Current Anomalies:
From Muon *g*-2 to *B*-physics and Neutrinos

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XIV INTERNATIONAL CONFERENCE ON INTERCONNECTIONS BETWEEN PARTICLE PHYSICS AND COSMOLOGY

The UNIVERSITY of OKLAHOMA

May 17, 2021

An Era of Anomalies

- A growing list of "anomalies".
- Could be due to
  - statistical fluctuations (e.g. 750 GeV diphoton)
  - systematics or background uncertainties (e.g. KOTO)
  - experimental error (e.g. OPERA)
  - unknown issues (e.g. DAMA?), or
  - **genuine new physics signal?**
- A good driver of scientific creativity (not just 'ambulance-chasing').

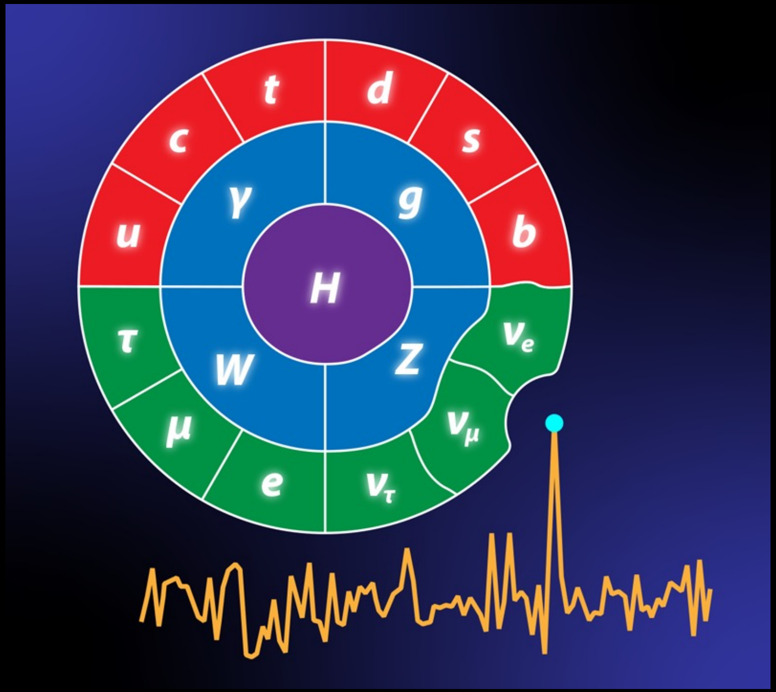


Figure credit: APS/Alan Stonebraker

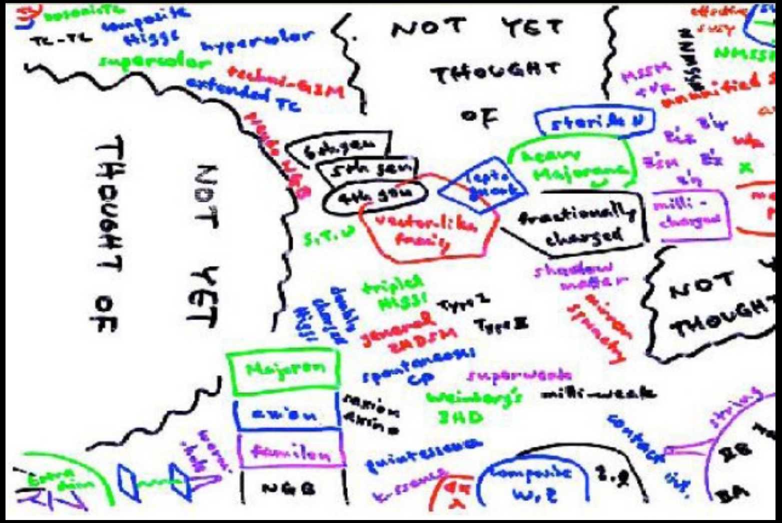


Figure credit: Quantum Diaries

(Partial) List of Existing Anomalies

Anomaly	Significance	Reference
Multileptons@LHC	2-5 σ	1901.05300
Dijet excess@LEP2	4-5 σ	1706.02255
Muon g-2	4.2 σ	2104.03281
LFUV in B-decays	3-5 σ	1909.12524
CKM unitarity	4 σ	2012.01580
LFUV in tau decay	~2 σ	1909.12524
LSND/MiniBooNE	6.1 σ	2006.16883
NOvA vs T2K	~2 σ	Neutrino 2020
IceCube HESE vs TG	~2 σ	2011.03545
ANITA upgoing events	~2 σ	2010.02869
Neutron lifetime	3.6 σ	2011.13272
^{8}Be transition	7.2 σ	1910.10459
Proton charge radius	5 σ	2105.00571

Anomaly	Significance	Reference
DAMA/LIBRA	12.9 σ	1907.06405
XENON1T e^--recoil	2-3 σ	2006.09721
Fermi-LAT GC excess	2-3 σ	1704.03910
AMS $e^+/\bar{p}$ excess	3-5 σ	Phys.Rep.894, 1
3.5 keV X-ray line	4 σ	2008.02283
511 keV gamma-ray line	58 σ	1512.00325
EDGES 21cm spectrum	3.8 σ	1810.05912
Primordial ^{7}Li problem	4-5 σ	1203.3551
Hubble tension	4.4 σ	2008.11284
σ_8 tension	3 σ	2005.03751
CMB anomalies	2-3 σ	1510.07929
NANOGRAV	>> 5 σ	2009.04496
Fast Radio Bursts	>> 5 σ	1906.05878

Repository: https://github.com/hepcomm/hepmist

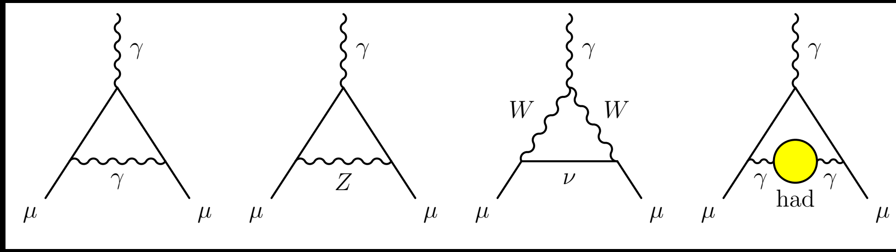
Outline

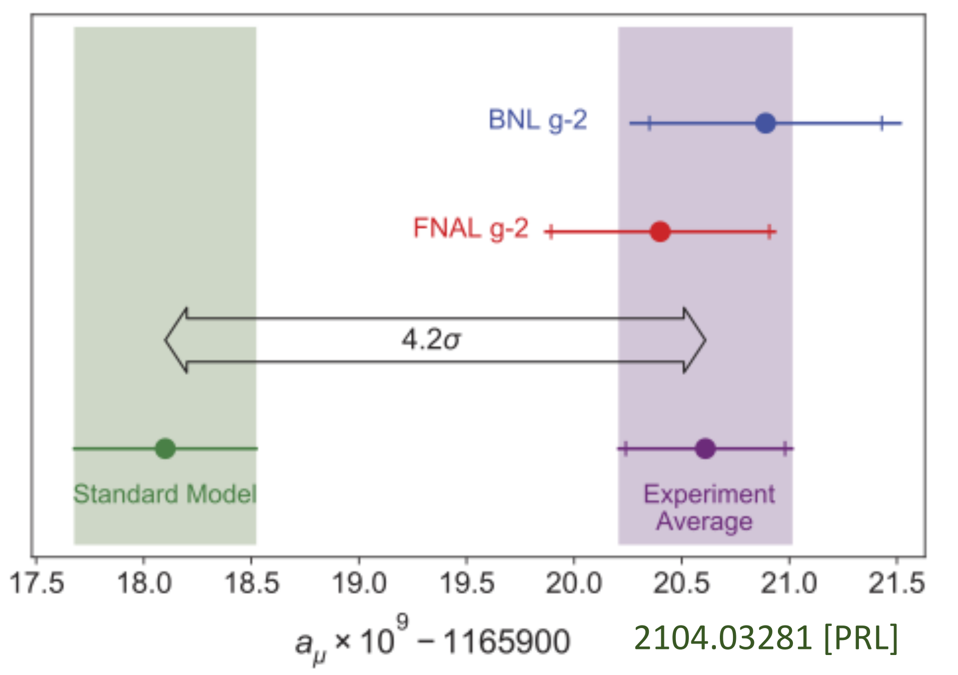
- *B*-anomalies: $R_D^{(*)}$ and $R_K^{(*)}$ **(see also Friday plenary talks by S. Stone and D. Robinson)**
  - Complementary high-p_T LHC tests
  - Common NP explanation

- Muon *g*-2: Recent update
  - Tests at LHC and future colliders
  - Connection to *B*-anomalies? **(see also parallel talks by A. Thapa and F. Xu)**

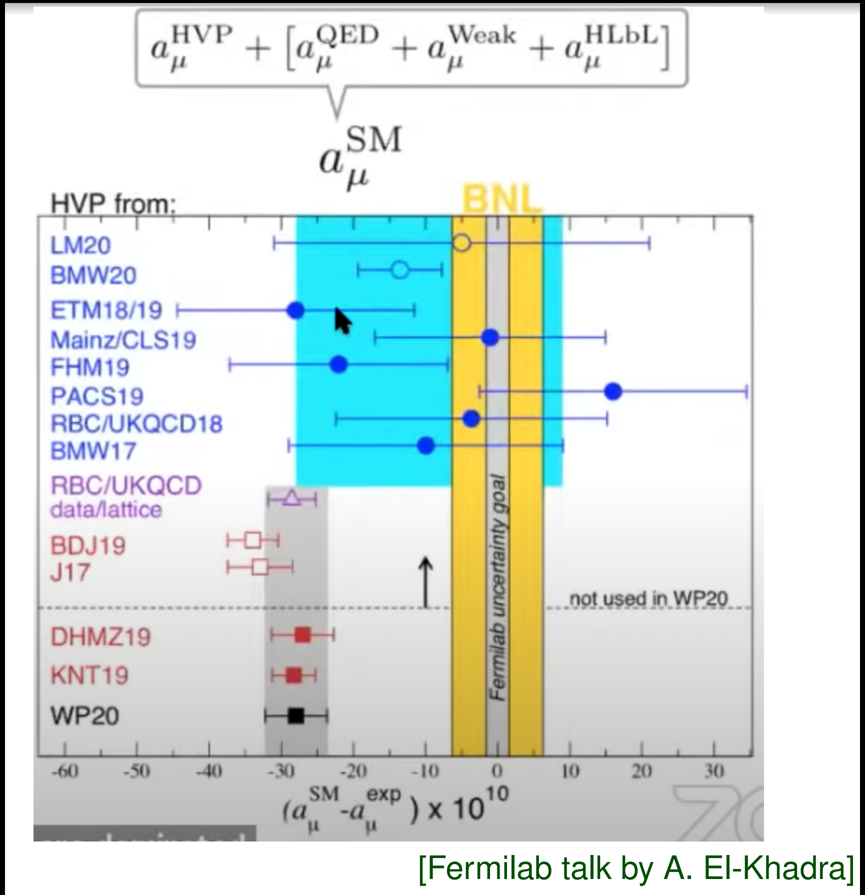
- Connection to neutrino mass **(see also Monday plenary talk by K.S. Babu)**

Muon Anomalous Magnetic Moment





$$a_\mu^{\text{exp}} = 116592061(41) \times 10^{-11}$$
$$a_\mu^{\text{SM}} = 116591810(43) \times 10^{-11}$$



More updates expected soon!

