Probing the Mystery:
Theory & Experiment in Quantum Gravity
Galiano Island, 17-20 Aug 2015

fixed points of quantum gravity

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QFTs beyond asymptotic freedom

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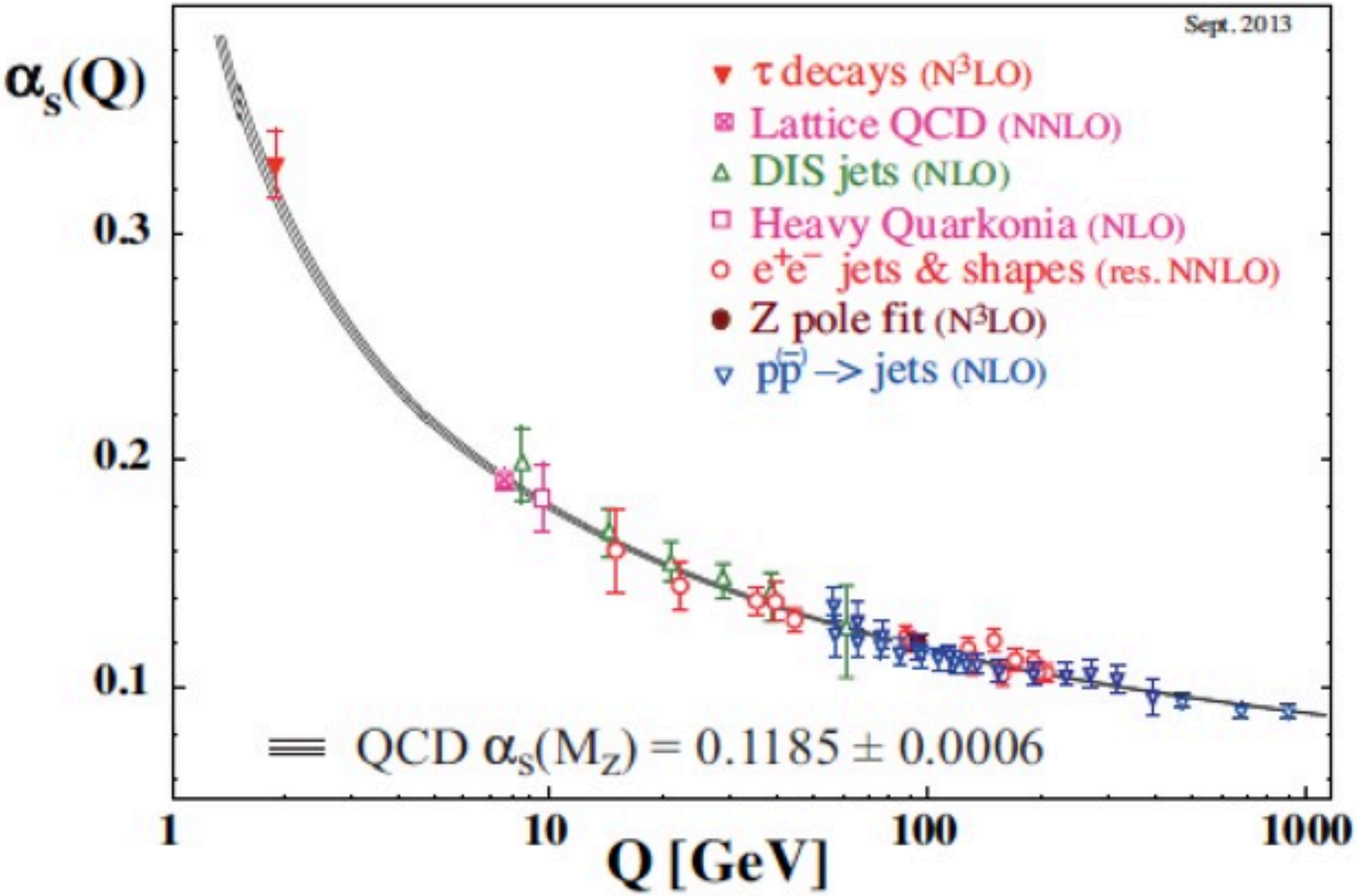
success story: standard model

running couplings

quantum fluctuations modify interactions
couplings depend on energy or distance



triumph of QFT

asymptotic freedom

't Hooft '74
Gross, Wilczek '74
Politzer '74

quantum gravity as a QFT

dynamics of space-time

degrees of freedom: **spin 2**

dimensionful coupling constant: $[G_N] = 2 - D < 0$

quantum gravity as a QFT

dynamics of space-time
degrees of freedom: **spin 2**
dimensionful coupling constant: $[G_N] = 2 - D < 0$

asymptotic safety conjecture:

what, if **running couplings** reach **finite values** in the UV?

Weinberg '79

fundamental definition of QFT ⟺ UV fixed point

Wilson '71

exact asymptotic safety

	dimension	coupling	
gravitons	$D = 2 + \epsilon :$	$\alpha = G_N(\mu)\mu^{D-2}$	Gastmans et al '78 Christensen, Duff '78 Weinberg '79 Kawai et al '90

exact asymptotic safety

	dimension	coupling
gravitons	$D = 2 + \epsilon :$	$\alpha = G_N(\mu)\mu^{D-2}$

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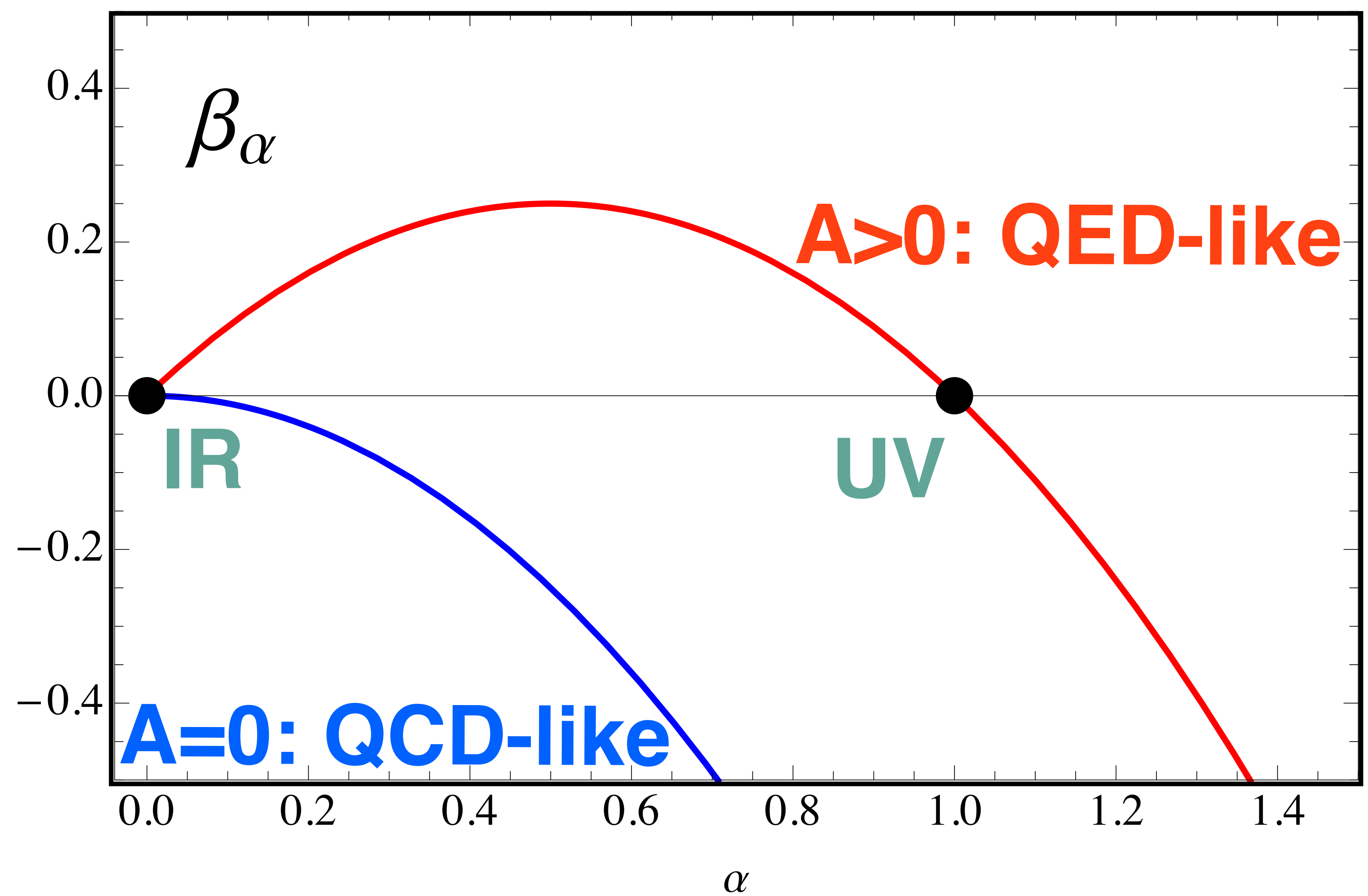
$$\partial_t \alpha = A\,\alpha - B\,\alpha^2$$

$$\alpha_* = A/B \ll 1$$



exact asymptotic safety

	dimension	coupling
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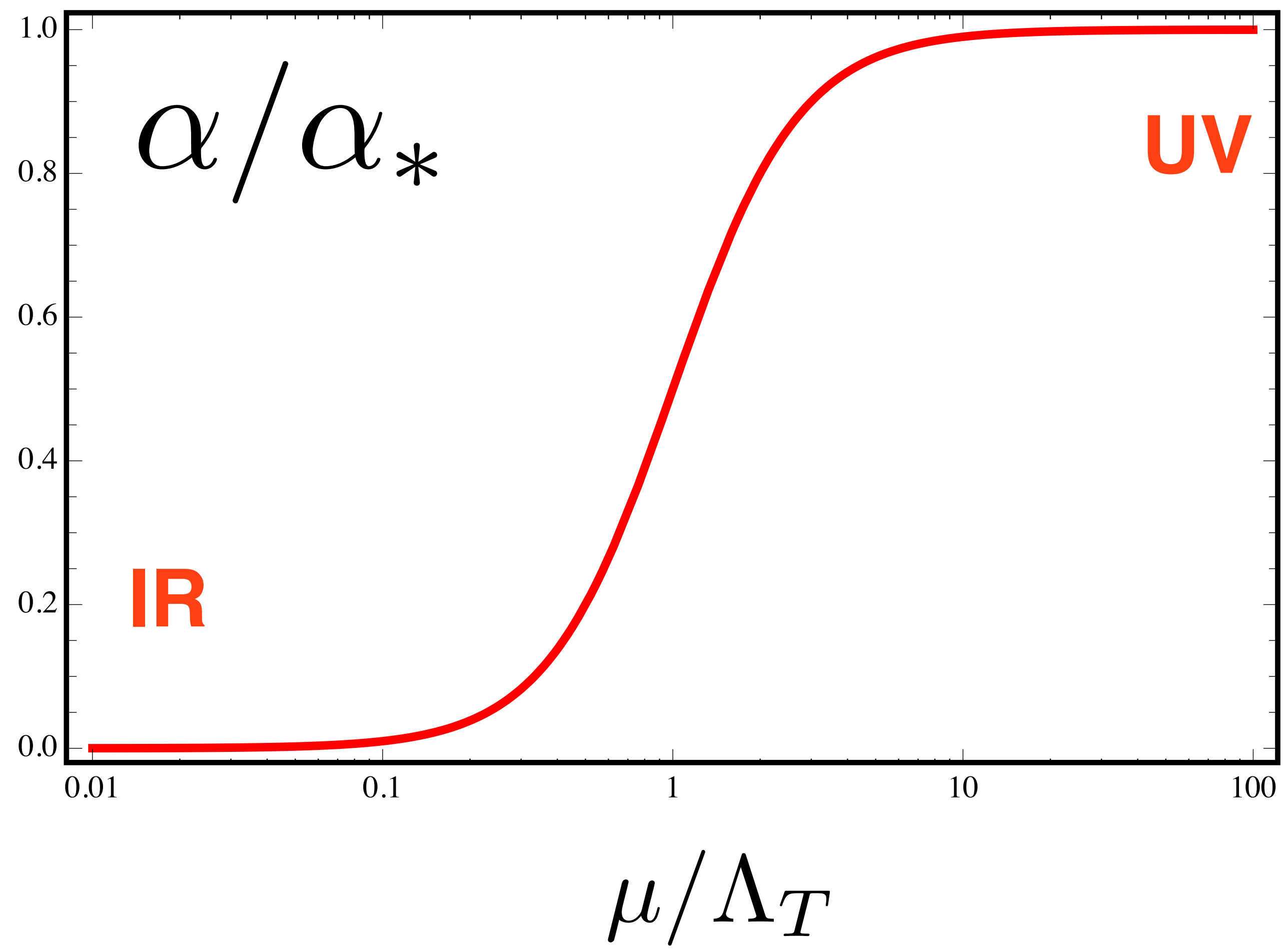
Gastmans et al ’78
Christensen, Duff ’78
Weinberg ’79
Kawai et al ’90

$$G(\mu) \approx G_N$$

classical GR



$$G(\mu) \approx \frac{\alpha_*}{\mu^{D-2}}$$

gravity weakens

how is this predictive?

UV: interactions are **softened by fluctuations**

UV behaviour characterised by

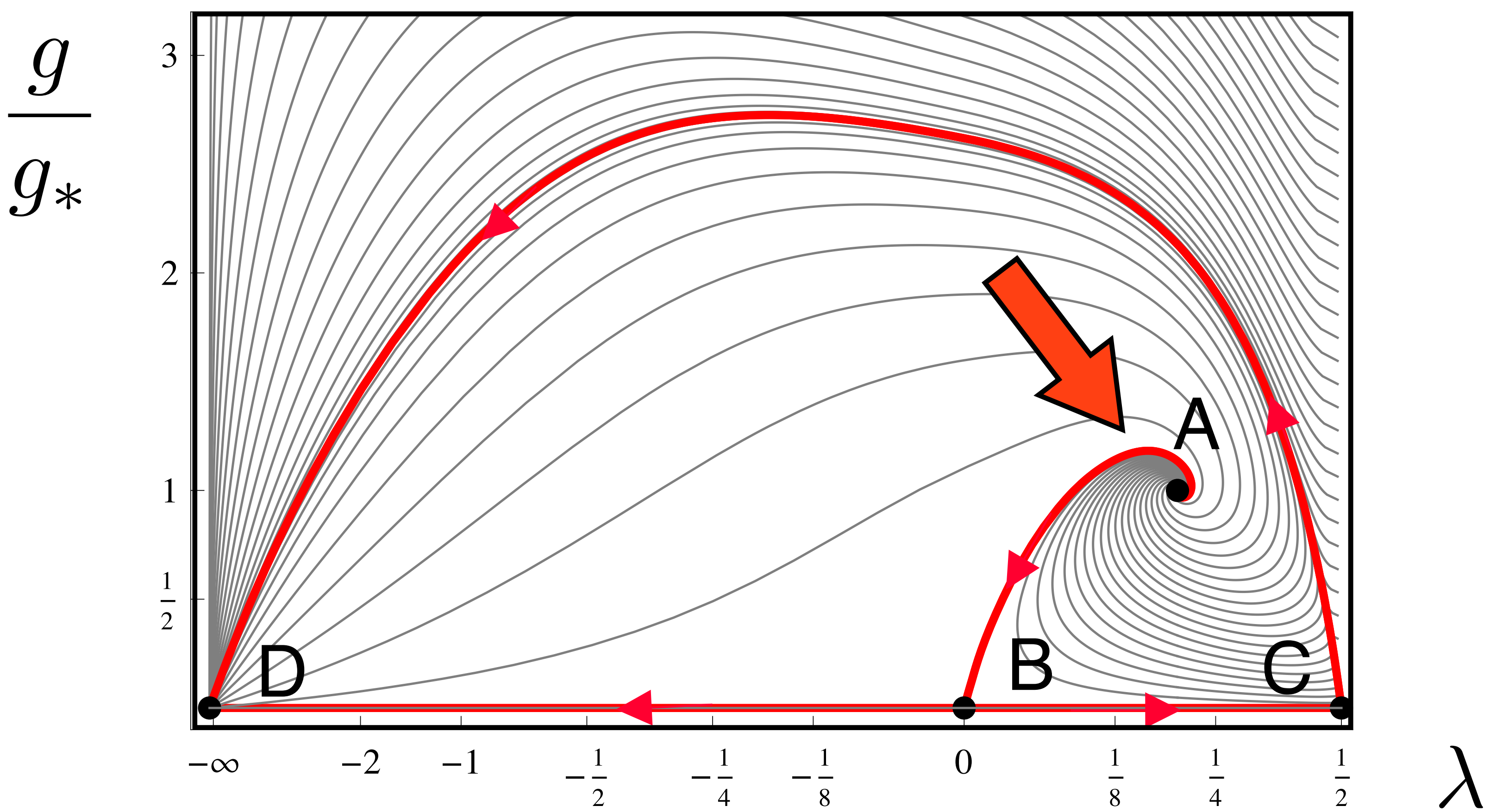
relevant, **marginal**, **irrelevant** invariants

predictivity ⟺ **finitely many** relevant invariants

how is this predictive?

