Title: Matter Unification at the TeV scale: Flavour anomalies and muon (g-2)

Speakers: Clara Murgui

Series: Particle Physics

Date: July 13, 2021 - 1:00 PM

URL: https://pirsa.org/21070002

Abstract: Several anomalies have been recently reported by different laboratory experiments: the flavor anomalies involving B meson semileptonic and leptonic decays by the LHCb and B-factories, as well as the anomalous muon (g-2) by the Fermilab (g-2) collaboration. These deviations, if not coming from underestimated experimental or theoretical uncertainties, are pointing to new degrees of freedom around the few TeV scale. Enlarging the field content of the Standard Model may lead to baryon number violation, whose aggressive experimental constraints can rule out a wide range of attractive candidates. Motivated by its safeness under unacceptable baryon number violation and the possibility for having TeV scale physics, I will introduce the simplest theory for matter (leptons-quarks) unification based on the Pati-Salam symmetry and show how this theory can address both the flavor anomalies and the muon (g-2) with the scalar leptoquarks that it predicts.

Zoom Link: https://pitp.zoom.us/j/95090784229?pwd=Q21oQUVkeXFiSmt5S3hKcGJ3SlEyZz09

Caltech

Matter Unification at the TeV scale:

Flavour anomalies and muon (g-2)

Clara Murgui

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

July 13th 2021

Perimeter Institute

Accessing High Energies

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

Construction of Super colliders

Precision Physics


Belle-II
LHCb

Lepton Flavour Universality (Violation)

e	μ	τ
ν_e	ν_μ	ν_τ

Lepton Flavour Universality (Violation)

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

e	μ	τ
ν_e	ν_μ	ν_τ

γ_μ	e	μ	τ			
g_μ						
W_μ	e_L	μ_L	τ_L	$(\nu_e)_L$	$(\nu_\mu)_L$	$(\nu_\tau)_L$
Z_μ	e	μ	τ	ν_e	ν_μ	ν_τ

Lepton Flavour Universality (Violation)

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

e	μ	τ
ν_e	ν_μ	ν_τ

H

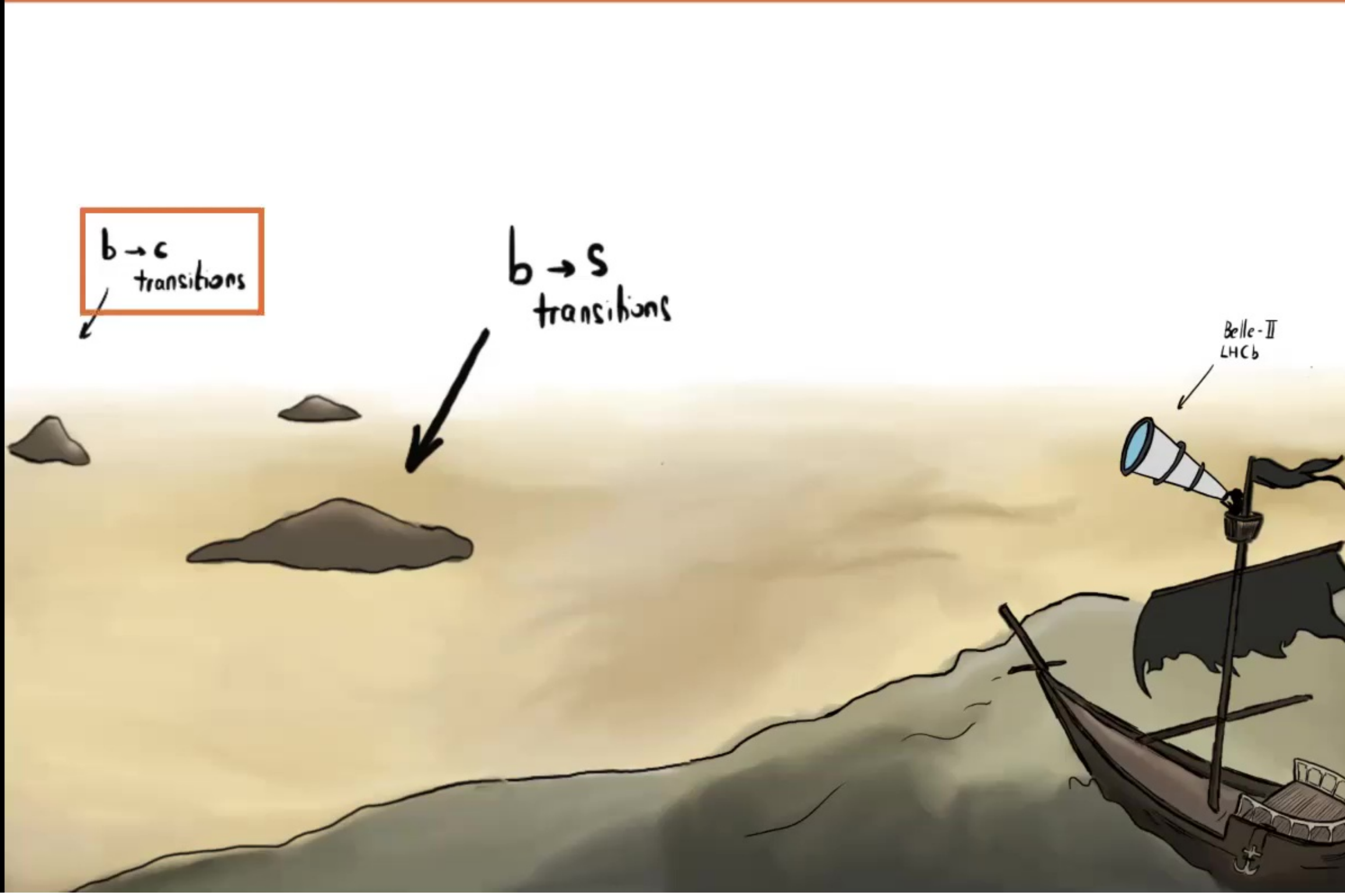
γ_μ e μ τ

g_μ

W_μ e_L μ_L τ_L $(\nu_e)_L$ $(\nu_\mu)_L$ $(\nu_\tau)_L$

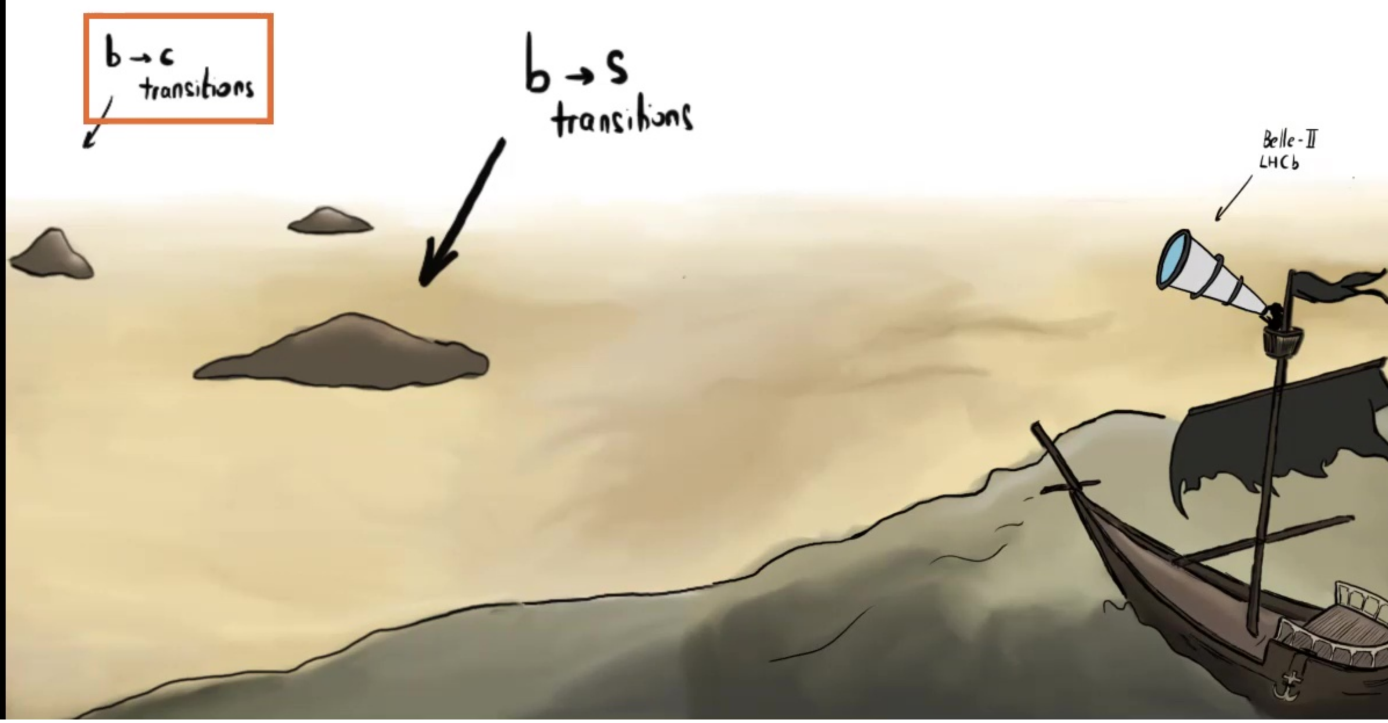
Z_μ e μ τ ν_e ν_μ ν_τ

Anomalies in $b \to c$ transitions



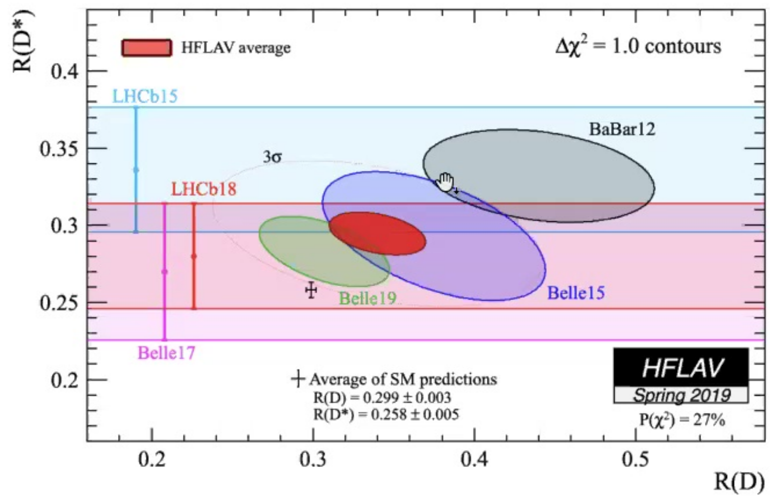
Anomalies in $b \to c$ transitions

[Based on Refs. **1904.09311** and **2004.06726**, in collaboration with **Martin Jung, Rusa Mandal, Ana Peñuelas and Antonio Pich.**]



Anomalies in $b \to c$ transitions

Status 2019

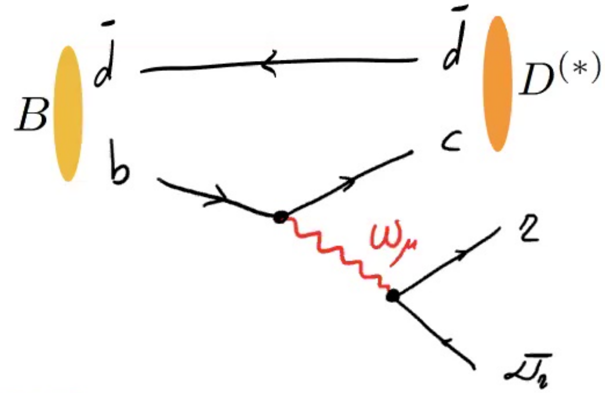


$3.9\,\sigma$	$4.0\,\sigma$	$3.9\,\sigma$	$3.6\,\sigma$	$3.1\,\sigma$
2015	2016	2017	2018	2019

