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Flavour physics: theory

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Why flavor matters in the LHC era?

- 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
- In case of observed deviations from SM, can point towards experimental targets both at high-p_T and at other venues
- Can help reduce fine-tuning in models addressing the EW hierarchy in light of null LHC NP search results

Introduction

SM phenomenologically very successful theory

Strong theoretical arguments to consider it as effective theory

Unification of interactions

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

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

EW scale stabilization

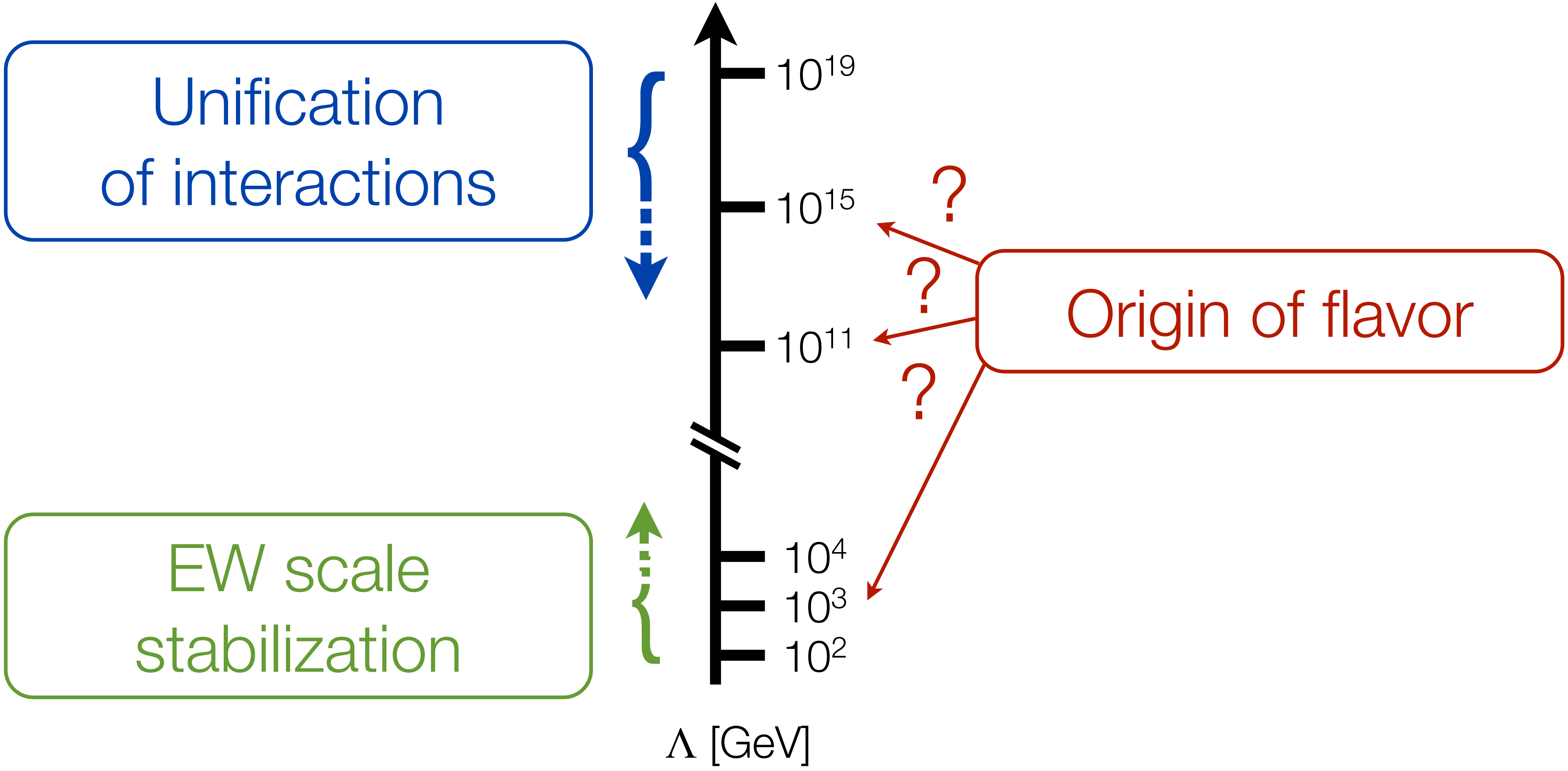
Origin of flavor

Need to understand/constrain size of additional terms in series

Introduction

SM phenomenologically very successful theory

Strong theoretical arguments to consider it as effective theory



(Over)constraining the SM flavor sector

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

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

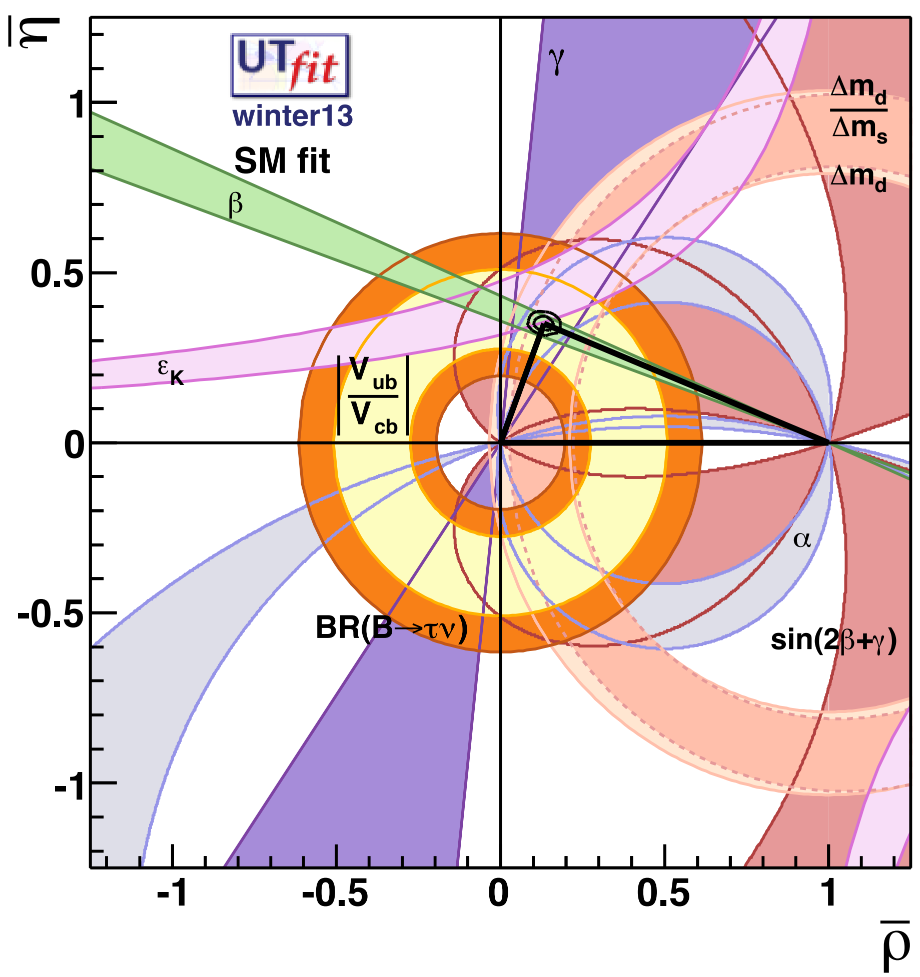
$$V = V_L^u V_L^{d\dagger}$$

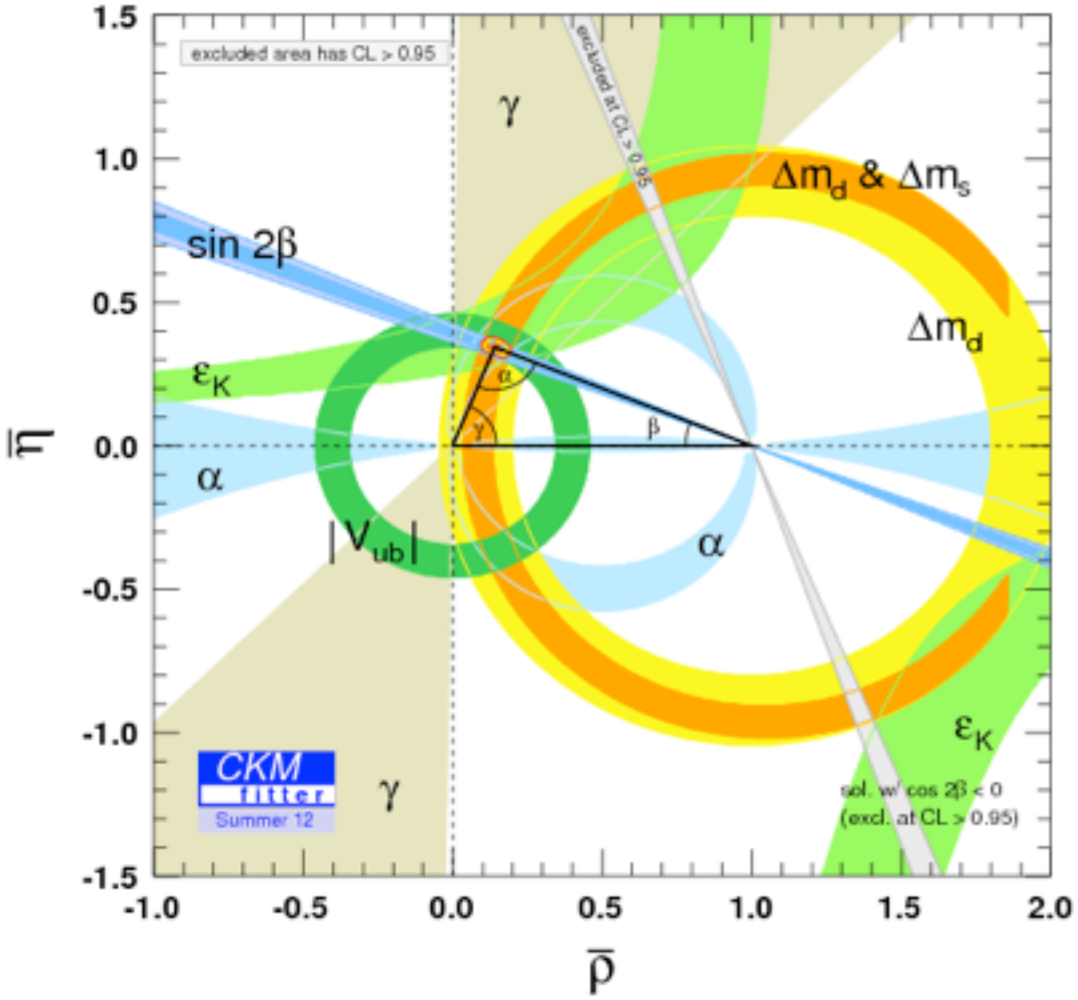
Determine all flavor phenomena in quark sector!

(Over)constraining the SM flavor sector

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

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



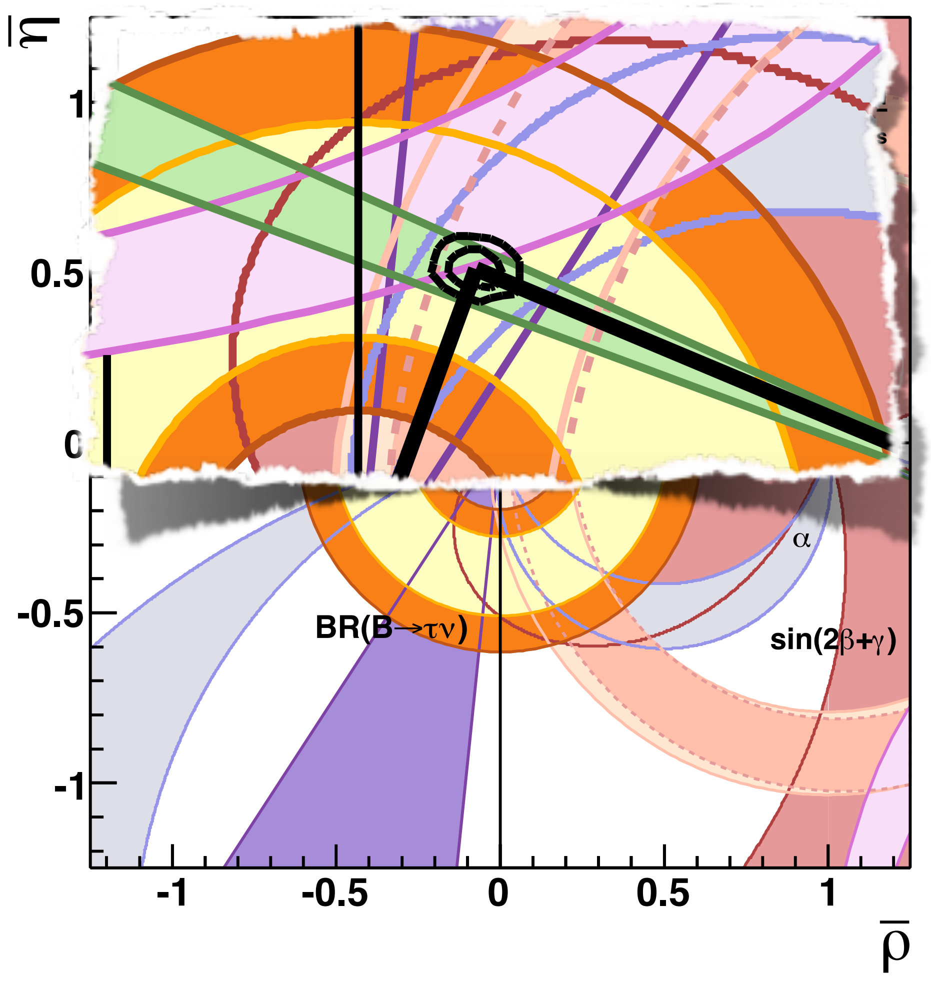


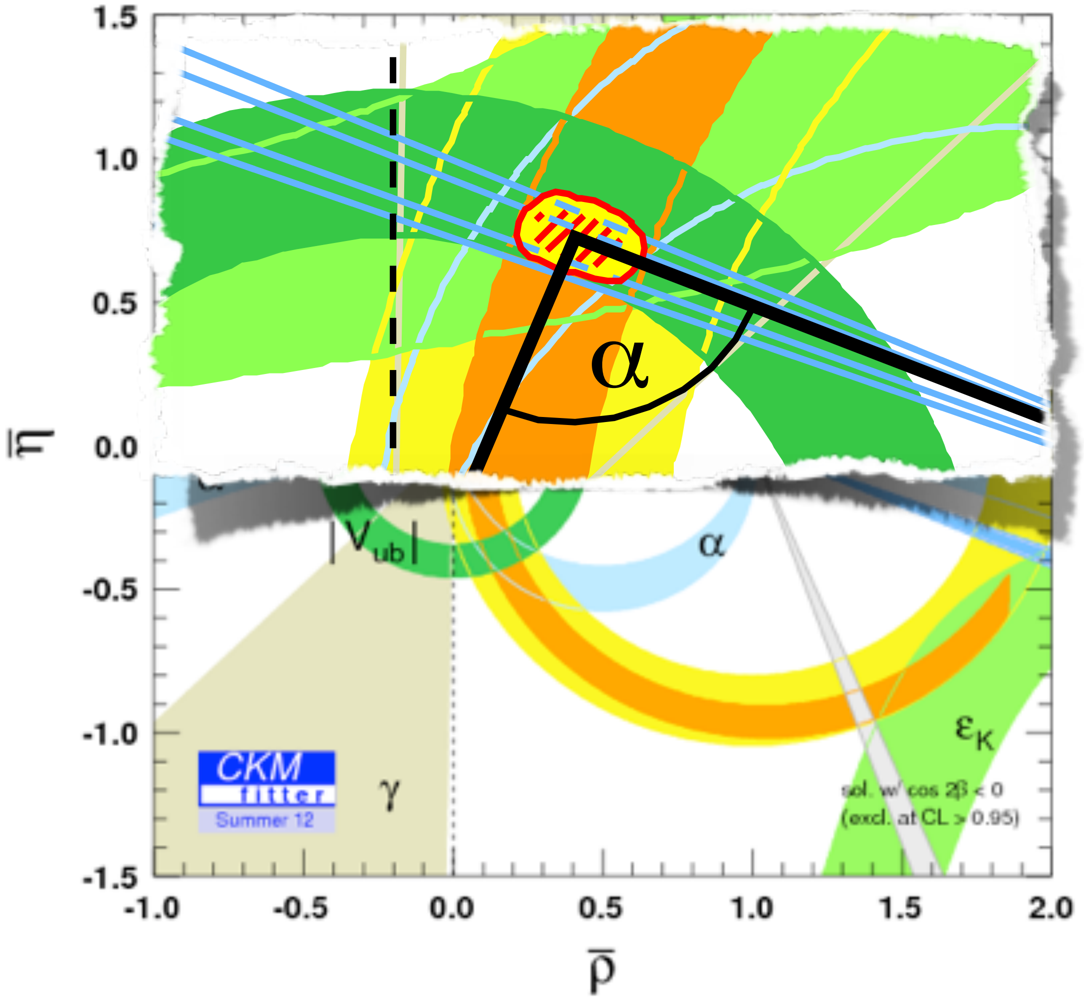
Generally excellent consistency!

