asymptotically safe gravity at colliders and beyond

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classical gravity

Einstein's theory $G_N = 6.7 \times 10^{-11} \frac{m^3}{\mathrm{kg}\, s^2}$

quantum gravity

Planck length	$\ell_{\mathrm{Pl}} = \left(\frac{\hbar G_N}{c^3}\right)^{1/2} \approx 10^{-33}\,\mathrm{cm}$
Planck mass	$M_{\mathrm{Pl}} \approx 10^{19}\mathrm{GeV}$
Planck time	$t_{\mathrm{Pl}} \approx 10^{-44}\,\mathrm{s}$
Planck temperature	$T_{\mathrm{Pl}} \approx 10^{32}\,\mathrm{K}$

expect **quantum modifications** at energy scales $E \approx M_{\mathrm{Pl}}$

quantum gravity

low-scale quantum gravity

what if the fundamental Planck scale is as low as

$$M_* \approx \mathcal{O}(M_{\rm EW}) \ll M_{\rm Pl}\,?$$

circumnavigates the SM hierarchy problem

scenario with extra dimensions

(Arkani-Hamed, Dimopoulos, Dvali '98)

$D = 4 + n$ compact extra dimensions of size L,

$$M_{\rm Pl}^2 \sim M_*^2 (M_*\, L)^n$$

scale separation $1/L \ll M_* \ll M_{\rm Pl}$

high-energetic particle colliders can test quantisation of gravity

quantum gravity

perturbation theory

effective expansion parameter: $g_{\text{eff}} \equiv G_N\, E^2 \sim \frac{E^2}{M_{\text{Pl}}^2}$

$[G] < 0$: dangerous interactions

perturbative non-renormalisability

gravity with matter interactions

pure gravity (Goroff-Sagnotti term)

renormalisation group

S. Weinberg ('79)

asymptotically safe gravity

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

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

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

non-Gaussian fixed point

$g_* \neq 0$ and $\eta = 2 - D$ **strong quantum effects**

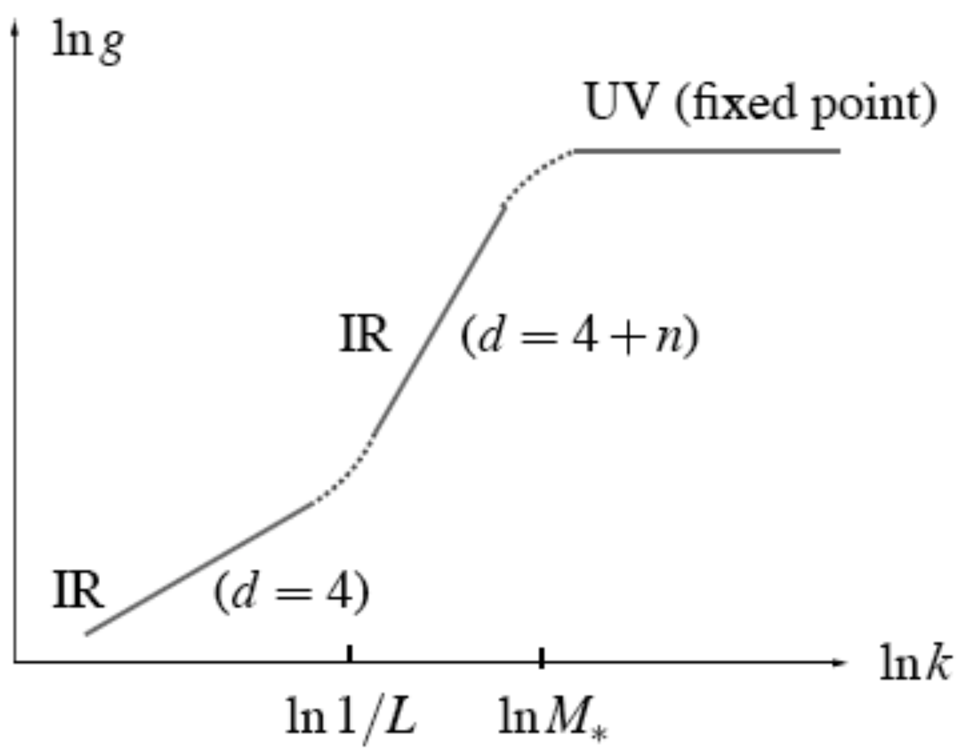
UV fixed point implies **weak coupling** at high energies