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

Anomalies in $b \to c$ transitions

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

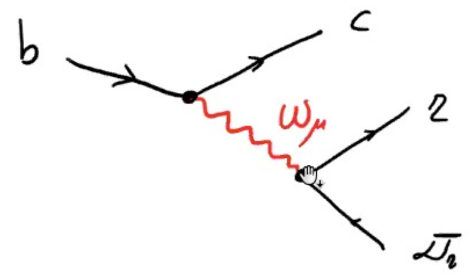


$$\mathcal{R}_{D^{(*)}} = \frac{|V_{cb}|^2 \langle \overset{\boxed{b}\,\boxed{c}}{\text{hadronic current}} \rangle \langle \overset{\boxed{\tau}\,\boxed{\nu}}{\text{leptonic current}} \rangle}{|V_{cb}|^2 \langle \overset{\boxed{b}\,\boxed{c}}{\text{hadronic current}} \rangle \langle \overset{\boxed{e,\mu}\,\boxed{\nu}}{\text{leptonic current}} \rangle}$$

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**

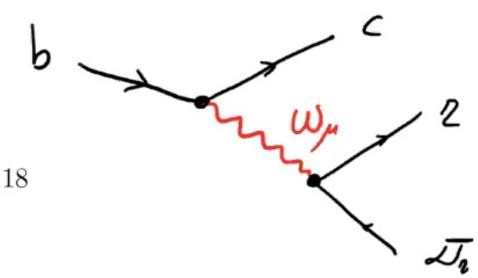
HFLAV, up to date



Tree level process!!

Anomalies in $b \to c$ transitions

Pattern of deviations in B-meson decays involving b to c transitions pointing to "the same direction"



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

  HFLAV, up to date

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

  LHCb, 2017 **1.7 σ**

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

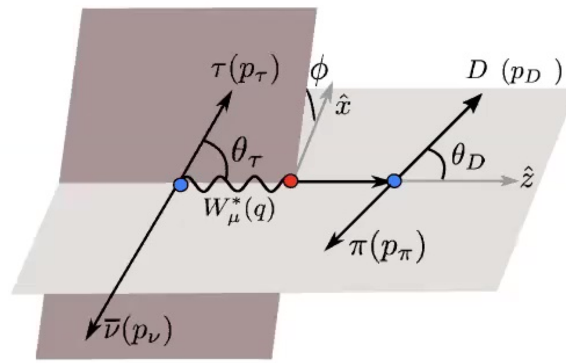
- $\bar{\mathcal{P}}_\tau^{D^*} = -0.38 \pm 0.51^{+0.21}_{-0.16}$

  Belle, 2016

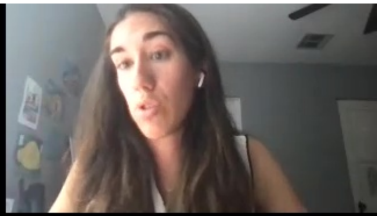
  $\mathcal{P}_\tau(D^*)_{SM} = -0.499 \pm 0.003$

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

  Belle, 2019

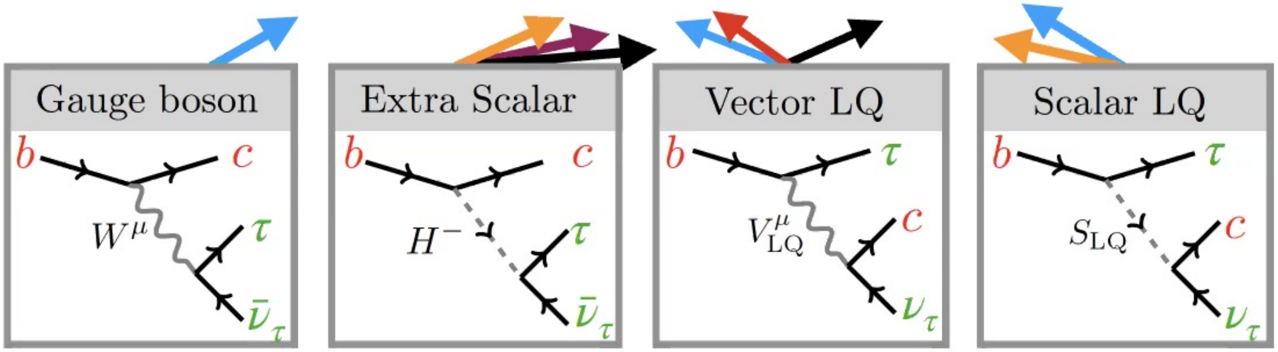


Bottom-up approach



- Most general effective dim 6 Hamiltonian:

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



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

$$\boxed{\mathcal{O}_{S_R}} = (\bar{c}\,P_R b)(\bar{\ell}\,P_L \nu_\ell), \qquad \boxed{\mathcal{O}_{S_L}} = (\bar{c}\,P_L b)(\bar{\ell}\,P_L \nu_\ell),$$

$$\boxed{\mathcal{O}_T} = (\bar{c}\,\sigma^{\mu\nu} P_L b)(\bar{\ell}\,\sigma_{\mu\nu} P_L \nu_\ell),$$

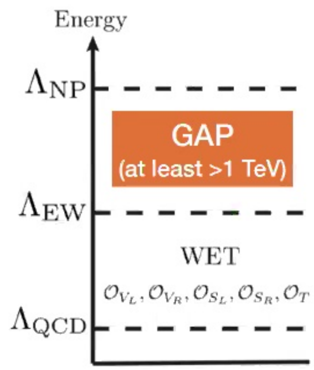
Bottom-up approach

- Most general effective dim 6 Hamiltonian:

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

- Assumptions:

EFT



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

$$\boxed{\mathcal{O}_{S_R}} = (\bar{c}\,P_R b)(\bar{\ell}\,P_L \nu_\ell), \qquad \boxed{\mathcal{O}_{S_L}} = (\bar{c}\,P_L b)(\bar{\ell}\,P_L \nu_\ell),$$

$$\boxed{\mathcal{O}_T} = (\bar{c}\,\sigma^{\mu\nu} P_L b)(\bar{\ell}\,\sigma_{\mu\nu} P_L \nu_\ell),$$

Bottom-up approach

- Most general effective dim 6 Hamiltonian:

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

- Assumptions:

  - EFT ✓
  - New physics only in the **third generation**

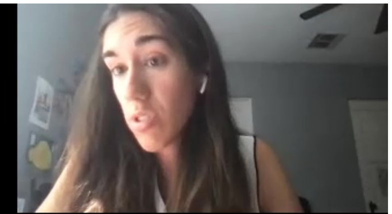
    NP effects negligible in $b \to c(e,\mu)\bar{\nu}_{(e,\mu)}$ analysis [Jung, Straub, 1801.01112]

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\tau}\,\gamma_\mu P_L \nu_\tau), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^\mu P_R b)(\bar{\tau}\,\gamma_\mu P_L \nu_\tau),$$

$$\boxed{\mathcal{O}_{S_R}} = (\bar{c}\,P_R b)(\bar{\tau}\,P_L \nu_\tau), \qquad \boxed{\mathcal{O}_{S_L}} = (\bar{c}\,P_L b)(\bar{\tau}\,P_L \nu_\tau).$$

$$\boxed{\mathcal{O}_T} = (\bar{c}\,\sigma^{\mu\nu} P_L b)(\bar{\tau}\,\sigma_{\mu\nu} P_L \nu_\tau),$$

Bottom-up approach



- Most general effective dim 6 Hamiltonian:

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

- Assumptions:

  - EFT
  - New physics only in the **third generation,**
  - C_{V_R} lepton flavour universal $\Rightarrow C_{V_R}^{\tau} \sim 0$

$$C_{V_R}^{\ell} \equiv C_{V_R} + \mathcal{O}\left(\frac{v^4}{\Lambda_{\rm NP}^4}\right)$$

Assuming SMEFT and no significant effect from NP in $b \to c(e,\mu)\bar{\nu}_{(e,\mu)}$ [Jung, Straub, 1801.01112]

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^{\mu} P_L b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^{\mu} P_R b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}),$$

$$\boxed{\mathcal{O}_{S_R}} = (\bar{c}\,P_R b)(\bar{\tau}\,P_L \nu_{\tau}), \qquad \boxed{\mathcal{O}_{S_L}} = (\bar{c}\,P_L b)(\bar{\tau}\,P_L \nu_{\tau}).$$

$$\boxed{\mathcal{O}_T} = (\bar{c}\,\sigma^{\mu\nu} P_L b)(\bar{\tau}\,\sigma_{\mu\nu} P_L \nu_{\tau}),$$

Bottom-up approach

- Most general effective dim 6 Hamiltonian:

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

- Assumptions:
  - EFT ✓
  - New physics only in the **third generation,**
  - C_{V_R} lepton flavour universal $\Rightarrow C_{V_R}^{\tau} \sim 0$
  - CP conserving W.C.

    Fitted complex W.C. without significant improvement

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^{\mu} P_L b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^{\mu} P_R b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}),$$

$$\boxed{\mathcal{O}_{S_R}} = (\bar{c}\,P_R b)(\bar{\tau}\,P_L \nu_{\tau}), \qquad \boxed{\mathcal{O}_{S_L}} = (\bar{c}\,P_L b)(\bar{\tau}\,P_L \nu_{\tau}).$$

$$\boxed{\mathcal{O}_T} = (\bar{c}\,\sigma^{\mu\nu} P_L b)(\bar{\tau}\,\sigma_{\mu\nu} P_L \nu_{\tau}),$$

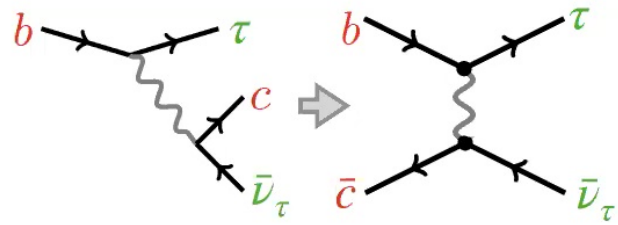
Bottom-up approach

- Most general effective dim 6 Hamiltonian:

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

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

$B \to D^{(*)}\tau\bar{\nu}$ $\quad$ $B_c \to \tau\bar{\nu}$



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

Bottom-up approach

- Most general effective dim 6 Hamiltonian:

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

- 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]

