Title: Quantum Gravity Seminar - TBA - VIRTUAL

Speakers: Jan Pawlowski

Series: Quantum Gravity

Date: January 25, 2024 - 2:30 PM

URL: https://pirsa.org/24010091

Abstract: Abstract TBA

Zoom link

Particle physics & quantum black holes from asymptotically safe correlation functions

Jan M. Pawlowski

Universität Heidelberg

Virtual seminar Perimeter Institute, January 25th 2024

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

STRUCTURES CLUSTER OF EXCELLENCE

isoQuant SFB1225

EMMI

Outline

- Asymptotic safety

- Asymptotically safe correlation functions

- Some remarks on unitarity

- Applications I: asymptotically safe Standard Model

- Applications II: asymptotically black holes

- Summary

Asymptotic safety

Einstein-Hilbert action

Metric g **Cosmological constant** Λ

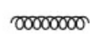
$$S[g] = \frac{1}{16\pi G_N} \int d^4x \sqrt{g} \left(-R(g) + 2\Lambda \right)$$

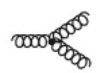
Newton constant G_N **Ricci scalar** $R(g)$

Momentum dimension of couplings

$$\dim G_N = -2 \qquad \dim \Lambda = 2$$

perturbatively non-renormalisable

graviton propagator :  $\propto \frac{1}{p^2}$

3 – grav. vertex :  $\propto \sqrt{G_N} p^2$

4 – grav. vertex :  $\propto G_N p^2$

$\vdots$

Asymptotic safety

Einstein-Hilbert action

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Correlation functions

diffeomorphism invariant

$$\langle R(g(x_1)) \cdots R(g(x_n)) \rangle$$

Ricci scalar correlations

not diffeomorphism invariant

$$\langle g(x_1) \cdots g(x_n) \rangle$$

metric correlations

Asymptotic safety

Weinberg `79: Ultraviolet Divergences in Quantum Theories of Gravitation

Consider an observable $\mathcal{O}(g)$ with fundamental coupling g

- **Standard perturbation theory**

$$\mathcal{O}(g) = O_0 + O_1\, g + \frac{1}{2} O_2\, g^2 + \cdots$$

- **Generalised perturbation theory**

$$\mathcal{O}(g) = O^* + O_1^*\,(g - g^*) + \frac{1}{2} O_2^*\,(g - g^*)^2 + \cdots$$

e.g. aiming at better convergence fundamental coupling

non-perturbative example: analytic perturbation theory in QCD

- **Renormalisation group fixed points**

beta functions

$$\partial_t g = \beta_g(g, \mu)$$

$$\partial_t \mu = \beta_\mu(g, \mu)$$

Logarithmic momentum (RG) scale: $t = \log \frac{k}{k_0}$

Asymptotic safety

Consider an observable $\mathcal{O}(g)$ **with fundamental coupling** g

- **Ultraviolet running**

QCD

$$\beta_g(g) = -\frac{1}{16\pi^2}\frac{22\,N_c}{3}g^3$$

Asymptotic freedom

quantum gravity

$$\beta_{g_N} = \Big[2 + \eta_N(g_N, \lambda)\Big]g_N$$

dimensional running **quantum fluctuations**

Asymptotic safety

$$g_N = G_N\,k^2 \qquad \lambda = \frac{\Lambda}{k^2}$$

- **Renormalisation group fixed points**

Logarithmic momentum scale

beta functions

$$\partial_t g = \beta_g(g, \mu)$$

$$\partial_t \mu = \beta_\mu(g, \mu)$$

Fixed points

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

$$\beta_\mu(g^*, \mu^*) = 0$$

Asymptotic safety

Consider an observable $\mathcal{O}(g)$ with fundamental coupling g

- **Ultraviolet running**

QCD

$$\beta_g(g) = -\frac{1}{16\pi^2}\frac{22\,N_c}{3}g^3$$

Asymptotic freedom

Gaußian fixed point

quantum gravity

$$\beta_{g_N} = \Big[2 + \eta_N(g_N,\lambda)\Big]g_N$$

dimensional running

quantum fluctuations

Asymptotic safety

$$\eta_N = -2$$

non-Gaußian fixed point

- **Renormalisation group fixed points**

Logarithmic momentum scale

$$(g_N^*, \lambda^*) \neq 0$$

beta functions

$$\partial_t g = \beta_g(g,\mu)$$

$$\partial_t \mu = \beta_\mu(g,\mu)$$

Fixed points

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

$$\beta_\mu(g^*,\mu^*) = 0$$

From vertex dressings/distribution functions to physics

aka
form factors

Effective action

$$\Gamma[\bar{g}, h, c_\mu, \bar{c}_\mu] = \int_x \left[\frac{2\Lambda - R}{16\pi G_N} + R\, f_R(\Delta)\, R + C f_C(\Delta) C + \cdots\right]_{\text{BRST-inv}} + S_{\text{gf}} + S_{\text{gh}}$$

Background effective action

$$\Gamma[g_{\mu\nu}] = \frac{1}{16\pi}\int_x \sqrt{g}\left\{\mathcal{R}(\Delta, R) + R f_{R^2}(\Delta) R + R_{\mu\nu} f_{R^2_{\mu\nu}}(\Delta) R^{\mu\nu} + \cdots\right\}$$

JMP, Tränkle, 2309.17043

Enforced by IR-UV consistence

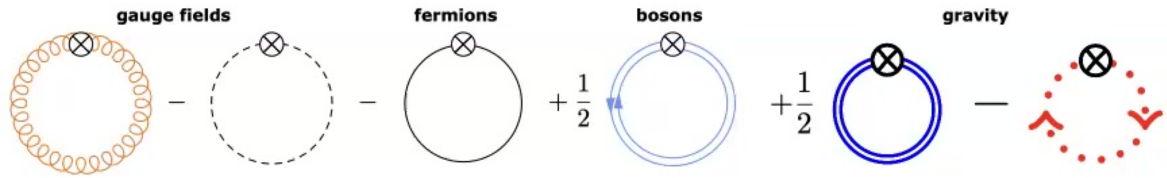
$$R\, f_{R^2}(\Delta, R)\, R = \mathcal{R}(\Delta, R) + R f_{R^2}(\Delta) R$$

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

Background independence in gravity

free energy

$$k\partial_k\Gamma_k[\bar{g},\phi] = \frac{1}{2}$$



Linear split

$$g = \bar{g} + h$$

Effective action

$$\Gamma_k[\bar{g},\bar{h}] = \Gamma_k[\bar{g}] + \Gamma_k^{(0,1)}[\bar{g}] * \bar{h} + \frac{1}{2}\Gamma_k^{(0,2)}[\bar{g}] * \bar{h}^2 + \frac{1}{6}\Gamma_k^{(0,3)}[\bar{g}] * \bar{h}^3 + \cdots \qquad \boxed{\bar{h} = \langle h \rangle}$$

$$\left\{\Gamma_k[\bar{g}]\,,\,\Gamma_k^{(0,1)}[\bar{g}]\,,\,\Gamma_k^{(0,2)}[\bar{g}]\,,\,\Gamma_k^{(0,3)}[\bar{g}]\,,\,\ldots\right\}$$

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

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gauge dependent

Background effective action

$$\Gamma[g_{\mu\nu}] = \frac{1}{16\pi} \int_x \sqrt{g} \left\{ \mathcal{R}(\Delta, R) + R f_{R^2}(\Delta) R + R_{\mu\nu} f_{R^2_{\mu\nu}}(\Delta) R^{\mu\nu} + \cdots \right\}$$

gauge independent

JMP, Tränkle, 2309.17043

Enforced by IR-UV consistence

$$R\, f_{R^2}(\Delta, R)\, R = \mathcal{R}(\Delta, R) + R f_{R^2}(\Delta) R$$

How much do they differ?

