Probing muon-philic forces at a Muon Collider

Snowmass EF08 Informal Meeting

14/May/2021

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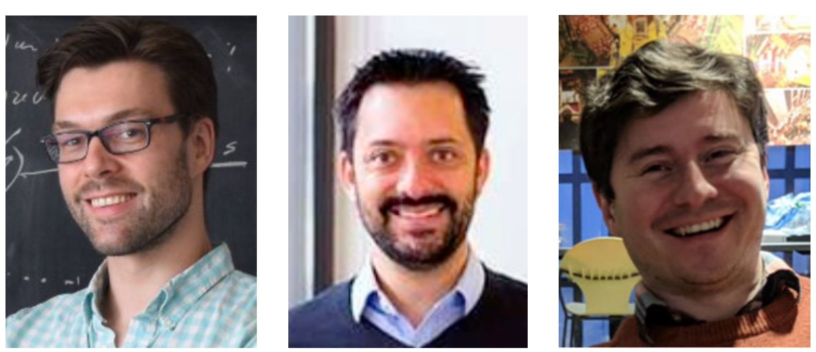
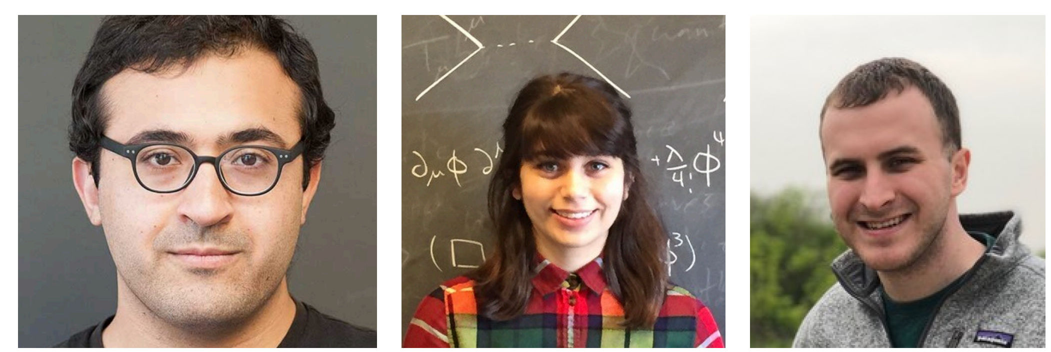
Perimeter Institute for Theoretical Physics



__RC__, David Curtin,
Yonatan Kahn, Gordan Krnjaic,
arXiv:2006.16277, arXiv:2101.10334



Pouya Asadi, __RC__,
Cari Cesarotti, Samuel Homiller,
arXiv:2104.05720

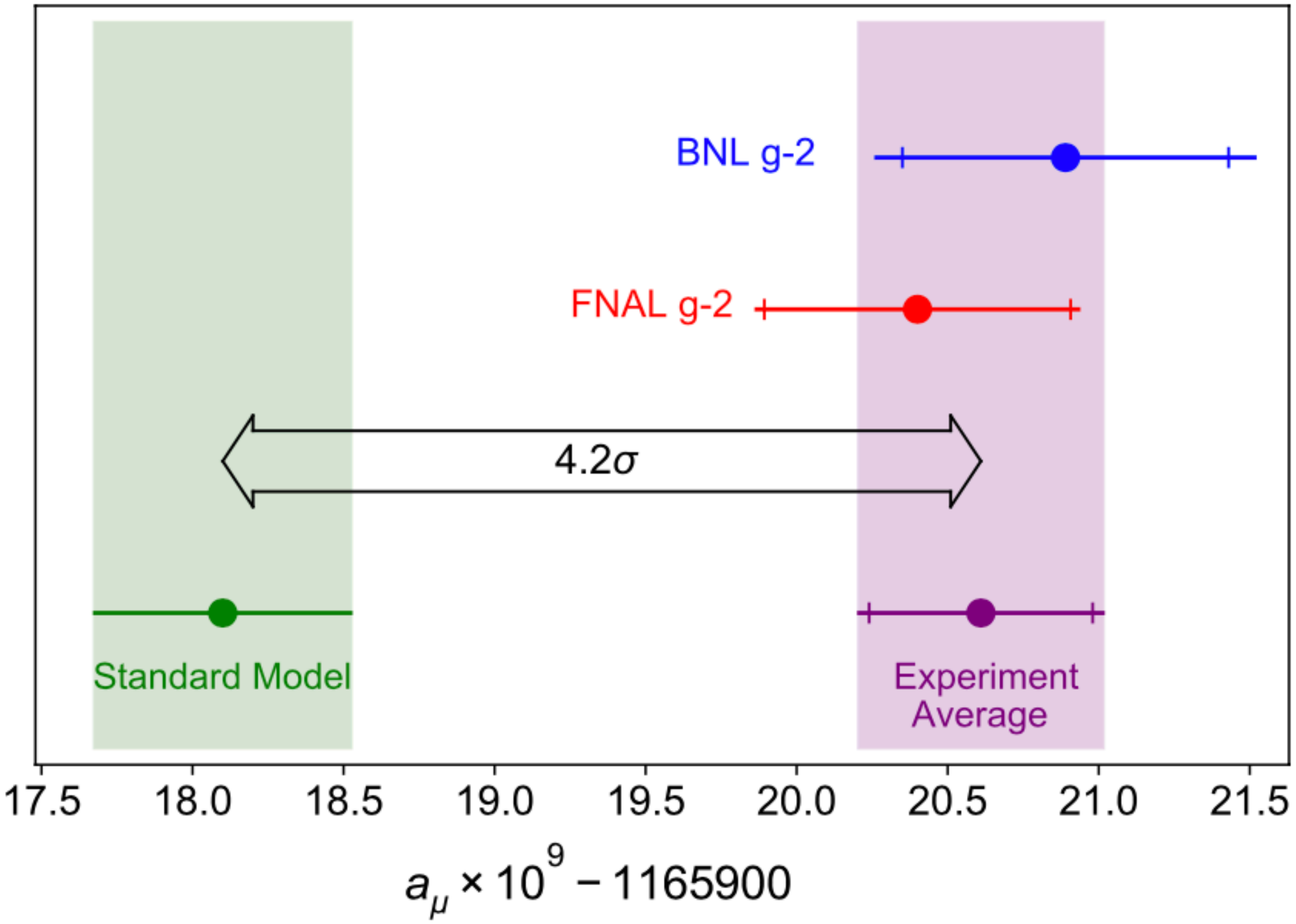
Outline

1. Light NP explanations for $(g-2)_\mu$

2. Vector leptoquark explanation for R(K)

1. Light NP explanations for (g-2)μ

- Status of (g-2)μ



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

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

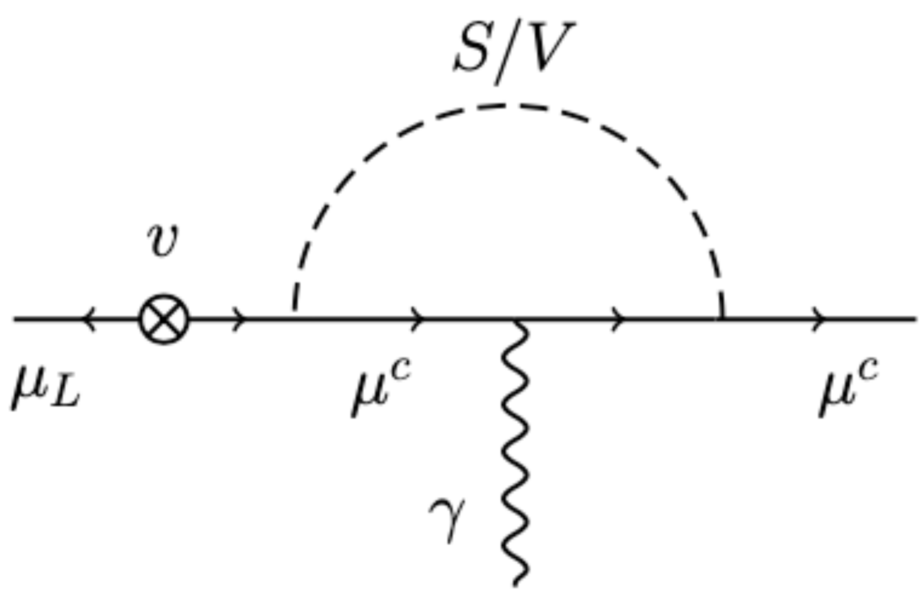
Muon g-2 Collaboration (FNAL), Phys. Rev. Lett. 126 (2021) 14, 141801

