National Center for Theoretical Sciences
Physics Division 國家理論科學研究中心 物理組

Dirac neutrino masses and meson decay anomalies with leptoquarks

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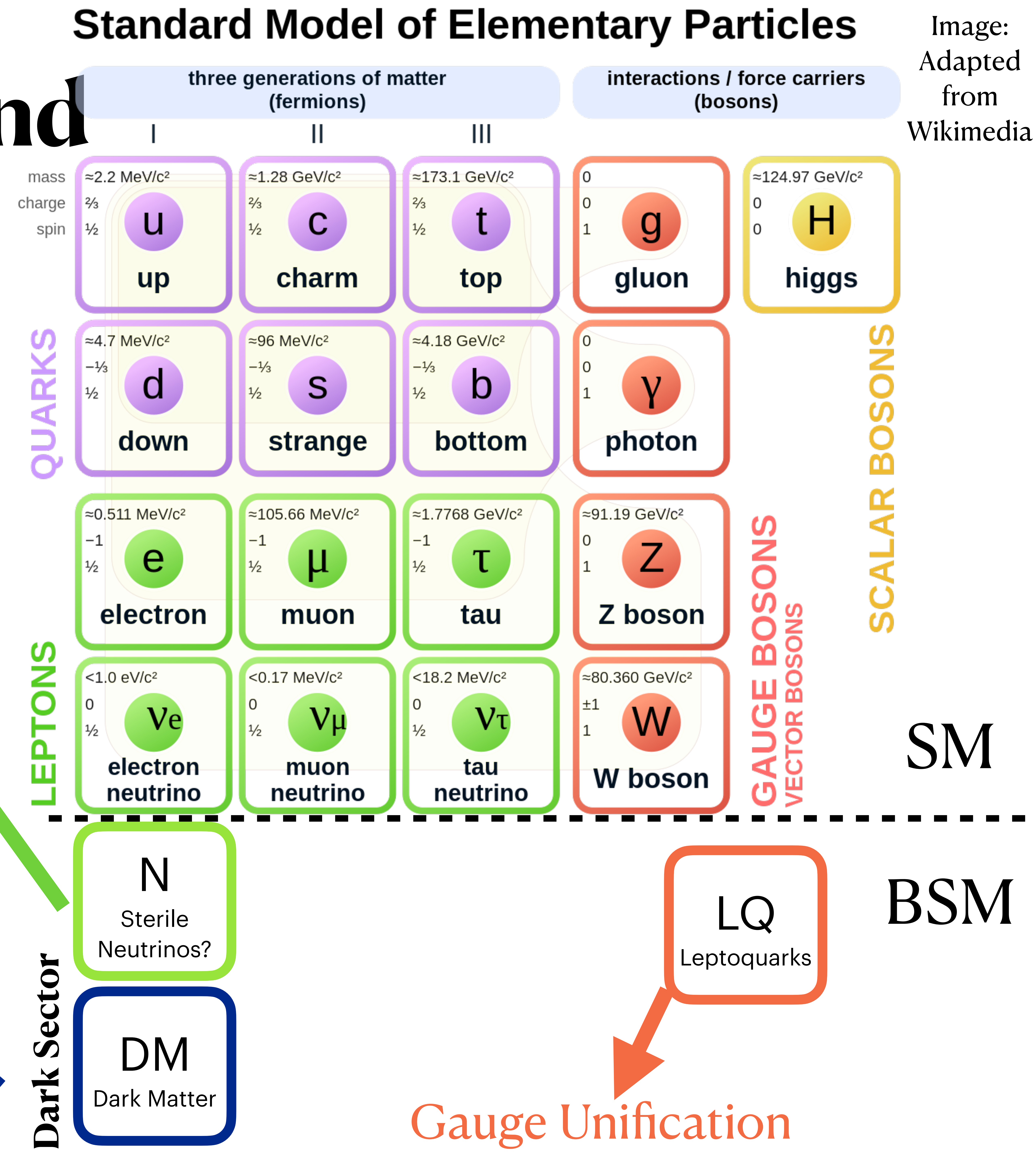
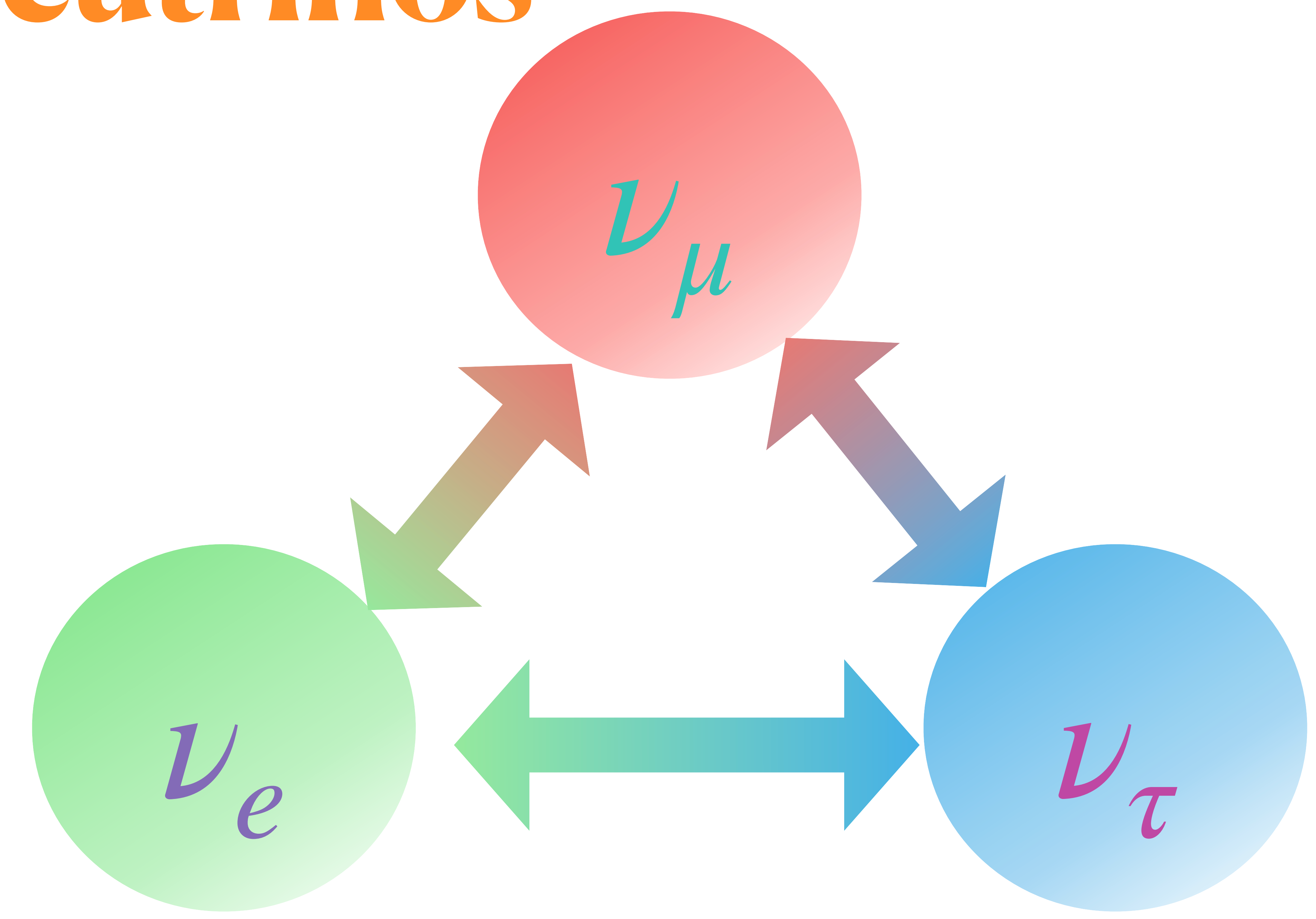


Massive Neutrinos

- Neutrino Oscillations
  - Super-Kamiokande + SNO
- Neutrino masses + mixing in leptonic sector



$$|\nu_e >= U_{e1}|\nu_1 > +U_{e2}|\nu_2 > +U_{e3}|\nu_3 >$$

$$P_{\alpha\to\beta} = \left|\, \langle\, \nu_\beta \mid \nu_\alpha(L)\,\rangle \,\right|^2 = \left| \sum_j U^*_{\alpha j}\, U_{\beta j}\, e^{-i\frac{m_j^2\, L}{2E}} \right|^2$$

