Anomalies and L_μ - L_τ

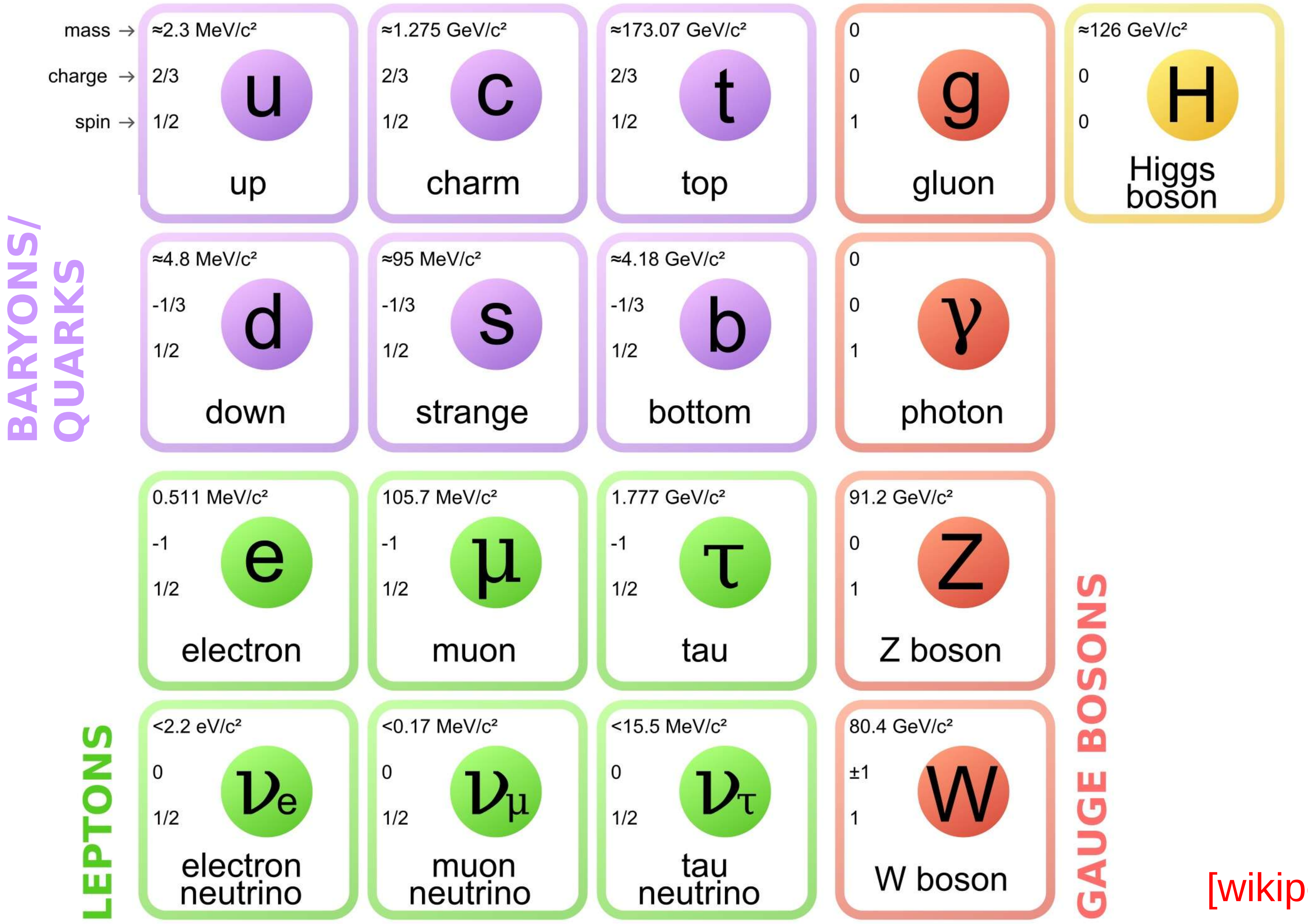
Julian Heeck

DWQ@25

12/15/2021

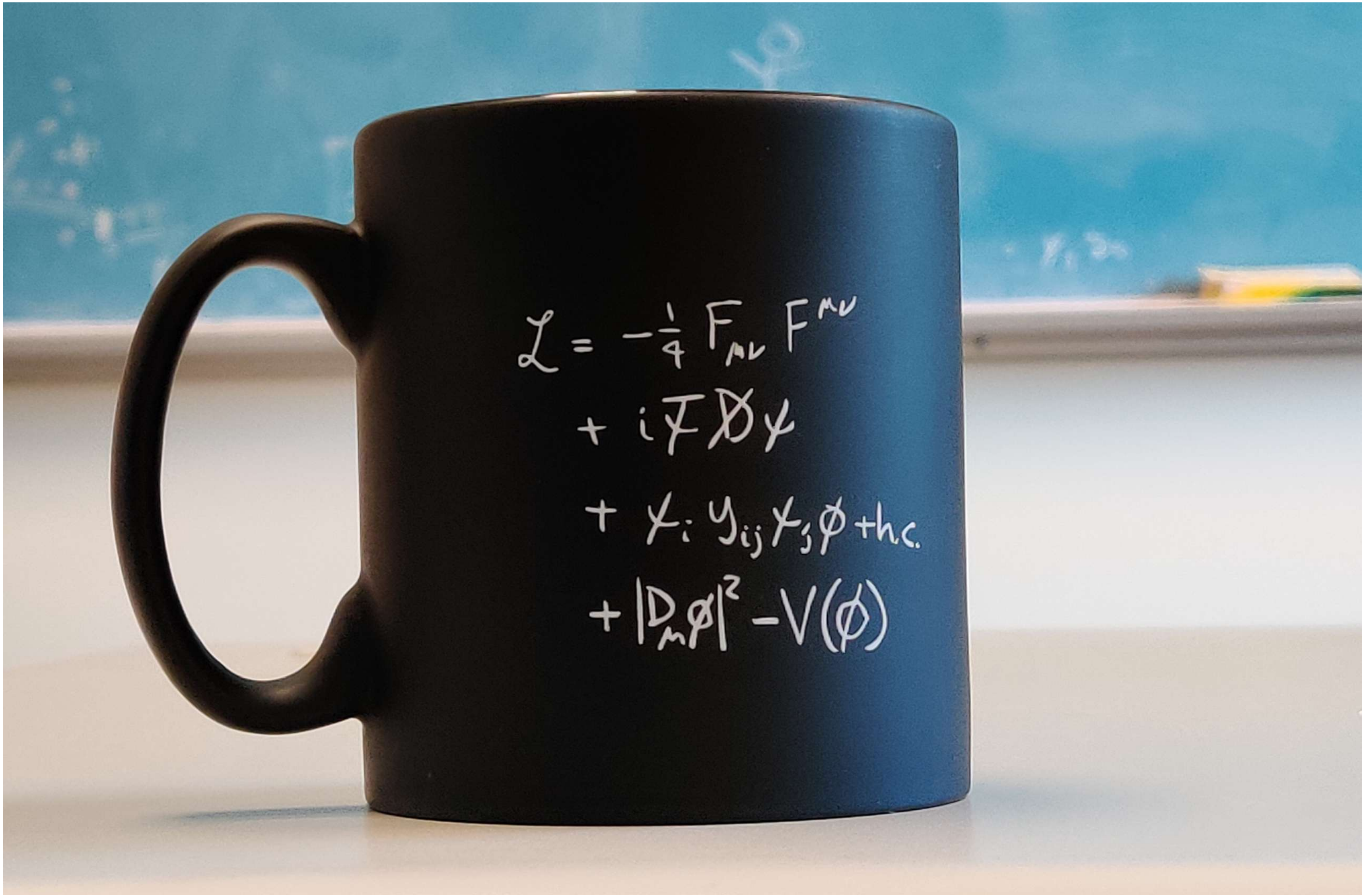
University of Virginia

Elementary particles



[wikipedia]

Interactions



Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$\mathsf{U}(1)_\mathsf{B} \times \mathsf{U}(1)_{\mathsf{L_e}} \times \mathsf{U}(1)_{\mathsf{L}_\mu} \times \mathsf{U}(1)_{\mathsf{L}_\tau}$$

$$=$$

$$\mathsf{U}(1)_{\mathsf{B+L}} \times \mathsf{U}(1)_{\mathsf{B-L}} \times \mathsf{U}(1)_{\mathsf{L}_\mu - \mathsf{L}_\tau} \times \mathsf{U}(1)_{\mathsf{L}_\mu + \mathsf{L}_\tau - 2\mathsf{L_e}}\,.$$

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$\mathrm{U}(1)_\mathrm{B} \times \mathrm{U}(1)_{\mathrm{L}_e} \times \mathrm{U}(1)_{\mathrm{L}_\mu} \times \mathrm{U}(1)_{\mathrm{L}_\tau}$$

