Phenomenology with trans-Planckian asymptotic safety

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in collaboration with
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Eur.Phys.J.C 81 (2021) 4, 272 (arXiv: 2007.03567)
Phys. Rev. D 103, 115032 (2021) (arXiv: 2012.15200)
JHEP 01 (2023) 164 (arXiv: 2209.07971)
Eur.Phys.J.C 83 (2023) 7, 644 (arXiv: 2304.08959)

Asymptotic safety in Quantum Field Theory: Grand Unification
Lyon, 5.06.2024

National Science Centre Poland

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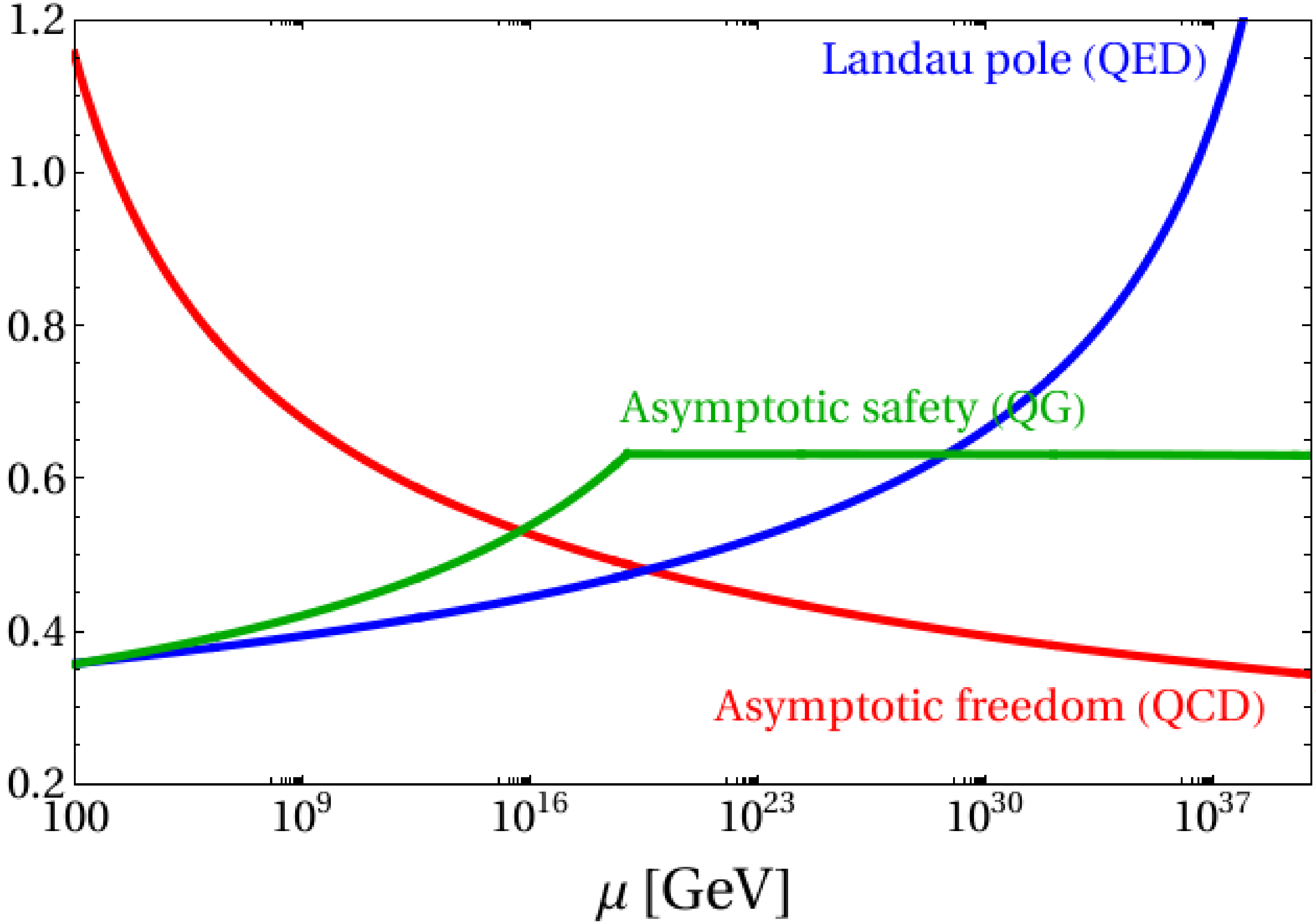
Outline

- **Asymptotic safety (AS)** – what is it all about?
- Evidence for a **trans-Planckian fixed point**
- **Phenomenological predictions** from trans-Planckian AS
- **Uncertainties** of the predictions
- Conclusions

Trans-Planckian asymptotic safety

Asymptotic safety



$g \to \infty$

$g^* \neq 0$

UV complete

$g^* = 0$

$$\beta_g = \frac{dg}{dt} = \frac{dg}{d \ln \mu}$$

$$\beta_g(g^*) = 0$$

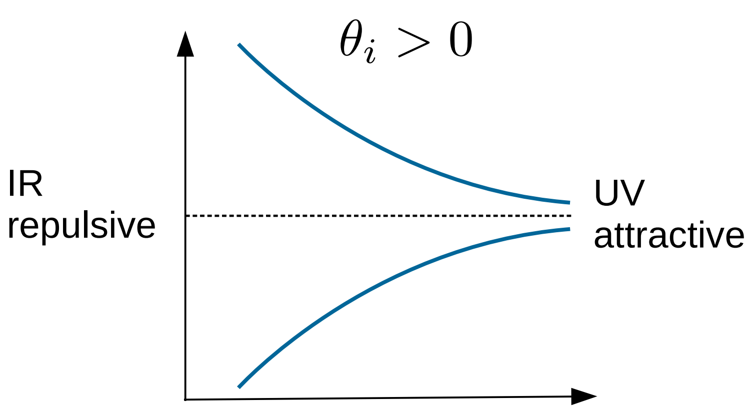
- AS originally proposed by Weinberg to improve the UV behavior of G_N
- Advocated in QFT as solution to $U(1)_Y$ triviality problem
- Allows non-perturbative renormalization

Fixed point and critical surface

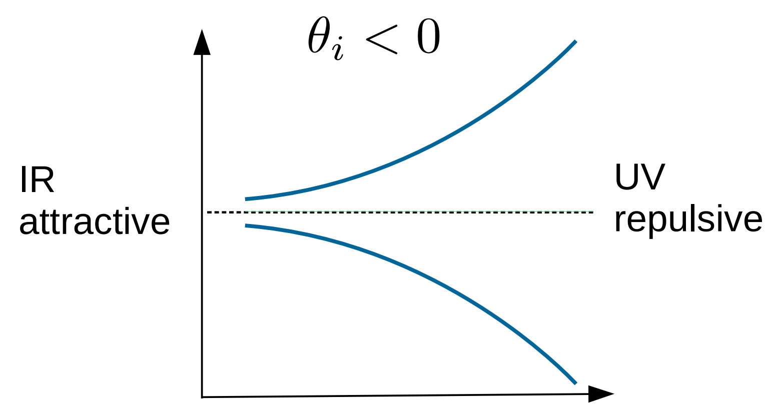
$$\boxed{\beta_i(\{\alpha_j^*\}) = 0} \longrightarrow M_{ij} = \partial\beta_i/\partial\alpha_j|_{\{\alpha_i^*\}} \longrightarrow \{-\theta_i\}$$