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

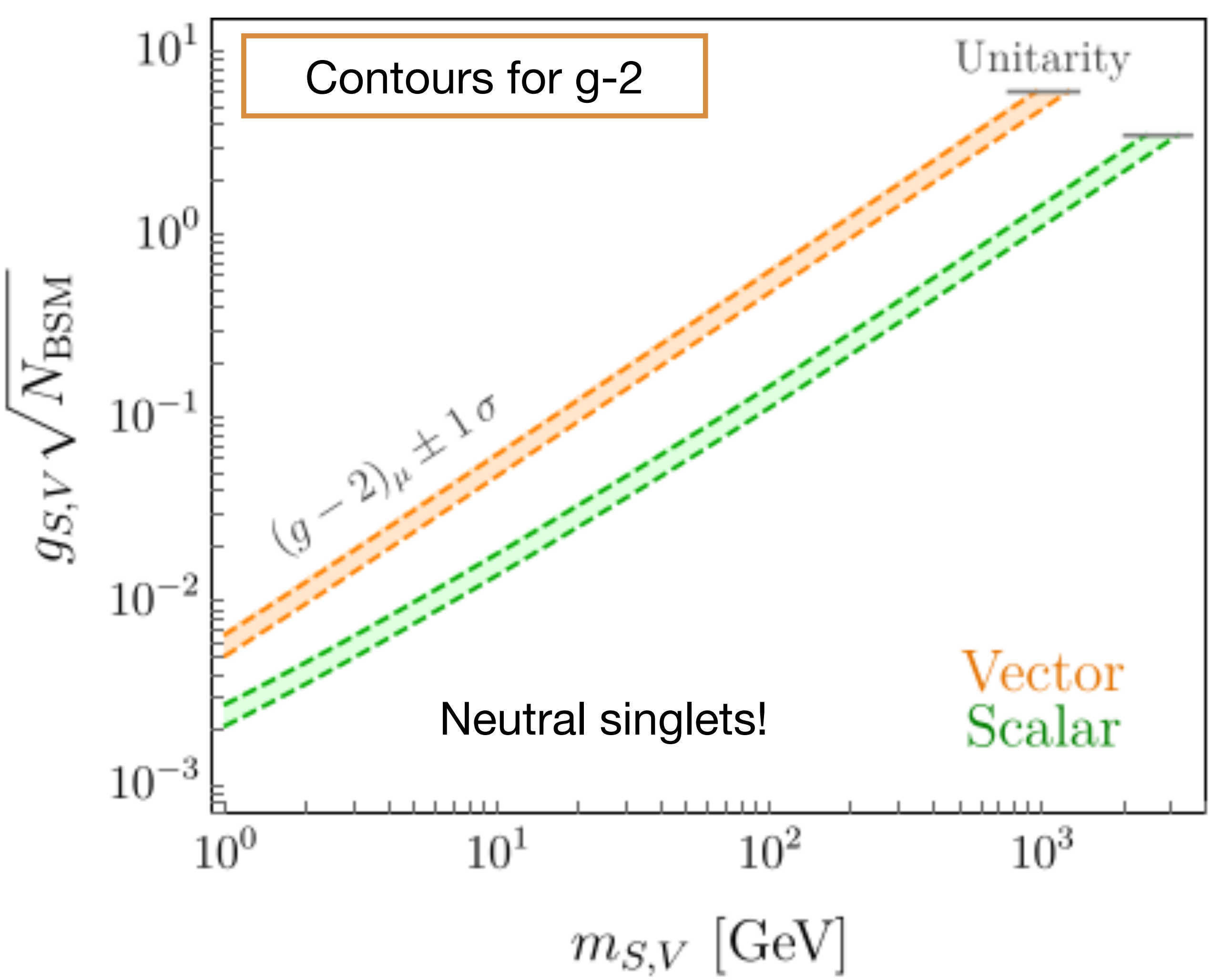
Muon g-2 Theory Initiative, Phys. Rept. 887 (2020) 1-166

1. Light NP explanations for (g-2)μ

- Singlet scenarios



$$\Delta a_\mu \sim N_{BSM} \frac{g^2}{4\pi^2} \frac{m_\mu^2}{M^2} C_{\rm loop}$$



Perturbative Unitarity

$$g_S^2 \leq \frac{4\pi}{N_{\rm BSM}} \qquad g_V^2 \leq \frac{12\pi}{N_{\rm BSM}}$$

Scalar — Vector

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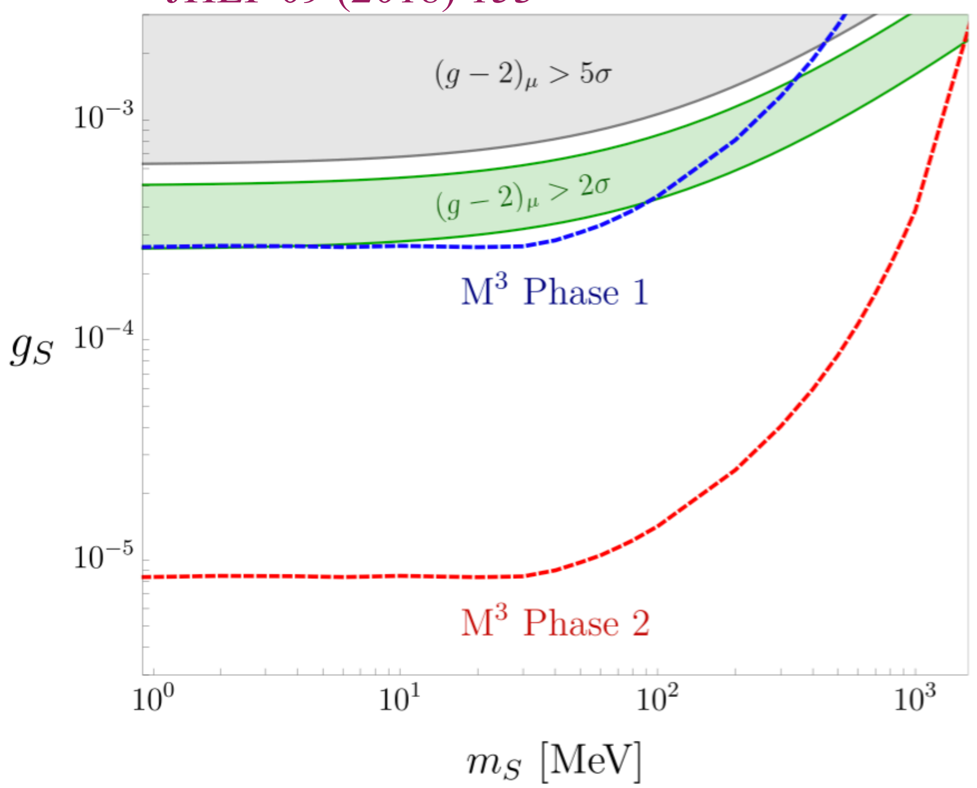
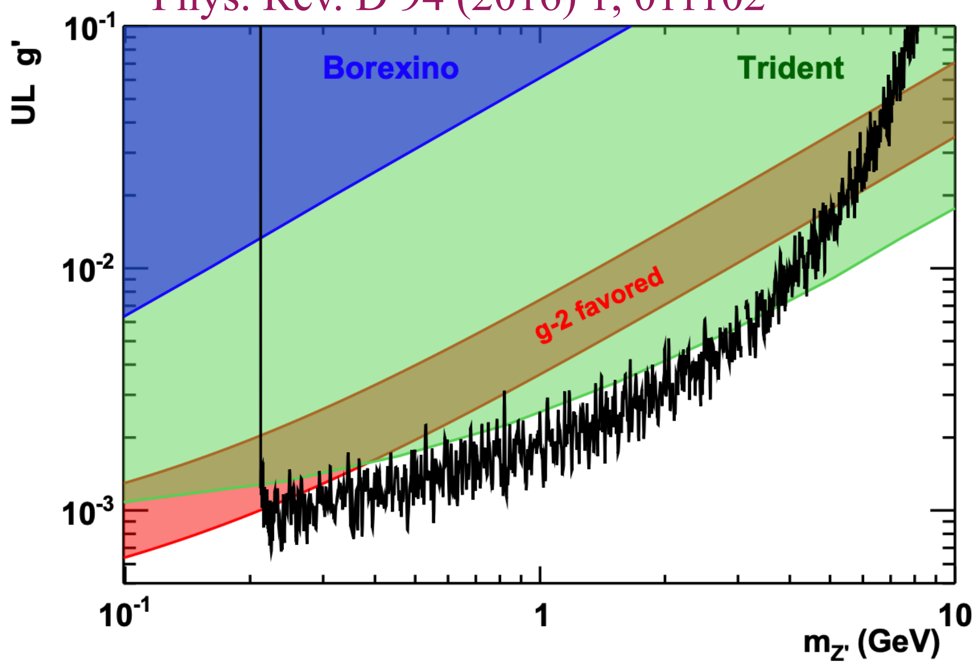
1. Light NP explanations for (g-2)μ

