Particle physics & quantum black holes from asymptotically safe correlation functions

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Sant'Elmo beach hotel, October 4th 2023

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Outline

- Asymptotically safe correlation functions
- Applications I: asymptotically safe Standard Model
- Applications II: asymptotically black holes
- Summary

Asymptotically safe correlation functions

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

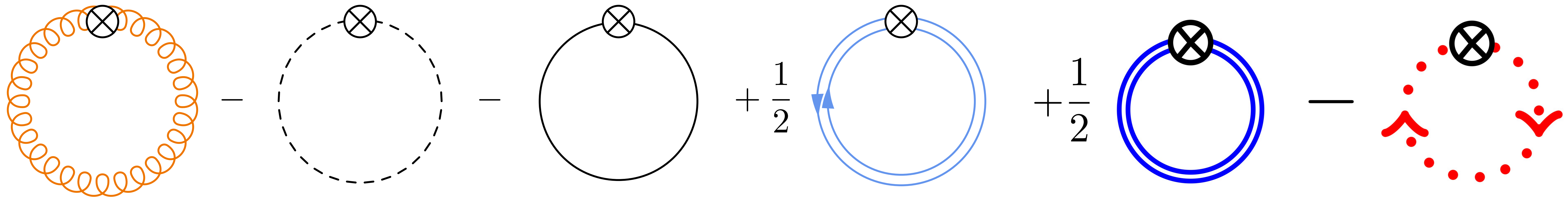
Background (in)dependence in gravity

aka

background and fluctuations fields, modified STIs and their importance

free energy

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



Linear split

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

Effective action

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

$$\bar{h} = \langle h \rangle$$

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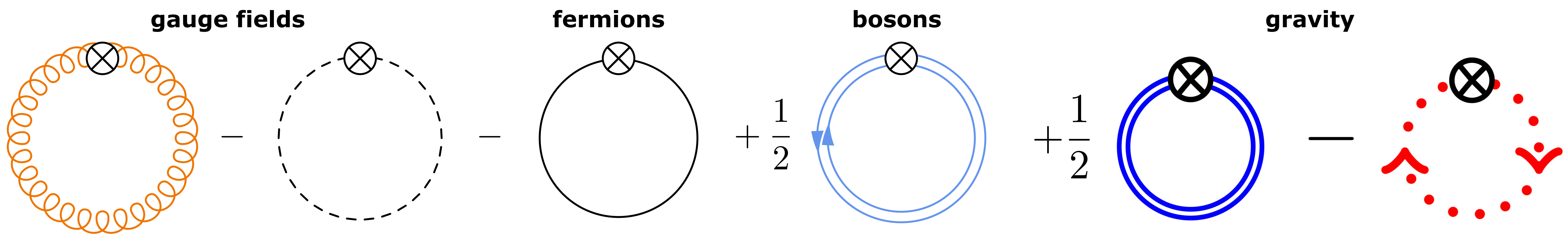
$$k\partial_k\Gamma_k[\bar g,\phi] = \frac{1}{2}$$



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$$\bar h = \langle h\rangle$$

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

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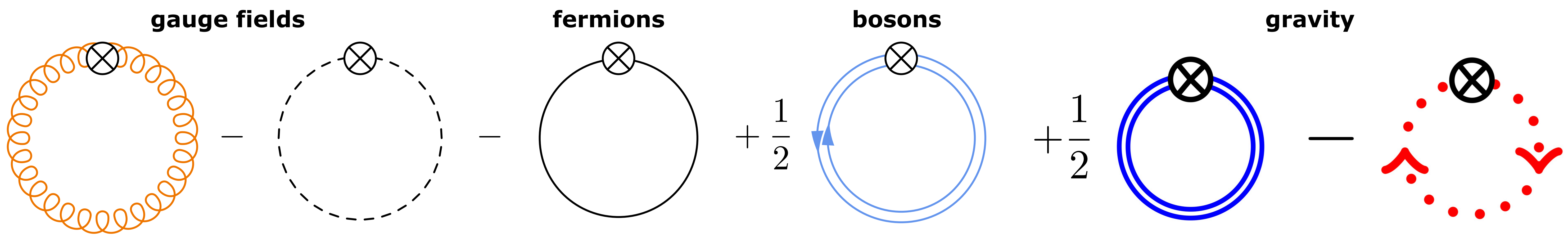

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$$\left\{ \Gamma_k[\bar{g}], \Gamma_k^{(0,1)}[\bar{g}]\,,\, \Gamma_k^{(0,2)}[\bar{g}]\,,\, \Gamma_k^{(0,3)}[\bar{g}]\,,\, \ldots \right\}$$

Se vogliamo che tutto rimanga come è,
bisogna che tutto cambi.

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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

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How much do they differ?

JMP, Reichert, Front.in Phys. 8 (2021) 527
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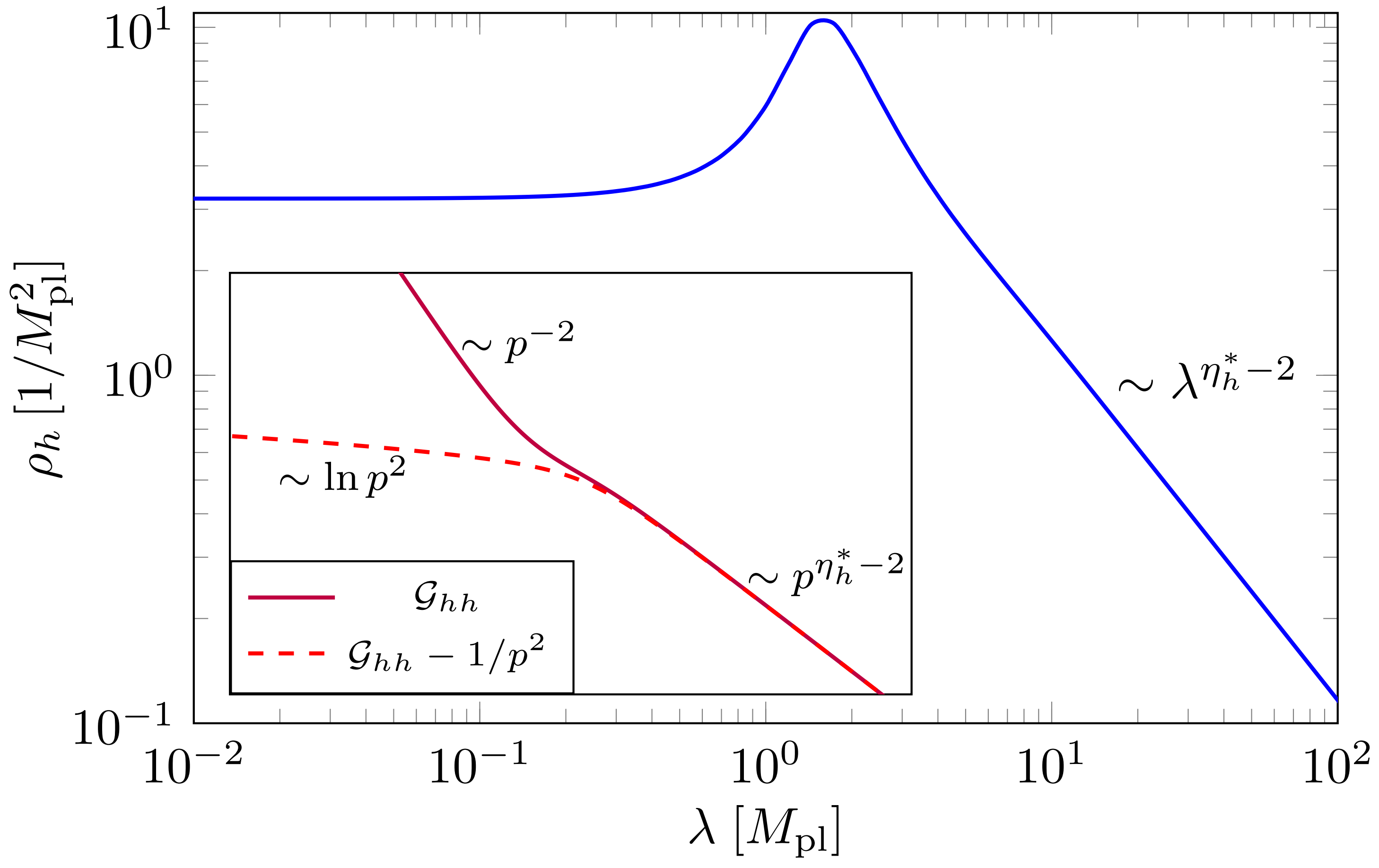
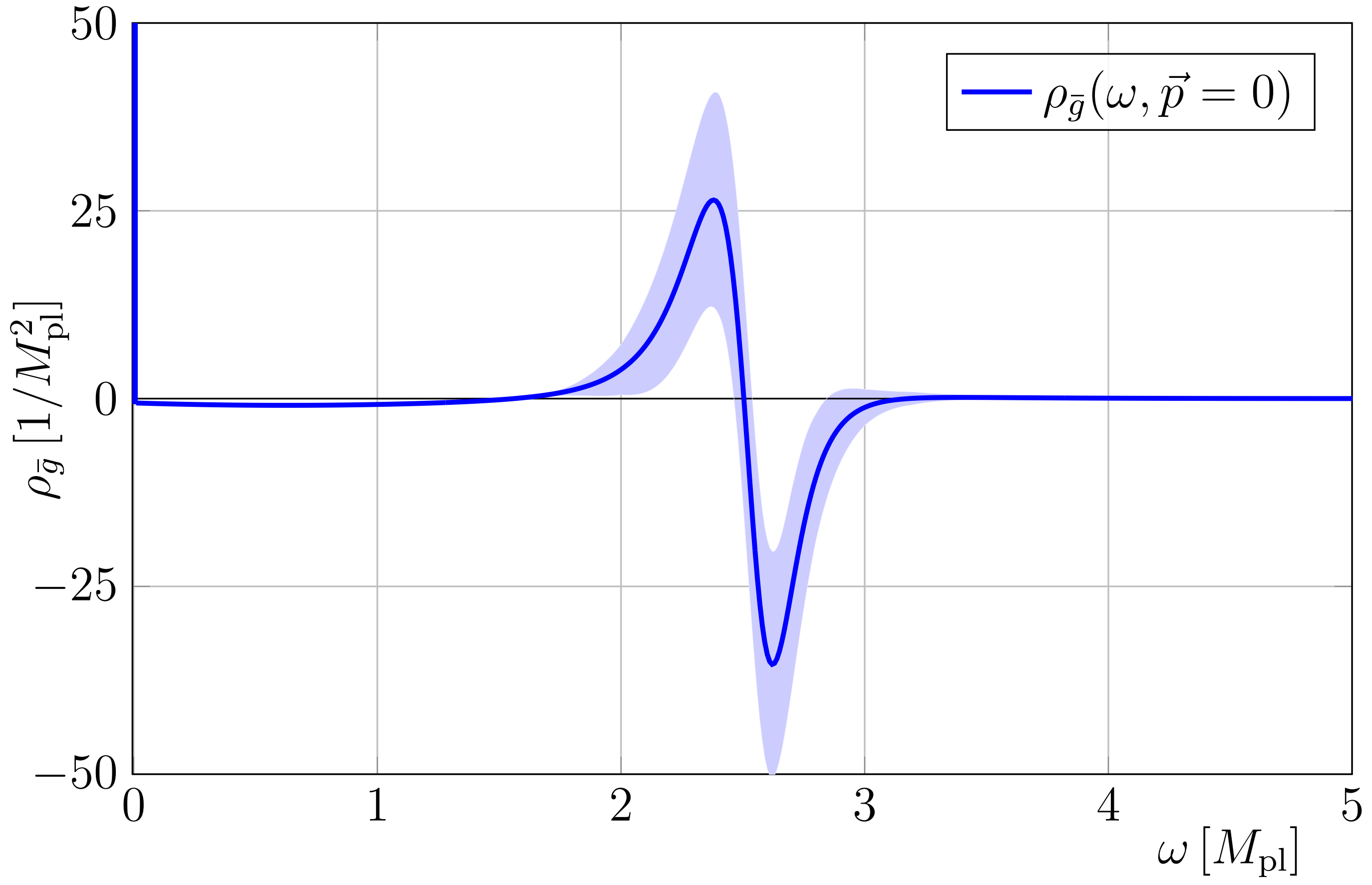
A lesson from graviton spectral functions

Spectral function of the fluctuating graviton



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

Spectral function of the background graviton



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

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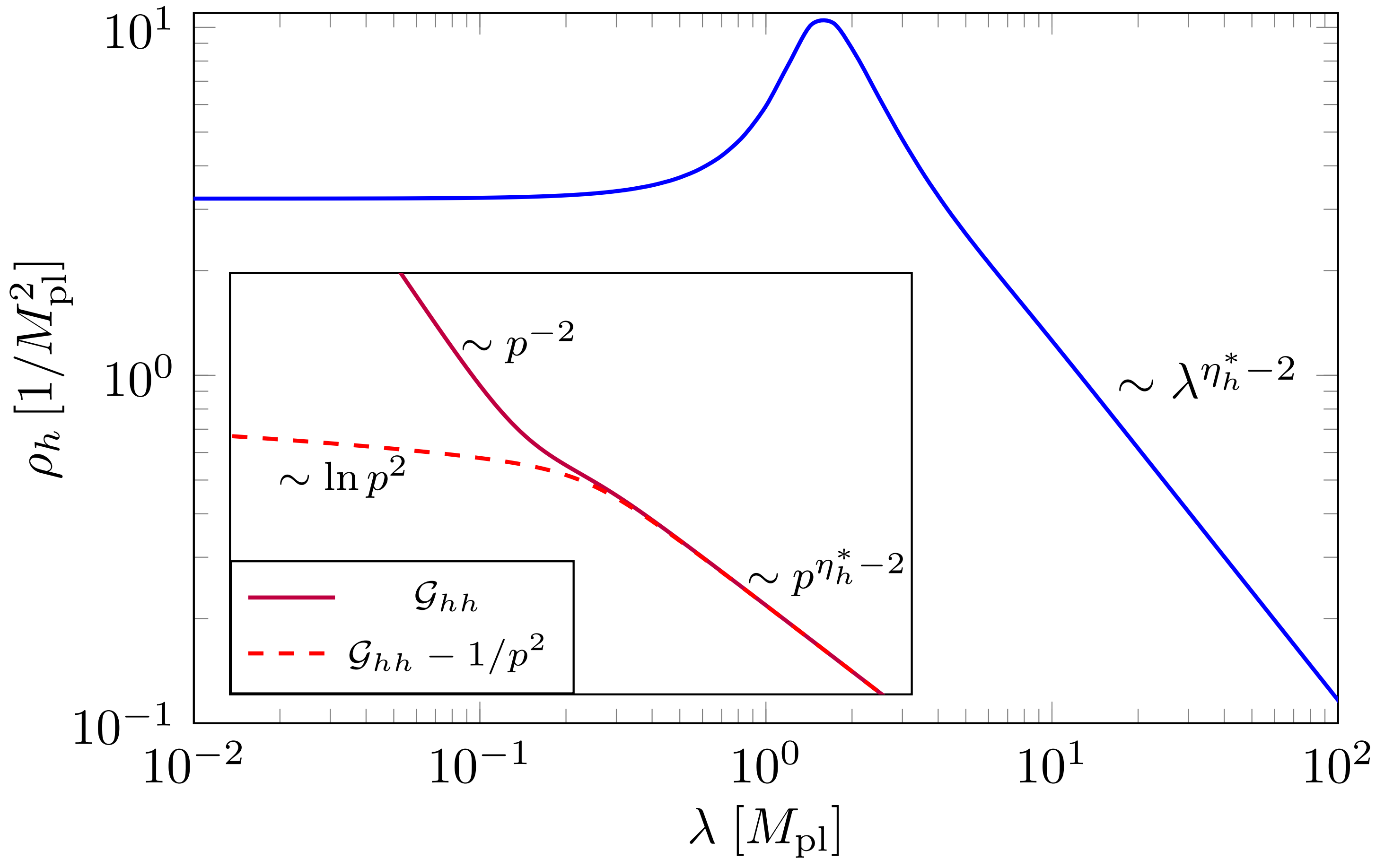

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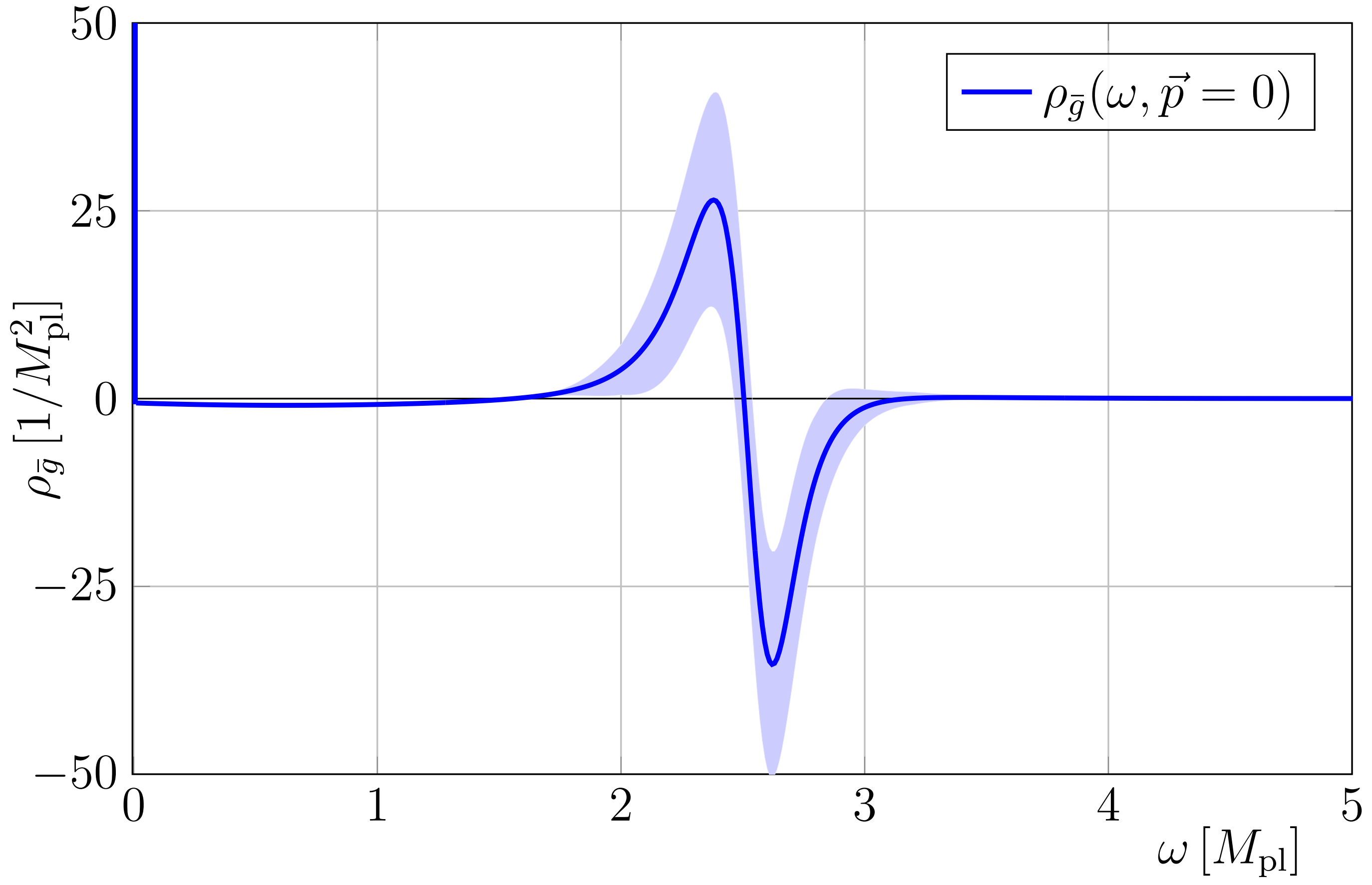

Bonanno, Denz, JMP, Reichert, *SciPost Phys.* 12 (2022) 1, 001

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

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

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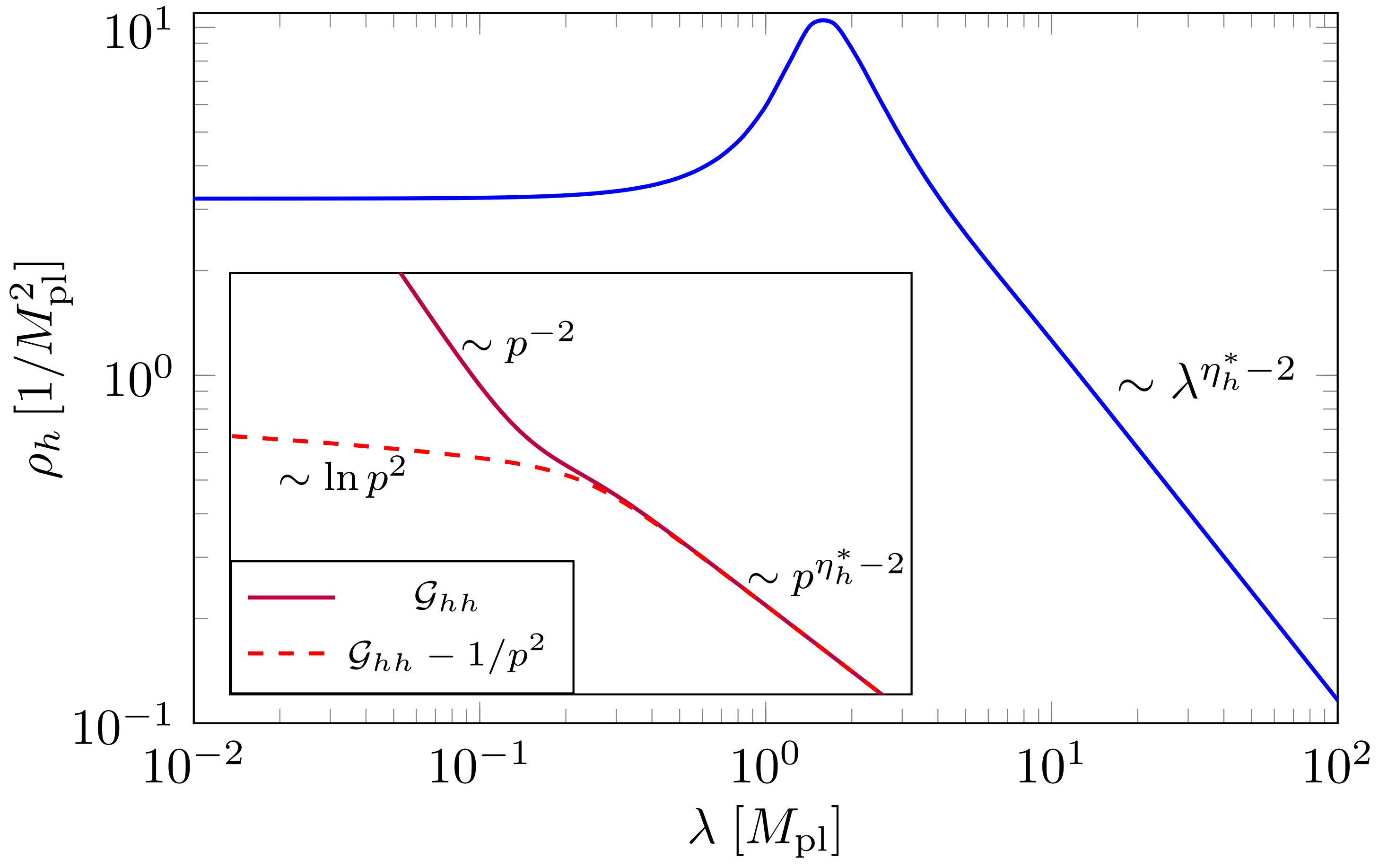

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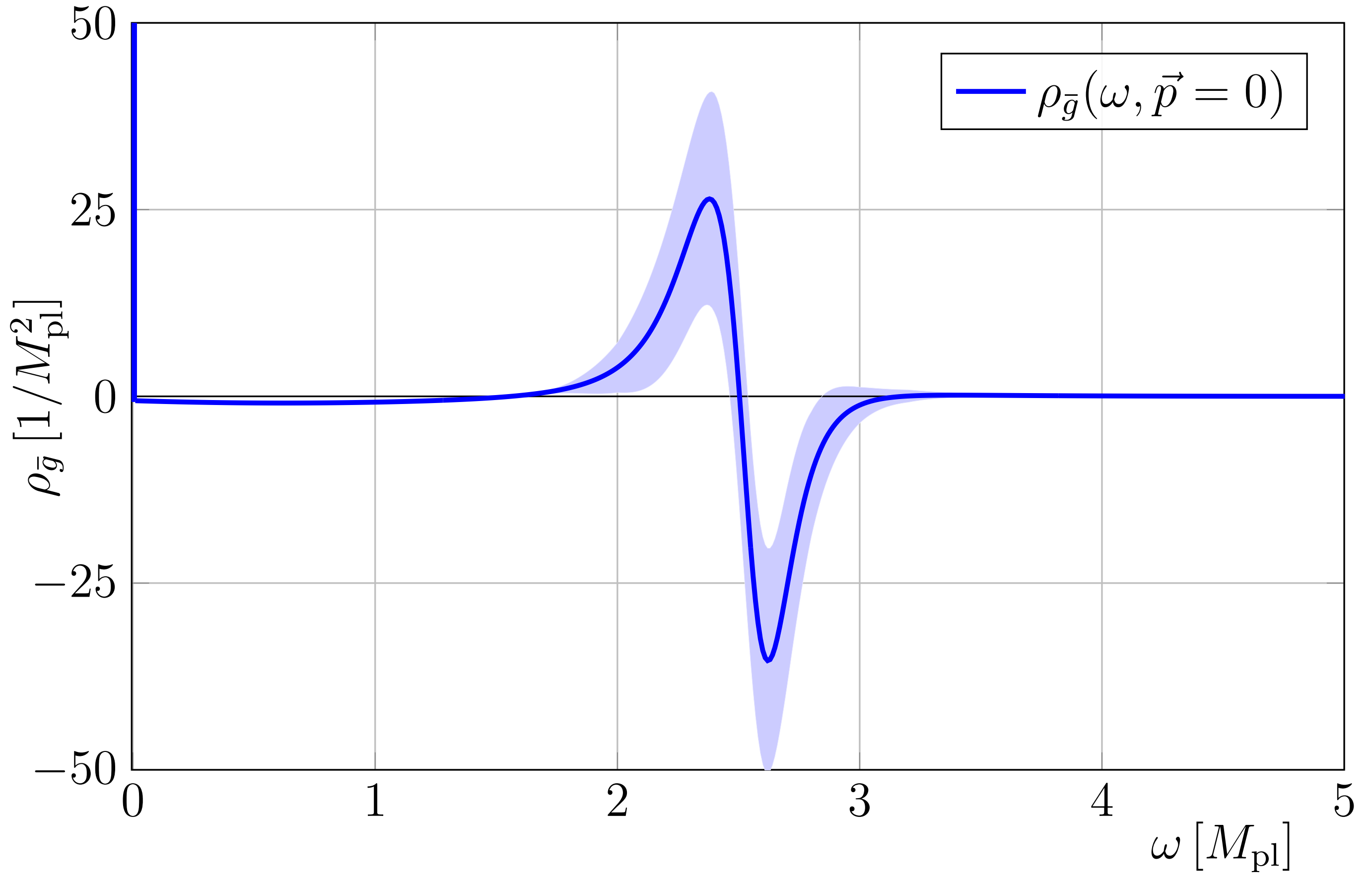

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much !

