Title: Perspectives for Asymptotic Safety

Date: Nov 08, 2009 11:00 AM

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Abstract:

asymptotic safety

- **RG scaling of gravitational coupling**

  dimensionless coupling $g(\mu) = Z_N(\mu)^{-1} \cdot G_N \cdot \mu^{D-2}$

  anomalous dimension $\eta_N = -\frac{\mathrm{d} \ln Z_N}{\mathrm{d} \ln \mu}$

  RG running $\frac{\mathrm{d}g}{\mathrm{d} \ln \mu} = (D - 2 + \eta_N)\, g$

- **fixed points**

  Gaussian: $g = 0$ **classical general relativity**

  non-Gaussian: $\eta_N = 2 - D$ **strong quantum effects**

asymptotic safety

- **RG scaling of gravitational coupling**

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- **fixed points**

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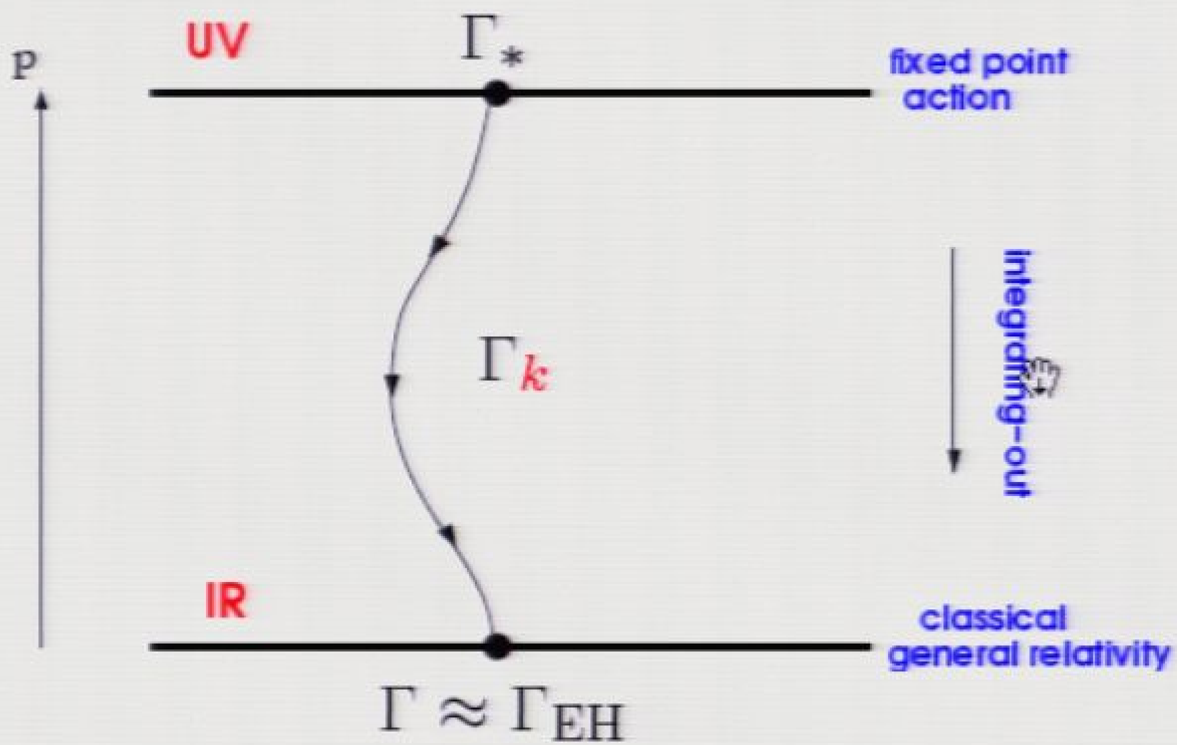
non-Gaussian: $\eta_N = 2 - D$ **strong quantum effects**

UV fixed point implies **weakly coupled gravity** at **high energies**

$$\mu \to \infty : \qquad G(\mu) \to g_* \mu^{2-D} \ll G_N$$

renormalisation group

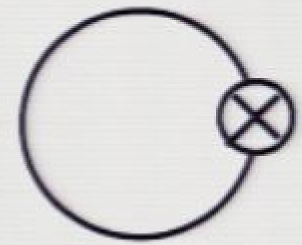
- **for quantum gravity:** "bottom-up"



renormalisation group

- **Callan-Symanzik equation** (Callan '70, Symanzik '70)

$$k\frac{\mathrm{d}\Gamma_k}{\mathrm{d}k} = \frac{1}{2}\,\mathrm{Tr}\left[\left(\frac{\delta^2\Gamma_k[\phi]}{\delta\phi\,\delta\phi} + k^2\right)^{-1} k\frac{\mathrm{d}k^2}{\mathrm{d}k}\right]_{\mathrm{ren.}} = \frac{1}{2}$$



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- **functional RG equation** (Wetterich '93)

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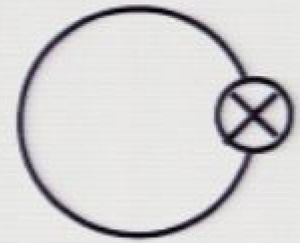

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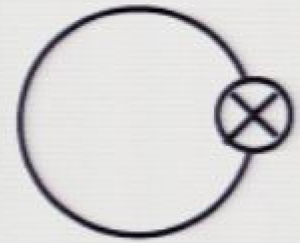

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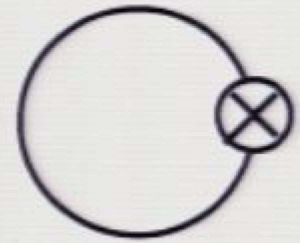

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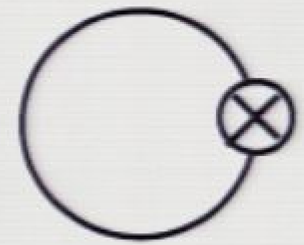
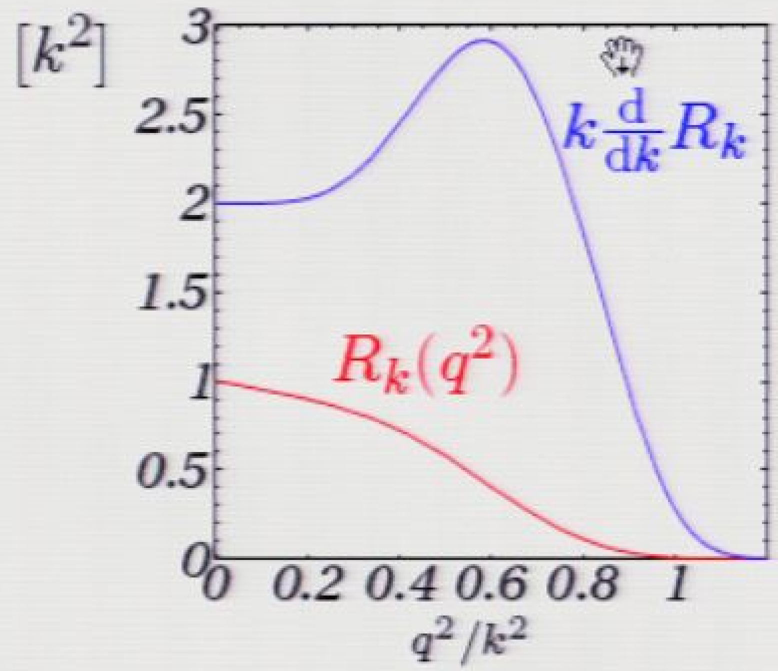


- **IR momentum cutoff**



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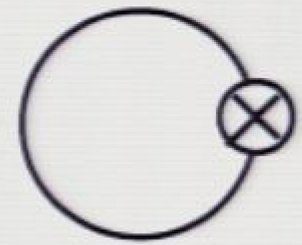

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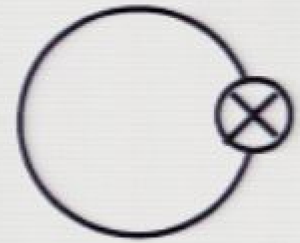

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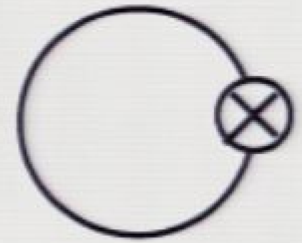

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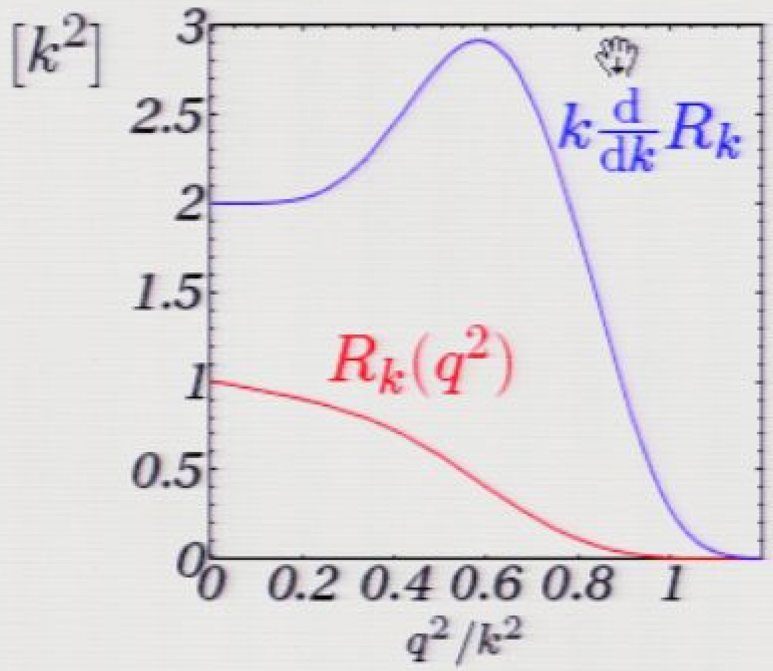

