Low scale quantum gravity

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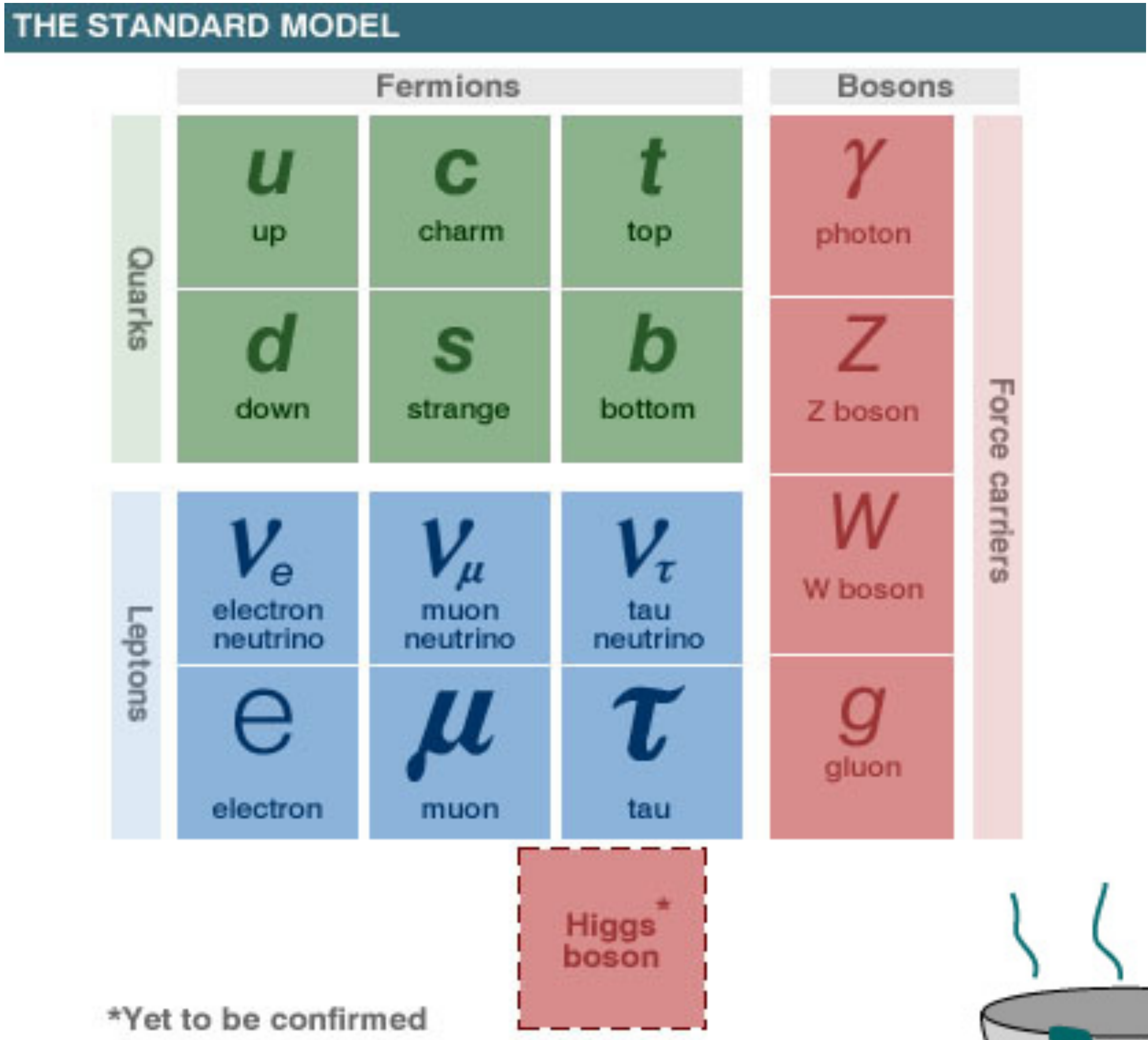
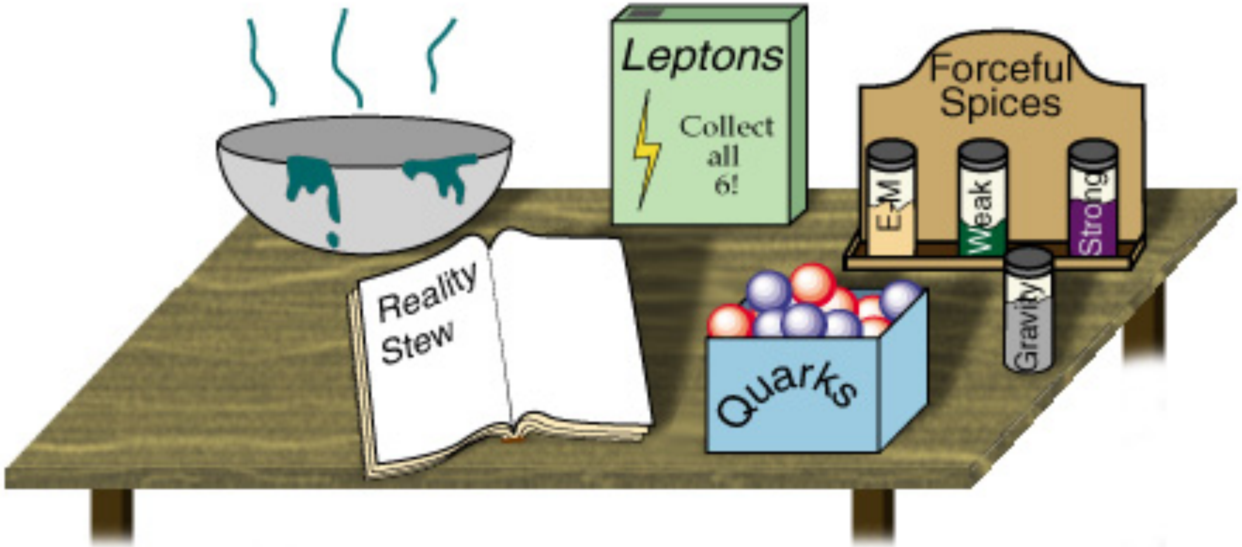
Standard Model of particle physics

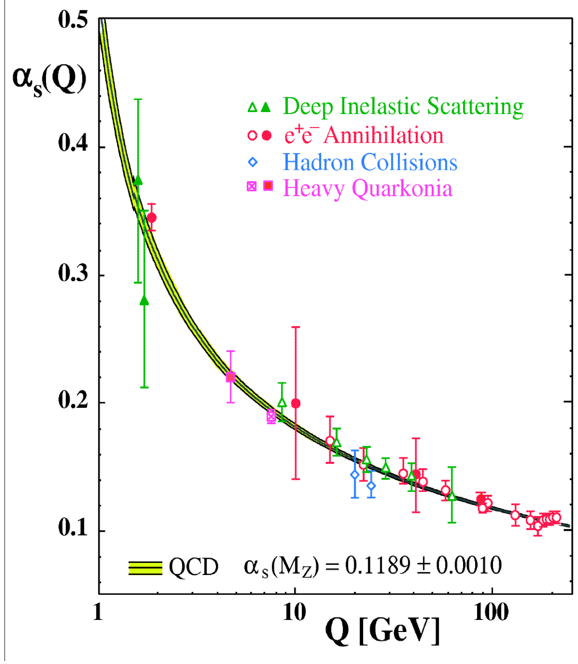


It is described by a quantum field theory.



