Natural Ultraviolet Complete Extensions of the Standard Model

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Motivations

New Physics Beyond the Standard Model (SM)?

No new particles so far... but several theoretical issues:

- naturalness
  gauge hierarchy, flavor hierarchy, strong CP, cosmological constant ...
- effectiveness
  locating the scale of new physics, assessing compositeness, questioning locality and symmetries

Enhancing the Predictivity of Quantum Field Theories

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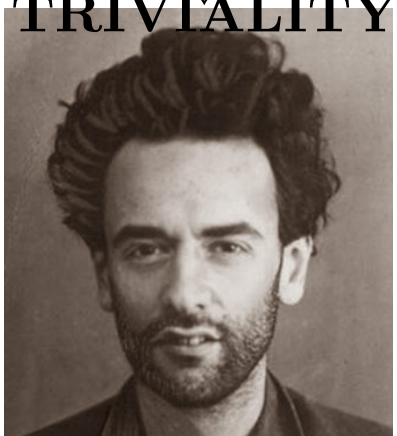
Enhancing the Predictivity of Quantum Field Theories

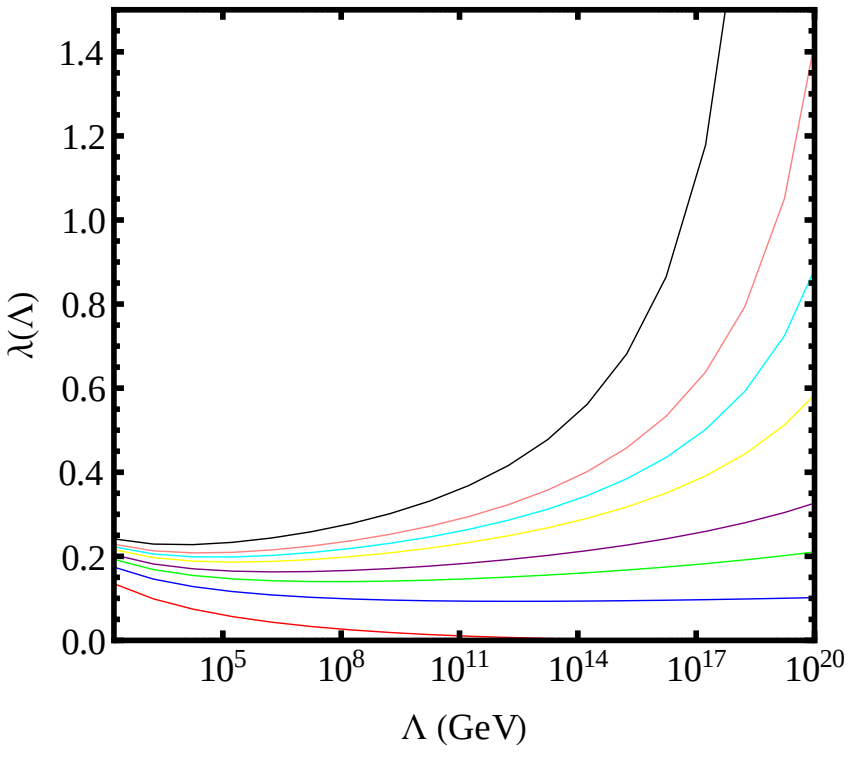
$\Downarrow$

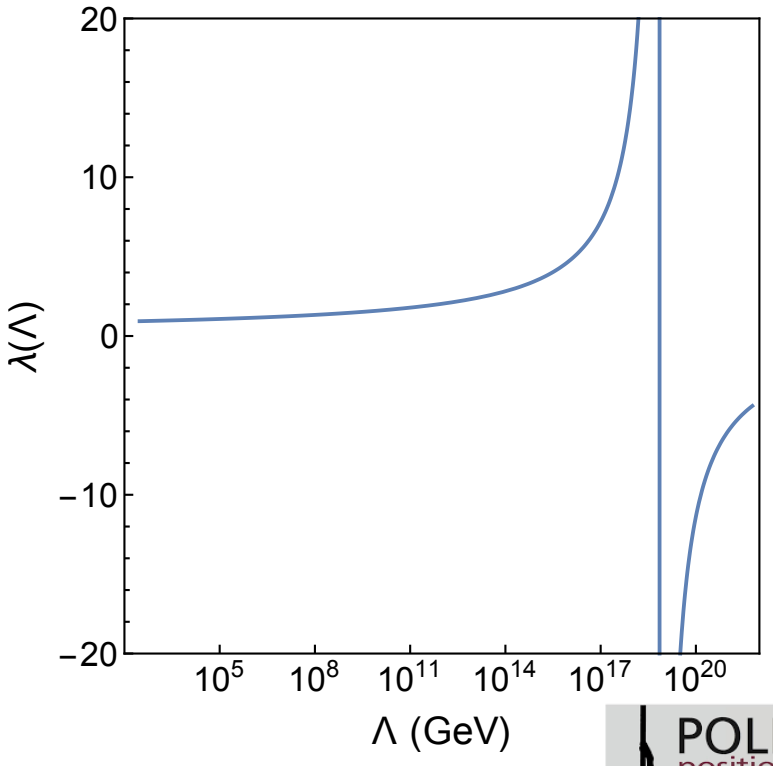
TRIVIALITY



Extrapolating the Standard Model

The SM is perturbatively renormalizable, but not UV complete





(Holthausen, Lim, Lindner '12)

Landau pole

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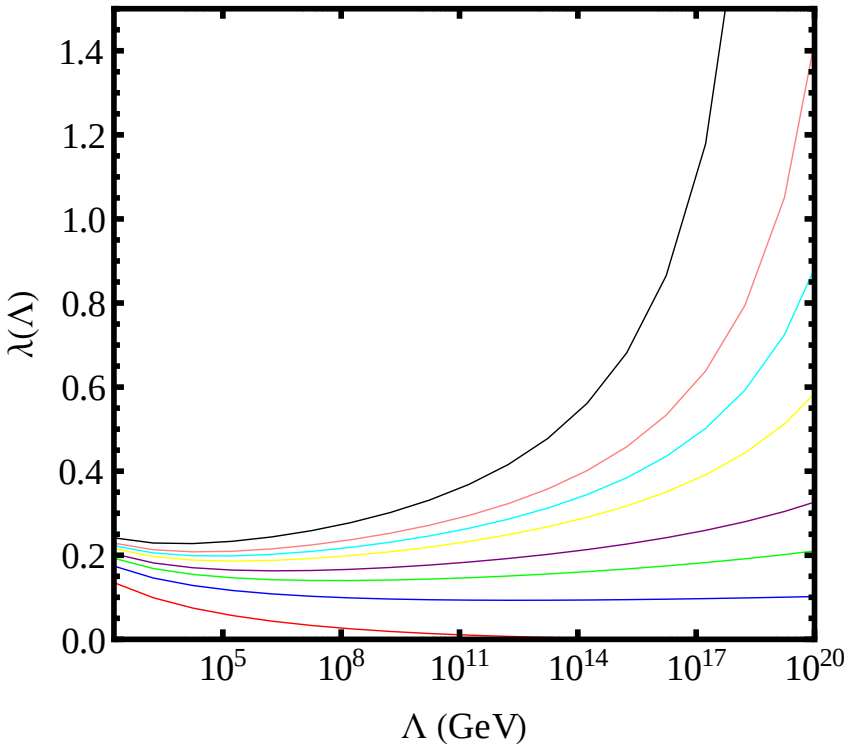

