Particle physics and unitarity from asymptotically safe correlation functions

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Nordita August 12th 2024

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Outline

- Asymptotic safety

- Asymptotically safe correlation functions

- Applications I: Scattering amplitudes, spectral properties & unitarity

- Applications II: Asymptotically safe Standard Model

- Summary

Asymptotic safety

Metric g **Cosmological constant** Λ

Einstein-Hilbert action $$S[g_{\mu\nu}] = \frac{1}{16\pi G_N} \int d^4x \sqrt{-\det g_{\mu\nu}}\, [R(g_{\mu\nu}) - 2\Lambda]$$

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

Asymptotic safety

Metric g Cosmological constant Λ

Einstein-Hilbert action

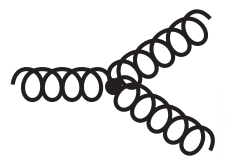
$$S[g_{\mu\nu}] = \frac{1}{16\pi G_N} \int d^4x \sqrt{-\det g_{\mu\nu}} \, [R(g_{\mu\nu}) - 2\Lambda]$$

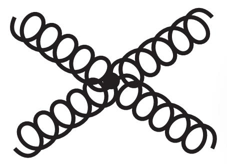
Newton constant G_N Ricci scalar $R(g)$

Momentum dimension of couplings $\dim G_N = -2$ $\dim \Lambda = 2$

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

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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

Asymptotic safety

Weinberg `79: Ultraviolet Divergences in Quantum Theories of Gravitation

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- **Standard perturbation theory**

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

Asymptotic safety

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- **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

non-perturbative example: analytic perturbation theory in QCD

Asymptotic safety

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- **Renormalisation group fixed points**

beta functions

dimensionless coupling g $\qquad \partial_t g = \beta_g(g, \mu)$

dimensionless mass parameter μ $\qquad \partial_t \mu = \beta_\mu(g, \mu)$

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

Asymptotic safety

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- Renormalisation group fixed points

	beta functions	Fixed points
dimensionless coupling g	$\partial_t g = \beta_g(g, \mu)$	$\beta_g(g^*, \mu^*) = 0$
dimensionless mass parameter μ	$\partial_t \mu = \beta_\mu(g, \mu)$	$\beta_\mu(g^*, \mu^*) = 0$

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

quantum gravity

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

dimensional running (→ 2)

quantum fluctuations (→ η_N)

Asymptotic safety

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

- **Renormalisation group fixed points**

beta functions

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

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

Fixed points

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

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Asymptotic safety

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

- **Ultraviolet running**

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

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

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

- **Renormalisation group fixed points**

beta functions

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

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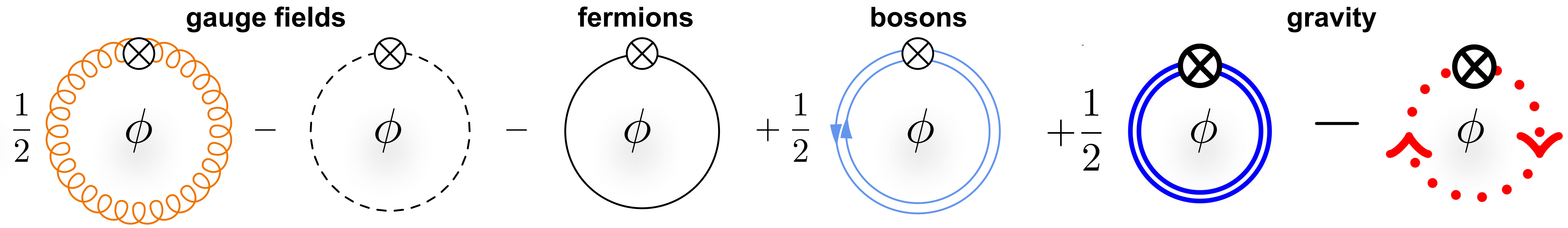
Computing the effective action

Common approach: the functional renormalisation group

Diagrammatic approach with gauge fixing

Effective action/free energy

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



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

Fluctuation fields $\phi = (\phi_{\text{grav}} \, , \, \phi_{\text{mat}})$

Computing the effective action

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Diagrammatic approach with gauge fixing

Pure Gravity: $\phi_{\text{grav}} = (h_{\mu\nu}\,,\, c_\mu, \bar{c}_\mu)$

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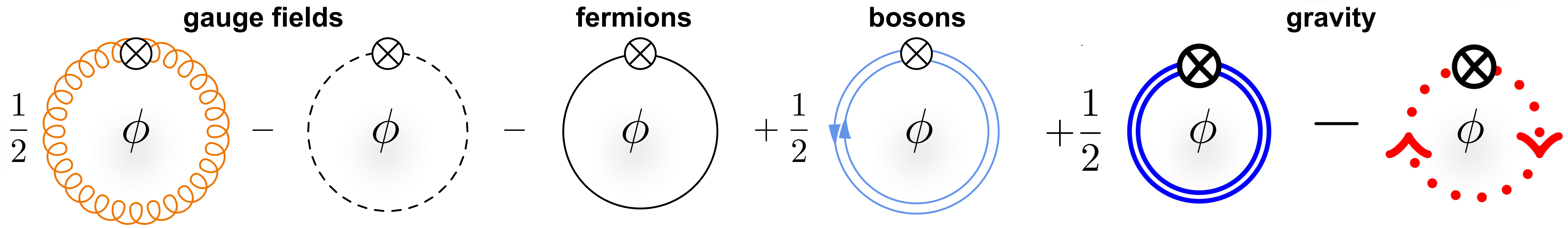

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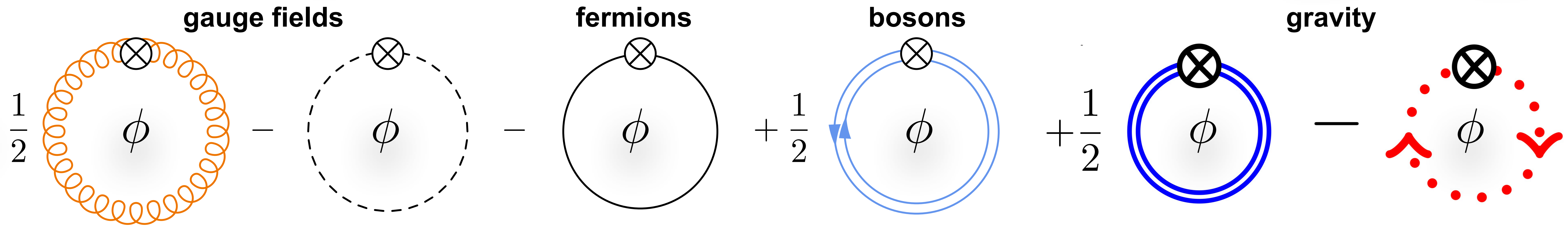

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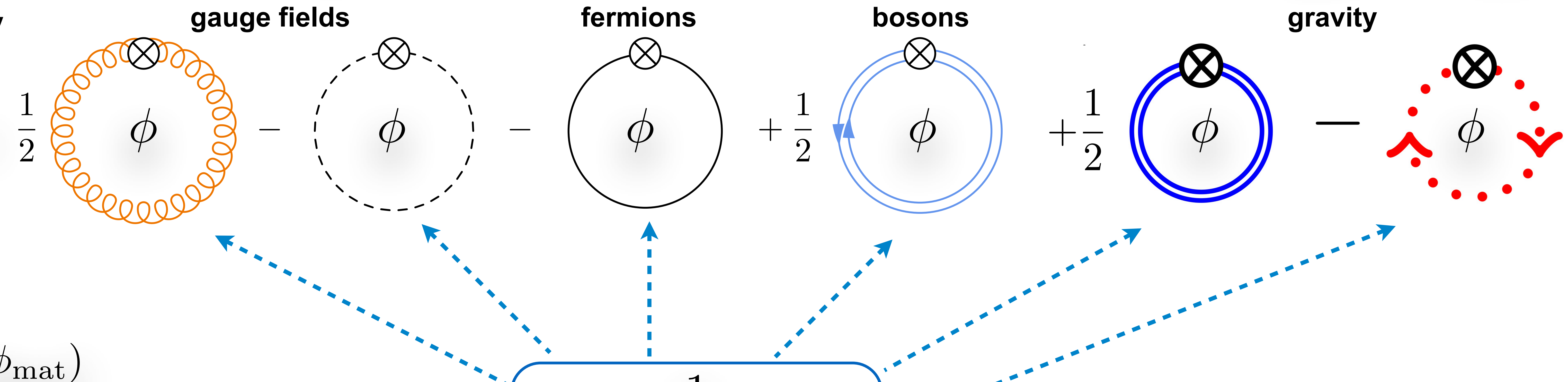

$$\frac{1}{\frac{\delta^2\Gamma}{\delta\phi^2}[\bar{g}, \phi] + R_k}$$

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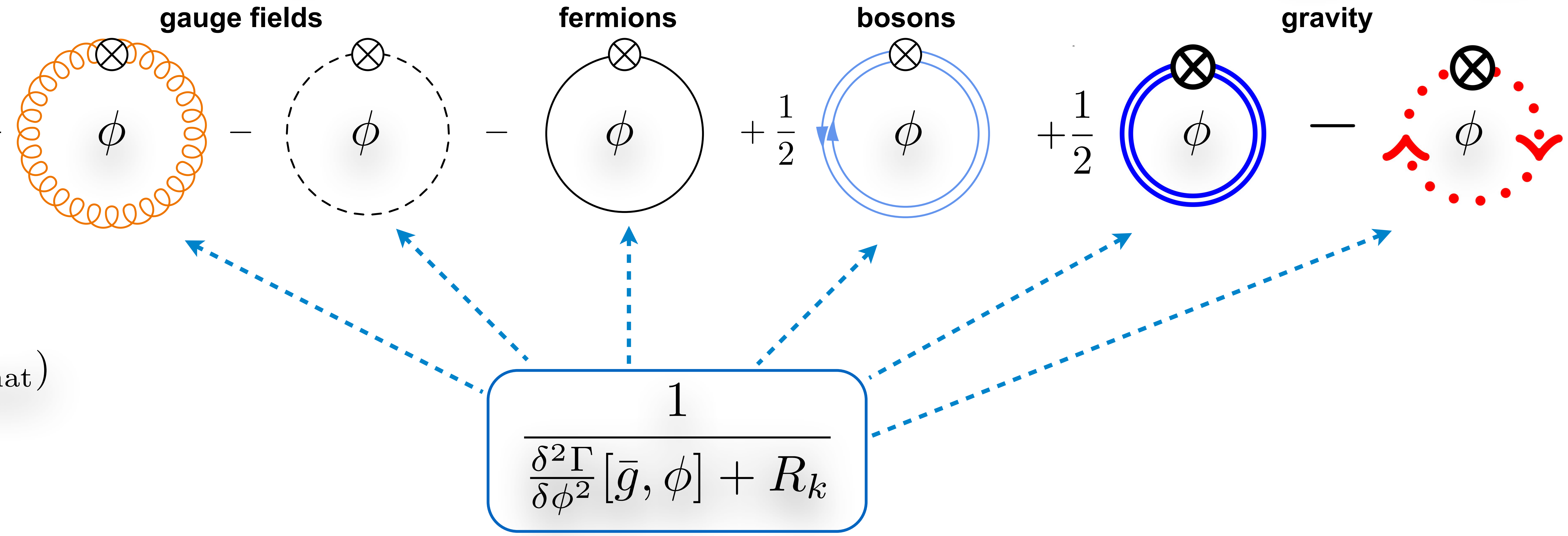

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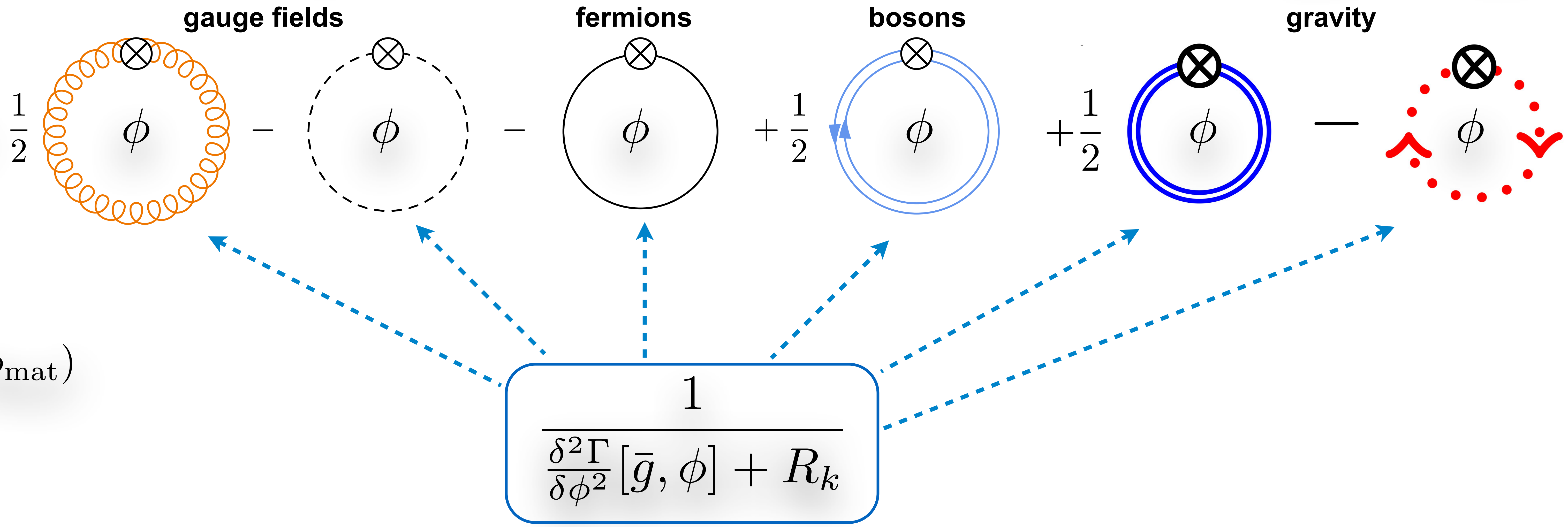

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Manifestly background independent effective action

Asymptotically safe observables

How to?

diffeomorphism invariant

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

Ricci scalar correlations

not diffeomorphism invariant

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

metric correlations

metric

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

background metric **fluctuation**

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Equations of motion ↑ **& derivatives**

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Gauge-fixed effective action $\Gamma[\bar{g}_{\mu\nu}, h_{\mu\nu}]$

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metric correlations

Reconstruction/unfolding

Reconstructing & unfolding, recent works:

Knorr, Saueressig, PRL 121 (2018) 161304

Fraaije, Platania, Saueressig, 834 (2022) 137399

JMP, Tränkle, 2309.17043

Asymptotically safe correlation functions

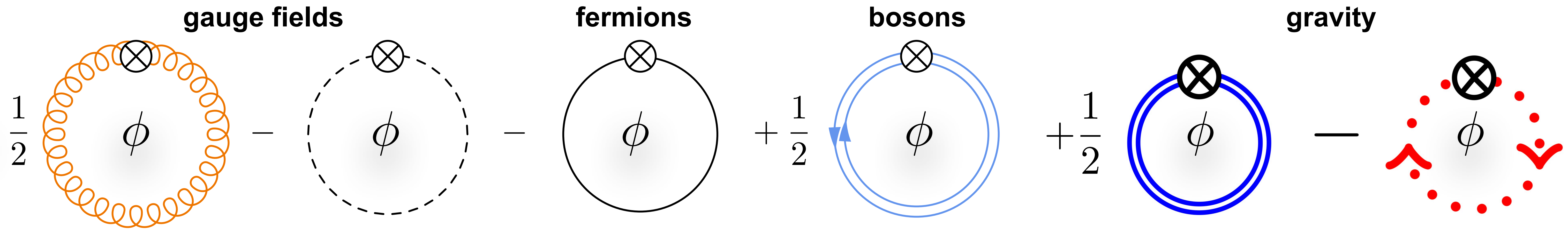
JMP, Reichert, Front.in Phys. 8 (2021) 527

2309.10785

Computing the effective action

Effective action/free energy

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



Computing the effective action

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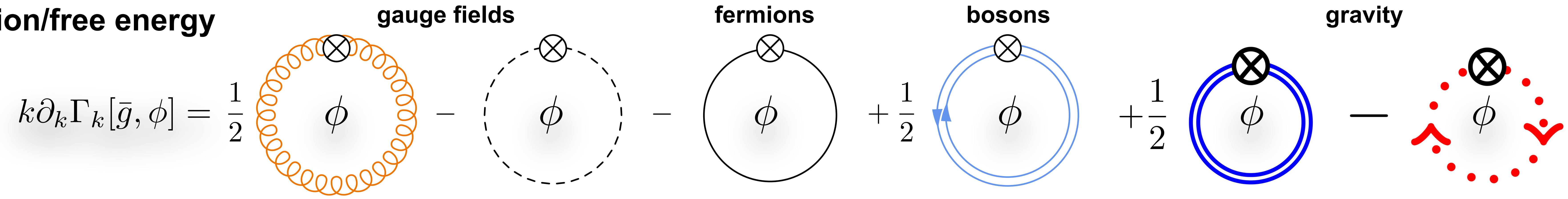

Loop: $\mathrm{Tr}\, f(\nabla_g, R, R_{\mu\nu}, ...; \partial, \phi, ...)$

Computing the effective action

Effective action/free energy

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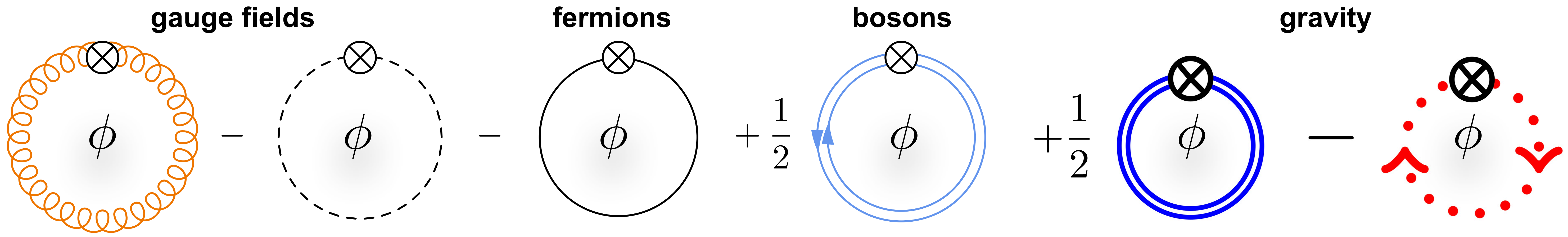

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Fluctuation approach

Background approximation

Computing the effective action

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Fluctuation approach

Background approximation

Compute $$\left.\frac{\delta^{n+m}\Gamma[\bar{g}, h]}{\delta h^n \delta\phi^m}\right|_{\phi=0} = f_n(\bar{\nabla}, \bar{R}, \bar{R}_{\mu\nu}, ...)$$

in a given background $\bar{g}$

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$\bar g$ **flat:** $f_n(\bar\nabla, \bar R, \bar R_{\mu\nu}, ...) \to f_n(p) = f_n(p, 0, 0, ...)$

Compute ‘standard’ momentum loops’

Background approximation

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Those are my backgrounds (principles),
and if you don't like them…well I have others

Covariantly constant backgrounds: Christiansen, Falls, JMP, Reichert, PRD 97 (2018) 046007

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Compute loops at vanishing fluctuation field $\bar{g} = g$

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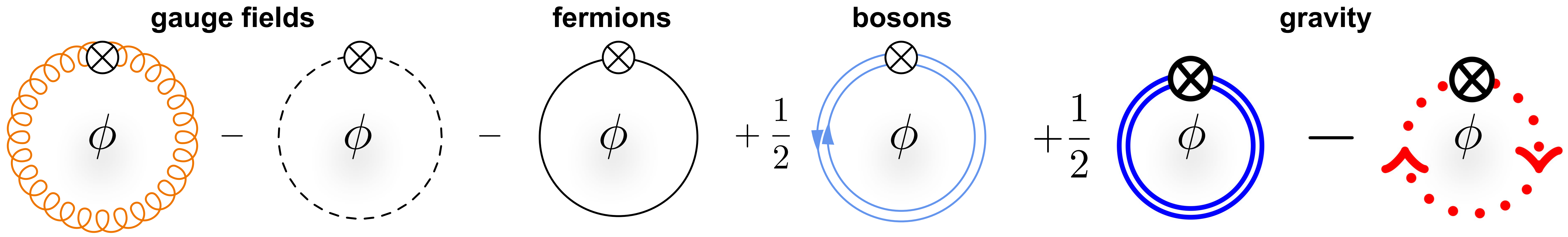
Heat kernel techniques with covariantly constant backgrounds

Background (in)dependence in gravity

aka
background and fluctuations fields, modified STIs and their importance

free energy

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



Linear split

$$g = \bar g + h$$

Effective action

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

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

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

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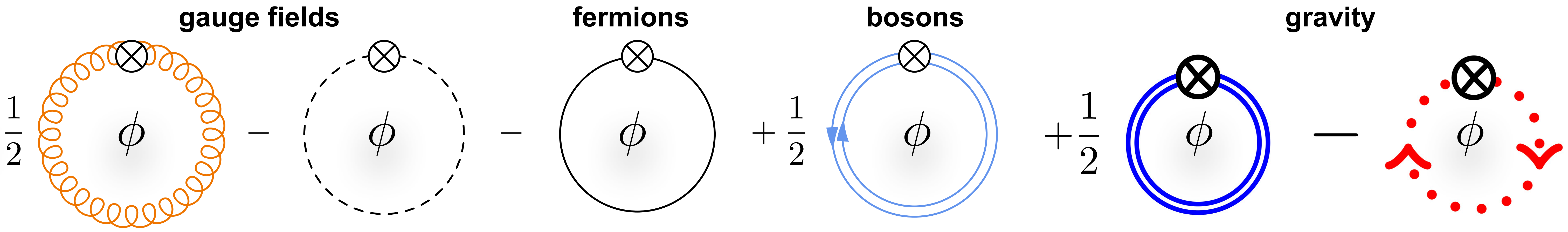

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$$\left\{ \Gamma_k[\bar g]\,,\, \Gamma_k^{(0,1)}[\bar g]\,,\, \Gamma_k^{(0,2)}[\bar g]\,,\, \Gamma_k^{(0,3)}[\bar g]\,,\, \ldots \right\}$$

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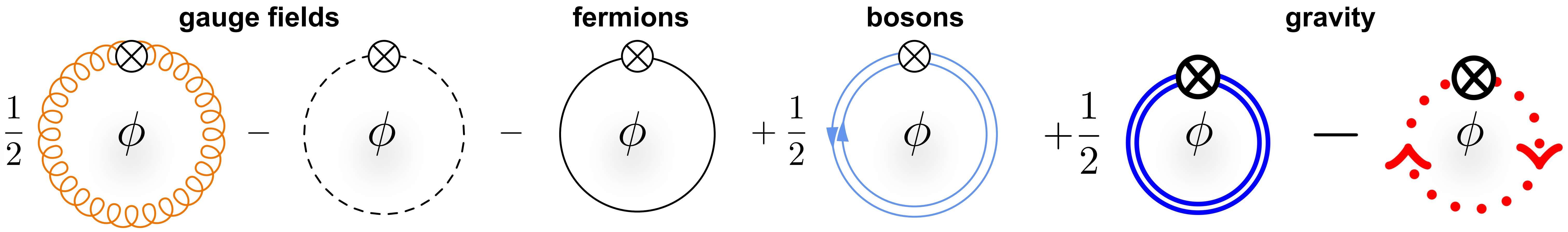

Linear split

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Effective action

background & gauge dependent

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

background independent

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

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

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

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

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Effective action

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

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

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

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

Il Gattopardo

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

From vertex dressings/distribution functions to physics

aka
form factors

Effective action

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gauge dependent

How much do they differ?

Background effective action

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

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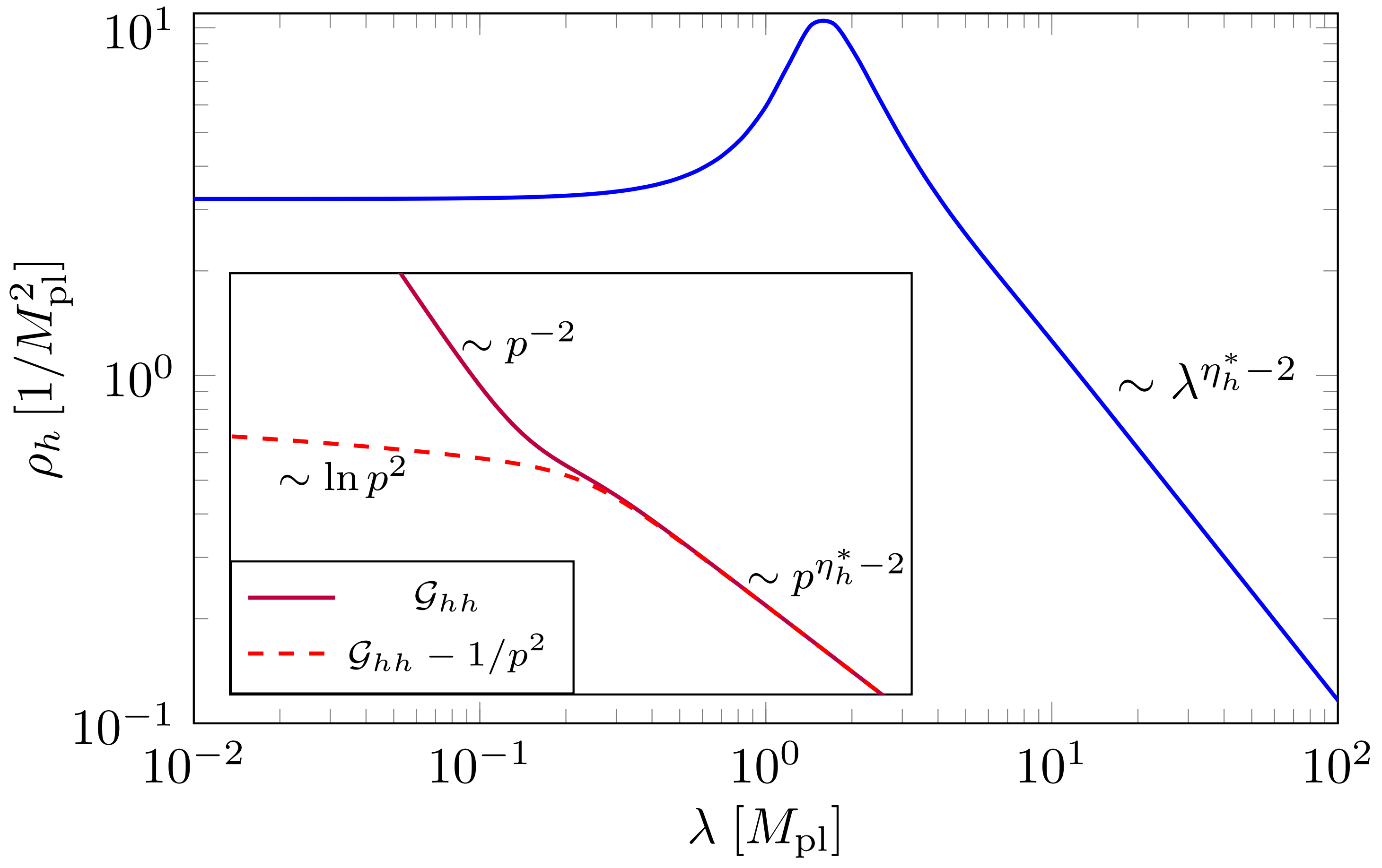
Sneak preview: a lesson from graviton spectral functions in a flat background

Spectral function of the fluctuating graviton



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

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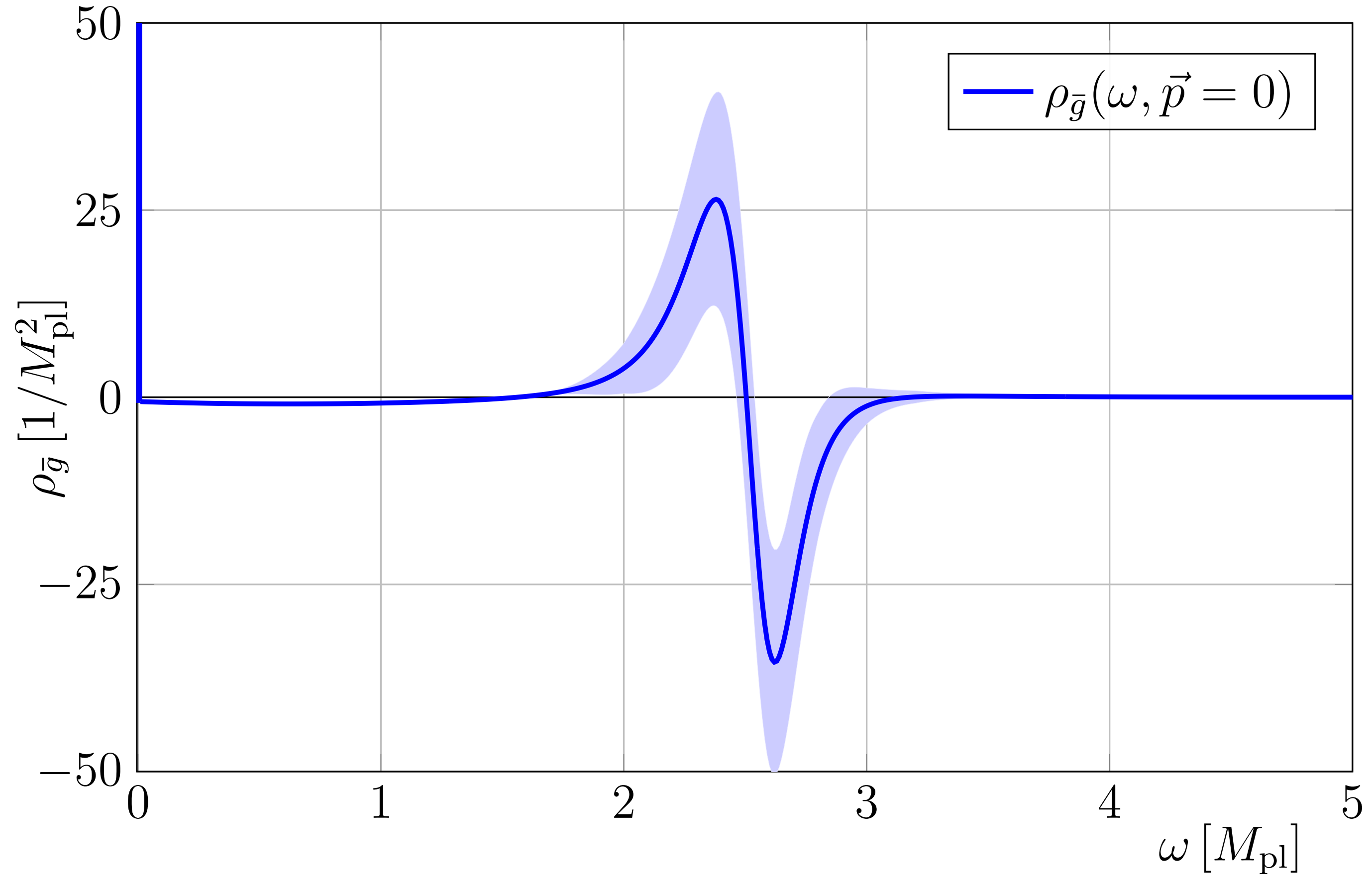

Bonanno, Denz, JMP, Reichert, *SciPost Phys.* 12 (2022) 1, 001

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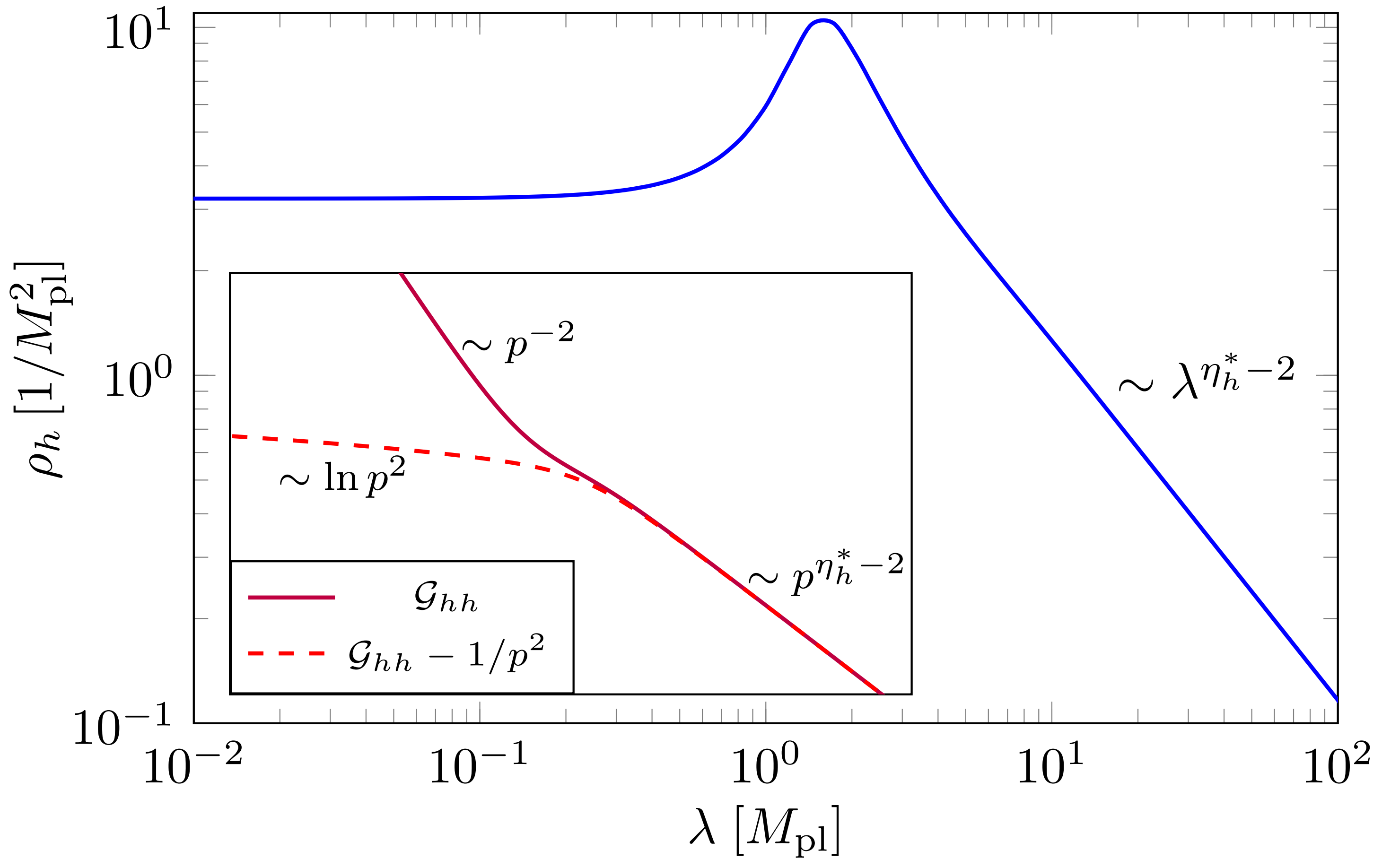

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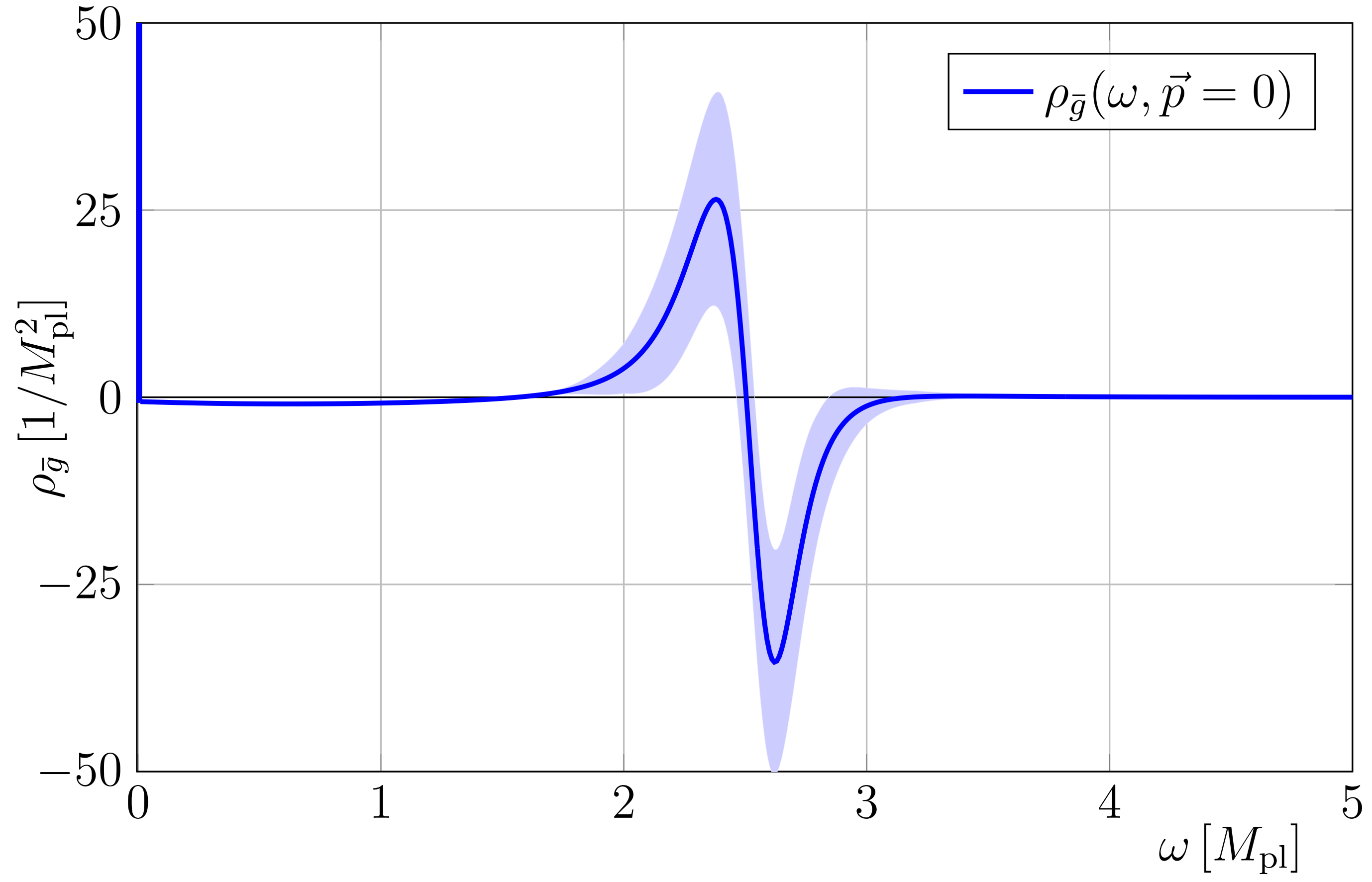

Bonanno, Denz, JMP, Reichert, *SciPost Phys.* 12 (2022) 1, 001

Spectral properties 'resemble' that of an asymptotic state

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

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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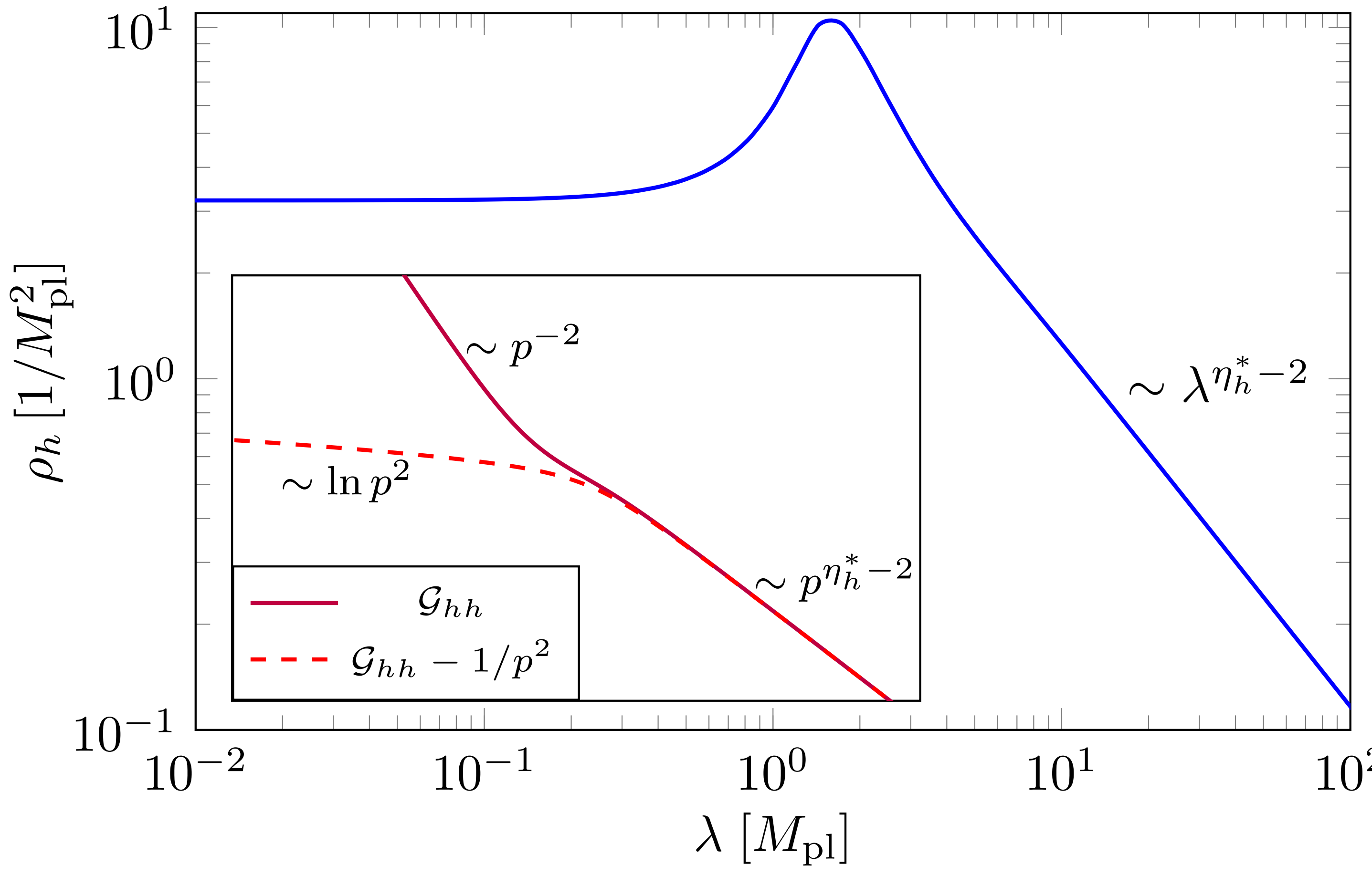
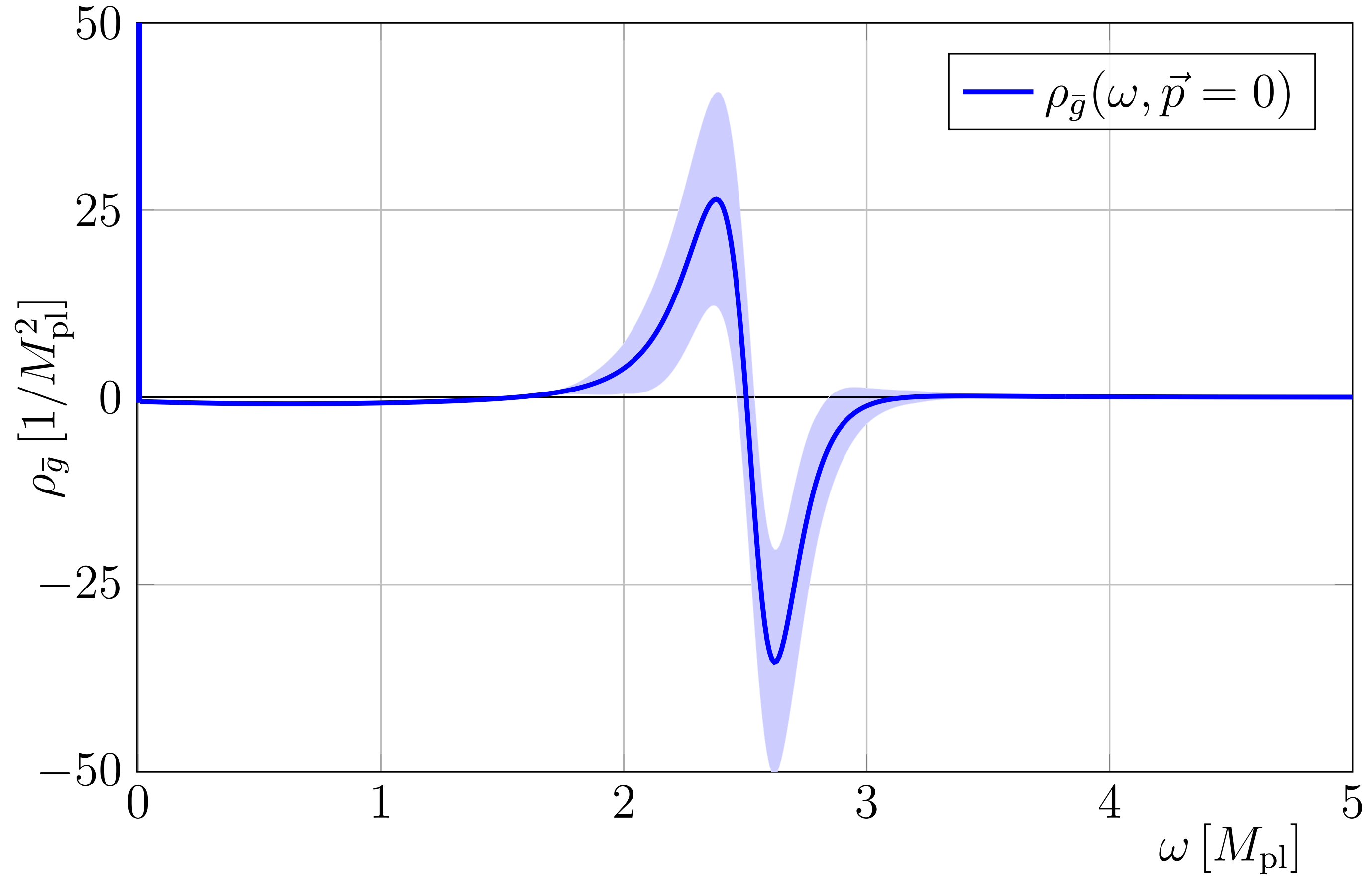


Fehre, Litim, JMP, Reichert, PRL 130 (2023) 081501

much !

Spectral function of the background graviton



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Il Gattopardo

JMP, Reichert, Front.in Phys. 8 (2021) 527
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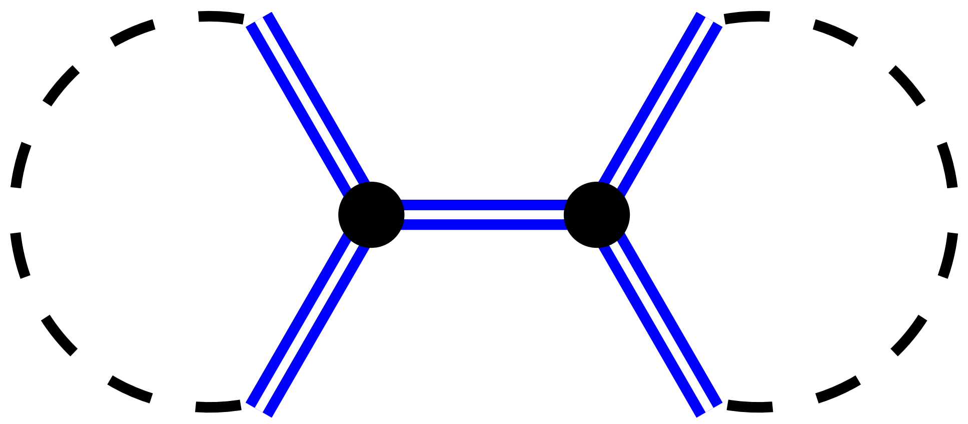
Scattering amplitudes and cross sections

Example: graviton-graviton scattering in a flat background



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

JMP, Reichert, Front.in Phys. 8 (2021) 527
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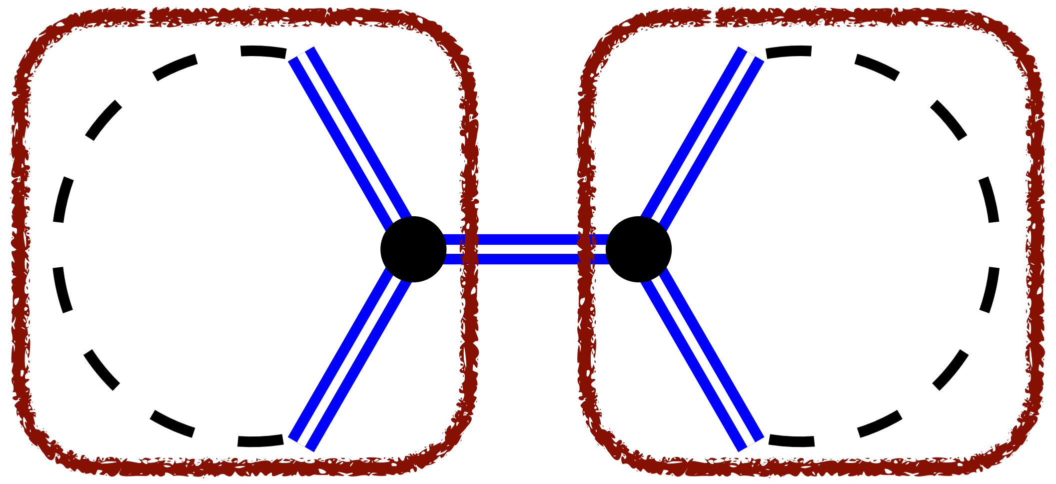
RG-invariant vertex

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

aka
RG-invariant coupling
/form factor



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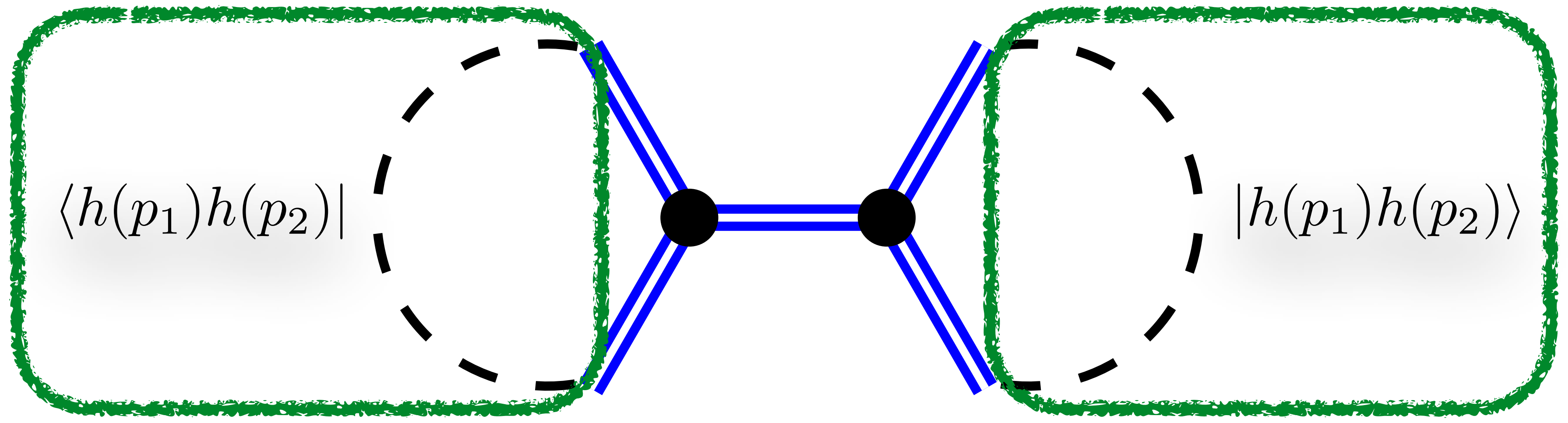

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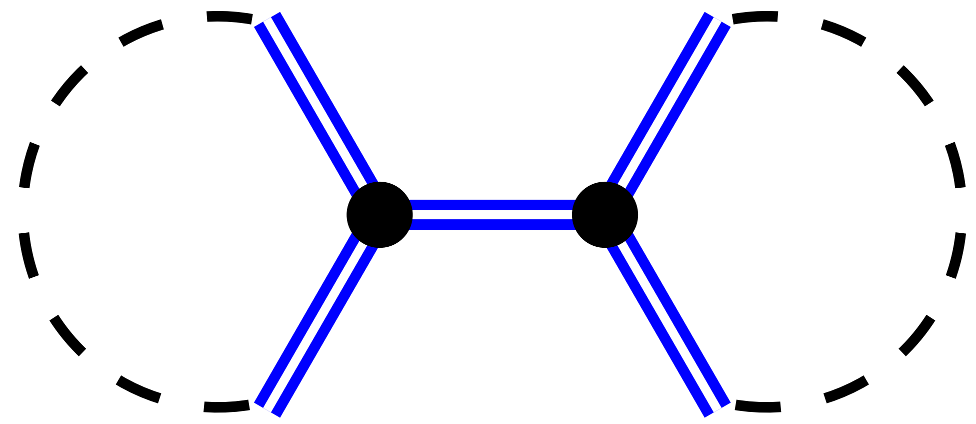

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/form factor

Fluctuation approach: 2012 ...

Knorr, Reichert, ...

Form factor approach: 2018 ...

Knorr, Ripken, Saueressig, ...

