Leptoquarks

Muon Collider Physics and Detector workshop

Fermilab

Dec 15, 2022

Rodolfo Capdevilla
Fermilab

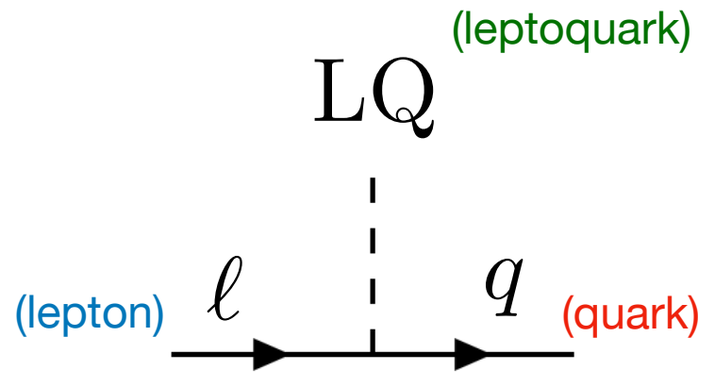
*Bansal, **RC**, Delgado, Kolda, Martin, Raj, Phys. Rev. D **98** (2018) 1, 015037*
*Bansal, **RC**, Kolda, Phys. Rev. D **99** (2019) 3, 035047*
*Asadi, **RC**, Cesarotti, Homiller, JHEP 10 (2021) 182*

Outline

1. Leptoquarks
   - Theoretical Motivations — Unification, RPV, Higgstability…
   - Pheno Motivations — B anomalies, g-2, Neutrino Masses…
2. Searches
   - Current Constraints — Low E: Meson Decays, Meson Mixing; High E: LHC
   - Muon Colliders
3. Summary

1) Leptoquarks

- LQ mediate interactions where a lepton turns into a quark



List of Scalar LQ:

Dorsner, Fajfer, Greljo, Kamenik, Kosnik, Phys. Rept. 641 (2016) 1-68

LQ	Interactions	B violation	RHN
$S_3(\bar{3},3,1/3)$	$y_3' L S_3 Q$	$y_{3,B} Q S_3^* Q$	-
$R_2(3,2,7/6)$	$y_2' L R_2 u^c + y_2 e^c R_2^* Q$	-	-
$\tilde{R}_2(3,2,1/6)$	$\tilde{y}_2' L \tilde{R}_2 d^c$	-	$y_{2,R} \nu^c \tilde{R}_2^* Q$
$\tilde{S}_1(\bar{3},1,4/3)$	$\tilde{y}_1 e^c \tilde{S}_1^* d^c$	$\tilde{y}_{1,B} u^c \tilde{S}_1 u^c$	-
$S_1(\bar{3},1,1/3)$	$y_1' L S_1 Q + y_1 e^c S_1^* u^c$	$y_{1,B_1} Q S_1^* Q + y_{1,B_2} u^c S_1 d^c$	$y_{1,R} \nu^c S_1^* d^c$
$\bar{S}_1(\bar{3},1,-2/3)$	-	$\bar{y}_{1,B} d^c \bar{S}_1 d^c$	$\bar{y}_{1,R} \nu^c \bar{S}_1^* u^c$

- All of them have color
- Different representations of EW SU(2)
- Interaction with different chiralities!
- Some can have B violating and/or RHN interactions

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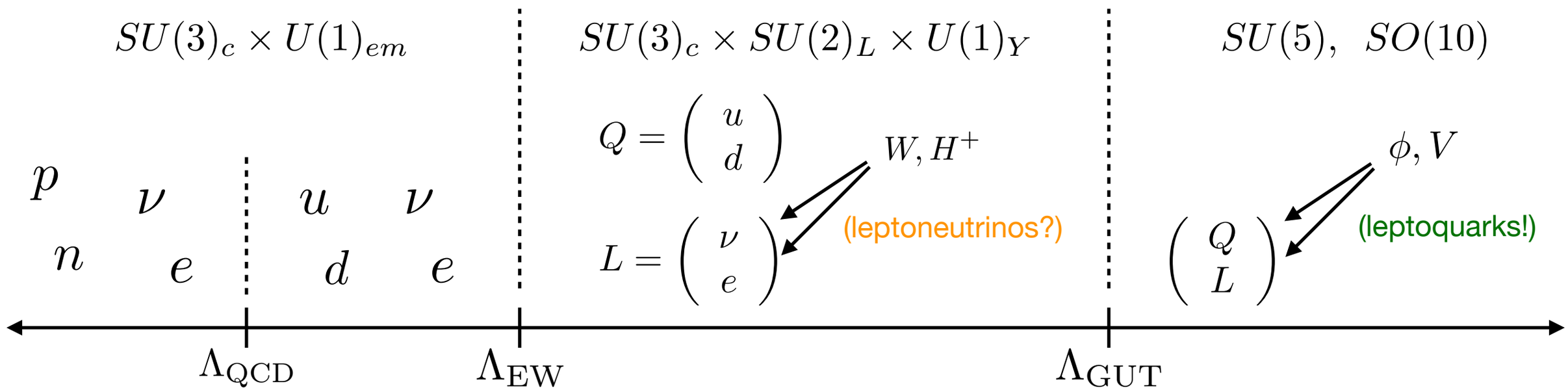
1.1) Theoretical Motivations

- Unification

Georgi, Glashow, Phys. Rev. Lett. 32 (1974) 438-441
Fritzsch, Minkowski, Annals Phys. 93 (1975) 193-266



- SUSY-RPV

Dawson, Nucl. Phys. B 261 (1985) 297-318

$$W \supset \hat{H}_u \hat{Q} \hat{U}^c \xrightarrow[\text{Yukawas}]{\left(\frac{\partial^2 W}{\partial \hat{\psi}_1 \partial \hat{\psi}_2}\right)_{\hat{\psi}_3 = \psi_{3,S}}} \mathcal{L} \supset H_u Q u^c$$

$$W \supset \hat{L} \hat{Q} \hat{D}^c$$

R-parity: Forbids B and L violation

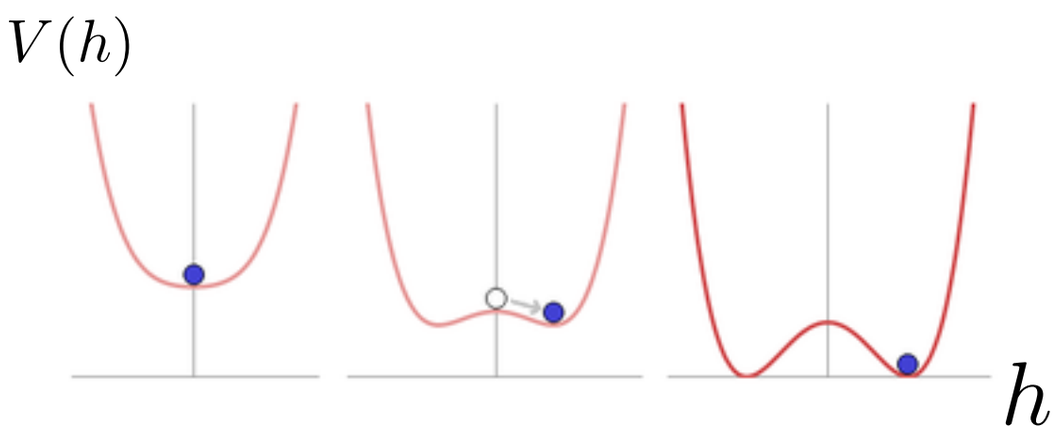
RPV

$$\mathcal{L} \supset \tilde{Q} L d^c$$

(leptoquark!)

