AS and matter

- quantising gravity is cool, but the real world also has more: matter

  = everything that isn't gravity

the ideal world

→ if your QG theory cannot embed the Standard Model, you are doing math, not physics

→ if your QG theory includes the SM but isn't compatible with measured values of masses, decay rates, …, you are doing math, not physics

⇒ good test for any QG candidate!

also: QG effects are tiny

recall correction to Newtonian potential & exp. constraints on $R^2 + C^2$ couplings

in practice: add pieces of SM bit by bit] the real world

goal: SM

→ three gauge groups:

spin 1 gauge bosons

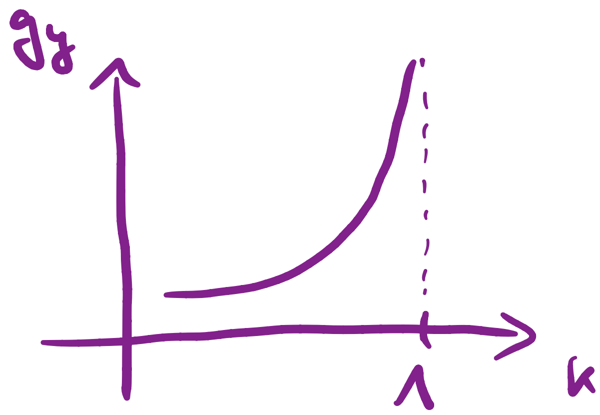
$U(1)_Y$ → Abelian, has Landau pole/ triviality problem

hypercharge

$SU(2)_L$
$SU(3)$
} non-Abelian, asymptotically free

$U(1)_Y$ at one-loop order:

$$\beta_{g_Y} = \frac{41}{6} \frac{g_Y^3}{16\pi^2} + \dots$$



Scale of Landau pole $\Lambda \gg M_{Pl}$

↳ signals need for new physics
<u>beyond</u> the Planck scale

→ quarks: spin 1/2 → fermions EM charge

up	charm	top	2/3
down	strange	bottom	-1/3

→ charged under everything

→ confinement: there are no free quarks at low energy, only bound states like protons

→ leptons: spin 1/2 → fermions

			EM charge
e	μ	τ	-1
ν_e	ν_μ	ν_τ	0

→ not charged under strong interaction

→ Higgs spin 0 → scalar

→ charged under weak interaction

→ important for electroweak symmetry breaking

→ Higgs mechanism

↪ $\langle H \rangle \sim 246\,\text{GeV}$

⇝ $\mathcal{L}_{SM} \supset$
- gauge field strength "$F_{\mu\nu} F^{\mu\nu}$"
- charged fermions "$\bar{\Psi} i \not{D} \Psi$"
- Higgs "$DH^\dagger DH + H^2 + H^4$"
- Yukawa coupling "$H \bar{\Psi} \Psi$"

with $\langle H \rangle \neq 0$ → gives fermions mass

total no. of free parameters ~ 25

→ all measured masses can be parametrized (by choosing appropriate Yukawa couplings y_f), but there is no explanation/mechanism

→ "hierarchy problem": $\langle H \rangle \ll M_{Pl}$

this needs a very special choice of mass parameter at the Planck scale

→ $M_H \simeq 125\,\text{GeV} \ll M_{Pl}$

needs quartic Higgs coupling to be ≈ 0 at Planck scale → why?

assuming that there are no other matter fields

(or that they couple to the SM very weakly, like dark matter)

a) QG must solve the U(1) triviality problem / Landau pole

b) QG must be compatible with measured values of couplings and masses

c) it would be nice if QG would explain some or all of the SM structure

Status of ASQG with matter

selection!

