The asymptotic safety paradigm for quantum spacetime and matter

Workshop on gravitational waves, black holes and spacetime singularities
Vatican Observatory
May 2017

Astrid Eichhorn
University of Heidelberg
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A. Platania:
Cosmic censorship in QEG

F. Saueressig:
Cosmic perturbations from Asymptotic Safety
Starting point: Singularities

- Incompleteness of General Relativity
- Incompleteness of the Standard Model of particle physics
Starting point: Singularities

- Incompleteness of General Relativity
- Incompleteness of the Standard Model of particle physics

→ Fundamental description of spacetime needs QFT and QFTs of matter need gravity
Starting point: Singularities

• Incompleteness of General Relativity

• Incompleteness of the Standard Model of particle physics

\[ \int Dg_{\mu\nu} D\phi_{\text{Standard Model}} e^{iS[g_{\mu\nu}, \phi]} \]
Starting point: Singularities

• Incompleteness of General Relativity

• Incompleteness of the Standard Model of particle physics

→ goal: \[ \int \mathcal{D}g_{\mu\nu} \mathcal{D}\phi_{\text{Standard Model}} e^{iS[g_{\mu\nu},\phi]} \]

quantum fluctuations
⇒ scale dependent (running) couplings
example: Quantum Electrodynamics
quantum vacuum = screening medium
Starting point: Singularities

• Incompleteness of General Relativity

• Incompleteness of the Standard Model of particle physics

→ goal: \[ \int \mathcal{D}g_{\mu\nu} \mathcal{D}\phi_{\text{Standard Model}} e^{iS[g_{\mu\nu}, \phi]} \]

  quantum fluctuations

⇒ scale dependent (running) couplings

  example: Quantum Electrodynamics

  quantum vacuum = screening medium

⇒ qm fluc’s of metric: scale dependent grav. coupling
High-energy behavior in QFTs

running coupling in QCD:
Asymptotic freedom

asymptotically: scale-invariance without interactions

[Gross, Wilczek; Politzer '73]
High-energy behavior in QFTs

running coupling in QCD:
Asymptotic freedom

asymptotically:
scale-invariance without interactions

running coupling in QED:
Landau pole/triviality

\[ \frac{1}{k} e^{\pm}(k) \]

new physics!

\[ \Lambda \]

[Gell-Mann, Low '54; Gockeler et al. '97; Gies, Jaeckel '04]

[Gross, Wilczek; Politzer '73]
High-energy behavior in QFTs

running coupling in QCD:
Asymptotic freedom

running coupling in QED:
Landau pole/triviality

asymptotically: scale-invariance without interactions

in Standard Model: $U(1)_{\text{hypercharge}}$ & Higgs quartic coupling affected

[Gell-Mann, Low '54; Gockeler et al. '97; Gies, Jaeckel '04]

[Gross, Wilczek; Politzer '73]
High-energy behavior in QFTs

running coupling in QCD:
Asymptotic freedom

asympotically: scale-invariance without interactions

running coupling in QED:
Landau pole/triviality

\[ \frac{1}{k} e^{\frac{1}{k}}(k) \]

[1/Gross, Wilczek; Politzer '73]

Asymptotic safety

\[ \log[k] \]

\[ e^2(k) \]

[2/Gell-Mann, Low '54; Gockeler et al. '97; Gies, Jaeckel '04]

[3/Weinberg '76]

asymptotically: scale-invariance with interactions

new physics!

[4]
High-energy behavior in QFTs

running coupling in QCD:
Asymptotic freedom

Asymptotically: scale-invariance without interactions

running coupling in QED:
Landau pole/triviality

[Asymptotic safety with interactions]

running coupling in gravity?
Asymptotic safety

[Asymptotic freedom without interactions]
High-energy behavior in QFTs

running coupling in QCD:
Asymptotic freedom

asymptotically: scale-invariance without interactions

running coupling in QED:
Landau pole/triviality

[Asymptotic safety asymptotically: scale-invariance with interactions]

running coupling in gravity?
Asymptotic safety

⇒ Quantum-field theoretic description of fundamental microscopic structure of spacetime

[New physics!]

\[ e^2(k) \]

\[ \frac{1}{k} \]

[diagram]

[Gell-Mann, Low '54; Gockeler et al. '97; Gies, Jaeckel '04]

[Gross, Wilczek; Politzer '73]

[Weinberg '76]
High-energy behavior in QFTs

running coupling in QCD: Asymptotic freedom

asymptotically: scale-invariance without interactions

running coupling in QED: Landau pole/triviality

Landau pole/triviality

running coupling in gravity? Asymptotic safety

\[ G(k) \]

\[ \Lambda \]

\[ \text{new physics!} \]

qm fluc’s of gravity: sizeable for \( E \approx M_{\text{Planck}} \) \[ \Rightarrow \] cannot probe running coupling directly (yet?)

