Quantum gravity contributions to the gauge and Yukawa couplings in proper time flow

Daniele Rizzo

in collaboration with

Gabriele Giacometti, Kamila Kowalska, Enrico Sessolo & Dario Zappalà

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The flow equation for the Wilsonian action in proper time regularization

$$k\partial_k S_k = -\frac{1}{2}\int_0^\infty \frac{ds}{s}\mathrm{Tr}\left[k\partial_k \rho_k\, e^{-s\, S_k''}\right]$$

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Parameterized by a number m.

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*Giacometti, **DR**, Zappala (2025)*

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The 2-loop beta function and anomalous dimension of the scalar O(N) theory are correct!

$$\beta^{2L}_{\mathrm{O(N)}} = \frac{\lambda^2}{(16\pi^2)}\,\frac{(N+8)}{3} - \frac{\lambda^3}{(16\pi^2)^2}\,\frac{(10N+44)}{9} + 2\eta^{2L}_{\mathrm{O(N)}}\lambda$$

Correctness of the purely local part is expected -- Litim, Pawlowski (2002)

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Using background gauge fixing, the 2-loop beta function of the Yang-Mills SU(N) theory is correct!

$$\beta_{\mathrm{SU(N)}} = -\frac{11}{3}\frac{N}{16\pi^2}g^3 - \frac{34}{3}\frac{N^2}{(16\pi^2)^2}g^5$$

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Bringing ASQG to particle physics: the SM at high energy

Generic 1-loop running of gauge couplings

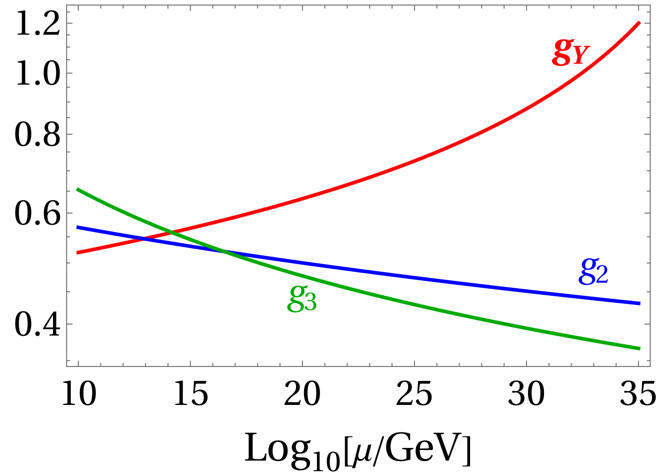
$$\beta(g_1) = +b_{11}\, g_1^3$$

Always positive, even with extra gauge groups

$$\beta(g_2) = -b_{22}\, g_2^3$$

$$\beta(g_3) = -b_{33}\, g_3^3$$

Can be negative, but in the SM they are positive

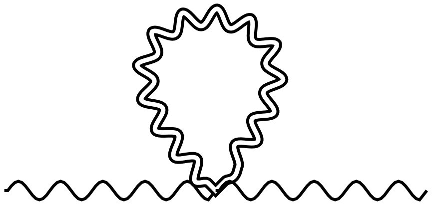


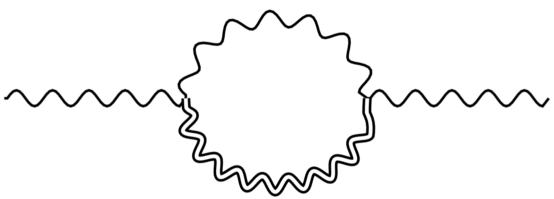
Landau Pole for hypercharge, which however is above the Planck scale

BSM physics (new fermions, new gauge groups) could realize GUT

But maybe QG ~ Planck scale change <u>qualitatively</u> the asymptotic behavior

How does gravity influence the running of the gauge sector of the SM?





$$\longrightarrow \quad \beta(g_i) \supset -f_g\, g_i$$

fg does not depend on the particular gauge coupling

Similarly, in the running of Yukawa couplings the quantum gravity contribution is universal, which defines fy.

Propertime calculations of fg and fy: setup

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The bare Wilsonian action is built from Einstein-Hilbert coupled to QED and a Yukawa-like interaction

$$S = -\frac{1}{16\pi G}\int d^4x\,\sqrt{g}\,(R-2\Lambda) + \frac{1}{32\pi G\,\alpha}\int d^4x\sqrt{\bar{g}}\,\bar{g}^{\mu\nu}F_\mu F_\nu + S_{\text{ghost}}$$
$$+\frac{1}{4}\int d^4x\,\sqrt{g}g^{\mu\nu}g^{\kappa\lambda}F_{\mu\kappa}F_{\nu\lambda} + \frac{1}{2\xi}\int d^4x\,\sqrt{\bar{g}}\,\left(\bar{g}^{\mu\nu}\bar{D}_\mu a_\nu\right)^2 + \int d^4x\,\sqrt{g}\,y\,\bar{\psi}\phi\psi$$

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We use background field method

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu} \qquad \psi = \tilde{\psi} + \delta\psi$$
$$A_\mu = \bar{A}_\mu + a_\mu \qquad \phi = \tilde{\phi} + \delta\phi$$

Usual De Donder gauge choice

$$F_\mu = \left(\bar{g}^{\alpha\gamma}\delta^\beta_\mu\bar{D}_\gamma - \frac{1}{2}\bar{g}^{\alpha\beta}\bar{D}_\mu\right)h_{\alpha\beta}$$

We extract fg from the gauge propagator rather than from three or four point functions for simplicity

Computations are performed in flat Euclidean background for simplicity

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No need to include matter fields charged under the (electromagnetic) abelian gauge symmetry

Einstein-Hilbert propertime calculation of fg

$$\mathbb{H} = \begin{pmatrix} \mathbb{H}_{hh}^{\alpha\beta\mu\nu} & \mathbb{H}_{ha}^{\alpha\beta\sigma} \\ \mathbb{H}_{ah}^{\rho\mu\nu} & \mathbb{H}_{aa}^{\rho\sigma} \end{pmatrix} = -\mathbb{K}\Box + 2\mathbb{V}^{\delta}\bar{D}_{\delta} + \mathbb{U}$$

$$k\partial_k S_k = -\frac{1}{2}\int_0^\infty \frac{ds}{s}\mathrm{Tr}\left[k\partial_k \rho_{k,k_{\mathrm{UV}}}(s) e^{-s\, S_k''}\right]$$

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Diagonalization is a standard procedure:

1) Canonicalize the heat kernel
by multiplying for the inverse of K

$$\mathbb{P}^{\rho\sigma}_{aa} = (16\pi G)^{-1}\left(g^{\rho\sigma} - (1-\xi)\,\frac{p^{\rho}p^{\sigma}}{p^2}\right)$$

$$\mathbb{P}^{\alpha\beta\mu\nu}_{hh} = g^{\alpha\mu}g^{\beta\nu} + g^{\alpha\nu}g^{\beta\mu} - g^{\alpha\beta}g^{\mu\nu} - (1-\alpha)\,\frac{g^{\alpha\mu}p^{\beta}p^{\nu} + g^{\alpha\nu}p^{\beta}p^{\mu} + g^{\beta\mu}p^{\alpha}p^{\nu} + g^{\beta\nu}p^{\alpha}p^{\mu}}{p^2}$$

Toms (2011)

