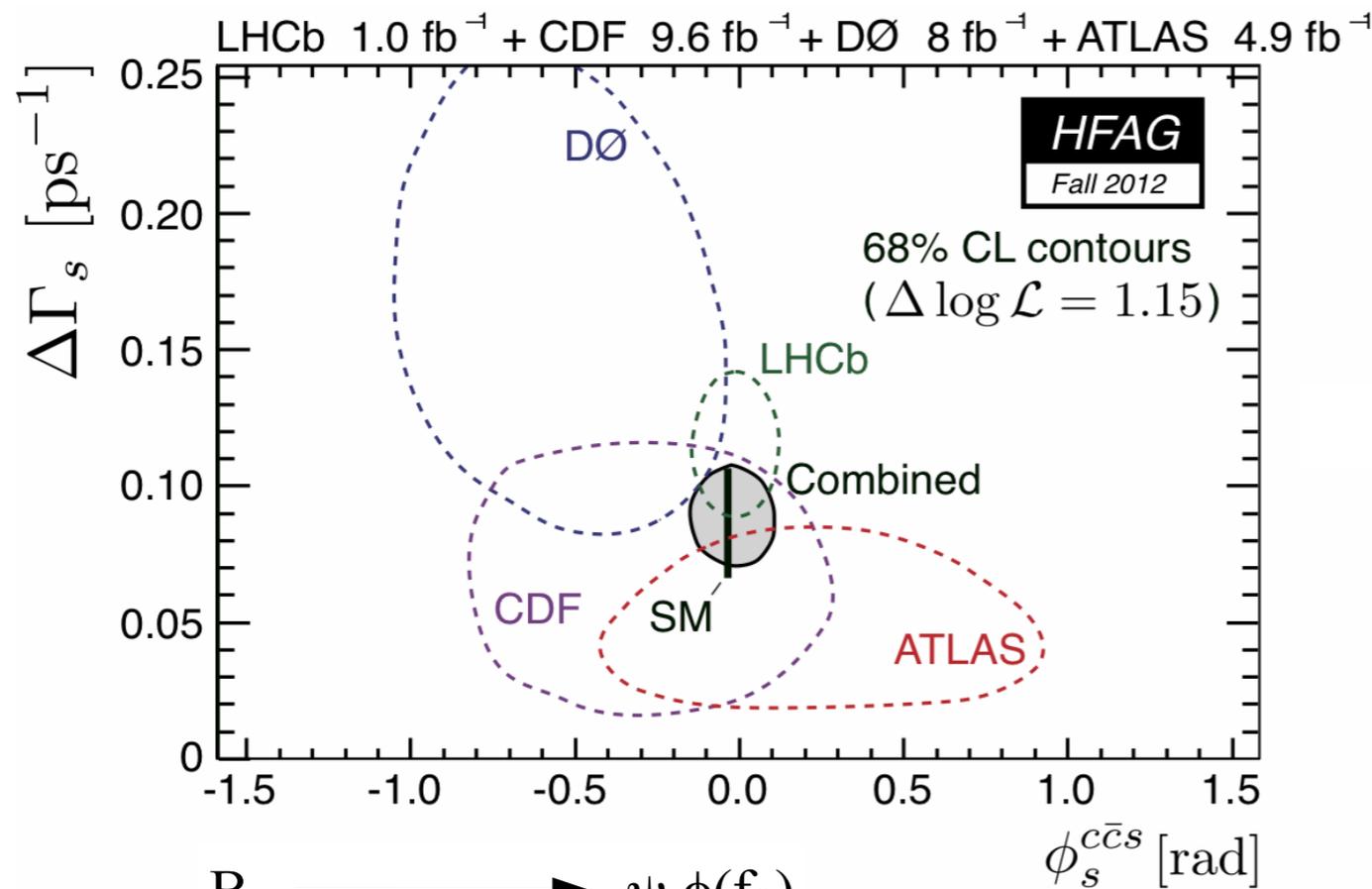
Signs of NP?