example:

gravitational phase diagram in 4D



here:
two relevant couplings

$$g = G_k \cdot k^2$$

$$\lambda = \Lambda_k / k^2$$

plot taken from
Litim, Satz 1205.4218

exact asymptotic safety

	dimension	coupling	
gravitons	$D = 2 + \epsilon :$	$\alpha = G_N(\mu)\mu^{D-2}$	Gastmans et al '78 Christensen, Duff '78 Weinberg '79 Kawai et al '90
fermions	$D = 2 + \epsilon :$	$\alpha = g_{\rm GN}(\mu)\mu^{2-D}$	Gawedzki, Kupiainen '85 de Calan et al '91
gluons	$D = 4 + \epsilon :$	$\alpha = g^2_{\rm YM}(\mu)\mu^{4-D}$	Peskin '80 Morris '04
scalars	$D = 2 + \epsilon :$	$\alpha = g_{NL}(\mu)\mu^{D-2}$	Brezin, Zinn-Justin '76 Bardeen, Lee, Shrock '76

exact asymptotic safety

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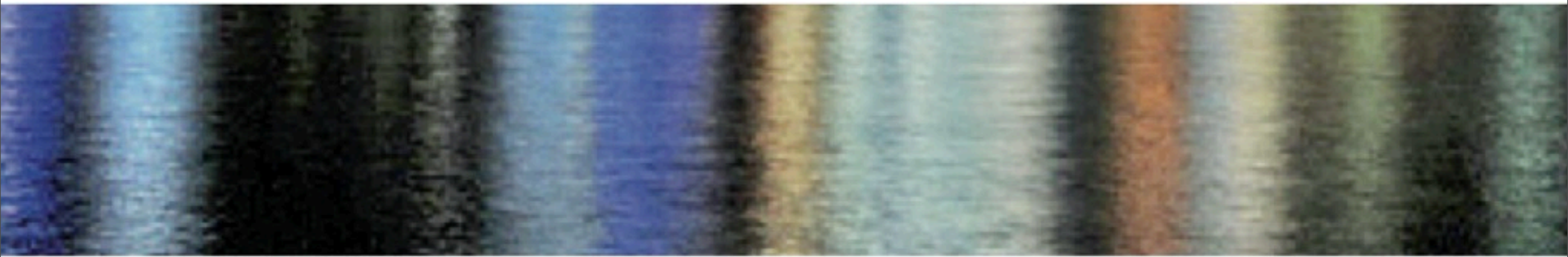
classes of gauge-Yukawa theories	$D = 4 :$ NEW	several α_i NEW	Litim, Sannino 1406.2337

exact asymptotic safety of 4D gauge-Yukawa theories

Litim, Sannino 1406.2337



gauge theory with fermions

SU(NC) YM with NF fermions: $$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$ $t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\,\alpha_g^2$$ $\alpha_* \ll 1$

gauge theory with fermions

SU(NC) YM with NF fermions: $$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$ $t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\, \alpha_g^2$$ $\alpha_* \ll 1$

$B > 0$ **: asymptotic freedom**

UV fixed point $\alpha_* = 0$

$B < 0$ **: no asymptotic freedom**

UV fixed point? $\alpha_* \neq 0$

gauge theory with fermions

SU(NC) YM with NF fermions: $\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$ $t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\, \alpha_g^2 + C \alpha_g^3$$

$\alpha_* \ll 1$

2-loop

gauge theory with fermions

SU(NC) YM with NF fermions: $\alpha_g = \dfrac{g^2\, N_c}{(4\pi)^2}$ $t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\, \alpha_g^2 + C \alpha_g^3$$

$\alpha_* \ll 1$

$$\alpha_* = 0 \qquad \alpha_g^* = B/C$$

gauge theory with fermions

SU(NC) YM with NF fermions: $\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$ $t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\alpha_g^3$$

$\alpha_* \ll 1$

$\alpha_* = 0$ $\alpha_g^* = B/C$

large-NF,NC (Veneziano) limit:

ϵ **continuous**

$$\epsilon = \frac{N_f}{N_c} - \frac{11}{2}$$

Veneziano '79

we consider $0 < -B \equiv -B\,(\epsilon) \ll 1$

gauge theory with fermions

SU(NC) YM with NF fermions:

$$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\alpha_g^3$$

$\alpha_* \ll 1$

~~$\alpha_g^* = B/C$~~

however:

no perturbative UV fixed point in gauge theories with fermionic matter $(C > 0)$

Caswell '74

gauge theory with fermions

SU(NC) YM with NF fermions:

$$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\alpha_g^3$$

$\alpha_* \ll 1$

$$\alpha_g^* = B/C$$

scalar fields & Yukawa couplings required

gauge-Yukawa theory

$$\alpha_y = \frac{y^2 N_c}{(4\pi)^2} \qquad \alpha_g = \frac{g^2 N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y$$

gauge-Yukawa theory

$$\alpha_y = \frac{y^2 N_c}{(4\pi)^2} \qquad \alpha_g = \frac{g^2 N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

$$\partial_t \alpha_g = -B\, \alpha_g^2 + C\, \alpha_g^3 - D\, \alpha_g^2\, \alpha_y$$

$$\partial_t \alpha_y = E\, \alpha_y^2 - F\, \alpha_g\, \alpha_y$$

gauge-Yukawa theory

$$\alpha_y = \frac{y^2 N_c}{(4\pi)^2} \qquad \alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

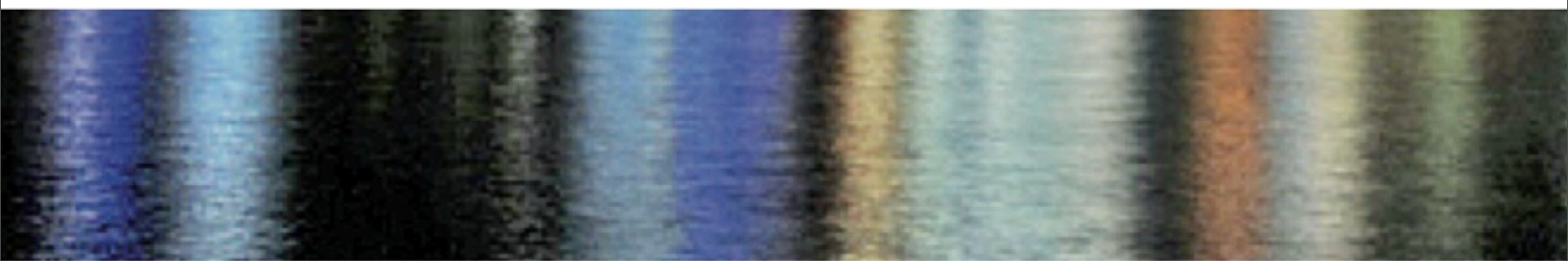
$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y$$

$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y$$

→ **sensible interacting UV fixed point**

$$D\,F - C\,E > 0$$

exact asymptotic safety:
a gauge-Yukawa template



gauge-Yukawa theory

Lagrangean

$$L_{\rm YM} = -\frac{1}{2}{\rm Tr}\,F^{\mu\nu}F_{\mu\nu}$$

gauge — Nc colours

$$L_F = {\rm Tr}\left(\overline{Q}\,i\not{D}\,Q\right)$$

$$L_Y = y\,{\rm Tr}\left(\overline{Q}\,H\,Q\right)$$

Yukawa — Nf flavours

$$L_H = {\rm Tr}\left(\partial_\mu H^\dagger\,\partial^\mu H\right)$$

$$L_U = -u\,{\rm Tr}\,(H^\dagger H)^2$$

$$L_V = -v\,({\rm Tr}\,H^\dagger H)^2\,.$$

Higgs — Nf times Nf

gauge-Yukawa theory

Lagrangean

$$L_{\rm YM} = -\frac{1}{2}{\rm Tr}\, F^{\mu\nu}F_{\mu\nu}$$

$$L_F = {\rm Tr}\left(\overline{Q}\, i\not{D}\, Q\right)$$

$$L_Y = y\, {\rm Tr}\left(\overline{Q}\, H\, Q\right)$$

$$L_H = {\rm Tr}\left(\partial_\mu H^\dagger\, \partial^\mu H\right)$$

$$L_U = -u\, {\rm Tr}\left(H^\dagger H\right)^2$$

$$L_V = -v\left({\rm Tr}\, H^\dagger H\right)^2 .$$

couplings

$$\alpha_g = \frac{g^2\, N_C}{(4\pi)^2}, \quad \alpha_y = \frac{y^2\, N_C}{(4\pi)^2}$$

$$\alpha_h = \frac{u\, N_F}{(4\pi)^2}, \quad \alpha_v = \frac{v\, N_F^2}{(4\pi)^2} .$$

small parameter:

$$0 < \epsilon \ll 1 \qquad \epsilon = \frac{N_f}{N_c} - \frac{11}{2}$$

no asymptotic freedom

gauge-Yukawa theory

$$\beta_g = \alpha_g^2 \left\{ \frac{4}{3}\epsilon + \left(25 + \frac{26}{3}\epsilon\right)\alpha_g - 2\left(\frac{11}{2} + \epsilon\right)^2 \alpha_y \right\}$$

gauge

$$\beta_y = \alpha_y \left\{ (13 + 2\epsilon)\,\alpha_y - 6\,\alpha_g \right\} .$$

Yukawa

$$\beta_h = -(11 + 2\epsilon)\,\alpha_y^2 + 4\alpha_h(\alpha_y + 2\alpha_h)$$

$$\beta_v = 12\alpha_h^2 + 4\alpha_v\,(\alpha_v + 4\alpha_h + \alpha_y) .$$

Higgs

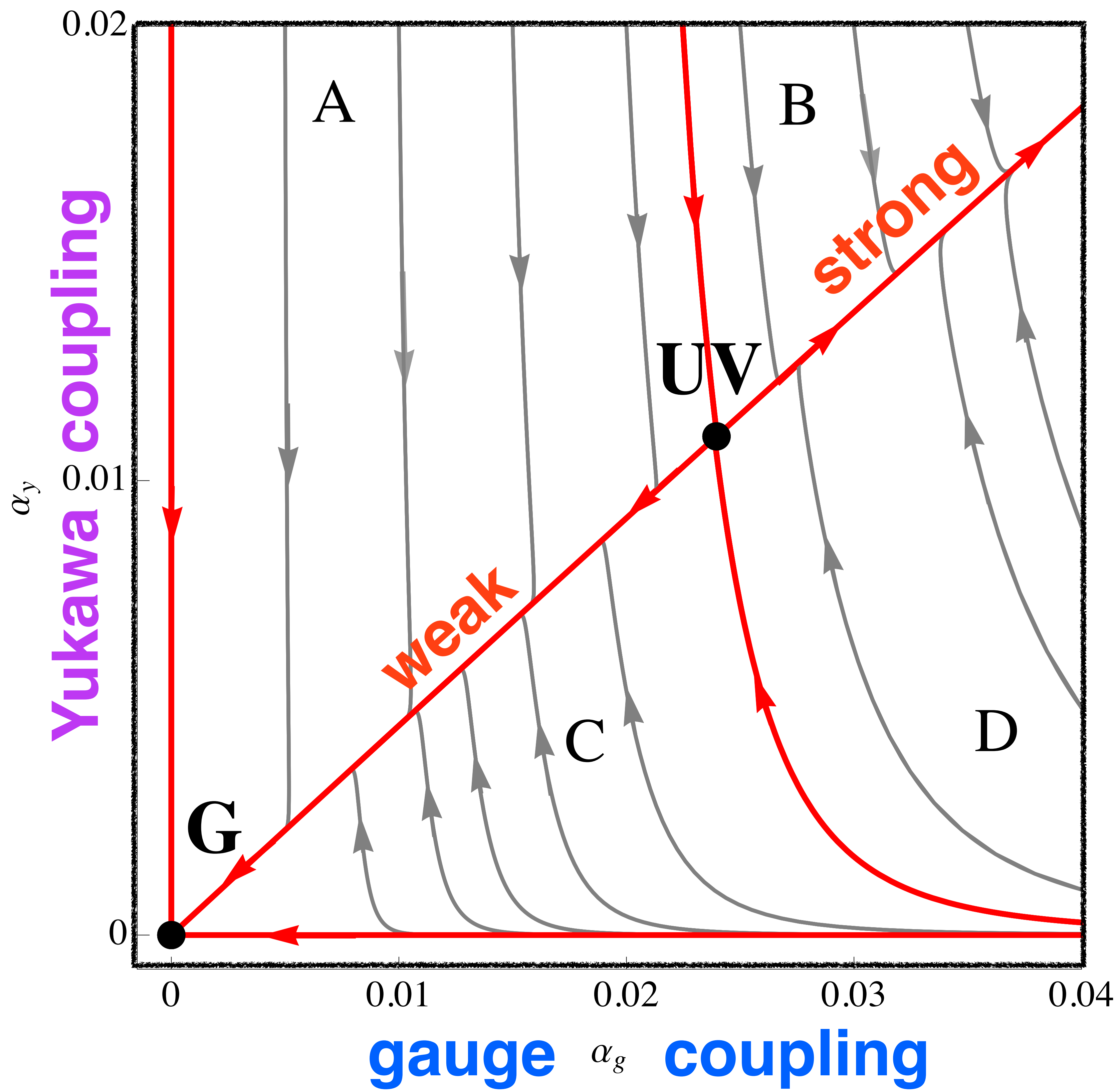
exact

UV fixed point

$$\begin{aligned}
\alpha_g^* &= 0.4561\,\epsilon + 0.7808\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\alpha_y^* &= 0.2105\,\epsilon + 0.5082\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\alpha_h^* &= 0.1998\,\epsilon + 0.5042\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\alpha_v^* &= -0.1373\,\epsilon + \mathcal{O}(\epsilon^2)
\end{aligned}$$