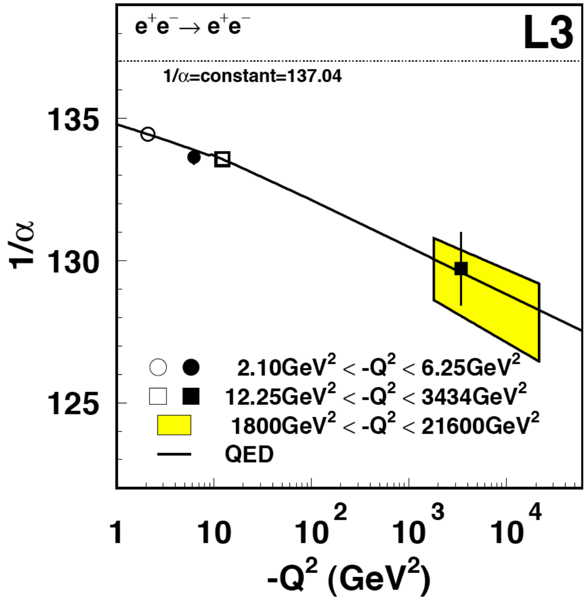
Like athletes, coupling constants run (with energy)….

fast

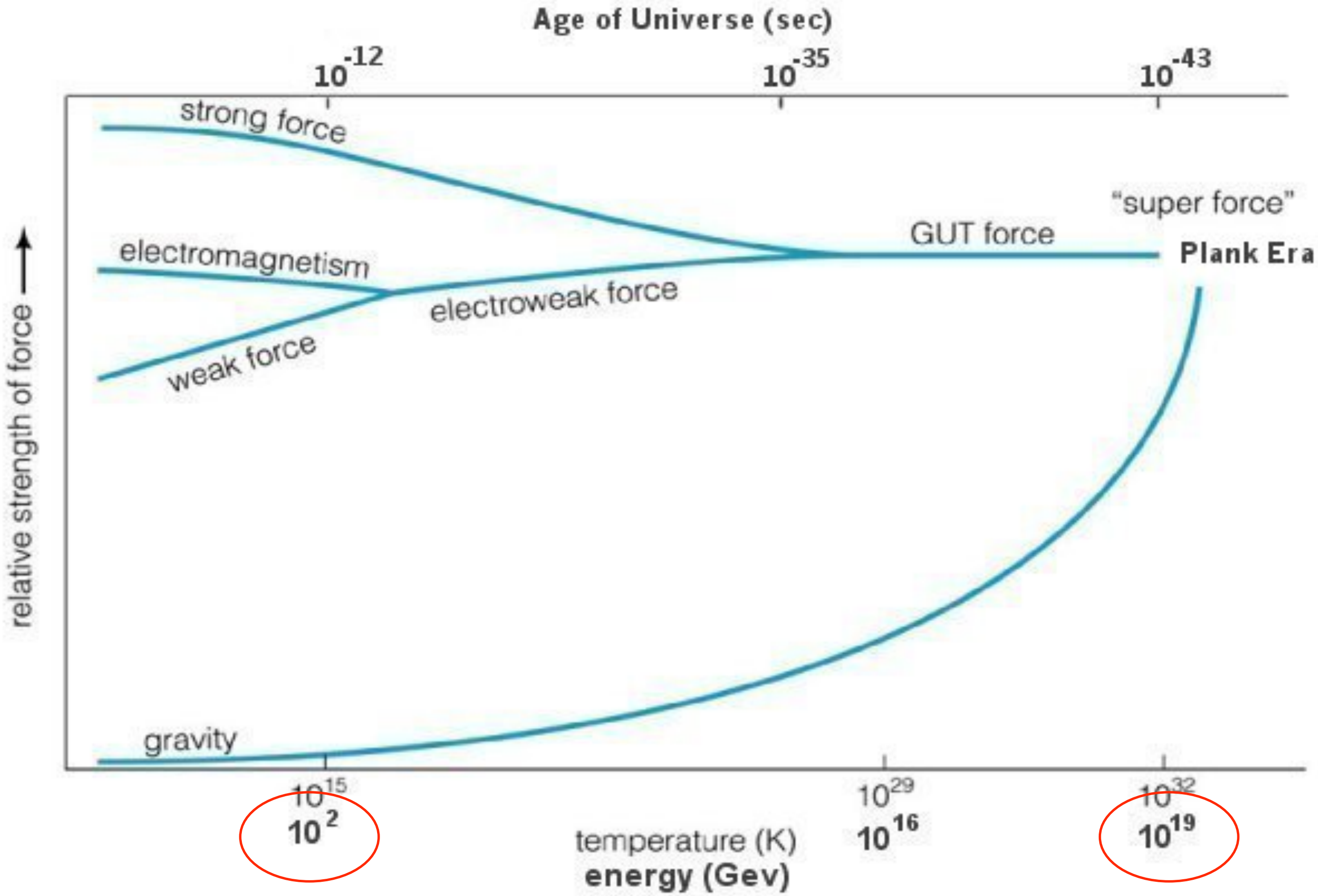


or

slow



When does gravity become important?



A grand unification?
Is there actually only
one fundamental interaction?