1.1) Theoretical Motivations

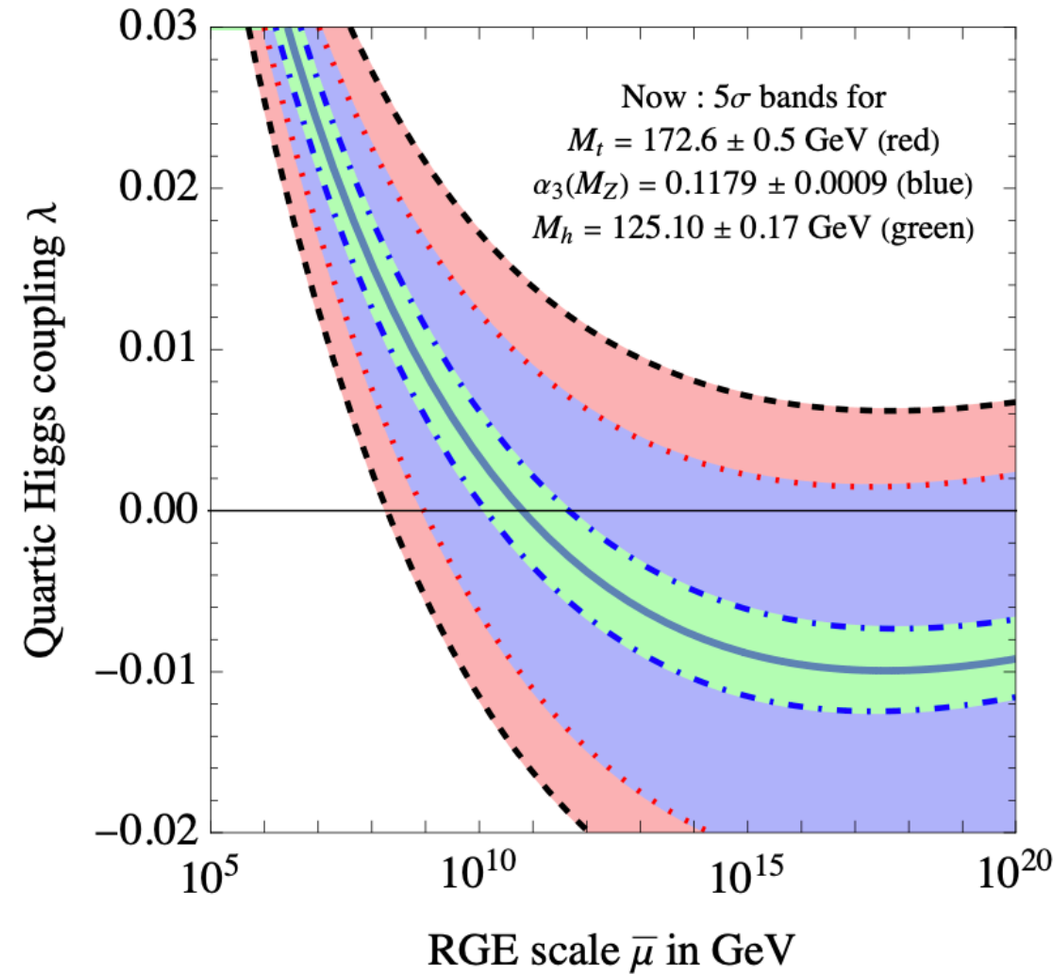
- Higgstability



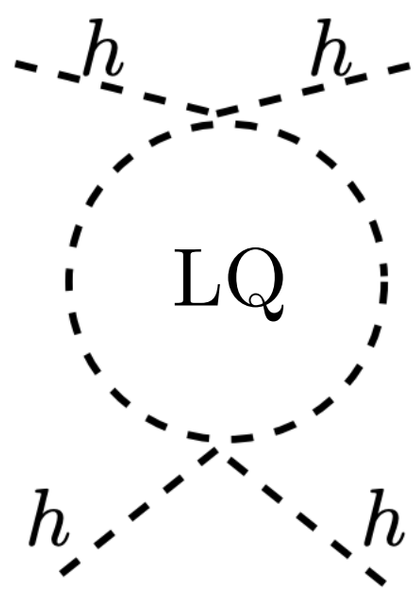
$$V^{\rm SM}(h) = -\frac{1}{2}m^2h^2 + \frac{\lambda}{8}h^4$$

$$\lambda \xrightarrow[\text{loops}]{} \lambda_{\rm eff}(\mu)$$

Franceschini, Strumia, Wulzer, JHEP 08 (2022) 229



LQ can save the day!



Bandyopadhyay, Mandal,
Phys. Rev. D 95 (2017) 3, 035007

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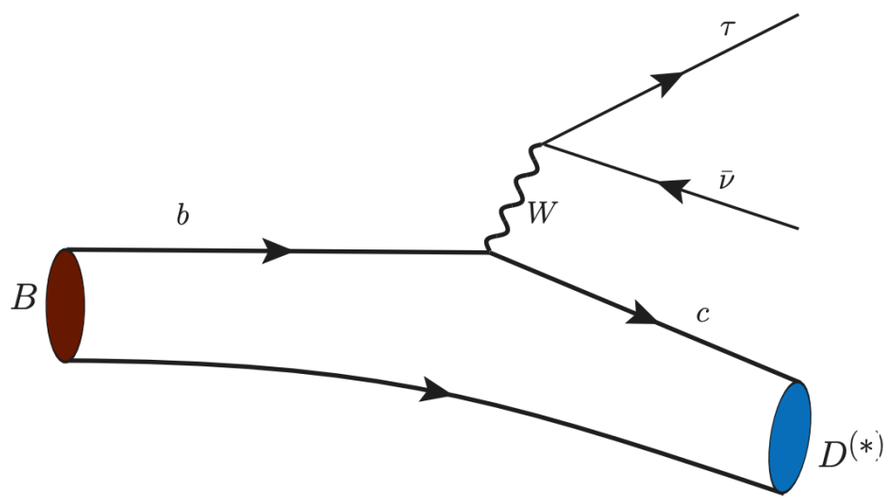
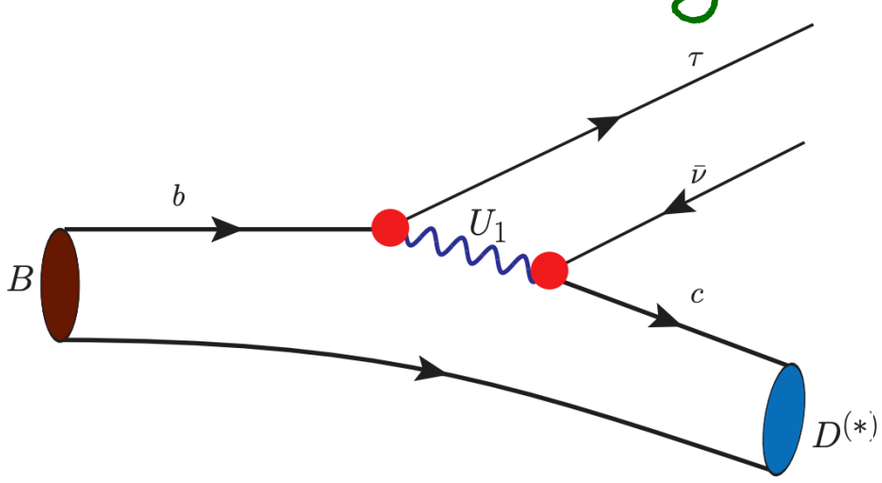
1.2) Pheno Motivations

- B Meson Decay Anomalies: Charged Current

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

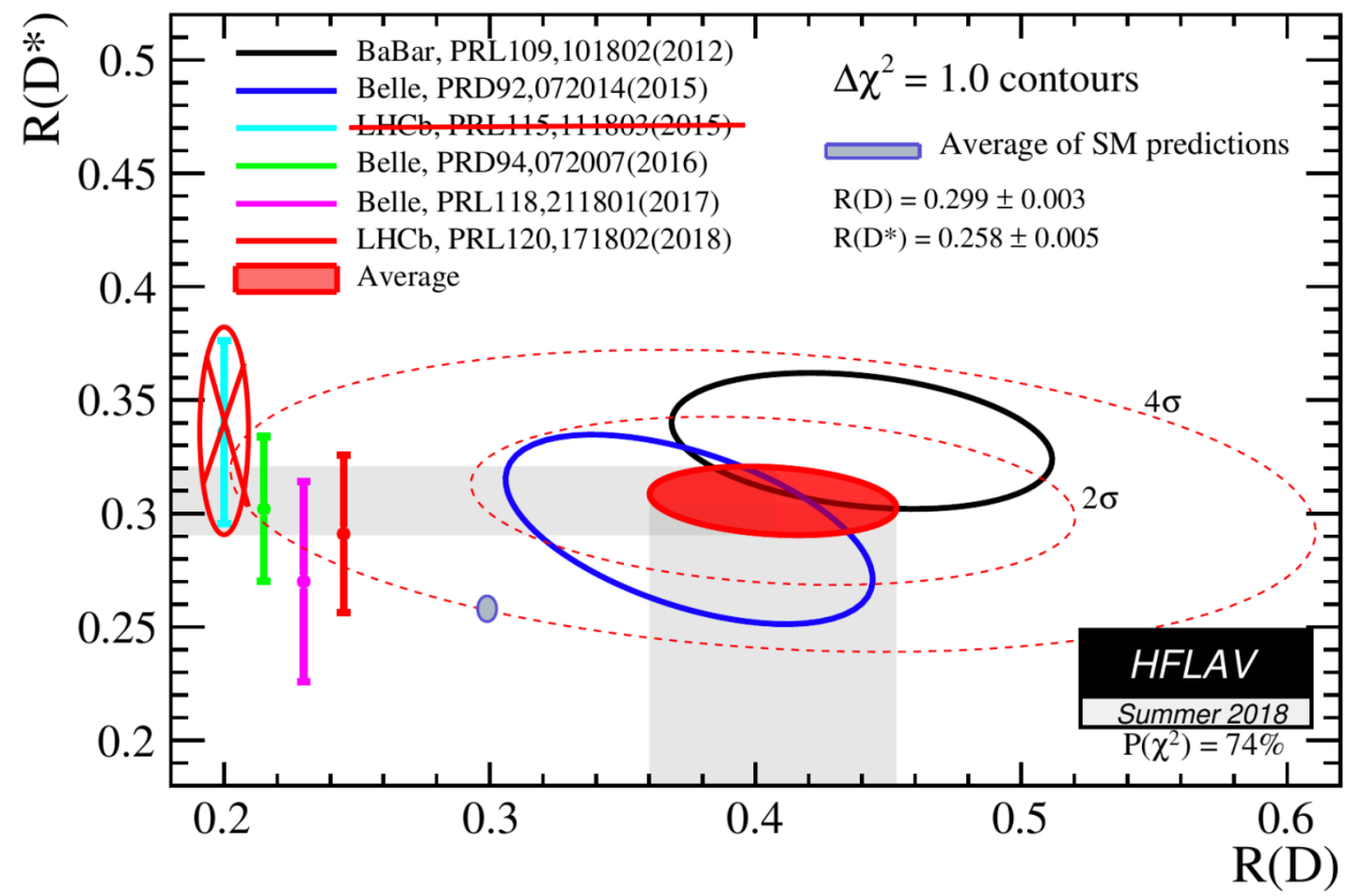


LQ can save the day!



