Building models for flavour anomalies

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based on work with A. Greljo, G. Isidori, D. Marzocca

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Introduction

$$\mathcal{L} \sim \Lambda^2 |H|^2 + \sum_i \lambda_i \mathcal{O}_i^{(4)} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i^{(6)} + \cdots$$

Naturalness of EW scale

$$\Lambda \lesssim 1\,\mathrm{TeV}$$

Flavour constraints

$$\Lambda \gg \mathrm{TeV}$$

- low Λ, small c's: flavour problem
- high Λ, c's ~ O(1): hierarchy problem

<u>Pre-LHC:</u>

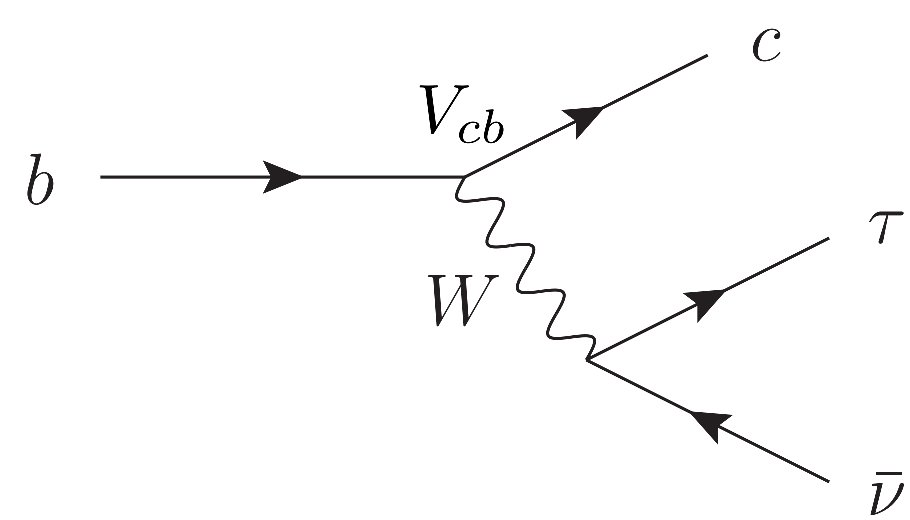
- exciting phenomena in high-pT experiments: ATLAS, CMS
- boring flavour physics (MFV)

<u>Post-LHC:</u>

- no light on-shell resonances
- very interesting anomalies in flavour observables

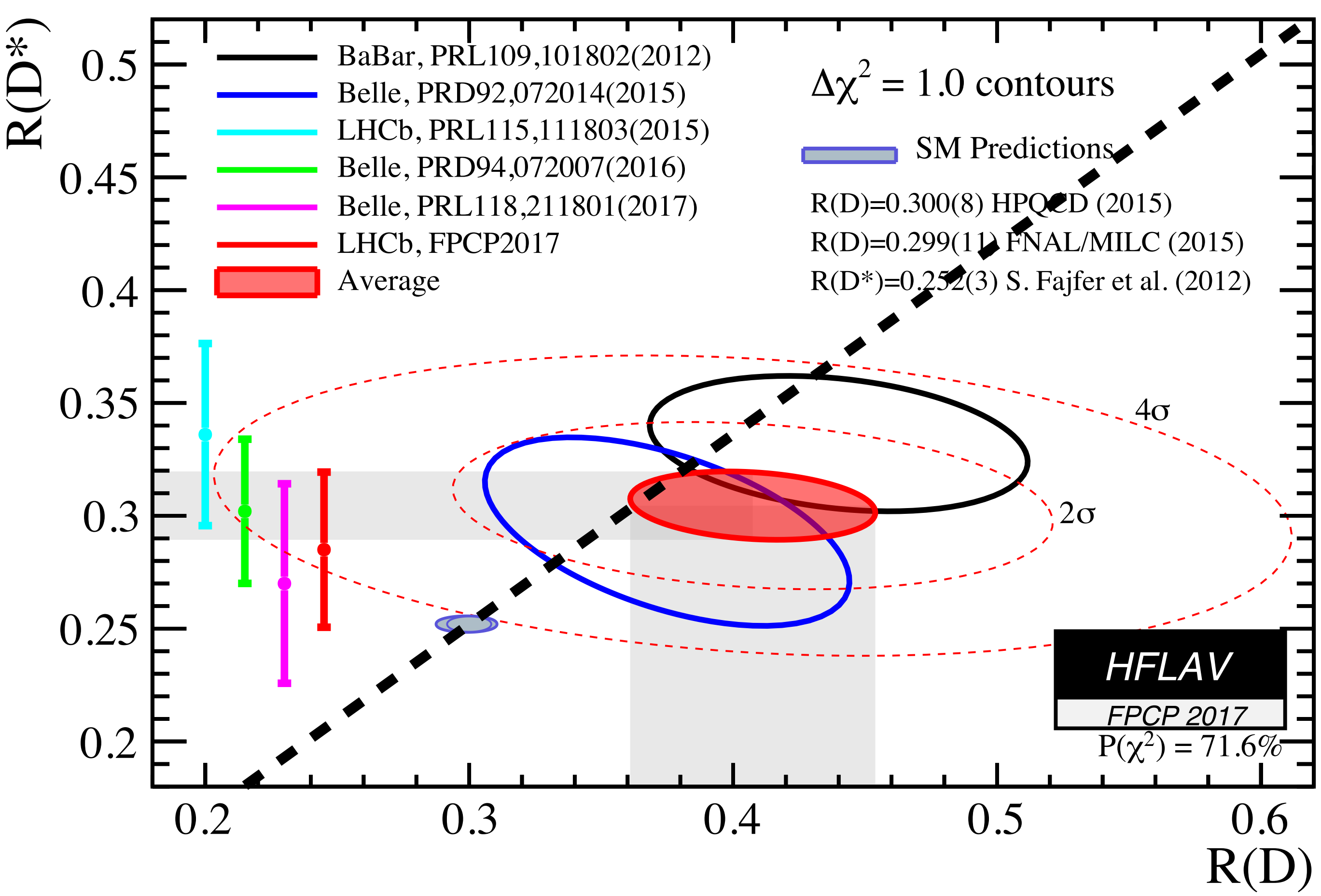
Semi-leptonic b to c decays

Charged-current interaction: **tree-level** effect in the SM, with mild CKM suppression



$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb}^* (\bar{b}_L \gamma_\mu c_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)$$

LFU ratios: $$R_{D^{(*)}} = \frac{{\rm BR}(B \to D^{(*)} \tau \bar{\nu})/{\rm SM}}{{\rm BR}(B \to D^{(*)} \ell \bar{\nu})/{\rm SM}} = 1.237 \pm 0.053$$

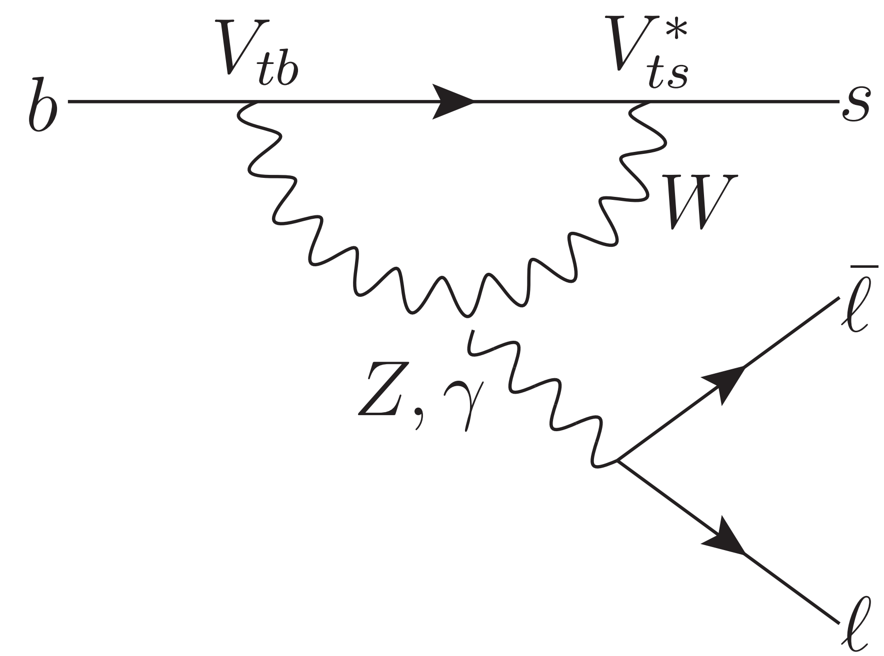


~ 20% enhancement in LH currents
~ 4σ from SM

- RH & scalar currents disfavoured
- SM predictions robust: form factors cancel in the ratio (to a good extent)
- Consistent results by three very different experiments, in different channels
- Large backgrounds & systematic errors

Semi-leptonic *b* to *s* decays

FCNC: occurs only at **loop-level** in the SM
+ **CKM** suppressed

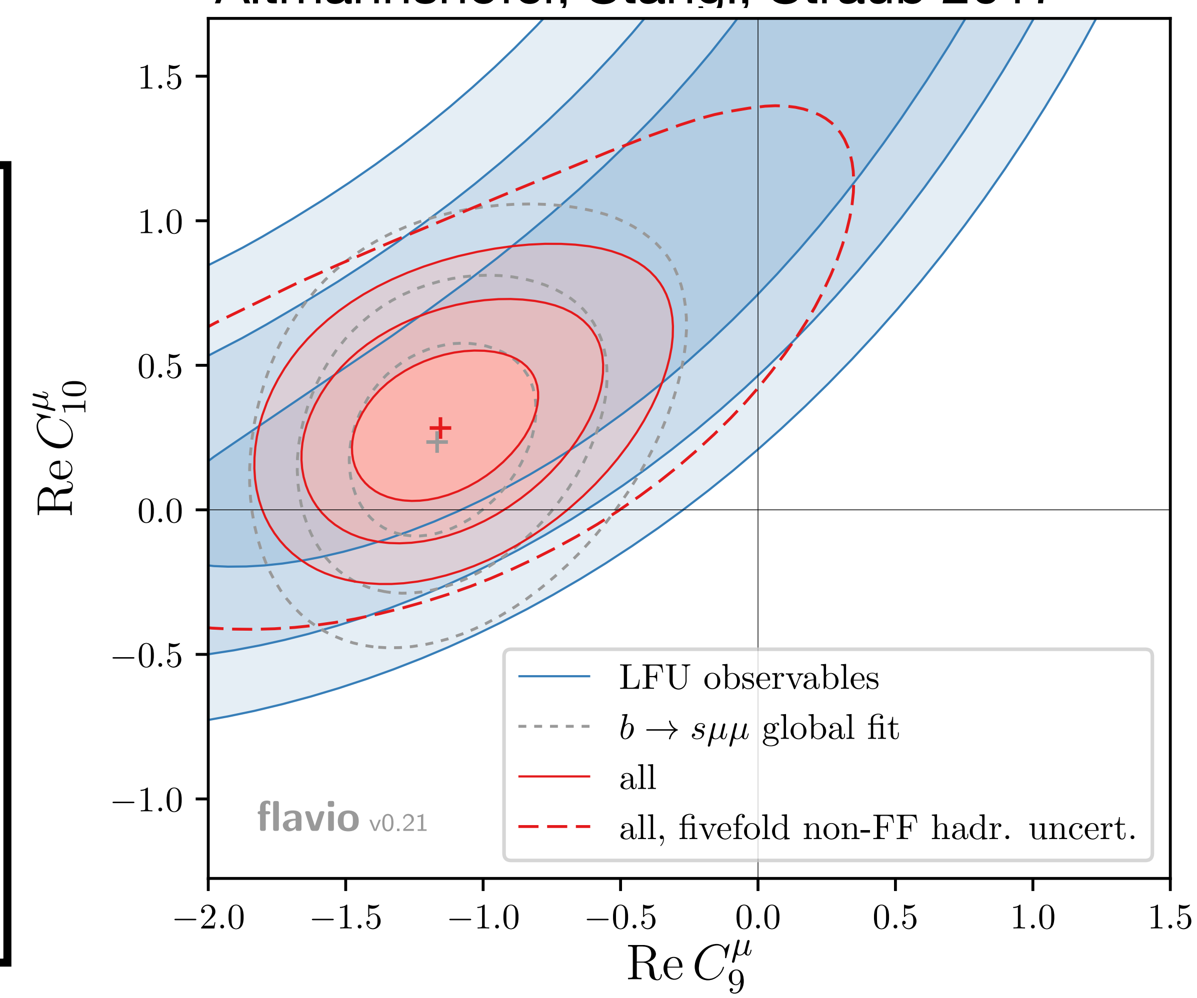


Semi-leptonic effective Lagrangian:

$$\mathcal{L} = \frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}V_{tb}^* V_{ts}\sum_i C_i\mathcal{O}_i + C_i'\mathcal{O}_i'$$

$$\mathcal{O}_7 = m_b(\bar{b}_R\sigma_{\mu\nu}s_L)eF^{\mu\nu}$$
$$\mathcal{O}_9 = (\bar{b}_L\gamma_\mu s_L)(\bar{\ell}\gamma^\mu\ell), \quad \mathcal{O}_{10} = (\bar{b}_L\gamma_\mu s_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

Altmannshofer, Stangl, Straub 2017



Deviations from SM in several observables

- Angular distributions in $B \to K^*\mu\mu$
- Various branching ratios $B_{(s)} \to X_s\,\mu\mu$
- LFU in R(K) and R(K^*)

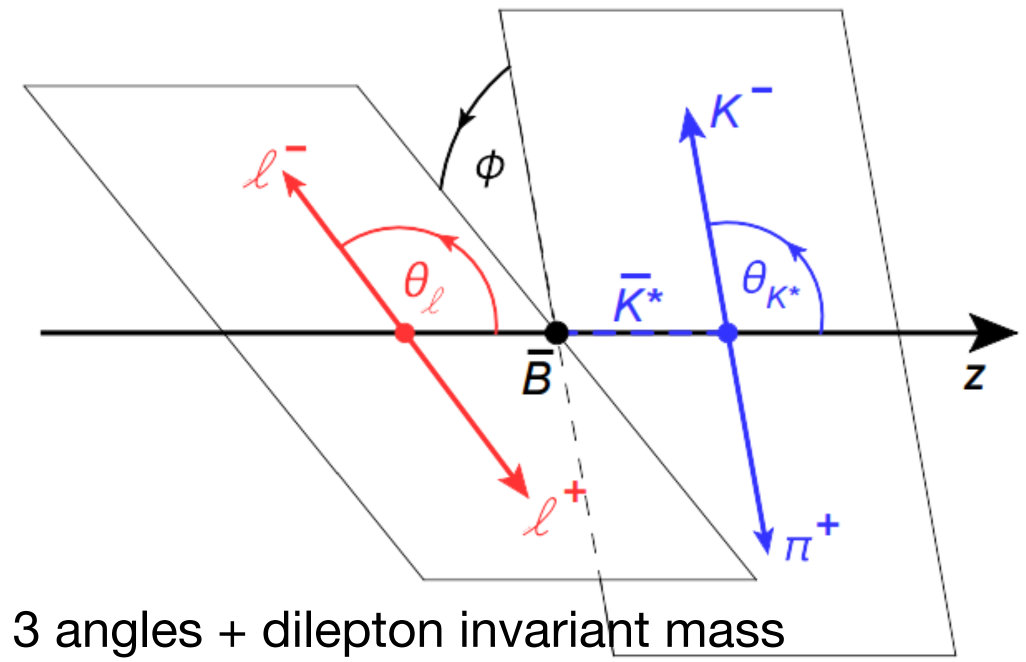
~ 20% NP contribution to LH currents

Globally ~ 5σ from SM

$B \to K^{*}\mu\mu$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} =$$

$$\frac{9}{16\pi}\frac{d\Gamma}{dq^2}\Big[F_L\cos^2\theta_K(1-\cos 2\theta_\ell)+\frac{1}{4}(1-F_L)\sin^2\theta_K(3+\cos 2\theta_\ell)$$
$$-\frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell+(1-F_L)\sin^2\theta_K\sin^2\theta_\ell\left(\frac{P_1}{2}\cos 2\phi-P_3\sin 2\phi\right)$$
$$+\sqrt{F_L(1-F_L)}\sin 2\theta_K\left(\frac{P_4'}{2}\sin 2\theta_\ell\cos\phi+\sin\theta_\ell(P_5'\cos\phi-P_6'\sin\phi)\right)\Big]$$



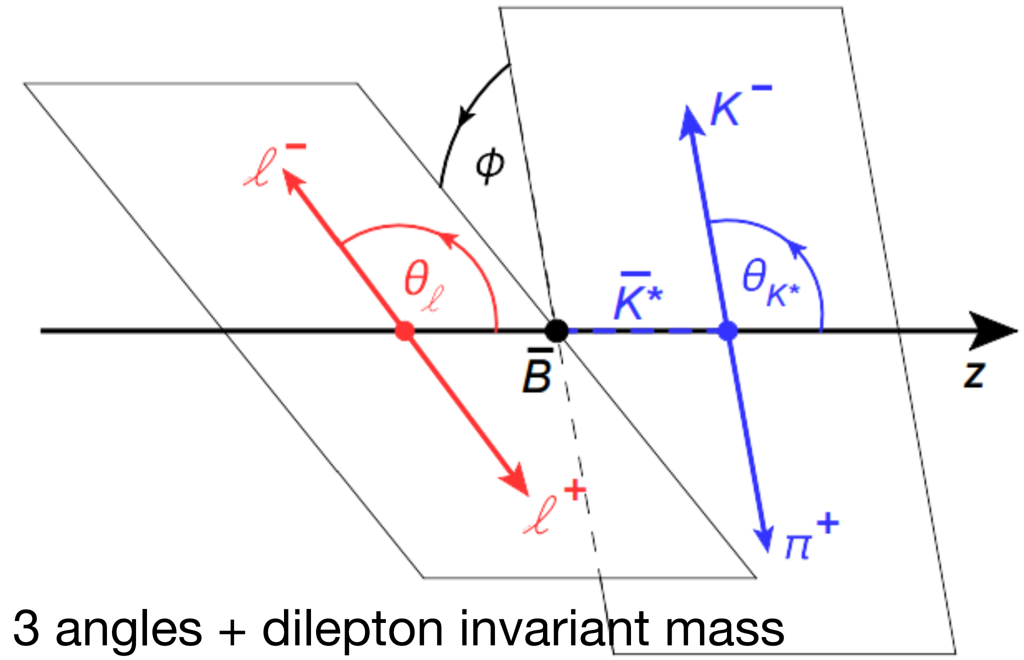
3 angles + dilepton invariant mass

$B \to K^*\mu\mu$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi}$$

width and angular observables are functions of Wilson coefficients C_i

$$\mathcal{A}_\lambda \propto (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} C_7 \mathcal{F}^T_\lambda(q^2) + \hat{\mathcal{H}}_\lambda(q^2)$$



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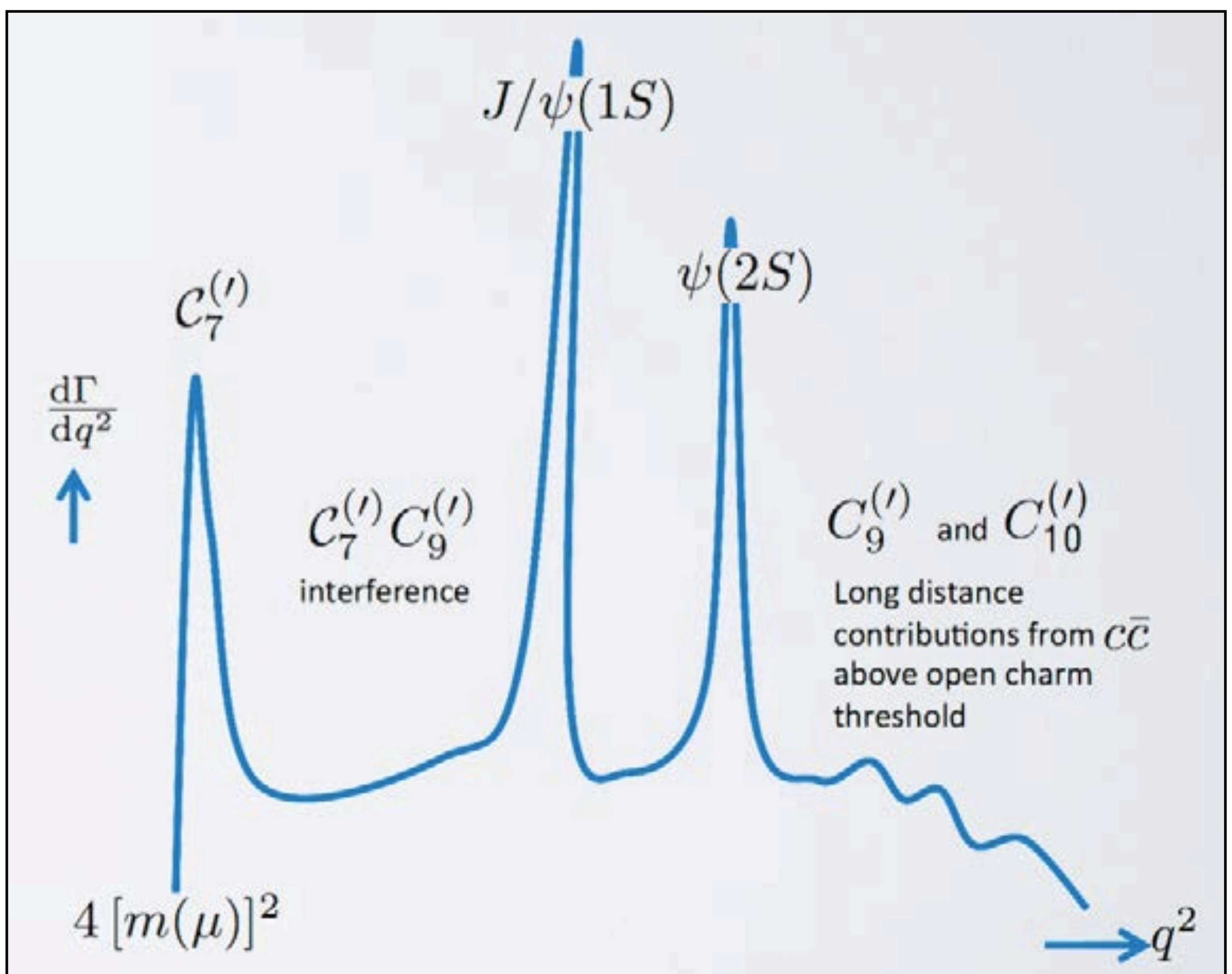
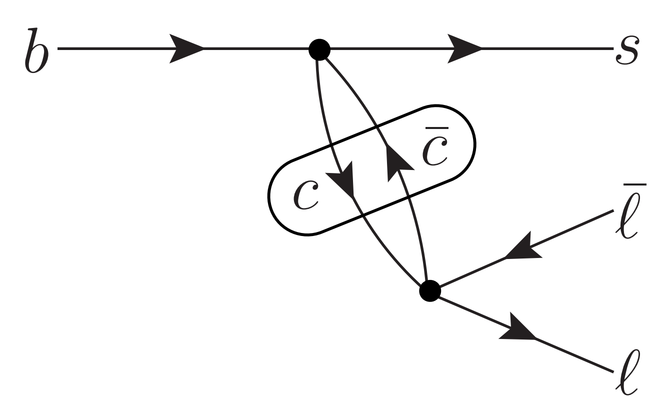


Long-distance contributions:

- Hadronic form-factors $\mathcal{F}_\lambda$: computed on lattice or light-cone sum rules
- Four-quark operators enter through charm loop: non-local term $\mathcal{H}_\lambda$



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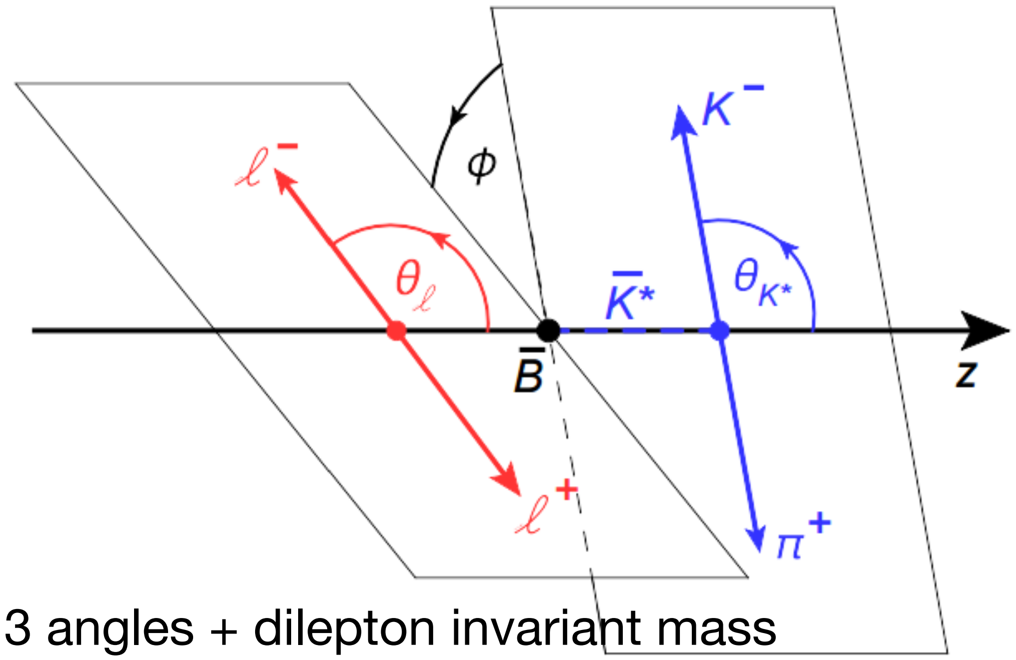