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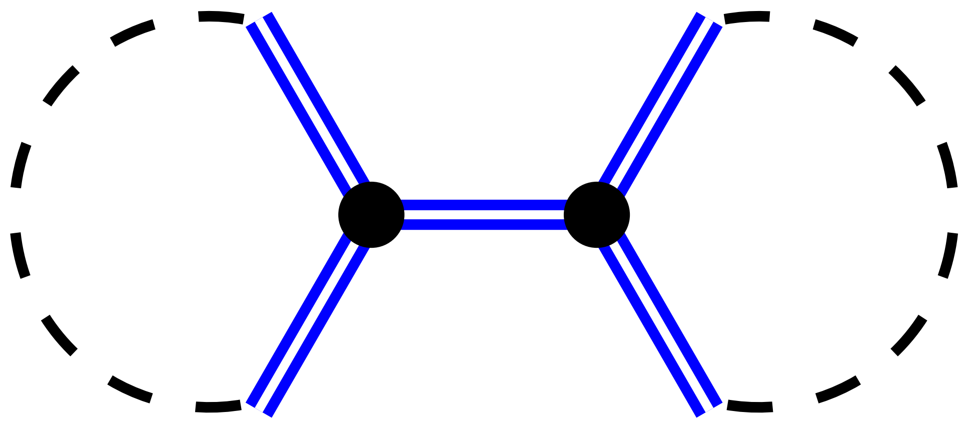
Background spectral function and scattering amplitudes

Graviton-graviton scattering



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Background spectral function and scattering amplitudes

RG-invariant vertex

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

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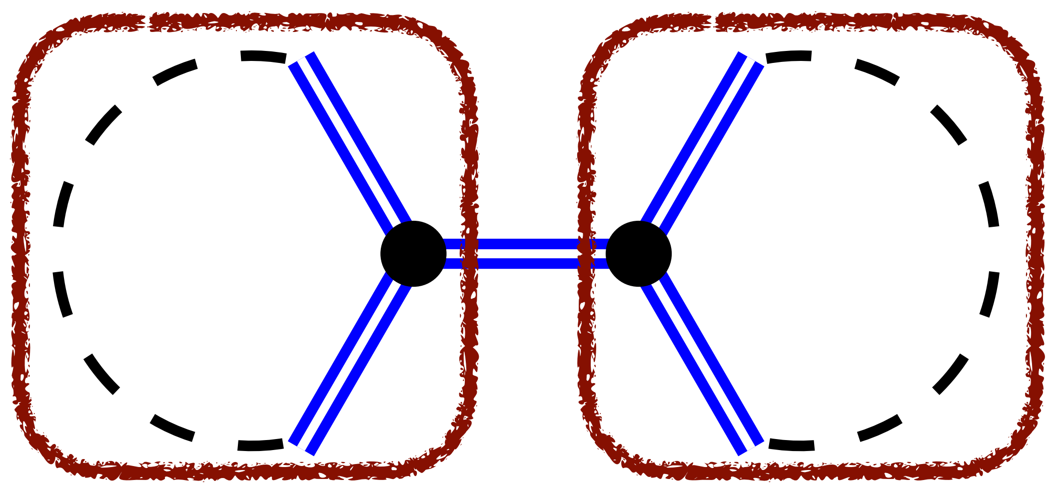

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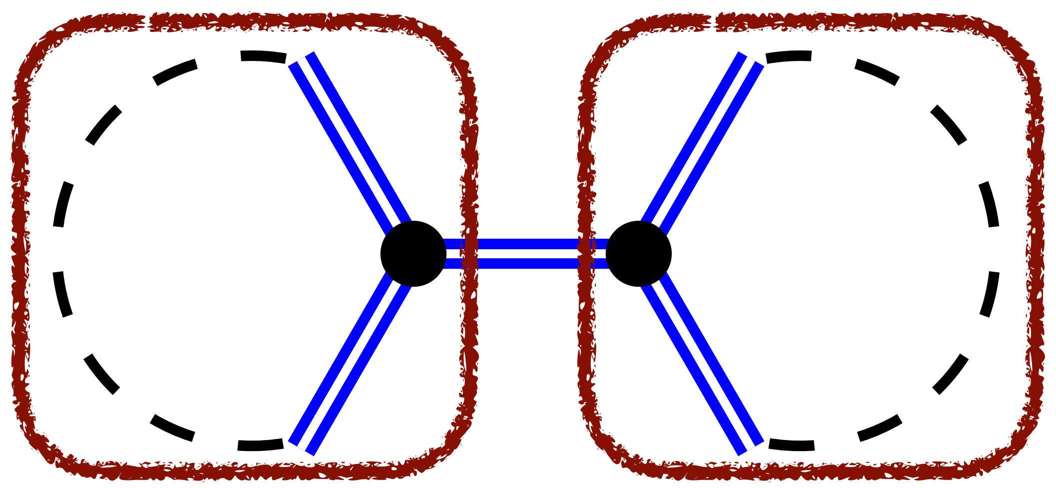

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Fluctuation approach: 2012 ···

Form factor approach: 2018 ···

Knorr, Ripken, Saueressig, …

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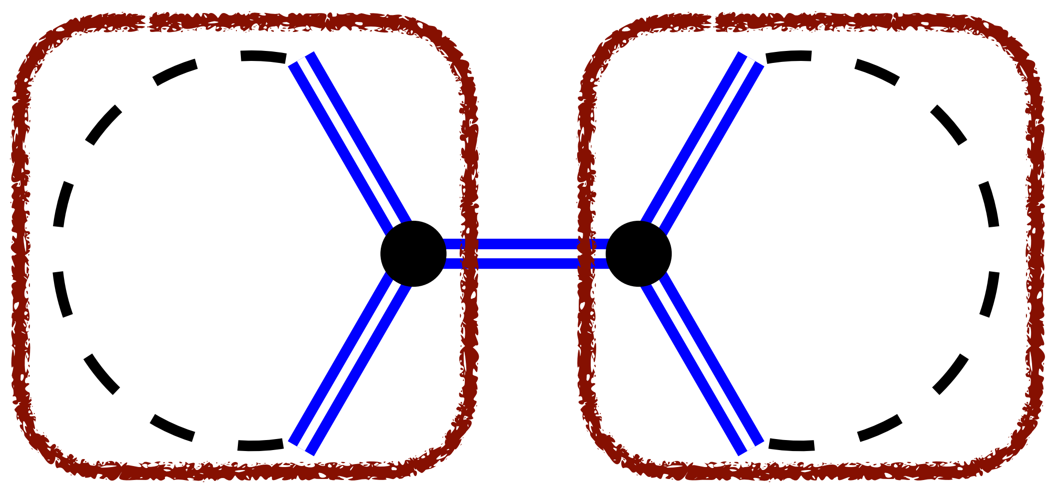

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Suggestive educated guess

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

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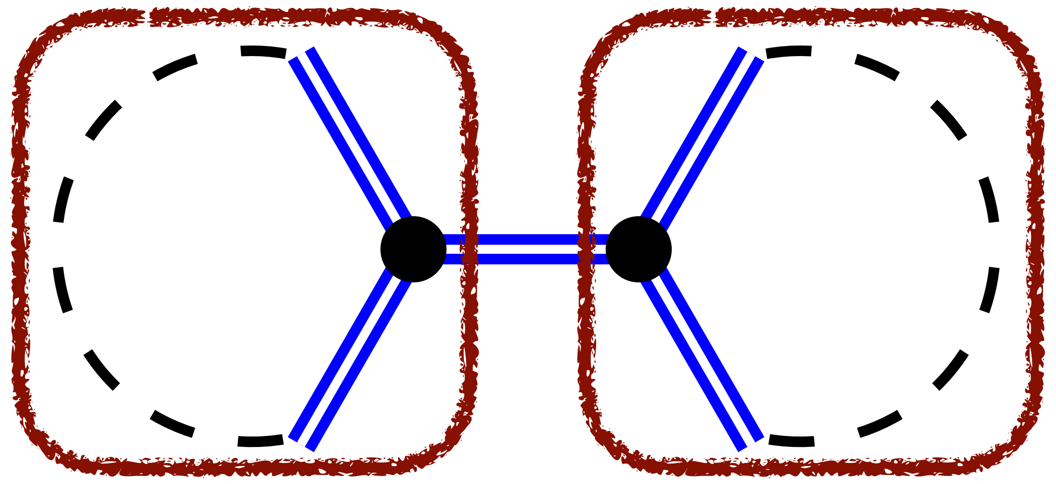

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Final comment

'Bar' propagator

$$\bar\Gamma^{(2)}(p_1,p_2)$$

$$\rho_g(\lambda) \in \mathbb{R}^+$$

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A bit of gauge invariance and all that

Some thoughts on vertex expansion schemes/fluctuation approach and covariant expansion schemes/background approximation

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Clear cut case: Einstein-Hilbert truncation & minimally coupled gravity matter systems

Exact map with additional truncation

Fluctuation approach with flat vertex expansion → **Background approximation with heat kernel methods**

Additional truncation: background approximation

Background approximation flows can be derived also in the flat vertex expansion

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claim also tested in QCD
where there are enough benchmark results from the lattice

Fluctuation approach rules

Relation to background approach via pinch technique

aka: if there are qualitative differences between results in the fluc. approach and the background approx., the former is conceptually more trustworthy

(a) better account of dynamics

(b) better account of physical diffeomorphism invariance

(c) better -tested- systematics

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Beware!
there are qualitative differences between flows in the fluc. approach & the background approximation in pure gravity and minimally coupled systems

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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

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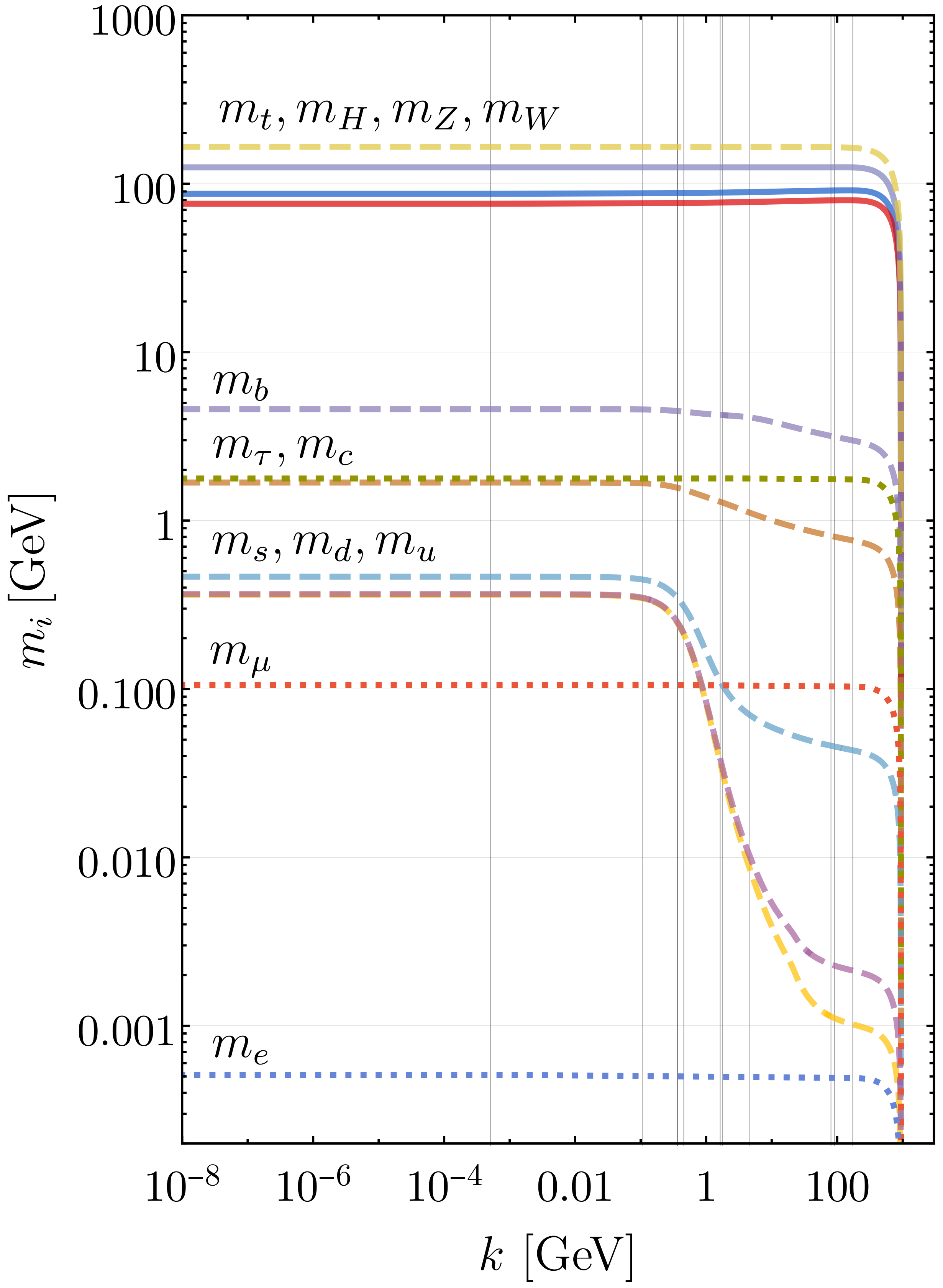
Standard Model masses

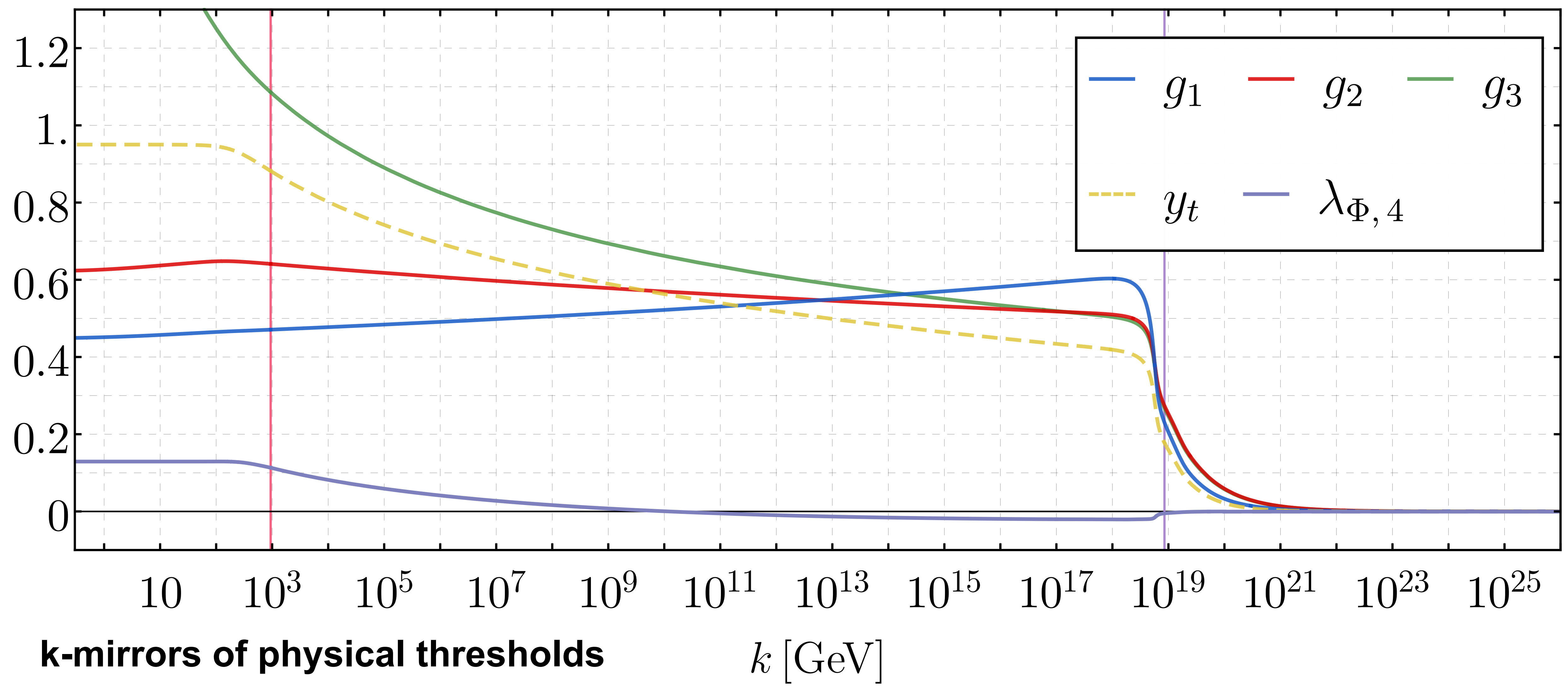


k-mirrors of physical thresholds

Example: asymptotically safe Standard Model

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

k-mirror of physical threshold



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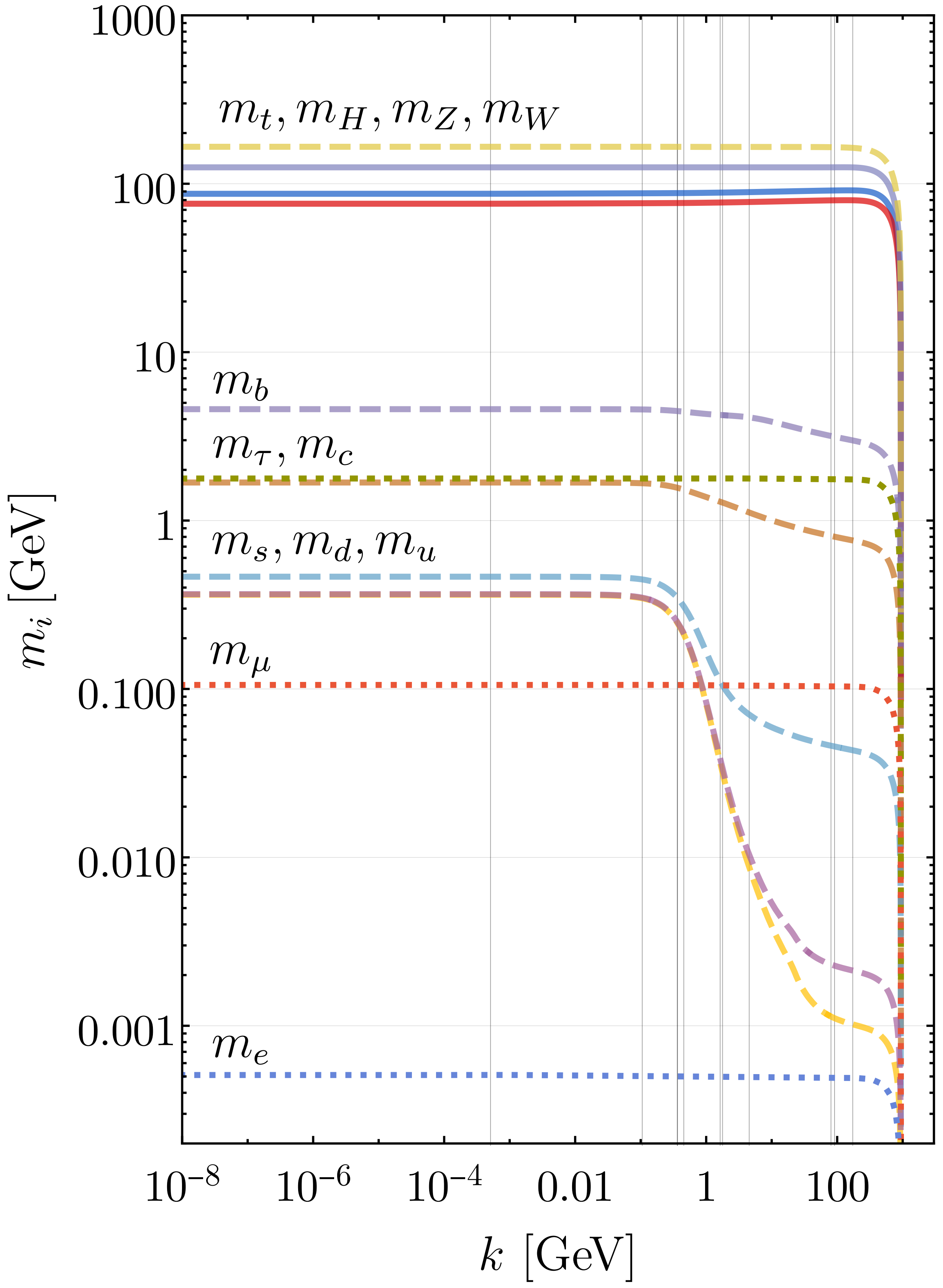

