Caltech

Flavourful footprints

towards TeV scale Physics

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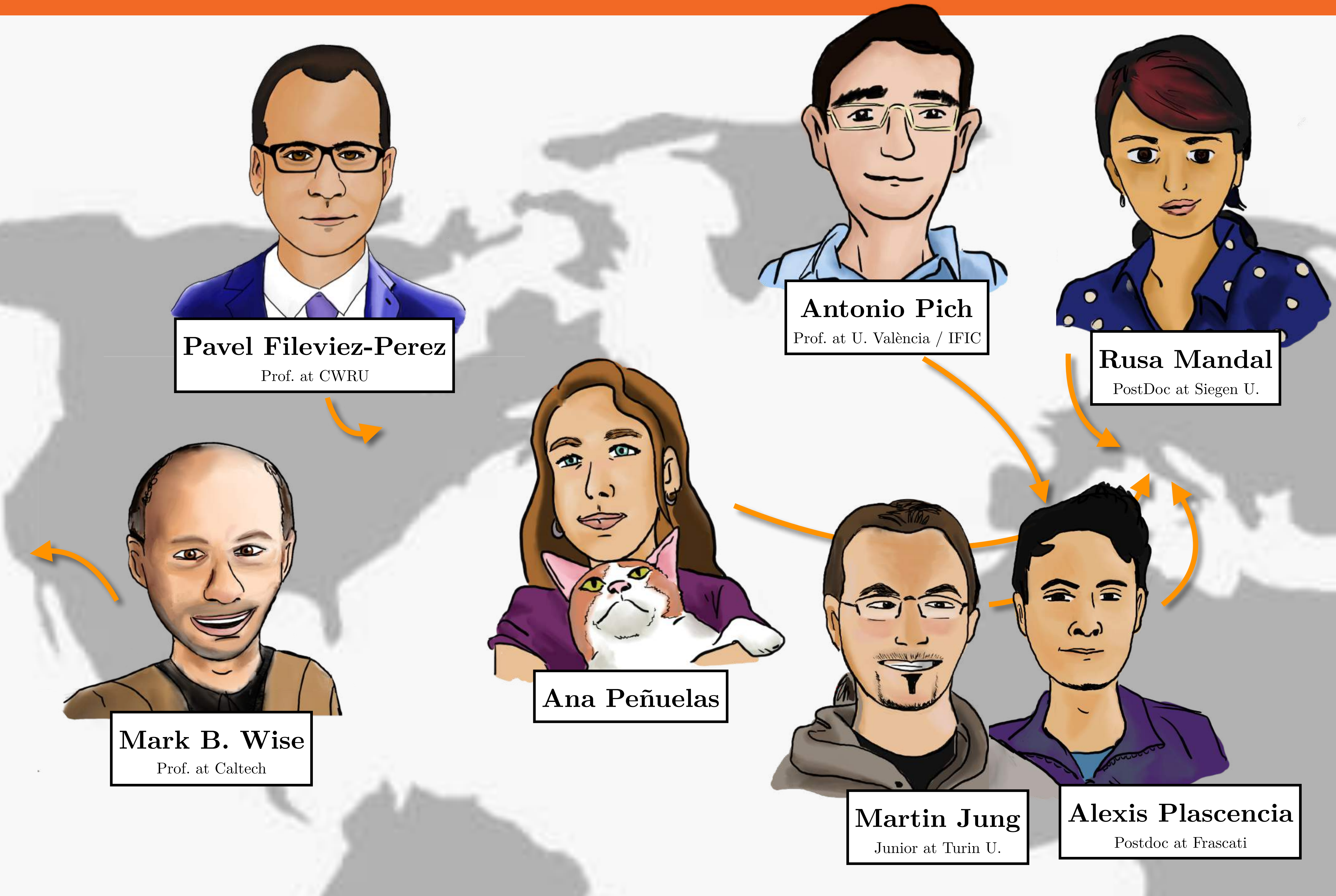
In collaboration with Pavel Fileviez Pérez (CWRU), Alexis Plascencia (Frascati), and Mark B. Wise (Caltech)

May 9th 2022

MPIK Heidelberg

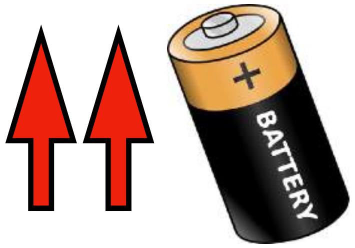
Collaborators



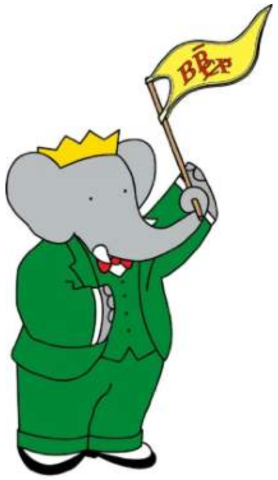
Accessing High Energies

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

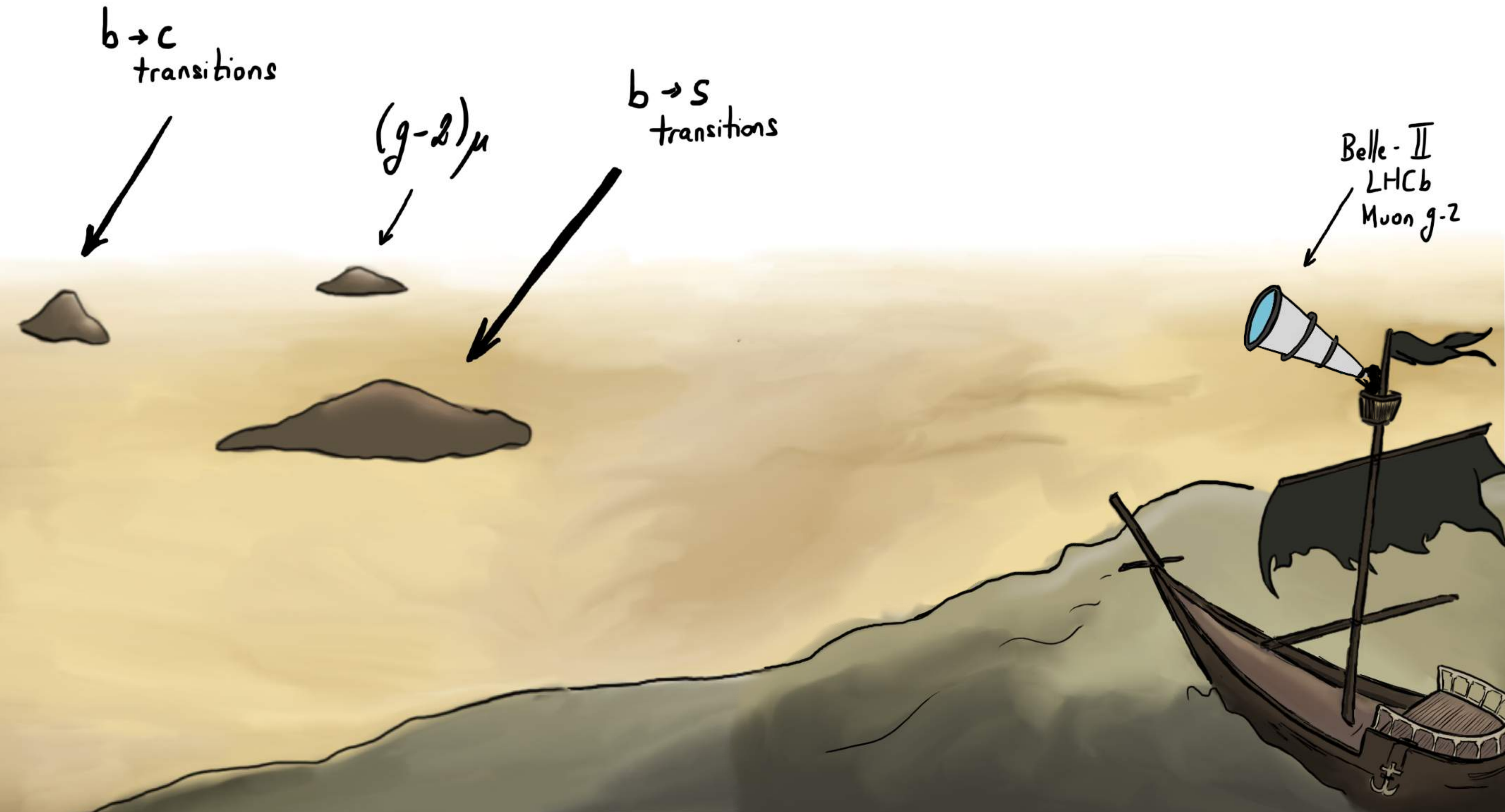
Construction of Super colliders



Precision Physics

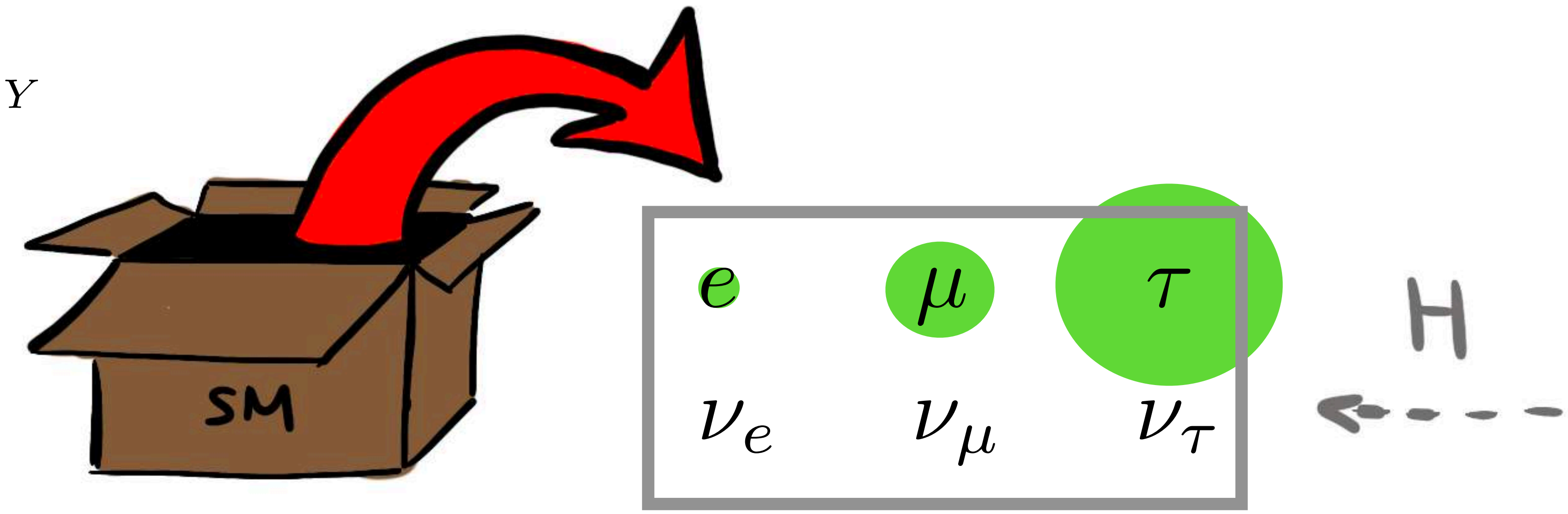


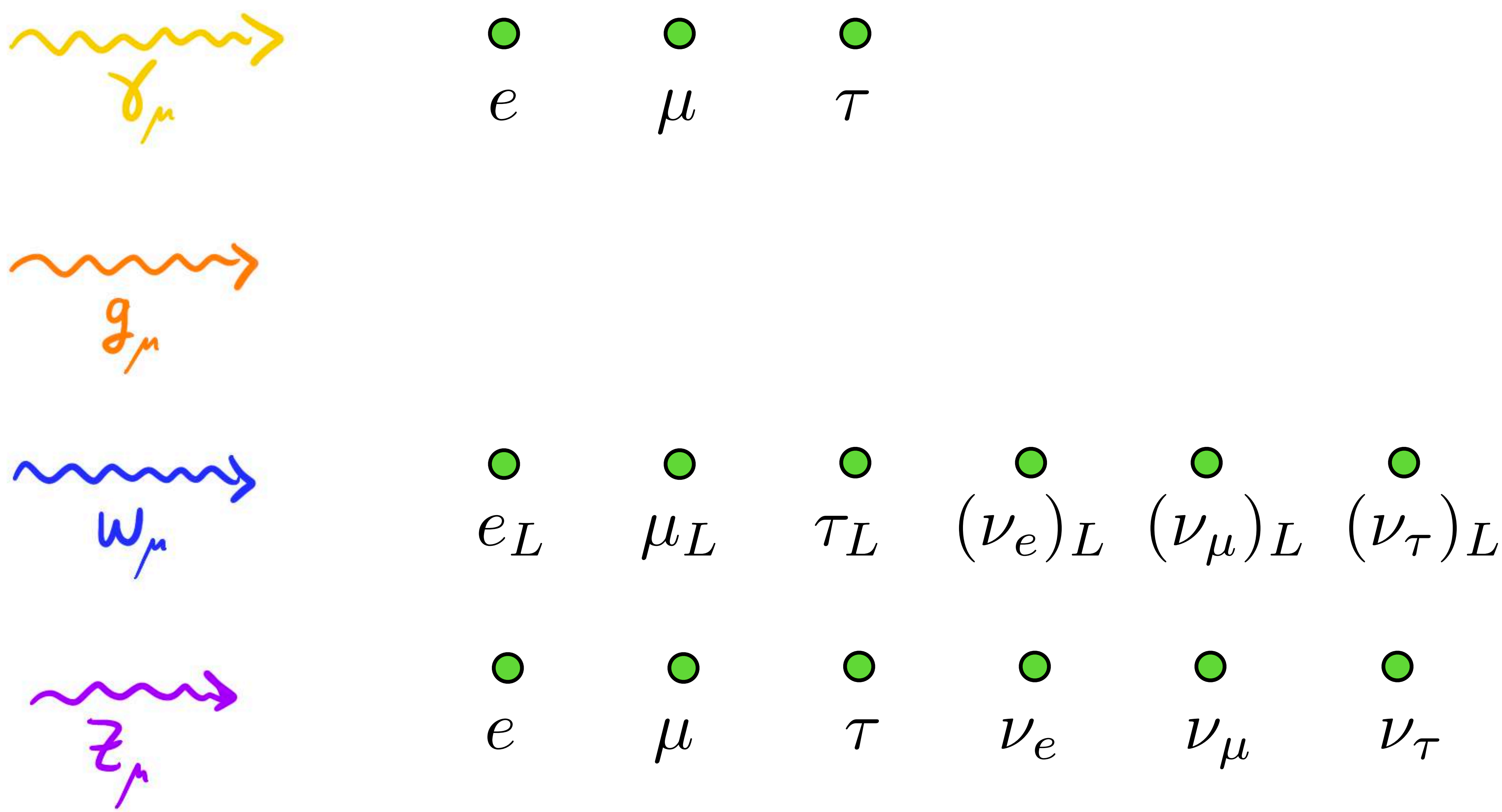
Lepton Flavor Universality Violation



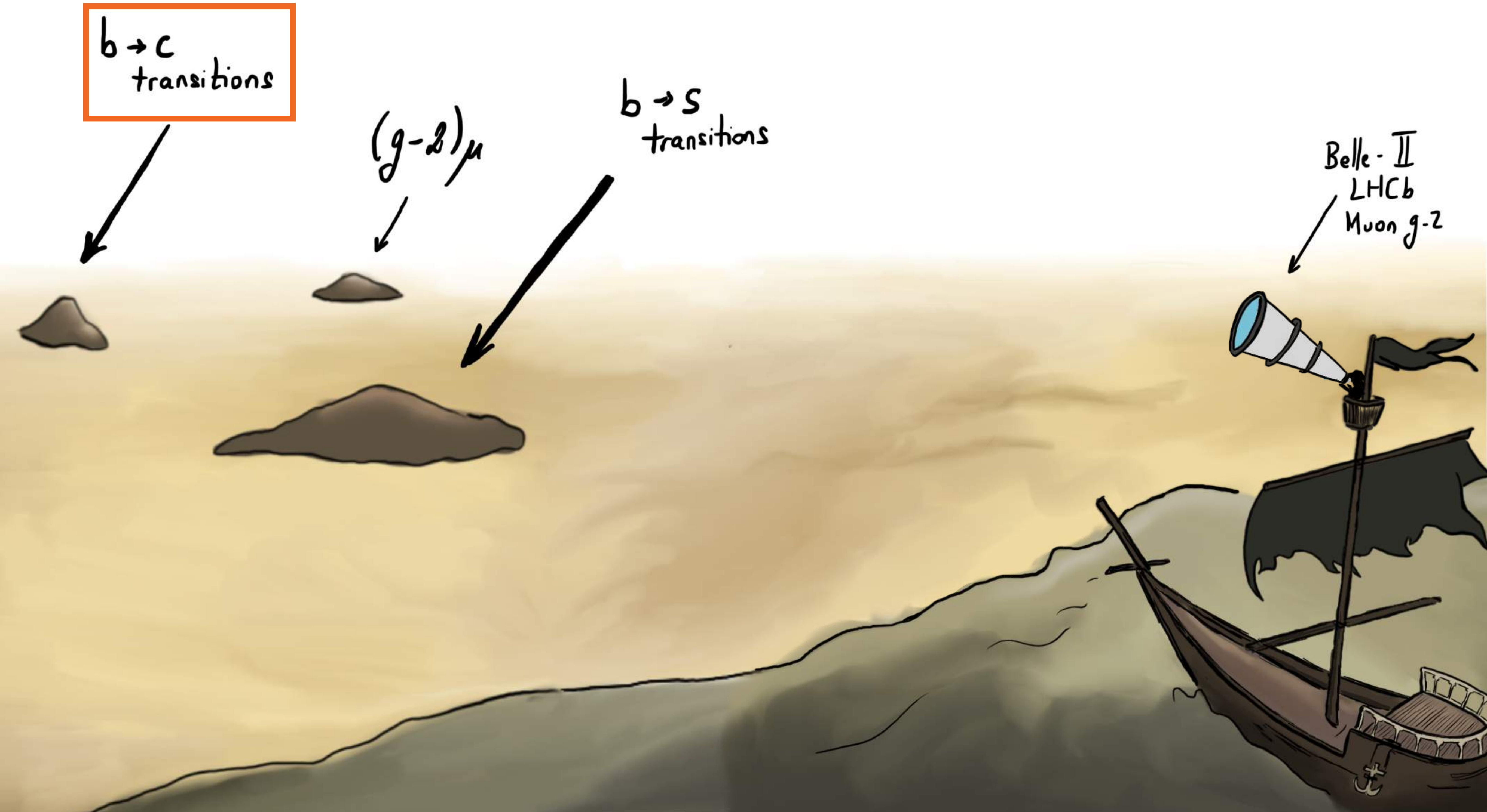
Lepton Flavour Universality (Violation)

$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$





Anomalies in $b \to c$ transitions



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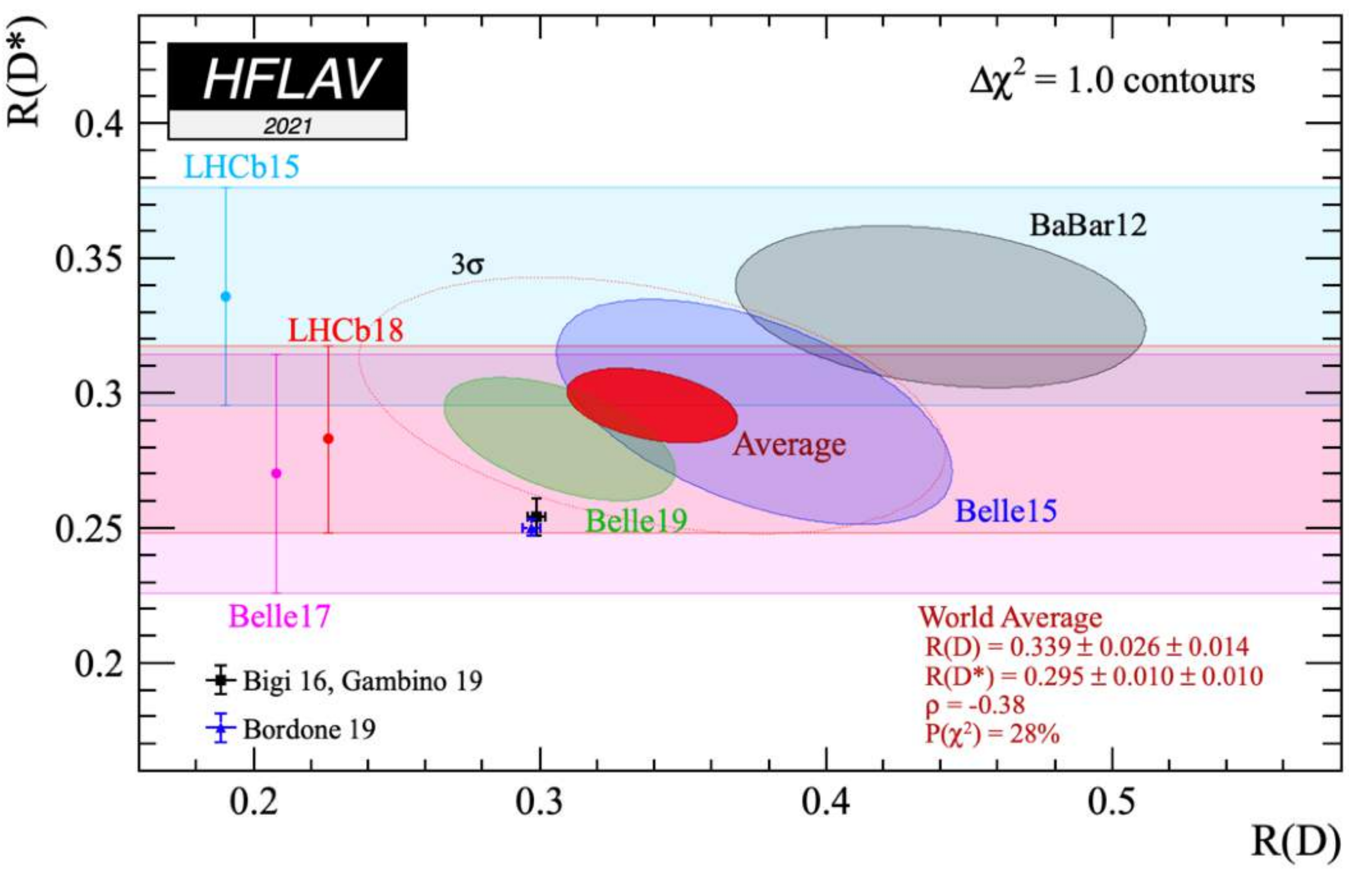
Status

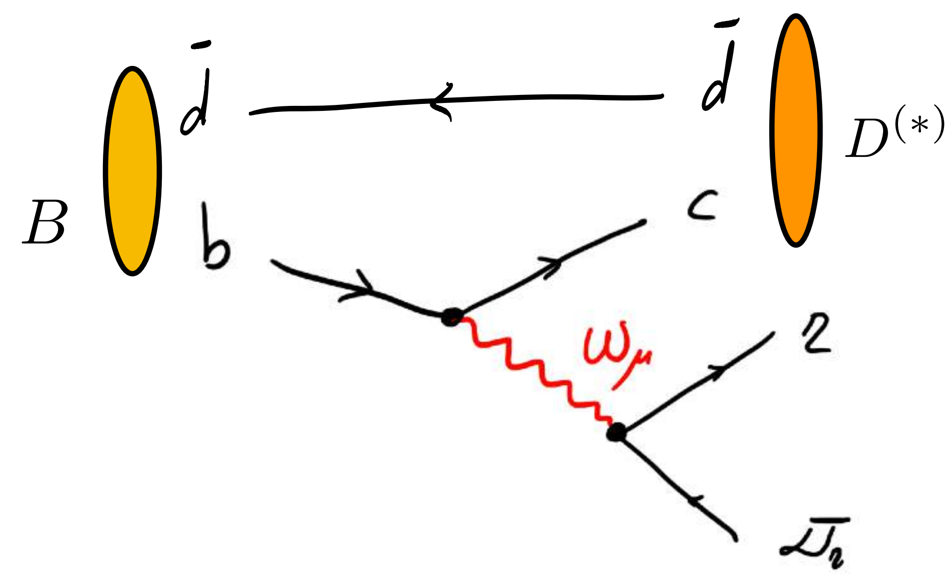


[LHCb, 1506.08614, 1708.08856, 1711.02505]
[Belle, 1507.03233, 1607.07923, 1612.00529, 1709.00129, 1904.02440]
[BaBar, 1205.5442, 1303.0571]

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

3.4 σ

HFLAV, up to date



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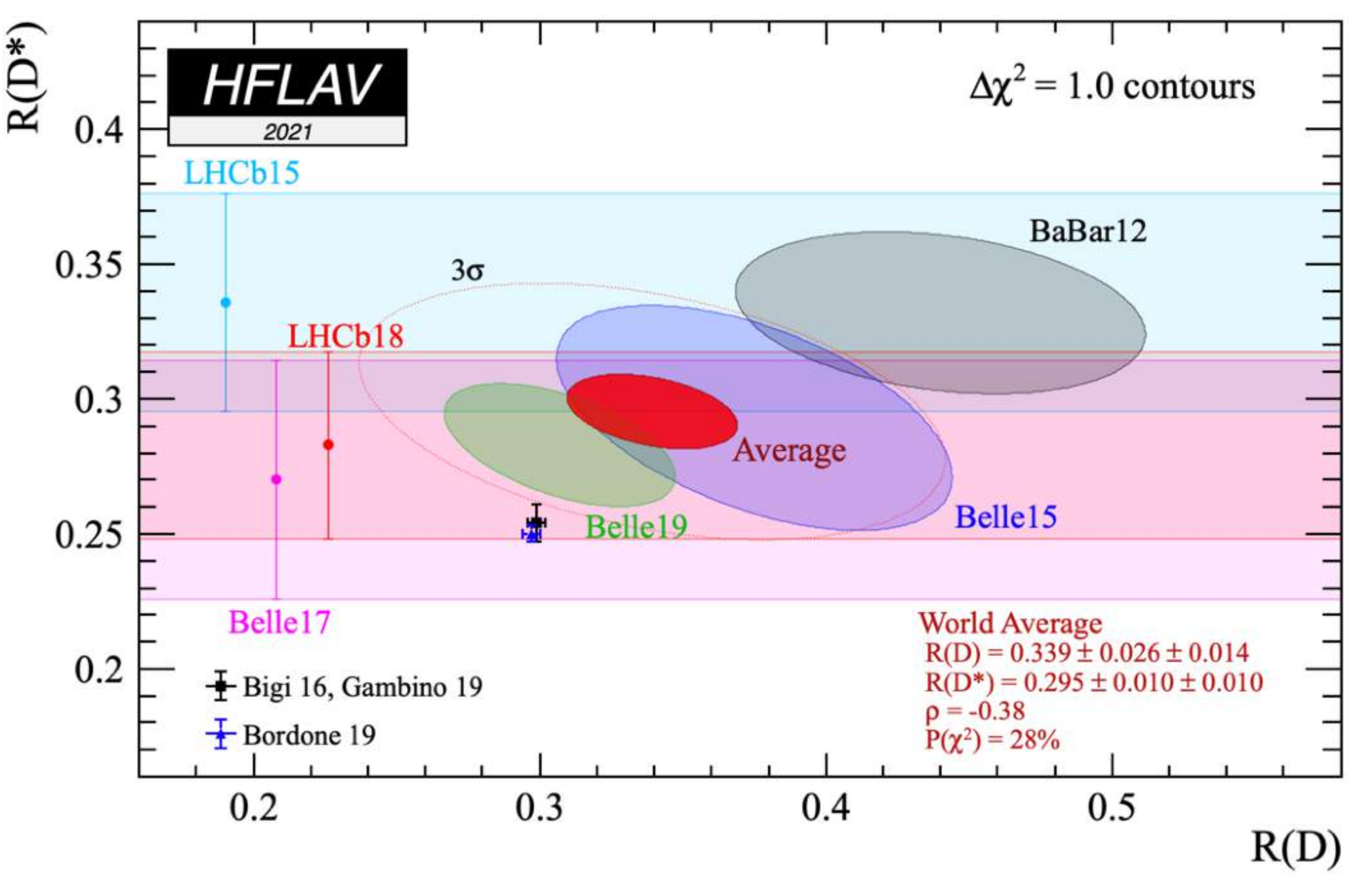

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$$\mathcal{R}_{J/\Psi} \equiv \frac{\mathcal{B}(B_c \to J/\Psi\tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\Psi\mu\bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18$$

LHCb, 2017 **1.7 σ**

$R_{J/\Psi\,SM} \sim 0.25 - 0.28$

$$\bar{\mathcal{P}}_\tau^{D^*} = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

Belle, 2016

$\mathcal{P}_\tau(D^*)_{SM} = -0.499 \pm 0.003$

$$\bar{F}_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$$ **1.6 σ**

Belle, 2019

$$\mathcal{R}_{\Lambda_c} = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

LHCb, 2022 **1 σ**

Anomalies in $b \to c$ transitions

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

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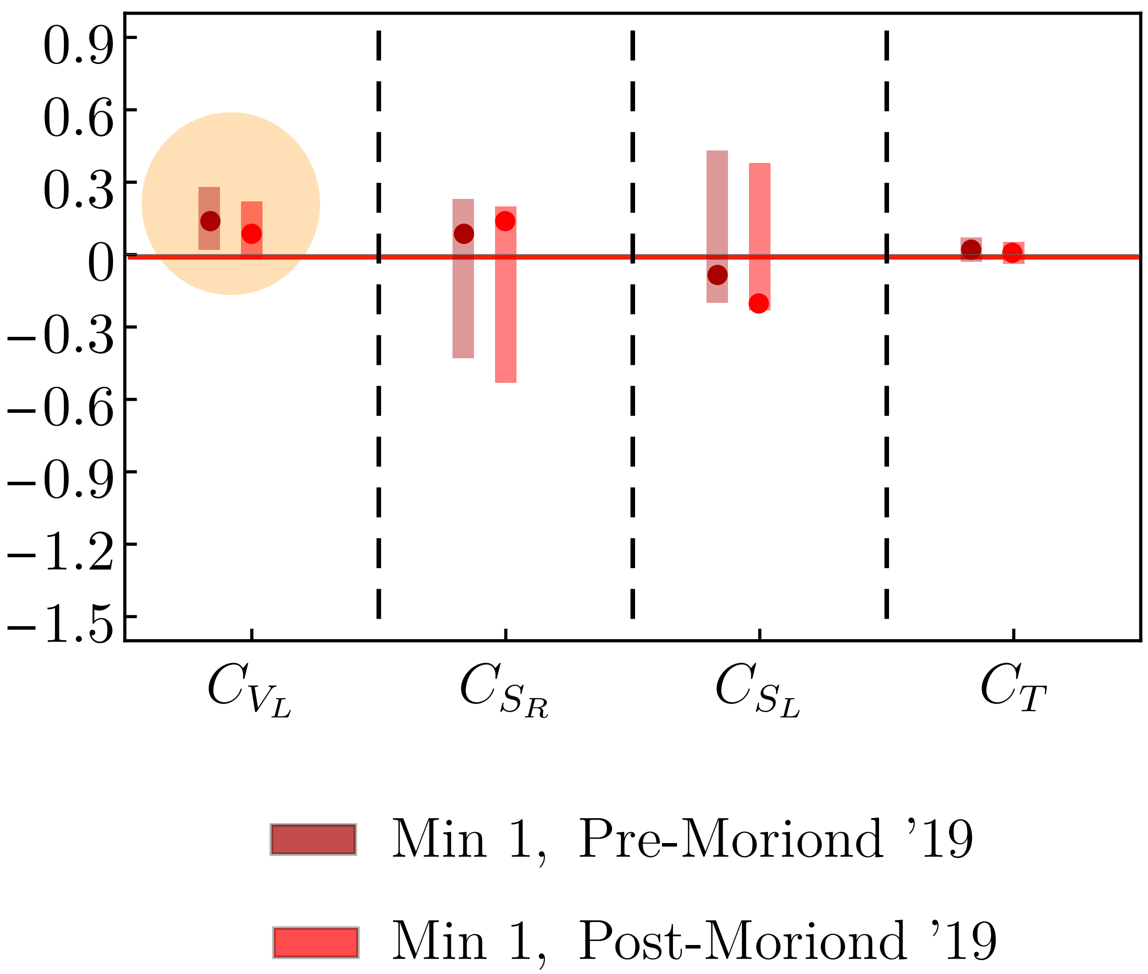

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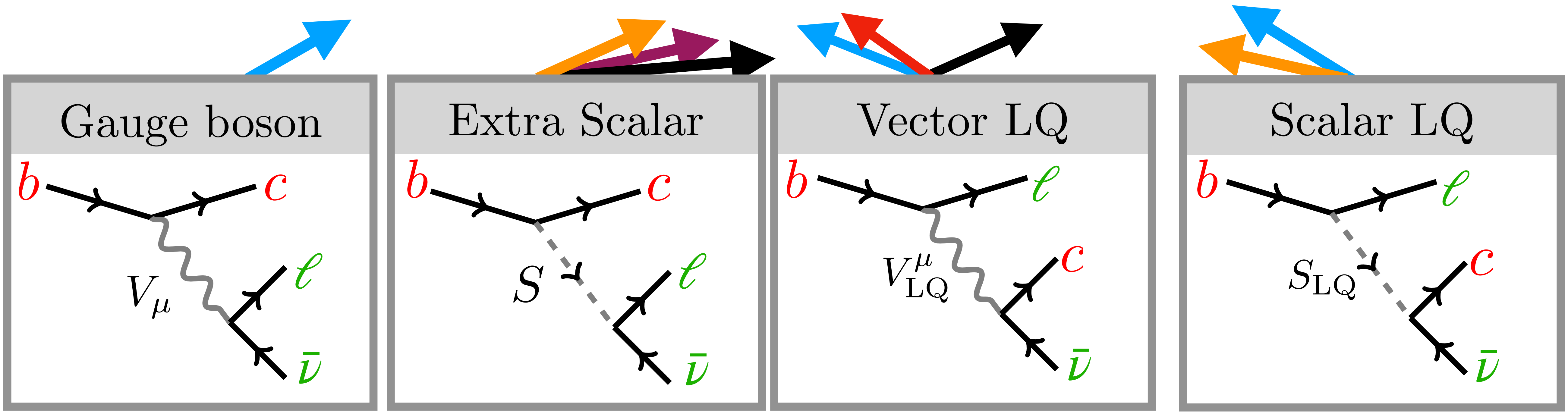
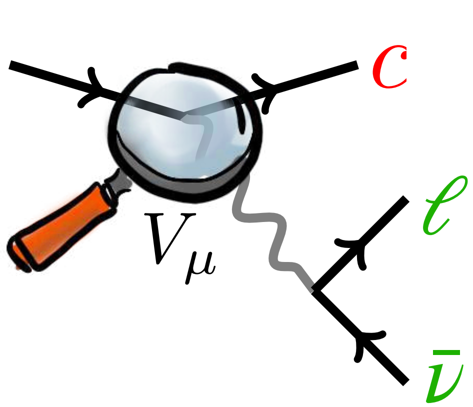
Wilson coefficients

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





$$\frac{-g_{\mu\nu} + \frac{q_\mu q_\nu}{M_V^2}}{q^2 - M_V^2} \xrightarrow{q^2 \ll M_V^2}$$

Taylor exp. $\dfrac{1}{1-x} = 1 - x + x^2 - x^3 + \cdots$

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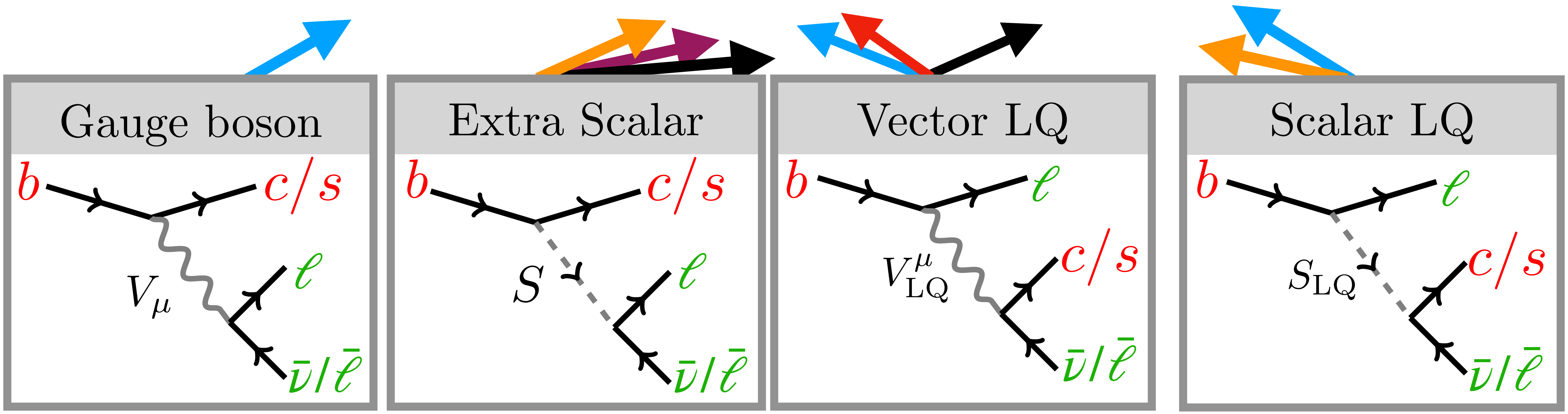

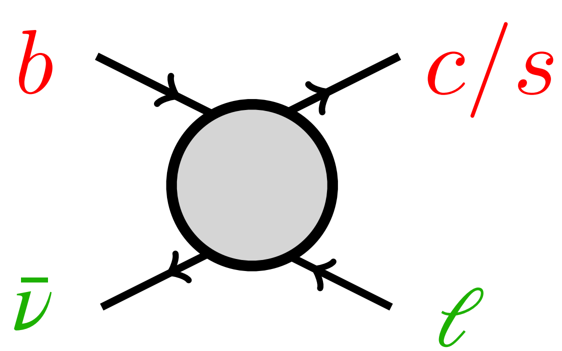

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$$\mathcal{O}_{V_L} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell),$$

Taylor exp. $\dfrac{1}{1-x} = 1 - x + x^2 - x^3 + \cdots$

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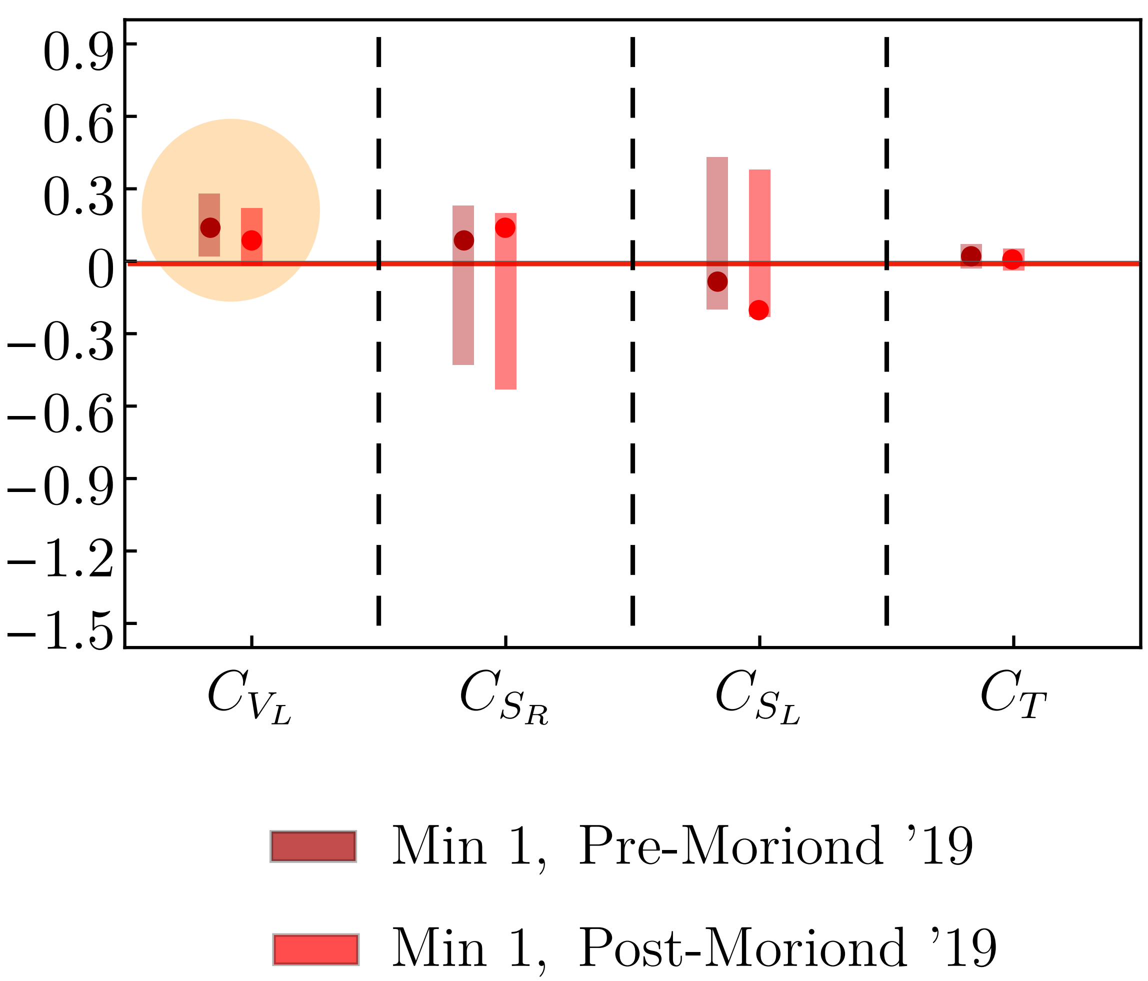

