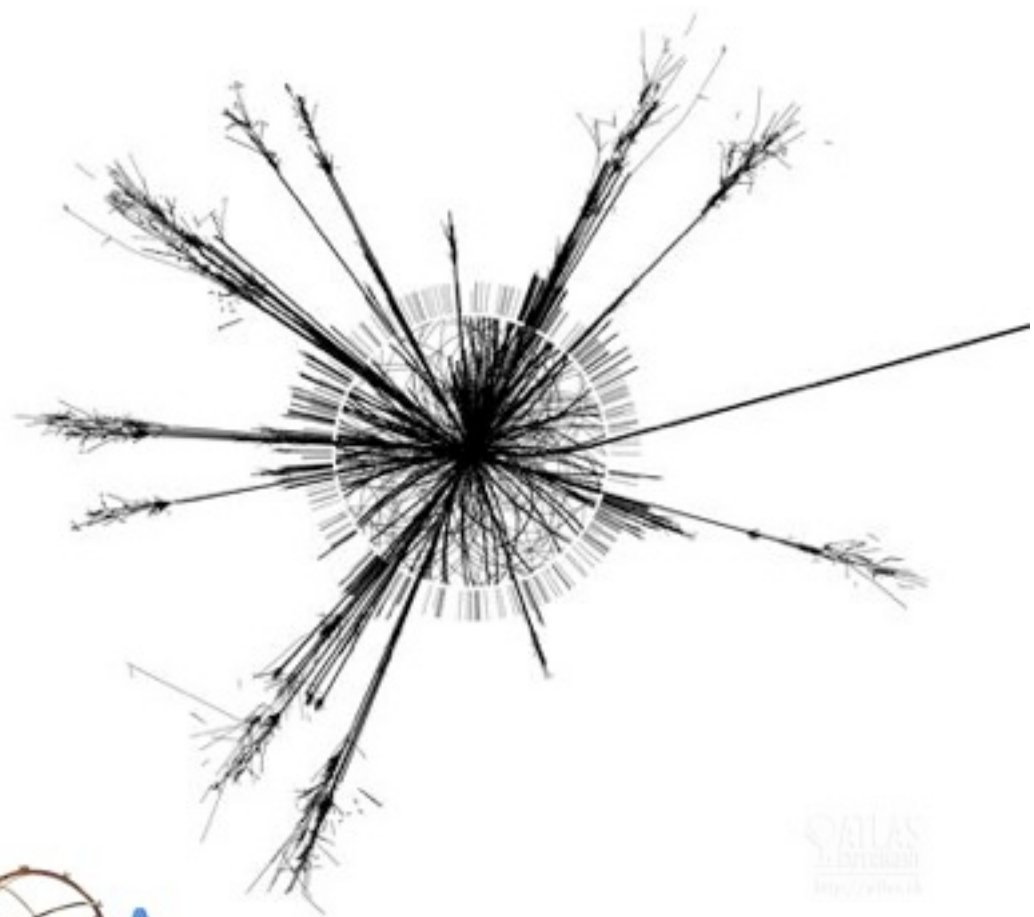
Black Holes, Extra Dimensions & the LHC



- Black Hole Recap
- The Problematic Standard Model
- Extra Dimensions & the Planck Scale
- Black Hole Production & Decay
- Current Constraints
- Signatures at the LHC

ATLAS

Queen Mary
University of London

Introduction

In last ~150 years physics has developed enormously

Three major pillars of modern physics have emerged

• general relativity	2×10^{-5}	Cassini photon freq. shift close to Sun
• thermodynamics	1×10^{-7}	WMAP precision of CMB fluctuations to 1%
• quantum mechanics	1×10^{-12}	Measurement of electron g-2

Tested to unprecedented precision

- Black Hole studies are unique - combines all three areas
- Raises some very interesting questions about the nature of spacetime
- Ideas have very appealing simplicity
- Potential to answer one or several fundamental puzzles

Classical Black Holes

In QM all particles associated with a compton wavelength

$$\lambda = 1/E$$

In GR any object with energy-momentum ($T_{\mu\nu}$) will cause curvature of space-time ($g_{\mu\nu}$)

Force of nature interacts with spacetime itself!

Riemann tensor $R_{\mu\nu}$ describes tidal forces: residual acc^n between test masses on initially parallel geodesics

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi \frac{1}{m_{\rm p}^2} T_{\mu\nu}$$

Planck scale

Thus objects warp space-time around themselves and this modifies the objects equations of motion

For fundamental particles expect this influence at Planck Scale - M_P

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

where G = Gravitational constant

$M_P \sim 10^{19}$ GeV (⇒ hierarchy problem)

Classical Black Holes

For a spherically symmetric mass distribution the solution is 4d line element given by:

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -\gamma(r)dt^2 + \gamma(r)^{-1}dr^2 + r^2 d\Omega^2$$

$$\gamma(r) = 1 - \frac{1}{m_p^2}\frac{2M}{r}$$

area element on surface of sphere

So, for masses small compared to M_P then $\gamma = 1$

For large energies metric is distorted by order $E/M^2{}_P$

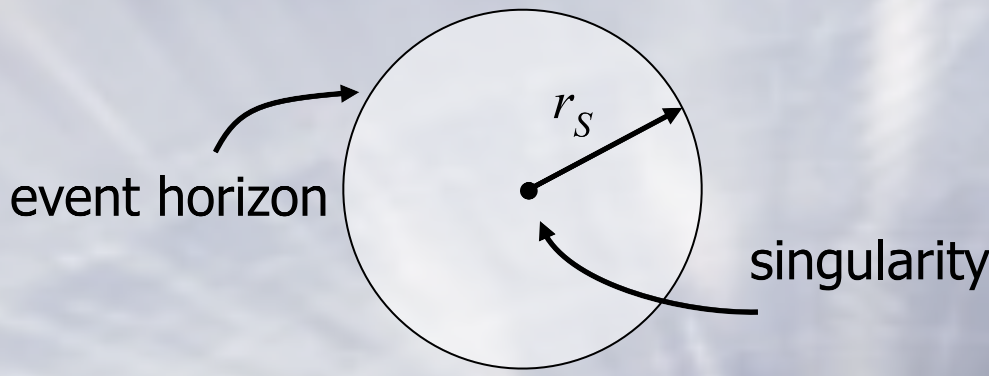
At energies close to Planck Mass distortions cannot be neglected

Metric becomes singular at $r = \frac{2M}{M_P^2} = r_s$ the Schwarzschild radius

Schwarzchild radius is sol^n of GR in case of non-rotating uncharged BHs

First solution to GR discovered 1 month after Einstein's publication

Alternatively, can write $r_s = \frac{2GM}{c^2}$



Bring mass M within a radius r_S and a singularity will form

Event horizon is all we can observe from our side of the universe

For Earth r_S= 1cm

Rotating Kerr solution published 1963

A more generic solution was found for charged rotating black holes

Solve classical electro-dynamics in GR field equations
yields the Kerr-Newmann metric

Size of event horizon generalises to r_h

Charged rotating BH
Kerr-Newmann solution published 1965

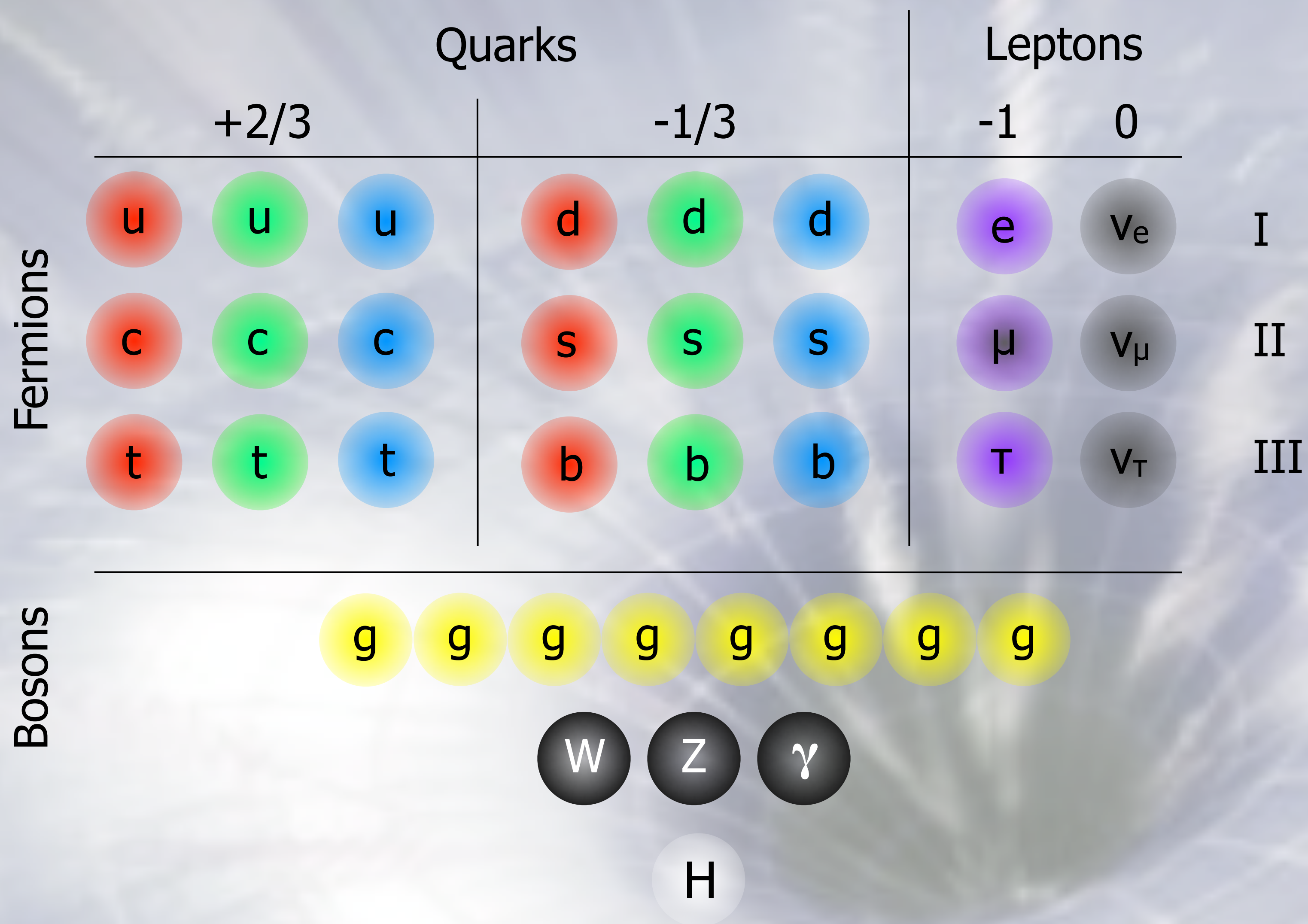
The Problematic Standard Model

Jump to particle physics...

The Standard Model is fantastically successful

... but ...

The Problematic Standard Model



61 'fundamental' particles in the SM! (including anti-particles)

The Problematic Standard Model

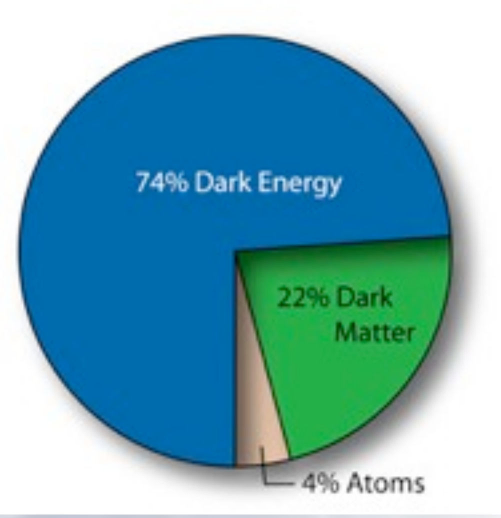
22 Parameters of the SM to be measured

- 6 quark masses
- 3 charged leptons masses
- 3 coupling constants
- 4 quark mixing parameters
- 4 neutrino mixing parameters
- 1 weak boson mass (other predicted from remaining EW params)
- 1 Higgs mass

(better than 105 params of generic SUSY)

We have no idea what 96% of the universe is!

- unknown form of dark energy
- unknown form of dark matter



No treatment of gravity in the Standard Model...
In a symmetric theory gauge bosons are massless
Higgs mechanism explains EW symmetry breaking
→ EW bosons acquire mass

...but there must be a deeper relationship between Higgs / mass / gravity / dark energy

The Problematic Standard Model

Dark energy acts to accelerate the expansion of the universe
i.e. repulsive gravity

Evidence from
- supernovae
- CMB - flat cosmological geometry
- blue shift of CMB photons in gravity wells
  (integrated Sachs-Wolfe effect)

Best guess is:
constant across cosmos
property of the vacuum

Summing zero-point vacuum fluctuations of SM fields incl. Higgs
yields energy density 10^{120} times larger than measured!!!

“the worst theoretical prediction in the history of physics!”*

(not surprising that it's related to what Einstein called “his greatest blunder”)

Back to particle physics:
insufficient CP violation & no Baryon number violation able to
account for our matter dominated universe

* MP Hobson, GP Efstathiou & AN Lasenby (2006). General Relativity: An introduction for physicists

Why is gravity ~10^{33} weaker than EW interactions?
Why is Higgs mass (~100 GeV) so much smaller than Planck mass (10^{19} GeV)?

Leads to fine tuning problem
self energy corrections to Higgs mass are quadratically divergent up to 10^{19} GeV

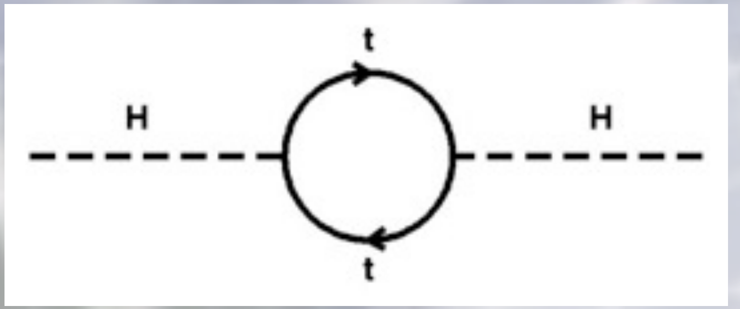
physical mass = bare mass + "loops" $m_H^2 = m_0^2 + \Delta m_H^2$

since Higgs is scalar field we get:

for top: $\Delta m_H^2 = -\frac{6}{16\pi^2} g_t^2 \Lambda^2$ (g is Yukawa coupling)

for EW bosons: $\Delta m_H^2 = +\frac{1}{16\pi^2} g^2 \Lambda^2$

for Higgs: $\Delta m_H^2 = +\frac{1}{16\pi^2} \lambda^2 \Lambda^2$ (λ is Higgs self-coupling)