$$=$$

$$\mathrm{U}(1)_{\mathrm{B+L}} \times \mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \,.$$

- Broken non-perturbatively, but unobservable. ['t Hooft, PRL '76]

- True accidental global symmetry:

$$\mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \,.$$

Symmetries of the Standard Model

- True accidental global symmetry:

$$U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e} .$$

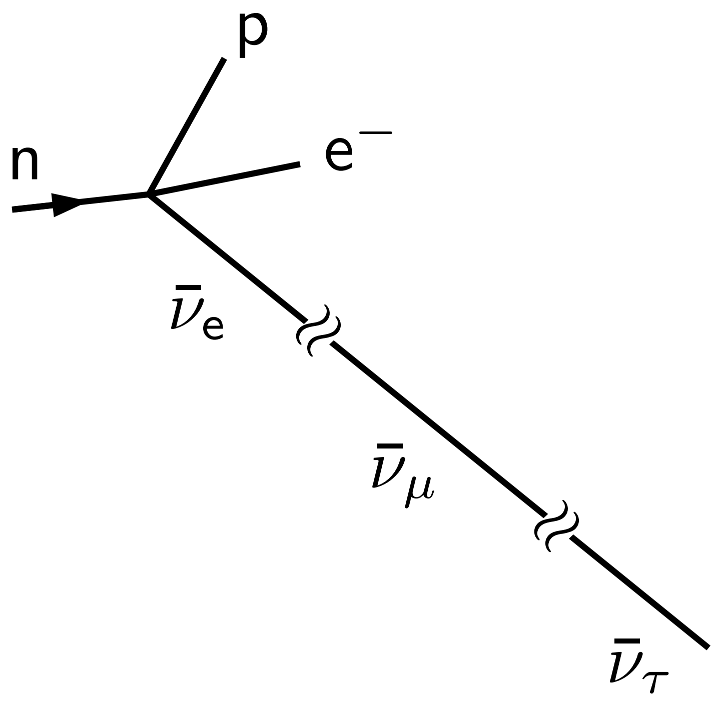
- A subgroup $U(1)_{L_\alpha - L_\beta}$ can be gauged without any new particles!
  [Foot ‘91; He, Joshi, Lew, Volkas, ‘91]
- With 3 N_R, the entire $U(1)^3$ can be gauged. [Araki, **JH**, Kubo, ‘12]
  - Gauging global SM symmetry gives neutrino masses, but no mixing angles...