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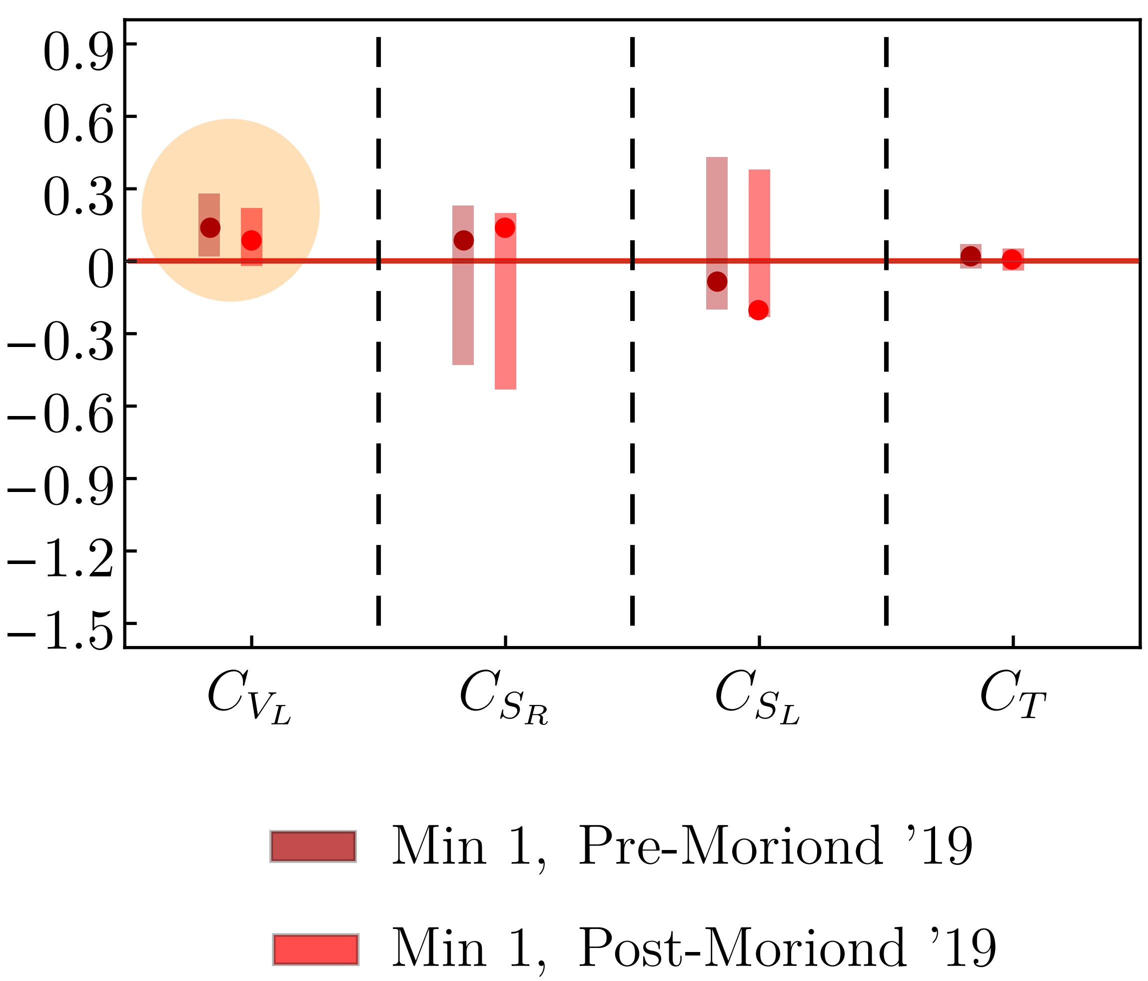

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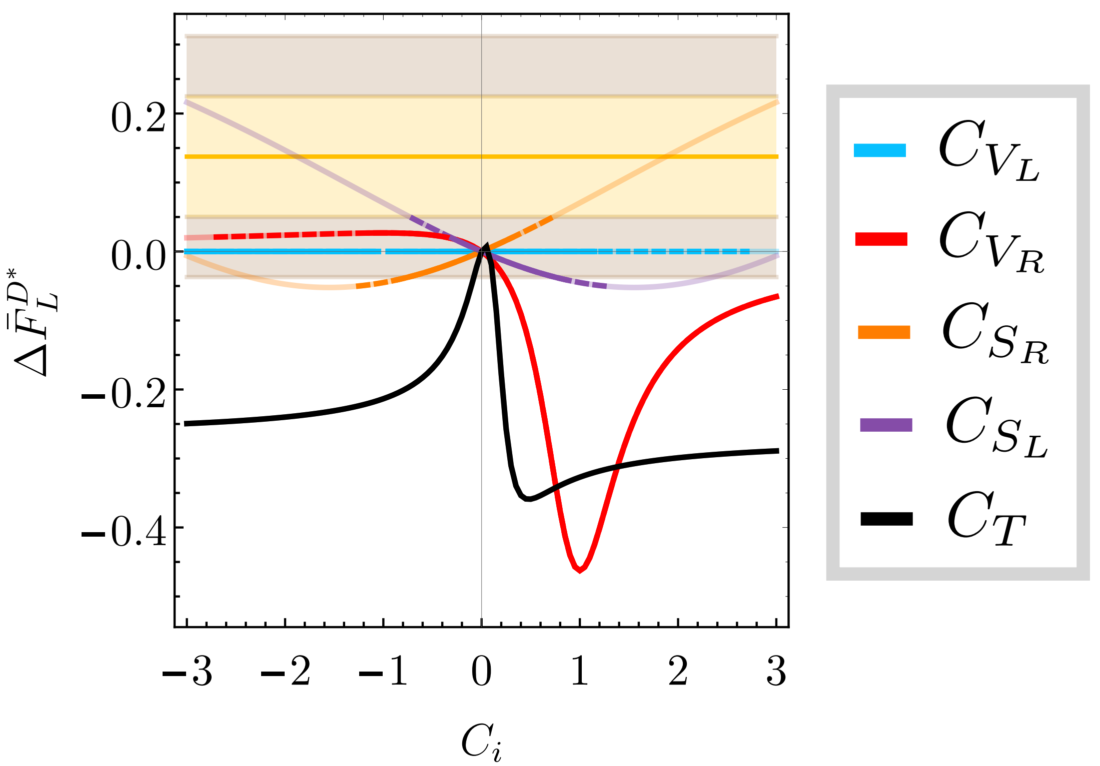

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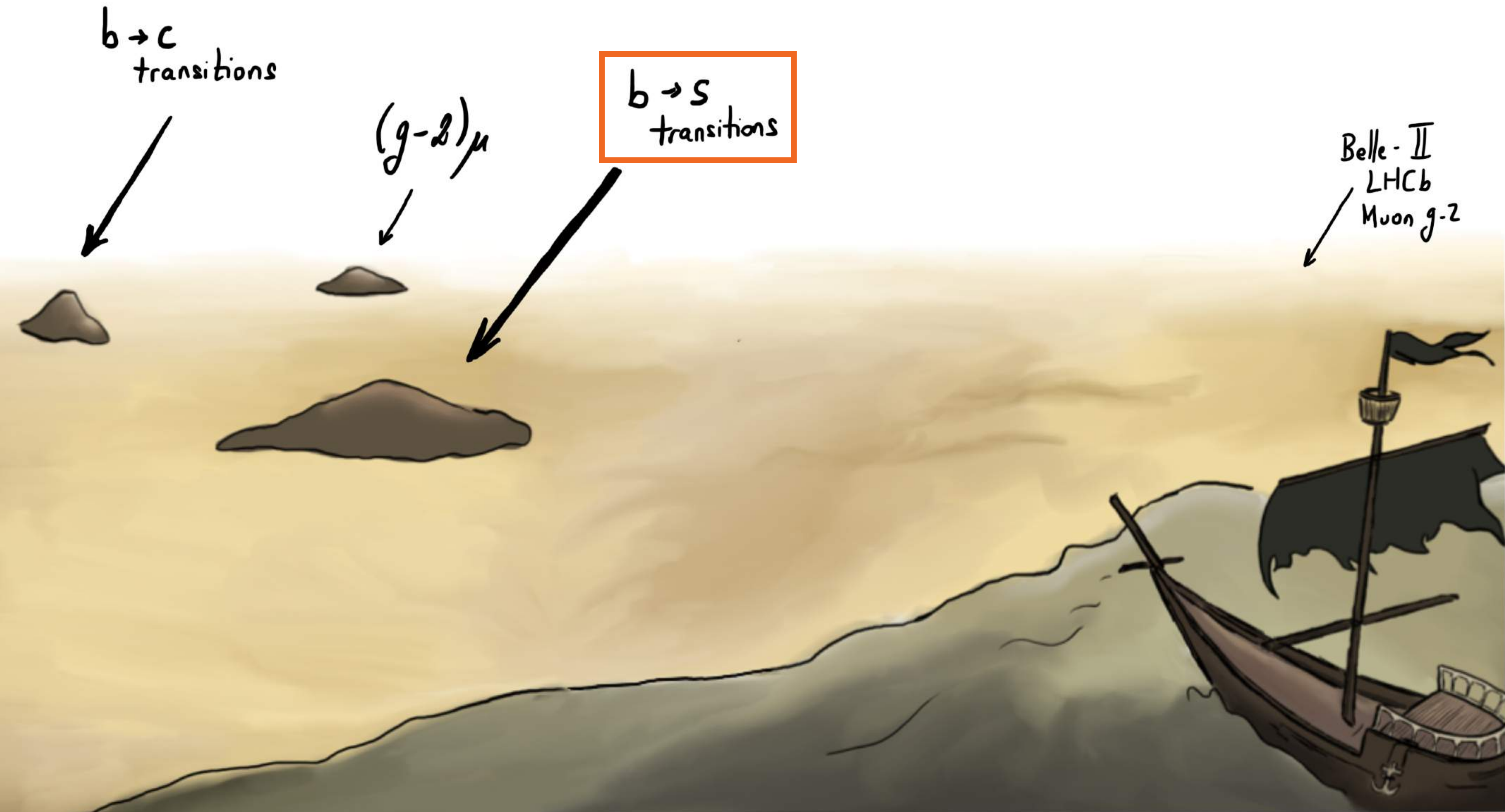
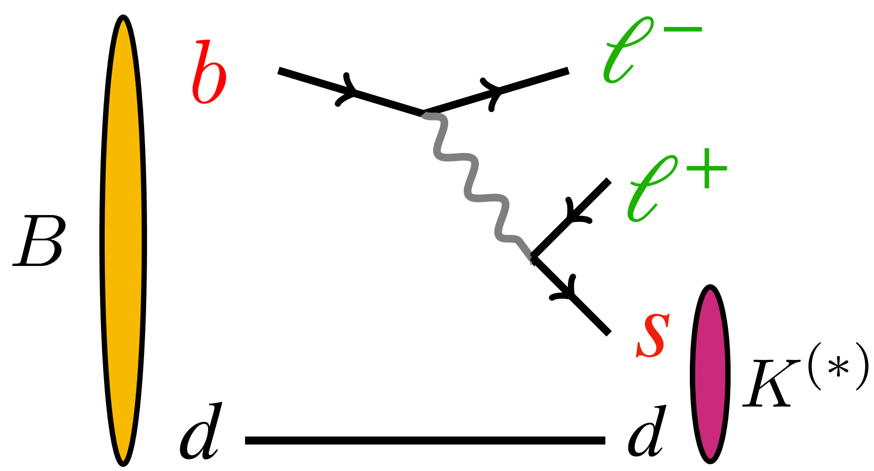
Anomalies in $b \to s$ transitions

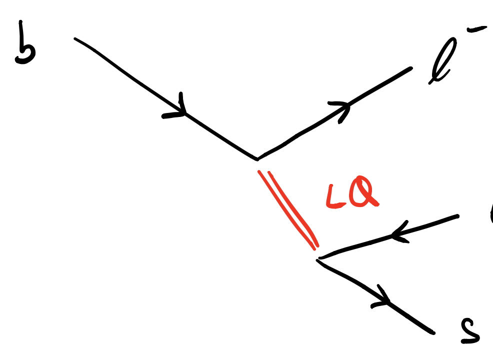


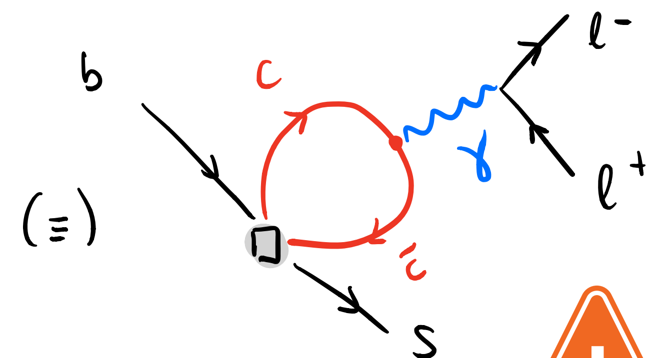
Anomalies in $b \to s$ transitions

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

Clean Observables!







Can mimik NP!

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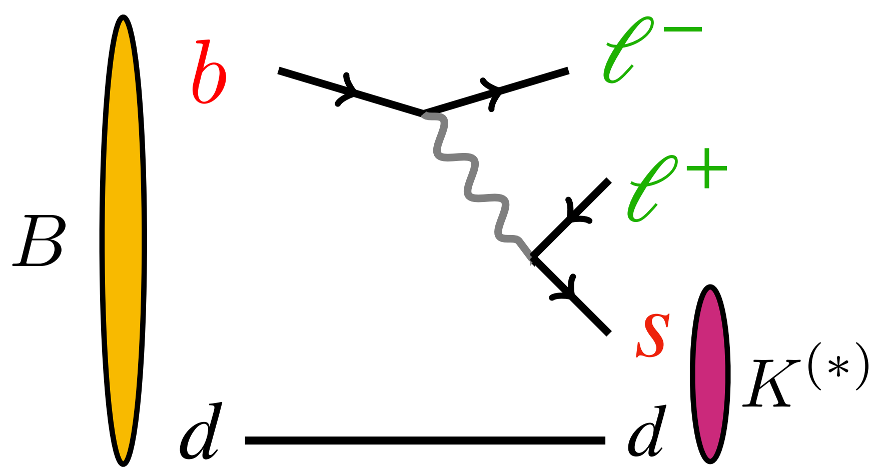

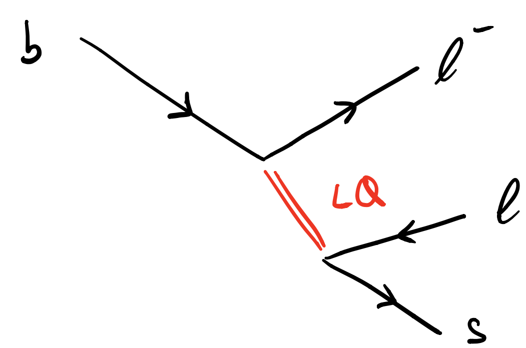

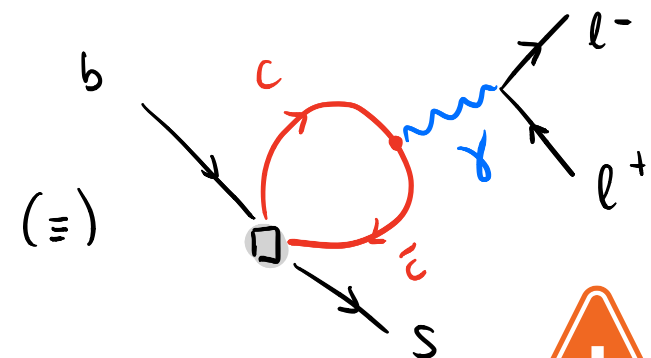

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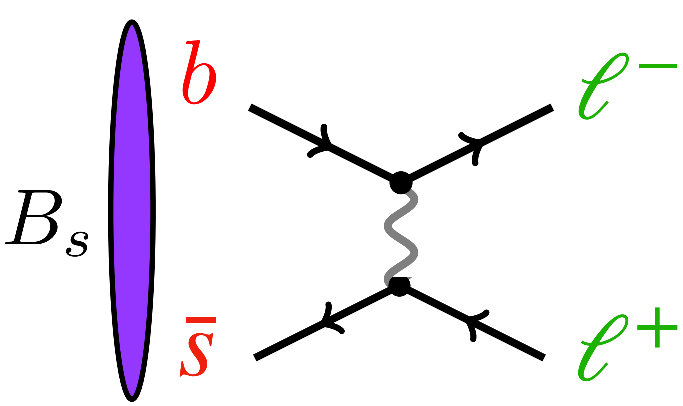
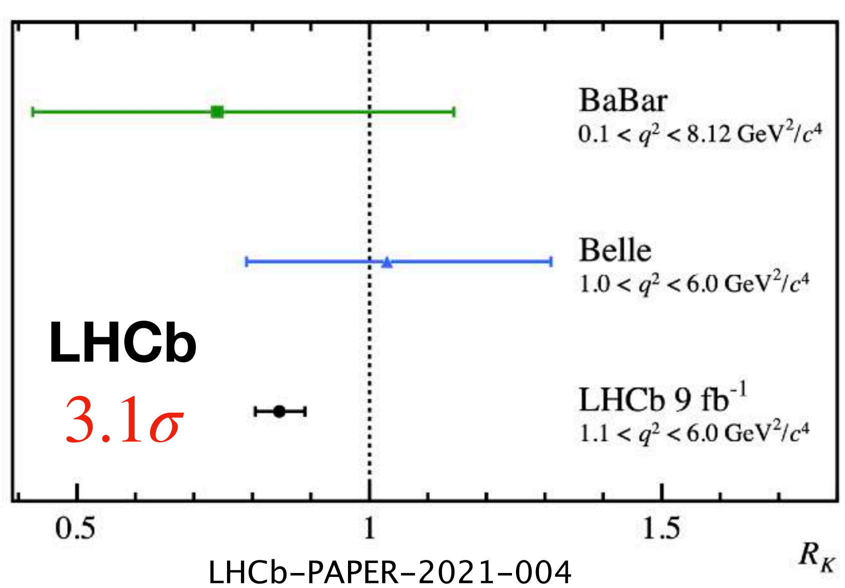
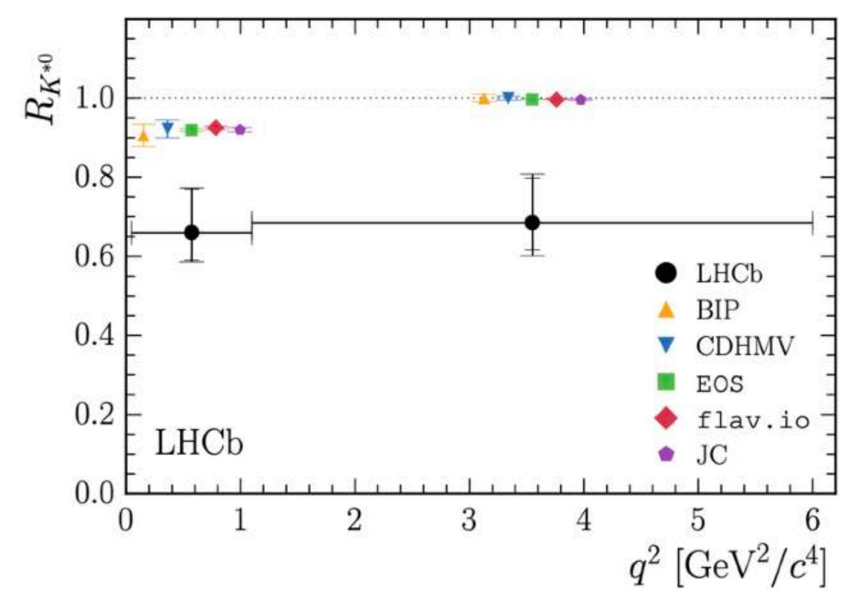
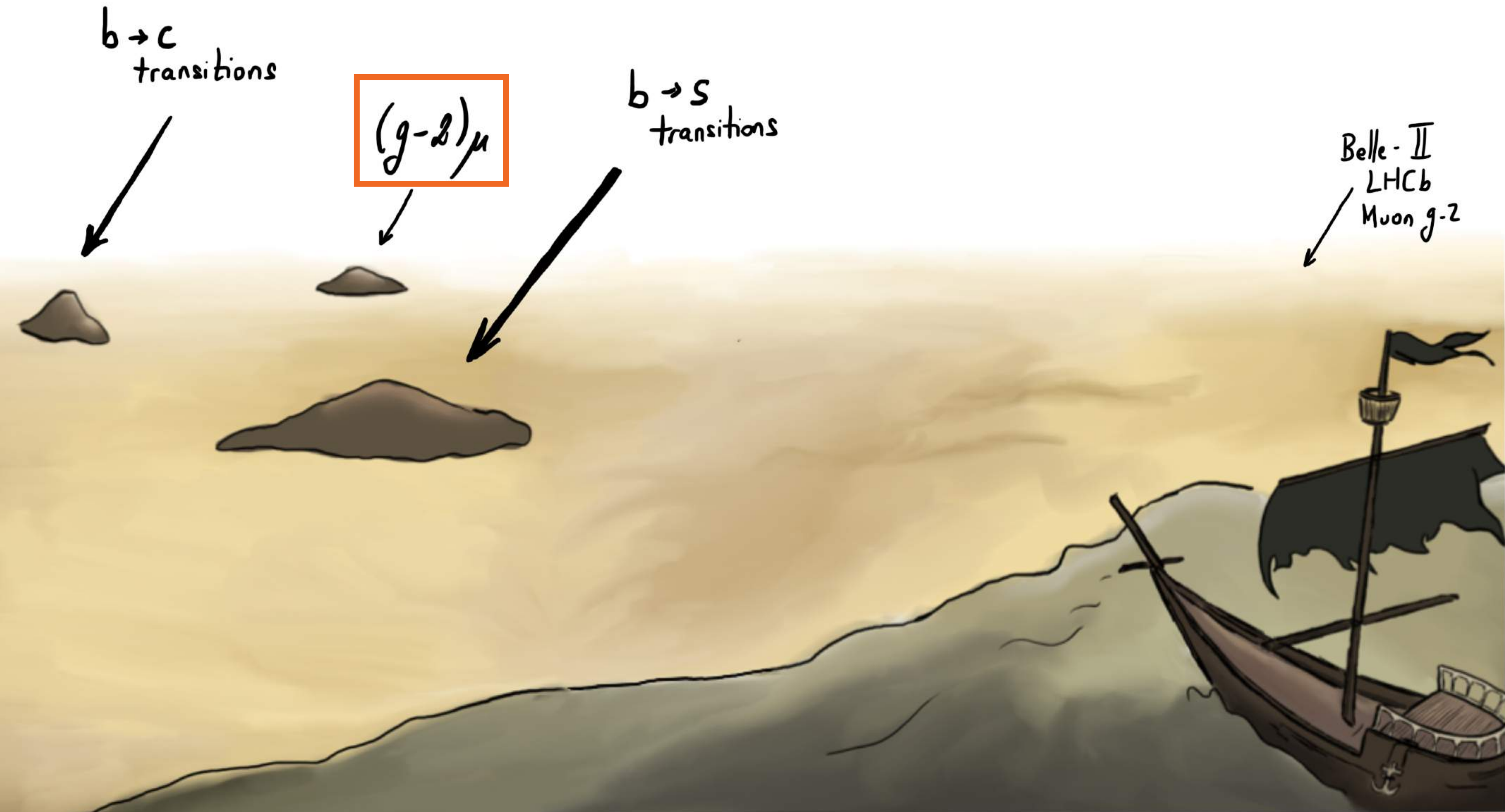






Muon (g-2)



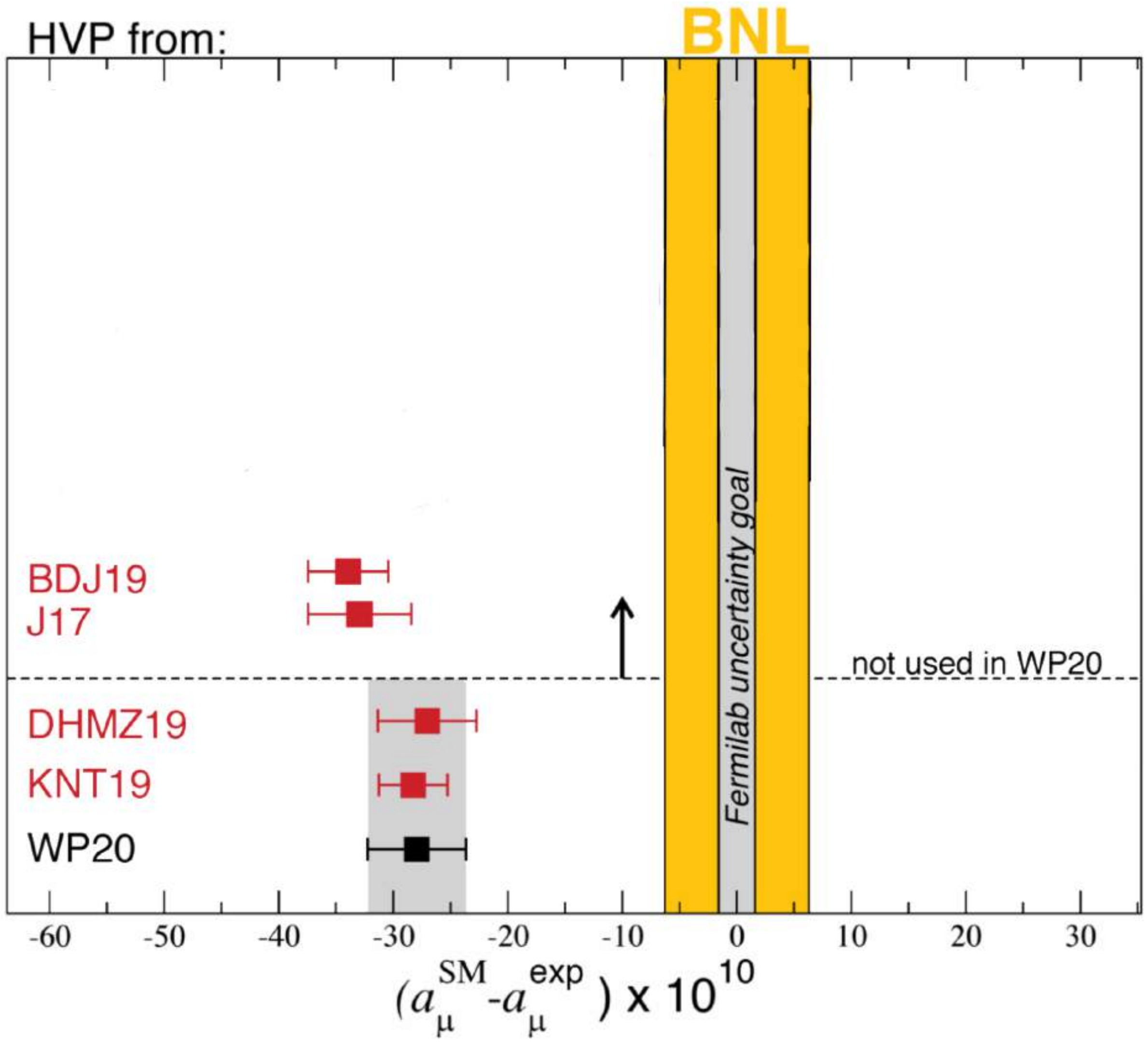
Muon (g-2)

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

($4.2\,\sigma$)

Fermilab Muon g-2, 2021

E821 experiment, BNL, 2006



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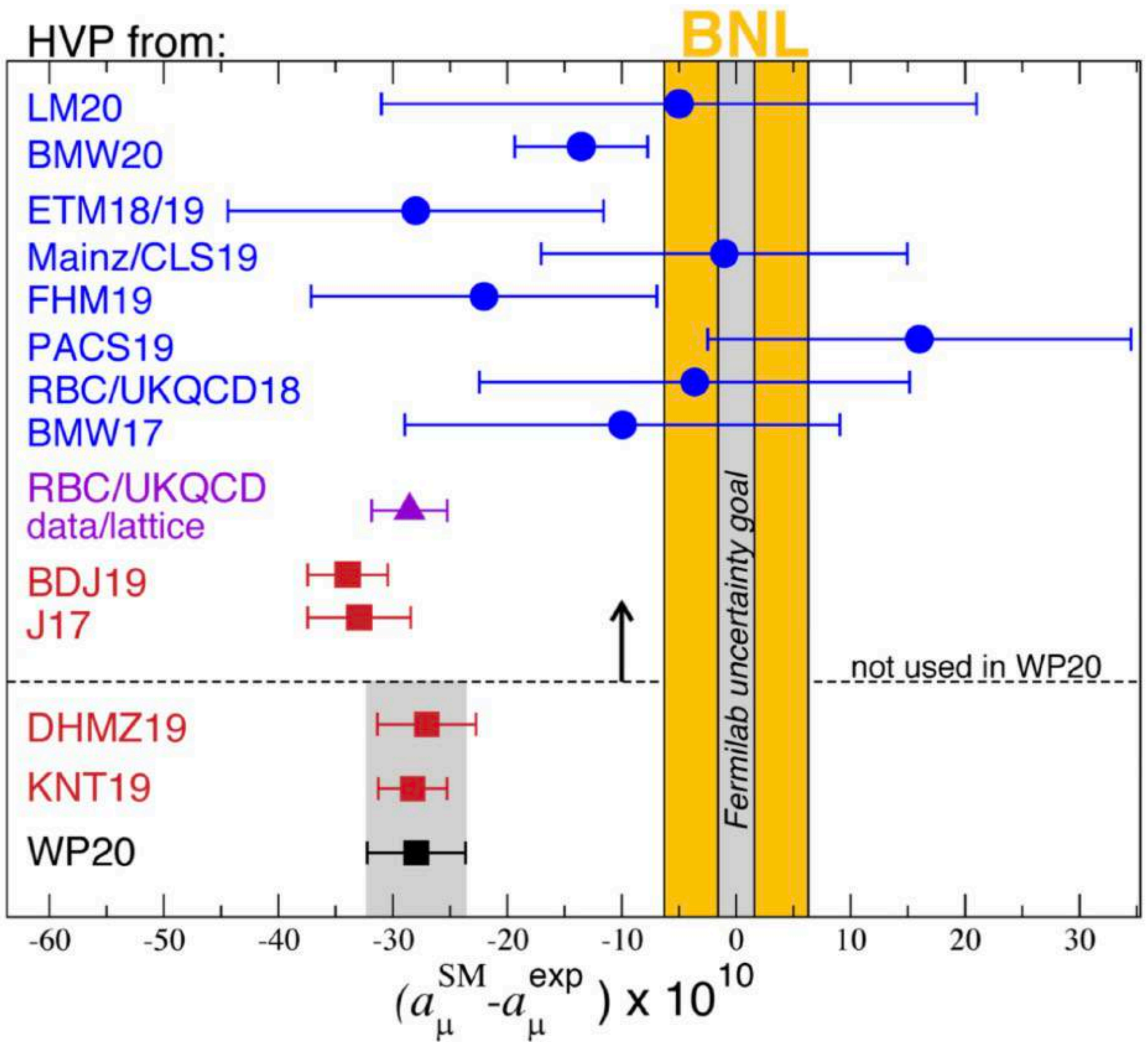
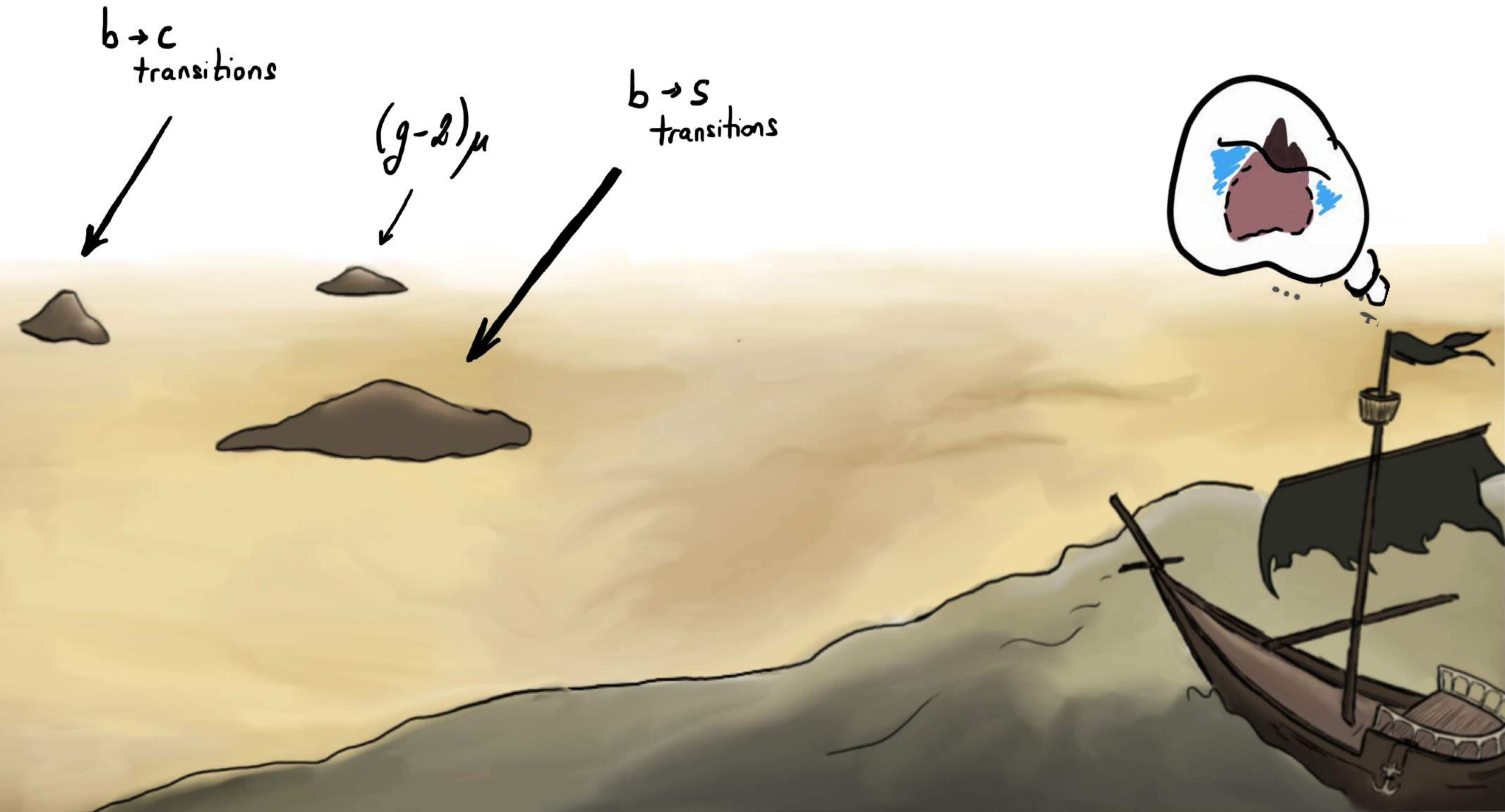


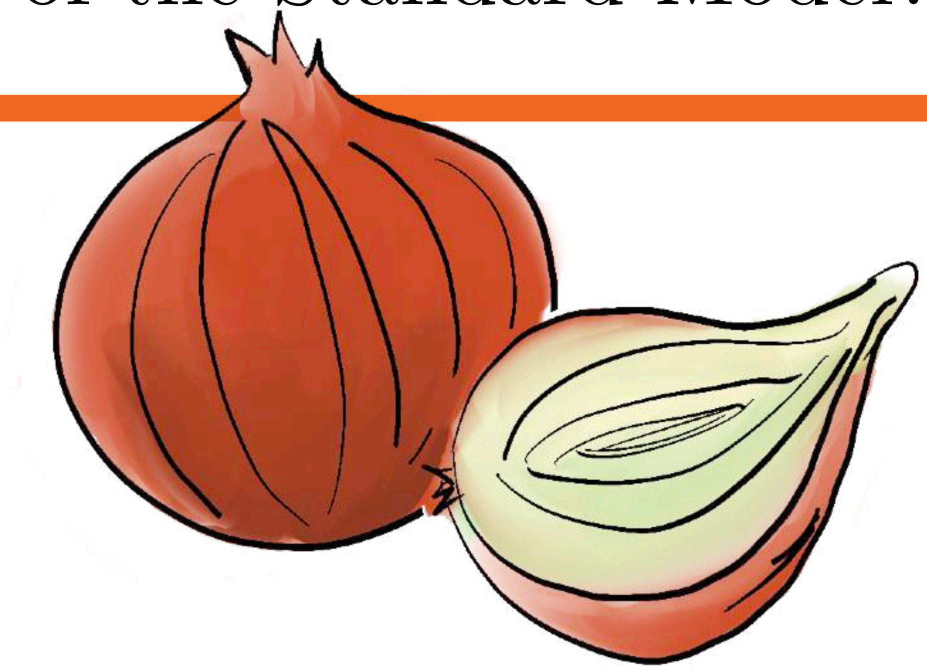
And now, what?



What is the next (**TeV scale**)

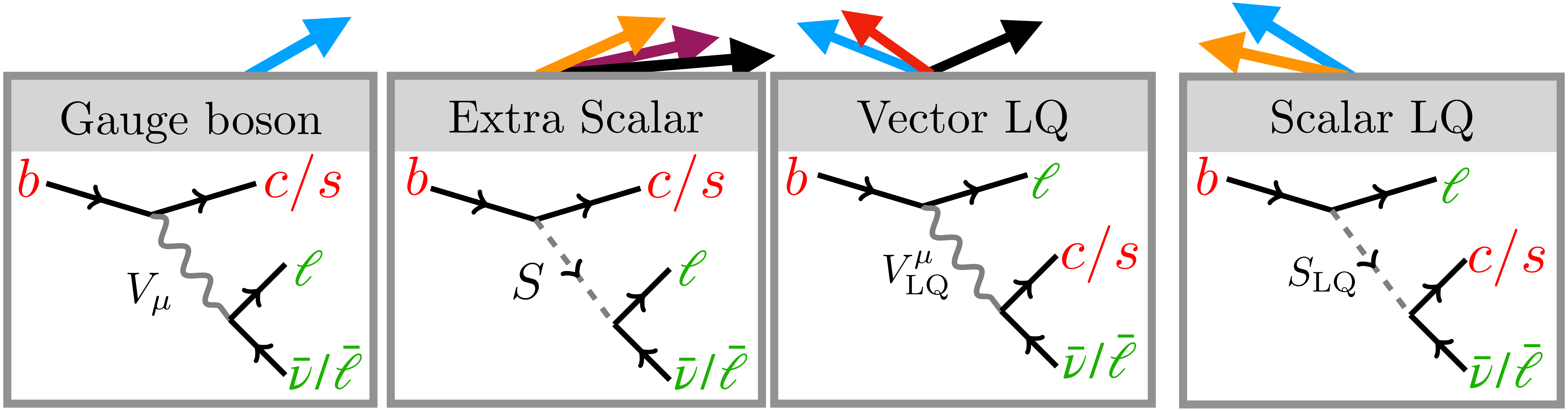
renormalizable completion

of the Standard Model?