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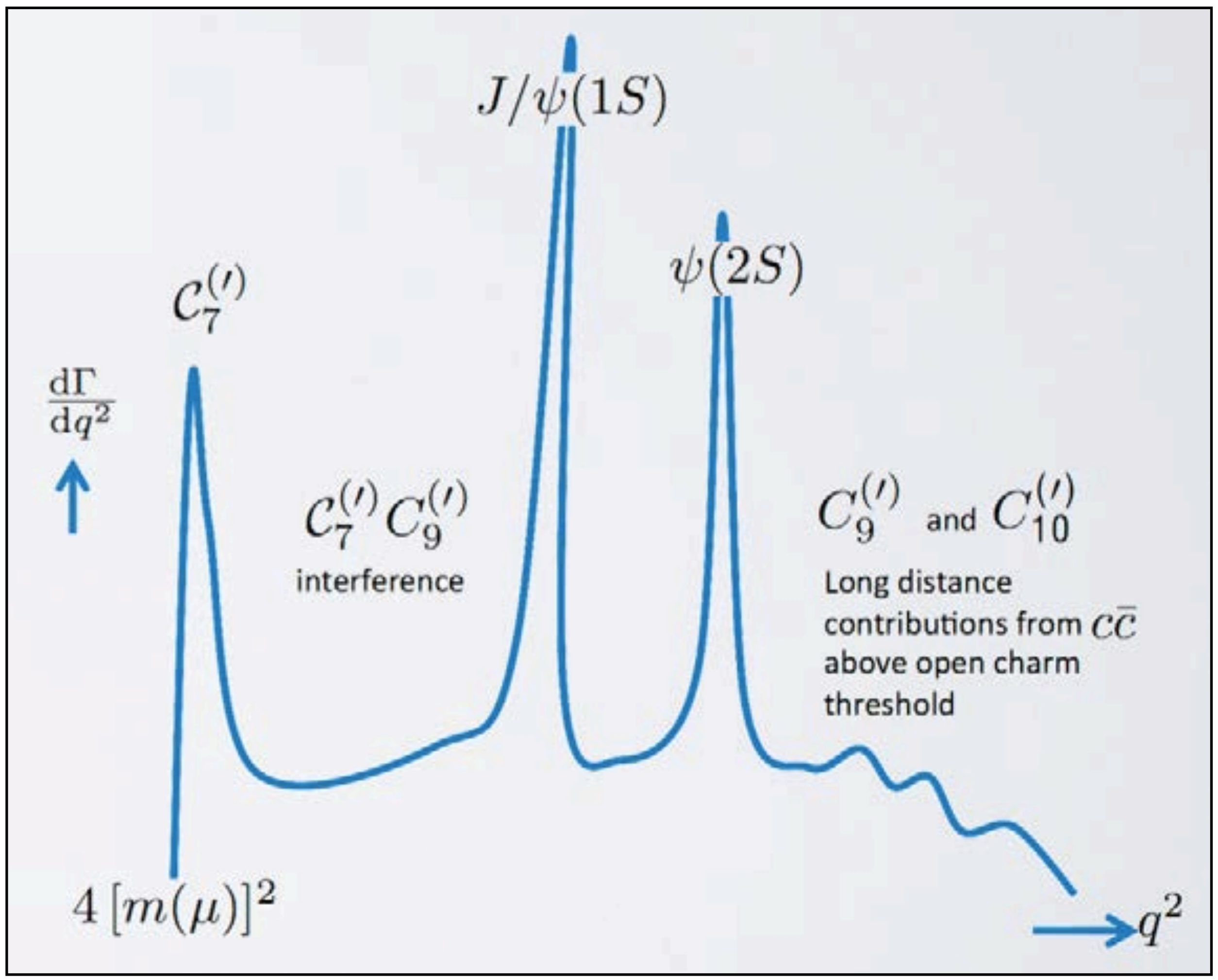

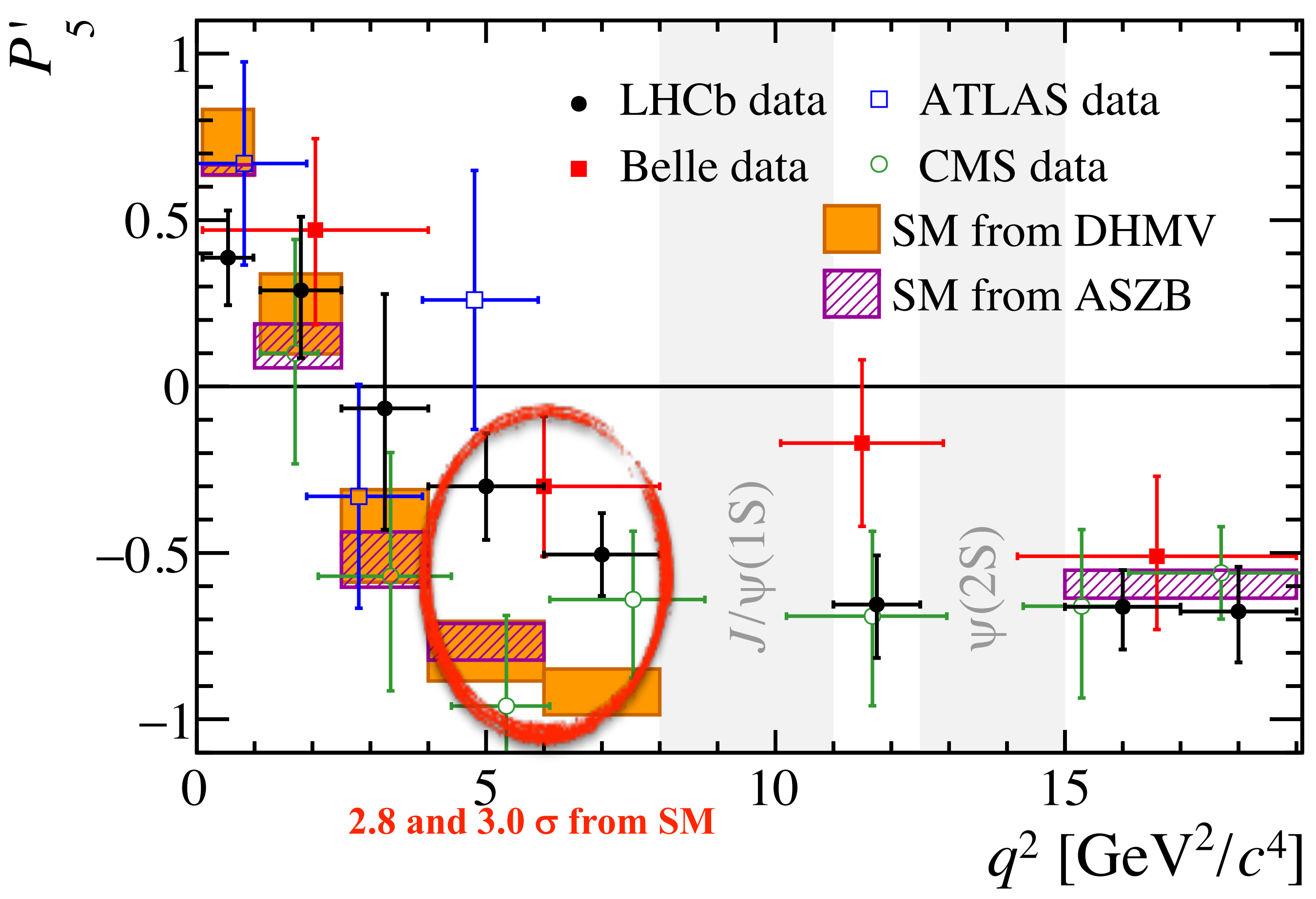

→ consistent with new physics in C_9

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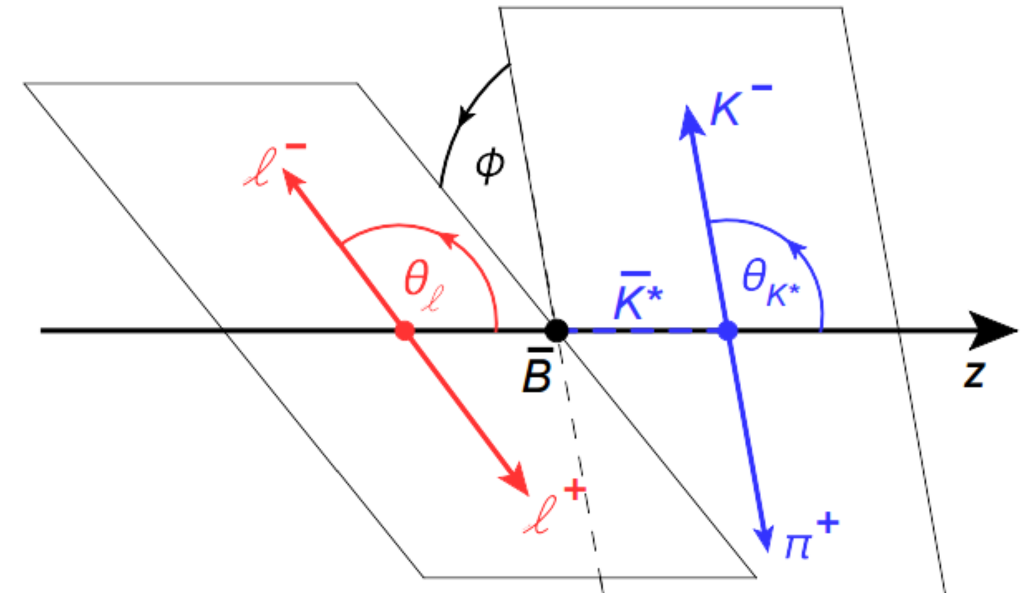

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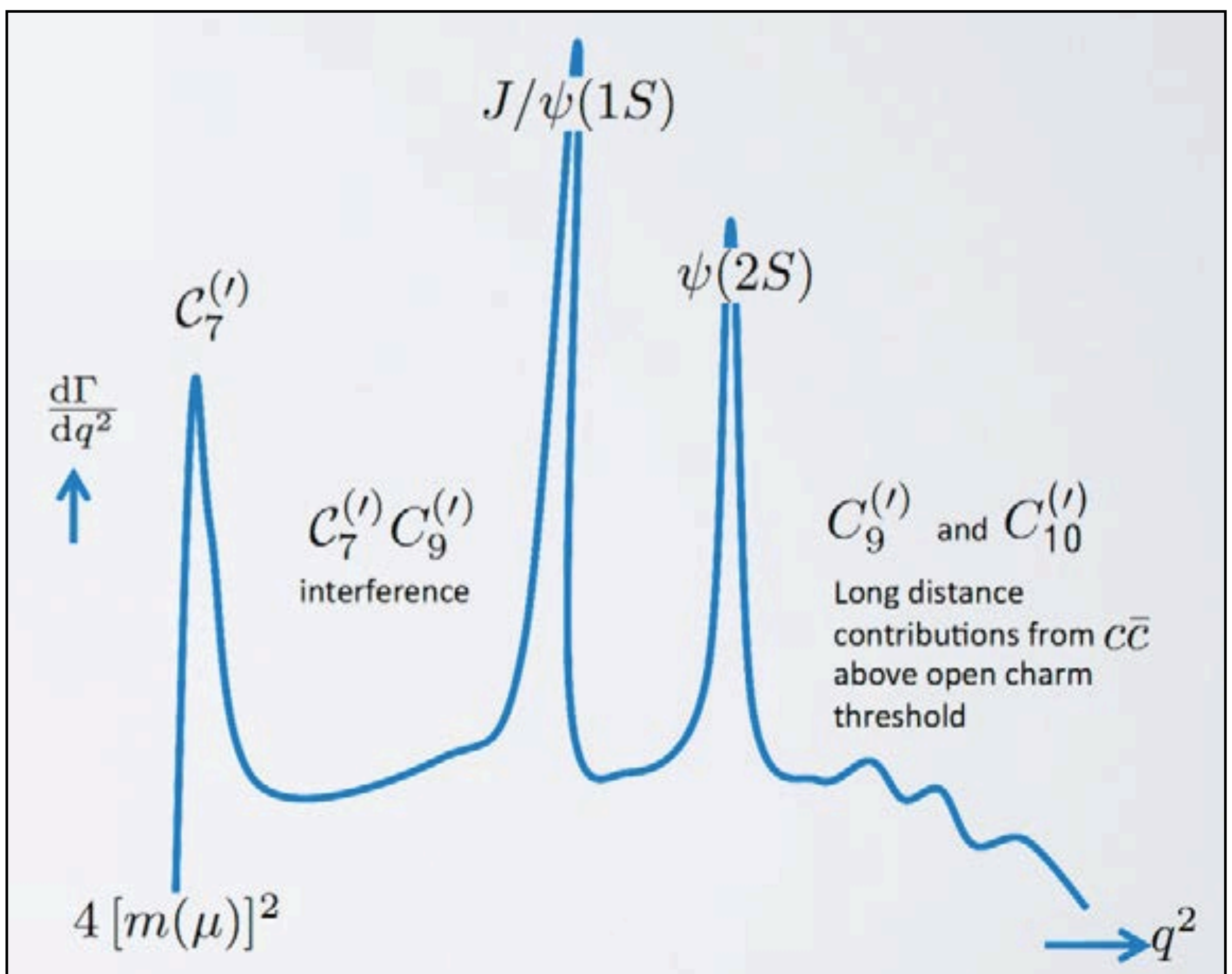

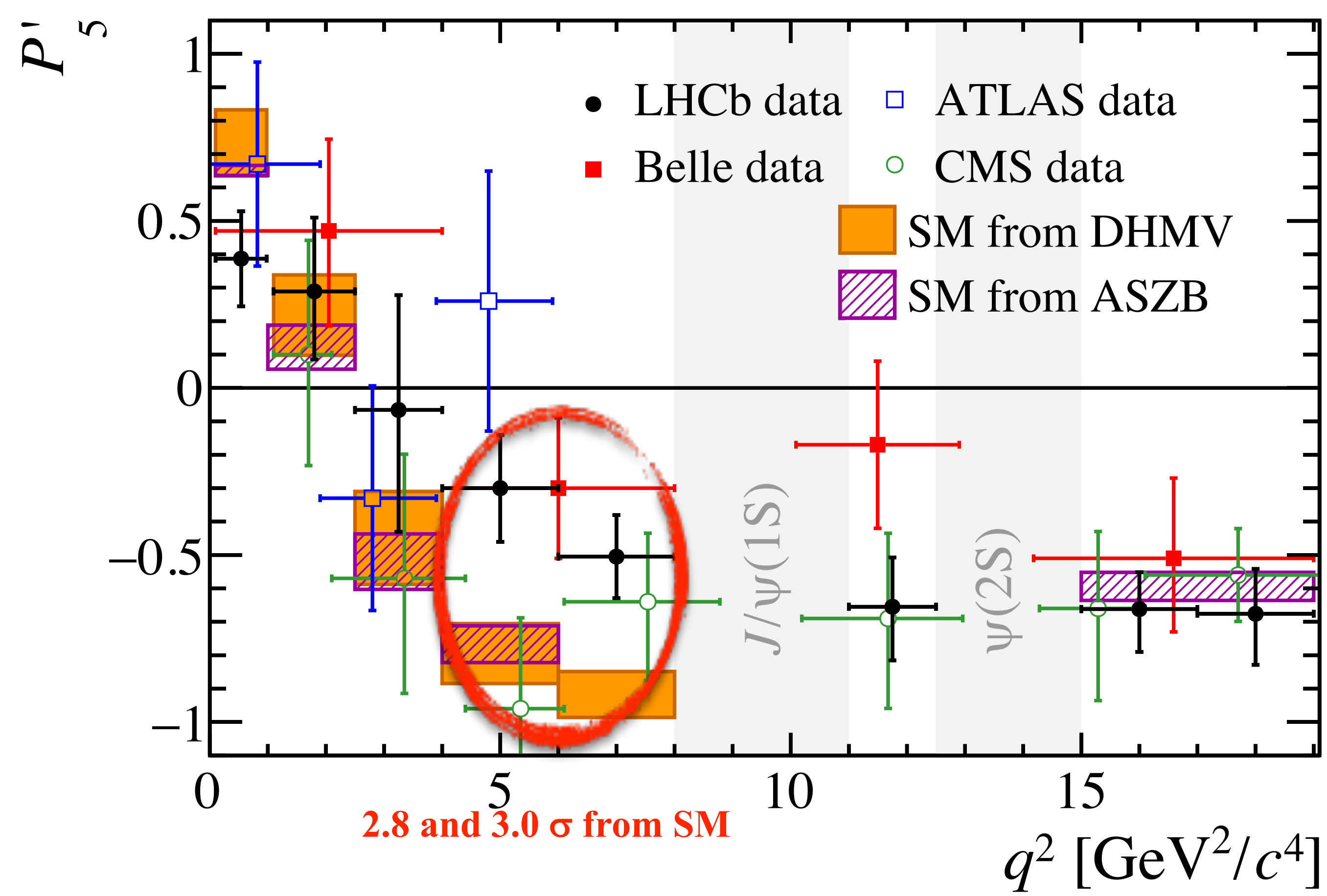

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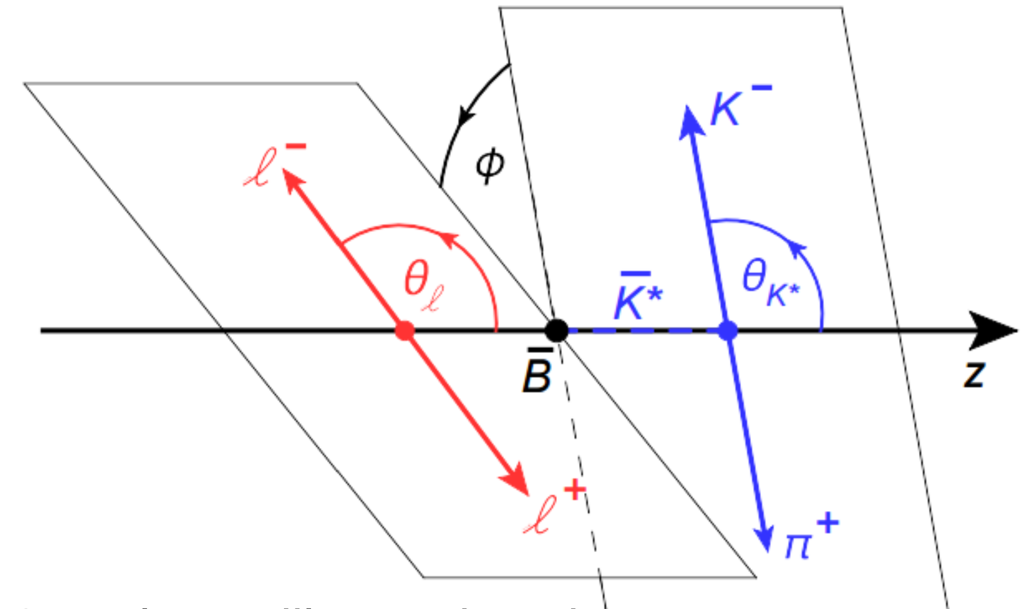

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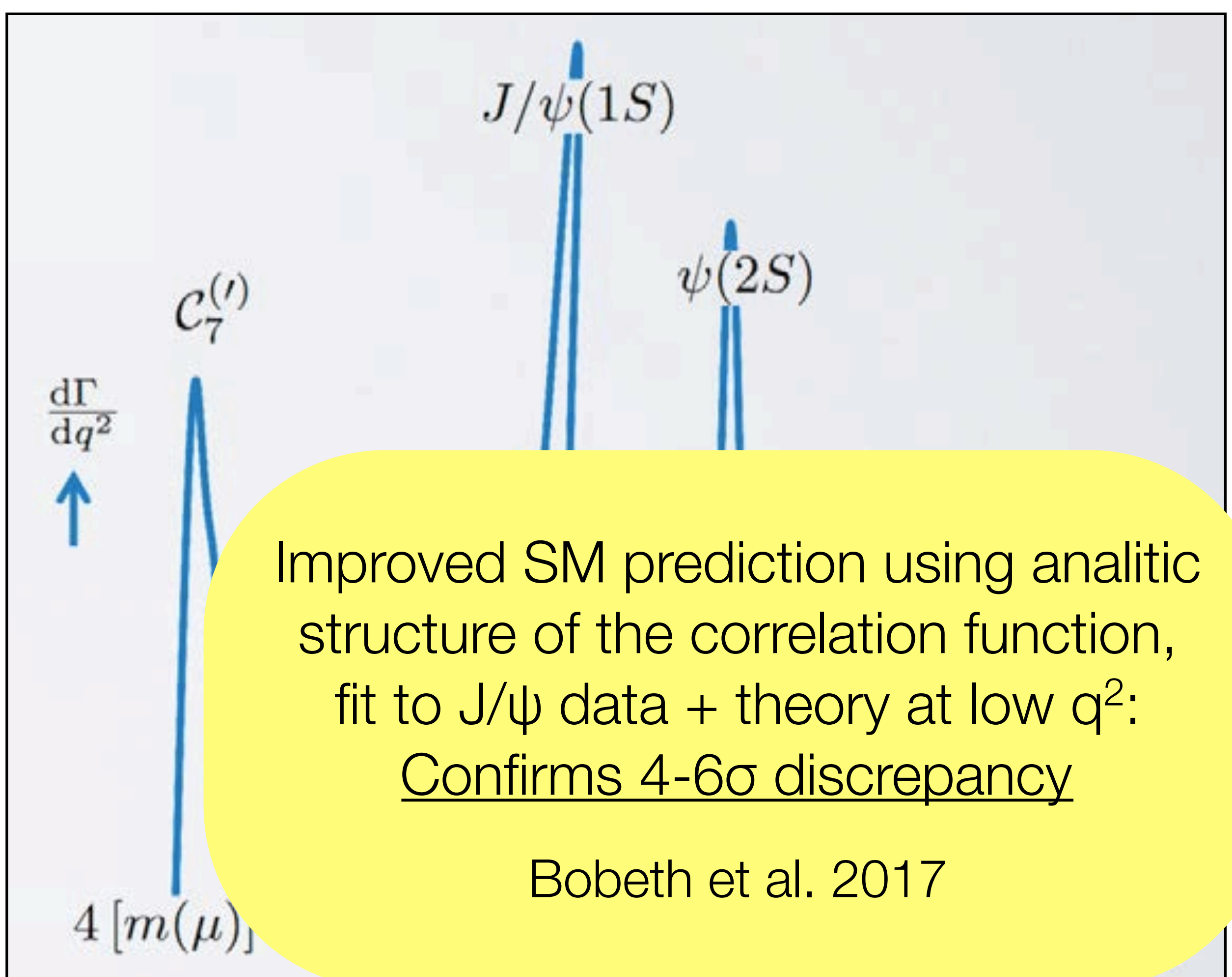
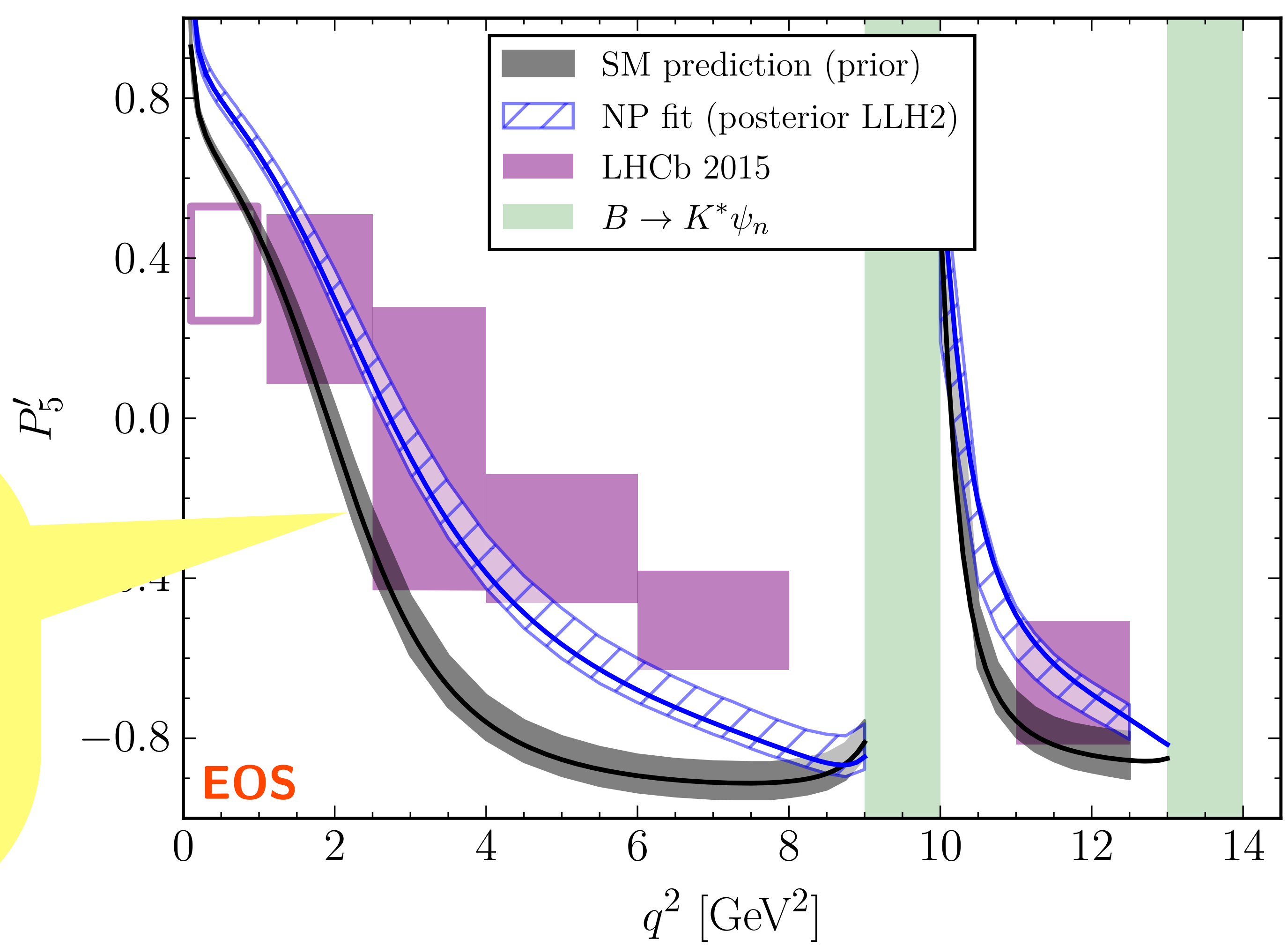
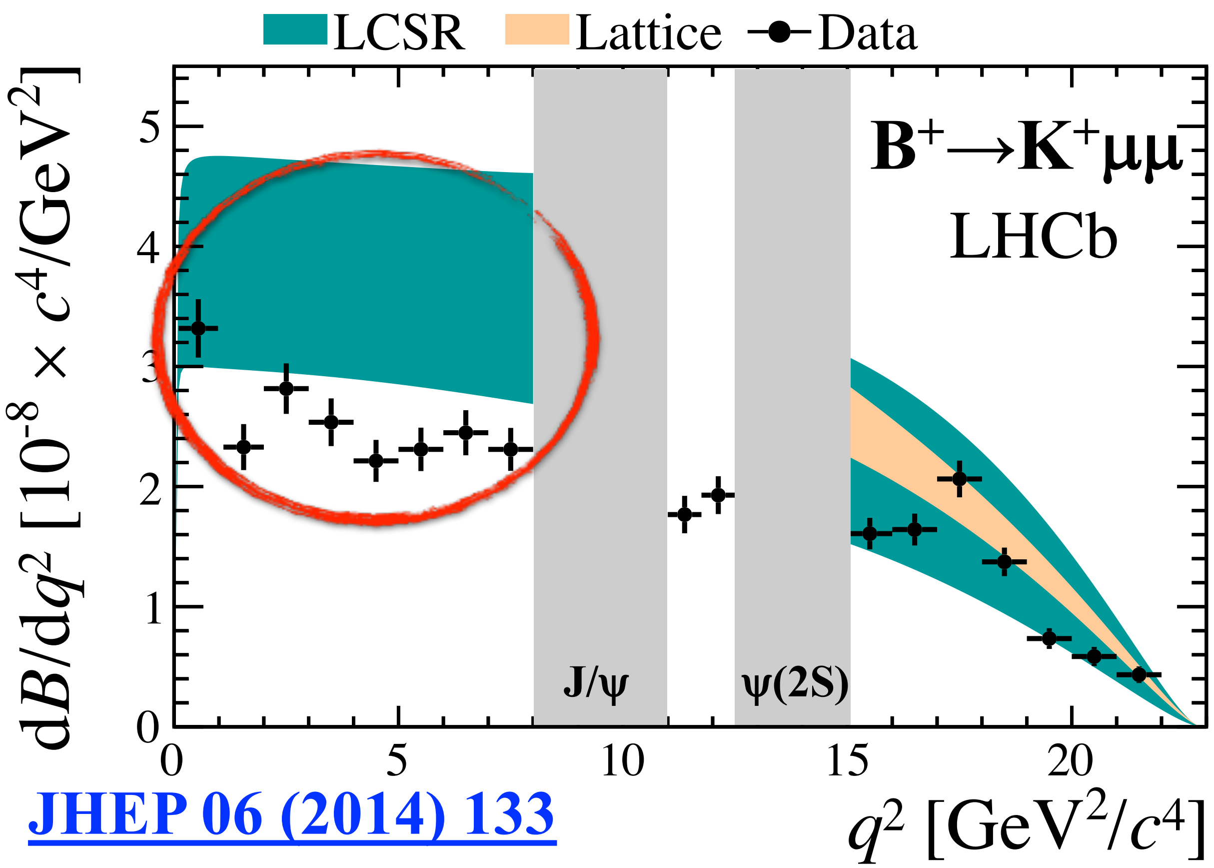