2) Complete the square to remove the
term linear in the covariant derivative

Jackiw (1978)

$$\tilde{\mathbb{W}}^{\alpha\beta\mu\nu}_{hh} = \mathbb{W}^{\alpha\beta\mu\nu}_{hh} + \mathbb{Y}^{\alpha\beta\kappa}_{ha}\mathbb{Y}^{\tau\mu\nu}_{ah\,\kappa}\left(\frac{4p_{\lambda}p_{\tau}}{p^2}\right)$$

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Sunset

Tadpole

3) The obtained hessian is block diagonal

$$\tilde{\mathbb{H}} = \begin{pmatrix} \tilde{\mathbb{H}}^{\alpha\beta\mu\nu}_{hh} & 0 \\ 0 & \tilde{\mathbb{H}}^{\rho\sigma}_{aa} \end{pmatrix} = -\Box + \tilde{\mathbb{W}}$$

$$\boxed{f_g = \frac{3m\tilde{G}}{2\pi\,(m-1)}\,(1+\alpha)}$$

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$$\boxed{f_g = \frac{3m\tilde{G}}{2\pi(m-1)}(1+\alpha)}$$

- Contribution only from 1st term of (photon) heat kernel
- No cosmological constant
- No exp suppression

Einstein-Hilbert propertime calculation of fy

$$\mathbb{H} = \begin{pmatrix} \mathbb{H}_{hh}^{\alpha\beta\mu\nu} & \mathbb{H}_{h\psi}^{\alpha\beta} & \mathbb{H}_{h\phi}^{\alpha\beta} \\ \mathbb{H}_{\bar{\psi}h}^{\mu\nu} & \mathbb{H}_{\bar{\psi}\psi} & \mathbb{H}_{\bar{\psi}\phi} \\ \mathbb{H}_{\phi h}^{\mu\nu} & \mathbb{H}_{\phi\psi} & \mathbb{H}_{\phi\phi} \end{pmatrix} = -\Box + \mathbb{W} \qquad \mathbb{W}^{\alpha\beta\mu\nu} = \left(\Lambda + 8\pi G y\, \bar{\tilde{\psi}}\tilde{\phi}\,\tilde{\psi}\right) \mathcal{O}^{\alpha\beta\mu\nu}$$

$$\mathcal{O}^{\alpha\beta\mu\nu} = -\left(g^{\alpha\mu}g^{\beta\nu} + g^{\alpha\nu}g^{\beta\mu}\right) + \frac{\alpha-1}{p^2}\left[2g^{\mu\nu}p^\alpha p^\beta - \left(g^{\beta\nu}p^\alpha p^\mu + g^{\alpha\nu}p^\beta p^\mu + g^{\beta\mu}p^\alpha p^\nu + g^{\alpha\mu}p^\beta p^\nu\right)\right]$$

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$$\mathrm{Tr}\, e^{-s\left(\Lambda + 8\pi G y\, \bar{\tilde{\psi}}\tilde{\phi}\tilde{\psi}\right)\mathcal{O}} = 6\, e^{2s\Lambda} e^{2s\left(8\pi G y\, \bar{\tilde{\psi}}\tilde{\phi}\tilde{\psi}\right)} + 4\, e^{2\alpha s\Lambda} e^{2\alpha s\left(8\pi G y\, \bar{\tilde{\psi}}\tilde{\phi}\tilde{\psi}\right)}$$

The running of the Yukawa coupling gets a contribution from QG

$$\boxed{f_y = -\frac{2\tilde{G}}{\pi}\frac{m}{m-1}\left[3\left(1 - 2\frac{\tilde{\Lambda}}{m}\right)^{1-m} + 2\alpha\left(1 - 2\alpha\frac{\tilde{\Lambda}}{m}\right)^{1-m}\right]}$$

Sharp cutoff: $\boxed{f_y = -\frac{2\tilde{G}}{\pi}\left(3\, e^{2\tilde{\Lambda}} + 2\alpha\, e^{2\alpha\tilde{\Lambda}}\right)}$

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- **Always negative!**

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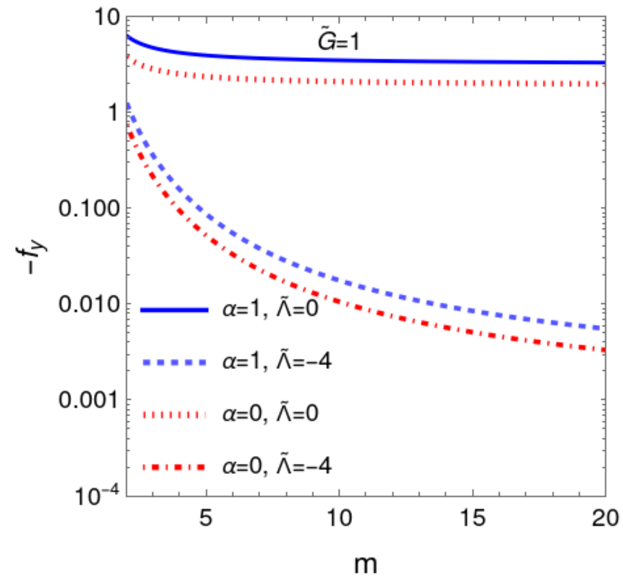

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The running on Newton and cosmological constants: *Donà, Eichhorn, Percacci (2014)*

$$\beta_{\tilde{\Lambda}} = (\eta_G - 2)\,\tilde{\Lambda} + \Phi + \frac{\tilde{G}}{4\pi}\,(N_S - 4N_D + 2N_V) + \frac{\tilde{G}\tilde{\Lambda}}{6\pi}\,(2N_D + N_S - 4N_V)$$

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Number of real scalars

$$\beta_{\tilde G} = 2\,\tilde G + \eta_G \tilde G + \frac{\tilde G^2}{6\pi}\,(2N_D + N_S - 4N_V)$$

The running on Newton and cosmological constants:

Donà, Eichhorn, Percacci (2014)

$$\beta_{\tilde{\Lambda}} = (\eta_G - 2)\,\tilde{\Lambda} + \Phi + \frac{\tilde{G}}{4\pi}\,(N_S - 4N_D + 2N_V) + \frac{\tilde{G}\tilde{\Lambda}}{6\pi}\,(2N_D + N_S - 4N_V)$$

Number of real scalars

Number of vector fields

$$\beta_{\tilde{G}} = 2\,\tilde{G} + \eta_G \tilde{G} + \frac{\tilde{G}^2}{6\pi}\,(2N_D + N_S - 4N_V)$$

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Number of Dirac fermions

Einstein-Hilbert propertime calculation of QG fixed point

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Number of Dirac fermions

In PTRG, in sharp cutoff limit, the anomalous dimensions are

$$\eta_G(m \to \infty) = \frac{\tilde{G}}{6\pi}\left(e^{-\frac{4\tilde{\Lambda}}{\alpha-3}} + \frac{(7\alpha-9)e^{-\frac{4\alpha\tilde{\Lambda}}{\alpha-3}}}{\alpha-3} + \frac{54-14\alpha}{\alpha-3} + (6-9\alpha)e^{2\alpha\tilde{\Lambda}} - 25e^{2\tilde{\Lambda}}\right)$$

$$\Phi(m \to \infty) = \frac{\tilde{G}}{2\pi}\left(e^{-\frac{4\tilde{\Lambda}}{\alpha-3}} + 3e^{2\alpha\tilde{\Lambda}} + e^{-\frac{4\alpha\tilde{\Lambda}}{\alpha-3}} + 5e^{2\tilde{\Lambda}} - 8\right)$$

