Title: Quantum Gravity and the Weak Interactions

Date: Oct 25, 2012 10:20 AM

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Abstract: Quantum Gravity and the Weak Interactions
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Non-thermal quantum black holes
Motivated by the lack of evidence for physics beyond the Standard Model in the TeV region, we discussed an alternative path for grand unification. We show that simple grand unification models based on e.g. SU(5) can work successfully even without low scale supersymmetry. In particular quantum gravitational effects could easily modify the unification conditions for the gauge and Yukawa couplings.
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Searches for Nonperturbative

Gravitational States at the LHC
Searches for black holes and string balls have recently be performed by LHC experiments. Upper limits have been placed on the production crosssections time experimental acceptance. Hard-disk production of thesestates have been ruled out over most of the current LHC energy reach.However the LHC has said little about nonperturbative states producedin model with reduced cross sections. I will discuss some popularmodels that have not yet been ruled out by the LHC experiments.
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Models of new physics beyond the

Standard Model of Particle Physics
Models of new physics beyond the Standard Model of Particle Physics suggest that the quantum scale of gravity could be as low as the electro-weak or TeV energy scale. If so, they offer the exciting possibility that quantum gravity becomes accessible, experimentally, at particle colliders such as the LHC. From the theory side, low-scale gravity scenarios often require extra dimensions, or a large number of additional particle species.
I propose to discuss the possibility for signatures of low-scale quantum gravity, the feasibility of concrete (quantitative) predictions based on eg. specific processes and quantum gravity set-ups, and options for experimental tests.
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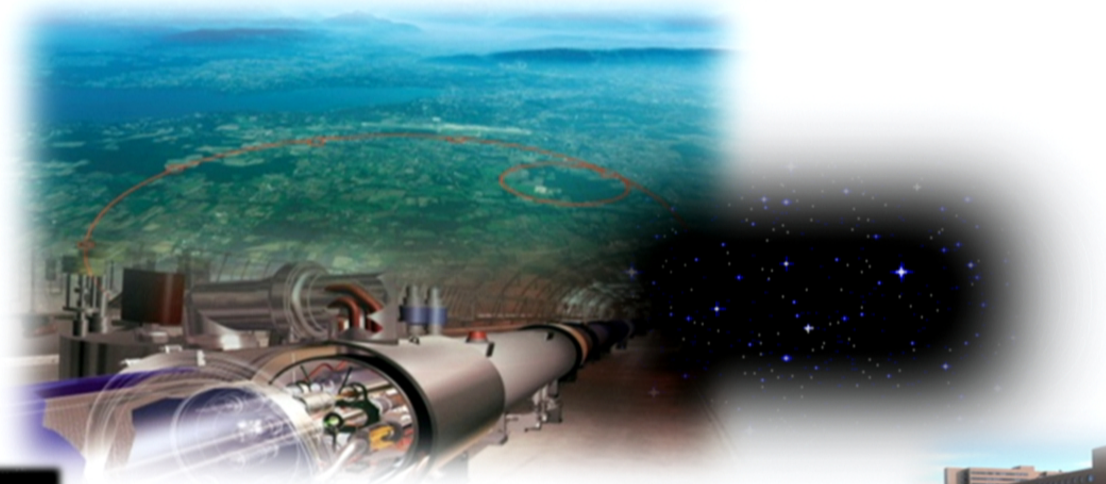
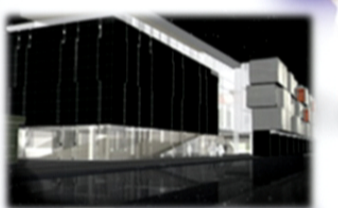
Unification of gravity with the electroweak
interactions

TeV scale gravity

Dejan Stojkovic

SUNY at Buffalo





Experimental Search for Quantum Gravity

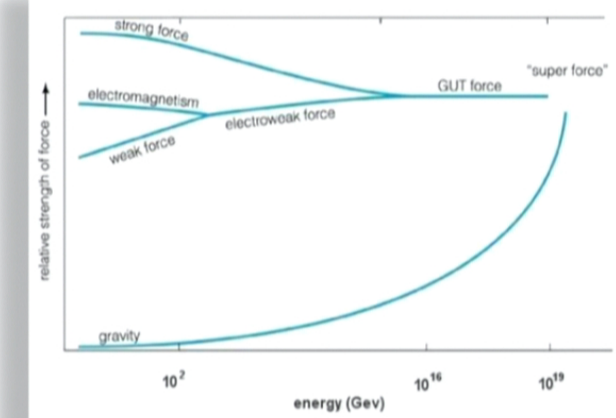
PI, Oct 22 - 25, 2012

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

University at Buffalo
The State University of New York

The hierarchy of energy scales:

- Planck scale: $M_{Pl} = 10^{19} GeV$
- Electroweak scale: $M_{EW} = 250 GeV$



- "Grand Desert" between the scales

$$G_{Newton} = \frac{1}{M_{Pl}^2}$$

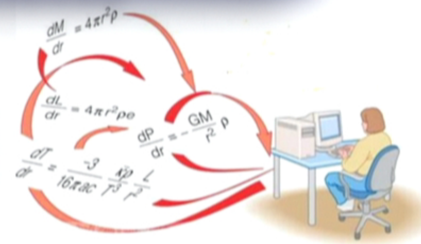
weak gravity

- Gravity is by far the weakest interaction
- For protons, gravity is 10^{36} times weaker than electromagnetism

$$F_{EM} = k\frac{q_1 q_2}{r^2} \qquad F_G = G\frac{m_1 m_2}{r^2}$$

3

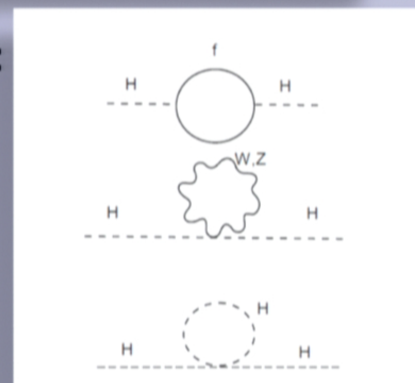
The hierarchy problem



The standard model Lagrangian

$$L_H = D_\mu \phi^+ D^\mu \phi^+ - \mu^2 \phi^+ \phi + \frac{\lambda}{2} \left(\phi^+ \phi \right)^2 - \sum_f g_f \phi \overline{\psi}_f \psi_f$$

•Radiative corrections to the Higgs mass:



$$\Delta m_h^2 \approx \Lambda^2 \frac{3(2m_W^2 + m_Z^2 + m_h^2 - 4m_t^2)}{32\pi^2 v^2}$$

• If SM is valid all the way to M_{Pl}
a rather fine-tuned cancellation must take place (about 1 part in 10^{17})

Strong gravity: ADD model

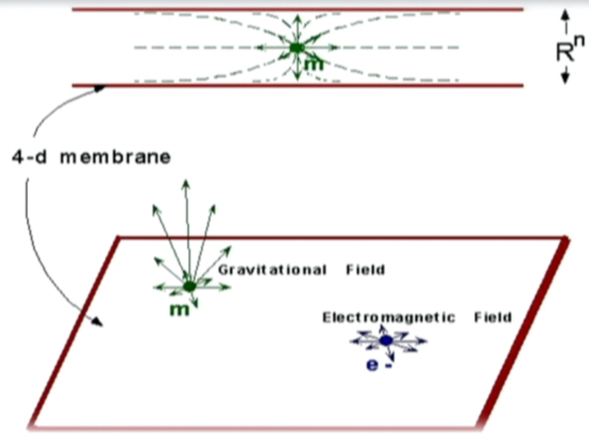
Arkani-Hamed, Dimopoulos and Dvali, *Phys. Lett. B 429, 263 (1998)*
Antoniadis, Arkani-Hamed, Dimopoulos and Dvali, *Phys. Lett. B 436,257 (1998)*

- Our universe consists of:
- 3+n space-like dimensions (bulk)
- n dimensions compactified to radius R

- ***Only gravitons are allowed to propagate in all dimensions***
- ***SM particles are bound to 3-dim submanifold (brane)***

In this framework:

- Gravity is as strong as the other interactions
- But gravitational force is diluted due to the presence of extra dimensions



Weak gravity is only an illusion for an observer located on the brane

NUMBERS

- **Volume of extra dimensions:** $V_{extra} = R^n$
- **Strength of gravity** $G_{Newton} = \frac{1}{M_{Pl}^2} = \frac{G_n}{V_{extra}}$
- **Solution to the hierarchy problem:** $M_* \approx TeV$

$$n=1 \quad \Rightarrow \quad R = 10^{13} m$$
$$n=2 \quad \Rightarrow \quad R = 1 mm$$
$$n=3 \quad \Rightarrow \quad R = 10^{-5} mm$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$n=6 \quad \Rightarrow \quad R = 10^{-11} mm$$

"Large" extra dimensions $R >> TeV^{-1} \approx 10^{-16} mm$

We can use CLASICALL solutions of Einstein's equations

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7

If $M_* = 1TeV = 10^3 GeV$

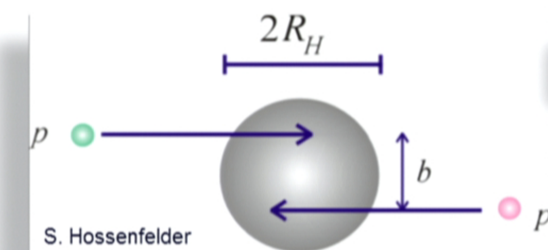
We can talk about non-perturbative quantum gravity effects in accelerators → Mini Black Holes

Black holes in accelerators

Particle accelerator (e.g. Large Hadron Collider):

Collision of two particles with COM energy E_c

If an impact parameter b is smaller than $2R_H$ for a given E_c



Trans-Planckian energies

Black hole with a mass M ~ Ec forms!

- The total black hole production cross section in pp collison is:

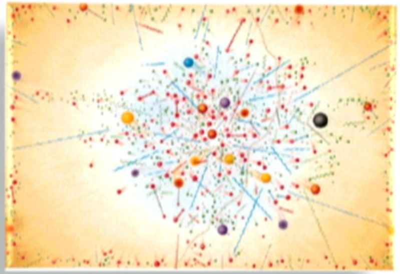
$$\sigma(pp \to BH) = \Sigma_{ij} \int_{\tau_{\min}}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} \hat{\sigma}_{ij}(\tau s) f_i(x) f_j(\frac{\tau}{x})$$

- The sum runs over all partons in the proton

$$\hat{\sigma}_{ij} = \pi R_H^2$$

- $\sqrt{s}$ is the proton-proton COM energy
- f_i are the parton distribution functions
- x_i is the momentum fraction carried by an i-th parton
- $\sqrt{\tau} = \sqrt{x_i x_j}$ is the momentum transfer
- $M_{\min} = \sqrt{\tau_{\min} s} \approx M_*$ is the minimal energy needed to form a black hole

Large Hadron Collider → CERN



LHC: E_c =14 TeV

$$\sigma(M) \approx \pi R_H^2$$

Numerical estimates:

10^7 black holes per year if M_* =1 TeV

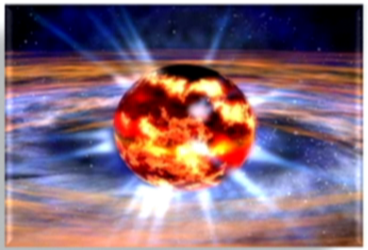
LHC - black hole factory!

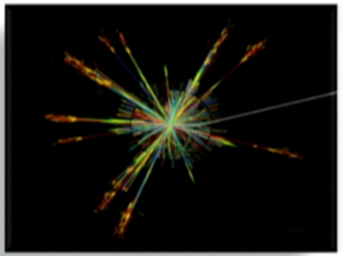
11

Life-time of a small black hole very short :

TeV black hole lives 10^{-27} seconds

→ disappears almost instantaneously





- Number of particles emitted equal to black hole entropy: $S = \frac{n+1}{n+2}\frac{M_{BH}}{T_{BH}}$
- e.g. 5 TeV black hole emits of the order of 30 particles

BH event may have a distinct signature in accelerators!

Higher dimensional black hole solutions

Schwarzschild-like solution (non-rotating)

Tangherlini, 1963

$$ds^2 = -(1 - \frac{r_H^{1+n}}{r^{1+n}})dt^2 + (1 - \frac{r_H^{1+n}}{r^{1+n}})^{-1} dr^2 + r^2 d\Omega_{2+n}^2$$

n: the number of extra dimensions

Kerr-like solution (rotating): 5D

Myers and Perry, 1986

$$ds^2 = d\gamma^2 + \frac{r^2 \rho^2}{\Delta} dr^2 + \rho^2 d\theta^2$$

$$d\gamma^2 = -dt^2 + (r^2 + a^2)\sin^2\theta d\phi^2 + (r^2 + b^2)\cos^2\theta d\psi^2 + \frac{r_0^2}{\rho^2}(dt + a\sin^2\theta d\phi + b\cos^2\theta d\psi)^2$$

$$\rho^2 = r^2 + a^2\cos^2\theta + b^2\sin^2\theta$$

$$\Delta = (r^2 + a^2)(r^2 + b^2) - r_0^2 r^2$$

Two parameters of rotation: a and b

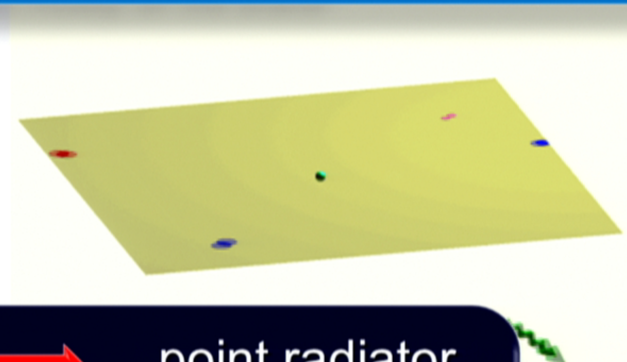
Five-dimensional rotating black holes: theory

V. Frolov, D. Stojkovic, **Phys.Rev.D67**:084004,2003; **Phys.Rev.D68**:064011,2003

	4D black hole	5D black hole
Parameters	**M, a**	**M, a, b**
Killing Vectors	$\partial_t, \partial_\Phi$	$\partial_t, \partial_\Phi, \partial_\psi$
Killing Tensor	**Yes**	**Yes**
Scalar field separation of variables	**Yes**	**Yes**
Higher spin fields separation of variables	**Yes**	**?**
Decoupling	**Yes**	**?**
Stable circular orbits	**Yes**	**No**
Superradiance	**Yes**	**Yes**
Algebraically special	**Yes**	**Yes**
Two principle null congruencies (PNC)	**Yes**	**Yes**
Petrov class D	**Yes**	**Yes**
PNC is shear free	**Yes**	**No**

Where do black holes mostly radiate? Brane or Bulk?

R. Emparan, G. Horowitz, R. Myers, **Phys. Rev. Lett.** 85 499 (2000)
"Black holes radiate mostly on the brane"



$\lambda_T > R_S$ → point radiator

→ s-mode dominant → radiates equally in all directions

Number of degrees of freedom much larger on the brane ?
(60 SM particles vs. 1 graviton)

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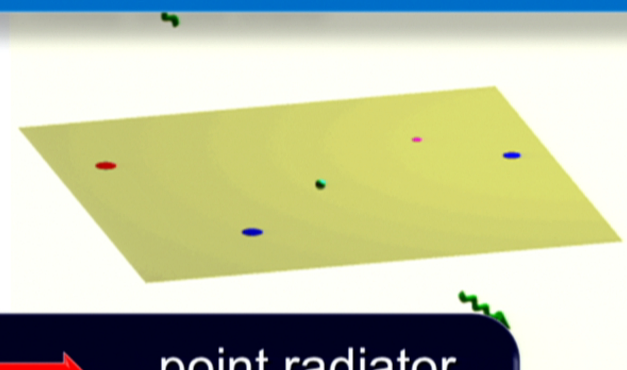

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15

Where do black holes mostly radiate? Brane or Bulk?

Objection 1:

\# of degrees of freedom of gravitons in the N+1-dimensional space-time is:

$$\mathcal{N} = (N+1)(N-2)/2 \Longrightarrow N = 9, \quad \mathcal{N} = 35$$

Objection 2:

- LHC: non-zero impact parameter → most of the black holes will be rotating
- Rotating black holes → superradiance → graviton emission dominant

V. Frolov, D. Stojkovic, **Phys. Rev. Lett.** 89:151302 (2002)

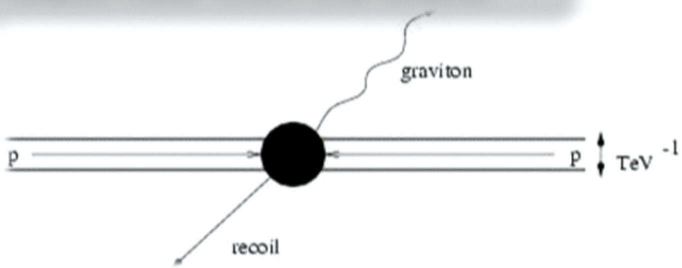
Black holes radiate mostly OFF the brane !

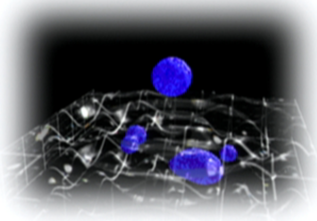
At least as long as they are rotating fast

Recoil Effect

V. Frolov, D. Stojkovic, **Phys. Rev. Lett.** 89:151302 (2002)

Any particle emitted in the bulk can cause a recoil of the black hole from the brane



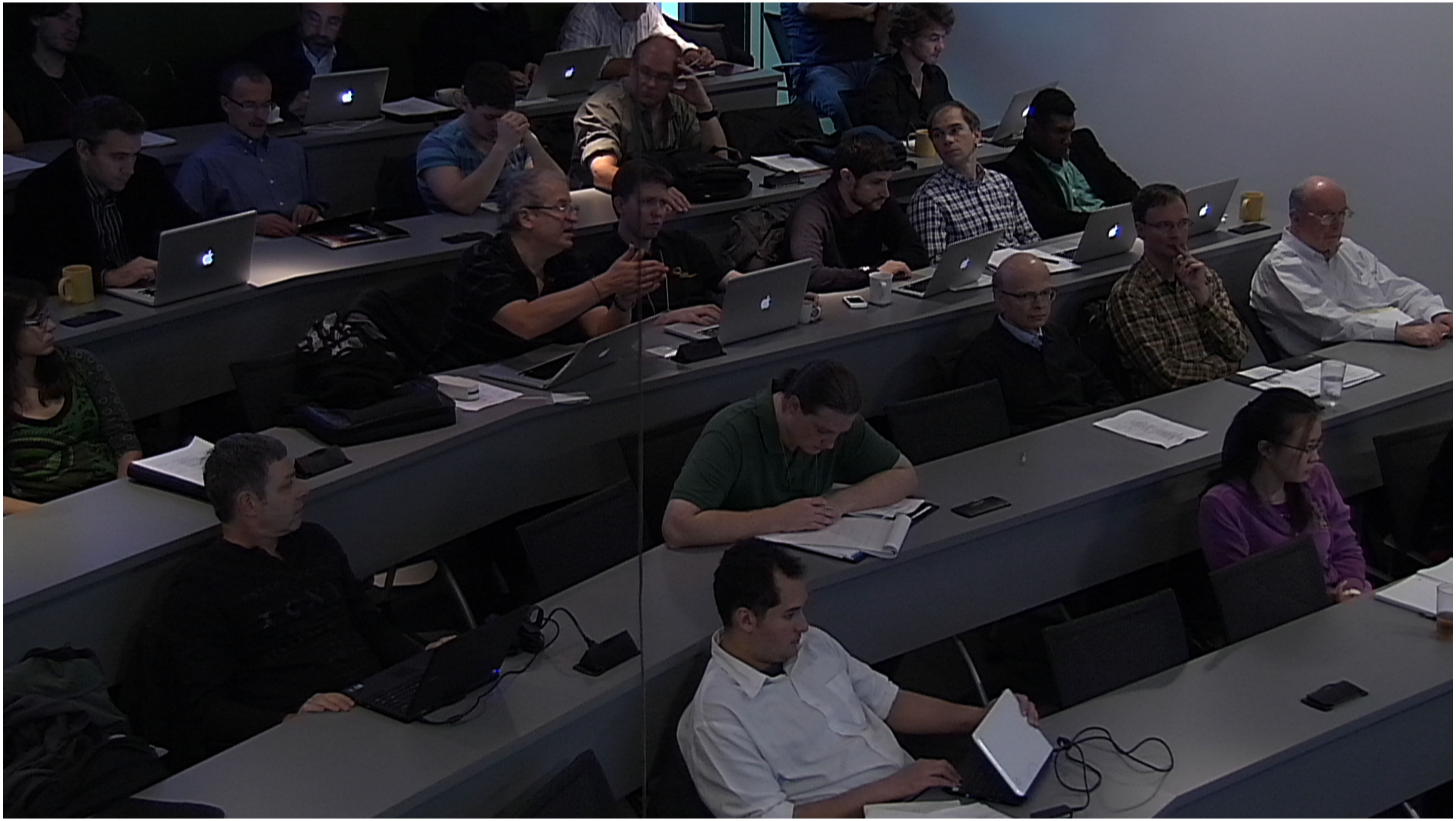


Recoil due to Hawking radiation can be very significant for small black holes (energy of emitted particles comparable to the mass of the black hole)

Consequences:

i) black hole radiation would be suddenly terminated
ii) observer located on the brane would register apparent energy non-conservation

17



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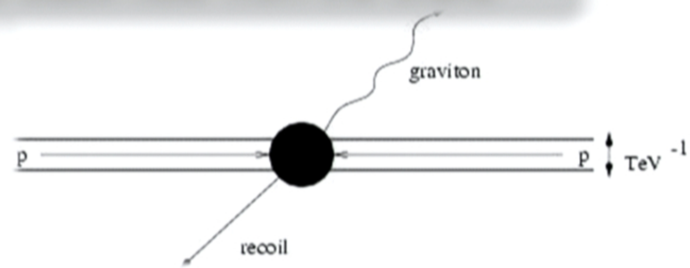

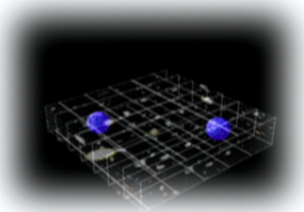

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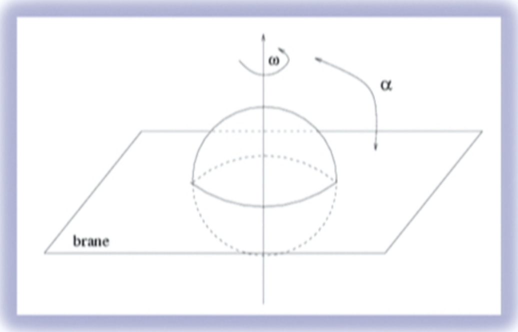
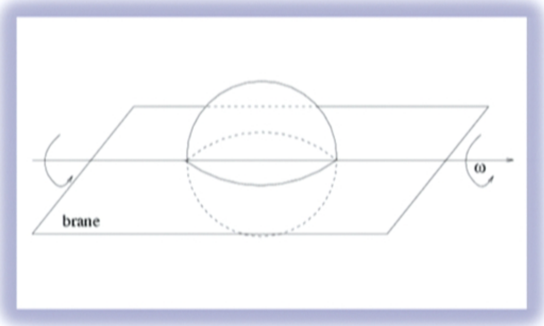
Friction between the black hole and the brane