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2309.10785

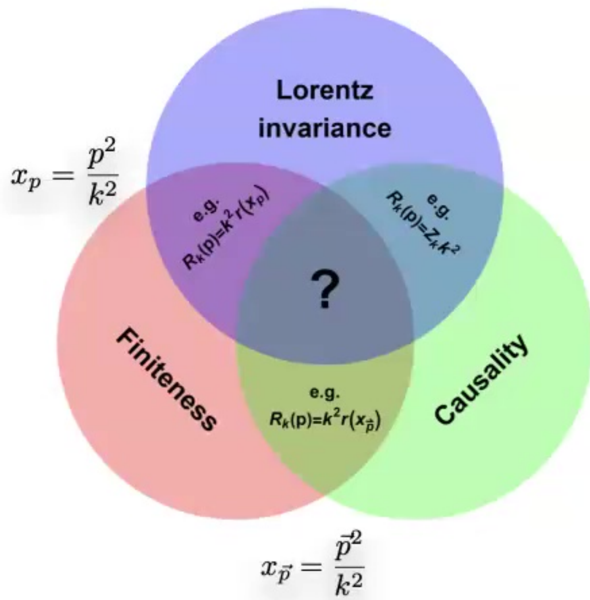
A lesson from graviton spectral functions

Spectral representation

$$G_k(p) = \int_{-\infty}^{\infty} \frac{d\lambda}{2\pi} \frac{\lambda\, \rho_k(\lambda, \vec{p})}{\lambda^2 + p_0^2}$$

Reconstruction (inverse problem): $\rho_k[G_k]$

Direct Lorentzian computation with symmetry preserving



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fQCD, Reichert, SciPost Phys.Core 6 (2023) 061
Fehre, Litim, JMP, Reichert, PRL 130 (2023) 081501

A lesson from graviton spectral functions

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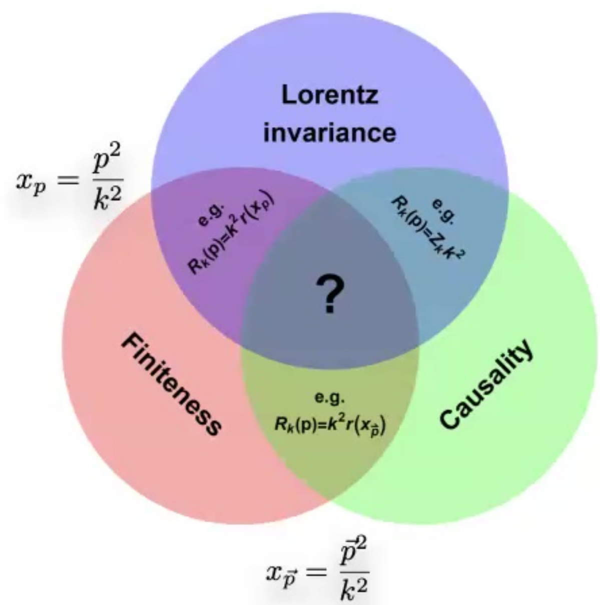


Lorentz invariance & Causality

Callan-Symanzik regulator

$$R_{\mathrm{CS}} = Z_\phi k^2$$

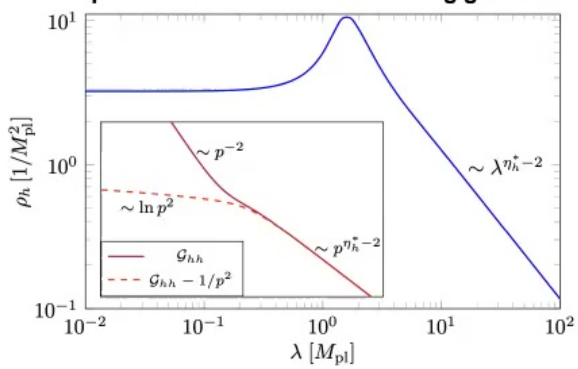
Finiteness lost

9

fQCD, Reichert, SciPost Phys.Core 6 (2023) 061
Fehre, Litim, JMP, Reichert, PRL 130 (2023) 081501

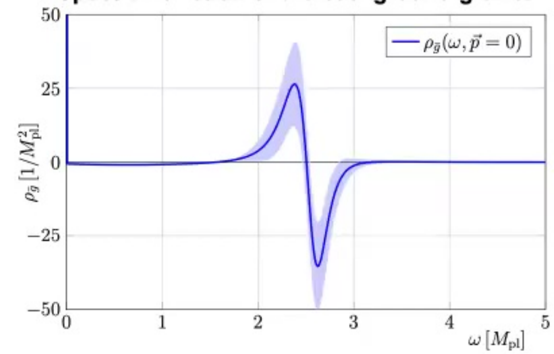
A lesson from graviton spectral functions

Direct computation



Fehre, Litim, JMP, Reichert, PRL 130 (2023) 081501

Reconstruction



Bonanno, Denz, JMP, Reichert, *SciPost Phys.* 12 (2022) 1, 001

Spectral properties ‘resemble’ that of an asymptotic

$$\rho_h(\lambda) \in \mathbb{R}^+ \qquad \int_{\mathbb{R}} \frac{d\lambda}{2\pi}\, \lambda \rho_h(\lambda) = \infty$$

Spectral properties of an unphysical mode

$$\rho_{\bar g}(\lambda) \in \mathbb{R} \qquad \int_{\mathbb{R}} \frac{d\lambda}{2\pi}\, \lambda \rho_{\bar g}(\lambda) = 0$$

How much do they differ?

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

Background spectral function and scattering amplitudes

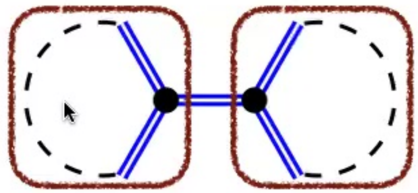
RG-invariant vertex

$$\frac{\Gamma^{(3)}_{hhh}(p_1,p_2,p_3)}{Z_h^{\frac{1}{2}}(p_1)Z_h^{\frac{1}{2}}(p_2)Z_h^{\frac{1}{2}}(p_3)}$$

aka

RG-invariant coupling /form factor

Graviton-graviton scattering



Bonanno, Denz, JMP, Reichert, *SciPost Phys.* 12 (2022) 1, 001

RG-invariant vertex

$$\frac{\Gamma^{(3)}_{hhh}(p_1,p_2,p_3)}{Z_h^{\frac{1}{2}}(p_1)Z_h^{\frac{1}{2}}(p_2)Z_h^{\frac{1}{2}}(p_3)}$$

aka

RG-invariant coupling /form factor

Fluctuation approach: 2012 ···

Form factor approach: 2018 ···

Knorr, Ripken, Saueressig, ...