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

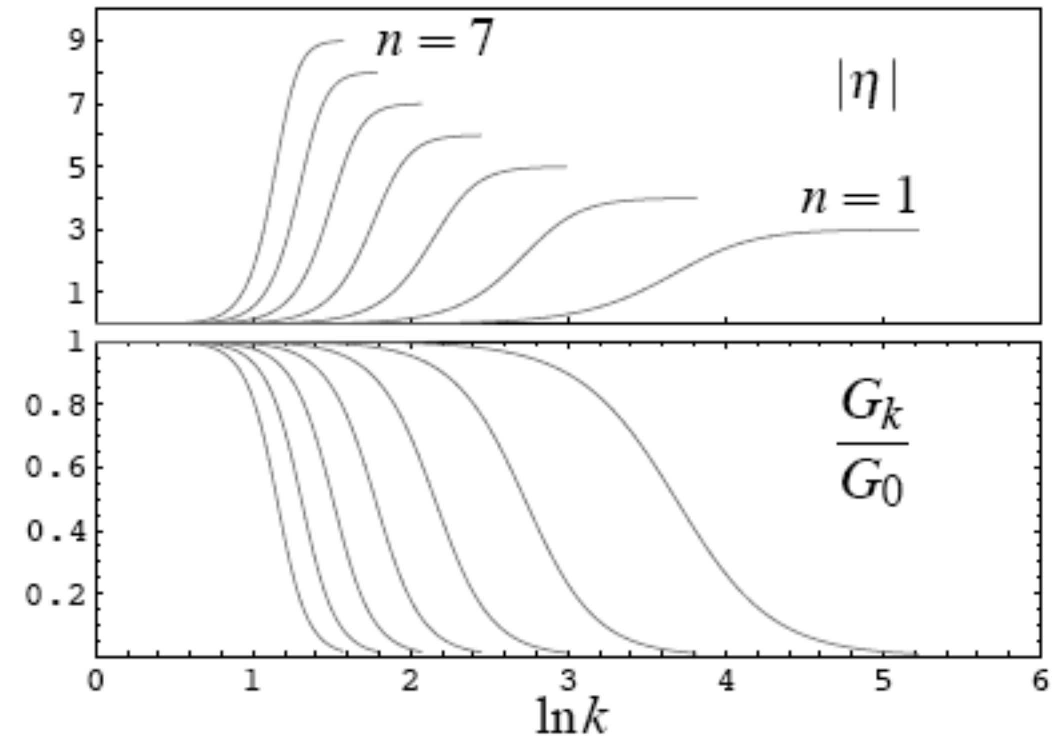
running gravitational coupling

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

a) schematically



b) numerically



$$g(\mu) \equiv G(\mu)\,\mu^2$$

$$G(\mu) = G_N \cdot Z_N(\mu)^{-1}$$

collider signatures of quantum gravity

- real gravitons

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

  signature: missing energy

- virtual gravitons

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

  signature: deviations in SM reference processes

- mini-black holes

  black hole production and decay

  signature: many body final states

Drell Yan production

effective theory Giudice, Rattazzi, Wells ('98)

scattering amplitude for Drell-Yan lepton production

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

$$\mathcal{S}(s) = \frac{1}{M_*^{n+2}} \int_0^\infty dm \frac{m^{n-1}}{s - m^2}$$

UV divergent for $n \geq 2$.

Drell Yan production

renormalisation group DL, Plehn ('07), Gerwick, DL, Plehn ('11)

RG improved scattering amplitude for Drell-Yan production

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

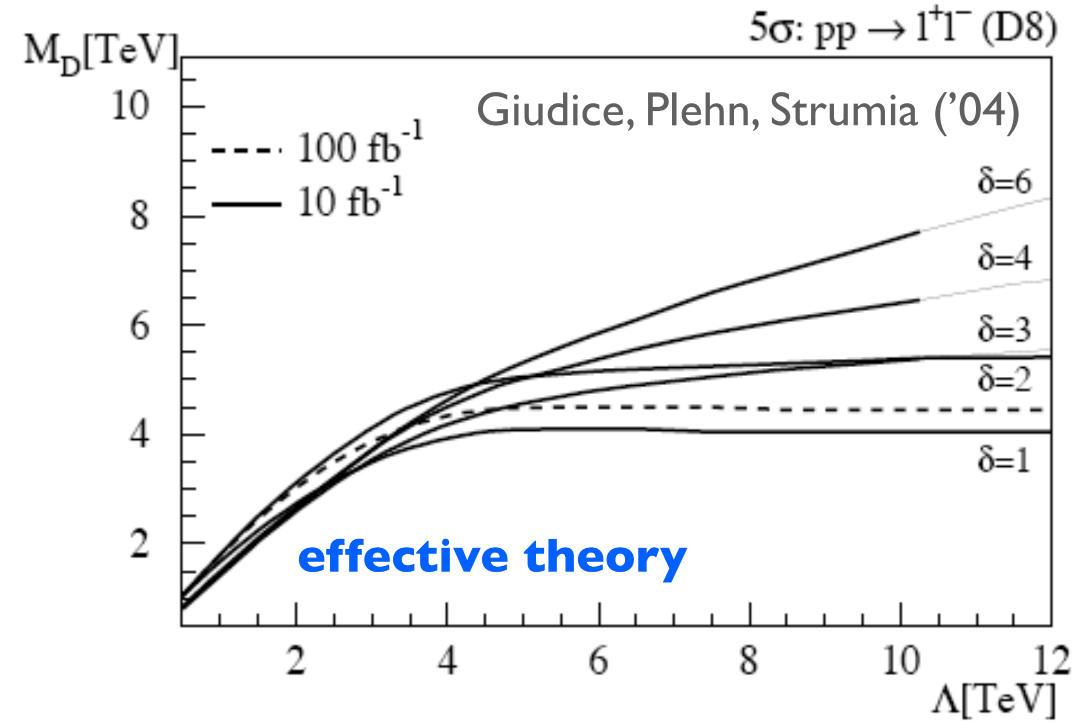
$$\mathcal{S}(s) = \frac{1}{M_*^{n+2}}\int_0^\infty dm\,\frac{m^{n-1}}{s-m^2}Z^{-1}(\mu(s,m^2,\Lambda_T))$$

