Flavor anomalies confront asymptotic safety

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based on
Eur. Phys. J. C 81 (2021) 4, 272 (arXiv: 2007.03567)
Phys. Rev. D 103, 115032 (2021) (arXiv: 2012.15200)

Portorož 2021: Physics of the flavourful Universe

21.09.2021

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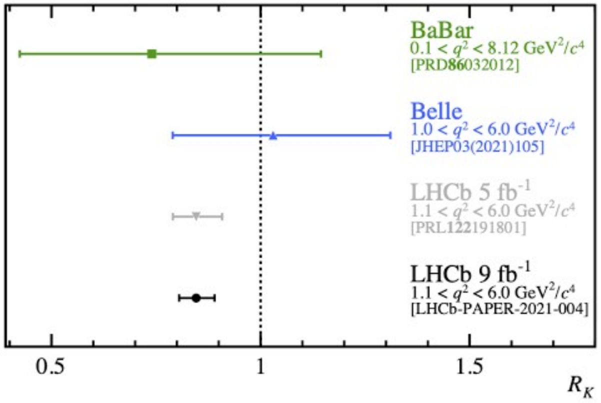
Anomalies in b to s transitions

- **lepton-flavor universality violation (LHCb: ~3.1 σ)**

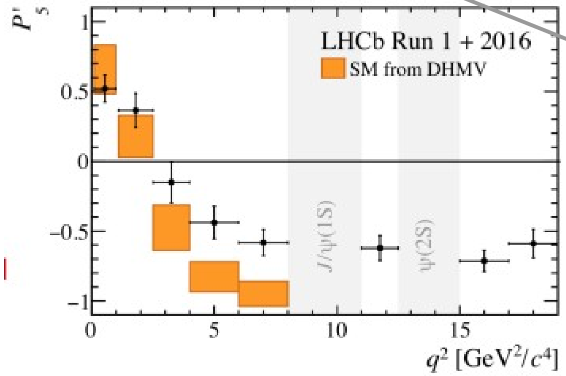
$$R_K = \frac{\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}(B^+ \to K^+e^+e^-)}$$

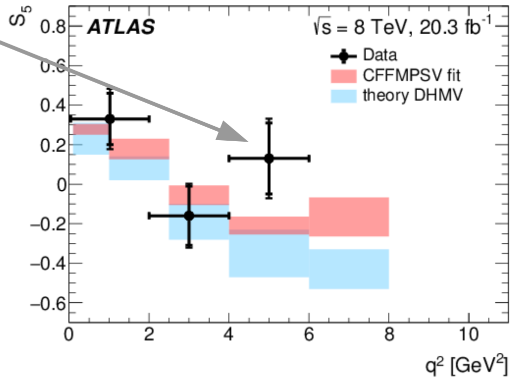
$$R_{K^*} = \frac{\mathrm{BR}(B^0 \to K^{0*}\mu^+\mu^-)}{\mathrm{BR}(B^0 \to K^{0*}\,e^+e^-)}$$



- **deviations in angular observables (LHCb: ~2.5 σ)**

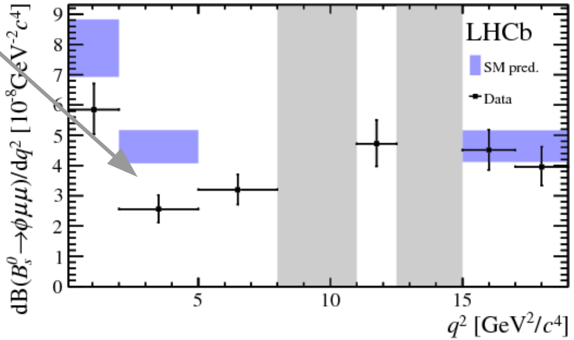
$$B^0 \to K^{0*}\mu^+\mu^-$$





- **deviations in branching ratios (LHCb: ~2-3.5 σ)**

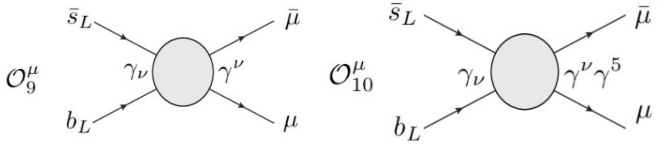
$$B^0 \to K^{0*}\mu^+\mu^-$$
$$B^0 \to K^{0}\mu^+\mu^-$$
$$B^0_s \to \phi\mu^+\mu^-$$
$$\Lambda^0_b \to \Lambda\mu^+\mu^-$$