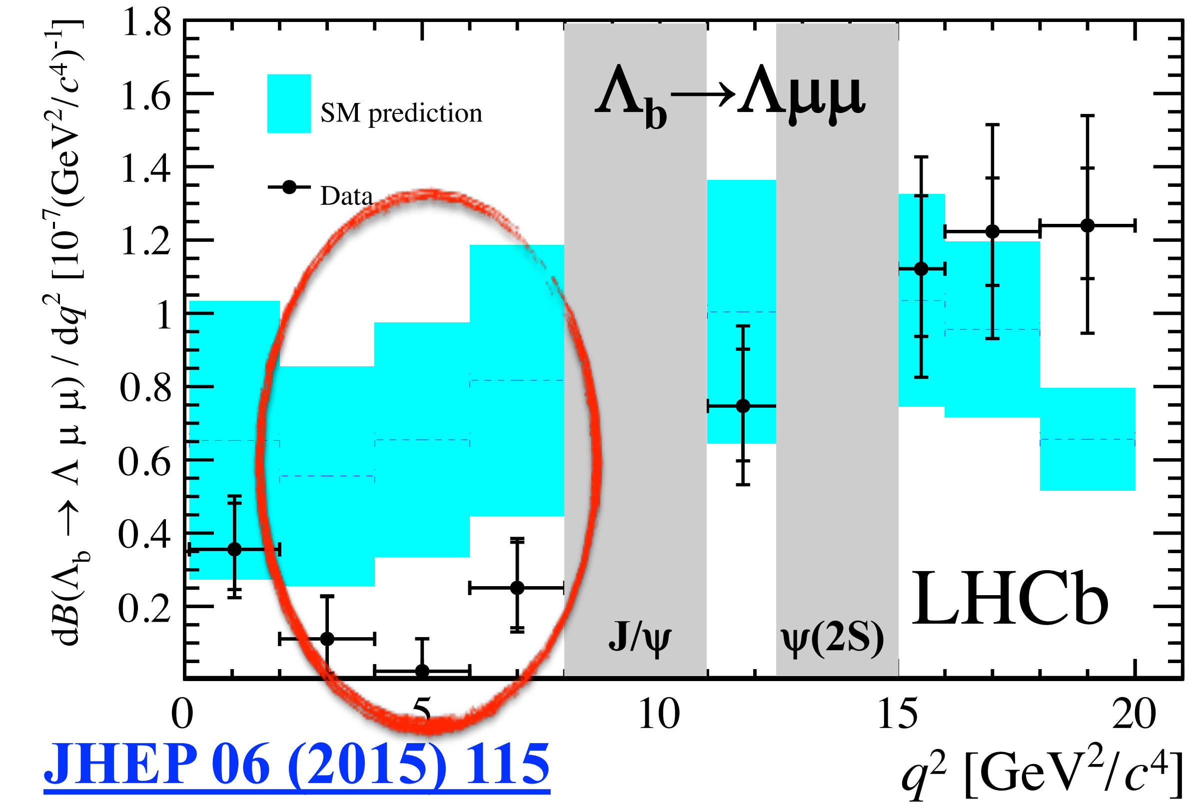
Improved SM prediction using analitic structure of the correlation function, fit to J/ψ data + theory at low q^2:
<u>Confirms 4-6σ discrepancy</u>

Bobeth et al. 2017

$b \rightarrow s\mu\mu$ branching ratios: a coherent picture



JHEP 06 (2014) 133



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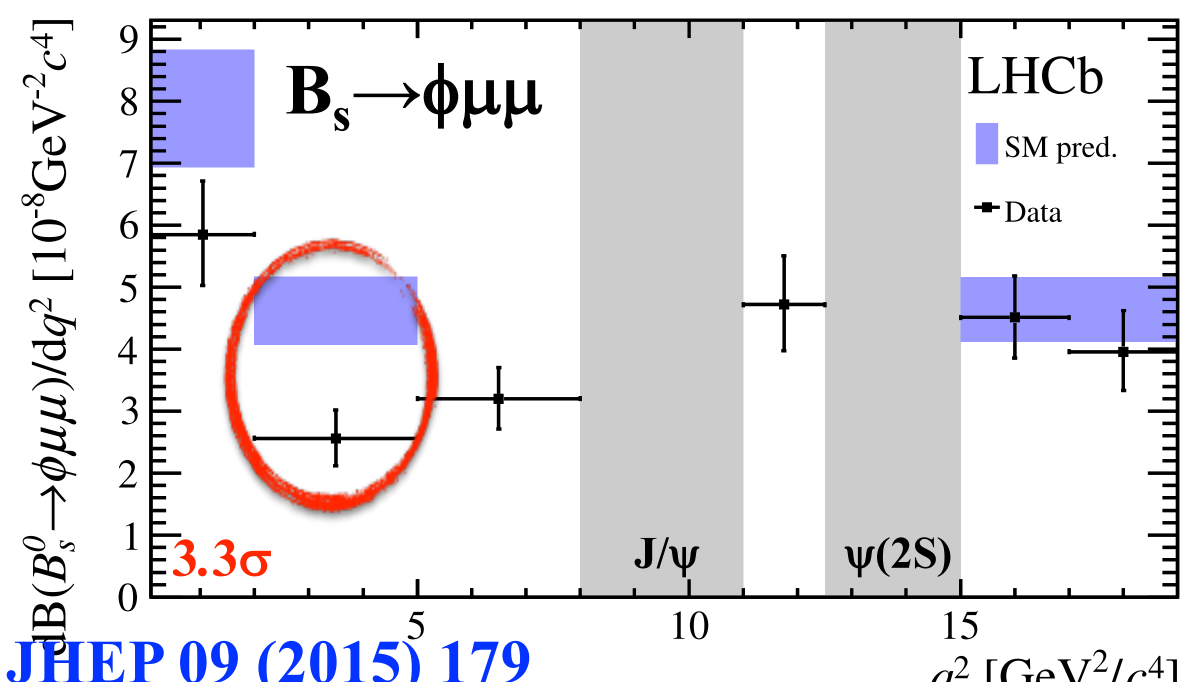

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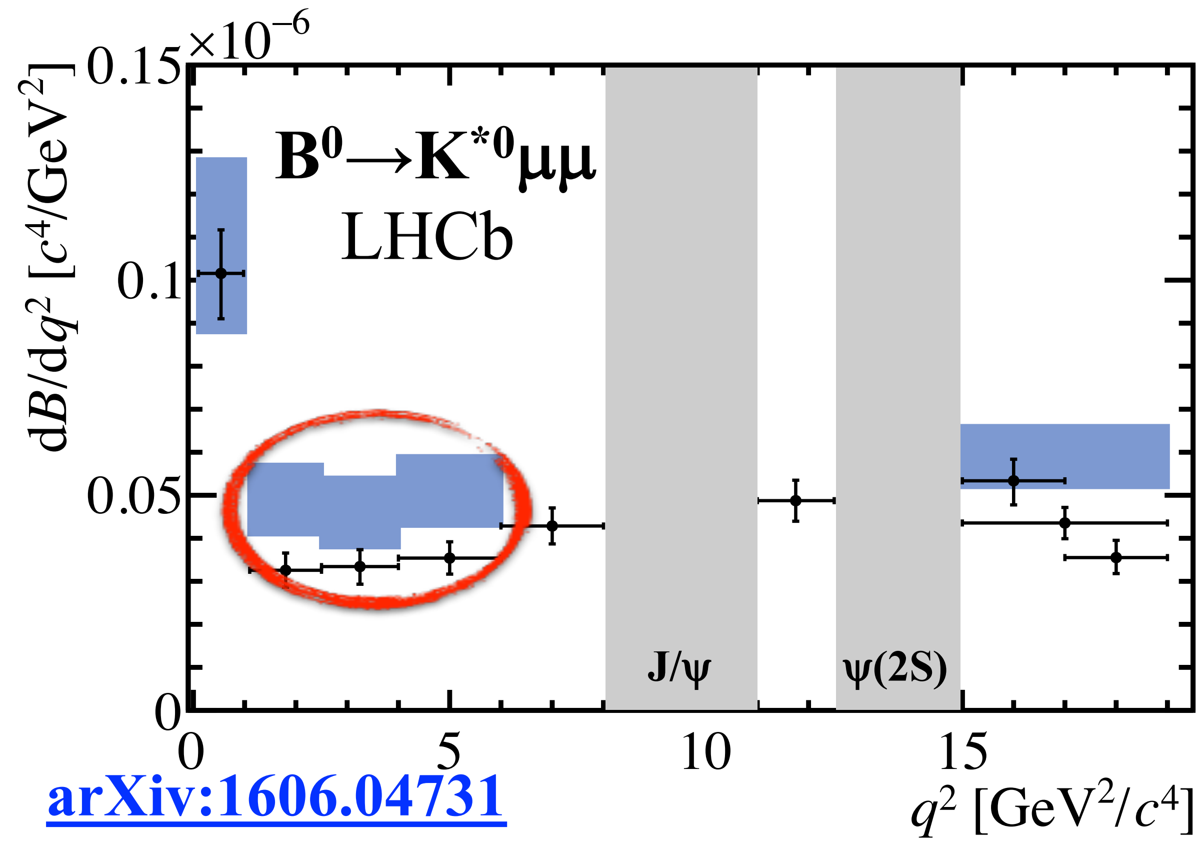
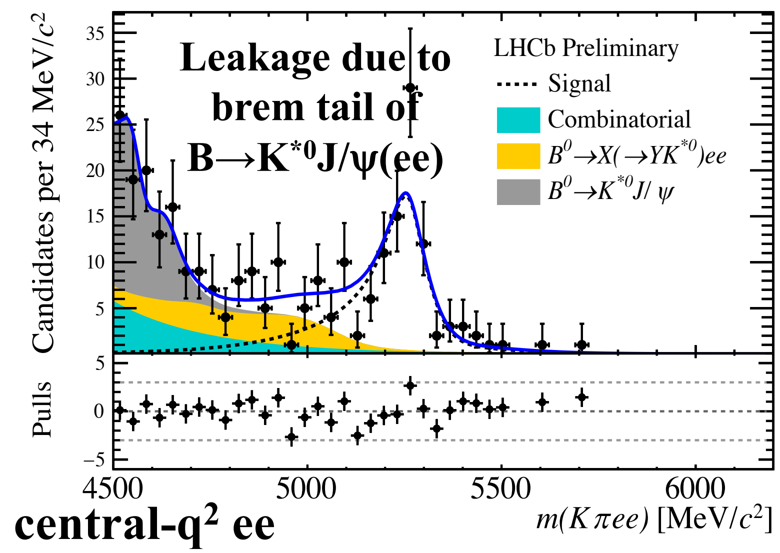


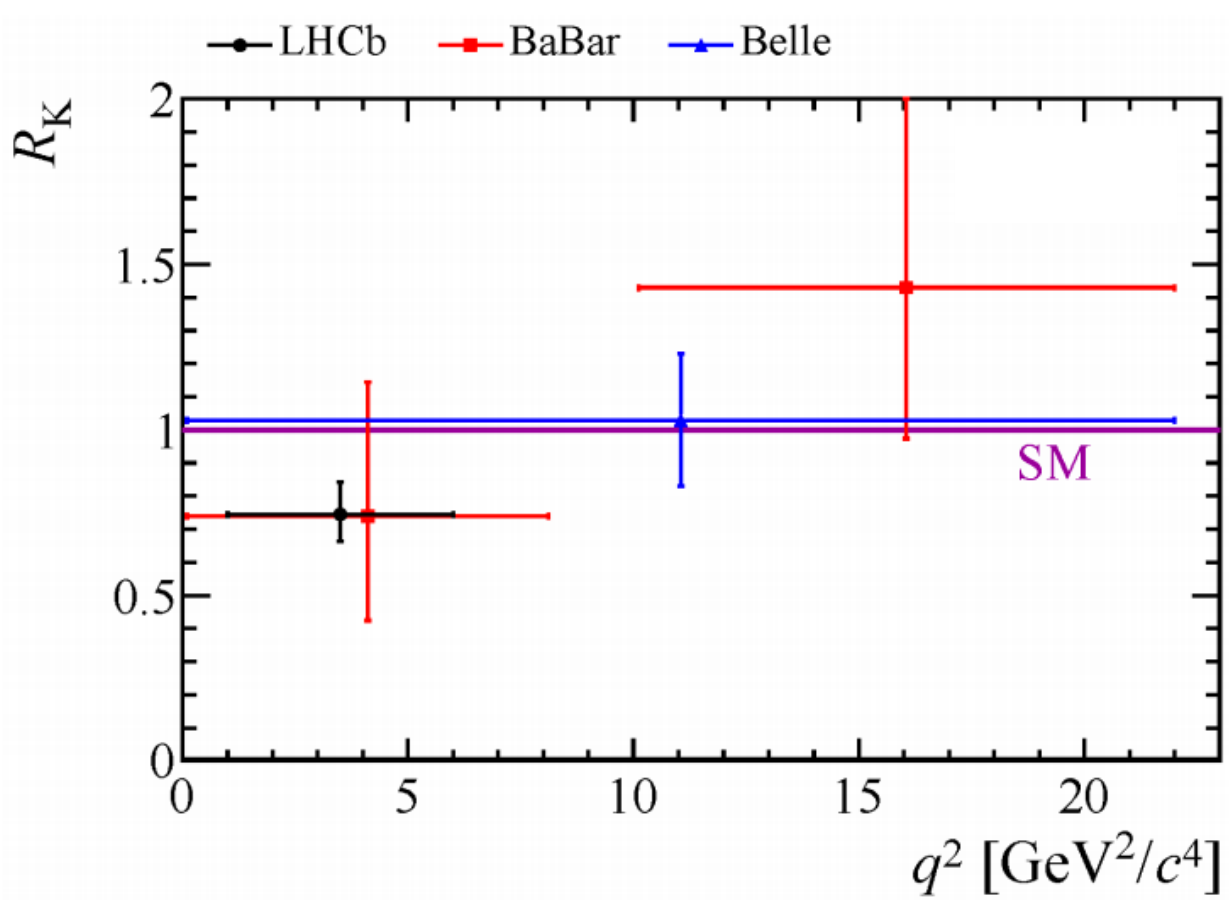
arXiv:1606.04731

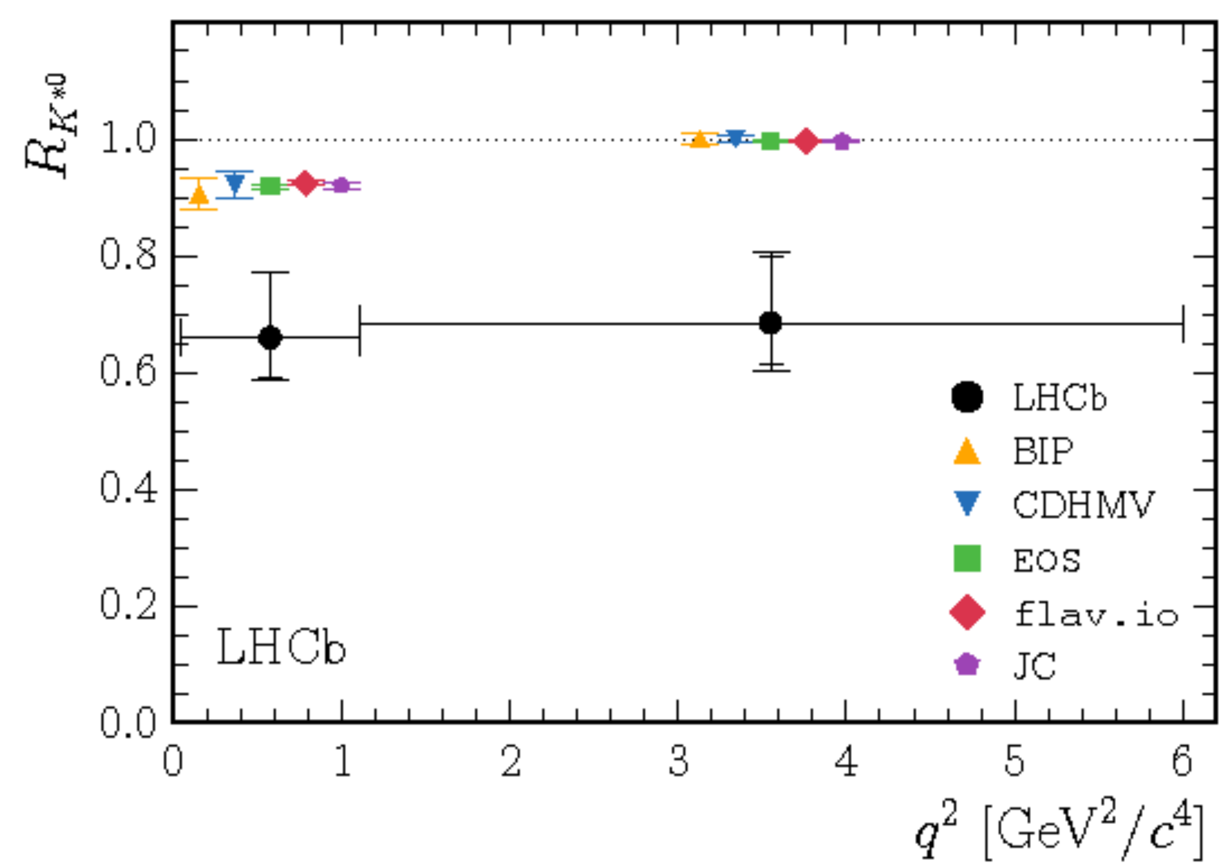
LFU ratios: R(*K*) & R(*K**)

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

- ✓ Very clean theory predictions: SM value is ~ 1, with error ~ 10^{-2}
- ✗ Electrons involved: experimentally difficult due to bremsstrahlung → large errors







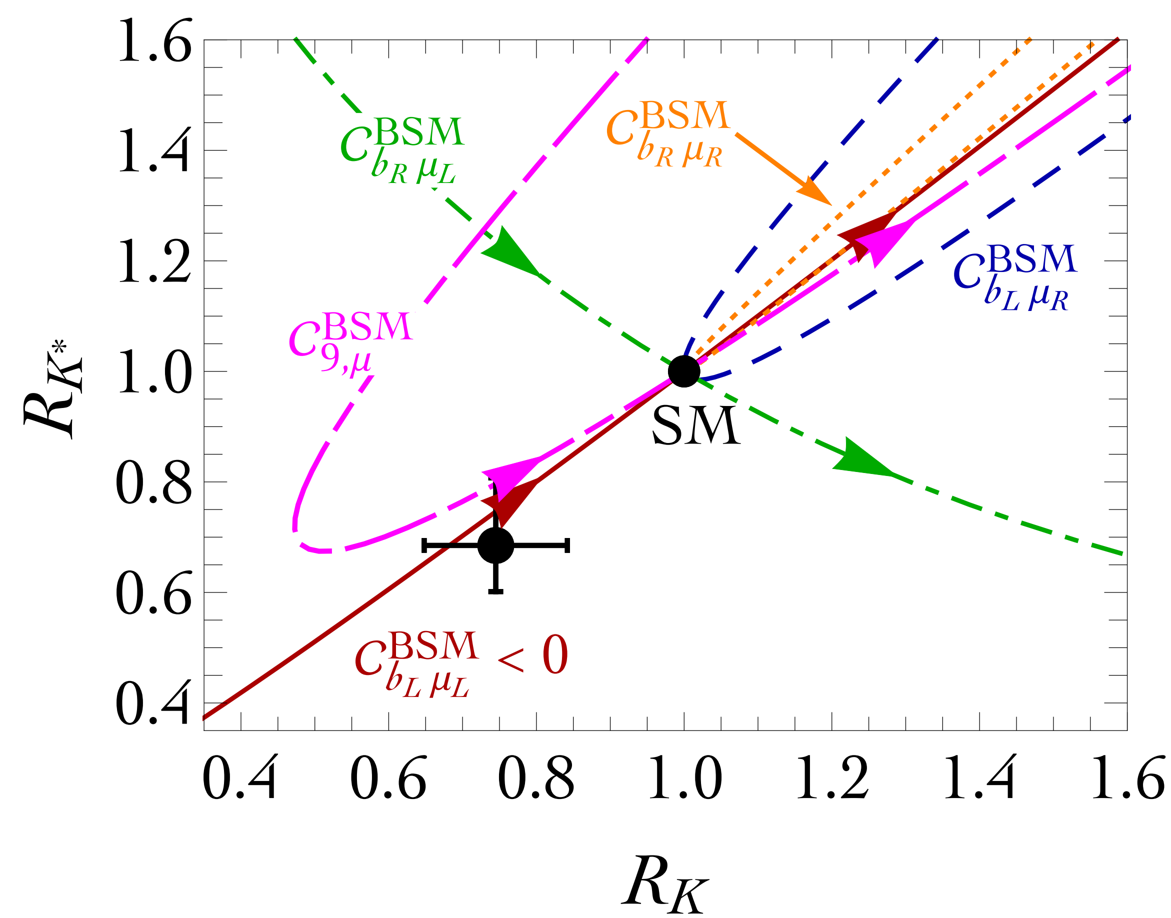
Combined significance of LFU ratios: 4.2σ

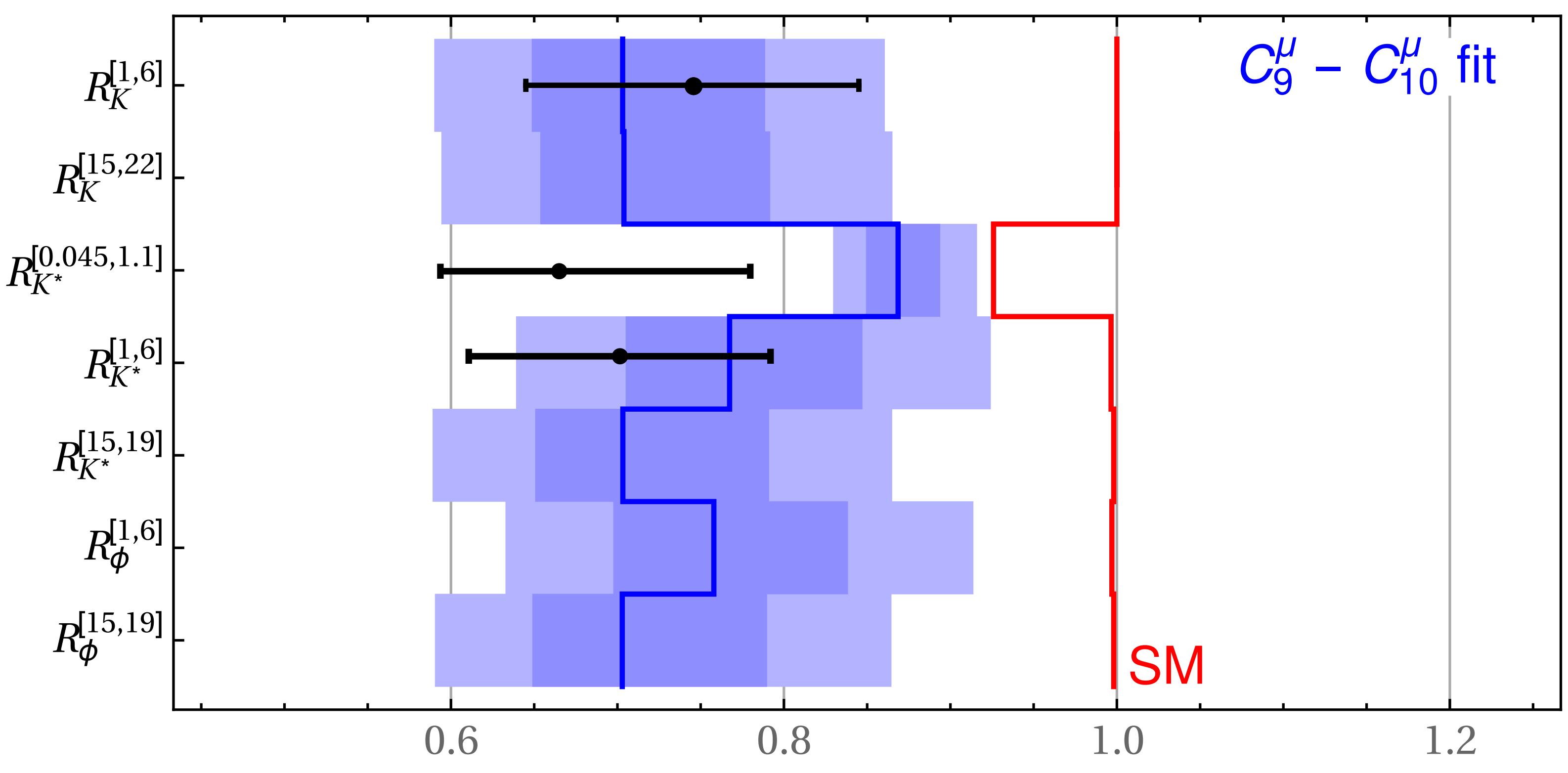
LFU ratios: R(*K*) & R(*K**)