(Over)constraining the SM flavor sector

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

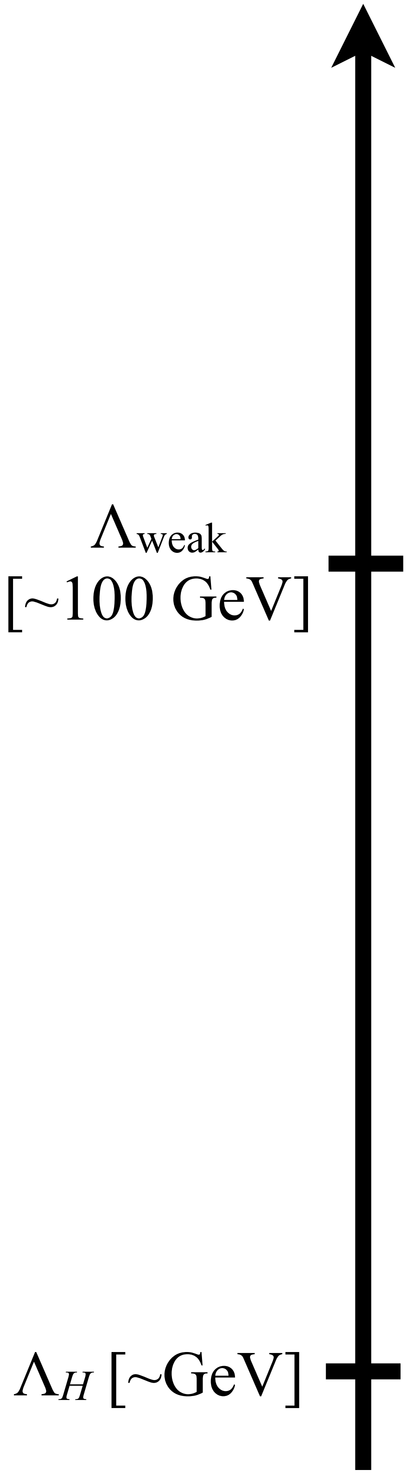
$$\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$$





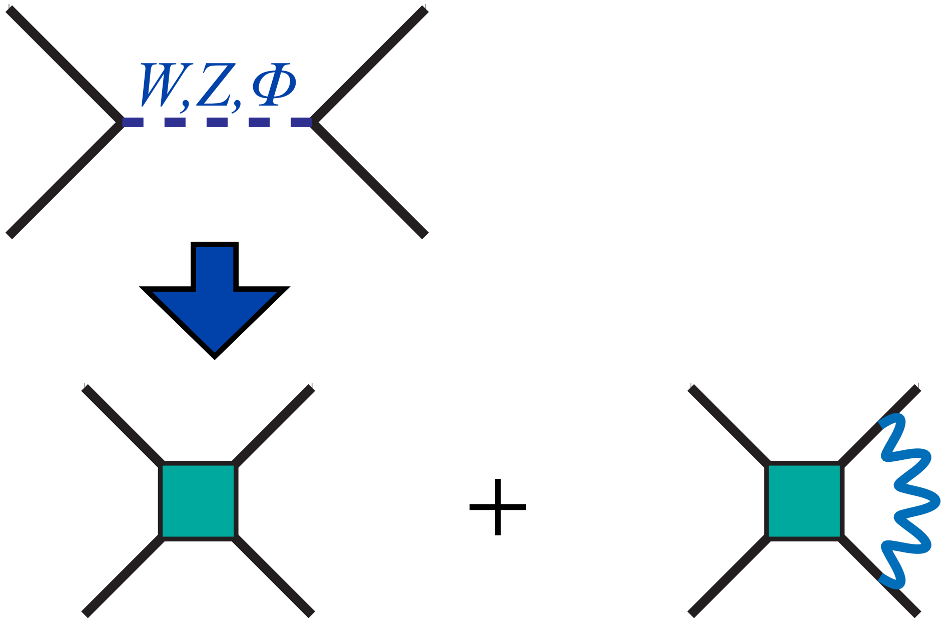
And continuing improvement! (see th. talks by Imbeault, Wingate)

(Over)constraining the SM flavor sector



$\mathcal{L}_{\text{SM}}$

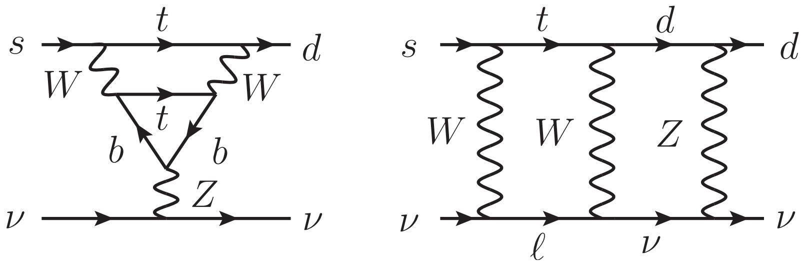
Weak scale operators



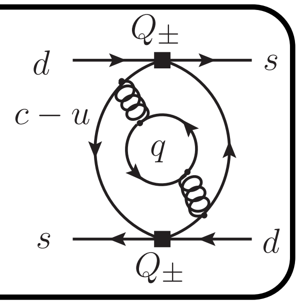
$$\mathcal{L}_{\text{weak}}^{\text{eff}}(\sim G_F \sum_i c_i \mathcal{Q}_i) + \mathcal{L}_{QCD+QED}$$

For most interesting observables known to N^{2}LO in QCD and NLO in EW, most recently

NLO EW in $K^+ \to \pi^+ \nu \bar{\nu}$



N^{2}LO $c\bar{c}$ in ϵ_K, Δm_K



Brod & Gorbahn, 1108.2036
Brod, Gorbahn & Stamou, 1009.0947

(Over)constraining the SM flavor sector

$\mathcal{L}_{\mathrm{SM}}$

Λ_{weak}
[~100 GeV]

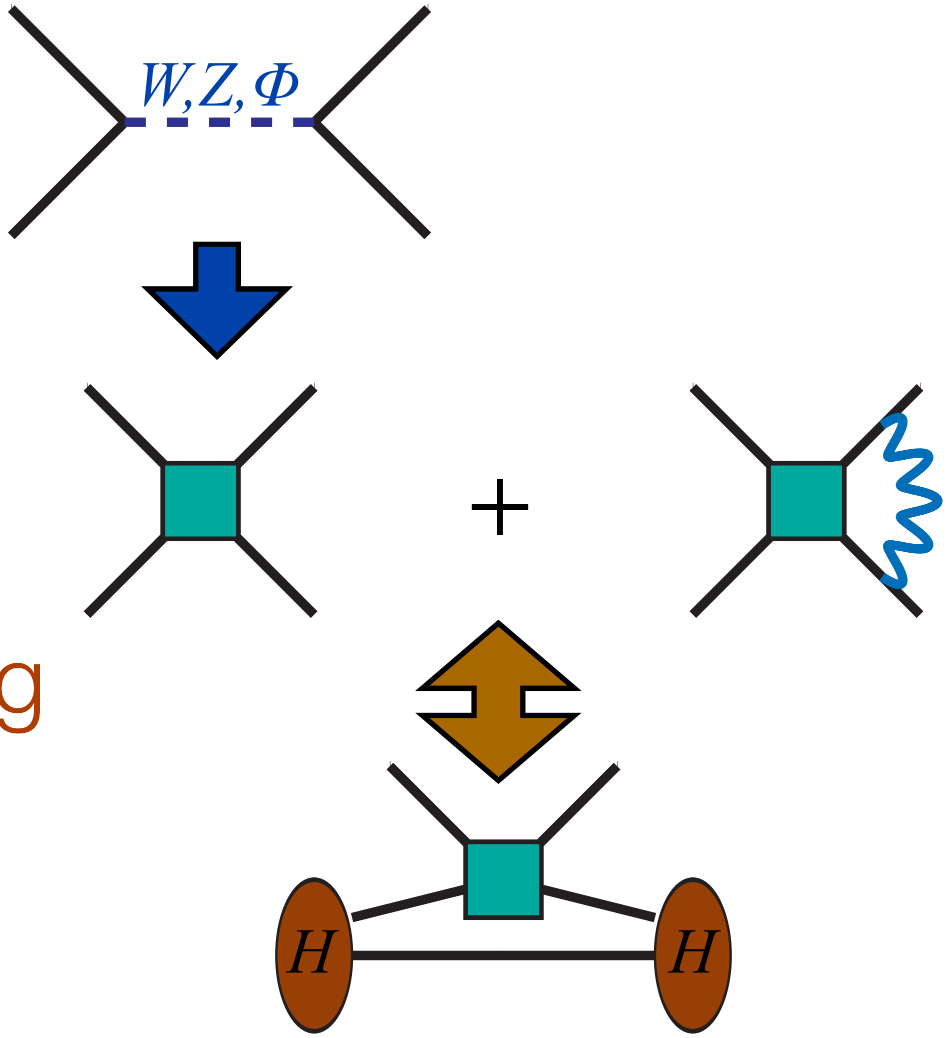
Weak scale operators

$$\mathcal{L}^{\mathrm{eff}}_{\mathrm{weak}}(\sim G_F \sum_i c_i \mathcal{Q}_i) + \mathcal{L}_{QCD+QED}$$

Non-perturbative matching
(or quark-hadron duality)

Λ_H [~GeV]

$$\mathcal{L}^{\mathrm{eff}}(\pi, N, K, D, B, \ldots)$$



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

$\Lambda_{\rm NP}$ $\mathcal{L}_{\rm BSM}$ **BSM dynamics**

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

$\Lambda_{\rm weak}$
[~100 GeV]

Weak scale operators

Buchmüller and D. Wyler,
Nucl. Phys. B 268 (1986) 621

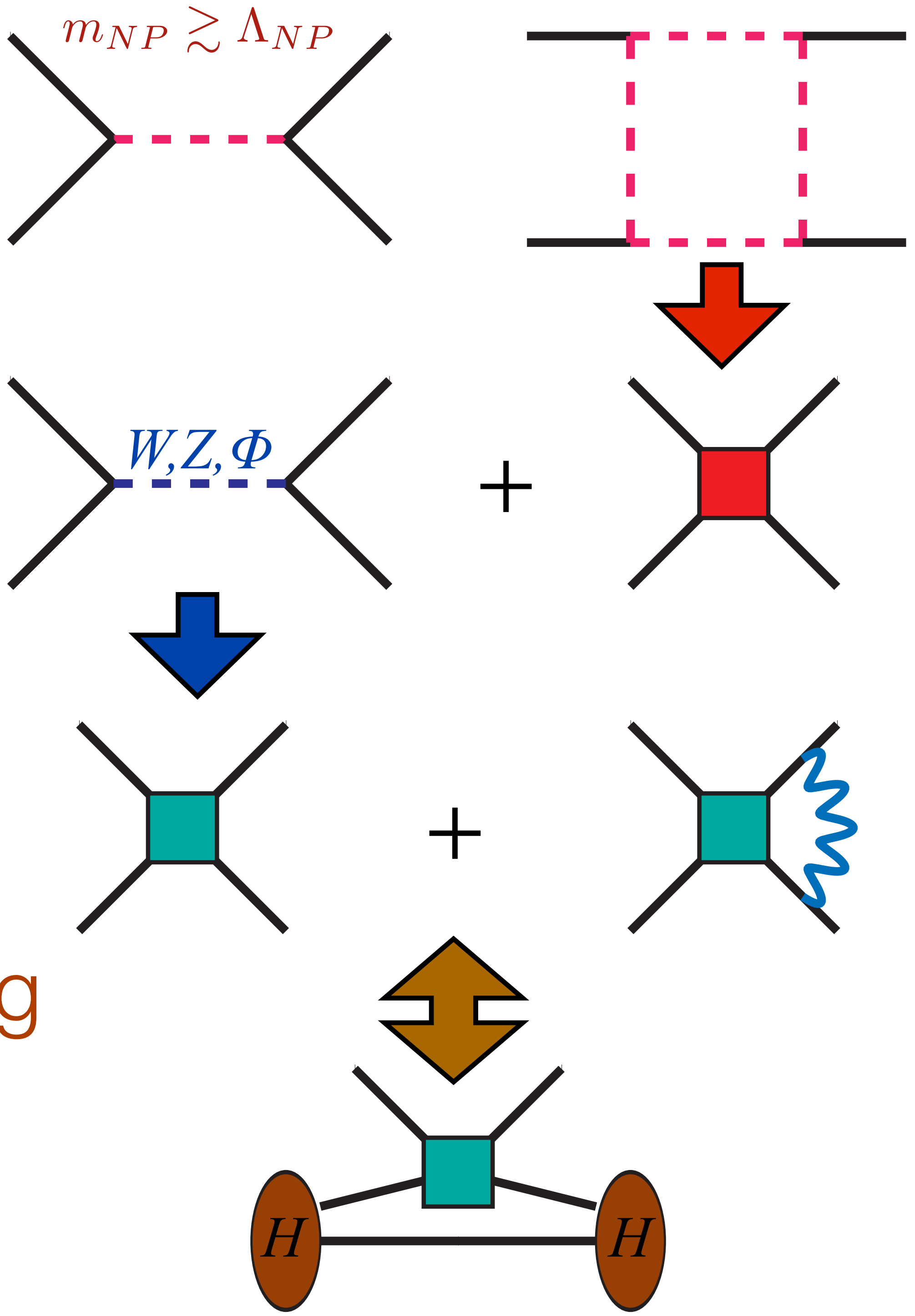
Grzadkowski et al., 1008.4884

J.F.K. & Smith, 1111.6402

$$\mathcal{L}^{\rm eff}_{\rm weak}(\sim G_F \sum_i c_i \mathcal{Q}_i) + \mathcal{L}_{QCD+QED}$$