Kahn, Krnjaic, Tran, Whitbeck,
JHEP 09 (2018) 153



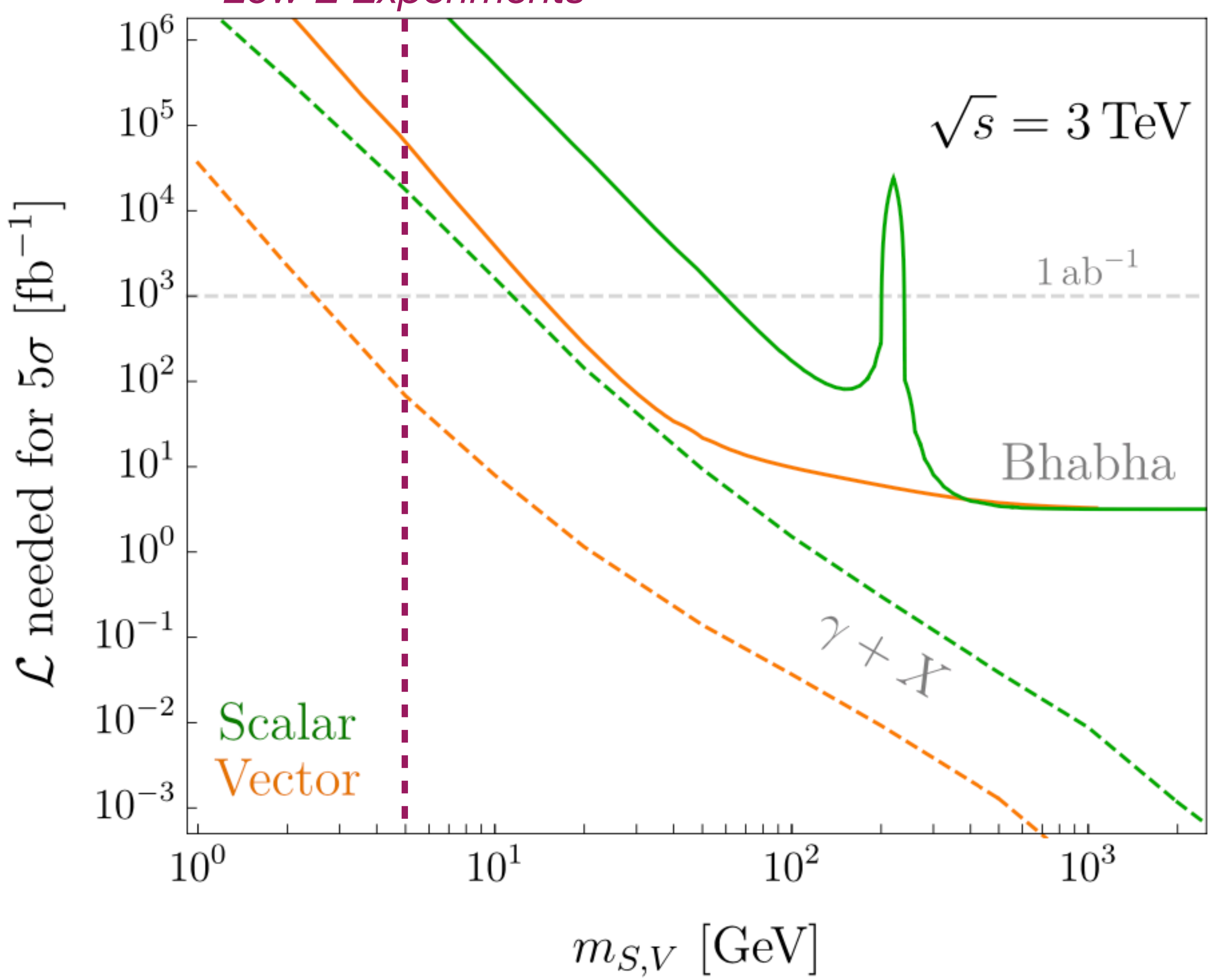
BaBar Collaboration,
Phys. Rev. D 94 (2016) 1, 011102



"Singlet scenarios"

A 3 TeV Muon Collider can probe all Singlet explanations for g-2

Low E Experiments



2. Vector leptoquark explanation for R(K)

- Status of R(K)

$$R_K^{\text{LHCb}} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

LHCb Collaboration, e-Print: 2103.11769

$$R_{K^*}^{\text{LHCb}} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 \end{cases}$$

LHCb Collaboration, JHEP 08 (2017) 055

$$R_K^{\text{SM}} = 1.0003 \pm 0.0001$$

Bobeth, Hiller, Piranishvili, JHEP 12 (2007) 040

Bordone, Isidori, Pattori, Eur. Phys. J. C 76 (2016) 8, 440

$$R_{K^*}^{\text{SM}} = \begin{cases} 0.92 \pm 0.02 \\ 1.00 \pm 0.01 \end{cases}$$

Alok et al., Phys. Rev. D 96 (2017) 9, 095009

Capdevila, Crivellin, Descotes-Genon, Matias, Virto, JHEP 01 (2018) 093

$$\sim 3.1\sigma$$

$$\begin{cases} \sim 2.2\sigma \\ \sim 2.4\sigma \end{cases}$$

2. Vector leptoquark explanation for R(K)

- Effective operator approach

$$\Delta\mathcal{L} \supset \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* (C_9 \mathcal{O}_9 + C_{10}\mathcal{O}_{10}) + \text{h.c.}$$

