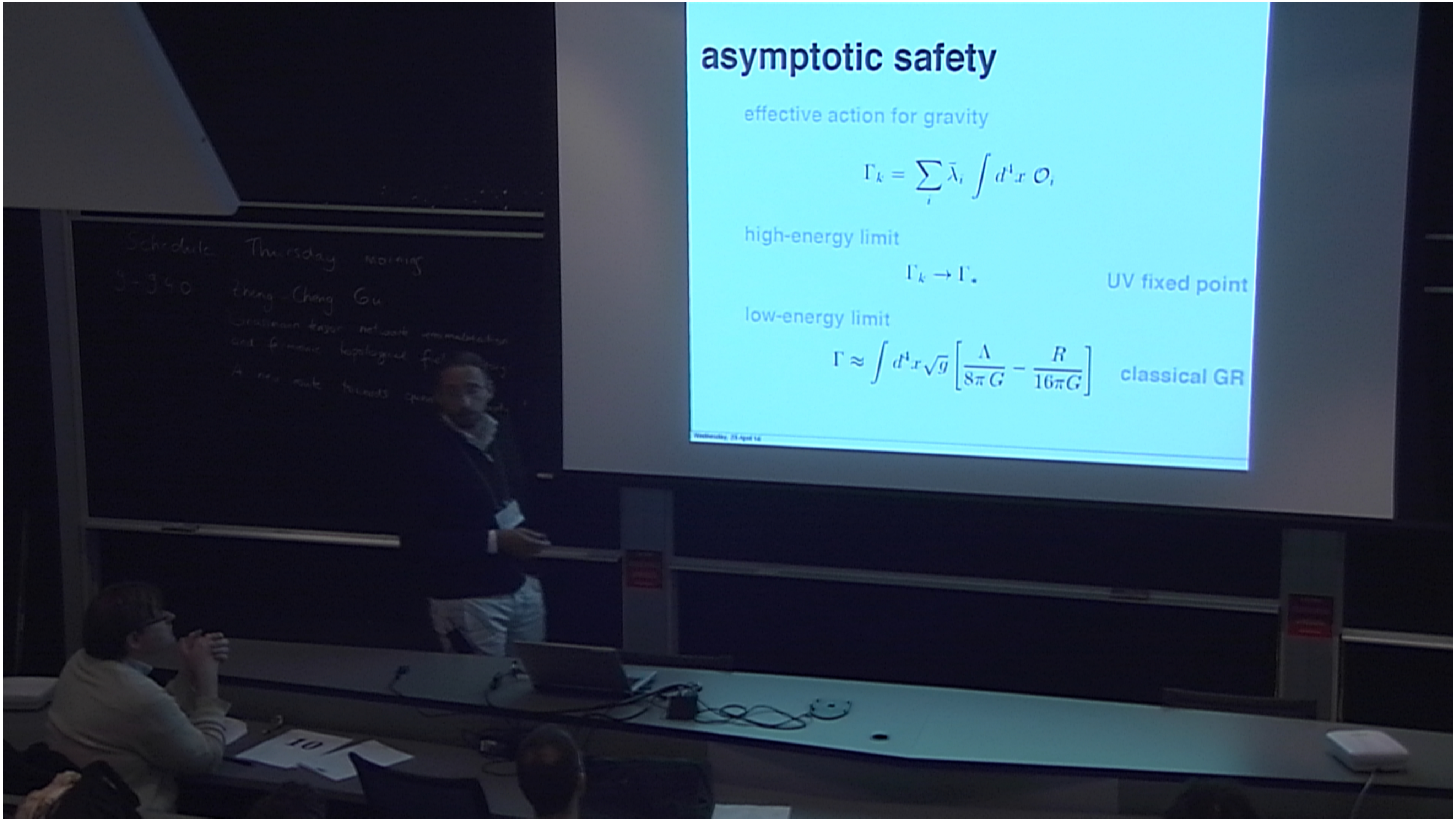
Title: Lessons from asymptotic safety

Date: Apr 23, 2014 09:40 AM

URL: http://pirsa.org/14040092

Abstract: Two aspects of asymptotic safety are highlighted. First, I discuss how asymptotic safety can be tested with the help of a bootstrap strategy. This is then applied to high-order polynomial actions of the Ricci scalar and beyond. Second, I discuss how phenomenological signatures of asymptotic safety can be searched for at particle colliders such as the LHC, provided that the quantum gravity scale is in the TeV energy regime.


asymptotic safety
effective action for gravity
$\Gamma_k = \sum_i \bar{\lambda}_i \int d^4x\, \mathcal{O}_i$
high-energy limit
$\Gamma_k \to \Gamma_*$
UV fixed point
low-energy limit
$\Gamma \approx \int d^4x \sqrt{g} \left[\frac{\Lambda}{8\pi G} - \frac{R}{16\pi G} \right]$
classical GR

asymptotic safety

running couplings

$$k\partial_k \lambda_i = \sum_j \mathbb{B}_{ij} \, (\lambda_j - \lambda_j^*) + \text{subleading}$$

vicinity of fixed point

$$\lambda_i(k) = \lambda_i^* + \sum_n c_n \, V_i^n \, k^{\vartheta_n} + \text{subleading}$$

scaling exponents $\begin{cases} \vartheta_n > 0 & \text{irrelevant} \\ \vartheta_n < 0 & \text{relevant} \end{cases}$

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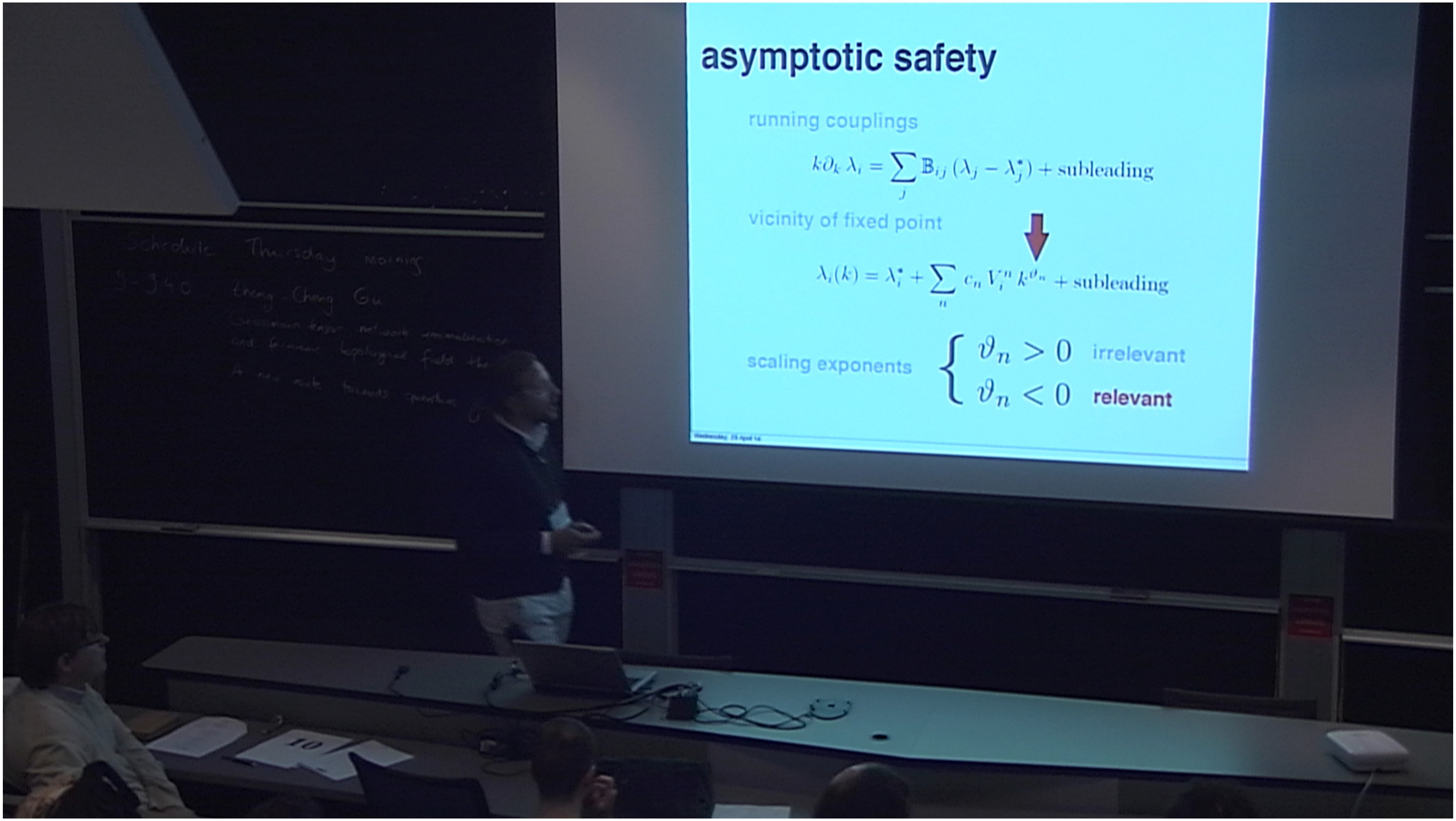
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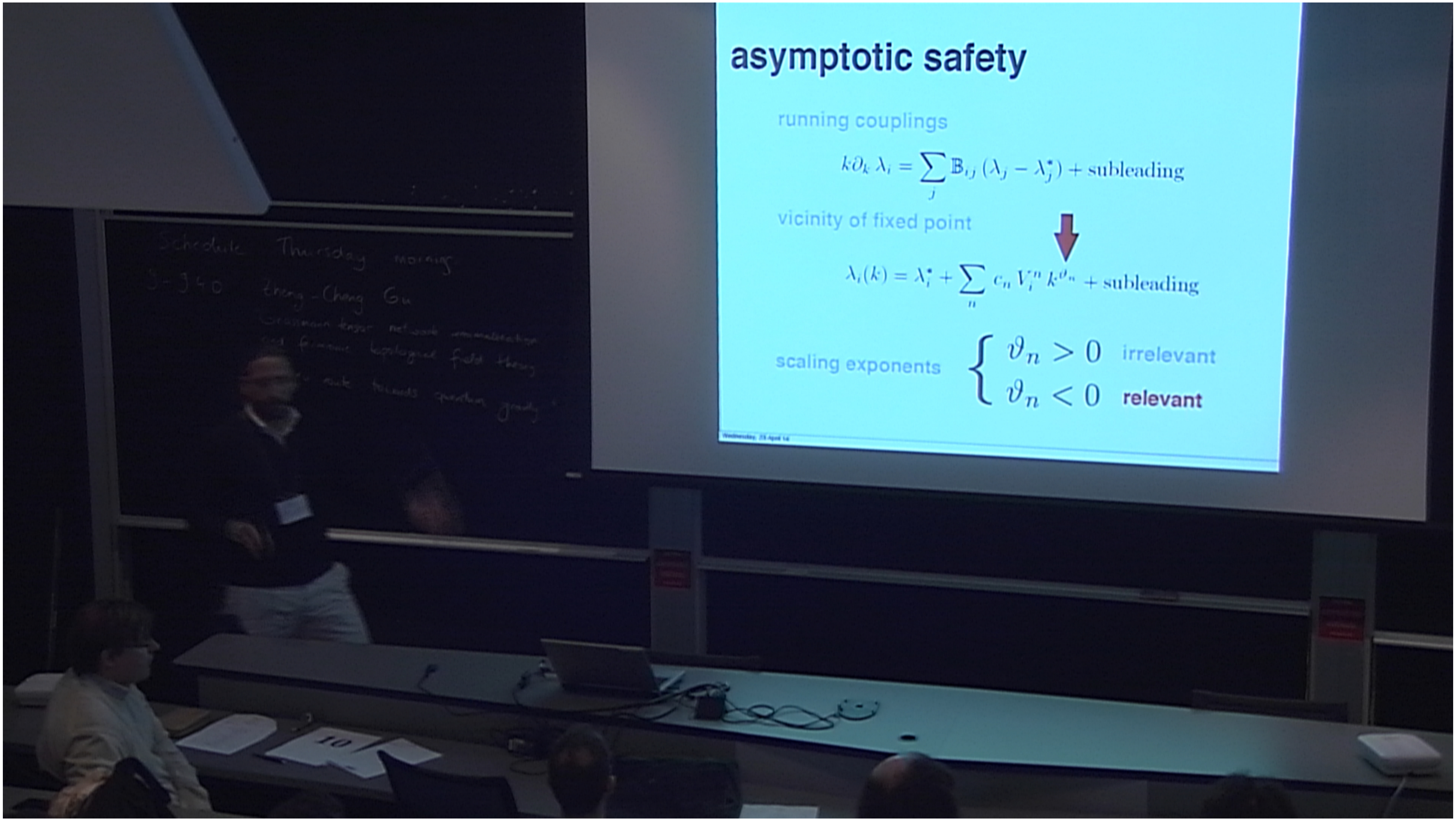
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knowns ...