- If a change in HVP brought SM value close to expt, problems might arise in global EW fit.
  Crivellin, Hoferichter, Manzari, Montull, 2003.04886 [PRL]

- (Related) unresolved issues in the electron g-2 sector:

$$\Delta a_e^{\text{Cs}} \equiv a_e^{\text{exp (Cs)}} - a_e^{\text{SM}} = (-8.7 \pm 3.6) \times 10^{-13}$$

Parker, Yu, Zhong, Estey, Mueller, 1812.04130 (Science) -2.4 σ

Recent development:

$$\Delta a_e^{\text{Rb}} \equiv a_e^{\text{exp (Rb)}} - a_e^{\text{SM}} = (4.8 \pm 3.0) \times 10^{-13}$$

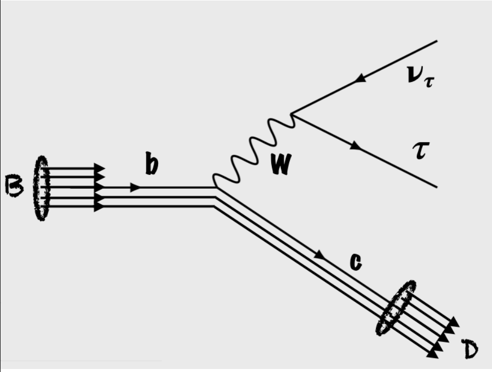
Morel, Yao, Clade, Guellati-Khelifa, Nature **588**, 61 (2020) +1.6 σ

$R_D^{(*)}$ Anomaly

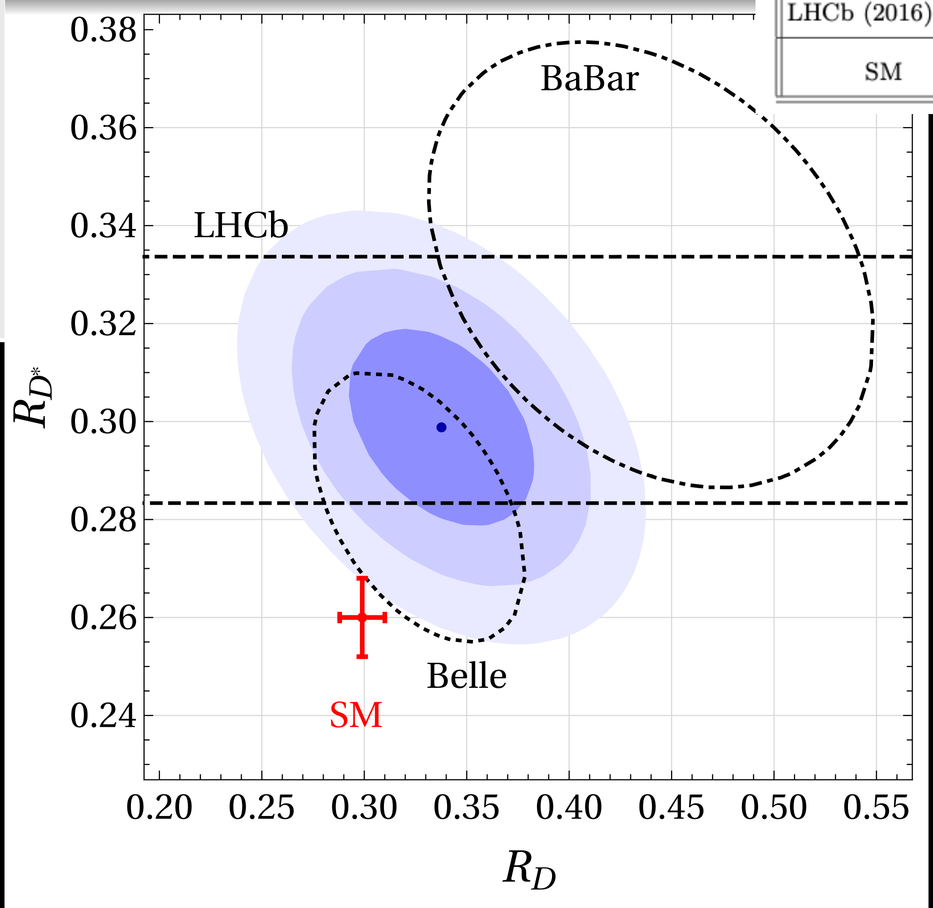
$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \quad (\text{with } \ell = e, \mu)$$

Experiment	Tag method	τ decay mode	R_D	R_{D^*}	$R_{J/\psi}$
Babar (2012) [1]	hadronic	$\ell\nu\nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.0.018$	
Belle (2015) [2]	hadronic	$\ell\nu\nu$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$	
LHCb (2015) [5]	hadronic	$\ell\nu\nu$	-	$0.336 \pm 0.027 \pm 0.030$	
Belle (2016) [2]	semileptonic	$\ell\nu\nu$	-	$0.302 \pm 0.030 \pm 0.011$	
Belle (2017) [3]	hadronic	$\pi(\rho)\nu$	-	$0.270 \pm 0.035 \pm 0.027$	
LHCb (2017) [6]	hadronic	$3\pi\nu$	-	$0.291 \pm 0.019 \pm 0.029$	
Belle (2019) [4]	semileptonic	$\ell\nu\nu$	$0.307 \pm 0.037 \pm 0.016$	$0.283 \pm 0.018 \pm 0.014$	
LHCb (2016) [67]	hadronic	$\ell\nu\nu$	-	-	$0.71 \pm 0.17 \pm 0.18$
SM	-	-	0.299 ± 0.011 [63]	0.260 ± 0.008 [64]	0.26 ± 0.02 [68]

Altmannshofer, BD, Soni, Sui, 2002.12910 [PRD]



Flavor-changing charged current: happens at tree-level in the SM.



All experimental measurements to date are consistently above the SM prediction.

$$\frac{R_D}{R_D^{\mathrm{SM}}} = \frac{R_{D^*}}{R_{D^*}^{\mathrm{SM}}} = 1.15 \pm 0.04$$

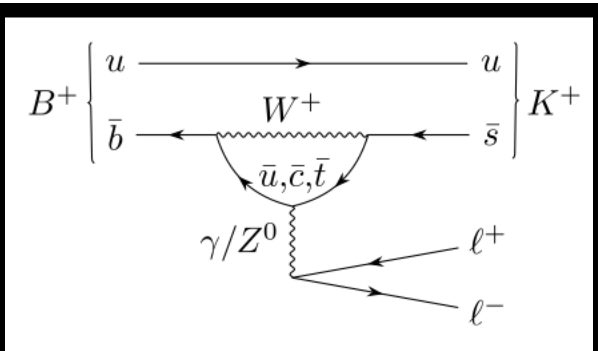
No such deviations in charmed meson decays:

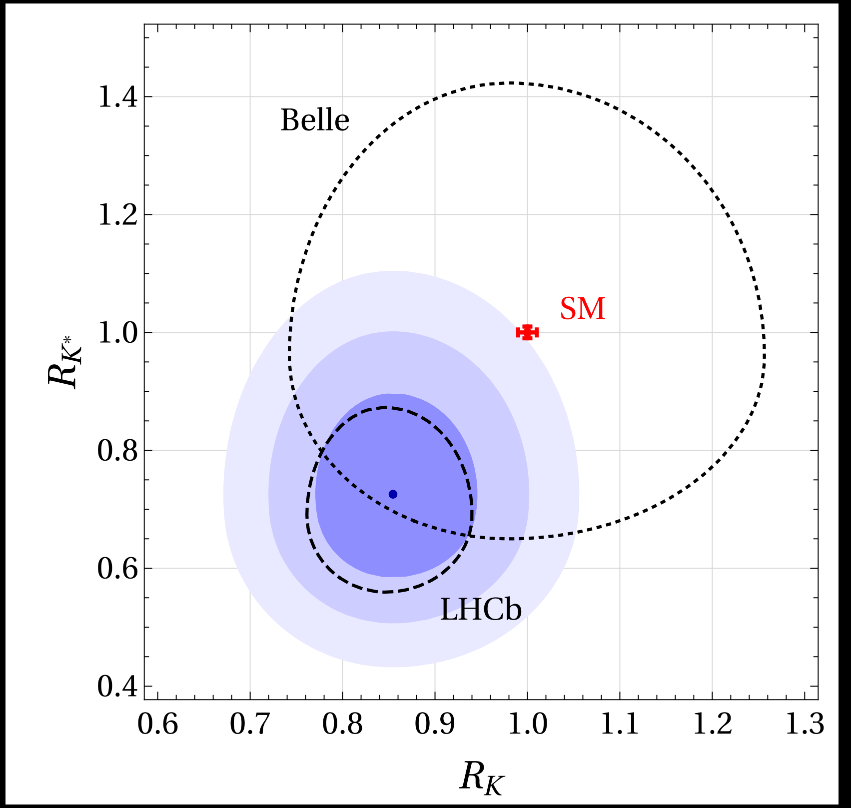
$$\frac{\mathrm{BR}(D^+ \to \omega\mu^+\nu_\mu)}{\mathrm{BR}(D^+ \to \omega e^+\nu_e)} = 1.05 \pm 0.14$$

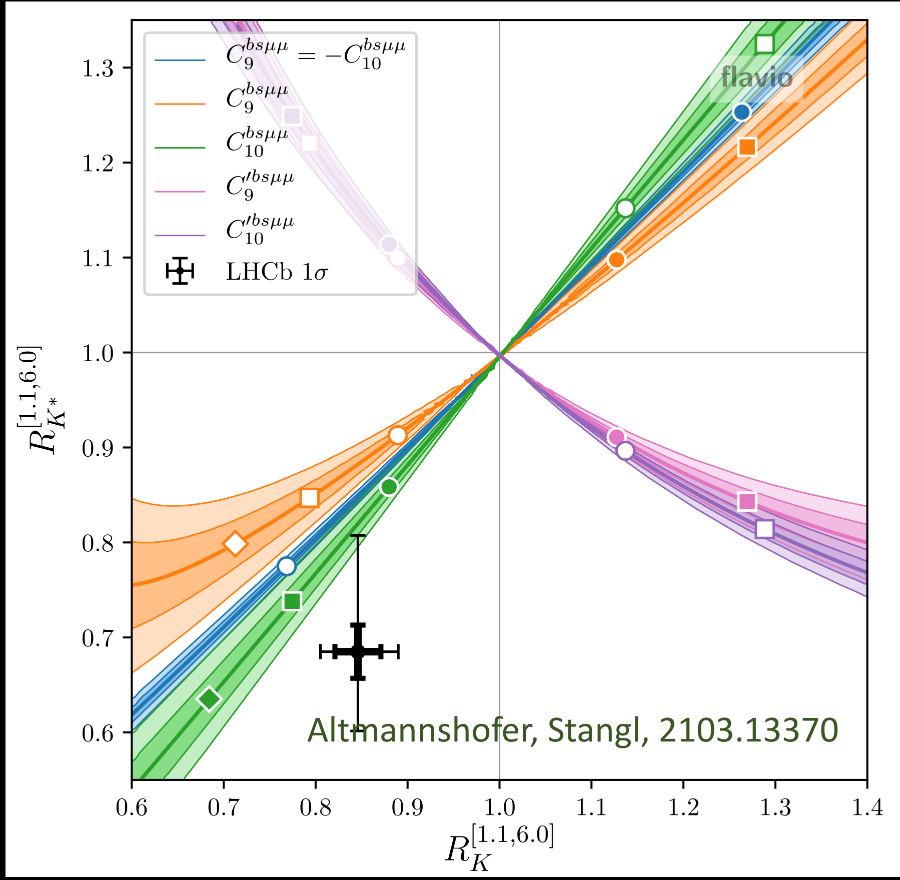
BESIII, 2002.10578 [PRD]

$R_K^{(*)}$ Anomaly

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$







Flavor-changing neutral current:
Loop-suppressed in the SM.

