Flavor phenomenology with scalar leptoquarks

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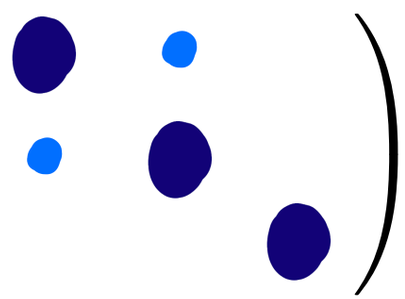
Flavor in the SM: Organized but not understood

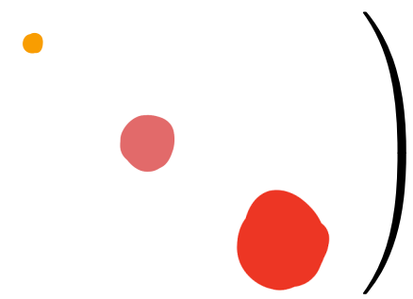
$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yuk}$$

Only a handful of parameters (flavor symmetric)!

Flavor sector is loose!

- Many **free parameters** (*fixed by data!*), which exhibit a **striking hierarchy** (*does not look accidental...*):

$V_{\rm CKM} =$ 

$M_{u,d,e} =$ 

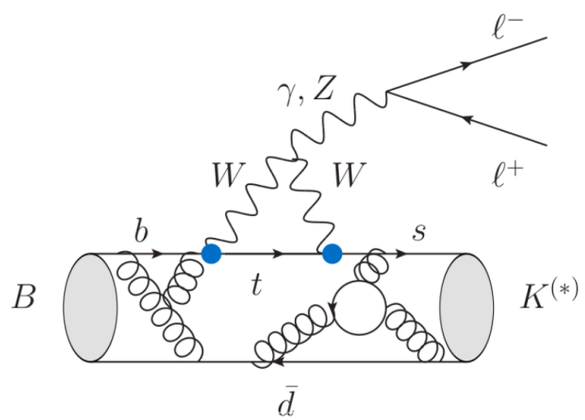
Is there a **flavor theory** that could **predict** the observed **pattern of Yukawas**?

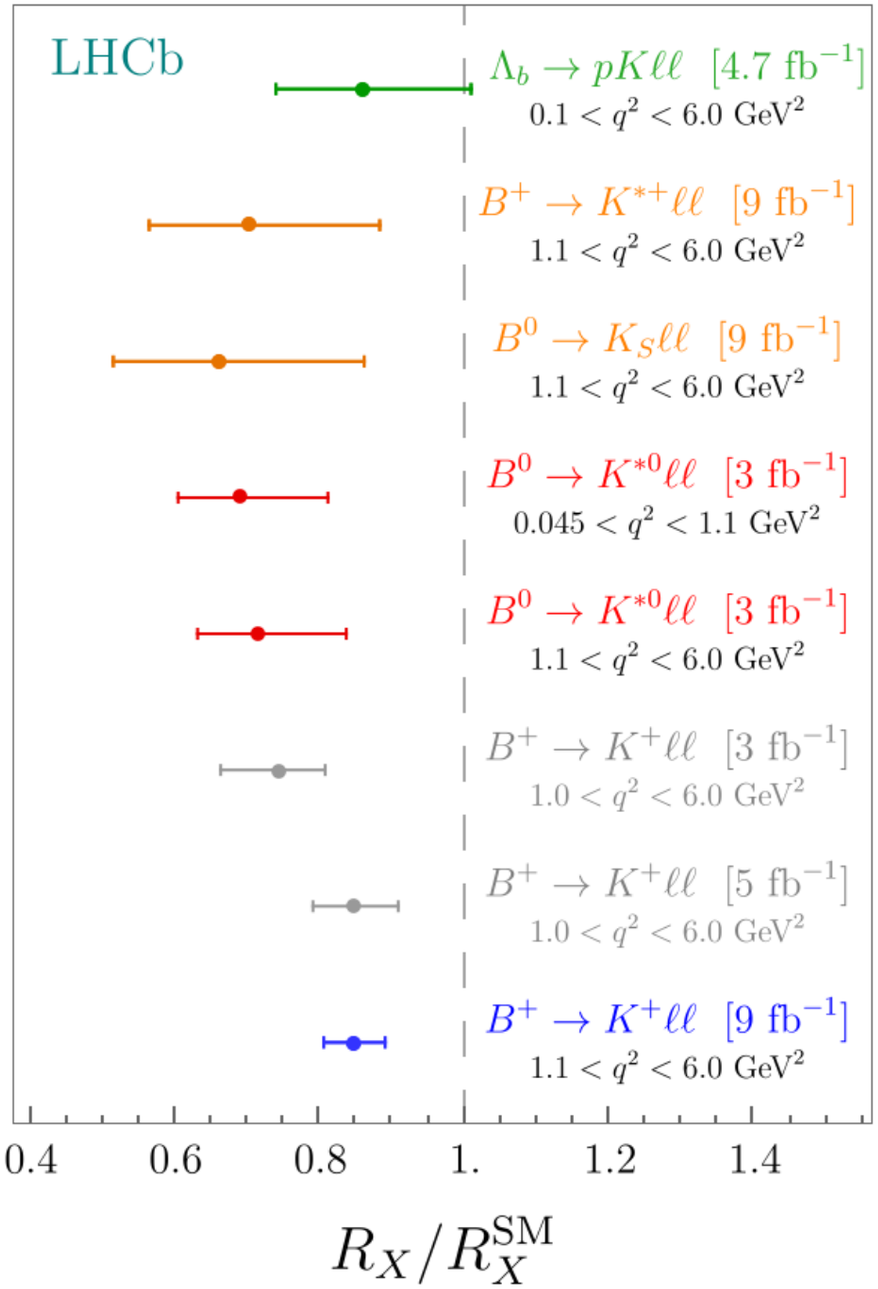
$\Rightarrow$ *Difficult problem to solve* (at which NP scale?) — **Exp. guidance needed**!

LFU in $b \to s\ell\ell$

Experiment

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$





Theory (loop induced)

- Hadronic uncertainties almost fully cancel.

  $\Rightarrow$ **Clean observables!** *[working below the narrow $c\bar{c}$ resonances]* [Hiller, Kruger. '04]

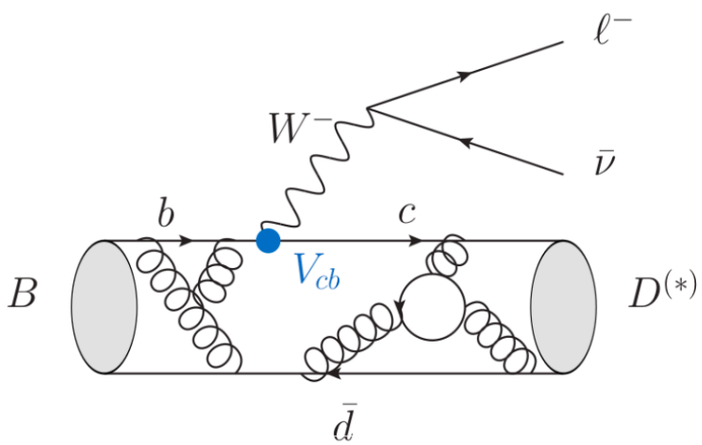
- However, QED corrections important, $R^{\rm SM}_{K^{(*)}} = 1.00(1)$ [Isidori et al. '20]

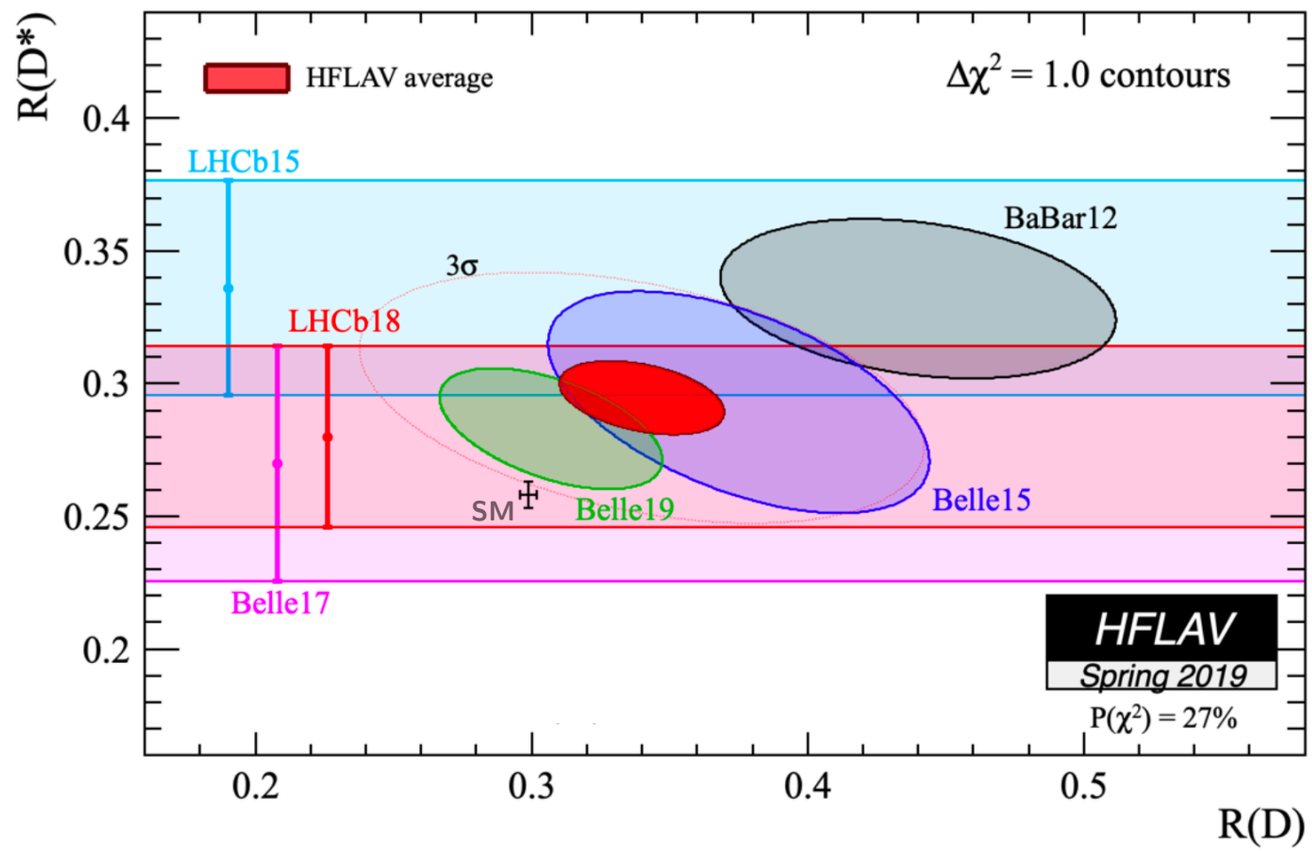
Needs independent cross-check from **Belle-II**

LFU in $b \to c\tau\bar{\nu}$

Experiment

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





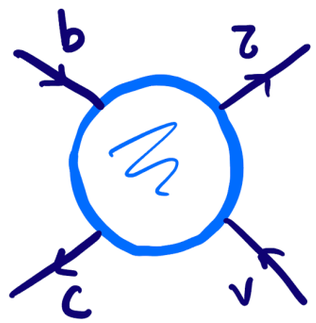
- $R_D^{\rm exp}$ and $R_{D^*}^{\rm exp}$: **dominated by BaBar!**
- LHCb confirmed tendency $R_{J/\psi}^{\rm exp} > R_{J/\psi}^{\rm SM}$, i.e. $B_c \to J/\psi\ell\bar{\nu}$ — *with large uncertainties.*

Needs clarification from **Belle-II** and **LHCb (run-2)** data!

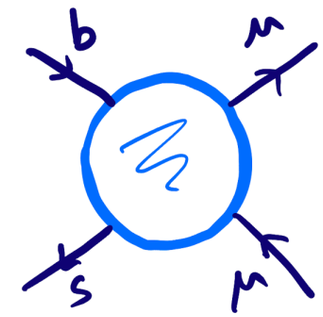
Why leptoquarks?