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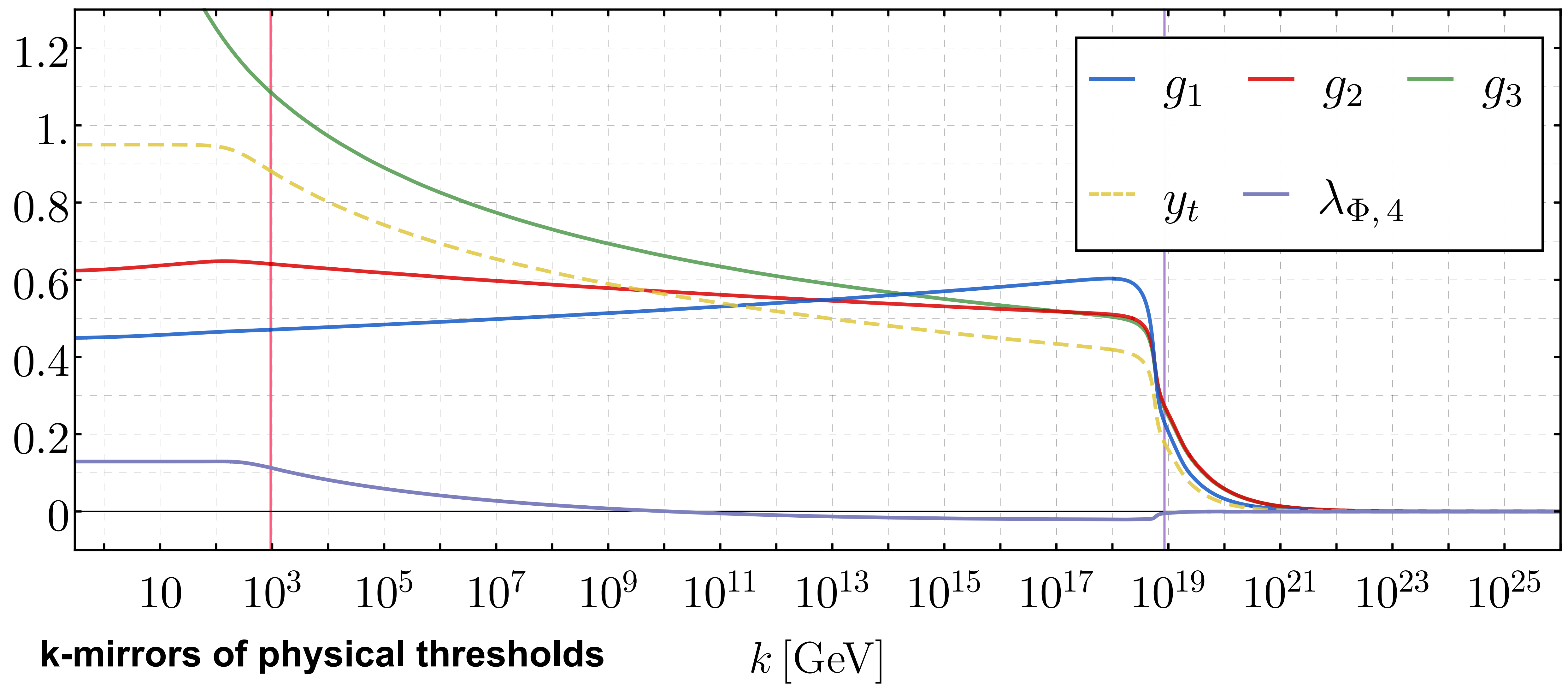

k-mirrors of physical thresholds

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

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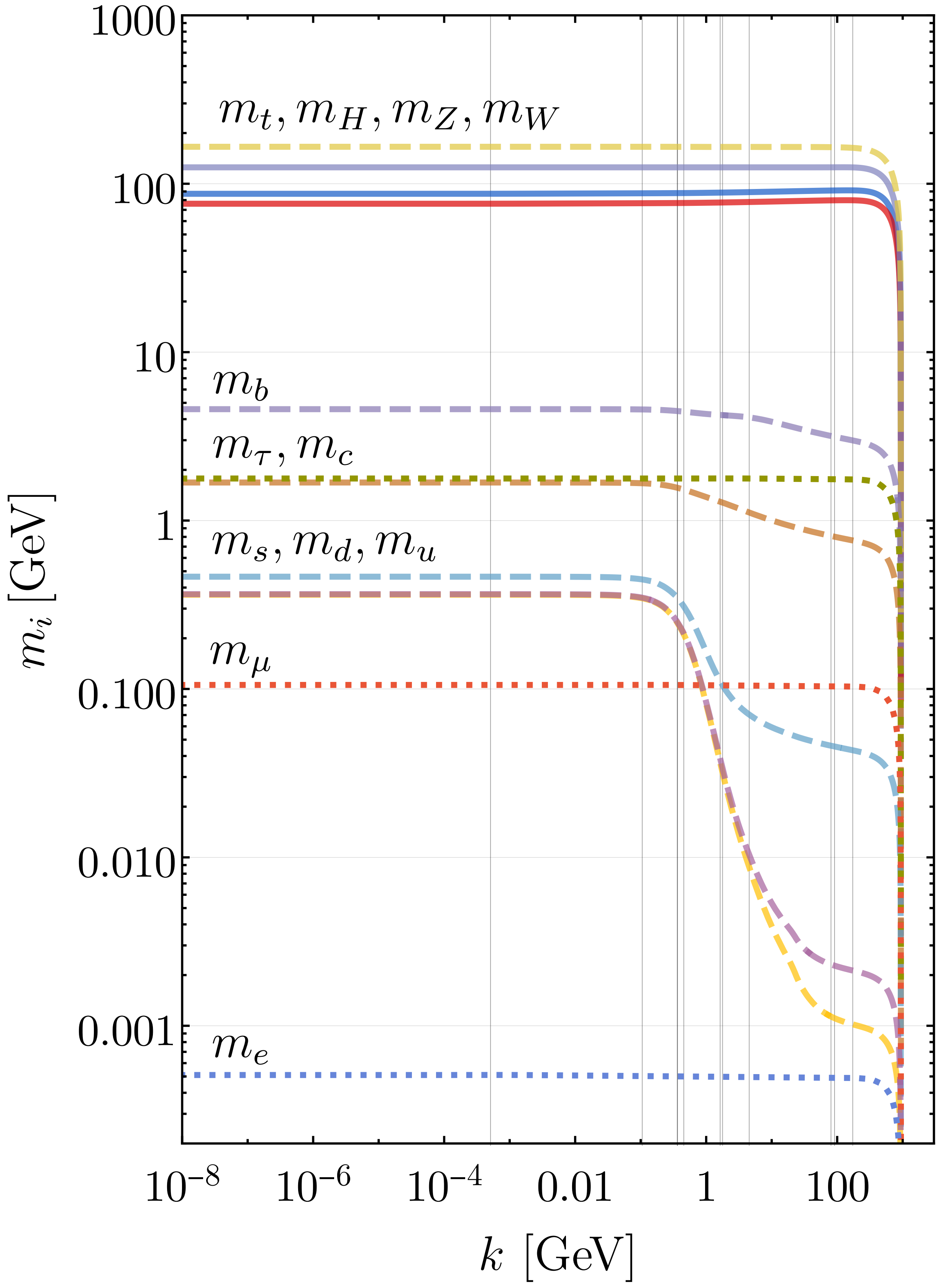

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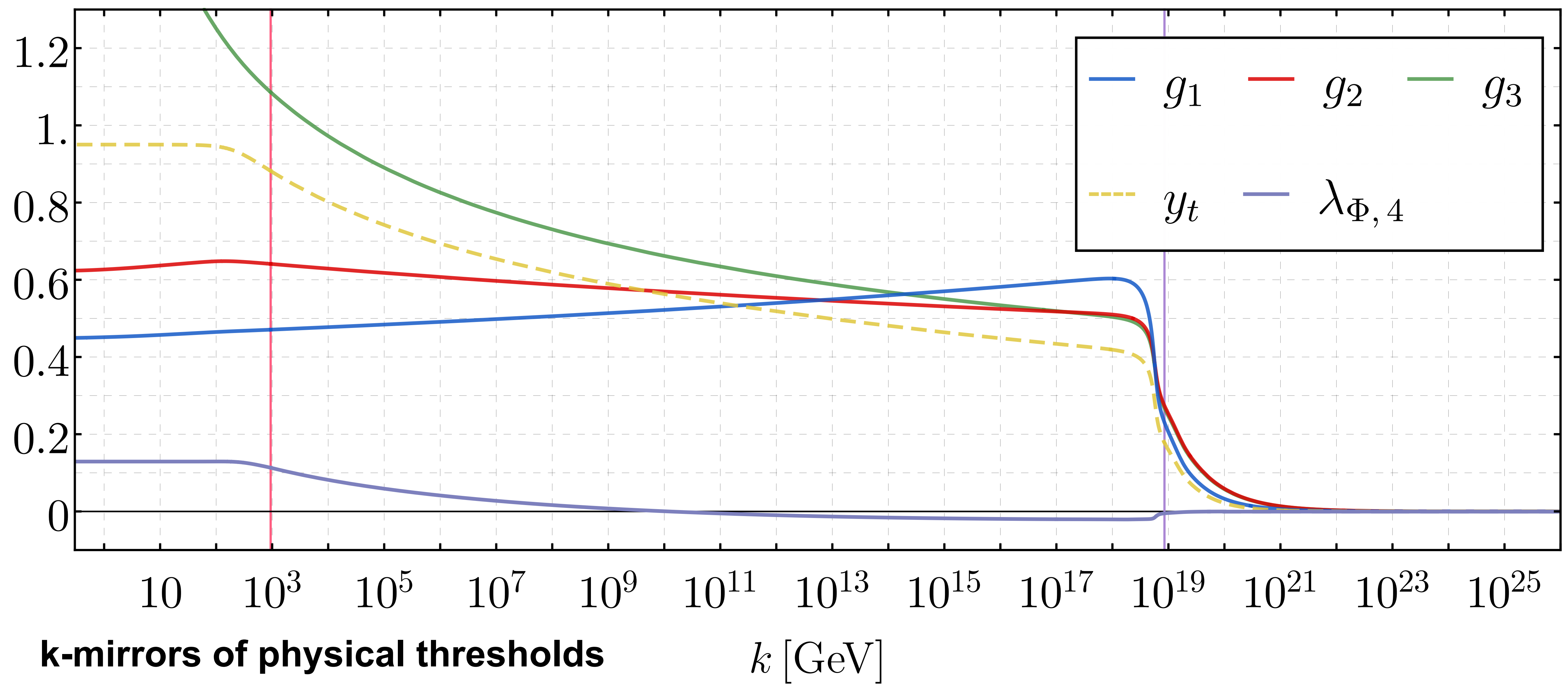

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Full physics: momentum-dependent correlation functions & S-matrix elements at k=0

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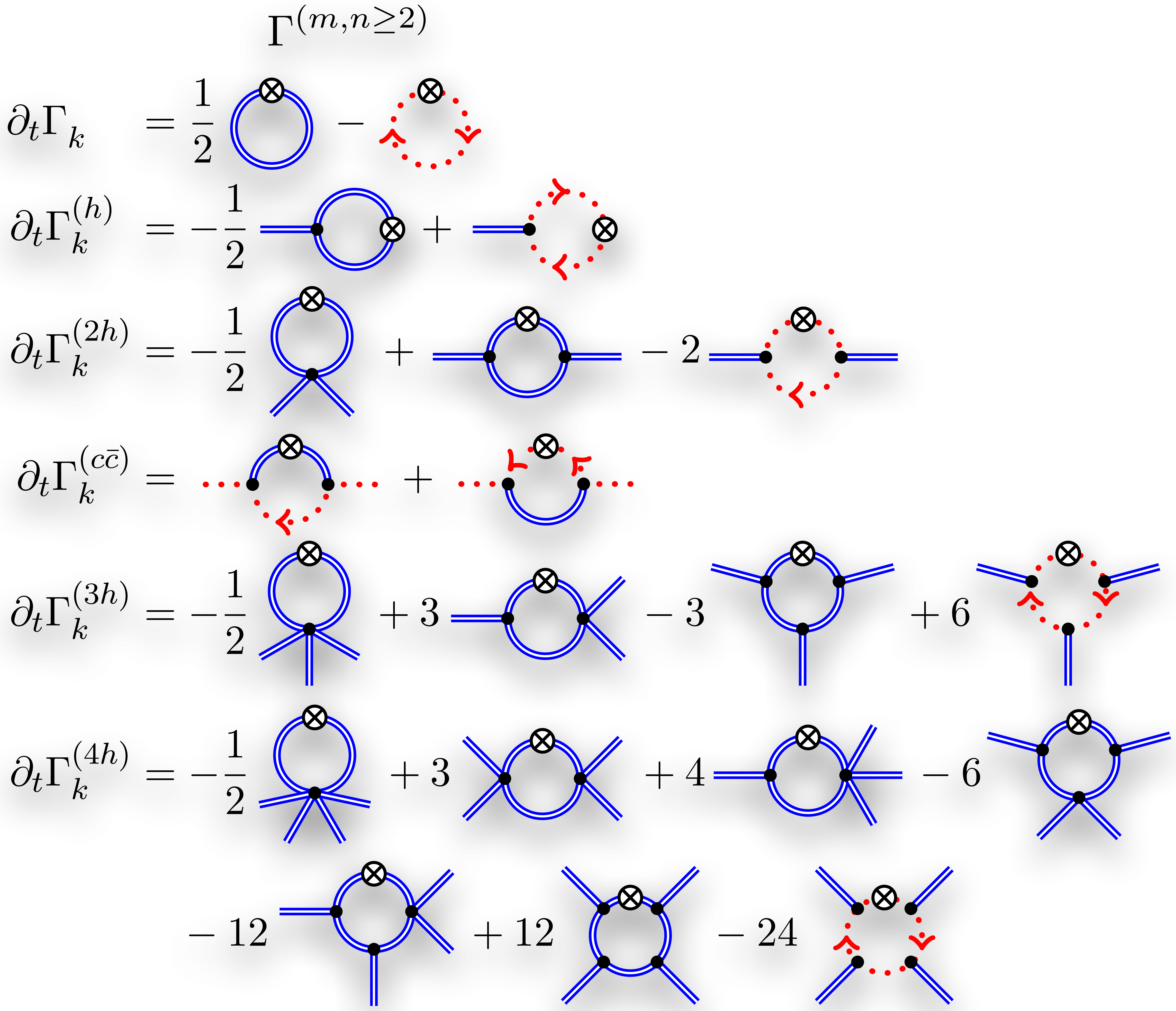
Towards apparent convergence in quantum gravity

vertex expansion



Aiming at apparent convergence

JMP, Reichert, Front.in Phys. 8 (2021) 527
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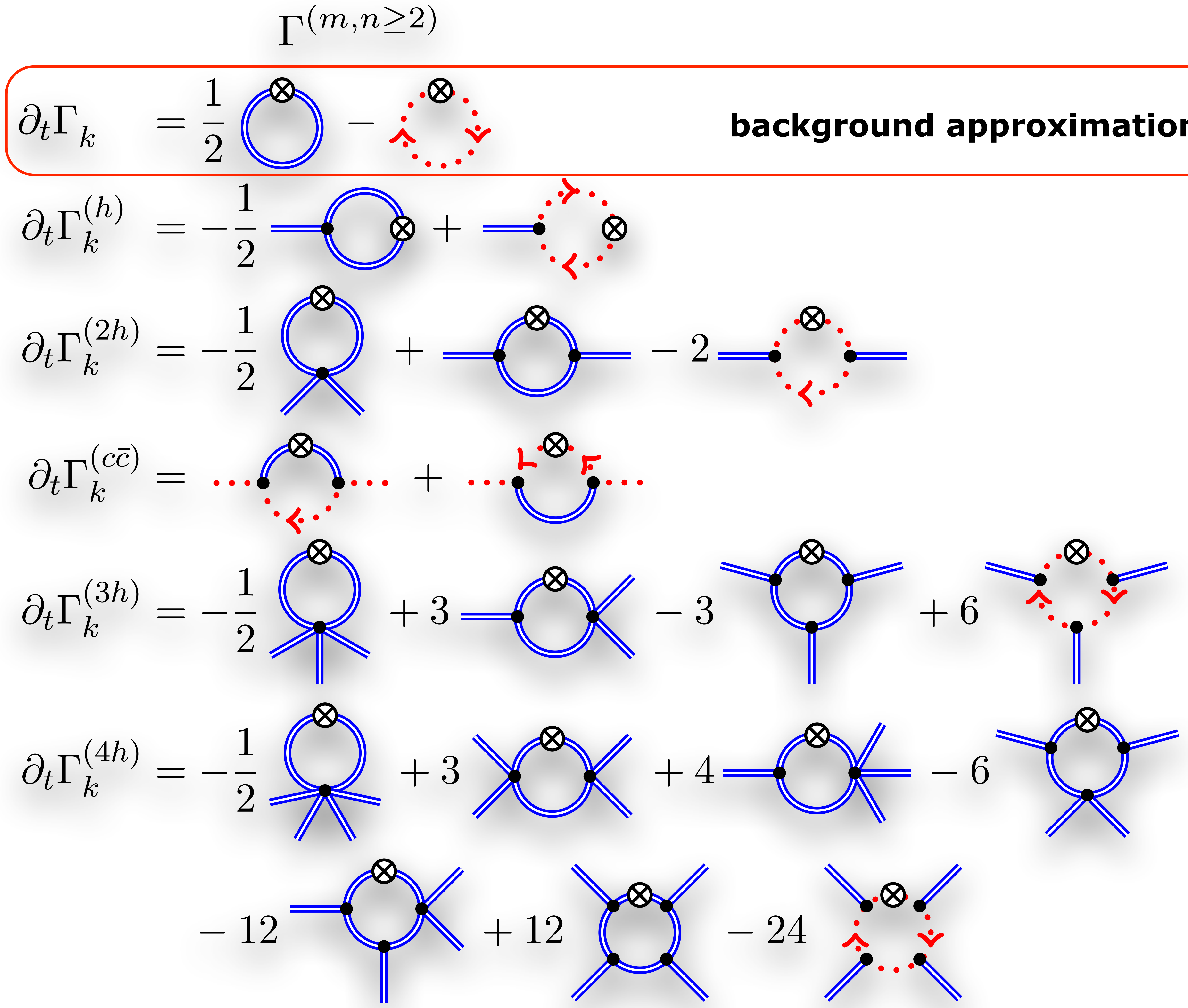
Reuter, PRD 57 (1998) 971, ...



background approximation: $\Gamma^{(m,n)} \approx \Gamma^{(m+n,0)}$

Aiming at apparent convergence

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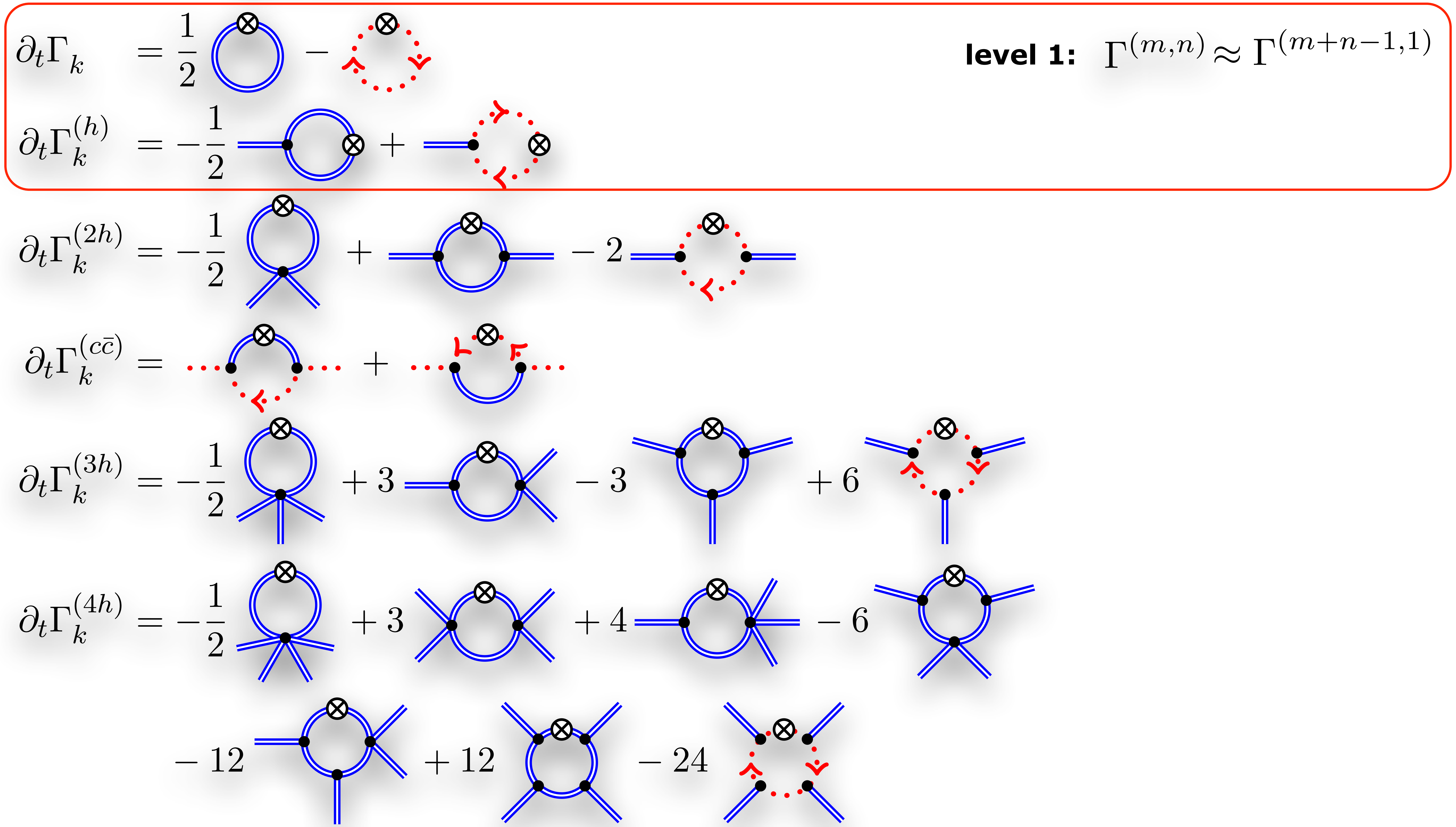
vertex expansion

$\Gamma^{(m,n\geq 2)}$

bi-metric approach: Manrique, Reuter, Saueressig, Annals Phys. 326 (2011) 463



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Towards apparent convergence in quantum gravity

