Caltech

Leptoquarks at the TeV scale

Flavor anomalies and Muon (g-2)

Clara Murgui

In collaboration with Pavel Fileviez Pérez (CWRU), Alexis Plascencia (CWRU)
and Mark B. Wise (Caltech)

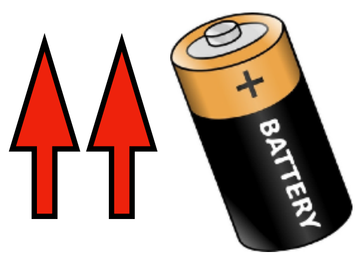
September 8th 2021

Anomalies and Precision in the Belle II Era - Workshop, Vienna

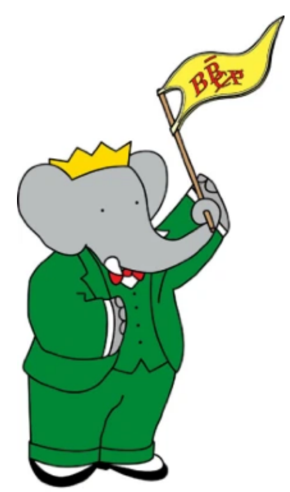
Accessing High Energies

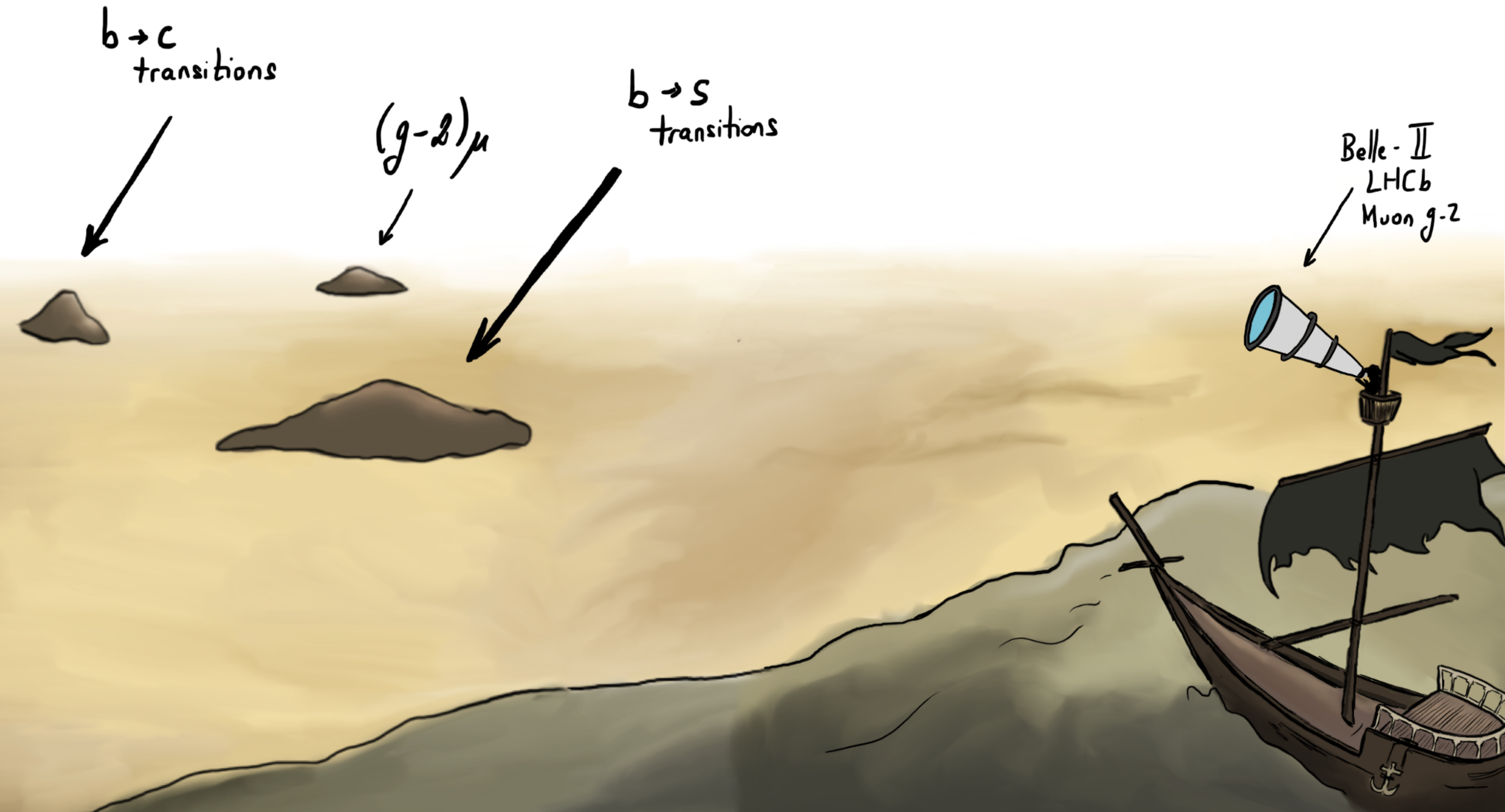
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{O}\left(\frac{\text{Energy}}{\Lambda_{\text{NP}}}\right)^n$$

Construction of Super colliders



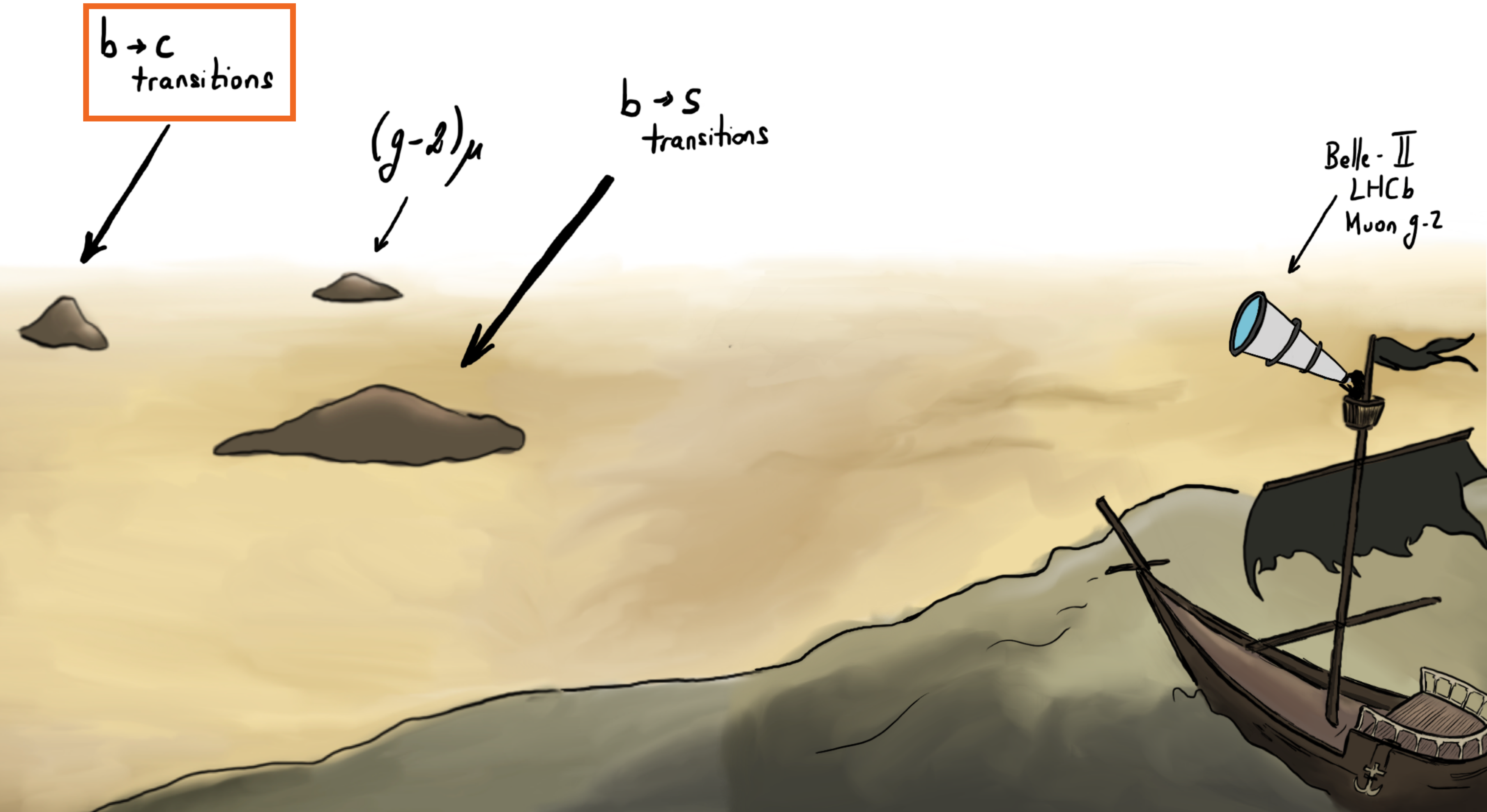
Precision Physics




$b \to c$ transitions
$(g-2)_\mu$
$b \to s$ transitions
Belle - II
LHCb
Muon g-2

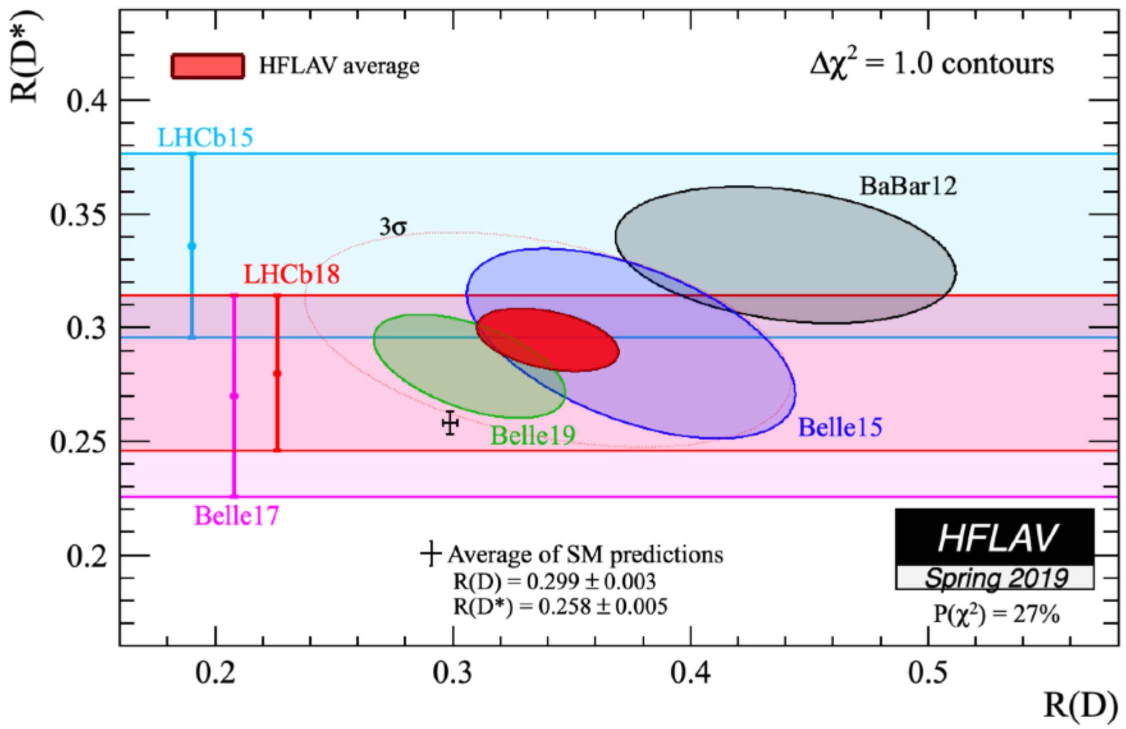
Anomalies in $b \to c$ transitions

[not this talk]



Anomalies in $b \to c$ transitions

Status 2019



3.9 σ	4.0 σ	3.9 σ	3.6 σ	3.1 σ
2015	2016	2017	2018	2019

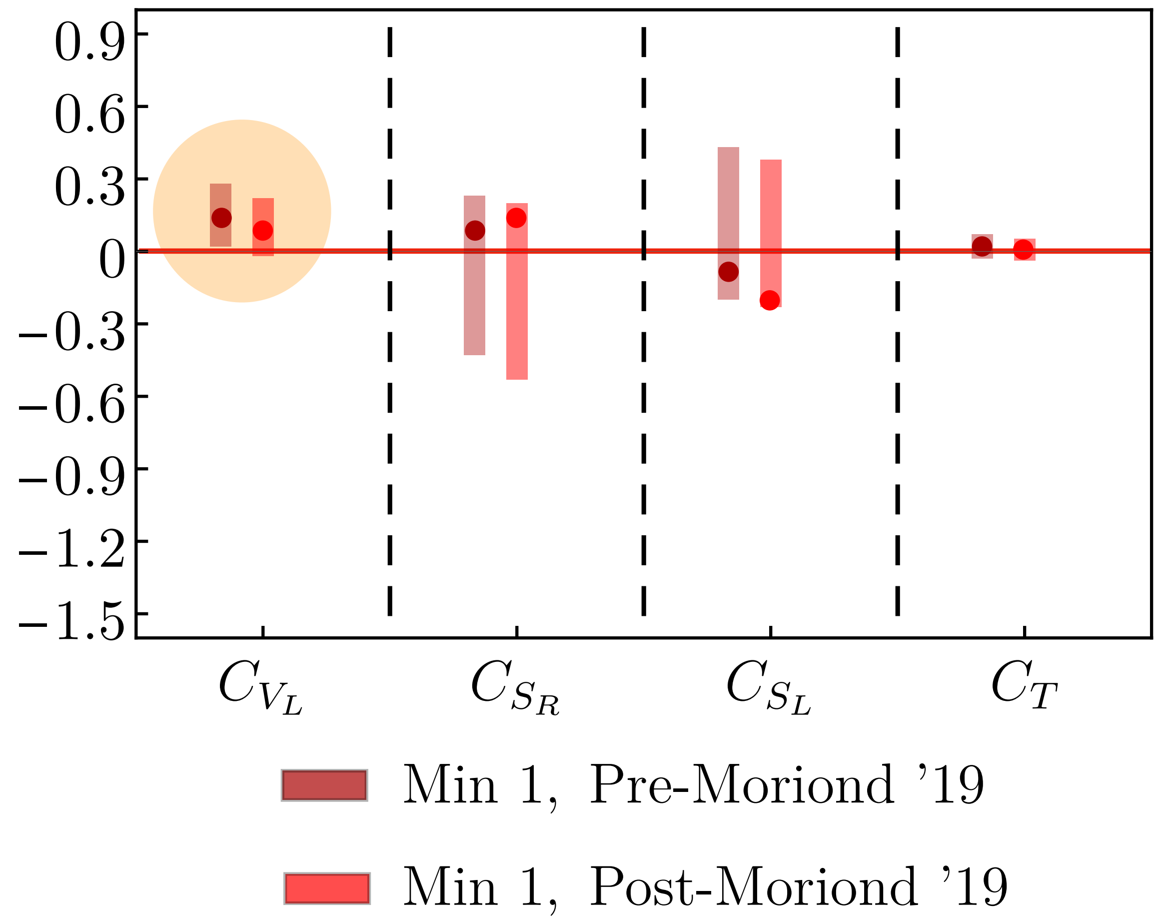
[LHCb, 1506.08614, 1708.08856, 1711.02505]
[Belle, 1507.03233, 1607.07923, 1612.00529, 1709.00129, 1904.02440]
[BaBar, 1205.5442, 1303.0571]

See Monika's talk on Tuesday!

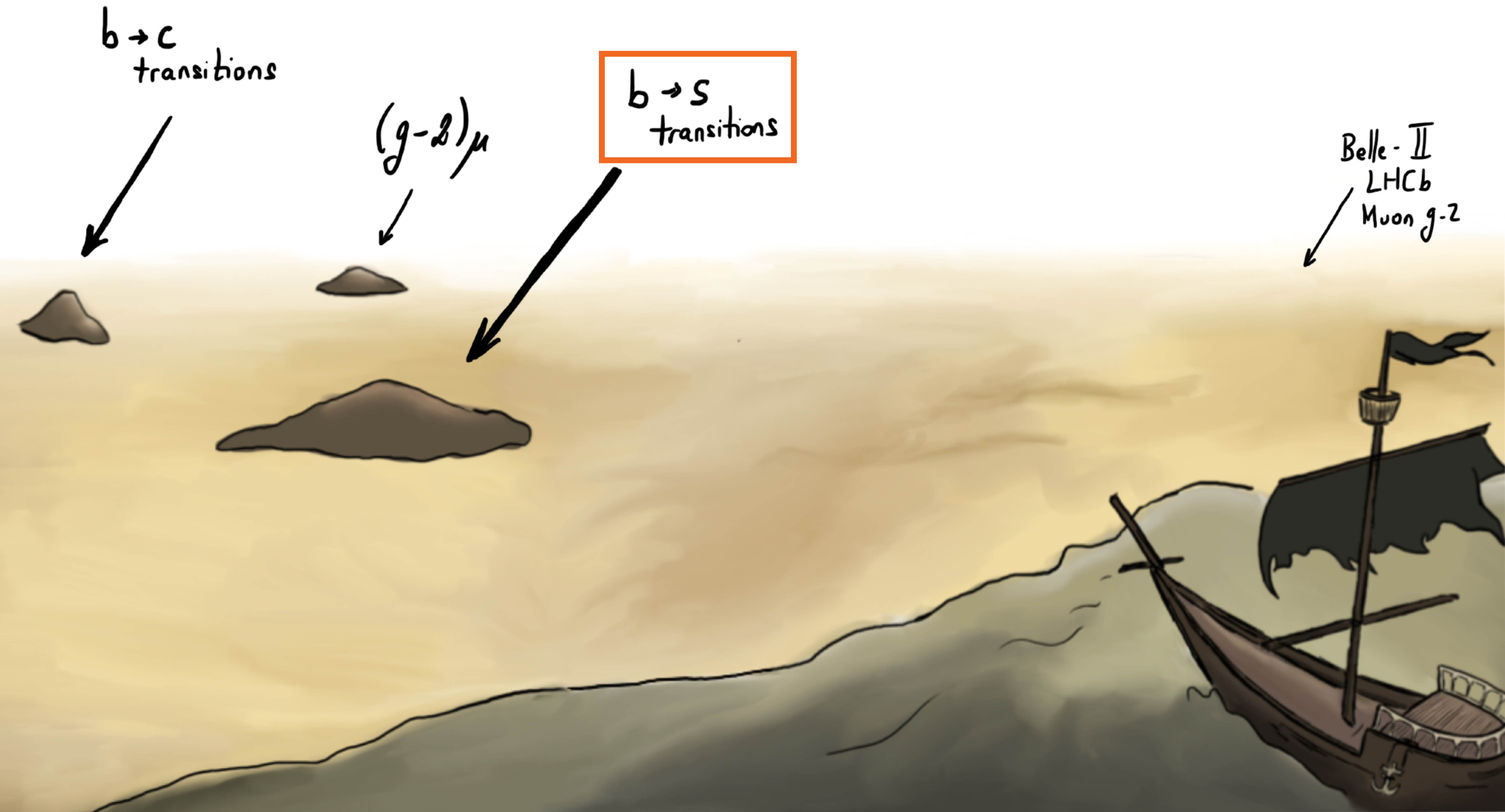
[1904.0931, C.M., Jung, Peñuelas, Pich]

GLOBAL FIT

- SM: $\chi^2_{SM} = 65.5\,/\,57$ d.o.f.
- New Physics: $\chi^2_{min1b} = 37.4\,/\,54$ d.o.f.



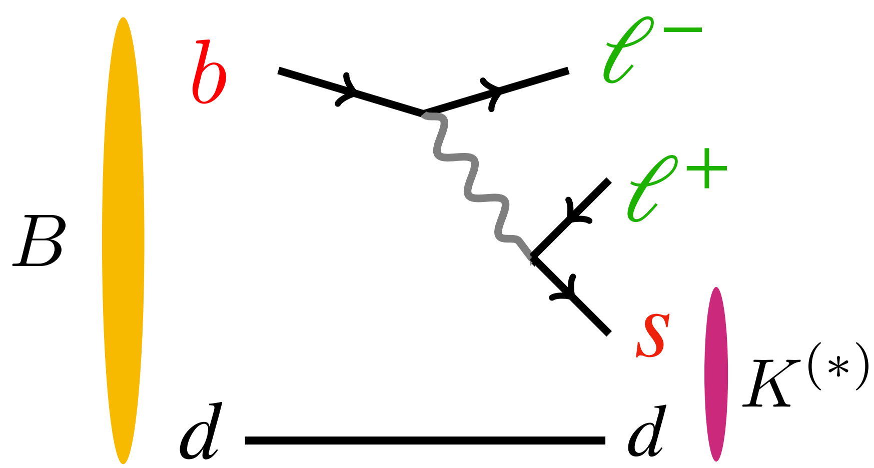
Anomalies in $b \to s$ transitions

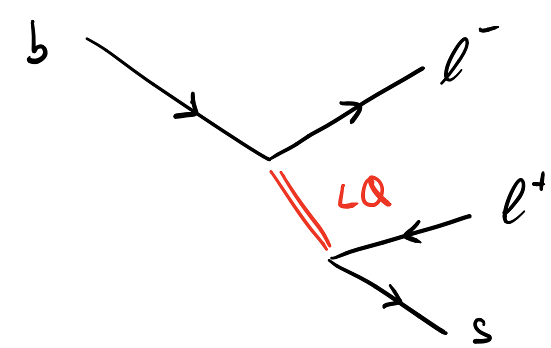


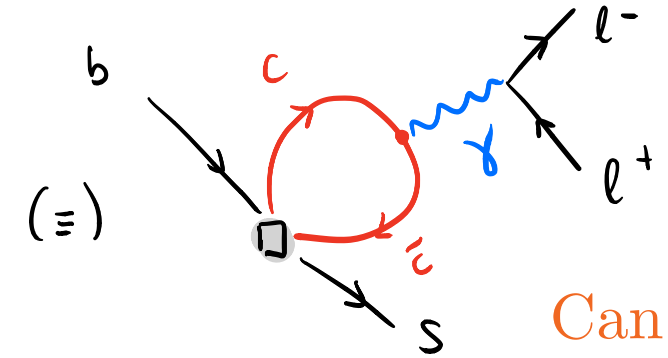
Anomalies in $b \to s$ transitions

$$\mathcal{R}_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{d\mathrm{Br}(B \to K\mu^+\mu^-)}{dq^2} dq^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{d\mathrm{Br}(B \to K e^+ e^-)}{dq^2} dq^2} \overset{\mathrm{SM}}{\simeq} \frac{\Delta_{\mathrm{SM}} + \Delta C_9^{\mathrm{univ}}}{\Delta_{\mathrm{SM}} + \Delta C_9^{\mathrm{univ}}} \simeq 1$$

Clean Observables!

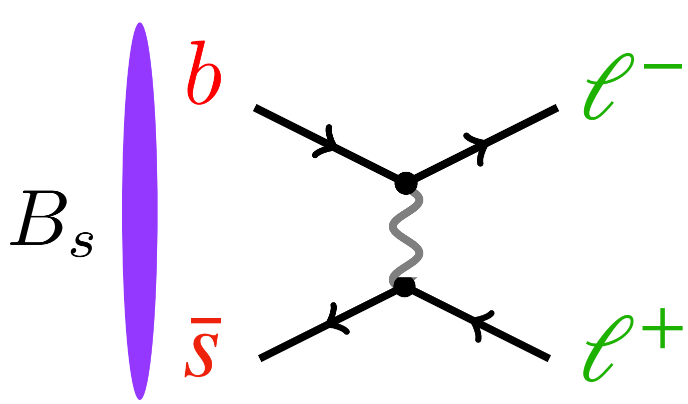


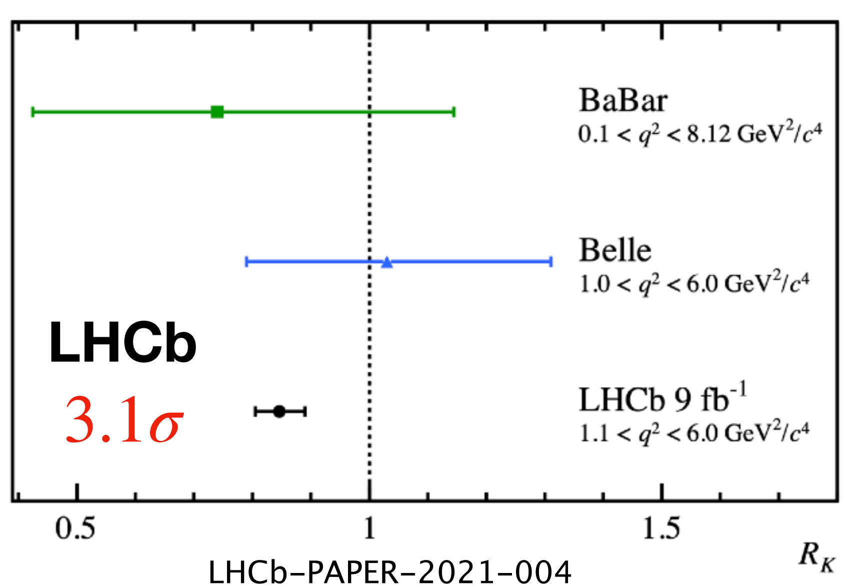


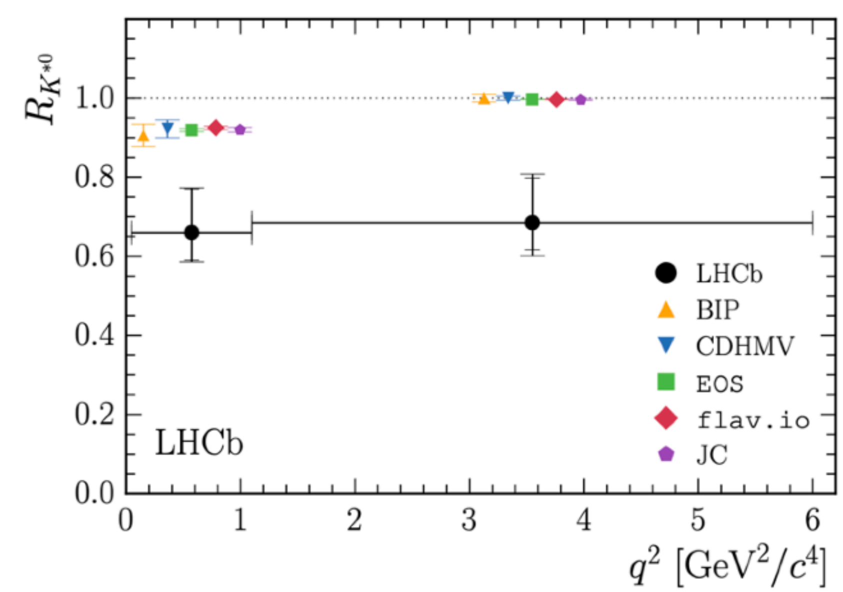


Can mimik NP!

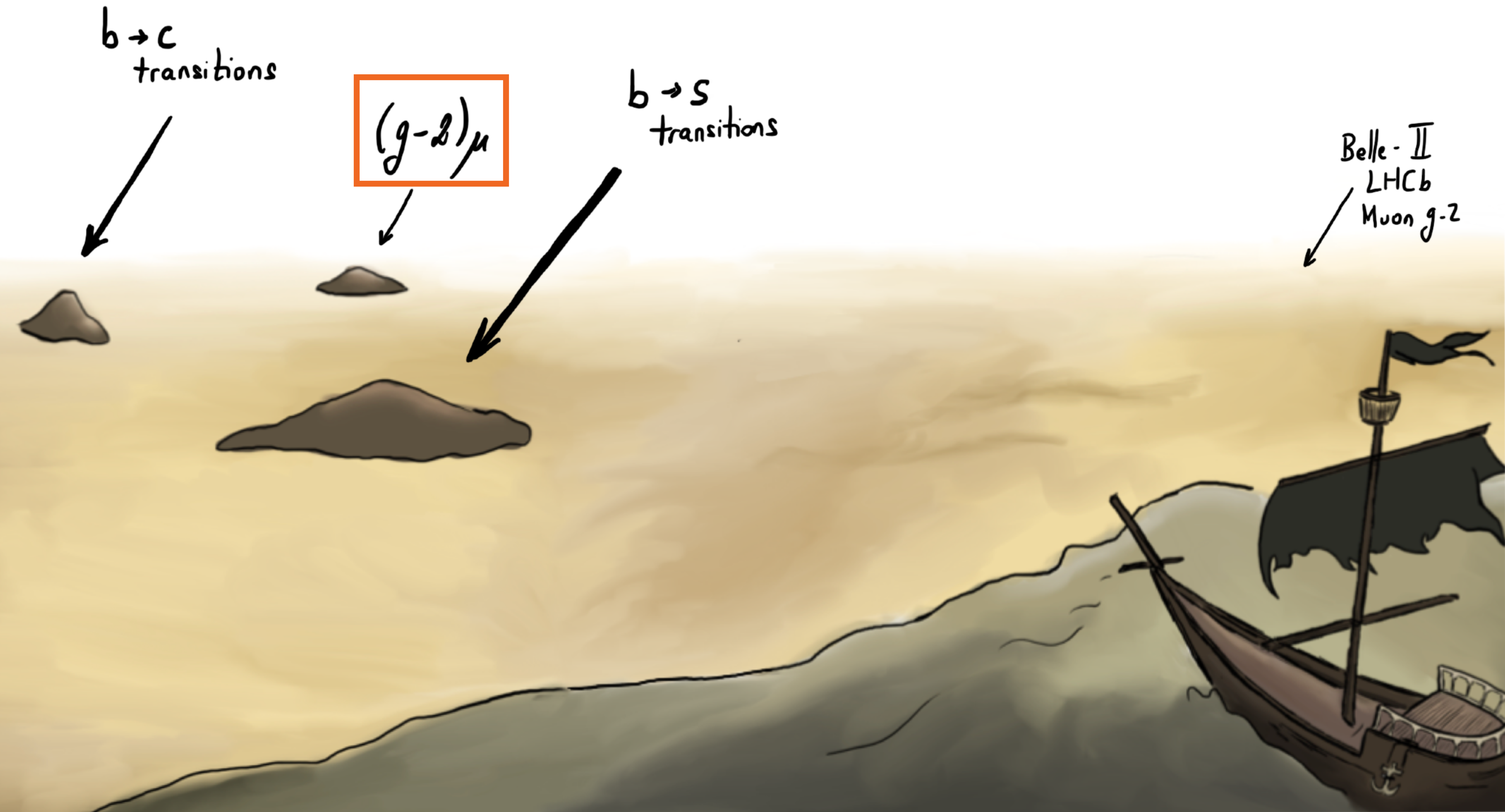
See Mitesh's and Nazila's talk on Monday







Muon (g-2)