Suggestive educated guess

$$\bar{\Gamma}^{(n)}_{\bar{g}^n}(p_1,...,p_n) \approx \frac{\Gamma^{(n)}_{h^n}(p_1,...,p_n)}{Z_h^{\frac{1}{2}}(p_1)\cdots Z_h^{\frac{1}{2}}(p_n)}$$

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

The physics of thresholds

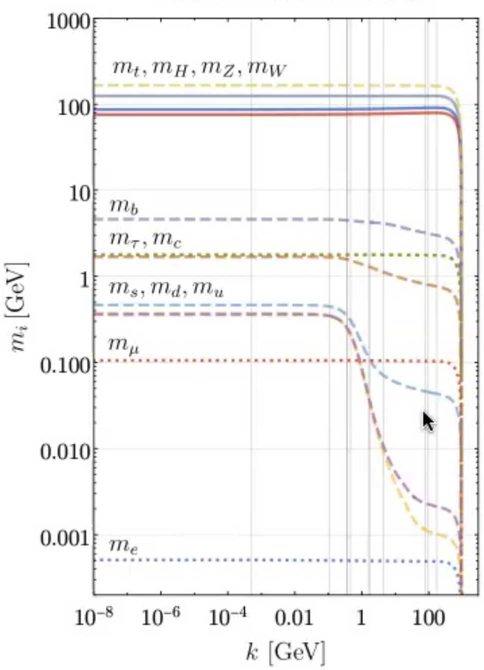
Bonanno et al., Critical reflections on asymptotically safe gravity, Front.in Phys. 8 (2020) 269

QCD & SM thresholds in the RG since (many) decades

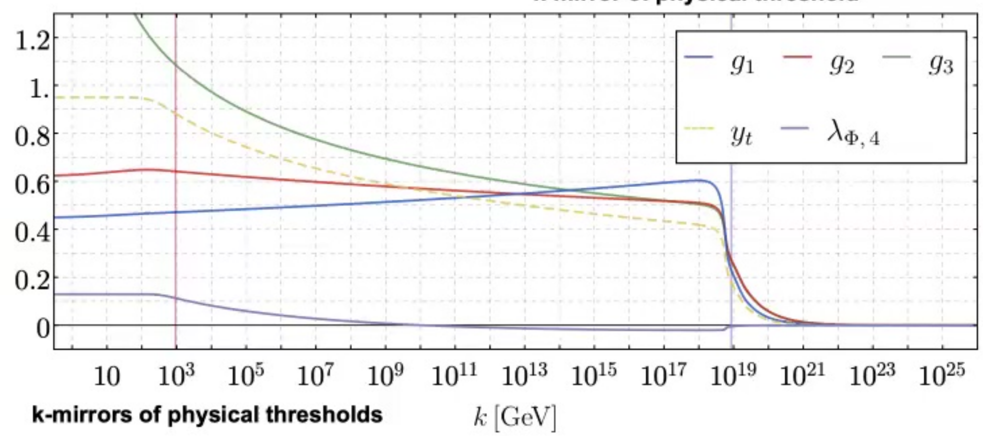
QCD with the fRG since a decade

Example: asymptotically safe Standard Model

Pastor-Gutiérrez, JMP, Reichert, SciPost Phys. 15 (2023) 105



k-mirrors of physical thresholds



k-mirrors of physical thresholds

k-mirrors of physical thresholds: feature, not bug!

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

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Bonanno et al., Critical reflections on asymptotically safe gravity, Front.in Phys. 8 (2020) 269

QCD & SM thresholds in the RG since (many) decades

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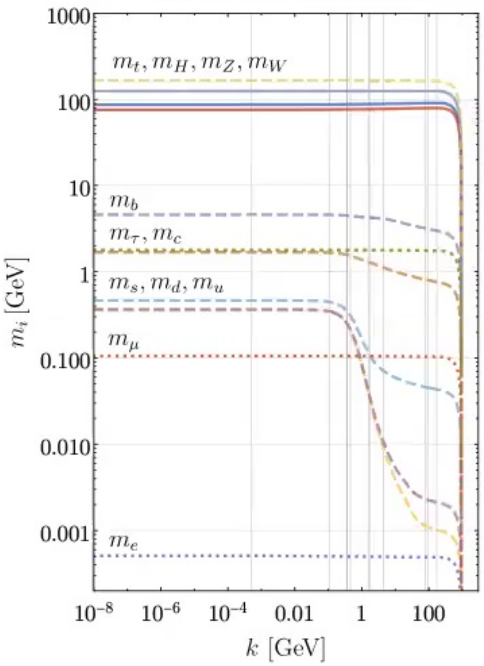
Standard Model masses



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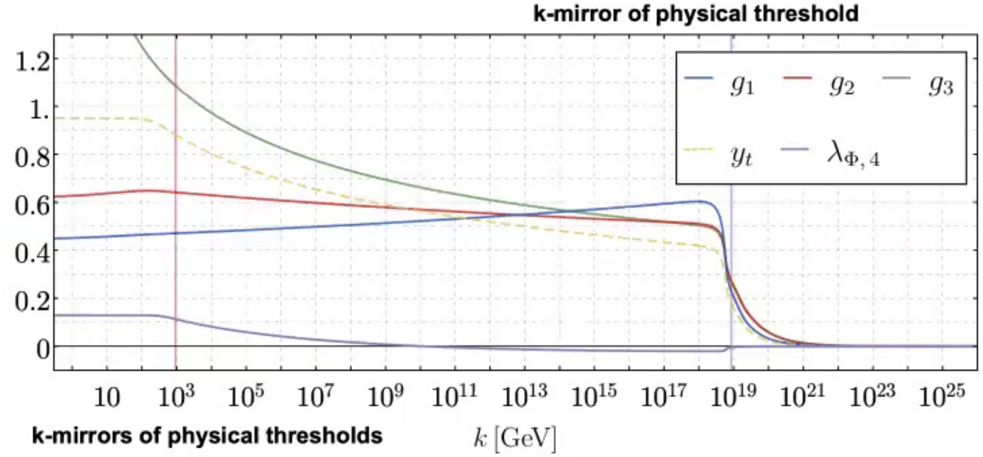
k-mirror of physical threshold



k-mirrors of physical thresholds

k-mirrors of physical thresholds: feature, not bug!

Full physics: momentum-dependent correlation functions & S-matrix elements at k=0

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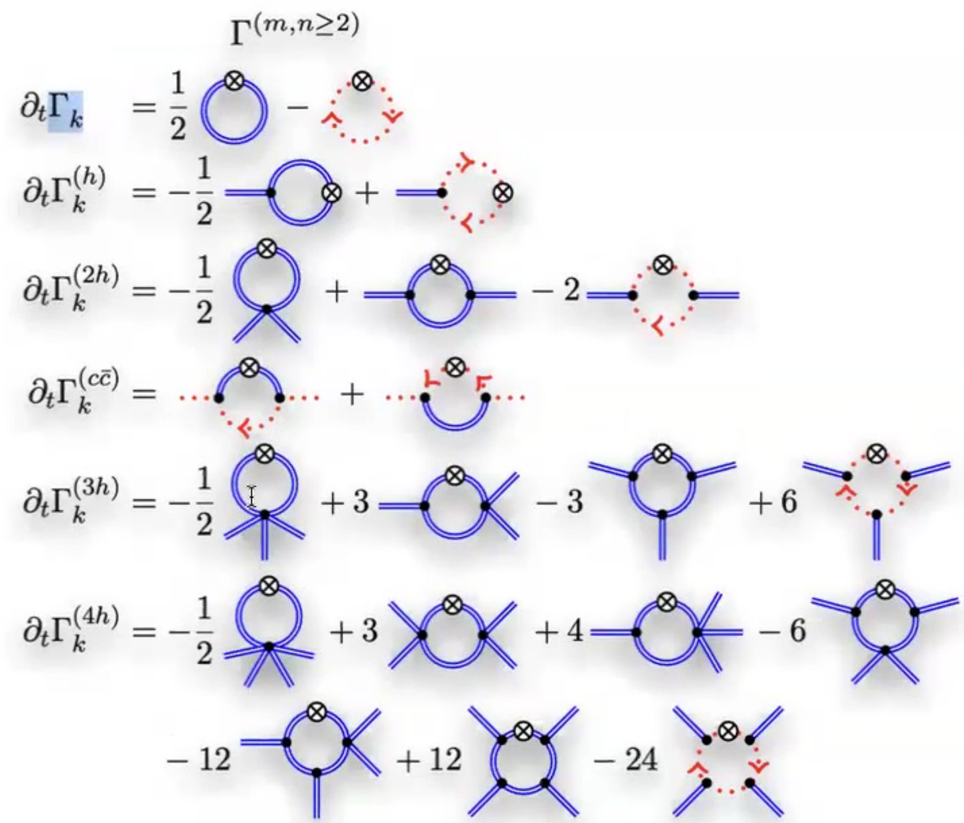
Towards apparent convergence in quantum gravity