New Physics explanations

- ~140 observables with experimental + theoretical correlations
- GLOBAL FIT

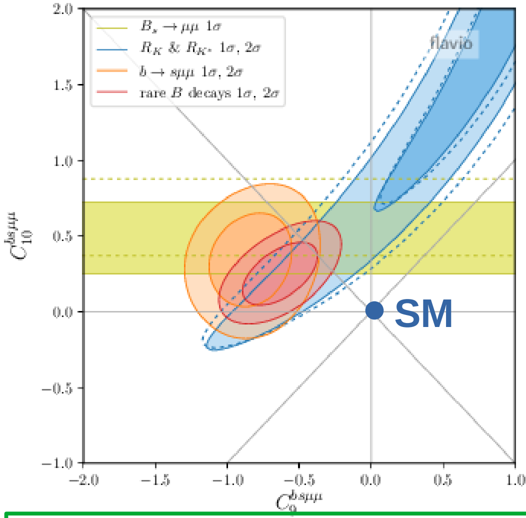
EFT approach:



$$\Longrightarrow C_9^\mu,\ C_{10}^\mu$$

pull of the best-fit point: **5.9 σ**

W.Altmannshofer, P.Stangl, arXiv: 2103.13370

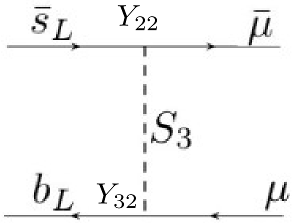


$$\boxed{C_9^\mu = -C_{10}^\mu \in (-0.6, -0.3)}$$

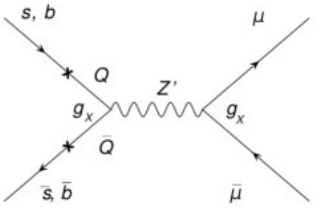
New Physics in the muon sector?

NP models:

$$C_9^\mu = -C_{10}^\mu = \frac{\pi v_h^2}{V_{33}V_{32}^*\alpha_{\rm em}} \boxed{\frac{\hat{Y}_{32}^L \hat{Y}_{22}^{L*}}{m_{S_3}^2}}$$