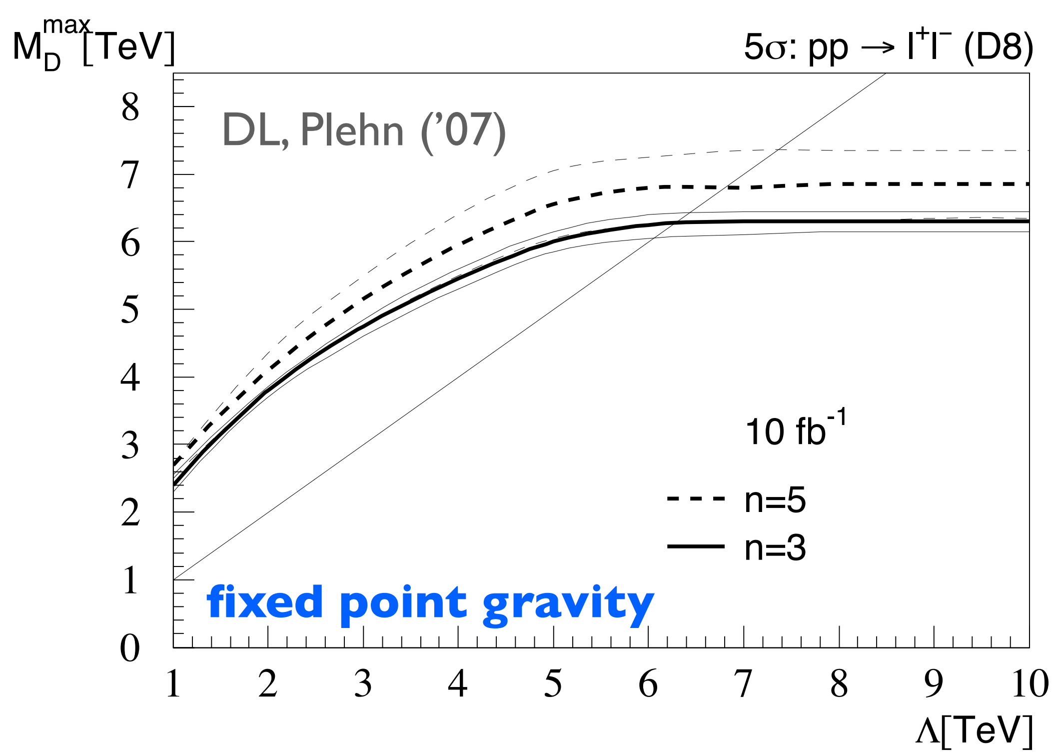
UV finite for all n.