(2) CP violation in semileptonic  $b$  decays

# CP violation in semileptonic $b$ decays

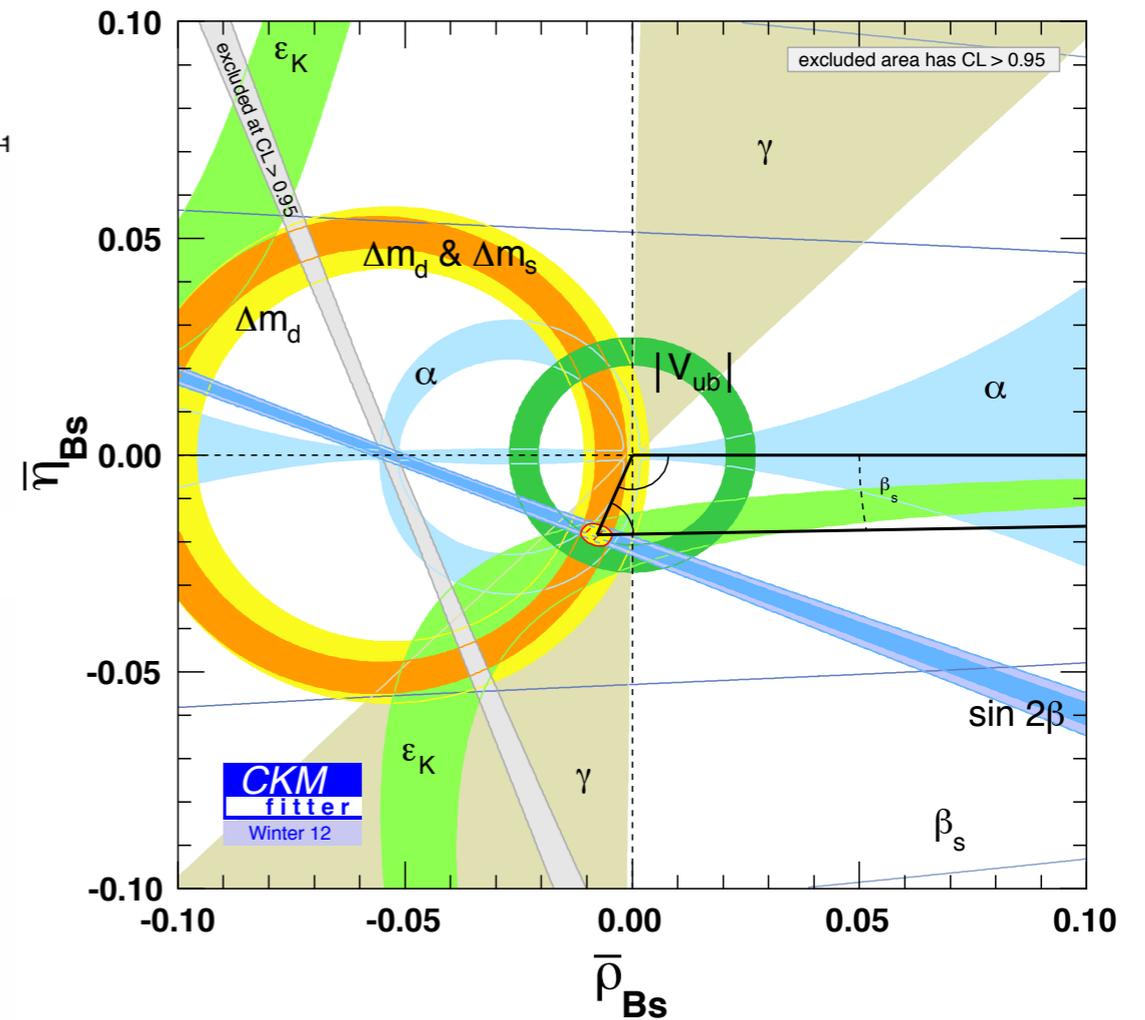
Given good consistency of global CKM fits, CPV in  $B_s$  mixing predicted precisely in SM

So far, no signs of deviations from the SM...



