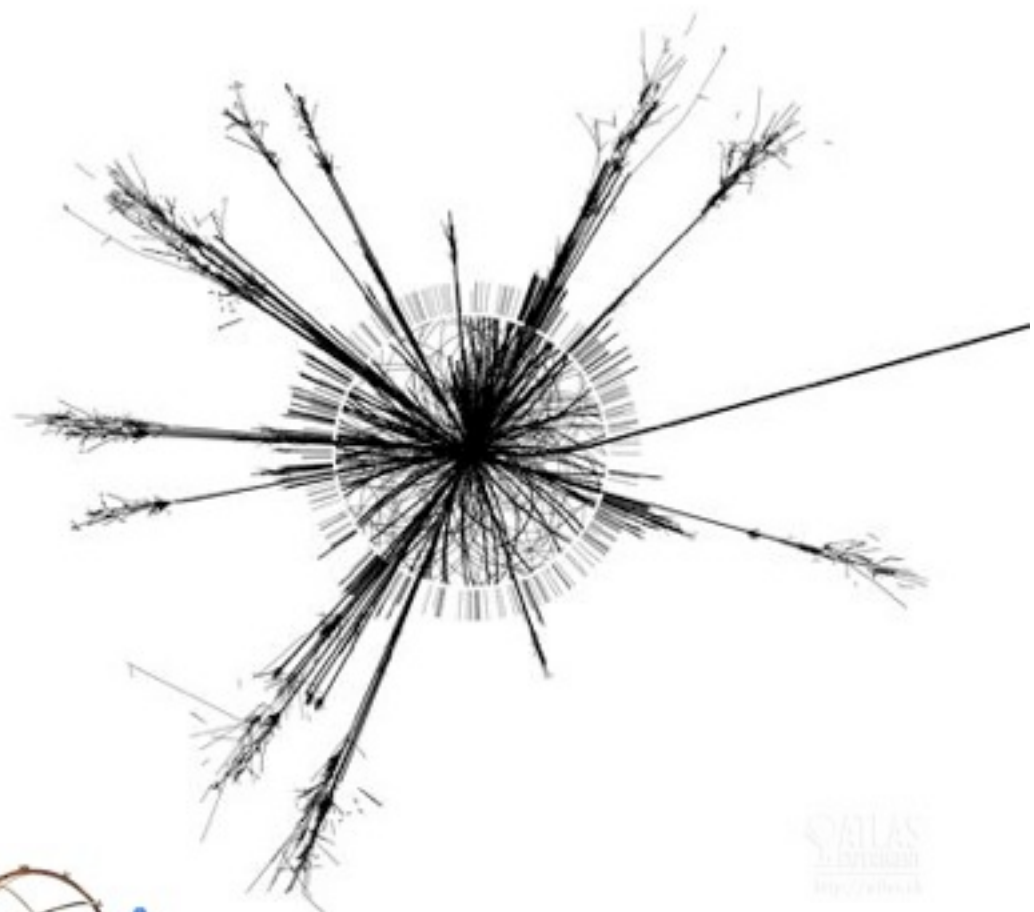
Black Holes, Extra Dimensions & the LHC



- 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

Classical to Quantum Gravity Winter School – 18th January 2013

In last ~150 years physics has developed enormously

Three major pillars of modern physics have emerged

• general relativity	2×10^{-5}	Cassini photon time delay 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

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

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

Planck scale

Thus objects warp space-time around themselves ⇒ modifies the object's 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)

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 $E/M^2{}_P$

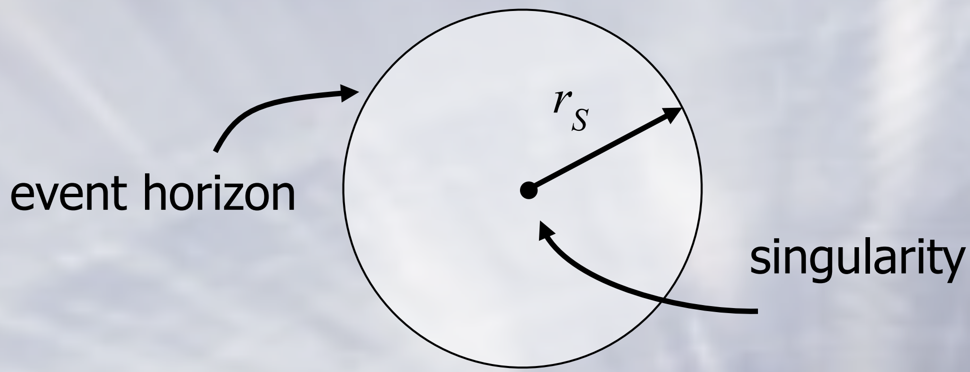
At energies close to Planck Mass distortions cannot be neglected

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 Kerr-Newmann metric

Size of event horizon generalises to r_h

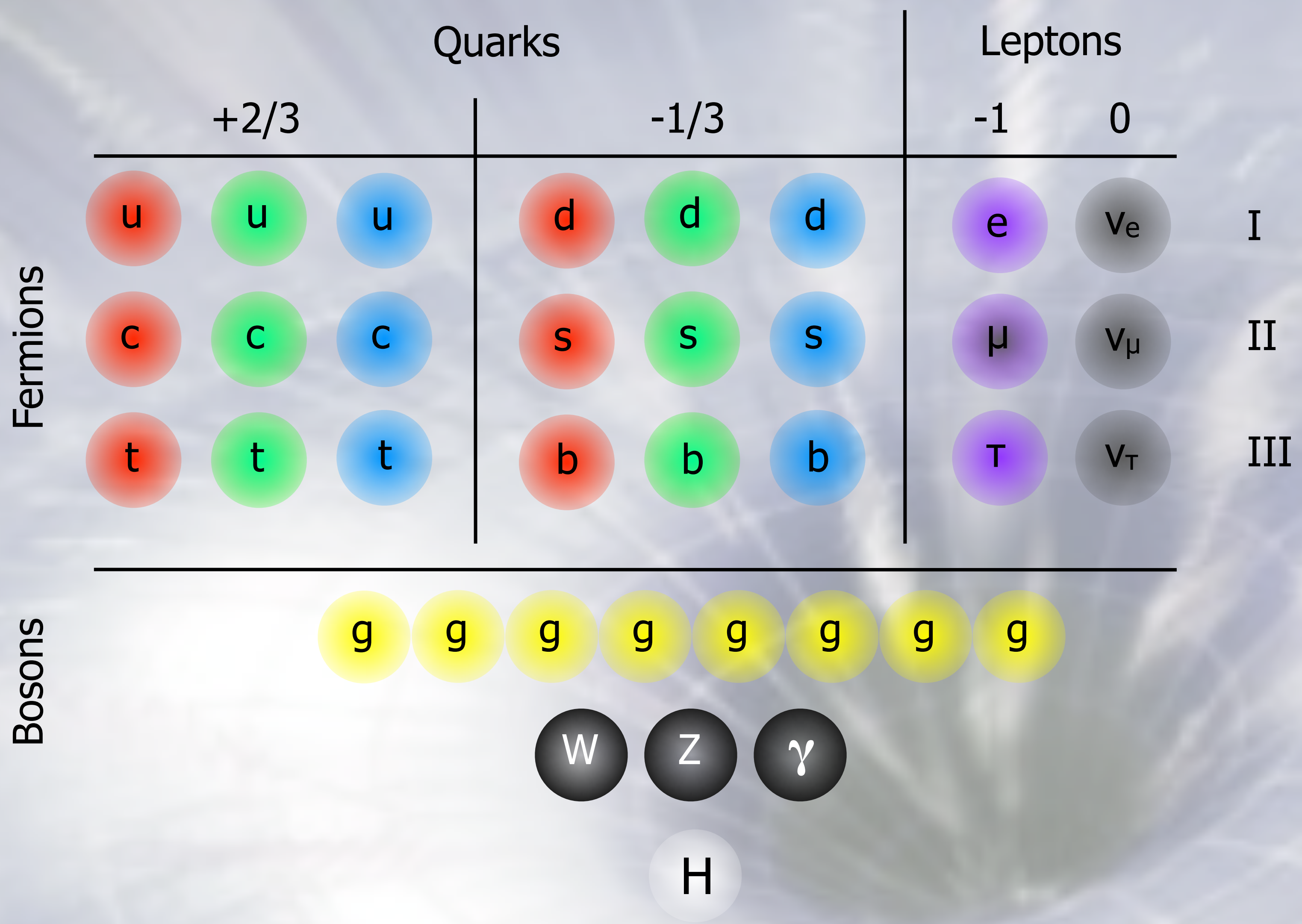
Charged rotating BH
Kerr-Newmann solution published 1965

Jump to particle physics...

The Standard Model is fantastically successful

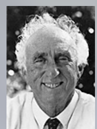
...

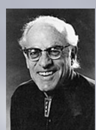
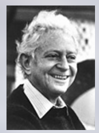
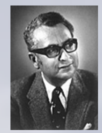
The Standard Model

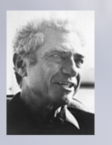
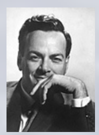
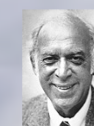


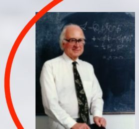
61 'fundamental' particles in the SM! (including anti-particles)

The Standard Model

 Perl
 Gross
 Rubbia
 van der Meer

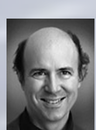
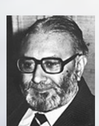
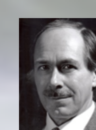
 Reines
 Lederman
 Gell-man
 Cronin

 Steinberger
 Feynman
 Glashow
 Taylor
 Friedman

 Hofstadter
 Schwinger
 Higgs
 Veltman
 Kendall

 Politzer
 Ting
 Alvarez
 Fitch

 Schwarz
 Richter
 Weinberg
 Yang

 Wilczek
 Salam
 Lee
 t'Hooft

29 Nobel prizes awarded for the Standard Model

1 more yet to come?

$$
\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
\frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w M A_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w} Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + \\
m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma d^\lambda_j)] + \frac{ig}{4c_w} Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \\
\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + \\
(\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}} W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 + \\
\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}} W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \gamma^5)u^\lambda_j)] + \\
\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1 + \\
\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \gamma^5)u^\kappa_j] - \\
\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + \\
igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + \\
igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + \\
igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \\
\frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0\phi^+ - \\
\bar{X}^- X^0\phi^-] + \frac{1}{2c_w} igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \\
\bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$

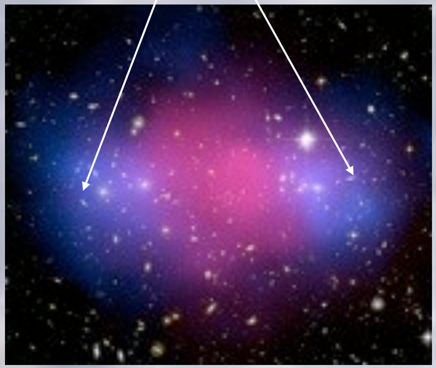
The lagrangian...

Welcome to the Standard Model of particle physics!

22 Parameters of the SM to be measured (better than 105 params of generic SUSY)

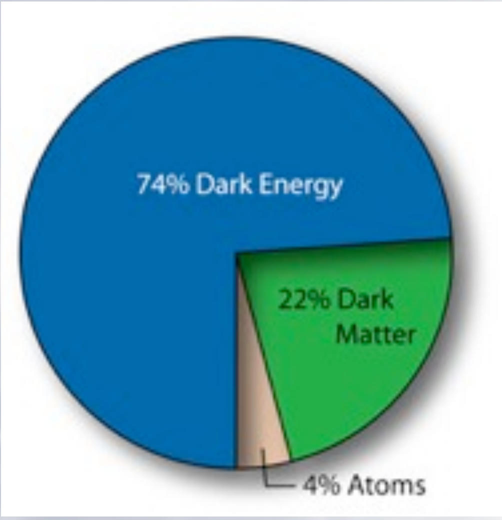
6 quark masses
3 charged leptons masses
3 coupling constants
4 quark mixing parameters
4 neutrino mixing parameters
1 weak boson mass (other predicted from remaining EW params)
1 Higgs mass

Two gas clouds collide
Clouds slow down
Dark matter passes through



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

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



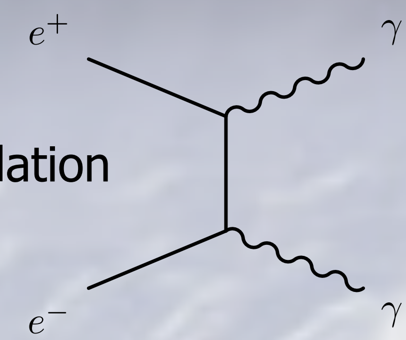
No treatment of gravity in the Standard Model...
In a symmetric theory gauge bosons are massless
Higgs mechanism explains EW symmetry breaking
→ EW bosons acquire mass

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

Standard Model is lacking:

why 3 generations of particles?
why do particles have the masses they do?
no consideration of gravity on quantum level...

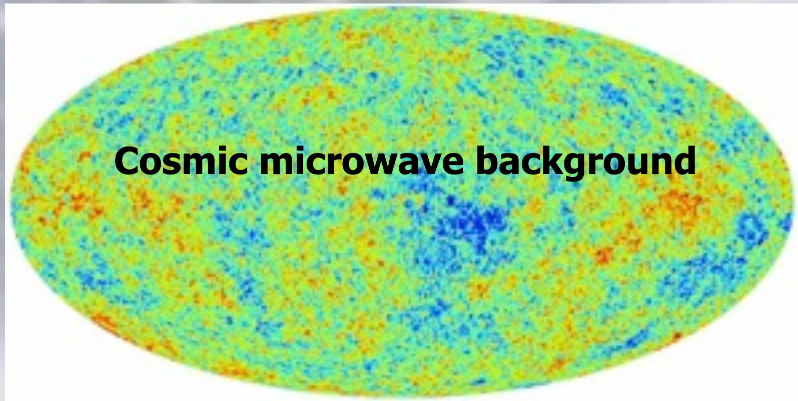
$e^+ e^-$ annihilation



In the Standard Model matter and anti-matter produced in equal quantities

In the Big Bang: for every quark, one anti-quark is also produced
As universe cools expect all particles and anti-particles to annihilate
$\Rightarrow$ soon after big bang all matter will have annihilated to photons

We should not exist!
For every $p/n/e$ in universe there are 10^9 photons (CMB - cosmic microwave background)
Matter/anti-matter asymmetry = $1:10^9$
We cannot see where this asymmetry lies...



Planck - 2012

(Actually SM can account for only 1000th of this asymmetry)

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”)

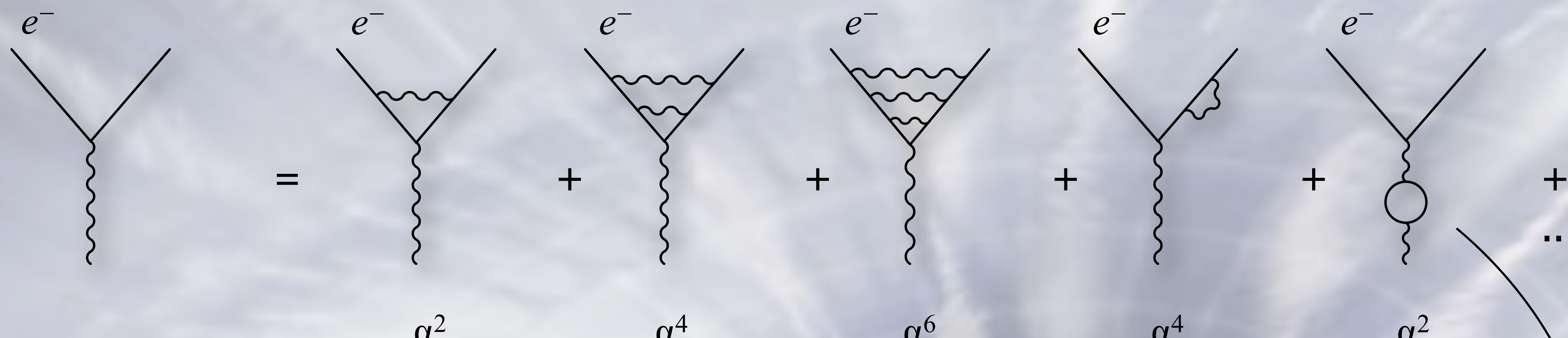
Back to particle physics:
insufficient CP violation & no Baryon number violation able to account for our matter dominated universe

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

g = ratio of magnetic dipole moment to it's spin

Quantum fluctuations affect all reaction rate measurements
Effects are subtle but measurable
Consider e⁻ scattering process:

e.g. photon converts into all possible fermion/anti-fermion pairs and back again:
$e^+e^-, \mu^+\mu^-, u\bar{u}, s\bar{s}...$



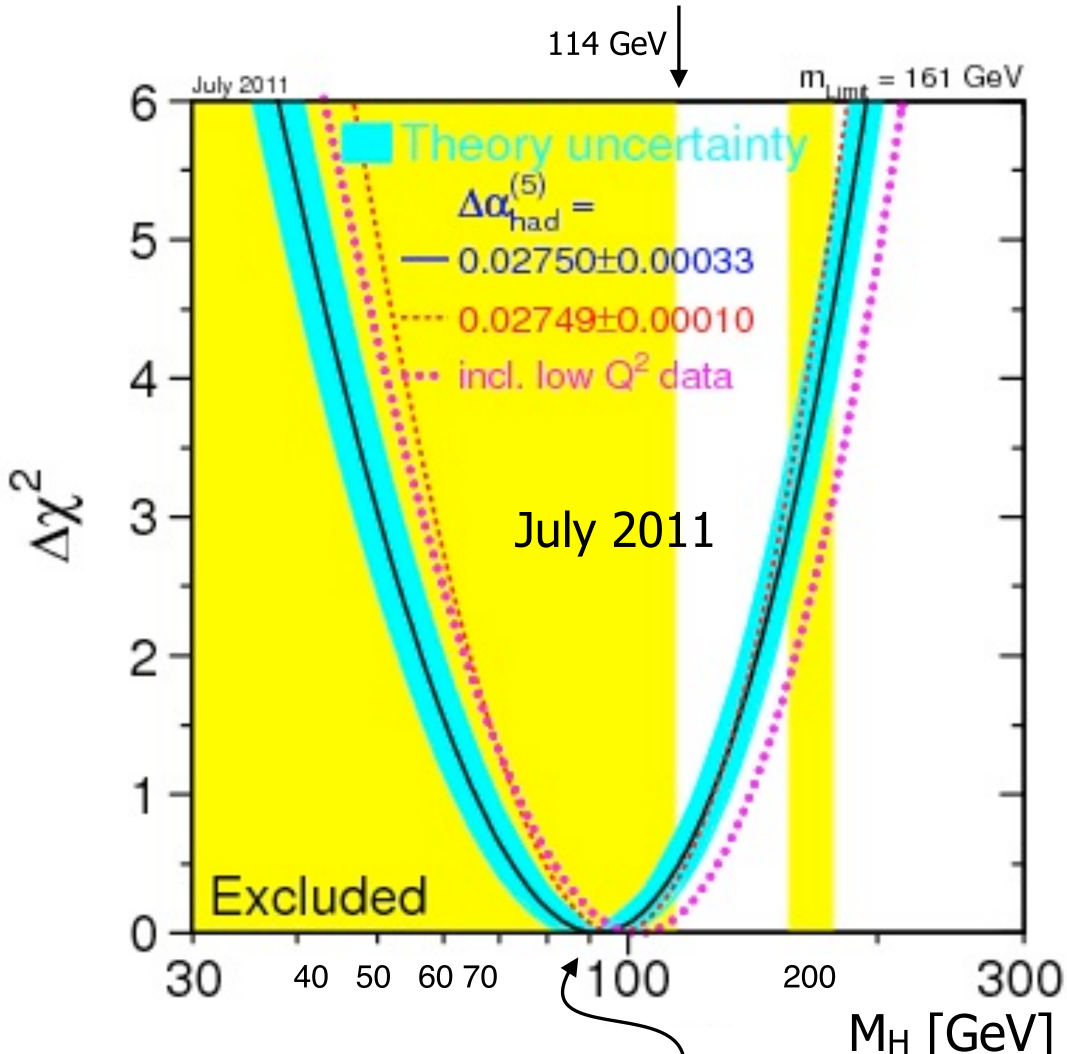
An infinite number of diagrams contribute to this scattering process
Result is finite due to cancellations

All these and more diagrams are required to calc g-2 of the electron with high precision
Precision measurements weakly sensitive to existence of new particles via "loop corrections"
Particle masses also affected by such quantum fluctuations
Particles have fixed mass...
... but experimentally measured mass = "bare" mass + quantum fluctuations

$$m_H^2 = m_0^2 + \Delta m_H^2$$

quantum fluctuations affect a "bare" particle mass resulting in experimentally measurable mass

Indirect sensitivity to Higgs mass:

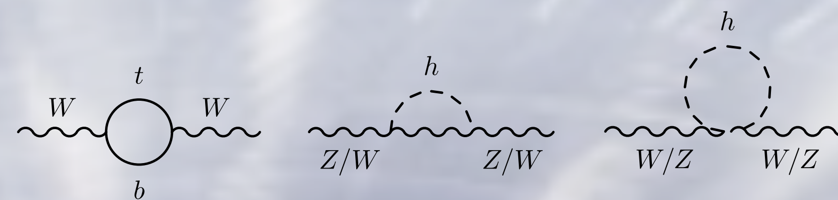


68% prob of SM Higgs in range 92^{+34}_{-26} GeV

95% prob of SM Higgs < 161 GeV

Precise measurements at low energy are sensitive to Higgs loops

Loop corrections to Z/W scattering reactions :



$\propto M_{top}^2$ $\propto \ln M_H$

Measurements at energy E < M_H are logarithmically sensitive to M_H

Confront data & theory: χ^2 test

Indicates light SM Higgs !

But large margin of error...

Triumph! we found a particle consistent with the Higgs within expected range

⇒ our loop calculations are correct

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

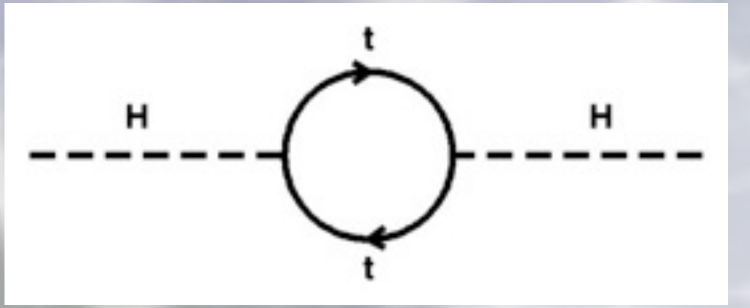
physical mass = bare mass + "loops" $$m_H^2 = m_0^2 + \Delta m_H^2$$

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)



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

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

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

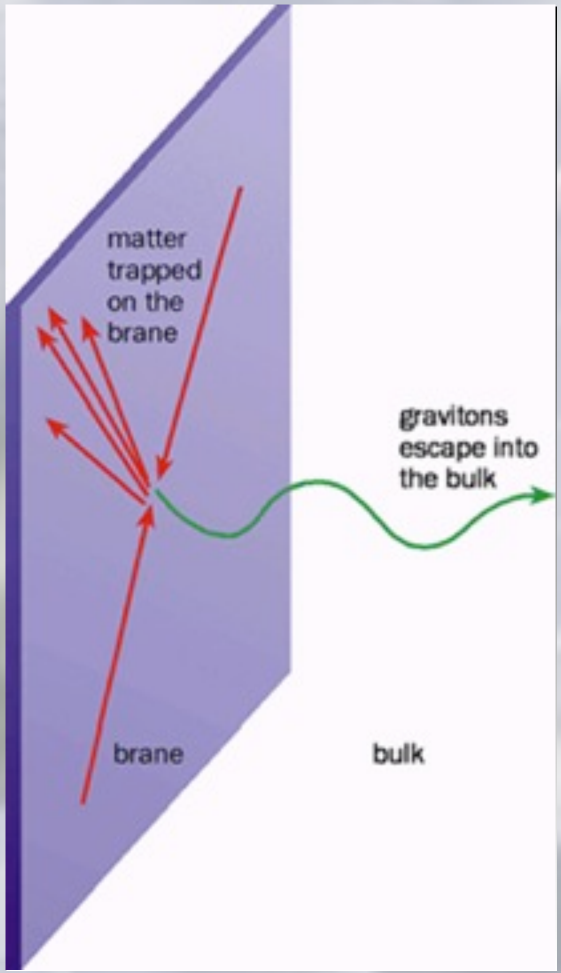
(of all possible universes with different physics parameter values only universes with our parameter settings could lead to humans existing)

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



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

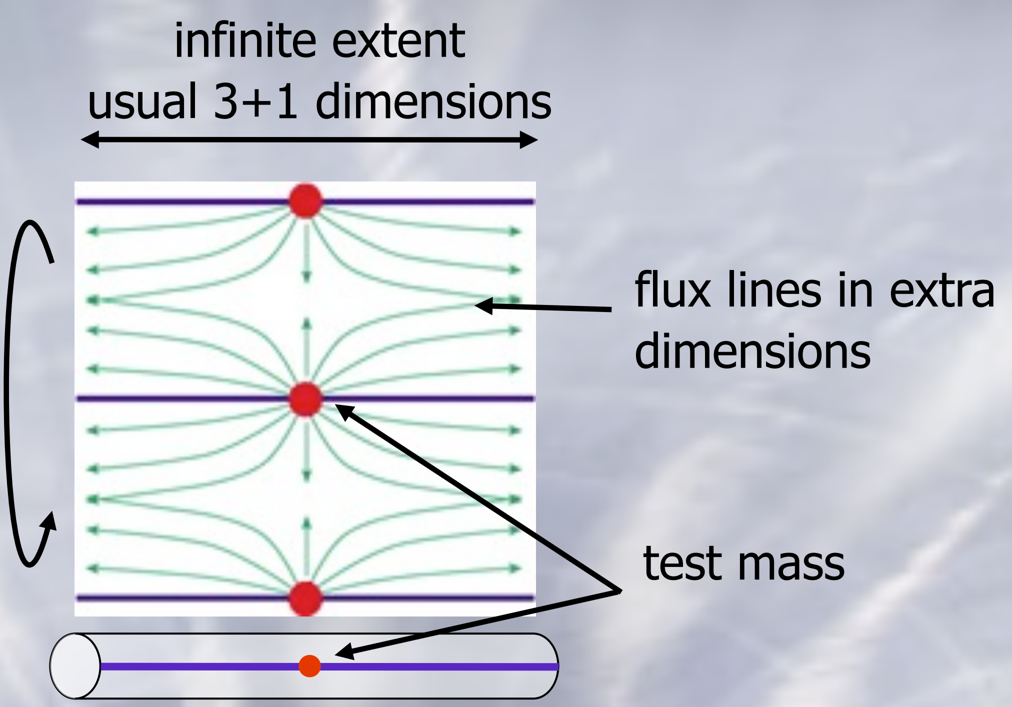
Theory suffered problems
- unable to explain vast difference in strengths of two interactions
- unable to combine with quantum mechanics
- later discoveries of weak & strong interactions did not fit into the scheme

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 2nd rank energy-momentum tensor)

Extra Dimensions and 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:

$$M^2 = E^2 - P_x^2 - P_y^2 - P_z^2 - P_n^2$$

Why are the extra dims < 1 mm ?

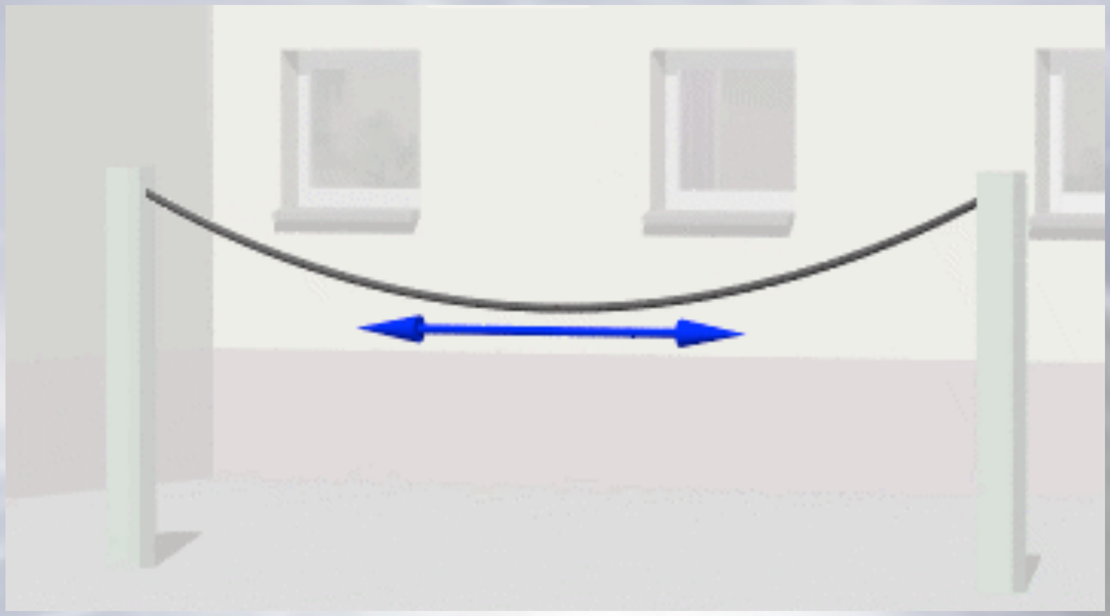
gravity has only been tested down to this scale!