UV candidates at the TeV scale?

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



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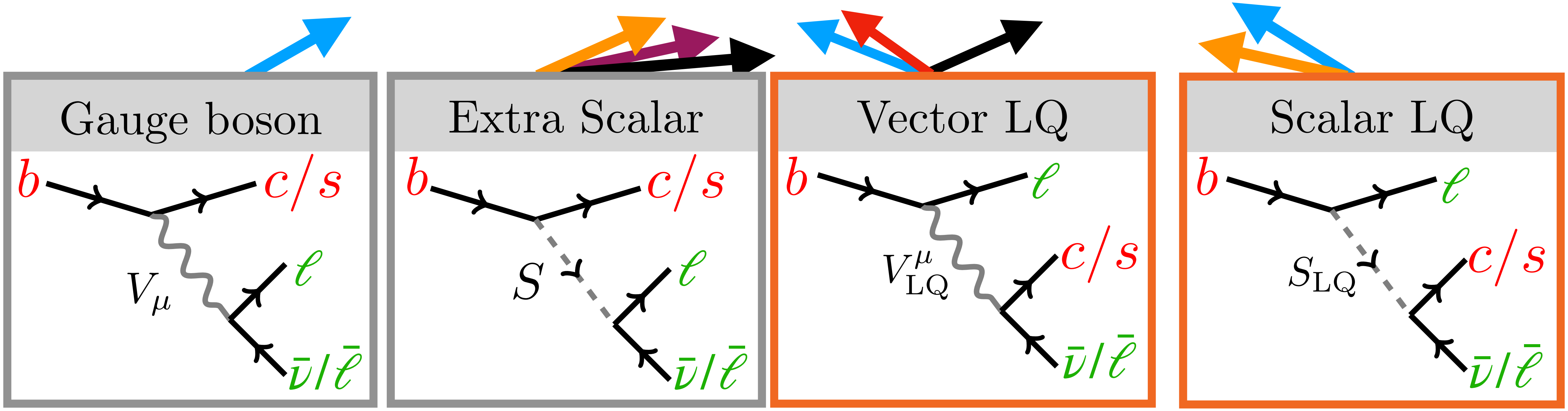

[Gripaios, 0910.1789]

Leptoquarks

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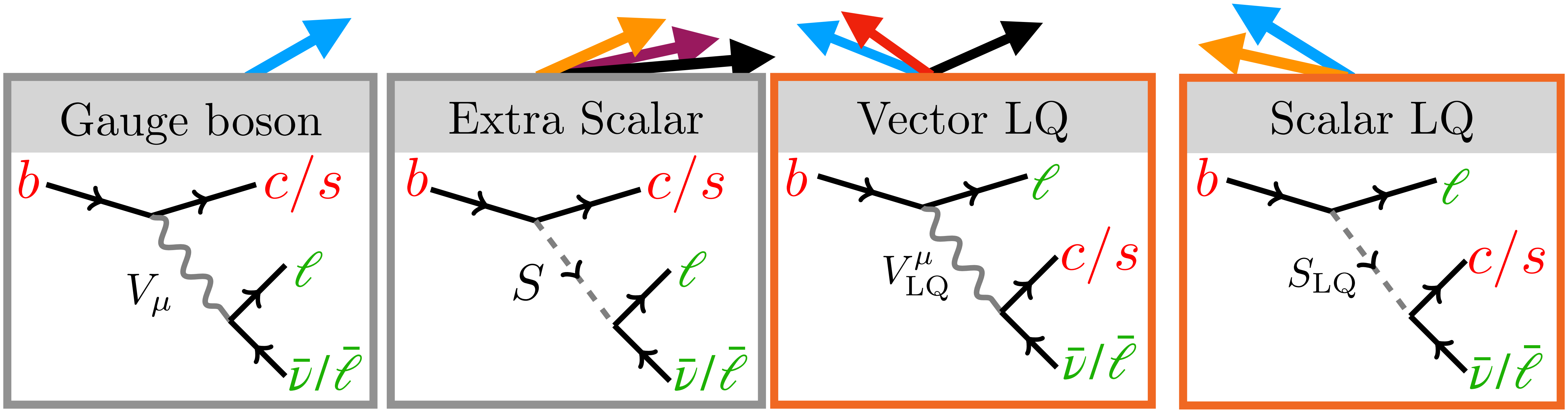
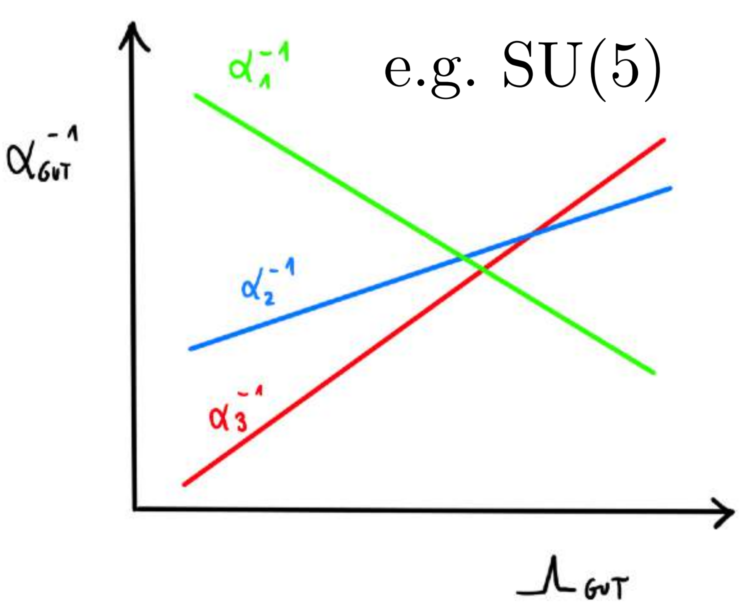
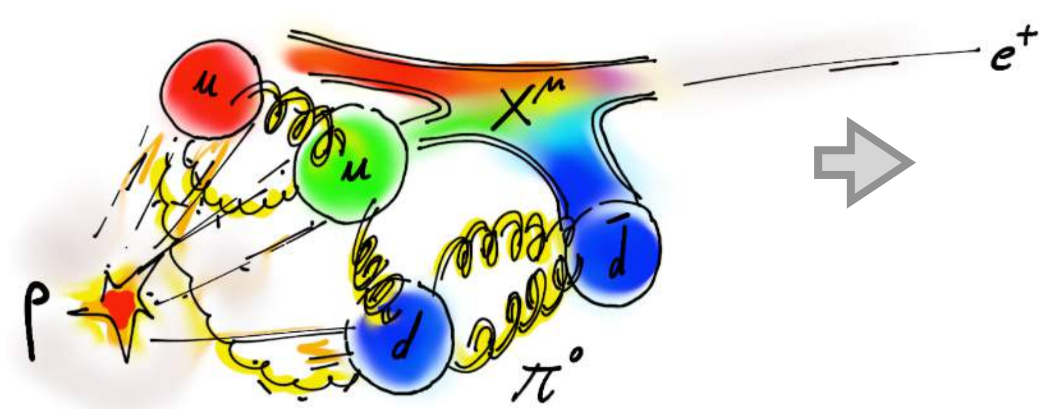


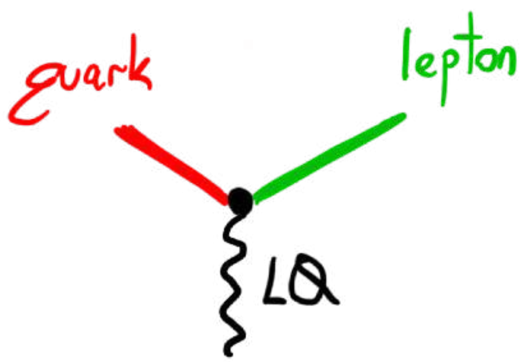


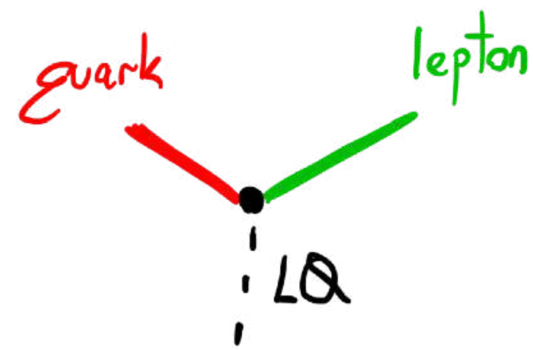


$\Lambda_{\text{GUT}} \gtrsim 10^{15}$ GeV

Leptoquarks

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





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

freedom ☹ ⇨ predictability ☺

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No Baryon Number violation at renormalizable level

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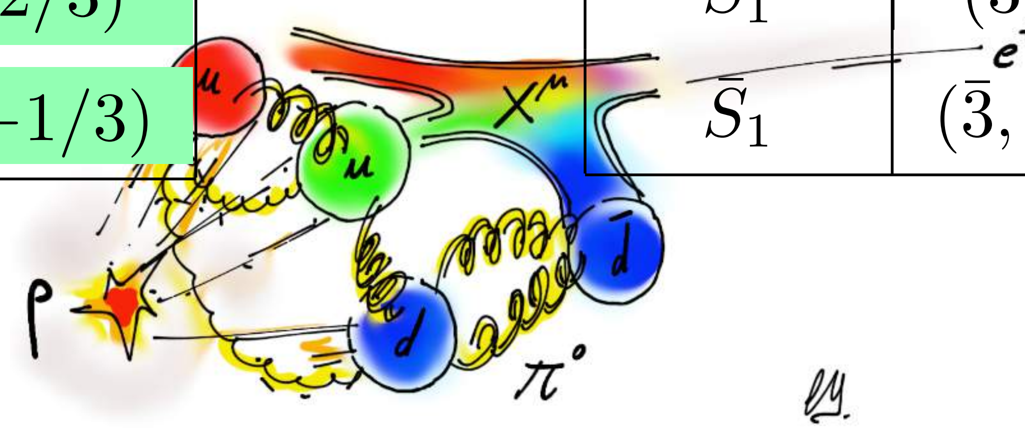
S_1	$(\bar{3}, 1, 1/3)$
$\bar{S}_1$	$(\bar{3}, 1, -2/3)$



Leptoquarks

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

No Baryon Number violation at renormalizable level

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

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

Quark-Lepton Unification
at the Low Scale

Quark-Lepton Unification

[Pati-Salam, 1974]

- A SM matter family

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

Quarks

$$\begin{array}{ccc} Q_L & d_R & u_R \\ Q_L & d_R & u_R \\ Q_L & d_R & u_R \end{array}$$

$$\begin{array}{cc} \ell_L & e_R \end{array}$$

Leptons

$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

Quark-Lepton Unification

[Pati-Salam, 1974]

- An (almost) SM matter family

Quarks

$$\begin{array}{ccc} Q_L & d_R & u_R \\ Q_L & d_R & u_R \\ Q_L & d_R & u_R \end{array}$$

$$\begin{array}{ccc} \ell_L & e_R & \nu_R \end{array}$$

Leptons

$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

Quark-Lepton Unification

[Pati-Salam, 1974]

- An (almost) SM matter family

Leptons are just the fourth color of the quarks!

$$\boxed{\begin{matrix} Q_L \\ Q_L \\ Q_L \\ \ell_L \end{matrix}} \quad \boxed{\begin{matrix} d_R \\ d_R \\ d_R \\ e_R \end{matrix}} \quad \boxed{\begin{matrix} u_R \\ u_R \\ u_R \\ \nu_R \end{matrix}}$$

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

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

Quark-Lepton Unification

[Pati-Salam, 1974]

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

Left-handed fermions

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

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

Right-handed fermions

$$\begin{array}{ccc} \boxed{\begin{array}{c} Q_L \\ Q_L \\ Q_L \\ \ell_L \end{array}} & \boxed{\begin{array}{c} d_R \\ d_R \\ d_R \\ e_R \end{array}} & \boxed{\begin{array}{c} u_R \\ u_R \\ u_R \\ \nu_R \end{array}} \\ \equiv & \equiv & \equiv \\ F_{QL} & F_d & F_u \end{array}$$

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

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

Unification of Matter: Pati-Salam

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

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

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

$$V_{15}^{\mu} \sim (15,1,0) \sim \underbrace{\begin{pmatrix} \overset{\mathrm{SU}(3)_C}{\boxed{G^{\mu}}} & U_1^{\mu} \\ \dagger & 0 \end{pmatrix}}_{\mathrm{SU}(4)_C} + T_4 B'^{\mu}$$

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

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

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

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

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

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$$V_{15}^\mu \sim (15,1,0) \sim \underbrace{\begin{pmatrix} G^\mu & U_1^\mu \\ \dagger & 0 \end{pmatrix}}_{\mathrm{SU}(4)_C} + T_4 B'^\mu$$

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

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

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

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

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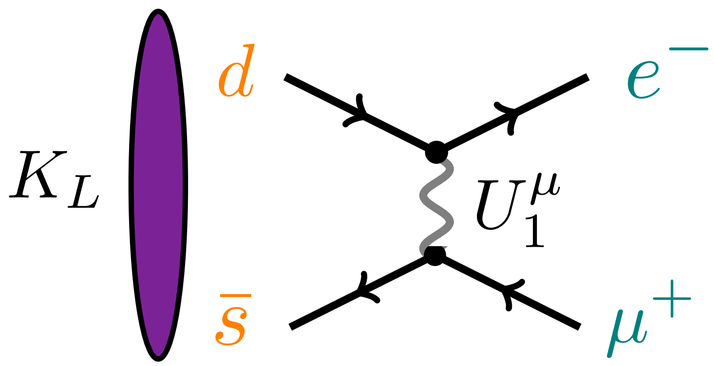

$\leq 4.7 \times 10^{-12}$

$$V_{15}^\mu \sim (15,1,0) \sim \underbrace{\begin{pmatrix} G^\mu & U_1^\mu \\ \dagger & 0 \end{pmatrix}}_{\mathrm{SU}(4)_C} + T_4 B'^\mu$$

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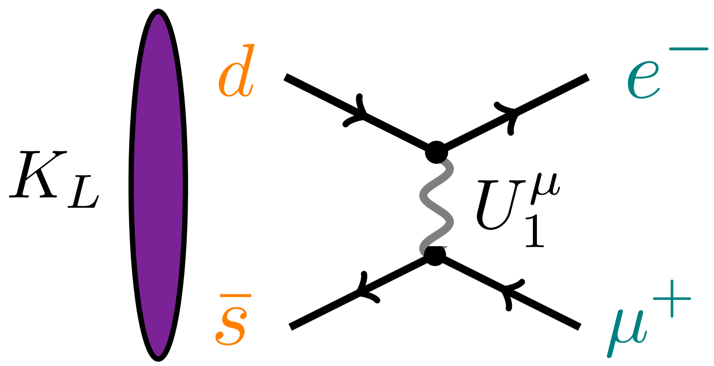
$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \Rightarrow \boxed{M_{U_1} \sim g_4 v_\chi} \gtrsim 10^3 \text{ TeV}$$

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

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

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



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

$$V_{15}^\mu \sim (15,1,0) \sim \underbrace{\begin{pmatrix} G^\mu & U_1^\mu \\ \dagger & 0 \end{pmatrix}}_{\mathrm{SU}(4)_C} + T_4 B'^\mu$$

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

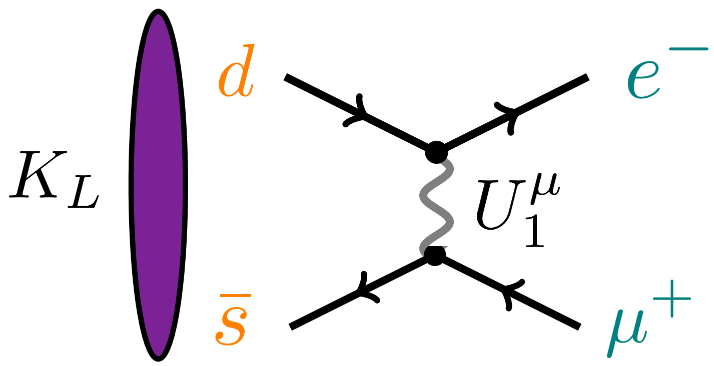
Naive bound!

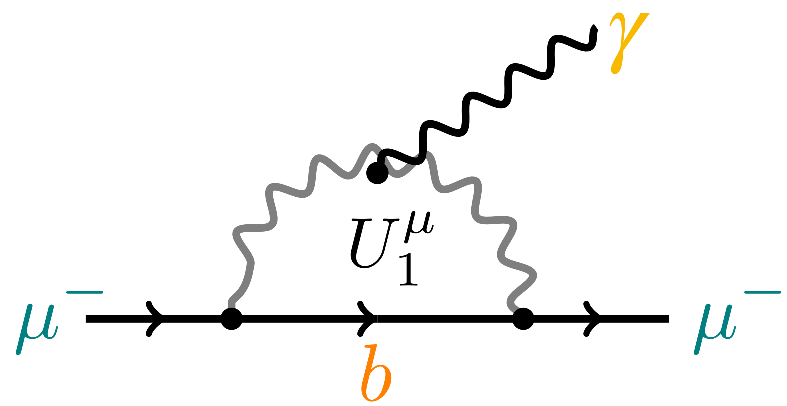
$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \Rightarrow \boxed{M_{U_1} \sim g_4 v_\chi} \gtrsim \cancel{10^3\ \mathrm{TeV}}$$

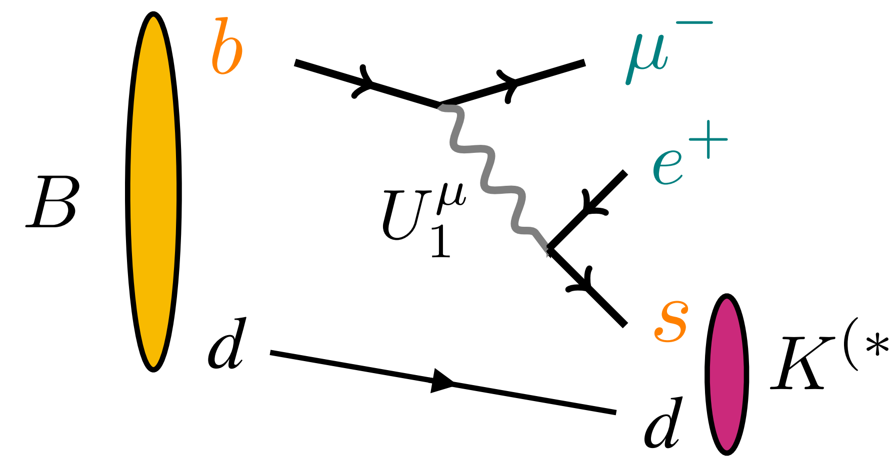
$$\cancel{SU}(4)_c \otimes SU(2)_L \otimes \cancel{U(1)}_R \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

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

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







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!

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

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

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

Quark-Lepton Unification

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

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

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

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

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

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

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

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

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

Quark-Lepton Unification

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

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

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

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

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

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

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\text{MW}} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2, \qquad H \sim (1, 2, 1/2)_{\text{SM}}$$

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

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

Quark-Lepton Unification

Inverse seesaw

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

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

$$\boxed{M_\chi^D} \gg \boxed{M_\nu^D} \gg \mu$$

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

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

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

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

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

$$\Phi \sim (15,2,1/2) = \begin{pmatrix} \Phi_{\text{MW}} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2, , \quad H \sim (1,2,1/2)_{\text{SM}}$$

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

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

Quark-Lepton Unification

- The theory predicts scalar LQs:

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

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

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

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

$$\boxed{\begin{aligned} M_D &= Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}}, \\ M_E &= Y_3 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}}. \end{aligned}}$$

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\text{MW}} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2, \qquad H \sim (1, 2, 1/2)_{\text{SM}}$$

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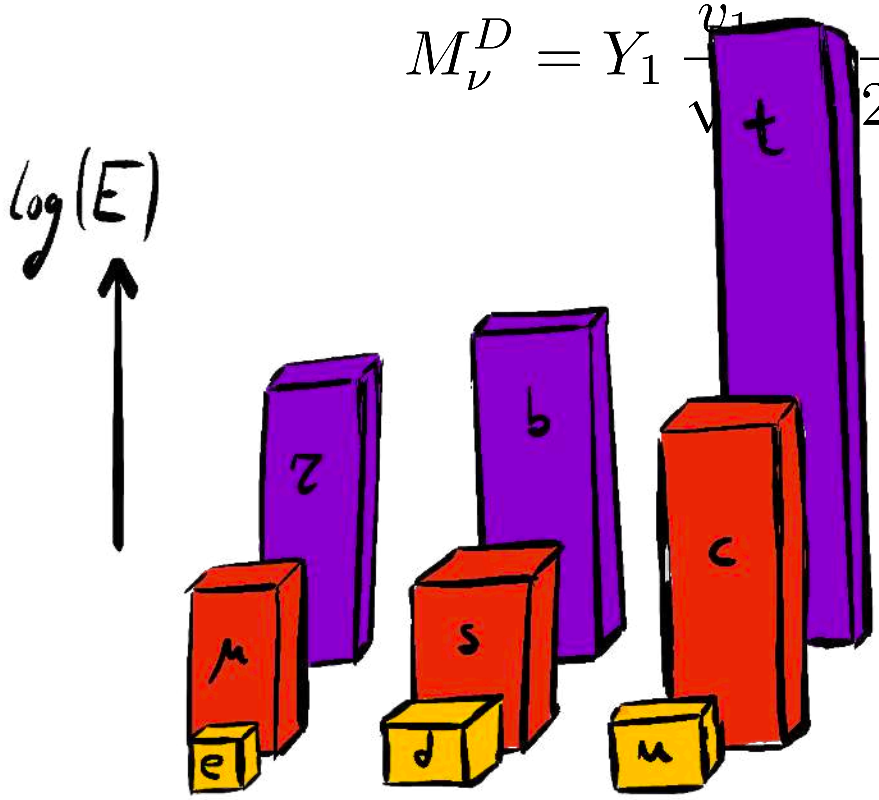

$$\Phi \sim \begin{pmatrix} \Phi_{\rm MW} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2, \qquad H \sim (1, 2, 1/2)_{\rm SM}$$

PREDICTED!!

Baryon Number in QL-Unification

- The theory predicts scalar LQs:

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

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

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

$$V_{\text{scalar}} \supset \cancel{\epsilon_{\alpha\beta\gamma} \Phi_3^\alpha \Phi_3^\beta \Phi_3^\gamma H}$$

[**C.M**, M. B. Wise, 2105.14029]

Baryon Number in QL-Unification

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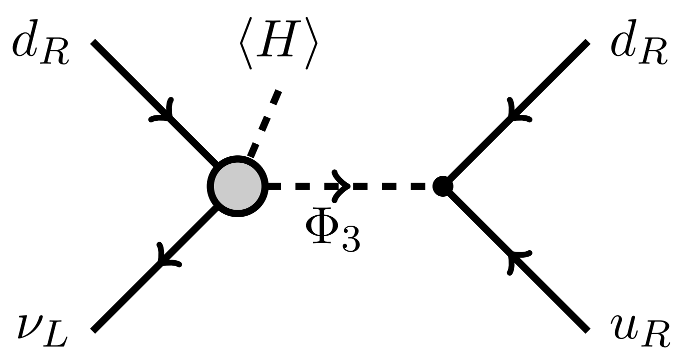
$$\text{e.g.} \quad \frac{1}{\Lambda} u_R^\alpha d_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}, \quad \frac{1}{\Lambda} d_R^\alpha d_R^\beta \Phi_4^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$



[Arnold, Fornal, Wise, 2013]

if $\Lambda \sim M_{\rm Pl}$ $\Rightarrow$ $M_{\Phi_{3,4}} > 10^8$ GeV

Baryon Number in QL-Unification

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

$$\frac{1}{\Lambda_{\rm PS}} F_d^A F_u^B (\Phi^\dagger)_B^C H^\dagger \quad \overset{?}{\rightarrow} \quad \frac{1}{\Lambda} d_R^\alpha u_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$

[**C.M**, M. B. Wise, 2105.14029]

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$$\boxed{\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\rm MW} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2}$$

$$\boxed{\chi \sim (4, 1, 1/2) = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle)}$$

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$$\frac{1}{\Lambda_{\rm PS}^2} F_d^A F_u^B (\Phi^\dagger)_D^C \chi^D H^\dagger \quad \overset{?}{\to} \quad \frac{1}{\Lambda} d_R^\alpha u_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$

[**C.M**, M. B. Wise, 2105.14029]

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Baryon Number in QL-Unification

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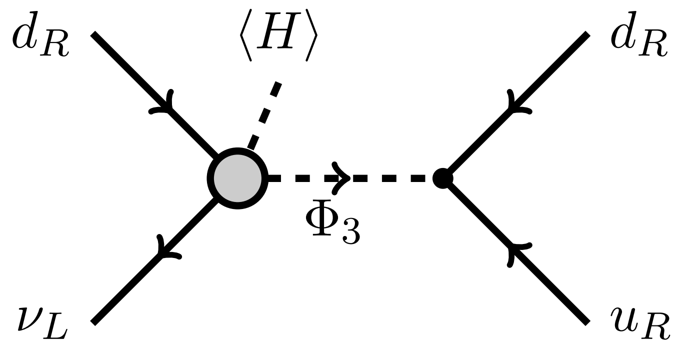
$$-\mathcal{L}_Y \supset Y_2\, Q_L \Phi_3 (\nu^c)_L + Y_2\, \ell_L \Phi_4 (u^c)_L + Y_4\, Q_L \Phi_4^\dagger (e^c)_L + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

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

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



[**C.M**, M. B. Wise, 2105.14029]

Baryon Number in QL-Unification

- The theory predicts scalar LQs:

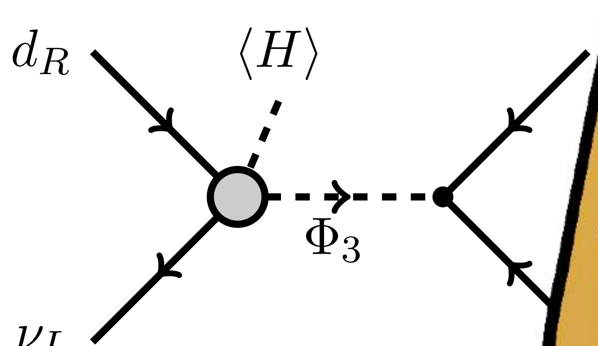
$$\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)_{\rm SM} \qquad R_2 \equiv \Phi_4 \sim (3, 2, 7/6)_{\rm SM}$$

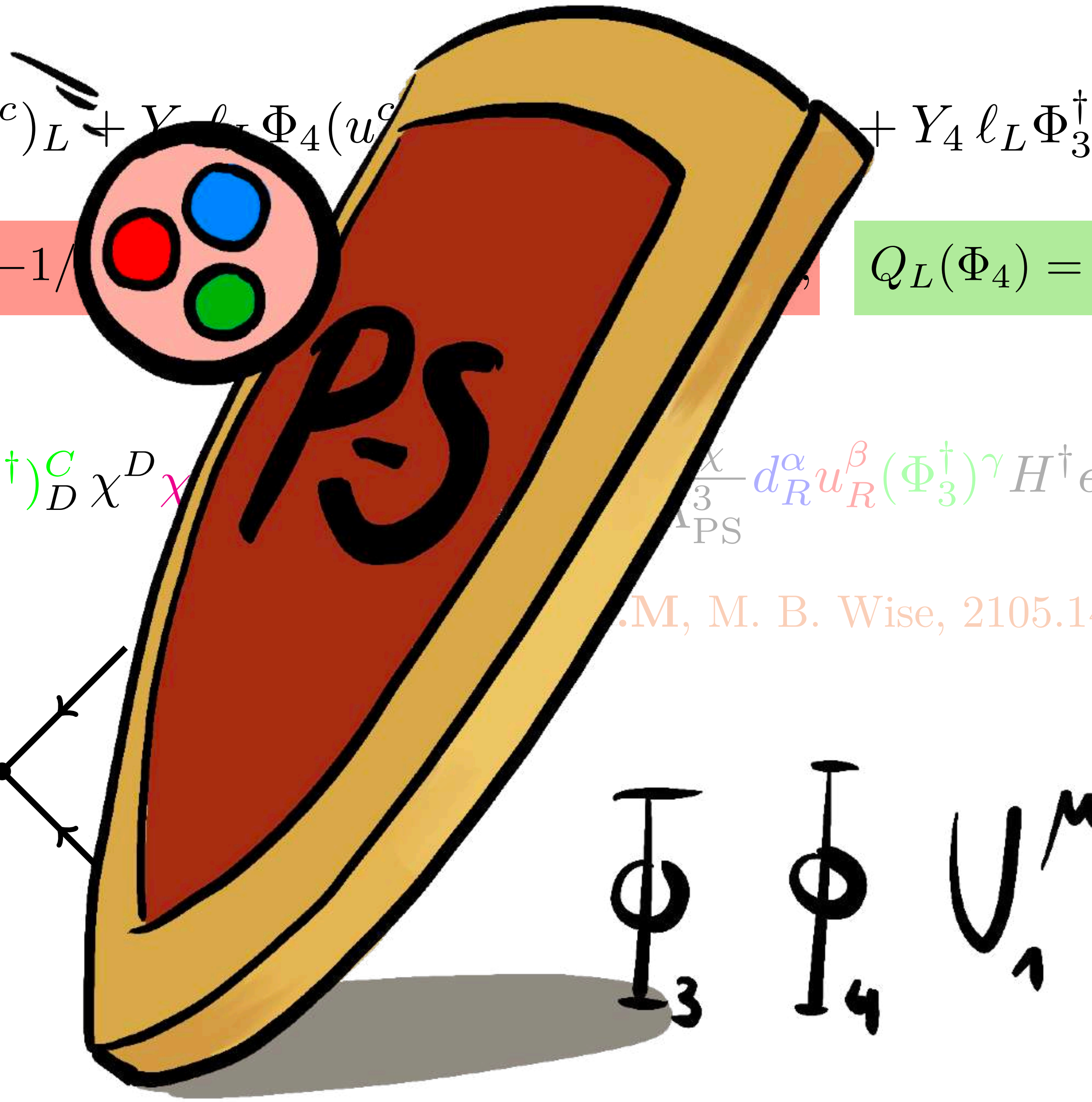
$$-\mathcal{L}_Y \supset Y_2\, Q_L \Phi_3 (\nu^c)_L + Y \;\ell\; \Phi_4 (u^c \quad + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

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

$$\frac{1}{\Lambda_{\rm PS}^3} F_d^A F_u^B (\Phi^\dagger)^C_D\, \chi^D \chi \qquad \frac{\chi}{\Lambda_{\rm PS}^3} d_R^\alpha u_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$

.M, M. B. Wise, 2105.14029]





Quark-Lepton Unification

- The theory predicts scalar LQs:

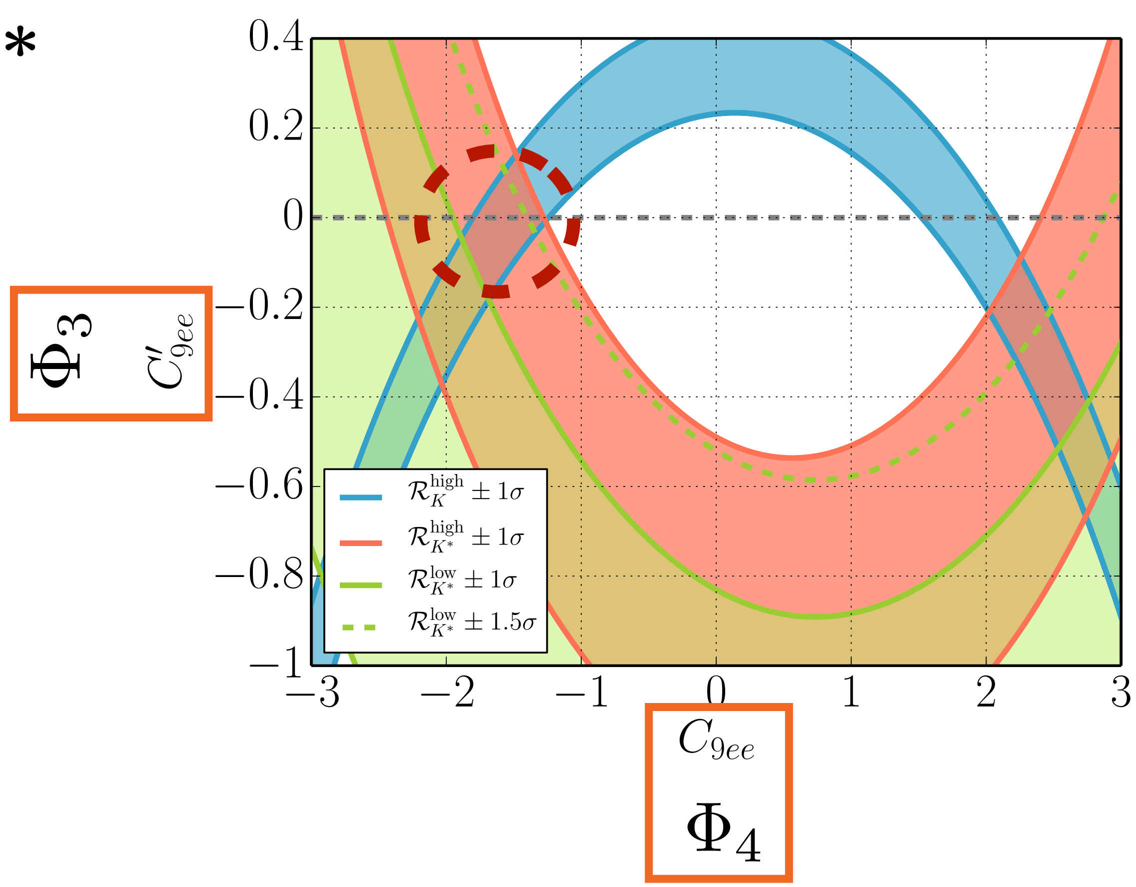
$\Phi_3 \sim (\bar{3}, 2, -1/6)_{\text{SM}}$	$\Phi_4 \sim (3, 2, 7/6)_{\text{SM}}$

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

****Spoilers on****

[O. Popov, M. A. Schimdt, G. White, 1905.06339]

[P. F. Perez, C.M., A. D. Plascencia, 2104.11229]



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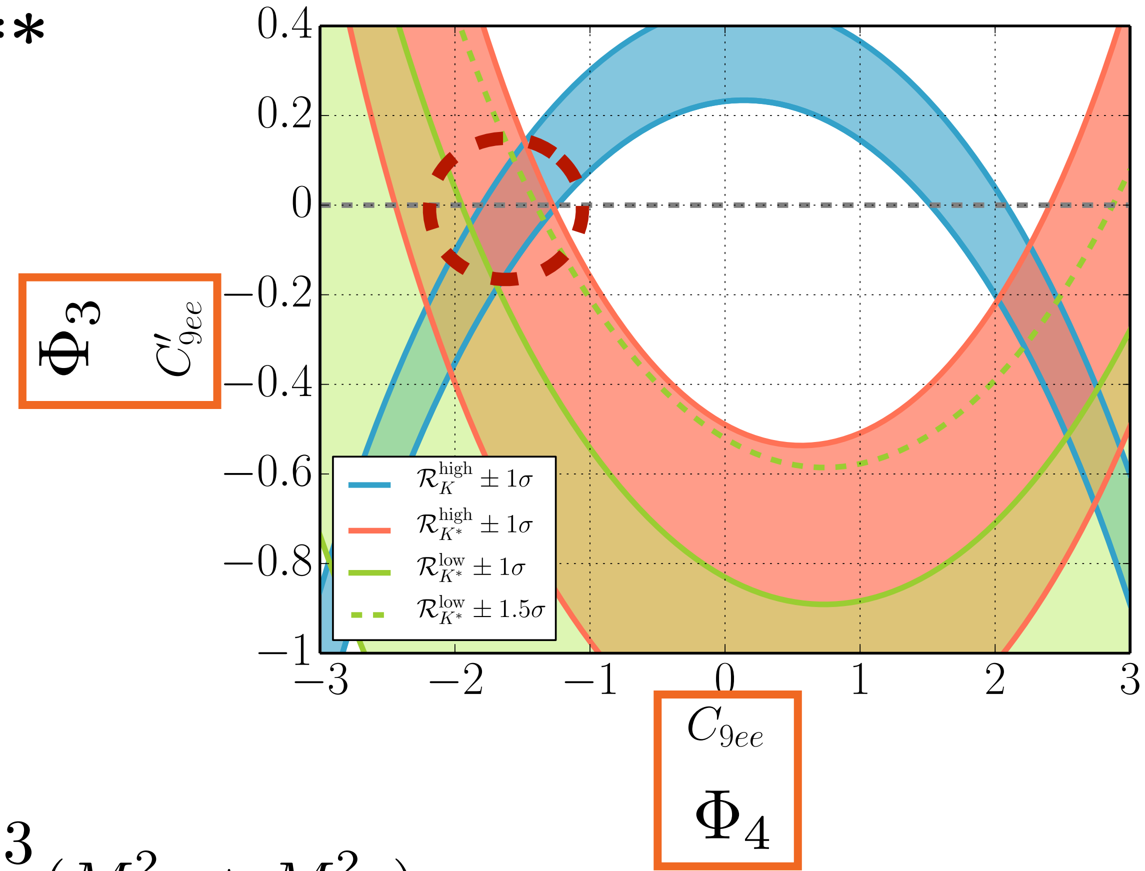

$$M^2_{\Phi_8} + 2M^2_{H_2} = \frac{3}{2}(M^2_{\Phi_3} + M^2_{\Phi_4})$$

[T. Faber, M. Hudec, et al, 1808.05511]

Quark-Lepton Unification

[P. Fileviez Perez and **C.M.** 2022]

$$\Phi_4 \sim (3, 2, 7/6)_{\rm SM}$$

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

$$M_D = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}},$$

$$M_E = Y_3 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}}.$$

$$\Downarrow$$

$$Y_4 = \sqrt{\frac{3}{2}} \frac{M_D - M_E}{v \sin\beta}$$

Quark-Lepton Unification

$$\Phi_4 \sim (3,2,7/6)_{\rm SM} = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix}$$

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

$$\supset \bar{d} \left[\sqrt{\frac{3}{2}} \frac{1}{v \sin\beta} (M_D^* - M_E^*) \right] P_R\, e\, \phi_4^{2/3}$$

$$Y_4 = \sqrt{\frac{3}{2}} \frac{M_D - M_E}{v \sin\beta}$$

Quark-Lepton Unification

$$\Phi_4 \sim (3, 2, 7/6)_{\rm SM} = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix}$$

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$$\supset \bar{d}\, D^\dagger \left[\sqrt{\frac{3}{2}} \frac{1}{v \sin\beta} \left(D\, M_D^{\rm diag}\, D_c^T - E\, M_E^{\rm diag}\, E_c^T \right) \right] E_c^*\, P_R\, e\, \phi_4^{2/3}$$

Quark-Lepton Unification

$$c_4 = \sqrt{\frac{3}{2}} \frac{1}{v \sin\beta} \begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s (V_c^*)^{21} & m_s (V_c^*)^{22} - m_\mu V^{22} & m_s (V_c^*)^{23} - m_\tau V^{23} \\ m_b (V_c^*)^{31} & m_b (V_c^*)^{32} - m_\mu V^{32} & m_b (V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}$$

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

$$\supset \bar{d} \left[\sqrt{\frac{3}{2}} \frac{1}{v \sin\beta} \left(M_D^{\text{diag}} V_c^* - V M_E^{\text{diag}} \right) \right] P_R \, e \, \phi_4^{2/3}$$

$$V = D^\dagger E$$

$$V_c = D_c^\dagger E_c$$

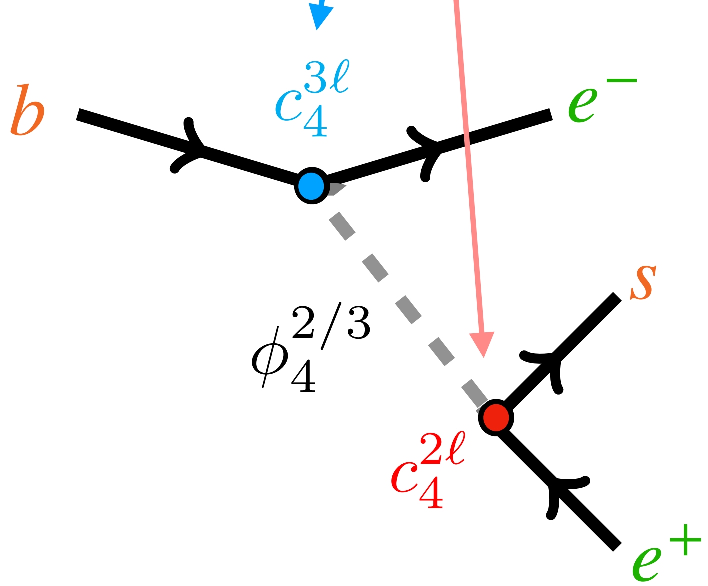
$\Rightarrow$ $Y = \text{L.C.}[M_{\text{f}}, \text{Unitary matrices}]$

What can we learn from

experiment?