$$\phi_s^{\text{SM}} = \arg \left[ - (V_{ub} V_{us}^*) / (V_{cb} V_{cs}^*) \right]$$

$$\bar{\rho}_{B_s} + i\bar{\eta}_{B_s} = - (V_{ub} V_{us}^*) / (V_{cb} V_{cs}^*)$$



# CP violation in semileptonic $b$ decays

...except persistent  $A_{sl}$  anomaly

$$A = (-0.787 \pm 0.172 \pm 0.093)\%$$

dimuon charge asymmetry by D0

If due to CPV in  $B_{s,d}$  mixing

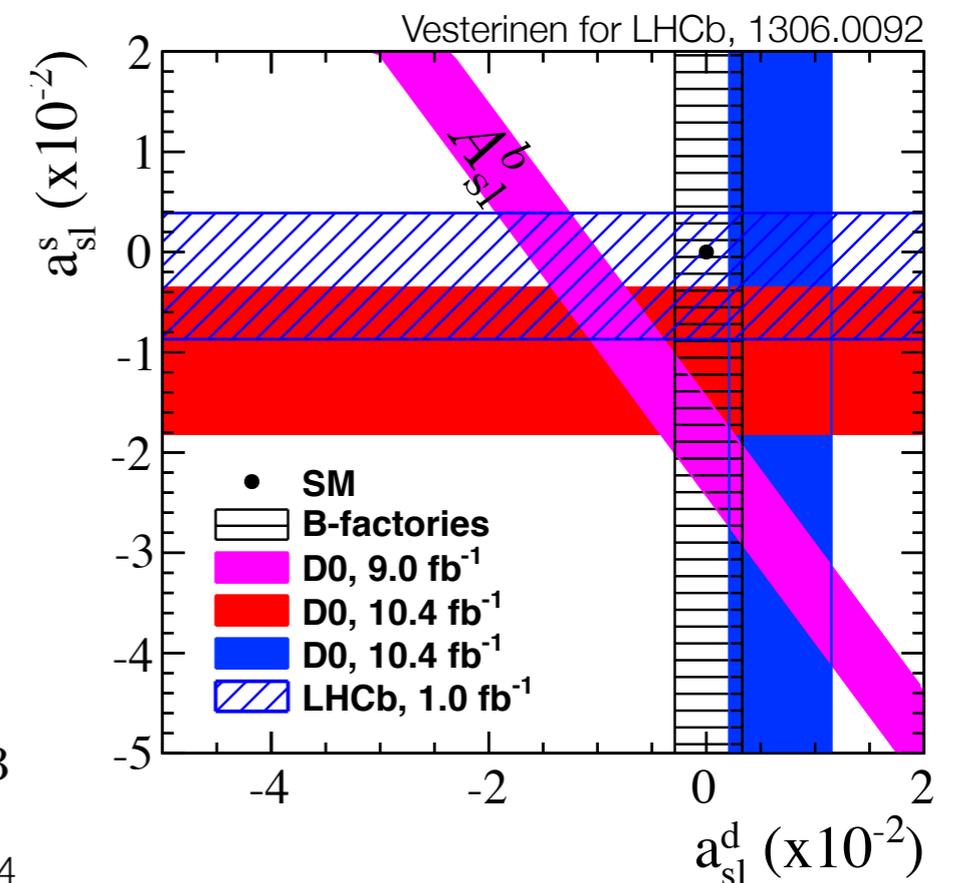
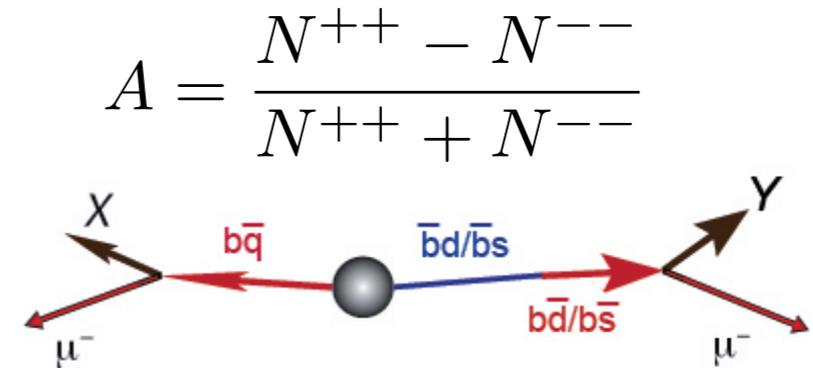
$$A_{sl}^b = f_d a_{sl}^d + f_s a_{sl}^s$$