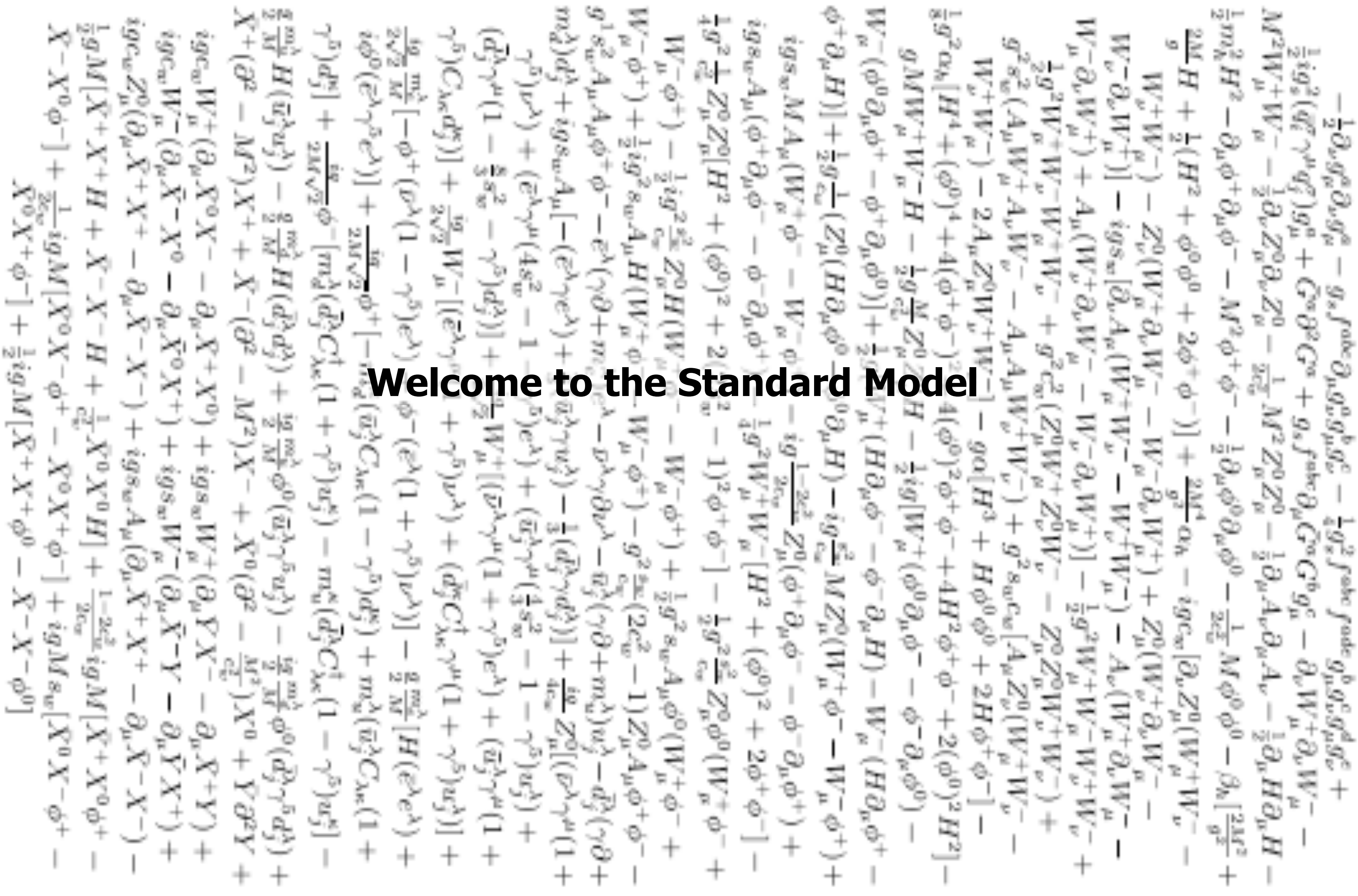


$m_H^2 = m_0^2 + \frac{1}{16\pi^2}\left(-6g_t^2 + g^2 + \lambda^2\right)\Lambda^2 -$ ... new physics ...

For $\Lambda^2 \sim (10^{19}\ \text{GeV})^2$ and $m_H^2 \sim (100\ \text{GeV})^2$ then

$$m_H^2 = m_0^2 + \frac{1}{16\pi^2}\left(-6g_t^2 + g^2 + \lambda^2\right)\cdot 10^{38} = (100\ \text{GeV})^2$$

- if SM is valid to this scale (i.e. no new physics from 1 TeV - 10^{19} GeV) incredible fine tuning required between bare mass and the corrections to maintain ~ 100 GeV Higgs mass



Welcome to the Standard Model

Extra Dimensions & The Planck Scale

What if there is no new scale in particle physics up to M_P?

We will have to live with the fine tuning problem

Use anthropic arguments

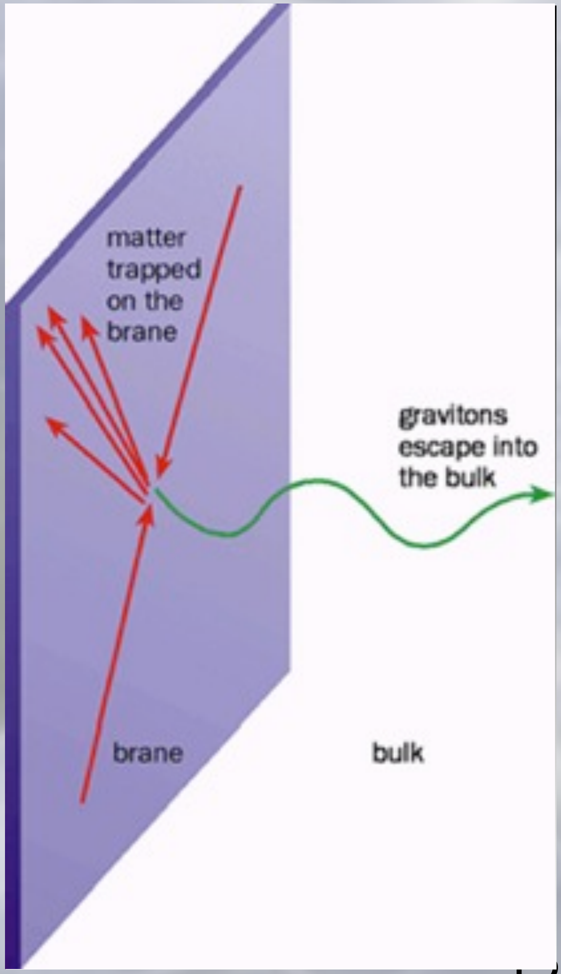
(of all possible universes with different physics parameter values
only universes with <u>our</u> parameter settings could lead to humans existing)

Alternative approach:

Perhaps we can bring M_P down to ~1 TeV

Introduce large extra spatial dimensions (large ~ 1 mm)

- Standard Model confined to a 3-brane
- Embedded in higher dimensional space
- Only gravity propagates in extra dimensions



Extra Dimensions & The Planck Scale

1920s - Kaluza & Klein attempted to unify general relativity & Maxwell's EM
- incorporated U(1) gauge symmetry into 5d spacetime
- if extra dimension is compactified then EM & Lorentz symmetries remain
- photon becomes 4d manifestation of 5d graviton

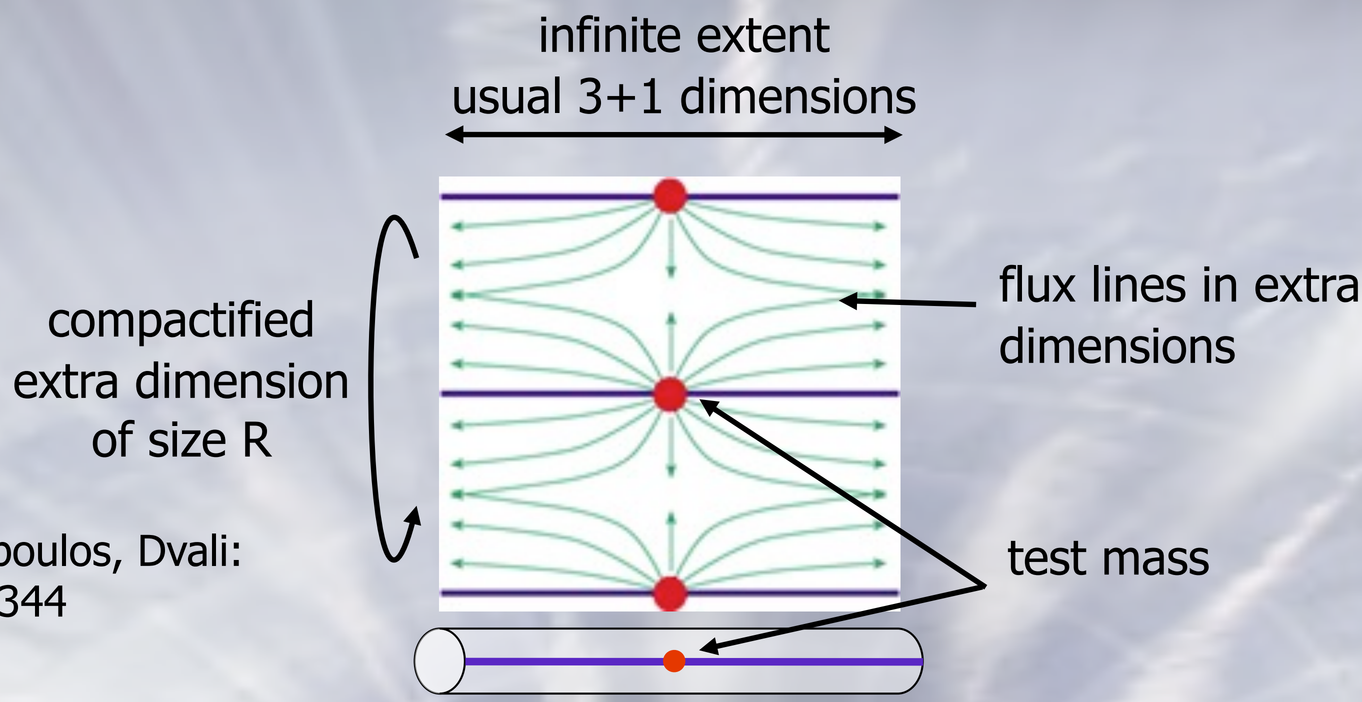
Theory suffered problems
- unable to explain vast difference in strengths of two interactions
- unable to combine with quantum mechanics
- later discoveries of weak & strong interactions did not fit into the scheme

Supersymmetry & string theory in 1970s / 1980s revived concept of extra dimensions

some of gravity's non-renormalizability could be accommodated in string theory
requires 10 / 11 spatial dimensions
predicted spin 2 massless particle (graviton)
- graviton is expected to be massless (gravity has infinite range)
- graviton is expected to be spin 2
  - (since gravity is described by 2^{nd} rank energy-momentum tensor)

Extra Dimensions & The Planck Scale

ADD Model of Large Extra Dimensions



Antoniadis, Arkani-Hamed, Dimopoulos, Dvali:
hep-ph/9803315, 9804398, 9807344

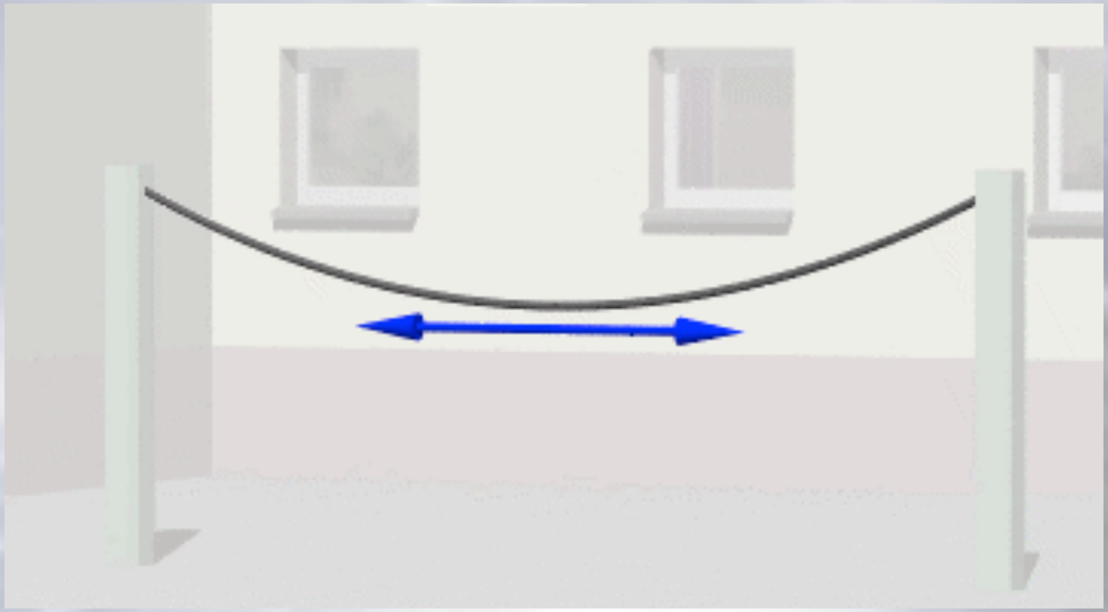
- All standard model particles are trapped to surface of this hyper-cylinder
- Particles moving in the bulk have quantised wave functions (like 1d potenial well)
- Higher order modes appear as higher energy excitations
- Mass difference between successive states related to size of dimension R
- Can lead to infinite Kaluza-Klein towers of particles

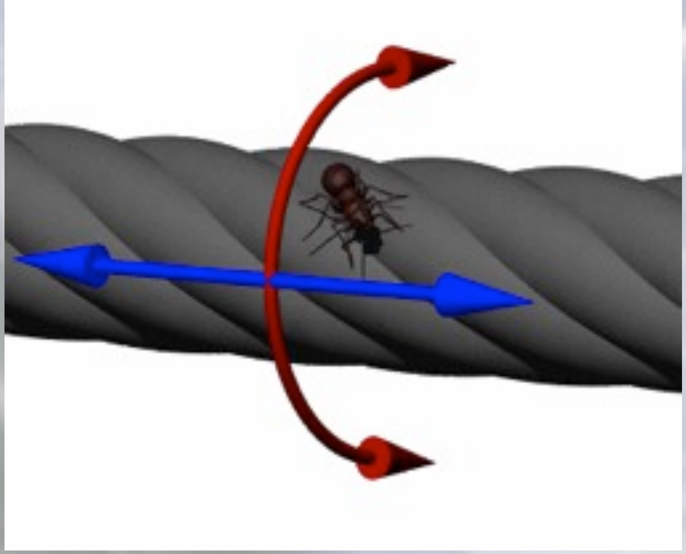
massless gravitons would appear as a tower of massive states on our brane
momentum in extra dim appears as additional mass: $M^2 = E^2 - P_x^2 - P_y^2 - P_z^2 - P_n^2$

Extra Dimensions & The Planck Scale

Why are the extra dims < 1 mm ?
gravity has only been tested down to this scale!
current torsion balance experiments set limit on $1/r^2$ dependence to <0.16 mm

Where are the extra dimensions?
curled up (compactified) and finite
only visible at small scales / high energies





Relative strength of gravity explained by dilution of gravitons propagating in very large volume of bulk space

Extra Dimensions & The Planck Scale

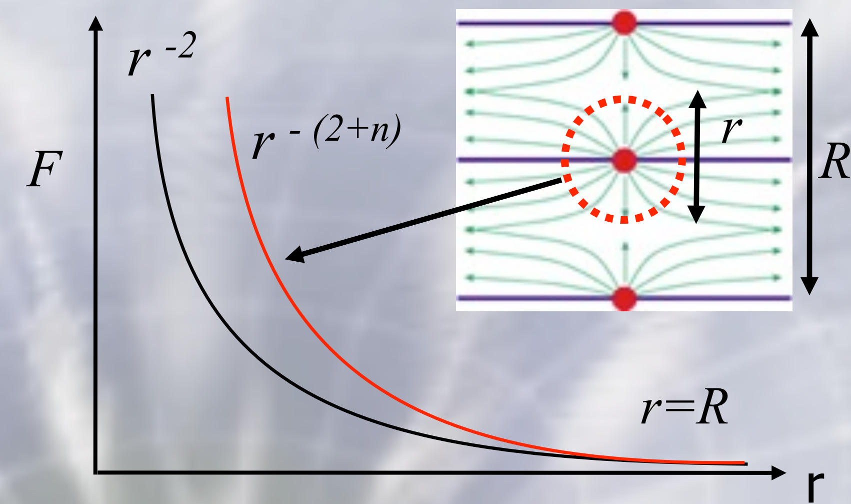
Gauss' Law for gravity: surface integral over closed volume containing vector field g gives total enclosed mass M

$$\int g \cdot dA = -4\pi M \quad \text{yields Newton's law} \quad F = \frac{m_1 m_2}{r^2}$$

With n extra spatial dimensions each of size R

$$F = G_D \frac{m_1 m_2}{r^{2+n}}$$

$$F = \left(\frac{G_D}{R^n}\right)\frac{m_1 m_2}{r^2} \qquad \text{i.e} \quad G = \frac{G_D}{R^n}$$