Non-perturbative matching
(or quark-hadron duality)

Λ_H [~GeV] $\mathcal{L}^{\rm eff}(\pi, N, K, D, B, \ldots)$

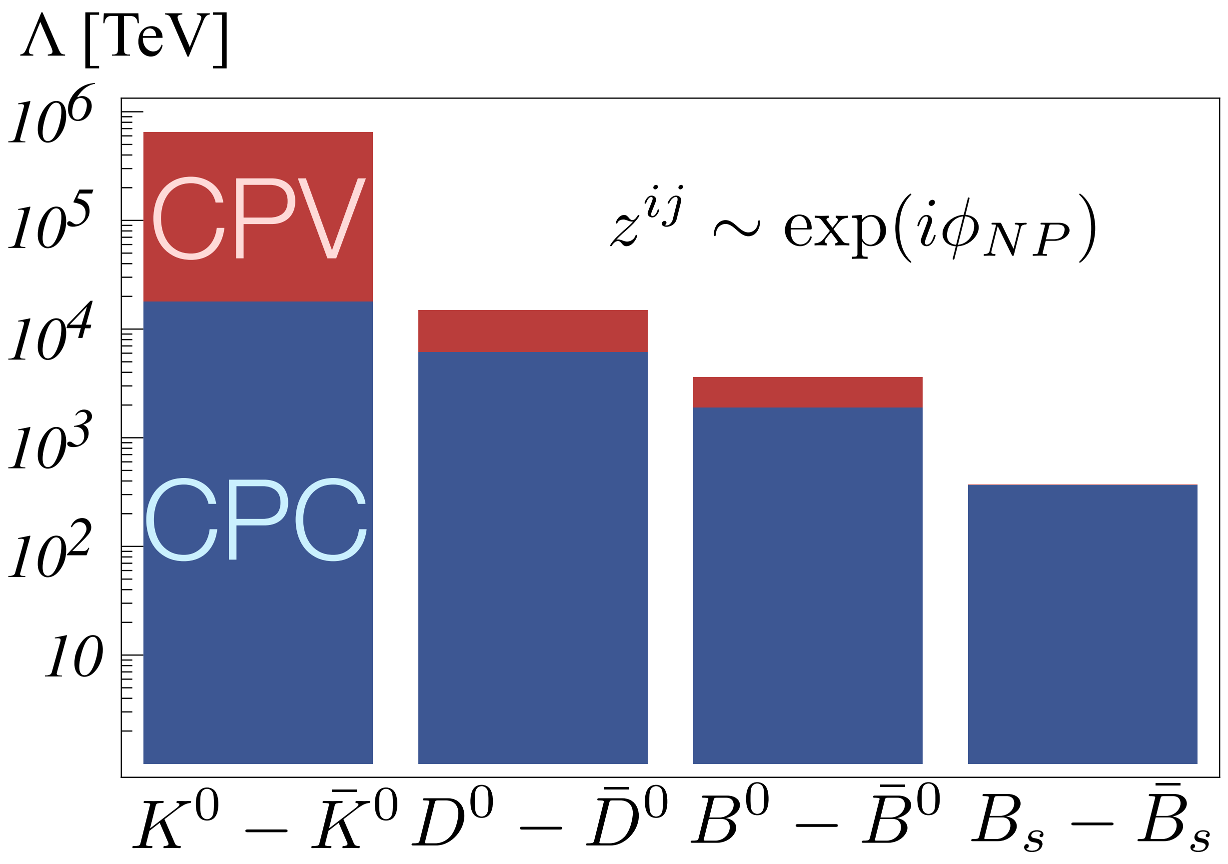


(Over)constraining the SM flavor sector (and NP)

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

Canonical example: NP in ΔF=2 processes

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



- Most constraints now limited by theory uncertainties (both SM & NP)

c.f. Buras & Girrbach, 1201.1302
Mescia & Virto, 1208.0534
see also talk by Buras

Need NLO QCD matching

- Crucial non-pert. QCD input

see talk by Sachrajda

Large NP mass gap / flavor symmetry-structure

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

Is flavor trivial NP safe from flavor constraints?

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

RBC/UKQCD Collaboration, 1305.7217

$$\mathcal{Q}^{(6)}_{\phi Q} \sim z^{ij} \bar{Q}^i_L \tau^a \gamma^\mu Q^j_L \phi^\dagger \tau_a \overleftrightarrow{D}_\mu \phi$$

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

Competitive EW precision constraints

Flavor probes of EW and Higgs sectors

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

Theoretically very clean (virtually no long-distance contributions)

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

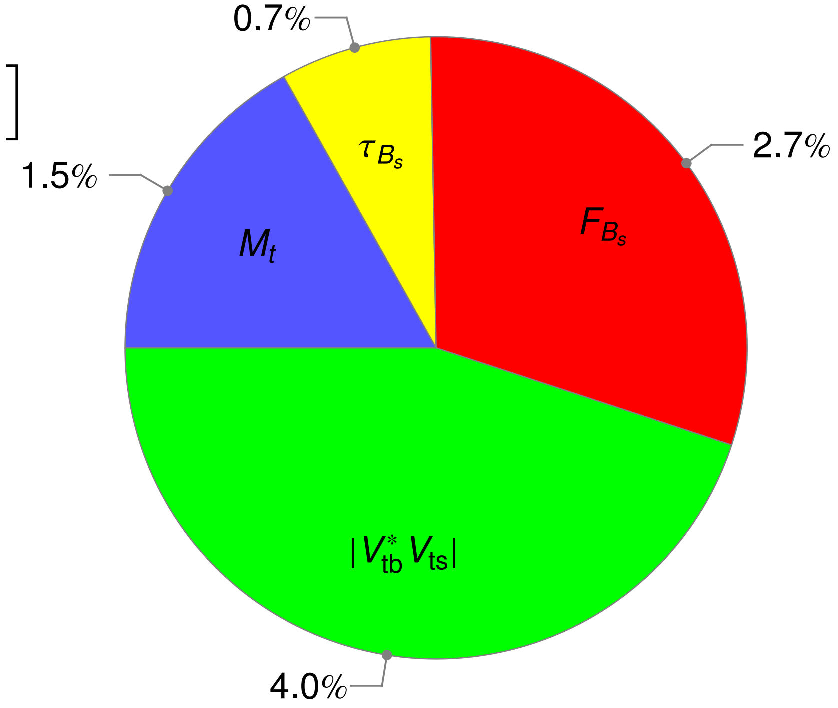
Buras et al., 1208.0934, 1303.3820

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

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

LHCb,1307.5024
CMS, 1307.5025

See talk by Hansmann-Menzemer

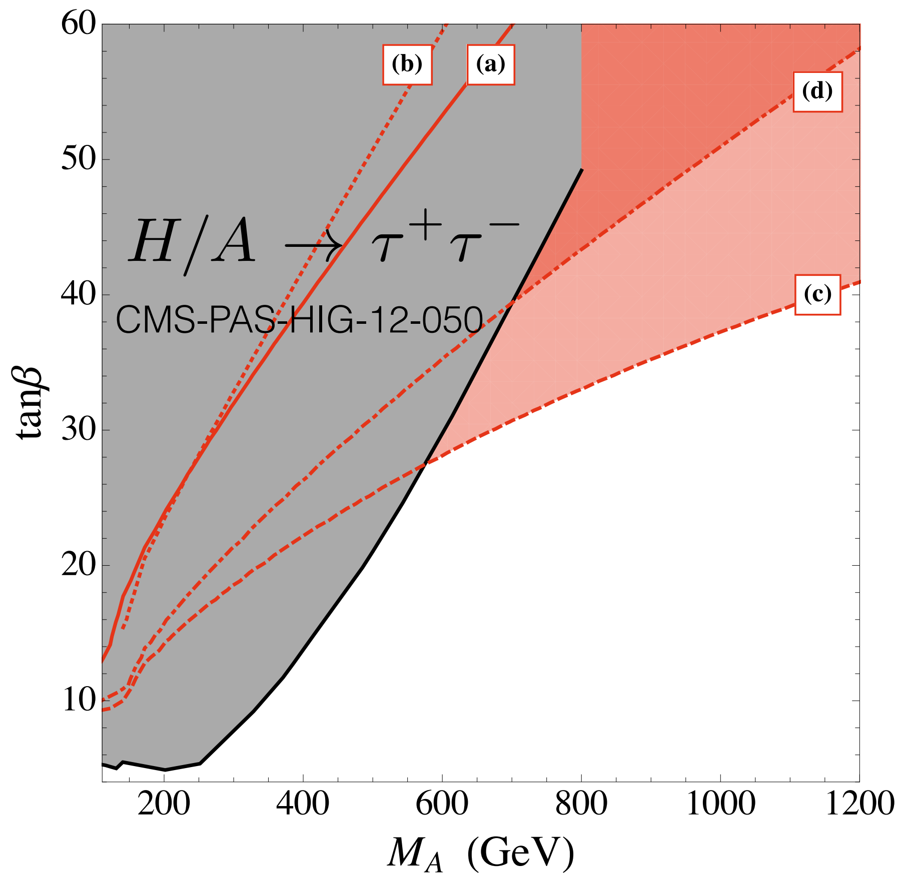
$B_{s,d} \to \mu^+\mu^-$

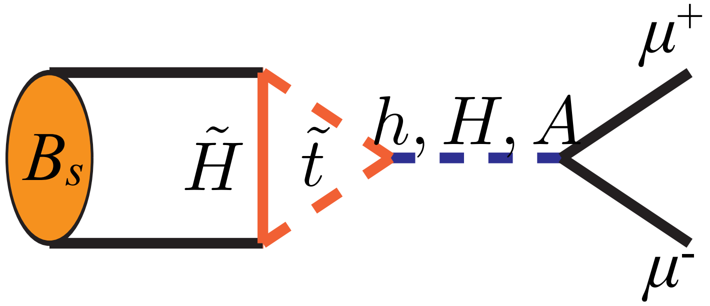
Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction (⇒ Higgs sector) beyond tree level

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

Altmannshofer et al., 1211.1976





$$\propto \frac{y_t^2}{16\pi^2}\frac{\mu A_t}{m_{\tilde{t}}^2}\frac{\tan\beta^3}{m_A^2}V_{tb}V_{ts}^*$$

Scenario	(a)	(b)	(c)	(d)	(e)
μ [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

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

Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction (⇒ Higgs sector) beyond tree level

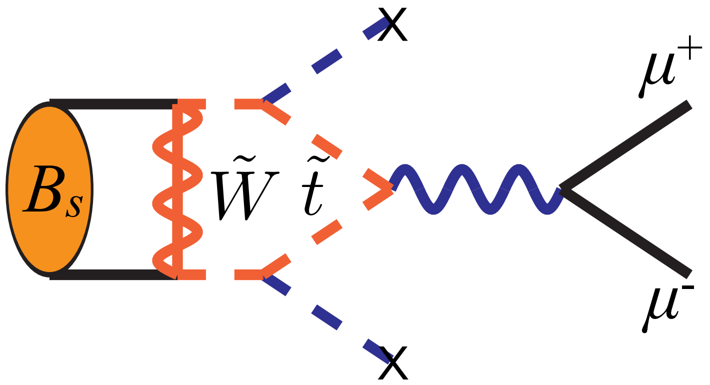
<u>Example</u>: general MSSM

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

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

⇓

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 $\delta\overline{\mathcal{B}}_s \sim 30\%$ provides relevant constraint on such couplings below stability bounds

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

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

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

Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction (⇒ Higgs sector) beyond tree level

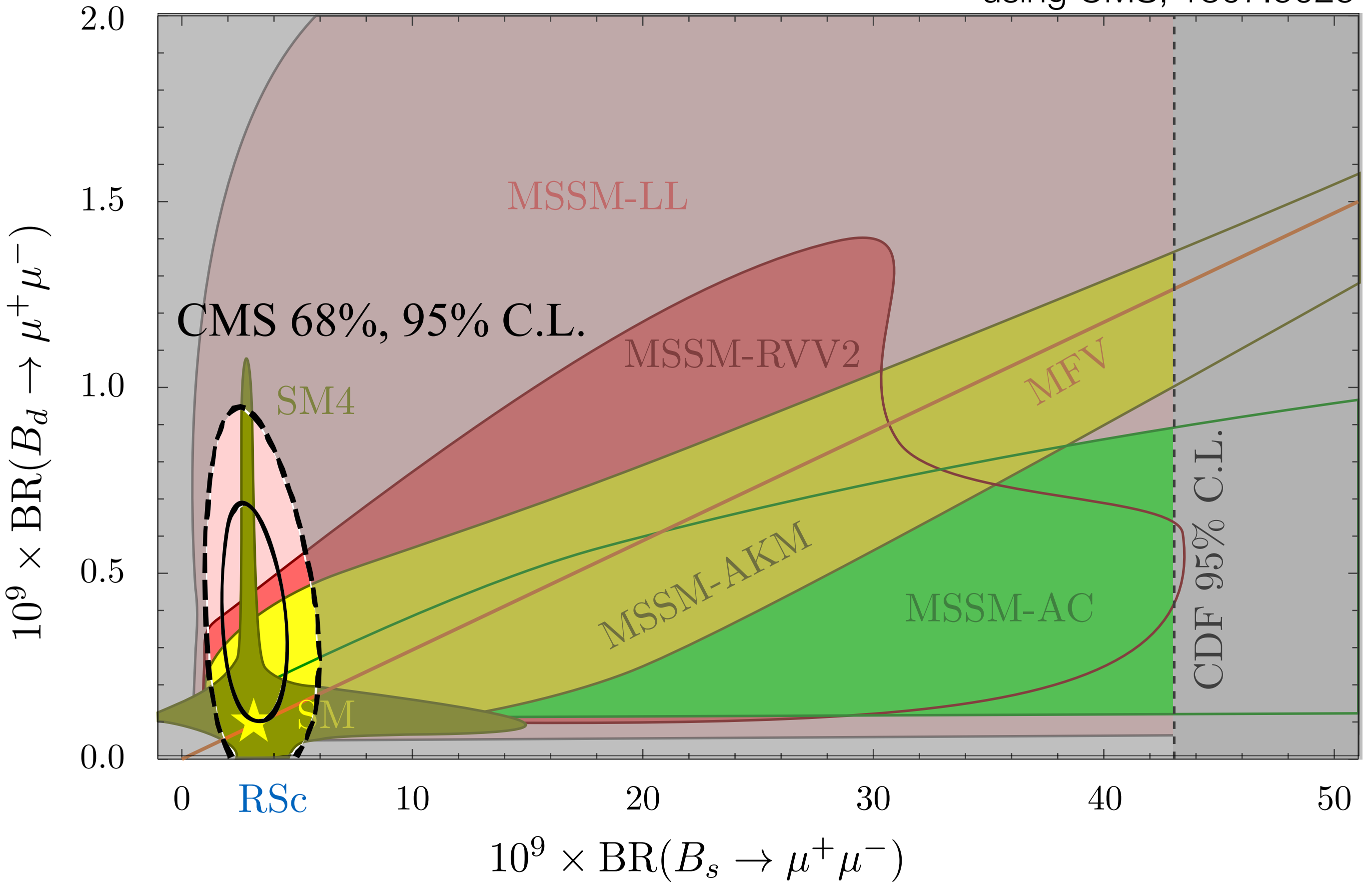
Latest results beginning to test possible $\mathcal{B}_d/\overline{\mathcal{B}}_s$ enhancement

see talk by Kohda

Nontrivial test of MFV.