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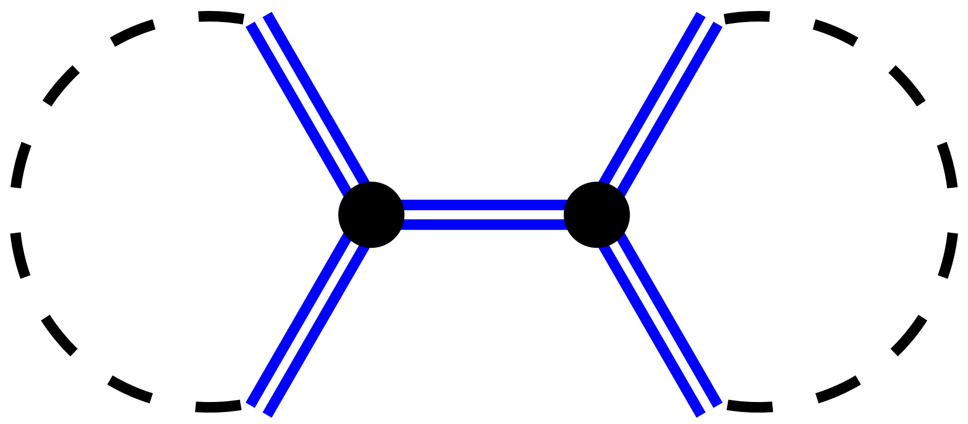

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/form factor

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
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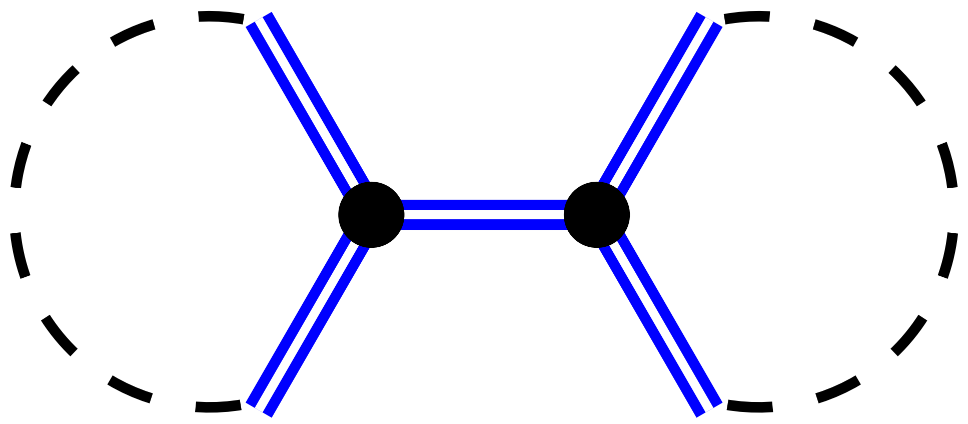

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'Bare' propagator

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

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

$$\int_{\mathbb{R}} \frac{d\lambda}{2\pi}\,\lambda\bar{\rho}(\lambda) = 1$$

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

Unfolding the background independent effective action

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

Revisited

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

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Revisited

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

JMP, Tränkle, 2309.17043

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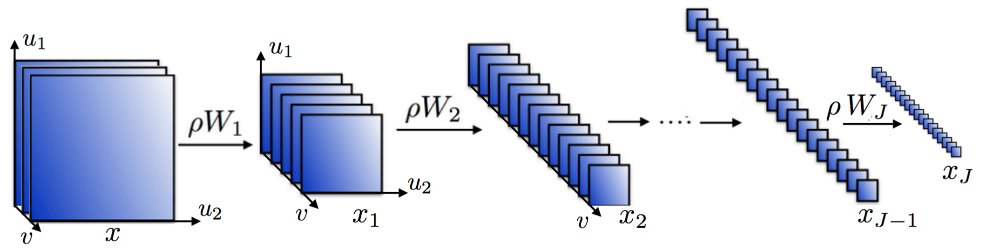
Revisited

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



JMP, Tränkle, 2309.17043

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Revisited

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

Unfolding

Maps

So far educated guess

JMP, Tränkle, 2309.17043

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

Revisited

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

So far educated guess

Future: Physics-informed RG flows

Ihssen, JMP, in preparation

JMP, Tränkle, 2309.17043

Unfolding the background independent effective action

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

Revisited

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

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

Maps

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

So far educated guess

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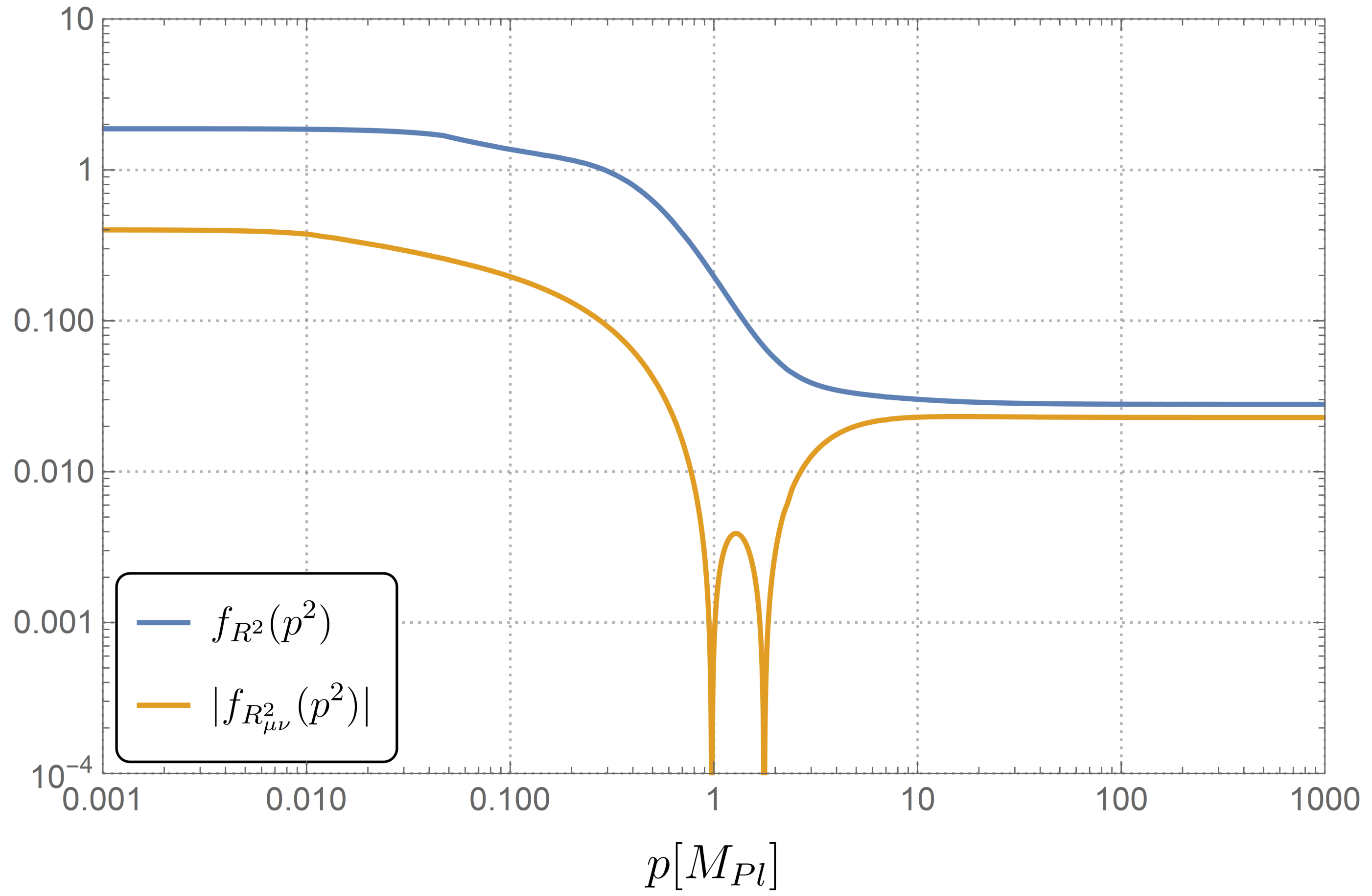


Results for form factors

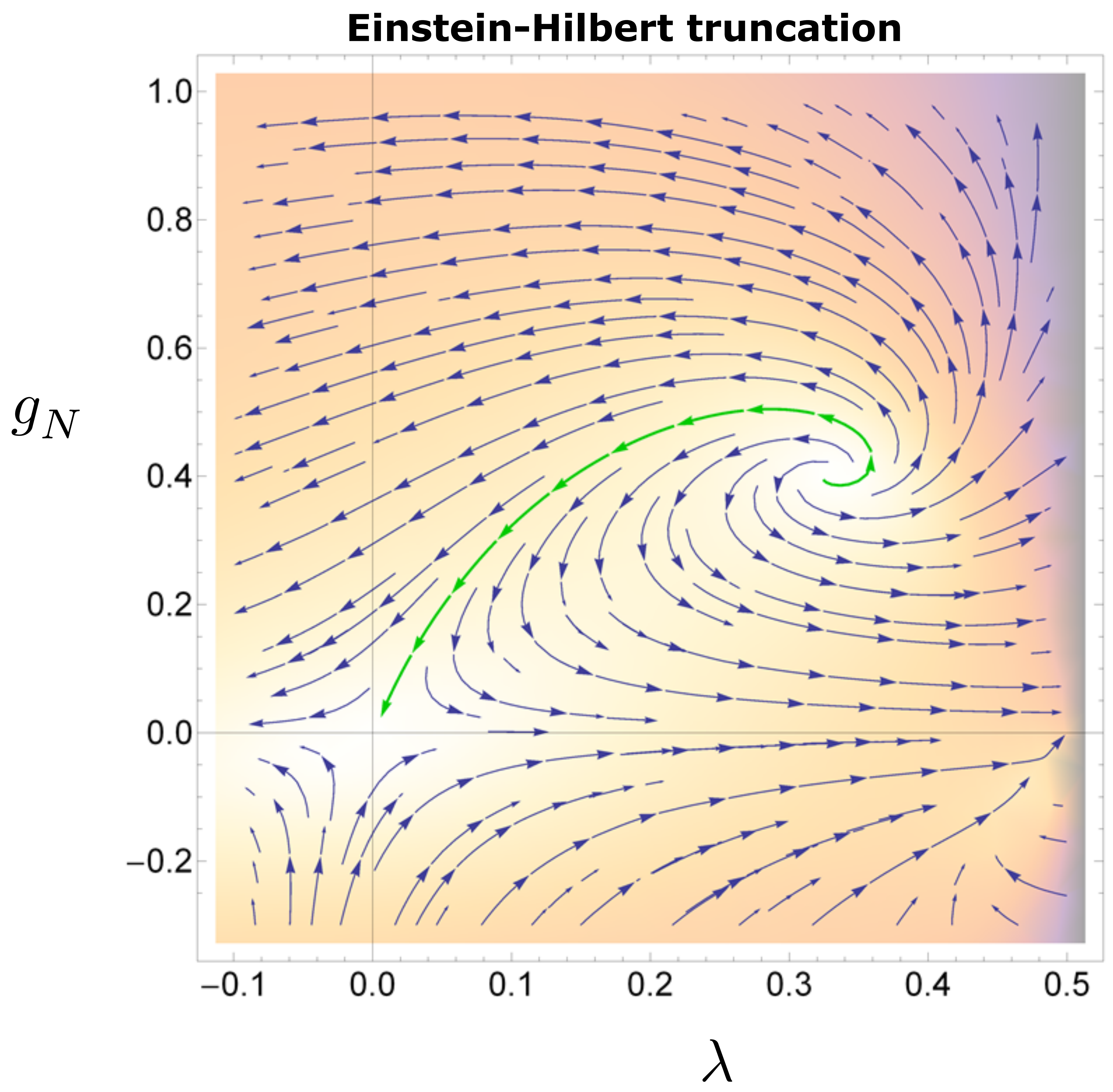
$$\mathcal{R}(\Delta, R) = R\,\frac{\gamma^{(3)}_g(\Delta) - \bar\gamma_3\Delta}{\Delta + R}\,R$$

JMP, Tränkle, 2309.17043

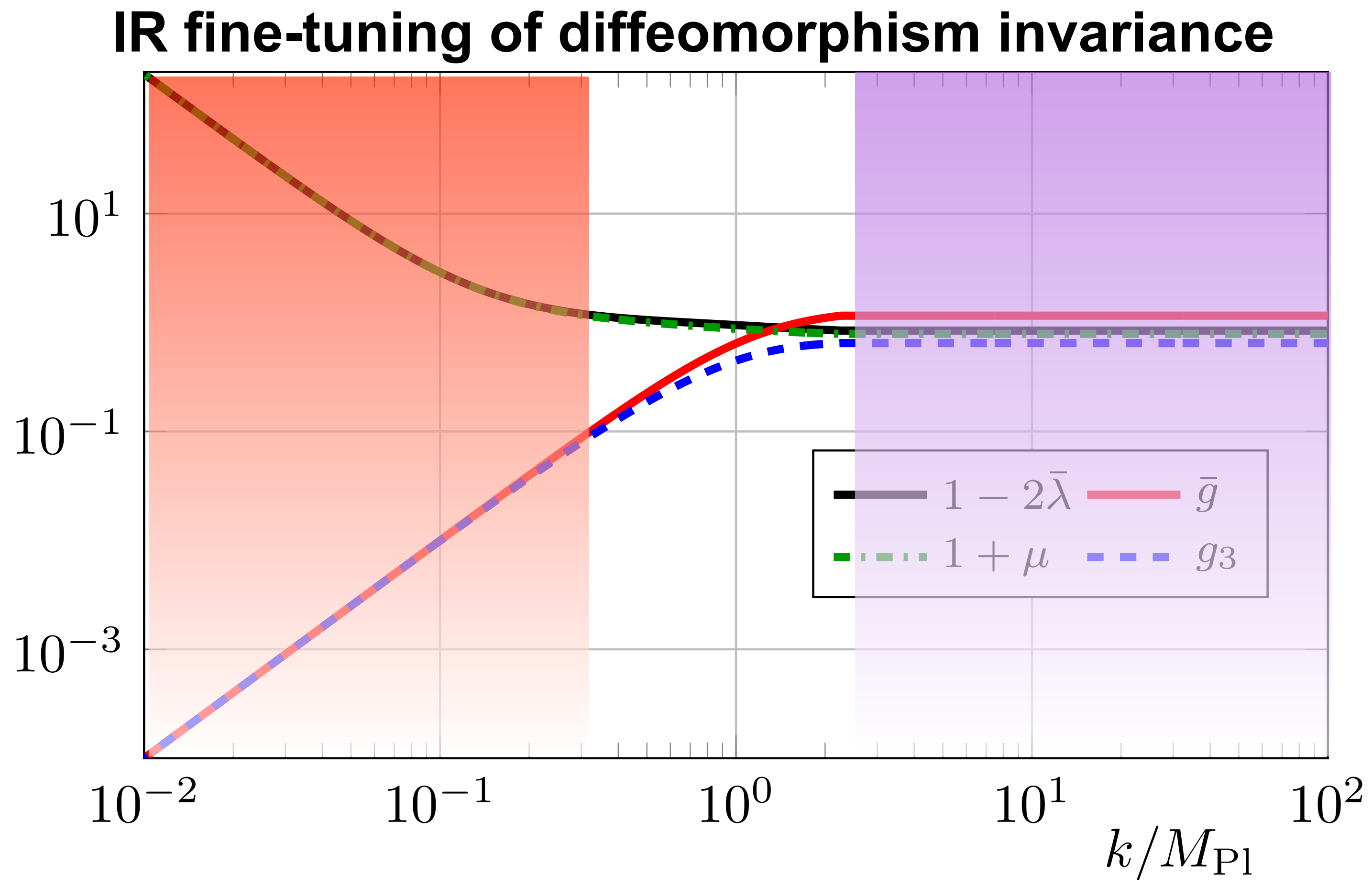
Apparent convergence in asymptotic safety

a community effort

Phase structure of asymptotically safe gravity



Reuter, Saueressig, PRD 65 (2002) 065016



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

classical general relativity

asymptotically save fixed point scaling

Reuter '96

⋮

Towards apparent convergence in quantum gravity I

expansion in curvature invariants

Quantum Effective Action: $\Gamma[g] = \sum_n c_{n,k} \int d^4x \sqrt{g}\, \mathcal{O}_n(g)$

$\mathcal{O}_n$

$\Lambda\,, R$ — **Reuter, PRD 57 (1998) 971**

$\Lambda\,, R\,, R^2$ — **Lauscher, Reuter, PRD 66 (2002) 025026**

$\Lambda\,, f(R)$ — **Codello, Percacci, Rahmede, AP 324 (2009) 414, Falls, Litim, Nikolakopoulos, Rahmede, arXiv:1301.4191, PRD 93 (2016) 10, 104022**

$\Lambda\,, R\,, C^{\mu\nu\kappa\lambda}C^{\kappa\lambda\rho\sigma}C^{\rho\sigma\mu\nu}$ — **Gies, Knorr, Lippoldt, Saueressig, PRL 116 (2016) 21, 211302**

Towards apparent convergence in quantum gravity I

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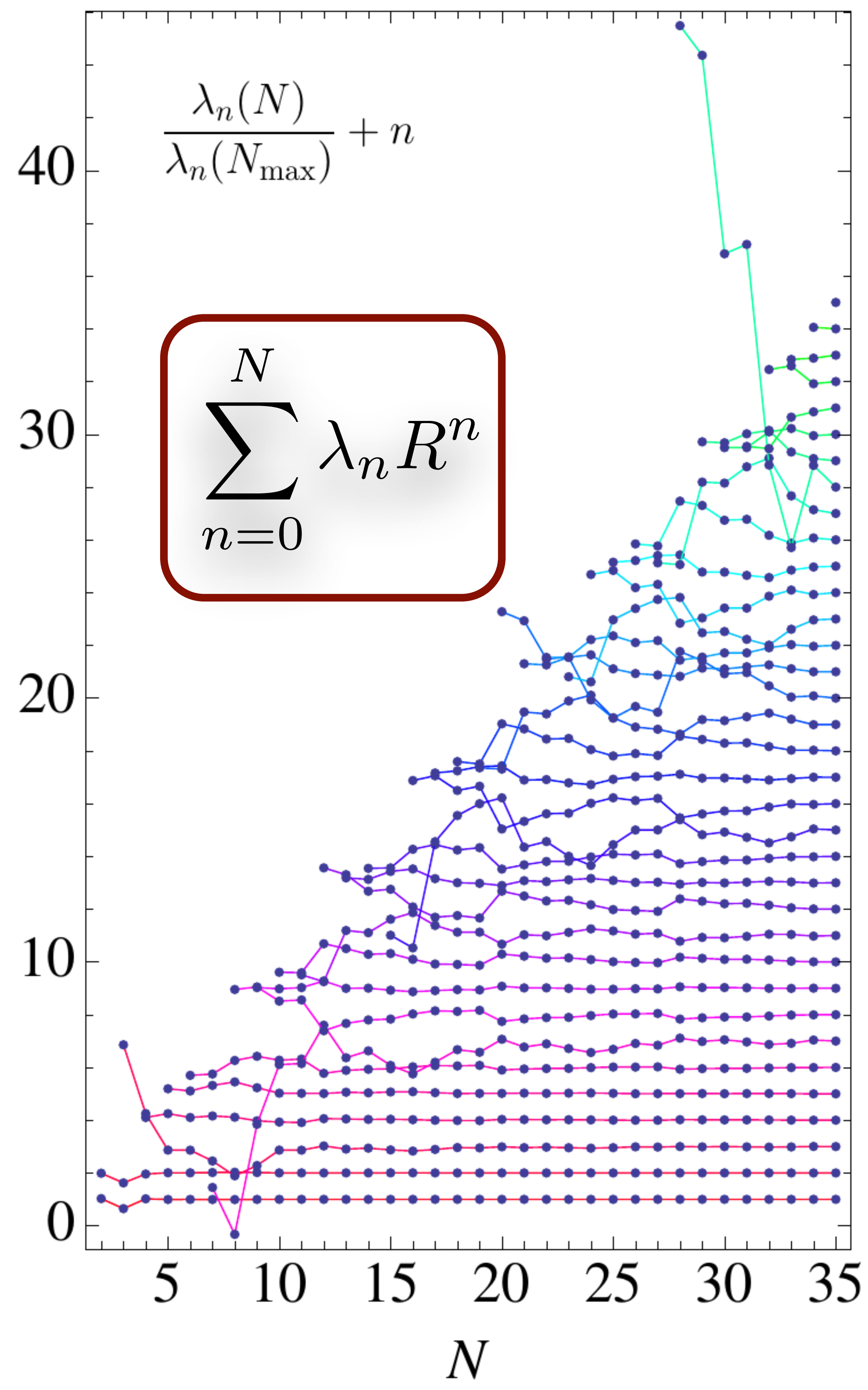
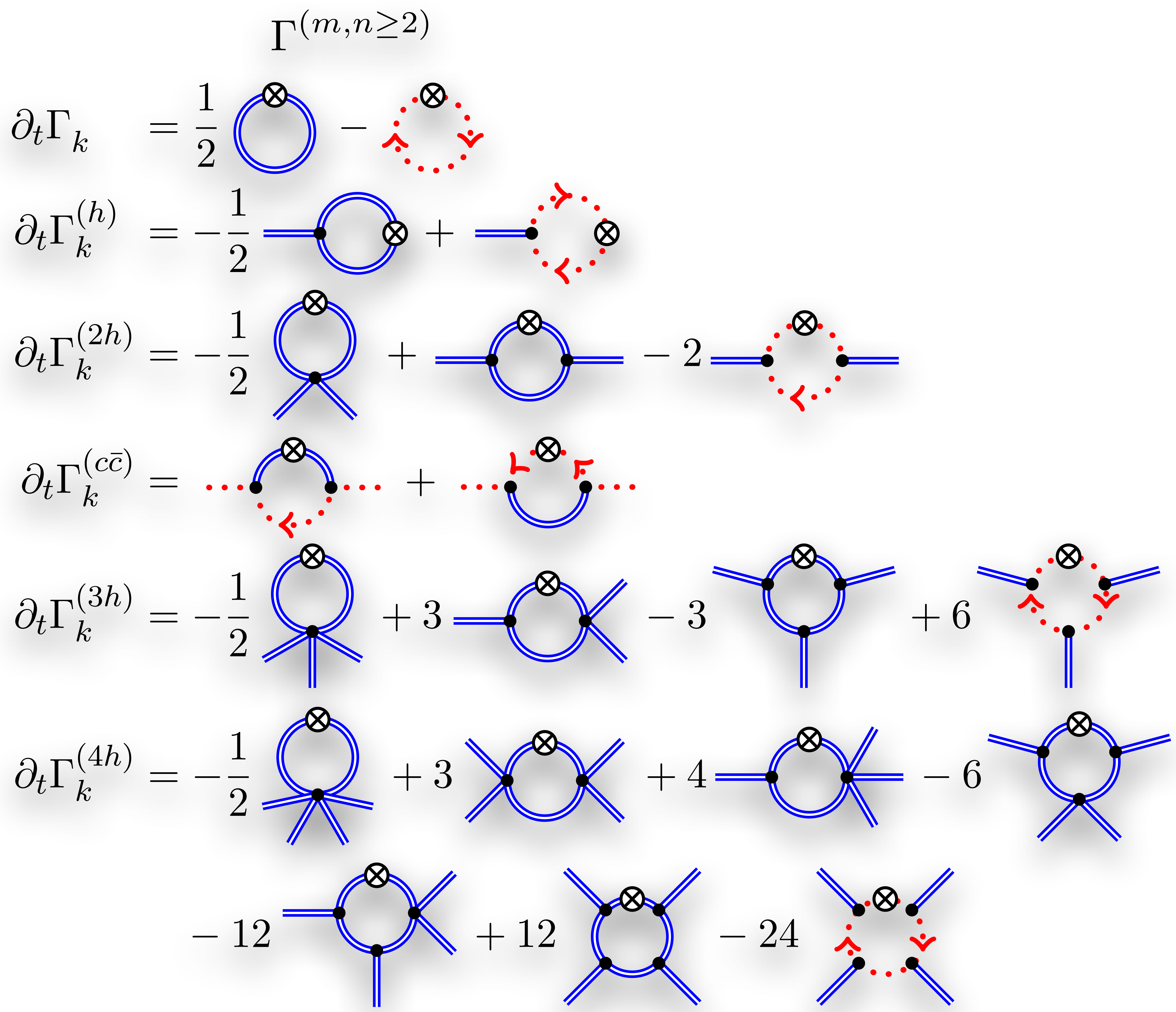


Falls, Litim, Nikolakopoulos, Rahmede, PRD 93 (2016) 10, 104022

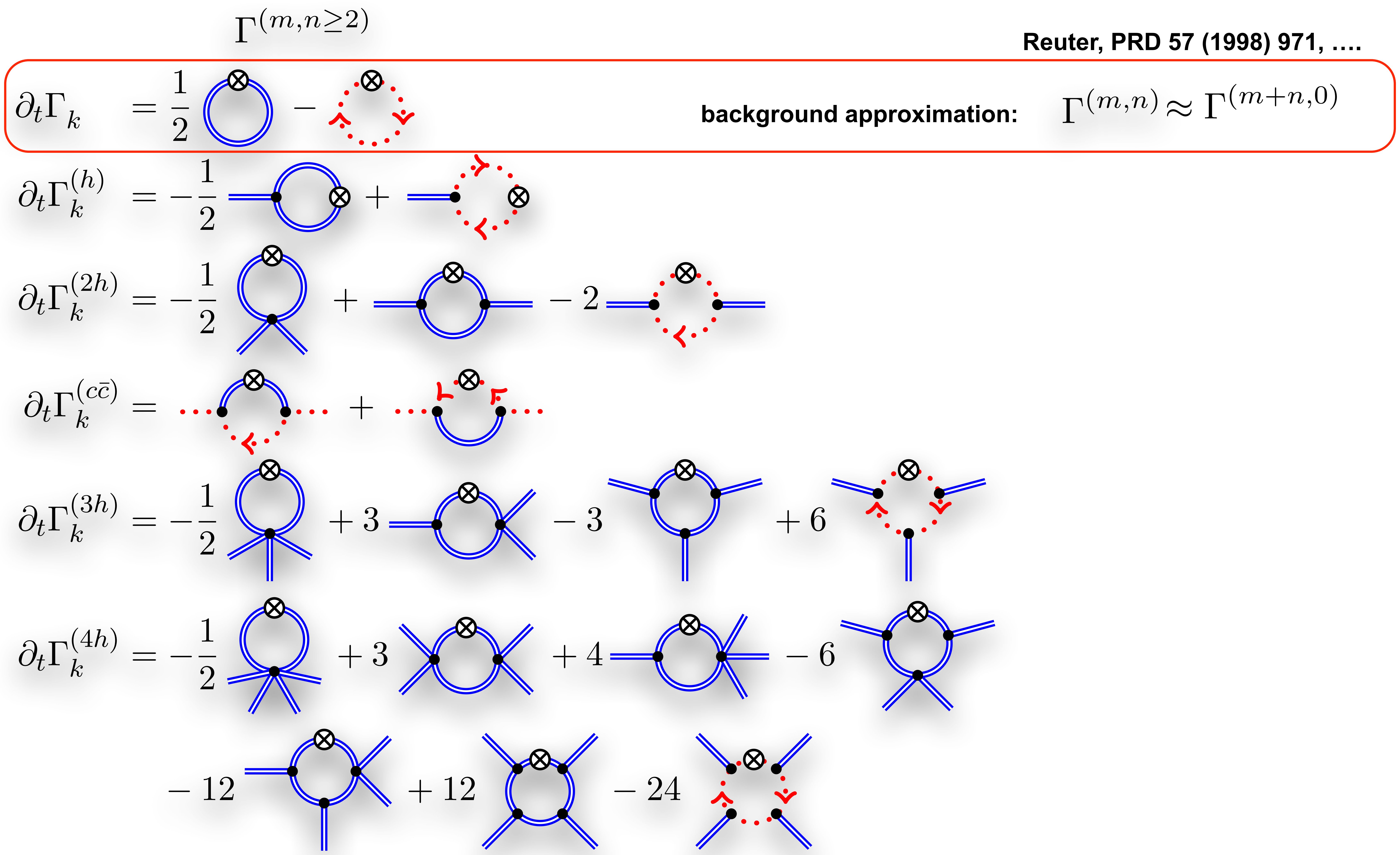
Towards apparent convergence in quantum gravity II

vertex expansion



Towards apparent convergence in quantum gravity II

vertex expansion



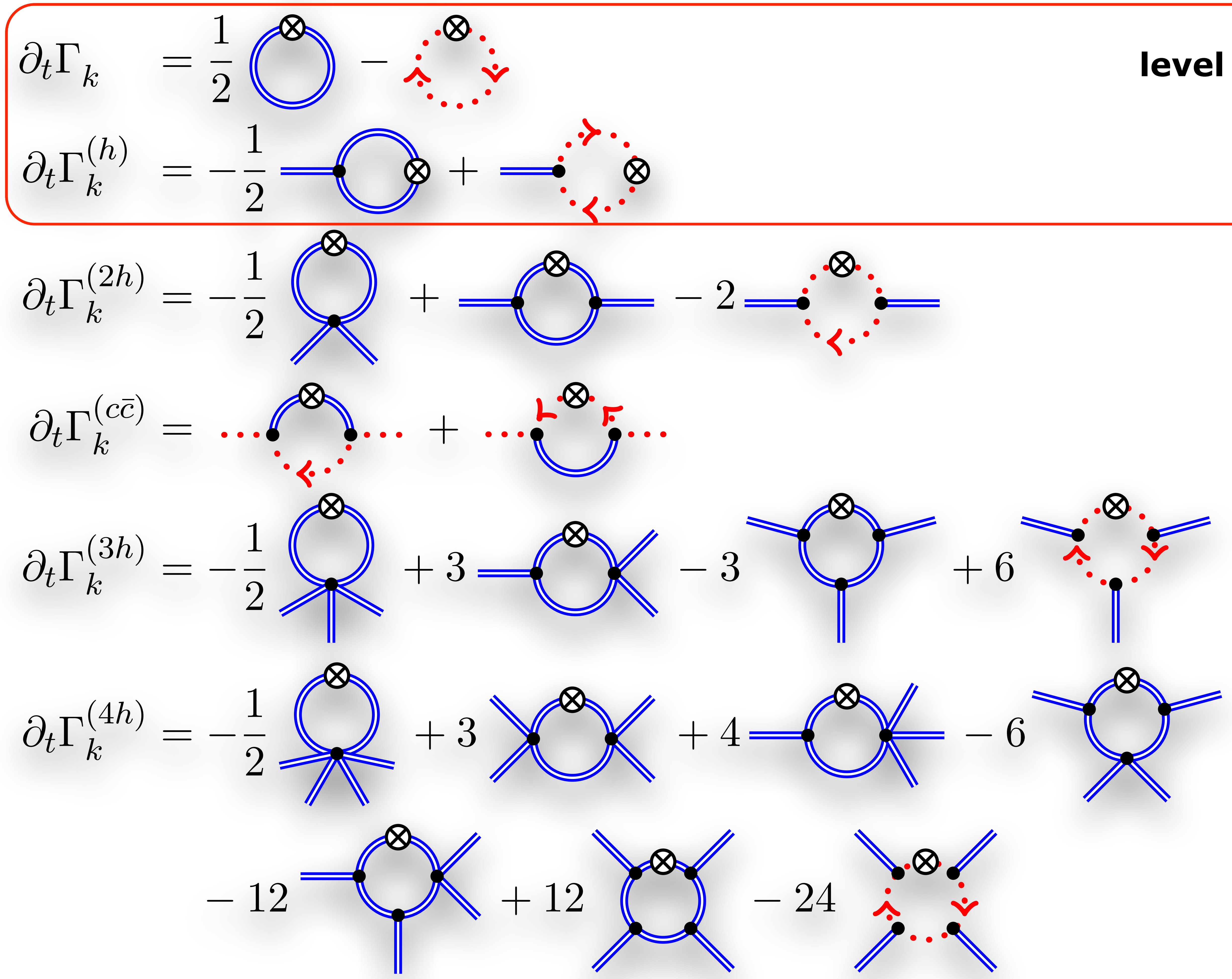
Towards apparent convergence in quantum gravity II

vertex expansion

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

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

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



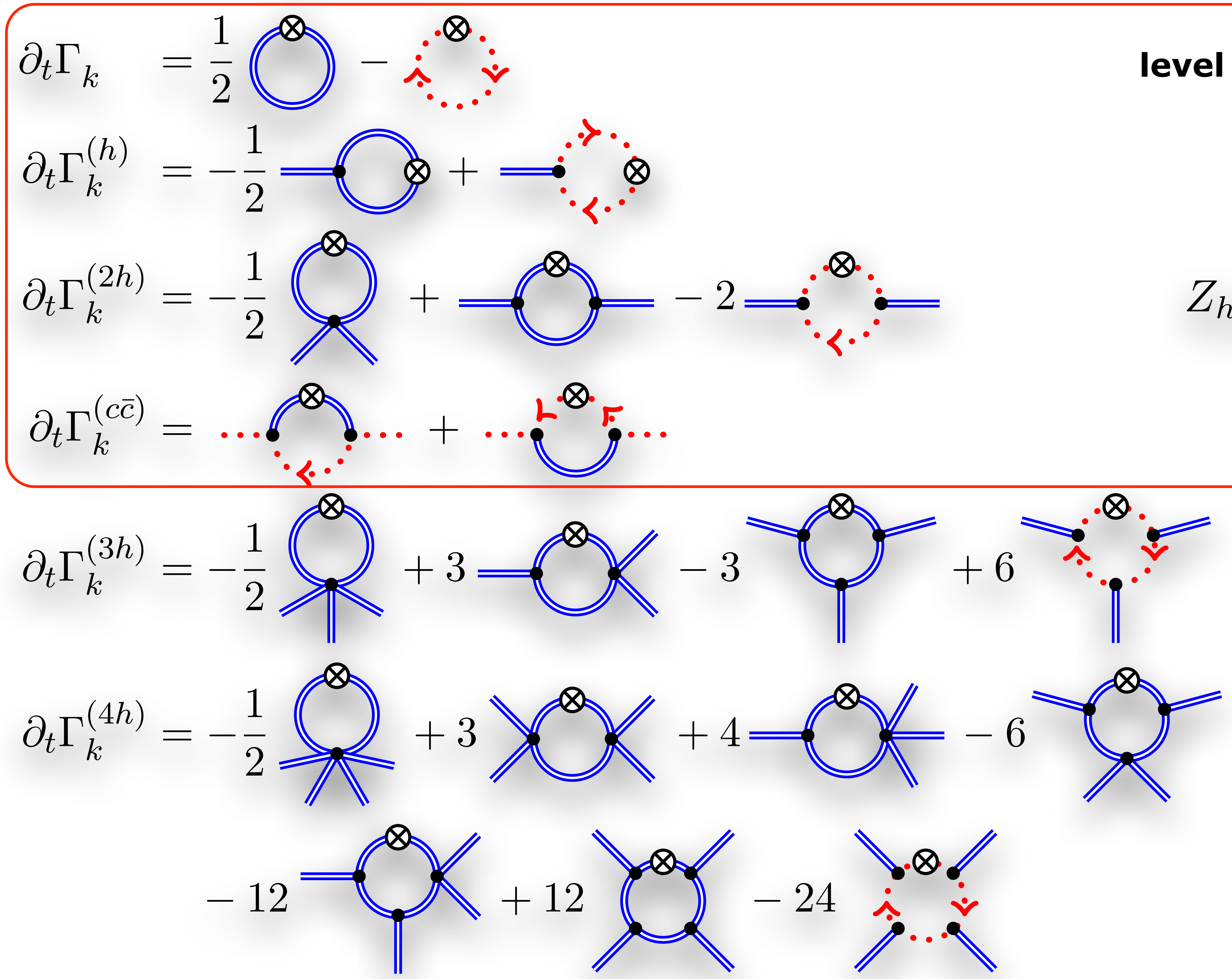
Towards apparent convergence in quantum gravity II

vertex expansion

geometrical approach: Donkin, JMP, arXiv:1203.4207

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

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



level 2: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-2,2)}$

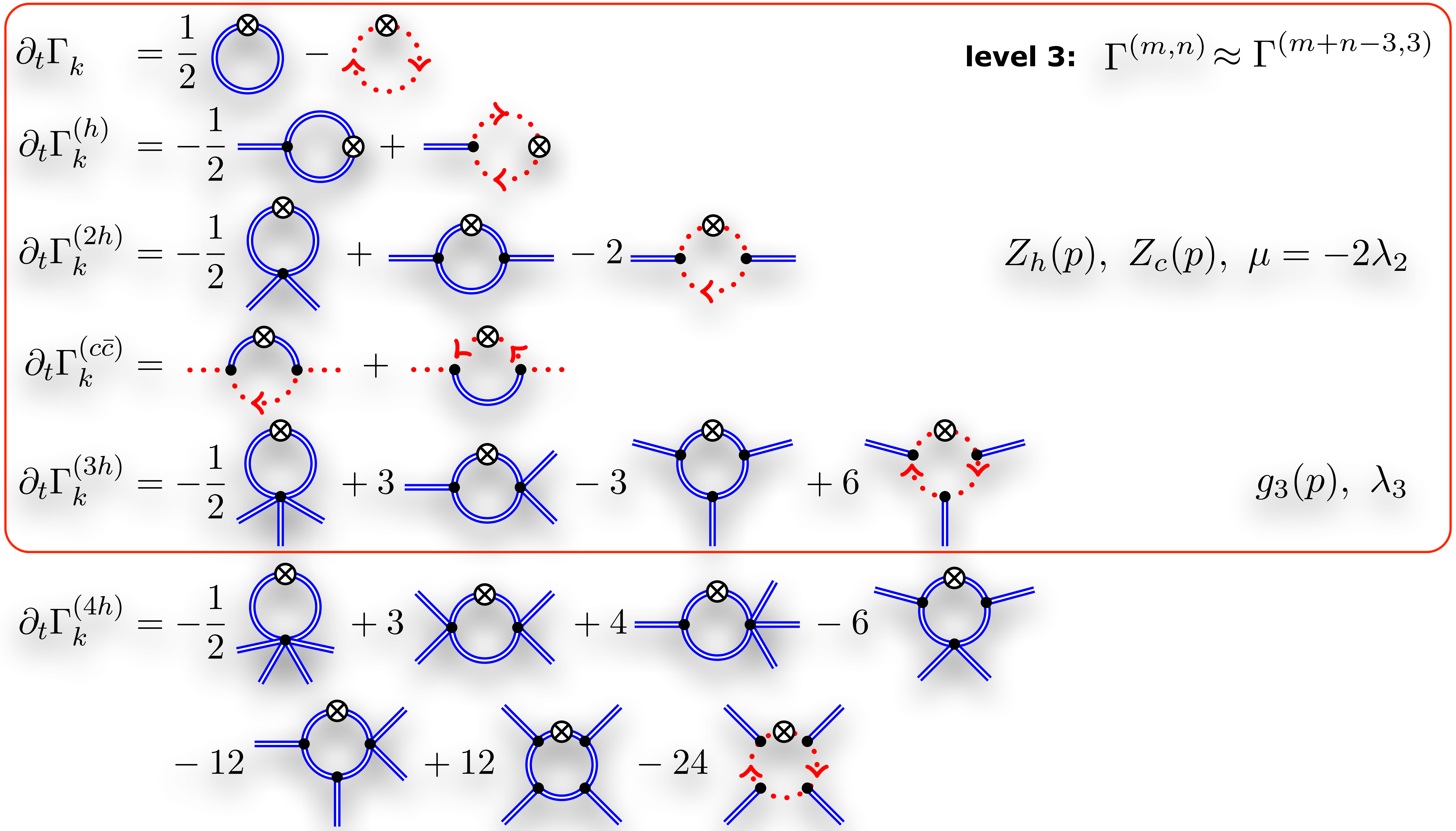
$Z_h(p),\ Z_c(p),\ \mu = -2\lambda_2$

Towards apparent convergence in quantum gravity II

vertex expansion

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

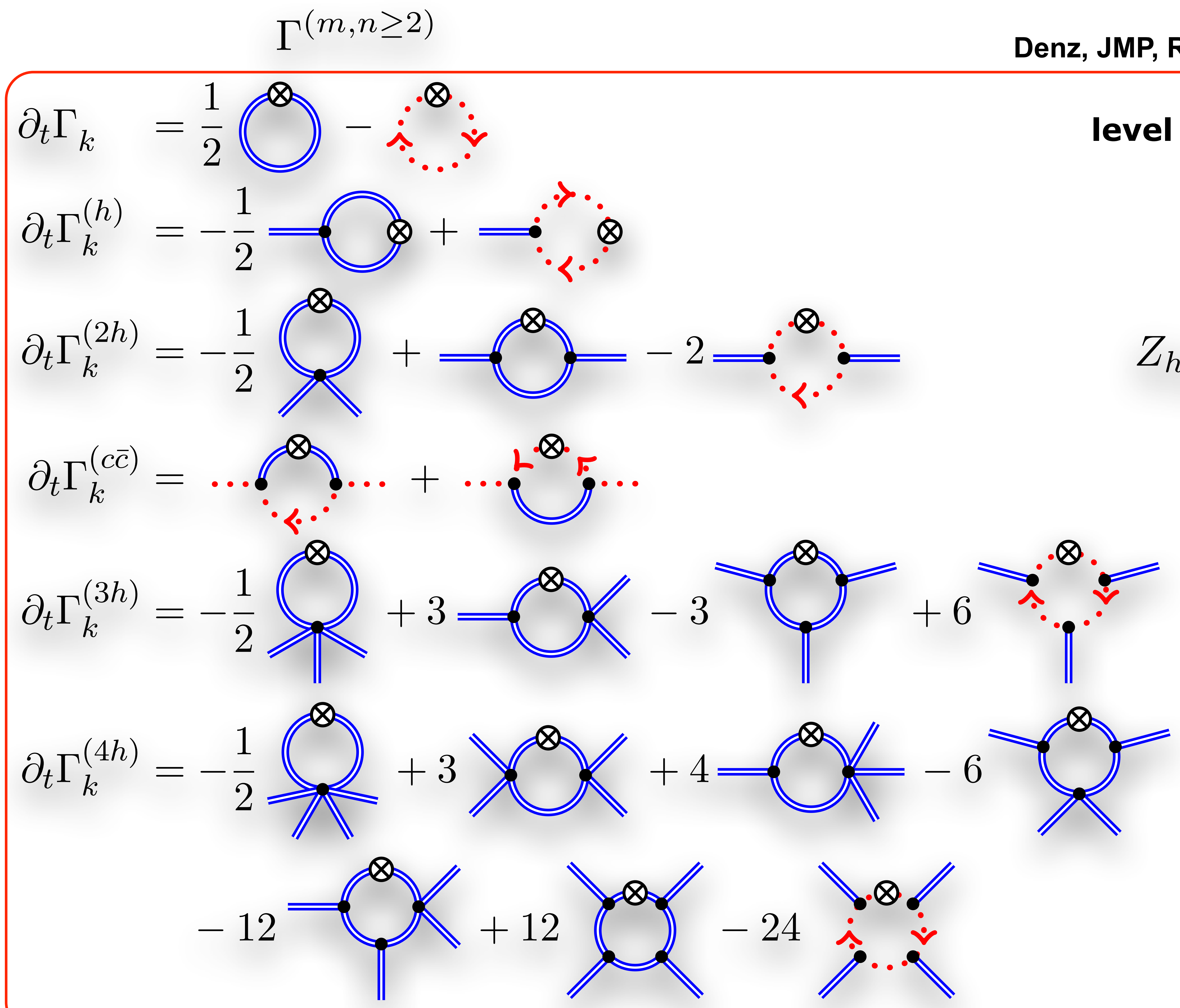
Christiansen, Knorr, Maibohm, JMP, Reichert, PRD 92 (2015) 12, 121501



Towards apparent convergence in quantum gravity II

vertex expansion

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



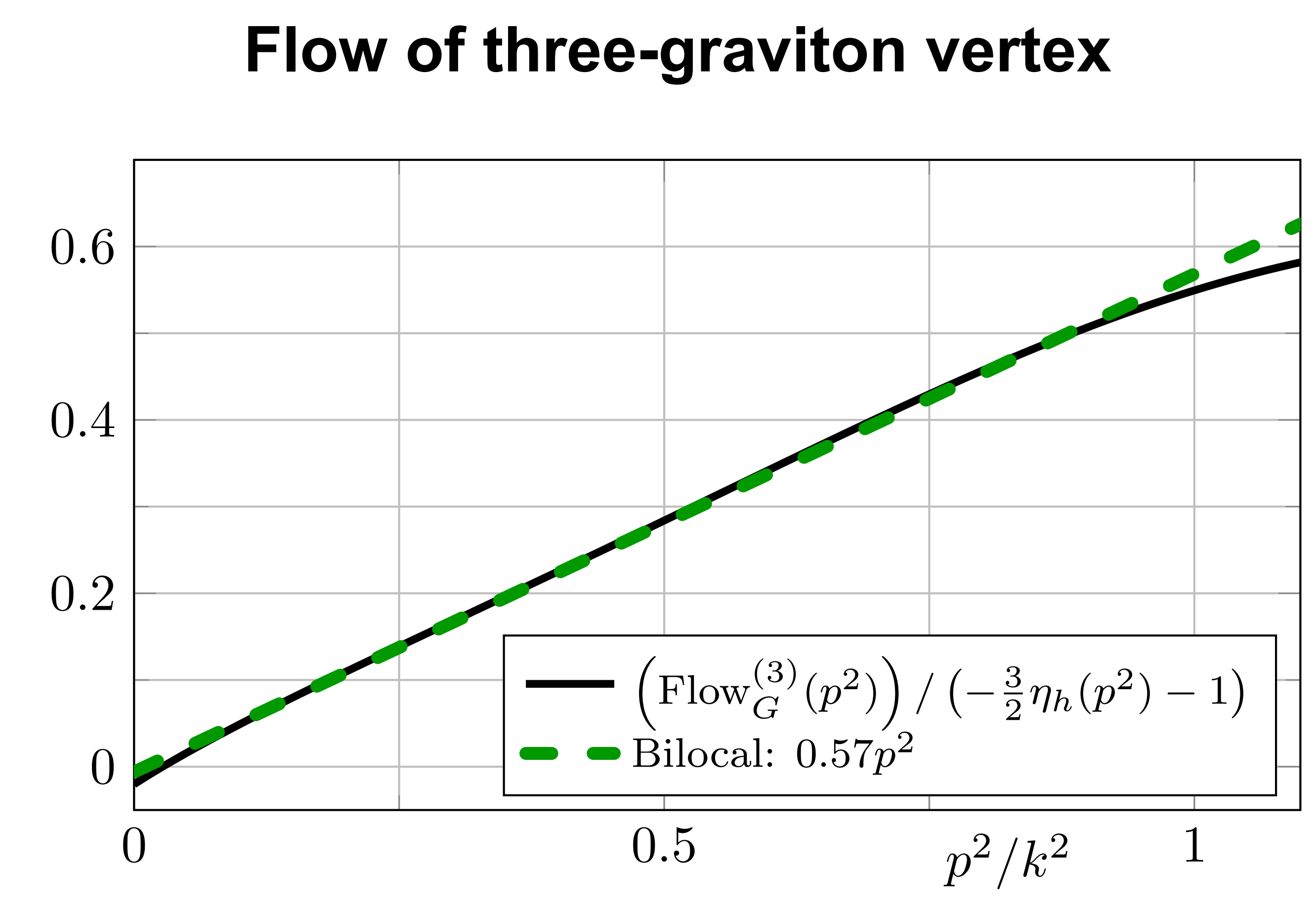
level 4: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-4,4)}$