asymptotic freedom

$$g_* = 0$$

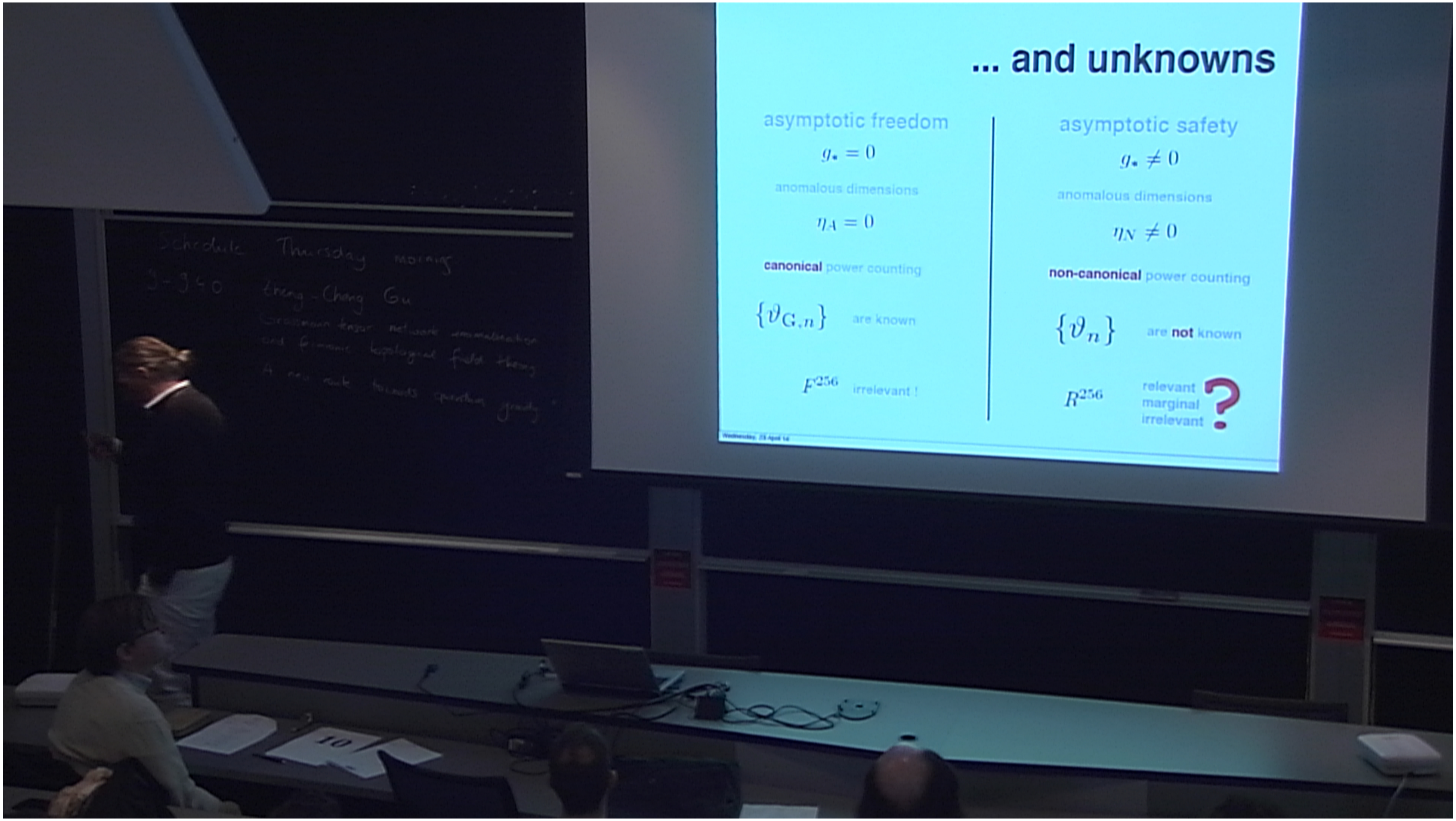
anomalous dimensions

$$\eta_A = 0$$

canonical power counting

$\{\vartheta_{\mathrm{G},n}\}$ are known

F^{256} irrelevant !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$\eta_N \neq 0$
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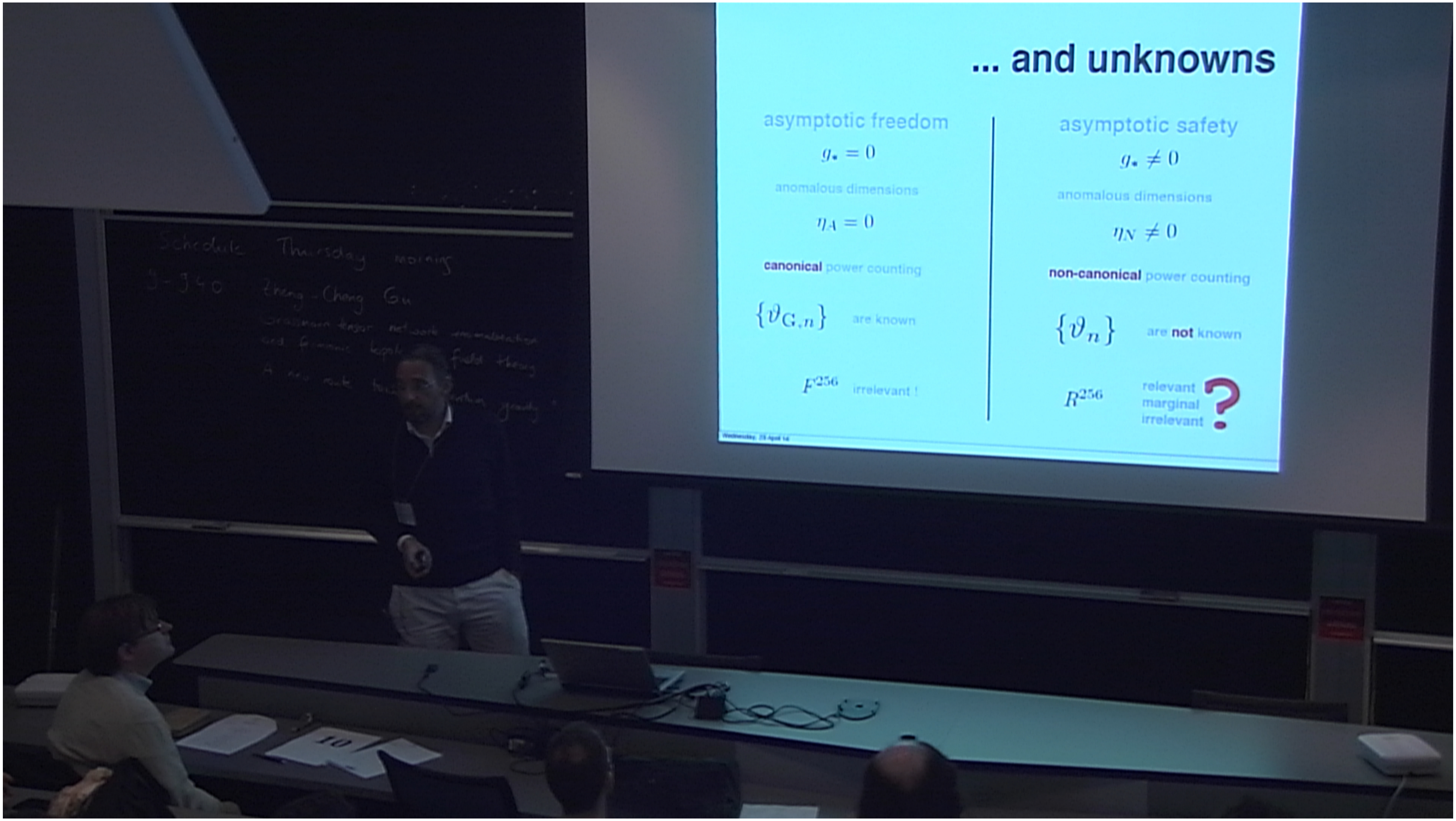
$\{\vartheta_n\}$ are **not** known
R^{256} relevant marginal irrelevant ?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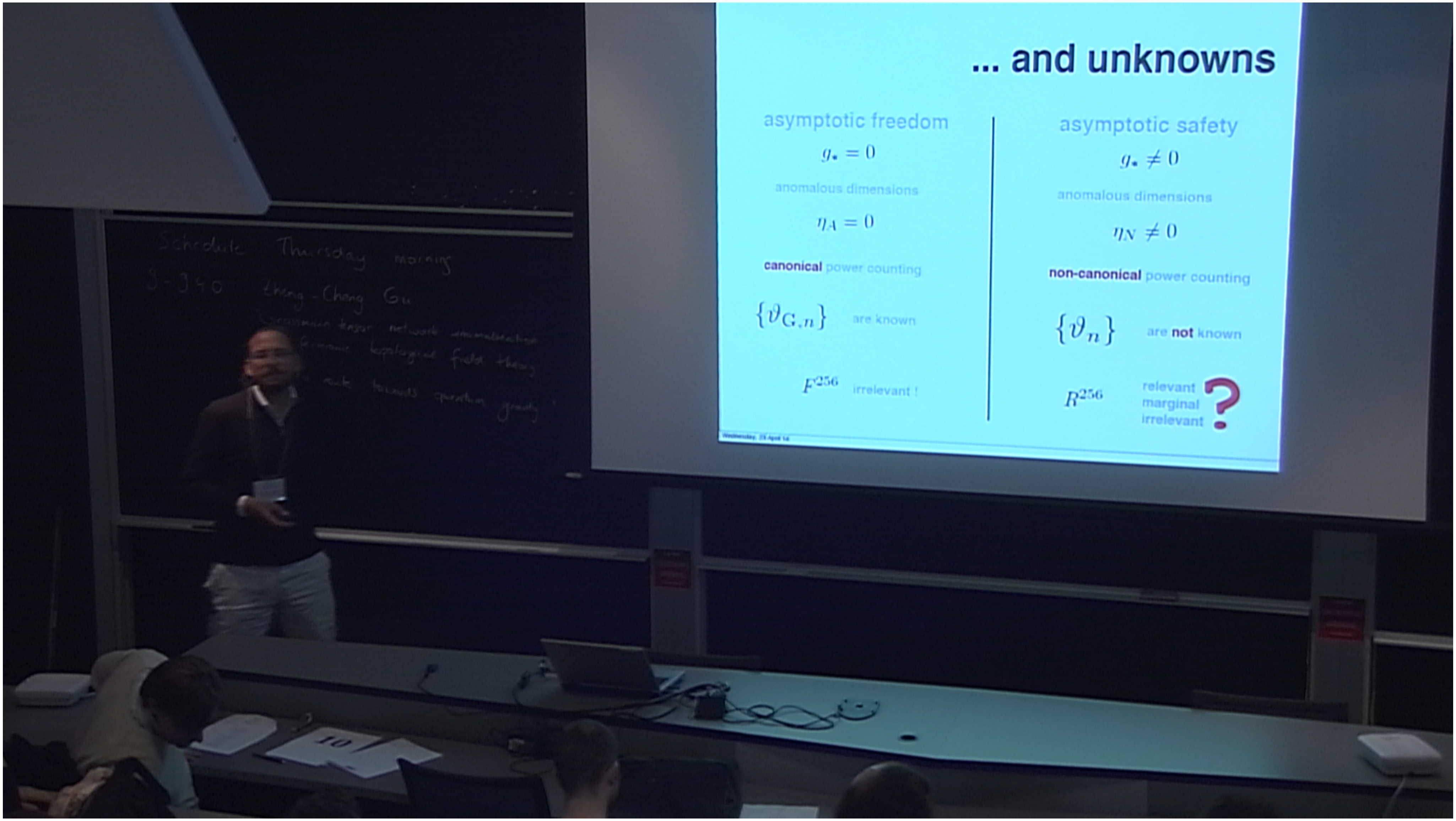
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Schedule Thursday morning