stability matrix

critical exponents



Relevant couplings are
free parameters of the theory

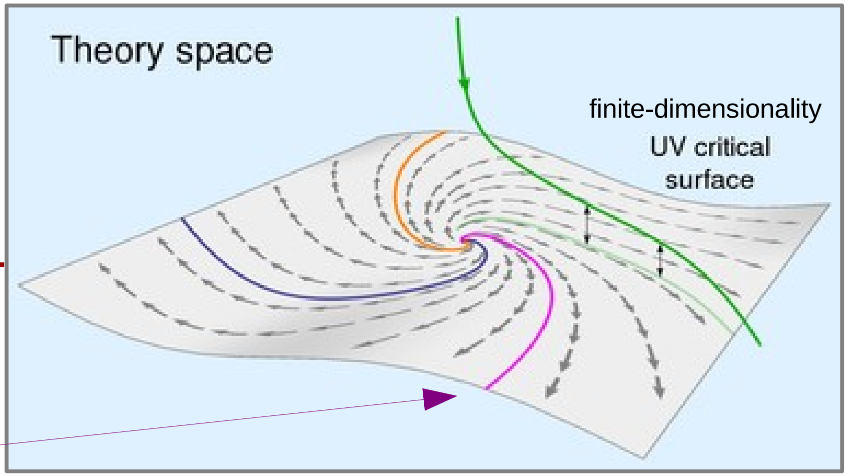


Irrelevant couplings provide
predictions

span the
UV critical surface

defines a fundamental QFT

once determined by the
experiment ...



from Wikipedia

can only deviate from
the FP along the
critical surface

… can be uniquely fixed

PREDICTIVITY

Wetterich flow equation

C.Wetterich, PLB 301, 90 (1993)

$$\partial_t \Gamma_k[\phi] = \frac{1}{2}\mathrm{Tr}\left[\partial_t R_k \left(\Gamma_k^{(2)}[\phi] + R_k\right)^{-1}\right]$$

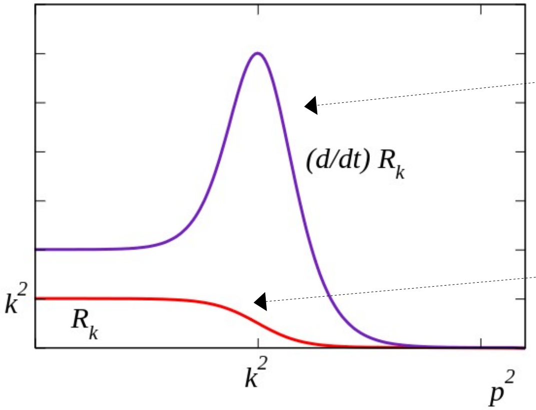
$\partial_t = k\partial_k$

$\Gamma_k^{(2)}[\phi] = \frac{\delta^2 \Gamma_k[\phi]}{\delta\phi\,\delta\phi}$

an exact differential equation

H. Gies,
Lect.Notes Phys. 852 (2012) 287-348

Regulator function $R_k(p^2)$

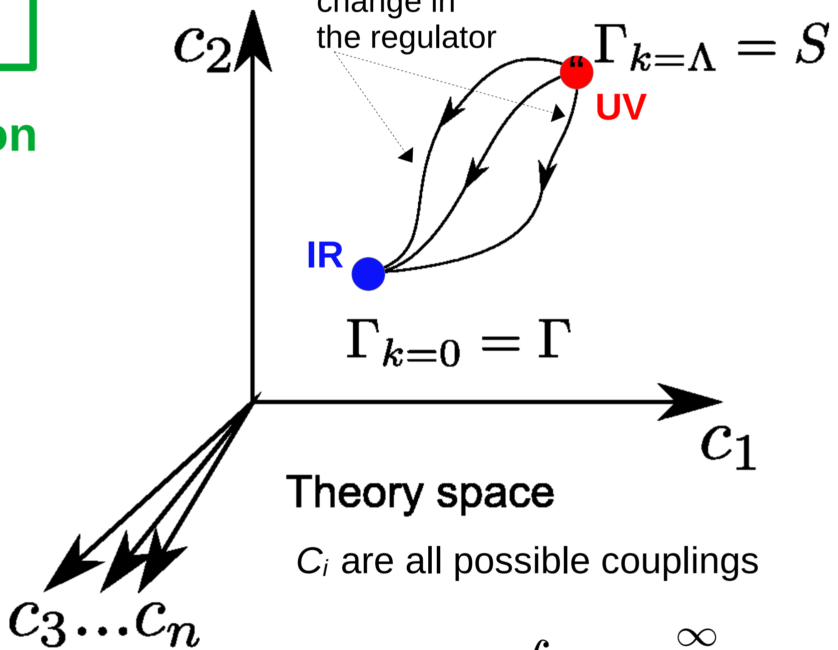


UV regularization
for $p^2 \approx k^2$

IR regularization
for $p^2 < k^2$

Wilsonian momentum-shell integration

H. Gies,
Lect.Notes Phys. 852 (2012) 287-348



Theory space

C_i are all possible couplings

$$\Gamma_k[\phi] = \int d^4x \sum_{i=0}^{\infty} c_i \mathcal{O}_i[\phi]$$

non-pert. RGEs $\partial_t \Gamma_k \to \partial_t c_i$

Asymptotic safety in quantum gravity

M. Reuter, PRD 57, 971 (1998)

Prototype example: **Einstein-Hilbert gravity**

$$S_{\mathrm{EH}}[g_{\mu\nu}] = \frac{1}{16\pi G_N}\int d^4x\sqrt{g}\,(2\Lambda - R)$$

Dimensionless couplings:

$$g = G_N k^2 \qquad \lambda = \Lambda k^{-2}$$

Beta functions for the gravity couplings:

$$k\partial_k g = [2 + \eta_g(g,\lambda)]\,g$$

$$k\partial_k \lambda = -2\lambda + g\eta_\lambda(g,\lambda)$$

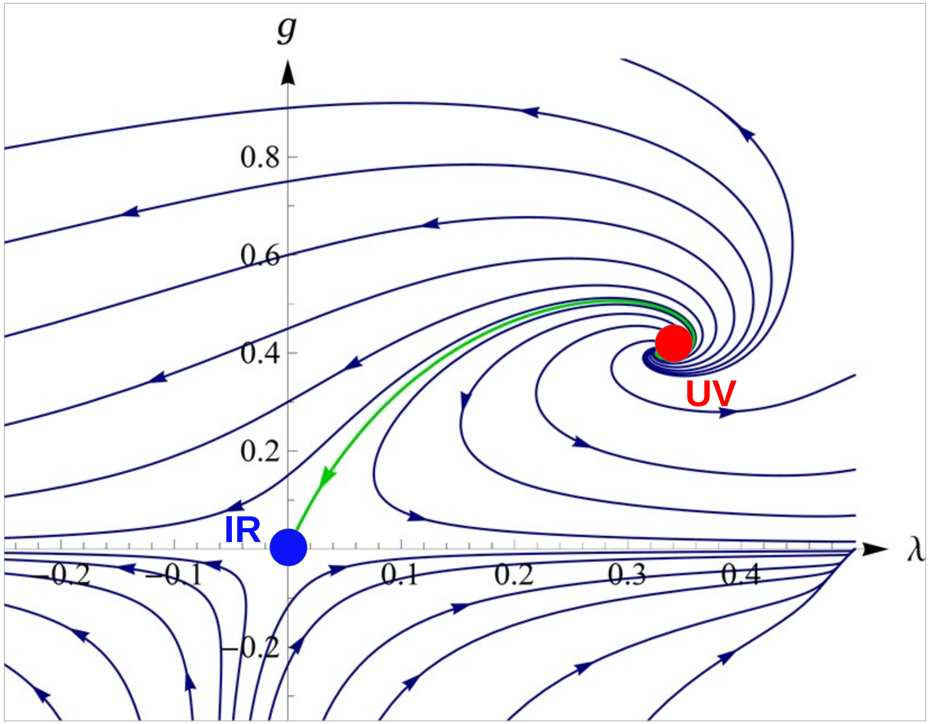
2 fixed points:

Gaussian: $g^* = 0 \qquad \lambda^* = 0$

Interactive: $g^* \neq 0 \qquad \lambda^* \neq 0$

Trans-Planckian fixed point

M. Reuter, F. Saueressig , PRD 65, 065016 (2002)



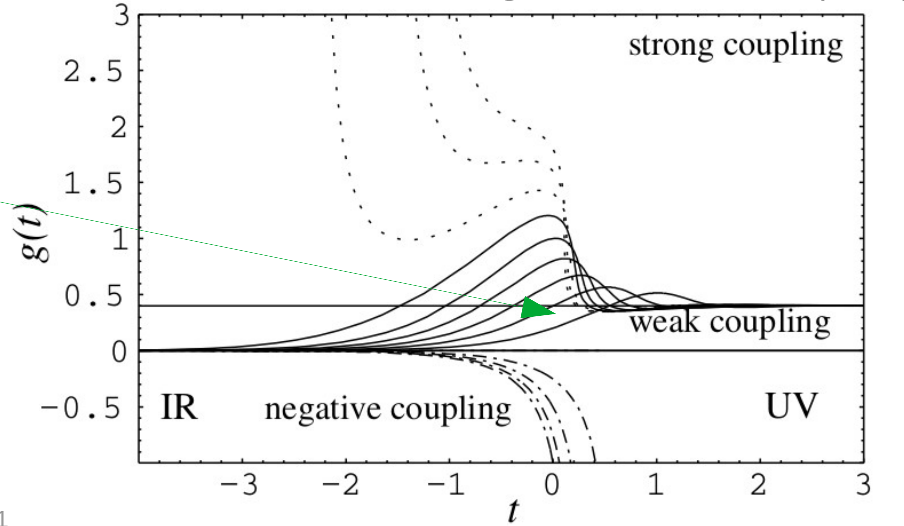
physical trajectory

$$G_N(\mathrm{IR}) = 1.22\times 10^{-22}\ \mathrm{GeV}^{-2}$$

$$G_N\Lambda(\mathrm{IR}) = 2.89\times 10^{-122}$$

Asymptotic safety in quantum gravity

M. Reuter, F. Saueressig , PRD 65, 065016 (2002)



Planck scale generated dynamically
at the cross-over

FP persists when adding new interactions

[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]

also in Lorentzian QG Fehre, Litim, Pawłowski, Reichert '21

Gravity contributions to matter RGEs

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

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

$$\beta_\lambda = \beta_\lambda^{\mathrm{SM+NP}} - \lambda\, f_\lambda$$

conitributions are universal

from the FRG calculations...

EXAMPLE : U(1) + Φ + E-H:

A.Eichhorn, F.Versteegen
JHEP 01 (2018) 030

$$f_g = G\frac{1-4\Lambda}{4\pi(1-2\Lambda)^2}$$

… but large uncertainties

(truncation in number of operators, cut-off scheme dependence, higher-order loop corrections in matter, etc…)

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

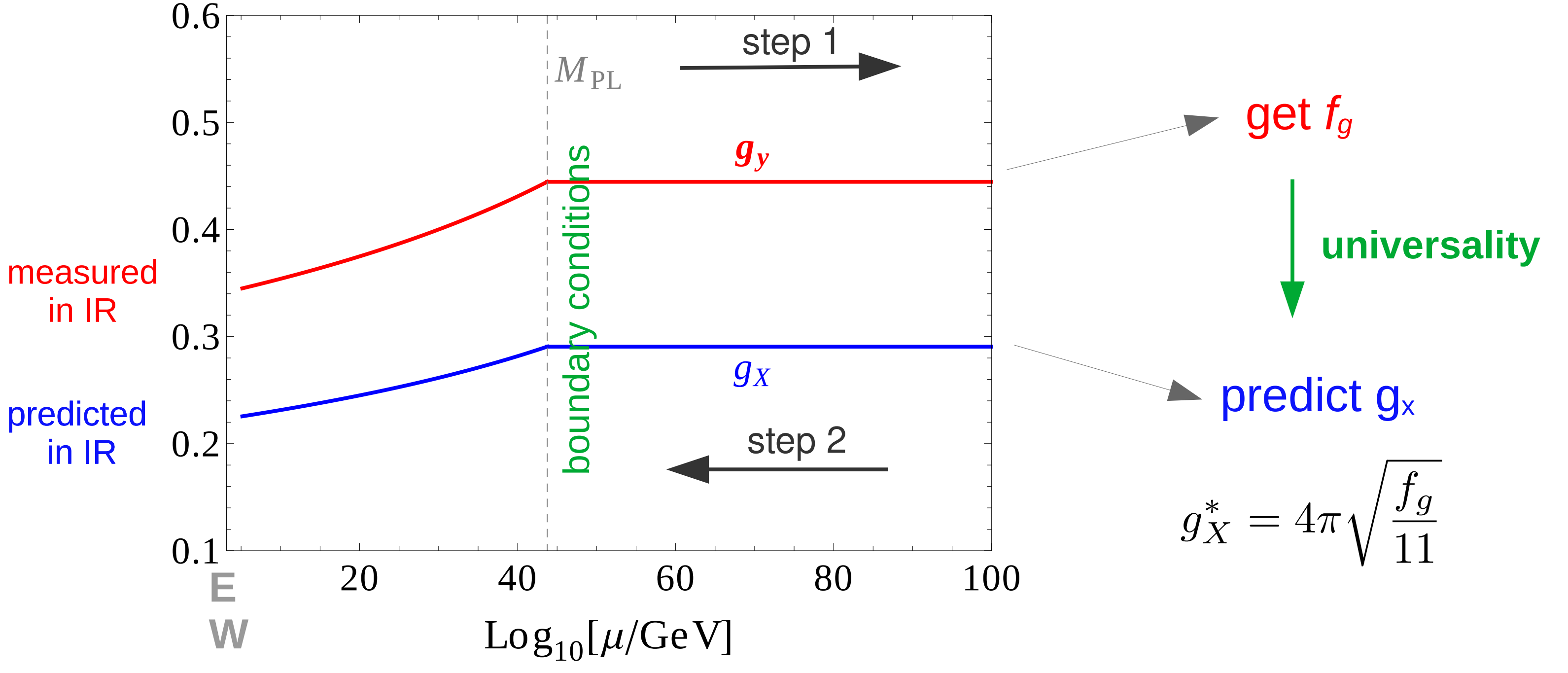
Interacting UV FP in the matter sector!

Predictions from trans-Planckian AS

FRG calculation is *not required* to get predictions...

Wetterich, Shaposhnikov '09, Eichhorn, Held '18, Reichert, Smirnov '19; Alkofer *et al.* '20, KK, Sessolo, Yamamoto '20, KK,Sessolo '21, Chikkaballi, Kotlarski, KK, Rizzo, Sessolo'22 ...