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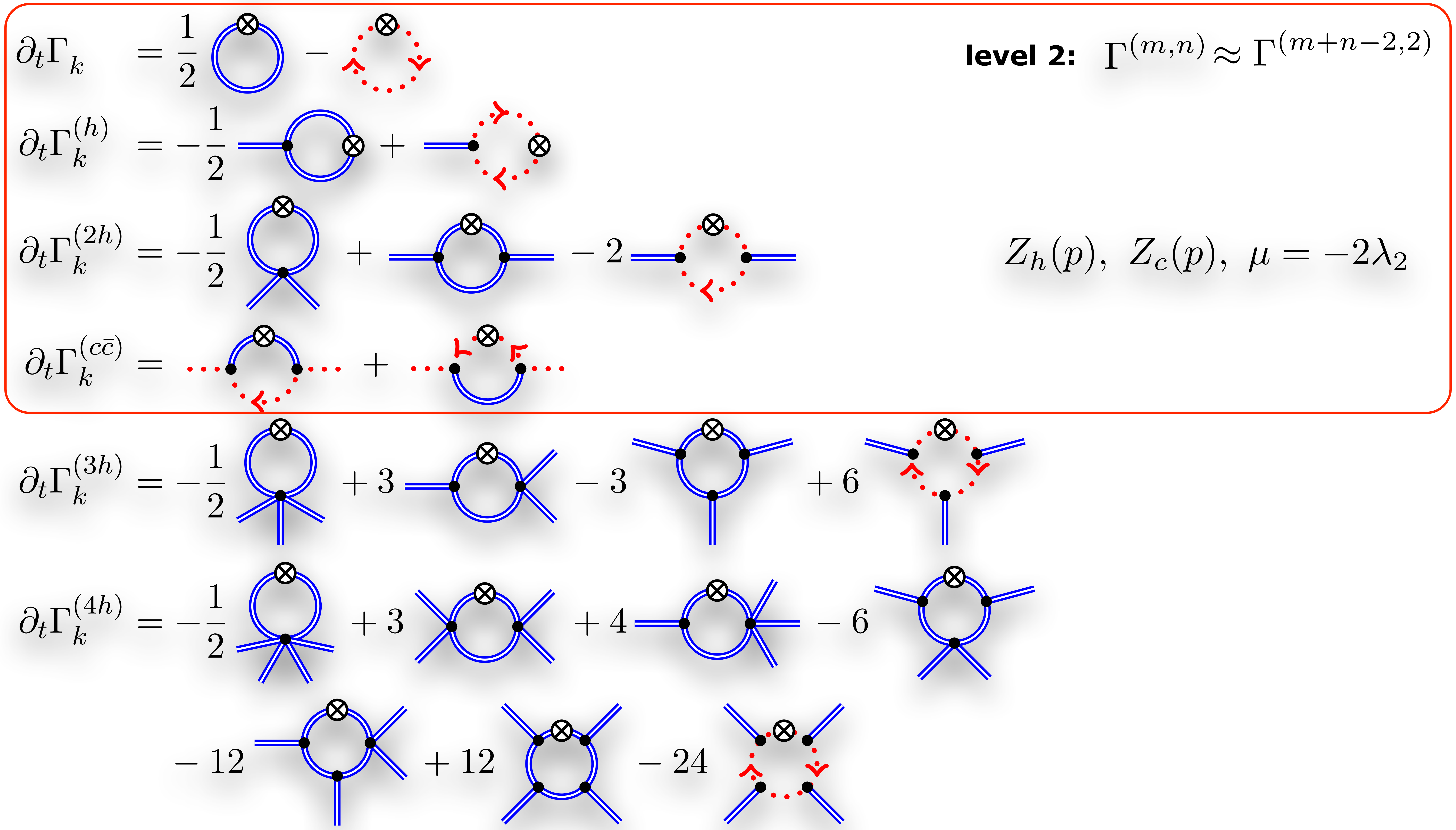
geometrical approach: Donkin, JMP, arXiv:1203.4207

flat expansion: Christiansen, Litim, JMP, Rodigast, PLB 728 (2014) 114

$\Gamma^{(m,n\geq 2)}$



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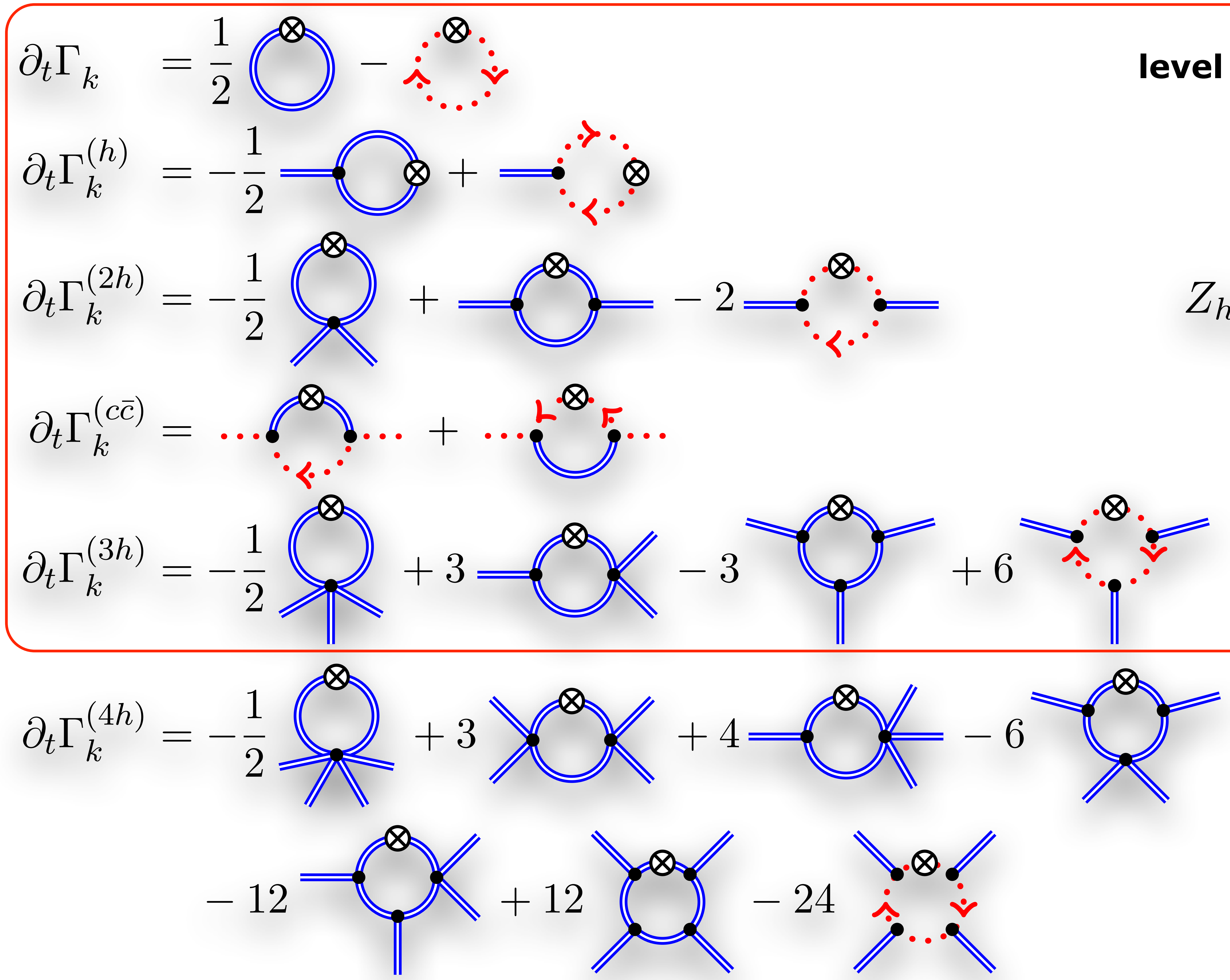
$\Gamma^{(m,n\geq 2)}$

Christiansen, Knorr, Maibohm, JMP, Reichert, PRD 92 (2015) 12, 121501



level 3: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-3,3)}$

$Z_h(p),\ Z_c(p),\ \mu = -2\lambda_2$

$g_3(p),\ \lambda_3$

Aiming at apparent convergence

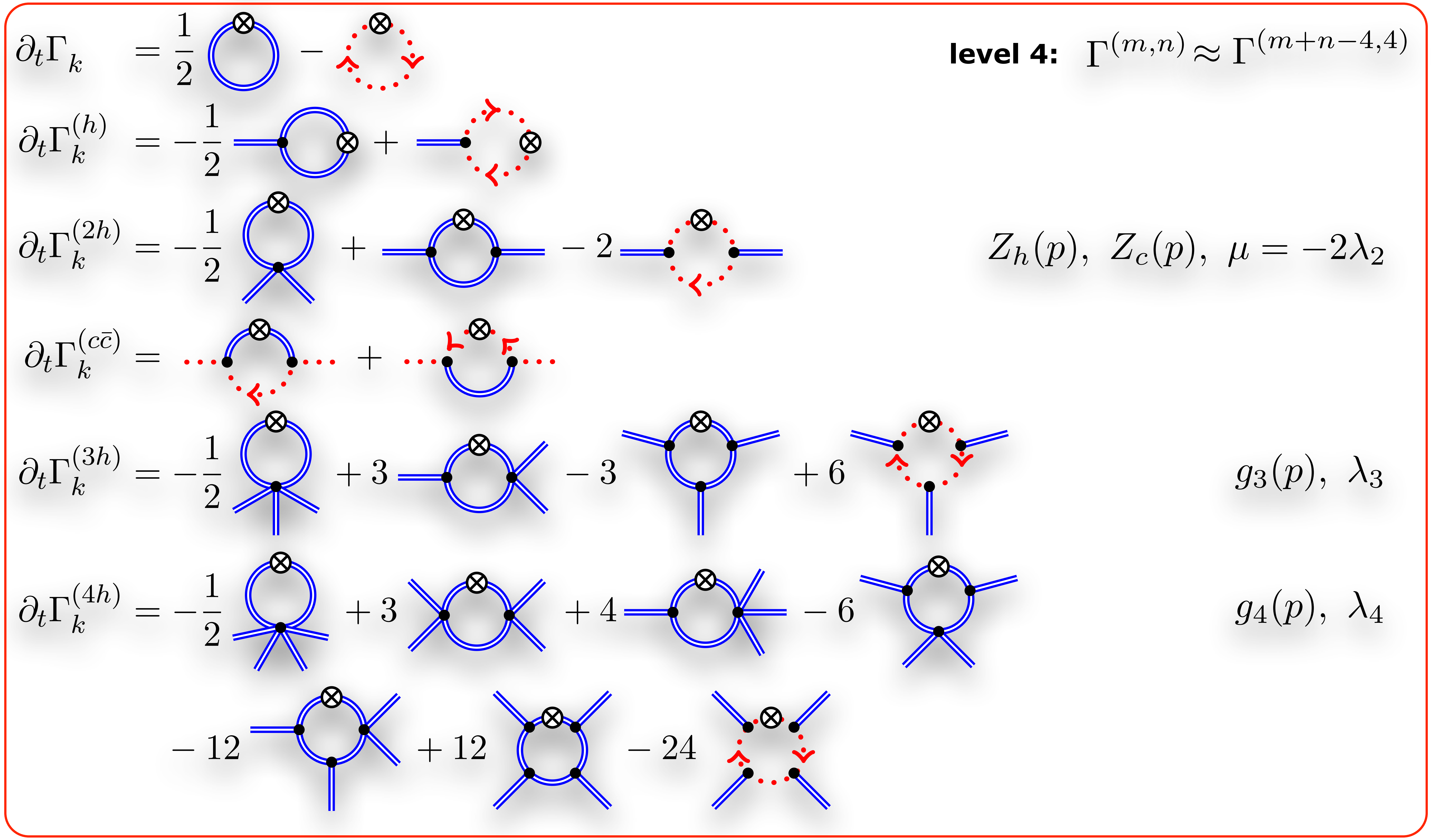
JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

Towards apparent convergence in quantum gravity

vertex expansion

$\Gamma^{(m,n\geq 2)}$

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

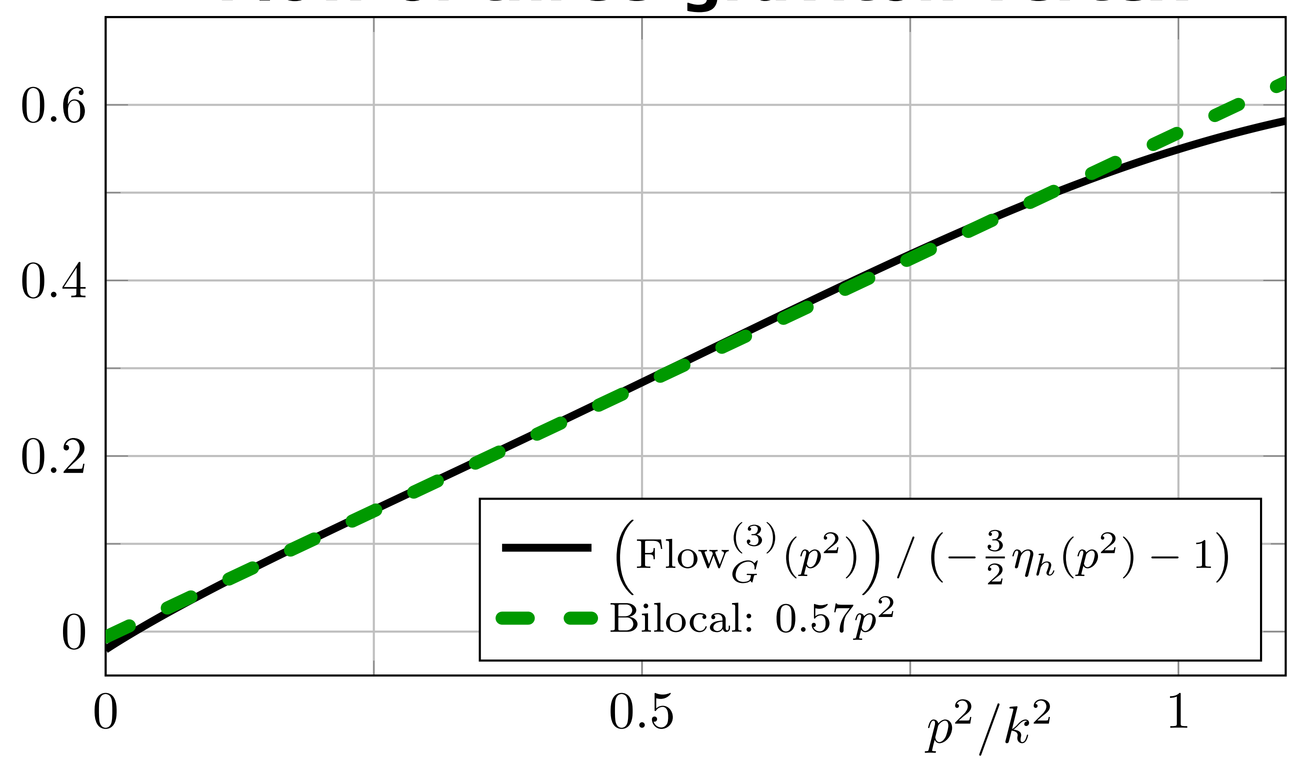


Aiming at apparent convergence

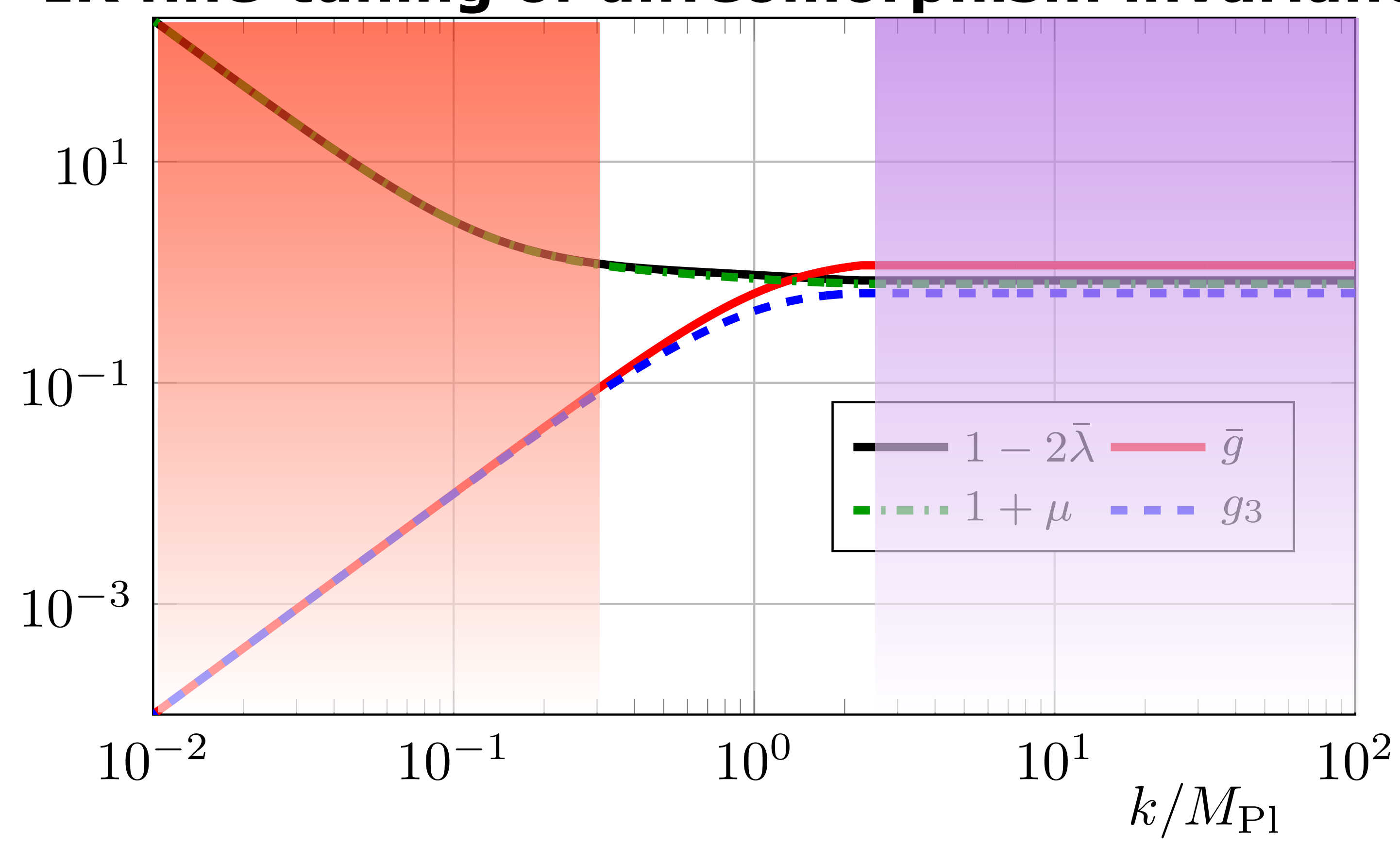
JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785

Momentum-dependent vertices

Flow of three-graviton vertex

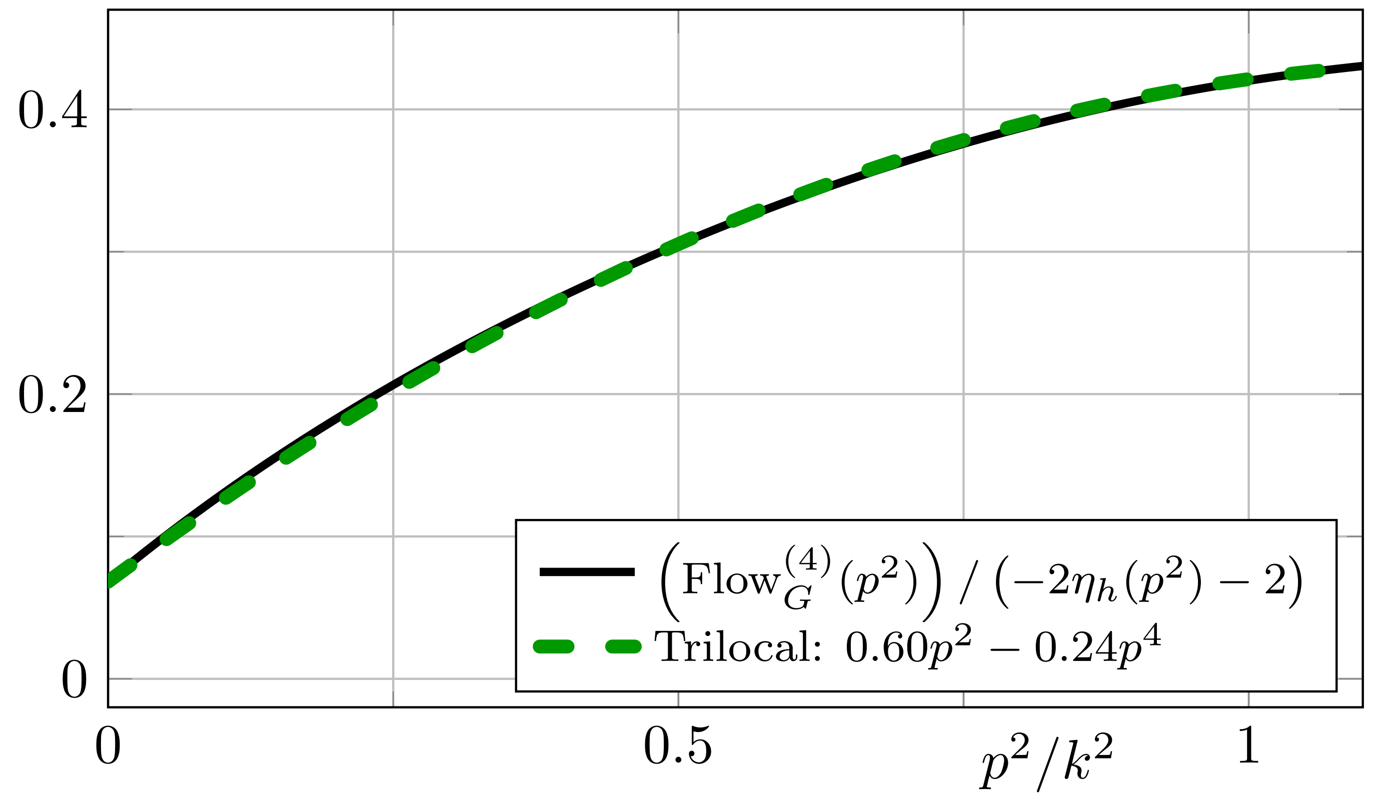


IR fine-tuning of diffeomorphism invariance



Denz, JMP, Reichert, EPJ C78 (2018)

Flow of four-graviton vertex



classical general relativity

asymptotically safe fixed point scaling

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

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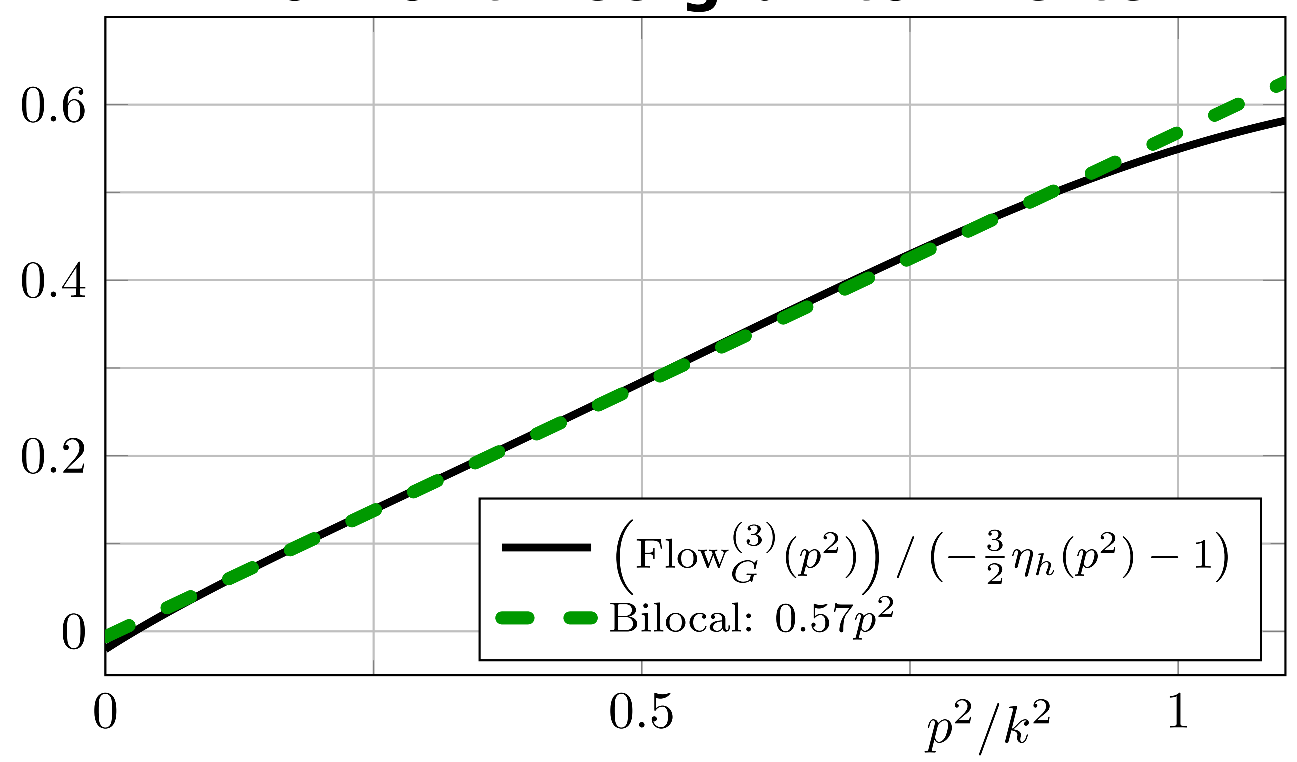

no $\mathbf{R}^2_{\mu\nu}$ - tensor structure generated!