Bhaskar, Das, Mandal, Mitra, Neeraj,
Phys. Rev. D 104 (2021) 3, 035016

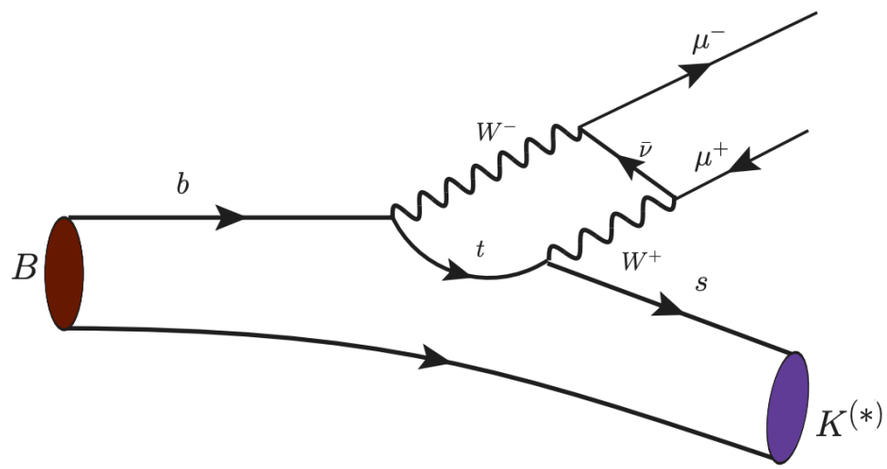
LHCb Collaboration, LHCb-PAPER-2022-039



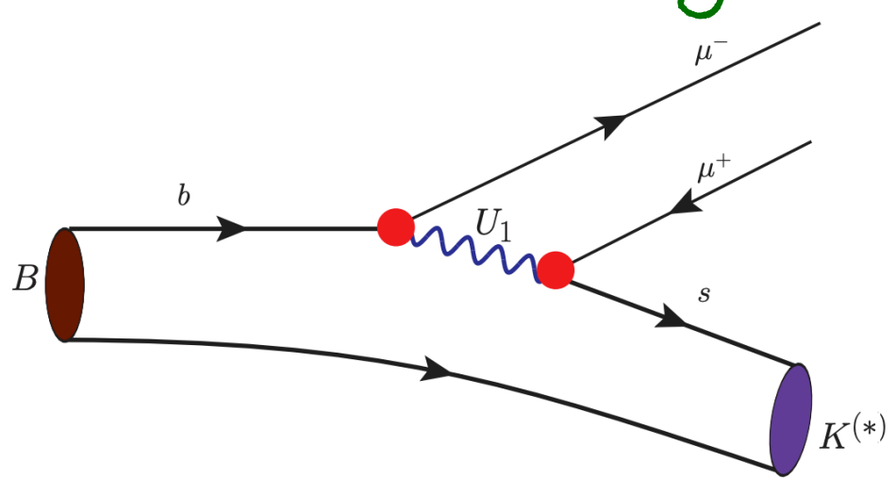
1.2) Pheno Motivations

- B Meson Decay Anomalies: Neutral Current

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

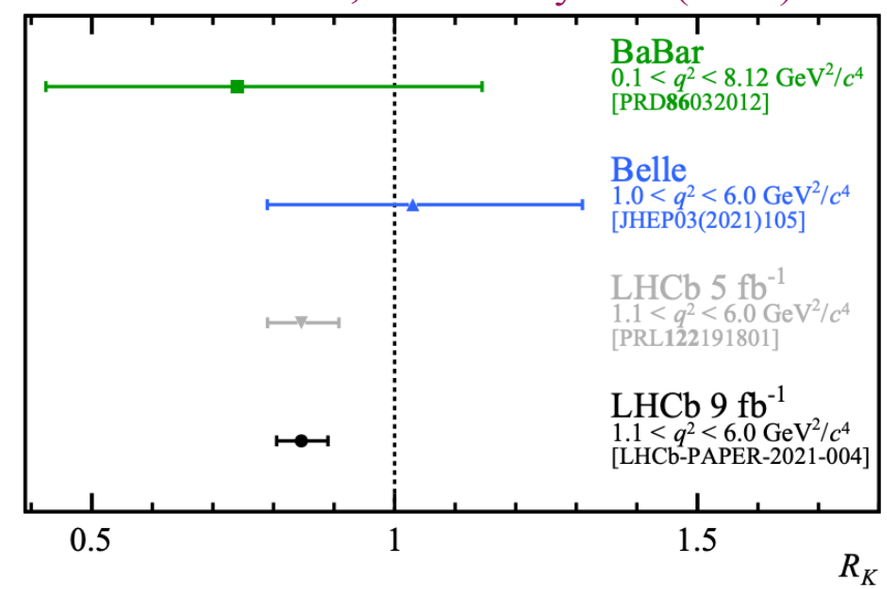


LQ can save the day!

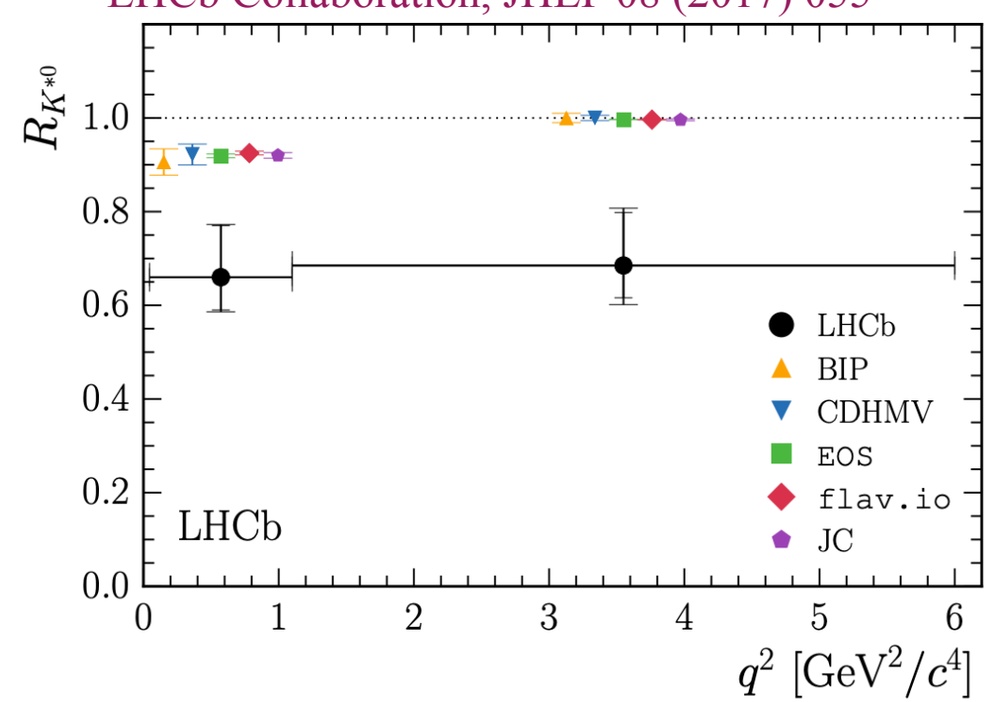


Bhaskar, Das, Mandal, Mitra, Neeraj, Phys. Rev. D 104 (2021) 3, 035016

LHCb Collaboration, Nature Phys. 18 (2022) 3



LHCb Collaboration, JHEP 08 (2017) 055



1.2) Pheno Motivations

- Muon g-2

$$a_\mu(\text{exp}) = 116\,592\,061(41) \times 10^{-11}$$

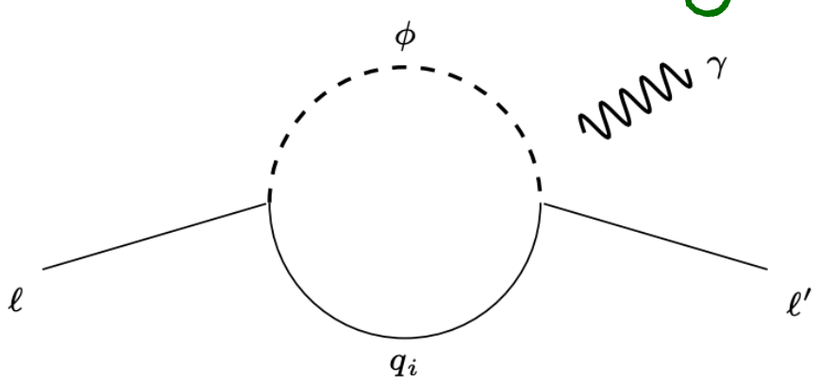
Muon g-2 Collaboration (BNL),
Phys. Rev. D 73 (2006) 072003

Muon g-2 Collaboration (FNAL),
Phys. Rev. Lett. 126 (2021) 14, 141801

$$a_\mu(\text{the}) = 116\,591\,810(43) \times 10^{-11}$$

Muon g-2 Theory Initiative,
Phys. Rept. 887 (2020) 1-166

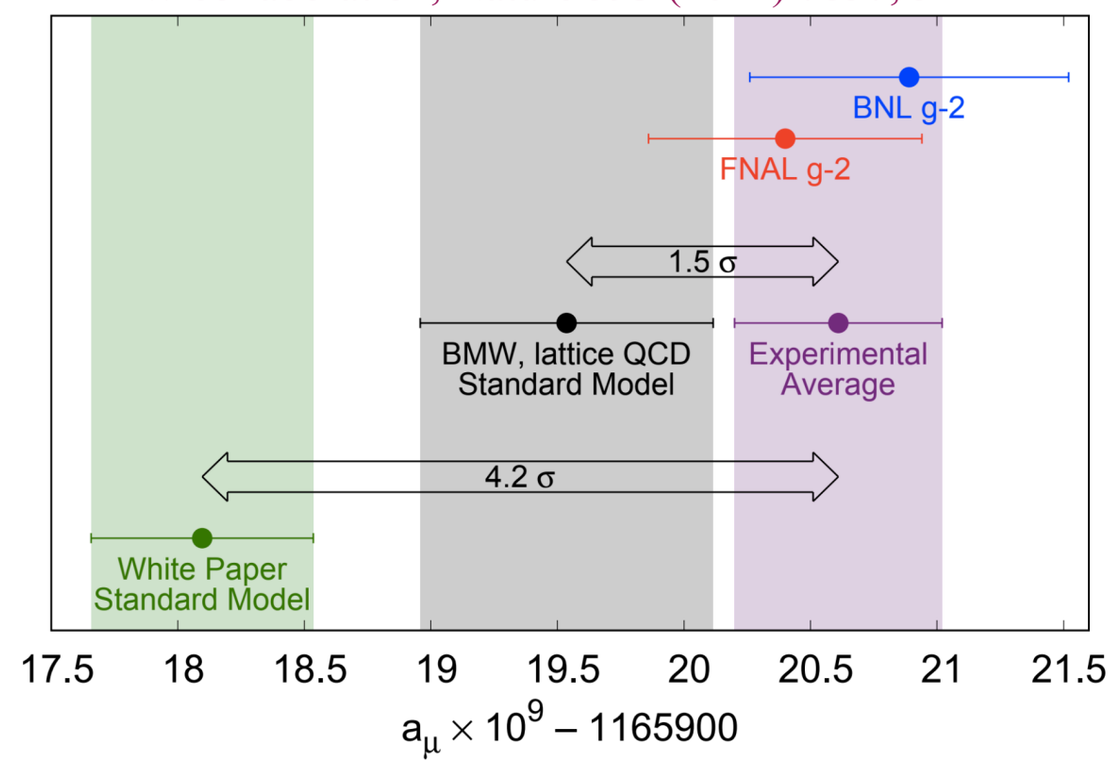
LQ can save the day!