... and unknowns

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$\{\vartheta_{\mathrm{G},n}\}$ are known	$\{\vartheta_n\}$ are **not** known
F^{256} irrelevant !	R^{256} relevant marginal irrelevant **?**

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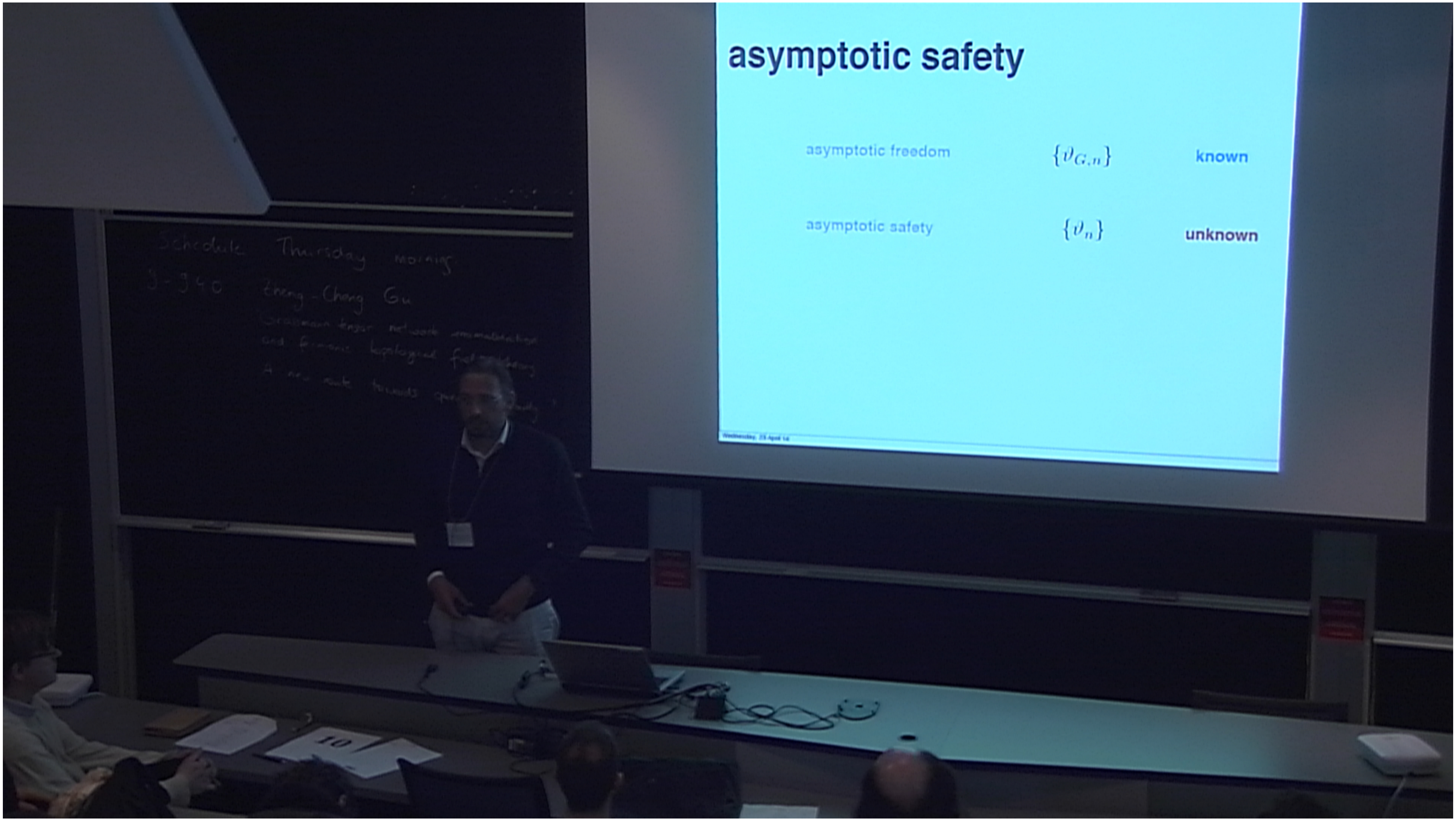
asymptotic safety

asymptotic freedom	$\{\vartheta_{G,n}\}$	known
asymptotic safety	$\{\vartheta_n\}$	unknown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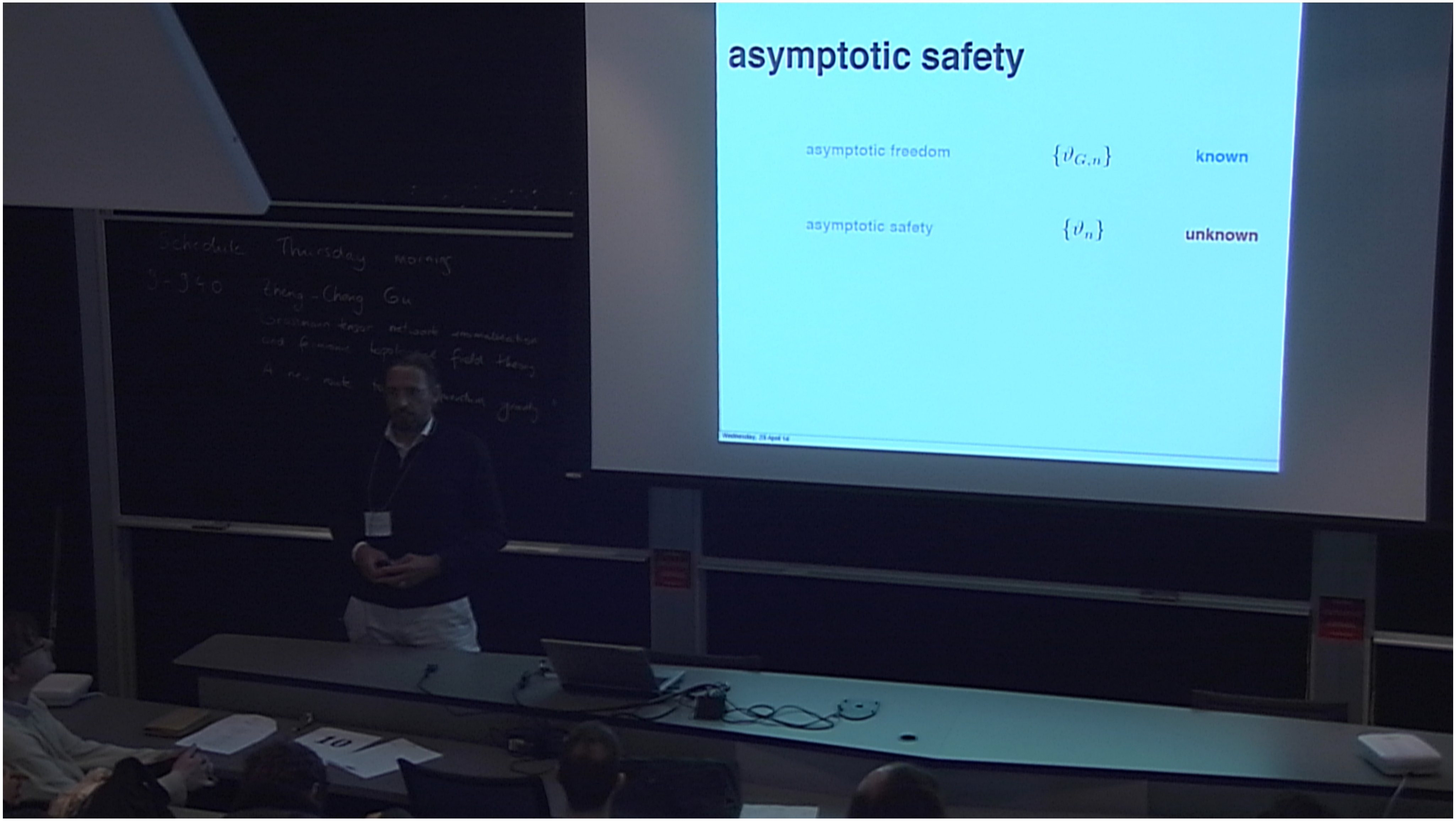
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asymptotic safety

asymptotic freedom	$\{\vartheta_{G,n}\}$	known
asymptotic safety	$\{\vartheta_n\}$	unknown
bootstrap hypothesis	$\{\vartheta_n\}$	mostly canonical

K Falls, DL, K Nikolakopoulos, C Rahmede **1301.4191.pdf**

bootstrap

K Falls, DL, K Nikolakopoulos, C Rahmede ('13)

hypothesis ordering follows canonical 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)

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Ricci scalars

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K Falls, DL, K Nikolakopoulos, C Rahmede **1301.4191.pdf**

f(R)

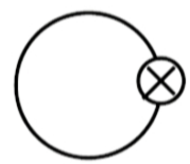
$$\Gamma_k \propto f(R)$$

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

invariants up to $D = 2(N-1)$

functional renormalisation:

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



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M Reuter hep-th/9605030

DL **hep-th/0103195**
hep-th/0312114

A Codello, R Percacci, C Rahmede 0705.1769, 0805.2909
P Machado, F Saueressig 0712.0445

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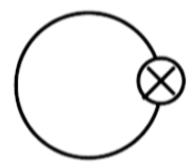

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identifying fixed points

$$f(R) = \sum_n \lambda_n R^n$$

polynomial expansion

generating function

$$\partial_t f + 4f - 2R\, f' = I[f]$$

$$I[f] = I_0[f] + I_1[f] \cdot \partial_t f' + I_2[f] \cdot \partial_t f''$$

recursive solution of $\beta_n \equiv \partial_t \lambda_n$ $\qquad \beta_{n-2} = 0$

family of FP candidates $\lambda_n = \lambda_n(\lambda_0, \lambda_1)$

\`free' parameters (λ_0, λ_1)

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Wilson-Fisher LPA

$$u(\rho) = \sum_{n=0} \frac{\lambda_n}{n!}\rho^n \qquad \rho = \frac{1}{2}\phi^a\phi_a$$

polynomial expansion

generating function

$$\partial_t u' = -2u' + (d-2)\rho u'' - A\frac{u''}{(1+u')^2} - B\frac{3u'' + 2\rho u'''}{(1+u'+2\rho u'')^2}$$

DL ('02)

recursive solution $(\lambda_1 \equiv m^2)$

$$\boxed{\lambda_n = \lambda_n(m^2)}$$

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Wilson-Fisher LPA

DL, hep-th/0203006

universal eigenvalues

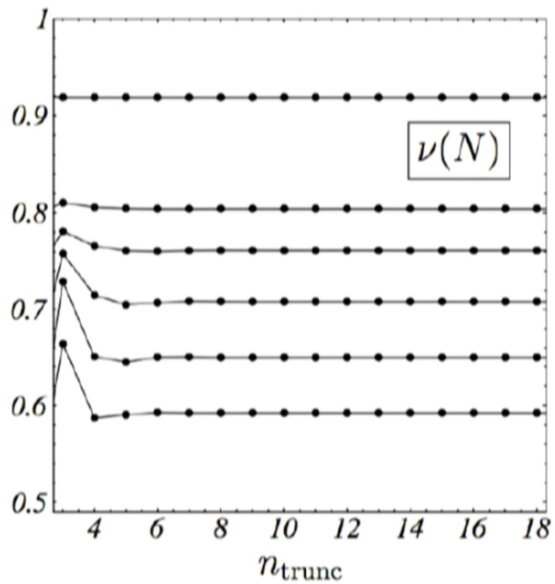

Figure 4: The exponent $\nu(N)$ as a function of N and of the order of the truncation. From top to bottom: $N = 10, 4, 3, 2, 1, 0$.