Neutrino oscillations = flavor violation

- Observations of $\nu_\alpha \to \nu_\beta$ prove that $M_\nu \neq 0$ and

  $$U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$$

  is broken!
- Charged lepton flavor violation will occur, not clear how fast.
- B-L could still be unbroken if neutrinos are Dirac. [**JH**, 1408.6845]
  - B-L often broken to get seesaw.



Are the U(1) symmetries not interesting if they're broken?

Majorana mass matrix $\mathcal{M}_\nu = U\text{diag}(m_1, m_2, m_3)U^T$ in special cases:

1. Normal hierarchy ($m_1 \simeq 0$) and best-fit values (phases zero):

$$\mathcal{M}_\nu \simeq \begin{pmatrix} 0.37 & 0.75 & 0.24 \\ \cdot & 2.47 & 2.11 \\ \cdot & \cdot & 2.99 \end{pmatrix} 10^{-2}\,\text{eV} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix} \leftarrow L_e$$

2. Inverted hierarchy ($m_3 \simeq 0$) and $\alpha = \pi/2$:

$$\mathcal{M}_\nu \simeq \begin{pmatrix} 1.84 & -3.11 & 3.22 \\ \cdot & -0.14 & 0.88 \\ \cdot & \cdot & -1.77 \end{pmatrix} 10^{-2}\,\text{eV} \sim \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix} \leftarrow L_e - L_\mu - L_\tau$$

3. Quasi-degenerate ($m_{1,2,3} \simeq 1\,\text{eV}$) and $\beta = \pi/2$:

$$\mathcal{M}_\nu \simeq \begin{pmatrix} 0.96 & -0.20 & -0.22 \\ \cdot & 0.11 & -0.97 \\ \cdot & \cdot & -0.07 \end{pmatrix} \text{eV} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \leftarrow L_\mu - L_\tau$$

- Three interesting zeroth order approximations:

$$\mathcal{M}_\nu^{L_e} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}, \quad \mathcal{M}_\nu^{L_e - L_\mu - L_\tau} \sim \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix}, \quad \mathcal{M}_\nu^{L_\mu - L_\tau} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

[G. Branco, W. Grimus, L. Lavoura, *NPB (1989)*; S. Choubey, W. Rodejohann, *EPJC 40 (2005)*]

- Normal, inverted, quasi-degenerate hierarchy might hint at "weakly broken" $\mathrm{B} - 3\mathrm{L}_e, \ \mathrm{B} + 3(\mathrm{L}_e - \mathrm{L}_\mu - \mathrm{L}_\tau), \ \mathrm{L}_\mu - \mathrm{L}_\tau$

makes it anomaly free

[**JH**, Rodejohann, 1203.3117]

- Connection of L_μ - L_τ to **neutrino mass anomaly**.

- Pressure on quasi-degenerate regime from cosmology bounds on Σm_ν. [Asai et al, 1811.07571]

Symmetries of the Standard Model

- True accidental global symmetry:

$$U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e} \,.$$

- With 3 N_R, the entire $U(1)^3$ can be gauged.

- First see the Z' with largest g' or smallest mass, coupled to

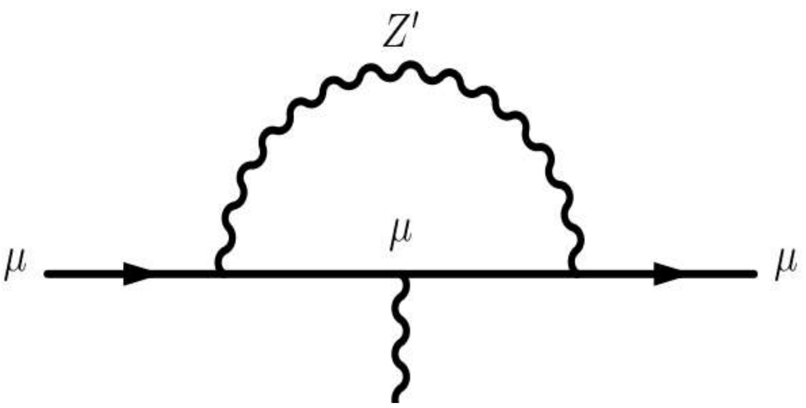
$$a(B-L) + b(L_\mu - L_\tau) + c(L_\mu + L_\tau - 2L_e) \,.$$

- Pheno dominated by electron coupling, except for a=c=0!