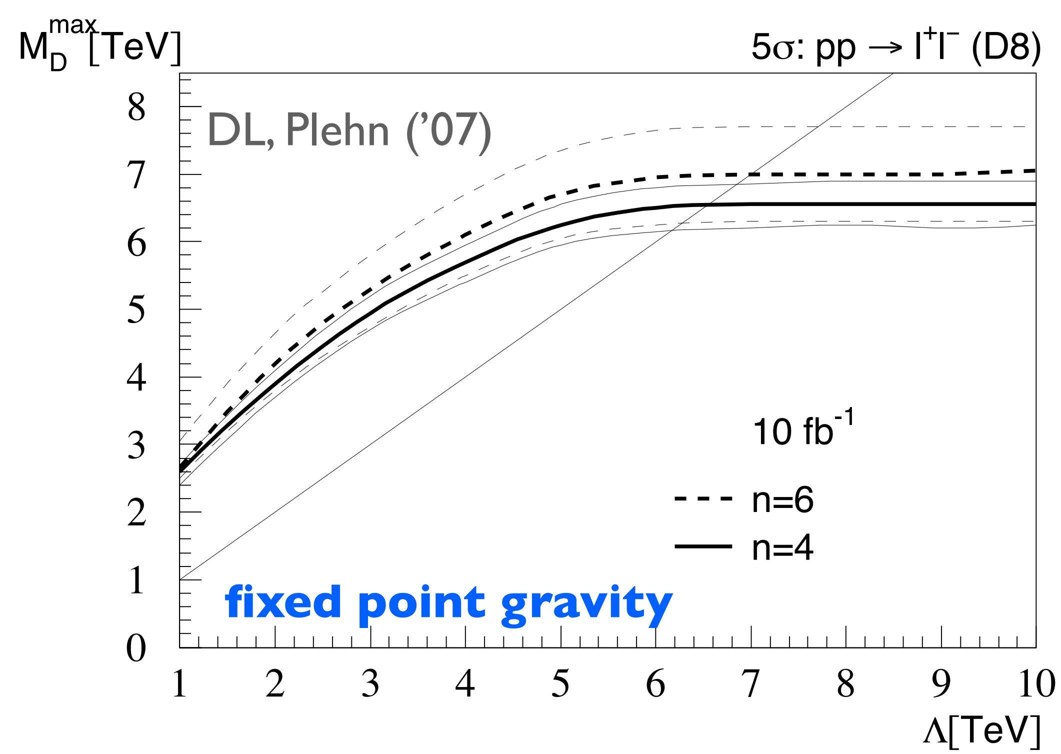
Drell Yan production

discovery reach

effective theory vs fixed point gravity

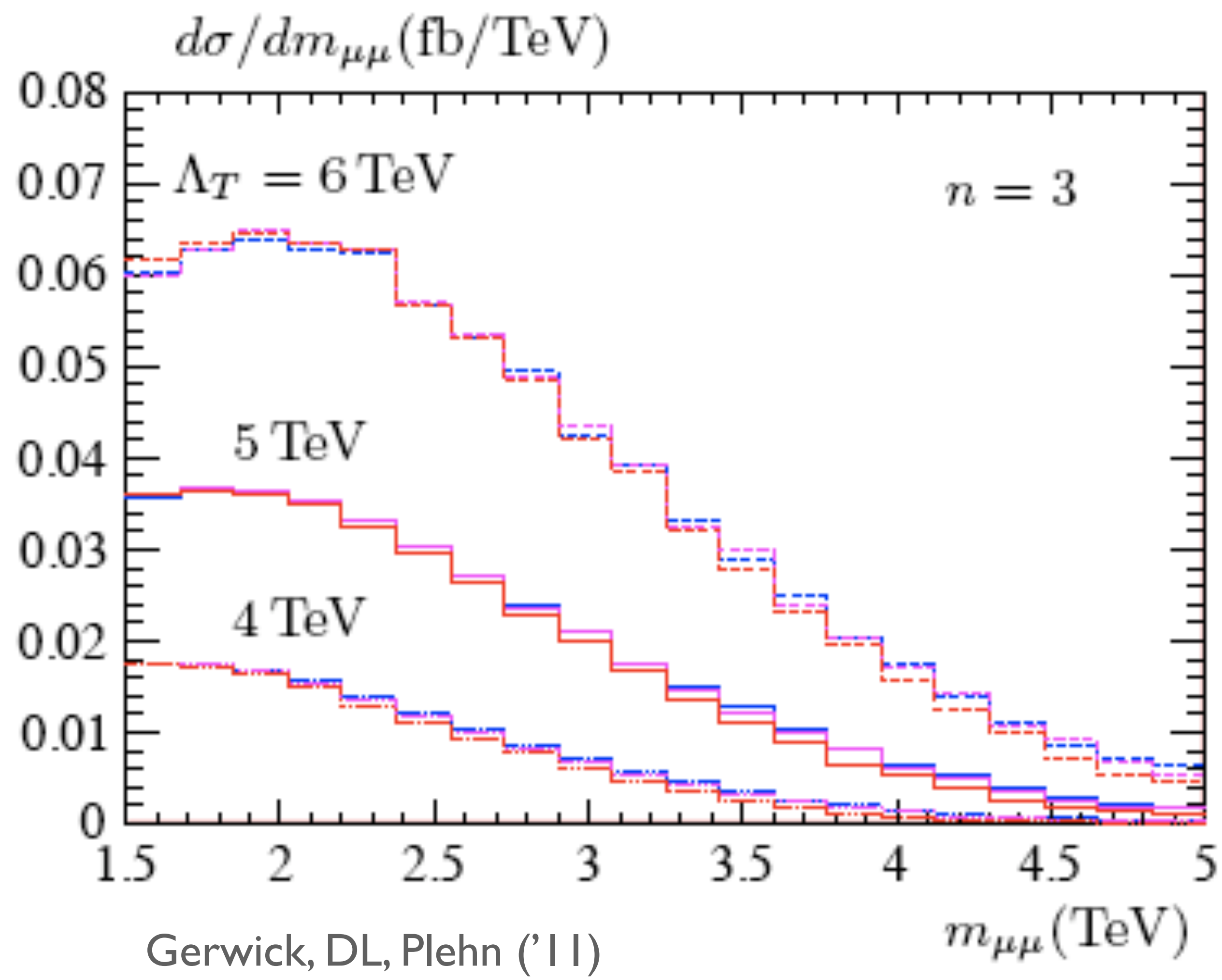






sensitivity

- **vary transition scale**