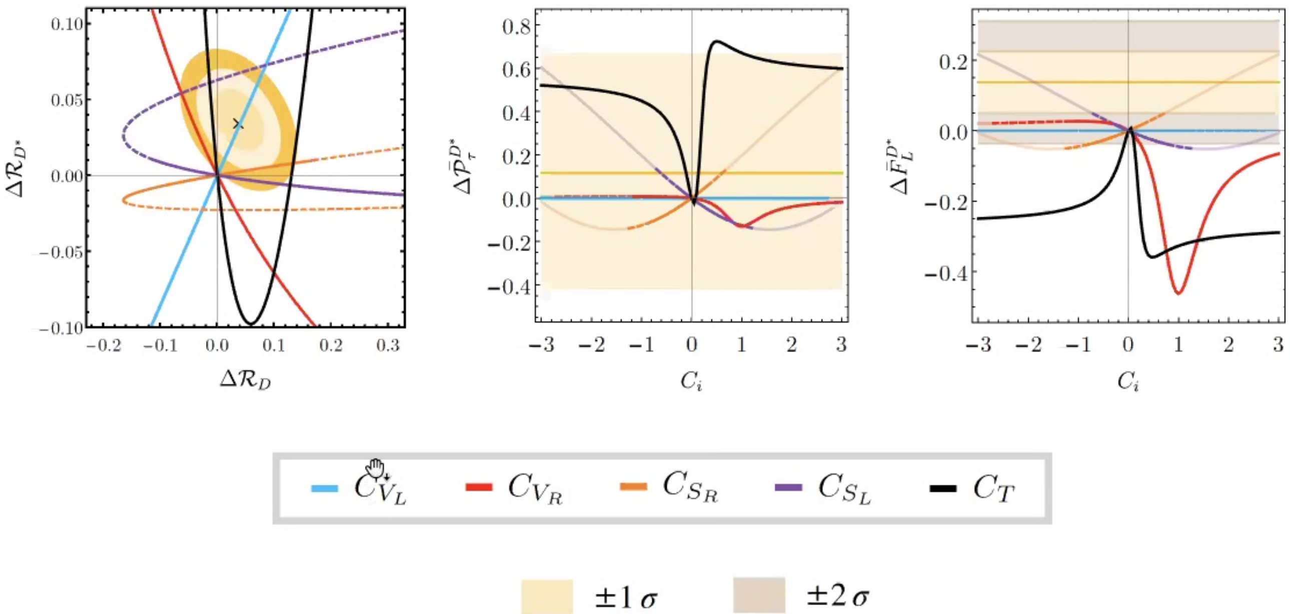
- Bound LEP Z peak:

[Akeroyd et al., 2017]

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

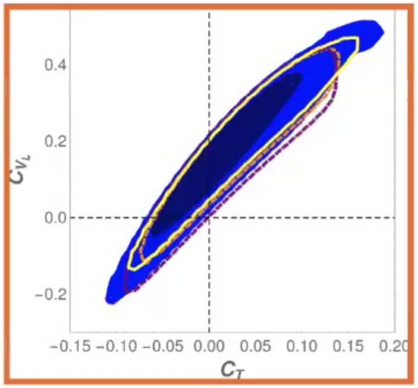
$$\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) = \#|V_{cb}|^2 \times \left|1 + C_{V_L} - C_{V_R} + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}\,(C_{S_R} - C_{S_L})\right|^2$$

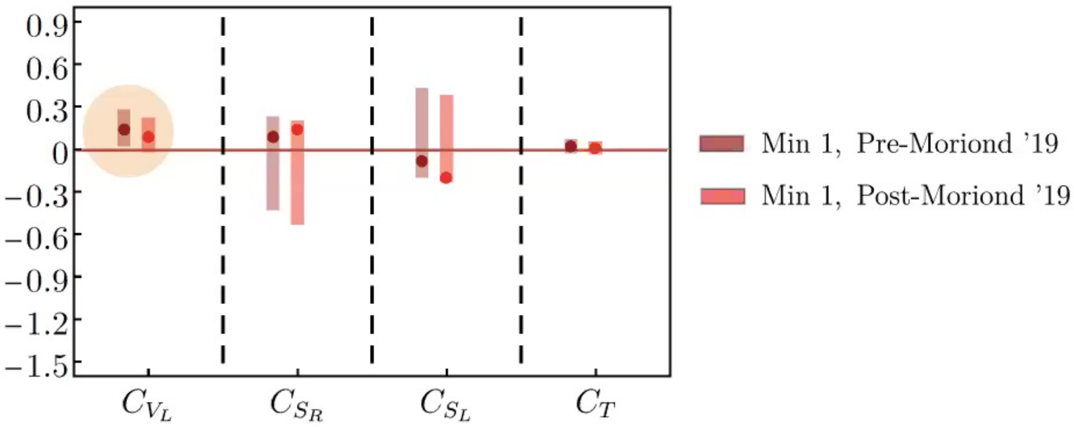
Fit independent analysis



Global Fit

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





Bottom-up approach

- Most general effective dim 6 Hamiltonian:

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

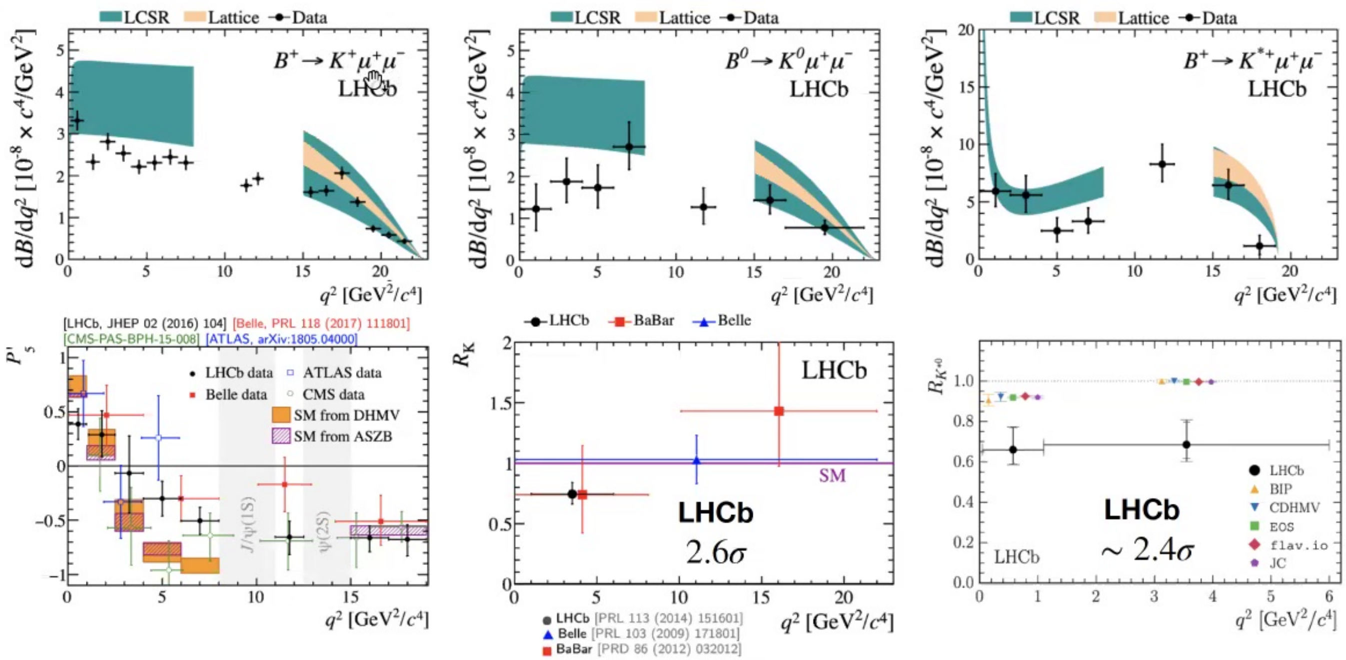
- Theoretical assumptions:

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

- Experimental measurements

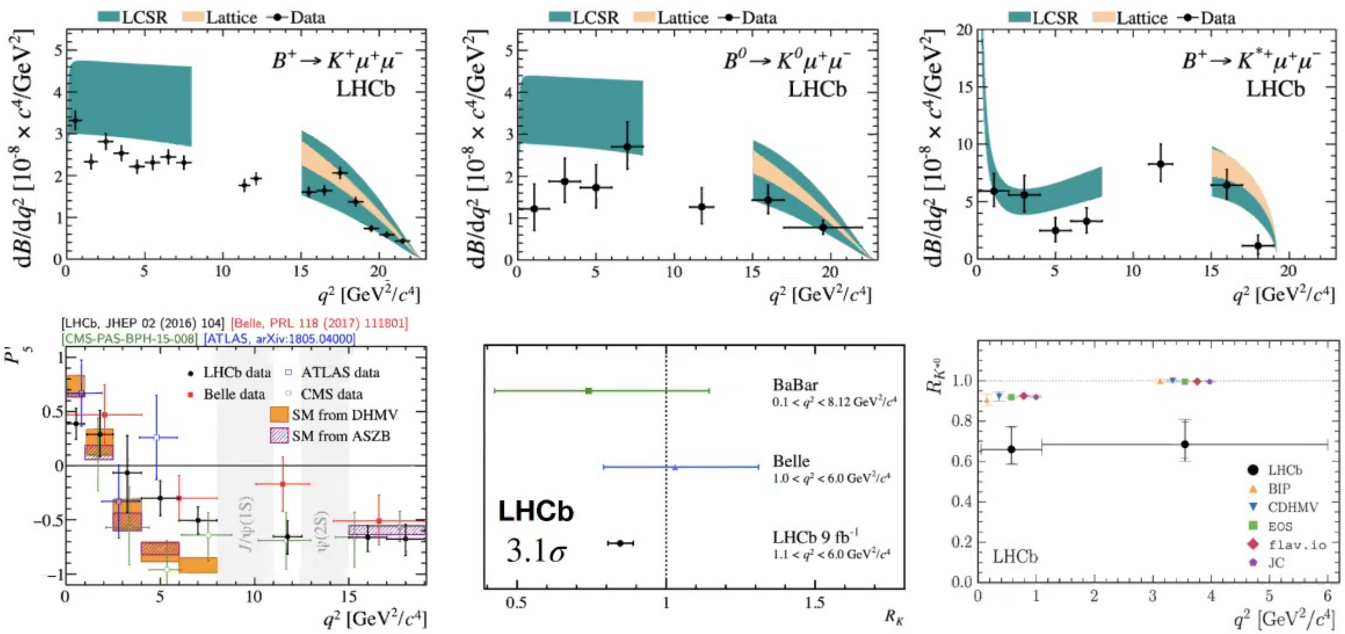
  An unidentified or underestimated systematic uncertainty...