vertex expansion



Aiming at apparent convergence

JMP, Reichert, Front.in Phys. 8 (2021) 527
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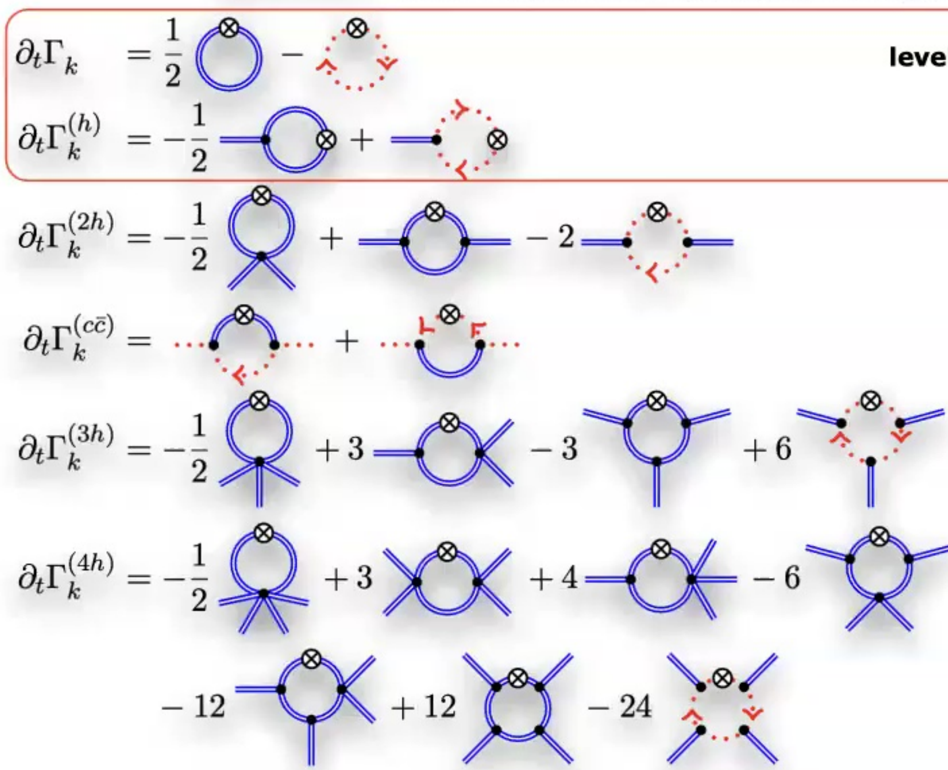
Towards apparent convergence in quantum gravity

vertex expansion

$\Gamma^{(m,n\geq 2)}$ **bi-metric approach: Manrique, Reuter, Saueressig, Annals Phys. 326 (2011) 463**

level 1: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-1,1)}$



Aiming at apparent convergence

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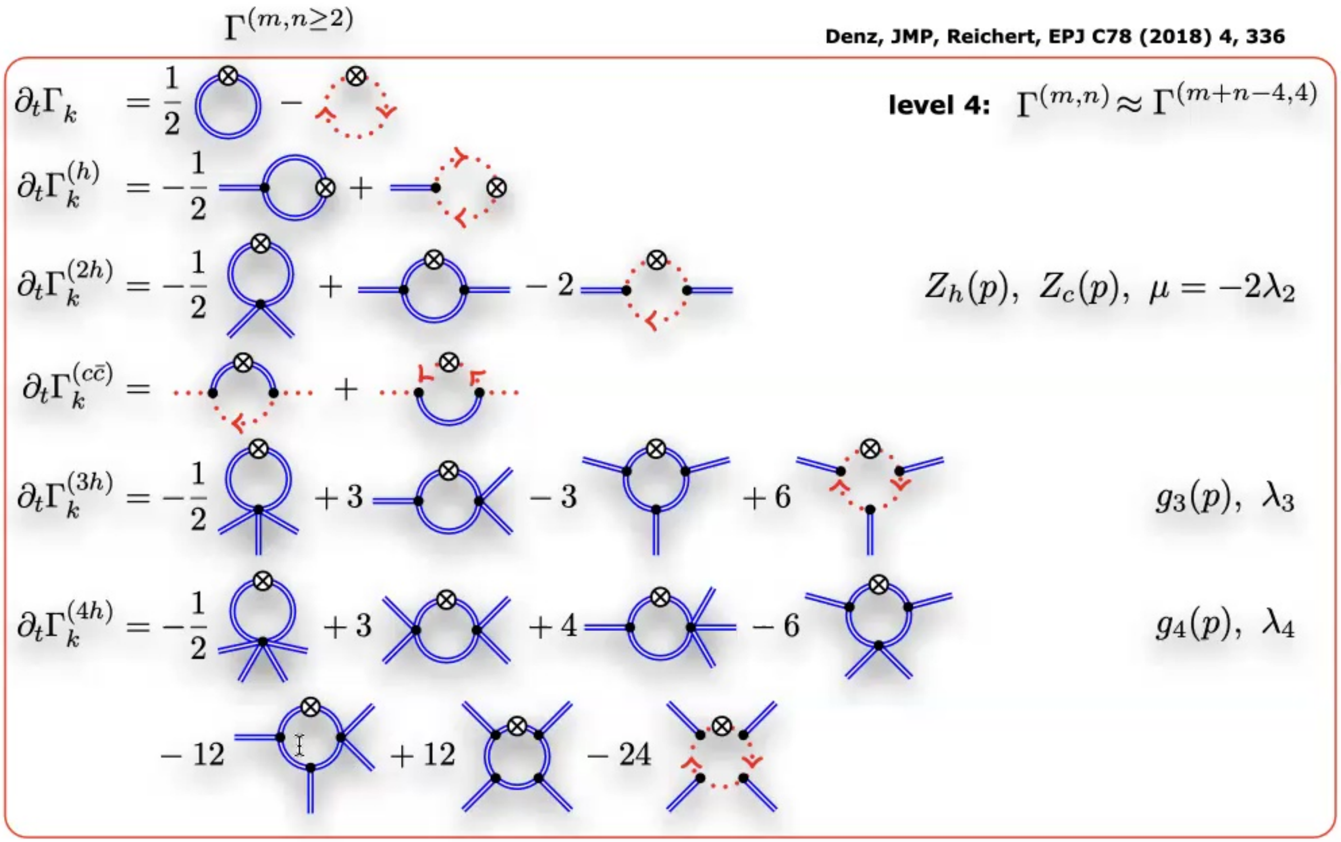
Towards apparent convergence in quantum gravity