results

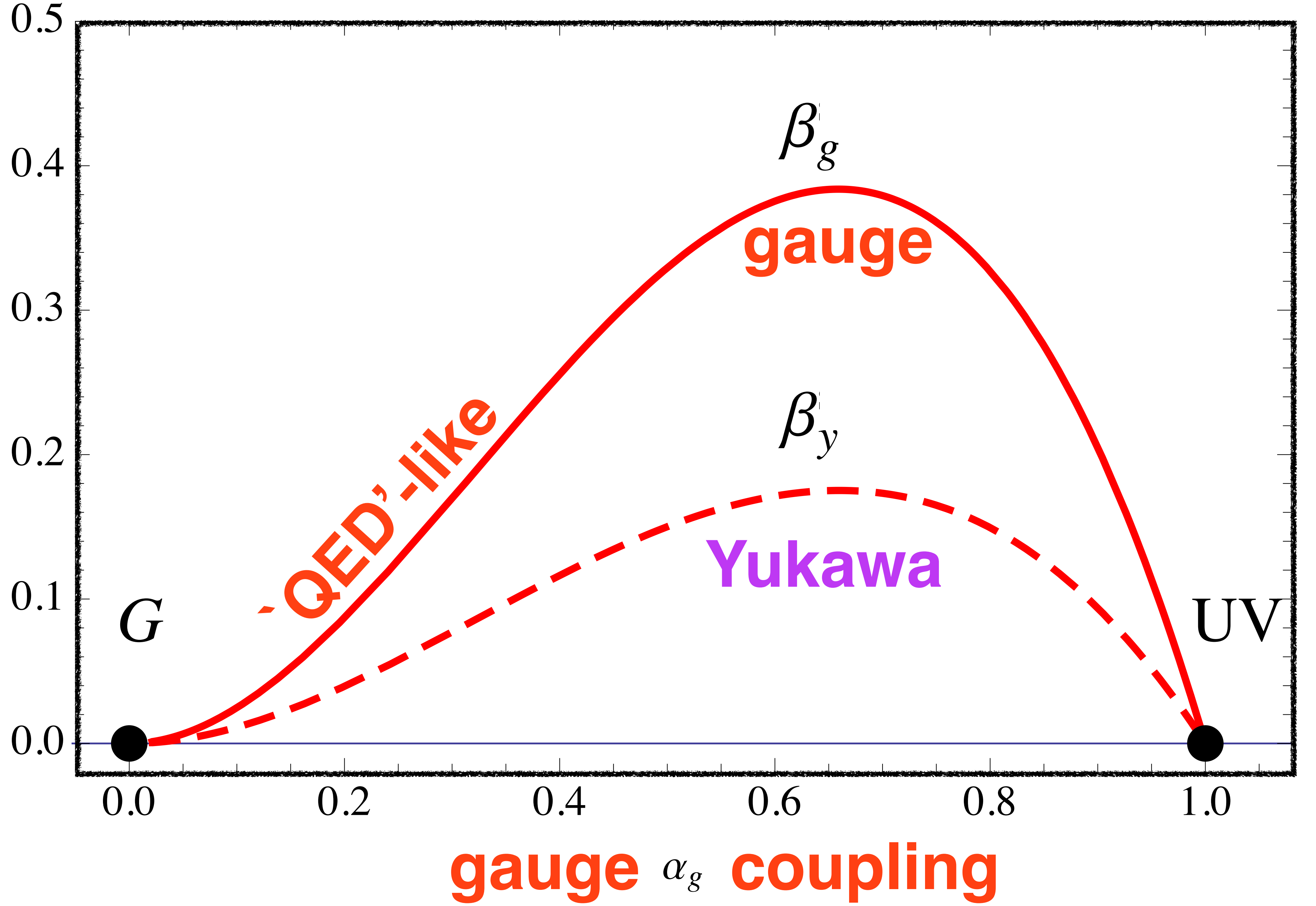
phase diagram



exact UV FP

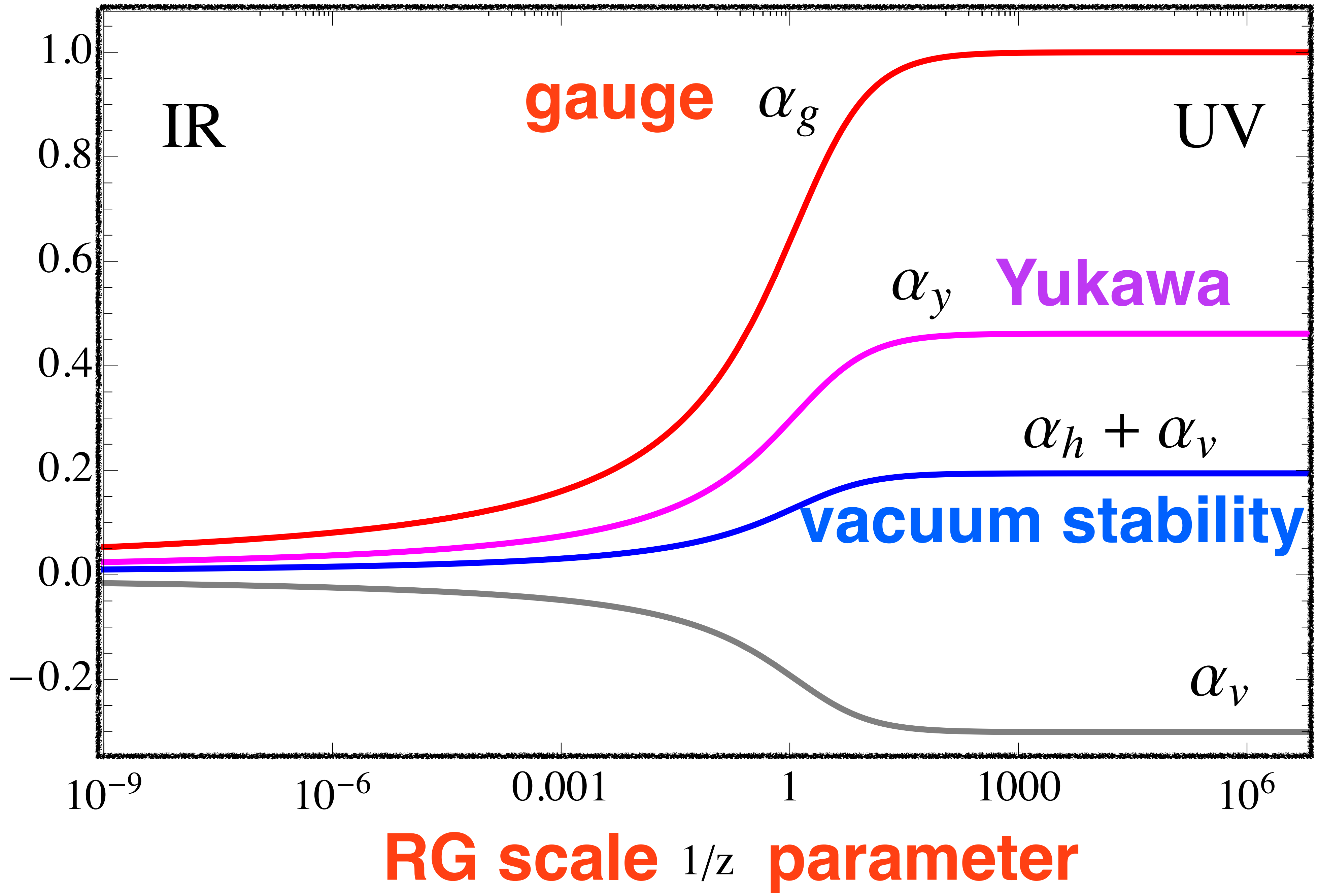
strict perturbative control

results



interacting UV fixed point entirely due to `fluctuations'

results

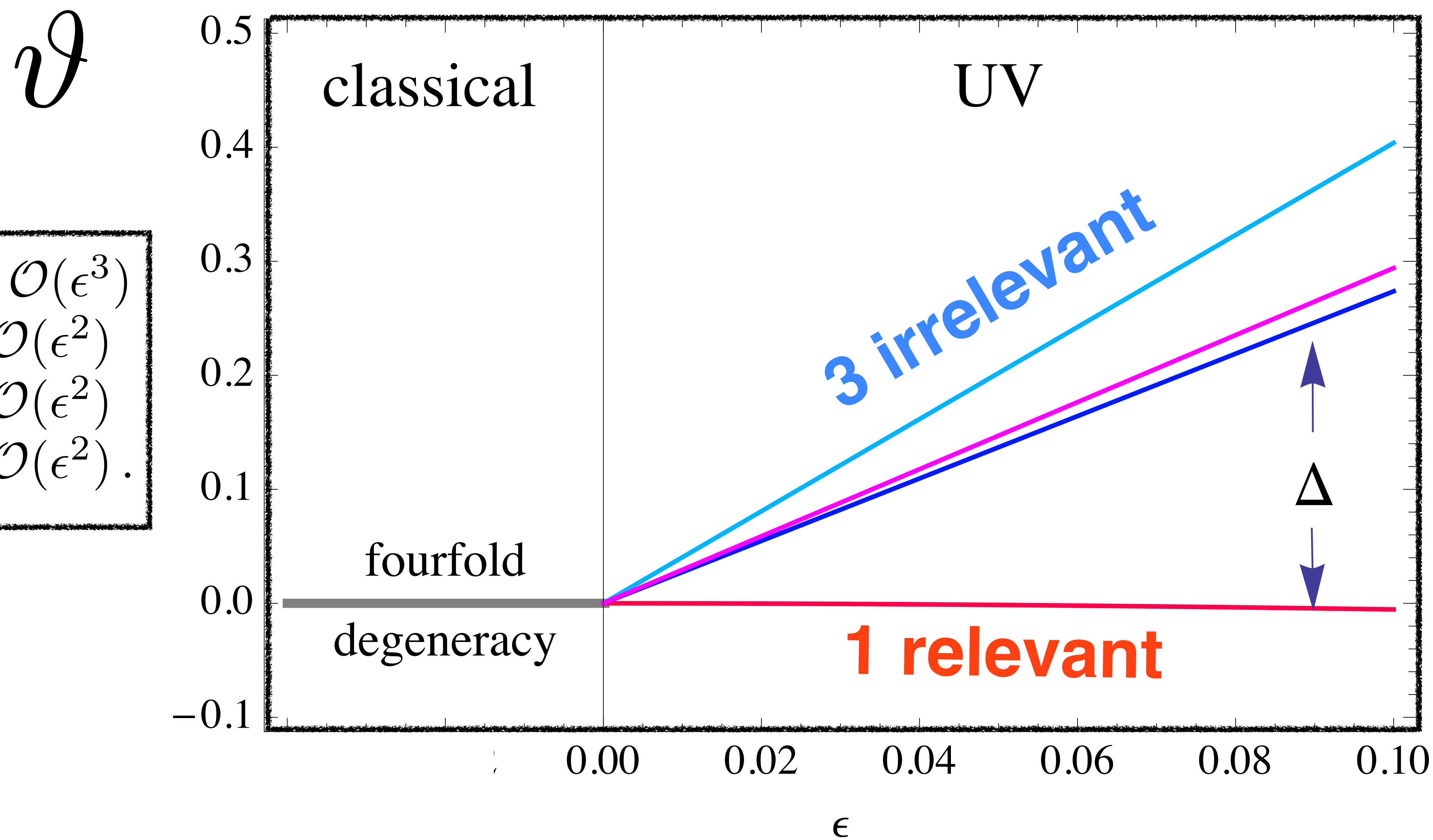

1.0
0.8
0.6
0.4
0.2
0.0
−0.2
IR
gauge α_g
UV
α_y Yukawa
$\alpha_h + \alpha_v$
vacuum stability
α_v
10^{-9}
10^{-6}
0.001
1
1000
10^6
RG scale 1/z parameter

results

UV scaling exponents

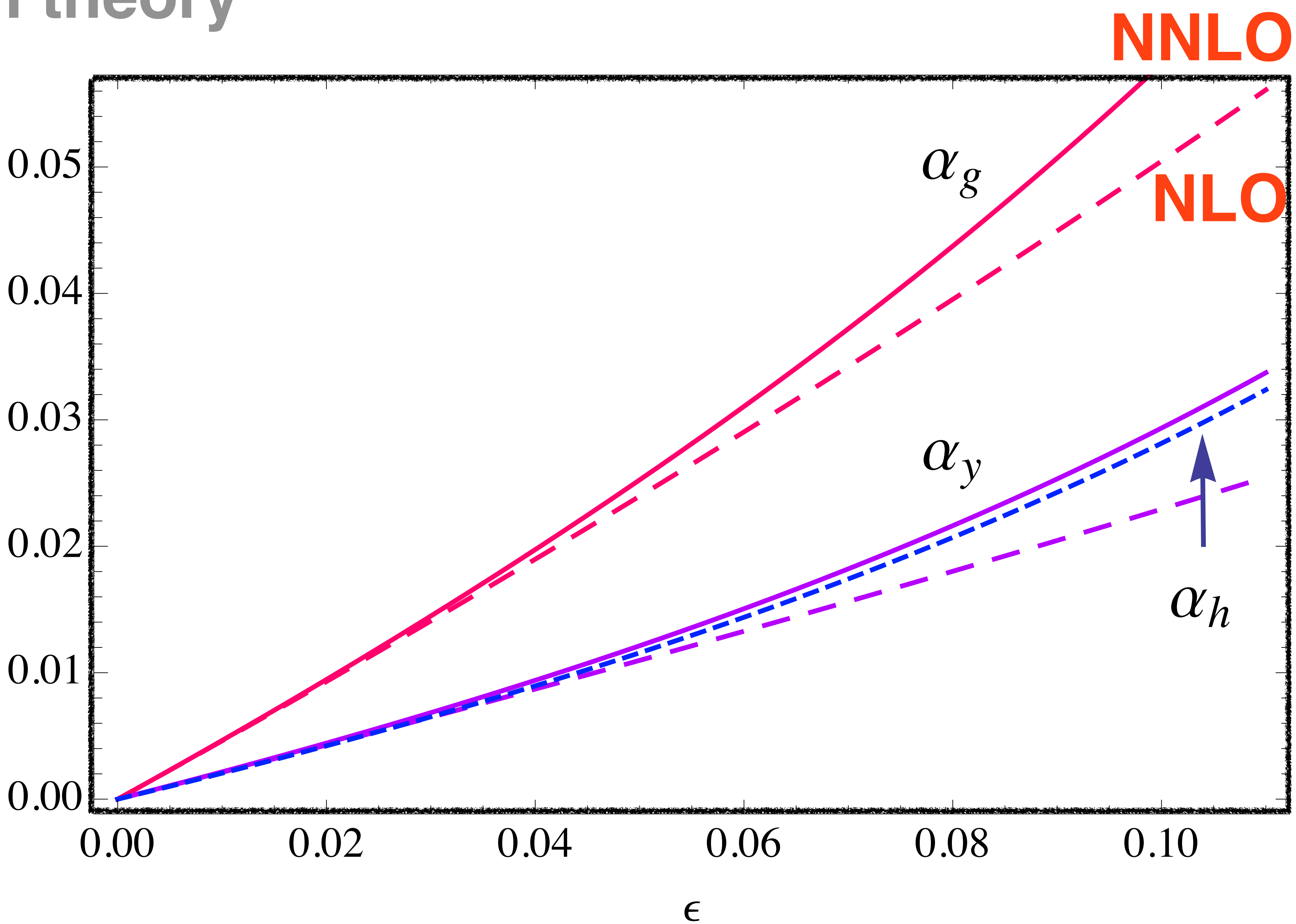
$$\vartheta_1 < 0 < \vartheta_2 < \vartheta_4 < \vartheta_3$$

$$\begin{aligned}
\vartheta_1 &= -0.608\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\vartheta_2 &= 2.737\,\epsilon + \mathcal{O}(\epsilon^2) \\
\vartheta_3 &= 4.039\,\epsilon + \mathcal{O}(\epsilon^2) \\
\vartheta_4 &= 2.941\,\epsilon + \mathcal{O}(\epsilon^2)\,.
\end{aligned}$$