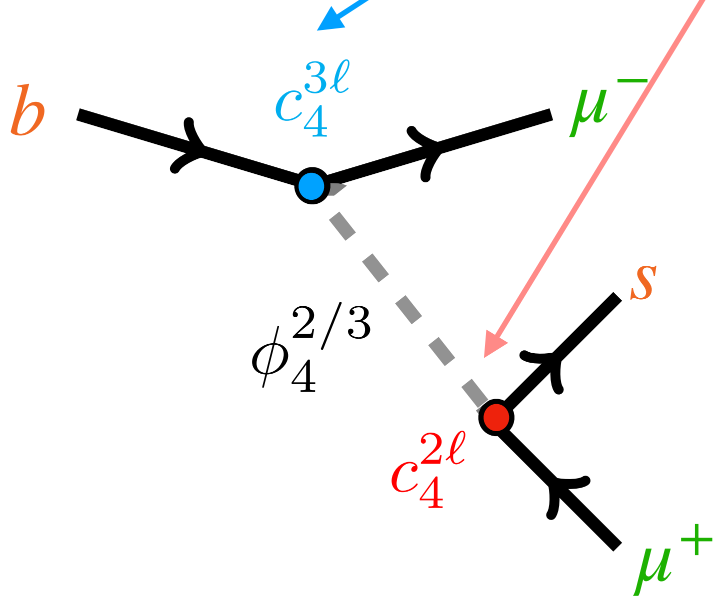
Neutral Anomalies

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$



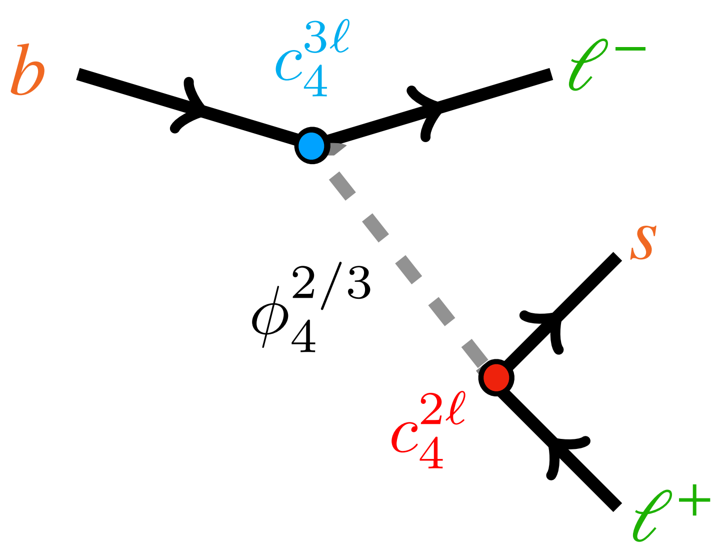
Neutral Anomalies

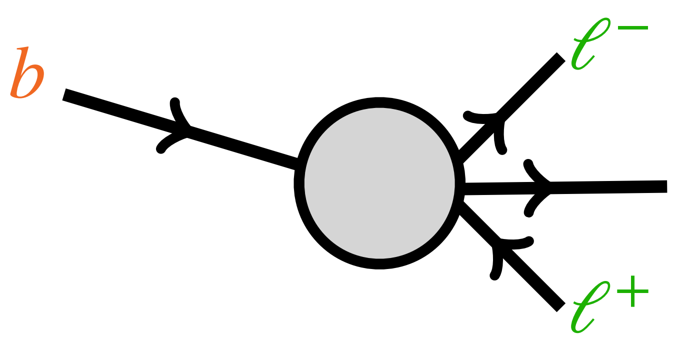
$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$



Neutral Anomalies

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$



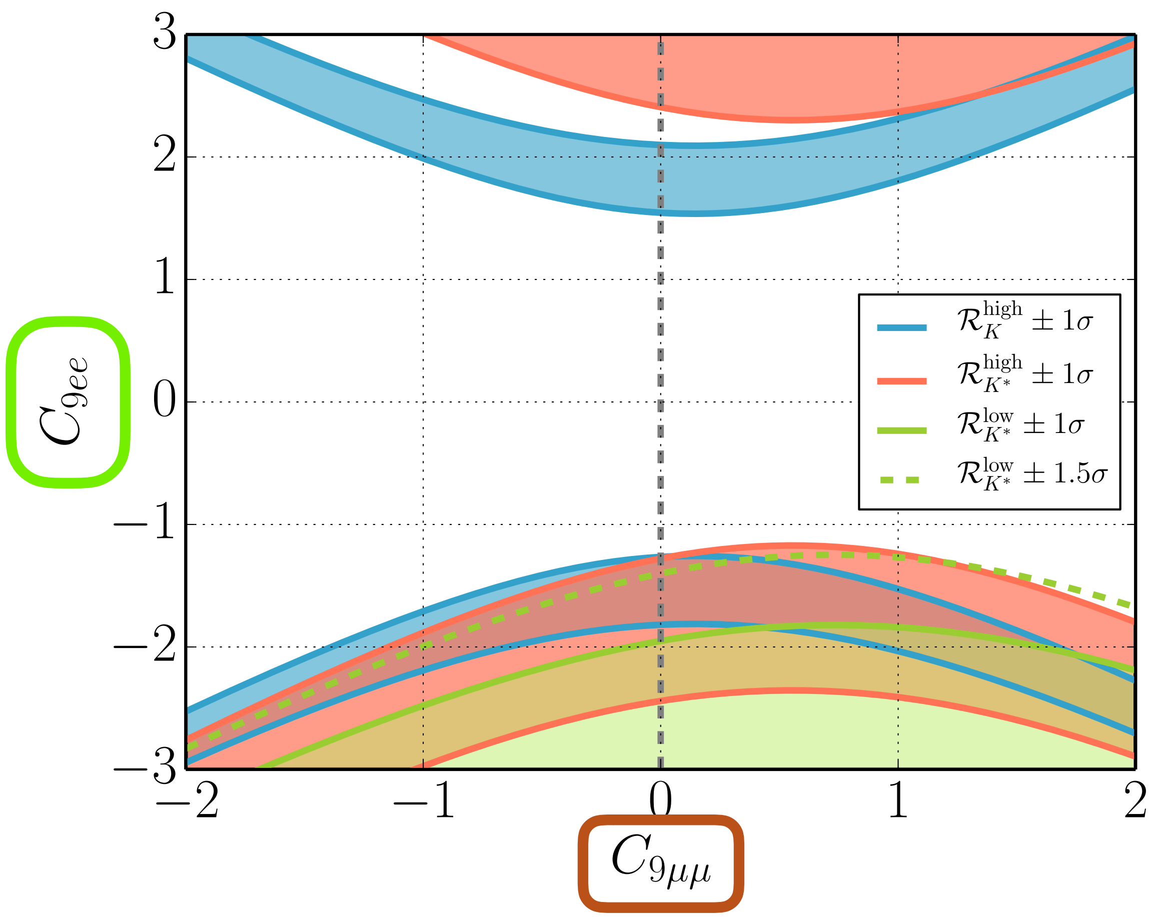


$$\frac{c_4^{2\ell}(c_4^{3\ell})^*}{2M_{\Phi_4}^2}$$

$$-\mathcal{L}_{\text{eff}}^{b\to s} \supset \frac{c_4^{2\ell}(c_4^{3\ell})^*}{2M_{\Phi_4}^2}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell) \quad \Rightarrow C_{9\ell\ell} = C_{10\ell\ell}$$

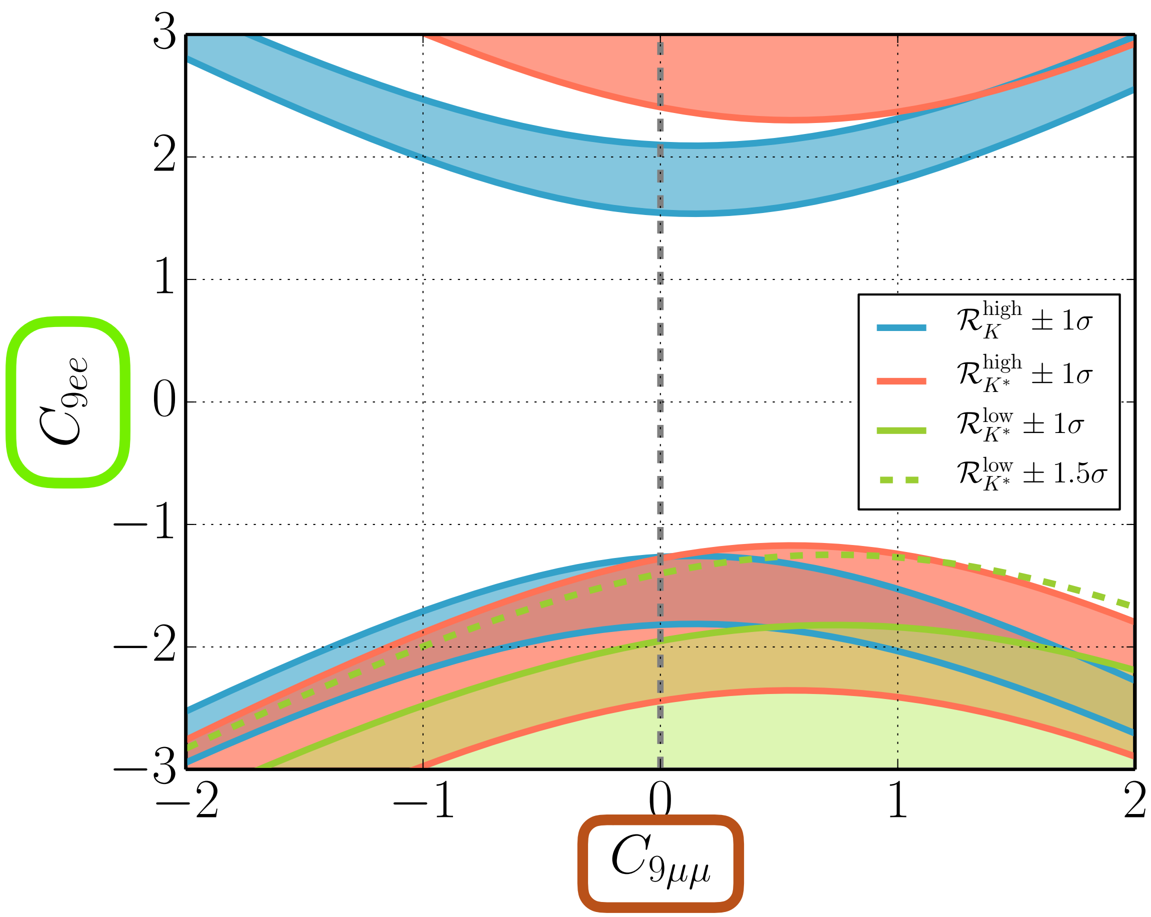
Neutral Anomalies

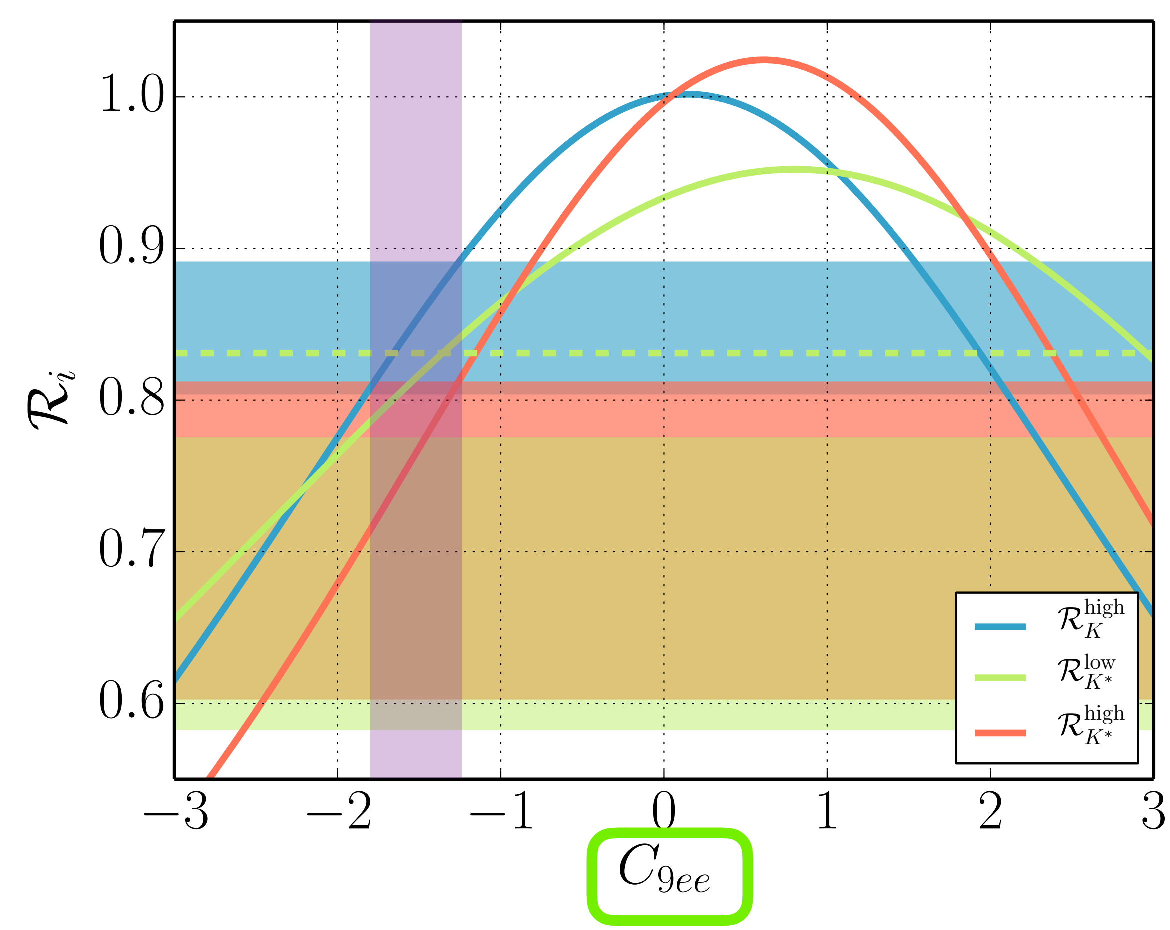
$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$



Neutral Anomalies

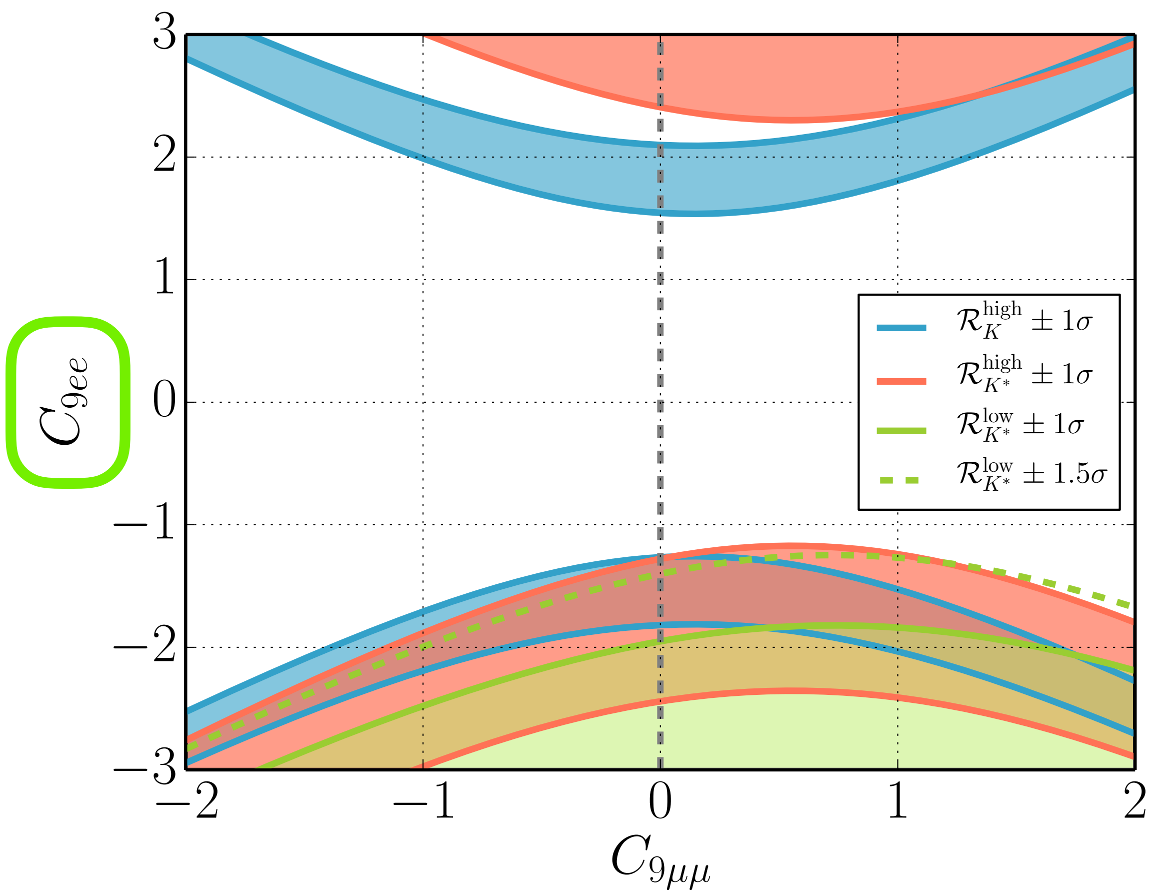
$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$

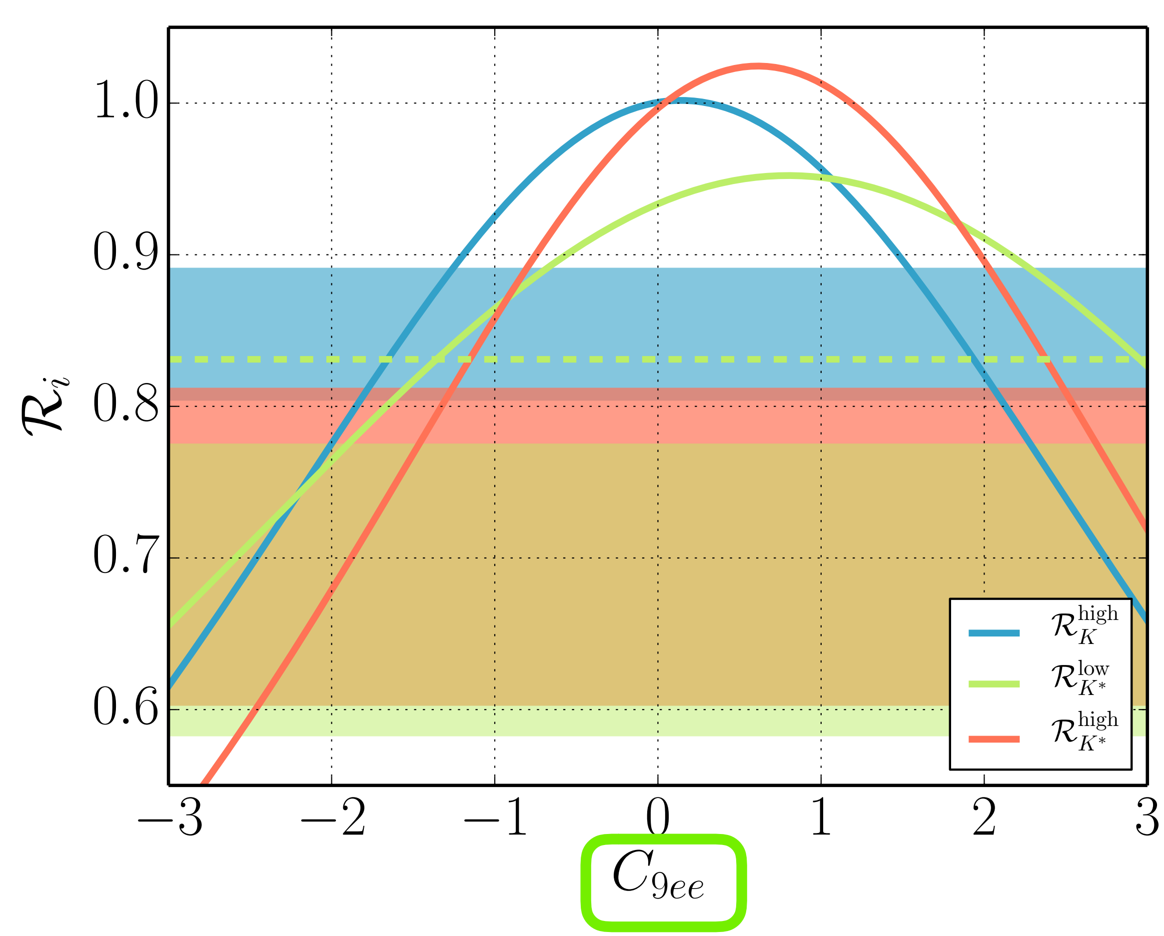




Neutral Anomalies

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$



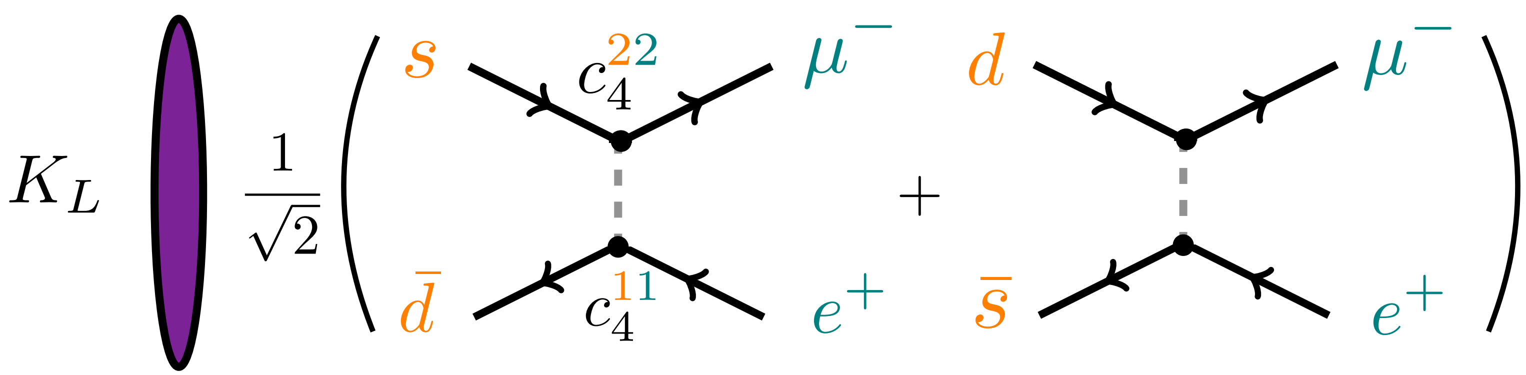


$$C_{9ee} (= C_{10ee}) \propto (G_F)^{-1}\frac{m_s\, m_b}{v^2}\frac{(V_c^*)^{21}V_c^{31}}{M_{\Phi_4}^2 \sin^2\beta}$$

$K_L \to \mu^\pm e^\mp$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$

$\Rightarrow$ $\mathrm{Br}(K_L \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$



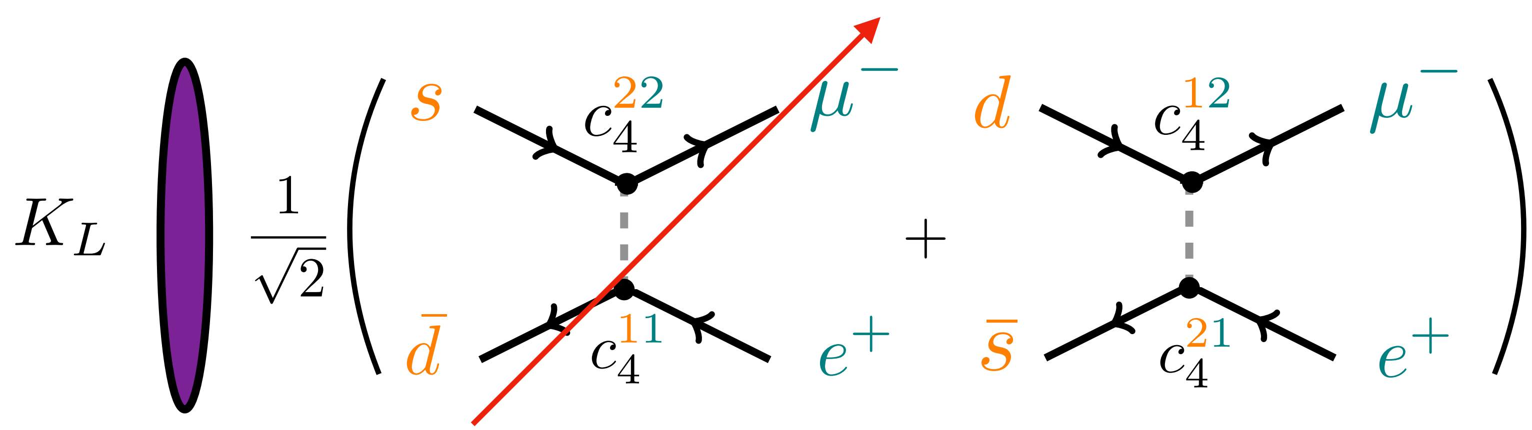
$$V_c = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

$K_L \to \mu^\pm e^\mp$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & -m_\mu V^{12} & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$

$\mathrm{Br}(K_L \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$



$$\sqrt{|V^{12}V_c^{21}|}\left(\frac{10\ \mathrm{GeV}}{M_{\Phi_4}\sin\beta}\right) < 0.10$$

$s_{12} \to 0$

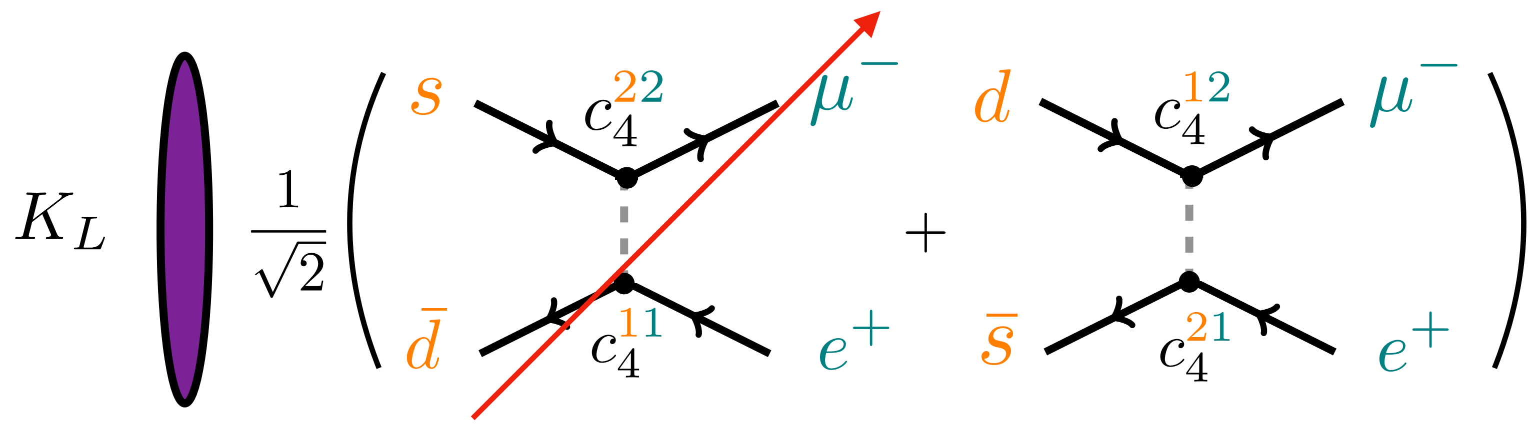
$$V_c = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

$K_L \to \mu^\pm e^\mp$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v \sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau V^{13} \\ m_s (V_c^*)^{21} & m_s (V_c^*)^{22} - m_\mu V^{22} & m_s (V_c^*)^{23} - m_\tau V^{23} \\ m_b (V_c^*)^{31} & m_b (V_c^*)^{32} - m_\mu V^{32} & m_b (V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$

$\Rightarrow$ $\mathrm{Br}(K_L \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$



$$\sqrt{|V^{12} V_c^{21}|}\left(\frac{10\ \mathrm{GeV}}{M_{\Phi_4}\sin\beta}\right) < 0.10$$

$$V_c = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

$$V = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{23}s_{13} & c_{23} & s_{23}c_{13} \\ -c_{23}s_{13} & -s_{23} & c_{23}c_{13} \end{pmatrix}$$

$\mu \to e\gamma$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau V^{13} \\ m_s(V_c^*)^{21} & m_s(V_c^*)^{22} - m_\mu V^{22} & m_s(V_c^*)^{23} - m_\tau V^{23} \\ m_b(V_c^*)^{31} & m_b(V_c^*)^{32} - m_\mu V^{32} & m_b(V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$

$\Rightarrow$ $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

$$V_c = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

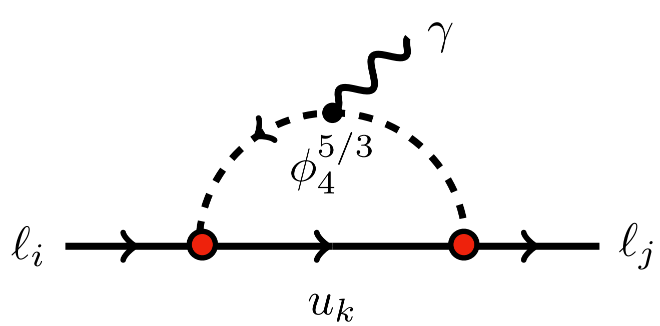
$$V = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{23}s_{13} & c_{23} & s_{23}c_{13} \\ -c_{23}s_{13} & -s_{23} & c_{23}c_{13} \end{pmatrix}$$

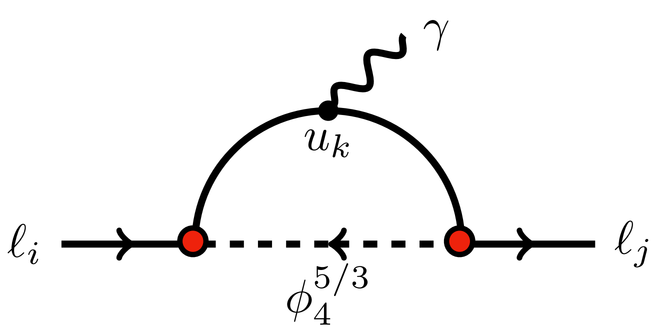
$\mu \to e\gamma$

$$c_4 = \sqrt{\frac{3}{2}} \frac{1}{v \sin\beta} \begin{pmatrix} 0 & 0 & -m_\tau V^{13} \\ m_s (V_c^*)^{21} & m_s (V_c^*)^{22} - m_\mu V^{22} & m_s (V_c^*)^{23} - m_\tau V^{23} \\ m_b (V_c^*)^{31} & m_b (V_c^*)^{32} - m_\mu V^{32} & m_b (V_c^*)^{33} - m_\tau V^{33} \end{pmatrix} .$$

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

$\Rightarrow$ $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$





$$V_c = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

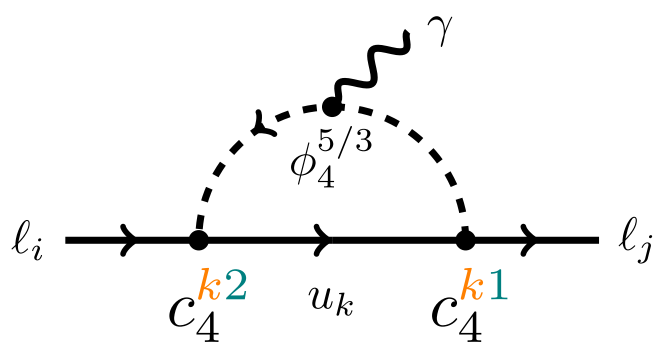
$$V = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{23}s_{13} & c_{23} & s_{23}c_{13} \\ -c_{23}s_{13} & -s_{23} & c_{23}c_{13} \end{pmatrix}$$

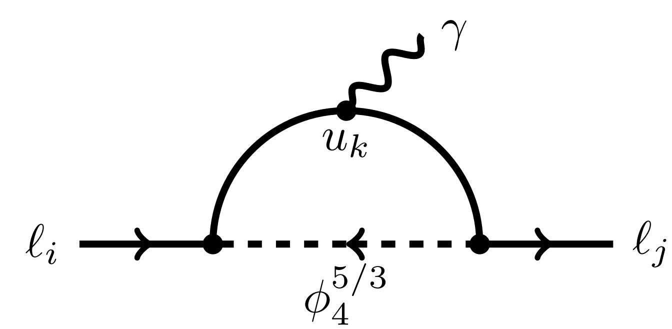
$\mu \to e\gamma$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau V^{13} \\ m_s (V_c^*)^{21} & m_s (V_c^*)^{22} - m_\mu V^{22} & m_s (V_c^*)^{23} - m_\tau V^{23} \\ m_b (V_c^*)^{31} & m_b (V_c^*)^{32} - m_\mu V^{32} & m_b (V_c^*)^{33} - m_\tau V^{33} \end{pmatrix}.$$

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

$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$





$c_{12} \to \epsilon$

$s_{13} \to \epsilon'$

$$\sqrt{\left|(V_c^*)^{31}\left[V_c^{32} - \frac{m_\mu}{m_b}(V^*)^{32}\right]\right|} < 0.011\left(\frac{M_{\Phi_4}|\sin\beta|}{10\ \mathrm{GeV}}\right)$$

$$V_c = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

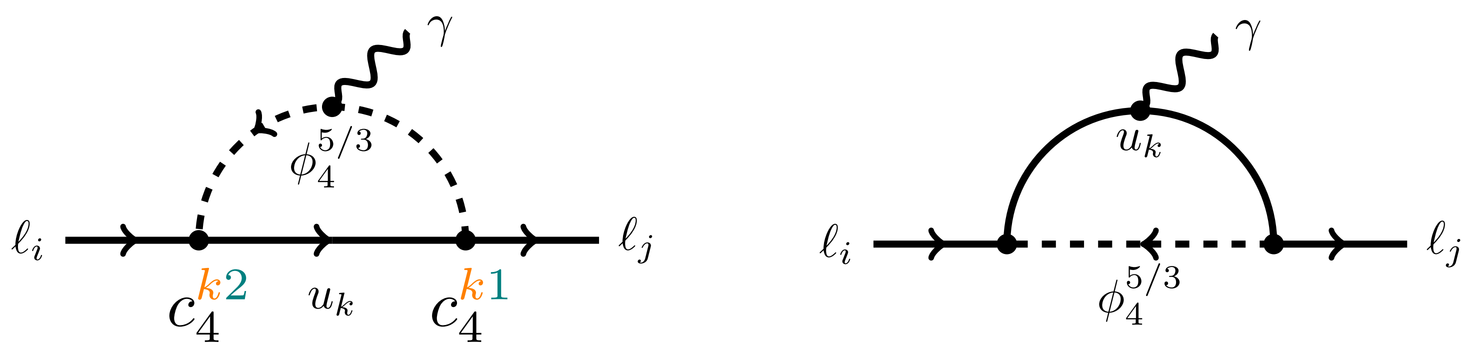
$$V = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{23}s_{13} & c_{23} & s_{23}c_{13} \\ -c_{23}s_{13} & -s_{23} & c_{23}c_{13} \end{pmatrix}$$

Fixing the textures: $\mu \to e\gamma$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau V^{13} \\ -m_s\cos\theta_c & -m_\mu V^{22} & m_s\sin\theta_c - m_\tau V^{23} \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c - m_\tau V^{33} \end{pmatrix}.$$

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

$\Rightarrow$ $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$



$$\sqrt{\left|(V_c^*)^{31}\left[V_c^{32} - \frac{m_\mu}{m_b}(V^*)^{32}\right]\right|} < 0.011\left(\frac{M_{\Phi_4}|\sin\beta|}{10\ \mathrm{GeV}}\right)$$

$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{23}s_{13} & c_{23} & s_{23}c_{13} \\ -c_{23}s_{13} & -s_{23} & c_{23}c_{13} \end{pmatrix}$$

$\mu \to e\gamma$

$$c_4 = \sqrt{\frac{3}{2}} \frac{1}{v \sin\beta} \begin{pmatrix} 0 & \boxed{0} & -m_\tau \sin\theta \\ -m_s \cos\theta_c & \boxed{0} & m_s \sin\theta_c - m_\tau \cos\theta \\ m_b \sin\theta_c & \boxed{0} & m_b \cos\theta_c \end{pmatrix} .$$

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

Unpopular Opinion

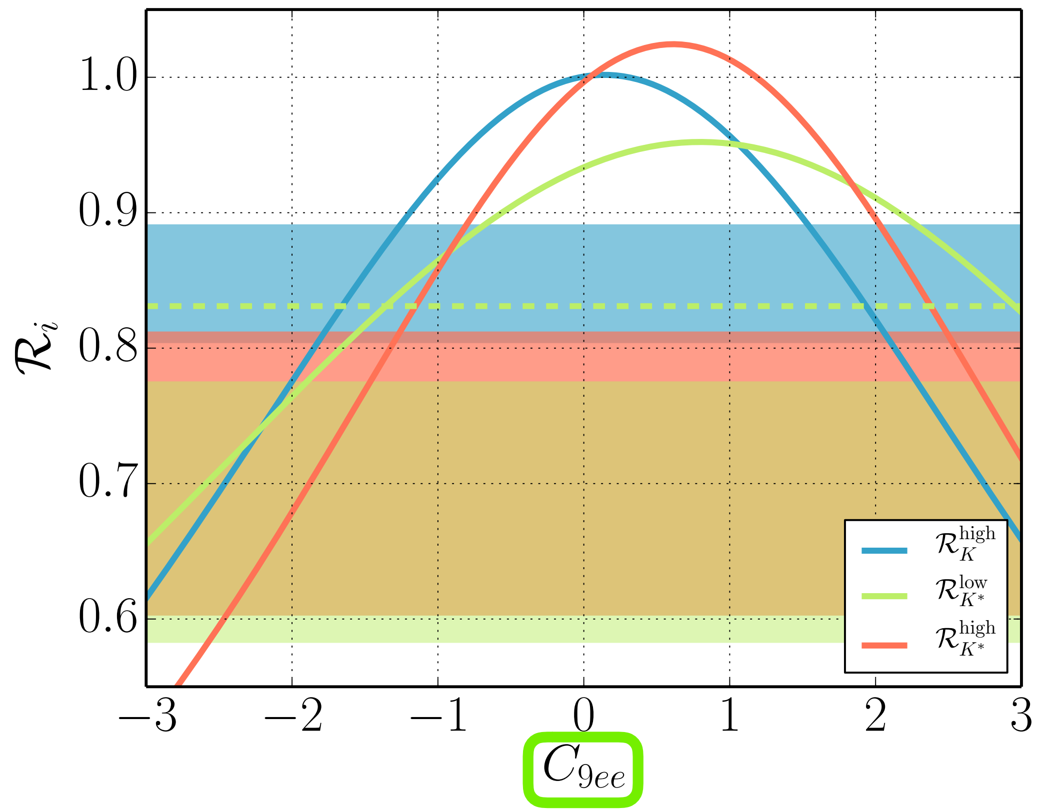
$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon \cos\theta_c - \epsilon' \sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon \sin\theta_c + \epsilon' \cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta \\ 0 & -1 & 0 \end{pmatrix}$$