vertex expansion

Denz, JMP, Reichert, EPJ C78 (2018) 4, 336



Aiming at apparent convergence

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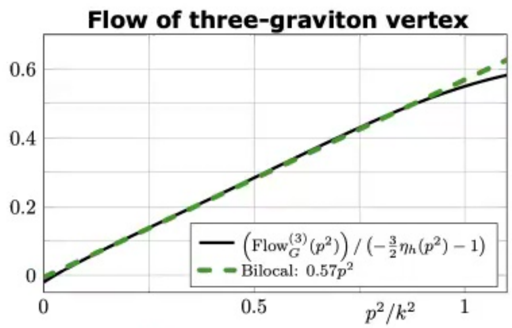
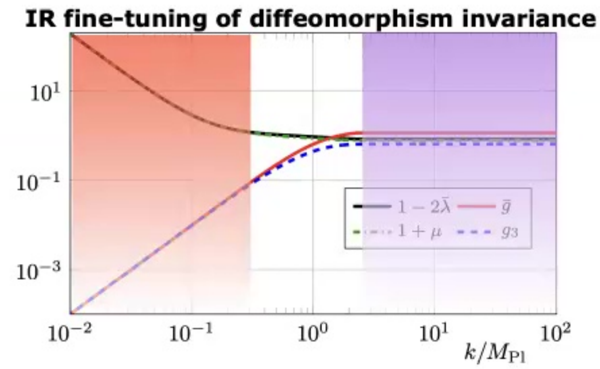
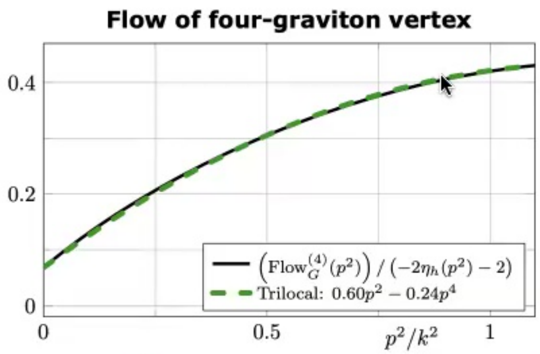
Momentum-dependent vertices



no $\mathbf{R}^2_{\mu\nu}$ - tensor structure generated!



Denz, JMP, Reichert, EPJ C78 (2018)



classical general relativity

asymptotically safe fixed point scaling

$\mathbf{R}^2$ - tensor structure generated

$\mathbf{R}$ - tensor structure sustained

Full momentum dependence
of
two-, three- and four-point function
at k=0

→ Spectral properties

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

Towards apparent convergence in quantum gravity

Why does/could it work?

Typically diagrams with higher order vertices are strongly suppressed

(a) couplings stay finite

(b) combinatorical suppression of diagrams with higher vertices

(c) phase space (angular) suppression of diagrams with higher vertices

turns out to be very efficient!

JMP, Reichert, Front.in Phys. 8 (2021) 527
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Why does/could it fail?

Resonant interaction channels and their interactions circumvent (b) and make (a) irrelevant

(a) couplings diverge

(b) hadrons, diquarks, glueballs, ... in QCD → **Emergent composites, BSE**

Gies, Wetterich, PRD 65 (2002) 0650016
JMP, AP 322 (2007) 2831
Flörchinger, Wetterich, PLB 680 (2009) 371

(c) graviballs in gravity → 

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

Towards apparent convergence in quantum gravity

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JMP, AP 322 (2007) 2831
Flörchinger, Wetterich, PLB 680 (2009) 371

(c) graviballs in gravity → 

QG as perturbative as possible & apparently converging

... slight oversimplification for the sake of this talk ...

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Applications I: asymptotically safe Standard Model

Pastor-Gutiérrez, JMP, Reichert, SciPost Phys. 15 (2023) 105

Dona, Eichhorn, Percacci, PRD 89 (2014) 084035

Meibohm, JMP, Reichert, EPJC 76 (2016) 285

Christiansen, Litim, JMP, Reichert PRD 97 (2018) 4, 046007

⋮

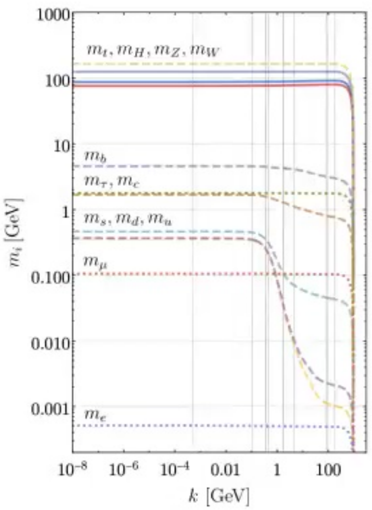
Shaposhnikov, Wetterich, PLB 683 (2010) 196

Eichhorn, Versteegen, JHEP 1801 (2018) 030

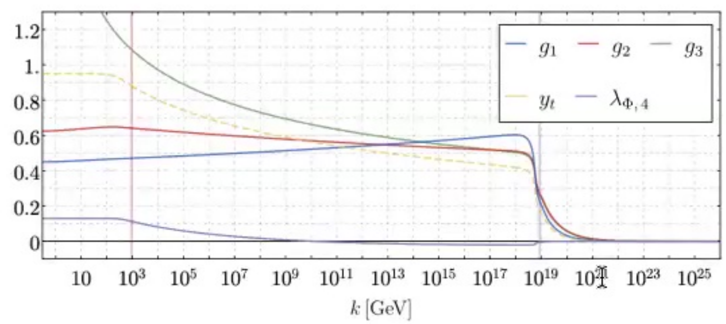
Eichhorn, Held, PRL 121 (2018) 151302

⋮

Latest ‘status report’: Eichhorn, Schiffer, 2212.07456



Asymptotically safe Standard Model



top pole mass (getting real)

$$M_{t,\text{pole}}^{(\text{exp})} = 172.5 \pm 0.7\,\text{GeV}$$

Experimental value (PDG)

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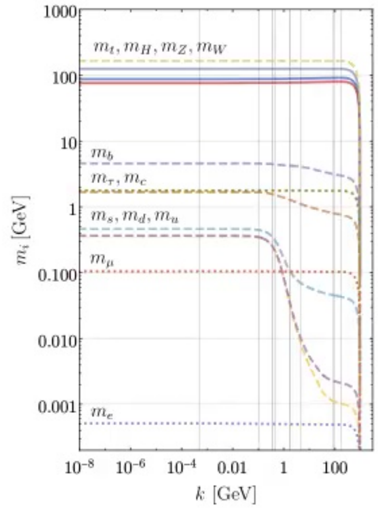
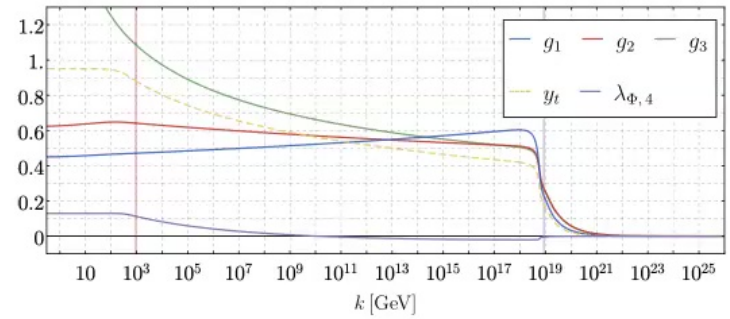
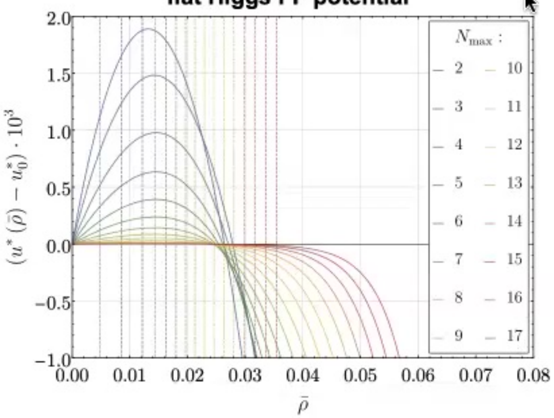
Asymptotically safe Standard Model