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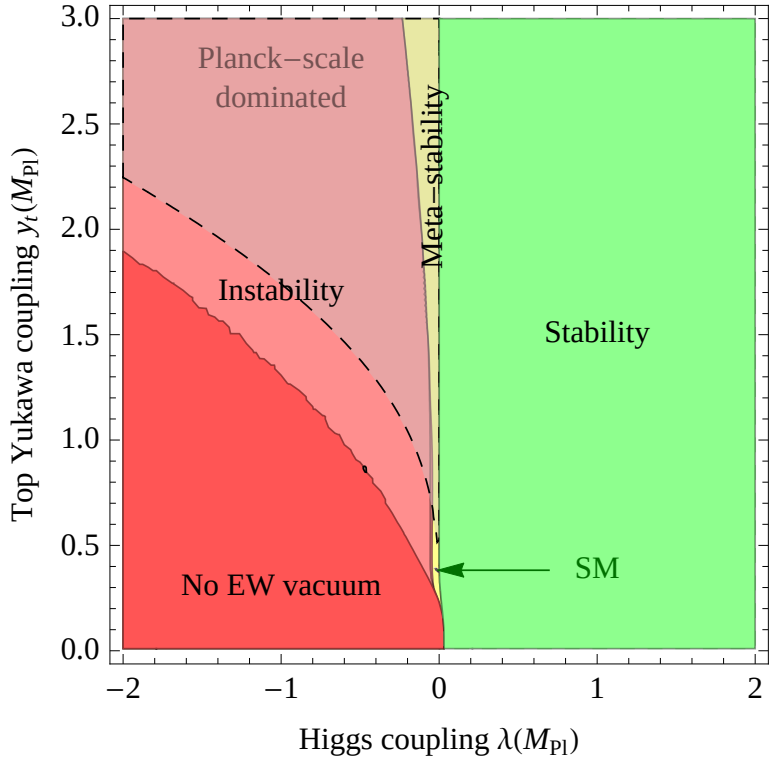
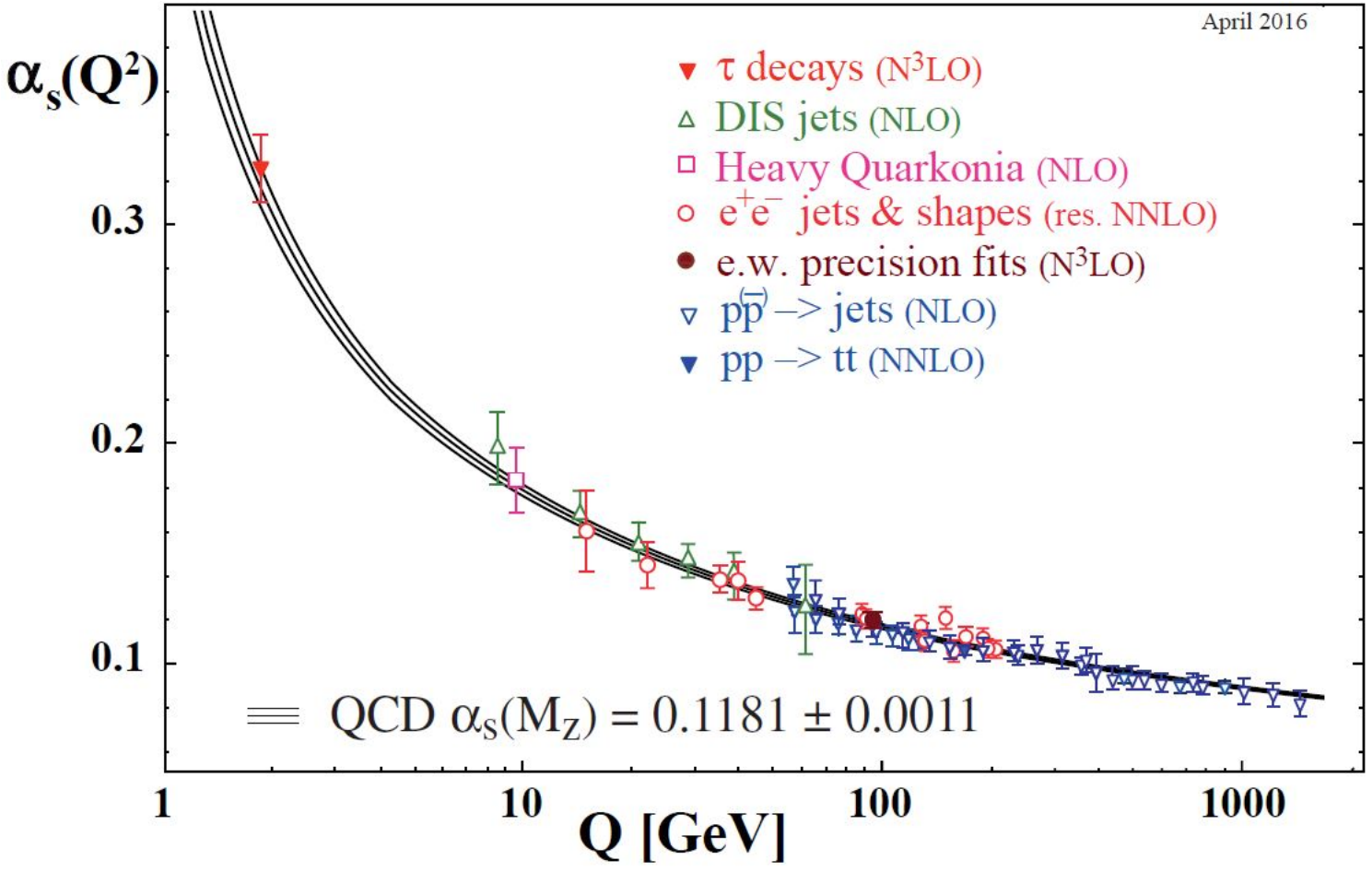


(Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia '13)

Light Higgs = almost vanishing self-interaction to high scales

Examples of UV Complete Theories

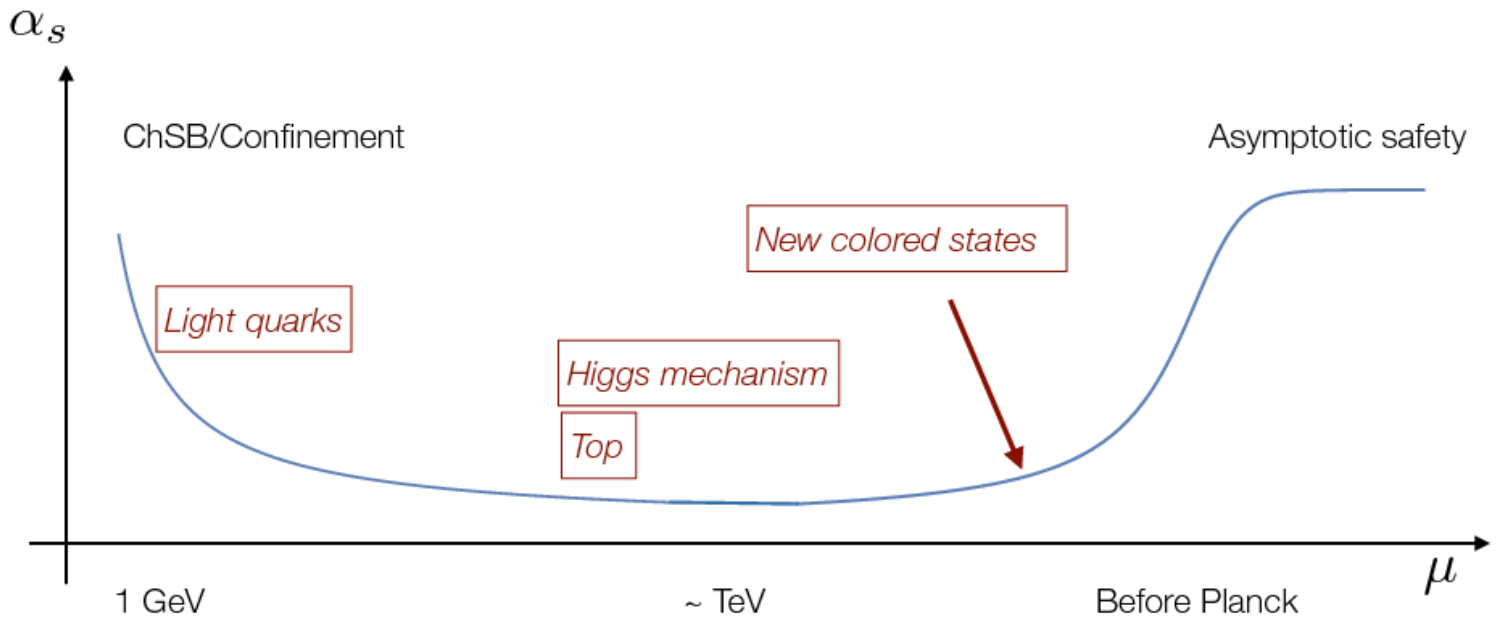
Asymptotic Freedom of the Strong coupling α_s in the SM