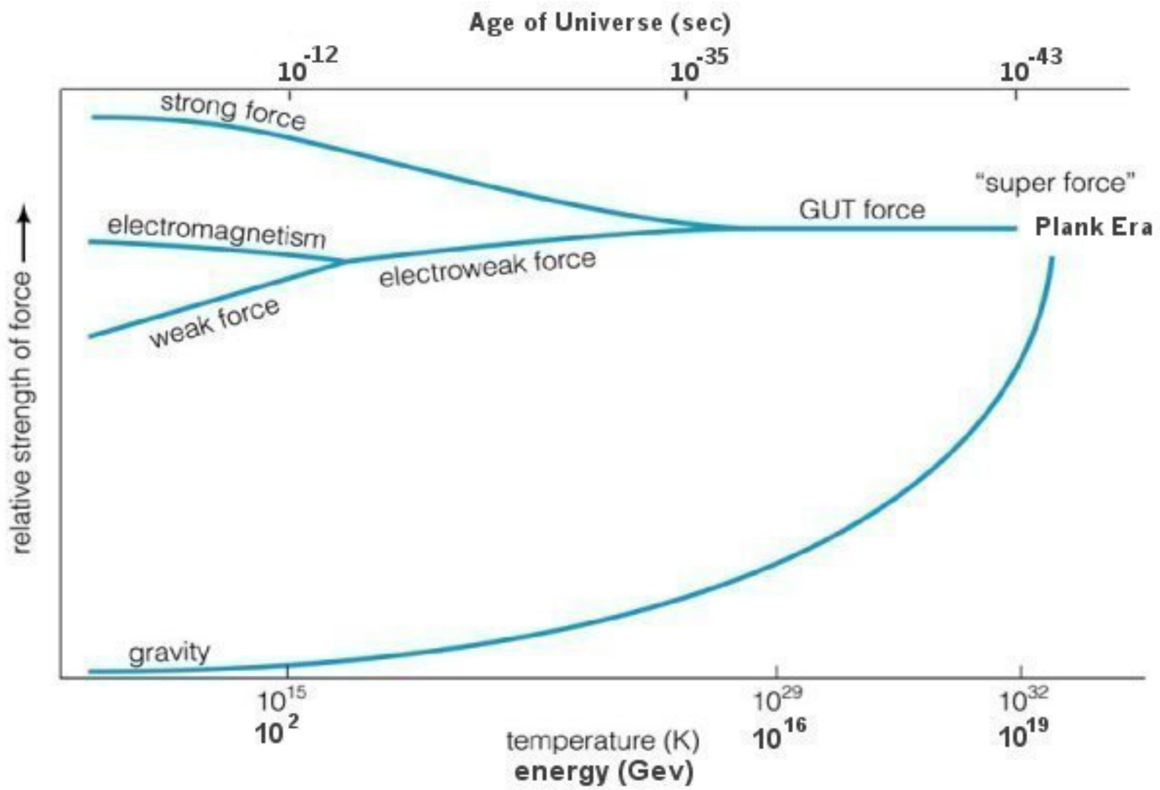
$$M_P = \sqrt{\frac{\hbar c}{G_N}}$$

The Planck mass
is the energy scale
at which quantum
gravitational effects
become important.

Doing quantum gravity is challenging

- We do not know how to do calculations in quantum gravity.
- Unifying gravity and quantum mechanics is difficult.
- New tools/theories are needed: string theory, loop quantum gravity, noncommutative geometry, nonperturbative quantum gravity, asymptotically safe gravity… maybe something completely different.

Quantization of gravity is an issue in the high energy regime which is tough to probe experimentally



Dimensional analysis:
$M_P \sim 10^{19}$ GeV
but we shall see
that it does not need
to be the case.

We actually do not even know at what energy scale quantum gravity becomes strong!

Let me give you two examples

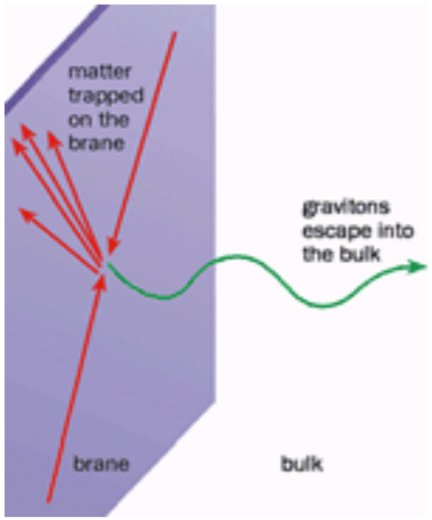
TeV gravity extra-dimensions

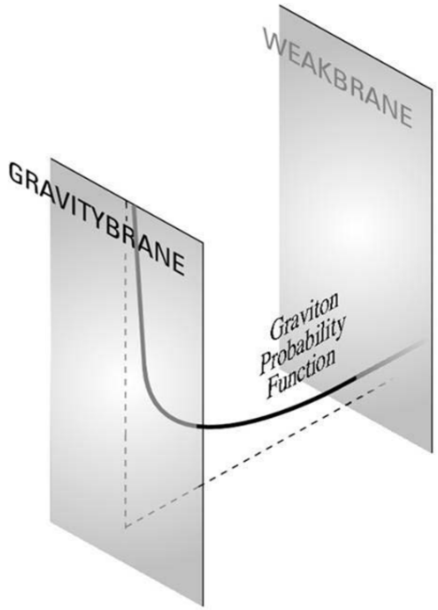
$$\int d^4x\, d^{d-4}x' \sqrt{-g}\ \left(M_*^{d-2}\mathcal{R} + \cdots \right) \qquad M_P^2 = M_*^{d-2}V_{d-4}$$

where M_P is the effective Planck scale in 4-dim

ADD brane world

RS warped extra-dimension



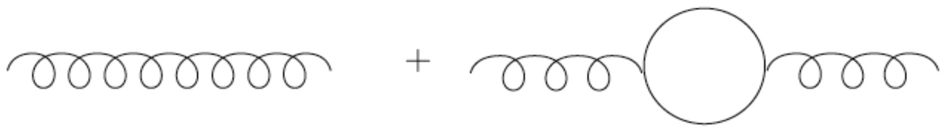


Running of Newton's constant

- 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:



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

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

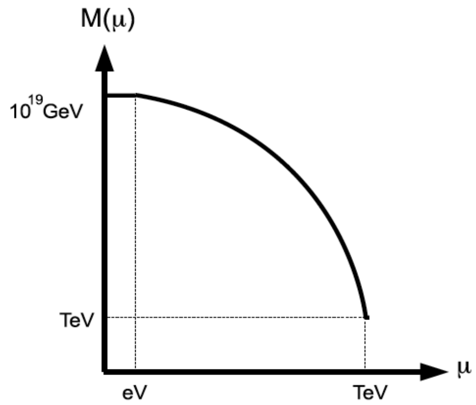
Theoretical physics can lead to anything…
even business ideas!

NEWTON® running

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.