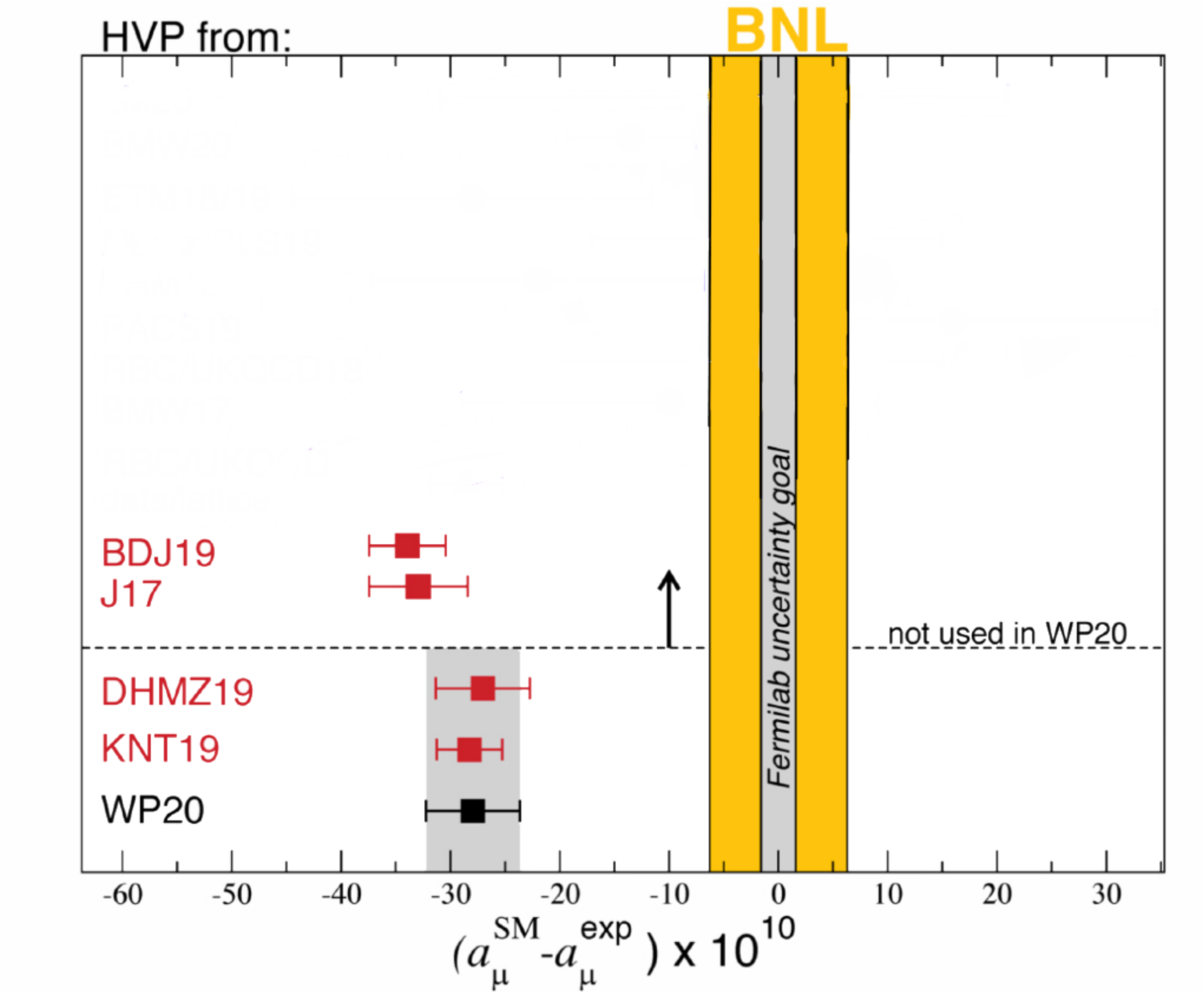
Muon (g-2)

[See Dominik's talk on Tuesday]

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}.$$ **(4.2 σ)**

Fermilab Muon g-2, 2021

E821 experiment, BNL, 2006



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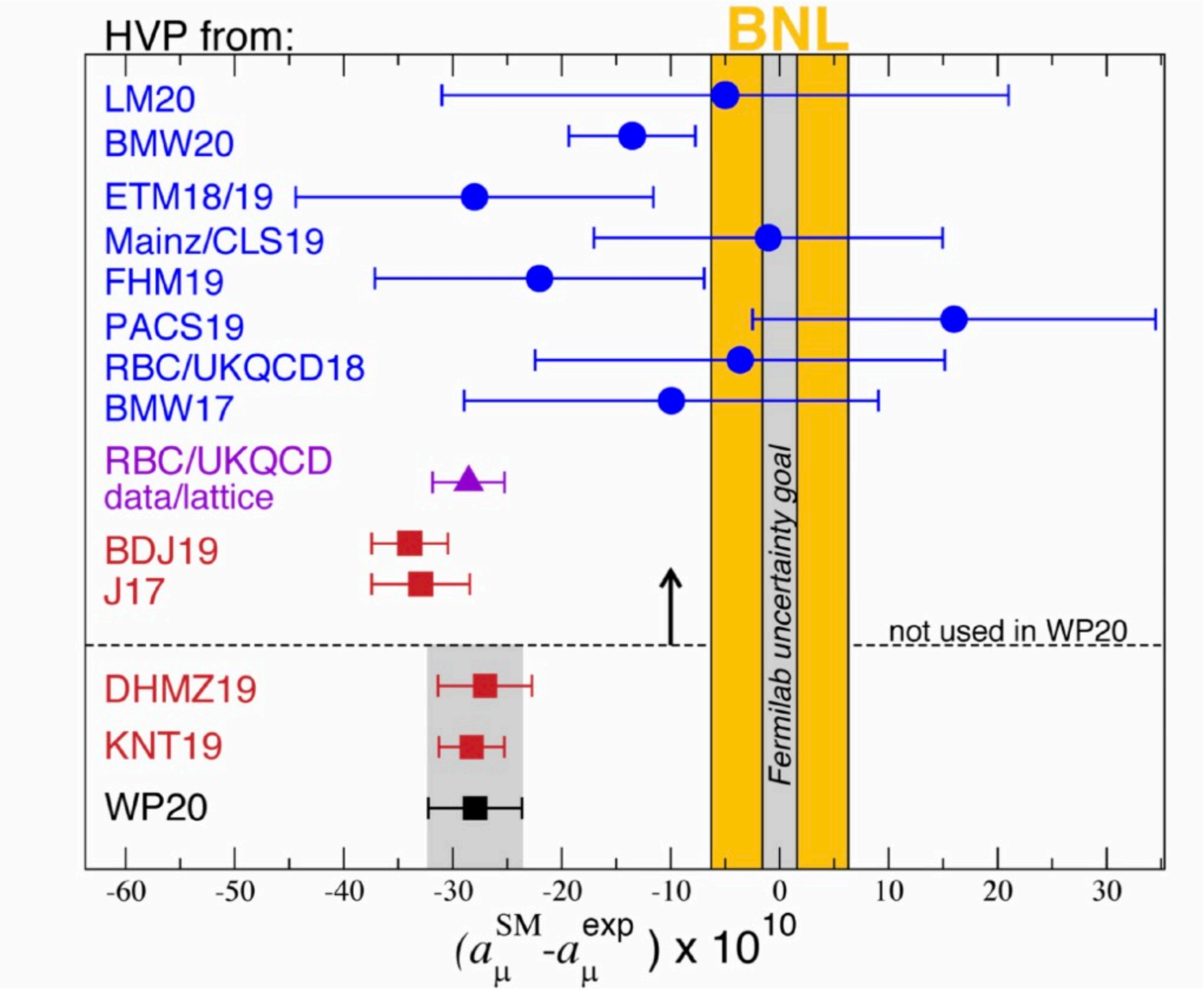


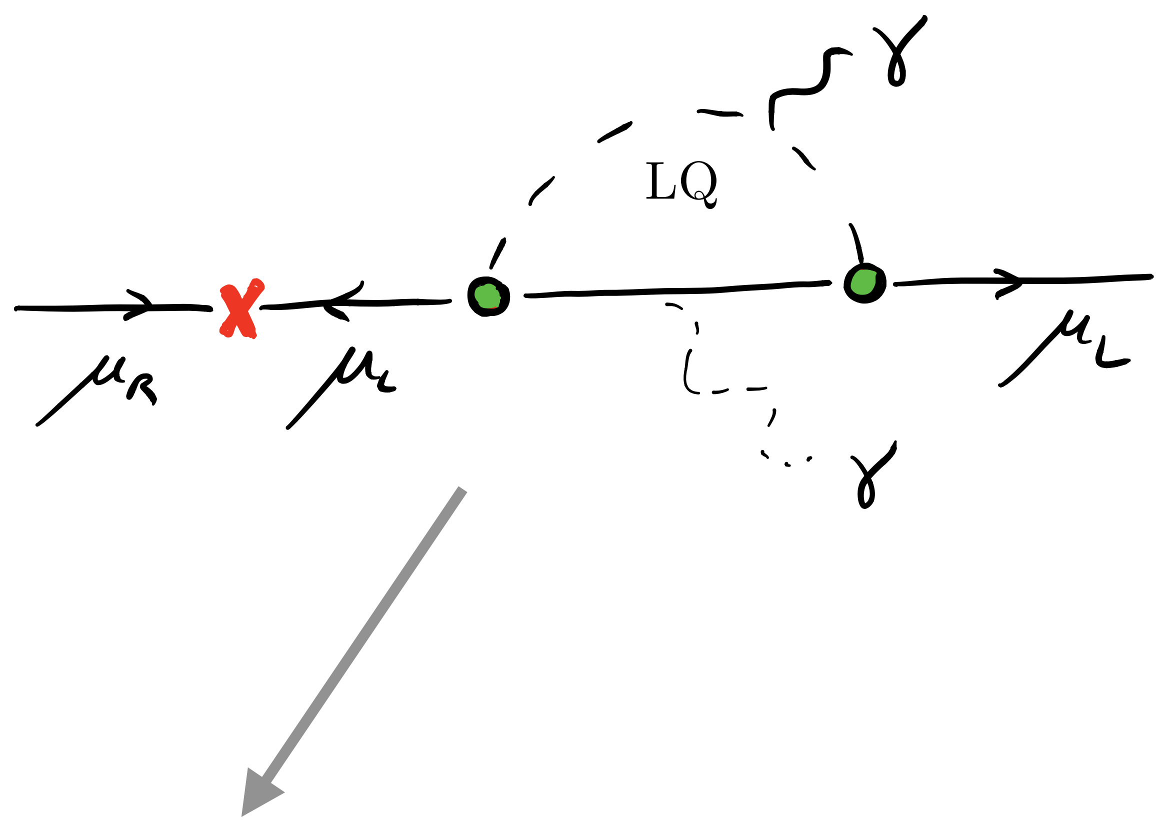
Muon (g-2)

[See Dominik's talk on Tuesday]

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}. \qquad \mathbf{(4.2\,\sigma)}$$

Fermilab Muon g-2, 2021

E821 experiment, BNL, 2006



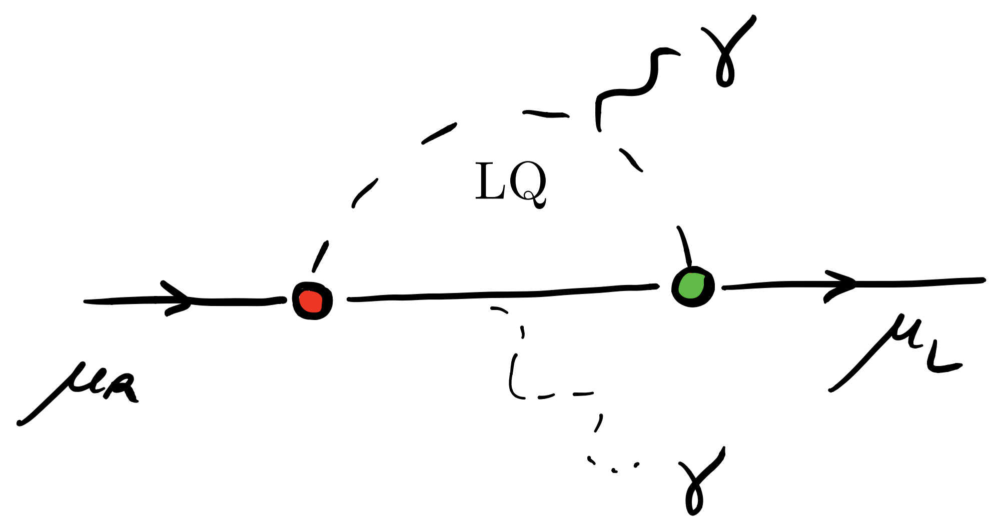
$$\Delta a_\mu^\alpha = \frac{-3}{16\pi^2}\frac{m_\mu^2}{M_{\Phi_\alpha}^2}\sum_j \left[\left(|\lambda_{\alpha L}^{2j}|^2 + |\lambda_{\alpha R}^{2j}|^2\right) \times f_{\text{loop}}\right]$$

Muon (g-2)

[See Dominik's talk on Tuesday]

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}.$$ **(4.2 σ)**

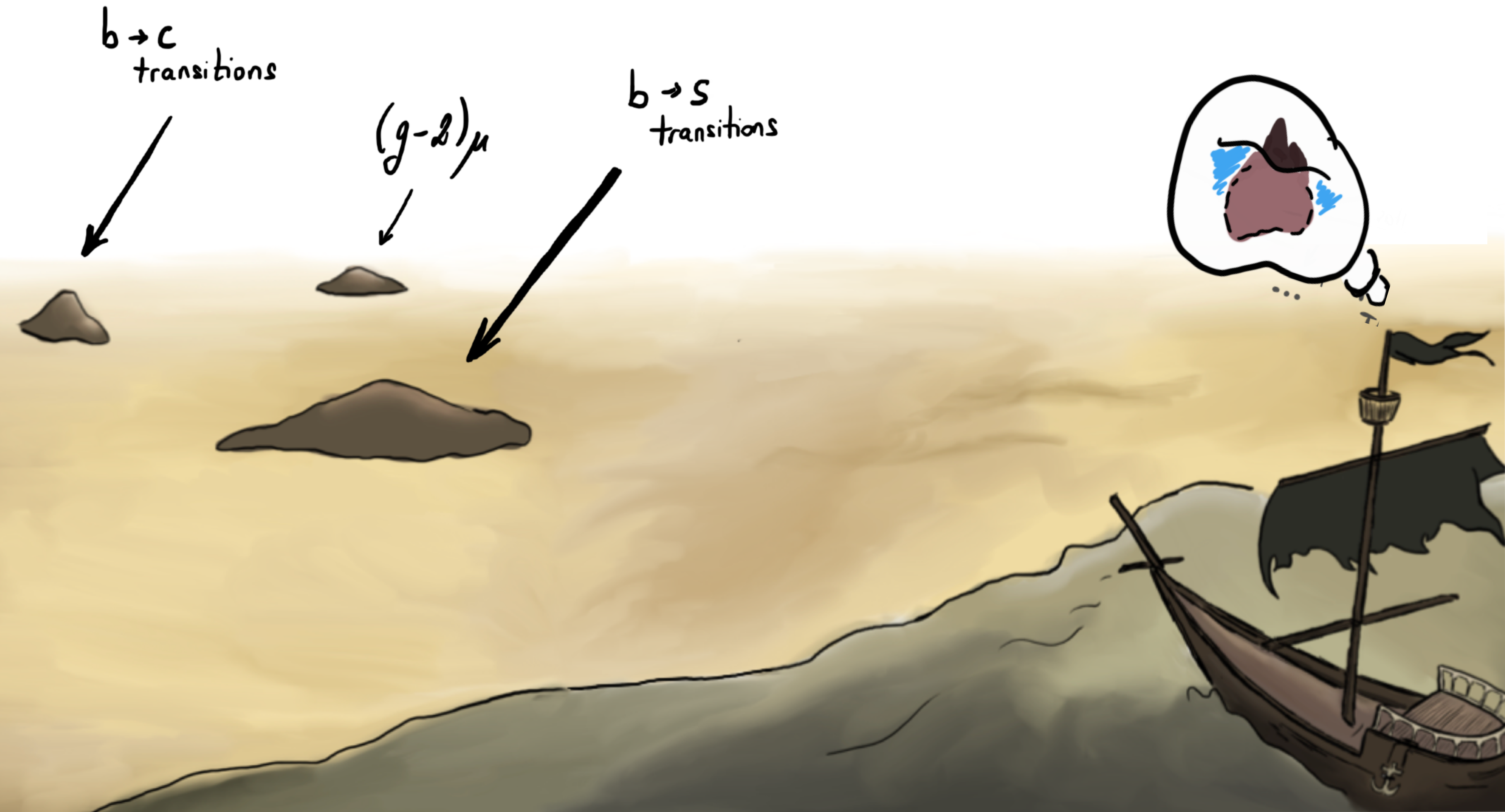
Fermilab Muon g-2, 2021
E821 experiment, BNL, 2006



Chiral enhancement!

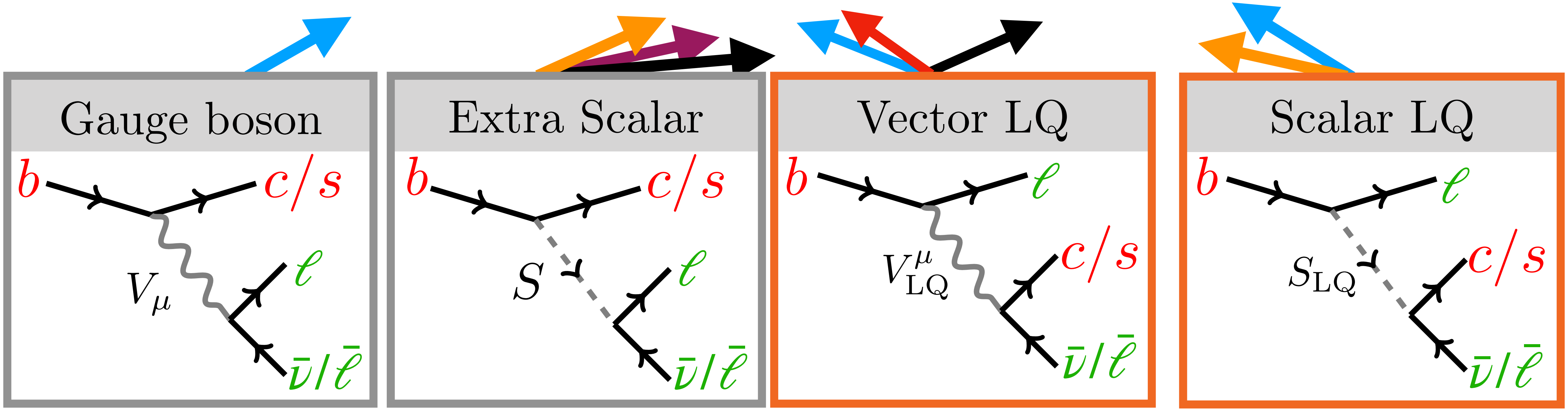
$$\Delta a_\mu^\alpha = \frac{-3}{16\pi^2}\frac{m_\mu^2}{M_{\Phi_\alpha}^2}\sum_j \left[\left(|\lambda_{\alpha L}^{2j}|^2 + |\lambda_{\alpha R}^{2j}|^2\right) \times f_{\rm loop} + \frac{m_q}{m_\mu}{\rm Re}[\lambda_{\alpha L}^{2j}(\lambda_{\alpha R}^{2j})^*] f'_{\rm loop}\right]$$

UV candidates at the TeV scale?



UV candidates at the TeV scale?

$$\mathcal{H}_{\text{eff}} = \frac{4\,G_F}{\sqrt{2}}\,[(1 + C_{V_L})\mathcal{O}_{V_L} + C_{V_R}\,\mathcal{O}_{V_R} + C_{S_R}\,\mathcal{O}_{S_R} + C_{S_L}\,\mathcal{O}_{S_L} + C_T\,\mathcal{O}_T] + \text{h.c.}$$



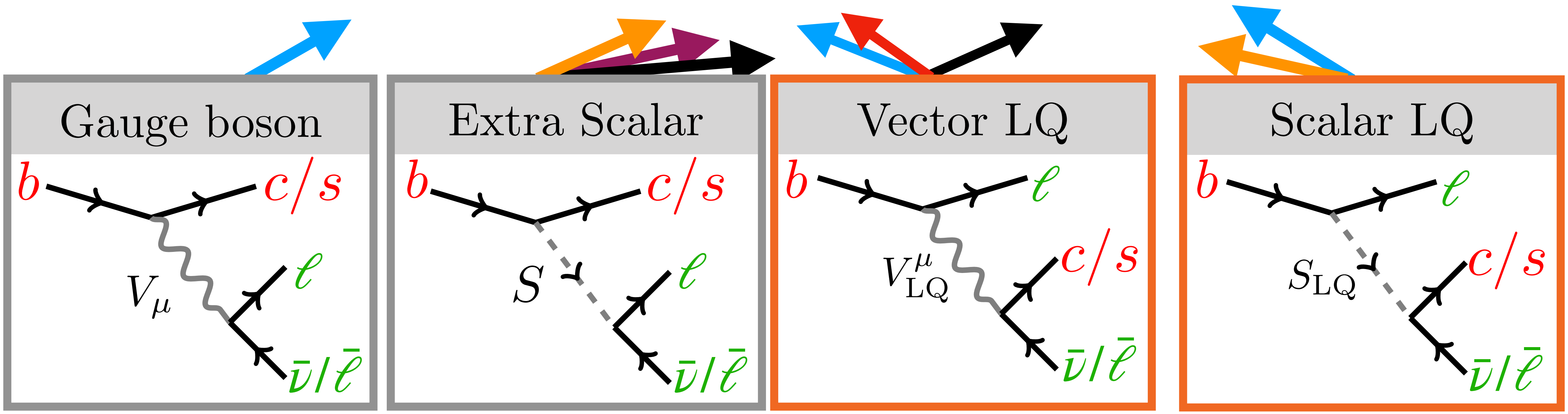
[Gripaios, 0910.1789]

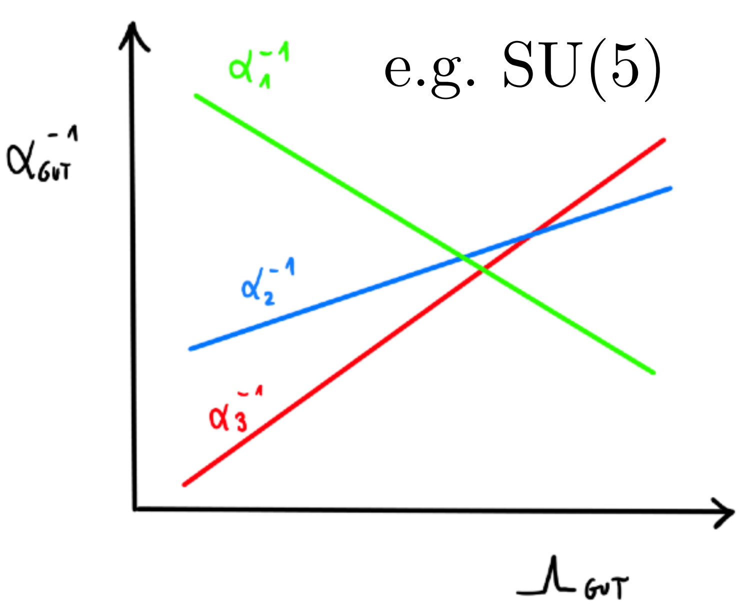
See talk by Joe, Rusa and Monika

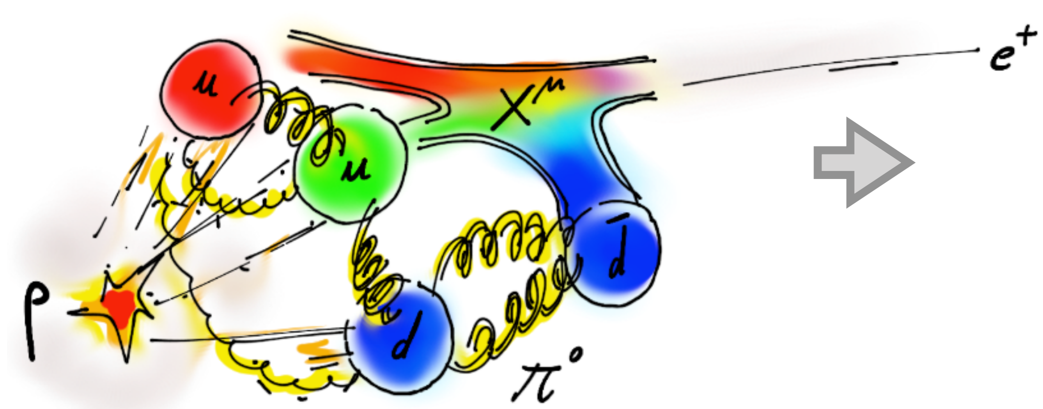
See talk by Monika

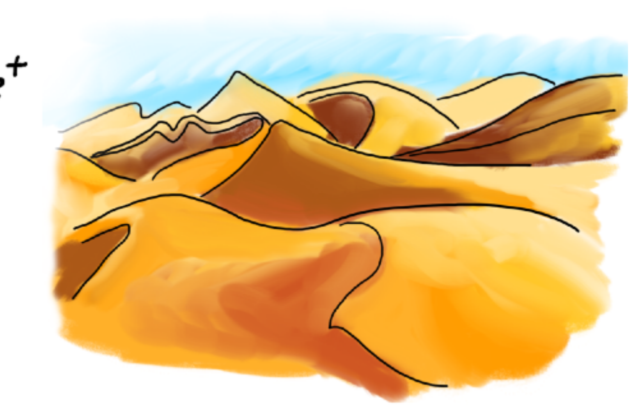
Leptoquarks

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}}\left[(1 + C_{V_L})\mathcal{O}_{V_L} + C_{V_R}\,\mathcal{O}_{V_R} + C_{S_R}\,\mathcal{O}_{S_R} + C_{S_L}\,\mathcal{O}_{S_L} + C_T\,\mathcal{O}_T\right] + \text{h.c.}$$





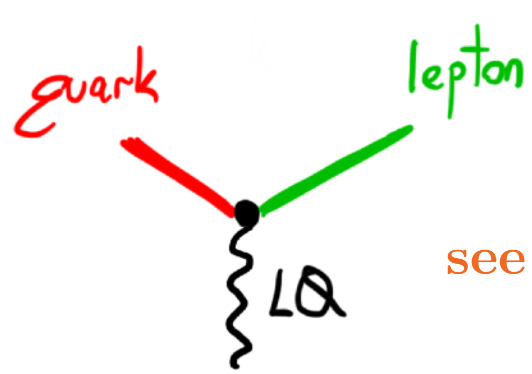




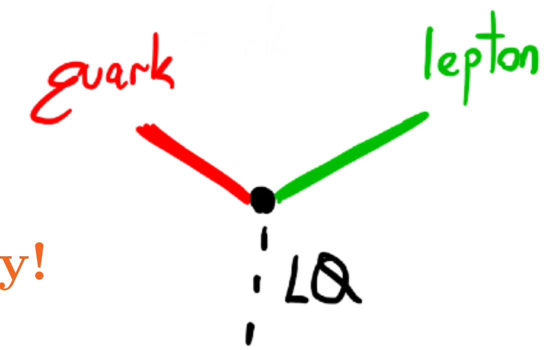
$\Lambda_{\text{GUT}} \gtrsim 10^{15}$ GeV

Leptoquarks

[Dorsner, Fajfer, et al. 1603.04993, Mandal, Pich, 1908.11155]



see Rusa's talk on Monday!



Vector LQs

Symbol	Q.N. (SM)
U_3	$(3, 3, 2/3)$
V_2	$(\bar{3}, 2, 5/6)$
$\tilde{V}_2$	$(\bar{3}, 2, -1/6)$
$\tilde{U}_1$	$(3, 1, 5/3)$
U_1	$(3, 1, 2/3)$
$\bar{U}_1$	$(3, 1, -1/3)$

freedom ☹ ⇨ predictability ☺

Scalar LQs

Symbol	Q.N. (SM)
S_3	$(\bar{3}, 3, 1/3)$
R_2	$(3, 2, 7/6)$
$\tilde{R}_2$	$(3, 2, 1/6)$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$
S_1	$(\bar{3}, 1, 1/3)$
$\bar{S}_1$	$(\bar{3}, 1, -2/3)$

freedom ☺ ⇨ predictability ☹

Leptoquarks

[Dorsner, Fajfer, et al. 1603.04993, Mandal, Pich, 1908.11155]

(green) No Baryon Number violation at renormalizable level

Vector LQs

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U_3	$(3, 3, 2/3)$
V_2	$(\bar{3}, 2, 5/6)$
$\tilde{V}_2$	$(\bar{3}, 2, -1/6)$
$\tilde{U}_1$	$(3, 1, 5/3)$
U_1	$(3, 1, 2/3)$
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Scalar LQs

Symbol	Q.N. (SM)
S_3	$(\bar{3}, 3, 1/3)$
R_2	$(3, 2, 7/6)$
$\tilde{R}_2$	$(3, 2, 1/6)$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$
S_1	$(\bar{3}, 1, 1/3)$
$\bar{S}_1$	$(\bar{3}, 1, -2/3)$

Remark: accidental symmetries could protect baryon number, **see Joe's talk on Monday!**

Leptoquarks

[Dorsner, Fajfer, et al. 1603.04993, Mandal, Pich, 1908.11155]

(green box) No Baryon Number violation at renormalizable level

(dashed orange box) Chiral enhancement in (g-2) at 1-loop level **[See Dominik's talk on Tuesday]**

Vector LQs

Symbol	Q.N. (SM)
U_3	$(3, 3, 2/3)$
V_2	$(\bar{3}, 2, 5/6)$
$\tilde{V}_2$	$(\bar{3}, 2, -1/6)$
$\tilde{U}_1$	$(3, 1, 5/3)$
U_1	$(3, 1, 2/3)$
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Scalar LQs

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S_3	$(\bar{3}, 3, 1/3)$
R_2	$(3, 2, 7/6)$
$\tilde{R}_2$	$(3, 2, 1/6)$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$
S_1	$(\bar{3}, 1, 1/3)$
$\bar{S}_1$	$(\bar{3}, 1, -2/3)$

$$\sim m_q/m_\mu \ln(M_{\mathrm{LQ}}/m_q)$$

Leptoquarks

[Dorsner, Fajfer, et al. 1603.04993, Mandal, Pich, 1908.11155]

No Baryon Number violation at renormalizable level

Chiral enhancement in (g-2) at 1-loop level

Vector LQs

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$\tilde{V}_2$	$(\bar{3}, 2, -1/6)$
$\tilde{U}_1$	$(3, 1, 5/3)$
U_1	$(3, 1, 2/3)$
$\bar{U}_1$	$(3, 1, -1/3)$

PREDICTED!!