Anomalies in $b \to s$ transitions



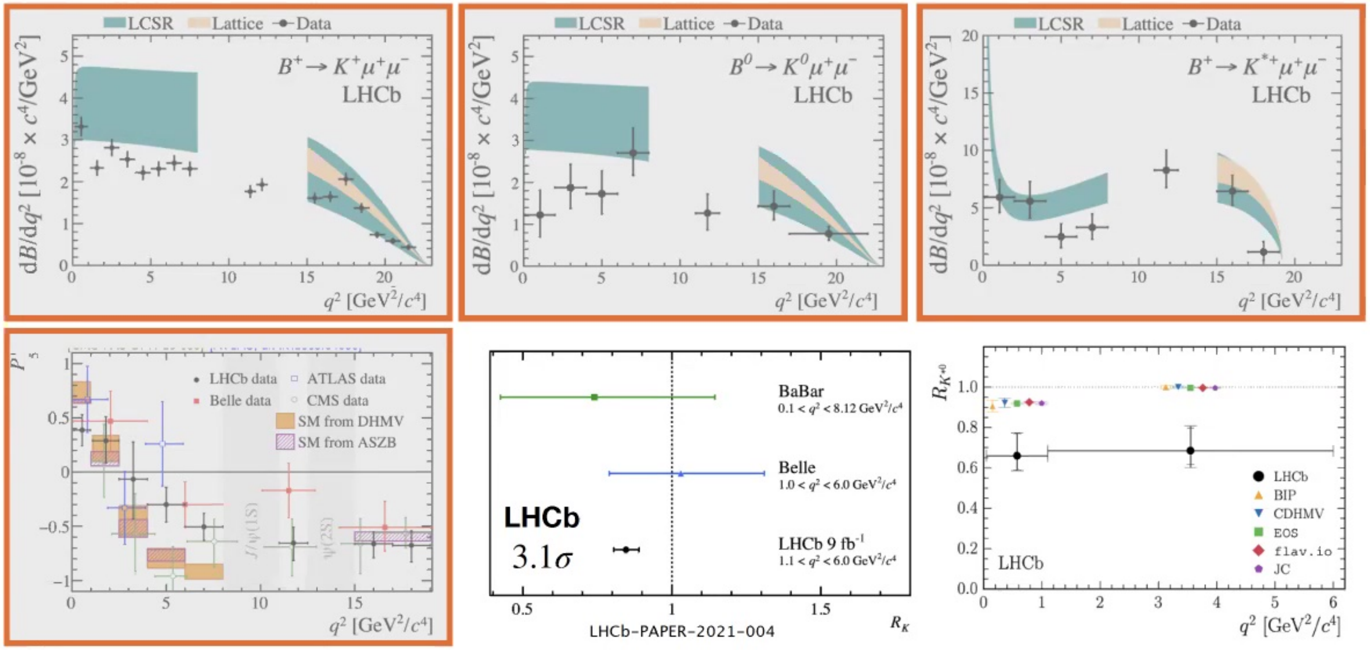
Status 2017

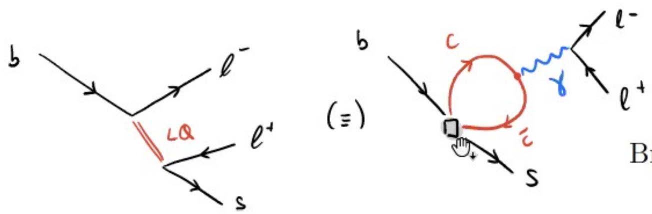
Anomalies in $b \to s$ transitions



Status NOW

Anomalies in $b \to s$ transitions



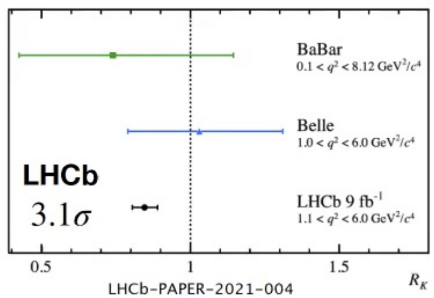


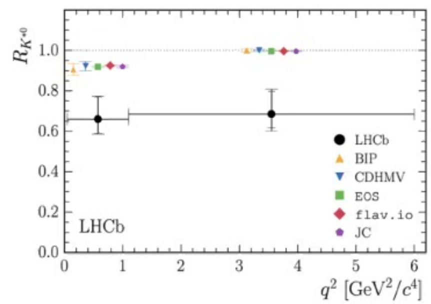
It could mimic NP!!!

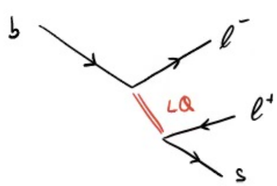
$$\mathrm{Br}(B \to K^{(*)}\ell^+\ell^-)^{\mathrm{exp}} = \mathrm{Br}(B \to K^{(*)}\ell^+\ell^-)^{\mathrm{SM}} + \Delta C_9^{\mathrm{univ}}$$

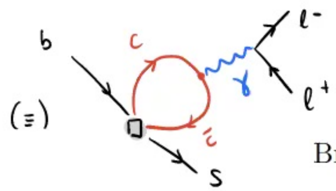
Anomalies in $b \to s$ transitions

$$\mathcal{R}_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{d\mathrm{Br}(B \to K\mu^+\mu^-)}{dq^2} dq^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{d\mathrm{Br}(B \to K e^+ e^-)}{dq^2} dq^2} \overset{\mathrm{SM}}{=} 1 \pm \mathcal{O}(10^{-2}) \text{ EM correction}$$







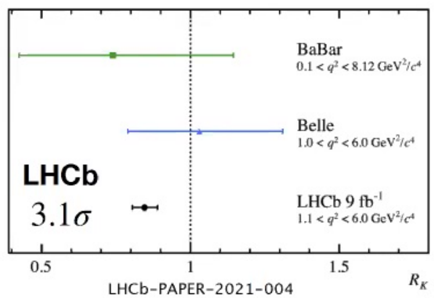


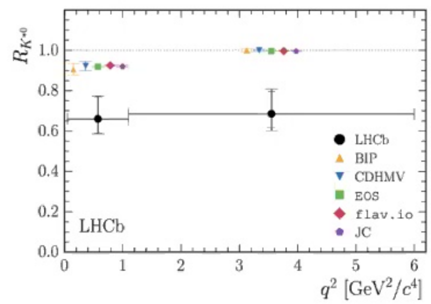
It could mimic NP!!!

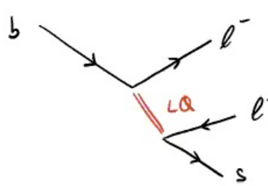
$$\mathrm{Br}(B \to K^{(*)}\ell^+\ell^-)^{\mathrm{exp}} = \mathrm{Br}(B \to K^{(*)}\ell^+\ell^-)^{\mathrm{SM}} + \Delta C_9^{\mathrm{univ}}$$

Anomalies in $b \to s$ transitions

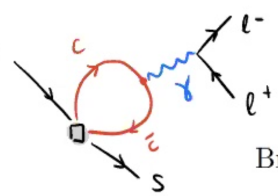
$$\mathcal{R}_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{d\mathrm{Br}(B \to K\mu^+\mu^-)}{dq^2} dq^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{d\mathrm{Br}(B \to K e^+ e^-)}{dq^2} dq^2} \overset{\mathrm{SM}}{\simeq} \frac{\Delta_{\mathrm{SM}} + \Delta C_9^{\mathrm{univ}}}{\Delta_{\mathrm{SM}}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







(≡)



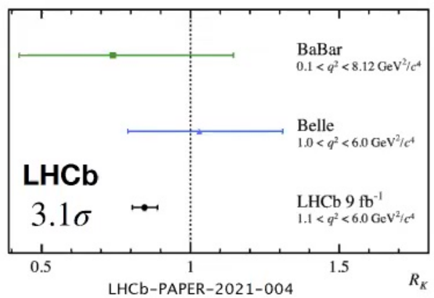
It could mimic NP!!!

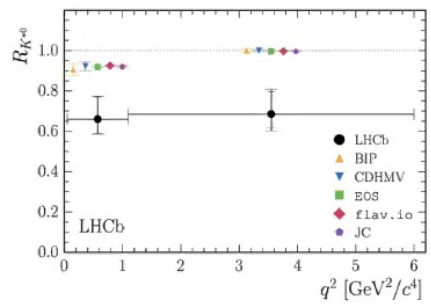
$$\mathrm{Br}(B \to K^{(*)}\ell^+\ell^-)^{\mathrm{exp}} = \mathrm{Br}(B \to K^{(*)}\ell^+\ell^-)^{\mathrm{SM}} + \Delta C_9^{\mathrm{univ}}$$

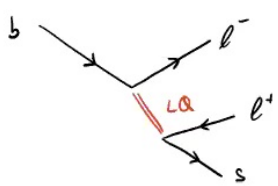
Anomalies in $b \to s$ transitions

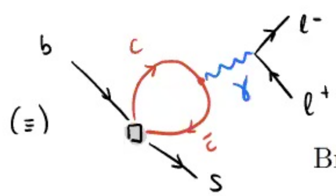
$$\mathcal{R}_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{d\mathrm{Br}(B \to K\mu^+\mu^-)}{dq^2} dq^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{d\mathrm{Br}(B \to K e^+ e^-)}{dq^2} dq^2} \overset{\mathrm{SM}}{\simeq} \frac{\Delta_{\mathrm{SM}} + \Delta C_9^{\mathrm{univ}}}{\Delta_{\mathrm{SM}}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

Clean Observables!



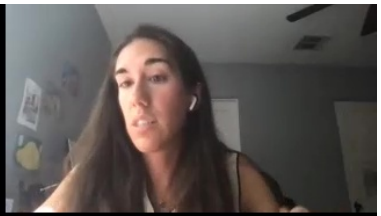






It could mimic NP!!!

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



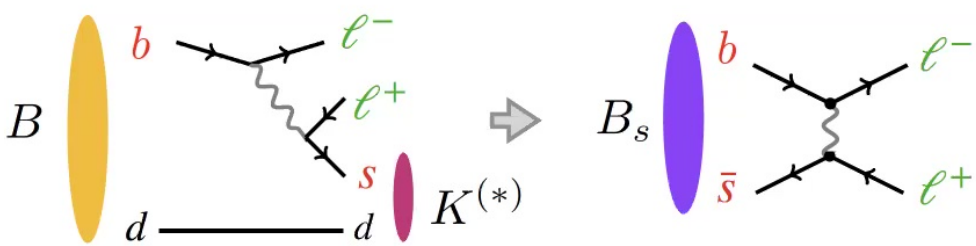
Anomalies in $b \to s$ transitions

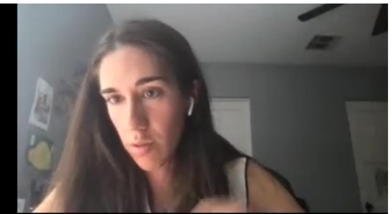
- Clean observables:

3.1σ $\quad \mathcal{R}_K^{\text{exp}}(1.1 < q^2 < 6.0\ \text{GeV}^2/c^4) = 0.846^{+0.042\,+0.013}_{-0.039\,-0.012}$

$$2.1\text{-}2.5\sigma \quad \mathcal{R}_{K^*}^{\text{exp}} = \begin{cases} 0.66^{+0.11}_{-0.07}\ (\text{stat}) \pm 0.03\ (\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4, \\ 0.69^{+0.11}_{-0.07}\ (\text{stat}) \pm 0.05\ (\text{syst}) & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2/c^4. \end{cases}$$

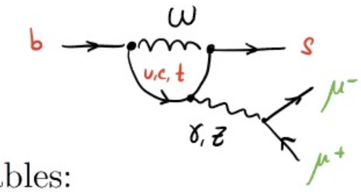
2.1σ $\quad \text{Br}(B_s \to \mu^+\mu^-)^{\text{exp}} = 2.69^{+0.37}_{-0.35} \times 10^{-9}$

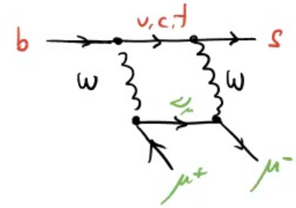




Anomalies in $b \to s$ transitions

- New Physics compites with the SM at the loop level!