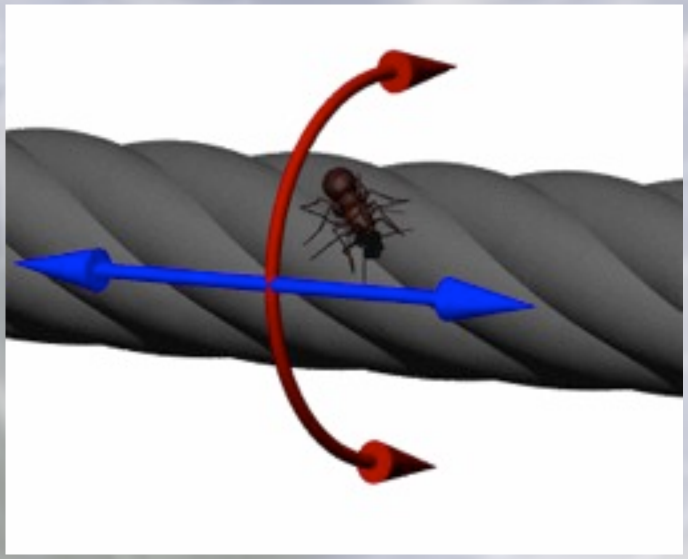
current torsion balance experiments set limit on $1/r^2$ dependence to <0.16 mm

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 and the Planck Scale

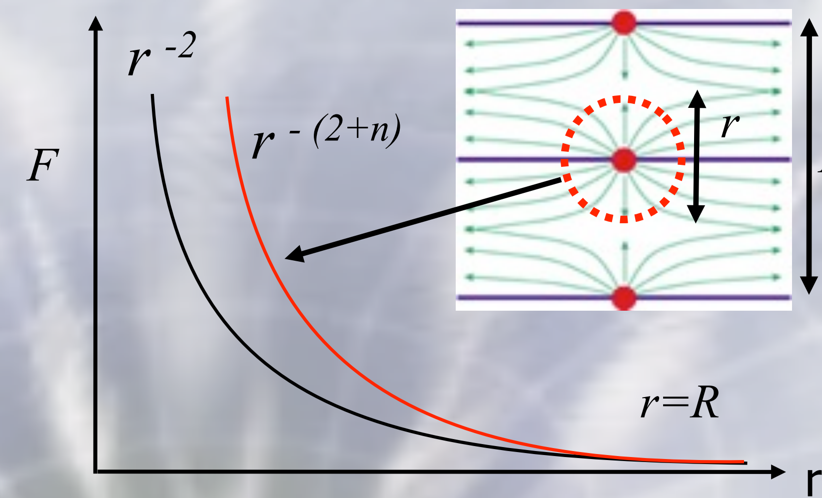
Gauss' Law for gravity: surface integral over closed volume containing vector field g gives total enclosed mass M

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

With n extra spatial dimensions each of size R

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

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



For $r \gg R$ we recover Newtonian gravity

dilution due to volume of extra dimensions

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

In extra dimensions full scale of gravity M_D is given by

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

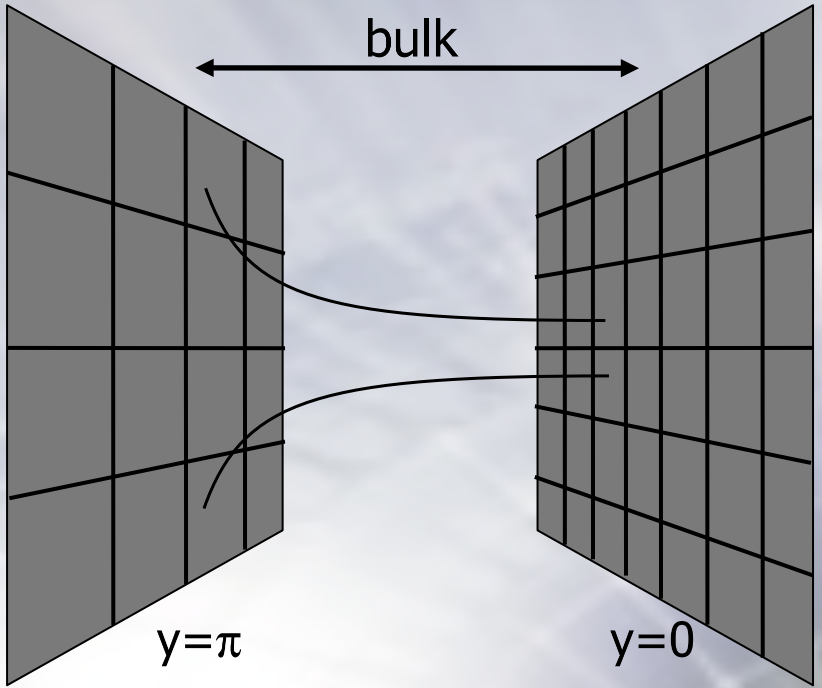
Thus M_D can be ~ 1 TeV when R^n is large

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

Randall-Sundrum Model of Warped Extra Dimensions

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

Standard Model
brane
TeV Scales



Planck brane

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

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

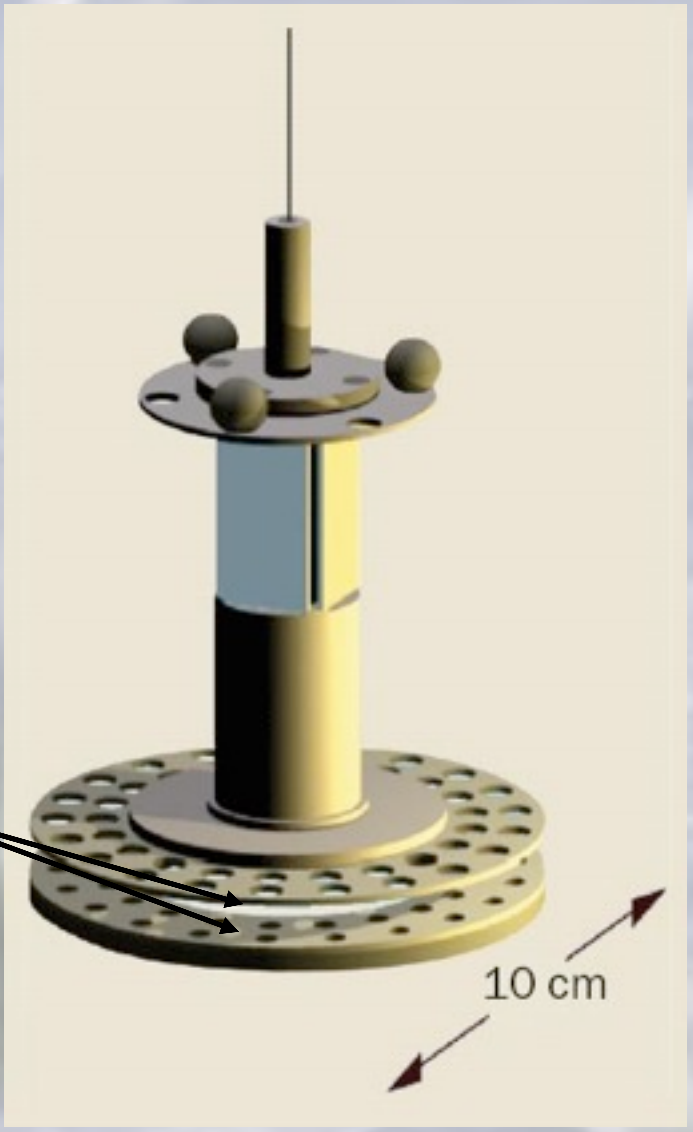
Extra dimension highly curved with an exponential warp factor
⇒ introduces scaling between 3-branes length $\propto 1/E$

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

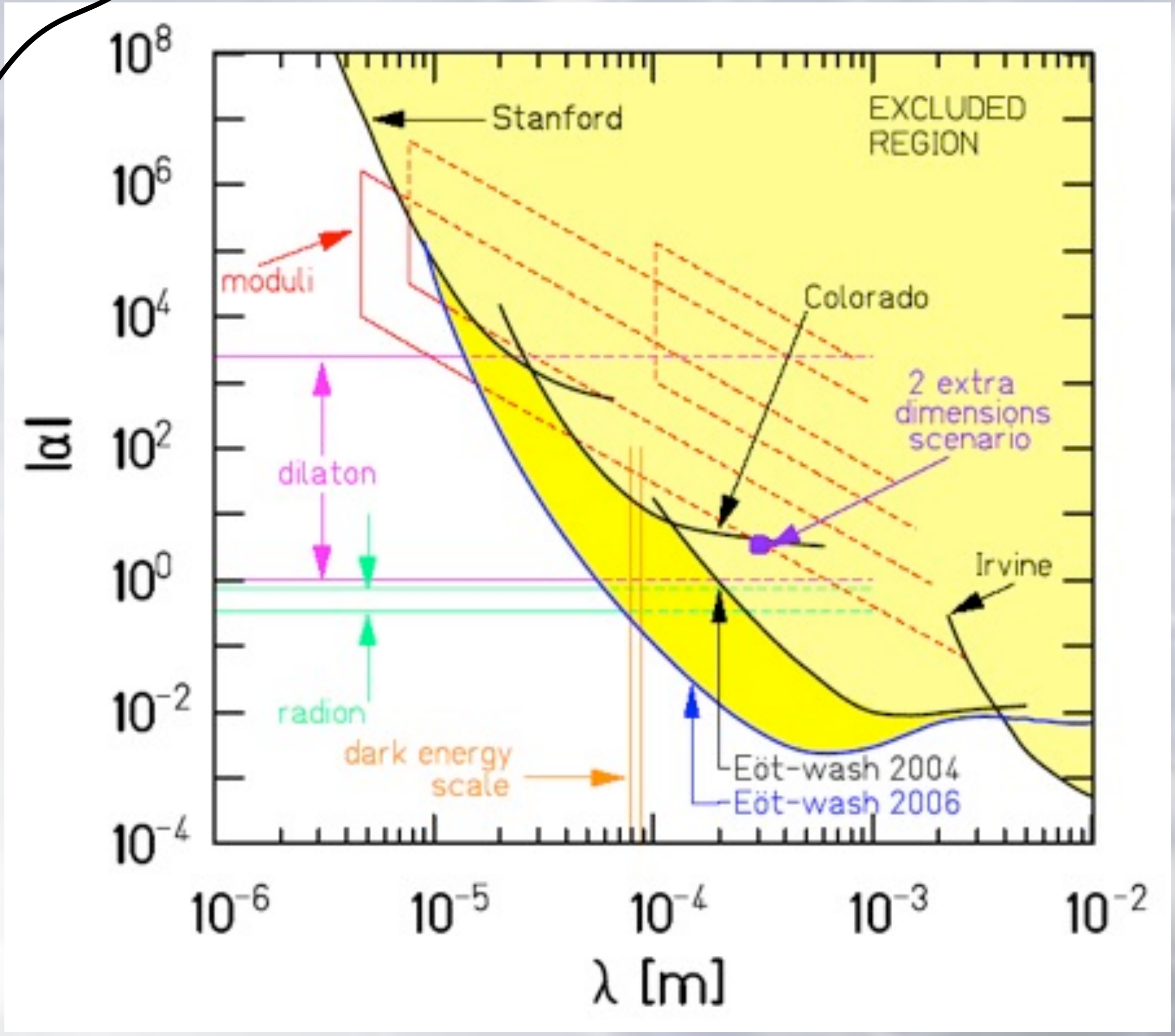
Sensitive to ~1 nanoradian twists
(angle subtended by 1 mm at distance of 1000 km)

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

strength of new Yukawa-like potential

range of new Yukawa-like potential

Phys.Rev.Lett.98:021101, 2007



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

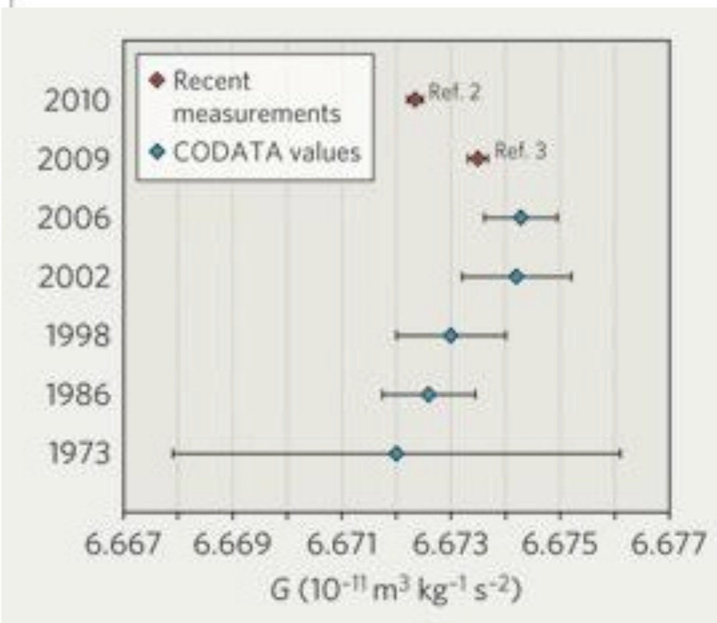
$\Rightarrow$ extra dims have

$R < 44\ \mu\text{m}$ 95% C.L.

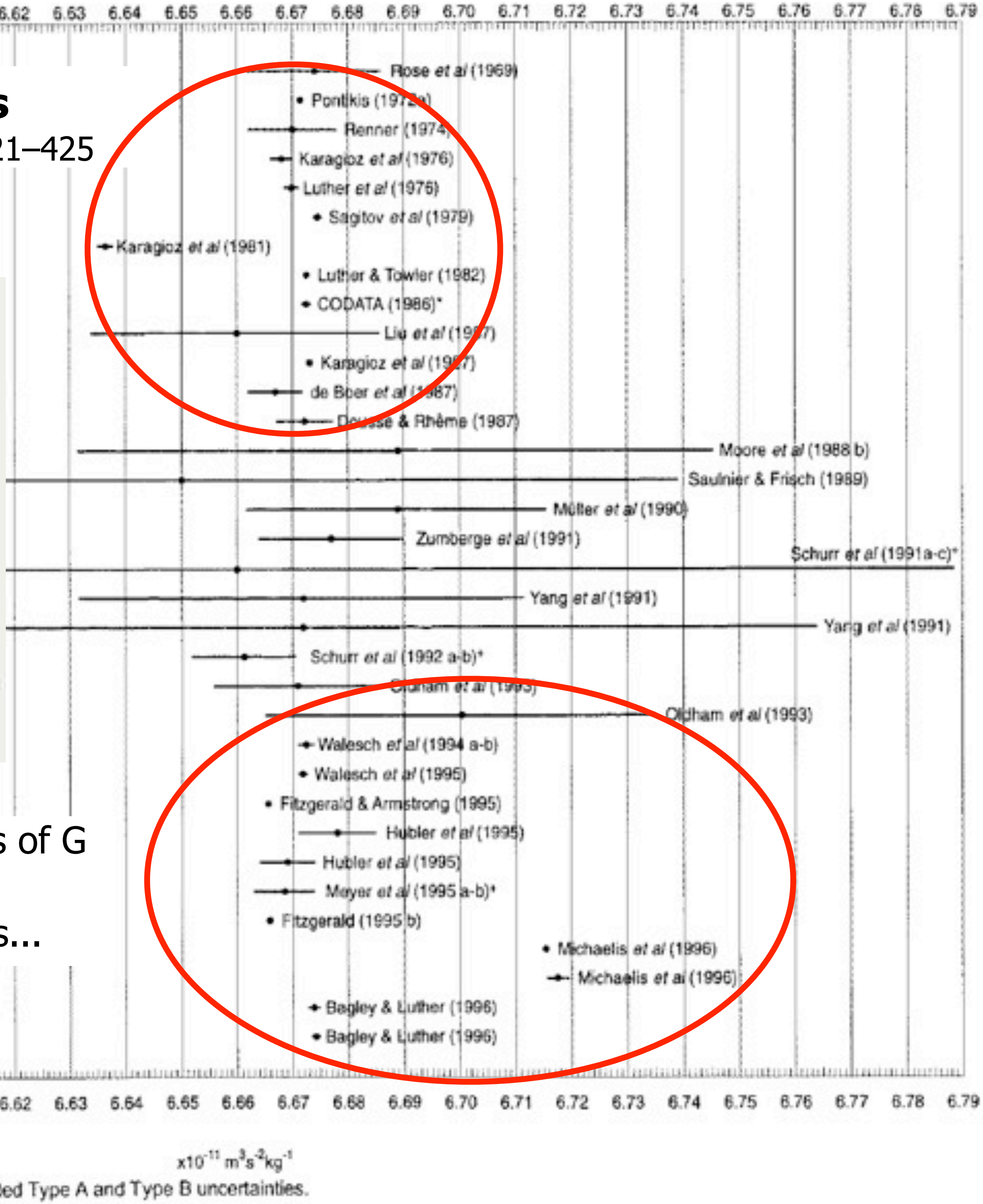
Gravity at Large Distances

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

Reich: Nature 466, 1030 (2010)



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

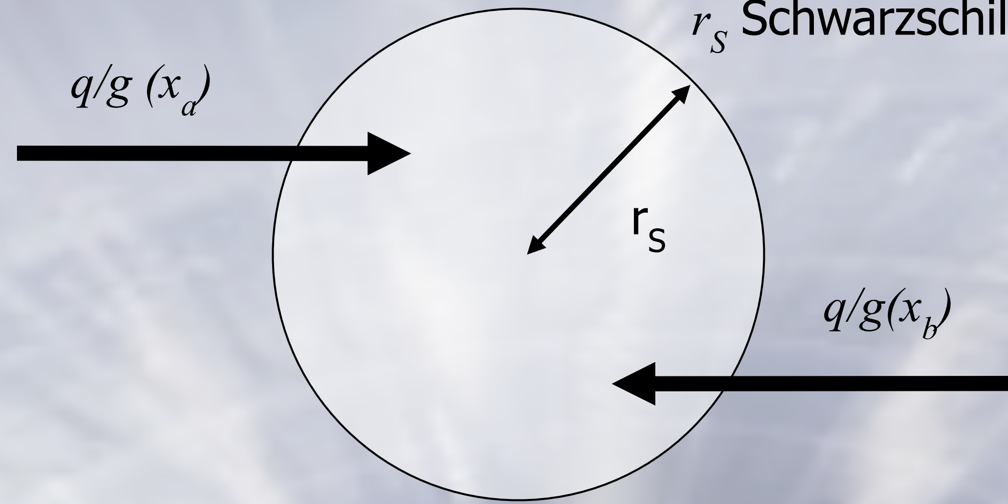


Micro Black Hole Production

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

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

r_S Schwarzschild radius



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

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:

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

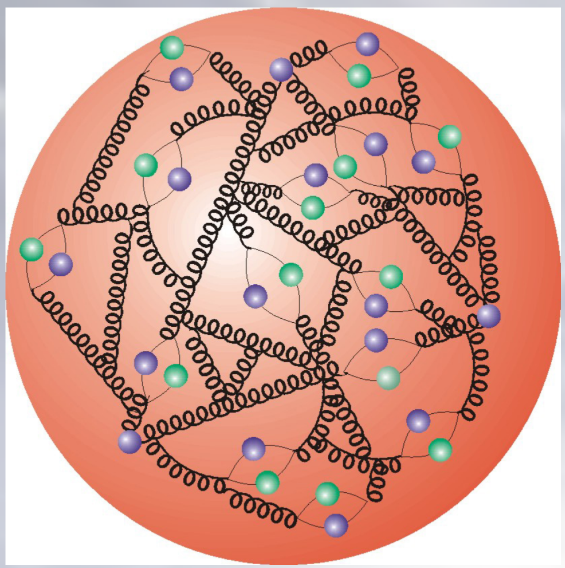
parton cross section
F = production form factors

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

convolute PDFs to get total production cross section

Simple but extremely robust prediction!

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



proton is a composite particle
its a bag of quarks + gluons = partons

$f_a(x_a)$ = probability to find a parton of flavour f with momentum fraction x_a

Rate at which interactions occur depends on two pieces:

- number of particles in your experiment - particle fluxes / target density
- intrinsic physics describing reaction between 2 particles = cross section

Think of cross section as proportional to the probability for a reaction to occur
It is quantified in units of area - effective area presented by target to beam

Consider two colliding beams

A = beam spot area
Flux of particles is Φ

$\Phi_1 = N_1/t$ and $\Phi_2 = N_2/t$

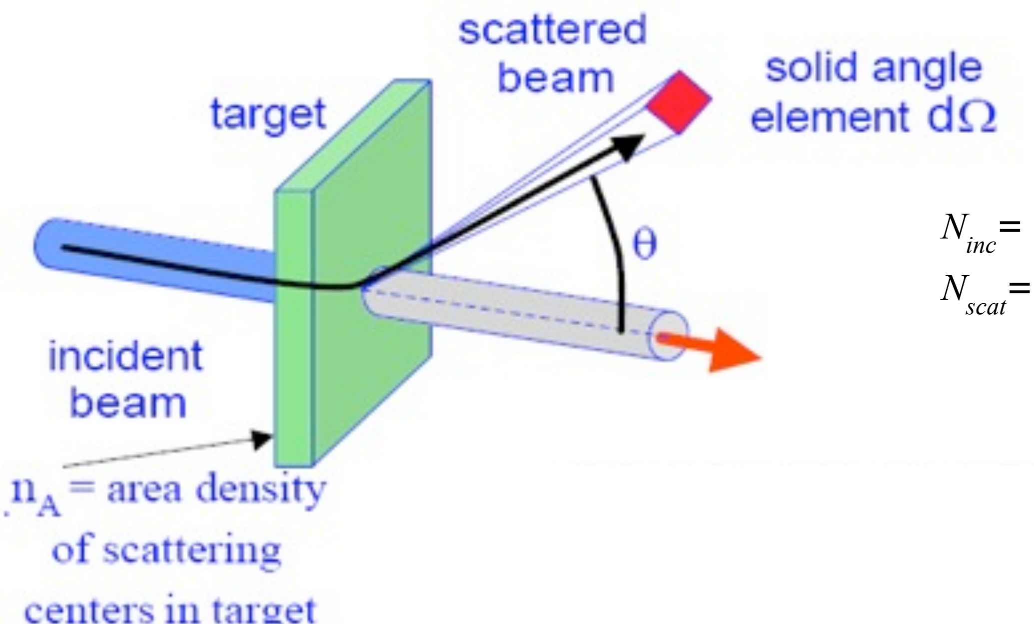
what is the interaction rate R_{int}?

interaction rate:

$$R_{int} \propto \frac{\Phi_1 \Phi_2}{A} \rightarrow \mathcal{L}$$
$$= \sigma \mathcal{L}$$

$\mathcal{L}$ = Luminosity [cm^{-2} s^{-1}]
no. of particles per unit area per unit time.
Depends only on design of your experiment

σ = constant of proportionality
depends on the fundamental physics only!



N_{inc} = number incident particles

N_{scat} = number scattered particles into solid angle $\mathrm{d}\Omega$

$$N_{scat}(\theta) \propto N_{inc} \cdot n_A \cdot \mathrm{d}\Omega \rightarrow \mathcal{L}$$
$$= \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \cdot N_{inc} \cdot n_A \cdot \mathrm{d}\Omega$$

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 ⇒ 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...

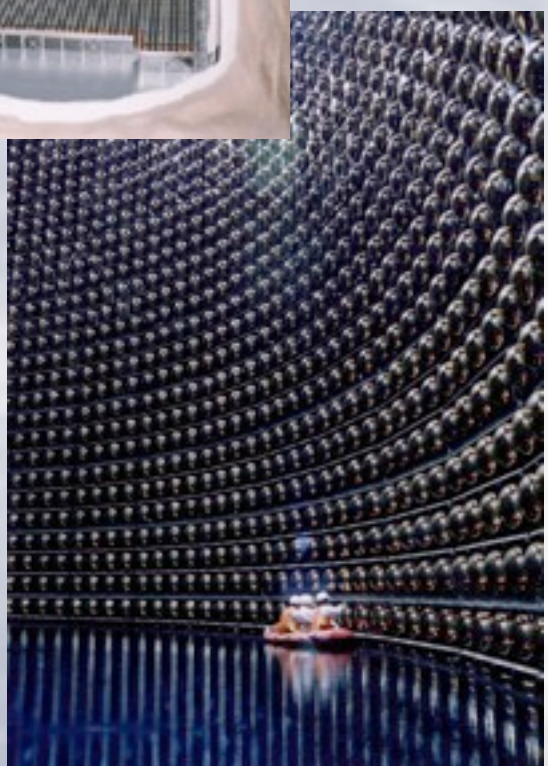
Proton kinematically allowed to decay to any lighter fermion
Only protected by B conservation (which must be violated at GUT scale!)
Only option is e^+ ⇒ thus p decay violates lepton number too

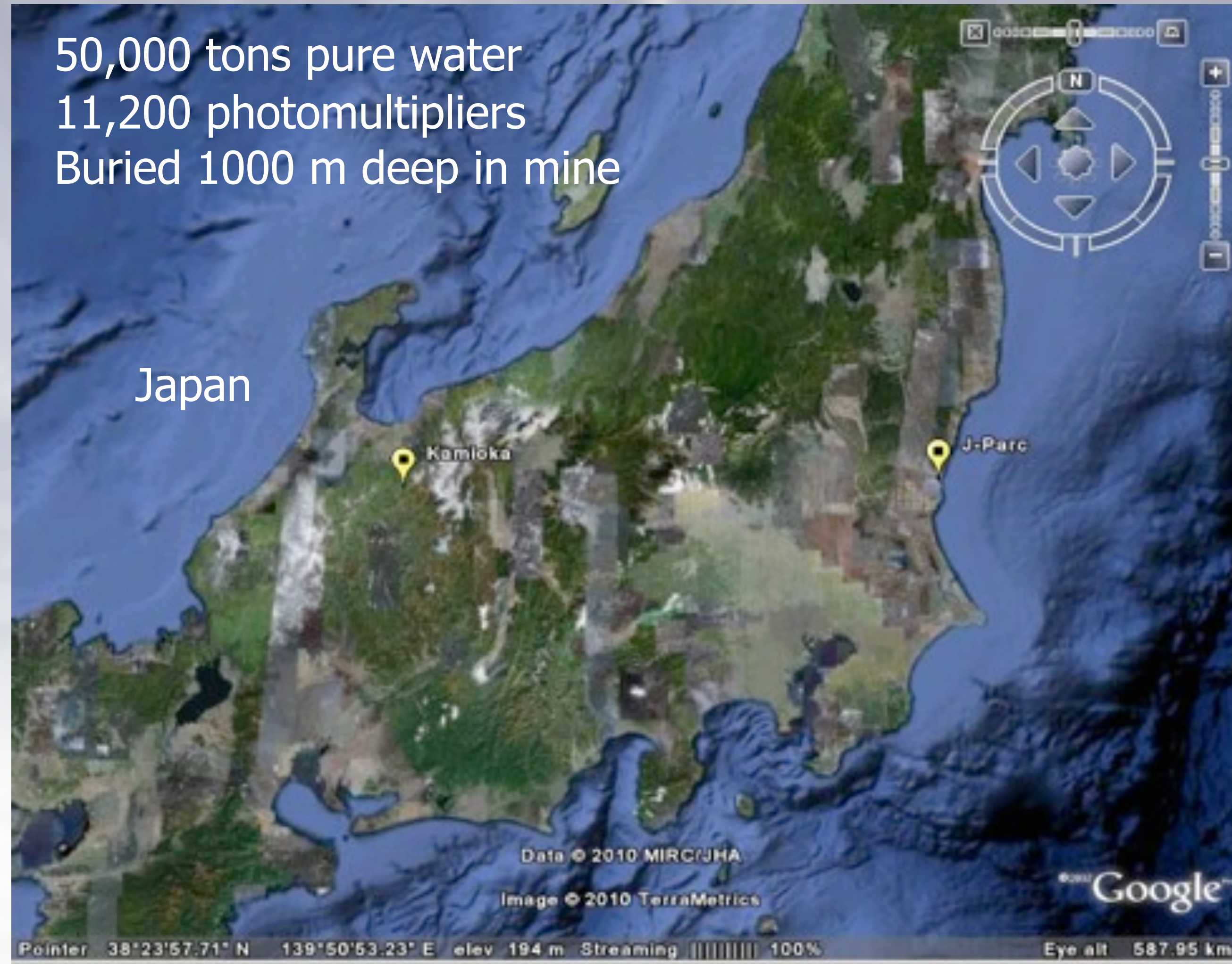
$$p \rightarrow e^+ + \gamma$$
$$p \rightarrow e^+ + \pi^0$$

Many ADD models predict too fast proton decay

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

Super Kamiokande





Experiment looks for decays in large volume of water

$$p \to e^{+} + \gamma$$

$$p \to e^{+} + \pi^{0}$$

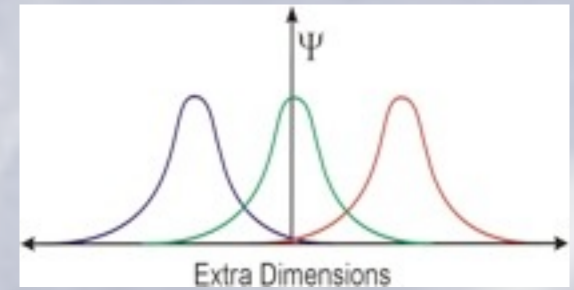
(mainly built for neutrino oscillation measurements)