Einstein-Hilbert propertime calculation of QG fixed point

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The running on Newton and cosmological constants:

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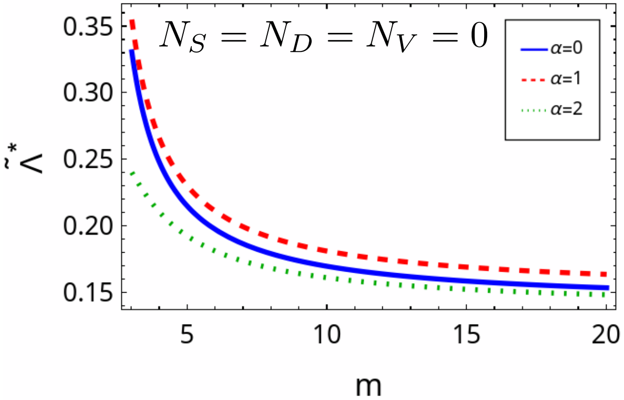

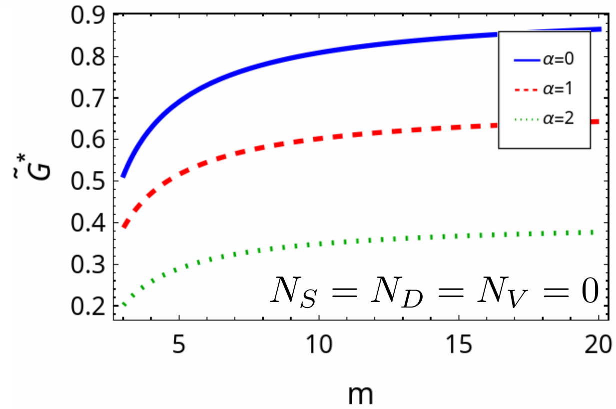

Numerical Results: Minimal Matter Model

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$$f_g = \frac{3m\tilde{G}}{2\pi\,(m-1)}\,(1+\alpha) \xrightarrow{\quad m\to\infty \quad} f_g = \frac{3\tilde{G}}{2\pi}\,(1+\alpha)$$

$$f_y = -\frac{2\tilde{G}}{\pi}\frac{m}{m-1}\left[3\left(1-2\frac{\tilde{\Lambda}}{m}\right)^{1-m} + 2\alpha\left(1-2\alpha\frac{\tilde{\Lambda}}{m}\right)^{1-m}\right]$$

$$\Big\downarrow\; m\to\infty$$

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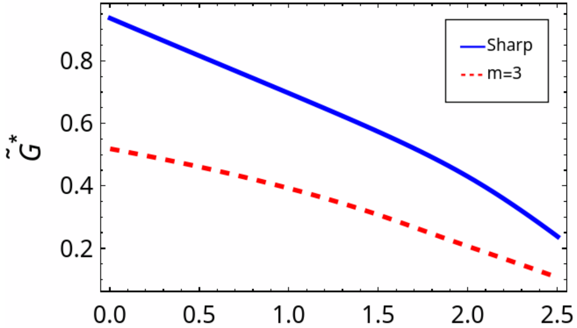
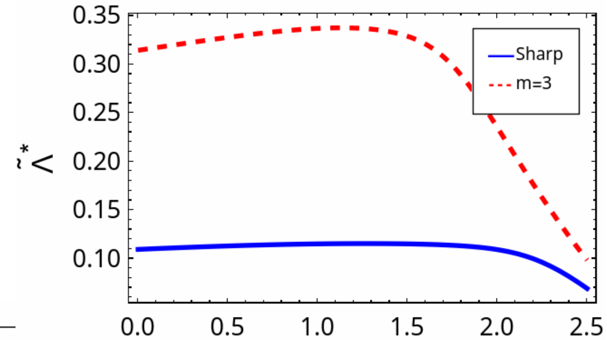
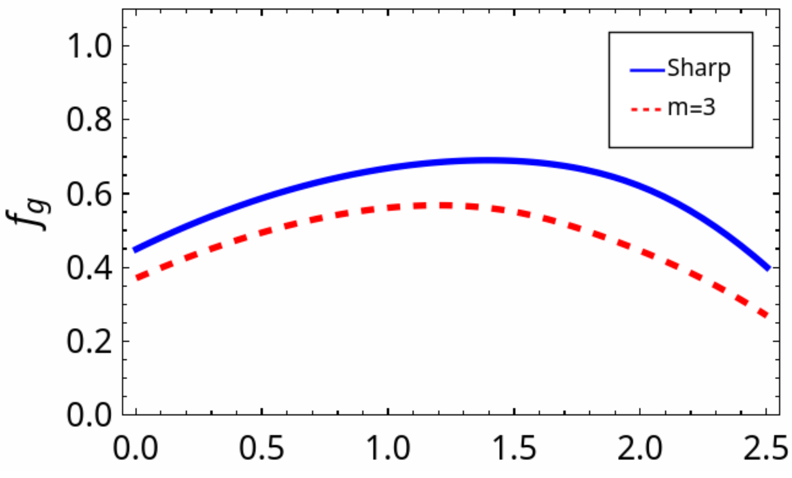
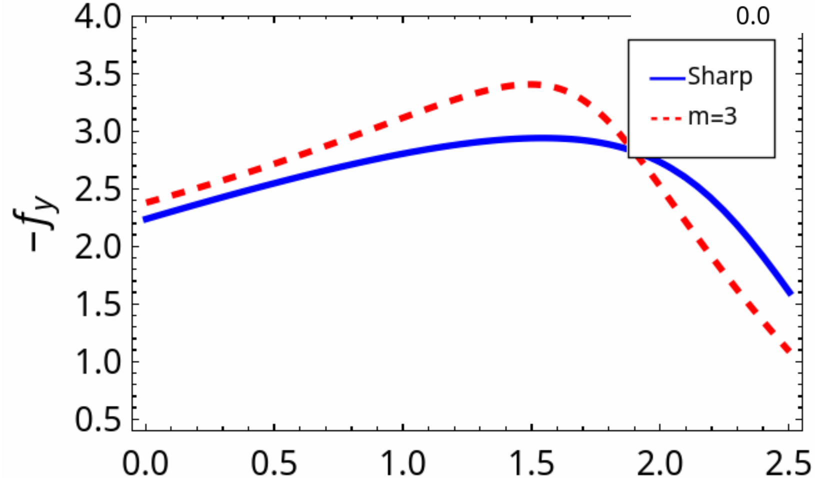




$$N_S = N_D = N_V = 1$$





On the x-axis it is always α

Numerical Results: Standard Model

$$f_g = \frac{3m\tilde{G}}{2\pi\,(m-1)}\,(1+\alpha) \xrightarrow{m\to\infty} f_g = \frac{3\tilde{G}}{2\pi}\,(1+\alpha)$$