… as the set of *irrelevant* couplings is overconstrained: 3 (or more) eqs (g_Y, y_t, y_X,...)
2 unknowns (f_g, f_y)



$$g_X^* = 4\pi\sqrt{\frac{f_g}{11}}$$

Effective approach - assumptions: (to be discussed later)

- 1-loop matter RGEs
- Planck scale set at 10^{19} GeV
- Gravity parameters *f* are constant
- Gravity decouples instantaneously

Predictions from trans-Planckian AS

Particularly useful to constrain NP models

NP operator (eg. Weinberg operator)

$$\frac{\mathcal{C}_{\rm NP}}{\Lambda^n} \approx \frac{c_i c_j}{m_{\rm NP}^n} \times \text{loop factor}$$

AS: irrelevant couplings c_i
fixed by the RG flow

⇒

Experimental anomaly

measurement of the operator

⇓

bounds on the NP mass derived from the measurement of the operator

AS leads to specific and testable signatures

eg. b→ s anomalies: KK, Sessolo, Yamamoto, Eur.Phys.J.C 81 (2021) 4, 272
Chikkaballi, Kotlarski, KK, Rizzo, Sessolo, JHEP 01 (2023) 164
b→ c anomalies: KK, Sessolo, Yamamoto, Eur.Phys.J.C 81 (2021) 4, 272
g - 2: KK. Sessolo, Phys. Rev. D 103, 115032 (2021)

Predictions for NP
- muon g-2

Predictions from AS: muon (g-2)

Measured value at BNL (2006):

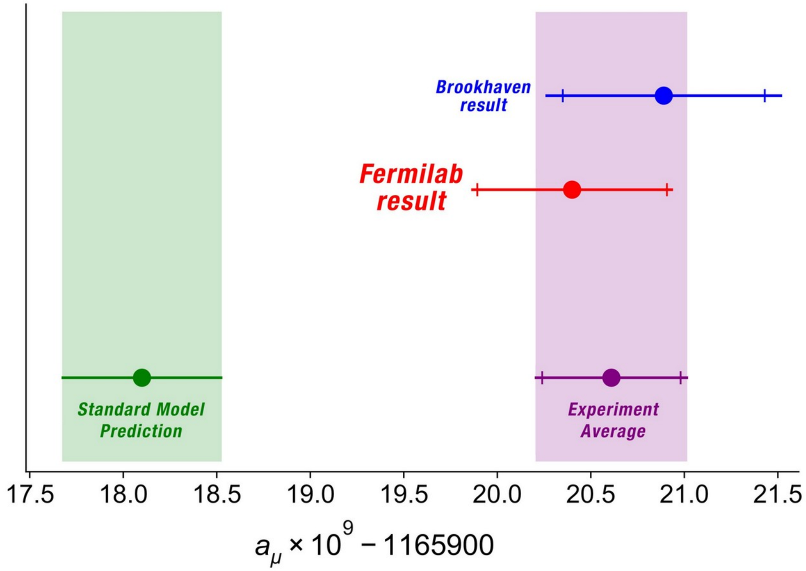
Bennet *et al*, Phys. Rev. D 73 (2006) 072003 (hep-ex/0602035)

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

Measured value at FNAL (2021,2023):

Muon g-2 Collaboration, Phys. Rev. Lett. 126 (2021) 141801
D. P. Aguillard et al. (Muon g-2) (2023), arXiv:2308.06230

$$a_\mu^{\rm FNAL} = (116592055 \pm 24) \times 10^{-11}$$



$$\Delta\, a_\mu = (24.9 \pm 4.8) \times 10^{-10}$$

discrepancy at ~ 5.1 σ

Calls for a NP explanation...

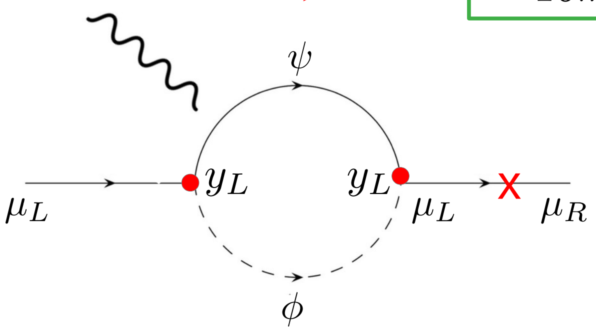
… although stay tuned for the lattice results

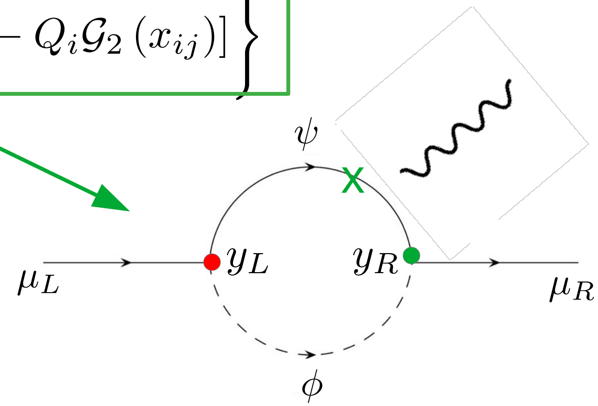
Predictions from AS: muon (g-2)

<u>1-loop contribution from scalar(s) ϕ_i and VL fermions ψ_j</u>

$$\delta(g-2)_\mu = m_\mu \frac{C_5^{\mu\mu\gamma}}{\Lambda} = \sum_{i,j} \left\{ -\frac{m_\mu^2}{16\pi^2 m_{\phi_i}^2} \left(|y_L^{ij\mu}|^2 + |y_R^{ij\mu}|^2 \right) \left[Q_j \mathcal{F}_1(x_{ij}) - Q_i \mathcal{G}_1(x_{ij}) \right] - \frac{m_\mu\, m_{\psi_j}}{16\pi^2 m_{\phi_i}^2} \mathrm{Re}\left(y_L^{ij\mu} y_R^{ij\mu *} \right) \left[Q_j \mathcal{F}_2(x_{ij}) - Q_i \mathcal{G}_2(x_{ij}) \right] \right\}$$

$x_{ij} = m_{\psi_j}^2 / m_{\phi_i}^2$





- minimal: 1 VL lepton and 1 scalar
- $m_\psi,\, m_\phi \sim \mathcal{O}(100\,\mathrm{GeV})$
- Yukawa couplings > 1
- **excluded by the LHC** see P. Athron et al., 2104.03691 for the most recent results
- **Landau Pole** e.g. KK. E.Sessolo, 1707.00753

- 2 VL + 1 S or 1 VL + 2 S needed
- parametrically enhanced
- LHC bounds easily avoided...