[Weinberg '76]

[Gell-Mann, Low '54; Gockeler et al. '97; Gies, Jaeckel '04]
Functional Renormalization Group - zooming in on quantum spacetime
Functional Renormalization Group - zooming in on quantum spacetime

probe scale dependence of QFT

$\Gamma_k$ contains effect of quantum fluctuations above $k$

$\Gamma_{k \to 0}$

UV scale-invariant regime

classical regime
Functional Renormalization Group - zooming in on quantum spacetime

probe scale dependence of QFT

\[ e^{-\Gamma_k[\phi]} = \int \mathcal{D}\varphi \, e^{-S[\varphi] - \frac{1}{2} \int \varphi(-p) R_k(p) \varphi(p)} \]

scale- and momentum-dependent "mass":
dials "resolution scale"

\[ \Gamma_k \]
contains effect of quantum fluctuations above \( k \)

\[ \Gamma_k \rightarrow 0 \]
Functional Renormalization Group - zooming in on quantum spacetime

probe scale dependence of QFT

\[ e^{-\Gamma_k[\phi]} = \int \mathcal{D}\phi \ e^{-S[\phi]} - \frac{1}{2} \int \varphi(-p) R_k(p) \varphi(p) \]

scale- and momentum-dependent "mass": dials "resolution scale"

Wetterich equation:

\[ \partial_k \Gamma_k = \frac{1}{2} \text{Str} \left( \Gamma_k^{(2)} + R_k \right)^{-1} \partial_k R_k = 0 \]
Asymptotic safety for quantum gravity

\[ \Gamma_k = -\frac{1}{16\pi G_N(k)} \int d^4 x \sqrt{g} \left( R - 2\tilde{\lambda}(k) \right) \]

\[ G(k) = G_N(k)k^2, \quad \lambda(k) = \tilde{\lambda}(k)/k^2 \]

Reuter, '96; Reuter, Saueressig '01, Litim, '03
towards IR
Asymptotic safety for quantum gravity

\[ \Gamma_k = -\frac{1}{16\pi G_N(k)} \int d^4x \sqrt{g} \left( R - 2\bar{\lambda}(k) \right) \]

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towards IR

Towards IR

Towards IR

UV scale-invariant regime

\[ k \partial_k G(k) = 0 \]

classical regime

Classical regime

\[ G_N(k) = \text{const} \]
Asymptotic safety for quantum gravity

\[ \Gamma_k = -\frac{1}{16\pi G_N(k)} \int d^4 x \sqrt{g} \left( R - 2\tilde{\lambda}(k) \right) \]

\[ G(k) = G_N(k) k^2, \quad \lambda(k) = \frac{\tilde{\lambda}(k)}{k^2} \]

quantum fluctuations of metric generate additional terms in the microscopic dynamics

\[ \Gamma_k = \Gamma_{EH} \]

\[ + a \int d^4 x \sqrt{g} R^2 + b \int d^4 x \sqrt{g} R_{\mu\nu} R^{\mu\nu} + c \int d^4 x \sqrt{g} \Box R + \ldots \]

finite number of free parameters (= predictivity)

\[ \rightarrow \] finite number of UV attractive directions

\[ \Rightarrow \] A.S. predicts values of all other couplings

Reuter, '96; Reuter, Saueressig '01, Litim, '03
Asymptotic safety for quantum gravity

\[
\Gamma_k = -\frac{1}{16\pi G_N(k)} \int d^4x \sqrt{g} \left( R - 2\bar{\lambda}(k) \right) \quad G(k) = G_N(k)k^2, \quad \lambda(k) = \bar{\lambda}(k)/k^2
\]

extended tests:

\[
f(R) = \sum_{n=0}^{N} a_n R^n
\]

perturbative counterterms: asymptotic safety

\[
R^2, \quad R_{\mu\nu}R^{\mu\nu}
\]