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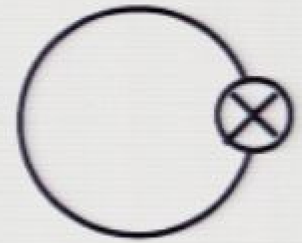

- **definition of the theory**

  finite initial (boundary) condition at $k = \Lambda$: Γ_Λ ,
  and finite flow equation $k\partial_k\Gamma_k$, regulator function R_k ,
  altogether:

$$\Gamma = \Gamma_\Lambda + \frac{1}{2}\int_\Lambda^0 \mathrm{d}k\,\partial_k\Gamma_k[\Gamma_k^{(2)}; R_k]$$

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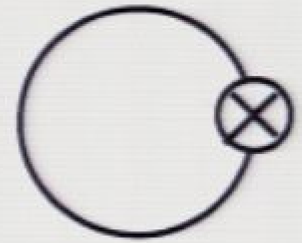

- **symmetries**

  global vs local

  if regulator respects symmetry: ok

  if not: **(modified) Ward identities** ensure that the physical theory $\Gamma_{k=0}$ respects the symmetry

renormalisation group

- **for quantum gravity** (Reuter '96)

$$k\frac{\mathrm{d}}{\mathrm{d}k}\Gamma_k[g_{\mu\nu};\bar{g}_{\mu\nu}] = \frac{1}{2}\,\mathrm{Tr}\,\left[\left(\Gamma_k^{(2)}[g_{\mu\nu};\bar{g}_{\mu\nu}] + R_k\right)^{-1} k\frac{\mathrm{d}R_k}{\mathrm{d}k}\right]$$

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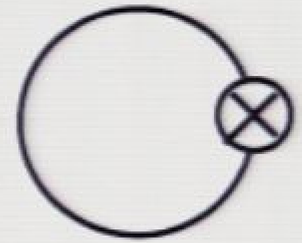

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- **effective action**

$$\Gamma_k = \frac{1}{16\pi G_k}\int\sqrt{g}\,(-R + 2\Lambda_k + \cdots) + S_{\mathrm{matter},k} + S_{\mathrm{gf},k} + S_{\mathrm{ghosts},k}$$

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- **running couplings**

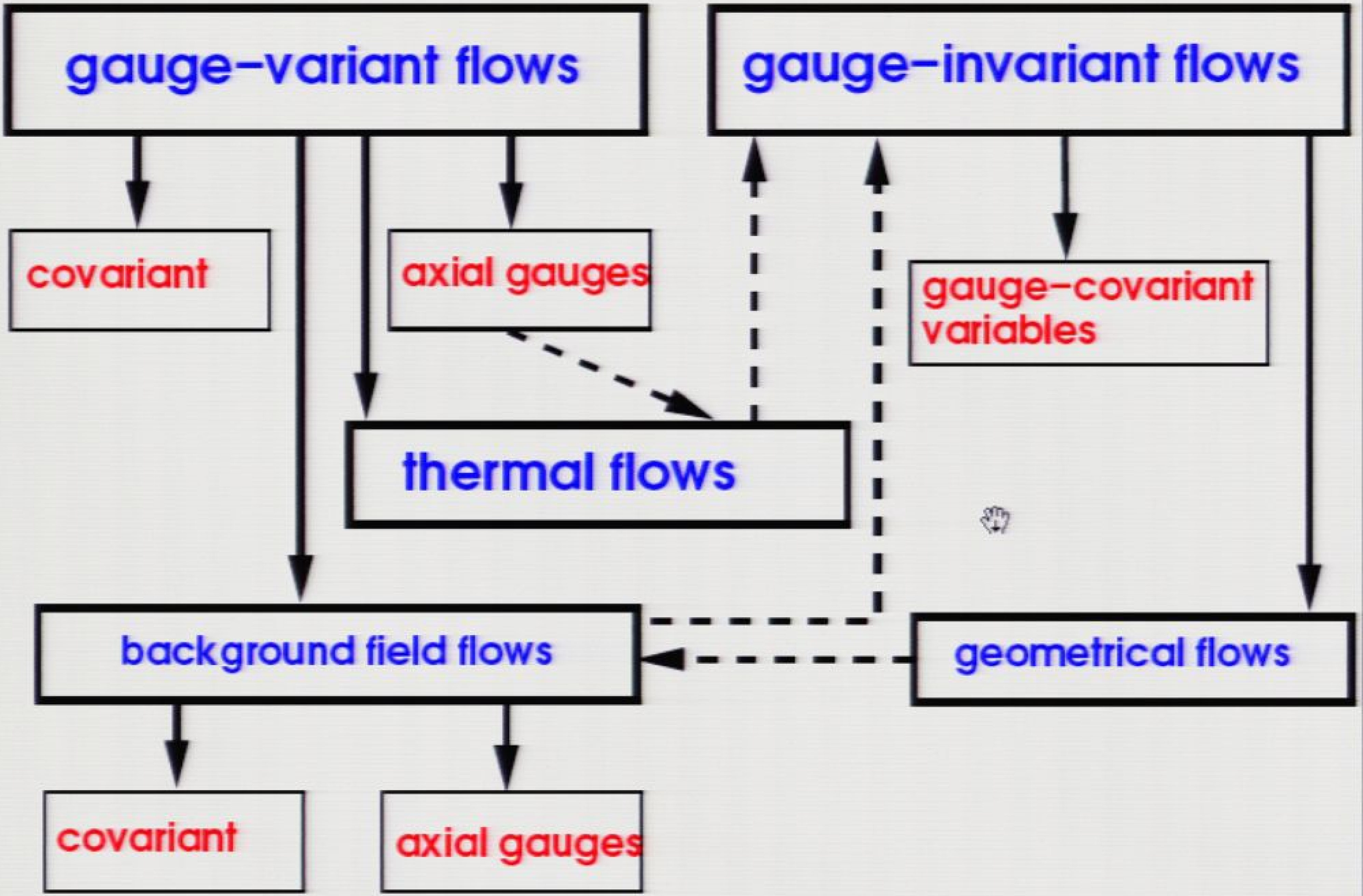
  projection of $k\partial_k\Gamma_k$ onto $\sqrt{g},\ \sqrt{g}R,\ \sqrt{g}R^2,\cdots$

- **optimisation** (DL '00, '01, '02, Pawlowski '05)

  choice of regulator function R_k

  stability $\leftrightarrow$ convergence $\leftrightarrow$ control of approximations

local symmetry


gauge−variant flows
gauge−invariant flows
covariant
axial gauges
gauge−covariant variables
thermal flows
background field flows
geometrical flows
covariant
axial gauges

Yang-Mills + gravity

S. Folkerts, DL, JM. Pawlowski ('09)

Yang-Mills + gravity

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- **background field flow**

ansatz

$$\Gamma_k = \int \sqrt{g} \left[\frac{Z_{N,k}}{16\pi G_N} \left(-R(g_{\mu\nu}) + 2\bar{\Lambda}_k \right) + \frac{Z_{A,k}}{4g^2} F^a_{\mu\nu} F^{\mu\nu}_a \right]$$

$$R_k[\bar{\phi}] = \Gamma_k^{(2)}[\bar{\phi}]\, r[\bar{\phi}]$$

$$r^{gg} = r^{gg}(-\Delta_{\bar{g}}) \quad r^{\bar{\eta}\eta} = -r^{\eta\bar{\eta}} = r^{\bar{\eta}\eta}(-\Delta_{\bar{g}})$$

$$r^{AA} = r^{AA}(-\Delta_{\bar{g}}(A) \quad r^{\bar{C}C} = -r^{C\bar{C}} = r^{\bar{C}C}(-\Delta_{\bar{g}}(A))$$

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- **background field flow**

  flow

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \mathrm{Tr}\, \frac{1}{1+r[\phi]} \partial_t r[\phi] + \mathrm{Tr}\, \frac{\partial_t \Gamma_k^{(2)}[\phi,\phi]}{\Gamma_k^{(2)}[\phi,\phi]} \frac{r[\phi]}{1+r[\phi]}$$

  result: no graviton contribution at one-loop

$$\beta_g\big|_{1-\mathrm{loop}} = \beta_{g,\mathrm{YM}}\big|_{1-\mathrm{loop}}$$

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- **background field flow**

  background field dependence

$$\int \frac{\delta R_k}{\delta \bar\phi} \frac{\delta \Gamma_k[\phi,\bar\phi]}{\delta R_k} = \frac{1}{2}\mathrm{Tr}\, \frac{1}{\Gamma_k^{(2)}[\phi,\bar\phi] + R_k[\bar\phi]} \frac{\delta R_k[\bar\phi]}{\delta \bar\phi}$$

- **YM theory**

  non-trivial contribution at 1-loop DL, JM. Pawlowski ('02)

- **here:**

$$\frac{1}{2}\mathrm{Tr}\, \frac{1}{1+r[\phi]} \frac{\delta r}{\delta \phi} + \mathrm{Tr}\, \frac{\delta \Gamma_k^{(2)}}{\delta \phi}[\phi,\phi] \frac{1}{\Gamma_k^{(2)}[\phi,\phi]} \frac{r[\phi]}{1+r[\phi]}$$