production (fragmentation) fractions

$$a_{sl}^q = \frac{\Gamma(\bar{B}_q \rightarrow \mu^+ X) - \Gamma(B_q \rightarrow \mu^- X)}{\Gamma(\bar{B}_q \rightarrow \mu^+ X) + \Gamma(B_q \rightarrow \mu^- X)}$$

SM prediction:  $A_{sl}^{b,SM} = -(0.20 \pm 0.03) \times 10^{-3}$

Lenz & Nierste, 1102.4274

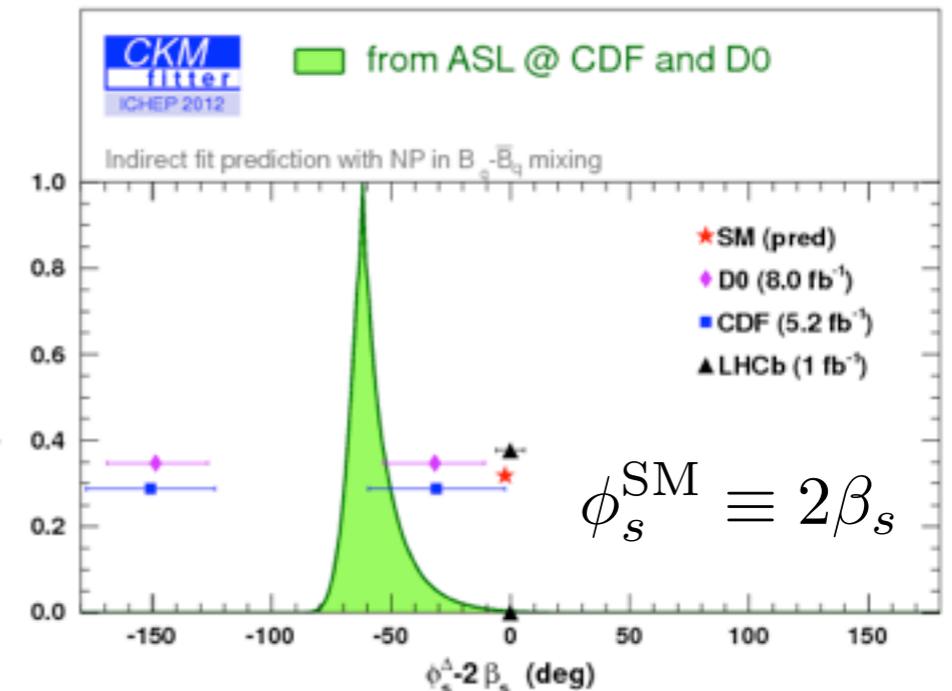
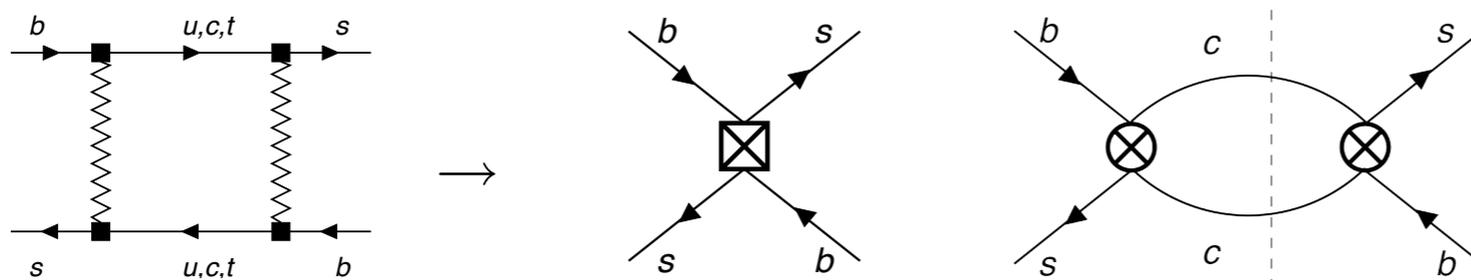