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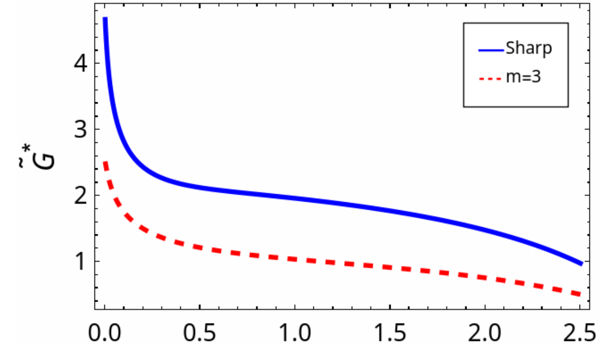
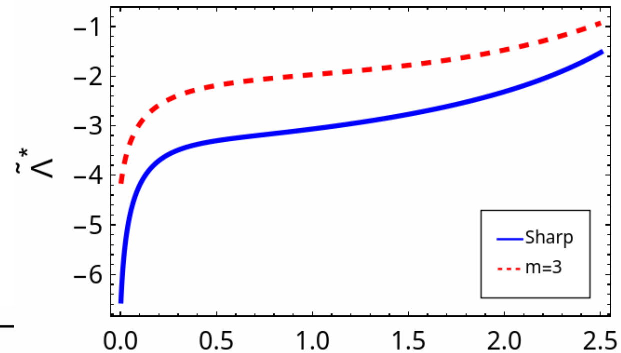
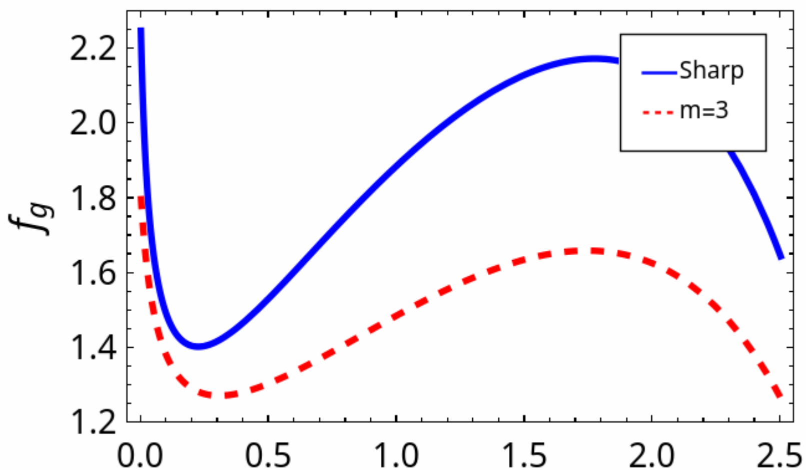
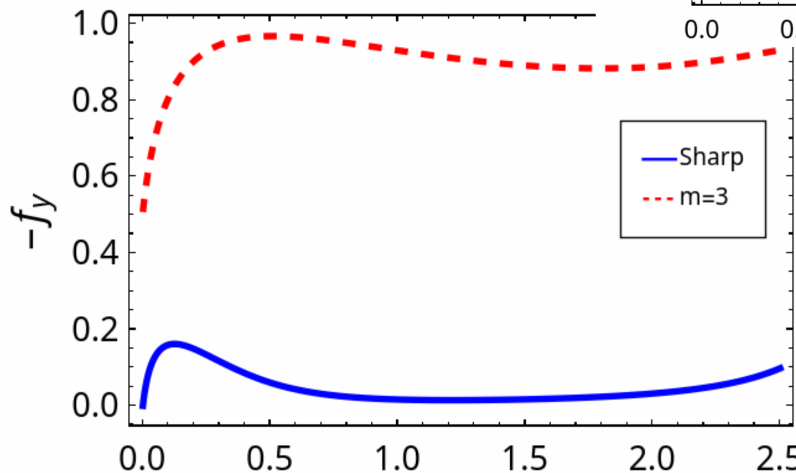
$$f_y = -\frac{2\tilde{G}}{\pi}\left(3\,e^{2\tilde{\Lambda}} + 2\alpha\,e^{2\alpha\tilde{\Lambda}}\right)$$

$N_S = 4\,,\ N_D = 45/2\,,\ N_V = 12$









On the x-axis it is always α

Renormalization Group Equations in the Sub-Planckian regime

$$\beta_g = \beta_g^{\mathrm{SM+NP}}$$

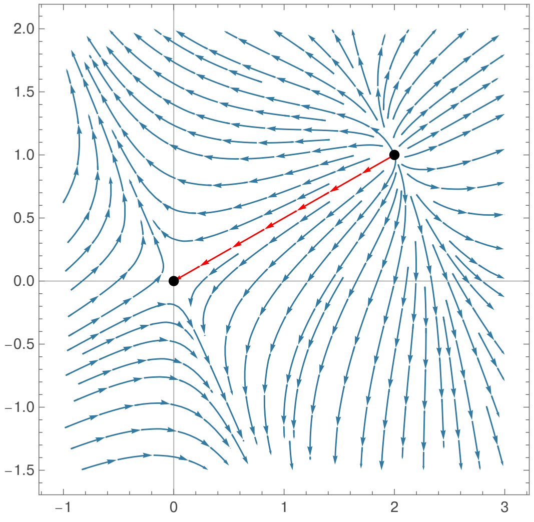
$$\beta_y = \beta_y^{\mathrm{SM+NP}}$$

Renormalization Group Equations in the Trans-Planckian regime

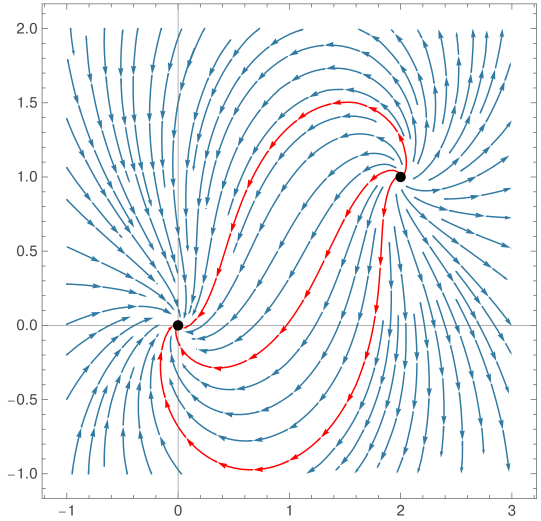
$$\beta_g = \beta_g^{\mathrm{SM+NP}} - g\, f_g$$

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

fg and fy are determined by matching the low-energy data.



Relevant → Free parameter



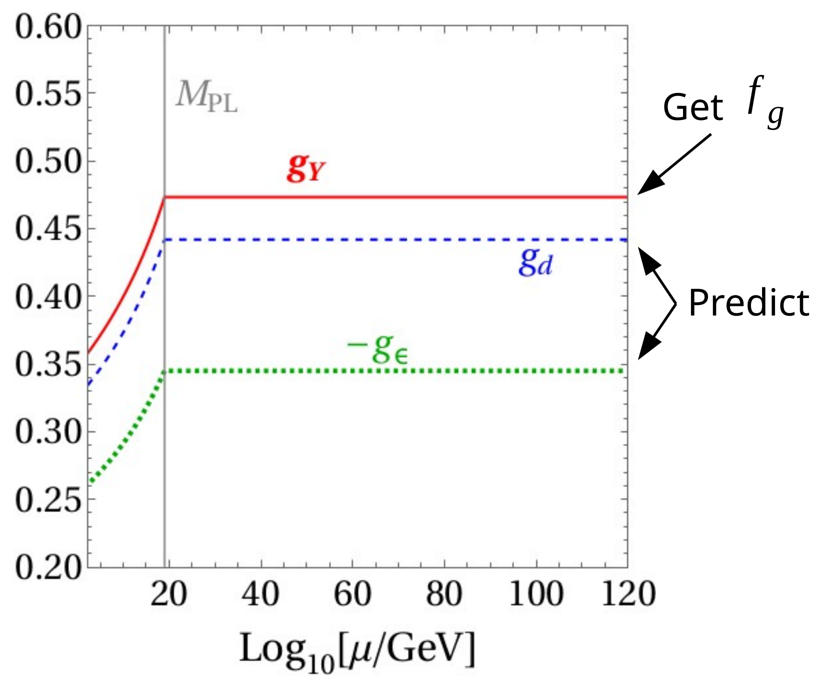
Irrelevant → Prediction

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu}$$

SM field strength

BSM field strength

Kinetic mixing



Universality of fg + the assumption of a FP gives **unique prediction** of 2 BSM couplings