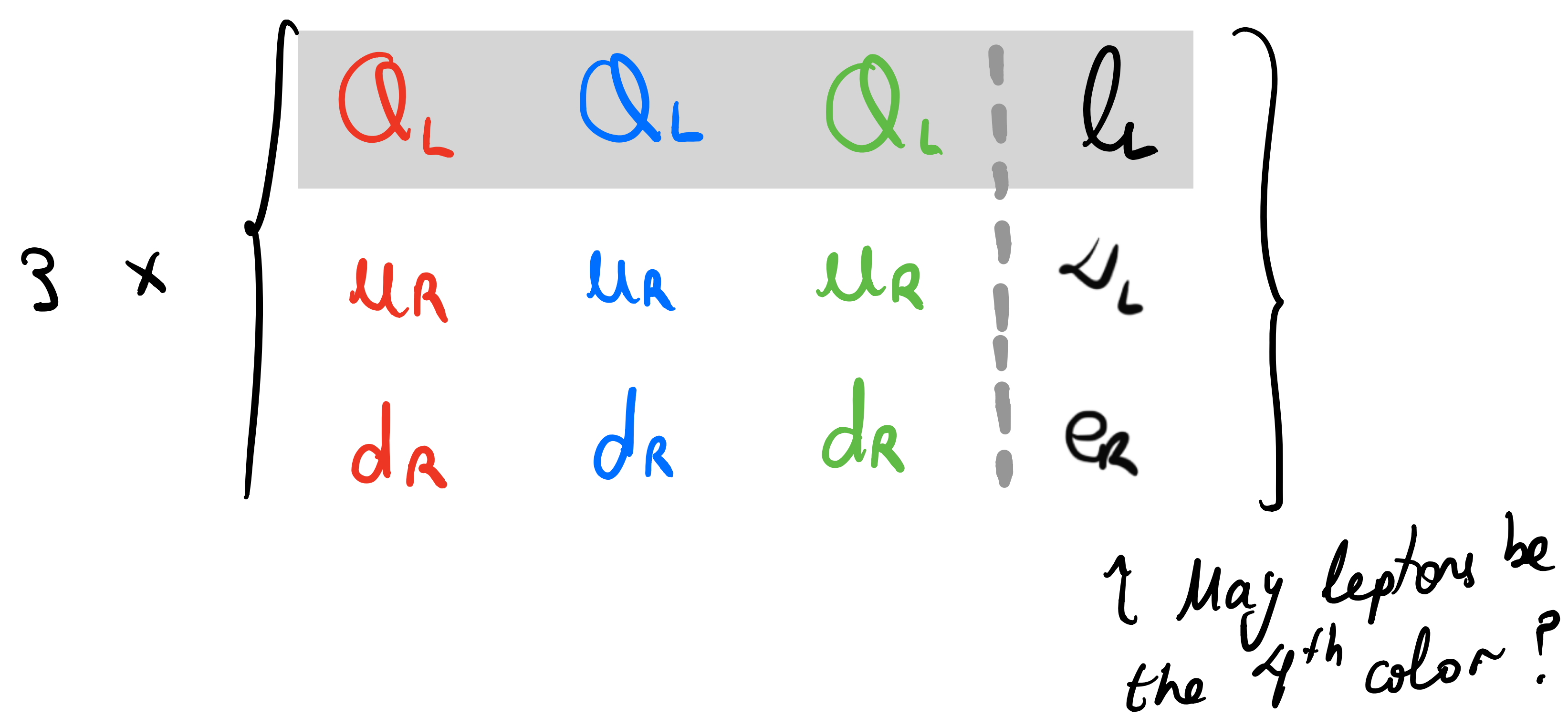
Scalar LQs

Symbol	Q.N. (SM)
S_3	$(\bar{3}, 3, 1/3)$
R_2	$(3, 2, 7/6)$
$\tilde{R}_2$	$(3, 2, 1/6)$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$
S_1	$(\bar{3}, 1, 1/3)$
$\bar{S}_1$	$(\bar{3}, 1, -2/3)$

$\sim m_q/m_\mu$

$\sim m_q/m_\mu \ln(M_{LQ}/m_q)$

Unification of Matter: Pati-Salam



$$\mathrm{PS} \supset SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

[J. Pati a and A. Salam 1974] [P. Fileviez Perez and M. B. Wise 2013]

Unification of Matter: Pati-Salam

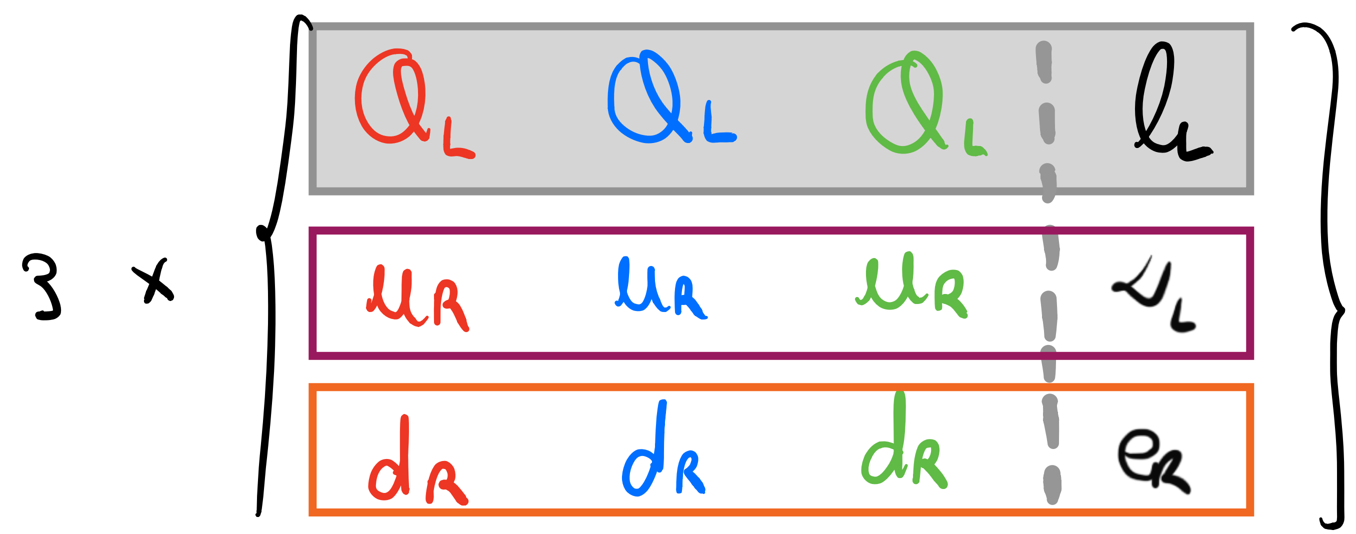
$$F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

Left-handed fermions

$$F_u = \begin{pmatrix} u^c & \nu^c \end{pmatrix}_L \sim (\bar{4}, 1, -1/2)$$

$$F_d = \begin{pmatrix} d^c & e^c \end{pmatrix}_L \sim (\bar{4}, 1, 1/2)$$

Right-handed fermions



$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

[J. Pati a and A. Salam 1974] [P. Fileviez Perez and M. B. Wise 2013]

Unification of Matter: Pati-Salam

$$F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

$$F_u = \begin{pmatrix} u^c & \nu^c \end{pmatrix}_L \sim (\bar{4}, 1, -1/2)$$

$$F_d = \begin{pmatrix} d^c & e^c \end{pmatrix}_L \sim (\bar{4}, 1, 1/2)$$

$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle)$$

$$SU(4)_c \otimes SU(2)_L \otimes U(1)_R \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Unification of Matter: Pati-Salam

$$F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

$$F_u = \begin{pmatrix} u^c & \nu^c \end{pmatrix}_L \sim (\bar{4}, 1, -1/2)$$

$$F_d = \begin{pmatrix} d^c & e^c \end{pmatrix}_L \sim (\bar{4}, 1, 1/2)$$

$$V_{15}^{\mu} \sim (15,1,0) = \underbrace{\begin{pmatrix} \overset{SU(3)_C}{G^{\mu}} & U_1^{\mu}/\sqrt{2} \\ (U_1^{\mu})^*/\sqrt{2} & 0 \end{pmatrix}}_{SU(4)} + T_4 B'^{\mu}$$

$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle)$$

$SU(4)_c \otimes SU(2)_L \otimes U(1)_R$ ⇒ $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Vector LQ $U_1^\mu \sim (3,1,2/3)$

$$F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

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$$\chi = (\chi_u, \chi_u, \chi_u, \langle\chi_R^0\rangle) \Rightarrow M_{U_1} \sim g_4 v_\chi \ ?$$

$$\cancel{SU(4)_c} \otimes SU(2)_L \otimes \cancel{U(1)_R} \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Vector LQ $U_1^\mu \sim (3,1,2/3)$

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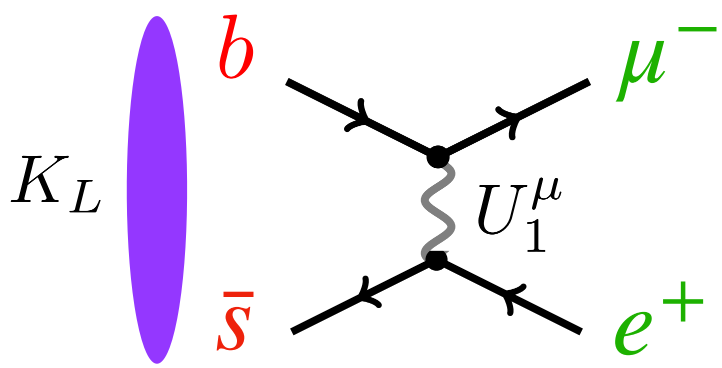
$$\mathcal{L}_K \supset \frac{g_4}{\sqrt{2}} U_1^\mu (\bar{Q}_L \gamma_\mu \ell_L + \bar{u}_R \gamma_\mu \nu_R + \bar{d}_R \gamma_\mu e_R) + \text{h.c.}$$

$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \Rightarrow M_{U_1} \sim g_4 v_\chi \ ?$$

$$SU(4)_c \otimes SU(2)_L \otimes U(1)_R \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Vector LQ $U_1^\mu \sim (3,1,2/3)$



$\leq 4.7 \times 10^{-12}$

$$V_{15}^\mu \sim (15,1,0) = \underbrace{\begin{pmatrix} \overset{SU(3)_C}{G^\mu} & U_1^\mu/\sqrt{2} \\ (U_1^\mu)^*/\sqrt{2} & 0 \end{pmatrix}}_{SU(4)} + T_4 B'^\mu$$

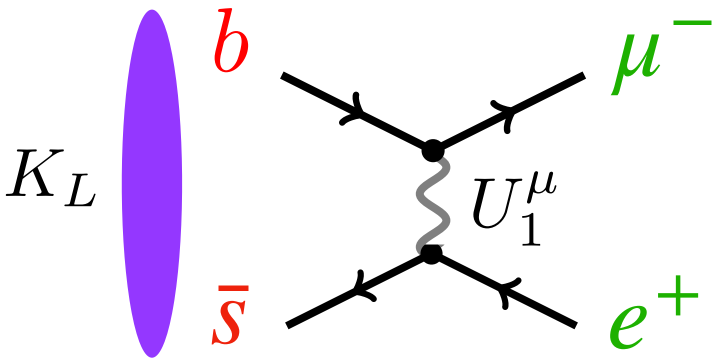
$$\mathcal{L}_K \supset \frac{g_4}{\sqrt{2}} U_1^\mu (\bar{Q}_L \gamma_\mu \ell_L + \bar{u}_R \gamma_\mu \nu_R + \bar{d}_R \gamma_\mu e_R) + \text{h.c.}$$

$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle)$ ⇨ $M_{U_1} \sim g_4 v_\chi$?

$SU(4)_c \otimes SU(2)_L \otimes U(1)_R$ ⇨ $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Vector LQ $U_1^\mu \sim (3,1,2/3)$



$$\leq 4.7 \times 10^{-12}$$

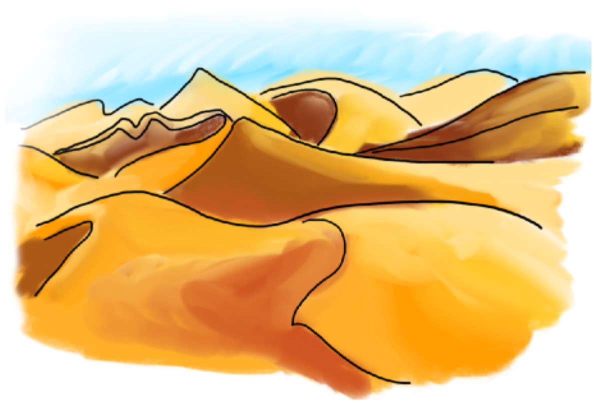
$$V_{15}^\mu \sim (15,1,0) = \underbrace{\begin{pmatrix} \overbrace{G^\mu}^{SU(3)_C} & U_1^\mu/\sqrt{2} \\ (U_1^\mu)^*/\sqrt{2} & 0 \end{pmatrix}}_{SU(4)} + T_4 B'^\mu$$

$$\mathcal{L}_K \supset \frac{g_4}{\sqrt{2}} U_1^\mu (\bar{Q}_L \gamma_\mu \ell_L + \bar{u}_R \gamma_\mu \nu_R + \bar{d}_R \gamma_\mu e_R) + \text{h.c.}$$

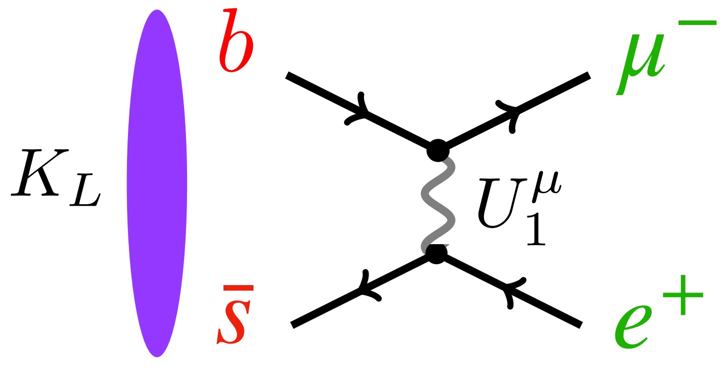
$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \Rightarrow M_{U_1} \sim g_4 v_\chi \gtrsim 10^3 \text{ TeV}$$

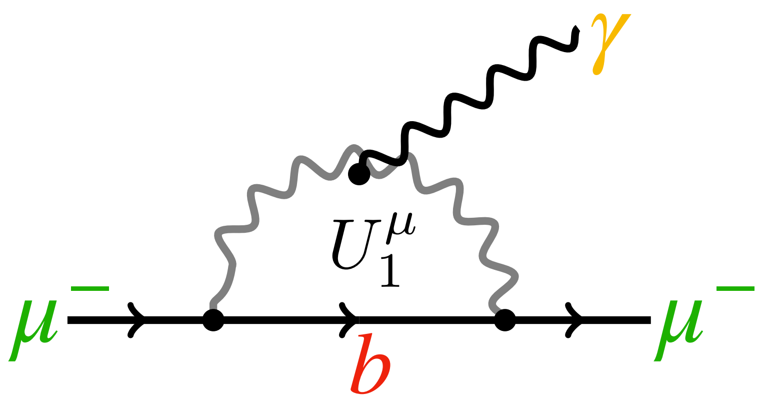
$$SU(4)_c \otimes SU(2)_L \otimes U(1)_R \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

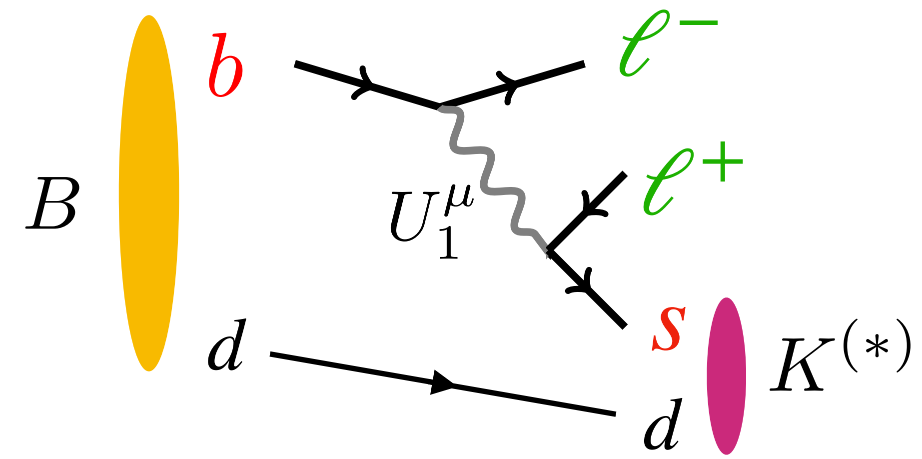
$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$



Vector LQ $U_1^\mu \sim (3,1,2/3)$







$$V_{15}^\mu \sim (15,1,0) = \underbrace{\begin{pmatrix} \overbrace{G^\mu}^{SU(3)_C} & U_1^\mu/\sqrt{2} \\ (U_1^\mu)^*/\sqrt{2} & 0 \end{pmatrix}}_{SU(4)} + T_4 B'^\mu$$

$$\mathcal{L}_K \supset \frac{g_4}{\sqrt{2}} U_1^\mu \left(\quad \cdots \quad + \qquad \bar{d}_R U_R^\dagger \gamma_\mu E_R e_R \right) + \text{h.c.}$$

Naive bound!

$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \quad \Rightarrow \quad M_{U_1} \sim g_4 v_\chi \gtrsim \sout{10^3\ \text{TeV}}$$

$$SU(4)_c \otimes SU(2)_L \otimes U(1)_R \quad \Rightarrow \quad SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

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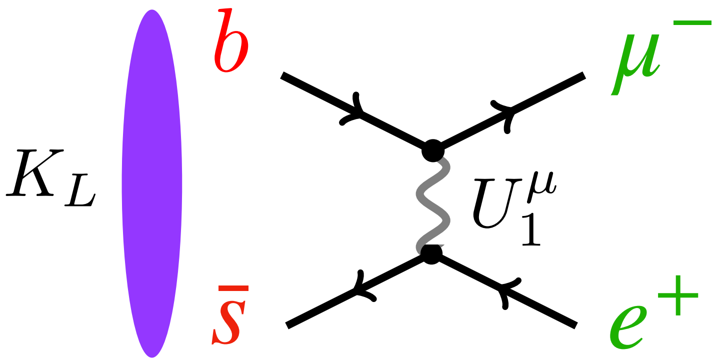

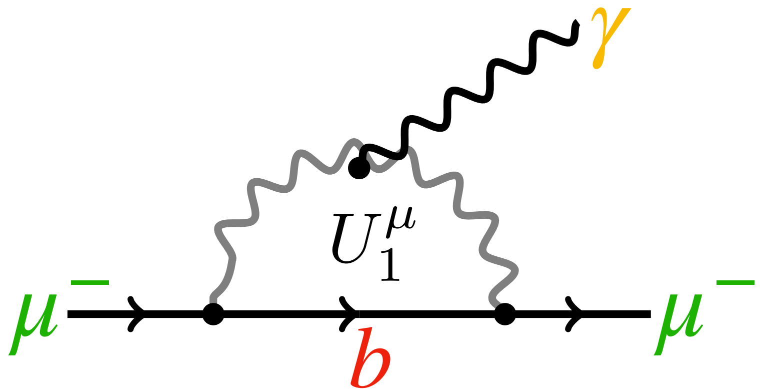

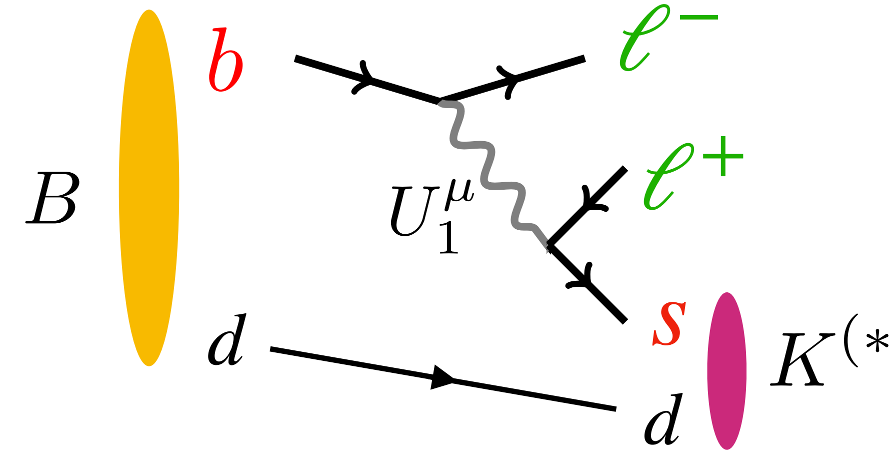

Way outs: extra vector-like fermions / enlarged gauge group

[Capdevilla, Crivellin, et al. 1704.05340, Calibbi, Crivellin, Li, 1709.00692, Luzio, Greijo, Nardecchia, 1708.08450, Assad, Fornal, Grinstein, 1708.06350, Bordone, Cornella et al. 1712.01368, Cornella, Fuentes-Martín, Isidori, 1903.11517, Cornella, Faroughy, et al. 2103.16558],

chiral Pati-Salam [Balaji, Schmidt, 1911.08873], ...

Naive bound!

$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle)$ ⇨ $M_{U_1} \sim g_4 v_\chi$ $\gtrsim$ ~~10^3 TeV~~

$SU(4)_c \otimes SU(2)_L \otimes U(1)_R$ ⇨ $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Unification of Matter

$$F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

$$F_u = \begin{pmatrix} u^c & \nu^c \end{pmatrix}_L \sim (\bar{4}, 1, -1/2)$$

$$F_d = \begin{pmatrix} d^c & e^c \end{pmatrix}_L \sim (\bar{4}, 1, 1/2)$$

$$\mathcal{L}_Y = Y_1\, F_{QL} F_u H + Y_3\, H^\dagger F_{QL} F_d$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} \qquad M_d = Y_3 \frac{v_1}{\sqrt{2}}$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} \qquad M_e = Y_3 \frac{v_1}{\sqrt{2}}$$

$$H \sim (1,2,1/2)_{\text{SM}}$$

$$SU(4)_c \otimes SU(2)_L \otimes U(1)_R \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \Rightarrow SU(3)_c \otimes U(1)_Q$$

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$$\mathcal{L}_Y = Y_1\, F_{QL} F_u H + Y_3\, H^\dagger F_{QL} F_d + Y_2\, F_{QL} F_u \Phi + Y_4\, \Phi^\dagger F_{QL} F_d + \text{h.c.}$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_d = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}},$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_e = Y_3 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}}.$$

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\text{MW}} & \tilde{R}_2 \\ R_2 & 0 \end{pmatrix} + T_4 H_2, \qquad H \sim (1, 2, 1/2)_{\text{SM}}$$

$$SU(4)_c \otimes SU(2)_L \otimes U(1)_R \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \Rightarrow SU(3)_c \otimes U(1)_Q$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Unification of Matter

Inverse seesaw

$$-\mathcal{L}^{\nu}_{QL} = Y_5 F_u \chi S \; + \; \frac{1}{2}\mu S S + \text{h.c.}. \xrightarrow[\langle\chi\rangle]{} M_\chi^D = Y_5 v_\chi/\sqrt{2}$$

$$(\nu \;\; \nu^c \;\; S) \begin{pmatrix} 0 & \text{EW} & 0 \\ \text{EW} & 0 & \text{LQ} \\ 0 & \text{LQ} & \mu \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$$M_\chi^D \gg M_\nu^D \gg \mu$$

$$\Rightarrow \; m_\nu \approx \mu \, \text{EW} / \text{LQ}$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}}$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}}$$

No need for $\langle\chi\rangle$ to be large!!

[P. Fileviez Perez and M. B. Wise 2013]

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\text{MW}} & \tilde{R}_2 \\ R_2 & 0 \end{pmatrix} + T_4 H_2, \quad H \sim (1,2,1/2)_{\text{SM}}$$

$$SU(4)_c \otimes SU(2)_L \otimes U(1)_R \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \Rightarrow SU(3)_c \otimes U(1)_Q$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Unification of Matter

- The theory predicts scalar LQs:

$$\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)_{\rm SM} \qquad R_2 \equiv \Phi_4 \sim (3, 2, 7/6)_{\rm SM}$$

$$-\mathcal{L}_Y \supset Y_2\, Q_L \Phi_3 (\nu^c)_L + Y_2\, \ell_L \Phi_4 (u^c)_L + Y_4\, Q_L \Phi_4^\dagger (e^c)_L + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_d = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}},$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_e = Y_3 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}}.$$

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\rm MW} & \tilde{R}_2 \\ R_2 & 0 \end{pmatrix} + T_4 H_2,, \quad H \sim (1, 2, 1/2)_{\rm SM}$$

PREDICTED!!

Baryon Number in Pati-Salam

- The theory predicts scalar LQs:

$$\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)_{\text{SM}} \qquad R_2 \equiv \Phi_4 \sim (3, 2, 7/6)_{\text{SM}}$$

$$-\mathcal{L}_Y \supset Y_2\, Q_L \Phi_3 (\nu^c)_L + Y_2\, \ell_L \Phi_4 (u^c)_L + Y_4\, Q_L \Phi_4^\dagger (e^c)_L + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

$$Q_B(\Phi_3) = -1/3, \quad Q_L(\Phi_3) = 1, \quad Q_B(\Phi_4) = 1/3, \quad Q_L(\Phi_4) = -1$$

Baryon Number in QL-Unification

- The theory predicts scalar LQs:

$$\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)_{\rm SM} \qquad R_2 \equiv \Phi_4 \sim (3, 2, 7/6)_{\rm SM}$$

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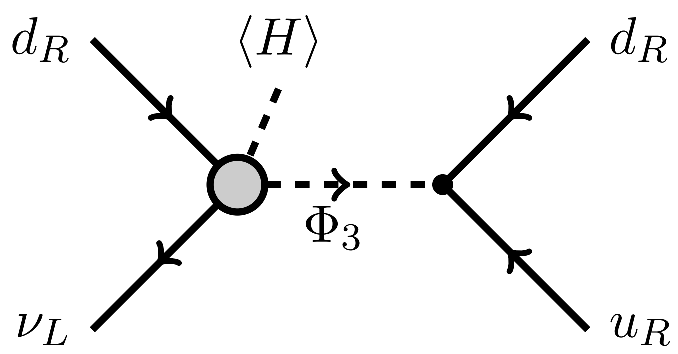
$Q_B(\Phi_3) = -1/3,$ $Q_L(\Phi_3) = 1,$ $Q_B(\Phi_4) = 1/3,$ $Q_L(\Phi_4) = -1$

$$\frac{1}{\Lambda_{\rm PS}^3} F_d^A F_u^B (\Phi^\dagger)_D^C \chi^D \chi^E H^\dagger \epsilon_{ABCD} \quad \xrightarrow{\langle \chi \rangle} \quad \frac{v_\chi^2}{\Lambda_{\rm PS}^3} d_R^\alpha u_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$

[Assad, Fornal, Grinstein, 1708.06350
C.M, M. B. Wise, 2105.14029]



$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \Rightarrow SU(3)_c \otimes U(1)_Q$$

Baryon Number in QL-Unification

- The theory predicts scalar LQs:

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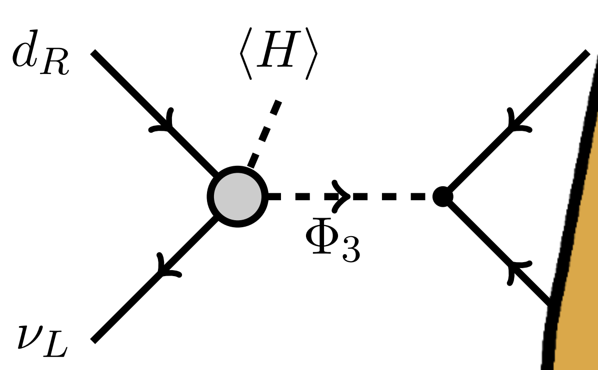
$$-\mathcal{L}_Y \supset Y_2\, Q_L \Phi_3 (\nu^c)_L + Y \ldots \ell_L \Phi_4 (u^c \ldots + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

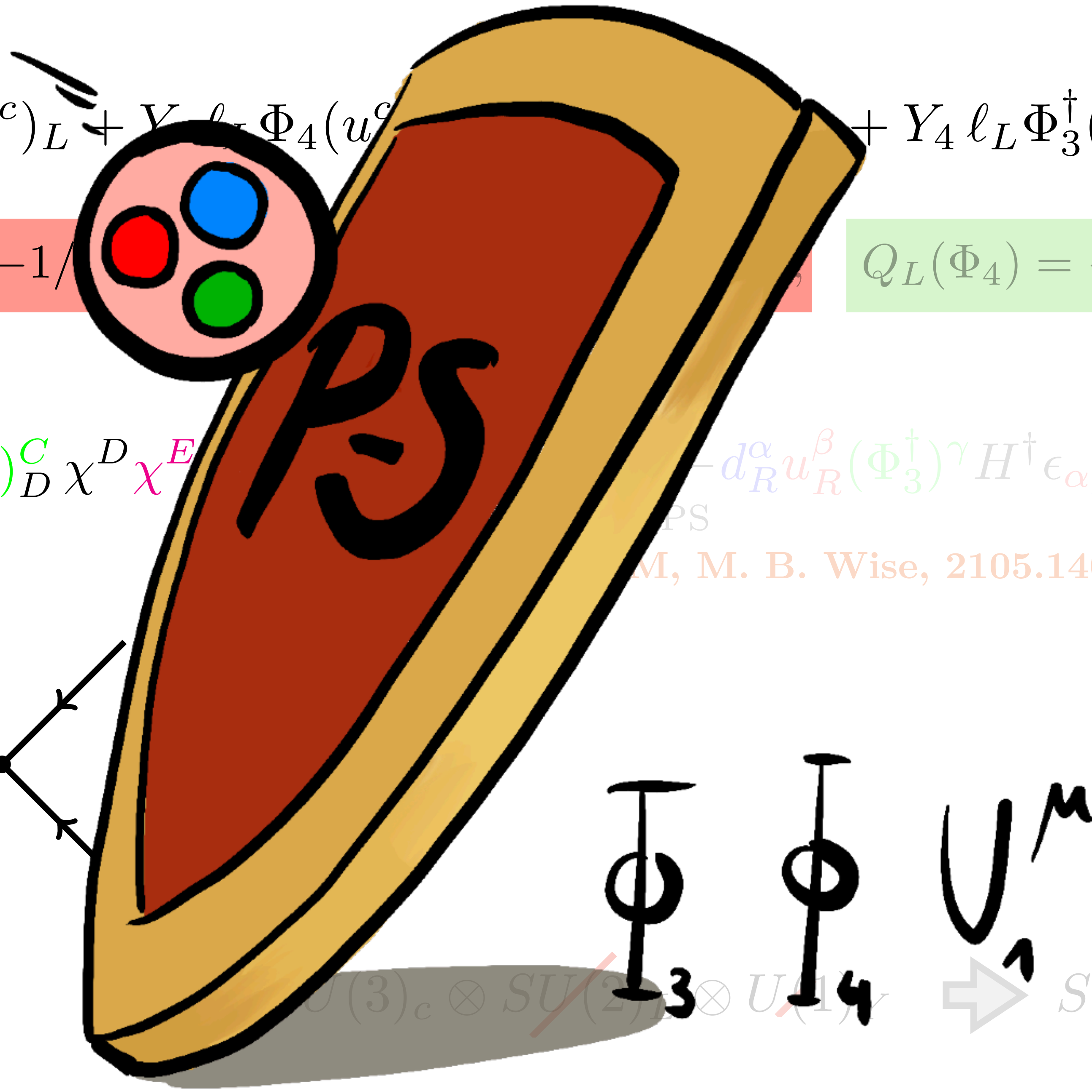
$Q_B(\Phi_3) = -1/\ldots$ $\qquad$ $Q_L(\Phi_4) = -1$

$$\frac{1}{\Lambda_{\text{PS}}^3} F_d^A F_u^B (\Phi^\dagger)_D^C \chi^D \chi^E \ldots \quad \ldots d_R^\alpha u_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$

…PS

…M, M. B. Wise, 2105.14029]





$\ldots U(3)_c \otimes SU(2)_L \otimes U(1)_Y \Rightarrow SU(3)_c \otimes U(1)_Q$

Scalar LQ: $\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)$

[Fileviez Perez, C.M, Plascencia, 2104.11229]

$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

$(\tilde{R}_2)$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions!