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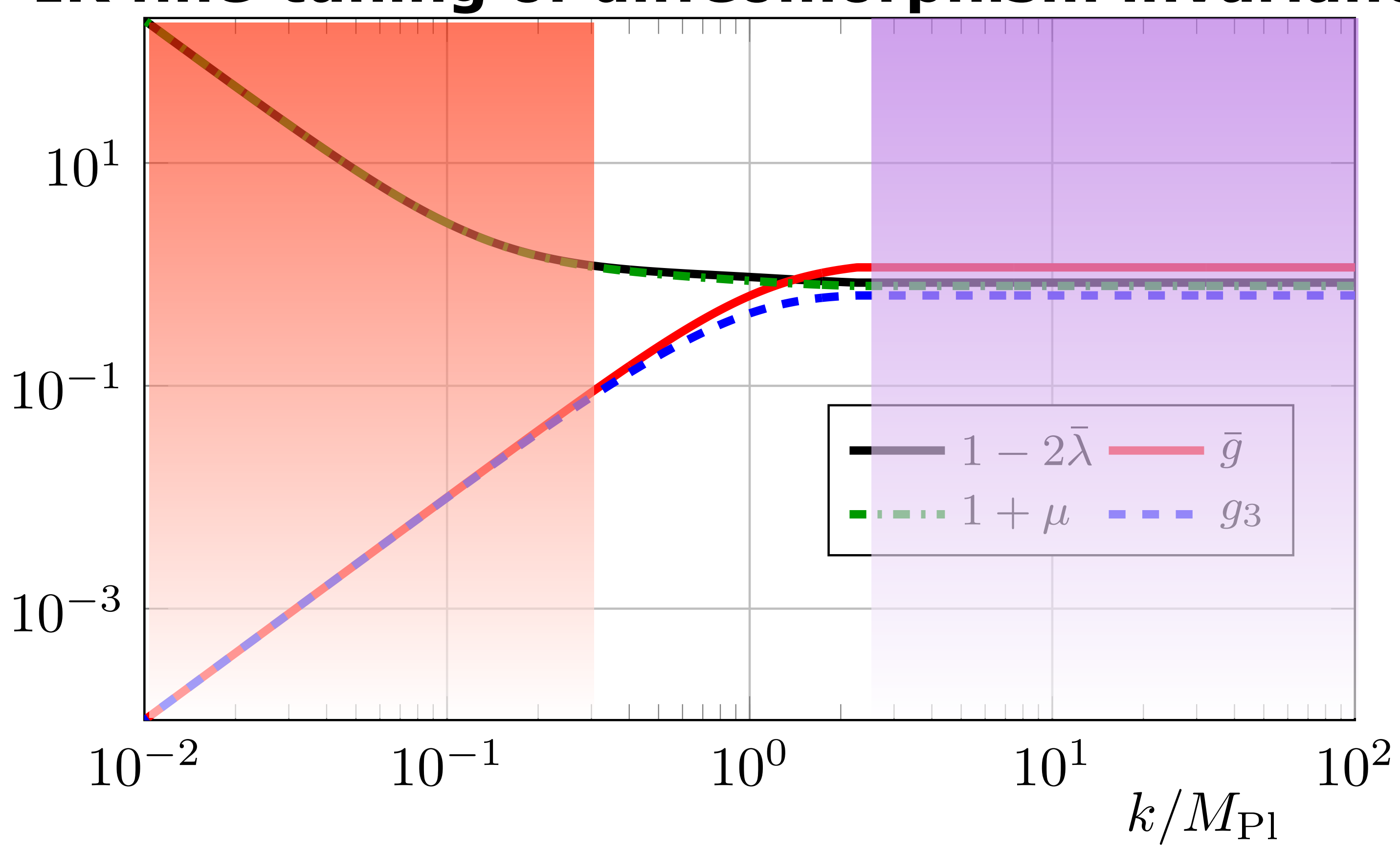

Denz, JMP, Reichert, EPJ C78 (2018)

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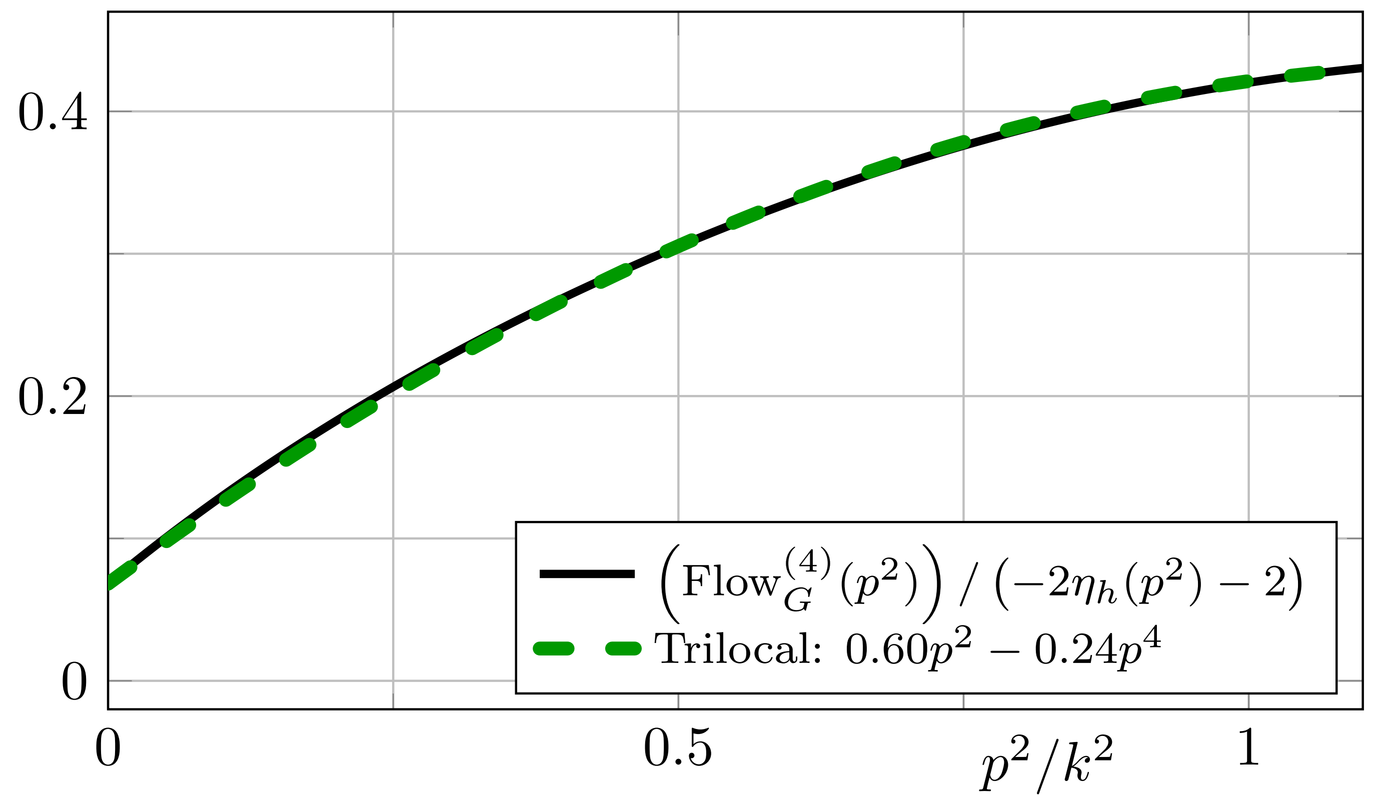

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2309.10785

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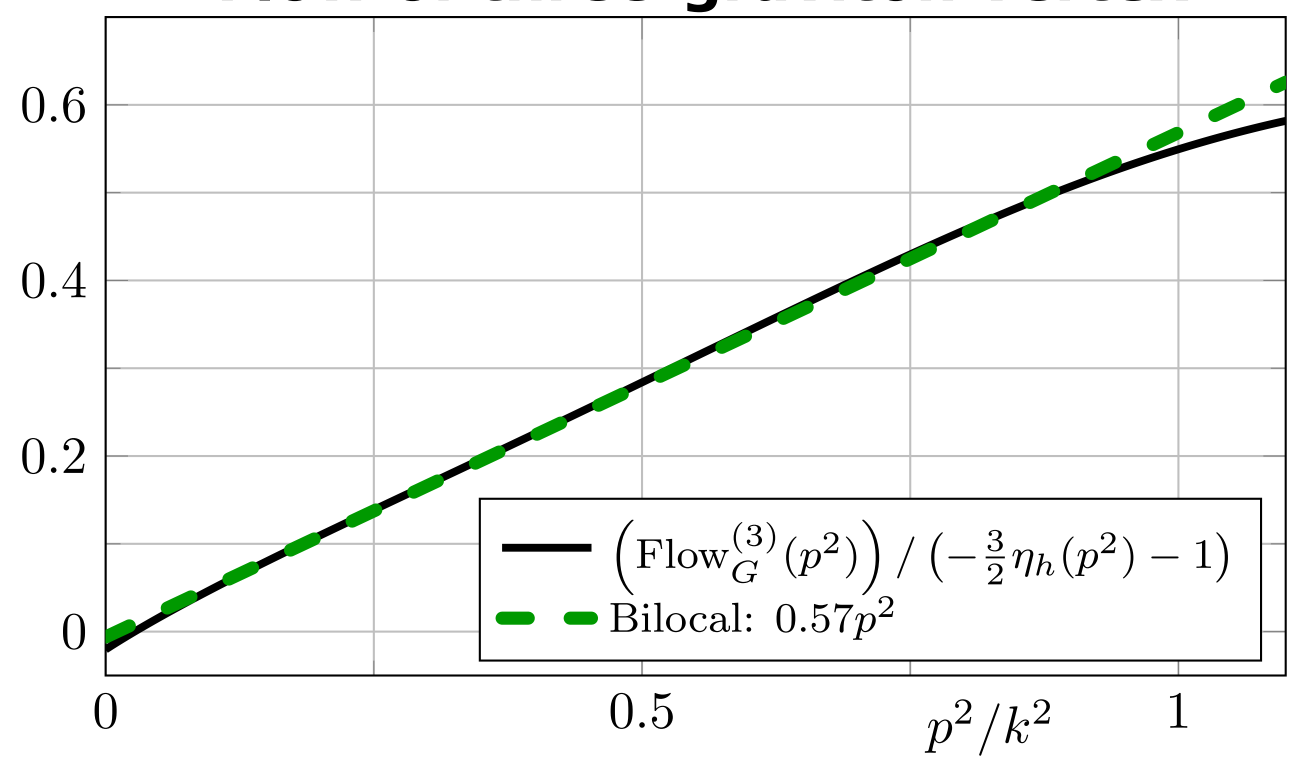

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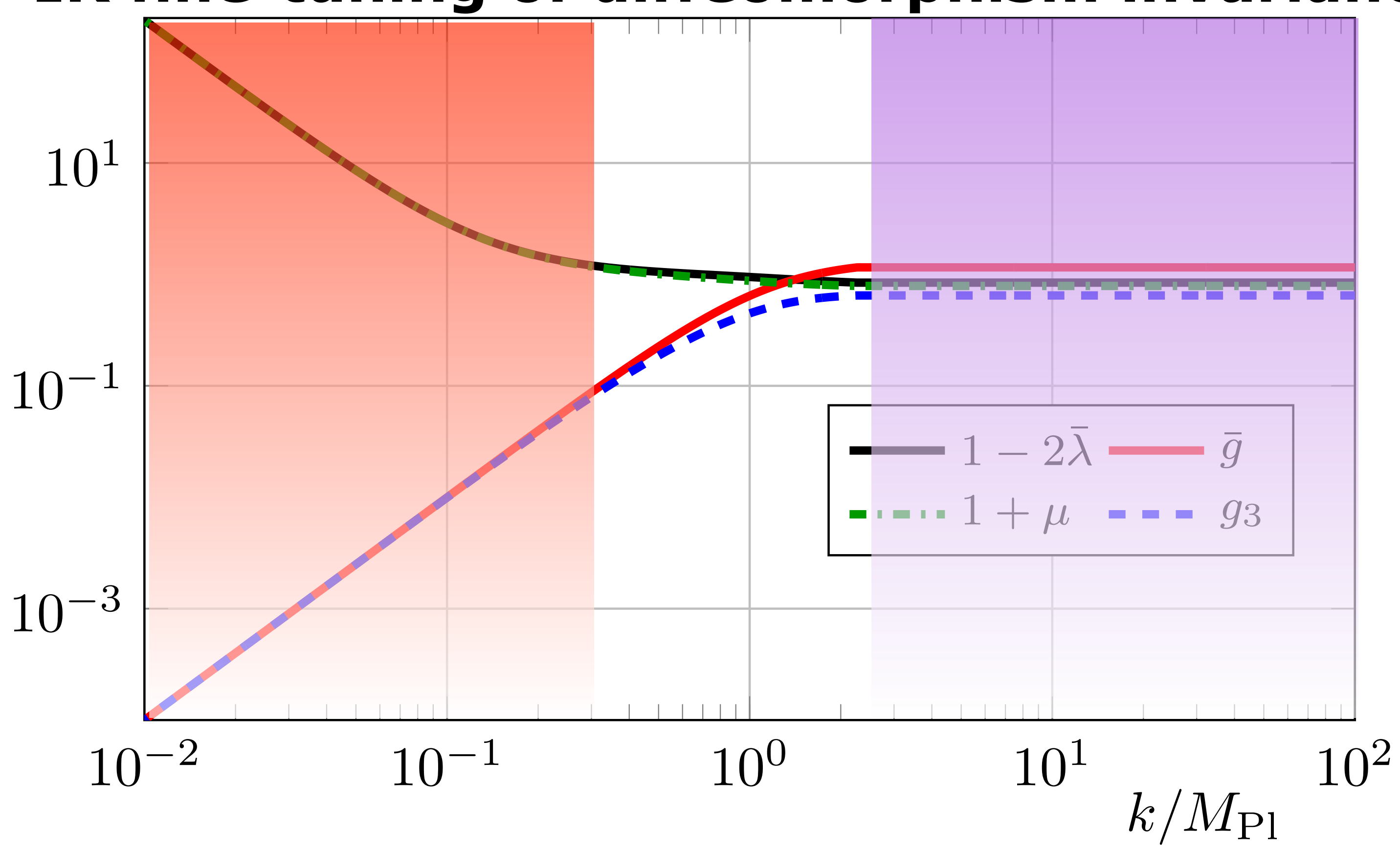

Denz, JMP, Reichert, EPJ C78 (2018)

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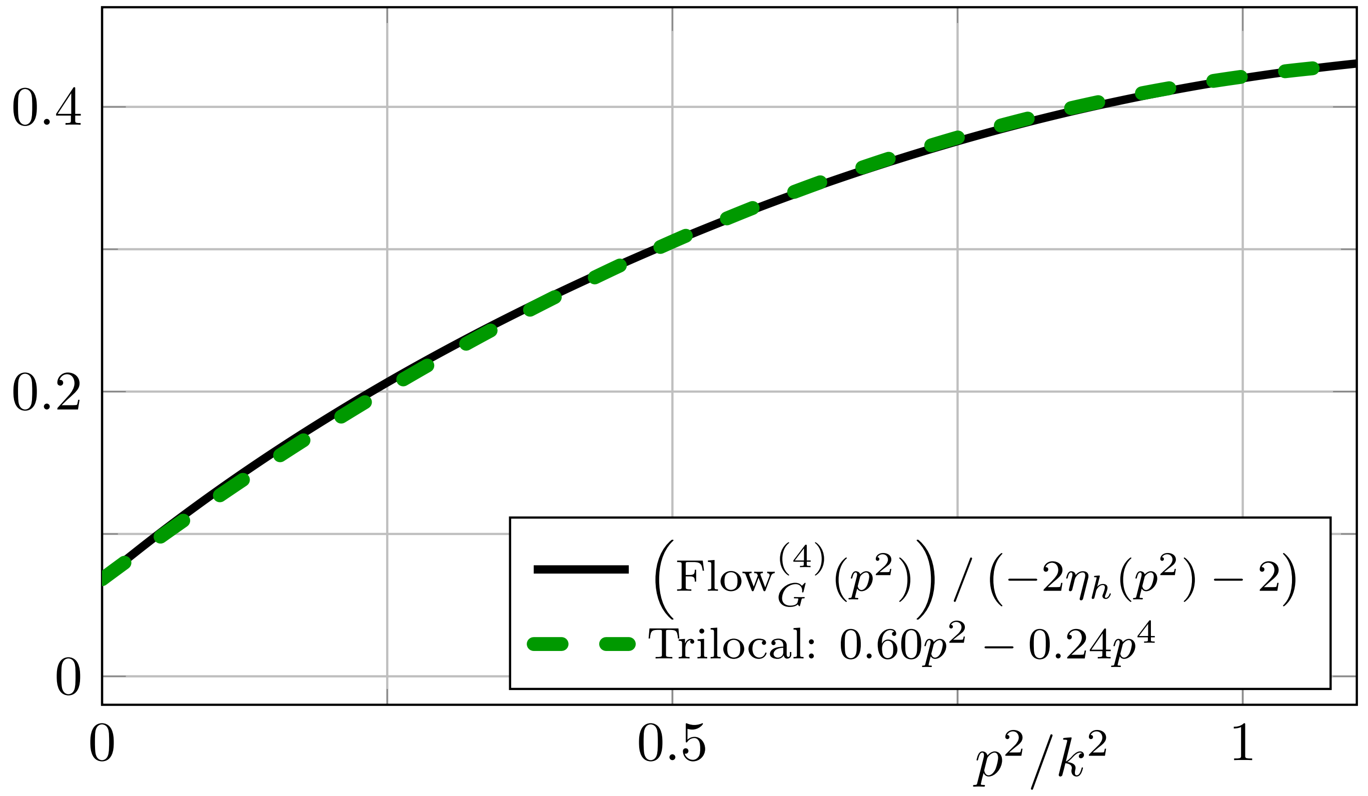

R^2 - tensor structure generated

R - tensor structure sustained

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

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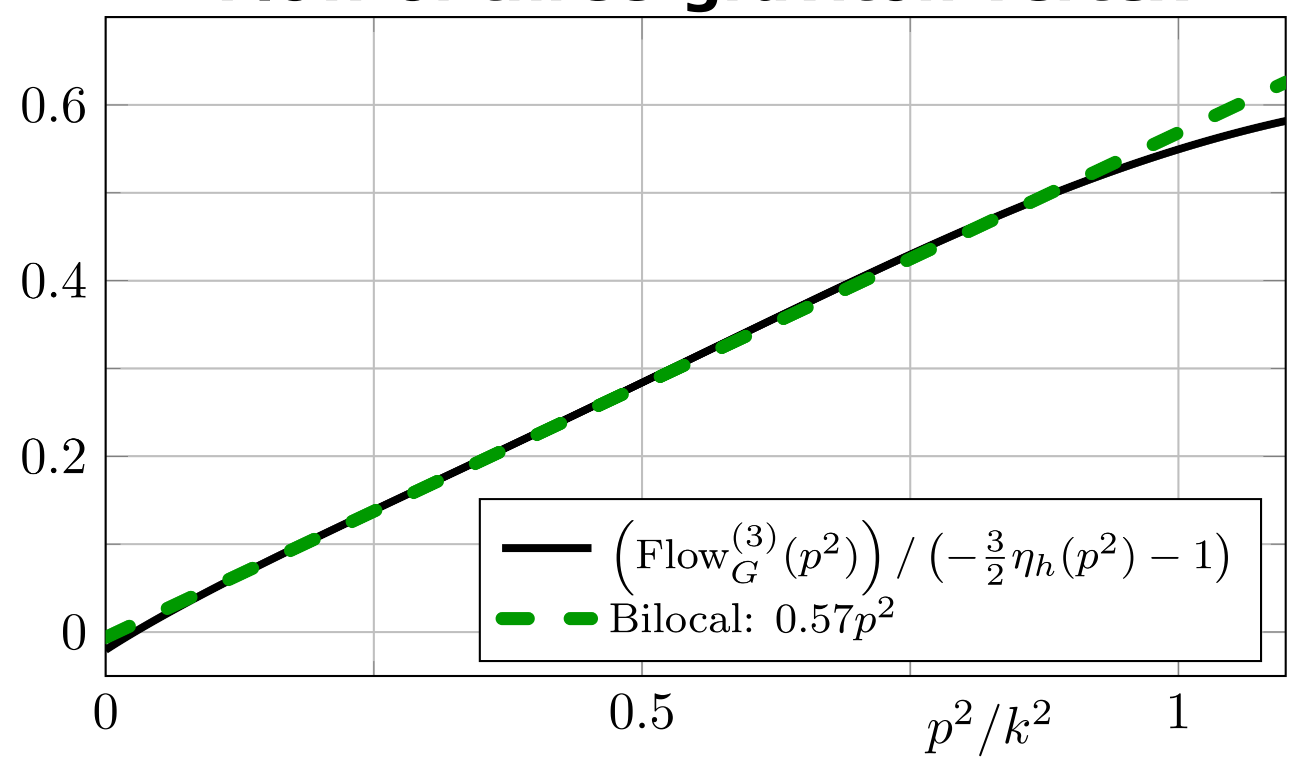

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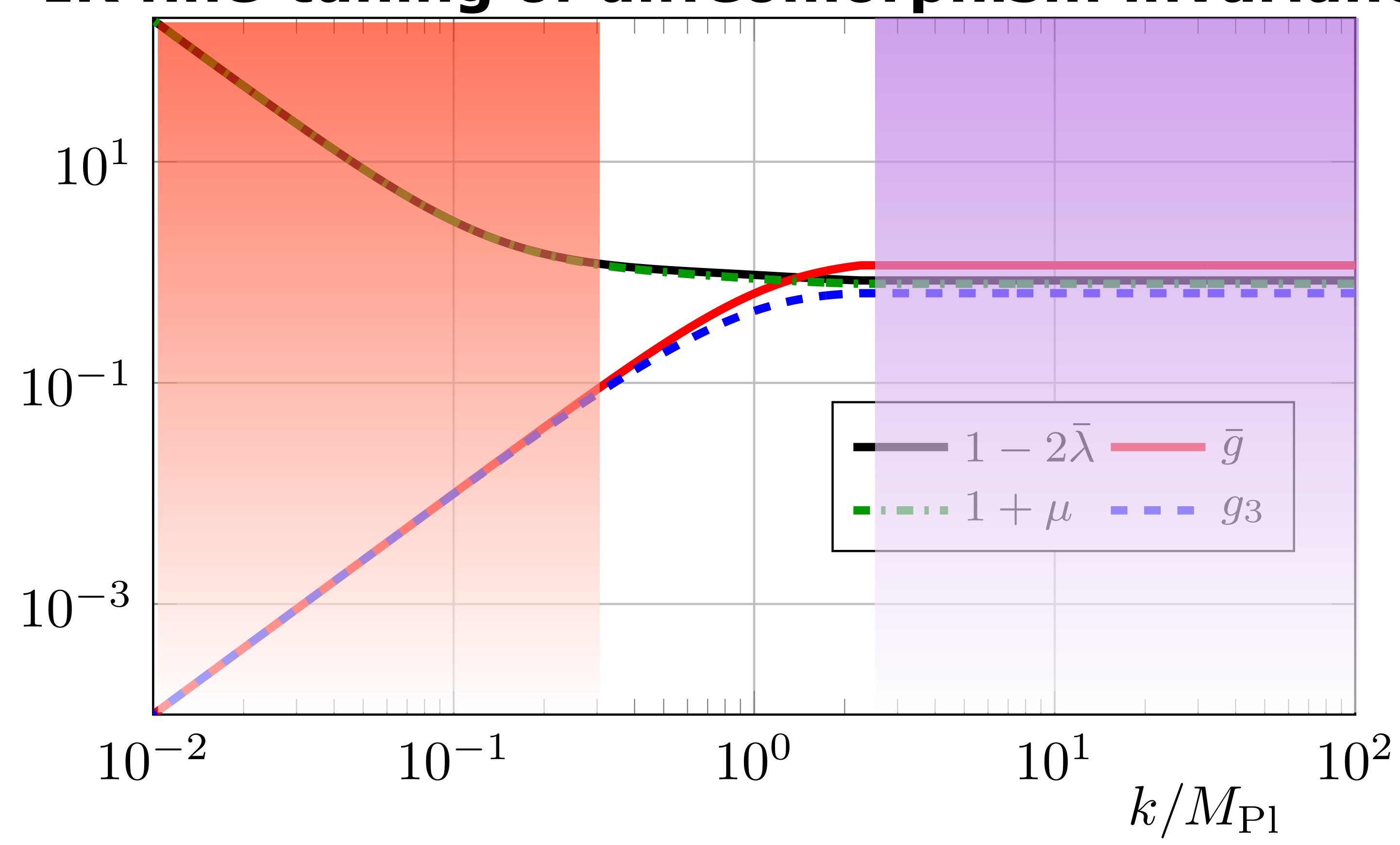