For $r \gg R$ we recover Newtonian gravity

dilution due to volume of extra dimensions

Planck scale: $M_P^2 = \dfrac{\hbar c}{G}$

In extra dimensions full scale of gravity M_D is given by

$$M_D^{2+n} = \frac{\hbar c}{G_D} = \frac{M_P^2}{R^n}$$

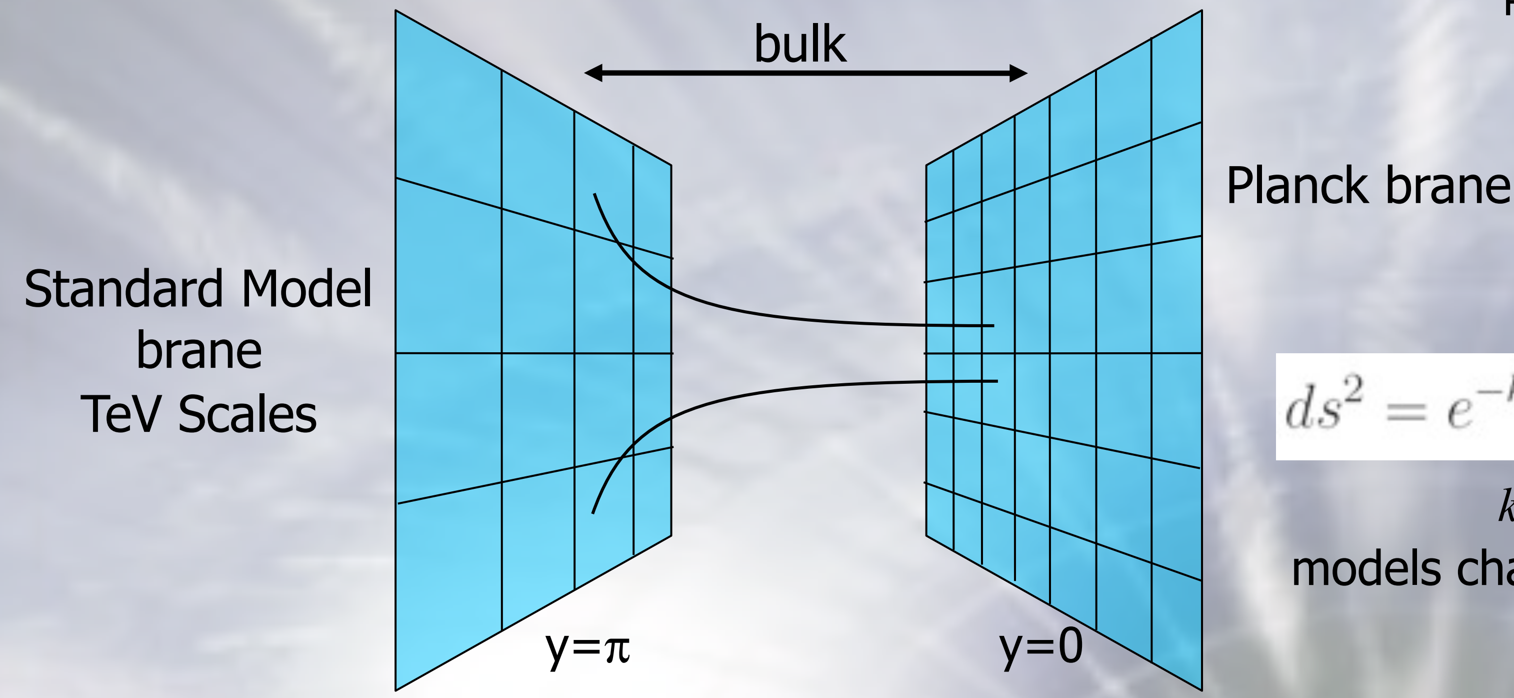
Thus M_D can be ~ 1 TeV when R^n is large

For n=1 and M_D=1 TeV then $R \sim 10^{16}$ m $\Rightarrow$ already excluded!

Extra Dimensions & The Planck Scale

Randall-Sundrum Model of Warped Extra Dimensions

Randall, Sundrum: Phys.Rev.Lett 83, 3370(1999)
Phys.Rev.Lett 83, 4690(1999)



$$ds^2 = e^{-k\pi y}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

k = warp factor
models characterised by scale k/M_P

Spacetime is structured as two separated 3-branes: SM and Planck

Two 3-branes connected with 1 extra dimension

$$M_P^2 = 8\pi \frac{M_D^3}{k}\left(1 - e^{2\pi kR}\right)$$

Gravitons propagate in the bulk

Extra dimension highly curved with an exponential warp factor
⇒ introduces scaling between 3-branes length $\propto 1/E$

Dark energy is ~74% of critical density of universe

⇒ density of dark energy ρ_d ~ 0.0038 MeV/cm^3

⇒distance scale $L_d = \sqrt[4]{\frac{\hbar c}{\rho_d}}$ ~ 85 μm

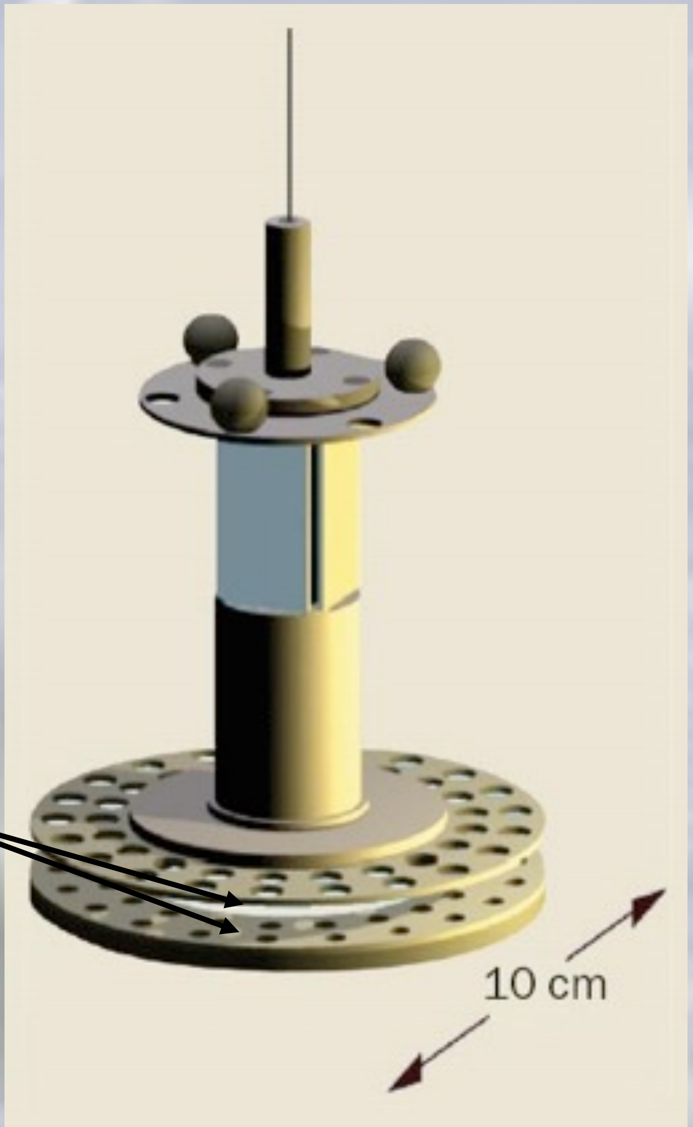
could be a fundamental distance scale...

Test inverse square law at small distances
with torsion balance experiments

Measure torsion forces between test and attractor
masses in horizontal plane (actually holes in two rings)

Measure torque vs vertical separation

Sensitive to ~1 nanoradian twists
(angle subtended by 1 mm at distance of 1000 km)



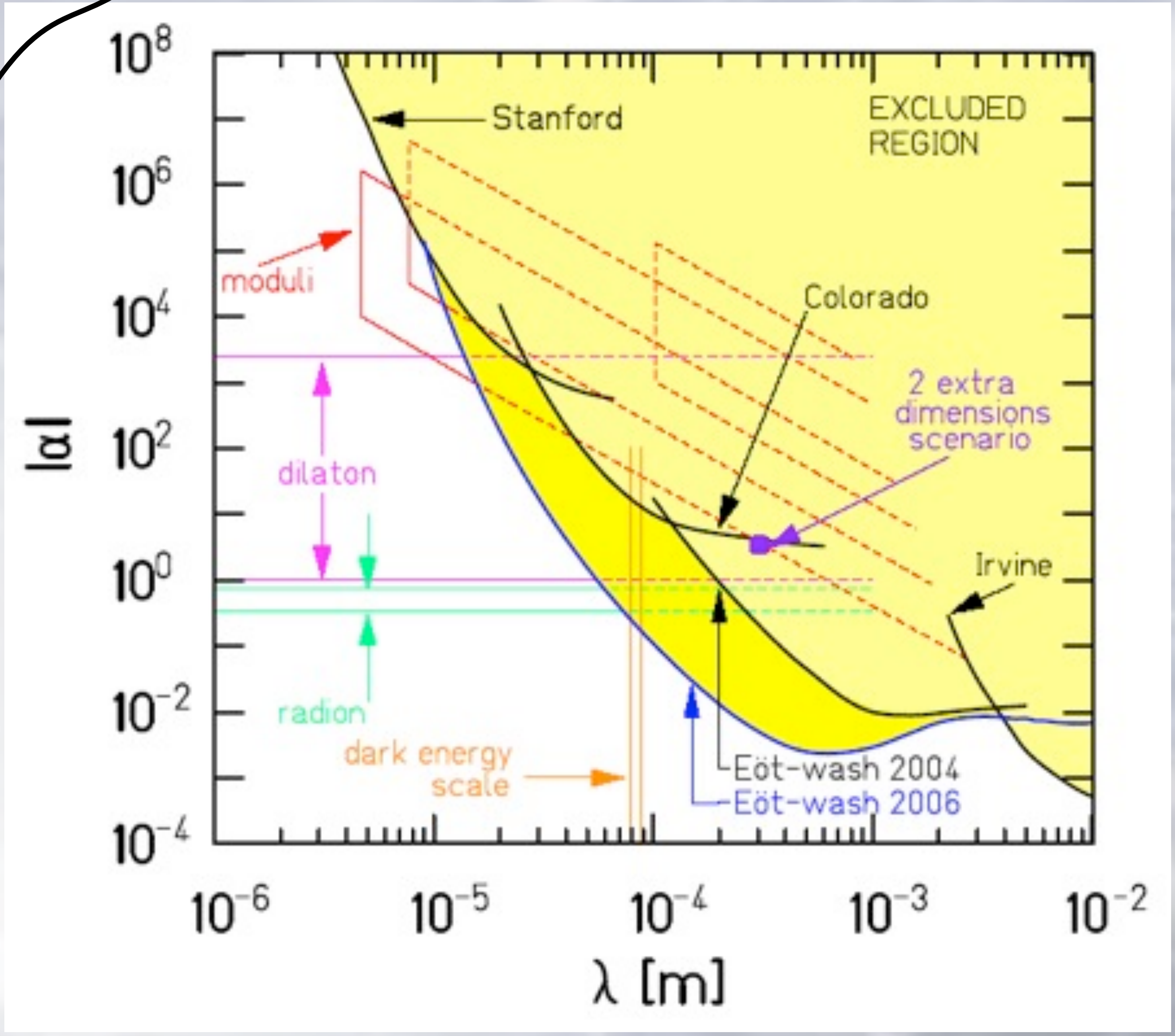
Gravity at Small Distances

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

strength of new Yukawa-like potential

range of new Yukawa-like potential

Phys.Rev.Lett.98:021101, 2007



Inverse square law holds for $\lambda < 56\ \mu m$

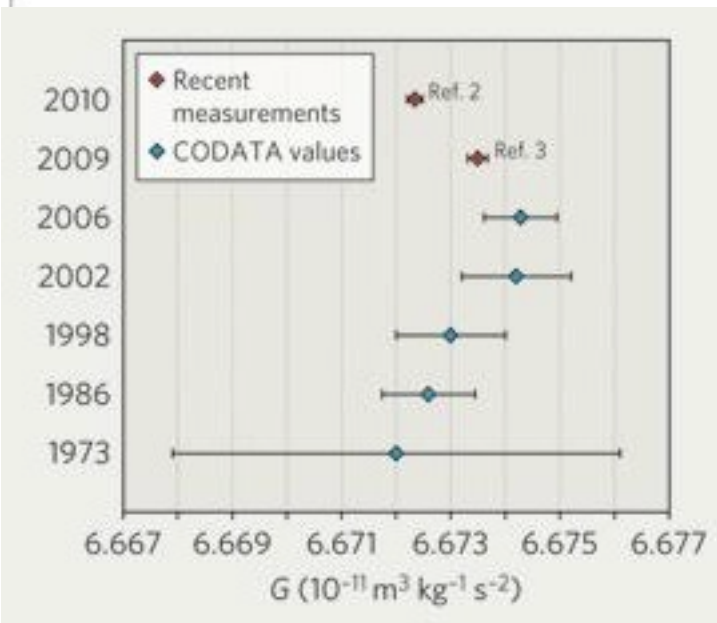
$\Rightarrow$ extra dims have

R < 44 μm 95% C.L.

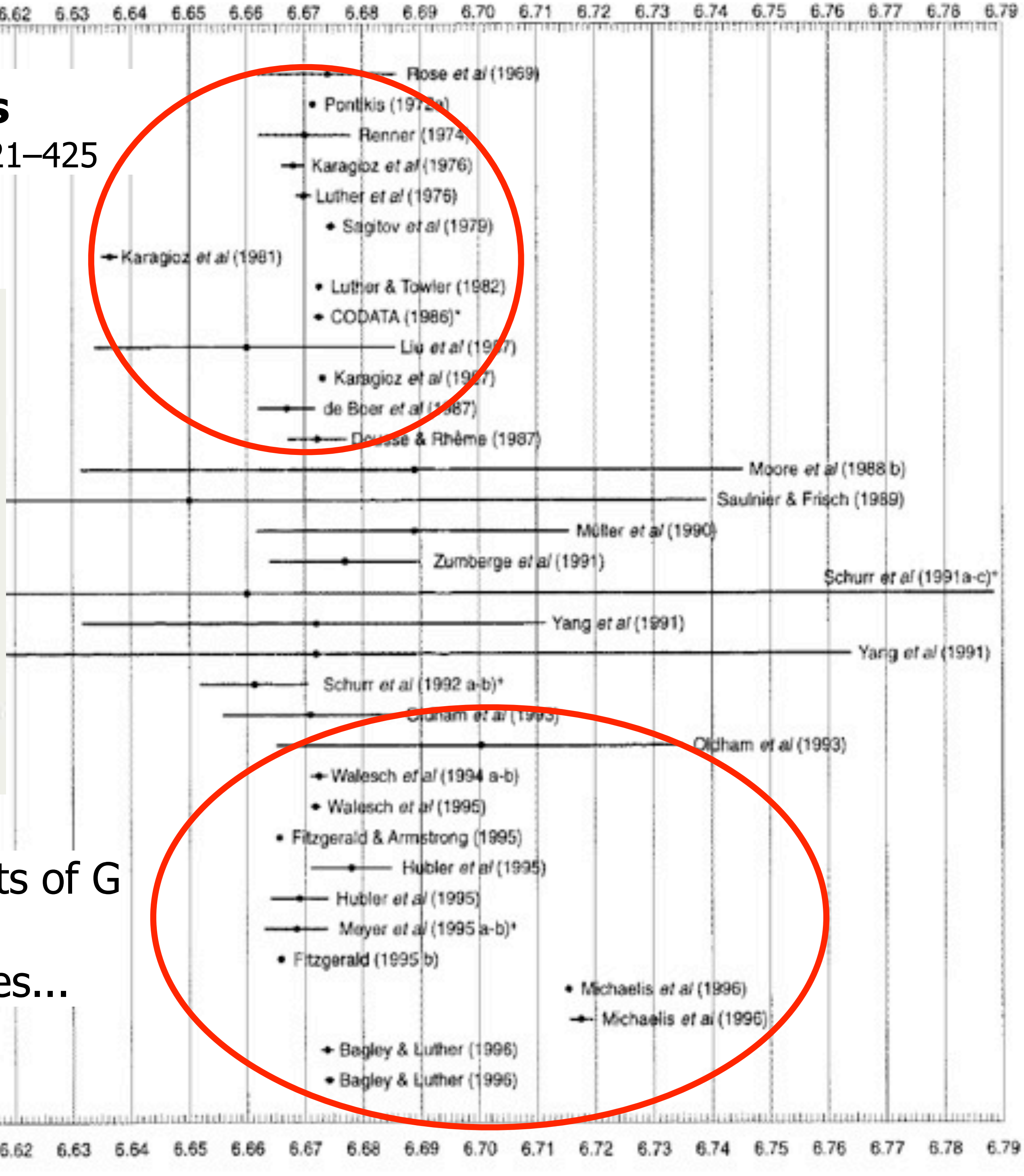
Gravity at Large Distances

Gillies, Meas.Sci.Technol. 10(1999)421–425

Reich: Nature 466, 1030 (2010)



Summary of measurements of G
1969-1999
Many large discrepancies...



