Quantum Gravity at the LHC

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motivation

- **standard model of particle physics**

  theory of the strong, weak, and electro-magnetic interactions

  very successful, up to $\sim \mathcal{O}(100)$ GeV

  LHC to explore physics of the electroweak scale, Higgs particle

motivation

- **standard model of particle physics**
- **what about gravity?**

  presently, no unified understanding of all fundamental forces

  Planck mass $M_{\rm Pl} \approx 10^{19}{\rm GeV} \gg M_{\rm EW}$

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- **standard model of particle physics**
- **what about gravity?**
- **hierarchy problem**

  coupling of Higgs particle to gravity

  one-loop level:

    either no symmetry breaking

    or Higgs particle mass of order M_{Pl}

    or non-trivial cancelations at loop level (fine-tuning)

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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

- **scenarios**

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

  RS I and RS II

  4d setup with many species, strong RG effects (G Dvali, et. al.)

low scale quantum gravity

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

  D=4+n compact spatial dimensions

  fundamental Planck mass $M_D \approx \mathcal{O}(M_{EW}) \ll M_{\rm Planck}$

low scale quantum gravity

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

  D=4+n compact spatial dimensions

  fundamental Planck mass $M_D \approx \mathcal{O}(M_{EW}) \ll M_{\text{Planck}}$

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

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

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

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- **quantum gravity scenarios**

  string theory

  effective theory for gravity (Donoghue '94)

  asymptotic safety for gravity (Weinberg '79)

  UV fixed points in $D = 4$ dimensions (Reuter '96)

  UV fixed points in $D > 4$ dimensions (DL '03, Fischer, DL '06)

renormalisation group

- **RG scaling of gravitational coupling**

gravitational coupling	$G(\mu) = Z_N(\mu)^{-1} \cdot G_N$
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	$\frac{\mathrm{d} g(\mu)}{\mathrm{d} \ln \mu} = (D - 2 + \eta_N)\, g(\mu)$

(DL ’06,Niedermaier ’06)

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- **fixed points**

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

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

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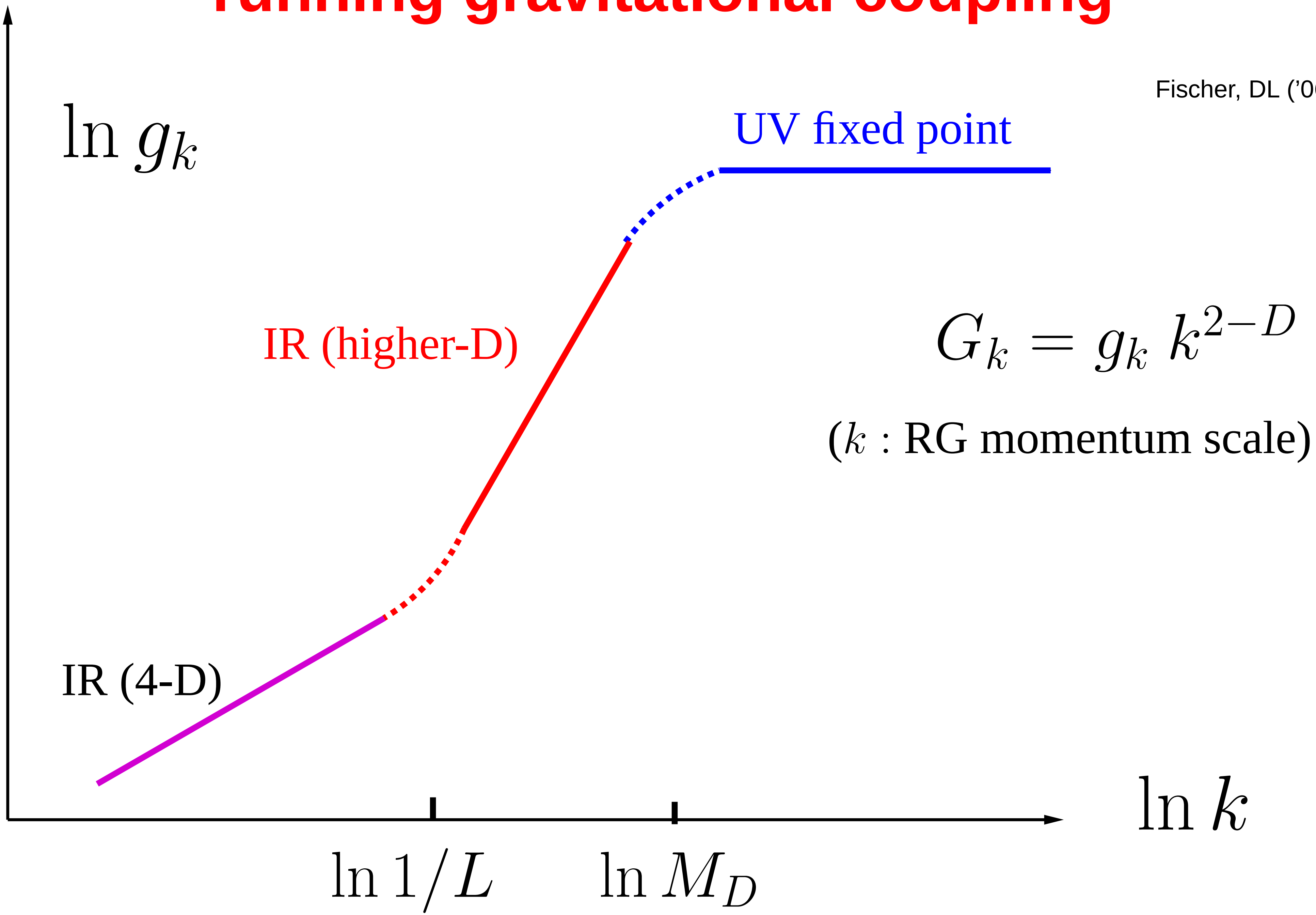
UV fixed point implies **weakly coupled gravity** at high energies