Scalar LQ: $\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)$

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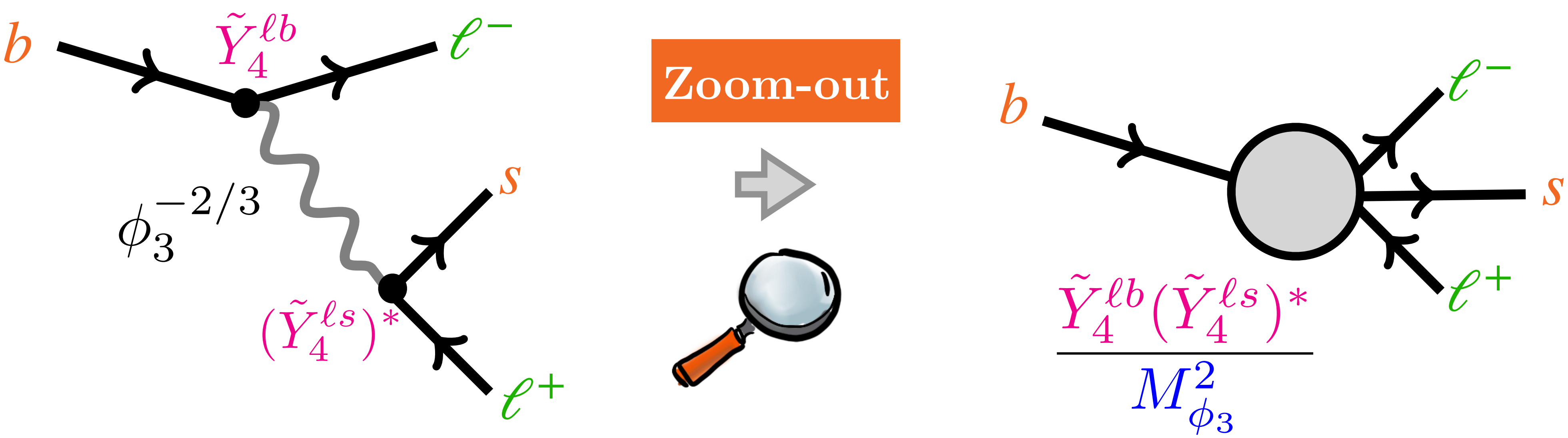

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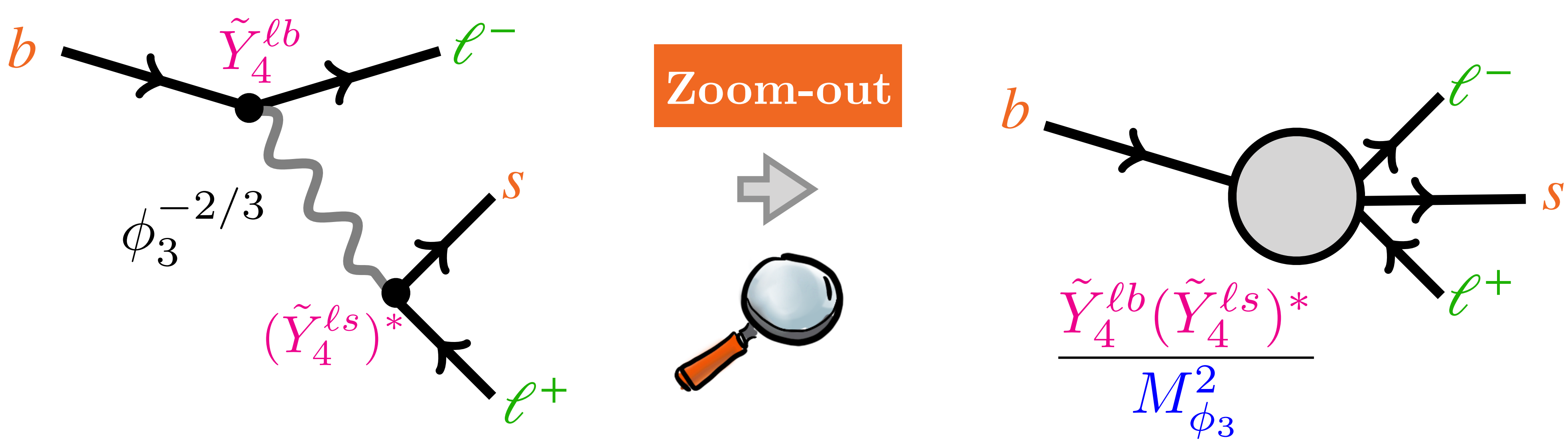

$$\mathcal{L}_{\text{eff}}^{\phi_3^{-2/3}} \supset \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \left[C'_{9\ell\ell} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell) + C'_{10\ell\ell} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma^5 \ell) \right]$$

$$\Rightarrow \quad C'_{10\ell\ell} = -C'_{9\ell\ell} = \left(\frac{\sqrt{2}\pi}{G_F V_{tb} V_{ts}^* \alpha} \right) \frac{\tilde{Y}_4^{\ell 3} (\tilde{Y}_4^{\ell 2})^*}{4 M^2_{\phi_3^{-2/3}}}$$

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$$C'_{10\ell\ell} = -C'_{9\ell\ell}$$

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$$\text{Br}(B_s \to \ell^+ \ell^-) = f_2(C'_{10\ell\ell}) \qquad \mathcal{R}_{K^{(*)}} = \frac{f_2(C'_{10\mu\mu})}{f_2(C'_{10ee})}$$

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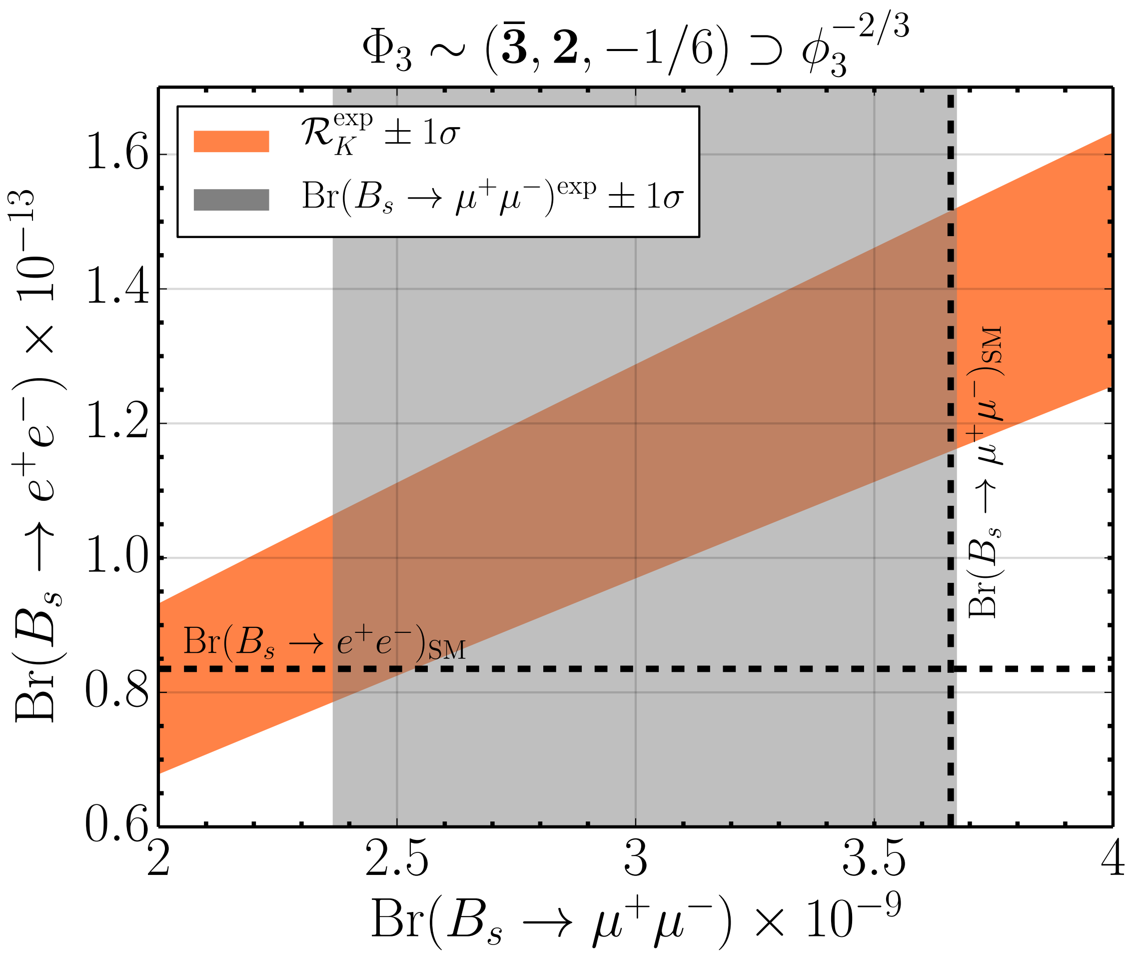

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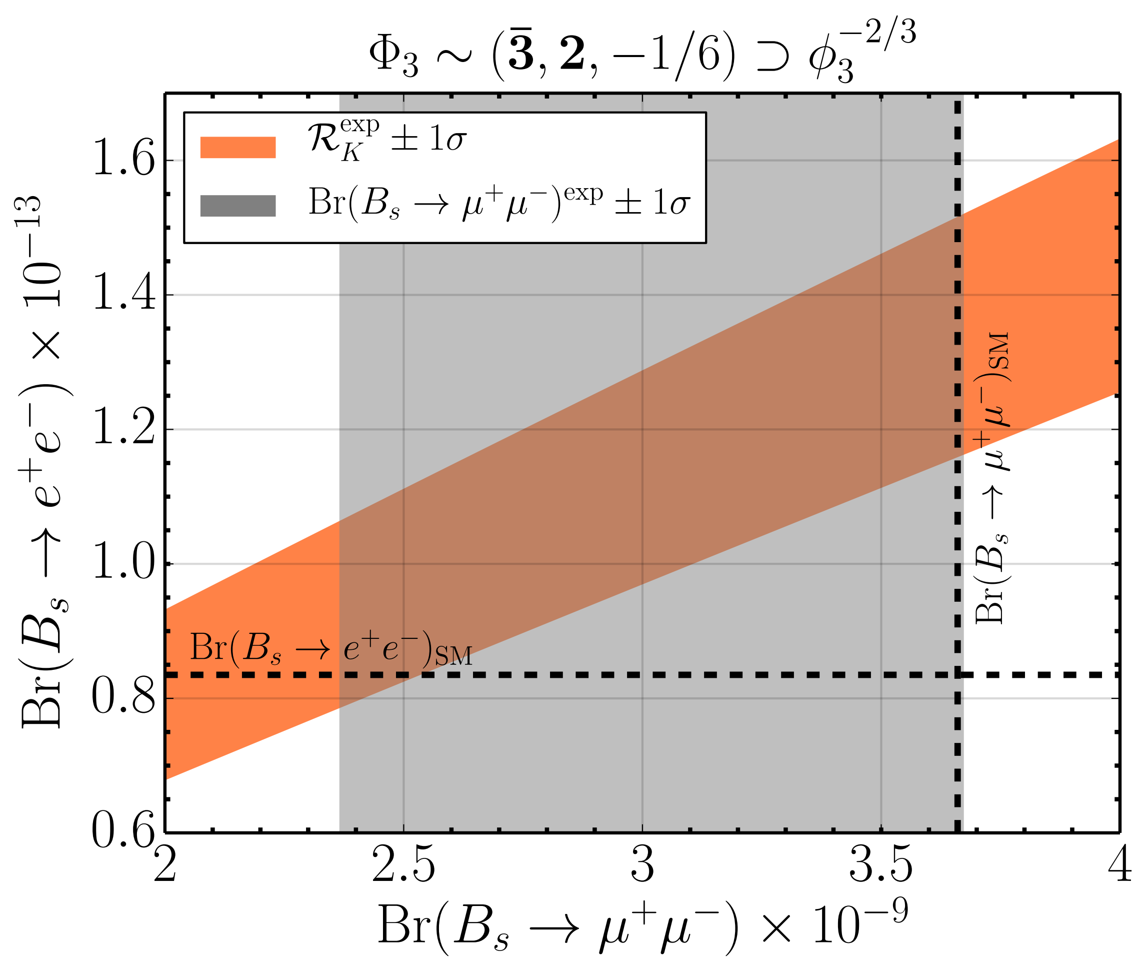

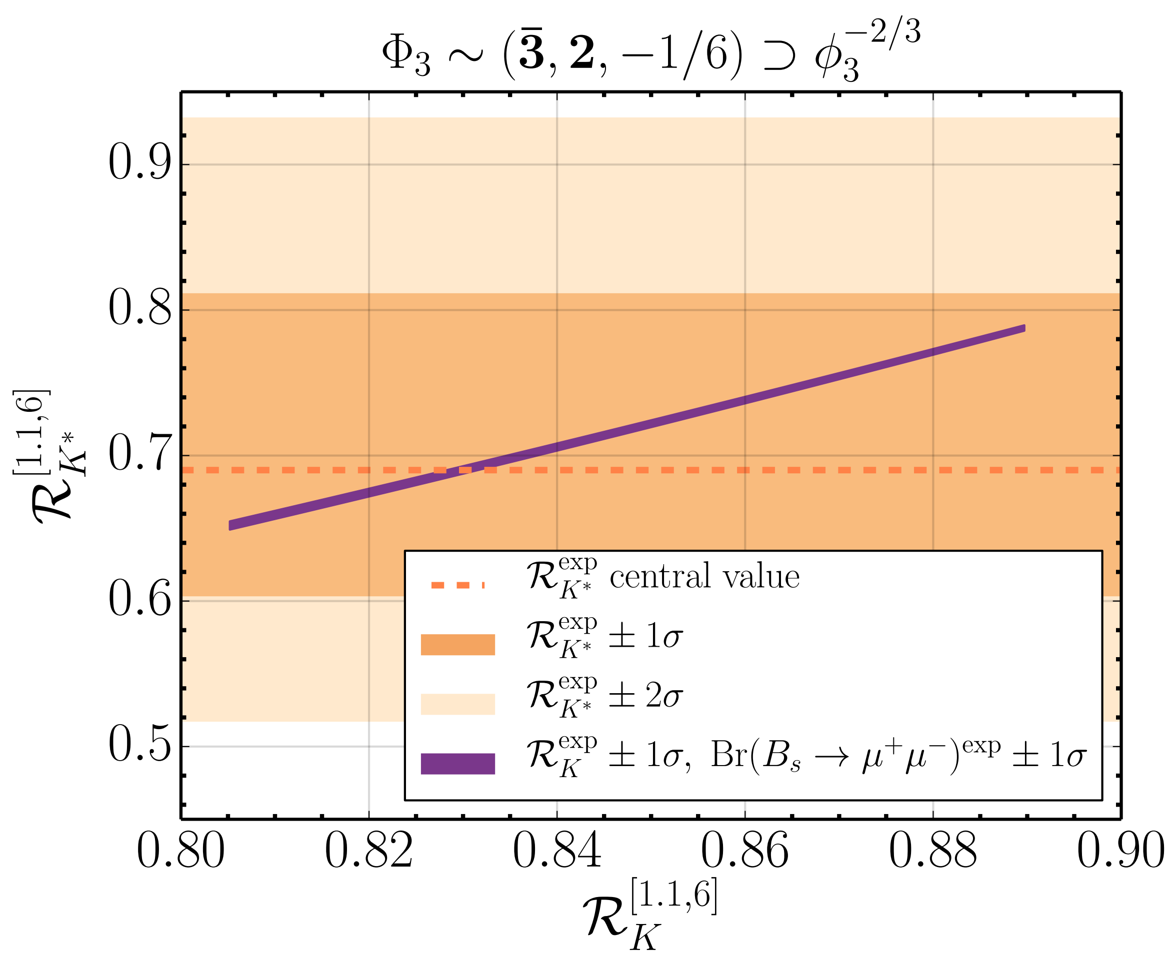

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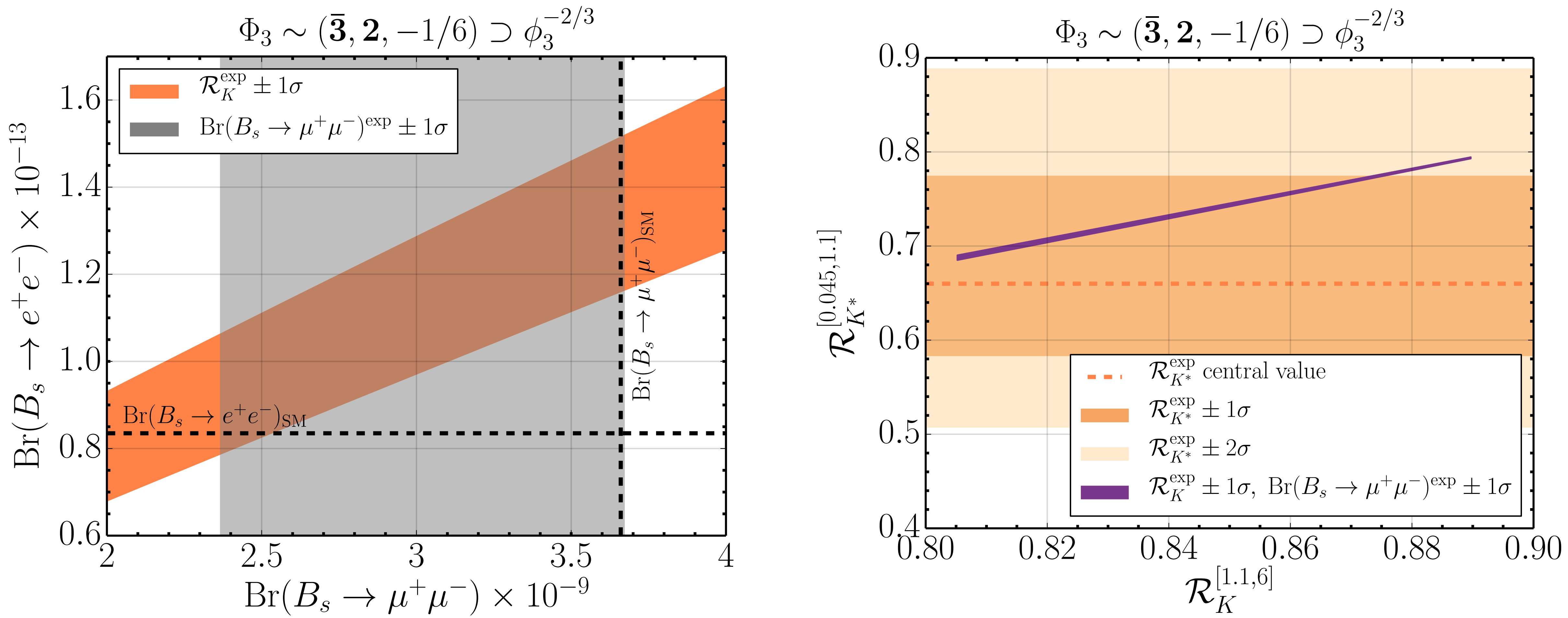

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$(\tilde{R}_2)$

$C'_{10\ell\ell} = -C'_{9\ell\ell}$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions! (also to other processes...)

$R_{K^{(*)}}$, $B_s \to \mu^+\mu^-$

$$\tilde{Y}_{\phi_3} = E Y_4 D^c = \begin{pmatrix} Y^{ed} & Y^{es} & Y^{eb} \\ Y^{\mu d} & Y^{\mu s} & Y^{\mu b} \\ Y^{\tau d} & Y^{\tau s} & Y^{\tau b} \end{pmatrix}$$

Scalar LQ: $\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)$

[Fileviez Perez, C.M, Plascencia, 2104.11229]

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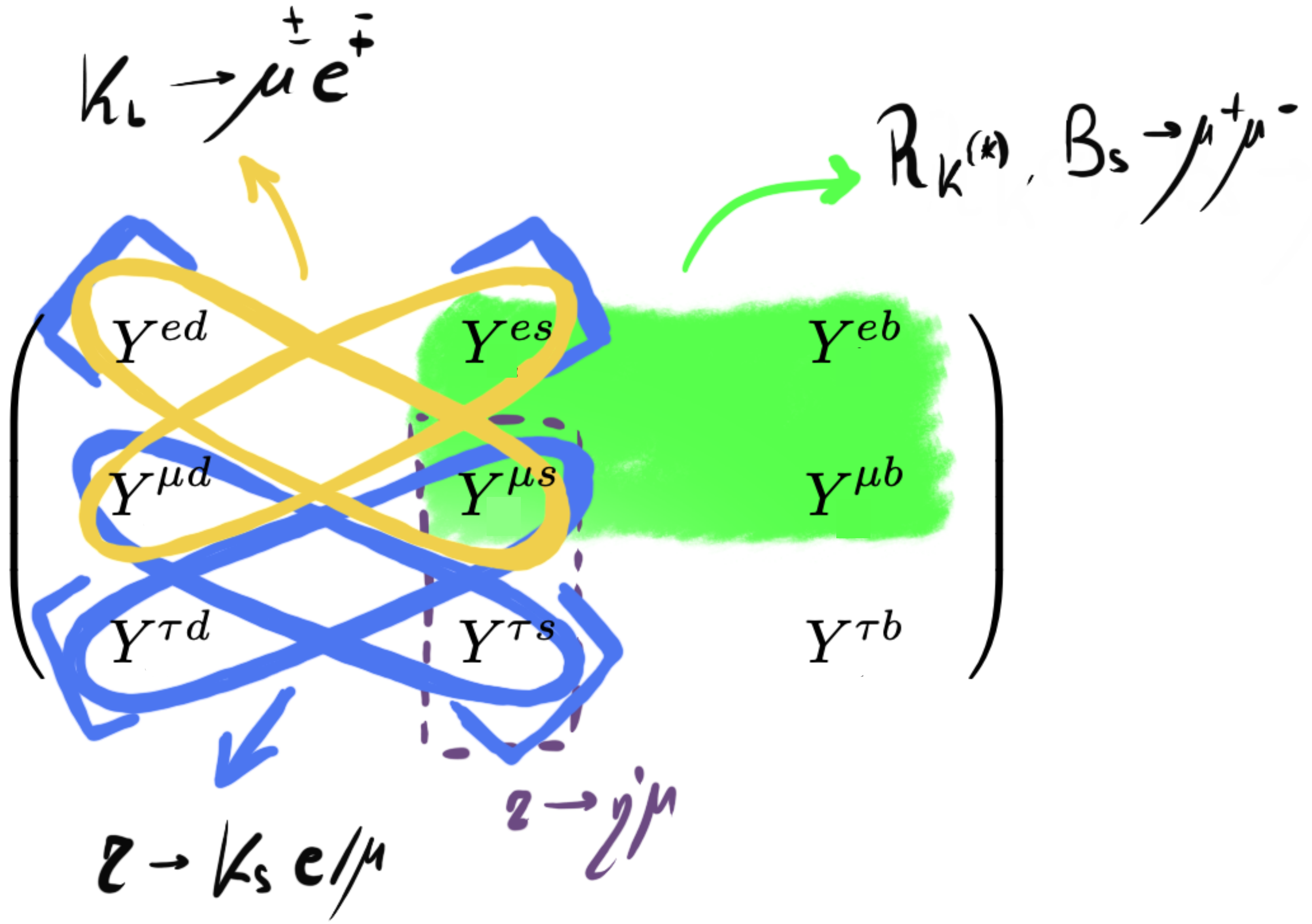


Scalar LQ: $\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)$

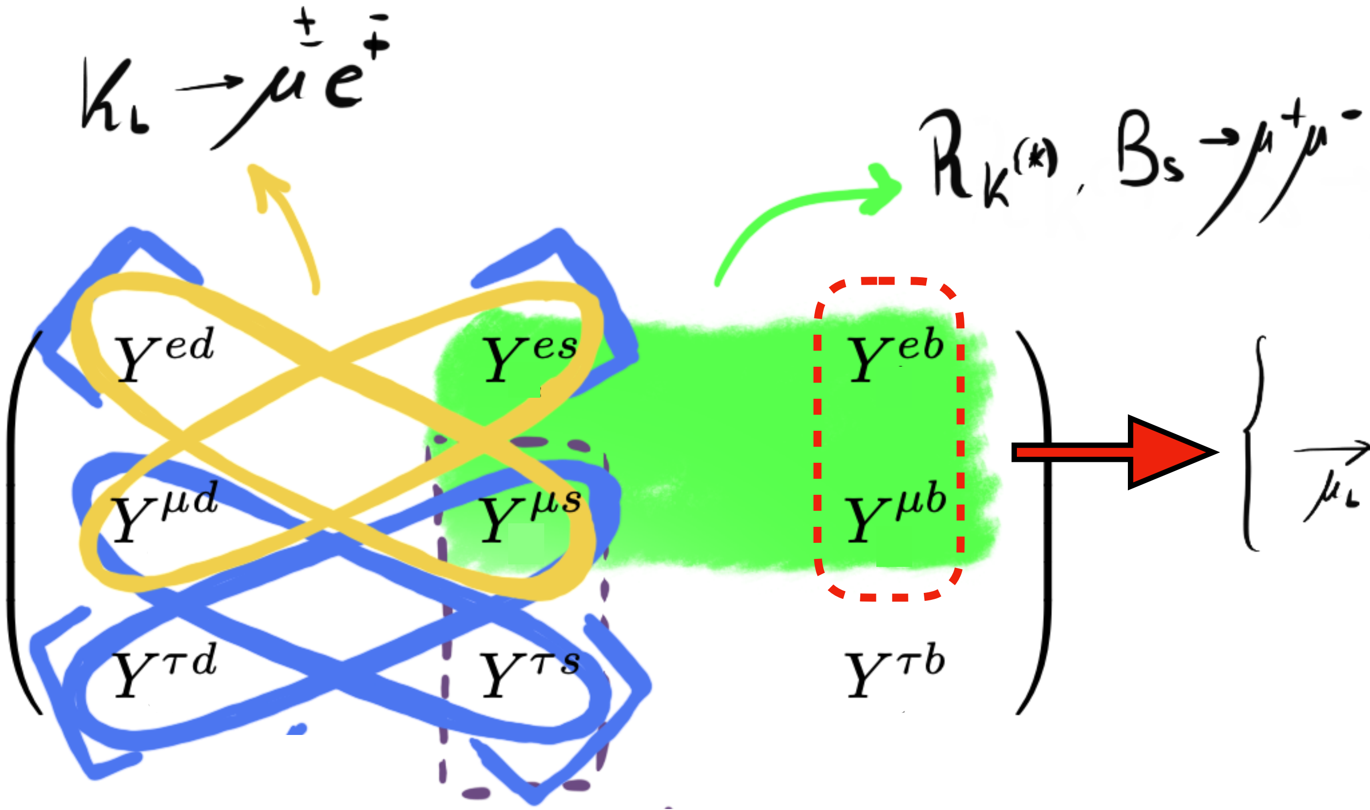
[Fileviez Perez, C.M, Plascencia, 2104.11229]

$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a + \text{h.c.}$$

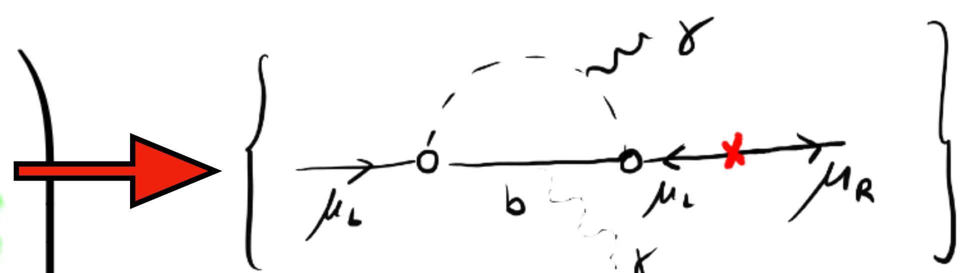
$(\tilde{R}_2)$

$C'_{10\ell\ell} = -C'_{9\ell\ell}$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions! (also to other processes...)



$$\tilde{Y}_{\phi_3} = E Y_4 D^c = \begin{pmatrix} Y^{ed} & Y^{es} & Y^{eb} \\ Y^{\mu d} & Y^{\mu s} & Y^{\mu b} \\ Y^{\tau d} & Y^{\tau s} & Y^{\tau b} \end{pmatrix}$$



$$\Gamma_{\mu \to e\gamma} \propto \frac{m_\mu^5}{M_{LQ}^4} \sum_q \left(\left| \lambda_L^{2q} (\lambda_L^{1q})^* \left[Q_q F_1 \left(\frac{m_q^2}{M_{LQ}^2} \right) + Q_{LQ} F_2 \left(\frac{m_q^2}{M_{LQ}^2} \right) \right] + \frac{m_q}{m_\mu} \lambda_L^{2q} \lambda_R^{1q*} \left[Q_q F_3 \left(\frac{m_q^2}{M_{LQ}^2} \right) + Q_{LQ} F_4 \left(\frac{m_q^2}{M_{LQ}^2} \right) \right] \right|^2 + |L \to R| \right)$$

$\frac{1}{3}$ $\qquad$ $\frac{1}{6}$

Scalar LQ: $\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)$

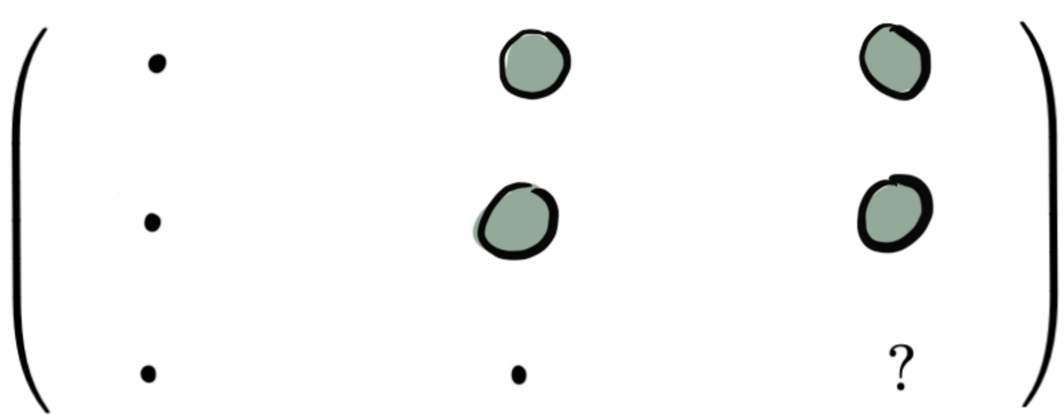
[Fileviez Perez, C.M, Plascencia, 2104.11229]

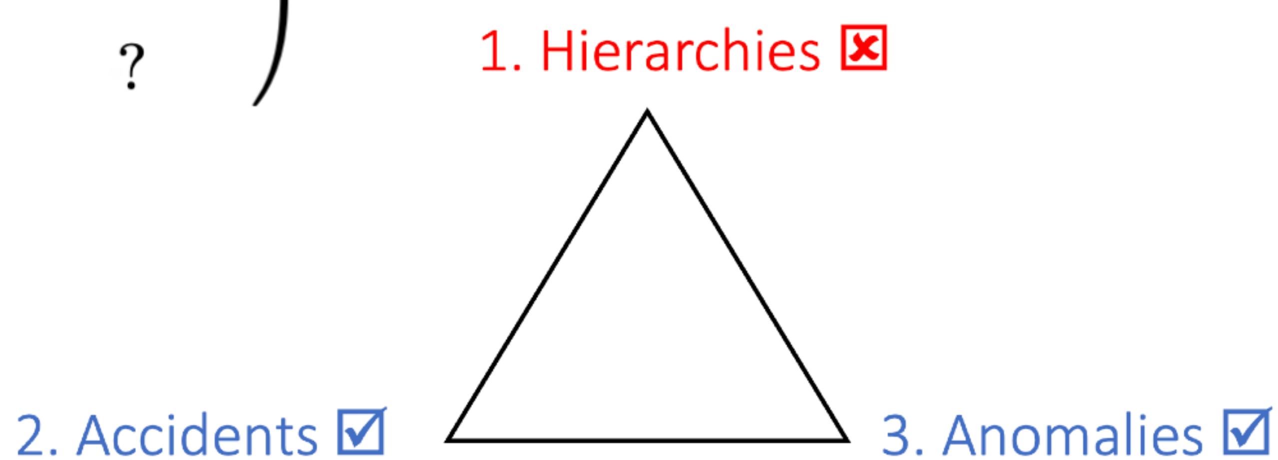
$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

$(\tilde{R}_2)$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions! (also to other processes...)

$\tilde{Y}_{\phi_3} = E Y_4 D^c =$





borrowed from Joe's talk on Monday

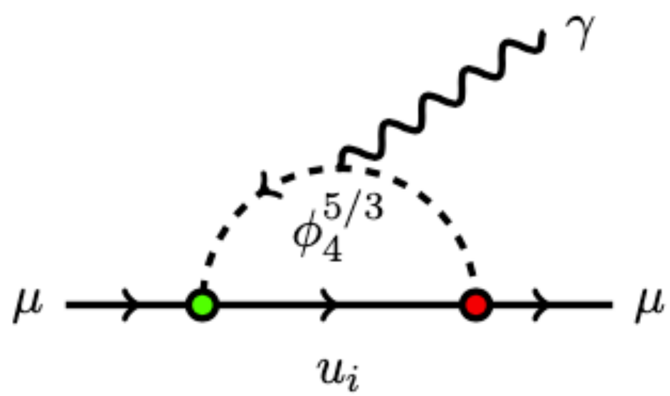
Bonus: $(g-2)_\mu$

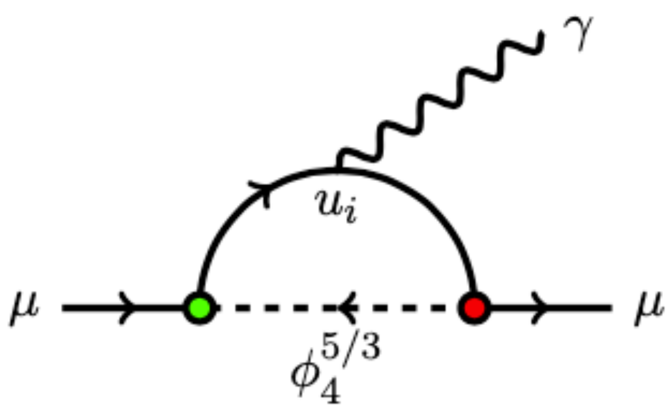
[Fileviez Perez, C.M, Plascencia, 2104.11229]

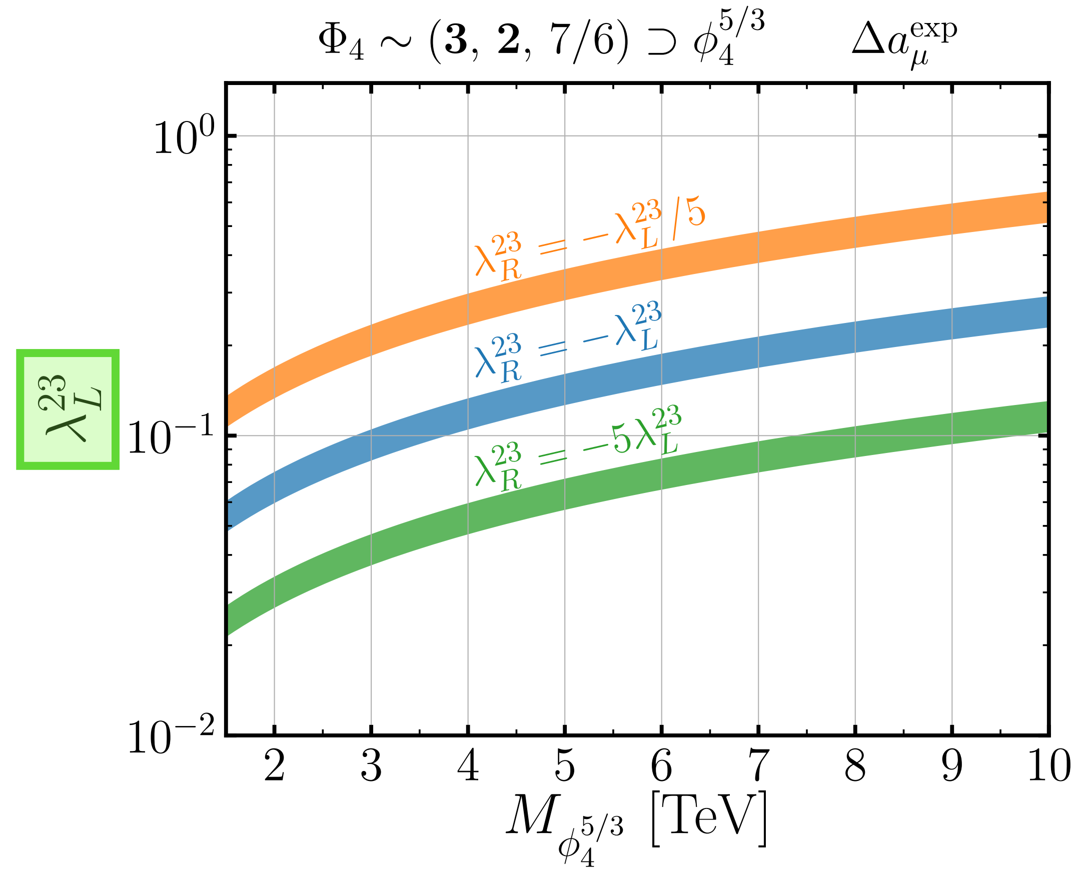
$$-\mathcal{L} \supset \tilde{Y}_2 e_L\, \phi_4^{5/3} (u^c)_L + \tilde{Y}_{\phi_4} \Big(u_L (\phi_4^{5/3})^* (e^c)_L + d_L (\phi_4^{2/3})^* (e^c)_L \Big) + \tilde{Y}_{\phi_3} e_L (\phi_3^{-2/3})^* (d^c)_L + \text{h.c.}$$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix}$$

(R_2)







Connections with $h \to \ell^+\ell^-$
[Fajfer, Kamelik, Tammaro, 2103.10859,
Crivellin, Müller, Saturnino, 2008.02643]

$$\Delta a_\mu^\alpha = \frac{-3}{16\pi^2} \frac{m_\mu^2}{M_{\Phi_\alpha}^2} \sum_j \left[\left(|\lambda_{\alpha L}^{2j}|^2 + |\lambda_{\alpha R}^{2j}|^2 \right) \times f_{\text{loop}} + \frac{m_q}{m_\mu} \text{Re}[\lambda_{\alpha L}^{2j} (\lambda_{\alpha R}^{2j})^*] f'_{\text{loop}} \right]$$

Bonus: $(g-2)_\mu$

[Fileviez Perez, C.M, Plascencia, 2104.11229]

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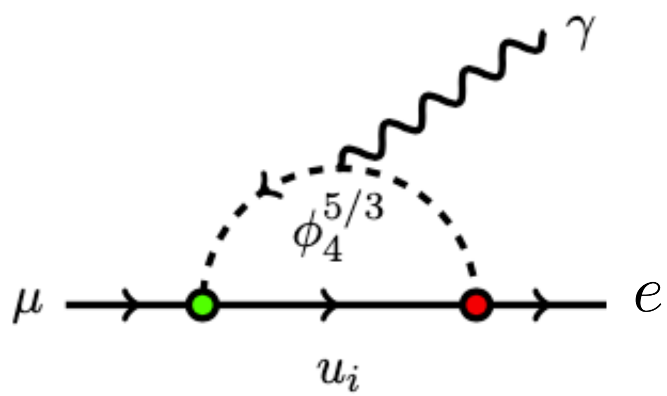
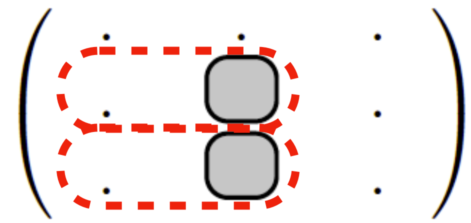
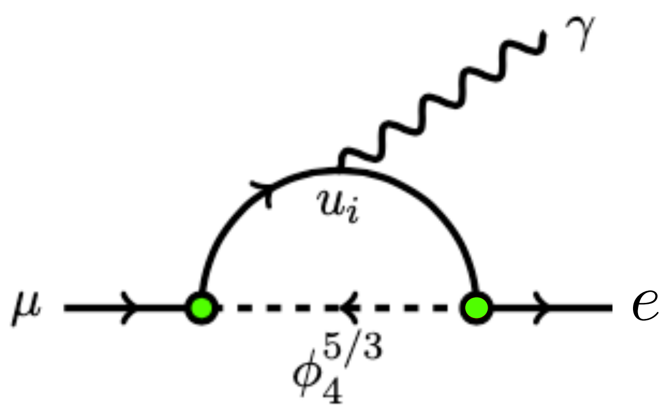
(R_2)



$\tilde{Y}_{\phi_4} =$



Mainly to muons!