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

- ✔ Combined measurement of R(K) and R(K*) determines the chirality of the interaction: LH current necessary to suppress both

- ✔ LFU ratios are consistent with predictions from a fit to $b \to s\mu\mu$ data only





Semi-leptonic b to s decays

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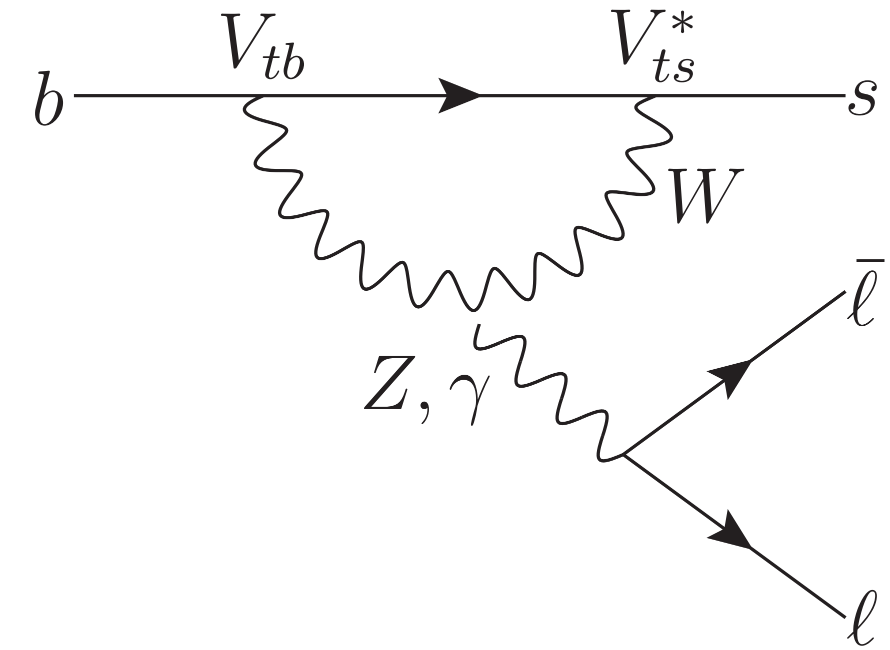
+ **CKM** suppressed



Semi-leptonic effective Lagrangian:

$$\mathcal{L} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V^*_{tb} V_{ts} \sum_i C_i \mathcal{O}_i + C'_i \mathcal{O}'_i$$

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- Angular distributions in $B \to K^* \mu\mu$
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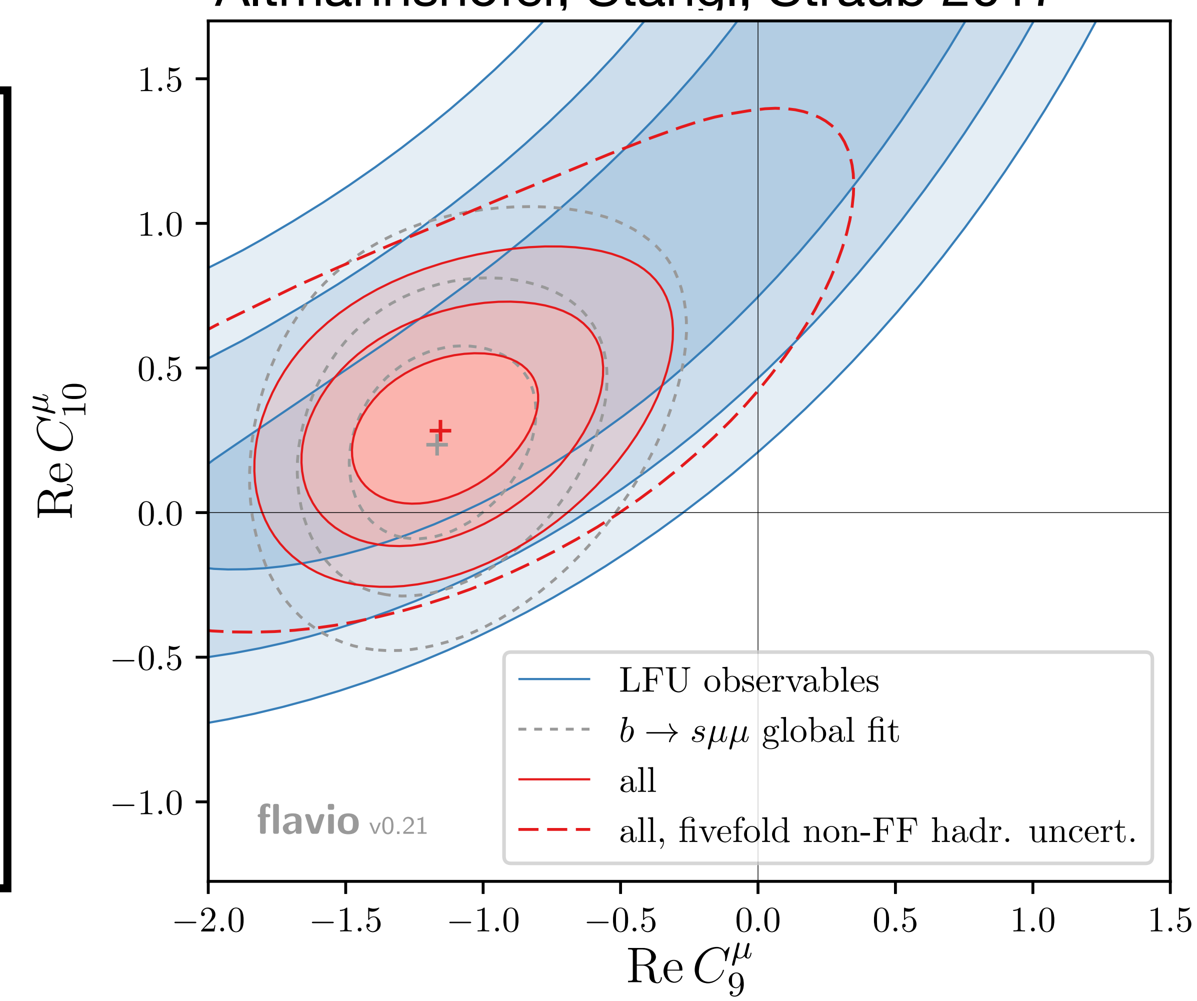
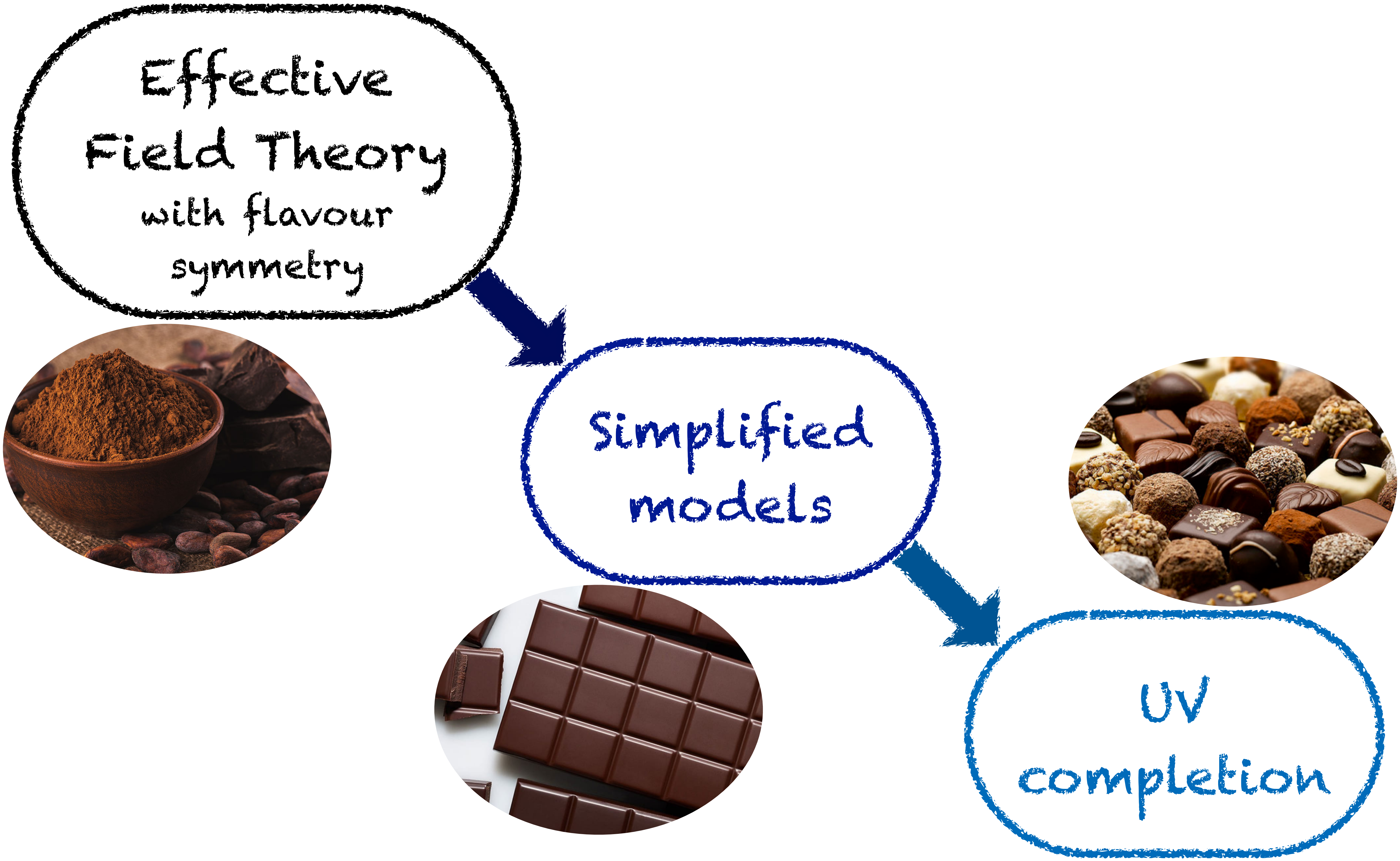
Globally ~ 5σ from SM

Altmannshofer, Stangl, Straub 2017



Is it possible to explain the whole set of anomalies in a coherent picture?



Lepton Flavour Universality

- (Lepton) flavour universality is an accidental property of the gauge Lagrangian, not a fundamental symmetry of nature

$$\mathcal{L}_{\text{gauge}} = i \sum_{j=1}^{3} \sum_{q,u,d,\ell,e} \bar{\psi}_j \not{D} \psi_j$$

- The only non-gauge interaction in the SM violates LFU maximally

$$\mathcal{L}_{\text{Yuk}} = \bar{q}_L Y_u u_R H^* + \bar{d}_L Y_d d_R H + \bar{\ell}_L Y_e e_R H \qquad Y_{u,d,e} \approx \text{diag}(0,0,1)$$

- LFU approximately satisfied in SM processes because Yukawa couplings are small

$$y_\mu \approx 10^{-3} \qquad y_\tau \approx 10^{-2}$$

➡ natural to expect LFU and flavour violations in BSM physics

What do we know?

1. Anomalies seen only in semi-leptonic processes: **quarks** x **leptons**

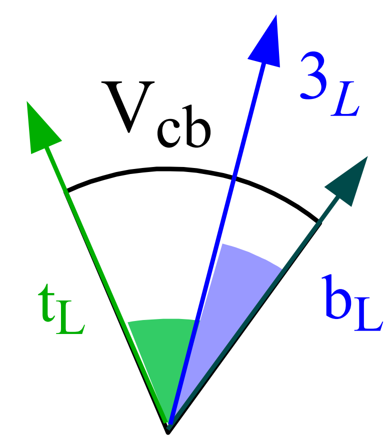
   nothing observed in pure **quark** or **lepton** processes

2. Large effect in **3rd generation**: b quarks, $\tau\nu$ competes with SM tree-level

   smaller non-zero effect in **2nd generation**: $\mu\mu$ competes with SM FCNC,

   no effect in 1st generation

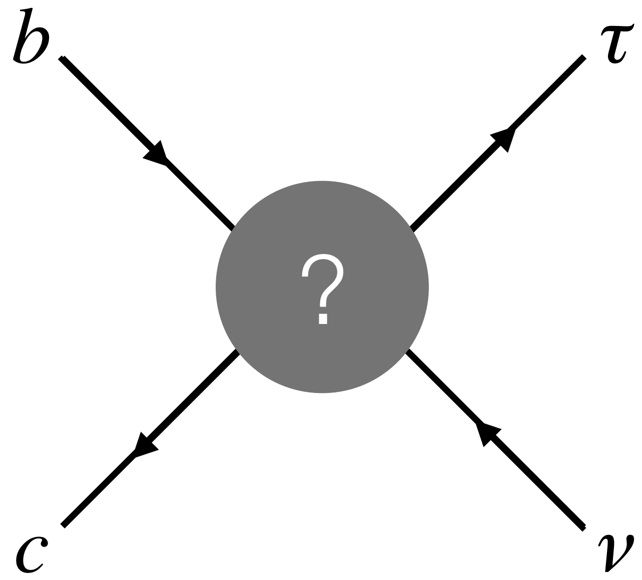
3. **Flavour alignment** with down-quark mass basis (to avoid large FCNC)



4. **Left-handed** four-fermion interactions

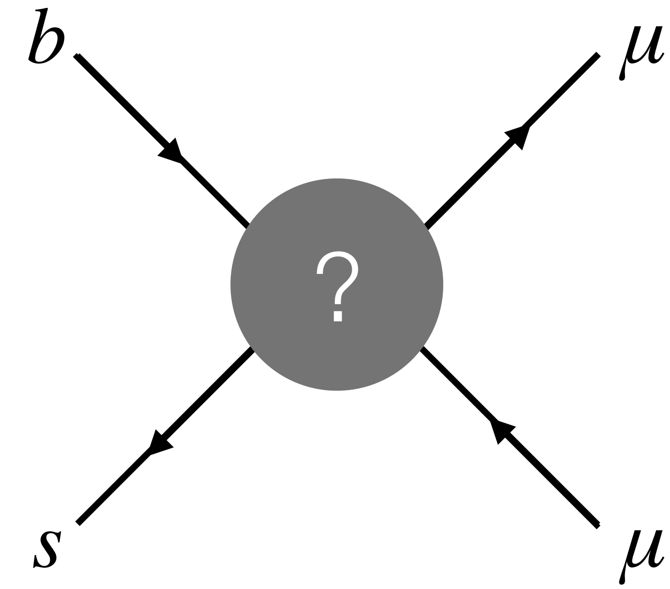
   RH and scalar currents disfavoured: can be present, but do not fit the anomalies (both in charged and neutral current), Higgs-current small or not relevant

Simultaneous explanations



$$\frac{1}{\Lambda_D^2}(\bar{b}_L\gamma_\mu c_L)(\bar{\tau}_L\gamma^\mu\nu_\tau)$$

$$\Lambda_D = 3.4\,\mathrm{TeV}$$



$$\frac{1}{\Lambda_K^2}(\bar{b}_L\gamma_\mu s_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

$$\Lambda_K = 31\,\mathrm{TeV}$$

- I. “vertical” structure: the two operators can be related by $SU(2)_L$

$$(\bar{q}_L\gamma_\mu\sigma^a q_L)(\bar{\ell}_L\gamma^\mu\sigma^a\ell_L)$$

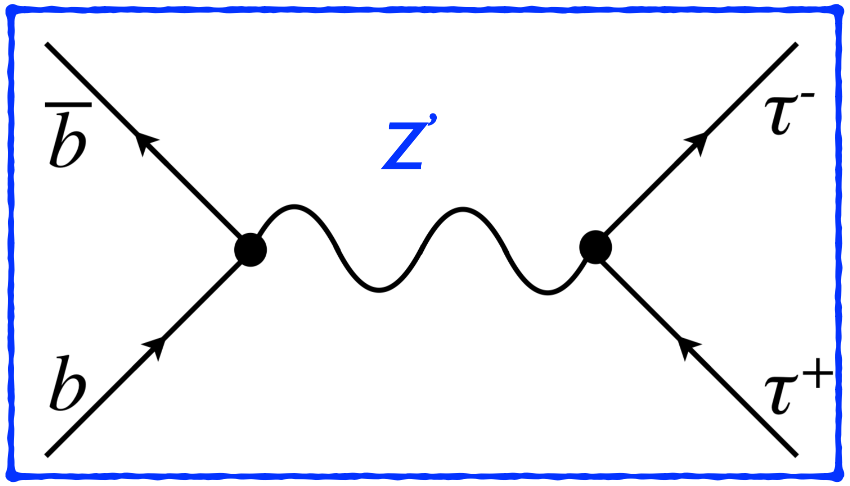
- II. “horizontal” structure: NP structure reminds of the Yukawa hierarchy

$$\Lambda_D \ll \Lambda_K\,, \qquad \lambda_{\tau\tau} \gg \lambda_{\mu\mu}$$

Problems

- **Direct searches:** large signal at high-pT

  $\Lambda_D \simeq 3.4\,\mathrm{TeV}$

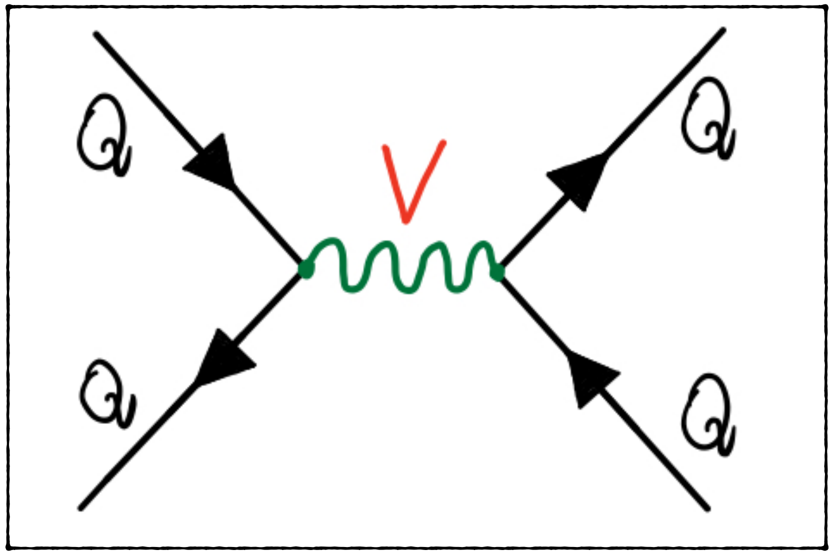


- **Flavour observables:**
  - other semi-leptonic observables

    model independent

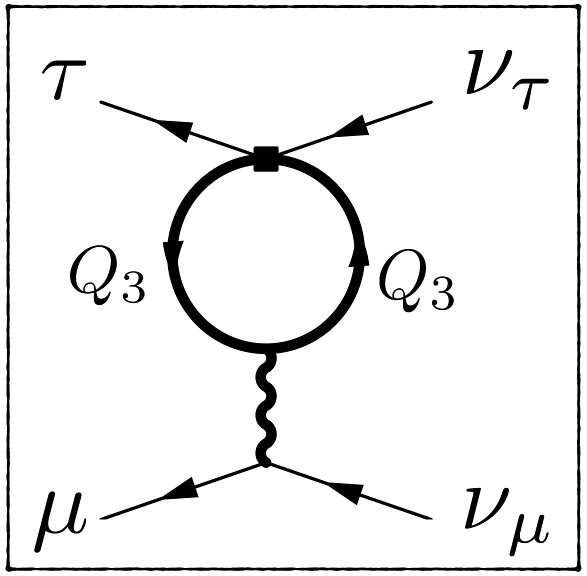
  - meson mixing, lepton flavour violation

    depend on the model, generally present



- **ElectroWeak precision tests:**
  W, Z couplings, τ decays

  generated radiatively at one-loop



Constructing the Effective Field Theory

1. Left-handed four-fermion interactions: two possible operators in SM-EFT

$$C_S(\bar{q}^i_L \gamma_\mu q^j_L)(\bar{\ell}^\alpha_L \gamma^\mu \ell^\beta_L)$$

— SU(2) singlet —

$$C_T(\bar{q}^i_L \gamma_\mu \sigma^a q^j_L)(\bar{\ell}^\alpha_L \gamma^\mu \sigma^a \ell^\beta_L)$$

— SU(2) triplet —

Alonso, Camalich, Grinstein 2015

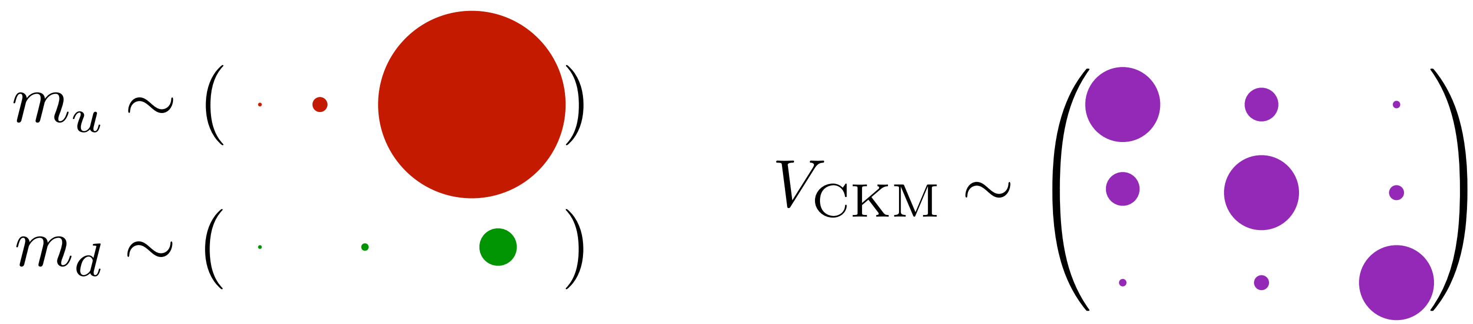
3. Flavour structure:

- Large effect in 3rd generation
- Smaller effect in 2nd generation
- Flavour alignment with CKM

→ connection with Yukawa coupling hierarchies: U(2) symmetry

U(2) flavour symmetry

SM Yukawa couplings exhibit an approximate $U(2)^3$ flavour symmetry:



$$U(2)_{q_L} \times U(2)_{u_R} \times U(2)_{d_R}$$

$$\psi_i = (\underbrace{\psi_1 \;\; \psi_2}_{\mathbf{2}} \; \underbrace{\psi_3}_{\mathbf{1}})$$

1. Good approximation of SM spectrum: $m_{light} \sim 0$, $V_{CKM} \sim 1$

Breaking pattern: $Y_{u,d} \approx \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \longrightarrow Y_{u,d} \approx \begin{pmatrix} \Delta & V_q \\ 0 & 1 \end{pmatrix}$

$$\Delta \sim (\mathbf{2}, \mathbf{2}, \mathbf{1}) \qquad V_q \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})$$

Barbieri, B, Sala, Straub, 2012

2. The *assumption* of a single spurion V_q connecting the 3rd generation with the other two ensures MFV-like FCNC protection
3. The most general symmetry that gives “CKM-like” interactions in a model-independent way

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$$C_S(\bar{q}_L^i \gamma_\mu q_L^j)(\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta) \qquad C_T(\bar{q}_L^i \gamma_\mu \sigma^a q_L^j)(\bar{\ell}_L^\alpha \gamma^\mu \sigma^a \ell_L^\beta)$$

— SU(2) singlet — — SU(2) triplet —

2. Flavour structure: minimally broken $U(2)_q$ x $U(2)_\ell$ symmetry

$U(2)_q$ x $U(2)_\ell$ breaking pattern:

$V_q = (V_{td}^*, V_{ts}^*)$ CKM structure for quarks

$V_\ell \approx (0, V_{\tau\mu})$ strong LFV constraints for electrons

no flavour-conserving coupling to light generations

$$Q_L^{(3)} \sim \begin{pmatrix} V_{ib}^* u_L^i \\ b_L \end{pmatrix}$$ + small terms (~ V_{CKM})

$$\lambda_{ij}^q \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & V_{ts} \\ \cdot & V_{ts}^* & 1 \end{pmatrix} \qquad \lambda_{\alpha\beta}^\ell \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & |V_{\tau\mu}|^2 & V_{\tau\mu} \\ \cdot & V_{\tau\mu}^* & 1 \end{pmatrix}$$

small small

B, Greljo, Isidori, Marzocca, 2017

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B, Greljo, Isidori, Marzocca, 2017

Effective Field Theory

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T(\bar{q}^i_L\gamma_\mu\sigma^a q^j_L)(\bar{\ell}^\alpha_L\gamma^\mu\sigma^a\ell^\beta_L) + C_S(\bar{q}^i_L\gamma_\mu q^j_L)(\bar{\ell}^\alpha_L\gamma^\mu\ell^\beta_L)\right]$$

B, Greljo, Isidori, Marzocca, 2017

LFU ratios in ***b* → *c*** charged currents:

- **τ**: $R^{\tau\ell}_{D^{(*)}} \simeq 1 + 2C_T\left(1 + \frac{\lambda^q_{bs}}{V_{cb}}\right) = 1.237 \pm 0.053$
- **μ vs. *e***: $R^{\mu e}_{D^{(*)}} \simeq 1 + 2C_T\left(1 + \frac{\lambda^q_{bs}}{V_{cb}}\right)\lambda_{\mu\mu} < 0.02$ ➡ $\lambda_{\mu\mu} \lesssim 0.1$

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B, Greljo, Isidori, Marzocca, 2017