Hurth et al., 0807.5039

update of Straub, 1012.3893
using CMS, 1307.5025



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:

Guadagnoli & Isidori
1302.3909

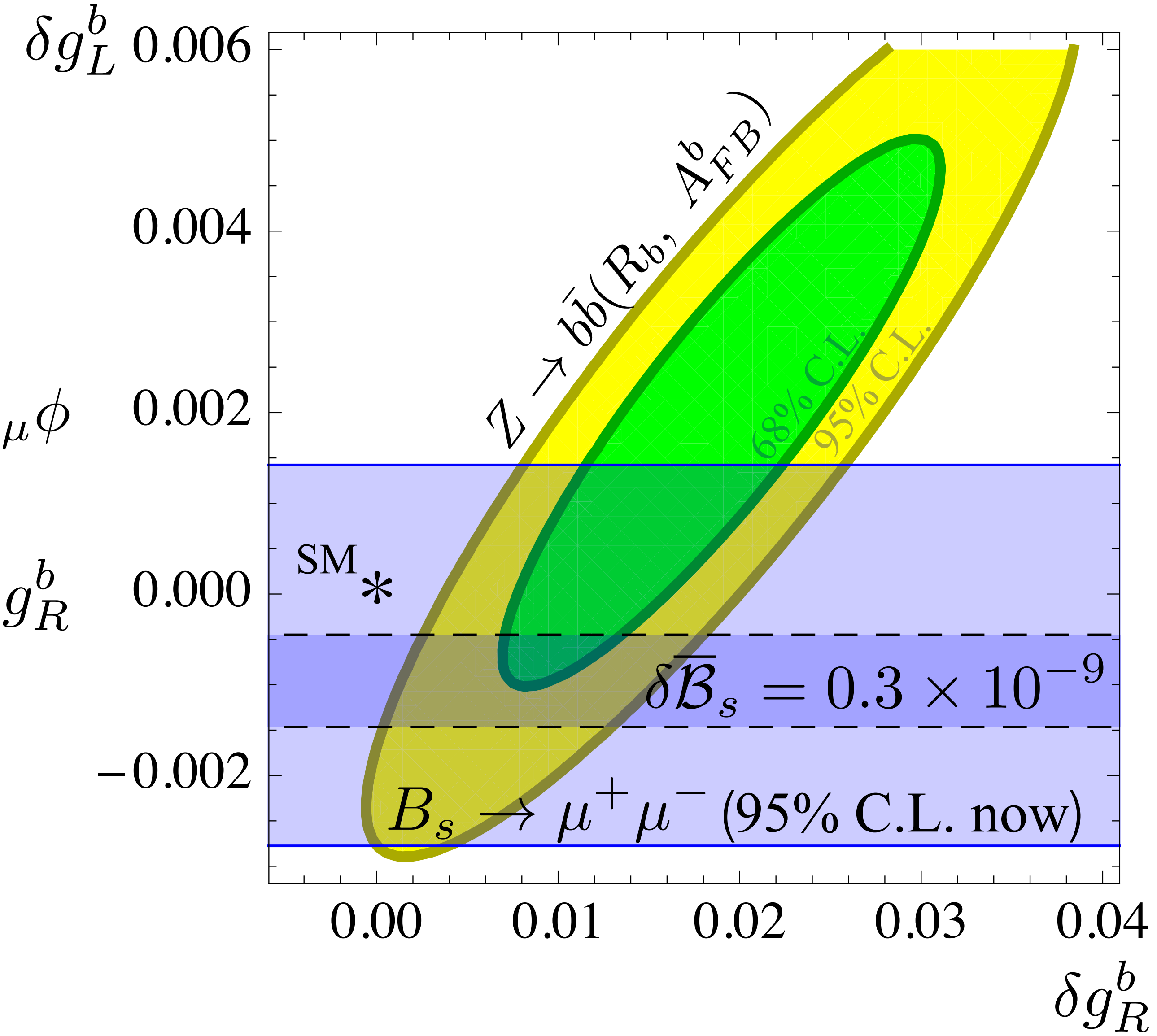
flavor (non)universality (*Zbb/Zqq*) vs. flavor violation (*Zbs*)

Example: MFV

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

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

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



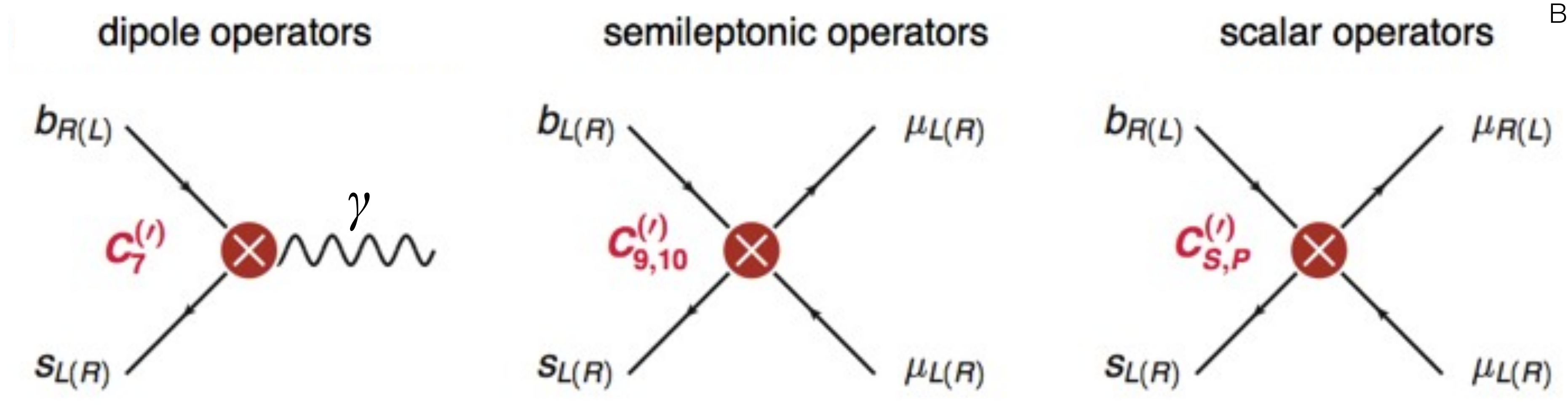
update using latest exp. results,
see talks by Baak, Hansmann-Menzemer

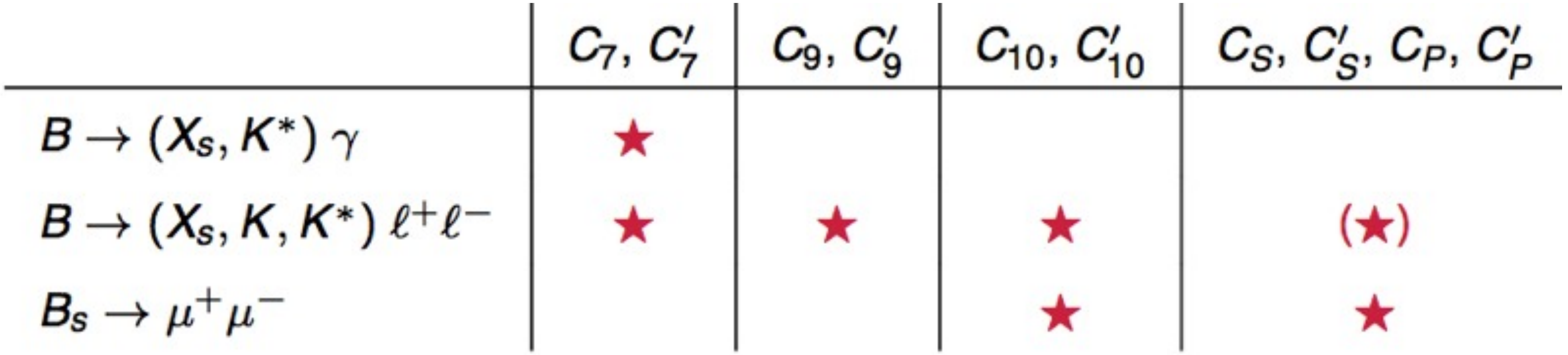
Deconstructing $b \to s(\gamma, \ell^+\ell^-)$ transitions

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
...

see talk by Matias





	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

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

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1111.2558, 1212.2321
Descotes-Genon et al., 1104.3342, 1202.4266,
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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
...

Can define theoretically clean complementary observables, sensitive to NP

- Angular observables (P_i ($A_T^{(i)}$, $H_T^{(i)}$), ...) in $B \to K^*\ell^+\ell^-$
- Time dependent decay observables in $B_s \to \mu^+\mu^-$

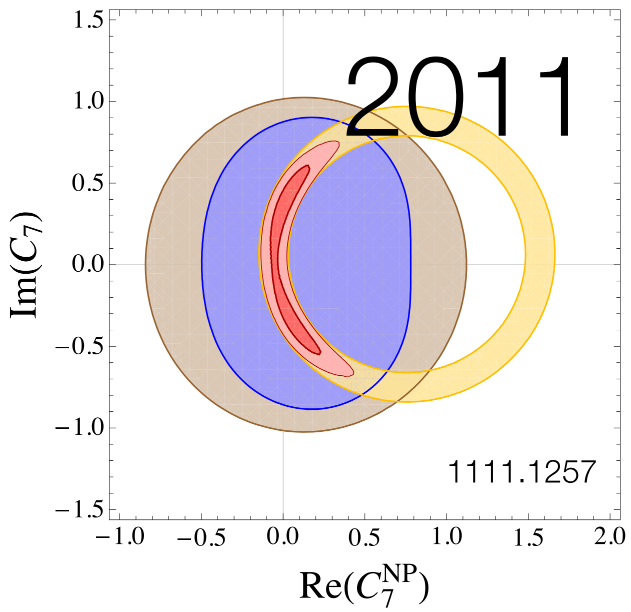
de Bruyn, 1204.1737
Buras et al., 1303.3820

- CPV asymmetries in $b \to s(\gamma, \ell^+\ell^-)$

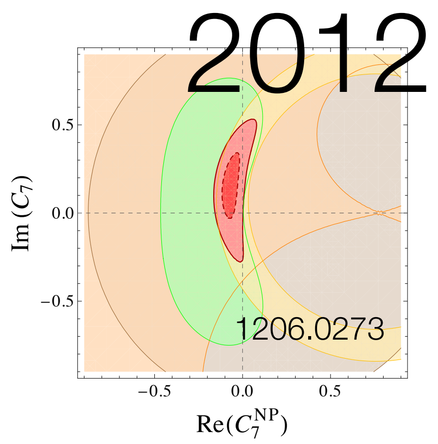
Impact of existing LHCb data

<u>Example</u>: NP in dipole operators

Impact of A_{FB} in $B \to K^*\ell^+\ell^-$
A_{CP} in $B \to X_s\gamma$



for latest fits
see talks by van Dyk, Matias



$B \to X_s\ell^+\ell^-$
$B \to K^*\ell^+\ell^-$
$B \to X_s\gamma$

Signs of NP?

(1) $B \to K^* \ell^+ \ell^-$ anomaly

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

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

- Mostly sensitive to $\mathcal{Q}_7 \sim C_7\, m_b [\bar{s}\sigma_{\mu\nu}(1+\gamma_5)b] e F^{\mu\nu}$

  $\mathcal{Q}_9 \sim C_9\, [\bar{s}\gamma_\mu(1-\gamma_5)b][\bar{\ell}\gamma^\mu \ell]$

  (+chirally flipped ops.)

- In ~4σ tension with SM estimates (dominated by P_5', also A_{FB}, P_2) see talk by Serra

- Can be reconciled by ~40% reduction of $\langle \mathcal{Q}_9 \rangle$ Descotes-Genon, Matias & Virto, 1307.5683

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

  Jager & Camalich, 1212.2263

  Khodjamirian et al., 1006.4945

First-principles QCD estimate possible?