results

UV fixed point from perturbation theory



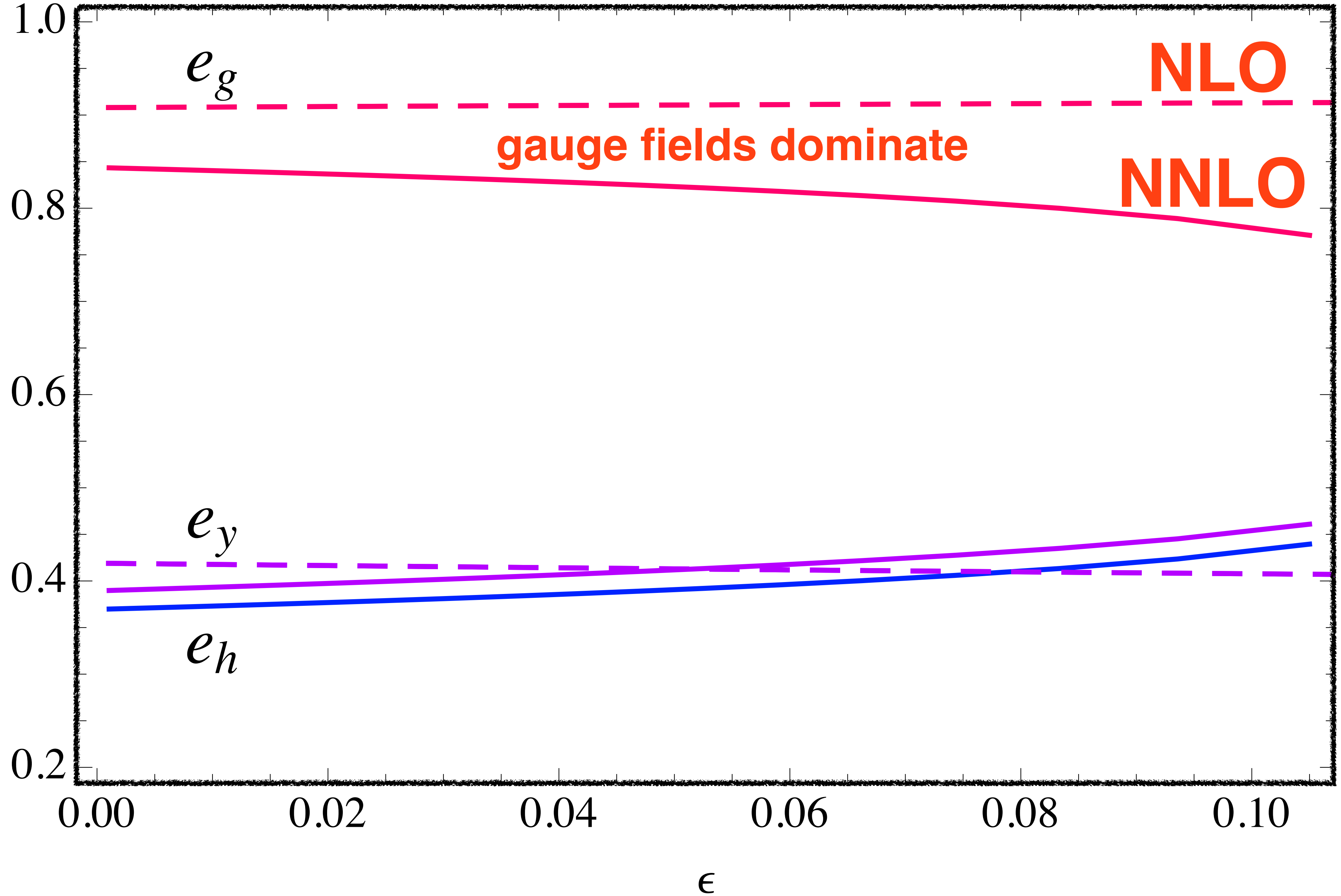
results

UV-relevant eigendirection

gauge

Yukawa

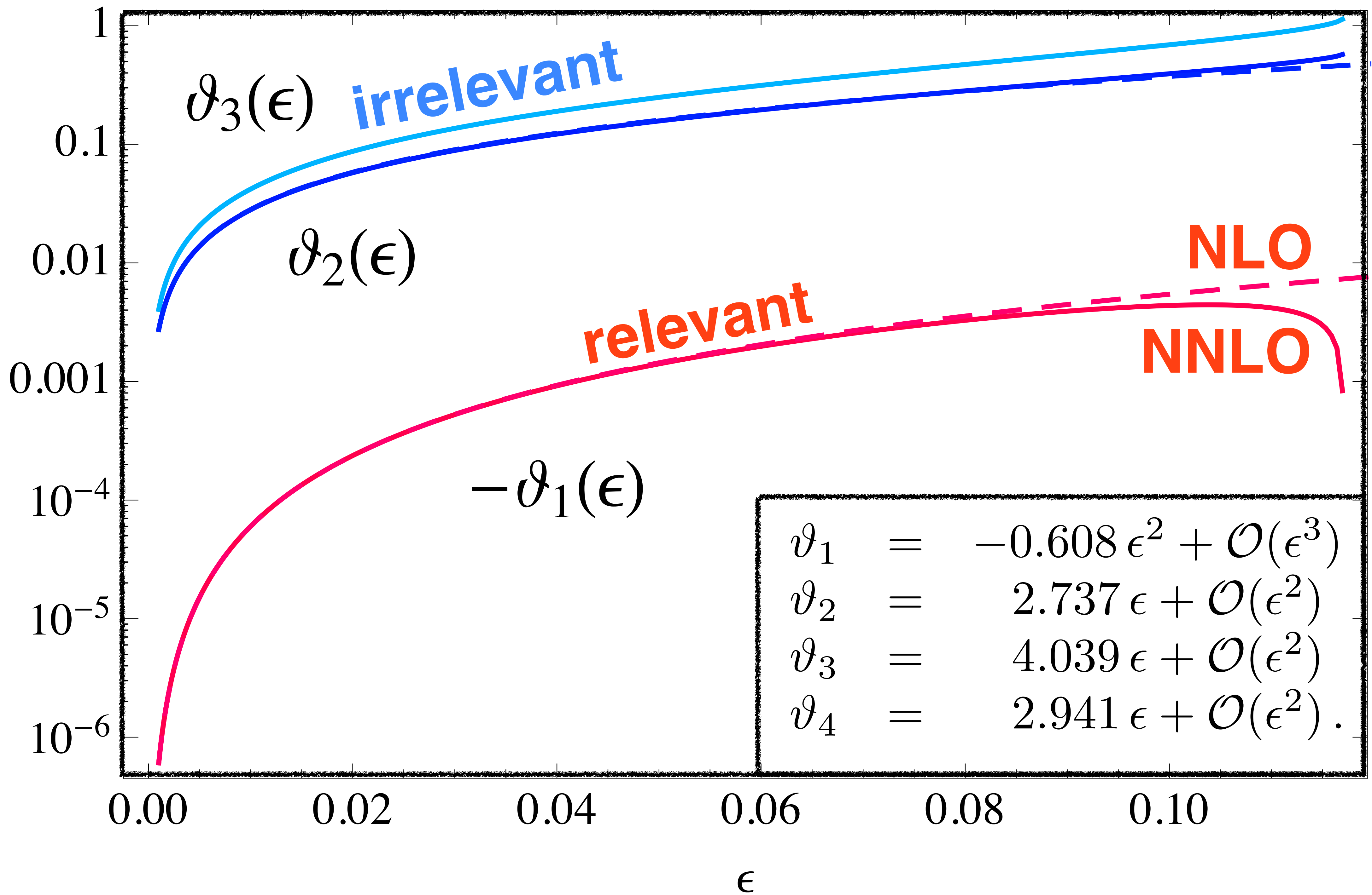
Higgs



results

UV scaling exponents

$$\vartheta_1 < 0 < \vartheta_2 < \vartheta_4 < \vartheta_3$$



vacuum stability

vacuum must be stable classically
and quantum-mechanically

$$V \propto \alpha_v \mathrm{Tr}(H^\dagger H)^2 + \alpha_h (\mathrm{Tr} H^\dagger H)^2$$

stability

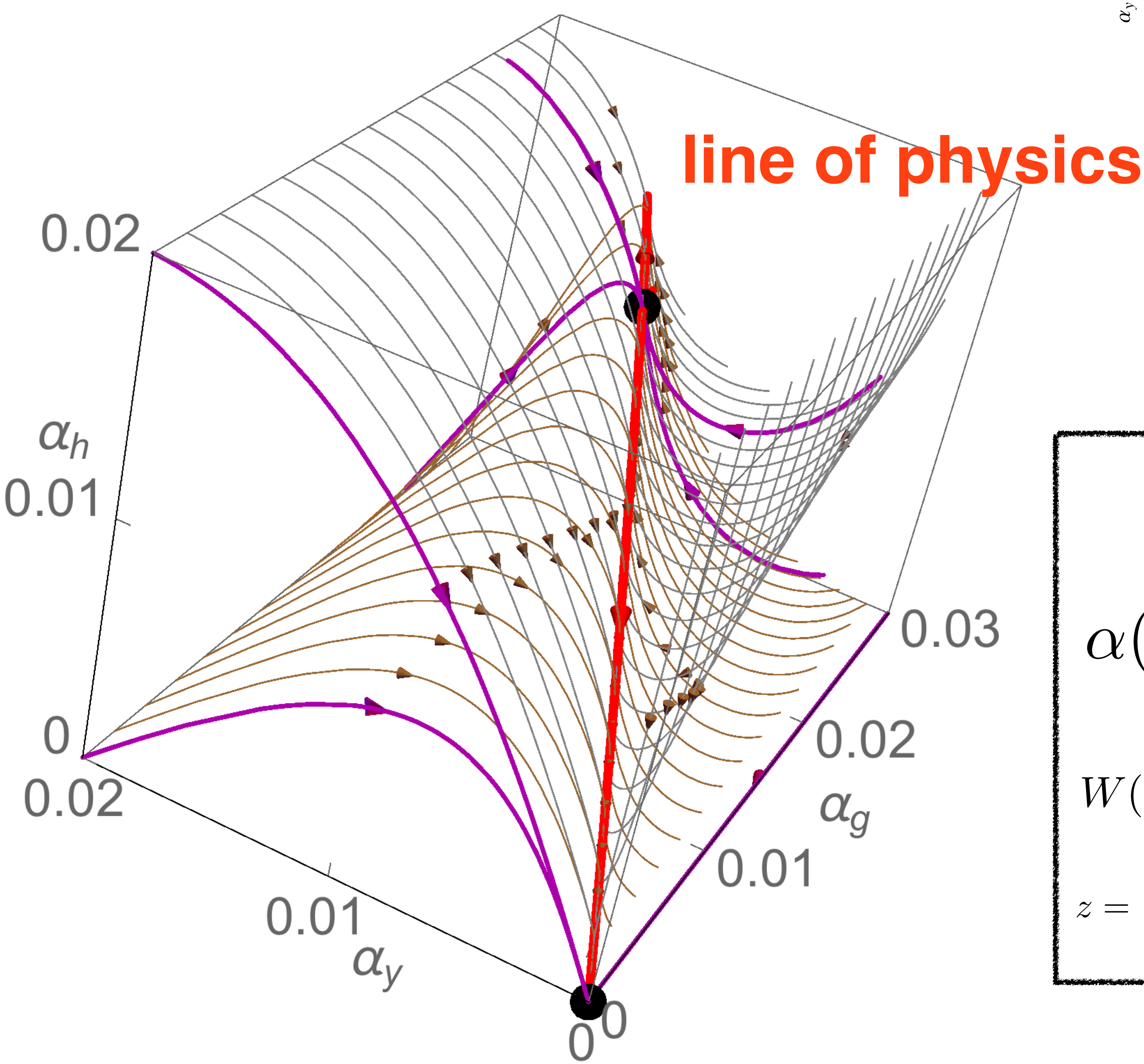
$$\alpha_h > 0 \quad \text{and} \quad \alpha_h + \alpha_v \geq 0 \qquad H_c \propto \delta_{ij}$$

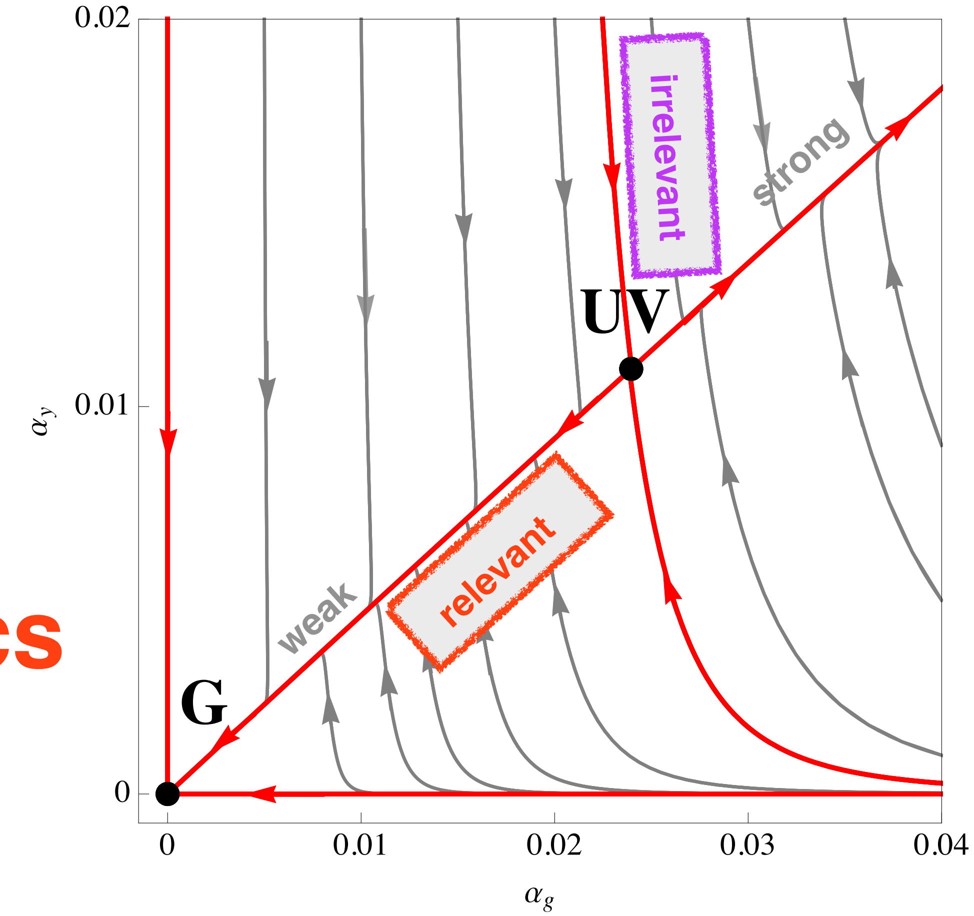
$$\alpha_h < 0 \quad \text{and} \quad \alpha_h + \alpha_v / N_F \geq 0 \qquad H_c \propto \delta_{i1}$$

UV FP:

$$0 < \alpha_h^* + \alpha_v^*$$ **ok**

phase diagram





leading order

$$\alpha(\mu) = \frac{\alpha_*}{1 + W(\mu)}$$

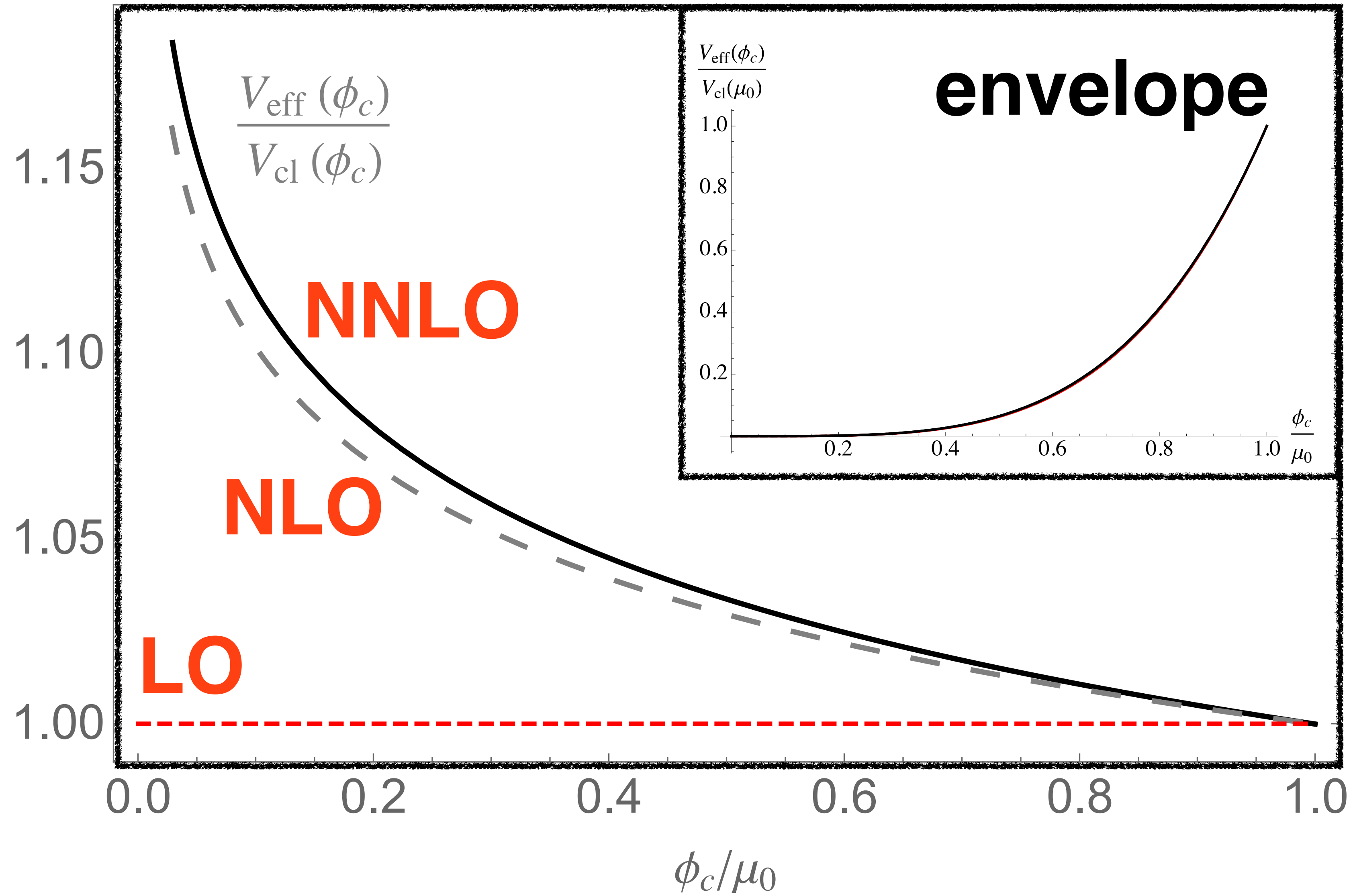
$$W(\mu) = W_{\text{Lambert}}[z(\mu)]$$

$$z = \left(\frac{\mu_0}{\mu}\right)^{-B\cdot\alpha_*} \left(\frac{\alpha_*}{\alpha_0} - 1\right) \exp\left(\frac{\alpha_*}{\alpha_0} - 1\right) .$$