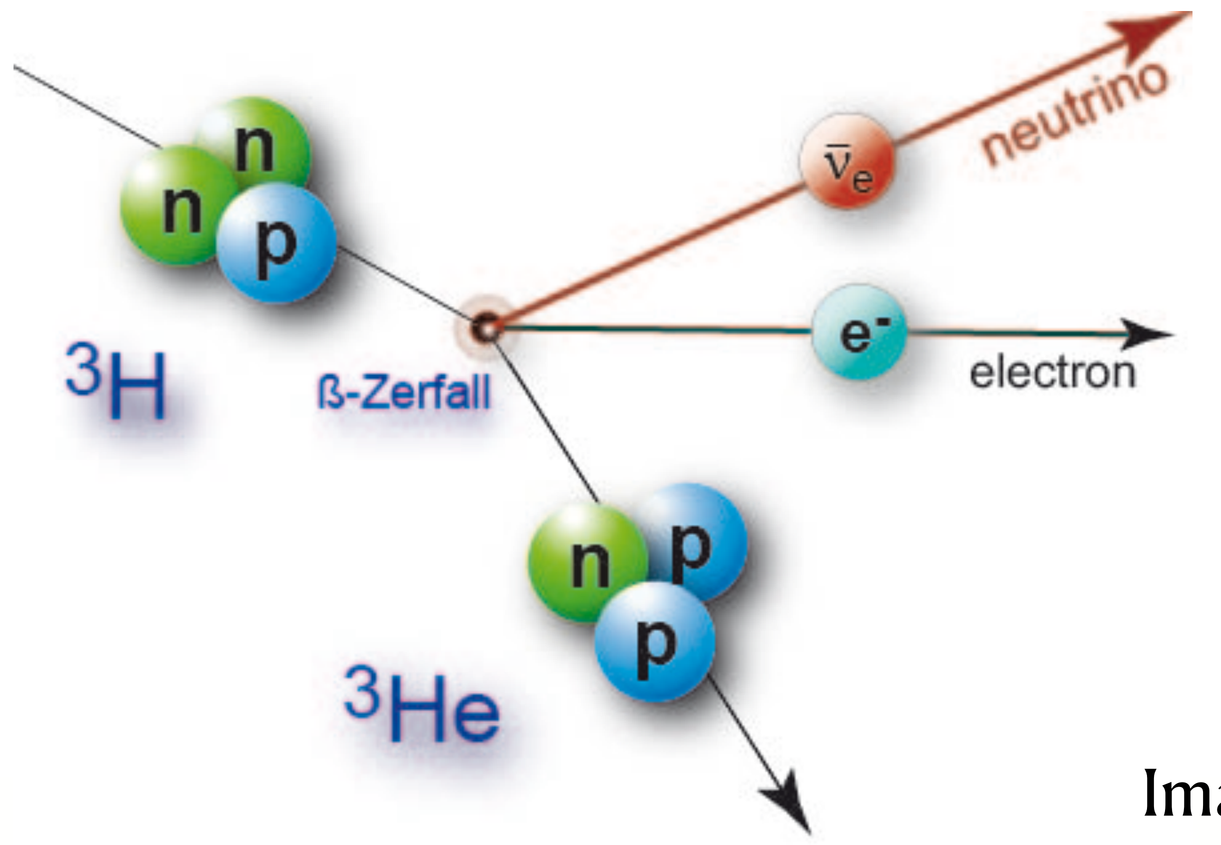
$$U^{\rm NO} = \begin{pmatrix} 0.7838 \to 0.8442 & 0.5135 \to 0.6004 & (-0.1568 \to 0.1489) + i(-0.1182 \to 0.1520) \\ (-0.4831 \to -0.2394) + i(-0.0749 \to 0.0962) & (0.4636 \to 0.6749) + i(-0.0521 \to 0.0668) & 0.6499 \to 0.7719 \\ (0.3068 \to 0.5391) + i(-0.0643 \to 0.0933) & (-0.6897 \to -0.4821) + i(-0.0446 \to 0.0644) & 0.6161 \to 0.7434 \end{pmatrix}$$

Neutrino Fit : de Salas, Forero, Gariazzo, Martínez-Miravé, Mena, Ternes, Tórtola & Valle

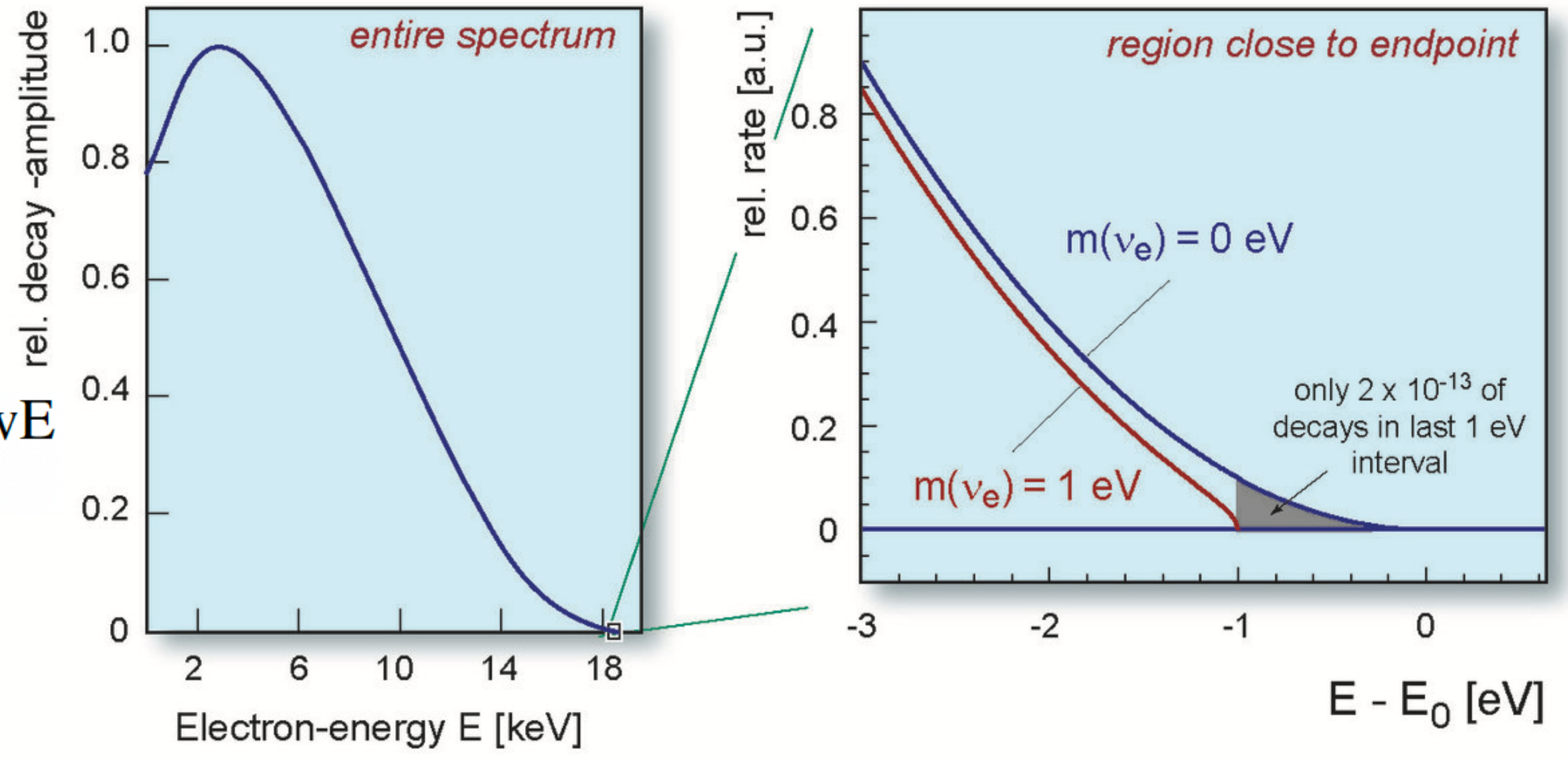
Neutrino mass scale

- Beta decay kinematics:
- $^{3}\text{H} \rightarrow ^{3}\text{He} + e^{-} + \bar{\nu}_e$
- KATRIN (arXiv:2406.13516, 259 d):
  - $m_{\nu}^{eff} < 0.45$ eV (90%) C.L.
- Cosmology

$\sum m_\nu < 0.13$ eV (95 %, *Planck* TT,TE,EE+lowE +BAO),



Images: KATRIN collaboration



Majorana and Dirac neutrinos

- Dirac mass terms (Charge conserving)
    - $M_D \bar{\nu}_R \nu_L$
- Needs additional right handed field $\nu_R \sim (1,1,0)$
- 4 d.o.f
- Majorana mass terms forbidden by a low energy symmetry :
    - global - gravity? , gauge - boson?
    - Why is the Yukawa coupling $Y_\nu \bar{L} \tilde{H} \nu_R$ so small? $\frac{m_\nu}{v_{EW}} \sim 10^{-11}$
    - Is $Y_\nu \bar{L} \tilde{H} \nu_R$ an effective coupling?