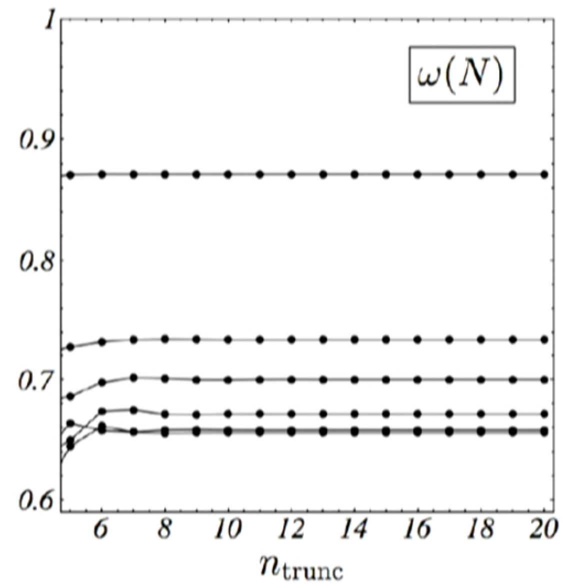

Figure 5: The eigenvalue $\omega(N)$ as a function of N and of the order of the truncation. From top to bottom: $N = 10, 4, 3, 2, 0, 1$.

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f(R)

recursive solution

$$\boxed{\lambda_n(\lambda_0, \lambda_1) = \frac{P_n(\lambda_0, \lambda_1)}{Q_n(\lambda_0, \lambda_1)}}$$

boundary condition

$$\lambda_N = 0 \quad \& \quad \lambda_{N+1} = 0$$

polynomials grow large, eg.

$P_{35} \approx 45.000$ terms

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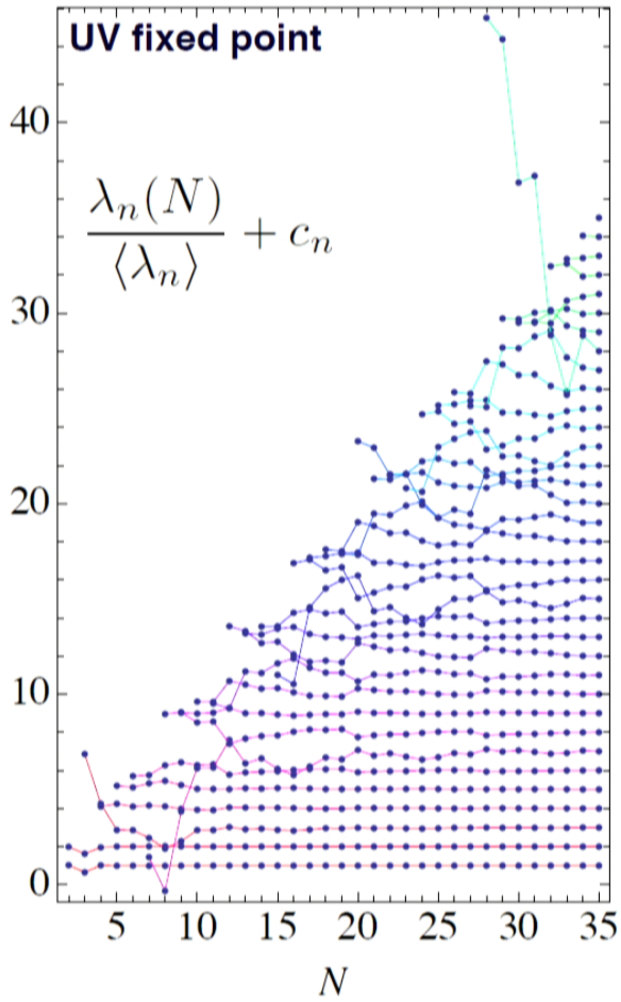
f(R)



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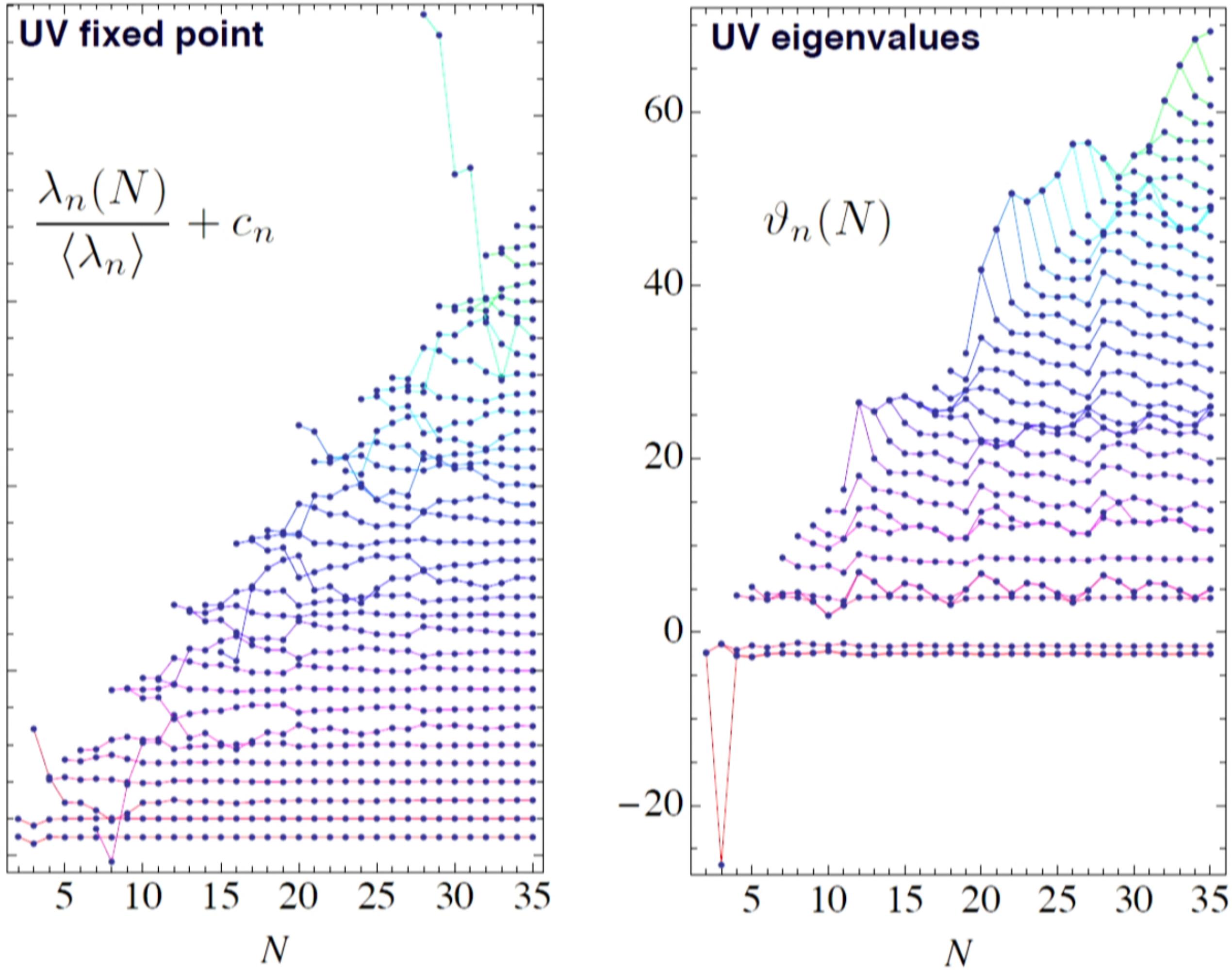

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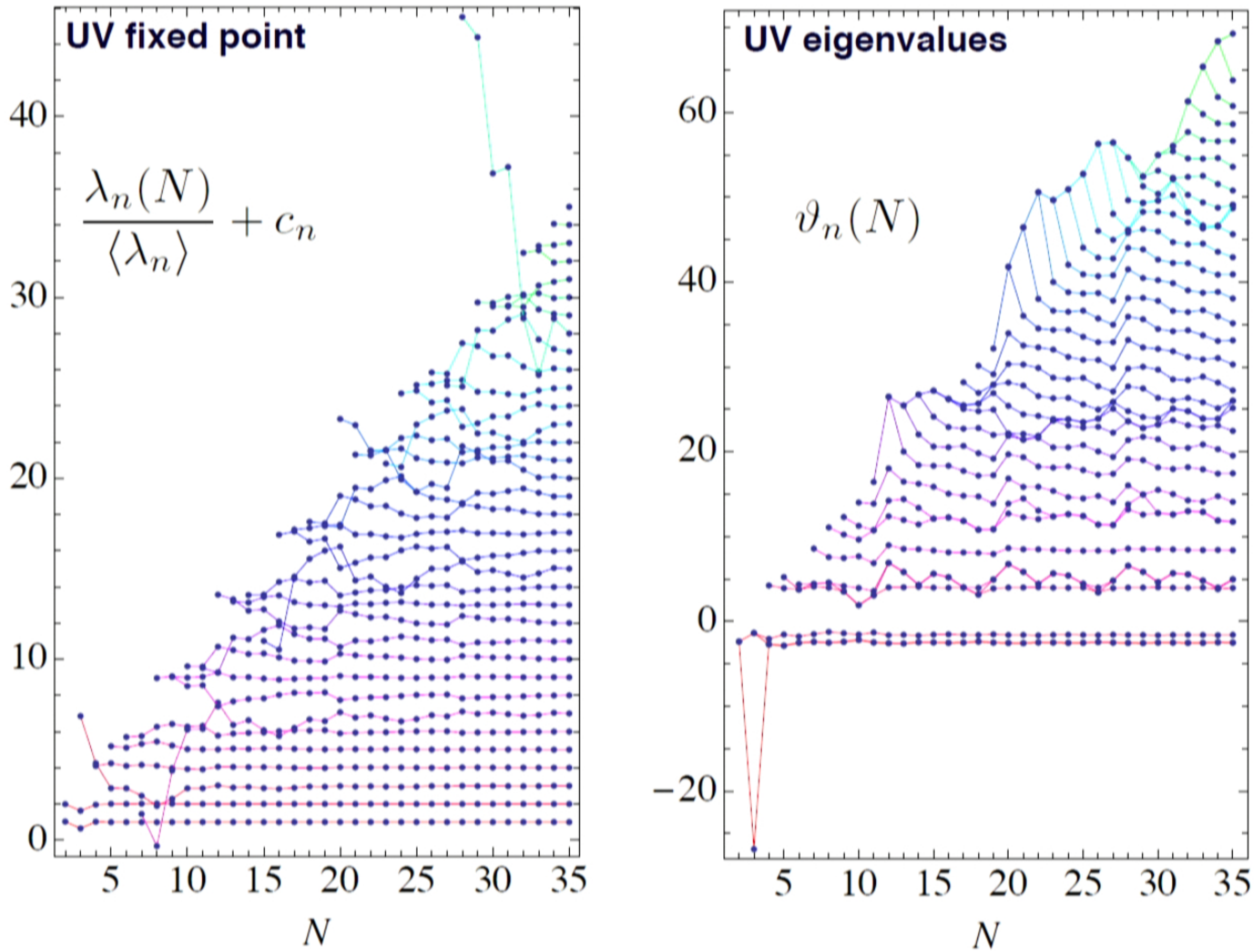