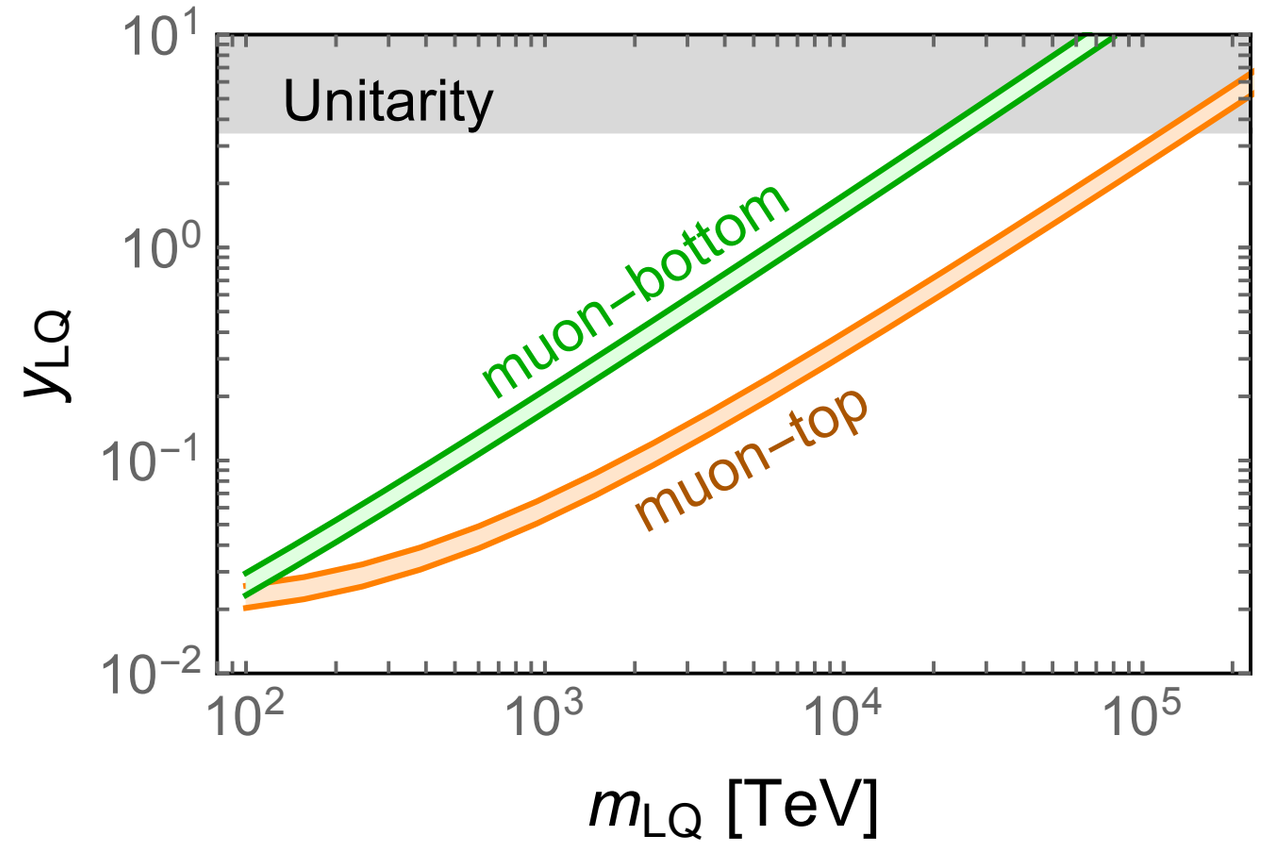


$$a_\mu \sim \frac{y_i^2 m_\mu m_i}{m_{\text{LQ}}^2}$$

Bigaran, Volkas, Phys. Rev. D 105 (2022) 1, 015002

BMW collaboration, Nature 593 (2021) 7857, 51

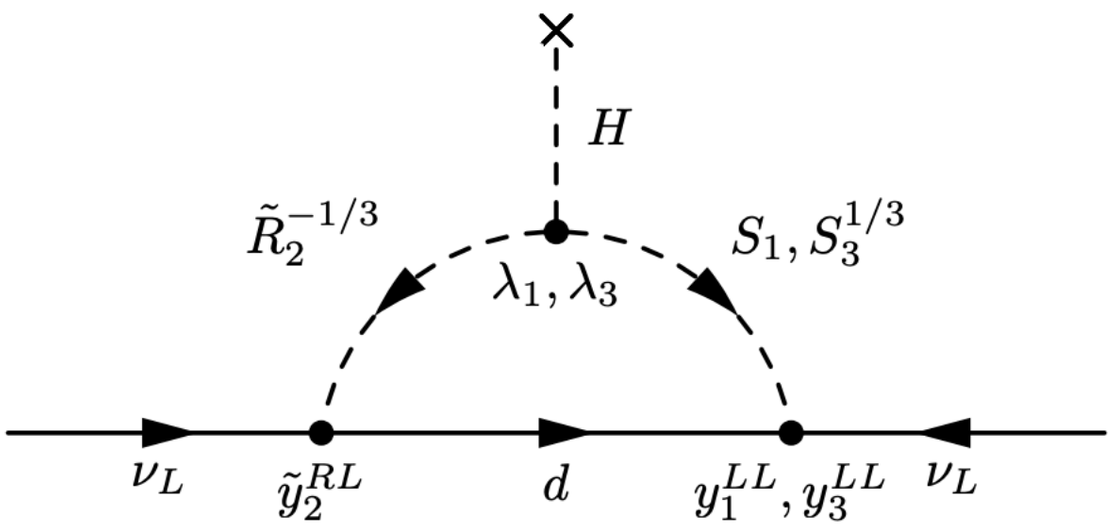




1.2) Pheno Motivations

- Neutrino Masses

$$\mathcal{L} \supset L\tilde{R}_2 d^c + LS_{1,3}Q + \tilde{R}_2 S_{1,3} H^\dagger$$



$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$SU(3)_c$
$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}^*$	$SU(2)_L$
$\frac{1}{6}$	$\frac{1}{3}$	$-\frac{1}{2}$	$U(1)_Y$
1	-1	0	B
-1	-1	0	L

$$(m_N)_{\alpha\beta} \approx \frac{3\sin 2\theta_{1,3}}{32\pi^2} \log \frac{m^2_{\mathrm{LQ}\,2}}{m^2_{\mathrm{LQ}\,1}} \sum_{\delta=1,2,3} m_\delta \left\{ (\tilde{y}_2^{RL})_{\delta\alpha} (y_{1,3}^{LL})_{\delta\beta} + (\tilde{y}_2^{RL})_{\delta\beta} (y_{1,3}^{LL})_{\delta\alpha} \right\}$$

Dorsner, Fajfer, Kosnik,
Eur. Phys. J. C 77 (2017) 6, 417

$m_\delta \propto m_d$ chiral flip!

$\sin 2\theta_{1,3} \propto \lambda_{1,3}$ L violation!

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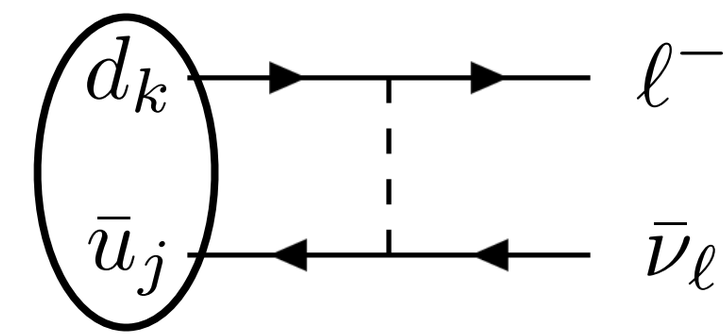
2.1) Current Constraints

Crivellin, Muller, Schnell,
Phys. Rev. D 103 (2021) 11, 115023,
Phys. Rev. D 104 (2021) 5, 055020

- Mesons

$$\mathcal{H}_{\rm eff}^{\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{jk} \hat{C}_{jk}^{e\nu} \left[\bar{u}_j \gamma^\mu P_L d_k\right] \left[\bar{e}\gamma_\mu P_L \nu_e\right]$$