V. Frolov, D. Fursaev, D. Stojkovic, **CQG,** 21:3483 (2004)
D. Stojkovic, **Phys. Rev. Lett.** 94: 011603 (2005)





Rate of loss of the angular momentum

$$\dot{J} = \pi \sigma a R_H \cos^2 \alpha$$

$\alpha = \pi / 2 \Rightarrow \dot{J} = 0$ **final stationary equilibrium configuration is:**

$$J_{bulk} = 0$$

$$\tau \approx (G \sigma \cos^2 \alpha)^{-1}$$

13

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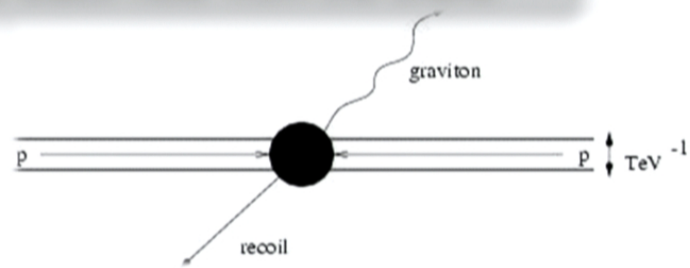

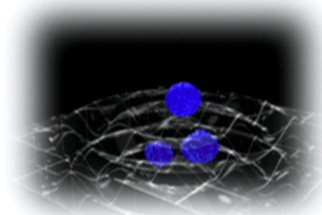

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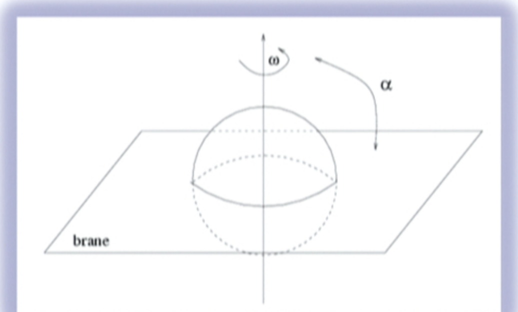

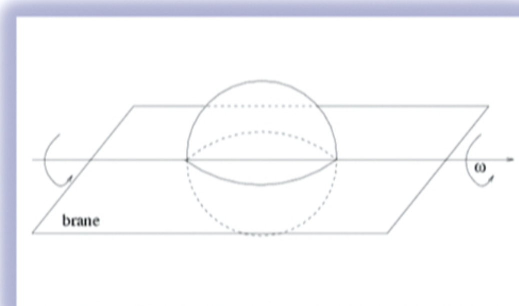

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Evaporation of a black hole off of a tense brane

D. Dai, N. Kaloper, G. Starkman, D. Stojkovic, **Phys.Rev.D75:**024043,2007

$$ds^2 = -(1-\frac{r_H^3}{r^3})dt^2 + (1-\frac{r_H^3}{r^3})^{-1} dr^2 + r^2\{d\theta^2 + \sin^2\theta[d\phi^2 + \sin^2\phi(d\chi^2 + B\sin^2\chi d\psi^2)]\}$$

6D black hole on a co-dimension 2 brane

$$B = 1 - \frac{T}{2\pi M_*^4}$$

deficit angle

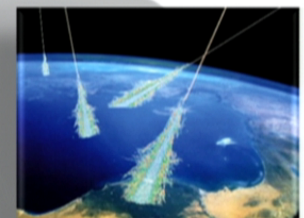
$$r_H = \frac{r_s}{B^{1/3}}$$

horizon radius

- Finite brane tension modifies the standard results
- Increasing tension increases the horizon radius
- Power carried away into the bulk diminishes

Black Holes from Cosmic Rays

J. Feng, A. Shapere, **Phys. Rev. Lett.** 88:021303 (2002)



- **Cosmic rays are Nature's free collider**
- Observed events produce COM energy of 100 TeV
- If $M_* \approx 1\mathrm{TeV}$ (quantum gravity energy scale), then

small black holes can be produced in the atmosphere

- Proposed mechanism:

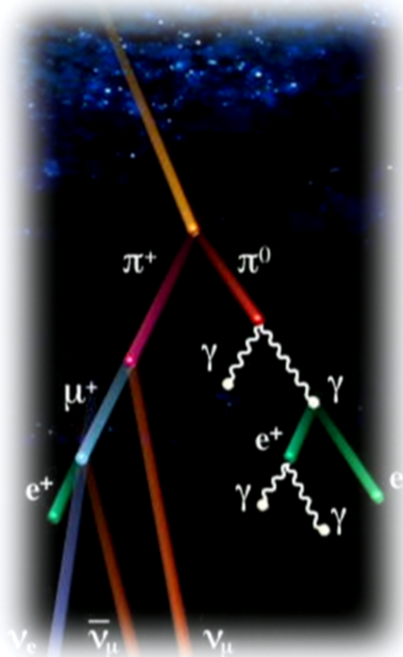
- neutrino-nucleon scattering deep in the atmosphere

20

Cosmic neutrinos

- **Cosmic protons scatter off the cosmic microwave background to create ultra-high energy neutrinos**

$$p+\gamma_{CMB} \to n+\pi^{+} \to n+\mu^{+}+\nu$$



- **These neutrinos enter Earth's atmosphere**

- **They have very weak SM interactions**

- **Dominant interaction:** $\nu N \to BH + X$

- The total black hole production cross section in neutrino-nucleon scattering is:

$$\sigma(\nu N \to BH) = \Sigma_i \int dx \hat{\sigma}_i(xs) f_i(x\widetilde{Q})$$

- The sum runs over all partons in the nucleon

$$s = 2m_N E_\nu \qquad E_{CM} = \sqrt{s}$$

- f_i are the parton distribution functions
- $\widetilde{Q}$ is momentum transfer

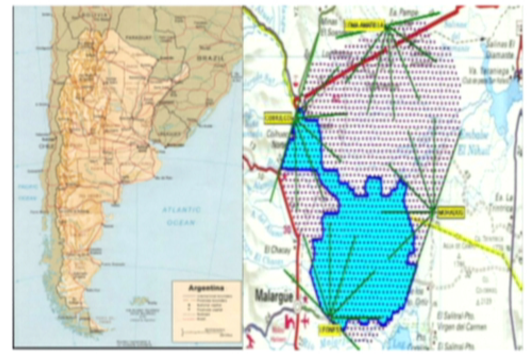
$$\hat{\sigma} = \pi R_H^2$$

- The cross section for black hole production is found to be several orders of magnitude higher than the SM cross section for $\nu N \to \nu L + X$ if $M_* \approx 1\text{-}10\,\text{TeV}$

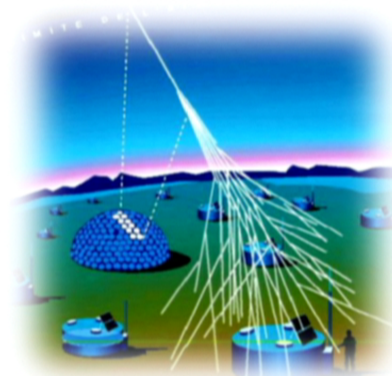
Auger Observatory

Pierre Auger

- Best current setup for cosmic ray studies (also IceCube)
- Located in Argentina (Pampa Amarillas)



- 1600 Water Cerenkov ground arrays
- 4 air fluorescence telescopes
- spread over 3000 km²



• Numerical estimates:

- Auger can detect ~ 100 black holes in 3 years (i.e. BEFORE the LHC data become available)

• This could be the first window into extra dimensions

• USA Today version:

> *"Dozens of tiny black holes may be forming right over our heads... A new observatory might start spotting signs of the tiny terrors, say physicists Feng and Shapere. They're harmless and pose no threat to humans."*

Nine years after…

Auger has reported some interesting results but NO black hole events!

Are TeV scale gravity models already excluded?

25

TeV scale gravity plagued with serious problems

- Some things have their natural habitat in the "grand desert" that is destroyed by a low scale gravity
- Like proton stability, neutrino masses...
- Large mixing between the neutrinos
- Large neutron-antineutron oscillations
- Large FCNC

$$\tau_{proton} = m_{proton}^{-1} \left(\frac{M_{Pl}}{m_{proton}} \right)^4$$

- Low scale quantum gravity implies very fast proton decay!

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Saving Proton

Gaging the baryon number

- One way out is to gauge the baryon number
  → promote a $U(1)_B$ into a gauge symmetry

- **Problems:**

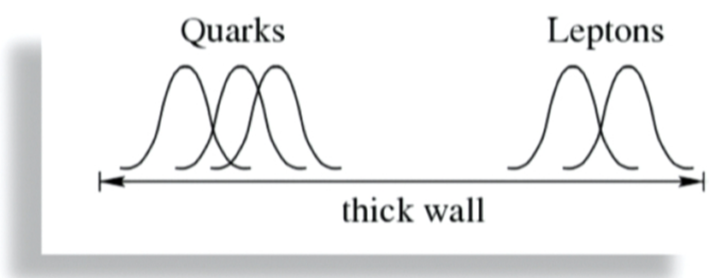
- **Baryogenesis**
  - Before: "We exist → proton must be stable“
  - After: "We exist → proton must be unstable“

- **So far, gauging the baryon number has not proved very attractive!**

An alternative: Split Fermions

N. Arkani-Hamed, M. Schmaltz, ***Phys. Rev. D 61****:033005 (2000)*

- In order to suppress a direct QQQL coupling
  we must separate quarks form leptons



- Quarks and leptons are localized at different points on a thick brane
- Or alternatively, on different branes

- The model yields exponentially small coupling (wave function overlap) between quarks and leptons

- Dangerous QQQL interaction is suppressed

- The propagator between fermions which are separated in extra dimensions (in the high energy and high momentum transfer limit) is

$$P_{extra} \approx P_4 e^{-d^2/\sigma^2}$$

d: separation between the quarks and leptons
σ: the width of the fermion wave function

- The propagator has the usual 4-dim form except that the coupling is suppressed by the exponentially small wave function overlap

- Suppression factor of $e^{-d^2/\sigma^2} \approx 10^{-26}$ (which can be achieved for a rather modest hierarchy of $d \approx 10\sigma$)

completely saves the proton!

D. Stojkovic, G. Starkman, D. Dai, Phys. Rev. Lett. 96, 041303 (2006)

Consequences: the price we to have pay

$$\hat{\sigma} = \pi R_H^2$$

- Spatial separation between [the quark and] lepton wave functions successfully suppresses p[...]

10^{52}

Consequences: the price we to have pay

D. Stojkovic, G. Starkman, D. Dai, **Phys. Rev. Lett.** 96, 041303 (2006)

- Spatial separation between the quark and lepton wave functions successfully suppresses proton decay
- However, this implies strong consequences for cosmic ray neutrino scattering off the atmosphere
- The correct black hole production cross section in collisions of neutrinos with each quark in a nucleon is not $\hat{\sigma} = \pi R_H^2$
- The correct cross section is divided by the large suppression factor of

10^{52}

Large suppression factors enter the total production cross section

$$\sigma(\nu N \to BH)$$

and render the corresponding probability for the black hole production by cosmic neutrinos *completely uninteresting* for the Auger Observatory!

⬇

Non-observation of BH events at the Auger

Large suppression factors enter the total production cross section

$$\sigma(\nu N \to BH)$$

and render the corresponding probability for the black hole production by cosmic neutrinos *completely uninteresting* for the Auger Observatory!

Non-observation of BH events at the Auger likely has no implications for the LHC

Black Max

"BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension"
D. Dai, G. Starkman, D. Stojkovic, C. Issever, E. Rizvi, J. Tseng
Phys.Rev.D77:076007,2008

+ X. Calmet, N. Gausmann, R. Buckingham, W. Carlson

32

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- The most comprehensive tool to study quantum gravity effects
- Based on phenomenologically realistic models, thus offering most realistic predictions for hadron-hadron colliders.
- Includes all of the black-hole greybody factors known to date
- Incorporates: the effects of black-hole rotation, splitting between the fermions, non-zero brane tension and black-hole recoil
- The generator is interfaced with Herwig and Pythia and is now official software at CERN

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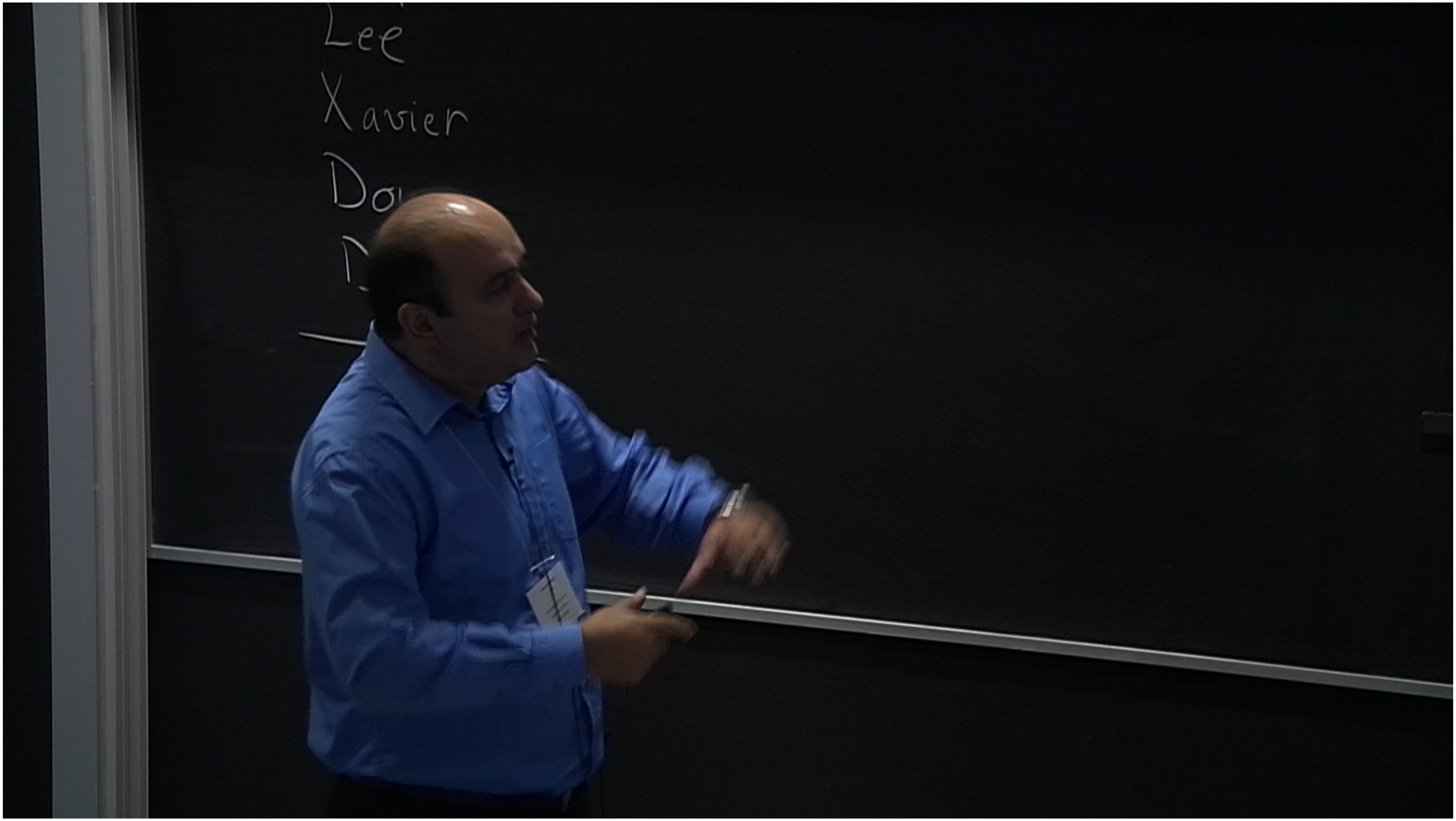
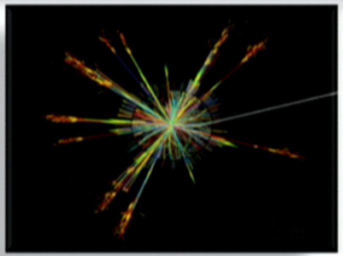
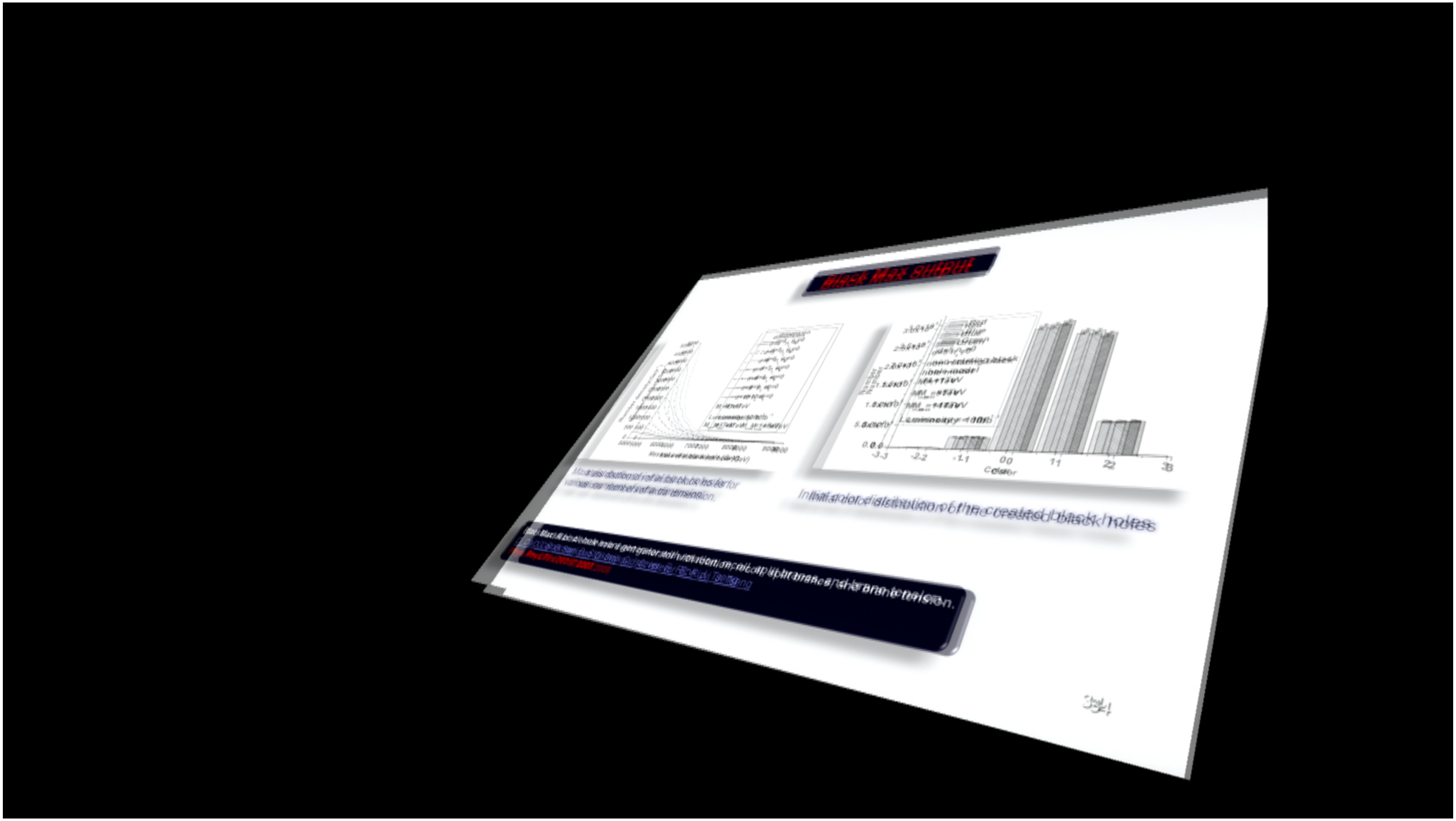
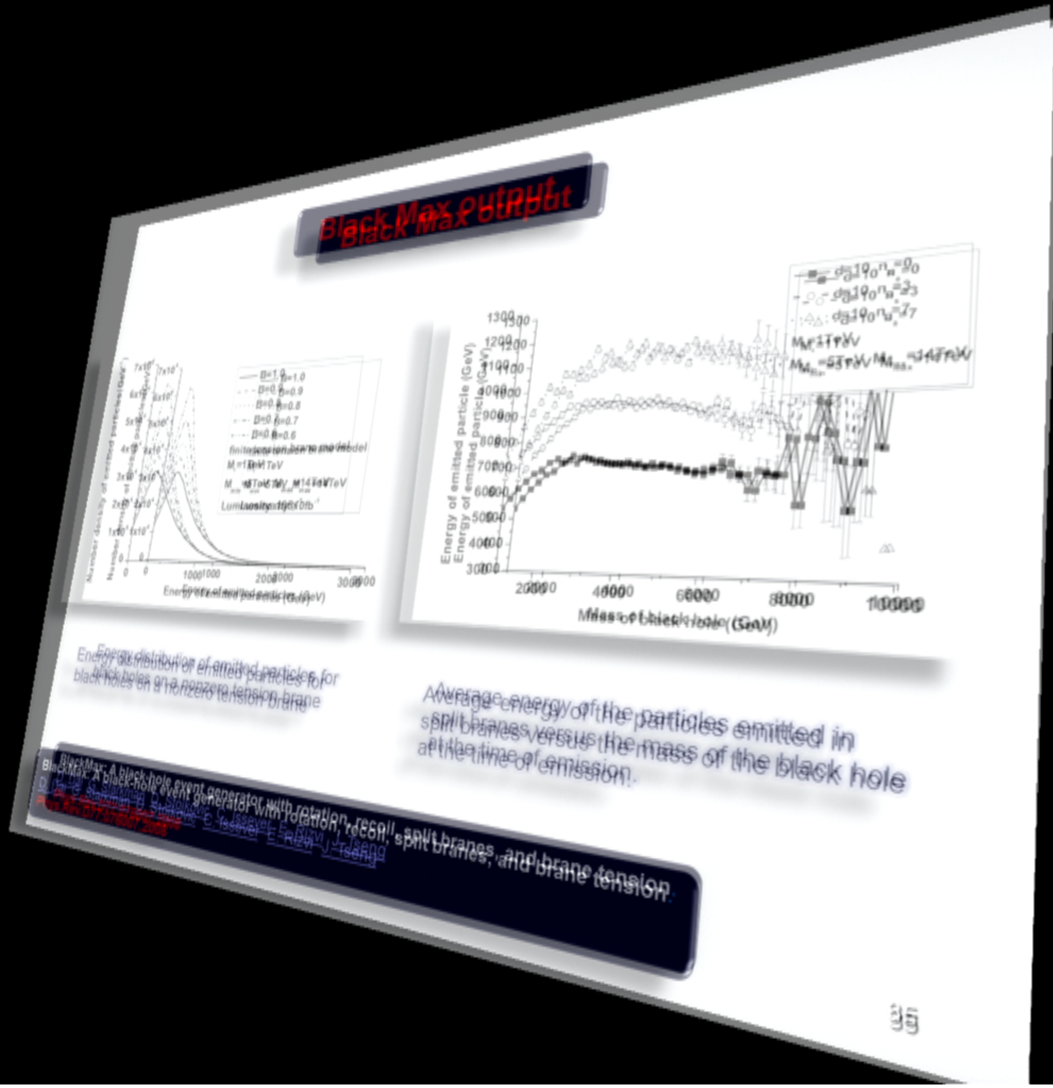

Lee
Xavier

Black Max procedure

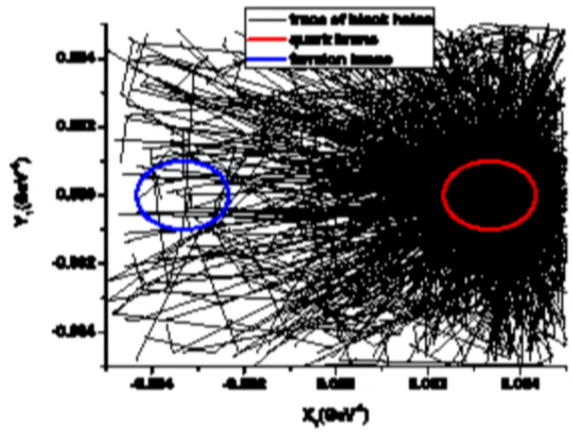


- The generator requires a well defined input, e.g. two colliding partons, which is obtained from the known parton distribution functions of a proton
- Then the probability for a black hole production is calculated with the basic characteristics of a formed black hole, like its mass, angular momentum, electromagnetic and color charge
- Next, the decay pattern via Hawking radiation is computed
- As the output, the generator gives the Standard Model particles with their energy, linear and angular momentum distributions


Black Max output
Initial color distribution of the created black holes


Black Max output
Mass of black hole (GeV)
Energy distribution of emitted particles for black holes on a nonzero tension brane
Average energy of the particles emitted in split branes versus the mass of the black hole at the time of emission.
BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension.