vacuum stability

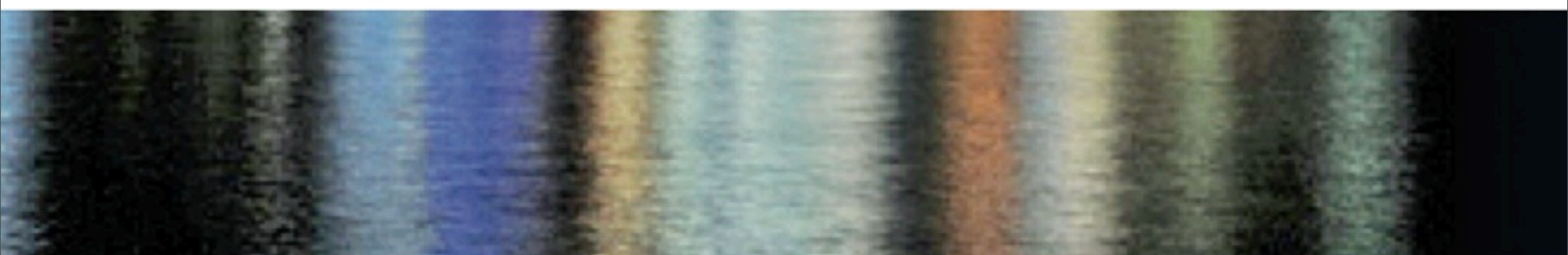
quantum stability: Coleman-Weinberg type resummation of logs

$$\left(\mu_0 \frac{\partial}{\partial \mu_0} - \gamma(\alpha_j)\,\phi_c \frac{\partial}{\partial \phi_c} + \sum_i \beta_i(\alpha_j) \frac{\partial}{\partial \alpha_i}\right) V_{\text{eff}}(\phi_c, \mu_0, \alpha_j) = 0$$



effective potential well-defined for all scales

asymptotic safety
and 4D quantum gravity



UV fixed points

overviews:
DL **0810.3675** and **1102.4624**

gravitation

Einstein-Hilbert (Reuter '96, Souma '99, Lauscher Reuter '01, Reuter, Saueressig '01, DL '03)

polynomials in R (Lauscher, Reuter '02, Codello, Percacci, Rahmede '08, Machado, Saueressig '09 Falls, DL, Nikolakopoulos, Rahmede '13)

f(R) actions (Machado, Saueressig '09, Benedetti, Caravelli, '12, Dietz, Morris, '12, Falls, DL, Nikolakopoulos, Rahmede '13,'14,'15)

higher-derivative gravity (Codello, Percacci '05, Benedetti, Saueressig, Machado '09, Niedermaier '09, DL, Rahmede, '13)

higher dimensions, dimensional reduction (DL '03, Fischer, DL '05 Alkofer, DL, Schaefer '15)

conformally reduced gravity (Reuter, Weyer '09, Machado, Percacci '10, DL, Satz '12)

Holst action + Immirzi parameter (Daum, Reuter '10, Benedetti, Speciale '11)

signature effects (Manrique, Rechenberger, Saueressig '11)

gravitation + matter

matter (Percacci '05, Perini, Percacci '05, Narain, Percacci '09, Narain, Rahmede '09, Codello '11 Folkerts, DL, Pawlowski '11, Dona, Eichhorn, Percacci '13, DL, Schroeder '15)

standard model Higgs (Shaposhnikov, Wetterich '11)

UV fixed point & holographic RG (DL, Percacci, Rachwal '11)

Yang-Mills gravity

1-loop: (Robinson, Wilzcek '05, Pietrokowski, '06, Toms '07, Ebert, Plefka, Rodigast '08)

beyond: (Manrique, Reuter, Saueressig '09, Folkerts, DL, Pawlowski, 11, Harst, Reuter '11)

computational methods

4D quantum gravity:

expect large couplings

non-perturbative tools mandatory

continuum: non-perturbative renormalisation group

lattice: Monte Carlo simulations

simplicial gravity

dynamical triangulations

computational methods

4D quantum gravity: expect large couplings
non-perturbative tools mandatory

continuum: non-perturbative renormalisation group
functional (Wilsonian) renormalisation
`effective average action'

Polchinski '84, Wetterich '92
Reuter '96, Dou, Percacci '97, Litim '00, '03

lattice: Monte Carlo simulations
simplicial gravity
dynamical triangulations

systematic search strategy (`bootstrap')
set of relevant couplings
not known beforehand

Falls, Litim, Nikolakopoulos, Rahmede, 1301.4191

asymptotic freedom `the knowns' vs asymptotic safety `the unknowns'

asymptotic freedom `the knowns'	asymptotic safety `the unknowns'
$g_* = 0$	$g_* \neq 0$
anomalous dimensions	anomalous dimensions
$\eta_A = 0$	$\eta_N \neq 0$
canonical power counting	**non-canonical** power counting
$\{\vartheta_{\mathrm{G},n}\}$ are known	$\{\vartheta_n\}$ are **not** known
F^{256} irrelevant !	R^{256} relevant / marginal / irrelevant ?

K Falls, DL, K Nikolakopoulos & C Rahmede, 1301.4191

bootstrap search strategy

hypothesis relevancy of invariants follows their canonical mass dimension

K Falls, DL, K Nikolakopoulos & C Rahmede, 1301.4191

bootstrap search strategy

hypothesis relevancy of invariants follows their canonical mass dimension

strategy

Step 1 retain invariants up to mass dimension D

Step 2 compute $\{\vartheta_n\}$ (eg. RG, lattice, holography)

Step 3 enhance D, and iterate

convergence (**no convergence**) of the iteration:

hypothesis supported (**refuted**)

f(R)

$$\Gamma_k \propto f(R)$$

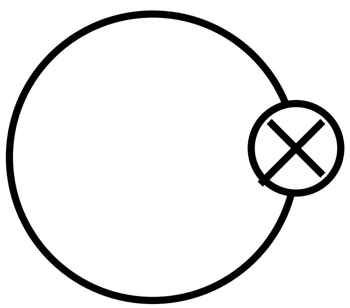
Ricci scalars

$$\Gamma_k = \sum_{n=0}^{N-1} \lambda_n \, k^{d_n} \int d^4x \sqrt{g}\, R^n$$

effective action with invariants up to mass dimension $D = 2(N-1)$

technicalities: functional renormalisation

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



here:

M Reuter hep-th/9605030

DL hep-th/0103195

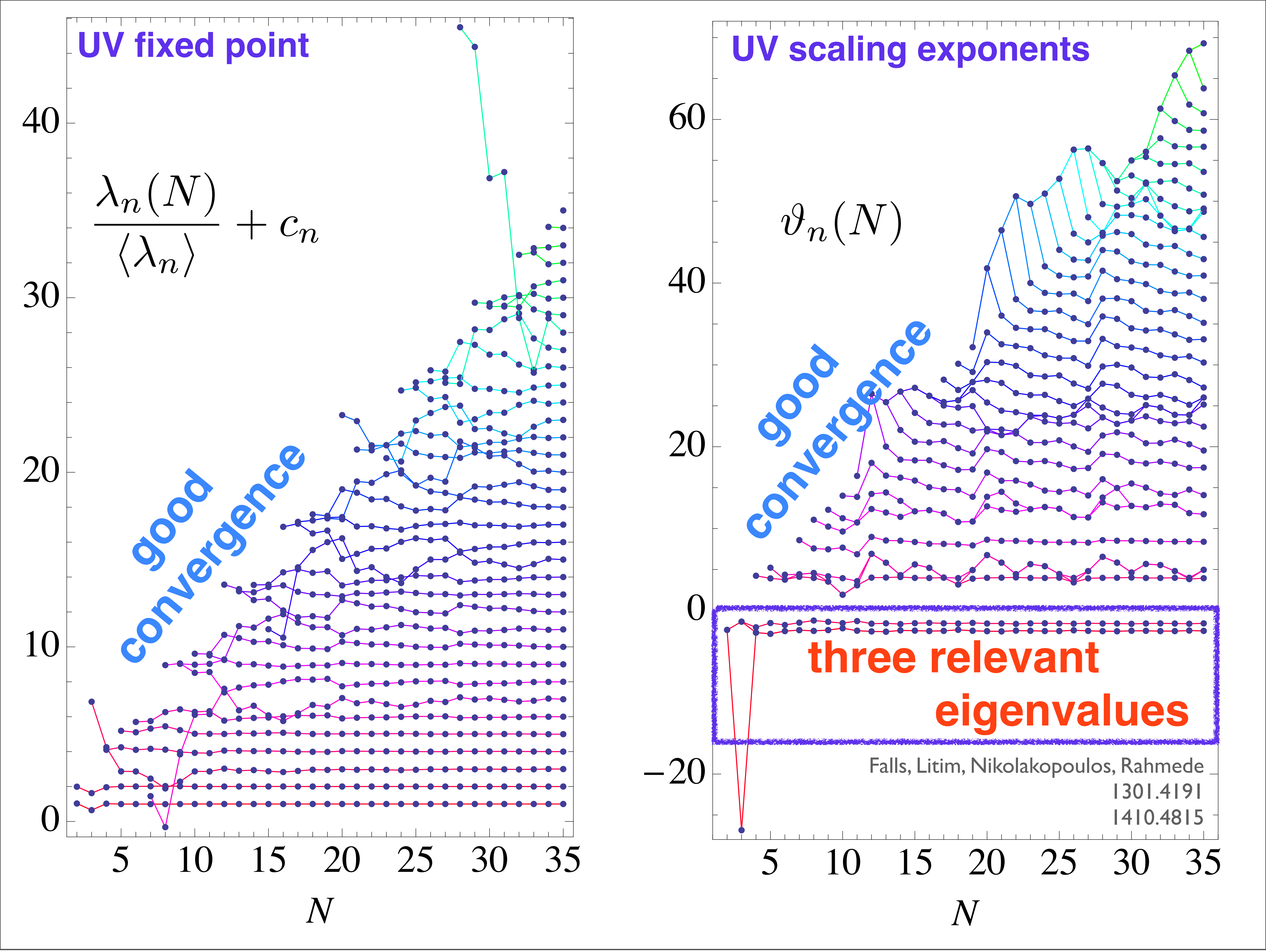
hep-th/0312114

Falls, DL, Nikolakopoulos, Rahmede 1301.4191.pdf

Falls, DL, Nikolakopoulos, Rahmede 1410.4815

A Codello, R Percacci, C Rahmede 0705.1769, 0805.2909

P Machado, F Saueressig 0712.0445

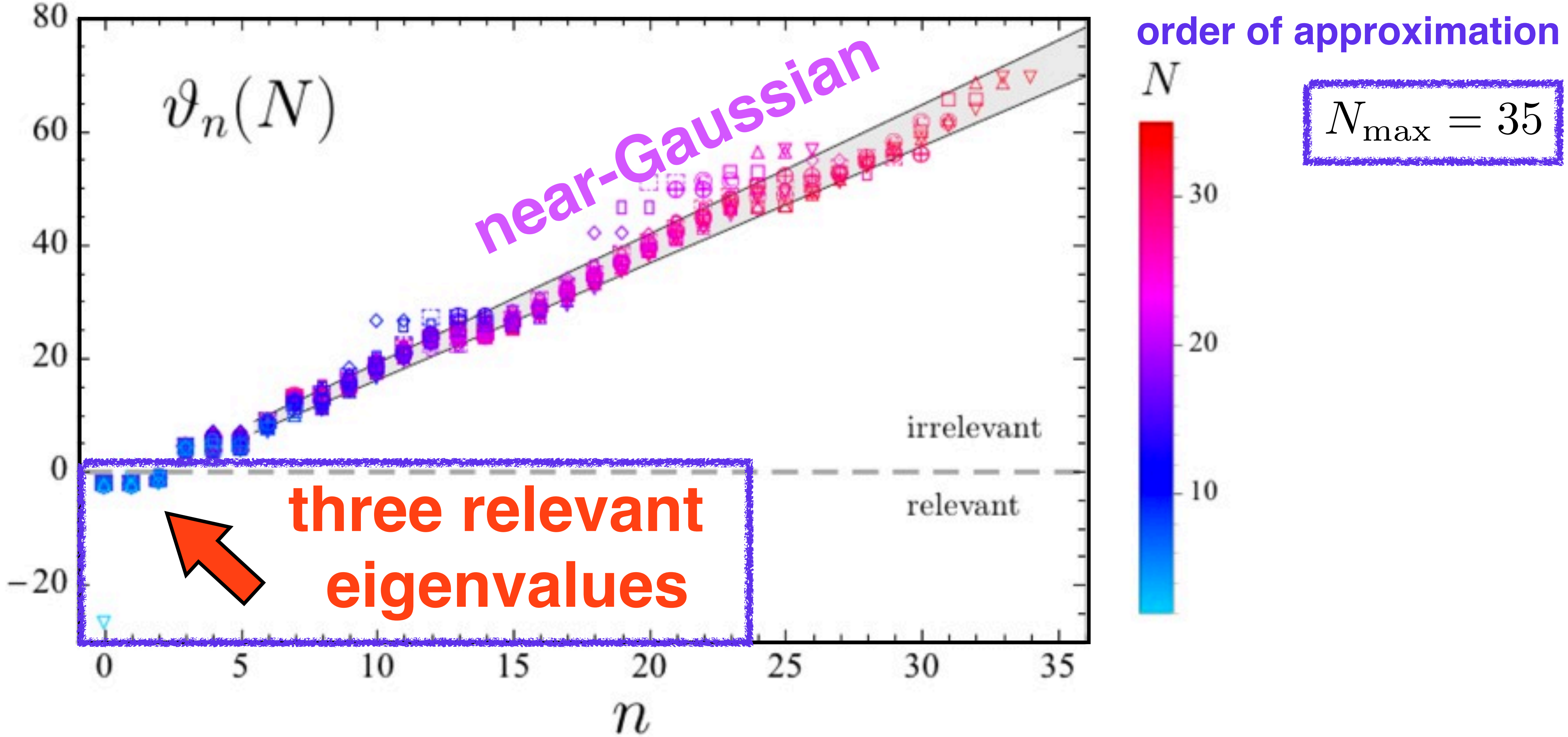


UV fixed point
$\frac{\lambda_n(N)}{\langle\lambda_n\rangle} + c_n$
good convergence
N
UV scaling exponents
$\vartheta_n(N)$
good convergence
three relevant eigenvalues
Falls, Litim, Nikolakopoulos, Rahmede
1301.4191
1410.4815
N

scaling exponents

f(R)-type gravity

$$\Gamma_k = \sum_{n=0}^{N-1} \lambda_n \, k^{d_n} \int d^4x \sqrt{g} \, R^n$$



Falls, Litim, Nikolakopoulos, Rahmede
1301.4191
1410.4815

K Falls, DL, K Nikolakopoulos & C Rahmede, (in prep, arXiv:1508.xyz)

f(Ricci)

$$\Gamma_k \propto \int d^dx\sqrt{g}\,[f_k(R_{\mu\nu}R^{\mu\nu}) + R\cdot z_k(R_{\mu\nu}R^{\mu\nu})]$$