LFV!!

$$\Delta a_\mu^\alpha = \frac{-3}{16\pi^2} \frac{m_\mu^2}{M_{\Phi_\alpha}^2} \sum_j \left[\left(|\lambda_{\alpha L}^{2j}|^2 + |\lambda_{\alpha R}^{2j}|^2 \right) \times f_{\text{loop}} + \frac{m_q}{m_\mu} \text{Re}[\lambda_{\alpha L}^{2j} (\lambda_{\alpha R}^{2j})^*] f'_{\text{loop}} \right]$$

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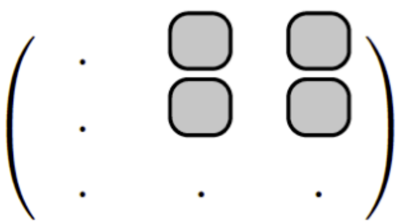
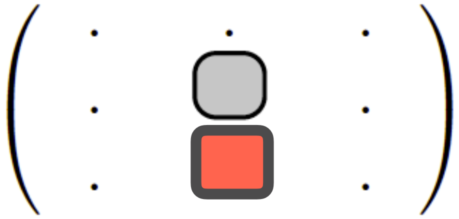
[Fileviez Perez, C.M, Plascencia, 2104.11229]

$$-\mathcal{L} \supset \tilde{Y}_2 \mu_L \phi_4^{5/3} (u^c)_L + \tilde{Y}_{\phi_4} \left(u_L (\phi_4^{5/3})^* (\mu^c)_L + d_L (\phi_4^{2/3})^* (\mu^c)_L \right) + \tilde{Y}_{\phi_3} e_L (\phi_3^{-2/3})^* (d^c)_L + \text{h.c.}$$

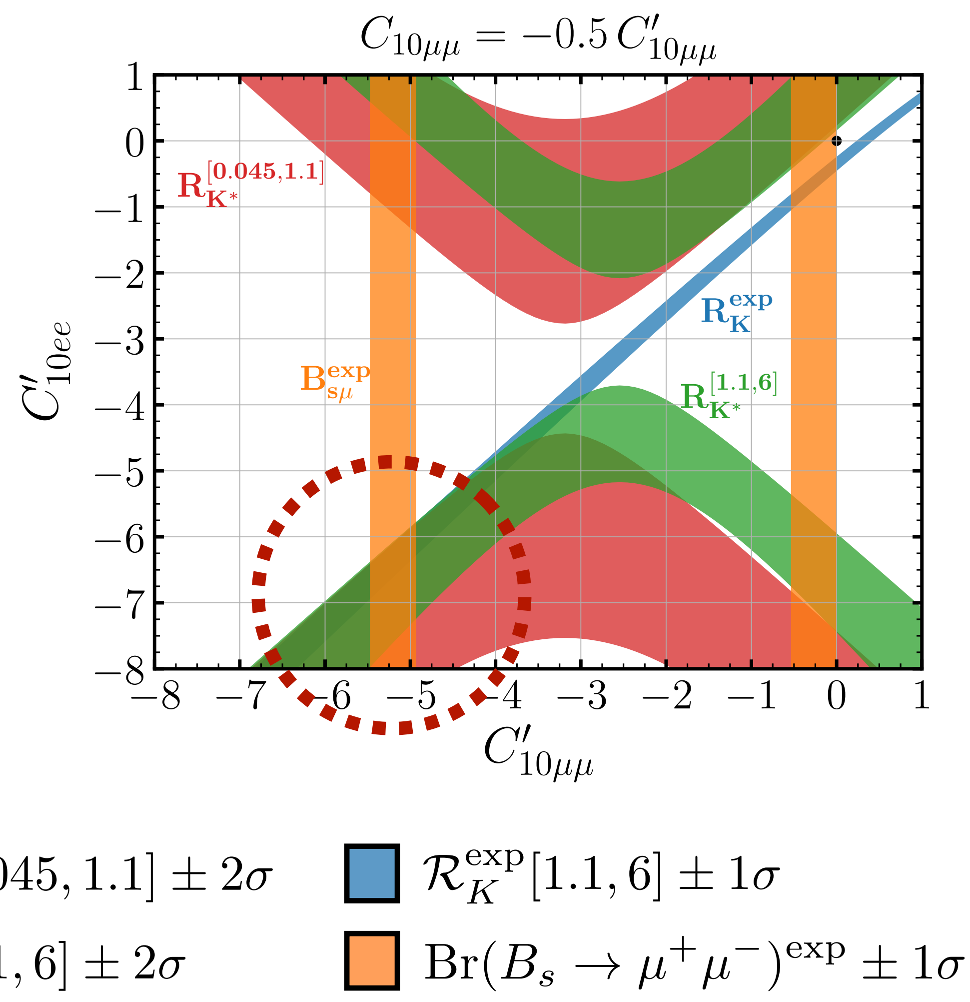
$\tilde{Y}_{\phi_3} =$ 

$\tilde{Y}_{\phi_4} =$ 

Mainly to muons!

$\phi_3^{-2/3}, \phi_4^{2/3}$

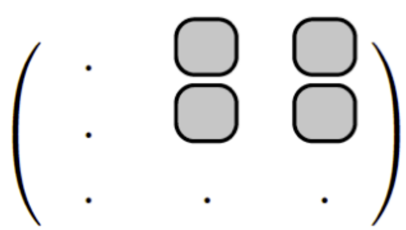
$(\tilde{R}_2^{5/3}, R_2^{2/3})$

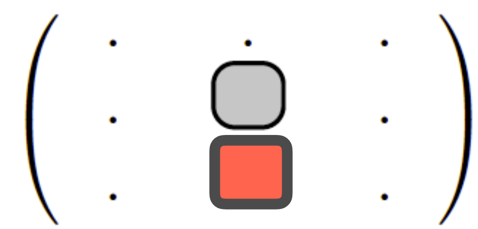


Bonus: $(g-2)_\mu$

[Fileviez Perez, C.M, Plascencia, 2104.11229]

$$-\mathcal{L} \supset \tilde{Y}_2 \mu_L \phi_4^{5/3} (u^c)_L + \tilde{Y}_{\phi_4} \left(u_L (\phi_4^{5/3})^* (\mu^c)_L + d_L (\phi_4^{2/3})^* (\mu^c)_L \right) + \tilde{Y}_{\phi_3} e_L (\phi_3^{-2/3})^* (d^c)_L + \text{h.c.}$$

$\tilde{Y}_{\phi_3} =$ 

$\tilde{Y}_{\phi_4} =$ 

Mainly to muons!

$\phi_3^{-2/3}, \phi_4^{2/3}$

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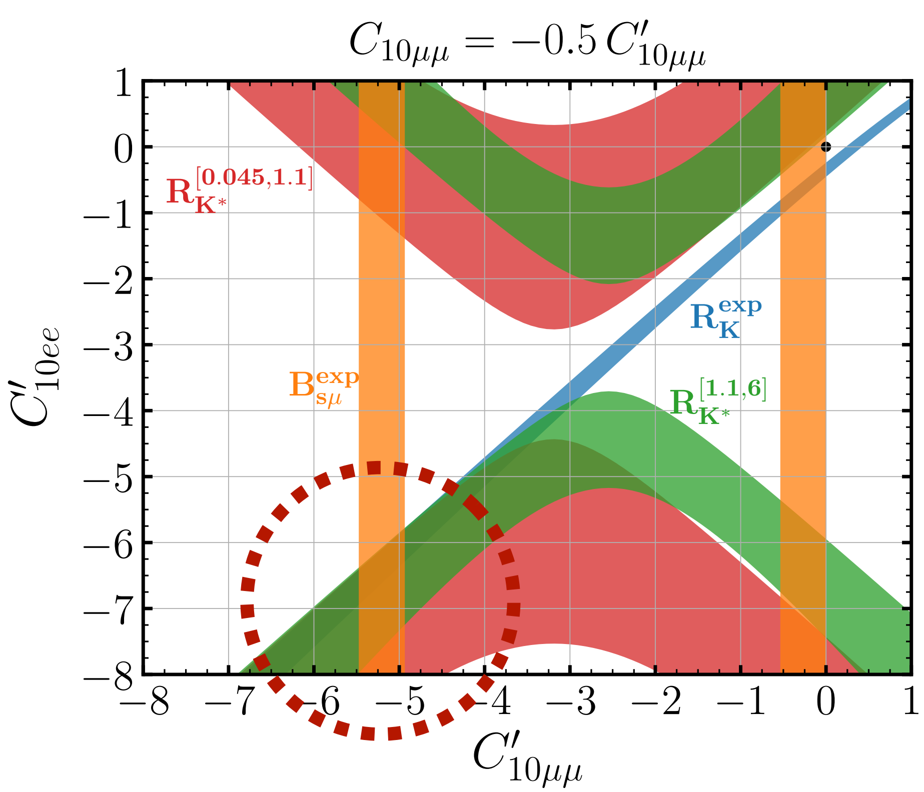
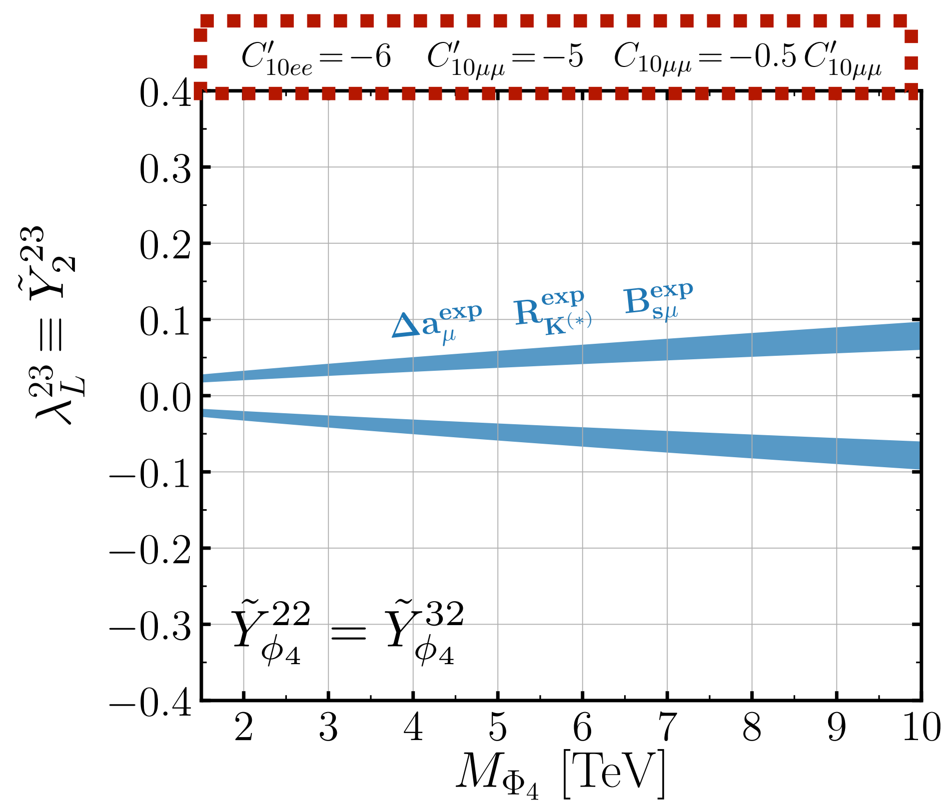
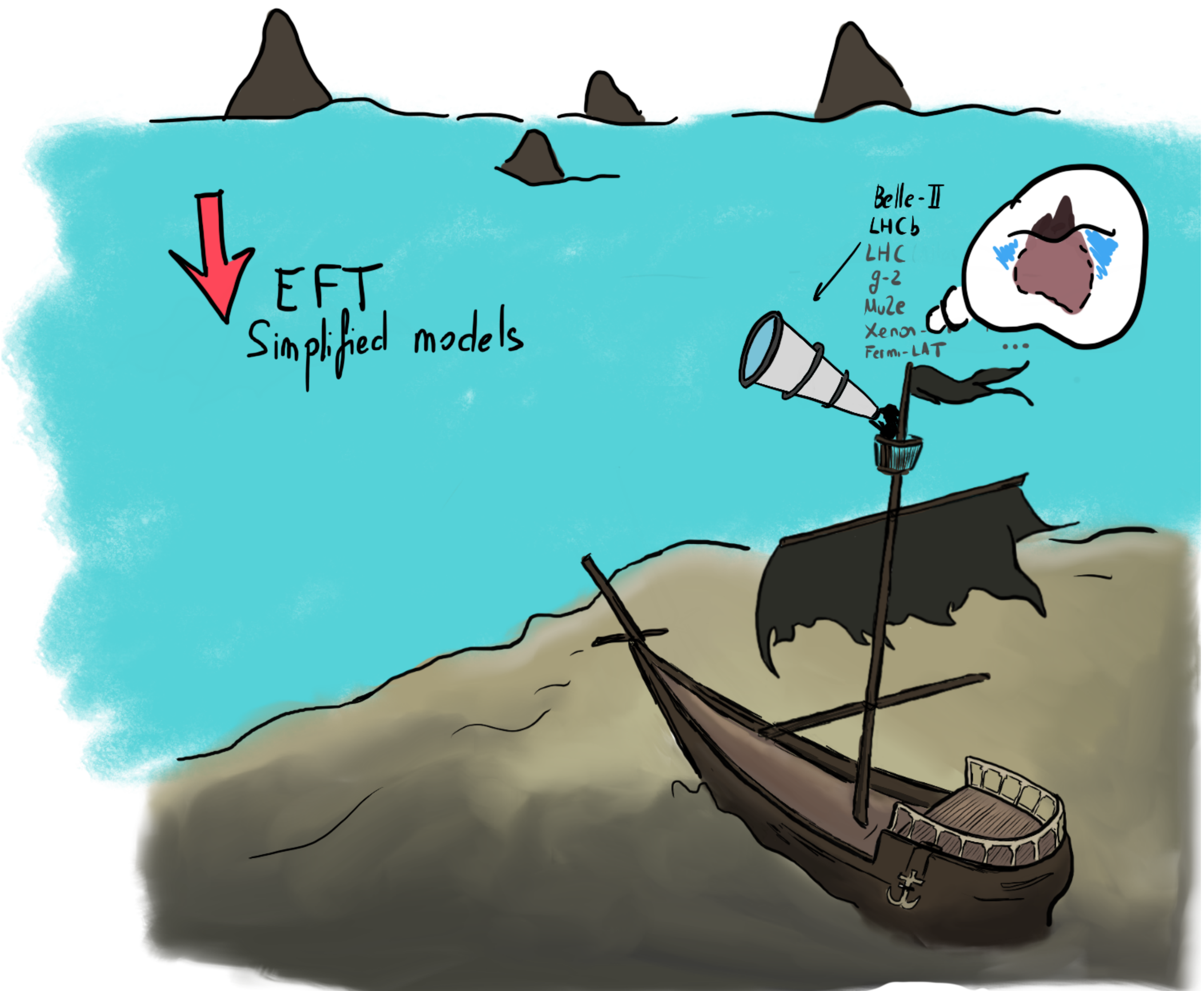




$\phi_4^{5/3}$

$(R_2^{5/3})$

- $\mathcal{R}_{K^*}^{exp}[0.045, 1.1] \pm 2\sigma$
- $\mathcal{R}_{K}^{exp}[1.1, 6] \pm 1\sigma$
- $\mathcal{R}_{K^*}^{exp}[1.1, 6] \pm 2\sigma$
- $\text{Br}(B_s \to \mu^+\mu^-)^{exp} \pm 1\sigma$


EFT
Simplified models
Belle-II
LHCb
LHC
g-2
Mu2e
Xenon-
Fermi-LAT
...

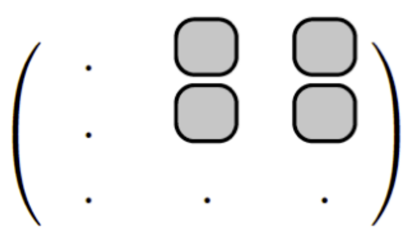

Belle-II
LHCb
LHC
g-2
MuZe
Xenon-1T
Fermi-LAT
ABRACADABRA
Dune
LISA
Fermi-LAT
...
UV-COMPLETION

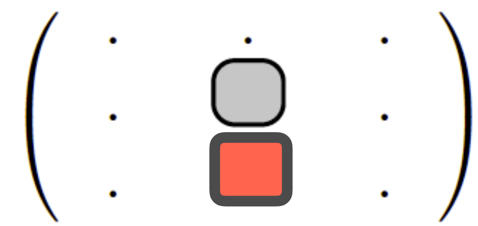
Thank you!

Bonus: $(g-2)_\mu$

[Fileviez Perez, C.M, Plascencia, 2104.11229]

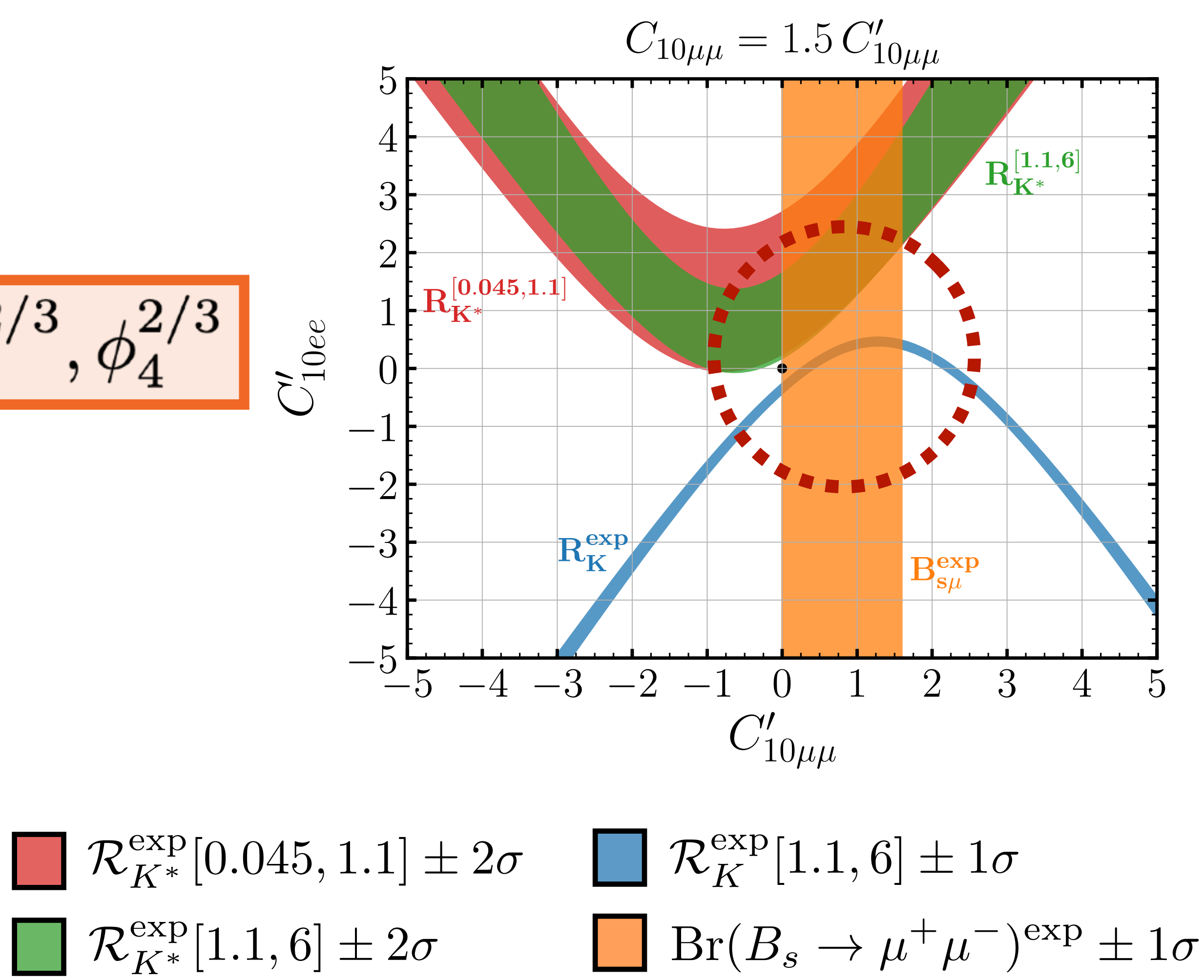
$$-\mathcal{L} \supset \tilde{Y}_2 \mu_L \phi_4^{5/3} (u^c)_L + \tilde{Y}_{\phi_4} \left(u_L (\phi_4^{5/3})^* (\mu^c)_L + d_L (\phi_4^{2/3})^* (\mu^c)_L \right) + \tilde{Y}_{\phi_3} e_L (\phi_3^{-2/3})^* (d^c)_L + \text{h.c.}$$

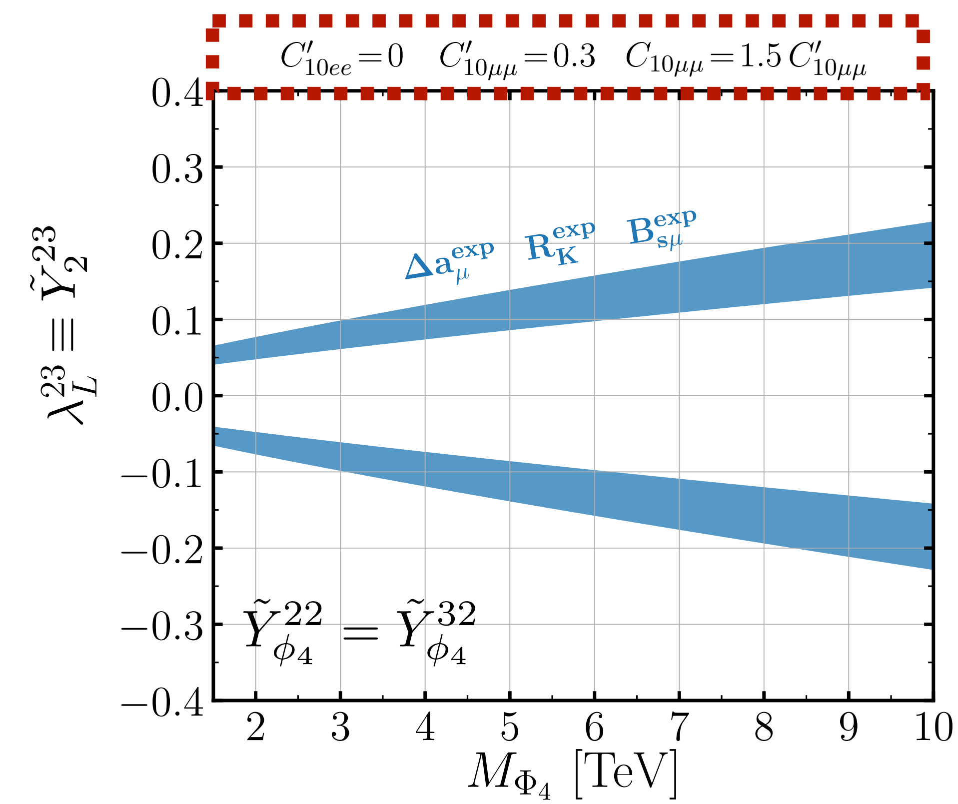
$\tilde{Y}_{\phi_3} =$ 

$\tilde{Y}_{\phi_4} =$ 

Mainly to muons!

$\phi_3^{-2/3}, \phi_4^{2/3}$





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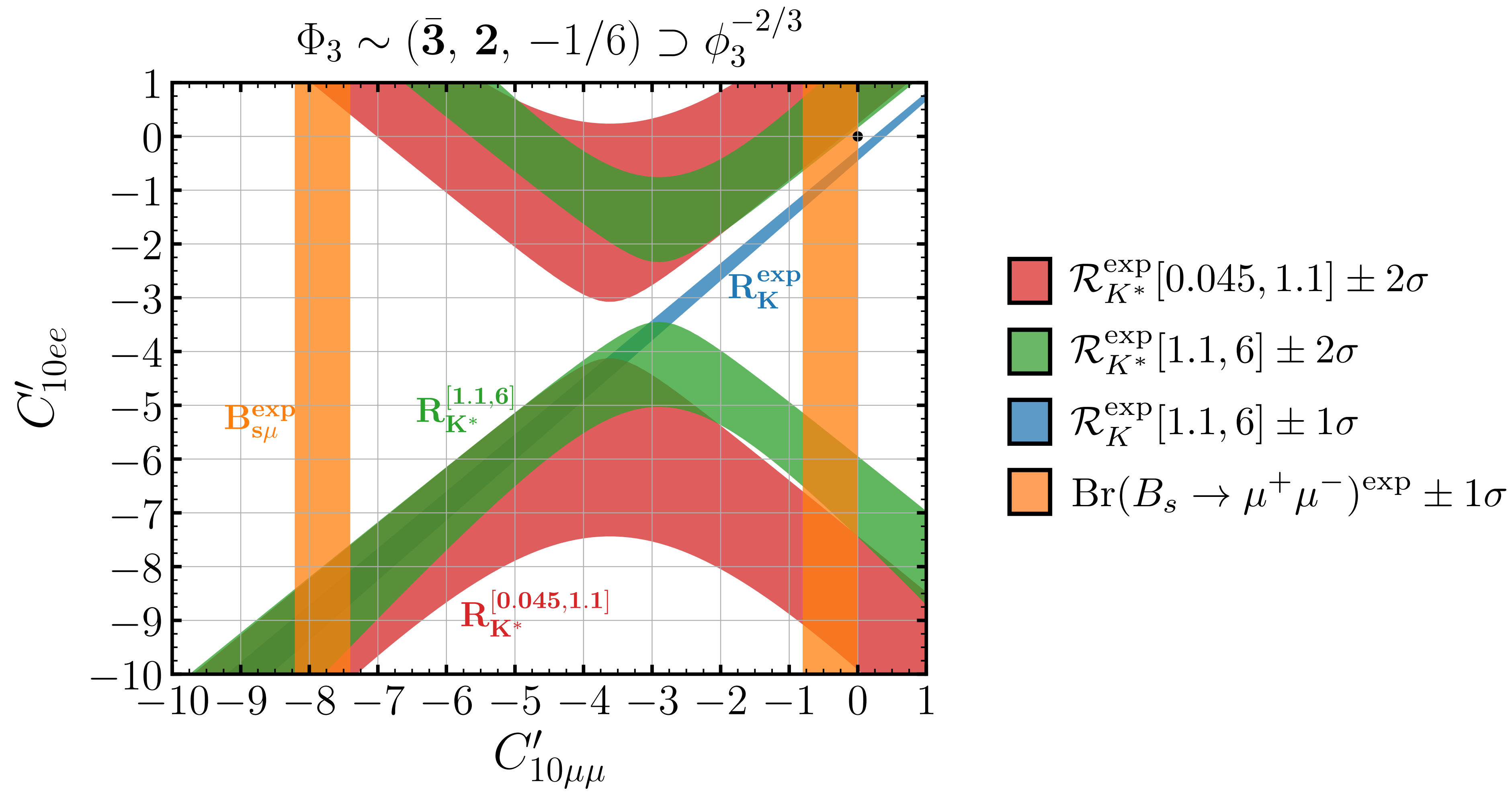
$$C'_{10\ell\ell} = -C'_{9\ell\ell}$$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions!