flat Higgs FP potential



Two relevant directions

top pole mass (getting real)

$$M_{t,\text{pole}}^{(\text{exp})} = 172.5 \pm 0.7\,\text{GeV} \longleftarrow m_t = 165.4^{+0.9}_{-0.2}\,\text{GeV}$$

Experimental value (PDG) **Euclidean curvature mass**

Prediction of decay width

$$\Gamma_{t,\text{pole}}^{(\text{theo})} = 1.72^{+0.09}_{-0.41}\,\text{GeV} \qquad \Gamma_{t,\text{pole}}^{(\text{exp})} = 1.42^{+0.19}_{-0.15}\,\text{GeV}$$

Experimental value (PDG)

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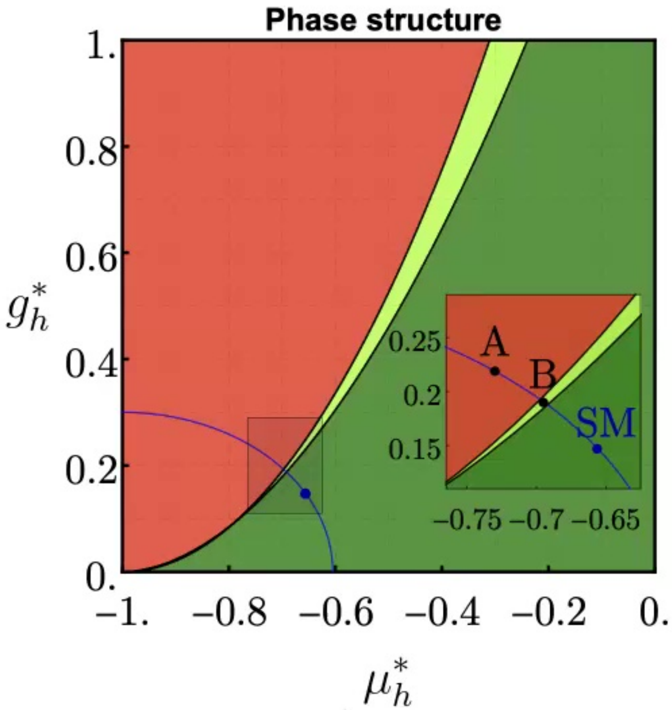
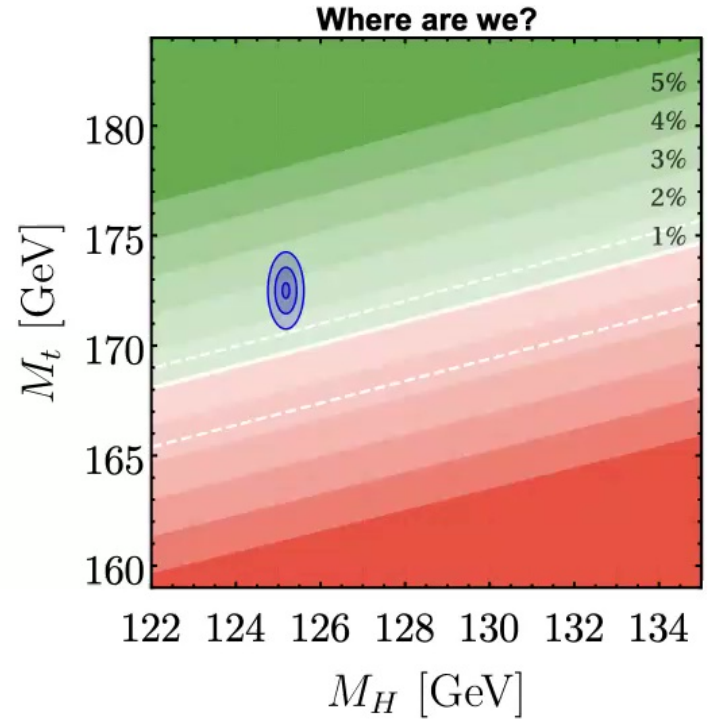
Asymptotically safe Standard Model





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Applications II: asymptotically black holes

JMP, Tränkle, 2309.17043

Black Holes in Asymptotically Safe Gravity: Platania, 2309.17043

and beyond: Held, Eichhorn, 2212.09495

Asymptotically black holes

Unfolding the background effective action

$$\Gamma[g_{\mu\nu}] = \frac{1}{16\pi}\int_x \sqrt{g}\left\{\mathcal{R}(\Delta, R) + R f_{R^2}(\Delta) R + R_{\mu\nu} f_{R^2_{\mu\nu}}(\Delta) R^{\mu\nu} + \cdots\right\}$$

gauge dependent

$$\bar{\Gamma}^{(2)}_{hh}(p)$$

$$\bar{\Gamma}^{(3)}_{h^3}(p) \longrightarrow$$

$$\bar{\Gamma}^{(4)}_{h^4}(p)$$

RG-invariant

$$\bar{\Gamma}^{(3)}_{\bar{g}^3}(p)$$

$$\bar{\Gamma}^{(4)}_{\bar{g}^4}(p)$$

JMP, Tränkle, 2309.17043

Asymptotically black holes

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gauge dependent		RG-invariant		gauge independent	
$\bar\Gamma^{(2)}_{hh}(p)$				$\mathcal{R}(\Delta, R)$ Unfolding	Educated guess
		$\bar\Gamma^{(3)}_{\bar g^3}(p)$			
$\bar\Gamma^{(3)}_{h^3}(p)$	$\rightarrow$		$\rightarrow$	$R f_{R^2}(\Delta) R$	
		$\bar\Gamma^{(4)}_{\bar g^4}(p)$		Maps	
$\bar\Gamma^{(4)}_{h^4}(p)$				$R_{\mu\nu} f_{R^2_{\mu\nu}}(\Delta) R^{\mu\nu}$	