Black Max output



Black hole recoil in the split brane scenario
- black lines are black holes traces
- red circle is a quark brane
- blue circle is a lepton brane

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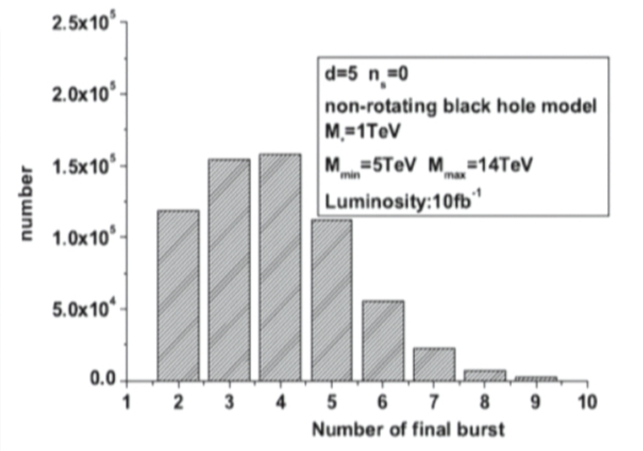
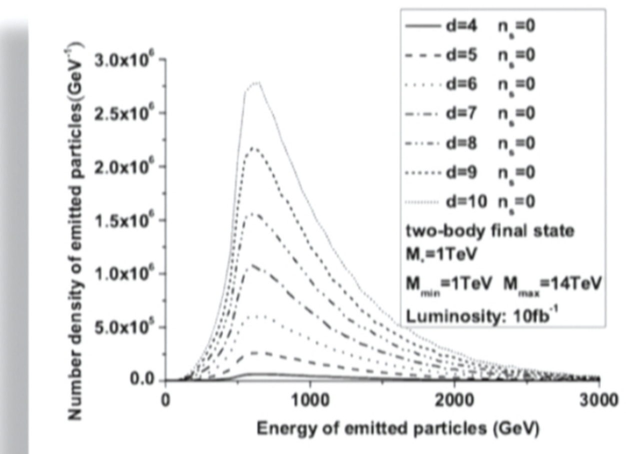
36

Black Max output

$$P_2 = \frac{\sum_{n=0}^{2} \frac{1}{n!} \langle N \rangle^n}{e^{\langle N \rangle}}$$



Number of particles emitted in the final burst
(when the black hole mass is about M.)



Energy distribution of emitted particles
for L. Randall's "two-body final states"

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ATLAS and CMS use BlackMax

Search for Microscopic Black Hole Signatures at the Large Hadron Collider
The CMS Collaboration
e-Print: **arXiv:1012.3375**

Search for strong gravity signatures in same-sign dimuon final states
The ATLAS Collaboration
e-Print: **arXiv:1111.0080**

ATLAS and CMS intensively use Black Max

- **Newest limit (2012): minimal black hole mass > 5 TeV**

38

Conclusions

- Fine tuning in the SM may imply strong gravity at a TeV scale
- If gravity is strong, we can expect non-perturbative quantum gravity effects at soon available energies in accelerators
- Like mini black hole production
- Our knowledge about higher dimensional BH improved significantly

HOWEVER:

- The weakest link in TeV scale gravity models → fast proton decay
- Realistic models with stable proton:
  Some of the channels for black hole production are strongly suppressed

Auger ≠ LHC

THANK YOU

Quantum Gravity and the Weak Interactions

Stephon Alexander
Dartmouth College

Some Questions

- Why is the Weak Interaction Maximally parity violating?
- Why is the standard model Chiral?
- Like gravity the weak force interacts universally with all fermions

A Lesson on Chiral Gauge Theory

$$\mathcal{L} = -\frac{1}{4}\mathrm{F}^{\mathrm{a}}_{\mu\nu}\mathrm{F}^{\mathrm{a}\mu\nu} + \mathrm{ig}_1\mathrm{A}^{\mathrm{a}}_{\mathrm{L}}\sigma_\mu\mathrm{J}^{\mu}_{\mathrm{L}} + \mathrm{ig}_2\mathrm{A}^{\mathrm{a}}_{\mathrm{R}}\sigma_\mu\mathrm{J}^{\mu}_{\mathrm{R}}$$

But Parity Violating if couplings are not the same.

Maximal Parity violation if right handed Connection is missing

The Lesson

Parity violation can emerge from a Chiral and Parity Symmetric Mother Theory.

But what could it be....

See Lee Smolin's talk

Isogravity

Nesti, Percacci J.Phys (07), Alexander hep-th 0706.4481

- Idea: View Gravity as the gauging of

$$SO(3,1;C) = \mathrm{SL}(2,\mathbb{C})_L \times \mathrm{SL}(2,\mathbb{C})_R$$

- This is realized by the fact that the Complex Ashtekar-Sen variable is Chiral.

Mechanism

- Treat one SL(2,C) as the connection for gravity (Jacobson, Smolin ’84)
- The other SL(2,C) connection as the weak interaction
- Prediction: Both gravity and weak interactions are maximally parity violating.

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Leptonic Coupling

Spin index Isospin index

$$\psi_L{}^{ab}$$

$$\mathcal{L}_{\text{fermion}} = \det(E) \left(\mathrm{i}\, \overline{\psi}_L{}^{\dot{a}\dot{b}}\, E_I{}^{\mu}\, \sigma^I{}_{a\dot{a}}\, s_{b\dot{b}}\, D_\mu \psi_L{}^{ab} + \text{h.c.} \right)$$

$$D_\mu \psi_L{}^{ab} = \partial_\mu \psi_L{}^{ab} + A^{La}_{\mu}{}_{c}\, \psi_L{}^{cb} + A^{Lb}_{\mu}{}_{d}\, \psi_L{}^{ad}$$

The Low Energy Effective Action

$$\mathcal{L}_{\text{gauge}} = \det(E)\left[\frac{1}{16\pi G}\left(E_I{}^{\mu}\,\sigma^I{}_{a\dot{a}}\,E_J{}^{\nu}\,\sigma^{J b\dot{a}}\,F^{L\ a}_{\mu\nu\ \ b} + \text{c.c.}\right)\right.$$
$$- \frac{1}{4g^2}\left((s^{-1})^{d\dot{a}}\,\overline{F}^{L\ \dot{b}}_{\mu\nu\ \ \dot{a}}\,s_{c\dot{b}}\,F^{L\mu\nu c}{}_{d}\right)$$
$$+ \frac{m^2}{16}\left((s^{-1})^{a\dot{d}}D_{\mu}s_{c\dot{d}}\right)\left((s^{-1})^{Lc\dot{b}}D^{\mu}s_{a\dot{b}}\right)$$

The s field breaks the SL(2,C) to SU(2) Weak

The Low Energy Effective Action

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The s field breaks the SL(2,C) to SU(2) Weak

Gravity Sector

Modified Metricity Condition

$$\frac{1}{8\pi G} D^L_\nu \left(E_I{}^\mu E_J{}^\nu \, \sigma^I \, \bar{\sigma}^J\right) = \frac{1}{2g^2} D^L_\nu \left(s^{-1} \, F^{L\dagger\mu\nu} \, s\right) - \frac{m^2}{8} s^{-1} D^{L\mu} s \quad = \quad 0 \, .$$

Perturbed Metricity Condition

$$\frac{1}{8\pi G}\left[\delta A^{IJ}_\mu \wedge \delta^{(\mu}_J \delta^{\nu)}_J \sigma^I \bar{\sigma}^J + 2\delta^{(\mu}_I \partial_\nu e^{\nu)}_J \sigma^{[I} \bar{\sigma}^{J]}\right] + \frac{1}{g^2}\partial^\mu \partial_{[\mu} \delta A_{\nu]} + m^2 \delta A^t_\nu = 0$$

Modified Gravity Wave

$$\Box h_i{}^j(t, \vec{x}) = \frac{1}{\sqrt{|g|}} \partial_\mu (\sqrt{|g|} \, g^{\mu\nu} \, \partial_\nu) \, h_i{}^j(t, \vec{x}) = \kappa (A^2_k) \eta^j_i + A^2_k h_i{}^j)$$

The Electroweak Sector

$$
\begin{aligned}
&\mathcal{L}_{\text{gauge+fermion}} \\
&= -\frac{1}{4g^2}\left(\mathrm{tr}\left[-\tilde{F}^L_{\mu\nu}\tilde{F}^{L\mu\nu} - [B^L_\mu, B^L_\nu]^2 + \left(\tilde{D}_\mu B^L_\nu - \tilde{D}_\nu B^L_\mu\right)^2 - \tilde{F}^L_{\mu\nu}[B^{L\mu}, B^{L\nu}]\right]\right) \\
&\quad + \frac{m^2}{2}\,\mathrm{tr}\left(B^L\right)^2 + \mathrm{h.c.} \\
&\quad + \mathrm{i}\,\overline{\nu}_L{}^{\dot{a}}\,E_I{}^\mu\,\overline{\sigma}^I_{a\dot{a}}\left[\partial_\mu \nu^a_L + \left(\tilde{A}^{La}_\mu{}_b + B^{La}_\mu{}_b\right)\nu_L{}^b + \begin{pmatrix} \tilde{A}^{L1}_\mu{}_1 & \tilde{A}^{L1}_\mu{}_2 \\ \tilde{A}^{L2}_\mu{}_1 & \tilde{A}^{L2}_\mu{}_2 \end{pmatrix}\begin{pmatrix} \nu_L{}^a \\ e_L{}^a \end{pmatrix}\right. \\
&\qquad\qquad\left. + \begin{pmatrix} B^{L1}_\mu{}_1 & B^{L1}_\mu{}_2 \\ B^{L2}_\mu{}_1 & B^{L2}_\mu{}_2 \end{pmatrix}\begin{pmatrix} \nu_L{}^a \\ e_L{}^a \end{pmatrix}\right] + \mathrm{h.c.} \\
&\quad + \mathrm{i}\,\overline{e}_L{}^{\dot{a}}\,E_I{}^\mu\,\overline{\sigma}^I_{a\dot{a}}\left[\partial_\mu e^a_L + \left(\tilde{A}^{La}_\mu{}_b + B^{La}_\mu{}_b\right)e_L{}^b + \begin{pmatrix} \tilde{A}^{L1}_\mu{}_1 & \tilde{A}^{L1}_\mu{}_2 \\ \tilde{A}^{L2}_\mu{}_1 & \tilde{A}^{L2}_\mu{}_2 \end{pmatrix}\begin{pmatrix} \nu_L{}^a \\ e_L{}^a \end{pmatrix}\right. \\
&\qquad\qquad\left. + \begin{pmatrix} B^{L1}_\mu{}_1 & B^{L1}_\mu{}_2 \\ B^{L2}_\mu{}_1 & B^{L2}_\mu{}_2 \end{pmatrix}\begin{pmatrix} \nu_L{}^a \\ e_L{}^a \end{pmatrix}\right] + \mathrm{h.c.}
\end{aligned}
$$

$$\nu_L{}^a = \psi_L{}^{a1}\,, \qquad e_L{}^a = \psi_L{}^{a2}$$

Standard Vertex

New Vertex

$$\mathrm{i}\,\overline{\nu}_L{}^{\dot{a}}\, E_I{}^{\mu}\, \overline{\sigma}^I_{a\dot{a}} \left[\partial_\mu \nu_L^a + \begin{pmatrix} \tilde{A}^{L1}_{\mu}{}_1 & \tilde{A}^{L1}_{\mu}{}_2 \\ \tilde{A}^{L2}_{\mu}{}_1 & \tilde{A}^{L2}_{\mu}{}_2 \end{pmatrix} \begin{pmatrix} \nu_L{}^a \\ e_L{}^a \end{pmatrix}\right]$$

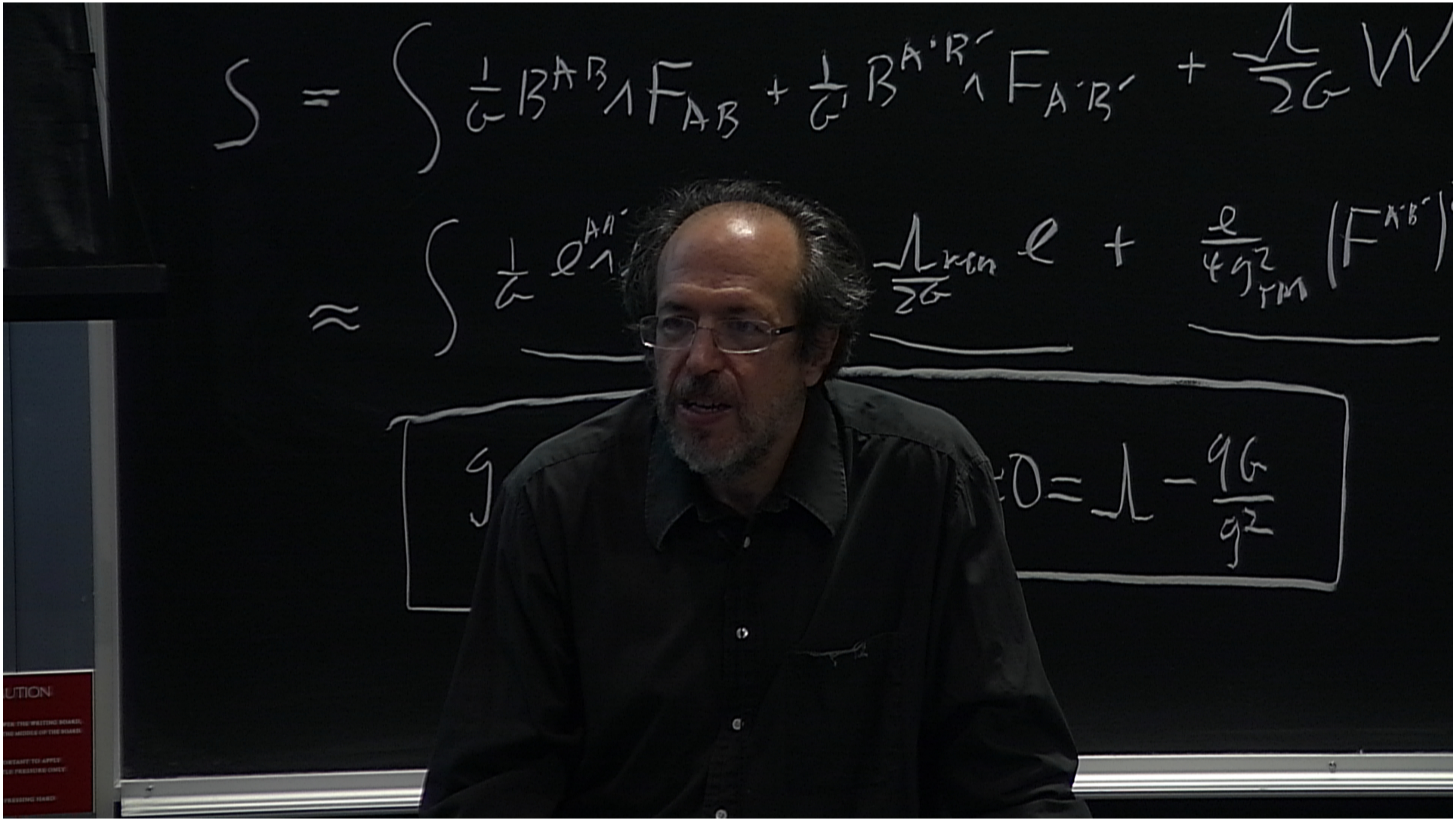
Quantization

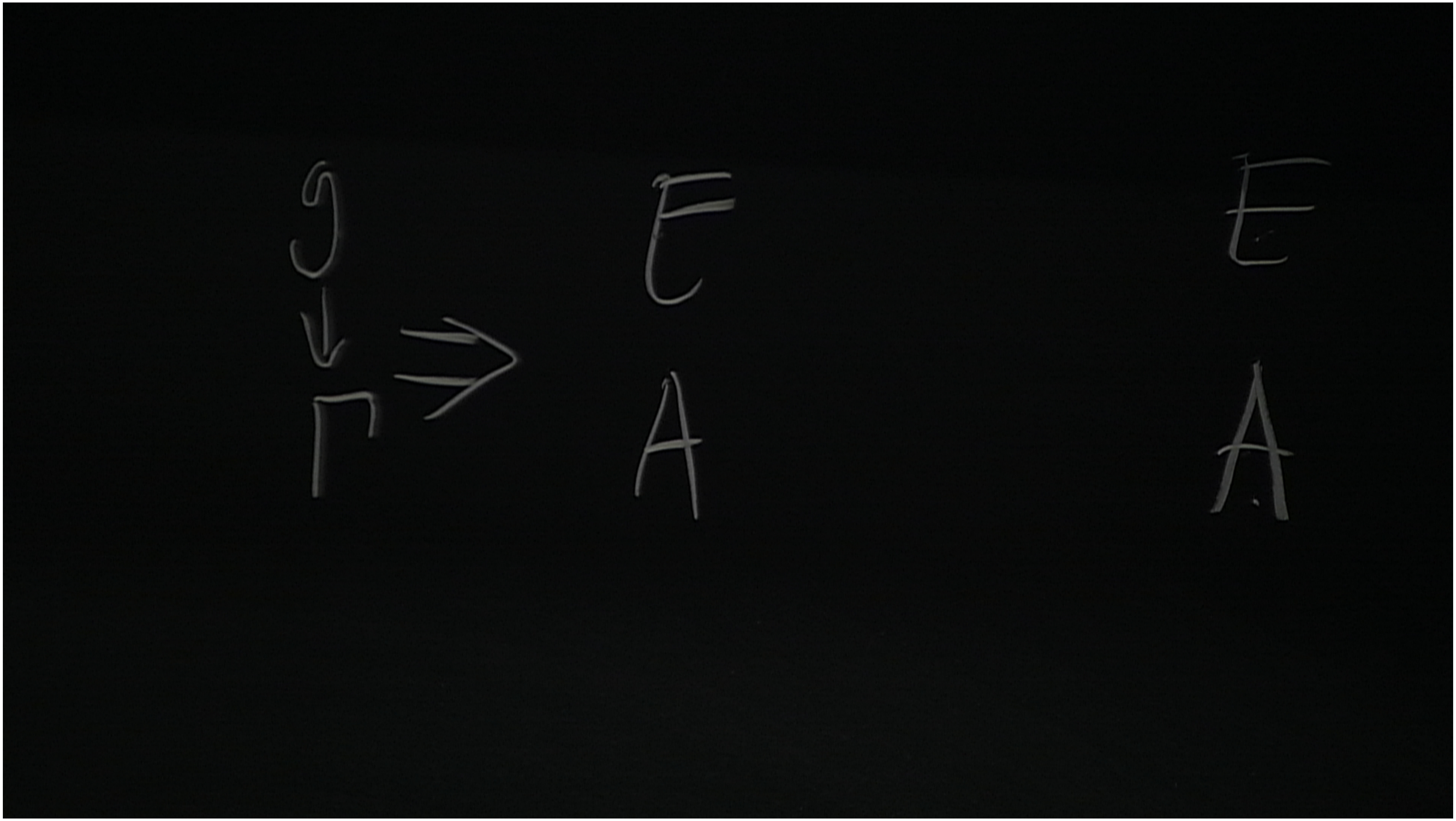
Work in progress S.A and Stojkovic

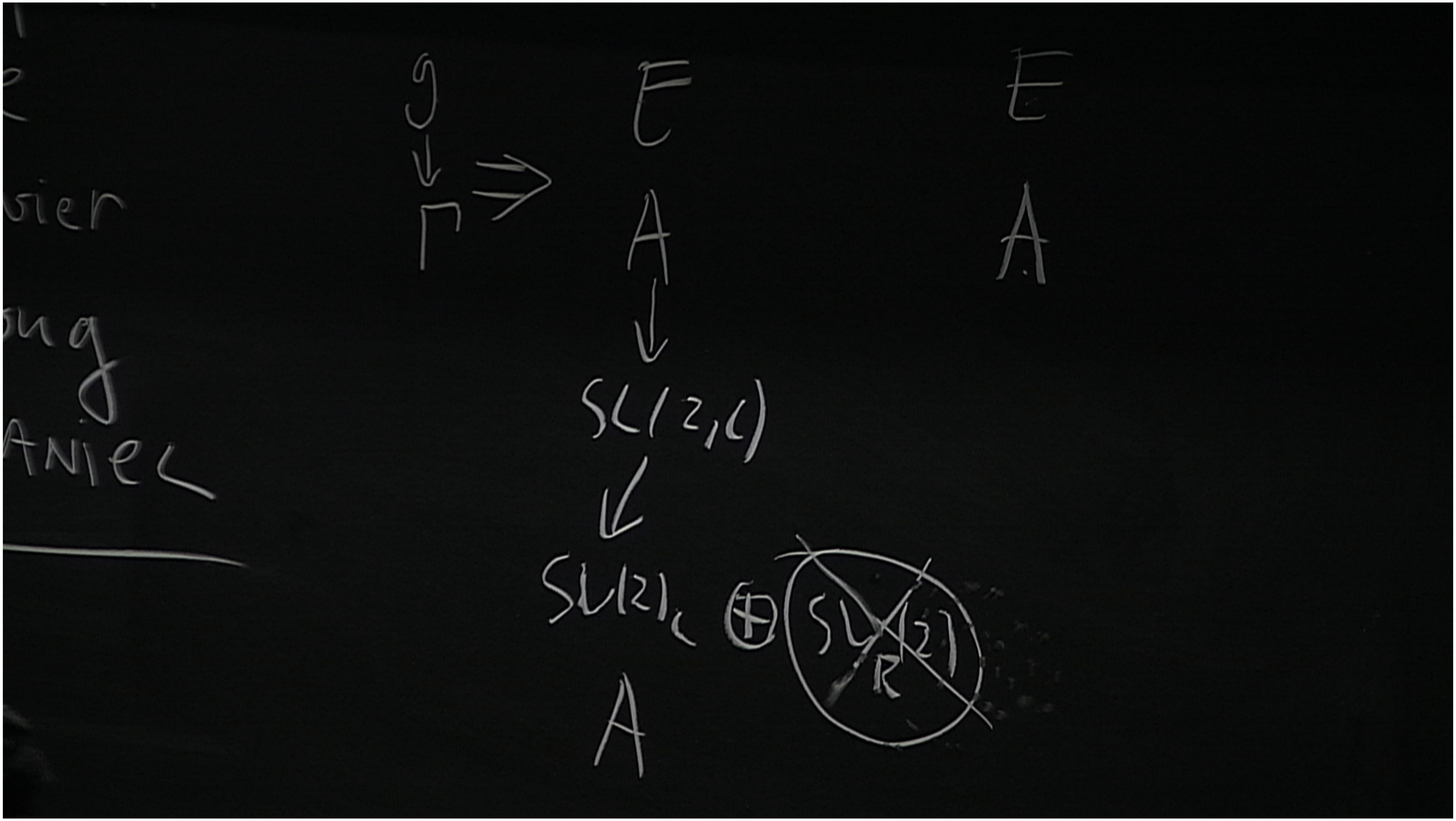
- What is the mother theory from which this parity symmetry breaking is realized?
- Quantum Gravity?
- This was studied in 3D by S.A, Marciano and Tacchi (Phys Lett B. 2012)