Majorana and Dirac neutrinos

- Majorana mass terms
  - $M_M \bar{\nu}_L^C \nu_L$
- Lepton number non-conserving:
  - LNV in 2 units
    - Neutrinoless double beta decay

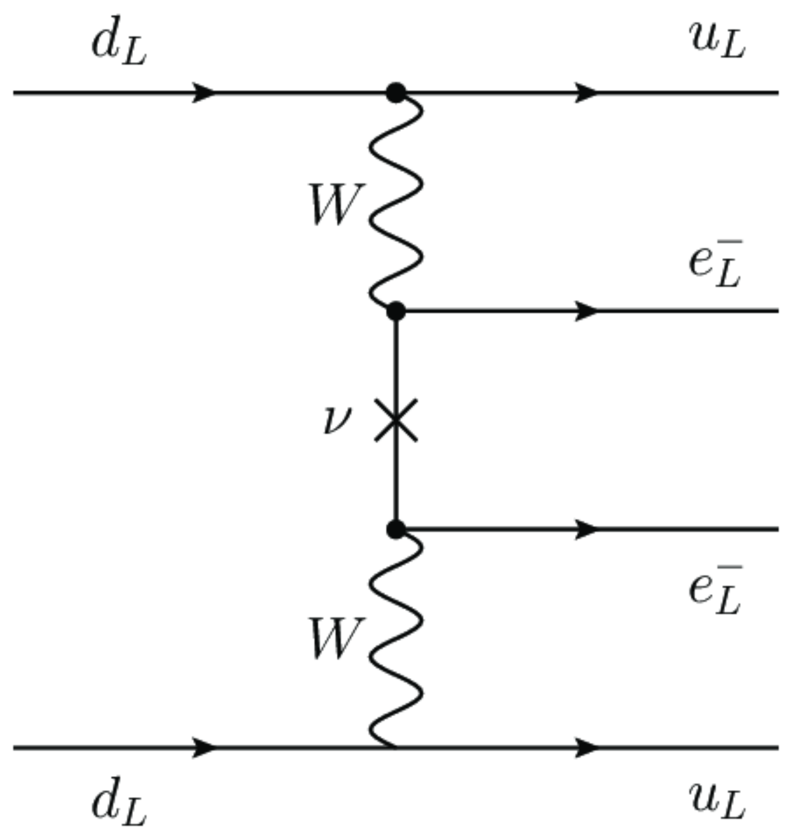
$$\langle m_{\beta\beta} \rangle = \left| U_{ei}^2 \, m_i \right|$$

$$T_{1/2}^{0\nu} = \left(G \, |\mathcal{M}|^2 \, \langle m_{\beta\beta} \rangle^2 \right)^{-1} \simeq 10^{27-28} \left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \mathrm{y}$$

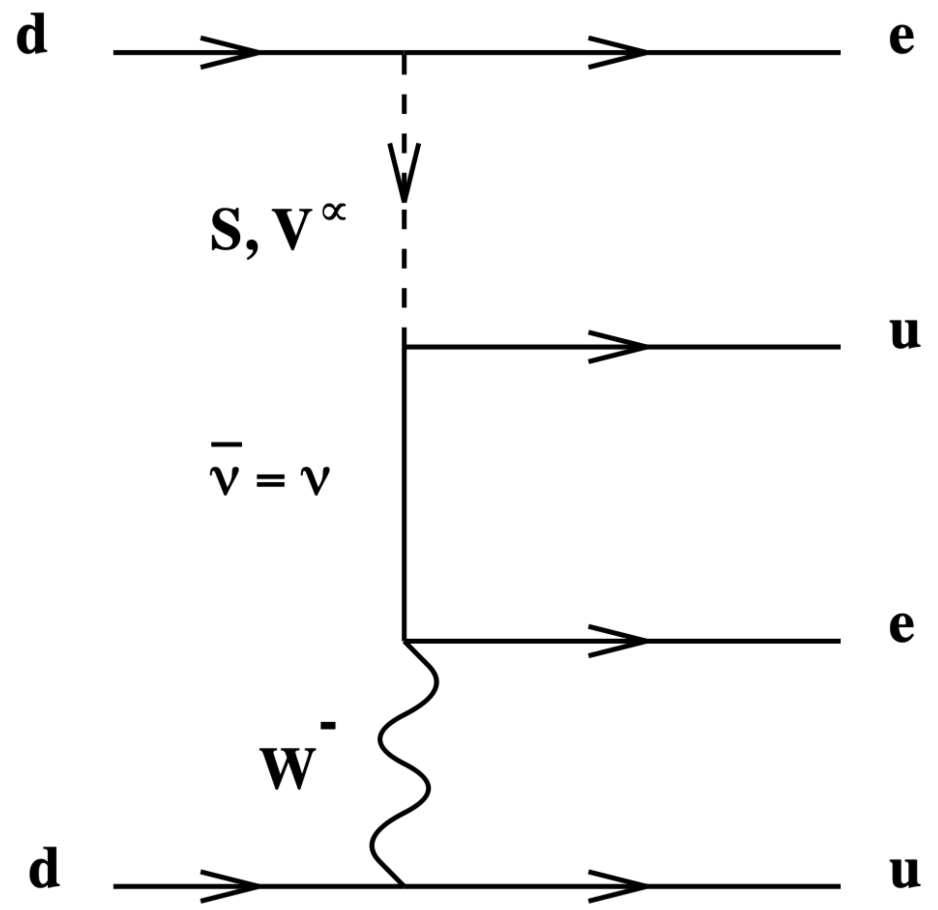
$$\langle m_{\beta\beta} \rangle < 0.028 - 0.122 \text{ eV}$$

KamLAND-ZEN

$$(A, Z) \rightarrow (A, Z+2) + 2\,e^- + Q_{\beta\beta}$$



+ N.P. ?



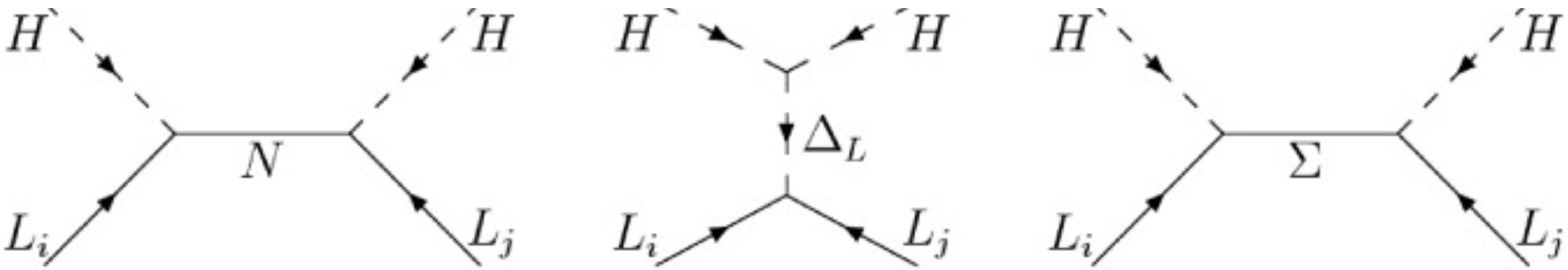
+ … ?

M. Hirsch, H.V. Klapdor-Kleingrothaus and S.G. Kovalenko, 1996

Neutrino mass models

Majorana masses

- Weinberg operator: $\frac{C_W}{\Lambda}\bar{L}^C\tilde{H}\tilde{H}L$
- Three tree level completions:



Minkowski 1977
Gellman, Ramond & Slansky 1980
Glashow & Yanagida 1979
Mohapatra & Senjanovic 1980
Schechter & Valle 1980 & 1982
Lazarides, Shafi & Weterrich 1981

Zee 1980
Babu 1988
Ma 2006

- Loop-level completions:
  - Zee, Scotogenic, ...
- LFV, Leptogenesis, Heavy Neutral Leptons, DM