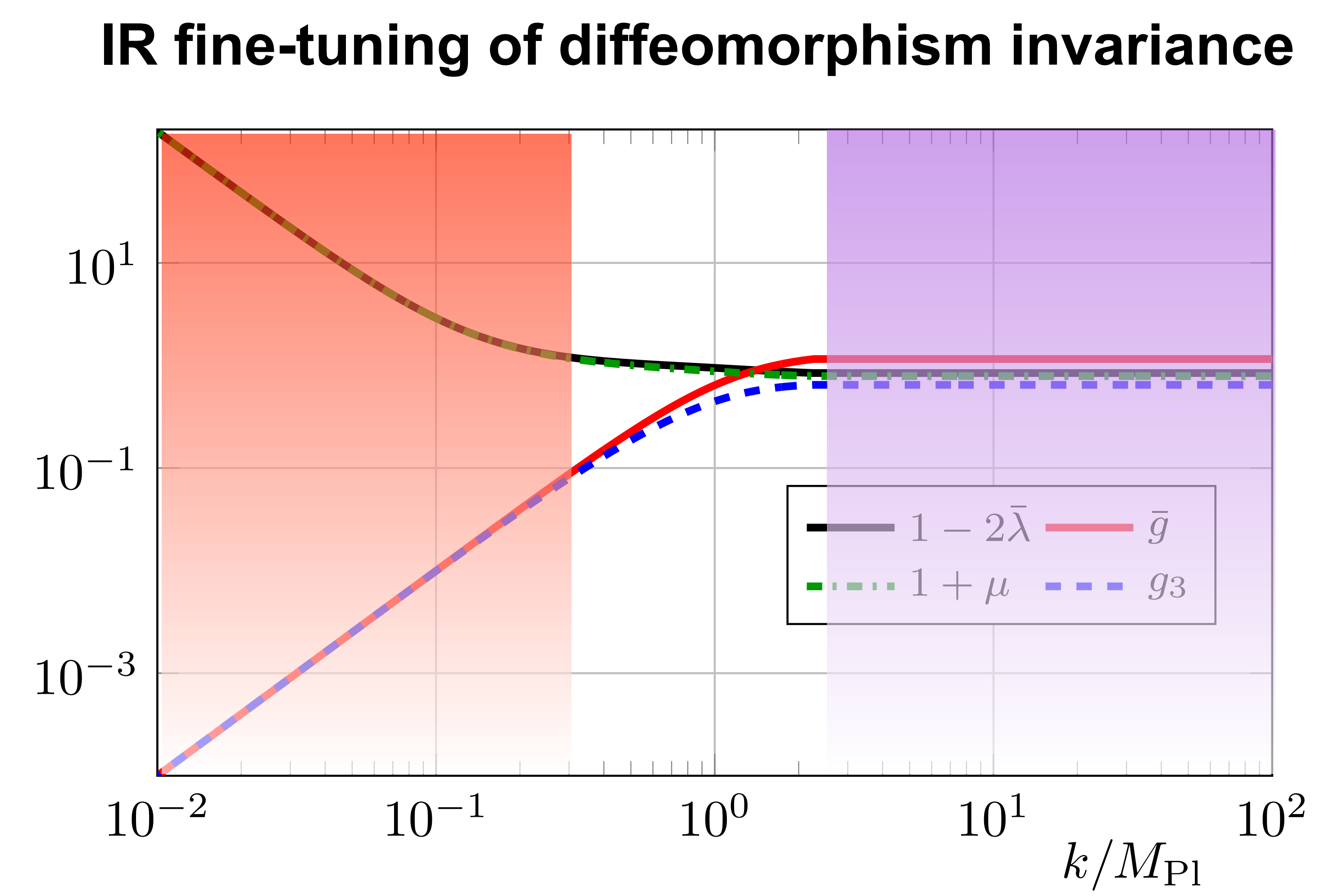
$Z_h(p),\ Z_c(p),\ \mu = -2\lambda_2$

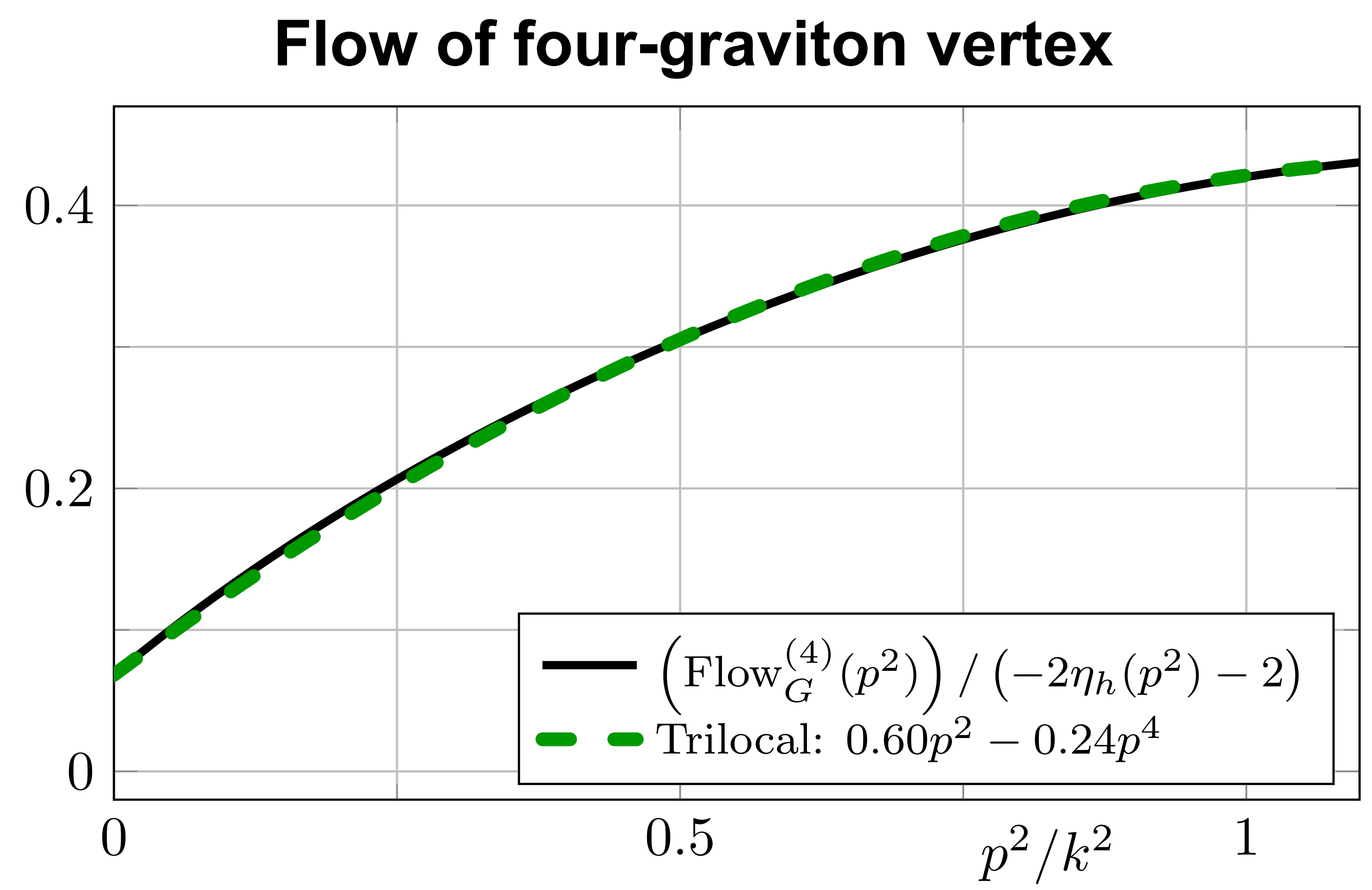
$g_3(p),\ \lambda_3$

$g_4(p),\ \lambda_4$

Momentum-dependent vertices







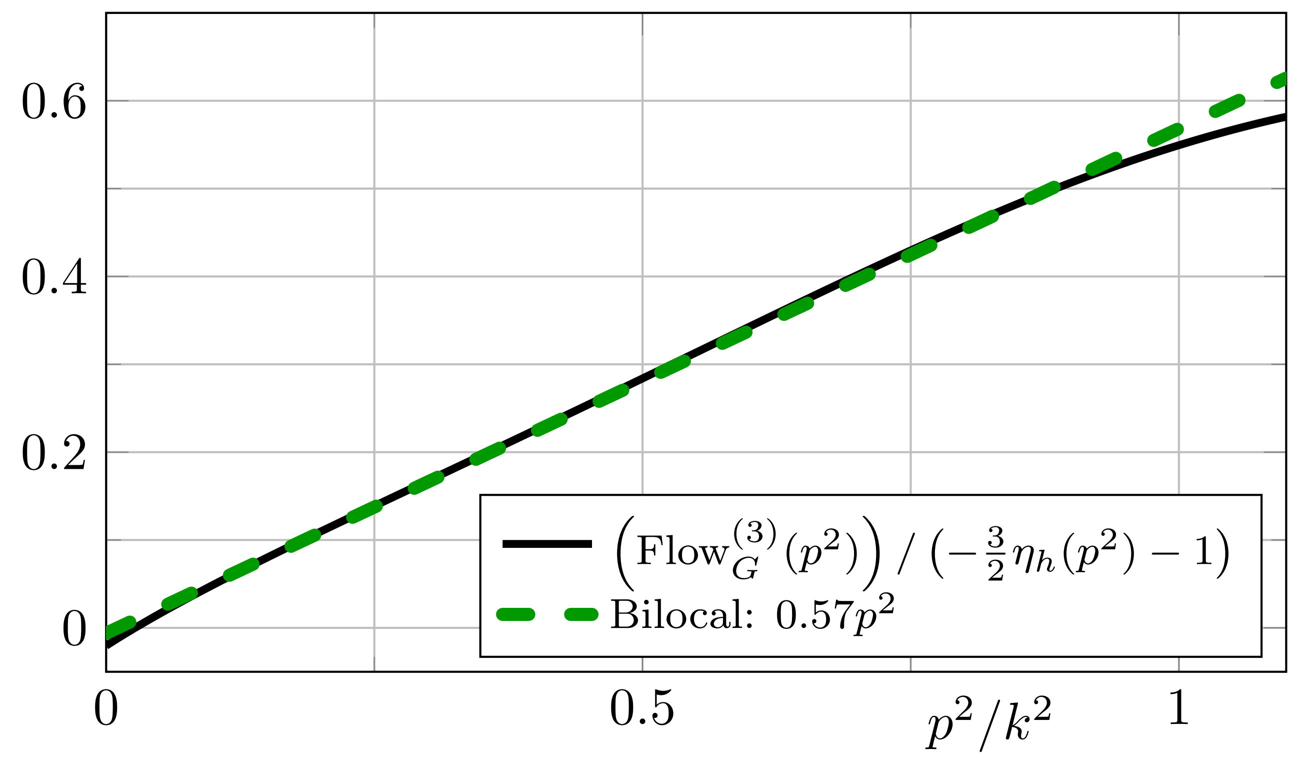
classical general relativity

asymptotically save fixed point scaling

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

Momentum-dependent vertices

Flow of three-graviton vertex



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

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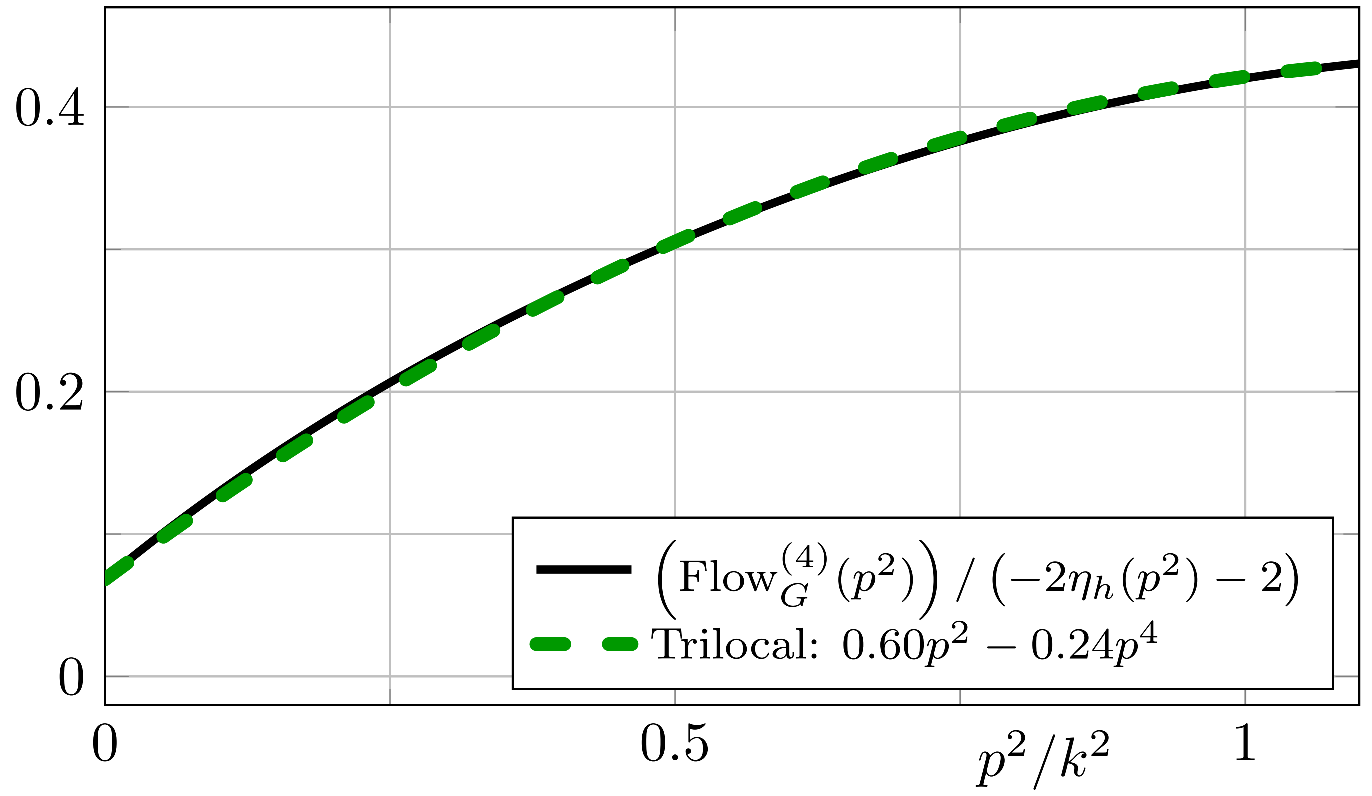
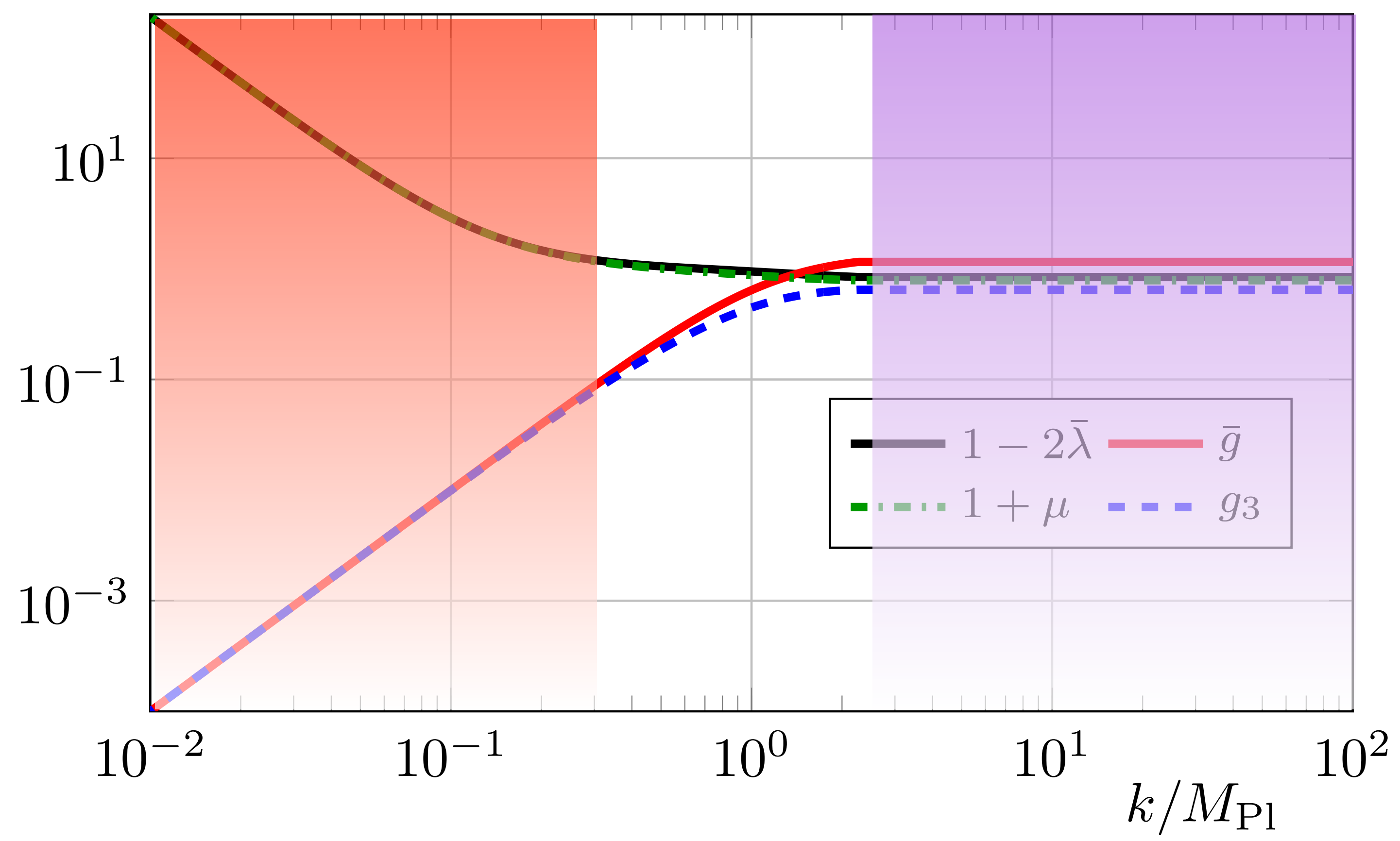


IR fine-tuning of diffeomorphism invariance



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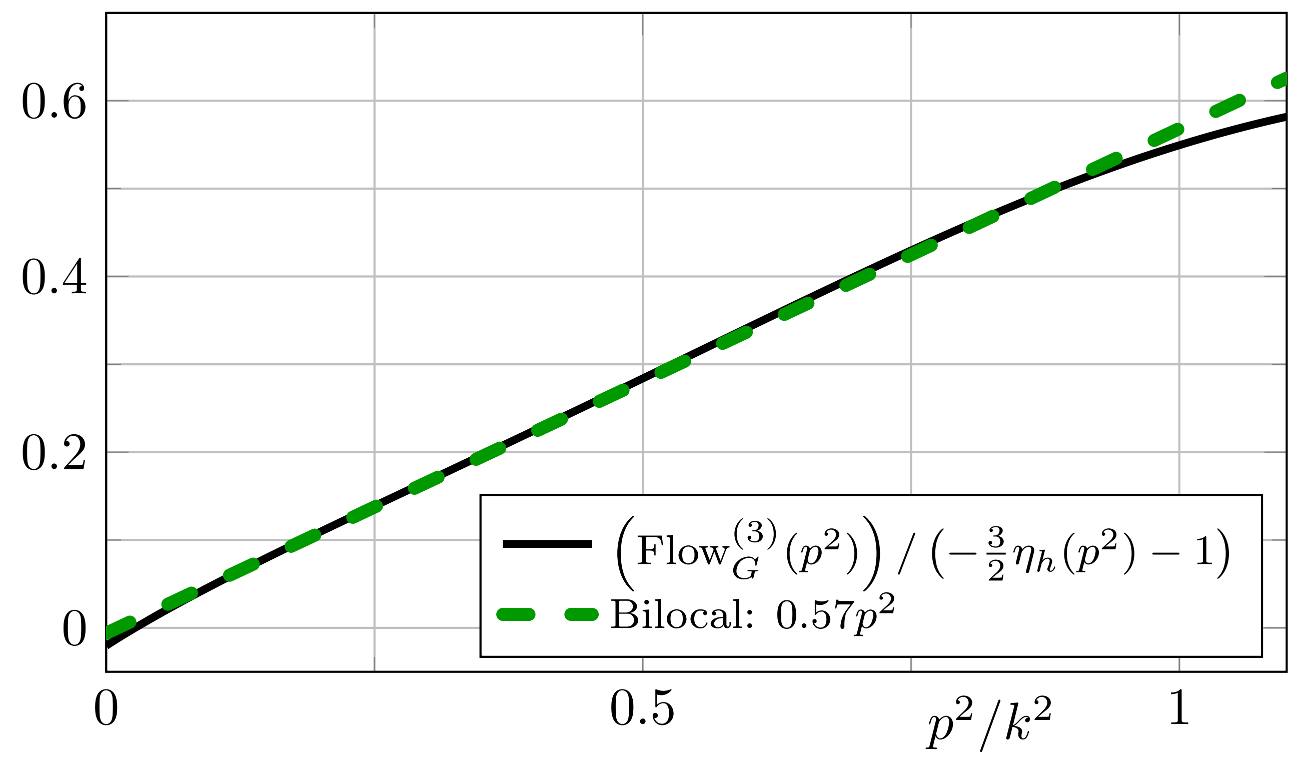

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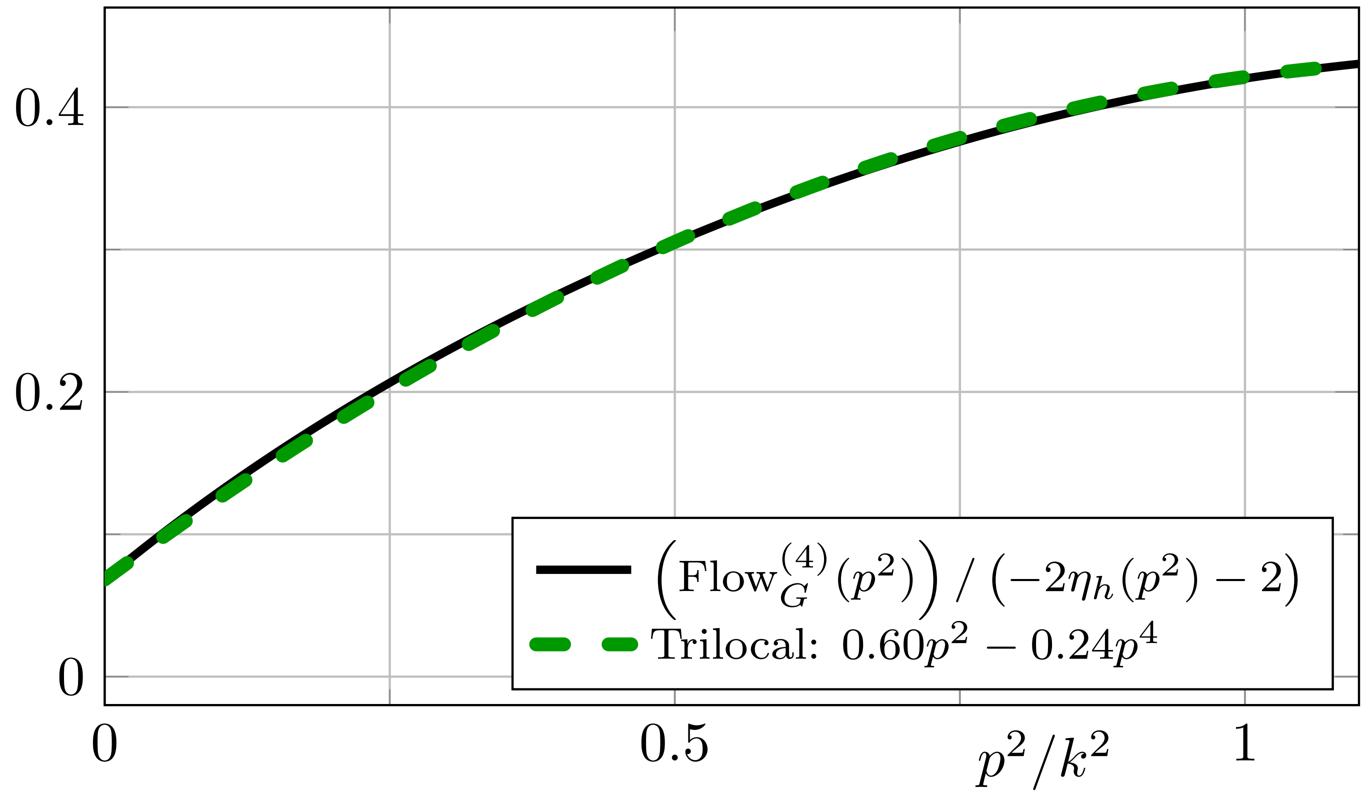

$\mathbf{R}^{\mathbf{2}}$- tensorstructure generated

$\mathbf{R}$- tensorstructure sustained

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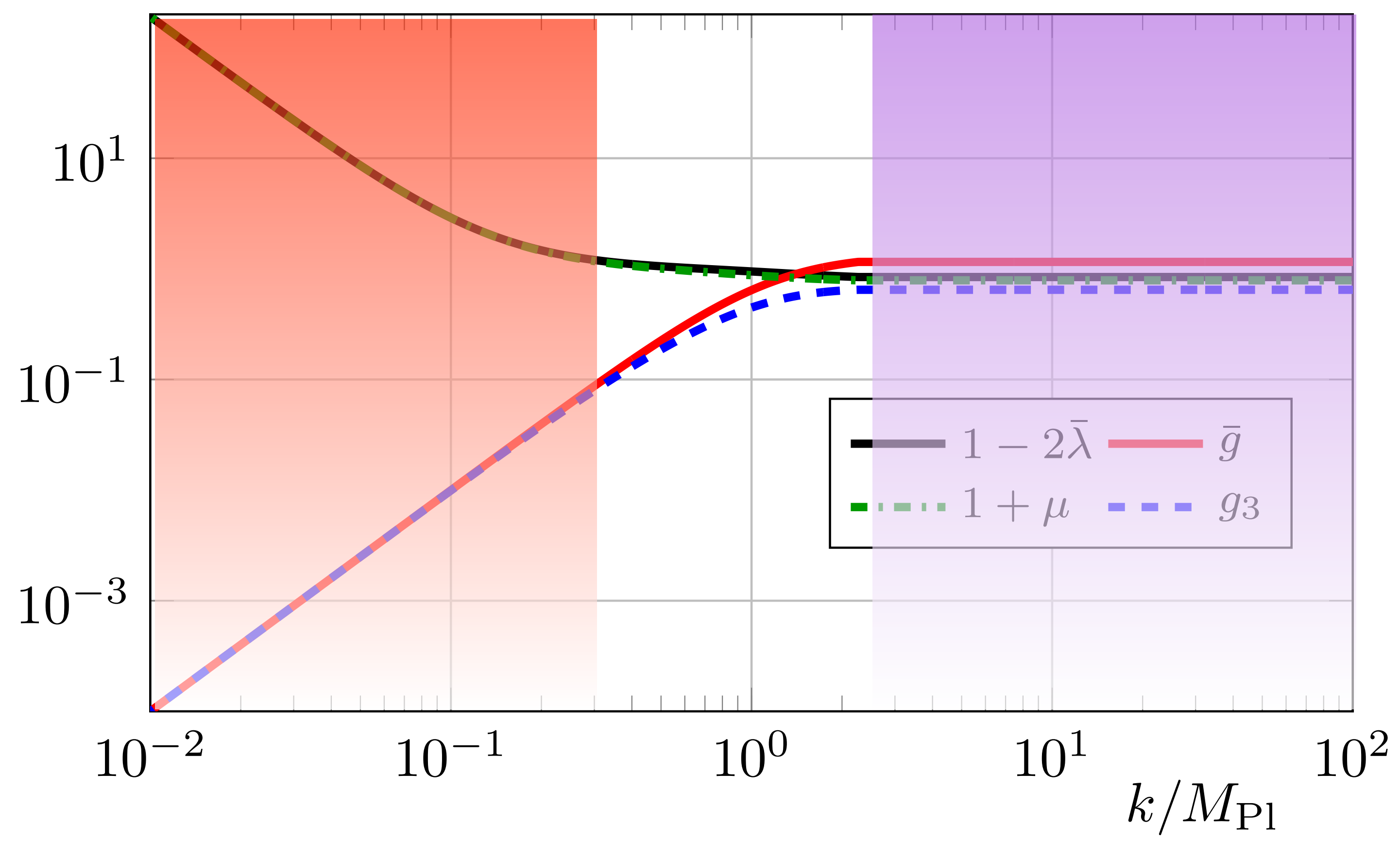

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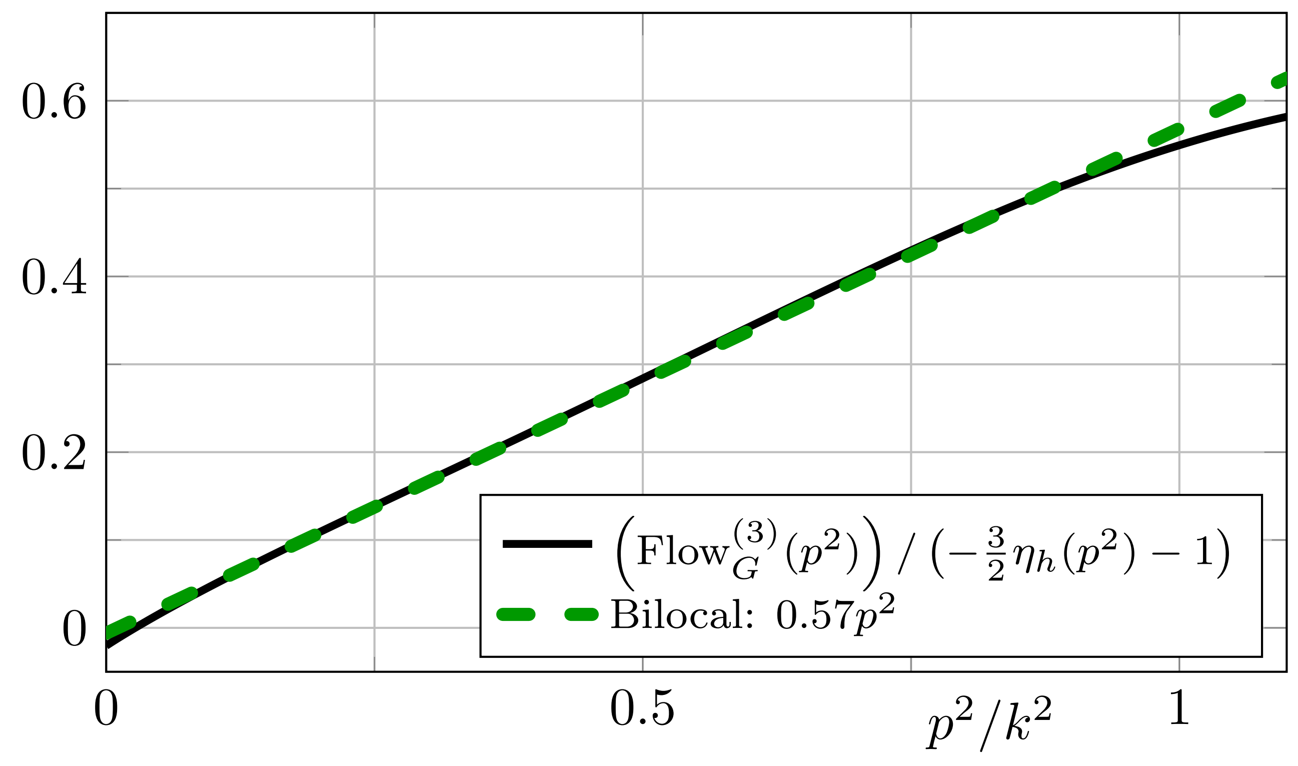

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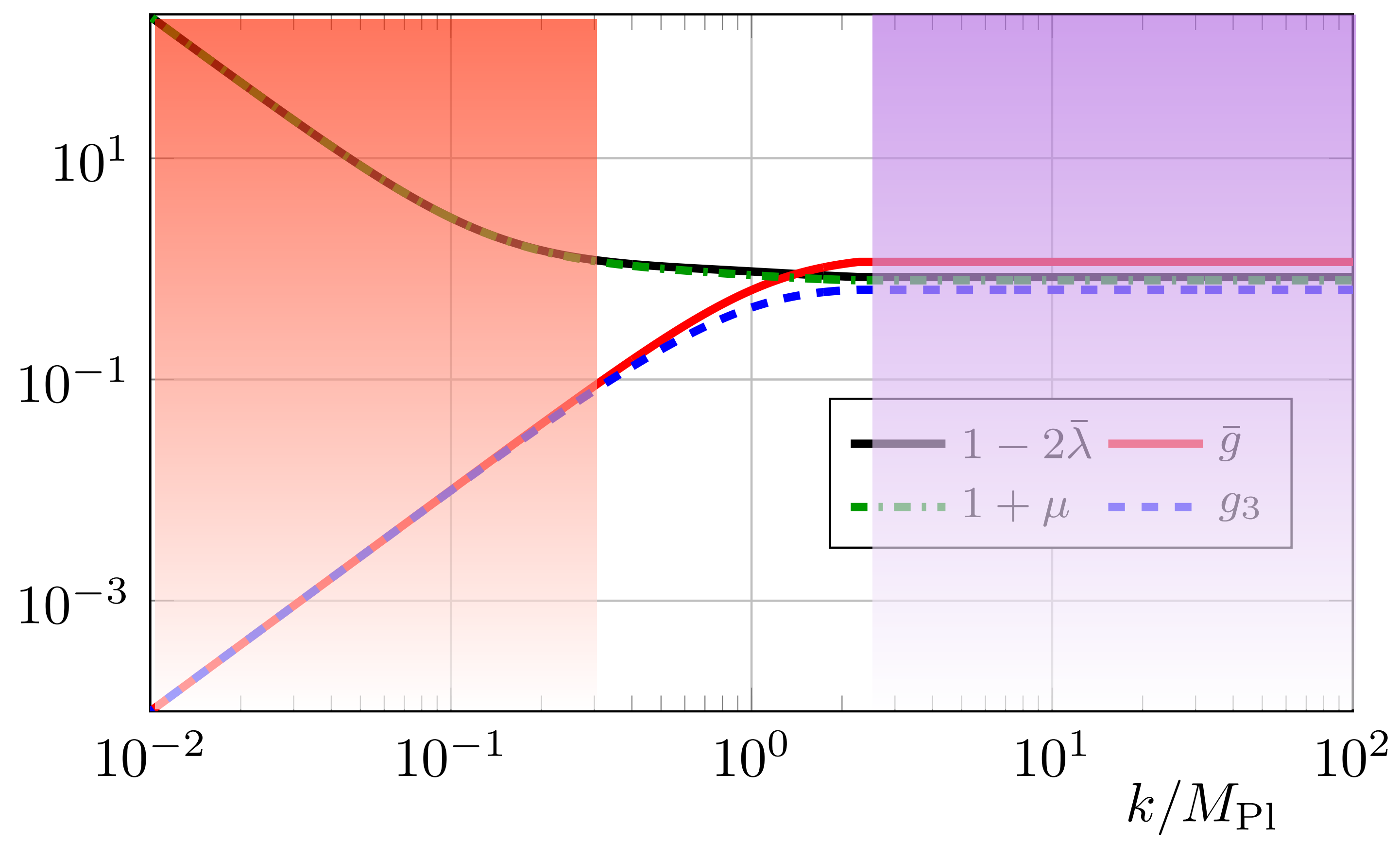

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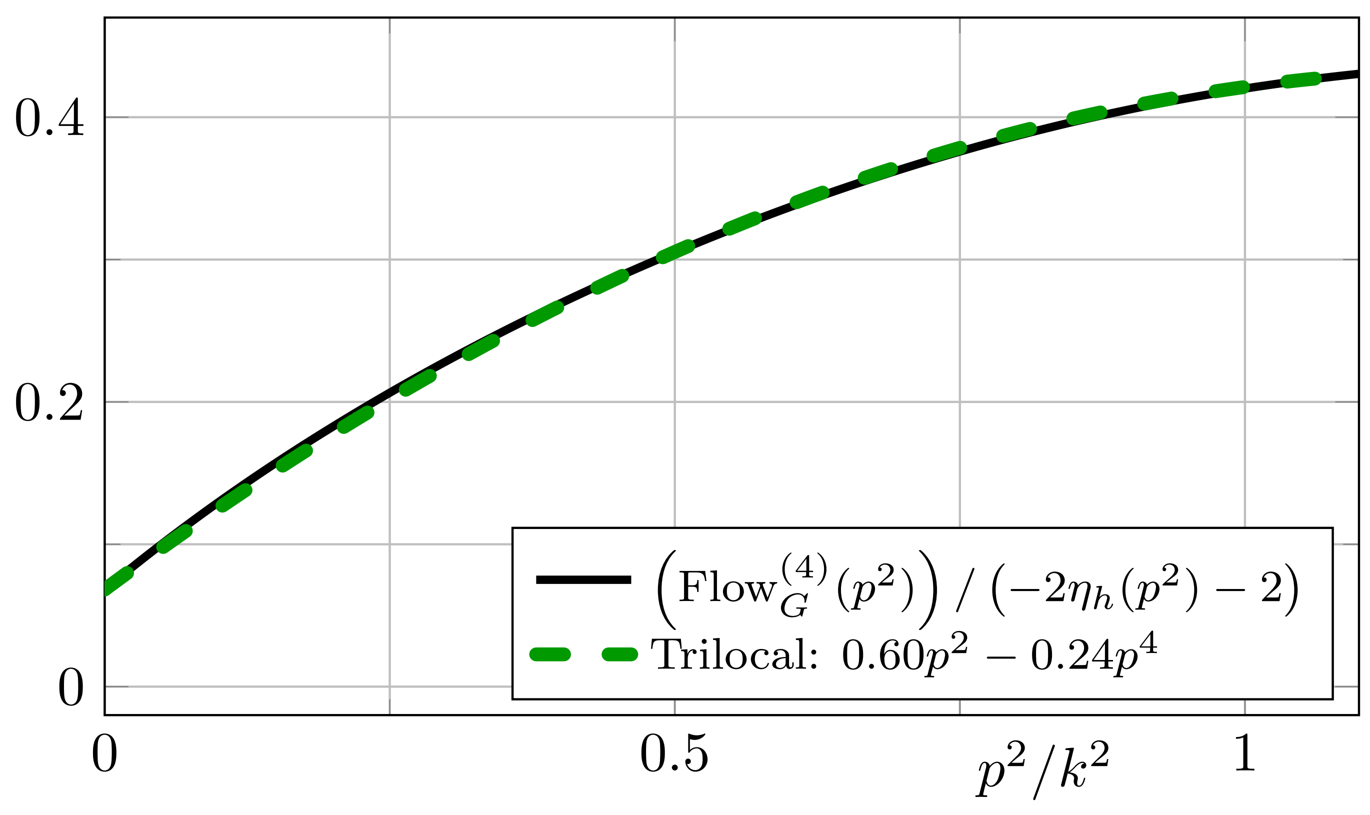

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Full momentum dependence
of
two-, three- and four-point function

at k=0

→ Spectral properties

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

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!

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(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

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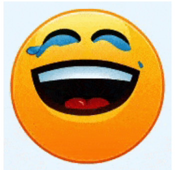
(c) graviballs in gravity → 

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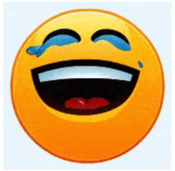
(c) graviballs in gravity → 

QG as perturbative as possible & apparently converging

… slight oversimplification for the sake of this talk …

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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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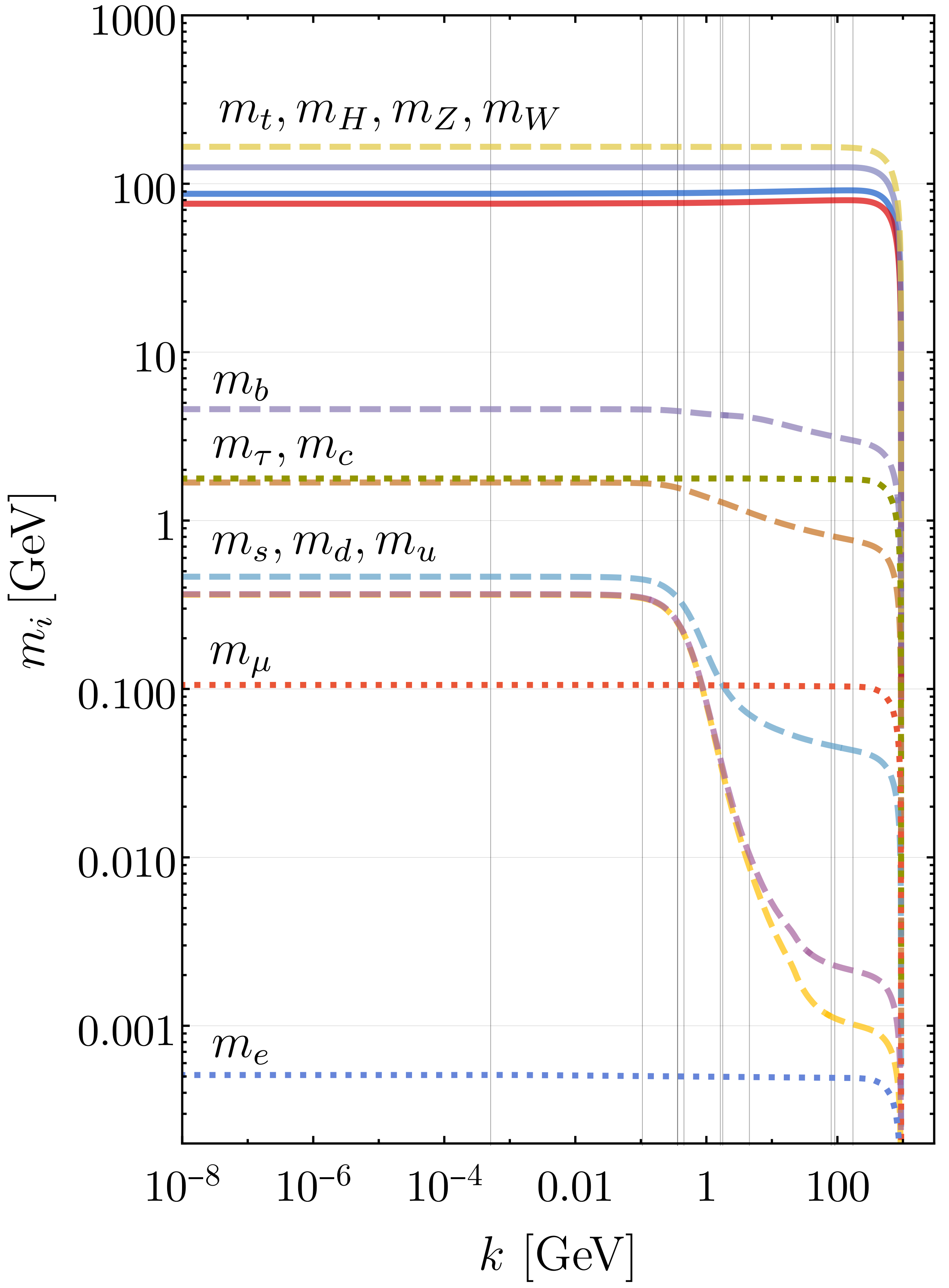
Example: asymptotically safe Standard Model

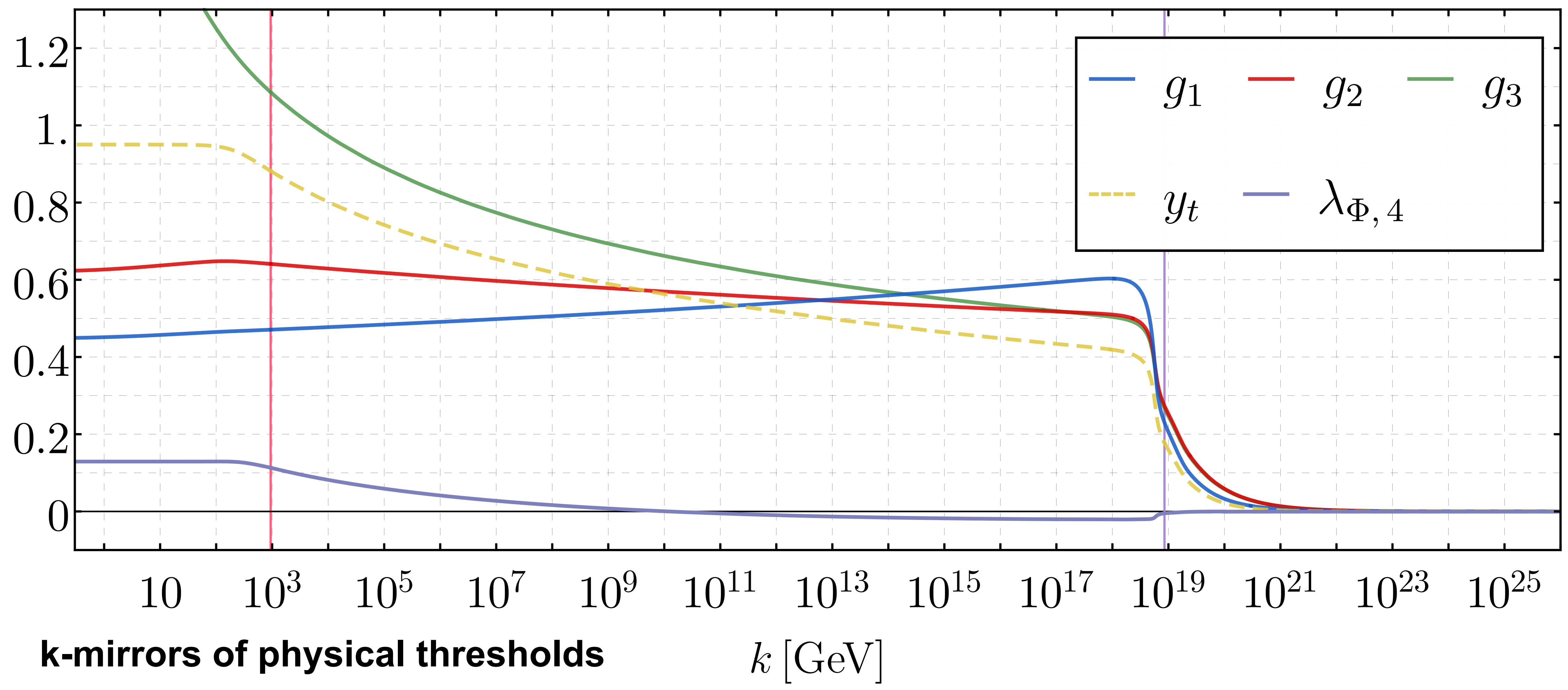
Standard Model masses



k-mirrors of physical thresholds

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

k-mirror of physical threshold



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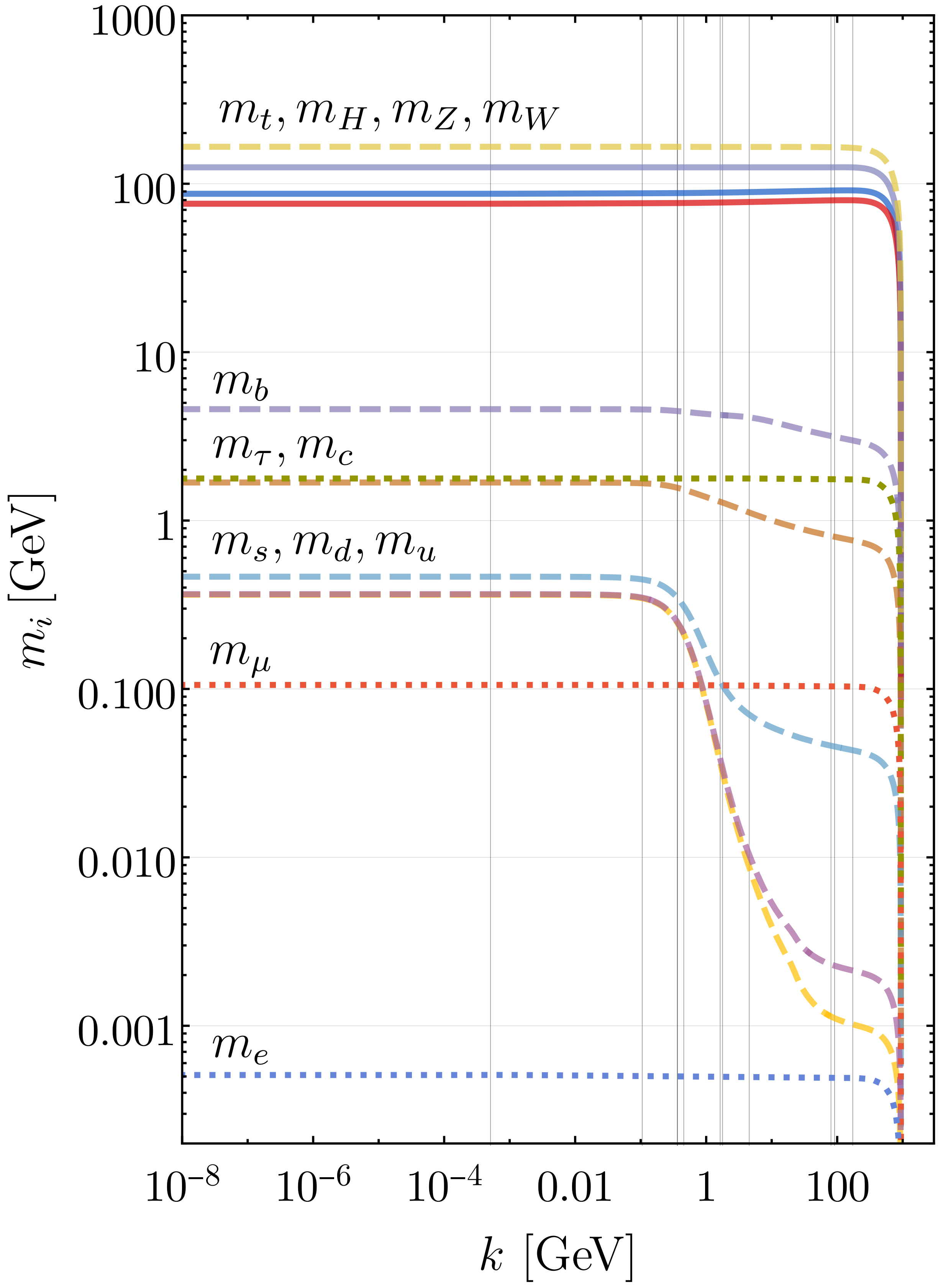

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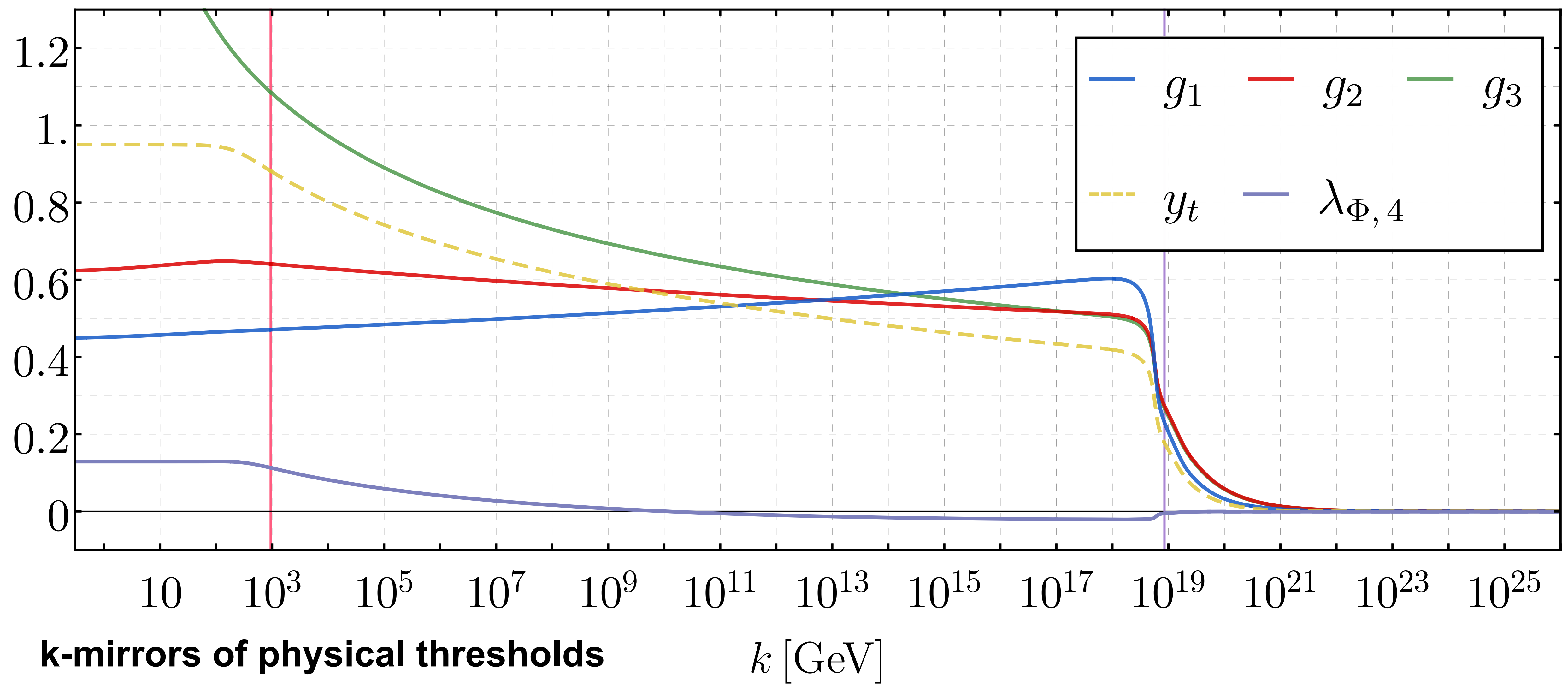

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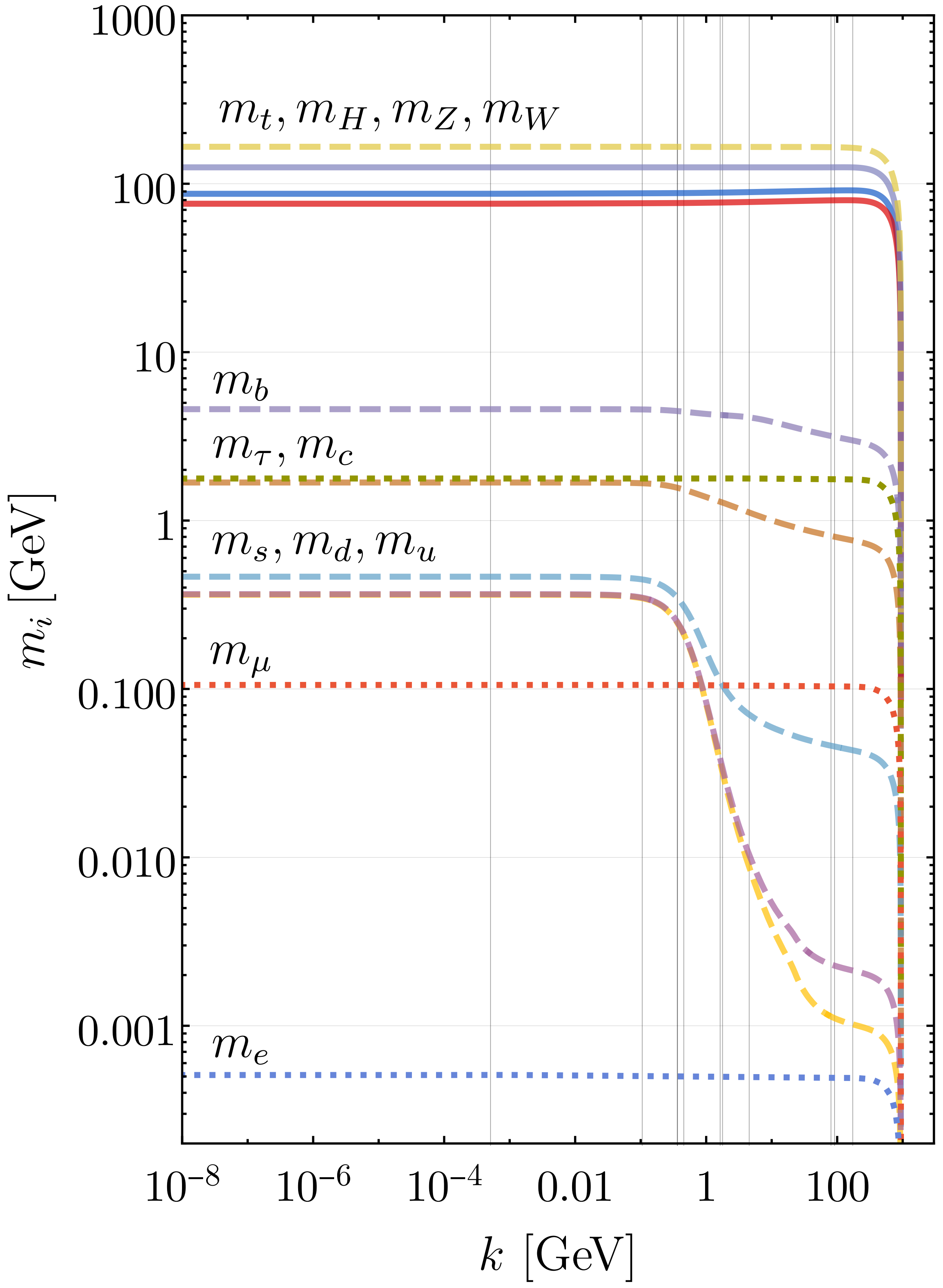

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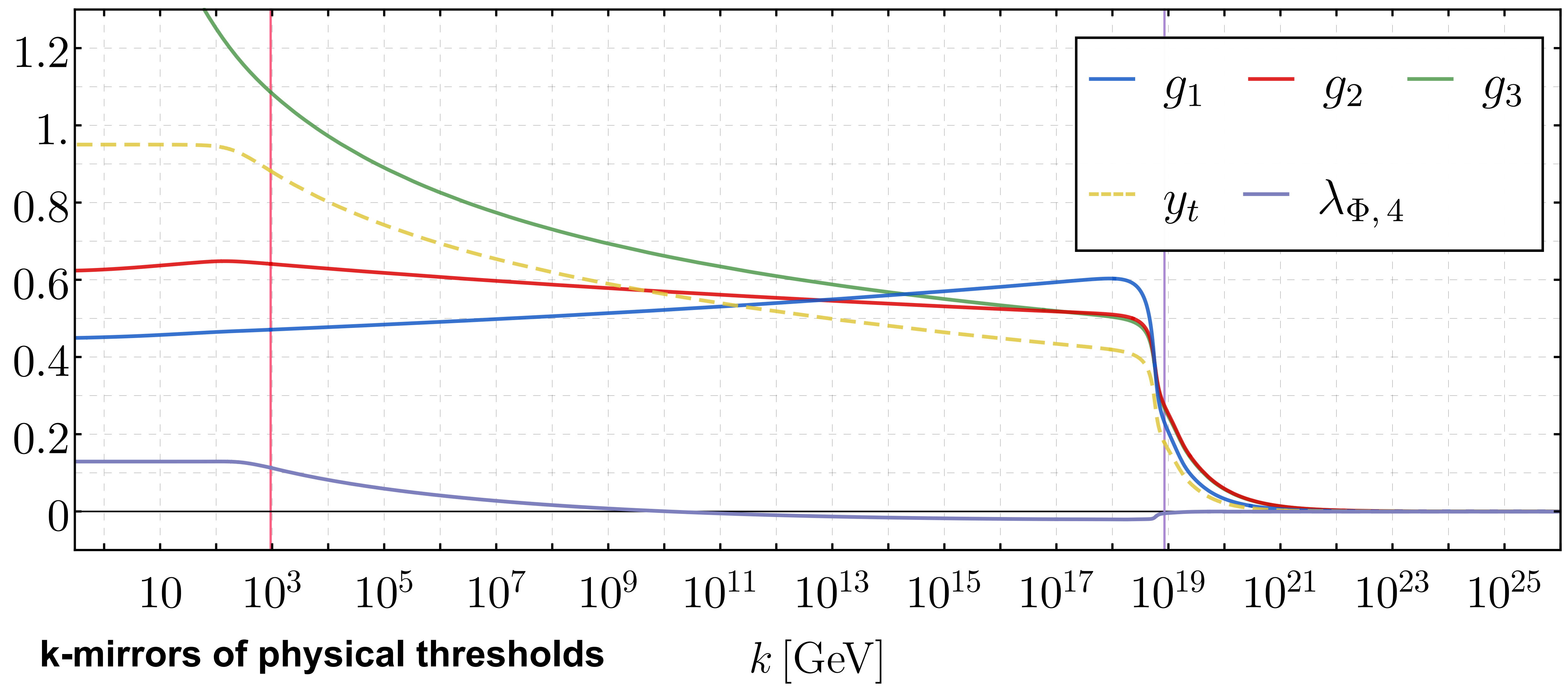

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Full physics: momentum-dependent correlation functions & S-matrix elements at k=0

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Scattering amplitudes, spectral properties & unitarity

Donoghue, Knorr, Litim, Platania, JMP, Percacci, Reichert, Saueressig, Wetterich, …

Spectral properties

$$\rho \simeq i \langle [\phi(x), \phi(y)] \rangle$$

Spectral function

$$F \simeq \langle \{\phi(x), \phi(y)\} \rangle$$

Statistical function

$$\rho(\omega, \vec{p}) \simeq 2 \, \mathrm{Im} \, G_{\mathrm{Eucl}} \left(-i(\omega + i\varepsilon), \vec{p} \right)$$

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Källen-Lehmann spectral representation

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

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Normalisation for physical fields

$$\frac{1}{2\pi} \int_{-\infty}^{\infty} d\lambda \, \lambda \rho_\phi(\lambda) = 1$$

Canonical computation relation

$$\left[\phi(t, \vec{x}) \, , \, \dot{\phi}(t, \vec{y})\right] = \delta(\vec{x} - \vec{y})$$

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Bjorken-Johnson-Low limit

$$\lim_{p_0 \to \infty} p_0^2 \int \frac{d^3p}{(2\pi)^3} G_\phi(p^2)\, e^{i\vec{p}\,(\vec{x}-\vec{y}\,)} = \left[\phi(t, \vec{x})\, ,\, \dot{\phi}(t, \vec{y})\right]$$

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'The wave function Z(p) of physical fields has a trivial UV-limit'

$$G_\phi(p) = \frac{1}{Z_\phi(p)} \frac{1}{p^2} \stackrel{p^2 \to \infty}{\longrightarrow} \frac{1}{p^2}$$

Beware
inherently gauge-dependent

Properties of the spectral function

$$G_\phi^{(\mathrm{IR})}(p) = \frac{Z_\phi^{(\mathrm{IR})}}{p^{2\left(1-\frac{\eta_\phi}{2}\right)}}$$

Analytic consequences & constraints

UV-asymptotics $$\mathrm{sign}\big[\rho_\phi(\lambda \to 0)\big] = -\mathrm{sign}\big[\partial_p^2 G_\phi(p^2 \to 0)\big] \qquad \lambda \geq 0$$

Cyrol, JMP, Rothkopf, Wink SciPost Phys. 5 (2018) 6, 065
Bonanno, Denz, JMP, Reichert, SciPost Phys. 12 (2022) 1, 001
Horak, JMP, Wink, 2202.09333, 2210.07597 (SciPost Phys.)