Conclusion

- Chirality and Parity Violation in EW Theory arises from its other gravitational "hand"
- What theory does this arise from? (Stay tuned for Smolin's talk)
- Where is the Higgs? Reality Conditions? (Stay tuned for Smolin's talk)
- A 3D spin-foam quantization shows that the quantum theory relates Yang-Mills lattice to quanta of space.
- We expect new predictions for upcoming LHC (or existing LHC experiments)




g ↓ Γ ⇒
E
A
E
A


g
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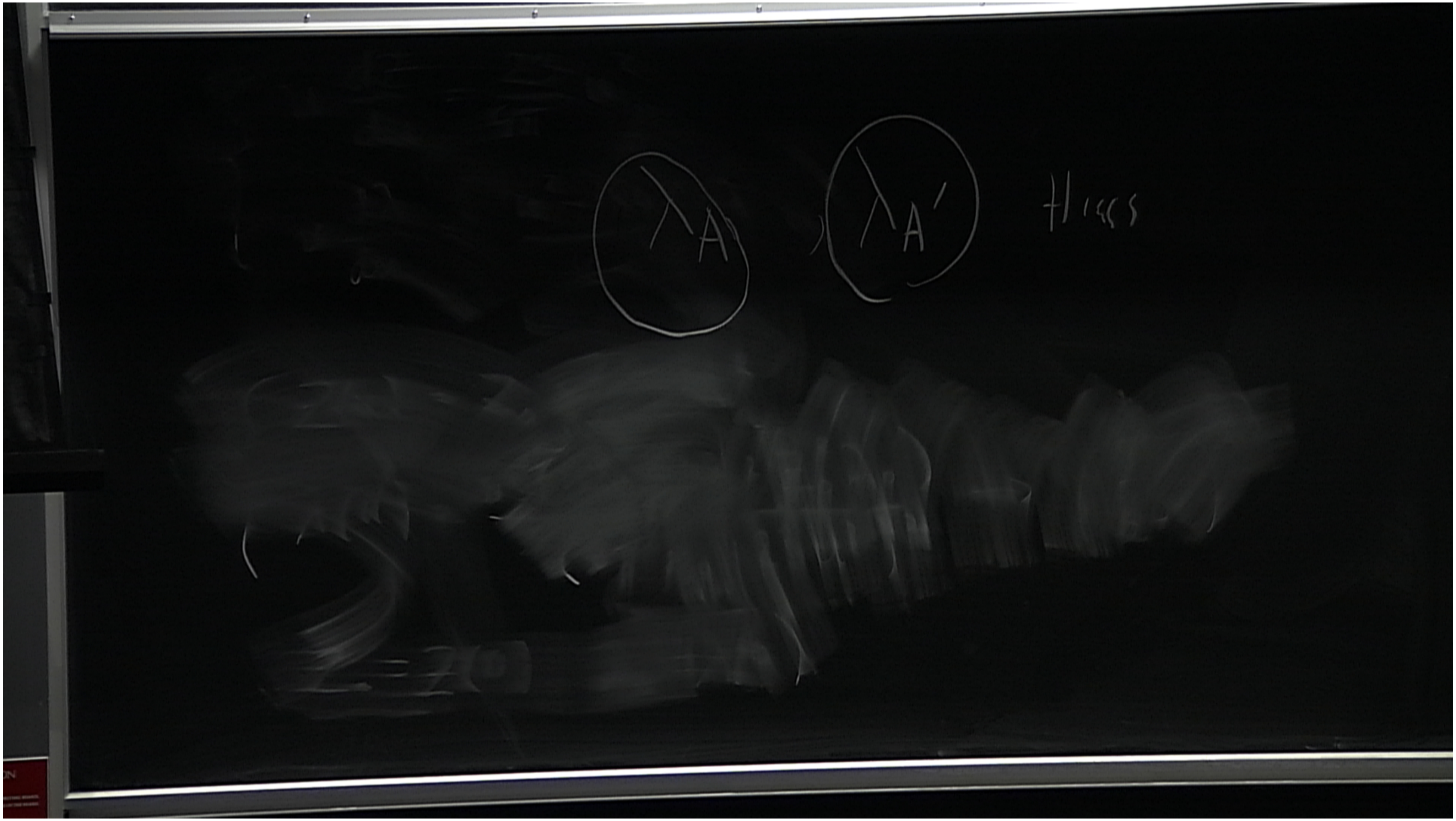
SL(2,C)
SL(2)_C ⊕ SL_R(2)
A
E
A


Higgs

$$S = S^L + S^R + S^{mix}$$

$$S^L = \int_{M_4} \frac{1}{G} B^{AB} \wedge F_{AB} - \frac{1}{2} \phi_{ABCD} B^{AB} \wedge B^{CD} - \frac{\Lambda}{2G} B^{AB} \wedge B_{AB}$$

$$S^{mix} = \int -\frac{1}{2} \phi_{ABA'B'} B^{AB} \wedge B^{A'B'} + \frac{g^2}{2} \Phi^2 \left(B_{AB} B^{AB} - B^{A'B'} \right)$$

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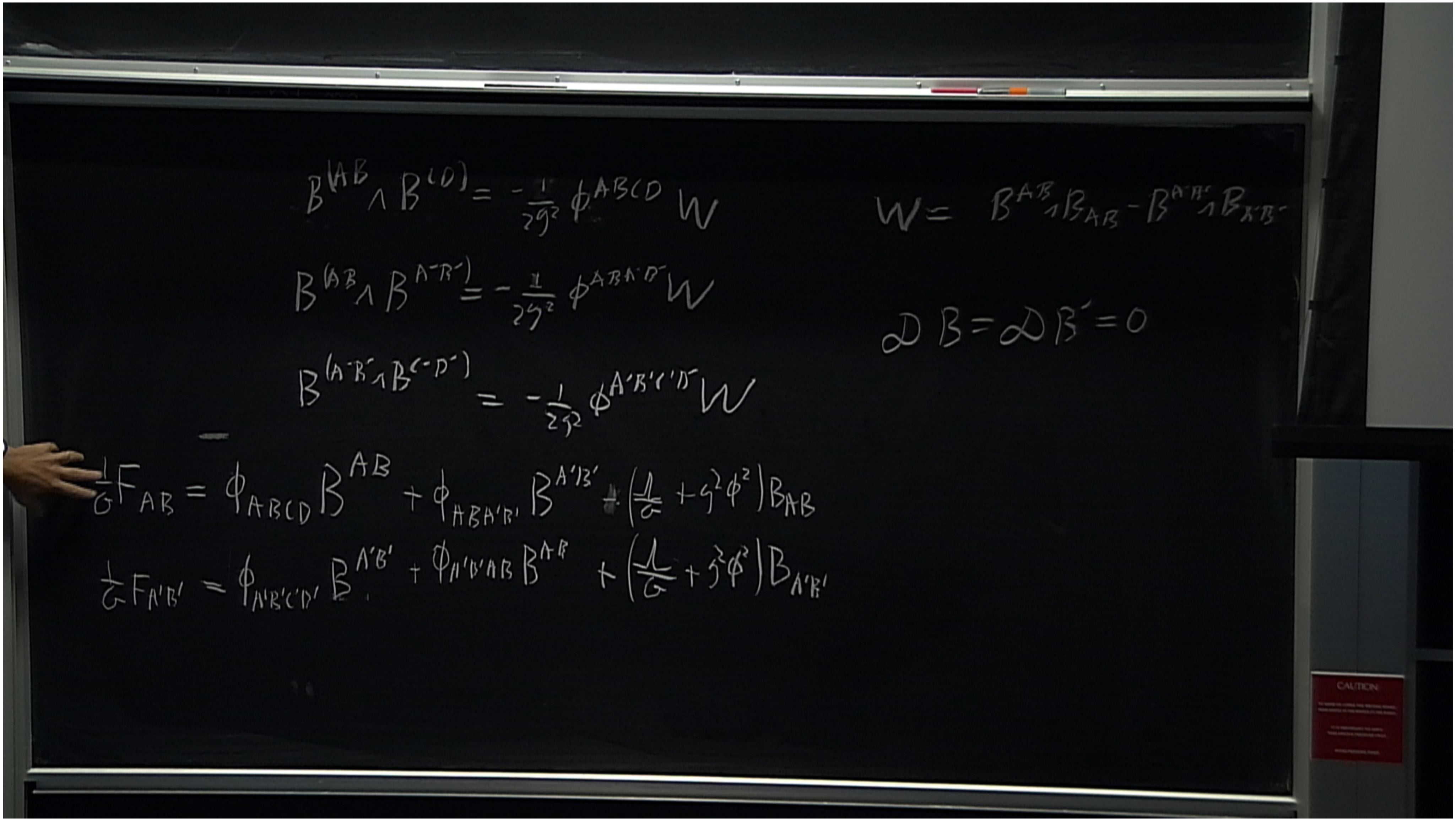
$B^{(AB} \wedge B^{CD)} = -\frac{1}{2g^2} \phi^{ABCD} W$
$B^{(AB} \wedge B^{A'B')} = -\frac{1}{2g^2} \phi^{ABA'B'} W$
$B^{(A'B'} \wedge B^{C'D')} = -\frac{1}{2g^2} \phi^{A'B'C'D'} W$
$\frac{1}{G} F_{AB} = \phi_{ABCD} B^{AB} + \phi_{ABA'B'} B^{A'B'} + \left(\frac{1}{G} + g^2\phi^2\right) B_{AB}$
$\frac{1}{G} F_{A'B'} = \phi_{A'B'C'D'} B^{A'B'} + \phi_{A'B'AB} B^{AB} + \left(\frac{1}{G} + g^2\phi^2\right) B_{A'B'}$
$W = B^{AB} \wedge B_{AB} - B^{A'B'} \wedge B_{A'B'}$
$\mathcal{D} B = \mathcal{D} B' = 0$

$$B^{(AB}\wedge B^{CD)} = -\frac{1}{2g^2}\phi^{ABCD}\, W$$

$$B^{(AB}\wedge B^{A'B')} = -\frac{1}{2g^2}\phi^{ABA'B'}\, W$$

$$B^{(A'B'}\wedge B^{C'D')} = -\frac{1}{2g^2}\phi^{A'B'C'D'}\, W$$

$$W = B^{AB}\wedge B_{AB} - B^{A'B'}\wedge B_{A'B'}$$

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$$\frac{1}{G}F_{A'B'} = \phi_{A'B'C'D'}B^{A'B'} + \phi_{A'B'AB}B^{AB} + \left(\frac{\Lambda}{G} + g^2\phi^2\right)B_{A'B'}$$

$$B^{(AB}\wedge B^{CD)} = -\frac{1}{2g^2}\phi^{ABCD}\, W$$

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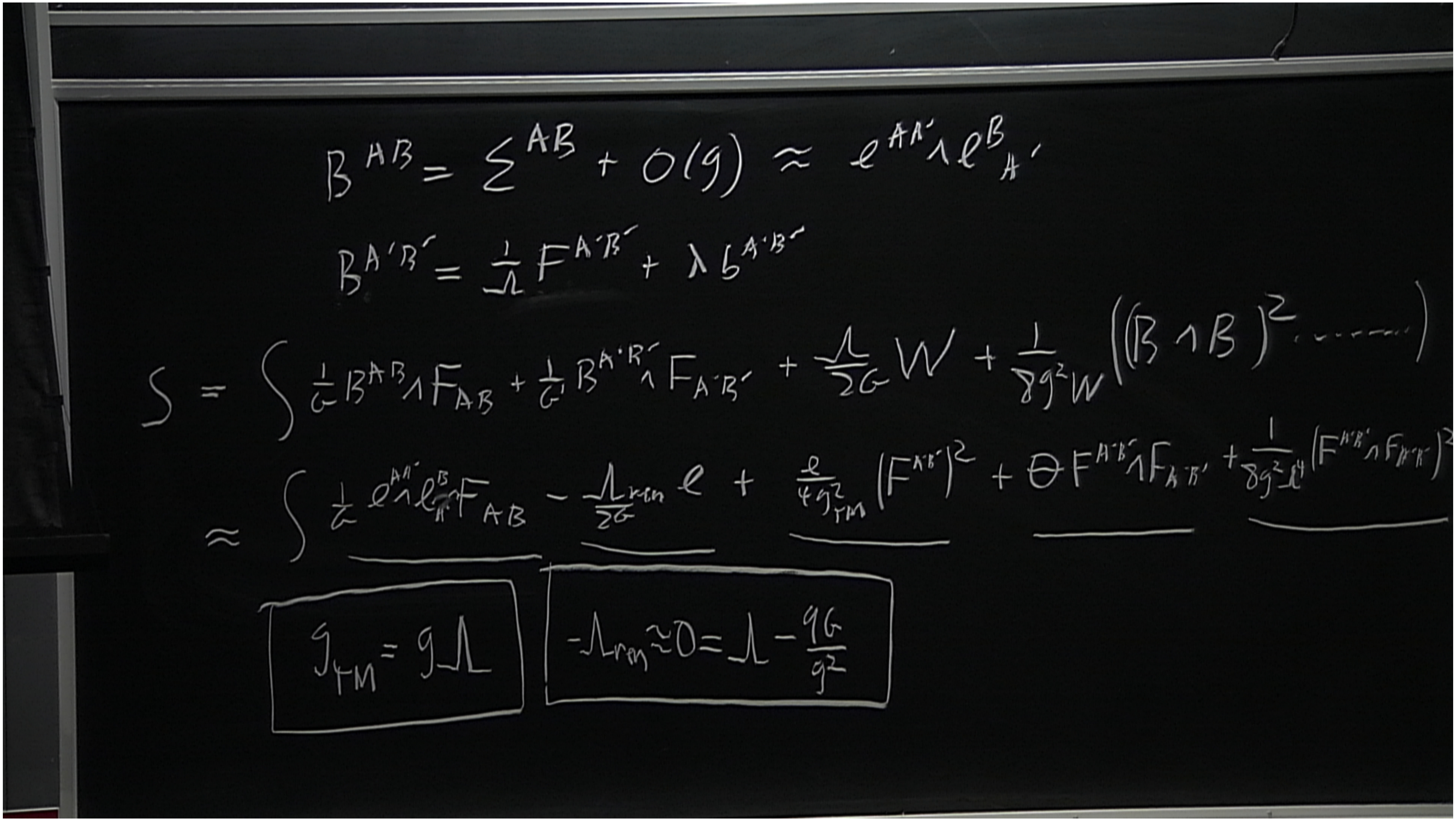
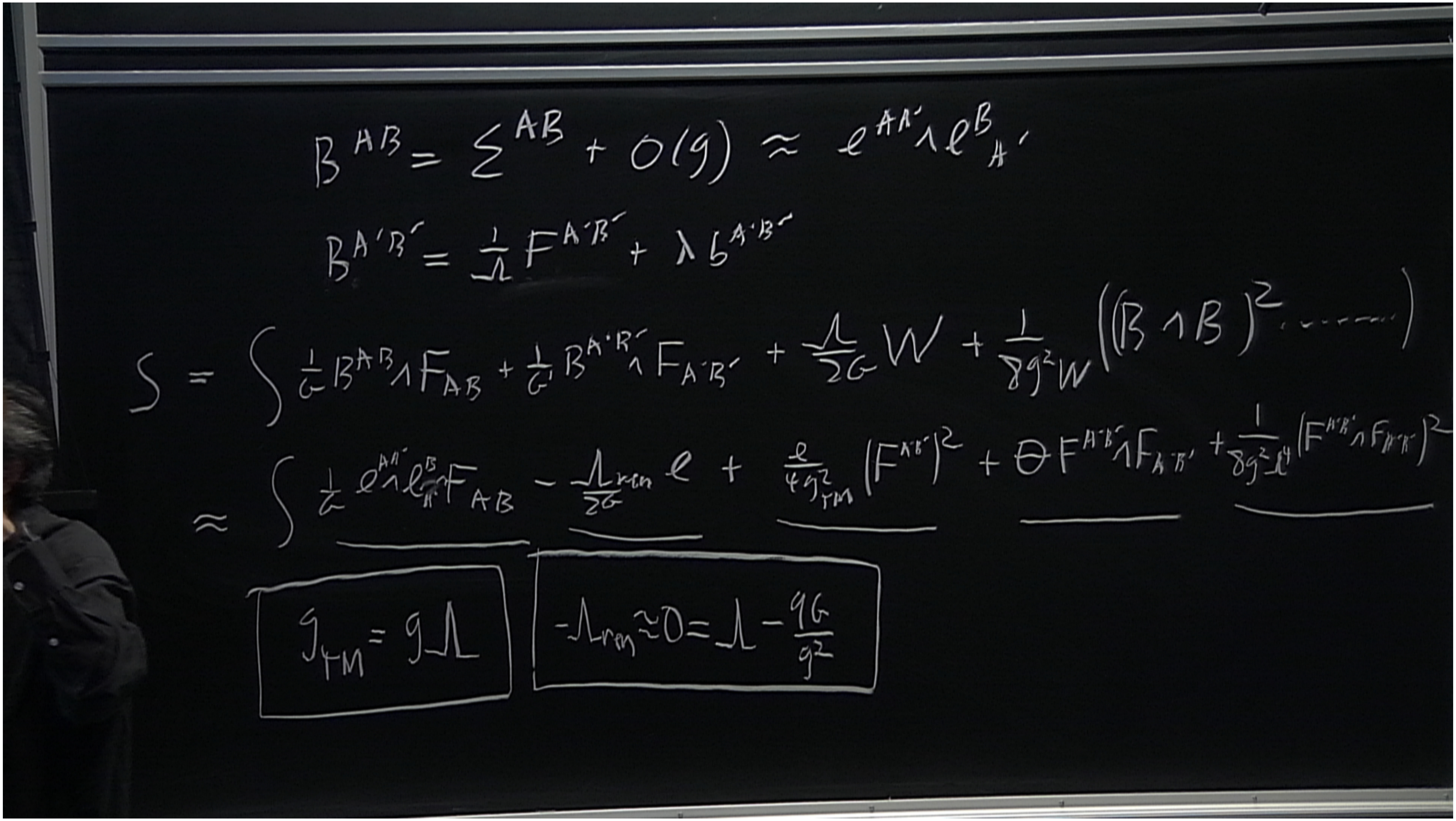

$B^{AB} = \Sigma^{AB} + O(g) \approx e^{AA'} \wedge e^{B}{}_{A'}$
$B^{A'B'} = \frac{1}{\Lambda} F^{A'B'} + \lambda b^{A'B'}$
$S = \int \frac{1}{G} B^{AB} \wedge F_{AB} + \frac{1}{G} B^{A'B'} \wedge F_{A'B'} + \frac{\Lambda}{2G} W + \frac{1}{8g^2 W}\left((B \wedge B)^2 \ldots\ldots\right)$
$\approx \int \frac{1}{G} e^{AA'} \wedge e^{B}{}_{A'} \wedge F_{AB} - \frac{\Lambda_{ren}}{2G} e + \frac{e}{4g^2_{YM}} (F^{A'B'})^2 + \Theta F^{A'B'} \wedge F_{A'B'} + \frac{1}{8g^2 e^4} (F^{A'B'} \wedge F_{A'B'})^2$
$g_{YM} = g\Lambda$
$-\Lambda_{ren} \simeq 0 = \Lambda - \frac{9G}{g^2}$



$B^{AB} = \Sigma^{AB} + O(g) \approx e^{AA'} \wedge e^{B}{}_{A'}$
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$-\Lambda_{ren} \simeq 0 = \Lambda - \frac{9G}{g^2}$

Non-thermal quantum black holes

Xavier Calmet

Physics & Astronomy
University of Sussex

Frameworks for Quantum Black Holes (QBHs) at 1 TeV

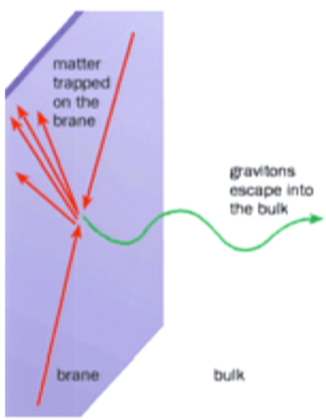
- Large extra-dimensions
- Large hidden sector (and 4 dimensions)
- Common feature: gravity becomes strong at 1 TeV and QBHs could be produced at colliders

TeV gravity extra-dimensions

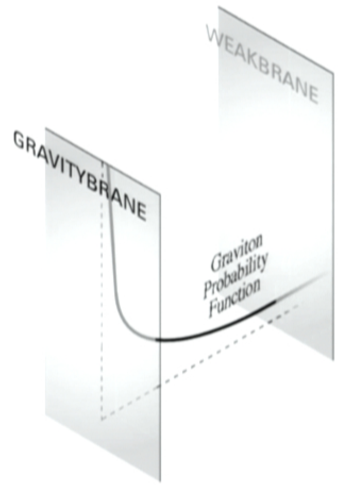
$$\int d^4x\, d^{d-4}x' \sqrt{-g}\ \left(M_*^{d-2}\mathcal{R} + \cdots \ \right) \qquad M_P^2 = M_*^{d-2} V_{d-4}$$

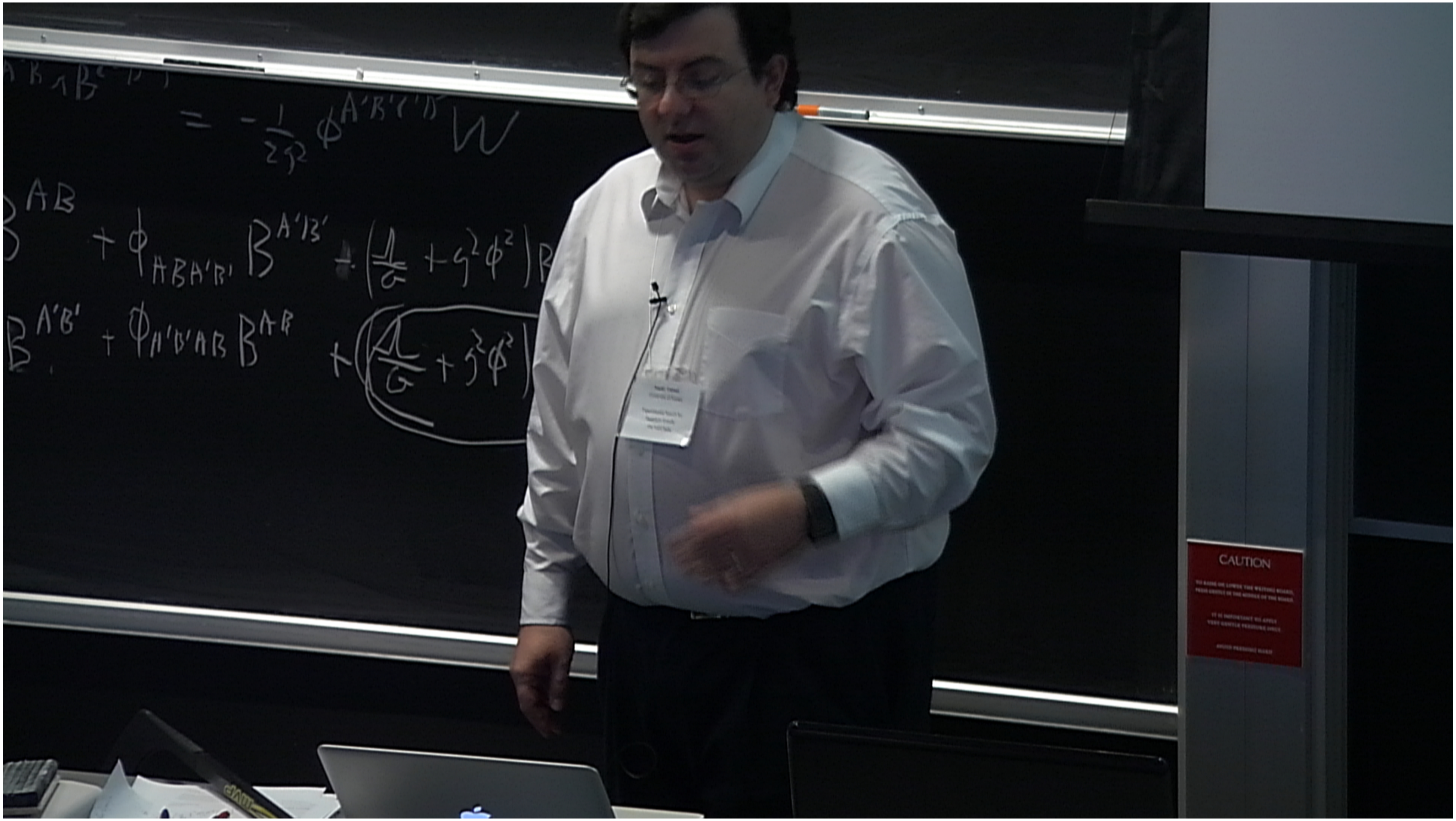
where M_P is the effective Planck scale in 4-dim