JMP, Tränkle, 2309.17043

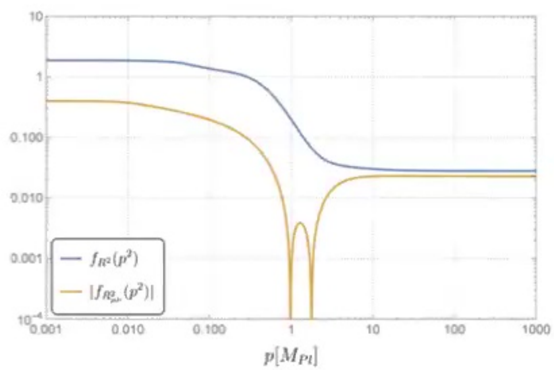
Asymptotically black holes

Unfolding the background effective action

$$\Gamma[g_{\mu\nu}] = \frac{1}{16\pi}\int_x \sqrt{g}\left\{\mathcal{R}(\Delta,R) + R f_{R^2}(\Delta) R + R_{\mu\nu} f_{R^2_{\mu\nu}}(\Delta) R^{\mu\nu} + \cdots\right\}$$

gauge dependent		RG-invariant		gauge independent	
$\bar\Gamma^{(2)}_{hh}(p)$				$\mathcal{R}(\Delta,R)$ Unfolding	Educated guess
$\bar\Gamma^{(3)}_{h^3}(p)$	$\rightarrow$	$\bar\Gamma^{(3)}_{\bar g^3}(p)$	$\rightarrow$	$R f_{R^2}(\Delta) R$	
$\bar\Gamma^{(4)}_{h^4}(p)$		$\bar\Gamma^{(4)}_{\bar g^4}(p)$		Maps $R_{\mu\nu} f_{R^2_{\mu\nu}}(\Delta) R^{\mu\nu}$	

Results for form factors



$$\mathcal{R}(\Delta,R) = R\,\frac{\gamma_g^{(3)}(\Delta) - \bar\gamma_3\Delta}{\Delta + R}\,R$$

JMP, Tränkle, 2309.17043

Asymptotically black holes

Infrared asymptotic effective action

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Spherical symmetric solution

$$ds^2 = -f(r)\mathrm{d}t^2 + \frac{1}{g(r)}\mathrm{d}r^2 + r^2 d\Omega^2$$

Weak field solutions

$$f(r) = 1 - \frac{2M}{r} + S_0\frac{e^{-m_0 r}}{r} + S_2\frac{e^{-m_2 r}}{r}$$

$$g(r) = 1 - \frac{2M}{r} - S_0\frac{e^{-m_0 r}}{r}(1+m_0 r) + \frac{1}{2}S_2\frac{e^{-m_2 r}}{r}(1+m_2 r)$$

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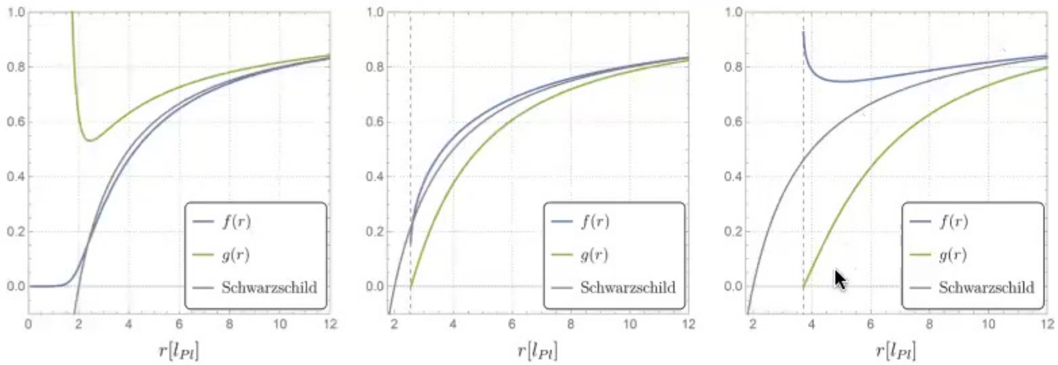
Numerical Solutions for $S_2 = 1 = M$



$S_0 = -1$ $\quad$ $S_0 = 1$ $\quad$ $S_0 = 4$

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Asymptotically black holes

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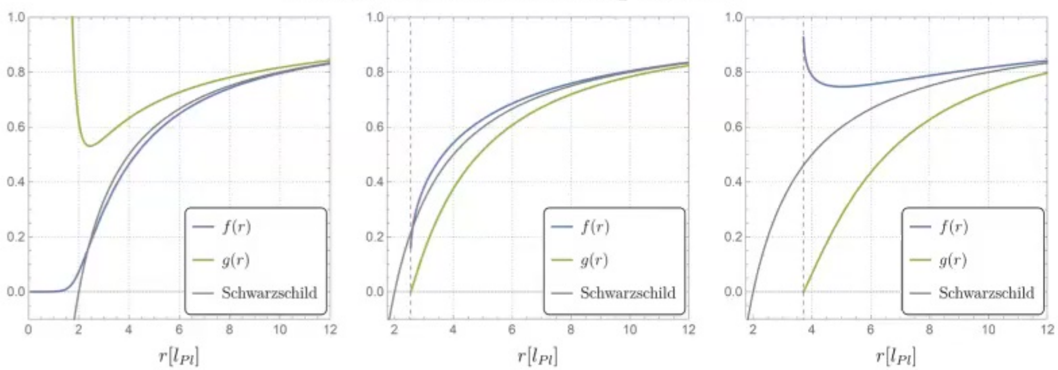

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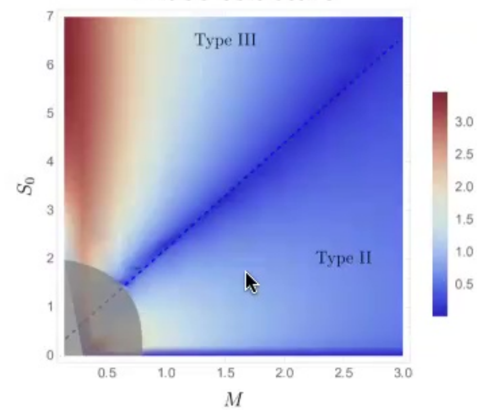
Phase structure



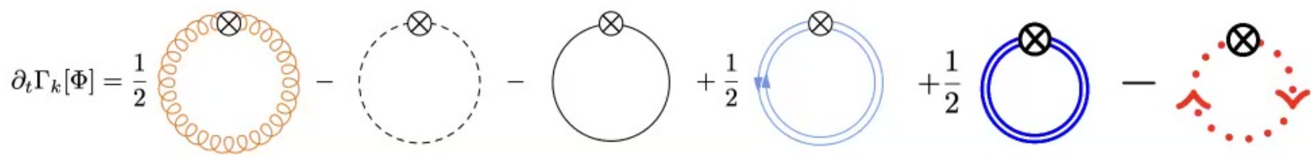
$$T = \frac{1}{4\pi}\sqrt{|f'(r_h) g'(r_h)|}$$

'Hawking temperature'

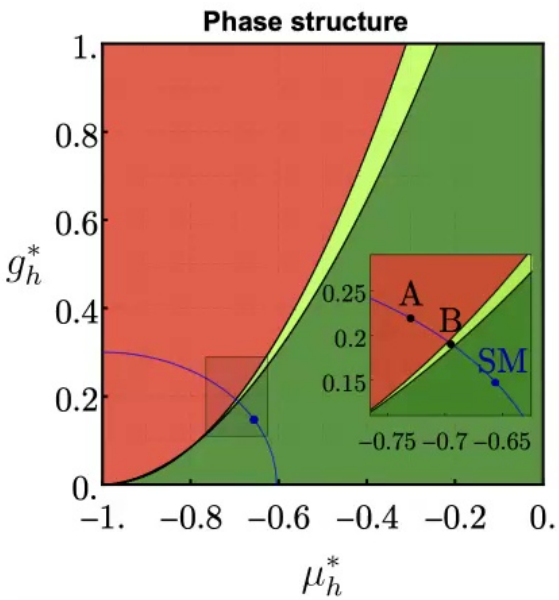
see also Borissova, Held, Afshordi, *CQuant.Grav.* 40 (2023) 7, 075011