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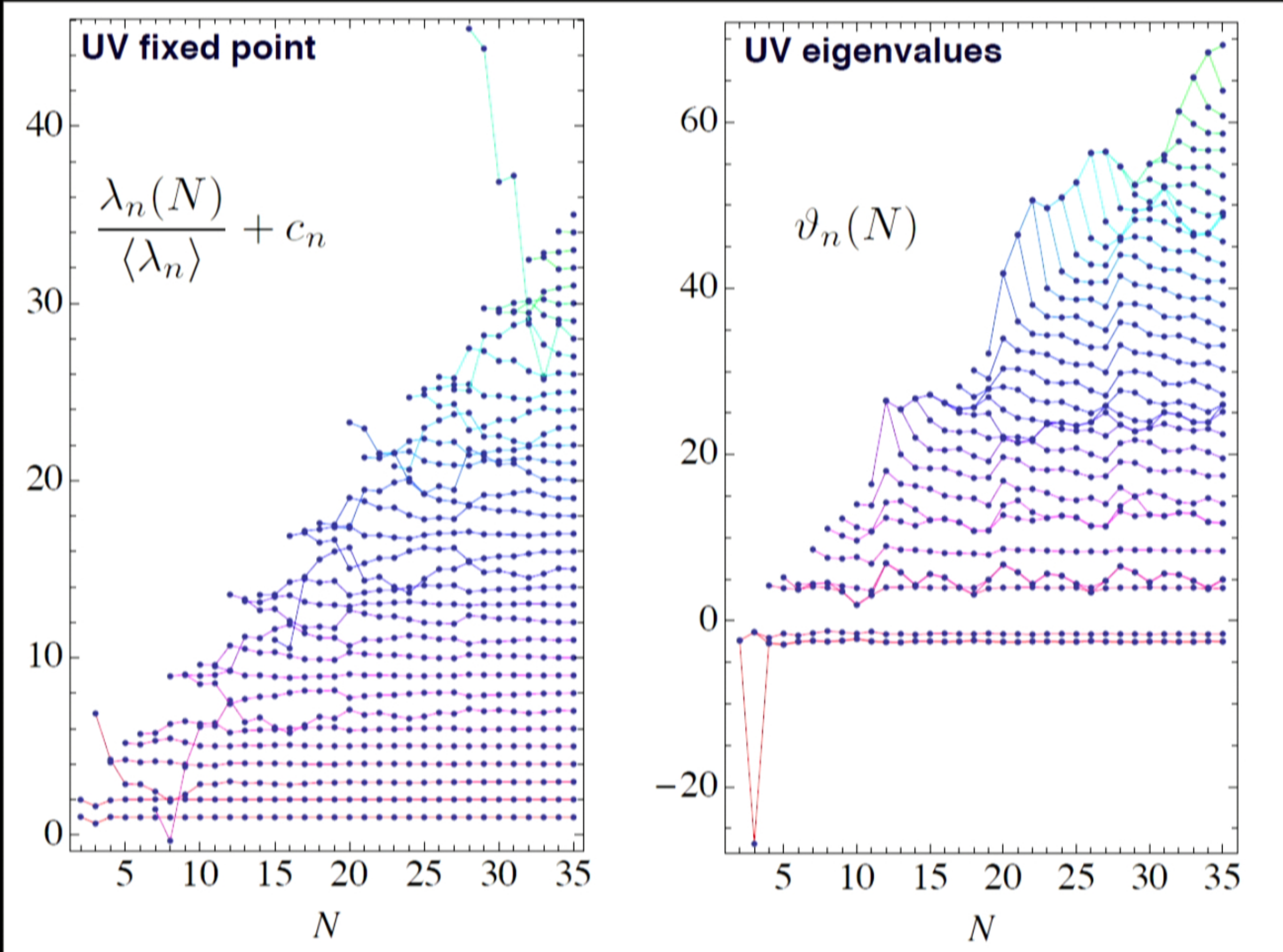

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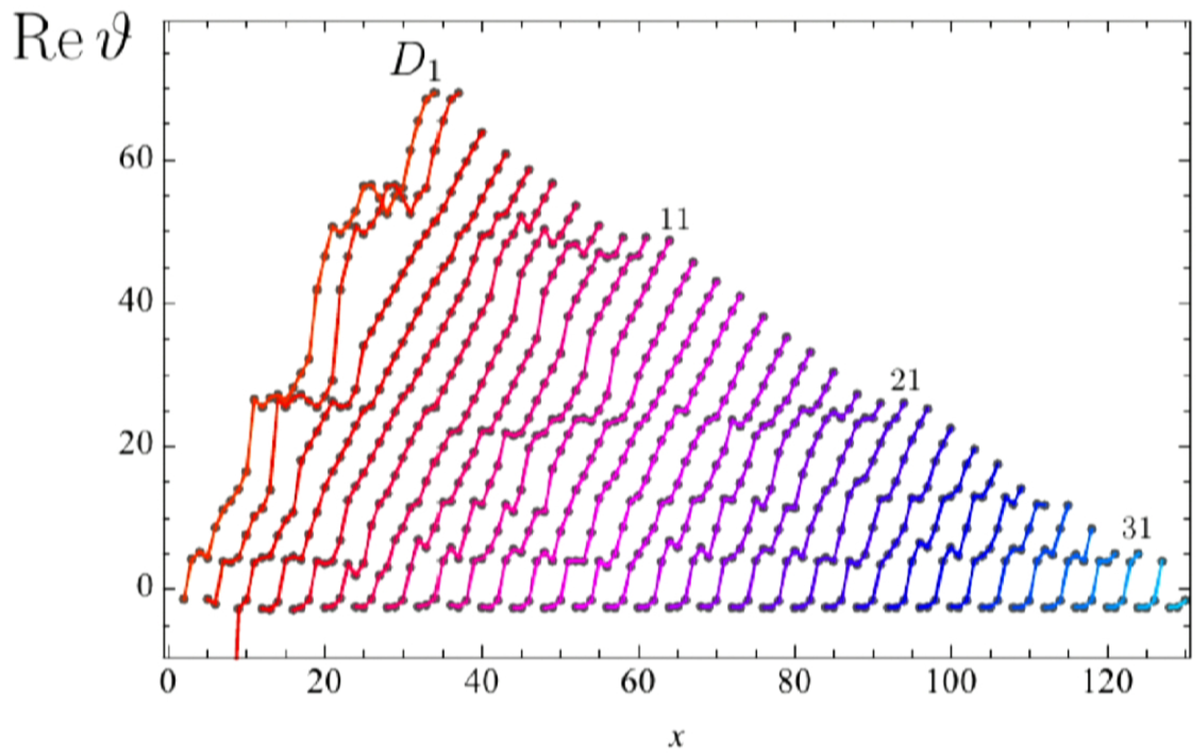
bootstrap test



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f(Ricci)

K Falls, DL, K Nikolakopoulos, C Rahmede (to appear, 2014)

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

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\partial_t \Gamma[\bar{g}, \bar{g}] =& \frac{1}{2}\mathrm{Tr}_{(2T)}\left[\frac{\partial_t \mathcal{R}_k^{h^T h^T}}{\Gamma^{(2)}_{h^T h^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}^T C^T}}{\Gamma^{(2)}_{\bar{C}^T C^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}^T c^T}}{\Gamma^{(2)}_{\bar{c}^T c^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{s}s}}{\Gamma^{(2)}_{\bar{s}s}}\right]
\end{aligned}$$

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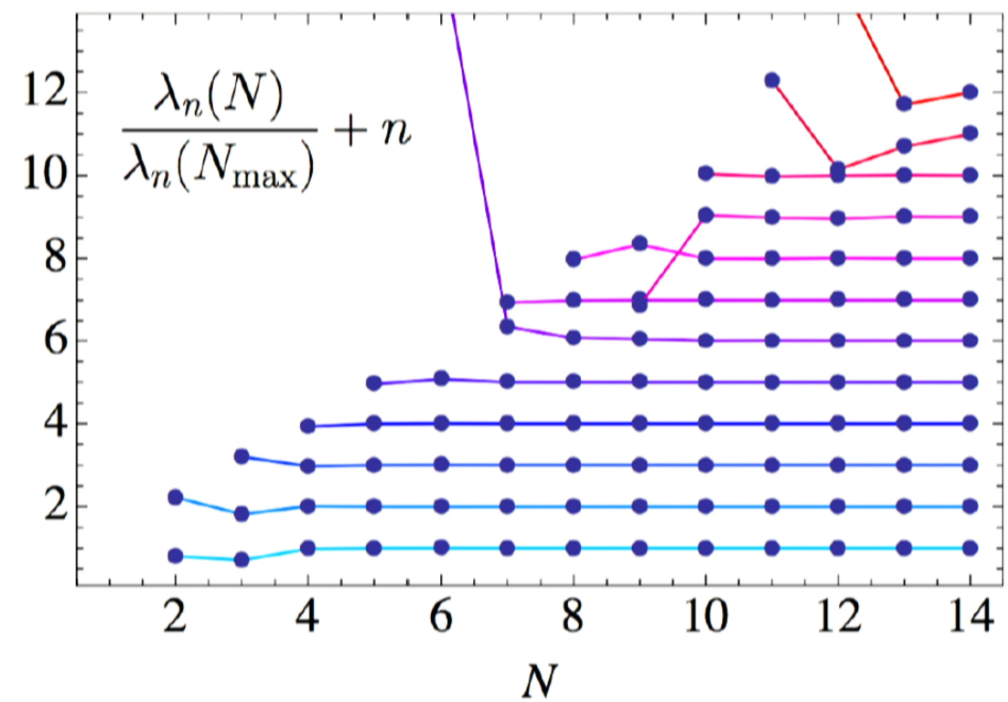
& + \frac{1}{2} \mathrm{Tr}''_{(0)} \left[\frac{\partial_t \mathcal{R}_k^{\omega\omega}}{\Gamma^{(2)}_{\omega\omega}} \right] - \mathrm{Tr}'_{(1T)} \left[\frac{\partial_t \mathcal{R}_k^{\bar{c}^T c^T}}{\Gamma^{(2)}_{\bar{c}^T c^T}} \right] + \frac{1}{2} \mathrm{Tr}'_{(1T)} \left[\frac{\partial_t \mathcal{R}_k^{\zeta^T \zeta^T}}{\Gamma^{(2)}_{\zeta^T \zeta^T}} \right] + \mathrm{Tr}'_{(0)} \left[\frac{\partial_t \mathcal{R}_k^{\bar{s}s}}{\Gamma^{(2)}_{\bar{s}s}} \right]
\end{aligned}$$

fixed points

K Falls, DL, K Nikolakopoulos, C Rahmede (to appear, 2014)