ADD brane world



RS warped extra-dimension



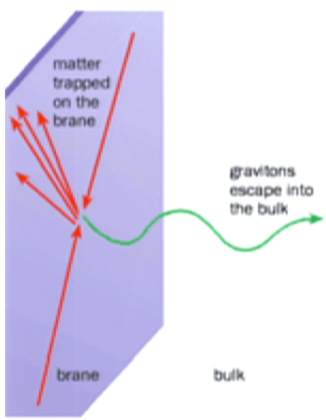

CAUTION

TeV gravity extra-dimensions

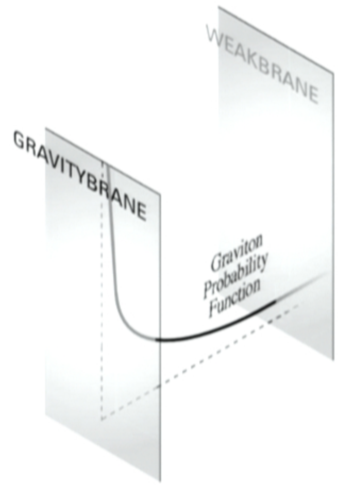
$$\int d^4x\, d^{d-4}x' \sqrt{-g}\ (M_*^{d-2}\mathcal{R} + \cdots\ ) \qquad M_P^2 = M_*^{d-2} V_{d-4}$$

where M_P is the effective Planck scale in 4-dim

ADD brane world



RS warped extra-dimension




CAUTION

Running of Newton's constant

- Consider GR with a massive scalar field

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{16\pi G} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{m^2}{2} \phi^2 \right)$$

- Let me consider the renormalization of the Planck mass:

$$M(\mu)^2 \;=\; M(0)^2 - \frac{\mu^2}{12\pi} \left(N_0 + N_{1/2} - 4N_1 \right)$$

- Can be derived rigorously using the heat kernel method (regulator preserves symmetries!)
- Gravity becomes strong if:

$$M(\mu_*) \sim \mu_*$$

NB: This is only QFT in curved space time

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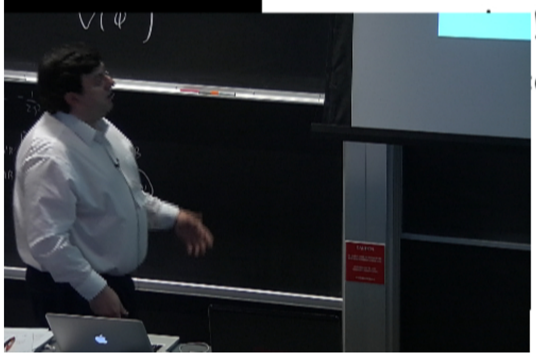

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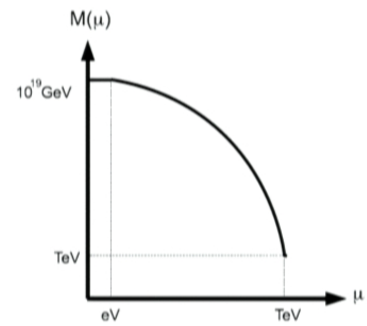
NB: This is only QFT in curved space time

Like any other coupling constant: Newton's constant runs!

A large hidden sector!

XC, Hsu & Reeb (2008)

- Gravity can be strong at 1 TeV if Newton's constant runs fast somewhere between eV range and 1 TeV.



- Strong gravity at μ_{*}=1 TeV takes N=10^{33} fields.

- We assume that these new fields only interact gravitationally with the standard model.

- This will reproduce a lot of the phenomenology of models with large extra-dimensions

We do not know at what energy scale quantum gravitational effects become large!

It could be between a few TeV and the traditional 10^{19} GeV

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Instead of indirect searches: let's look for QG effects directly and in particular small black holes.

We could potentially probe the symmetries of quantum gravity.

LHC is a quantum gravity machine.

A brief review on the formation of black holes

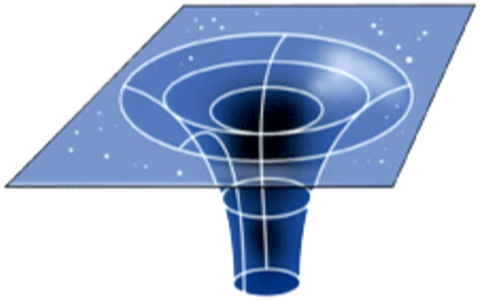
Even if the Planck scale is at 10^{19} GeV we learned a lot about black hole formation (i.e. GR)!

When does a black hole form?

This is well understood in general relativity with symmetrical distribution of matter:

$$c^2 d\tau^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \frac{dr^2}{1 - \frac{r_s}{r}} - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$r_s = \frac{2GM}{c^2}$$



But, what happens in particle collisions at extremely high energies?

Small black hole formation

(in collisions of particles)

- In trivial situations (spherical distribution of matter), one can solve explicitly Einstein's equations e.g. Schwarzschild metric.
- In more complicated cases one can't solve Einstein equations exactly and one needs some other criteria.
- Hoop conjecture (Kip Thorne): if an amount of energy E is confined to a ball of size R, where $R < E$, then that region will eventually evolve into a black hole.

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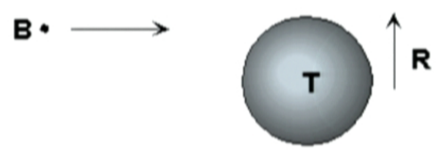
- Cross section for semi-classical BHs (closed trapped surface constructed by Eardley & Giddings):

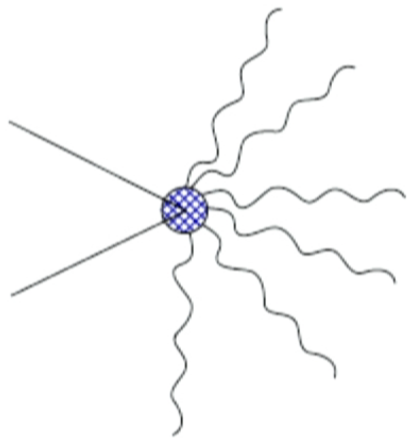
$$\hat{\sigma} \approx \pi r_s^2 \qquad r_s(M_{\mathrm{BH}}) = \frac{1}{M_D}\left[\frac{M_{\mathrm{BH}}}{M_D}\right]^{\frac{1}{1+n}}\left[\frac{2^n \pi^{(n-3)/2}\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{1+n}}$$

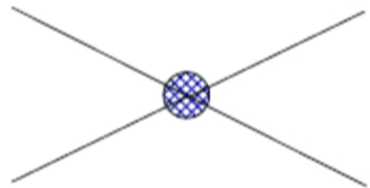


$$r_s = \frac{2GM}{c^2}$$

The cross section for point-like particles colliding with a sphere is just the area of the sphere projected onto the transverse plane, that is, a circular disk of radius R.

From Semi-classical (thermal) to quantum black hole:





Eardley and Giddings construction only works for $m_{BH}>>M_P$. Thus semi-classical BHs will not be produced at the LHC, but quantum black holes could!

Assumptions on Quantum Black Holes decays

- Gauge invariance is preserved (conservation of U(1) and $SU(3)_C$ charges)
- Quantum Black Holes do not couple to long wavelength and highly off-shell perturbative modes.
- Global charges can be violated. Lepton flavor is not necessarily conserved. Lorentz invariance could be broken or not.
- Gravity is democratic.
- We can think of quantum black holes as gravitational bound states.
- These considerations apply to the d=4 model but also to ADD and RS.

QCD for Quantum Black Holes

- Quantum Black Holes are classified according to representations of $SU(3)_C$.
- For LHC the following Quantum Black Holes are relevant:

$$\mathbf{3} \times \overline{\mathbf{3}} = \mathbf{8} + \mathbf{1}$$

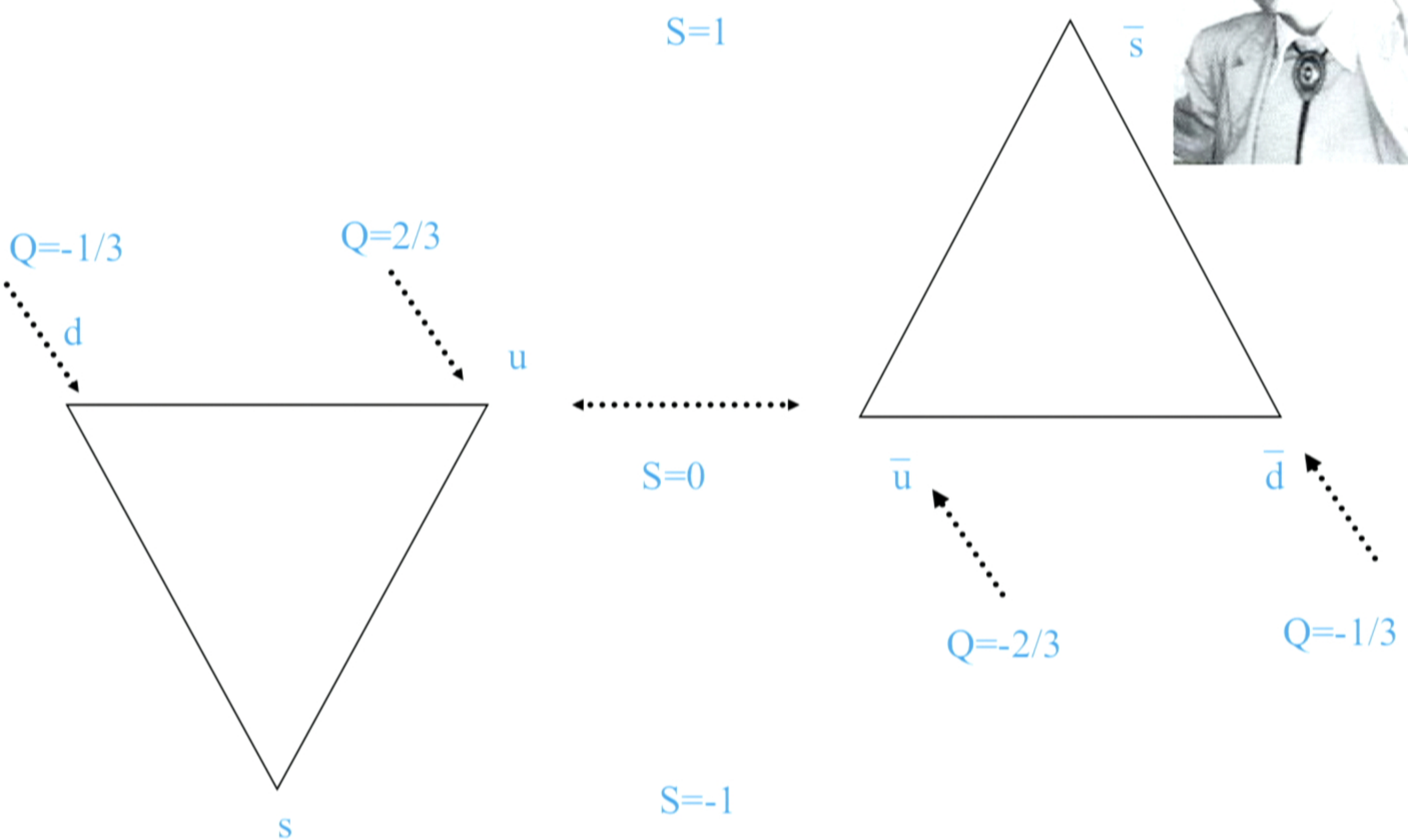
$$\mathbf{3} \times \mathbf{3} = \mathbf{6} + \overline{\mathbf{3}}$$

$$\mathbf{3} \times \mathbf{8} = \mathbf{3} + \overline{\mathbf{6}} + \mathbf{15}$$

$$\mathbf{8} \times \mathbf{8} = \mathbf{1}_S + \mathbf{8}_S + \mathbf{8}_A + \mathbf{10} + \overline{\mathbf{10}}_A + \mathbf{27}_S$$

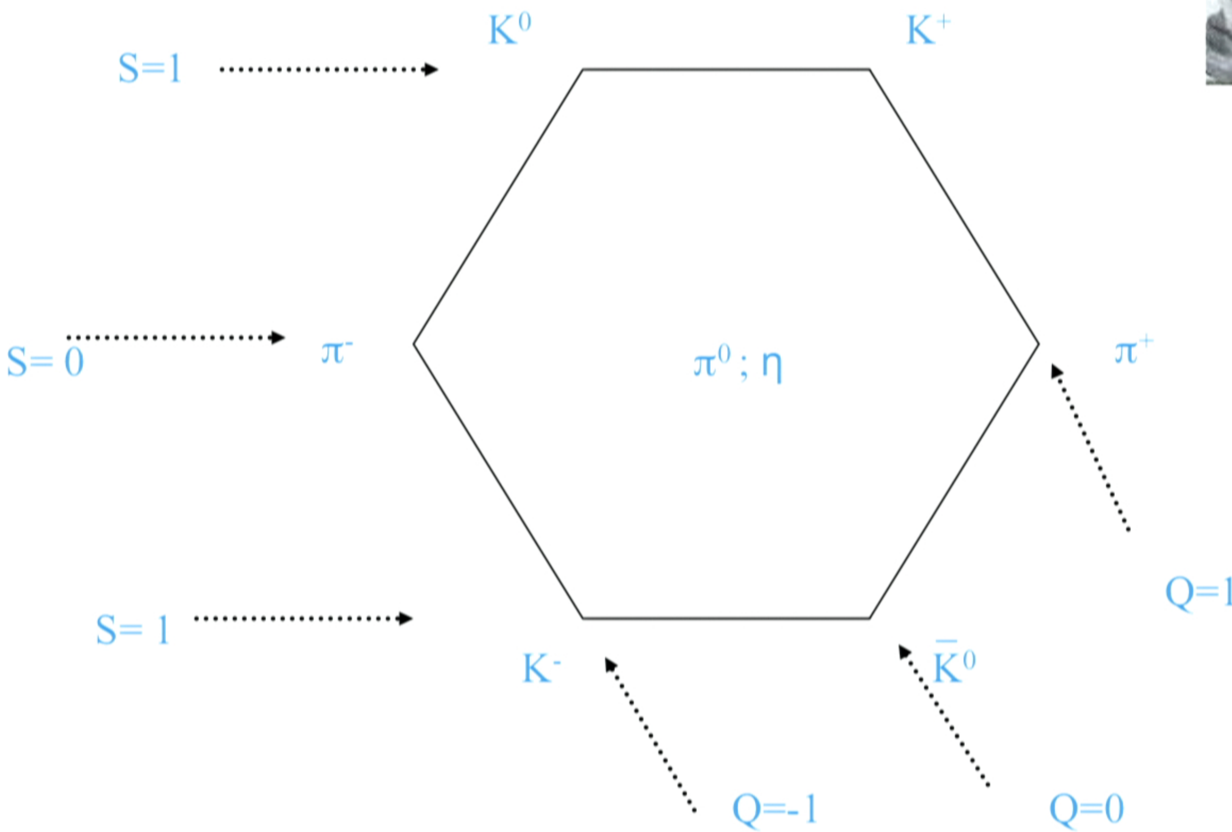
- They can have non-integer QED charges.
- They can carry a $SU(3)_C$ charge.

The Quark Model



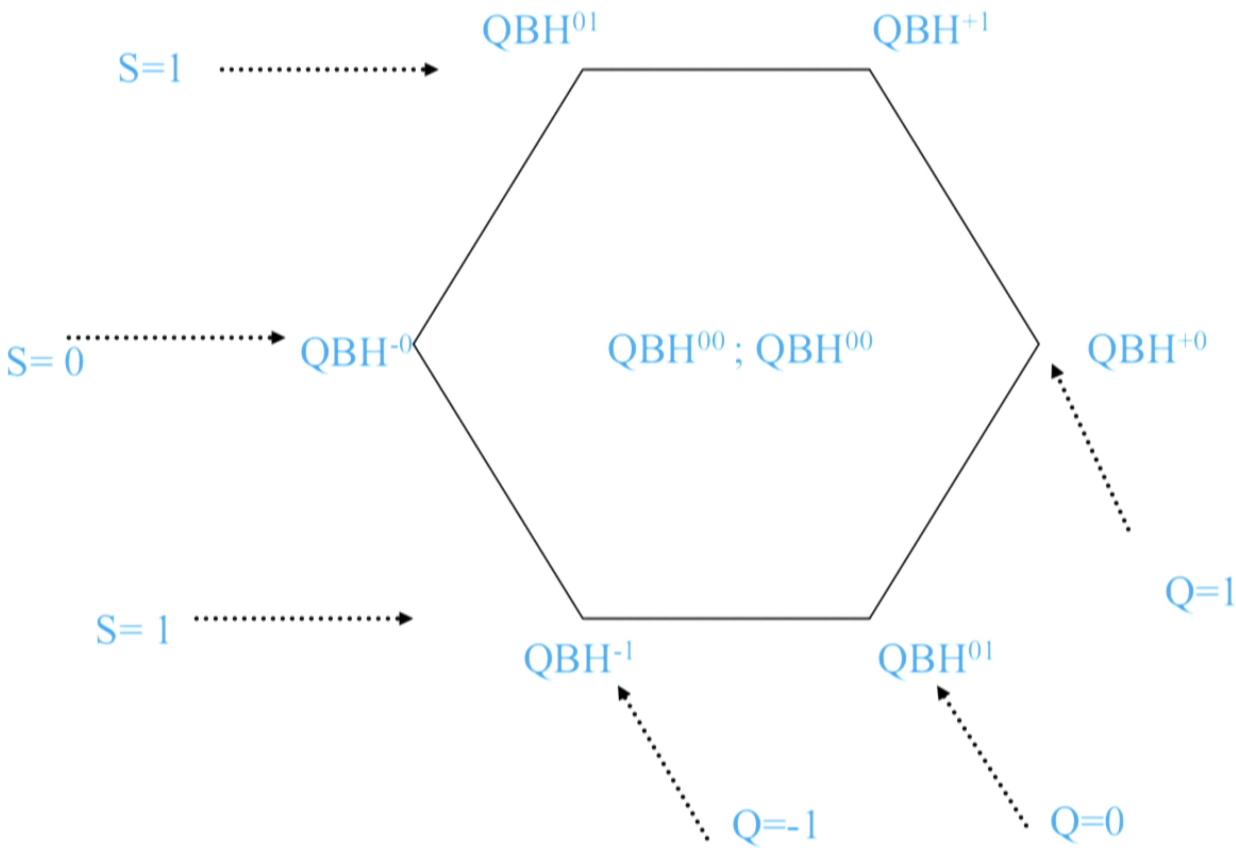
THE EIGHTFOLD WAY

The Meson Octet



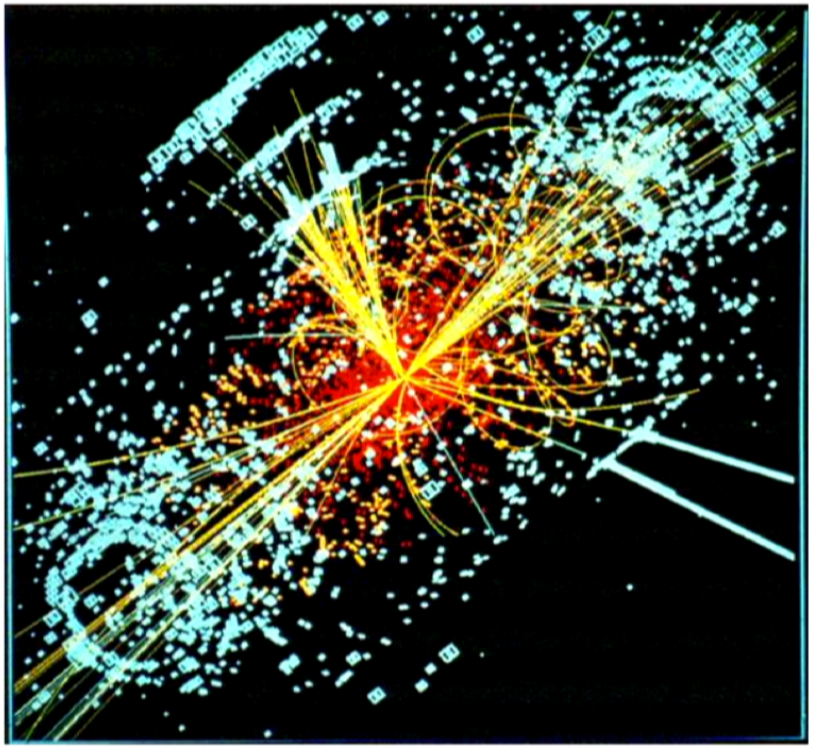
THE EIGHTFOLD WAY FOR QUANTUM BLACK HOLES

The Quantum Black Hole Octet



LHC signatures

If a BH is produced at the LHC it's important to understand how it will decay in order to find the needle in the haystack.



It is important to model the decay of small BHs

TeV Quantum Gravity @ LHC

- At 14 TeV LHC

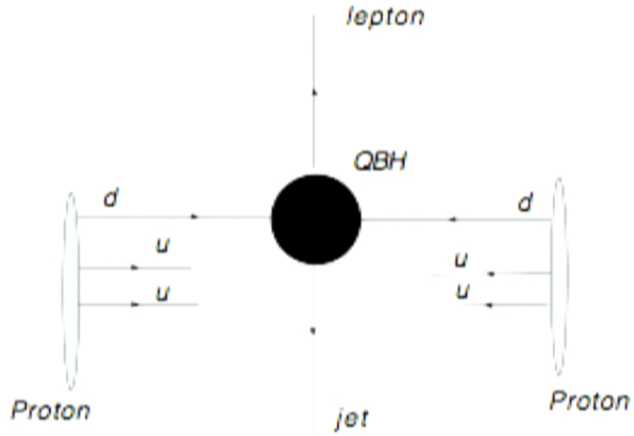
Models	RS	ADD $n = 5$	ADD $n = 6$	ADD $n = 7$	4 dim
σ(p+p $\rightarrow$ any QBH) in fb	4.41×10^2	7.94×10^3	1.06×10^4	1.35×10^4	16.83

for a reduced Planck scale of 3 TeV and minimal BH mass of 3 TeV.