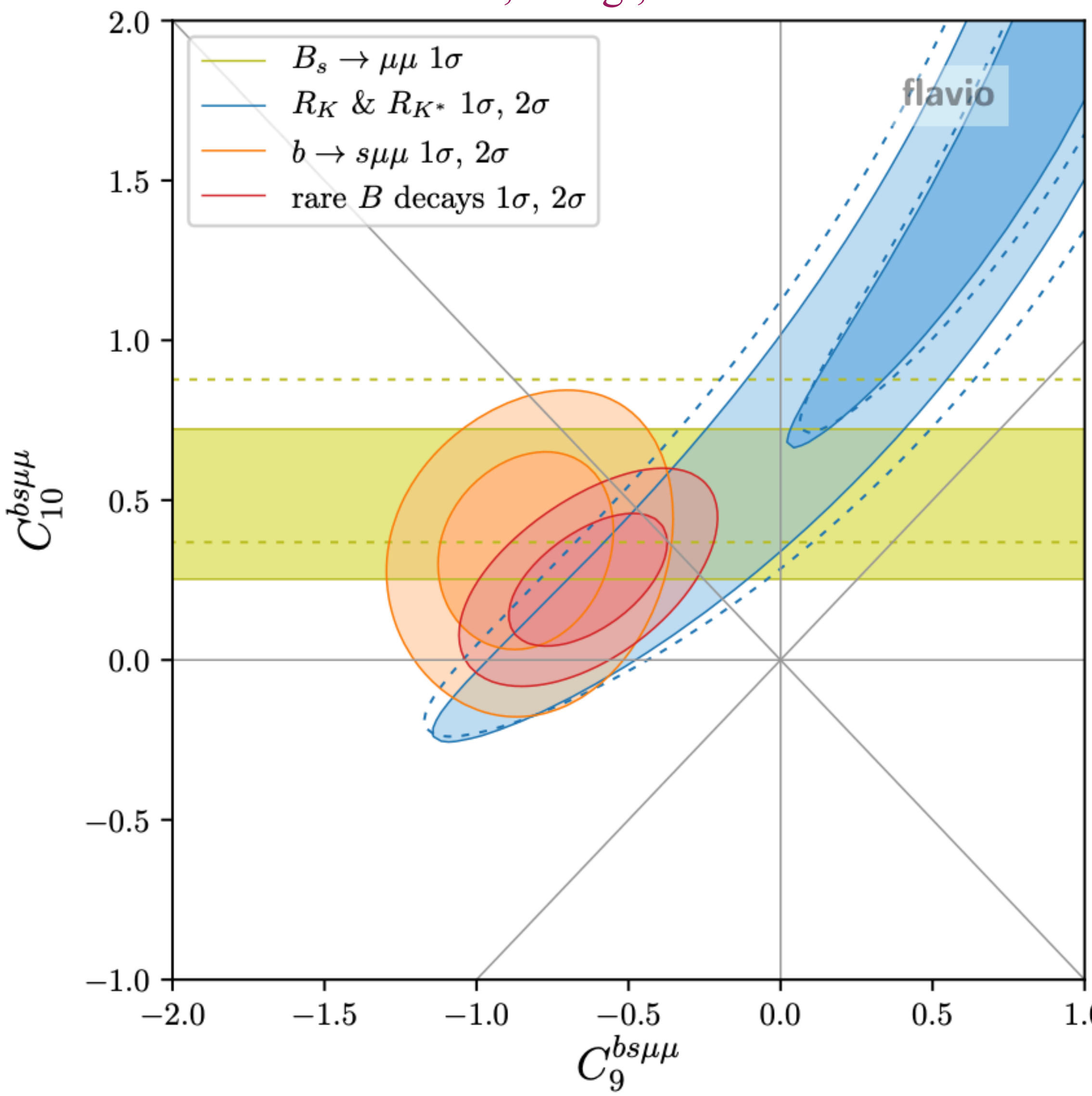
$$\mathcal{O}_9 = \frac{\alpha}{4\pi}(\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha \mu)$$

$$\mathcal{O}_{10} = \frac{\alpha}{4\pi}(\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

Pure left-hand best fit

$$C_9 = -0.43$$
$$C_{10} = -C_9$$

Altmannshofer, Stangl, e-Print: 2103.13370



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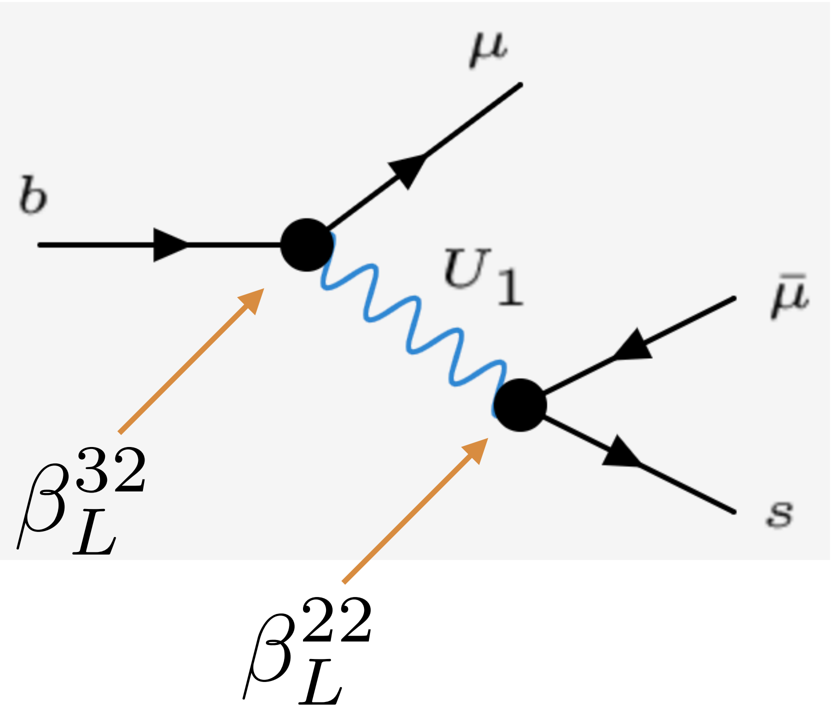
2. Vector leptoquark explanation for R(K)

- The U1 vector leptoquark

$$\mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}}\left[U_1^{\mu}\left(\beta_L^{ij}\bar{Q}_L^i\gamma_\mu L_L^j + \beta_R^{ij}\bar{d}_R^i\gamma_\mu e_R^j\right) + \text{h.c.}\right]$$

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



From best fit

$$\frac{\beta_L^{22}\beta_L^{32}}{m_{\text{LQ}}^2} = 1.98 \times 10^{-3}\ \text{TeV}^{-2}$$

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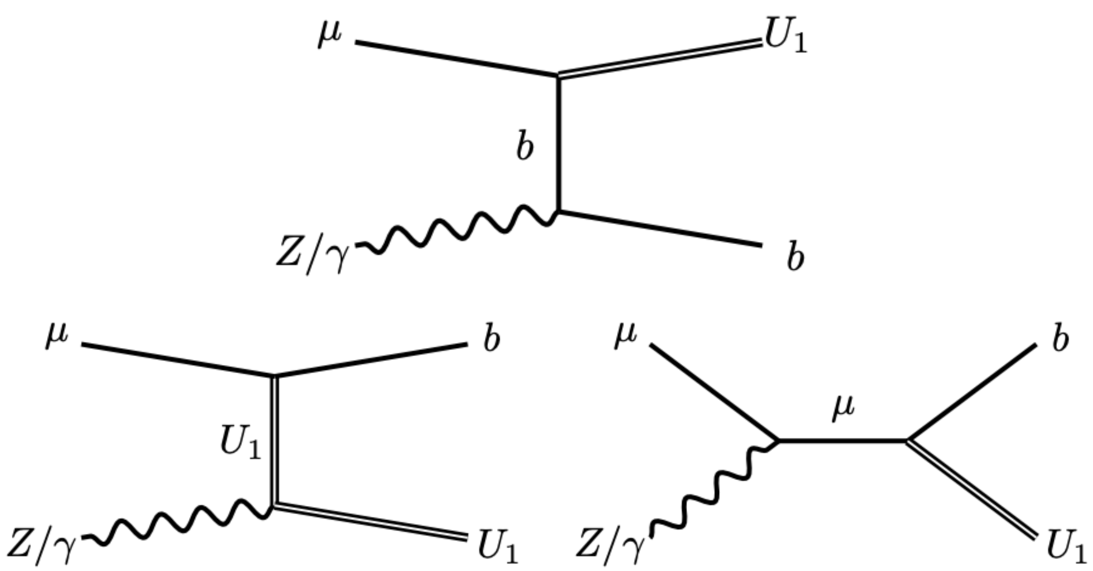
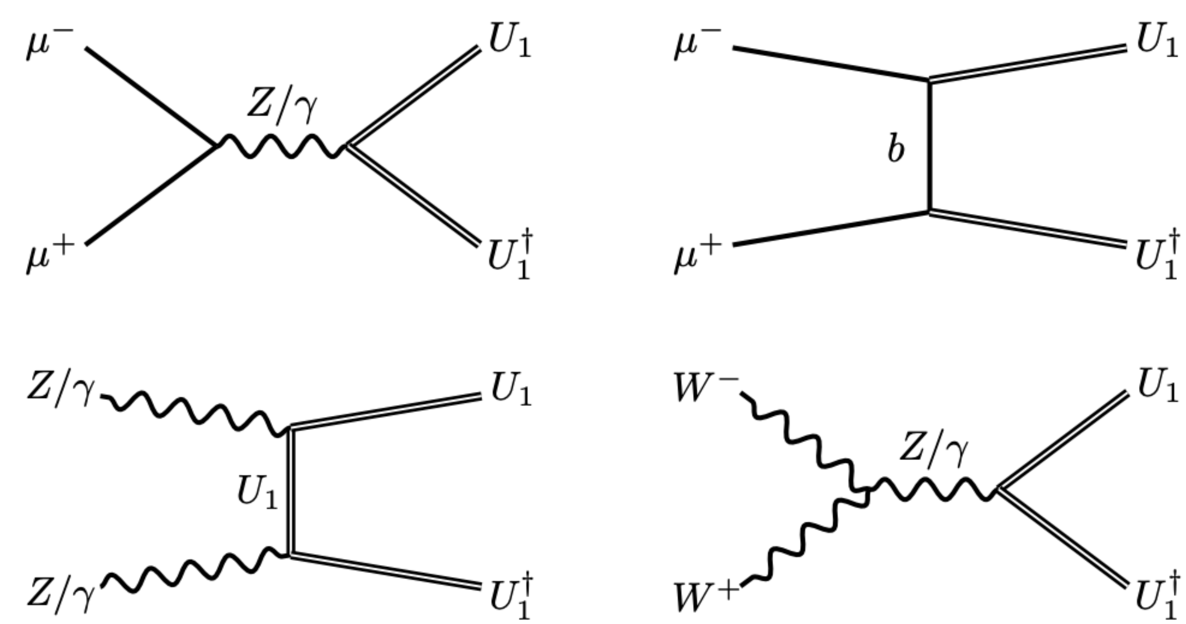
2. Vector leptoquark explanation for R(K)