Eichhorn, Schiffer

2212.07456

Upshot:

a) evidence that issue is solved

b) evidence that this is the case

c) · mechanism to predict y_t and y_b with $y_t \gg y_b$,

but not yet quantitatively accurate

· mechanism to enforce $\lambda_H \approx 0$ at M_{Pl}

· no explanation for $\langle H \rangle \ll M_{Pl}$

· some hints to explain quark mixing

Some generalities:

- gravity contributes new terms to β functions of SM couplings
- this includes a term that is linear in the respective coupling

example: hypercharge coupling g_y

$$\beta_{g_y} = - f_{g_y} \, g_y + \frac{41}{6} \frac{g_y^3}{16\pi^2} + \dots$$

$$f_{g_y} = f_{g_y}(G, \Lambda, \dots) > 0$$

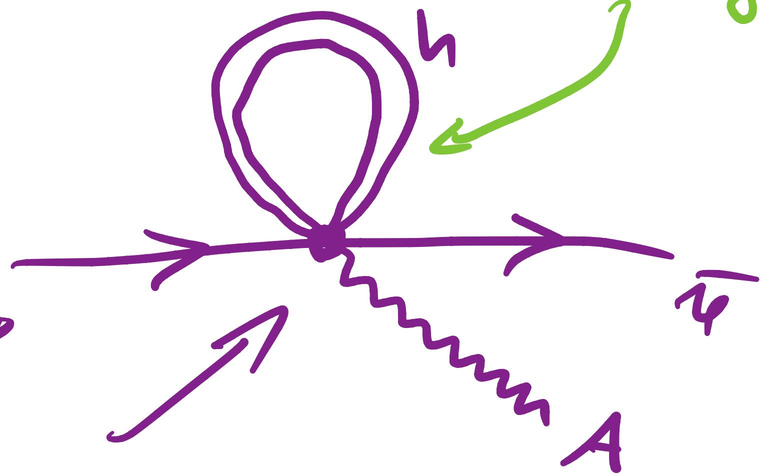
↳ why linear? because everything couples to gravity

→ $\sqrt{-g}$ in front of everything

→ generates vertices with gravitons

for hypercharge, $\sim \sqrt{-g}\; i g_y \bar{\psi} \not{A} \psi$

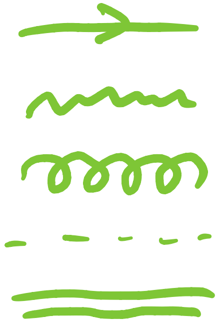
generates diagram



$\propto g_y G_N$

note: different types of lines:

(conventions differ)



fermion
photon
gluon
scalar
graviton ← double line

→ additional factors of the metric or Christoffel symbol (or spin connection for fermions) can also be present, depending on spacetime indices of fields and derivatives of a vertex

→ gravity is blind to internal symmetries

↖ e.g. gauge/Dirac/...