leptoquarks

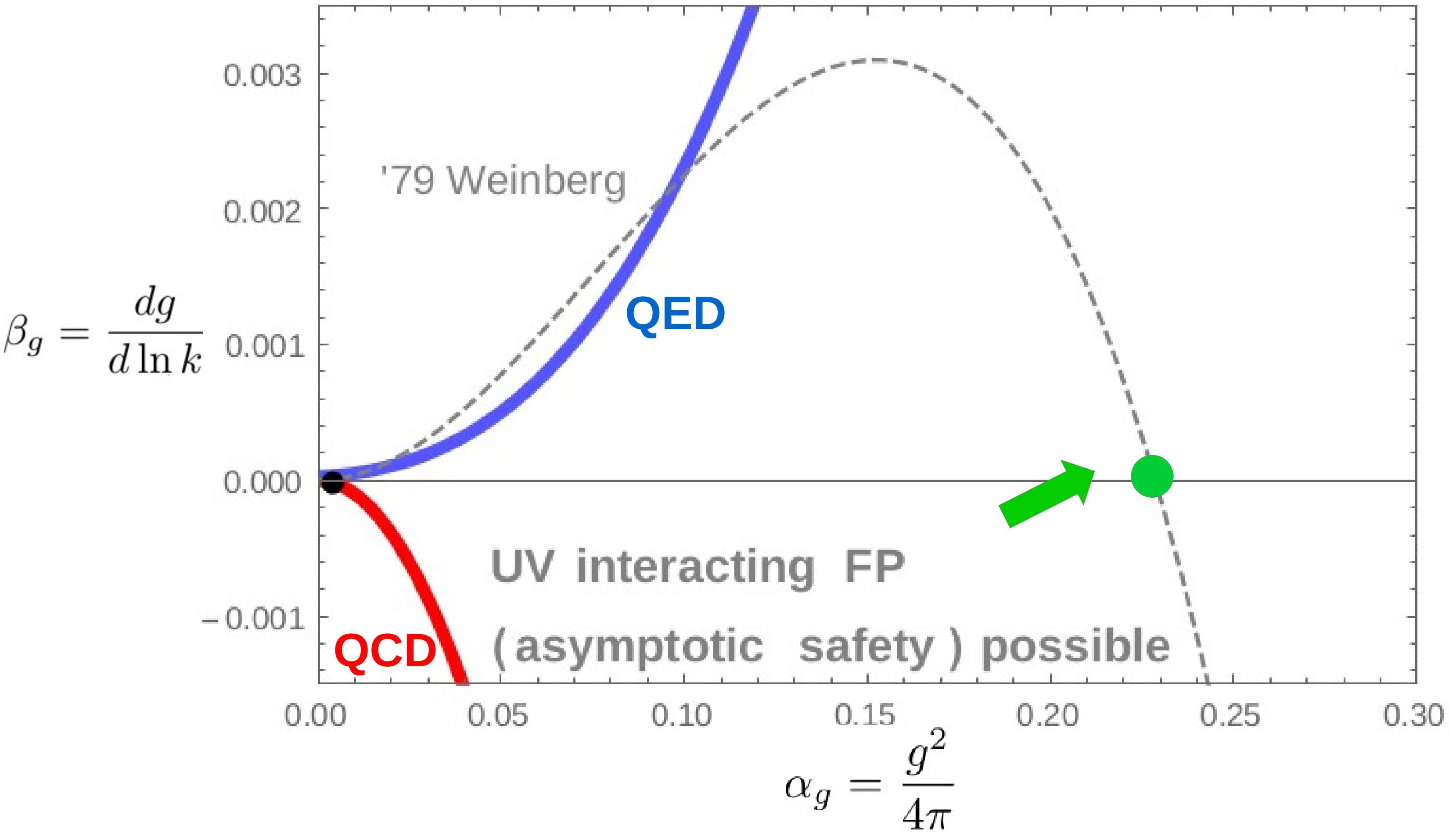


Z' with VL fernions

Problem: we know only coupling/mass ratio → no prediction for the NP scale

Question: how to get a prediction? → **asymptotic safety**

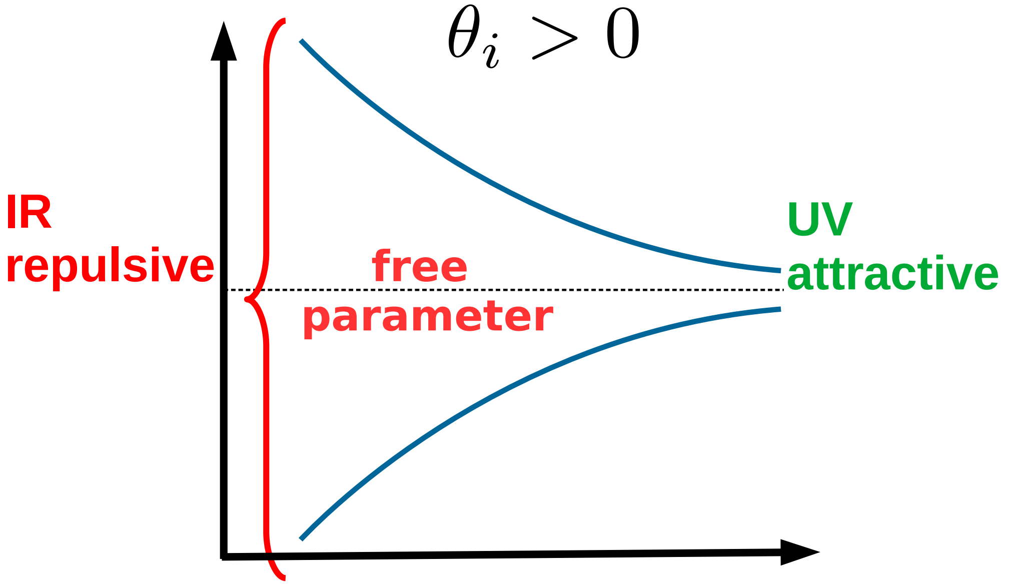
Asymptotic behaviours

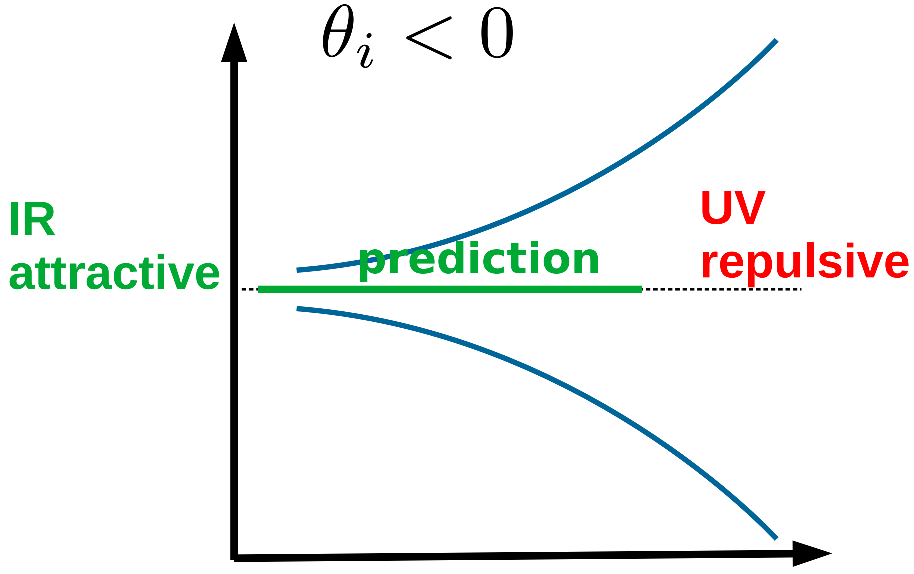


- AS originally advocated by Weinberg to improve the UV behavior of G_N
- Advocated in QFT as solution to $U(1)_Y$ triviality problem

Fixed point properties

$$\boxed{\beta_i(\{\alpha_j^*\}) = 0} \longrightarrow \underset{\text{stability matrix}}{M_{ij} = \partial\beta_i/\partial\alpha_j\big|_{\{\alpha_i^*\}}} \longrightarrow \underset{\text{critical exponents}}{\{-\theta_i\}}$$





Relevant couplings are free parameters of the theory

Irrelevant couplings provide predictions

Asymptotic safety in QG

Quantum gravity and quantum gravity + matter might feature interactive UV fixed points

[Reuter '96, Reuter, Saueressig '01, Litim '04, Codello, Percacci, Rahmede '06, Benedetti, Machado, Saueressig '09, Narain, Percacci '09, Manrique, Rechenberger, Saueressig '11, Falls, Litim, Nikolakopoulos '13, Dona', Eichhorn, Percacci '13, Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Christiansen, Eichhorn '17, Eichhorn, Versteegen '17, Zanusso *et al.* '09, Oda, Yamada '15, Eichhorn, Held, Pawlowski '16, Pawlowski *et al.* '18 … many more]