- The U1 vector leptoquark

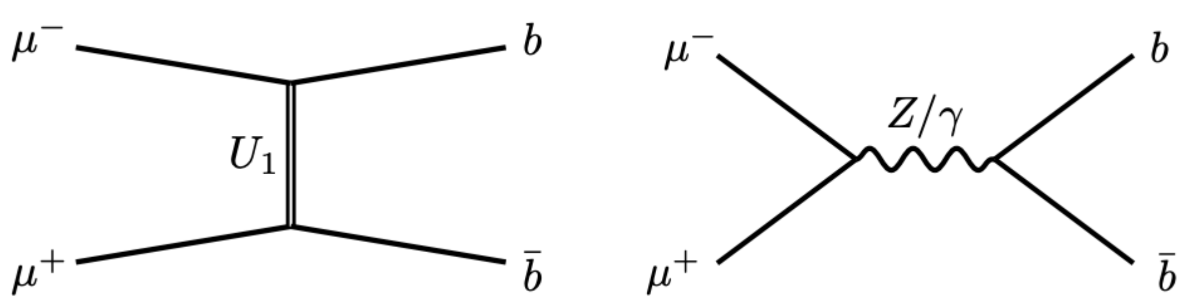
Single Production



Double Production



Drell-Yan



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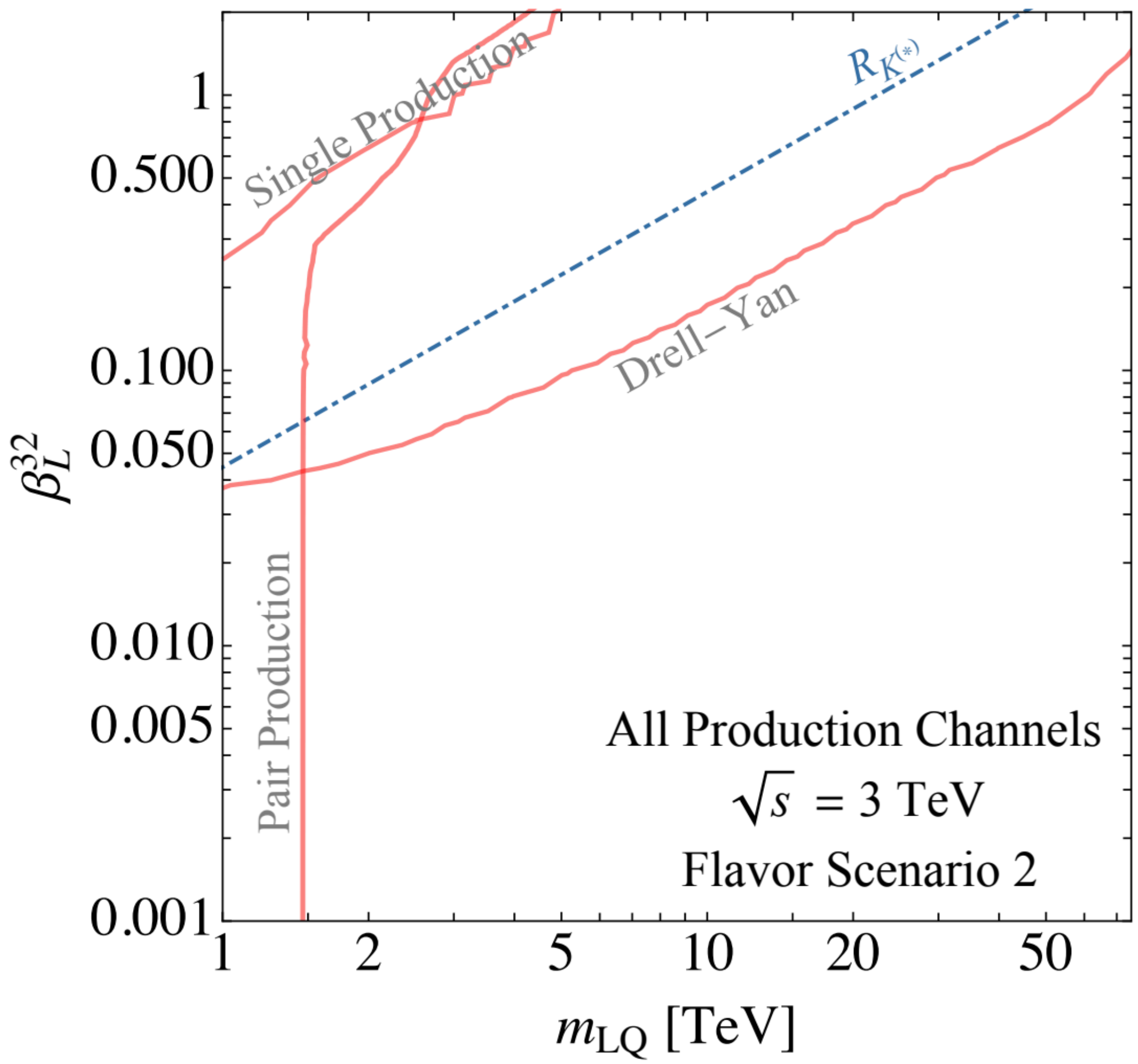
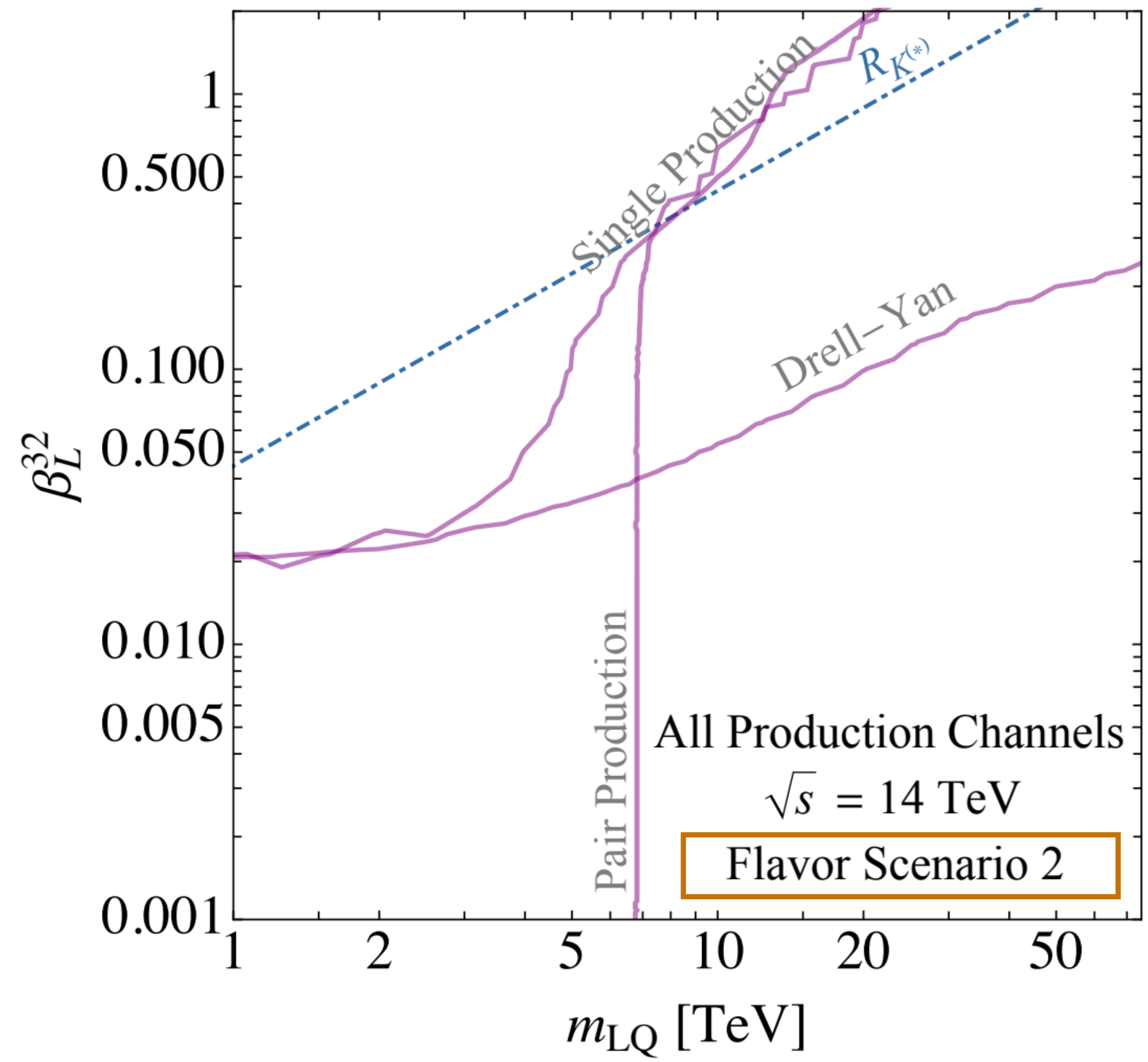
2. Vector leptoquark explanation for R(K)