Observables	LHCb [9, 17]	Belle [18, 19]	SM
R_K [1, 6] GeV^2	–	$1.03^{+0.28}_{-0.24} \pm 0.01$	$1.0004^{+0.0008}_{-0.0007}$
R_K [1.1, 6] GeV^2	$0.846^{+0.042+0.013}_{-0.039-0.012}$	–	$1.0004^{+0.0008}_{-0.0007}$
R_{K^*} [0.045, 1.1] GeV^2	$0.66^{+0.11}_{-0.07} \pm 0.03$	$0.52^{+0.36}_{-0.26} \pm 0.06$	$0.920^{+0.007}_{-0.006}$
R_{K^*} [1.1, 6] GeV^2	$0.69^{+0.11}_{-0.07} \pm 0.05$	$0.96^{+0.45}_{-0.29} \pm 0.11$	$0.996^{+0.002}_{-0.002}$
R_{K^*} [15, 19] GeV^2	–	$1.18^{+0.52}_{-0.32} \pm 0.11$	$0.998^{+0.001}_{-0.001}$

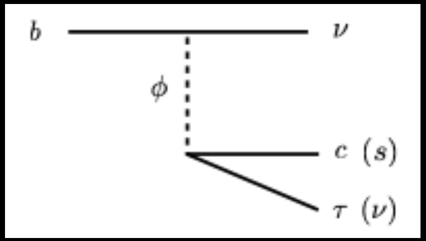
Li, Shi, Geng, 2105.06768

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} \left(C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i'^{bs\ell\ell} O_i'^{bs\ell\ell}\right) + \mathrm{h.c.}\,.$$

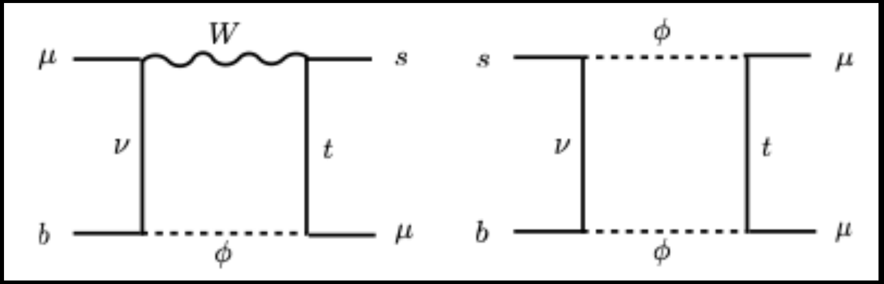
$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

Best fit: $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ $\quad -0.41^{+0.07}_{-0.07} \quad 5.9\sigma$

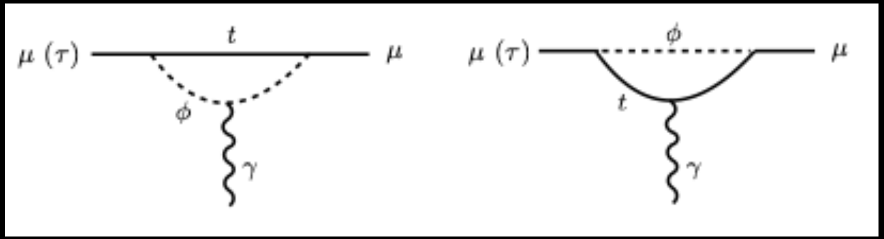
Possible New Physics Solutions



- A popular choice: Leptoquarks.
- Single scalar LQ solution. Bauer, Neubert, 1511.01900 [PRL]
- Now disfavored by global fits.
  Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504



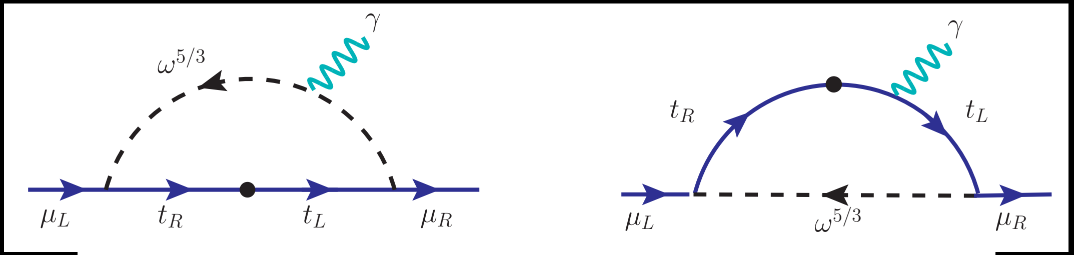
- Single vector LQ still a viable option, but must be embedded into some UV-completion.
  Crivellin, Greub, Mueller, Saturnino, 1807.02068 [PRL];
  Fornal, Gadam, Grinstein, 1812.01603 [PRD];
  Cornella, Fuentes-Martin, Isidori, 1903.11517 [JHEP];
  BD, Mohanta, Patra, Sahoo, 2004.09464 [PRD];
  Iguro, Kawamura, Okawa, Omura, 2103.11889.



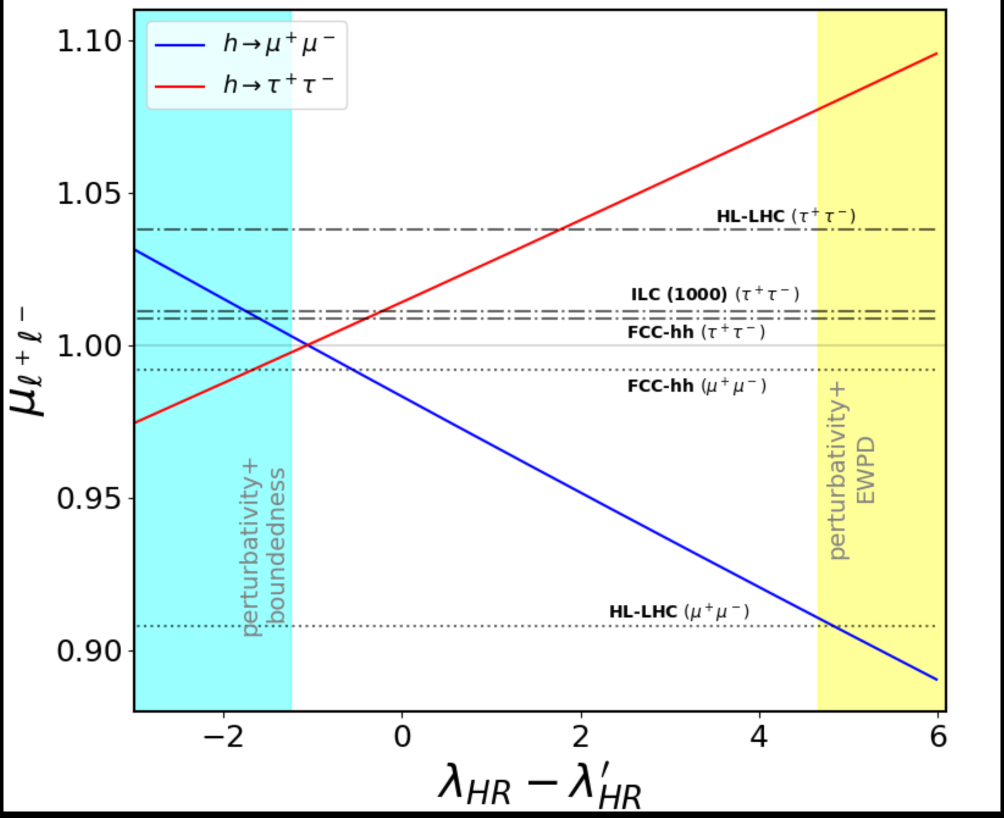
- Or invoke more than one scalar LQ.
  Chen, Nomura, Okada, 1703.03251 [PLB];
  Bigaran, Gargalionis, Volkas, 1906.01870 [JHEP];
  Saad, 2005.04352 [PRD];
  Babu, BD, Jana, Thapa, 2009.01771 [JHEP].

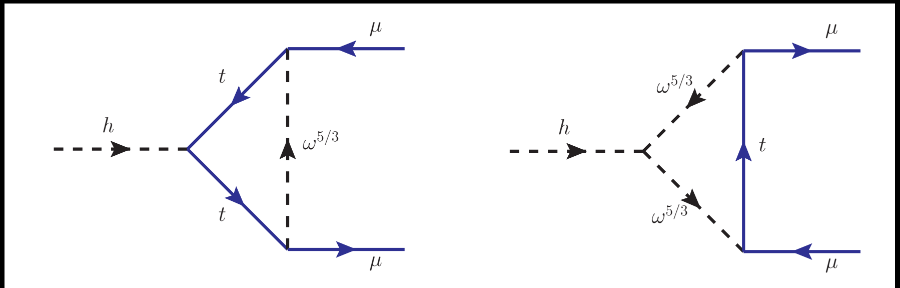
Model		$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1	$(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3	$(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

Chiral Enhancement for Muon g-2



$$\Delta a_\ell = -\frac{3}{16\pi^2}\frac{m_\ell^2}{m_{R_2}^2}\sum_q \Big[\left(|f_{q\ell}|^2 + |(V^\star f')_{q\ell}|^2\right)\left(Q_q F_5(x_q) + Q_S F_2(x_q)\right) - \frac{m_q}{m_\ell}\mathrm{Re}[f_{q\ell}\,(V^\star f')^\star_{q\ell}]\left(Q_q F_6(x_q) + Q_S F_3(x_q)\right)\Big]$$





Connection with Higgs decay to dileptons

Crivellin, Mueller, Saturnino, 2008.02643

$$\mu_{\mu^+\mu^-} \equiv \frac{\mathrm{BR}(h\to\mu^+\mu^-)}{\mathrm{BR}(h\to\mu^+\mu^-)_{\rm SM}} = \left|1 - \frac{3}{8\pi^2}\frac{m_t}{m_\mu}\frac{f_{32}(V^\star f')^\star_{32}}{m_{R_2}^2}\left\{\frac{m_t^2}{8}\mathcal{F}\left(\frac{m_h^2}{m_t^2},\frac{m_t^2}{m_{R_2}^2}\right) + v^2\left(\lambda_{HR} - \lambda'_{HR}\right)\right\}\right|^2$$

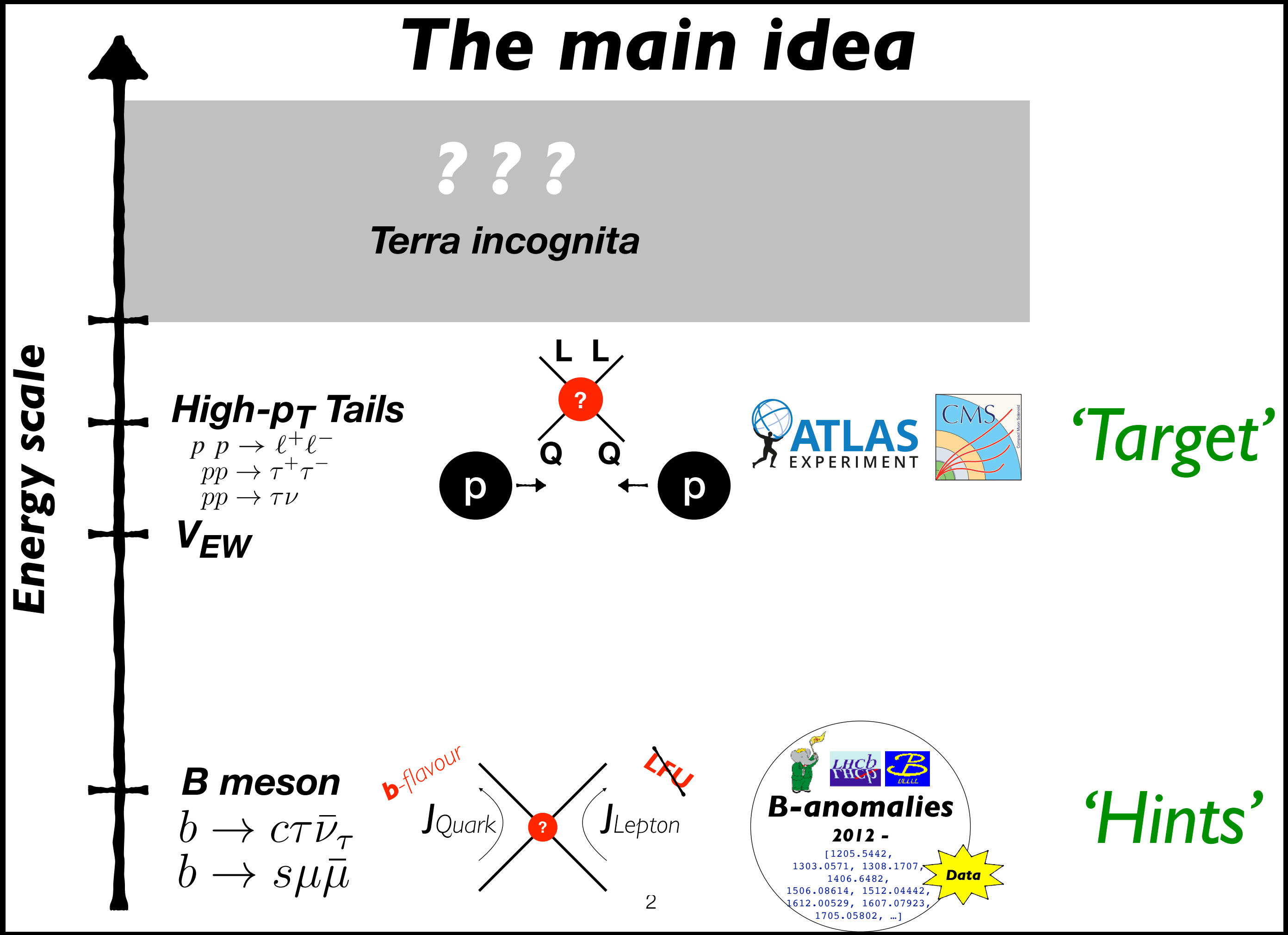
$$\mathcal{F}(x,y) = -8 + \frac{13}{3}x - \frac{1}{5}x^2 - \frac{1}{70}x^3 + 2(x-4)\log y\,.$$

Depends on quartic couplings $\lambda_{HR}(H^\dagger H)(R_2^\dagger R_2) + \lambda'_{HR}(H^\dagger \tau_a H)(R_2^\dagger \tau_a R_2)$

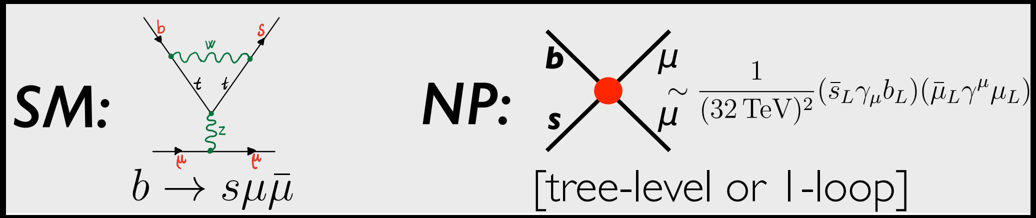
Leptoquark solution to muon g-2 can be tested in precision Higgs data at LHC and future colliders.