Prototype example: Einstein-Hilbert gravity

$$S_{\rm EH} = \frac{1}{16\pi G_N}\int d^4x\sqrt{g}\,(-R(g)+2\Lambda)$$

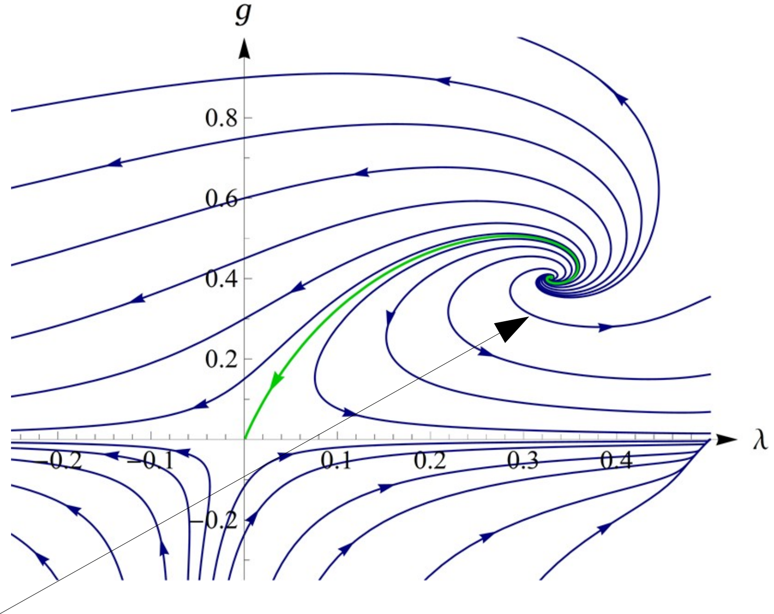
Functional renormalization group techniques (Wetterich Equation) lead to 2 fixed points

$$\beta_g \equiv \frac{dg}{d\ln k} = 0 \qquad \beta_\lambda \equiv \frac{d\lambda}{d\ln k} = 0$$

(gaussian) $g = 0 \quad \lambda = 0$

(interactive) $\boxed{g = g^* \quad \lambda = \lambda^*}$

Reuter, Saueressig, hep-th/0110054



Fixed point persists under the addition of new interactions

Asymptotic safety with matter

Gravity affects matter:

Gauge-Yukawa system coupled to gravity:

$$\beta_g = \beta_g^{\mathrm{SM+NP}} - \boxed{g\, f_g}$$

$$\beta_y = \beta_y^{\mathrm{SM+NP}} - \boxed{y\, f_y}$$

Quantum-gravitational contribution
(in principle via FRG)

[Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Christiansen, Eichhorn '17, Eichhorn, Versteegen '17, Zanusso *et al.* '09, Oda, Yamada '15, Eichhorn, Held, Pawlowski '16, …]

In practice *fg*, *fy* are subject to large uncertainties
(truncation in number of operators, cut-off scheme dependence, etc.)