$$m_\nu \sim \frac{v^2}{M_N} = \frac{(246\ \text{GeV})^2}{M_N} < 1\ \text{eV}$$

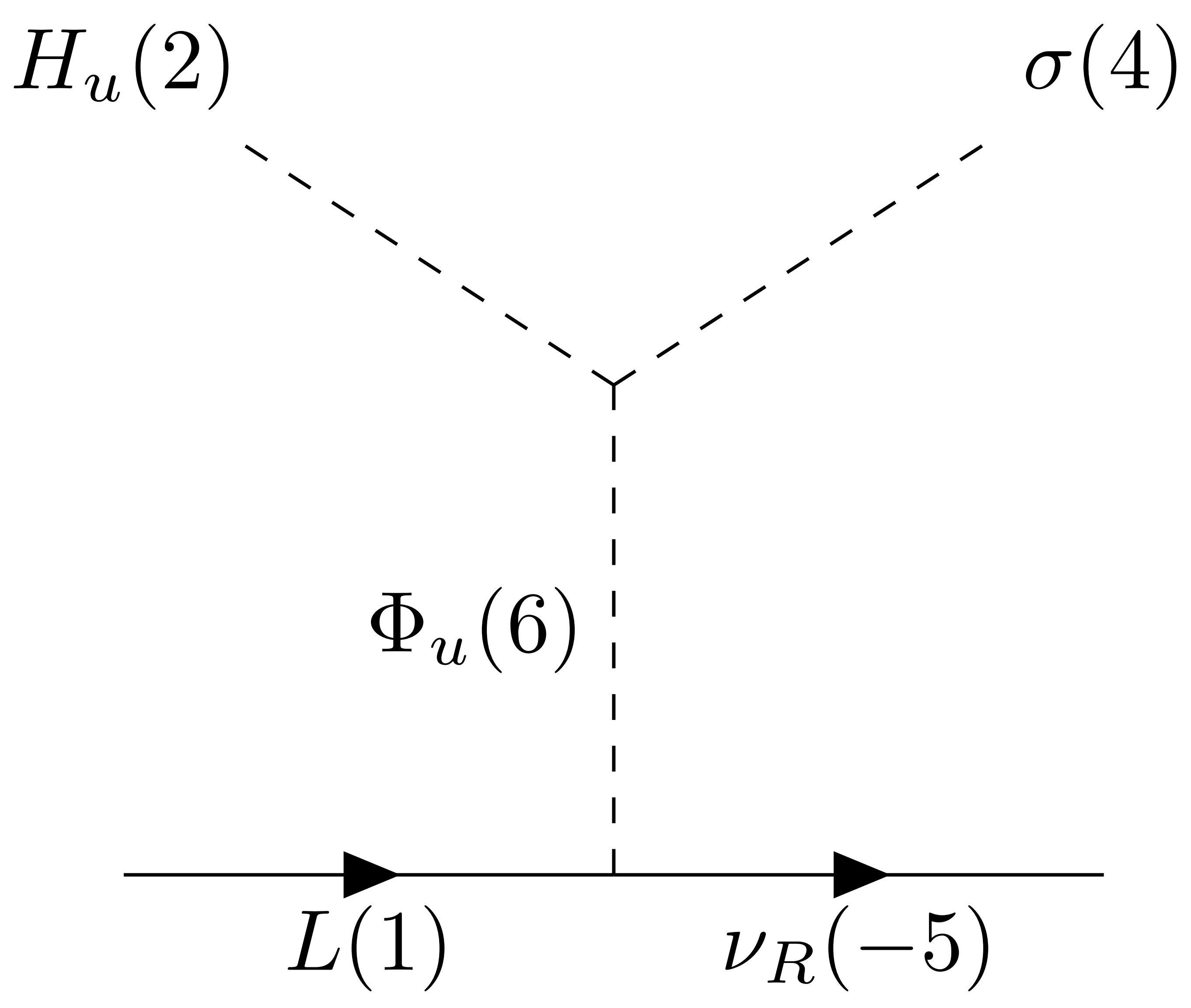
$$M_N > \sim 10^{13}\ \text{GeV}$$

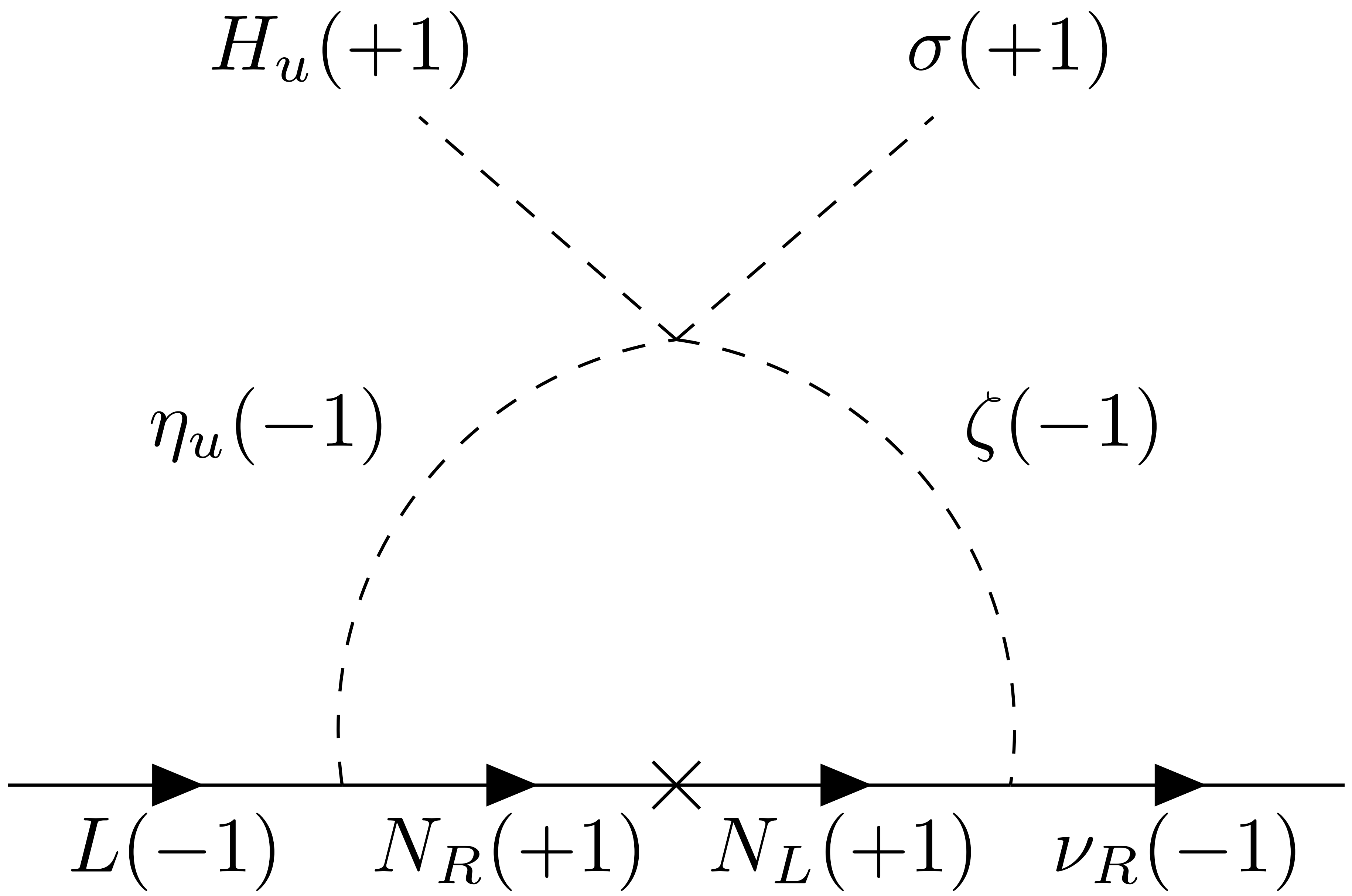
Neutrino mass models

Dirac masses

- Effective operator : $\frac{C_D}{\Lambda^N}\bar{L}\tilde{H}\nu_R(\phi)^N$
- Dirac Seesaws, loop level masses
- Remnant symmetries- Lepton number

Babu & He, 1989
Peltionemi, Tommasini & Valle, 1993
Centelles-Chulia, Srivastava & Valle, 2016

