B-physics and viable NP(LQ) scenarios

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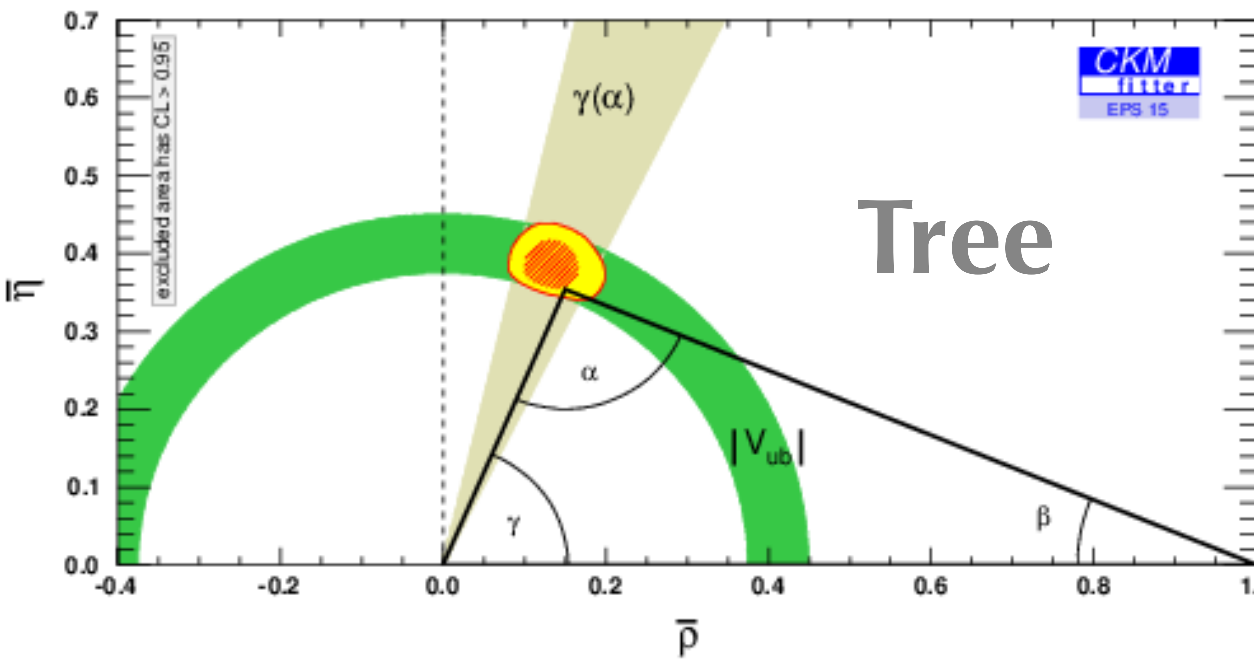
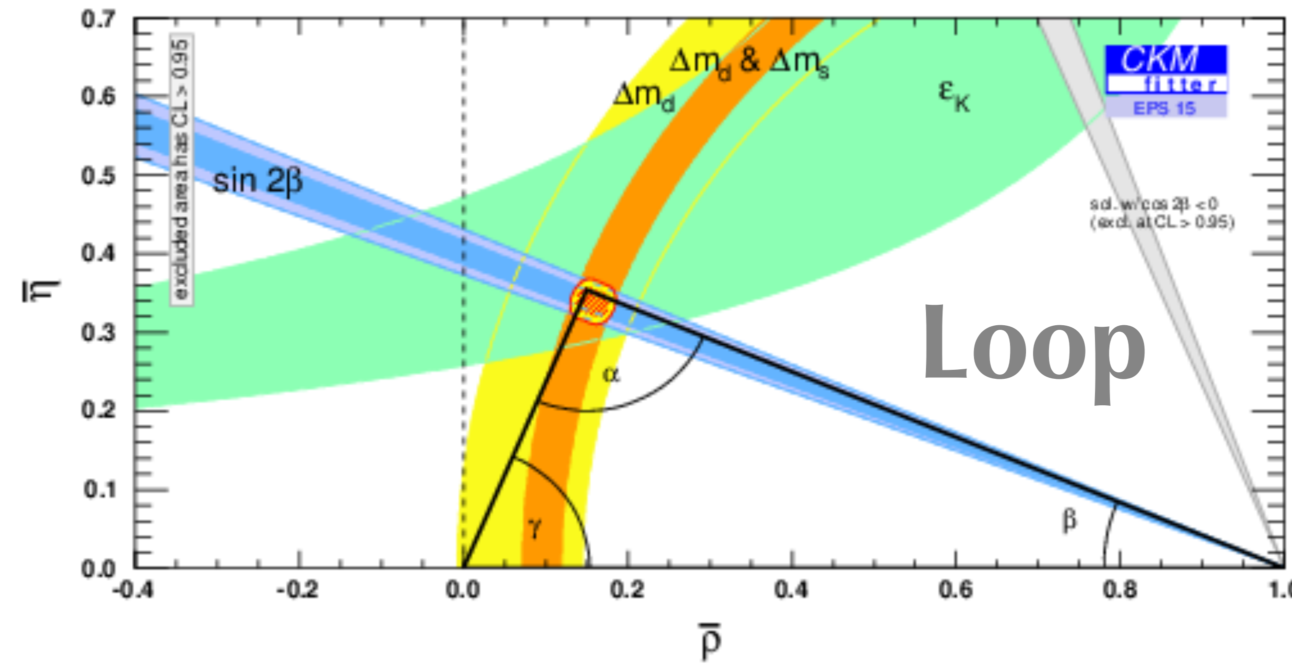
Workshop FCC-France (May 2020)

based on works done with
A. Angelescu, P. Arnan, I. Doršner, S. Fajfer, D. Faroughy, N. Košnik,
F. Mescia, O. Sumensari, R. Zukanovich-Funchal

Turn of the 21st century CKM



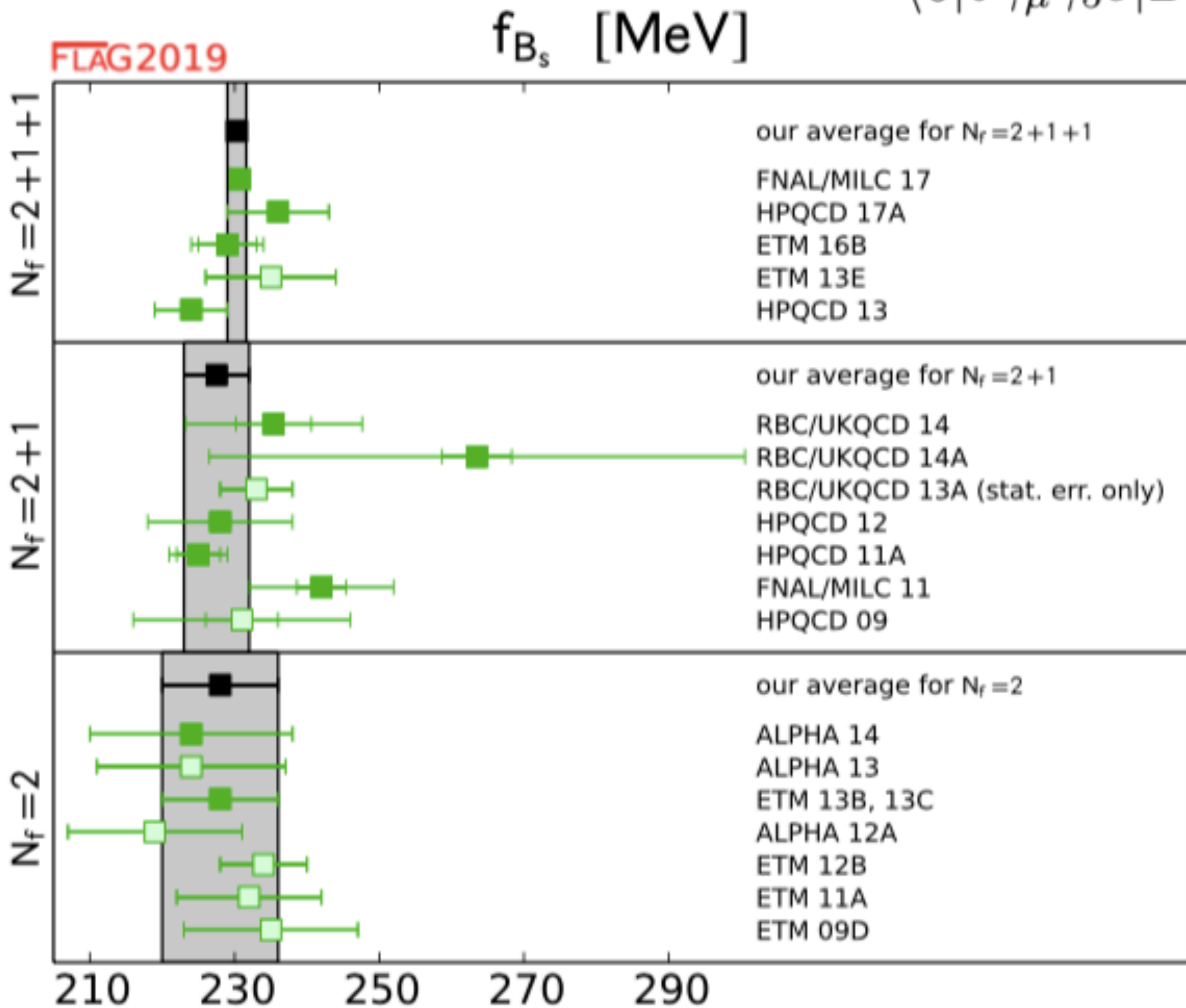


Impressively — TL UT and LP UT agree to less than 10%
CPV phase is non-zero but too small to accommodate the observes BAU

[Experiment - high precision era! Lattices huge improvement!]
Only tensions in Vub and Vcb (inclusive Vs. exclusive) but all in all, CKM is very unitary!
2008, Nobel Prize