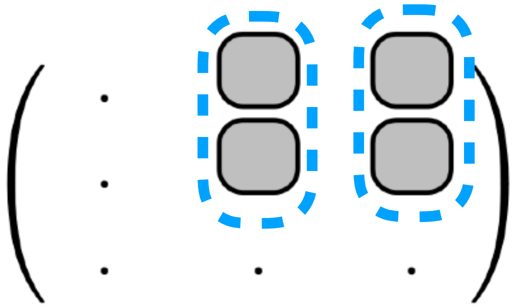
$$\text{Br}(B_s \to \ell^+\ell^-) = f_2(C'_{10\ell\ell}) \qquad \mathcal{R}_{K^{(*)}} = \frac{f_2(C'_{10\mu\mu})}{f_2(C'_{10ee})}$$

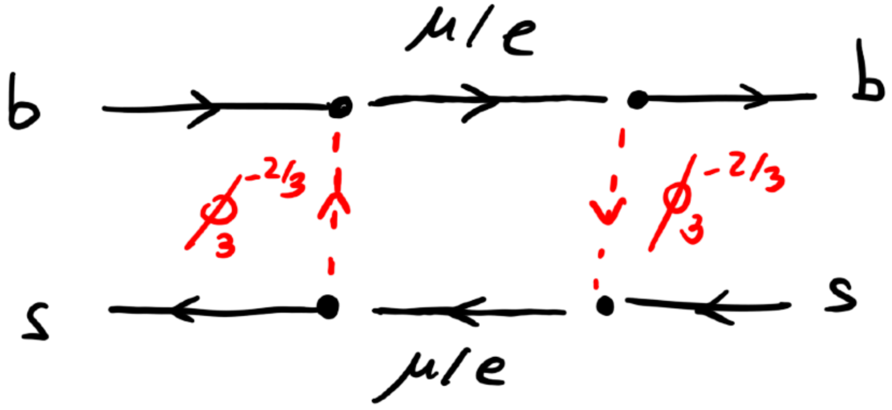


Signatures

- $B_s - \bar{B}_s$ mixing

  [Becirevic, Fajfer, Kosnik, 1503.09024]

$\tilde{Y}_{\phi_3} =$ 



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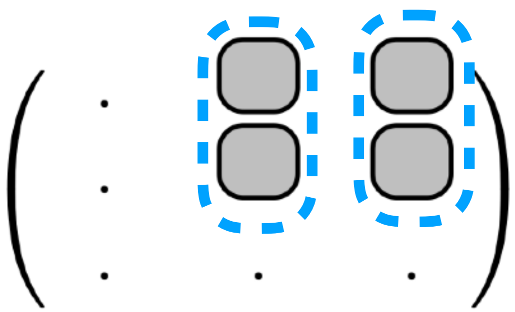
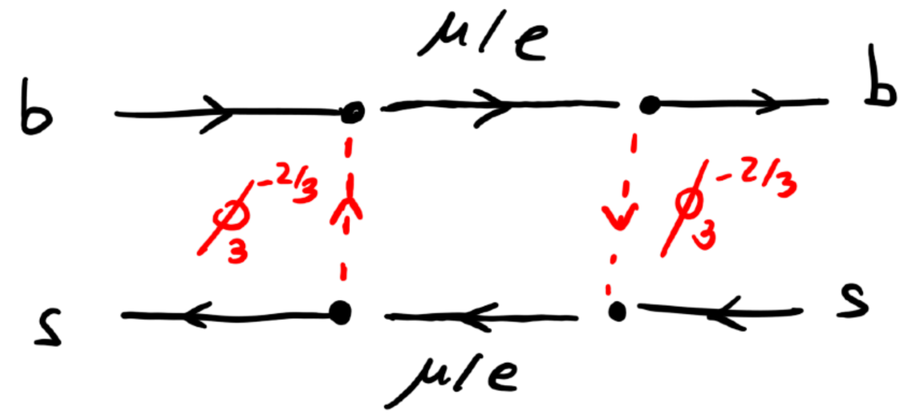
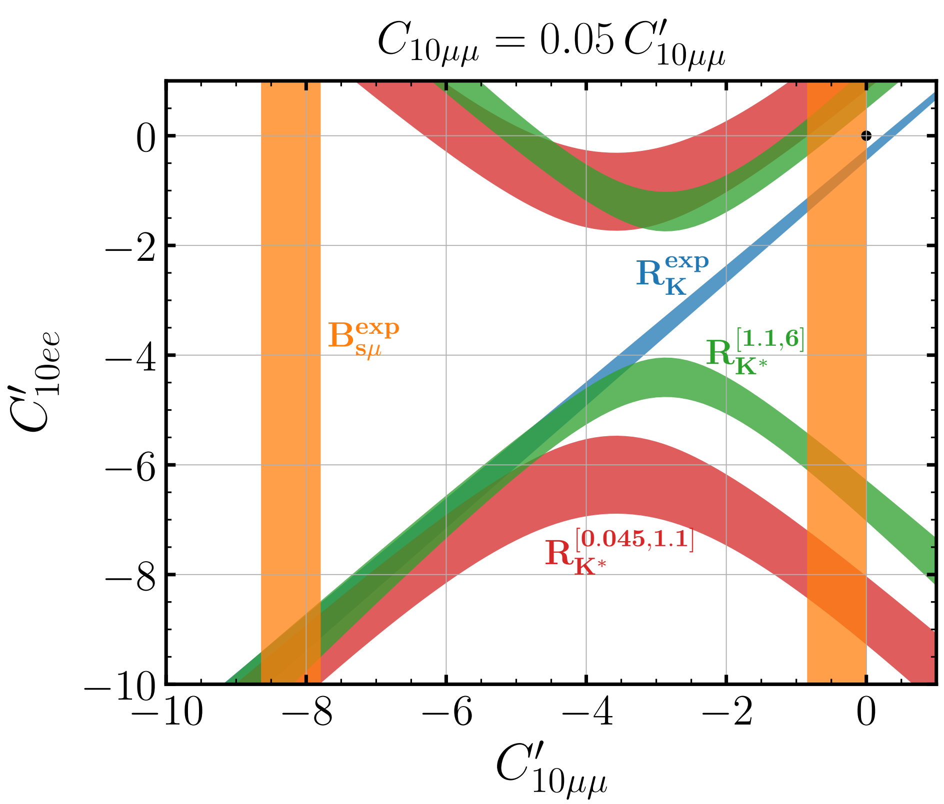
$\tilde{Y}_{\phi_3} =$ 



$$\Delta m_{B_s} = \frac{G_F^2 m_W^2}{6\pi^2} |V_{tb}^* V_{ts}|^2 f_{B_s}^2 m_{B_s} B_{B_s} \eta_B S_0(x_t) \left| 1 - \frac{1}{2\pi^2} \frac{\alpha^2}{S_0(x_t)} (C_{10}^{\prime *})^2 \frac{m_\Delta^2}{m_W^2} \right|$$



$$\Rightarrow |C'_{10}| M_{\phi_3^{2/3}} \lesssim 10^3 \text{ TeV}$$

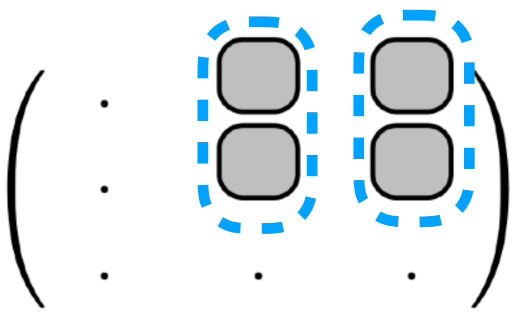
$$\Delta m_{B_s}^{\text{exp}} = 17.2(2) \text{ ps}^{-1}$$

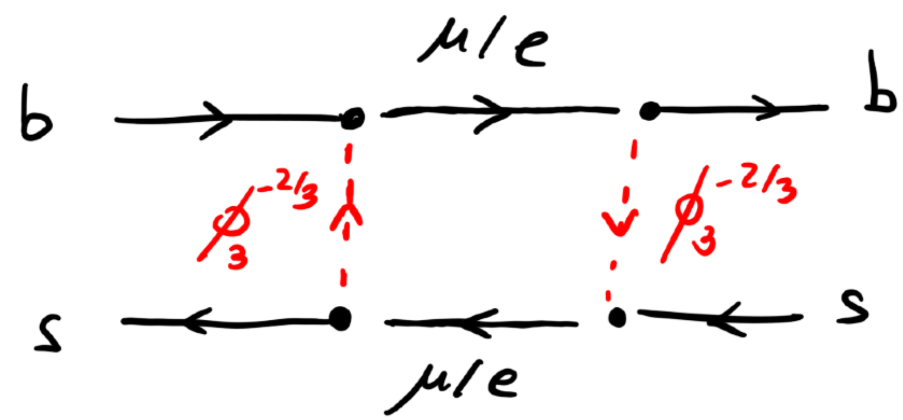
$$C'_{10} \sim \mathcal{O}(10) \Rightarrow M_{\text{LQ}} \lesssim 10 \text{ TeV}$$

Signatures

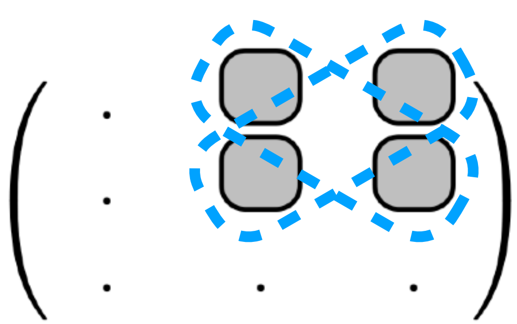
- $B_s - \bar{B}_s$ mixing

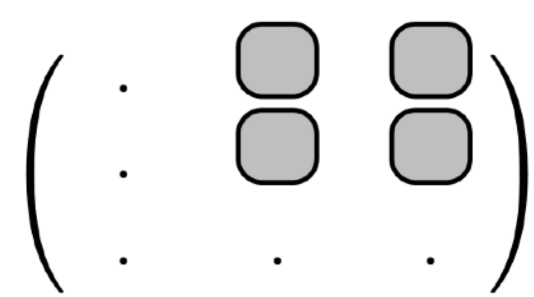
  [Becirevic, Fajfer, Kosnik, 1503.09024]

$\tilde{Y}_{\phi_3} =$ 



- LFU & LFV, $B_s \to$ missing energy, $B \to K^{(*)}$ + missing energy

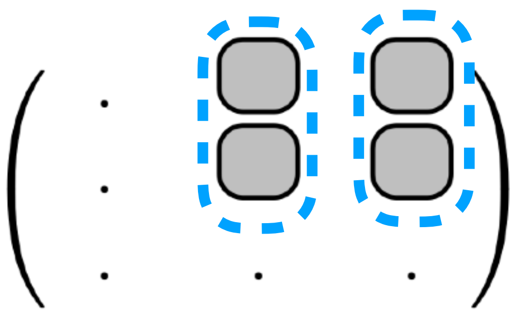
$\tilde{Y}_{\phi_3} =$ 

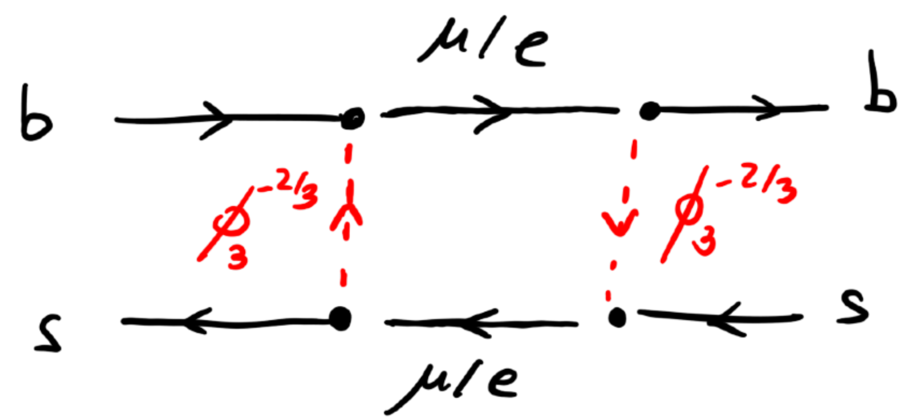
$V_{\text{PMNS}}^T K_3 \tilde{Y}_{\phi_3} \sim V_{\text{PMNS}}^T$ 

$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a} + Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a + \text{h.c.}$$

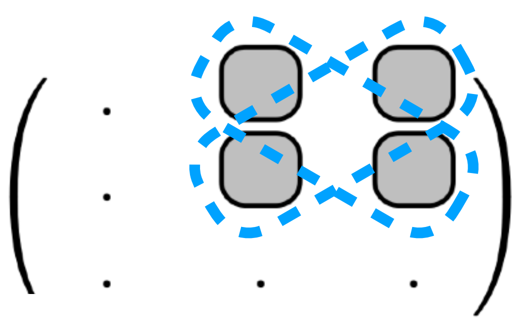
Signatures

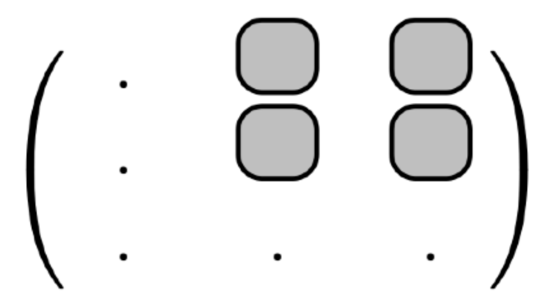
- $B_s - \bar{B}_s$ mixing
  [Becirevic, Fajfer, Kosnik, 1503.09024]

$\tilde{Y}_{\phi_3} =$ 



- LFU & LFV, $B_s \to$ missing energy, $B \to K^{(*)}$ + missing energy

$\tilde{Y}_{\phi_3} =$ 

$V^T_{\text{PMNS}} K_3 \tilde{Y}_{\phi_3} \sim V^T_{\text{PMNS}}$ 

L~~F~~U $\overset{\text{BSM}}{\longleftrightarrow}$ L~~F~~ **See Gaetano's talk**

See Filippo's and Rusa's talk

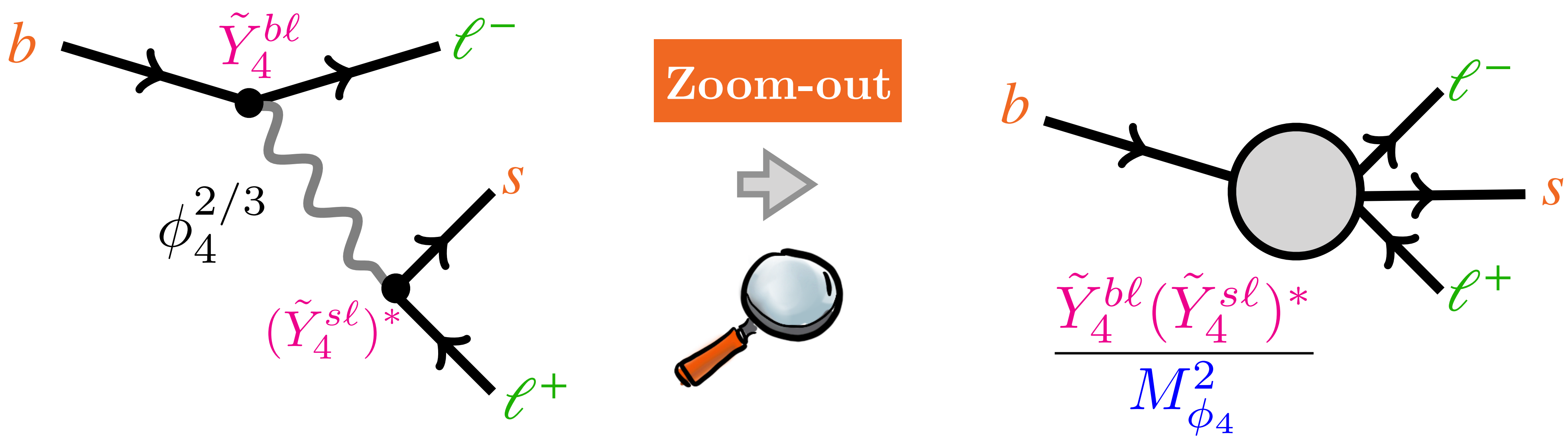
- Phenomenological relations exploting the Pati-Salam symmetry
  [Fileviez, Golias, Plascencia, 2107.06895]

e.g. $\Gamma_T(\phi_3^{1/3} \to \bar{d}\nu) = \left(\dfrac{M_{\phi_3}^{1/3}}{M_{\phi_4}^{2/3}}\right) \Gamma_T(\phi_4^{2/3} \to \bar{e}d) \qquad \Gamma_T(\phi_3^{-2/3} \to \bar{d}e) = \left(\dfrac{M_{\phi_3}^{1/3}}{M_{H_2}^{2/3}}\right) \Gamma_T(H_2 \to \bar{e}e)$

Scalar LQ: $R_2 \equiv \Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a + \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a} + \text{h.c.}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions!



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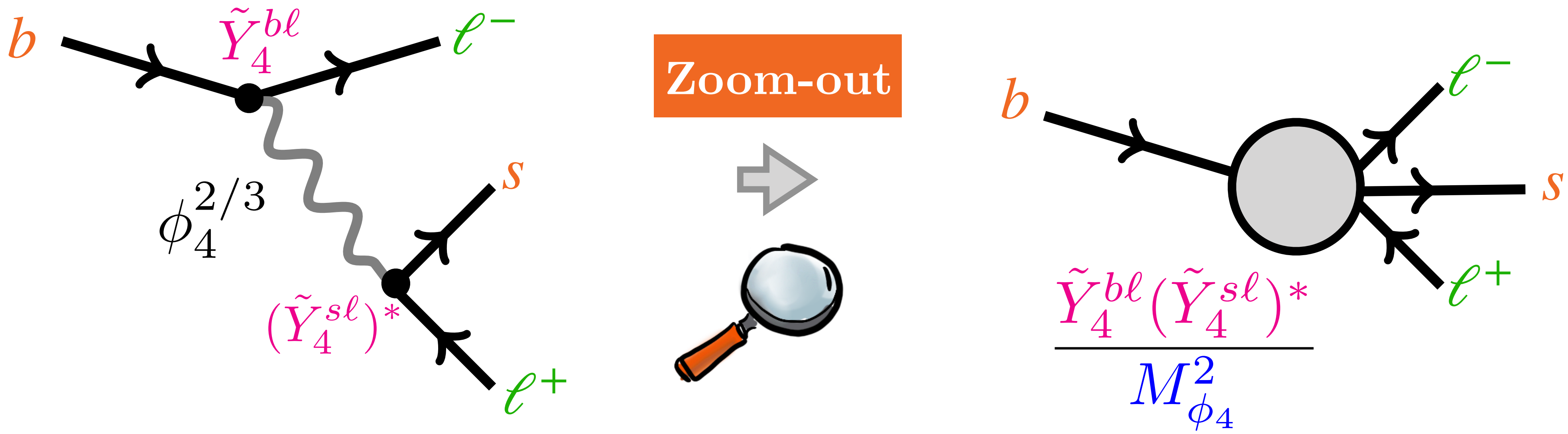


$$\mathcal{L}_{\text{eff}}^{\phi_4^{2/3}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \left[C_{9\ell\ell} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) + C_{10\ell\ell} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \right]$$

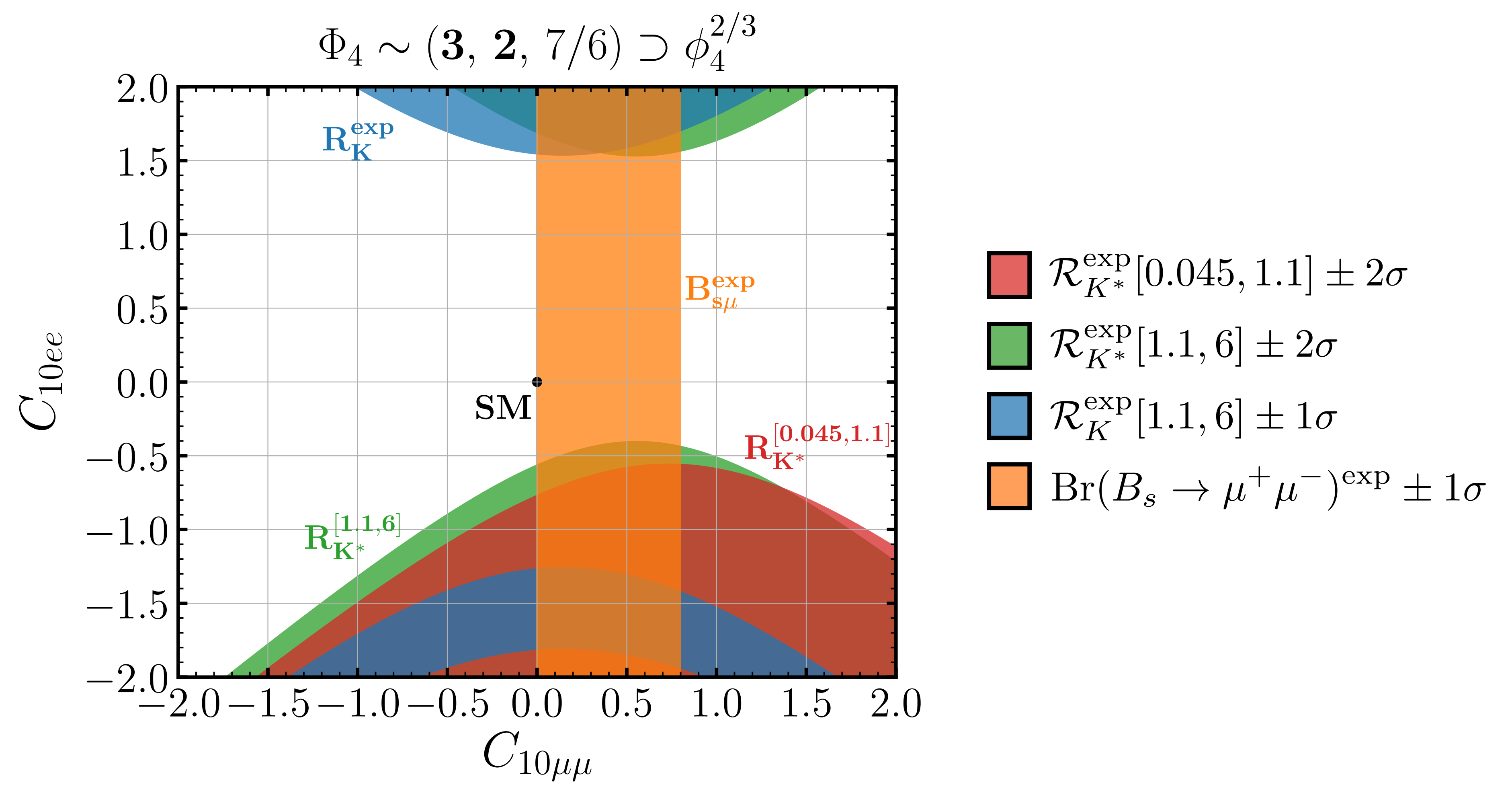
$$\Rightarrow \quad C_{10\ell\ell} = C_{9\ell\ell} = -\left(\frac{\pi\sqrt{2}}{G_F\, V_{tb} V_{ts}^*\, \alpha} \right) \frac{\tilde{Y}_4^{3\ell}(\tilde{Y}_4^{2\ell})^*}{4 M_{\phi_4^{2/3}}^2}$$

Scalar LQ: $R_2 \equiv \Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a + \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a} + \text{h.c.}$$

$$C_{10\ell\ell} = C_{9\ell\ell}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions!



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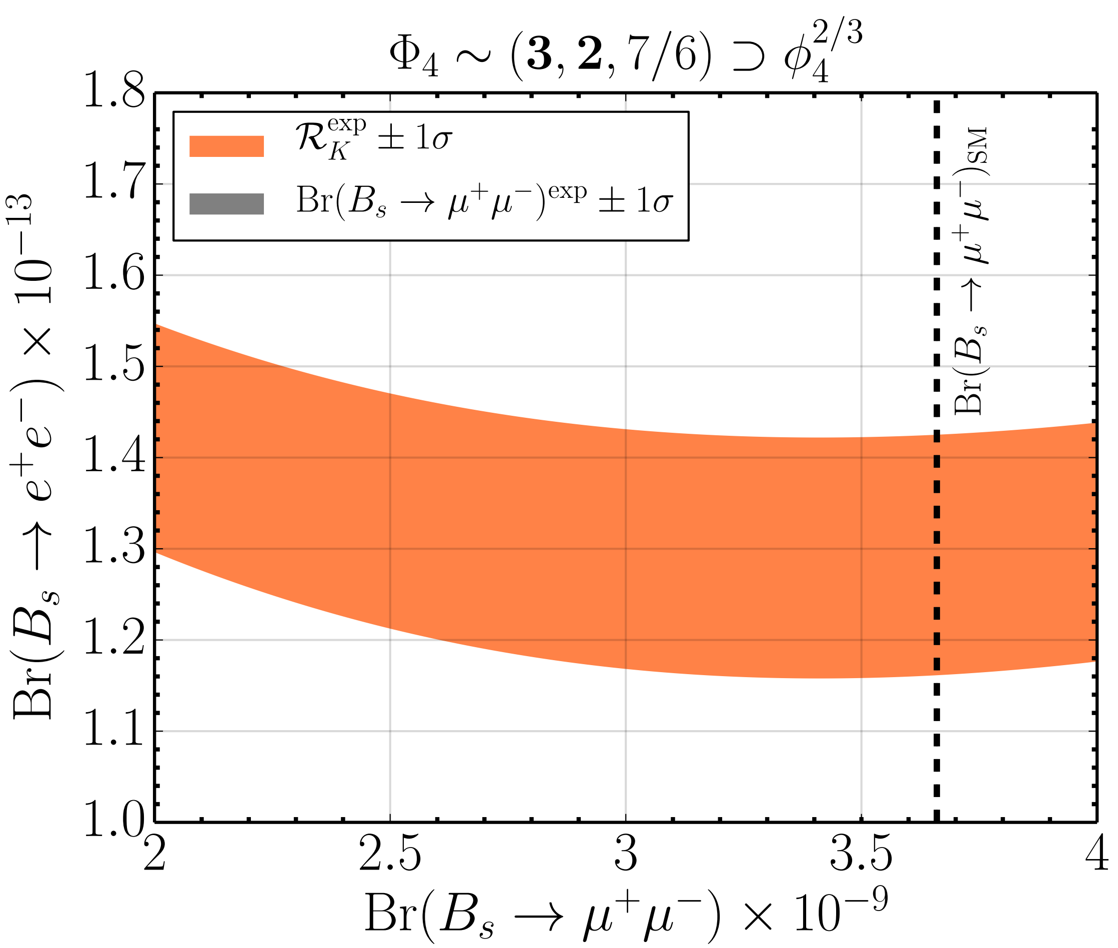
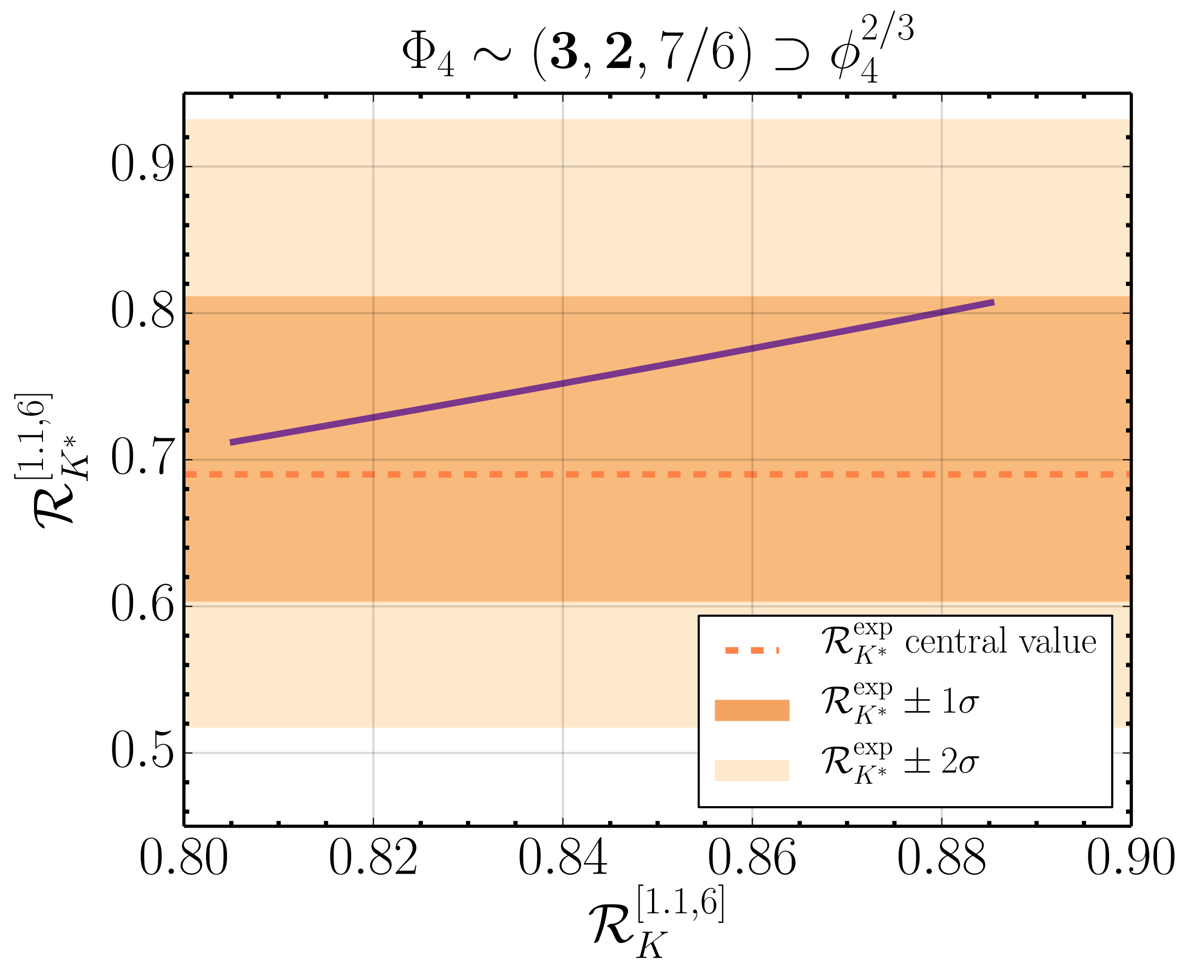
- $\phi_4^{2/3}$ contributes to $b \to s$ transitions!

$$\text{Br}(B_s \to \ell^+\ell^-) = f_2(C_{10\ell\ell}) \qquad \mathcal{R}_{K^{(*)}} = \frac{f_2(C_{10\mu\mu})}{f_2(C_{10ee})}$$





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$$C_{10\ell\ell} = C_{9\ell\ell}$$