Yang-Mills + gravity

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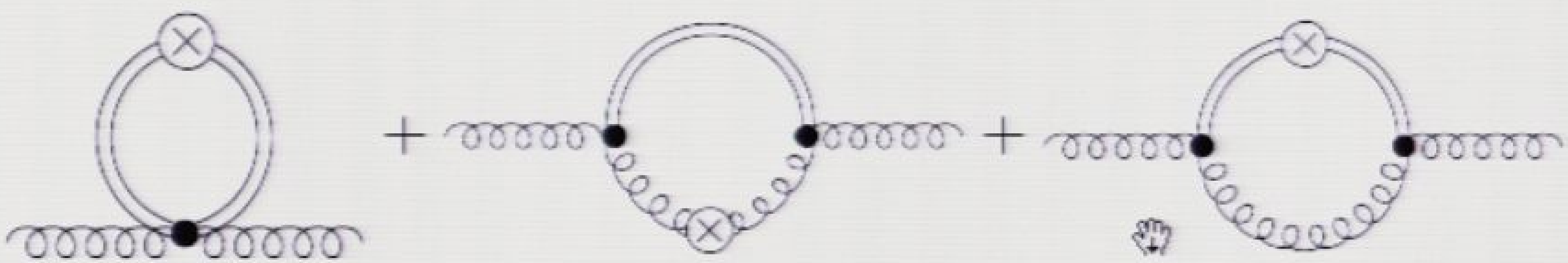
- **flat background**



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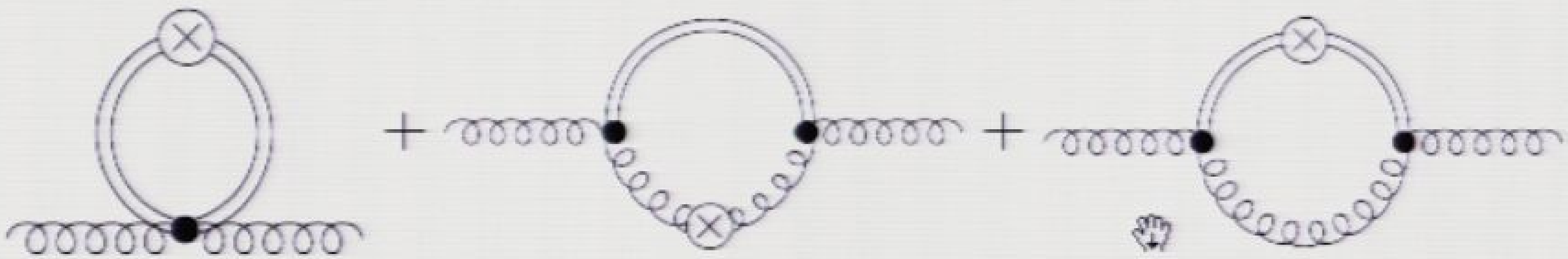

- **1-loop result**

$$\beta_{\text{YM}}\big|_{\text{grav}} = -\frac{6\,I}{\pi} G_N\, g_{\text{YM}}\, E^2$$

$$I = \int_0^\infty dx\, \frac{1+\alpha}{1+r_g(x)} \left(1 - \frac{1}{1+r_A(x)}\right) \geq 0$$

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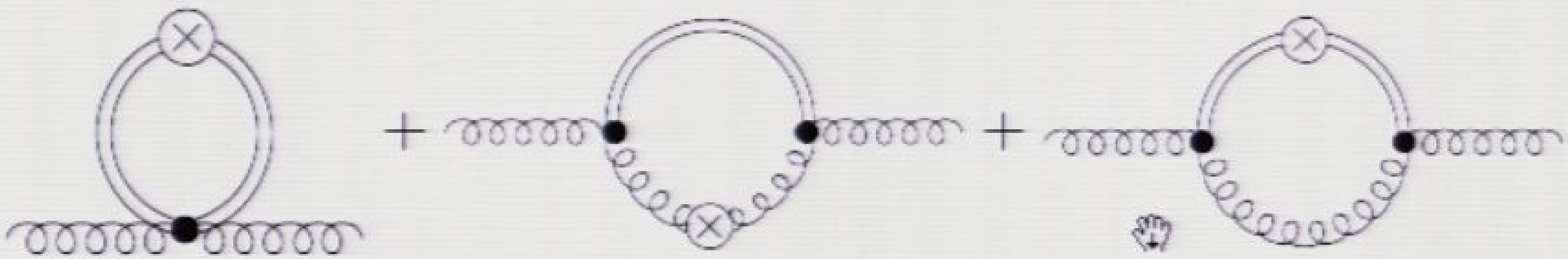

- **beyond 1-loop**

$$\beta_{\text{YM}}\big|_{\text{grav}} < 0$$

asymptotic freedom persists in presence of gravity FP

Yang-Mills + gravity

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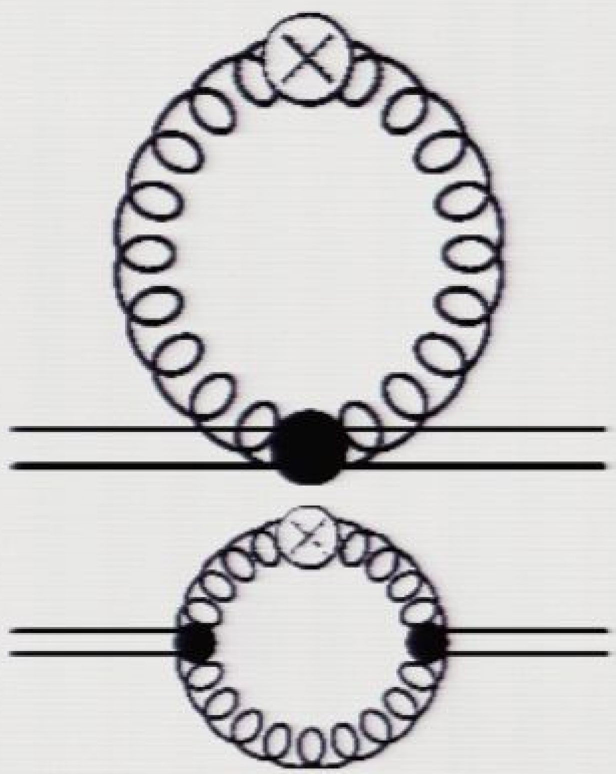
- **Yang-Mills contribution to gravity**

  diagrams



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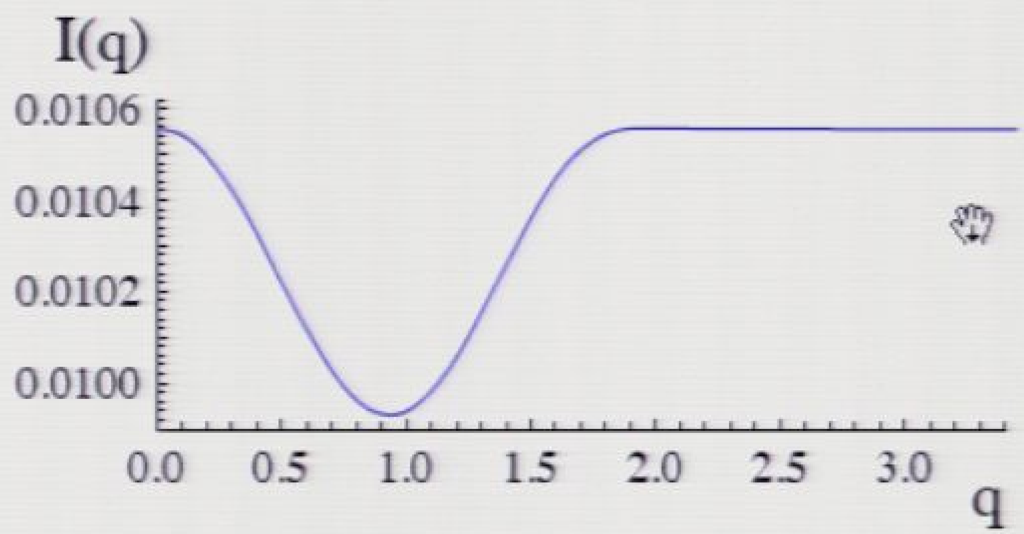

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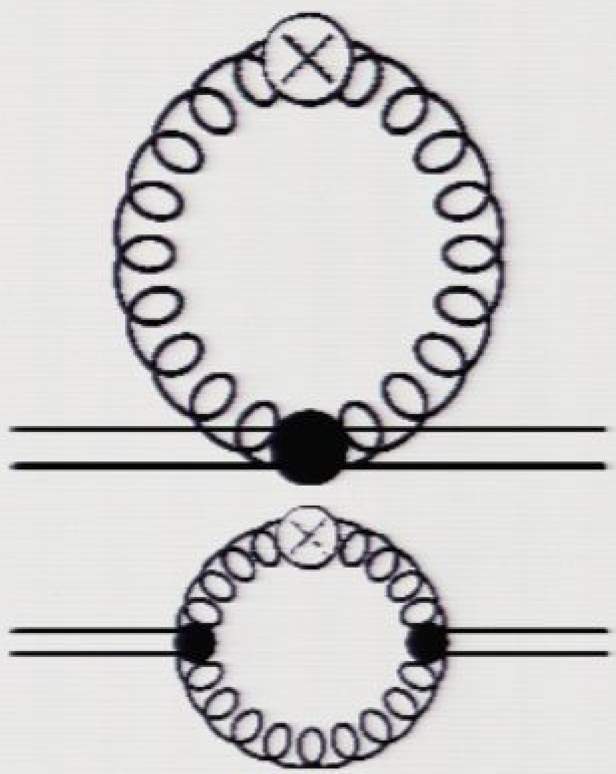