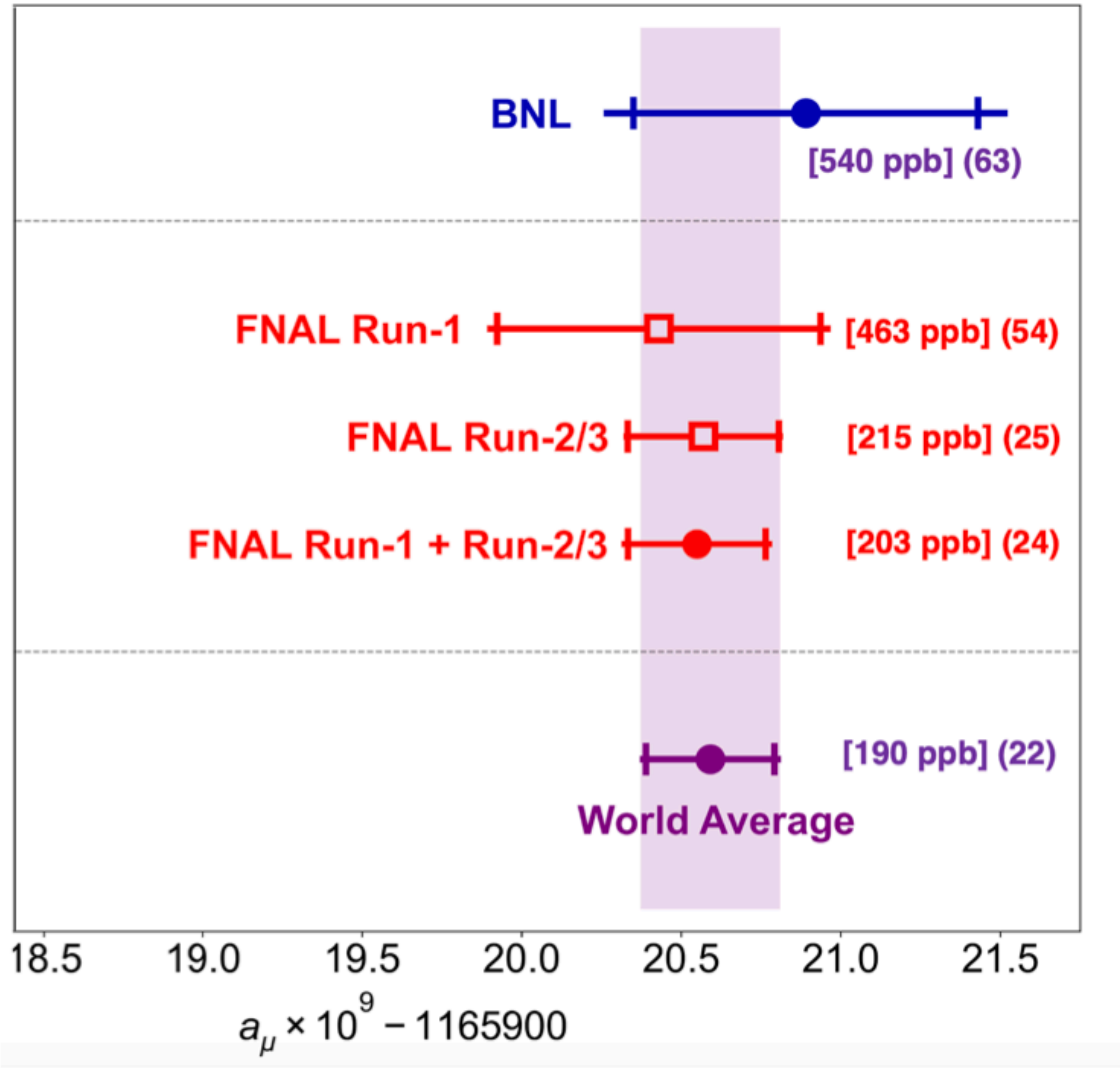


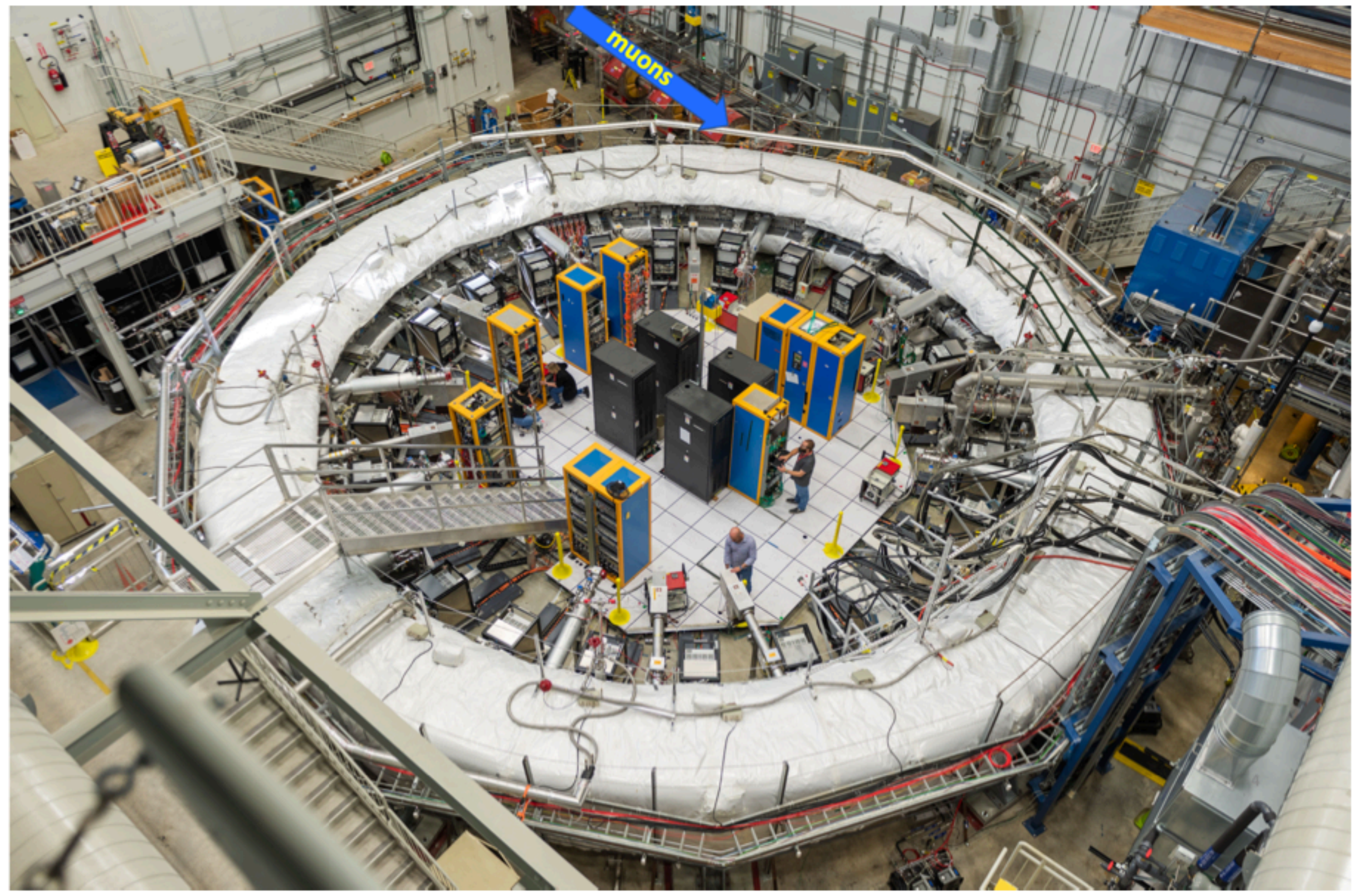


New Physics?

g-2

- Muon g-2 results in tension with the SM(?)





Muon g-2 @ Fermilab

New Physics?