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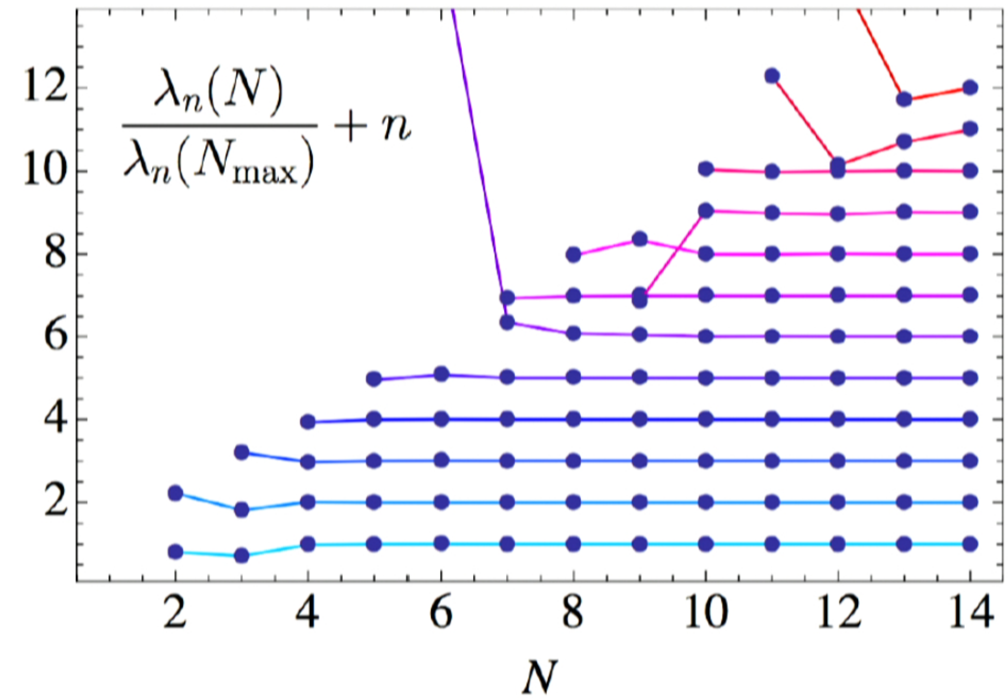

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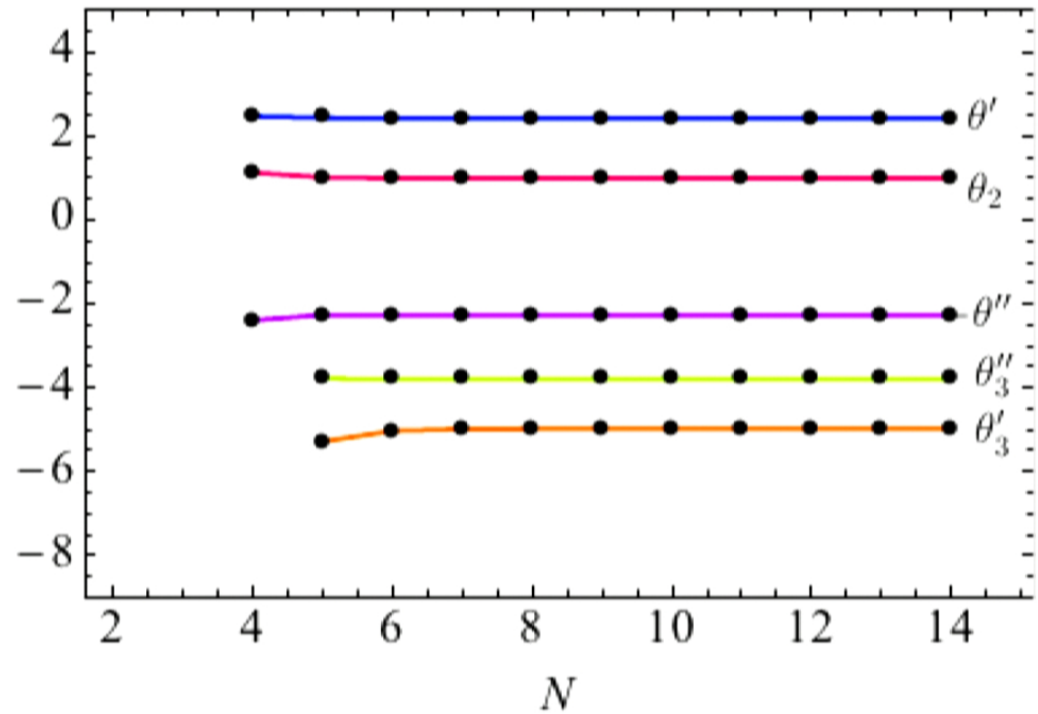
scaling exponents

K Falls, DL, K Nikolakopoulos, C Rahmede (to appear, 2014)



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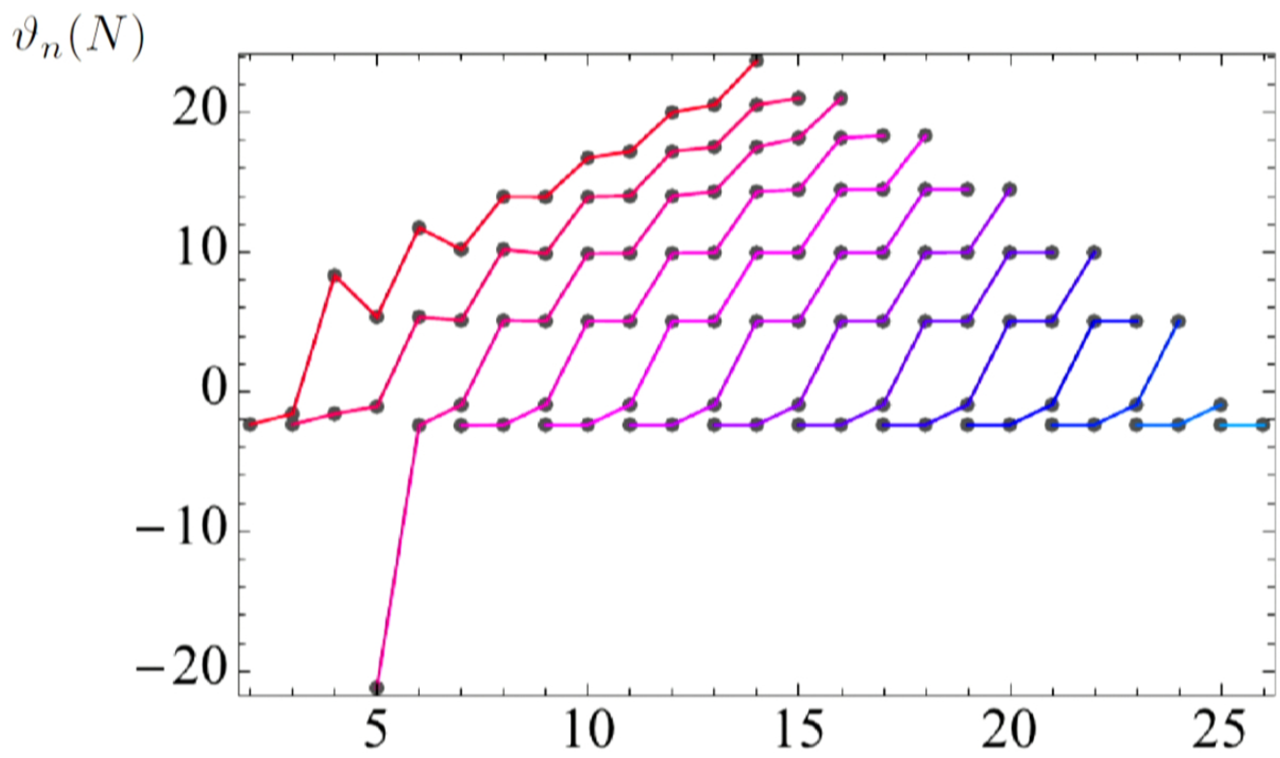
bootstrap test

K Falls, DL, K Nikolakopoulos, C Rahmede (to appear, 2014)



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lesson 1

- testable search strategy available
  - bootstrap applicable to generic asymptotically safe theories
    - consistent picture in f(R)-type theories & extensions
      - signs of near-Gaussian scaling

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quantum gravity at colliders

- **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**

- **UV fixed point in higher dimensions** Fischer, Litim (2006)

  tests of asymptotic safety

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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 $n \geq 2$.

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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)

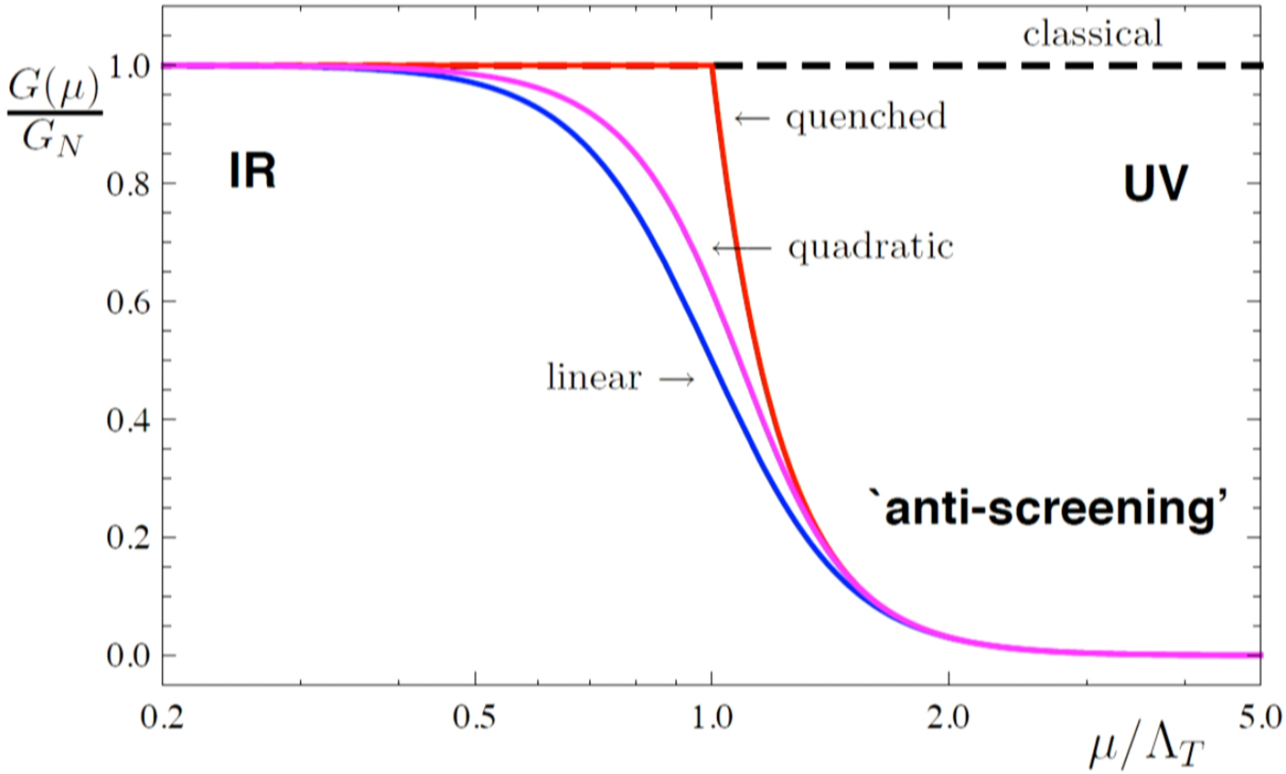
RG improved scattering amplitude for Drell-Yan production

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

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

UV finite for all n.

cross-over scale Λ_T



(DL '03)

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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.