- Very interesting signatures pp -> QBH -> lepton+ jet.
- Gravity is democratic: lepton can be e, μ or τ.
- A lot of two jets back to back events (dominant decay mode for QBH at LHC).
- LHC will put the tightest limit on the Planck scale and is probing quantum gravity

cross sections @ LHC

$$\mathbf{3} \times \mathbf{3} = \mathbf{6} + \overline{\mathbf{3}}$$



For illustration we assumed that lorentz symmetry was violated

cross-sections in fb	CHR	RS	ADD $n=5$	ADD $n=6$	ADD $n=7$
$\sigma(\text{p+p} \to \text{QBH}_{\bar{3}}^{4/3} \to l^+ + \bar{d})$	372	5.8×10^3	3.3×10^4	3.7×10^4	4×10^4
$\sigma(\text{p+p} \to \text{QBH}_{\bar{3}}^{-2/3} \to l^- + \bar{d})$	47	734	3.7×10^3	4×10^3	4.2×10^3
$\sigma(\text{p+p} \to \text{QBH}_{\bar{3}}^{1/3} \to \nu_i + \bar{d})$	160	2.5×10^3	1.4×10^5	1.5×10^4	1.6×10^4
$\sigma(\text{p+p} \to \text{QBH}_{\bar{3}}^{-2/3} \to \nu_i + \bar{u})$	47	734	3.7×10^3	4×10^3	4.2×10^3
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$\sigma(\text{p+p} \to \text{QBH}_{1}^{0} \to e^+ + \mu^-)$	0	93	447	491	511

New ideas/developments

- Major effort underway to update BlackMax.
- Mass spectrum of black holes could be discrete: cross sections are much smaller. This would affect the bounds.
- Cross sections:

$$\sigma^{pp}_{tot}(s, n, M_D) \ = \ \sum_i \sigma^{pp}_{QBH}(s, M^i_{QBH}, n, M_D)$$

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Discrete spectrum

cross section in fb	Model for low scale quantum gravity				
$\sigma\,(\mathrm{QBH} \rightarrow e^+ + e^-)$	4 dim [3]	ADD n = 5	ADD n = 6	ADD n = 7	RS
$M_D = 3$ TeV					
Model 1	3.95×10^{-3}	2.43	3.27	4.17	0.12
Model 2	3.24×10^{-3}	1.99	2.68	3.41	9.98×10^{-2}
Model 3	3.06×10^{-3}	1.89	2.54	3.24	9.46×10^{-2}
Model 4	2.90×10^{-3}	1.79	2.41	3.07	8.96×10^{-2}
Model 5	2.76×10^{-3}	1.70	2.29	2.92	8.52×10^{-2}

1. Lepton flavor, quark flavor, B-L and Lorentz invariance conserved,
2. lepton flavor violated, everything else conserved,
3. quark flavor violated, everything else conserved,
4. quark and lepton flavor violated, B-L conserved,
5. and everything violated except Lorentz invariance.

Work with
D. Fragkakis &
N. Gausmann

Only black hole on Earth spotted so far was in Belgium

There is a Belgian beer called "black hole".

So far Belgium has not imploded…
despite black holes

Conclusions

- There are different options for TeV quantum gravity.
- Quantum gravity could be around the corner even in 4 dimensions: this is really an experimental question.
- Unique opportunity to learn about gravity at short distances and in particular about black holes.
- Gravity is still a fascinating playground.
- LHC phenomenology would be extremely rich.
- Exciting flavor physics in quantum black holes scenarios.

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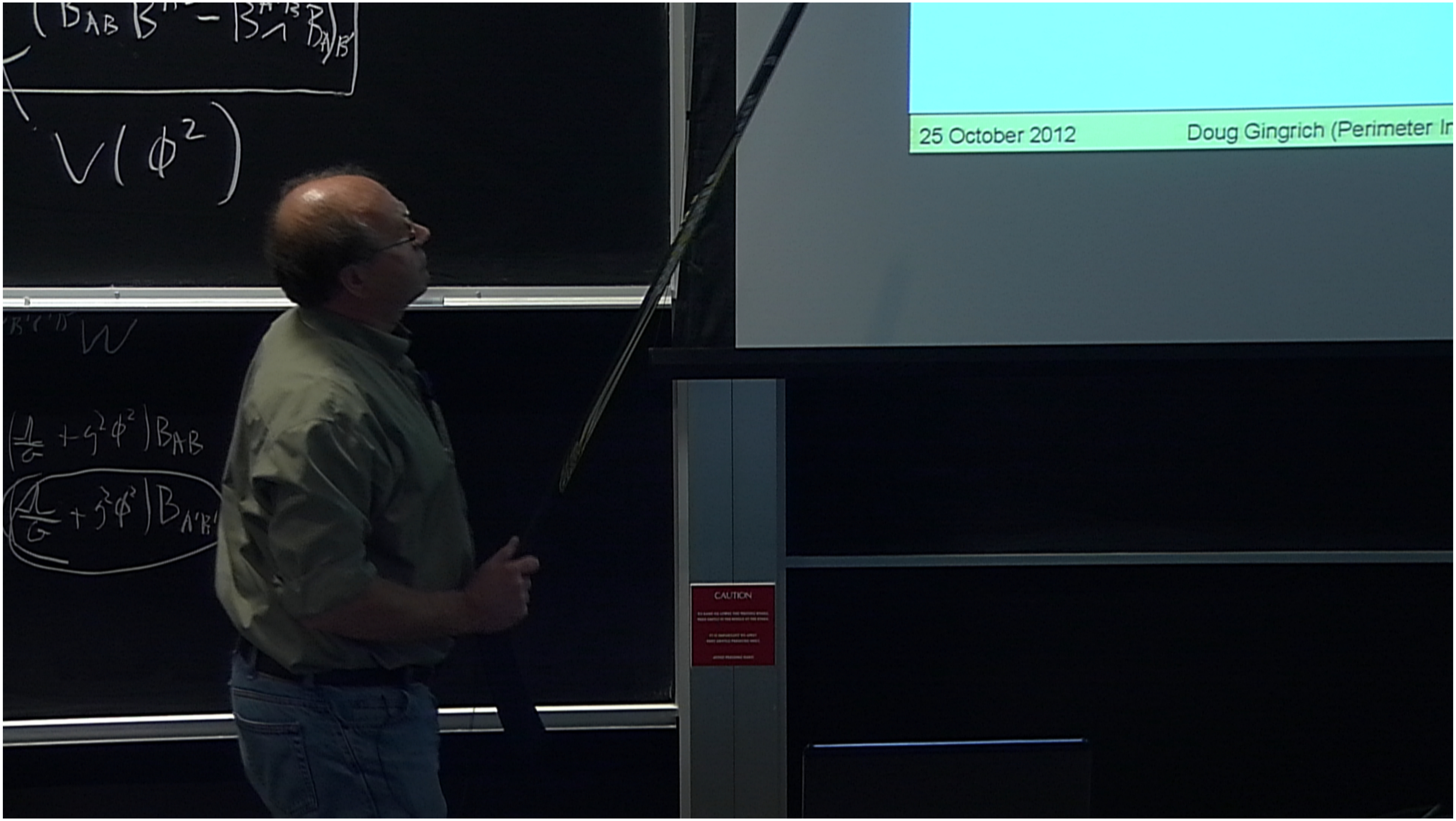
From Classical to Quantum GR:
Applications to Black Holes
A Winter School at the University of Sussex
January 16-18 2012
https://indico.cern.ch/conferenceDisplay.py?confId=209759
This school is sponsored by the COST action MP0905
black holes in a violent universe
University of Sussex
BRIGHTON PIER
Speakers:
David Chamption (MPIfR Bonn)
Panagiota Kanti (U. Ioannina)
Claus Kiefer (U. Cologne)
Iossif Papadakis (U. Crete)
Eram Rizvi (Queen Mary U.)
Elizabeth Winstanley (U. Sheffield)
Local organizer:
Xavier Calmet (U. Sussex)

Searches for Nonpertubative Gravitational States at the LHC

Doug Gingrich
University of Alberta/TRIUMF

Outline/Topics

- What should we take as limits on the fundamental Planck scale M_D?
- GR black holes and hard disk production cross section in the LHC phase space.
- Non-thermal quantum black holes.
- Non-communative geometry inspired black holes.
- Black holes and string balls in split fermion models.

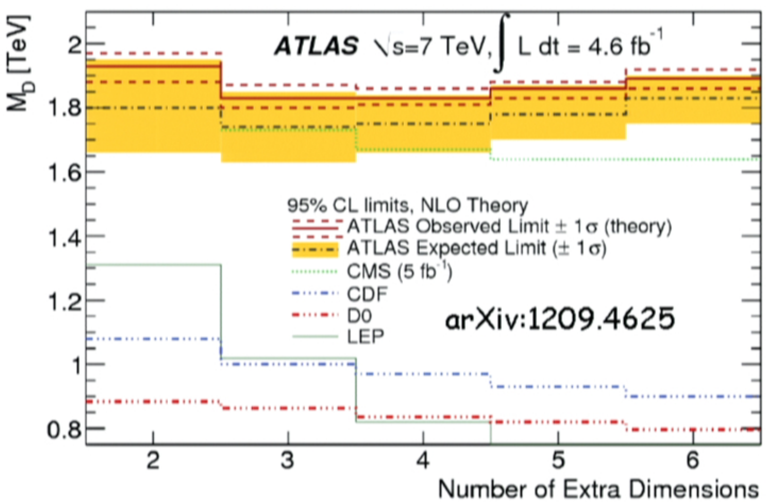

25 October 2012
Doug Gingrich (Perimeter In

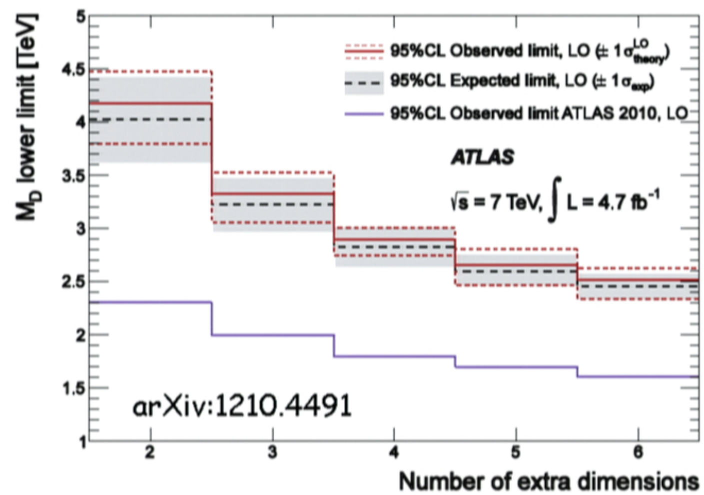
Which Planck Scale?

- What should we take as the limits on fundamental Planck scale M_D?
- Virtual graviton emission depends on ultra-violet cutoff M_S, which is not M_D.
- Real graviton emission depends on M_D: mono-jet and mono-photon searches.
  - But is this the scale for GR or non-thermal black holes?
- Limits from classical black hole searches, M_D function of M_{th} (mass threshold).
- Limits from non-termal black hole searches, $M_D = M_{th}$ (stringent limits from di-jet searches).

Best Limits on Planck Scale

ATLAS mono-jet (M_D > 2.5-4.2 TeV, n = 6-2).





What about n > 6?

Most calculations that assume M_D = 1 TeV should be revised.

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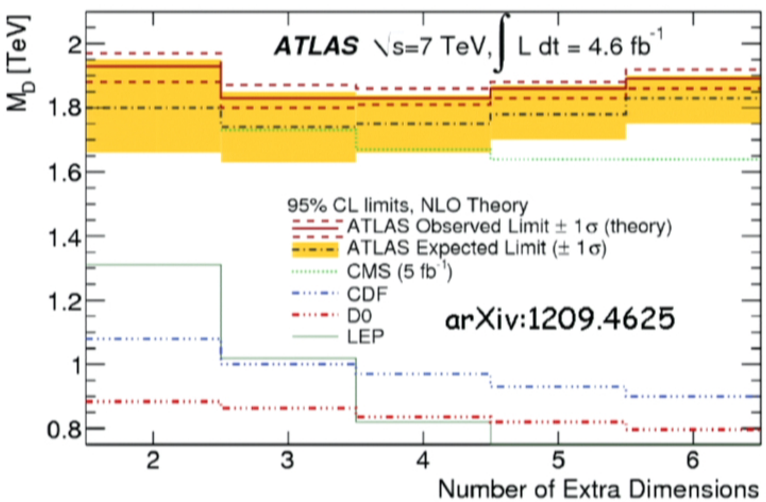

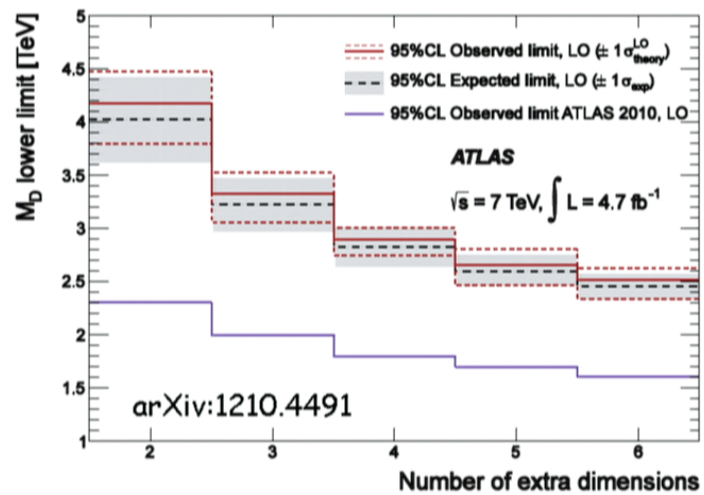

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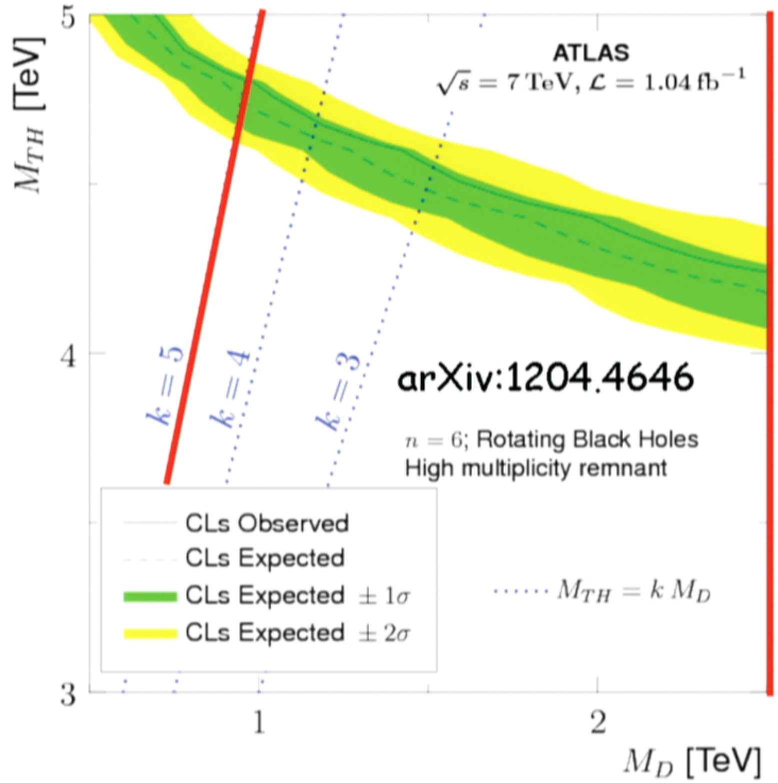
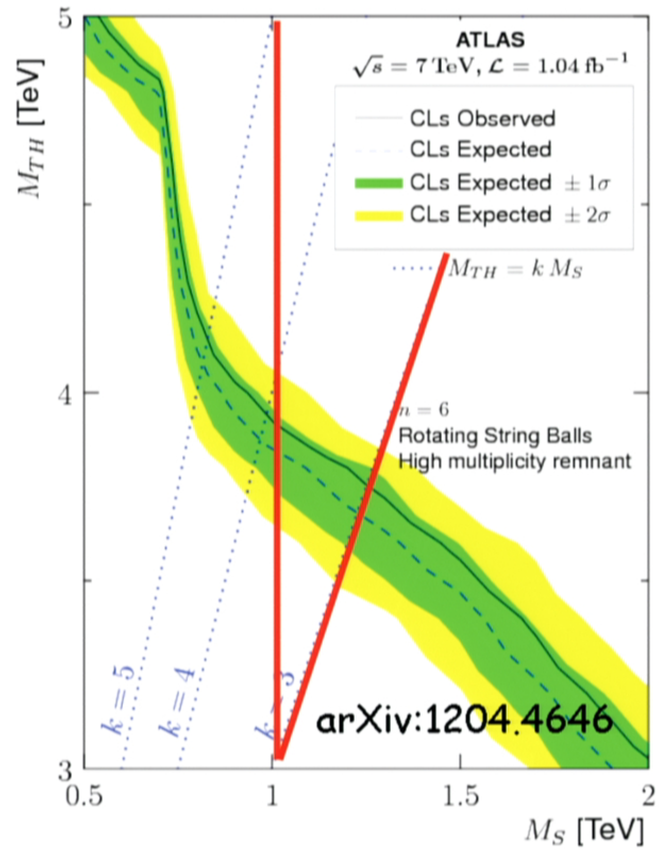
GR Black Holes Not at LHC

- Current limits on $M_D > 2.5$ TeV.
- For GR black holes $M_{th} > 5 \times 2.5 \sim 12.5$ TeV.
- Current limits on M_D exclude GR black hole searches.



String Balls Sill Possible at LHC

- LHC exclusion limits on a variety of exotics physics means string scale ~1 TeV.
- For string balls in weakly couple string theory $M_{th} > 3\times 1 \sim 1$ TeV.
- Perhaps current exotics searches do not yet exclude string ball production in current LHC phase space.



Non-thermal Quantum Black Holes

- ATLAS and CMS have set limits on particular models using di-jet data.
- No dedicated searches in di-lepton channel yet.
- On-going searches in lepton+jet and gamma+jet data.
- No model dependent uncertainties given in di-jet searches:
  - Usual uncertainties due to PDFs, QCD scale, not all energy trapped behind horizon, etc.
  - Branching ratio interpretations and branch ratio to di-jets.

    $\rightarrow$ model uncertainties gives ±5% change in mass threshold limit.

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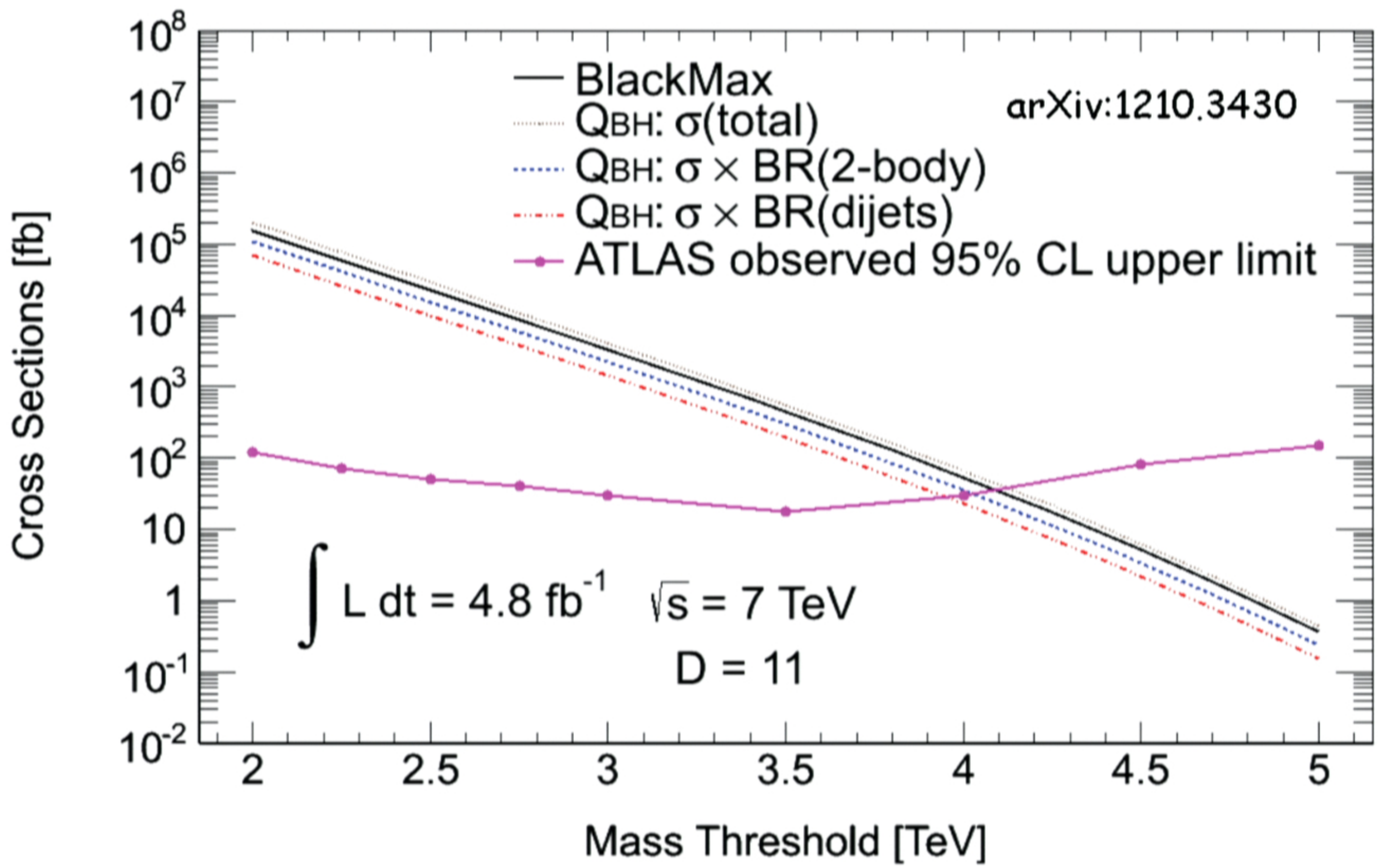
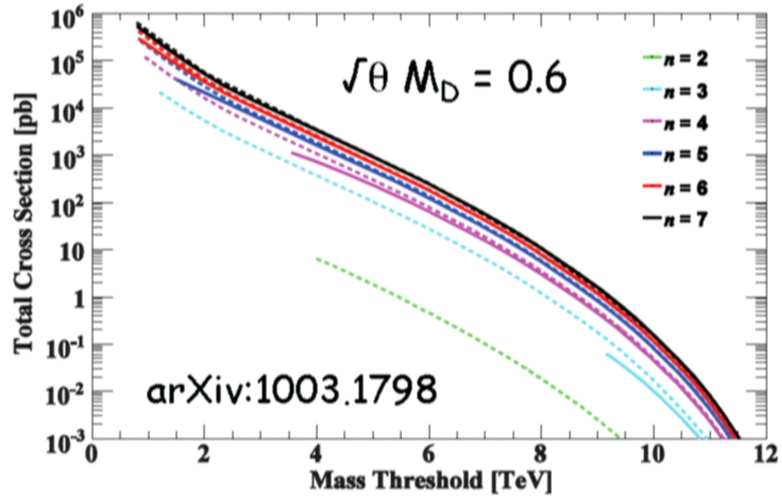


Non-communative Geometry

Non-communative geometry inspired black holes

- Smear matter distributions with resolution of non-communativity scale (extra parameter $\sqrt{\theta}$).
- Temperature well behaved.
  - Canonical ensemble treatment of entropy valid for entire decay.
- Gravitational radius has non-zero minimum.
  - Stable remnant with mass different from Planck scale.