Reuter, Lauscher, '02; Codello, Percacci, Rahmede, '09; Benedetti, Caravelli, '12; Dietz, Morris, '12; Falls, Litim, Nikolakopoulos, Rahmede, '13, '14; Demmel, Saueressig, Zanusso, '15; Eichhorn '15

Benedetti, Machado, Saueressig, '09

Christiansen, '16, Oda, Yamada '17

Gies, Knorr, Lippoldt, Saueressig '16

't Hooft, Veltman '74; Deser, Niewenhuisen '74; Christensen, Duff '80; Goroff, Sagnotti '85, '86; Van de Ven '92

Reuter, '96; Reuter, Saueressig '01, Litim, '03
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compelling hints for existence of UV scale invariance in quantum gravity

perturbative counterterms: asymptotic safety

\[ f(R) = \sum_{n=0}^{N} a_n R^n \]

\[ R^2, \quad R_{\mu\nu}R^{\mu\nu} \]

Extended tests:

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- Reuter, Lauscher '02; Codello, Percacci, Rahmede, '09; Benedetti, Caravelli, '12; Dietz, Morris, '12; Falls, Litim, Nikolakopoulos, Rahmede, '13, '14; Demmel, Saueressig, Zanusso, '15; Eichhorn '15
- Benedetti, Machado, Saueressig, '09
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quantum fluctuations of metric generate additional terms in the microscopic dynamics

\[ \Gamma_k = \Gamma_{EH} \]

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microscopic values = fixed-point values

→ observational constraints ? (e.g. grav. waveforms)

Reuter, '96; Reuter, Saueressig '01, Litim, '03
Microscopic structure of spacetime:
Microscopic structure of spacetime: Hints for dimensional reduction to 2

Probe (Eucl.) spacetime by a fictitious diffusing particle:
Microscopic structure of spacetime: Hints for dimensional reduction to 2

Probe (Eucl.) spacetime by a fictitious diffusing particle:

classically:
spectral dimension from return probability

\[(\partial_\sigma - \nabla^2) P(x, x', \sigma) = 0\]
Microscopic structure of spacetime:
Hints for dimensional reduction to 2

Probe (Eucl.) spacetime by a fictitious diffusing particle:

classically:
spectral dimension from return probability

\[
(\partial_\sigma - \nabla^2) P(x, x', \sigma) = 0
\]

\[
ds = -2 \frac{\partial \ln P(x, x, \sigma)}{\partial \ln \sigma} = 4
\]
Microscopic structure of spacetime: Hints for dimensional reduction to 2

Probe (Eucl.) spacetime by a fictitious diffusing particle:

classically: spectral dimension from return probability

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(\partial_\sigma - \nabla^2) P(x, x', \sigma) = 0
\]

\[
d_s = -2 \frac{\partial \ln P(x, x, \sigma)}{\partial \ln \sigma} = 4
\]

quantum-gravity regime: scale-invariance encoded in diffusion equation

Lauscher, Reuter '05
Microscopic structure of spacetime: Hints for dimensional reduction to 2

Probe (Eucl.) spacetime by a fictitious diffusing particle:

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Quantum-gravity regime:

scale-invariance encoded in diffusion equation

\[
(\partial \sqrt{\sigma} - \nabla^2) P(x, x', \sigma) = 0
\]

\[
d_s = 2
\]

Lauscher, Reuter '05

Calcagni, A.E., Saueressig, '13
Microscopic structure of spacetime: Hints for dimensional reduction to 2

Probe (Eucl.) spacetime by a fictitious diffusing particle:

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quantum-gravity regime:
scale-invariance encoded in diffusion equation

\[ (\partial \sqrt{\sigma} - \nabla^2) P(x, x', \sigma) = 0 \]

\[ d_s = 2 \]

dimensional reduction:
common theme in quantum gravity

Lauscher, Reuter '05
Calcagni, A.E., Saueressig, '13
Ambjorn, Jurkiewicz, Loll '05; Carlip '09; Horava '09
Microscopic structure of spacetime:

Cosmic censorship in QEG
→ talk by A. Platania

Cosmic perturbations from Asymptotic Safety
→ talk by F. Saueressig
Asymptotic safety for quantum gravity and matter
Asymptotic safety for quantum gravity and matter

Can quantum fluctuations of matter destroy consistent quantum gravity model?