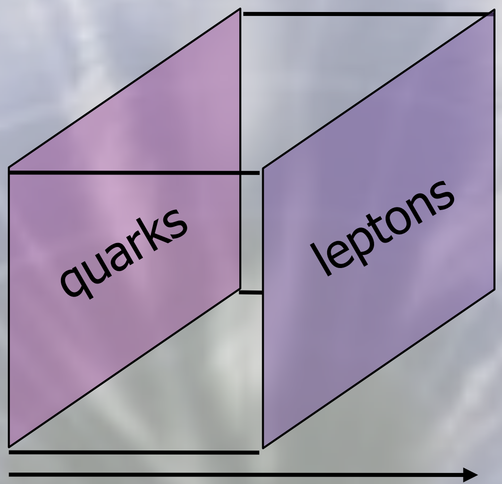
Split Fermion Model

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

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

entropy $\propto$ surface area $$r_s = \frac{2GM_{BH}}{c^2}$$

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

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

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

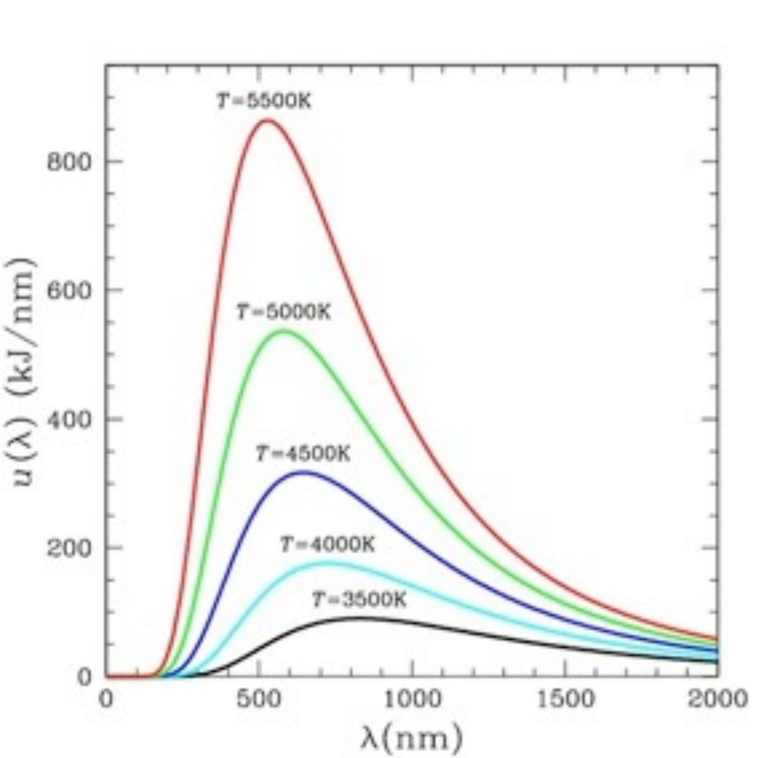
Near event horizon vacuum fluctuations interact with warped spacetime
Negative energy particle of virtual pair falls into BH, other becomes real

⇒ BH loses mass

radiate a black body spectrum with temp T_H

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

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



Astro-BHs have temp < CMB
Micro BHs are very hot - radiate intensely

⇒ BH evaporate

Hawking radiation is purely thermal

only depends on M , Q , J , Col

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:

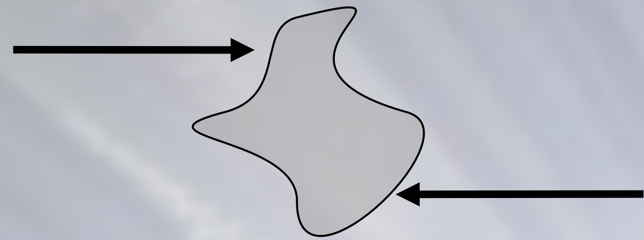
initial state $\langle \psi | \psi \rangle = \langle \psi | U^\dagger U | \psi \rangle = \langle \psi' | \psi' \rangle$ final state

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

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

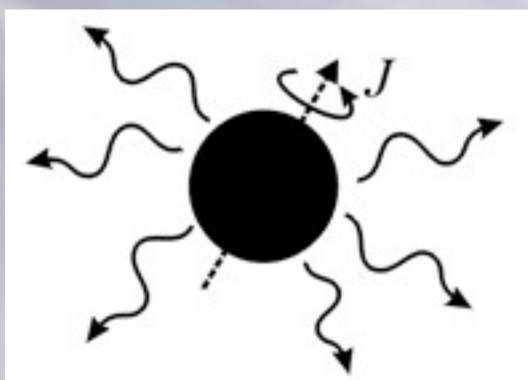
Thus unitary transforms are reversible – but pure thermal state → e.g. pure baryon state cannot happen unless additional info / quantum numbers are known!

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

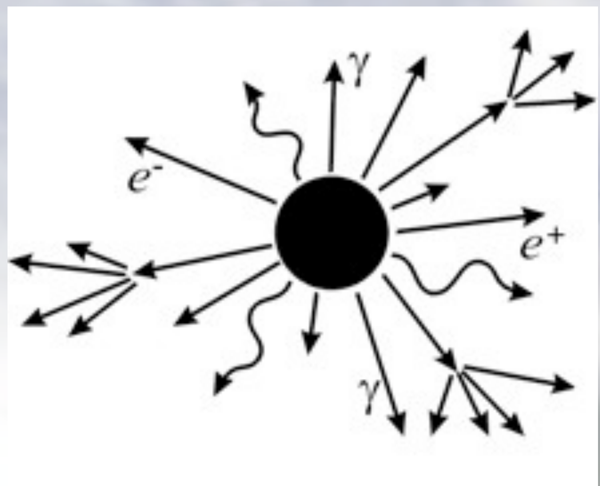


Collision produces complex state as horizon forms
Not all energy is trapped behind horizon

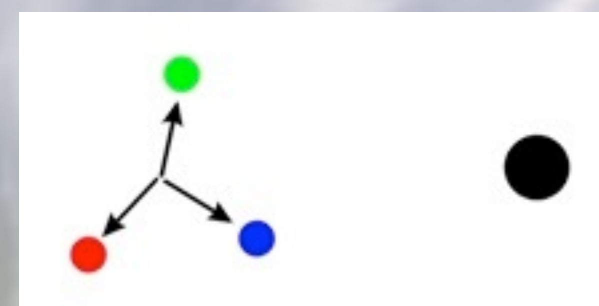
Extremely short lifetime ~ 10^{-25} s



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

Gingrich: hep-ph/0609055

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

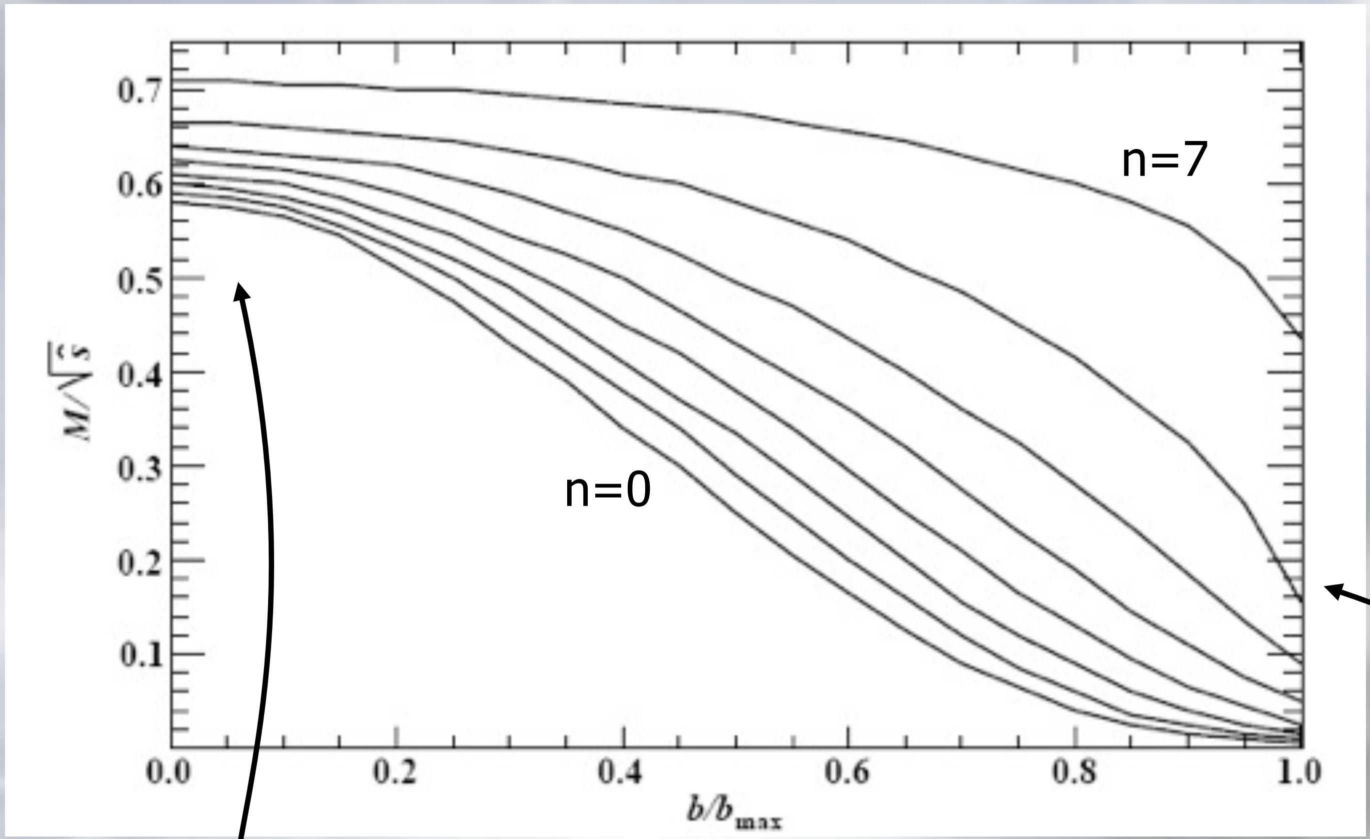
parton cross section
F = production form factors

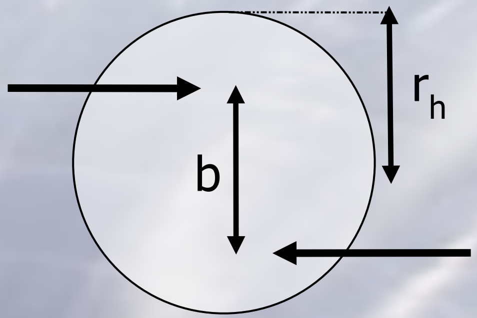
r_h is generalisation of r_S for spinning BHs

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

Form factors

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

Limitations of the Models

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

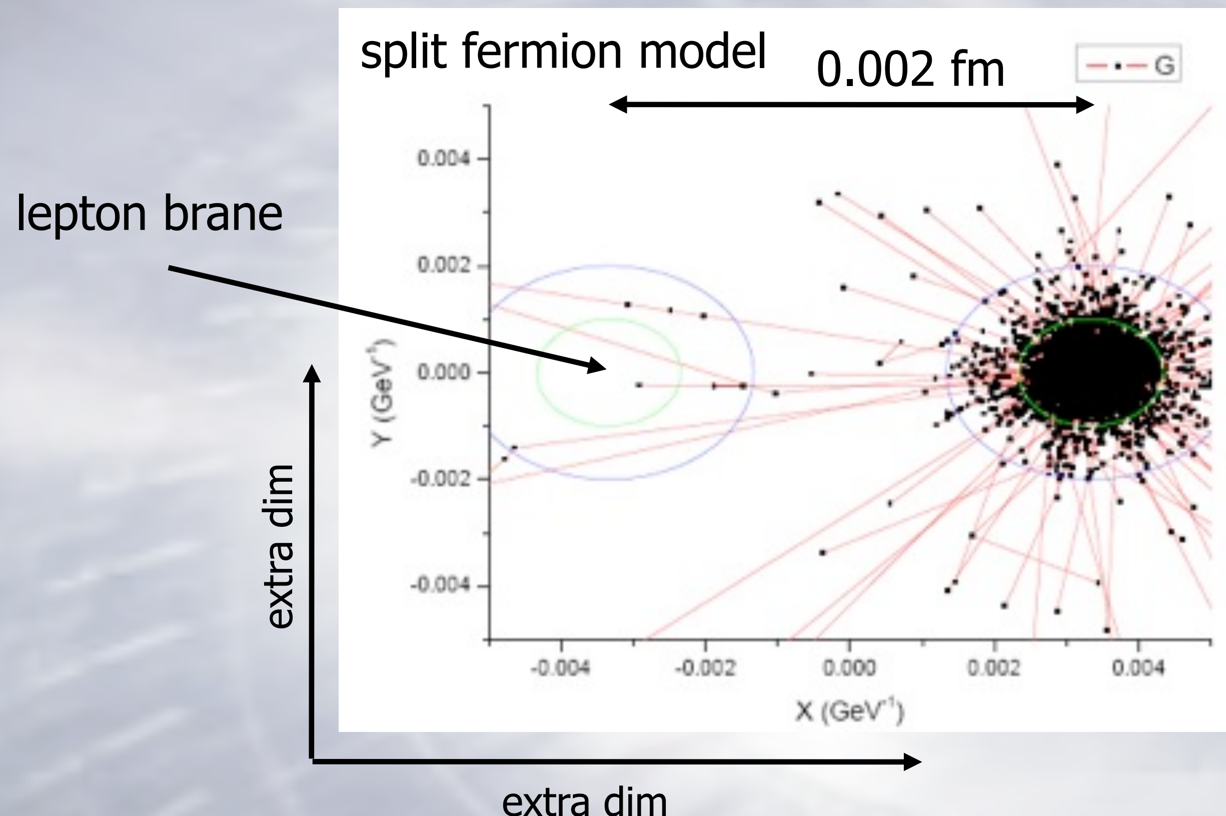
- Important to explore full phenomenological space
- Include all effects into MC simulations

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



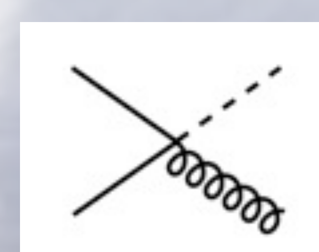
BH recoils at each emission
Affects emission spectra
Mostly emits quarks/gluons

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

ep
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 $\pm\lambda$ has unknown sign of interference with SM

LEP: $\gamma + \not\!E_T$

$e^+ e^-$
$M_D > 1.60$ 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

$p\bar{p}$

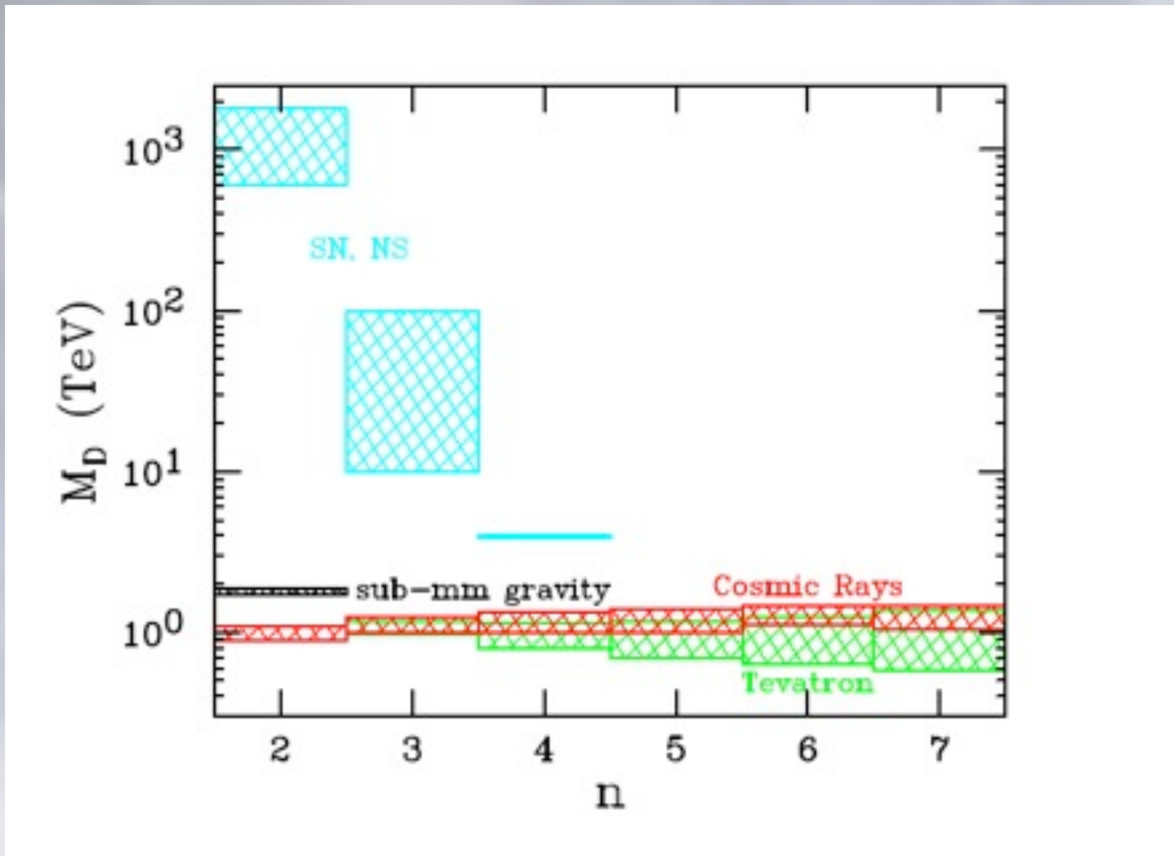
D0: ee, γγ, jet-jet
$M_D > 2.16$ TeV for n = 2
$M_D > 1.31$ TeV for n = 7

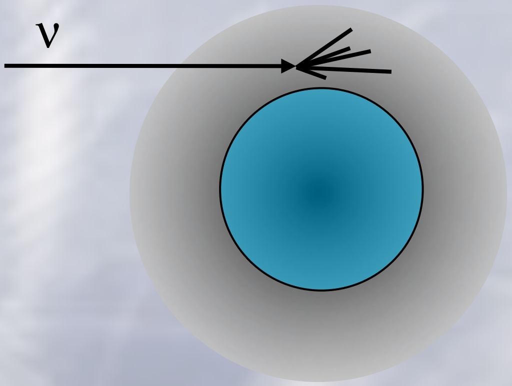
Variety of limits exclude ~ 1 TeV

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)

Pre LHC 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

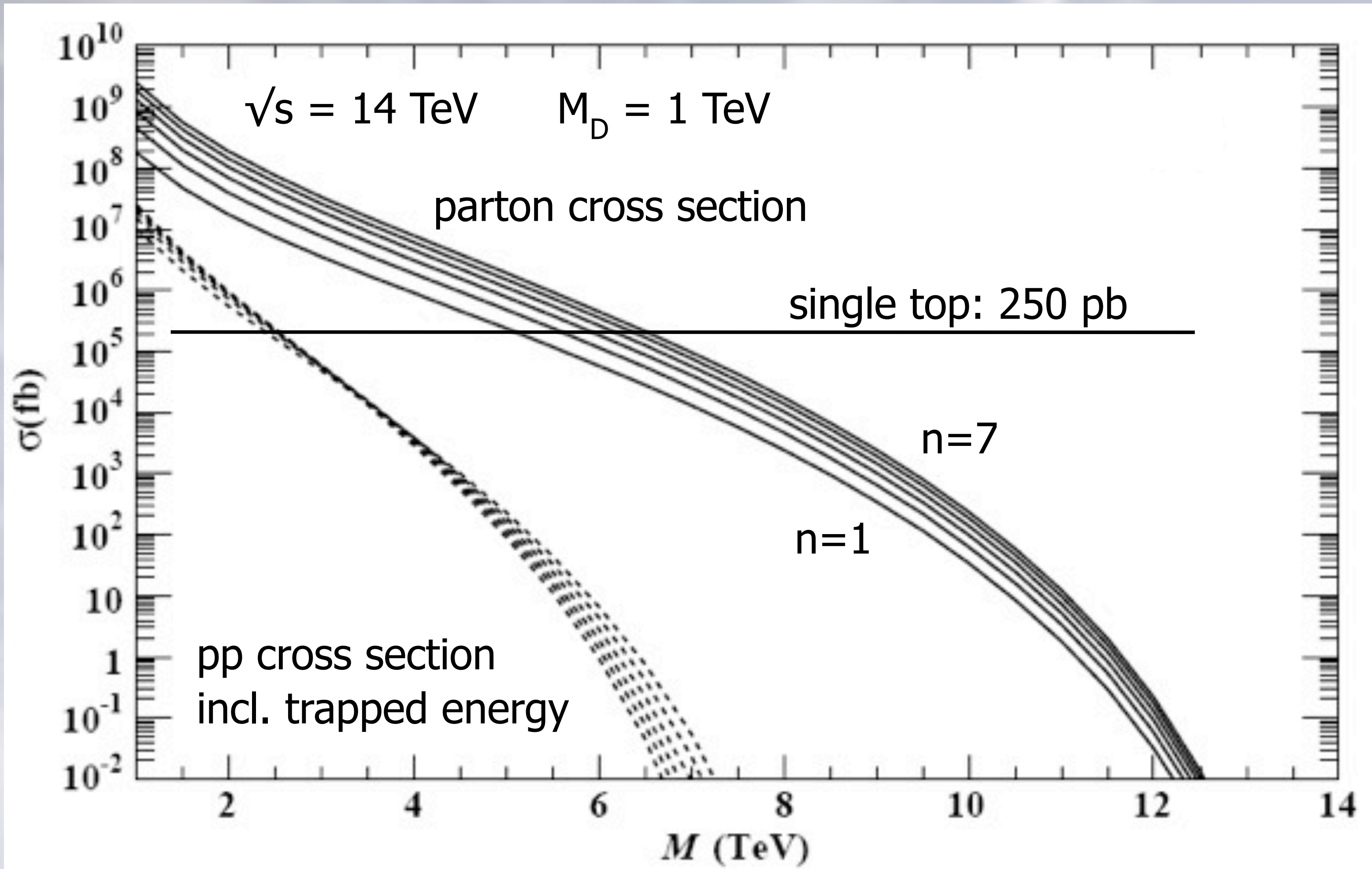
A graviton flux would cause reduced neutrino flux from supernova

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

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

Cross section lower limits

Gingrich: hep-ph/0609055



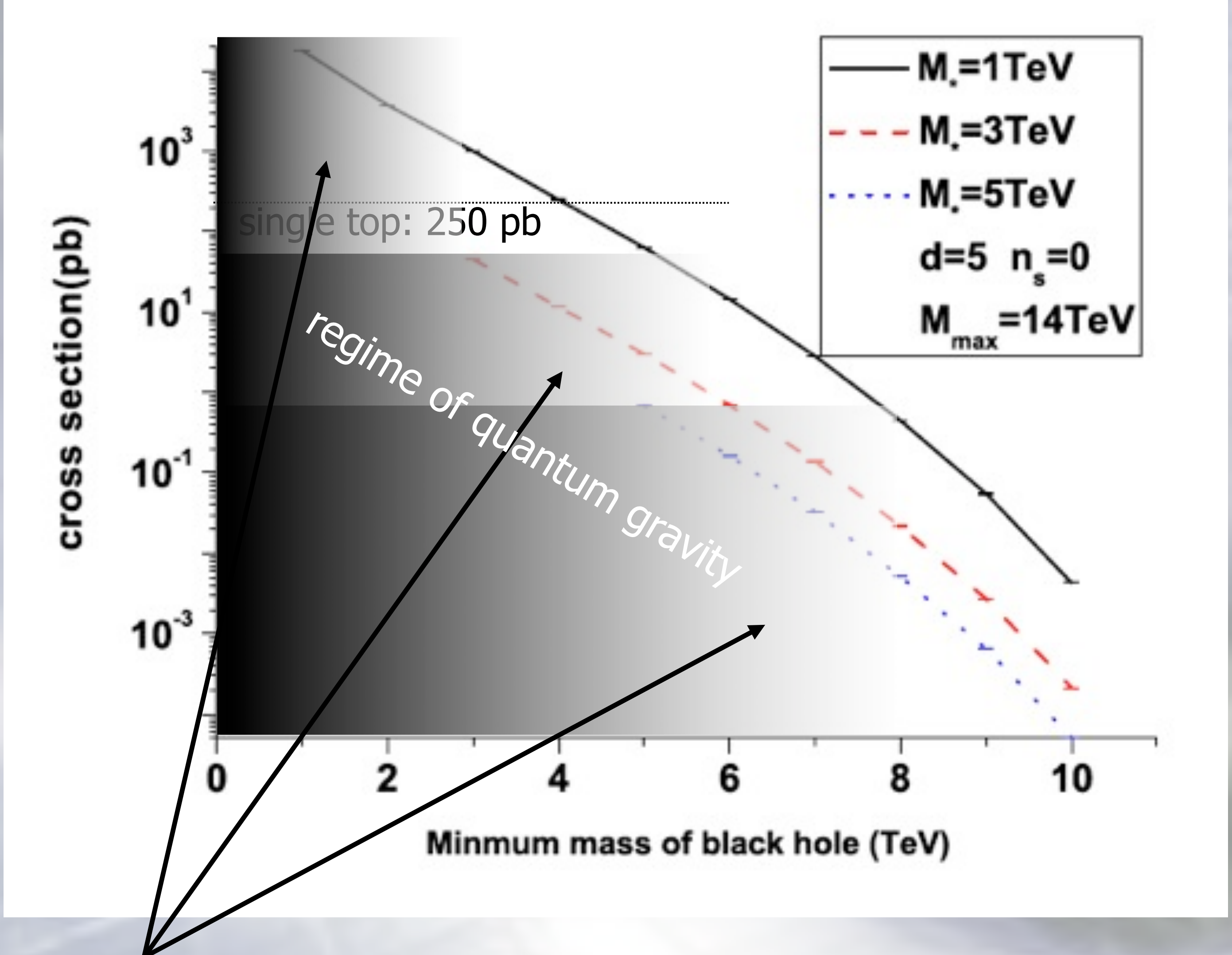
Potentially very large cross sections predicted

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

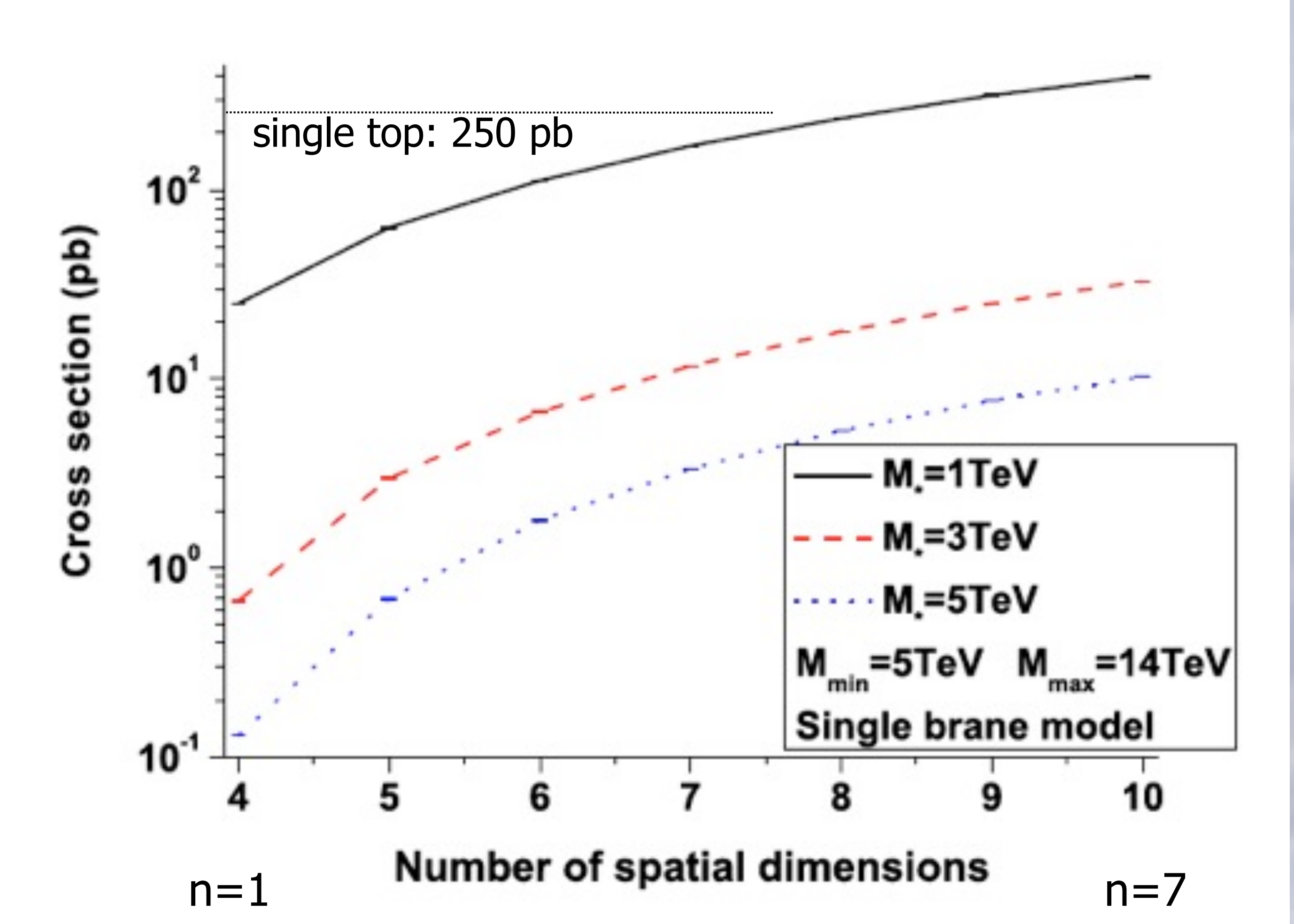
Factor ~10^2 suppression for M_D=1 to 5 TeV