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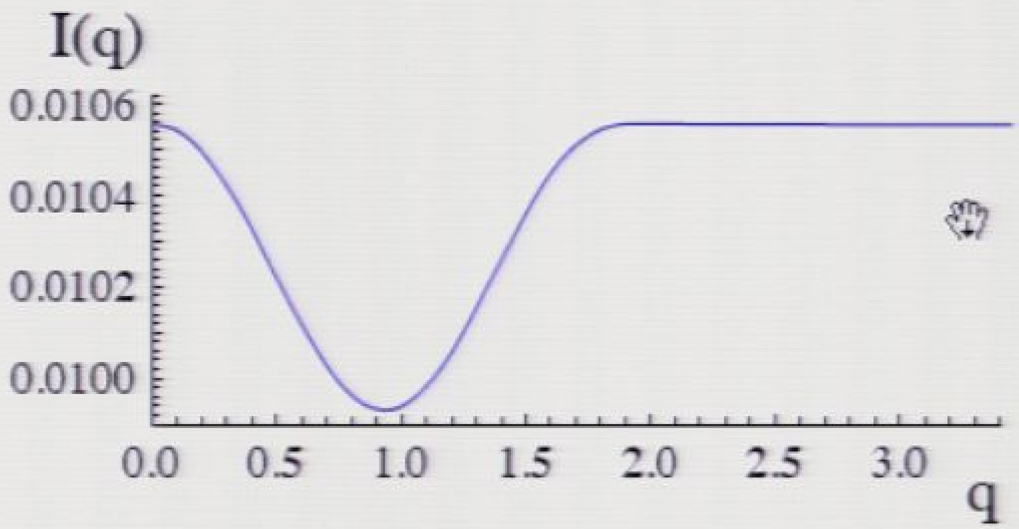

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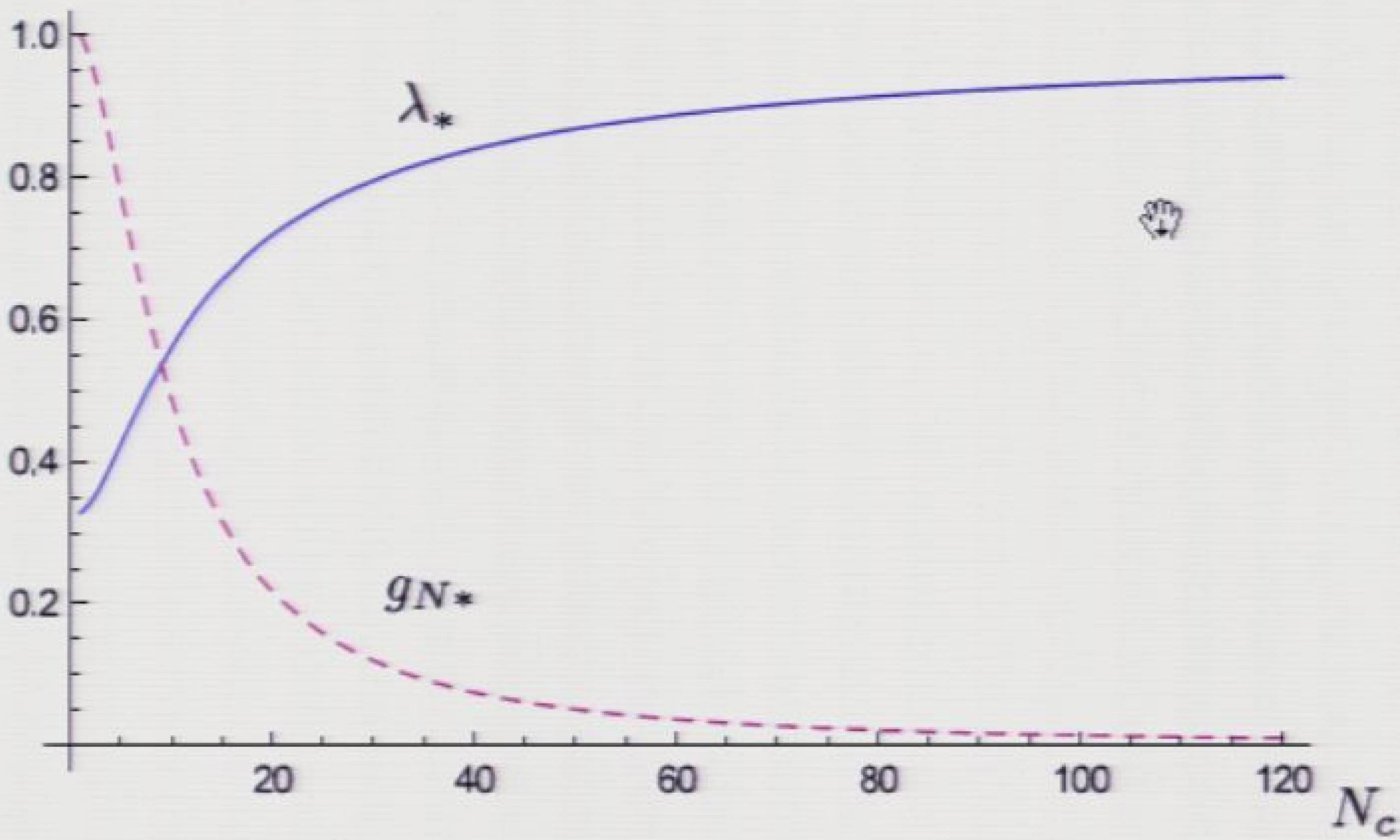
  UV fixed point of coupled system



phenomenology for asymptotic safety

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- **low-scale quantum gravity**

  what if the **fundamental** Planck scale M_D obeys

  $$M_D \approx \mathcal{O}(M_{\rm EW}) \approx \mathcal{O}(1\,{\rm TeV}) \ll M_{\rm Pl}$$

  quantum gravity accessible at colliders

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  quantum gravity accessible at colliders

- **large extra dimensions** (Arkani-Hamed, Dimopoulos, Dvali '98)

  D=4+n compact spatial dimensions

  compact extra dimensions $M^2_{\rm Planck} \sim M^2_D (M_D\, L)^n$

  roughly $L \sim 10^{\frac{30}{n}-17}{\rm cm}\ \left(\frac{1{\rm TeV}}{m_{EW}}\right)^{1+\frac{2}{n}}$

  scale separation $1/L \ll M_D \ll M_{\rm Planck}$

gravitational fixed point

DL ('03), P. Fischer, DL ('06)

- **higher dimensions**

  critical dimension for gravity $D = 2$
  expect similarities under RG flow for $D > 2$

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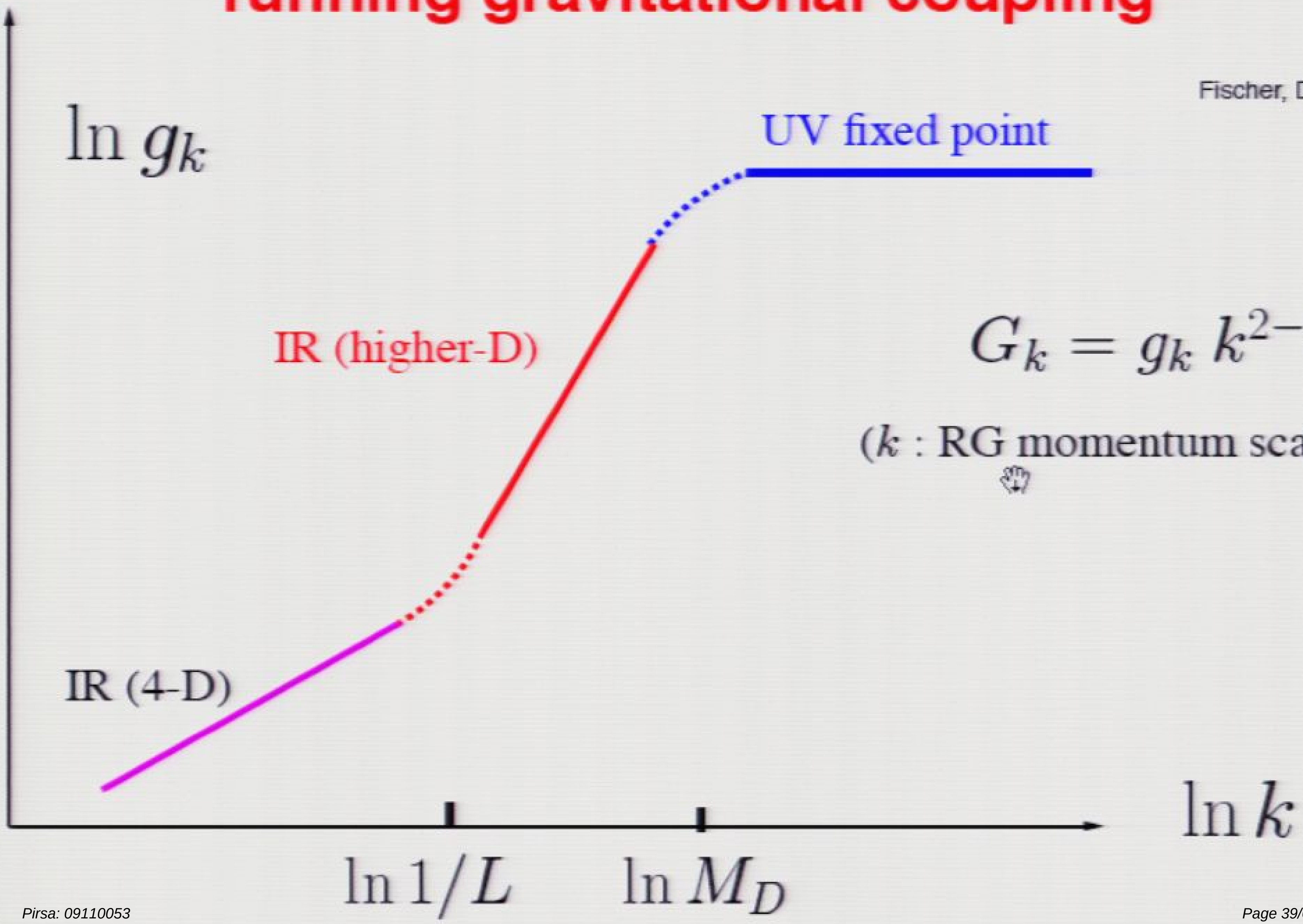
- **Einstein-Hilbert scaling exponents**