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Neutral currents: ***b* → *s*$\nu_\tau\nu_\tau$** transitions not suppressed by lepton spurion

$$\Delta C_\nu \simeq \frac{\pi}{\alpha V^*_{ts}V_{tb}}\lambda^q_{sb}(C_S - C_T)$$

strong bounds from $B \to K^*\nu\nu$

➡ $C_T \sim C_S$

***b* → *s*$\tau\tau$** ~ $C_T + C_S$ is large (100 x SM), weak experimental constraints

Effective Field Theory

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T(\bar{q}^i_L\gamma_\mu\sigma^a q^j_L)(\bar{\ell}^\alpha_L\gamma^\mu\sigma^a\ell^\beta_L) + C_S(\bar{q}^i_L\gamma_\mu q^j_L)(\bar{\ell}^\alpha_L\gamma^\mu\ell^\beta_L)\right]$$

B, Greljo, Isidori, Marzocca, 2017

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Neutral currents: ***b* → *sν***

$$\Delta C_\nu \simeq \frac{\pi}{\alpha V^*_{ts}V_{tb}}\lambda^q_{sb}(C_S - C_T)$$

strong bounds from $B \to K^*\nu\nu$

→ $C_T \sim C_S$

b* → *sττ ~ $C_T + C_S$ is large (100 x SM), weak experimental constraints

b* → *sμμ is an independent quantity:
fixes the size of $\lambda_{\mu\mu}$

$$\Delta C_{9,\mu} = -\frac{\pi}{\alpha V^*_{ts}V_{tb}}\lambda^q_{sb}\lambda_{\mu\mu}(C_T + C_S)$$

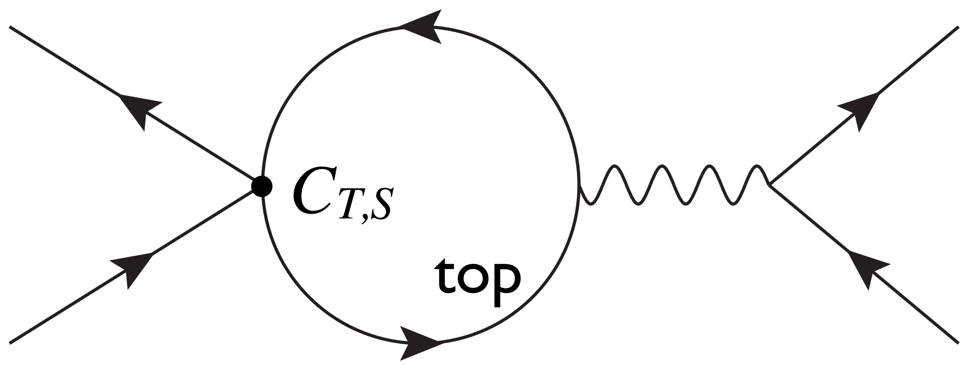
Radiative corrections

Purely leptonic operators generated at the EW scale by RG evolution

Feruglio et al. 2015

- **LFU in τ decays** $\tau \to \mu\nu\nu$ vs. $\tau \to e\nu\nu$ (effectively modification of W couplings)

$$\delta g_\tau^W = -0.084\, C_T = (9.7 \pm 9.8) \times 10^{-4}$$



- ***Z$\tau\tau$* couplings**

$$\delta g_{\tau_L}^Z = -0.047 C_S + 0.038 C_T = -0.0002 \pm 0.0006$$

- ***Z$\nu\nu$* couplings** (number of neutrinos)

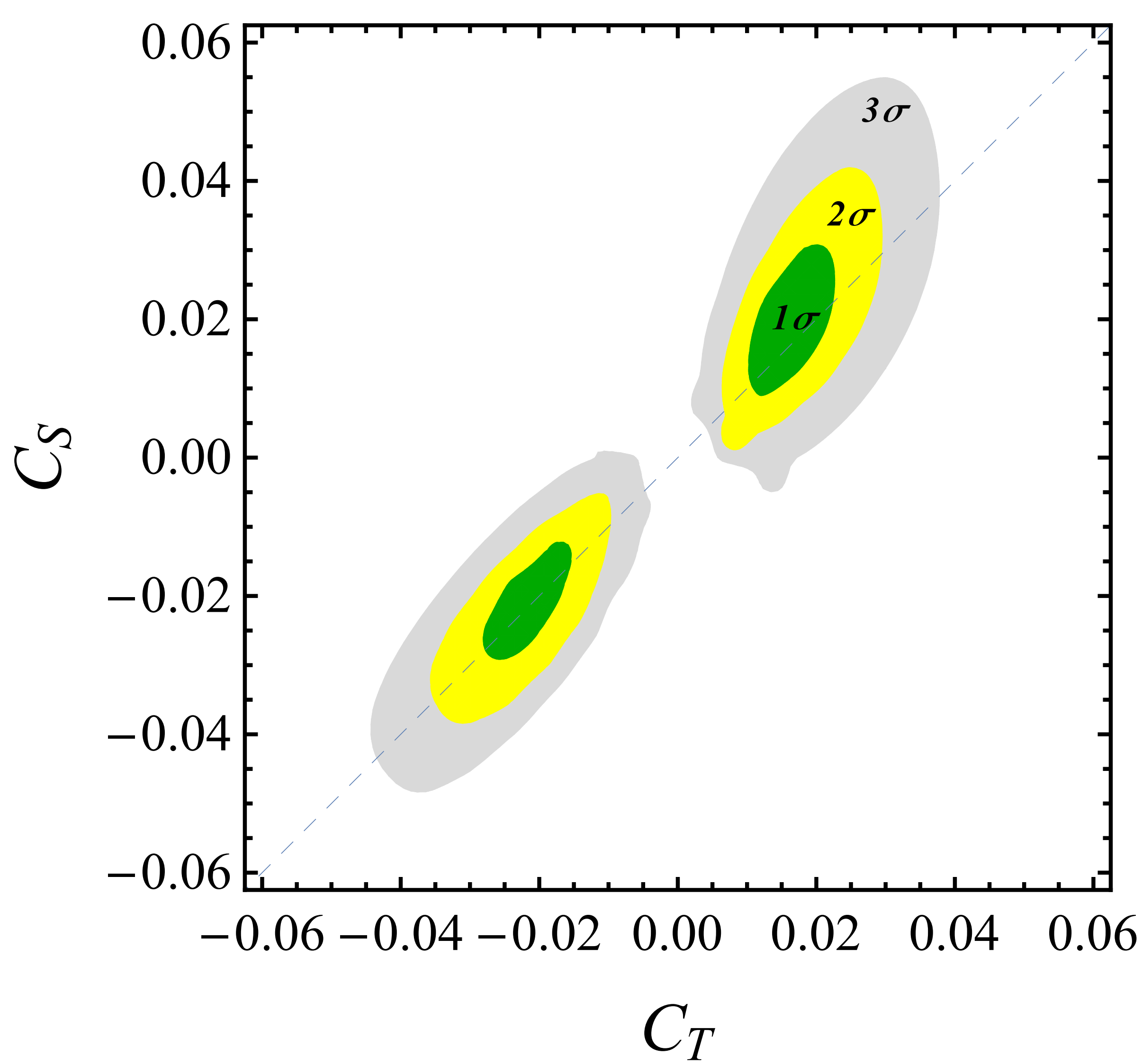
$$N_\nu = 3 - 0.19\, C_S - 0.15\, C_T = 2.9840 \pm 0.0082$$

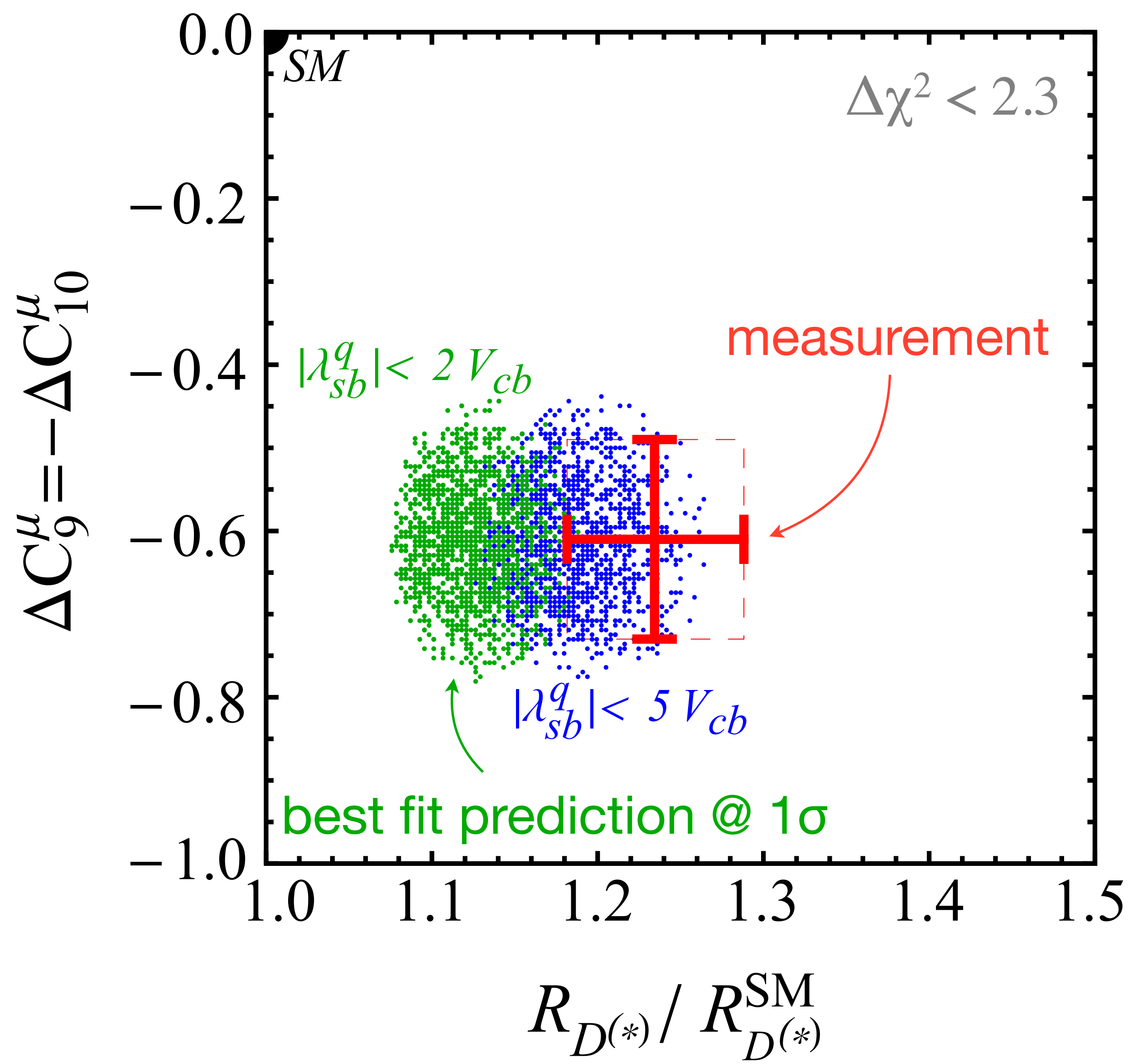
(RG-running corrections to four-quark operators suppressed by the τ mass)

→ strong bounds on the scale of NP ($C_{S,T} \lesssim$ 0.02-0.03)

Fit to semi-leptonic observables

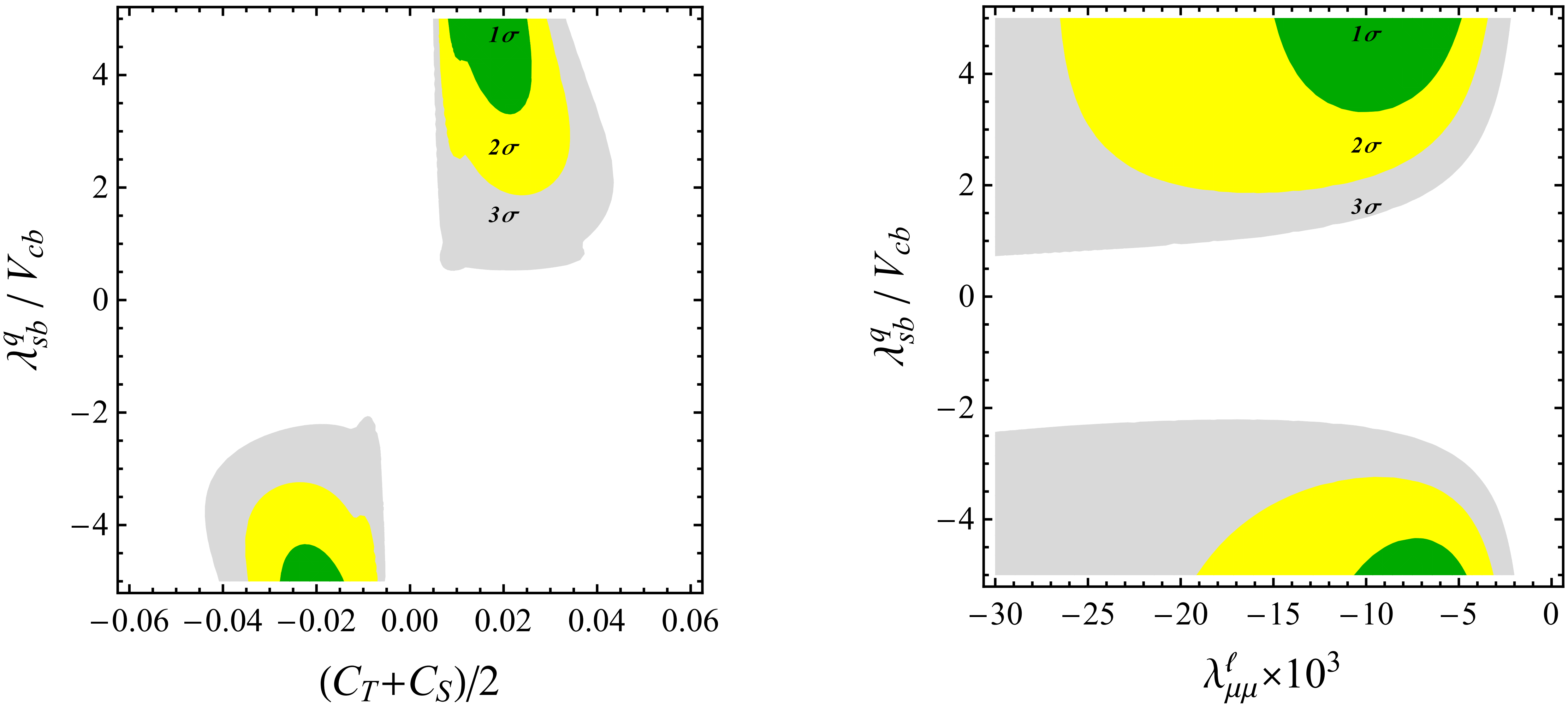
- EFT fit to all semi-leptonic observables + radiative corrections to EWPT
- Don't include any UV contribution to other operators
  (they will depend on the dynamics of the specific model)





Good fit to all anomalies, with couplings compatible with the U(2) assumption

Fit to semi-leptonic observables



- Large values of λ_{bs} required to fit R_{D^*}

  (this is because the NP scale is forced to be high enough for radiative corrections)

- $\lambda_{\mu\mu}$ must be negative to fit C_9

  this rules out the “pure mixing” scenario in the lepton sector (where $\lambda_{\mu\mu} \sim \sin\theta_{\tau\mu}^2$)

Relation to other observables: charged currents

- **LH currents:** universality of all ***b*** → ***c*** transitions:

  $BR(B \to D\tau\nu)/BR_{SM} = BR(B \to D^*\tau\nu)/BR_{SM} = BR(B_c \to \psi\tau\nu)/BR_{SM}$

  $= BR(\Lambda_b \to \Lambda_c\tau\nu)/BR_{SM} = \ldots$

- **U(2) symmetry:** ***b*** → ***c*** vs. ***b*** → ***u*** universality ($V_q \sim V_{CKM}$)

  $BR(B \to D^{(*)}\tau\nu)/BR_{SM} = BR(B \to \pi\tau\nu)/BR_{SM} = BR(B^+ \to \tau\nu)/BR_{SM}$

  $= BR(B_s \to K^*\tau\nu)/BR_{SM} = BR(\Lambda_b \to p\tau\nu)/BR_{SM} = \ldots$

  ✓ $BR(B_u \to \tau\nu)_{exp}/BR_{SM} = 1.31 \pm 0.27$ (UTfit 2016)

- Other leptonic final states more difficult: ***μ* vs. *e*** universality ratio?

  $$R_D^{\mu/e} = R_D^{\tau/\mu} \times \lambda_{\mu\mu} \approx 10^{-3}$$

Relation to other observables: neutral currents

Lepton flavour →

Isidori 2017

Quark flavour ↓ — U(2) symmetry (b → s, b → d); SU(2) (ττ, νν)

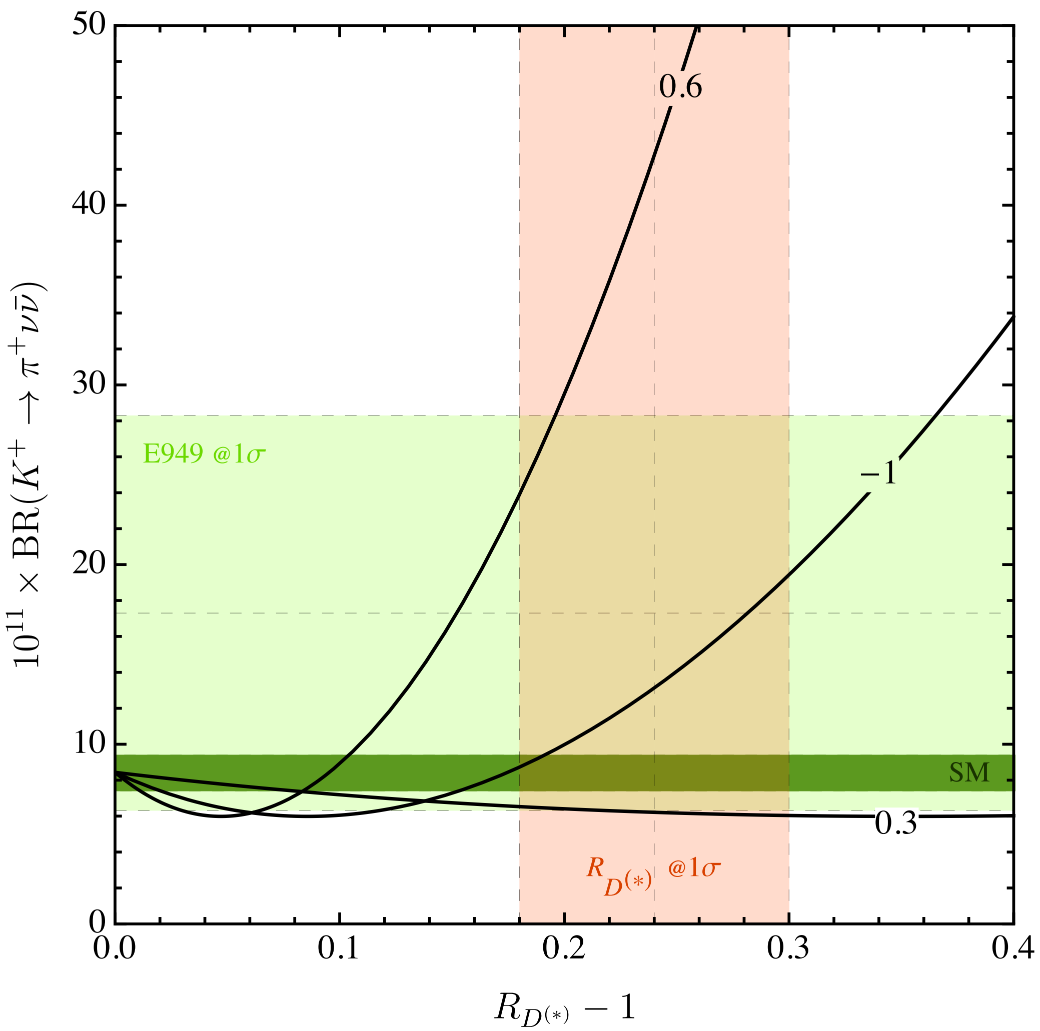
	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ $\to$ 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ $\to \sim 10^{-6}$	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi \tau\tau$ $\to$ 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ $\to \sim 10^{-7}$	$B \to \pi \mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi \nu\nu$ O(1)	*NA*	$K \to \mu e$???

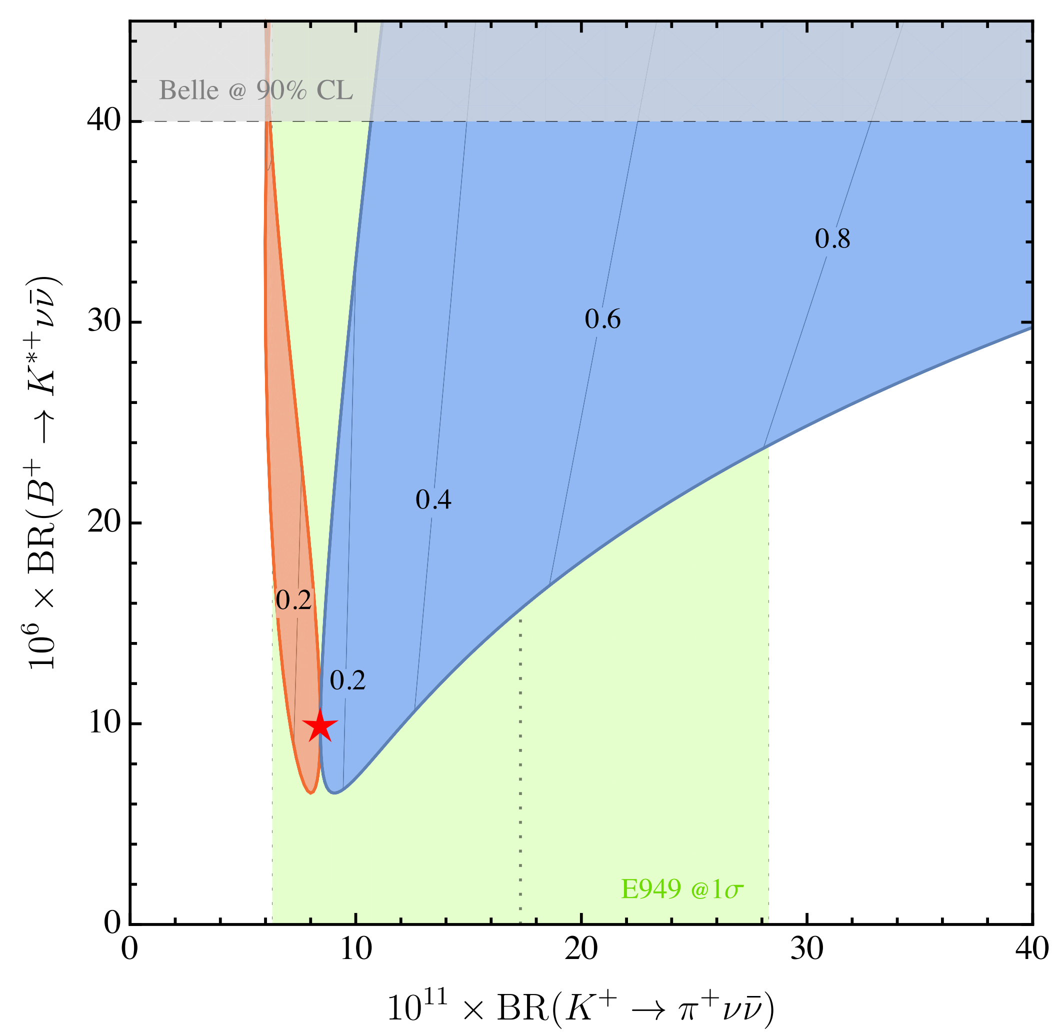
Several correlated effects in other flavour observables.