Fixing the textures

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau \sin\theta \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau\cos\theta \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$

$$\boxed{C_{9ee}(=C_{10ee})} \propto (G_F)^{-1}\frac{m_s\, m_b}{v^2}\frac{(V_c^*)^{21}V_c^{31}}{M_{\Phi_4}^2\sin^2\beta} \sim -1.4$$



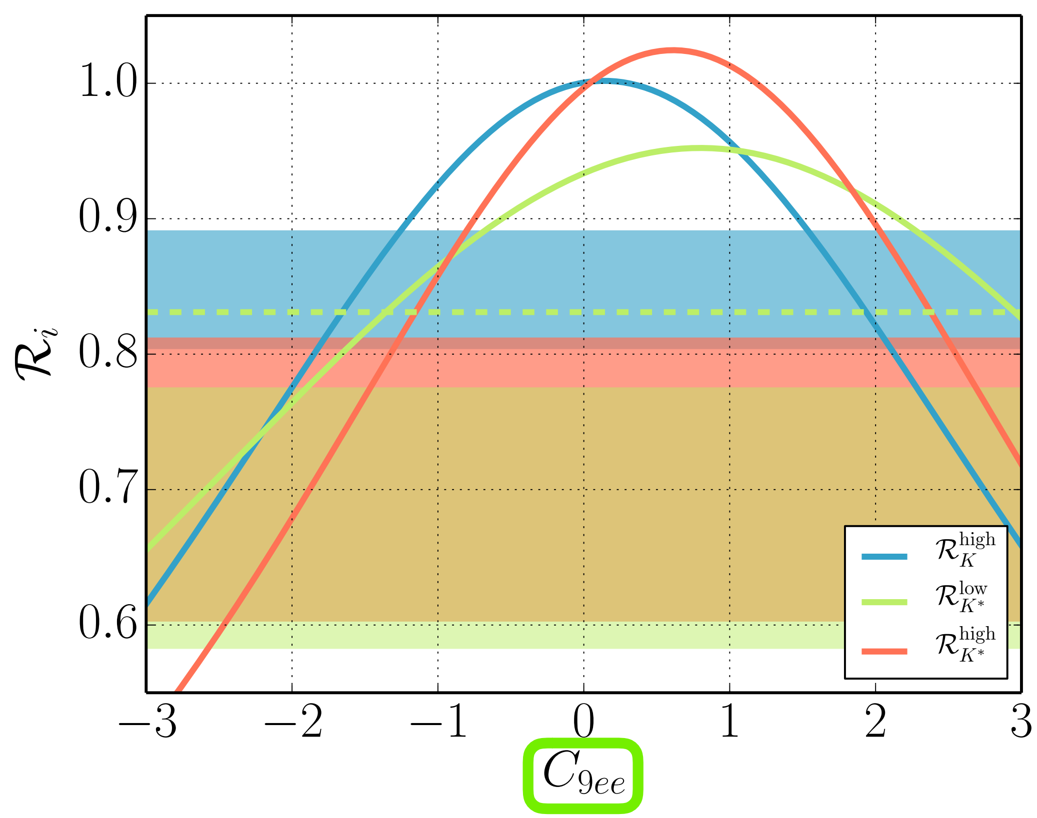
$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta \\ 0 & -1 & 0 \end{pmatrix}$$

Fixing the textures

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau \sin\theta \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau\cos\theta \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$

$$\boxed{C_{9ee}(=C_{10ee})} \propto (G_F)^{-1}\frac{m_s m_b}{v^2}\frac{\sin 2\theta_c}{M_{\Phi_4}^2\sin^2\beta} \sim \quad 1.4$$



$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

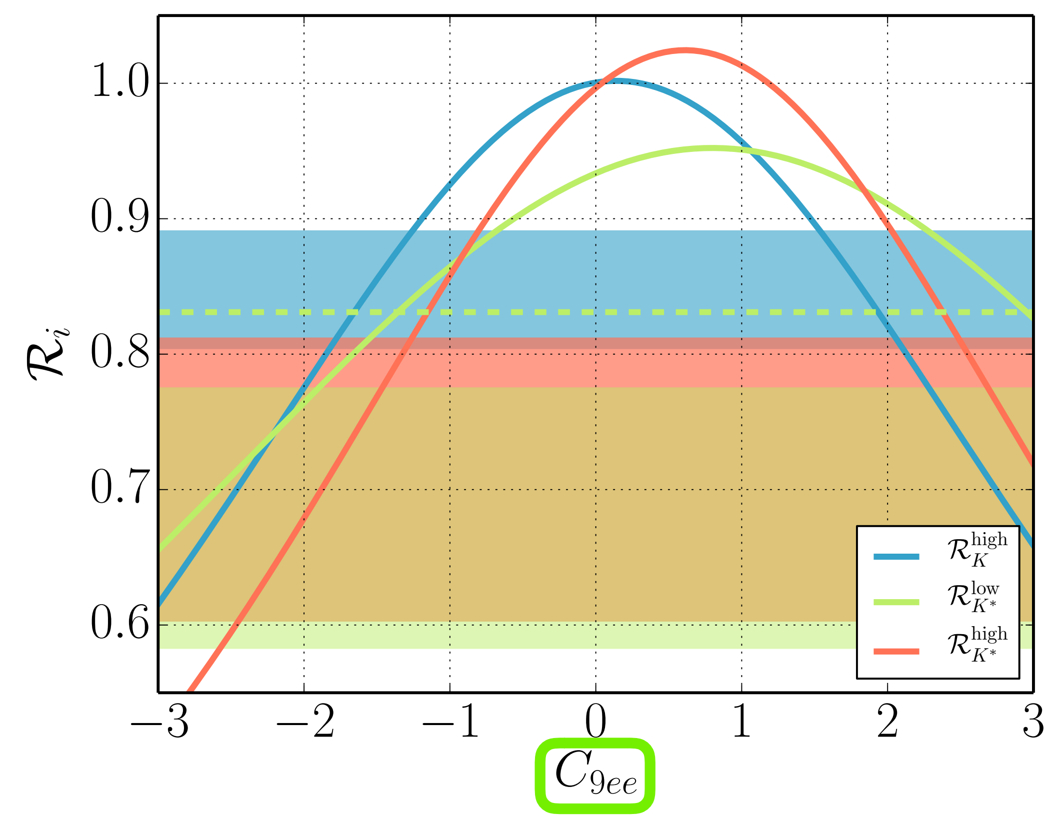
$$V = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta \\ 0 & -1 & 0 \end{pmatrix}$$

Fixing the textures

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau \sin\theta \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau\cos\theta \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$

$$\boxed{C_{9ee}(=C_{10ee})} \propto (G_F)^{-1}\frac{m_s m_b}{v^2}\frac{\sin 2\theta_c}{M_{\Phi_4}^2\sin^2\beta} \sim \quad 1.4$$

$$\boxed{\frac{\sin 2\theta_c}{\sin^2\beta\, M_{\Phi_4}^2} \simeq \frac{1}{1174\ \mathrm{GeV}^2}}$$



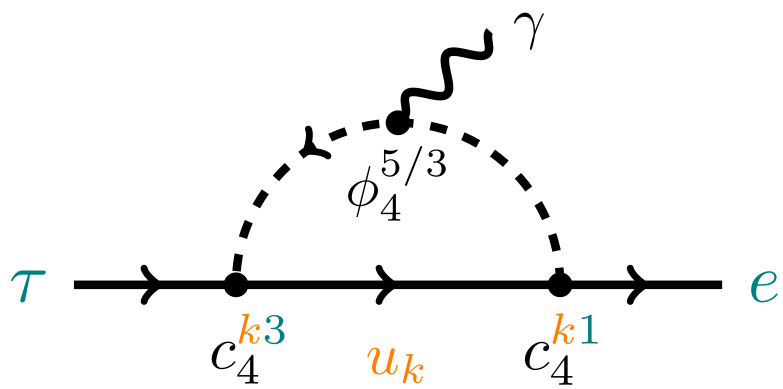
$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta \\ 0 & -1 & 0 \end{pmatrix}$$

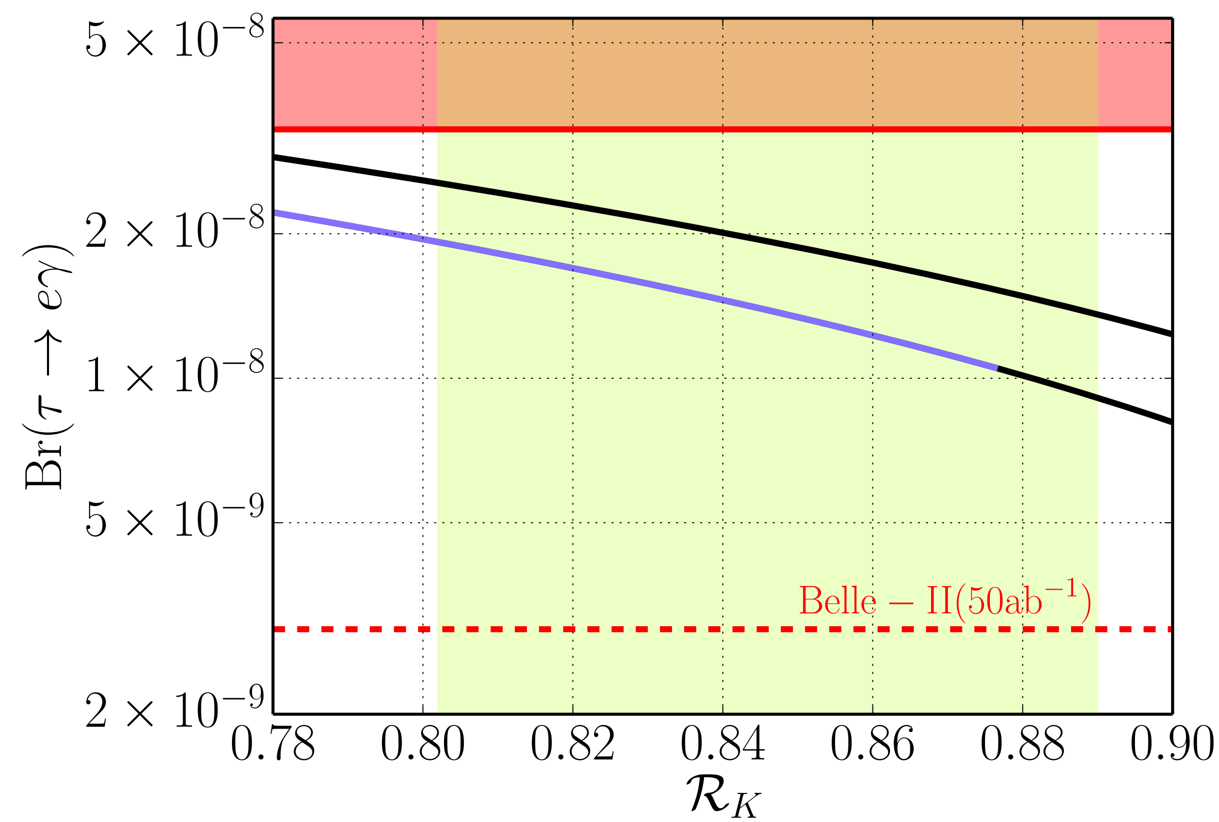
PREDICTIONS

$\tau \to e\gamma$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau \sin\theta \\ -m_s \cos\theta_c & 0 & m_s \sin\theta_c - m_\tau \cos\theta \\ \boxed{m_b \sin\theta_c} & 0 & \boxed{m_b \cos\theta_c} \end{pmatrix}.$$



$$\boxed{\frac{\sin 2\theta_c}{\sin^2\beta\, M_{\Phi_4}^2} \simeq \frac{1}{1174\ \mathrm{GeV}^2}}$$

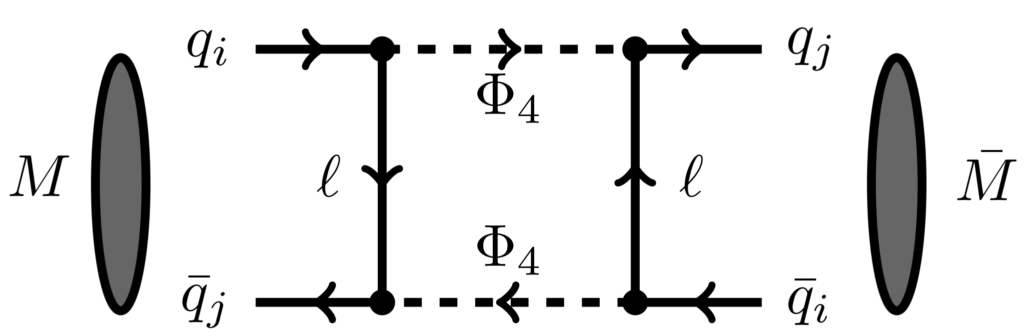


$$\mathrm{Br}(\tau \to e\gamma)_{\mathrm{exp}} < 3.3\times10^{-8}$$ [BaBar, 2009]

$$\mathrm{Br}(\tau \to e\gamma) \simeq \tau_\tau \frac{\alpha}{4} m_\tau^5 \left(\frac{3}{64\pi^2}\right)^2 \left(\frac{3}{2}\right)^2 \frac{m_b^4}{4v^4}\left|\frac{\sin 2\theta_c}{M_{\Phi_4}^2 \sin^2\beta}\right|^2 \simeq 1.1\times10^{-8}$$

Meson mixing

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau \sin\theta \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau\cos\theta \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



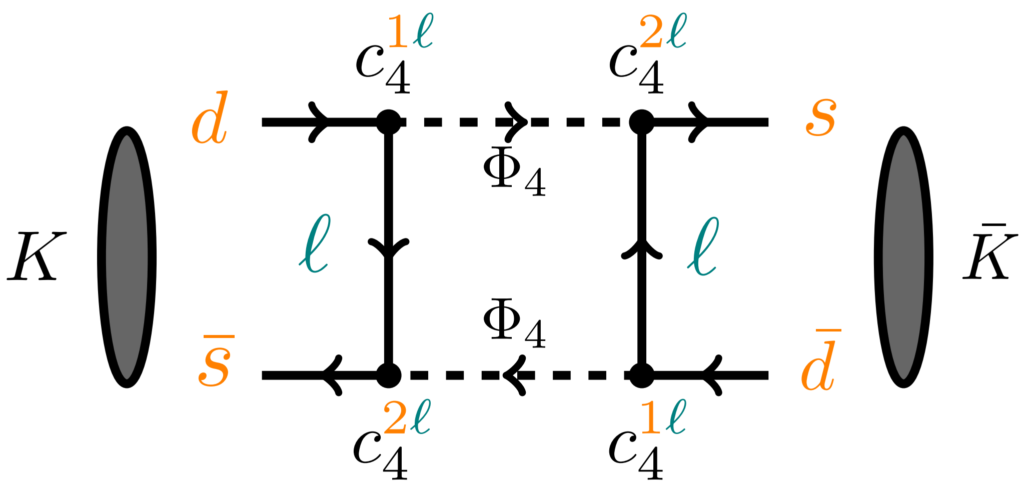
$$H^{\Phi_4}_{\Delta F=2} \simeq \frac{\left(\sum_\ell (c_4^{q_i\ell})^* c_4^{q_j\ell}\right)^2}{128\pi^2 M^2_{\Phi_4}} \left(\bar{q}_i\gamma_\mu P_R\, q_j\right)\left(\bar{q}_i\gamma^\mu P_R\, q_j\right)$$

$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta \\ 0 & -1 & 0 \end{pmatrix}$$

Meson mixing

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau \sin\theta \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau\cos\theta \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



$$K\text{ - }\bar{K} \propto \left(c_4^{23}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.81\ \text{TeV}\left|\frac{\sin 2\theta_c}{\sin 2\theta}\right|$$

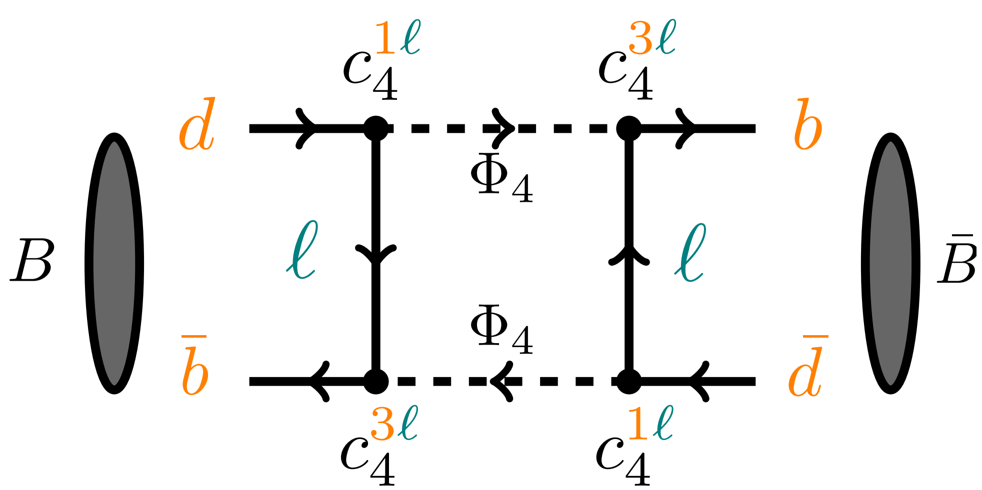
$$H^{\Phi_4}_{\Delta F=2} \simeq \frac{\left(\sum_\ell (c_4^{q_i\ell})^* c_4^{q_j\ell}\right)^2}{128\pi^2 M^2_{\Phi_4}}\left(\bar{q}_i\gamma_\mu P_R\, q_j\right)\left(\bar{q}_i\gamma^\mu P_R\, q_j\right)$$

$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta \\ 0 & -1 & 0 \end{pmatrix}$$

Meson mixing

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & -m_\tau \sin\theta \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau\cos\theta \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



$$K\text{-}\bar{K} \propto \left(c_4^{23}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.81\ \text{TeV}\left|\frac{\sin 2\theta_c}{\sin 2\theta}\right|$$

$$B\text{-}\bar{B} \propto \left(c_4^{33}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.62\ \text{TeV}\left|\frac{\sin \theta_c}{\sin \theta}\right|$$

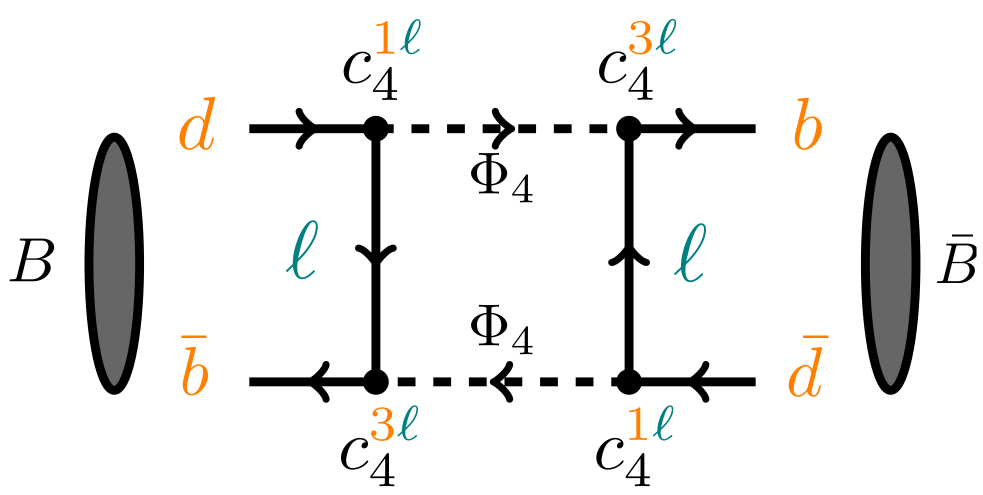
$$H^{\Phi_4}_{\Delta F=2} \simeq \frac{\left(\sum_\ell (c_4^{q_i\ell})^* c_4^{q_j\ell}\right)^2}{128\pi^2 M^2_{\Phi_4}}\left(\bar{q}_i\gamma_\mu P_R\, q_j\right)\left(\bar{q}_i\gamma^\mu P_R\, q_j\right)$$

$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta \\ 0 & -1 & 0 \end{pmatrix}$$

Meson mixing

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



$$K\text{-}\bar{K} \propto \left(c_4^{23}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.81\ \text{TeV}\left|\frac{\sin 2\theta_c}{\sin 2\theta}\right|$$

$$B\text{-}\bar{B} \propto \left(c_4^{33}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.62\ \text{TeV}\left|\frac{\sin\theta_c}{\sin\theta}\right|$$

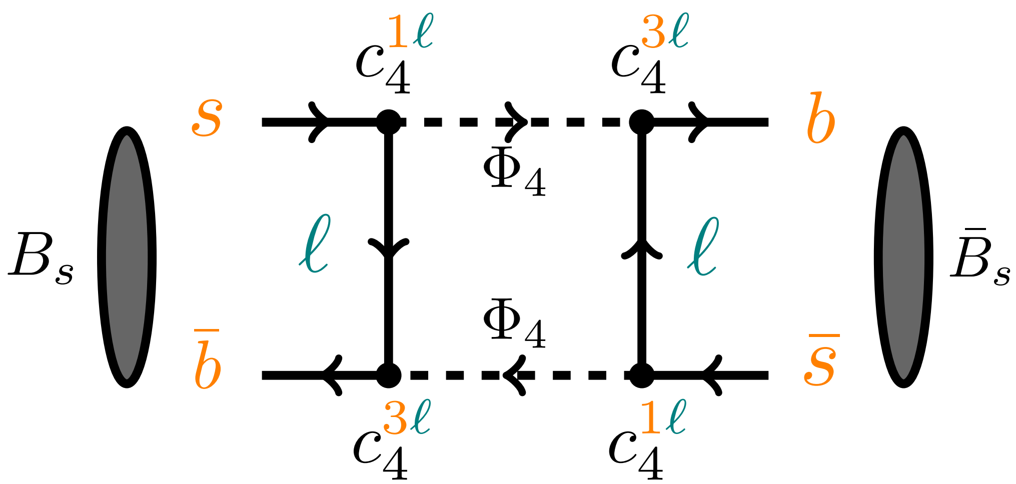
$$H_{\Delta F=2}^{\Phi_4} \simeq \frac{\left(\sum_\ell (c_4^{q_i\ell})^* c_4^{q_j\ell}\right)^2}{128\pi^2 M_{\Phi_4}^2}\left(\bar{q}_i\gamma_\mu P_R\, q_j\right)\left(\bar{q}_i\gamma^\mu P_R\, q_j\right)$$

$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix}$$

Meson mixing

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ \boxed{-m_s\cos\theta_c} & 0 & m_s\sin\theta_c - m_\tau \\ \boxed{m_b\sin\theta_c} & 0 & m_b\cos\theta_c \end{pmatrix}.$$



$$K\text{-}\bar{K} \propto \left(c_4^{23}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.81\ \text{TeV}\left|\frac{\sin 2\theta_c}{\sin 2\theta}\right|$$

$$B\text{-}\bar{B} \propto \left(c_4^{33}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.62\ \text{TeV}\left|\frac{\sin \theta_c}{\sin \theta}\right|$$

$$B_s\text{-}\bar{B}_s \propto \left(c_4^{31}(c_4^{21})^* + c_4^{33}(c_4^{23})^*\right)^2$$

$$\Rightarrow M_{\Phi_4} \lesssim 3.0\ \text{TeV}\left|\frac{\sin \theta_c}{\cos \theta}\right|$$

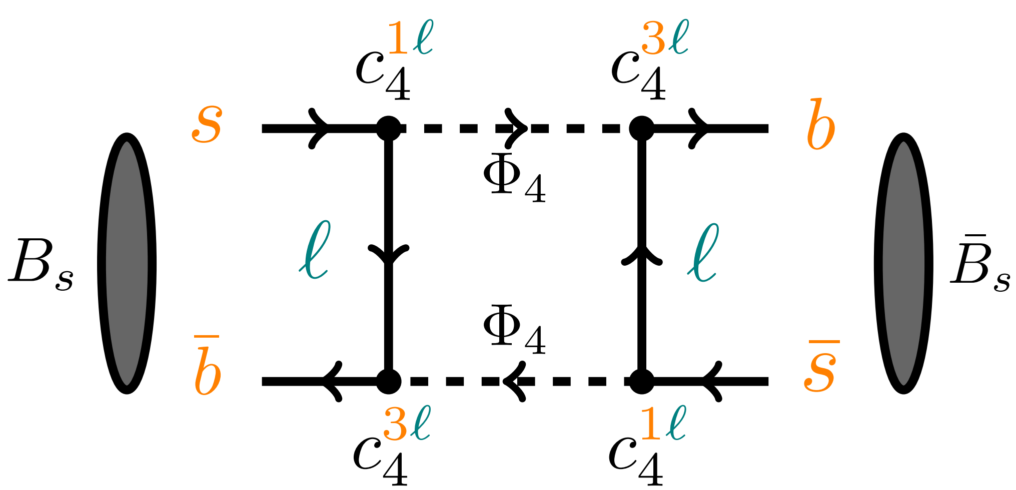
$$H_{\Delta F=2}^{\Phi_4} \simeq \frac{\left(\sum_\ell (c_4^{q_i\ell})^* c_4^{q_j\ell}\right)^2}{128\pi^2 M_{\Phi_4}^2}\left(\bar{q}_i\gamma_\mu P_R\, q_j\right)\left(\bar{q}_i\gamma^\mu P_R\, q_j\right)$$

$$V_c = \begin{pmatrix} \epsilon & 1 & \epsilon' \\ -\cos\theta_c & \epsilon\cos\theta_c - \epsilon'\sin\theta_c & \sin\theta_c \\ \sin\theta_c & -\epsilon\sin\theta_c + \epsilon'\cos\theta_c & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix}$$

Meson mixing

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



$$K\text{-}\bar{K} \propto \left(c_4^{23}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.81\ \text{TeV}\left|\frac{\sin 2\theta_c}{\sin 2\theta}\right|$$

$$B\text{-}\bar{B} \propto \left(c_4^{33}(c_4^{13})^*\right)^2 \Rightarrow M_{\Phi_4} \lesssim 0.62\ \text{TeV}\left|\frac{\sin\theta_c}{\sin\theta}\right|$$

$$B_s\text{-}\bar{B}_s \propto \left(c_4^{31}(c_4^{21})^* + c_4^{33}(c_4^{23})^*\right)^2$$

$$\Rightarrow M_{\Phi_4} \lesssim 3.0\ \text{TeV}\left|\frac{\sin\theta_c}{\cos\theta}\right|$$

$$H_{\Delta F=2}^{\Phi_4} \simeq \frac{\left(\sum_\ell (c_4^{q_i\ell})^* c_4^{q_j\ell}\right)^2}{128\pi^2 M_{\Phi_4}^2}\left(\bar{q}_i\gamma_\mu P_R\, q_j\right)\left(\bar{q}_i\gamma^\mu P_R\, q_j\right)$$

$$V_c = \begin{pmatrix} \frac{m_\mu}{m_b\sin\theta_c} & 1 & 0 \\ -\cos\theta_c & 0 & \sin\theta_c \\ \sin\theta_c & m_\mu/m_b & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix}$$

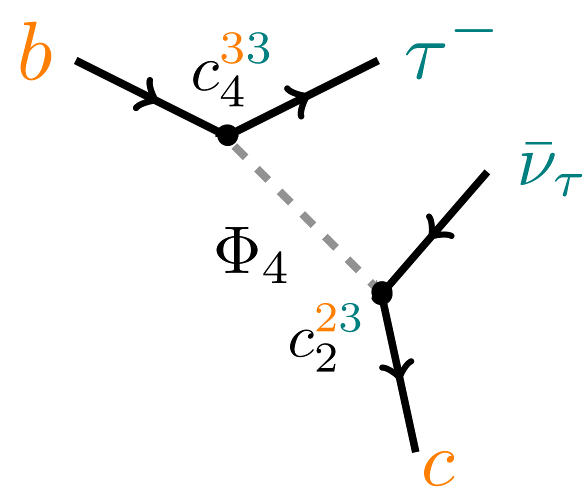
Extra: Charged Anomalies

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$

$$\mathcal{H}_{\text{eff}}^{b\to c} \supset \frac{c_2^{il}(c_4^*)^{jk}}{2M_{\Phi_4}^2}\left[(\bar{u}_R^i d_L^j)(\bar{e}_R^k \nu_L^l) + \frac{1}{4}(\bar{u}_R^i \sigma^{\mu\nu} d_L^j)(\bar{e}_R^k \sigma_{\mu\nu}\nu_L^l)\right] + \text{h.c.}$$

$c_2 = U_C^T Y_2^T N$

$$\boxed{C_{LL}^S = 4\,r\,C_{LL}^T \propto (G_F)^{-1}\frac{c_2^{23}(c_4^{33})^*}{2M_{\Phi_4}^2}}$$



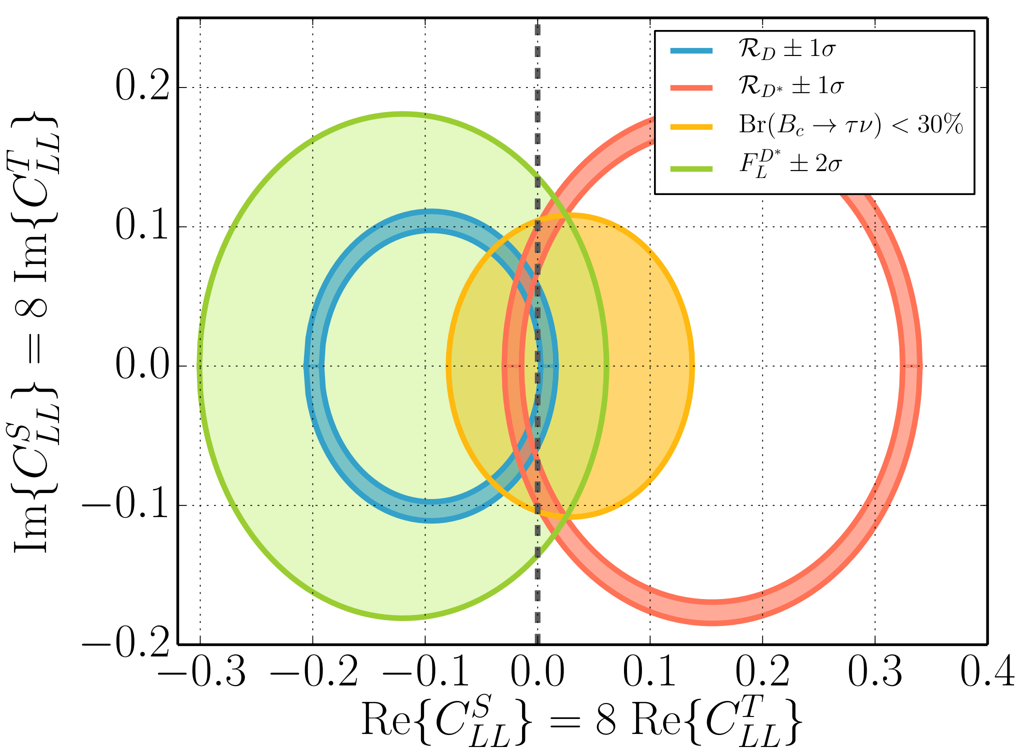
Extra: Charged Anomalies

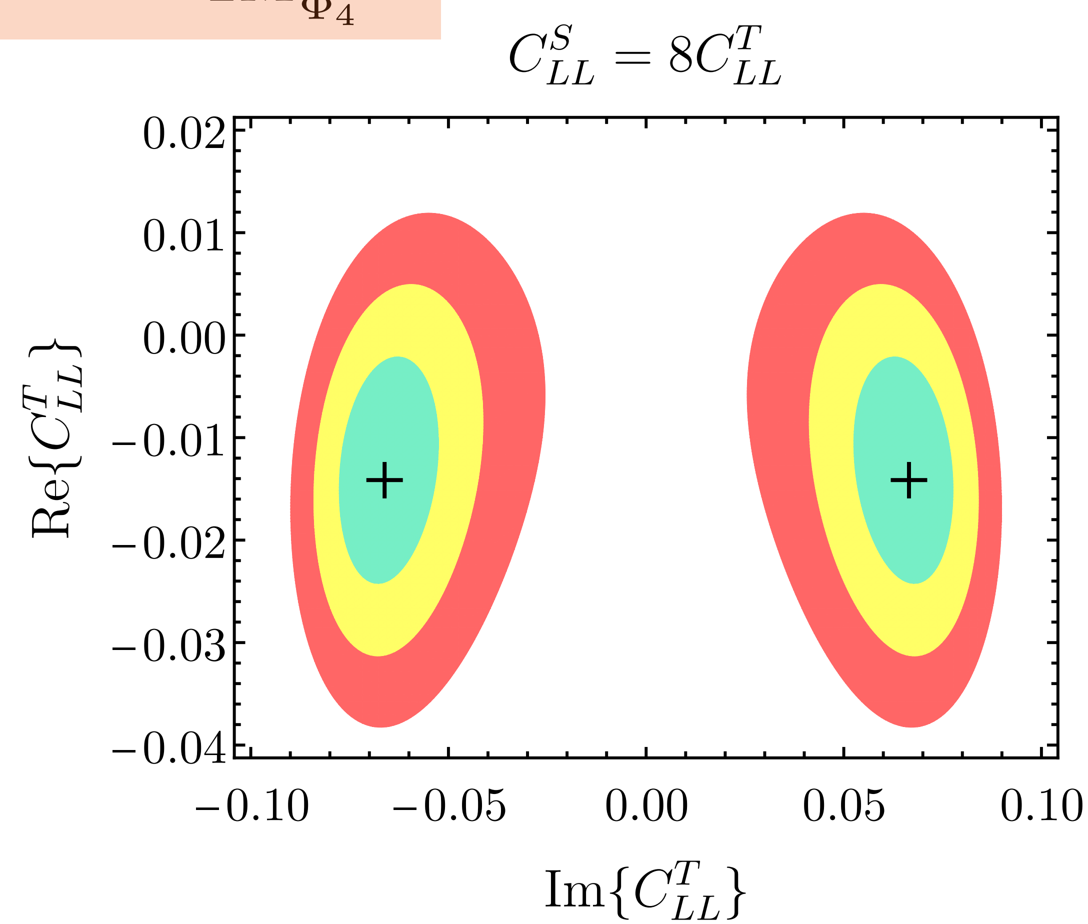
$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & \boxed{m_b\cos\theta_c} \end{pmatrix}.$$

$$\mathcal{H}_{\text{eff}}^{b\to c} \supset \frac{c_2^{il}(c_4^*)^{jk}}{2M_{\Phi_4}^2}\left[(\bar{u}_R^i d_L^j)(\bar{e}_R^k \nu_L^l) + \frac{1}{4}(\bar{u}_R^i \sigma^{\mu\nu} d_L^j)(\bar{e}_R^k \sigma_{\mu\nu}\nu_L^l)\right] + \text{h.c.}$$

$$c_2 = U_C^T Y_2^T N$$

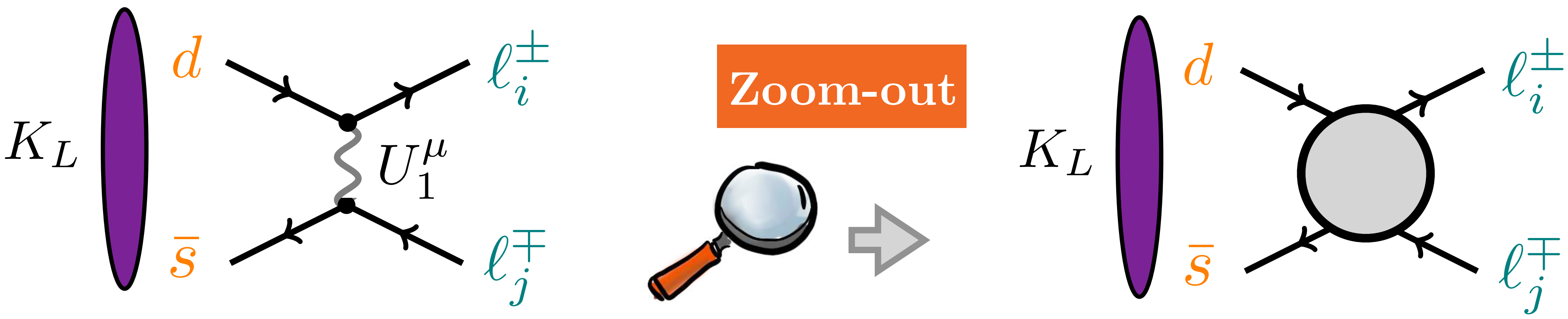
$$C_{LL}^S = 4\,r\,C_{LL}^T \propto (G_F)^{-1}\frac{c_2^{23}(c_4^{33})^*}{2M_{\Phi_4}^2}$$





Quark-Lepton Unification Scale

$$\bar{d}_i e_j U_1^\mu : \qquad i\,\frac{g_4}{\sqrt{2}}\,\left[V^{ij} P_R + (V_c^*)^{ij} P_L\right]\gamma^\mu$$



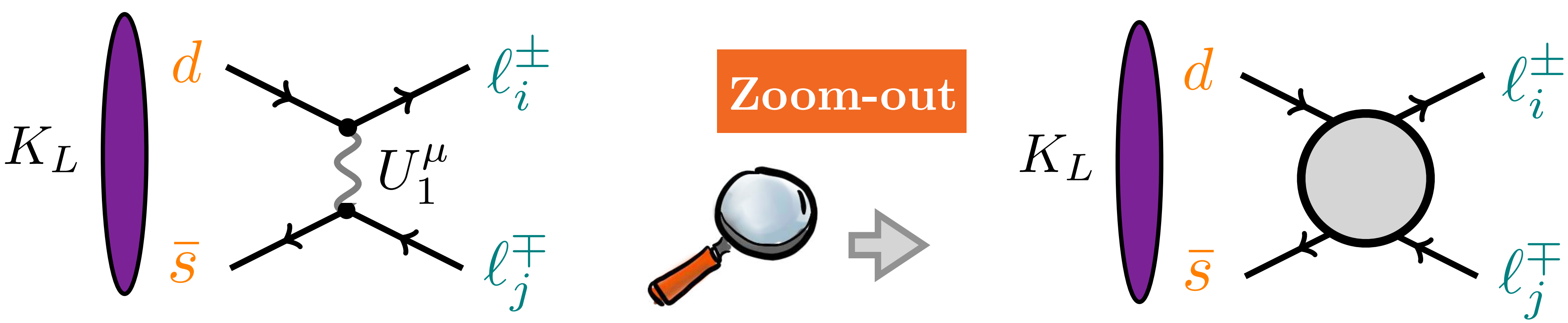
$$\mathrm{Br}(K_L \to \mu^\pm e^\mp) \propto \left(\left| (C_9 - C_9')^{\bar{\ell}_i \ell_j \bar{d}_k d_\ell} (m_{\ell_1} - m_{\ell_2}) + (C_S - C_S')^{\bar{\ell}_i \ell_j \bar{d}_k d_\ell} \frac{m_M^2}{m_{d_k} + m_{d_l}} \right|^2 + \left| (C_{10} - C_{10}')^{\bar{\ell}_i \ell_j \bar{d}_k d_\ell} (m_{\ell_1} + m_{\ell_2}) + (C_P - C_P')^{\bar{\ell}_i \ell_j \bar{d}_k d_\ell} \frac{m_M^2}{m_{d_k} + m_{d_l}} \right|^2 \right)$$

$$V_c = \begin{pmatrix} \frac{m_\mu}{m_b \sin\theta_c} & 1 & 0 \\ -\cos\theta_c & 0 & \sin\theta_c \\ \sin\theta_c & m_\mu/m_b & \cos\theta_c \end{pmatrix}$$