Babu, BD, Jana, Thapa, 2009.01771 [JHEP]

High-p_T LHC Tests

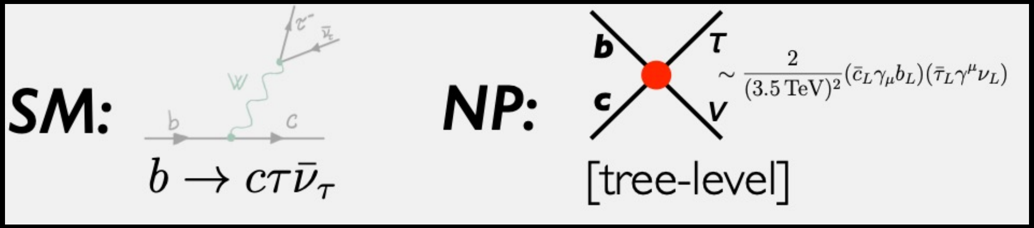


A. Greljo, CERN Implications Workshop 2018



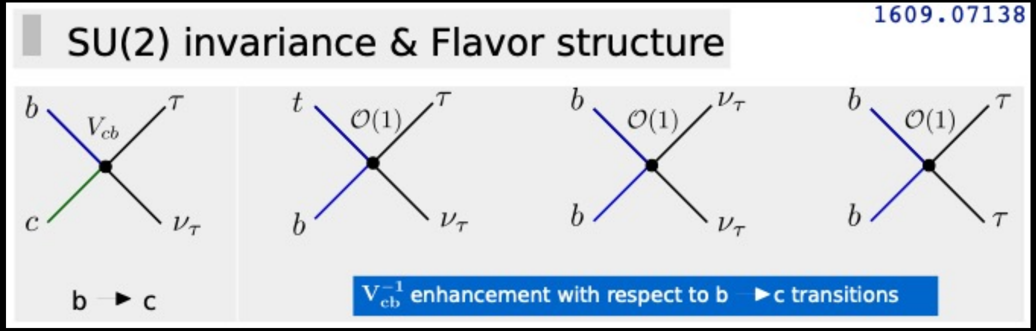
Greljo, Marzocca, 1704.09015 [EPJC]

$pp \to \ell^+\ell^-$



$pp \to \tau\nu$ inclusive

Greljo, Camalich, Ruiz-Alvarez, 1811.07920 [PRL]



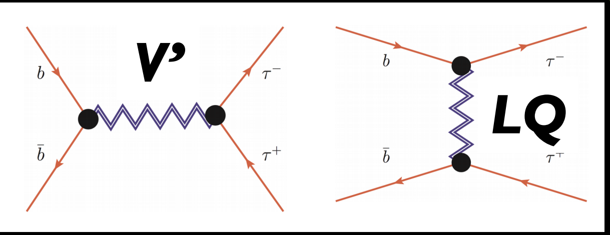
Faroughy, Greljo, Kamenik, 1609.07138 [PLB]

Large!

$pp \to \tau^+\tau^-$

EFT validity $\hat{s} \lesssim M_X^2$

Simplified models

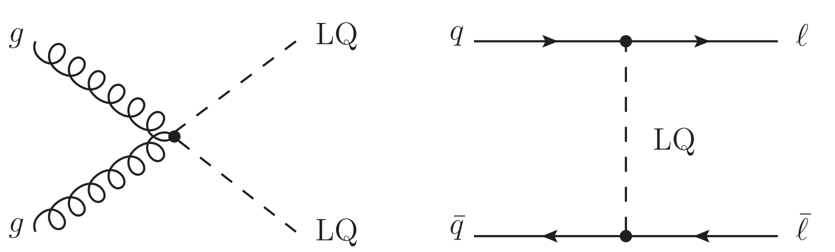


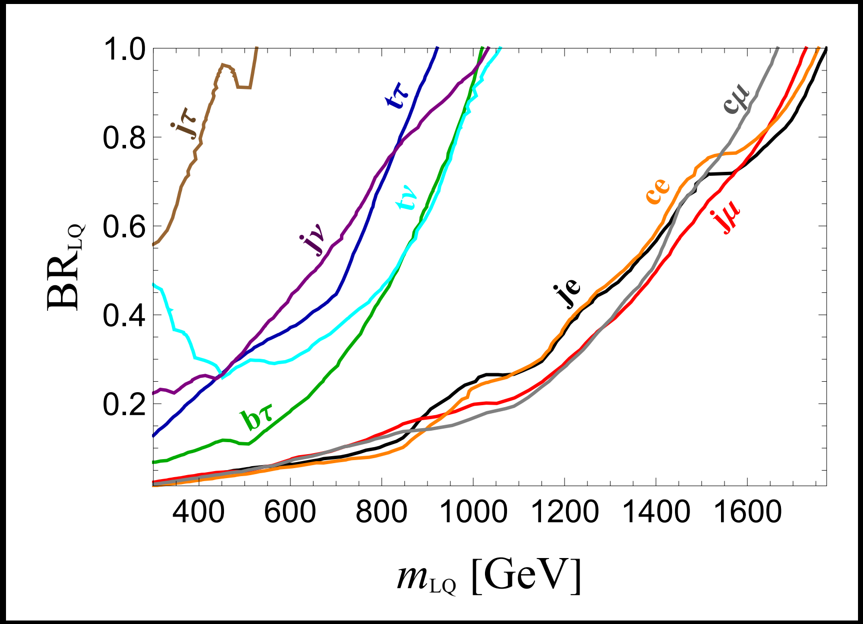
Implications for LQ Models

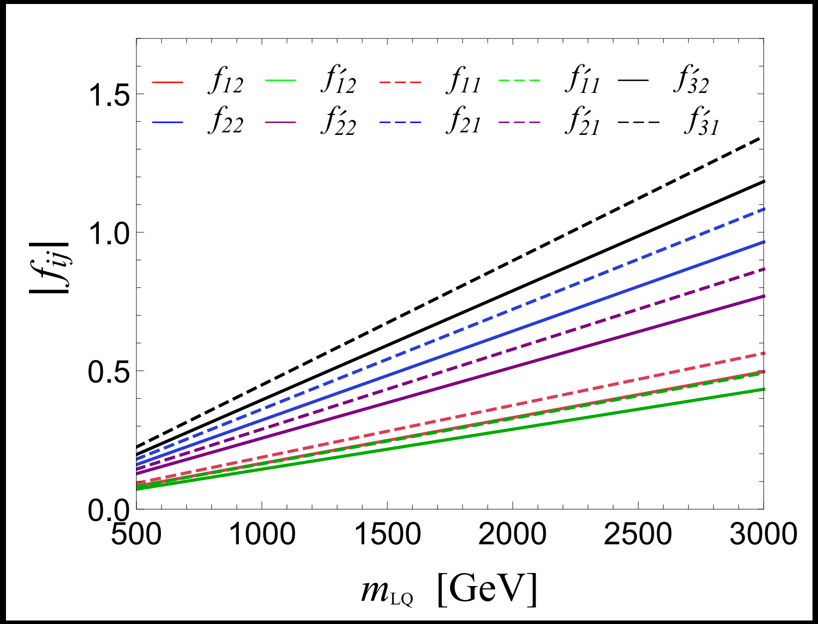
$$R_2\ (\mathbf{3},\mathbf{2},7/6)\ =\ \left(\omega^{5/3}\ \omega^{2/3}\right)^T$$

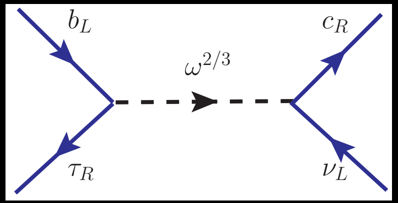
$$S_3\ (\bar{\mathbf{3}},\mathbf{3},1/3)\ =\ \left(\rho^{4/3}\ \rho^{1/3}\ \rho^{-2/3}\right)^T$$

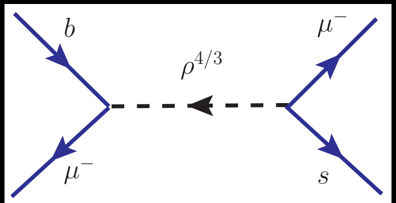
$$\mathcal{L}_Y\ =\ u^{cT}Cf\nu\omega^{2/3} - u^{cT}Cfe\omega^{5/3} + u^TC(V^\star f')e^c\omega^{-5/3} + d^TCf'e^c\omega^{-2/3} - u^TC(V^\star y)\nu\rho^{-2/3} + u^TC(V^\star y)e\frac{\rho^{1/3}}{\sqrt{2}} + d^TCy\nu\frac{\rho^{1/3}}{\sqrt{2}} + d^TCye\rho^{4/3} + \text{H.c.}$$

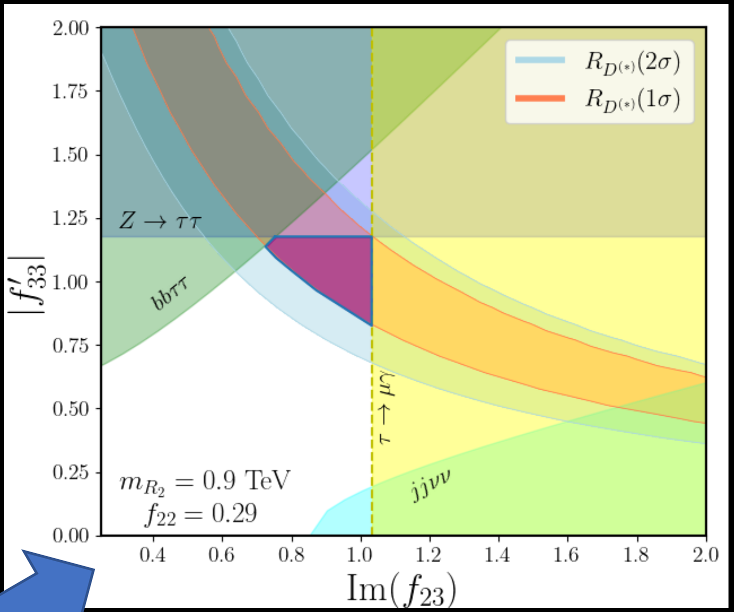








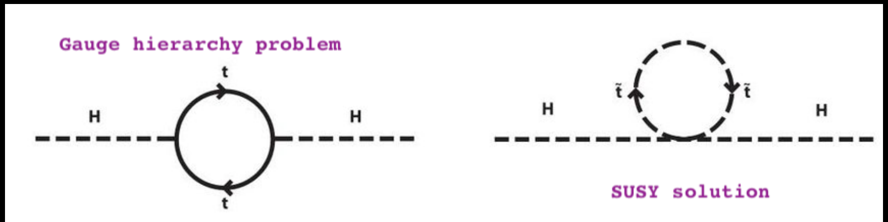




Babu, BD, Jana, Thapa, 2009.01771 [JHEP]; **see also parallel talk by A. Thapa**

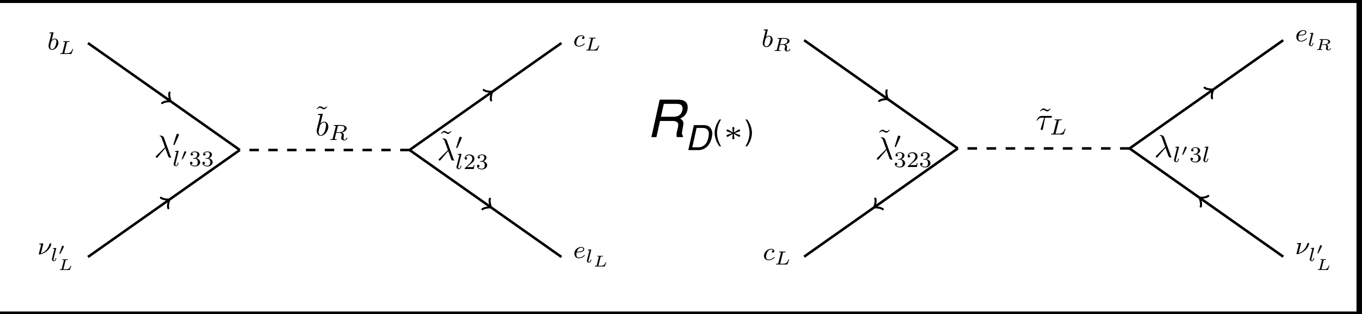
Non-resonant dilepton searches at LHC severely restrict the allowed LQ parameter space for B-anomalies.