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

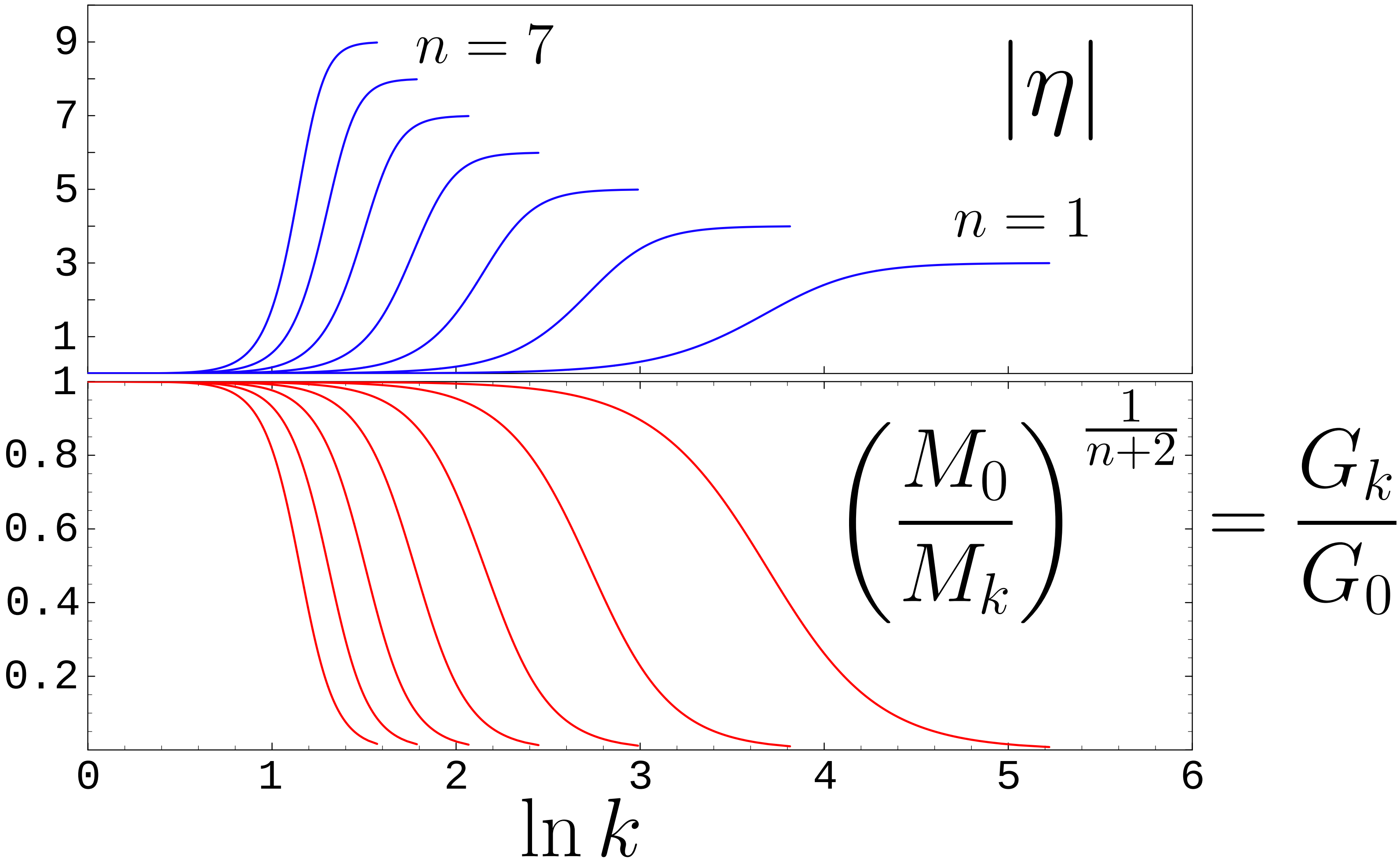
running gravitational coupling

Fischer, DL ('06)



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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- **