(Particle Data Group '16)

Examples of UV Complete Theories

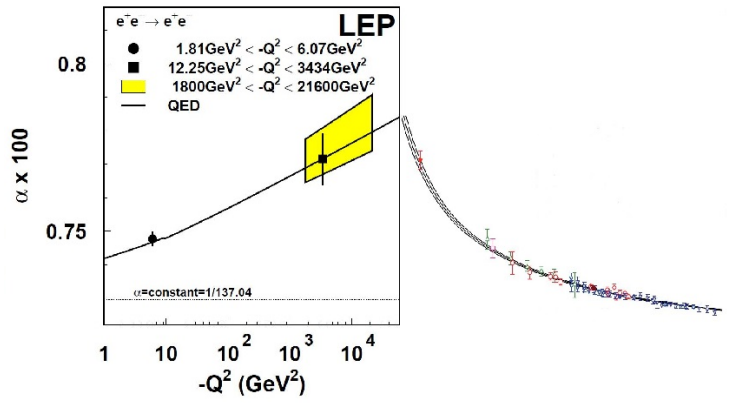
Asymptotic Safety of α_s beyond the SM?



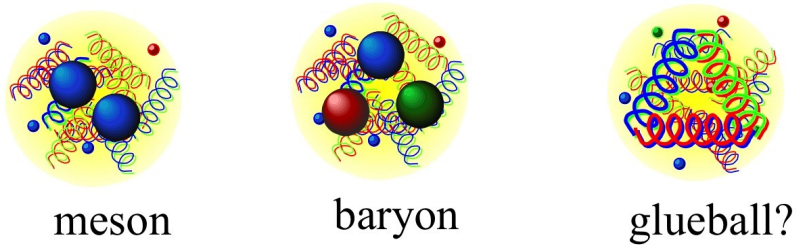
(Litim Sannino '15)

Objectives of the Project

- **Constructing Asymptotically Free/Safe Extensions of the SM**



- **Exploring the Hierarchy of Masses and Approximate Scale Invariance in these Theories**



Asymptotic Freedom Beyond the SM

Beyond the SM, is **Total Asymptotic Freedom** possible?

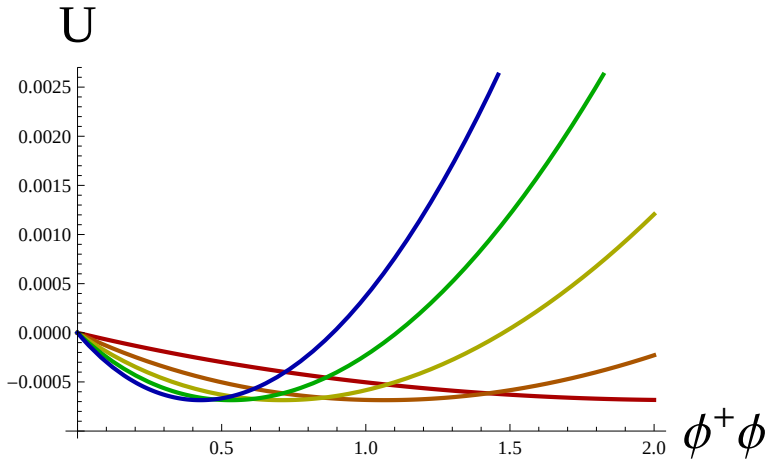
- within perturbative renormalizability: it is rare
  needs many new particles

  (Giudice, Isidori, Salvio, Strumia '15) (Holdom, Ren, Zhang '15)

- beyond perturbative renormalizability: it is common

  ✓ non-Abelian Higgs-Yukawa models (e.g. GUT)

  (Gies, **LZ** '15 & '16) (Gies, Sondenheimer, Ugolotti, **LZ** '18 & '19)



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  ?? SM-like Higgs-Yukawa models (with $U(1)_Y$):

  work in progress: SM + higher-dimensional operators (Gies, Vacca, **LZ**)

  work in progress: SM + hidden sector (Litim, Vacca, **LZ**)

Asymptotic Safety Beyond the SM

Beyond the SM, is **Asymptotic Safety** possible?