# CP violation in semileptonic $b$ decays

If  $A$  would be due to NP phase in  $B_s$  mixing: in conflict with measured  $\phi_s$  (similarly for  $B_d$  mixing) c.f. Lenz et al., 1203.0238

Additional possibilities:

## 1. NP in absorptive amplitudes



- in  $B_s$  system conflict with  $\Delta\Gamma_s$ ,  $\Delta m_s$
- in  $B_d$  system severe constraints from  $\Delta F=1$ , possibility remains Bobeth & Haisch, 1109.1826

# CP violation in semileptonic $b$ decays

If  $A$  would be due to NP phase in  $B_s$  mixing: in conflict with measured  $\phi_s$  (similarly for  $B_d$  mixing) c.f. Lenz et al., 1203.0238

Additional possibilities:

2. NP in direct CP asymmetries (in semileptonic  $b$  or  $c$  decays)

- Need  $O(0.1\%)$  asym. in  $B_q$  decays,  $O(1\%)$  asym. in  $D_q$  decays

Descotes-Genon & J.F.K., 1207.4483

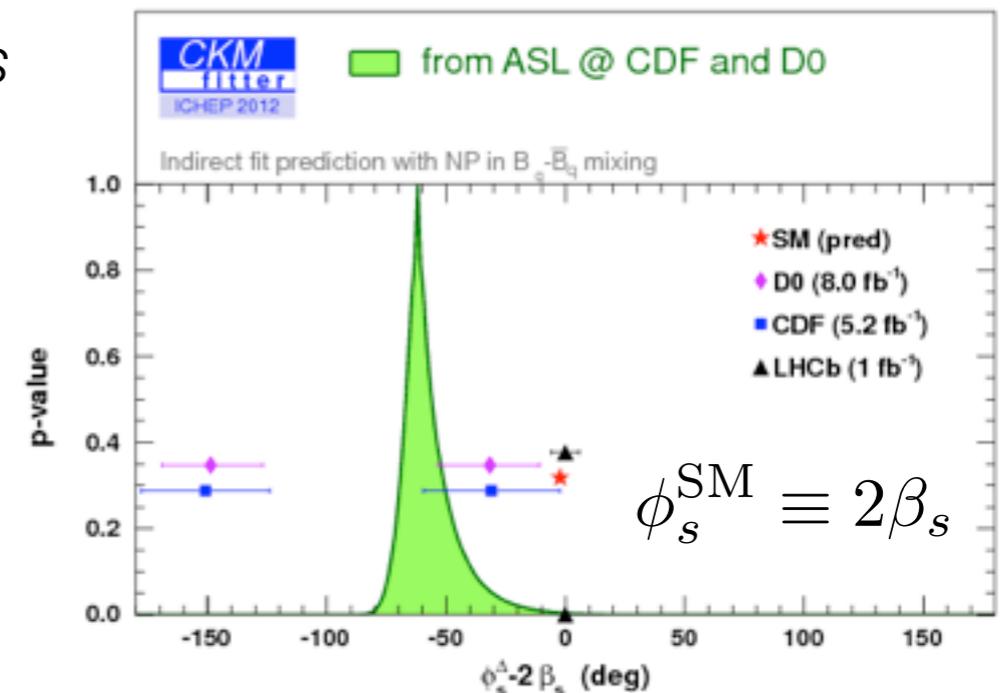
- Negligible in SM

Bar Shalom, Gronau & Rosner, 1008.4354

- Difficult to obtain in NP models

- Could be tested at LHC using  $b$ 's from  $t$  decays

Gedalia et al., 1212.4611





Signs of NP?