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

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

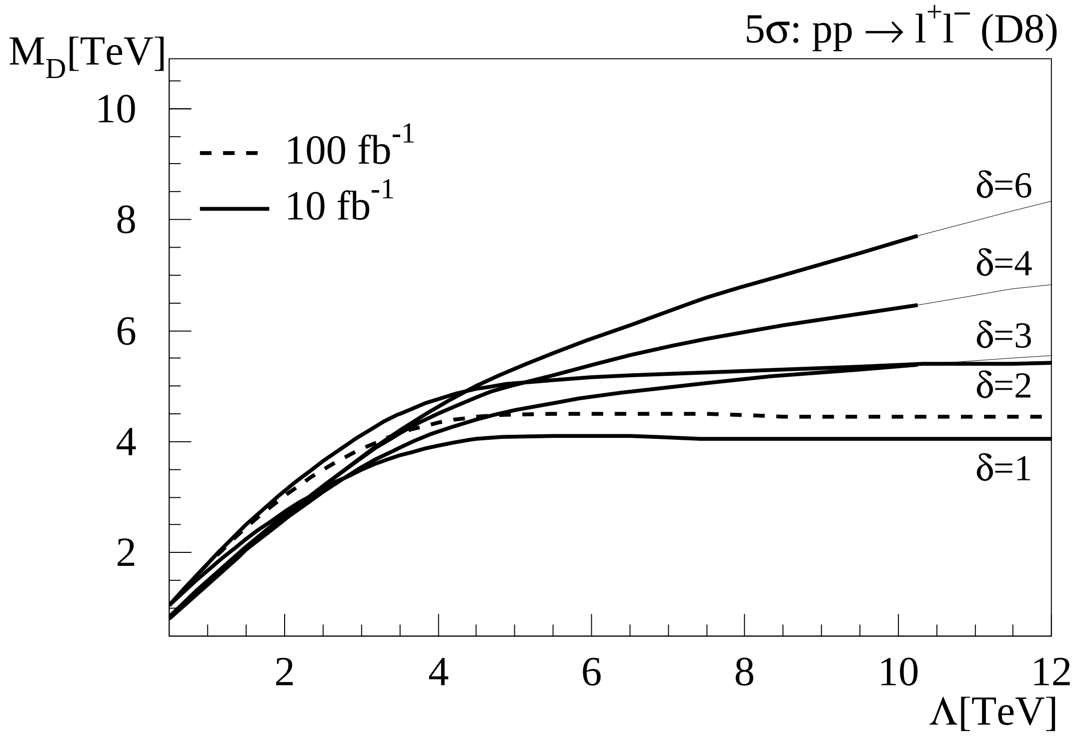
$$\mathcal{S}(s) = \frac{1}{M_D^{n+2}} \int_0^\infty \mathrm{dm_{kk}}\, \mathrm{m_{kk}}^{n-1}\, \frac{1}{s + \mathrm{m_{kk}}^2}$$