* See Cohen and Taylor (1987).

* The error bars represent the quadrated sum of the individually listed Type A and Type B uncertainties.

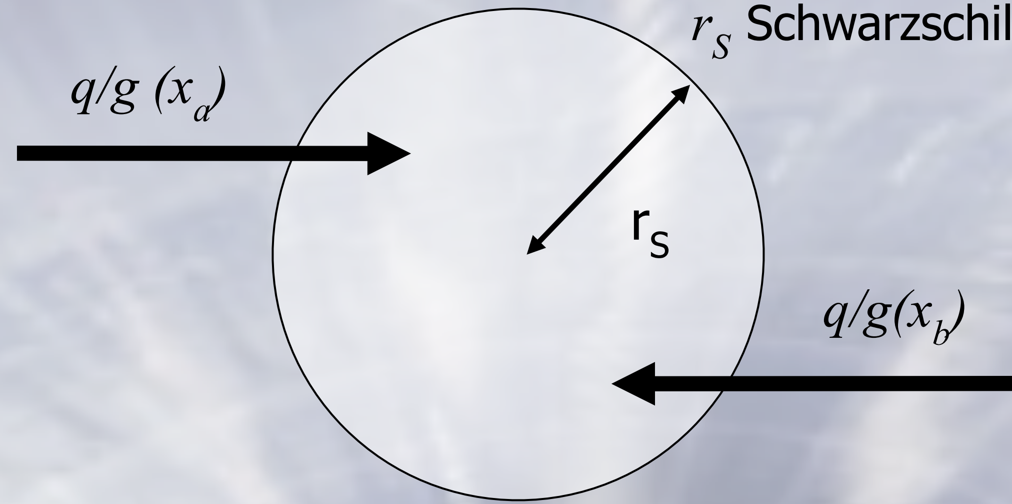
Micro Black Hole Production

Giddings, Thomas: hep-ph/0106219
Dimopolous, Landsberg: hep-ph/0106295

In collisions Black Hole forms when impact parameter < $2r_S$

$$M_{BH} = \sqrt{s \cdot x_a \cdot x_b} = \sqrt{\hat{s}}$$

r_S Schwarzschild radius



r_S increased by factor R^n

$$r_s = \frac{2GR^n M_{BH}}{c^2}$$

Should observe continuous mass spectrum of BHs
$M > M_D$

In absence of any real theory use classical cross section:

$$\sigma_{BH}(\hat{s}) = F \pi r_s^2$$

parton cross section
F = production form/fudge factors

$$\sigma_{BH}(s) = \sum_{a,b} \iint dx_a \cdot dx_b \cdot f_a(x_a) \cdot f_b(x_b) \cdot \sigma_{BH}(\hat{s})$$

convolute PDFs to get total production cross section

Simple but extremely robust prediction!

Micro Black Hole Production

Cross section increases with s

For $s \gg M_D$ BH production will dominate over SM processes

For example very high E_T jets no longer produced $\Rightarrow$ form BH

Energy redistributed as lower momenta thermal emissions

"The end of short distance physics" Giddings, Thomas: hep-ph/0106219v4

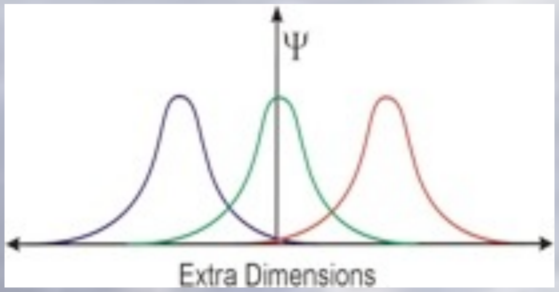
Split Fermion Model

BHs do not conserve B, L, or flavour

⇒ Raises problems: proton decay, n-nbar oscillations...

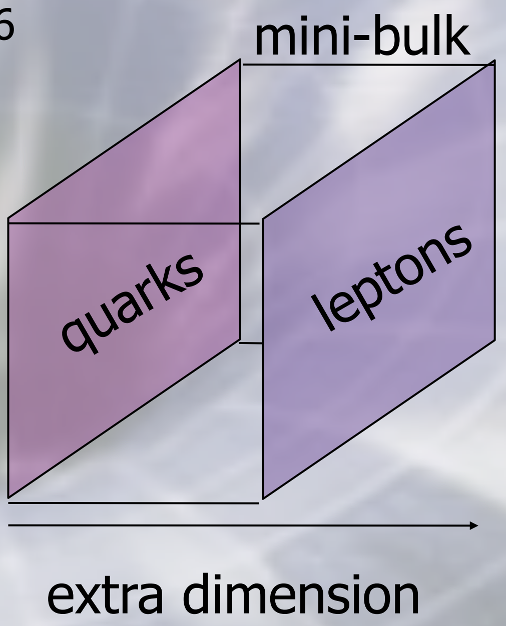
Proton kinematically allowed to decay to any lighter fermion
Only protected by B conservation (which must be violated at GUT scale!)
Only option is e^+ ⇒ thus p decay violates lepton number too

$$p \to e^+ + \gamma$$
$$p \to e^+ + \pi^0$$



Many ADD models predict too fast proton decay

(Super Kamiokande limit: t ~ 10^{33}y arXiv:0903.0676



Split Fermion Model

In this model spacetime structure is further modified

SM fermions exist on separated 3d branes

SM bosons propagate in the 'mini bulk' between them

Split fermion model may also explain
fermion mass hierarchy

Arkani-Hamed,Schmaltz DOI:10.1103/PhysRevD.61.033005
Dai, Starkman, Stojkovic: hep-ph/0605085

Micro Black Hole Production

Astrophysical black holes characterised by 3 numbers only

- M mass
- Q electric charge
- J angular momentum

Metaphorically: 'bald' BH has only 3 hairs

In context of micro BH - they can also carry colour charge
(astro BHs only absorb colourless hadrons anyway)

Infalling matter has entropy, 2nd law then implies BH have entropy too
BH cannot be a single microstate!
- infalling matter will always increase r_S never decrease $r_s = \frac{2GM_{BH}}{c^2}$

entropy $\propto$ surface area

Then it follows that an object with entropy has a temperature...

$$\frac{\partial S}{\partial E} = \frac{1}{T}$$

Hawking Radiation

Hawking: Commun.Math.Phys.43:199-220,1975

Near event horizon vacuum fluctuations interact with warped spacetime

Negative energy particle of virtual pair falls into BH, other becomes real

$\Rightarrow$ BH loses mass

radiate a black body spectrum with temp T_H

$$T_H = \frac{1}{8\pi}\frac{\hbar c^3}{Gk_B}\frac{1}{M_{BH}}$$

First formula to connect fundamental constants of thermodynamics, GR & QM!

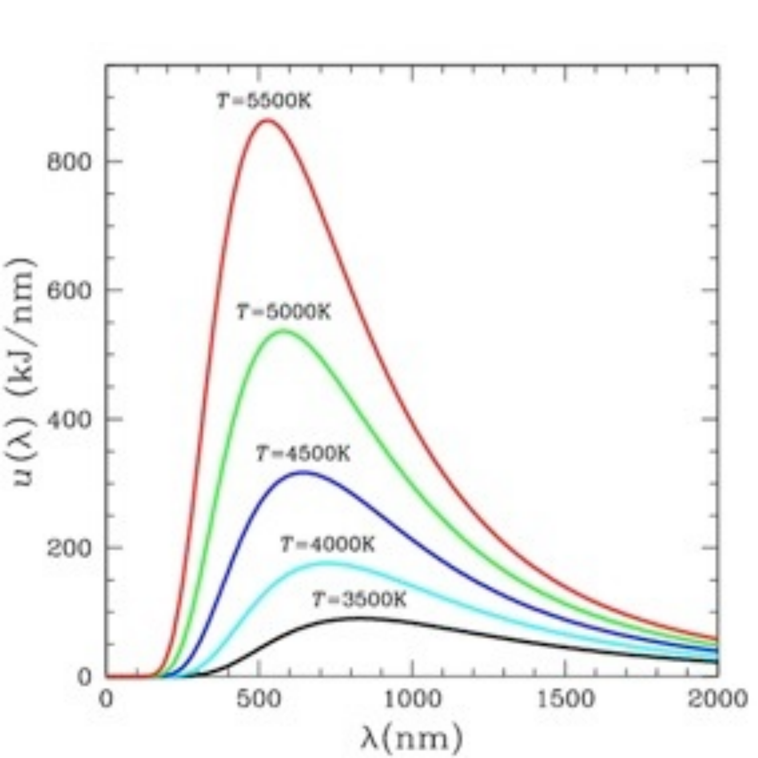
Astro-BHs have temp < CMB

Micro BHs are very hot - radiate intensely

$\Rightarrow$ BH evaporate

Hawking radiation is purely thermal

only depends on M , Q , J , Col



Information Paradox

No hair (bald) theorem of BHs ⇒ violation of baryon nr, lepton nr, flavour

Two BHs of equal M , J , Q , but made of matter and anti-matter are identical

Independent of all other information - i.e. what 'stuff' fell into BH

Information loss paradox - else BH must remember what it swallowed
info remains inside BH? What happens when it decays?

In QM time evolution is unitary transformation:

initial state $$\langle\psi|\psi\rangle = \langle\psi|U^{\dagger}U|\psi\rangle = \langle\psi'|\psi'\rangle$$ final state

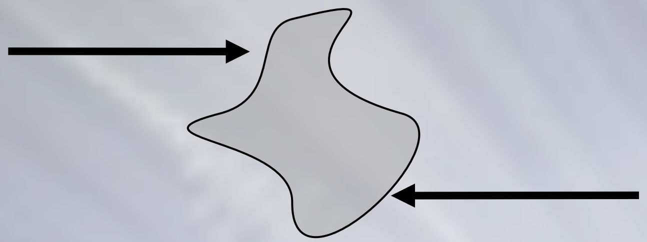
Initial state BH transforms to final state of purely thermal radiation (M , Q , J)

$$U^{\dagger}U = I \Rightarrow U^{-1} = U^{\dagger}$$

Thus unitary transforms are reversible – but pure thermal state → e.g. pure baryon state cannot happen unless additional info / quantum numbers are known!

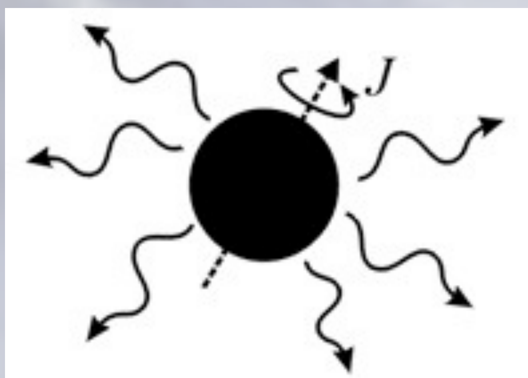
Hawking now claims non-thermal info-preserving radiation S. Hawking: hep-th/0507171

The Tragic Life of a Black Hole

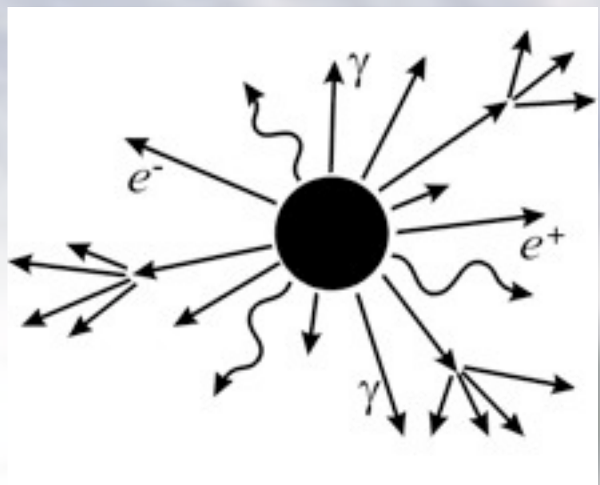


Collision produces complex state as horizon forms
Not all energy is trapped behind horizon

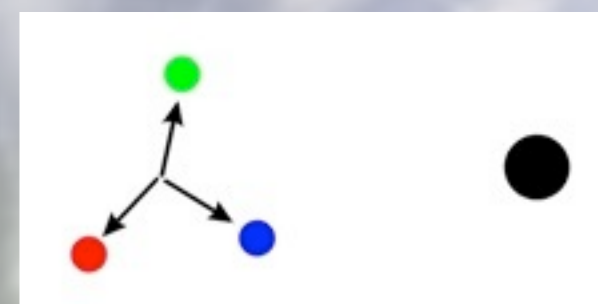
Extremely short lifetime ~ 10^{-25} s



Balding
Energy lost as BH settles into 'hairless' state



Evaporation
Thermal Hawking radiation in form of SM particles & gravitons
Greybody factors give emission probs for all quanta



Plank Phase
For $M_{BH} \sim M_D$ unknown quantum gravity effects dominates. BH left as stable remnant or final burst of particles **????**

pics: backreaction.blogspot.com

Clearly much is missing in these models

No knowledge of true quantum gravity

Semi-classical approximation fails for $M_{BH} \sim M_D$

Formation of event horizon $\Rightarrow$ not all energy trapped inside

Greybody emission factors - QFT in strongly curved spacetime
they have credence since solutions yield thermal spectra
i.e. conspiracy of nature to be self-consistent!

Several calculations performed yield agreement at ~1% level

Nevertheless calcs assume fixed metric...