Another NP Solution: RPV SUSY



$$\mathcal{L}_{LQD} = \lambda'_{ijk}\left[\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} - \tilde{e}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}e_{iL} - \tilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\right] + \mathrm{H.c.}$$

$$\mathcal{L}_{LLE} = \frac{1}{2}\lambda_{ijk}\left[\tilde{\nu}_{iL}\bar{e}_{kR}e_{jL} + \tilde{e}_{jL}\bar{e}_{kR}\nu_{iL} + \tilde{e}^*_{kR}\bar{\nu}^c_{iL}e_{jL} - (i \leftrightarrow j)\right] + \mathrm{H.c.}$$

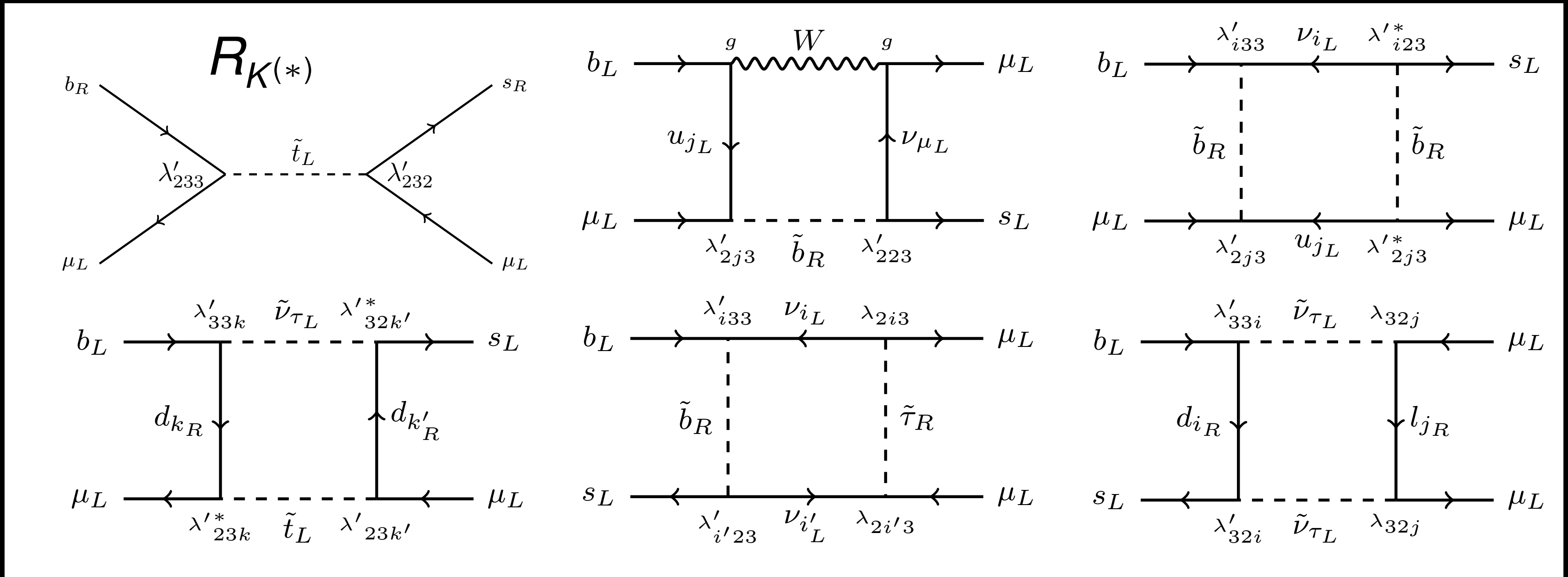


$$\frac{R_D^{\text{LHCb}}}{R_D^{\text{SM}}} = \frac{R_{D^*}^{\text{LHCb}}}{R_{D^*}^{\text{SM}}} = \frac{|\Delta^c_{31}|^2 + |\Delta^c_{32}|^2 + |1+\Delta^c_{33}|^2}{|\Delta^c_{21}|^2 + |1+\Delta^c_{22}|^2 + |\Delta^c_{23}|^2}\,, \tag{23}$$

where

$$\Delta^c_{ll'} = \frac{v^2}{4m^2_{\tilde{b}_R}}\lambda'_{l'33}\left(\lambda'_{l33} + \lambda'_{l23}\frac{V_{cs}}{V_{cb}} + \lambda'_{l13}\frac{V_{cd}}{V_{cb}}\right)\,, \tag{24}$$

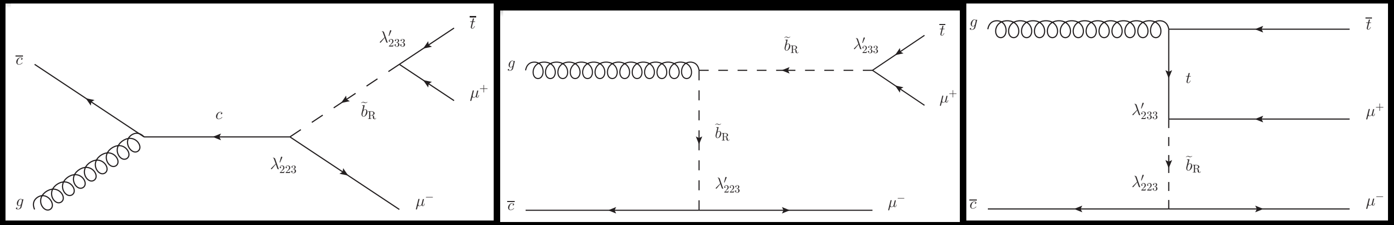
Deshpande, He, 1608.04817[EPJC];
Altmannshofer, BD, Soni, 1704.06659 [PRD].



$$\begin{aligned}(C_9)^\mu = -(C_{10})^\mu = {} & \frac{m_t^2}{m^2_{\tilde{b}_R}}\frac{|\lambda'_{233}|^2}{16\pi\alpha_{\text{em}}} - \frac{v^2}{16m^2_{\tilde{b}_R}}\frac{X_{bs}X_{\mu\mu}}{e^2V_{tb}V^*_{ts}} \\ & - \frac{v^2}{16(m^2_{\tilde{t}_L} - m^2_{\tilde{\nu}_\tau})}\log\left(\frac{m^2_{\tilde{t}_L}}{m^2_{\tilde{\nu}_\tau}}\right)\frac{X_{b\mu}X_{s\mu}}{e^2V_{tb}V^*_{ts}} \\ & - \frac{v^2}{16(m^2_{\tilde{b}_R} - m^2_{\tilde{\tau}_R})}\log\left(\frac{m^2_{\tilde{b}_R}}{m^2_{\tilde{\tau}_R}}\right)\frac{\tilde{X}_{b\mu}\tilde{X}_{s\mu}}{e^2V_{tb}V^*_{ts}} \\ & - \frac{v^2}{16m^2_{\tilde{\nu}_\tau}}\frac{\tilde{X}_{bs}\tilde{X}_{\mu\mu}}{e^2V_{tb}V^*_{ts}}\,,\end{aligned} \tag{43}$$

Das, Hati, Kumar, Mahajan, 1605.06313 [PRD];
Earl, Gregoire, 1806.01343 [JHEP];
Trifinopoulos, 1807.01638 [EPJC];
Altmannshofer, BD, Soni, Sui [PRD].

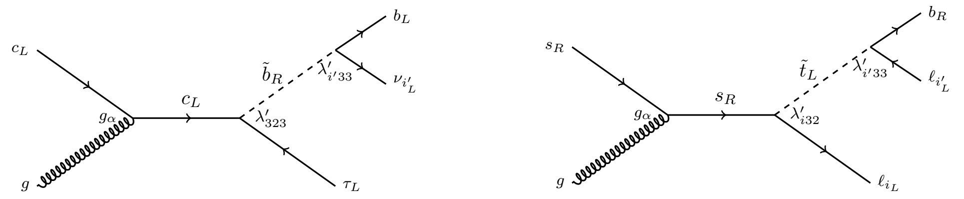
Distinct LHC Signals

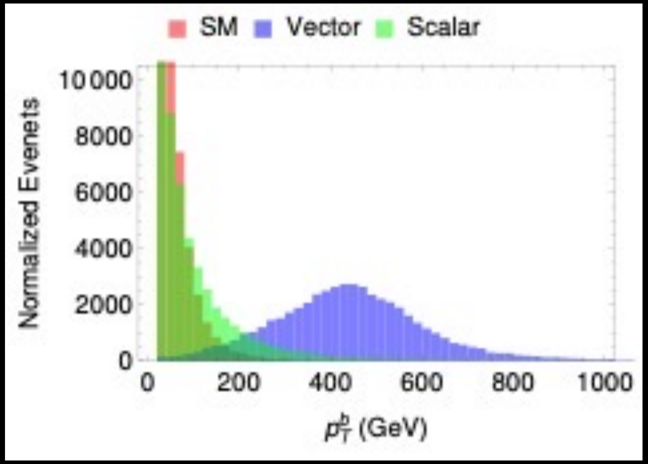


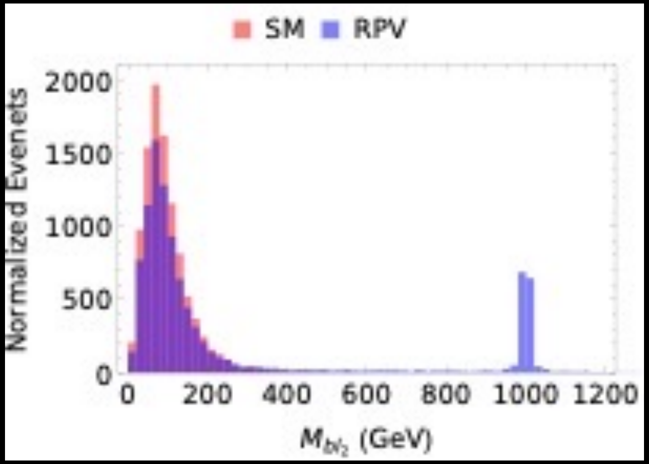
$R_{D^{(*)}}$: $\mathcal{O}_{V_L} = (\bar{c}\gamma^{\mu} P_L b)(\bar{\tau}\gamma_{\mu} P_L \nu)$