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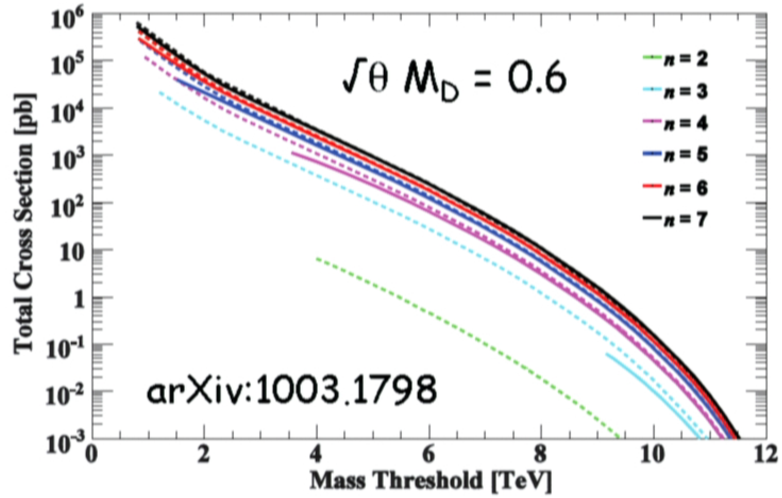
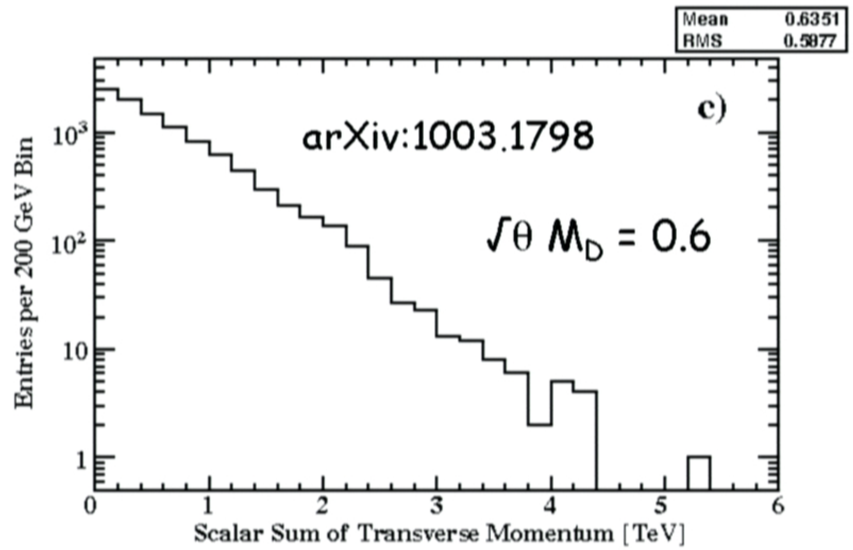


Non-communative Geometry

- Main experimental differences from GR black holes:
  - Larger missing energy.
  - Soft Σp_T sepctra.
- Possible trigger issues.



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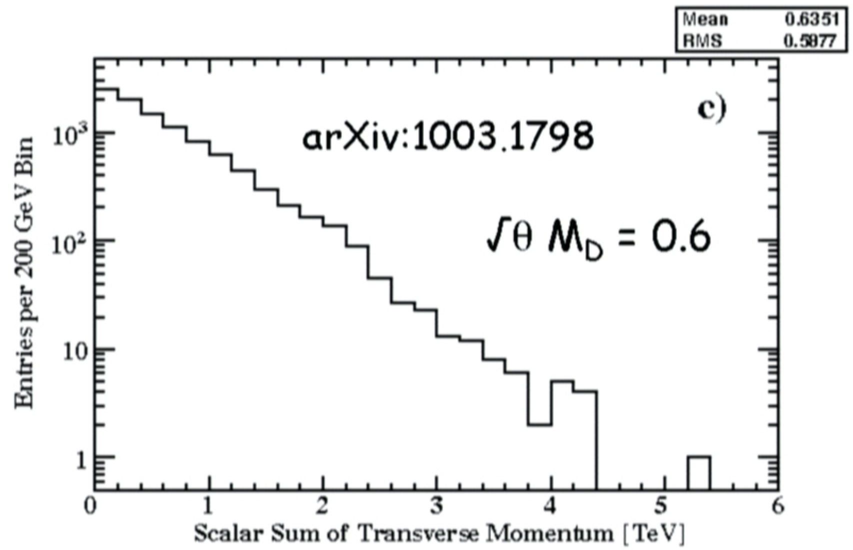
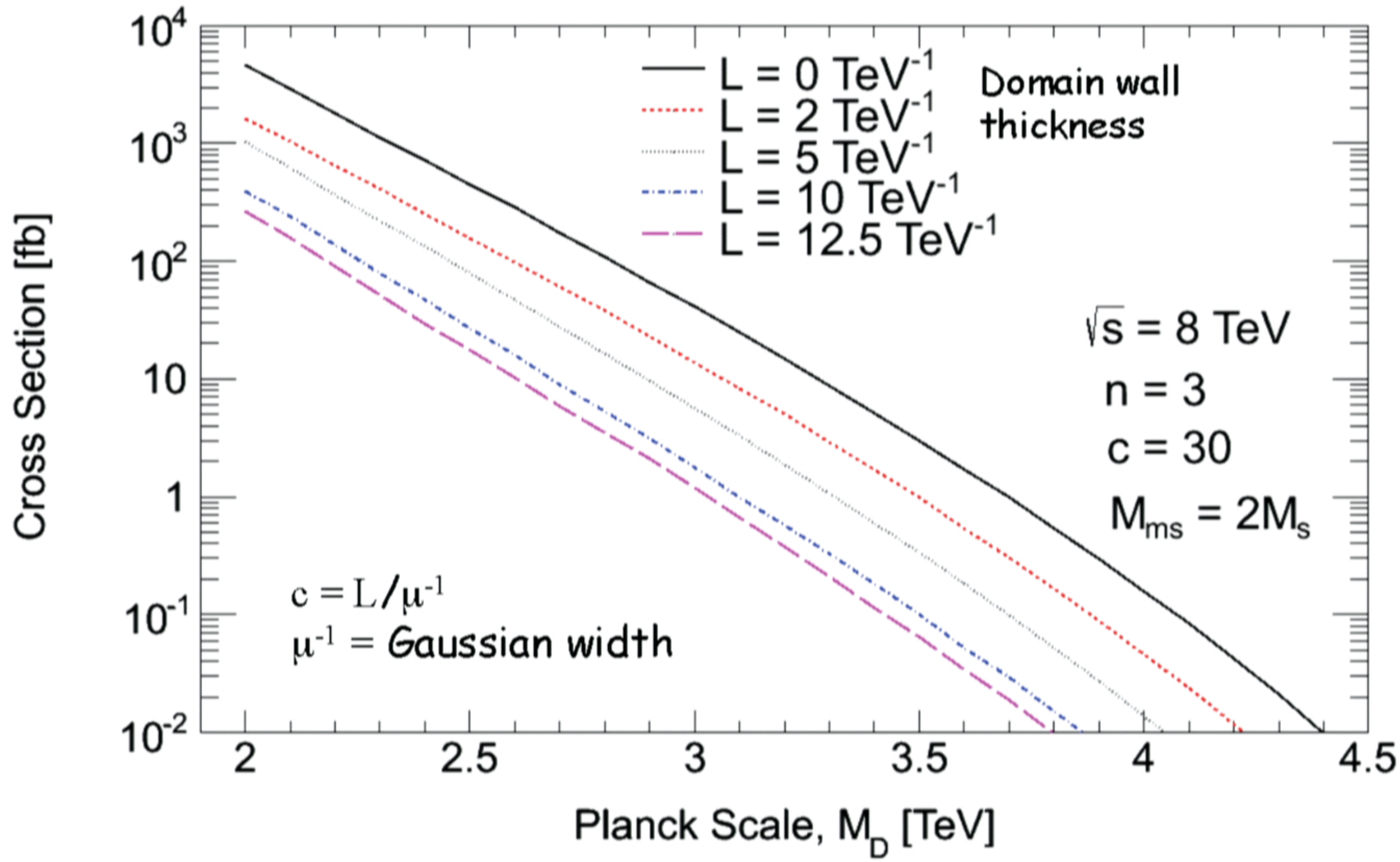


Split Fermion Models

- Black holes and string balls in split fermion models.
- Mechanism for generating Yukawa hierarchies by displacing the Standard Model fermion fields in a high-dimensional space.
  - Overlap of wave functions gives couplings.
- Causes reduction in cross section relative to usual ADD case.
- Set of spacings giving masses consistent with data has been determined.

Split Fermion pp Cross Section



low-scale quantum gravity and particle physics

Daniel F Litim

University of Sussex

Experimentally quantum gravity: the hard facts

Perimeter Institute

25 October 2012

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,

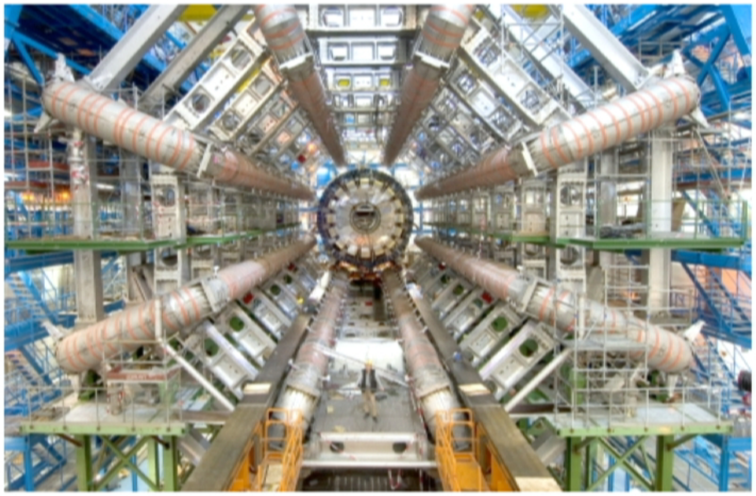
$$M_{\rm Pl}^2 \sim M_*^2 (M_*\, L)^n$$

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

high-energetic particle colliders can **test quantisation of gravity**

quantum gravity

low-scale quantum gravity



high-energetic particle colliders can **test quantisation of gravity**

collider signatures of quantum gravity

real gravitons

graviton emission $pp \to \mathrm{G}$ **+ anything (jets...)**

signature: missing transverse energy

virtual gravitons

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

signature: deviations in SM reference processes

mini-black holes

black hole production and decay

signature: (many) body final states

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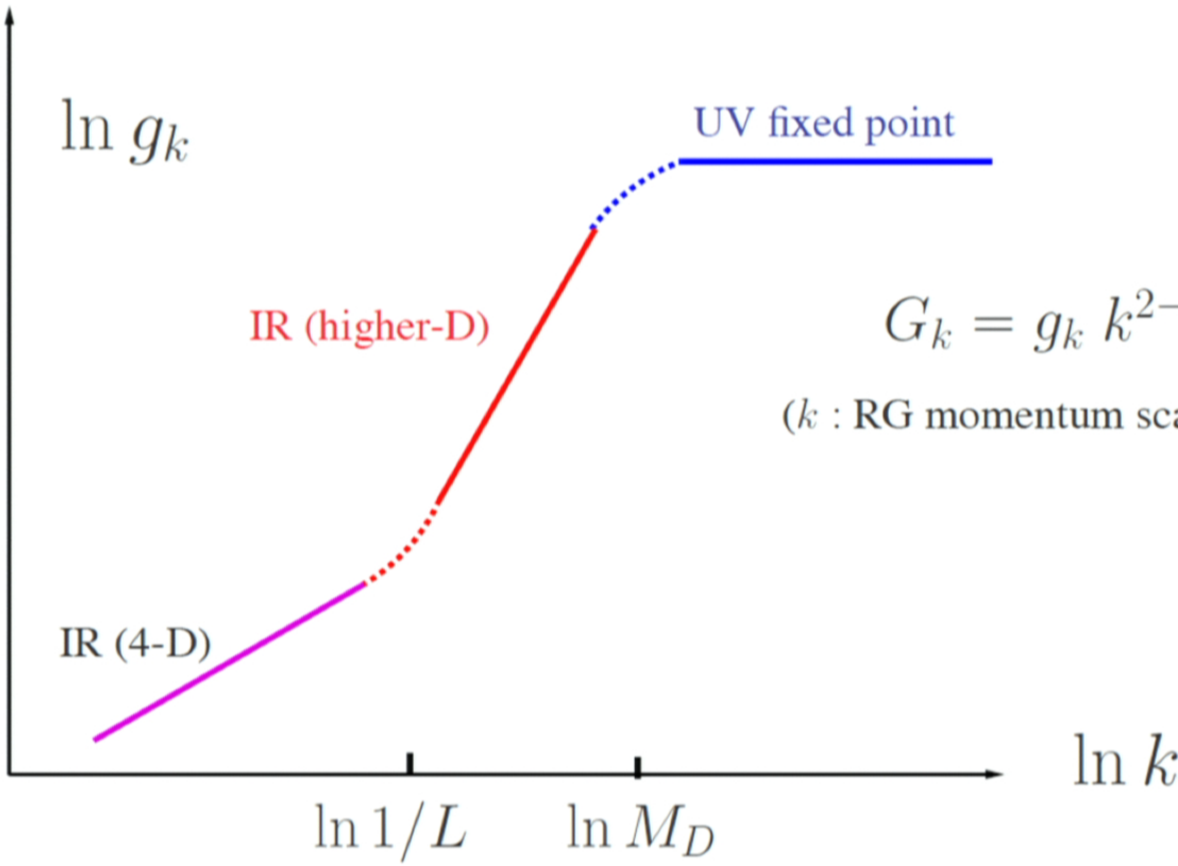
quantum gravity with extra dimensions

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



$G_k = g_k\, k^{2-D}$

(k : RG momentum scale)

quantum gravity with extra dimensions

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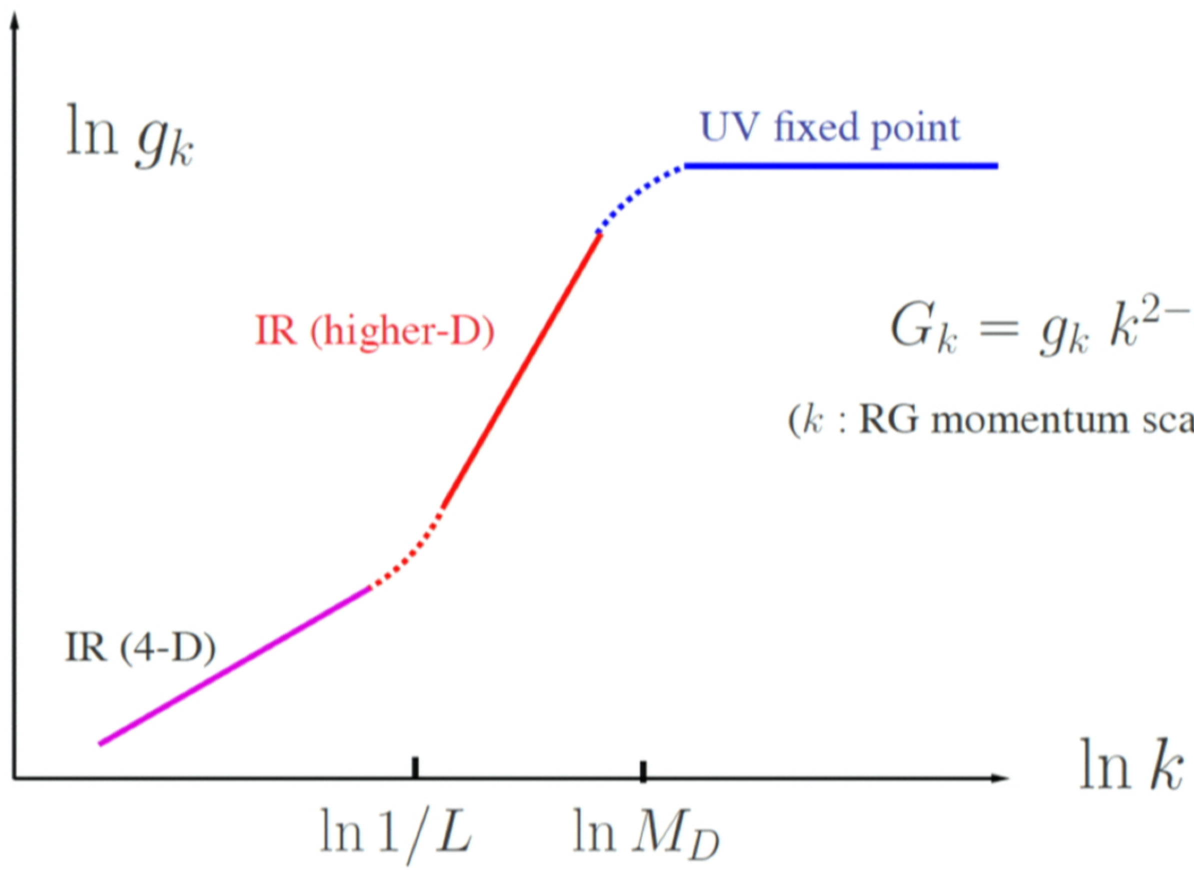

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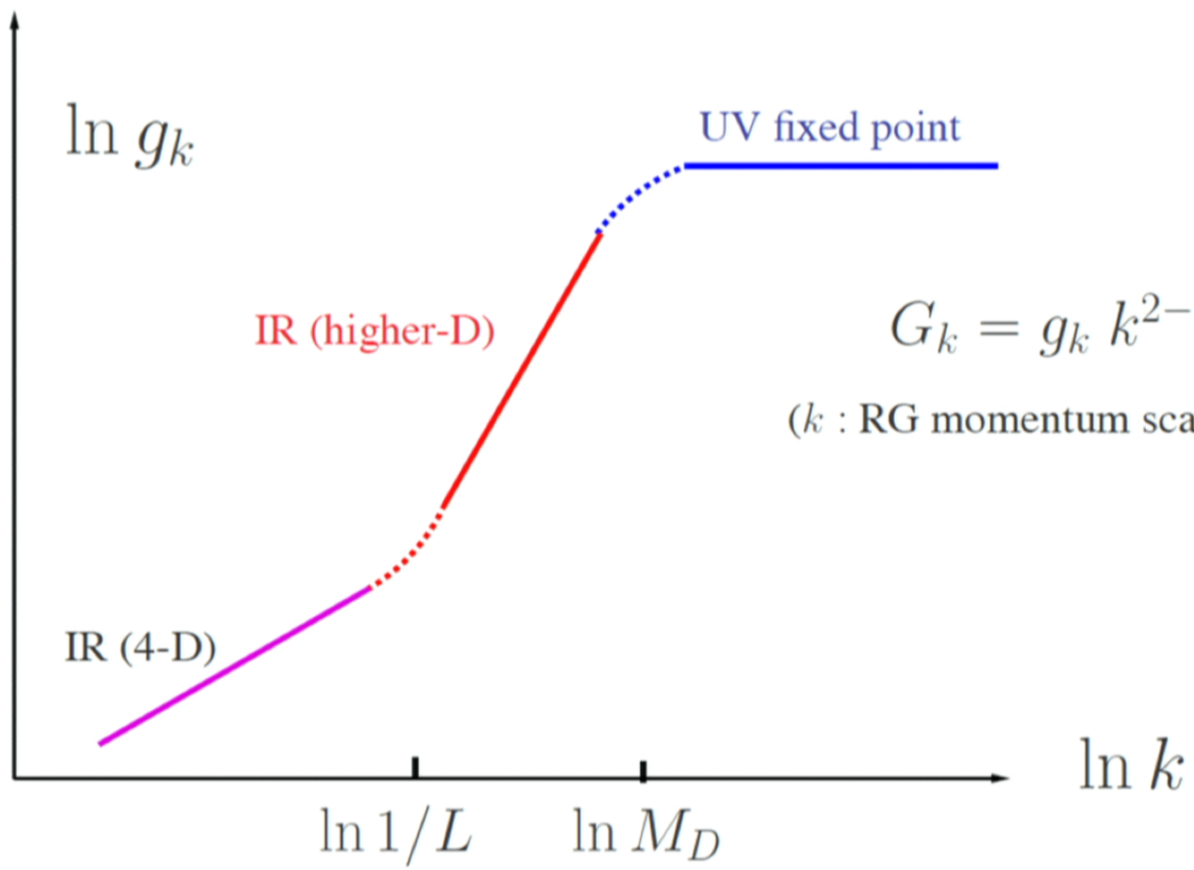
quantum gravity with extra dimensions

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



$$G_k = g_k\, k^{2-D}$$

(k : RG momentum scale)

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.

relevant scales

IR Planck scale M_*

UV Planck scale Λ_T

Kaluza-Klein mass m

cross-over behaviour

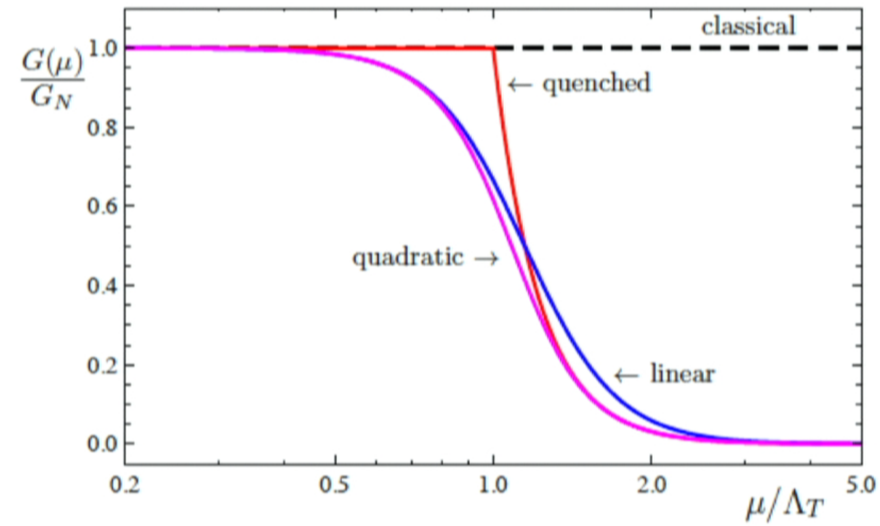


FIG. 1: Crossover of the gravitational coupling $G(\mu)/G_N$ from classical (dashed line) to fixed point scaling (full lines) in the Einstein Hilbert theory with $n = 3$ extra dimensions: classical behavior (black), linear crossover (19) (blue), quadratic crossover (20) (magenta) and the quenched approximation (18) (red) with $\Lambda_T = \Lambda_T^{(0)} = \Lambda_T^{(1)} = \Lambda_T^{(2)}$ (see text).