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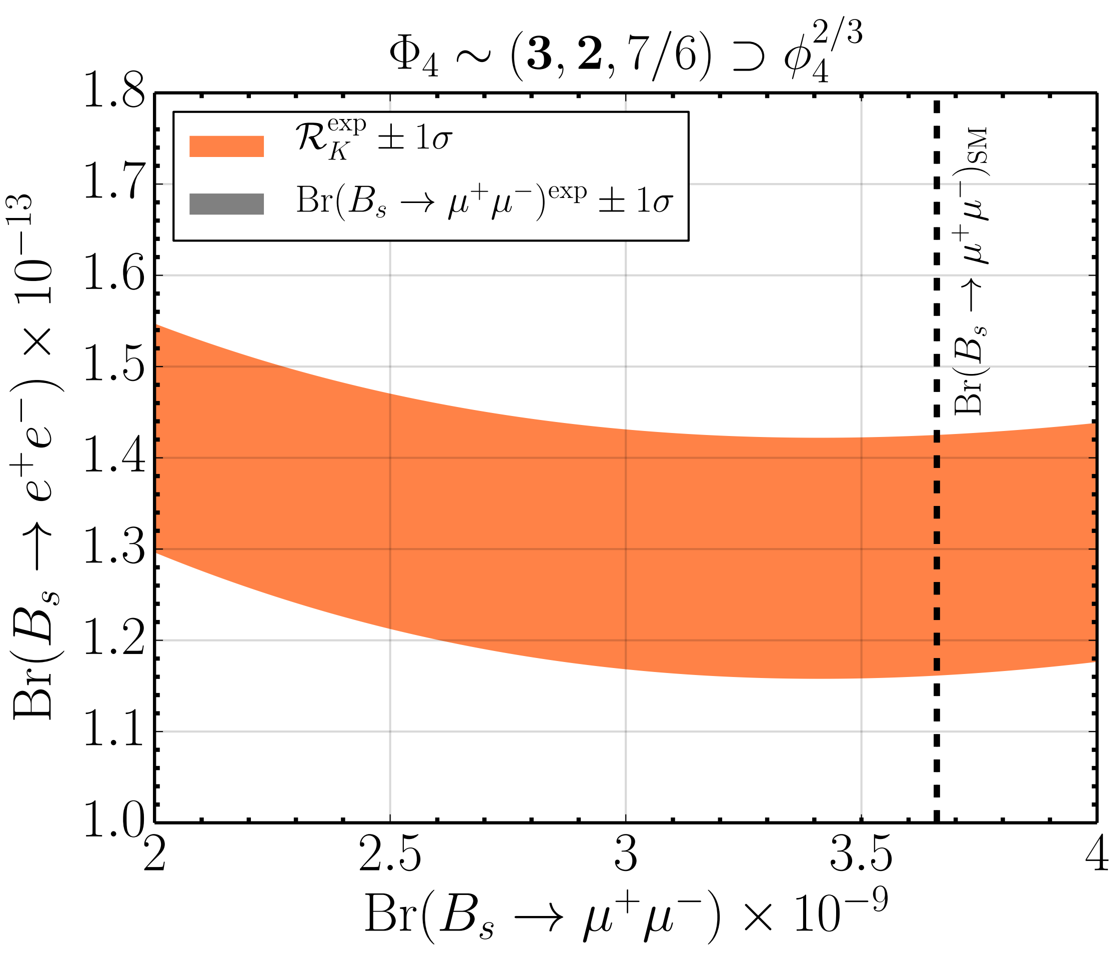
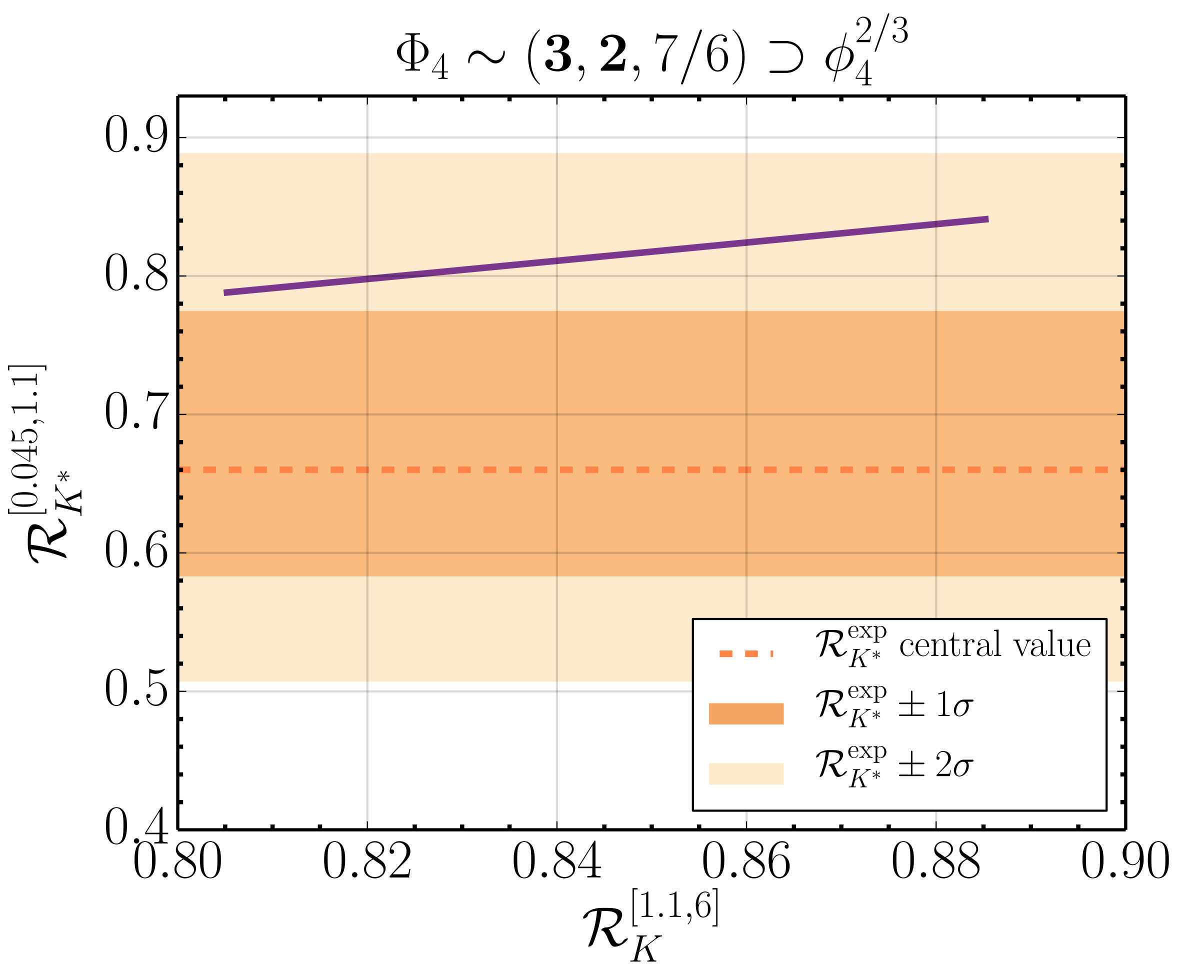


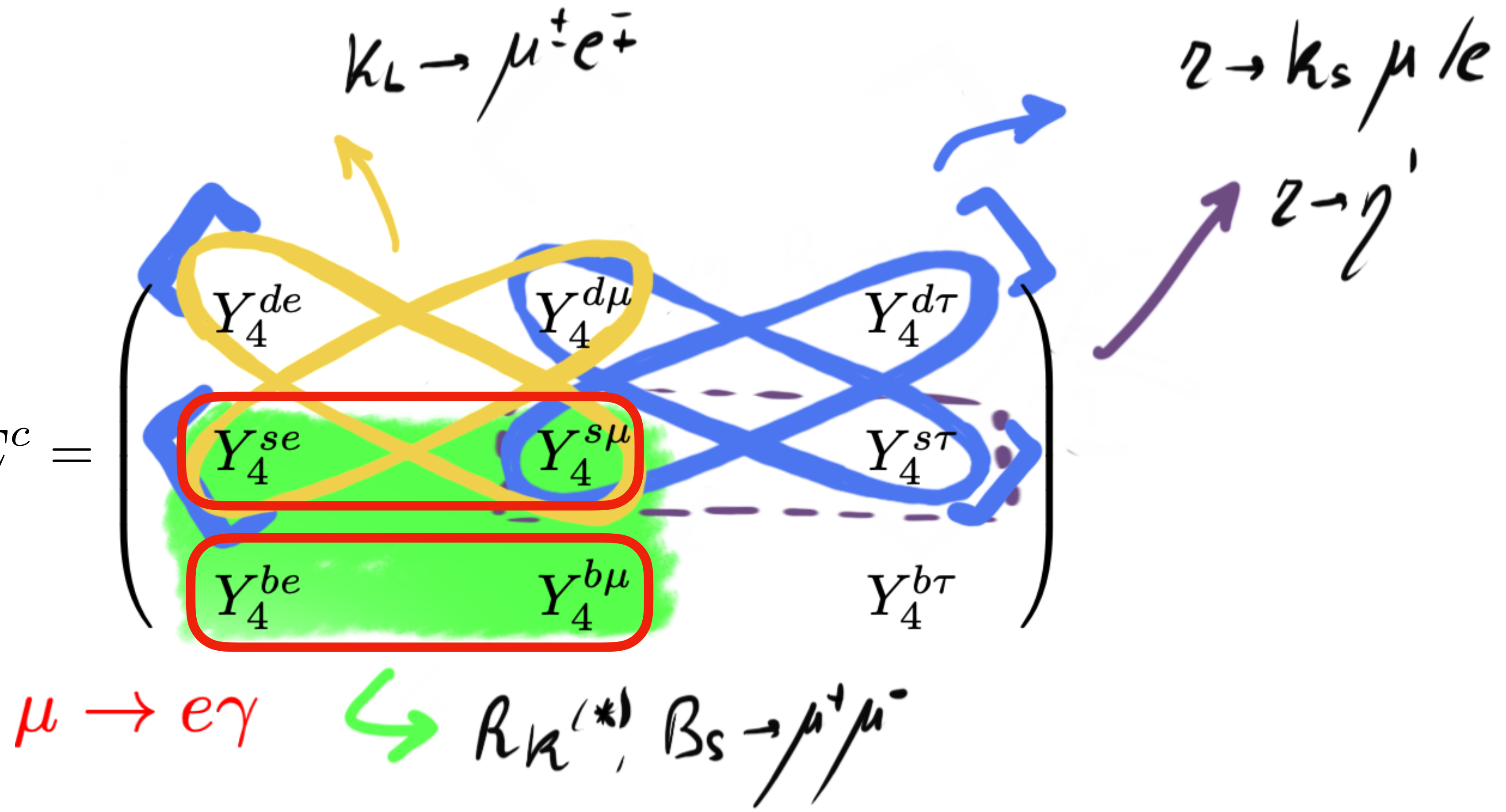


Scalar LQ: $R_2 \equiv \Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a + \boxed{\tilde{Y}_{\phi_4}^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a} + \text{h.c.}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions! (and also to other processes...)

$$\tilde{Y}_{\phi_4} = D Y_4 E^c = \begin{pmatrix} Y_4^{de} & Y_4^{d\mu} & Y_4^{d\tau} \\ Y_4^{se} & Y_4^{s\mu} & Y_4^{s\tau} \\ Y_4^{be} & Y_4^{b\mu} & Y_4^{b\tau} \end{pmatrix}$$



Scalar LQ: $R_2 \equiv \Phi_4 \sim (3, 2, 7/6)$

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- $\phi_4^{2/3}$ contributes to $b \to s$ transitions! (and also to other processes...)

$$\tilde{Y}_{\phi_4} = D Y_4 E^c = \begin{pmatrix} \cdot & \cdot & \cdot \\ \bigcirc & \cdot & \cdot \\ \bigcirc & \cdot & ? \end{pmatrix}$$

Scalar LQ: $R_2 \equiv \Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a} + Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a + \text{h.c.}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions! (and also to other processes...)

$$\tilde{\tilde{Y}}_4 = K_2 V_{\text{CKM}} K_1 \tilde{Y}_{\phi_4}$$

$$\tilde{\tilde{Y}}_4 = \begin{pmatrix} \cdot & \cdot & \cdot \\ \bullet & \cdot & \cdot \\ \bullet & \cdot & ? \end{pmatrix}$$

Scalar LQ: $R_2 \equiv \Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a} + Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a + \text{h.c.}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions! (and also to other processes...)

$$\tilde{\tilde{Y}}_4 = K_2 \mathbb{I} K_1 \tilde{Y}_{\phi_4}$$

$$Y_4 = \begin{pmatrix} \cdot & \cdot & \cdot \\ Y_4^{ce} & \cdot & \cdot \\ Y_4^{te} & \cdot & ? \end{pmatrix}$$

$\Rightarrow$ $\mathrm{Br}(t \to c e^+ e^-) \sim 2 \times 10^{-7}$

Leptoquarks: LH currents

Global fit: preferred solution

$$(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \ell)$$

Borrowed from Nazila's talk on Monday

[Altmannshofer, Stangl 2103.13370]
[Buttazzo, Greljo, et al. 1706.07808]

Only $R_{K^{(*)}}, B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\rm SM} = 28.19$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-1.00 ± 6.00	28.1	0.2σ
δC_9^e	0.80 ± 0.21	11.2	4.1σ
δC_9^μ	-0.77 ± 0.21	11.9	4.0σ
δC_{10}	0.43 ± 0.24	24.6	1.9σ
δC_{10}^e	-0.78 ± 0.20	9.5	4.3σ
δC_{10}^μ	0.64 ± 0.15	7.3	4.6σ
$\delta C_{\rm LL}^e$	0.41 ± 0.11	10.3	4.2σ
$\delta C_{\rm LL}^\mu$	-0.38 ± 0.09	7.1	4.6σ

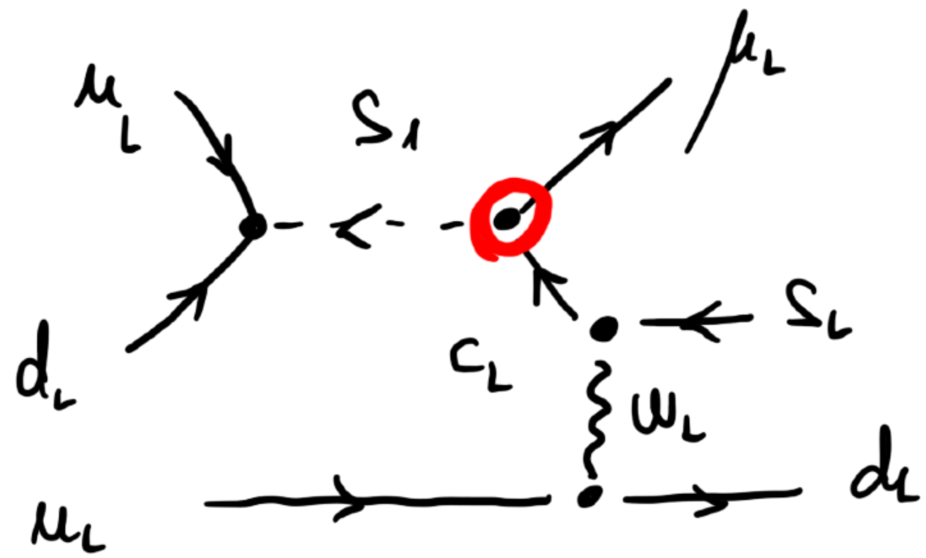
Vector LQs

Symbol	Q.N. (SM)
U_3	$(3, 3, 2/3)$
V_2	$(\bar{3}, 2, 5/6)$
$\tilde{V}_2$	$(\bar{3}, 2, -1/6)$
$\tilde{U}_1$	$(3, 1, 5/3)$
U_1	$(3, 1, 2/3)$
$\bar{U}_1$	$(3, 1, -1/3)$

Scalar LQs

Symbol	Q.N. (SM)
S_3	$(\bar{3}, 3, 1/3)$
R_2	$(3, 2, 7/6)$
$\tilde{R}_2$	$(3, 2, 1/6)$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$
S_1	$(\bar{3}, 1, 1/3)$
$\bar{S}_1$	$(\bar{3}, 1, -2/3)$

Leptoquarks: LH currents



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Scalar LQs

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$\bar{S}_1$	$(\bar{3}, 1, -2/3)$

Leptoquarks

[Dorsner, Fajfer, et al. 1603.04993, Mandal, Pich, 1908.11155]

(green) No Baryon Number violation at renormalizable level

(orange dashed box) Chiral enhancement in (g-2) at 1-loop level [Bigaran, Volkas, 2002.12544]

Vector LQs

Symbol	Q.N. (SM)
U_3	$(3, 3, 2/3)$
V_2	$(\bar{3}, 2, 5/6)$
$\tilde{V}_2$	$(\bar{3}, 2, -1/6)$
$\tilde{U}_1$	$(3, 1, 5/3)$
U_1	$(3, 1, 2/3)$
$\bar{U}_1$	$(3, 1, -1/3)$

$\sim m_q/m_\mu$

Scalar LQs

Symbol	Q.N. (SM)
S_3	$(\bar{3}, 3, 1/3)$
R_2	$(3, 2, 7/6)$
$\tilde{R}_2$	$(3, 2, 1/6)$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$
S_1	$(\bar{3}, 1, 1/3)$
$\bar{S}_1$	$(\bar{3}, 1, -2/3)$

$\sim m_q/m_\mu \ln(M_{\rm LQ}/m_q)$

[Dorsner, Fajfer, Summensari, 1910.03877]

$\theta_{\rm LQ} \propto v^2/M_{\rm LQ}^2$

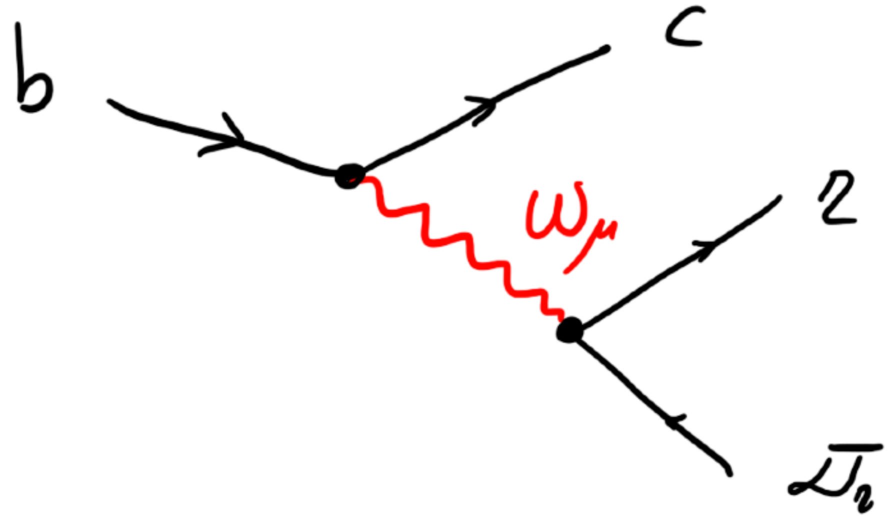
High pT bounds

Charged anomalies

Anomalies in $b \to c$ transitions

➪ $\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)}$ **3.1 σ**

HFLAV, up to date

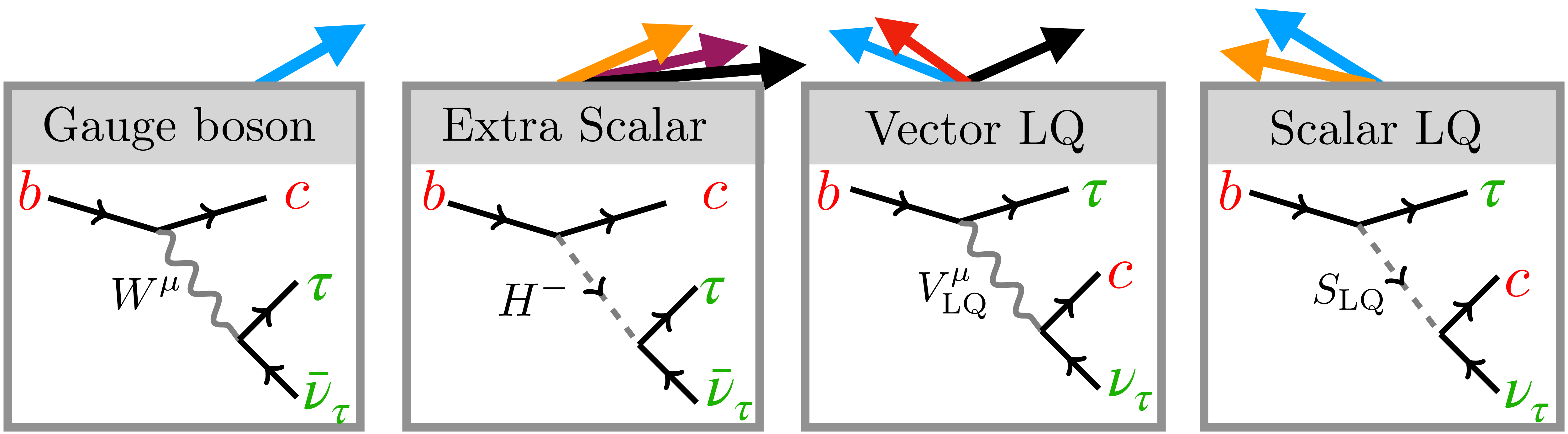


Tree level process!!

Bottom-up approach

- Most general effective dim 6 Hamiltonian:

$$\mathcal{H}_{\rm eff}^{b\to c\ell\nu} = \frac{4\,G_F}{\sqrt{2}} V_{cb}[(1 + C_{V_L})\mathcal{O}_{V_L} + C_{V_R}\,\mathcal{O}_{V_R} + C_{S_R}\,\mathcal{O}_{S_R} + C_{S_L}\,\mathcal{O}_{S_L} + C_T\,\mathcal{O}_T] + \text{h.c.}$$



$$\mathcal{O}_{V_L} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell),$$
$$\mathcal{O}_{V_R} = (\bar{c}\,\gamma^\mu P_R b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell),$$
$$\mathcal{O}_{S_R} = (\bar{c}\,P_R b)(\bar{\ell}\,P_L \nu_\ell),$$
$$\mathcal{O}_{S_L} = (\bar{c}\,P_L b)(\bar{\ell}\,P_L \nu_\ell),$$
$$\mathcal{O}_T = (\bar{c}\,\sigma^{\mu\nu} P_L b)(\bar{\ell}\,\sigma_{\mu\nu} P_L \nu_\ell),$$

Bottom-up approach

- Most general effective dim 6 Hamiltonian:

$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu} = \frac{4\,G_F}{\sqrt{2}} V_{cb}[(1 + C_{V_L})\mathcal{O}_{V_L} + C_{S_R}\,\mathcal{O}_{S_R} + C_{S_L}\,\mathcal{O}_{S_L} + C_T\mathcal{O}_T] + \text{h.c.}$$

- Inputs:

  - $\mathcal{R}_D$
  - $\mathcal{R}_{D^*}$
  - $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
  - $B_c \to \tau\bar{\nu}_\tau$
  - $F_L^{D^*}$

- Bc lifetime:

$\Rightarrow \text{Br}(B_c \to \tau\bar{\nu}_\tau) \leq 30 - 40\%$

[Alonso et al., 2016]

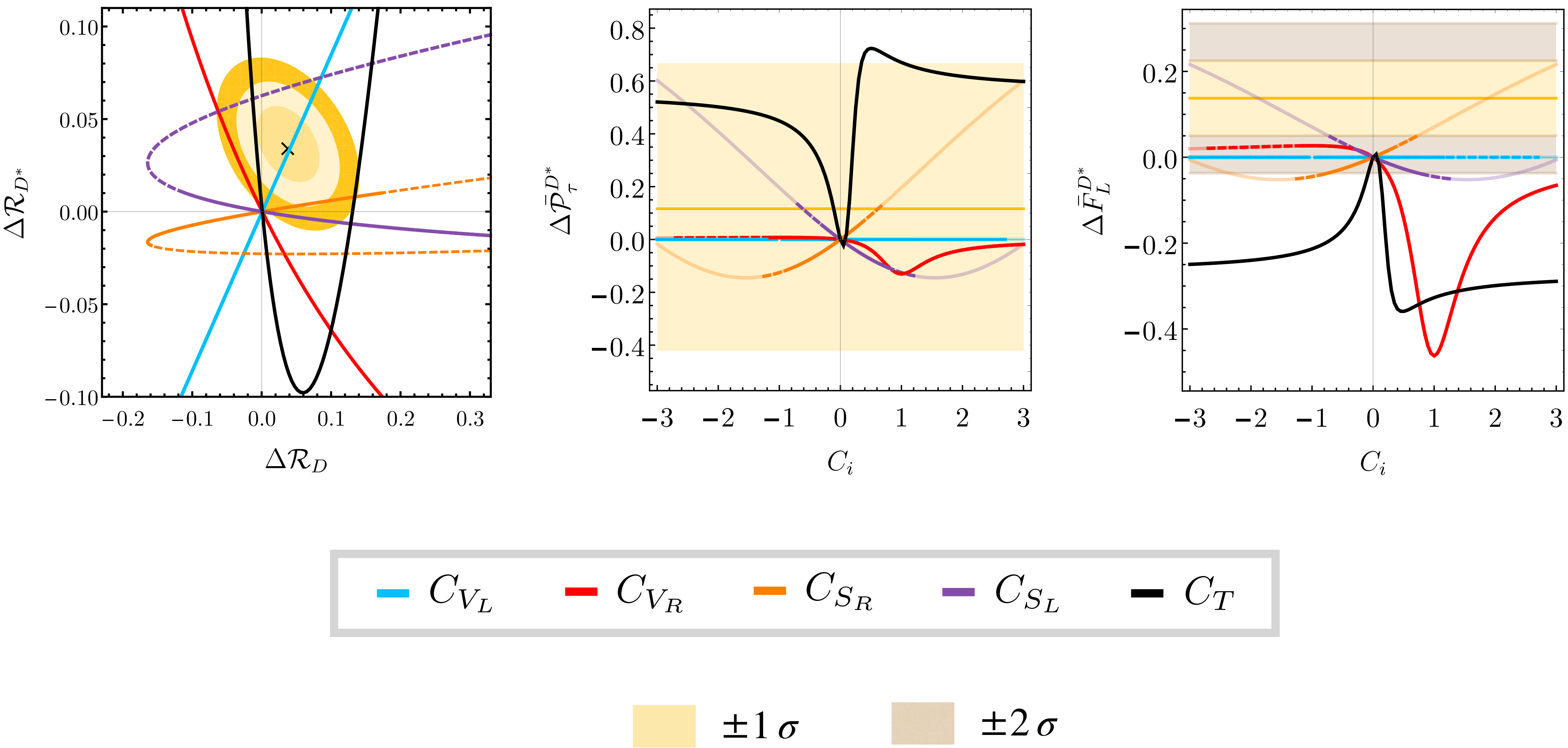
- Bound LEP Z peak:

[Akeroyd et al., 2017]

$\Rightarrow \text{Br}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$

$$\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) = \#|V_{cb}|^2 \times \left|1 + C_{V_L} - C_{V_R} + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}\left(C_{S_R} - C_{S_L}\right)\right|^2$$

Fit independent analysis



Bottom-up approach

- Most general effective dim 6 Hamiltonian:

$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu} = \frac{4\,G_F}{\sqrt{2}} V_{cb}[(1 + C_{V_L})\mathcal{O}_{V_L} + \cancel{C_{V_R}\mathcal{O}_{V_R}} + C_{S_R}\,\mathcal{O}_{S_R} + C_{S_L}\,\mathcal{O}_{S_L} + C_T\,\mathcal{O}_T] + \text{h.c.}$$

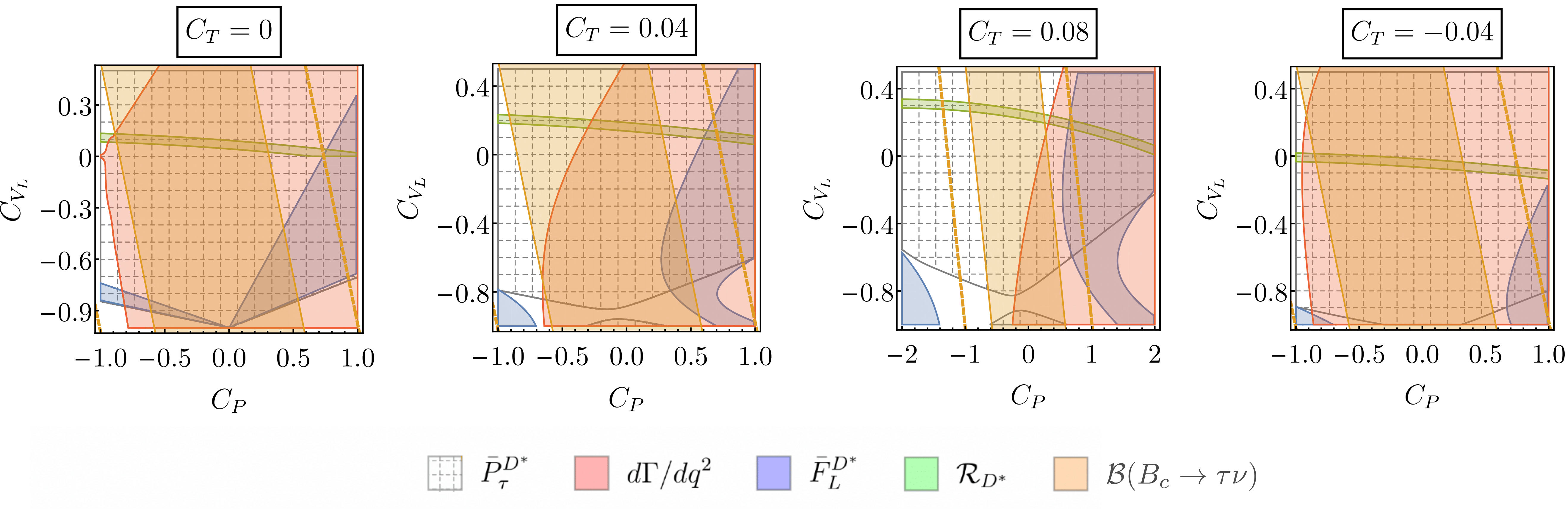
- Theoretical assumptions:

  - EFT ✓
  - New physics only in the **third generation,** [C. Bobeth et al., two months ago]
  - C_{V_R} lepton flavour universal $\Rightarrow C_{V_R}^{\tau} \sim 0$
  - CP conserving W.C.

- Experimental measurements

An unidentified or underestimated systematic uncertainty…

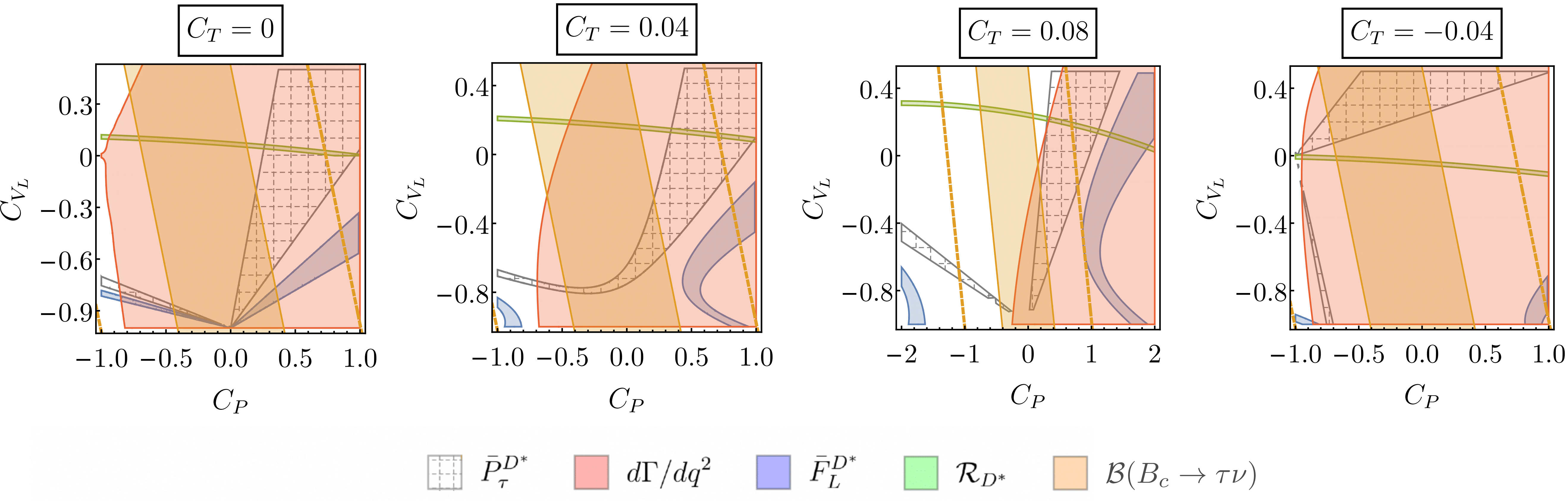
Fit-independent analysis



- $\mathcal{R}_{D^*}$ C_{V_L} C_P C_T
- $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
- $B_c \to \tau\bar{\nu}_\tau$ C_{V_L} C_P
- $F_L^{D^*}$ C_{V_L} C_P C_T

Implications of new measurements?

[Speculating...]