… but PS largely unconstrained

Predictions from AS: muon (g-2)

KK, E.M.Sessolo (PRD '21, arXiv: 2012.15200)

minimal SM extension: two <u>different</u> VL leptons + extra scalar

extra assumption: a DM particle and a symmetry to stabilize it

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

Minimally coupled to QG above the Planck scale

$$\frac{dg_Y}{dt} = \frac{g_Y^3}{16\pi^2} B_Y - \underline{f_g\, g_Y}$$

$$\frac{dy_t}{dt} = \frac{1}{16\pi^2}\left[\frac{9}{2}y_t^2 + C_1(Y_1^2+Y_2^2) - \frac{17}{12}g_Y^2 - \frac{9}{4}g_2^2 - 8g_3^2\right] y_t - \underline{f_y\, y_t}$$

$$\frac{dY_1}{dt} = \frac{1}{16\pi^2}\left[3y_t^2 + C_3\, Y_2^2 + \frac{5}{2}C_1\, Y_1^2 + C_6\, Y_L^2 + C_7\, Y_R^2 - G_Y\, g_Y^2 - G_2\, g_2^2\right] Y_1 - f_y\, Y_1$$

$$\frac{dY_2}{dt} = \frac{1}{16\pi^2}\left\{\left[3y_t^2 + \frac{5}{2}C_1\, Y_2^2 + C_3\, Y_1^2 + C_4\, Y_L^2 + \frac{1}{2}Y_R^2 - G_Y\, g_Y^2 - G_2\, g_2^2\right] Y_2 + C_5\, y_\mu\, Y_L\, Y_R\right\} - f_y\, Y_2$$

$$\frac{dY_L}{dt} = \frac{1}{16\pi^2}\left\{\left[C_4\, Y_2^2 + C_6\, Y_1^2 + C_8\, Y_L^2 + C_9\, Y_R^2 + \frac{1}{2}y_\mu^2 - H_Y\, g_Y^2 - H_2\, g_2^2\right] Y_L + C_5\, y_\mu\, Y_R\, Y_2\right\} - f_y\, Y_L$$

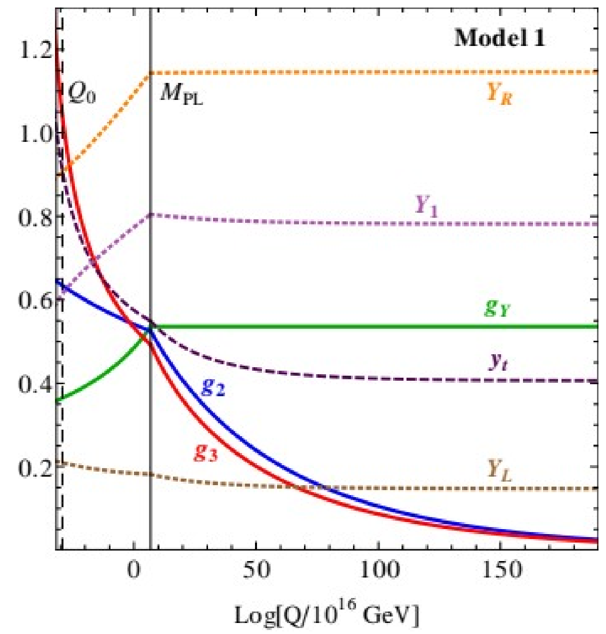
$$\frac{dY_R}{dt} = \frac{1}{16\pi^2}\left\{\left[Y_2^2 + 2\, C_7\, Y_1^2 + 2\, C_9\, Y_L^2 + C_{10}\, Y_R^2 + y_\mu^2 - J_Y\, g_Y^2 - J_2\, g_2^2\right] Y_R + 2\, C_5\, y_\mu\, Y_L\, Y_2\right\} - f_y\, Y_R$$

Predictions from AS: muon (g-2)

KK, E.M.Sessolo (PRD ’21, arXiv: 2012.15200)

IR predictions ←

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



UV fixed point

$Y_R^* \neq 0$

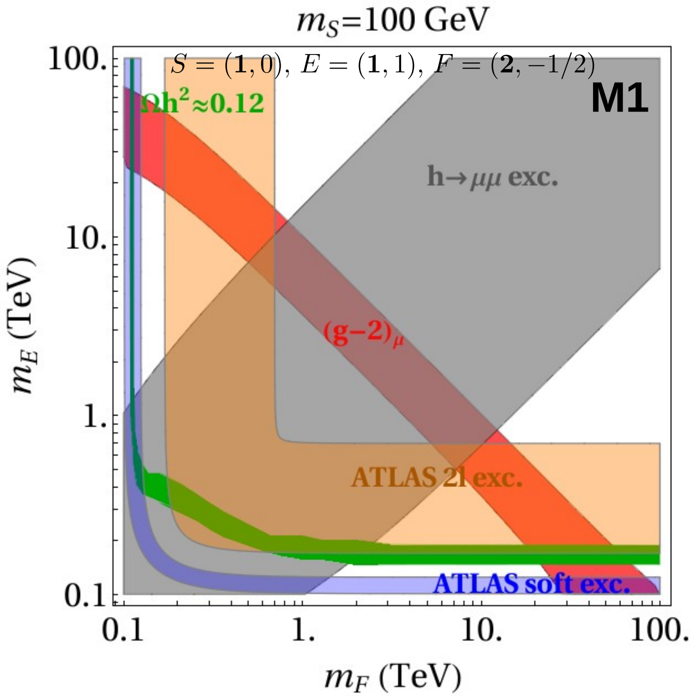
$Y_1^* \neq 0$

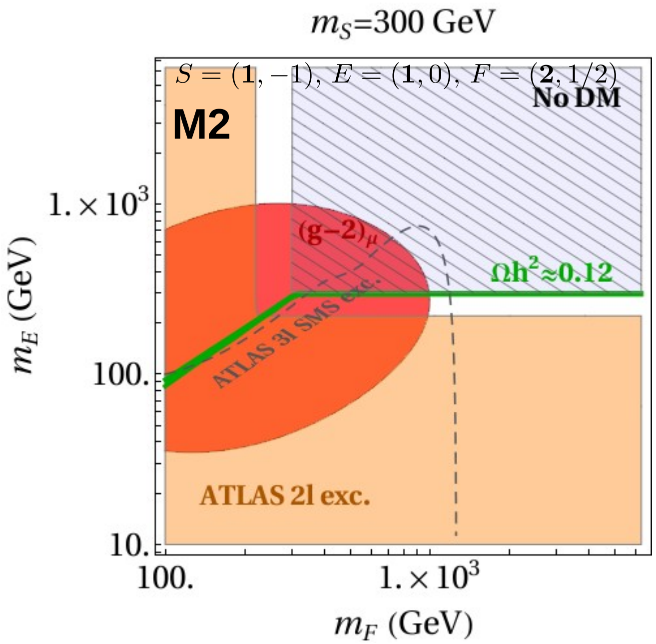
$g_Y^* = 4\pi\sqrt{\frac{f_g}{B_Y}}$

$y_t^* = F(f_g, f_y)$

$Y_L^* \neq 0$

free parameters: m_S, m_E, m_F





1) Fundamentally different and testable signatures.

Entirely consequence of asymptotic safety.

2) Relevant parameters constrained.

Other BSM predictions can be made...