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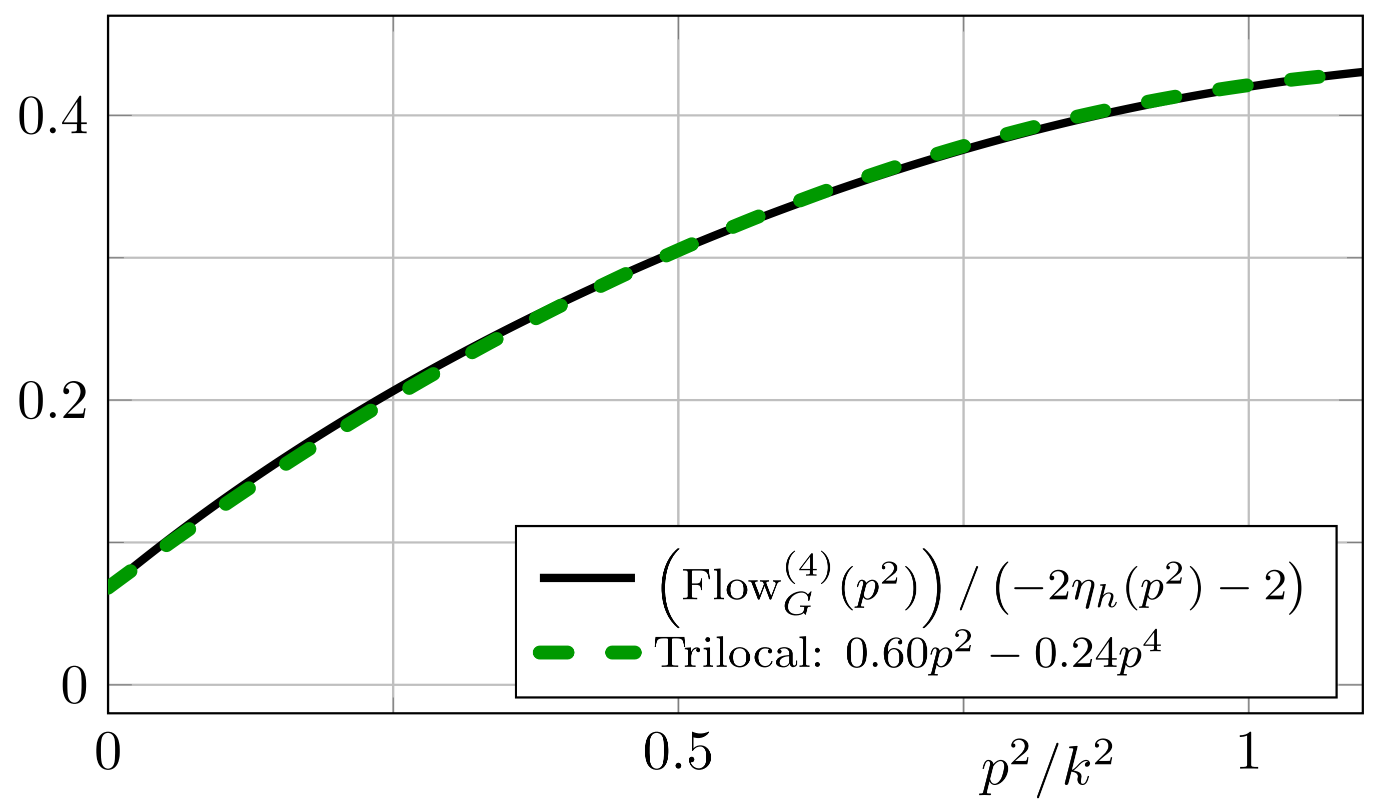

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Full momentum dependence
of
two-, three- and four-point function
at k=0

→ **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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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

JMP, Reichert, Front.in Phys. 8 (2021) 527
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(c) graviballs in gravity

JMP, Reichert, Front.in Phys. 8 (2021) 527
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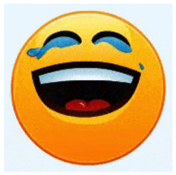
(c) graviballs in gravity → 

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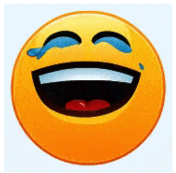
(c) graviballs in gravity → 

QG as perturbative as possible & apparently converging

… slight oversimplification for the sake of this talk …

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

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

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Shaposhnikov, Wetterich, PLB 683 (2010) 196

Eichhorn, Versteegen, JHEP 1801 (2018) 030

Eichhorn, Held, PRL 121 (2018) 151302

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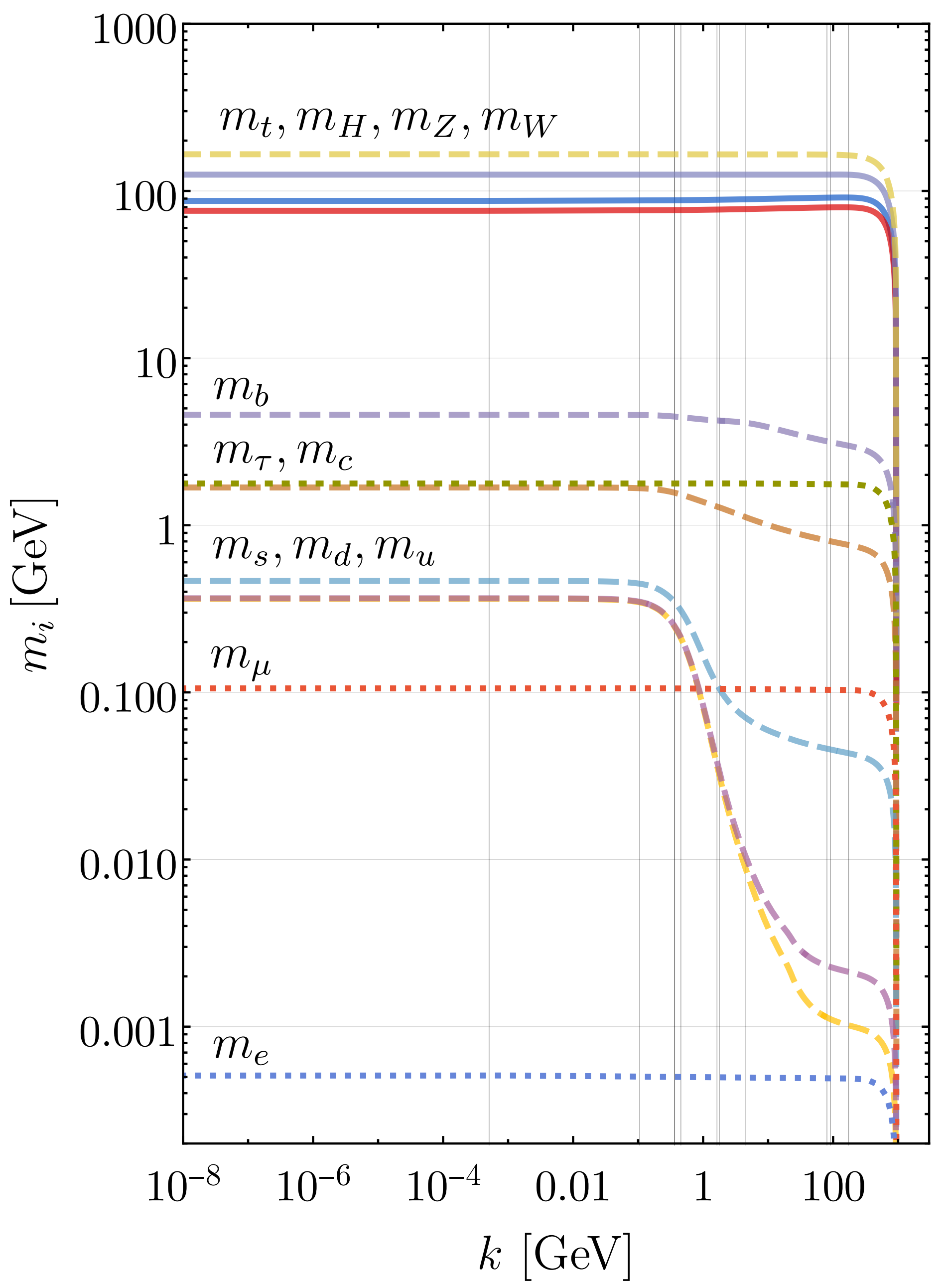
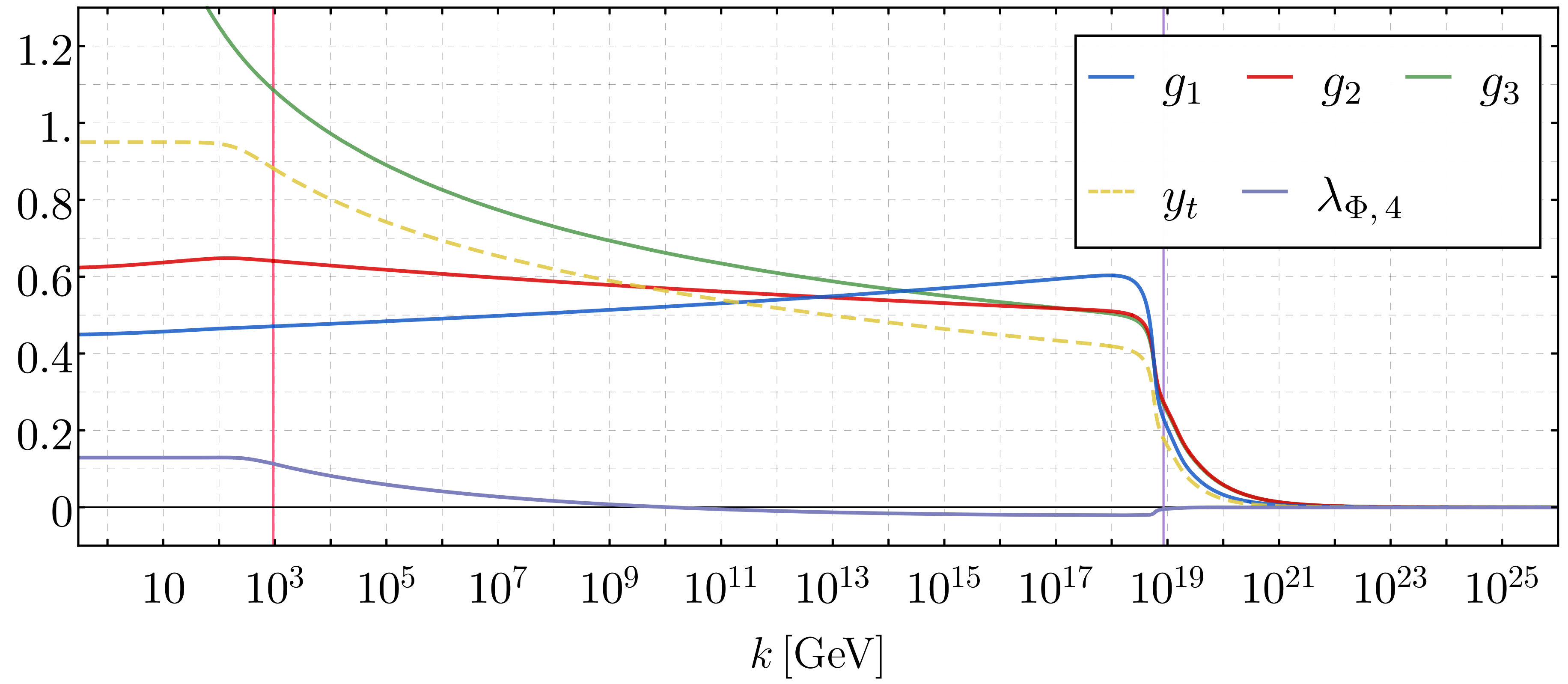
Latest ‘status report’: Eichhorn, Schiffer, 2212.07456



Asymptotically safe Standard Model



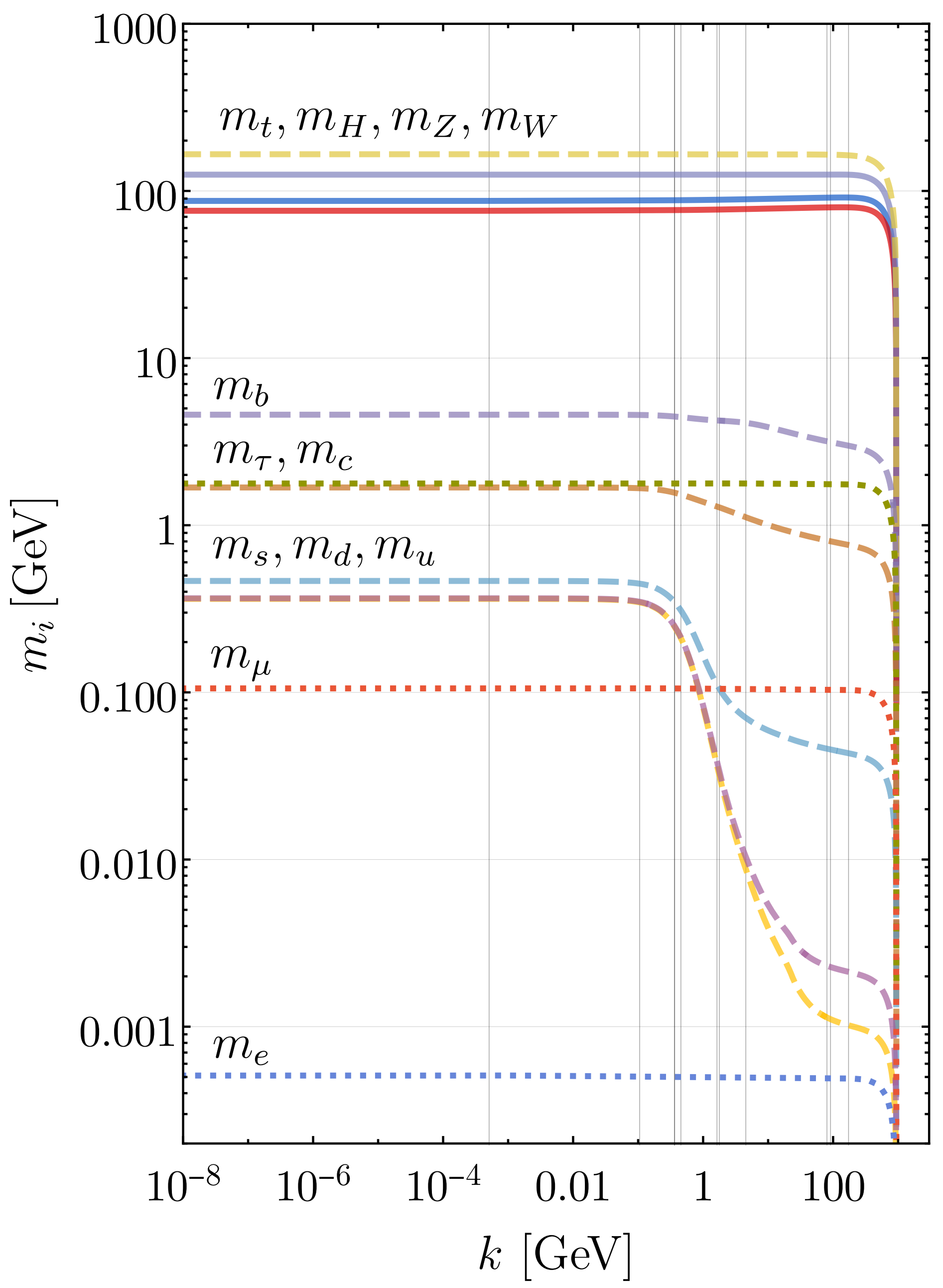
top pole mass (getting real)

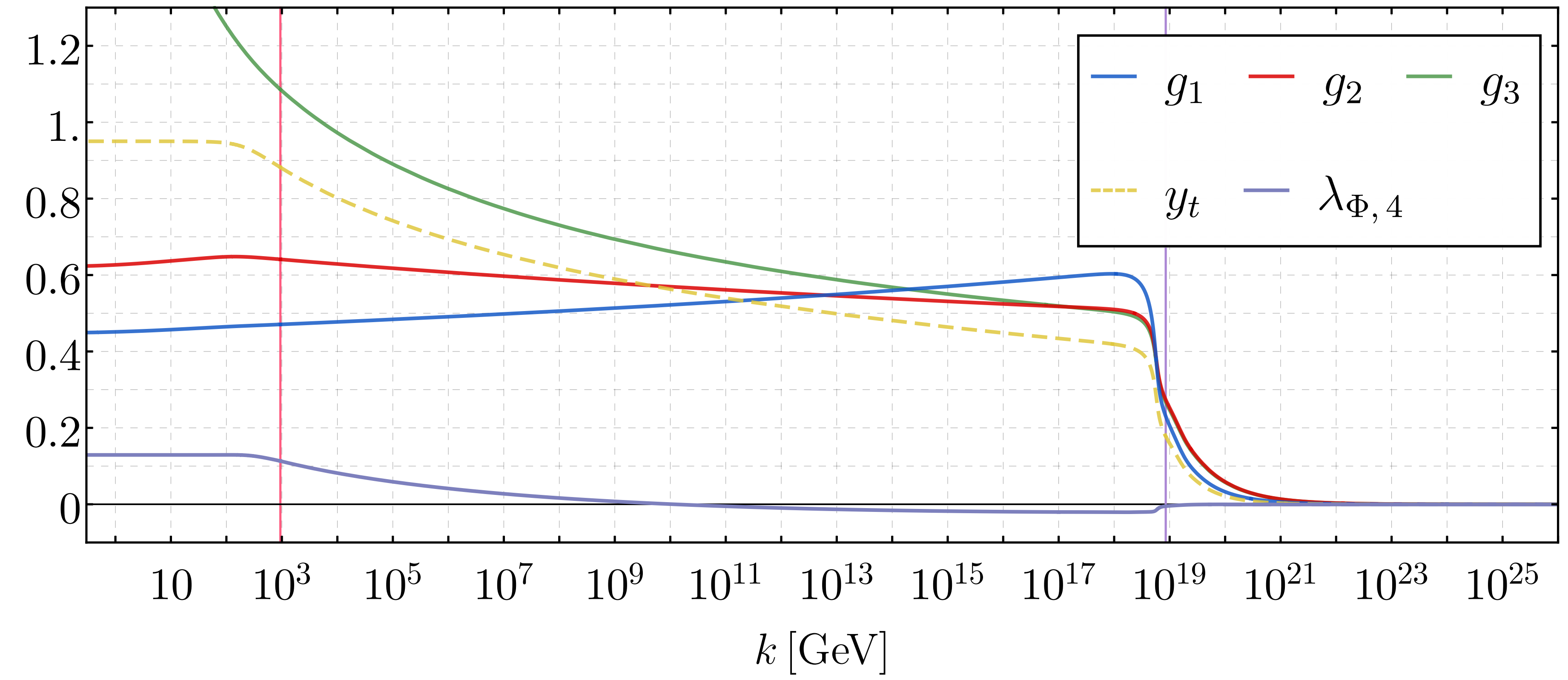
$$M_{t,\text{pole}}^{(\text{exp})} = 172.5 \pm 0.7\,\text{GeV}$$

Experimental value (PDG)

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

Asymptotically safe Standard Model





top pole mass (getting real)

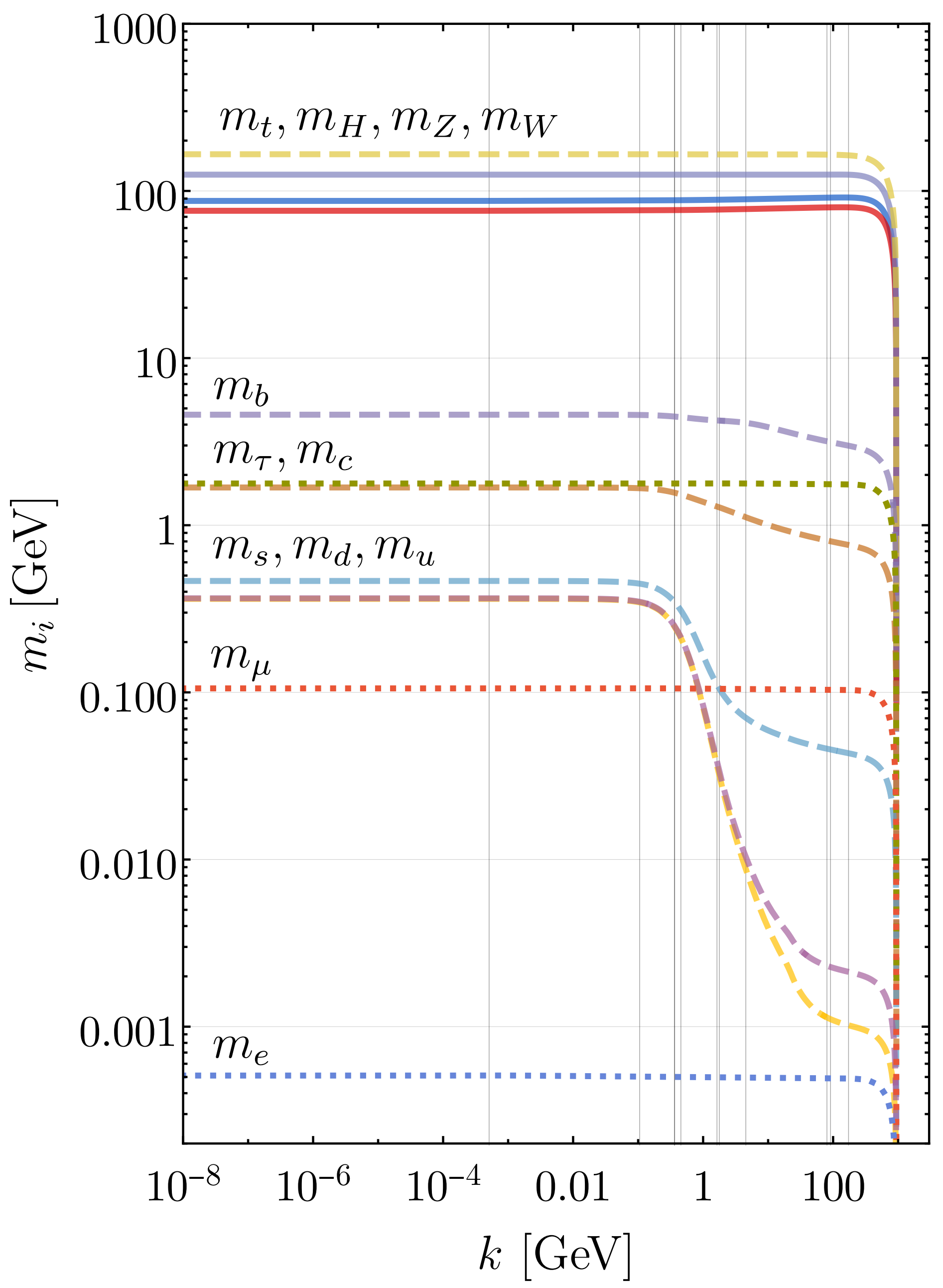
$$M_{t,\text{pole}}^{(\text{exp})} = 172.5 \pm 0.7\,\text{GeV} \quad \longleftarrow \quad m_t = 165.4^{+0.9}_{-0.2}\,\text{GeV}$$