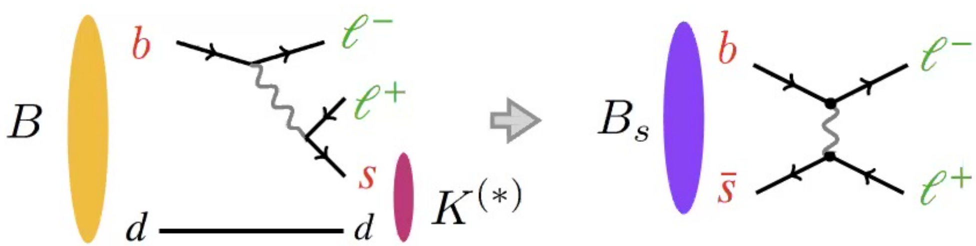


- Clean observables:

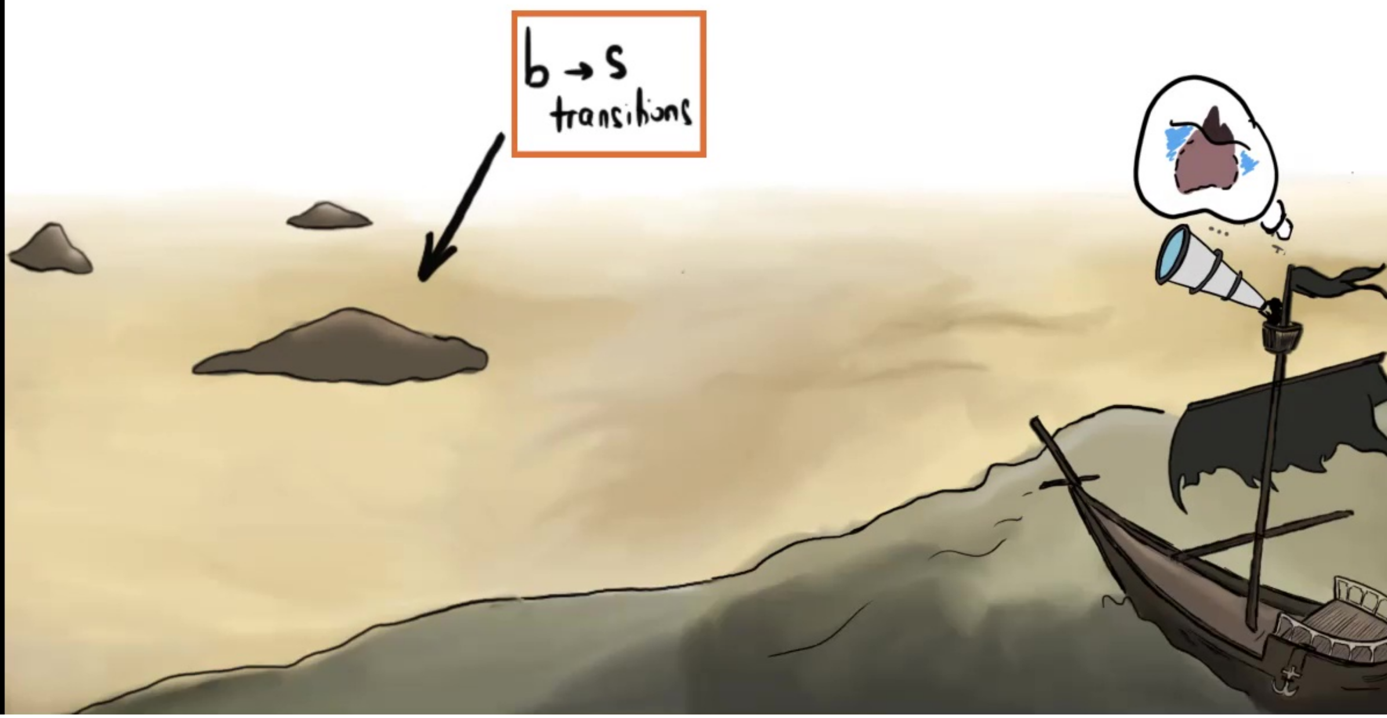
3.1σ $\mathcal{R}_K^{\text{exp}}(1.1 < q^2 < 6.0\ \text{GeV}^2/c^4) = 0.846^{+0.042\,+0.013}_{-0.039\,-0.012}$

2.1-2.5σ $\mathcal{R}_{K^*}^{\text{exp}} = \begin{cases} 0.66^{+0.11}_{-0.07}\ (\text{stat}) \pm 0.03\ (\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4, \\ 0.69^{+0.11}_{-0.07}\ (\text{stat}) \pm 0.05\ (\text{syst}) & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2/c^4. \end{cases}$

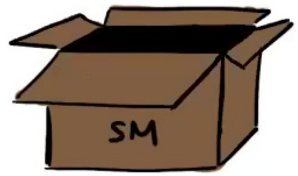
2.1σ $\text{Br}(B_s \to \mu^+\mu^-)^{\text{exp}} = 2.69^{+0.37}_{-0.35} \times 10^{-9}$



Anomalies in $b \to s$ transitions



Unification of Matter



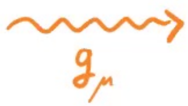
$3 \times$

Q_L	Q_L	Q_L	l_L
u_R	u_R	u_R	ν_L
d_R	d_R	d_R	e_R

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

Unification of Matter

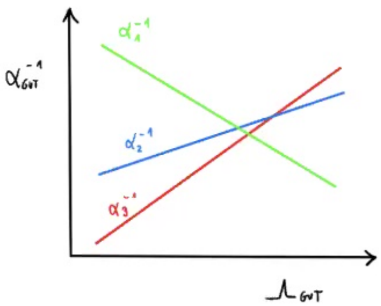
$$3 \times \begin{array}{cccc} Q_L & Q_L & Q_L & \ell_L \\ u_R & u_R & u_R & \nu_L \\ d_R & d_R & d_R & e_R \end{array}$$

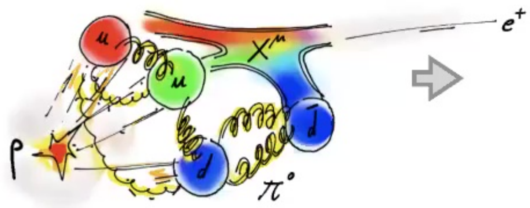


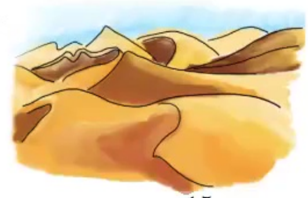
u u u d d d

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

Unification of Matter





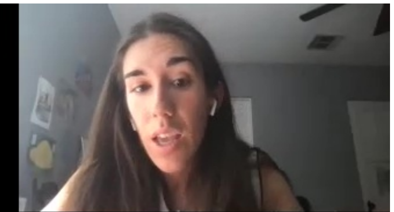


$\Lambda_{\mathrm{GUT}} \gtrsim 10^{15}$ GeV

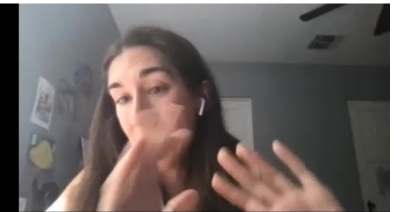
$3 \times$

Q_L	Q_L	Q_L	l_L
u_R	u_R	u_R	ν_L
d_R	d_R	d_R	e_R

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



Unification of Matter: Pati-Salam



$$
3 \times \left\{ \begin{array}{ccc|c} Q_L & Q_L & Q_L & \ell_L \\ u_R & u_R & u_R & \nu_L \\ d_R & d_R & d_R & e_R \end{array} \right\}
$$

↑ May leptons be the 4th color?

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

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

Unification of Matter: Pati-Salam

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

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

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

$$3 \times \left\{ \begin{array}{ccc:c} Q_L & Q_L & Q_L & l_L \\ u_R & u_R & u_R & \nu_L \\ d_R & d_R & d_R & e_R \end{array} \right\}$$

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

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

Unification of Matter: Pati-Salam

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

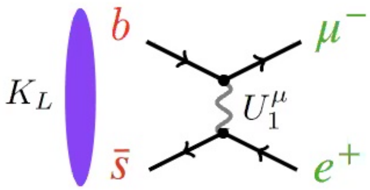
$$\mathcal{L}_K \supset \frac{g_4}{\sqrt{2}} U_1^\mu (\bar{Q}_L \gamma_\mu \ell_L + \bar{u}_R \gamma_\mu \nu_R + \bar{d}_R \gamma_\mu e_R) + \text{h.c.}$$

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

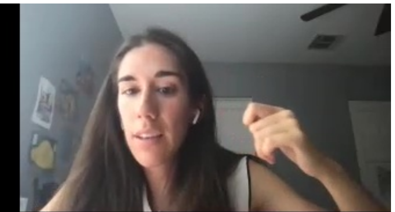
$$\cancel{SU}(4)_c \otimes SU(2)_L \otimes U(\cancel{1})_R \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

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

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



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



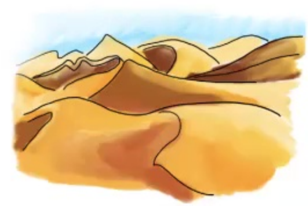
$$V_{15}^\mu \sim (15,1,0) = \underbrace{\begin{pmatrix} \overset{SU(3)_C}{\boxed{G^\mu}} & U_1^\mu/\sqrt{2} \\ (U_1^\mu)^*/\sqrt{2} & 0 \end{pmatrix}}_{SU(4)} + T_4 B'^\mu$$

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

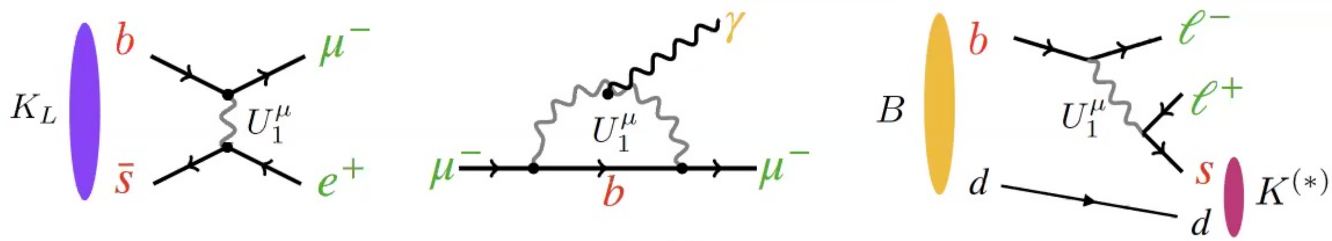
$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \Rightarrow M_{U_1} \sim g_4 v_\chi \gtrsim 10^3 \text{ TeV}$$

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

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



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



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

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

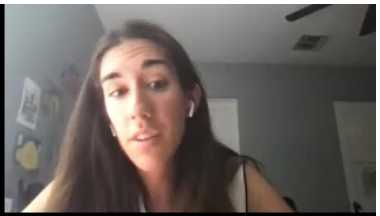
Naive bound!