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

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

Emission spectra change depending on the models chosen

Typical ratio ~ 8:1 hadrons:leptons

Leptons heavily suppressed in split fermion model

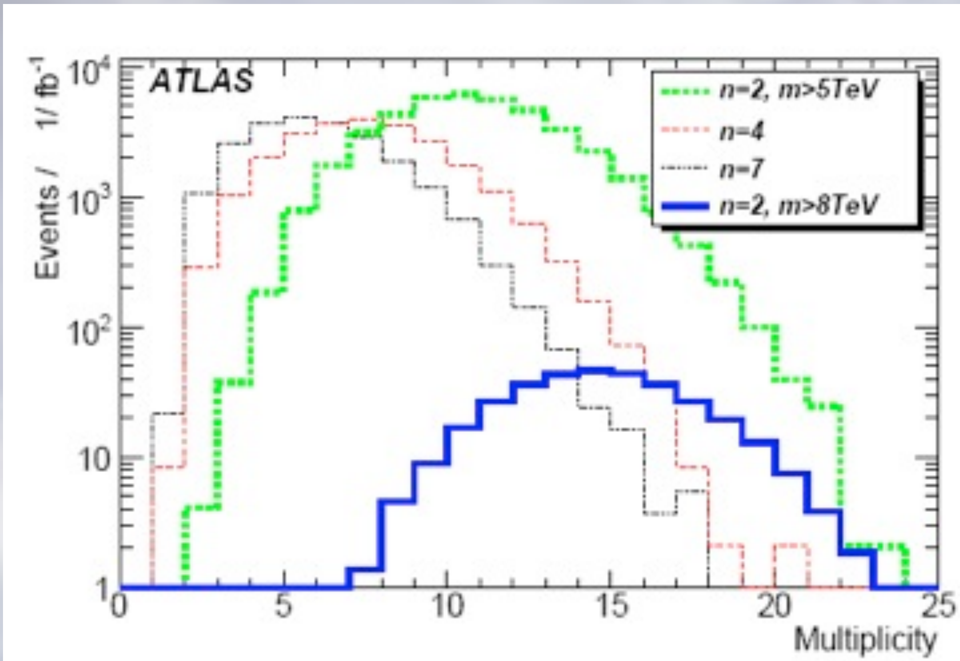
Graviton modes suppressed at low n

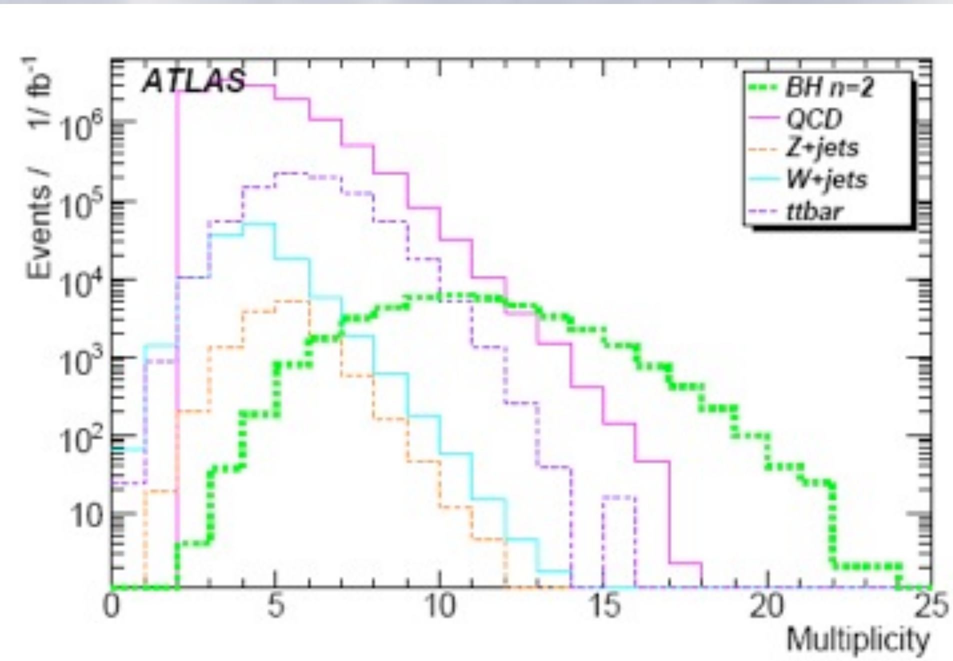
scenario	q+g	leptons	neutrinos	W/Z	G	H	photons
n=1 / J=0	79.0%	9.5%	3.9%	5.7%	0.2%	0.9%	0.8%
n=7 / J=0	74.0%	7.7%	3.2%	6.8%	6.5%	0.7%	1.5%
n=7 / J=0 / split=7	84.0%	1.8%	0.5%	5.4%	6.7%	0.3%	1.6%
n=7 / J>0	78.0%	6.5%	2.5%	9.6%	??	0.7%	2.6%

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

High multiplicity events: 10-40 particles from heavy state

Hard P_T spectrum of decay particles

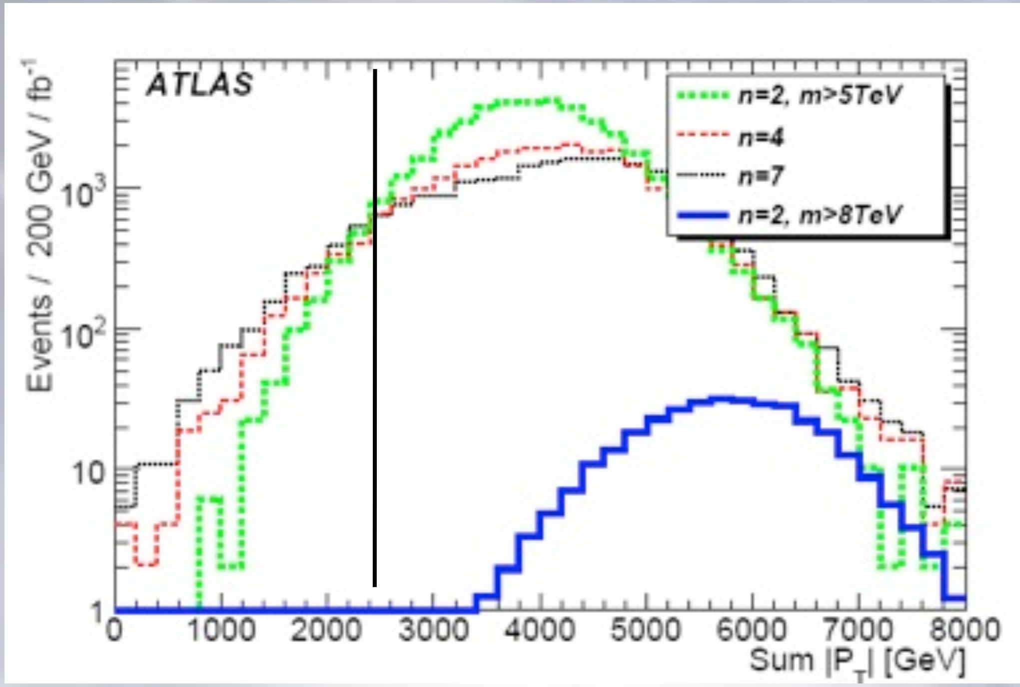


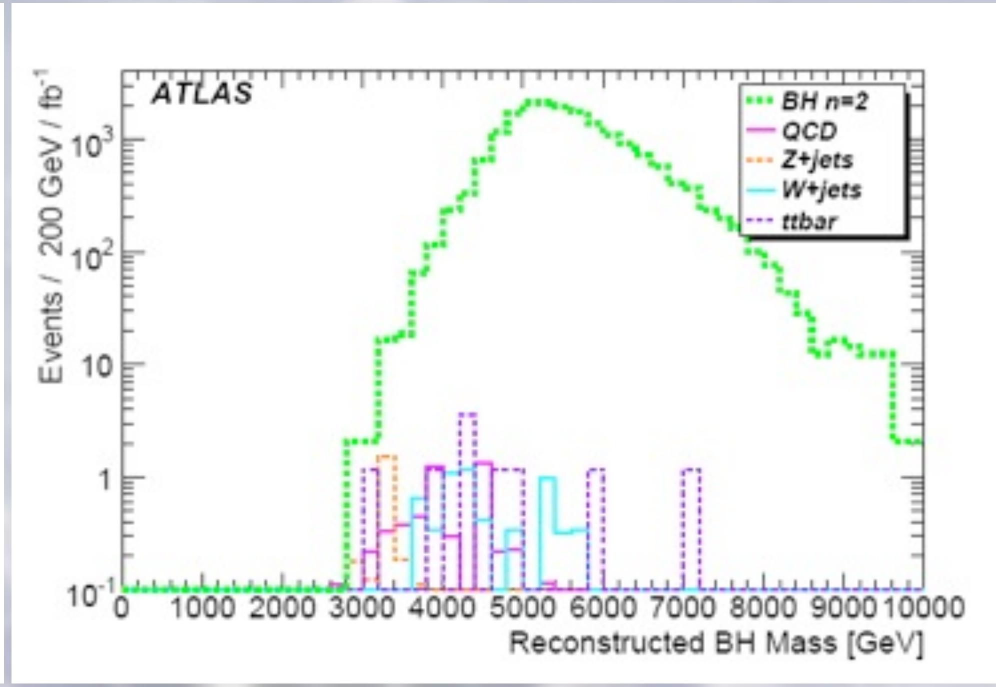


<N> falls as n increases
(BH temp increases)

Multiplicity compared to SM

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





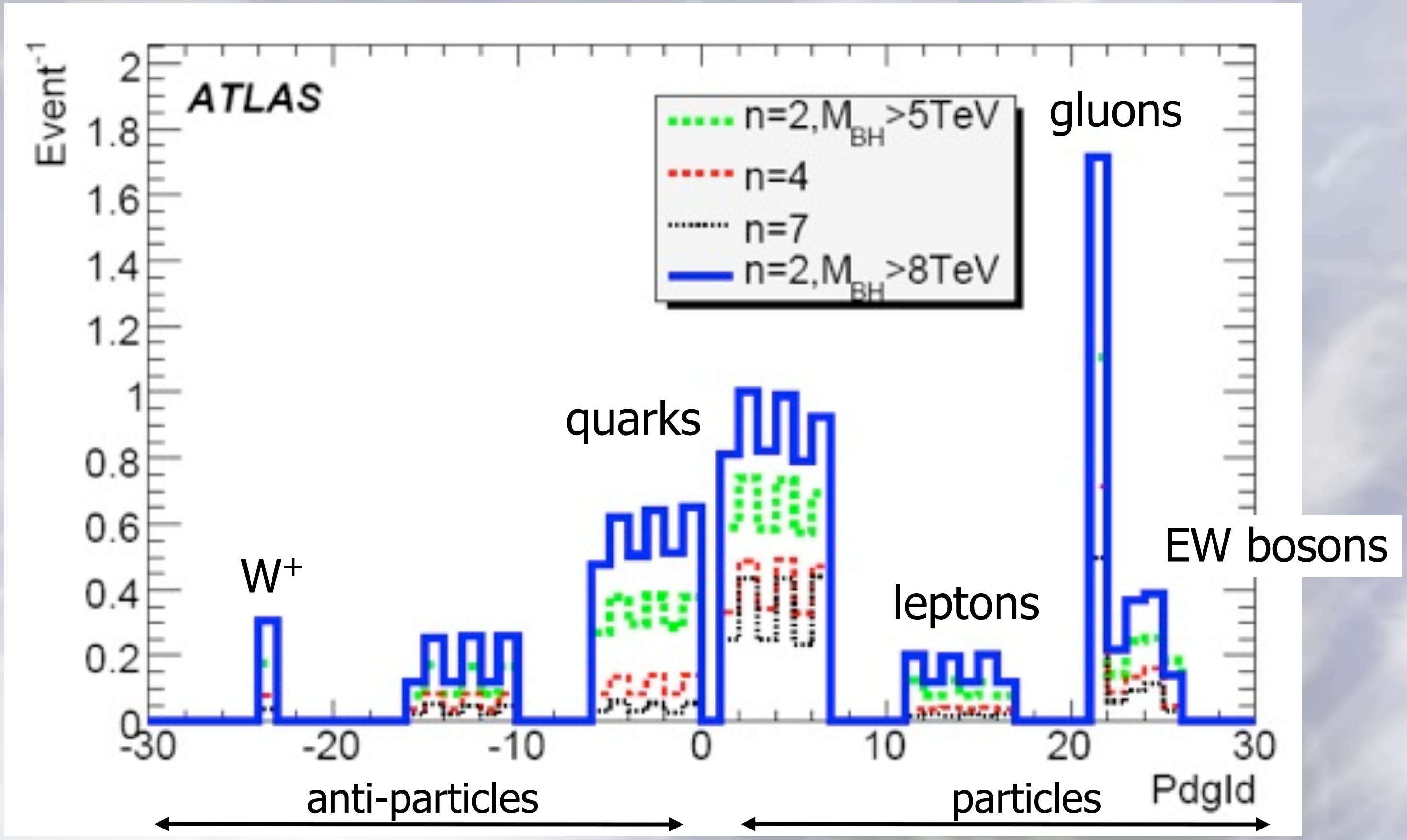
- $\Sigma|P_T|$ > 2.5 TeV

- $\Sigma|P_T|$ > 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, $\varepsilon = 100\%$

Multiplicity of particles by type in different models



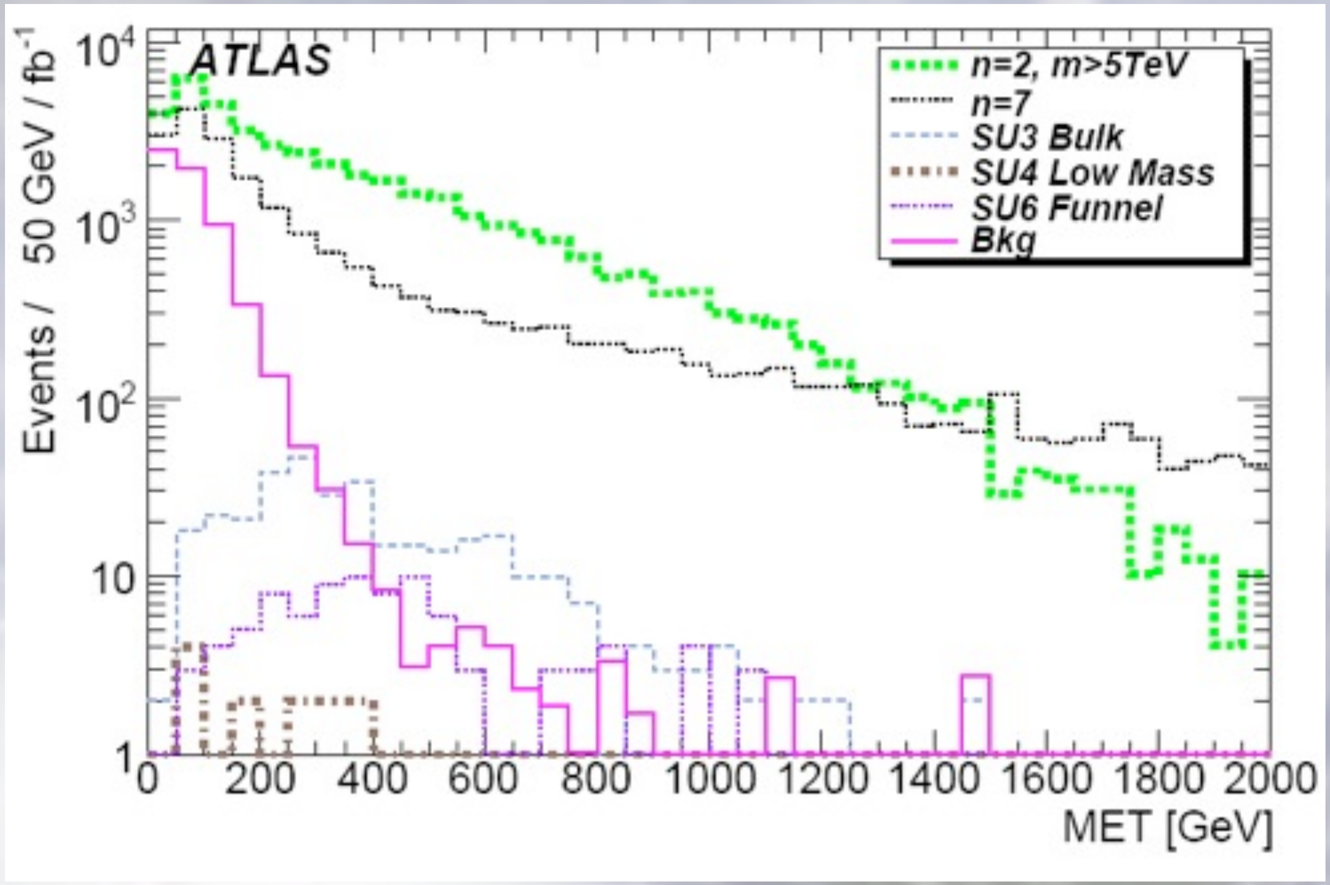
Higher multiplicity for larger M_{BH}

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

More particles than anti-particles due to pp initial state

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

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 $M_{BH} \geq 3M_D$
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 Black Holes

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

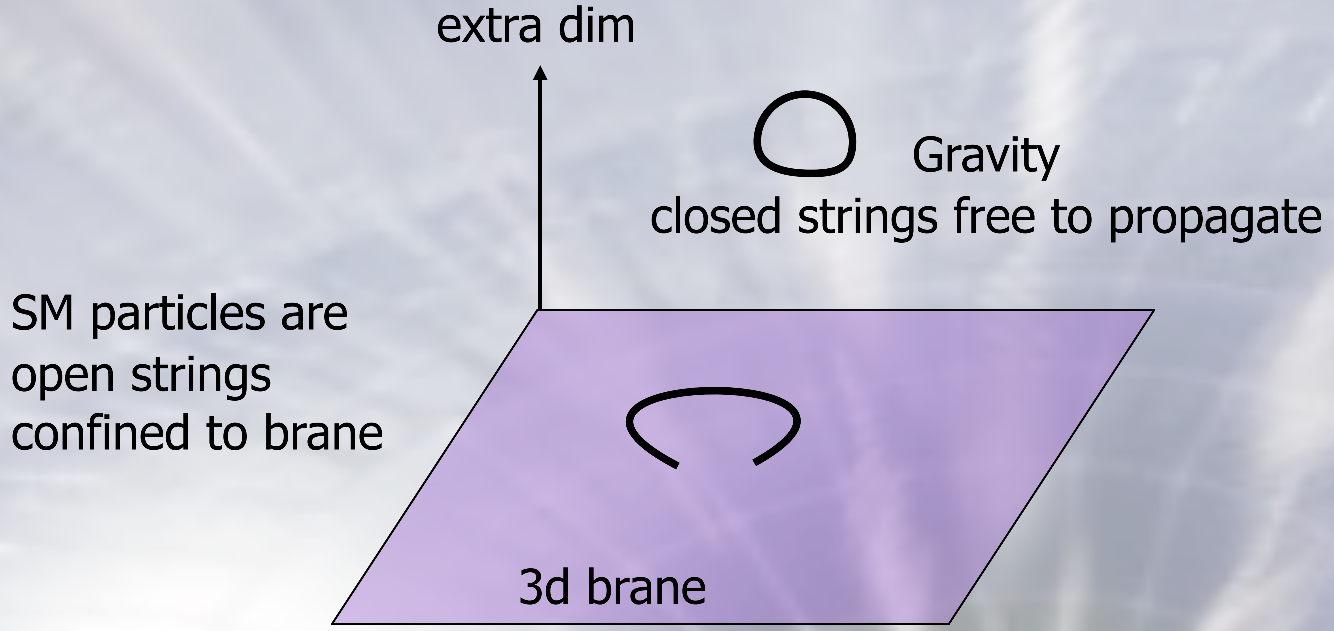
Close to threshold: $M_{BH} \sim M_D$ gravity is strongly coupled → non-perturbative

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 $\sim 1/M_{BH}$ $\Rightarrow J \sim 1$

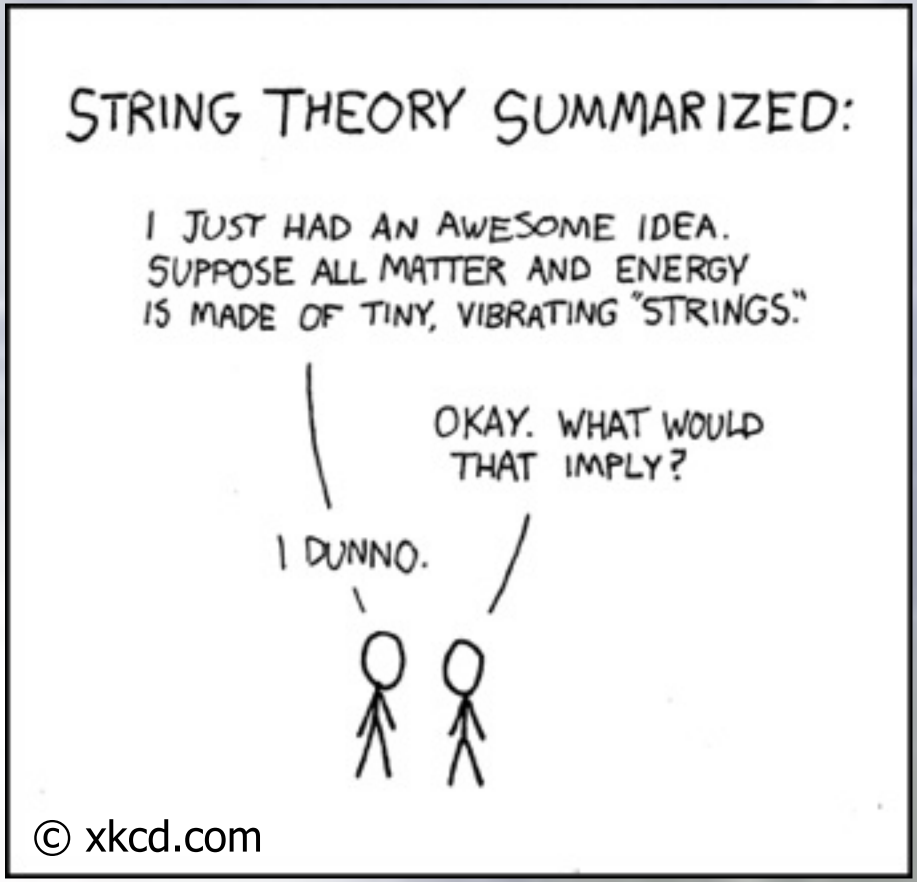
True theory is missing



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

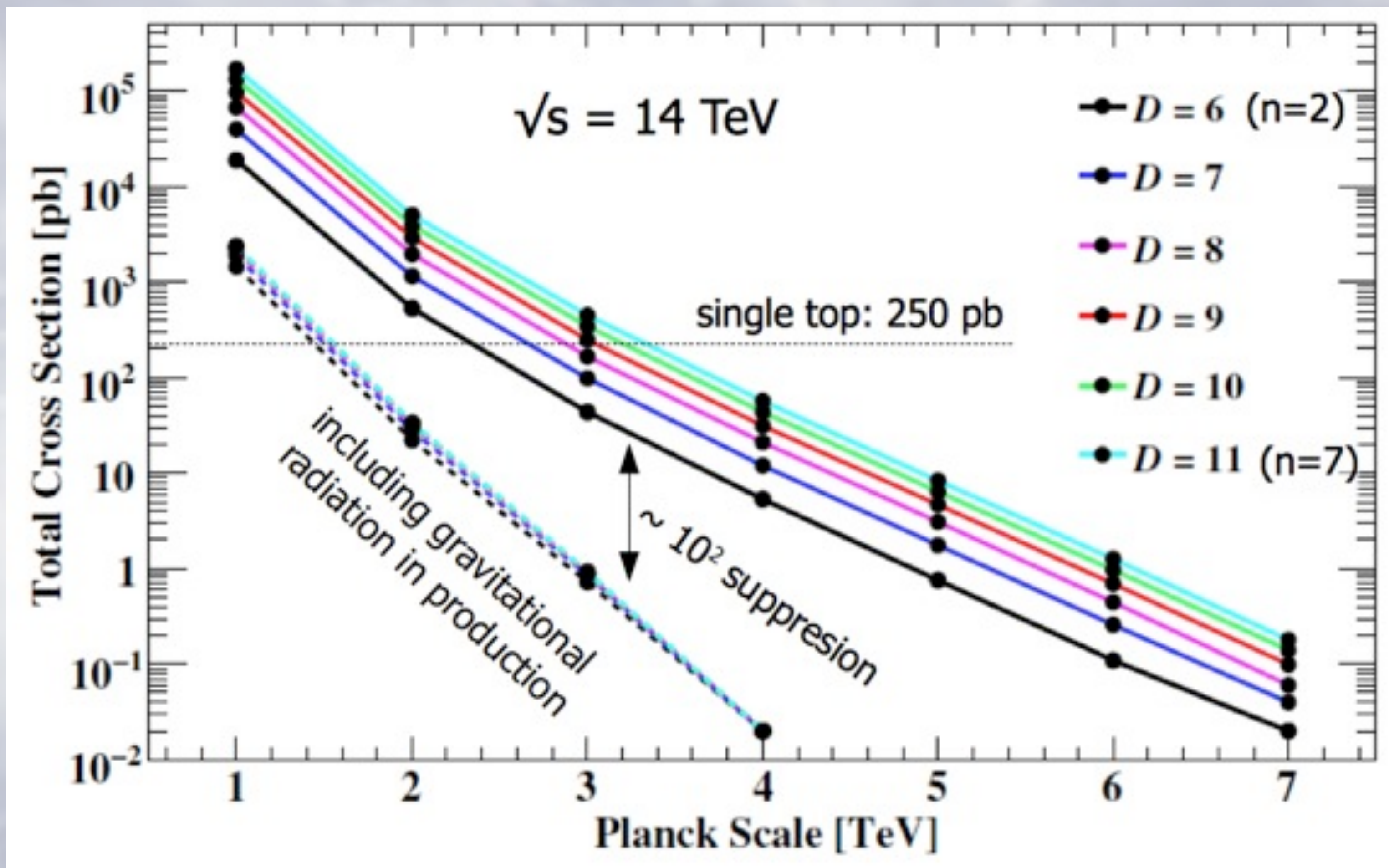

STRING THEORY SUMMARIZED:
I JUST HAD AN AWESOME IDEA. SUPPOSE ALL MATTER AND ENERGY IS MADE OF TINY, VIBRATING "STRINGS."
OKAY. WHAT WOULD THAT IMPLY?
I DUNNO.
© xkcd.com