- **anomalies in $b \to s$**

  KK, E.M.Sessolo, Y.Yamamoto,
  Eur.Phys.J.C 81 (2021) 4, 272

  A.Chikkaballi, W. Kotlarski, KK, D.Rizzo, E.M.Sessolo,
  JHEP 01 (2023) 164

- **anomalies in $b \to c$**

  KK, E.M.Sessolo, Y.Yamamoto,
  Eur.Phys.J.C 81 (2021) 4, 272

- **neutrino masses**

  KK, S.Pramanick, E.M.Sessolo,
  JHEP 08 (2022) 262

  A.Chikkaballi, KK, E.M.Sessolo,
  arXiv: 2308.06114

→ **Naturally small parameters**

see Enrico's talk

- **dark matter, baryon number, ALPs, GWs**

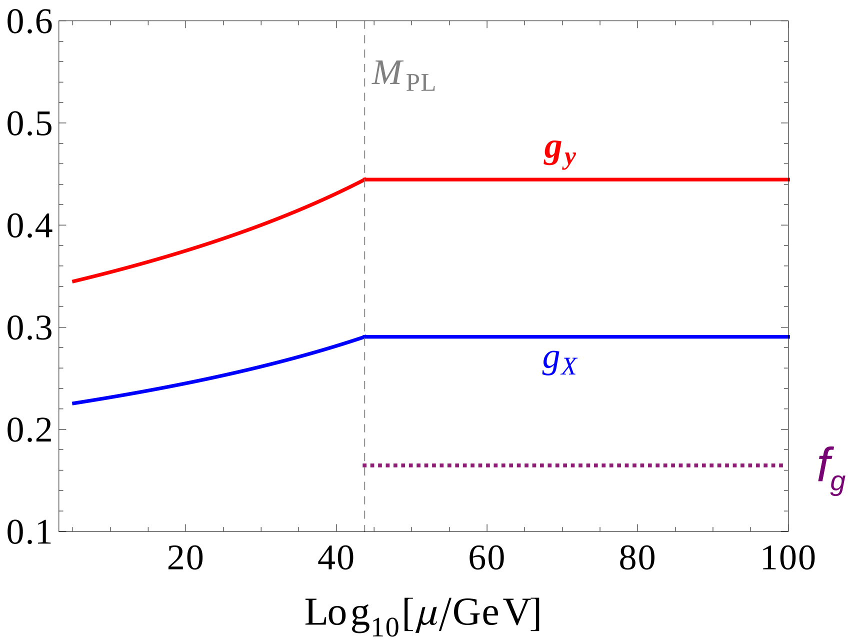
  see eg. Reichert, Smirnov, 1803.04027; Grabowski, Kwapisz, Meissner, 1810.08461; Hamada, Tsumura, Yamada, 2002.03666, Eichhorn, Pauly, 2005.03661; de Brito, Eichhorn, Lino dos Santos, 2112.08972, Boos, Carone, Donald, Musser, 2206.02686, 2209.14268, Eichhorn, dos Santos, Miqueleto, 2306.17718, ….

Uncertainties of the effective approach

Predictions for NP - assumptions

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC '23, arXiv: 2304.08959

- 1-loop matter RGEs
- Planck scale set at 10^{19} GeV
- Gravity parameters *f* are constant
- Gravity decouples instantaneously



Predictions for NP - assumptions

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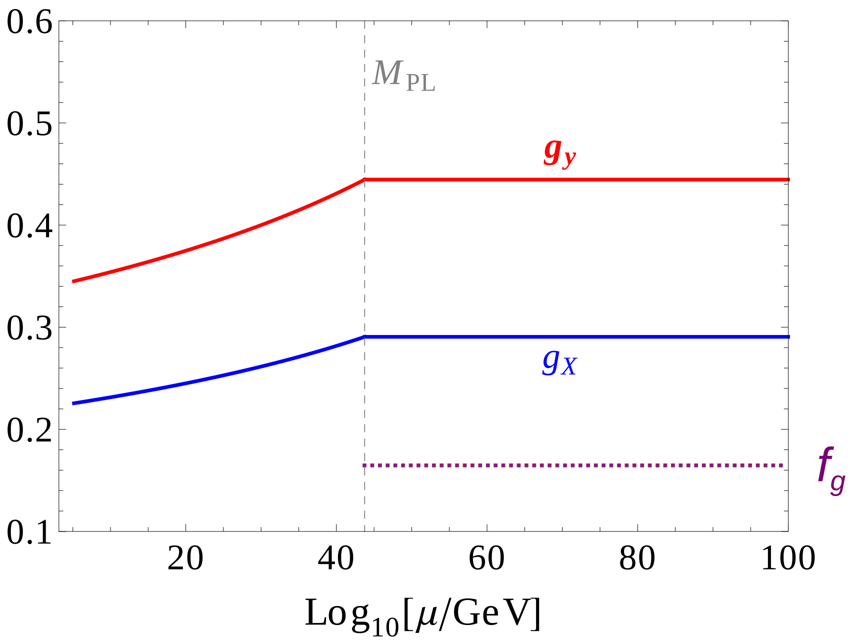
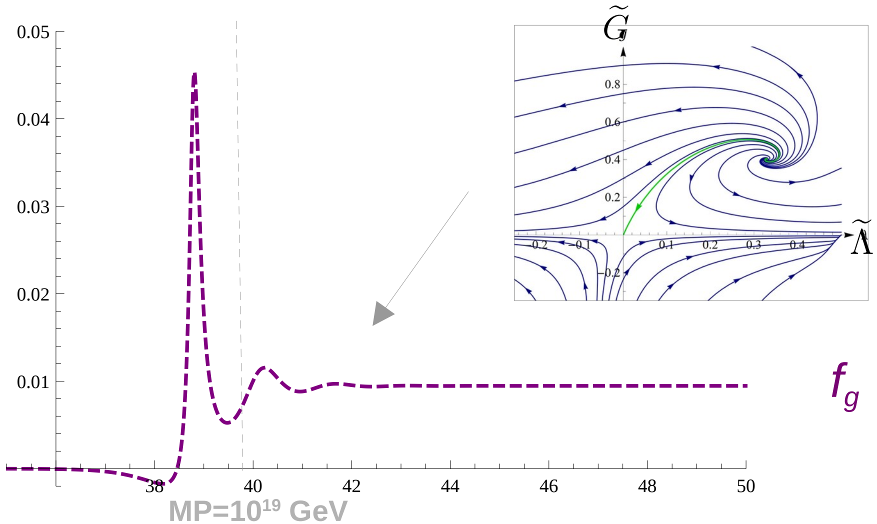


But in FRG:

eg. EH truncation, α=0, β=1 g.f
A. Eichhorn, F. Versteegen, JHEP 01 (2018) 030

$$f_g(t) = \tilde{G}(t)\frac{1-4\tilde{\Lambda}(t)}{4\pi\left(1-2\tilde{\Lambda}(t)\right)^2}$$



Let's drop the assumptions...

Predictions for NP - assumptions

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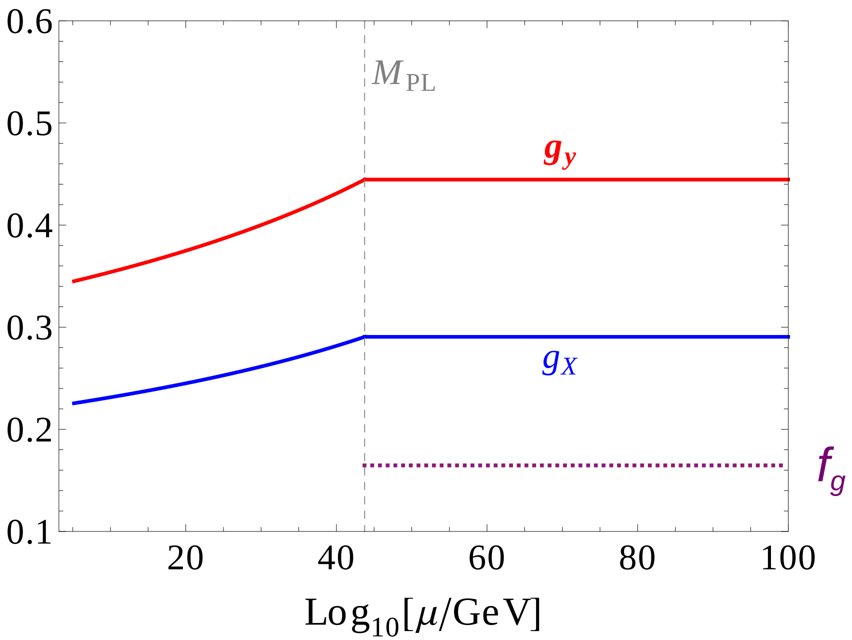


uncertainties from FP analysis
should be below
experimental uncertainties of Wilson coefficients

ex. for g-2: $$\frac{\delta C_{NP}}{C_{NP}} \sim \frac{1}{5(\sigma)} \approx 20\%$$