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Oehme-Zimmermann superconvergence

Quarks, gluons, background graviton

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No field in the SM!
Example: scalar field in d<4

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$$G_\phi^{(\mathrm{UV})}(p) = \frac{Z_\phi^{(\mathrm{UV})}}{p^{2\left(1-\frac{\eta_\phi}{2}\right)}}$$

fluctuating graviton

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Scalar field in 3d at Wilson-Fisher FP

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(3) $\eta_\phi = 0, 2$ → $\rho_\phi^{(\mathrm{IR})}[c_{\log}\log p^2\,,\, m_{\mathrm{gap}}^2]$ — **'Physical' fields, decoupling gluon prop & ghost dressing**, **Fluctuating & background gravitons**

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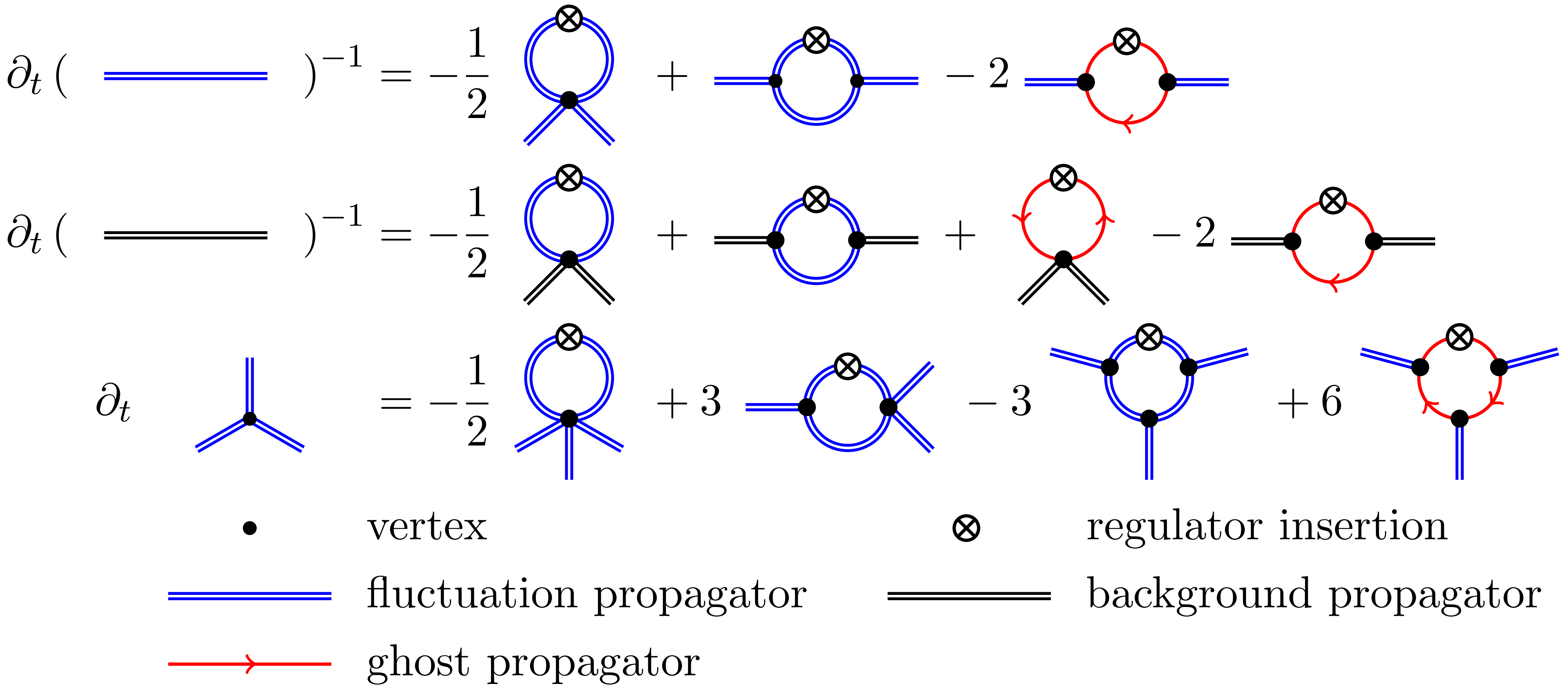
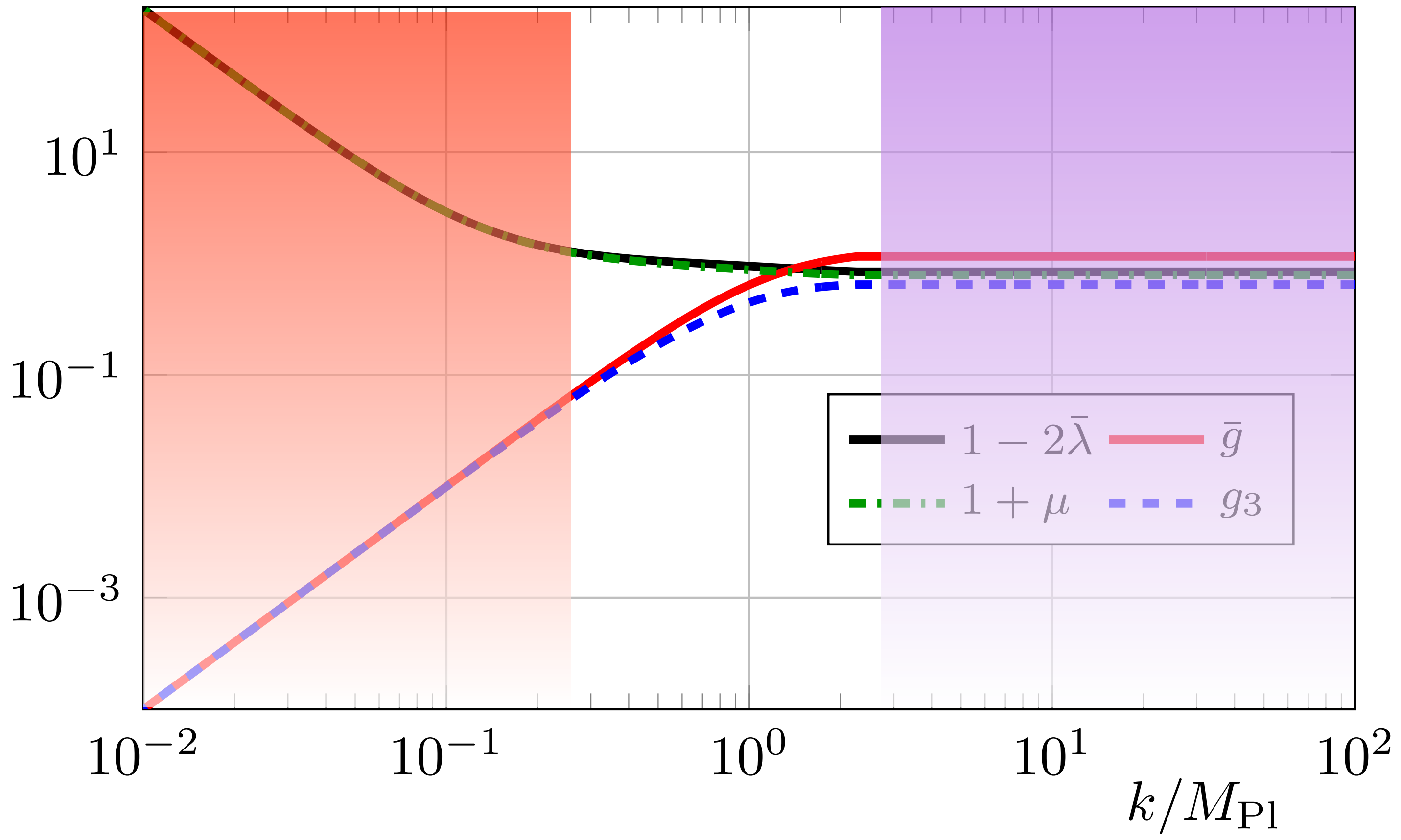
Unitarity & the graviton spectral function

Reconstruction

Flows for two- and three point functions



IR fine-tuning of diffeomorphism invariance



classical general relativity

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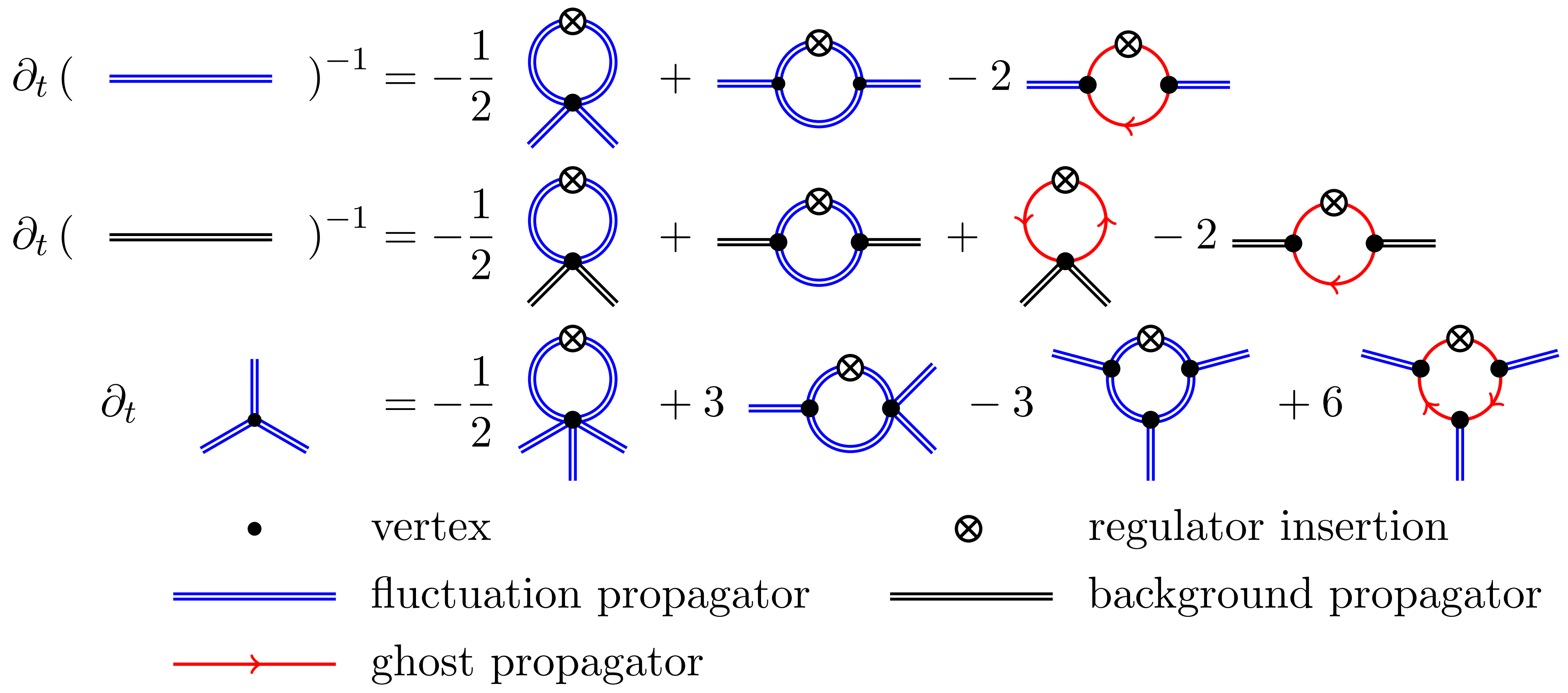
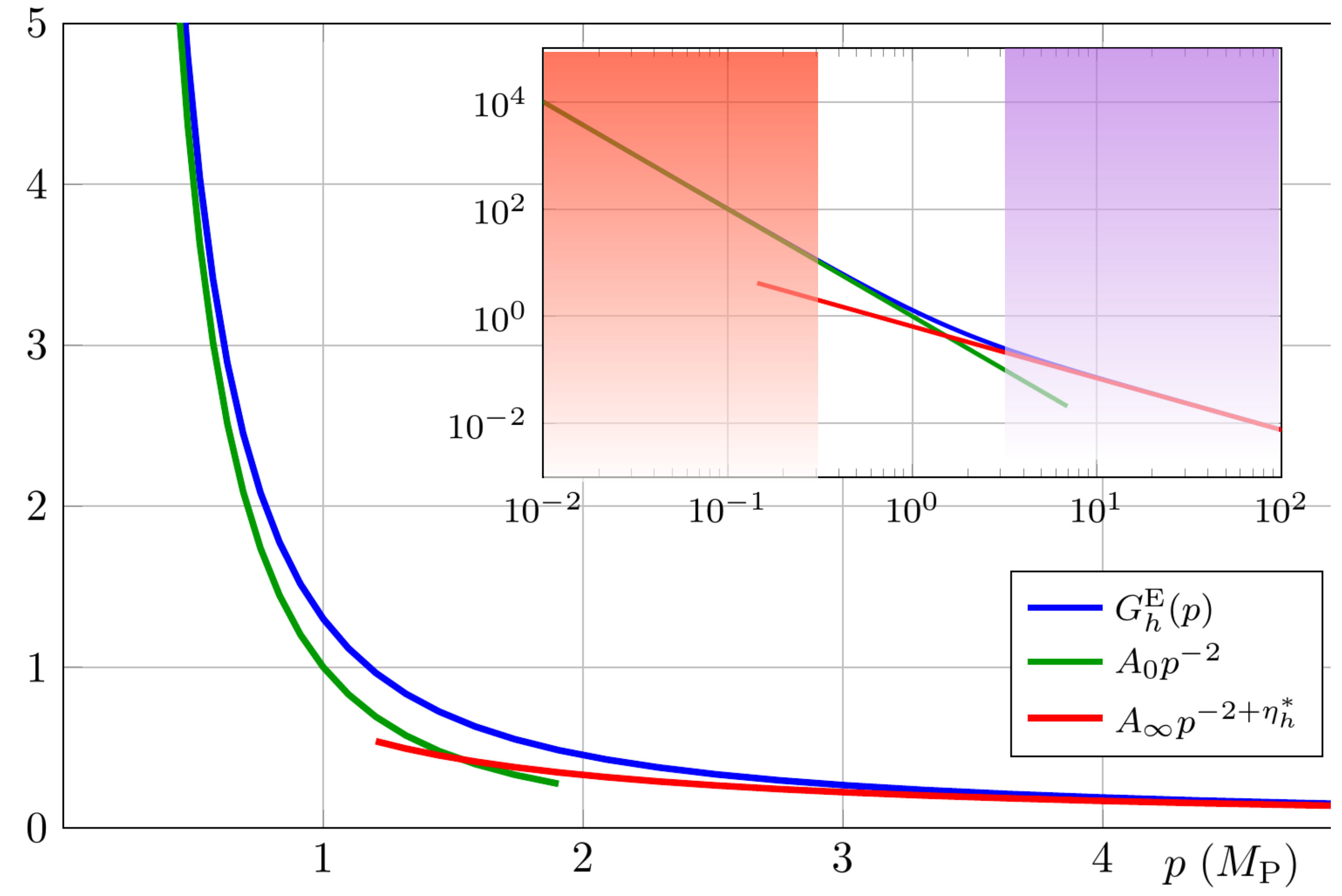
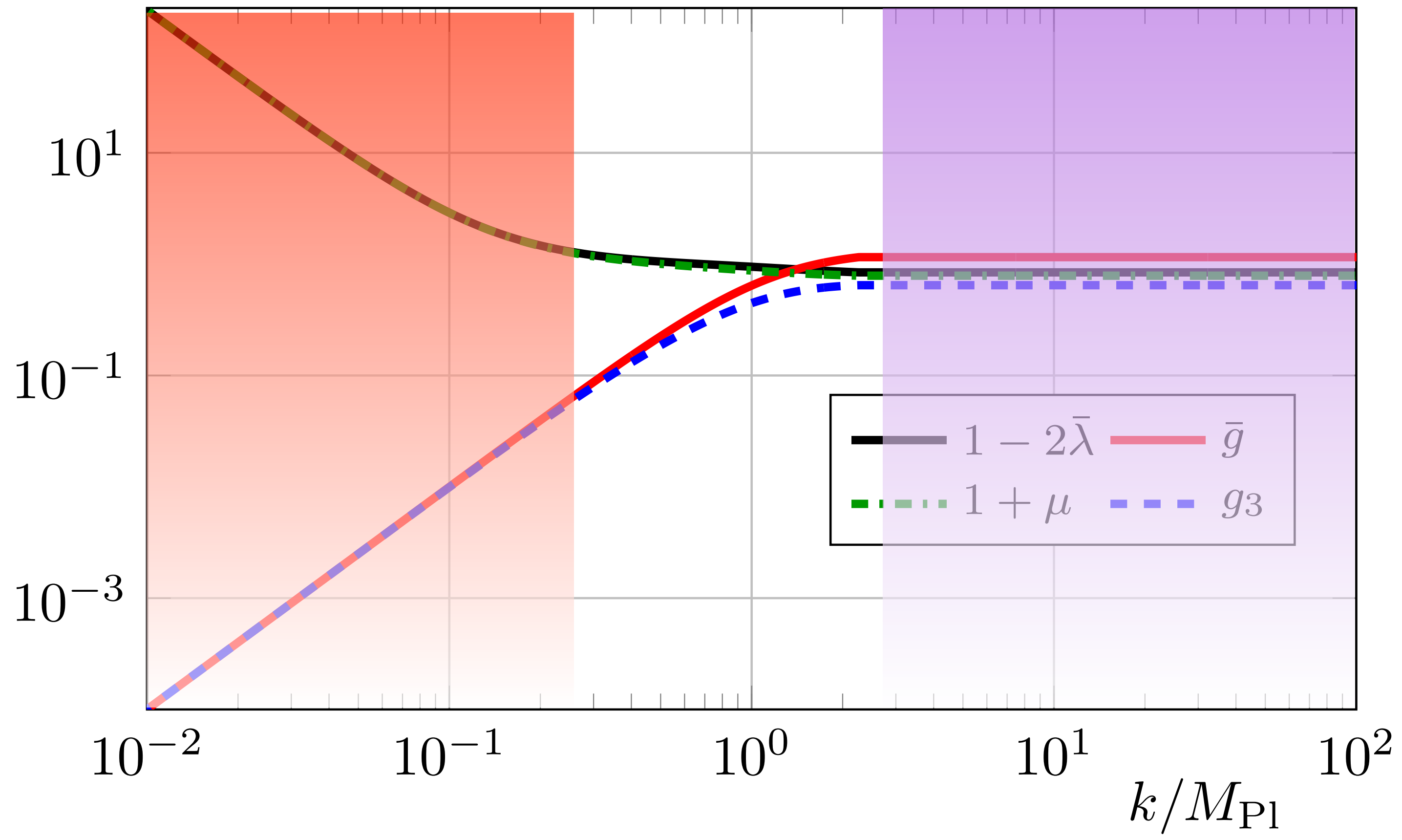
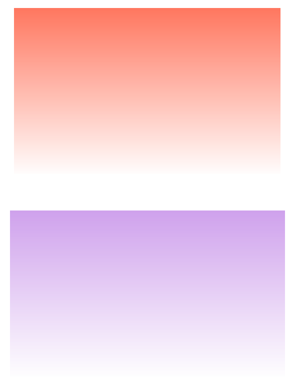


Fluctuation propagator at vanishing cutoff scale



IR fine-tuning of diffeomorphism invariance





classical general relativity

asymptotically save fixed point scaling

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

General basis

$$\hat G^{\mathrm{BW}}(p_0) = \sum_{k=1}^{N_{\mathrm{ps}}} \prod_{j=1}^{N_{\mathrm{pp}}^{(k)}} \left(\frac{\hat{\mathcal{N}}_k}{(\hat p_0 + \hat\Gamma_{k,j})^2 + \hat M_{k,j}^2} \right)^{\delta_{k,j}}$$

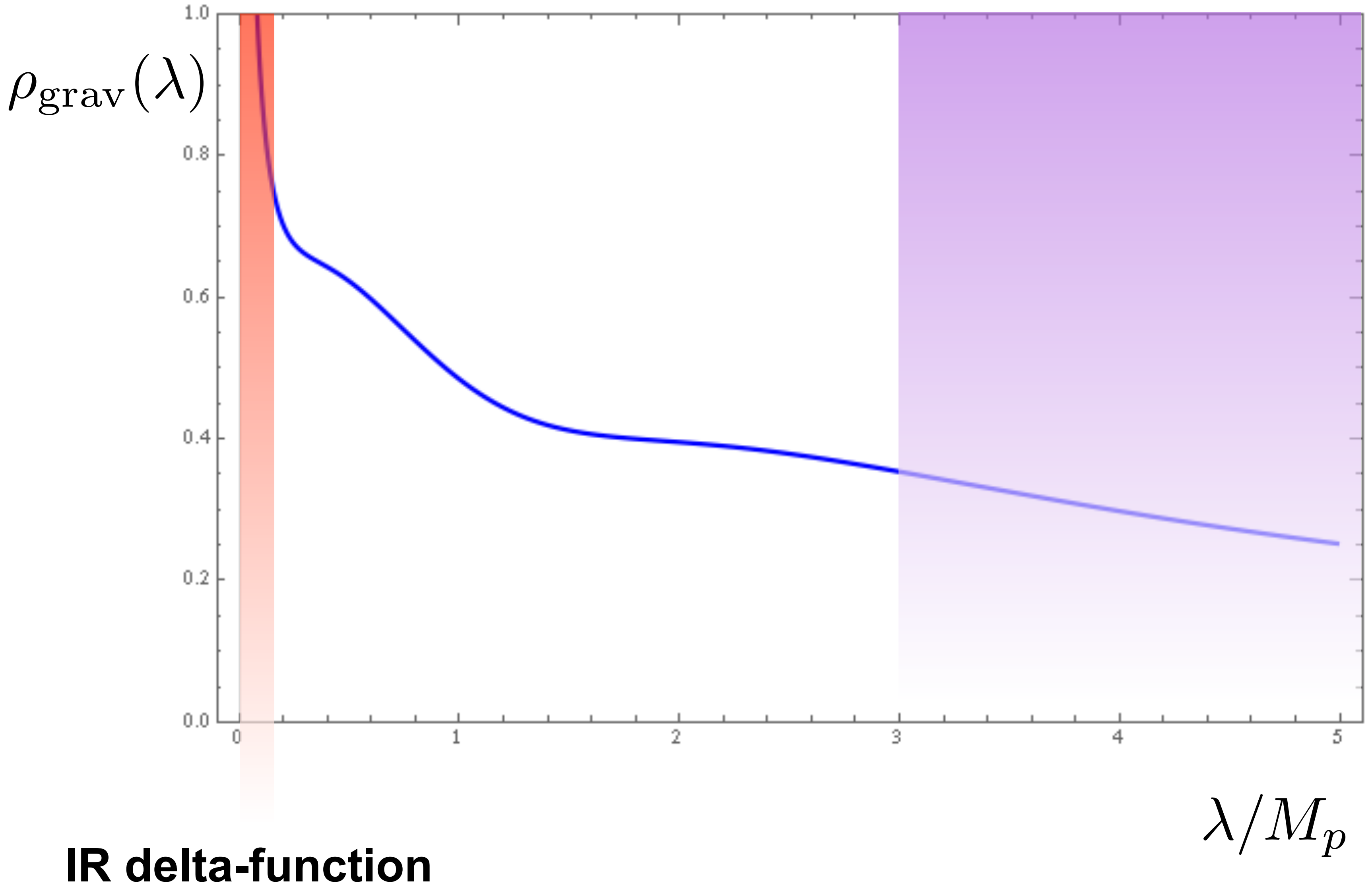
$$G^{\mathrm{BW}}(p_0) = \mathcal{K}\,(p_0^2)^{-1-2\alpha} \left(\sum_{j=1}^{N_{\mathrm{poly}}} \hat a_j (\hat p_0^2)^{\frac{j}{2}} \right) \hat G^{\mathrm{BW}}(p_0)$$

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

Unitarity & the graviton spectral function

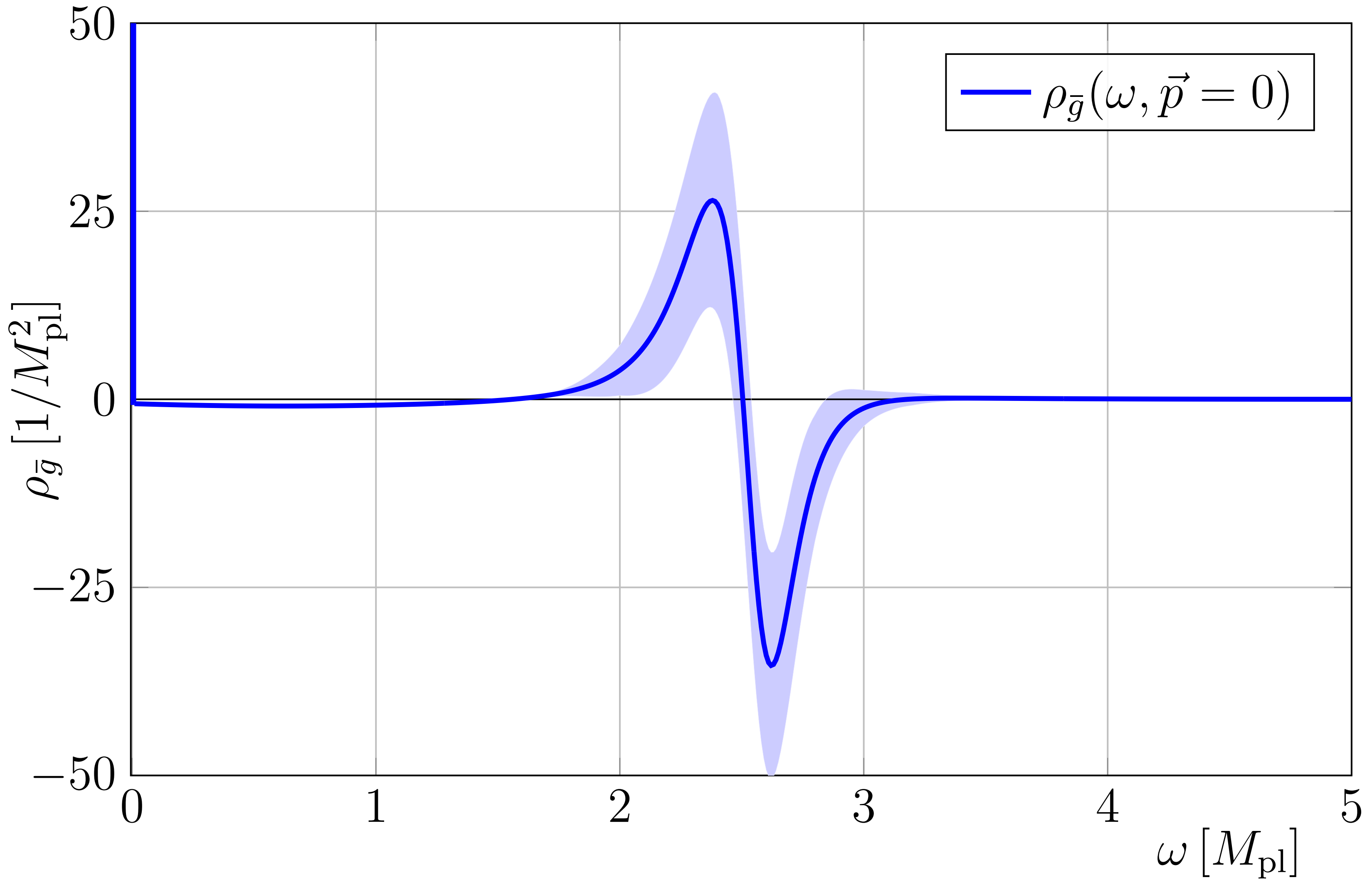
Reconstruction

Graviton spectral function



IR delta-function

Spectral function of the background graviton



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

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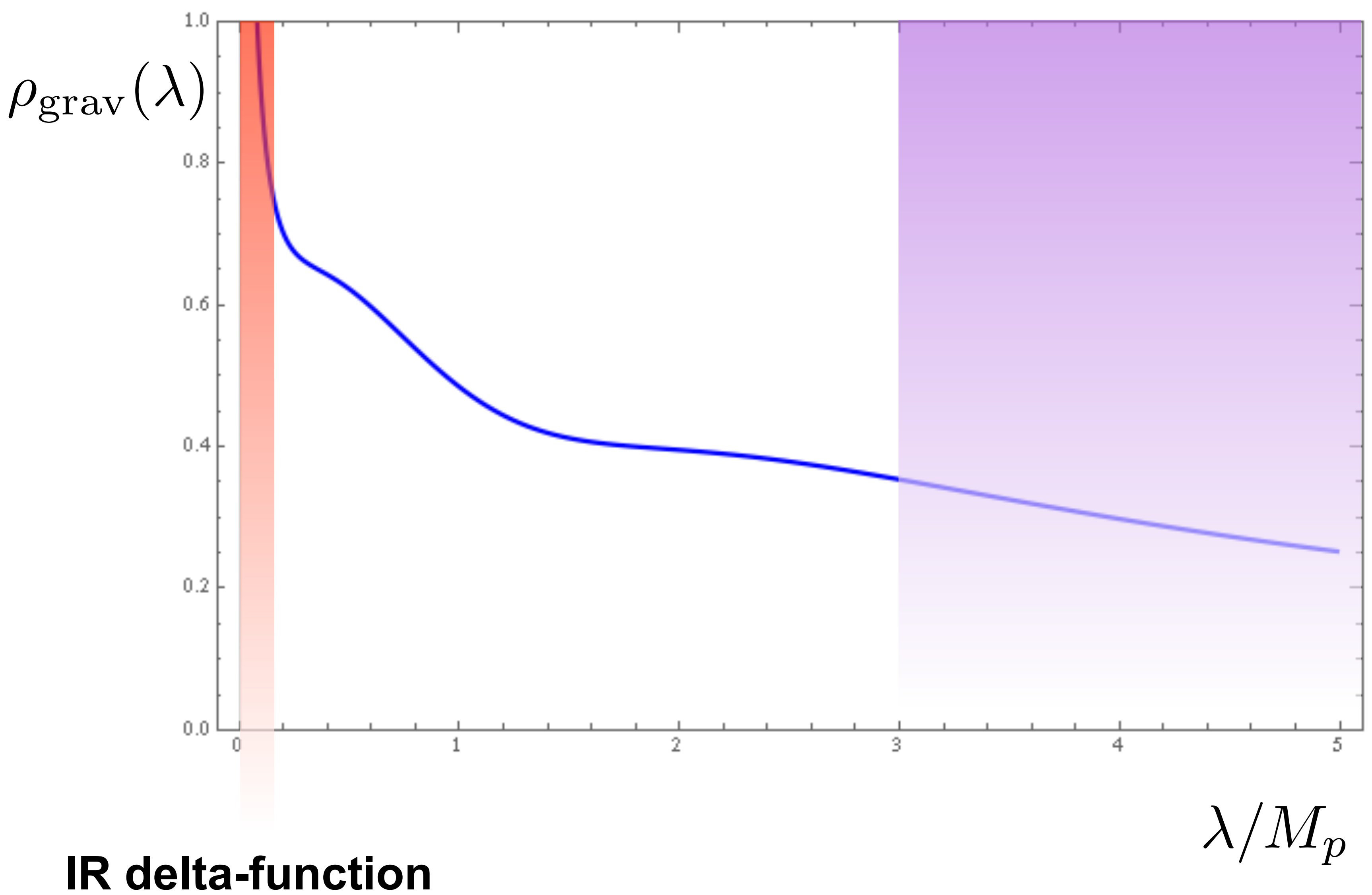
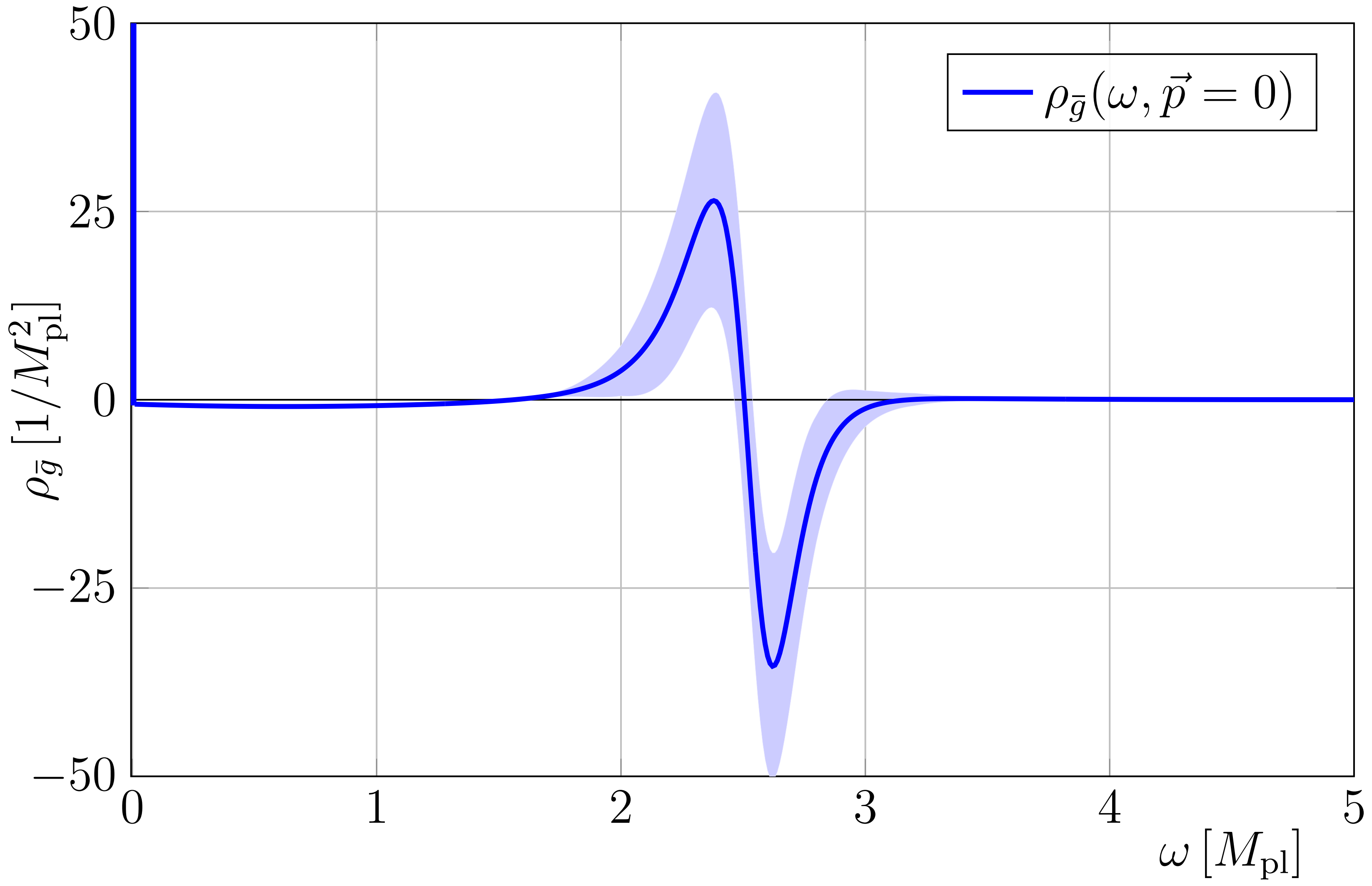


Spectral function of the background graviton



Spectral properties 'resemble' that of an asymptotic state

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

Spectral properties of an unphysical mode

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

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

Spectral flows

Fehre, Litim, JMP, Reichert, PRL 130 (2023) 8, 081501

Braun, Chen, Fu, Geißel, Horak, Huang, Ihssen, JMP, Reichert, Rennecke,

Tan, Töpfel, Wessely, Wink,SciPost Phys.Core 6 (2023) 061

Horak, Wessely, JMP, Wink, arXiv:2303.16719

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Fehre, Litim, JMP, Reichert, PRL 130 (2023) 8, 081501

fQCD, Reichert, SciPost Phys.Core 6 (2023) 061

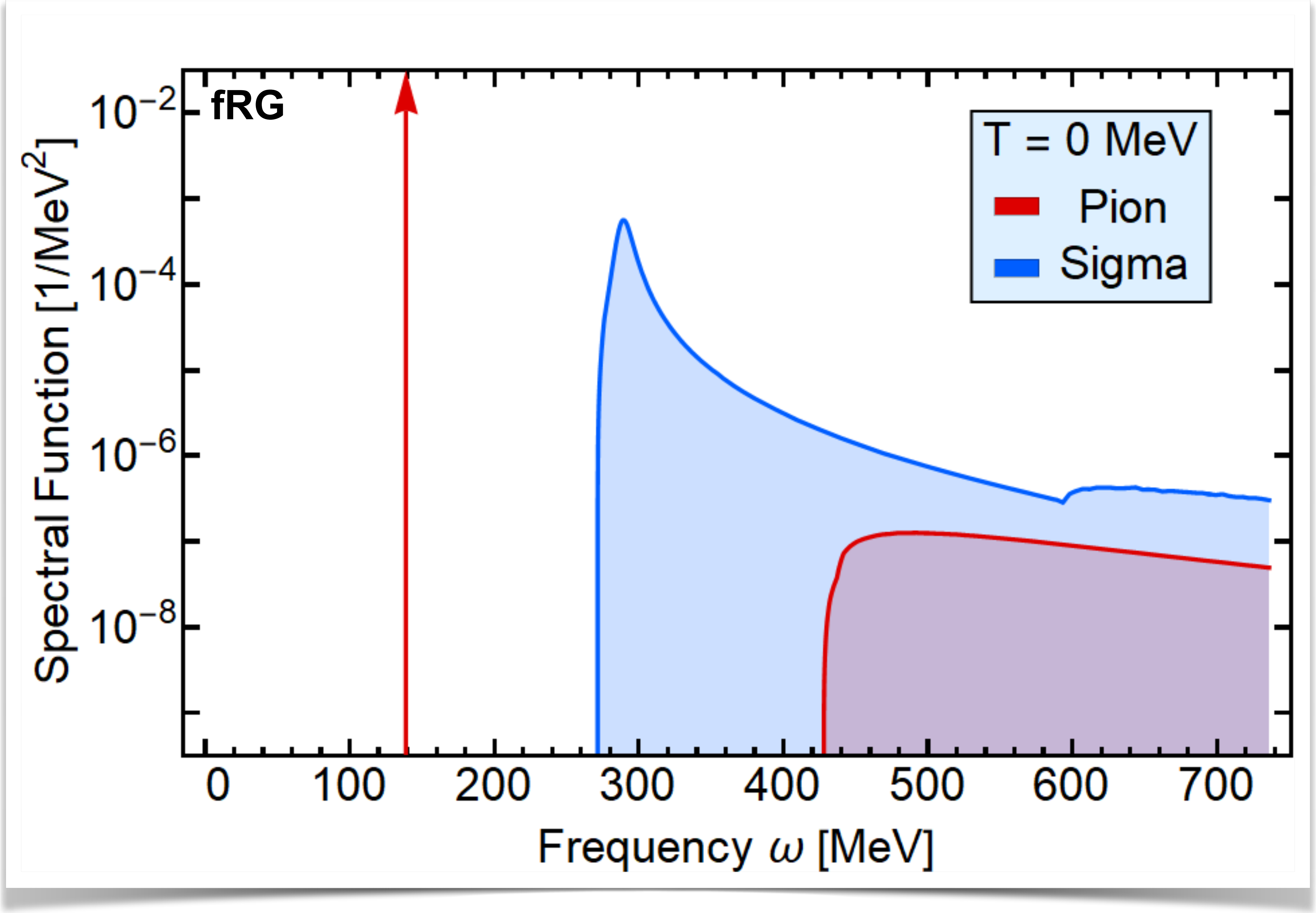
Horak, Wessely, JMP, Wink, arXiv:2303.16719

Realtime functional approaches at work in standard QFT

'… and now for something
Completely different…'

Finite T Sigma & Pion spectral functions

Linear sigma model/ scalar O(4)-model



JMP, Strodthoff, Wink, PRD 98 (2018) 074008

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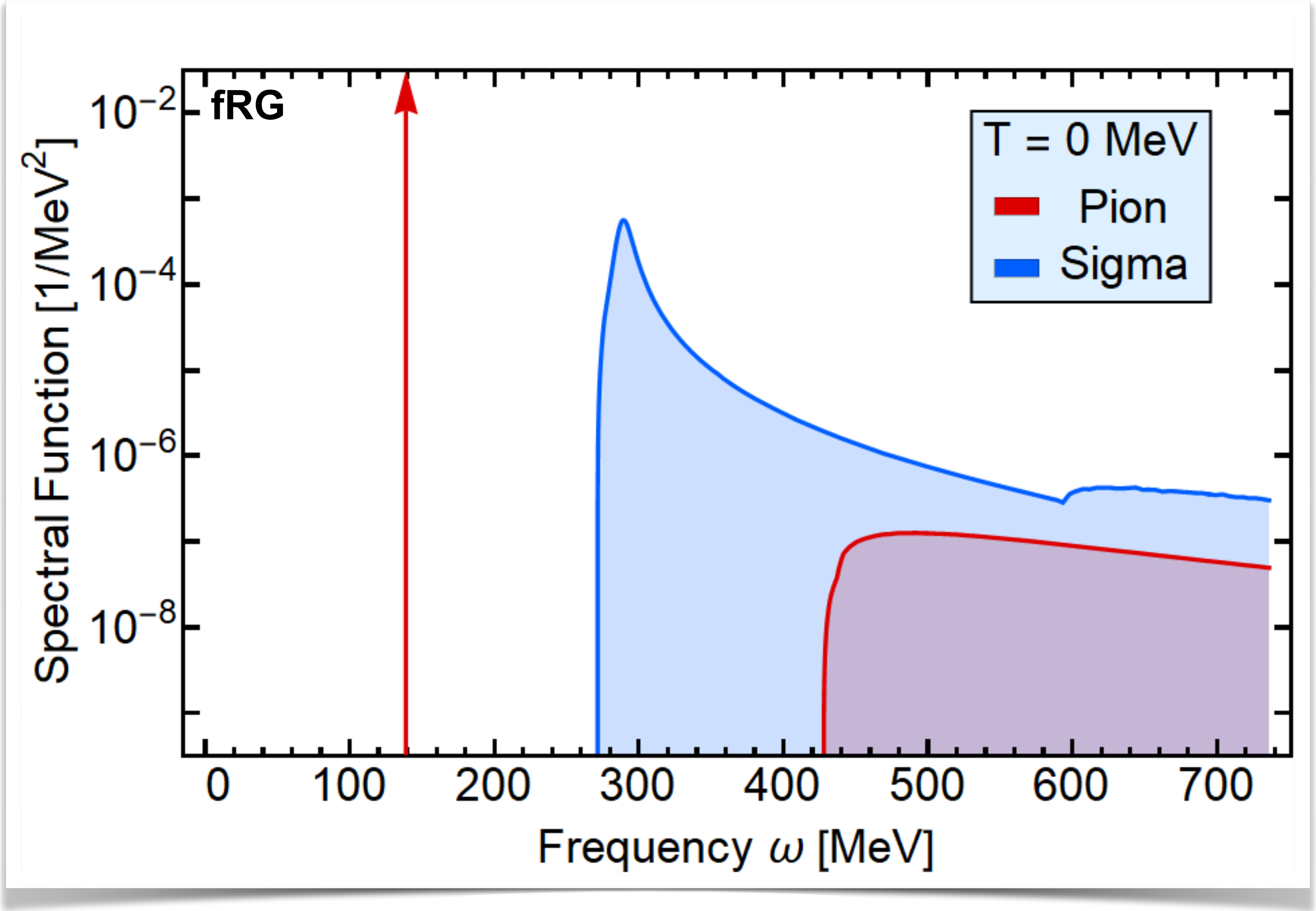