Impressive progress in LQCD

$$\langle 0|\bar{b}\gamma_\mu\gamma_5 s|B_s(p)\rangle = i f_{B_s} p_\mu$$

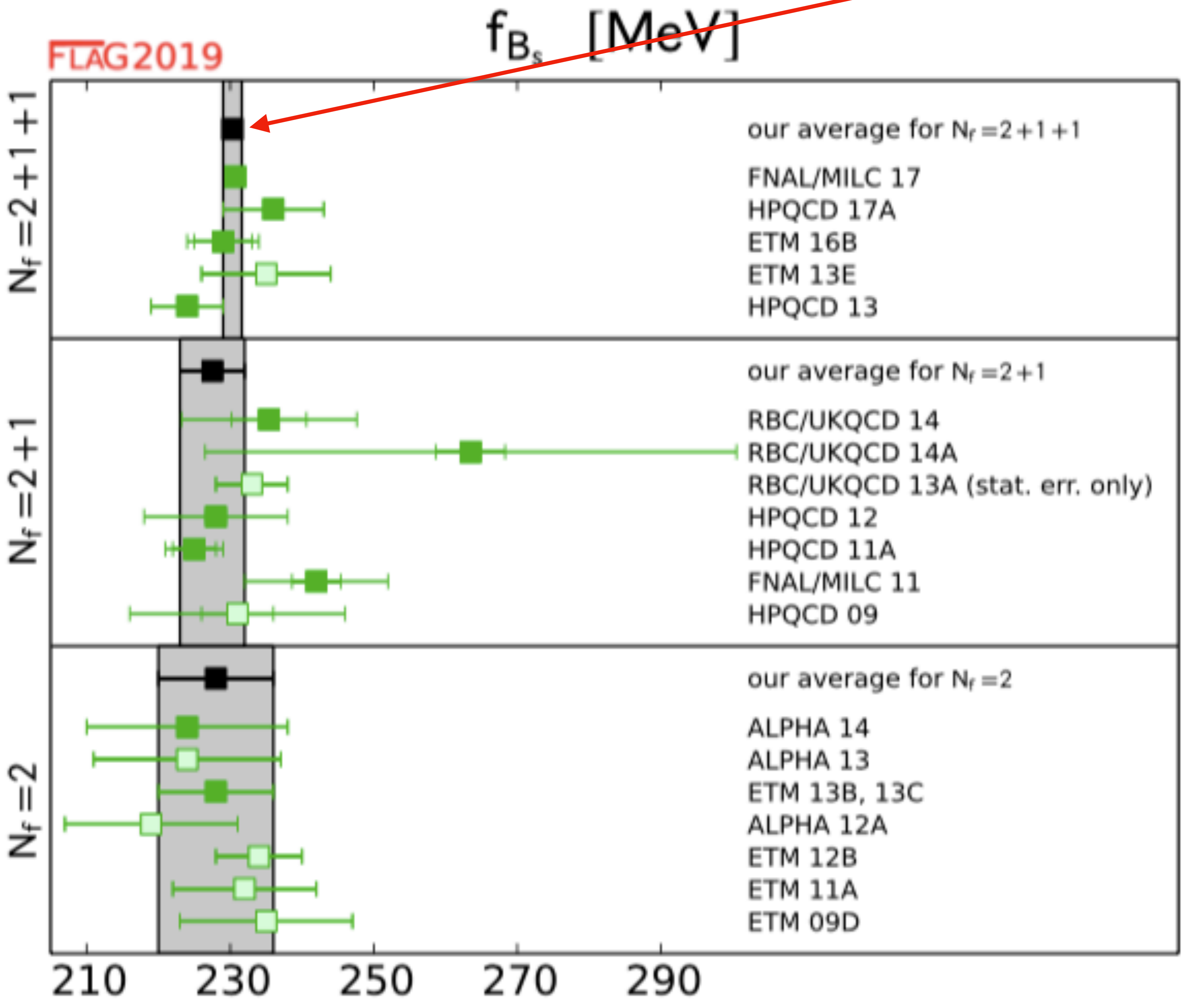


cf. FLAG review 2019, 1902.08191

Impressive progress in LQCD

$$f_{B_s} = 230.3 \pm 1.3 \text{ MeV}$$

$< 0.6\%$ -precision!

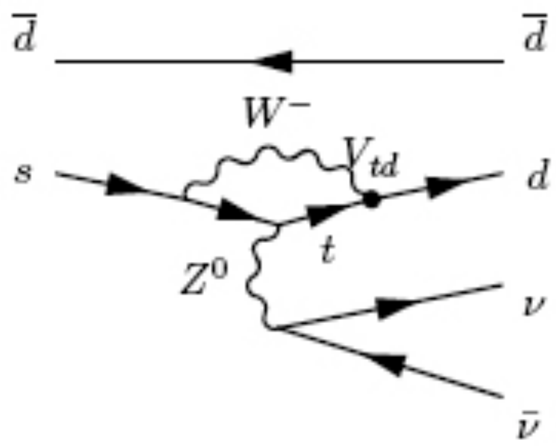


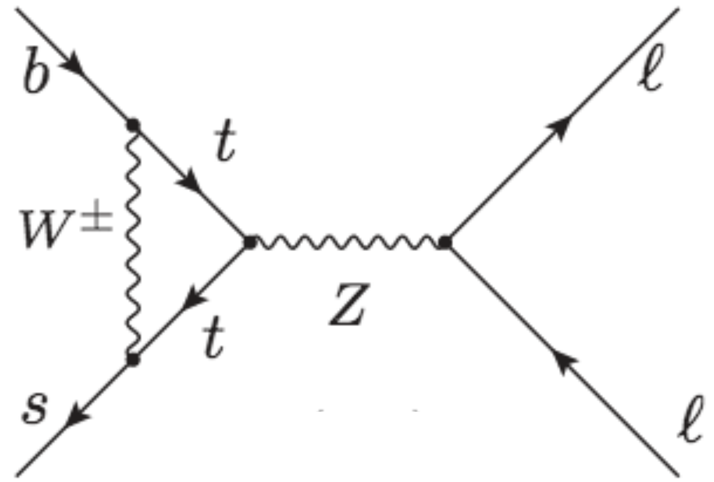
cf. FLAG review 2019, 1902.08191

Or else… NP searches

Strategy:

fix V_{ij} from tree level processes, then look for NP in FCNC



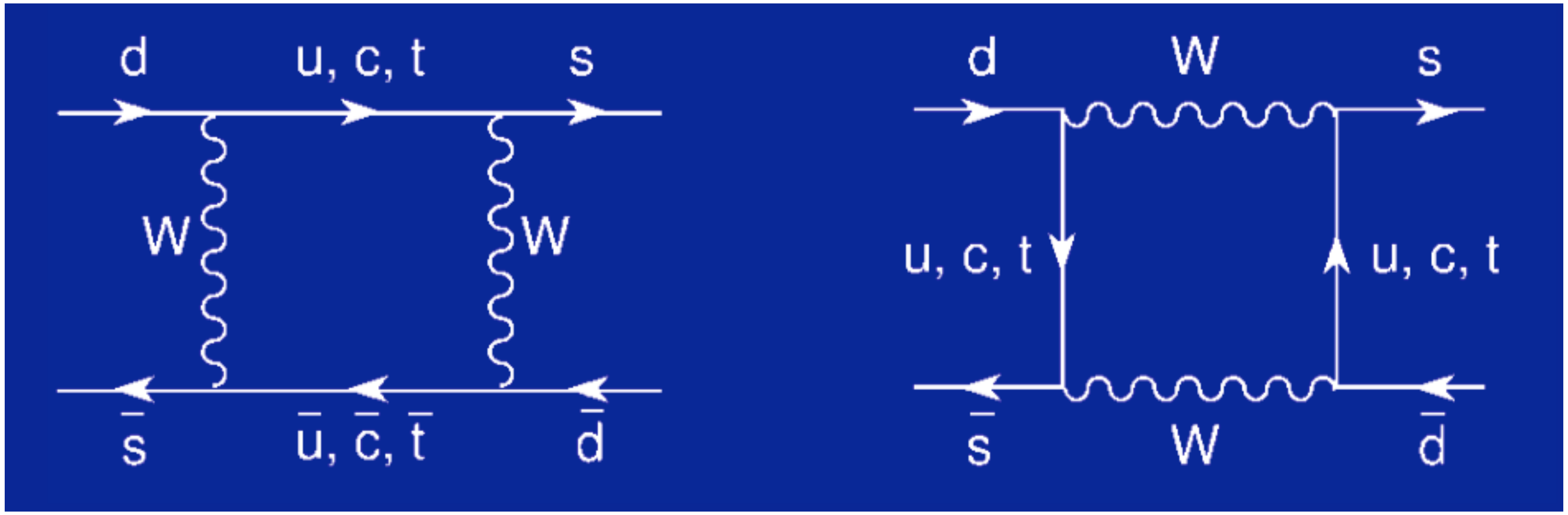


$\mathcal{B}(B_s \to \mu^+\mu^-)_{\text{theo.}} = 3.34\,\left(^{+13}_{-25}\right) \times 10^{-9}$ $\mathcal{B}(B_s \to \mu^+\mu^-)_{\text{LHCb+CMS}} = 2.9(7) \times 10^{-9}$

C_{ij}	1	$V_{ti}V_{tj}^*$
$B_s \to \mu^+\mu^-$	> 10 TeV	> 2.5 TeV
$K \to \pi\nu\bar{\nu}$	> 100 TeV	> 1.8 TeV

$$O = \frac{1}{\Lambda^2} C_{ij} \bar{Q}_i \gamma^\mu Q_j H^\dagger D_\mu H$$

Strategy:
fix V_{ij} by tree level processes, then look for NP in FCNC



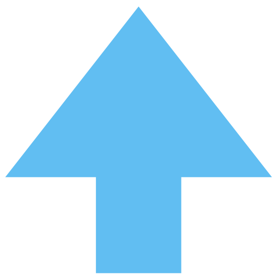
$$O = \frac{1}{\Lambda^2} C'_{ij} \bar{Q}_i \gamma^\mu Q_j \bar{Q}_i \gamma_\mu Q_j$$

C'_{ij}	1	$\|V_{ti}V^*_{tj}\|^2$
$K^0 - \overline{K}^0$	$> 2 \times 10^4$ TeV	> 8 TeV
$B^0 - \overline{B}^0$	$> 0.5 \times 10^4$ TeV	> 5 TeV
$B^0_s - \overline{B}^0_s$	$> 0.1 \times 10^4$ TeV	> 5 TeV

Flavor puzzle

C_{ij}	1	$V_{ti}V_{tj}^*$
$B_s \to \mu^+\mu^-$	> 10 TeV	> 2.5 TeV
$K \to \pi\nu\bar{\nu}$	> 100 TeV	> 1.8 TeV

C'_{ij}	1	$\lvert V_{ti}V_{tj}^*\rvert^2$
$K^0 - \overline{K}^0$	$> \; 2 \times 10^4$ TeV	> 8 TeV
$B^0 - \overline{B}^0$	$> \; 0.5 \times 10^4$ TeV	> 5 TeV
$B_s^0 - \overline{B}_s^0$	$> \; 0.1 \times 10^4$ TeV	> 5 TeV



- **For natural C~O(1), NP scale is huge**
- **Need lots of fine tuning to reduce NP scale to O(1TeV) as needed to mend the hierarchy problem**
- **Way out: NP is (almost) aligned with the SM**
- **MFV**

2012 - 202X : LFUV was and still is exciting

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \qquad \& \qquad R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}}$$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\bigg|_{q^2\in[q^2_{\text{min}},q^2_{\text{max}}]} \qquad \& \qquad R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}}$$

Also corroborated by LHCb through $R^{\text{exp}}_{J/\psi} > R^{\text{SM}}_{J/\psi}$, $R^{\text{exp}}_{pK} > R^{\text{SM}}_{pK}$

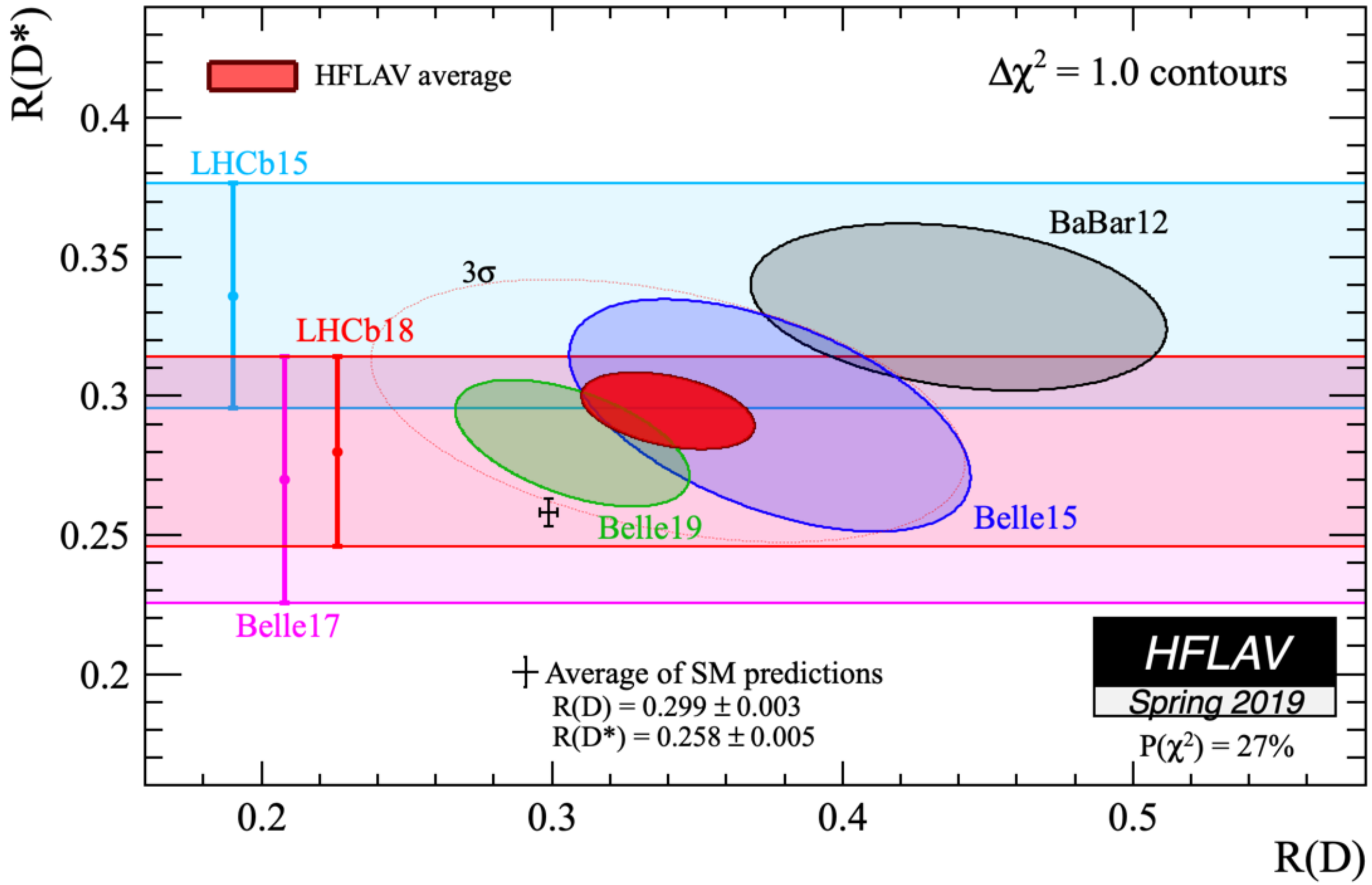
$$R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}} \quad \Rightarrow \quad \Lambda_{\text{NP}} \lesssim 3 \text{ TeV}$$