K Falls, DL, K Nikolakopoulos & C Rahmede, (in prep, arXiv:1508.xyz)

f(Ricci)

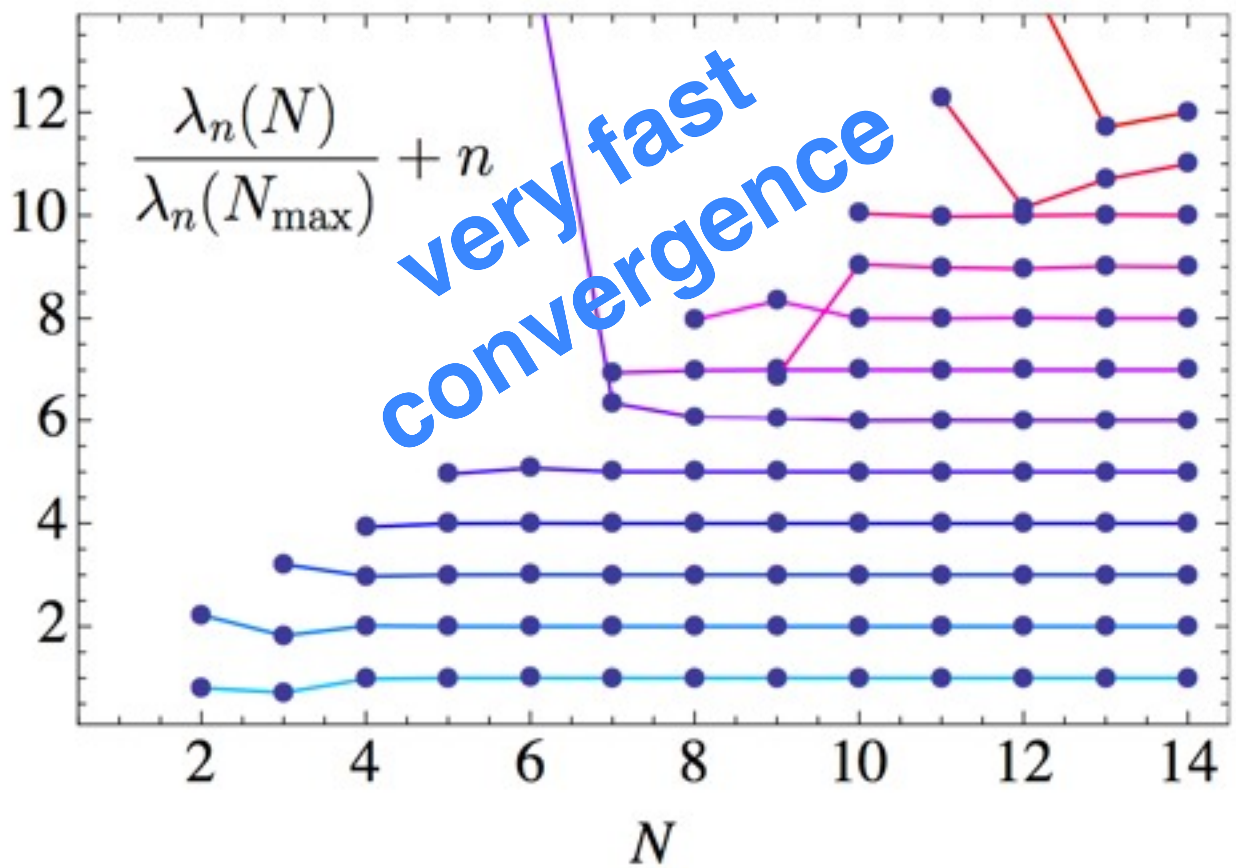
$$\Gamma_k \propto \int d^dx\sqrt{g}\,[f_k(R_{\mu\nu}R^{\mu\nu}) + R\cdot z_k(R_{\mu\nu}R^{\mu\nu})]$$

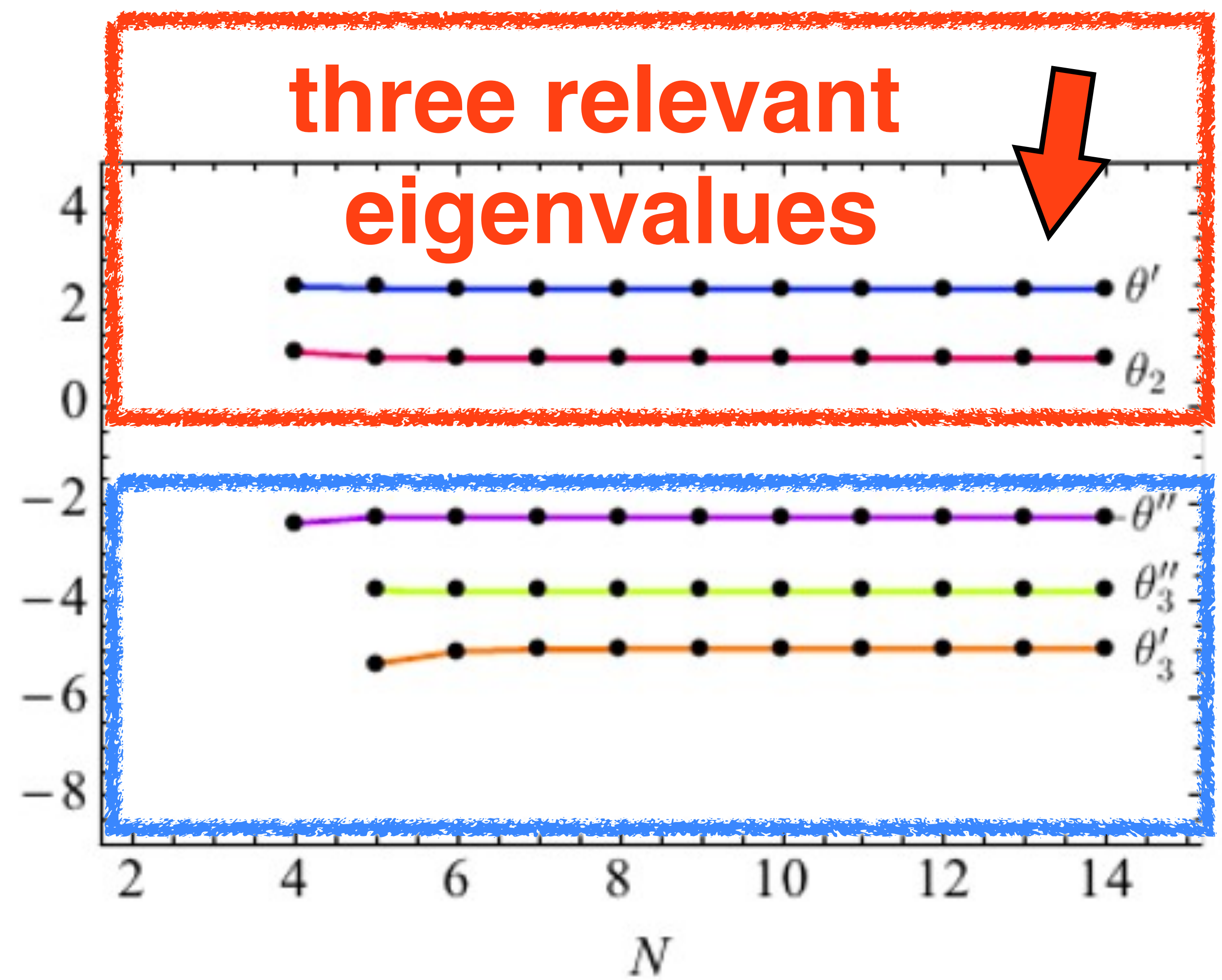
$$\begin{aligned}\partial_t\Gamma[\bar g,\bar g] =& \frac{1}{2}\mathrm{Tr}_{(2T)}\left[\frac{\partial_t\mathcal{R}_k^{h^Th^T}}{\Gamma^{(2)}_{h^Th^T}}\right] + \frac{1}{2}\mathrm{Tr}'_{(1T)}\left[\frac{\partial_t\mathcal{R}_k^{\xi\xi}}{\Gamma^{(2)}_{\xi\xi}}\right] + \frac{1}{2}\mathrm{Tr}''_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\sigma\sigma}}{\Gamma^{(2)}_{\sigma\sigma}}\right] + \frac{1}{2}\mathrm{Tr}_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{hh}}{\Gamma^{(2)}_{hh}}\right]\\ &+ \mathrm{Tr}''_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\sigma h}}{\Gamma^{(2)}_{\sigma h}}\right] - \mathrm{Tr}_{(1T)}\left[\frac{\partial_t\mathcal{R}_k^{\bar C^TC^T}}{\Gamma^{(2)}_{\bar C^TC^T}}\right] - \mathrm{Tr}_{(0)'}\left[\frac{\partial_t\mathcal{R}_k^{\bar\eta\eta}}{\Gamma^{(2)}_{\bar\eta\eta}}\right] - \mathrm{Tr}''_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\bar\lambda\lambda}}{\Gamma^{(2)}_{\bar\lambda\lambda}}\right]\\ &+ \frac{1}{2}\mathrm{Tr}''_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\omega\omega}}{\Gamma^{(2)}_{\omega\omega}}\right] - \mathrm{Tr}'_{(1T)}\left[\frac{\partial_t\mathcal{R}_k^{\bar c^Tc^T}}{\Gamma^{(2)}_{\bar c^Tc^T}}\right] + \frac{1}{2}\mathrm{Tr}'_{(1T)}\left[\frac{\partial_t\mathcal{R}_k^{\zeta^T\zeta^T}}{\Gamma^{(2)}_{\zeta^T\zeta^T}}\right] + \mathrm{Tr}'_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\bar ss}}{\Gamma^{(2)}_{\bar ss}}\right]\end{aligned}$$

f(Ricci)

$$\Gamma_k \propto \int d^dx\sqrt{g}\,[f_k(R_{\mu\nu}R^{\mu\nu}) + R\cdot z_k(R_{\mu\nu}R^{\mu\nu})]$$

results:





RG vs lattice

simplicial gravity

lattice fixed point in 4D Hamber ’00, ’15

scaling exponent	lattice		RG	
ν	$0.335(9)$	Hamber ’00	0.375	Litim ’03
	$0.335(4)$	Hamber ’15 as quoted in 1503.06233	0.3333	Falls 1503.06233

dynamical triangulations (casual vs euclidean)

lattice fixed point in 4D CDT Ambjoern, Jordan, Jurkiewicz, Loll ‘11

spectral dimension $\mathcal{D}_s$	CDT	Ambjoern, Jurkiewicz, Loll ’05	$\mathcal{D}_s = \frac{2D}{2+\delta}$
	EDT	Laiho, Coumbe ’11	
	RG	Lauscher, Reuter, ’05 Reuter, Saueressig, ’11	

testing asymptotic safety in the physical world

cosmology

early universe and inflation, late-time acceleration
asymptotically safe cosmology

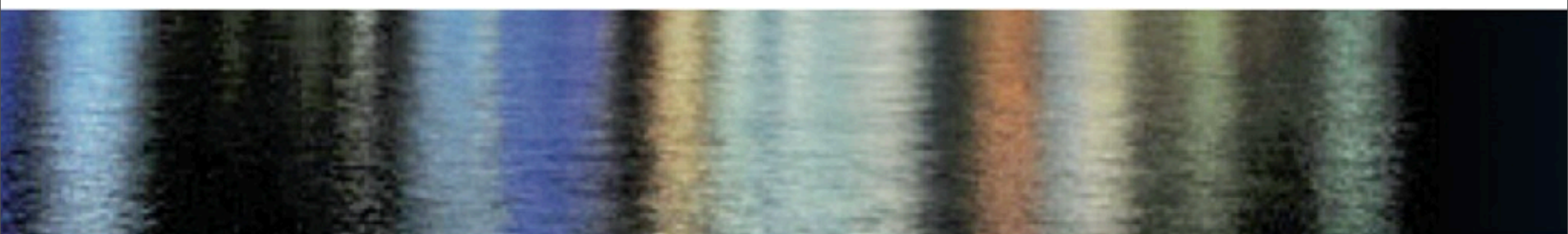
particle physics

towards a Standard Model including quantum gravity
gravitational scattering: signatures at particle colliders

black holes

quantum corrections to BH space-times
quantum aspects of black hole thermodynamics

phenomenology of low-scale quantum gravity



low-scale quantum gravity

Standard Model of particle physics

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**

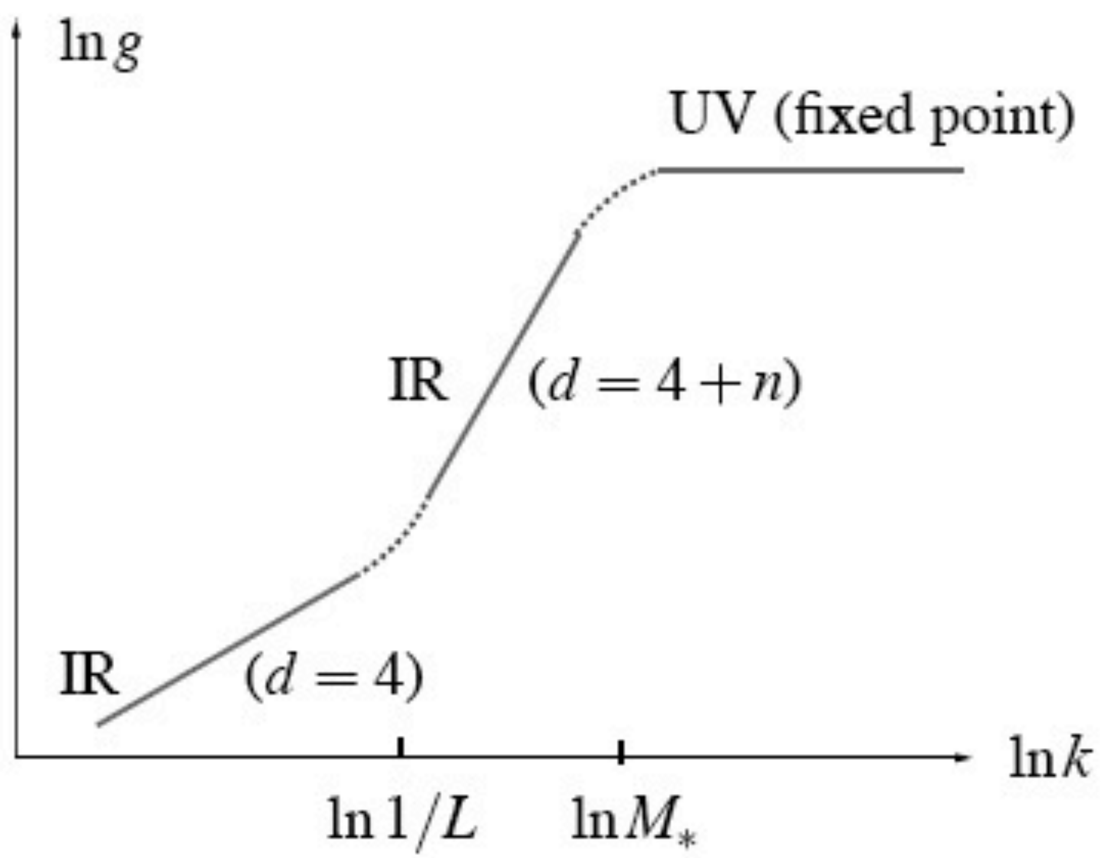
challenges

- **theory**:
  fundamental parameters M_D Λ_T g_*
  predictions for LHC experiments