Gingrich: hep-ph/0609055

Phenomenological suppression of modes that increase |Q| or Colour

Important to explore full phenomenological space

Include all effects into MC simulations

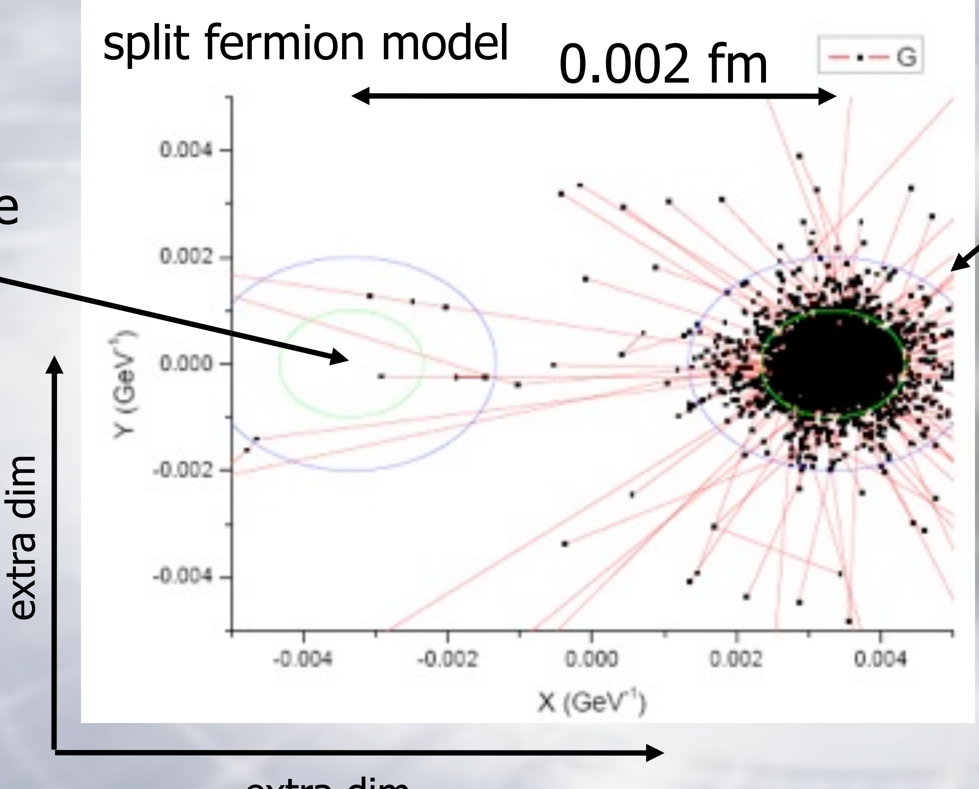
Incorporate all effects into MC models

- energy loss prior to horizon formation
- grey body particle emission factors
- rotation of BH (ang.mom)
- recoil of BH
- conservation/violation of B,L,flavour
- number, size & location of extra dimensions

obtained by equating BH absorption of radiation to change in spacetime metric

BlackMax Dai et.al. arXiv:0711.3012
Charybdis Frost et.al. arXiv:0904.0979

Downloads: hepforge.org



BH is formed on quark brane at pp colliders

BH recoils at each emission

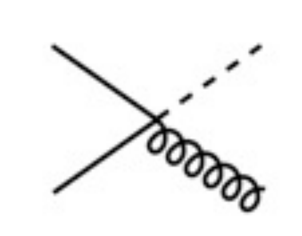
Affects emission spectra

Mostly emits quarks/gluons

Current Constraints

Search for deviations from SM cross sections with increasing m Q^2 $\sqrt{s}$ ...
Look for $qq \rightarrow Gg$ scattering - monojet events (graviton unseen in extra dim)

Graviton scattering derived as low energy effective field theory
Giudice, Rattazzi, Wells: hep-ph/9811291



HERA: e-jet
H1: M_{D^-} > 0.90 TeV and M_{D^+}>0.91 TeV
ZEUS: M_{D^-} > 0.94 TeV and M_{D^+}>0.94 TeV

coupling ±λ has unknown sign of interference with SM

LEP: $\gamma + \not{E}_T$
M_D > 1.60 TeV for n = 2 (equiv: R < 0.19 mm)
M_D > 0.66 TeV for n = 6 (equiv: R < 0.05 nm)

convert to equivalent compactification radius using relation with Newton's const.

$$G_N^{-1} = 8\pi R^n M_D^{n+2}$$

CDF: γ/jet + $\not{E}_T$
M_D > 1.40 TeV for n = 2
M_D > 0.94 TeV for n = 6

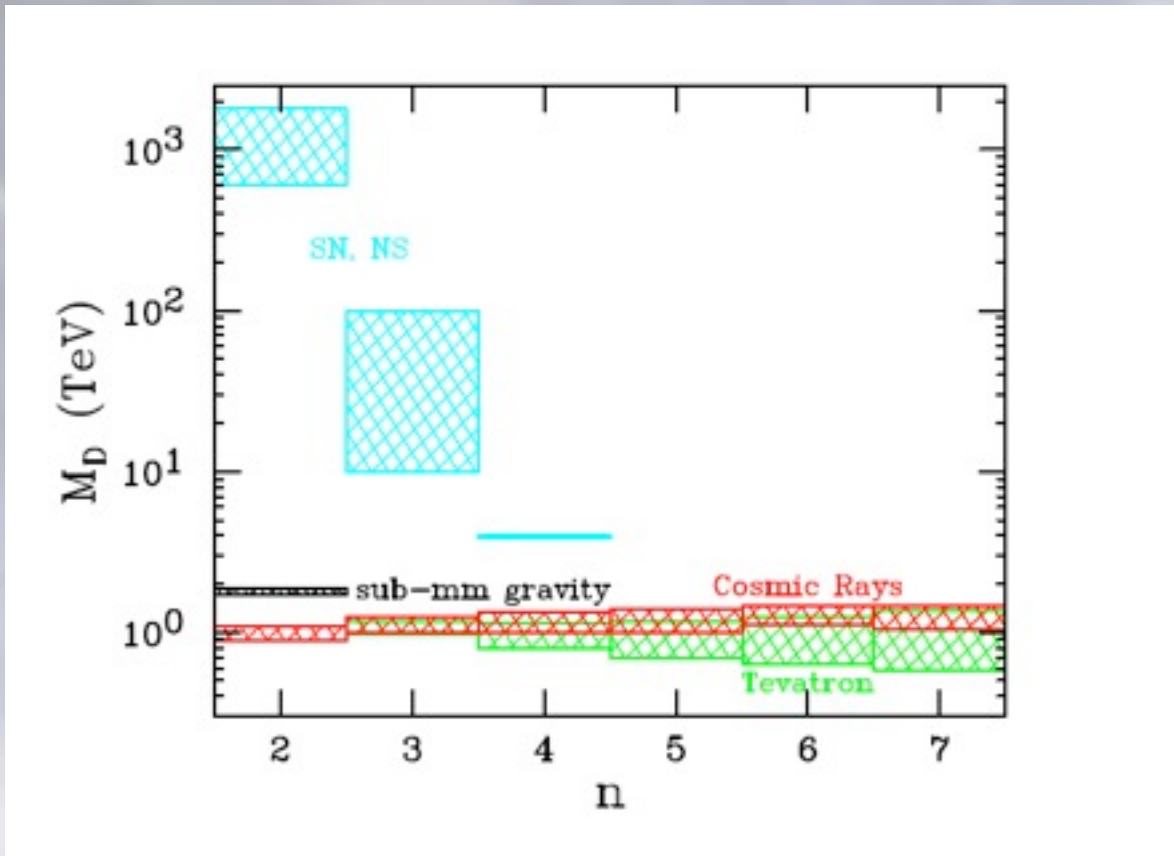
D0: ee, γγ, jet-jet
M_D > 2.16 TeV for n = 2
M_D > 1.31 TeV for n = 7

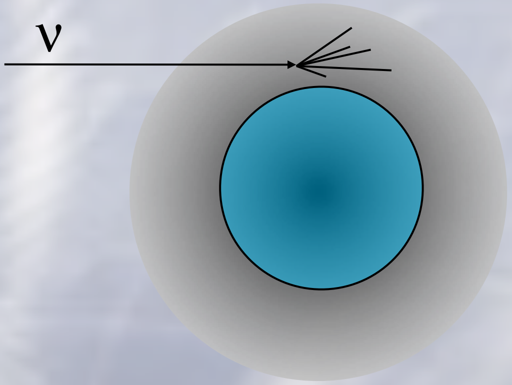
Variety of limits exclude ~ 1 TeV

LEP: arXiv: hep-ex/0410004
H1: H1prelim-10-161 (2010)
ZEUS: ZeusPrel-09-013 (2009)
CDF: Phys. Rev. Lett. 101, 181602 (2008)
D0: Phys. Rev. Lett. 102, 051601 (2009)
D0: Phys. Rev. Lett. 103, 191803 (2009)

Current Constraints

Anchordoqui et al: arXiv:hep-ph/0307228





ultra high energy neutrino showers
- deep in atmosphere
- horizontal

BH mediated cross section ≫ SM

Summary of constraints from astrophysical measurements & colliders (2003)

Colliders probe large n

Supernovae & neutron stars probe low n: nucleon graviton-strahlung NN → NNG

A graviton flux would cause reduced neutrino flux from supernova

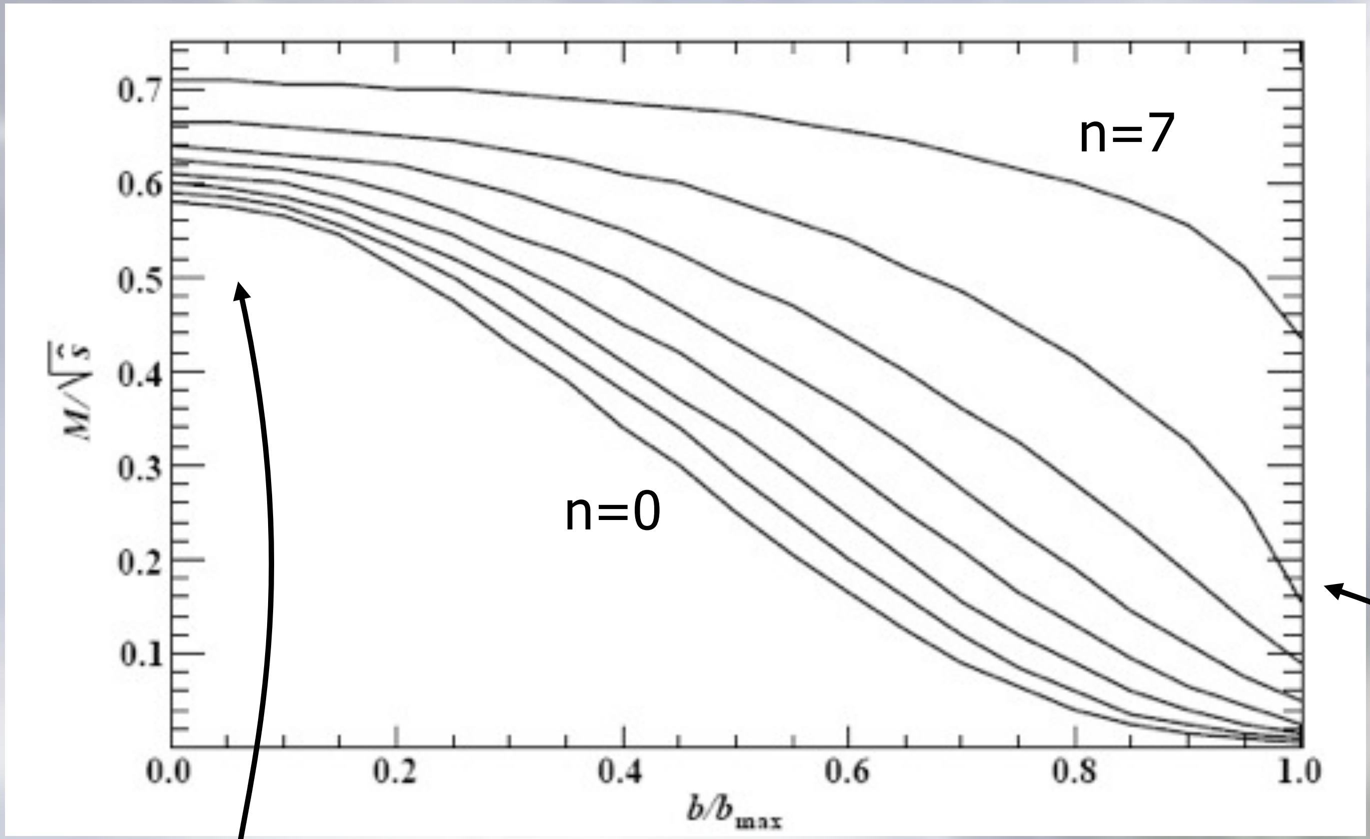
→ place strong limits on M_D for n=2,3

Cullen, Perelstein: Phys.Rev.Lett. 83 (1999) 268-271

Gingrich: hep-ph/0609055

Lower limits on fraction of trapped energy (indep. of M_D)