JMP, Strodthoff, Wink, PRD 98 (2018) 074008

Real time flows

Spectral representation

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

$$\rho \simeq i \, \langle [\phi(x), \phi(y)] \rangle \qquad F \simeq \langle \{\phi(x), \phi(y)\} \rangle$$

fQCD, Reichert, SciPost Phys.Core 6 (2023) 061

Real time flows

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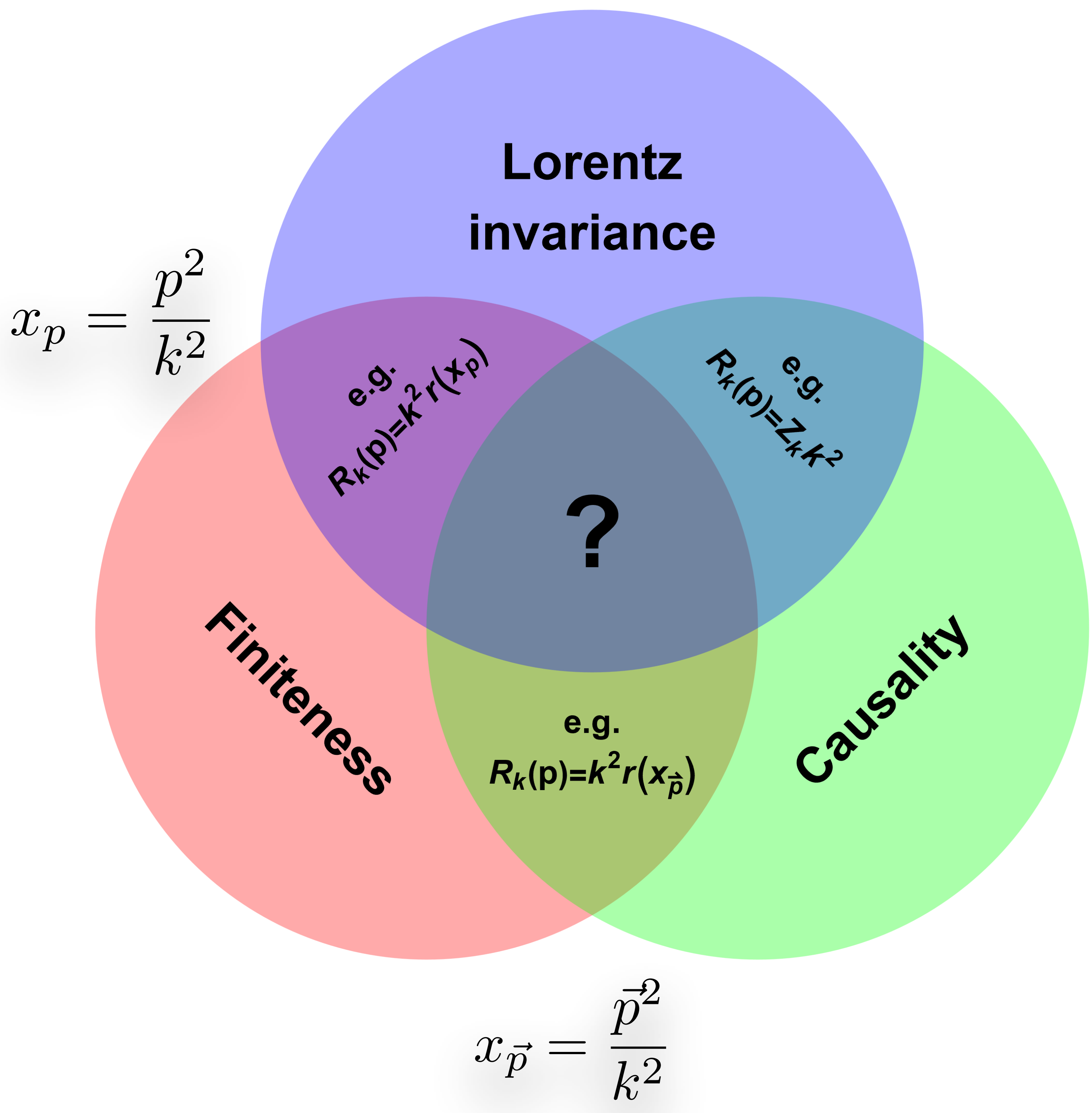
Symmetry preserving regulators



fQCD, Reichert, SciPost Phys.Core 6 (2023) 061

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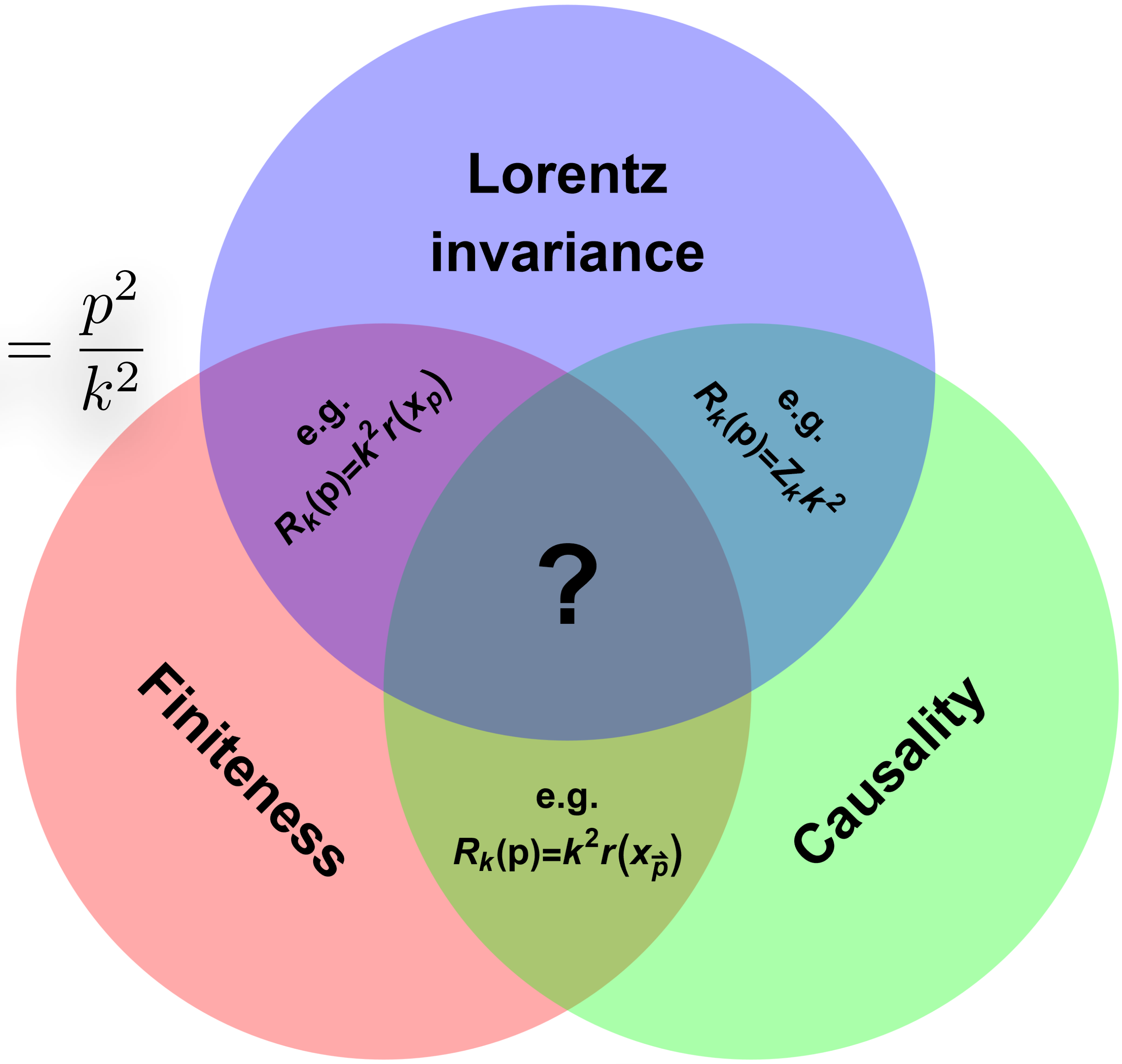
Symmetry preserving regulators

$$x_p = \frac{p^2}{k^2}$$



$$x_{\vec{p}} = \frac{\vec{p}^2}{k^2}$$

Lorentz invariance & Causality

Callan-Symanzik regulator

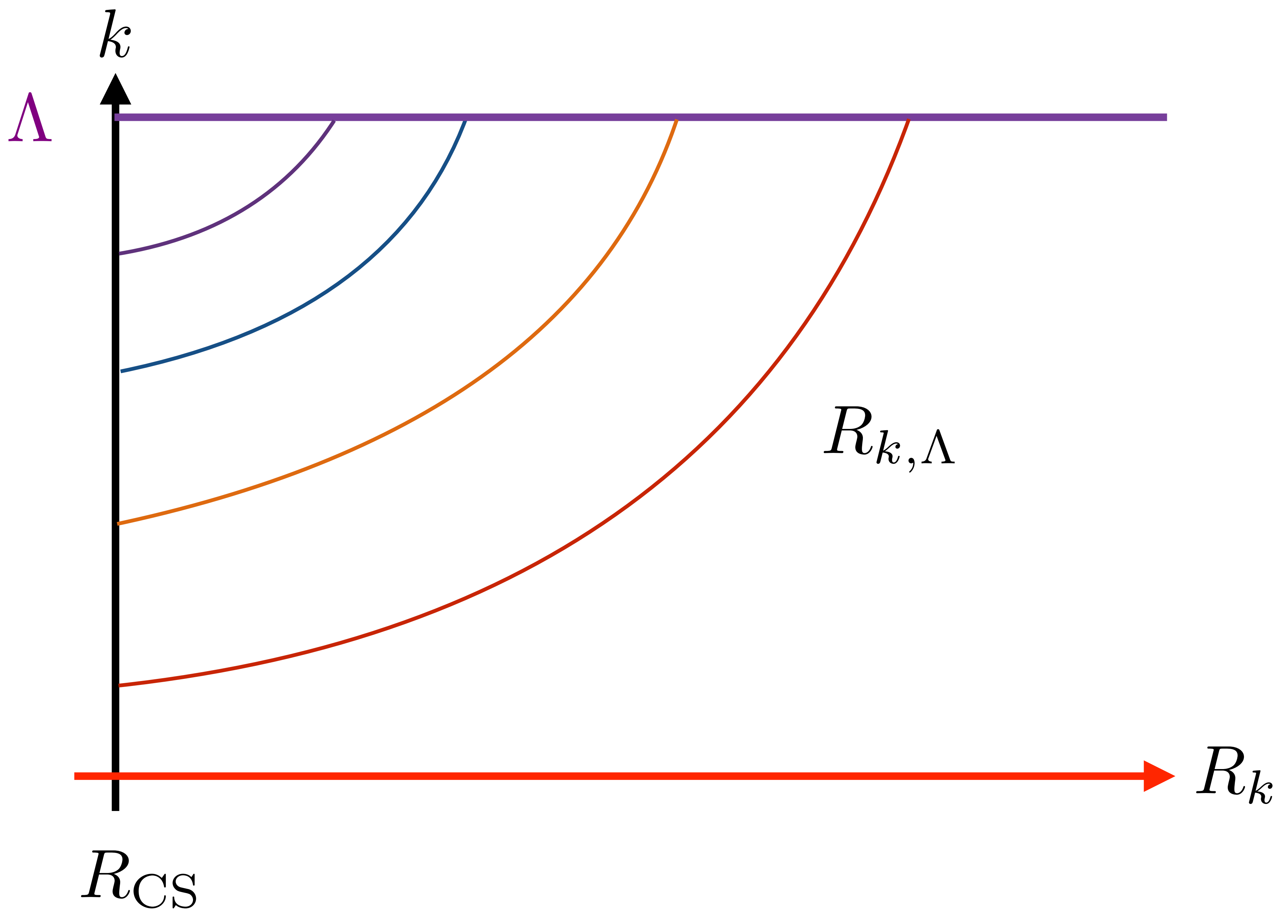
$$R_{\rm CS} = Z_\phi k^2$$

Finiteness lost

fQCD, Reichert, SciPost Phys.Core 6 (2023) 061

Renormalised renormalisation group flows

Idea



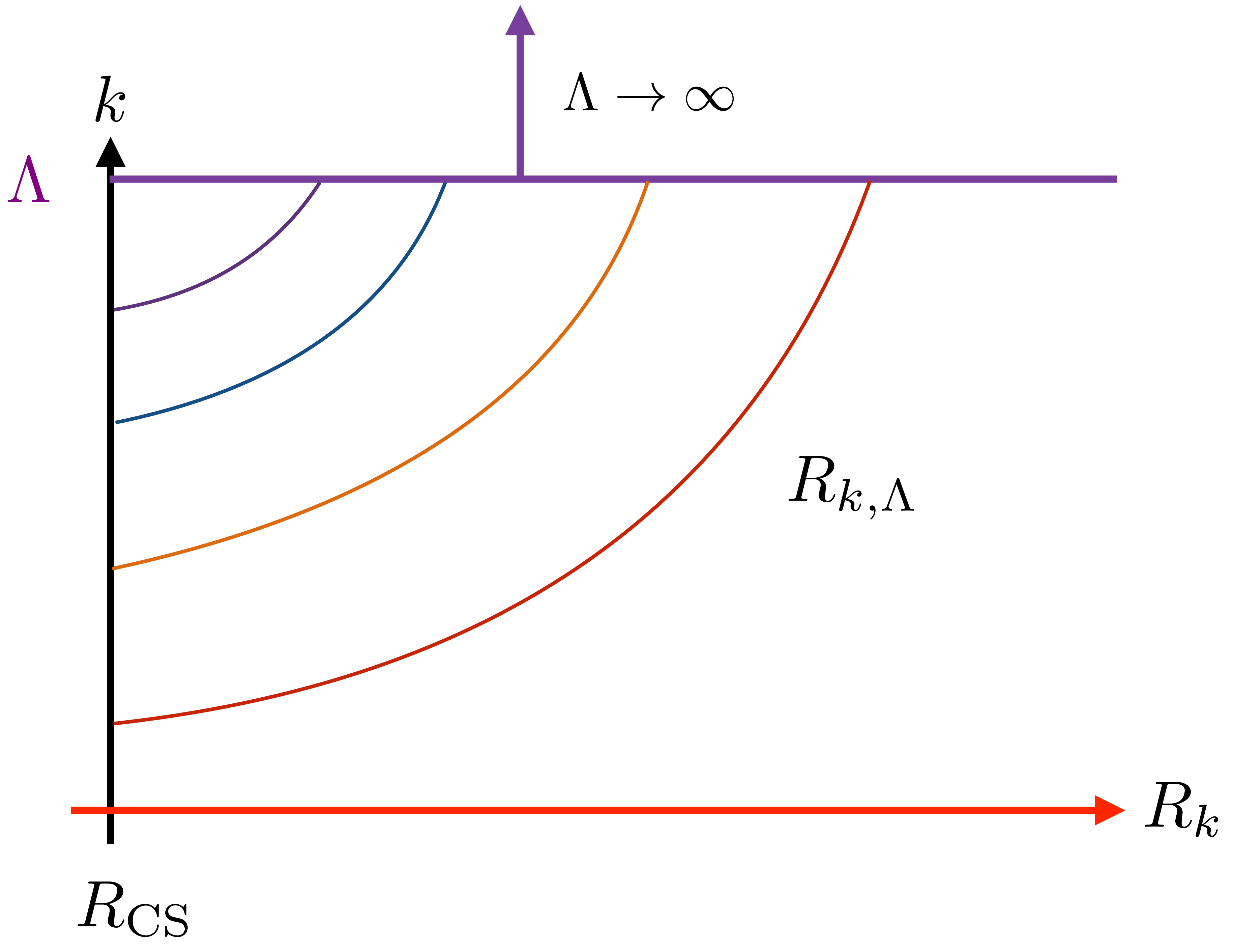
Composite UV-IR fRG flow

$$\left(\partial_t\big|_\Lambda + \mathcal{D}_k\,\partial_{t_\Lambda}\right)\Gamma_{k,\Lambda} = \frac{1}{2}\mathrm{Tr}\,G^{\Phi}_{k,\Lambda}\left(\partial_t\big|_\Lambda R^{\Phi}_{k,\Lambda} + \mathcal{D}_k\,\partial_{t_\Lambda} R^{\Phi}_{k,\Lambda}\right)$$

fQCD, Reichert, SciPost Phys.Core 6 (2023) 061

Renormalised renormalisation group flows

Idea



Limes $\Lambda \to \infty$

$$\mathcal{D}_k\, \partial_{t_\Lambda} \Gamma_{k,\Lambda} - \frac{1}{2} \text{Tr}\, G^{\phi}_{k,\Lambda}\, \mathcal{D}_k\, \partial_{t_\Lambda} R^{\phi}_{k,\Lambda} \to \partial_t S_{\text{cl}}[\phi]$$

Local

Composite UV-IR fRG flow

$$\left(\partial_t\big|_\Lambda + \mathcal{D}_k\, \partial_{t_\Lambda}\right) \Gamma_{k,\Lambda} = \frac{1}{2} \text{Tr}\, G^{\Phi}_{k,\Lambda} \left(\partial_t\big|_\Lambda R^{\Phi}_{k,\Lambda} + \mathcal{D}_k\, \partial_{t_\Lambda} R^{\Phi}_{k,\Lambda}\right)$$

fQCD, Reichert, SciPost Phys.Core 6 (2023) 061

Renormalised renormalisation group flows

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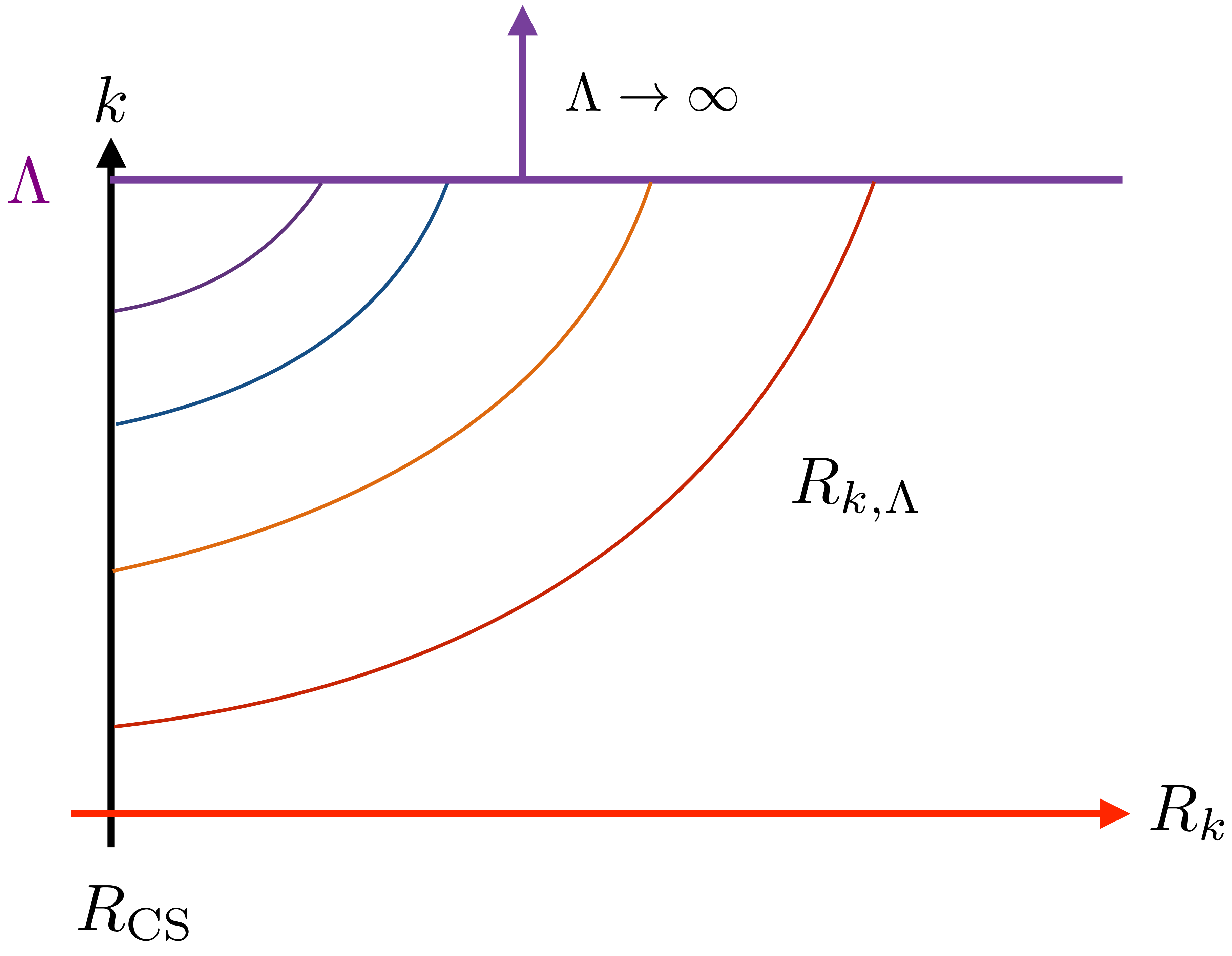

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Local

fRG flow with flowing renormalisation

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \text{Tr}\, G_\phi[\phi]\, \partial_t R^{\phi} - \partial_t S_{\text{ct}}[\phi]$$

fQCD, Reichert, SciPost Phys.Core 6 (2023) 061

Renormalised renormalisation group flows

Spectral CS-fRG flow with flowing renormalisation

$$\partial_t \Gamma_k[\phi] = \mathrm{Tr}\, G_\phi[\phi]\, k^2 - \partial_t S_{\mathrm{ct}}[\phi]$$

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

fQCD, Reichert, arXiv:2206.10232 (SciPost Core)

Renormalised renormalisation group flows

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Flowing on-shell renormalisation

$$\lim_{\Lambda\to\infty} \Gamma^{(2)}_{k,\Lambda}[\bar\phi](p)\Big|_{p_0^2=-\mu^2(k)} = -k^2$$

Controlled UV-limit

fQCD, Reichert, arXiv:2206.10232 (SciPost Core)

Renormalised renormalisation group flows

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fQCD, Reichert, arXiv:2206.10232 (SciPost Core)

Renormalised renormalisation group flows

Spectral CS-fRG flow with flowing renormalisation

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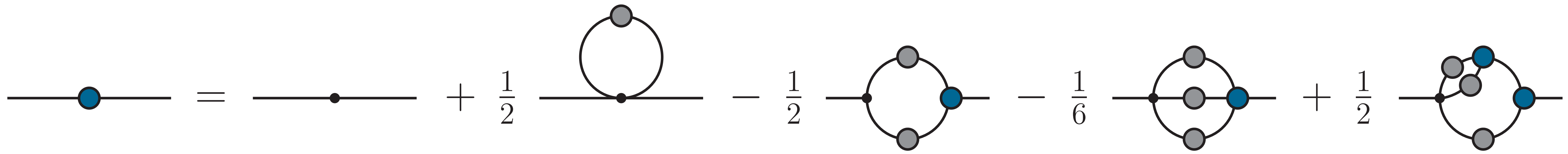
Controlled UV-limit

Similarly for wave function and coupling renormalisation

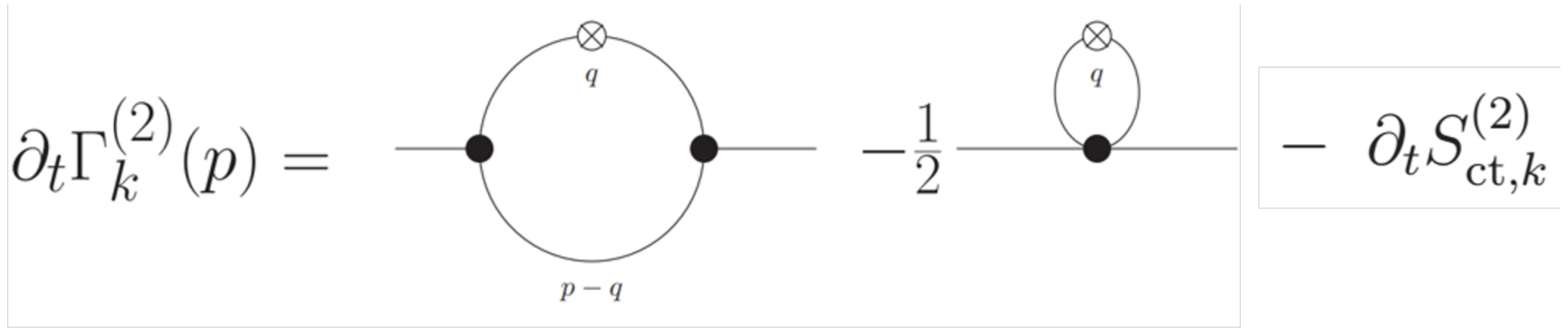
fQCD, Reichert, arXiv:2206.10232 (SciPost Core)

Spectral functional approaches at work

DSE



fRG



Horak, JMP, Wink, PRD 102 (2020) 125016
Horak, Ihssen, JMP, Wessely, Wink, arXiv:2303.16719
accepted at PRD

Spectral functional approaches at work

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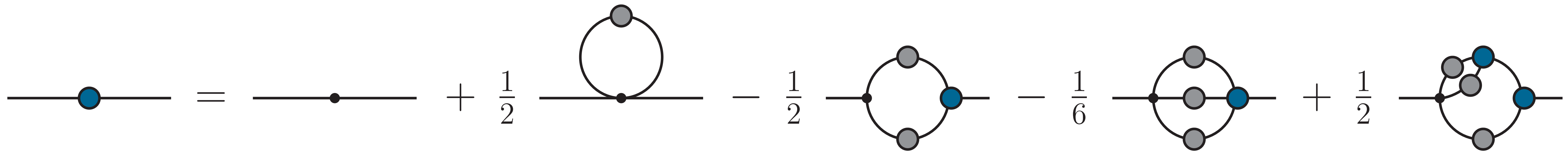

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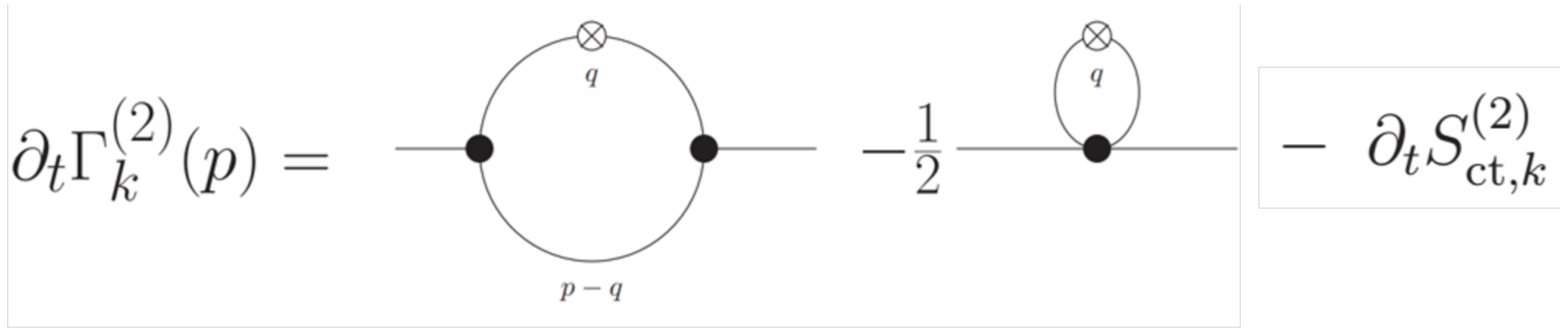

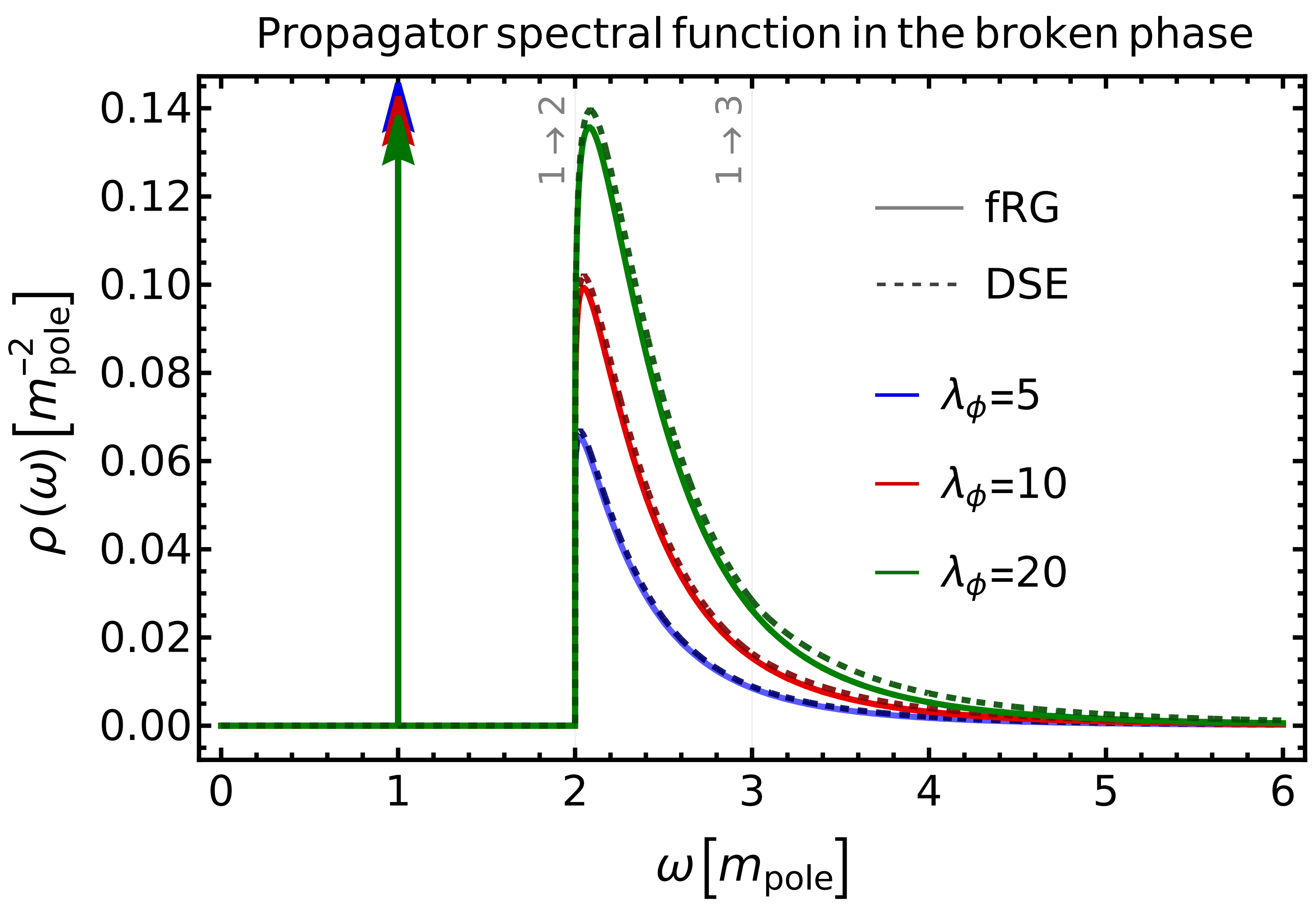

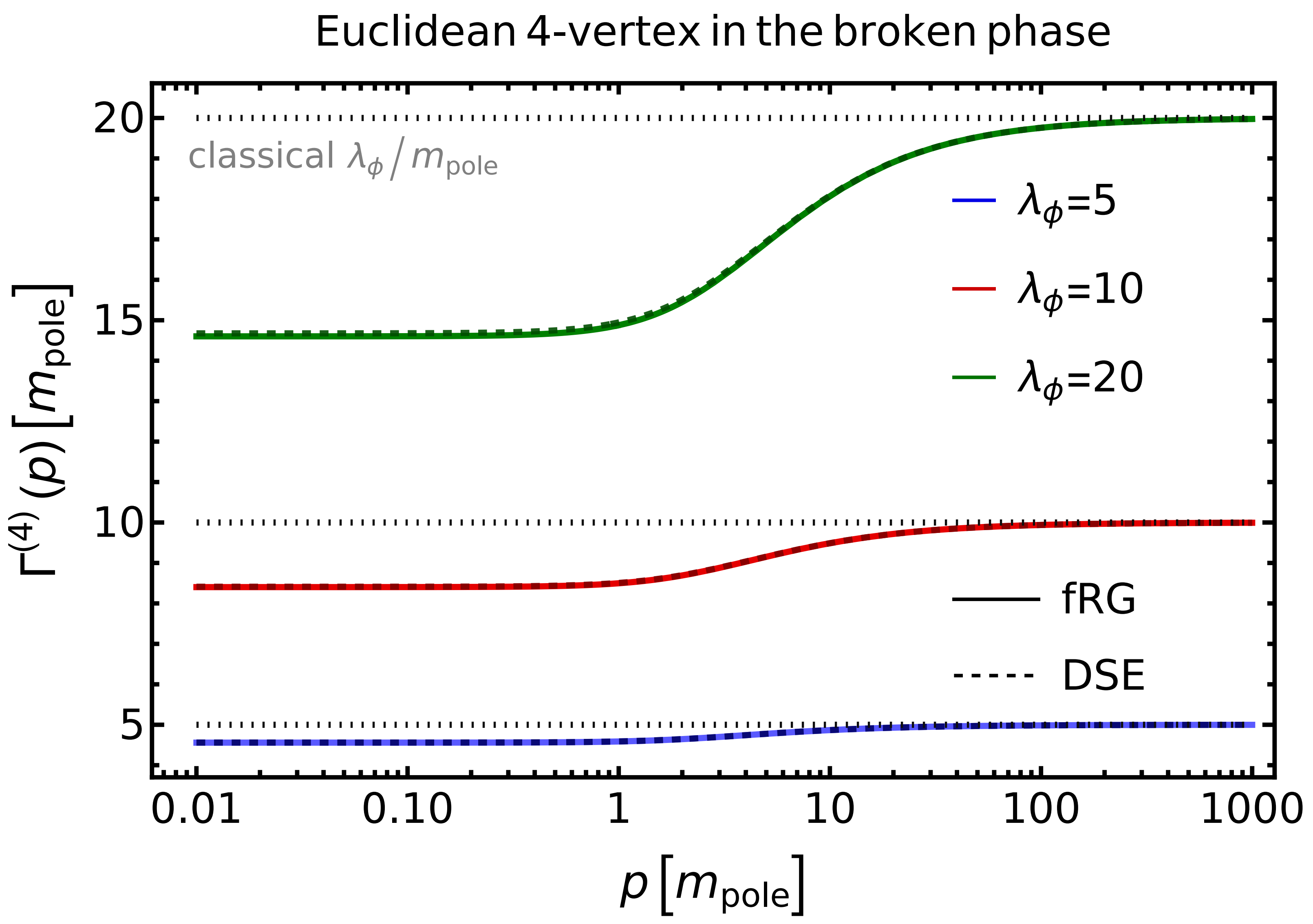

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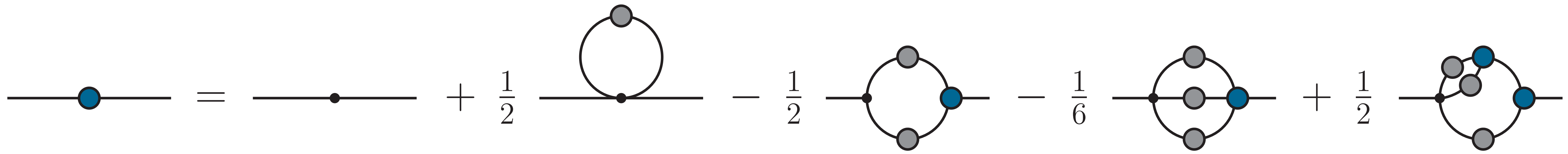

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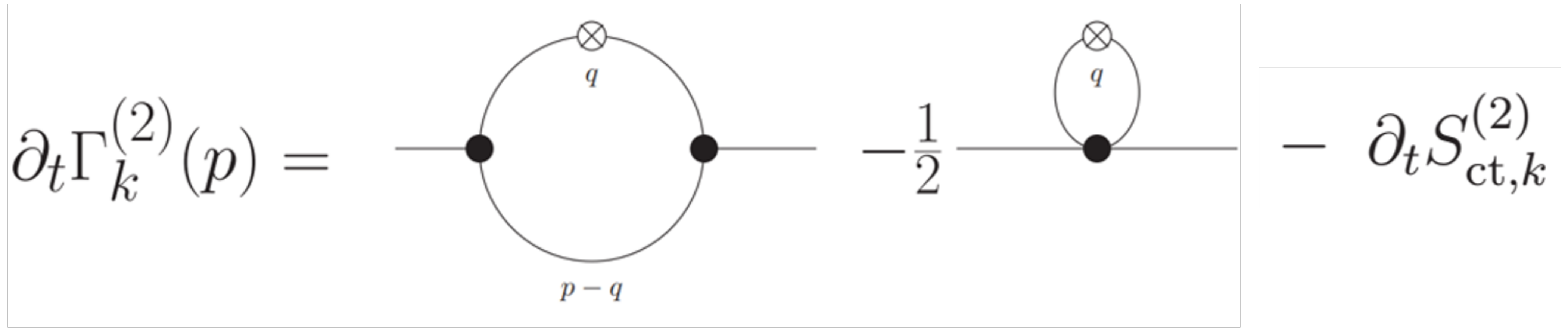

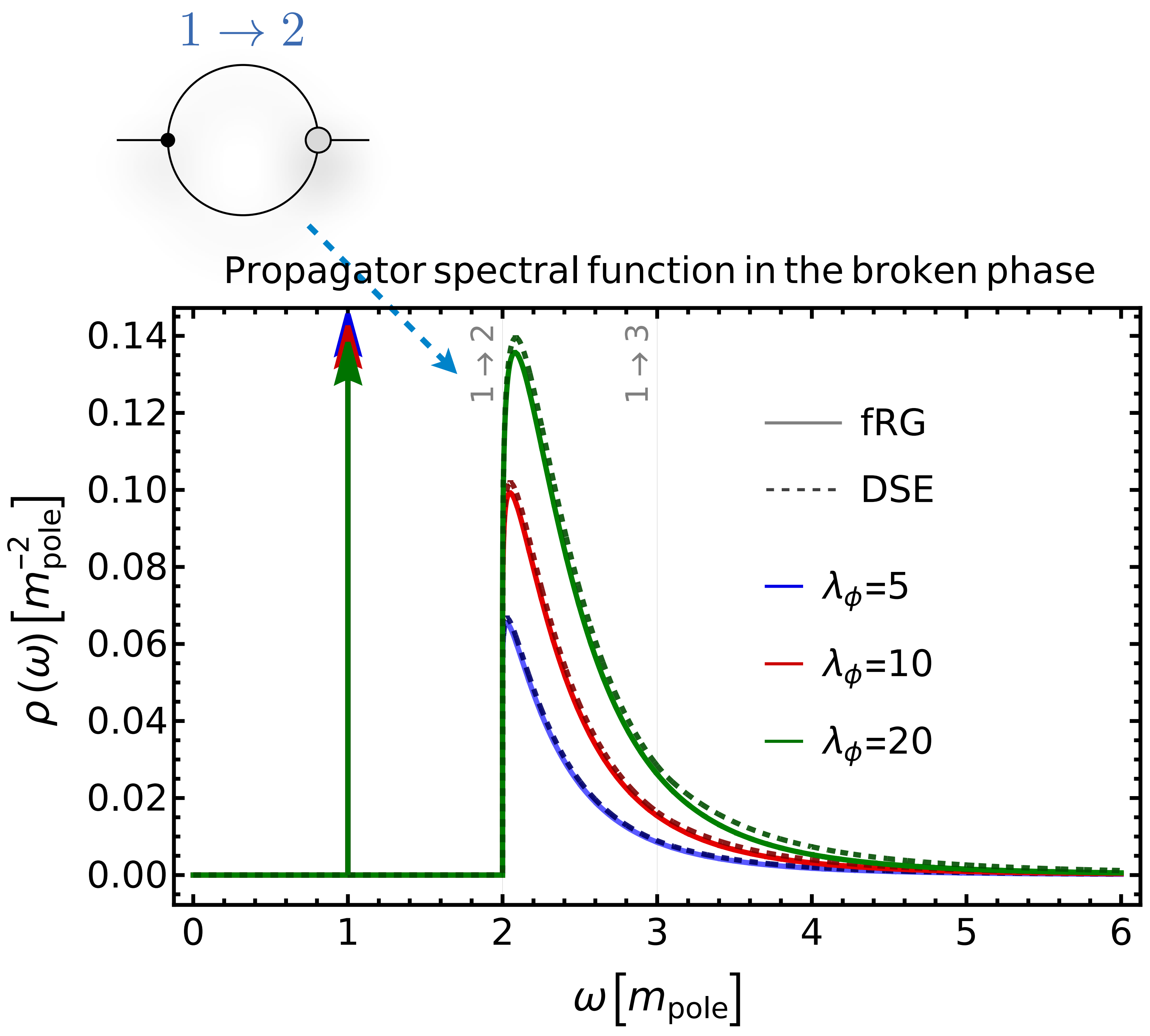

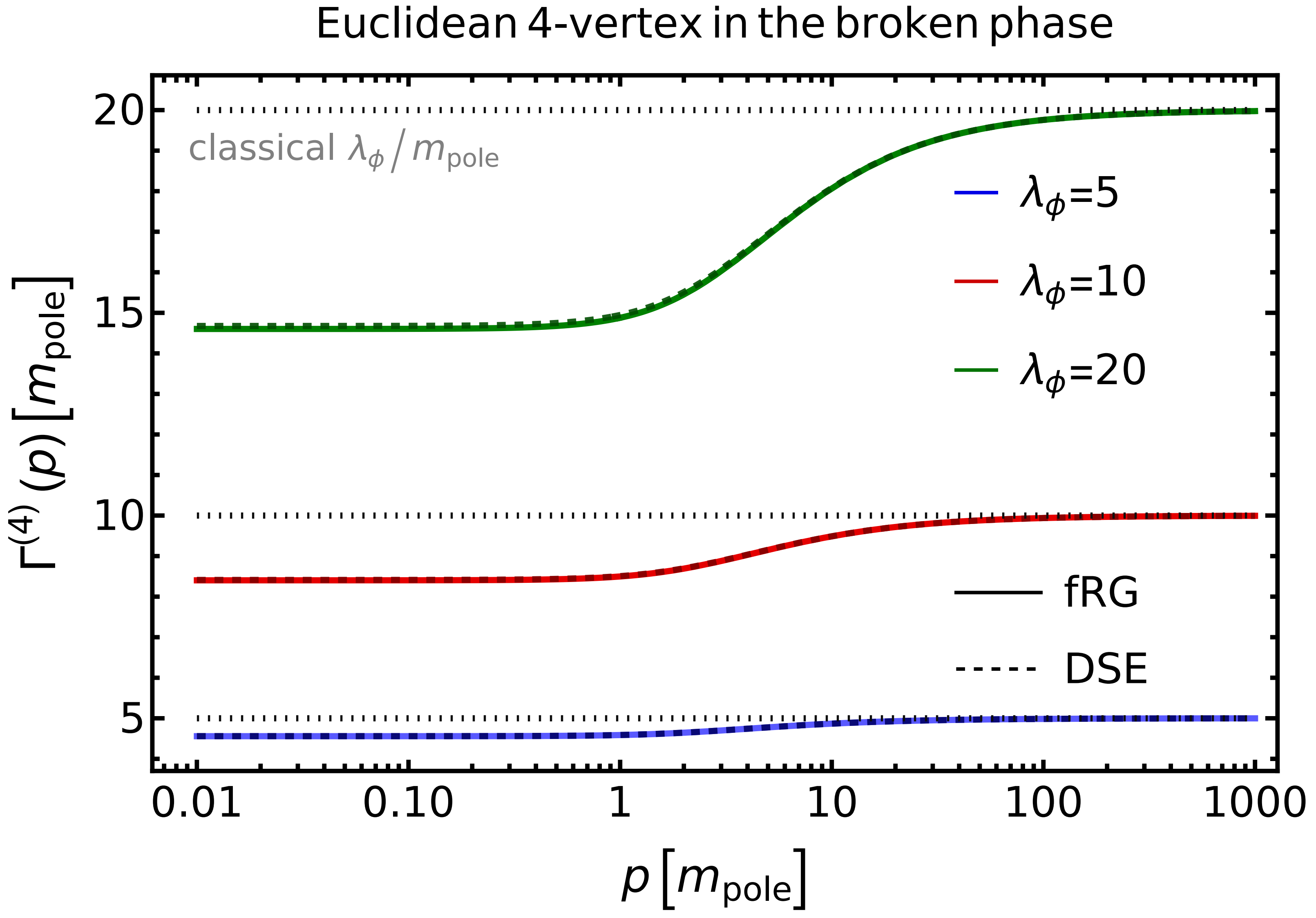

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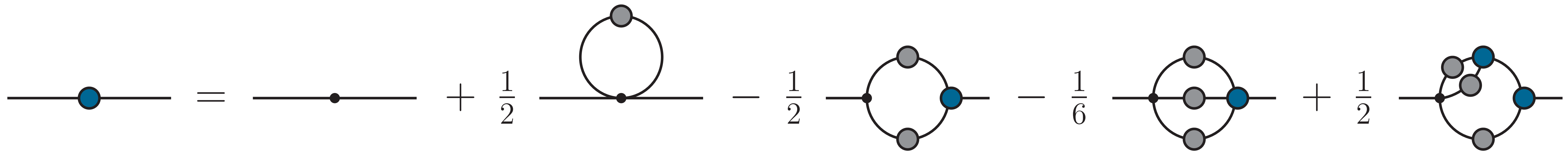

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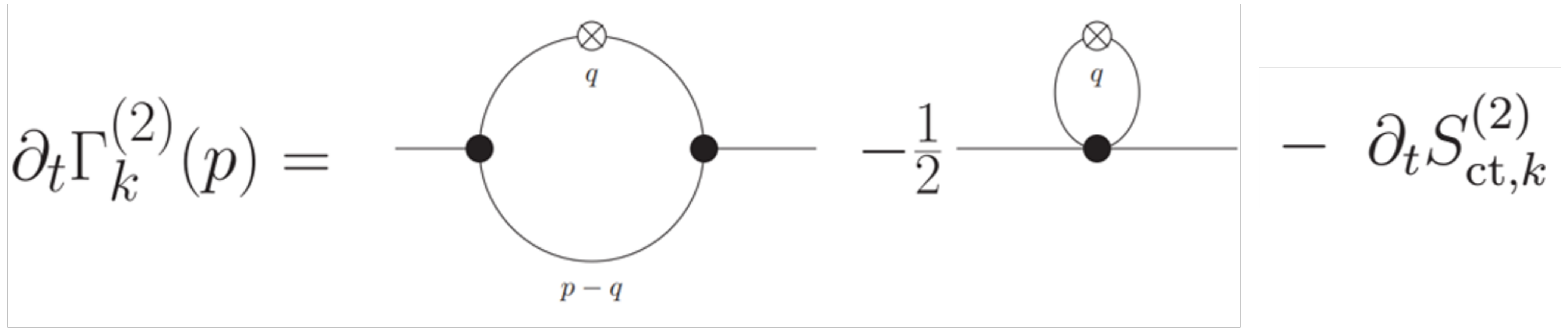

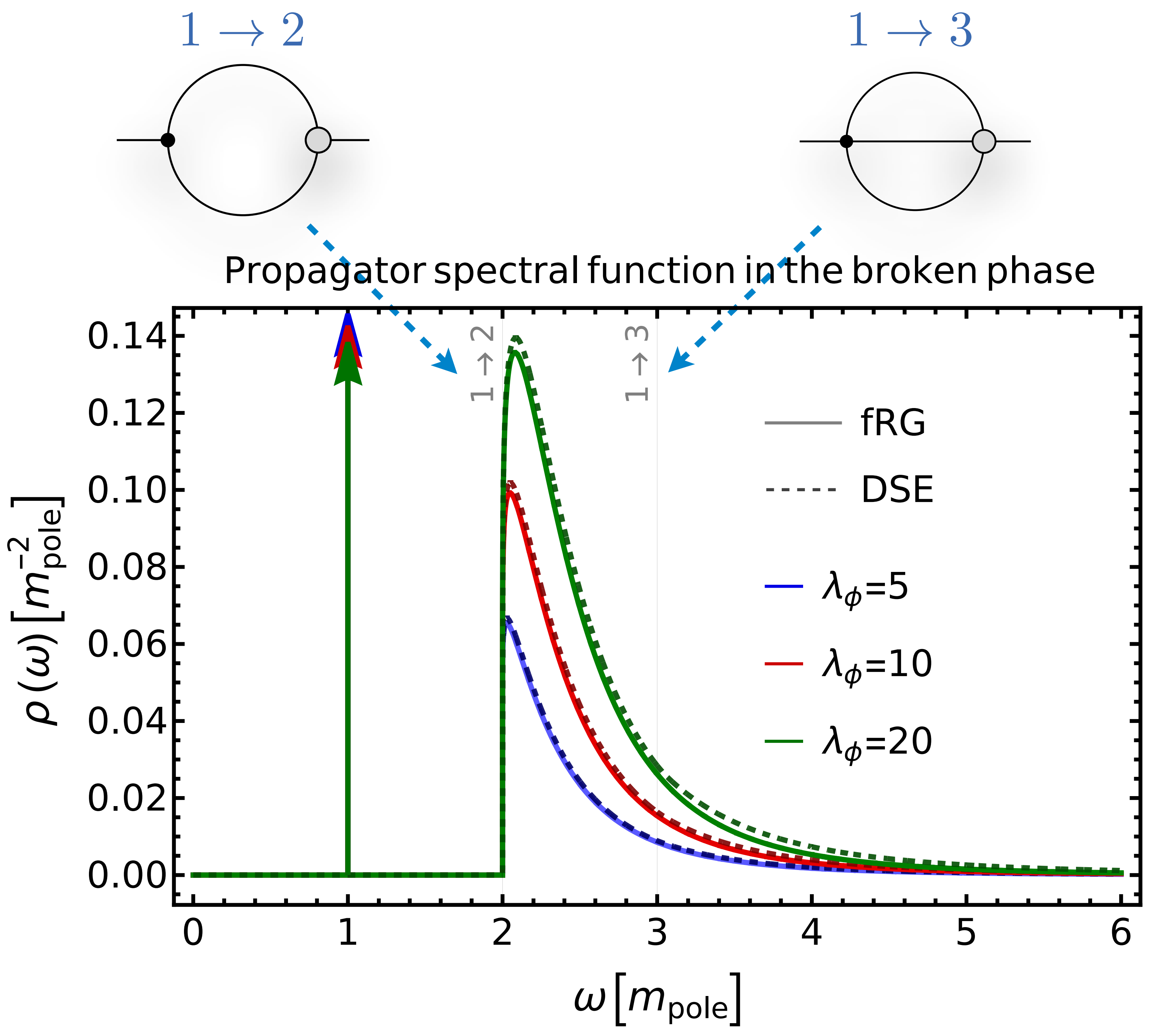

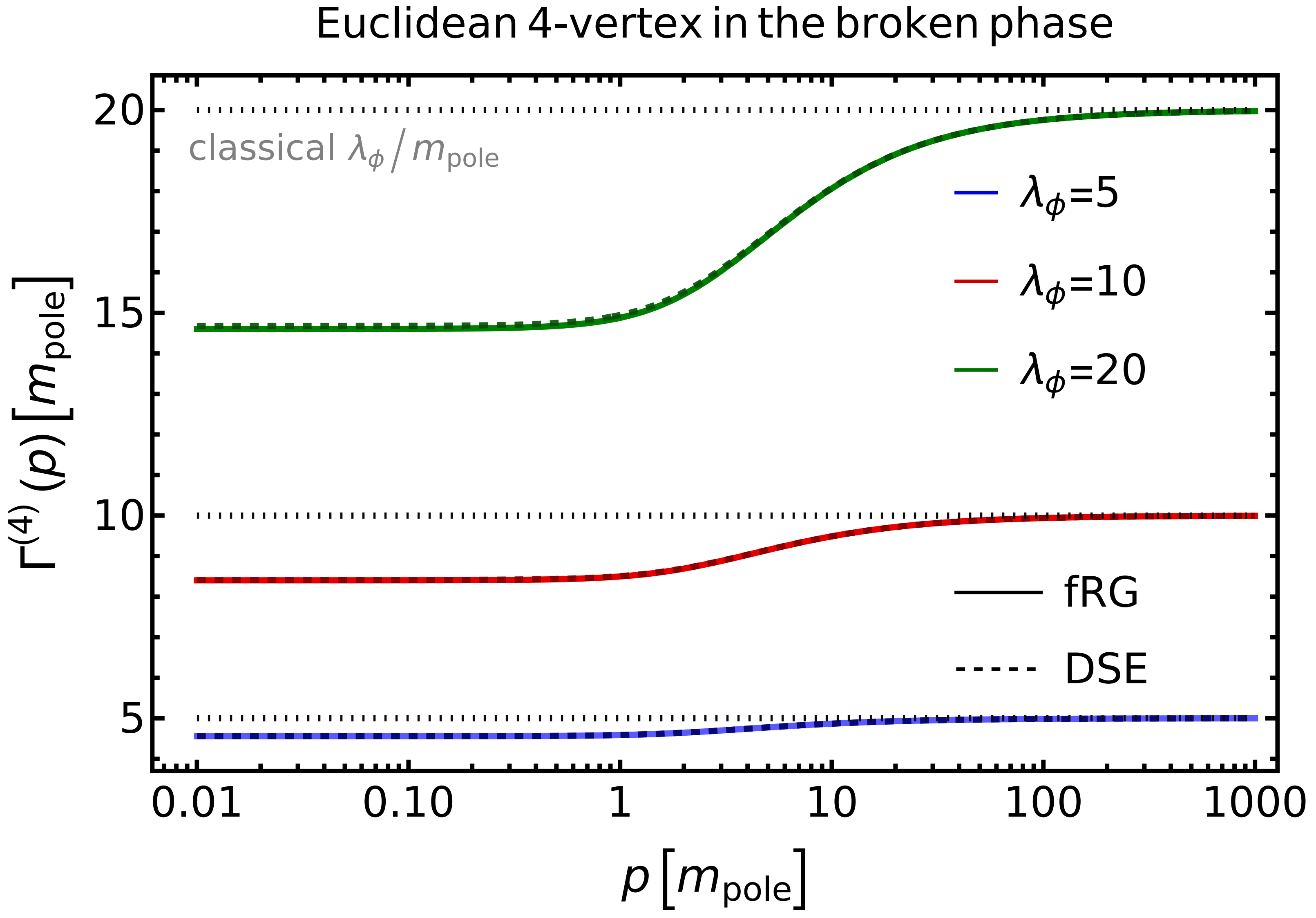

Horak, JMP, Wink, PRD 102 (2020) 125016
Horak, Ihssen, JMP, Wessely, Wink, arXiv:2303.16719
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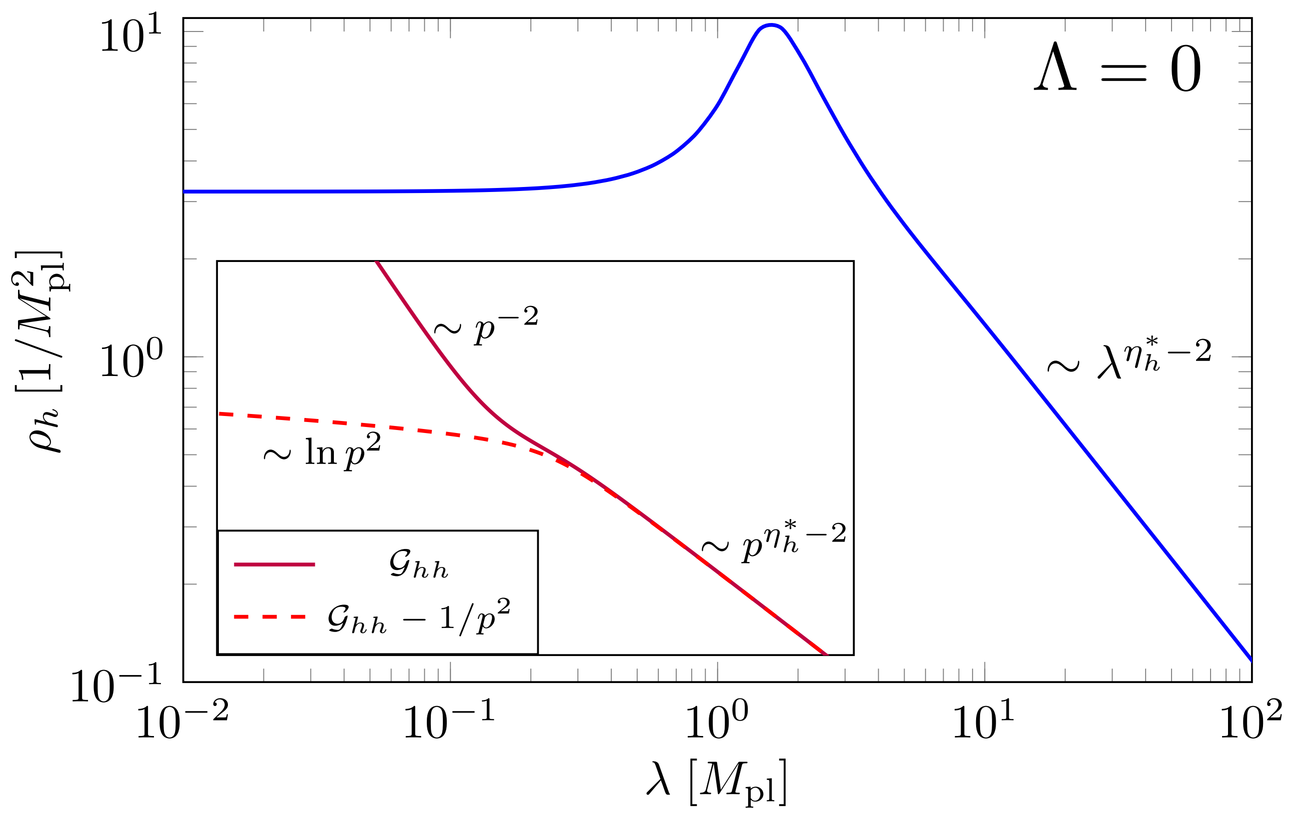
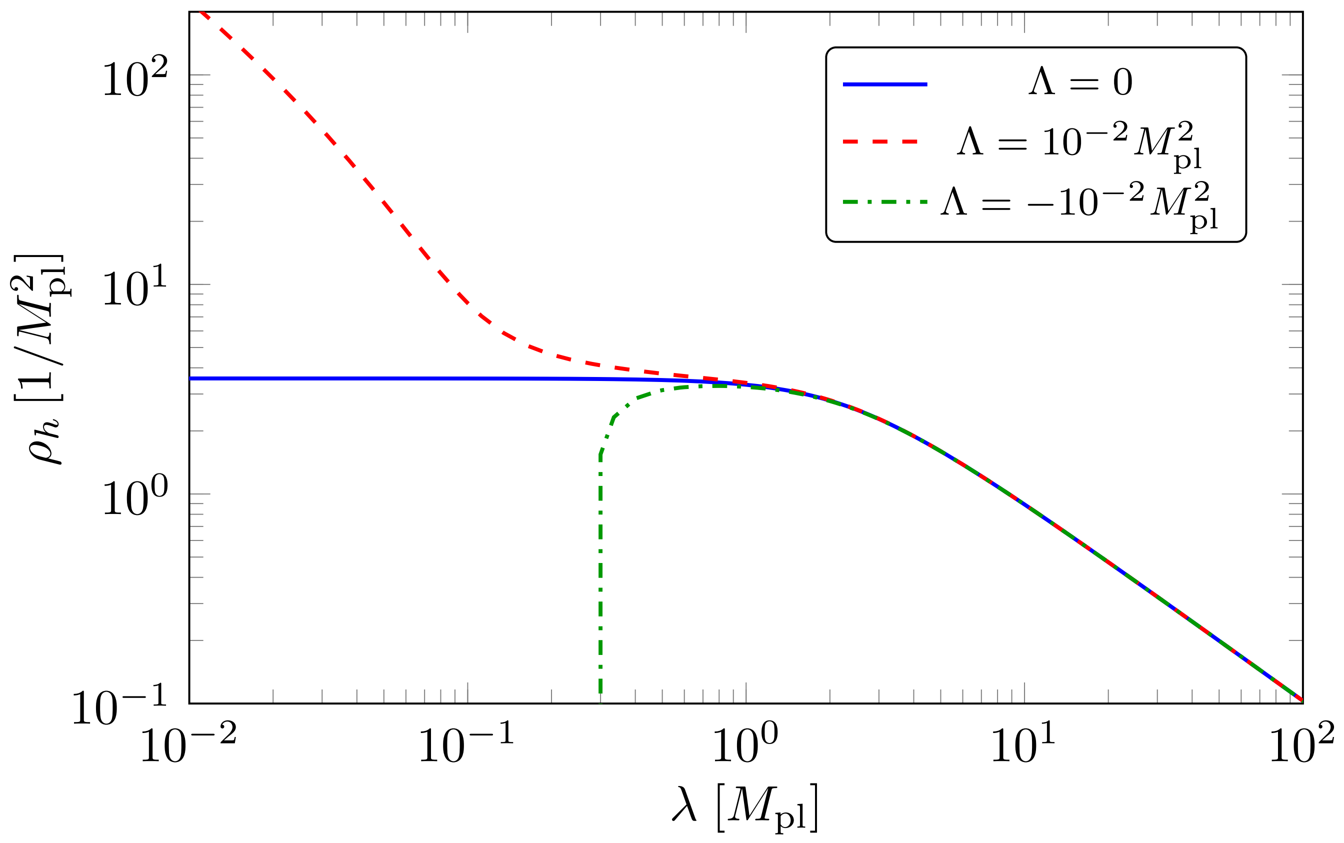
Renormalised renormalisation group flows