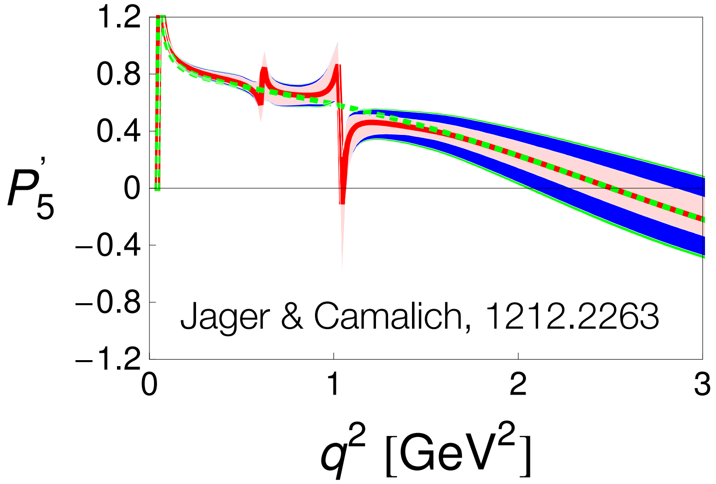
$B \to K^* \ell^+ \ell^-$ anomaly

Possible experimental tests:

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

  - less sensitive to non-local (resonance) contributions

  - fine binning could enhance sensitivity to QCD effects



Jager & Camalich, 1212.2263

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

  - different theory systematics (HQET OPE)

- 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

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

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

If NP, should couple universally to both lepton chiralities

$$\mathcal{Q}_9 \xrightarrow{\Lambda_{\rm NP} > \Lambda_{\rm EW}} \mathcal{Q}_{L+R} \sim z_{ij} \bar{Q}^i \gamma_\mu Q^j (\bar{L} \gamma^\mu L + e_R \gamma^\mu e_R)$$

- Cannot be due to anomalous *Zbs* coupling
  - but known *Z*' model examples could be compatible

Buras, De Fazio & Girrbach, 1211.1896

Descotes-Genon, Matias & Virto, 1307.5683

- Effect in $B \to (K, K^*, X_s)\nu\nu$?
  - No non-local QCD contributions (but need precise form factor estimates)
  - Expect (~50%) reduction compared to SM predicted rates
- If chiral cancelation not perfect, also $B_s \to \mu^+\mu^-$

Signs of NP?
(2) CP violation in charm decays

CP violation in charm decays

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

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

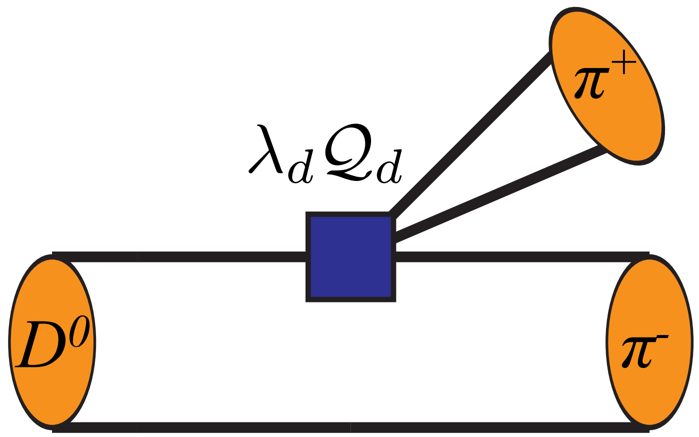
HFAG, March 2013

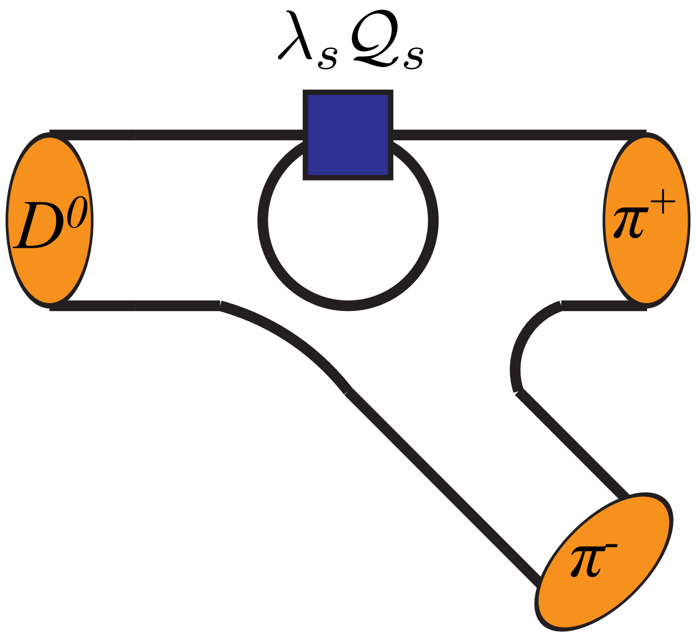
see talk by Göbel

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

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

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





CP violation in charm decays

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

CKM
suppression

matrix element ratio:
$$\frac{\text{“disconnected”}}{\text{“connected”}}$$

$\Delta R^{\mathrm{SM}} > 1$ is not what we expect for $m_c >> \Lambda_{QCD}$, 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
...

see talks by Schacht, Soni

CP violation in charm decays

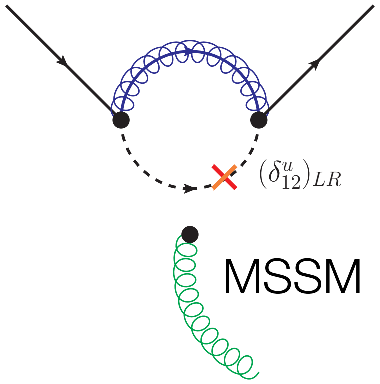
Could it be NP?

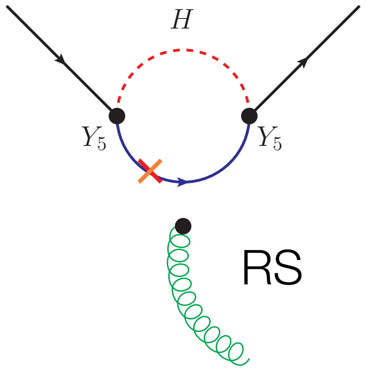
Isidori, J.F.K, Ligeti & Perez
1111.4987

- typical scales probed for $\mathcal{Q}^{(6)} \sim [\bar{c}\,\Gamma_A u] \otimes [\bar{q}\,\Gamma_B q] \;:\; \Lambda \sim 15\,\mathrm{TeV}$
- important constraints from *D* oscillations, CPV in *K* decays, EDMs, ...
- needs to involve new $SU(3)_U$ flavor breaking

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

- can be generated in well-motivated models (SUSY, warped extra-dim. / composite Higgs,....)





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

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 et al., 1208.1499
...

Using charm data:

- isospin sum rules violated if NP ($a_{CP}(D+\longrightarrow\pi^+\pi^0)=0,...$)

Grossman, Kagan & Zupan, 1204.3557

- CPV in radiative *D* decays ($D\longrightarrow(P^+P^-)_V\gamma$; also $D\longrightarrow(P^+P^-)_V\, l^+l^-$)

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
...
see talks by Rok Ko,
Bevan, Soni

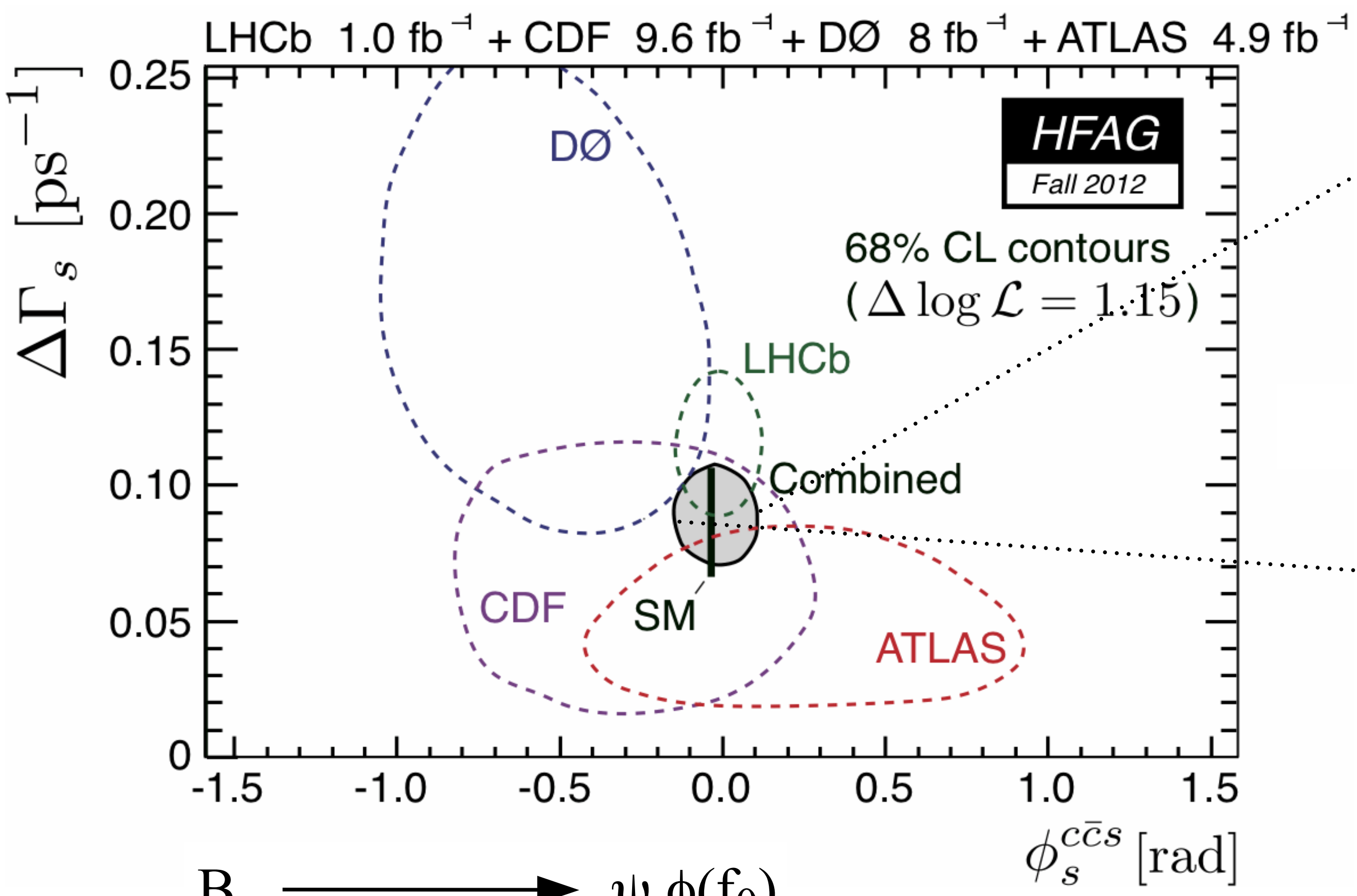
Signs of NP?
(3) CP violation in semileptonic *b* decays

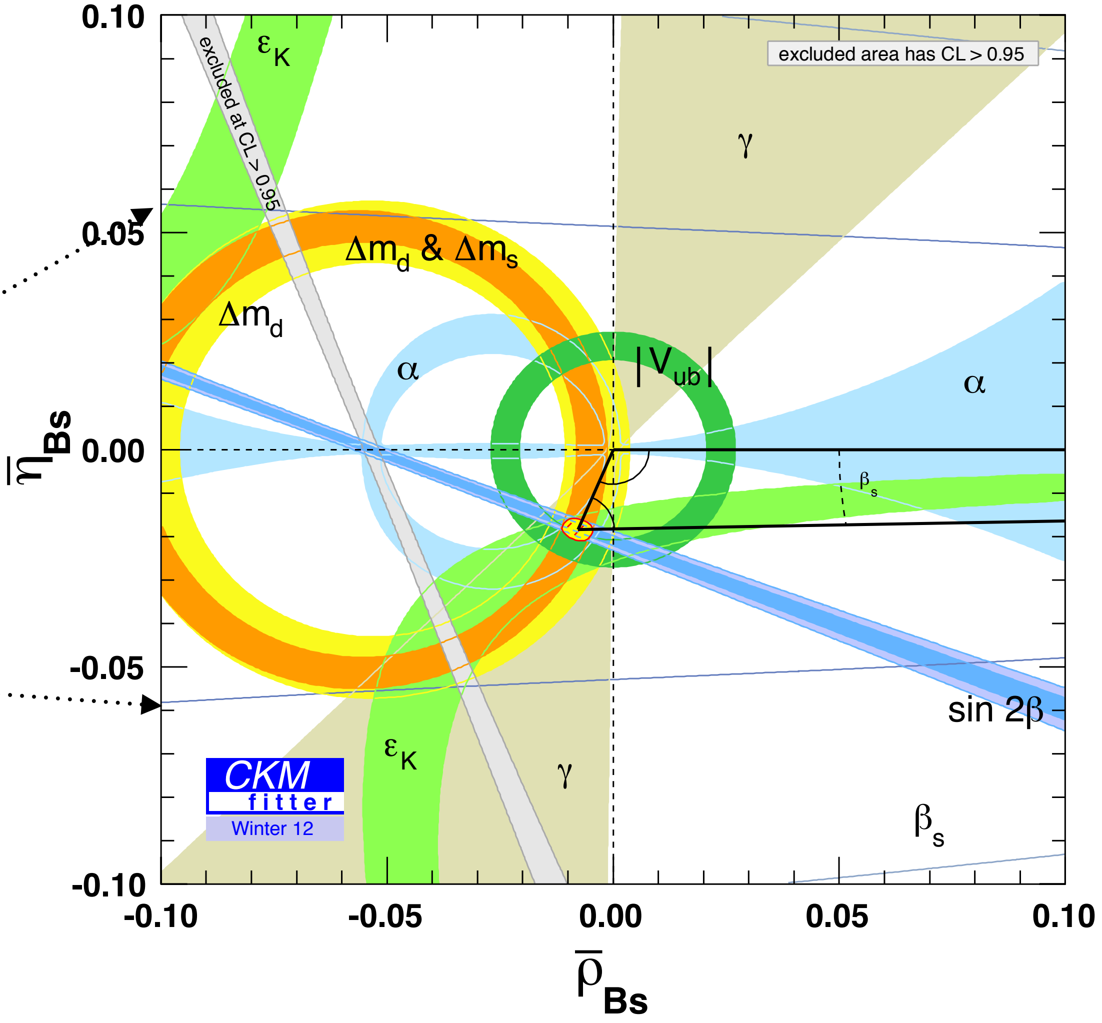
CP violation in semileptonic *b* decays

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...

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





$$\begin{tikzcd}
B_s \arrow[rr] \arrow[dr] & & \psi\ \phi(f_0) \\
& \bar{B}_s \arrow[ur] &
\end{tikzcd}$$

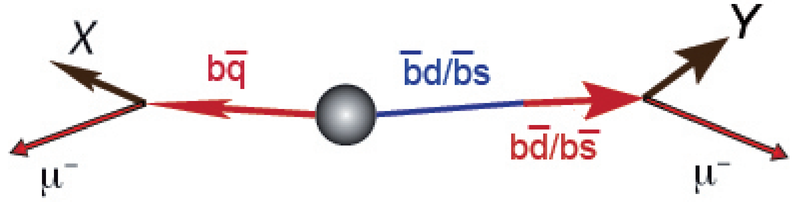
$$\phi_s^{\mathrm{SM}} = \arg\left[-(V_{ub}V_{us}^*)/(V_{cb}V_{cs}^*)\right]$$

see talk by Wandernoth

CP violation in semileptonic *b* decays

...except persistent A_{sl} anomaly

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$



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

dimuon charge asymmetry by D0

see talks by Hoeneisen, Williams

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

$$A^b_{\rm sl} = f_d a^d_{sl} + f_s a^s_{sl}$$

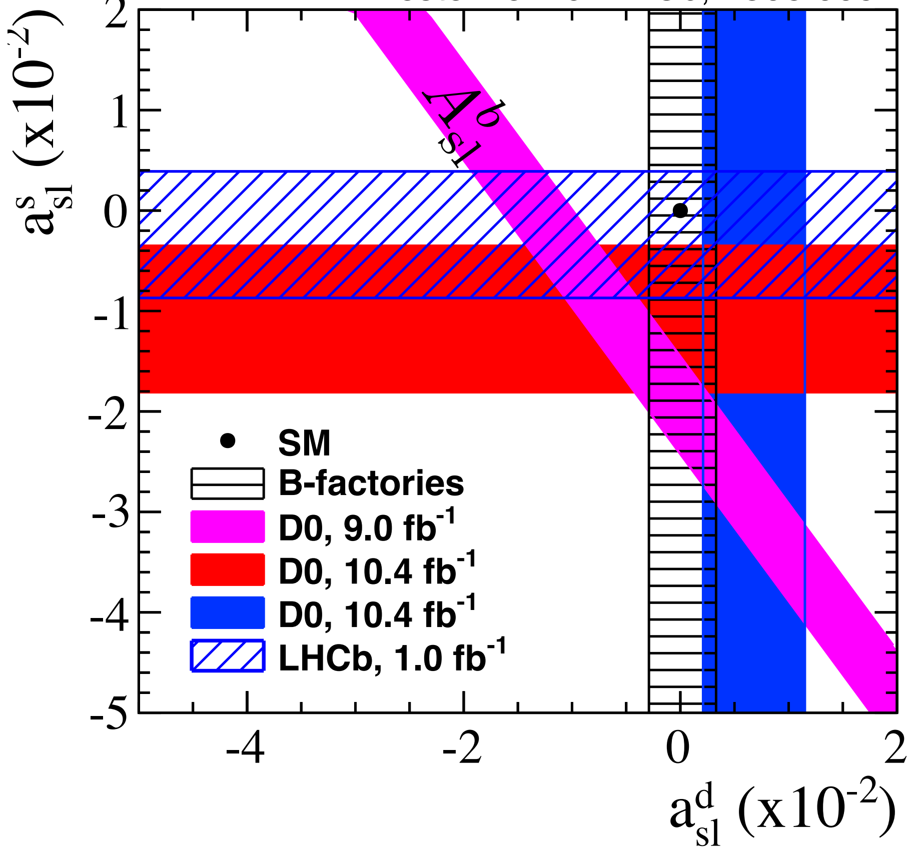
production (fragmentation) fractions

$$a^q_{sl} = \frac{\Gamma(\bar{B}_q \to \mu^+ X) - \Gamma(B_q \to \mu^- X)}{\Gamma(\bar{B}_q \to \mu^+ X) + \Gamma(B_q \to \mu^- X)}$$