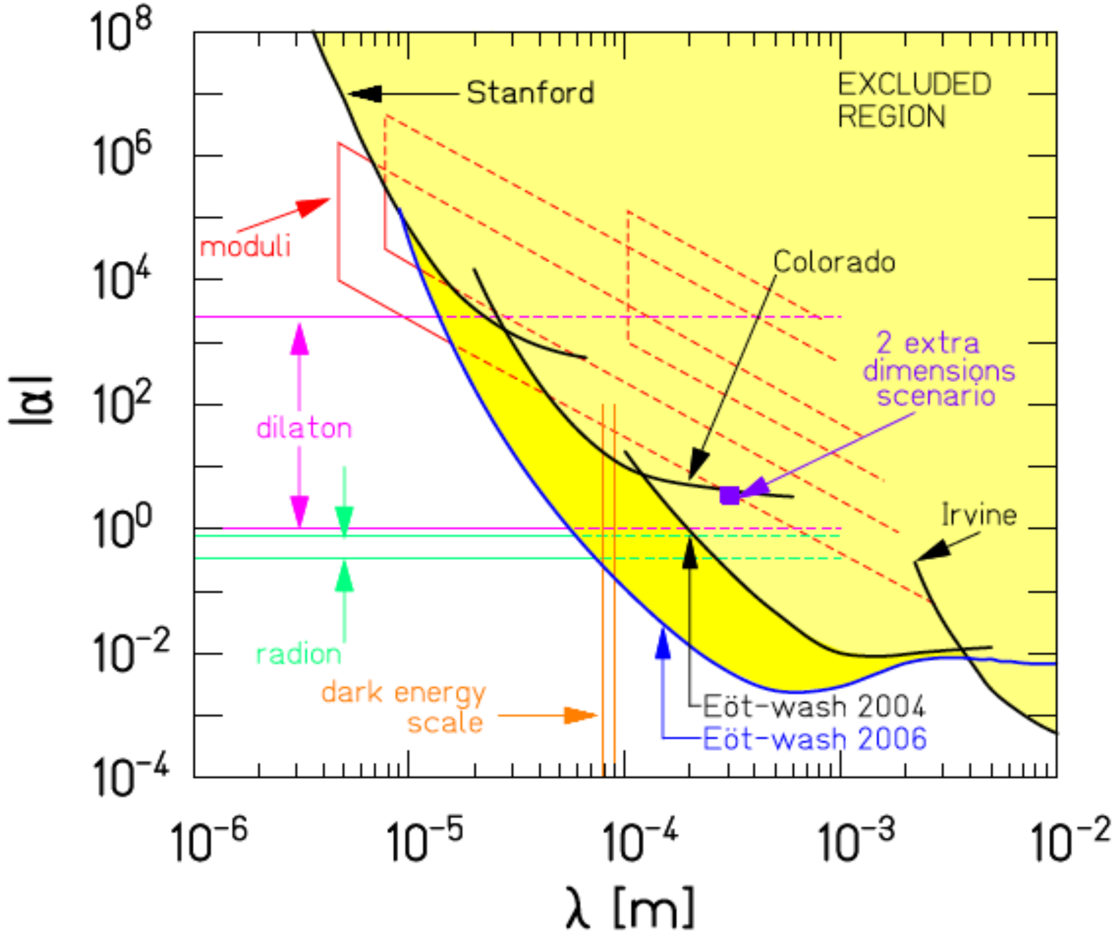
- We assume that these new fields only interact gravitationally with the standard model.

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

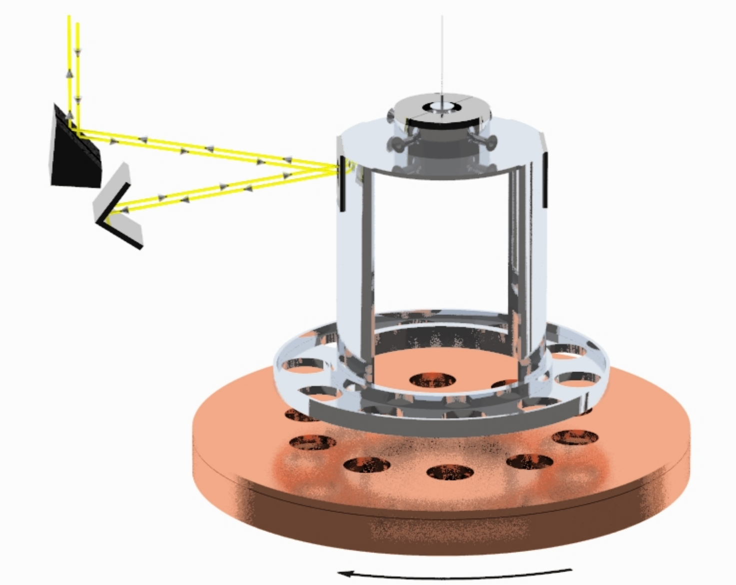
Quantum gravity effects could become important at any energy scale!

It is really an experimental question.

Why are these models viable?



Gravity has only been tested up to distances of the order of 10^{-3} eV!

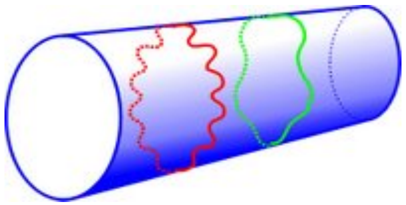


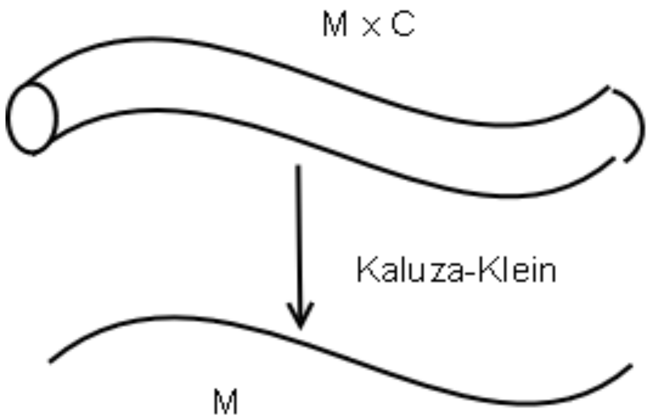
Schematic drawing of the Eöt-Wash Short-range Experiment

$$V(r) = -G_N \frac{m_1 m_2}{r} \left[1 + \alpha \exp\left(-r/\lambda\right)\right]$$

Typical problems of models with TeV Quantum Gravity:

- Light Kaluza-Klein gravitons in ADD:





- Graviton KKs lead to astrophysical constraints: supernovae cooling and neutron stars heating: limits on the scale/number of dimensions

Bounds (orders of magnitude) on ADD brane-world model

n	1	2	3	4	5	6
Gravity exp.	10^7 km	0.2mm				0.1 fm
LEP2		1 TeV	1 TeV	1 TeV	1 TeV	1 TeV
Tevatron		1 TeV	1 TeV	1 TeV	1 TeV	1 TeV
Astro. SN+NS		10^3 TeV	10^2 TeV	5 TeV	none	none
Cosmic rays	1 TeV	1 TeV	1 TeV	1 TeV	1 TeV	1 TeV

LHC is now dominating and probing quantum gravity!