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

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

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

Unification of Matter



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

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

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

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

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

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

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

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

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

Unification of Matter

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

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

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

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

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

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

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

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

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

Inverse seesaw mechanism

- Add a fermion singlet $S \sim (1,1,0)$

$$-\mathcal{L}^{\nu}_{QL} = Y_5 F_u \chi S \; + \; \frac{1}{2}\mu S S + \text{h.c.}.$$

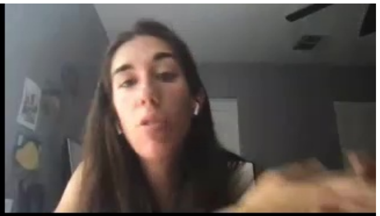
$$\xRightarrow{\langle\chi\rangle} M^D_\chi = Y_5 v_\chi/\sqrt{2}$$

- Mass matrix for neutral fermions:

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

$$\boxed{M^D_\chi} \gg \boxed{M^D_\nu} \gg \mu \;\Rightarrow\; m_\nu \approx \mu \boxed{\text{EW}}/\boxed{\text{LQ}}$$

Inverse seesaw mechanism



- Add a fermion singlet $S \sim (1,1,0)$

Protected by fermion symmetry

$$-\mathcal{L}^{\nu}_{QL} = Y_5 F_u \chi S \; + \; \frac{1}{2}\boxed{\mu} SS + \text{h.c.}.$$

$$\xrightarrow{\langle\chi\rangle} M^D_\chi = Y_5 v_\chi / \sqrt{2}$$

- Mass matrix for neutral fermions:

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

$$\boxed{M^D_\chi} \gg \boxed{M^D_\nu} \gg \mu \;\Rightarrow\; m_\nu \approx \boxed{\mu}\boxed{\text{EW}}/\boxed{\text{LQ}}$$

Inverse seesaw mechanism

- Add a fermion singlet $\quad S \sim (1,1,0)$

$$-\mathcal{L}^{\nu}_{QL} = Y_5 F_u \chi S \; + \; \frac{1}{2}\boxed{\mu} S S + \text{h.c.}.$$

$$\xrightarrow{\langle \chi \rangle} M_\chi^D = Y_5 v_\chi / \sqrt{2}$$

- Mass matrix for neutral fermions:

$$(\nu \;\, \nu^c \;\, S) \begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & M_\chi^D \\ 0 & (M_\chi^D)^T & \boxed{\mu} \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$$M_\chi^D \gg M_\nu^D \gg \mu \quad \Rightarrow \quad m_\nu \approx \boxed{\mu} (M_\nu^D)^2 / (M_\chi^D)^2,$$

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

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

Unification of Matter

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

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

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

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

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

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

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

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

Unification of Matter

- The theory predicts scalar LQs:

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

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

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

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

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

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

Unification of Matter

- The theory predicts scalar LQs:

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

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

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

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

Unification of Matter

- The theory predicts scalar LQs:

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

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

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

e.g. $\frac{1}{\Lambda} u_R^\alpha d_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}, \quad \frac{1}{\Lambda} d_R^\alpha d_R^\beta \Phi_4^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$ [Arnold, Fornal, Wise, 2013]

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

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

Unification of Matter

- The theory predicts scalar LQs:

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

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

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

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

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

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

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

Unification of Matter

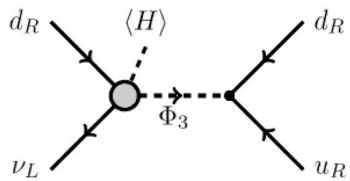
- The theory predicts scalar LQs:

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

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

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

e.g. $\frac{1}{\Lambda} u_R^\alpha d_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}, \quad \frac{1}{\Lambda} d_R^\alpha d_R^\beta \Phi_4^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$ [Arnold, Fornal, Wise, 2013]



$$\Rightarrow \quad M_{\Phi_3} > 10^8 \text{ GeV} \left(\frac{M_{PL}}{\Lambda}\right)$$

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

Unification of Matter

- The theory predicts scalar LQs:

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

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

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

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

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

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

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

Unification of Matter

- The theory predicts scalar LQs:

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

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

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

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

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

$v_\chi \sim \mathcal{O}(10^3)$ TeV, and $\Lambda_{PS} > 10^{15}$ GeV $\Rightarrow$ Φ_3 and Φ_4 are safe if embedded in Pati-Salam!

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

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

Pati-Salam shielding

- The theory predicts scalar LQs:

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

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

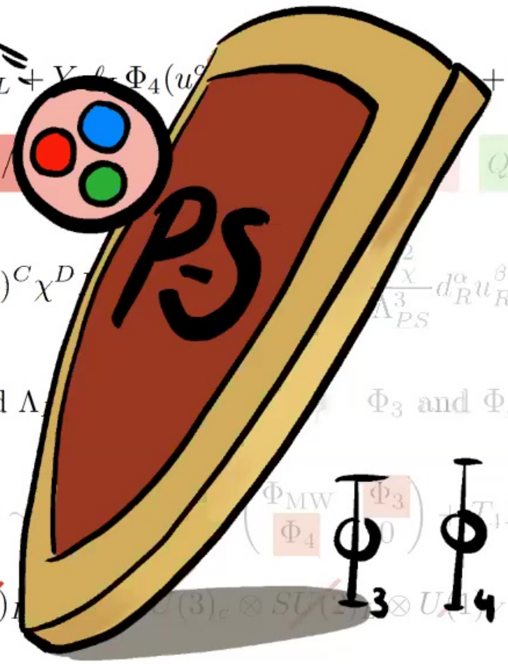
$Q_B(\Phi_3) = -1/\ldots$ $\quad Q_L(\Phi_4) = -1$

$\frac{1}{\Lambda_{PS}^3} F_u^A F_d^B (\Phi^\dagger \chi)^C \chi^D \ldots \frac{v_\chi^2}{\Lambda_{PS}^3} d_R^\alpha u_R^\beta (\Phi_3^\dagger)^\gamma \epsilon H^\dagger \epsilon_{\alpha\beta\gamma},$

$v_\chi \sim \mathcal{O}(10)$ TeV, and $\Lambda \ldots$ $\quad \Phi_3$ and Φ_4 are safe if embedded in Pati-Salam!

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

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



$\Phi_3 \quad \Phi_4 \quad U_1^\mu$

Unification of Matter

- The theory predicts scalar LQs:

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

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

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

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

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

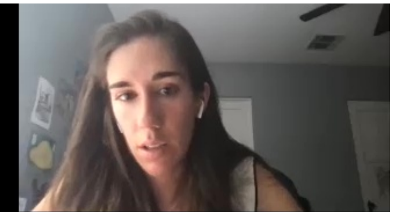
$$\cancel{SU}(4)_c \otimes SU(2)_L \otimes \cancel{U(1)}_R \Rightarrow SU(3)_c \otimes \cancel{SU}(2)_L \otimes \cancel{U}(1)_Y \Rightarrow SU(3)_c \otimes U(1)_Q$$

Pati-Salam shielding

- The theory predicts scalar LQs:

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

[P. Fileviez, CM and A. D. Plascencia, 2104.11229]

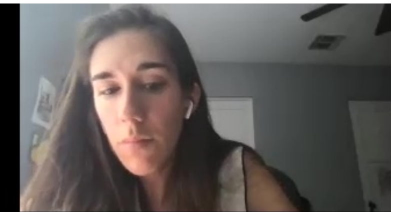


Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

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

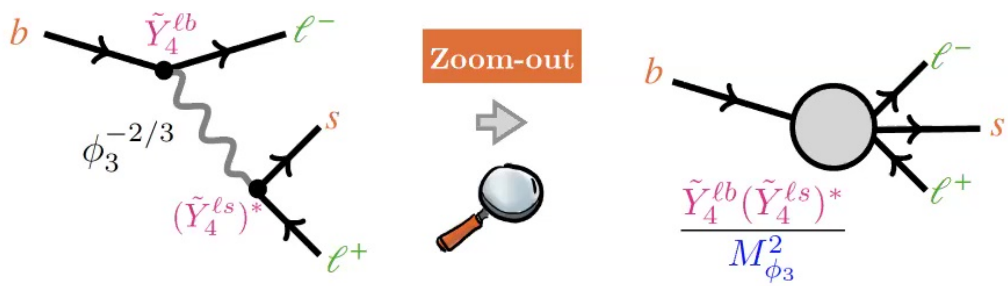
- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions!

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



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

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



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

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

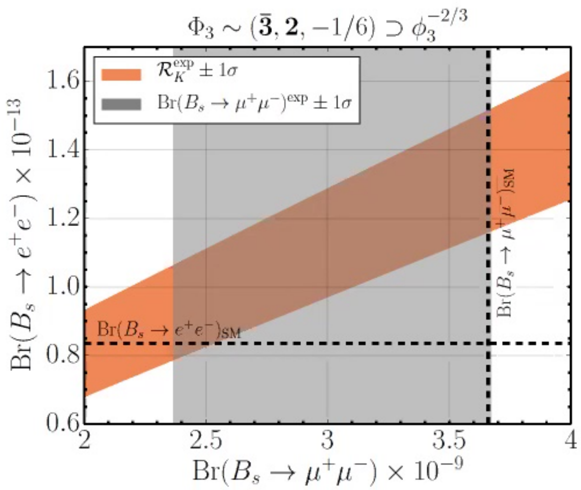
Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

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

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

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

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



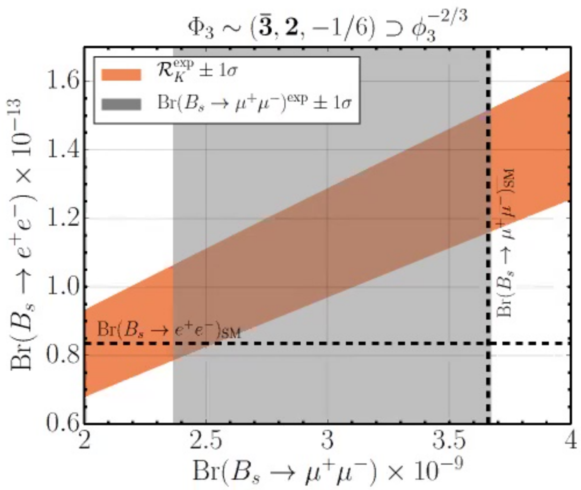
Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

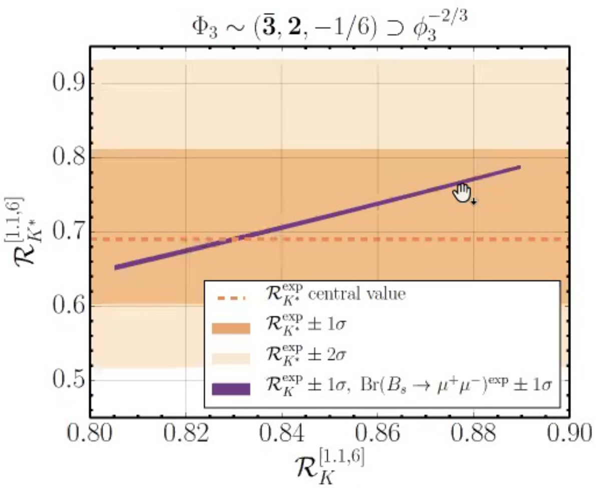
$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

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

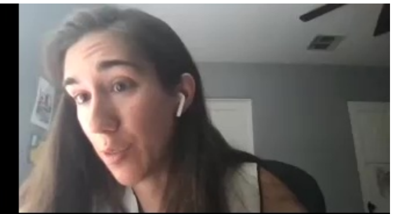
- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions!