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

Lenz & Nierste, 1102.4274

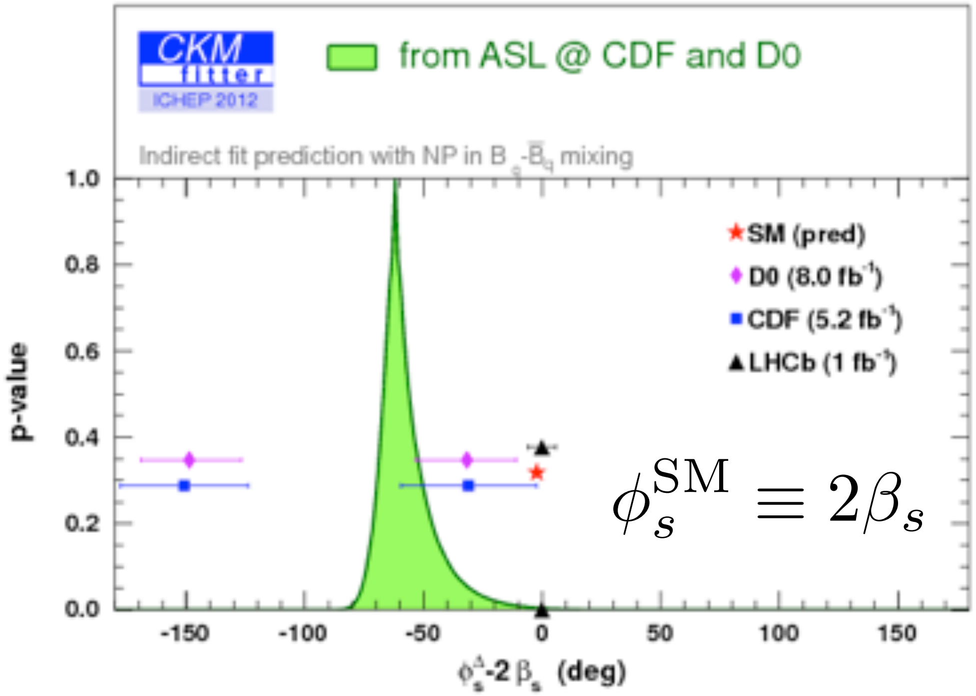
see talk by Hansmann-Menzemer



Vesterinen for LHCb, 1306.0092

CP violation in semileptonic b decays

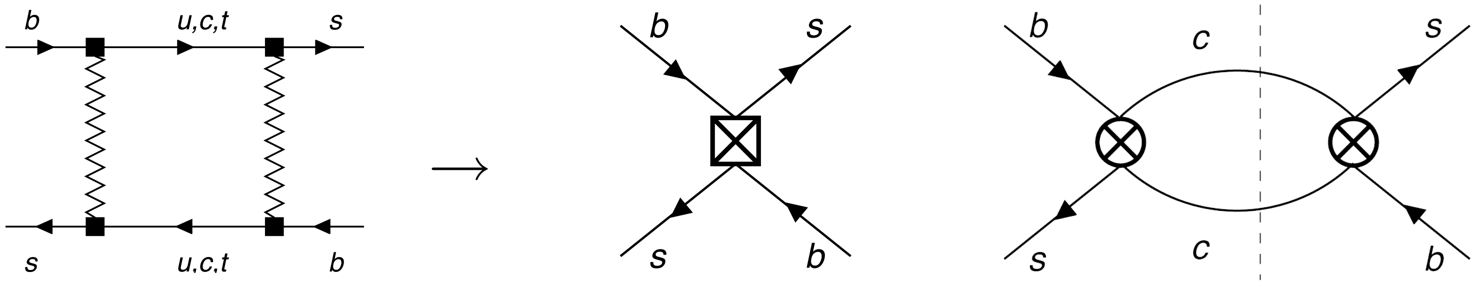
If A would be due to NP phase in B_s mixing: in conflict with measured ϕ_s (similarly for B_d mixing) c.f. Lenz et al.,1203.0238



$$\phi_s^{\mathrm{SM}} \equiv 2\beta_s$$

Additional possibilities:

1. NP in absorptive amplitudes

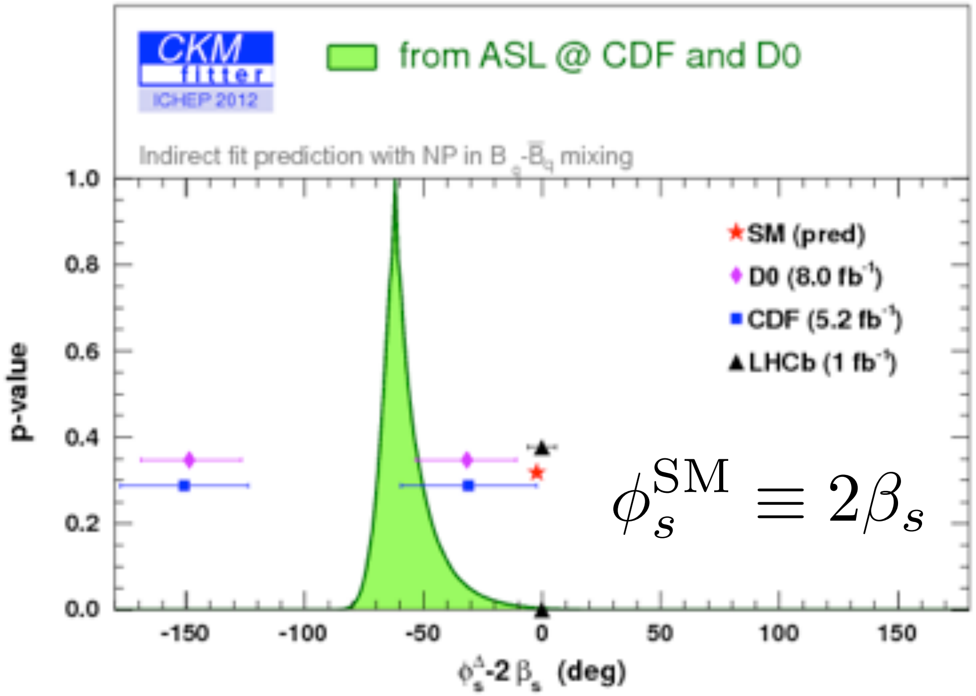


- in B_s system conflict with $\Delta\Gamma_s$, Δm_s
- in B_d system severe constraints from $\Delta F\!=\!1$, possibility remains Bobeth & Haisch, 1109.1826

CP violation in semileptonic *b* decays

If A would be due to NP phase in B_s mixing: in conflict with measured ϕ_s (similarly for B_d mixing)

c.f. Lenz et al.,1203.0238



$$\phi_s^{\rm SM} \equiv 2\beta_s$$

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

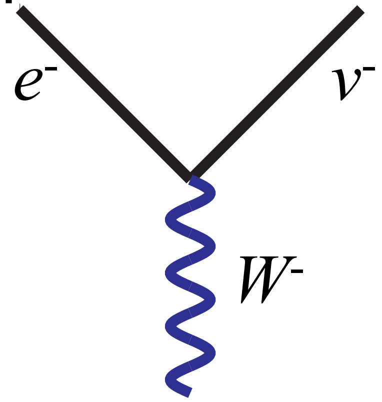
- Difficult to obtain in NP models
- Could be tested at LHC using *b*'s from *t* decays

Gedalia et al., 1212.4611

Signs of NP?
(4) Lepton flavor universality in B decays

LFU in (semi)leptonic B decays

In SM weak charged current interactions are lepton flavor universal



- Tested directly at colliders via *W* decays ~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 ~(0.1-1)%

c.f. HFAG, 1010.1589
talk by Fantechi

LFU in (semi)leptonic B decays

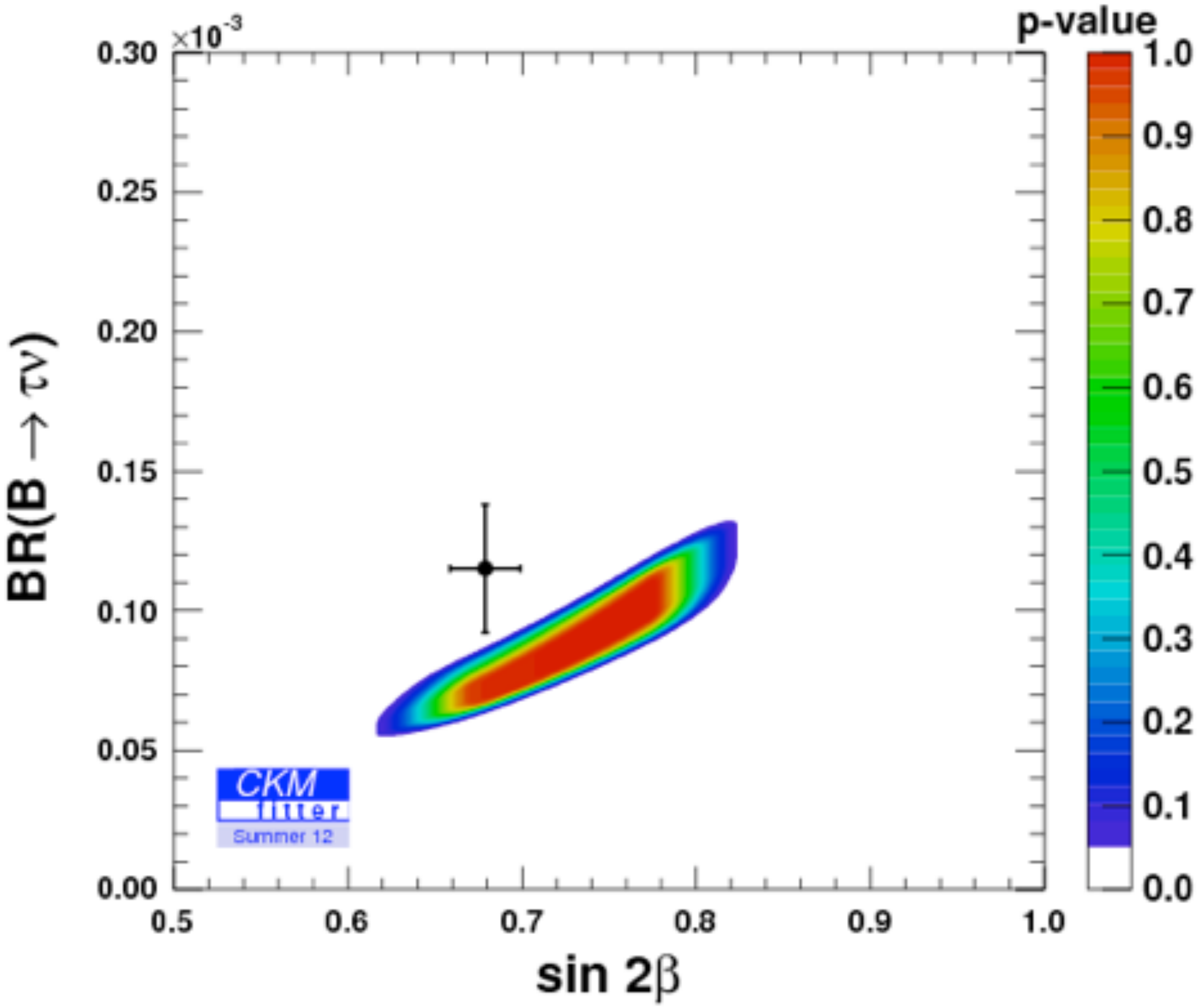
Apparent tension in global CKM unitarity fits

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

Most pronounced for taunic B decay

Somewhat reduced with recent Belle result Belle, 1208.4678

see talk by Hasenbusch



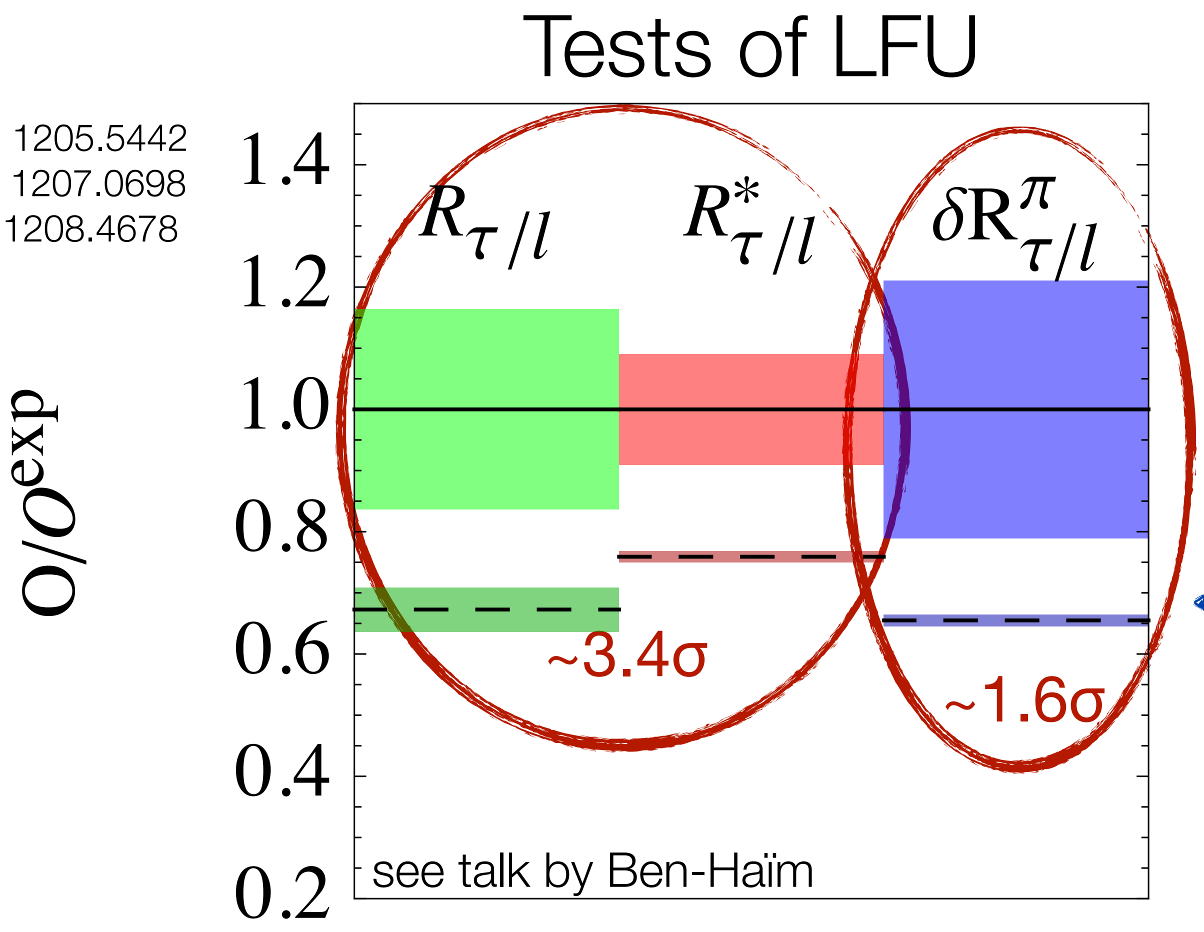
LFU in (semi)leptonic B decays

However, maybe not CKM issue at all

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

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

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

see also talk by Wingate

LFU in (semi)leptonic B decays

Can it be NP? Need to satisfy severe constraints:

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

$\Big\}$ require flavor alignment

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

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

A number of possibilities suggested:
general THDM, leptoquarks, 3rd gen. compositeness...

see talks by Crivelin, Celis

Crivellin, Greub & Kokulu
1206.2634
Celis et al., 1210.8443
He & Valencia, 1211.0348
Dorsner et al., 1306.6493

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

see talk by Bečirević

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: $pp \to t + E_T^{\rm miss}\,,\ \tau + E_T^{\rm miss}\,, t\bar{b}$

Conclusions

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

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

- Measurements of $B_{s,d} \to \mu^+\mu^-$ (and semileptonic $b \to s$ modes) probe the Yukawa sector at loop level
- Higgs discovery offers new direct probes of flavor dynamics

see talk by Grojean

Conclusions

Implications of open experimental flavor puzzles

- Angular fit of $B \to K^* \ell^+ \ell^-$ exhibits deviations from SM estimates
  - important to understand the origin of the C_9 shift (QCD or NP)
- If due to NP, observed Δa_{CP} points towards new flavor sources in u_R sector
  - important to verify in other charm decay modes
- D0 A_{sl} value 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

Extras

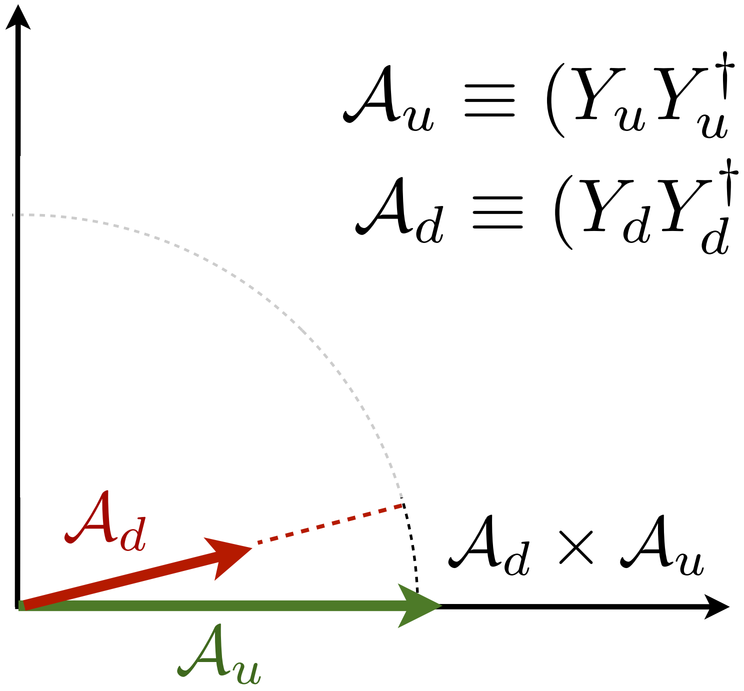
Reclaiming flavorful NP at EW scale

Reclaiming flavorful NP at EW scale

Global flavor symmetry of SM broken by Yukawas:

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

$$\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\text{tr}}}\,,$$
$$\mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\text{tr}}}$$



Reclaiming flavorful NP at EW scale

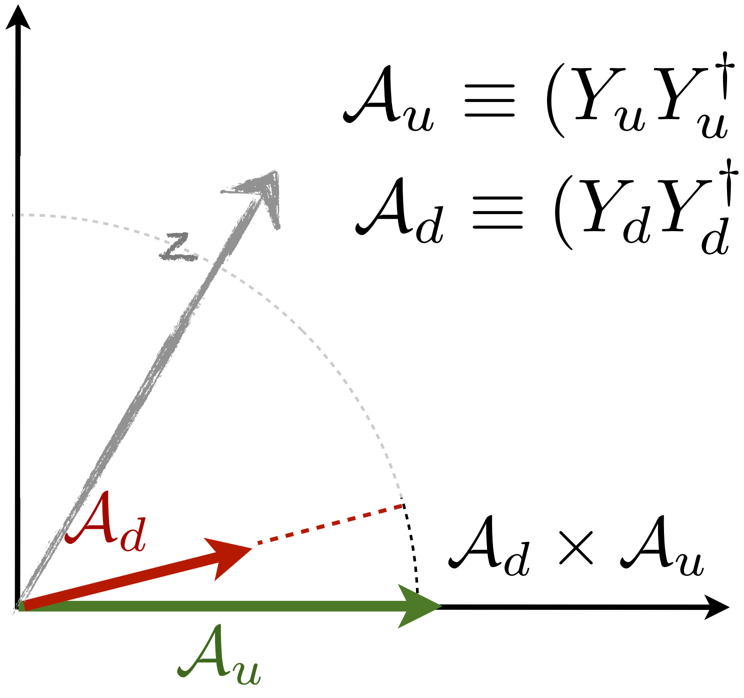
Global flavor symmetry of SM broken by Yukawas:

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

Formally, <u>NP flavor cannot be completely trivial</u>

$$\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\mathrm{tr}}}\,,$$

$$\mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\mathrm{tr}}}$$



$$\int d^4x\, T\{\mathcal{Q}_{\mathrm{NP}}\, \mathcal{H}_{\mathrm{SM}}\}$$

Reclaiming flavorful NP at EW scale

Global flavor symmetry of SM broken by Yukawas:

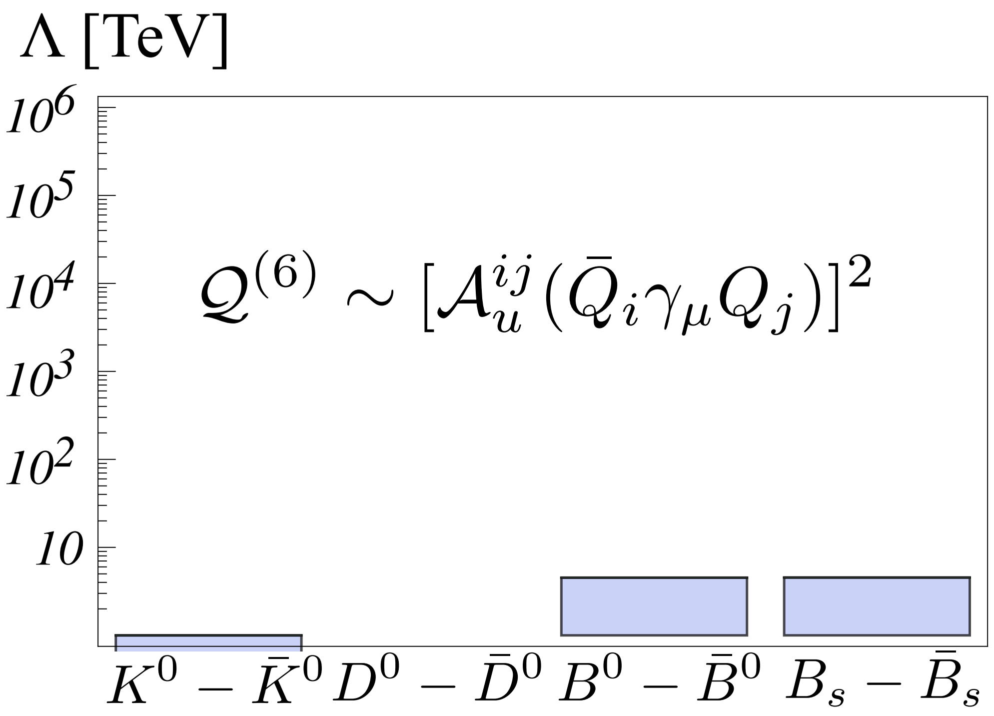
$$G_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D$$

Formally, NP flavor cannot be completely trivial

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

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

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



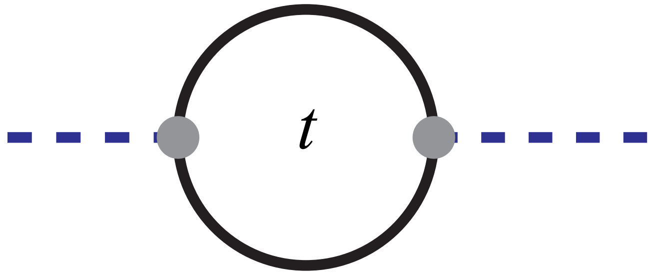
NP in loops

$\Downarrow$

probe EW scale masses

Reclaiming flavorful NP at EW scale

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



In SM, top Yukawa imposes largest fine-tuning in Higgs potential ⇒

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

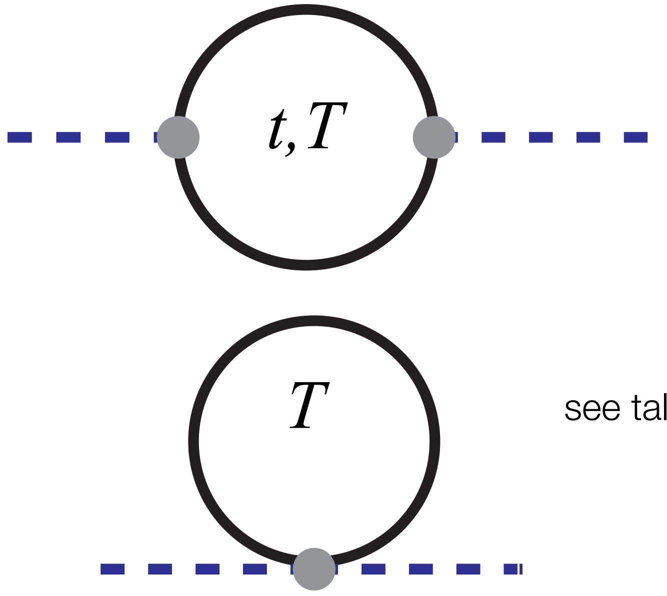
Reclaiming flavorful NP at EW scale

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

In SM, top Yukawa imposes largest fine-tuning in Higgs potential ⇒

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

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



see talk by Han

Reclaiming flavorful NP at EW scale

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

In SM, top Yukawa imposes largest fine-tuning in Higgs potential ⇒

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

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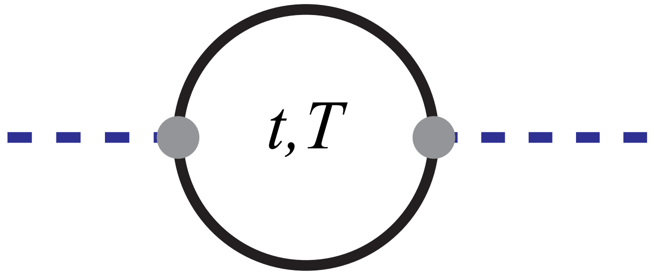
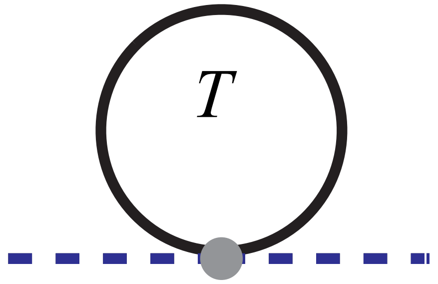


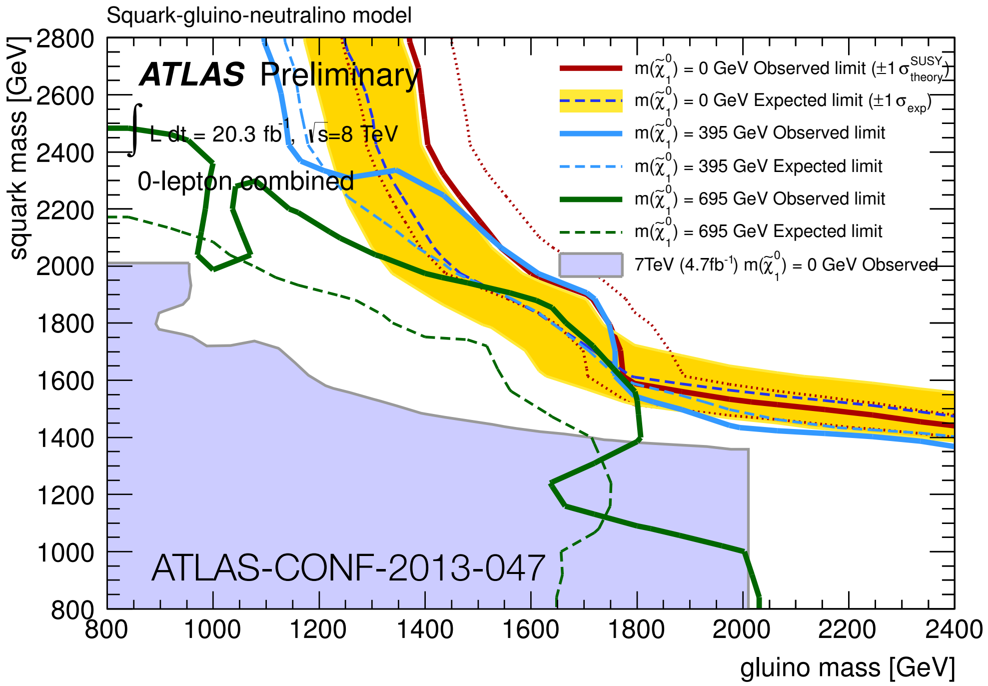


see talk by Han

avoiding flavor bounds though triviality ⇒ presence of u,d,... partners (m_U~m_T)