Note: mass gap grows with n. In RS bounds of the order of 1 TeV due to mass gap.

One of the smoking guns of low scale quantum gravity would be the observation of a small quantum black hole in the collisions of particles at colliders.

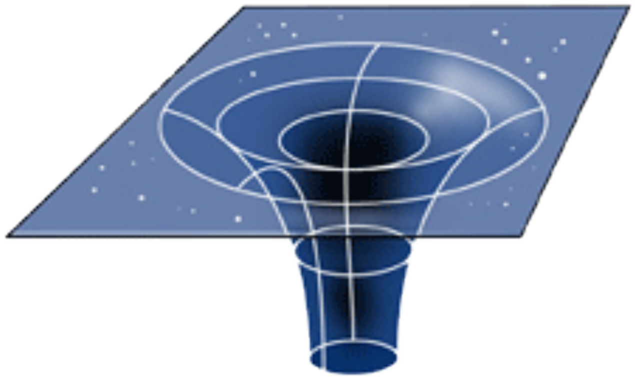
A brief review on the formation of black holes

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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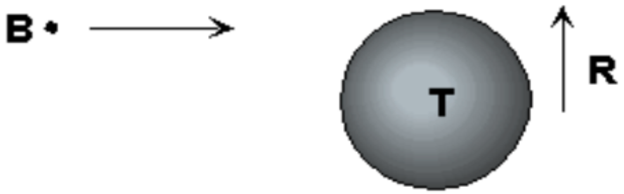
- Cross-section for semi-classical BHs (closed trapped surface constructed by Penrose; D'Eath & Payne; Eardley & Giddings):

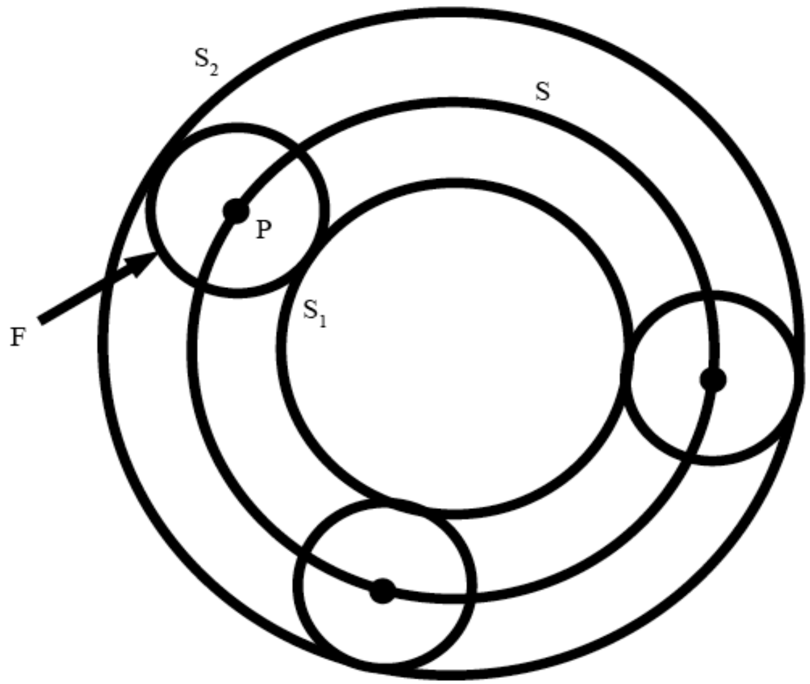
$$\hat{\sigma} \approx \pi r_s^2 \qquad r_s(M_{\mathrm{BH}}) = \frac{1}{M_D}\left[\frac{M_{\mathrm{BH}}}{M_D}\right]^{\frac{1}{1+n}}\left[\frac{2^n \pi^{(n-3)/2}\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{1+n}}$$



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

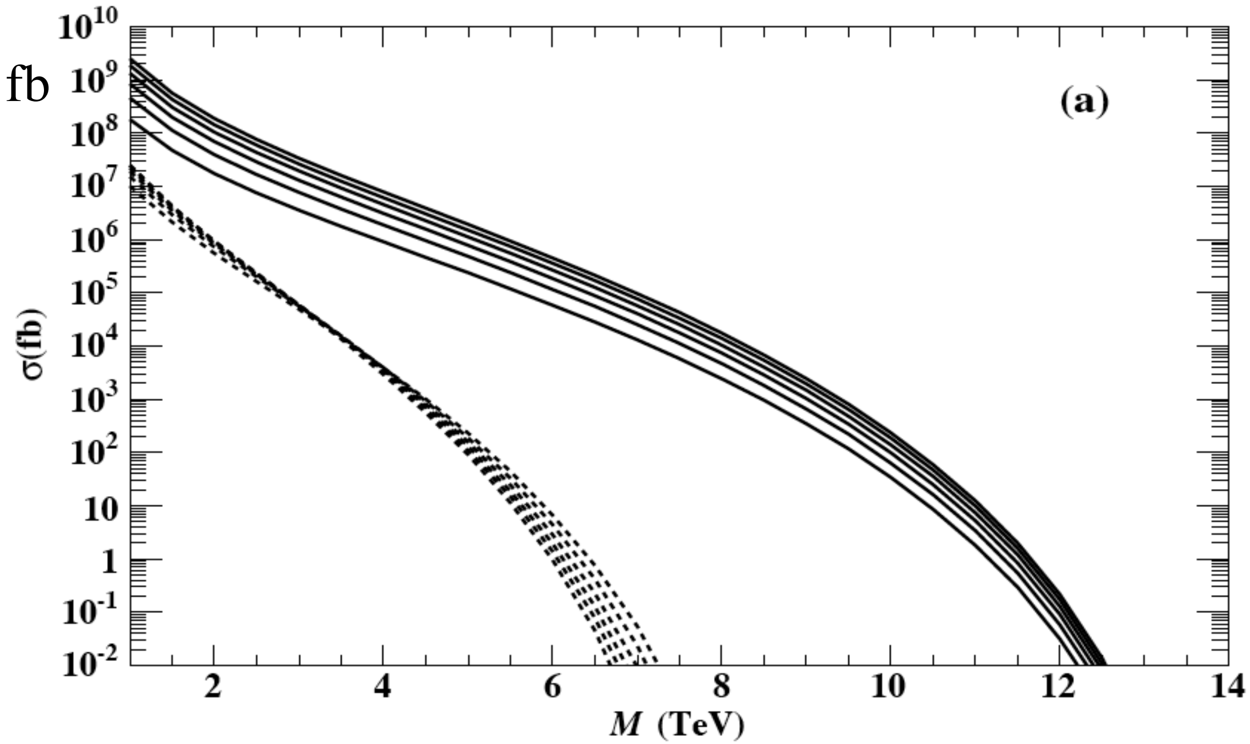
The cross section for point-like particles colliding with a sphere is just the area of the sphere projected onto the transverse plane, that is, a circular disk of radius R.