[Lauscher, Reuter '02, Codello, Percacci, Rahmede '07-'08, Benedetti, Machado, Saueressig '09, Narain, Percacci '09, Dona', Eichhorn, Percacci '13, Falls, Litim, Schroeder '18, ...]

↓

fg, *fy* free parameters determined by matching to the low-energy data

applied in SM and simple SM extensions

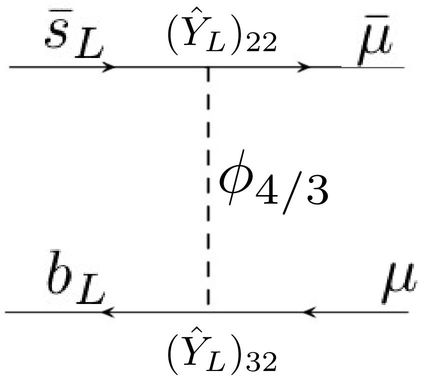
see *e.g.* Eichhorn, Held, 1707.01107, 1803.04027; Reichert, Smirnov, 1911.00012; Alkofer *et al.* 2003.08401

b-s anomalies: SM + S_3 LQ

see, ex: I. Doršner, S. Fajfer, A. Greljo, J. Kamenik, and N. Košnik, Phys. Rept. 641 (2016) 1–68
G. Hiller, D. Loose, and K. Schönwald, JHEP 12 (2016) 027
I. Doršner, S. Fajfer, D. A. Faroughy, and N. Košnik, JHEP 10 (2017) 188

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

$$\mathcal{L} \supset (Y_L)_{ij}\, Q_i^T (i\sigma_2) S_3 L_j + \text{H.c.}$$



flavor basis

$$\hat{Y}^L = D_L^T Y_L$$
$$\tilde{Y}^L = U_L^T Y_L$$

quark mass basis

$$\mathcal{L} \supset \hat{Y}_{ij}^L \sqrt{2} \phi_{4/3} d_{L,i} e_{L,j} + \widetilde{Y}_{ij}^L \phi_{1/3} u_{L,i} e_{L,j} + \text{H.c.}$$

down-origin scenario

$$\hat{Y}^L = \begin{pmatrix} d & s & b \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \hat{Y}_{22}^L & 0 \\ 0 & \hat{Y}_{32}^L & 0 \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

FEATURES

1) running of the CKM matrix

2) $\hat{Y}_{12}^L$ generated through the running via CMK, can affect $BR(K_L^0 \to \mu^+\mu^-)$

under control

Fixed-point analysis

System of beta functions to solve:

$$\underbrace{g_Y\,,\ g_2,\ g_3,}_{\text{gauge}}\ \underbrace{y_t,\ y_b,\ V_{33},}_{\text{SM Yukawa}}\ \underbrace{\hat{Y}^L_{22},\ \hat{Y}^L_{32}}_{\text{LQ Yukawa}}$$

- 2^{nd} + 3^{rd} generation approximation
- CKM described by V_{33}

↓

UV fixed-point:

SM: $g_3^* = 0,\ \ g_2^* = 0$

$g_Y^* = 0.48$ fixes f_g

$y_t^* = 0,\ \ y_b^* = 0.03$ fixes f_y

$V_{33} = 0$

LQ: $\hat{Y}^{L*}_{22} = 0$

$\hat{Y}^{L*}_{32} = 0.19$

↓ irrelevant

low-scale predictions

Prediction for the LQ mass

$$C_9^{\mu} = -C_{10}^{\mu} = \frac{\pi v_h^2}{V_{33}V_{32}^{*}\alpha_{\rm em}}\,\frac{\hat{Y}_{32}^{L}\hat{Y}_{22}^{L*}}{m_{S_3}^2}$$