  strong sensitivity
- **vary RG scheme**
  weak sensitivity



Gerwick, DL, Plehn ('11)

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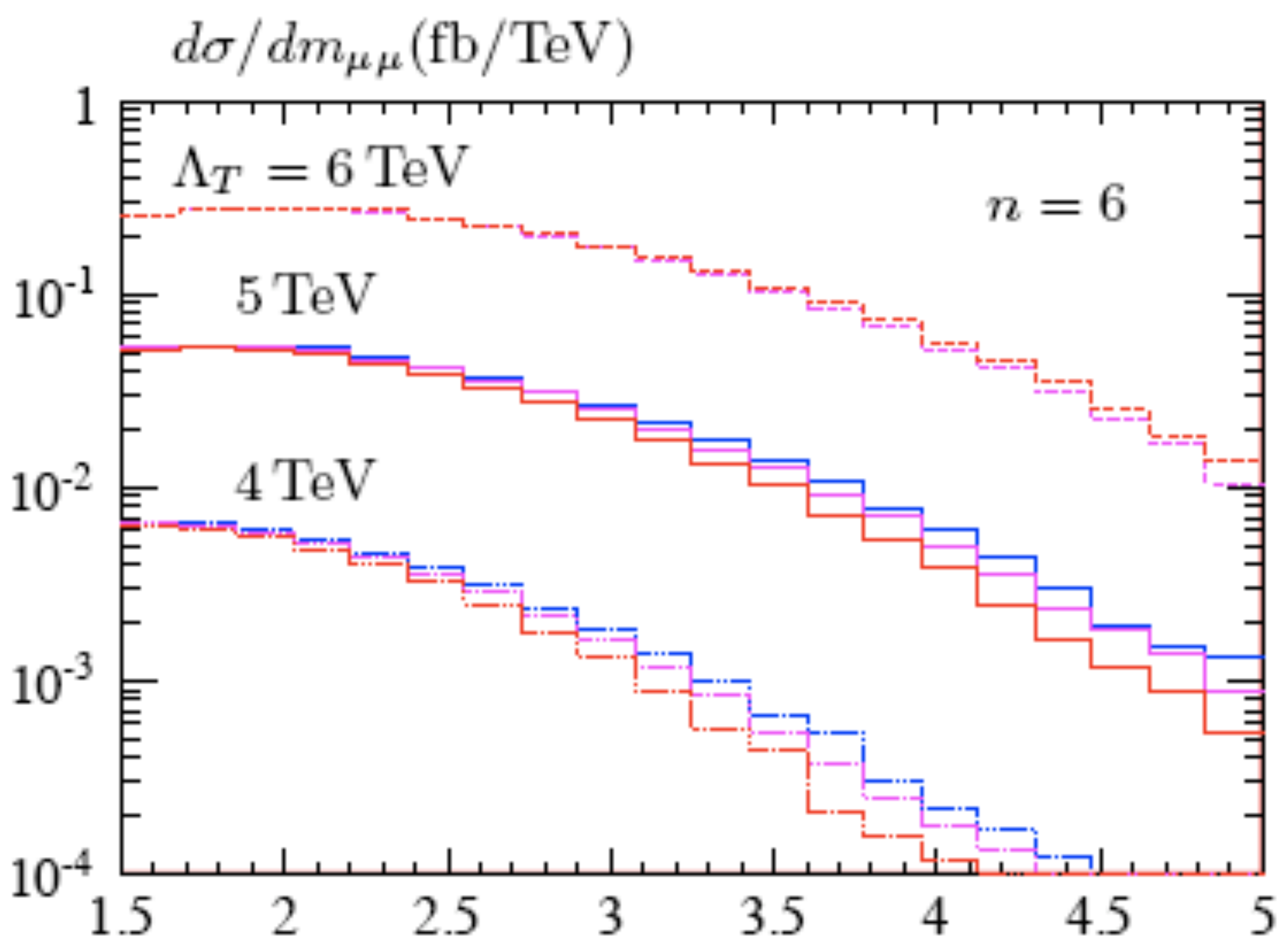
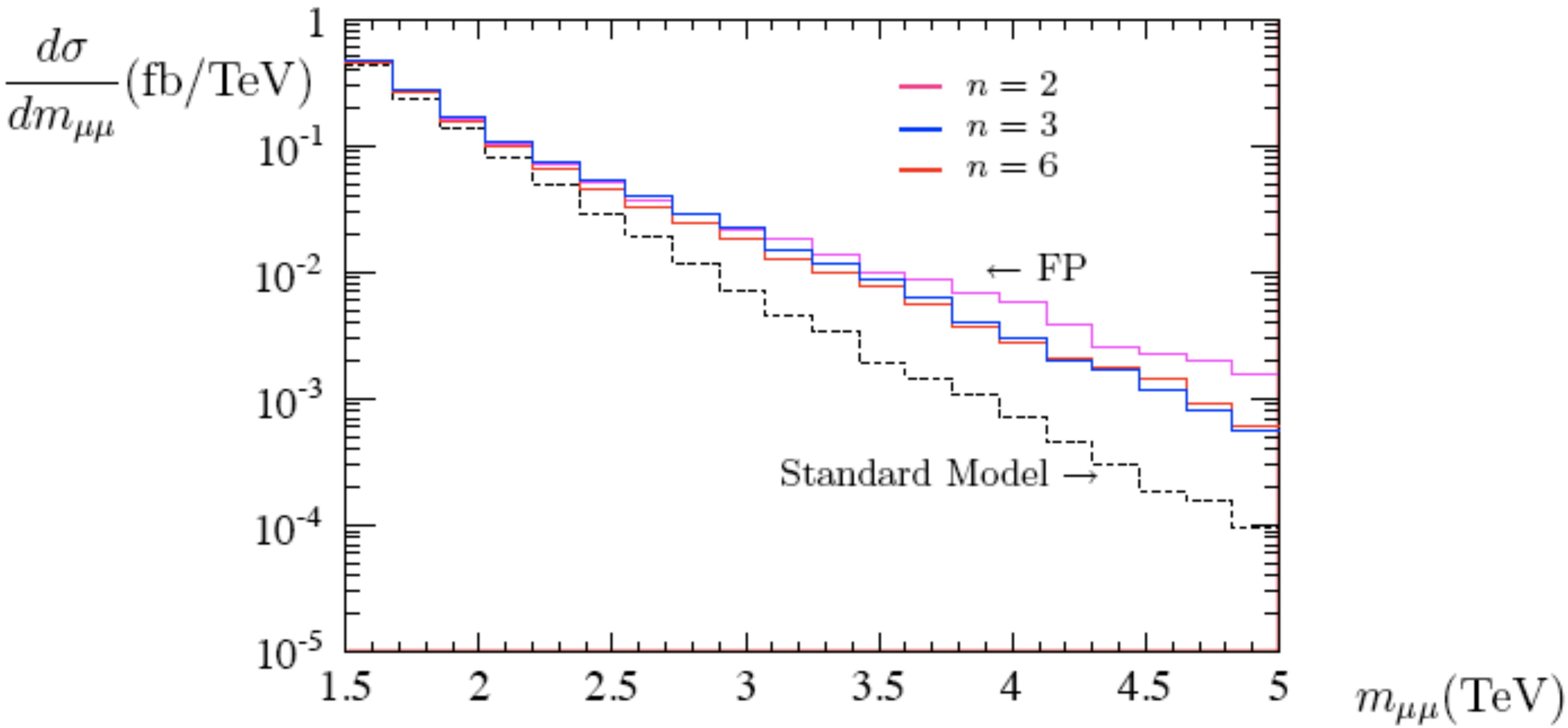