quantum gravity dynamics

matter dynamics
Matter matters

\[ k \partial_k G(k) = \beta_G = 2G + \frac{G^2}{6\pi} (-46) \] + ...
Matter matters

\[ k \partial_k G(k) = \beta_G = 2G + \frac{G^2}{6\pi} (-46) \]

canonical scaling  \( [G]=-2 \)

quantum fluctuations

\[ k \partial_k G(k) = \beta_G = 2G + \frac{G^2}{6\pi} (-46) \]  

\( \beta_G \)  

\[ \begin{array}{c}
\text{asymptotic safety} \\
\end{array} \]
Matter matters

\( k \partial_k G(k) = \beta_G = 2G + \frac{G^2}{6\pi} (-46 + N_S + 2N_D - 4N_V) + \ldots \)

Scalars (Higgs)  Fermions (quarks & leptons)  Vectors (gauge bosons)

[approximation: Einstein-Hilbert & minimally coupled matter]

[Dona, AE, Percacci ’13, ’14]
Matter matters

\[ k \partial_k G(k) = \beta_G = 2G + \frac{G^2}{6\pi} (-46 + N_S + 2N_D - 4N_V) + \ldots \]

- Scalars (Higgs)
- Fermions (quarks & leptons)
- Vectors (gauge bosons)

Standard Model matter content compatible with asymptotically safe quantum gravity

(@ 12 Nv)

approximation: Einstein-Hilbert & minimally coupled matter

[Dona, AE, Percacci '13, '14]
Asymptotic safety for quantum gravity and matter

Can quantum fluctuations of matter destroy consistent quantum gravity model?

Can quantum fluctuations of gravity generate a viable UV completion for matter?
Asymptotic safety for quantum gravity and matter

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triviality in Higgs & U(1)
Asymptotic safety for quantum gravity and matter

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triviality in Higgs & U(1)

QG-induced asymptotic safety

QG generated fixed point

$M_{\text{Planck}}$
Asymptotic safety for quantum gravity and matter

- Can quantum fluctuations of matter destroy a consistent quantum gravity model?
- Can quantum fluctuations of gravity generate a viable UV completion for matter?
- QG-induced asymptotic safety
- QG-induced asymptotic freedom
- QG generated fixed point
- Triviality in Higgs & U(1)

Diagram:
- Quantum gravity dynamics
- Matter dynamics
- Planck length $k$
Asymptotic safety for quantum gravity and matter

Can quantum fluctuations of matter destroy consistent quantum gravity model?

Can quantum fluctuations of gravity generate a viable UV completion for matter?

Quantum gravity dynamics

Matter dynamics

Match onto SM at Planck scale

QG generated fixed point

QG-induced asymptotic freedom

QG-induced asymptotic safety

Triviality in Higgs & U(1)

Buttazzo et al. ‘13
Asymptotically safe gravity & the Standard Model

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{D} \gamma y + \text{h.c.} \]
\[ + X_i y_{ij} y_{\phi} \text{h.c.} \]
\[ + |D_\mu \phi|^2 - V(\phi) \]

* (truncated RG flow)
Asymptotically safe gravity & the Standard Model

\[ L = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{D} D \psi + h.c. + \chi_i \chi_j \chi_3 \phi + h.c. + |D_{\mu} \phi|^2 - V(\phi) \]

fixed point at vanishing potential

[Shaposhnikov, Wetterich '09]

\[ \rightarrow \quad \text{Higgs mass} \quad \gtrsim \quad 126 \text{ GeV} \]

[Shaposhnikov, Wetterich '09]

* (truncated RG flow)
Asymptotically safe gravity & the Standard Model *

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} D\phi - \bar{\psi} \gamma^\mu \psi F_{\mu\nu} \psi + \sqrt{2} y_1 y_1 y_3 \phi + \text{h.c.} + |D_{\mu} \phi|^2 - V(\phi) \]

\( y_1 = 0 \) only admits \( m_{\text{top}} = 176 \text{ GeV} \) for restricted UV-values of grav. couplings

\( \rightarrow \) \text{``pheno'' constraint on QG}

[A.E., Held, Pawlowski '16; A.E., Held '17]

fixed point at vanishing potential

[Narain, Percacci '09; A.E. '13; Percacci, Vacca '15]

\( \rightarrow \) Higgs mass \( \gtrsim 126 \text{ GeV} \)

[Shaposhnikov, Wetterich '09]

* (truncated RG flow)
Asymptotically safe gravity & the Standard Model *

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} D \psi + \text{h.c.} + \lambda_i y_{ij} y_{i} \phi + \text{h.c.} + |D \phi|^2 - V(\phi) \]