[Di Luzio et al. '17]

- **EFT interpretations:**

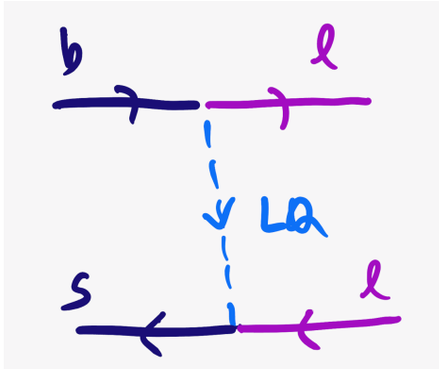


$\Lambda_{R_{D^{(*)}}} \lesssim 5$ TeV

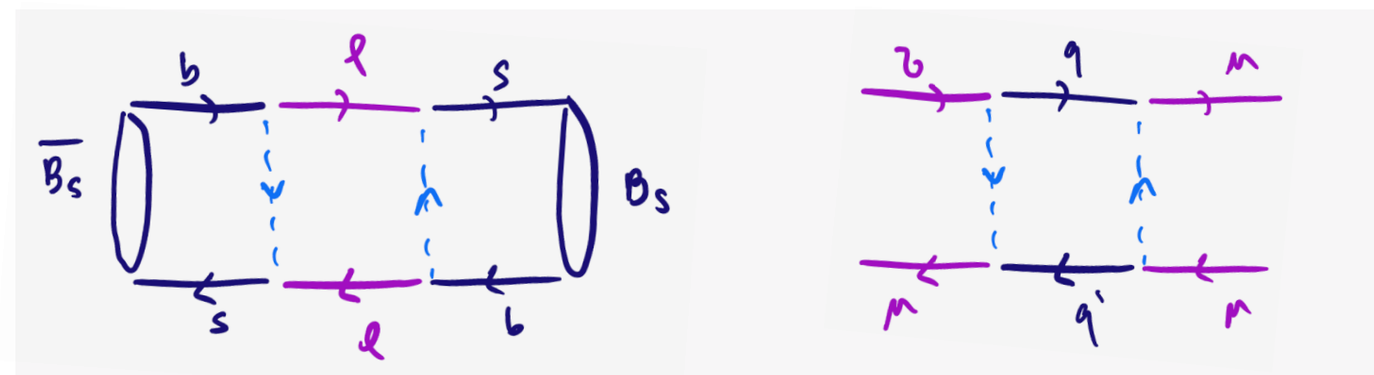


$\Lambda_{R_{K^{(*)}}} \lesssim 30$ TeV

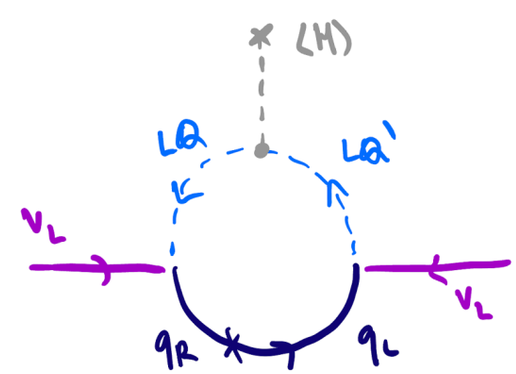
- **Leptoquarks** induce **large semileptonic contributions** *(at tree-level)*, while remaining **consistent** with purely **leptonic** and **quark-level** observables (*loop-level*):



$\gg$



- Well-motivated theoretically:
  - *GUTs;*
  - *Neutrino masses;* →
  - *...*



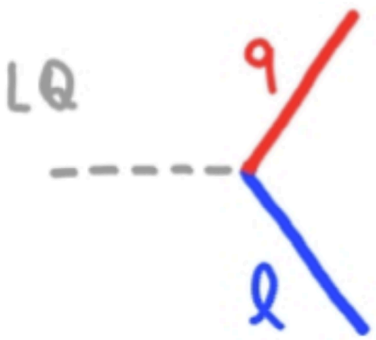
see e.g. [Dorsner et al. '17]

Which leptoquark?

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

[Buchmuller, Wyler. '88]

$(SU(3)_c,\, SU(2)_L,\, U(1)_Y)$



	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Spin 0	$S_3 \quad (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
	$S_1 \quad (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
	$R_2 \quad (\mathbf{3}, \mathbf{2}, 7/6)$	✗*	✓	✗
Spin 1	$U_1 \quad (\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
	$U_3 \quad (\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

Which leptoquark?

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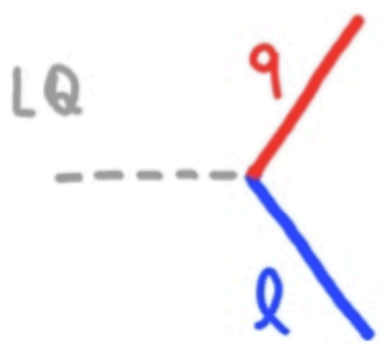

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Spin 0	$S_3 \quad (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
	$S_1 \quad (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
	$R_2 \quad (\mathbf{3}, \mathbf{2}, 7/6)$	✗*	✓	✗
Spin 1	$U_1 \quad (\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
	$U_3 \quad (\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

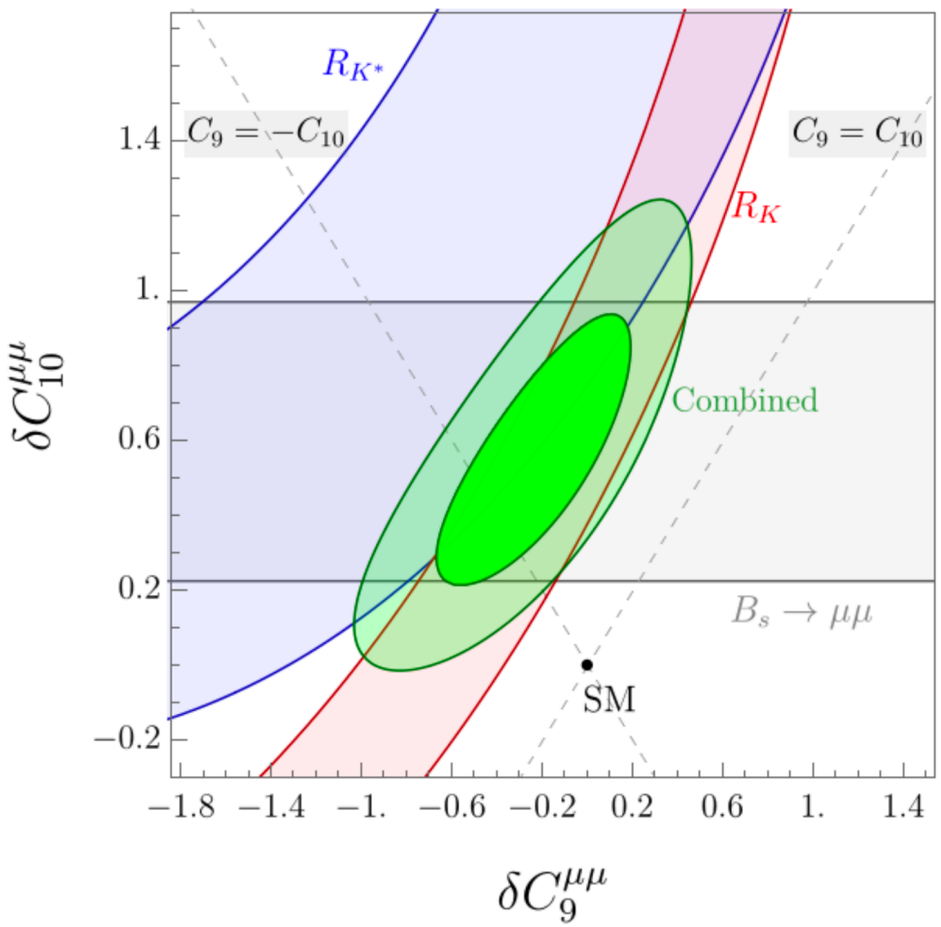
- The U_1 LQ can do the job alone, but UV completion needed.

  See talk by D. Faroughy!

  - $\mathcal{G}_{\rm PS} = SU(4) \times SU(2)_L \times SU(2)_R$ contains $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$
  - Viable TeV models proposed: $U_1 + Z' + g'$ [Di Luzio et al. '17, Bordone et al. '18, Blanke et al. '18...]

- **This talk**: Two scalar LQs are also viable! [Crivellin et al. '17, Marzocca '18] [Becirevic et al. '18]

Scalar LQs for $b \to s\mu\mu$ $\qquad S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

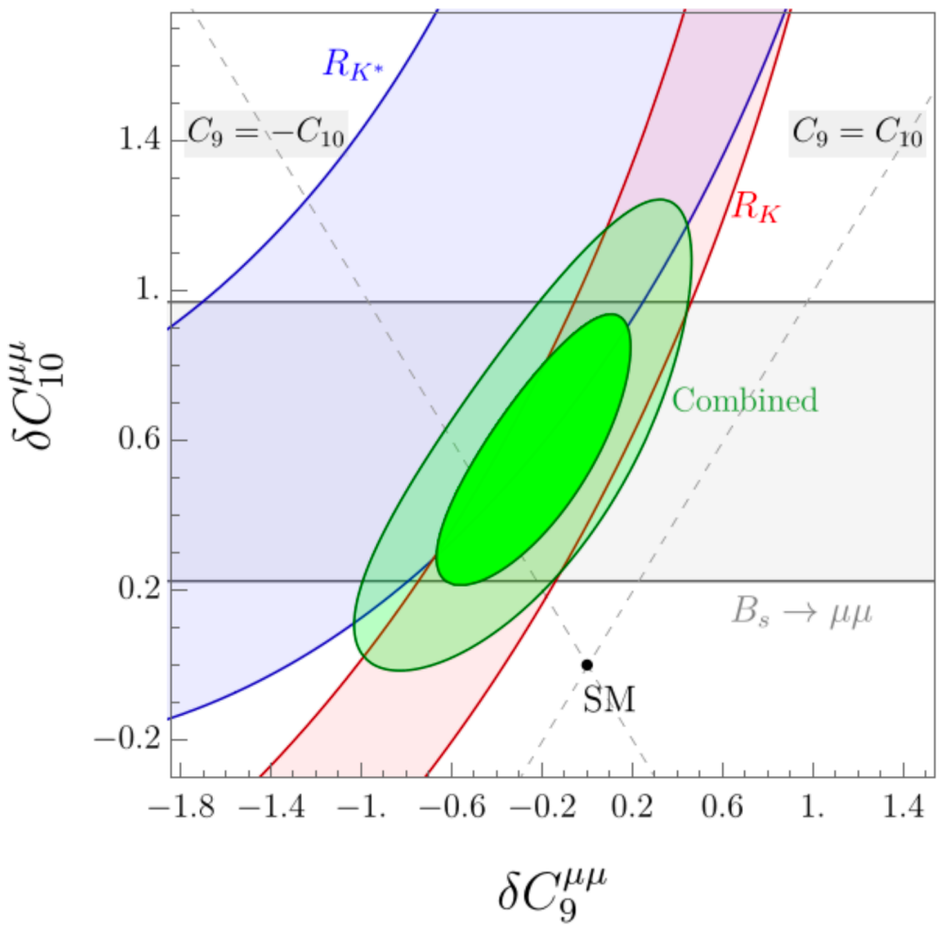


$$\mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_{\text{em}}}{4\pi} \left[\bar{s}_L \gamma^\mu b_L\right] \left[\bar{\ell}(C_9 + C_{10}\gamma_5)\ell\right] + \ldots$$

- Purely left-handed operator preferred [4.6σ]:

$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} = -0.41 \pm 0.09$$

Scalar LQs for $b \to s\mu\mu$ $\qquad S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$



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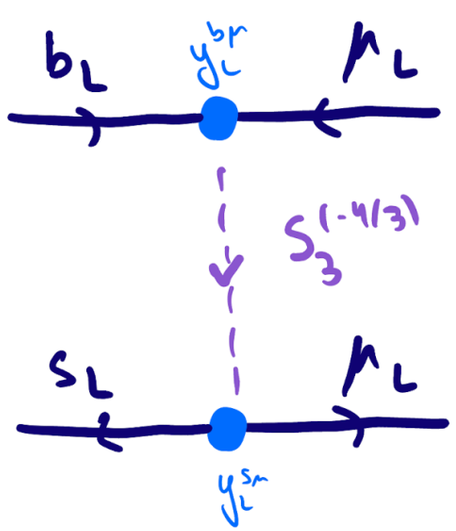
- Purely left-handed operator preferred [4.6σ]:

$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} = -0.41 \pm 0.09$$

- Tree-level prediction:

$$\mathcal{L}_{S_3} = y_L^{ij}\, \overline{Q^C} i\tau_2 (\vec{\tau}\cdot\vec{S}_3) L_j + \text{h.c.}$$



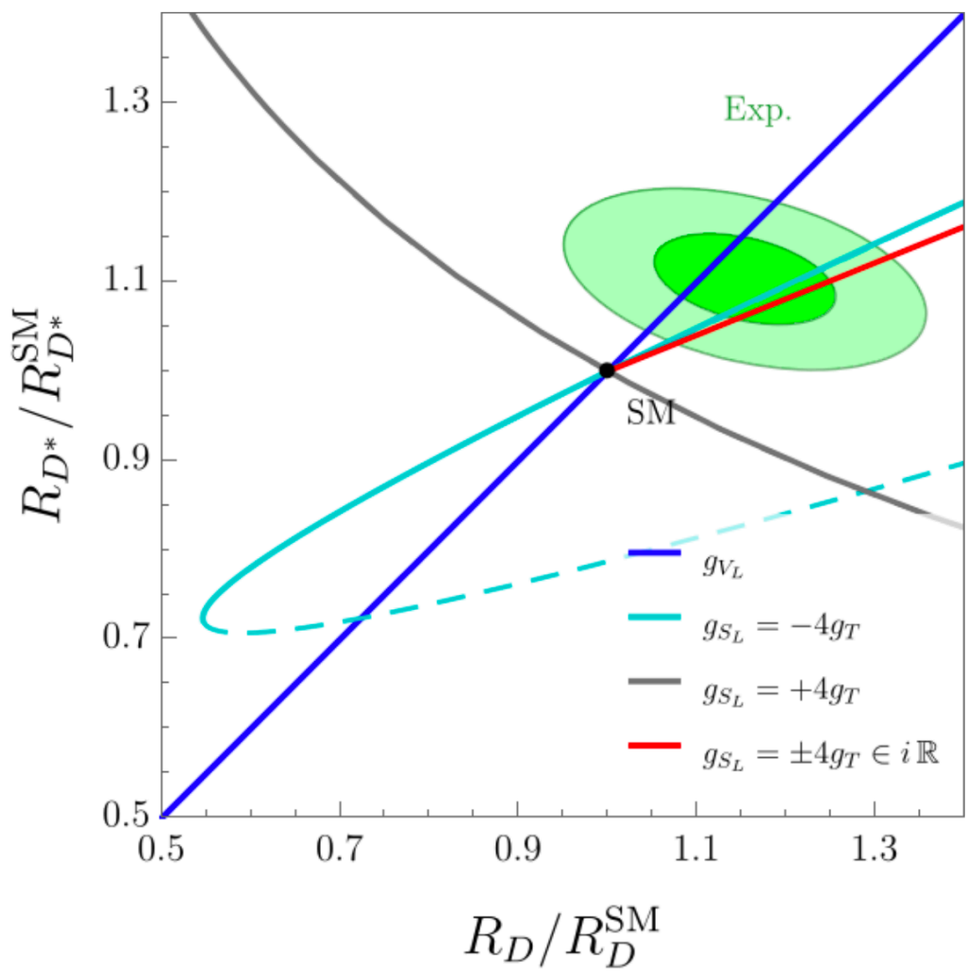
$$\delta C_9 = -\delta C_{10} \propto \frac{v^2}{m_{S_3}^2} y_L^{s\mu} y_L^{b\mu *}$$

NB. Consistent with other constraints: Δm_{B_s}, $B \to K\nu\bar{\nu}$, ...