Semileptonic Decays



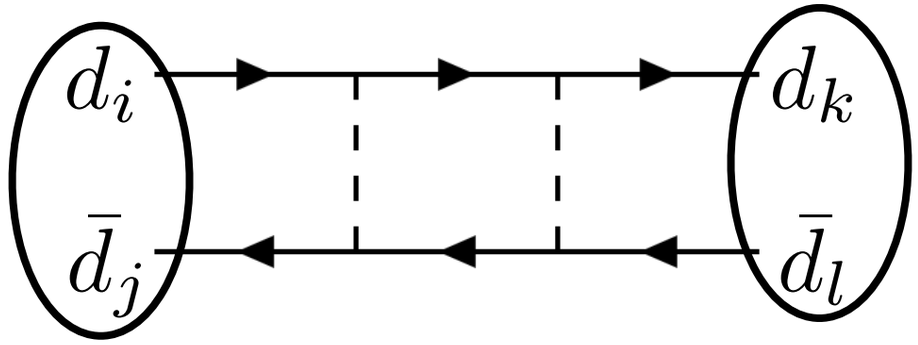
$\pi^-, K^- ...$

$$\left.\frac{K \to \mu\nu}{K \to e\nu}\right|_{\rm exp} = 0.9978(18)$$

$$\left.\frac{\pi \to \mu\nu}{\pi \to e\nu}\right|_{\rm exp} = 1.0010(9)$$

$$\vdots$$

Mixing



$K^0, B^0 ...$

$$\Delta m_K = 3.484(6) \times 10^{-12}\,\text{MeV}$$

$$\Delta m_B = 3.337(33) \times 10^{-10}\,\text{MeV}$$

$$\vdots$$

APV

$$\mathcal{L}_{S.M.}^{PV} = \frac{G_F}{2\sqrt{2}} g_A^e \bar{e}\gamma_\mu\gamma_5 e \sum_f g_V^f \bar{f}\gamma^\mu f$$

$$\mathcal{L}_{NEW}^{PV} = \frac{4\pi\kappa^2}{\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_f h_V^f \bar{f}\gamma^\mu f$$

$$\Delta Q_W^P = \zeta(2h_V^u + h_V^d)$$

$$\Delta Q_W^N = \zeta(h_V^u + 2h_V^d)$$

$$\Delta Q_W^e = \zeta h_V^e \quad ,$$

$$\zeta = \frac{8\sqrt{2}\pi\kappa^2}{\Lambda^2 G_F}$$

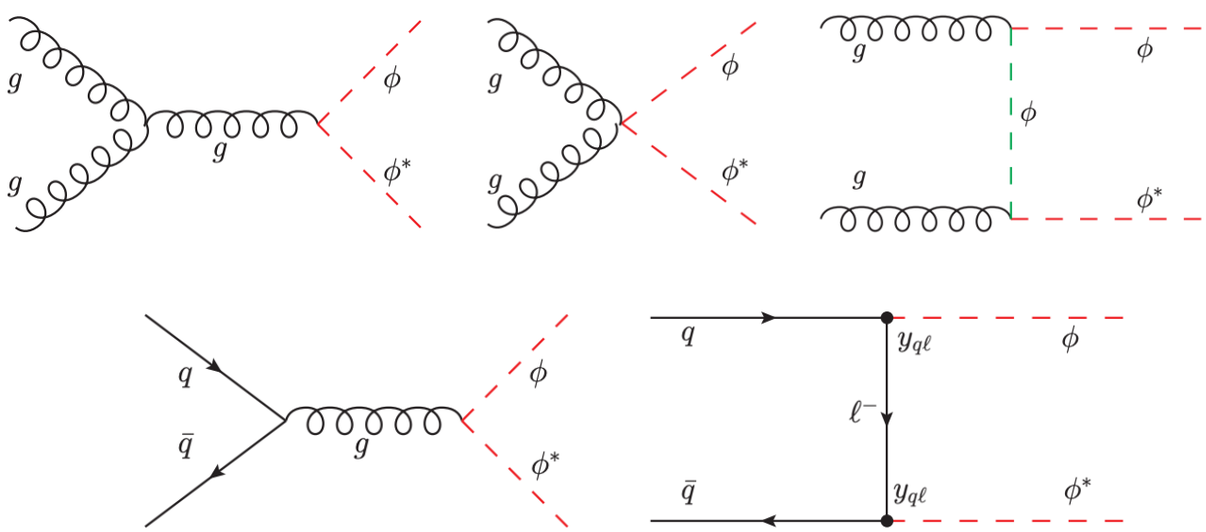
2.1) Current Constraints

- LHC

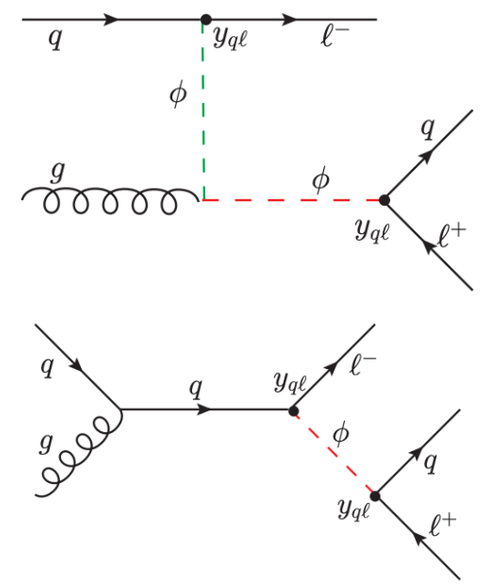
Nirmal Raj, Phys. Rev. D 95 (2017) 1, 015011