- **Chiral structure (light fermions)** preserved
  - [A.E., Gies '11; Meibohm, Pawlowski '16; A.E., Lippoldt '16]

- \( y_\ast = 0 \) only admits \( m_{\text{top}} = 176 \text{ GeV} \)
  - for restricted UV-values of grav. couplings
  - \( \rightarrow \) "pheno" constraint on QG
  - [A.E., Held, Pawlowski '16; A.E., Held '17]

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  \( \rightarrow \) Higgs mass \( \gtrsim 126 \text{ GeV} \)
  - [Shaposhnikov, Wetterich '09 ]

* (truncated RG flow)
Asymptotically safe gravity & the Standard Model *

- Asymptotically safe solution to the Landau pole/triviality problem in U(1)?
  - [Daum, Harst, Reuter '09; Harst, Reuter '11; Folkerts, Litim, Pawlowski '11; Christiansen, A.E. '17]

- Chiral structure (light fermions) preserved
  - [A.E., Gies '11; Meibohm, Pawlowski '16; A.E., Lippoldt '16]
  - $y_* = 0$ only admits $m_{\text{top}} = 176\text{ GeV}$ for restricted UV-values of grav. couplings
    - ``pheno” constraint on QG
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- Fixed point at vanishing potential
  - [Narain, Percacci '09; A.E. '13; Percacci, Vacca '15]

- $\rightarrow$ Higgs mass $\gtrsim 126\text{ GeV}$
  - [Shaposhnikov, Wetterich '09 ]

* (truncated RG flow)
Asymptotically safe solution to the U(1) triviality problem

Quantum-Gravity effects on U(1) gauge theory *

* (truncated RG flow)
Asymptotically safe solution to the U(1) triviality problem

Quantum-Gravity effects on U(1) gauge theory *:
* (truncated RG flow)

- asymptotic freedom for the running charge

\[ \beta_e = -\frac{e}{4\pi}G + \frac{e^3}{12\pi^2} + \ldots \]

\[ e_k = \frac{e}{4\pi}G + \frac{e^3}{12\pi^2} + \ldots \]

\[ \ln\left[\frac{k}{M_{\text{Planck}}}\right] \]

\[ \ln\left[\frac{k}{M_{\text{Planck}}}\right] \]

[Harst, Reuter ’11; Christiansen, A.E. ’17]
[Robinson, Wilczek ’06; Pietrykowski ’07; Toms ’07, ’08, ’09, ’10, ’11]
Asymptotically safe solution to the U(1) triviality problem

Quantum Gravity effects on U(1) gauge theory *:

* (truncated RG flow)

1. asymptotic freedom for the running charge

\[
\beta_e = -\frac{e}{4\pi} G + \frac{e^3}{12\pi^2} + \ldots
\]

[Harst, Reuter '11; Christiansen, A.E. '17]

[Robinson, Wilczek 06; Pietrykowski '07;
Toms '07, '08, '09, '10,'11]

2. asymptotic safety for induced photon-photon interactions

\[
\rightarrow w_2 (F^2)^2
\]

Quantum gravity fluctuations induce new interactions beyond M_{Planck}
Asymptotically safe solution to the U(1) triviality problem

Quantum-Gravity effects on U(1) gauge theory *:

* (truncated RG flow)

• asymptotic freedom for the running charge

\[ \beta_e = -\frac{e}{4\pi} G + \frac{e^3}{12\pi^2} + \ldots \]

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\[ \rightarrow w_2 \left( F^2 \right)^2 \]
Asymptotically safe solution to the U(1) triviality problem

Quantum-Gravity effects on U(1) gauge theory *
*(truncated RG flow)

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Quantum-Gravity effects on U(1) gauge theory *:

- asymptotic freedom for the running charge
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[Harst, Reuter '11; Christiansen, A.E. '17]

[Robinson, Wilczek 06; Pietrykowski '07; Toms '07, '08, '09, '10,'11]

QG too strong: destruction of UV completion for matter: divergence in photon interactions
Asymptotically safe solution to the U(1) triviality problem

Quantum-Gravity effects on U(1) gauge theory *:

- asymptotic freedom for the running charge

\[ \beta_e = -\frac{e}{4\pi} G + \frac{e^3}{12\pi^2} + \ldots \]