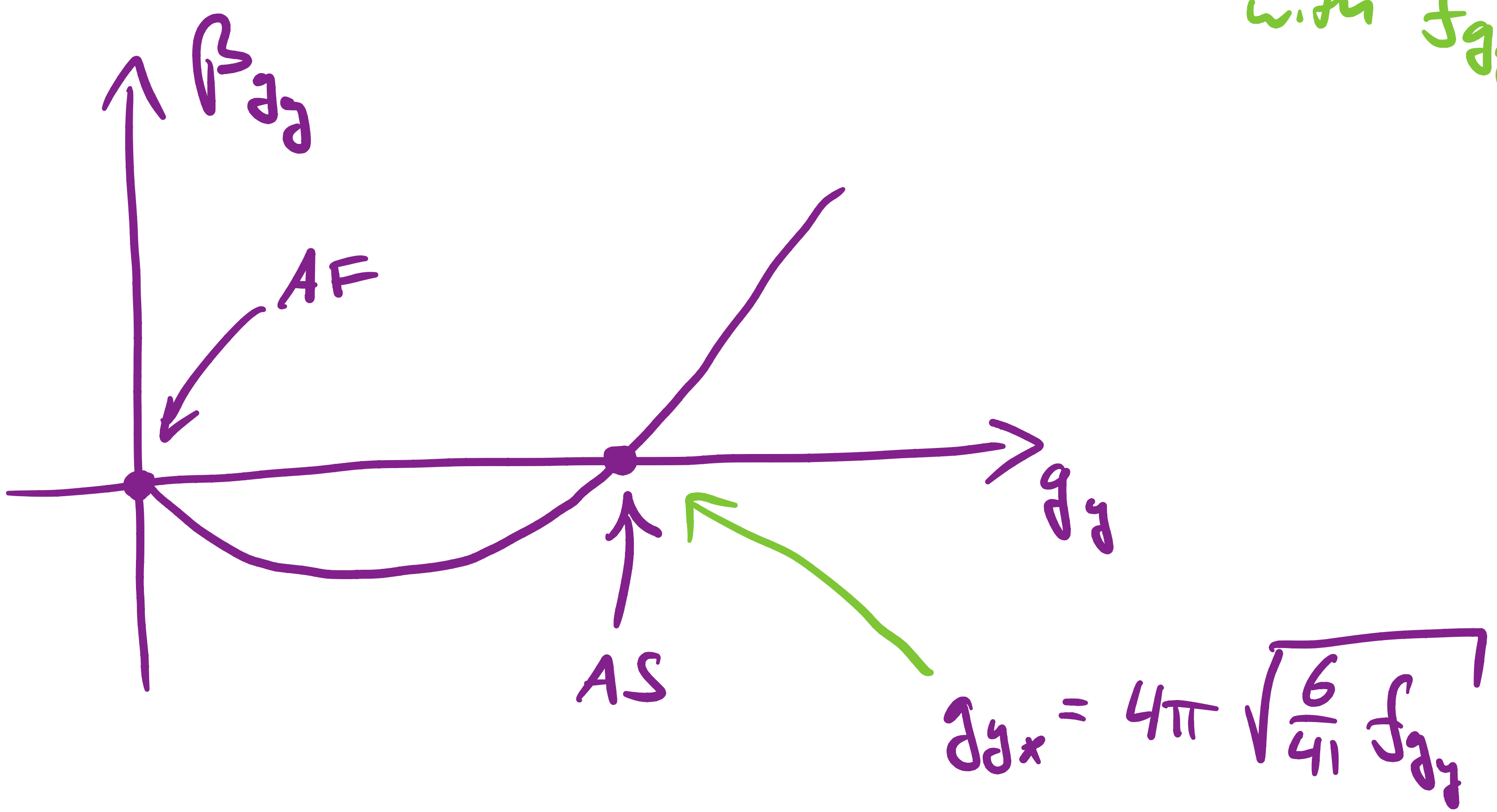
⇒ gravity depends on spacetime structure only

⇒ couples to stress-energy only

Consequence: f_g is the same for weak and strong coupling!

↳ what is the effect on g_y?