fg and fy values that give FP and BSM predictions

fg and fy values that give FP and BSM predictions

Safe = interactive

Free = Gaussian relevant

Zero = Gaussian irrelevant

Model	f_g	predictions	f_y	predictions
SM [58, 59, 61]	$f_g = 0.0096$ $f_g > 0.0096$	g_Y safe g_Y free	$[-10^{-4}, 10^{-3}]$ $[-10^{-4}, 10^{-4}]$	y_t safe y_b safe
$B-L$ [64, 106]	$f_g = 0.0097$ $[0.0097, 0.05]$	g_Y, g_X, g_ϵ safe g_Y free; g_X, g_ϵ safe	$f_y = 0.002$ $[-0.004, 0.005]$	y_t, y_ν, y_N safe y_t safe; y_N safe/zero
SU(6) GUT [71]	$f_g \geq 0$	g_6 free	$[0.003, 0.04]$	y_t safe GUT Yukawa sect. safe/zero

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Potential gravitational waves signatures

Emergence of Dark Matter

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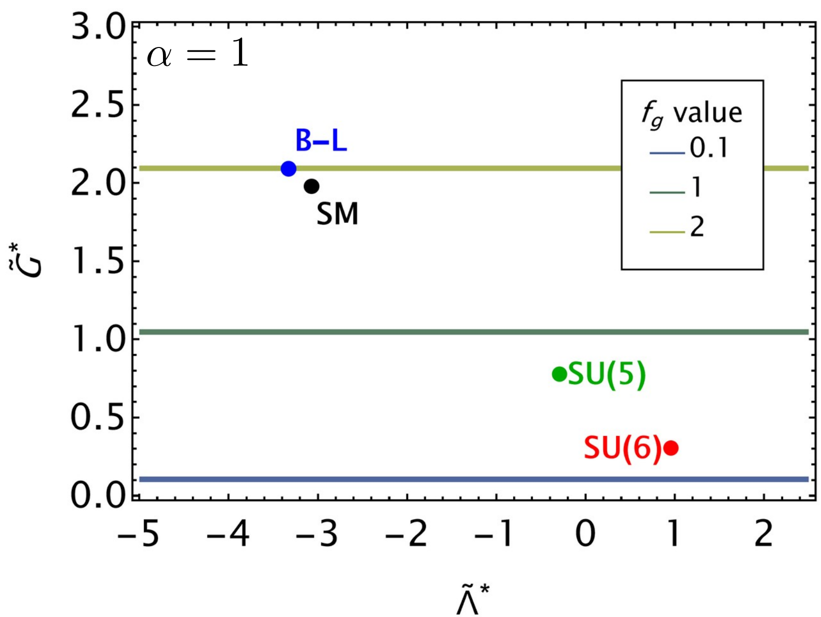

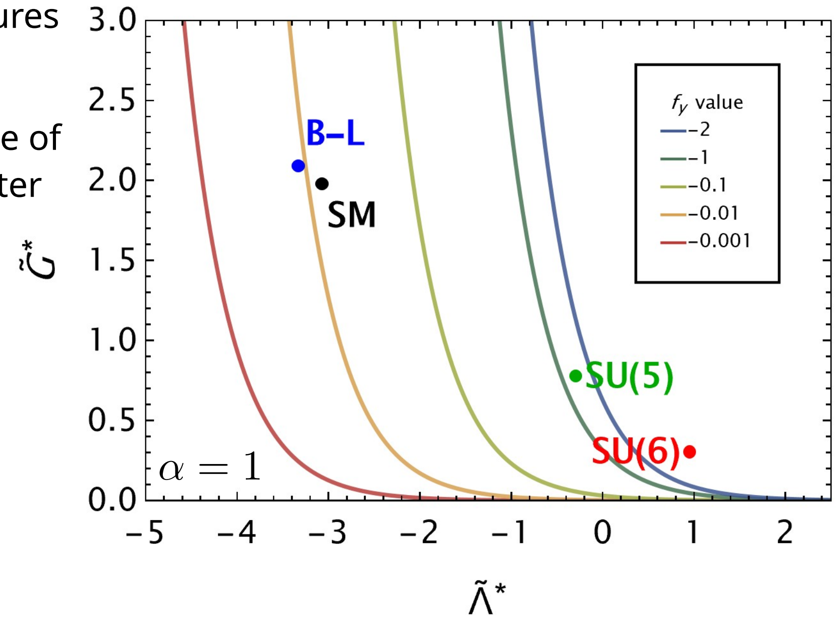

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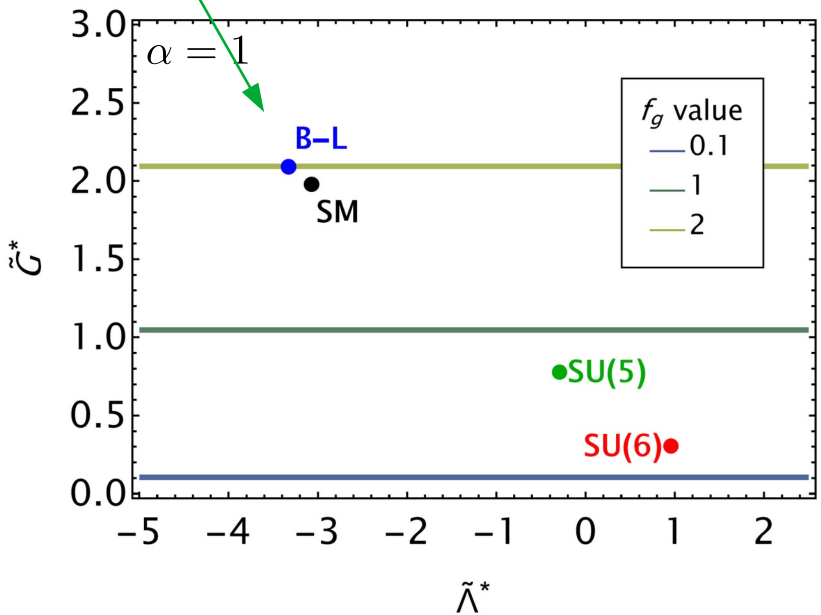
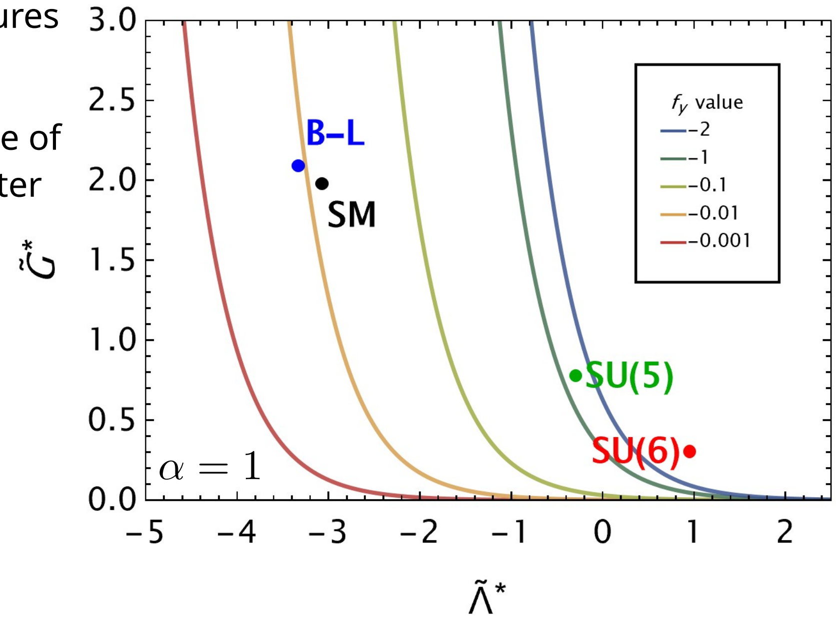
fg is too big to generate an interactive fixed point