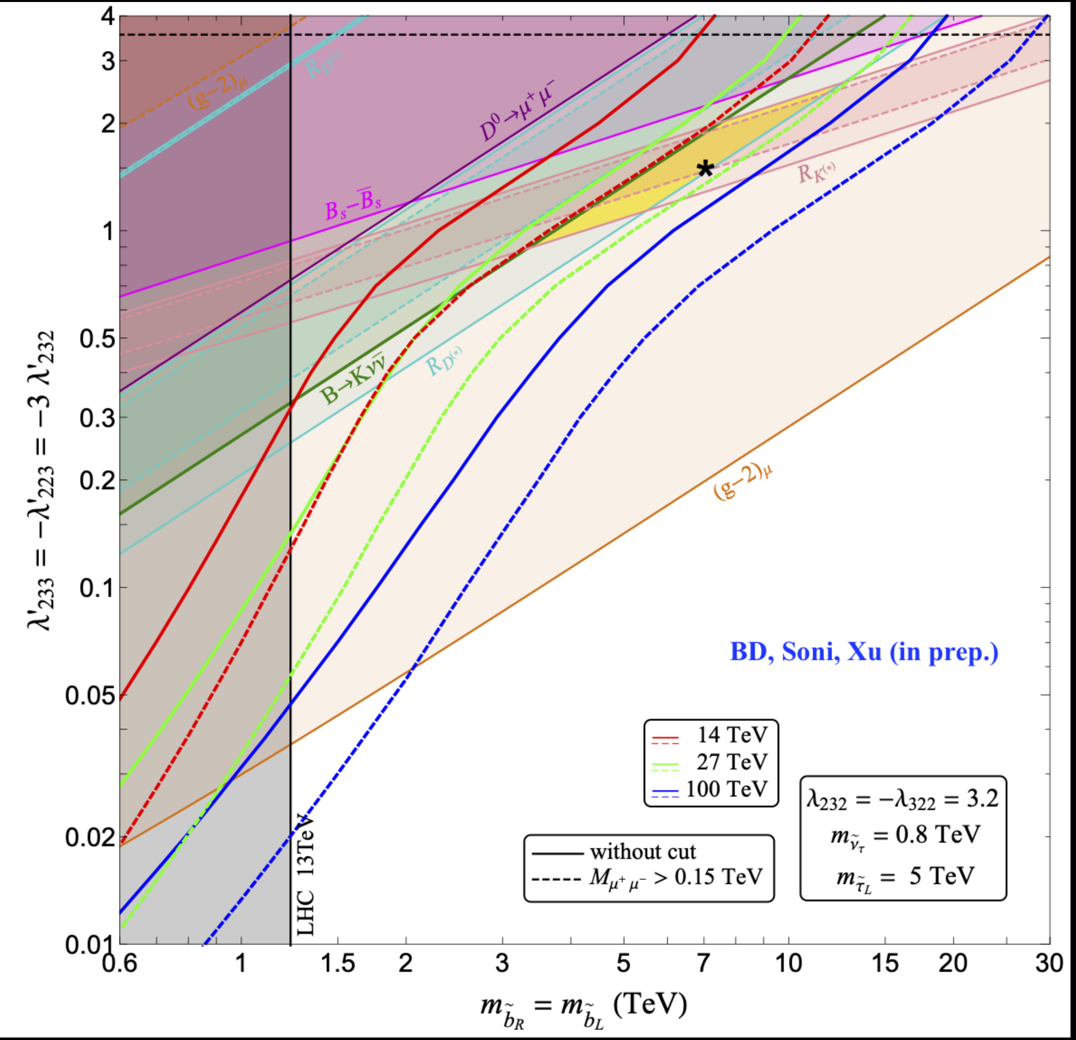
$R_{K^{(*)}}$: $Q^{\ell}_{9(10)} = (\bar{s}\gamma^{\mu} P_L b)(\bar{\ell}\gamma_{\mu}(\gamma_5)\ell)$

Crossing symmetry: $b \to c\tau\nu$ leads to $gc \to b\tau\nu$, and $b \to s\ell\ell$ leads to $gs \to b\ell\ell$.





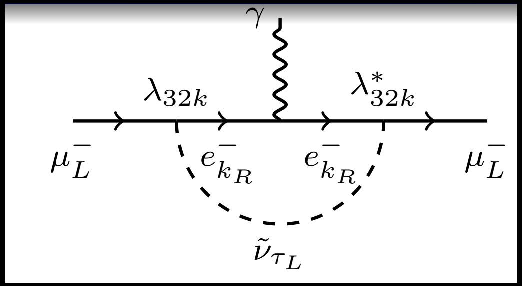


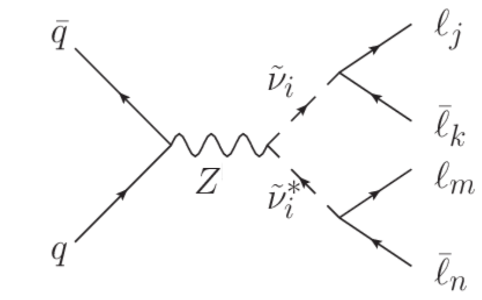


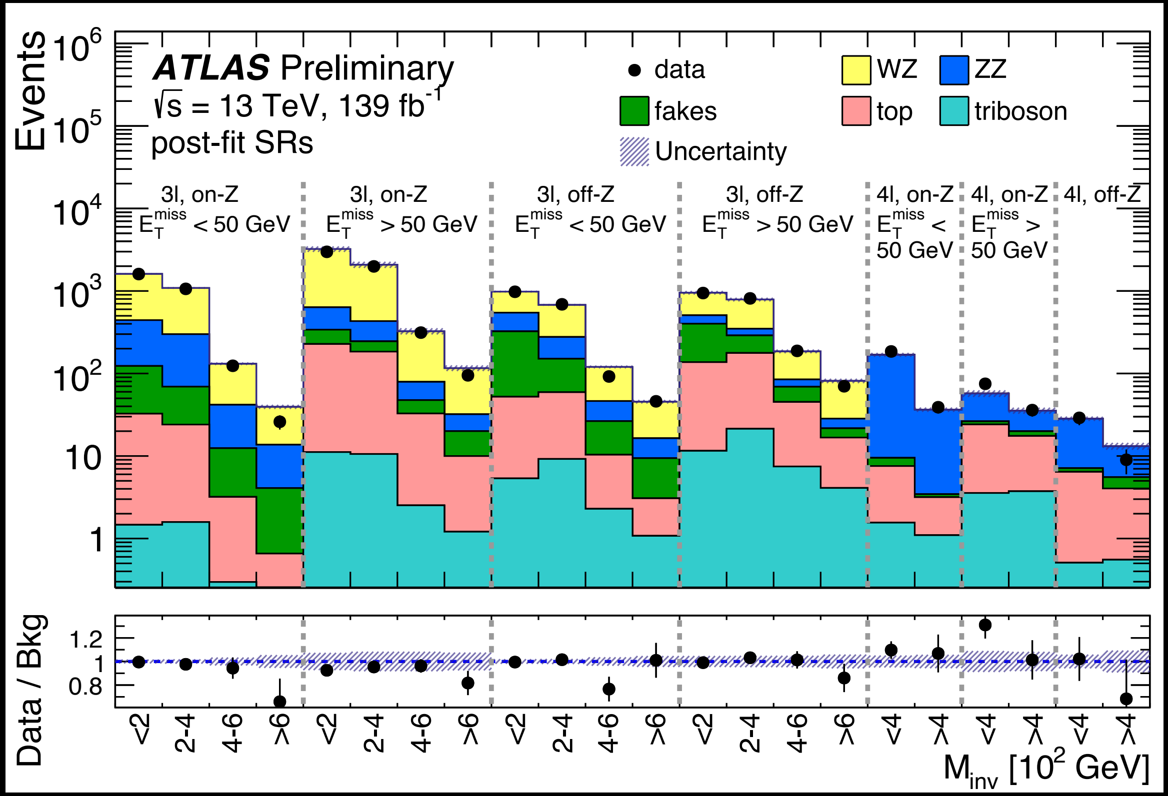
Altmannshofer, BD, Soni, 1704.06659 [PRD];
Altmannshofer, BD, Soni, Sui, 2002.12910 [PRD]

See also parallel talk by F. Xu

An LHC Test of Muon g-2







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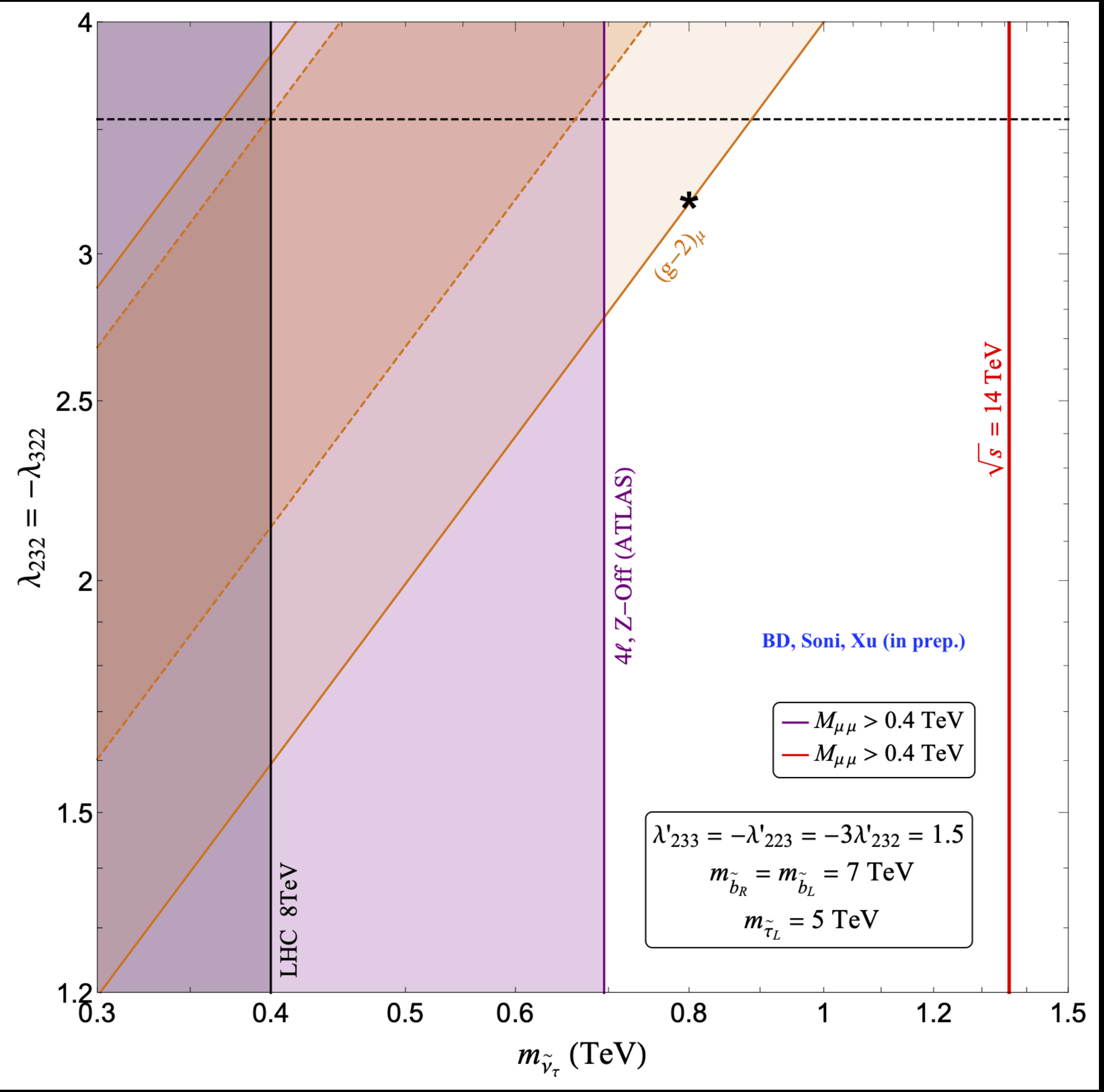
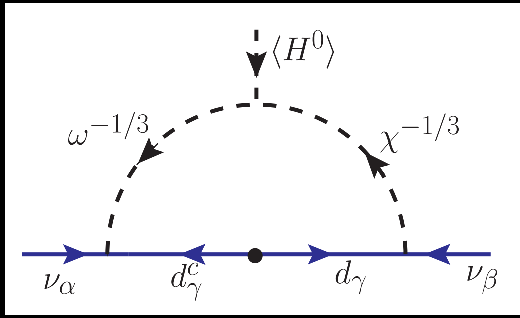
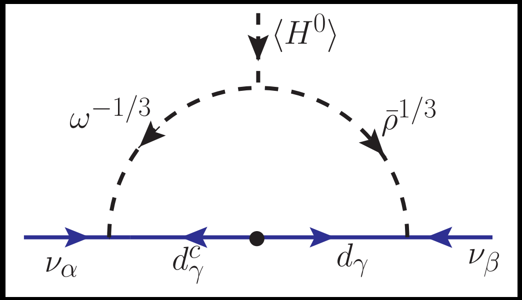