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

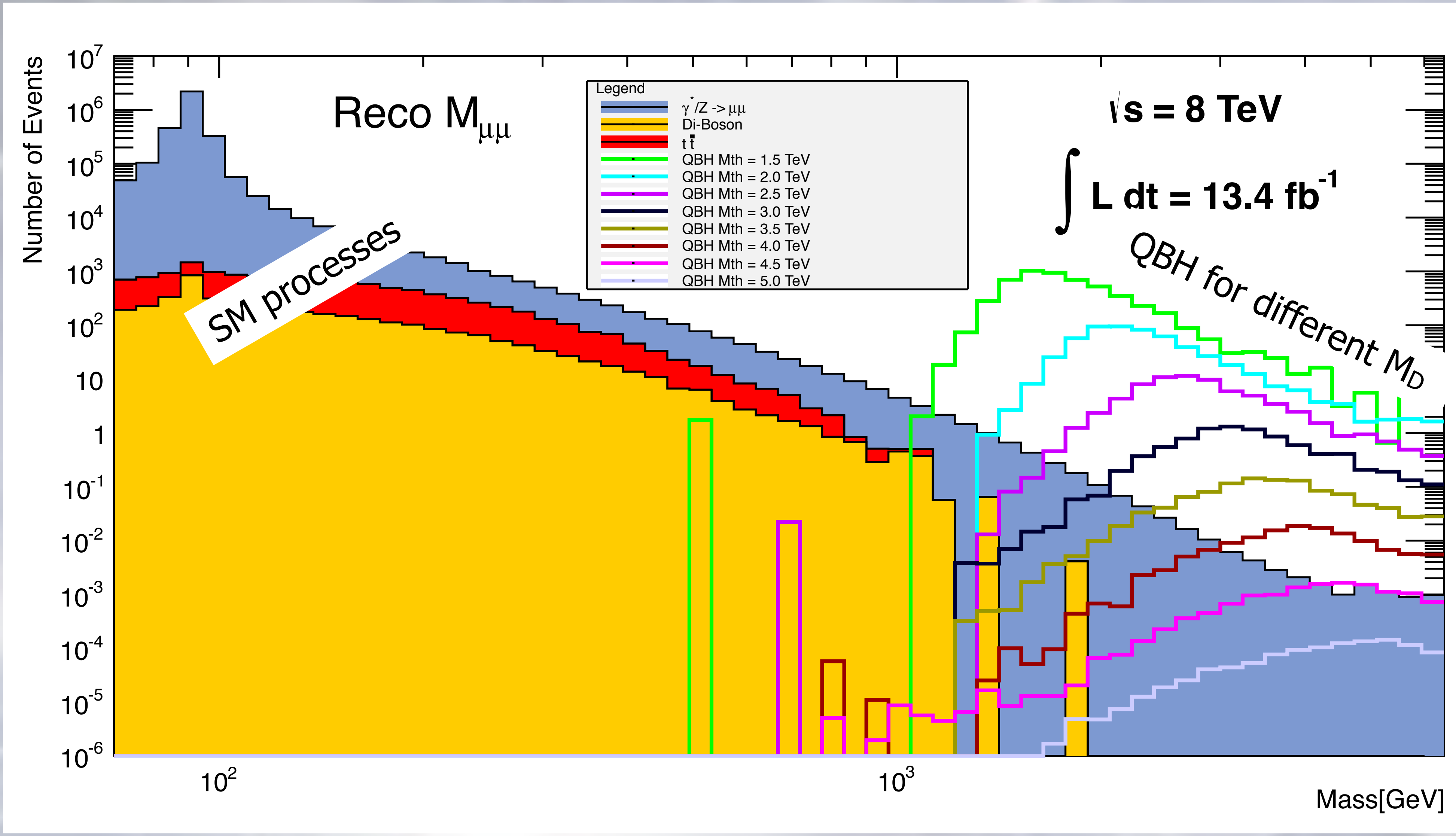
$QBH^{4/3}_{\bar{3}}$	$QBH^{4/3}_{6}$			
QBH^{1}_{1}	QBH^{1}_{8}			
$QBH^{2/3}_{3}$	$QBH^{2/3}_{\bar{6}}$	$QBH^{2/3}_{15}$		
$QBH^{1/3}_{\bar{3}}$	$QBH^{1/3}_{6}$	$QBH^{1/3}_{\bar{15}}$		
QBH^{0}_{1}	QBH^{0}_{8}	QBH^{0}_{10}	$QBH^{0}_{\bar{10}}$	QBH^{0}_{27}

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

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



Predictions for QBH production decaying to $\mu^+\mu^-$



Simulation only

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

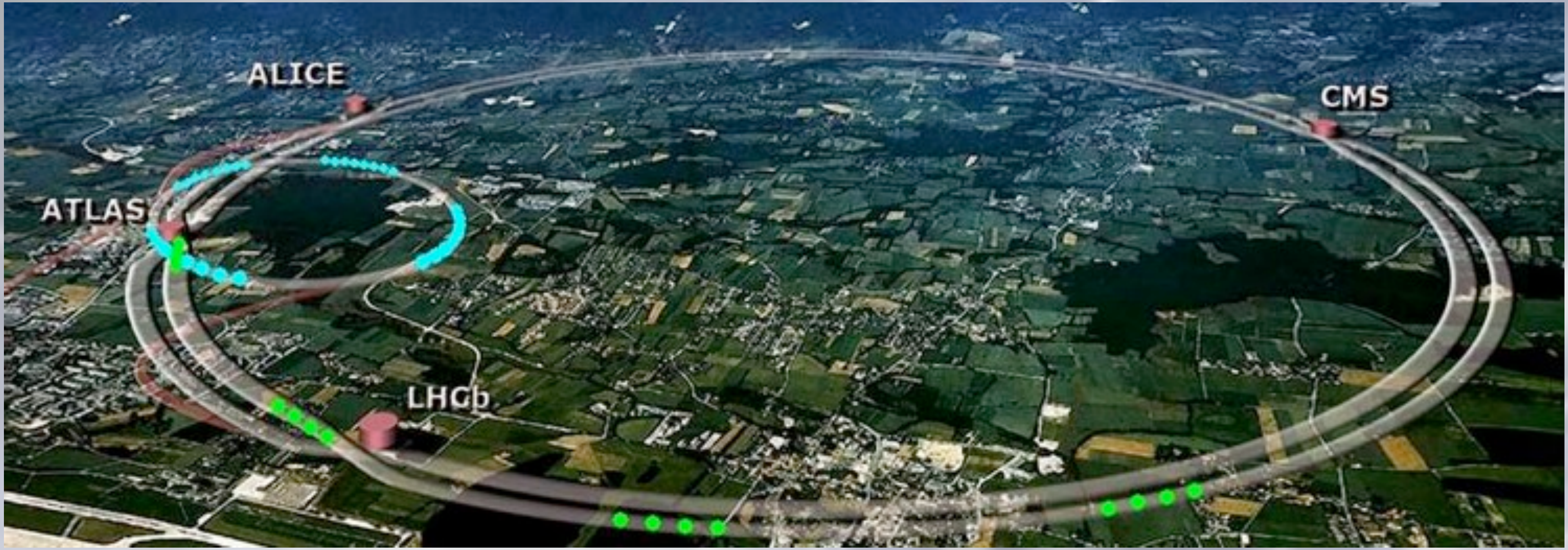
Anchordoqui et.al. arXiv:0808.0497v3

Neutrinos have mass ⇒ TeV scale gravity can democratically couple to

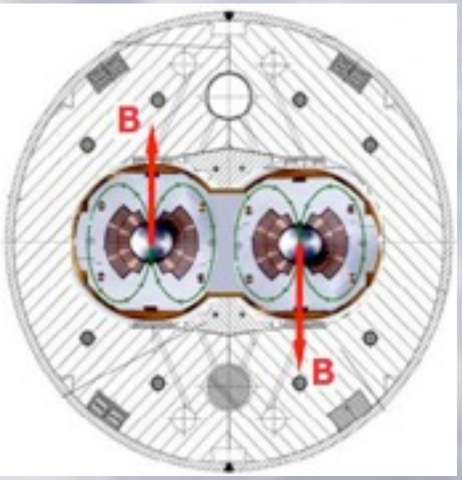
… left / right handed neutrinos
… heavy sterile neutrinos

The Large Hadron Collider

The Large Hadron Collider



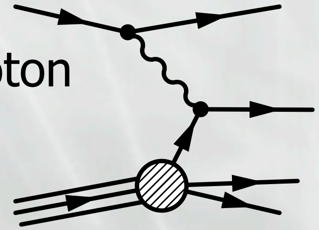
27 km circumference tunnel in France / Switzerland - near Geneva
Highest energy accelerator in the world
Protons accelerated to 7,000 GeV = 99.9999991% speed of light
High vacuum
Super cold superconducting magnets achieve strong magnetic fields
17,000 A current in magnets



Four experiments:
Atlas , CMS
LHCb , Alice

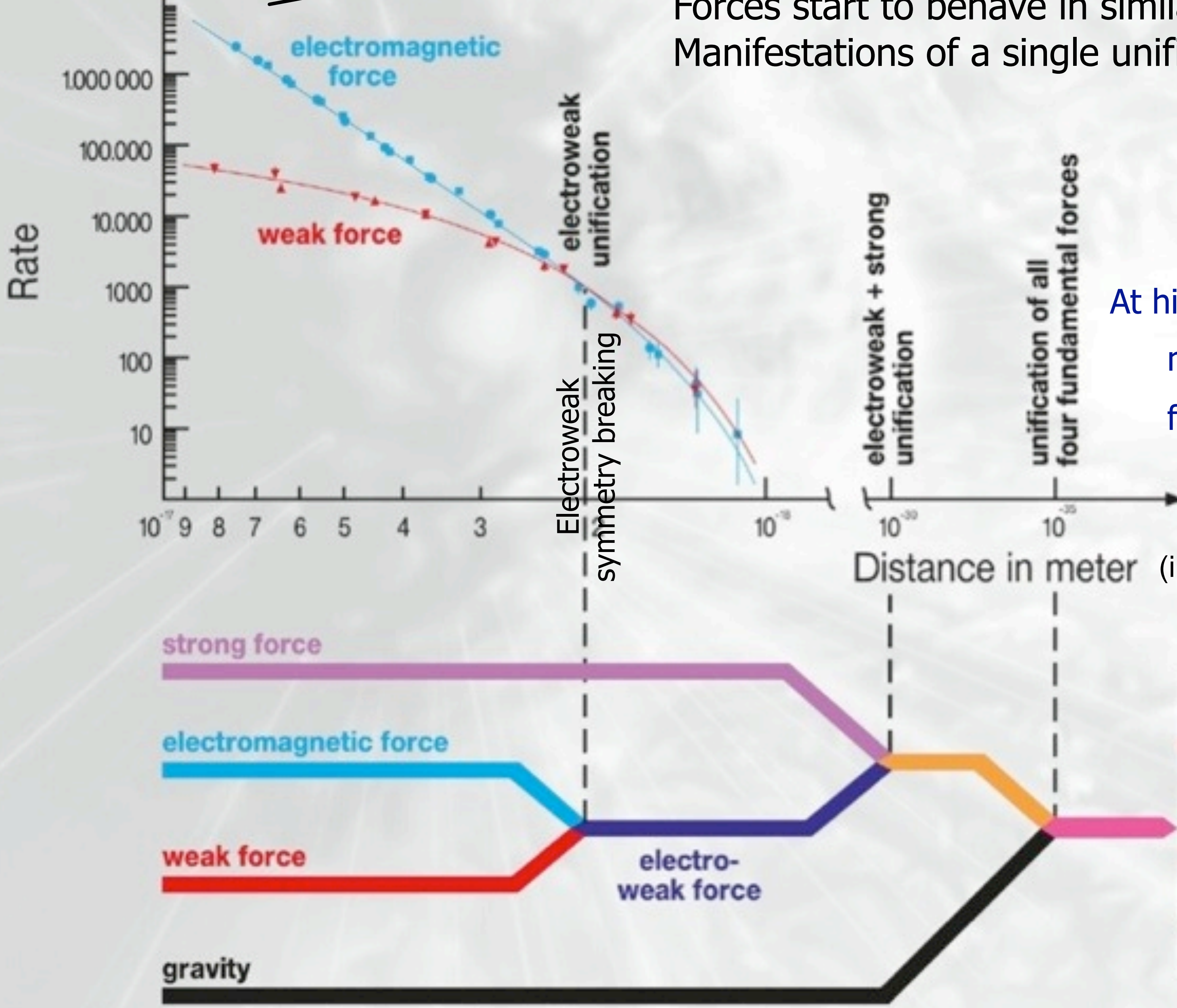
Operating temperature: -271°C One of the coldest places in universe
High energy collisions equivalent to temperatures 100,000 times hotter than sun's core
High vacuum needed to avoid unwanted collisions with air molecules - less dense than solar system
1200 dipole magnets to bend the protons
Protons circulate 11,000 times per second
Generates up to 600 million collisions per second
LHC costs for material, construction, personnel (excluding experiments) = € 3, 000 , 000 , 000

electron - proton scattering



Higher energy → probing particle interactions closer to the big bang

Forces start to behave in similar ways
Manifestations of a single unified high energy force



At high energy /momentum(Q):

masses M_W & M_Z are small

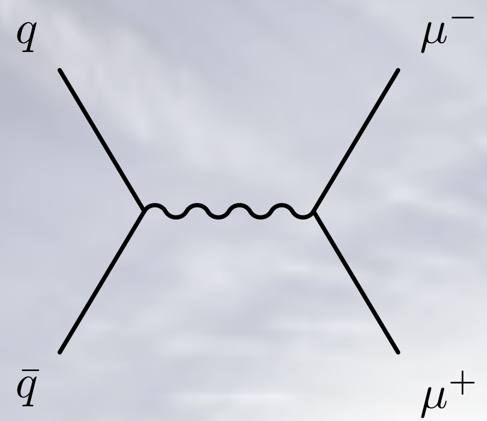
forces are ~ equal

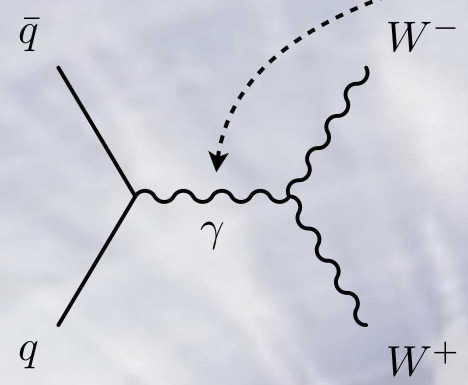
big bang

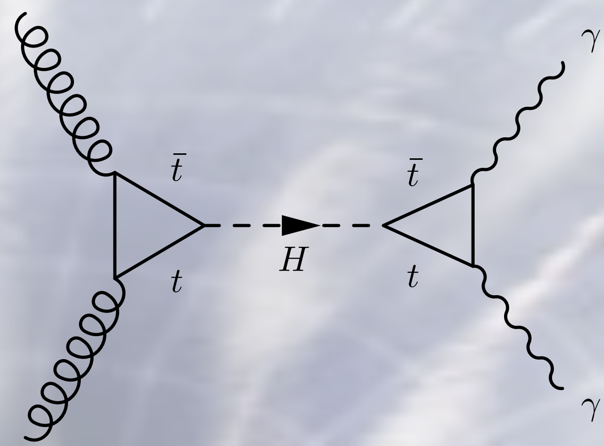
The Large Hadron Collider

Examples processes at LHC

4-momentum transfer² = Q^2 = M^2







$$q\bar{q} \to \mu^+\mu^-$$

$$q\bar{q} \to W^+W^-$$

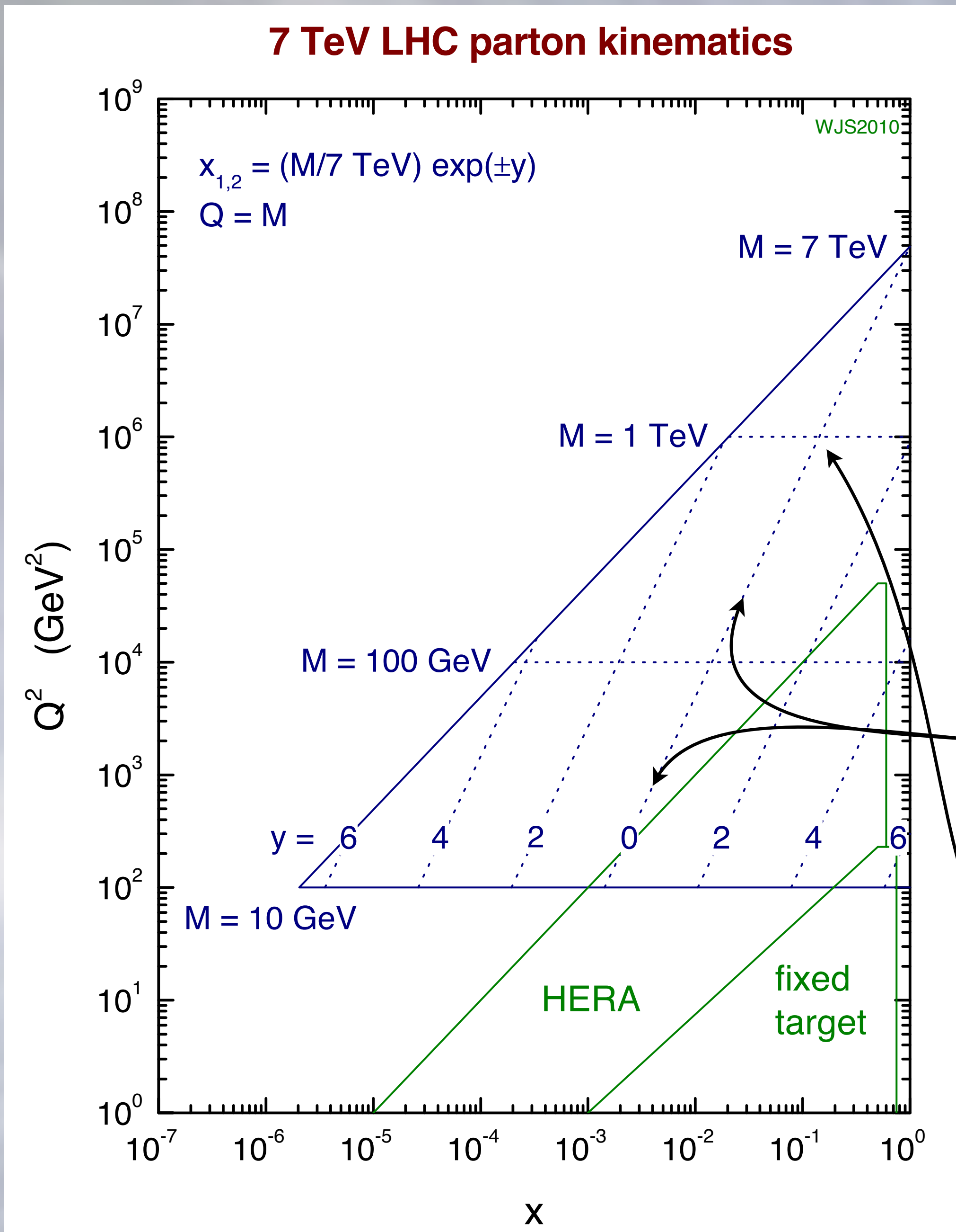
$$gg \to H \to \gamma\gamma$$

Incoming partons carry momentum fraction x

Reaction rates depend on flux of incoming partons
⇒ need a “map” of parton densities in proton

PDFs = parton density functions

LHC Kinematics



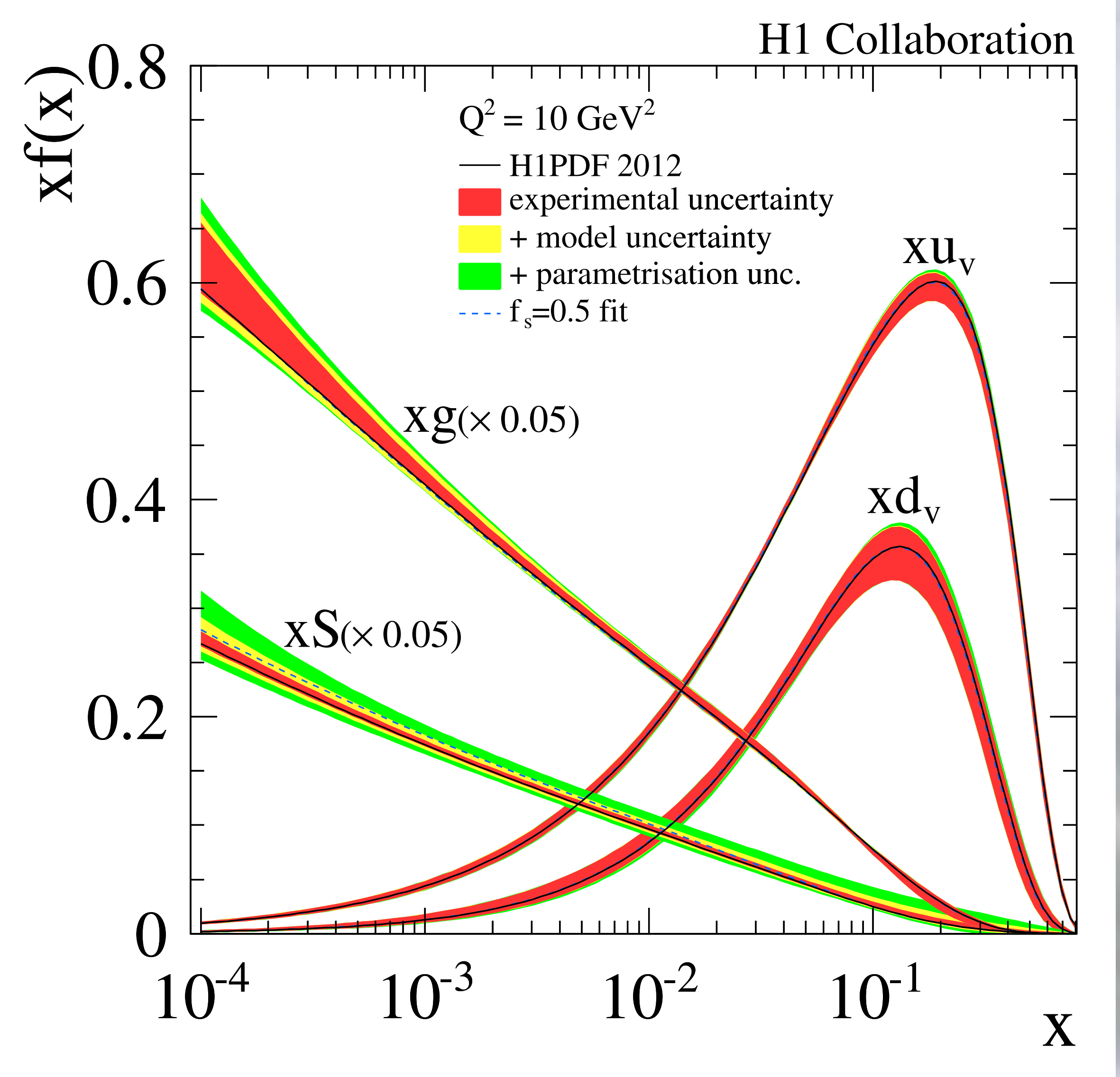
Kinematic plane for the LHC

LHC is a parton (= quark / gluon) collider
Each parton has momentum fraction x_1 and x_2 from either proton

$$x_{1,2} = \frac{M}{\sqrt{s}}\, e^{\pm y}$$

M = mass of any new particle / state
y = relates to polar production angle
y = 0 means particle produced at rest
$\sqrt{s}$ = LHC centre of mass energy

A new particle of M=1 TeV is produced centrally in detector (y=0) when $x_1 = x_2 = 10^{-1}$



Measure parton densities in *ep* collisions

Relies on precision measurements precision QCD calculations

At high x the densities fall rapidly
$\Rightarrow$ high mass states have low production cross section

What are we looking for ?

e+e e+μ e+μ+2b+2ν e+2μ+ν μ+j+ν μ+μ

e+j e+μ+j e+2τ+2b+3ν

2e+3j 3e+3ν+j 2μ+2τ+j 2μ+2b

e+τ+2j e+2τ+ν+j μ+τ+2b 2μ+2j+2ν

τ+τ

e+2j+ν 2e+τ+2ν+2j 2τ+2b 2τ+2j+ν 2b+4j

γ+e+ν γ+μ+ν+2j γ+τ+ν e+μ+τ+3ν 4j+ν 2b+2ν

γ+γ γ+c+ν γ+2e+ν γ+b+2j 2b+2j

γ+ν 2γ+2j 2γ+2μ+3j j+j j+ν

What are we looking for ?

Higgs boson
spin-2 gravitons G
$\tilde{l}^{\pm}$
χ_1^0
e+e
e+μ
e+μ+2b+2ν
e+2μ+ν
μ+μ
μ+j+ν
Axigluon
e+j
e+μ+j
e+2τ+2b+3ν
b'
$\tilde{g}$
2μ+2b
2e+3j
t'
3e+3ν+j
$\tilde{\tau}$
2μ+2τ+j
$\tilde{t}_1$
W'
e+τ+2j
e+2τ+ν+j
μ+τ+2b
2μ+2j+2ν
KK particle
τ+τ
Z'
q^*
$\tilde{q}$
e+2j+ν
2e+τ+2ν+2j
2τ+2b
2τ+2j+ν
LQ
2b+4j
$\overline{LQ}$
e+μ+τ+3ν
CMLLPs
2b+2ν
γ+e+ν
γ+μ+ν+2j
γ+τ+ν
SUSY
4j+ν
R-hadrons
γ+2e+ν
2b+2j
$\chi_1^{\pm}$
γ+γ
$\tilde{\nu}$
γ+c+ν
Coloron
γ+b+2j
j+ν
γ+ν
E_6 diquark
2γ+2j
2γ+2μ+3j
j+j
E_6 GUT model

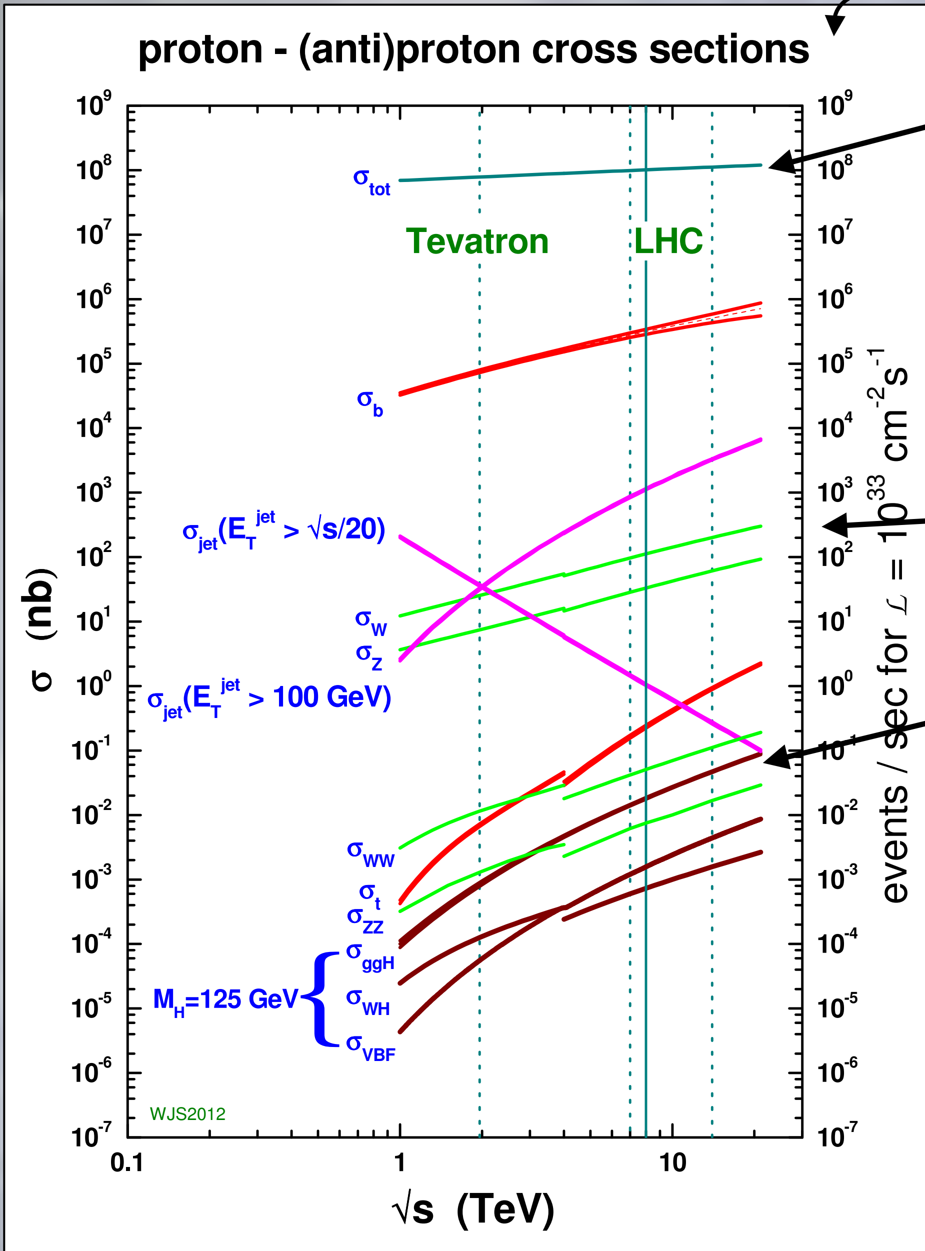
Zombies at the LHC!