  UV divergent for $n \geq 2$.

gravitational Drell-Yan

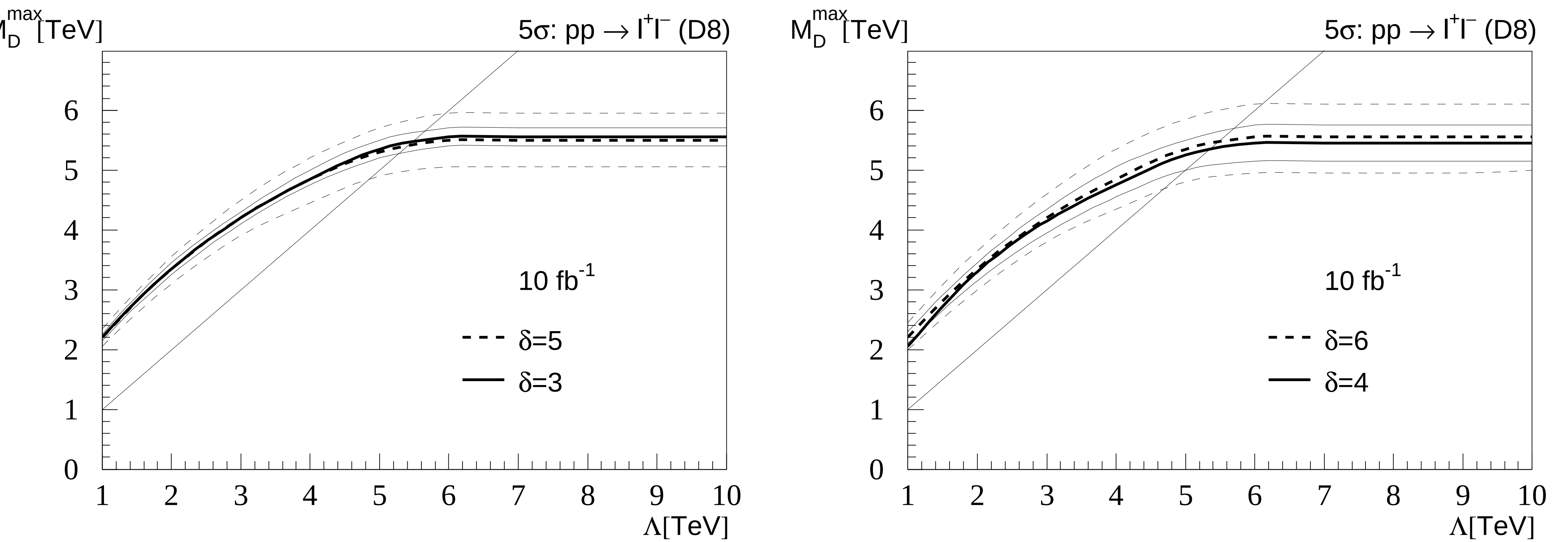
- **effective theory + Monte Carlo simulations**

Giudice, Plehn, Strumia ('04)



gravitational Drell-Yan

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



mini-black holes

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

mini-black holes

- **RG improved black holes** Falls, DL, Raghuraman (ERG ’08, and to appear)