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix}$$

Quark-Lepton Unification Scale

$$\bar{d}_i e_j U_1^\mu : \qquad i\,\frac{g_4}{\sqrt{2}}\left[V^{ij} P_R + (V_c^*)^{ij} P_L\right]\gamma^\mu$$



$$\mathrm{Br}(K_L \to \mu^\pm e^\mp) \propto \left(\left| (C_9 - C_9')^{\bar{\ell}_i \ell_j \bar{d}_k d_\ell}(m_{\ell_1} - m_{\ell_2}) + (C_S - C_S')^{\bar{\ell}_i \ell_j \bar{d}_k d_\ell} \frac{m_M^2}{m_{d_k} + m_{d_l}} \right|^2 + \left| (C_{10} - C_{10}')^{\bar{\ell}_i \ell_j \bar{d}_k d_\ell}(m_{\ell_1} + m_{\ell_2}) + (C_P - C_P')^{\bar{\ell}_i \ell_j \bar{d}_k d_\ell} \frac{m_M^2}{m_{d_k} + m_{d_l}} \right|^2 \right)$$

$$V_c = \begin{pmatrix} \frac{m_\mu}{m_b \sin\theta_c} & 1 & 0 \\ -\cos\theta_c & 0 & \sin\theta_c \\ \sin\theta_c & m_\mu/m_b & \cos\theta_c \end{pmatrix}$$

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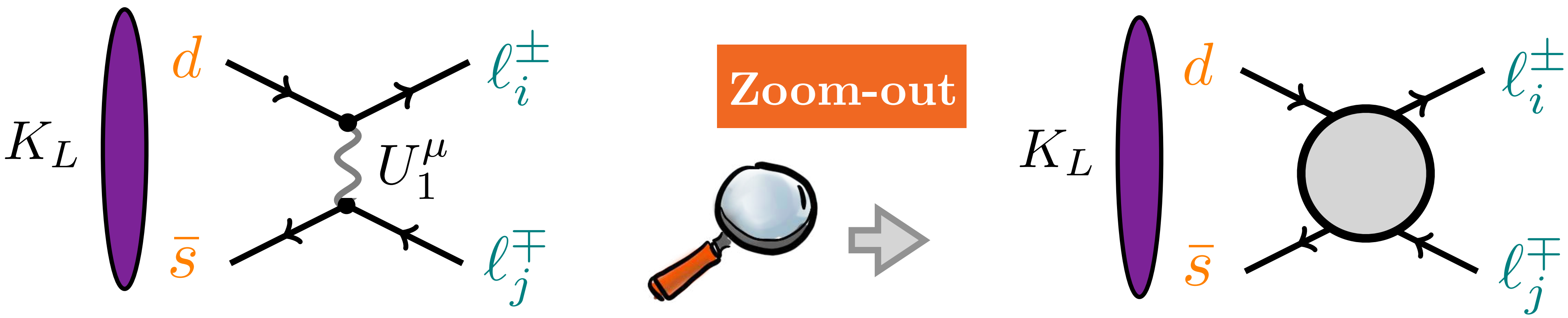

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$$\left. + \left|(C_{10} - C_{10}')^{\bar{\ell}_i\ell_j\bar{d}_k d_\ell}(m_{\ell_1} + m_{\ell_2}) + (C_P - C_P')^{\bar{\ell}_i\ell_j\bar{d}_k d_\ell}\frac{m_M^2}{m_{d_k}+m_{d_l}}\right|^2\right)$$

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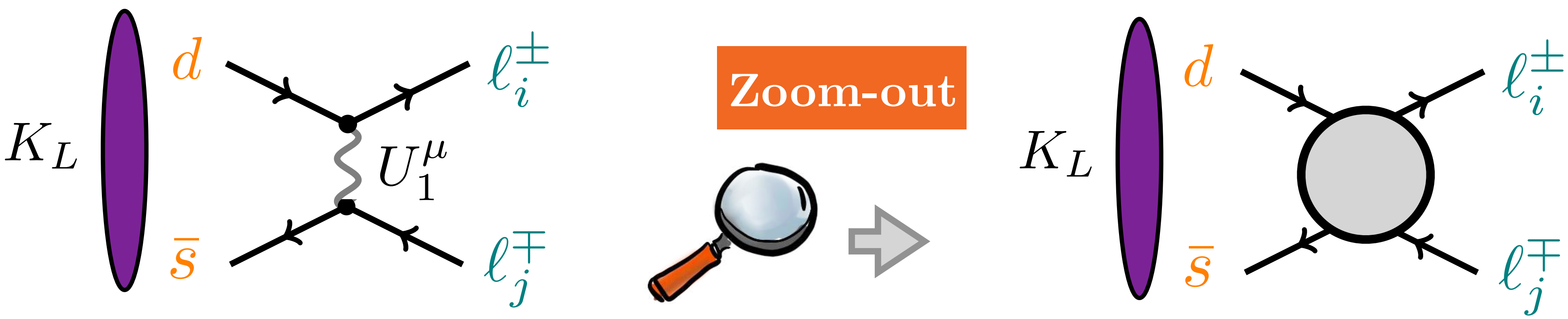

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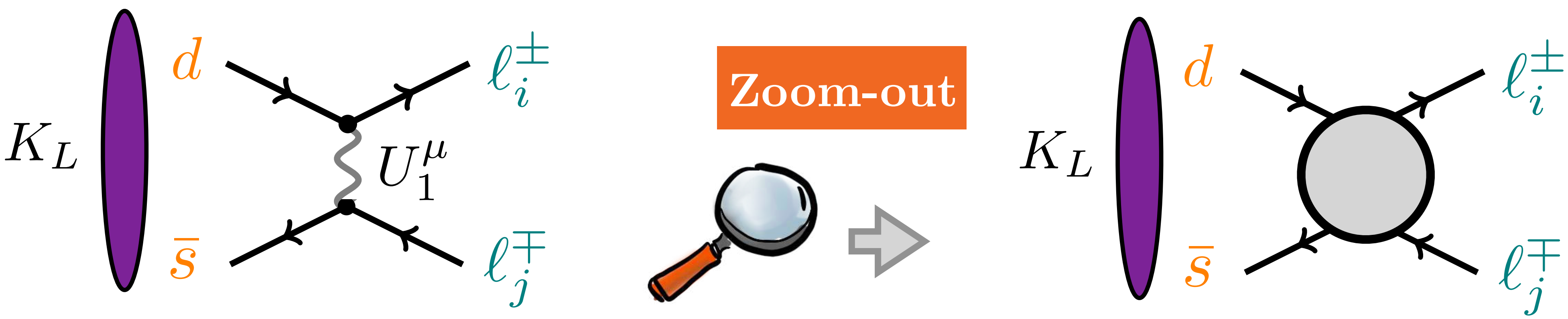

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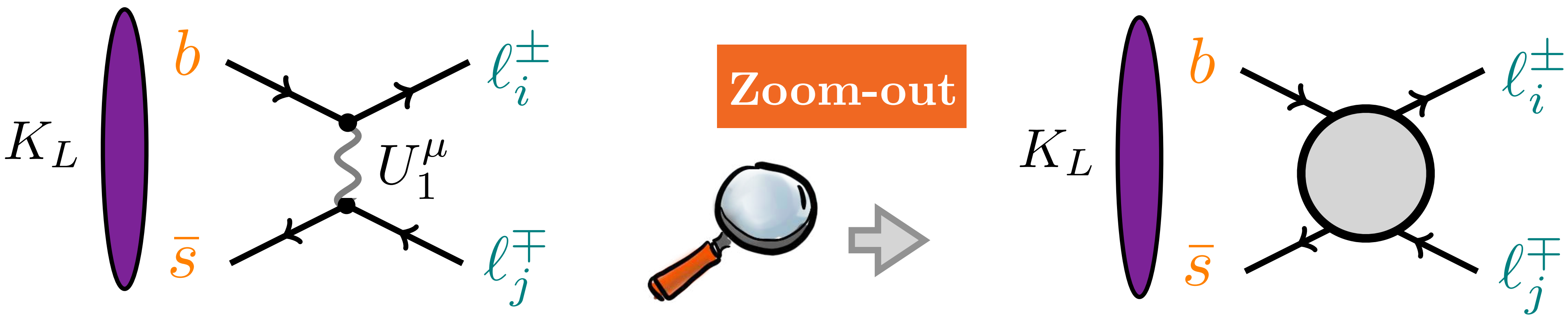

$$\mathrm{Br}(K_L \to \mu^\pm e^\mp) \propto \Bigg(\left|(C_9 - C_9')^{\bar{\ell}_i\ell_j\bar{d}_k d_\ell}(m_{\ell_1} - m_{\ell_2}) + \cancel{(C_S - C_S')^{\bar{\ell}_i\ell_j\bar{d}_k d_\ell}\frac{m_M^2}{m_{d_k}+m_{d_l}}}\right|^2$$

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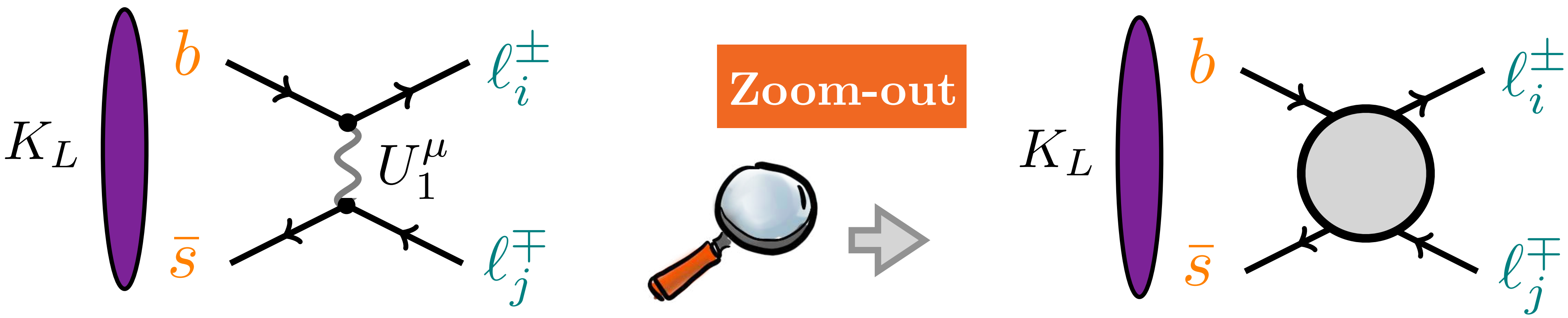

$$\frac{g_4^2}{4M_{U_1}^2}V_c^{12}(V_c^{21})^*$$

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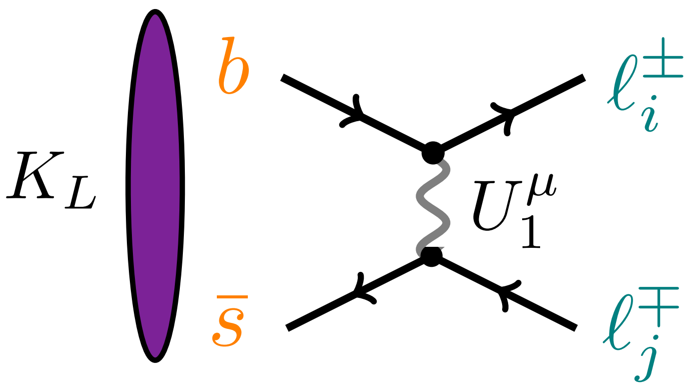

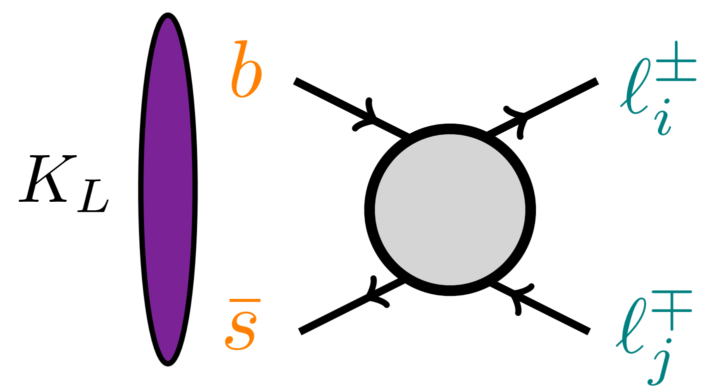

$$\frac{g_4^2}{4M_{U_1}^2}V_c^{12}(V_c^{21})^*$$

$$\mathrm{Br}^{U_1}_{K_L\to\mu^\pm e^\mp} \simeq \frac{\tau_{K_L}\pi}{32}\frac{f_K^2}{m_K^3}(m_K^2 - m_\mu^2)^2 m_\mu^2\left(\frac{\alpha_4}{M_{U_1}^2}\right)^2 \cos^2\theta_c$$

Reminder

$$B_s\text{-}\bar{B}_s \propto \left(c_4^{31}(c_4^{21})^* + c_4^{33}(c_4^{23})^*\right)^2$$

$$\Rightarrow M_{\Phi_4} \lesssim 3.0\ \mathrm{TeV}\left|\frac{\sin\theta_c}{\cos\theta}\right|$$

$$V_c = \begin{pmatrix} \frac{m_\mu}{m_b\sin\theta_c} & 1 & 0 \\ -\cos\theta_c & 0 & \sin\theta_c \\ \sin\theta_c & m_\mu/m_b & \cos\theta_c \end{pmatrix}$$

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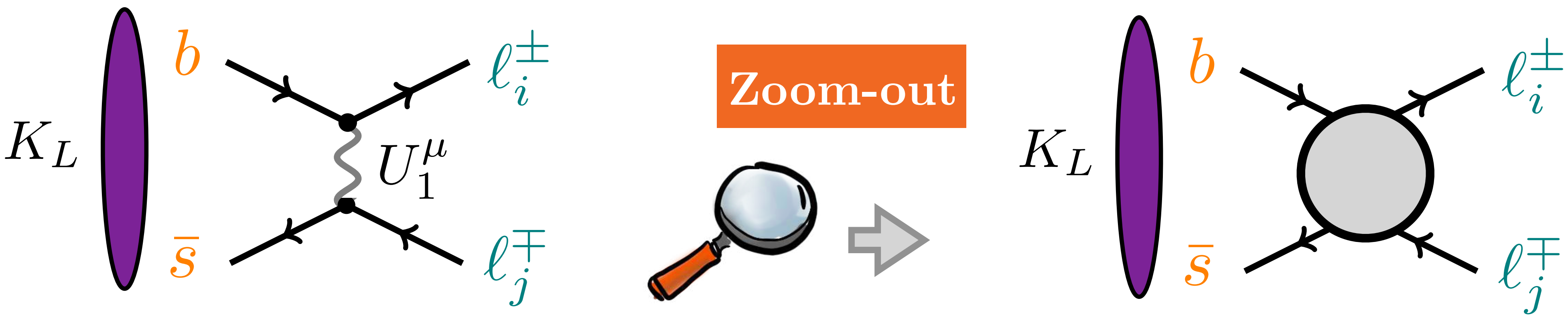

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$$\boxed{M_{U_1} \gtrsim 74\ \text{TeV}\left(\frac{\alpha_4}{0.118}\right)^{1/2}\left|\frac{\cos\theta_c}{0.1}\right|^{1/2}}$$

$$V_c = \begin{pmatrix} \frac{m_\mu}{m_b\sin\theta_c} & 1 & 0 \\ -\cos\theta_c & 0 & \sin\theta_c \\ \sin\theta_c & m_\mu/m_b & \cos\theta_c \end{pmatrix}$$

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Summary

Different experiments (LHCb, B-factories) have reported deviations of LFU

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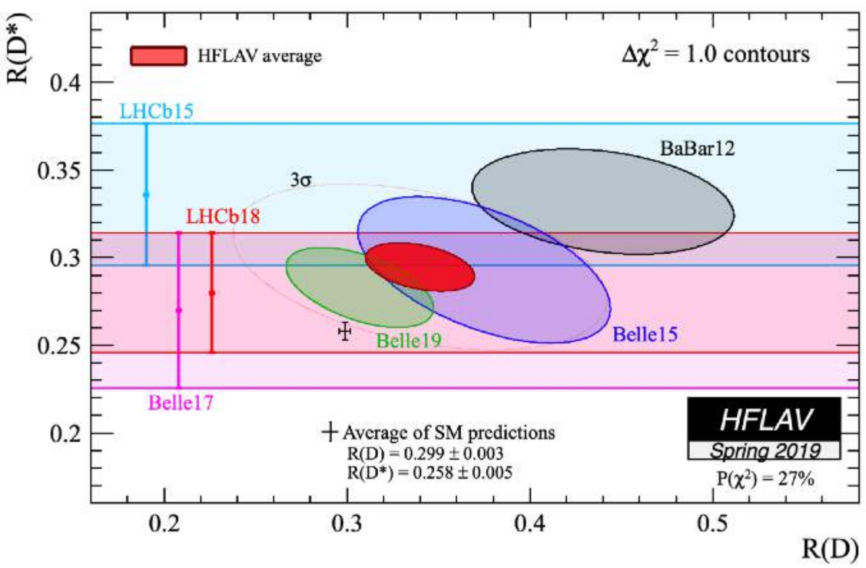
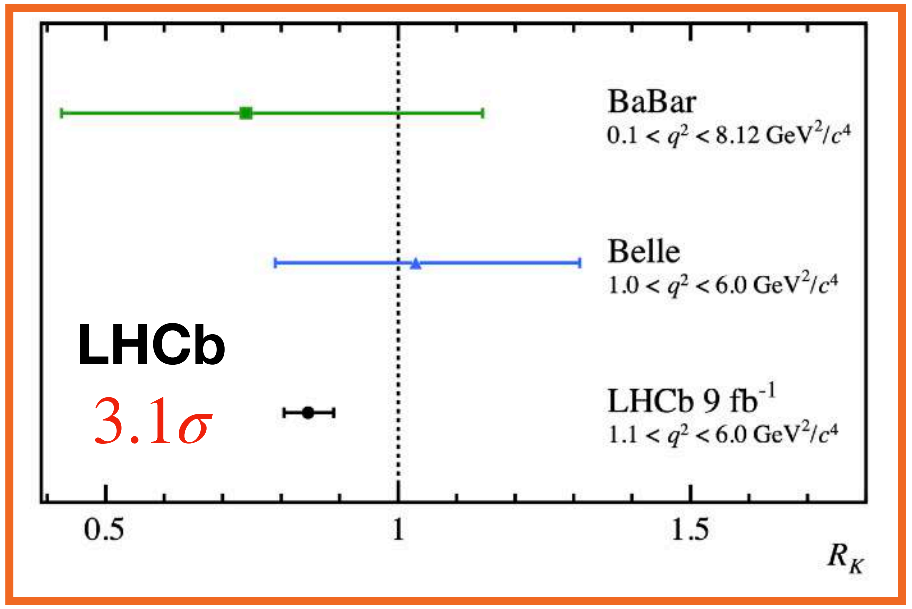
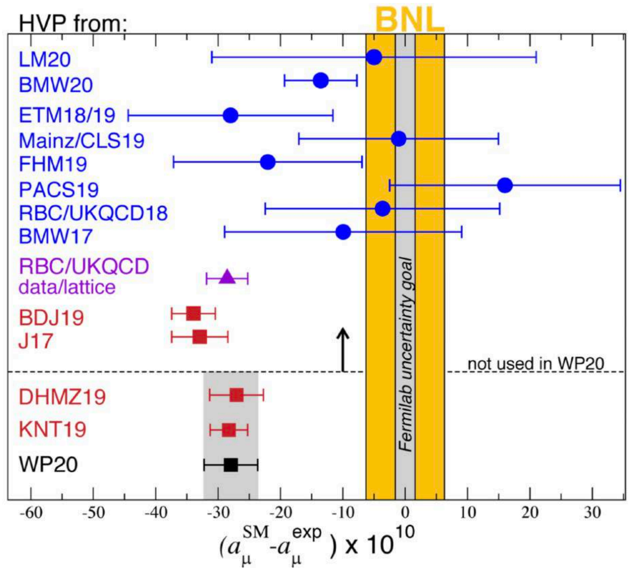


Charged anomalies

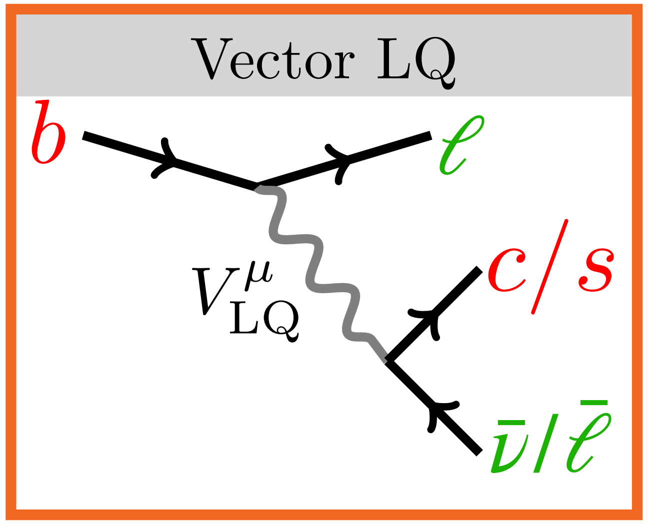


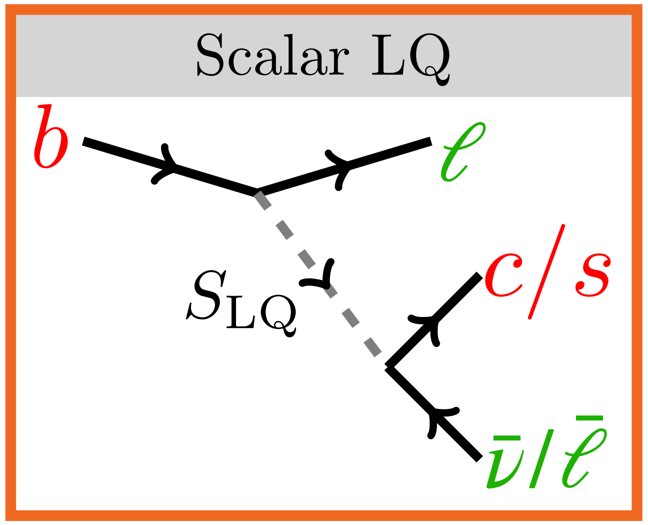
Neutral anomalies



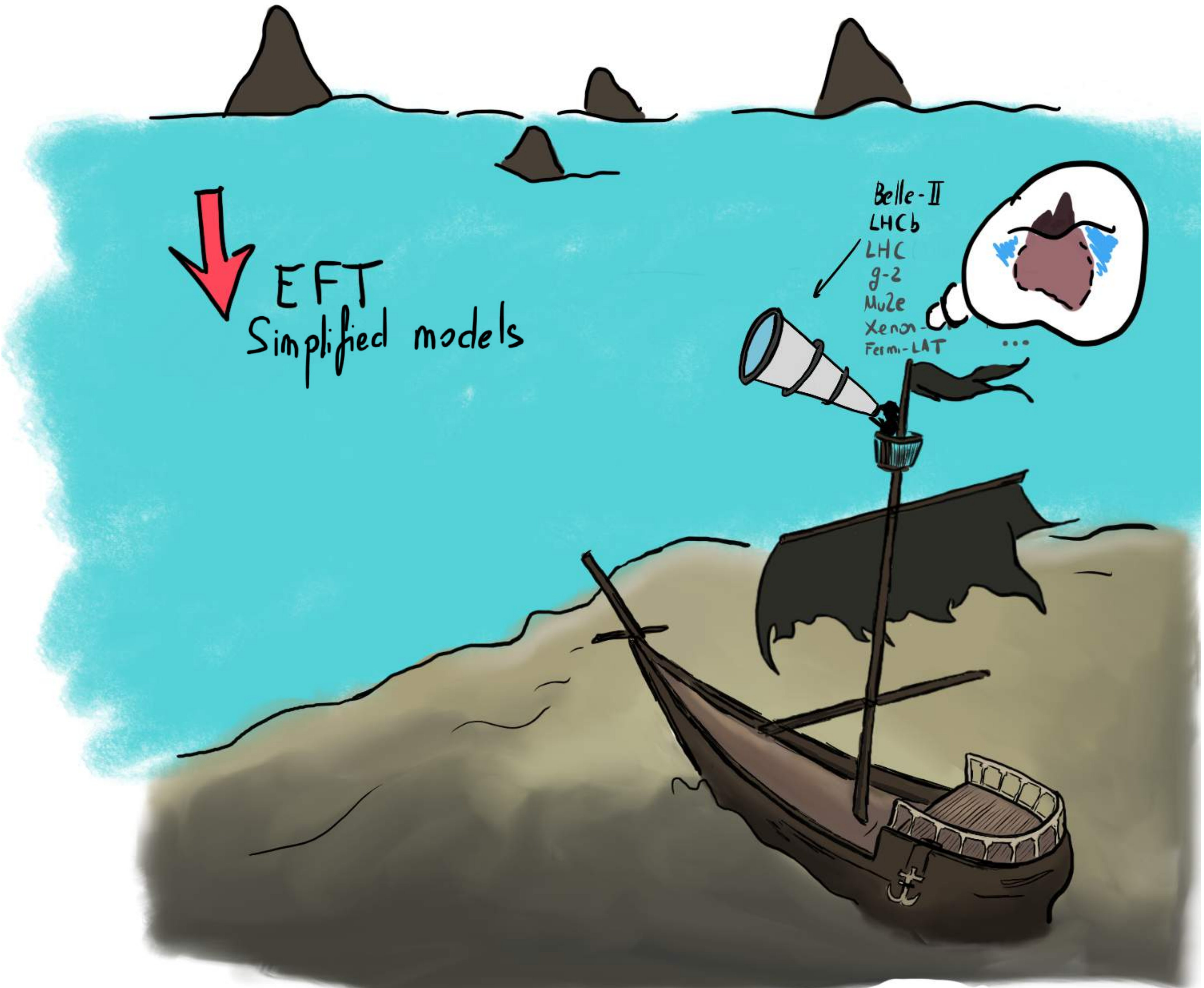
(g-2) ????

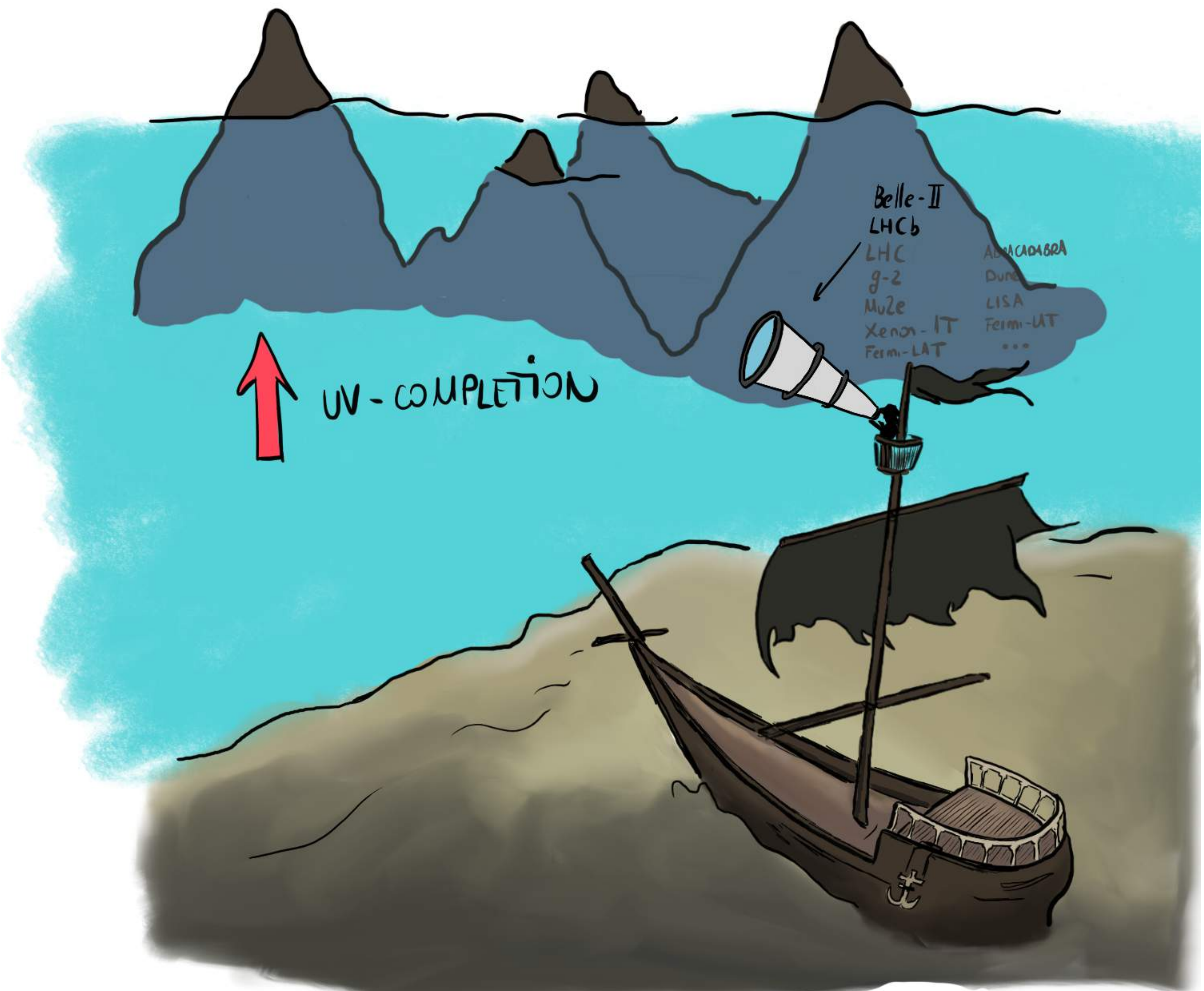
Leptoquarks are kind of nice





Hints of TeV scale physics!


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



UV-COMPLETION
Belle-II
LHCb
LHC
g-2
Mu2e
Xenon-1T
Fermi-LAT
ABRACADABRA
LISA
Fermi-LAT
...

Quark-Lepton Unification

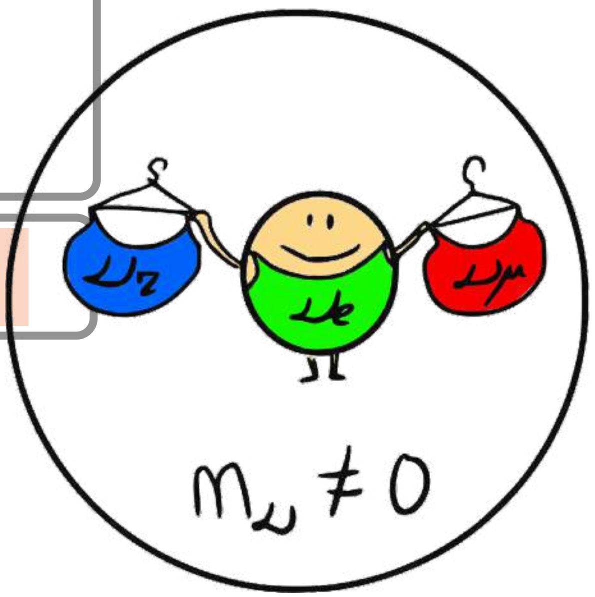
$$SU(4) \otimes SU(2) \otimes U(1)_R$$

Very economical fermion content [Pati, Salam, 1974]

Quarks

Q_L	d_R	u_R
Q_L	d_R	u_R
Q_L	d_R	u_R
ℓ_L	e_R	ν_R

Leptons



Quark-Lepton Unification

$$\mathrm{SU}(4) \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)_R$$

- Very economical fermion content
- **Quarks and leptons are treated under the same footing**

[Pati, Salam, 1974]

$$\underbrace{\begin{pmatrix} Q_L \\ Q_L \\ Q_L \\ \ell_L \end{pmatrix}}_{F_{QL}} \quad \underbrace{\begin{pmatrix} d_R \\ d_R \\ d_R \\ e_R \end{pmatrix}}_{F_d} \quad \underbrace{\begin{pmatrix} u_R \\ u_R \\ u_R \\ \nu_R \end{pmatrix}}_{F_u}$$

Quark-Lepton Unification

$$\mathrm{SU}(4) \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)_R$$

- Very economical fermion content
- Quarks and leptons are treated under the same footing
- **Only one step away from the SM**

[Smirnov, 1995], [Fileviez-Perez, Wise, 2013]

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

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

Quark-Lepton Unification

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

- Very economical fermion content
- Quarks and leptons are treated under the same footing
- Only one step away from the SM
- **Allows for a unification framework** [Pati, Salam, 1974]

$$SO(10) \supset \; SU(4) \otimes SU(2) \otimes U(1)_R$$

Quark-Lepton Unification

$$\mathrm{SU}(4) \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)_R$$

- Very economical fermion content
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- Allows for a unification framework
- **Predicts fermion flavor violation**

[Smirnov, 1995], [Fileviez-Perez, Wise, 2013]

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\mathrm{MW}} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2,$$

$$\boxed{Y_4 = \sqrt{\frac{3}{2}} \frac{M_D - M_E}{v \sin\beta}}$$

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$$\mathrm{SU}(4) \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)_R$$

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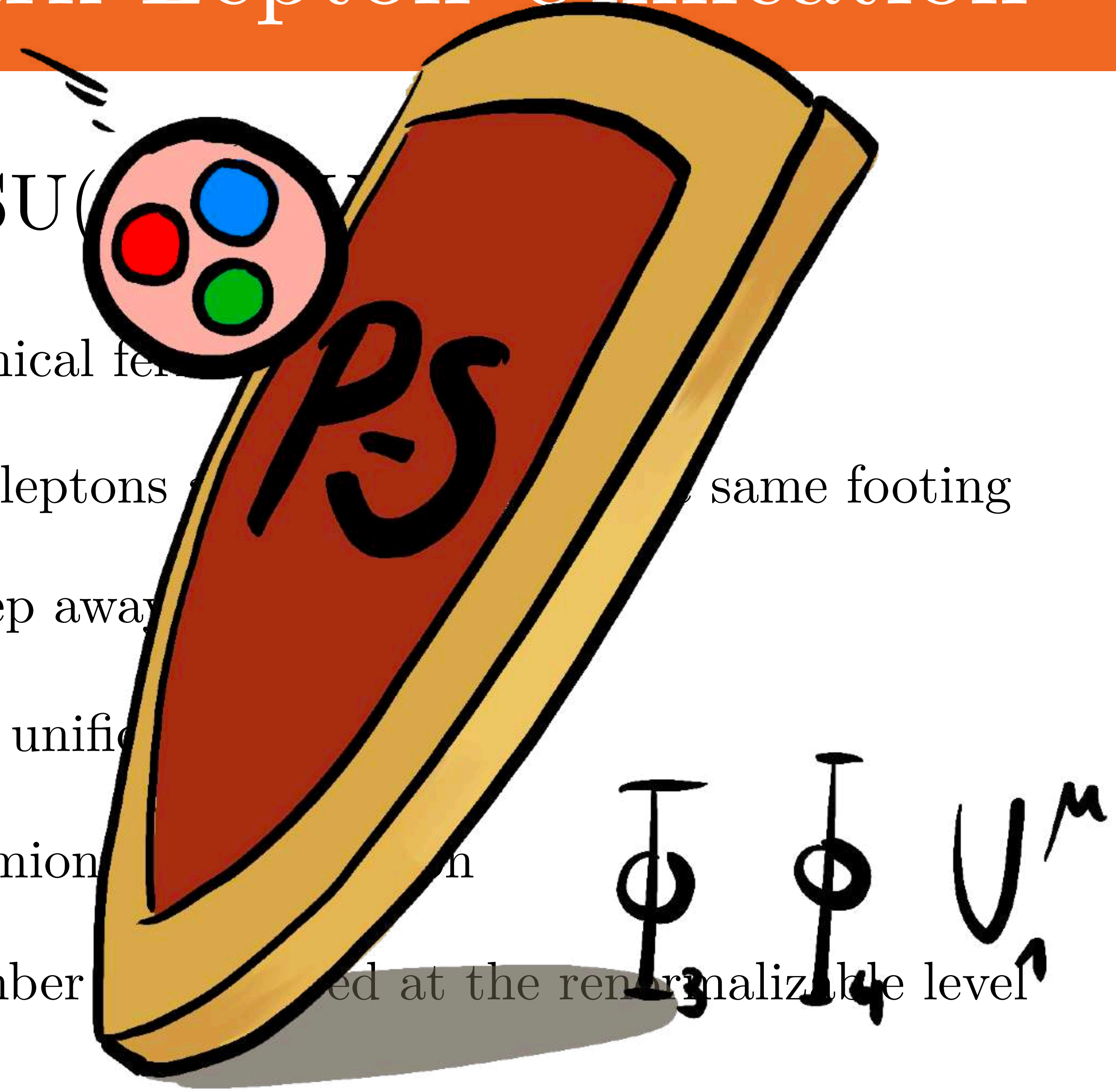
- Predicts fermion flavor violation
- **Baryon number is preserved at the renormalizable level**

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

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

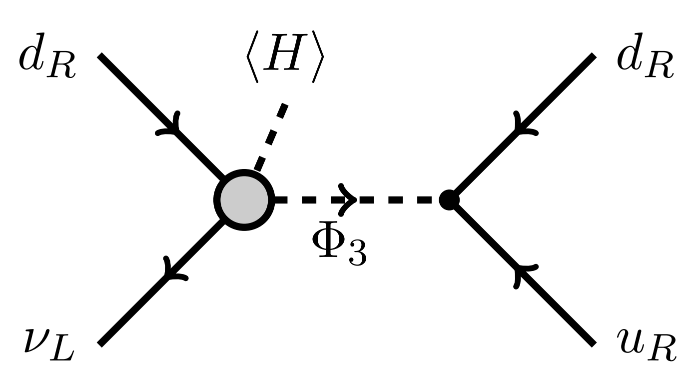
Quark-Lepton Unification

SU(



- Very economical fe
- Quarks and leptons … same footing
- Only one step awa
- Allows for a unific
- Predicts fermion … n
- Baryon number … ed at the renormalizable level
- **PS-symmetry protects baryon number at the non-renormalizable too!**

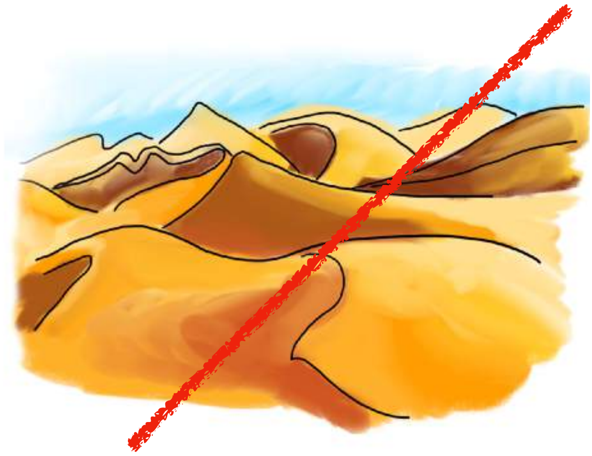
[**C.M**, Wise, 2021]



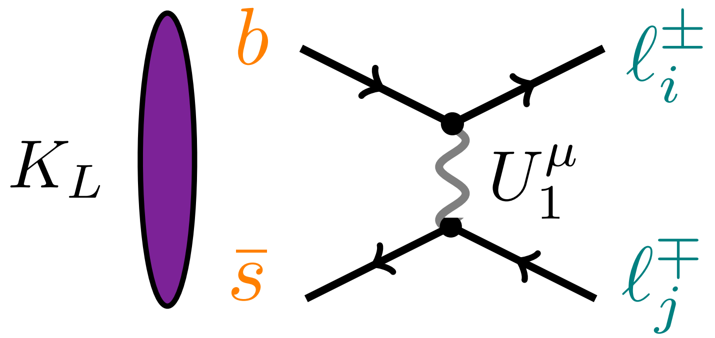
Quark-Lepton Unification

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

- Very economical fermion content
- Quarks and leptons are treated under the same footing
- Only one step away from the SM
- Allows for a unification framework
- Predicts fermion flavor violation
- Baryon number is preserved at the renormalizable level
- PS-symmetry protects baryon number at the non-renormalizable too!
- **Can be realized at the low scale**