Drell Yan production

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

RG improved scattering amplitude for Drell-Yan production

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Gerwick, DL, Plehn ('11)

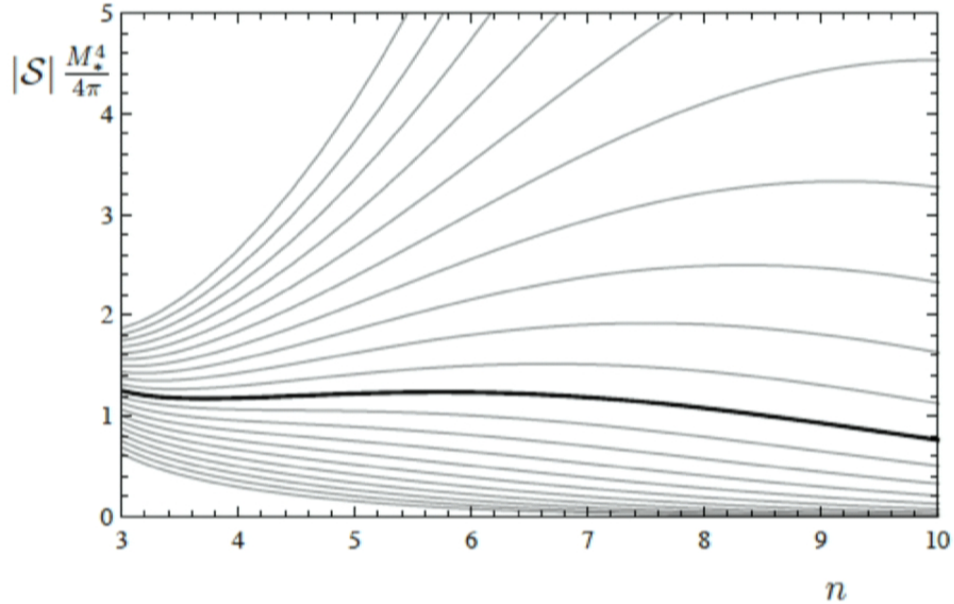
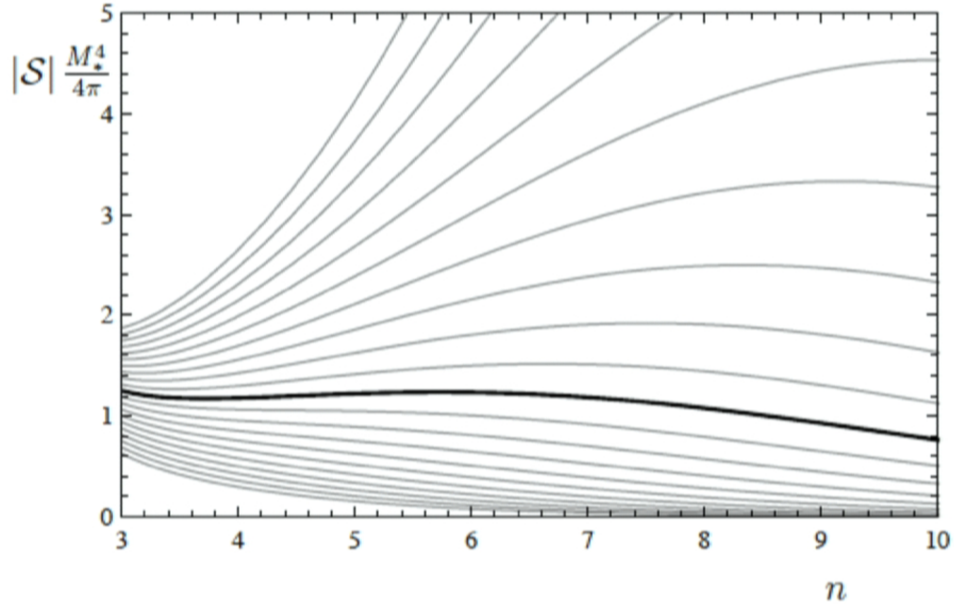


FIG. 5: The n-dependence of the amplitude $|\mathcal{S}|\,M_*^4/(4\pi)$ defined in (22). Thin grey lines cover $\Lambda_T/M_* = 0.5$ to 1.5 in steps of 0.05 (from bottom to top). Close to $\Lambda_T/M_* = 1$ (thick black line), the overall n-dependence of the amplitude is very weak.

cross-over behaviour

Gerwick, DL, Plehn ('11)



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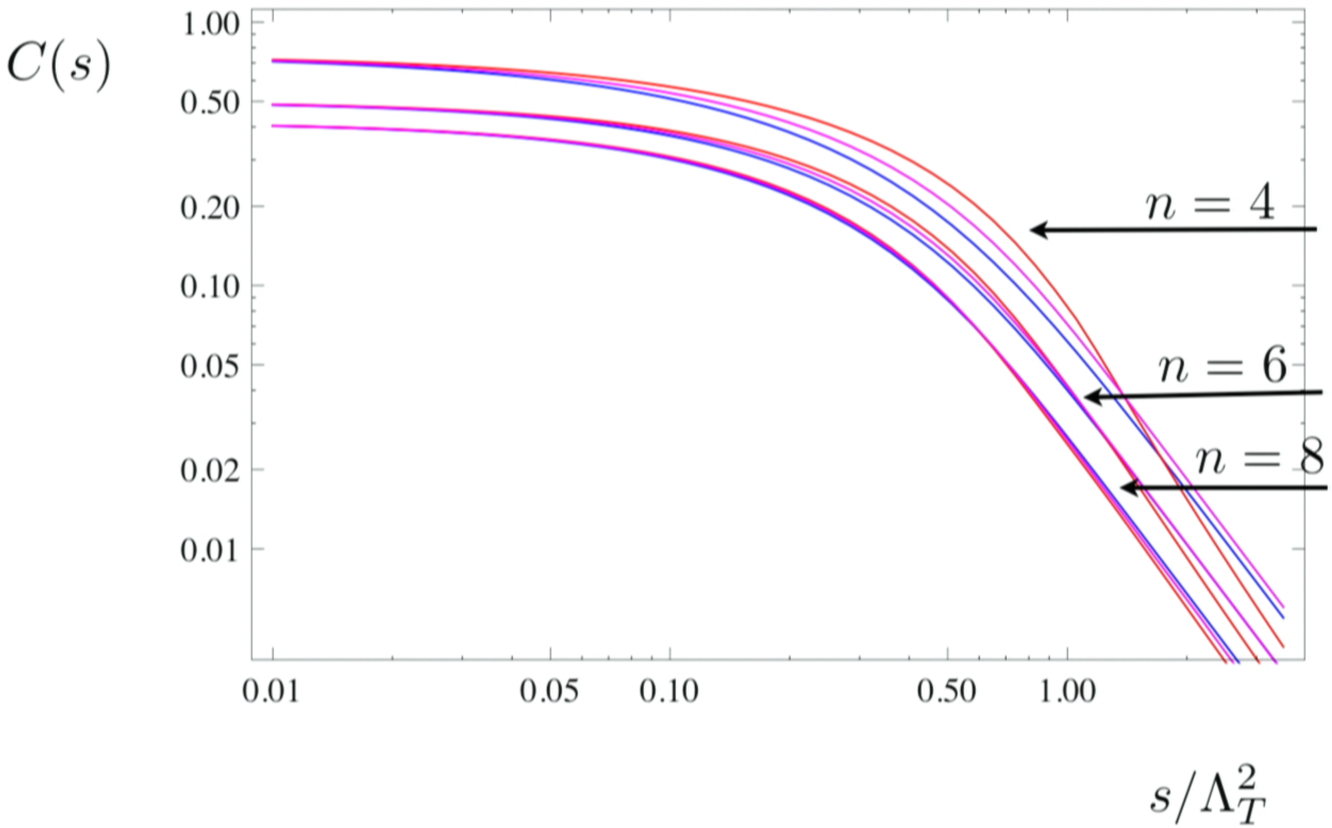
cross-over behaviour

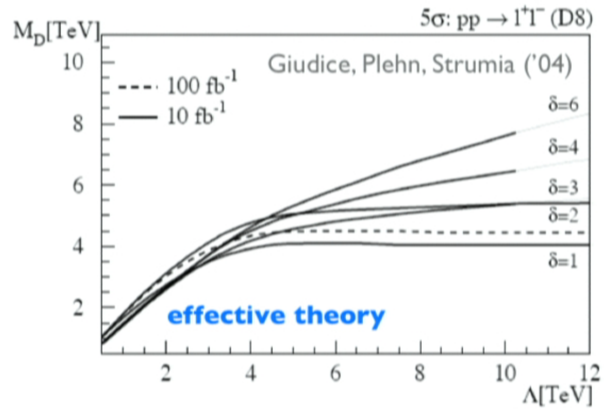
RG scheme variations

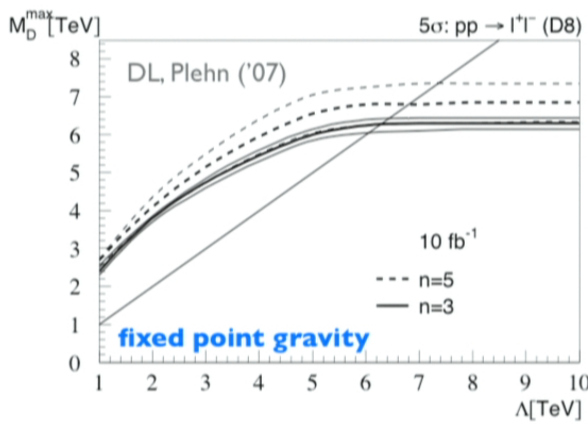


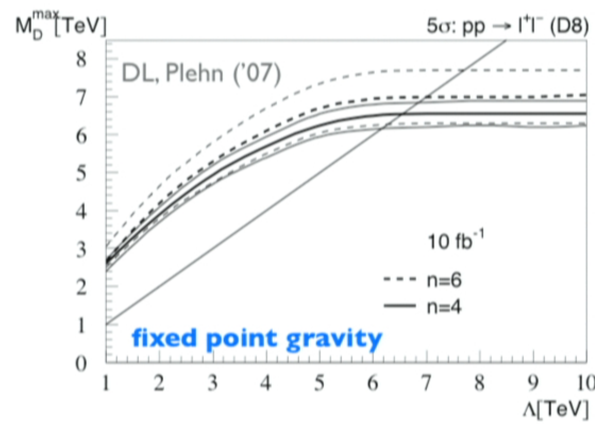
Drell Yan production

discovery reach

effective theory vs fixed point gravity

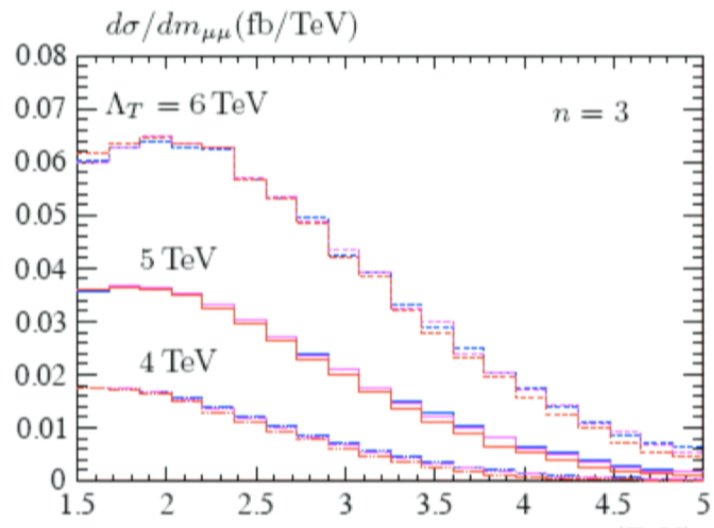






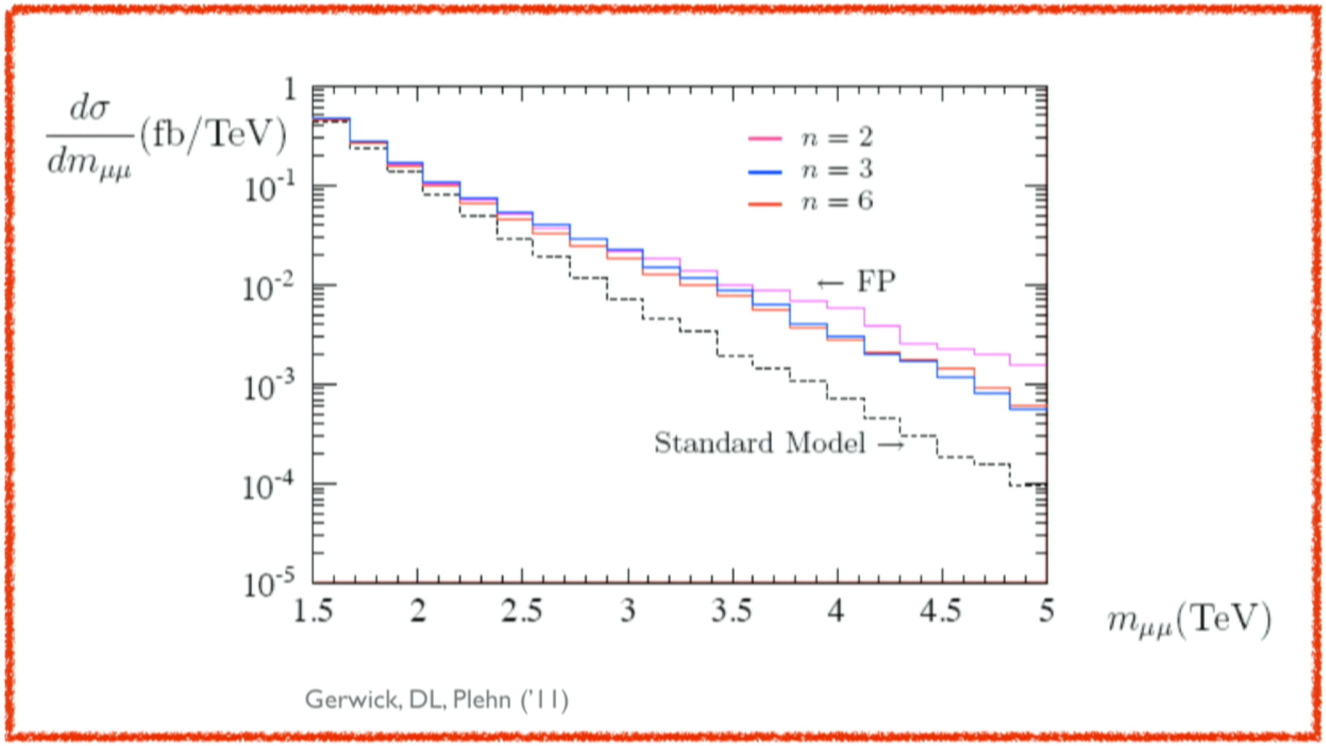
sensitivity

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



Gerwick, DL, Plehn ('11)

signal vs background



(Gerwick, DL, Plehn '11)

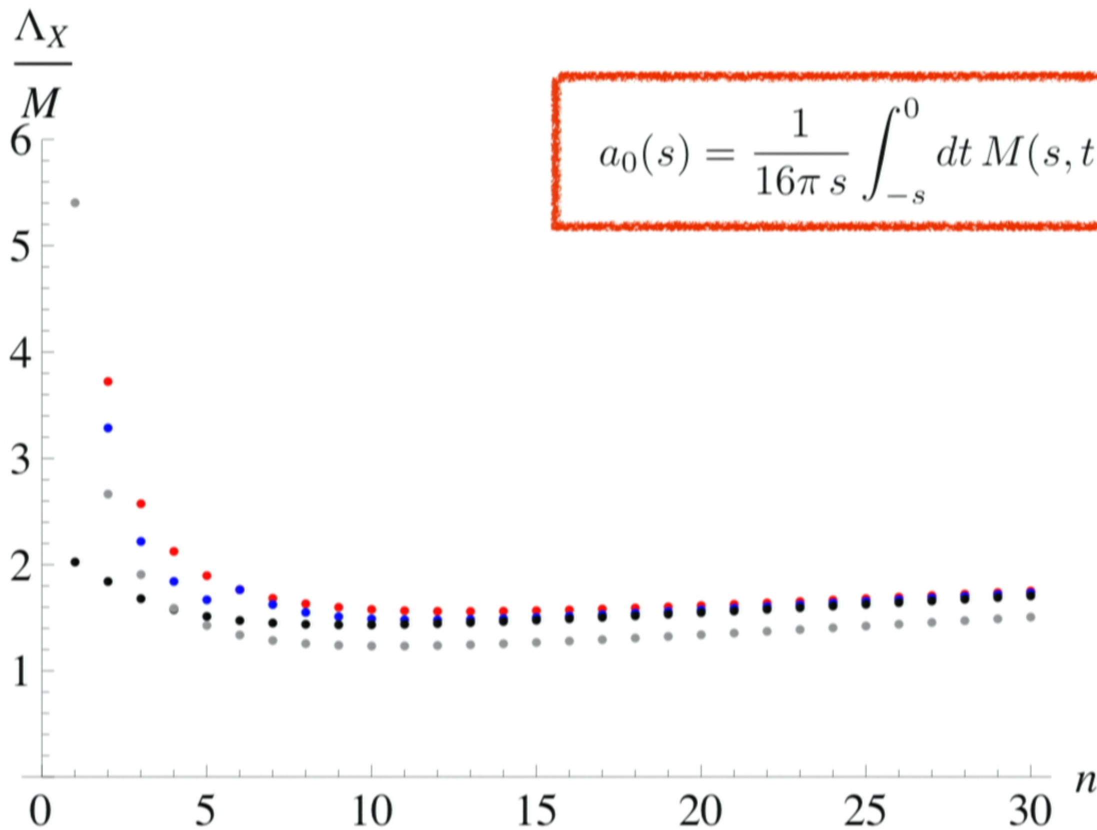
$$\sqrt{s} = 14\,\text{TeV} \qquad M_* = \Lambda_T = 5\,\text{TeV}$$

unitarity

bounds on transition scale

(Brinkmann, Hiller , DL, Schroeder, in prep.)

$$a_0(s) = \frac{1}{16\pi\, s} \int_{-s}^{0} dt\, M(s,t)$$



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**

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

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

mini-black hole production

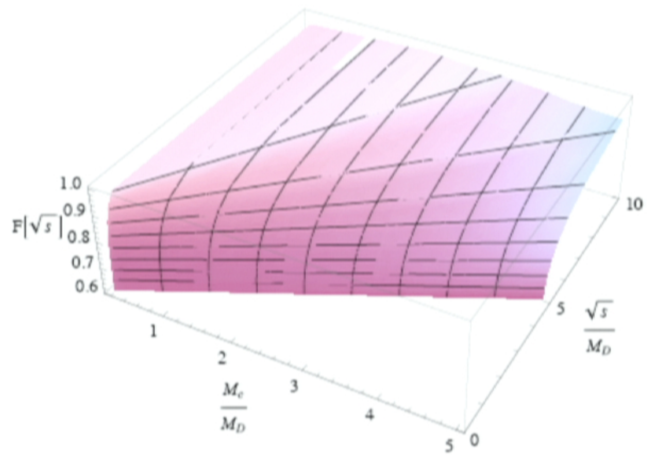
RG quantum corrections

Falls, DL, Raghuraman ('10)
DL, Nikolakopoulos (in prep.)

quantum corrected production cross section

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

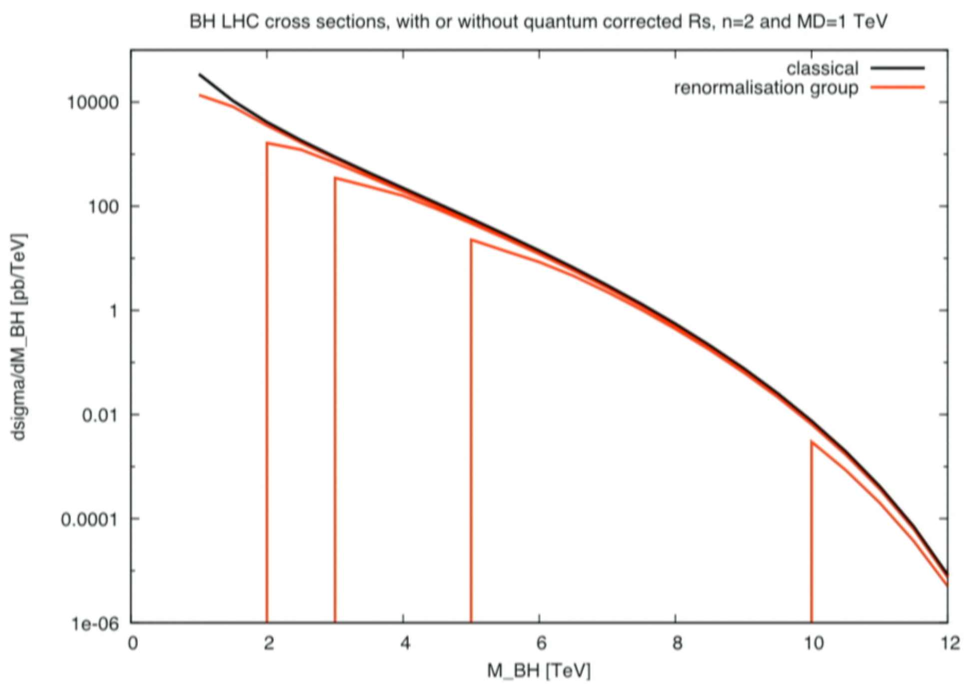
new form factor F



mini-black hole production

RG quantum corrections

Falls, Hiller, DL (in prep.)



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conclusion

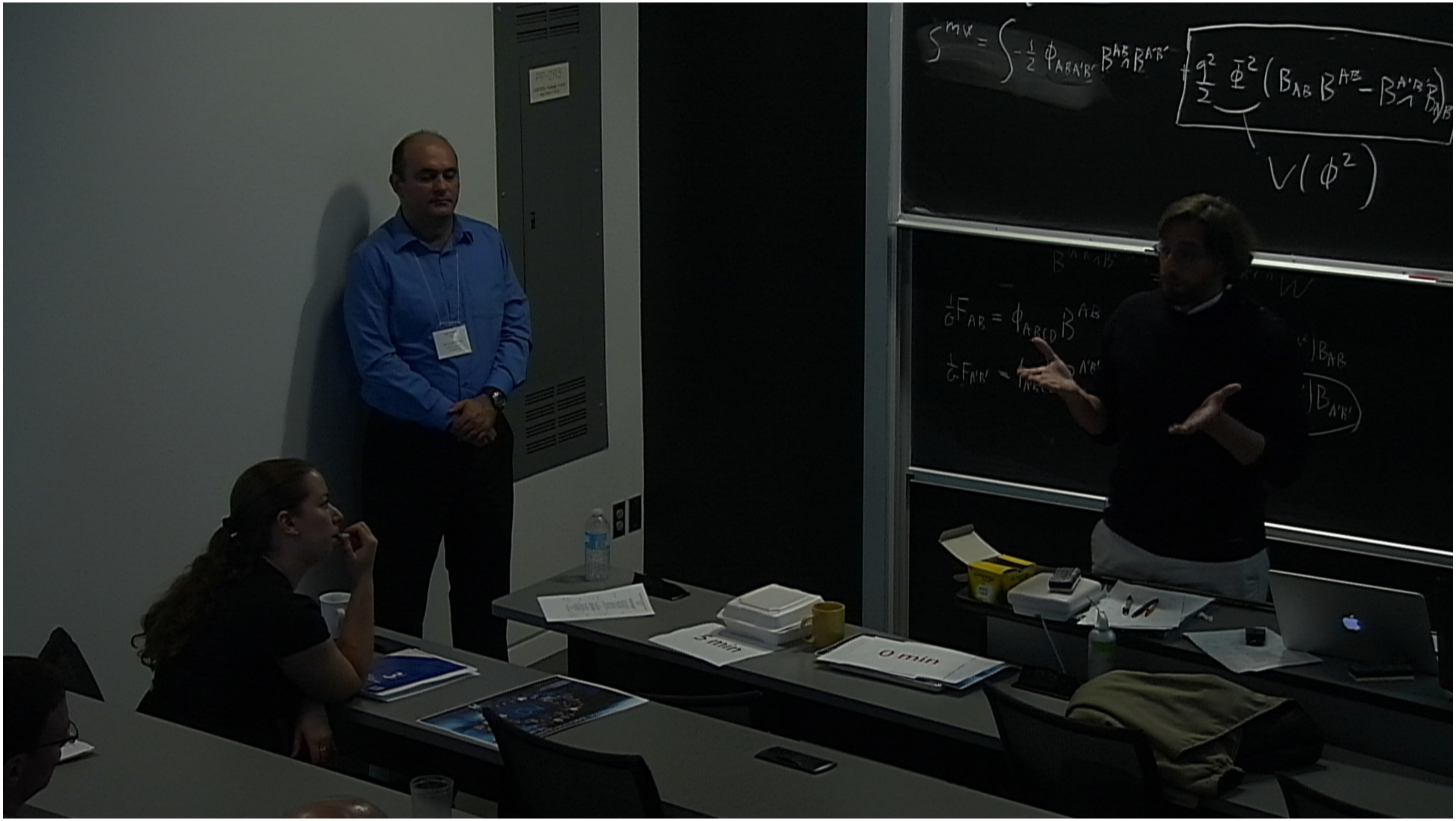
asymptotically safe gravity

strong indications for gravitational fixed point
compatible with extra spatial dimensions

low-scale quantum gravity

computable QG effects
moderate RG scheme dependence
access to various observables
good sensitivity at the LHC
revisit bounds on Planck scale

thank you!


5 min
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