  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

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

mini-black holes

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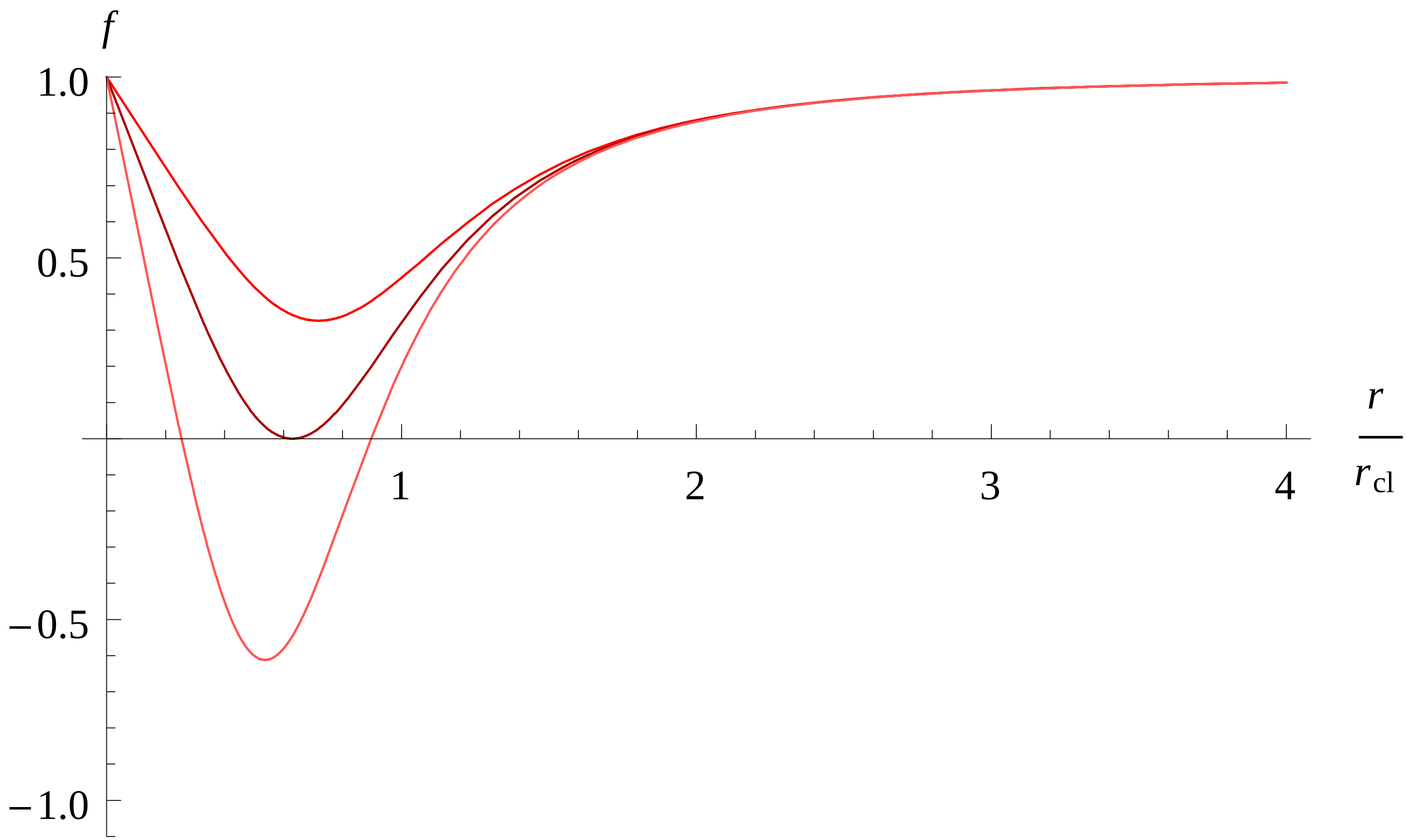
  metric, dependence on M **(D=6)**