[Fileviez-Perez, Wise, 2013], [Fileviez-Perez, **C.M.**, 2022]



$$\boxed{M_{U_1} \gtrsim 74 \text{ TeV} \left(\frac{\alpha_4}{0.118}\right)^{1/2} \left|\frac{\cos\theta_c}{0.1}\right|^{1/2}}$$

Quark-Lepton Unification

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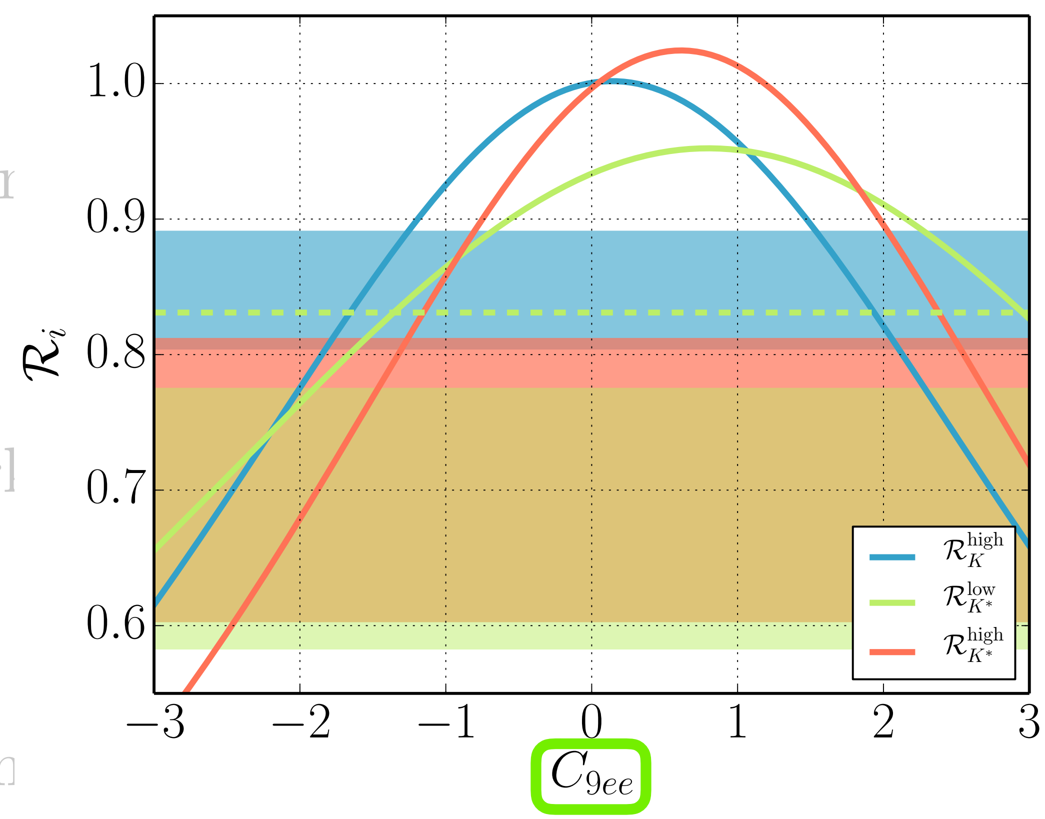
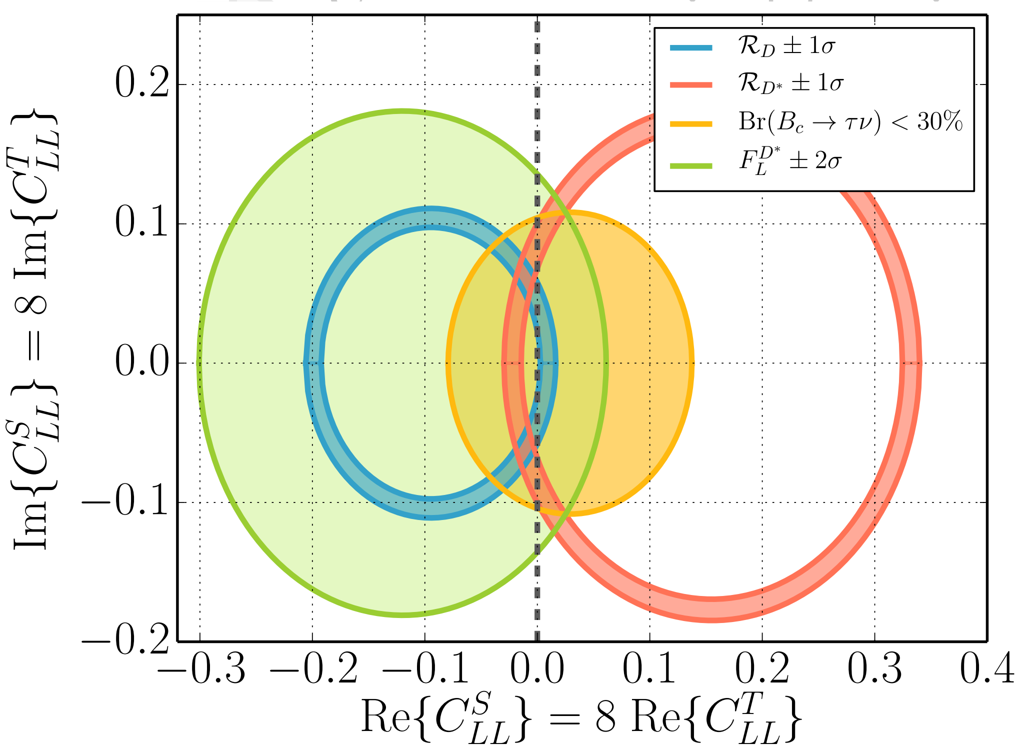


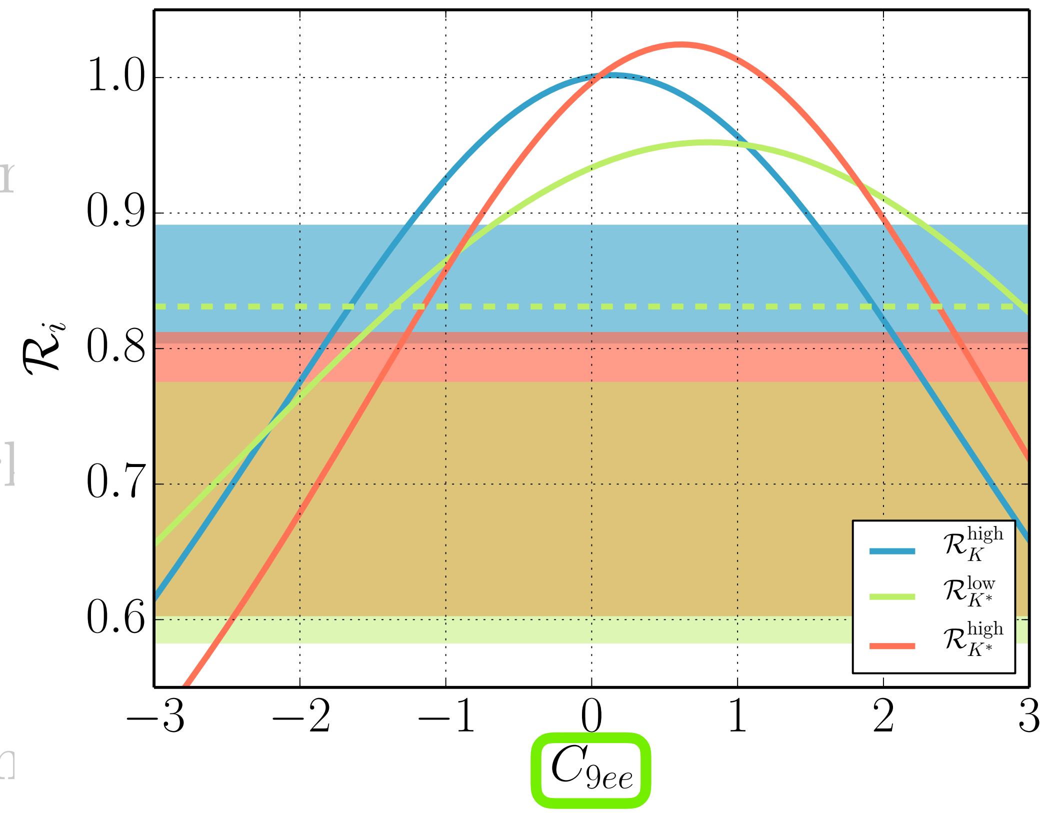
- PS-symmetry protects baryon number at the non-renormalizable too!
- Can be realized at the low scale
- **Can address the ratios** $\mathcal{R}_{K^{(*)}}$

[Fileviez-Perez, **C.M.**, Plascencia, 2021], [Fileviez-Perez, **C.M.**, 2022]

Quark-Lepton Unification

$$\mathrm{SU}(4) \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)_R$$



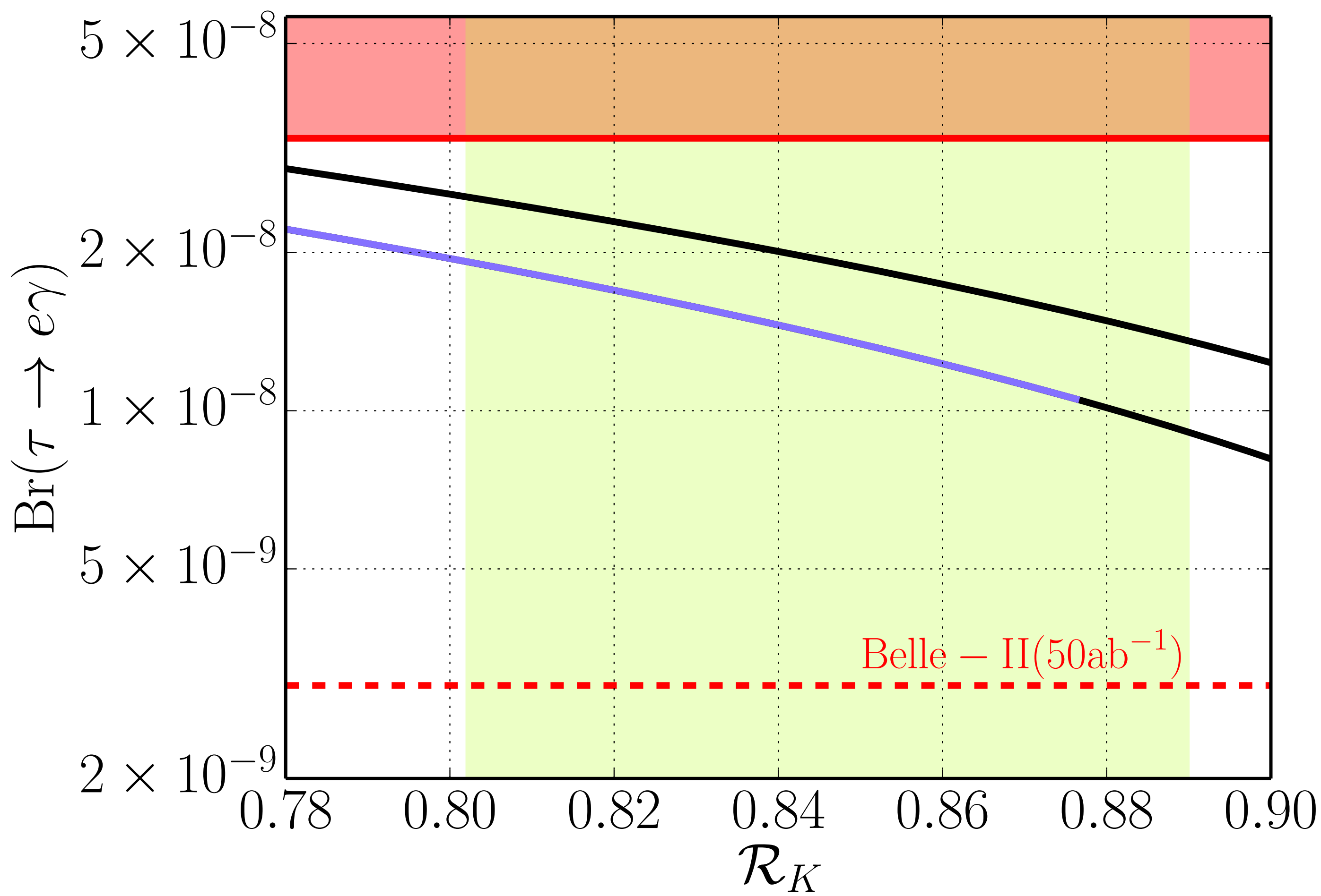


- PS-symmetry protects baryon number at the non-renormalizable too!
- Can be realized at the low scale
- **Can address the ratios $\mathcal{R}_{K^{(*)}}$ and $\mathcal{R}_{D^{(*)}}$** [Fileviez-Perez, **C.M.**, 2022]

Quark-Lepton Unification

$$\mathrm{SU}(4) \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)_R$$

- Very economical fermion content
- Qu ... ng
- On
- All
- Pr
- Ca
- Ba ... vel
- PS ... normalizable too!



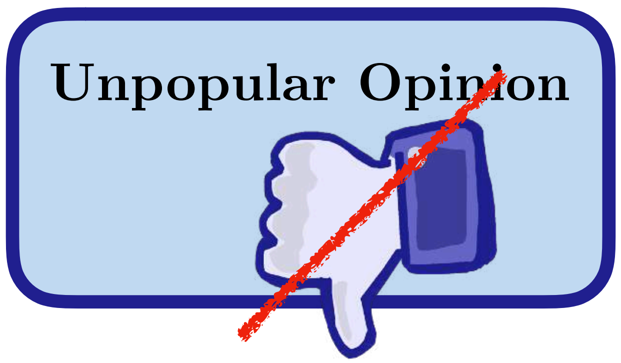
- Can address the ratios $\mathcal{R}_{K^{(*)}}$ and $\mathcal{R}_{D^{(*)}}$
- **And we'll be able to test that soon!** [Fileviez-Perez, **C.M.**, 2022]

Thank you!

Back-up slides

New Physics ❤ electrons

[Altmannshofer, Stangl 2103.13370]



	Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
	$C_9^{bs\mu\mu}$	$-0.75^{+0.22}_{-0.23}$	3.4σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.73^{+0.15}_{-0.15}$	5.2σ
	$C_{10}^{bs\mu\mu}$	$+0.42^{+0.23}_{-0.24}$	1.7σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.54^{+0.12}_{-0.12}$	4.7σ
	$C_9^{\prime bs\mu\mu}$	$+0.24^{+0.27}_{-0.26}$	0.9σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.18^{+0.13}_{-0.14}$	1.4σ
	$C_{10}^{\prime bs\mu\mu}$	$-0.16^{+0.16}_{-0.16}$	1.0σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.02^{+0.10}_{-0.10}$	0.2σ
	$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.20^{+0.15}_{-0.15}$	1.3σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$+0.05^{+0.12}_{-0.12}$	0.4σ
U_1^μ	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.53^{+0.13}_{-0.13}$	3.7σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.39^{+0.07}_{-0.07}$	5.6σ
	C_9^{bsee}			$+0.74^{+0.20}_{-0.19}$	4.1σ	$+0.75^{+0.20}_{-0.19}$	4.1σ
	C_{10}^{bsee}			$-0.67^{+0.17}_{-0.18}$	4.2σ	$-0.66^{+0.17}_{-0.17}$	4.3σ
	$C_9^{\prime bsee}$			$+0.36^{+0.18}_{-0.17}$	2.1σ	$+0.40^{+0.19}_{-0.18}$	2.3σ
	$C_{10}^{\prime bsee}$			$-0.31^{+0.16}_{-0.16}$	2.1σ	$-0.30^{+0.15}_{-0.16}$	2.0σ
Φ_4	$C_9^{bsee} = C_{10}^{bsee}$			$-1.39^{+0.26}_{-0.26}$	4.0σ	$-1.28^{+0.24}_{-0.23}$	4.1σ
	$C_9^{bsee} = -C_{10}^{bsee}$			$+0.37^{+0.10}_{-0.10}$	4.2σ	$+0.37^{+0.10}_{-0.10}$	4.3σ
	$\left(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}\right) \times \text{GeV}$			$-0.004^{+0.002}_{-0.002}$	2.1σ	$-0.003^{+0.002}_{-0.002}$	1.4σ
	$\left(C_S^{\prime bs\mu\mu} = C_P^{\prime bs\mu\mu}\right) \times \text{GeV}$			$-0.004^{+0.002}_{-0.002}$	2.1σ	$-0.003^{+0.002}_{-0.002}$	1.4σ

Extra: Charged Anomalies

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$

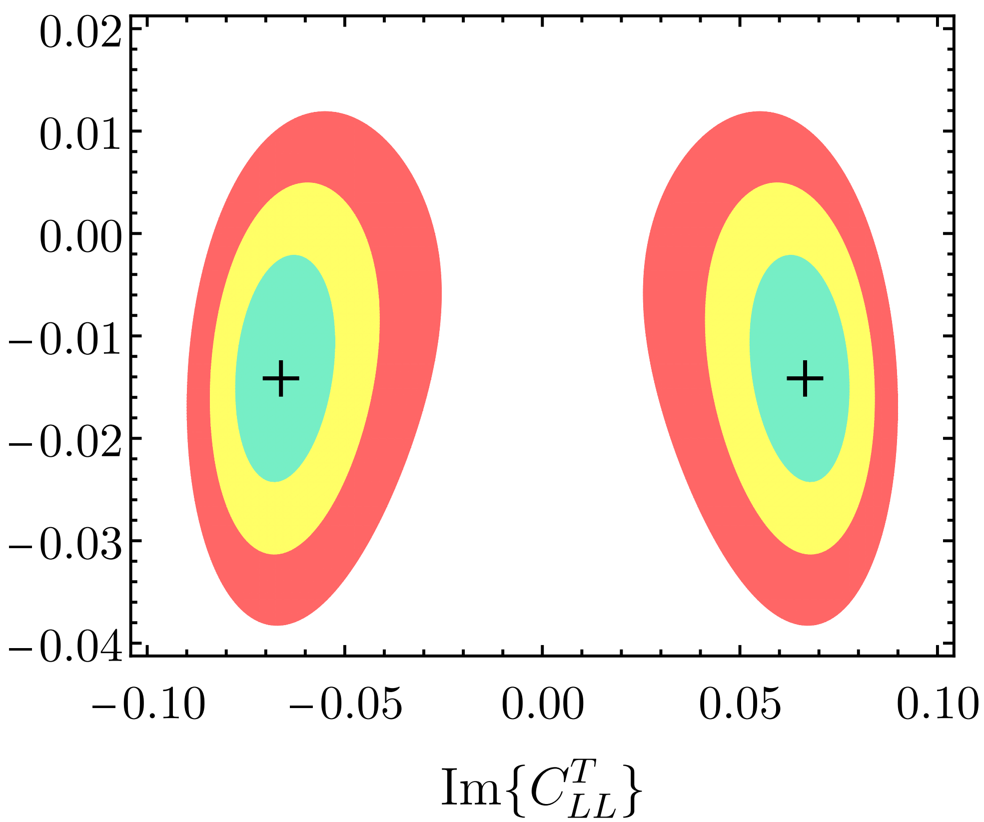
$$\mathcal{H}_{\rm eff}^{b\to c} \supset \frac{c_2^{il}(c_4^*)^{jk}}{2M_{\Phi_4}^2}\left[(\bar u_R^i d_L^j)(\bar e_R^k \nu_L^l) + \frac{1}{4}(\bar u_R^i \sigma^{\mu\nu} d_L^j)(\bar e_R^k \sigma_{\mu\nu}\nu_L^l)\right] + \text{h.c.}$$

$c_2 = U_C^T Y_2^T N$

$$C_{LL}^S = 4\, r\, C_{LL}^T \propto (G_F)^{-1}\frac{c_2^{23}(c_4^{33})^*}{2M_{\Phi_4}^2}$$

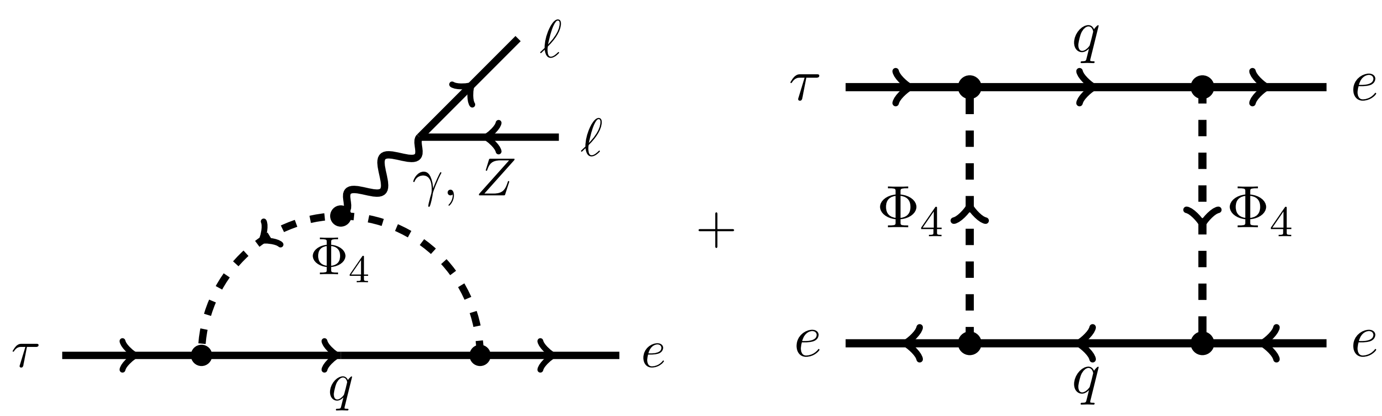
$$\Rightarrow \quad \text{Im}\{C_{LL}^S\} \sim 6.75\frac{\sin\beta}{\sin\theta_c}c_2^{23} \sim 0.5$$

$C_{LL}^S = 8C_{LL}^T$



$\tau \to \ell_i \bar{\ell}_j \ell_k$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



$\mathrm{Br}(\tau^- \to \mu^-\mu^+\mu^-)$

$\mathrm{Br}(\tau^- \to \mu^- e^+ e^-)$

$\mathrm{Br}(\tau^- \to e^+\mu^+\mu^-)$

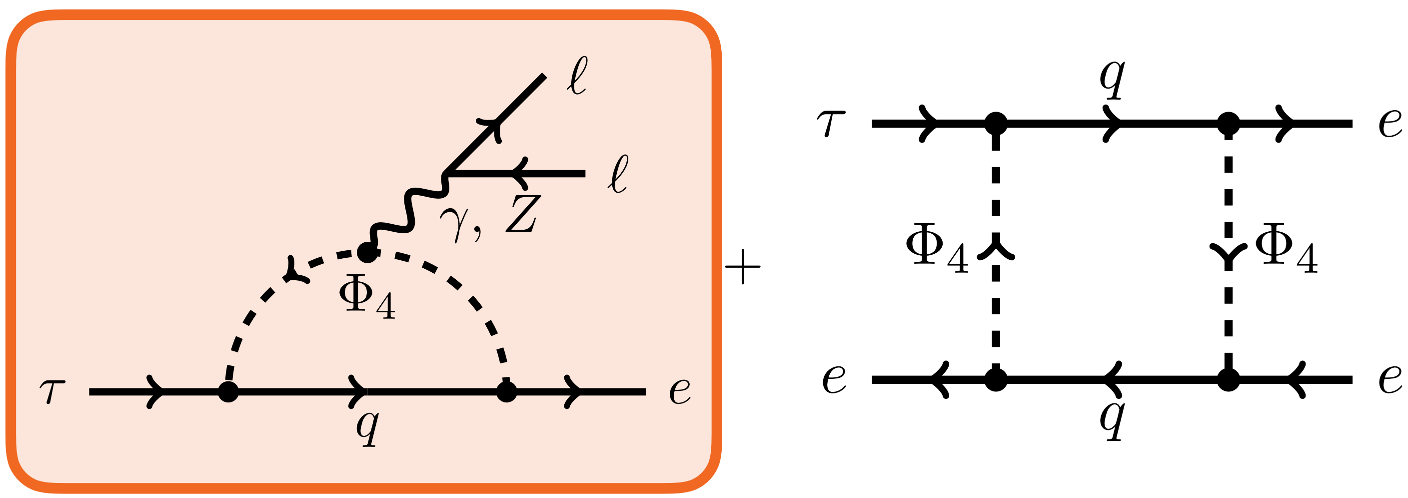
$\mathrm{Br}(\tau^- \to \mu^+ e^+ e^-)$

$\mathrm{Br}(\tau^- \to e^-\mu^+\mu^-)$

$\mathrm{Br}(\tau^- \to e^- e^+ e^-)$

$\tau \to \ell_i \bar{\ell}_j \ell_k$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & \boxed{\begin{matrix}0\\0\\0\end{matrix}} & 0 \\ -m_s\cos\theta_c & & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & & m_b\cos\theta_c \end{pmatrix}.$$



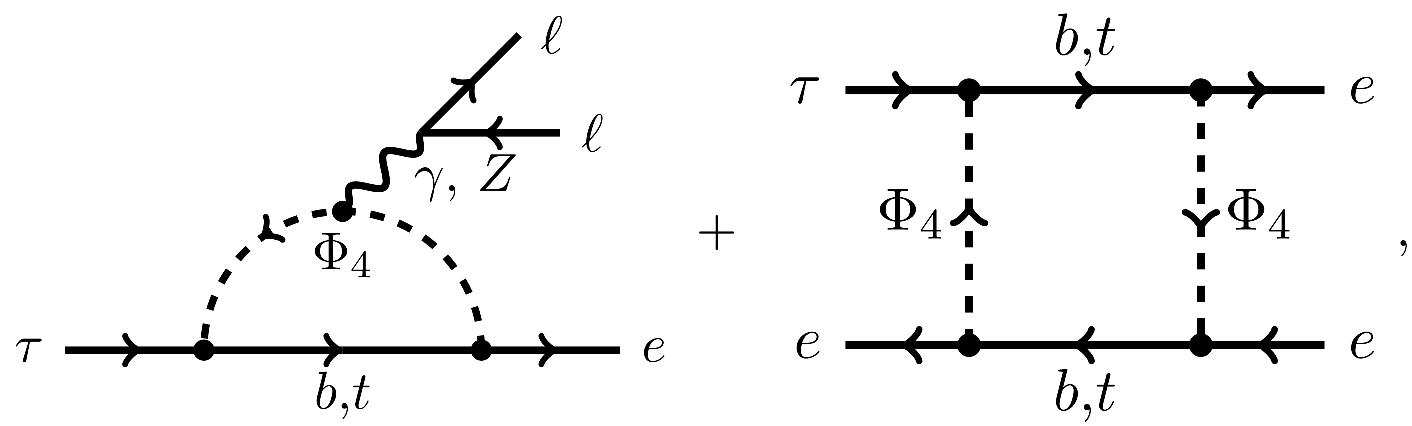
$\mathrm{Br}(\tau^- \cancel{\to \mu^-\mu^+}\mu^-)$ $\mathrm{Br}(\tau^- \to \cancel{\mu^+e^+}e^-)$

$\mathrm{Br}(\tau^- \cancel{\to \mu^-e^+}e^-)$ $\boxed{\mathrm{Br}(\tau^- \to e^-\mu^+\mu^-)}$

$\mathrm{Br}(\tau^- \cancel{\to e^+\mu^+}\mu^-)$ $\mathrm{Br}(\tau^- \to e^-e^+e^-)$

$\tau \to \ell_i \bar{\ell}_j \ell_k$

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



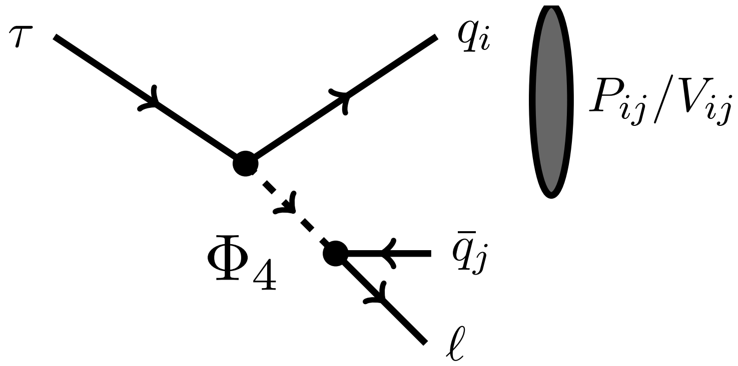
$$\mathrm{Br}(\tau^- \cancel{\to \mu^-\mu^+}\mu^-) \qquad \mathrm{Br}(\tau^- \cancel{\to \mu^+ e^+} e^-)$$

$$\mathrm{Br}(\tau^- \cancel{\to \mu^- e^+} e^-) \qquad \mathrm{Br}(\tau^- \to e^-\mu^+\mu^-)$$

$$\mathrm{Br}(\tau^- \cancel{\to e^+ \mu^+}\mu^-) \qquad \mathrm{Br}(\tau^- \to e^- e^+ e^-) \quad \sim \mathcal{O}(10^{-10})$$

Hadronic τ decays

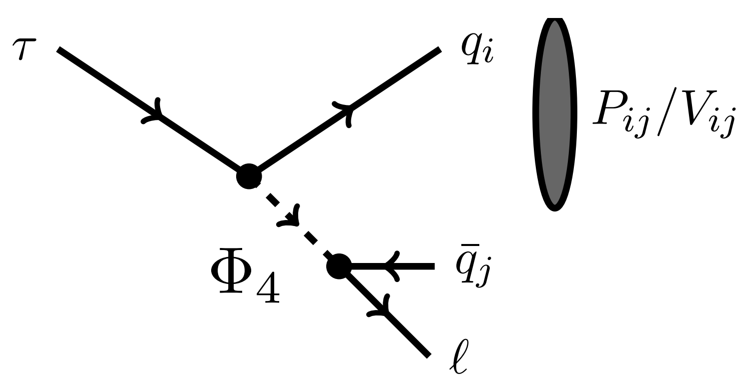
$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



$$\mathrm{Br}(\tau \to P_{\bar{i}j}\,\ell_k) \simeq \tau_\tau \frac{f_P^2}{128\pi}\frac{(m_\tau^2 - m_P^2)^2}{m_\tau}\left|\frac{c_4^{i3}(c_4^{jk})^*}{M_{\Phi_4}^2}\right|^2$$

Hadronic τ decays

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$



$$\mathrm{Br}(\tau \to P_{\bar{i}j}\,\ell_k) \simeq \tau_\tau \frac{f_P^2}{128\pi}\frac{(m_\tau^2 - m_P^2)^2}{m_\tau}\left|\frac{c_4^{i3}(c_4^{jk})^*}{M_{\Phi_4}^2}\right|^2$$

Channel	Non-zero contributions	Exp. bound	Prediction / Constraint
$\mathrm{Br}(\tau \to \eta\, e)$	$\propto \lvert c_4^{23}(c_4^{21})^*\rvert^2$	$< 9.2\times10^{-8}$	$\lvert\sin\theta_c\rvert \gtrsim 0.042$
$\mathrm{Br}(\tau \to \eta'\, e)$	$\propto \lvert c_4^{23}(c_4^{21})^*\rvert^2$	$< 1.6\times10^{-7}$	$\simeq 6.7\times10^{-11}\,(\sin\theta_c)^{-2}$
$\mathrm{Br}(\tau \to \phi\, e)$	$\propto \lvert c_4^{23}(c_4^{21})^*\rvert^2$	$< 3.1\times10^{-8}$	$\lvert\sin\theta_c\rvert \gtrsim 0.16$

Meson leptonic decays

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s \cos\theta_c & 0 & m_s \sin\theta_c - m_\tau \\ m_b \sin\theta_c & 0 & m_b \cos\theta_c \end{pmatrix}.$$

$$\mathrm{Br}(M[q_j\bar{q}_i] \to \ell_1^- \ell_2^+) = \frac{\tau_M}{256\pi}\frac{f_M^2}{m_M^3}\lambda^{1/2}(m_M^2, m_{\ell_1}^2, m_{\ell_2}^2)\left|\frac{c_4^{i\ell_2}(c_4^{j\ell_1})^*}{M_{\Phi_4}^2}\right|^2 \times$$
$$\left(m_M^2(m_{\ell_1}^2 + m_{\ell_2}^2) - (m_{\ell_1}^2 - m_{\ell_2}^2)^2\right),$$

Channel	Non-zero contributions	Exp. bound [?]	Prediction / Constraint
$\mathrm{Br}(B_s \to e^+e^-)$	$\propto \lvert c_4^{21}(c_4^{31})^*\rvert^2$	$< 2.8\times 10^{-7}$	$\simeq 1.2\times 10^{-13}$
$\mathrm{Br}(B_s \to e^+\tau^-)$	$\propto \lvert c_4^{31}(c_4^{23})^*\rvert^2$	–	$\simeq 1.3\times 10^{-5}\,(\cos\theta_c)^{-2}$
$\mathrm{Br}(B_s \to \tau^+e^-)$	$\propto \lvert c_4^{33}(c_4^{21})^*\rvert^2$	–	$\simeq 3.7\times 10^{-8}\,(\tan\theta_c)^{-2}$
$\mathrm{Br}(B_s \to \tau^+\tau^-)$	$\propto \lvert c_4^{33}(c_4^{23})^*\rvert^2$	$< 6.8\times 10^{-3}$	$\lvert\sin\theta_c\rvert \gtrsim 0.06$

Charged semileptonic decays of mesons

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$

$$\mathrm{Br}(B_{(s)} \to M^{(*)}\ell_1^+\ell_2^-) = a + b\,\mathrm{Re}\{C_9\} + c\,|C_9|^2$$

$$C_9 = C_{10} = \frac{\sqrt{2}\pi}{\alpha G_F V_{\rm CKM}^{tb}(V_{\rm CKM}^{ts})^*}\frac{c_4^{q_i\ell_1}(c_4^{q_j\ell_2})^*}{4M_{\Phi_4}^2}$$

$$\begin{aligned}
\mathrm{Br}(B \to K e^+e^-) &\simeq 1.15 \times \mathrm{Br}(B \to K e^+e^-)_{\rm SM}, & \text{for } q^2 \supset [1.1, 6]\ \mathrm{GeV}^2 \\
\mathrm{Br}(B \to K^* e^+e^-) &\simeq 1.23 \times \mathrm{Br}(B \to K^* e^+e^-)_{\rm SM}, & \text{for } q^2 \supset [0.045, 6]\ \mathrm{GeV}^2 \\
\mathrm{Br}(B_s \to \phi\, e^+e^-) &\simeq 1.27 \times \mathrm{Br}(B_s \to \phi\, e^+e^-)_{\rm SM}, & \text{for } q^2 \supset [1.1, 6]\ \mathrm{GeV}^2.
\end{aligned}$$

Charged semileptonic decays of mesons

$$c_4 = \sqrt{\frac{3}{2}}\frac{1}{v\sin\beta}\begin{pmatrix} 0 & 0 & 0 \\ -m_s\cos\theta_c & 0 & m_s\sin\theta_c - m_\tau \\ m_b\sin\theta_c & 0 & m_b\cos\theta_c \end{pmatrix}.$$

Coefficient	e^+e^- $[c_4^{21}(c_4^{31})^*]$	$e^+\tau^-$ $[c_4^{31}(c_4^{23})^*]$ and τ^+e^- $[c_4^{33}(c_4^{21})^*]$		$\tau^+\tau^-$ $[c_4^{33}(c_4^{23})^*]$
	$q^2 \subset [1.1, 6]$	full q^2 range	$q^2 \subset [(m_e + m_\tau)^2, 6]$	full q^2 range
$a_{B\to K\ell_1\ell_2}$	1.43×10^{-7}	0	0	1.29×10^{-7}
$b_{B\to K\ell_1\ell_2}$	-2.56×10^{-9}	0	0	-2.47×10^{-8}
$c_{B\to K\ell_1\ell_2}$	9.13×10^{-9}	1.96×10^{-8}	1.22×10^{-9}	8.10×10^{-9}
$a_{B\to K^*\ell_1\ell_2}$	4.74×10^{-6}	0	0	2.43×10^{-6}
$b_{B\to K^*\ell_1\ell_2}$	-4.21×10^{-7}	0	0	5.96×10^{-7}
$c_{B\to K^*\ell_1\ell_2}$	3.44×10^{-7}	7.65×10^{-7}	4.19×10^{-8}	1.79×10^{-7}
$a_{B_s\to \phi\ell_1\ell_2}$	5.11×10^{-6}	0	0	2.27×10^{-6}
$b_{B_s\to \phi\ell_1\ell_2}$	-4.67×10^{-7}	0	0	5.98×10^{-7}
$c_{B_s\to \phi\ell_1\ell_2}$	3.73×10^{-7}	7.74×10^{-7}	4.44×10^{-8}	1.70×10^{-7}