$$R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}} \quad \Rightarrow \quad \Lambda_{\text{NP}} \lesssim 30 \text{ TeV}$$

Di Luzio et al. 2017

After Moriond EW 2019

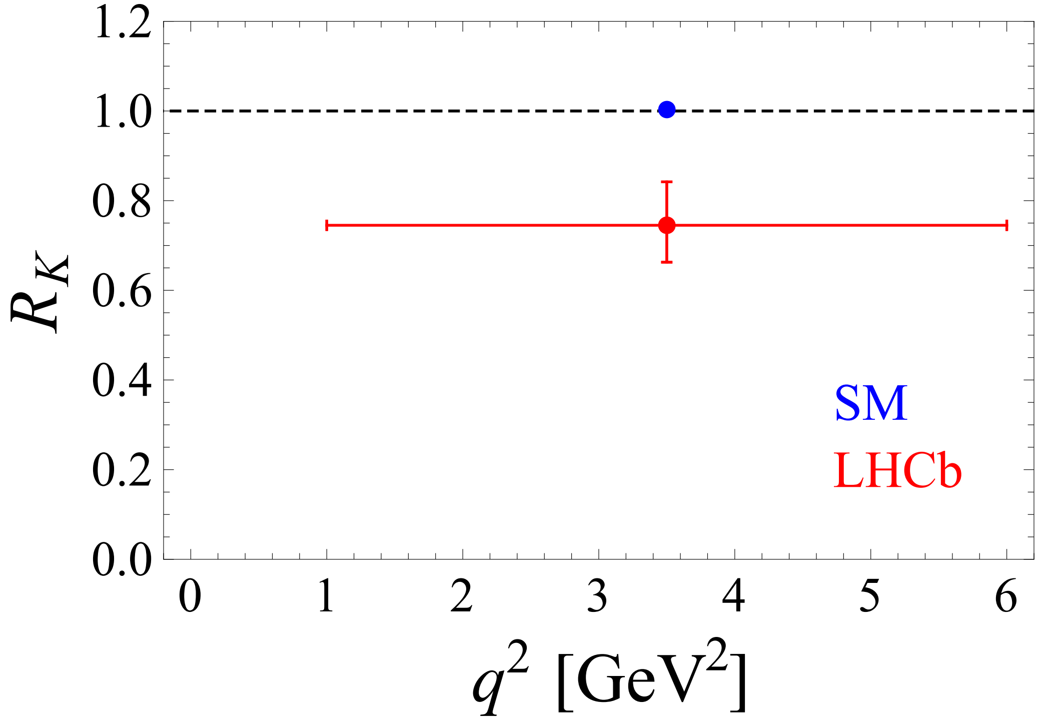
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$

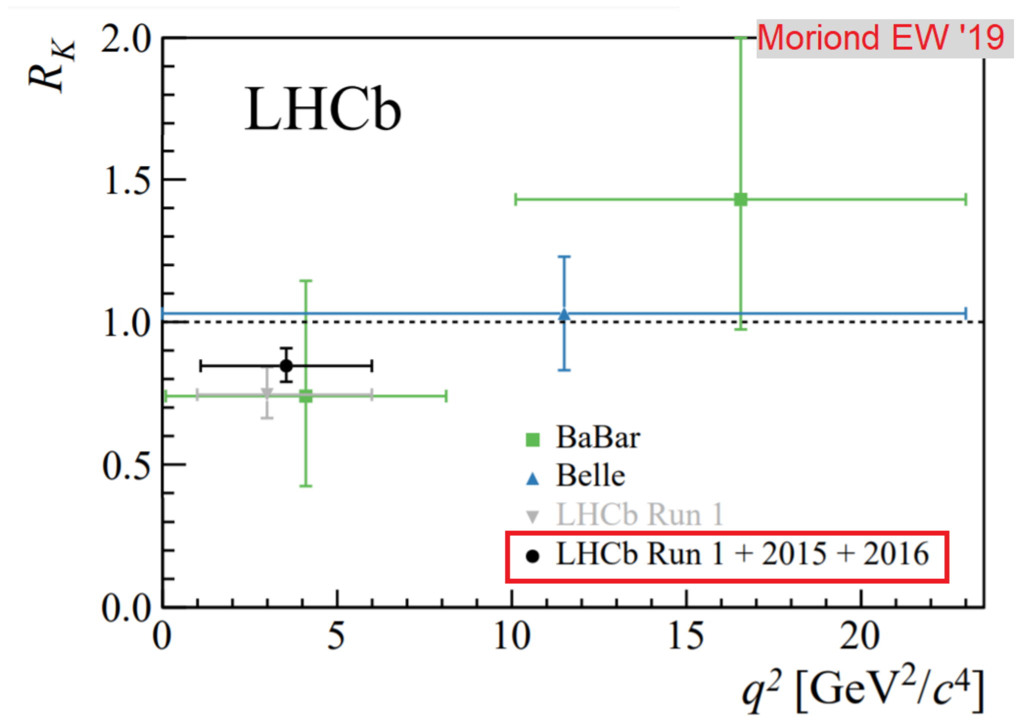


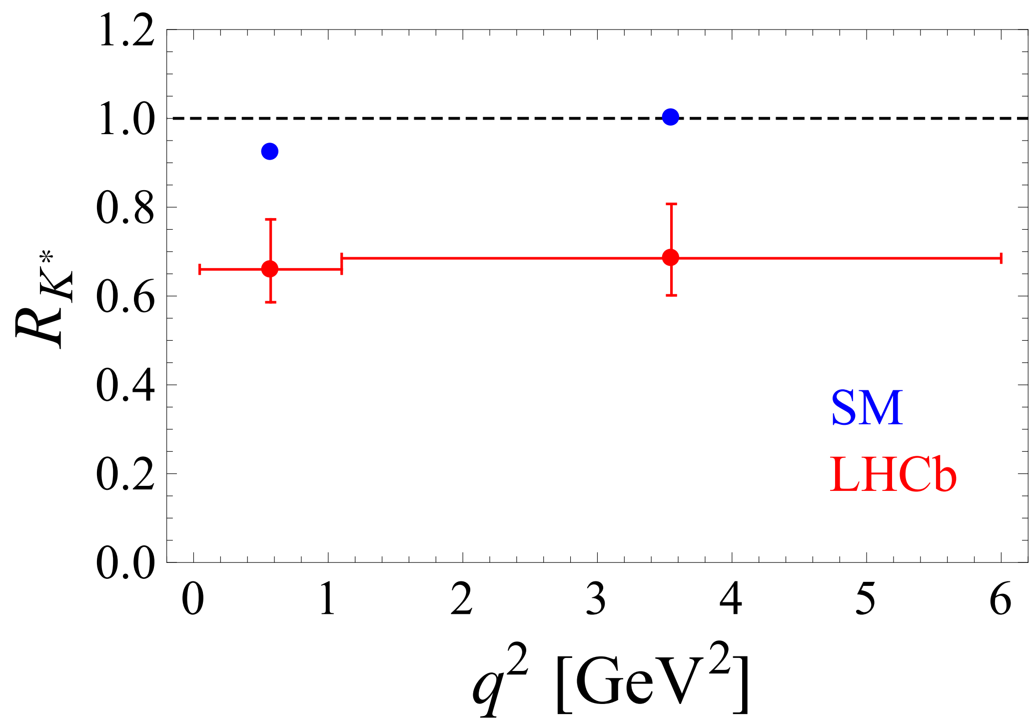
- NEW [Belle]: $R_D = 0.31(4)$, $R_{D^*} = 0.28(2)$.
- $R_{D^{(*)}}$ discrepancy w.r.t. SM predictions decreases from 3.8σ to 3.1σ.
- Large disagreement between BaBar and Belle results.

$\Rightarrow$ **Unclear exp. situation!**

After Moriond EW 2019







- NEW [LHCb]:

$$[R_K^{\text{new}}]_{\text{avg}} = 0.85(6)$$

- Discrepancy between Run 1 and Run 2 [$\approx 2\sigma$]:

$$[R_K^{\text{new}}]_{\text{run 1}} = 0.71(8)$$

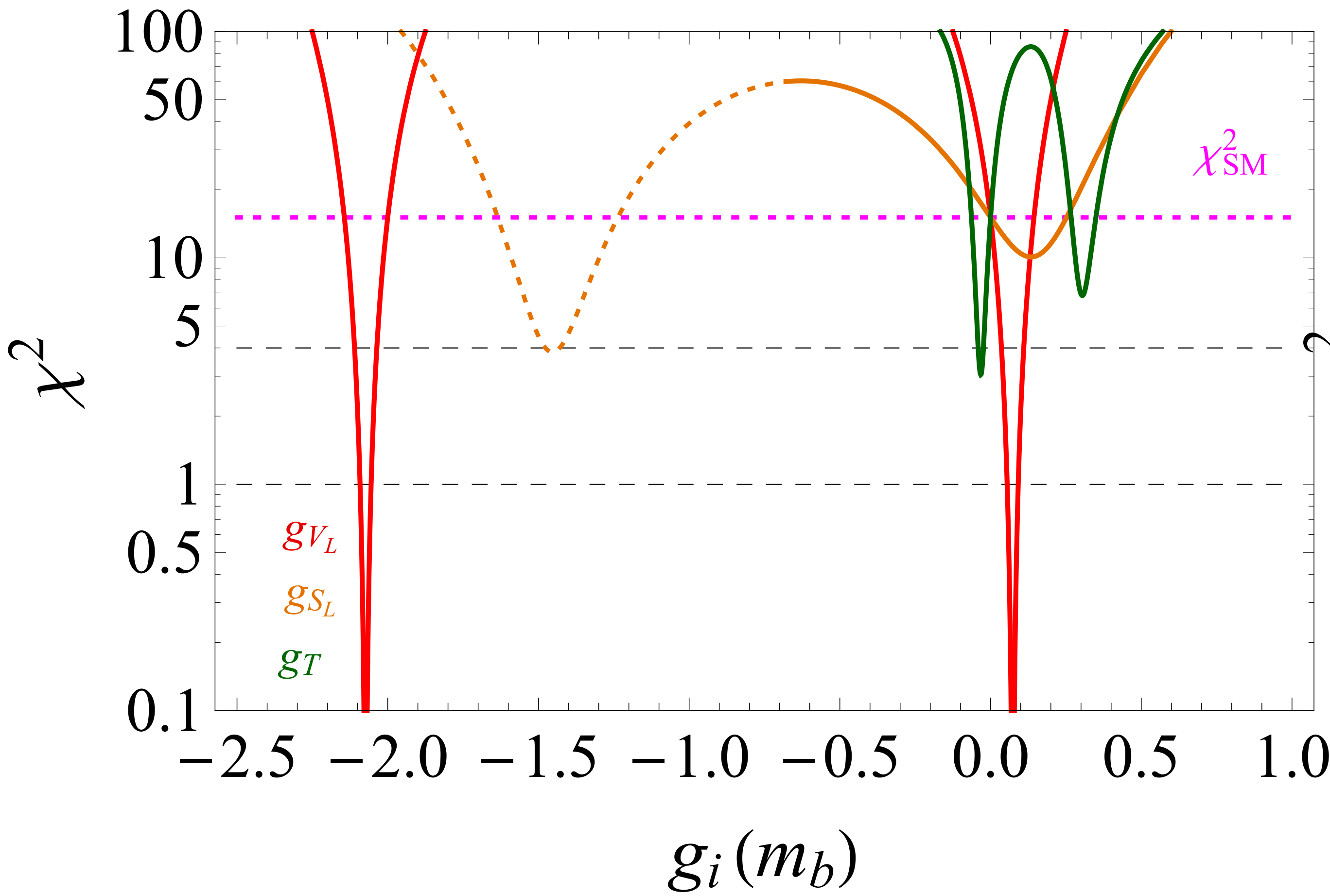
$$[R_K^{\text{new}}]_{\text{run 2}} = 0.92(8)$$