LFU in charged currents

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

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



Viable solutions:

- $g_{V_L} > 0$
- $g_{S_L} = -4g_T > 0$

$\Rightarrow$ $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

- $g_{S_L} = +4g_T \in i\,\mathbb{R}$ $\Rightarrow$ $R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$

NB. More information is needed to distinguish among the viable solutions.

$\Rightarrow$ *e.g., $B \to D^{(*)}\tau\nu$ angular observables.*

See talk by Damir Becirevic

Combined explanation: R_2 & S_3

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

*See Gherardi et al. '20

This talk!

Combined explanation: R_2 & S_3

[Becirevic et al. '18]

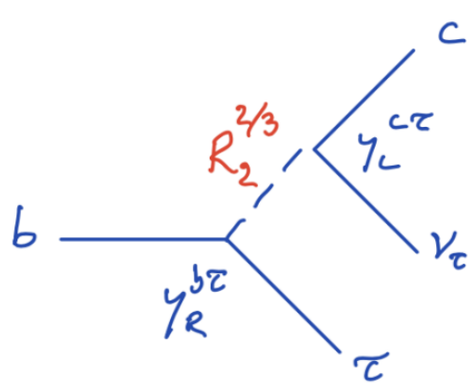
$$\mathcal{L} \supset y_R^{ij}\, \bar{Q}_i \ell_{Rj} R_2 + y_L^{ij}\, \bar{u}_{Ri} L_j \widetilde{R}_2^\dagger + y^{ij}\, \bar{Q}_i^C i\tau_2(\tau_k S_3^k) L_j + \text{h.c.}$$

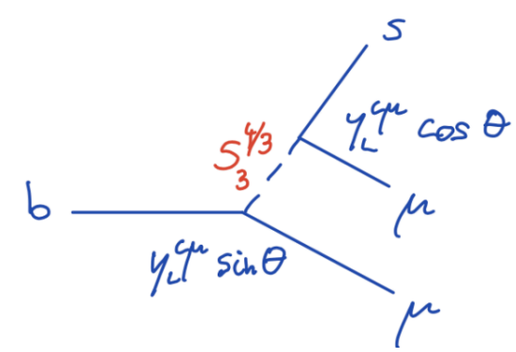
$$R_2 = (3, 2, 7/6),\ S_3 = (\bar{3}, 3, 1/3)$$

Flavor ansatz motivated by a $SU(5)$ *GUT* scenario: $y_R = y_R^T$ & $y = -y_L$

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

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





Complex!

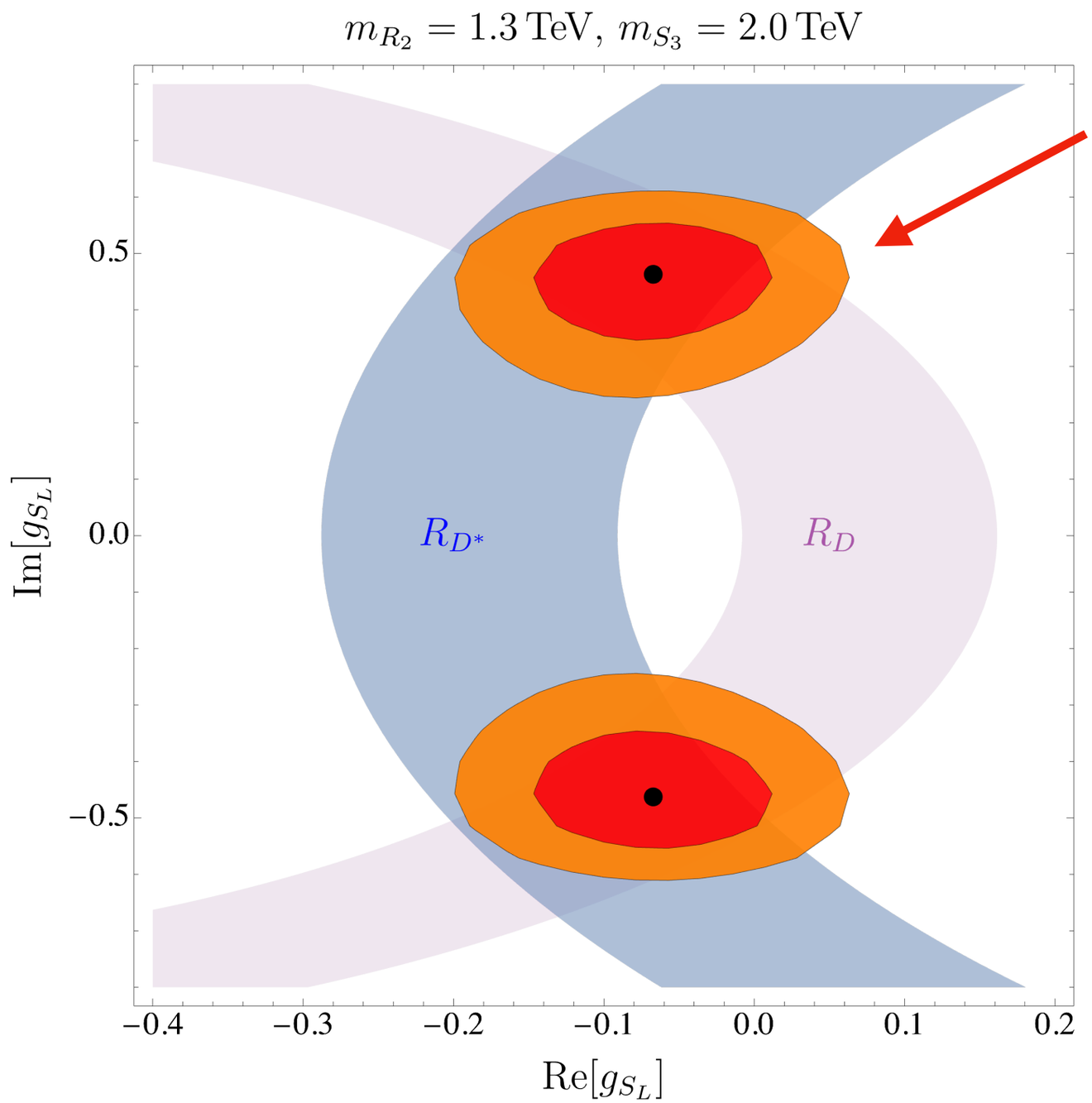
$\theta \approx \pm\pi/2$

$$g_{S_L}(\Lambda) = 4\, g_T(\Lambda) = \frac{y_L^{c\tau}\, y_R^{b\tau\,*}}{4\sqrt{2} G_F\, V_{cb}\, m_{R_2}^2}$$

$$\delta C_9{}^{\mu\mu} = -\delta C_{10}^{\mu\mu} = -\frac{\pi v^2}{\lambda_t \alpha_{\text{em}}} \frac{\sin 2\theta |y_L^{c\mu}|^2}{2 m_{S_3}^2}$$

Results and predictions

NB. $g_{S_L}(\Lambda) = 4 g_T(\Lambda)$



Allowed by (numerous) low-energy observables!

See back-up!

[Becirevic et al. '22]

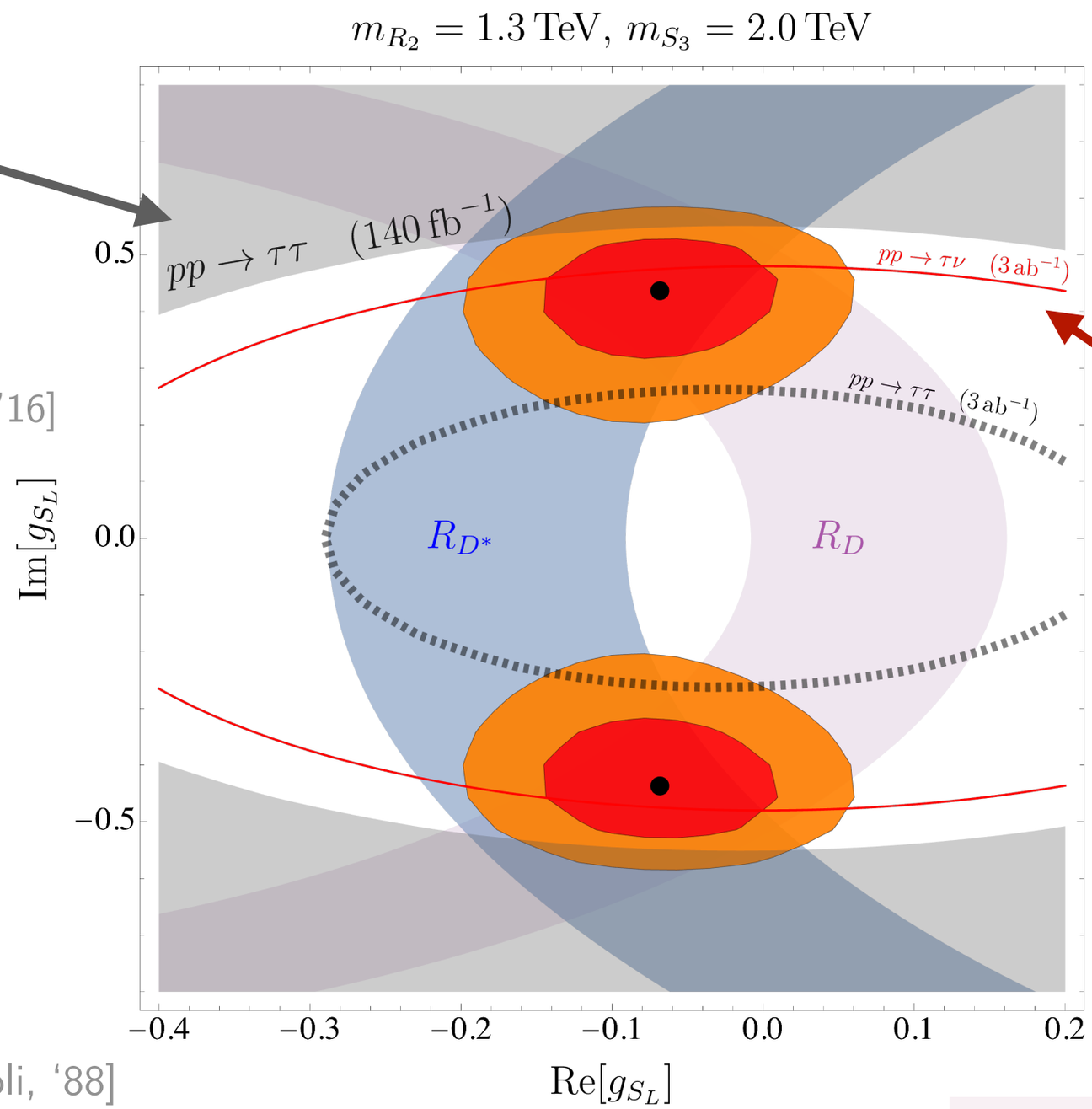
Suitable couplings: $y_L^{c\mu} = 0.2, \quad y_L^{c\tau} = 1.0, \quad y_R^{b\tau} = -0.2 - 1.2i, \quad \theta = -1.5$

LHC constraints

$pp \to \tau\tau$

[ATLAS, 2002.12223]

See also [Faroughy et al. '16]

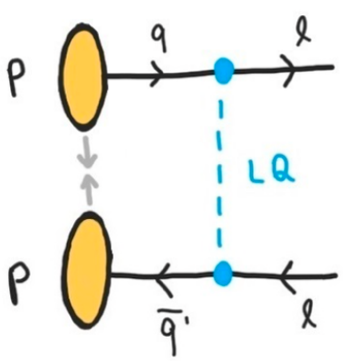


$pp \to \tau\nu$

[ATLAS-CONF-2021-025]

[F. Jaffredo '21]

See also [Greljo et al' 18]



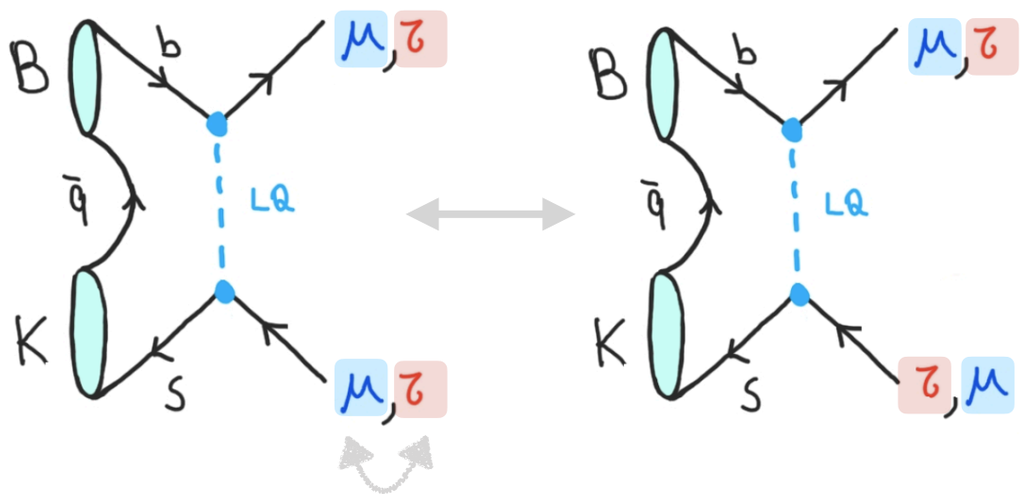
First considered by [Eboli, '88]

See talks by Lukas Allwicher and Florentin Jaffredo this afternoon!