2001: $(g\text{-}2)_\mu$

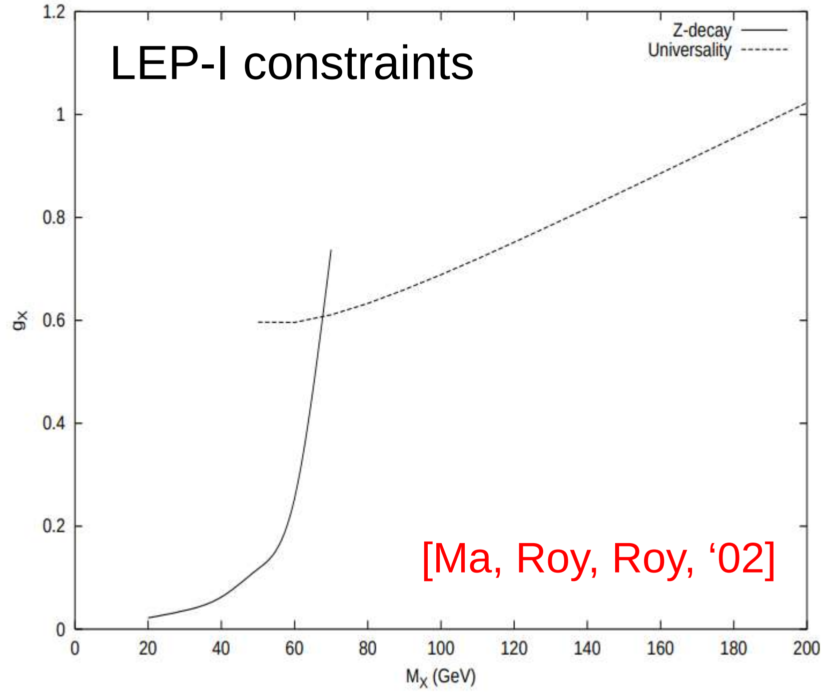
- Quickly realized that $L_\mu - L_\tau$ Z' can explain BNL result.

  [Baek, Deshpande, He, Ko, '01; Ma, Roy, Roy, '02]



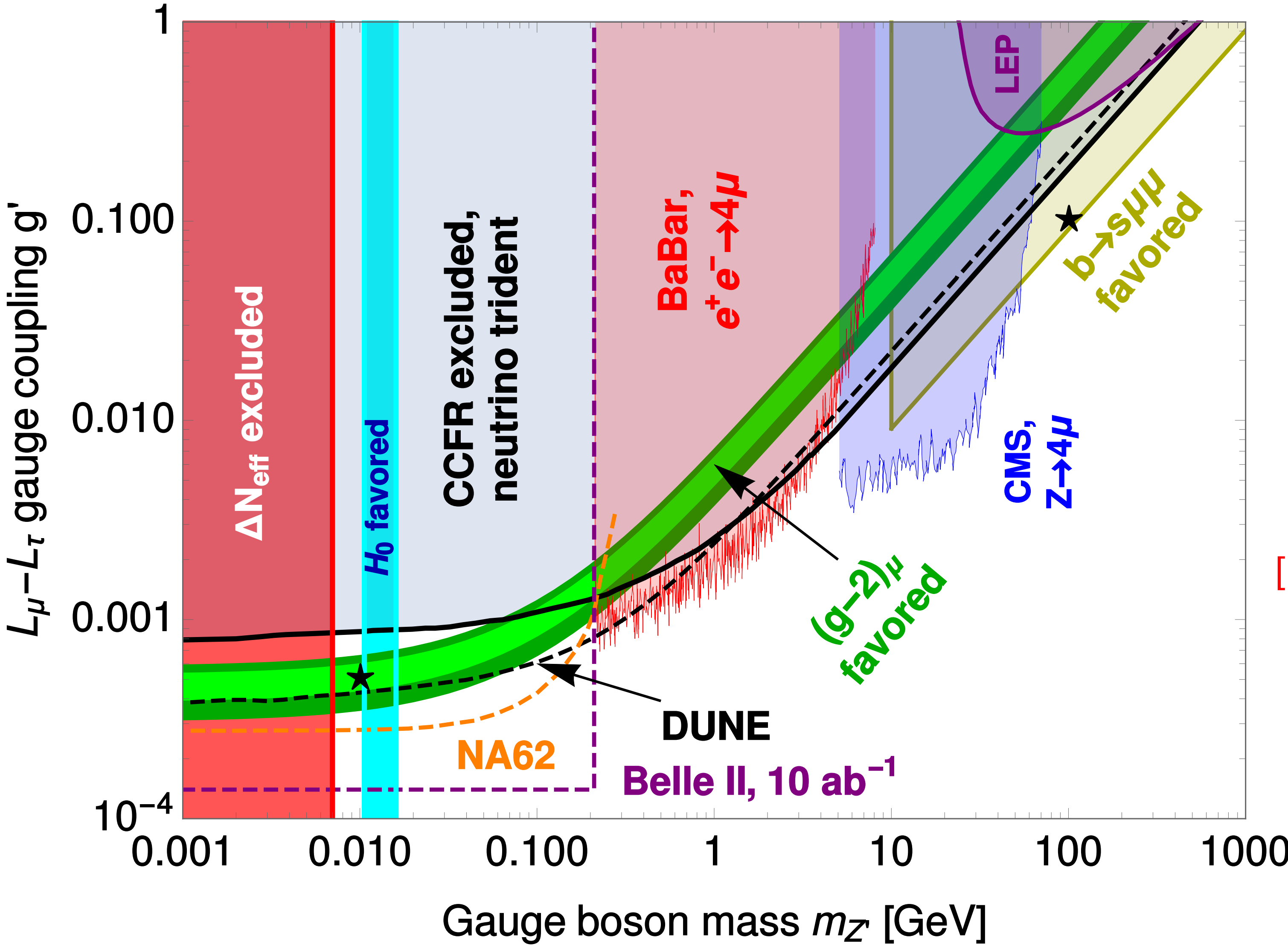
- Back then, *many* other simple models worked, but $L_\mu - L_\tau$ has survived for 20 years.