Gerwick, DL, Plehn ('11)

signal vs background

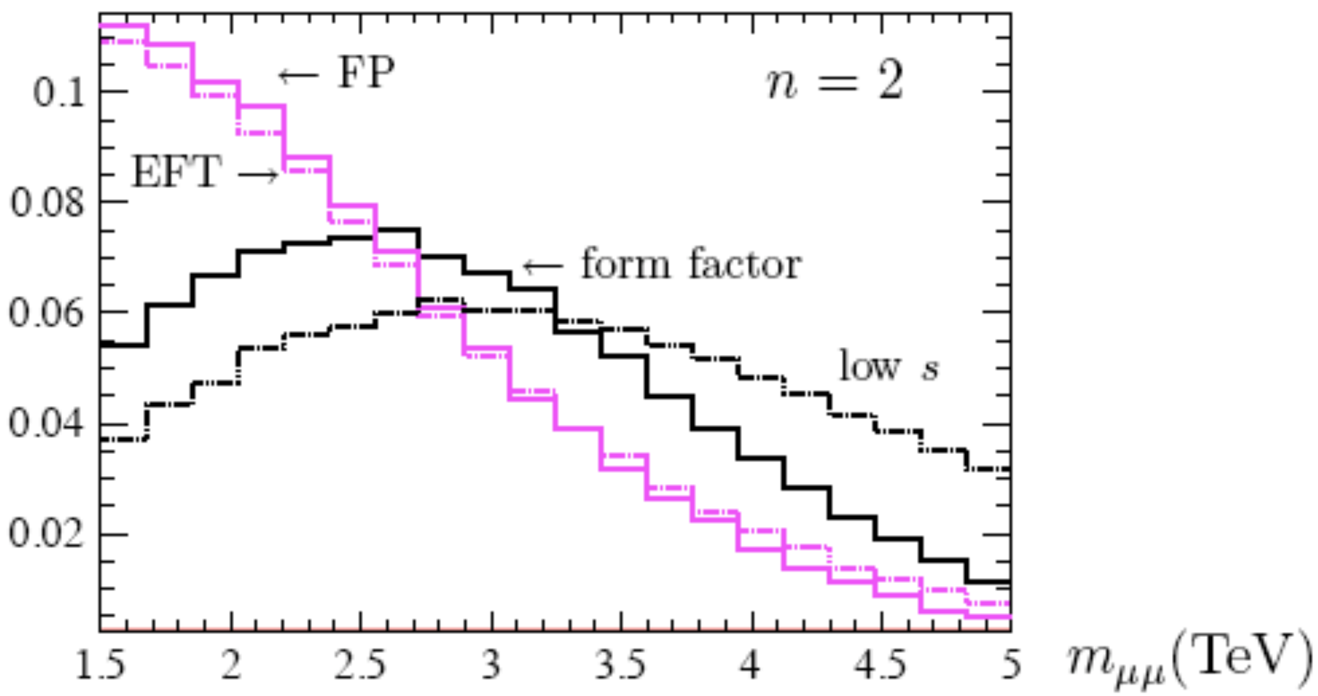


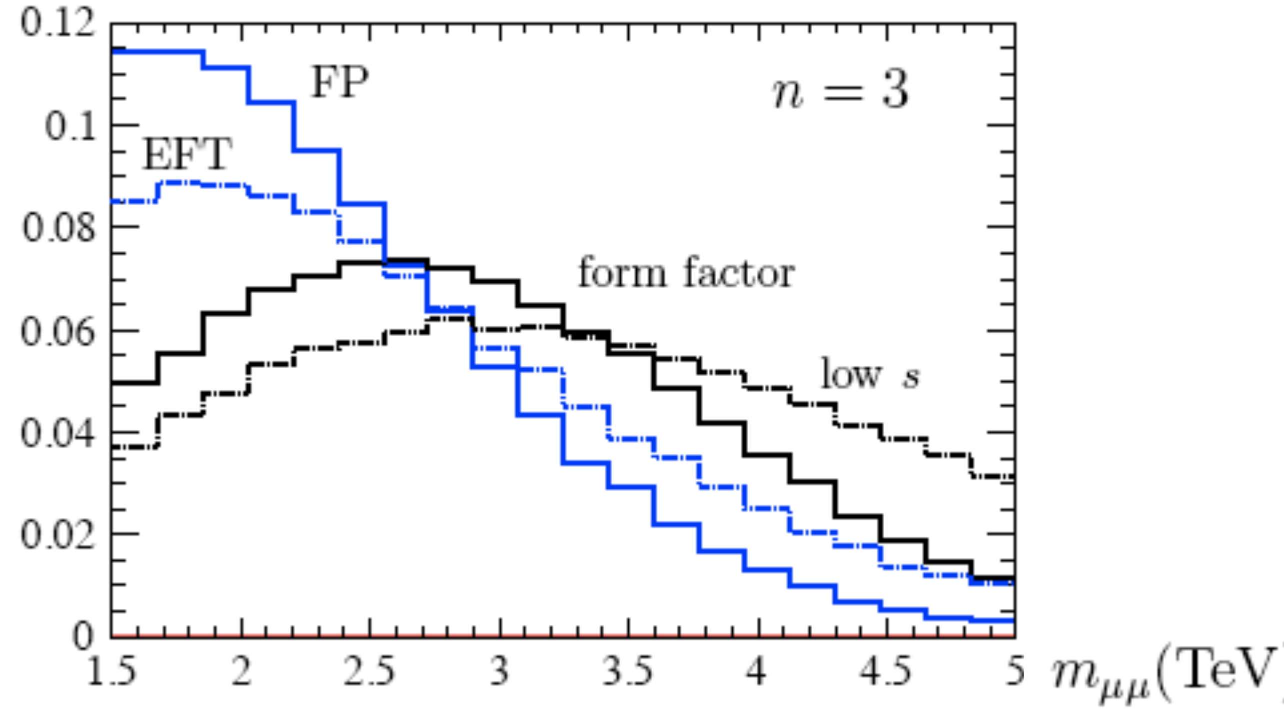
Gerwick, DL, Plehn ('11)

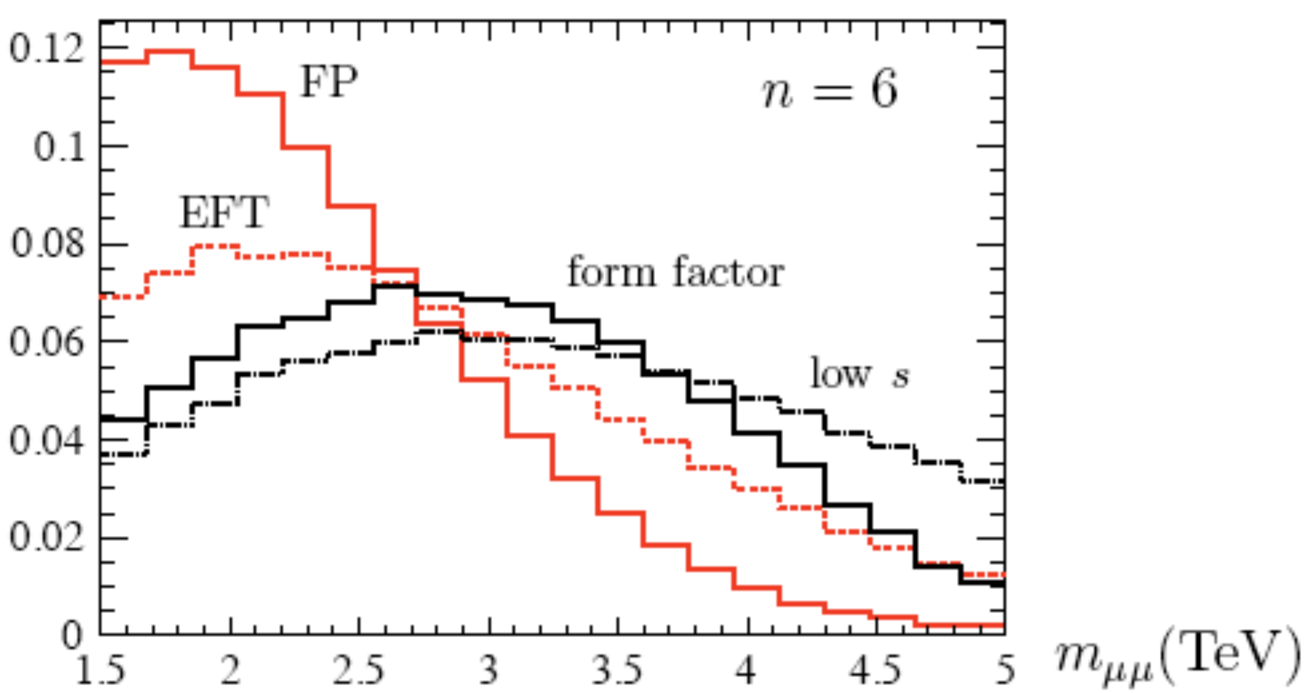
(Gerwick, DL, Plehn '11, to appear in PRD)