Potential gravitational waves signatures

Emergence of Dark Matter





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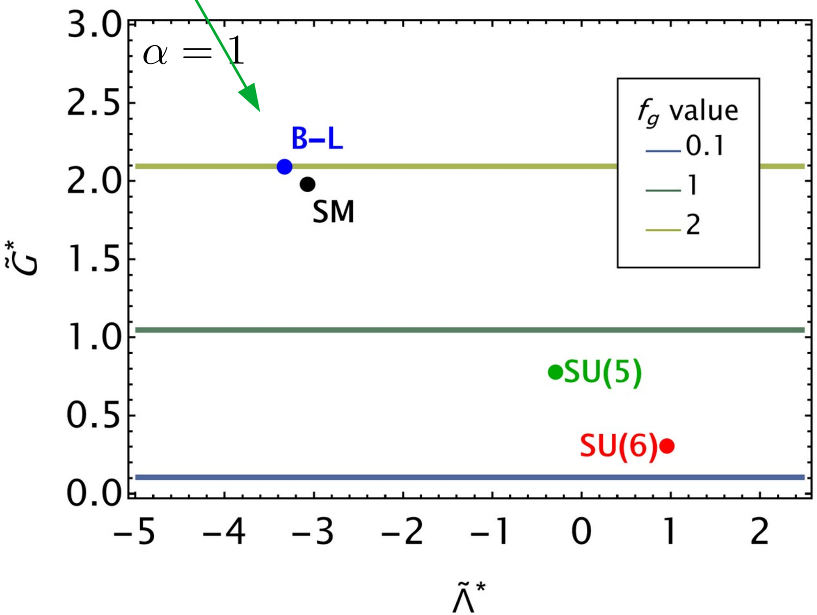
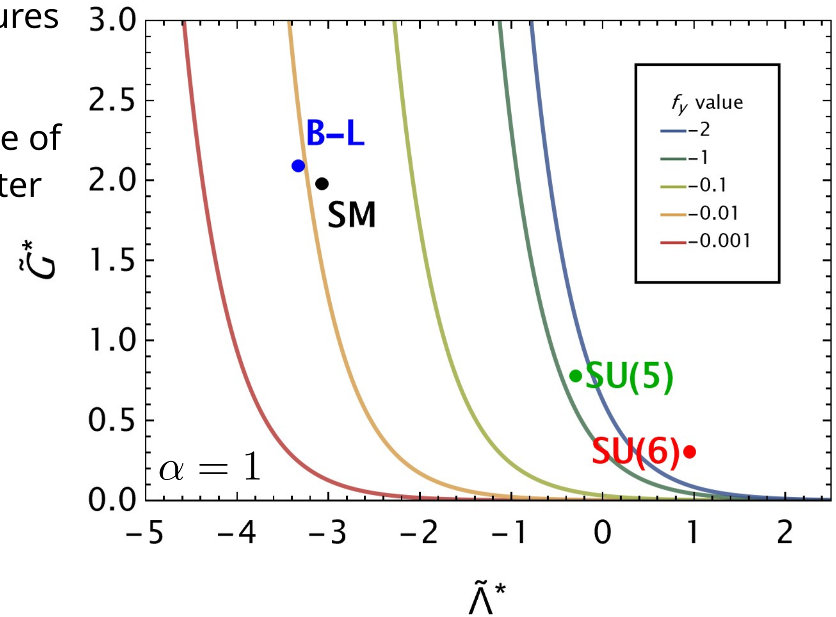
fg is too big to generate an interactive fixed point → Asymptotic freedom, not safety

Potential gravitational waves signatures

Emergence of Dark Matter





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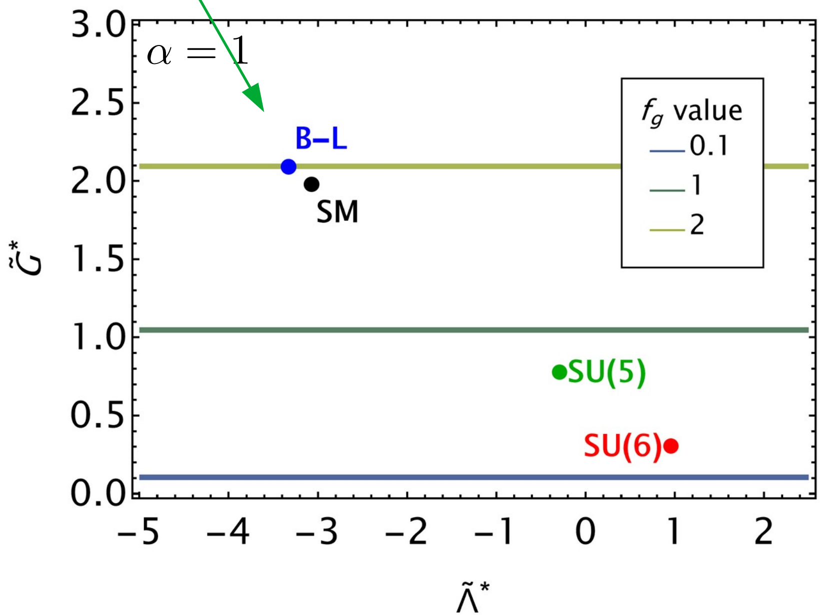
fg is too big to generate an interactive fixed point