Lepton Flavor Violation

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

- **LFU**V ↔ **LFV**:



LFV B- and **τ-decays** are **bounded** from **above** and **below!**

NB. Similar conclusions for other minimalistic solutions of B-anomalies:

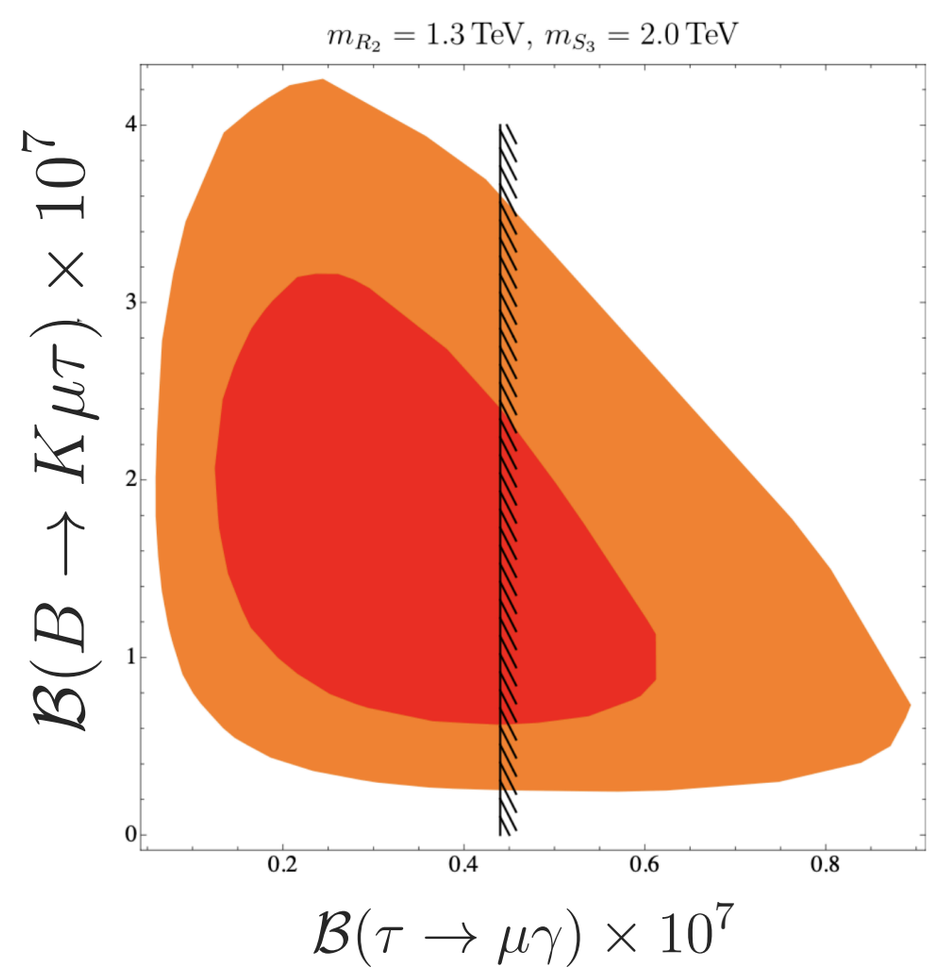
See e.g. [Cornella et al. '21]

Predictions for

$$B_s \to \mu\tau \qquad B \to K^{(*)}\mu\tau$$

New searches (95% CL): [LHCb]

$$\mathcal{B}(B_s \to \mu\tau)^{\rm exp} < 4.2 \times 10^{-5}$$
$$\mathcal{B}(B \to K^{(*)}\mu\tau)^{\rm exp} < 4.5 \times 10^{-5}$$



B-decays with missing energy

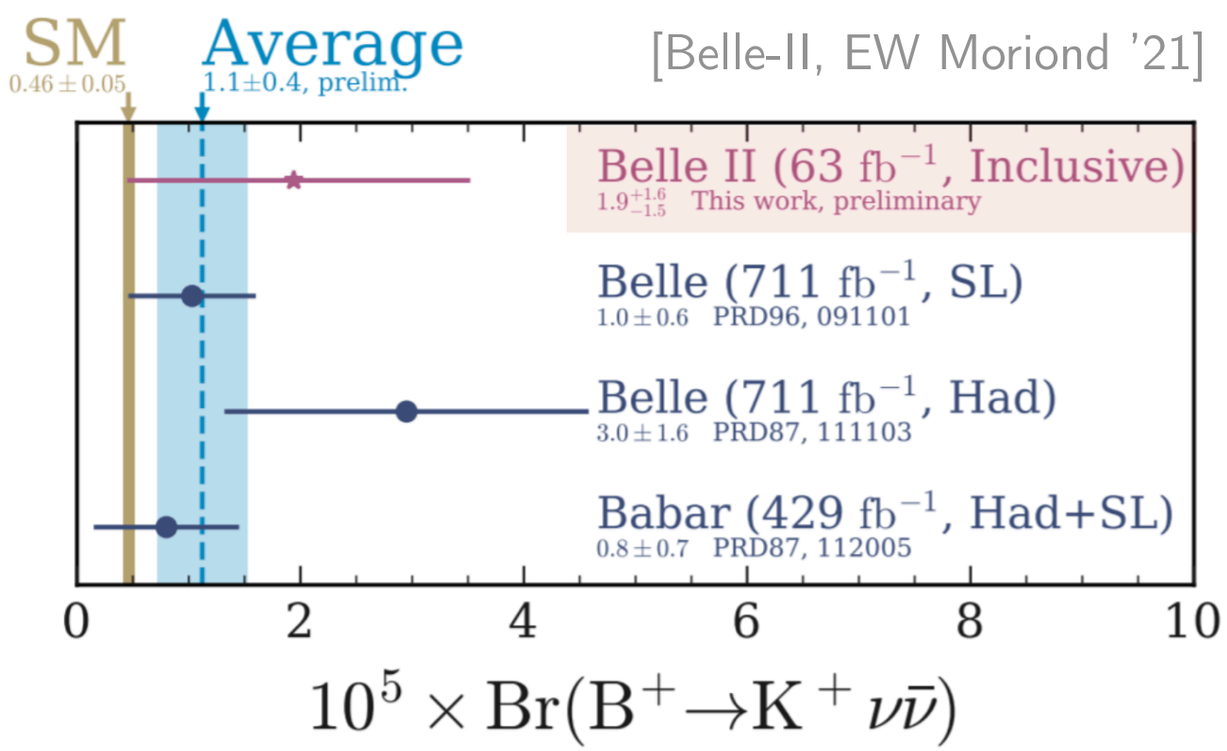
e.g. [Becirevic et al. '22]

- Relatively **clean observable** in the SM:

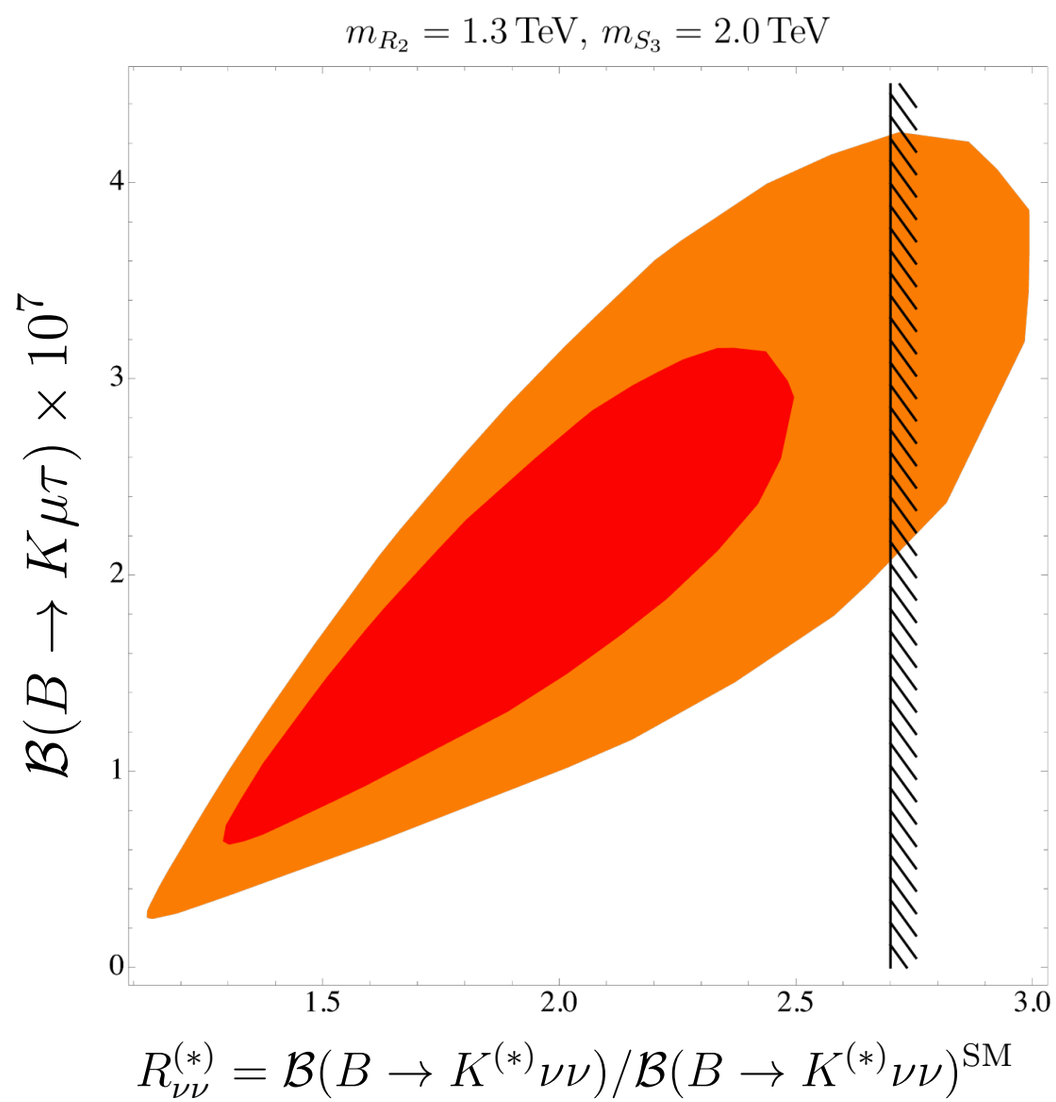
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{\rm SM} = 4.6(5) \times 10^{-6}$$

[Buras et al. '14, Blake et al. '16]

- Models for the ***B*-anomalies** predict **sizable deviations** from SM predictions.



[Belle-II, EW Moriond '21]



Promising results from early **Belle-II data!**

What about loop-level solutions?

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

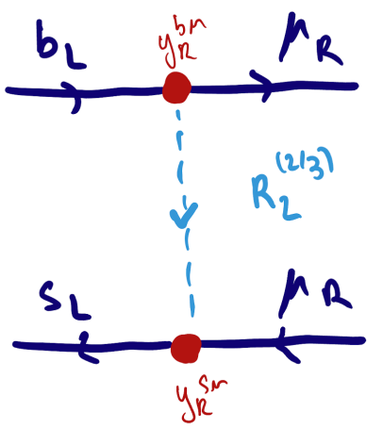
$R_2 = (3, 2, 7/6)$

[Becirevic, **OS.**, '17]

- **LFU violation** can also be generated **via loops**! First attempt in [Bauer, Neubert, '15]. A compelling scenario can be obtained with R_2 :

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

- **Tree-level** prediction **strongly disfavored** by current data:



$$\delta C_9^{\mu\mu} = \delta C_{10}^{\mu\mu} \overset{\text{tree}}{=} -\frac{\pi v^2}{2\lambda_t \alpha_{\text{em}}} \frac{y_R^{s\mu} \left(y_R^{b\mu}\right)^*}{m_{R_2}^2}$$

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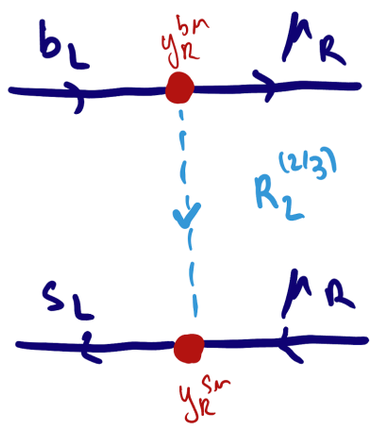

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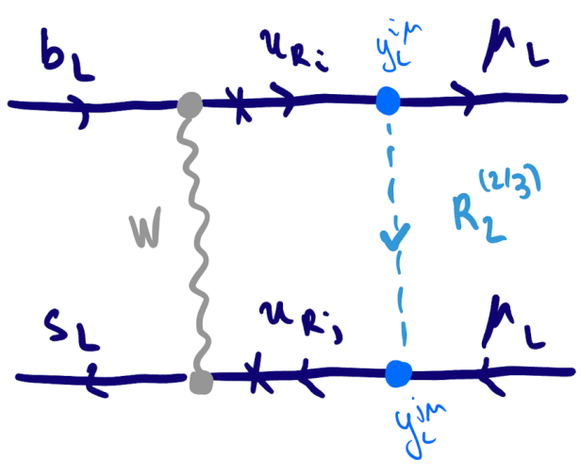
- For $y_R = 0$, leading contributions are **loop-induced** (with the **correct pattern**!):