Several scenarios have been proposed:

- with Quantum Gravity (Reuter et al.) (Percacci et al.) ...
- Large N_f & N_c (Litim, Sannino '14)

  but $U(1)_Y$ needs a cure (Dondi, Dunne, Reichert, Sannino '20)

  work in progress: (Litim, Vacca, **LZ**)
- in Nonlinear Sigma Models (Percacci, Codello '09)

  (Percacci, Fabbrichesi et al. '10 & '11)

  in preparation: (Vacca, **LZ**)

Methodology

In UV complete theories one can give a rigorous definition of:

- Exact/Approximate **Scale Invariance**
- **Hierarchies of Scales**

but, studying these aspects remains **hard!** (nonperturbative)

Methodological Innovations are needed.

We use:

- Functional methods
- Exact RG Equations
- Effective Field Theory
- Conformal Field Theory

Methodology

New methods to address these questions have been developed for:

1. SM and BSM gauge hierarchy problem

   to appear soon: (Gies, Schmieden, **LZ**)

2. SM and BSM flavor hierarchy problem

   in preparation: (Vacca, **LZ**)

3. dynamical mass generation in non-Abelian gauge theories

   (Gies, Gkiatas, **LZ** '22)

   to appear soon: (Asnafi, Gies, Gkiatas, **LZ**)

4. critical nonlinear sigma models

   (Baldazzi, Percacci, **LZ** '21)

   in preparation: (Vacca, **LZ**)

Conclusions

Perspective summary, by the end of the fellowship:

- New totally asymptotically free extensions of the SM? ✓
- New asymptotically safe extensions of the SM? ?
- Methodological advances in the study of hierarchies? ✓
- Study of gauge hierarchy problem vs approximate scale invariance ?
- Phenomenological viability study? ×

Asymptotically Free U(1)?

The mechanism that cures λ might cure α?

- Couple the trivial sector to an asymptotically free sector
  $U(1)_Y \times SU(2)_L \times SU(3)_c$ ✓
- Add higher dimensional operators that change the β
  SMEFT, HEFT, ... ✓
- Allow for large masses in the UV
  no asymptotic symmetry: $\kappa > 0$ ✓

Asymptotically Free U(1)?

In QED higher dimensional operators, e.g. Pauli-Fierz, can change the running of α (Djukanovic, Gegelia, Meißner '17)

Even induce asymptotic safety (Gies, Ziebell '20 & '22)

Asymptotic freedom: a proof of concept: quarks+photons+gluons

$$S_{\rm cl} = \int d^4x \Big[\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{4} G_{I\,\mu\nu} G_I^{\mu\nu} + \bar{\psi}^A \mathrm{i} \not{D}^{AB} \psi^B + \mathrm{i} n\, \bar{\psi}^A \sigma_{\mu\nu} F^{\mu\nu} \psi^A \Big]$$