- While initially almost unconstrained due to vanishing first-generation couplings, it has now been pushed into a corner.

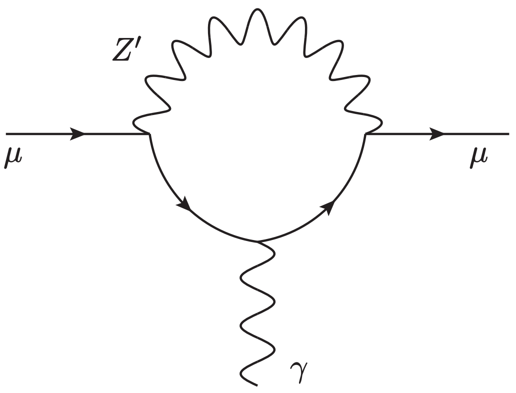


Current Z' constraints

[**JH**, Garani, 1906.10145]



$(g-2)_\mu$:

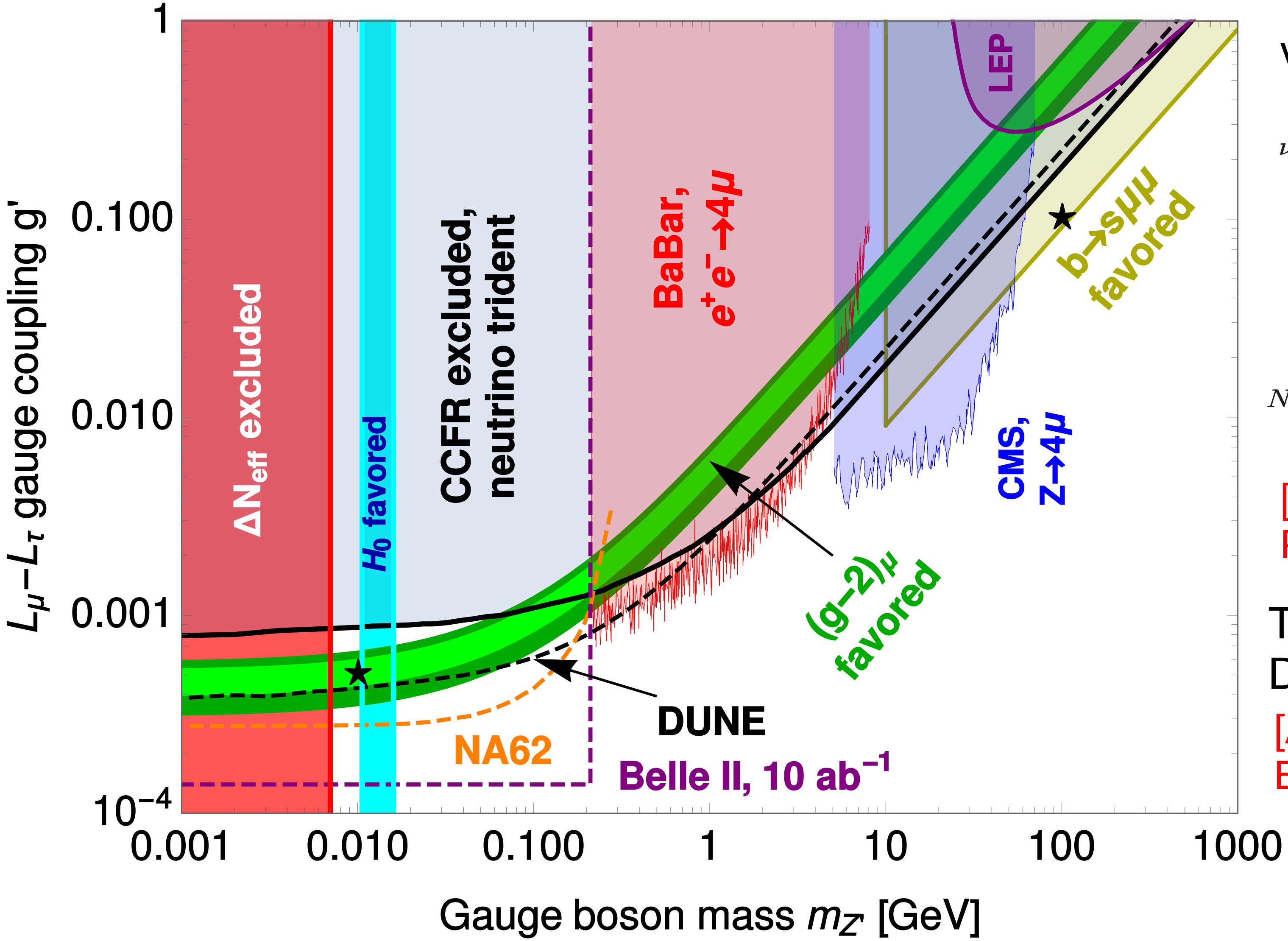


[He, Joshi, Lew, Volkas, '91]

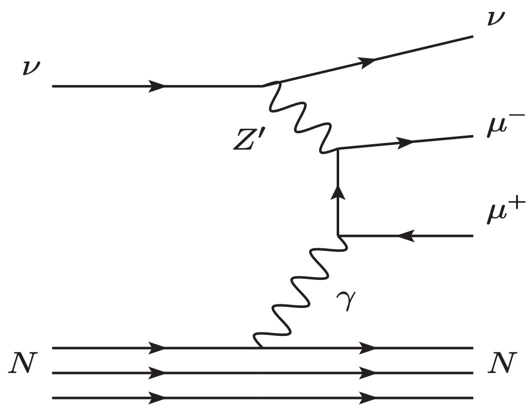
~4σ deviation!