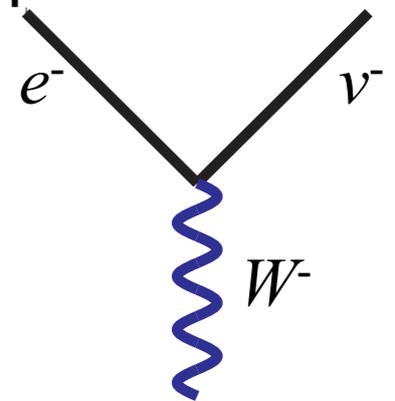
(3) Lepton flavor universality in B decays

# LFU in (semi)leptonic B decays

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In SM weak charged current interactions are lepton flavor universal

- Tested directly at colliders via  $W$  decays  $\sim 1\%$



Additional charged (scalar) interactions could induce LFU violation in processes at low energies

Can be predicted accurately even in hadronic processes, since most QCD uncertainties cancel in ratios

- Pion, kaon,  $D$  processes well consistent with LFU expectations  $\sim (0.1-1)\%$

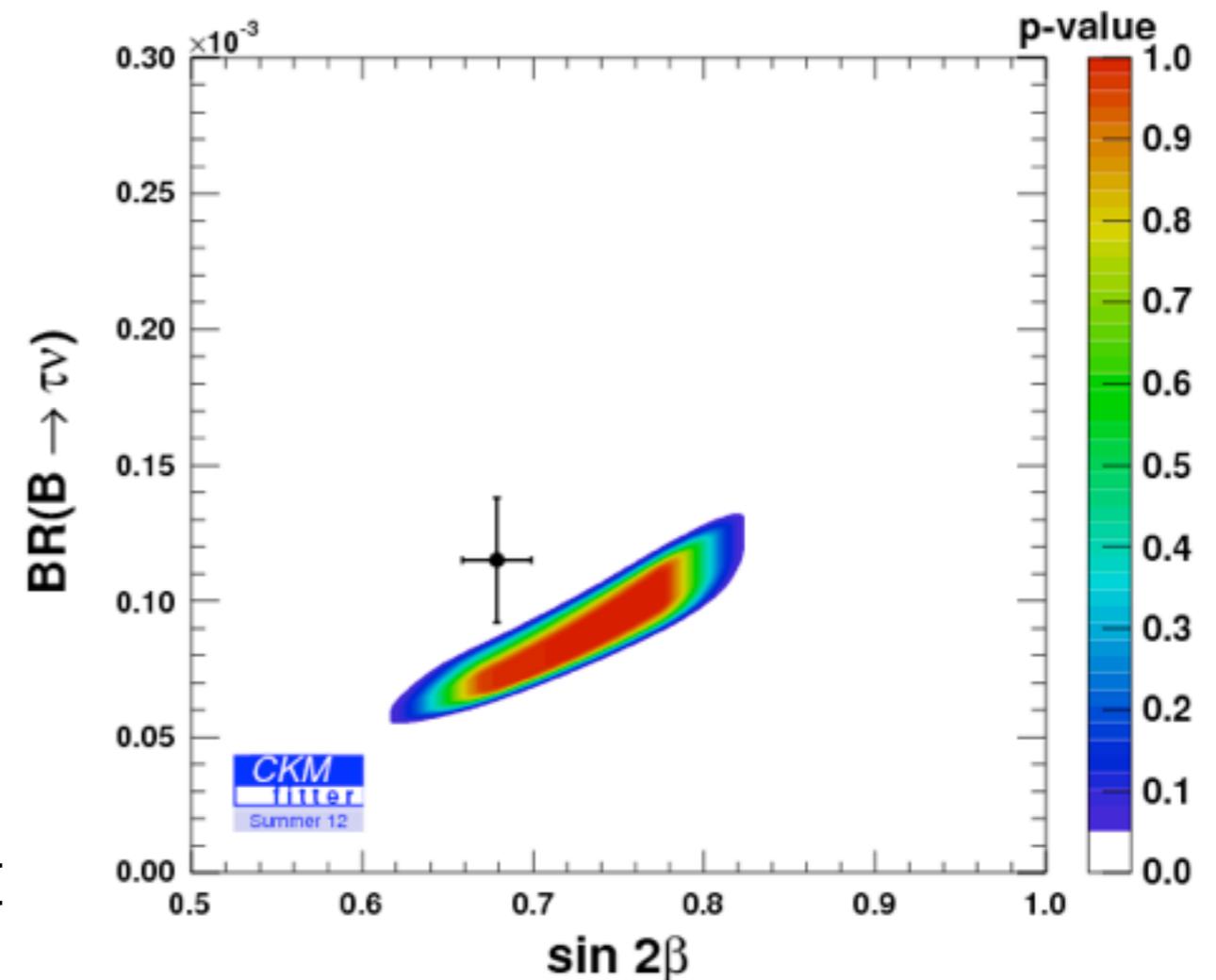
# LFU in (semi)leptonic B decays

Apparent tension in global CKM unitarity fits

Discrepancy between  $|V_{ub}|$  determinations c.f. Ligeti @ CKM2012, Cincinnati