Uncertainties – gauge sector

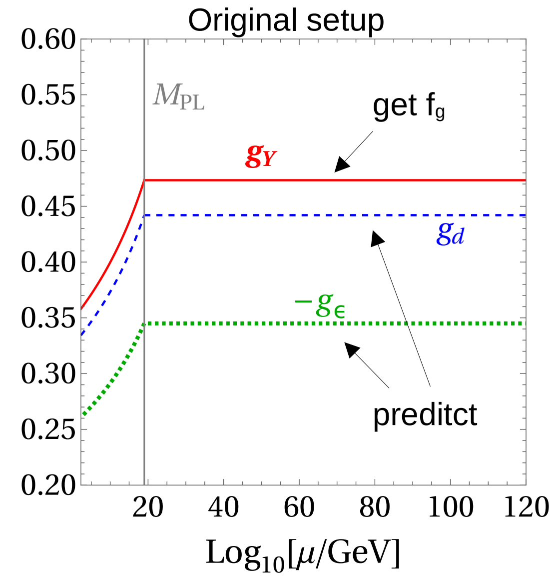
W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC '23, arXiv: 2304.08959

eg. $U(1)_Y \times U(1)_D$

$$\frac{dg_Y}{dt} = \frac{1}{16\pi^2} \overbrace{\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right)}^{\tilde{b}_Y} g_Y^3 - g_Y\, f_g(t)$$

$$\frac{dg_d}{dt} = \frac{1}{16\pi^2} \left[\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right) g_d g_\epsilon^2 + \left(b_d + \Pi^{(d)}_{n\geq 2}\right) g_d^3 + \left(b_\epsilon + \Pi^{(\epsilon)}_{n\geq 2}\right) g_d^2 g_\epsilon\right] - g_d\, f_g(t)$$

$$\frac{dg_\epsilon}{dt} = \frac{1}{16\pi^2} \left[\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right) \left(g_\epsilon^3 + 2 g_Y^2 g_\epsilon\right) + \left(b_d + \Pi^{(d)}_{n\geq 2}\right) g_d^2 g_\epsilon + \left(b_\epsilon + \Pi^{(\epsilon)}_{n\geq 2}\right) \left(g_Y^2 g_d + g_d g_\epsilon^2\right)\right] - g_\epsilon\, f_g(t)$$

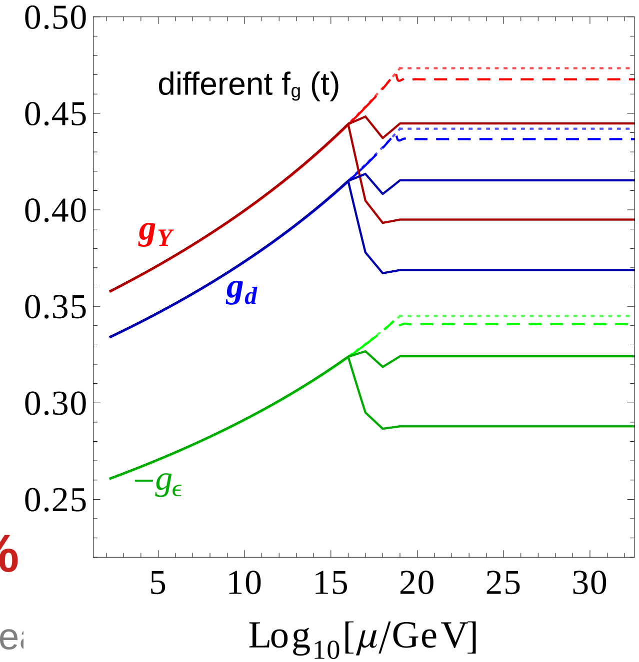


The coupling ratios do not depend on f_g
(due to the universality of QG)

$$\frac{g_d^*}{g_Y^*}(n \text{ loops}) \approx \frac{2\tilde{b}_Y}{\sqrt{4\tilde{b}_Y \tilde{b}_d - \tilde{b}_\epsilon^2}}$$

$$\frac{g_\epsilon^*}{g_Y^*}(n \text{ loops}) \approx -\frac{\tilde{b}_\epsilon}{\sqrt{4\tilde{b}_Y \tilde{b}_d - \tilde{b}_\epsilon^2}}$$

Invariant of the RGE flow ⇒



PREDICTIONS VERY STABLE

$\delta g \leq 0.1\%$

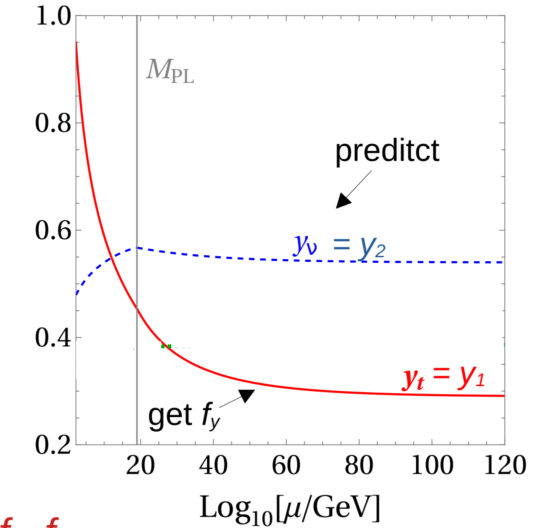
Uncertainties – Yukawa sector

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC '23, arXiv: 2304.08959

2-Yukawa system

$$\frac{dy_1}{dt} = \frac{y_1}{16\pi^2}\left(a_1^{(1)} y_1^2 + a_2^{(1)} y_2^2 - a'^{(1)} g_1^2 + \sum_{n\geq 2} \Pi_n^{(1)}\right) - y_1 f_y(t)$$

$$\frac{dy_2}{dt} = \frac{y_2}{16\pi^2}\left(a_1^{(2)} y_1^2 + a_2^{(2)} y_2^2 - a'^{(2)} g_1^2 + \sum_{n\geq 2} \Pi_n^{(2)}\right) - y_2 f_y(t)$$



The FP ratio y_2 to y_1 depends on FP of other couplings

fixed f_g and f_y — shift due to the running f_g, f_y

$$\frac{y_2^*}{y_1^*}(1\text{ loop}) \approx \left[\frac{\left(a_1^{(2)} - a_1^{(1)}\right) + \left(a'^{(1)} - a'^{(2)}\right) g_1^{*2}/y_1^{*2}}{a_2^{(1)} - a_2^{(2)}} + \frac{\left(a_1^{(2)} - a_1^{(1)}\right)\delta y_1^{*2} + \left(a'^{(1)} - a'^{(2)}\right)\delta g_1^{*2}}{y_1^{*2}(a_2^{(1)} - a_2^{(2)})}\right]^{1/2}$$