See also parallel talk by F. Xu

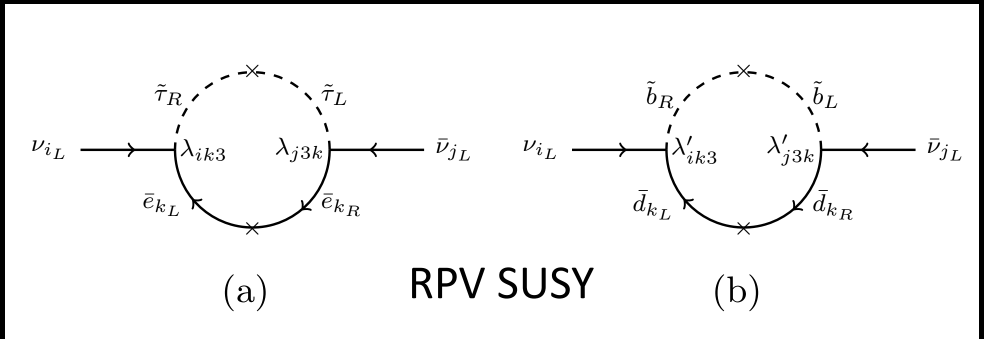
Connection to Neutrino Physics

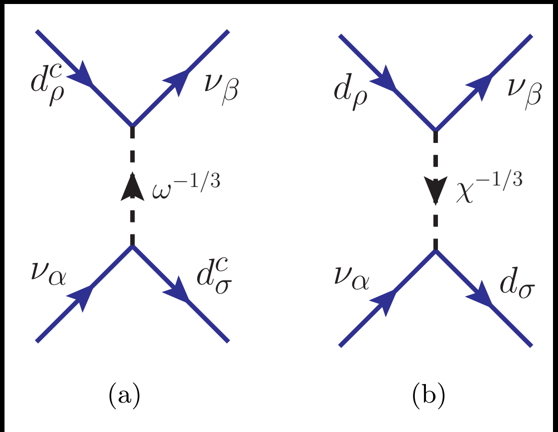


Singlet-doublet LQ



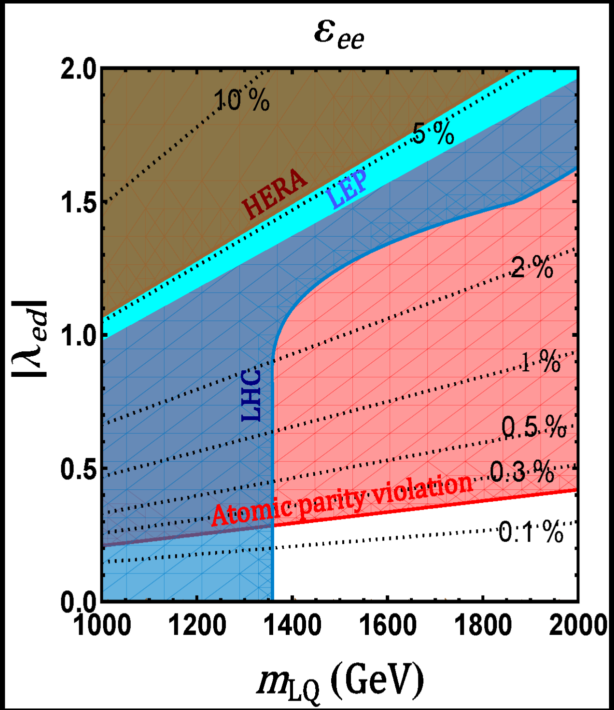
Doublet-triplet LQ

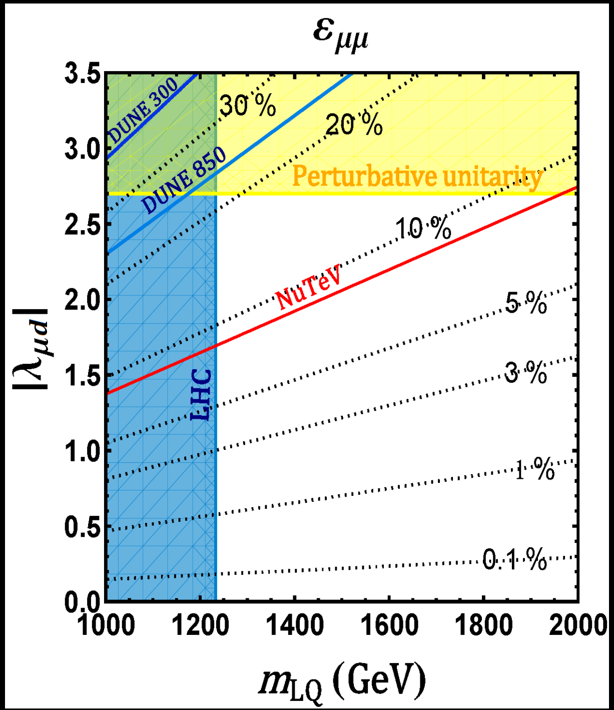


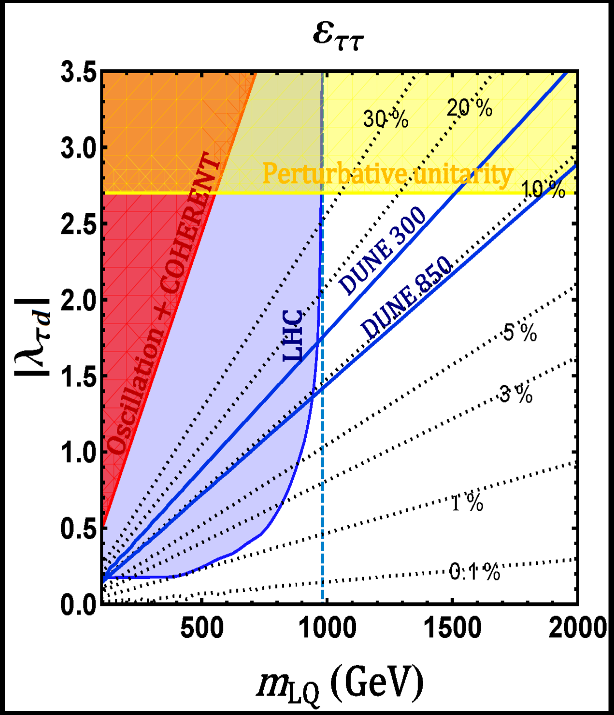


Neutrino NSI

$$\varepsilon_{\alpha\beta} \equiv 3\varepsilon^d_{\alpha\beta} = \frac{3}{4\sqrt{2}\,G_F}\left(\frac{\lambda^\star_{\alpha d}\lambda_{\beta d}}{m^2_\omega} + \frac{\lambda'^\star_{\alpha d}\lambda'_{\beta d}}{m^2_\chi}\right)$$

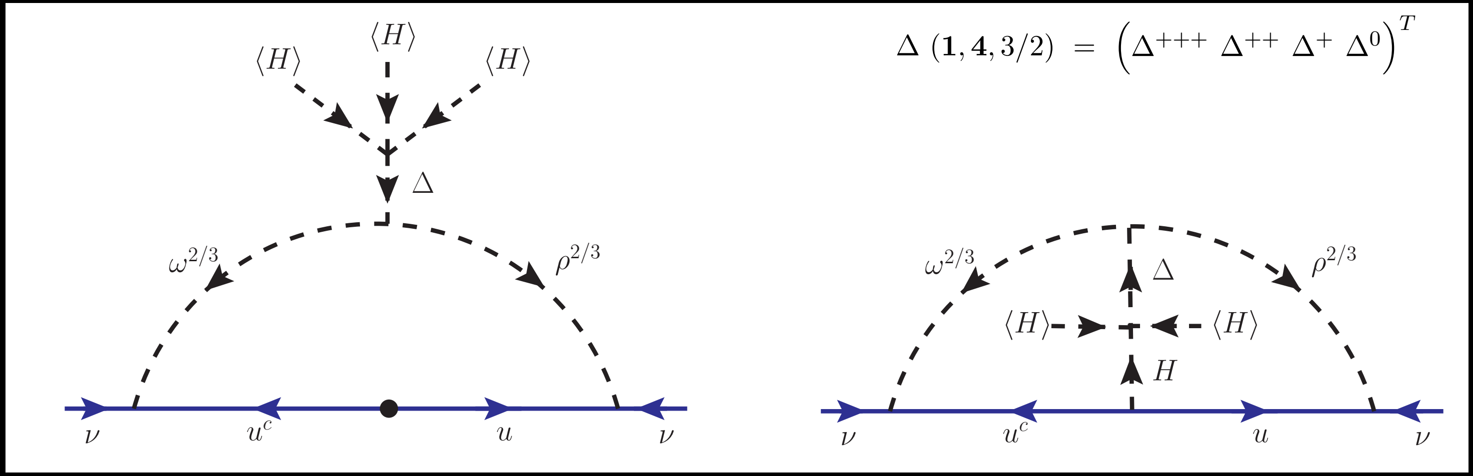


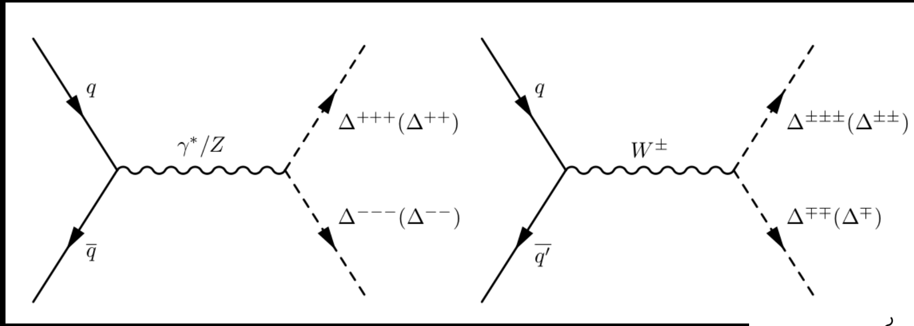


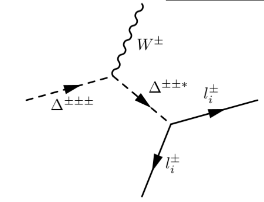


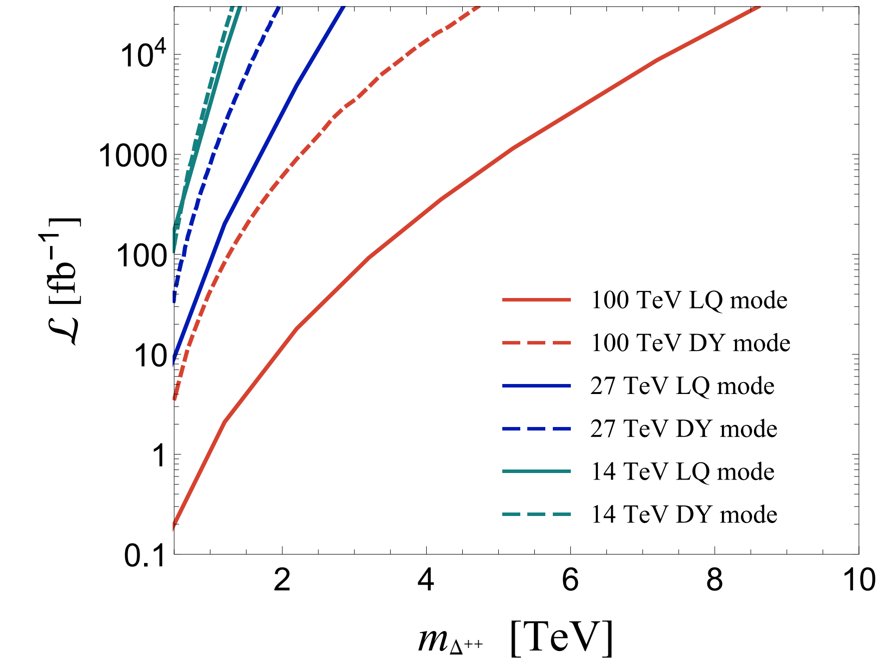
Babu, BD, Jana, Thapa, 1907.09498 [JHEP]