- **experiment**:
  data to fix or constrain theory parameters

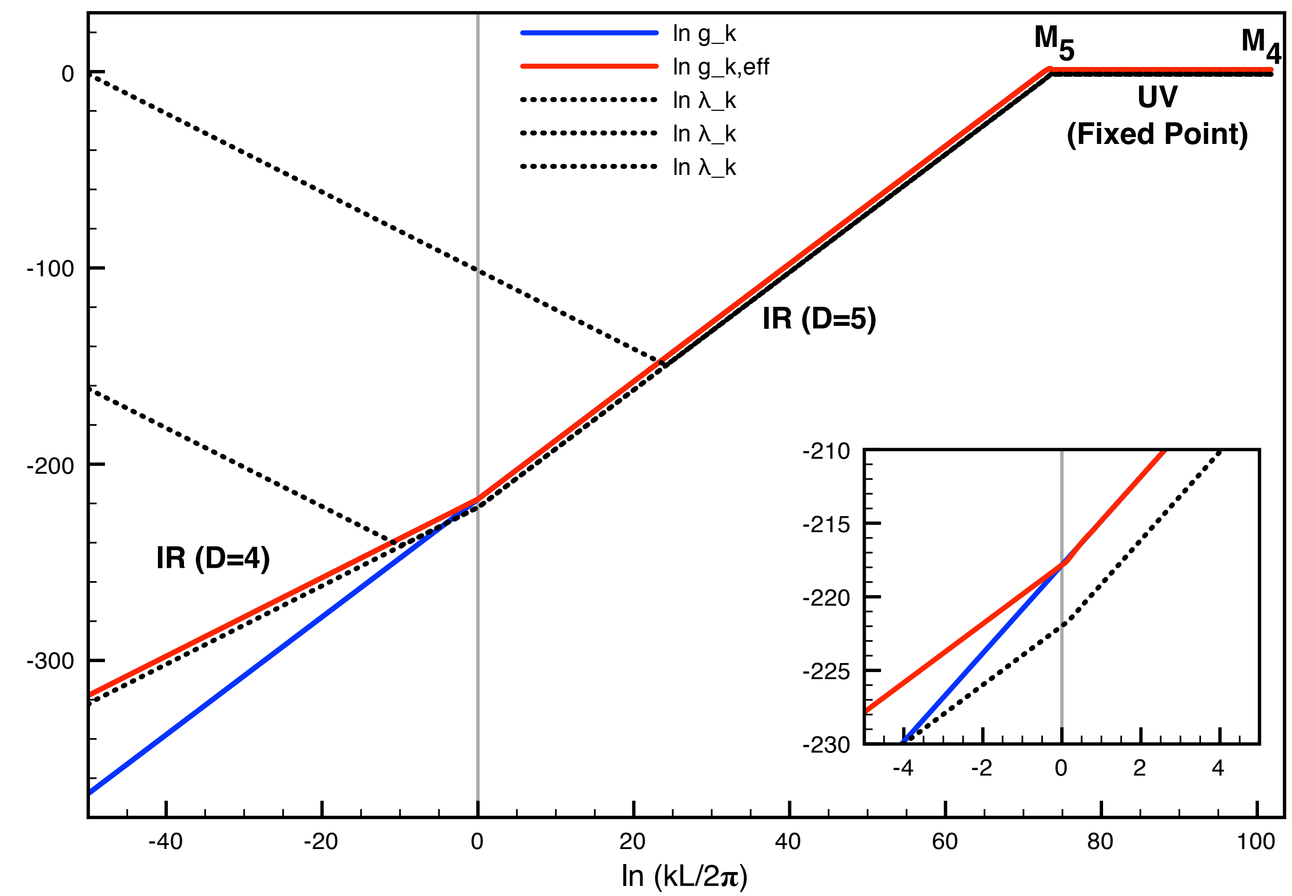
running couplings in ADD

a) schematically



Fischer, DL '05

b) numerically



Alkofer, DL, Schaefer, '15

real gravitons+jet

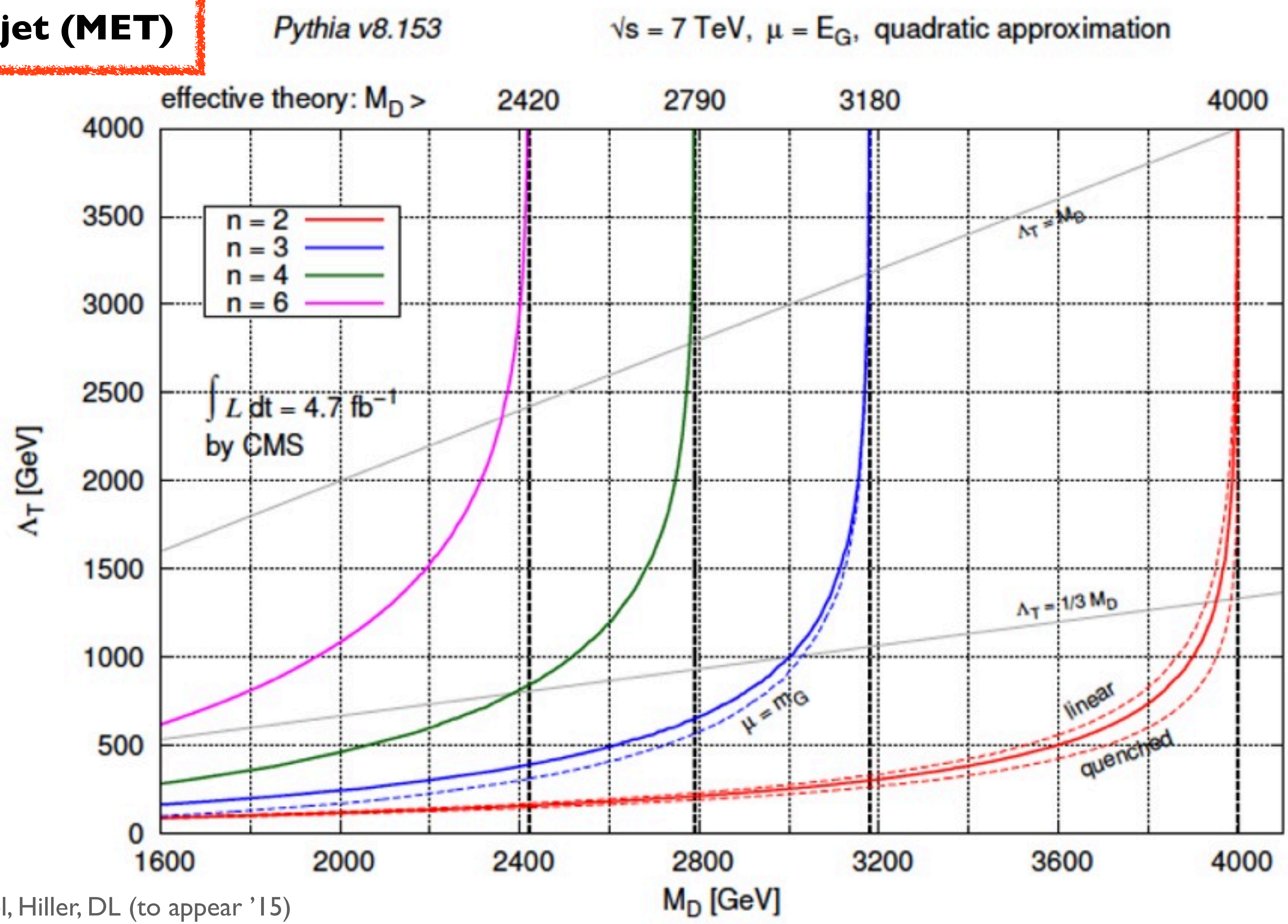
bounds from effective theory

		n	2	3	4	5	6	
LEP	$0.65\,\mathrm{fb}^{-1}$	$e^+e^- \to \gamma + \not{E}$	1.60	1.20	0.94	0.77	0.66	[27]
CDF	$1.1\,\mathrm{fb}^{-1}$	$p\bar{p} \to \mathrm{jet} + \not{E}$	1.31	1.08	0.98	0.91	0.88	[28]
CMS	$36\,\mathrm{pb}^{-1}$	$pp \to \mathrm{jet} + \not{E}$	2.29	1.92	1.74	1.65	1.59	[29]
ATLAS	$33\,\mathrm{pb}^{-1}$	$pp \to \mathrm{jet} + \not{E}$	2.30	2.00	1.80	n/a	n/a	[30]
ATLAS	$1.0\,\mathrm{fb}^{-1}$	$pp \to \mathrm{jet} + \not{E}$	3.16	2.56	2.27	2.10	1.99	[31]
CMS	$1.1\,\mathrm{fb}^{-1}$	$pp \to \mathrm{jet} + \not{E}$	3.67	2.96	2.66	2.41	2.25	[32]
CMS	$4.7\,\mathrm{fb}^{-1}$	$pp \to \mathrm{jet} + \not{E}$	4.00	3.18	2.78	2.52	2.37	[33]

Table 4.1.: The 95% CL lower limits on M_D in effective theory for $n = 2, \ldots, 6$ extra dimensions and different datasets collected by LEP, CDF, ATLAS and CMS. Values are given in TeV.

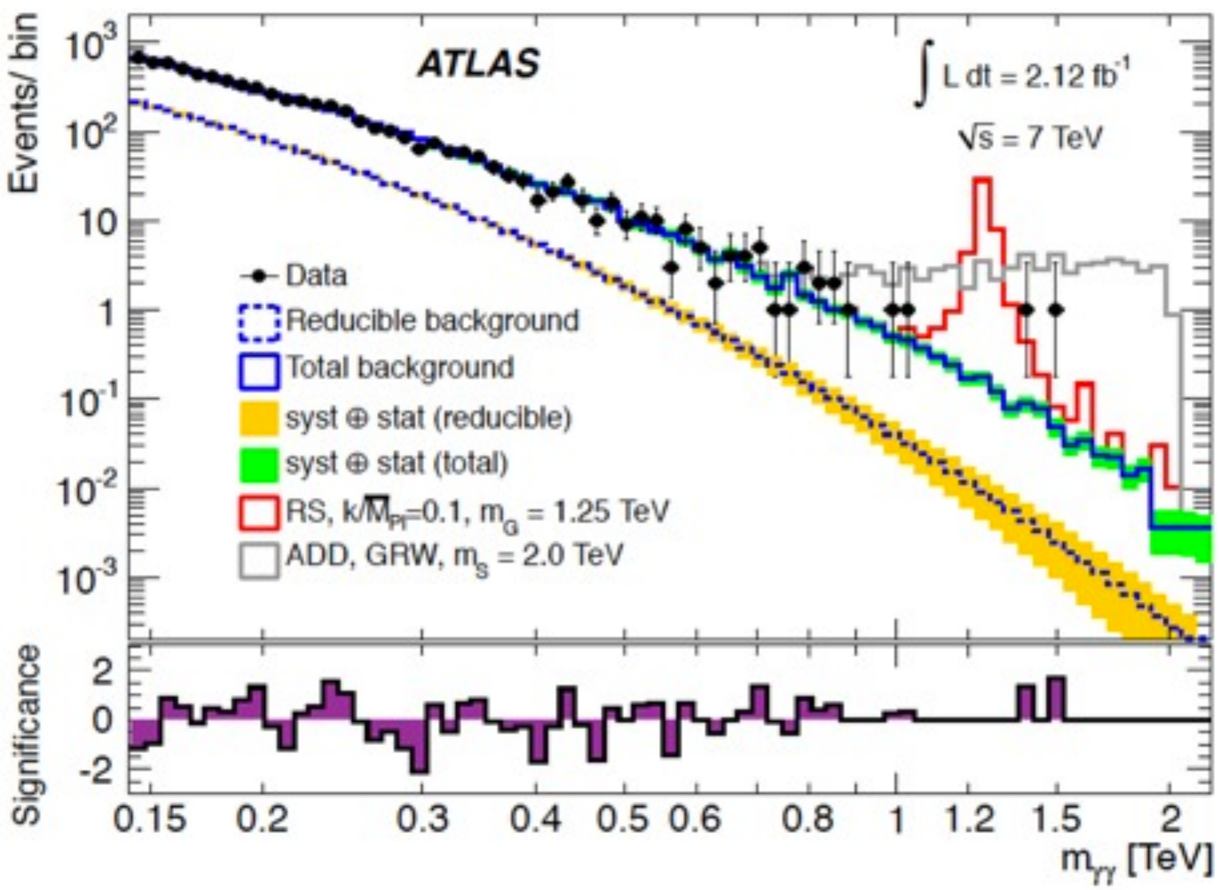
reinterpreting LHC data

graviton+jet (MET)

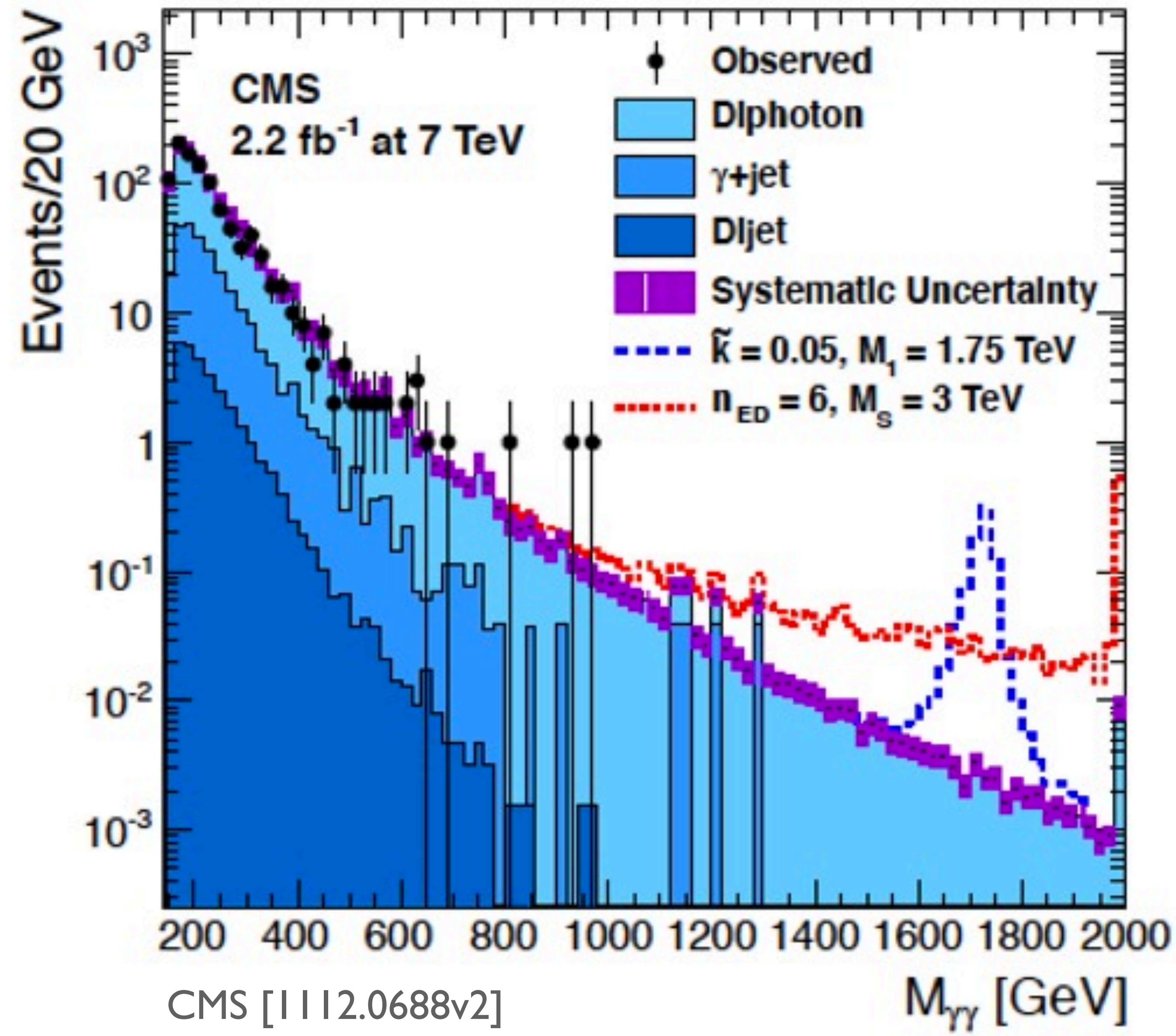


Dabruck, Demmel, Hiller, DL (to appear '15)

2) virtual gravitons + diphotons



ATLAS [1112.2194v2]



CMS [1112.0688v2]

No signifcant excess → 95% confidence level lower limits

k	$\Lambda_{\text{eff. Th.}}$
1	3.05 TeV
1.7	3.29 TeV

ATLAS (Oct 2012)