Most pronounced for taunic  $B$  decay

Somewhat reduced with recent Belle result Belle, 1208.4678



# LFU in (semi)leptonic B decays

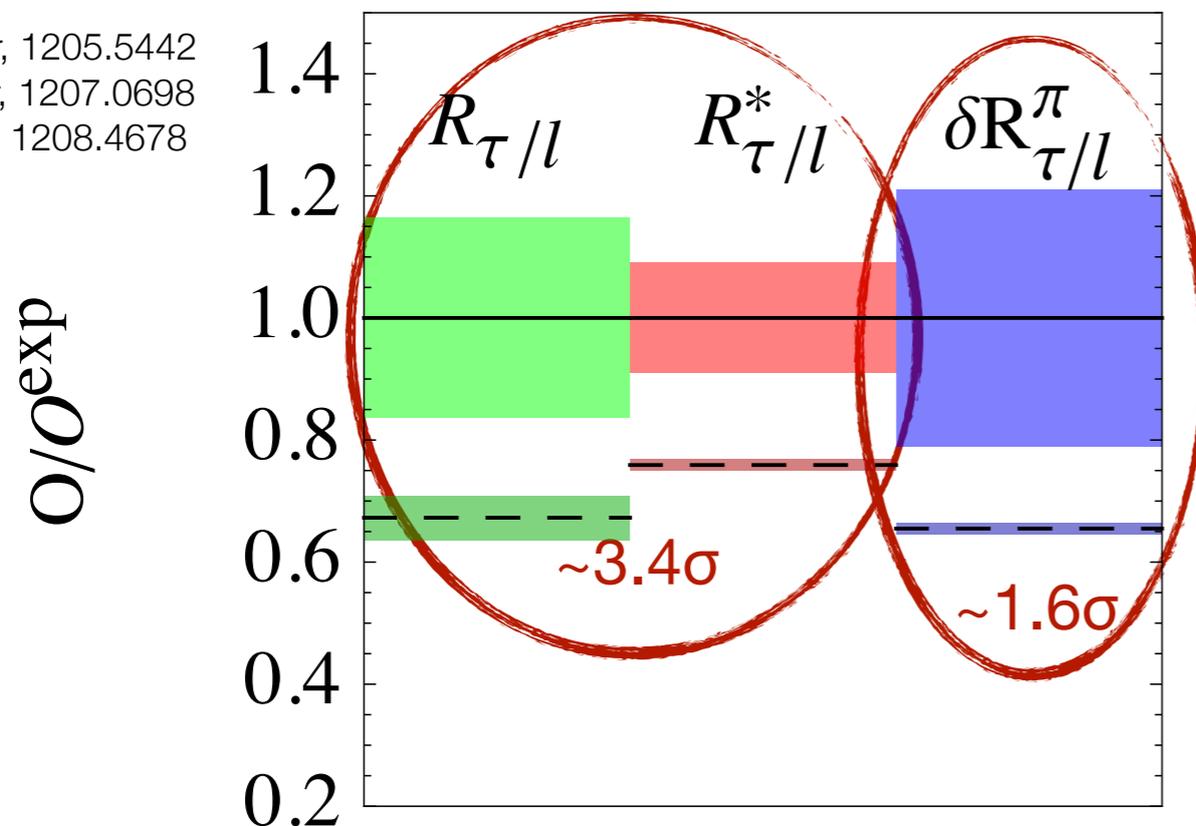
However, maybe not CKM issue at all

Can eliminate  $|V_{ub}|$  in ratio  $\Delta\mathcal{R}_{\tau/\ell}^{\pi} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu})}{\Delta\mathcal{B}(\bar{B}^0 \rightarrow \pi^+ \ell^- \bar{\nu})}$

Similarly in semitauonic decays  $\mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B \rightarrow D\tau\nu)}{\mathcal{B}(B \rightarrow D\ell\nu)}$   $\mathcal{R}_{\tau/\ell}^* \equiv \frac{\mathcal{B}(B \rightarrow D^*\tau\nu)}{\mathcal{B}(B \rightarrow D^*\ell\nu)}$

## Tests of LFU

BaBar, 1205.5442  
Babar, 1207.0698  
Belle, 1208.4678



Fajfer, J.F.K., Nisandzic, 1203.2654  
J.F.K. & Mescia, 0802.3790  
Nierste, Trine & Westhoff, 0801.4938  
Tanaka & Watanabe, 1005.4306  
Becirevic, Kosnik, Tayduganov, 1206.4977  
Bailey et al., 1206.4992  
Khodjamirian et al., 1103.2655  
Fajfer, J.F.K., Nisandzic & Zupan, 1206.1872

SM predictions very robust

# LFU in (semi)leptonic B decays

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Can it be NP? Need to satisfy severe constraints:

- no tree-level down quark / charged lepton FCNCs
  - no LFU violations in pion, kaon sectors
- } require flavor alignment

Points towards low NP scale:  $\Lambda \lesssim 100 \text{ GeV}$  for  $Q_{AB}^{(6)} \sim V_{qb} [\bar{b} \Gamma_A q] \otimes [\bar{\nu} \Gamma_B \tau]$

Fajfer, J.F.K., Nisandzic & Zupan,  
1206.1872

A number of possibilities suggested:

general THDM, leptoquarks, 3rd gen. compositeness...