Diaz, Schmaltz, Zhong, JHEP 10 (2017) 097

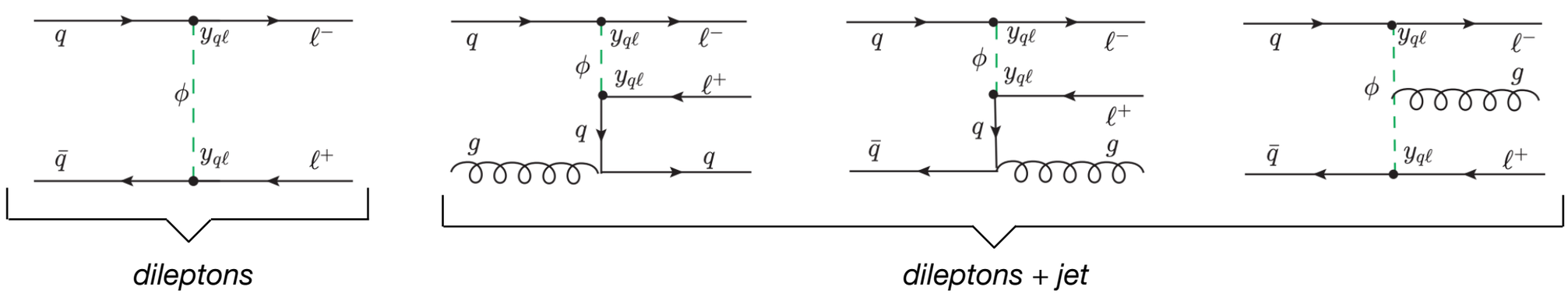
Double Production



Single Production

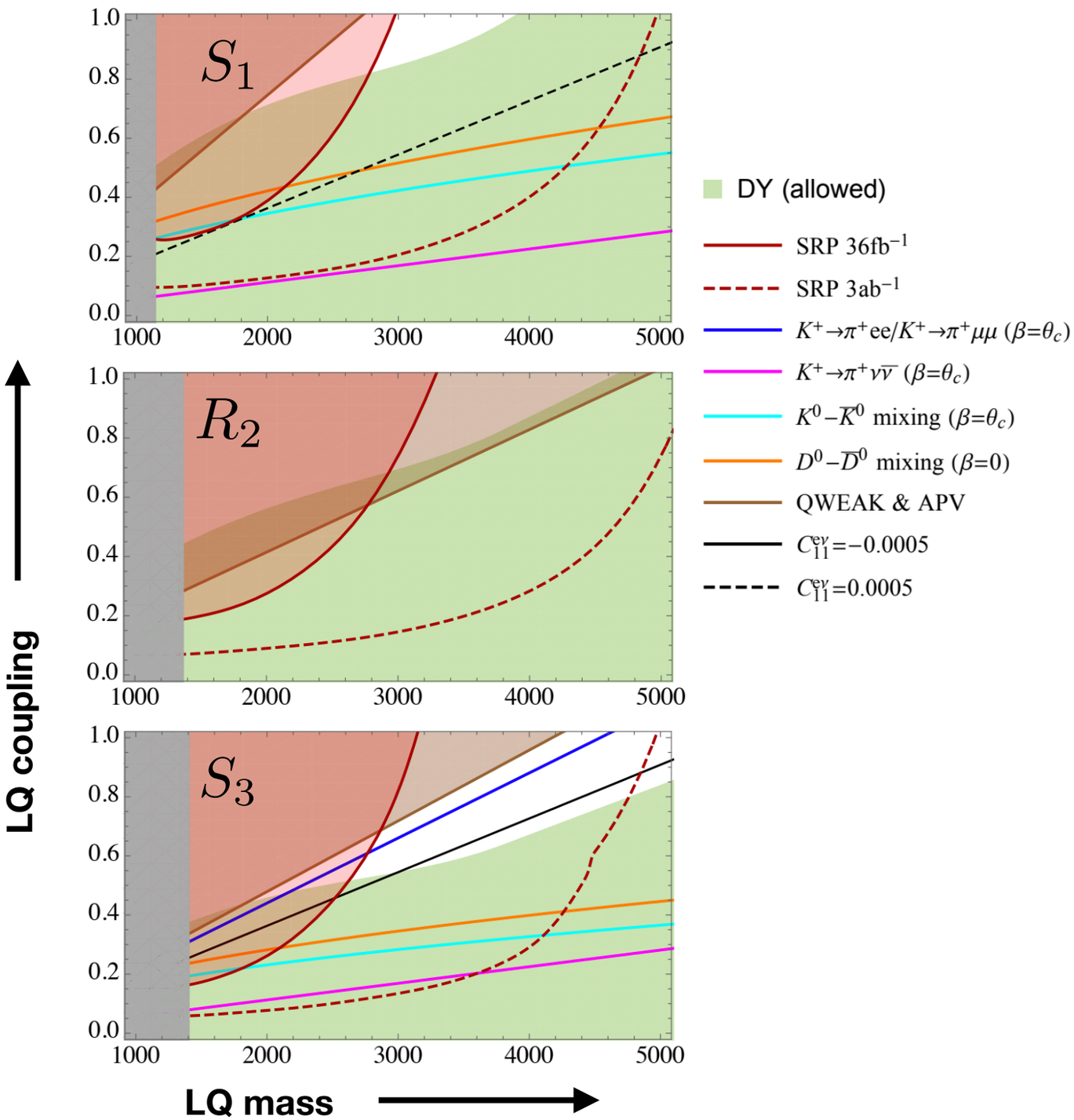


Drell-Yan



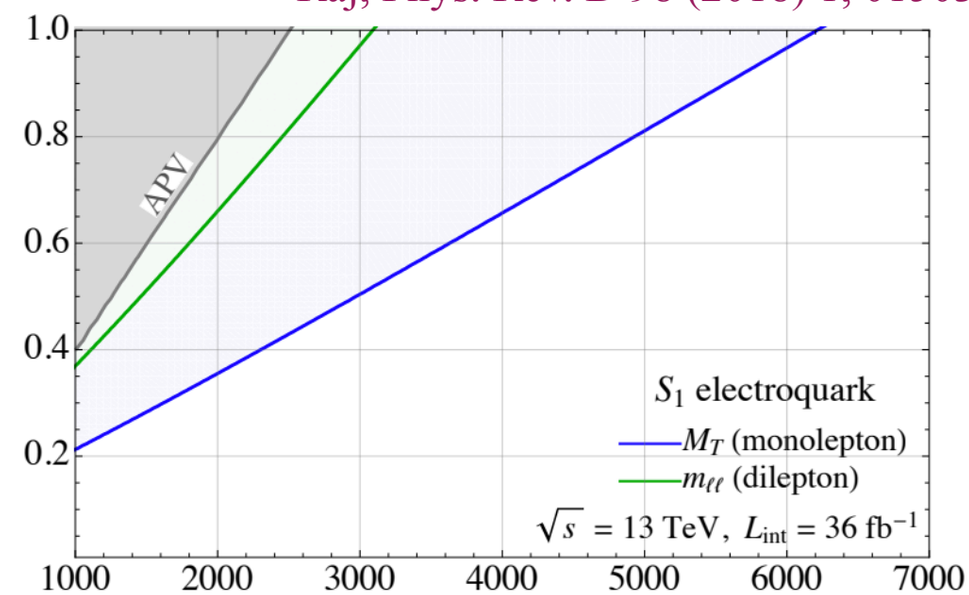
2.1) Current Constraints

- First Generation LQ: up/down-LQ-electron

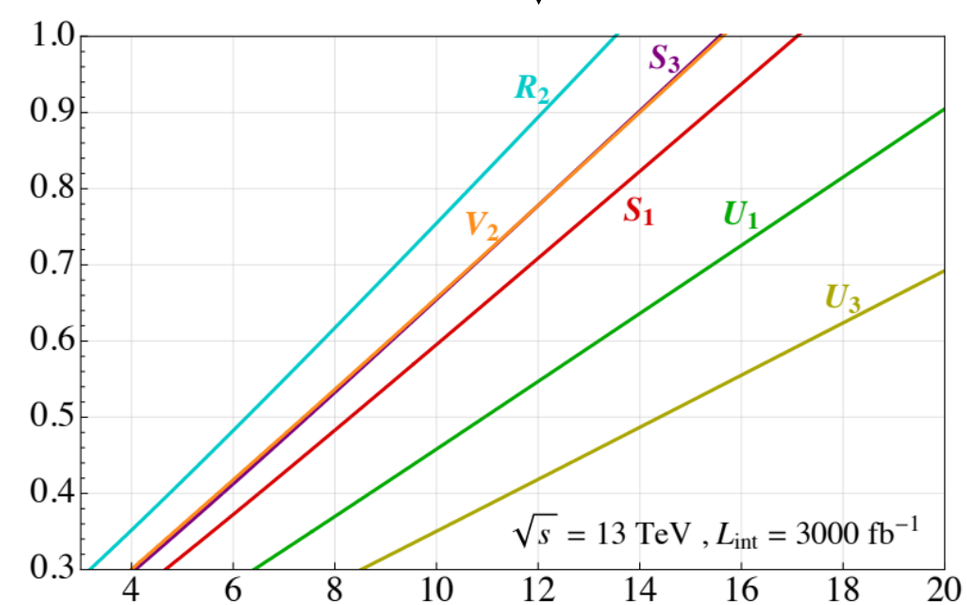


Crivellin, Muller, Schnell,
Phys. Rev. D 103 (2021) 11, 115023

Bansal, RC, Delgado, Kolda, Martin,
Raj, Phys. Rev. D 98 (2018) 1, 015037



HL-LHC



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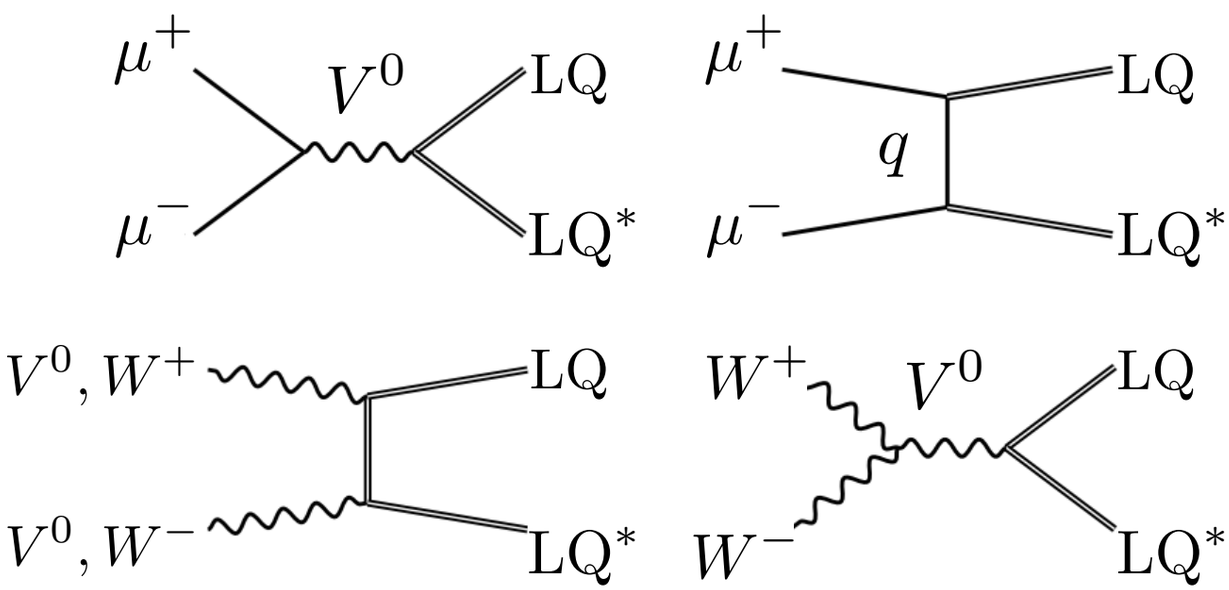
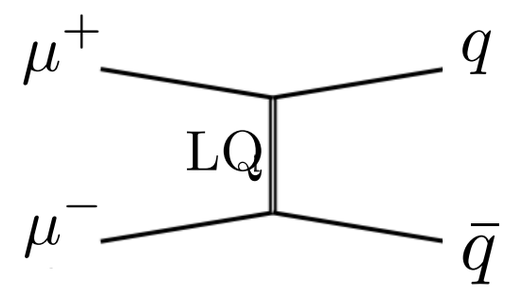
2.2) Muon Colliders