θ'	pow	mexp	exp	mod	opt
$D = 4$	1.63	1.51	1.53	1.51	1.48
5	3.19	2.80	2.83	2.77	2.69
6	5.31	4.58	4.60	4.50	4.33
7	7.83	6.71	6.68	6.54	6.27
8	10.7	9.14	9.03	8.86	8.46
9	13.9	11.9	11.6	11.4	10.9
10	17.4	14.9	14.5	14.2	13.5
11	21.3	18.2	17.6	17.3	16.4

running gravitational coupling



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(k : RG momentum scale)

gravitational fixed point

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- **higher dimensions**

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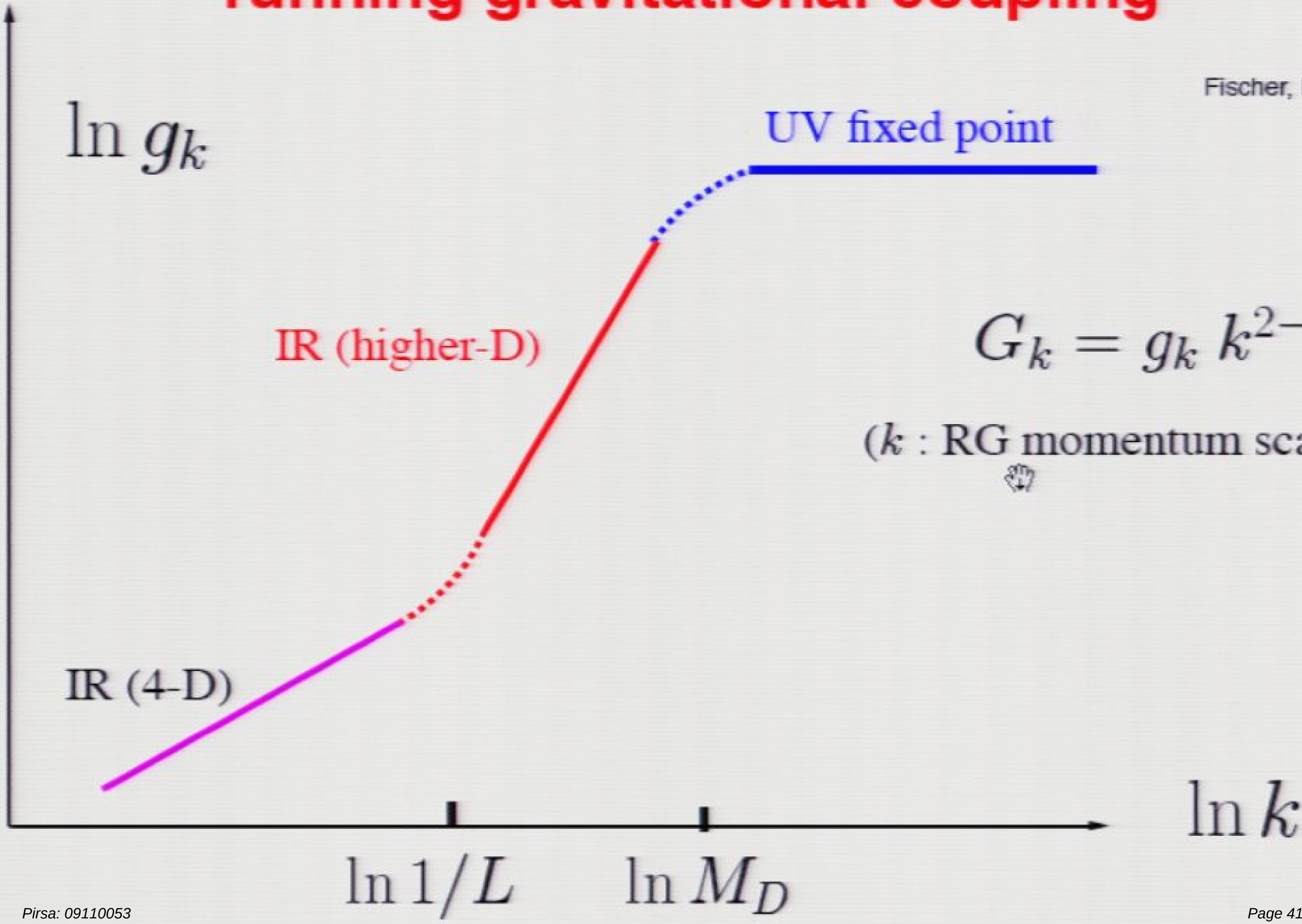
  expect similarities under RG flow for $D > 2$

- **weak cutoff sensitivity**

τ	pow	mexp	exp	mod	opt
$D = 4$	0.132	0.132	0.134	0.135	0.137
5	0.463	0.461	0.468	0.469	0.478
6	0.943	0.933	0.946	0.946	0.963
7	1.528	1.502	1.521	1.521	1.544
8	2.186	2.142	2.165	2.162	2.192
9	2.900	2.834	2.858	2.853	2.888
10	3.655	3.568	3.591	3.585	3.623
11	4.445	4.336	4.356	4.348	4.389

running gravitational coupling

Fischer, DL ('06)



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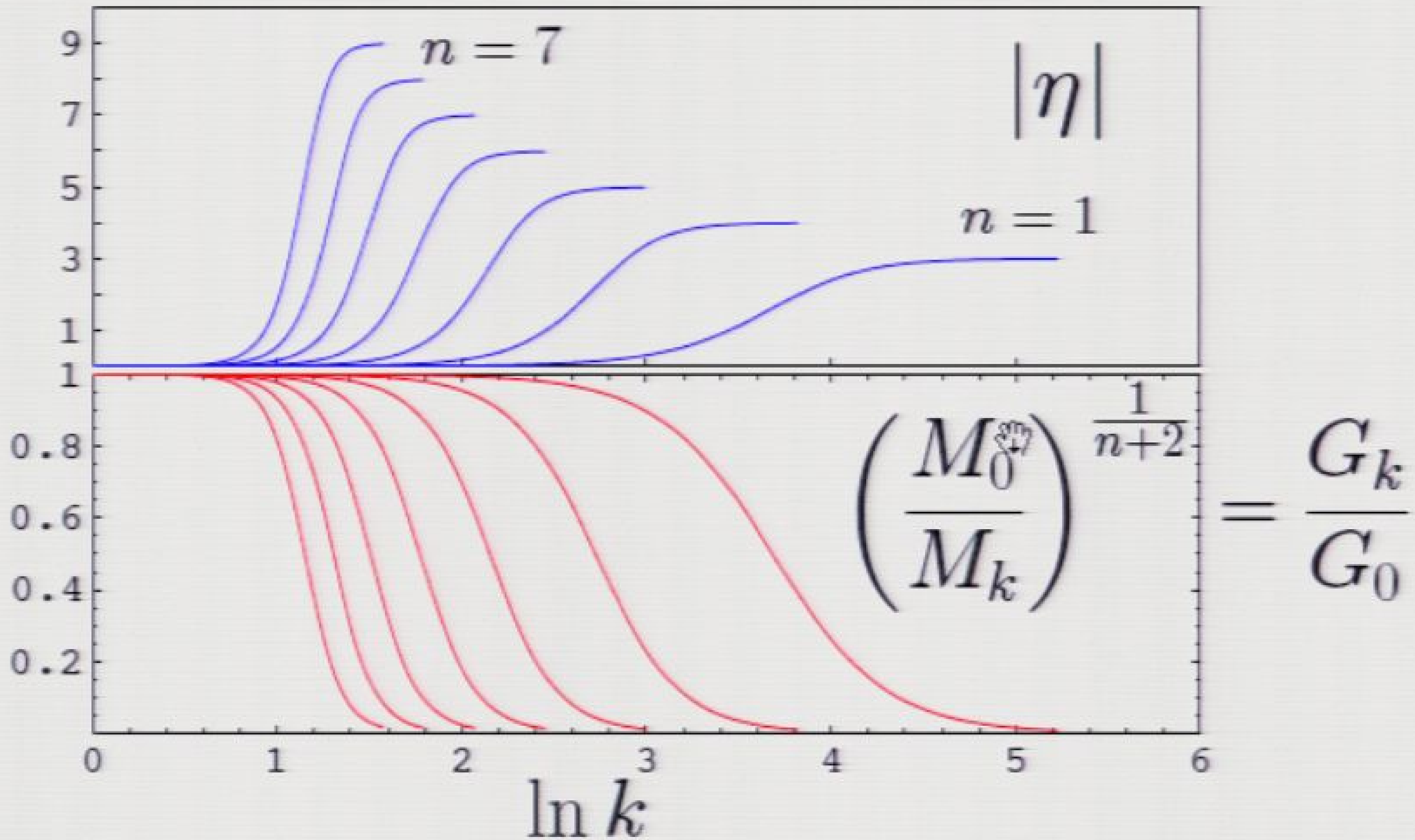
RG running and anomalous dimension

DL ('03), Fischer, DL ('05,'06)



collider signatures of quantum gravity

- **real gravitons**

  graviton production via p p $\longrightarrow$ jet + G

  signature: missing energy

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- **virtual gravitons**

  lepton production $q\bar{q} \longrightarrow \ell^+\ell^-$ via graviton exchange

  signature: deviations in SM reference processes

- **mini-black holes**

  black hole production and decay

  signature: spectacular (many body final states)

gravitational Drell-Yan

- **effective theory** Giudice, Rattazzi, Wells ('98)

  scattering amplitude for Drell-Yan lepton production

$$A = \mathcal{S}(s) \times T\,, \qquad T = T^{\mu\nu} T_{\mu\nu} - \frac{1}{n+2} T^{\mu}_{\mu} T^{\nu}_{\nu}$$

$$\mathcal{S}(s) = \frac{1}{M_D^{n+2}} \int_0^\infty \mathrm{dm_{kk}}\, \mathrm{m_{kk}}^{n-1} \frac{1}{s + \mathrm{m_{kk}}^2}$$

UV divergent for $n \geq 2$.