comparison

$(1/\sigma)\, d\sigma/dm_{\mu\mu}\,(\mathrm{TeV}^{-1})$







Gerwick, DL, Plehn ('11)

mini-black hole production

semi-classical picture

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

semi-classical production cross section

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

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

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

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

mini-black hole production

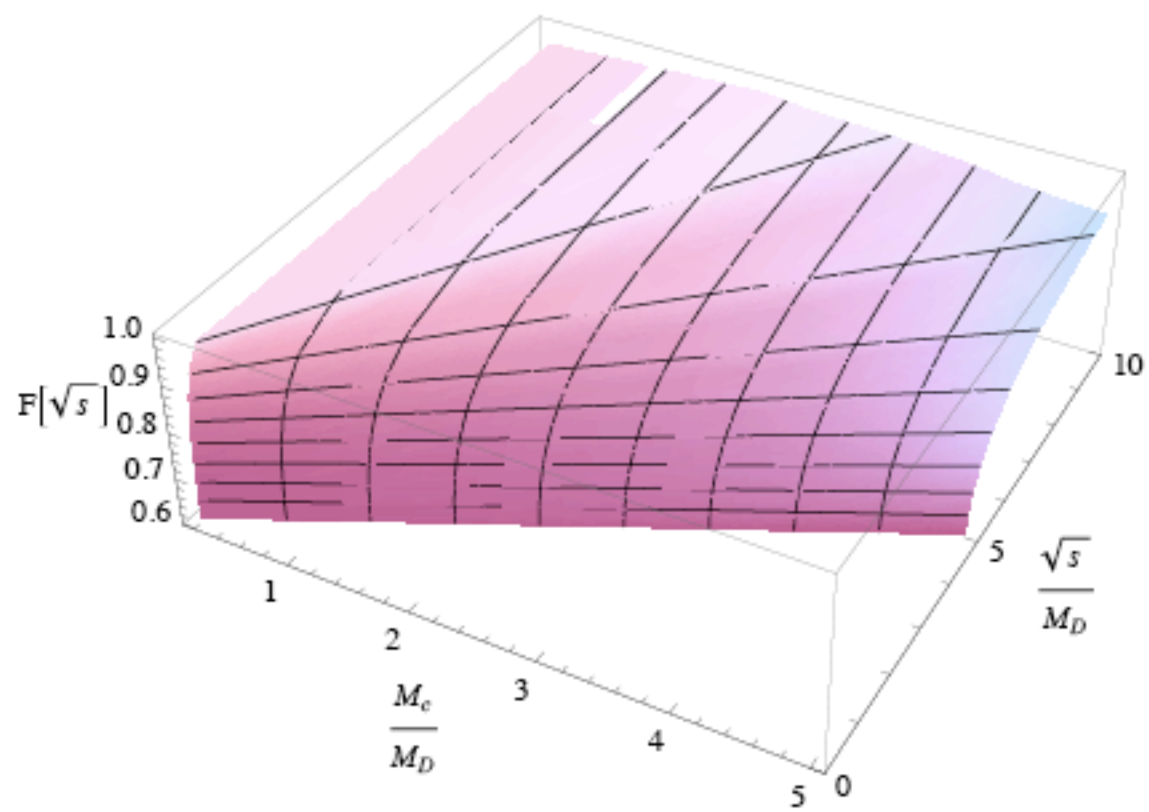
RG quantum corrections

Falls, DL, Raghuraman ('10)

quantum corrected production cross section

$$\hat{\sigma} \to \hat{\sigma} = F(\sqrt{s}) \times \pi r_{\rm cl}^2(M = \sqrt{s}) \times \theta(\sqrt{s} - M_c)$$