H2ZZ PRODUCTIONS PRESENTS "DECAY" ZOË HATHERELL, TOM PROCTER, STEWART MARTIN-HAUGH, SARA MAHMOUD AND WILLIAM P.MARTIN ORIGINAL MUSIC BY TOM MCLAUGHLAN MAKE UP ARTIST ROB CANTRILL EDITED BY BURTON DEWILDE VISUAL EFFECTS BY LUKE THOMPSON PRODUCTION DESIGNER JOHANNES EBKE DIRECTOR OF PHOTOGRAPHY BURTON DEWILDE 1st ASSISTANT CAMERA JOSEPH MCCARTIN STUNT/FIGHT COORDINATOR HUGO DAY ASSISTANT DIRECTOR CLARA NELLIST LINE PRODUCER ELLIE DAVIES CO-DIRECTED BY MICHAEL MAZUR PRODUCED BY MICHAEL MAZUR, LUKE THOMPSON AND BURTON DEWILDE WRITTEN AND DIRECTED BY LUKE THOMPSON

The LHC

σ = reaction rate

current LHC
operating energy



Number of events (i.e. collisions) per second

Total rate of data produced by LHC: 100,000,000 events/s

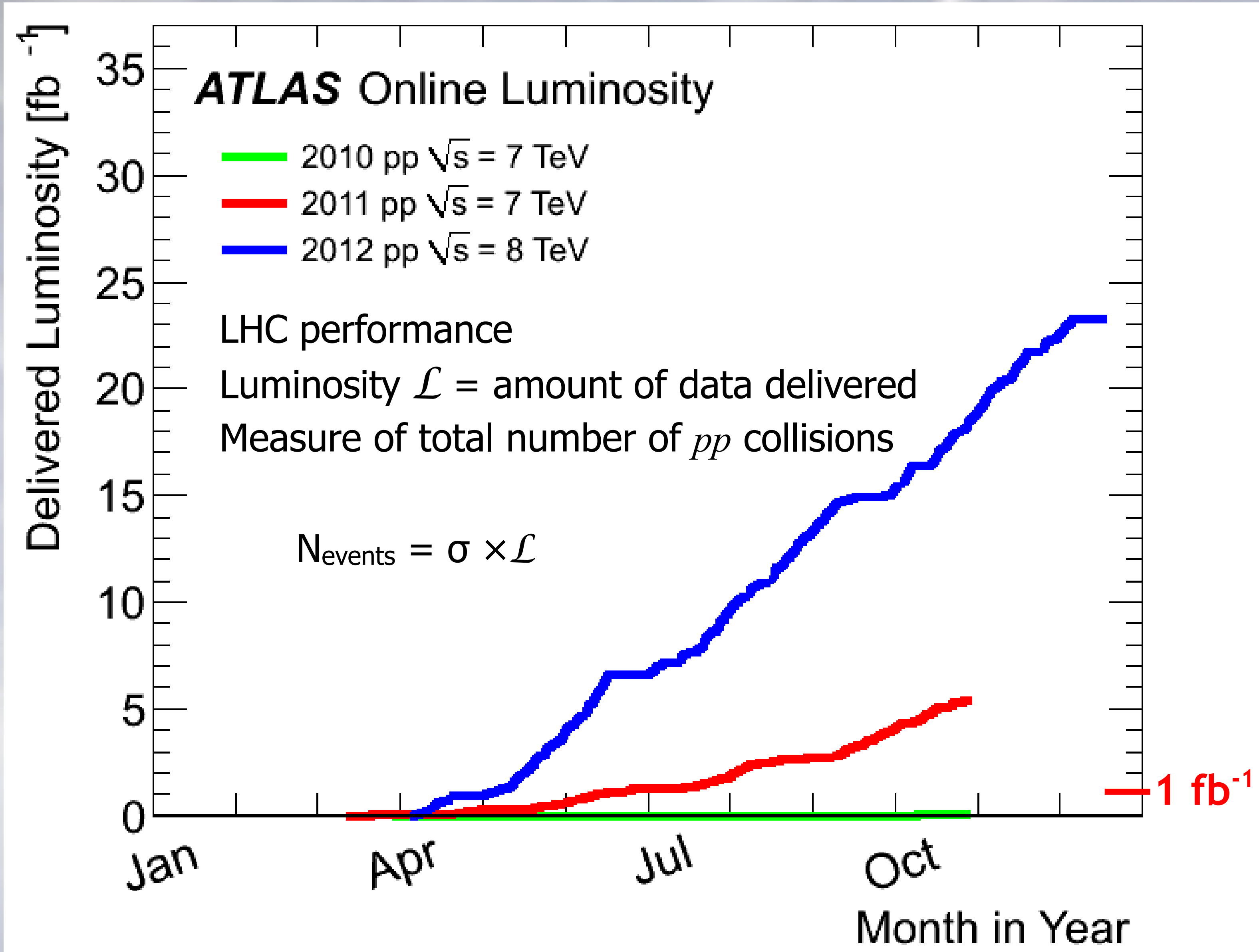
Huge event rates
New physics swamped!
Need to filter events 1:10^7 online

Maximum recording rate of ATLAS experiment
200 events/second

Production rate of 125 GeV Higgs: 0.01 events/second

Like trying to find cheapest plumber
from entire human population in 2 μs

Particle physicists measure reaction rates
in units of barn: 1b = 10^{-28} m^2


ATLAS Online Luminosity
2010 pp √s = 7 TeV
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
LHC performance
Luminosity $\mathcal{L}$ = amount of data delivered
Measure of total number of pp collisions
$N_{events} = \sigma \times \mathcal{L}$
Delivered Luminosity [fb^{-1}]
35
30
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Month in Year
1 fb^{-1}

ATLAS Collaboration

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- Armenia
- Australia
- Austria
- Azerbaijan
- Belarus
- Brazil
- Canada
- Chile
- China
- Colombia
- Czech Republic
- Denmark
- France
- Georgia
- Germany
- Greece
- Israel
- Italy
- Japan
- Morocco
- Netherlands
- Norway
- Poland
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- Romania
- Russia
- Serbia
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- Slovenia
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- Spain
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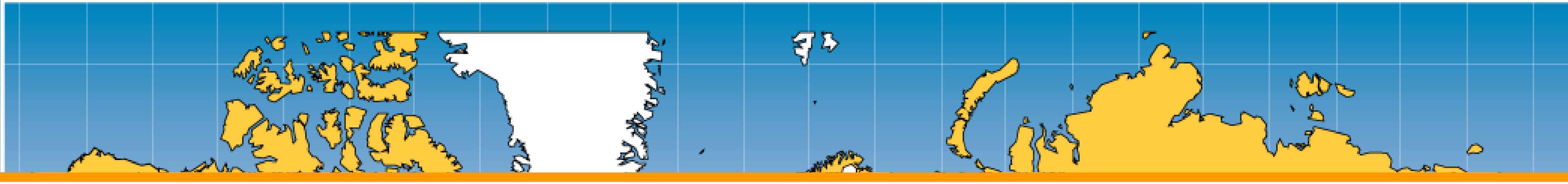

Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, **Birmingham**, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brazil Cluster, Brookhaven NL, Buenos Aires, Bucharest, **Cambridge**, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, **Edinburgh**, Frascati, Freiburg, Geneva, Genoa, Giessen, **Glasgow**, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, **Lancaster**, UN La Plata, Lecce, Lisbon LIP, **Liverpool**, Ljubljana, **QM London**, **RH London**, **UC London**, Lund, UA Madrid, Mainz, **Manchester**, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois University, BINP Novosibirsk, NPI Petersburg, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, **Oxford**, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, **RAL-STFC**, DAPNIA Saclay, Santa Cruz UC, **Sheffield**, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa Cluster, Stockholm, KTH Stockholm, Stony Brook, Sydney, **Sussex**, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, **Warwick**, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

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Georgia	Taiwan
Germany	Turkey
Greece	UK
Israel	USA
Italy	CERN
Japan	JINR

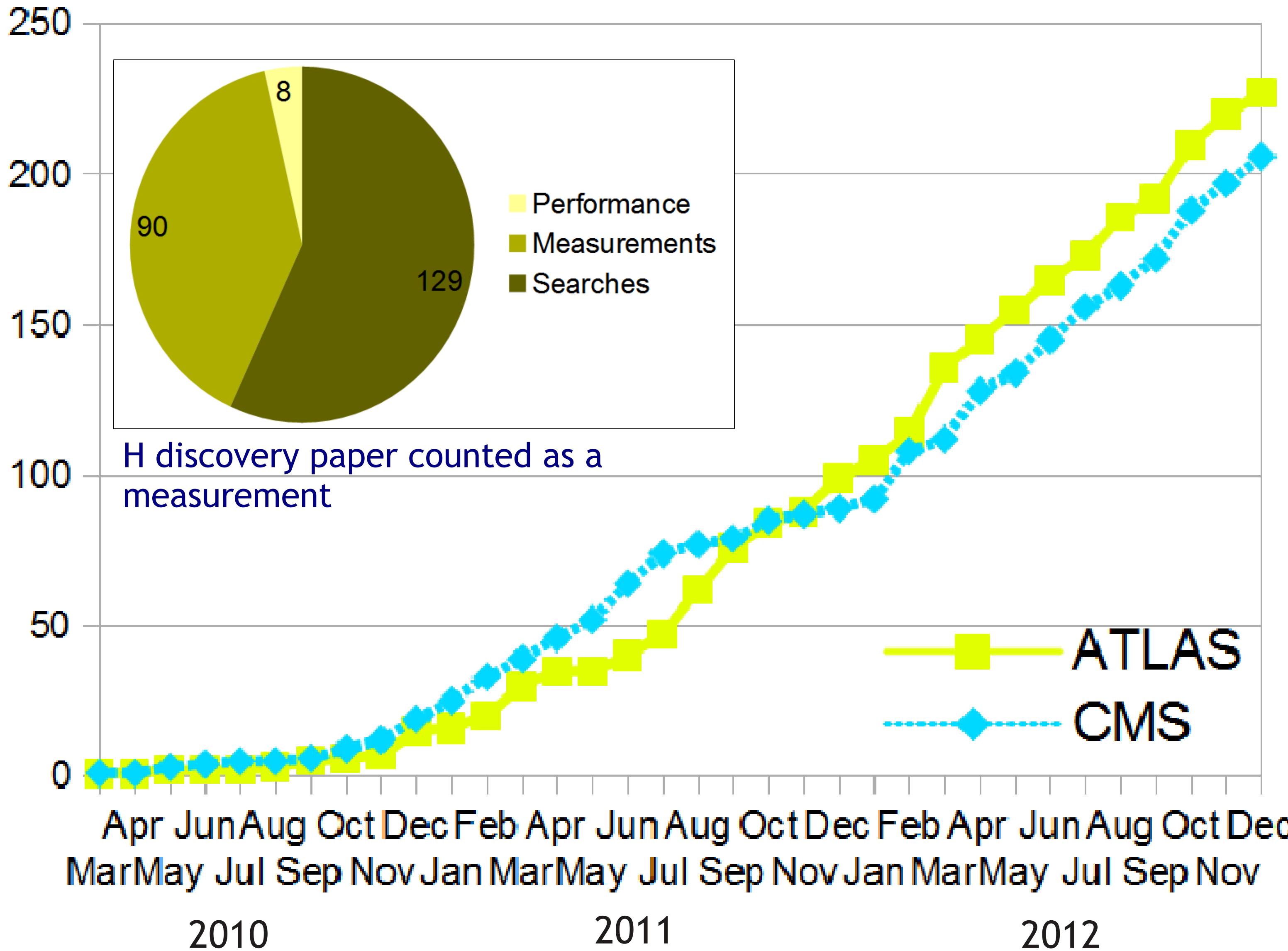
ATLAS Collaboration

2900 physicists
174 universities
38 countries

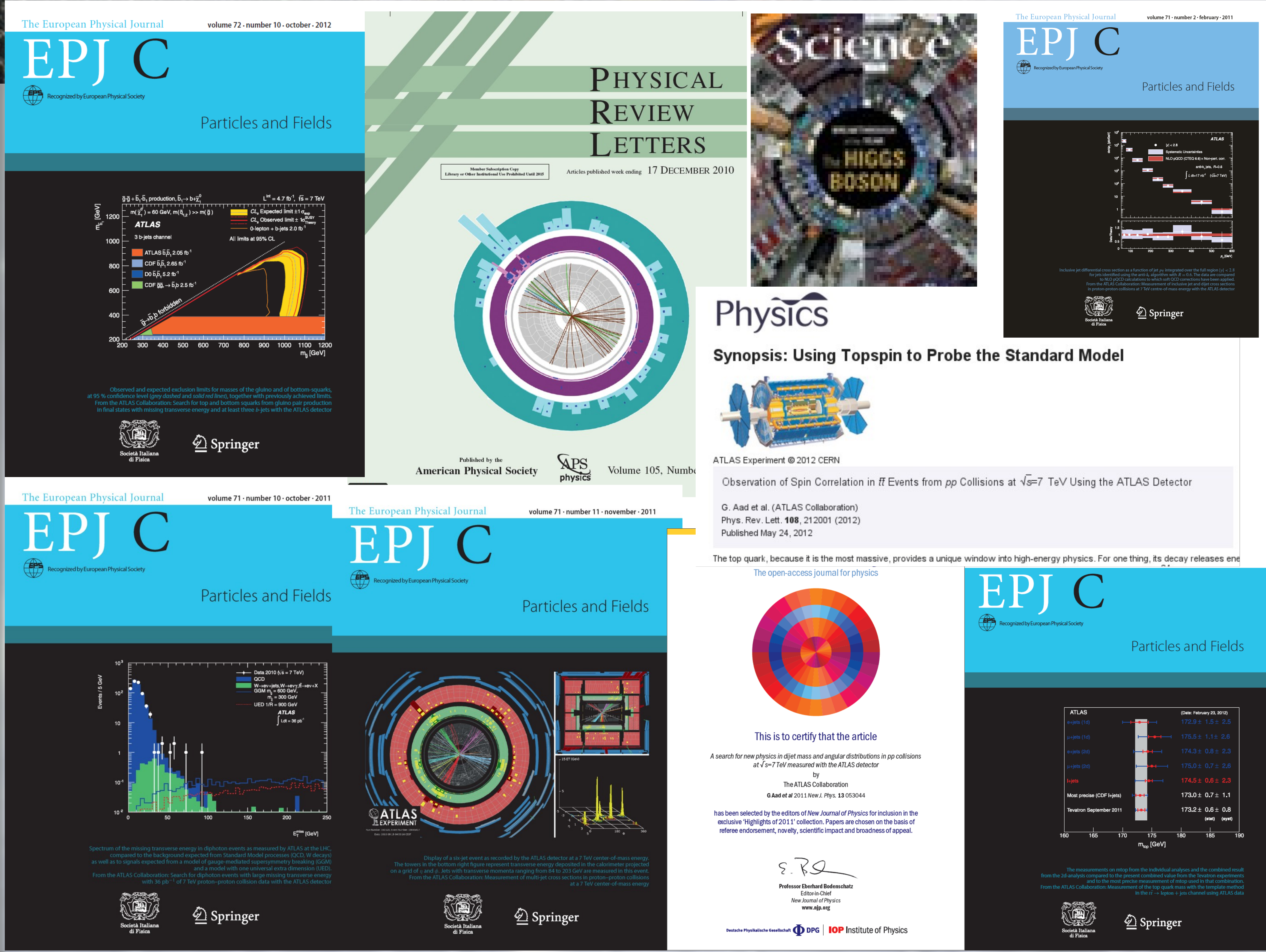
July 2010

Publications

Sustained output of papers ~10 / month



H discovery paper counted as a measurement



The European Physical Journal
volume 72 · number 10 · october · 2012
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Particles and Fields
ATLAS
3 b-jets channel
All limits at 95% CL
Observed and expected exclusion limits for masses of the gluino and of bottom-squarks, at 95 % confidence level (grey dashed and solid red lines), together with previously achieved limits. From the ATLAS Collaboration: Search for top and bottom squarks from gluino pair production in final states with missing transverse energy and at least three b-jets with the ATLAS detector
Società Italiana di Fisica
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Published by the American Physical Society
APS physics
Volume 105, Numb
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The European Physical Journal
volume 71 · number 2 · february · 2011
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ATLAS
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Physics
Synopsis: Using Topspin to Probe the Standard Model
ATLAS Experiment © 2012 CERN
Observation of Spin Correlation in $t\bar{t}$ Events from pp Collisions at $\sqrt{s}$=7 TeV Using the ATLAS Detector
G. Aad et al. (ATLAS Collaboration)
Phys. Rev. Lett. 108, 212001 (2012)
Published May 24, 2012
The top quark, because it is the most massive, provides a unique window into high-energy physics. For one thing, its decay releases ene
The European Physical Journal
volume 71 · number 10 · october · 2011
EPJ C
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Particles and Fields
ATLAS
Spectrum of the missing transverse energy in diphoton events as measured by ATLAS at the LHC, compared to the background expected from Standard Model processes (QCD, W decays) as well as to signals expected from a model of gauge-mediated supersymmetry breaking (GGM) and a model with one universal extra dimension (UED). From the ATLAS Collaboration: Search for diphoton events with large missing transverse energy with 36 pb⁻¹ of 7 TeV proton–proton collision data with the ATLAS detector
Società Italiana di Fisica
Springer
The European Physical Journal
volume 71 · number 11 · november · 2011
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Particles and Fields
ATLAS EXPERIMENT
Display of a six-jet event as recorded by the ATLAS detector at a 7 TeV center-of-mass energy. The towers in the bottom right figure represent transverse energy deposited in the calorimeter projected on a grid of η and φ. Jets with transverse momenta ranging from 84 to 203 GeV are measured in this event. From the ATLAS Collaboration: Measurement of multi-jet cross sections in proton–proton collisions at a 7 TeV center-of-mass energy
Società Italiana di Fisica
Springer
The open-access journal for physics
This is to certify that the article
A search for new physics in dijet mass and angular distributions in pp collisions at √s=7 TeV measured with the ATLAS detector
by
The ATLAS Collaboration
G Aad et al 2011 New J. Phys. 13 053044
has been selected by the editors of New Journal of Physics for inclusion in the exclusive 'Highlights of 2011' collection. Papers are chosen on the basis of referee endorsement, novelty, scientific impact and broadness of appeal.
Professor Eberhard Bodenschatz
Editor-in-Chief
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Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
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Particles and Fields
ATLAS
(Date: February 23, 2012)
Most precise (CDF l+jets)
Tevatron September 2011
Società Italiana di Fisica
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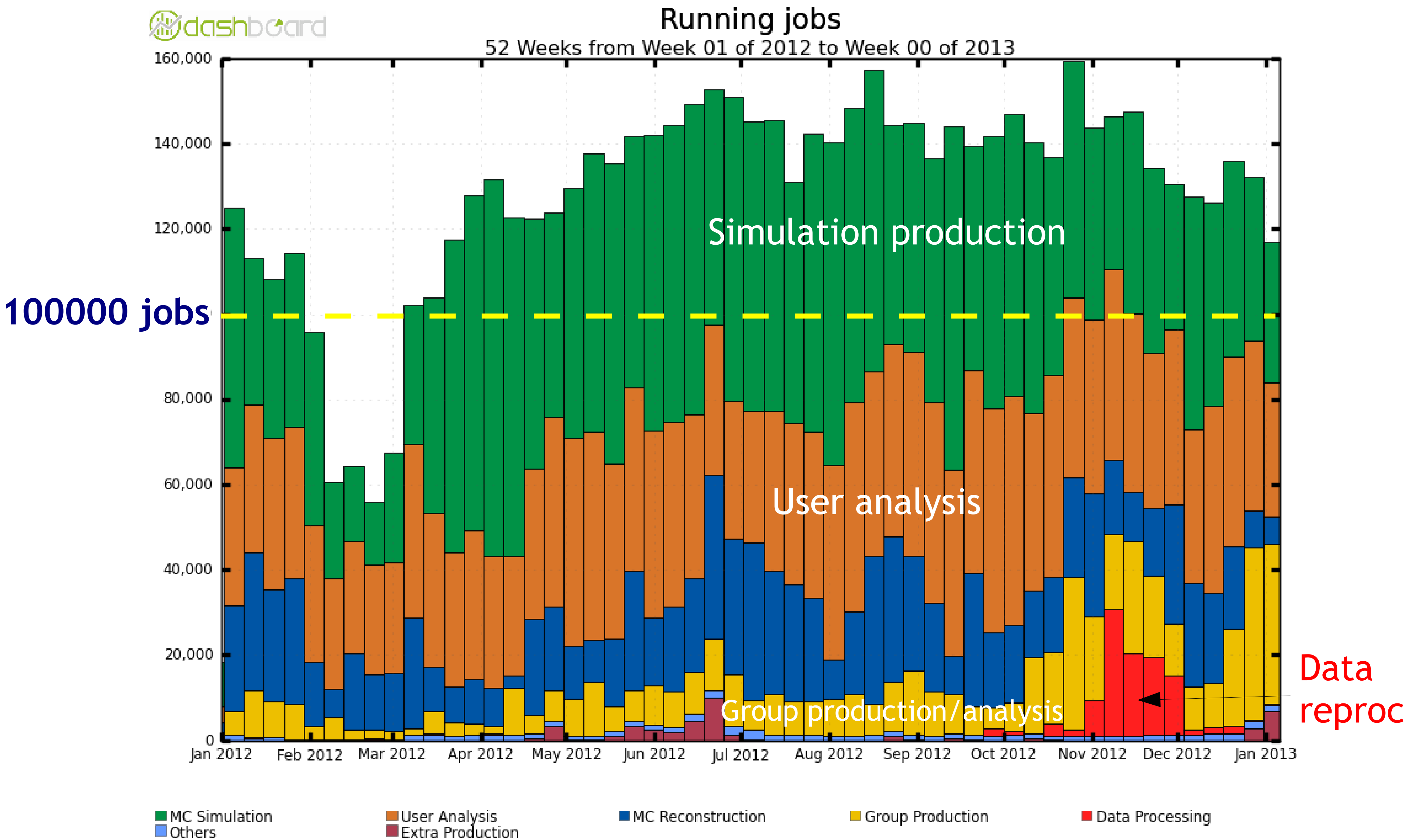
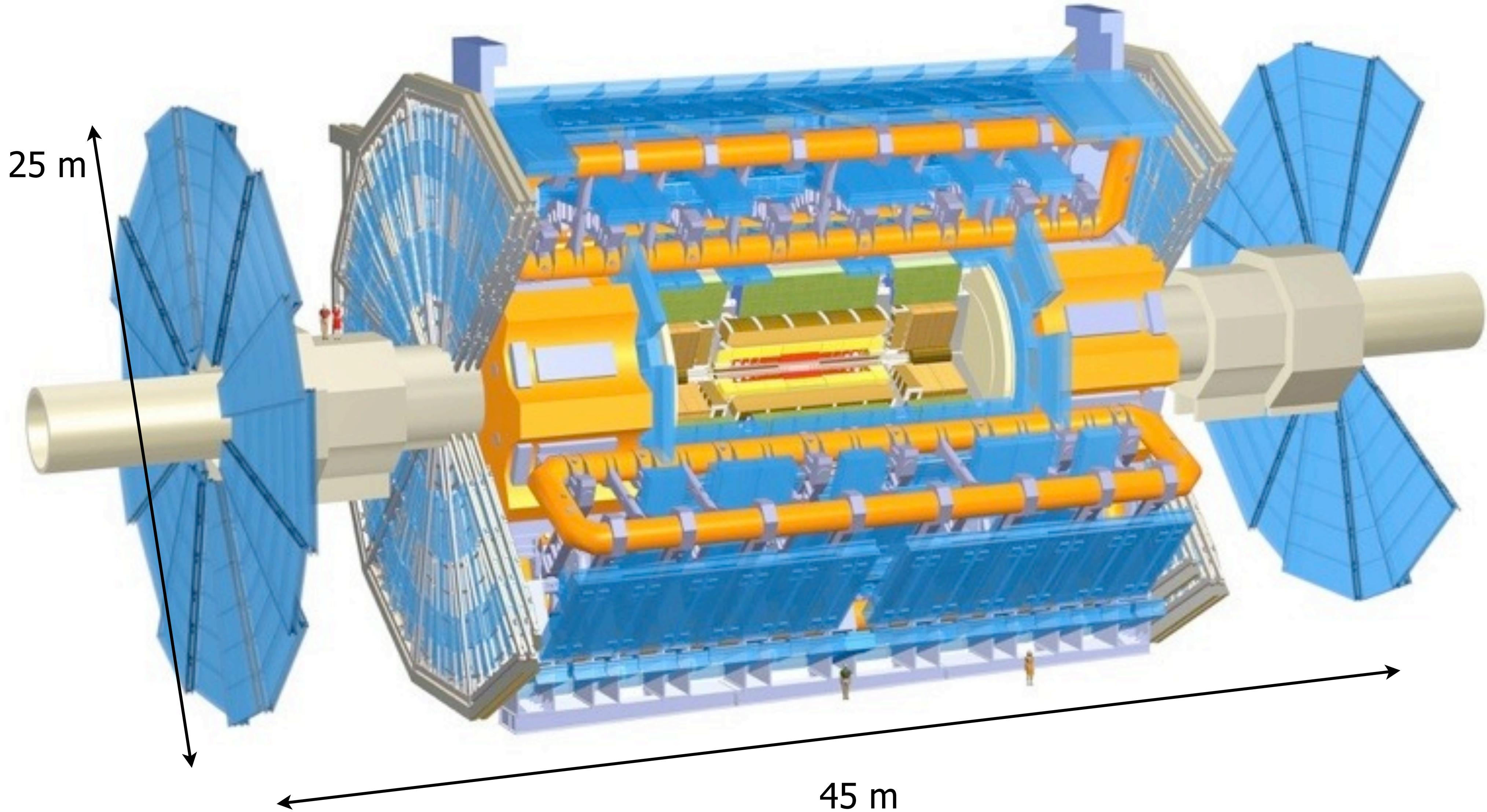
The power of the WLCG

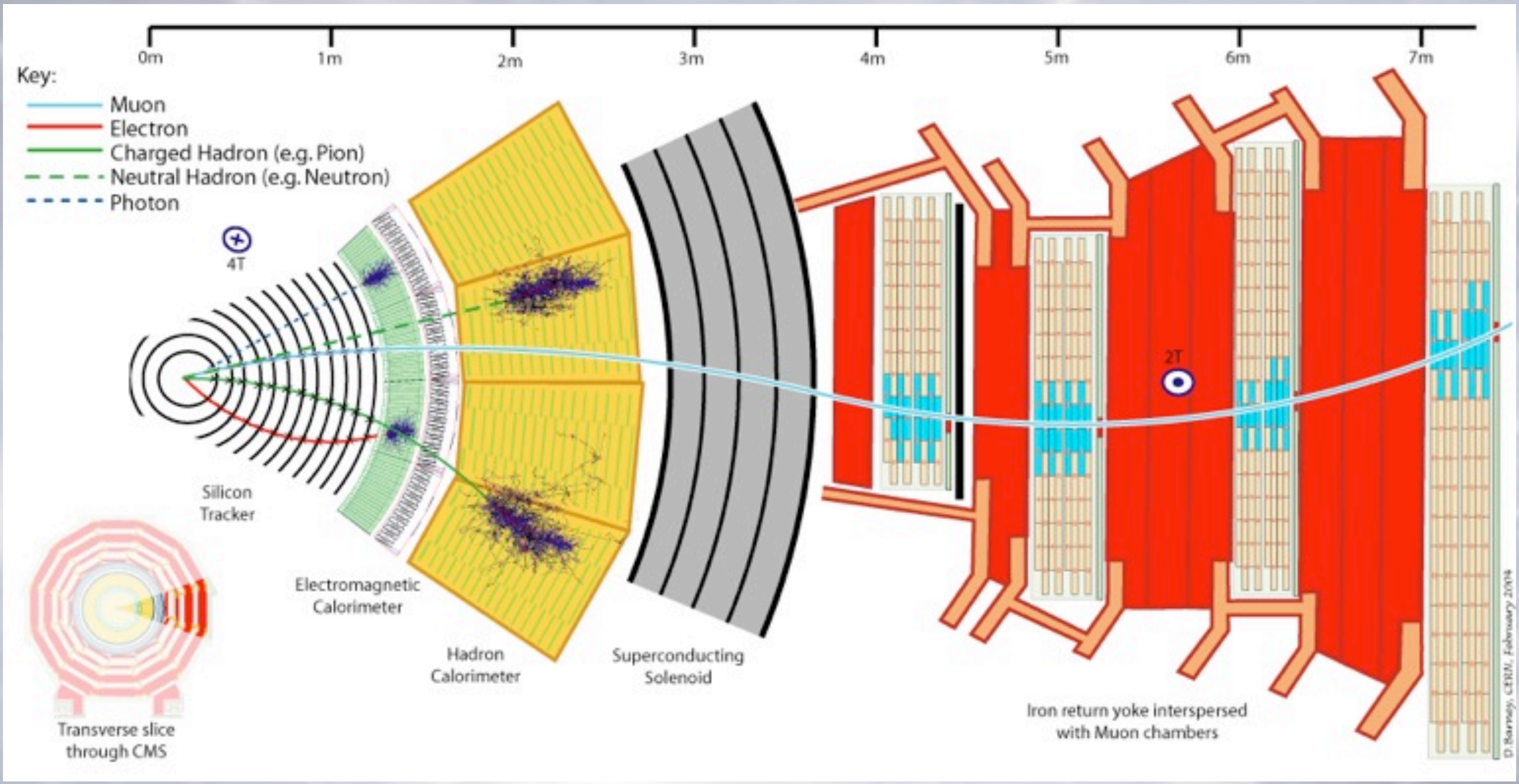


The ATLAS experiment

7000 tonnes
Mass of the Eiffel Tower
Half the size of Notre Dame
data rate: 20,000,000 Gb/s



Large experiments needed to measure outgoing particles from collisions
Experiment consists of layered detectors each sensitive to different types of particle
Look for signatures of particle types