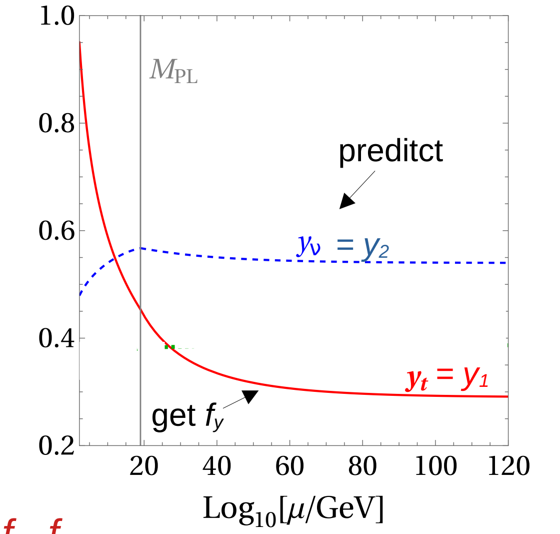
Uncertainties – Yukawa sector

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC '23, arXiv: 2304.08959

<u>2-Yukawa system</u>

$$\frac{dy_1}{dt} = \frac{y_1}{16\pi^2}\left(a_1^{(1)}y_1^2 + a_2^{(1)}y_2^2 - a'^{(1)}g_1^2 + \sum_{n\geq 2}\Pi_n^{(1)}\right) - y_1 f_y(t)$$

$$\frac{dy_2}{dt} = \frac{y_2}{16\pi^2}\left(a_1^{(2)}y_1^2 + a_2^{(2)}y_2^2 - a'^{(2)}g_1^2 + \sum_{n\geq 2}\Pi_n^{(2)}\right) - y_2 f_y(t)$$



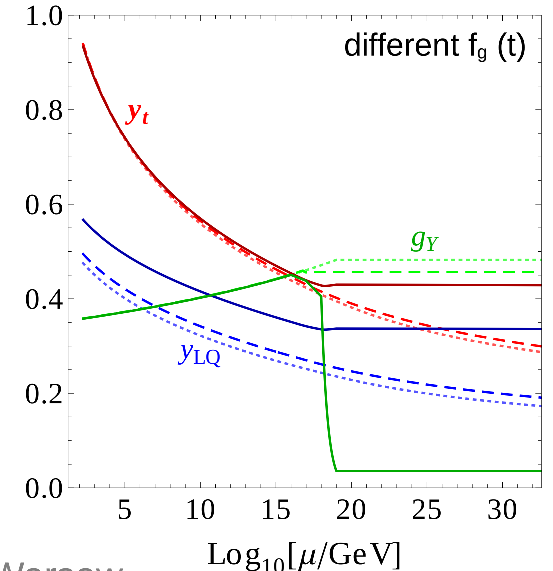
The FP ratio y_2 to y_1 depends on FP of other couplings

fixed f_g and f_y — shift due to the running f_g, f_y

$$\frac{y_2^*}{y_1^*}(1\text{ loop}) \approx \left[\frac{\left(a_1^{(2)} - a_1^{(1)}\right) + \left(a'^{(1)} - a'^{(2)}\right) g_1^{*2}/y_1^{*2}}{a_2^{(1)} - a_2^{(2)}} + \frac{\left(a_1^{(2)} - a_1^{(1)}\right)\delta y_1^{*2} + \left(a'^{(1)} - a'^{(2)}\right)\delta g_1^{*2}}{y_1^{*2}(a_2^{(1)} - a_2^{(2)})}\right]^{1/2}$$

<u>eg. LQ S_3 model:</u>

$$\mathcal{L} \supset -Y_{\mathrm{LQ}}\, Q^T \tilde{\epsilon} S_3\, L + \mathrm{H.c.}$$



PREDICTION UNSTABLE ...

Uncertainties – Yukawa sector

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$$\frac{dy_1}{dt} = \frac{y_1}{16\pi^2}\left(a_1^{(1)}y_1^2 + a_2^{(1)}y_2^2 - a'^{(1)}g_1^2 + \sum_{n\geq 2}\Pi_n^{(1)}\right) - y_1 f_y(t)$$

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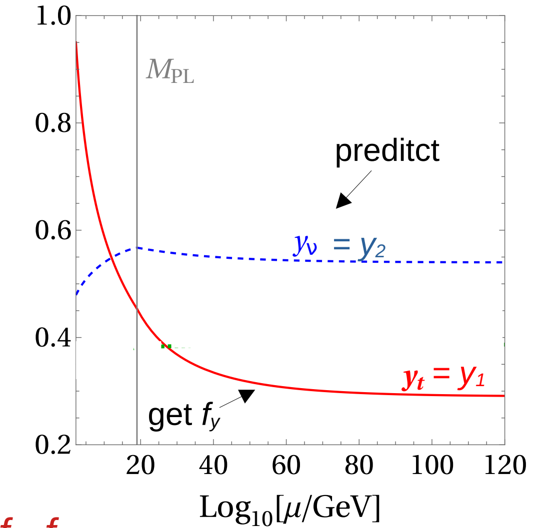

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$$\frac{y_2^*}{y_1^*}(1\ \text{loop}) \approx \left[\frac{\left(a_1^{(2)} - a_1^{(1)}\right) + \left(a'^{(1)} - a'^{(2)}\right) g_1^{*2}/y_1^{*2}}{a_2^{(1)} - a_2^{(2)}} + \frac{\left(a_1^{(2)} - a_1^{(1)}\right)\delta y_1^{*2} + \left(a'^{(1)} - a'^{(2)}\right)\delta g_1^{*2}}{y_1^{*2}(a_2^{(1)} - a_2^{(2)})}\right]^{1/2}$$

eg. LQ S_3 model:

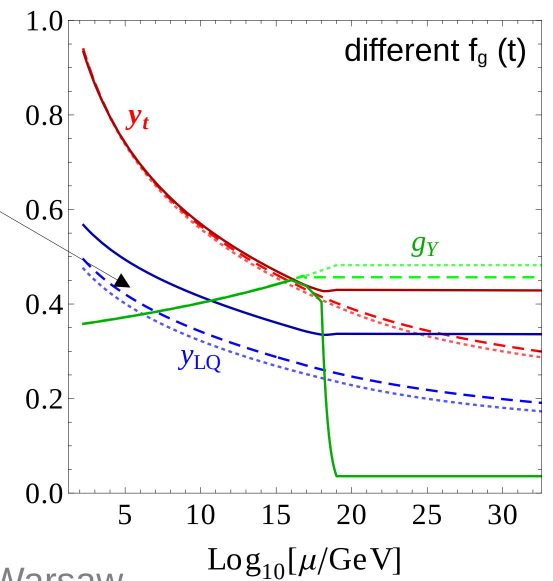
$$\mathcal{L} \supset -Y_{\mathrm{LQ}}\, Q^T \tilde{\epsilon} S_3\, L + \mathrm{H.c.}$$

... but not so much in FRG

... IR focusing helps

PREDICTION UNSTABLE ...

$\delta y \leq 20\%$



Conclusions

- Trans-Planckian AS is a **very predictive UV framework.** Applications for SM and NP.
- Flavor anomalies, *g-2* anomaly, dark matter, etc. can lead to very **testable signatures**.
- **AS predictions** in the **gauge sector** are **stable** under higher-order corrections and running of the gravity parameters.
- **Uncertainties** of the AS predictions in **the Yukawa sector** do **not exceed 20%**.