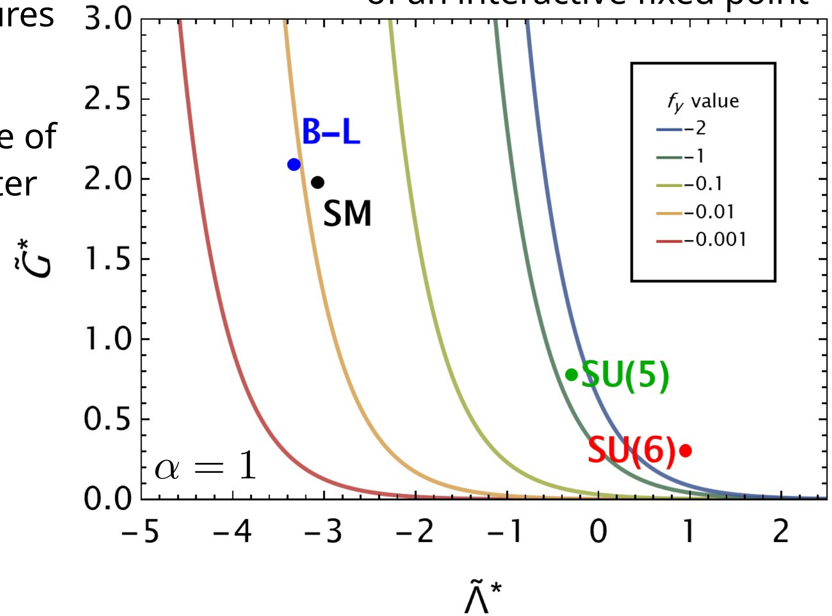
Asymptotic freedom, not safety

Potential gravitational waves signatures

Emergence of Dark Matter

fy is compatible with the assumption of an interactive fixed point





Conclusions

- The running of gauge and Yukawa couplings in the SM and simple extensions is well described perturbatively up to Plank scale, where quantum gravity contributions must be considered.
- At leading order these corrections are linear in the coupling itself, through universal coefficients called fg/fy. Calculations using Wetterich equation show that fg>0 while the sign of fy is unclear.
- In our work, we have computed for the first time <u>fg and fy in propertime RG flow</u> within the most simple Einstein-Hilbert truncation, and studied the gauge-fixing and regulator dependency.
- <u>fg is O(1)</u>, with no dependency on the cosmological constant, because only the 1st coefficient of the HK is non-zero. Moreover, fg is photon gauge-fixing independent.
- <u>fy is always negative</u>, in agreement with the FRG calculations, <u>and cosmological constant suppressed</u>.
- For both fg and fy the dependency on regulator and graviton gauge-fixing is small for minimal matter content and becomes more relevant for higher number of particles in the theory, e.g. the SM.
- Comparing our results with the phenomenological studies, we find that propertime RG <u>favours</u> <u>asymptotic freedom</u> for the abelian gauge coupling of the SM, and fixed points for the Yukawa sector are not yet accessible and should be studied in a richer truncation of gravity.

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Thank you for the attention!

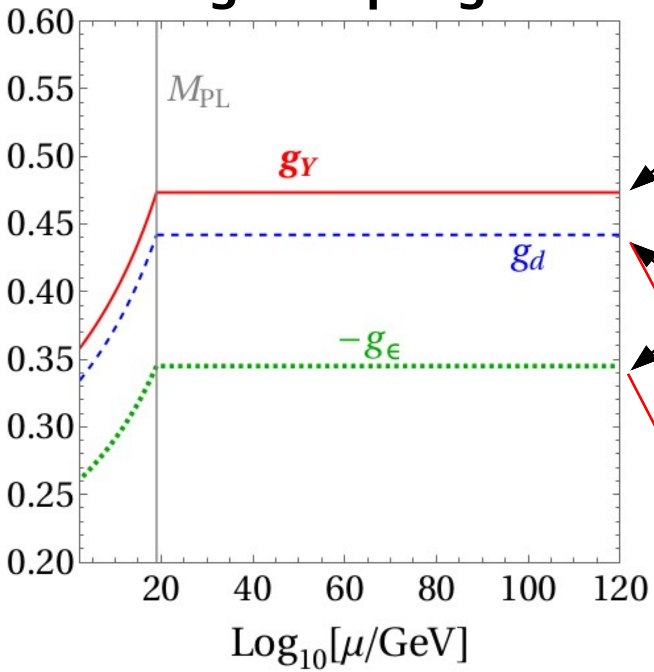
Backup

How the heuristic approach is used in BSM pheno

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu}$$

$$\mathcal{L} \supset -Y_\nu N\,(\tilde{\epsilon}H^*)^\dagger L - \frac{1}{2}Y_N SNN + \text{H.c.}$$

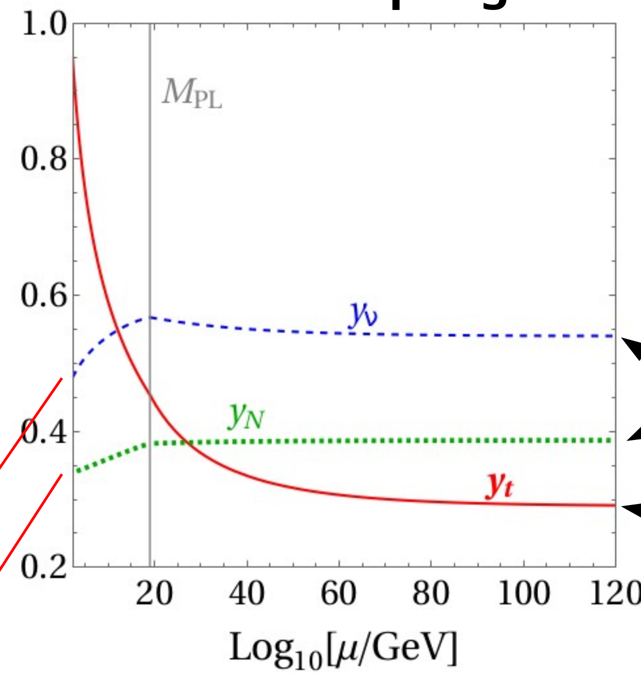
Gauge couplings



Get f_g

Predict

Yukawa couplings



Predict

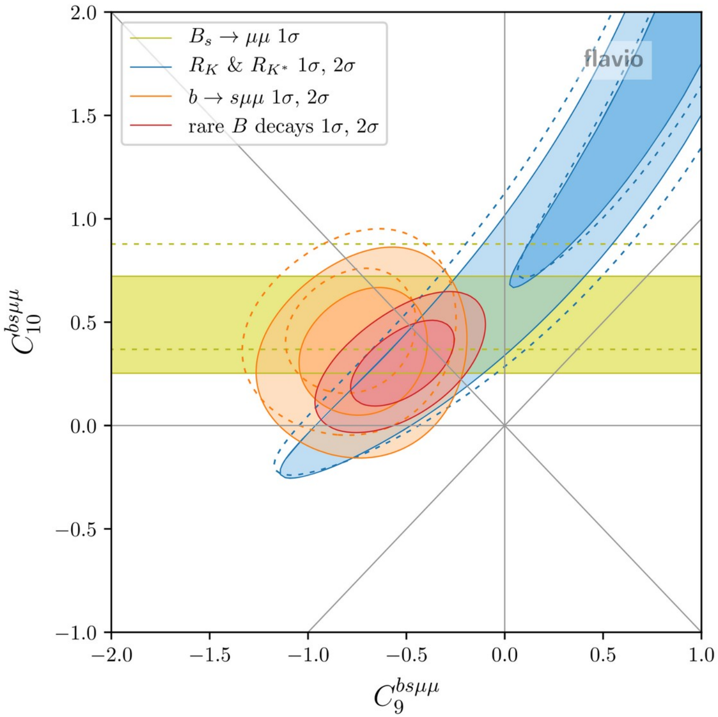
Get f_y

Phenomenology!