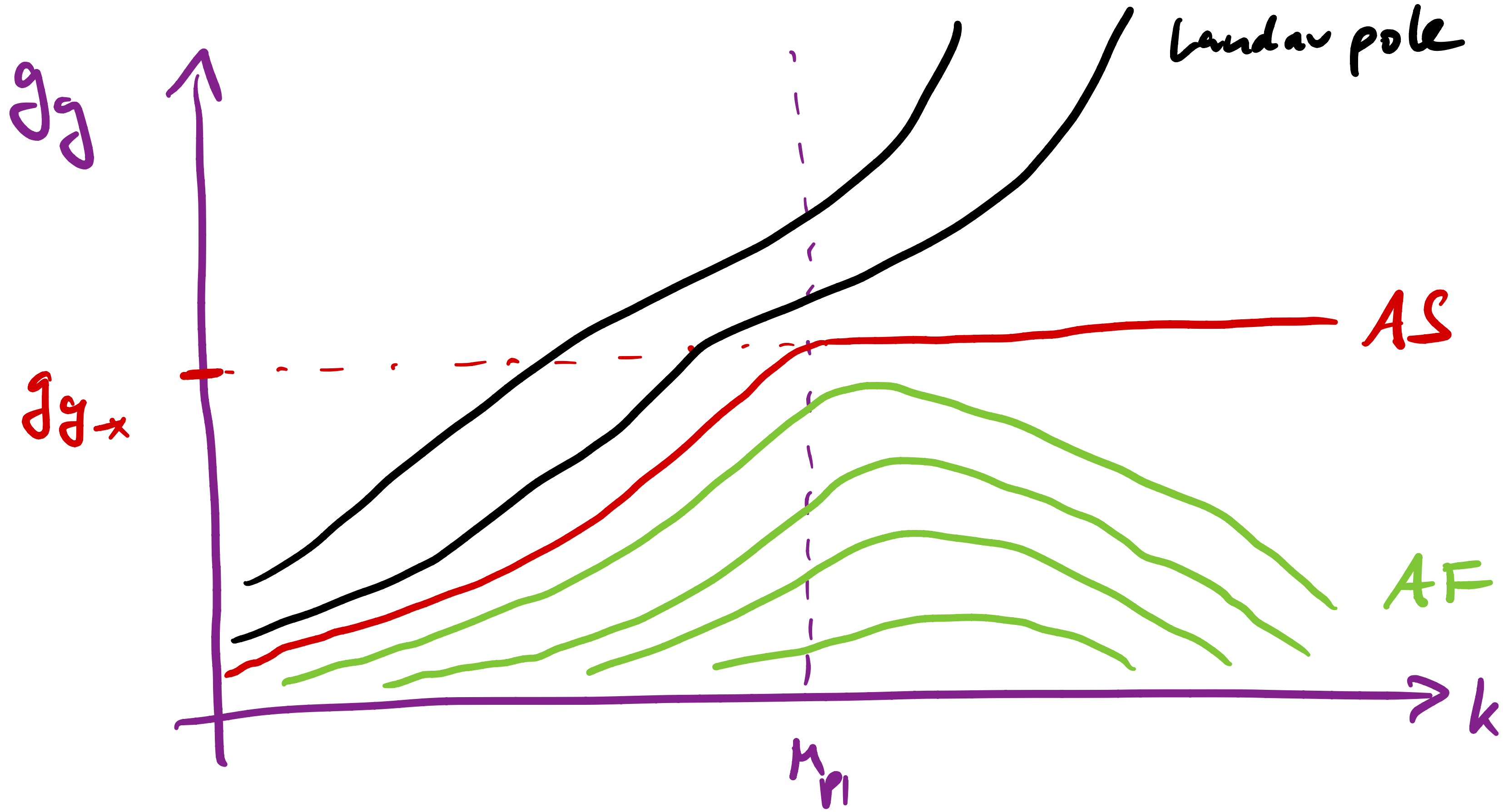
with $f_{gy} > 0$



AF FP: $\theta = f_g > 0$ relevant

AS FP: $\theta = -2 f_g < 0$ irrelevant

what does this mean? sketch trajectories:



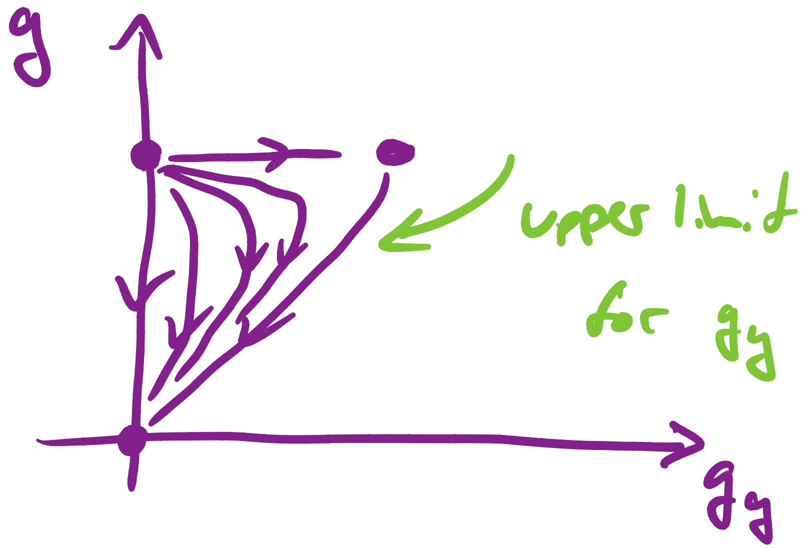
⇒ Landau pole problem can be solved if hypercharge coupling is below critical value