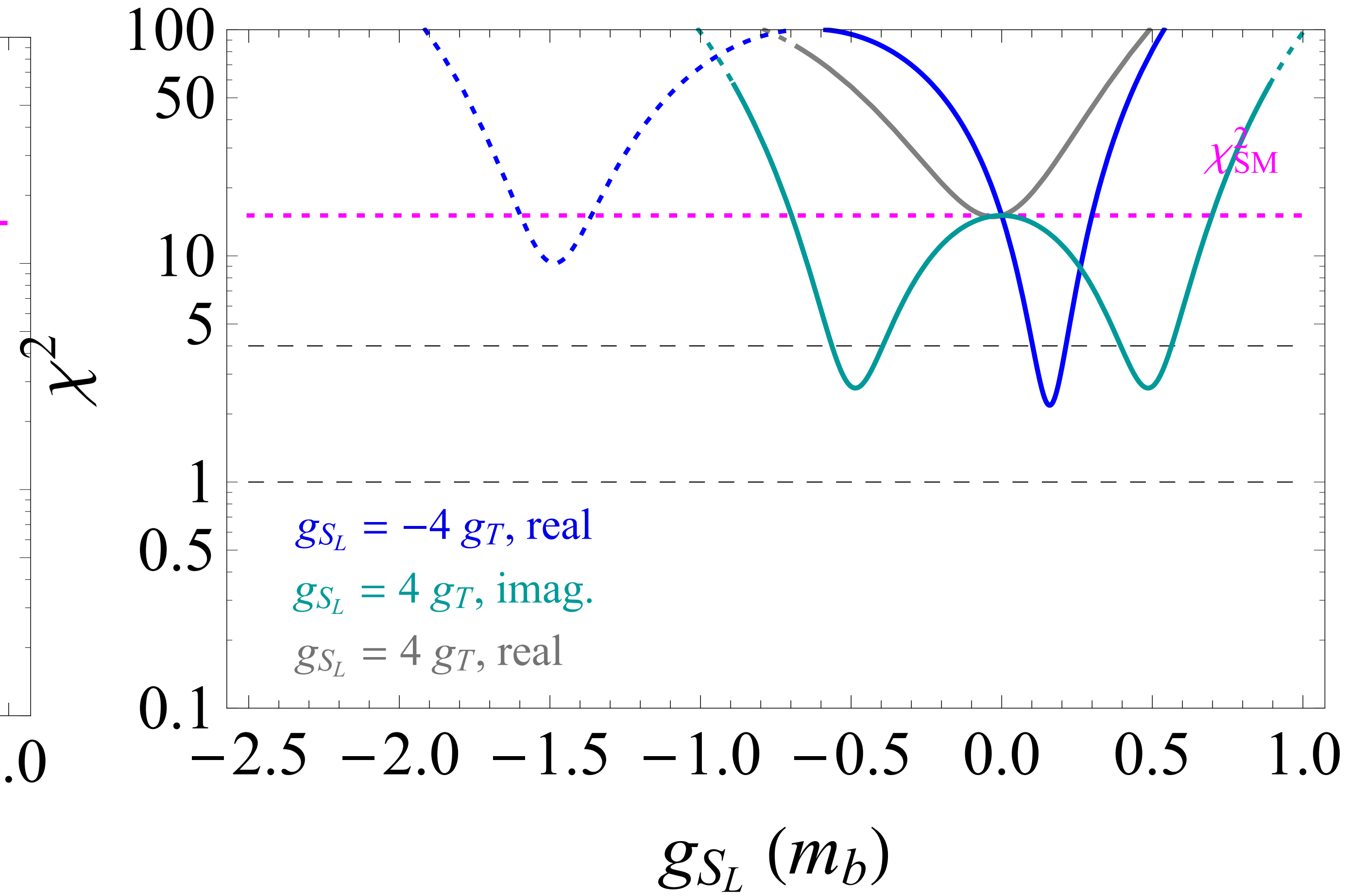
EFT - exclusive $b \to c\ell\nu$

$$\mathcal{L}_{\rm eff} = -2\sqrt{2} G_F V_{cb} \Big[(1 + g_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) + g_{V_R} (\bar{c}_R \gamma_\mu b_R)(\bar{\ell}_L \gamma^\mu \nu_L)$$
$$+ g_{S_R} (\bar{c}_L b_R)(\bar{\ell}_R \nu_L) + g_{S_L} (\bar{c}_R b_L)(\bar{\ell}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \Big] + \text{h.c.}$$

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:
  - $\Rightarrow$ g_{V_R} is LFU at dimension 6 ($W \bar{c}_R b_R$ vertex).
  - $\Rightarrow$ Four coefficients left: g_{V_L}, g_{S_L}, g_{S_R} and g_T.
- Several viable solutions to $R_{D^{(*)}}$: [Freytsis et al. 2015]
  - ○ e.g. $g_{V_L} \in (0.04, 0.11)$, but not only!

Which coupling? Situation after Moriond EW 2019





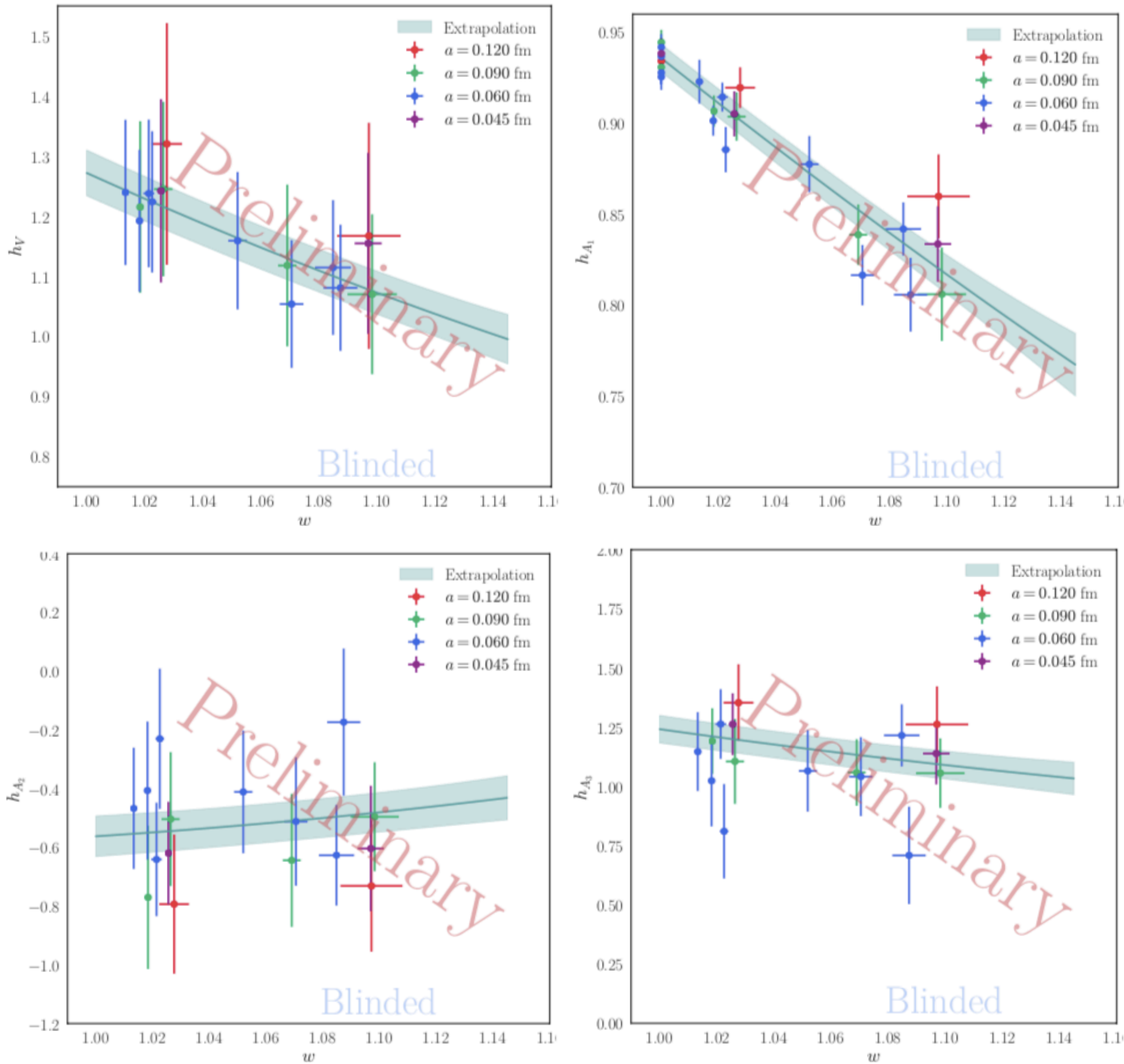
Updates of Freytsis et al. '15 Angelescu et al. '18

Which Lorentz structure to pick?

Observables from angular distribution of $B \to D^*(D\pi)\ell\nu$ can help

cf. 1907.02257

LQCD - WORK IN PROGRESS



MILC-Fermilab 1912.05886

What LQ scenario for R_D and R_{D^*} ?

Model	$g_{\text{eff}}^{b\to c\tau\bar{\nu}}(\mu = m_\Delta)$	$R_{D^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	g_{V_L}, $g_{S_L} = -4\, g_T$	✓
$R_2 = (3, 2, 7/6)$	$g_{S_L} = 4\, g_T$	✓
$S_3 = (\bar{3}, 3, 1/3)$	g_{V_L}	✗
...	...	...
$U_1 = (3, 1, 2/3)$	g_{V_L}, g_{S_R}	✓
$U_3 = (3, 3, 2/3)$	g_{V_L}	✗
...	...	...

Viable models for $R_{D^{(*)}}$:

- U_1 (g_{V_L}), S_1 (g_{V_L} and $g_{S_L} = -4\, g_T$), and R_2 ($g_{S_L} = 4\, g_T \in \mathbb{C}$)
- Some models are excluded by other flavor constraints: $B \to K\nu\bar{\nu}$, Δm_{B_s}...
- Possibility to distinguish them by using other $b \to c\ell\nu$ observables!