Current Z' constraints

[**JH**, Garani, 1906.10145]



ν trident:



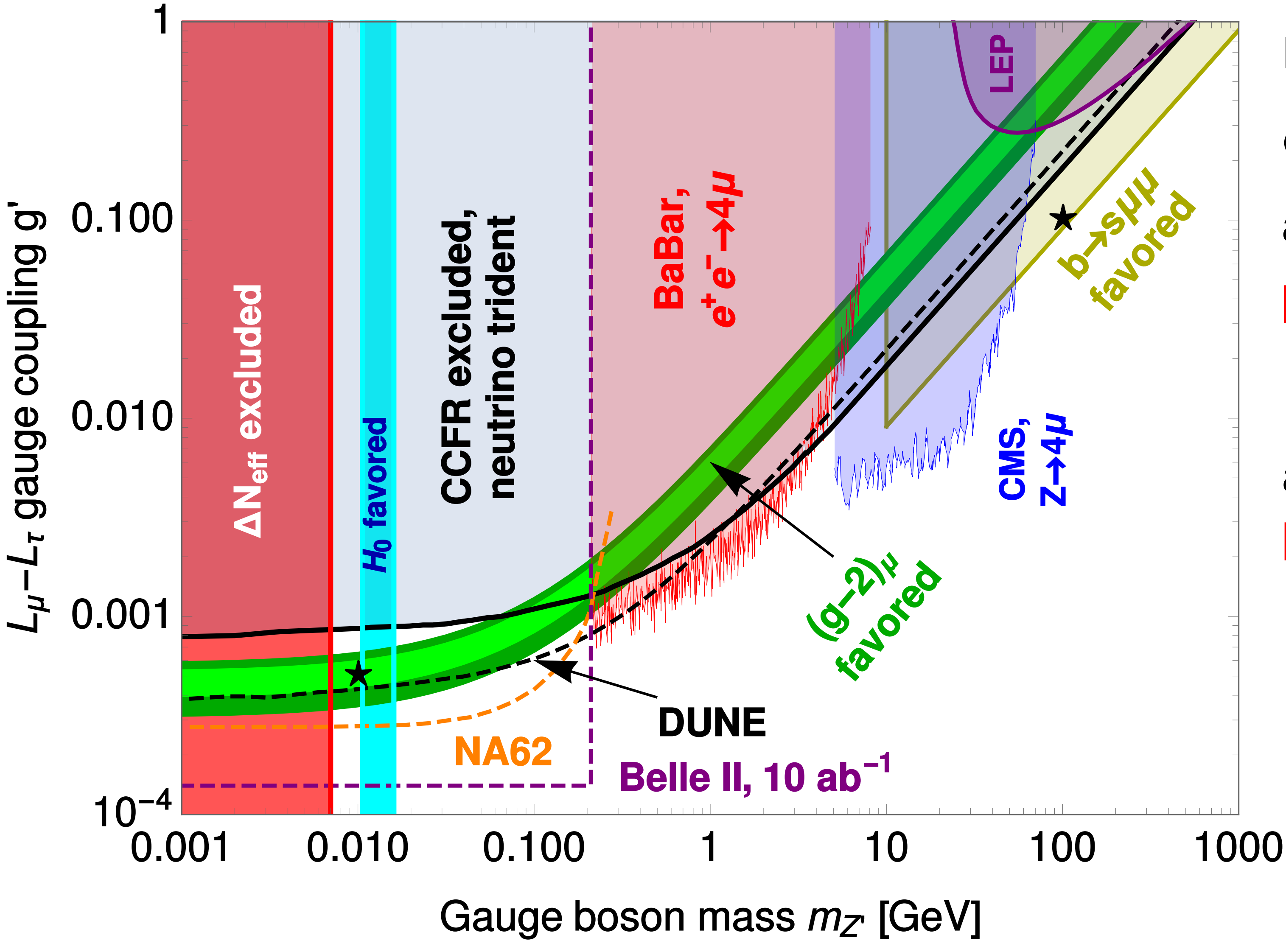
[Altmannshofer, Gori, Pospelov, Yavin, '14]

To be improved by DUNE!

[Altmannshofer++, '19; Ballett++, '19]

Current Z’ constraints

[**JH**, Garani, 1906.10145]



Invisible Z’:

$e^+e^- \to \mu^+\mu^- Z'$

at Belle II.