g-2

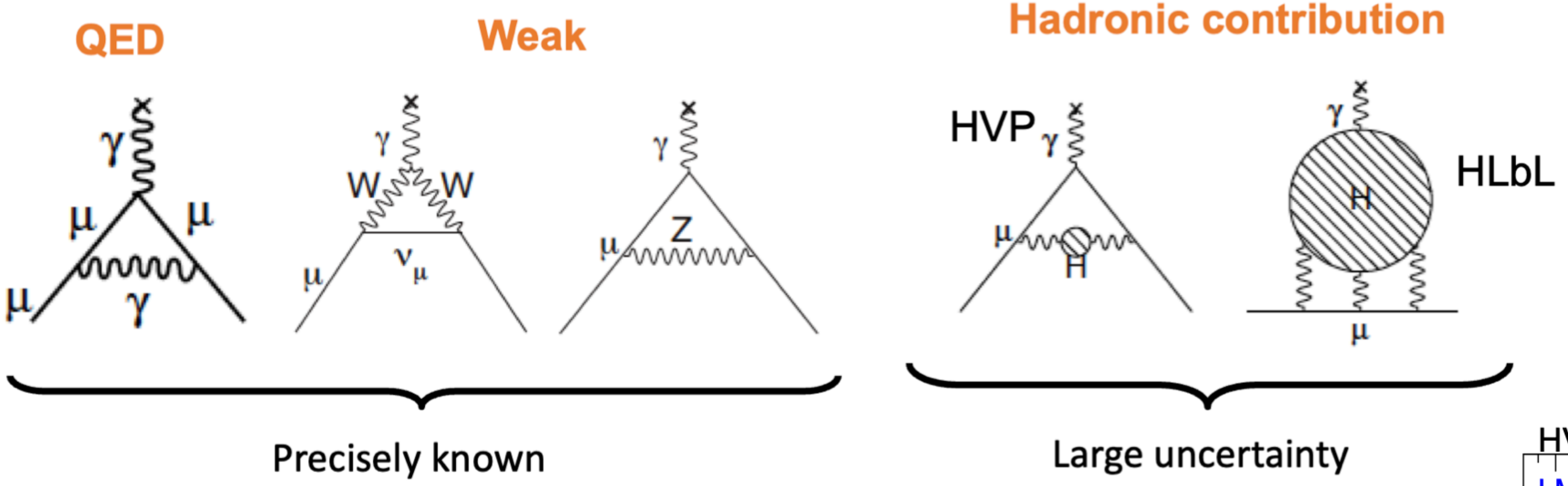


Fig. 5 from Venanzoni, 2023, New results from the Muon g-2 Experiment

Data Driven vs. Lattice

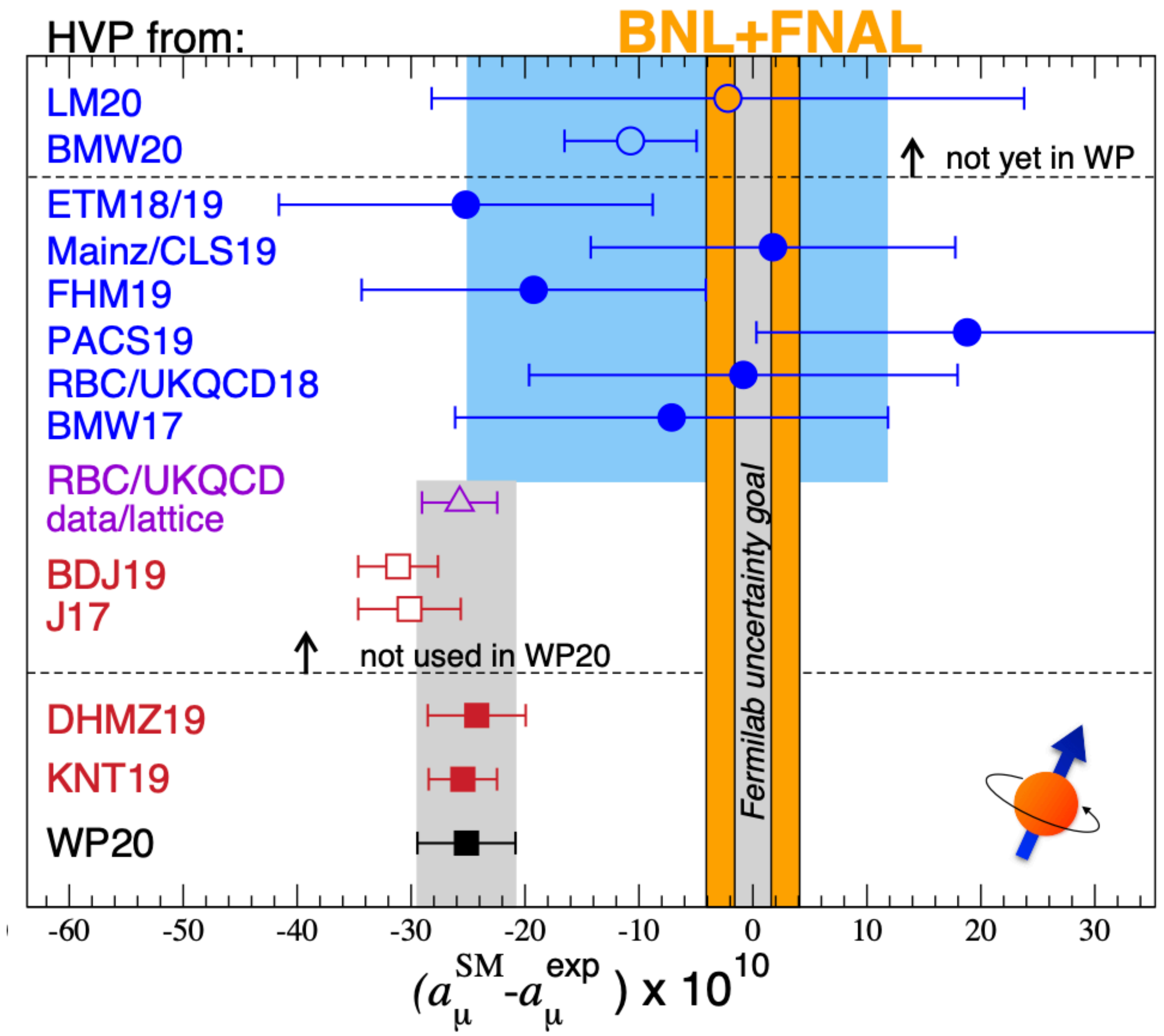


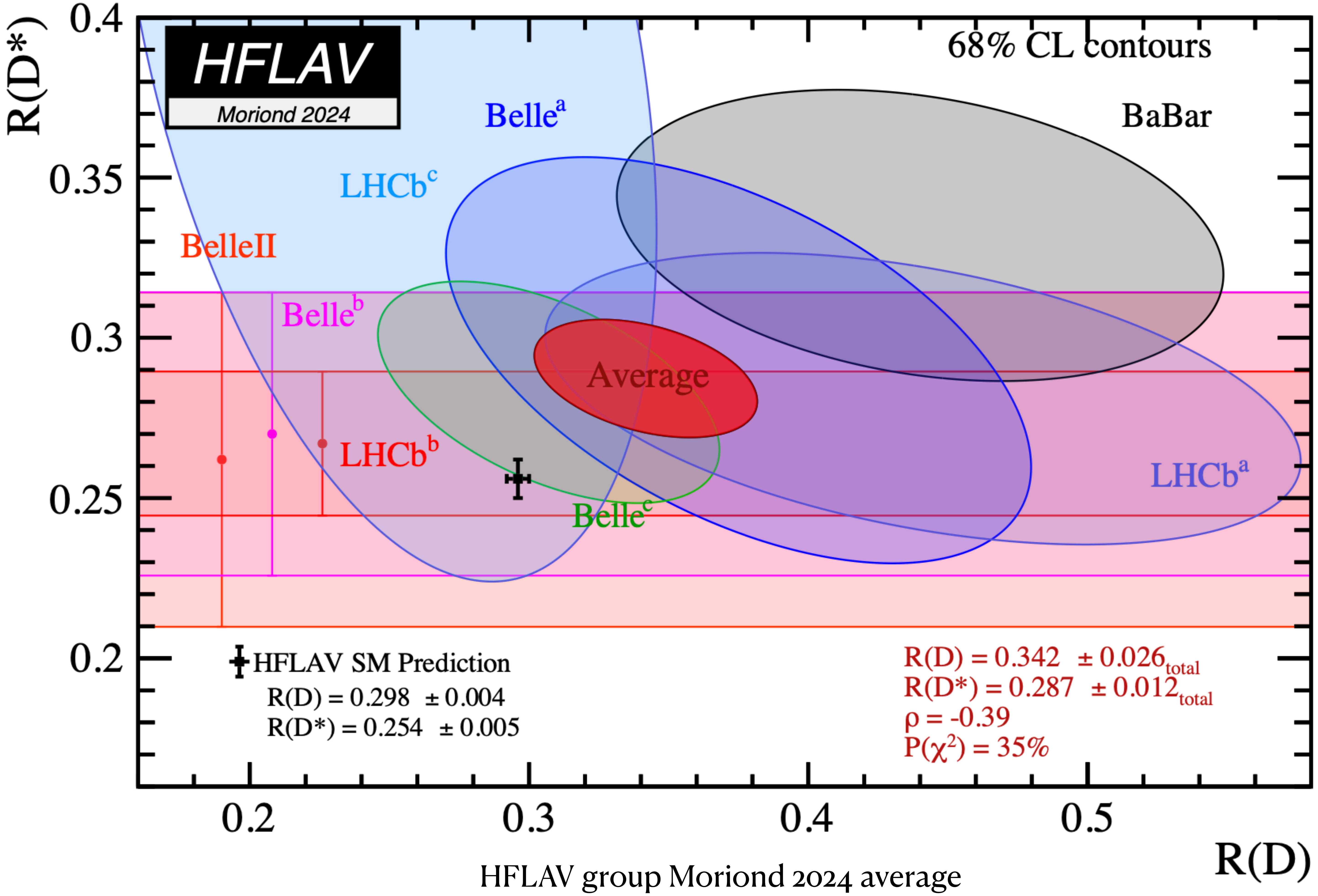
Fig 1 from Colangelo et. al. , 2022 Prospects for precise predictions of a_μ in the Standard Model

New Physics?

Meson decay anomalies

- $R_{D^{(*)}} : b \to c l \nu$
- Test of Lepton Flavor Universality - Weak processes are driven by lepton flavour blind couplings - Different decay widths, cs should only depend on kinematics

$$R_D \equiv \frac{\mathcal{B}(\overline{B} \to D\tau\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D\ell\overline{\nu}_\ell)}, \qquad R_{D^*} \equiv \frac{\mathcal{B}(\overline{B} \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^*\ell\overline{\nu}_\ell)}$$

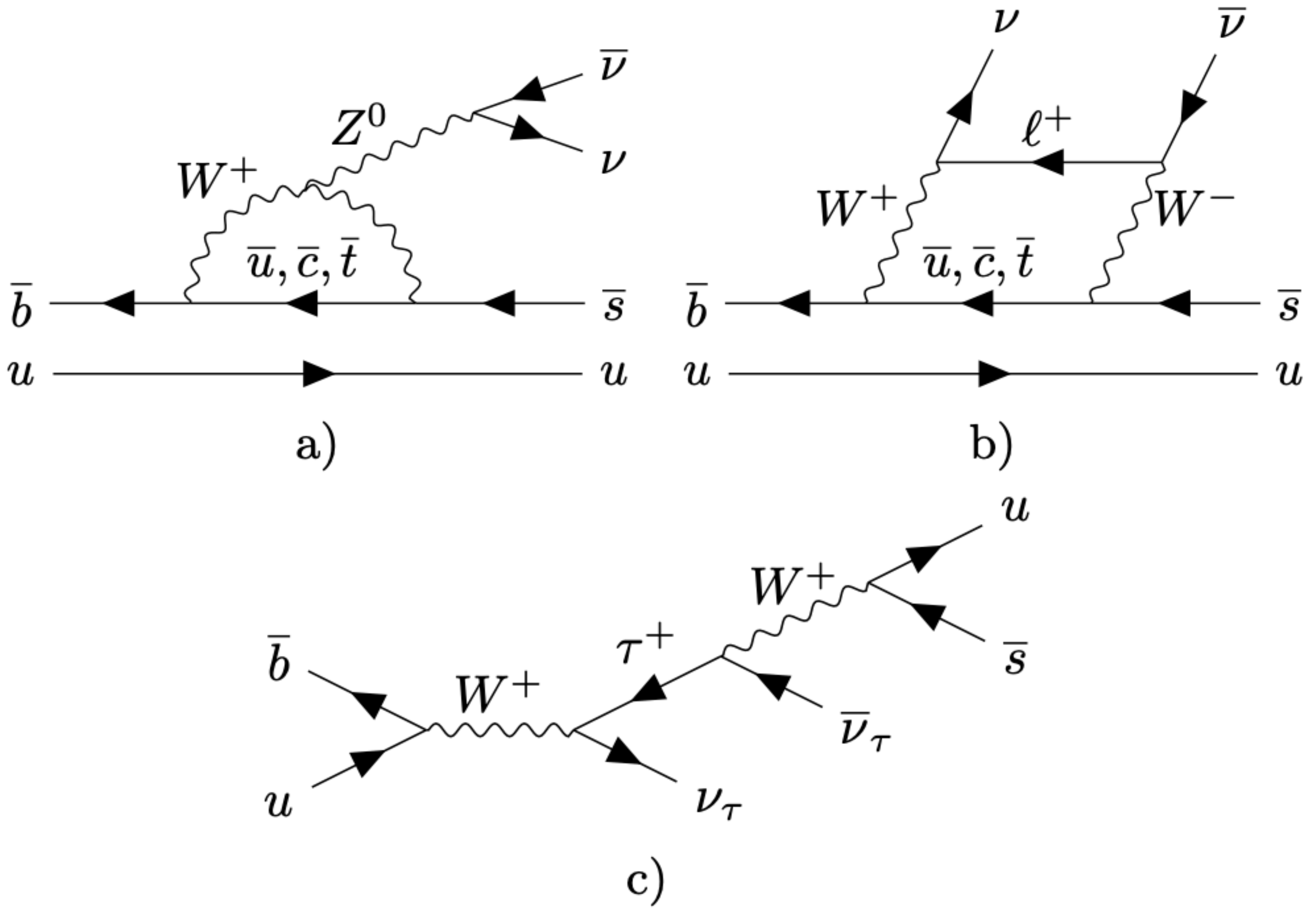


HFLAV group Moriond 2024 average

New Physics?