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  graviton production via **p p → jet + G**

  signature: missing energy

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$$A = \mathcal{S}(s) \times T\,, \qquad T = T^{\mu\nu}T_{\mu\nu} - \frac{1}{n+2}T^{\mu}_{\mu}T^{\nu}_{\nu}$$

$$\mathcal{S}(s) = \frac{1}{M_D^{n+2}} \int_0^\infty \mathrm{dm_{kk}}\, \mathrm{m_{kk}}^{n-1} \frac{1}{s + \mathrm{m_{kk}}^2}$$

UV divergent for $n \geq 2$.

collider signatures of quantum gravity

- **real gravitons**

  graviton production via **p p → jet + G**

  signature: missing energy

- **virtual gravitons**

  lepton production $q\bar{q} \longrightarrow \ell^+\ell^-$ via graviton exchange

  signature: deviations in SM reference processes

- **mini-black holes**

  black hole production and decay

  signature: spectacular (many body final states)

gravitational Drell-Yan

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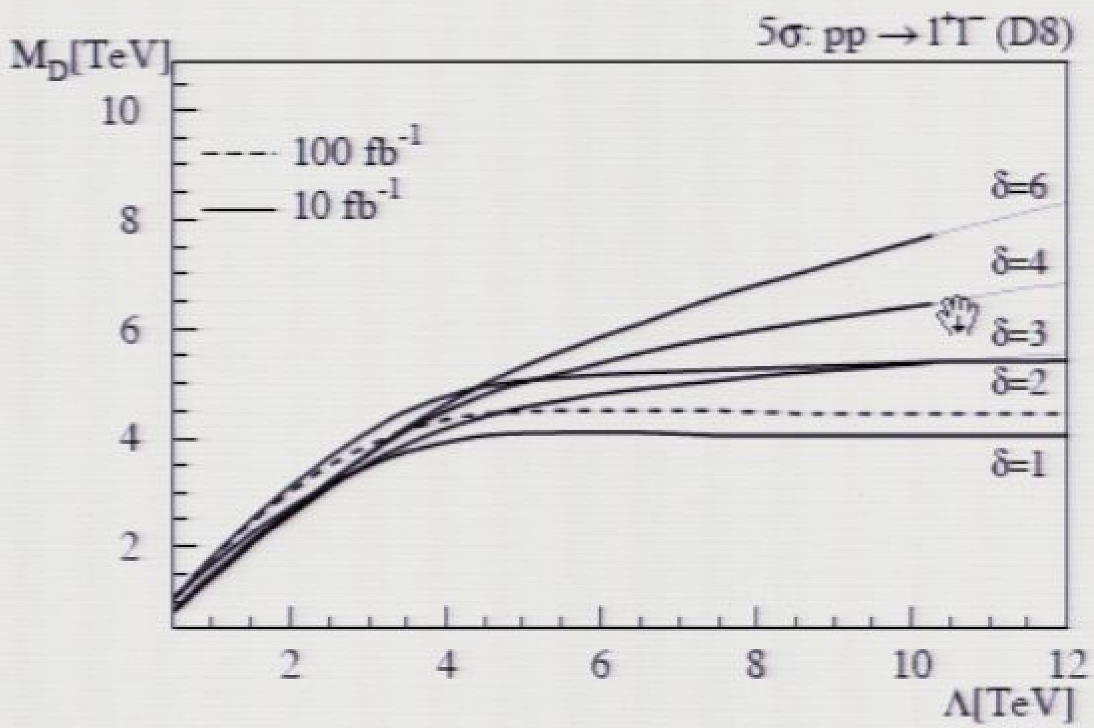
gravitational Drell-Yan

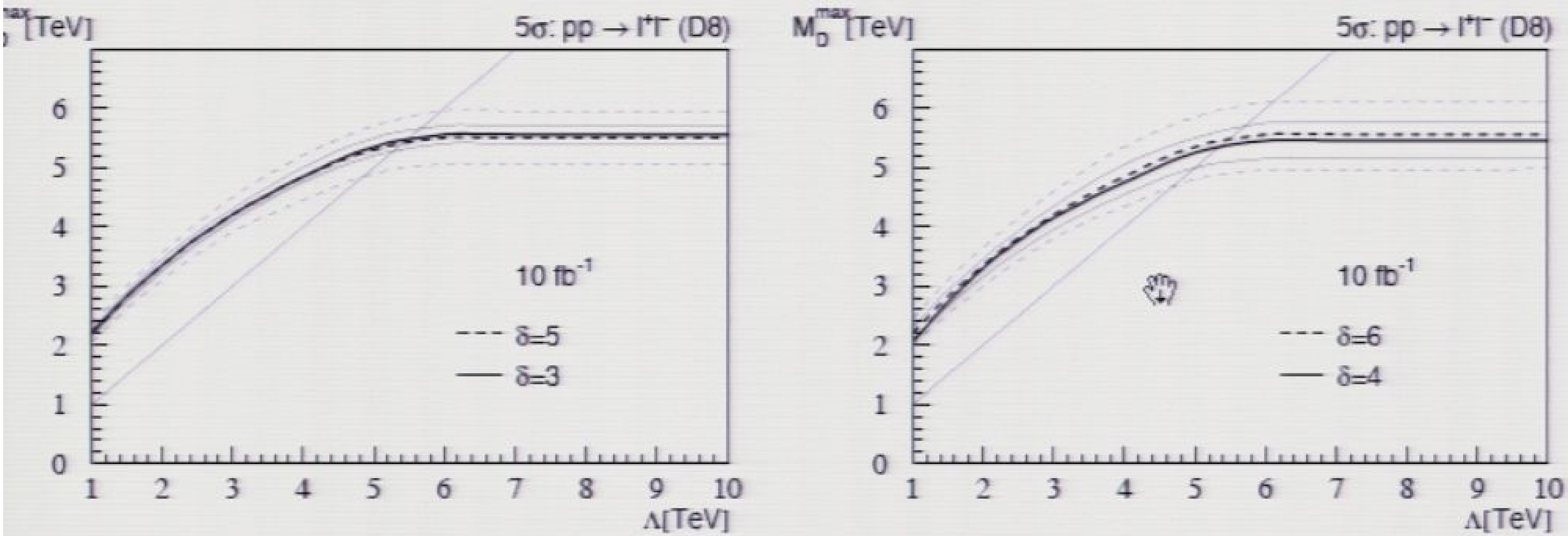
- effective theory + Monte Carlo simulations

Giudice, Plehn, Strumia ('04)



gravitational Drell-Yan

- renormalisation group + Monte Carlo simulation DL, Plehn ('07)



black holes at the LHC

Dimopoulos, Landsberg ('01)
Giddings, Thomas ('01)

- **classical Schwarzschild black holes**

  metric

$$ds^2 = -f(r)\,dt^2 + f^{-1}(r)\,dr^2 + r^2 d\Omega_{d-2}^2\,, \quad f = 1 - \frac{G_N\,M}{r^{d-3}}$$

  classical Schwarzschild radius

$$r_{\rm cl} = (G_N\,M)^{1/(d-3)}$$

- **production cross section**

  semi-classical $\hat{\sigma} = F \times \pi r_{\rm cl}^2(M = \sqrt{s}) \times \theta(\sqrt{s} - M_{\rm min})$

  form factor F

gravitational Drell-Yan

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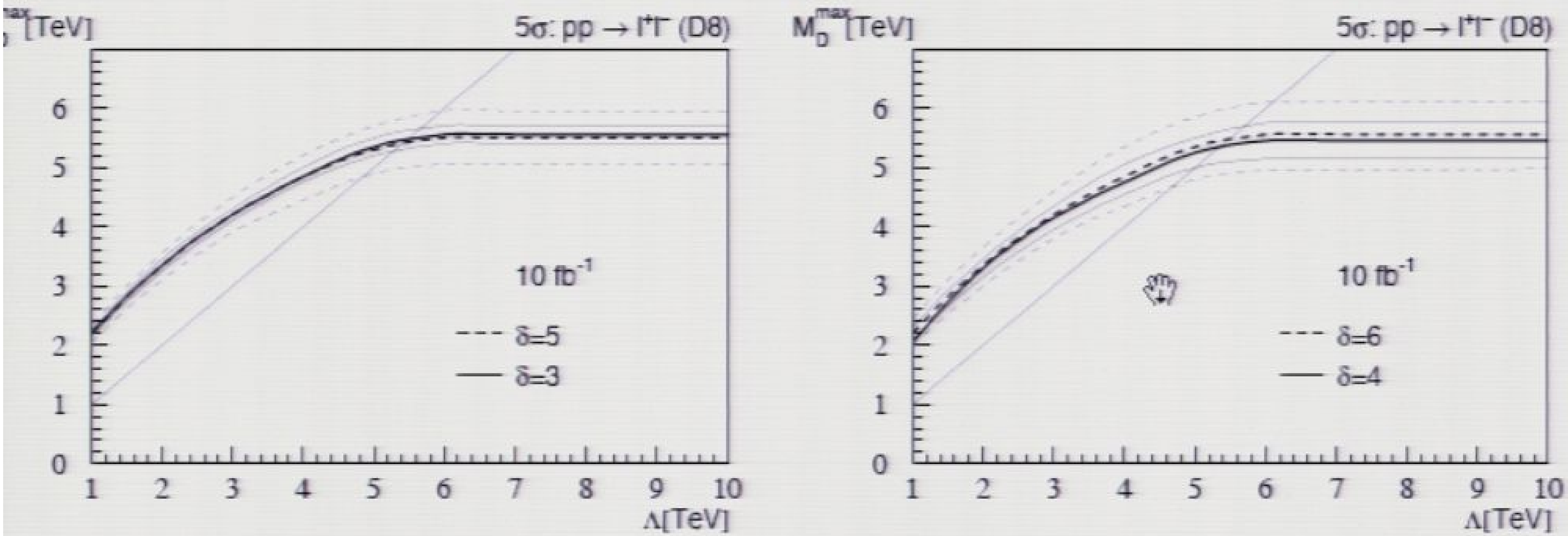