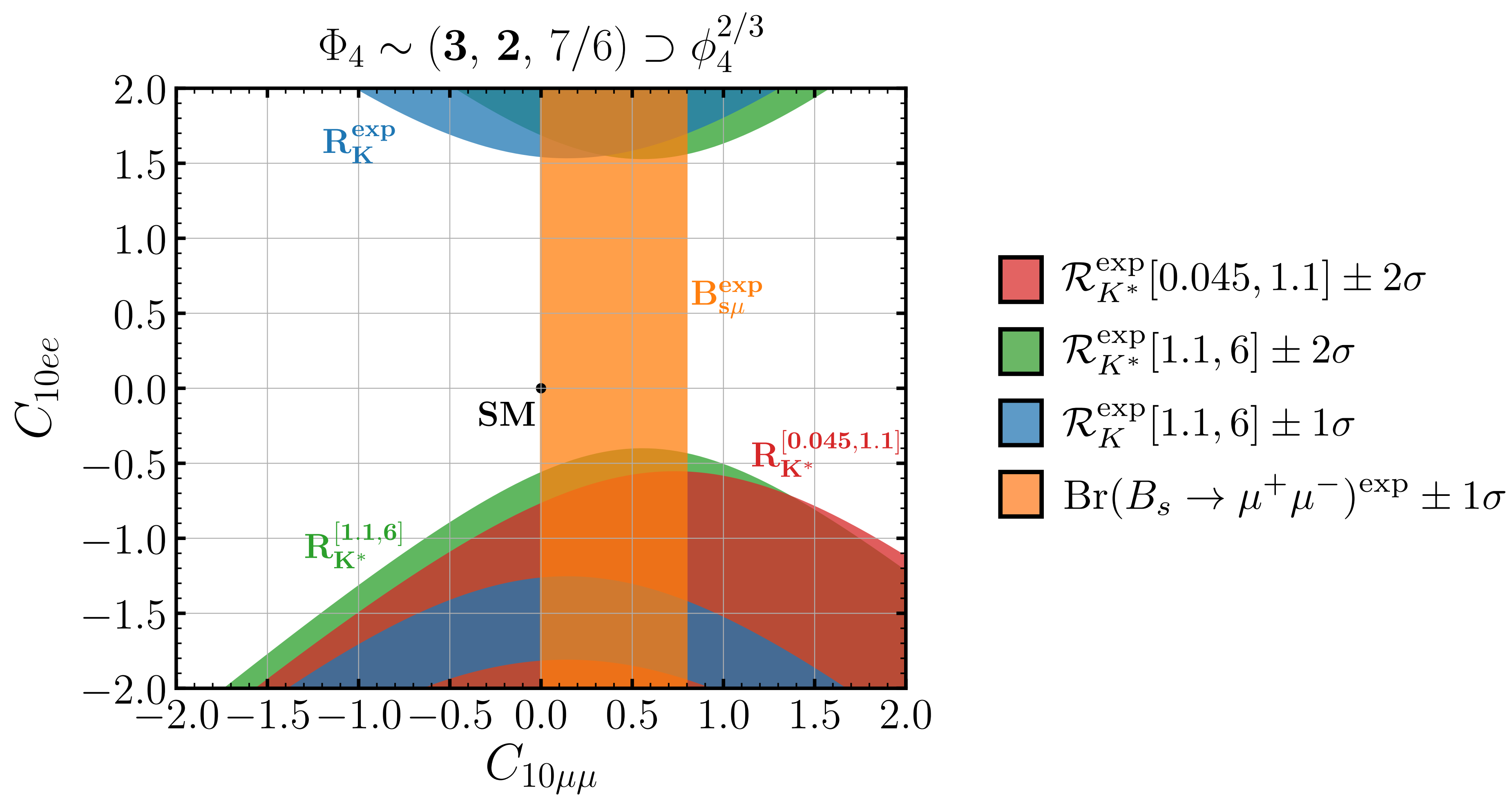
From empirical point of view

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

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

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

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



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

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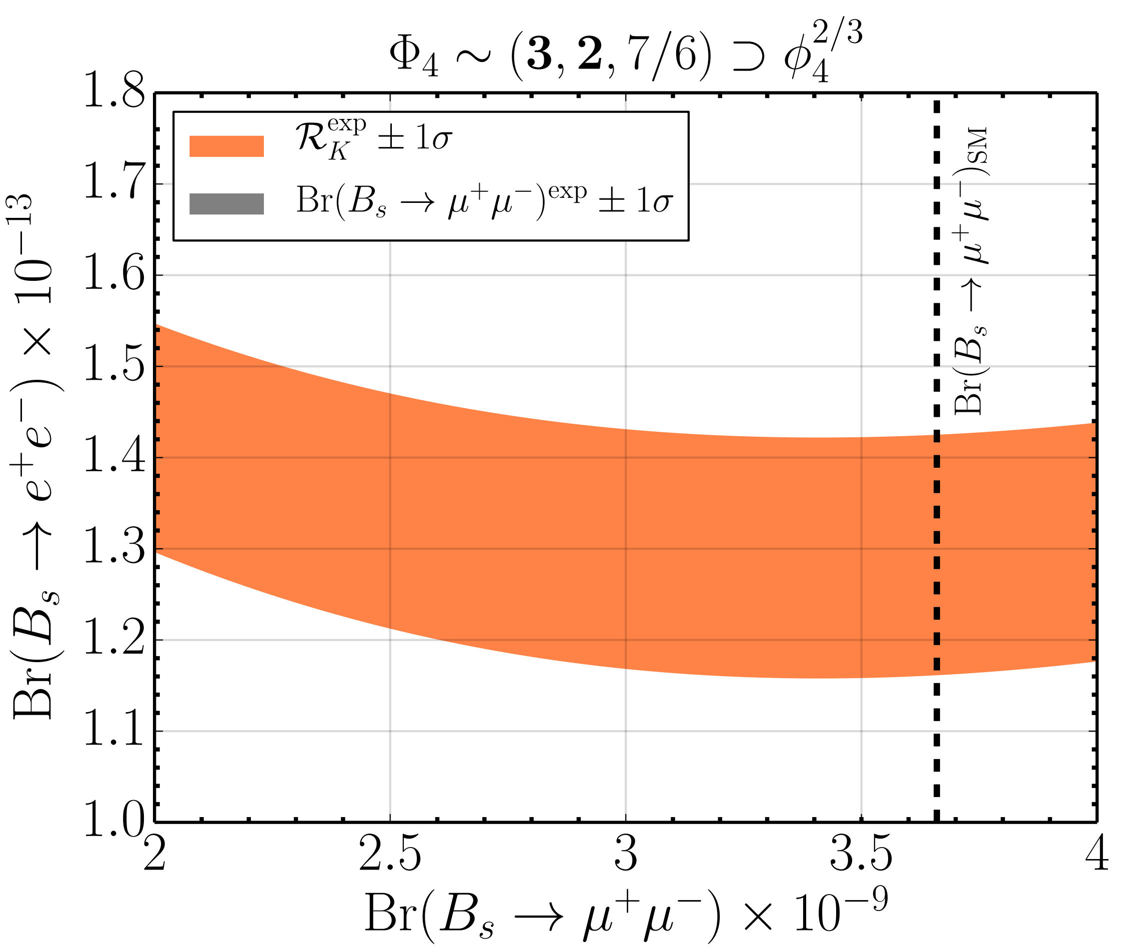
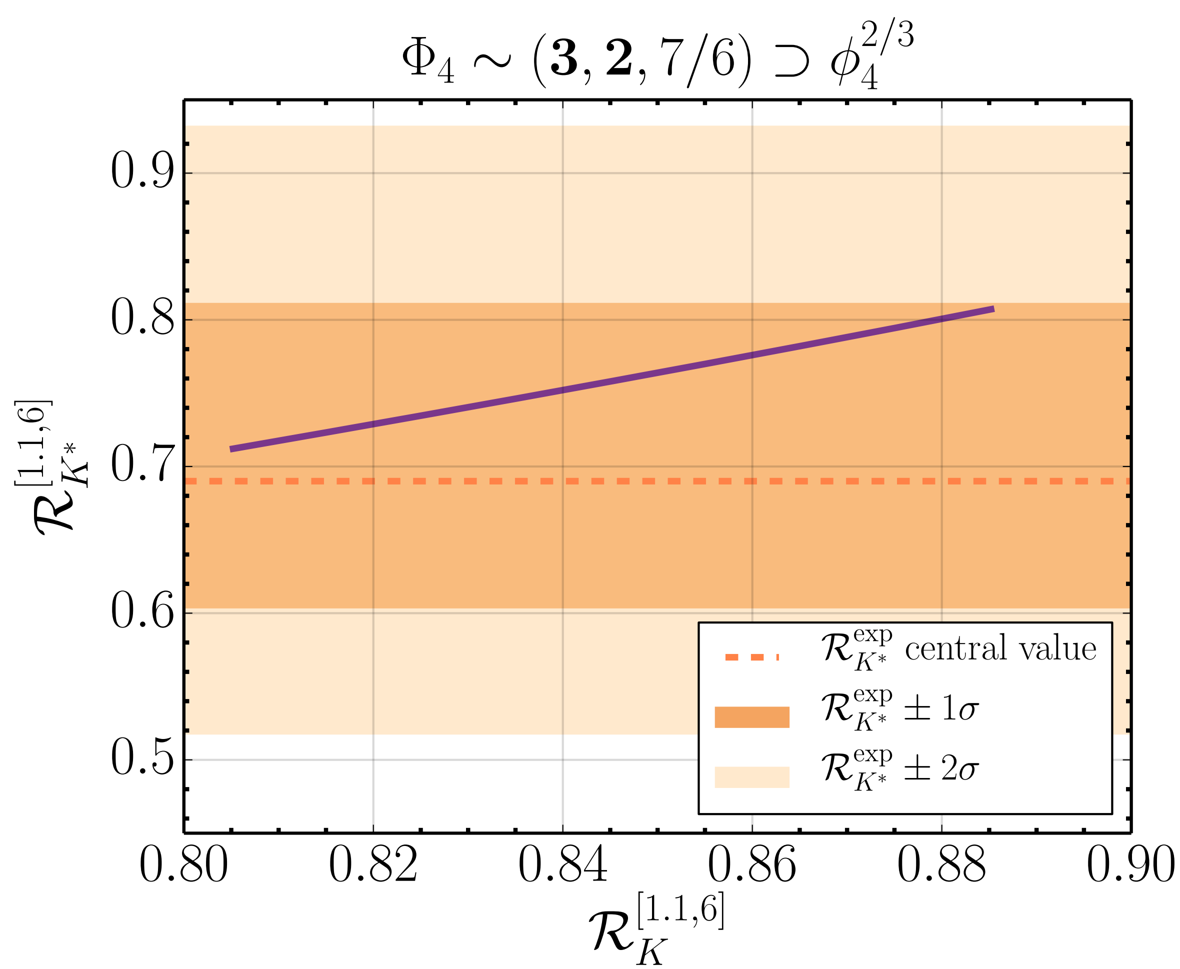
$$\text{Br}(B_s \to \ell^+\ell^-) = f_2(C_{10\ell\ell}) \qquad \mathcal{R}_{K^{(*)}} = \frac{f_2(C_{10\mu\mu})}{f_2(C_{10ee})}$$





From empirical point of view

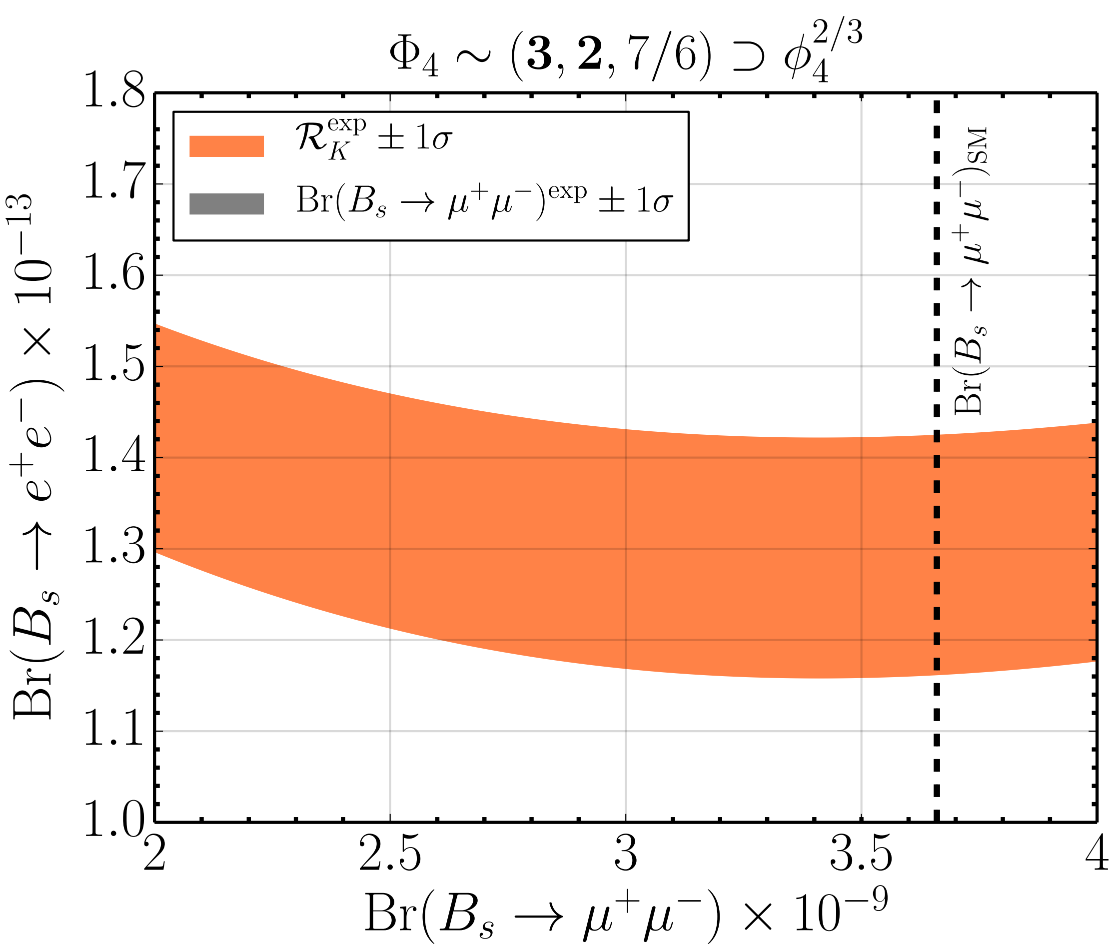
[Fileviez Perez, C.M, Plascencia, 2104.11229]

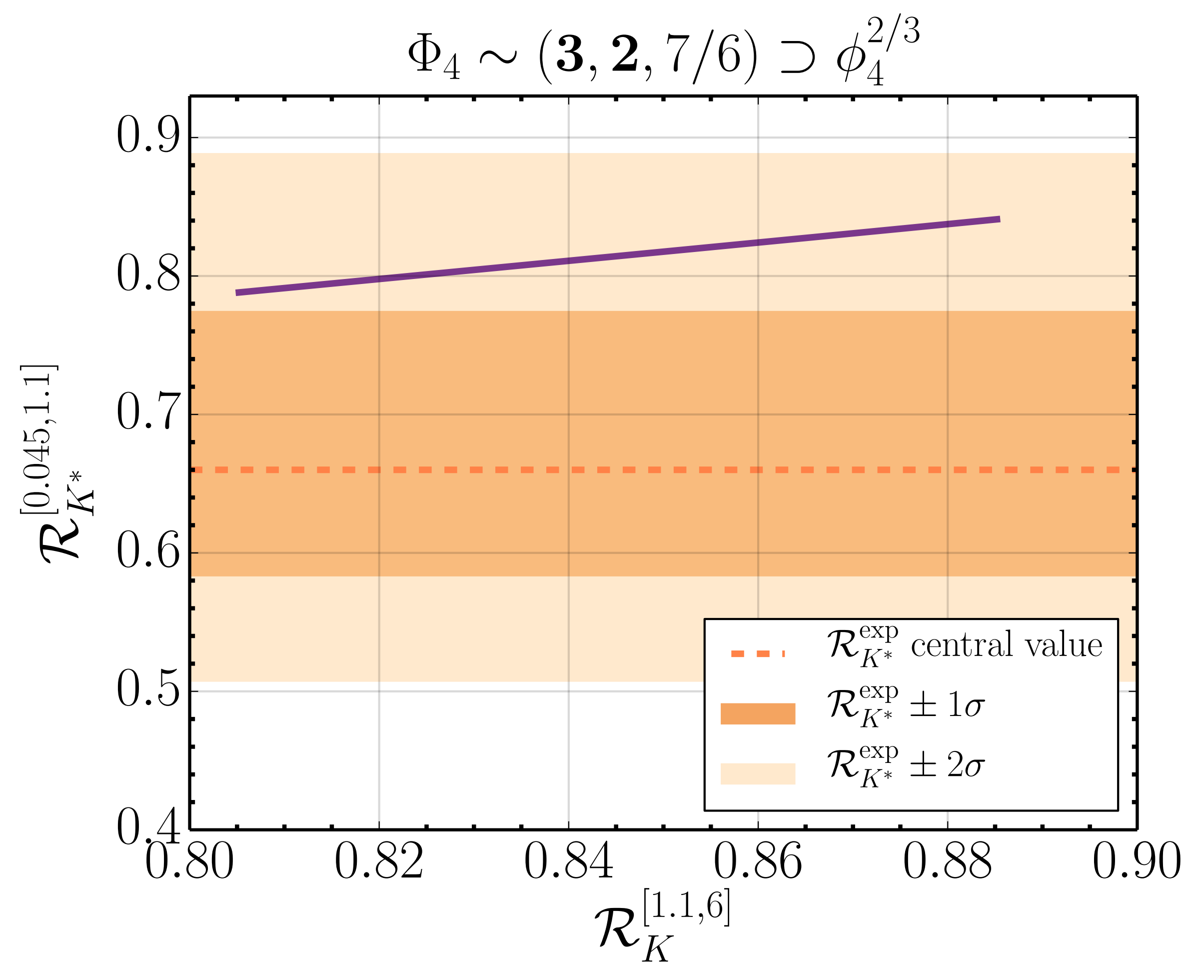
$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a + \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a} + \text{h.c.}$$

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

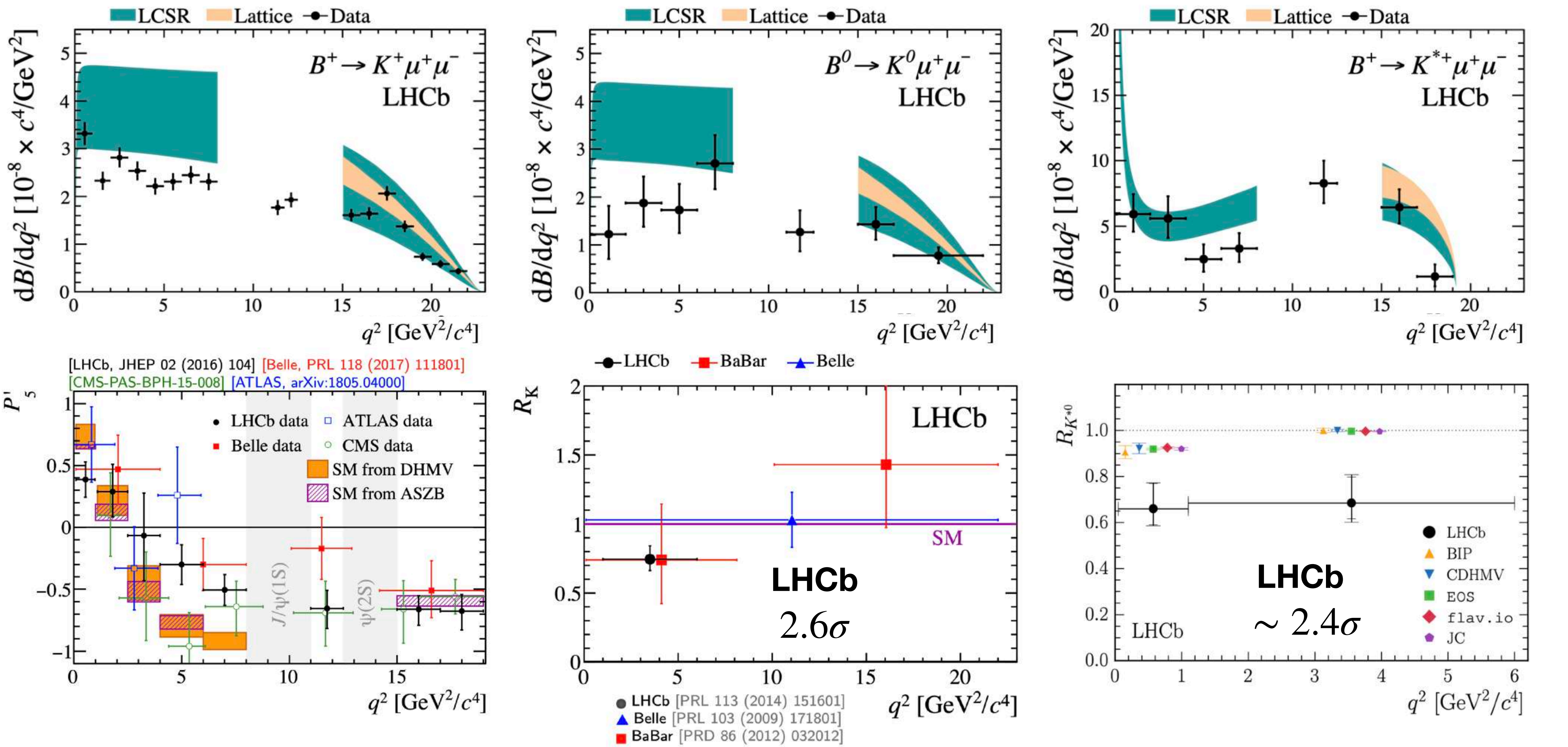
- $\phi_4^{2/3}$ contributes to $b \to s$ transitions!

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



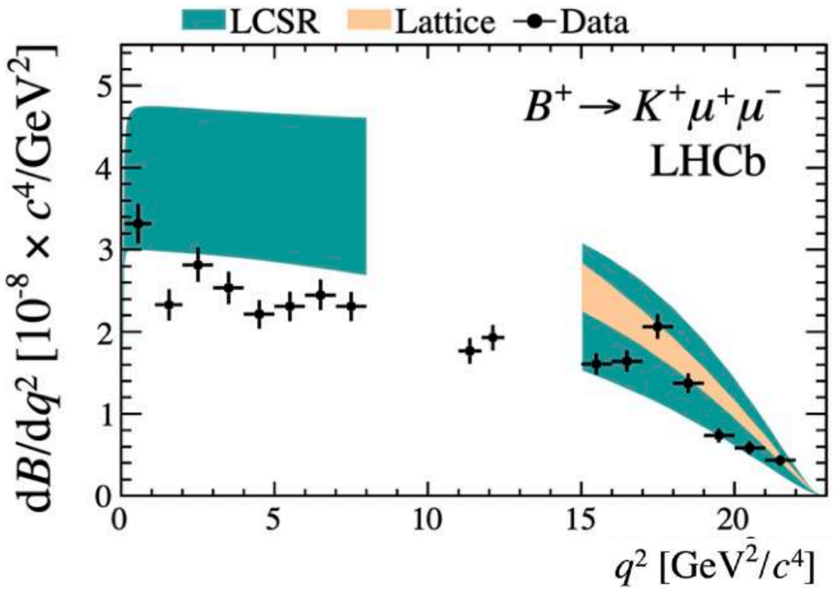


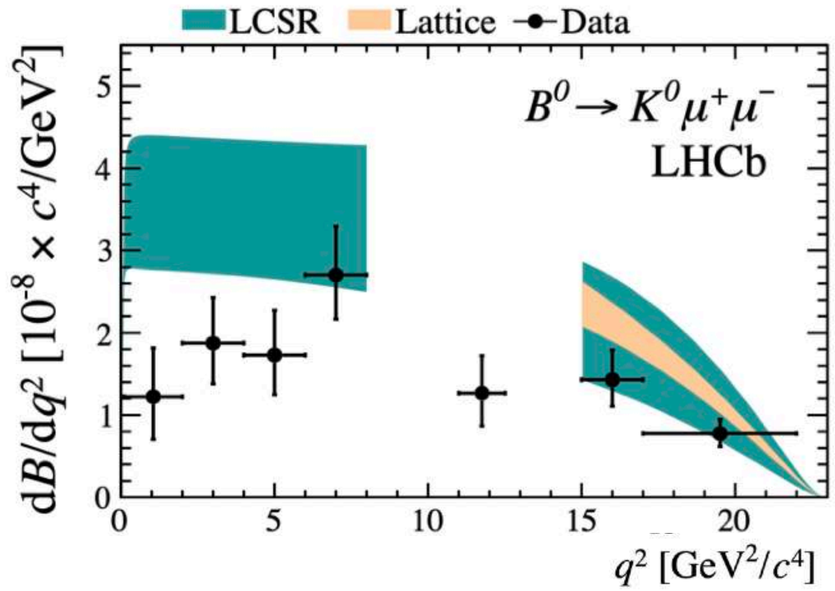
Anomalies in $b \to s$ transitions

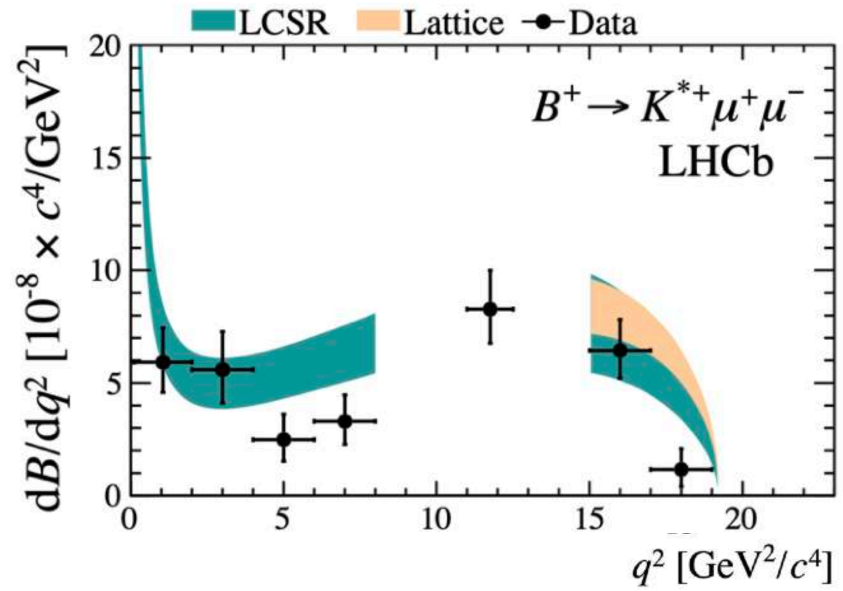


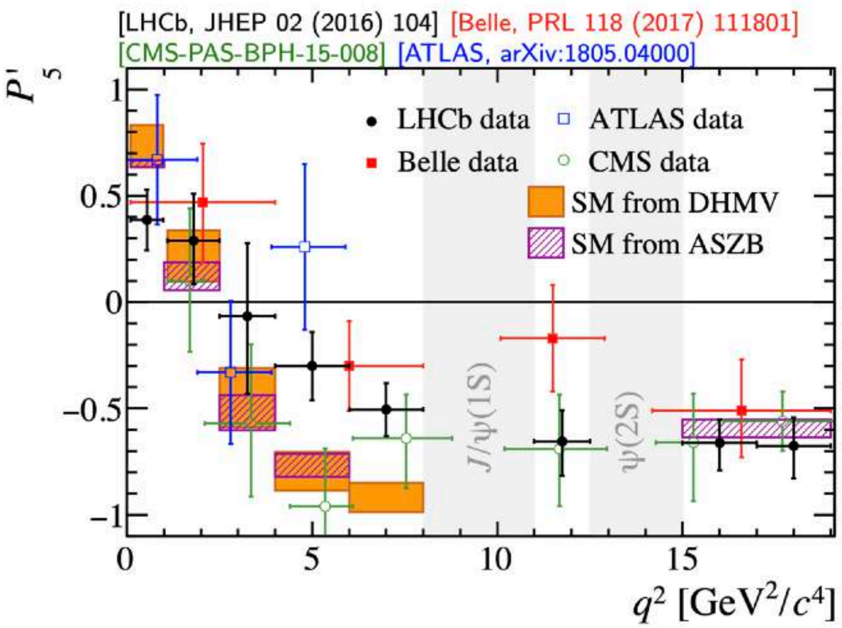
Status 2017

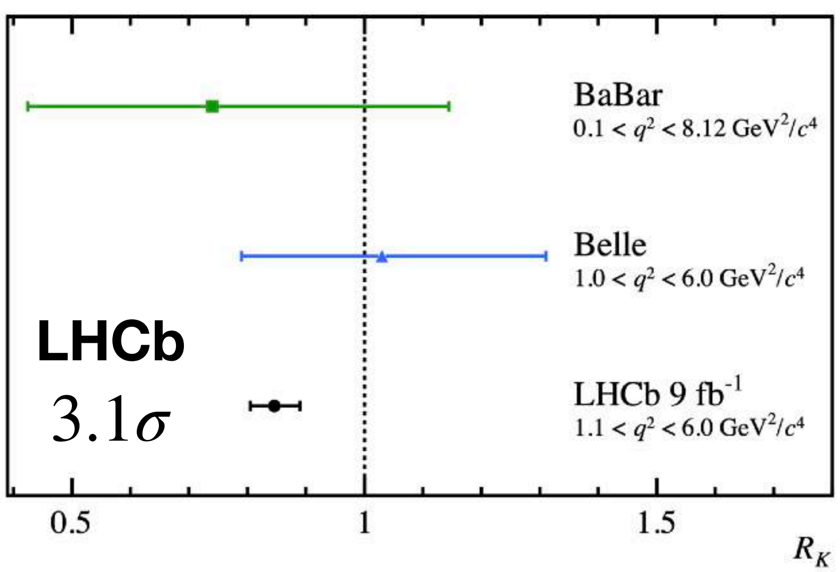
Anomalies in $b \to s$ transitions

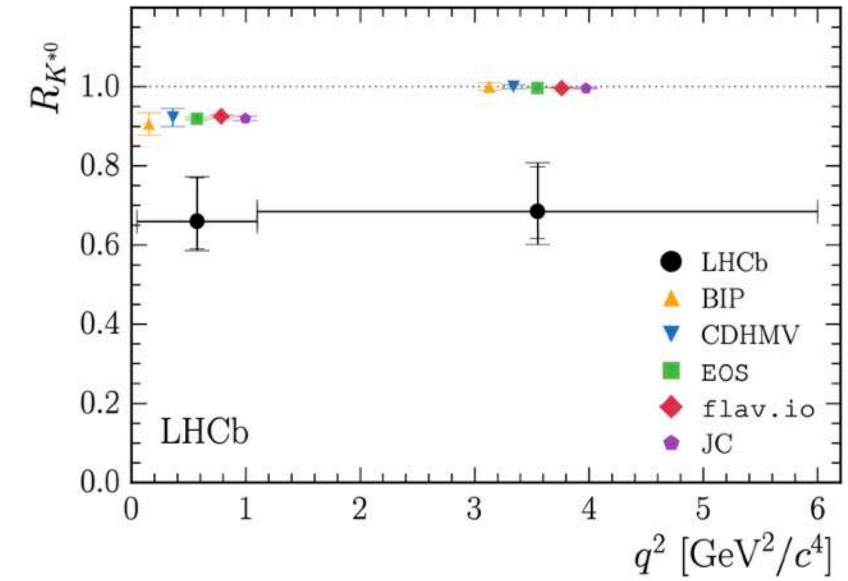






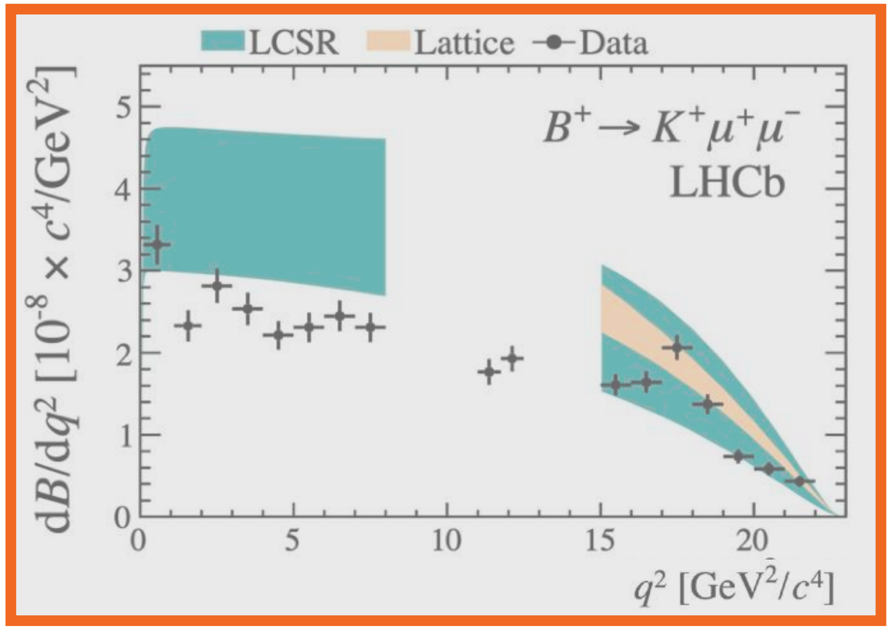


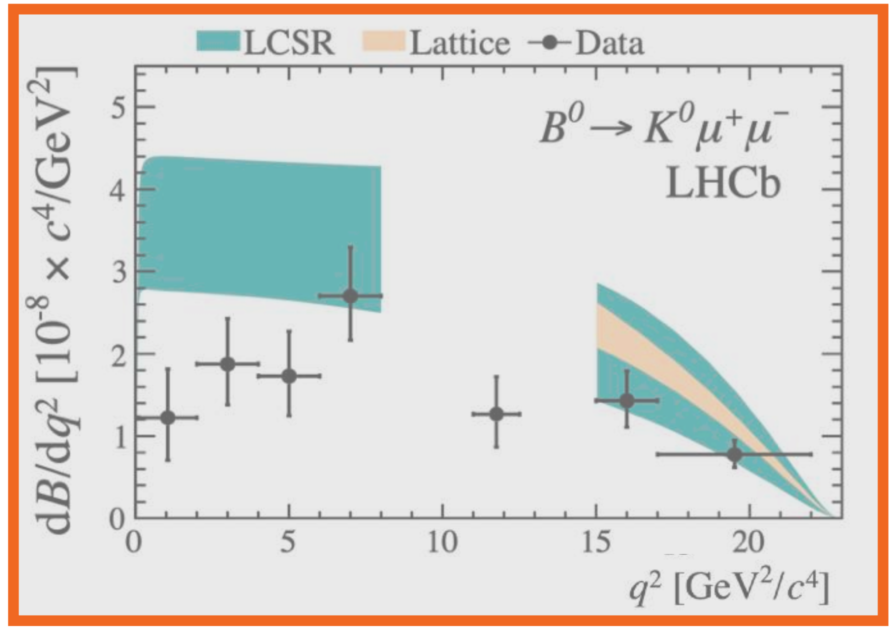


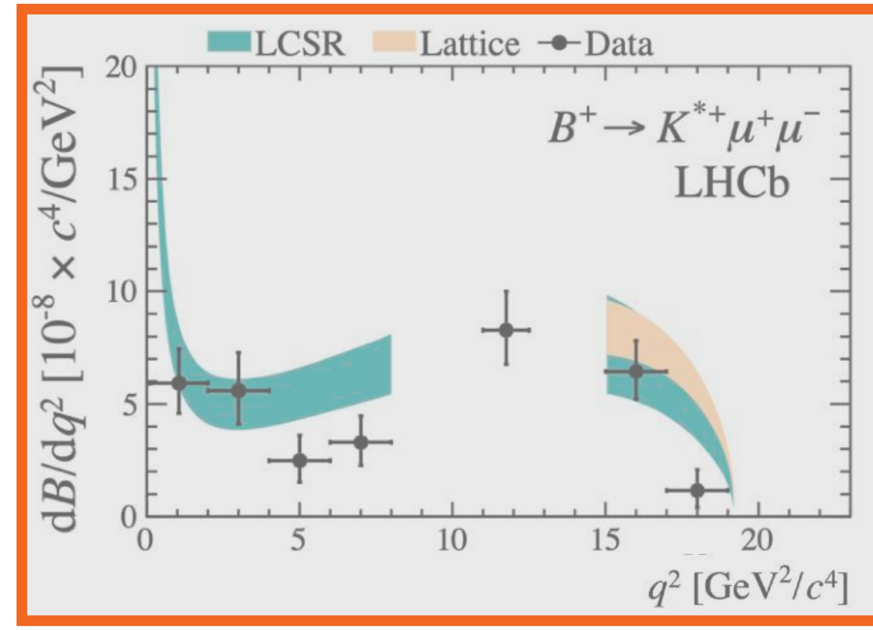


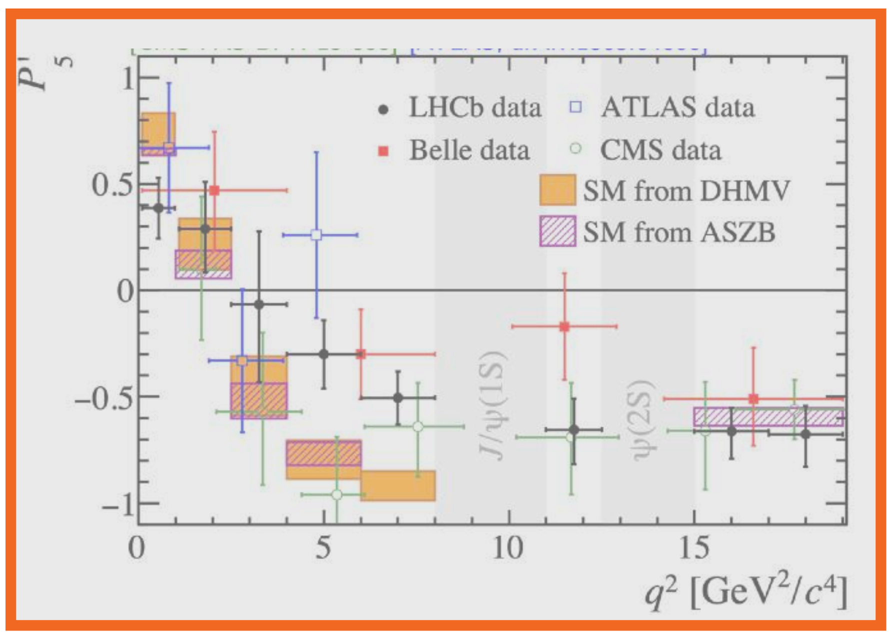
Status NOW

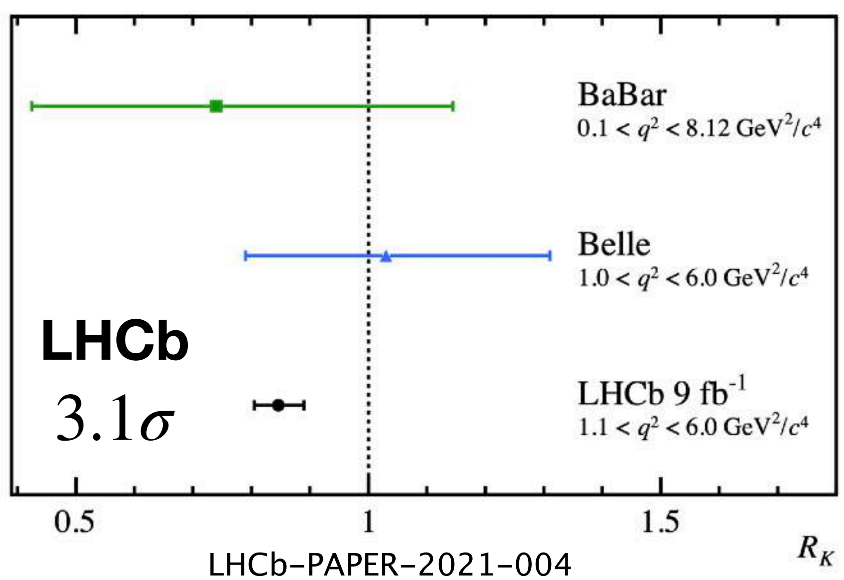
Anomalies in $b \to s$ transitions

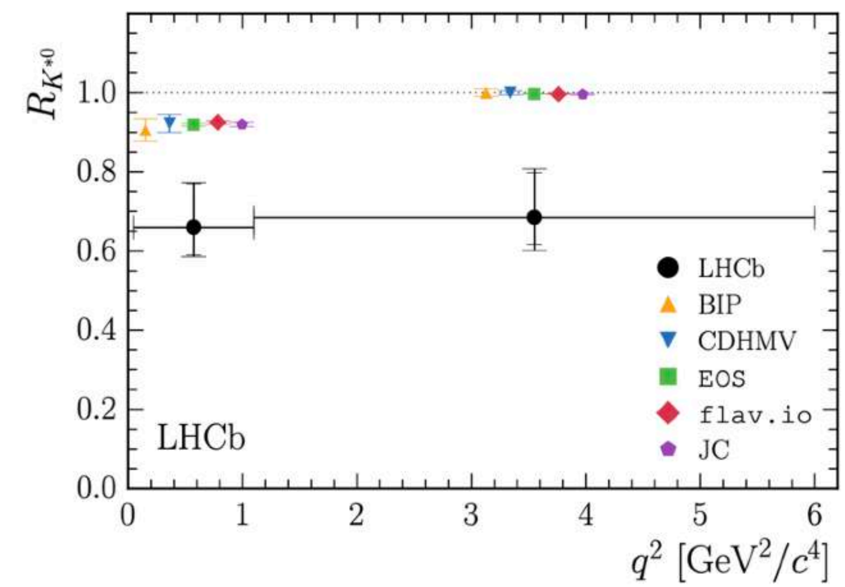


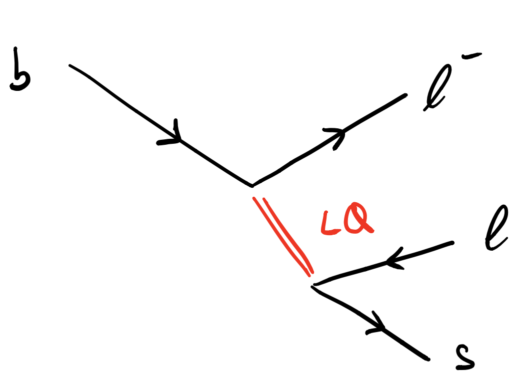


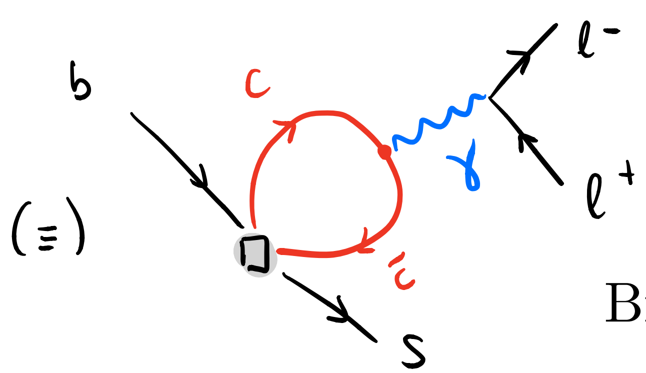












It could mimic NP!!!

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