- The U1 vector leptoquark

$$\beta_L^{22} = \beta_L^{32}$$





"Vector Leptoquarks"

A 3 TeV Muon Collider can probe the parameter space for R(K)

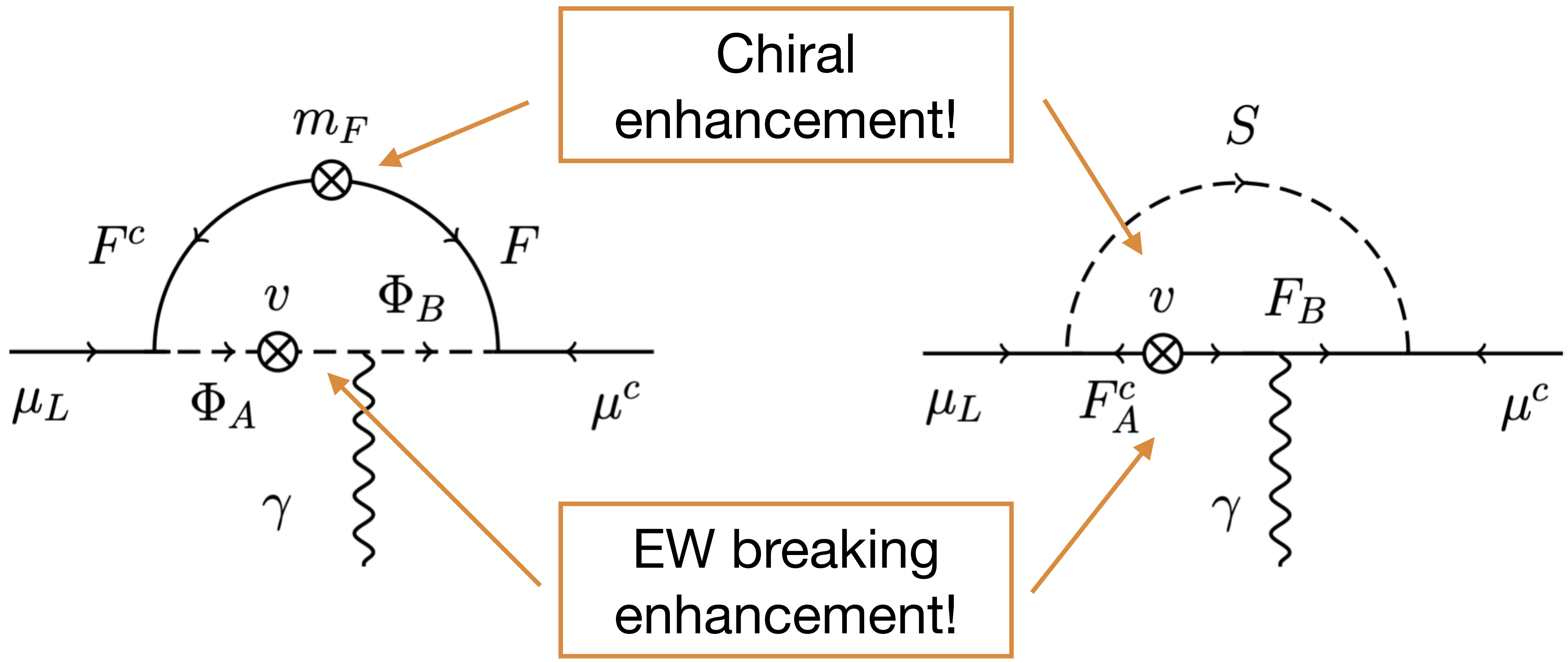
Thanks!

5. Probing g-2 at a Muon Collider

R. Capdevilla et al., e-Print: 2101.10334
R. Capdevilla et al., e-Print: 2006.16277

- Is it possible to discover all BSM solutions to the (g–2)μ anomaly?