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black holes at the LHC

- **RG improved black holes** K. Falls, DL, A. Raghuraman (ERG '08, '09)

  running gravitational coupling

$$G_N \to G(r)\,, \quad f(r) \to f_{\rm imp}(r) = 1 - \frac{G(r)\,M}{r^{d-3}}$$

  improved Schwarzschild radius r_s from

$$f'_{\rm imp}(r_s) = 0$$

  critical black hole mass M_c from

$$(d-3)M_c = r\partial_r\, G(r)|_{r=r_c(M_c)}$$

black holes at the LHC

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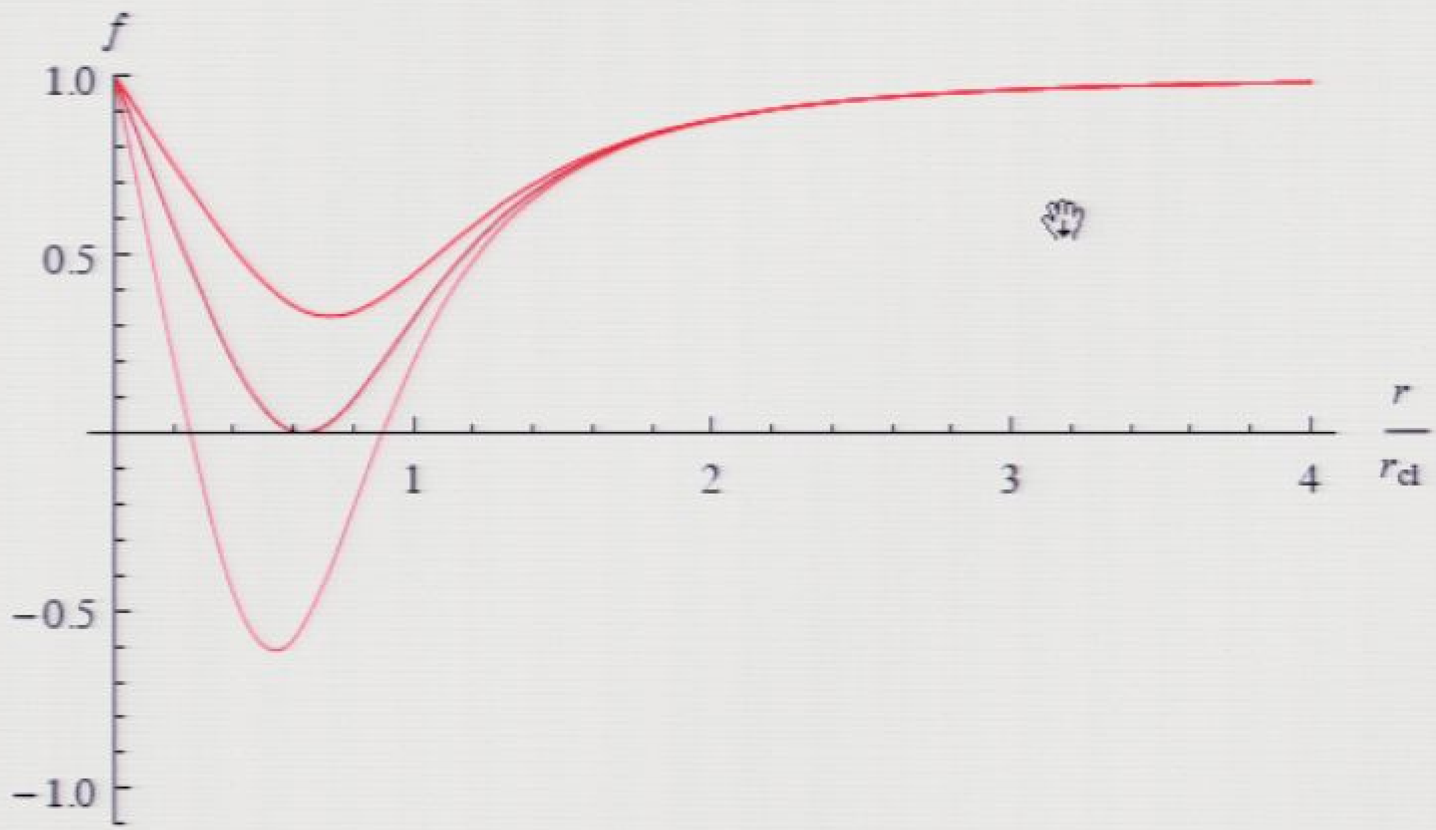
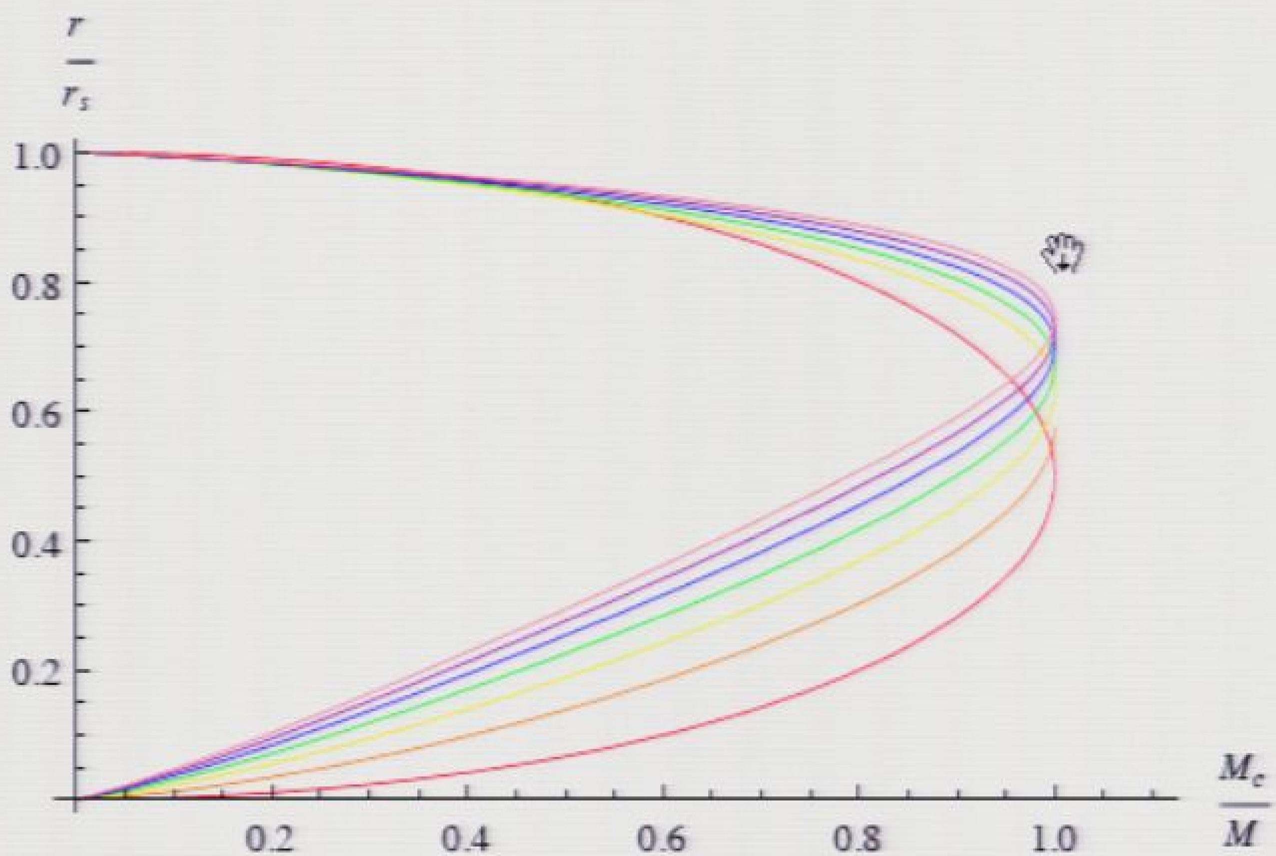
  smallest black hole M_c D=6:



black holes at the LHC

- **RG improved black holes** K. Falls, DL, A. Raghuraman (ERG '08, '09)

improved Schwarzschild radii, various dimension



black holes at the LHC

- semi-classical vs renormalisation group

G. Hiller, DL ('09)

elastic BH production $pp \to$ **BH**

$$\frac{d\sigma}{dM} = \frac{2M}{s} \sum_{i,j} \int_{M^2/s}^{1} \frac{dx}{x} f_i\left(\frac{M^2}{xs}\right) f_j(x)\, \hat{\sigma}(q_i q_j \to \mathrm{BH})|_{\hat{s}=M^2}.$$