$K \to \pi\nu\nu$

- The only $s \to d$ decay with 3rd generation leptons in the final state: sizeable deviations can be expected
- U(2) symmetry relates $b \to q$ transitions to $s \to d$ (up to model-dependent parameters of order 1): $\lambda_{sd} \sim V_q V_q^* \sim V_{ts}^* V_{td} \qquad \lambda_{bq} \sim V_q \sim V_{tq}^*$

Bordone, B, Isidori, Monnard 2017

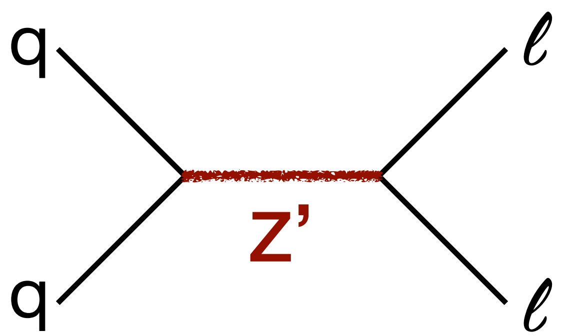


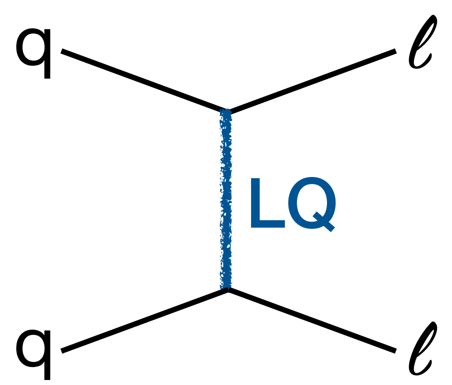


Simplified models

Mediators that can give rise to the $b \to c\ell\nu$ and $b \to s\ell\ell$ amplitudes:

	Spin 0	Spin 1
Colour singlet	~~2HDM~~ no LL operator	Vector resonance
Colour triplet	Scalar lepto-quark	Vector lepto-quark





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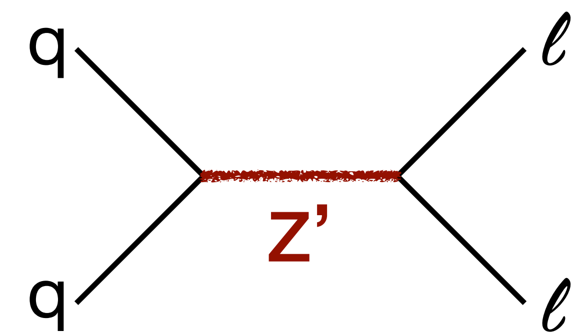

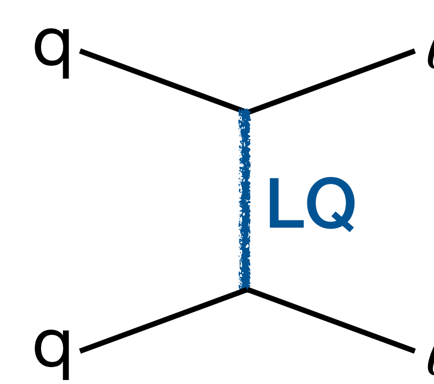

$$W' \sim (\mathbf{1}, \mathbf{3}, 0)$$
$$B' \sim (\mathbf{1}, \mathbf{1}, 0)$$

$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$$
$$S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$
$$U_3 \sim (\mathbf{3}, \mathbf{3}, 2/3)$$

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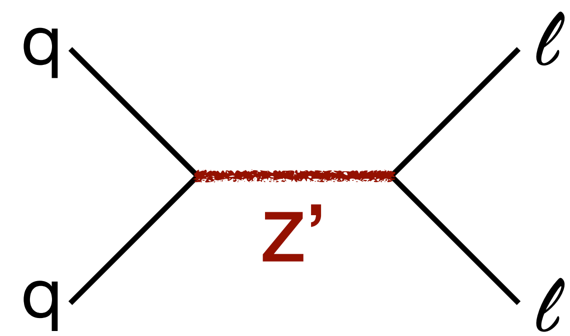
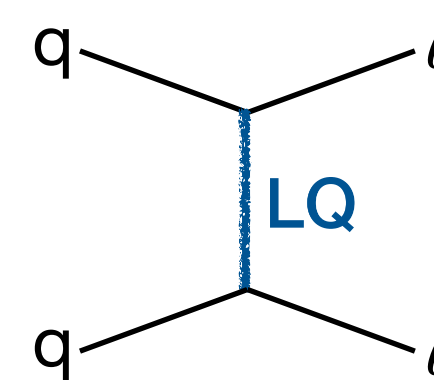
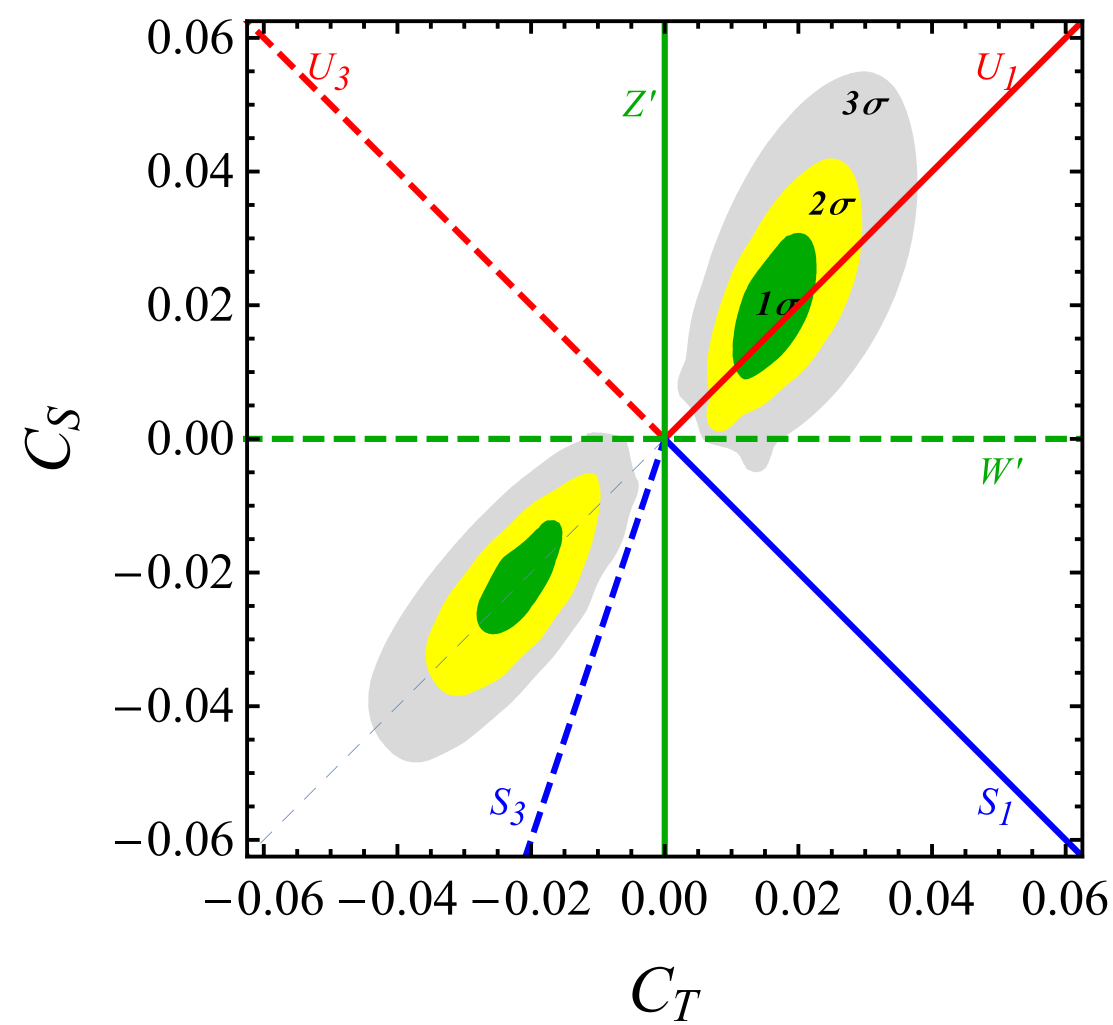




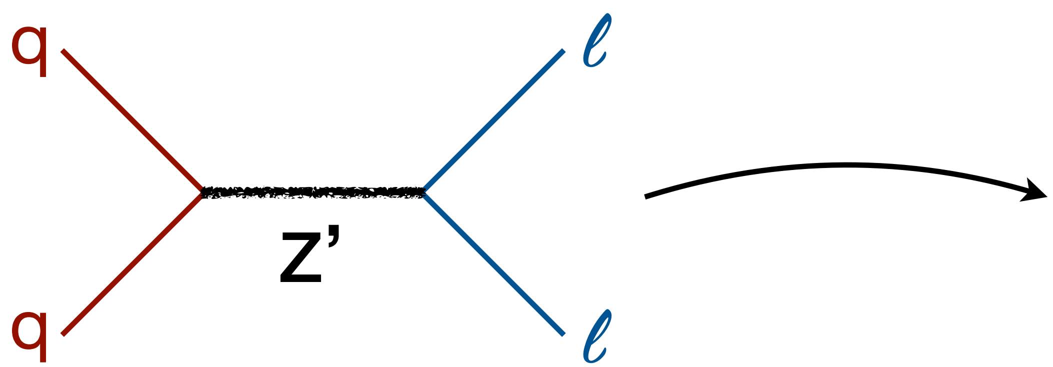
Contributions to C_T and C_S from different mediators:

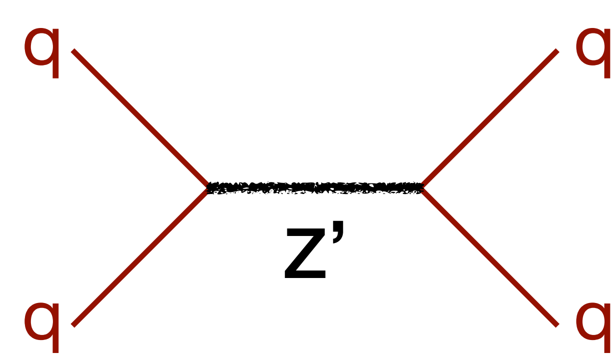
- A **vector leptoquark** is the only single mediator that can fit all the anomalies alone: $C_T \sim C_S$
- Combinations of two or more mediators also possible
  (often the case in concrete models)

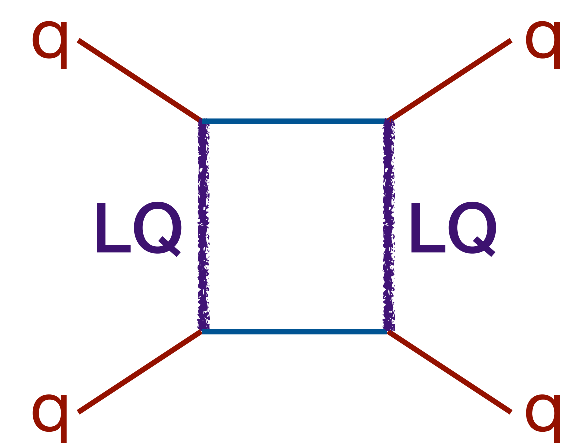


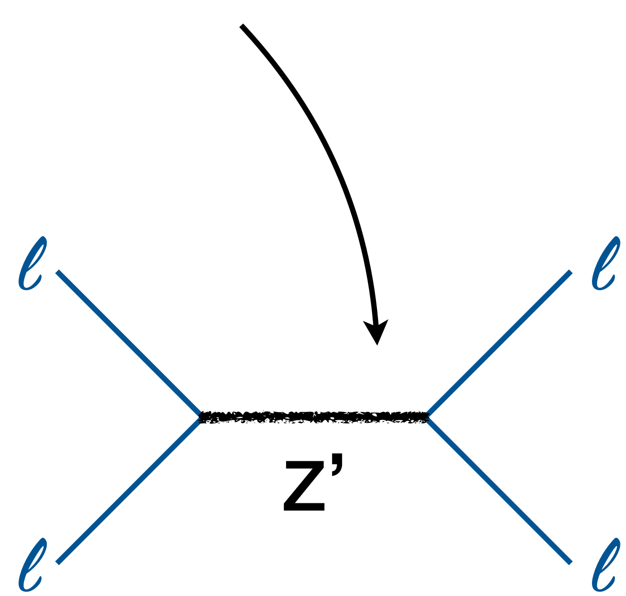
Connection to other observables

In most explicit models, four-quark and four-lepton operators are also present



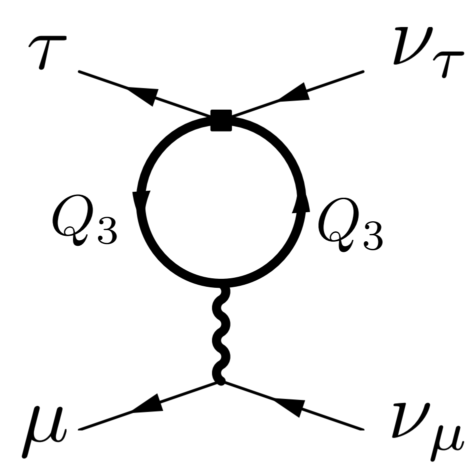






- B_d and B_s mixing:
  O(few %) deviations from SM expected, already in tension with present bounds in most models
- CP violation in D mixing:
  O(0.1 %) deviations from SM

- $\tau \to 3\mu$:
  large effect expected, possibly close to experimental bound, BR ~ 10^{-9}
- τ vs μ LFU:
  O(0.1 %) deviation in $\tau \to \mu\nu\nu$ vs. $\tau \to e\nu\nu$ and in $G_F(\tau)$ vs. $G_F(\mu)$

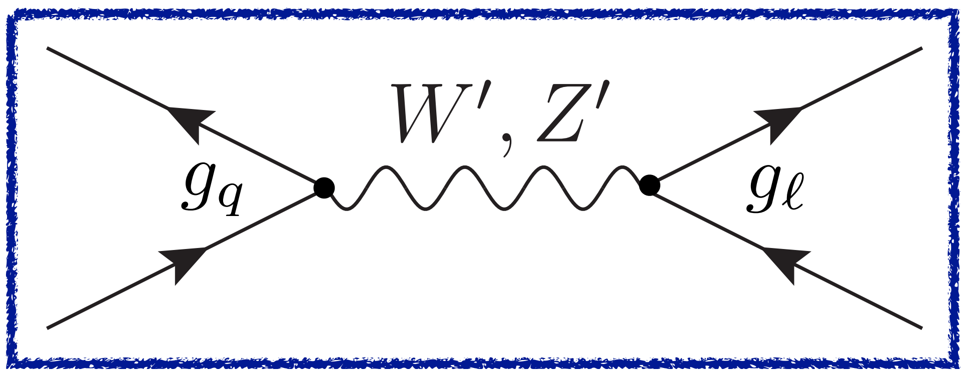


Vector resonances

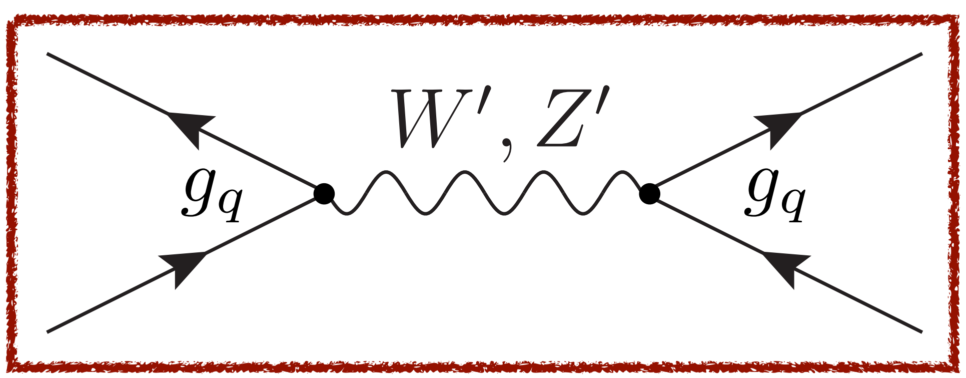
Triplet and singlet colourless vectors: $\mathcal{L}_{\rm int} = W'^a_\mu J^a_\mu + B'_\mu J^0_\mu$

$$J^a_\mu = g_q \lambda^q_{ij} \left(\bar{Q}^i_L \gamma_\mu T^a Q^j_L\right) + g_\ell \lambda^\ell_{\alpha\beta} \left(\bar{L}^\alpha_L \gamma_\mu T^a L^\beta_L\right)$$

$$J^0_\mu = \frac{g^0_q}{2} \lambda^q_{ij} \left(\bar{Q}^i_L \gamma_\mu Q^j_L\right) + \frac{g^0_\ell}{2} \lambda^\ell_{\alpha\beta} \left(\bar{L}^\alpha_L \gamma_\mu L^\beta_L\right)$$



$$C_{T,S} = \frac{4v^2}{m_V^2} g_q g_\ell$$



Large contribution to B_s mixing

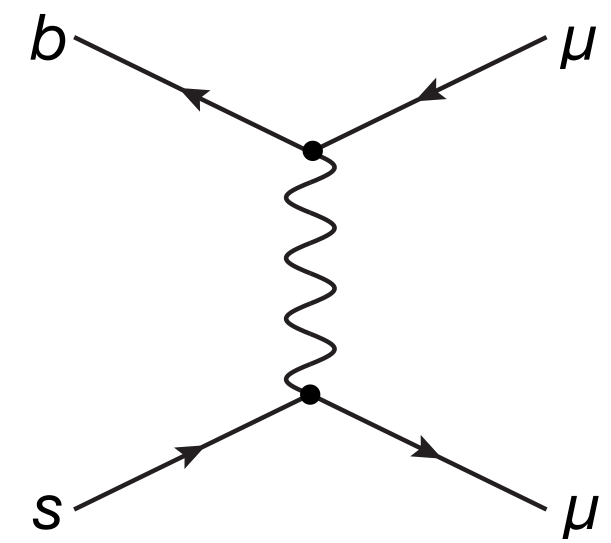
$$\Delta\mathcal{A}_{B_s\text{-}\bar{B}_s} \approx \frac{v^2}{m_V^2} \lambda^2_{bs} \left(g_q^2 + (g_q^0)^2\right)$$
$$\approx \left(C_T + C_S\right) \lambda^2_{bs}$$

Problem less severe for large $C_{T,S}$ — stronger tension with EW precision tests.

In models with more couplings (e.g. Higgs current) can partially cancel the contributions

Vector leptoquarks

SU(2)$_L$ singlet vector LQ: $U_\mu \sim (\mathbf{3}, \mathbf{1}, 2/3)$



$$\mathcal{L}_{\rm LQ} = g_U U_\mu \beta_{i\alpha} \left(\bar{Q}_L^i \gamma^\mu L_L^\alpha\right) + \text{h.c.}$$

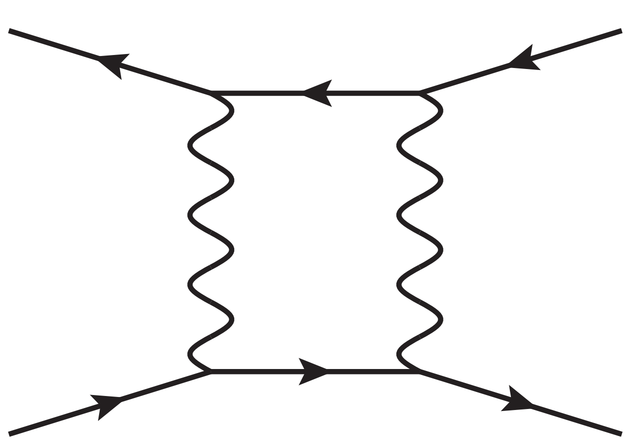
- $C_T = C_S$ automatically satisfied at tree-level

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{v^2} C_U \beta_{i\alpha}\beta^*_{j\beta} \left[(\bar{Q}^i\gamma_\mu\sigma^a Q^j)(\bar{L}^\alpha\gamma^\mu\sigma^a L^\beta) + (\bar{Q}^i\gamma_\mu Q^j)(\bar{L}^\alpha\gamma^\mu L^\beta)\right]$$

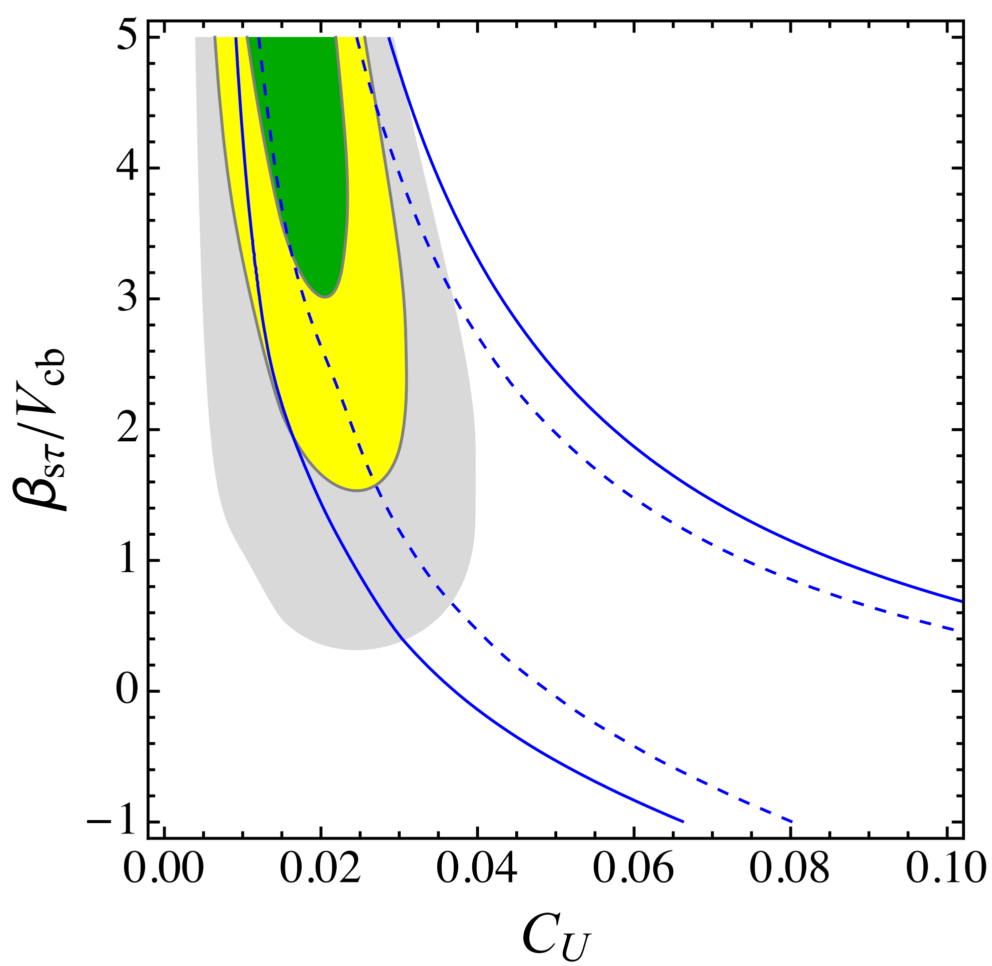
$$C_U = \frac{v^2 |g_U|^2}{2 m_U^2}$$

- No tree-level contribution to $B_{(s)}$-$\bar{B}_{(s)}$ mixing, but UV contributions not calculable

naïve estimate:



$$\approx C_U |\beta_{s\tau}|^2 \frac{g_U^2}{(4\pi)^2}$$

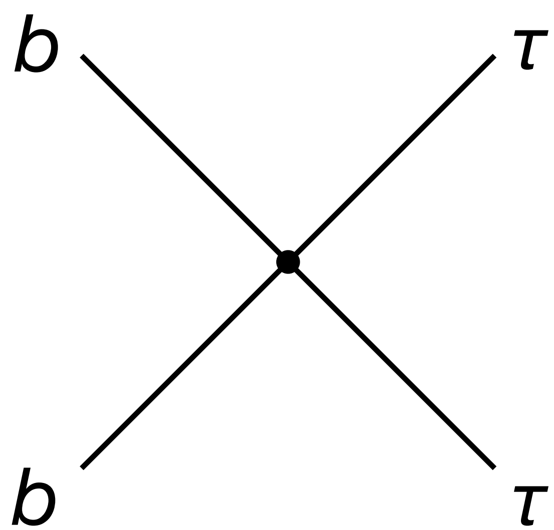


High-pT searches at LHC

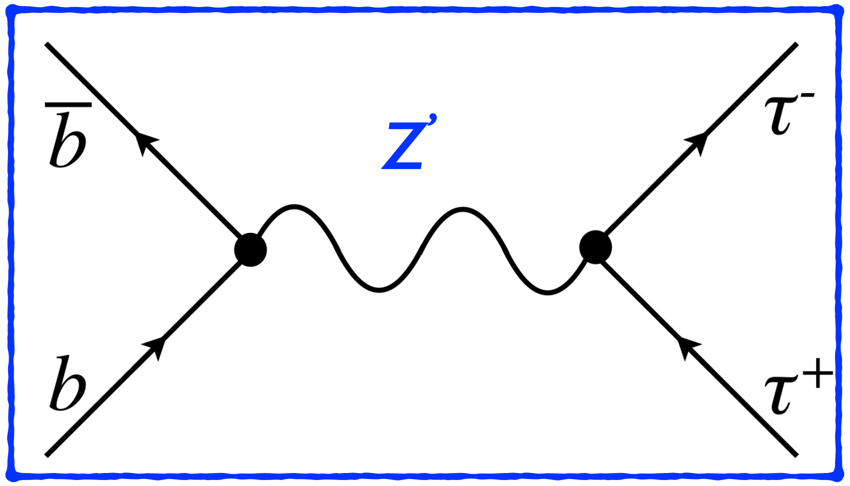
A general feature of any model: large coupling to b and τ

➡ searches in $\tau\tau$ final state at high energy at LHC

PDF of b quark small, but still dominant
if compared to flavour suppression

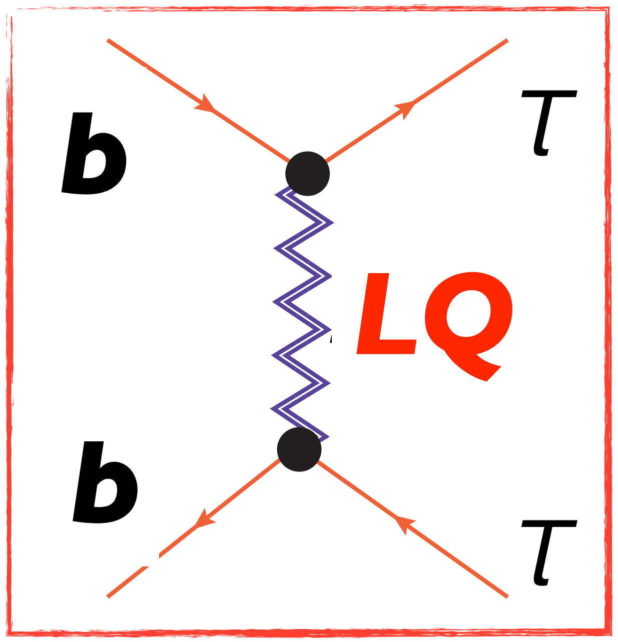


- s-channel resonances



must be broad to escape searches
if below ~ 2 TeV

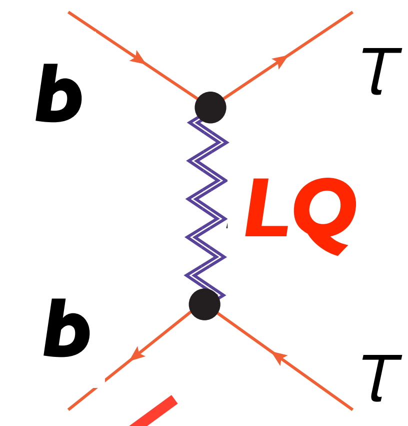
- t-channel exchange: leptoquarks

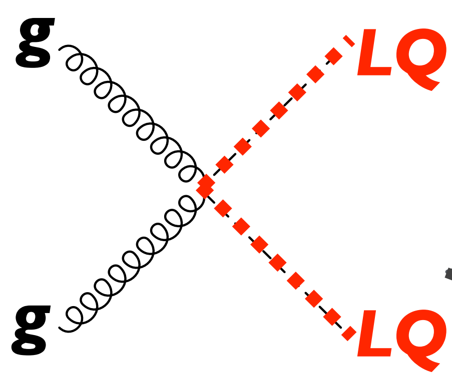


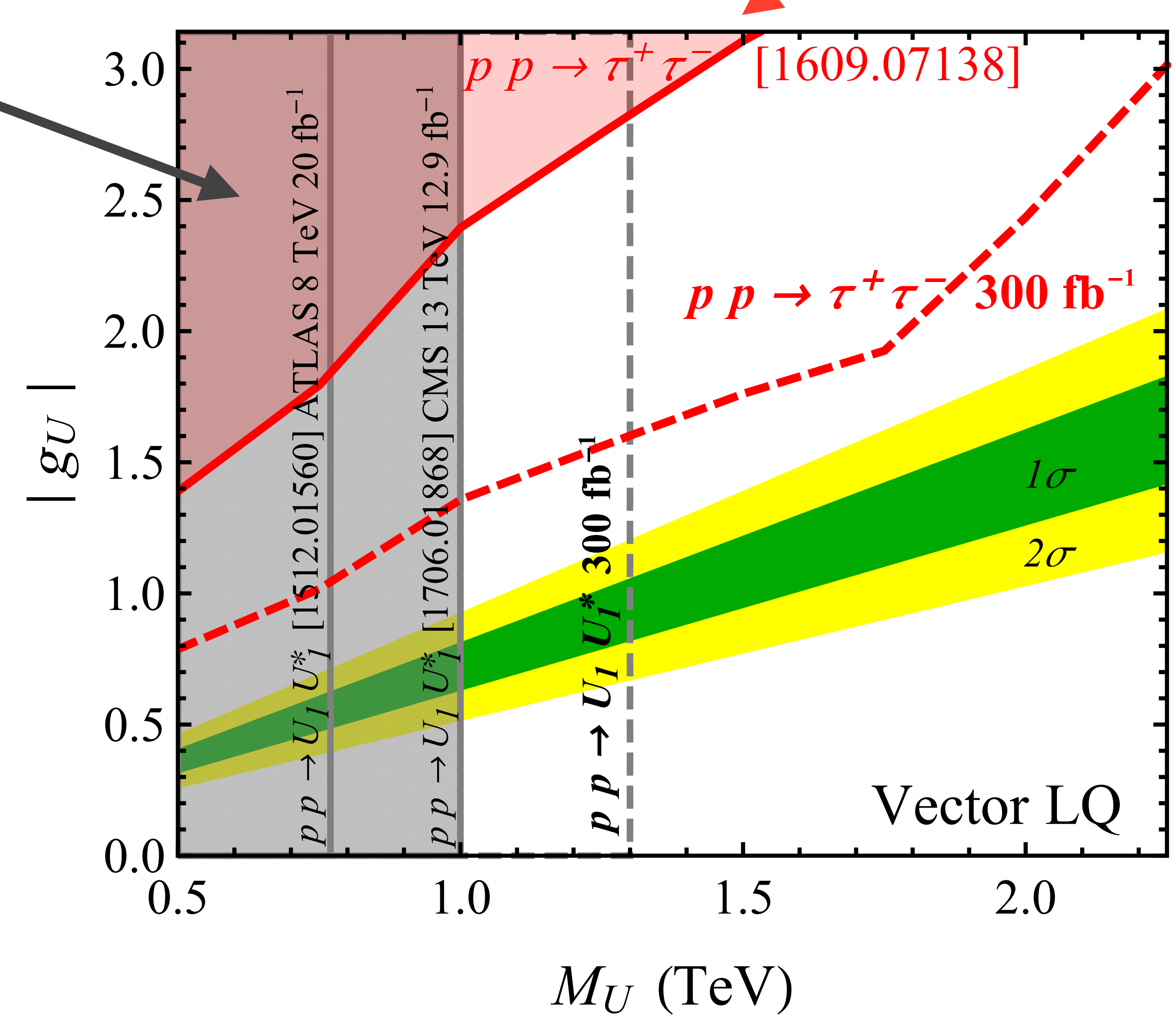
High-pT searches at LHC: leptoquarks

- *bb*-fusion, searches in $\tau\tau$ invariant mass distribution
- Pair-production through QCD interaction

Faroughy, Greljo Kamenik 2016







If heavier than ~ 1.3 TeV, could not be visible at LHC!