EFT - exclusive $b \to s\ell\ell$

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}}\,V_{tb}\,V_{ts}^{*}\left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\ldots}\Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i'\Big)\right] + \text{h.c.}$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma^5 \ell)$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

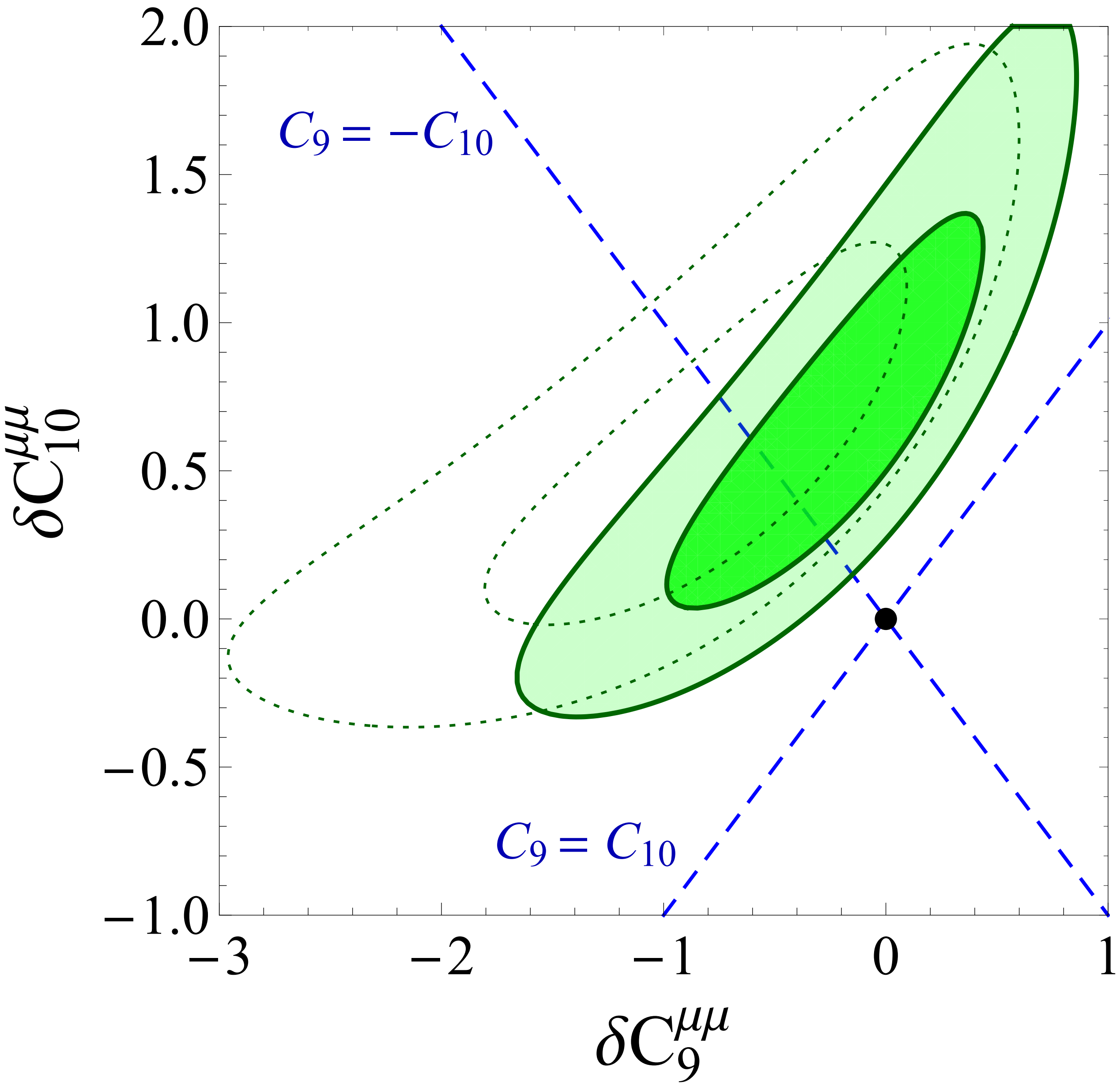
$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

$$\mathcal{B}(B_s \to \mu\mu)^{\rm exp} = \big(3.0 \pm 0.6^{+0.3}_{-0.2}\big)\times 10^{-9}$$

[LHCb, '17], [CMS, Atlas. '18]

Fit to clean quantities: $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$

EFT for $b \to s\ell\ell$



- Only vector (axial) coefficients can accommodate data.
- $C'_{9,10}$ disfavored by $R_{K^*}^{\text{exp}} < R_{K^*}^{\text{SM}}$
- $C_9 = -C_{10}$ allowed – consistent with a left-handed $SU(2)_L$ invariant operator!

OK with global fits by Descotes-Genon et al, Hurth et al, Guadagnoli et al.

What LQ scenario for R_K and R_{K^*} ?

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

N.B. U_1 is the only one to accommodate both!

Observable
$b \to s\mu\mu$
$b \to c\tau\nu$
$\mathcal{B}(\tau \to \mu\phi)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(D_s \to \mu\nu)$
$\mathcal{B}(D_s \to \tau\nu)$
$r_K^{e/\mu}$
$r_K^{\tau/\mu}$
$R_D^{\mu/e}$

U_1

$$\mathcal{L} = x_L^{ij}\, \bar{Q}_i \gamma_\mu U_1^\mu L_j + x_R^{ij}\, \bar{d}_{Ri} \gamma_\mu U_1^\mu \ell_{Rj} + \text{h.c.}\,,$$

Assumptions:

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}, \qquad x_R \approx 0\,.$$

- $b \to c\tau\bar{\nu}$:

$$g_{V_L} = \frac{v^2}{2m_{U_1}^2} \left(x_L^{b\tau}\right)^* \left(x_L^{b\tau} + \frac{V_{cs}}{V_{cb}} x_L^{s\tau}\right) \neq 0$$

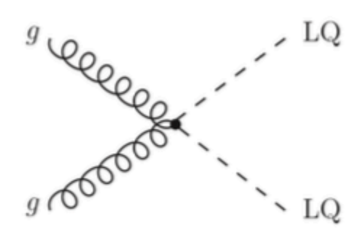
$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$$

- $b \to s\mu\mu$:

$$C_9^{\mu\mu} = -C_{10}^{\mu\mu} \propto -\frac{\pi v^2}{m_{U_1}^2} \left(x_L^{b\mu}\right)^* x_L^{s\mu} \neq 0$$

- Other observables: $\tau \to \mu\phi$, $B \to \tau\bar{\nu}$, $D_{(s)} \to \mu\bar{\nu}$, $D_s \to \tau\bar{\nu}$, $K \to \mu\bar{\nu}/K \to e\bar{\nu}$, $\tau \to K\bar{\nu}$ and $B \to D^{(*)}\mu\bar{\nu}/B \to D^{(*)}e\bar{\nu}$.

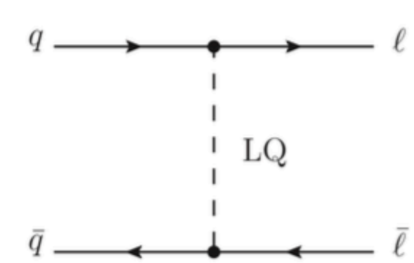
- LQ pair-production via QCD: [CMS-PAS-EXO-17-003]



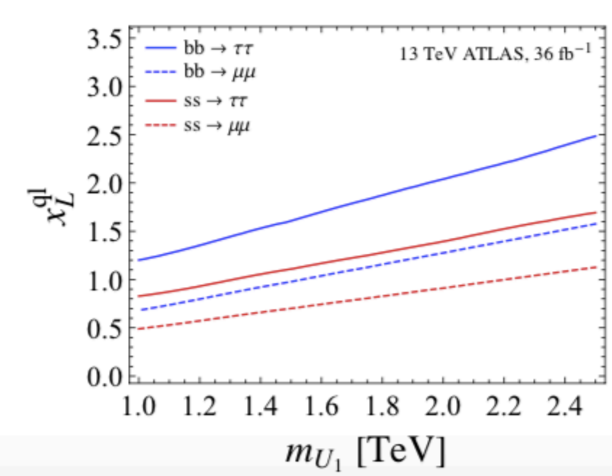
$m_{U_1} \gtrsim 1.5$ TeV

[assuming $\mathcal{B}(U_1 \to b\tau) \approx 0.5$]

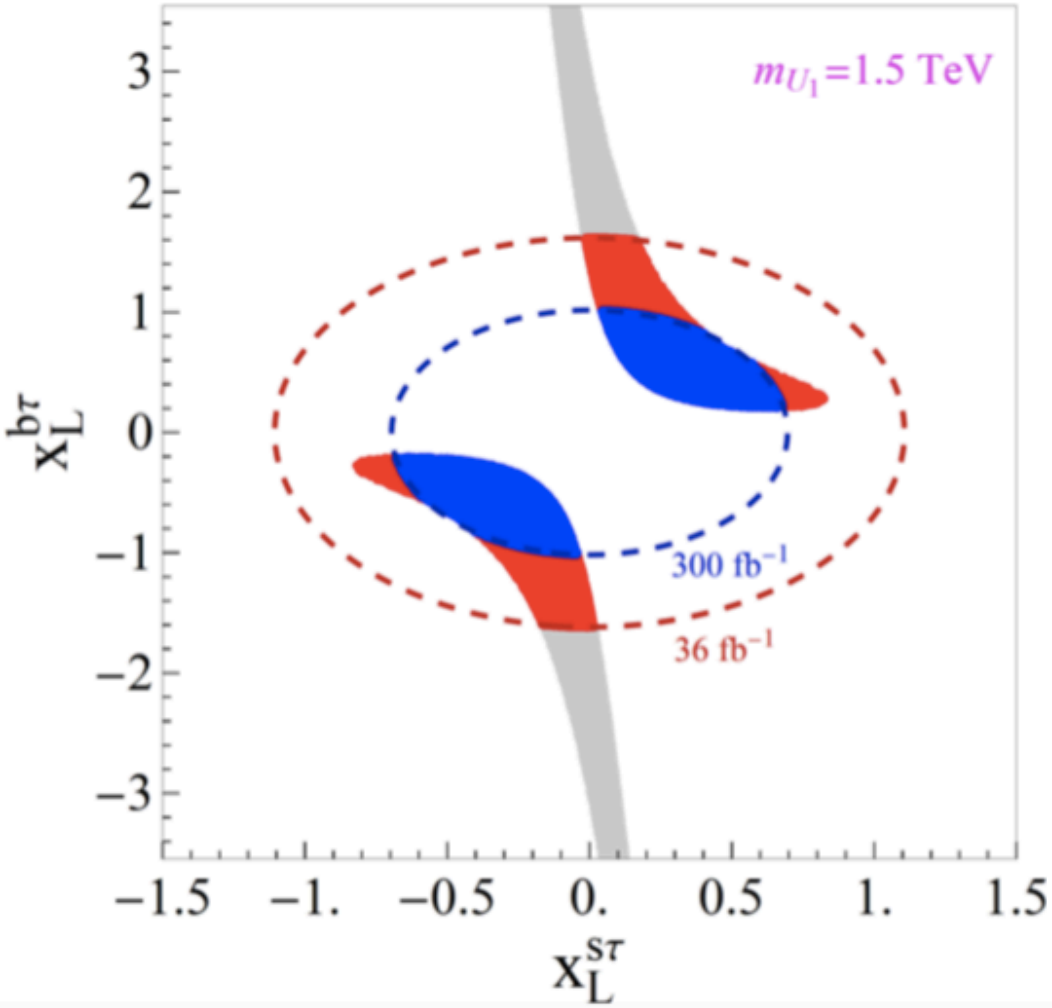
- Di-lepton tails at high-pT: [ATLAS. 1707.02424,1709.07242]