- Production Channels

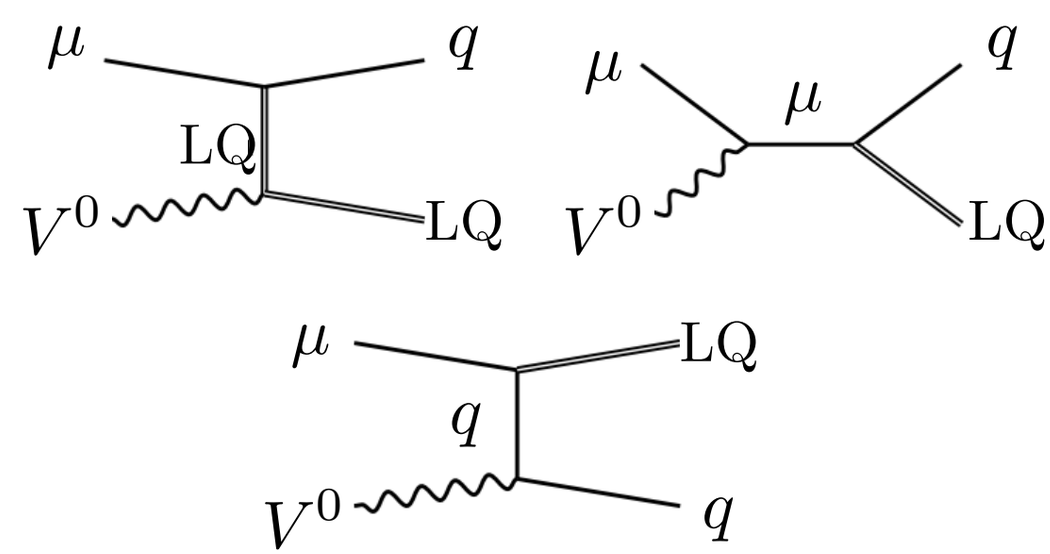
Double Production



Drell-Yan

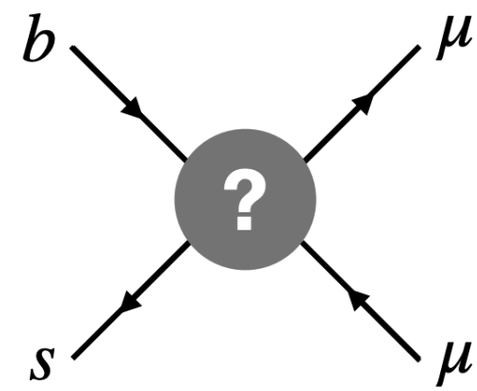


Single Production



2.2) Muon Colliders

- RK: Minimal Scenario

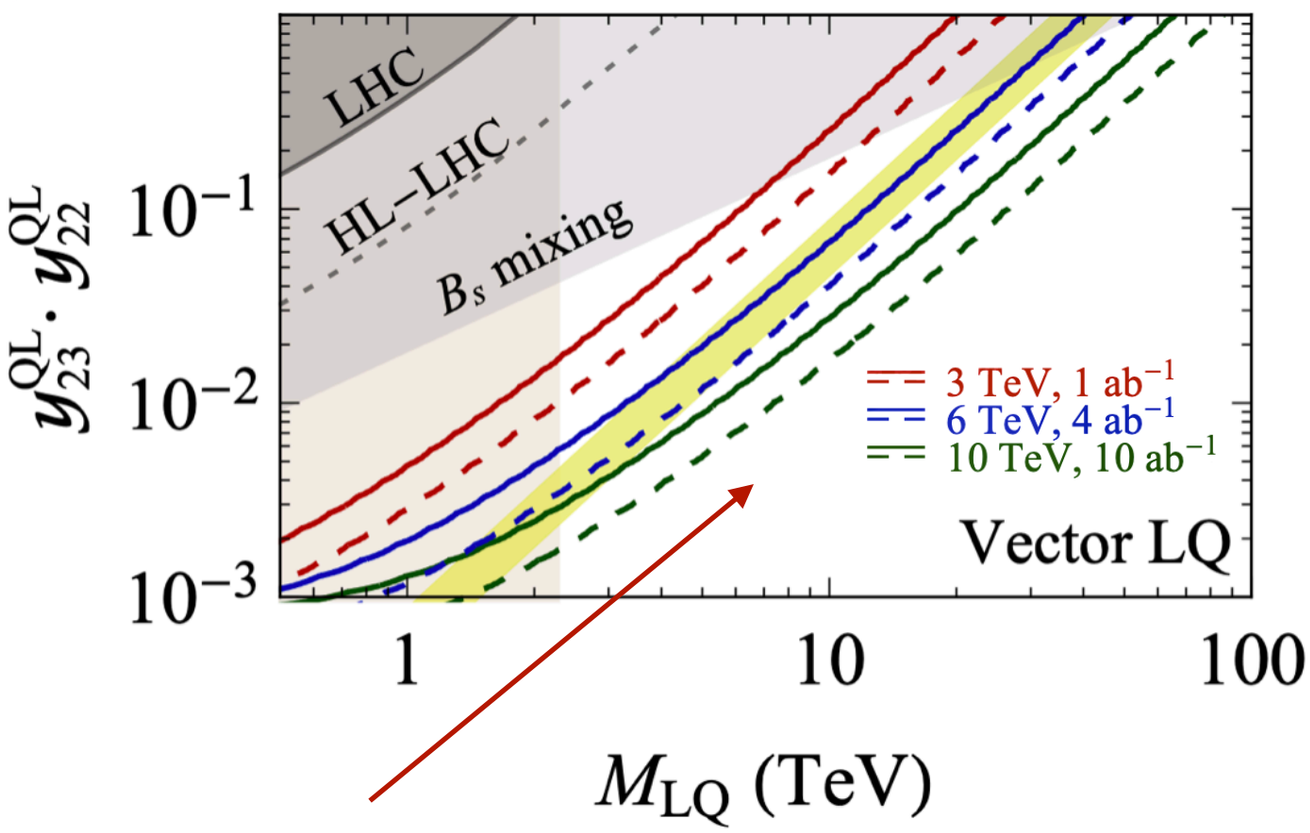


$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma_\nu s_L)(\bar{\mu}_L\gamma^\nu\mu_L)$$

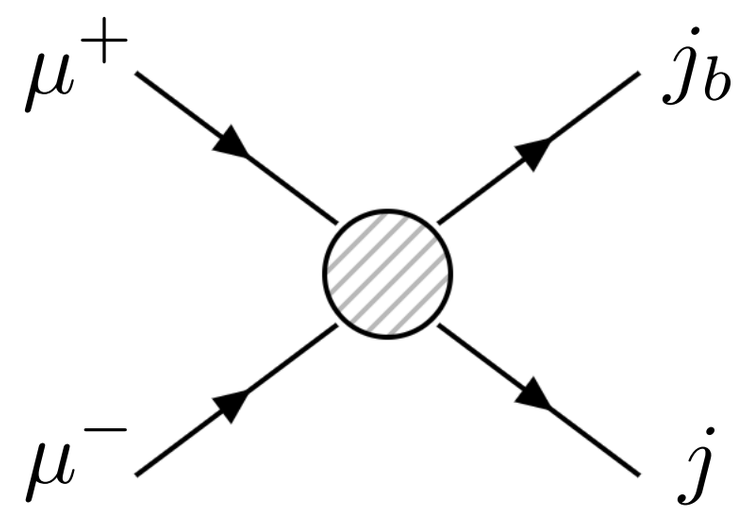
$$\Lambda \sim 40\,\mathrm{TeV}$$

$$\mathcal{L}_{U_1} = -M_{U_1}^2\,|U_1|^2 + y_{i\alpha}^{\mathrm{LQ}}\overline{Q^i}\gamma_\mu L^\alpha U_1^\mu + \mathrm{h.c.}$$

Huang, Jana, Queiroz, Rodejohann,
Phys. Rev. D 105 (2022) 1, 015013



$$C_9^\mu = -C_{10}^\mu = \frac{\pi}{\sqrt{2}G_{\mathrm{F}}M_{U_1}^2\alpha}\left(\frac{y_{32}^{\mathrm{LQ}}y_{22}^{\mathrm{LQ}*}}{V_{tb}V_{ts}^*}\right)$$



conservative tagging performance

$\epsilon_b = 70\%$ $\epsilon_{uds} = 1\%$ $\epsilon_c = 10\%$

Probing the U1 LQ scenario for RK requires 10 TeV muon collider

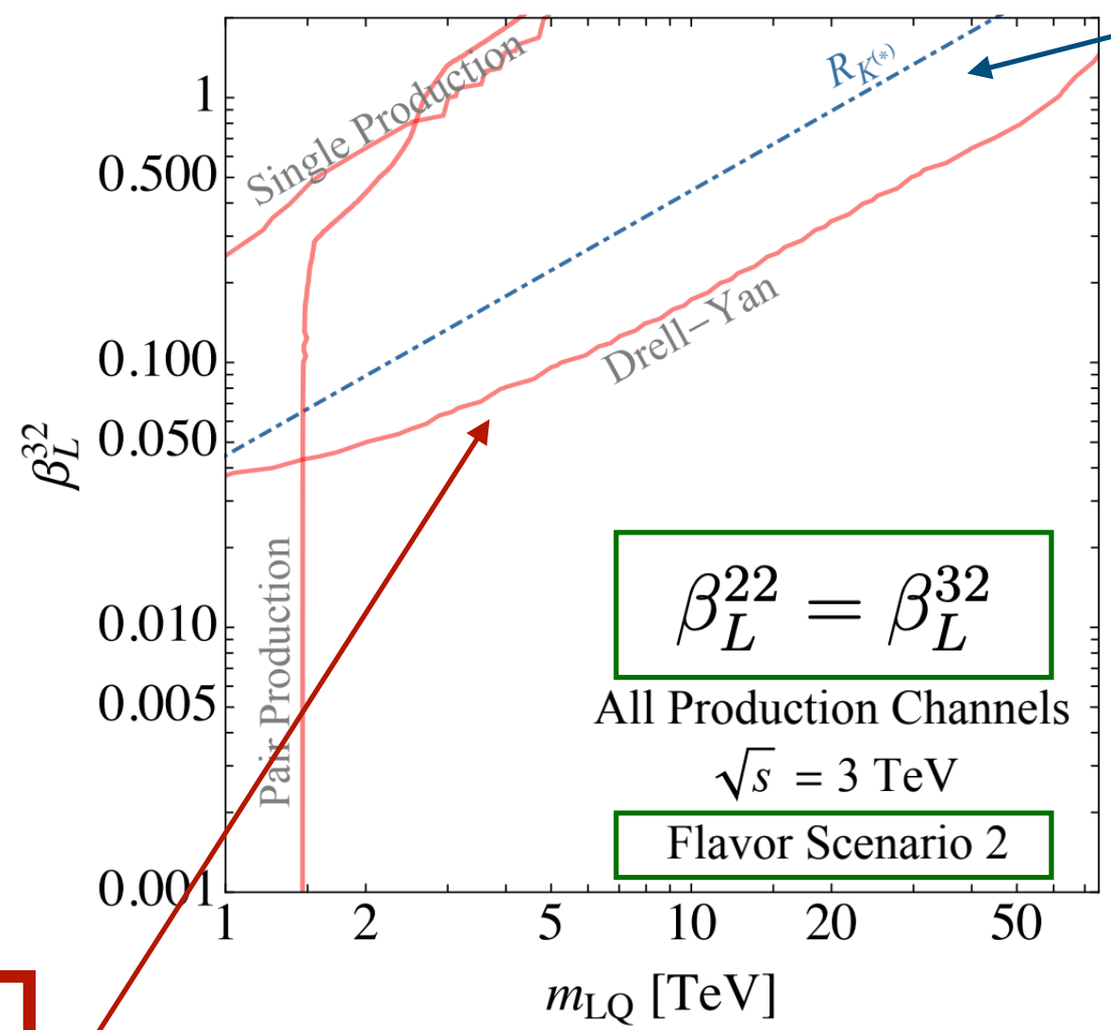
2.2) Muon Colliders

- RK: Democratic Couplings

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}}\beta_L^{32}\left[\bar{b}_L\gamma_\alpha\mu + \left(V_{ub}^*\bar{u}_L + V_{cb}^*\bar{c}_L + V_{tb}^*\bar{t}_L\right)\gamma_\alpha\nu_\mu\right]U_1^\alpha$$

best fit

$$\frac{\beta_L^{22}\beta_L^{32}}{m_{\rm LQ}^2} = 1.98\times10^{-3}\ {\rm TeV}^{-2}$$