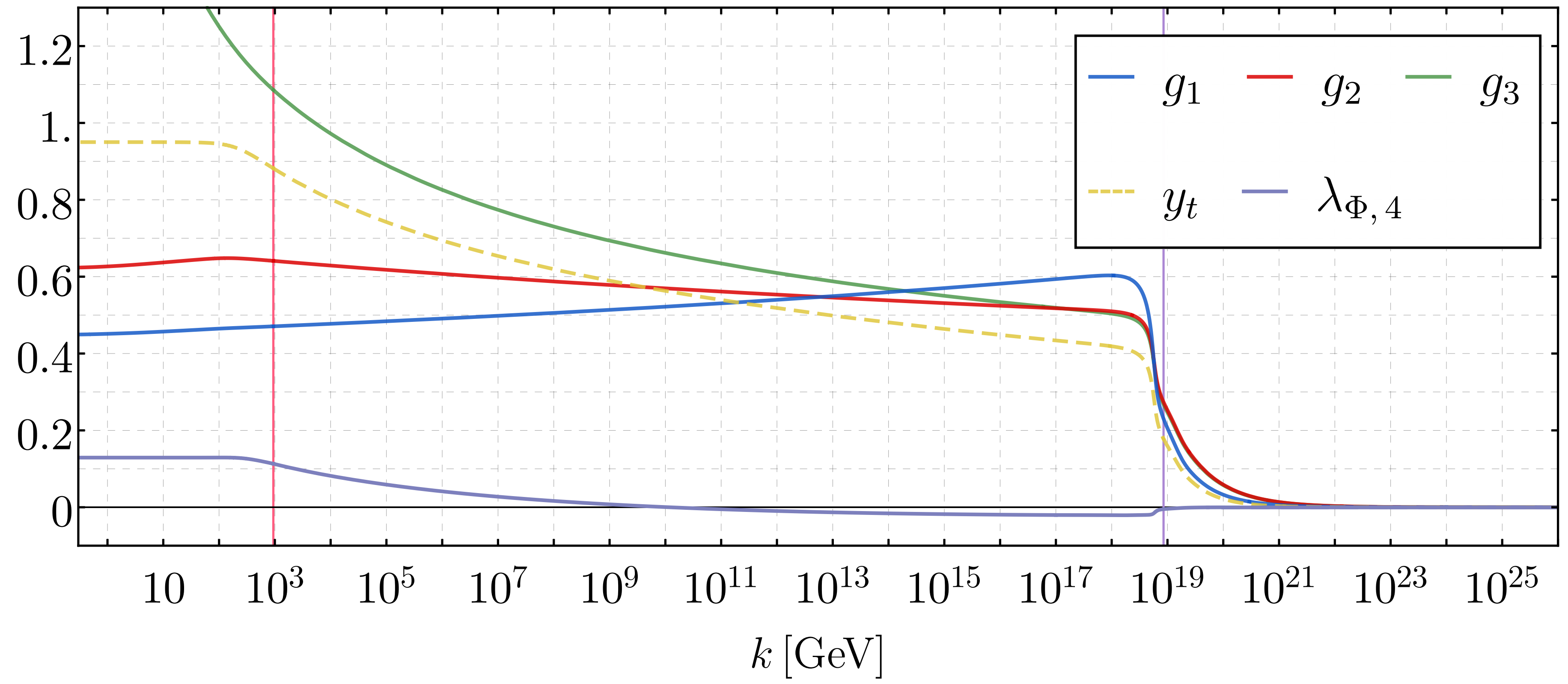
Experimental value (PDG)

Euclidean curvature mass

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

Asymptotically safe Standard Model





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

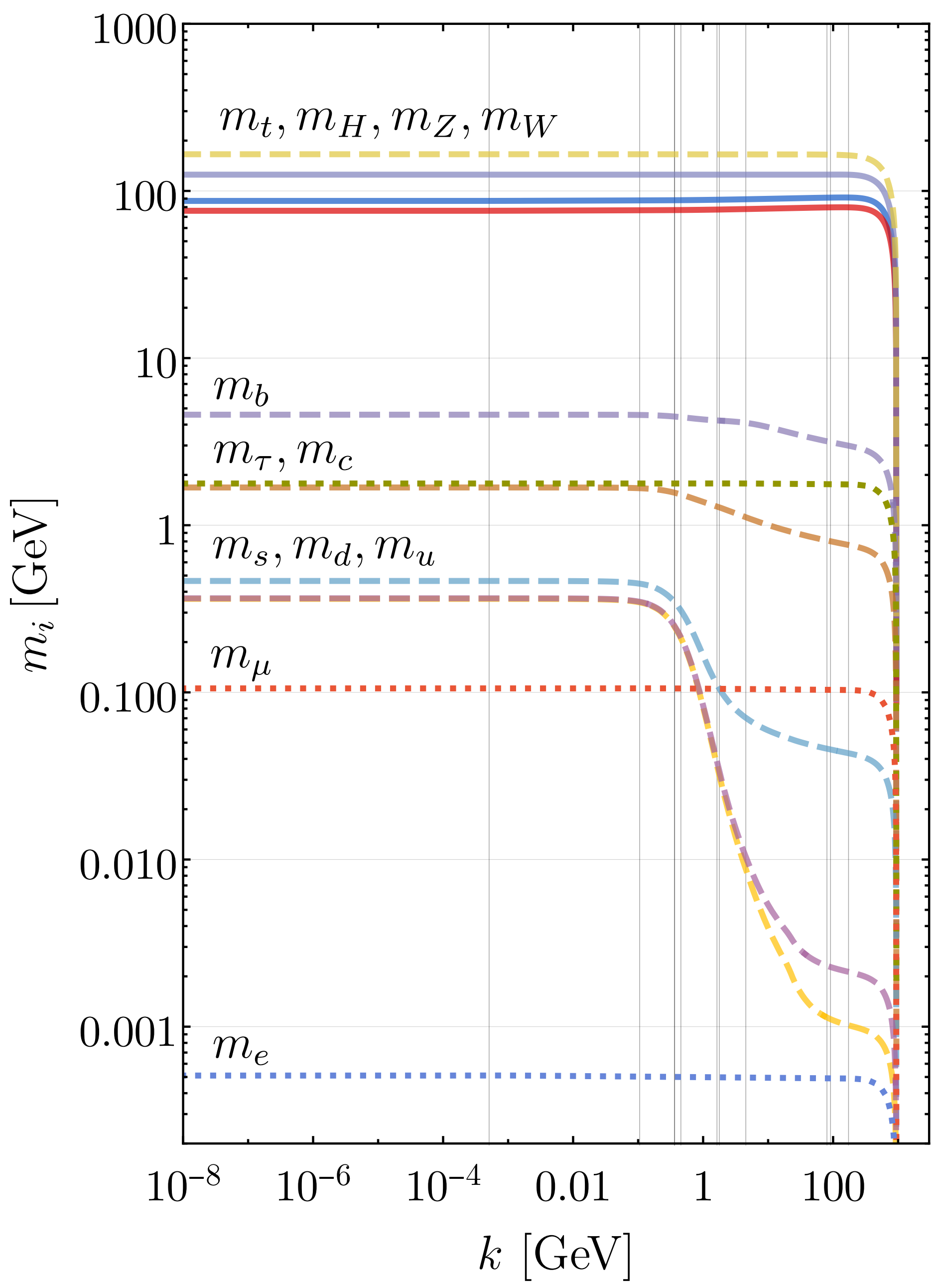
Prediction of decay width

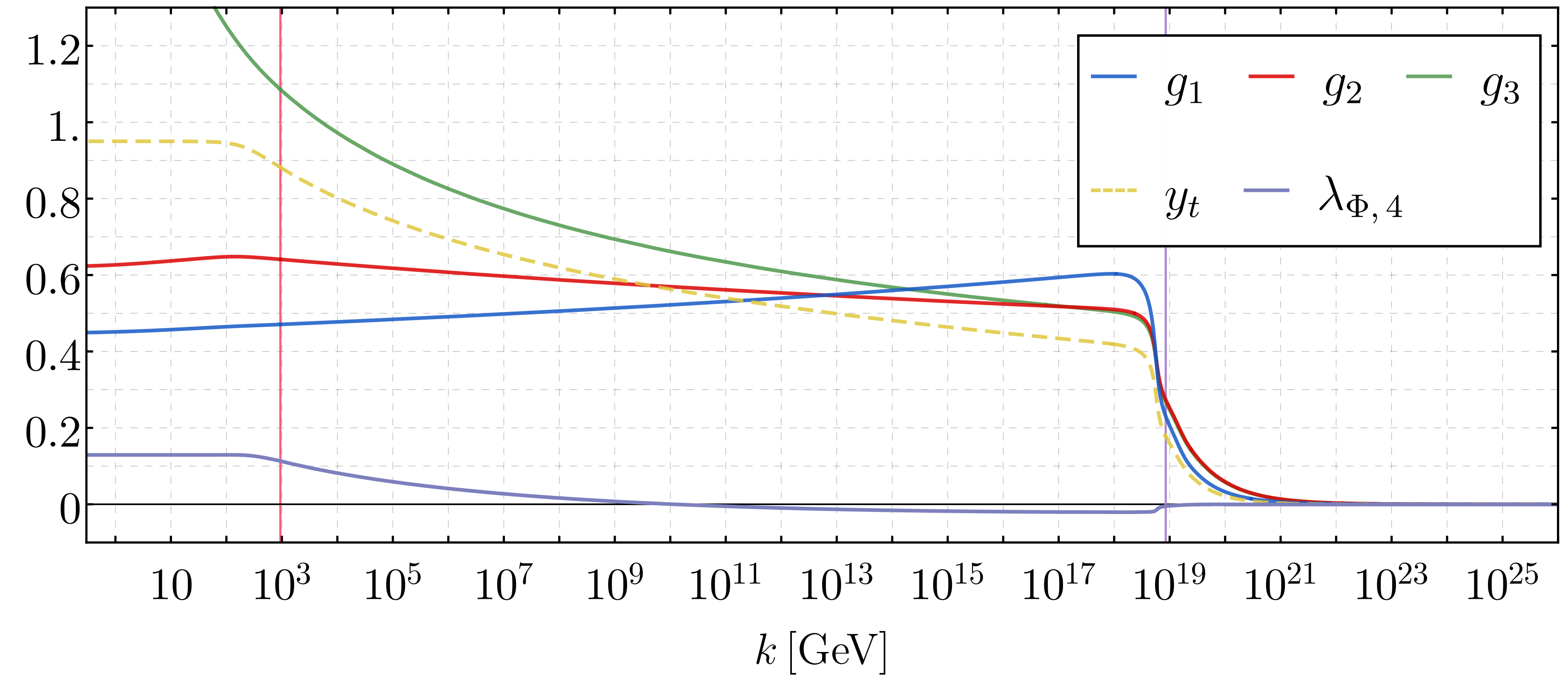
$$\Gamma_{t,\mathrm{pole}}^{(\mathrm{theo})} = 1.72^{+0.09}_{-0.41}\,\mathrm{GeV} \qquad \Gamma_{t,\mathrm{pole}}^{(\mathrm{exp})} = 1.42^{+0.19}_{-0.15}\,\mathrm{GeV}$$

Experimental value (PDG)

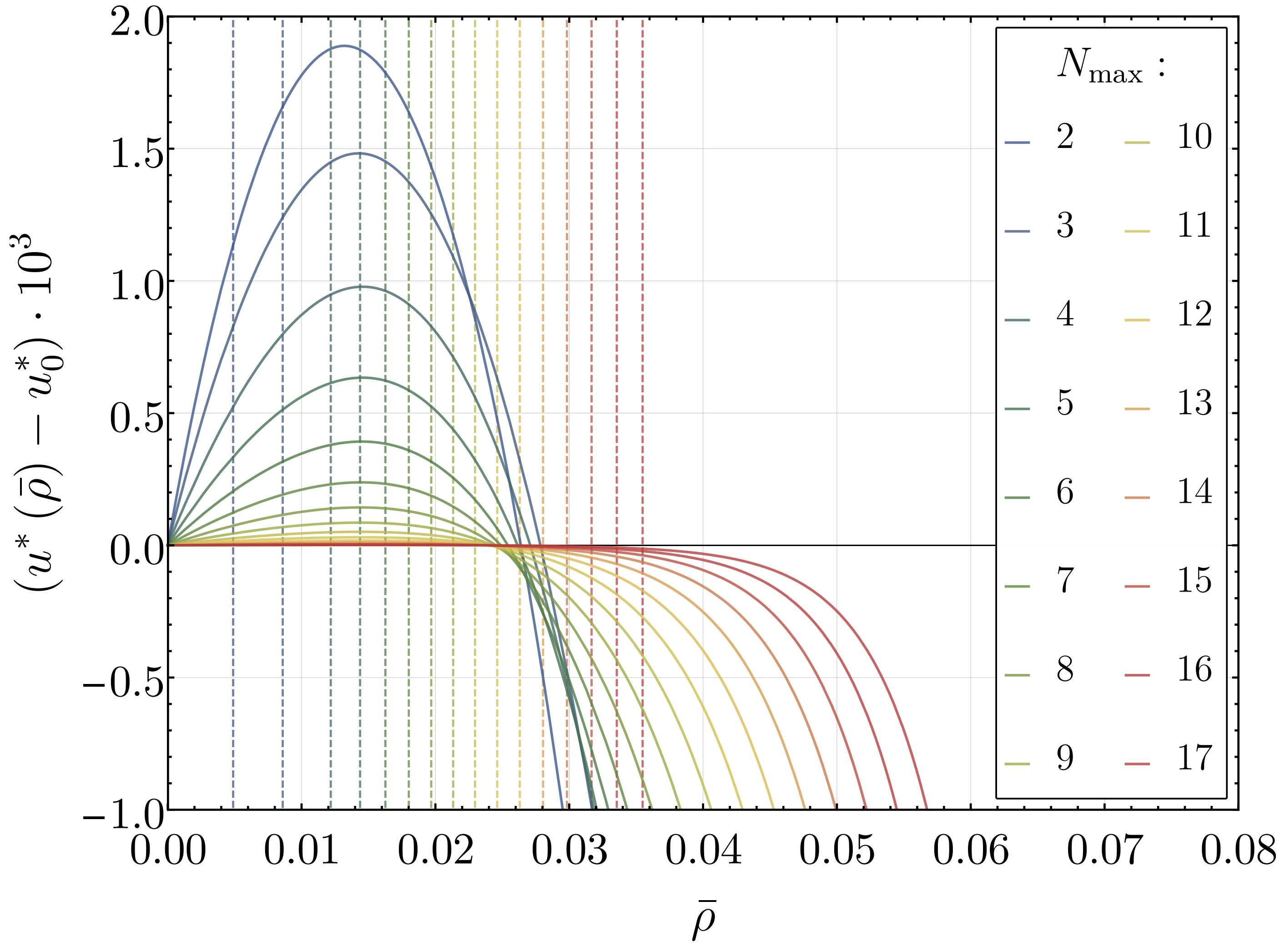
Pastor-Gutiérrez, JMP, Reichert, SciPost Phys. 15 (2023) 105

Asymptotically safe Standard Model





flat Higgs FP potential



Two relevant directions

top pole mass (getting real)

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

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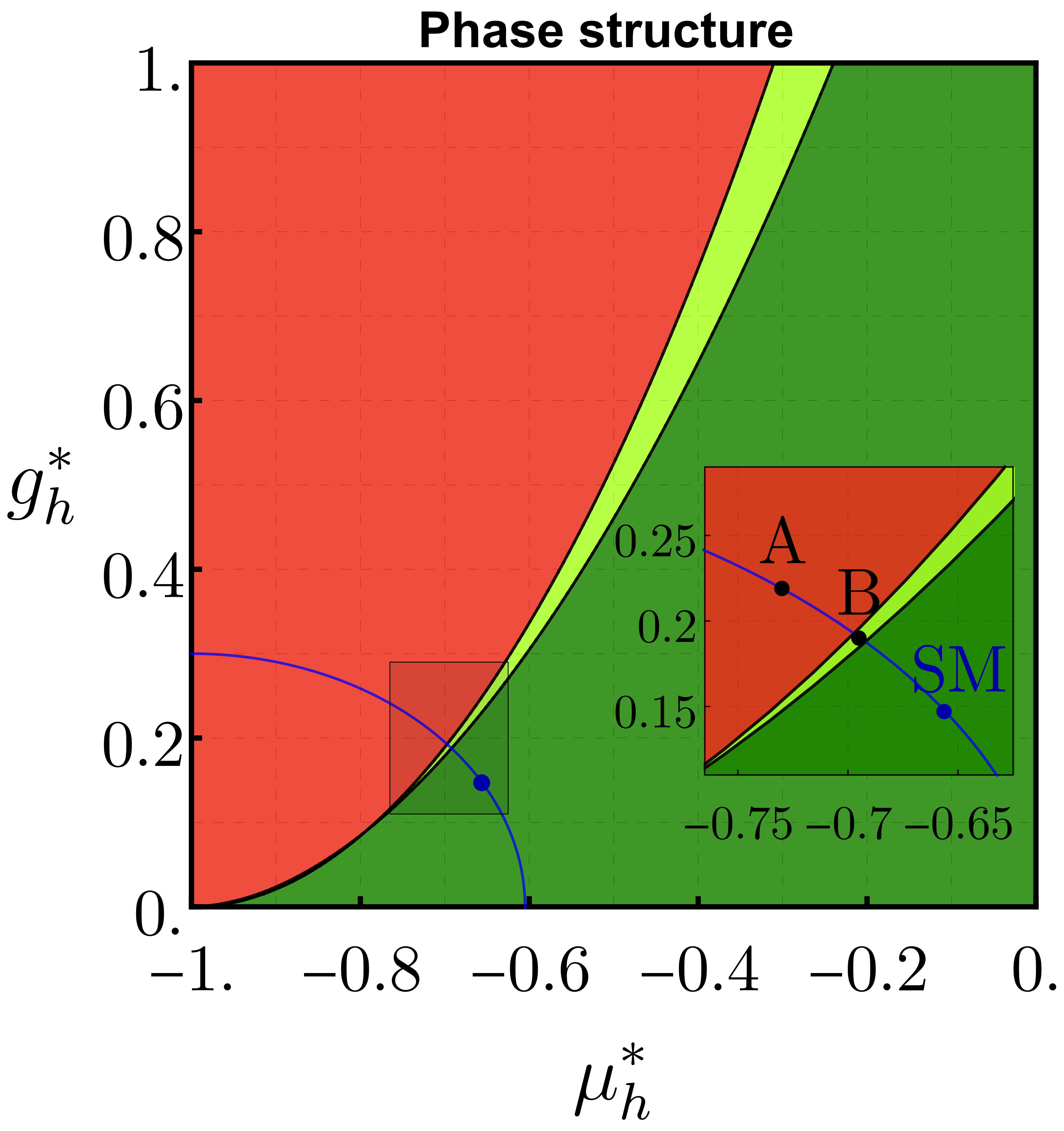

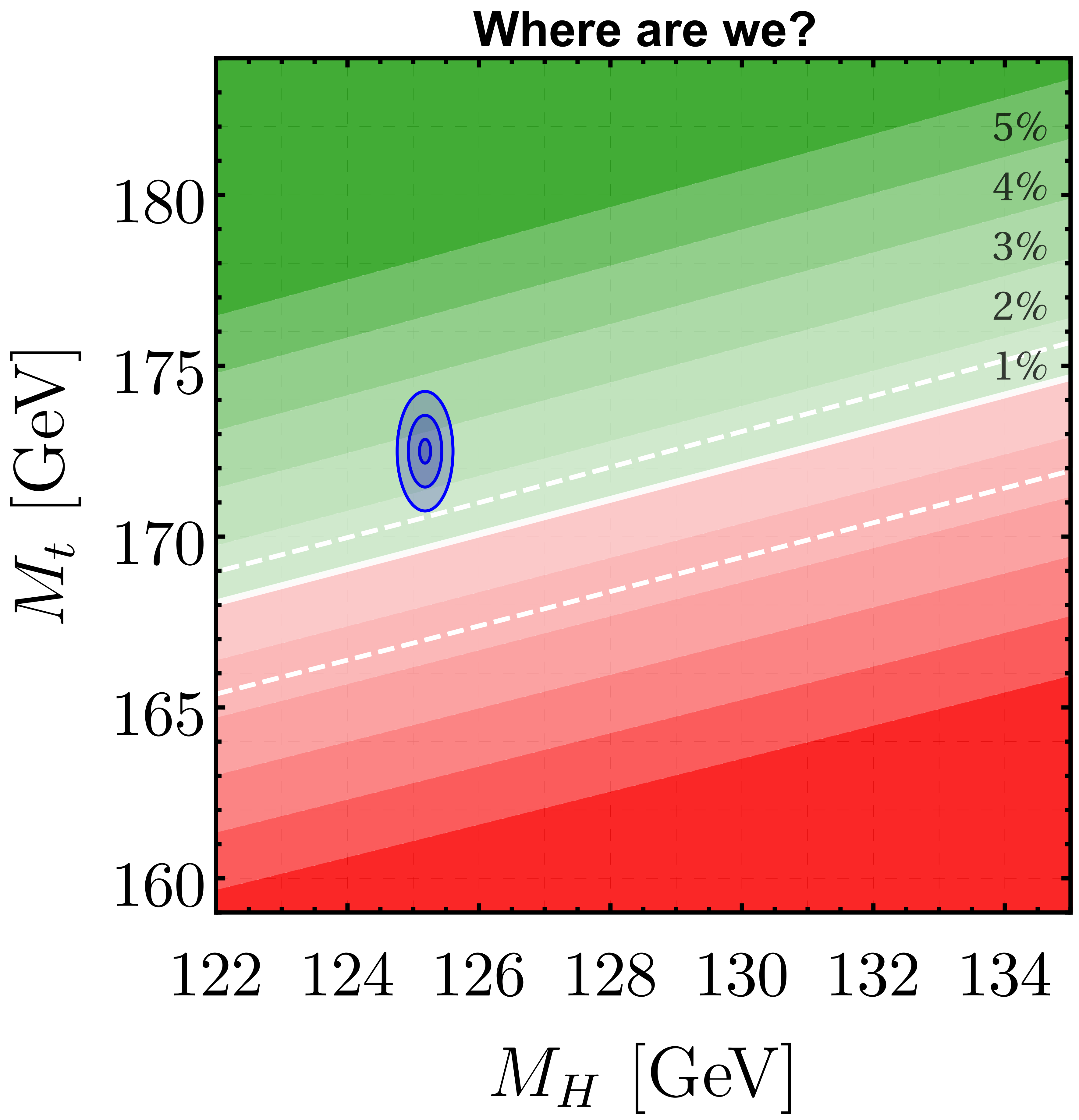

Pastor-Gutiérrez, JMP, Reichert, SciPost Phys. 15 (2023) 105

Applications II: asymptotically black holes

JMP, Tränkle, 2309.17043

Black Holes in Asymptotically Safe Gravity: Platania, 2309.17043

and beyond: Held, Eichhorn, 2212.09495

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

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

$\bar\Gamma^{(3)}_{h^3}(p)$ →

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

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
$\bar{\Gamma}^{(2)}_{hh}(p)$		$\bar{\Gamma}^{(3)}_{\bar{g}^3}(p)$		$\mathcal{R}(\Delta, R)$
$\bar{\Gamma}^{(3)}_{h^3}(p)$	→		→	$R f_{R^2}(\Delta) R$
$\bar{\Gamma}^{(4)}_{h^4}(p)$		$\bar{\Gamma}^{(4)}_{\bar{g}^4}(p)$		$R_{\mu\nu} f_{R^2_{\mu\nu}}(\Delta) R^{\mu\nu}$