- asymptotic safety for induced photon-photon interactions

\[ \rightarrow w_2 \left( F^2 \right)^2 \]

\[ \text{weak-gravity bound:} \]
\[ \text{viable UV completion for matter only for weak QG} \]

[Harst, Reuter '11; Christiansen, A.E. '17]
[Robinson, Wilczek 06; Pietrykowski '07; Toms '07, '08, '09, '10, '11]

[Christiansen, A.E. '17]

[A.E. '13; A.E., Held, Pawlowski '16; A.E., Held '17]

bound satisfied in all approximations tested so far
Summary

Asymptotic safety paradigm: UV complete Quantum Field Theory of gravity and matter

Reuter, '96; Reuter, Saueressig '01, Litim, '03
Summary

Asymptotic safety paradigm:
UV complete Quantum Field Theory of gravity and matter

Hints for dynamical dimensional reduction in the UV
(⇔ scale invariance)
Summary

Asymptotic safety paradigm:
UV complete Quantum Field Theory of gravity and matter

Hints for dynamical dimensional reduction in the UV
(\leftrightarrow \text{scale invariance})

Matter matters for the microscopic dynamics of spacetime

Standard Model matter content compatible with asymptotically safe quantum gravity
Summary

Asymptotic safety paradigm:
UV complete Quantum Field Theory of gravity and matter

Hints for dynamical dimensional reduction in the UV
($\leftrightarrow$ scale invariance)

Matter matters for the microscopic dynamics of spacetime

Hints for quantum-gravity induced UV completion for the Standard Model of particle physics
Starting point: Singularities

- Incompleteness of General Relativity

- Incompleteness of the Standard Model of particle physics
  
  → Where should we expect new physics?

  Possible interpretation of LHC data: New physics at the Planck scale
Starting point: Singularities

• Incompleteness of General Relativity

• Incompleteness of the Standard Model of particle physics

→ Where should we expect new physics?

Possible interpretation of LHC data: New physics at the Planck scale

\[ m_h \approx 126 \text{ GeV} \]

[ATLAS, CMS]
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- Incompleteness of General Relativity
- Incompleteness of the Standard Model of particle physics
  → Where should we expect new physics?
  Possible interpretation of LHC data: New physics at the Planck scale
  \[ m_h \approx 126 \text{ GeV} \]
  [ATLAS, CMS]

How does the Higgs mass tell us about the scale of new physics?
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- Incompleteness of the Standard Model of particle physics
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Possible interpretation of LHC data: New physics at the Planck scale

\[ m_h \approx 126 \text{ GeV} \]

[ATLAS, CMS]

How does the Higgs mass tell us about the scale of new physics?

\[ m_h \]

\[ \text{strong coupling/triviality bound} \]

175 GeV

$10^{19}$ GeV

[Maiani, Parisi, Petronzio ’78; Cabibo, Maiani, Parisi, Petronzio ’79; Dashed, Neuberger ’83; Callaway ’84, Lindner ’86…]
Starting point: Singularities

- Incompleteness of General Relativity
- Incompleteness of the Standard Model of particle physics

→ Where should we expect new physics?

Possible interpretation of LHC data: New physics at the Planck scale

$$m_h \approx 126 \text{ GeV}$$

[ATLAS, CMS]

How does the Higgs mass tell us about the scale of new physics?

[Maiani, Parisi, Petronzio ’78; Cabibo, Maiani, Parisi, Petronzio ’79; Dashed, Neuberger ’83; Callaway ’84, Lindner ’86…]

[Krive, Linde ’76; Krasnikov ’78; Hung ’79; Politzer, Wolfram ’79; Linde ’80; Lindner, Sher, Zaglauer ’89; Ford, Jones, Stephenson, Einhorn ’93…]

[Espinosa, Quiros ’95; Ellis, Espinosa, Giudice, Hoecker, Riotto ’09; Elias-Miro, Espinosa, Giudice, Isidori, Riotto, Strumia ’12; Bezrukov, Kalmikov, Kniehl, Shaposhnikov ’12…]
Matter matters

analogy: destruction of asymptotic freedom by matter

\[ \beta \alpha_s = - \left( 11 - \frac{2}{3} N_f \right) \frac{\alpha_s^2}{2\pi} + \ldots \]

\( \Rightarrow \) antiscreening vacuum (asymptotic freedom) only for \( N_f \lesssim 16.5 \)

- gluons
- anti-screen
- fermions
- screen