[Jho++, 1904.1305]

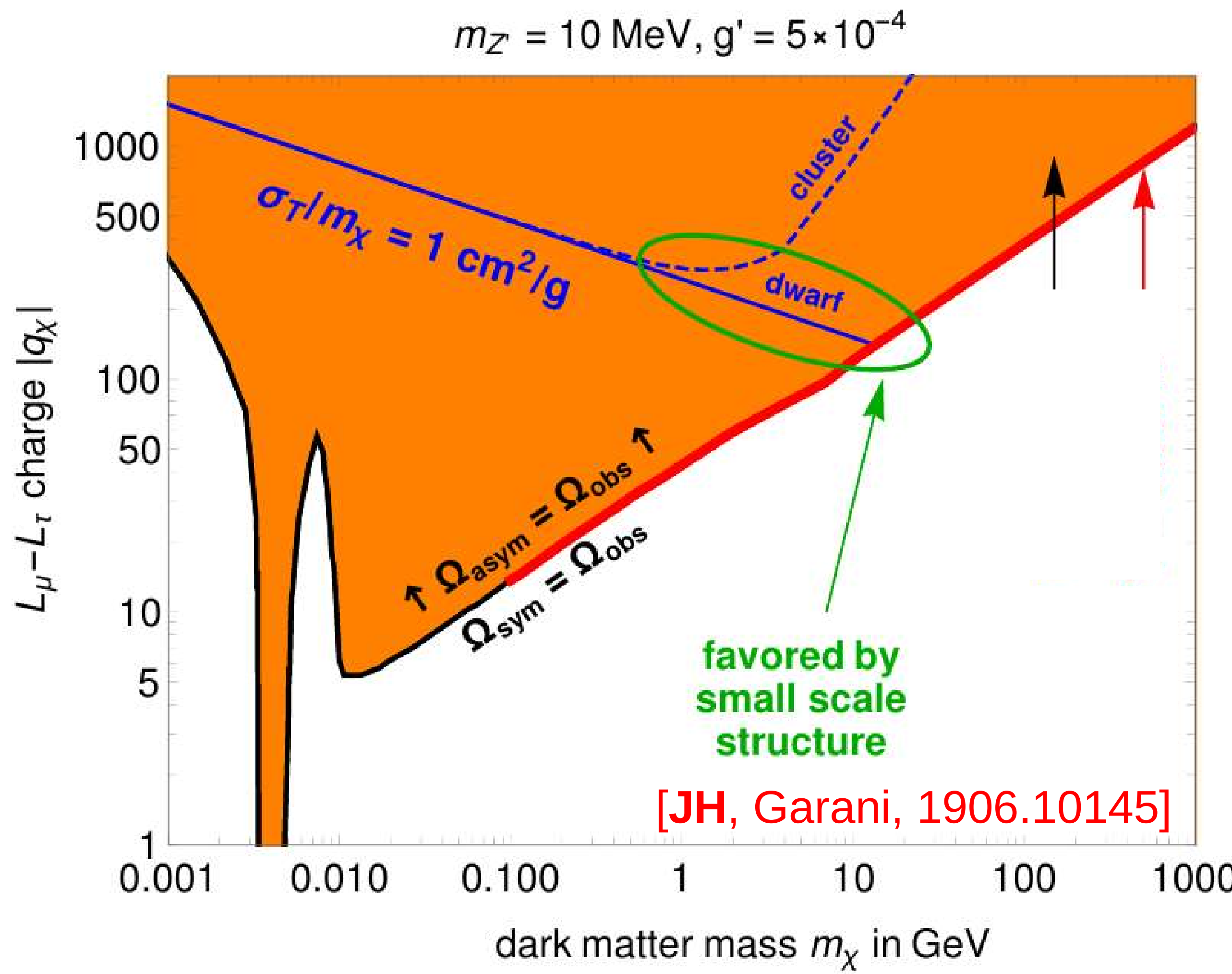
$K \to \mu\nu Z'$

at NA62.

[Krnjaic++, 1902.07715]

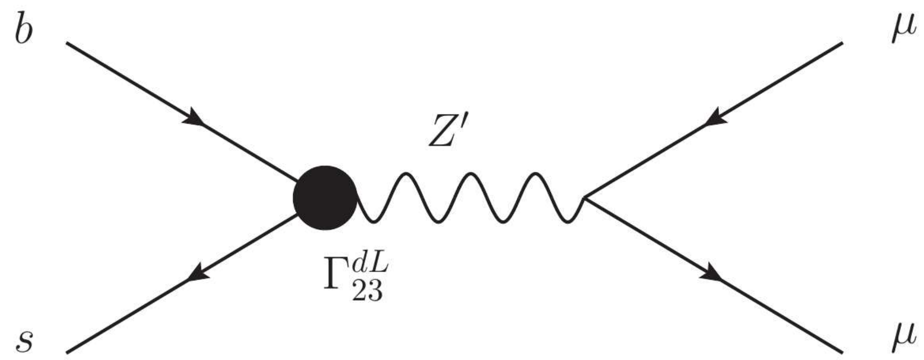
$L_\mu - L_\tau$ and g-2

- Pushed into corner 10 MeV < $m_{Z'}$ < 200 MeV, probed decisively in near future.
- Light Z' could be a mediator to a DM sector; can easily generate large DM self-interaction cross sections that solve small-scale structure problems.
- DM stability: U(1)'.



Non-minimal $L_\mu - L_\tau$

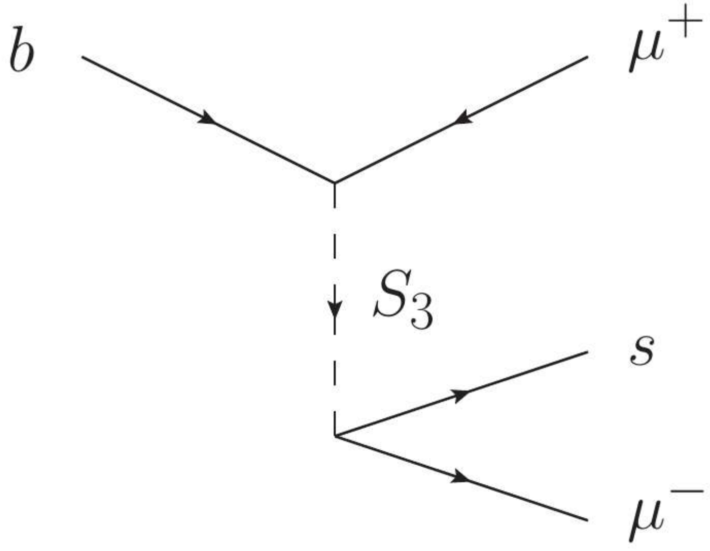
- Can induce additional Z' couplings, e.g. in the quark sector, via heavy fermions [Altmannshofer, Gori, Pospelov, Yavin, '14] or Higgs fields. [Crivellin, D'Ambrosio, **JH**, PRL & PRD '15]