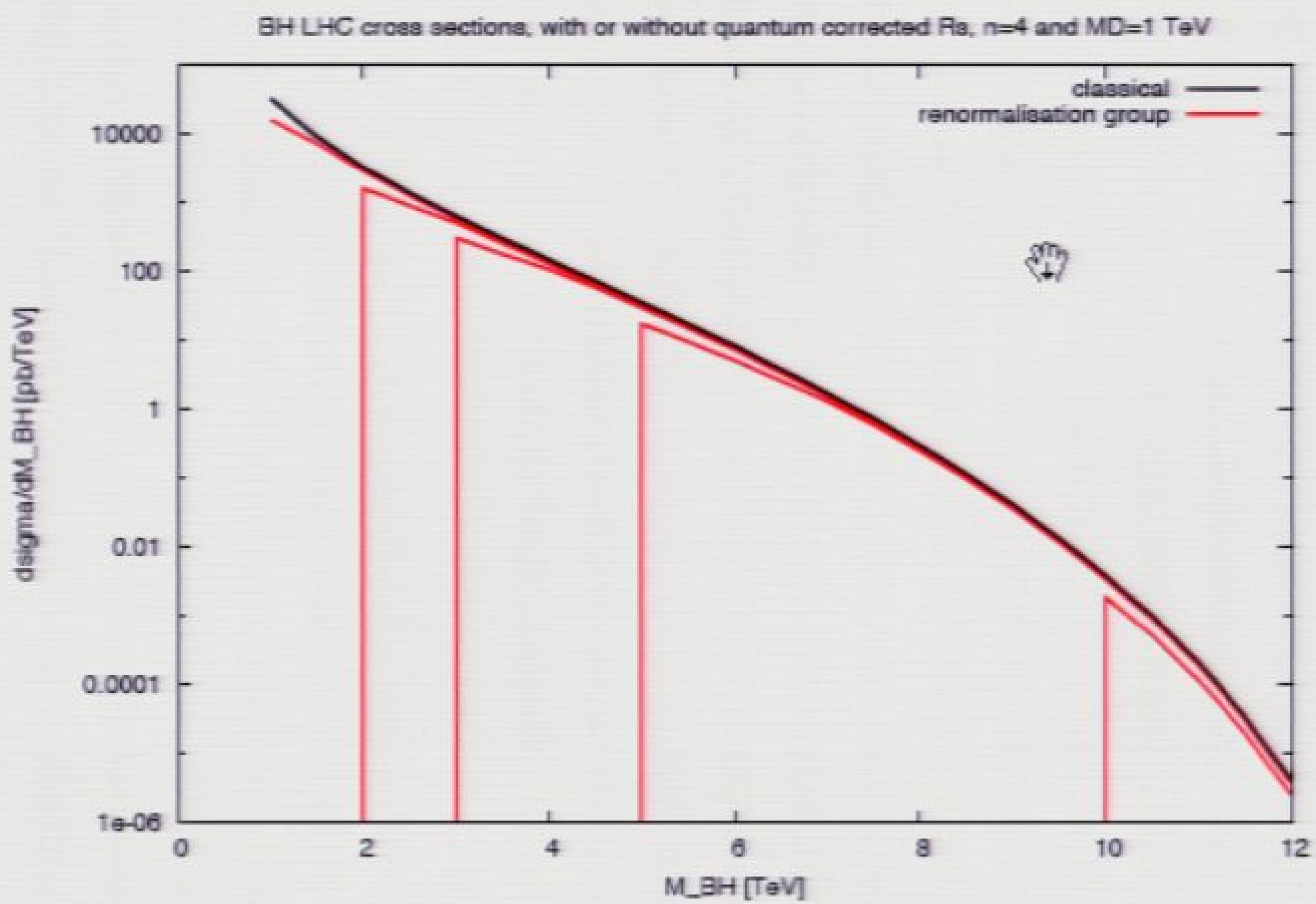
parton distribution functions from **CTEQ61**
evaluated at $Q^2 = M_{\mathrm{BH}}^2$.

black holes at the LHC

- **semi-classical vs renormalisation group**

G. Hiller, DL ('09)

$n = 4$ extra dimensions



unitarity bounds

J. Brinkmann, G. Hiller, DL ('09)

- **Higgs-Higgs elastic scattering**

extra dimensions, gravity-mediated, KK modes

effective theory study X.G. He ('00)
partial wave decomposition:

$$M(s,t) = 16\pi \sum_J (2J+1)\, a_J(s)\, P_J(\cos\theta), \quad t = t(\cos\theta)$$

$$\sigma \approx 16\pi \frac{|a_0(s)|^2}{s}, \quad a_0(s) = \frac{1}{16\pi} \frac{1}{s - 4m_h^2} \int_{4m_h^2 - s}^{0} dt\, M(s,t)$$

optical theorem, unitarity bound

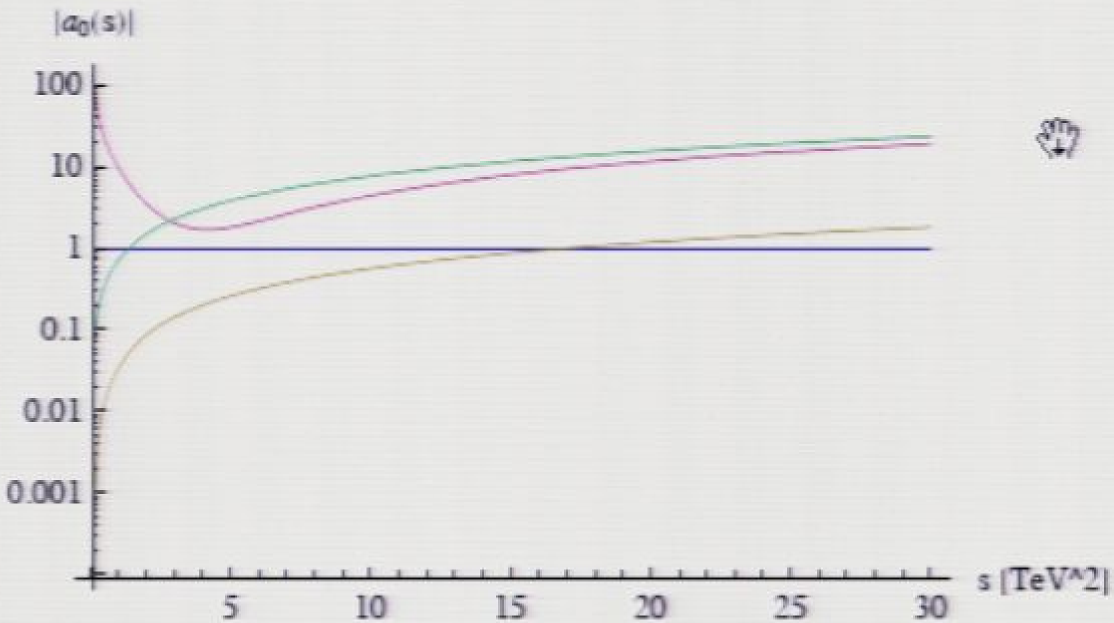
$$|a_0(s)| \leq 1$$

unitarity bounds

- **results** $|a_0(s)| \to c_n \frac{s}{M_D}$

effective theory: valid for $s < M_D^2$

RG study: $c_n \ll 1$ J. Brinkmann, G. Hiller, DL ('09)



parameter: $m_h = 0, n = 2, M_D = 1\text{TeV}, \Lambda_X = 1, 5, \frac{1}{5}\text{TeV}$

conclusions

- **30 years of asymptotic safety**

  fascinating idea, many scenarios

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    eg. PT / renormalisation group / lattice

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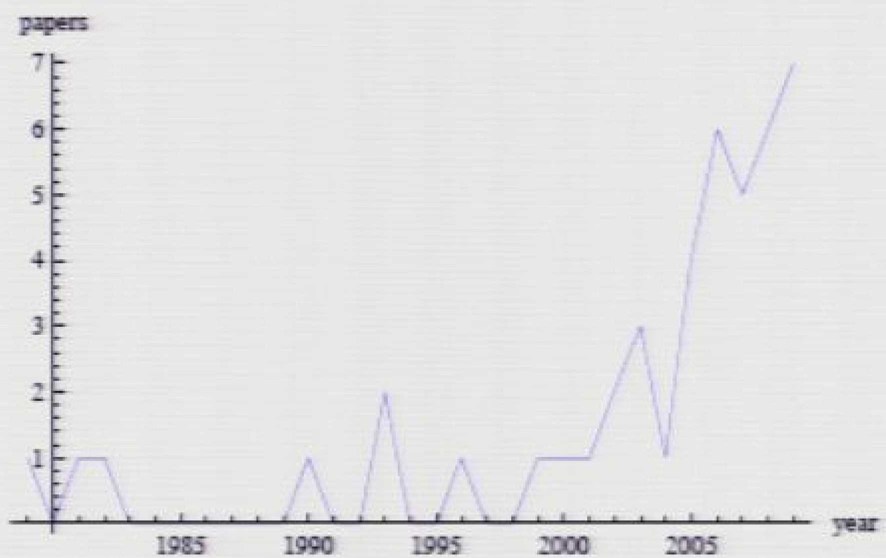

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- **challenges for theory and experiment**

  physics at the Planck scale

  lattice $\leftrightarrow$ continuum RG $\leftrightarrow$ spin foams $\leftrightarrow$ LQG