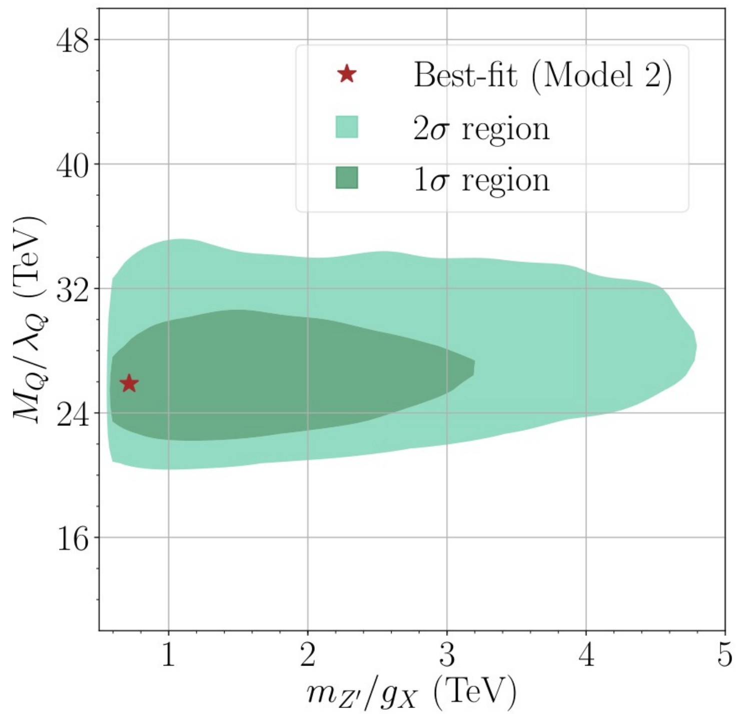
Source: Kamila Kowalska & Enrico Sessolo

Heuristic ASQG on Z' solutions to the flavor anomalies

Explain flavor anomalies → Z' vector-like quark vector-like lepton → Wilson coefficients constrain ratio coupling/mass → **ASQG determines uniquely the couplings**



Altmannshofer, Stangl, Eur. Phys. J. C 81 (2021)



Kowalska, Kumar, Sessolo, Eur. Phys. J. C (2019)

At 2 TeV:

	$\mathrm{FP}_{1\mathrm{A},a}$	$\mathrm{FP}_{1\mathrm{A},b}$
g_D	0.305	0.305
g_ϵ	0	0
$\lambda_{Q,3}$	-0.381	0.034
$\lambda_{Q,2}$	0.016	0.803
$\lambda_{L,2}$	0.823	0.606

	$\mathrm{FP}_{1\mathrm{B},a}$	$\mathrm{FP}_{1\mathrm{B},b}$
g_D	0.318	0.318
g_ϵ	0.110	0.110
$\lambda_{Q,3}$	-0.612	0.004
$\lambda_{Q,2}$	0.296	0.874
$\lambda_{L,2}$	0.652	0.499

*Chikkaballi, Kotlarski, Kowalska, **DR**, Sessolo JHEP 01 (2023) 164*

How robust are particle physics predictions in ASQG?

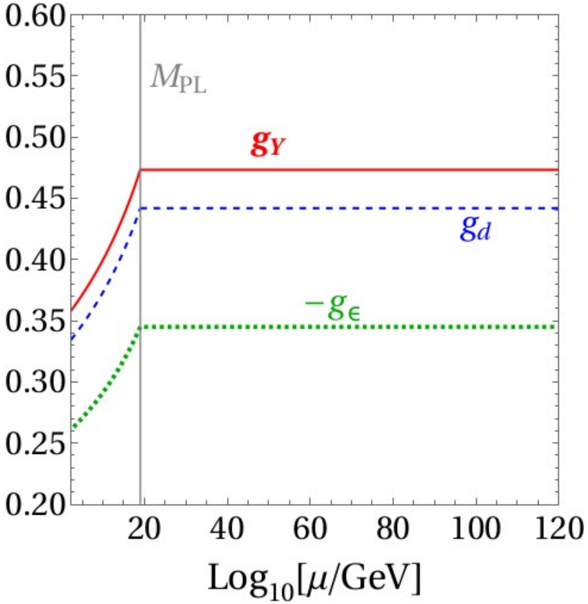
The heuristic approach to ASQG has assumptions. What happens when we relax them?

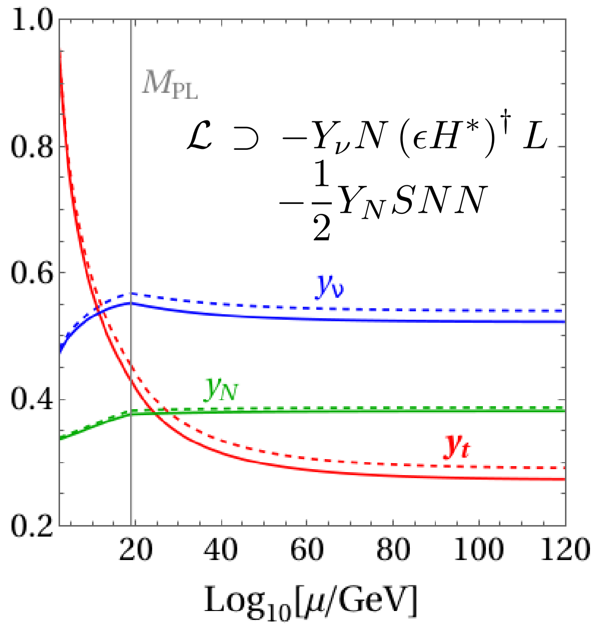
Sources of uncertainties →

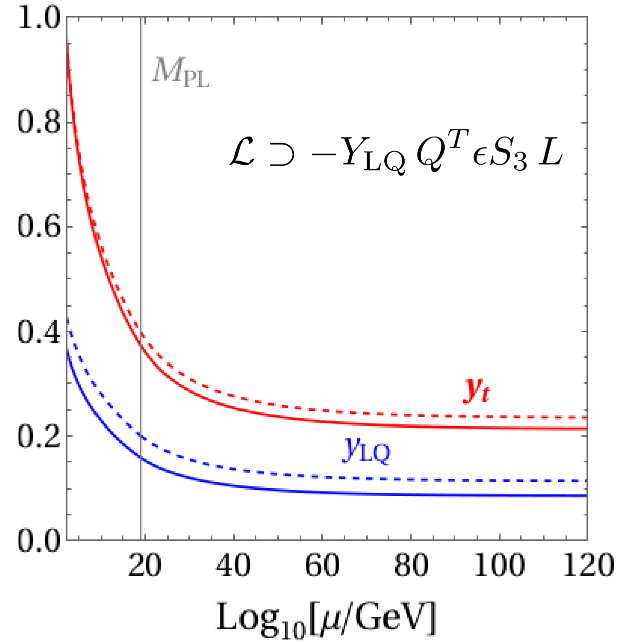
1 - Computations of the beta functions are performed at 1-loop level.

2 - Planck scale is set arbitrarily at 10^{19} GeV.

3 - Gravity decouples instantaneously at the Planck scale.







Shifting gy shifts the new-physics → $\sim\ 0.1\%$

New-physics Yukawa big → $\sim\ 1\%$

New-physics Yukawa small → $\sim\ 10\%$

*Kotlarski, Kowalska, **DR**, Sessolo (2023)*