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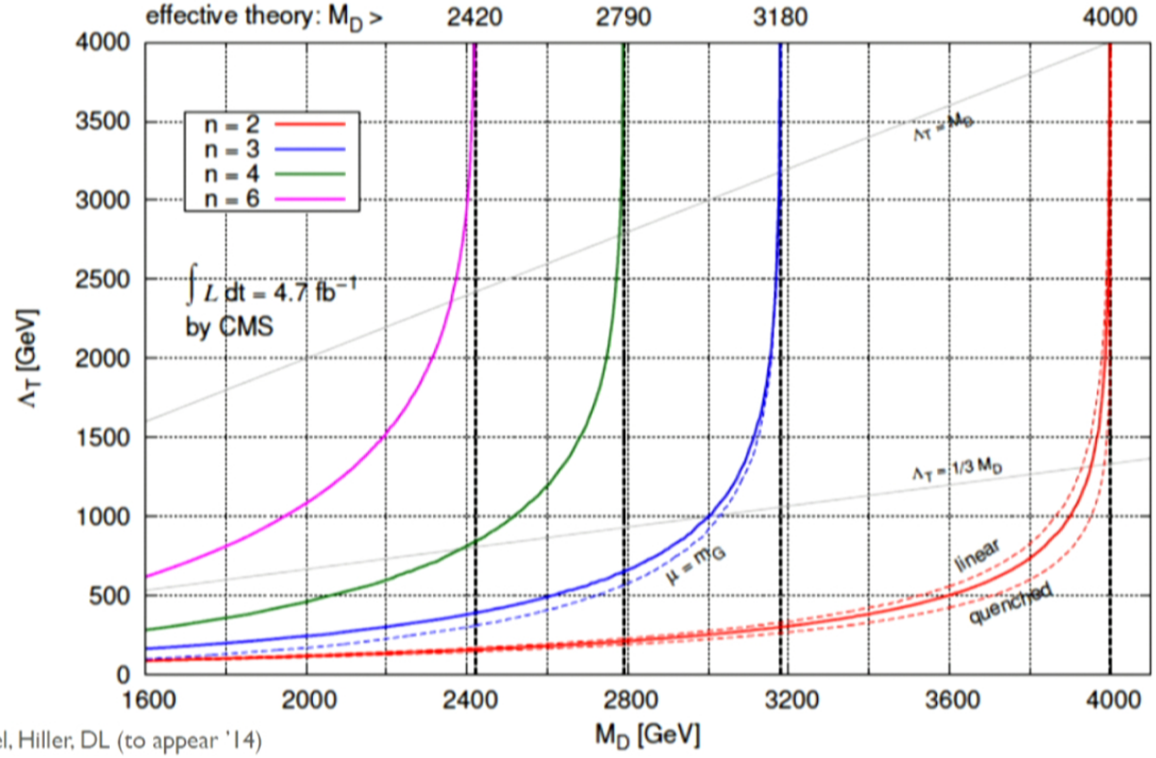
interpreting LHC data

graviton+jet (MET)

Pythia v8.153 $\sqrt{s}$ = 7 TeV, $\mu = E_G$, quadratic approximation



Dabruck, Demmel, Hiller, DL (to appear '14)

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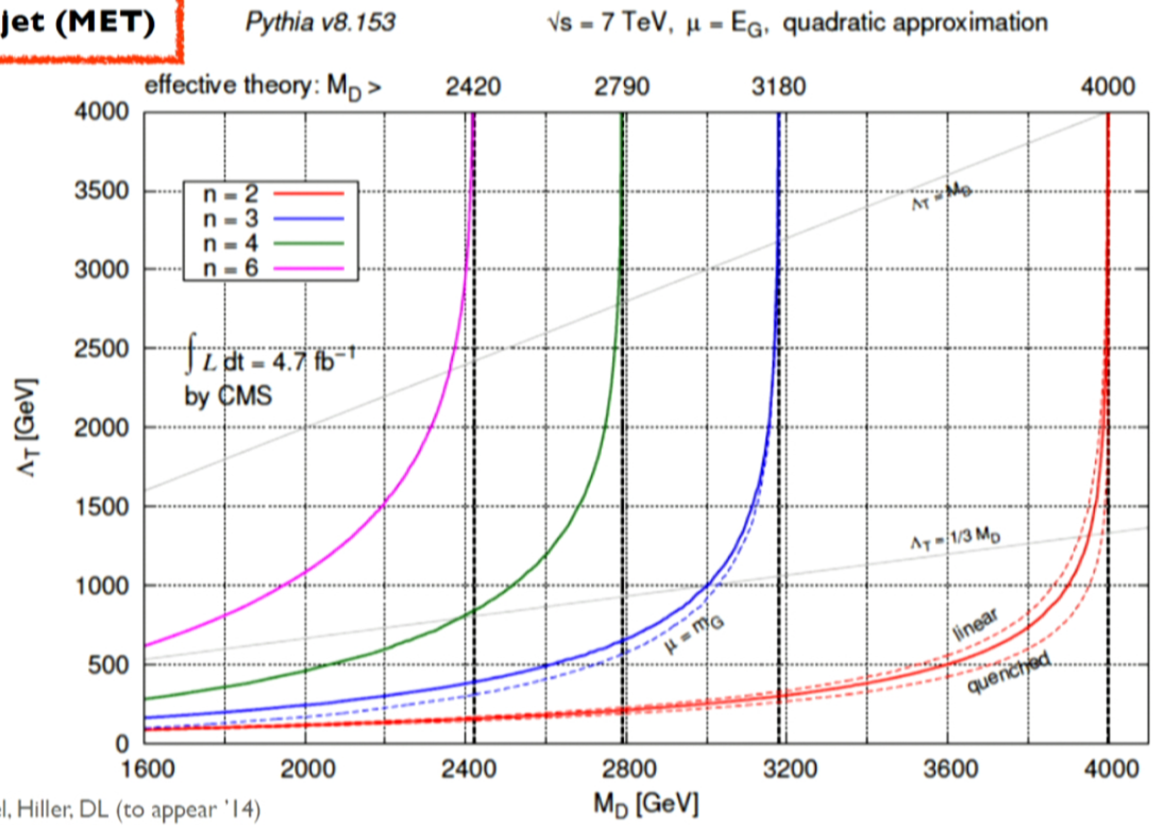
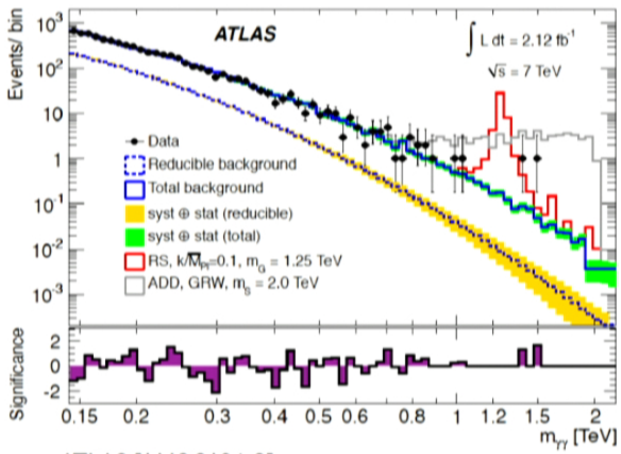
interpreting LHC data

graviton+jet (MET)

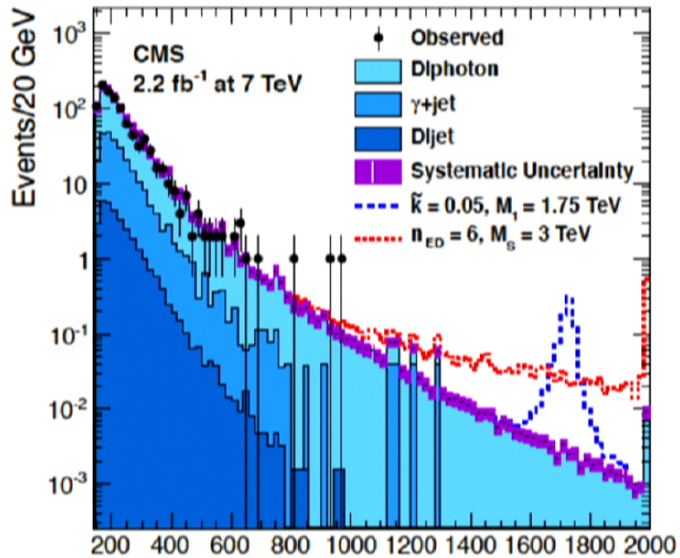


Dabruck, Demmel, Hiller, DL (to appear '14)

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)

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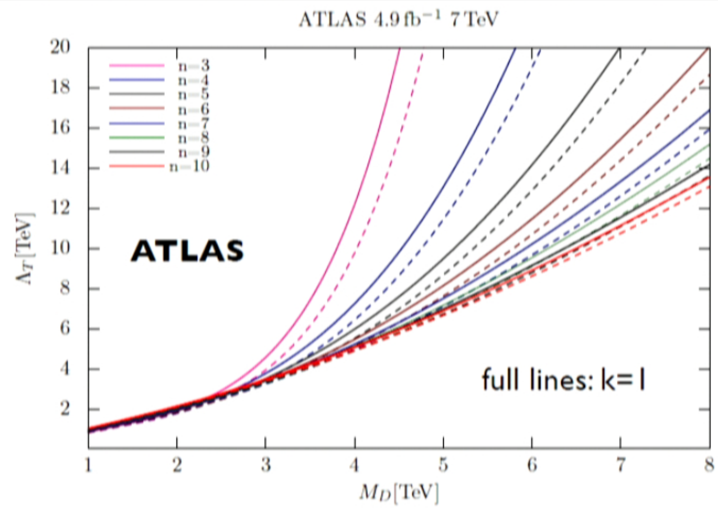
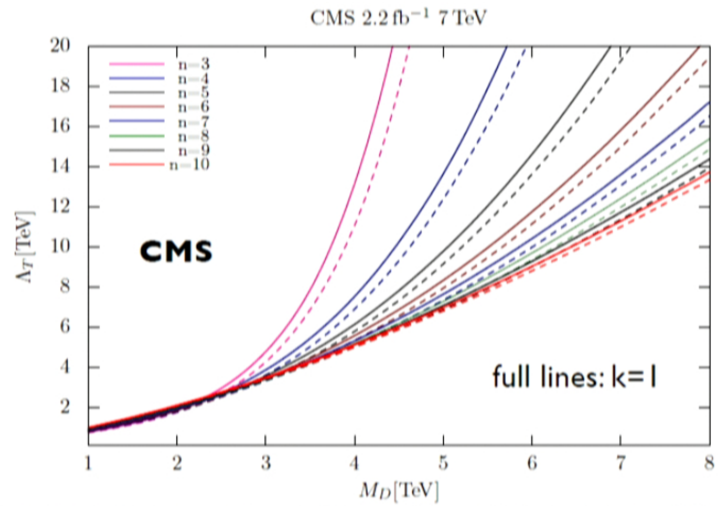
interpreting LHC data

virtual gravitons + diphotons

implementation in Pythia8
weak PDF dependence
weak scheme dependence

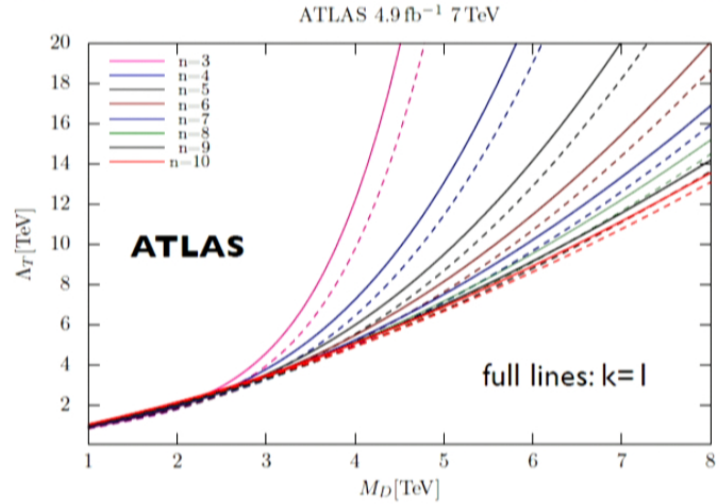


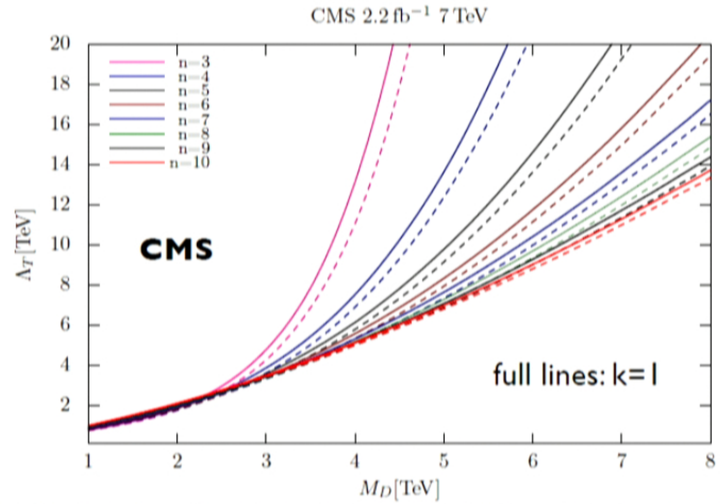


(Hiller, DL, Zenglein, 2014)

interpreting LHC data

virtual gravitons + diphotons





implementation in Pythia8
weak PDF dependence
weak scheme dependence

(Hiller, DL, Zenglein, 2014)