JMP, Tränkle, 2309.17043

Asymptotically black holes

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gauge dependent

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

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

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

→

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

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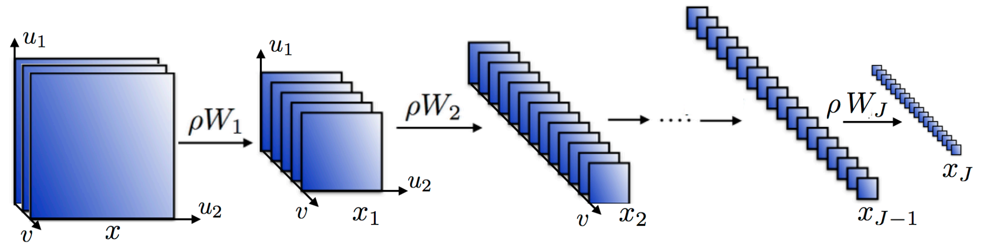
→

gauge independent

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

Unfolding



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

Maps

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

JMP, Tränkle, 2309.17043

Asymptotically black holes

Unfolding the background effective action

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

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

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

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

→

RG-invariant

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

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

→

gauge independent

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

Unfolding

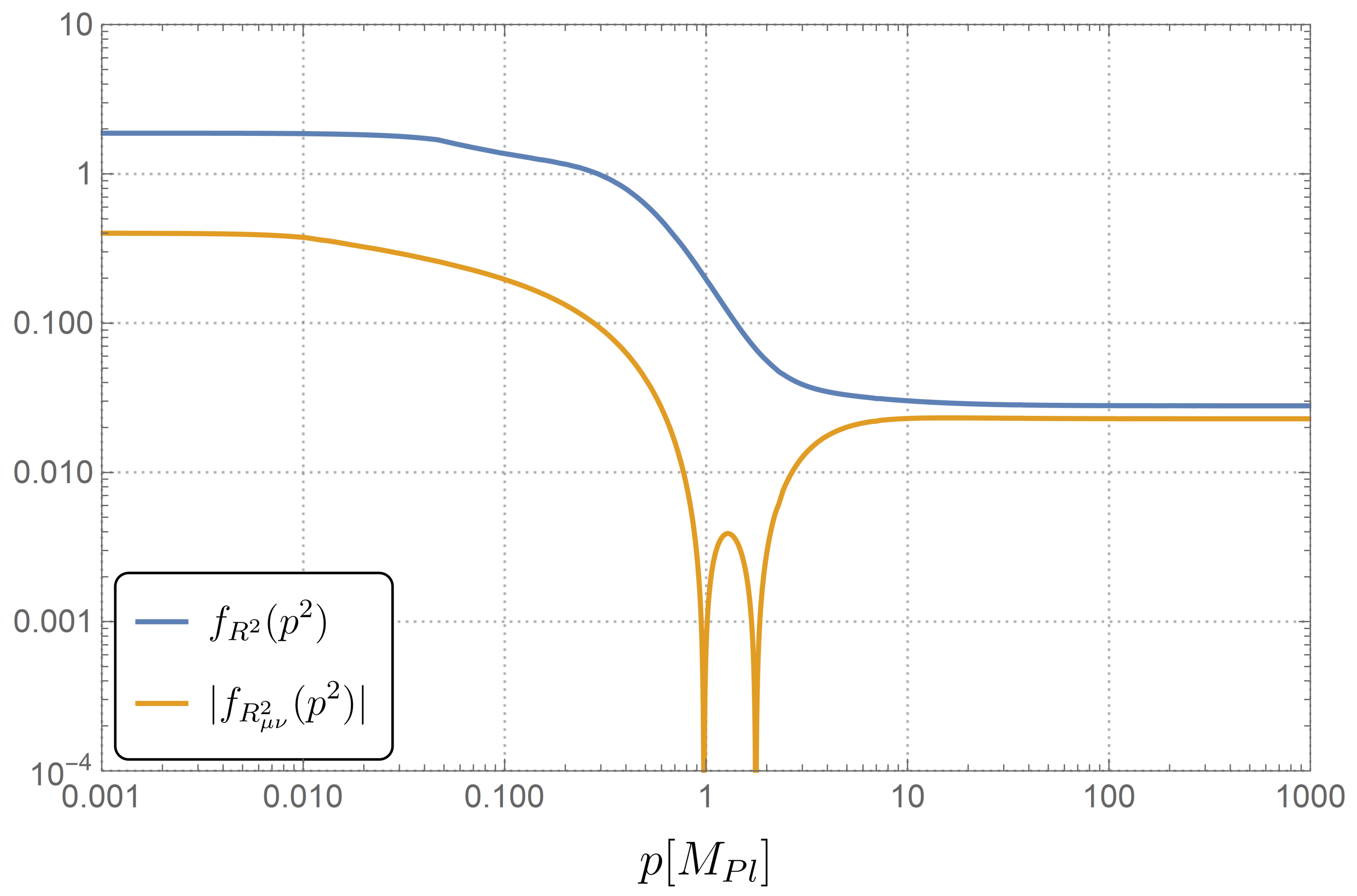
Educated guess

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

Maps

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

Results for form factors



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

JMP, Tränkle, 2309.17043

Asymptotically black holes

Infrared asymptotic effective action

$$\Gamma_{\rm IR}[g_{\mu\nu}] = \frac{1}{16\pi}\int_x \sqrt{-g}\left(G_N^{-1}R + g_{R^2_{\mu\nu}} R_{\mu\nu}R^{\mu\nu} + g_{R^2}R^2 + c_1 R_{\mu\nu}\Box R^{\mu\nu} + c_2 R\Box R\right)$$

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

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

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

JMP, Tränkle, 2309.17043

Asymptotically black holes

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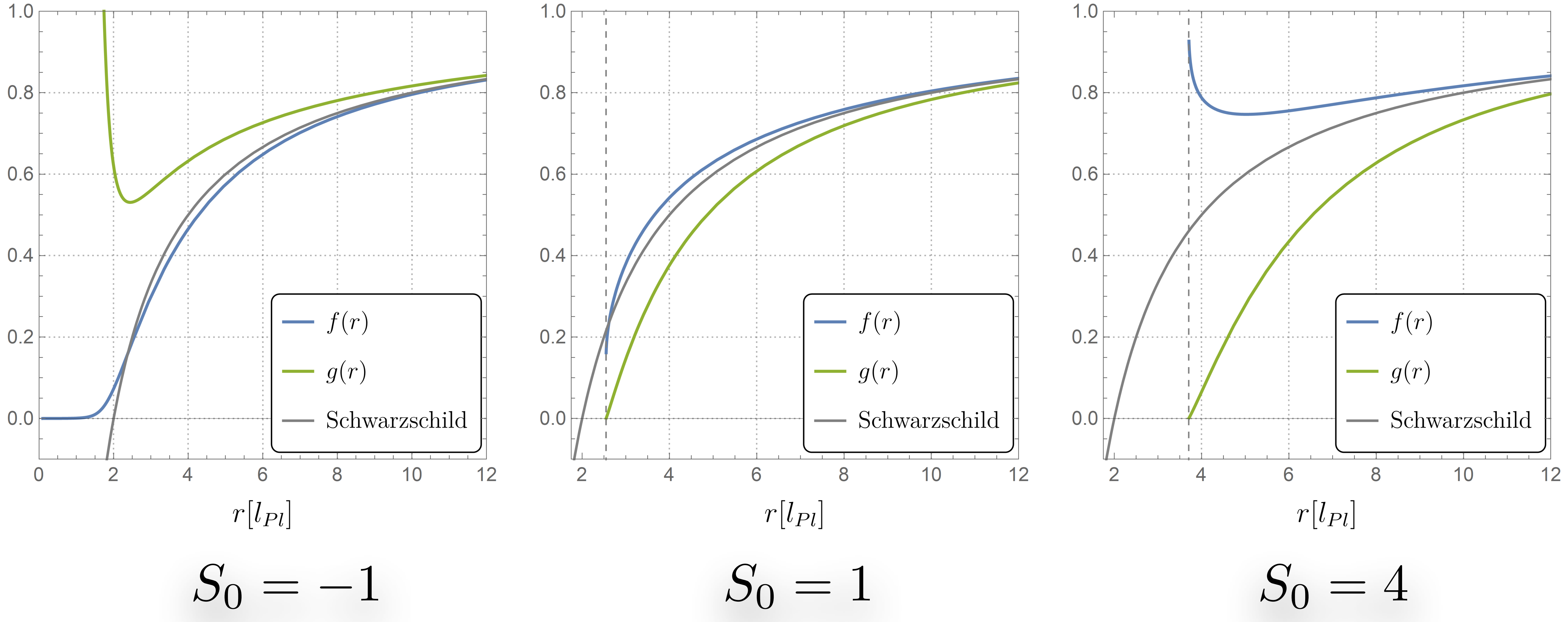
Numerical Solutions for $S_2 = 1 = M$



JMP, Tränkle, 2309.17043

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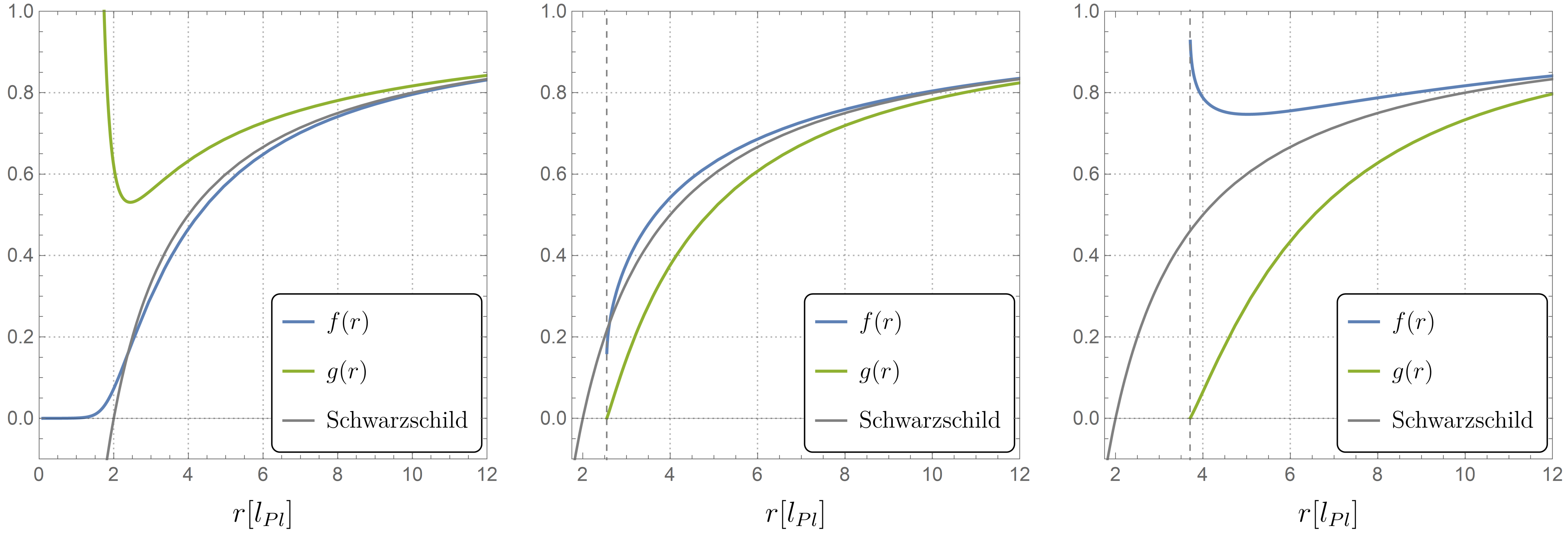
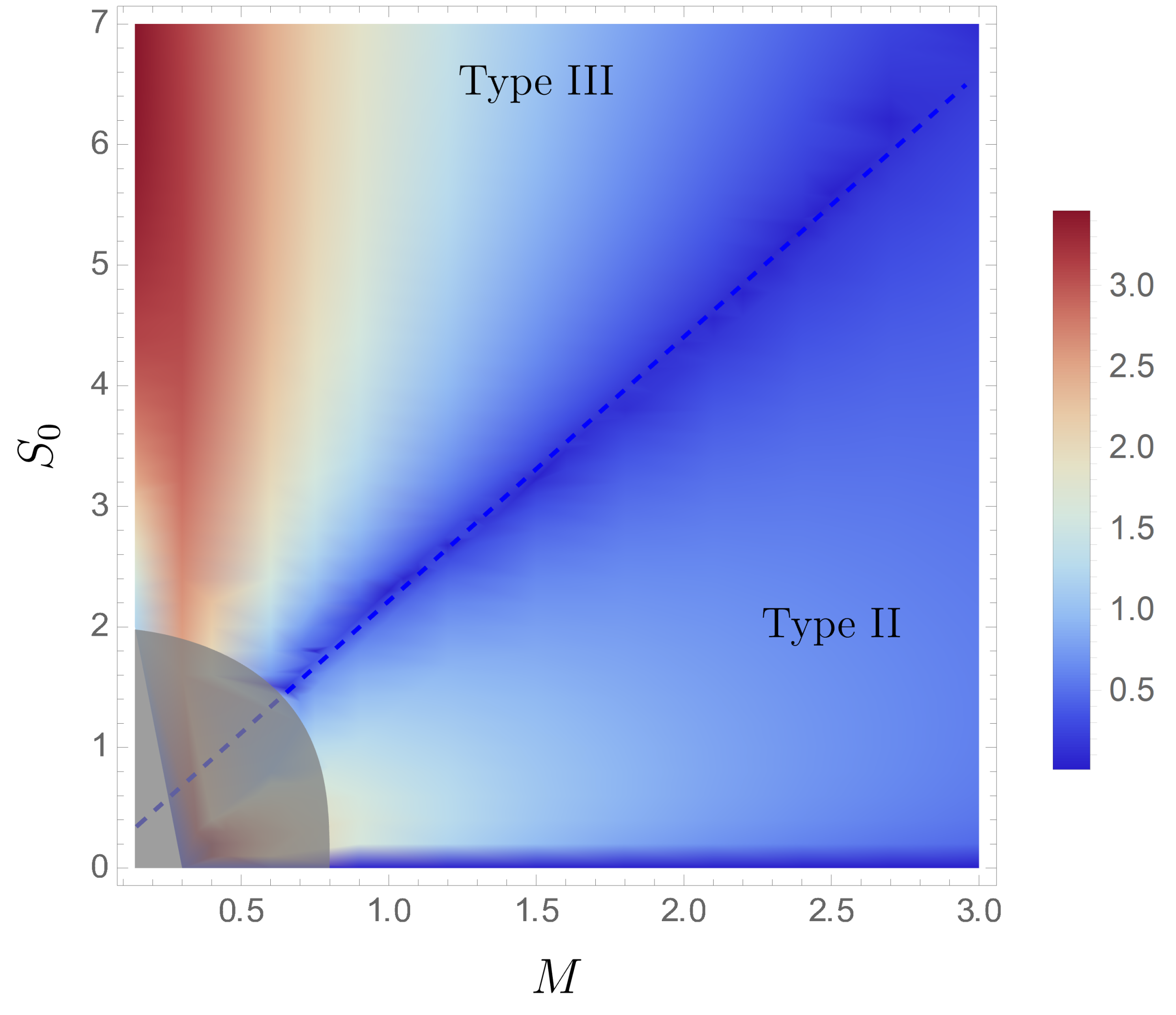


$S_0 = -1$ $\quad$ $S_0 = 1$ $\quad$ $S_0 = 4$

Phase structure



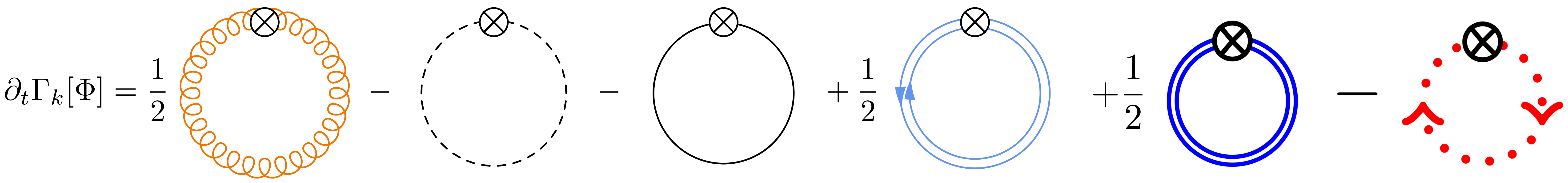
$$T = \frac{1}{4\pi}\sqrt{|f'(r_h)g'(r_h)|}$$

'Hawking temperature'

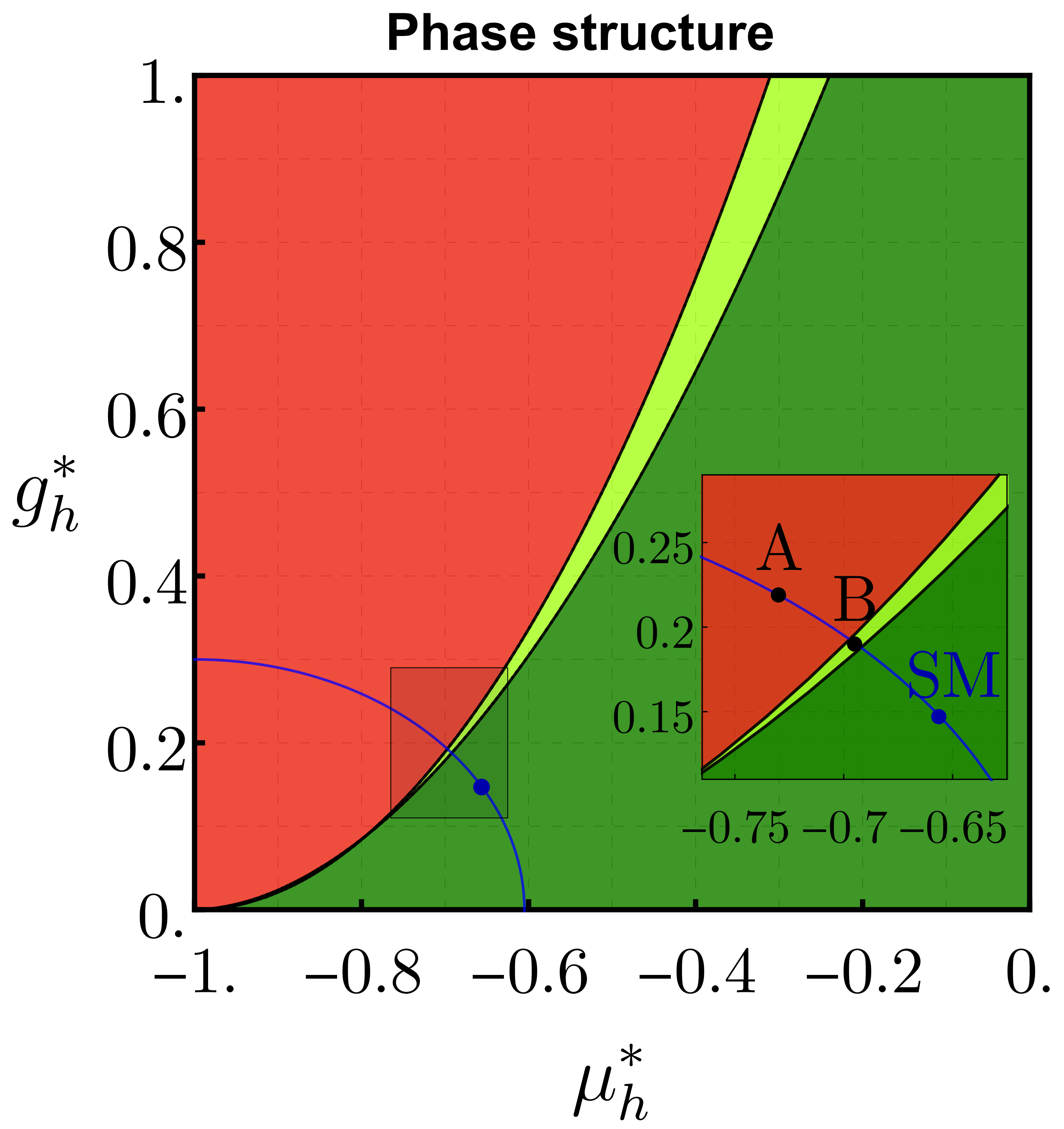
see also Borissova, Held, Afshordi, *CQuant.Grav.* 40 (2023) 7, 075011

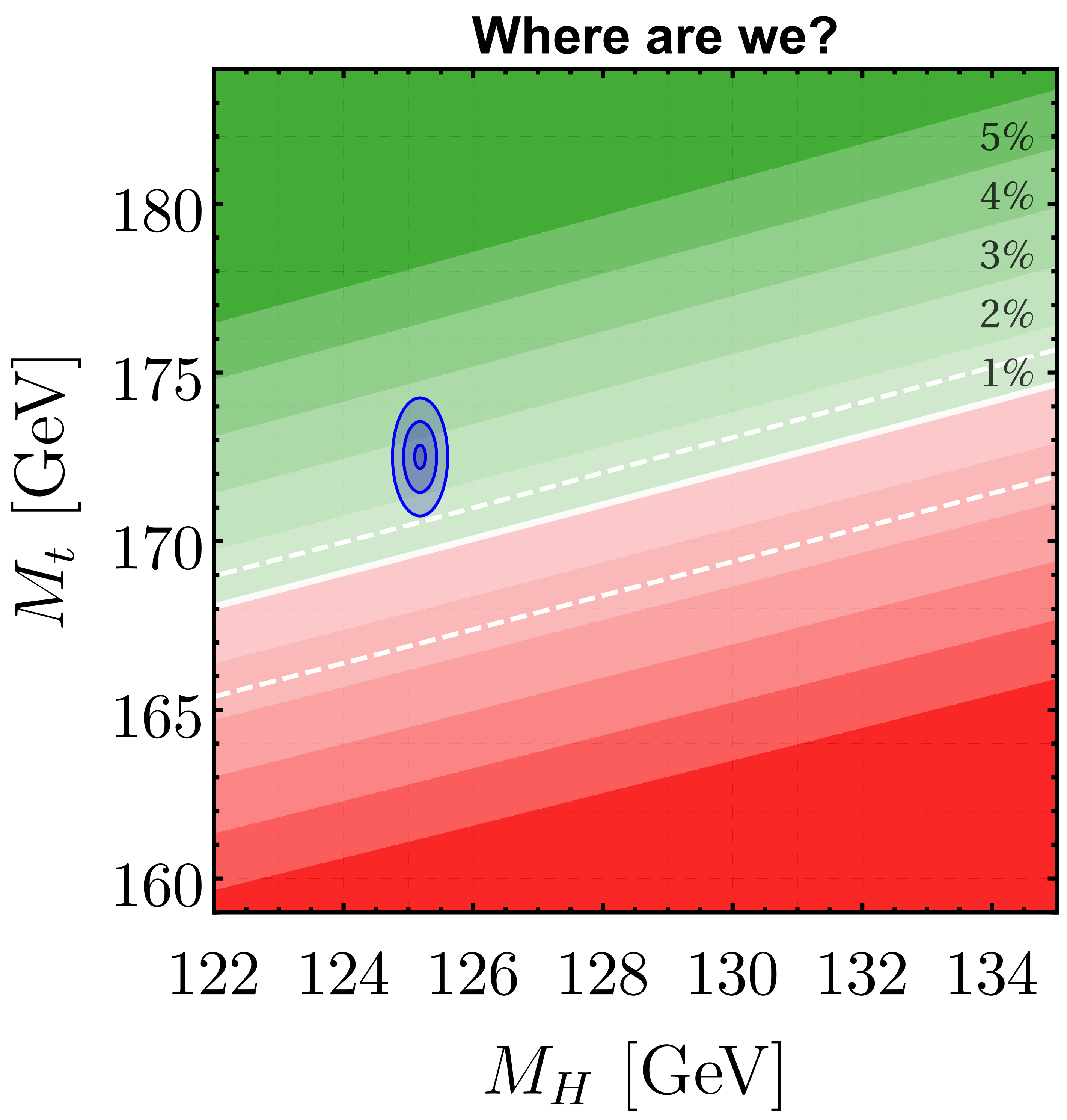
JMP, Tränkle, 2309.17043

Summary



Asymptotically safe SM





Quantum black holes