0.63

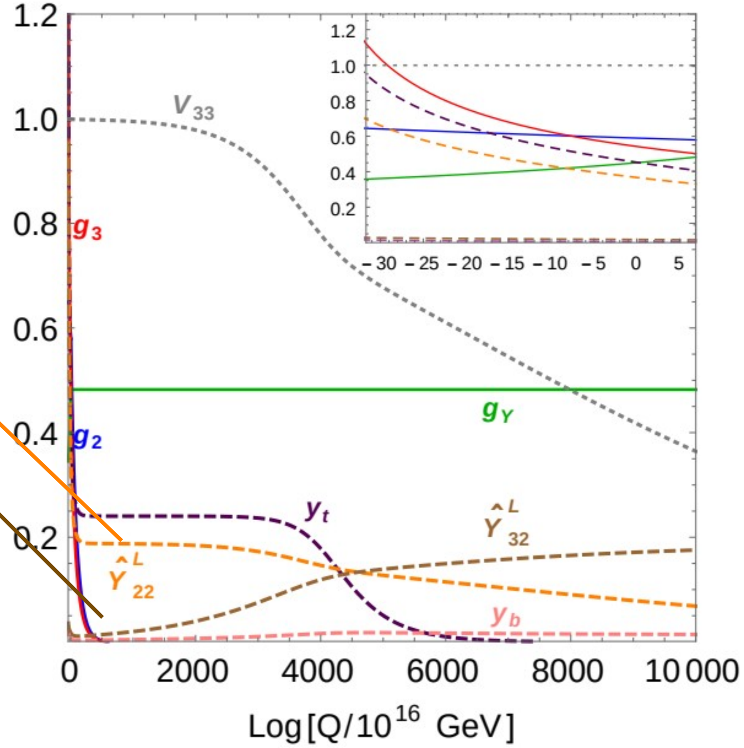
0.03

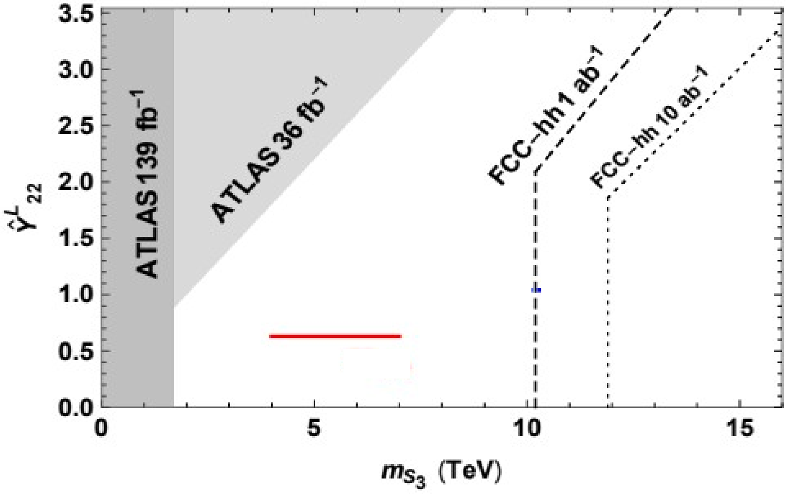
global fits:

$$C_9^{\mu} = -C_{10}^{\mu} \in (-0.6, -0.3)$$

$$\boxed{M_{S_3} \in (4.5, 7)\ \text{TeV}}$$

Mass predicted !





In the reach of the FCC!

complementary predictions in flavor:

eg. D-mesons decay

Muon g-2 anomaly

Measured value at BNL (2006):

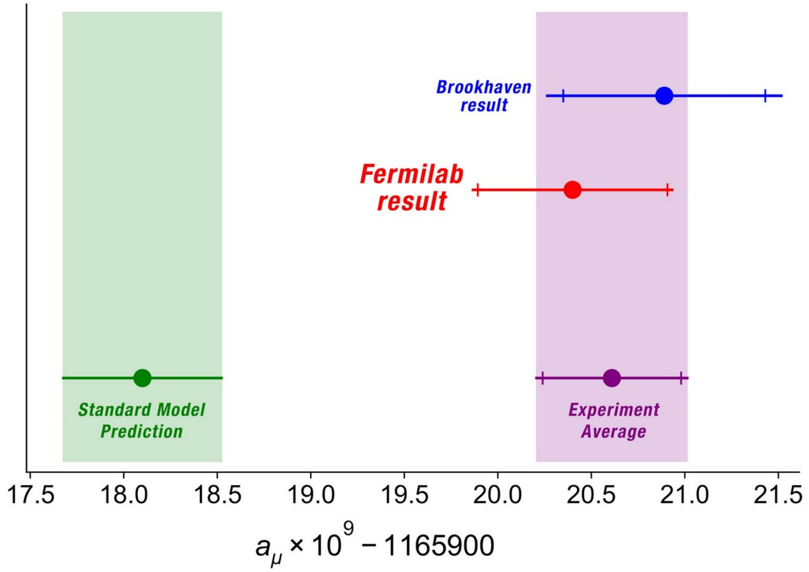
Bennet *et al*, Phys. Rev. D 73 (2006) 072003 (hep-ex/0602035)

$$a_\mu^{\rm BNL} = (116592089 \pm 63) \times 10^{-11}$$

Measured value at FNAL (2021):