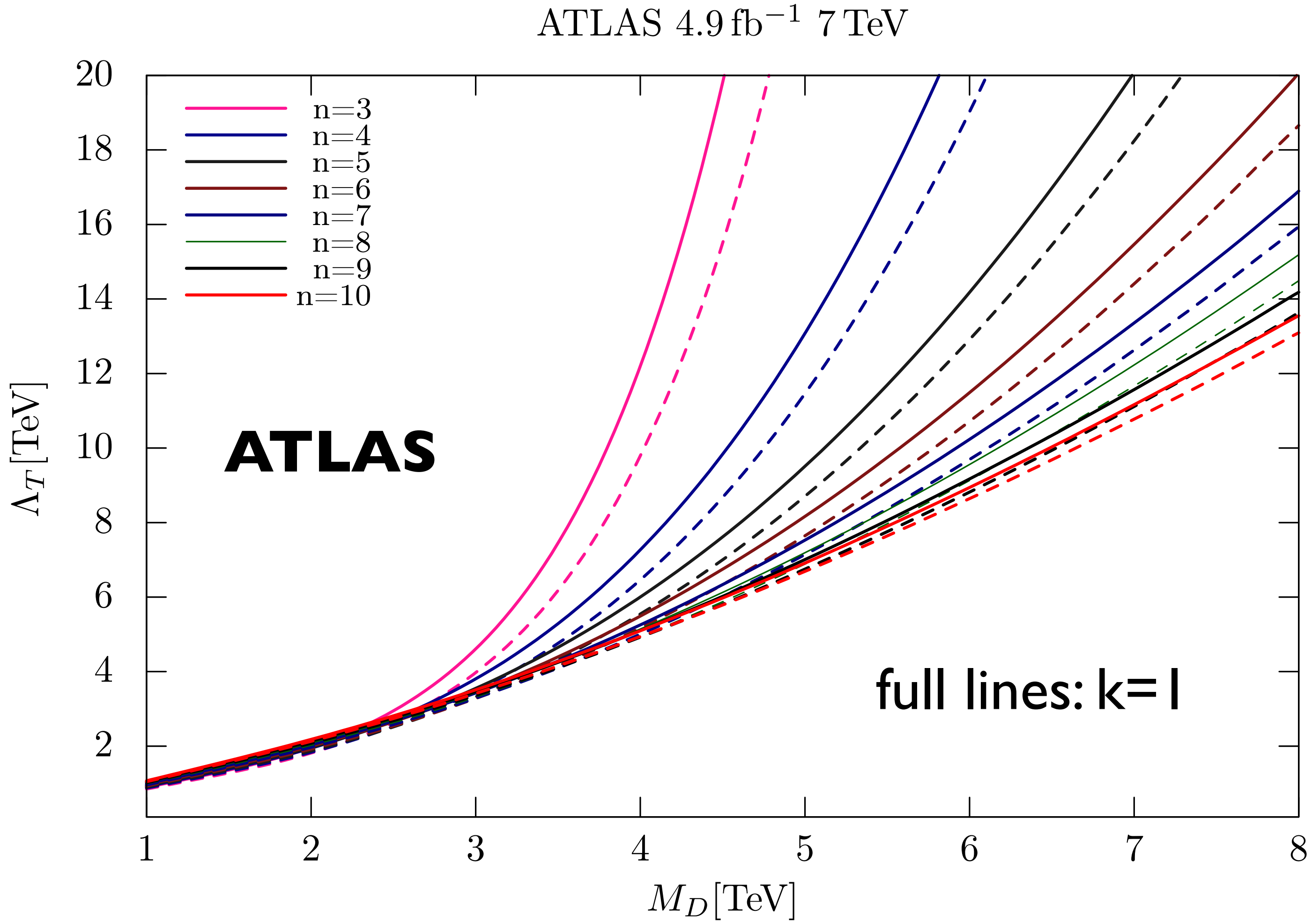
k	$\Lambda_{\text{eff. Th.}}$
1	2.94 TeV
1.6	3.18 TeV

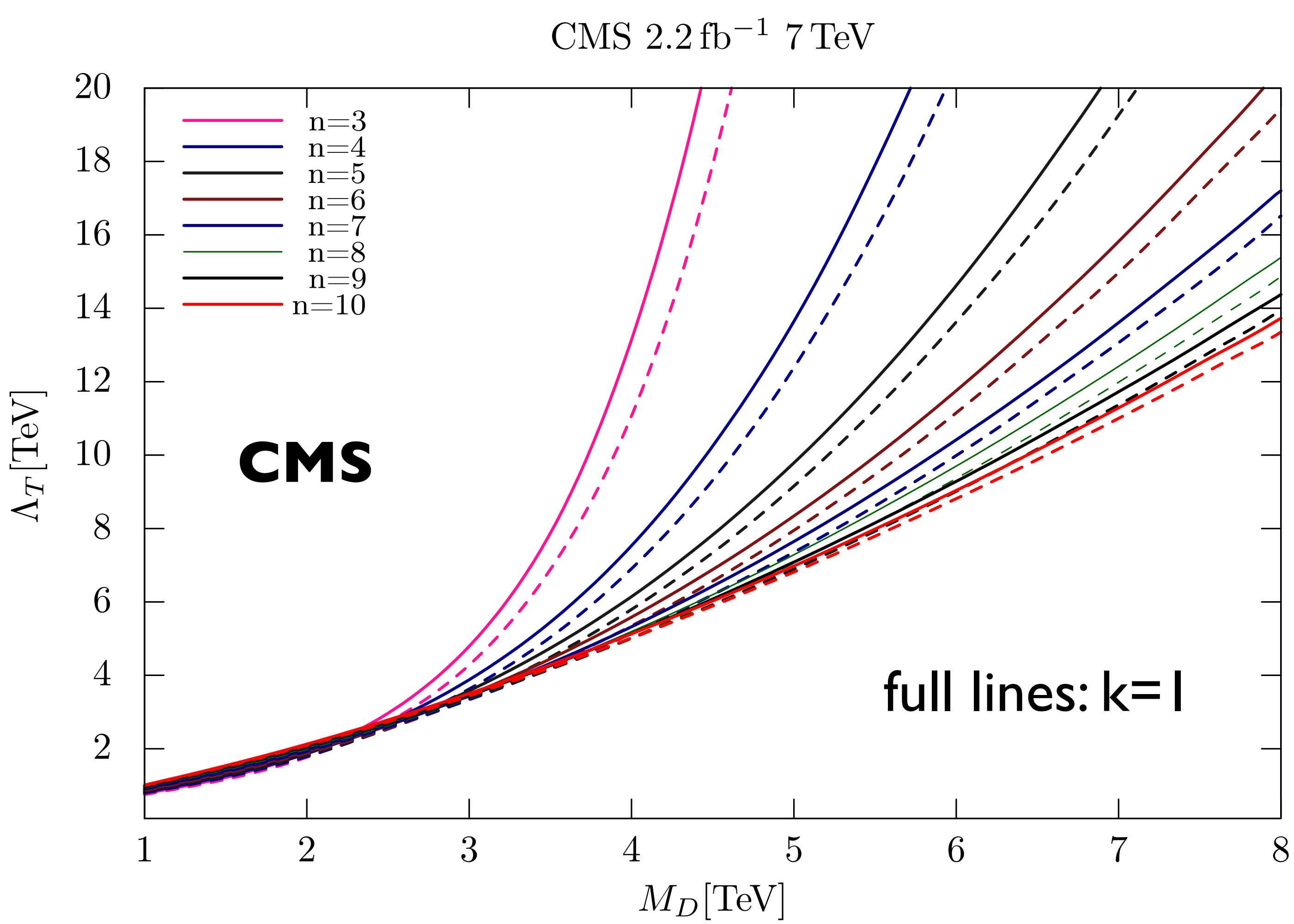
CMS (Dec 2011)

reinterpreting LHC data

virtual gravitons + diphotons

implementation in Pythia8
weak PDF dependence
weak scheme dependence





(Hiller, DL, Zenglein, '15)

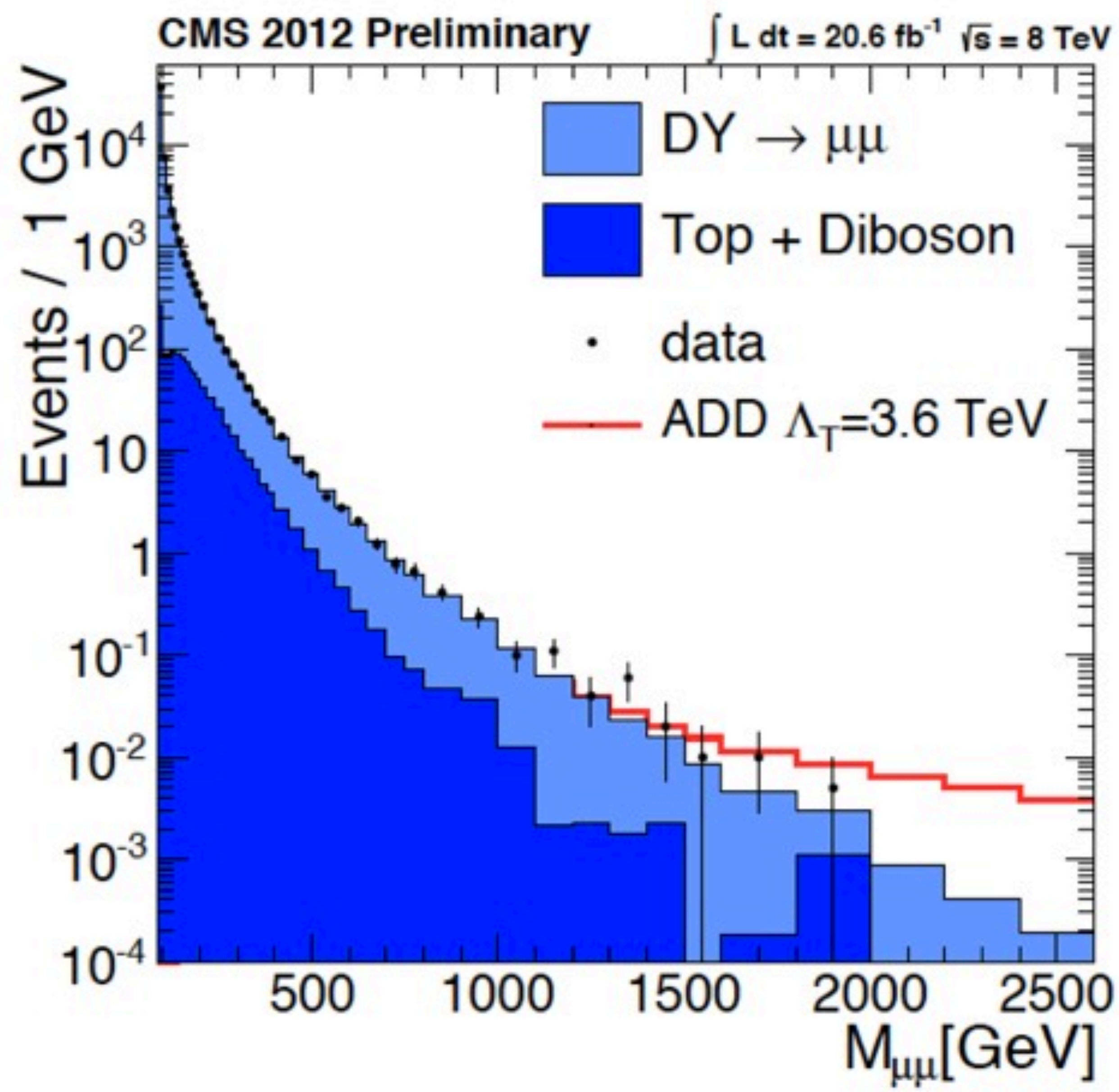
3) virtual gravitons + dileptons

$$\mathcal{S}_{\text{eff}} = -\frac{4\pi}{\Lambda_{\text{eff}}^4}$$

combined 95% CL

$$\Lambda_{\text{eff}} > 4.15\ \text{TeV}$$

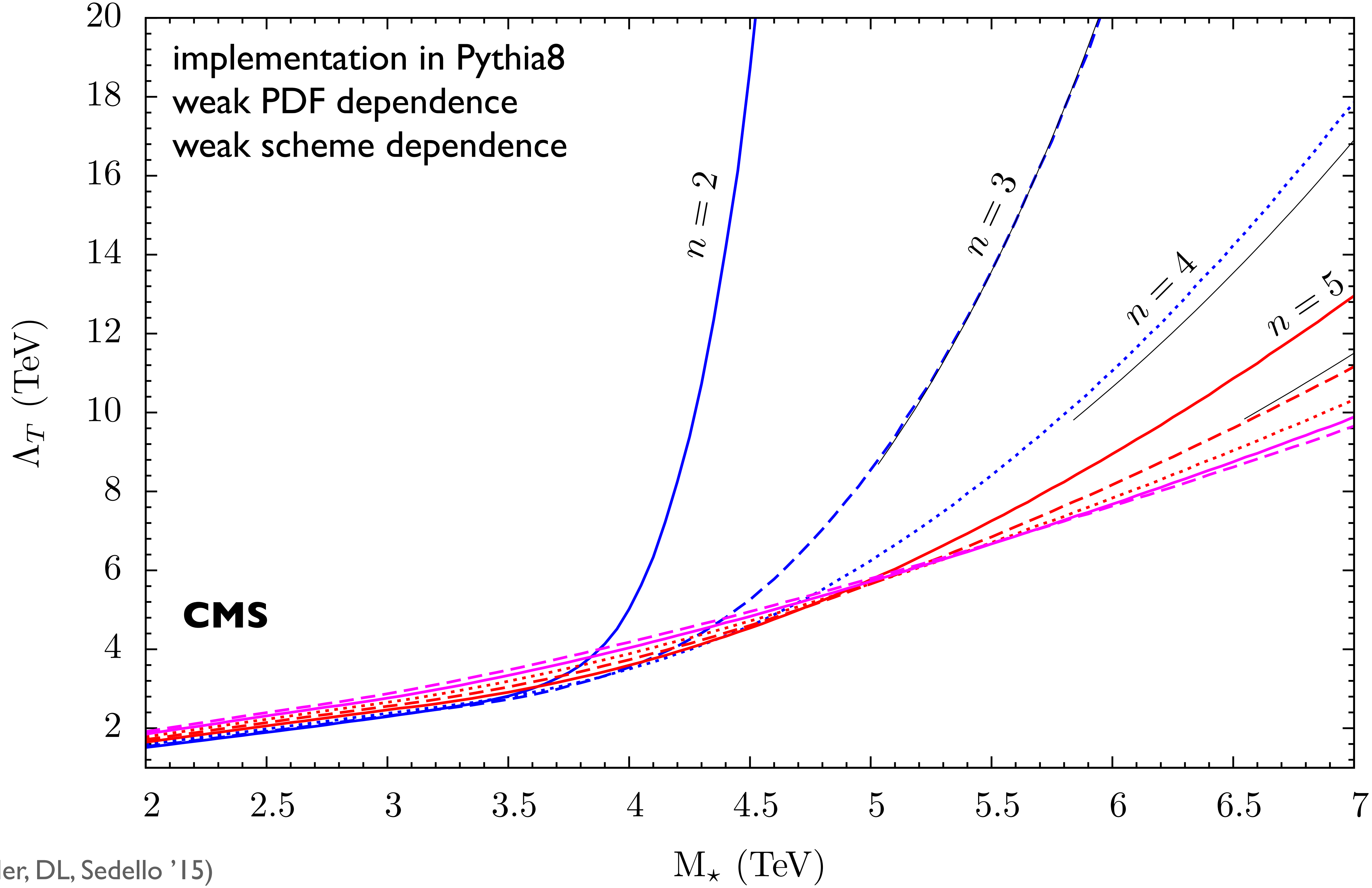
based on $20.6\ \text{fb}^{-1}$



CMS [EXO-12-027]

reinterpreting LHC data

virtual gravitons + dileptons



(Hiller, DL, Sedello '15)

conclusions

QFTs beyond asymptotic freedom

4D matter-gauge theories

exact proof of asymptotic safety
all types of fields required
sensible **UV finite theory**
no additional (super-)symmetry

4D quantum gravity

systematic **non-perturbative** search strategies
strong hints for interacting UV fixed point
intriguing **near Gaussianity**