- A CTS is a compact spacelike two-surface in space-time such that outgoing null rays perpendicular to the surface are not expanding.



- At some instant, the sphere S emits a flash of light. At a later time, the light from a point P forms a sphere F around P, and the envelopes S_1 and S_2 form the ingoing and outgoing wavefronts respectively. If the areas of both S_1 and S_2 are less than of S, then S is a closed trapped surface.

Small BHs @ LHC
(studied by Anchordoqui et al. and many other people, this plot is from Gingrich, hep-ph/0609055)



σ(pp->BH+X), M_D=1 TeV

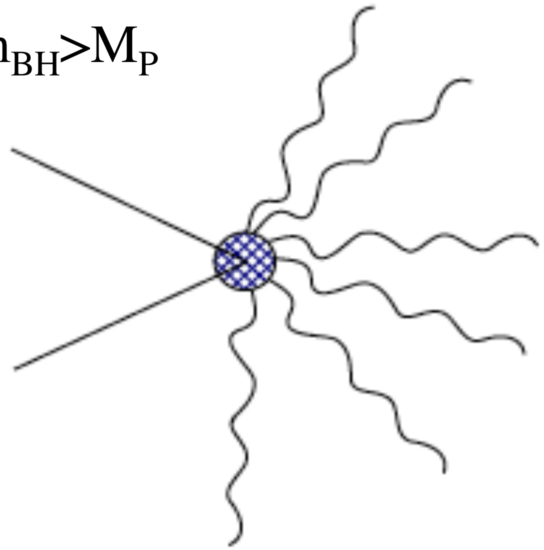
$$\sigma \sim \frac{1}{M_D^2} \left(\frac{\sqrt{s}}{M_D} \right)^{\frac{2}{1+n}}$$

For partons, σ increases with energy but note that PDFs go so fast to zero that they dominate. In other words quantum black holes dominate!

This shows the significance of the inelasticity in BH production

Semi-classical (thermal) versus quantum black hole: calculate the entropy!

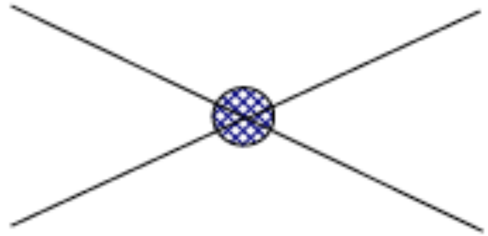
$m_{BH} > M_P$



thermal black hole
large entropy

$m_{BH} \sim M_P$

XC Gong & Hsu (2008)



quantum black hole
small entropy

$$S = \frac{1+n}{2+n} \frac{M_{BH}}{T_{BH}}$$

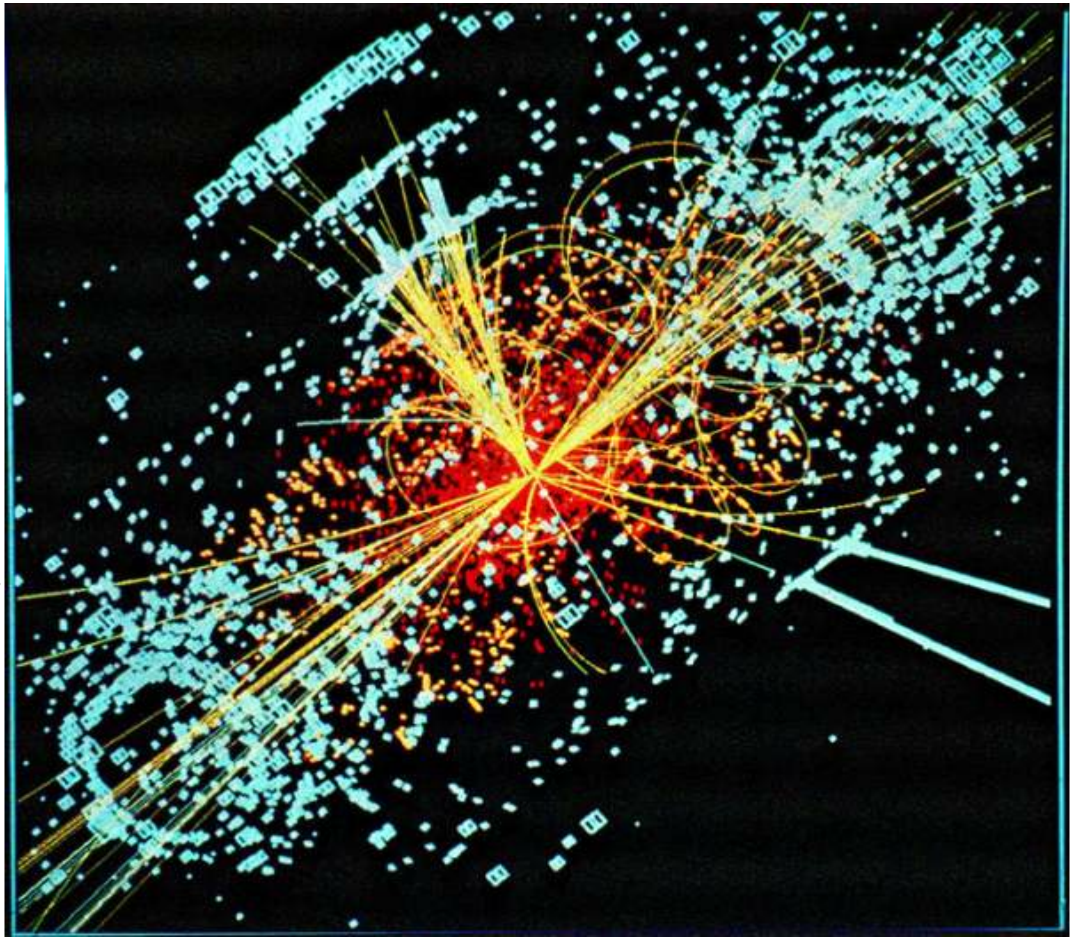
$$\langle N \rangle \propto \left(\frac{M_{BH}}{M_\star} \right)^{\frac{n+2}{n+1}}$$

Keep in mind that E-G construction only works for $m_{BH} >> M_P$

We need to understand the formation of quantum BHs

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.

Does it have spin?
To what particles does it decay (greybody factor)?



It is important to model the decay of small BHs: see talk of Elizabeth Winstanley.