"Electroweak scenarios"

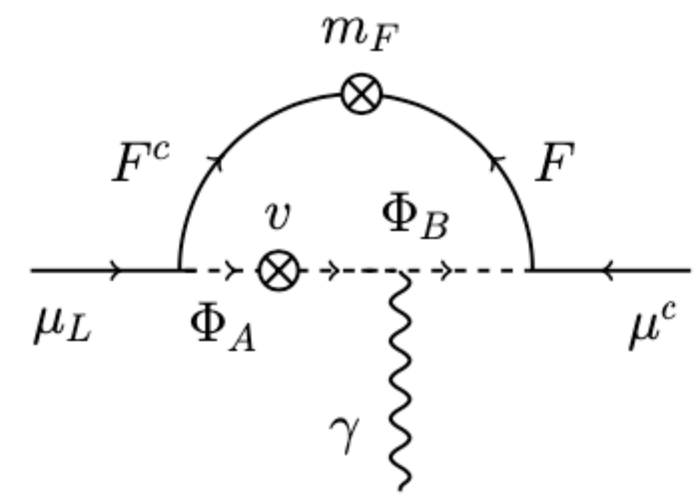


SM gauge invariance:

$$\mathbf{1} \subset R^A \otimes R \otimes \mathbf{2}$$
$$R^B = \bar{R}$$
$$Y^A = -\frac{1}{2} - Y$$
$$Y^B = -1 - Y,$$

can just list off all such representations up to some maximum Q (we take Q <= 2)

5. Model Exhaustive Approach: EW Scenarios

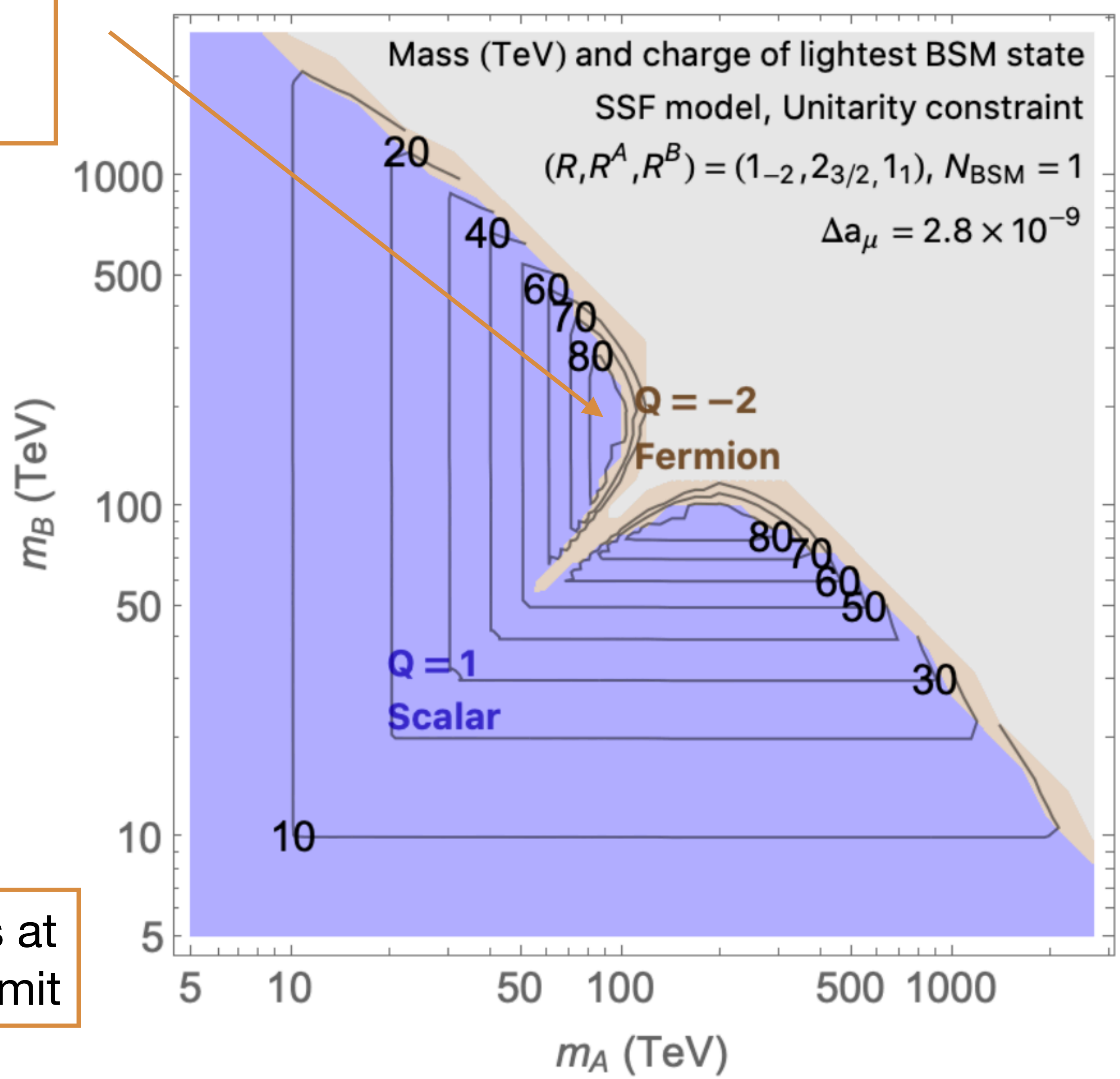


If only perturbative unitarity

Heaviest states at

$\sim 100\,\mathrm{TeV}$

Unitarity only

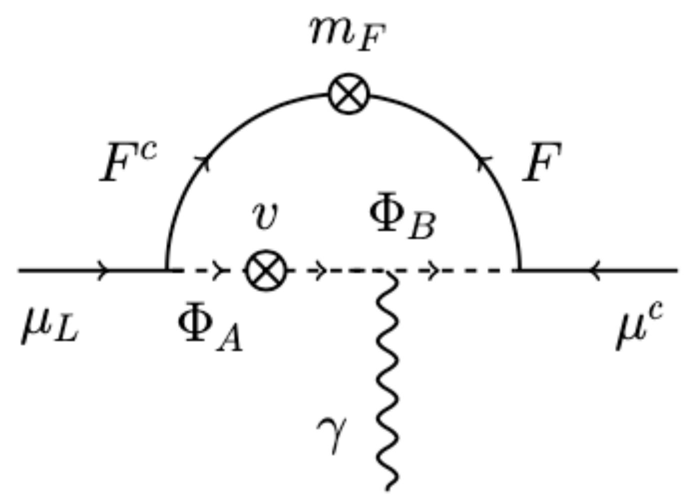


- EW representations up to **3**
- Models with charged scalars up to Q = 2
- BSM number of flavours up to 10

N_{BSM}

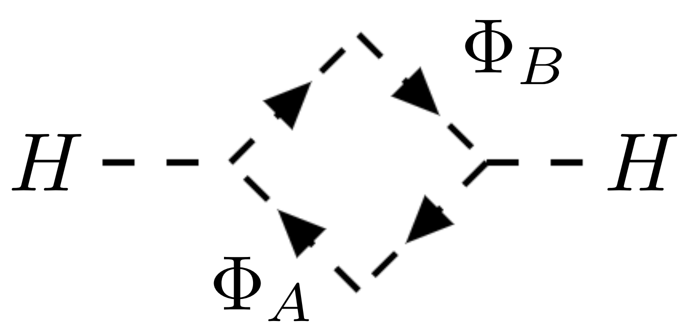
Maximal couplings at the perturbativity limit

5. Model Exhaustive Approach: EW Scenarios

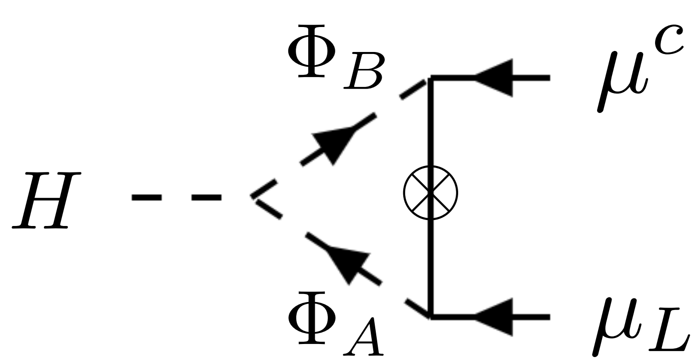


- Naturalness?

Two calculable hierarchy problem!