→ HL-LHC or HE-LHC needed to probe the best-fit region

UV completions: vector leptoquark

Leptoquark quantum numbers are consistent with Pati-Salam unification

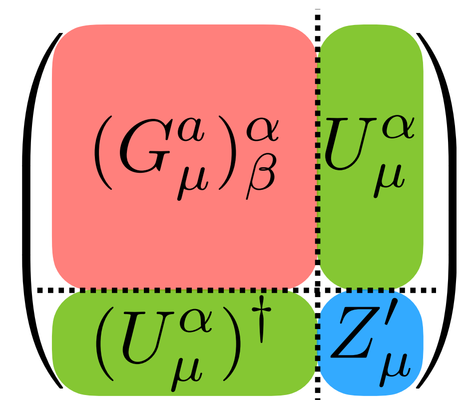
$$SU(4) \times SU(2)_L \times SU(2)_R \supset SU(3)_c \times SU(2)_L \times U(1)_Y$$

Lepton number = 4th color

$$\psi_L = (q_L^1, q_L^2, q_L^3, \ell_L) \sim (\mathbf{4}, \mathbf{2}, \mathbf{1}),$$
$$\psi_R = (q_R^1, q_R^2, q_R^3, \ell_R) \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}).$$

Gauge fields: $\mathbf{15} = \mathbf{8}_0 \oplus \mathbf{3}_{2/3} \oplus \bar{\mathbf{3}}_{-2/3} \oplus \mathbf{1}_0$

→ vector leptoquark U_1^μ



- No proton decay: protected by gauge $U(1)_{B-L} \subset SU(4)$
- U_μ gauge vector: unitary couplings to fermions

➡ bounds of O(100 TeV) from light fermion processes, e.g. $K \to \mu e$

UV completions: vector leptoquark

Non-universal couplings to fermions needed!

- **Elementary vectors:** color can't be completely embedded in SU(4)

$$SU(4) \times SU(3) \to SU(3)_c$$

Di Luzio et al. 2017
Isidori et al. 2017

only the 3rd generation is charged under SU(4)

- **Composite vectors:** resonances of a strongly interacting sector with global $SU(4) \times SU(2) \times SU(2)$

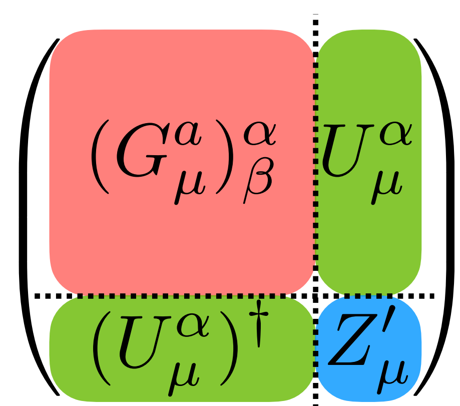
the couplings to fermions can be different (e.g. partial compositeness)

Barbieri, Tesi 2017

In all cases, additional heavy vector resonances (color octet and Z') are present

Searches for broad resonances at LHC!

in progress with Barbieri, Pierini, Tesi



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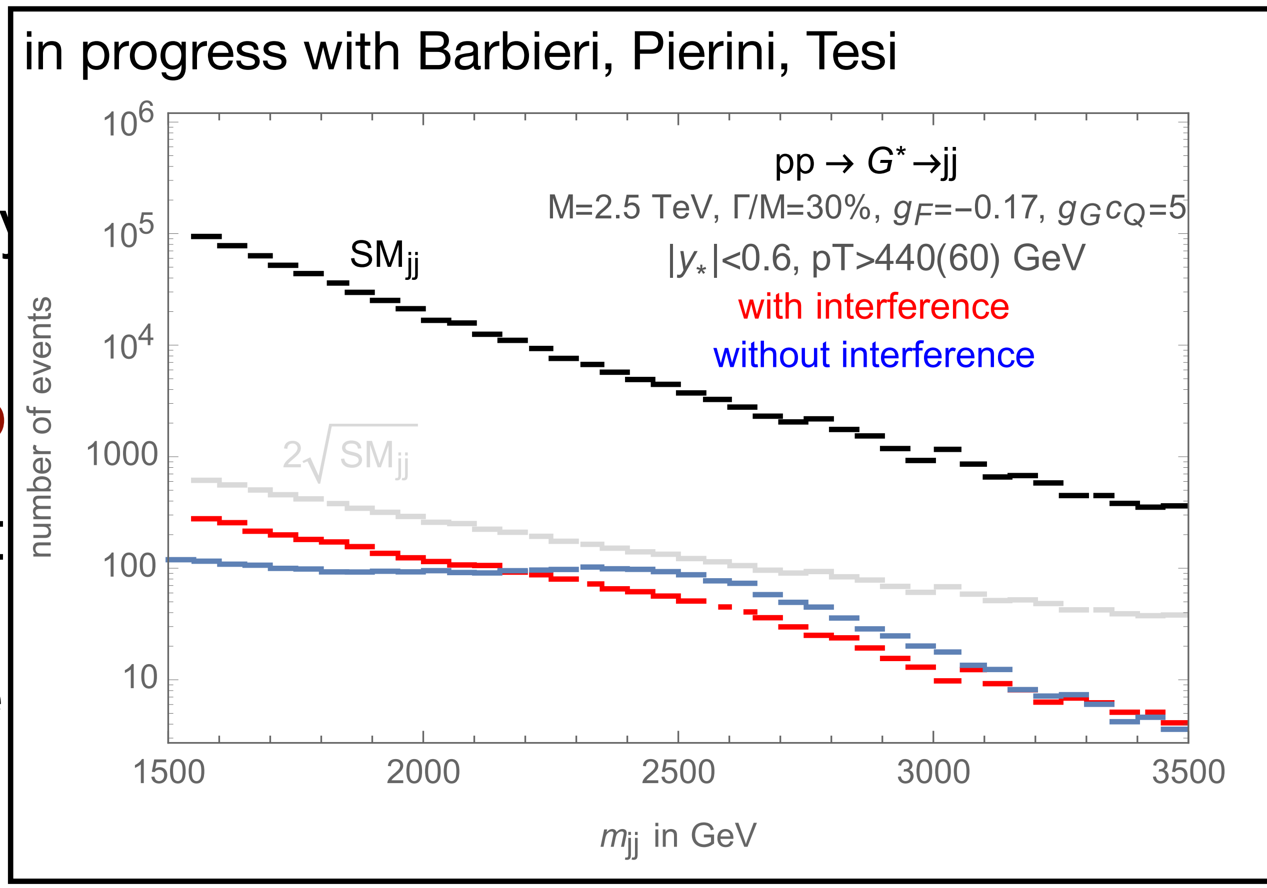

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- Co ngly interacting sector

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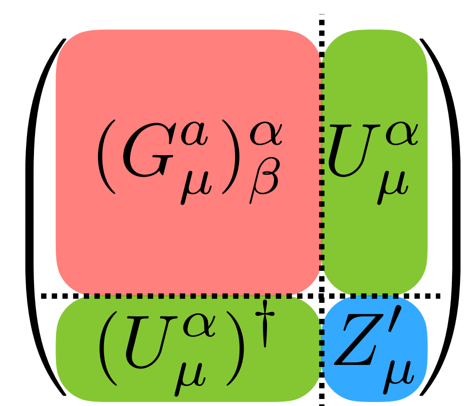
Barbieri, Tesi 2017



In all cases, additional heavy vector resonances (color octet and Z') are present

Searches for broad resonances at LHC!

Composite scalar leptoquarks

- New strong interaction that confines at a scale Λ ~ few TeV

$$\Psi \sim \Box, \qquad \bar{\Psi} \sim \bar{\Box}$$ N new (vector-like) fermions

$$\langle \bar{\Psi}^i \Psi^j \rangle = -f^2 B_0 \delta^{ij} \quad \longrightarrow \quad \mathrm{SU}(N)_L \times \mathrm{SU}(N)_R \to \mathrm{SU}(N)_V$$

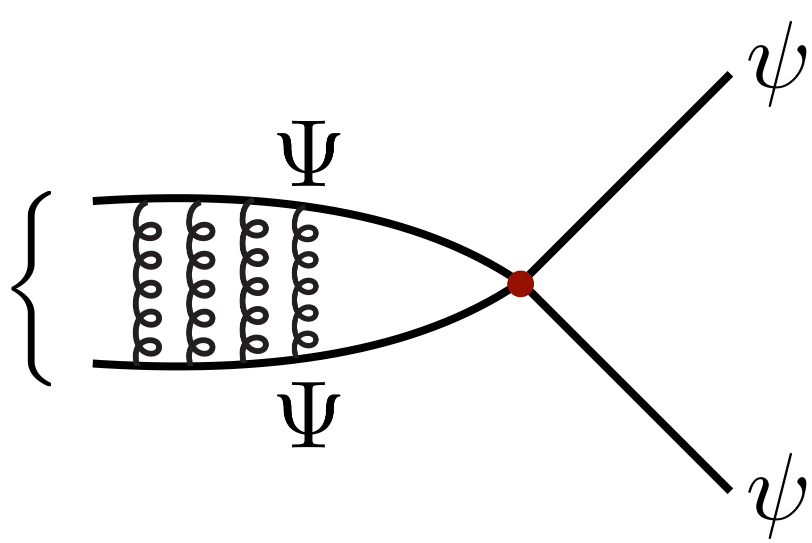
(more in general *G* → *F*)

- If the fermions transform under SM gauge group, also the Pseudo Nambu-Goldstone bosons have SM charges:

$$\Psi_Q \sim (\mathbf{3}, \mathbf{2}, Y_Q), \qquad \Psi_L \sim (\mathbf{1}, \mathbf{2}, Y_L) \quad \longrightarrow \quad \begin{array}{l} S_1 \sim (\mathbf{3}, \mathbf{1}, Y_Q - Y_L), \\ S_3 \sim (\mathbf{3}, \mathbf{3}, Y_Q - Y_L), \\ \eta \sim (\mathbf{1}, \mathbf{1}, 0), \\ \pi \sim (\mathbf{1}, \mathbf{3}, 0), \ \cdots \end{array}$$

the scalar LQ are naturally light (pNGB) and couple to fermions

$$\varphi = [\bar{\Psi}\Psi]$$



B, Greljo, Isidori, Marzocca 2017
➡ Marzocca, 2018

Composite scalar leptoquarks

- New strong interaction that confines at a scale Λ ~ few TeV

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the scalar LQ are naturally light (pNGB) and couple to fermions

$$\Psi_E \sim (\mathbf{1}, \mathbf{1}, -1), \qquad \Psi_N \sim (\mathbf{1}, \mathbf{1}, 0) \longrightarrow H \sim (\mathbf{1}, \mathbf{2}, \pm 1/2)$$

composite Higgs as a pNGB can be included in the picture

- Vector resonances (with the same quantum numbers) are heavier

$$W'_\mu, B'_\mu, U_\mu, \cdots$$

B, Greljo, Isidori, Marzocca 2017
➡ Marzocca, 2018

Conclusions & outlook

Is the SM breaking down in the flavour sector? We don't know…

- ➡ many new data in the coming years
- ➡ low scale: flavour measurements VS high-pT searches

Model-independent description: EFT

- CKM-like flavour violation
- Triplet and Singlet operators with similar size
- EWPT and meson mixing give important constraints

Leptoquarks are interesting!

Pati-Salam unification?!

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Pati-Salam unification?!

Thank you for your attention!

Backup slides

Fit to semi-leptonic operators

Observables that enter in the fit:

Observable	Exp. bound	Linearised expression
$R_{D^{(*)}}^{\tau\ell}$	1.237 ± 0.053	$1 + 2C_T(1 + \lambda_{sb}^q \frac{V_{cs}}{V_{cb}})(1 - \lambda_{\mu\mu}^\ell/2)$
$\Delta C_9^\mu = -\Delta C_{10}^\mu$	-0.61 ± 0.12	$-\frac{\pi}{\alpha_{\rm em} V_{tb} V_{ts}^*} \lambda_{\mu\mu}^\ell \lambda_{sb}^q (C_T + C_S)$
$R_{b\to c}^{\mu e} - 1$	0.00 ± 0.02	$2C_T(1 + \lambda_{sb}^q \frac{V_{cs}}{V_{cb}})\lambda_{\mu\mu}^\ell$
$B_{K^{(*)}\nu\nu}$	0.0 ± 2.6	$1 + \frac{2}{3} \frac{\pi}{\alpha_{\rm em} V_{tb} V_{ts}^* C_\nu^{\rm SM}} (C_T - C_S)\lambda_{sb}^q (1 + \lambda_{\mu\mu})$
$\delta g_{\tau_L}^Z$	-0.0002 ± 0.0006	$0.38 C_T - 0.47 C_S$
N_ν	2.9840 ± 0.0082	$3 - 0.19 C_S - 0.15 C_T$
$\lvert g_\tau^W / g_\ell^W \rvert$	1.00097 ± 0.00098	$1 - 0.09 C_T$

- Include all the terms generated in the RG running
- Do not include any UV contribution to non-semi-leptonic operators (they will depend on the dynamics of the specific model)

Semi-leptonic effective operators

Two simple current-current structures:

1. **QQ x LL** $\mathcal{L}_{\rm eff} \propto J_{QQ} J_{LL} + \text{h.c.}$

$$J^{\mu}_{QQ} = \left(\bar{q}^i_L \gamma^\mu q^j_L\right) \left[\delta_{i3}\delta_{j3} + a_q \delta_{i3}(V^*_q)_j + a^*_q (V_q)_i \delta_{j3} + b_q\,(V_q)_i (V^*_q)_j\right] \equiv \lambda^q_{ij} \bar{q}^i_L \gamma^\mu q^j_L$$

$$J^{\mu}_{LL} = \left(\bar{\ell}^\alpha_L \gamma^\mu \ell^\beta_L\right) \left[\delta_{\alpha 3}\delta_{\beta 3} + a_\ell \delta_{\alpha 3}(V^*_\ell)_\beta + a^*_\ell (V_\ell)_\alpha \delta_{\beta 3} + b_\ell\,(V_\ell)_\alpha (V^*_\ell)_\beta\right] \equiv \lambda^\ell_{\alpha\beta} \bar{\ell}^\alpha_L \gamma^\mu \ell^\beta_L$$

4 + 2 free parameters:

$$\lambda^q_{bs} = a_q V_{ts}, \qquad \lambda^\ell_{\tau\mu} = a_\ell V_{\tau\mu},$$

$$\lambda^\ell_{\mu\mu} = b_\ell |V_{\tau\mu}|^2, \qquad \lambda^q_{sd} = b_q V^*_{ts} V_{td}$$

2. **LQ x QL** $\mathcal{L}_{\rm eff} \propto J_{LQ} J^\dagger_{LQ}$

$$J^{\mu}_{LQ} = \left(\bar{q}^i_L \gamma^\mu \ell^\alpha_L\right) \left[\delta_{i3}\delta_{\alpha 3} + a^*_q (V_q)_i \delta_{\alpha 3} + a_\ell \delta_{i3} (V^*_\ell)_\alpha + b\,(V_q)_i (V^*_\ell)_\alpha\right] \equiv \beta_{i\alpha} \bar{q}^i_L \gamma^\mu \ell^\alpha_L$$

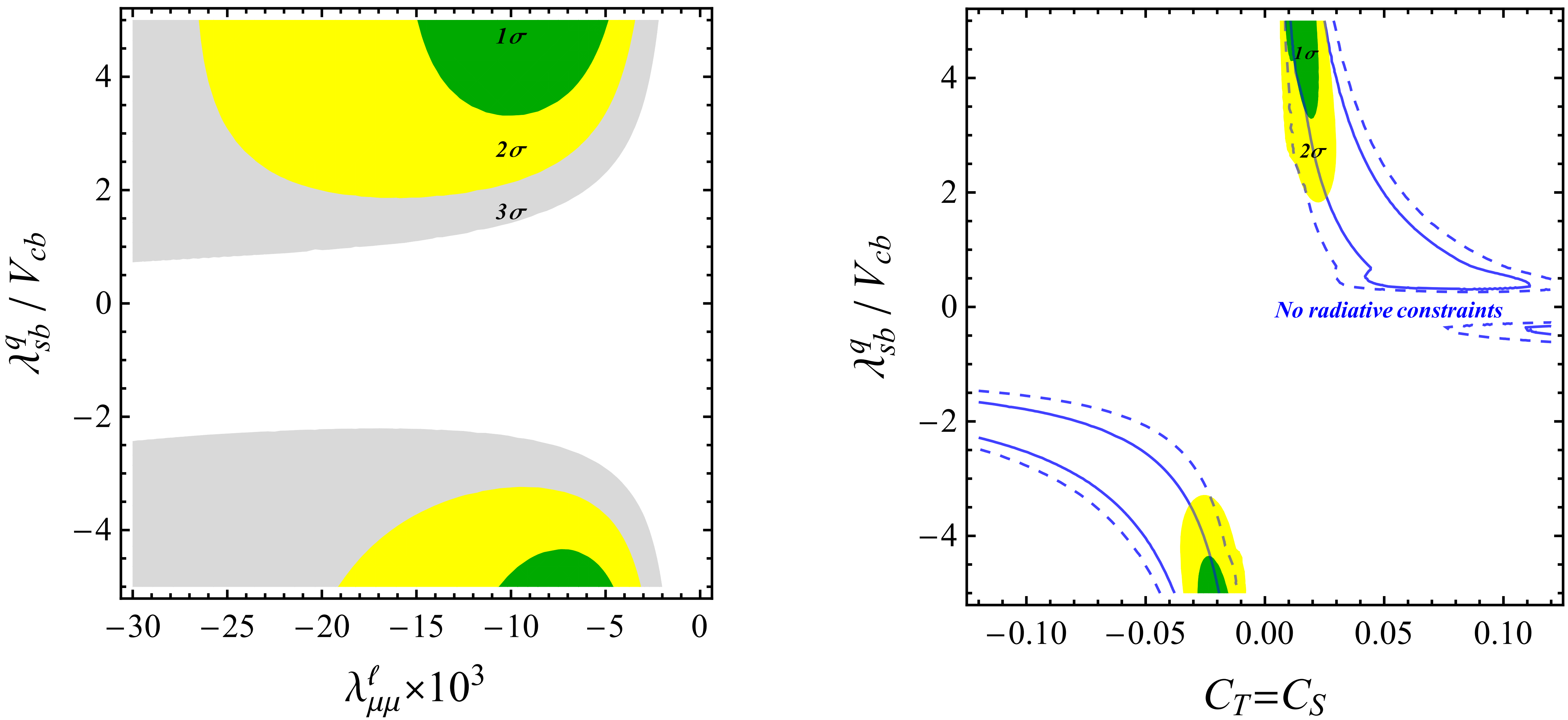
3 + 3 free parameters:

$$\beta^*_{s\tau} = a_q V_{ts}, \qquad \beta_{b\mu} = a_\ell V_{\tau\mu},$$

$$\beta_{b\mu}\beta^*_{s\mu} = a_\ell\, b |V_{\tau\mu}|^2$$

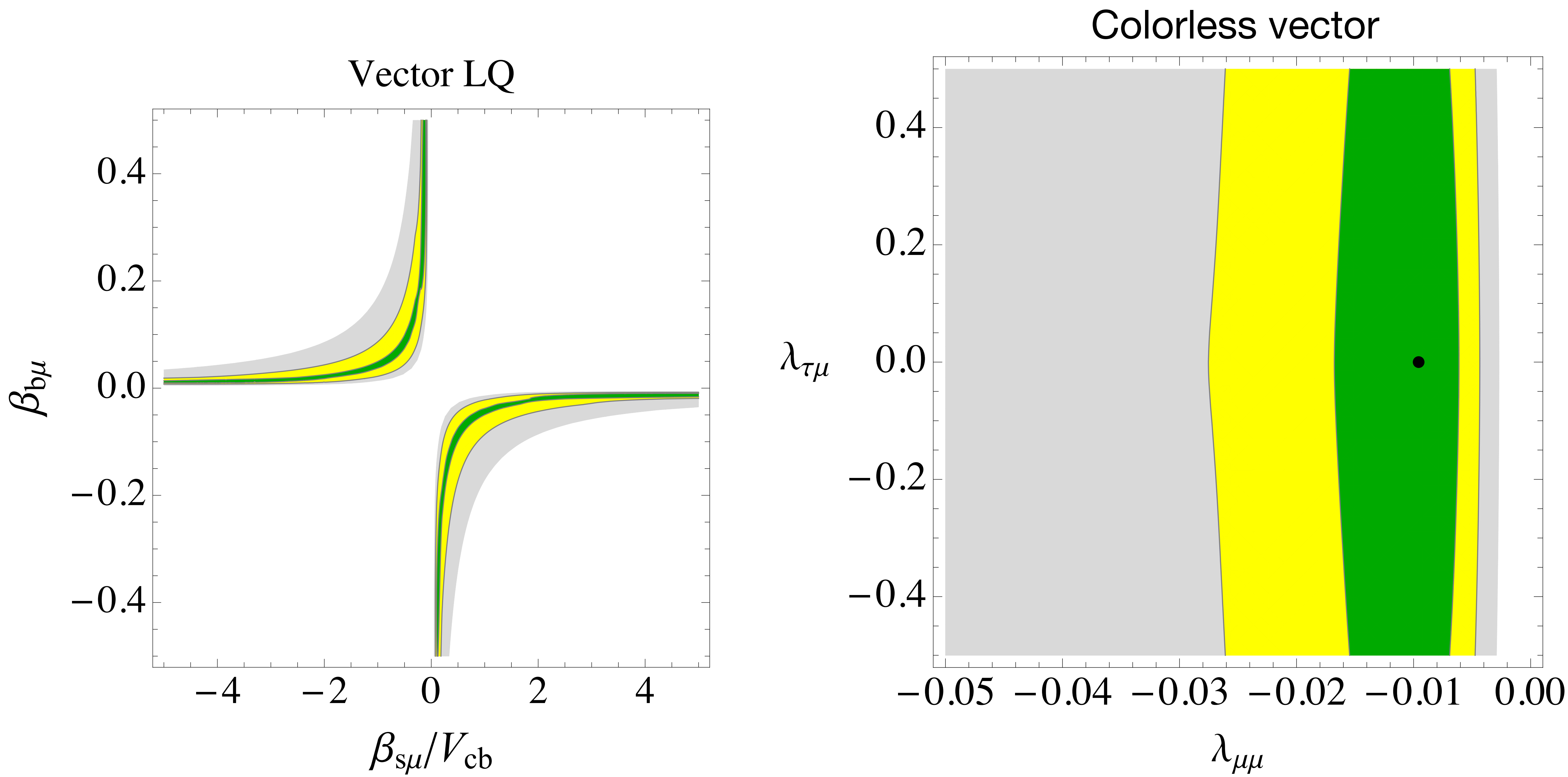
Non-equivalent, if terms with more than one spurion are considered!