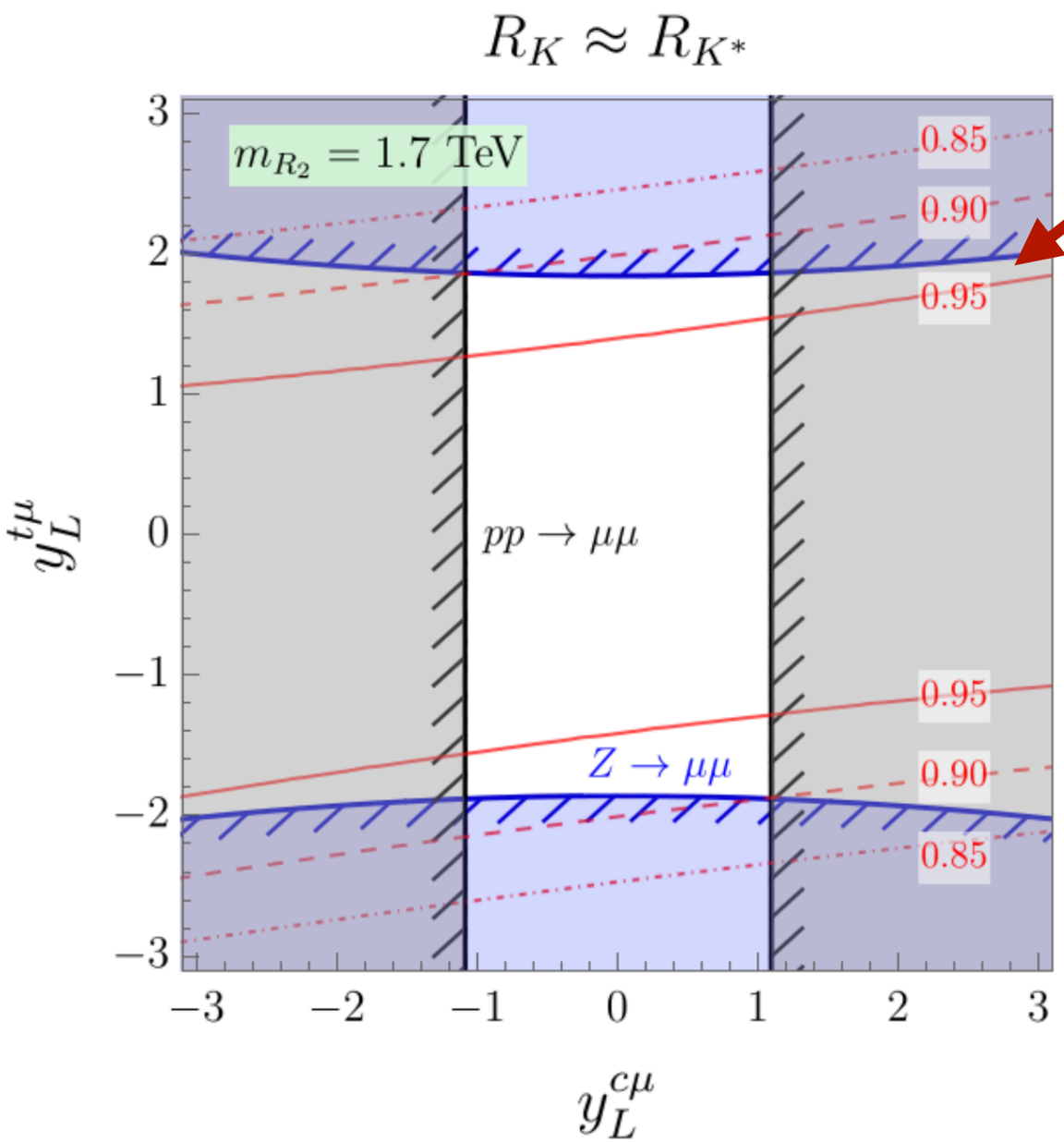
$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} \overset{\text{loop}}{=} \sum_{i\in\{u,c,t\}} \frac{V_{ib}V_{is}^*}{V_{tb}V_{ts}^*} \frac{y_L^{i\mu}\left(y_L^{j\mu}\right)^*}{m_{R_2}^2} \mathcal{G}(x_{u_i}, x_{u_j})$$

$$= \frac{|y_L^{t\mu}|^2}{16\pi\alpha_{\text{em}}} \underbrace{\frac{m_t^2}{m_{R_2}^2} \log\left(\frac{m_t}{m_{R_2}}\right)}_{<0} + \ldots$$

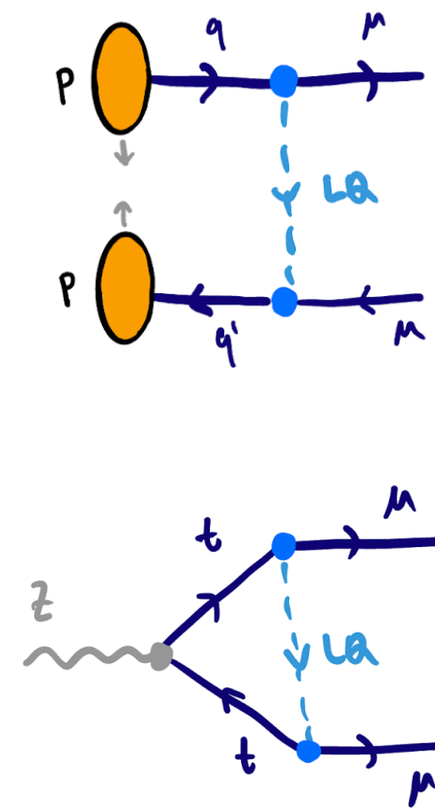
As we want!

$R_2 = (3, 2, 7/6)$

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS.**, '21]



Predictions: $R_{K^{(*)}}$ contours



[Arnan, Becirevic, Mescia, **OS**, '19]

- **Current deviations** ($\approx 15\%$) are **too large** to be explained by R_2.
- If the *deviations* turn out to be *smaller*, this scenario would be interesting again!

Perspectives / Beyond LFU anomalies

Perspectives / Beyond LFU anomalies

- Experimental situation remains unclear!
  - Wait for Belle-II for an independent cross-check!

- We identified the mediators that can explain $R_{K^{(*)}}$ and/or $R_{D^{(*)}}$.
  - The vector U_1 is viable. Two scalar LQs can do the job too.
  - Interesting phenomenology of R_2 (at one-loop!).

- Upcoming low- and high-energy measurements will be fundamental to refute or confirm the remaining viable models.

$pp \to \ell\ell'$ $\quad R_{D^{(*)}, D_s^{(*)}, \Lambda_c^{(*)}, \ldots}$ $\quad R_{K^{(*)}, \phi, \ldots}$ $\quad B \to K^{(*)}\mu\tau$ $\quad B \to K^{(*)}\nu\bar{\nu}$

- Even if the LFU anomalies disappear, we definitely *have learned a lot*:

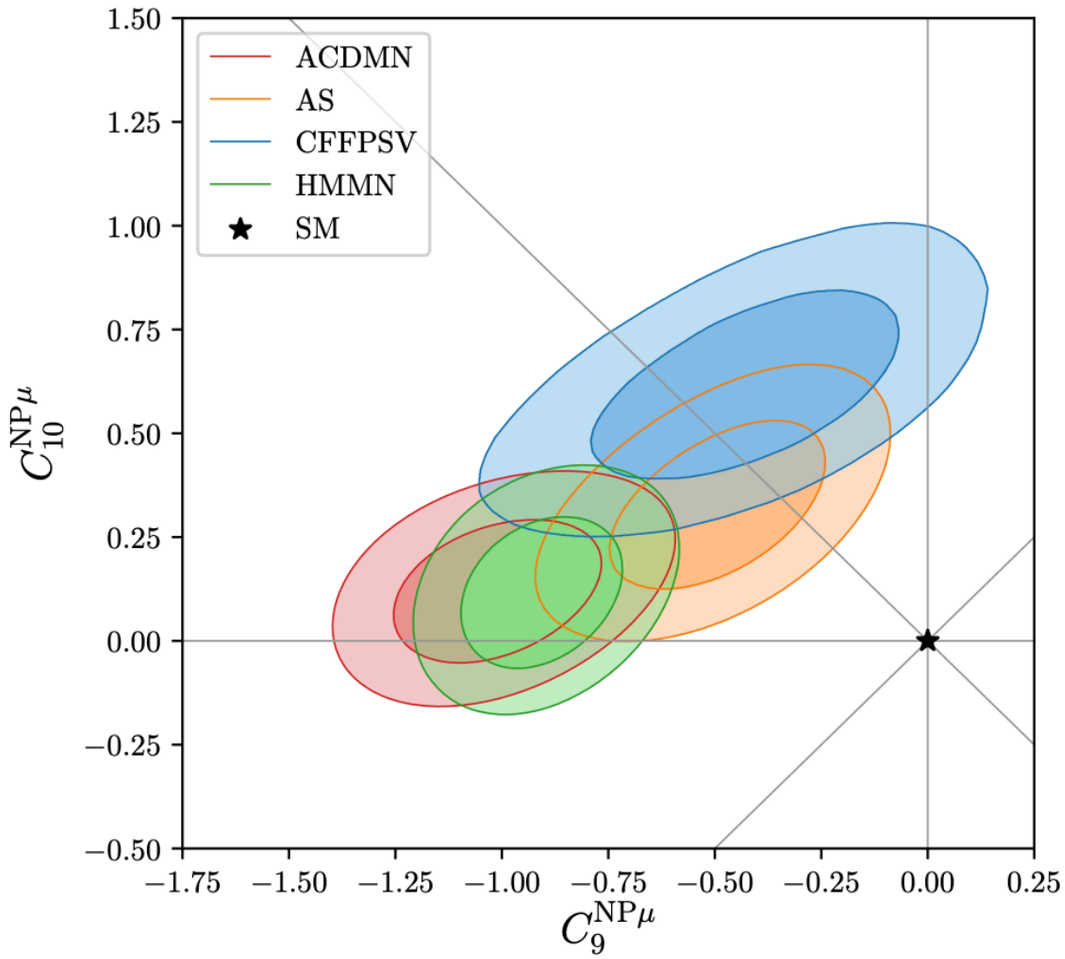
  - We **need theoretically clean observables**!
  - **Flavor physics** at **high-p_T** .
  - **New attempts** to address the **flavor problem** at the TeV scale!
  - ...

Thank you!

Back-up

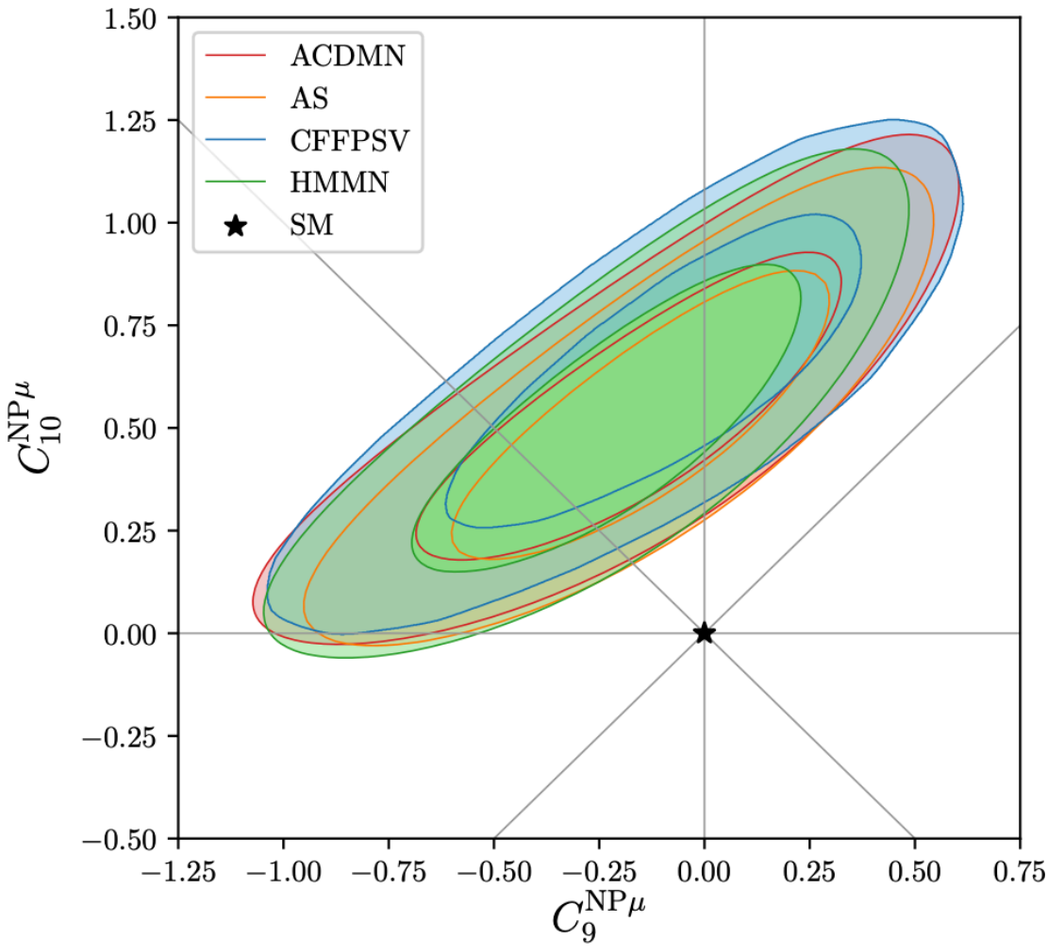
[Intermezzo] - Lesson from LFU anomalies!

Global $b \to s\ell\ell$ fit



vs.

LFU + $\mathscr{B}(B_s \to \mu\mu)$



See talk by B. Capdevilla, M. Fedele, S. Neshatpour, P. Stangl at LHCb Implications '21

We **need observables** that are **mildly sensitive** to **hadronic uncertainties**!