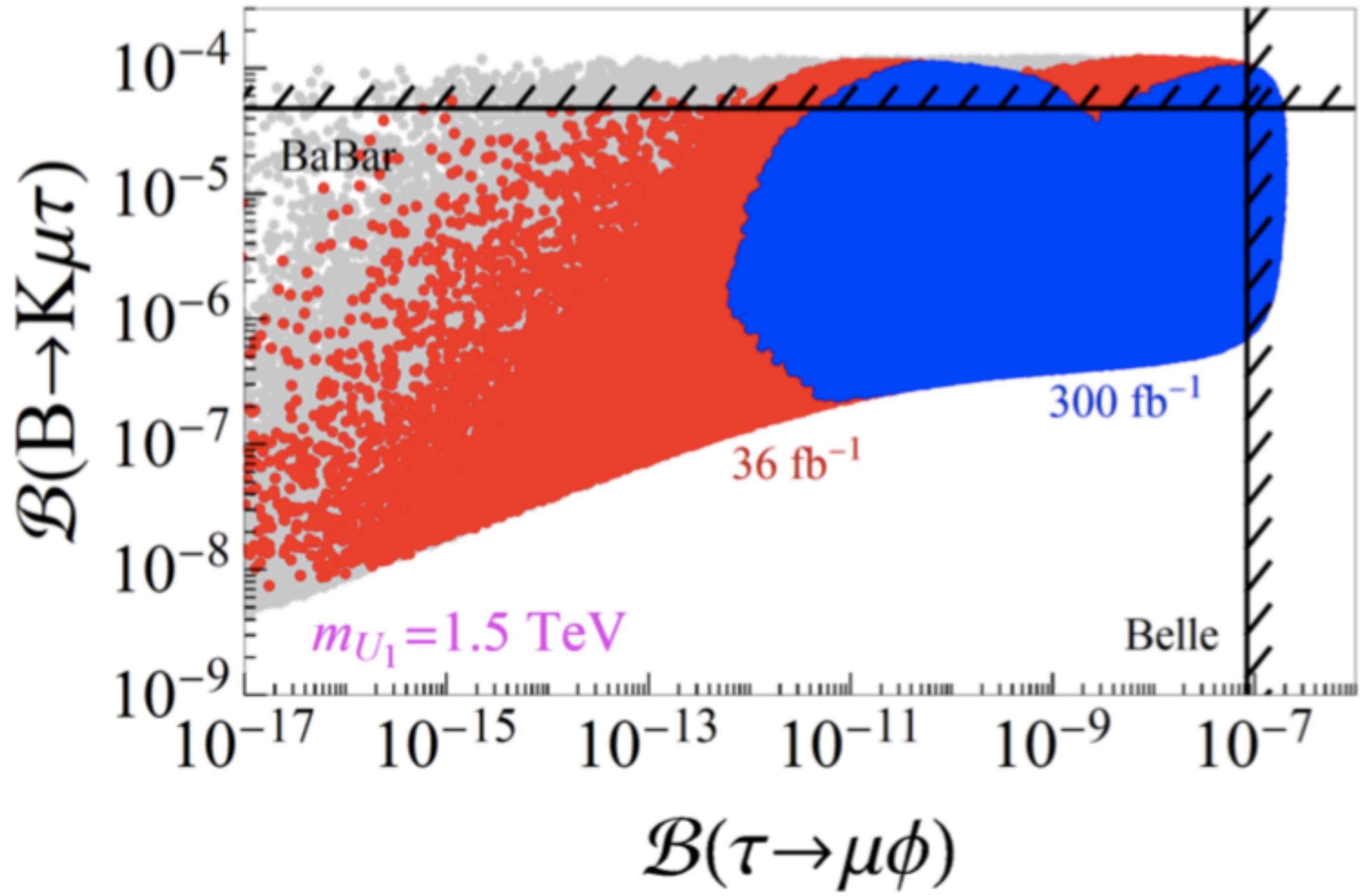


Angelescu et al '18, Faroughy et al '15



U_1





$\mathcal{B}(B \to K\mu\tau) \gtrsim \text{few} \times 10^{-7}$

UV completion:

- Pati-Salam group, $\mathcal{G}_{PS} = SU(4) \times SU(2)_L \times SU(2)_R$, contains $U_1 = (3, 1, 2/3)$.
- Viable extensions of $\mathcal{G}_{PS}$ at the TeV scale have been proposed:
  $\Rightarrow U_1 + Z' + g'$ [+new fermions]. Di Luzio et al '17, Bordone et al. '17, Cornella et al '19

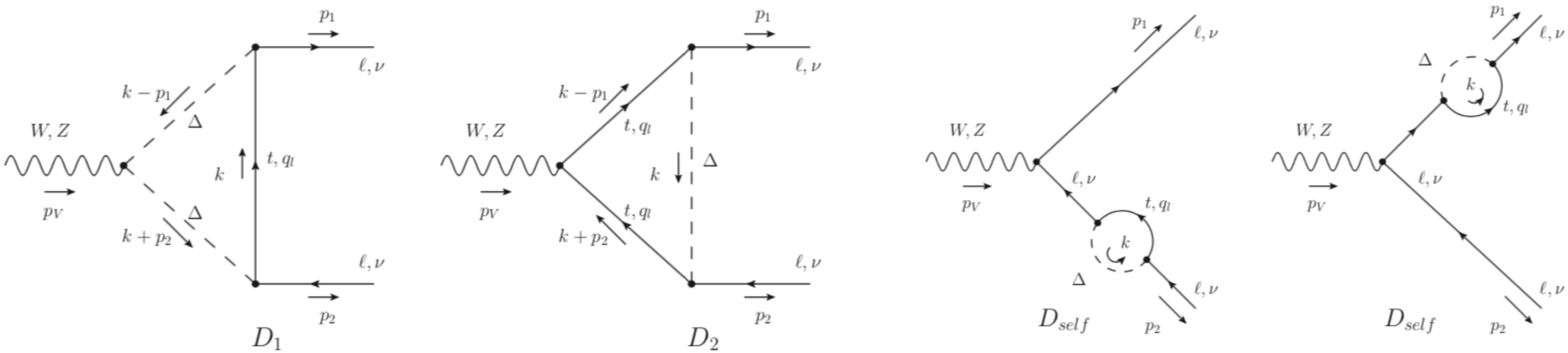
Back to SLQ's

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

Observable
$b \to s\mu\mu$
$b \to c\tau\nu$
$\mathcal{B}(\tau \to \mu\phi)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(D_s \to \mu\nu)$
$\mathcal{B}(D_s \to \tau\nu)$
$r_K^{e/\mu}$
$r_K^{\tau/\mu}$
$R_D^{\mu/e}$

$Z \to \ell\ell$ and $Z \to \nu\nu$

Arnan, D.B., Mescia, Sumensari '19 [arXiv:1901.06315]



$$\delta\mathcal{L}_{\text{eff}}^{Z} = \frac{g}{\cos\theta_W} \sum_{f,i,j} \bar{f}_i \gamma^\mu \left[g_{f_L}^{ij}\, P_L + g_{f_R}^{ij}\, P_R \right] f_j\, Z_\mu$$

$$g_{f_{L(R)}}^{ij} = \delta_{ij}\, g_{f_{L(R)}}^{\text{SM}} + \delta g_{f_{L(R)}}^{ij}$$

$$g_{f_L}^{\text{SM}} = I_3^f - Q^f \sin^2\theta_W$$

$$g_{f_R}^{\text{SM}} = -Q^f \sin^2\theta_W$$

$$g_V^{e,\,\text{exp}} = -0.03817(47) \qquad g_A^{e,\,\text{exp}} = -\,0.50111(35)$$

$$g_V^{\mu,\,\text{exp}} = -0.0367(23) \qquad g_A^{\mu,\,\text{exp}} = -\,0.50120(54)$$

$$g_V^{\tau,\,\text{exp}} = -0.0366(10) \qquad g_A^{\tau,\,\text{exp}} = -\,0.50204(64)$$

Not in Phys.Rep. by Dorsner et al '16

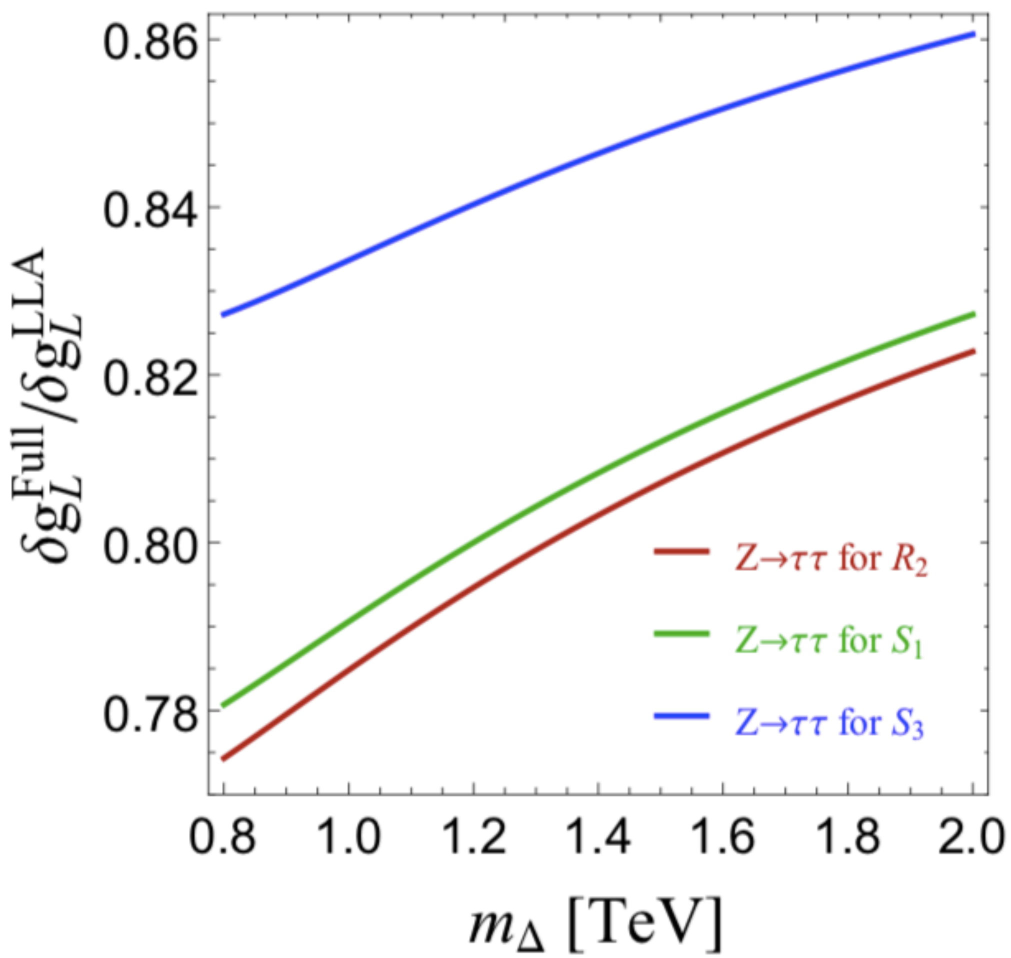
$$\delta\mathcal{L}_{\rm eff}^{Z} = \frac{g}{\cos\theta_W} \sum_{f,i,j} \bar{f}_i \gamma^\mu \left[g_{f_L}^{ij}\, P_L + g_{f_R}^{ij}\, P_R \right] f_j\, Z_\mu$$