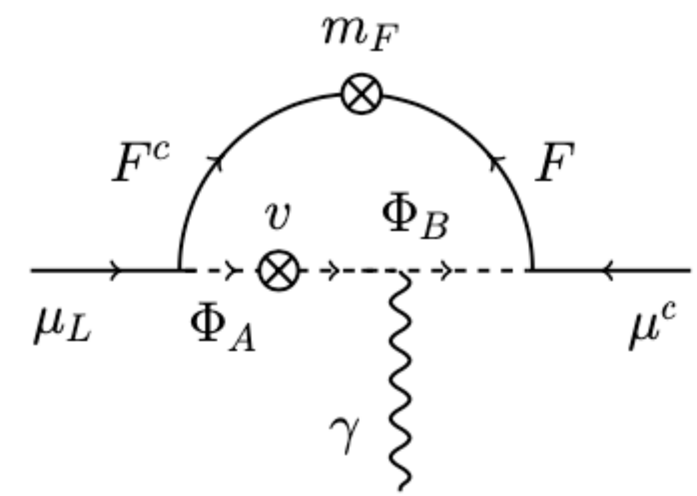
$$\Delta\mu_H^2 \sim \frac{\kappa^2}{16\pi^2} C'_{\text{loop}}$$



$$\Delta y_\mu \sim \frac{y_1 y_2 m_F \kappa}{16\pi^2 M_{A/B}^2} C_{\text{loop}}$$

Muon mass technically unnatural

5. Model Exhaustive Approach: EW Scenarios



- Flavor?

$$-\mathcal{L} \supset y_1^i F^c L_i \Phi_A^* + y_2^i F \ell_i^c \Phi_B^*$$

Flavor Specific couplings?

B. Batell, A. Freitas, A. Ismail, D. Mckeen, e-Print: 1712.10022

$$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$
$$\mathrm{Br}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

$$\frac{y_{1,2}^e}{y_{1,2}^\mu} \lesssim 10^{-5}$$

$$\frac{y_{1,2}^\tau}{y_{1,2}^\mu} \lesssim 10^{-1}$$

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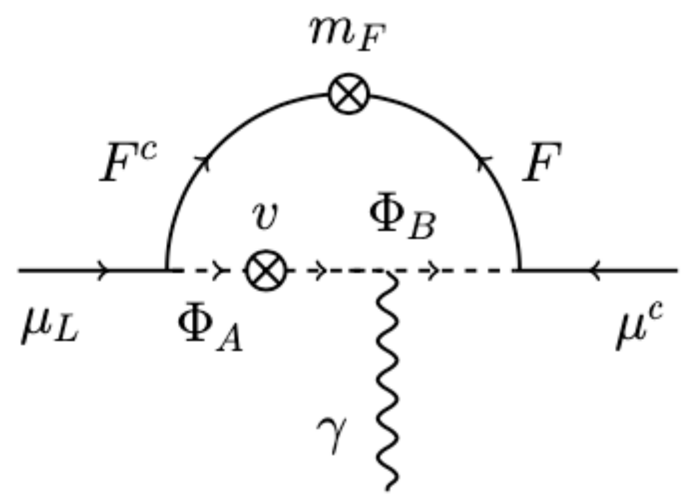
5. Model Exhaustive Approach: EW Scenarios



- Minimal Flavor Violation?

$$-\mathcal{L} \supset Y_1^i \left(F^c L \Phi_A^*\right)_i + Y_2^i \left(F \ell^c \Phi_B^*\right)_i$$

Proportional to SM yukawas

Can transform under the flavour group

$$L \sim (3,1)$$
$$e^c \sim (1,\bar{3})$$
$$F \sim (3,1)$$
$$F^c \sim (\bar{3},1)$$
$$S_{A,B} \sim (1,1)$$

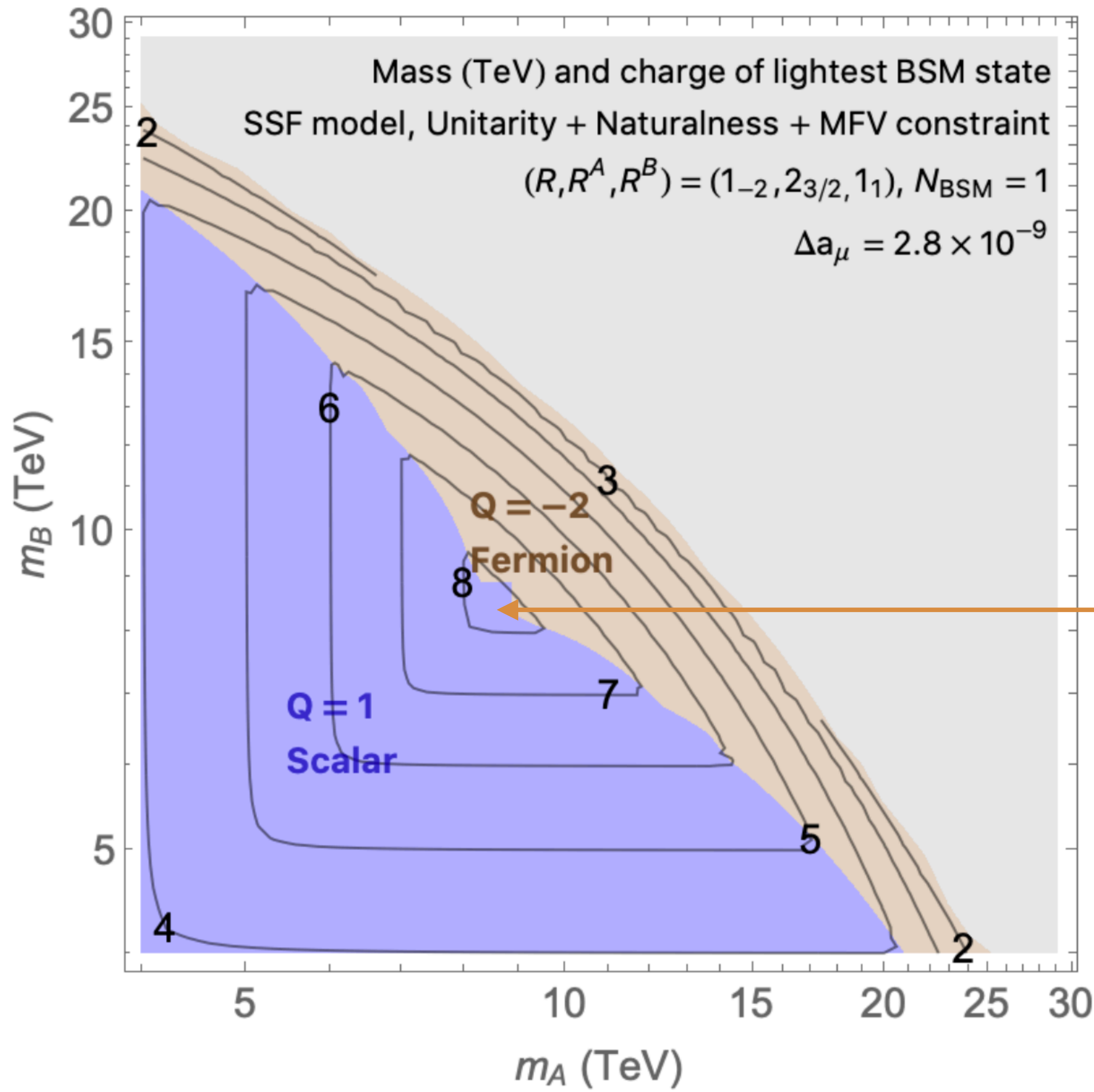
An example

$$y_2 \sim y_e \sim (\bar{3},3)$$
$$y_1 \sim (1,1)$$

$$\frac{(y_{1,2})_\tau}{(y_{1,2})_\mu} \sim \frac{(y_{SM})_\tau}{(y_{SM})_\mu}$$

- The tauonic coupling reaches the perturbativity limit before the muonic one.
- The relevant coupling for g-2 is reduced by ~ one order of magnitude!

5. Model Exhaustive Approach: EW Scenarios



Unitarity
Naturalness
MFV

Heaviest states at
$\sim 10\,\text{TeV}$

- Large couplings
- MFV
- *"Empirical"* Fine tuning
  (Higgs ***and*** muon mass)

LEP

~ 20 TeV Muon Collider

$\sim 100\,\text{GeV}$

Reasonable assumptions
$y_{\text{BSM}} \sim 1$
$N_{\text{BSM}} < 10$

$\sim 20\,\text{TeV}$
$(\lesssim 100\,\text{ab}^{-1})$

M_{BSM}