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

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

- **Semileptonic operators:**

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

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

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

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

- Dimension-6 *tensor operator* is *not allowed* by $SU(2)_L \times U(1)_Y$

[Buchmuller, Wyler. '85]

- *(Pseudo)scalar operators* are *tightly constrained* by

$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\rm exp} = (2.85 \pm 0.22) \times 10^{-9}$$

[Our exp. average: CMS, ATLAS, LHCb]

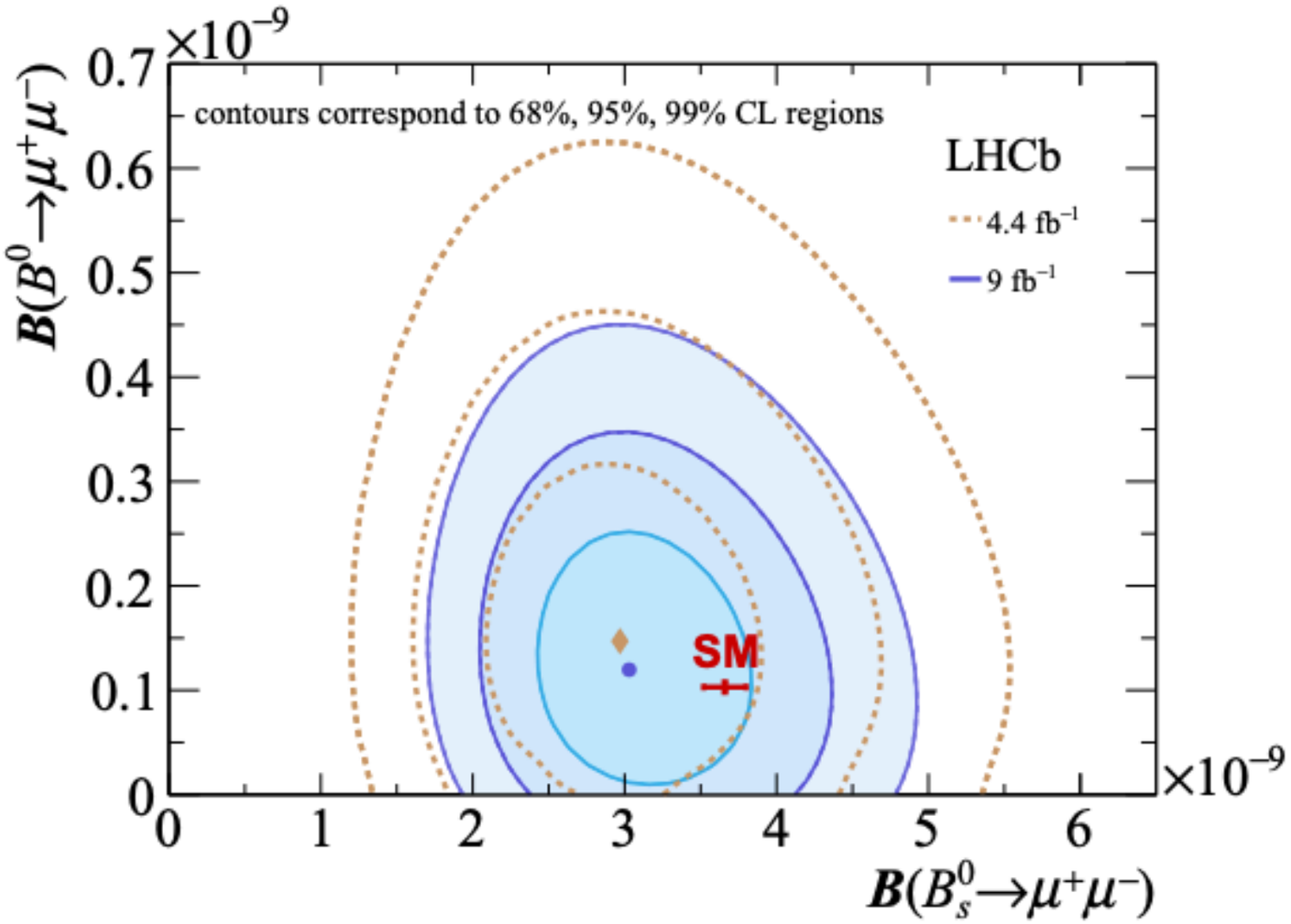
$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\rm SM} = (3.66 \pm 0.14) \times 10^{-9}$$

[Beneke et al. '19]

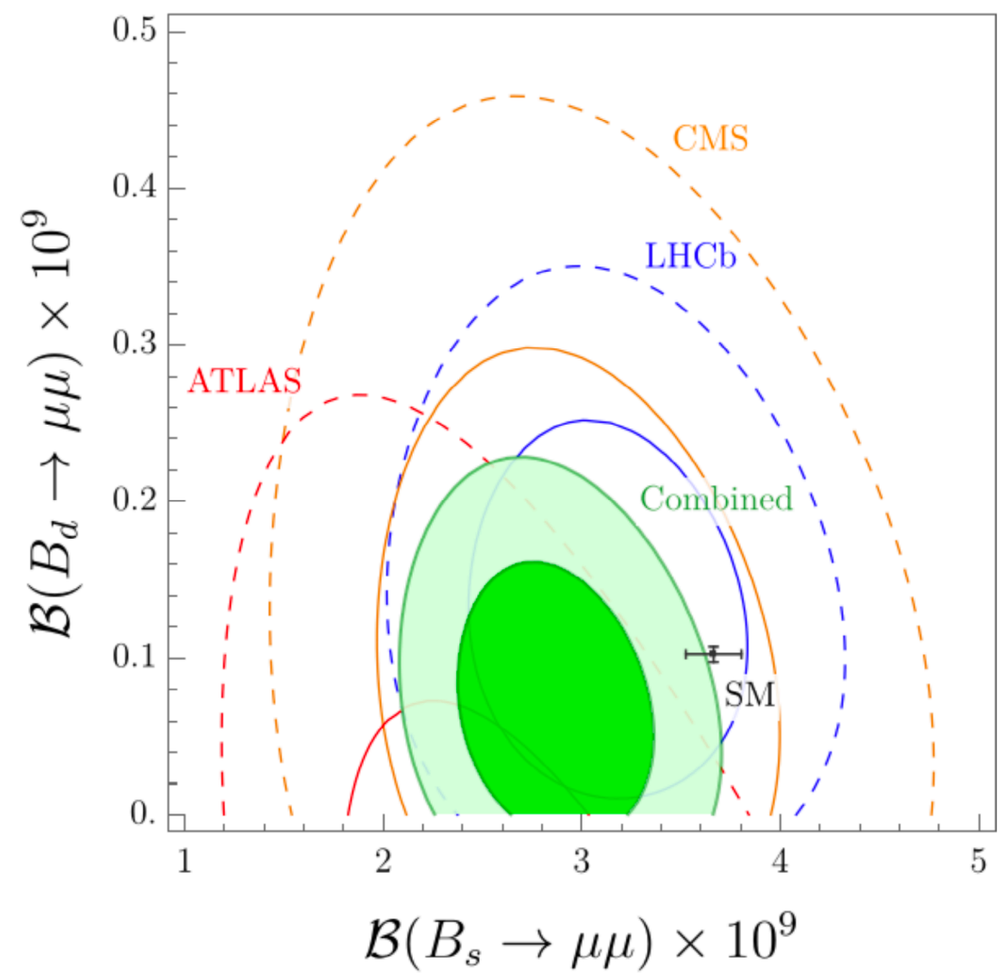
[Intermezzo] $B_s \to \mu\mu$

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

[LHCb '21]



[Our exp. average: CMS, ATLAS, LHCb]

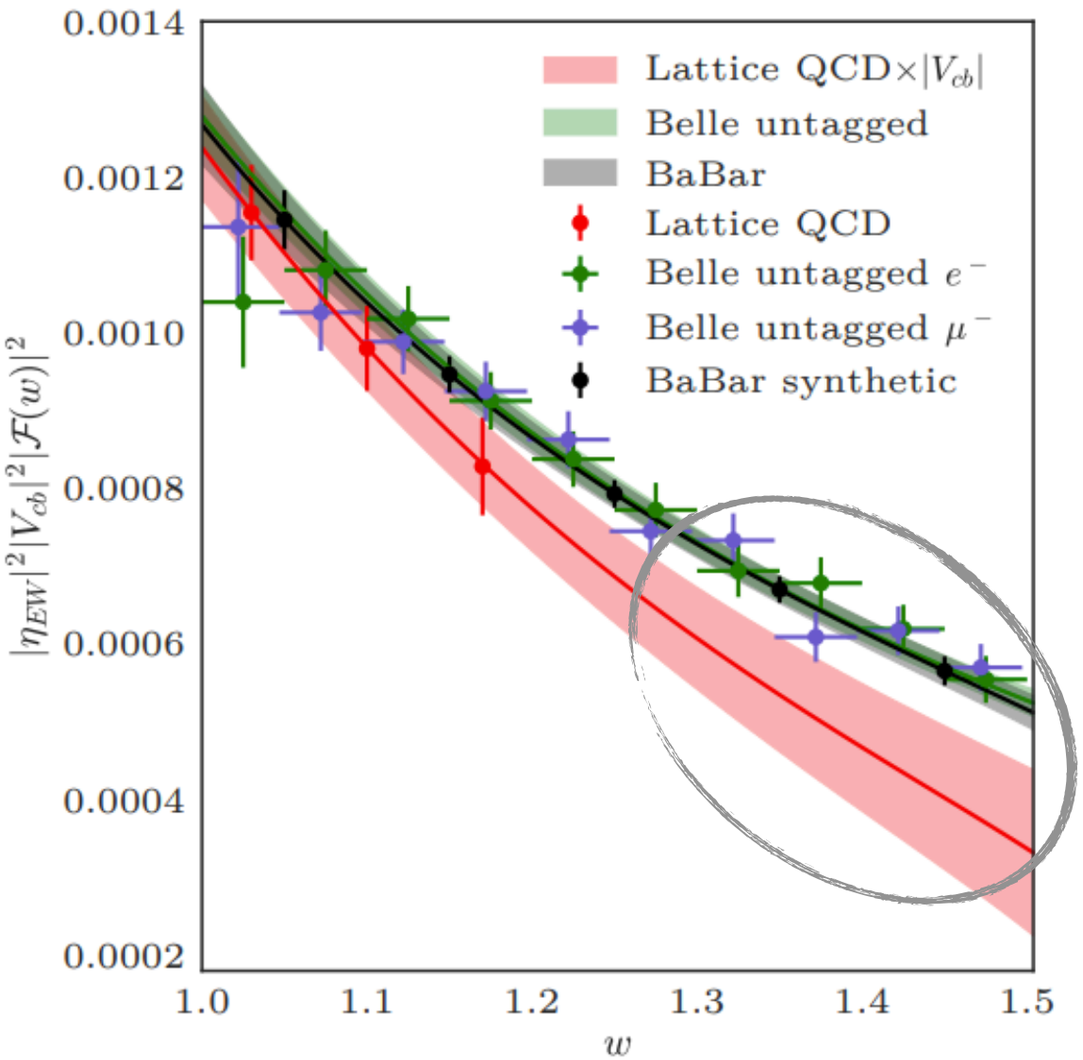


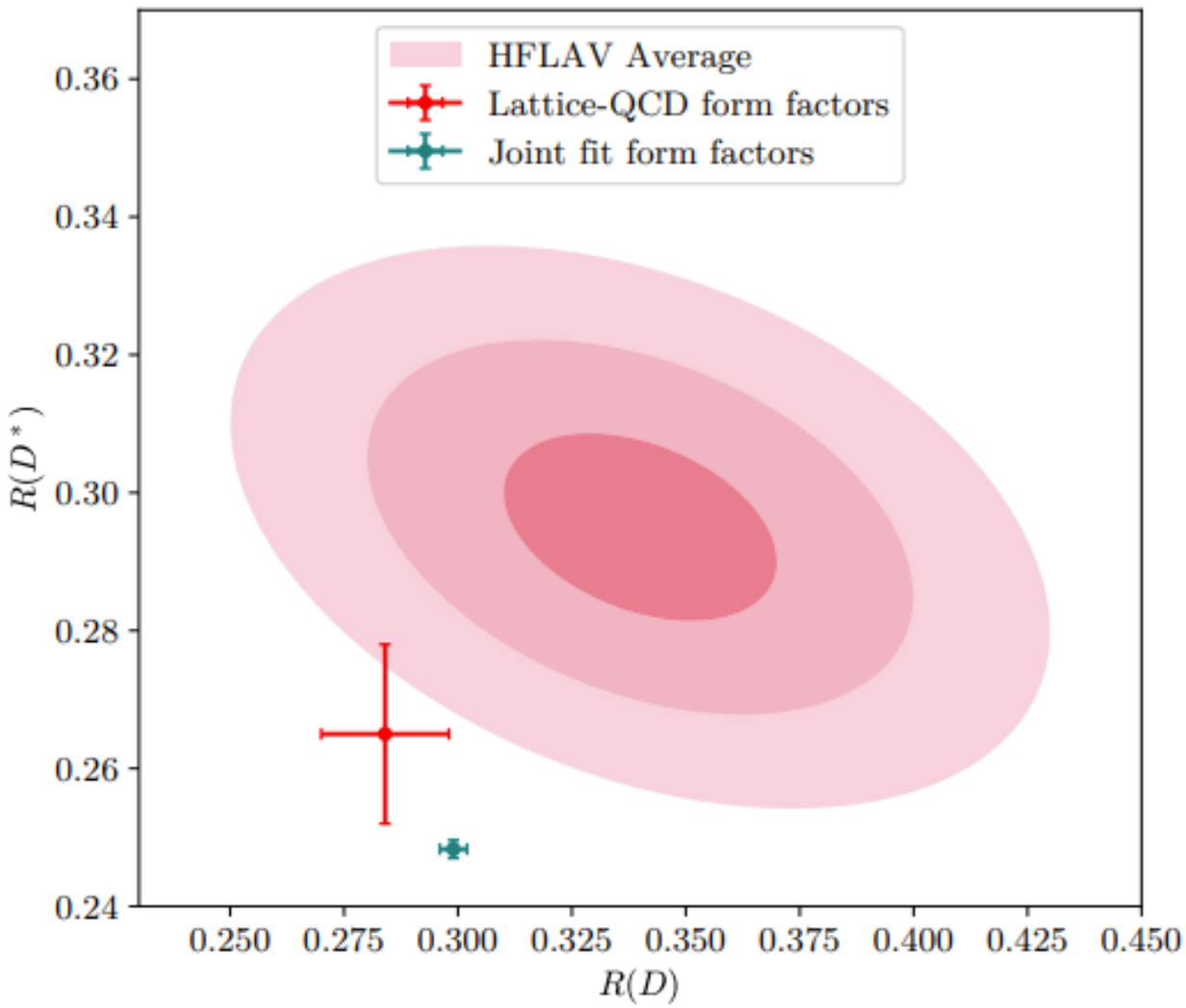
- **Good agreement** between **LHCb** results and the SM predictions;
- Small deficit in the exp. average — *due to ATLAS measurement*.