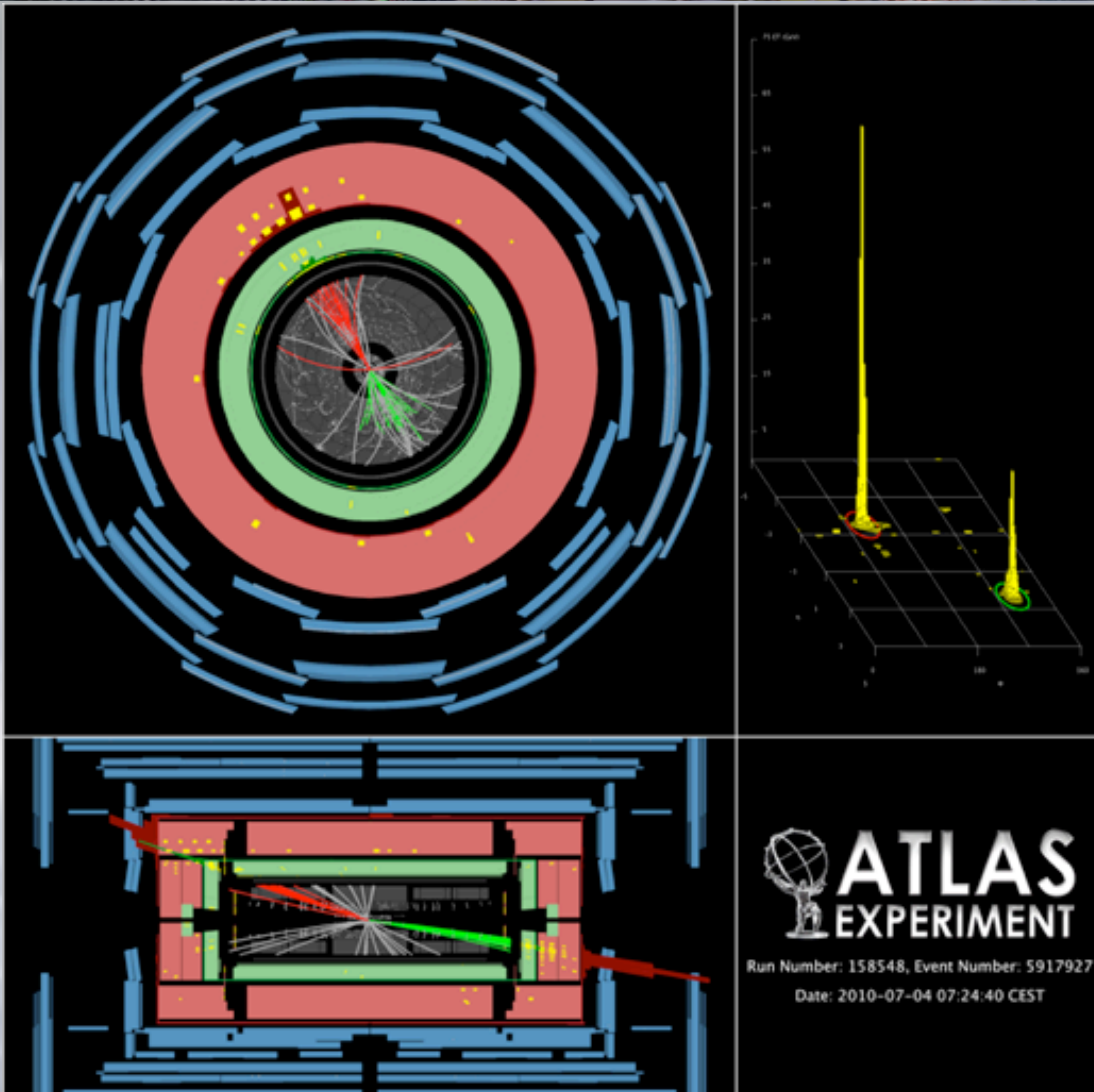
Particle Signatures

Measuring cross-section of a process requires recognising event properties:

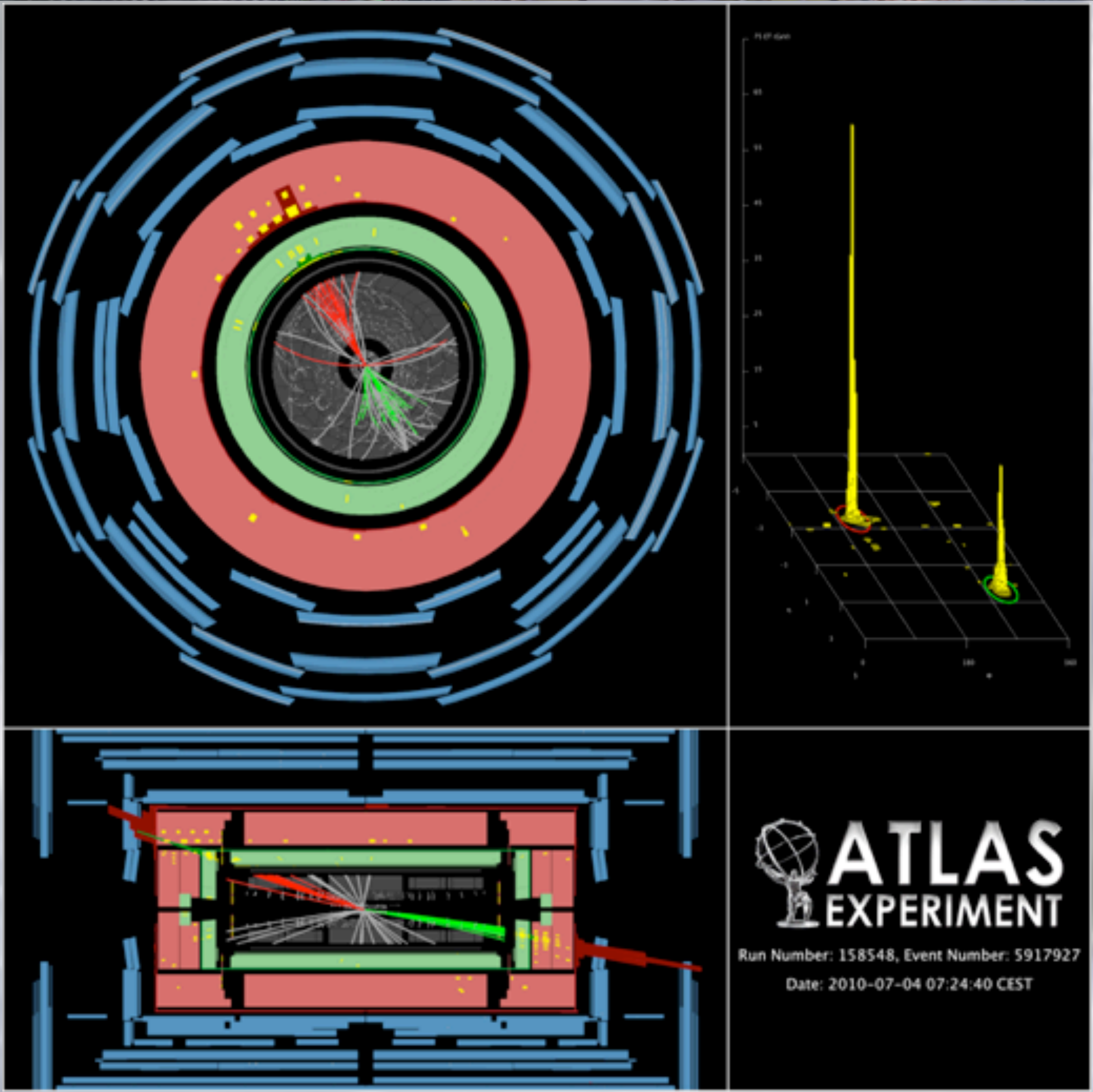
Electromagnetic energy with a charged track	e^+ or e^-
Electromagnetic energy without track	photon
collimated 'jet' of particles	gluon/quark induced jet
penetrating charged track	μ^+ or μ^-
missing transverse energy $\not{E}_T$	ν
missing longitudinal energy	beam remnants
displaced secondary vertex	in-flight decay of 'long lived' particle

Look at the event topology...

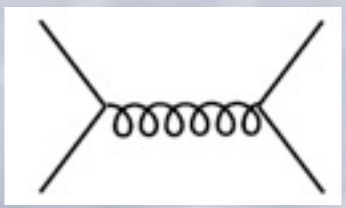
Particle Signatures



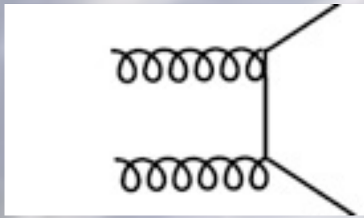
2 jets of particles:
quarks / gluons



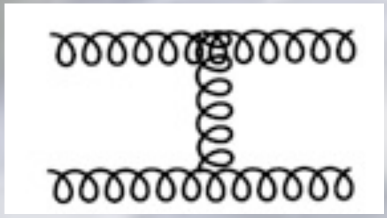
A 'di-jet' event at high energy



or:

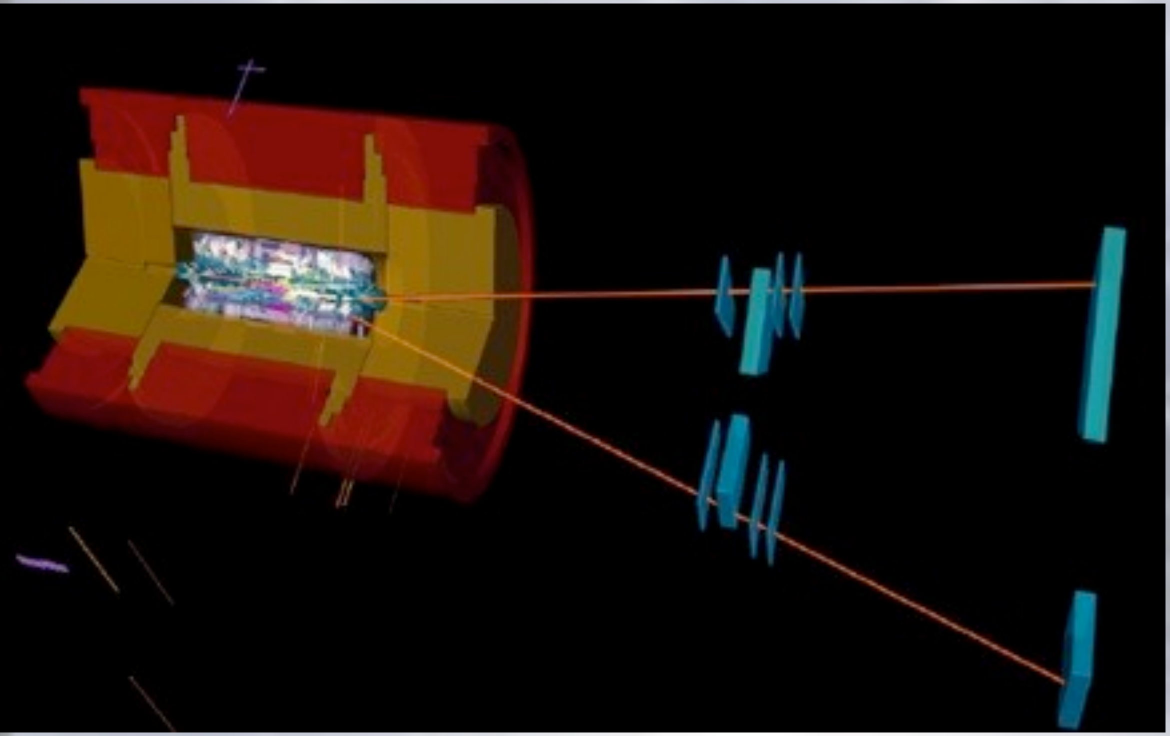


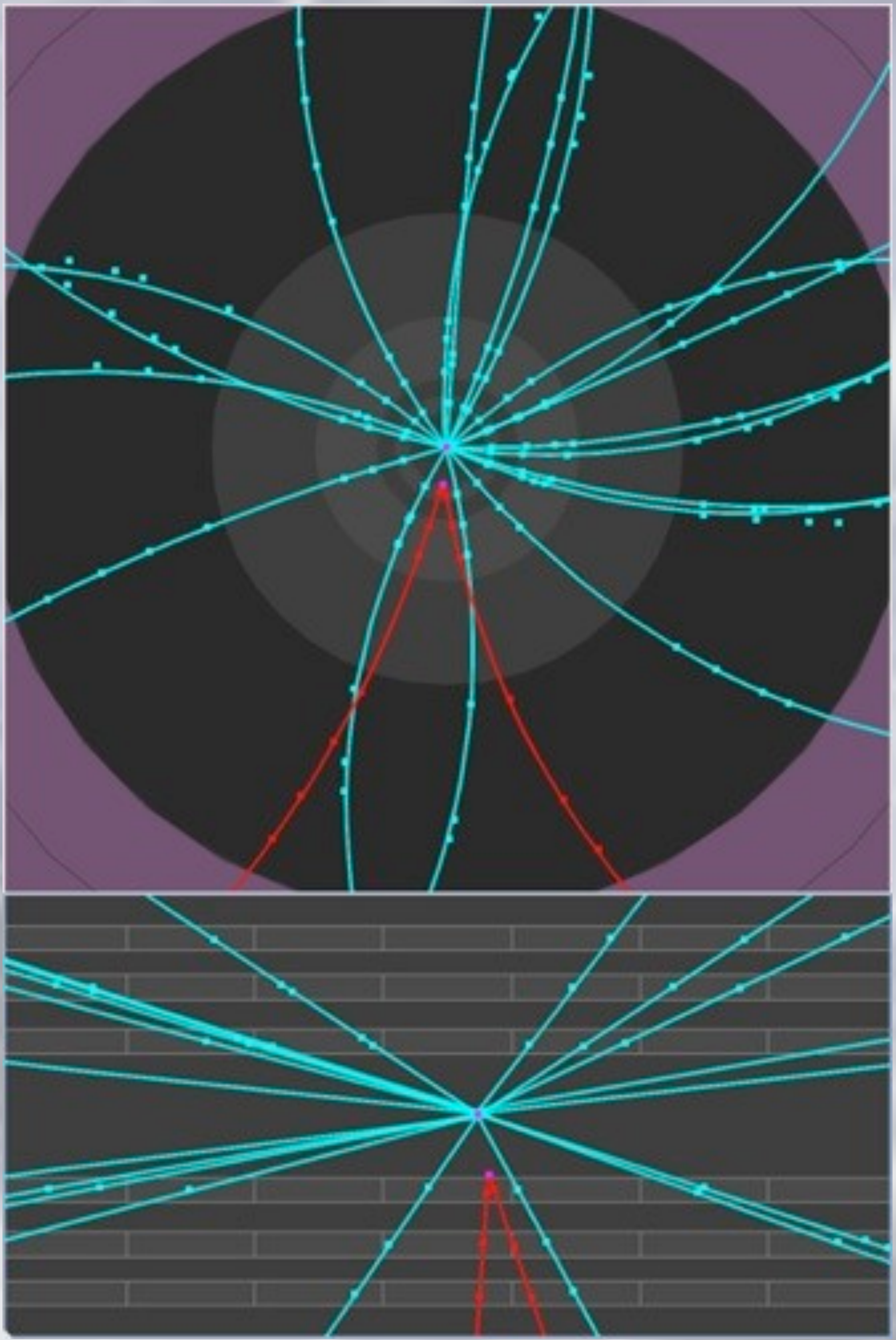
or:



Particle Signatures

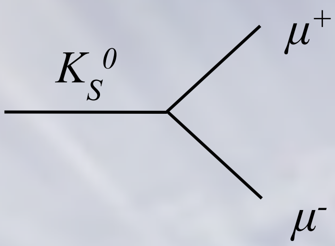
Two penetrating particles
opposite charge

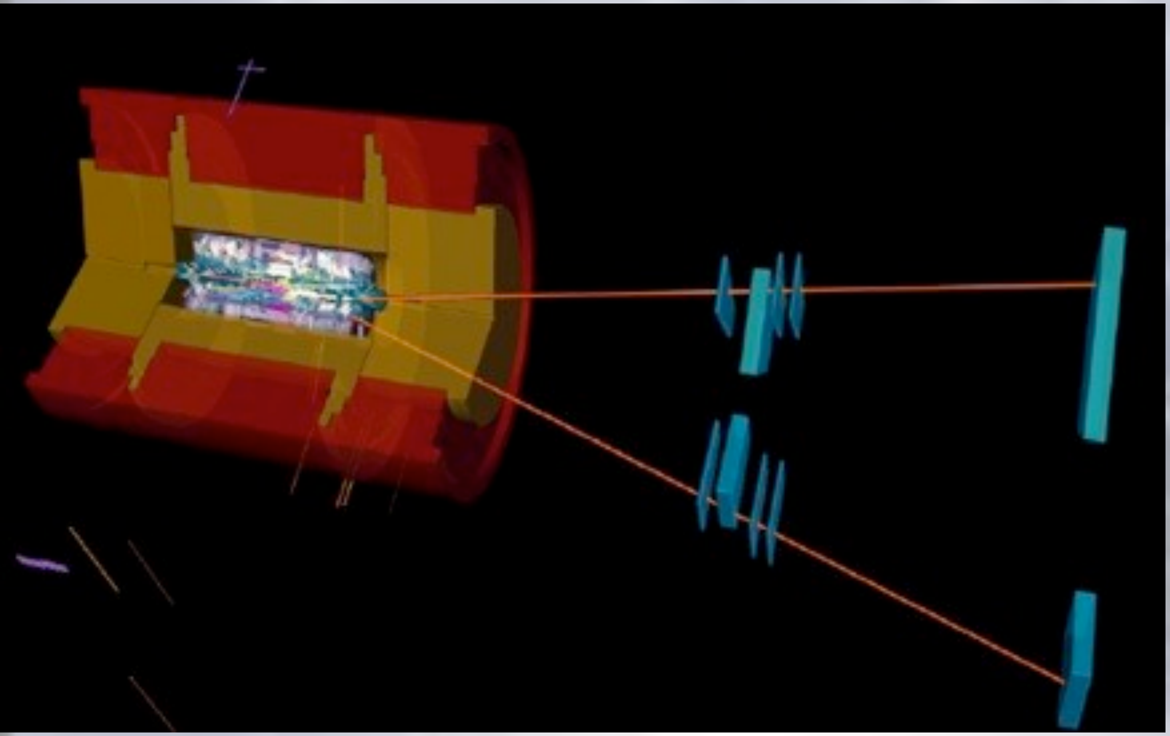


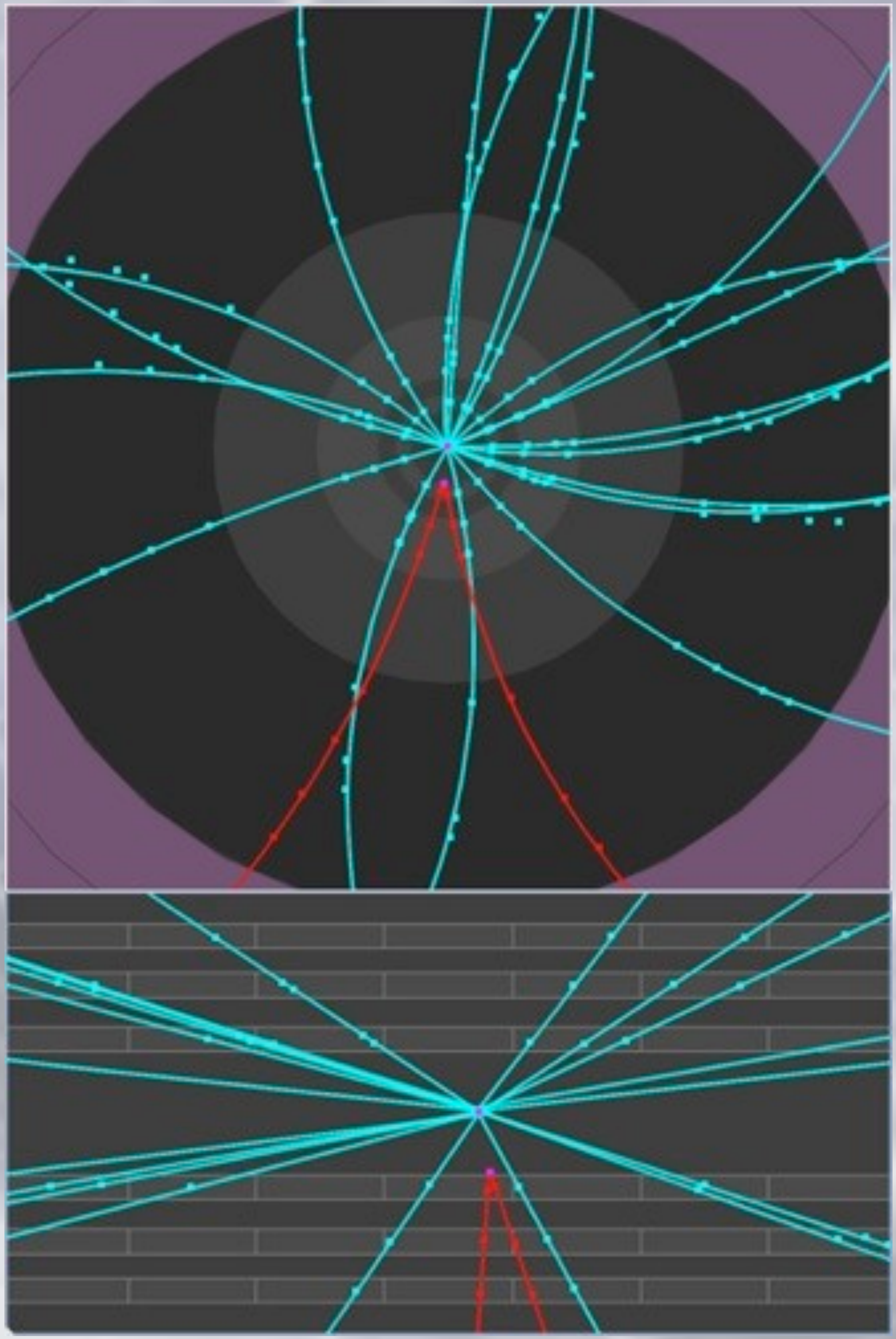


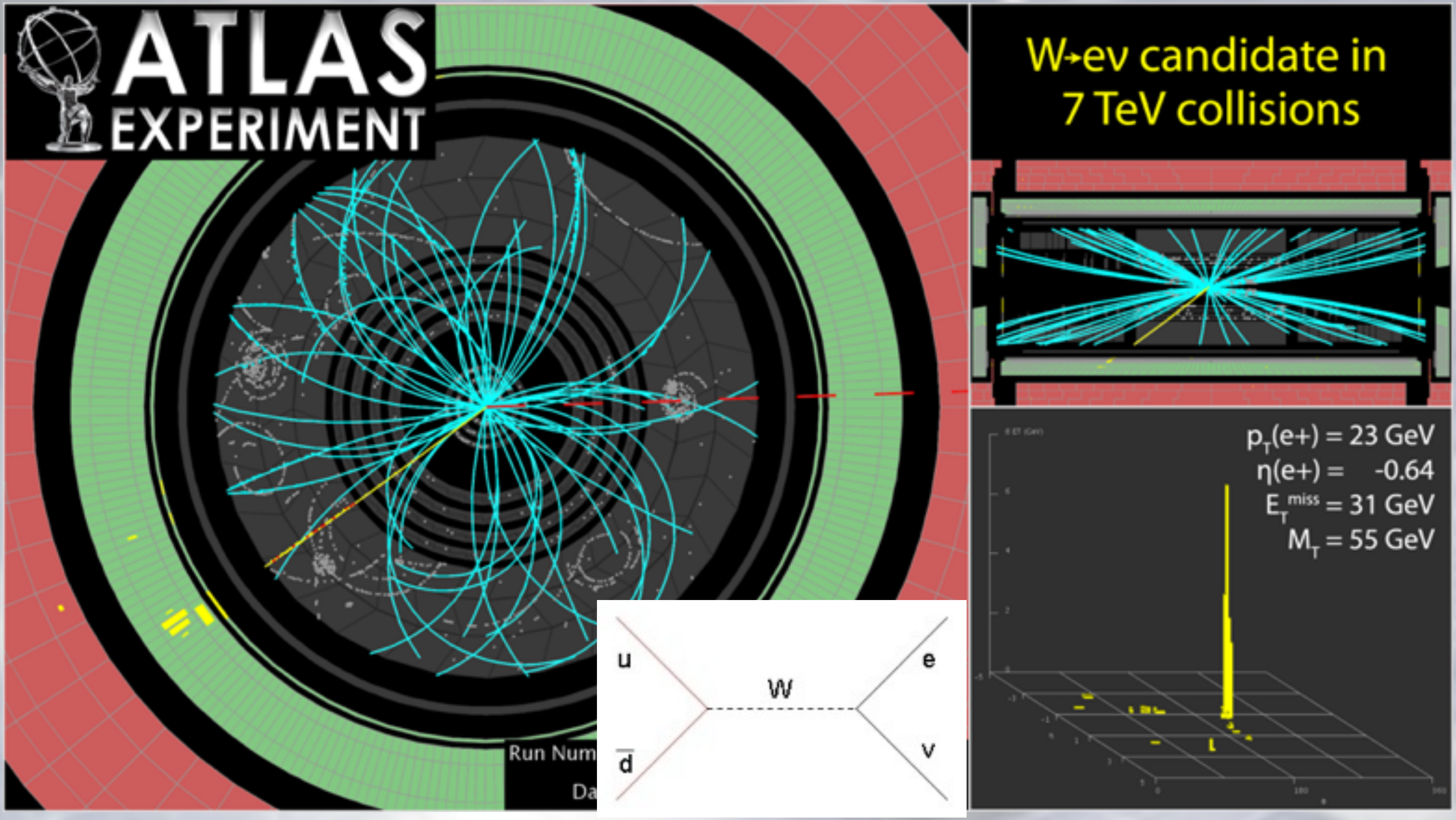
Decay of a long-lived composite particle

- Two oppositely curved tracks
- Penetrating tracks
- Displaced secondary vertex









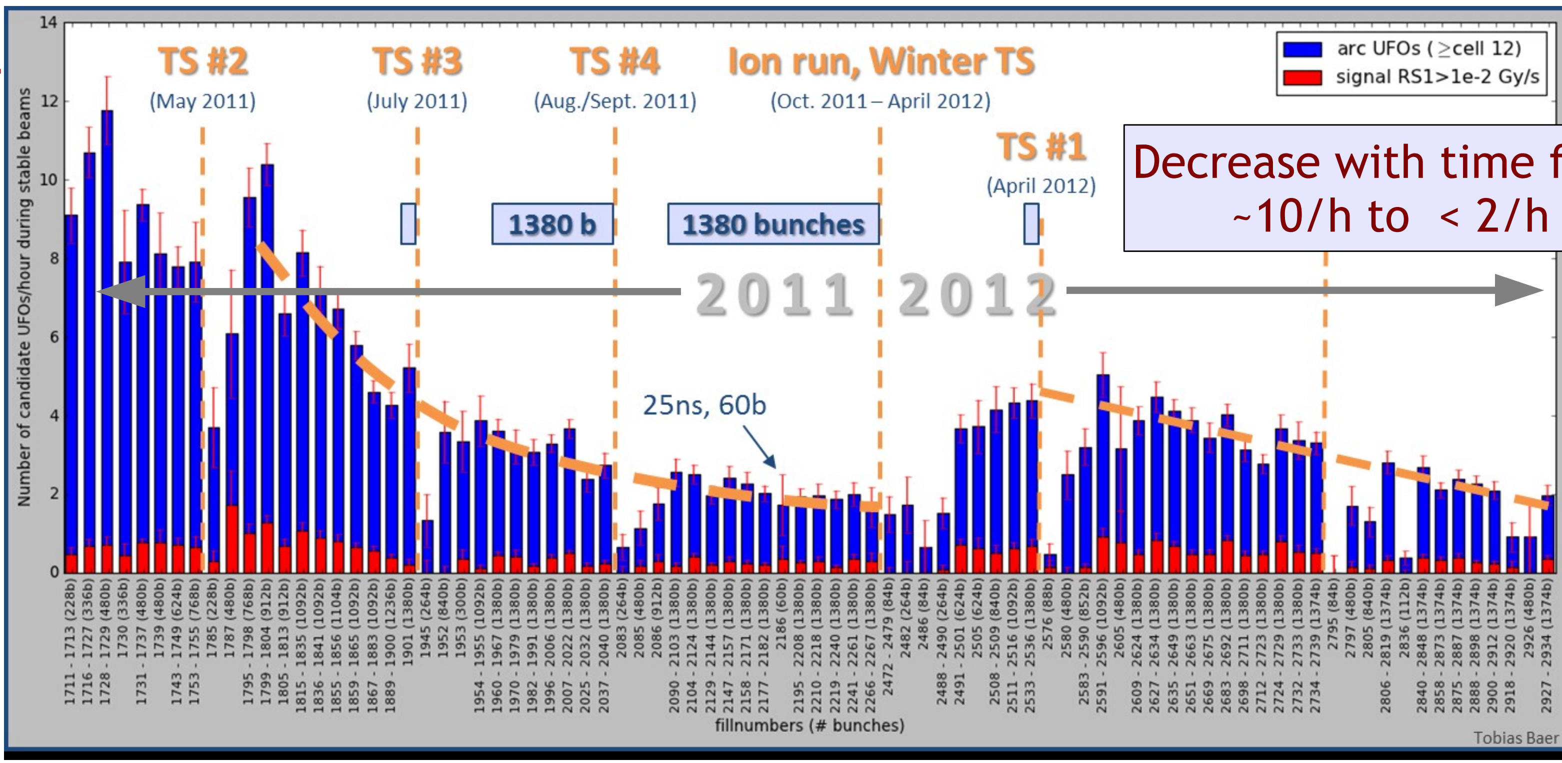
Production and decay of a W boson particle

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.9%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	99.5%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	97.7%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	99.7%

UFOs: unidentified falling objects

Beam losses thought due to dust particles falling into the beam

Candidate UFOs / hour
most don't cause dumps!