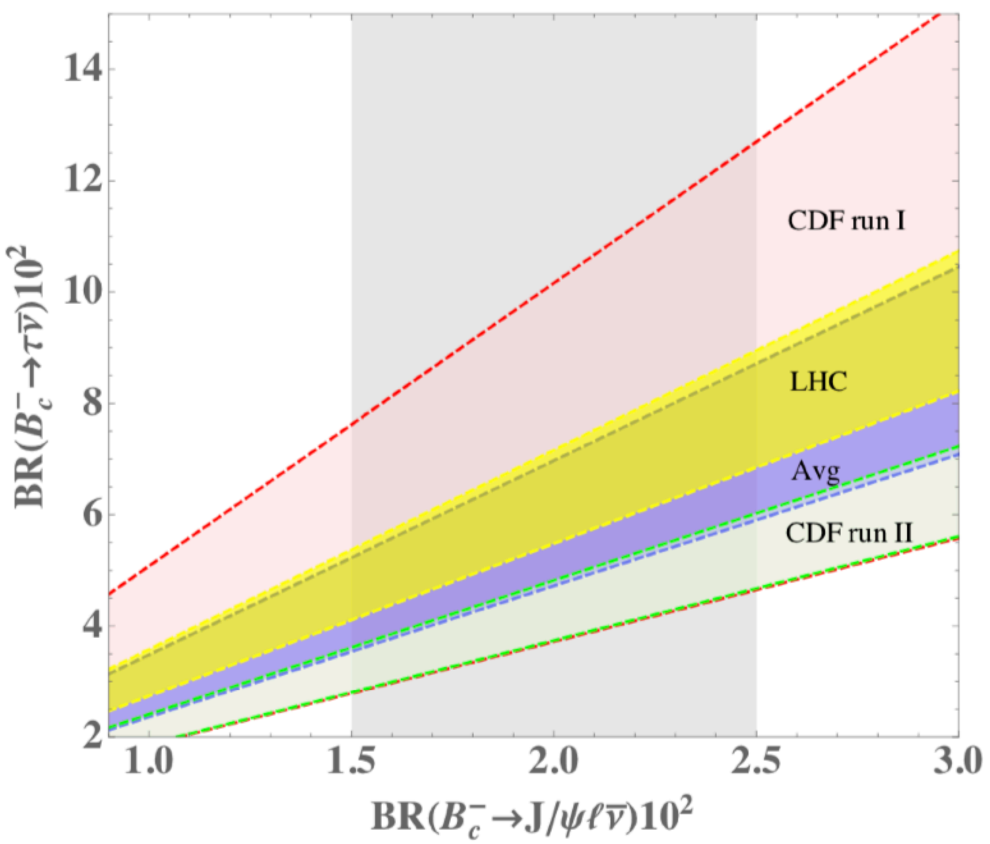
Belle-II	5 ab^{-1}	50 ab^{-1}
$\mathcal{R}_{D^*}$	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$\bar{P}_\tau^{D^*}$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

My guess: $F_L^{D^*} \sim 15\%$ ⇨ 5%

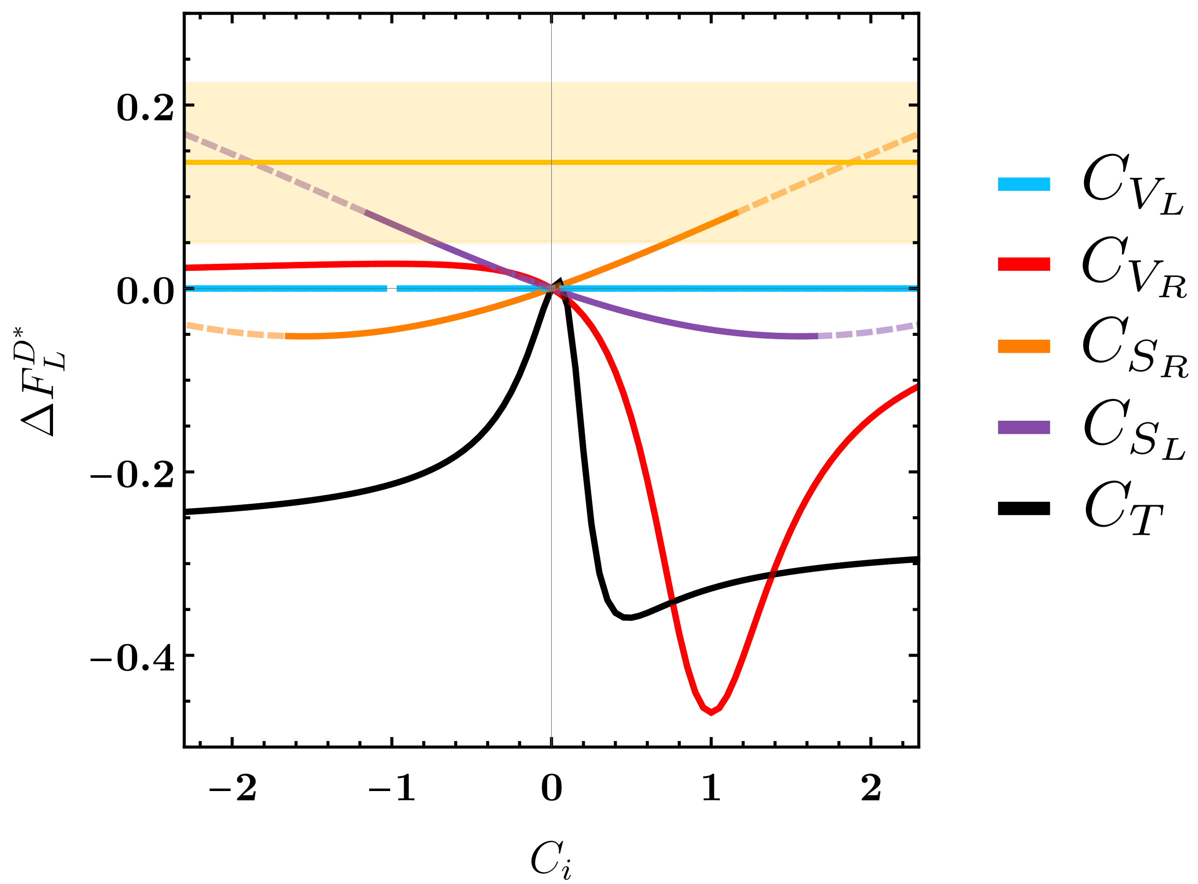
Bounds on Br($B_c \to \tau\bar{\nu}$)

Resurrection of the scalar candidates ?

[Akeroyd et al., 2017]



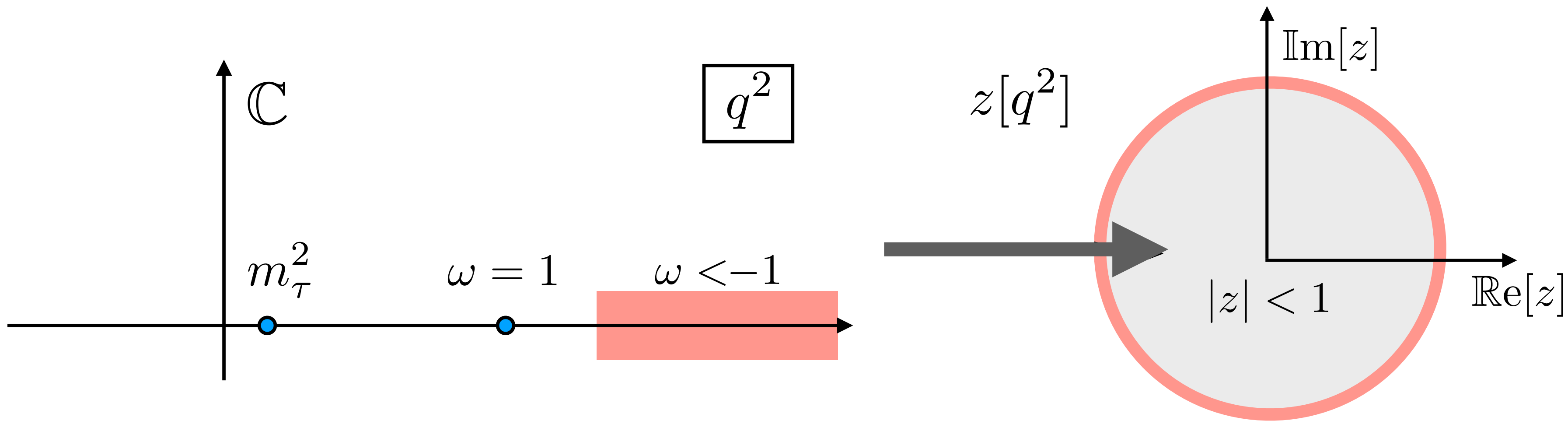
$\mathcal{B}(B_c \to \tau\bar{\nu}) < 60\%$



See discussion in [M. Blanke et al., 2019]

Global fit: Form Factors

$\mathcal{O}(\alpha_s,\ 1/m_{b,c},\ \text{and partially } 1/m_c^2)$

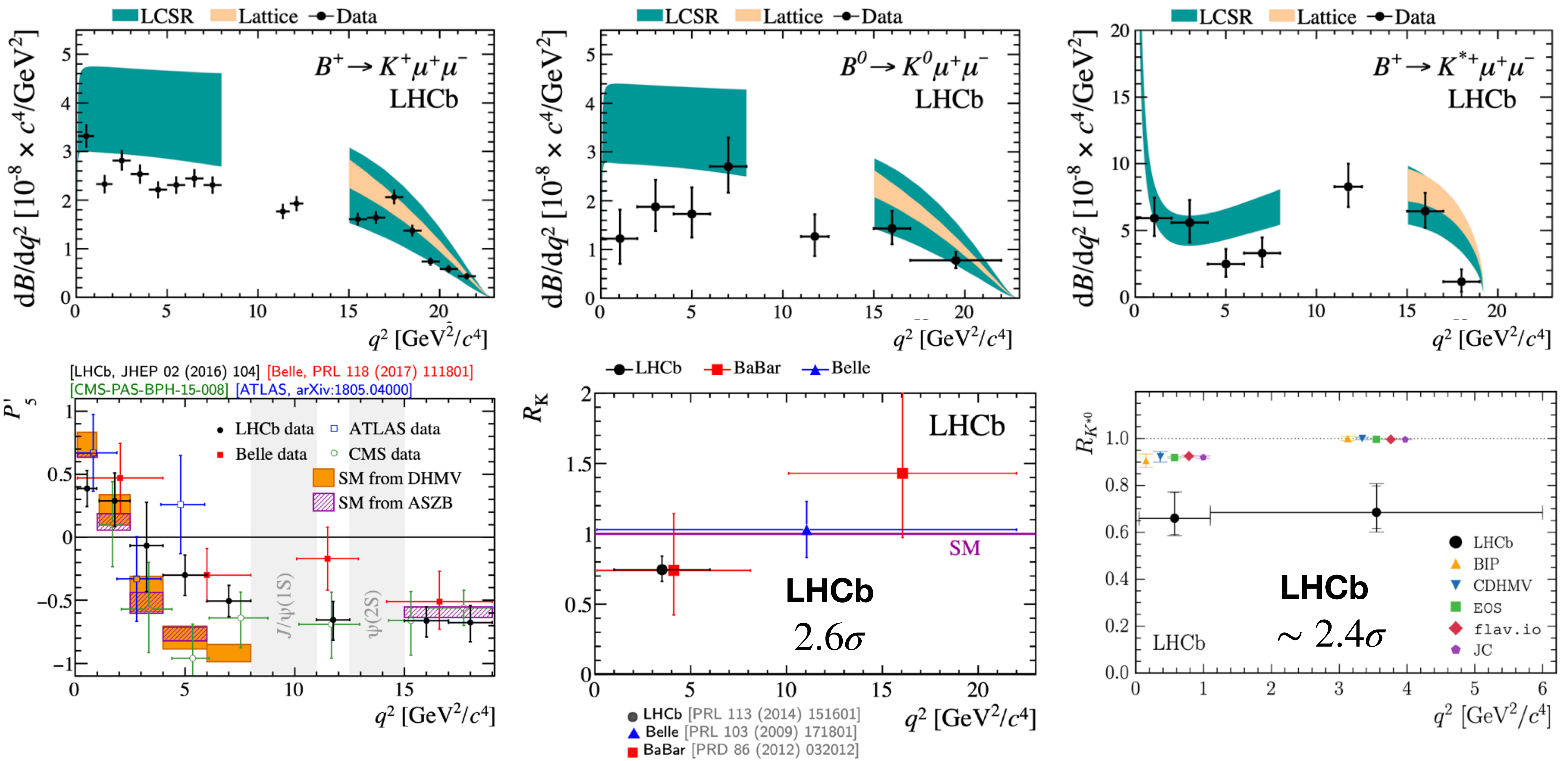


$J^P(H)$	Γ	Form factors
0^-	γ_μ	f_0, f_+
0^-	$\sigma_{\mu\nu}$	f_T
1^-	γ_μ	A_0, A_1, A_2
1^-	$\gamma_\mu\gamma_5$	V
1^-	$\sigma_{\mu\nu}$	T_2, T_3
1^-	$\sigma_{\mu\nu}\gamma_5$	T_1

Parameter	Value	
ρ^2	1.32 ± 0.06	$\xi(q^2) \supset \mathcal{O}(z^4)$
c	1.20 ± 0.12	
d	-0.84 ± 0.17	
$\chi_2(1)$	-0.058 ± 0.020	$\mathcal{O}(1/m_{c,b})$
$\chi_2'(1)$	0.001 ± 0.020	
$\chi_3'(1)$	0.036 ± 0.020	
$\eta(1)$	0.355 ± 0.040	
$\eta'(1)$	-0.03 ± 0.11	
$l_1(1)$	0.14 ± 0.23	$\mathcal{O}(1/m_c^2)$
$l_2(1)$	2.00 ± 0.30	

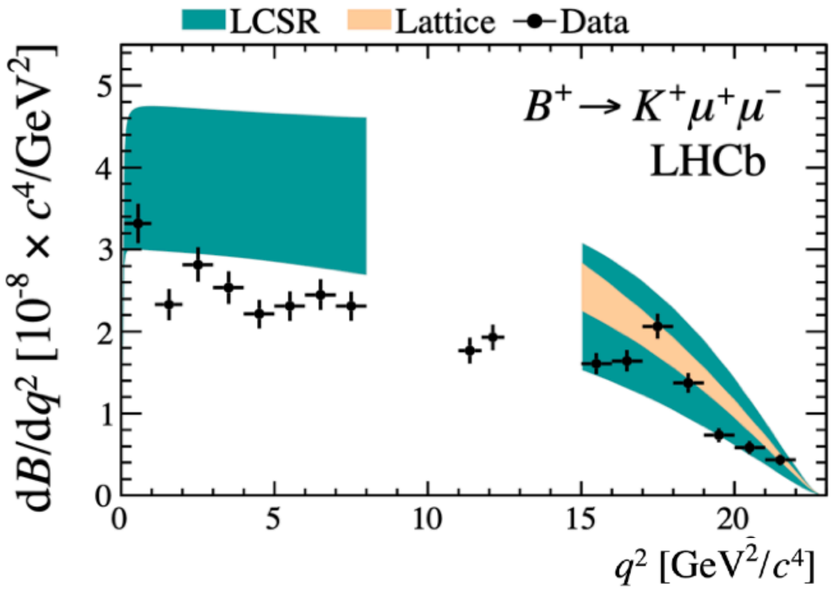
Neutral anomalies

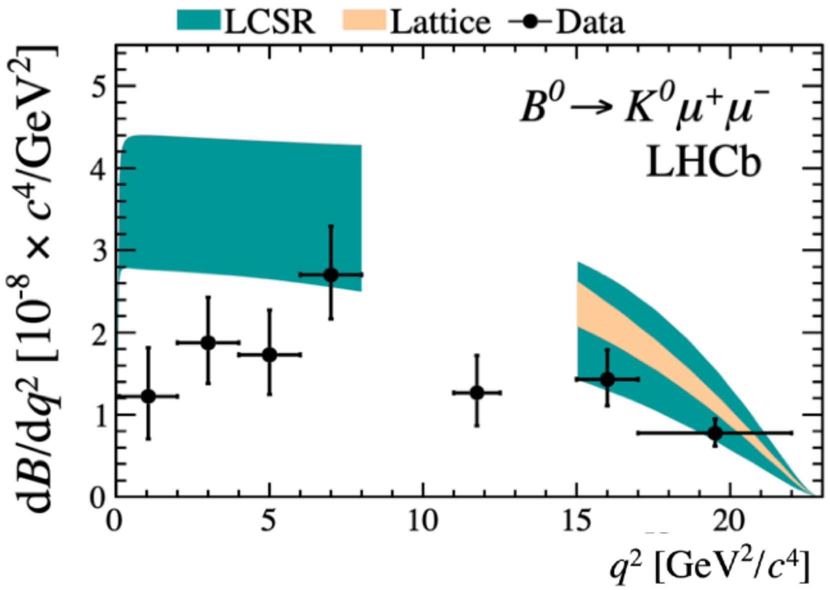
Anomalies in $b \to s$ transitions

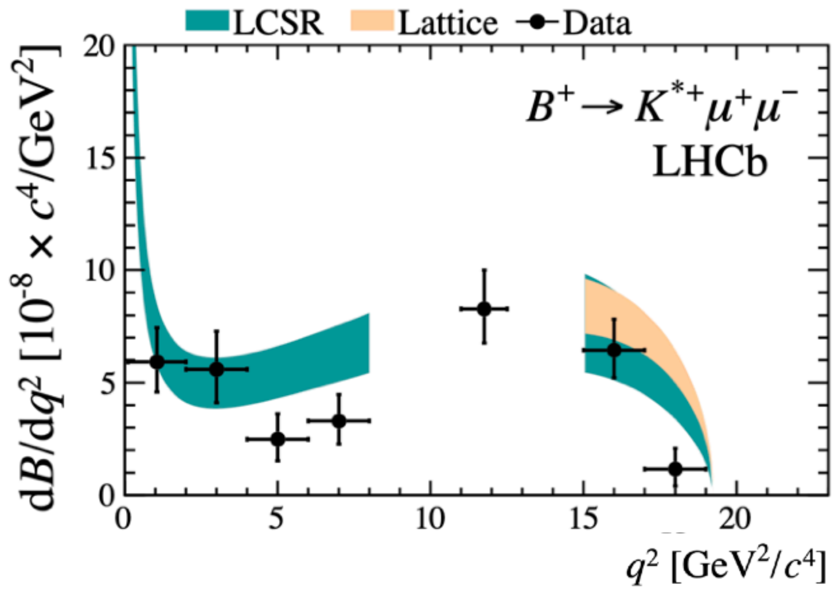


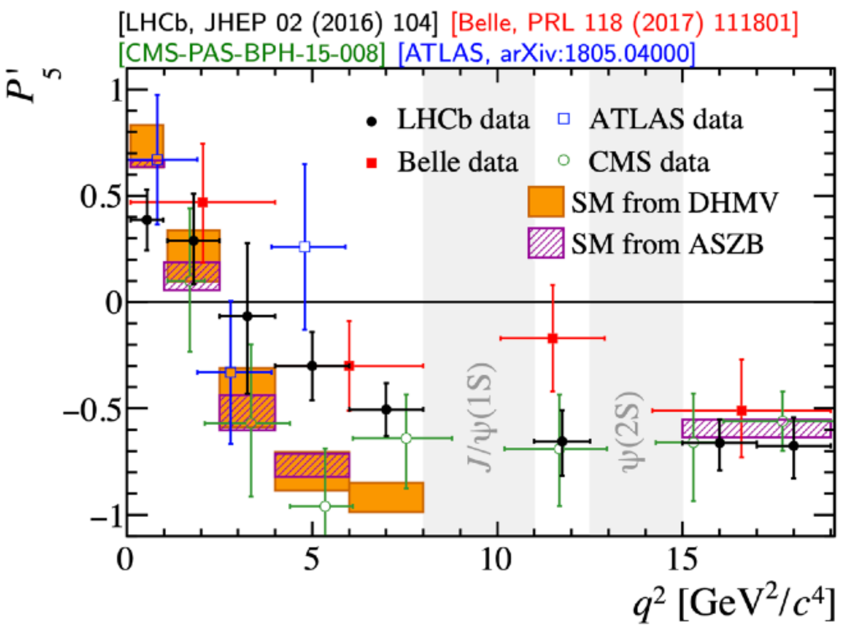
Status 2017

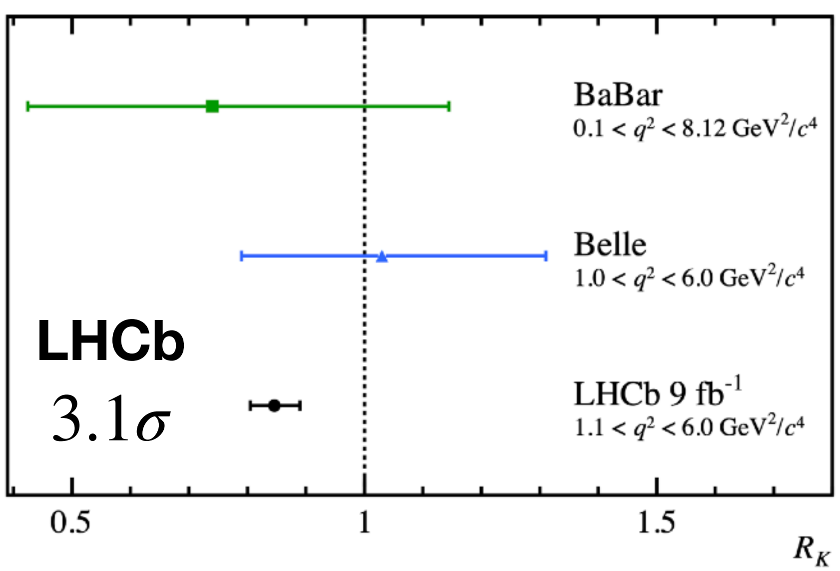
Anomalies in $b \to s$ transitions

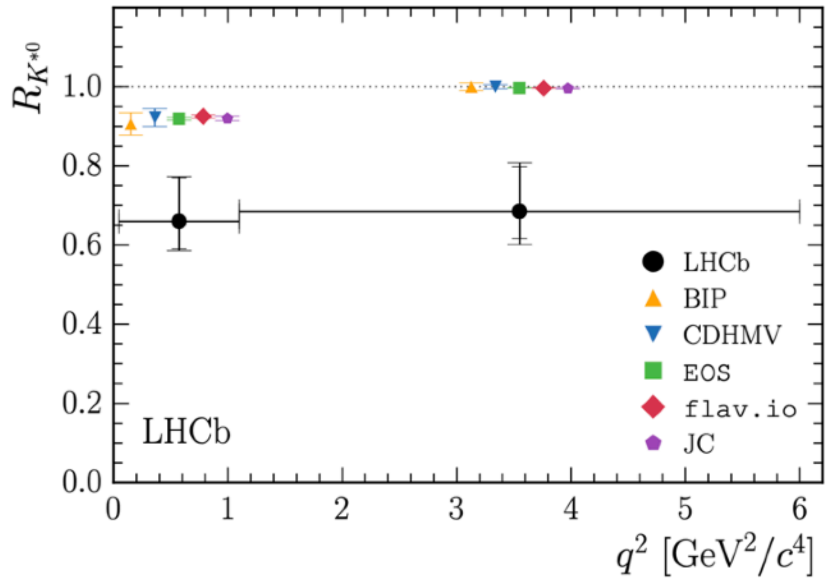






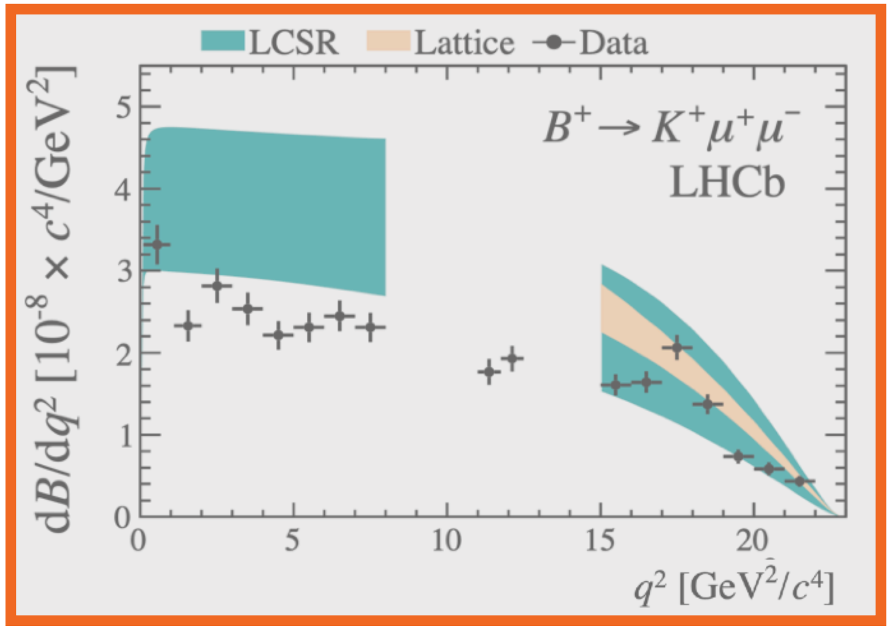


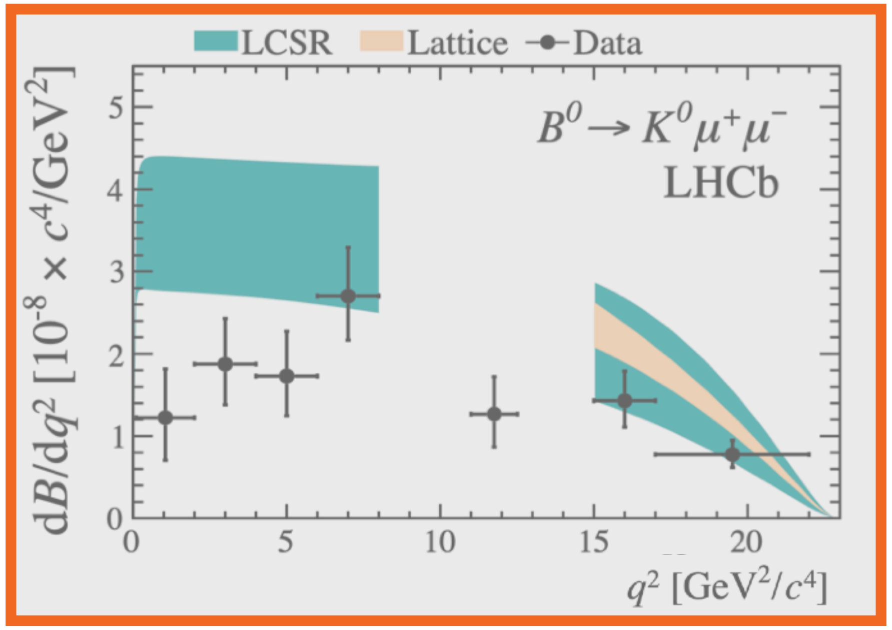


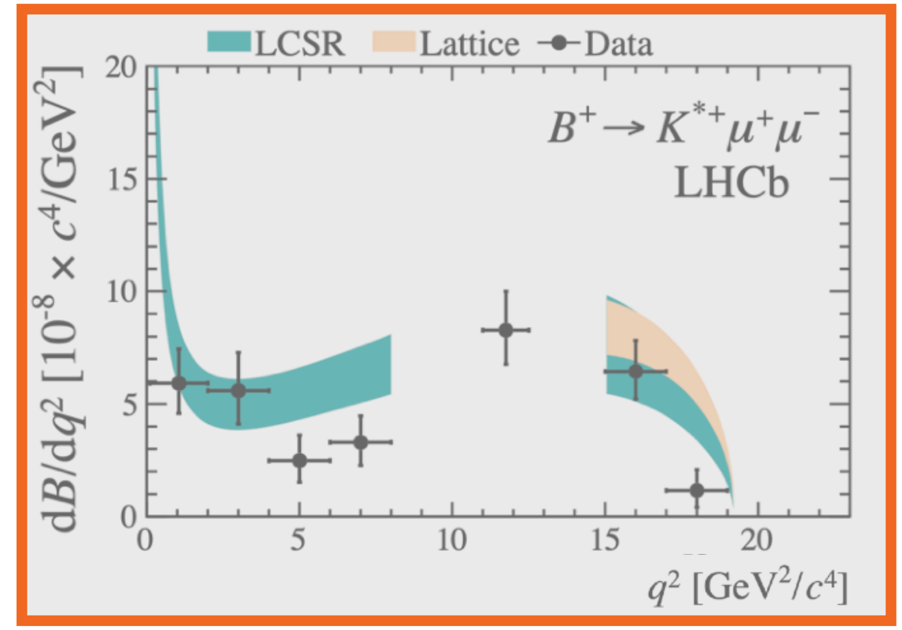


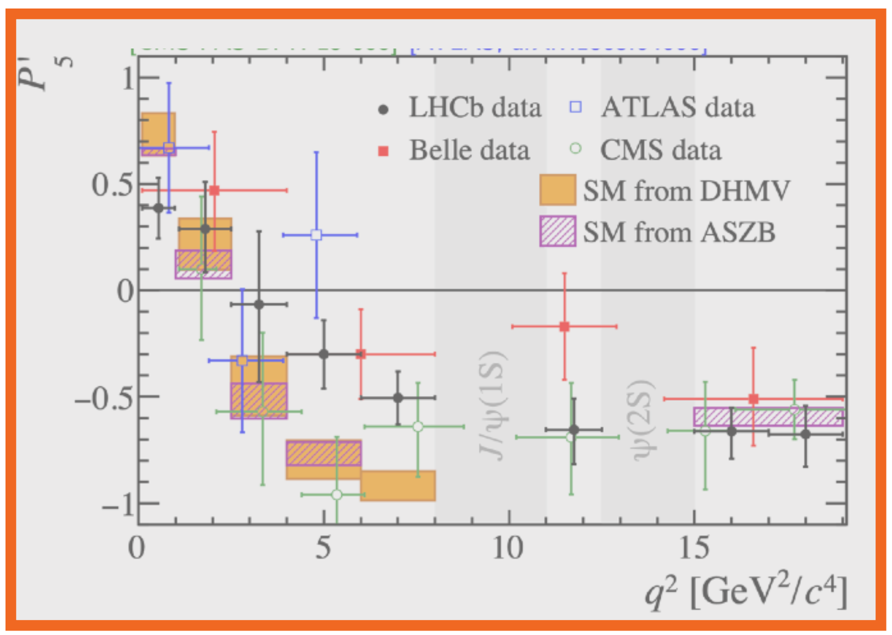
Status NOW

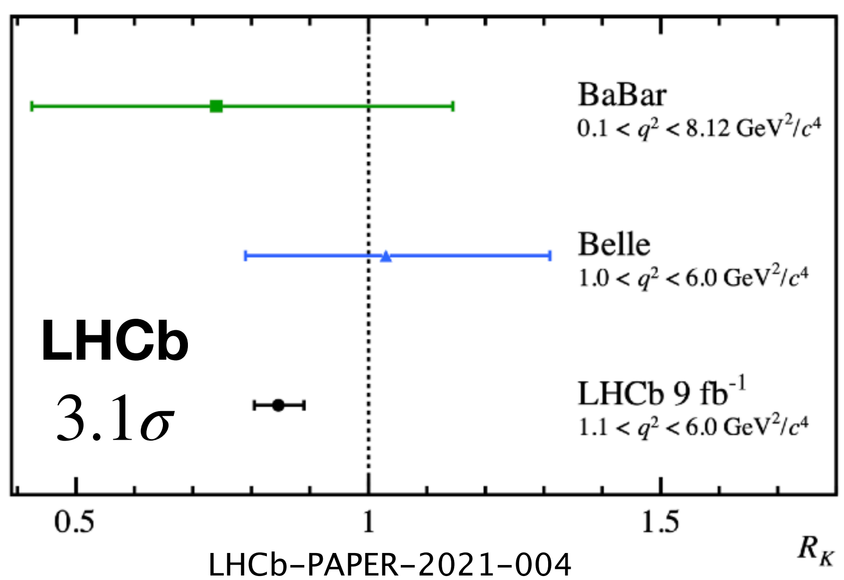
Anomalies in $b \to s$ transitions

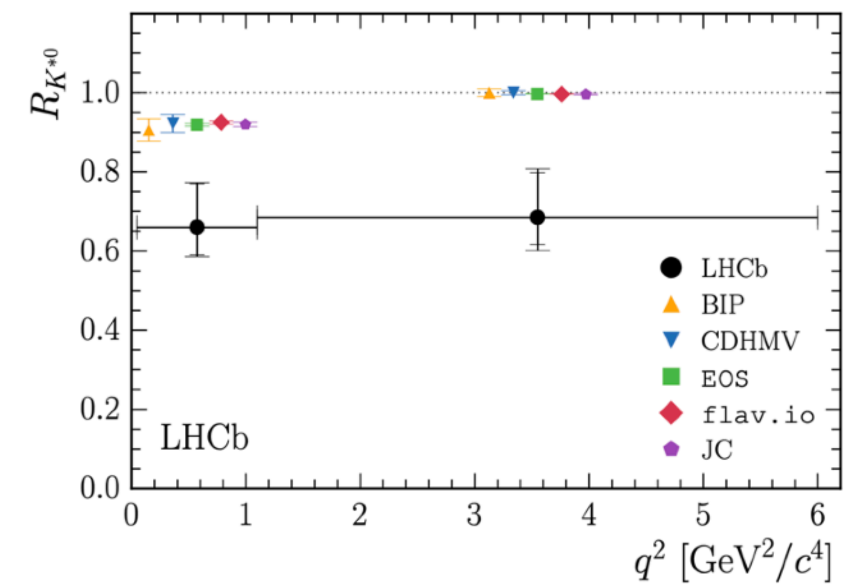


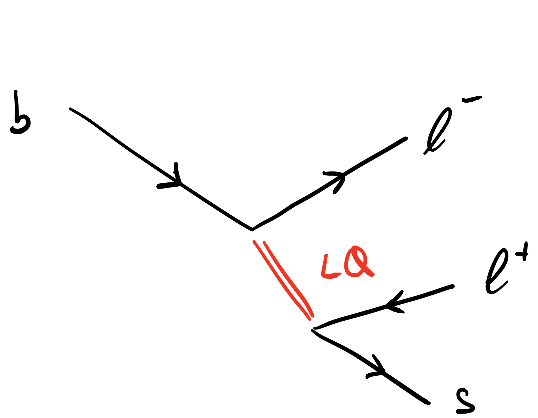


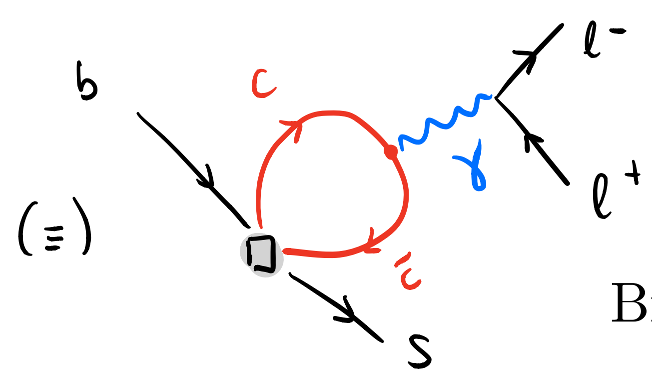












It could mimic NP!!!

$$\mathrm{Br}(B \to K^{(*)}\ell^+\ell^-)^{\mathrm{exp}} = \mathrm{Br}(B \to K^{(*)}\ell^+\ell^-)^{\mathrm{SM}} + \Delta C_9^{\mathrm{univ}}$$