Strong LHC direct search constraints (MSSM example)

see talk by Hoecker



Reclaiming flavorful NP at EW scale

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

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

Kagan et al., 0903.1794

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

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

Buras & Girrbach, 1206.3878

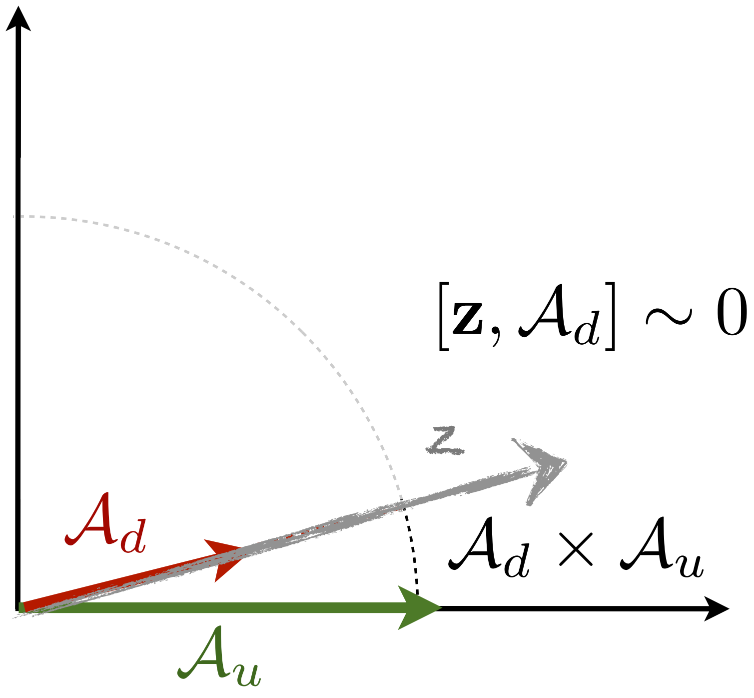
- examples in MSSM, partial compositeness
  ⇒ allow for lighter 3rd generation partners

Barbieri et al., 1105.2296
1108.5125
1203.4218
1206.1327
1211.5085

Reclaiming flavorful NP at EW scale

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

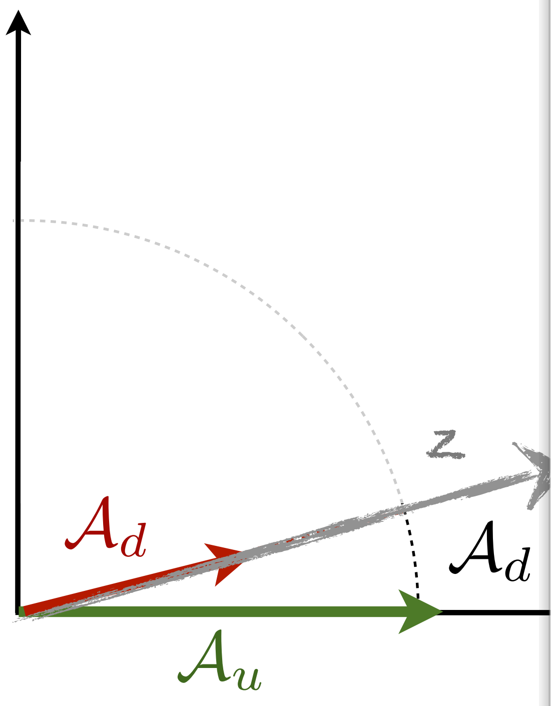
Gedalia et al., 1202.5038

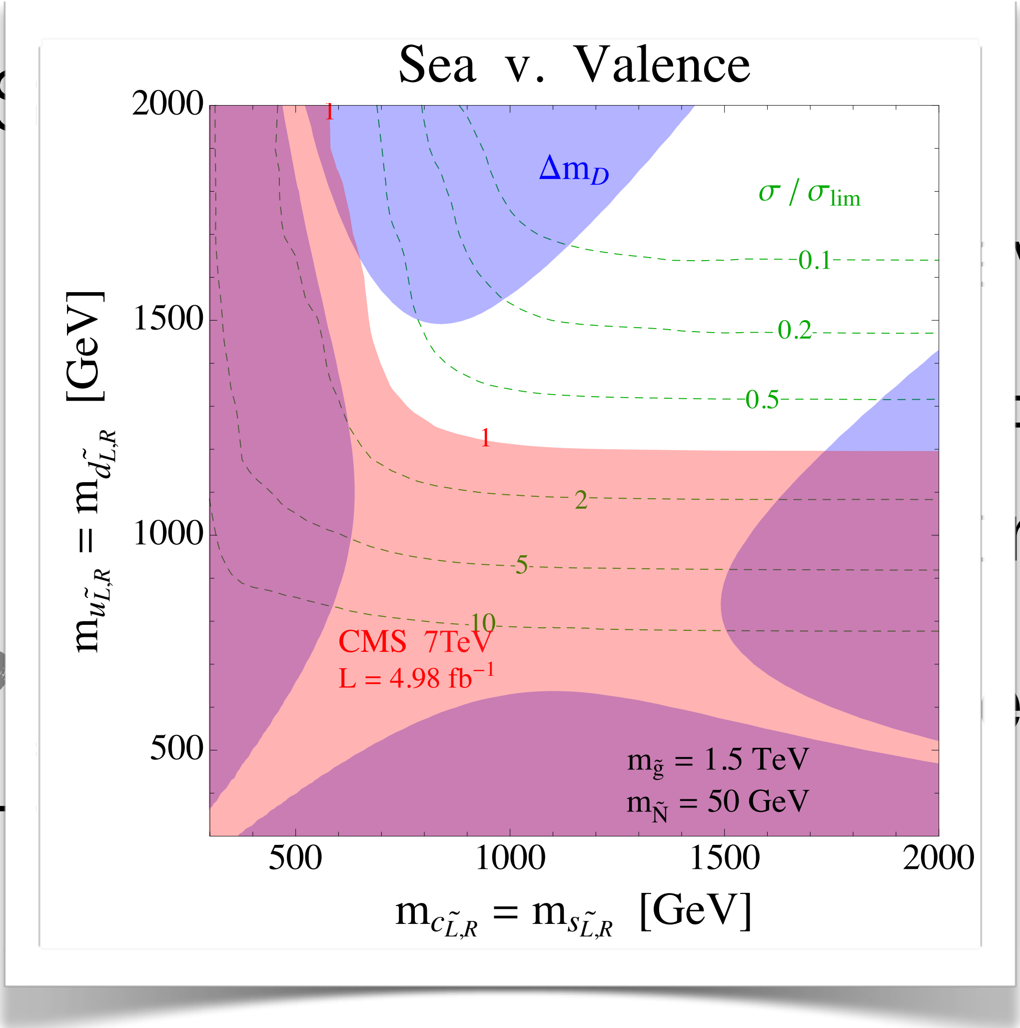
Allows split NP spectrum

Reclaiming flavorful NP at EW scale

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

Alternatively, align





vor charges

Nir & Seiberg, hep-ph/9304307

FCNCs

ressed

Gedalia et al., 1202.5038

ectrum

<u>Example</u>: 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 $t j_c E_T^{\rm miss}$

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

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

<u>Example</u>: large $\tilde{t}_R - \tilde{c}_R$ mixing

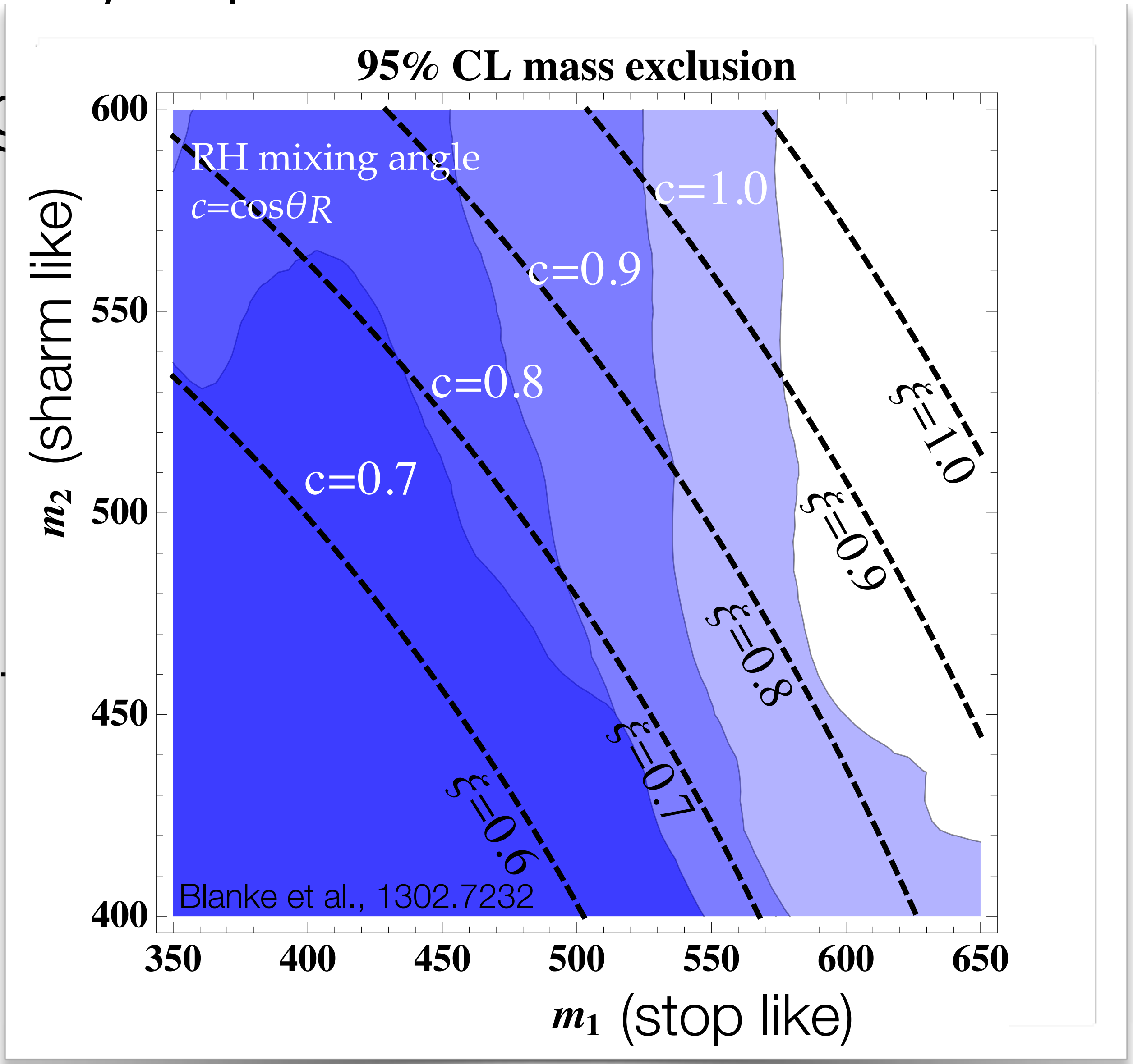
new signature $t j_c E_T^{\text{miss}}$

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

Tuning measure:
(compared to
pure stop)

$$\xi = \frac{c^2 m_1^2 + s^2 m_2^2}{m_0^2}$$

(shown for c=0.7)



Higgs as probe of flavor

Testing flavor through Higgs observables

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
...

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

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

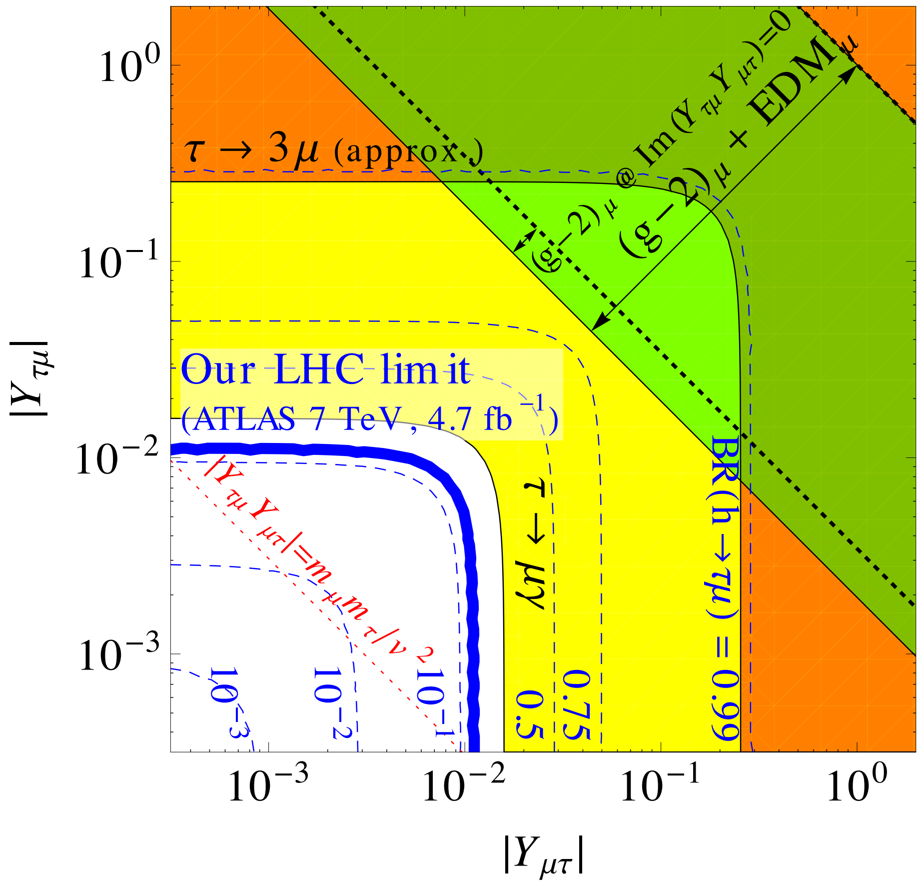
Cheng & Sher,
Phys.Rev. D35, 3484 (1987)

New neutral currents

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

Testing flavor through Higgs observables

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



Harnik, Kopp, Zupan, 1209.1397

Target benchmark flavor model predictions

Dery et al., 1302.3229

Model	$\left(\frac{\sigma(pp\to h)^{\rm SM}}{\sigma(pp\to h)}\frac{\Gamma_{\rm tot}}{\Gamma_{\rm tot}^{\rm SM}}\right) R_{\tau^+\tau^-}$	$X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$	$\bar{Y}_{\mu\tau}$
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	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{23}\rvert^2 v^4/\Lambda^4)$
GL	9	$25/9$	$\mathcal{O}(X_{\mu^+\mu^-})$

$$R_{\tau^+\tau^-} \equiv \frac{\mathrm{BR}(h \to \tau^+\tau^-)}{\mathrm{BR}(\mathrm{h} \to \tau^+\tau^-)^{\rm SM}} \qquad X_{\mu^+\mu^-} \equiv \frac{\mathrm{BR}(h \to \mu^+\mu^-)}{\mathrm{BR}(h \to \tau^+\tau^-)}$$

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