Crivellin, Greub & Kokulu  
1206.2634

Celis et al., 1210.8443

He & Valencia, 1211.0348

Can be disentangled using  $B \rightarrow D^{(*)} \tau \bar{\nu}$  differential rate information

Fajfer, J.F.K., Nisandzic, 1203.2654

Sakaki & Tanaka, 1205.4908

Datta et al., 1206.3760

Tanaka & Watanabe, 1212.1878

Biancofiore, Colangelo & De Fazio, 1302.1042

Generic high- $p_T$  predictions:  $pp \rightarrow t + E_T^{\text{miss}}, \tau + E_T^{\text{miss}}, t\bar{b}$

# Conclusions

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Success of SM in describing flavor-changing processes implies that **large new sources of flavor symmetry breaking at TeV scale are mostly excluded**. At the same time, if present

- can significantly affect NP searches high  $p_T$
- have implications for EW fine-tuning

However, there are sectors of the theory that are just starting to be tested

- Higgs discovery offers new direct probes of flavor dynamics
- Measurements of  $B_{s,d} \rightarrow \mu^+\mu^-$  probe the Higgs Yukawa sector at loop level

# Conclusions

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## Implications of open experimental flavor puzzles

- If due to NP, observed  $\Delta a_{CP}$  points towards new flavor sources in  $U_R$  sector
  - important to verify in other decay modes
- D0  $A_{sl}$  measurement inconsistent with measured CPV in  $B_{s,d}$  mixing
  - implications for (direct) semileptonic  $B$  (and  $D$ ) asymmetries
- If confirmed, observed LFU violations in  $B$  decays point towards new charged current interactions of 3rd gen. matter fields
  - interesting top, tau physics at LHC