Physics news

- We have LHC data.
- So far no signal from QBHs (as expected..), more in the talk of Greg Landsberg
- LHC is setting the tightest limit to date on the Planck scale.
- Probably implies that we have to think of alternative ways to probe quantum gravity.

LHC black holes if they exist have not ended the world!

The New York Times
nytimes.com

March 29, 2008

Asking a Judge to Save the World, and Maybe a Whole Lot More

By DENNIS OVERBYE

More fighting in Iraq. Somalia in chaos. People in this country can't afford their mortgages and in some places now they can't even afford rice.

None of this nor the rest of the grimness on the front page today will matter a bit, though, if two men pursuing a lawsuit in federal court in Hawaii turn out to be right. They think a giant particle accelerator that will begin smashing protons together outside Geneva this summer might produce a black hole or something else that will spell the end of the Earth — and maybe the universe.

Scientists say that is very unlikely — though they have done some checking just to make sure.

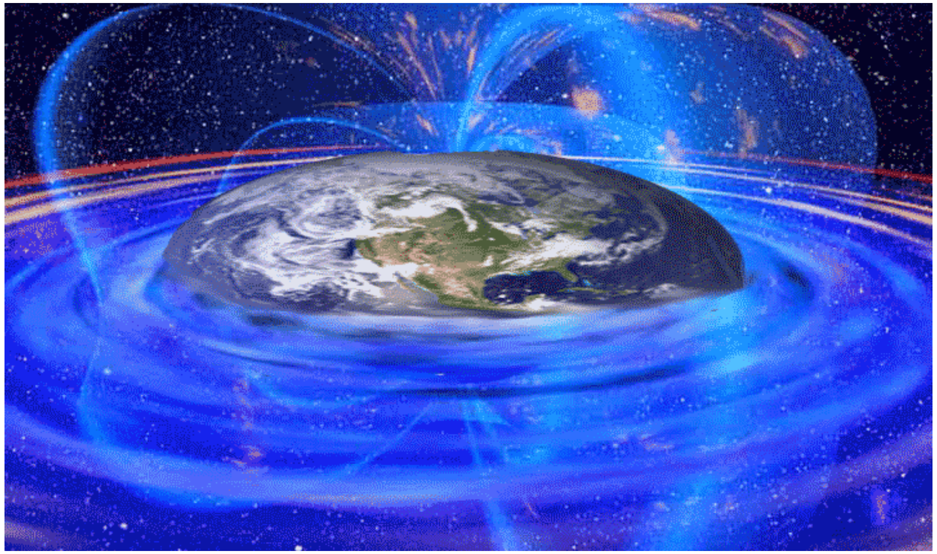
The world's physicists have spent 14 years and $8 billion building the Large Hadron Collider, in which the colliding protons will recreate energies and conditions last seen a trillionth of a second after the Big Bang. Researchers will sift the debris from these primordial recreations for clues to the nature of mass and new forces and symmetries of nature.

But Walter L. Wagner and Luis Sancho contend that scientists at the European Center for Nuclear Research, or CERN, have played down the chances that the collider could produce, among other horrors, a tiny black hole, which, they say, could eat the Earth. Or it could spit out something called a "strangelet" that would convert our planet to a shrunken dense dead lump of something called "strange matter." Their suit also says CERN has failed to provide an environmental impact statement as required under the National Environmental Policy Act.

Although it sounds bizarre, the case touches on a serious issue that has bothered scholars and scientists in recent years — namely how to estimate the risk of new groundbreaking experiments and who gets to decide whether or not to go ahead.

The lawsuit, filed March 21 in Federal District Court, in Honolulu, seeks a temporary restraining order prohibiting CERN from proceeding with the accelerator until it has produced a safety report and an environmental assessment. It names the federal Department of Energy, the Fermi National Accelerator Laboratory, the National Science Foundation and CERN as defendants.

According to a spokesman for the Justice Department, which is representing the Department of Energy, a scheduling meeting has been set for June 16.



CMS paper on semi-classical holes: see Greg's talk.

Physics Letters B 697 (2011) 434–453

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for microscopic black hole signatures at the Large Hadron Collider ☆

CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 15 December 2010
Received in revised form 5 February 2011
Accepted 13 February 2011
Available online 15 February 2011
Editor: M. Doser

Keywords:
CMS
Physics
Black holes
Extra dimensions

ABSTRACT

A search for microscopic black hole production and decay in pp collisions at a center-of-mass energy of 7 TeV has been conducted by the CMS Collaboration at the LHC, using a data sample corresponding to an integrated luminosity of 35 pb^{-1}. Events with large total transverse energy are analyzed for the presence of multiple high-energy jets, leptons, and photons, typical of a signal expected from a microscopic black hole. Good agreement with the standard model backgrounds, dominated by QCD multijet production, is observed for various final-state multiplicities and model-independent limits on new physics in these final states are set. Using simple semi-classical approximation, limits on the minimum black hole mass are derived as well, in the range 3.5–4.5 TeV. These are the first direct limits on black hole production at a particle accelerator.

QBHs

However bounds should be taken with care: theorists are not ready yet!

CERN-PH-EP-2011-030

Search for New Physics in Dijet Mass and Angular Distributions in pp Collisions at $\sqrt{s} = 7$ TeV Measured with the ATLAS Detector