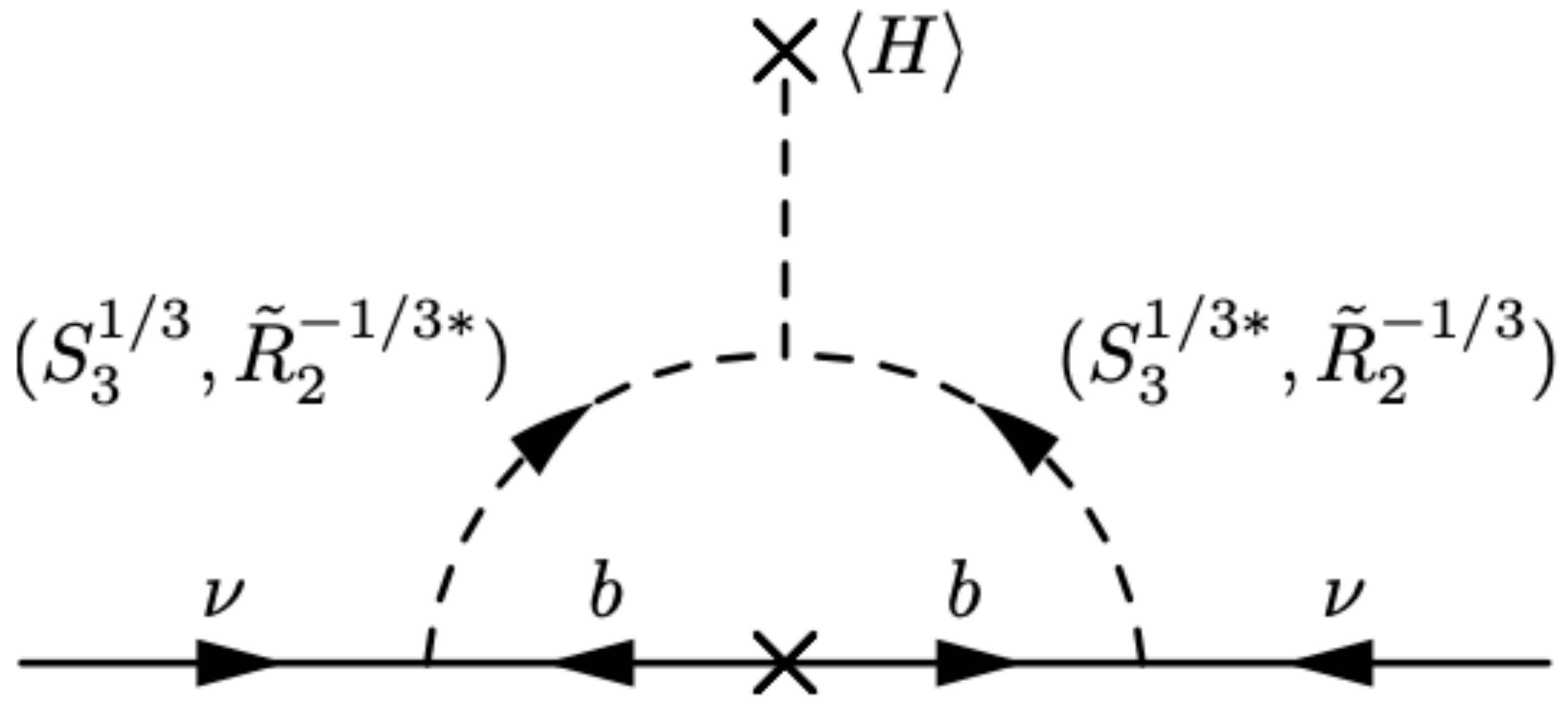
Meson decay anomalies

- $B^+ \rightarrow K^+\nu\nu$
- SM BR:
- $\mathscr{B}(B^+ \rightarrow K^+\nu\nu)_{SM} = (5.58 \pm 0.37) \times 10^{-6}$
- Belle- II 2023 result:
- $\mathscr{B}(B^+ \rightarrow K^+\nu\nu)_{exp} = (2.3 \pm 0.7) \times 10^{-5}$
- 2.7σ tension - excess



Neutrino masses + new physics w. LQs

- Majorana Masses with LQs:
- LQs have definite lepton number
- Majorana masses require L breaking:
  - At least 2 leptoquarks with different L must be introduced and L broken with LQ mixing



$$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$\tilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$$

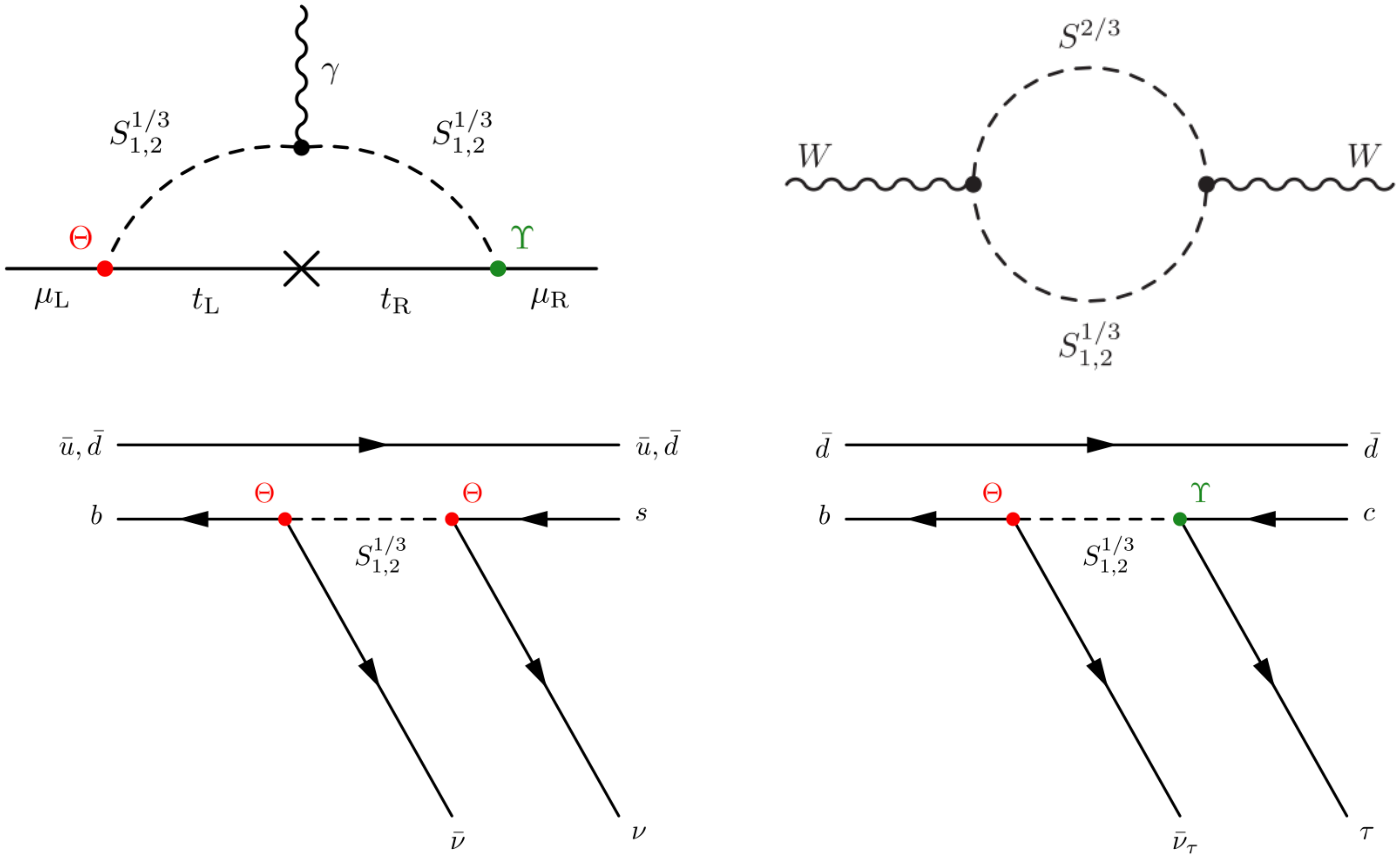
Chua, He & Hwang , 2000

From I. Doršner et. al., Physics of leptoquarks in precision experiments and at particle colliders

Neutrino masses + new physics w. LQs

S3+R2 model

- muon g-2
- R_D
- CDF M_W
- $B \to K\nu\nu$



Freitas et. al. Interplay between flavor anomalies and neutrino properties, 2023

Dirac neutrinos and Leptoquarks

- For Dirac ν no L breaking is necessary: only one type of LQ is needed (+ the right handed ν). No LQ contribution to $0\nu\beta\beta$
- To forbid dim-4 neutrino mass a symmetry must be introduced and kept at low energies
- Consider $S \sim (3,1,-2/3)$

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
L_i	1	2	-1/2	0
e_i	1	1	-1	0
Q_L	1	2	1/6	x/2
u_R	1	1	2/3	x/2
d_R	1	1	-1/3	x/2
ν_R	1	1	1	x
H	1	2	1/2	0
S	3	1	-2/3	x/2
S'	3	1	-2/3	3x/2