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

$$a_\mu^{\rm FNAL} = (116592040 \pm 54) \times 10^{-11}$$



$$\boxed{\Delta\, a_\mu = (25.1 \pm 5.9) \times 10^{-10}}$$

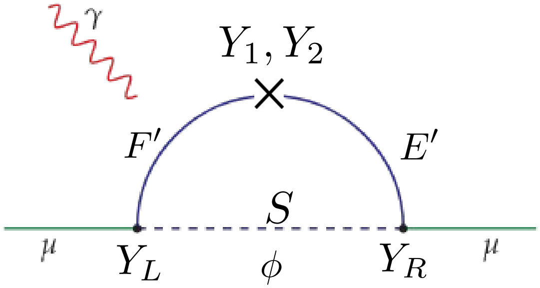
discrepancy at ~ 4.2 σ

g-2: new scalar and VL fermions

VL fermions (*E, E'*) and (*F, F'*) + scalar *S*

$$\mathcal{L}_{\rm NP} \supset \left(Y_R\, \mu_R E' S + Y_L\, F' S^\dagger l_\mu + Y_1\, E\, h^\dagger F + Y_2\, F' h\, E' + \text{H.c.}\right)$$

induce chiral enhancement

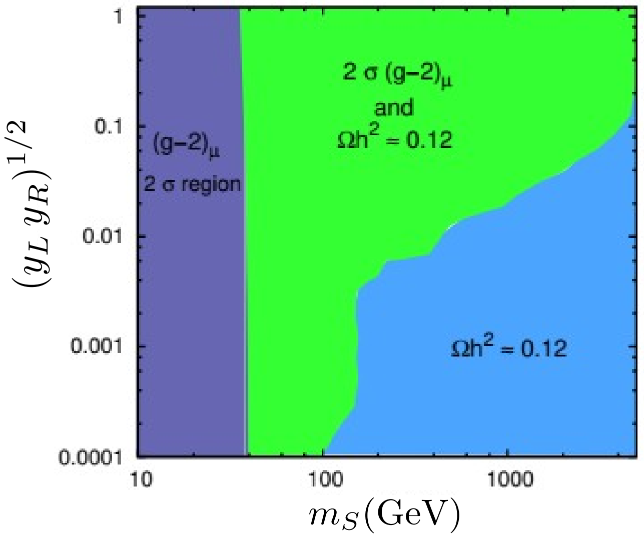


the models:

also: KK, E.M.Sessolo, JHEP 09 (2017) 112
L.Calibbi, R.Ziegler, J.Zupan, JHEP 07 (2018) 046
J.Kawamura, S.Okawa, Y.Omura,JHEP 08 (2020) 042

	S	E	F
$\underline{M_1}$	$(\mathbf{1},0)$	$(\mathbf{1},1)$	$(\mathbf{2},-\frac{1}{2})$
$\underline{M_2}$	$(\mathbf{1},-1)$	$(\mathbf{1},0)$	$(\mathbf{2},\frac{1}{2})$
$\underline{M_3}$	$(\mathbf{2},-\frac{1}{2})$	$(\mathbf{2},\frac{1}{2})$	$(\mathbf{1},0)$
M_4	$(\mathbf{2},\frac{1}{2})$	$(\mathbf{2},\frac{3}{2})$	$(\mathbf{1},-1)$
M_5	$(\mathbf{2},-\frac{3}{2})$	$(\mathbf{2},-\frac{1}{2})$	$(\mathbf{1},1)$
$\underline{M_6}$	$(\mathbf{2},-\frac{1}{2})$	$(\mathbf{2},\frac{1}{2})$	$(\mathbf{3},0)$
M_7	$(\mathbf{2},\frac{1}{2})$	$(\mathbf{2},\frac{3}{2})$	$(\mathbf{3},-1)$
M_8	$(\mathbf{2},-\frac{3}{2})$	$(\mathbf{2},-\frac{1}{2})$	$(\mathbf{3},1)$
M_9	$(\mathbf{3},0)$	$(\mathbf{3},1)$	$(\mathbf{2},-\frac{1}{2})$
$\underline{M_{10}}$	$(\mathbf{3},-1)$	$(\mathbf{3},0)$	$(\mathbf{2},\frac{1}{2})$
M_{11}	$(\mathbf{3},1)$	$(\mathbf{3},2)$	$(\mathbf{2},-\frac{3}{2})$
M_{12}	$(\mathbf{3},-2)$	$(\mathbf{3},-1)$	$(\mathbf{2},\frac{3}{2})$