↪ upper bound on g_y in AS

is the experimental value below this bound?

likely **yes**!

rough sketch of phase diagram:



Yukawa sector

we focus on top and bottom quarks → $y_t\,,\,y_b$

they are the largest in the SM

$$\beta_{y_{t/b}} = -f_y\, y_{t/b} + \frac{y_{t/b}}{16\pi^2}\left[\frac{3}{2}y_{b/t}^2 + \frac{9}{2}y_{t/b}^2 + \text{weak/strong}\right]$$

AF ↓ (weak/strong)

$$- \frac{3}{16\pi^2}\, y_{t/b}\, g_y^2 \times \begin{cases} \frac{17}{36} & \text{top} \\ \frac{5}{36} & \text{bottom} \end{cases}$$

↑ due to charge

t: 2/3

b: −1/3

if g_y is AF: no distinction between t&b

$$\beta_{y_t} = \beta_{y_b} \quad \text{(at FP!)}$$

if g_y is AS: also Yukawas have AS FP!

check: $g_{y*}^2 = 16\pi^2 \frac{6}{41} f_y \Rightarrow f_y = \frac{41}{6} \frac{g_{y*}^2}{16\pi^2}$

$$\rightarrow \beta_{y_{t/b}} = \frac{y_{t/b}}{16\pi^2}\left[-\frac{41}{6} g_{y*}^2 + \frac{3}{2} y_{b/t}^2 + \frac{9}{2} y_{t/b}^2 - g_{y*}^2 \begin{cases} \frac{17}{12} & t \\ \frac{5}{12} & b \end{cases}\right] \overset{!}{=} 0$$

$$t-b: \quad \frac{3}{2}\left[y_b^2 - y_t^2\right] + \frac{9}{2}\left[y_t^2 - y_b^2\right] - g_{y*}^2 = 0$$

$$\Rightarrow \quad y_{t*}^2 - y_{b*}^2 = \frac{1}{3} g_{y*}^2$$

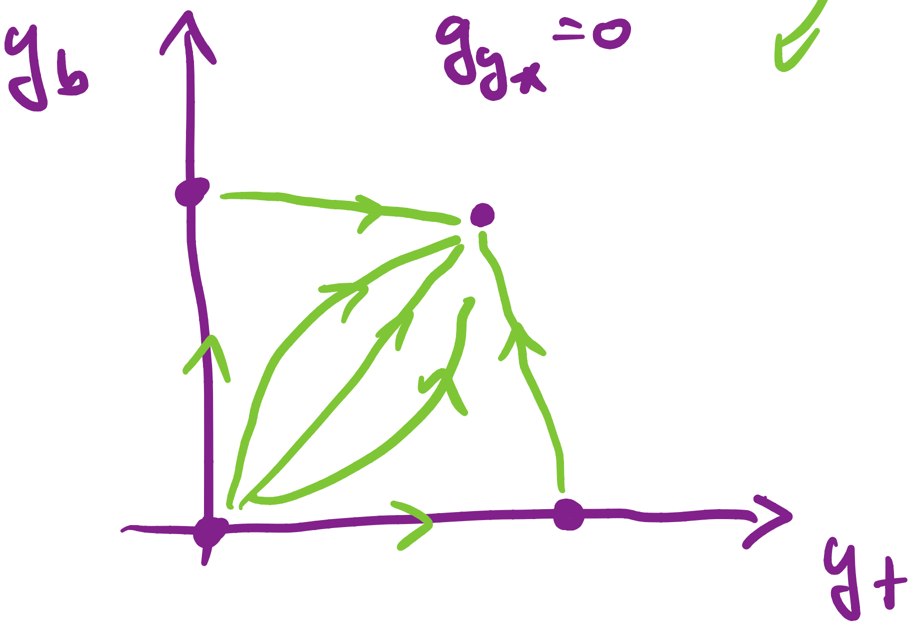
can also compute $t+b$ to fix FP completely