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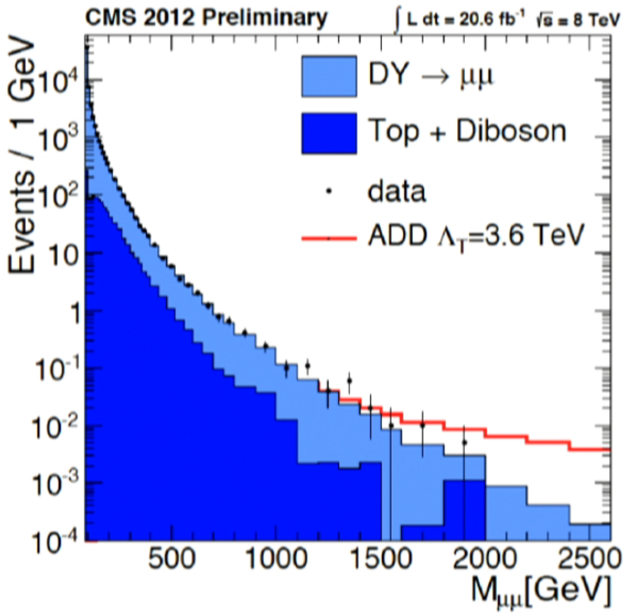
3) virtual gravitons + dileptons

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

combined 95% CL

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

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



CMS [EXO-12-027]

Wednesday, 23 April 14

lesson 2

- asymptotic safety offers QFT-based description of gravity even at high energies
    - framework for SM & BSM particle physics
      predictive at the LHC and beyond
      no UV cutoff
        - LHC sensitive to theory parameters
          DY, MET+jet, photons, BHs
          re-interpretation of LHC bounds

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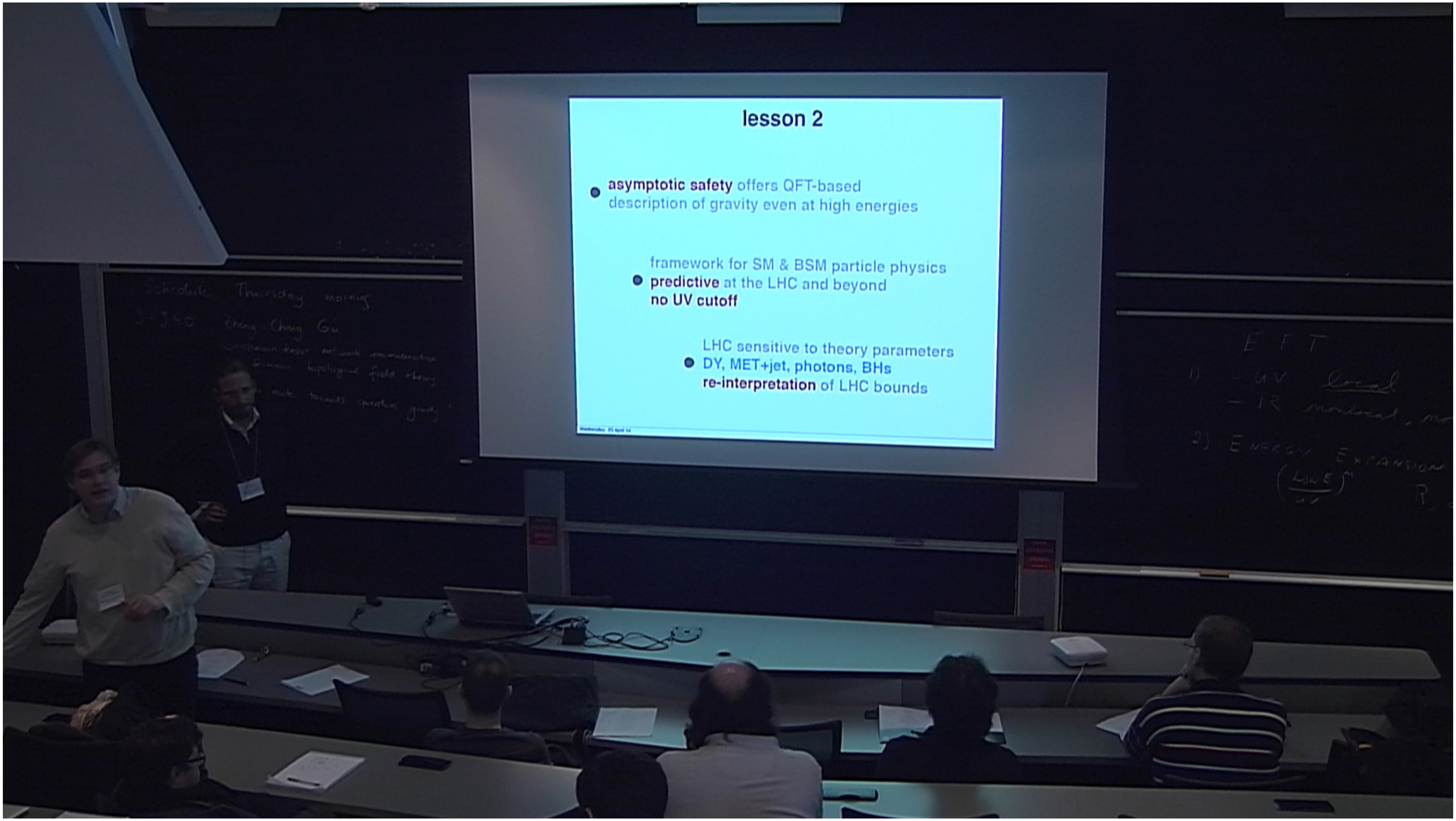
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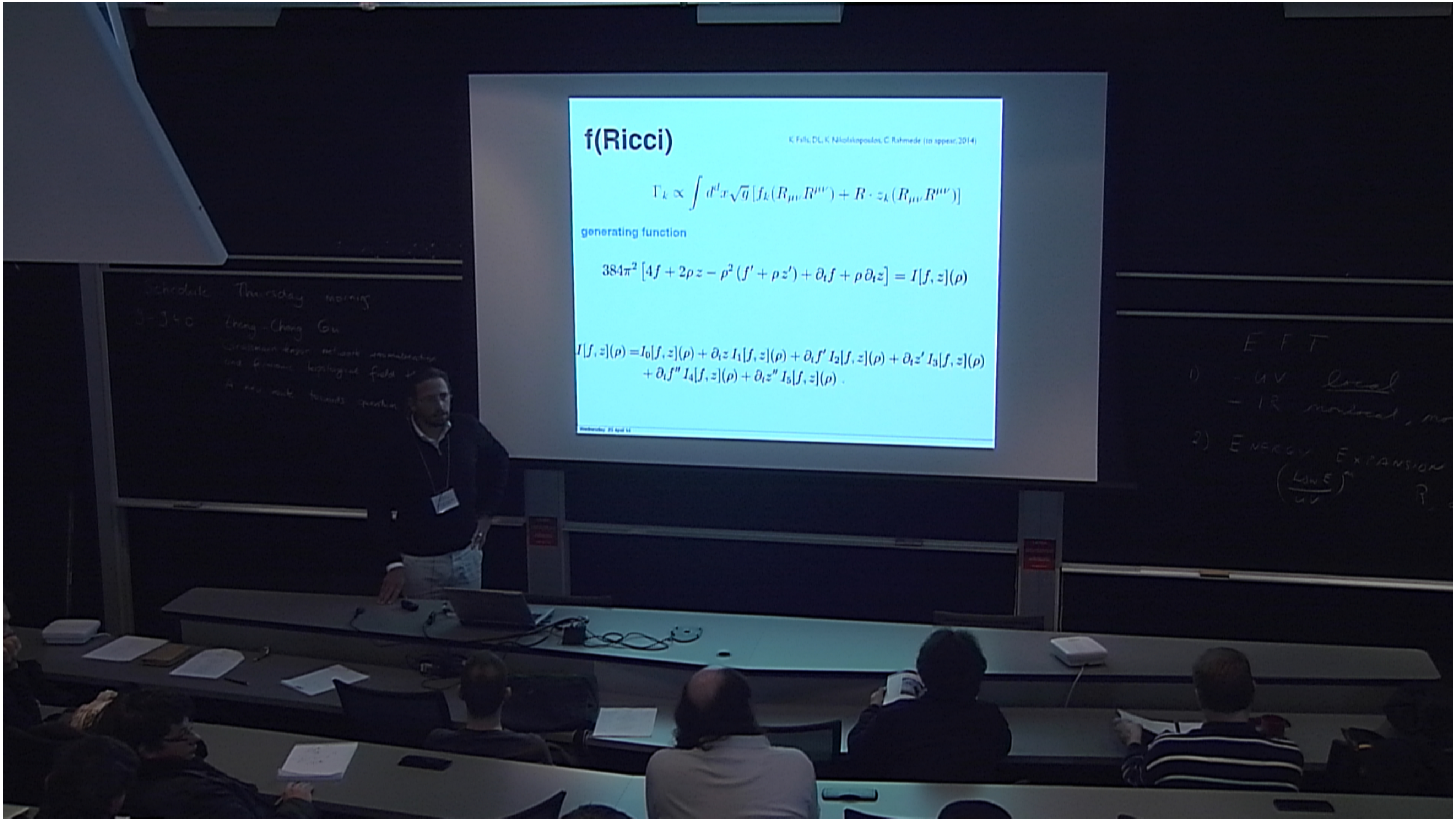
f(Ricci)
K Falls, DL, K Nikolakopoulos, C Rahmede (to appear, 2014)
$\Gamma_k \propto \int d^d x \sqrt{g}\, [f_k(R_{\mu\nu}R^{\mu\nu}) + R \cdot z_k(R_{\mu\nu}R^{\mu\nu})]$
generating function
$384\pi^2 \left[4f + 2\rho z - \rho^2 (f' + \rho z') + \partial_t f + \rho\, \partial_t z\right] = I[f, z](\rho)$
$I[f,z](\rho) = I_0[f,z](\rho) + \partial_t z\, I_1[f,z](\rho) + \partial_t f'\, I_2[f,z](\rho) + \partial_t z'\, I_3[f,z](\rho) + \partial_t f''\, I_4[f,z](\rho) + \partial_t z''\, I_5[f,z](\rho)\,.$