KK, E.M.Sessolo, JHEP 09 (2017) 112



Wide open PS…
predictions difficult

How to constrain the PS?

asymptotic safety

Predictions for the masses

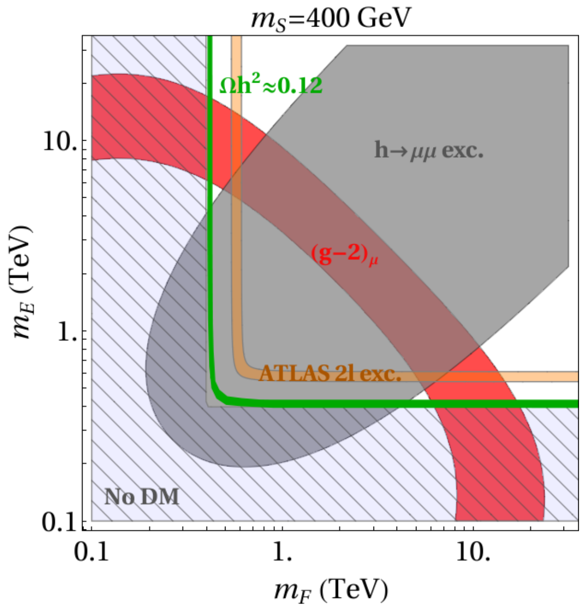
Fixed point fixes couplings:

different low-scale predictions –
different phenomelogy?

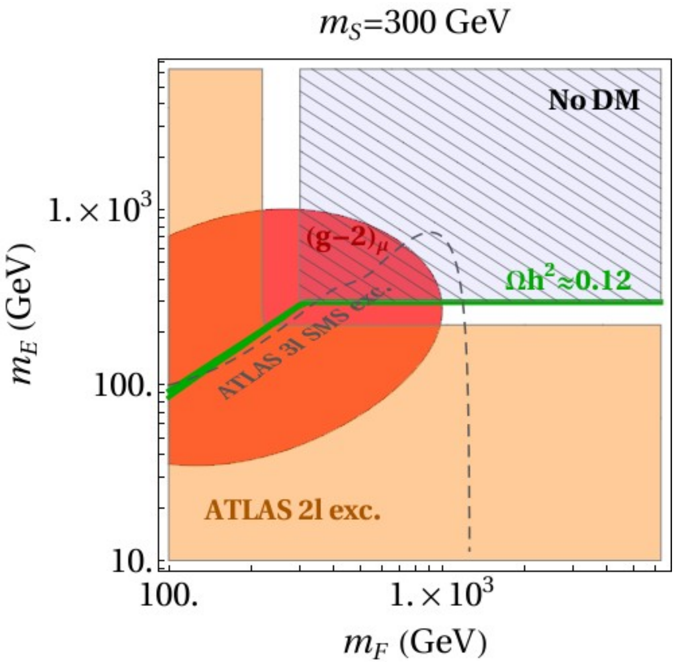
	$y_t(Q_0)$	$Y_L(Q_0)$	$Y_R(Q_0)$	$Y_1(Q_0)$	$Y_2(Q_0)$
M_1	0.91	0.21	0.91	0.62	9×10^{-4}
M_2	1.07	0.65	0.59	0.03	6×10^{-4}
M_3	0.95	0.01	0.77	0.18	3×10^{-5}
M_6	0.93	0.04	0.78	0.65	9×10^{-5}
M_{10}	1.03	0.98	0.87	0.03	1×10^{-3}

$Q_0 \simeq 2\,\mathrm{TeV}$

Model 1



Model 2



fundamentally different parameter space

Consequence of asymptotic safety!

To take home

- EFT alone is not predictive enough → theoretical analysis of UV completions is needed
- Via fixed point, AS can enhance predictivity of the New Physics models
- Other applications possible, case-by-case study needed
- Overall, AS in UV can provide a new tool for phenomenology