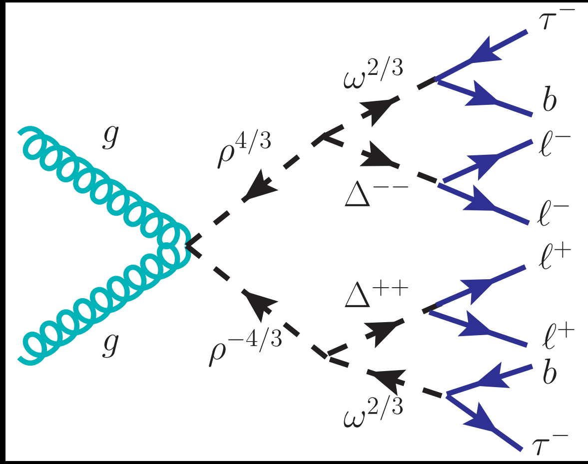
More LHC Signals

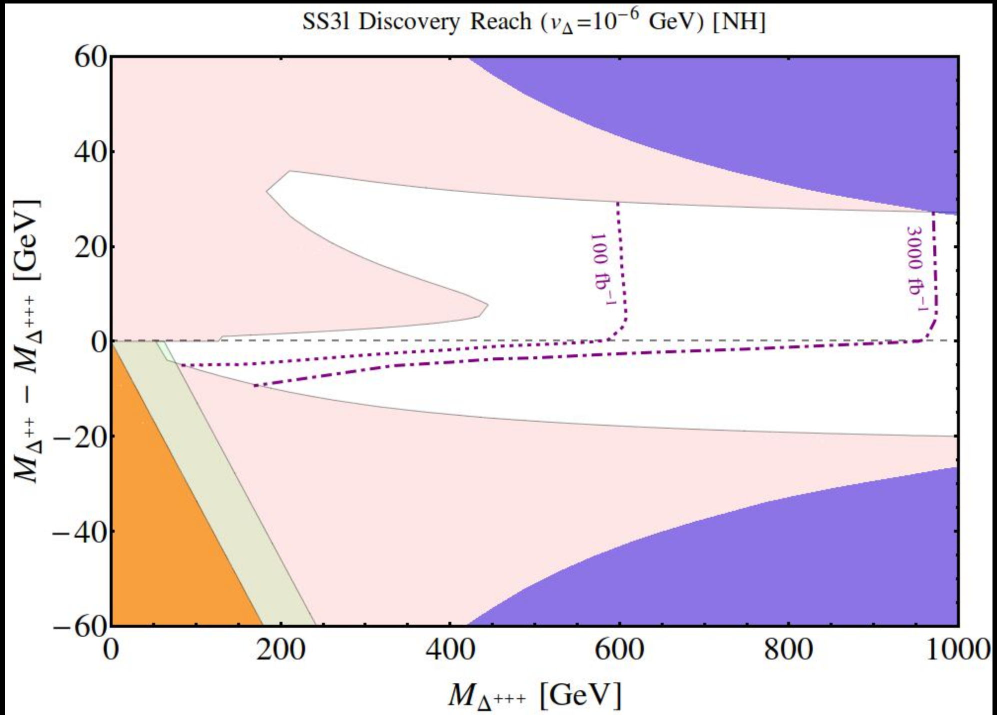








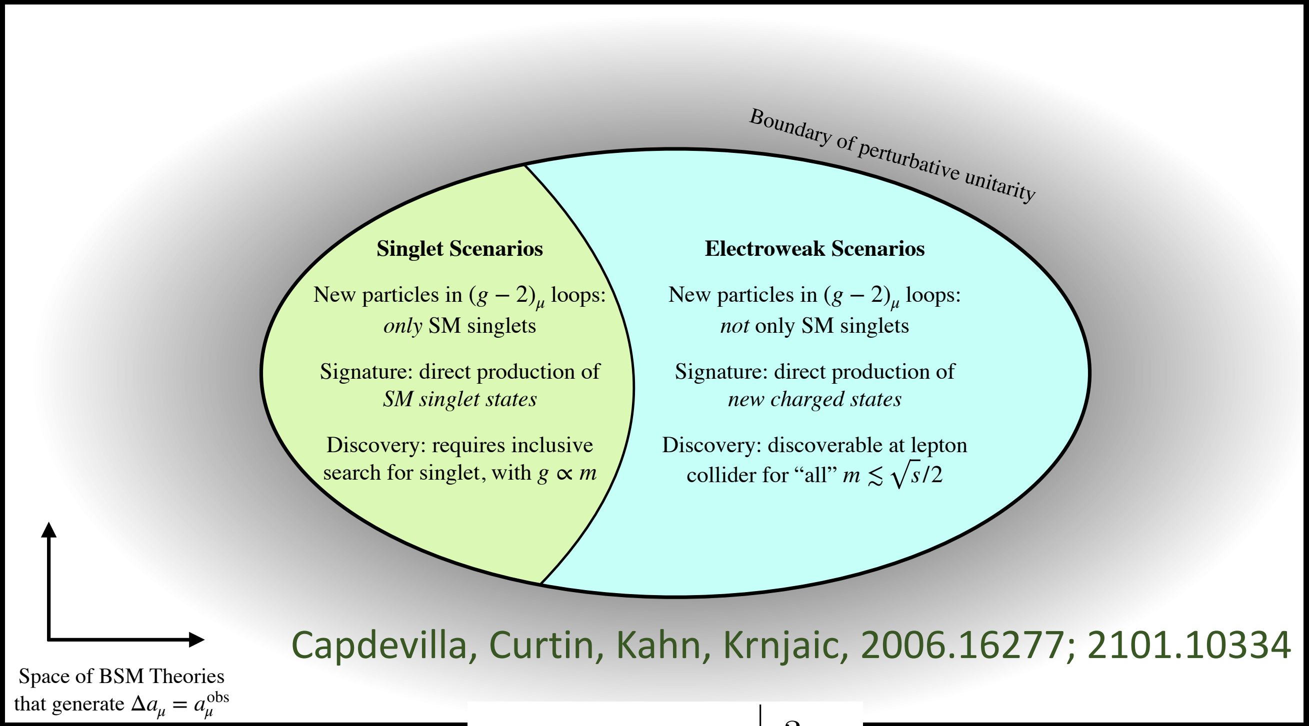


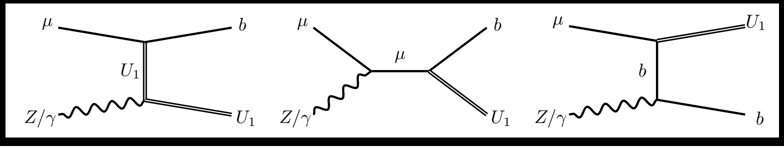


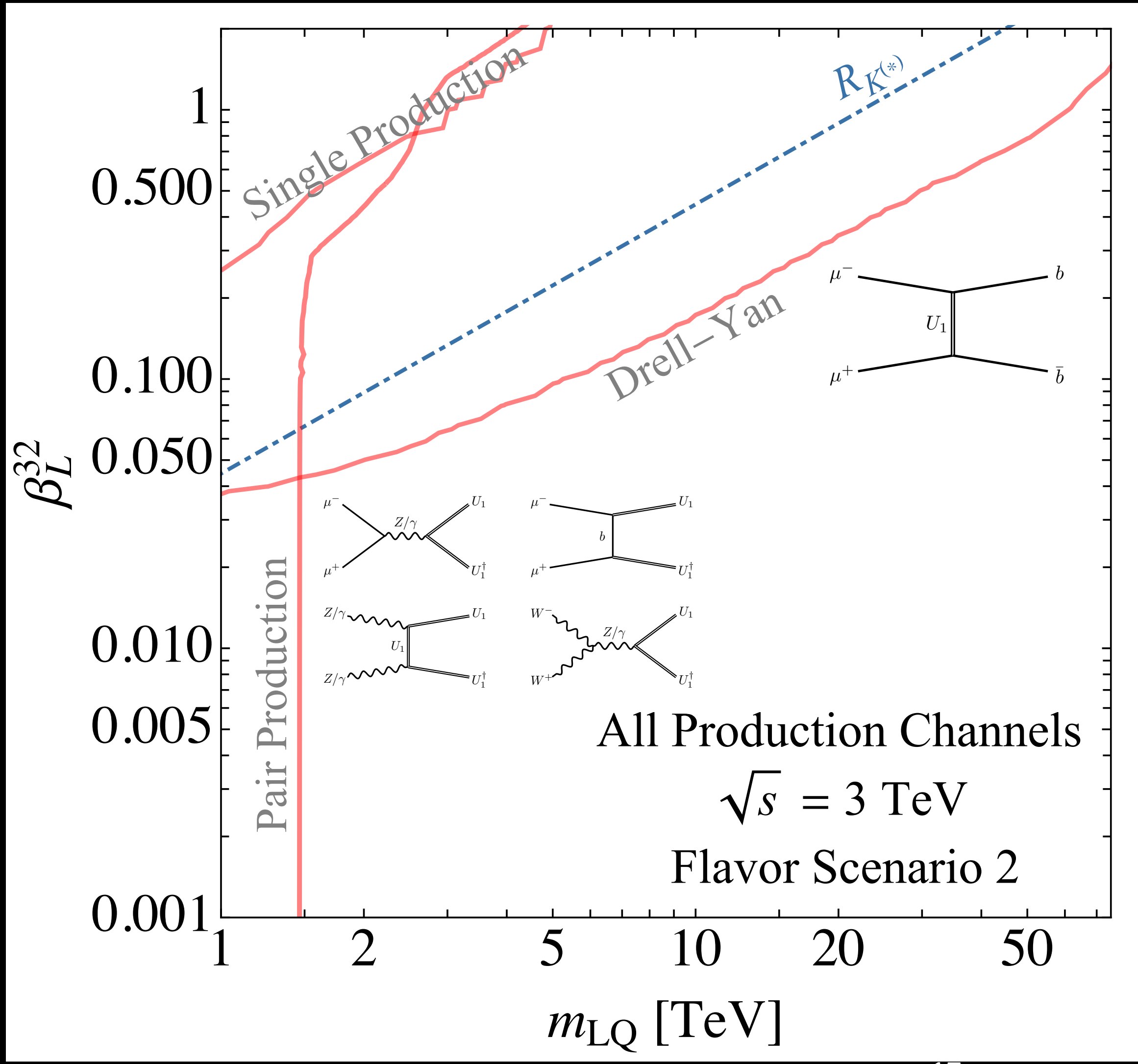
Ghosh, Jana, Nandi, 1802.09251 [PRD]

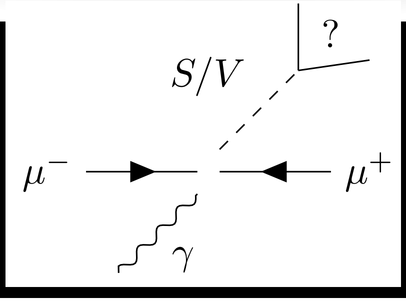
Babu, BD, Jana, Thapa, 2009.01771 [JHEP]

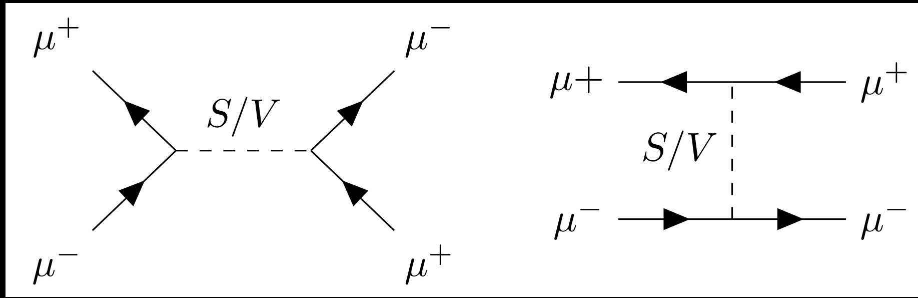
No-Lose Theorem for Muon Collider











Asadi, Capdavilla, Cesarotti, Homiller, 2104.05720

Conclusion

- Conspicuous paths to new physics have remained stubbornly out of reach so far.
- Look for inspiration from anomalies as possible alternative routes.
- Need coherent community effort, active theory-experiment collaborations and open-access data to resolve the existing anomalies.
- Flavor anomalies might be the breadcrumps leading to the right path to new physics.
- Important to establish independent tests (at colliders and elsewhere).

Thank You !