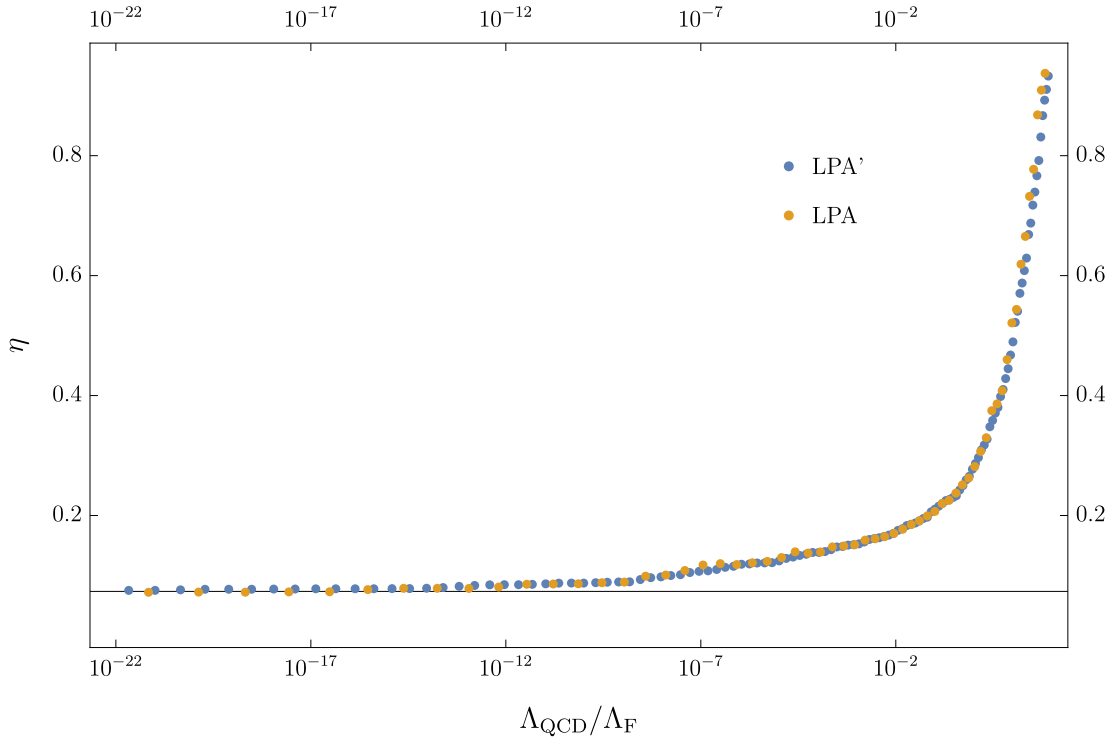
Treating the coupling n as a free parameter supports fixed-point solutions

$$\hat{\alpha}_* = \frac{\alpha}{g_{\rm s}^{2S}} > 0, \qquad 0 < S \leq 1$$

Functional analysis is needed for a fully consistent picture.

Gauge Hiererchy Problem VS Strongly Coupled Gauge Sectors

How much is the Higgs mass fine tuned? $\Theta = 2 - \eta$



Mass and Nonlinear Gauge Fixing

Yang-Mills theory with a nonlinear gauge fixing

$$\mathsf{F}^a[A] = A^{b\mu}\mathsf{Q}^{abc}_{\mu\nu}A^{c\nu} + \mathsf{L}^{ab}_{\mu}A^{a\mu}$$

where

$$\mathsf{Q}^{abc}_{\mu\nu} = \frac{v^a}{2|v|^2}\left(\bar{m}^2\delta_{\mu\nu} - \frac{1}{\xi}\partial_\mu\partial_\nu\right)\delta^{bc}$$

$$\mathsf{L}^{ab}_{\mu} = \left(1 + \frac{\bar{m}^2_{\rm gh}}{-\partial^2}\right)\partial_\mu\delta^{ab}$$

Lorentz gauge plus **gluon and ghost mass parameters**

$$S_{\rm gf} = \frac{1}{2}\bar{m}^2 A^a_\mu A^{a\mu} + \frac{1}{2\xi}\left(\partial^\mu A^a_\mu\right)^2 + v^a\left(1 + \frac{\bar{m}^2_{\rm gh}}{-\partial^2}\right)\partial^\mu A^a_\mu$$

$$S_{\rm gh} = -\bar{c}^a\left(1 + \frac{\bar{m}^2_{\rm gh}}{-\partial^2}\right)\partial^\mu\left(D_\mu c\right)^a - \frac{v^a}{|v|^2}\bar{c}^a\left(\bar{m}^2 A^{b\mu} + \frac{1}{\xi}\left(\partial^\nu A^b_\nu\right)\partial^\mu\right)\left(D_\mu c\right)^b$$