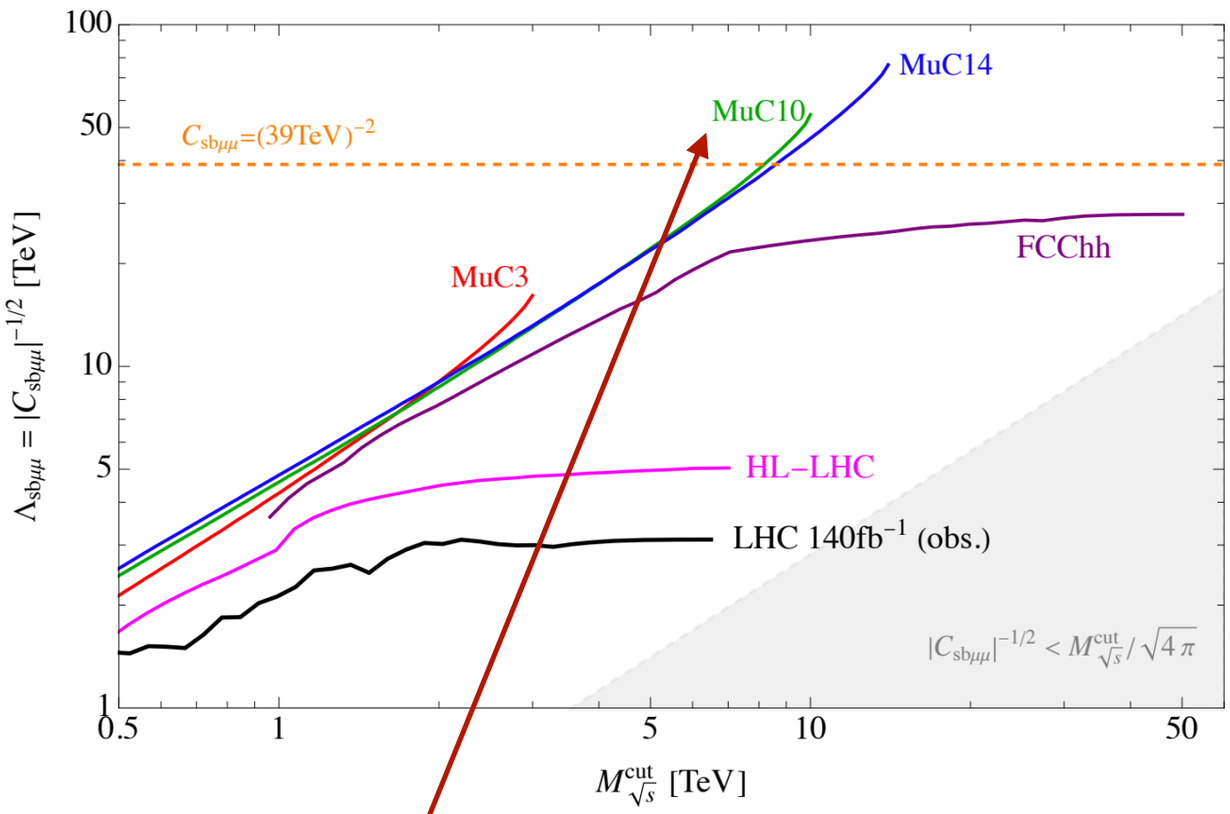


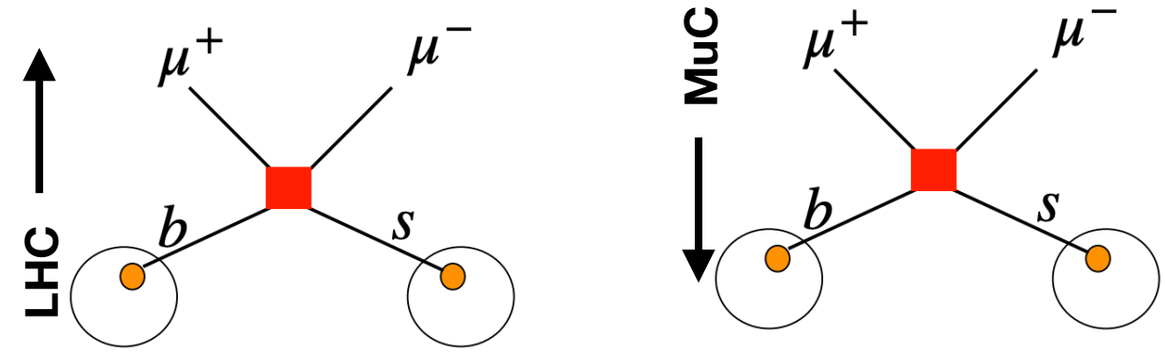
Asadi, RC, Cesarotti, Homiller, JHEP 10 (2021) 182

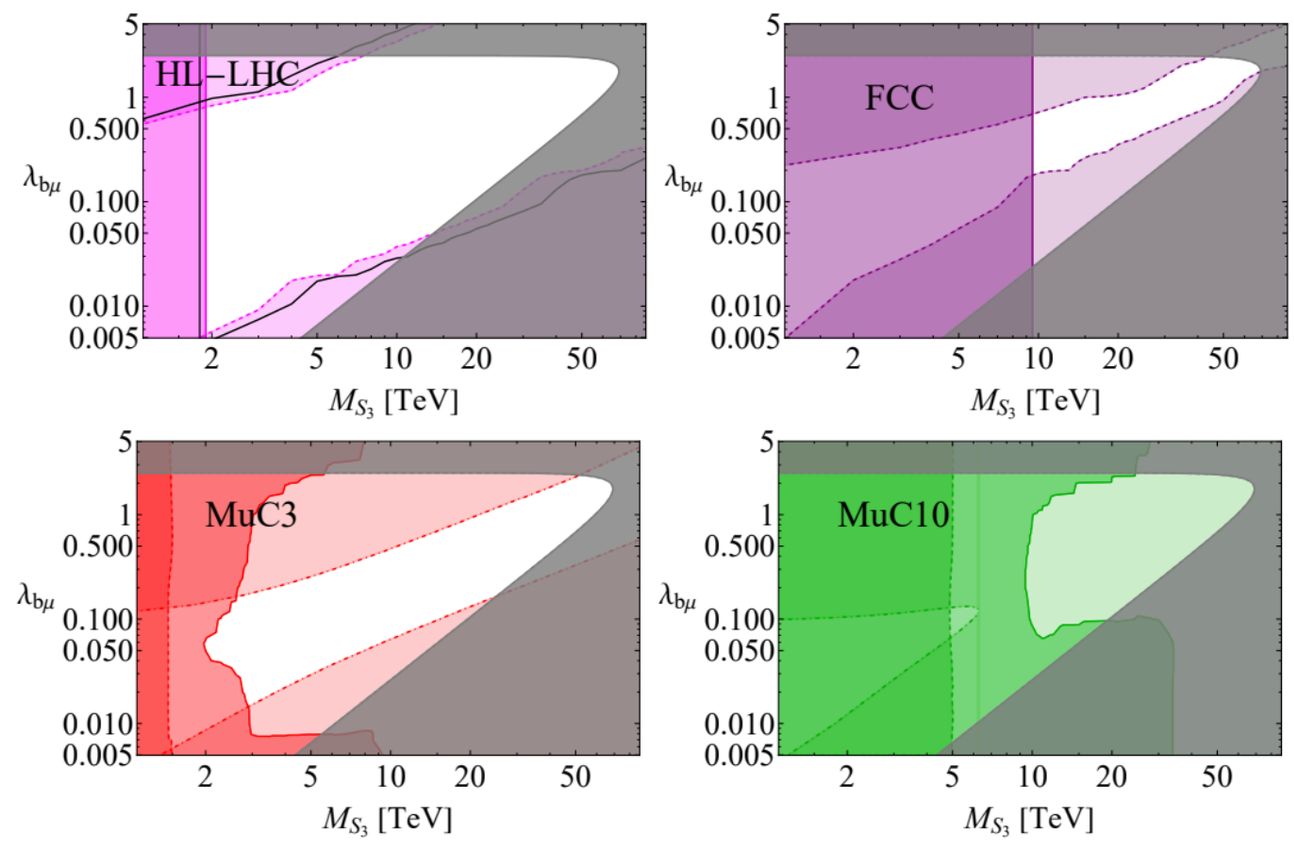
A 3 TeV Muon Collider will entirely probe this scenario for RK

2.2) Muon Colliders

- RK:







Azatov, Garosi, Greljo, Marzocca, Salko, Trifinopoulos, JHEP 10 (2022) 149

The 10 TeV Muon Collider will entirely probe RK

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Summary

1. LQ are awesome! They appear in multiple theoretical scenarios

2. LQ are useful! They can provide BSM explanations to multiple anomalies

3. Muon colliders can produce lots of LQ: Parameter space for some anomalies fully probed!

Thanks!