Spectral properties of Lorentzian asymptotically safe gravity

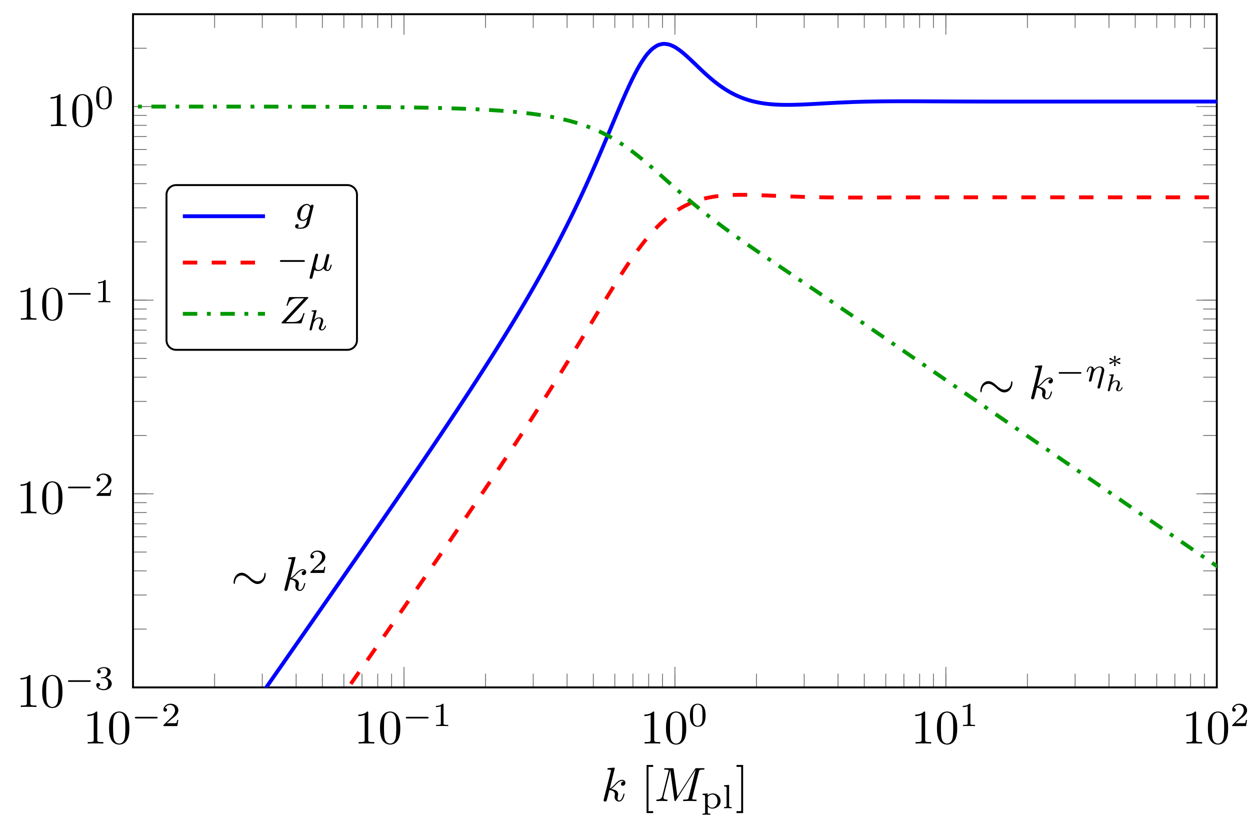
Graviton spectral function



Dependence on Λ



Asymptotically safe couplings



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

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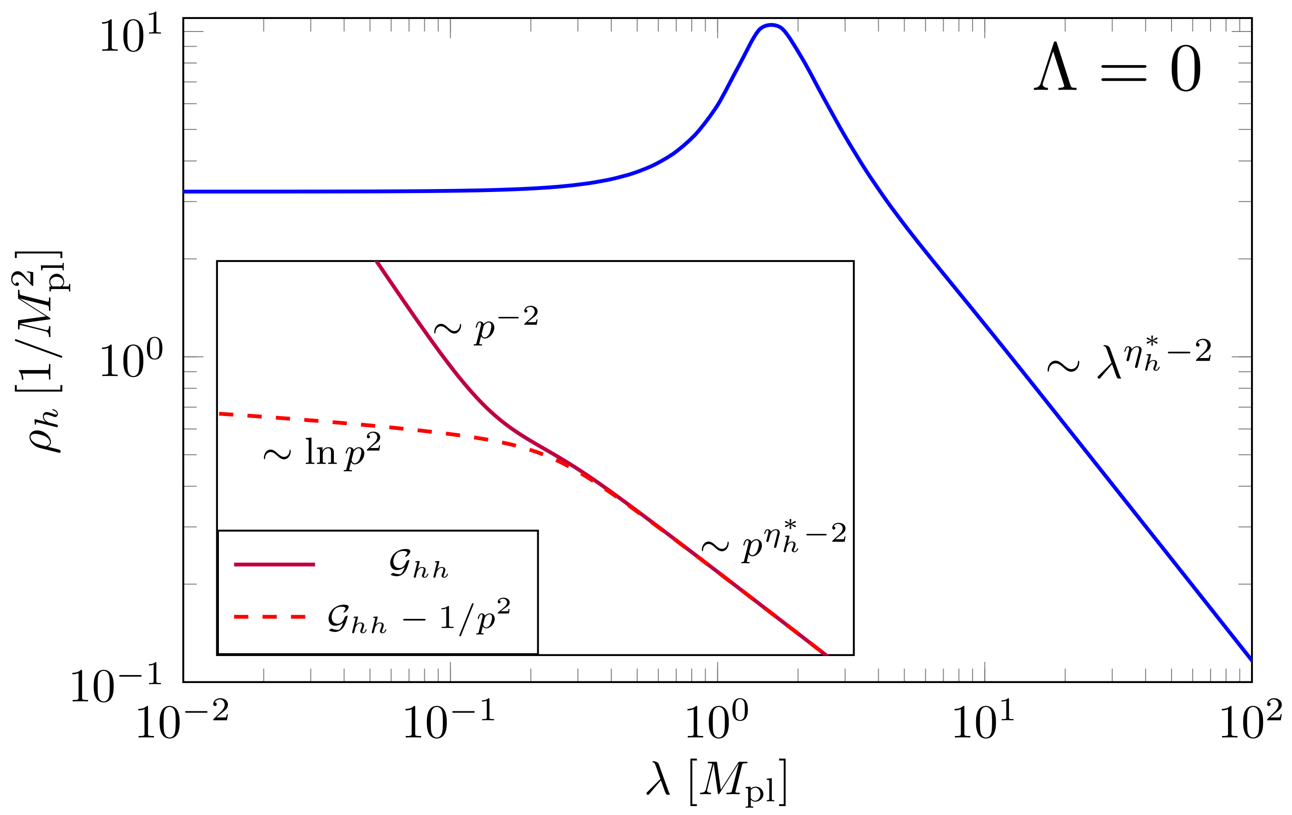

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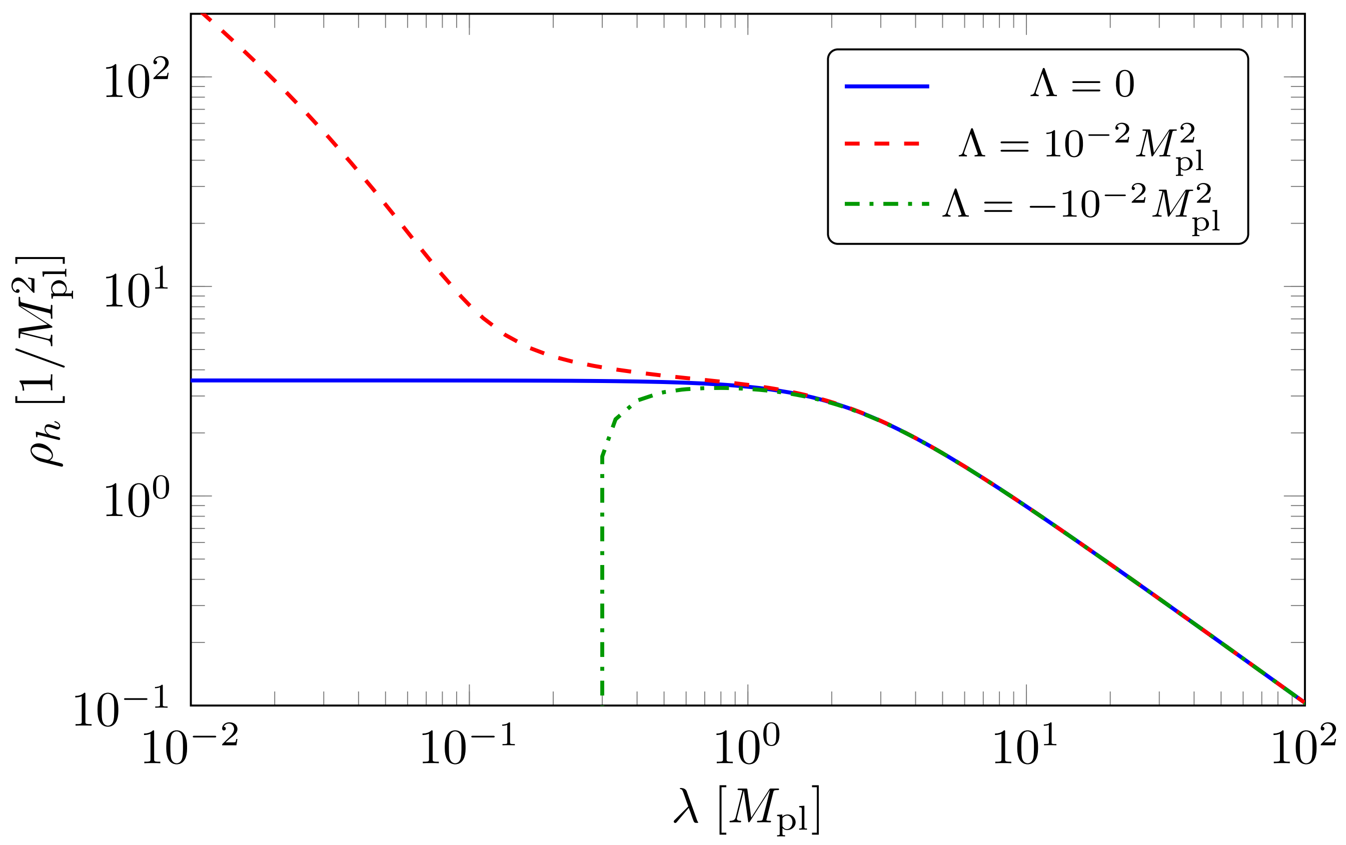

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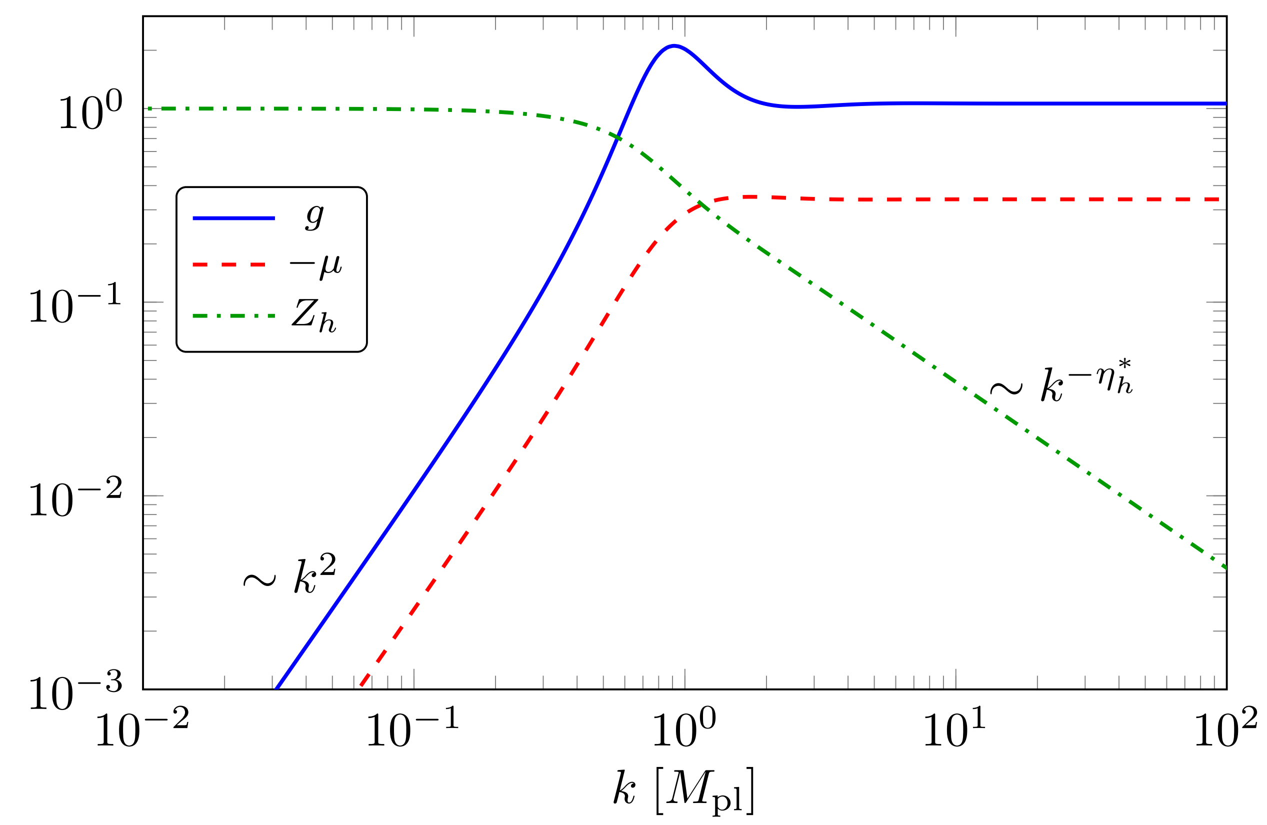
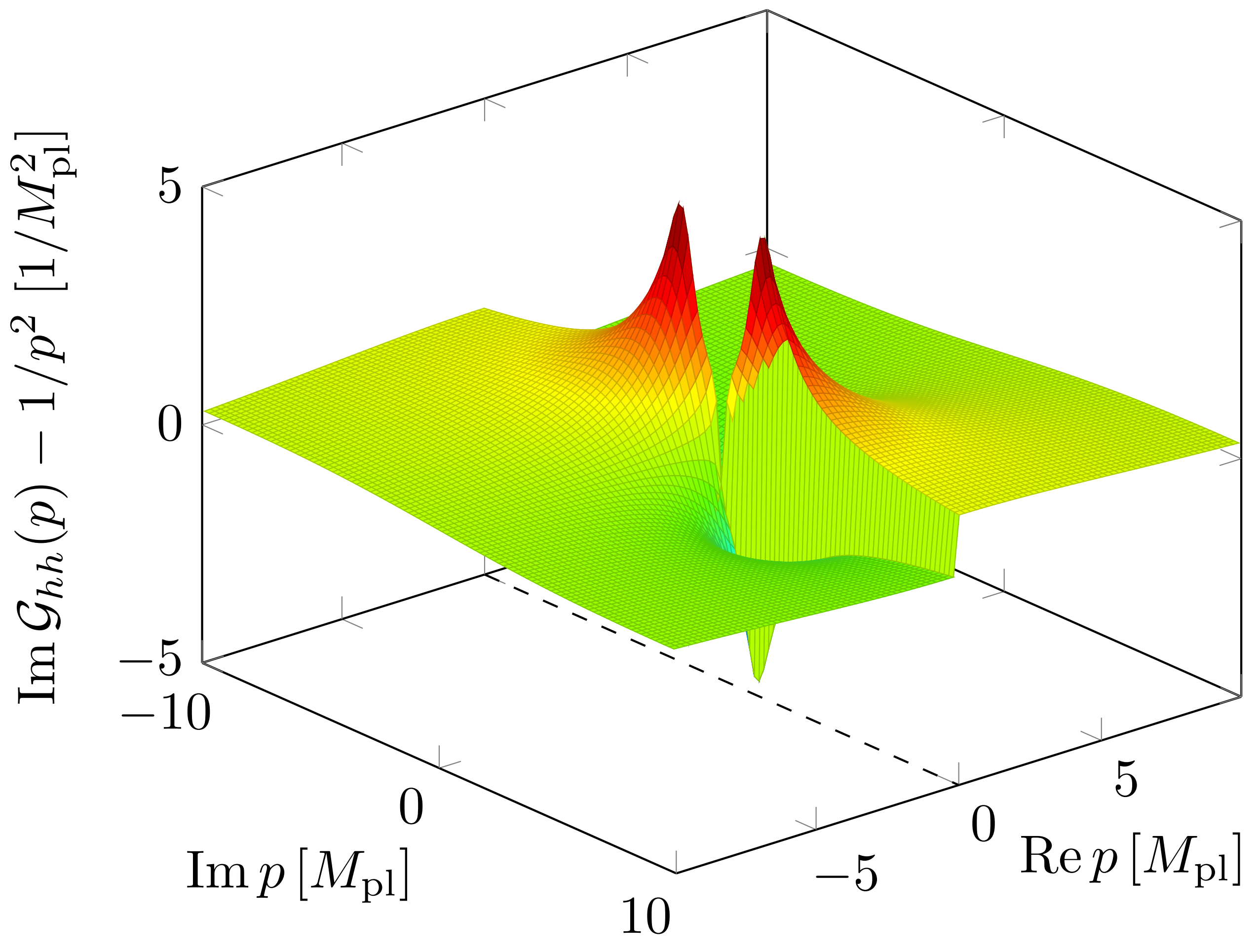
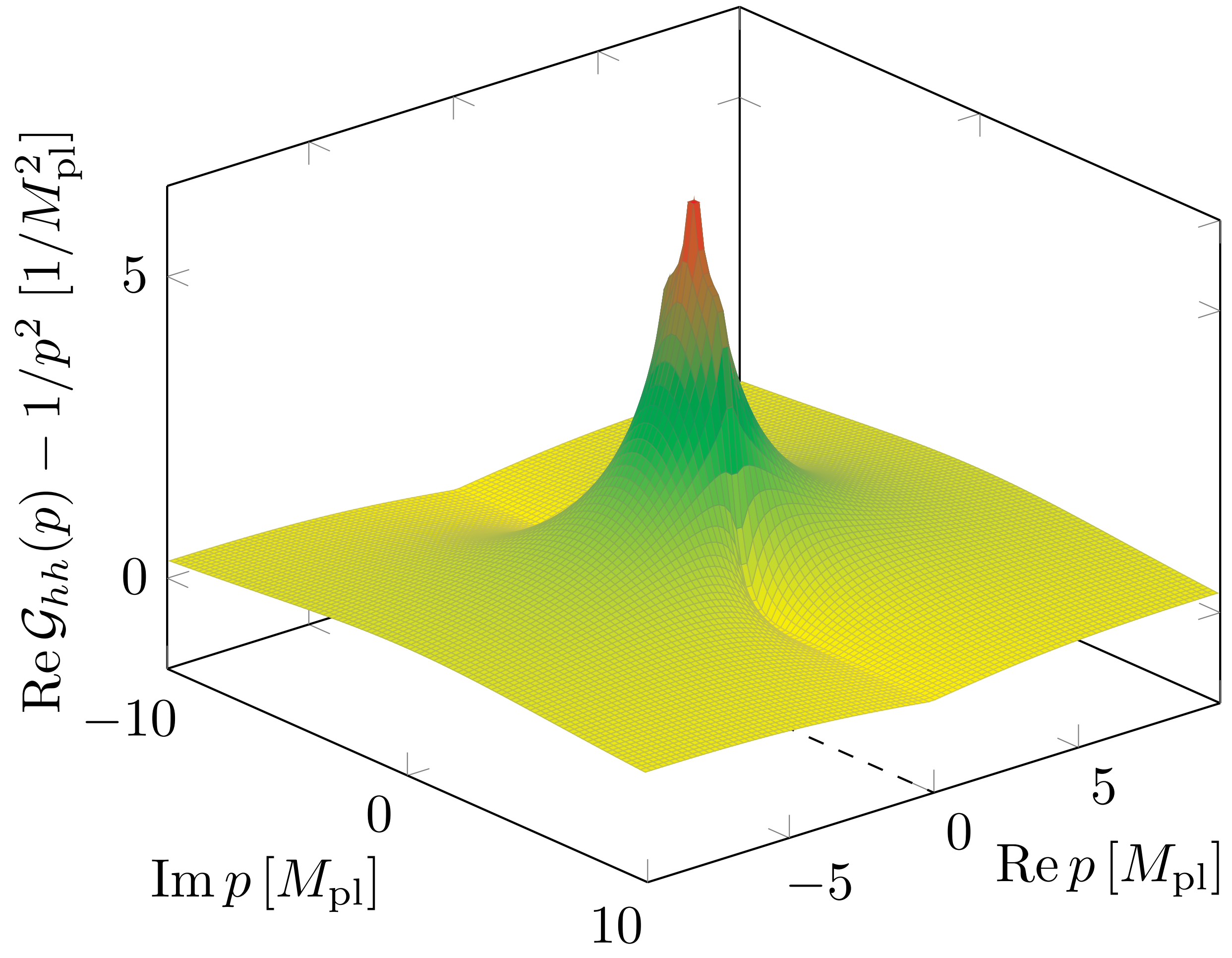


Real part



$$\langle h_{TT}(p) h_{TT}(-p) \rangle$$

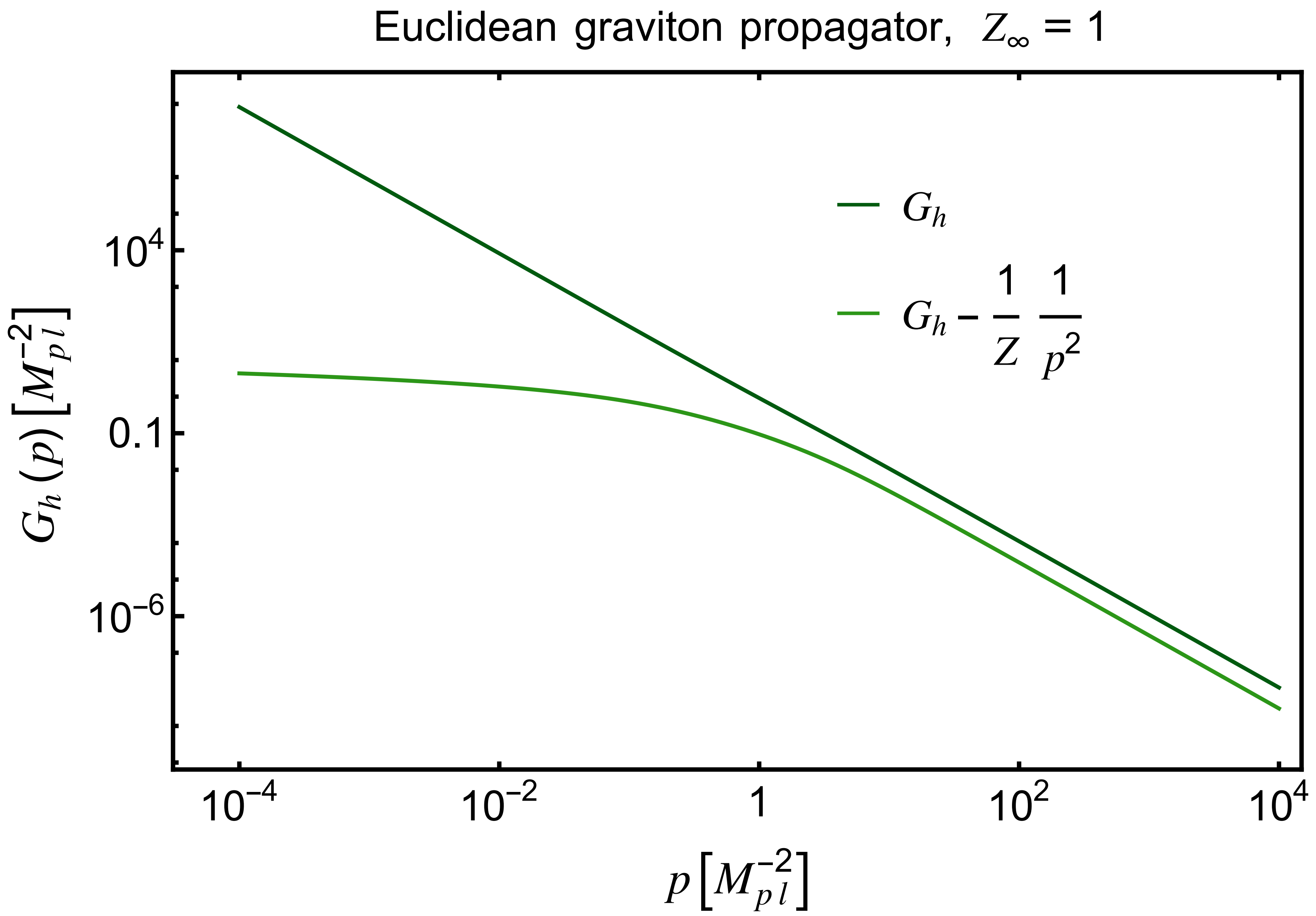
Imaginary part



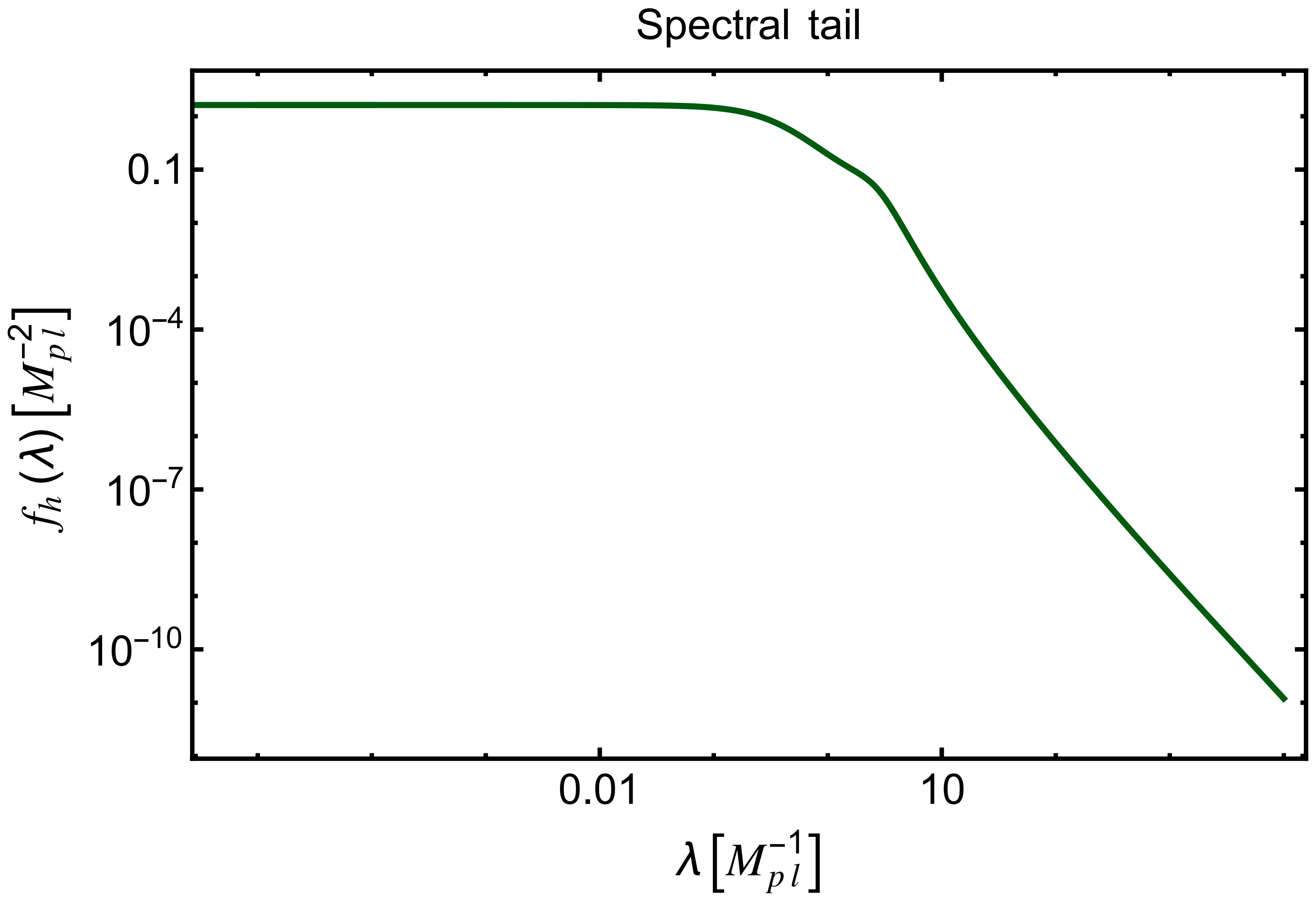
Fehre, Litim, JMP, Reichert, PRL 130 (2023) 081501

Fully self-consistent graviton spectral function with ‘on-shell’ renormalisation

Space-like fluctuation propagator



Spectral function of the fluctuation graviton



JMP, Reichert, Wessely, in preparation

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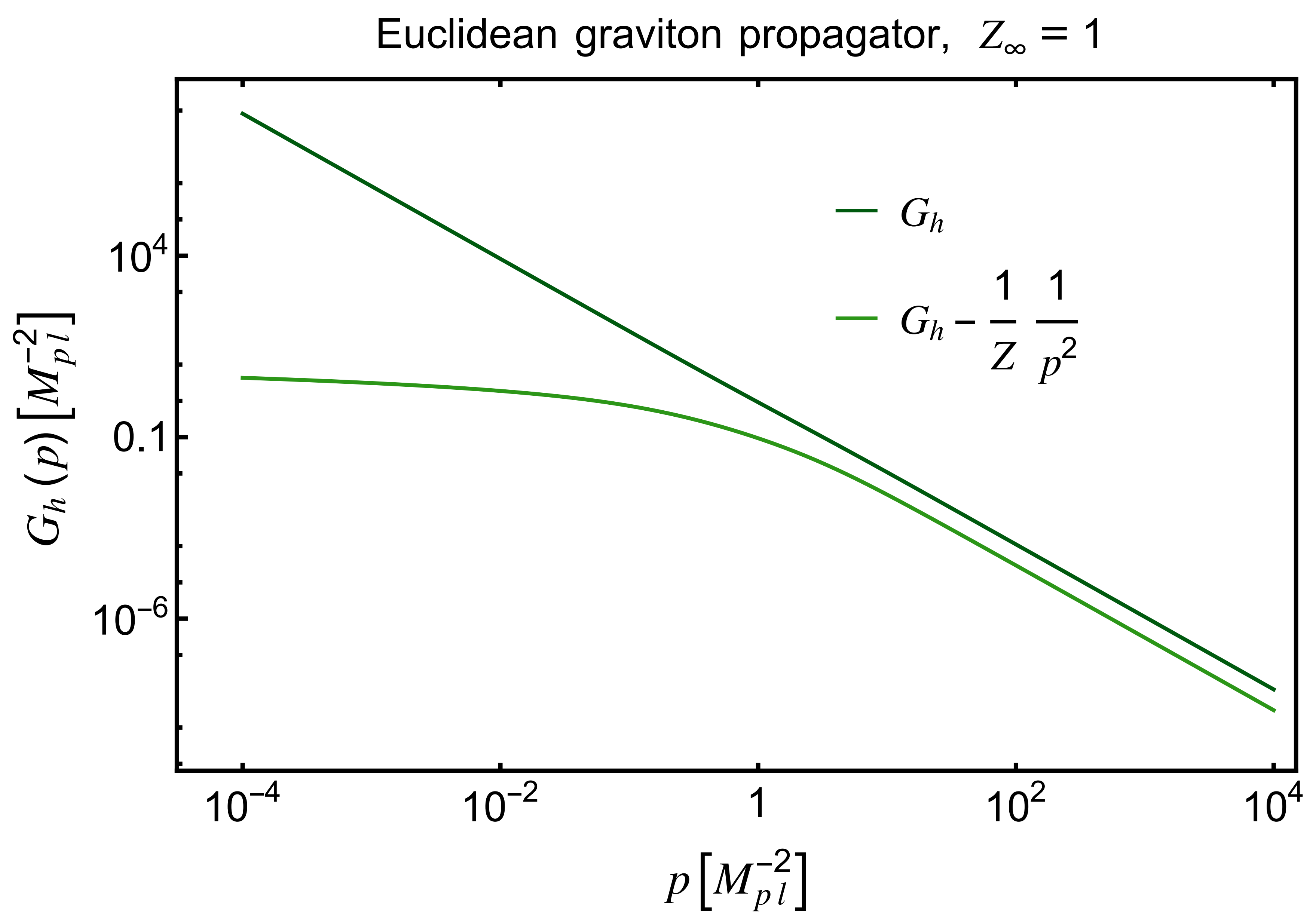

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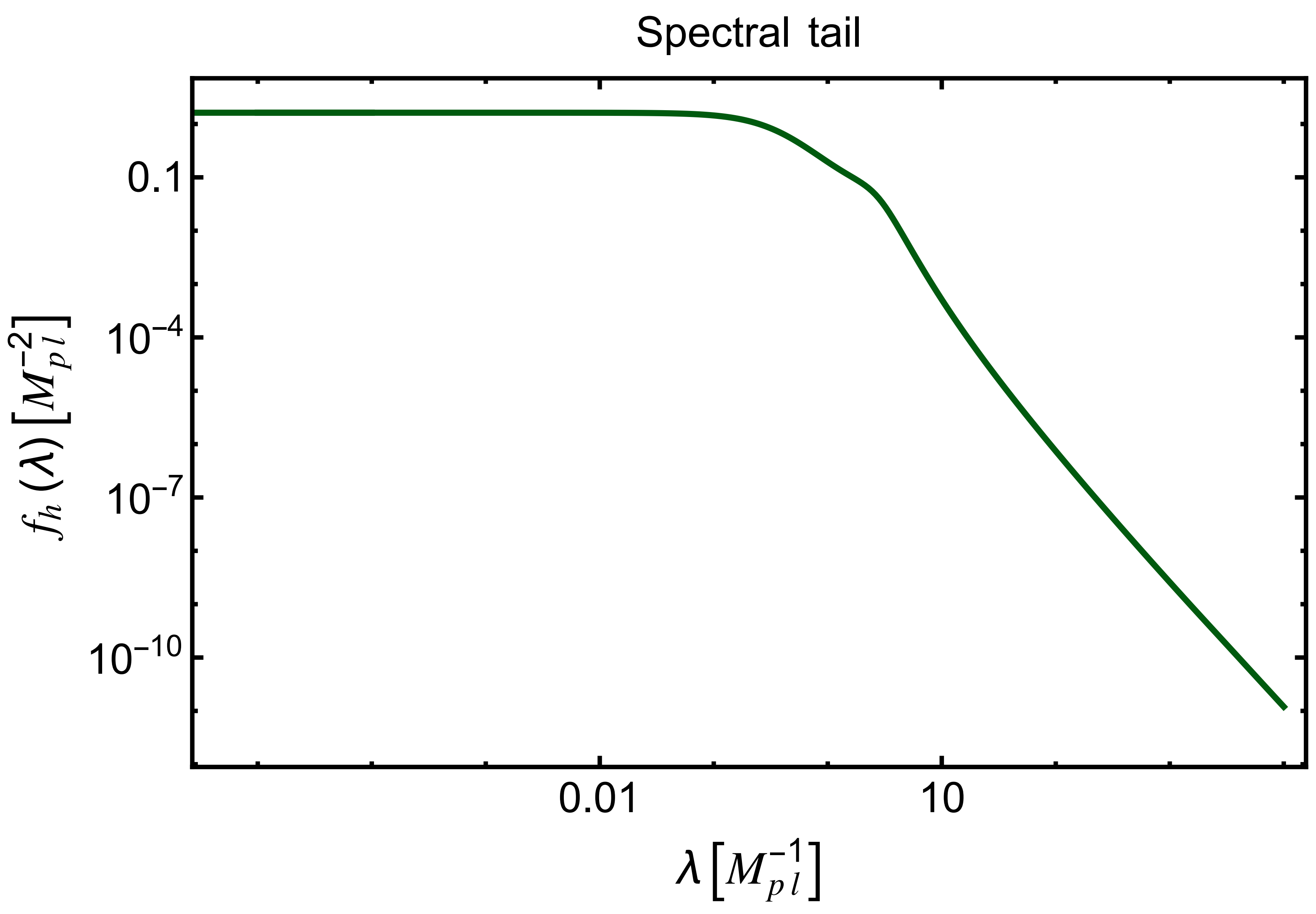


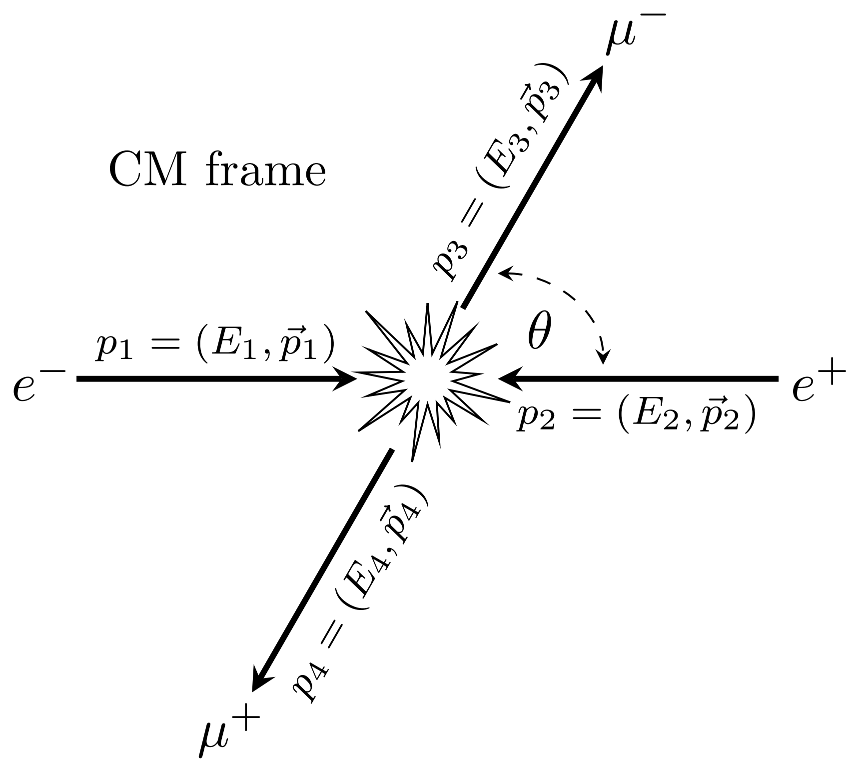
Spectral sum rule

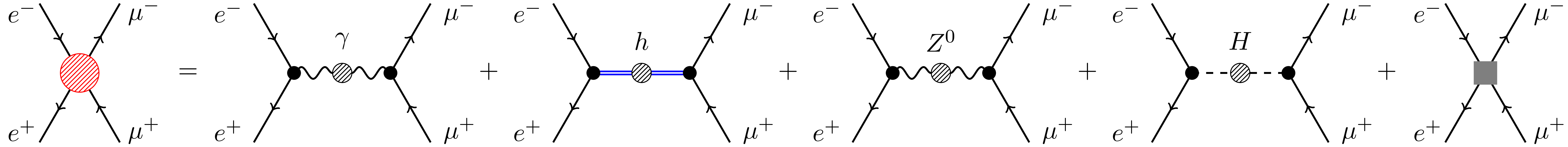
$$\int_{\mathbb{R}} \frac{d\lambda}{2\pi}\,\lambda\,\rho_h(\lambda) = 1$$

JMP, Reichert, Wessely, in preparation

Scattering amplitudes

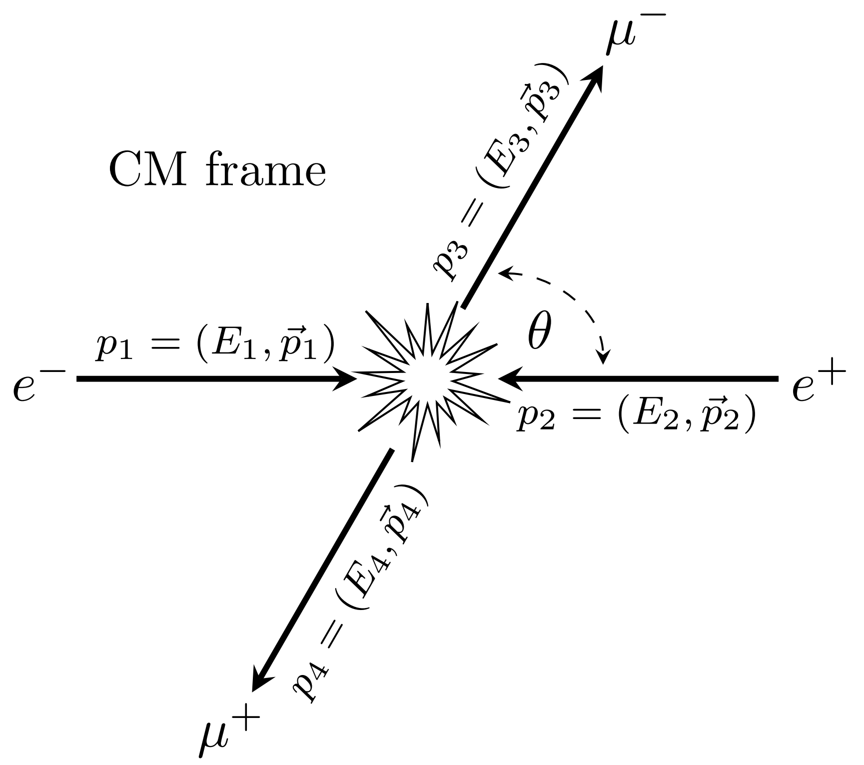
Scattering amplitude $e^+e^- \to \mu^+\mu^-$

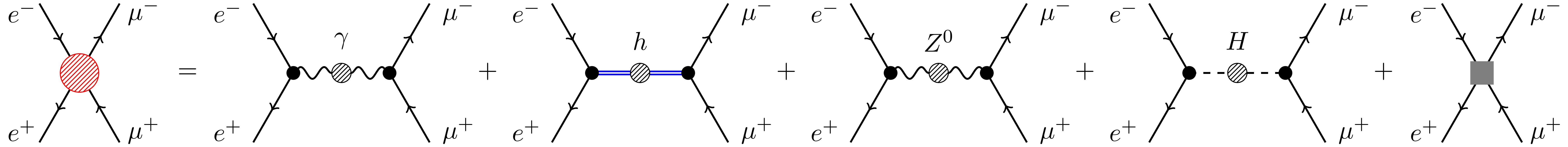


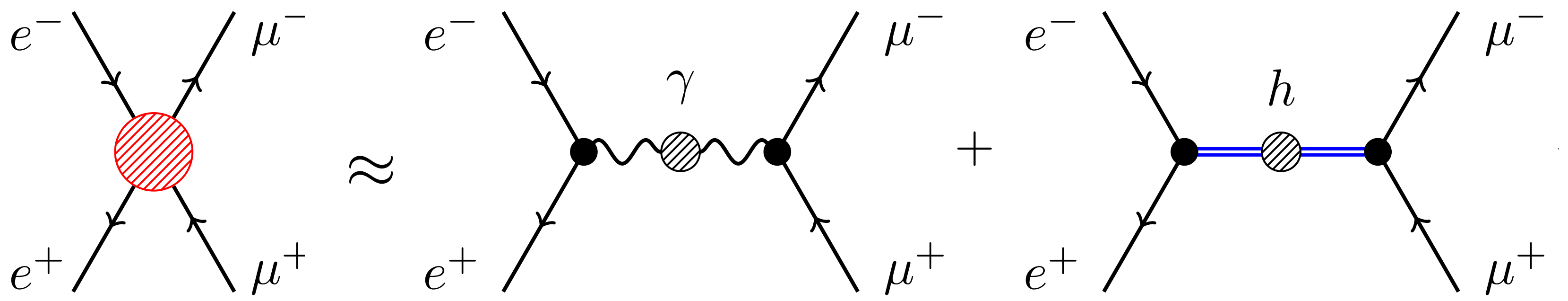


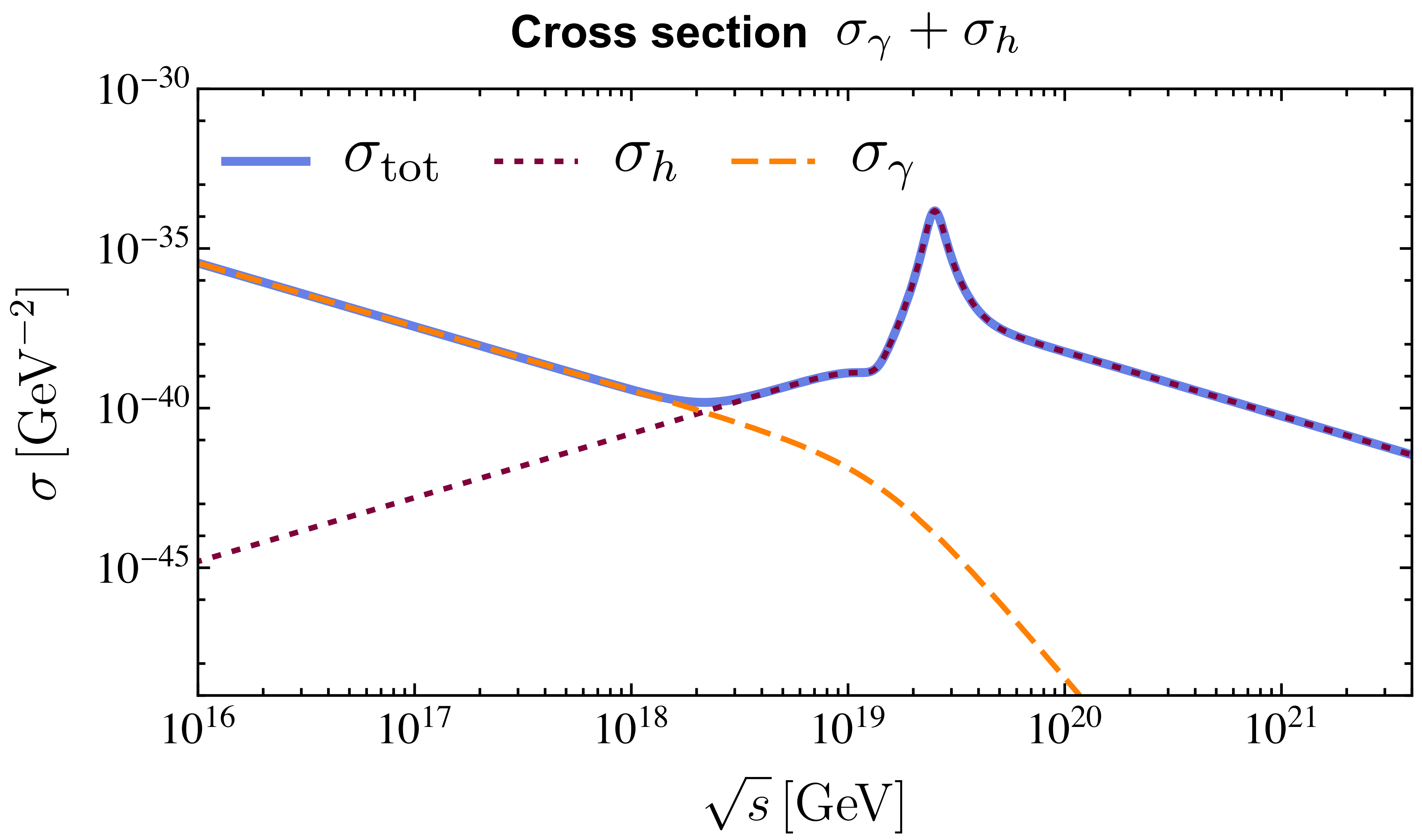
Pastor-Gutiérrez, JMP, Reichert, Ruisi, in preparation

Scattering amplitude $e^+e^- \to \mu^+\mu^-$





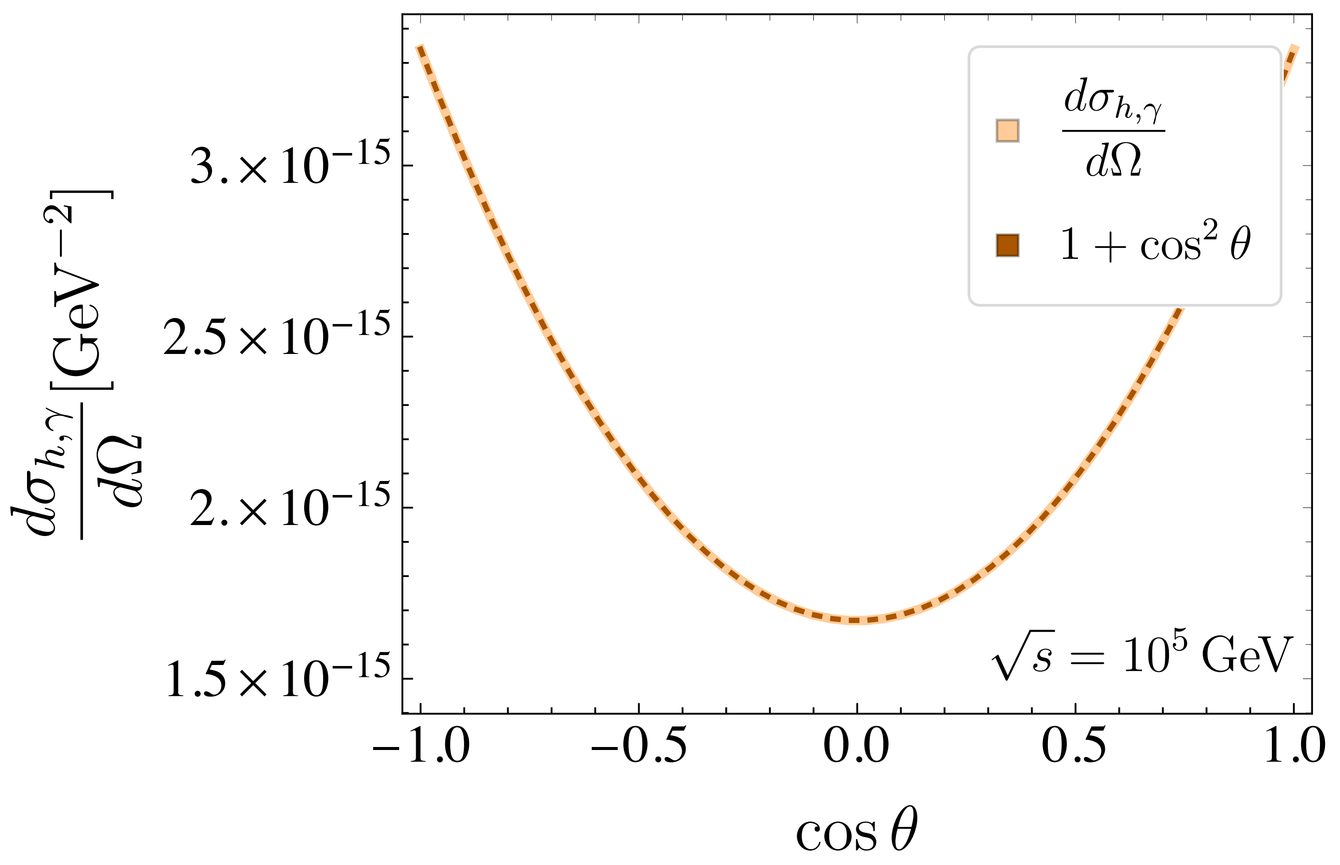


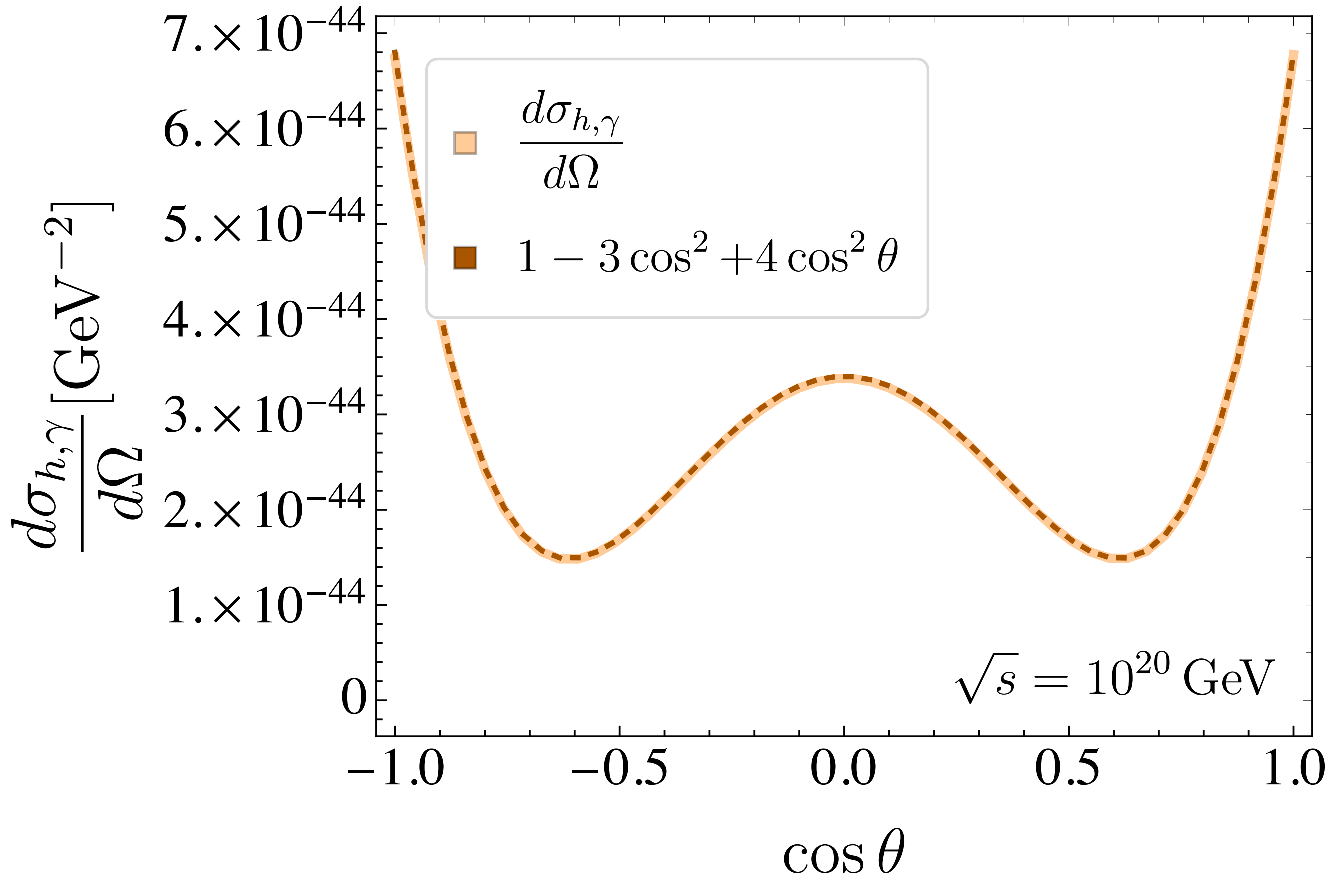


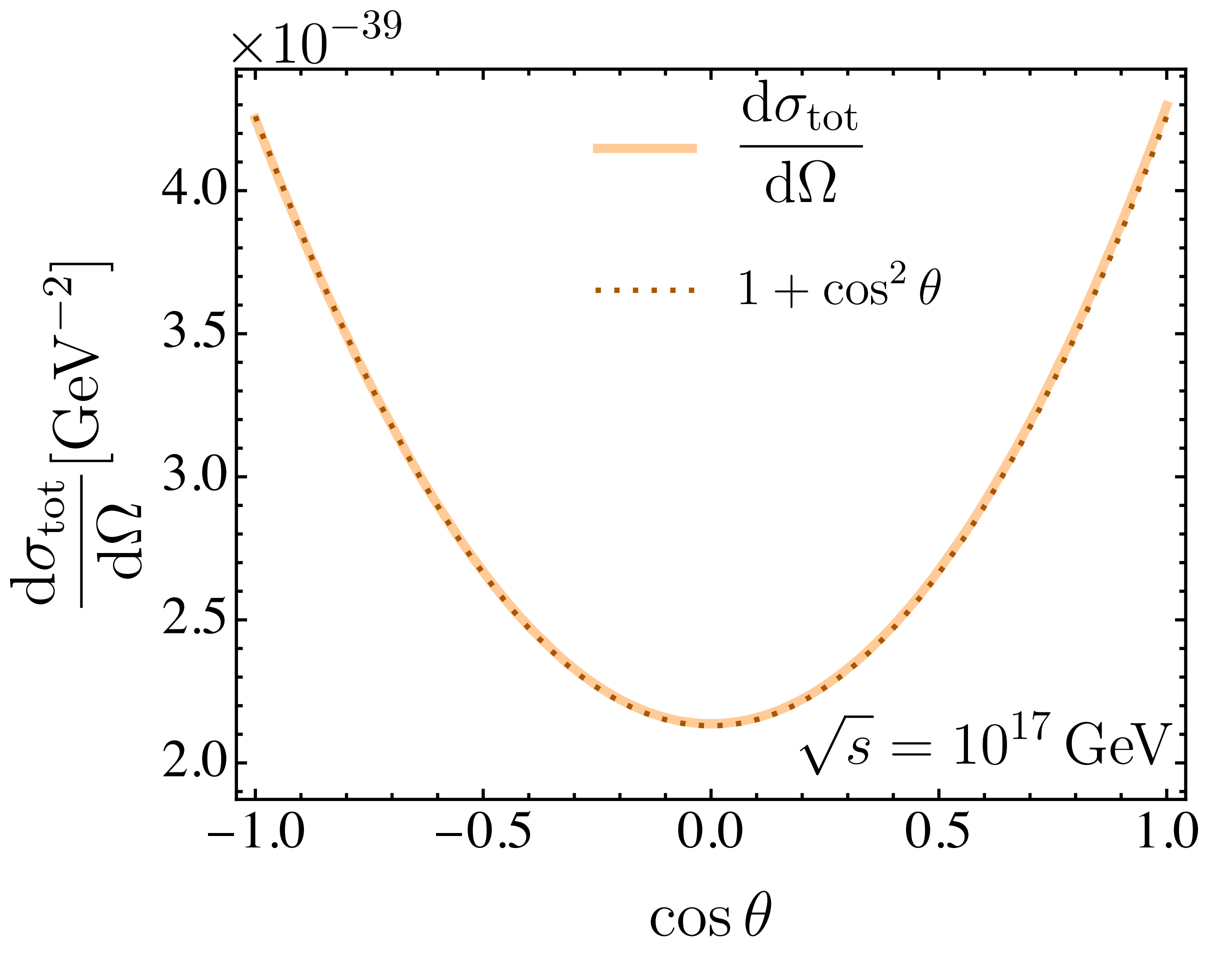
Pastor-Gutiérrez, JMP, Reichert, Ruisi, in preparation