mini-black holes

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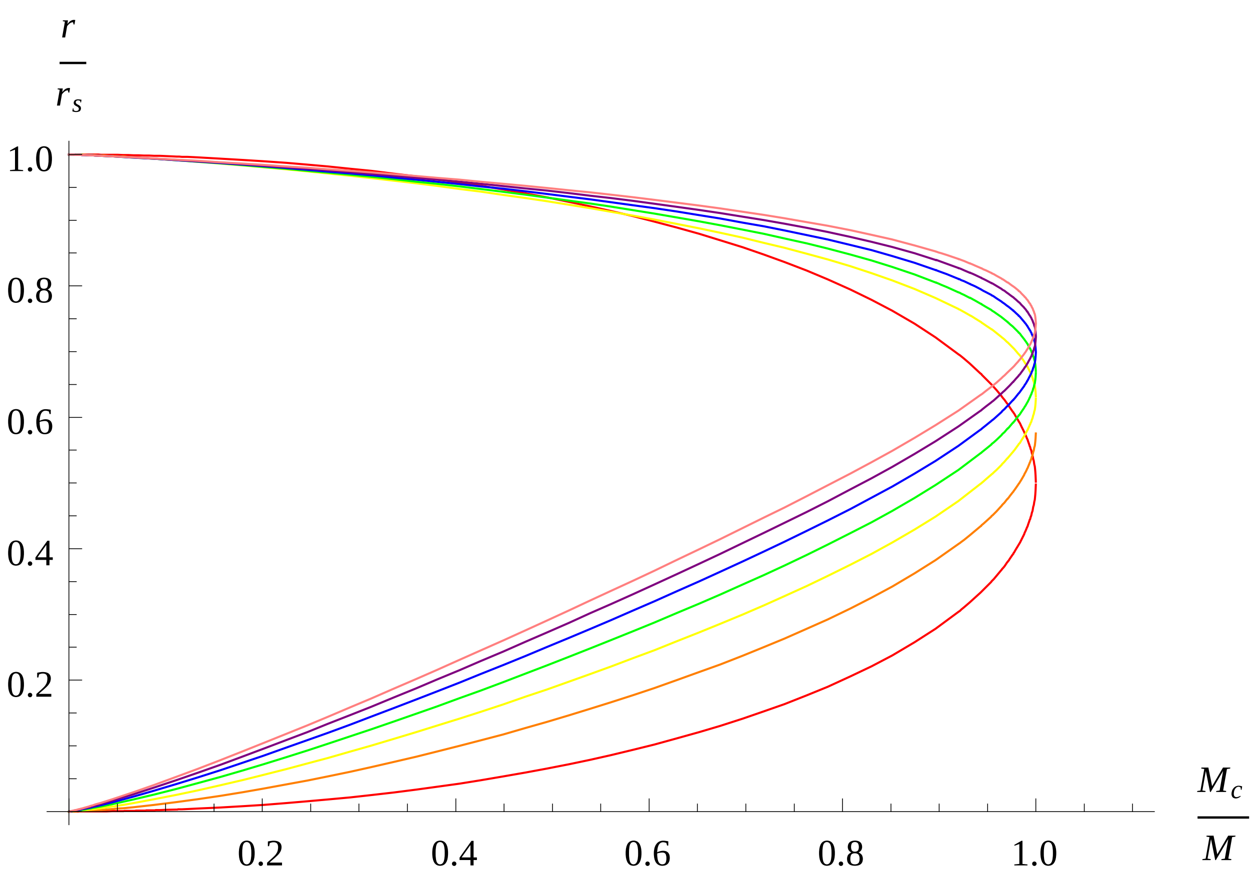
improved Schwarzschild radii, various dimension



BH production at the LHC

- **semi-classical vs renormalisation group**

Hiller, DL (to appear)

production cross section at the LHC $pp \longrightarrow$ **final state**

$$\sigma = \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 \, f_i(x_1) \, f_j(x_2) \, \hat{\sigma}(q_i q_j \longrightarrow \textbf{final state})$$

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

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elastic BH production $pp \longrightarrow$ **BH**