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





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

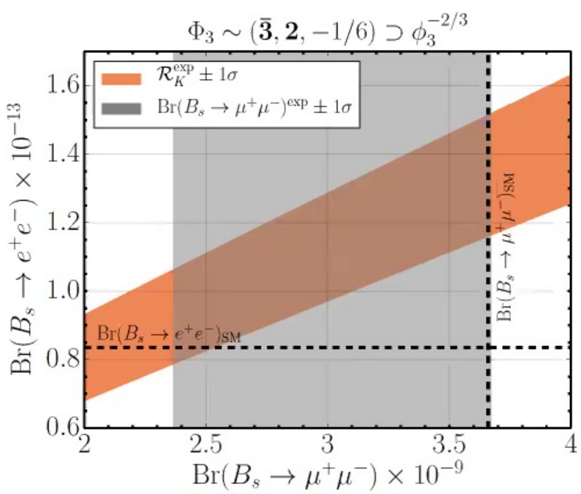


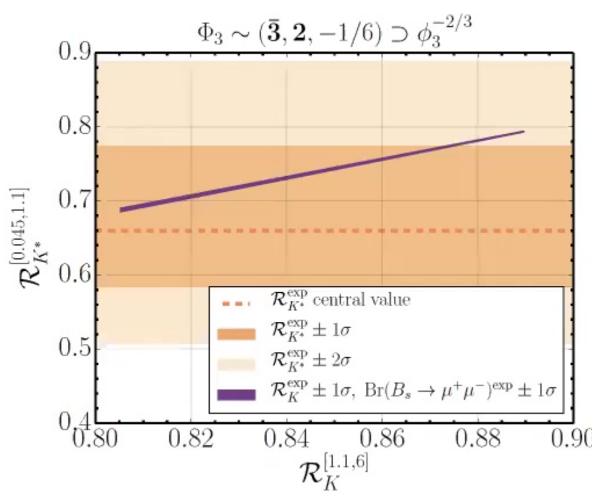
$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

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

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

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





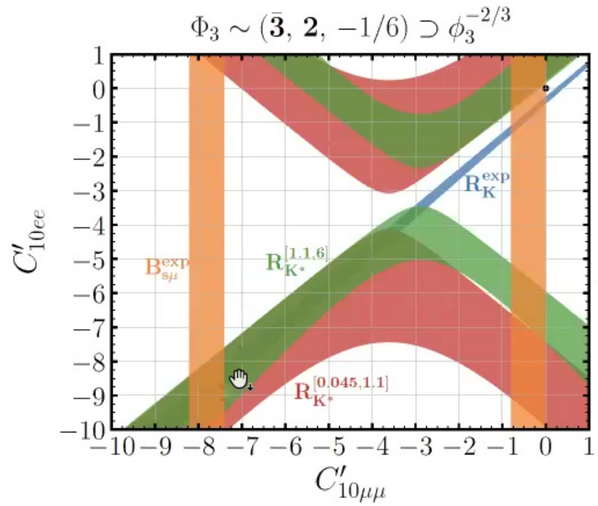
Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

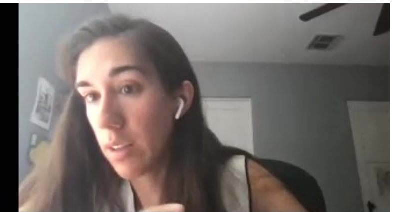
$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

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

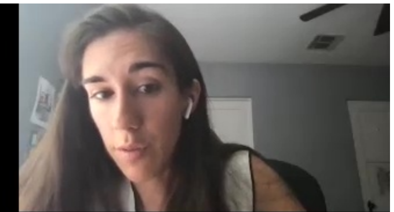
- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions!

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





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



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

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

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

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

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

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

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

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

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

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

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

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

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

$\tau \to K_S e/\mu$

$\tau \to \gamma\mu$

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

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

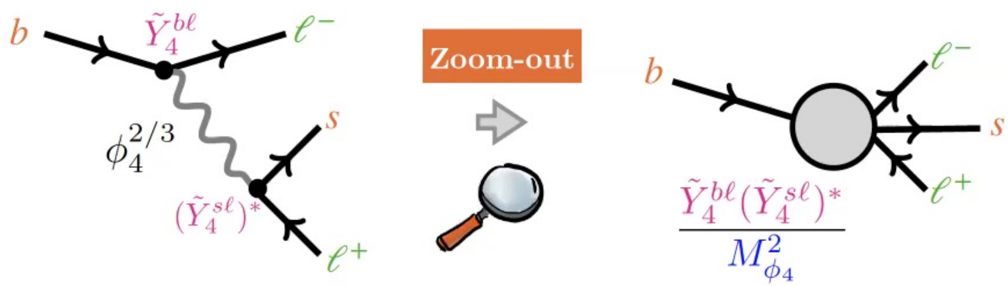
- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions! (also to other processes...)

$$\tilde{Y}_{\phi_3} = E Y_4 D^c = \begin{pmatrix} \cdot & \bigcirc & \bigcirc \\ \cdot & \bigcirc & \bigcirc \\ \cdot & \cdot & ? \end{pmatrix}$$

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

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

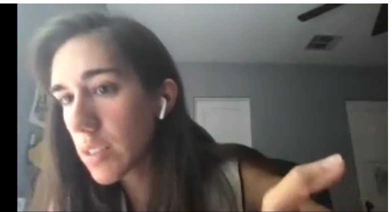
- $\phi_4^{2/3}$ contributes to $b \to s$ transitions!



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

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

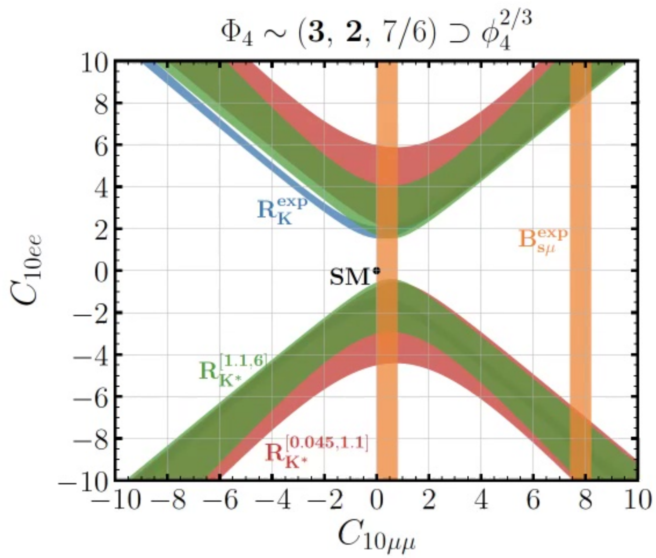
Scalar LQ: $\Phi_4 \sim (3, 2, 7/6)$



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

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

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



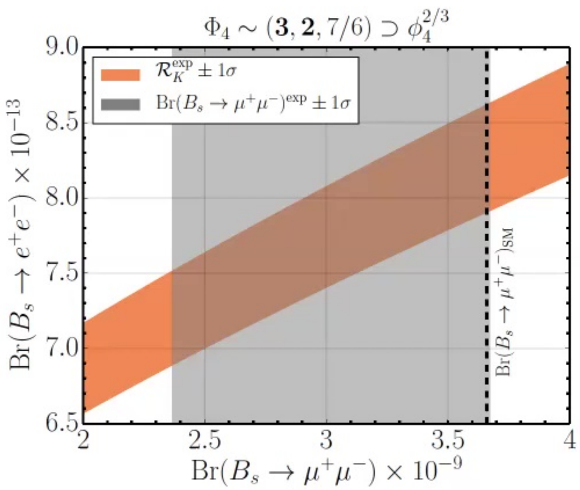
Scalar LQ: $\Phi_4 \sim (3, 2, 7/6)$

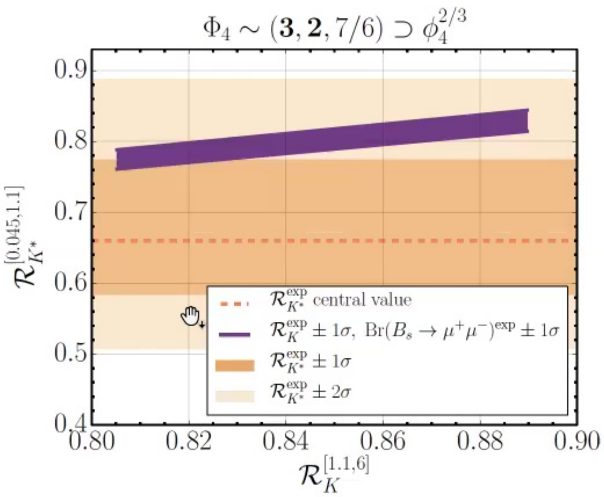
$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a + \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a} + \text{h.c.}$$

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

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

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





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

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

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

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

$Z \to K_s\, \mu/e$

$Z \to \eta'$

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

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

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

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

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

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

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

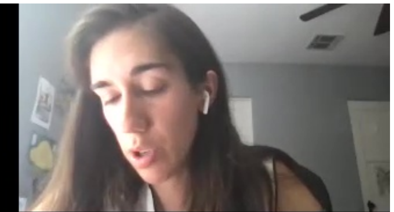
$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset \boxed{\tilde{\tilde{Y}}_4^{ab}\; \bar{e}_R^b (\phi_4^{5/3})^* u_L^a} + \tilde{Y}_{\phi_4}^{ab}\; \bar{e}_R^b (\phi_4^{2/3})^* d_L^a + \text{h.c.}$$

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

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

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

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



$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset \boxed{\tilde{\tilde{Y}}_4^{ab}\; \bar{e}_R^b (\phi_4^{5/3})^* u_L^a} + \tilde{Y}_{\phi_4}^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a + \text{h.c.}$$

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

$$\tilde{\tilde{Y}}_4 \simeq \tilde{Y}_{\phi_4}$$

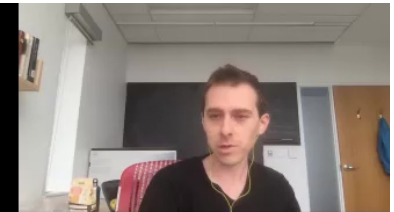
$$Y_4 = \begin{pmatrix} \cdot & \cdot & \cdot \\ Y^{ce} & Y^{c\mu} & \cdot \\ Y^{te} & Y^{t\mu} & ? \end{pmatrix}$$

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

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

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

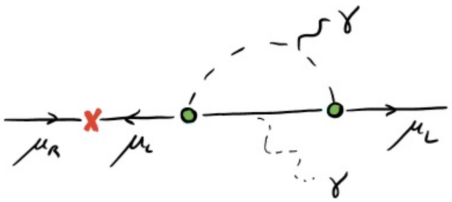
Fermilab Muon g-2, 2021



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

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

Fermilab Muon g-2, 2021

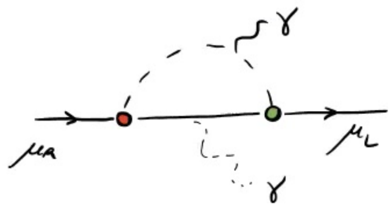


$$\Delta a_\mu^\alpha = \frac{-3}{16\pi^2}\frac{m_\mu^2}{M_{\Phi_\alpha}^2}\sum_j\left[\left(|\lambda_{\alpha L}^{2j}|^2 + |\lambda_{\alpha R}^{2j}|^2\right)\times f_{\rm loop}\right]$$

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

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

Fermilab Muon g-2, 2021



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

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

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

Fermilab Muon g-2, 2021

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

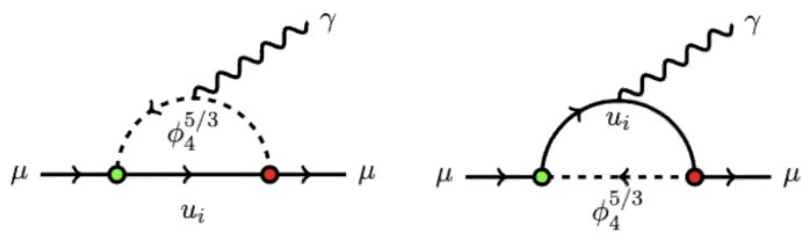
$$\Delta a_\mu^\alpha = \frac{-3}{16\pi^2} \frac{m_\mu^2}{M_{\Phi_\alpha}^2} \sum_j \left[\left(|\lambda_{\alpha L}^{2j}|^2 + \cancel{|\lambda_{\alpha R}^{2j}|^2} \right) \times f_{\text{loop}} + \frac{m_q}{m_\mu} \cancel{\text{Re}[\lambda_{\alpha L}^{2j} (\lambda_{\alpha R}^{2j})^*] f'_{\text{loop}}}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

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

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

Fermilab Muon g-2, 2021

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



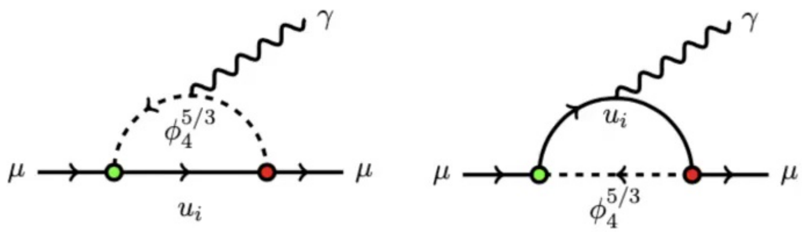
Chiral enhancement!