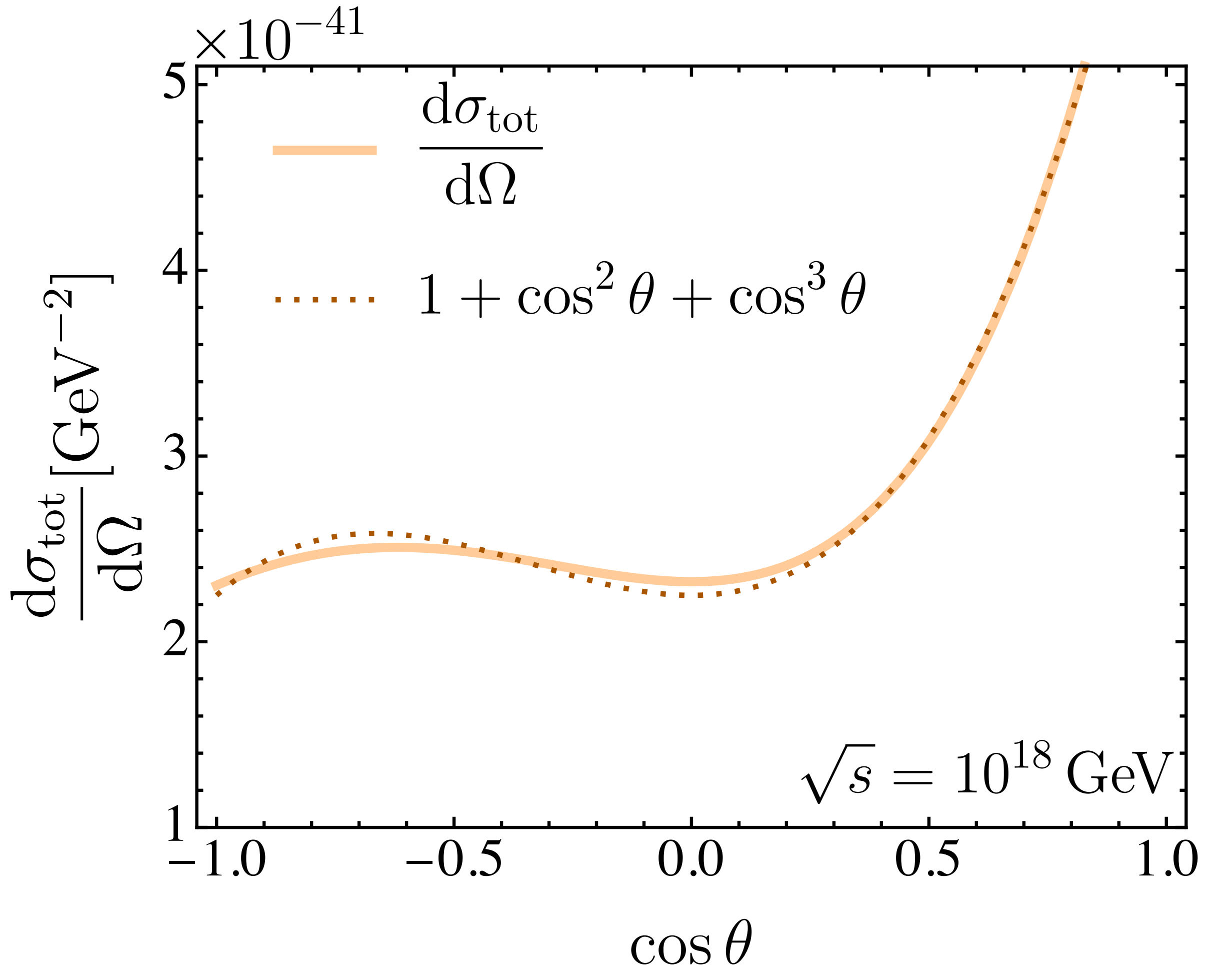
Scattering amplitude $e^+e^- \to \mu^+\mu^-$

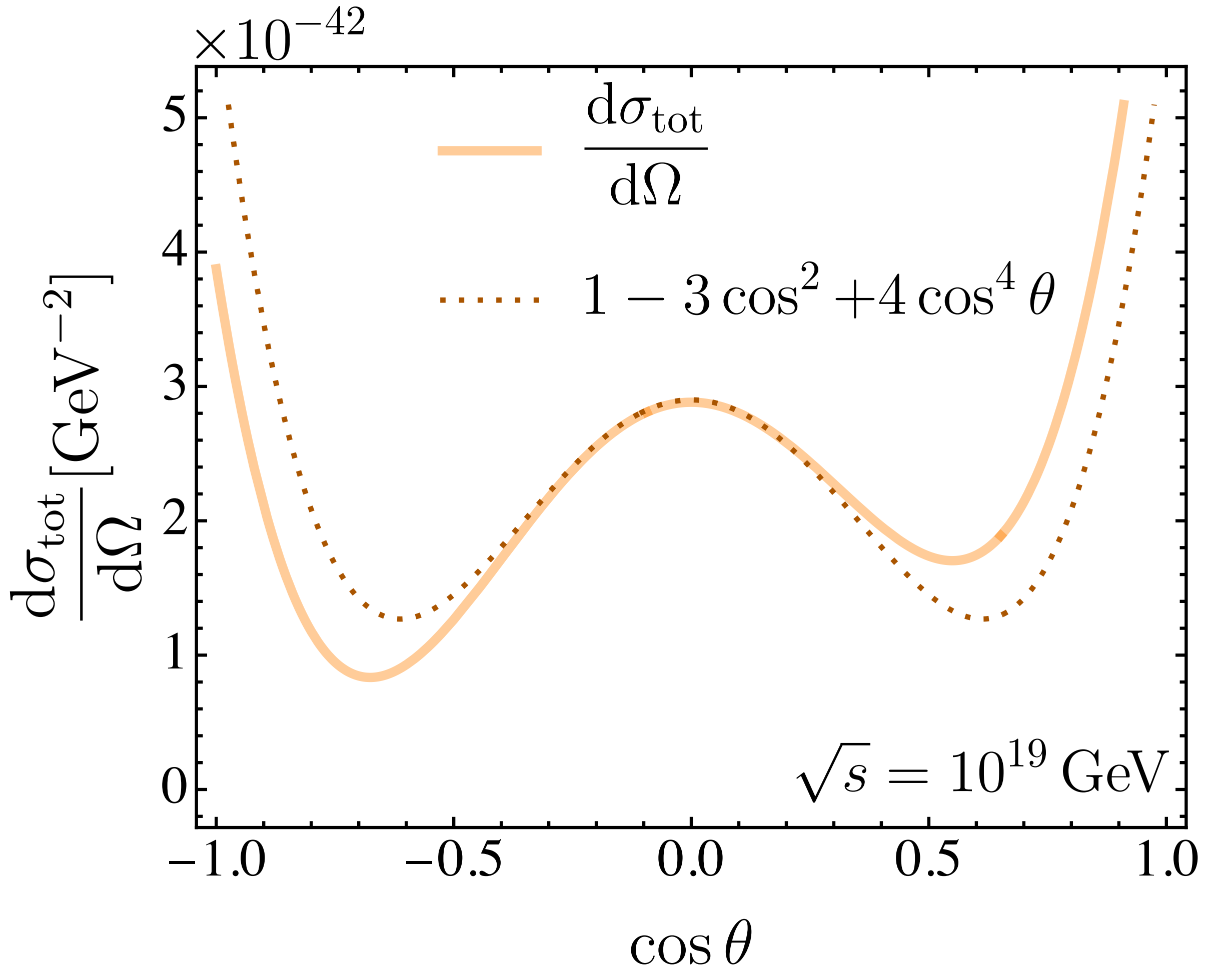
Angular dependence of the differential cross section











Pastor-Gutiérrez, JMP, Reichert, Ruisi, in preparation

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

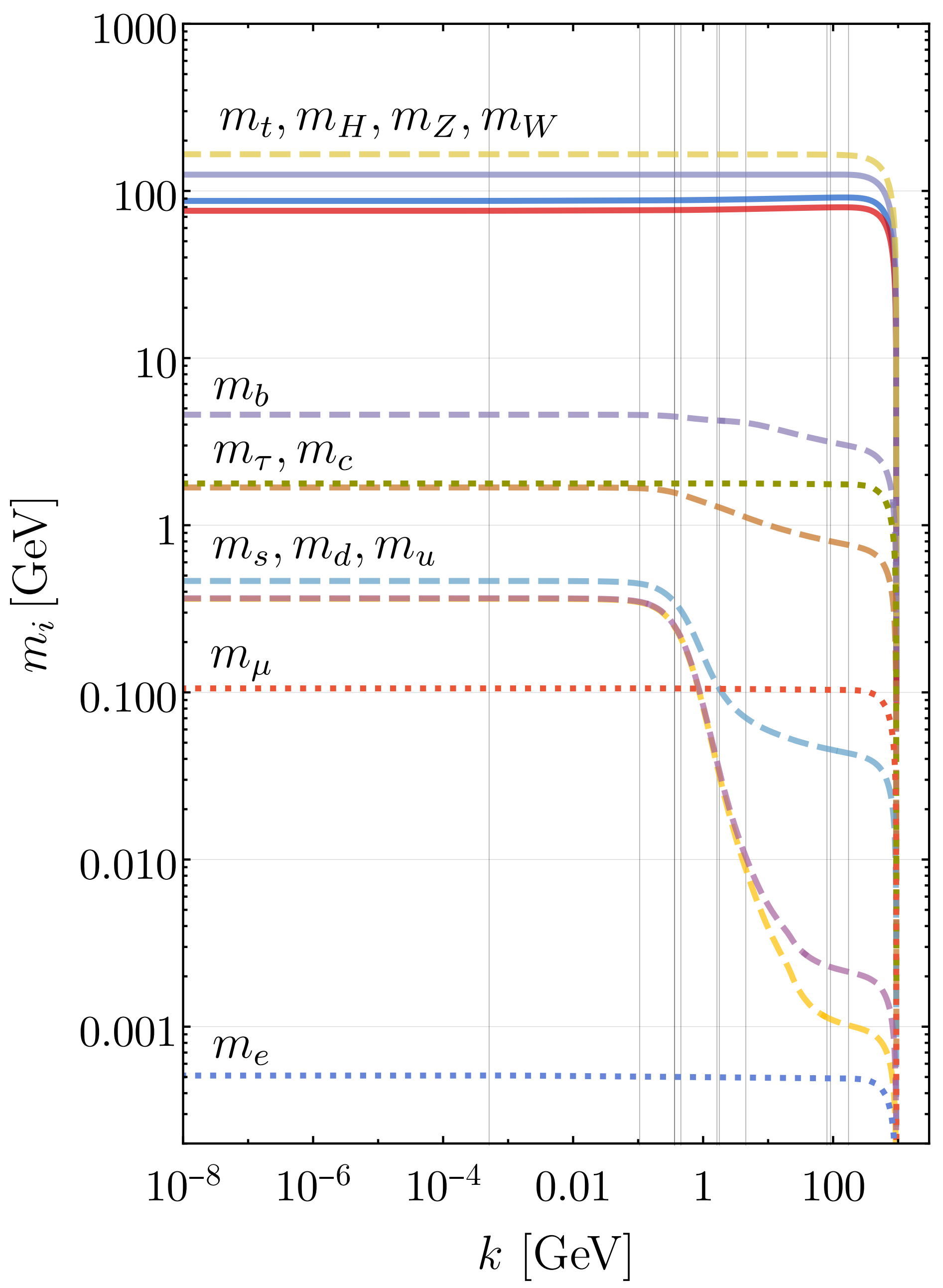
Eichhorn, Versteegen, JHEP 1801 (2018) 030

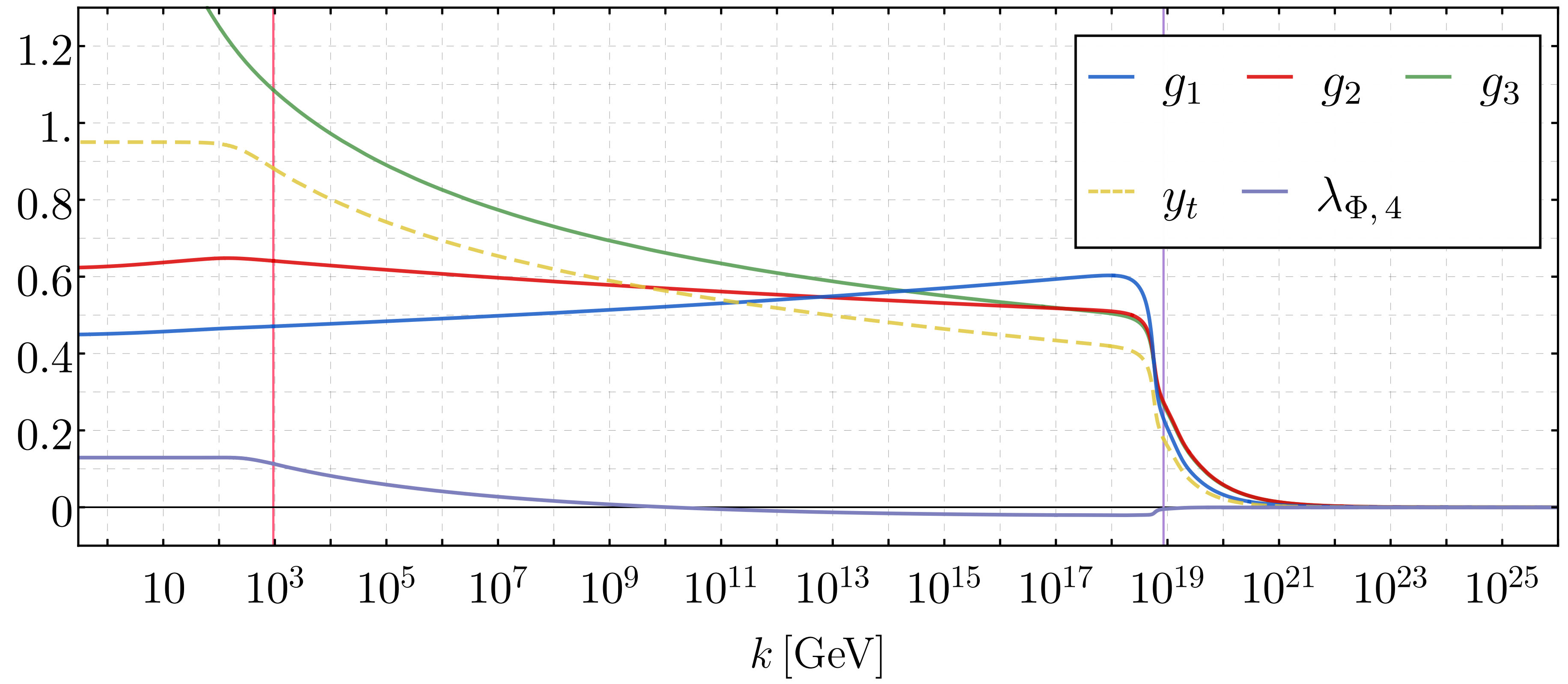
Eichhorn, Held, PRL 121 (2018) 151302

⋮

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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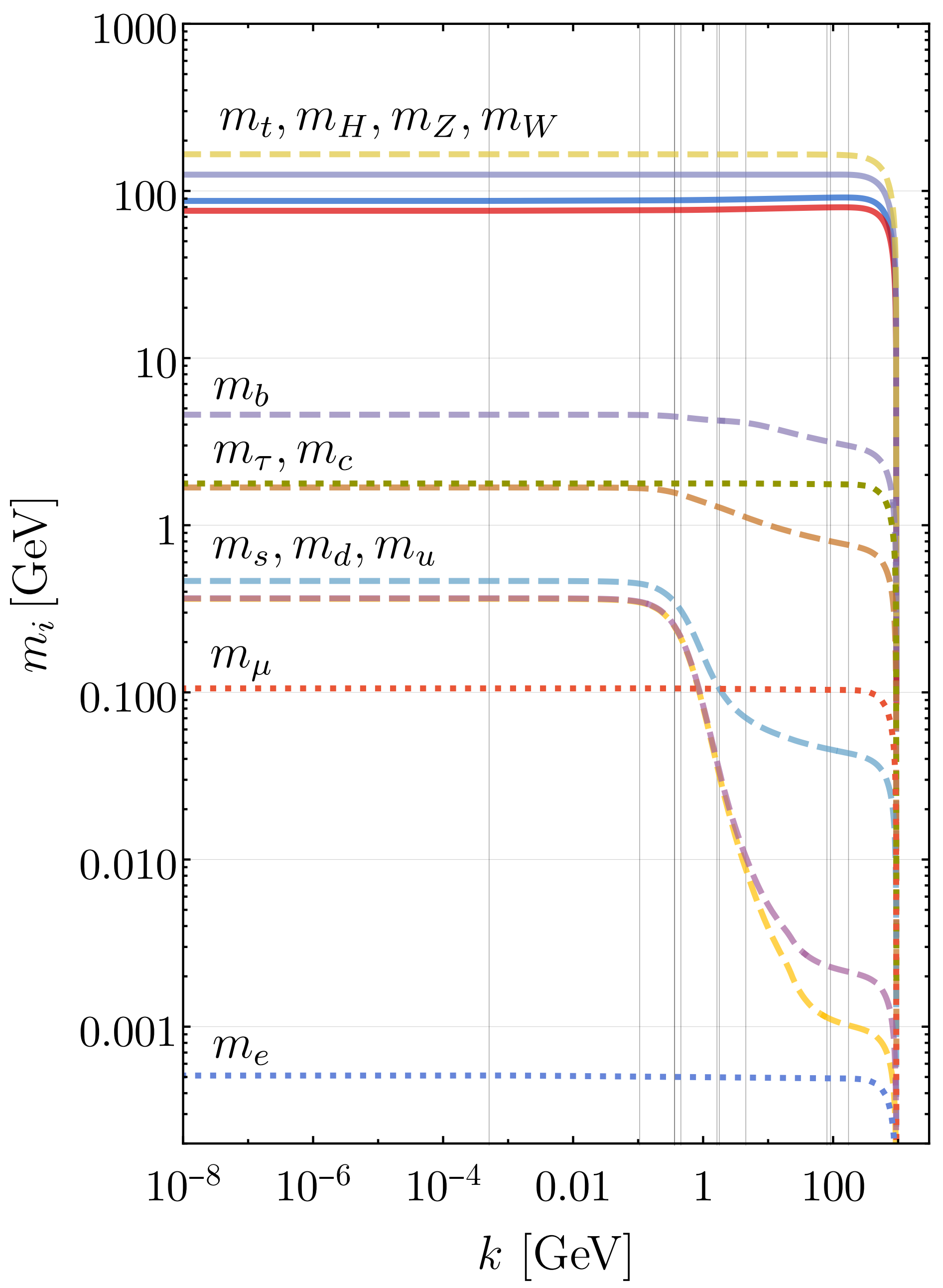
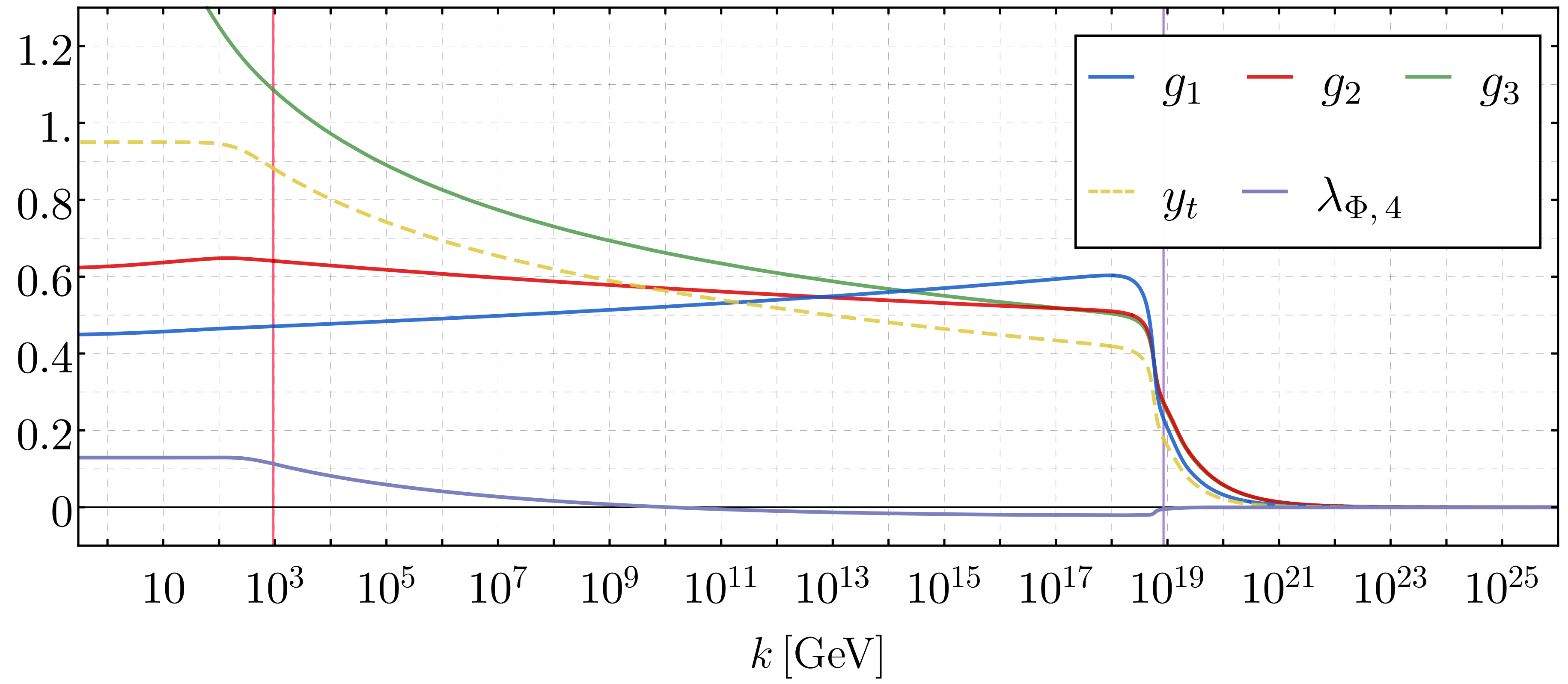
Asymptotically safe Standard Model





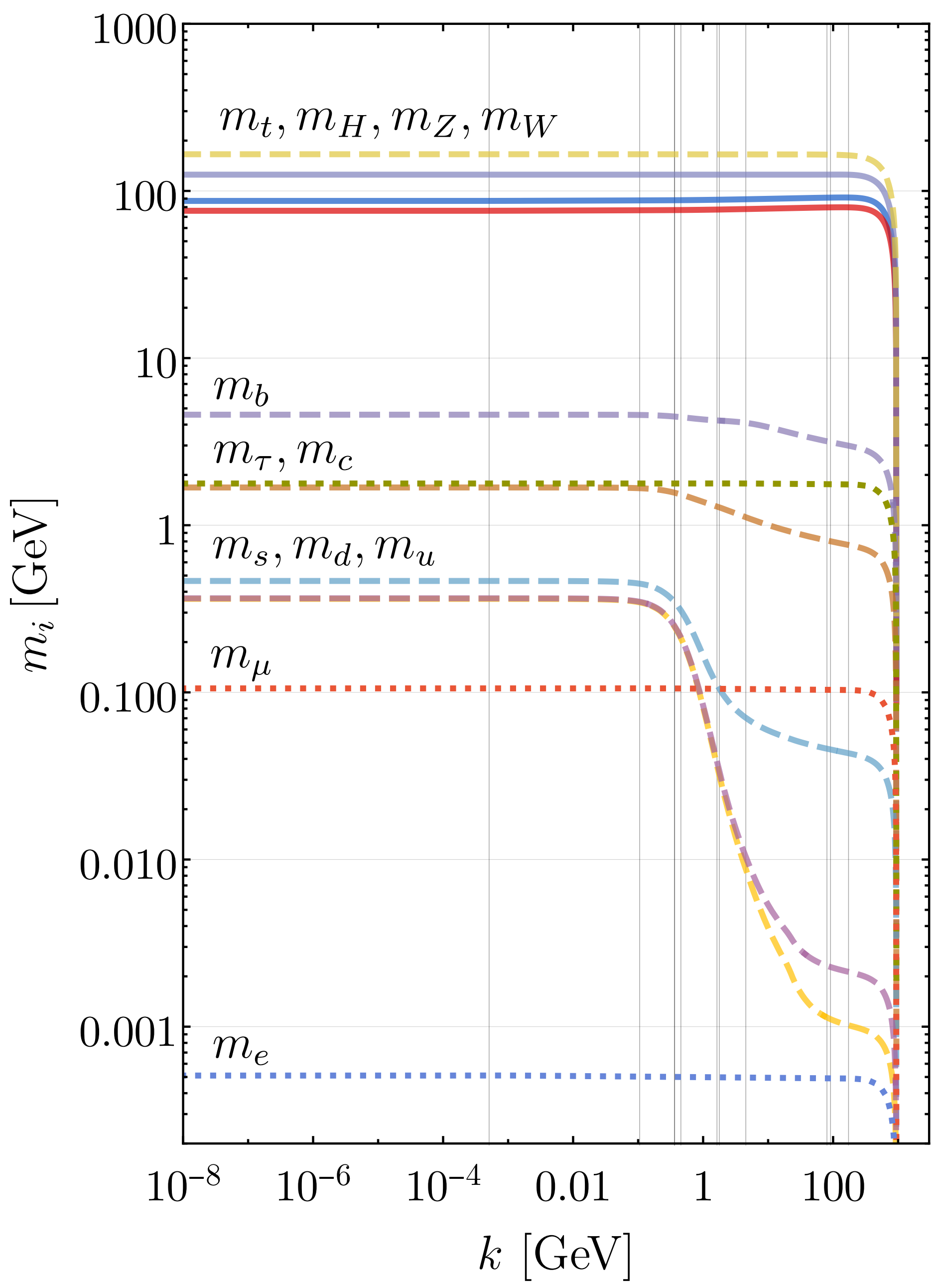
top pole mass (getting real)

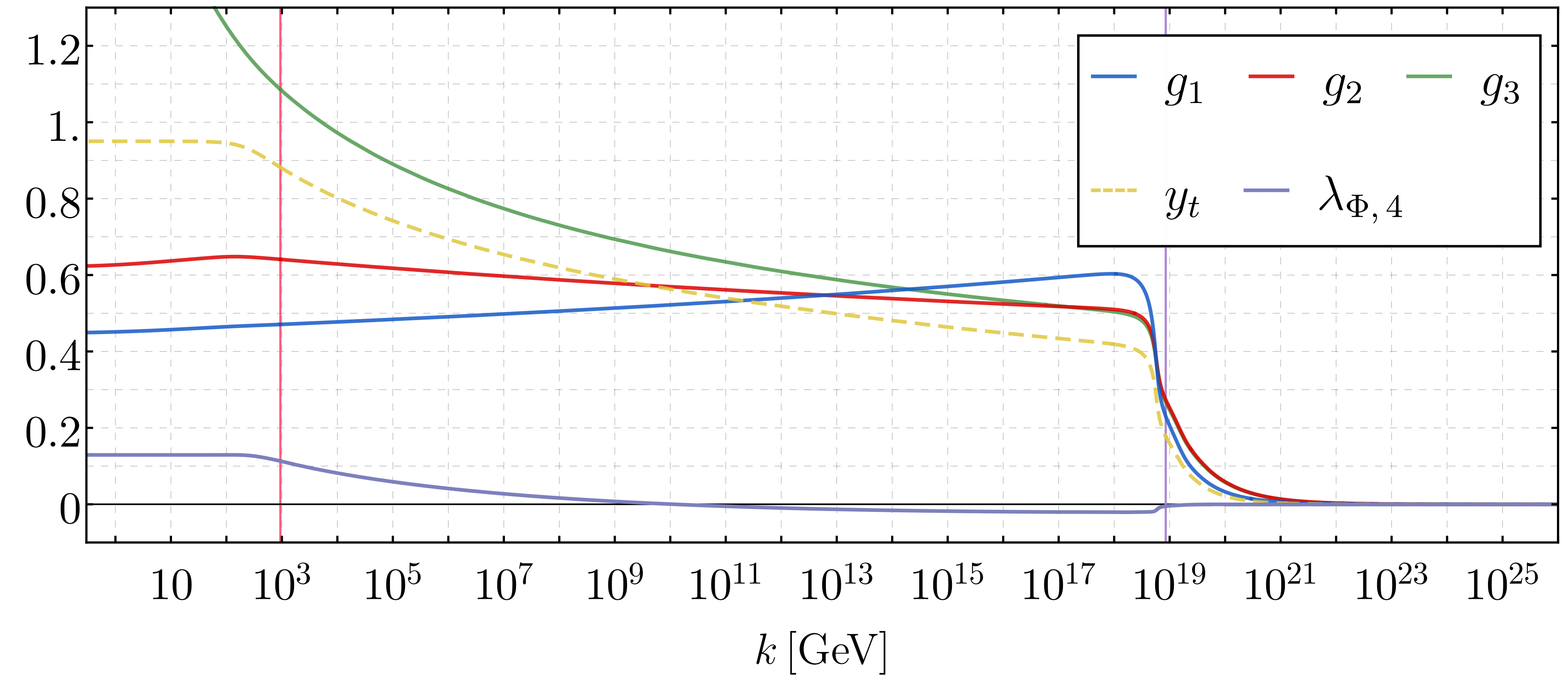
$M_{t,\mathrm{pole}}^{(\mathrm{exp})} = 172.5 \pm 0.7\,\mathrm{GeV}$ ← $m_t = 165.4^{+0.9}_{-0.2}\,\mathrm{GeV}$

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

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

Asymptotically safe Standard Model





top pole mass (getting real)

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

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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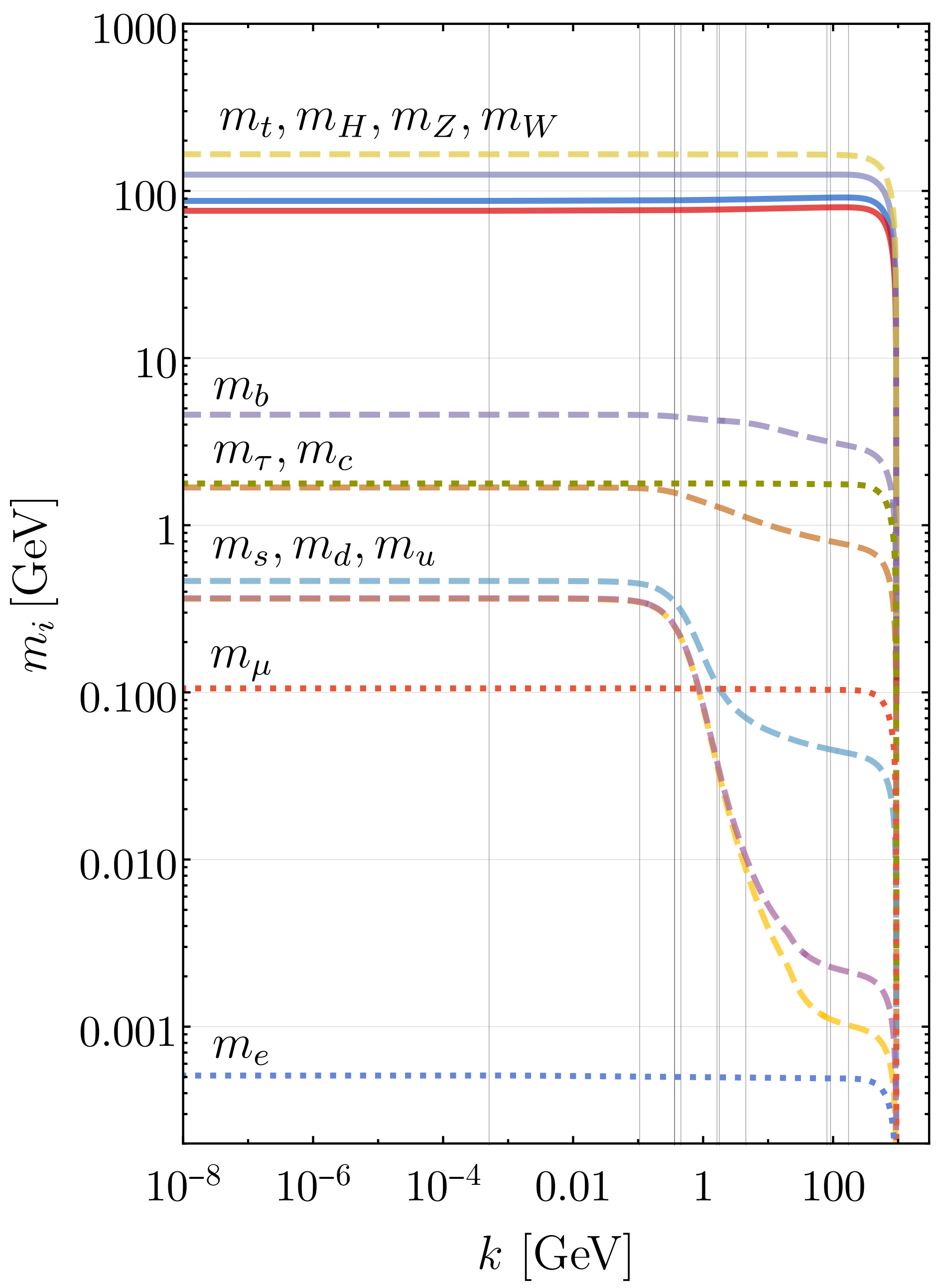
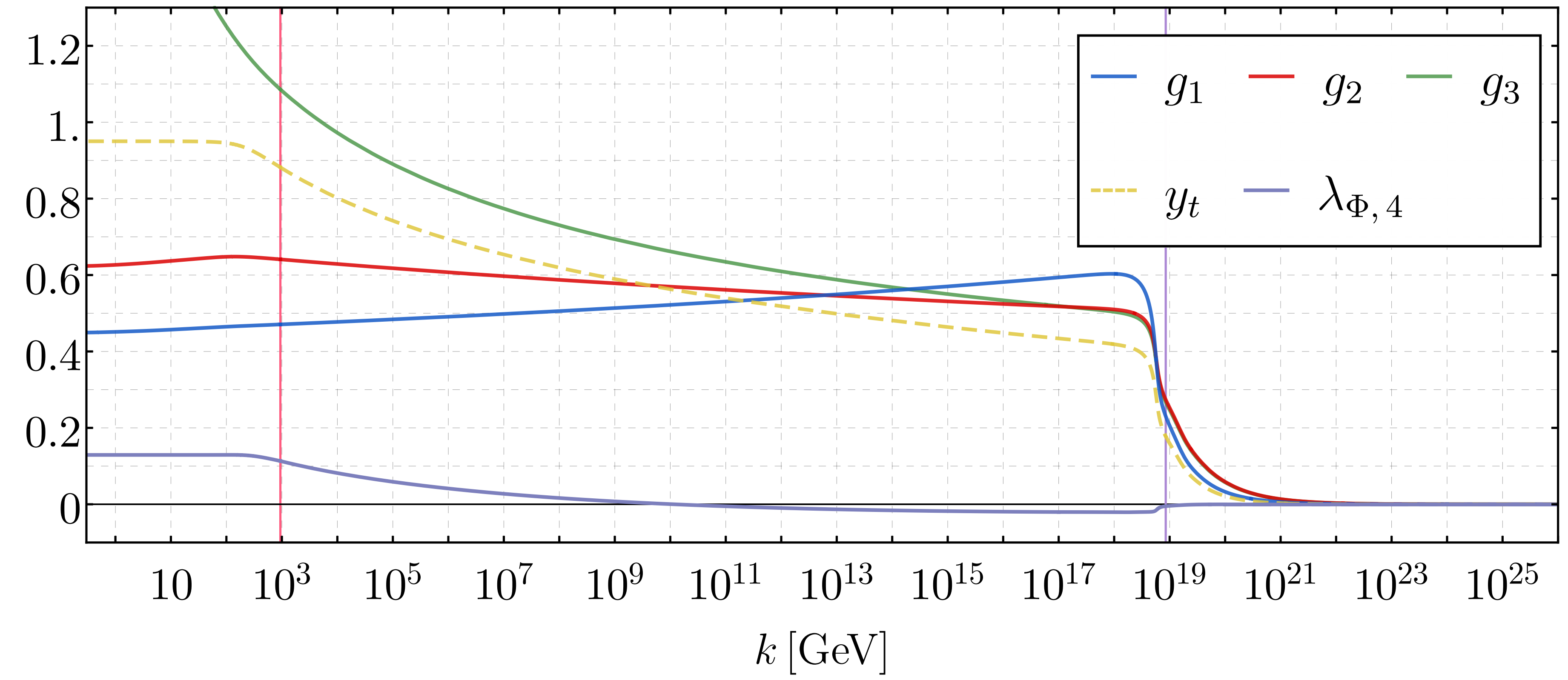
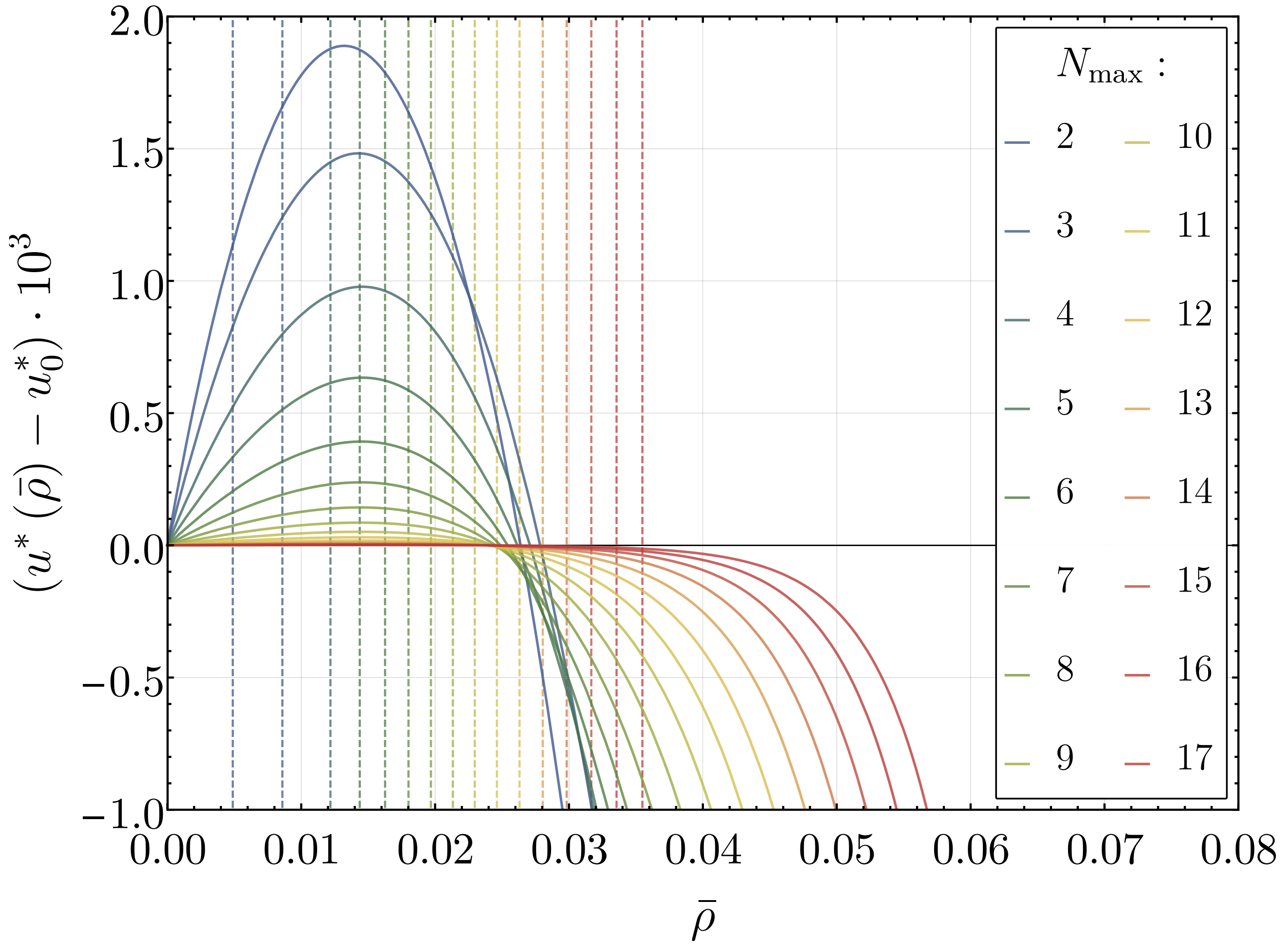
Asymptotically safe Standard Model





flat Higgs FP potential



Two relevant directions

top pole mass (getting real)

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

Experimental value (PDG)

$$m_t = 165.4^{+0.9}_{-0.2}\,\text{GeV}$$

Euclidean curvature mass

Prediction of decay width

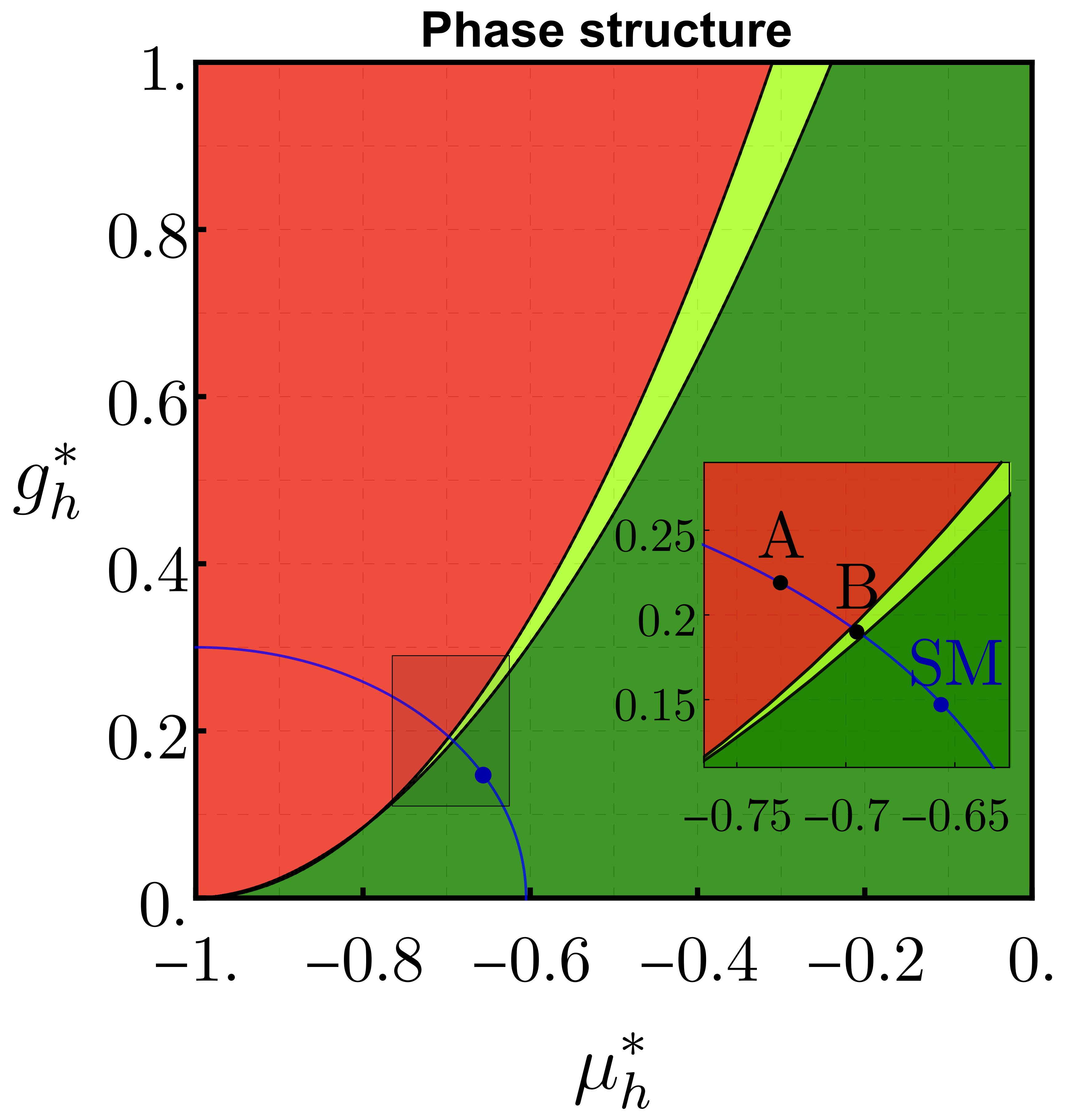
$$\Gamma_{t,\text{pole}}^{(\text{theo})} = 1.72^{+0.09}_{-0.41}\,\text{GeV}$$

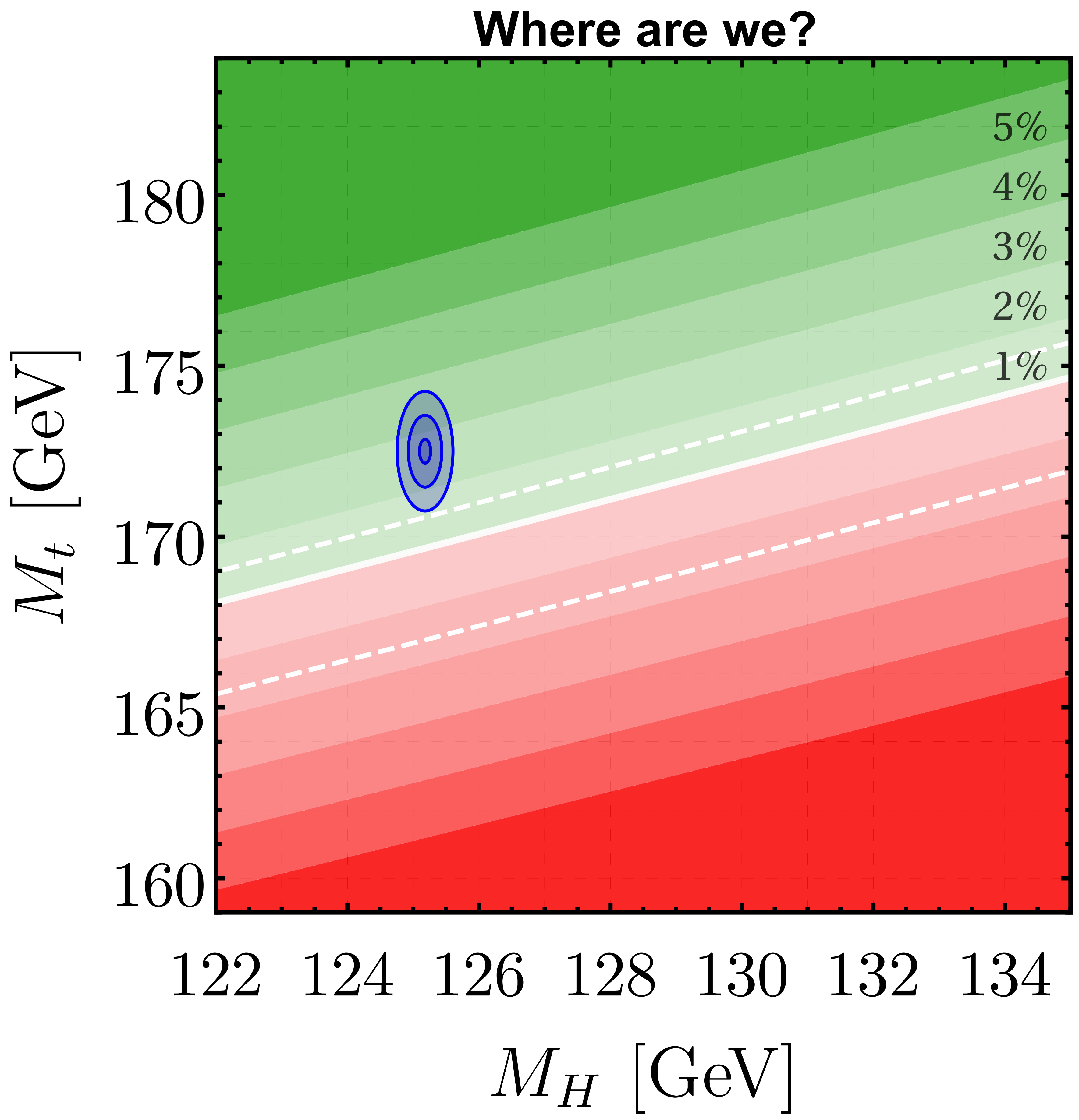
$$\Gamma_{t,\text{pole}}^{(\text{exp})} = 1.42^{+0.19}_{-0.15}\,\text{GeV}$$

Experimental value (PDG)