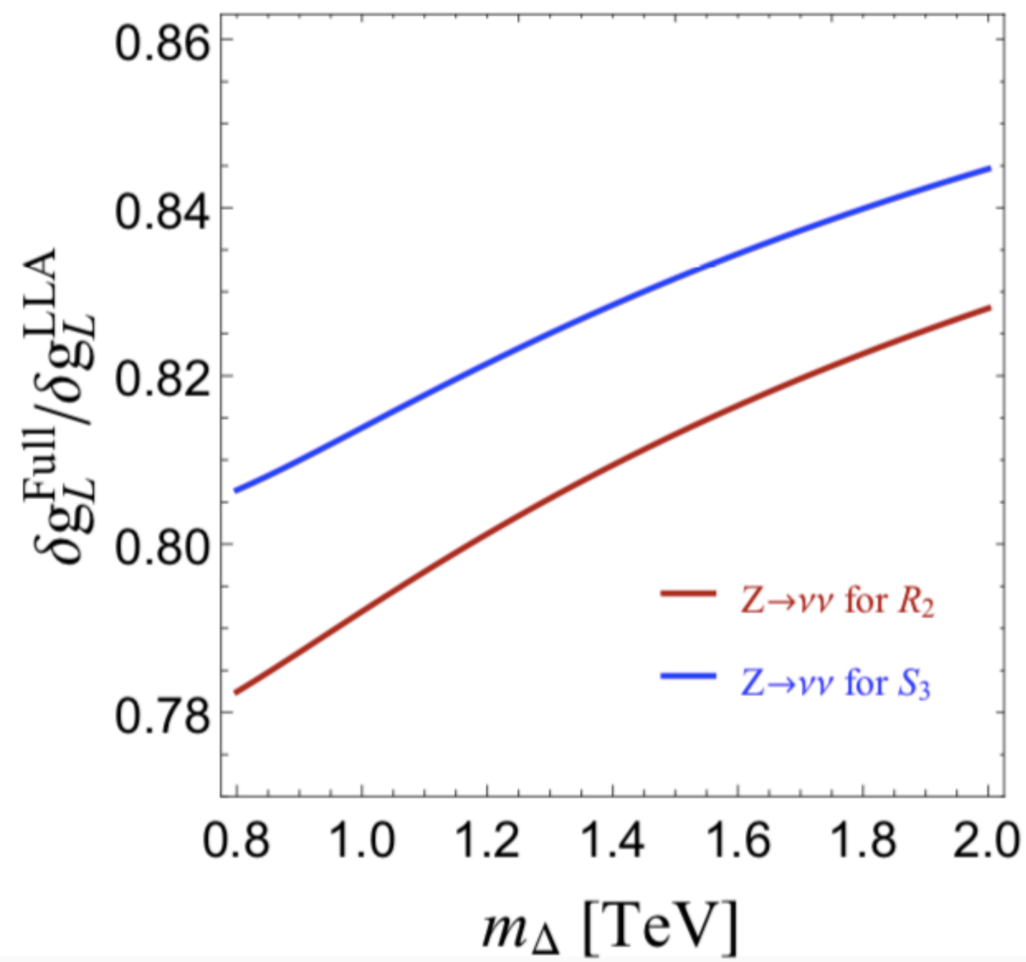
$$g_{f_{L(R)}}^{ij} = \delta_{ij}\, g_{f_{L(R)}}^{\rm SM} + \delta g_{f_{L(R)}}^{ij}$$

$$g_{f_L}^{\rm SM} = I_3^f - Q^f \sin^2\theta_W$$

$$g_{f_R}^{\rm SM} = -Q^f \sin^2\theta_W$$

Arnan, D.B., Mescia, Sumensari '19 [arXiv:1901.06315]





LLA: $\mathcal{O}(x_t \log x_t)$, $\mathcal{O}(x_Z \log x_Z)$ $\quad x_j = m_j^2/m_\Delta^2$ $\quad$ Feruglio et al. '17 and '18

Full: most significant $\mathcal{O}(x_Z \log x_t)$

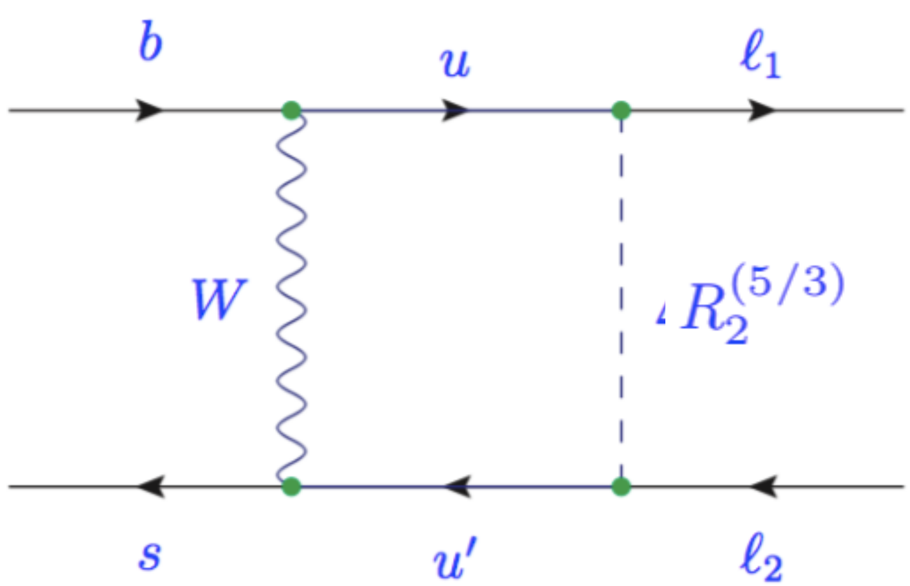
R_2

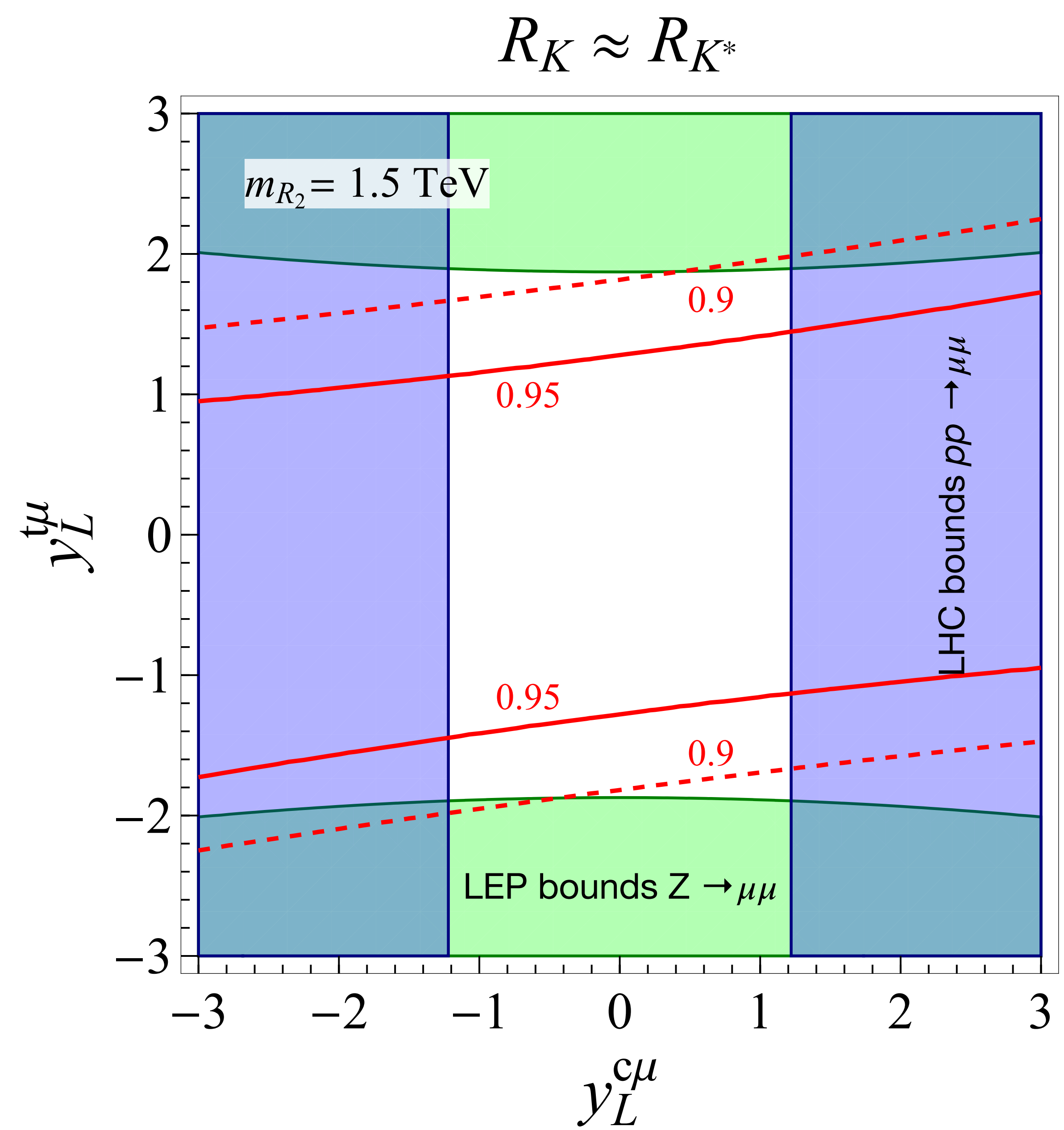
$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{Rj}\, R_2 - y_L^{ij}\,\overline{u}_{Ri} R_2 i\tau_2 L_j + \text{h.c.}$$

$$C_9^{kl} = C_{10}^{kl} \overset{\text{tree}}{=} -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}}\frac{y_R^{sl}\left(y_R^{bk}\right)^*}{m_{R_2}^2}$$

$$C_9^{kl} = -C_{10}^{kl} \overset{\text{loop}}{=} \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub}V_{u's}^*}{V_{tb}V_{ts}^*} y_L^{u'k}\left(y_L^{ul}\right)^* \mathcal{F}(x_u, x_{u'})$$

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{t\mu} & 0 \end{pmatrix}, \qquad y_R = 0$$





Accommodating all of them - R_D , R_{D^*}, R_K , R_{K^*}

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

- Two scalar LQs can also do the job (no extra parameters):

  $\Rightarrow$ S_1 and S_3 [Crivellin et al. '17, Marzocca. '18], R_2 and S_3 D.B. et al '18

S_3 & R_2 Model

D.B., Dorsner, Fajfer, Faroughy, Kosnik, Sumensari '18 [arXiv:1806.05689]

- In flavor basis

$$\mathcal{L} \supset y_R^{ij}\, \bar{Q}_i \ell_{Rj} R_2 + y_L^{ij}\, \bar{u}_{Ri} L_j \widetilde{R}_2^\dagger + y^{ij}\, \bar{Q}_i^C i\tau_2 (\tau_k S_3^k) L_j + \mathrm{h.c.}$$

$$R_2 = (3, 2, 7/6),\ S_3 = (\bar{3}, 3, 1/3)$$

- In mass-eigenstates basis

$$\begin{aligned}\mathcal{L} \supset\ & (V_{\mathrm{CKM}}\, y_R\, E_R^\dagger)^{ij}\, \bar{u}'_{Li} \ell'_{Rj} R_2^{(5/3)} + (y_R\, E_R^\dagger)^{ij}\, \bar{d}'_{Li} \ell'_{Rj} R_2^{(2/3)} \\ & + (U_R\, y_L\, U_{\mathrm{PMNS}})^{ij}\, \bar{u}'_{Ri} \nu'_{Lj} R_2^{(2/3)} - (U_R\, y_L)^{ij}\, \bar{u}'_{Ri} \ell'_{Lj} R_2^{(5/3)} \\ & - (y\, U_{\mathrm{PMNS}})^{ij}\, \bar{d}'^C_{Li} \nu'_{Lj} S_3^{(1/3)} - \sqrt{2}\, y^{ij}\, \bar{d}'^C_{Li} \ell'_{Lj} S_3^{(4/3)} \\ & + \sqrt{2} (V_{\mathrm{CKM}}^*\, y\, U_{\mathrm{PMNS}})_{ij}\, \bar{u}'^C_{Li} \nu'_{Lj} S_3^{(-2/3)} - (V_{\mathrm{CKM}}^*\, y)_{ij}\, \bar{u}'^C_{Li} \ell'_{Lj} S_3^{(1/3)} + \mathrm{h.c.}\end{aligned}$$

and assume

$$\underline{y_R = y_R^T \qquad y = -y_L}$$

$$y_R\, E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix},\quad U_R\, y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix},\quad U_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