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

BH production at the LHC

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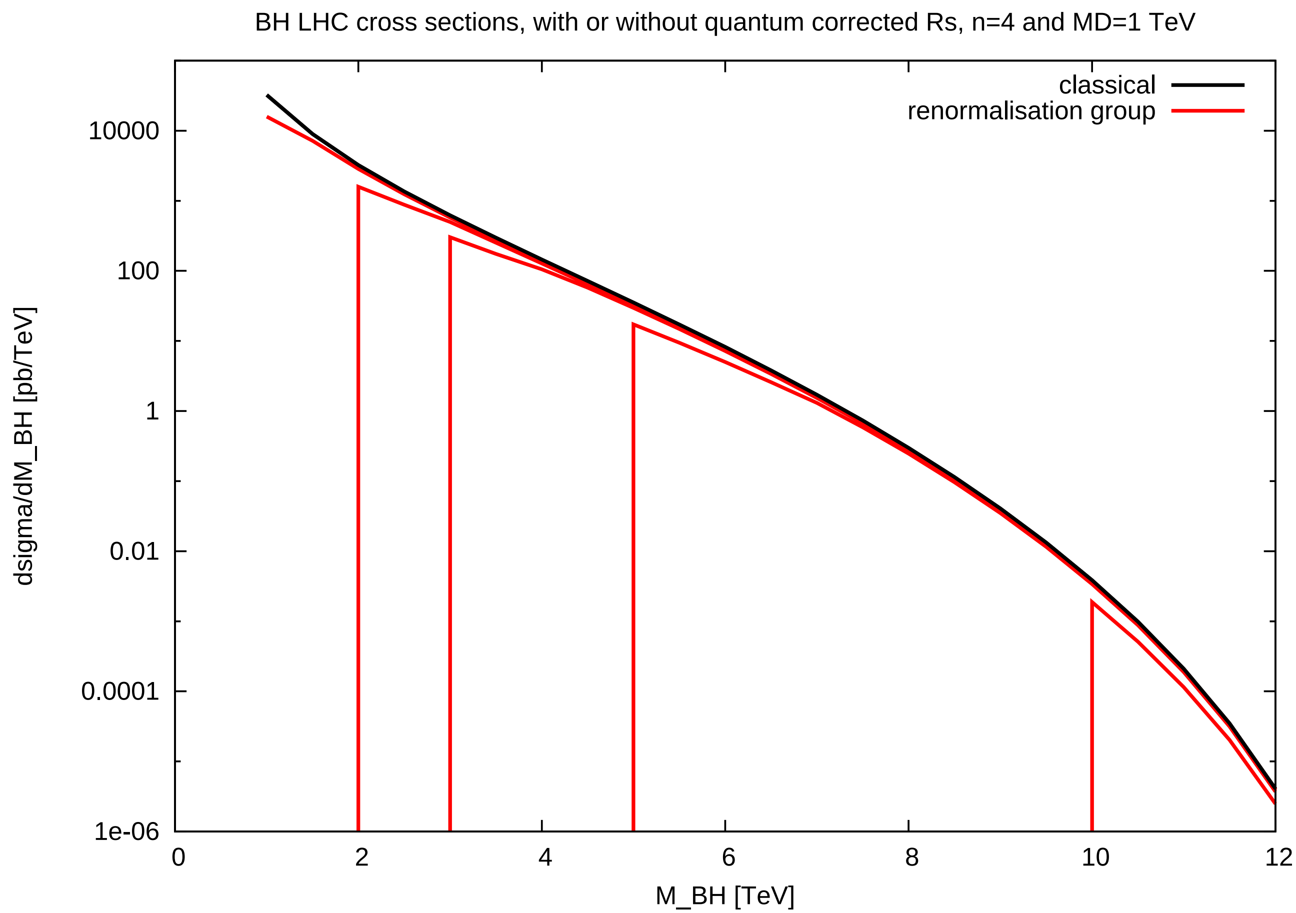
$n = 4$ **extra dimensions**



conclusions

- **low scale quantum gravity**

  exciting idea, signatures at particle colliders

  many scenarios, eg. ADD, RS I, RS II, $N = 10^{32}, \cdots$

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  renormalisation group: non-trivial UV fixed point

  asymptotic safety in four and higher dimensions

Reuter (1996), Souma (1999)
Lauscher, Reuter (2001), Reuter, Saueressig (2001)
Forgacs, Niedermayer (2002), Niedermayer (2002)
DL (2003), Percacci, Perini (2003)
Bonnano, Reuter (2004), Percacci (2004)
Bonanno (2005), Lauscher, Reuter (2005)
Percacci (2005), Fischer, DL (2006)
Codello, Percacci (2006)
Codello, Percacci, Rahmede (2007), DL (2008), $\cdots$

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- **signatures of quantum gravity at the LHC**

  if Planck scale of order TeV

  QG effects accessible, insensitive to UV cutoff

  implications for eg. di-lepton production, mini-black holes

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- **challenges for theory and experiment**

  determine the Planck scale

  differentiate amongst quantum gravity scenarios

  distinguish QG from other new physics signatures

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thanks!