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

Asymptotically safe Standard Model

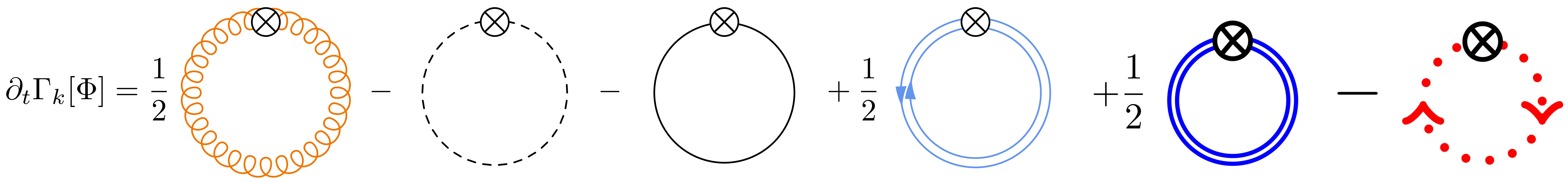




Pastor-Gutiérrez, JMP, Reichert, SciPost Phys. 15 (2023) 105

Summary

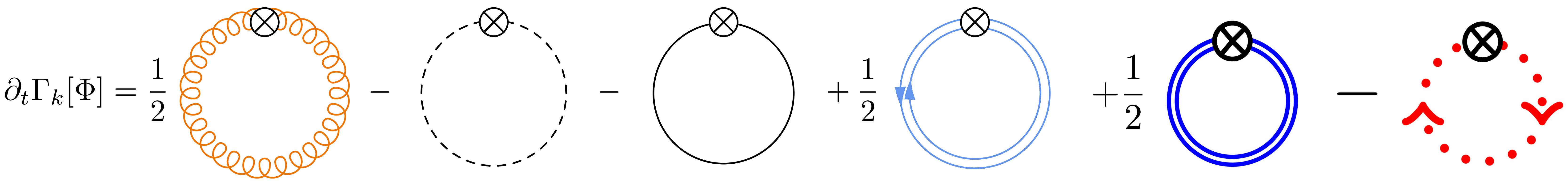
Summary



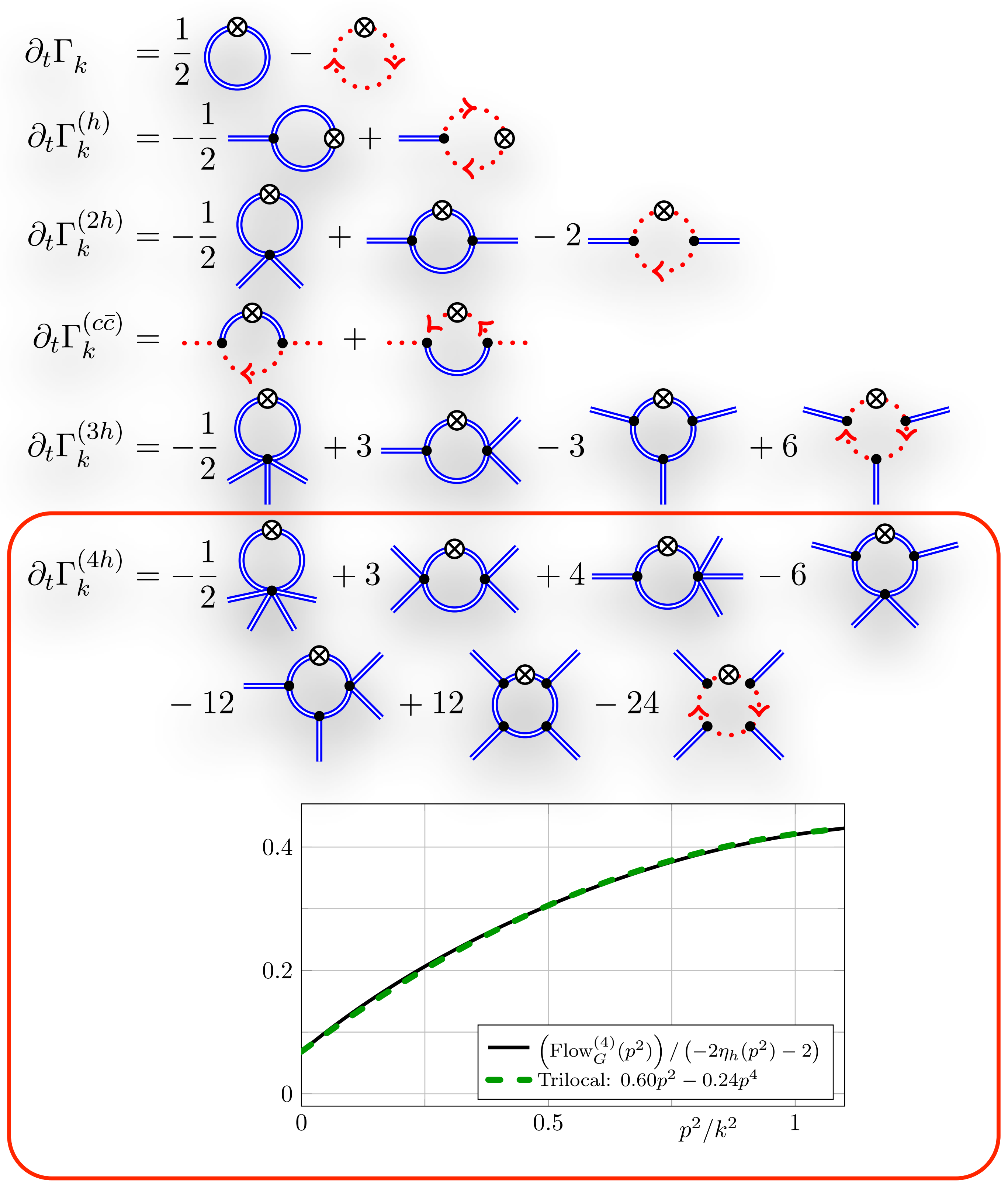
Getting real I: Apparent convergence

Getting real II: Scattering & spectral properties

Summary

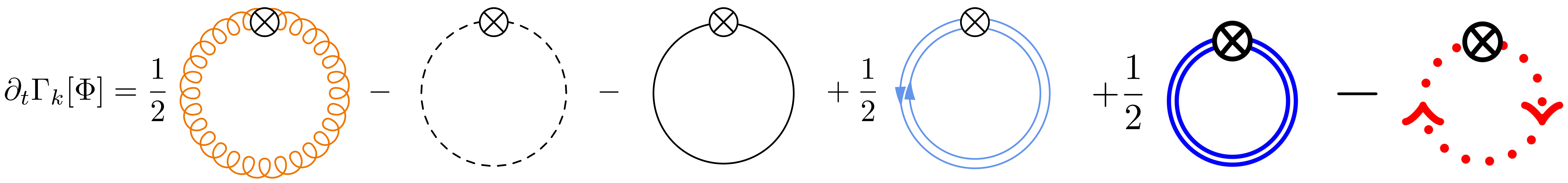


Getting real I: Apparent convergence

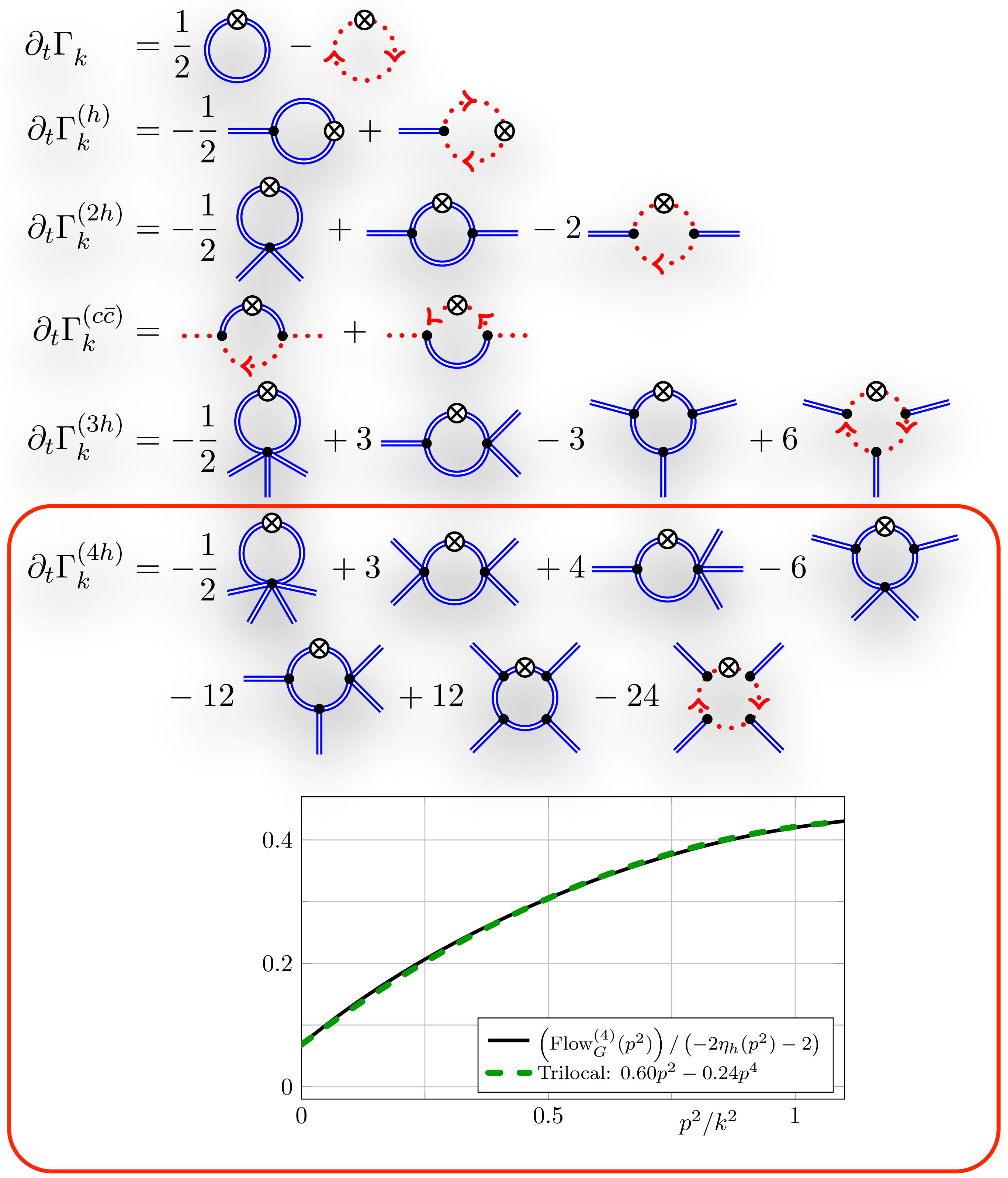


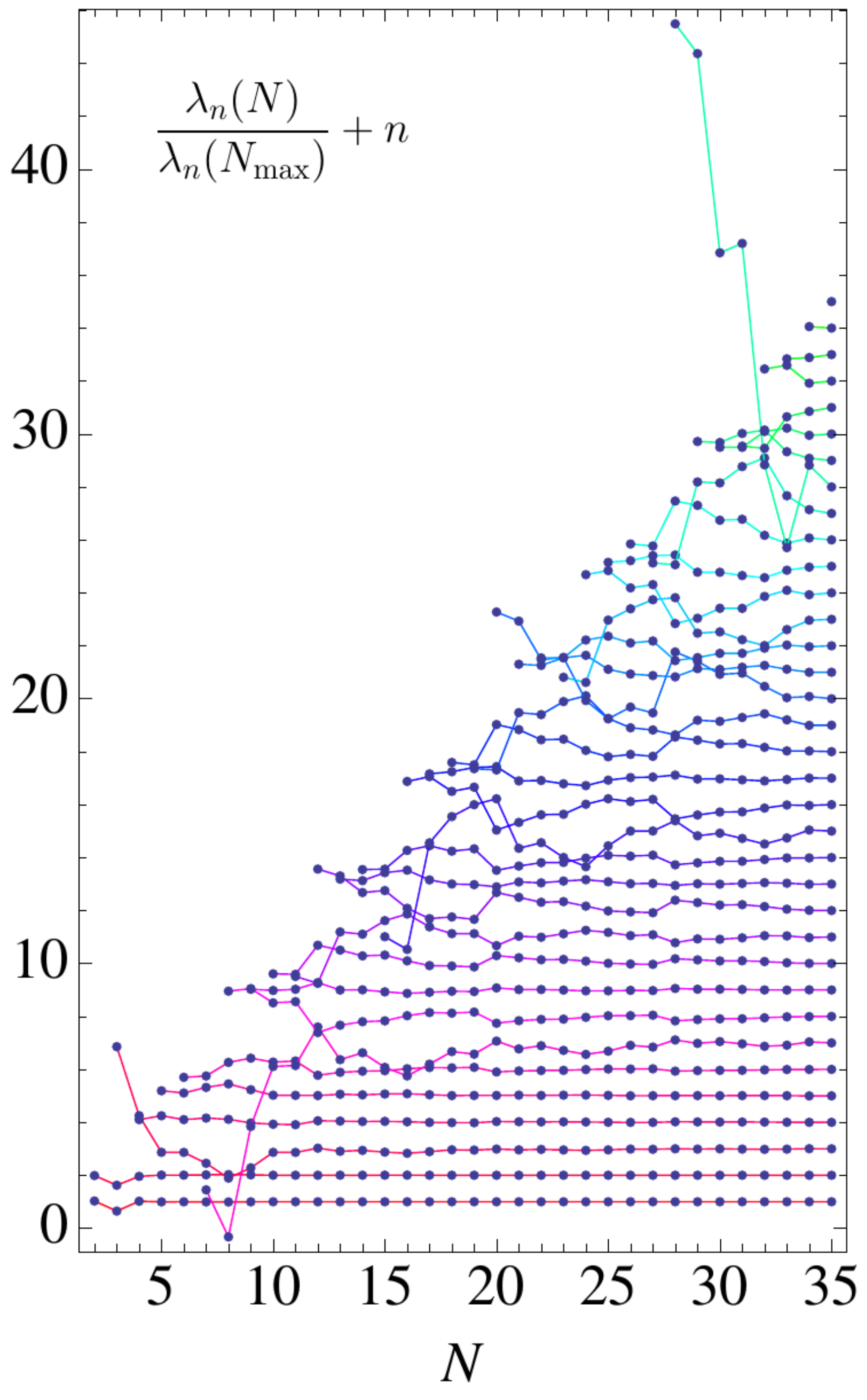
Getting real II: Scattering & spectral properties

Summary



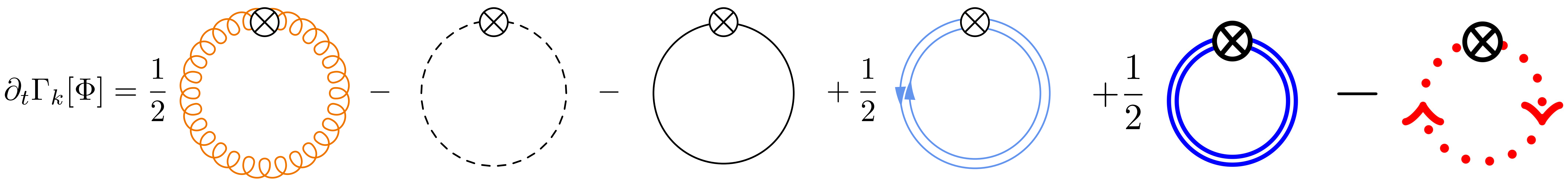
Getting real I: Apparent convergence



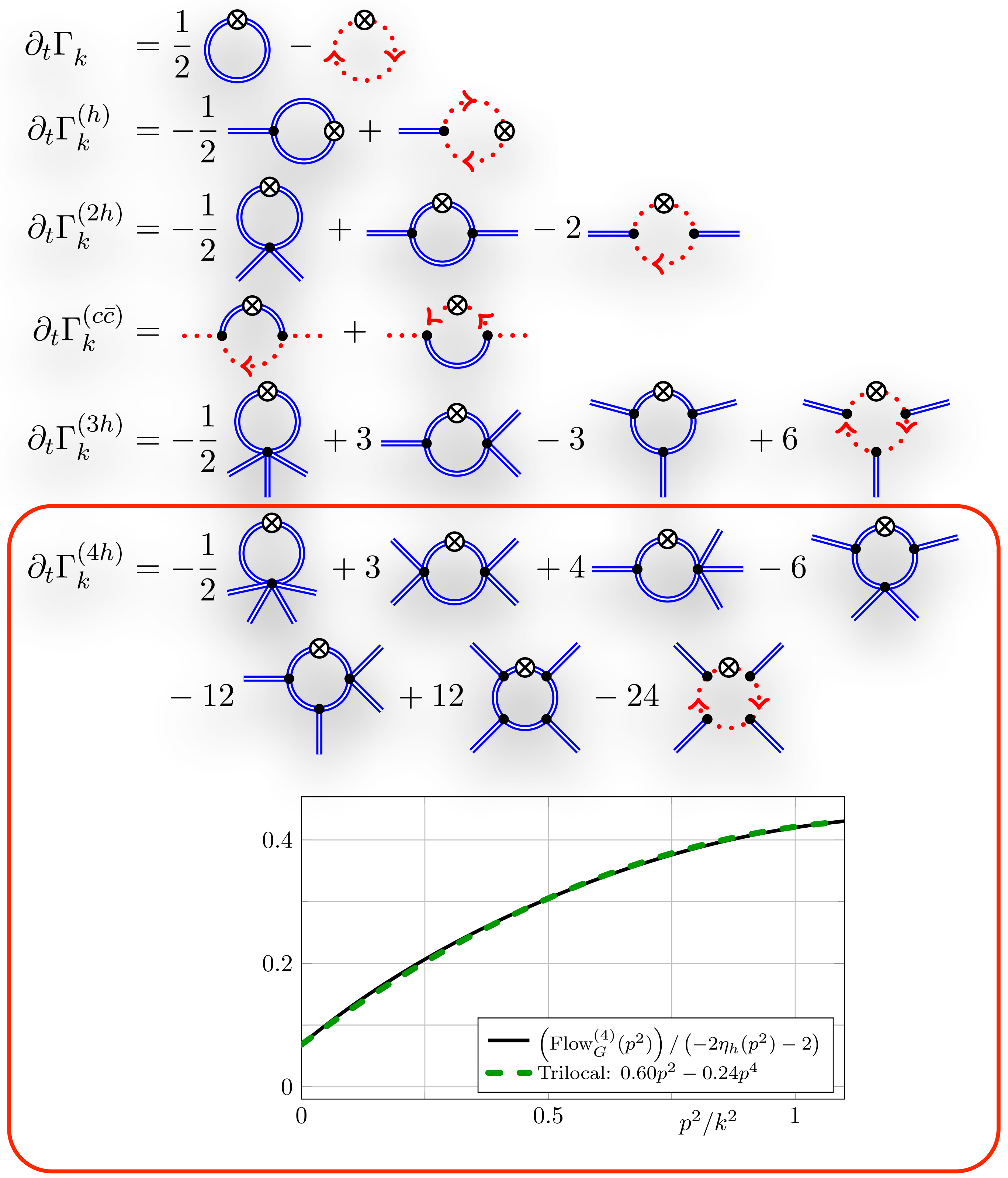


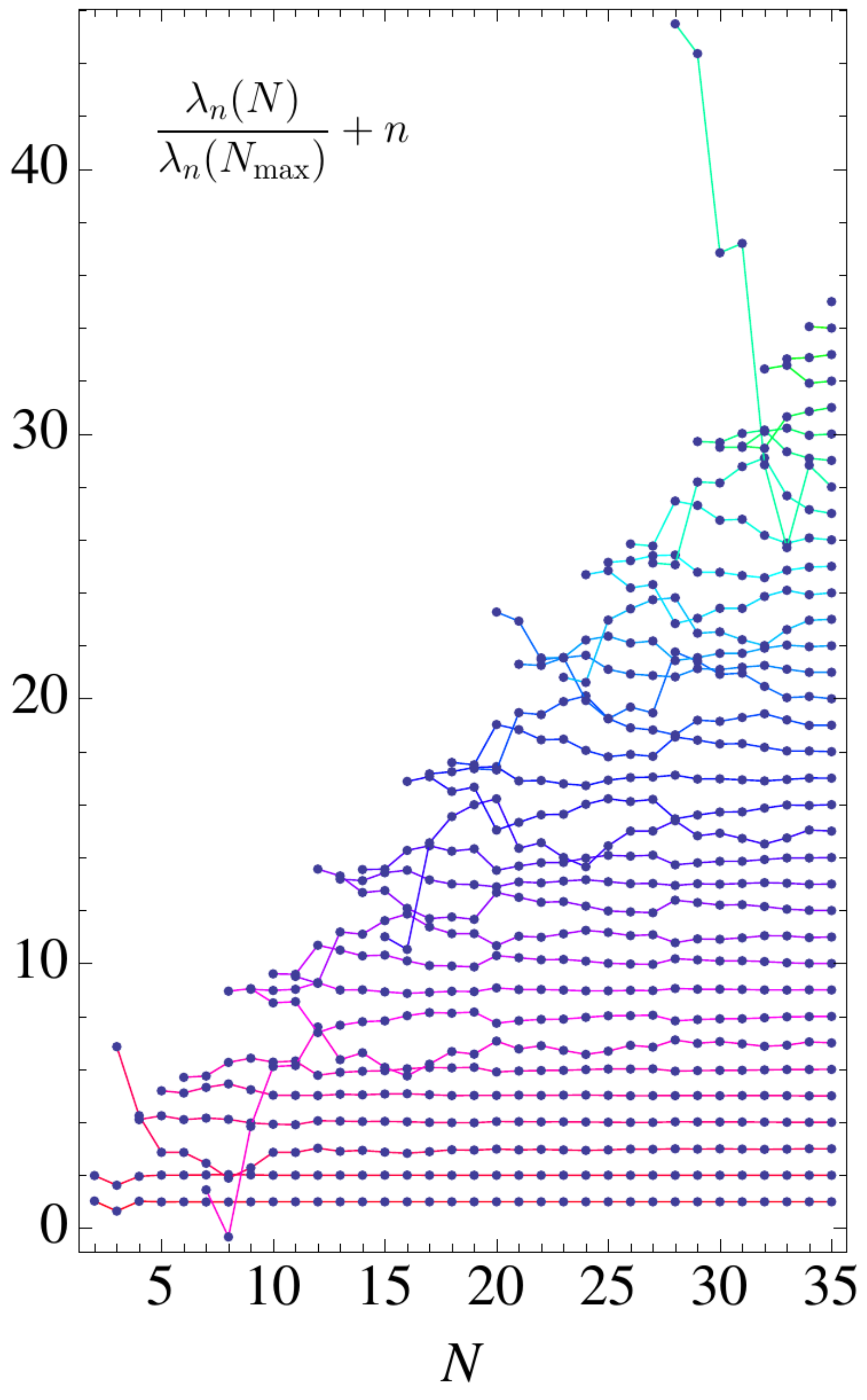
Getting real II: Scattering & spectral properties

Summary



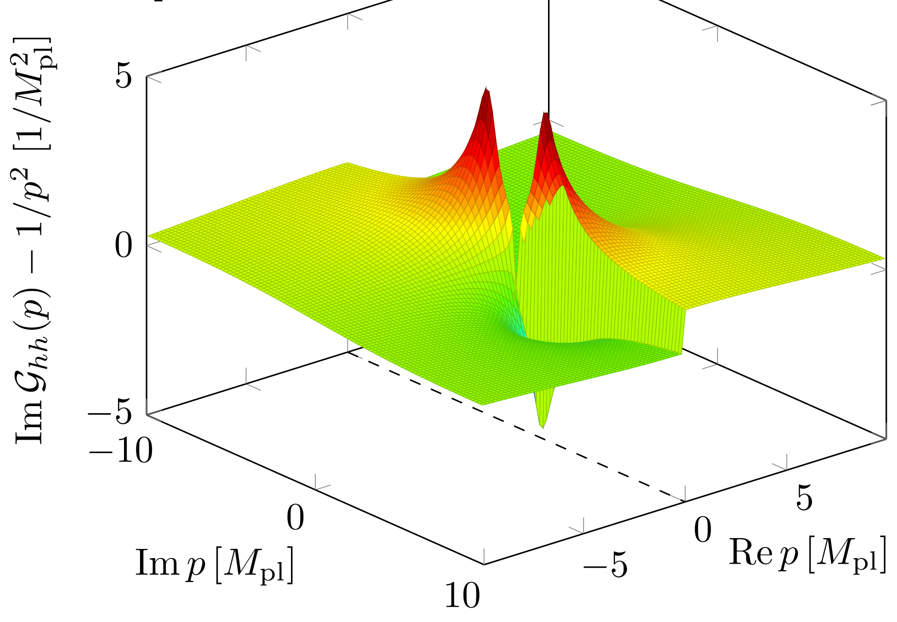
Getting real I: Apparent convergence



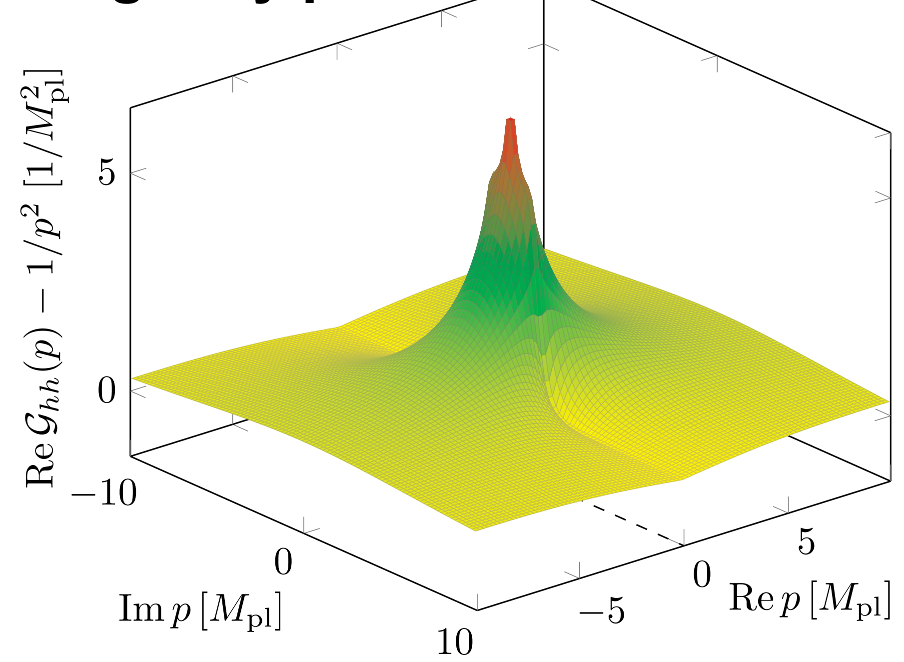


Getting real II: Scattering & spectral properties

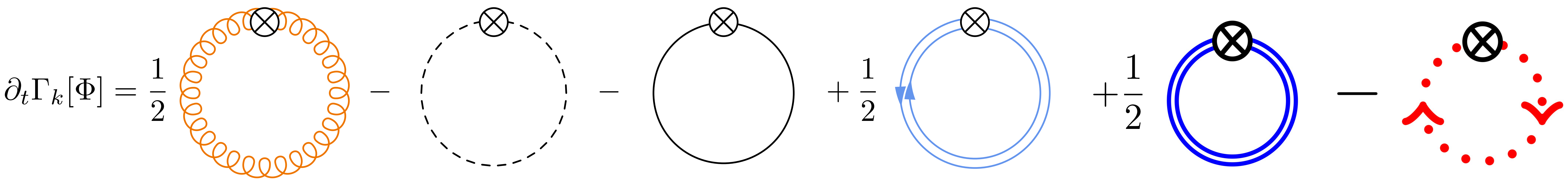
Real part



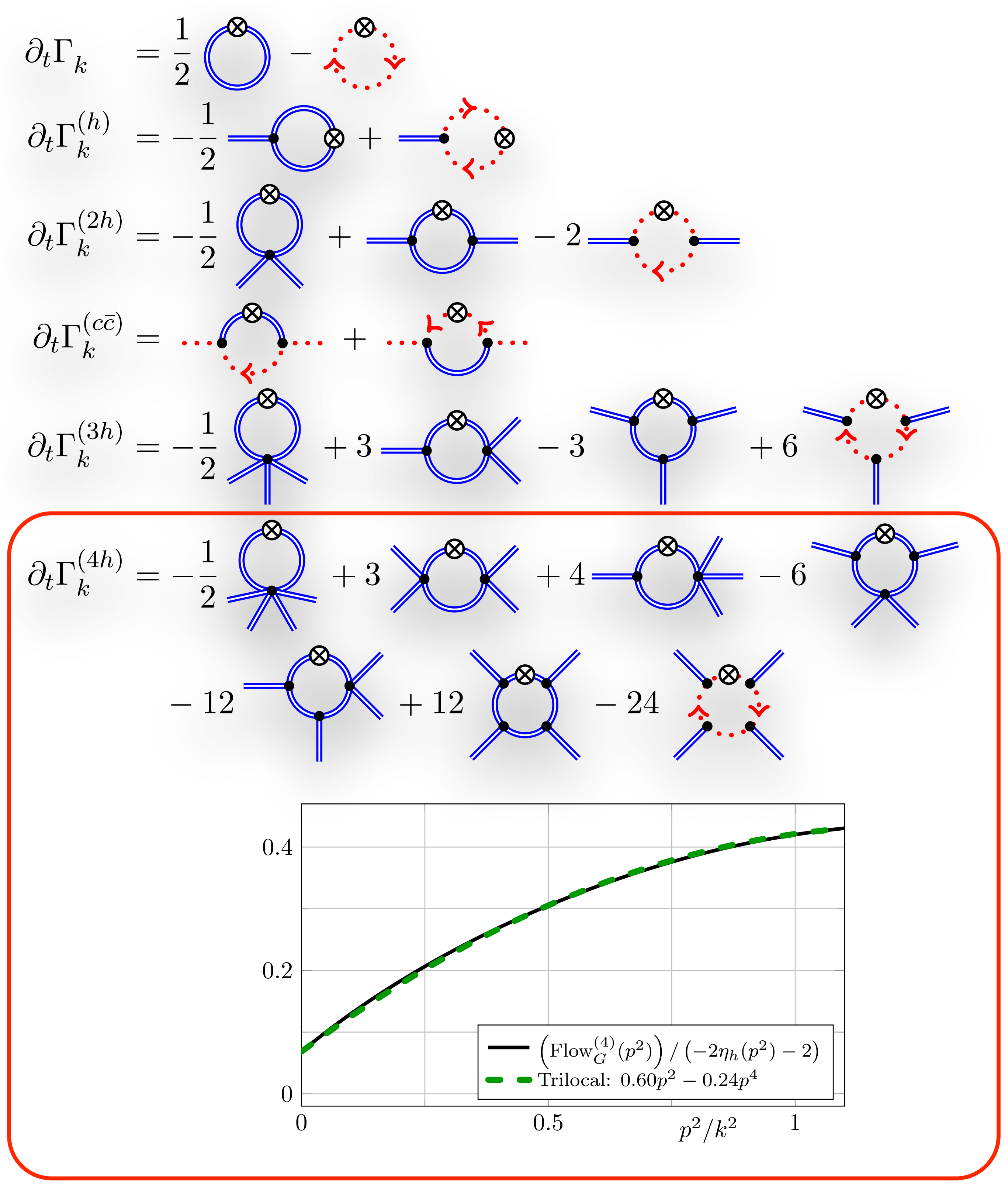
Imaginary part

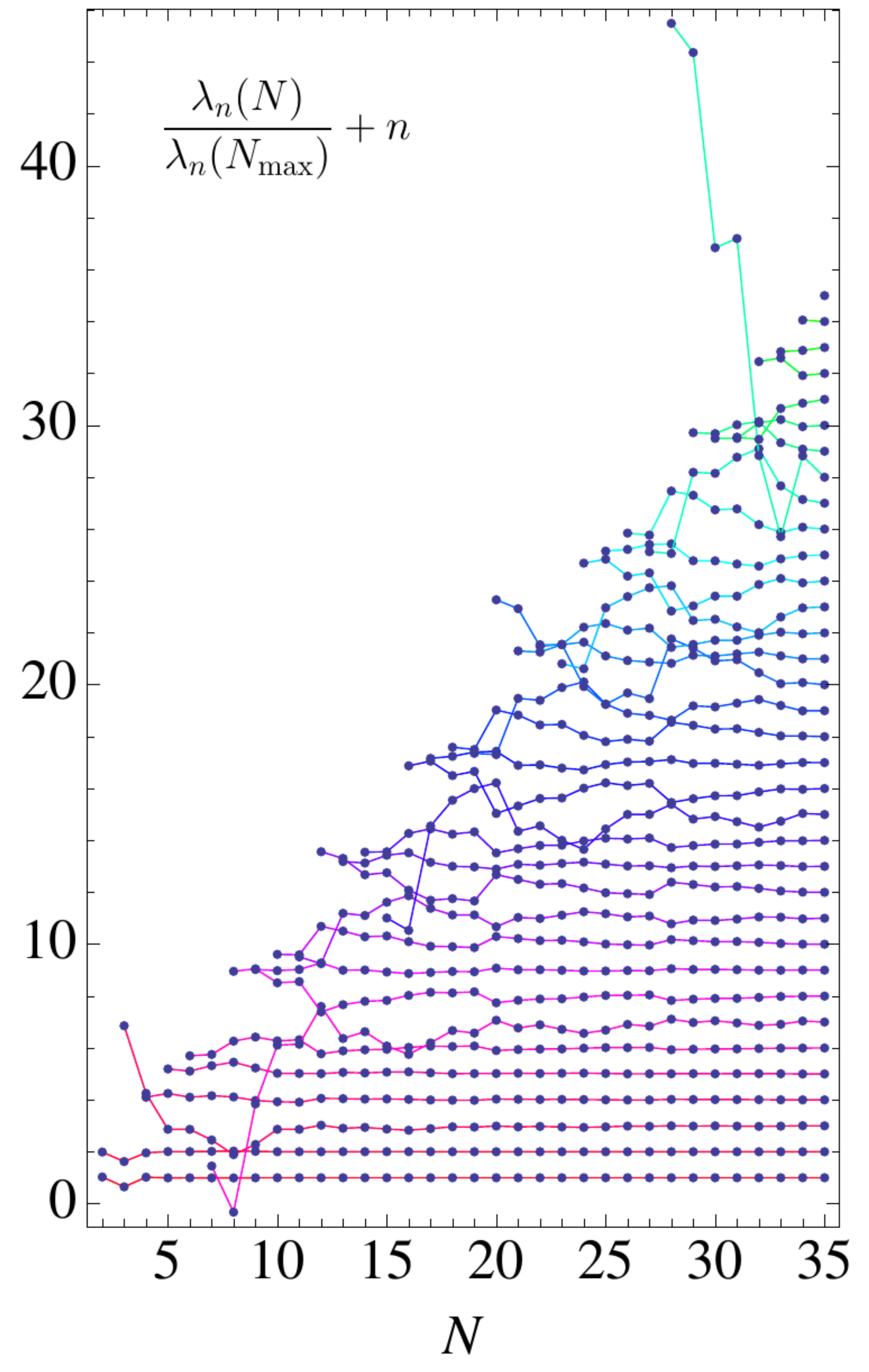


Summary



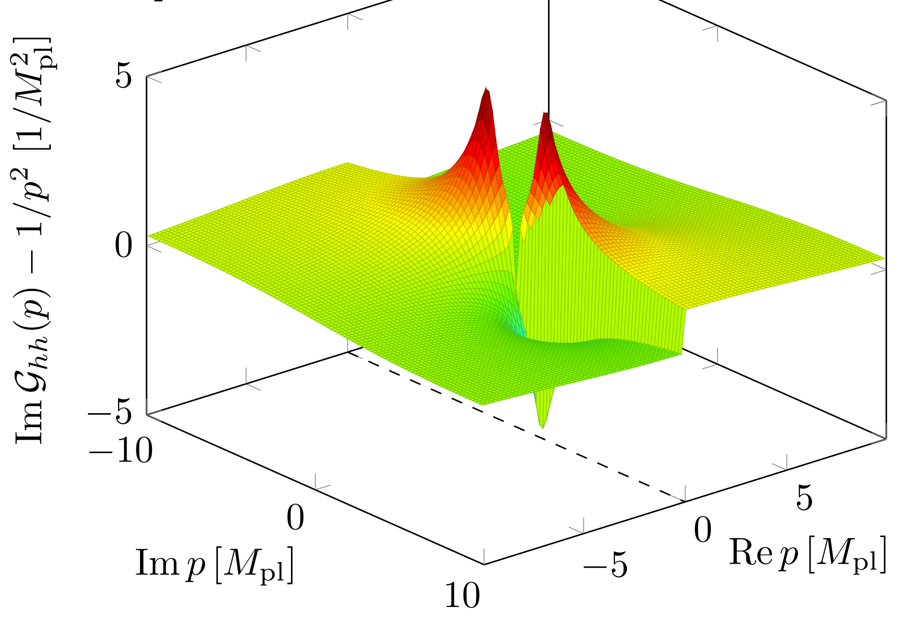
Getting real I: Apparent convergence





Getting real II: Scattering & spectral properties

Real part



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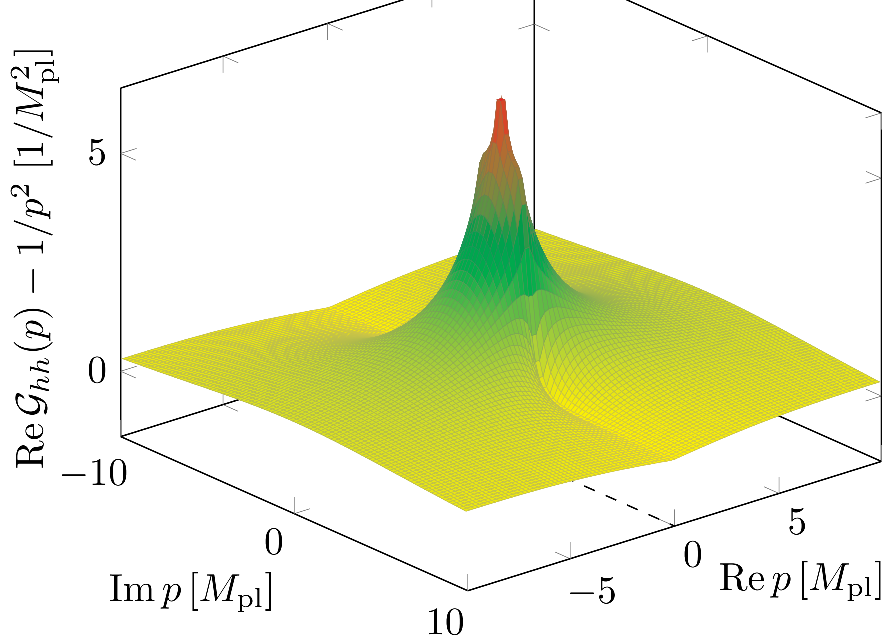
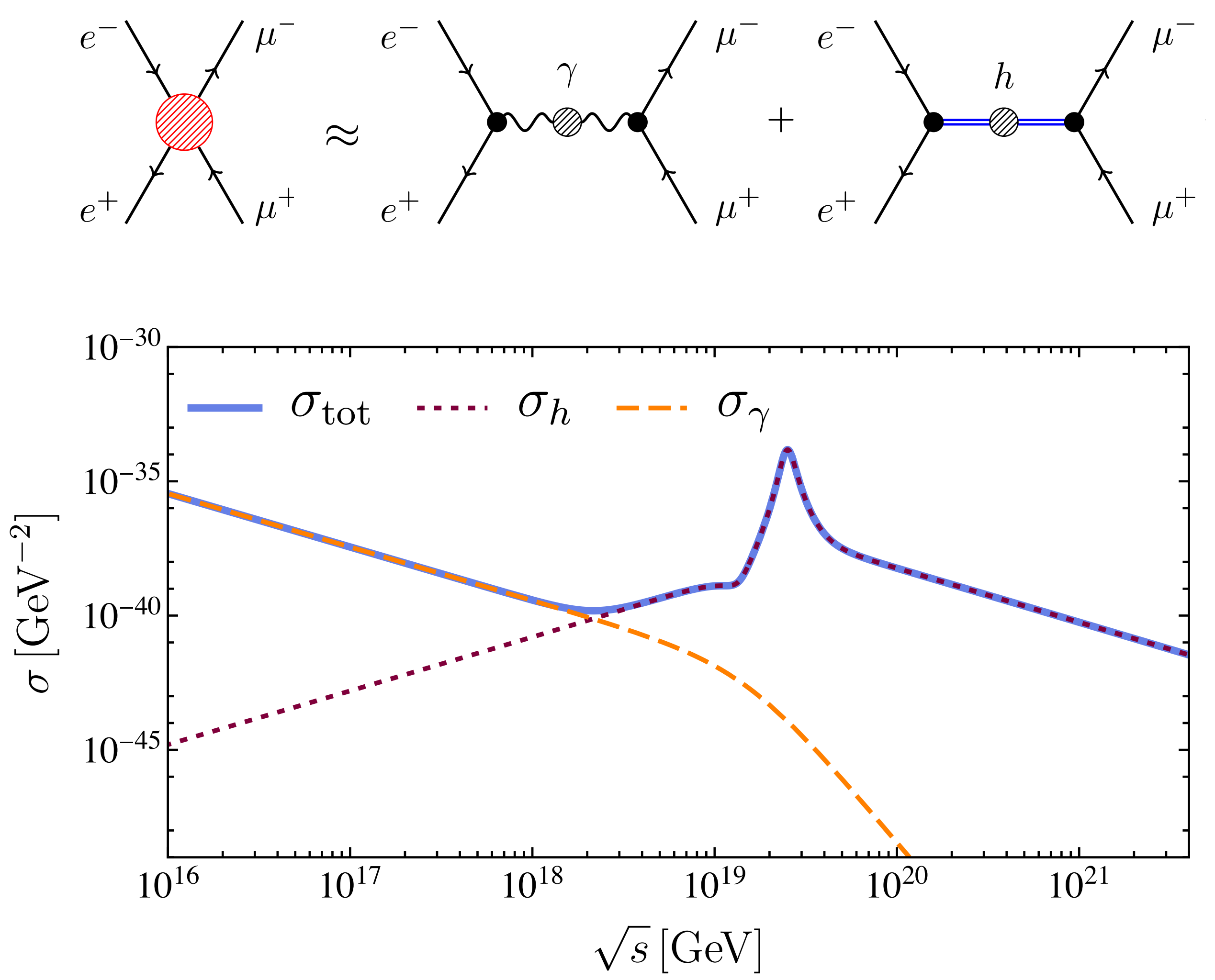
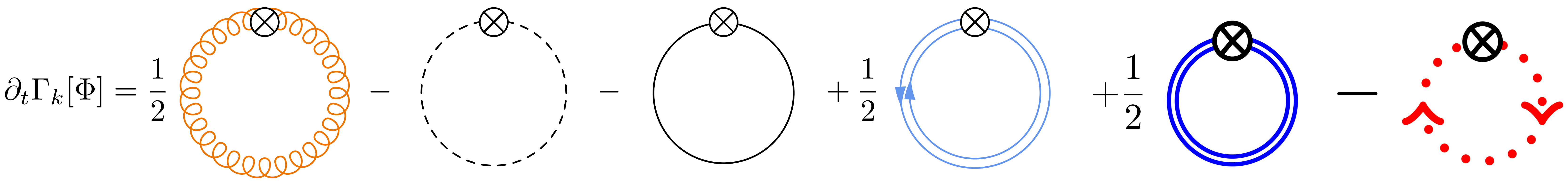


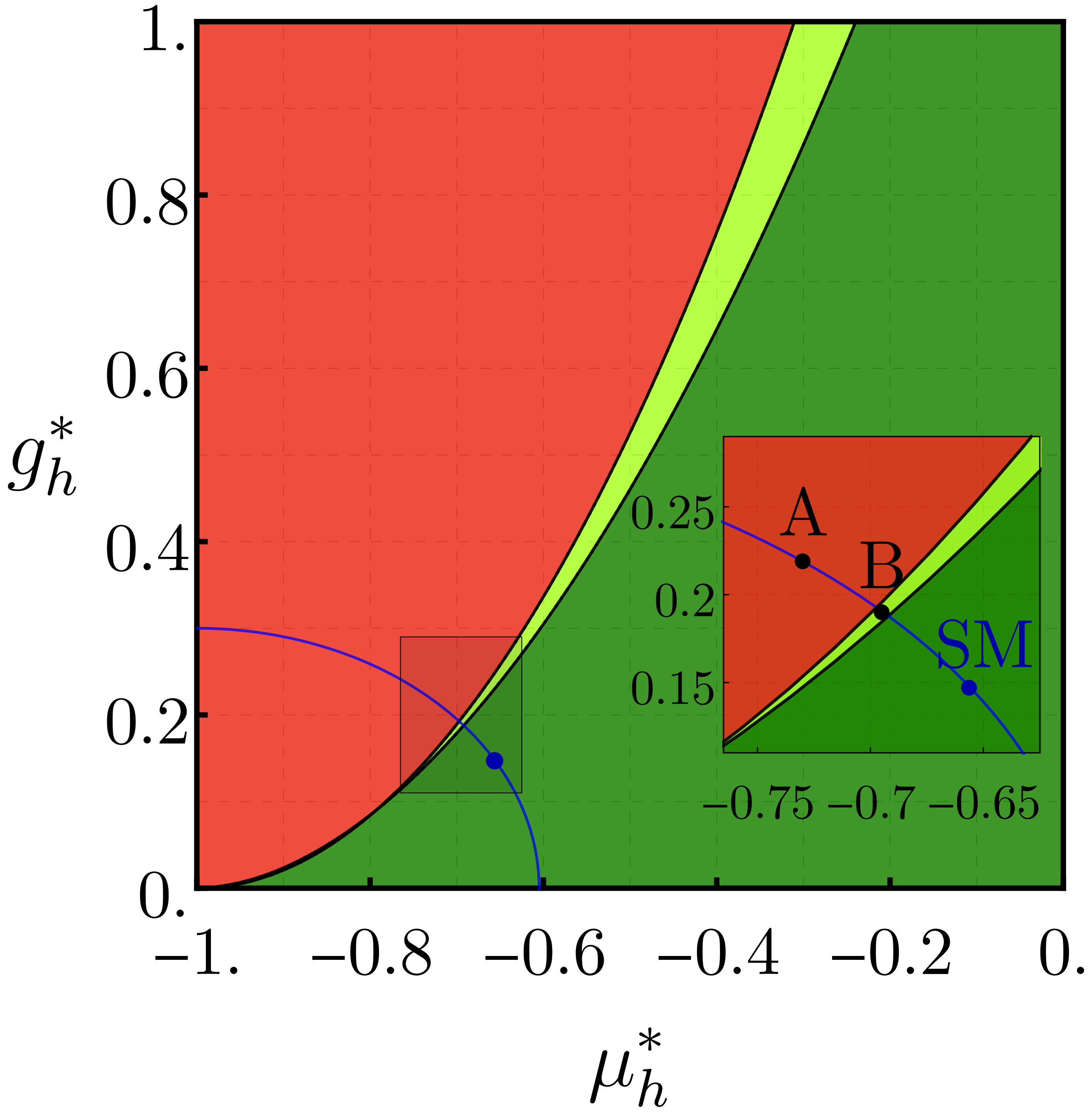


Summary

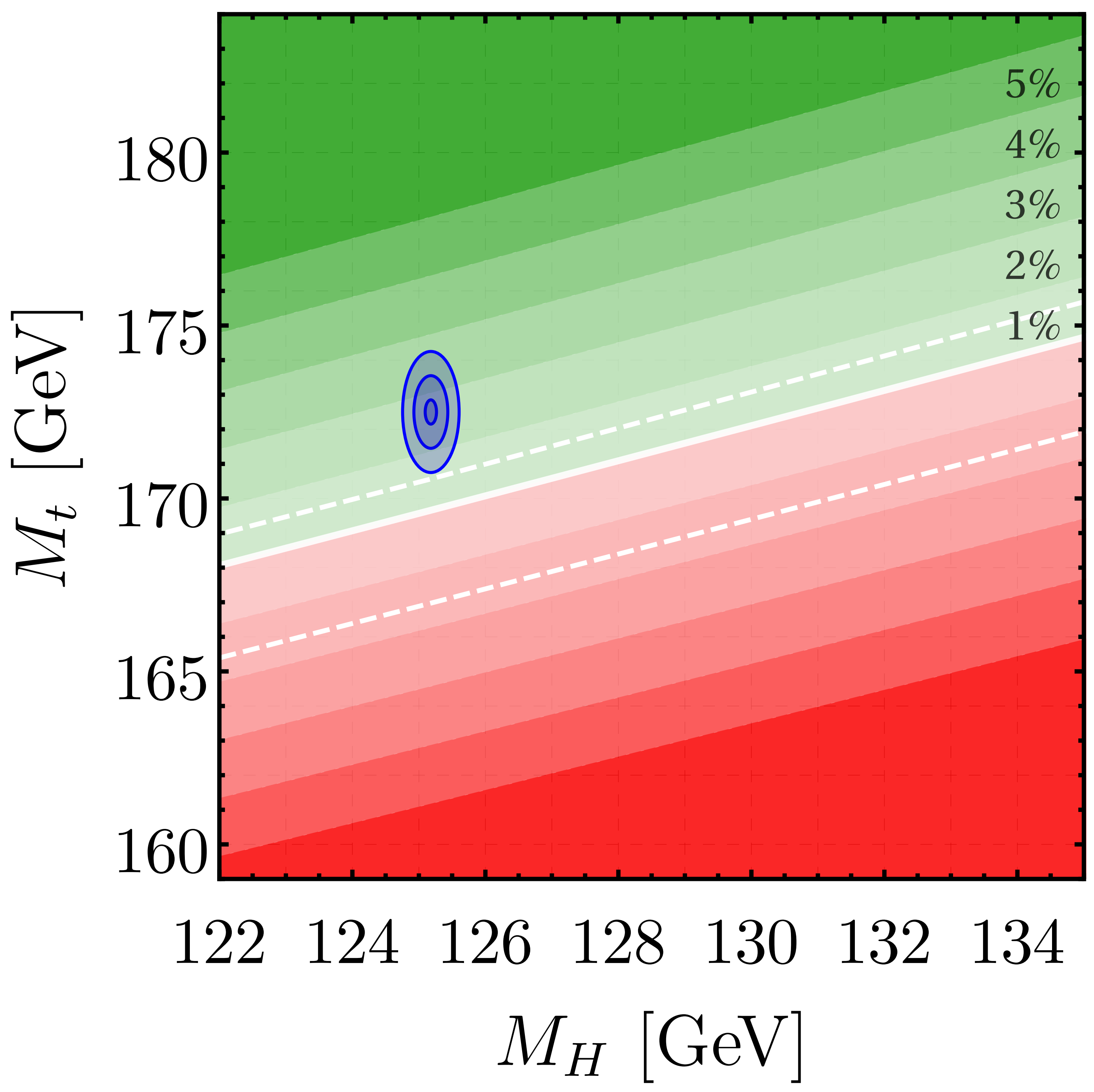


Asymptotically safe SM

Phase structure

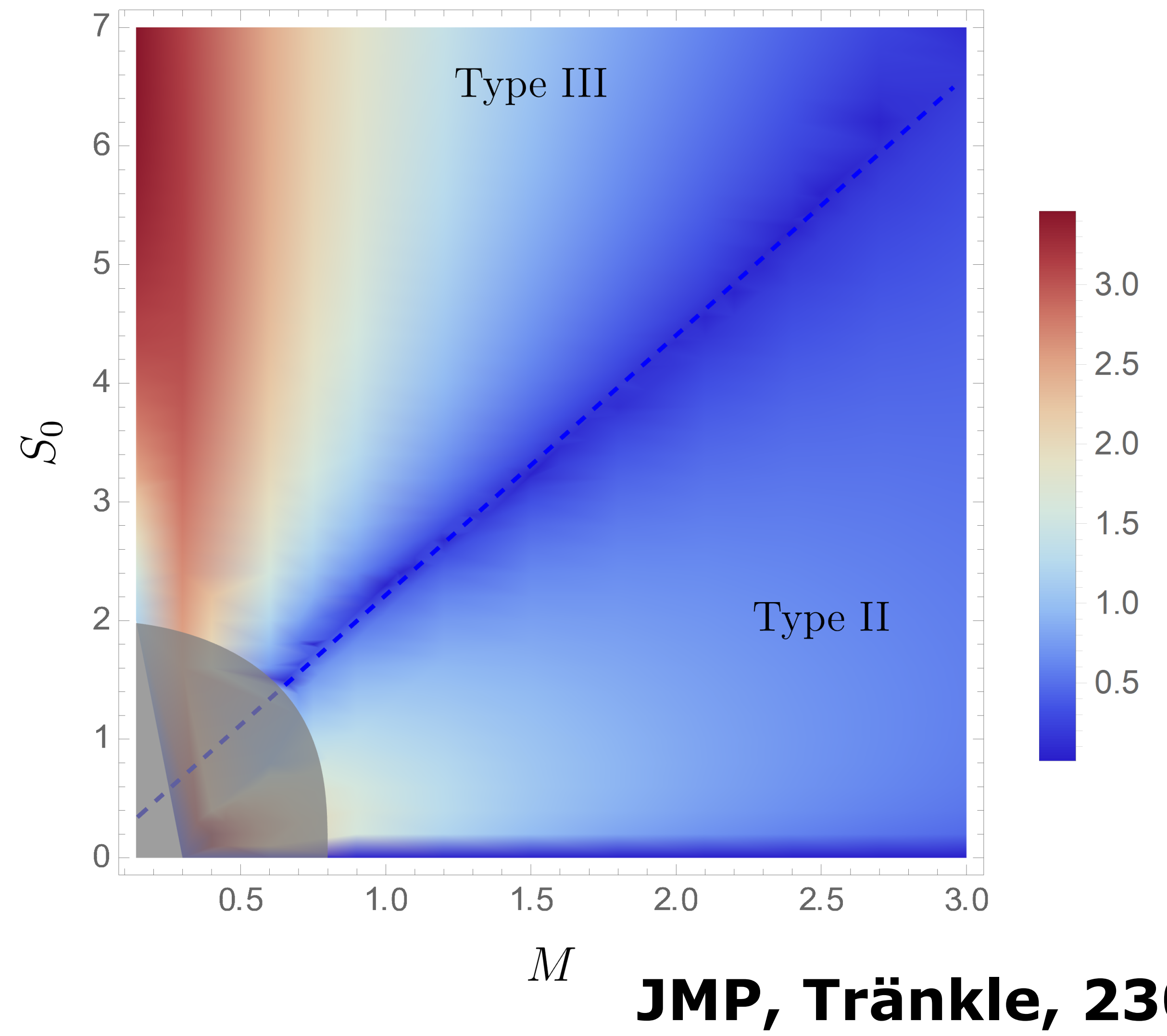


Where are we?



Quantum black holes

Phase structure



JMP, Tränkle, 2309.17043