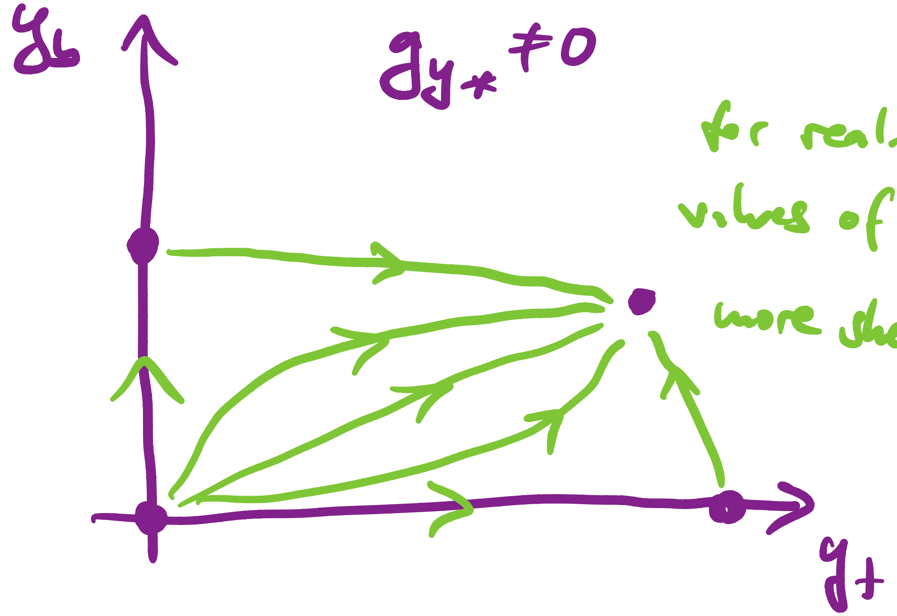
at this FP, $y_t \gg y_b$ automatically!

consistent with SM pheno!

phase diagrams:

Symmetric along diagonal





for realistic values of g_{y*}: more skewed!

Some remarks:

- computations sensitive to top mass

  → if m_t is too large by 5–10 GeV, no agreement with SM anymore

  but: systematic errors unknown

- Yukawas of other generations cannot be neglected at high scales:

  → other Yukawas small, but CKM mixing

  → CKM elements also run, triggering some changes

  ↑ at VERY high energies $\sim 10^{10^4}$ GeV

Alkofer, Eichhorn, Held, Nieto, Percacci, Schröfl
2003.08401

Eichhorn, Gyftopoulos, Held 2507.18304

Higgs sector

- Higgs vev is relevant

$\Rightarrow$ can choose it such that

$$\langle H \rangle = 246 \text{ GeV}$$

$\hookrightarrow$ no dynamical explanation why this value

- quartic coupling λ:

Yukawas & gauge couplings ↙

$$\beta_\lambda = f_\lambda \lambda + \frac{3}{2\pi^2}\lambda^2 + \dots$$

Shaposhnikov, Wetterich 0912.0208 ← before measurement of Higgs!

if gauge couplings and Yukawas are AF

<u>and</u> $f_\lambda > 0$, then $\lambda_* = 0$

this FP is IR-attractive ⇒ QG fluctuations

ensure that λ @ M_{Pl} ≈ 0

LHC fact: this is needed to obtain

measured Higgs mass !

estimate by Shaposhnikov & Wetterich: 129 GeV

close !

how: below Planck scale, λ is generated by gauge and (mostly) top quark fluctuations

→ unique mapping of $\lambda(M_{Pl})=0$ to precise value at EW scale

⇒ determines ratio of Higgs mass and vev

$$\lambda(k_{EW}) = \frac{1}{2}\left(\frac{M_H}{\langle H\rangle}\right)^2$$

note: · mechanism is independent of value of f_λ,
only sign matters

· there is evidence that $f_\lambda > 0$! ☺

other possibility: ASFP for $g_y + y_t$ $\Rightarrow$ $\lambda_* \neq 0$

→ depends also on value of f_λ

→ indications that this scenario is incompatible with observations if there is no new physics beyond the SM