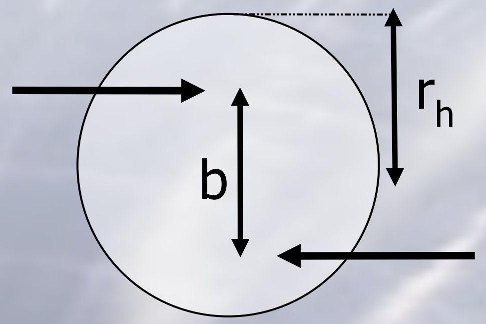
Form factors



r_h is generalisation of r_S for spinning BHs

b = impact parameter

b_{max} = horizon radius $2r_h$



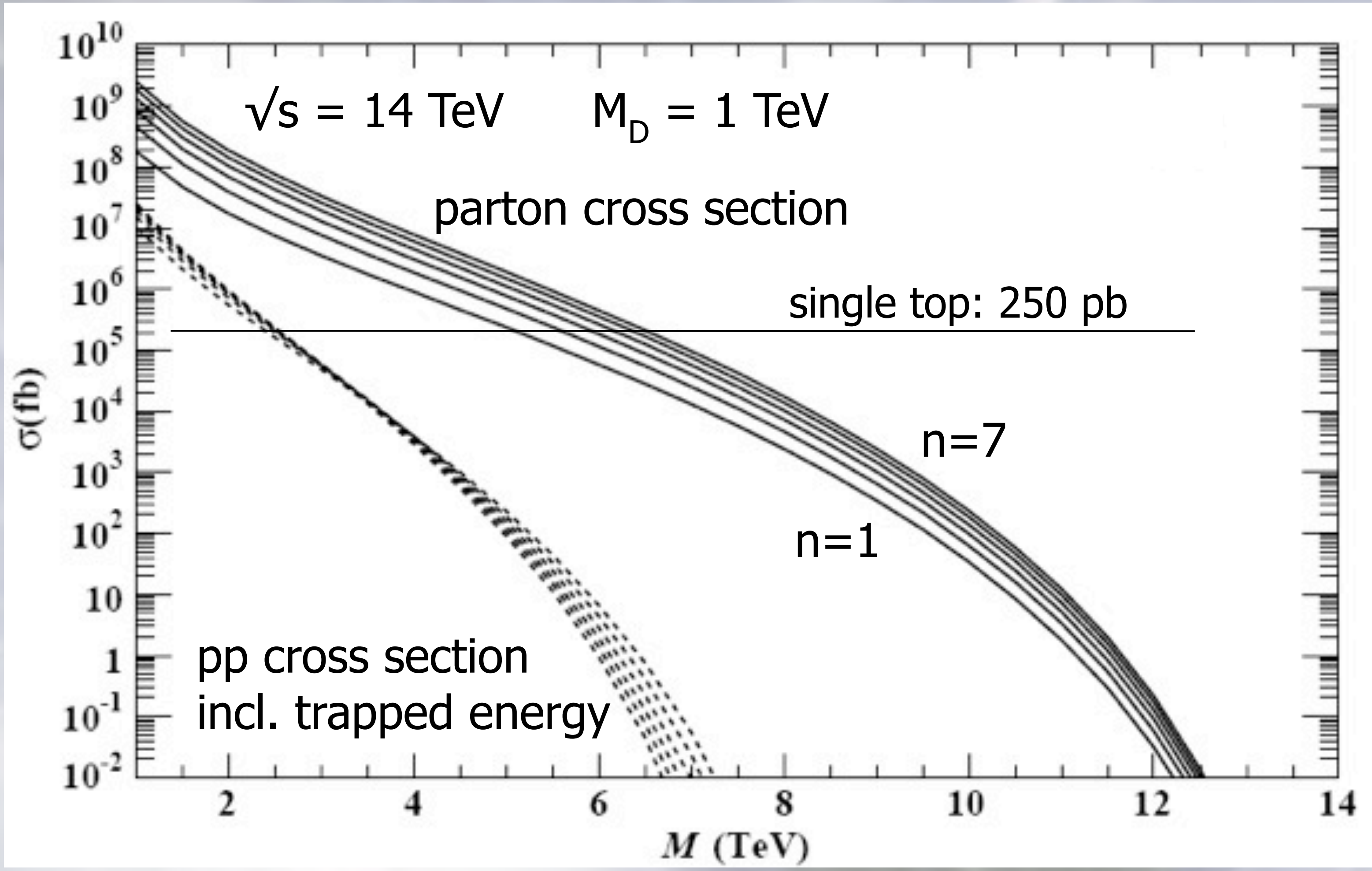
Large b ⇒ large ang mom states

For 'head on' collisions (b=0) ~70% of energy is trapped in event horizon

For large impact parameter only 1% - 50% of energy forms BH

Cross section lower limits

Gingrich: hep-ph/0609055



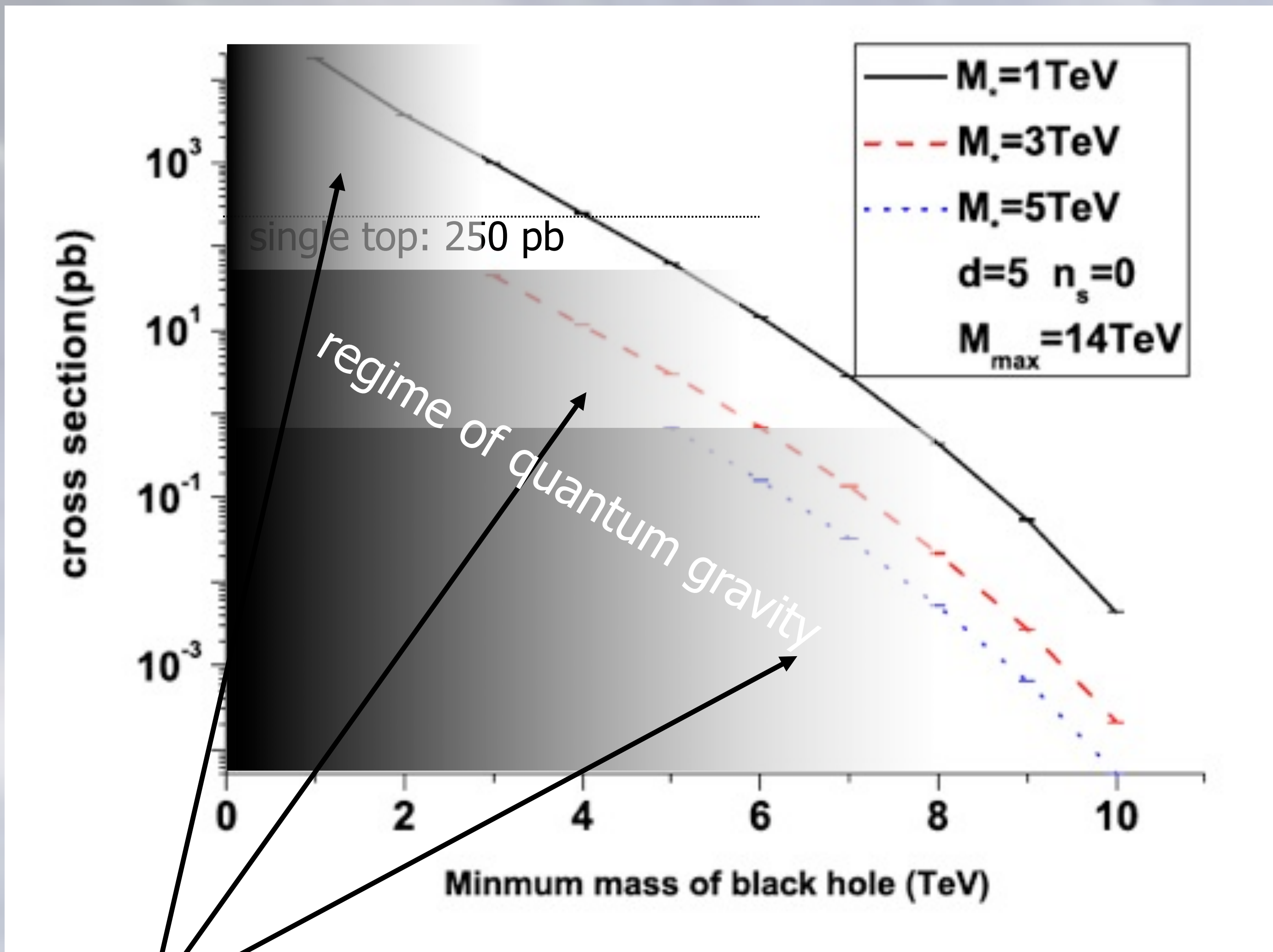
Potentially very large cross sections predicted

Horizon radius increases with n ⇒ cross sections increase with n

Factor 10 variation in cross section for n=1 to 7

BlackMax prediction for non-rotating BHs

Dai et al: arXiv 0711.3012



Close to M_D observe jump in 2→2 scattering? May be dominant effect

Meade, Randall: arXiv 0808.3017

Factor ~10^2 suppression for M_D=1 to 5 TeV

Semi-classical approach fails when $M_{BH} \sim M_D$

Don't expect BH to form - but gravitational scattering...? quasi bound state of quantum BH

LHC Signatures

Emission spectra change depending on the models chosen

Typical ratio ~ 8:1 hadrons:leptons

Leptons heavily suppressed in split fermion model

Graviton modes suppressed at low n

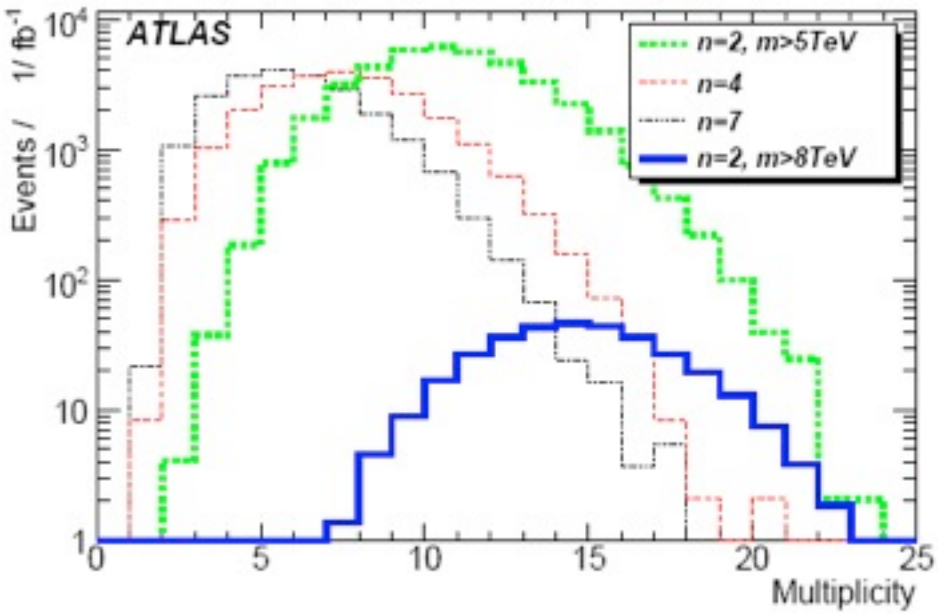
scenario	q+g	leptons	neutrinos	W/Z	G	H	photons
n=1 / J=0	79.0%	9.5%	3.9%	5.7%	0.2%	0.9%	0.8%
n=7 / J=0	74.0%	7.7%	3.2%	6.8%	6.5%	0.7%	1.5%
n=7 / J=0 / split=7	84.0%	1.8%	0.5%	5.4%	6.7%	0.3%	1.6%
n=7 / J>0	78.0%	6.5%	2.5%	9.6%	??	0.7%	2.6%

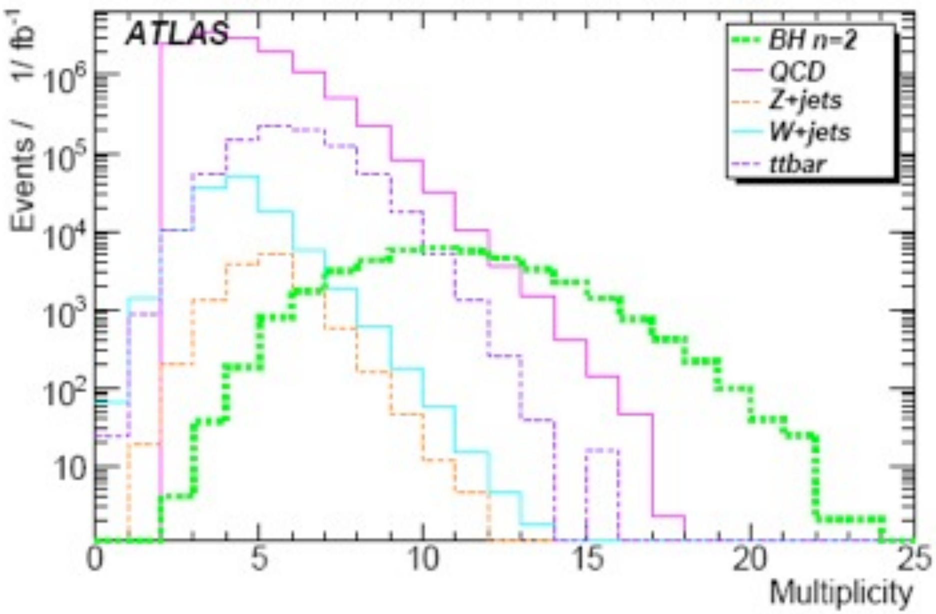
Uncalculated graviton greybody factors for J>0
Expected to be large - super irradiance
Gravitons are spin-2 tensors

LHC Signatures

High multiplicity events: 10-40 particles from heavy state

Hard P_T spectrum of decay particles



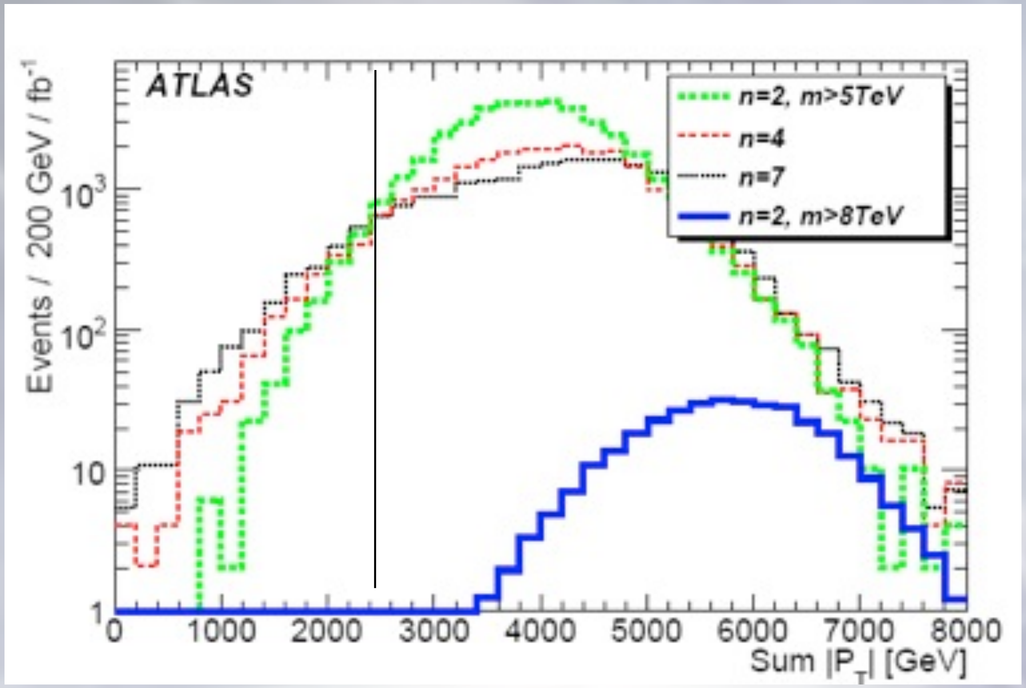


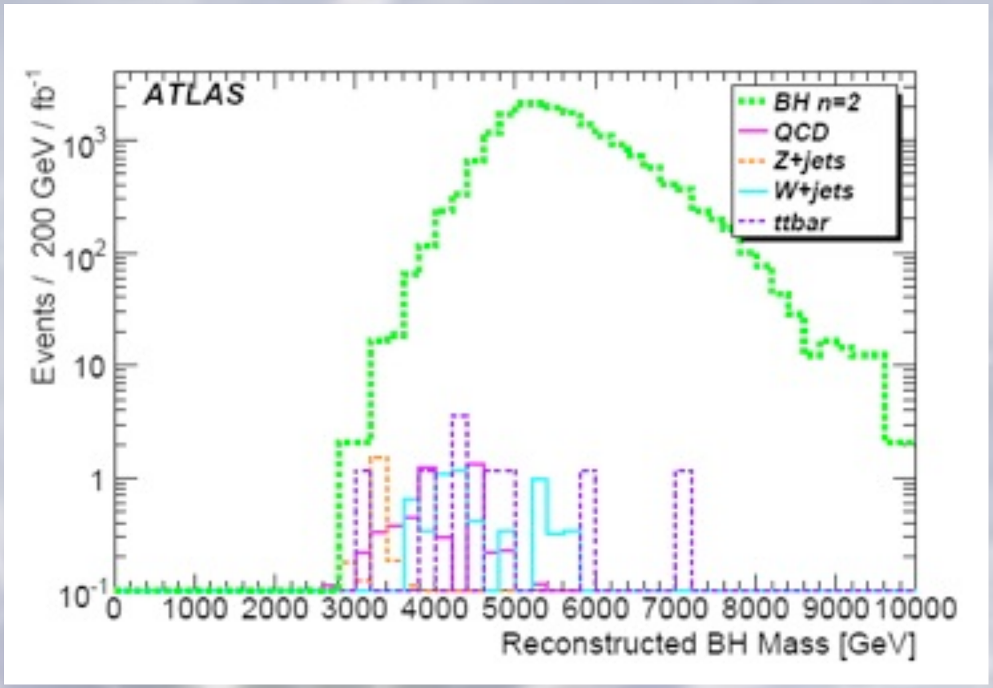
<N> falls as n increases
(BH temp increases)

Multiplicity compared to SM

LHC Signatures

$\mathcal{L}$ = 1 fb^{-1} M_{BH} > 5 TeV M_D=1 TeV n=2





- $\Sigma|P_T|$ > 2.5 TeV

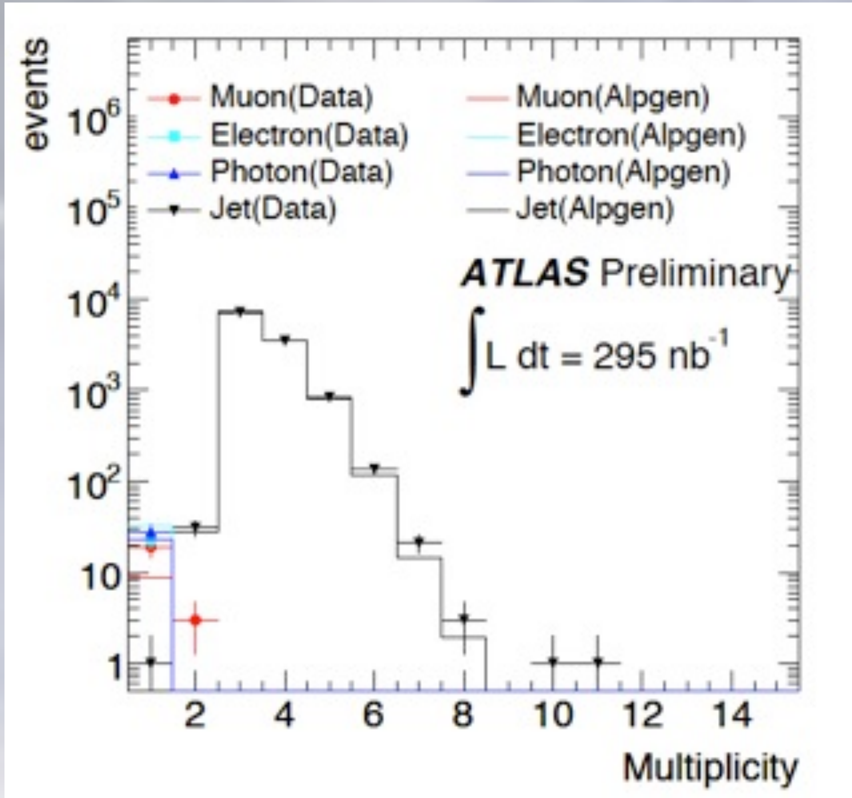
- $\Sigma|P_T|$ > 2.5 TeV
- lepton P_T > 50 GeV