Warning!

[MILC/Fermilab, 2105.14019]

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \ell \nu) \propto |V_{cb}|^2 \, |\mathcal{F}(w)|^2 \qquad \left[w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}} \right]$$





SM predictions

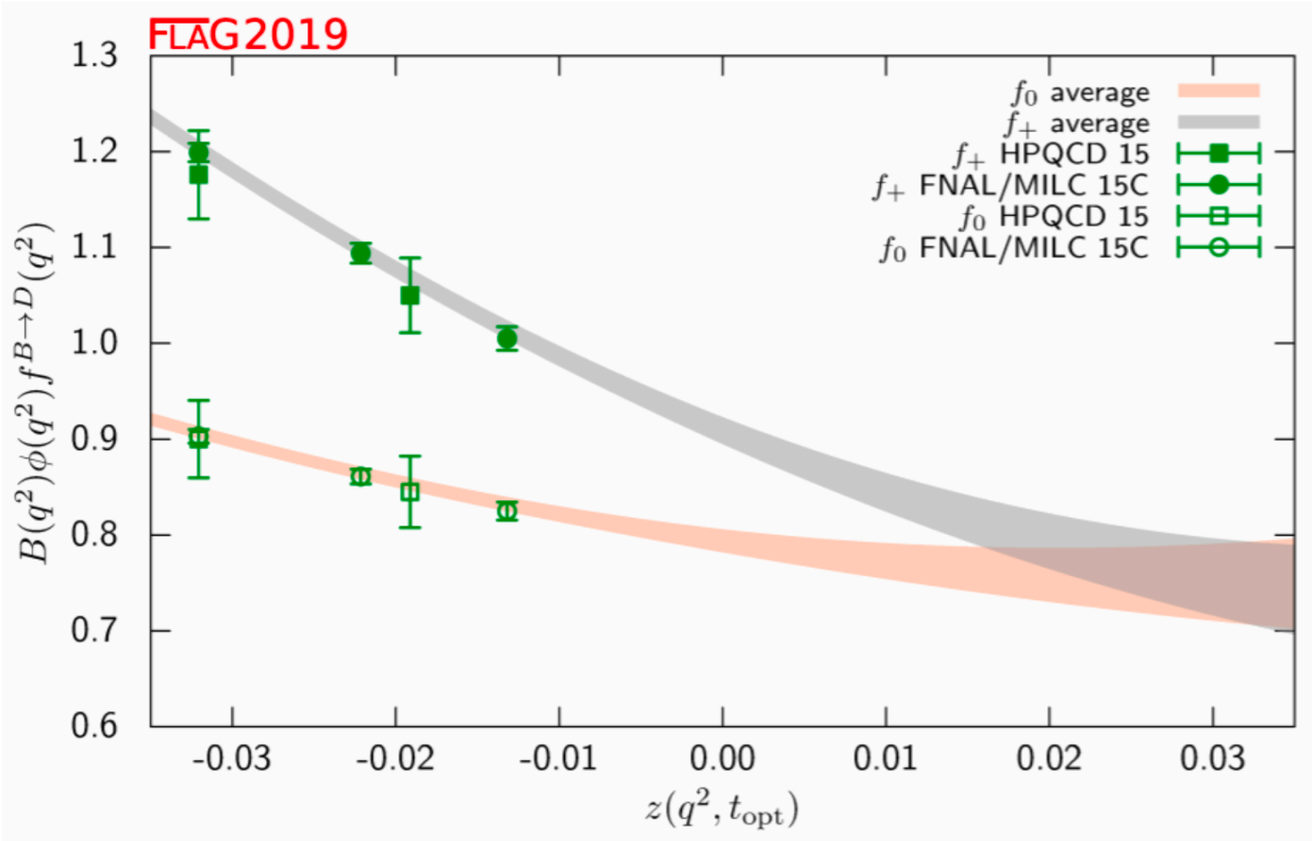
Form-factors: R_D

- **Lattice QCD** at $q^2 \neq q^2_{\rm max}$ ($w \neq 1$) available for both leading (vector) and subleading (scalar) form-factors:

$$\langle D(k)|\bar{c}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_D^2}{q^2} q^2\right] f_+(q^2) + q^\mu \frac{m_B^2 - m_D^2}{q^2} f_0(q^2)$$

with $f_+(0) = f_0(0)$

[MILC/Fermilab '15, HPQCD '15]



[FLAG' 21] average:

$$R_D^{\rm SM} = 0.300(10)$$

[Intermezzo] How to improve the SM prediction for R_{D^*} ?

- Theory uncertainties are related to m_τ, i.e the only source of LFU breaking in the SM:

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \ell \bar{\nu}) = \Phi(q^2)\,\omega_\ell(q^2)\left[\underbrace{H_V(q^2)^2}_{\propto A_1(q^2),\ A_2(q^2),\ V(q^2)} + \frac{m_\ell{}^2}{m_\ell{}^2 + 2q^2}\underbrace{H_S(q^2)^2}_{\propto A_0(q^2)}\right]$$

(see back-up)

- A **simple redefinition** can reduce these uncertainties:

$$R_{D^*}^{(\tau/\mu)} = \frac{\displaystyle\int_{m_\tau^2}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \tau \bar{\nu})}{\displaystyle\int_{m_\mu^2}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \mu \bar{\nu})} \longrightarrow R_{D^*}^{(\tau/\mu)}[q^2_{\min}] = \frac{\displaystyle\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \tau \bar{\nu})}{\displaystyle\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \mu \bar{\nu})}$$

	Observable	Latt.	Latt. +Exp
Usual definition	R_{D^*}	0.27(1) [5%]	0.248(1) [0.5 %]
Definition with same bins	$R_{D^*}[m_\tau^2]$	0.343(6) [2%]	0.337(1) [0.4%]
	$R_{D^*}[5\ \mathrm{GeV}^2]$	0.422(3) [0.5 %]	0.422(1) [0.2%]

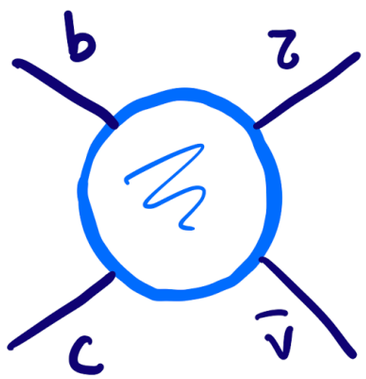
[Isidori, **OS**. '20]

NB. Re-weighting of the muon rate by $\omega_\tau(q^2)/\omega_\mu(q^2)$ can further reduce the theory uncertainties.

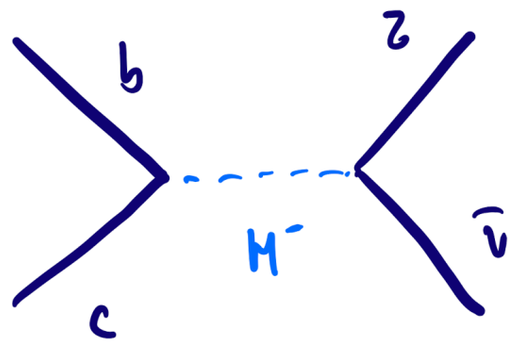
From EFTs to concrete models

Many papers in the literature...

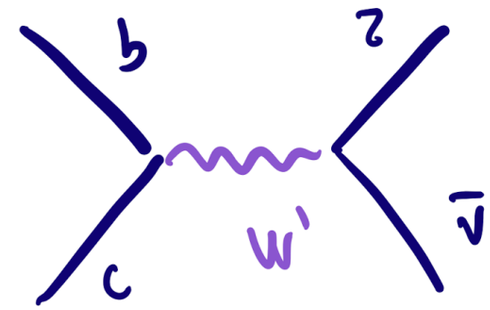
- $b \to c\tau\bar{\nu}$:



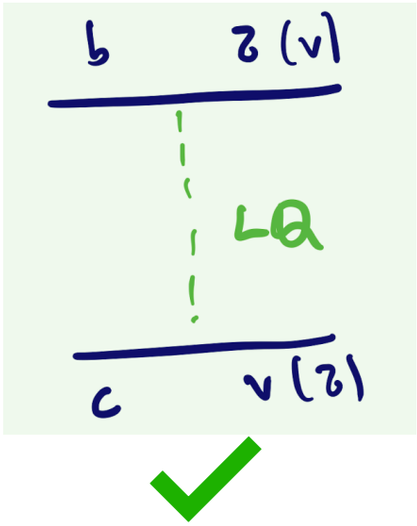
$\Lambda_{R_{D^{(*)}}} \lesssim 3$ TeV



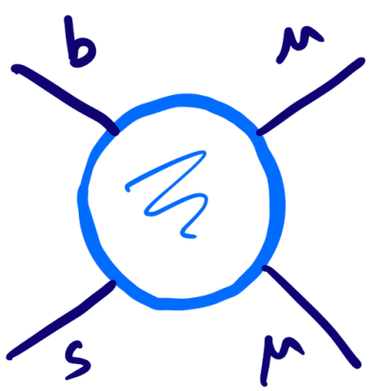
(*B_c-meson lifetime*)



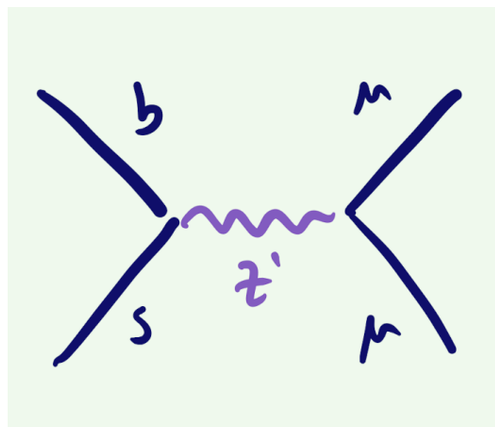
($\Delta F = 2, pp \to \tau\tau$...)

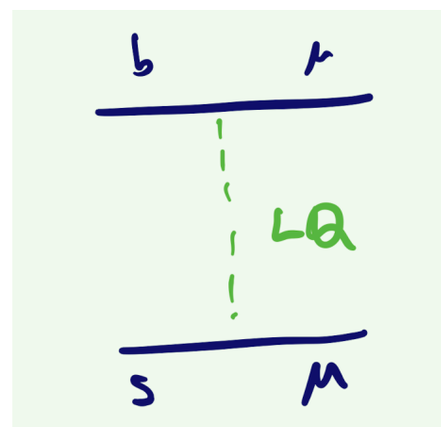


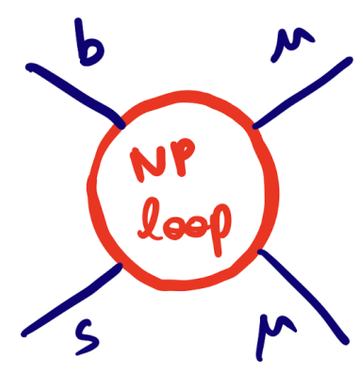
- $b \to s\ell\ell$:



$\Lambda_{R_{K^{(*)}}} \lesssim 30$ TeV







Challenging task because of the numerous exp. constraints: *flavor, LHC, EWPT...*

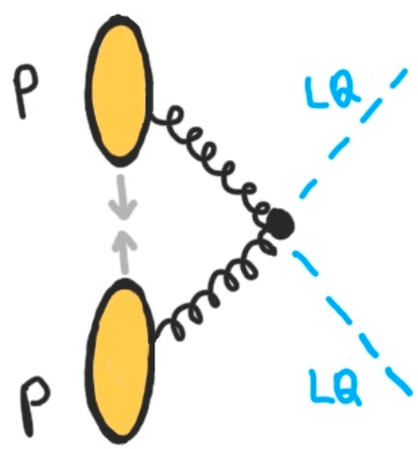
LHC constraints

See talk by K. Yong Sheng!

i. LQ pair-production

Production dominated by QCD:

$$\sigma(pp \to \mathrm{LQ}\,\mathrm{LQ}^\dagger) \times \underbrace{\mathcal{B}(\mathrm{LQ} \to \ell q)^2}_{\equiv \beta^2}$$



$+ \ \ldots$

see [Dorsner et al. '18] for a recent review

ATLAS and CMS results for $\beta = 1\,(\text{or } 0.5)$

Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$ / Ref.
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1} [39]
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1} [40]
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$b\bar{b}\,\mu\bar{\mu}$	1.7 (1.5) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$t\bar{t}\,\mu\bar{\mu}$	1.5 (1.3) TeV	2.0 (1.8) TeV	140 fb^{-1} [42]
$jj\,\nu\bar{\nu}$	1.0 (0.6) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$b\bar{b}\,\nu\bar{\nu}$	1.1 (0.8) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$t\bar{t}\,\nu\bar{\nu}$	1.2 (0.9) TeV	1.8 (1.6) TeV	140 fb^{-1} [44]

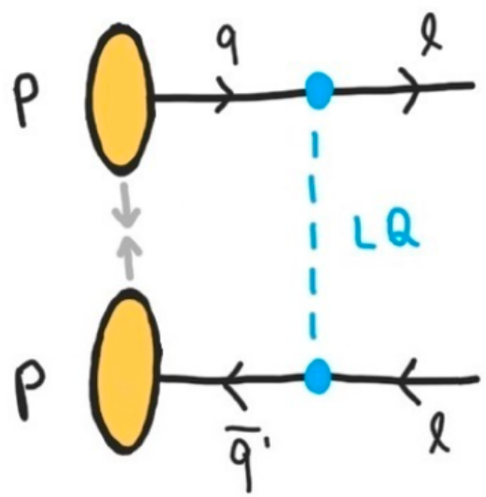
[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