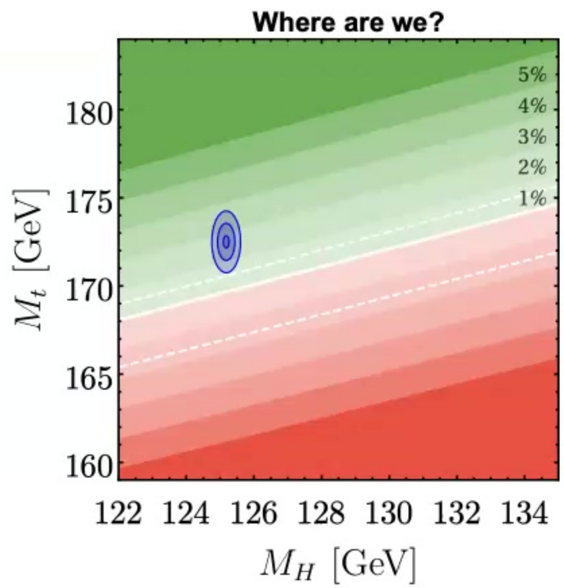
JMP, Tränkle, 2309.17043

Summary

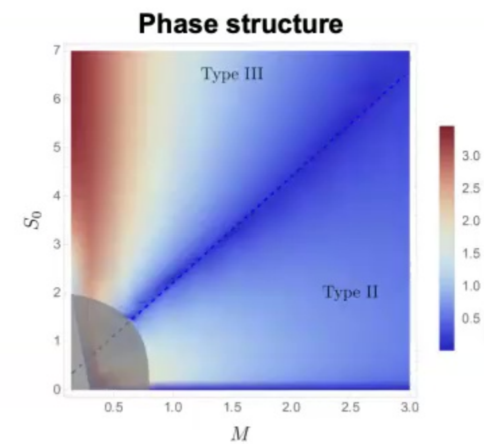


Asymptotically safe SM





Quantum black holes



Asymptotically black holes

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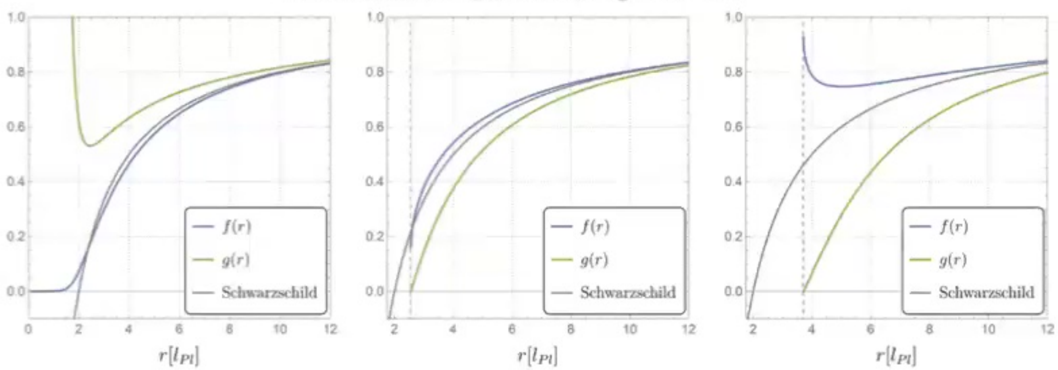
Numerical Solutions for $S_2 = 1 = M$



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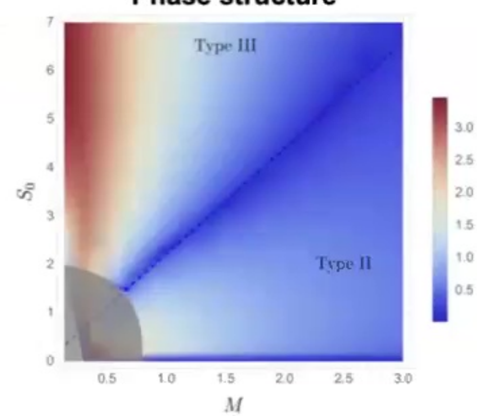
Phase structure



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Asymptotically black holes

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gauge dependent

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$\rightarrow$

RG-invariant

$\bar\Gamma^{(3)}_{\bar g^3}(p)$

$\bar\Gamma^{(4)}_{\bar g^4}(p)$

$\rightarrow$

gauge independent

$\mathcal{R}(\Delta, R)$

Unfolding

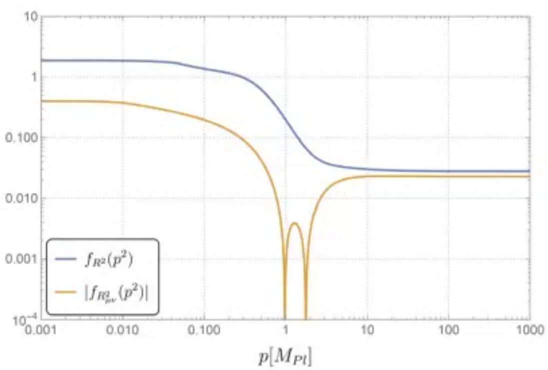
Educated guess

$R f_{R^2}(\Delta) R$

Maps

$R_{\mu\nu} f_{R^2_{\mu\nu}}(\Delta) R^{\mu\nu}$

Results for form factors



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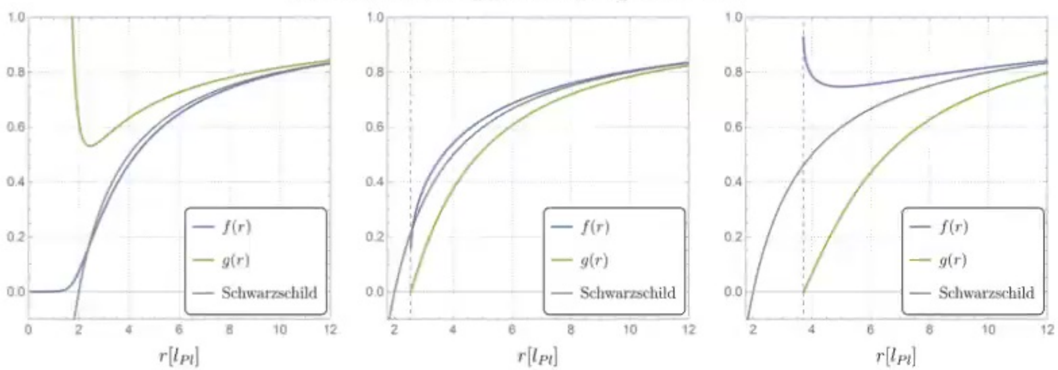

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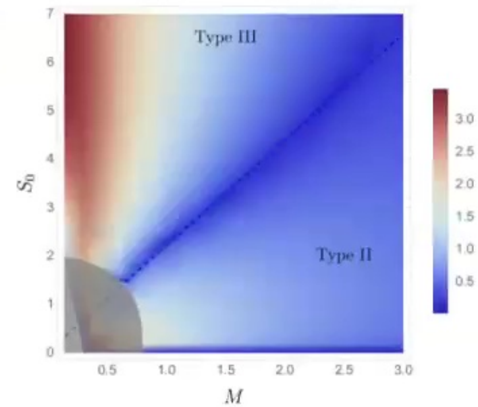

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