Fit to semi-leptonic operators



- Small values of C_T required by radiative constraints
- $\lambda_{\mu\mu}$ must be negative to fit C_9

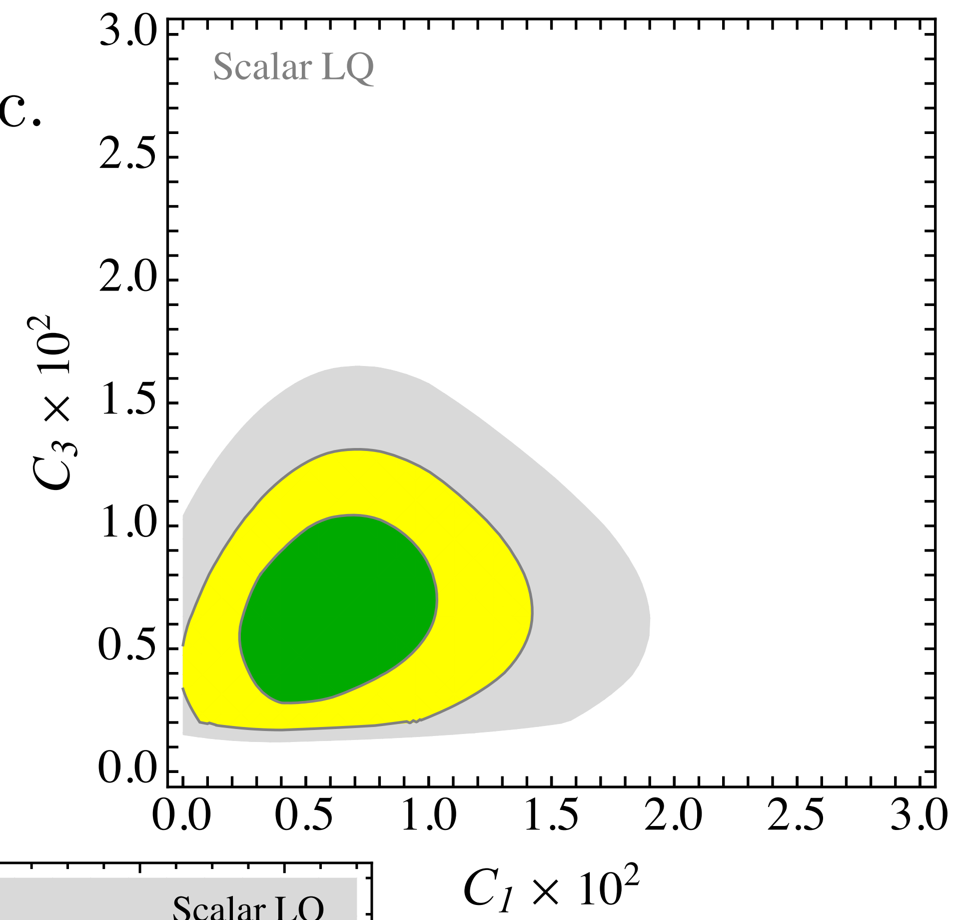
  this rules out the "pure mixing" scenario in the lepton sector (where $\lambda_{\mu\mu} \sim \sin\theta_{\tau\mu}^2$)


Vector LQ
0.4
0.2
0.0
−0.2
−0.4
$\beta_{b\mu}$
−4
−2
0
2
4
$\beta_{s\mu}/V_{cb}$
Colorless vector
0.4
0.2
0.0
−0.2
−0.4
$\lambda_{\tau\mu}$
−0.05
−0.04
−0.03
−0.02
−0.01
0.00
$\lambda_{\mu\mu}$

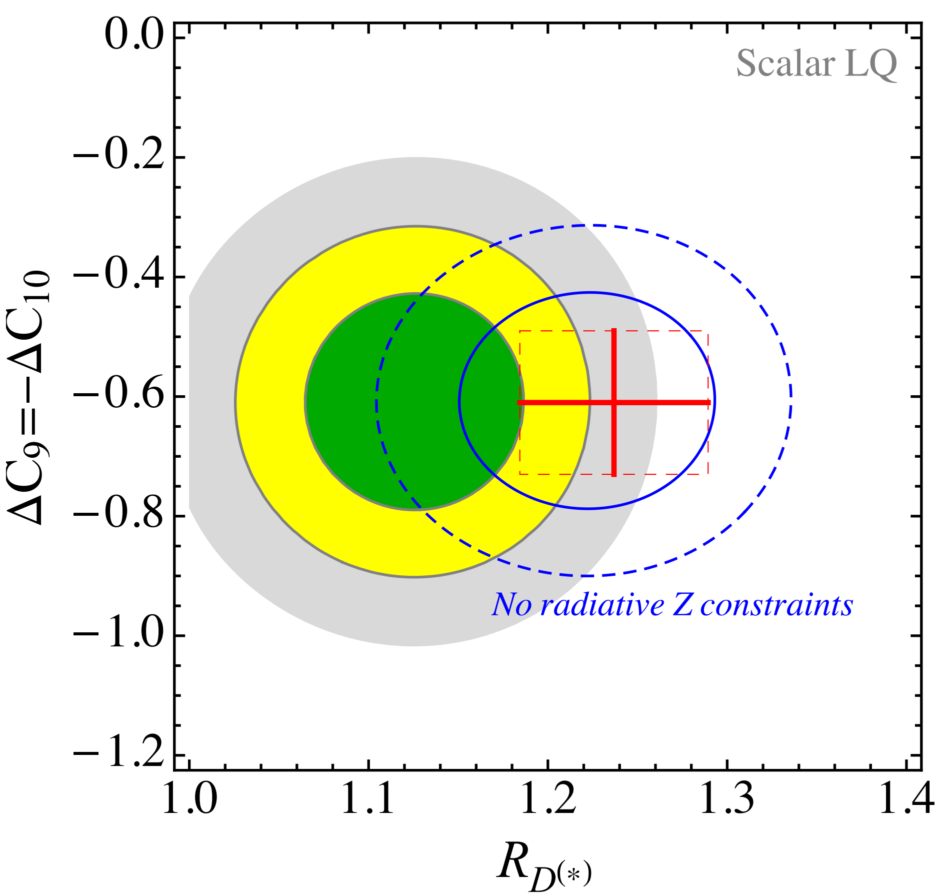
Scalar leptoquarks

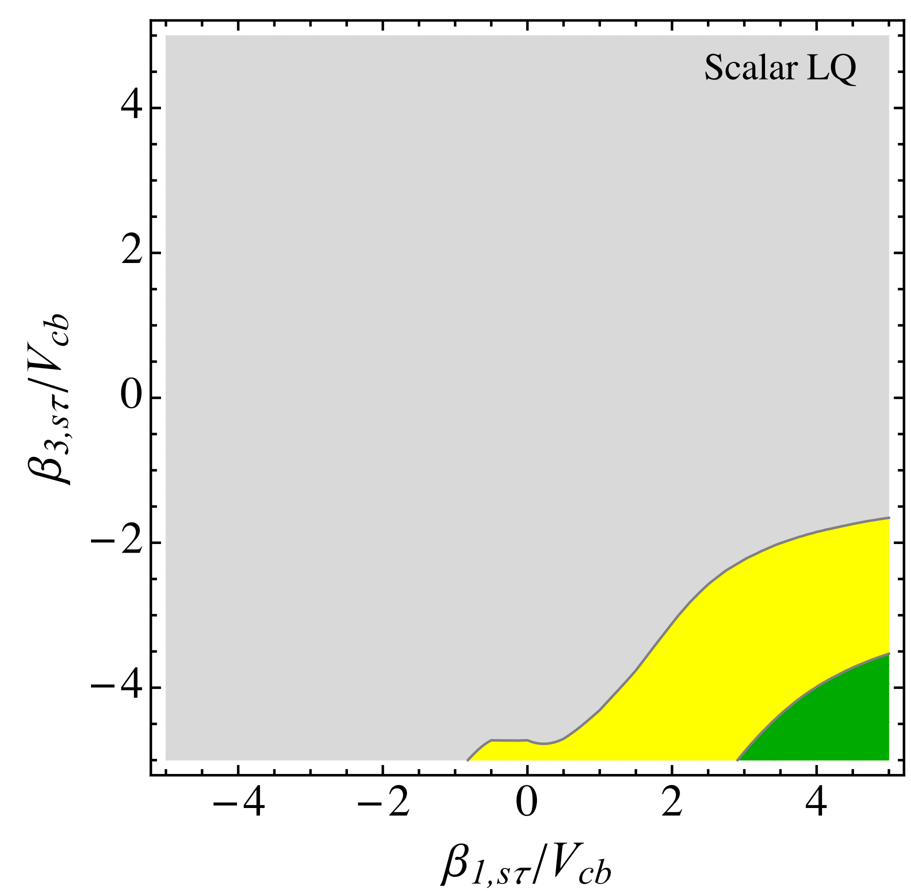
$$\mathcal{L} \supset g_1 y_{1\,i\alpha}(\bar{Q}_L^{c\,i}\epsilon L_L^\alpha)S_1 + g_3 y_{3\,i\alpha}(\bar{Q}_L^{c\,i}\epsilon\sigma^a L_L^\alpha)S_3^a + \text{h.c.}$$

In general, different flavour couplings of singlet and triplet



✓ Renormalisable model:
no contribution to meson mixing

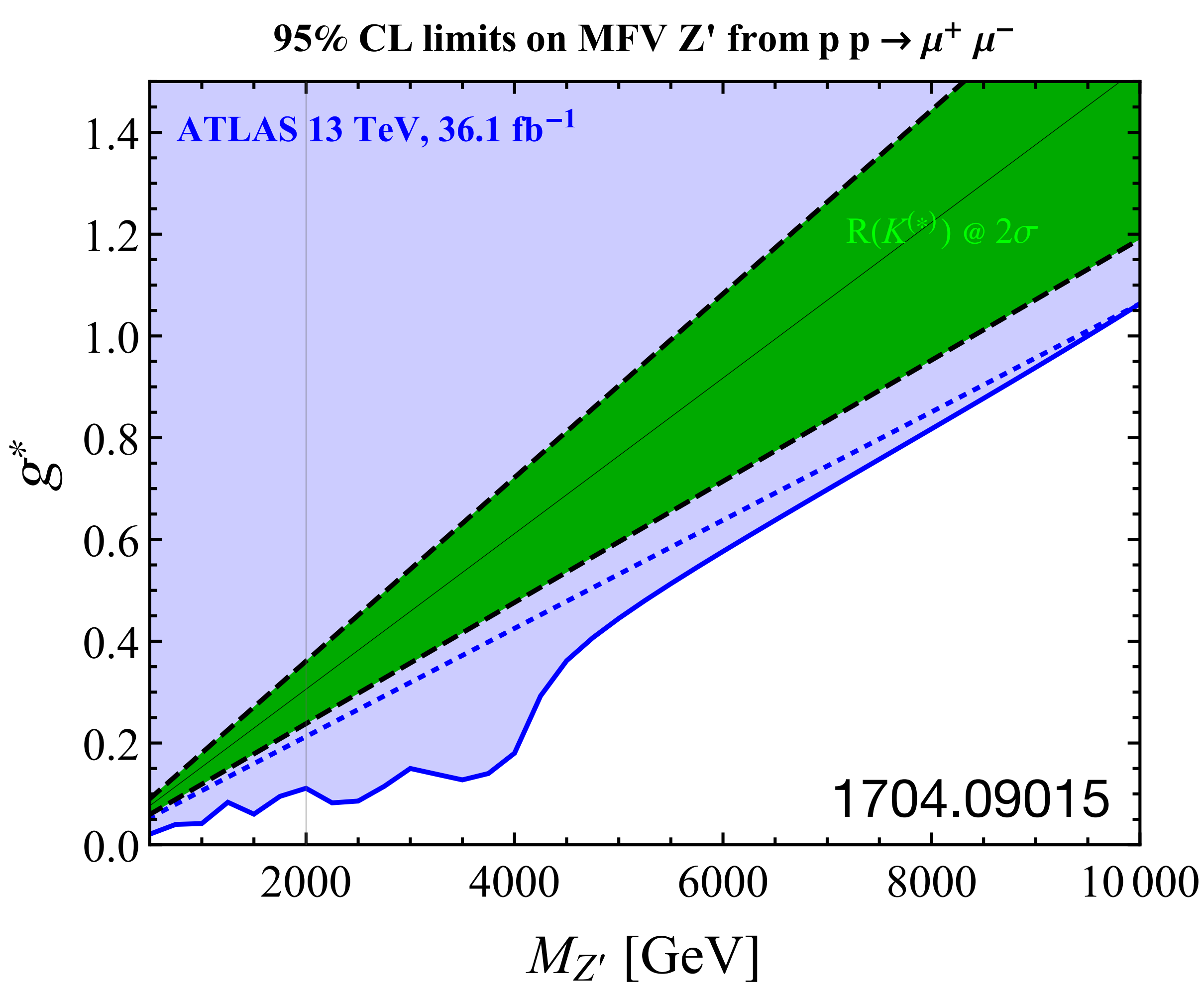


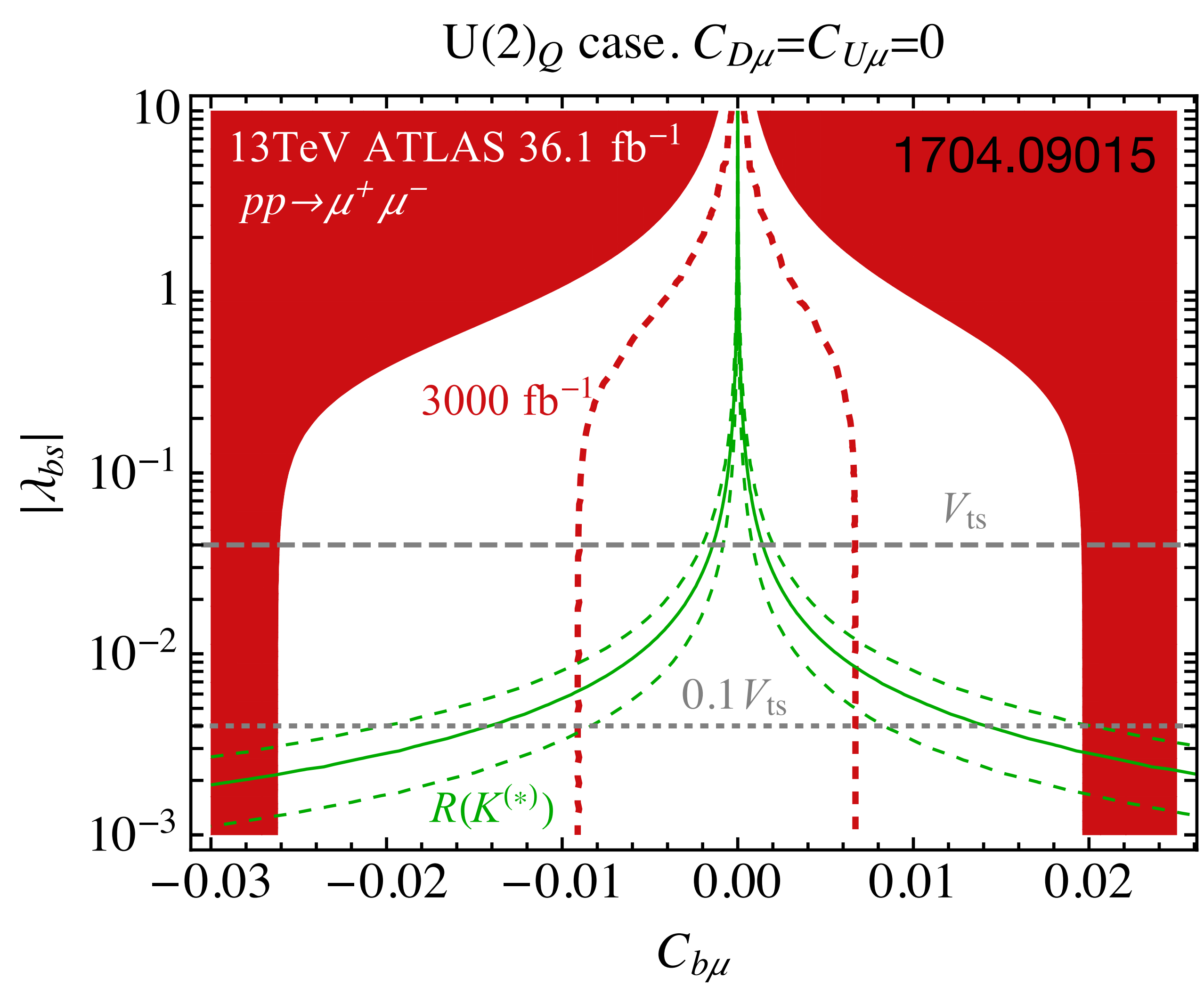


High-pT searches at LHC

- $bb \to \mu\mu$ suppressed by small $\lambda_{\mu\mu}$ (but better experimental sensitivity)
- Searches in tails of the $\mu\mu$ invariant mass distribution:
  - MFV case already excluded
  - Not a relevant bound for U(2) models

Greljo & Marzocca 2017

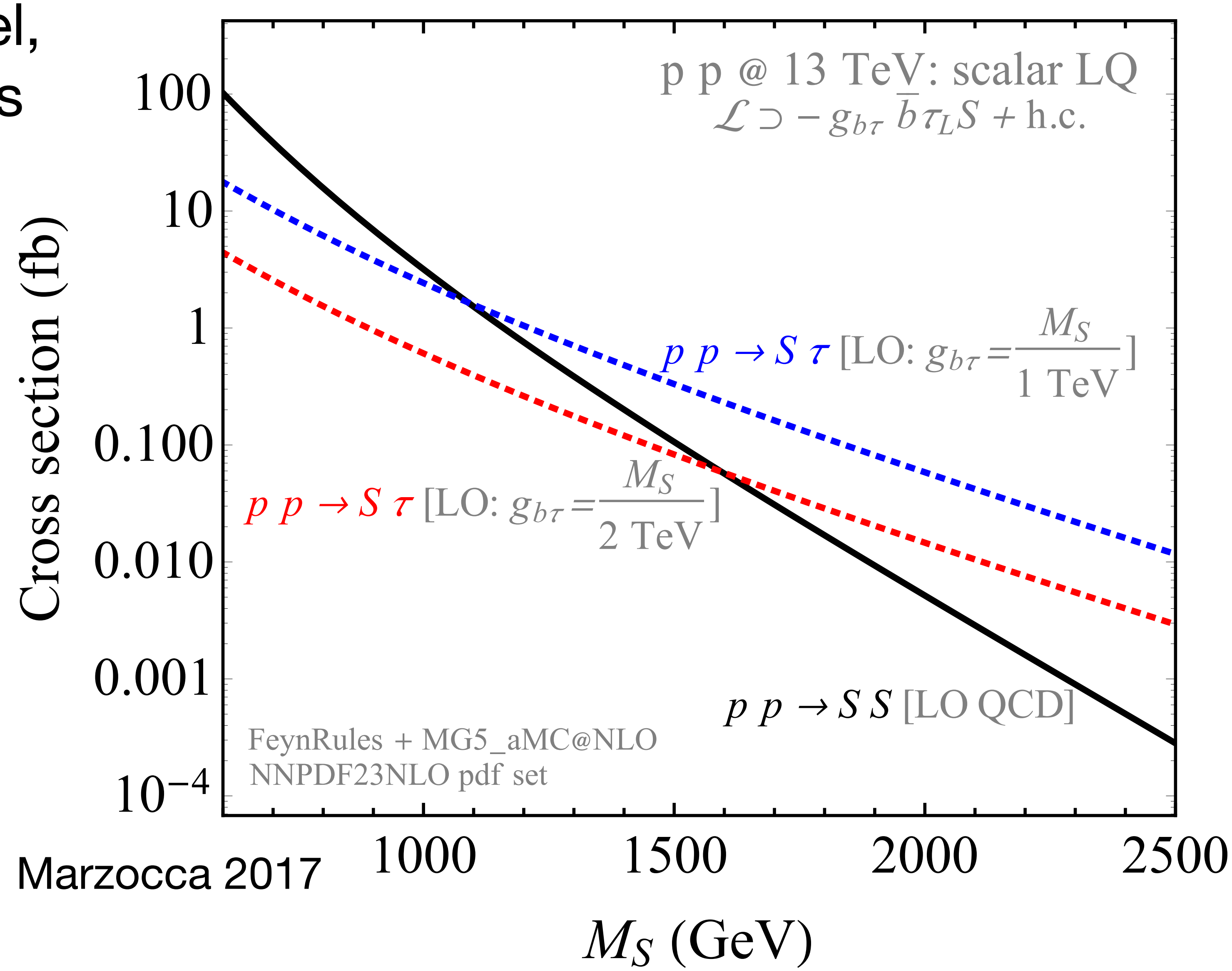




High-pT searches at LHC

- Single LQ production depends on the coupling to fermions
- For high masses (above the LHC reach in double production) single production becomes the dominant production mechanism

$pp \to S\tau$ important search channel, for couplings that fit the anomalies

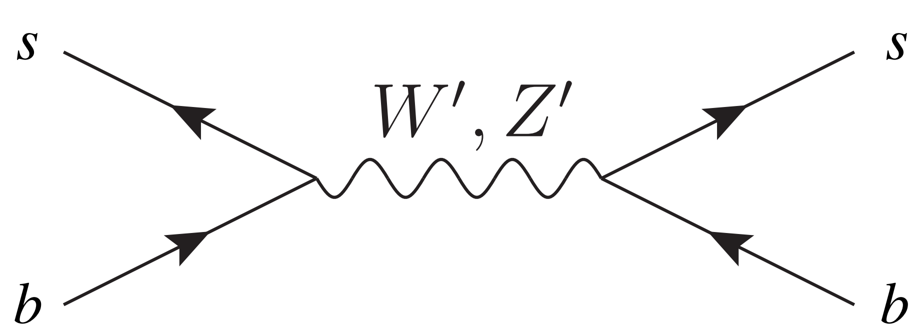


B, Greljo, Isidori, Marzocca 2017

$B_{(s)}$-$\bar{B}_{(s)}$ mixing

- Tree-level contribution to $\Delta F = 2$ amplitudes

$$\Delta A_{B_s}^{\Delta F=2} \simeq \frac{154}{(V_{tb}^* V_{ts})^2} \left[\epsilon_q^2 \lambda_{bs}^2 + (\epsilon_q^0)^2 (\lambda_{bs}^2 + (\lambda_{bs}^d)^2 - 7.14 \lambda_{bs} \lambda_{bs}^d)\right] = 0.07 \pm 0.09$$



tuning of ~ few x 10^{-3}
to satisfy the constraint

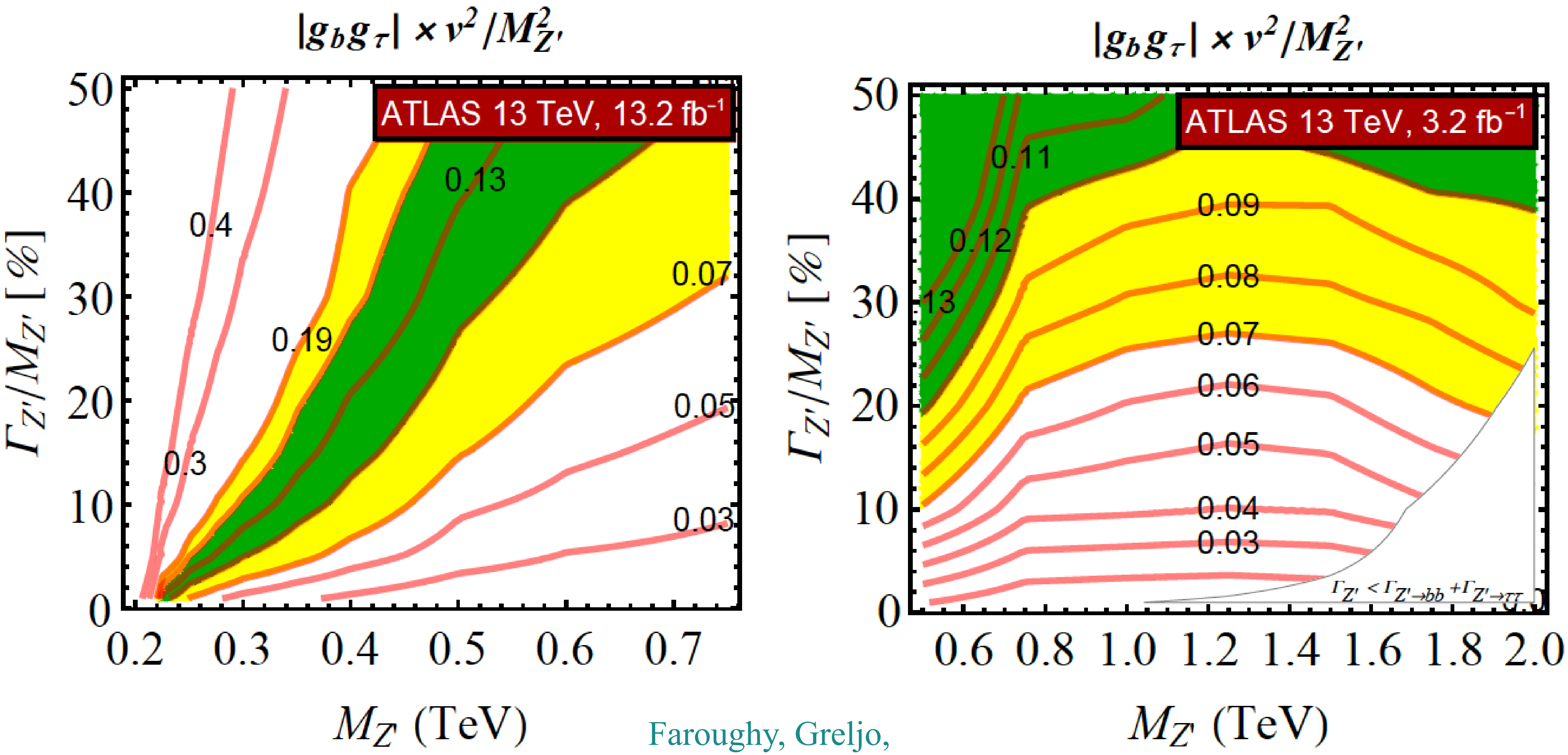
- Can have a mild tuning if C_T is large. Solve the tension with radiative corrections introducing a coupling to the Higgs current…

$$\Delta J_\mu^a = \frac{1}{2}\epsilon_H \left(i H^\dagger \overset{\leftrightarrow}{D^a}_\mu H\right) , \qquad \Delta J_\mu^0 = \frac{1}{2}\epsilon_H^0 \left(i H^\dagger \overset{\leftrightarrow}{D}_\mu H\right)$$

Many free parameters, can find points with mild tuning satisfying the bounds

$$\begin{array}{llll} \epsilon_\ell \approx 0.2 , & \epsilon_q \approx 0.5 , & \epsilon_H \approx -0.01 , & \lambda_{sb}^q / |V_{cb}| \approx -0.07 , \\ \epsilon_\ell^0 \approx 0.1 , & \epsilon_q^0 \approx -0.1 , & \epsilon_H^0 \approx -0.03 , & \lambda_{\mu\mu}^\ell \approx 0.2 . \end{array}$$

ATLAS heavy vector searches



Faroughy, Greljo, Kamenik '16