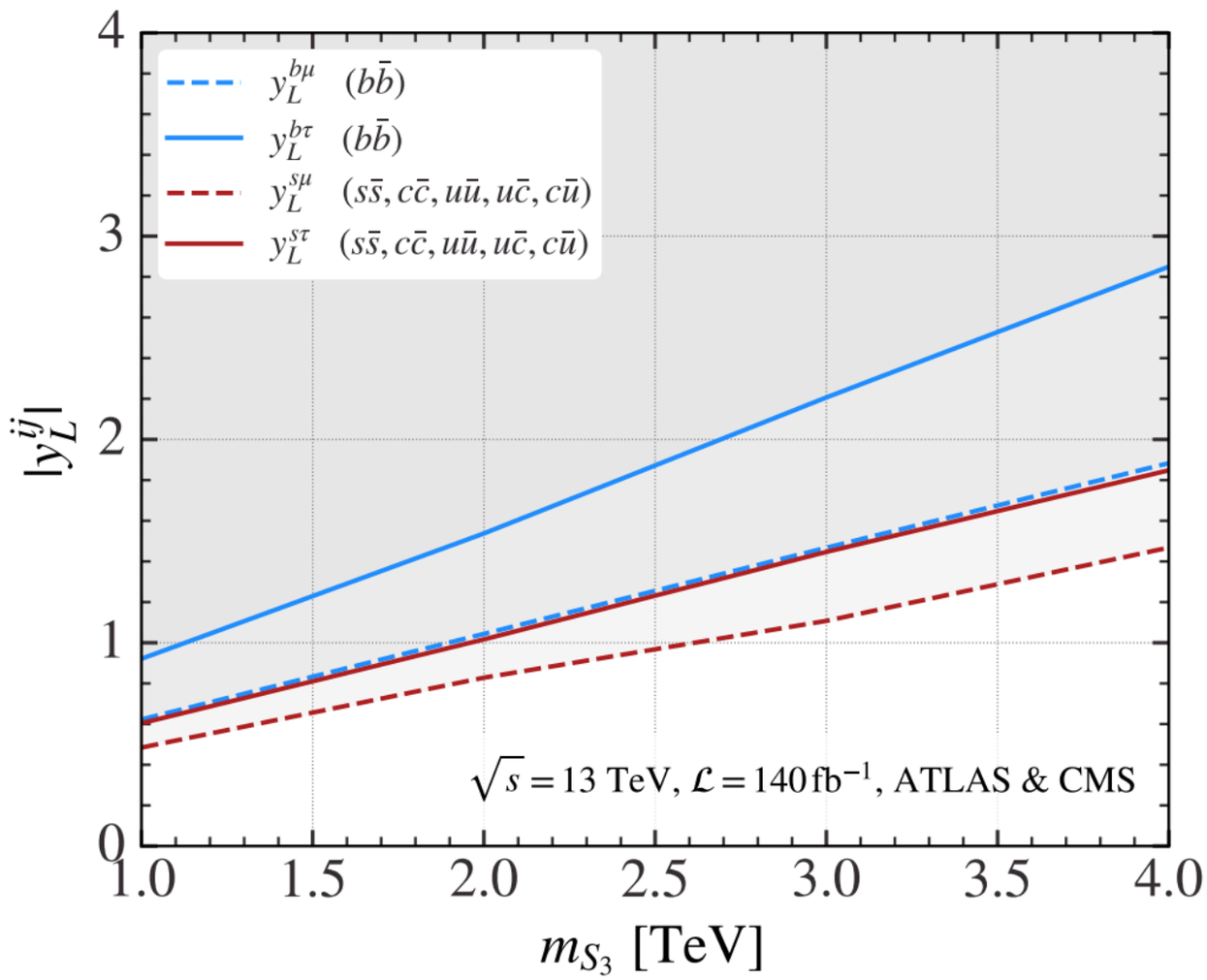
LHC constraints

ii. Di-lepton production at high-p_T

See talks by Lukas Allwicher and Florentin Jaffredo this afternoon!

Useful upper limits on LQ couplings:





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

$$\mathcal{L}_{S_3} = y_L^{ij}\, \overline{Q^C} i\tau_2 (\vec{\tau} \cdot \vec{S}_3) L_j + \text{h.c.}$$

First considered by [Eboli, '88]

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

High-p_T package

[Allwicher, Faroughy, Jaffredo, **OS**, Wilsch. 2204.XXXXX]

```
<<HighPT`
```

HighPT : High-p_T Tails

Authors : Lukas Allwicher, Darius A. Faroughy, Florentin Jaffredo, Olcyr Sumensari, and Felix Wilsch

Reference : arXiv:22xx.xxxxx

Website : https://github.com/HighPT/HighPT

HighPT is free software under the terms of the MIT License.

Please submit bugs and feature requests using GitHub's issue system at:

https://github.com/HighPT/HighPT/issues

Recast of LHC searches for the SMEFT and simplified scenarios

$pp \to \tau\tau$	[arXiv:2002.12223]
$pp \to ee,\ \mu\mu$	CMS-PAS-EXO-19-019
$pp \to \tau\nu$	ATLAS-CONF-2021-025
$pp \to e\nu,\ \mu\nu$	[arXiv:1906.05609]
$pp \to e\mu,\ e\tau,\ \mu\tau$	CMS-PAS-EXO-19-014

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

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

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

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

Other notable constraints...

- $R_{e/\mu}^{K\ \mathrm{exp}} = 2.488(10) \times 10^{-5}$ [PDG], $R_{e/\mu}^{K\ \mathrm{SM}} = 2.477(1) \times 10^{-5}$ [Cirigliano 2007]

$$R_{e/\mu}^{K} = \frac{\Gamma(K^- \to e^- \bar{\nu})}{\Gamma(K^- \to \mu^- \bar{\nu})}$$

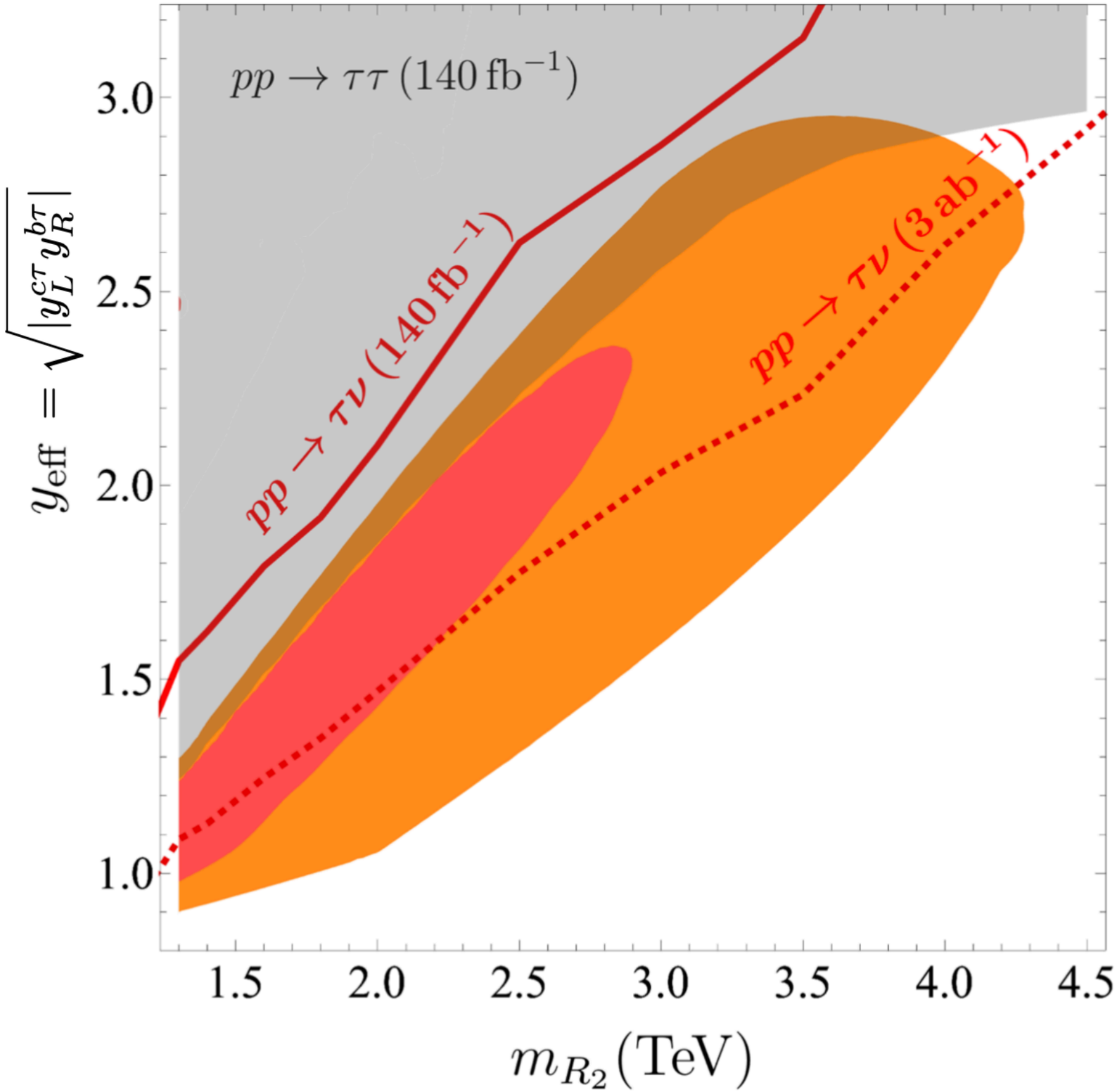
- $R_{\mu/e}^{D\ \mathrm{exp}} = 0.995(45)$ [Belle 2017], $R_{\mu/e}^{D^*\ \mathrm{exp}} = 1.04(5)$ [Belle 2016]

$$R_{\mu/e}^{D^{(*)}} = \frac{\Gamma(B \to D^{(*)} \mu \bar{\nu})}{\Gamma(B \to D^{(*)} e \bar{\nu})}$$

- $\mathcal{B}(\tau \to \mu\phi) < 8.4 \times 10^{-8}$ [PDG]
- Loops: $\Delta m_{B_s}^{\mathrm{exp}} = 17.7(2)\ \mathrm{ps}^{-1}$ [PDG], $\Delta m_{B_s}^{\mathrm{SM}} = (19.0 \pm 2.4)\ \mathrm{ps}^{-1}$ [FLAG 2016]
- Loops: $Z \to \mu\mu$, $Z \to \tau\tau$, $Z \to \nu\nu$ [PDG]

$$\frac{g_V^\tau}{g_V^e} = 0.959(29)\,, \quad \frac{g_A^\tau}{g_A^e} = 1.0019(15) \qquad \frac{g_V^\mu}{g_V^e} = 0.961(61)\,, \quad \frac{g_A^\mu}{g_A^e} = 1.0001(13)$$

$$N_\nu^{\mathrm{exp}} = 2.9840(82)$$


$pp \to \tau\tau\,(140\,\mathrm{fb}^{-1})$
$pp \to \tau\nu\,(140\,\mathrm{fb}^{-1})$
$pp \to \tau\nu\,(3\,\mathrm{ab}^{-1})$
$y_{\mathrm{eff}} = \sqrt{|y_L^{c\tau} y_R^{b\tau}|}$
3.0
2.5
2.0
1.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
$m_{R_2}\,(\mathrm{TeV})$

CPV ASPECTS OF R_2

Nejc Kosnik slides at Invisibles'22

- How to test large CPV phase $y_R^{b\tau} = -0.2 - 1.2i$?
  - Charm electric dipole moment induces neutron EDM

W. Dekens, J. de Vries, M. Jung, K. K. Vos, 1809.09114

$$d_c = 0.1 \times Q_c\, e\, m_c \frac{1}{m_{R_2}^2} \mathrm{Im}\left[V_{cb}^* y_R^{b\tau\,*} y_L^{c\tau}\right]$$

$$\langle N|\bar{c}\sigma^{\mu\nu}\gamma_5 c|N\rangle = g_T^c\, \bar{u}_N \sigma^{\mu\nu}\gamma_5 u_N$$

neutron charm tensor charge, $d_n = g_T^c\, d_c$

Neutron on the lattice: $g_T^c = -(2.4 \pm 1.6) \times 10^{-4}$ — C. Alexandrou, et al, 1909.00485

Neutron EDM: $d_n < 1.8 \times 10^{-26}\, e\,\mathrm{cm}$ — PSI, 2001.11966

$$\Longrightarrow |\Im(g_{S_L})| < 0.76$$

Improving precision of the lattice result could well probe relevant range $|\Im(g_{S_L})| \approx 0.5$

  - Angular spectra of $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu$

P. Böer, A. Kokulu, J. N. Toelstede, D. van Dyk, 1907.12554

$$\frac{d^4\mathcal{B}}{dq^2 d\cos\theta_\tau d\cos\theta d\phi} = 8\pi \Big[\mathcal{A}_1 + \mathcal{A}_2\cos\theta$$
$$+ (\mathcal{B}_1 + \mathcal{B}_2\cos\theta)\cos\theta_\tau + (\mathcal{C}_1 + \mathcal{C}_2\cos\theta)\cos^2\theta_\tau$$
$$+ (\mathcal{D}_3\sin\theta\cos\phi + \mathcal{D}_4\sin\theta\sin\phi)\sin\theta_\tau$$
$$+ (\mathcal{E}_3\sin\theta\cos\phi + \mathcal{E}_4\sin\theta\sin\phi)\sin\theta_\tau\cos\theta_\tau\Big],$$