- Can get bsμμ operator, explains R(K) and R(K*)!
- LFUV from $L_\mu - L_\tau$, but Z' needs to be heavier than for g-2.
- Predicts deviations in $b \to s\tau\tau$ and $b \to s\nu\nu$, but tough to test.
- Strong constraint from B-$\overline{\text{B}}$ oscillations.

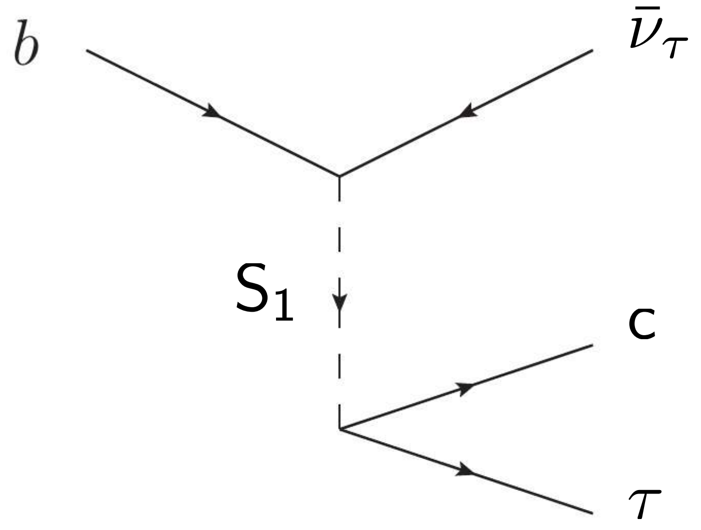
$L_\mu - L_\tau$ beyond the Z'

- Can use $L_\mu - L_\tau$ (or other flavor U(1)') to forbid or enforce couplings.
- Take leptoquark S_3 ~ (**3**,**3**,-1/3): $\mathcal{L} = y_{ij} \bar{Q}_i S_3 L_j^c + x_{ij} Q_i Q_j S_3$
- Charge S_3 ~ +1 under $L_\mu - L_\tau$ to get $x_{ij} = 0$, $y_{ij} = y_{i\mu}$.
  → no more proton decay, no lepton flavor violation, only coupling to muons!
- Perfect for R(K) & R(K*)!
  [Hambye, **JH**, PRL '18; Davighi, Kirk, Nardecchia, '20; Greljo, Stangl, Thomsen, '21]
- $L_\mu - L_\tau$ global or gauged, just need to break it in neutrino sector.



$L_\mu - L_\tau$ beyond the Z'

- Can use $L_\mu - L_\tau$ (or other flavor U(1)') to forbid or enforce couplings.
- Take LQ $S_1 \sim$ (**3**,**1**,-1/3): $\mathcal{L} = y_{ij} \bar{Q}_i S_1 L_j^c + x_{ij} Q_i Q_j S_1 + \dots$
- Charge $S_1 \sim -1$ under $L_\mu - L_\tau$ to get $x_{ij} = 0$, $y_{ij} = y_{i\tau}$.
  → no more proton decay, no lepton flavor violation, only coupling to tauons!
- Perfect for R(D) & R(D*)!
  [Angelescu++, 2103.12504, **JH** & Thapa, in preparation]
- $L_\mu - L_\tau$ global or gauged, just need to break it in neutrino sector.



A simple $L_\mu - L_\tau$ model

- Gauge $L_\mu - L_\tau$ and break it in neutrino sector to get M_ν.
- Add LQ $S_1 \sim (\mathbf{3},\mathbf{1},-1/3)$ with $L_\mu - L_\tau \sim -1$ to explain R(D) and LQ $S_3 \sim (\mathbf{3},\mathbf{3},-1/3)$ with $L_\mu - L_\tau \sim +1$ to explain R(K).
  - U(1) eliminates proton decay and lepton flavor violation.
- Z’ in mass range 10-100 MeV explains $(g-2)_\mu$.
- Charge new singlet fermions/scalars under $L_\mu - L_\tau$.
  - Stability through U(1)’ → dark matter!
  - Relic abundance through Z’.
  - Self-interactions via light Z’ explain small-scale structure!

[**JH** & Thapa, in preparation]

Only $L_\mu - L_\tau$ can do all this!

Summary

- Standard Model symmetry/prediction:

$$\mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \,.$$

- Easy to gauge any subgroup of this.
- $L_\mu - L_\tau$ special:
  - Only acts on 2nd & 3rd gen particles → weak constraints.
  - Good flavor symmetry for quasi-degenerate neutrinos.
  - Only Z' left to explain muon g-2, soon fully probed.
  - Breaks lepton flavor universality, can explain R(K) & R(D).

Arguably most useful U(1)!