Parameters: m_{R_2}, m_{S_3}, $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$ and θ

Effective Lagrangian at $\mu \approx m_{\rm LQ}$:

- $b \to c\tau\bar{\nu}$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 1$ TeV

$$\propto \frac{y_L^{c\tau}\, y_R^{b\tau\,*}}{m_{R_2}^2}\left[(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu}\nu_L)\right] + \dots$$

- $b \to s\mu\mu$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 30$ TeV

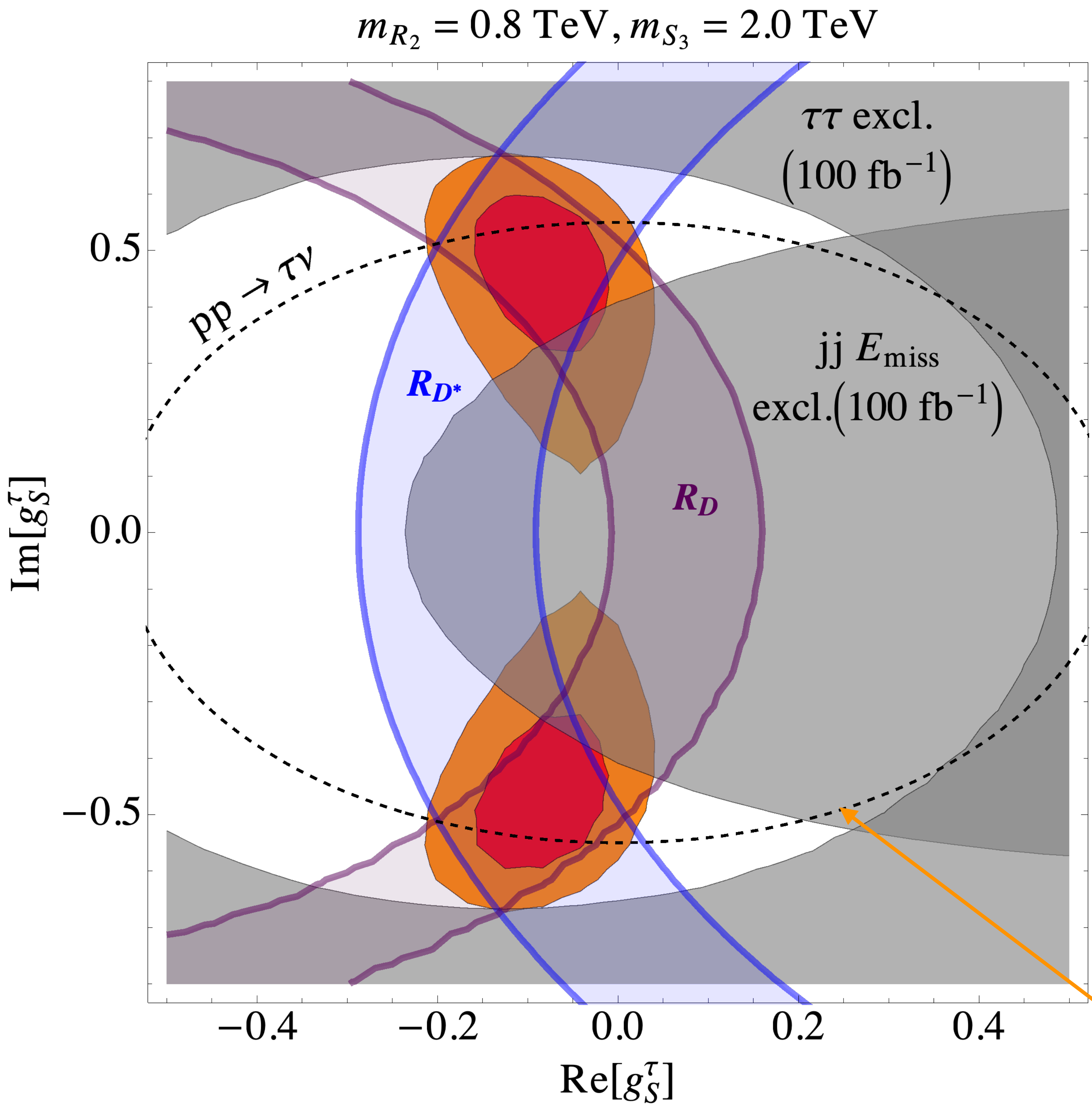
$$\propto \sin 2\theta \, \frac{|y_L^{c\mu}|^2}{m_{S_3}^2}\,(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

- Δm_{B_s}:

$$\propto \sin^2 2\theta \, \frac{\left[\left(y_L^{c\mu}\right)^2 + \left(y_L^{c\tau}\right)^2\right]^2}{m_{S_3}^2}(\bar{s}_L \gamma^\mu b_L)^2$$

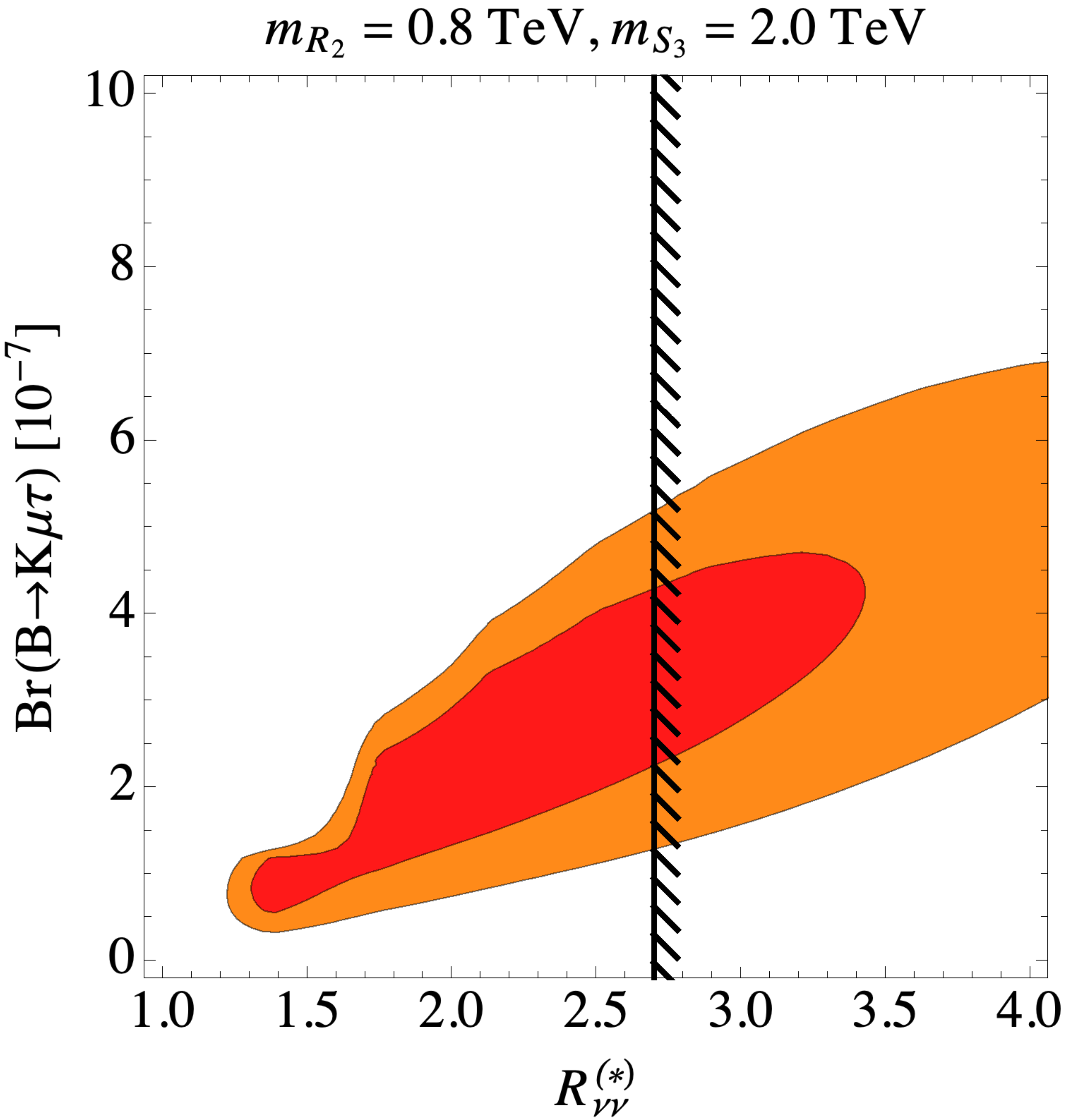
$\Rightarrow$ Suppression mechanism of $b \to s\mu\mu$ wrt $b \to c\tau\bar{\nu}$ for small $\sin 2\theta$.

$\Rightarrow$ Phenomenology suggests $\theta \approx \pi/2$ and $y_R^{b\tau}$ complex



Greljo et al. '18

Bounds should be less stringent
when considering propagating LQ!


$m_{R_2} = 0.8$ TeV, $m_{S_3} = 2.0$ TeV
Br(B→Kμτ) [10^{-7}]
$R_{\nu\nu}^{(*)}$
0
2
4
6
8
10
1.0
1.5
2.0
2.5
3.0
3.5
4.0

Simple and viable $SU(5)$ GUT

- Choice of Yukawas was biased by $SU(5)$ GUT aspirations
- Scalars: $R_2 \in \underline{\mathbf{45}}, \underline{\mathbf{50}}$, $S_3 \in \underline{\mathbf{45}}$. SM matter fields in $\mathbf{5}_i$ and $\mathbf{10}_i$
- Operators $\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{45}}$ forbidden to prevent proton decay [Dorsner et al 2017]
- Available operators

$$\mathbf{10}_i \mathbf{5}_j \underline{\mathbf{45}}: \quad y_{2\,ij}^{RL}\, \overline{u}_R^i R_2^a \varepsilon^{ab} L_L^{j,b}, \quad y_{3ij}^{LL}\, \overline{Q^C}_L^{i,a} \varepsilon^{ab} (\tau^k S_3^k)^{bc} L_L^{j,c}$$

$$\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{50}}: \quad y_{2\,ij}^{LR}\, \overline{e}_R^i R_2^{a\,*} Q_L^{j,a}$$

- While breaking $SU(5)$ down to SM the two R_2's mix – one can be light and the other (very) heavy. Thus our initial Lagrangian!
- The **Yukawas** determined from flavor physics observables at low energy **remain perturbative** ($\lesssim \sqrt{4\pi}$) up to the GUT scale, using one-loop running [Wise et al 2014, c.f. back-up]

Summary and perspectives

- Flavor anomalies are still there but the experimental situation unclear.

  Needs clarification from Belle-II!

- Many questions could be answered if we had exp. info on $b \to s\tau\tau$ modes, eg. $B \to K^{(*)}\tau\tau$. Improving $\mathcal{B}(B \to K^{(*)}\tau\mu)$ – very helpful to model builders.

  Belle-II and FCC

- (Even partial) angular distributions of $B_{(s)} \to D_{(s)}^{(*)}\tau\nu_\tau$, $B_c \to J/\psi\tau\nu_\tau$ and $\Lambda_b \to \Lambda_c^{(*)}\tau\nu_\tau$ could help discriminating among various NP scenarios.

  LHCb and Belle II but FCC

- Viable single mediator explanations to $R_{K^{(*)}}$ and/or $R_{D^{(*)}}$ (and friends).

  Only the vector U_1 is viable. Two scalar LQs can do the job too.

- Many scenarios with upper and lower bounds for $\mathcal{B}(Z \to \tau\mu)$. Can someone measure $\mathcal{B}(Z \to \tau\tau)$ and $\mathcal{B}(W \to \tau\nu_\tau)$?

  FCC