Requirement of additional high P_T lepton reduces QCD b/g dramatically

If Atlas / CMS cannot trigger these events we should give up now!
highest threshold jet trigger (400 GeV P_T) unprescaled, $\varepsilon=100\%$

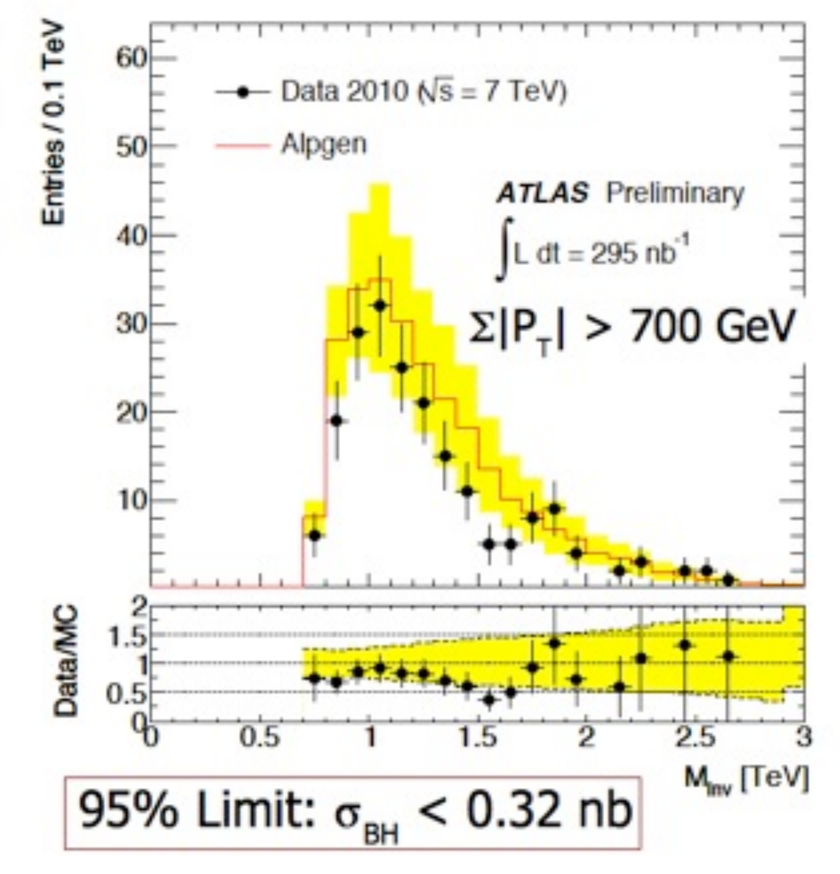
Atlas Results

Object Multiplicity for $\Sigma|P_T| > 300$ GeV



Jets: $P_T > 40$ GeV $|\eta| < 2.8$
e/γ : $P_T > 20$ GeV $|\eta| < 2.47/2.37$
μ : $P_T > 20$ GeV $|\eta| < 2.0$
$\not{E}T$: calo cells $|\eta| < 4.8$

Large uncertainties:
Alpgen/Pythia diff ~ 26%
JES ~ 11% & PDFs ~ 12%



Require ≥ 3 objects

3-jet events dominate

Normalise MC to region
300<M<800 && $\Sigma|P_T| > 300$ GeV

Z / W / t / τ reconstruction not needed

Semi-classical BHs produced for $M_{BH} \gg M_D$ – true thermodynamic objects

Entropy $S = k_B \ln(\Omega)$ Ω=number of microstates

Close to M_D this is not expected to hold – effects of QM dominate dynamics
These two regimes can be distinguished: semi-classical approach valid when

Compton Wavelength $$\lambda_C = \frac{h}{M_{BH}c} < r_s$$

→ $M_{BH} \gtrsim 3M_D$

σ_{BH} increases as $\sqrt{\hat{s}}$

semi-classical BHs formed when $M_{BH} \gtrsim 3M_D$

But proton PDFs fall rapidly with increasing $\hat{s} \Rightarrow \sigma_{BH}$ largest at lowest masses

"LHC will only see QBHs not semi-classical BHs"

Semi-classical BHs may tell us nothing about quantum gravity (QG)
QBHs could allow us to probe different models of QG

Quantum Blackholes

QBHs → even less known territory!

No idea of production cross section → assume geometric cross section

A “true” BH probably doesn't form i.e. no event horizon

Close to threshold: $M_{BH} \sim M_D$ gravity is strongly coupled → non-perturbative

QBH is more like a resonance / bound state
entropy is small
difficult to describe BH in terms of entropy / temperature
expect high multiplicity decay states to be strongly suppressed
unlikely to decay thermally

Thus, expect modifications to Standard Model 2 → 2 scattering
(interference effects not accounted for...)

Ignore spin effects for QBHs:
r_S and impact parameter b are both $\sim 1/M_{BH}$ $\Rightarrow J \sim 1$

Quantum Blackholes

Calmet, Wong, Hsu: Phys.Lett.B 68 (2008) 20-23
Gingrich: J.Phys.G **37** (2010) 105008

$QBH^{4/3}_{\bar{3}}$ $QBH^{4/3}_{6}$

QBH^{1}_{1} QBH^{1}_{8}

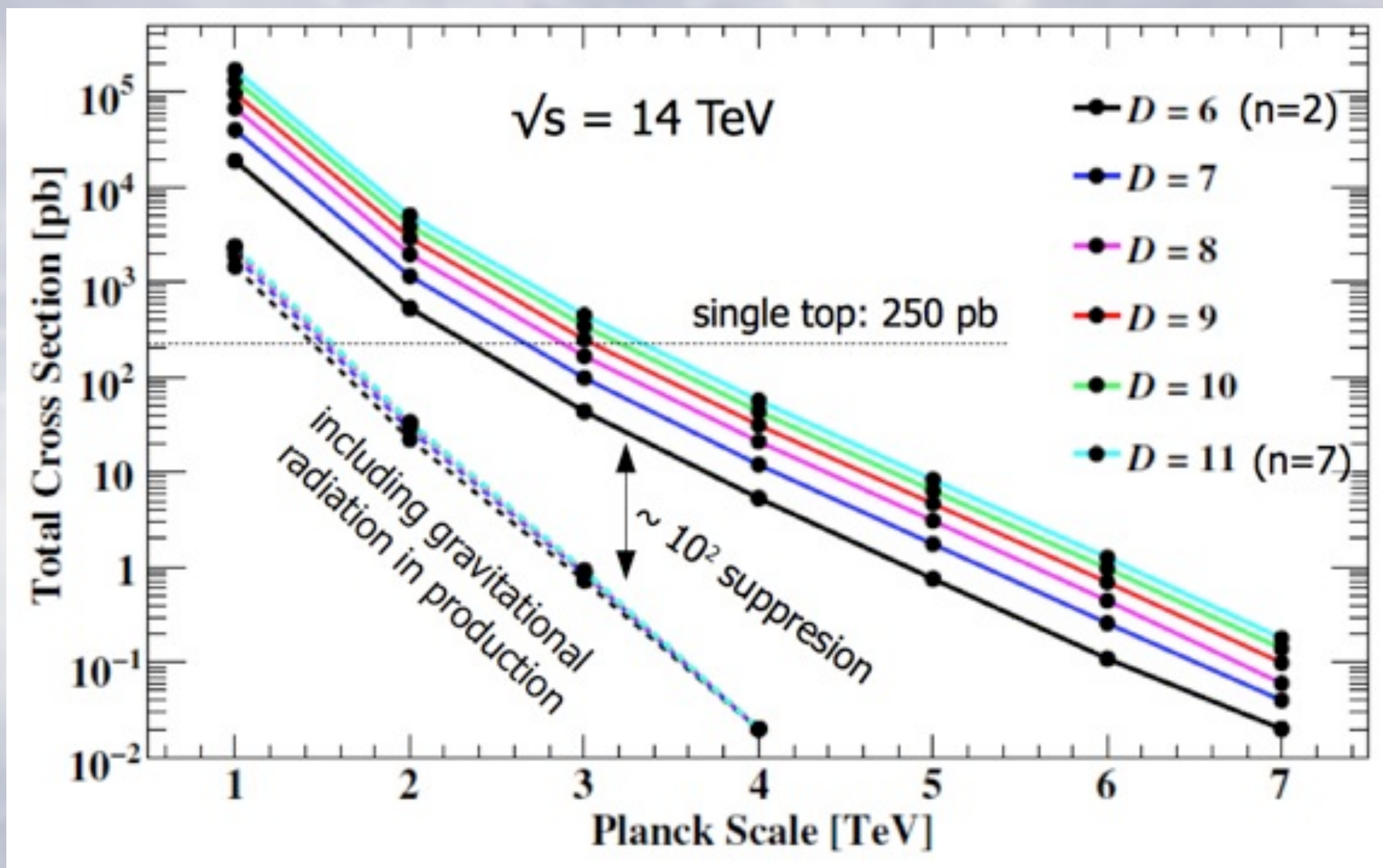
$QBH^{2/3}_{3}$ $QBH^{2/3}_{\bar{6}}$ $QBH^{2/3}_{15}$

$QBH^{1/3}_{\bar{3}}$ $QBH^{1/3}_{6}$ $QBH^{1/3}_{\overline{15}}$

QBH^{0}_{1} QBH^{0}_{8} QBH^{0}_{10} $QBH^{0}_{\overline{10}}$ QBH^{0}_{27}

15 different types of QBH in pp collisions depending on initial parton combination

$$qq \quad qg \quad gg \quad \bar{q}g \quad q\bar{q} \quad \overline{qq}$$



Quantum Blackholes

Much is still missing in the phenomenology of quantum BHs
- no real treatment of spin
- brane tension
- no interference effects accounted for
- production cross sections assumed to extrapolate from semi-classical regime

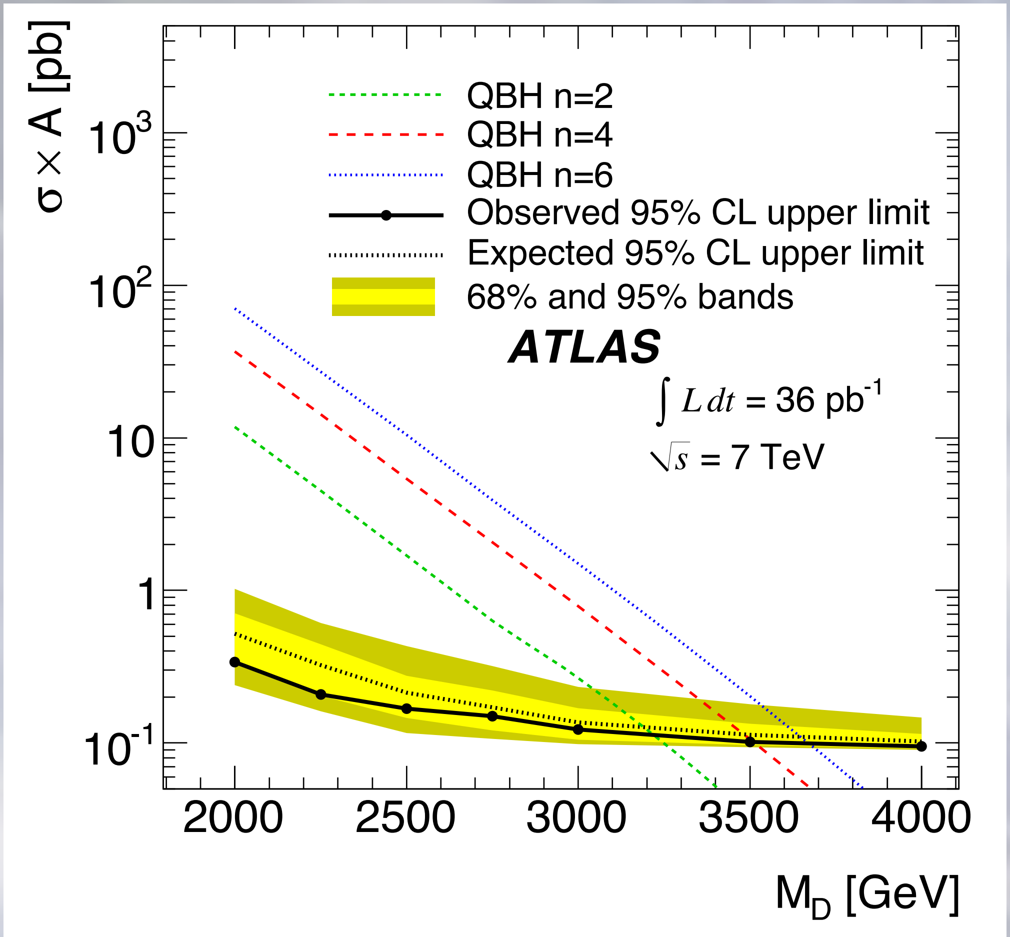
Starting to see string theory motivated predictions of measurable cross sections
- regime of low string mass scales ~ TeV and weak coupling

Anchordoqui et.al. arXiv:0808.0497v3

Neutrinos have mass ⇒ TeV scale gravity can democratically couple to

… left / right handed neutrinos
… heavy sterile neutrinos

Quantum Blackholes



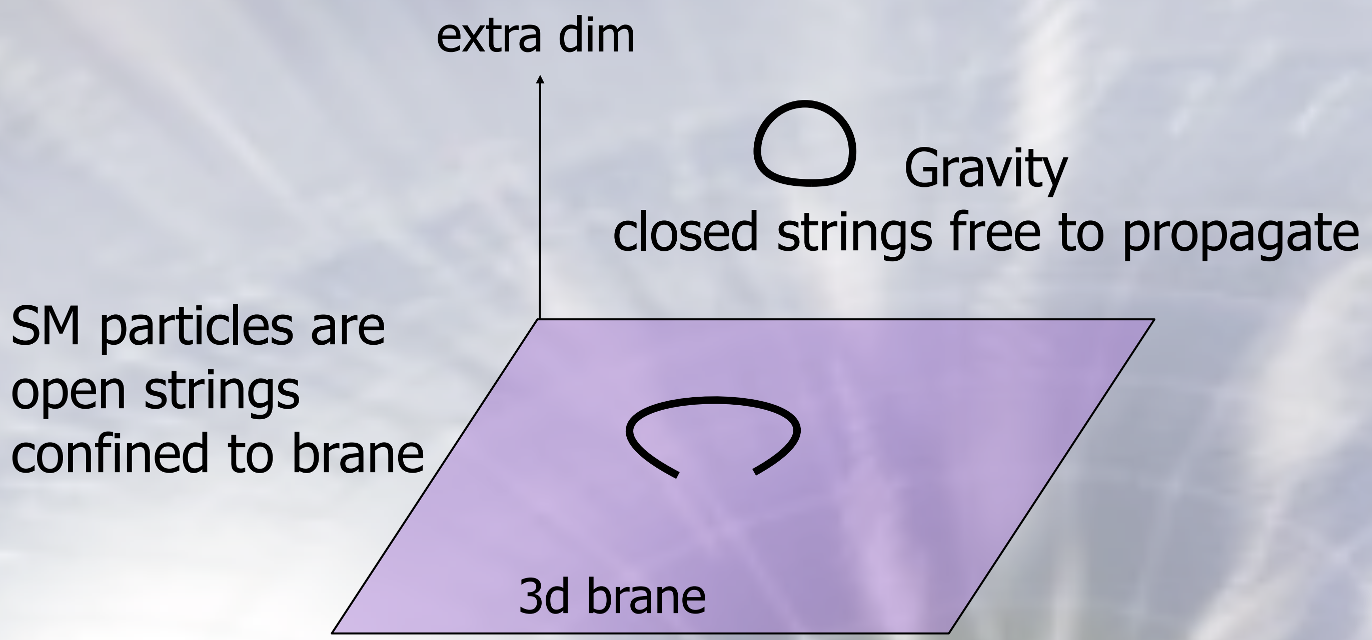
Published with full 2010 dataset

Compare the di-jet mass spectrum with QCD
QBHs produce threshold effects
Large cross section close to threshold
Long tails to larger masses