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

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

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

$$-\mathcal{L} \supset \bar{e}_i \left(\boxed{\lambda_R^{ij}} P_L + \boxed{\lambda_L^{ij}} P_R \right) u^j \left(\phi_4^{5/3}\right)^* + \text{h.c.}$$

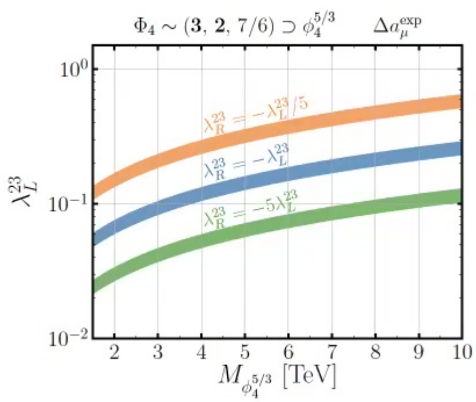


$$\Delta a_\mu^\alpha = \frac{-3}{16\pi^2}\frac{m_\mu^2}{M_{\Phi_\alpha}^2}\sum_j \left[\left(|\lambda_{\alpha L}^{2j}|^2 + |\lambda_{\alpha R}^{2j}|^2\right)\times f_{\text{loop}} + \frac{m_q}{m_\mu}\text{Re}[\lambda_{\alpha L}^{2j}(\lambda_{\alpha R}^{2j})^*] f'_{\text{loop}}\right]$$

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

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

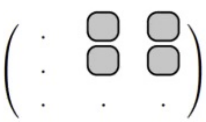
$$-\mathcal{L} \supset \bar{e}_i \left(\boxed{\lambda_R^{ij}} P_L + \boxed{\lambda_L^{ij}} P_R \right) u^j \left(\phi_4^{5/3} \right)^* + \text{h.c.}$$

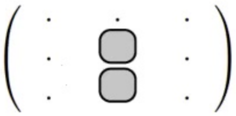


$$\Delta a_\mu^\alpha = \frac{-3}{16\pi^2} \frac{m_\mu^2}{M_{\Phi_\alpha}^2} \sum_j \left[\left(|\lambda_{\alpha L}^{2j}|^2 + |\lambda_{\alpha R}^{2j}|^2 \right) \times f_{\rm loop} + \frac{m_q}{m_\mu} \mathrm{Re}[\lambda_{\alpha L}^{2j} (\lambda_{\alpha R}^{2j})^*] f'_{\rm loop} \right]$$

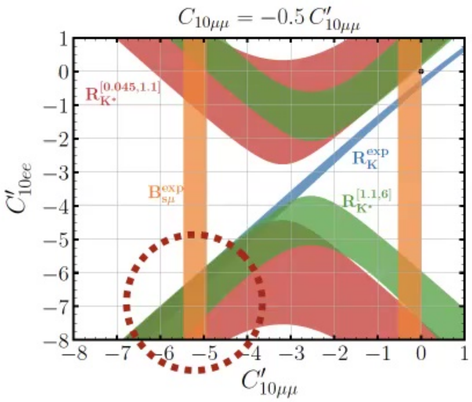
Bonus: $(g-2)_\mu$

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

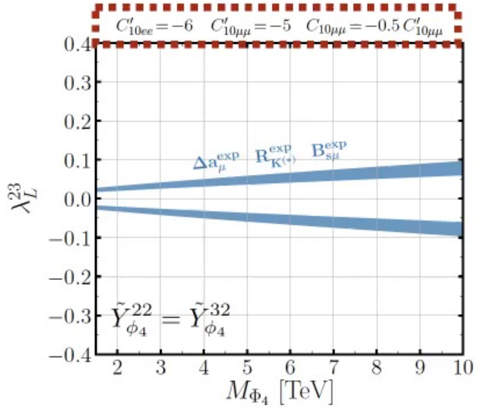
$\tilde{Y}_{\phi_3} =$ 

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

$\phi_3^{-2/3}$



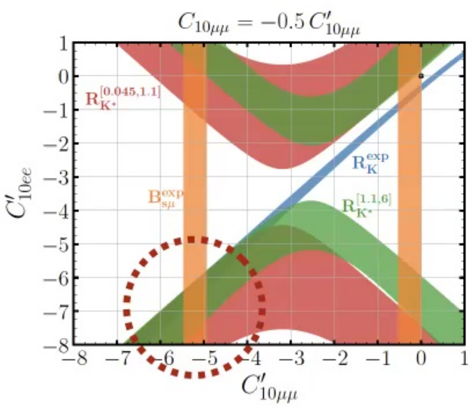
$\phi_4^{5/3}$



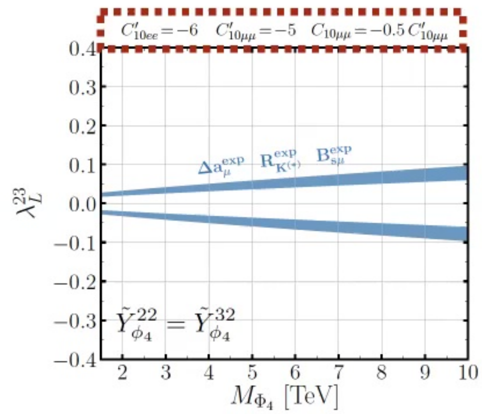
Bonus: $(g-2)_\mu$

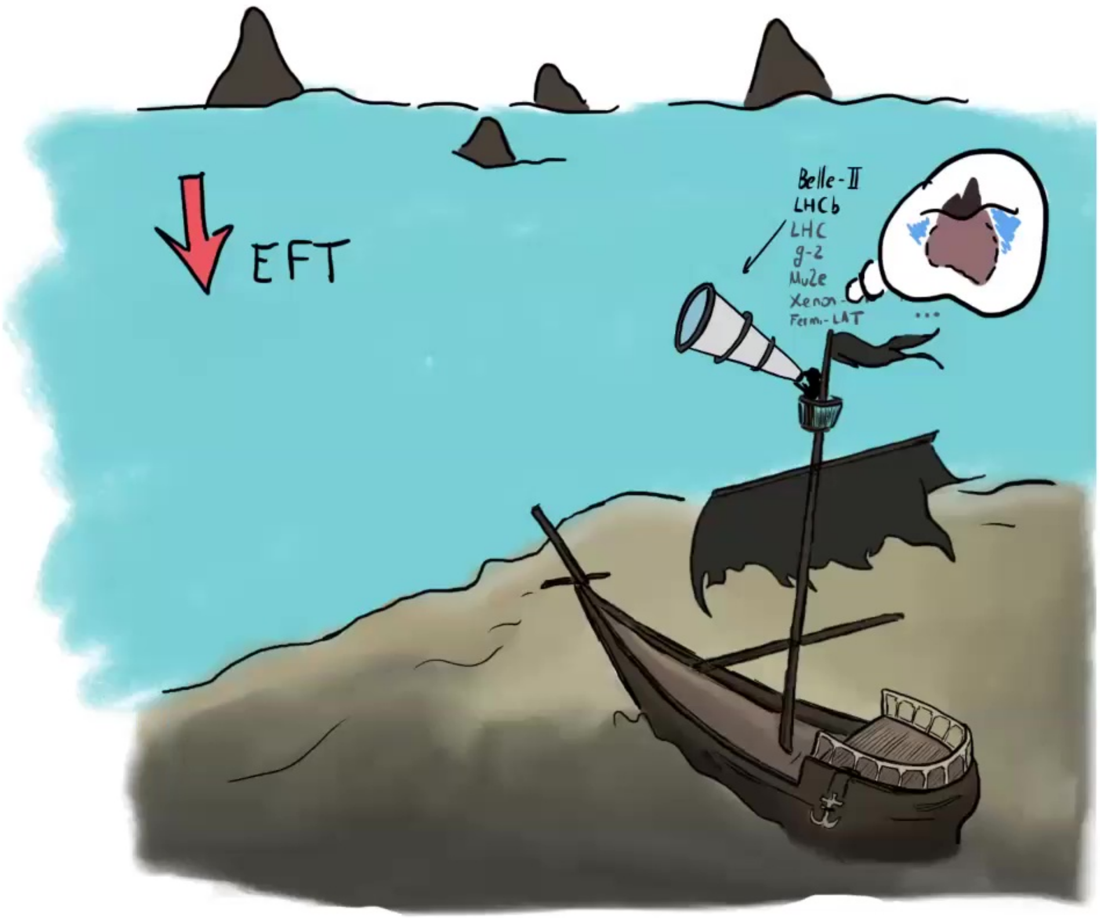
$$-\mathcal{L} \supset \boxed{\tilde{Y}_2 \mu_L \phi_4^{5/3} (u^c)_L} + \tilde{Y}_{\phi_4} \left(\boxed{u_L (\phi_4^{5/3})^* (\mu^c)_L} + \boxed{d_L (\phi_4^{2/3})^* (\mu^c)_L} \right) + \boxed{\tilde{Y}_{\phi_3} e_L^i (\phi_3^{-2/3})^* (d^c)_L} + \text{h.c.}$$

$\boxed{b \to s}$

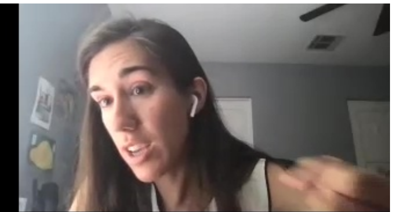


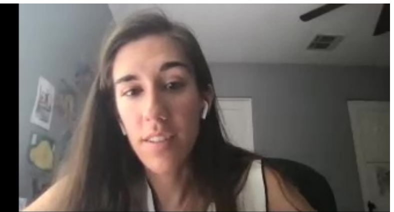
$\boxed{(g-2)_\mu}$




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

Belle-II
LHCb
LHC
g-2
MuZe
UV-COMPLETION





Thank you!