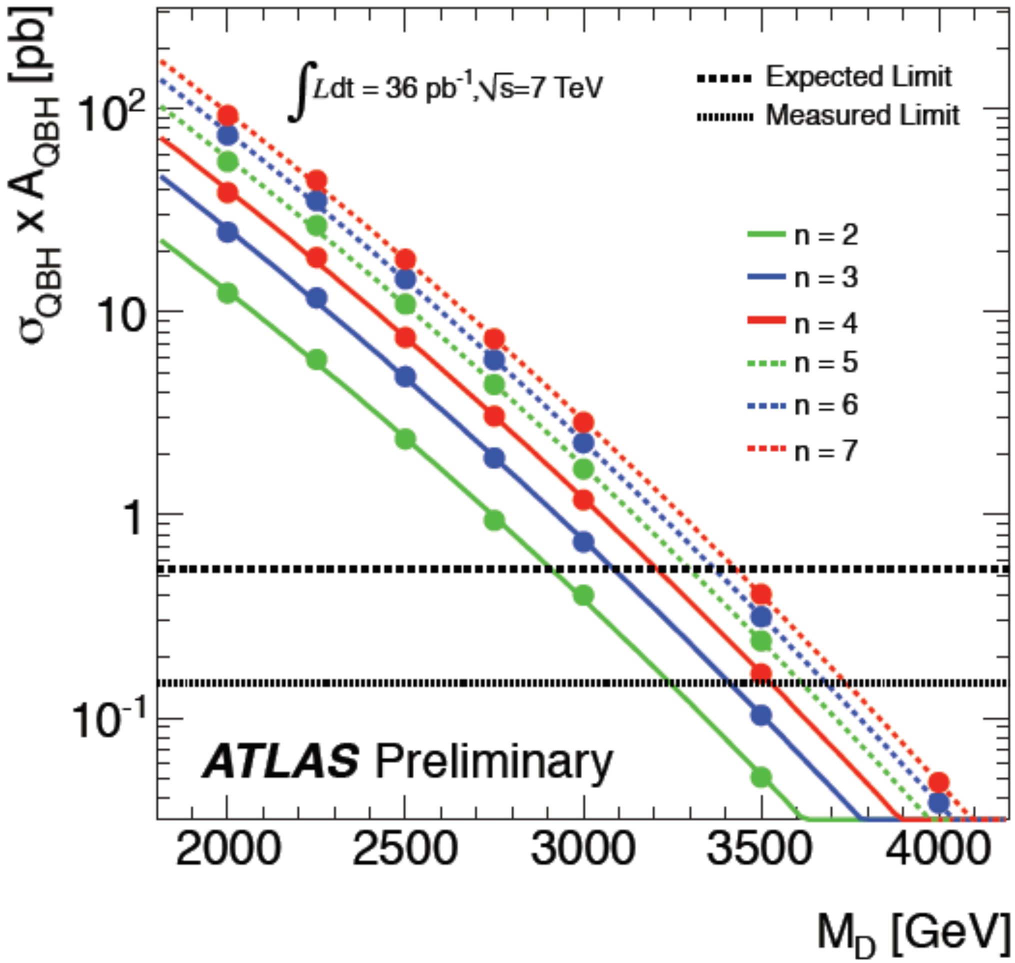
The ATLAS Collaboration

Submitted to: *New J. Phys.*

Abstract. A search for new interactions and resonances produced in LHC proton-proton (pp) collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV has been performed with the ATLAS detector. Using a data set with an integrated luminosity of 36 pb^{-1}, dijet mass and angular distributions have been measured up to dijet masses of ~ 3.5 TeV and found to be in good agreement with Standard Model predictions. This analysis sets limits at 95% C.L. on various models for new physics: an excited quark is excluded with mass between 0.60 and 2.64 TeV, an axigluon hypothesis is excluded for axigluon masses between 0.60 and 2.10 TeV and Randall-Meade quantum black holes are excluded in models with six extra space-time dimensions for quantum gravity scales between 0.75 and 3.67 TeV. Production cross section limits as a function of dijet mass are set using a simplified Gaussian signal model to facilitate comparisons with other hypotheses. Analysis of the dijet angular distribution using a novel technique simultaneously employing the dijet mass excludes quark contact interactions with a compositeness scale Λ below 9.5 TeV.

PACS numbers: 12.60.Rc, 13.85.-t, 13.85.Rm, 14.80.-j, 14.70.Kv

Quantum Black Holes

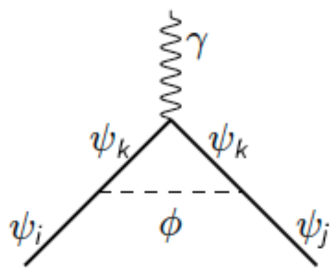


Used BlackMax to simulate a simple two-body decay for a given fundamental quantum gravity scale, M_D.

n = number of extra space time dimensions

Work in progress

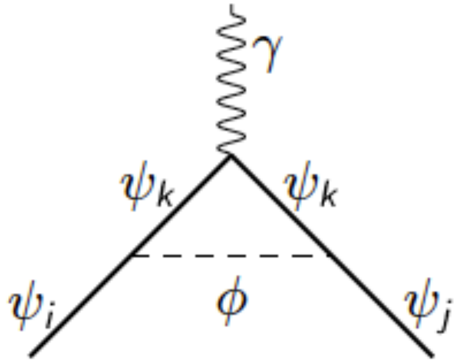
- Developing tools for the LHC: there are still several technical problems to address.
- Probing virtual quantum black holes in low energy experiments.
- Currently developing an effective field theory approach treating QBHs as fields (model independent).
- Trying to get limits from e.g. g-2 or rare decays (see Nina's talk).



Extracted from Nina's talk:

Effective Lagrangian

$$L_{eff} = \sum_{ij} \frac{A}{\bar{M}_P} \bar{\psi}_i \sigma_{\mu\nu} \psi_j F^{\mu\nu}$$



1. anomalous magnetic moment
(e.g. of $\mu \to \bar{M}_P > 2 \times 10^8\,\mathrm{GeV}$)
2. "forbidden" lepton flavor violating processes
(e.g. $\mu \to e\gamma \to \bar{M}_P > 7.2 \times 10^{12}\,\mathrm{GeV}$)

- Experimental bounds on EDM of leptons and quarks
(or e.g. for neutron, if no further suppression factors
$\bar{M}_P > 4.5 \times 10^{16}\,\mathrm{GeV}$)

Conclusions from my talk in Bonn:

A few personal remarks/Conclusions

- It is very unlikely that the scale of quantum gravity is really within the LHC reach. We have shown that models with large extra-dimensions or a large hidden sector suffer from unitarity problem (M. Atkins & XC 2010).
- However, there is little theoretical prejudice for the energy scale at which quantum gravity effects become important: It is an experimental physics question.
- LHC physics is a good excuse to think about fundamental gravity questions: a lot of progress has be made that way using thought experiments.
- It remains crucial to find ways to probe quantum gravity experimentally: primordial black holes could be useful or maybe systems with strong gravitational fields.
- More interaction between high energy/relativists and astronomers hopefully will lead to new ideas on how to probe quantum gravity.

No QG at the LHC?

- Early LHC data indicates that the Planck mass is not in the few TeV region (as expected if you recall my talk in Bonn last year).
- It is time to think of other ways to probe quantum gravity.
- Astrophysics/cosmology seems the obvious way to go e.g. primordial black holes: see the talks of Anne and Bernard in plenary and that of Klaus in the WG1 session.
- It is worth thinking about using astrophysical BHs as a way to probe high energy physics and deviations of the SM.

News from WG1

Members who cannot join us this time:

- Peter D'Eath is in the US

- Sabine Hossenfelder had twins a few months ago.

A very productive year from all points of view!

Ongoing collaborations

- 2 STSMs so far (Piero to Sussex & Sheffield)
- First papers out and published which are a direct product of the 1st working group meeting in Bonn.
- Papers in preparation.
- Please keep me posted on papers which result from WG1 collaborations.
- First PhD student involved in WG1.

Thanks for your attention!