Meade-Randall QBHs excluded at 95% CL for M_D < 3.67 TeV (n=6)

Quantum Gravity & String Theory

True theory is missing



String theory may be candidate theory for quantum gravity

Requires 6-7 extra spatial dimensions

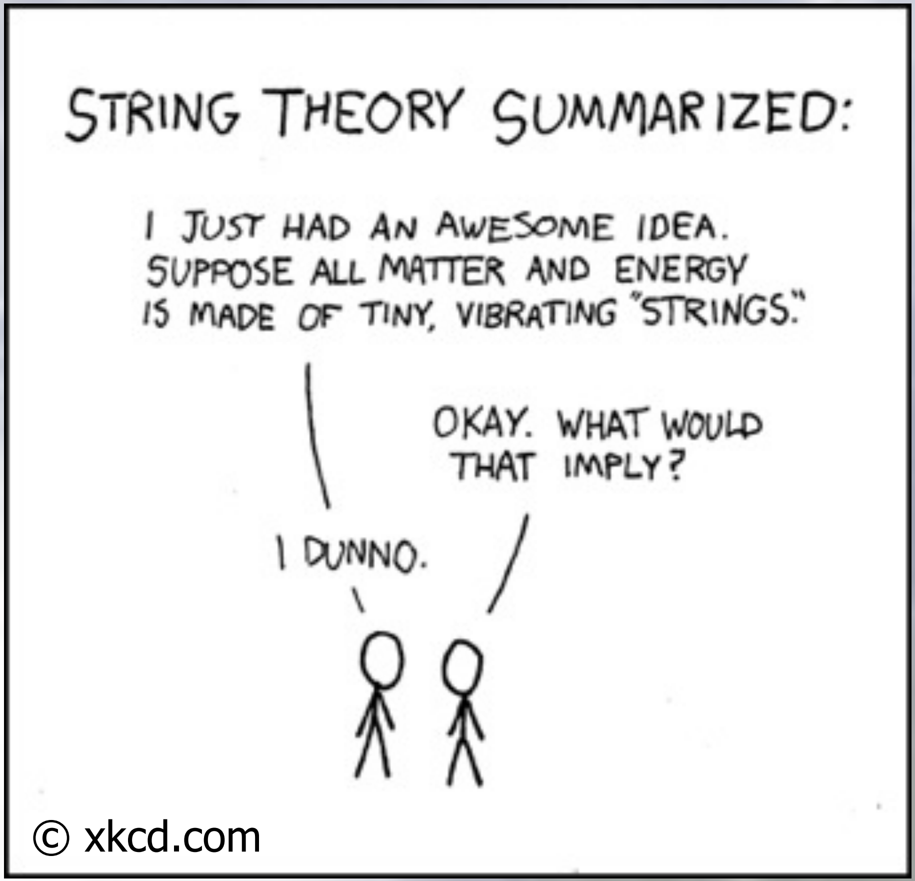
String balls: high entropy low mass string states - BH progenitors

Summary

- TeV scale gravity can potentially address many shortcomings of SM
- No fundamental theory yet - but very rich phenomenology!
- Large parameter space to be explored
- Some models do appear contrived...
  ... but nature is weird (who could have predicted quantum mechanics?)
- Nevertheless, we should look because we can!
- The 'holy grail' of quantum gravity may be experimentally within reach

"The landscape is magic, the trip is far from being over"

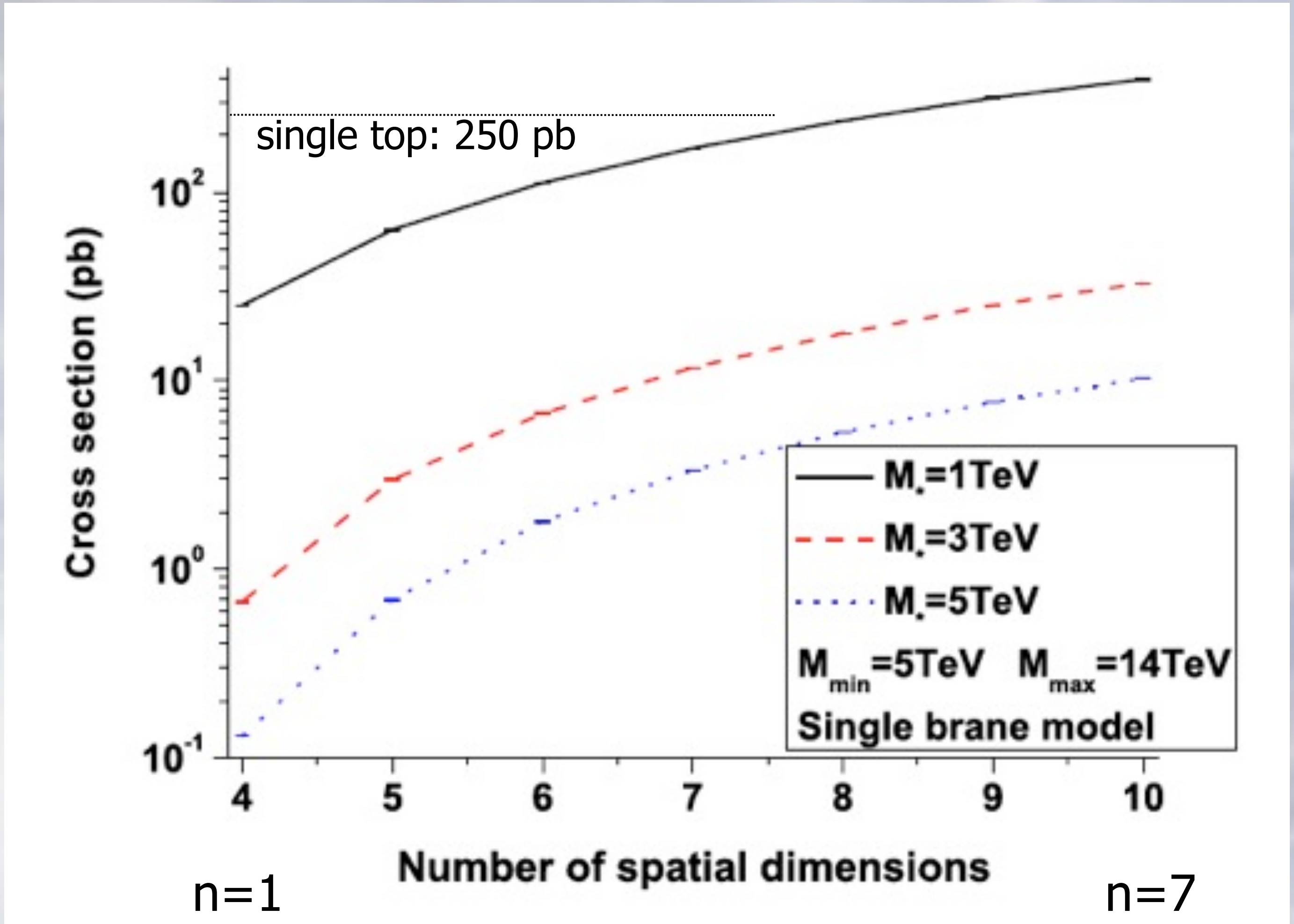
Carlo Rovelli
Quantum Gravity


STRING THEORY SUMMARIZED:
I JUST HAD AN AWESOME IDEA. SUPPOSE ALL MATTER AND ENERGY IS MADE OF TINY, VIBRATING "STRINGS."
OKAY. WHAT WOULD THAT IMPLY?
I DUNNO.
© xkcd.com

Backup Slides

BlackMax prediction for non-rotating BHs

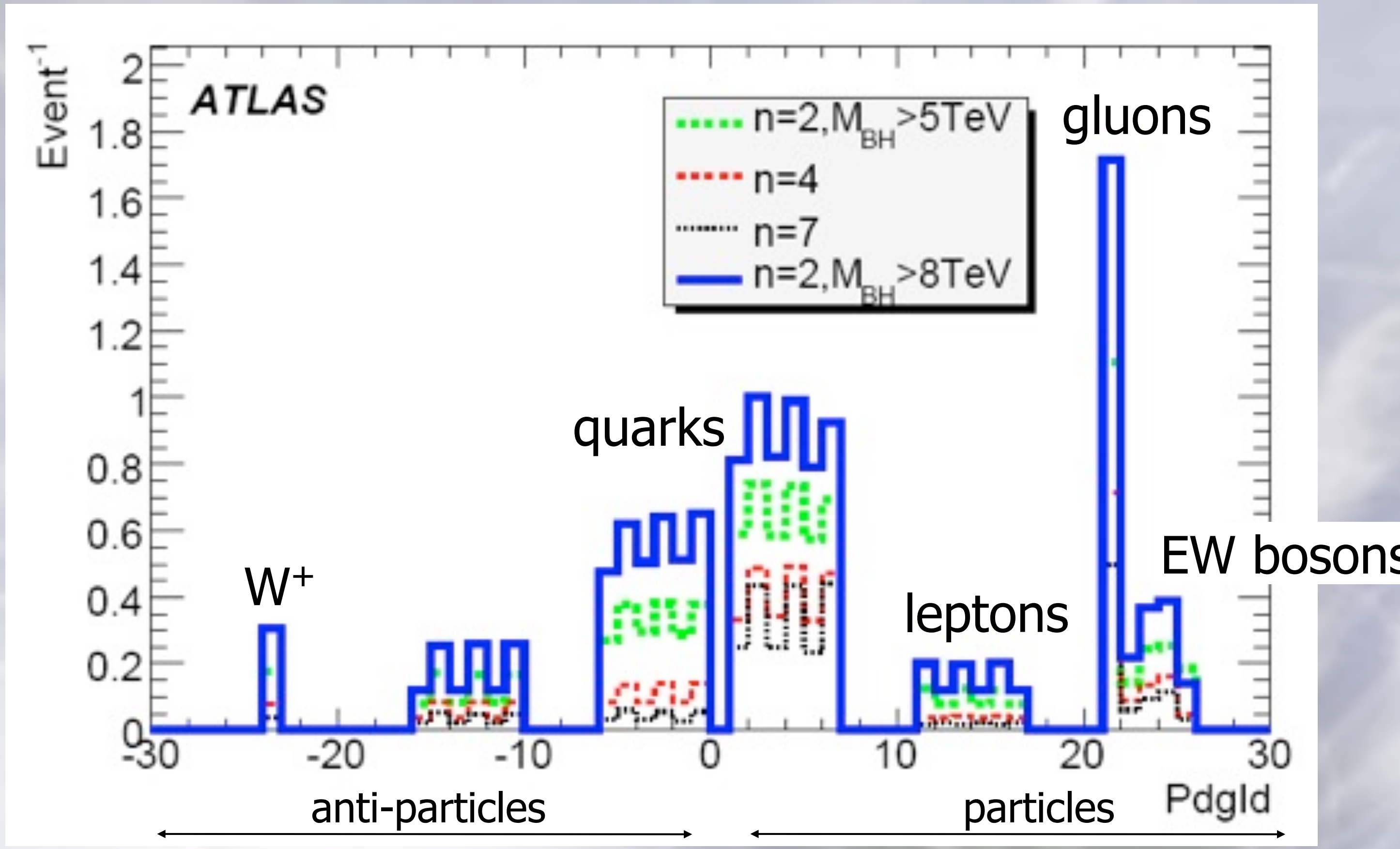
Dai et al: arXiv 0711.3012



Cross sections vary by ~ factor 10 for n = 1→7

Factor ~30 suppression for M_D = 1 → 3 TeV

Multiplicity of particles by type in different models



Higher multiplicity for larger mass

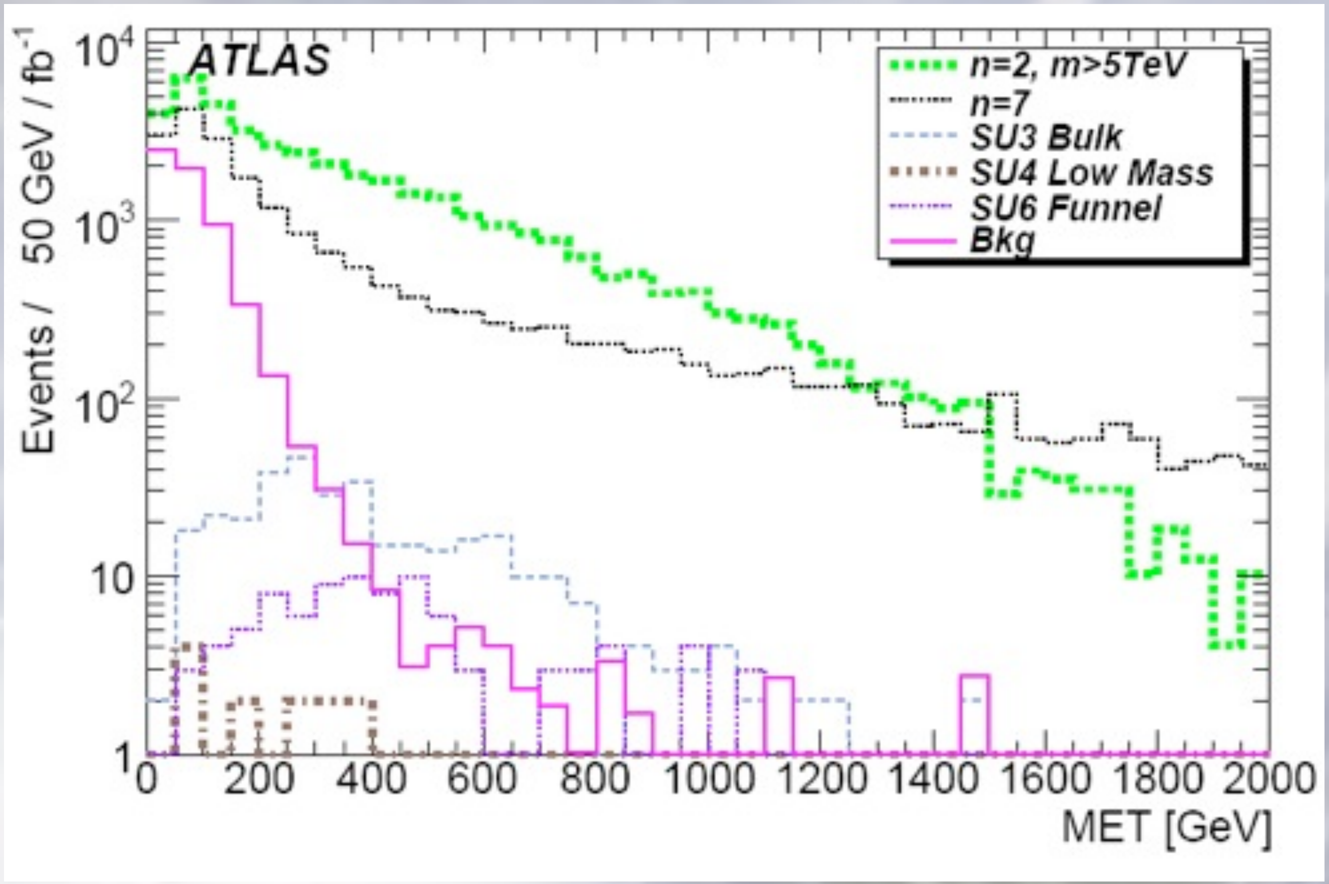
Quasi-democratic decays - fewer tops due to energy-momentum constraints

More particles than anti-particles due to pp initial state

LHC Signatures

Missing E_T spectrum

Alternative selection: $\not{E}_T$ > 500 GeV



Largely from graviton emission in balding and Hawking phases

Compare:

- SUSY models at 3 different scales
- Soft SM expectation

But:

- Difficult to calibrate
- Limits M_{BH} measurement