Dirac neutrinos and Leptoquarks

$$\mathcal{L}_Y = Y^l \overline{L} H e_R + Y^u \overline{Q} \tilde{H} u_R + Y^d \overline{Q} H d_R + Y^{LL} \overline{Q}^C \epsilon L S^* + \overline{Y}^{RR} \overline{d_R}^C S'^* \nu_R + Y^{RR} \overline{u_R}^C S^* e_R + h.c.$$

After LQ mixing and charged fermion diagonalization we have the following physical Yukawa couplings

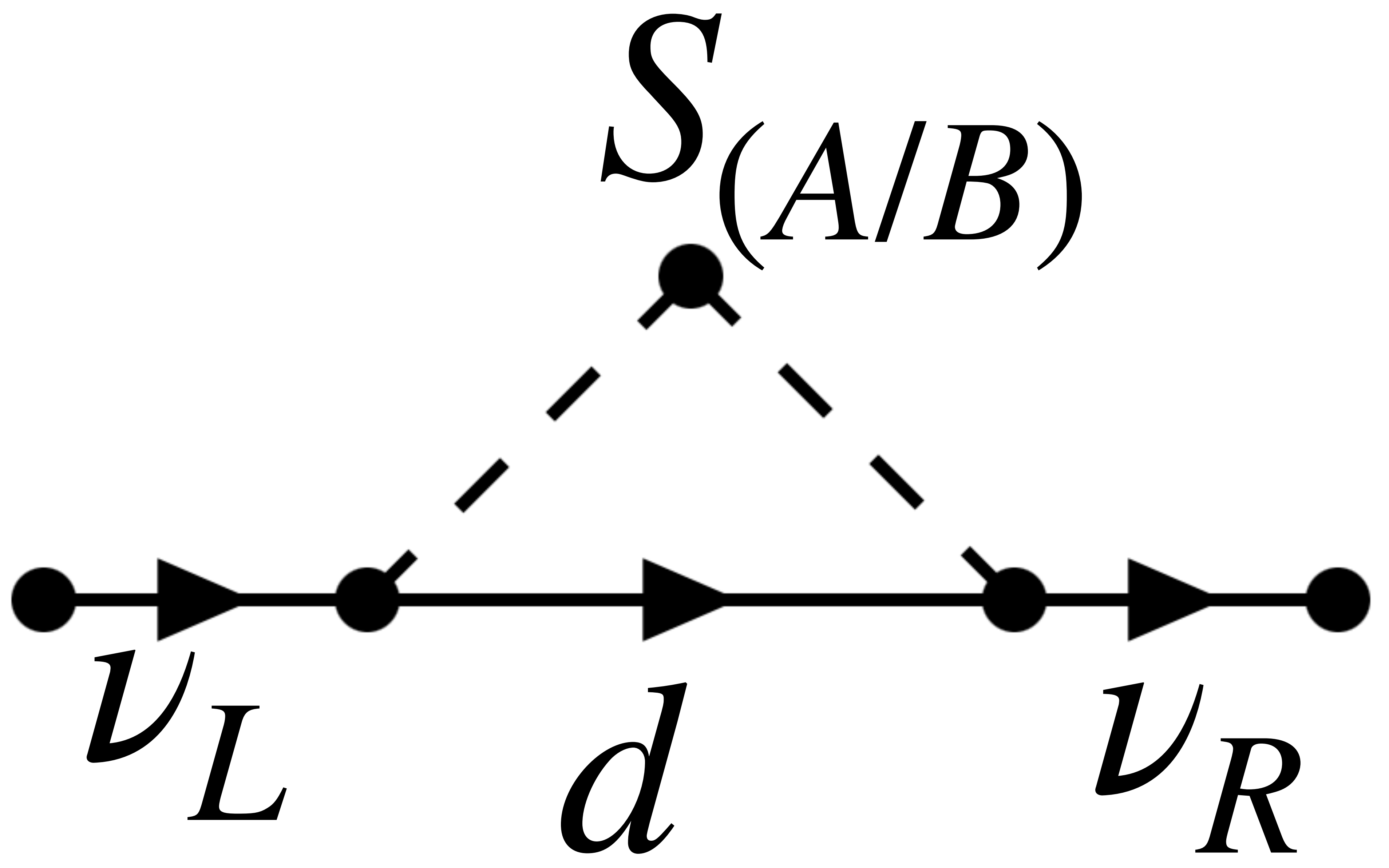
$$\mathcal{L}_Y \supset (\overline{u_L'^C} \xi_1 e_L' + \overline{d_L'^C} \xi_2 \nu_L + \overline{u_R}^C \xi_4 e_R)(\cos\theta_S S_A - \sin\theta_S S_B) + (\overline{d_R}^C \xi_3 \nu_R)(\sin\theta_S S_A + \cos\theta_S S_B) + h.c.$$

$$\xi_1 = U^T_{CKM} \xi_2 U^\dagger_{PMNS}$$

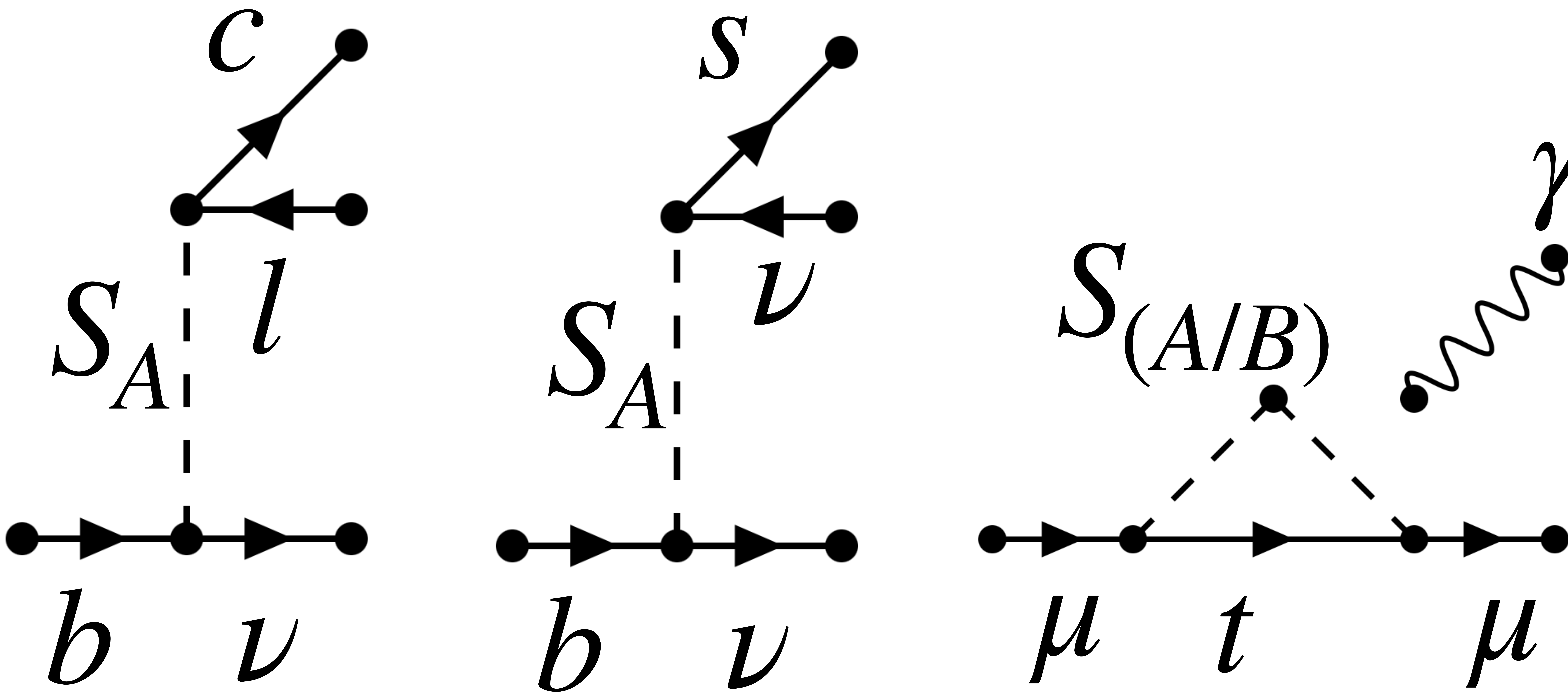
Dirac neutrino masses are induced at one loop:

$$M_\nu = f(M_A, M_B, \theta_S) \xi_2^\dagger m_d \xi_3,$$

$$f(M_A, M_B, \theta_S) = \frac{\cos\theta_S \sin\theta_S}{(4\pi)^2} \ln\left(\frac{M_A^2}{M_B^2}\right)$$



Dirac neutrinos and Leptoquarks



Dirac neutrinos and Leptoquarks

- Example B.P.

- N.H. $\sum m_\nu = 0.8eV,\ m_A = 1500\text{GeV}, m_B = 2000\text{GeV}, \theta_{LQ} = 10^{-6}$
- $R_D = 0.347, R_{D*} = 0.288, R_K = 2.94,$
- $a_\mu = 2.242 \times 10^{-9}$
- $BR(\mu \to e\gamma) = 1.2 \times 10^{-13},\ BR(\mu \to 3e) = 6.5 \times 10^{-17}$

D. Straub, “flavio: a Python package for flavour and precision phenomenology in the Standard Model and beyond” arXiv:1810.08132

Summary

- New physics linked to neutrino masses can be lighter - not behind a desert
- BSM physics linked to neutrino mass may already be visible
- Low energy and collider physics are necessary to ellucidate neutrino mass mechanisms