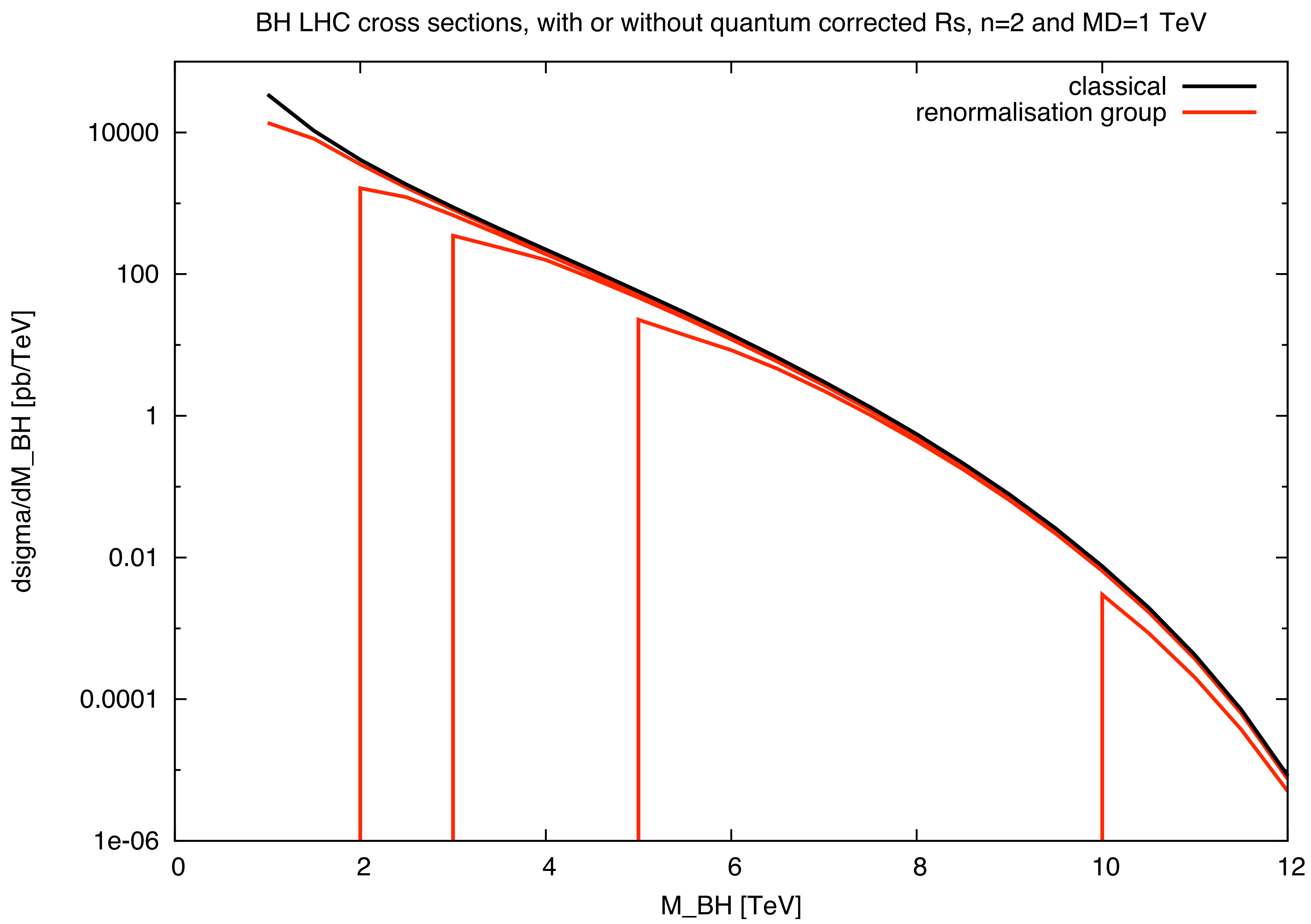
new form factor F



mini-black hole production

Falls, Hiller, DL (Pascos '09 and in prep.)

RG quantum corrections



higher-dimensional black holes

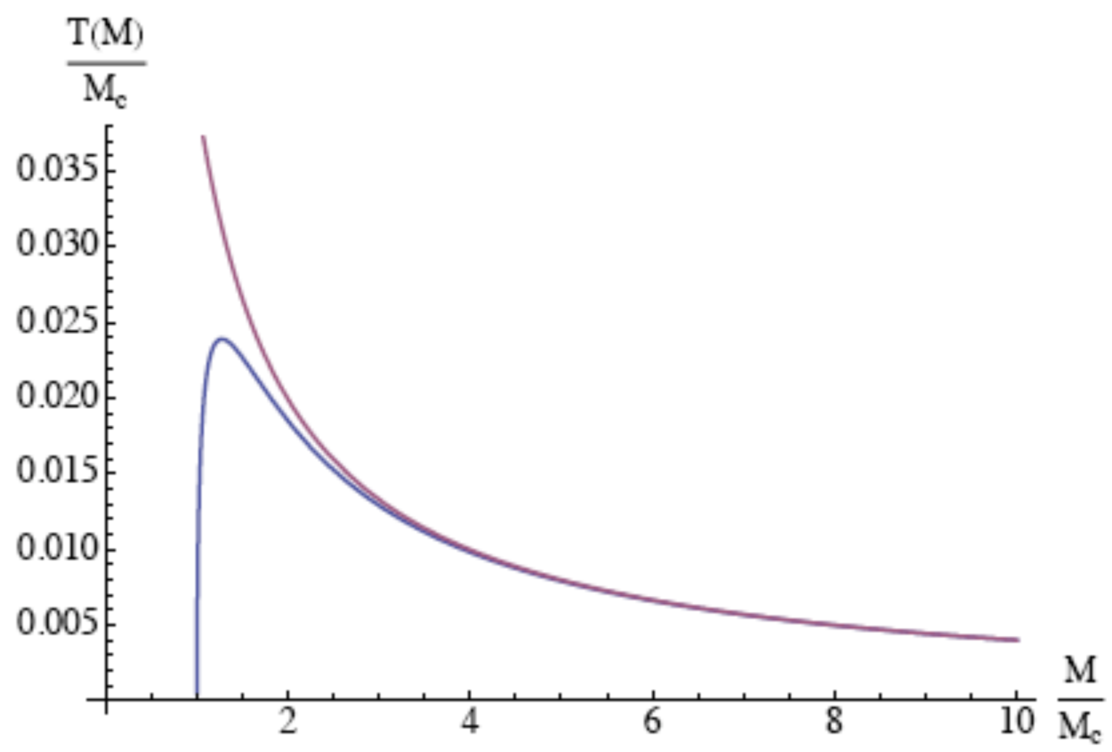
thermodynamics

Falls, DL, Raghuraman ('10)

temperature from surface gravity

$$T = \frac{\kappa}{2\pi} = \frac{d-3}{4\pi\, r_s}\left(1 + \frac{\eta(r_s)}{d-3}\right)$$

vanishes at $M = M_c$.



conclusion

asymptotically safe gravity

strong indications for gravitational fixed point

low-scale quantum gravity

strong sensitivity on the cross-over scale at the LHC

moderate RG scheme dependence

access to several observables

thank you!