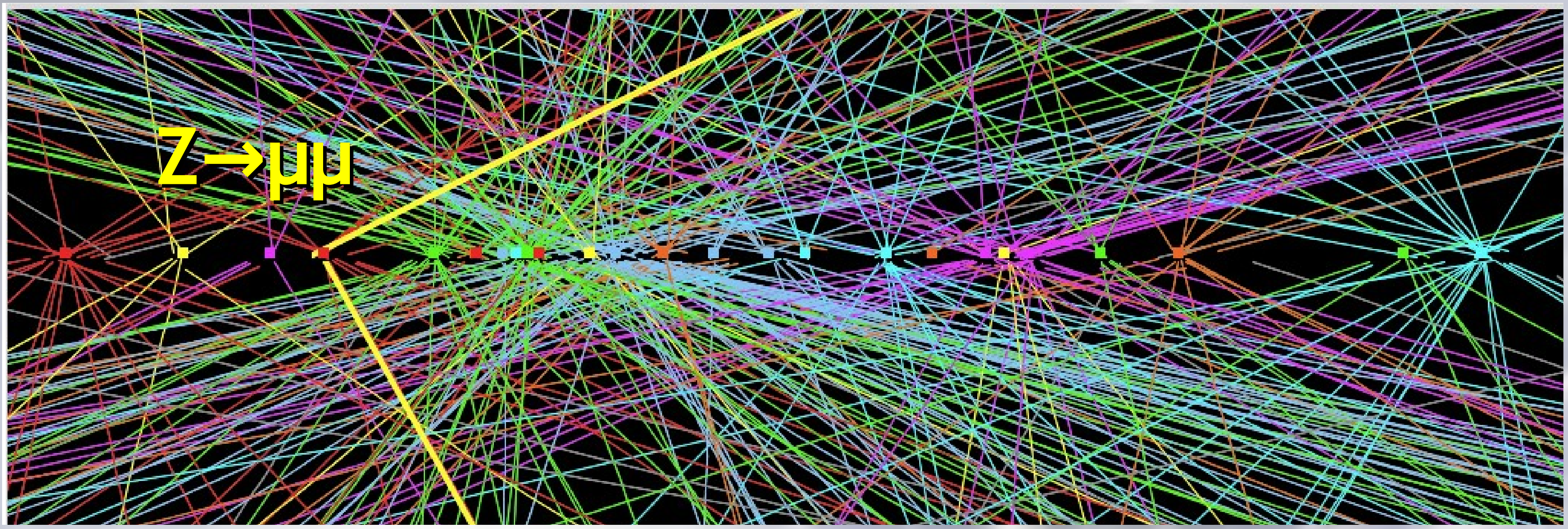


Decrease with time from ~10/h to < 2/h

Not a big problem in 2012 (20 beam dumps, cf 17 in 2011)

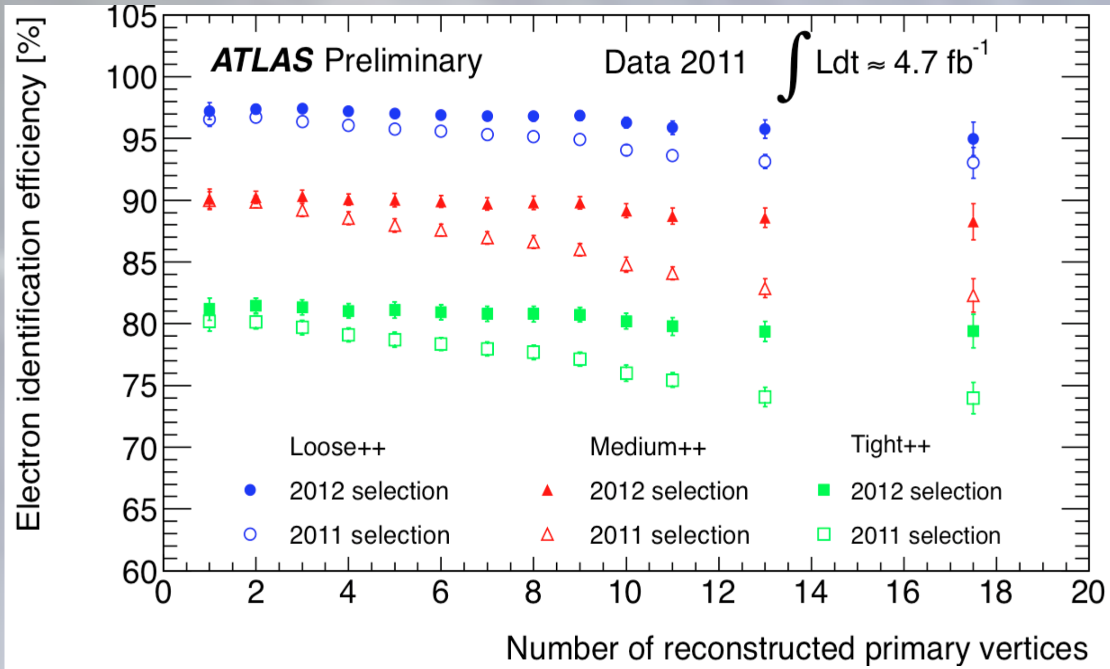
But potentially a big problem at E_{beam}=7 TeV – scaling suggests at least one beam dump **per day** from UFOs

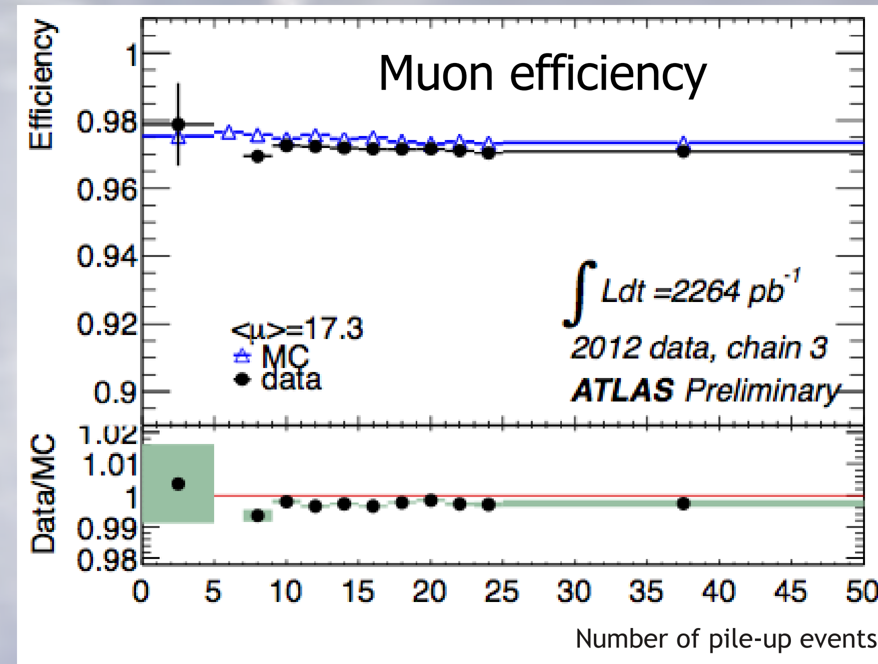
Have to contend with pile-up: multiple pp collisions within a single bunch crossing

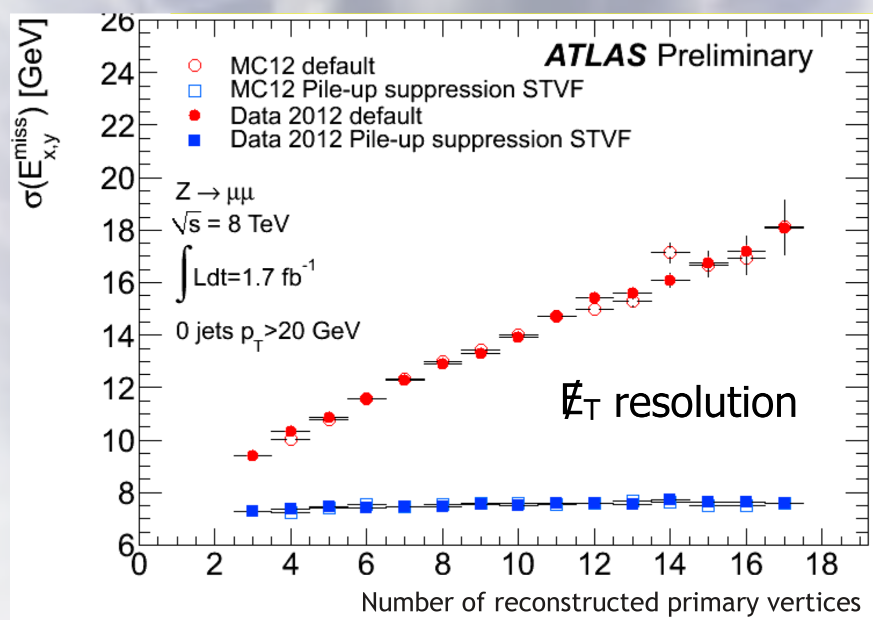


Z→μμ event from 2012 with 25 reconstructed primary vertices

Gives rise to complex track reconstruction environment
Additional energy in calorimeters → spoils missing E_T measurements







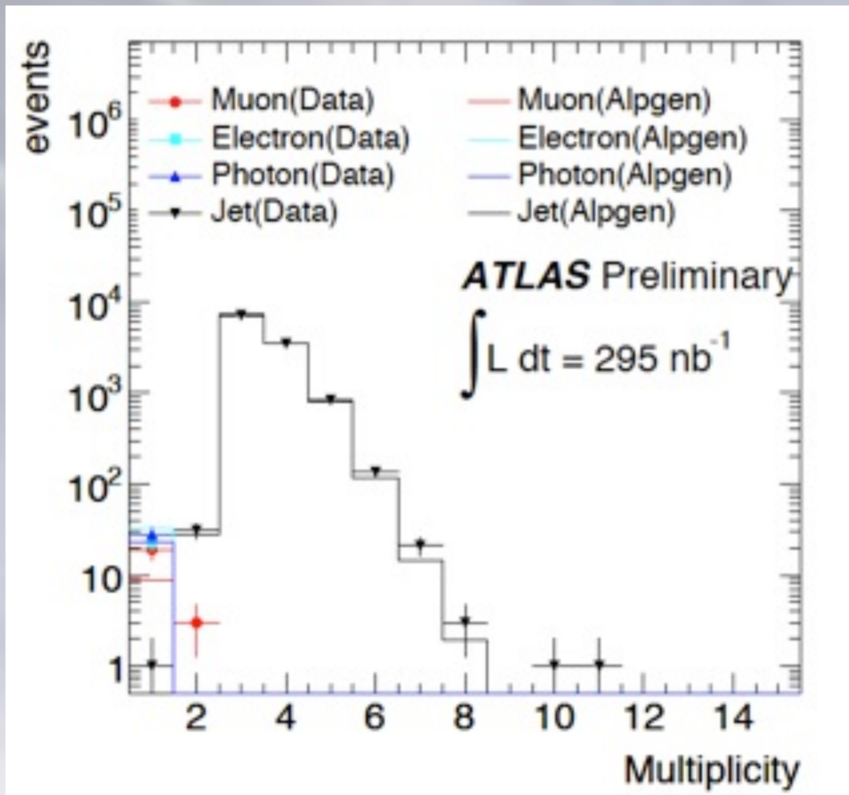
Need to understand efficiency for finding electrons, muons in high pile-up

Ensure missing E_T resolution does not degrade at high pile-up

Ensure MC simulation models effects

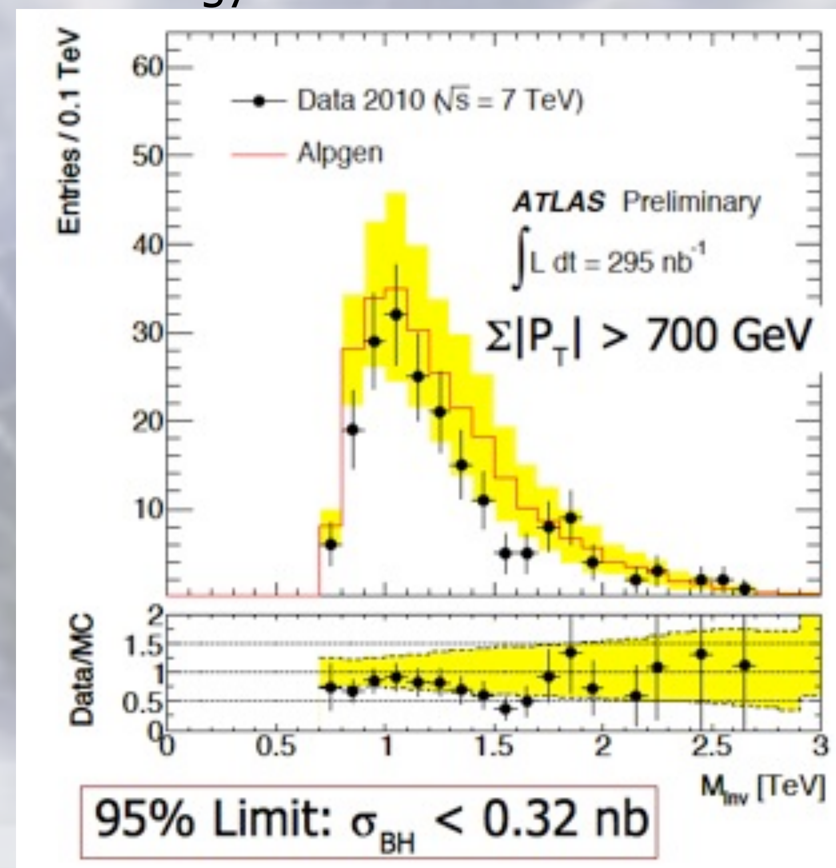
Early LHC result based on 1/5000th of the data collected now

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:
MC simulation differences ~ 26%
Jet energy scale ~ 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

Searching for new physics is like searching for the Loch Ness Monster

If you observe the Loch for 24 hours and see nothing, then either:

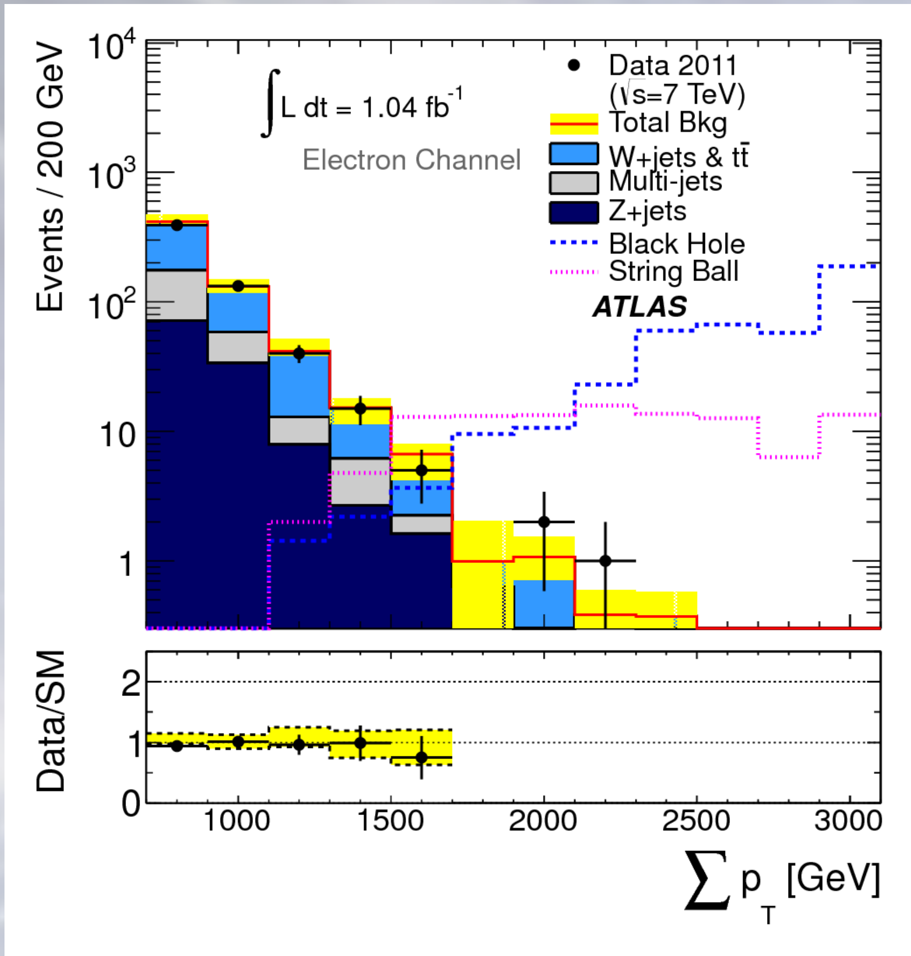
- "Nessie" doesn't exist
- your camera has poor efficiency for spotting animals (larger than 2m long)
- it exists but comes to the surface less than once per day

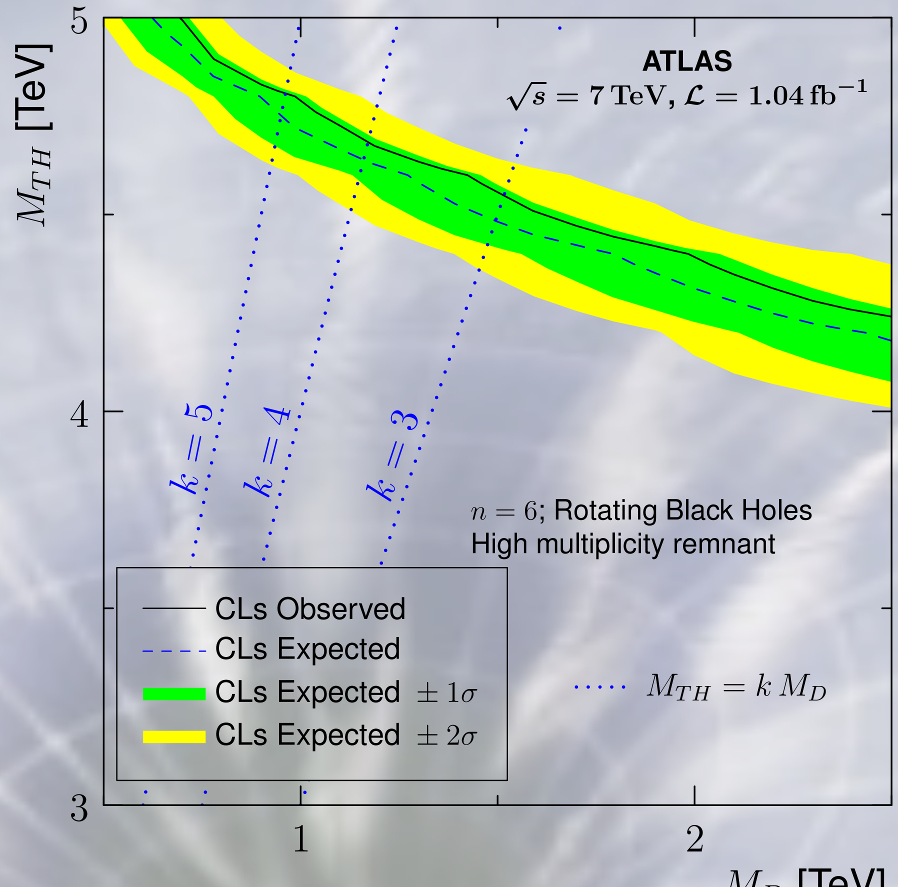
In physics searches usually a model predicts a reaction rate

If you observe no such reaction rate (i.e. zero collisions) then you can calculate upper limit on allowable reaction rate

You need to carefully consider your detector's efficiency in observing similar topology collisions

Updated analysis with 1 fb^{-1}
Require at least 3 objects (e, μ, jet) with p_T > 100 GeV

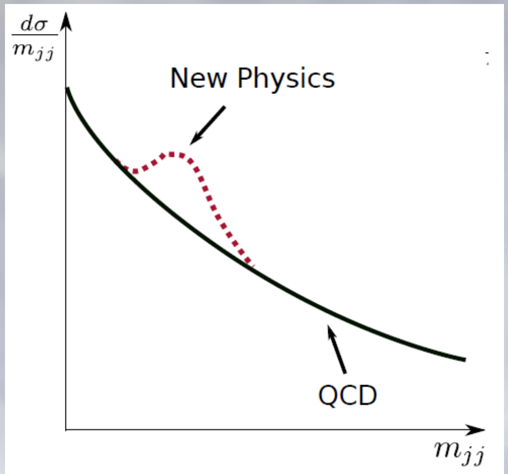


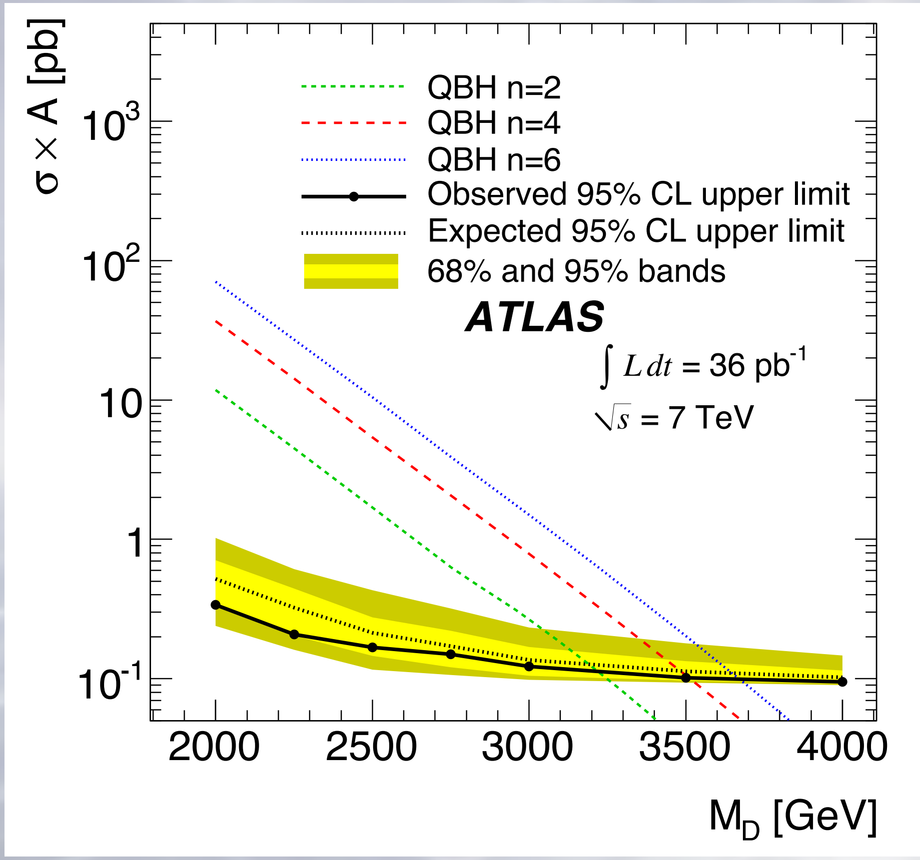


Limit set for n=6 rotating BHs
For classical threshold $M_{TH}=3M_D$
then M_D>1.5 TeV @95% CL

Classical black holes expected to decay ~democratically i.e. 20% chance of leptonic decay
Typically expect high multiplicity final states

Atlas Collab. arXiv:1103.3864v1





Published with full 2010 dataset

Search for deviations in dijet channel: M_{JJ}
Compare the di-jet mass spectrum with QCD
QBHs produce threshold effects
Large cross section close to threshold
Long tails to larger masses

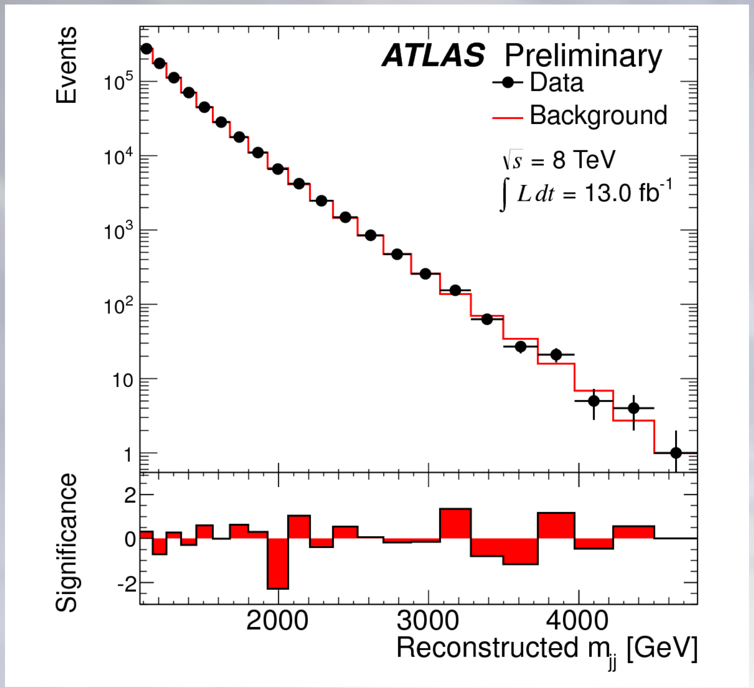
Simulation predicts cross section × Acceptance

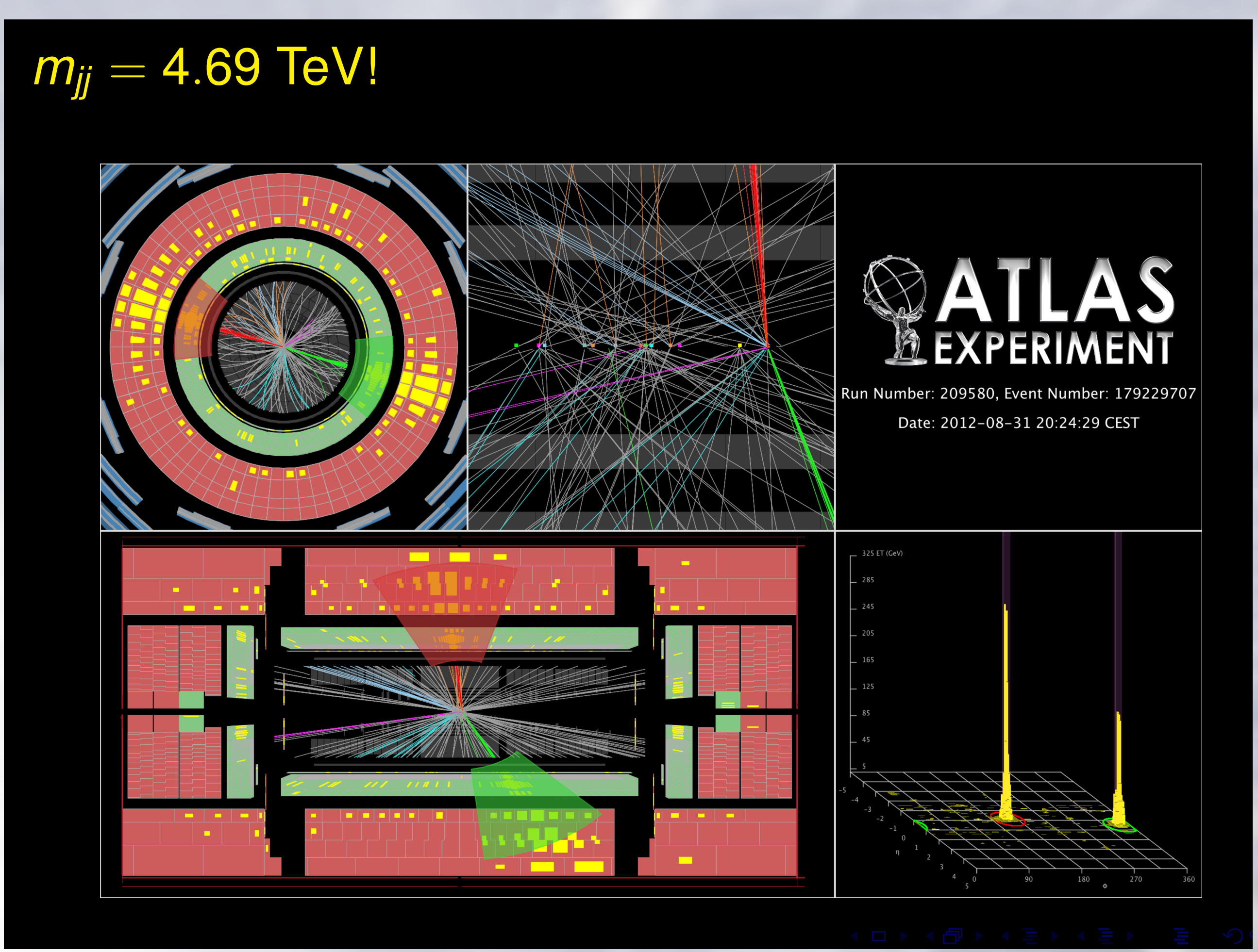
Acceptance = kinematic region visible in detector

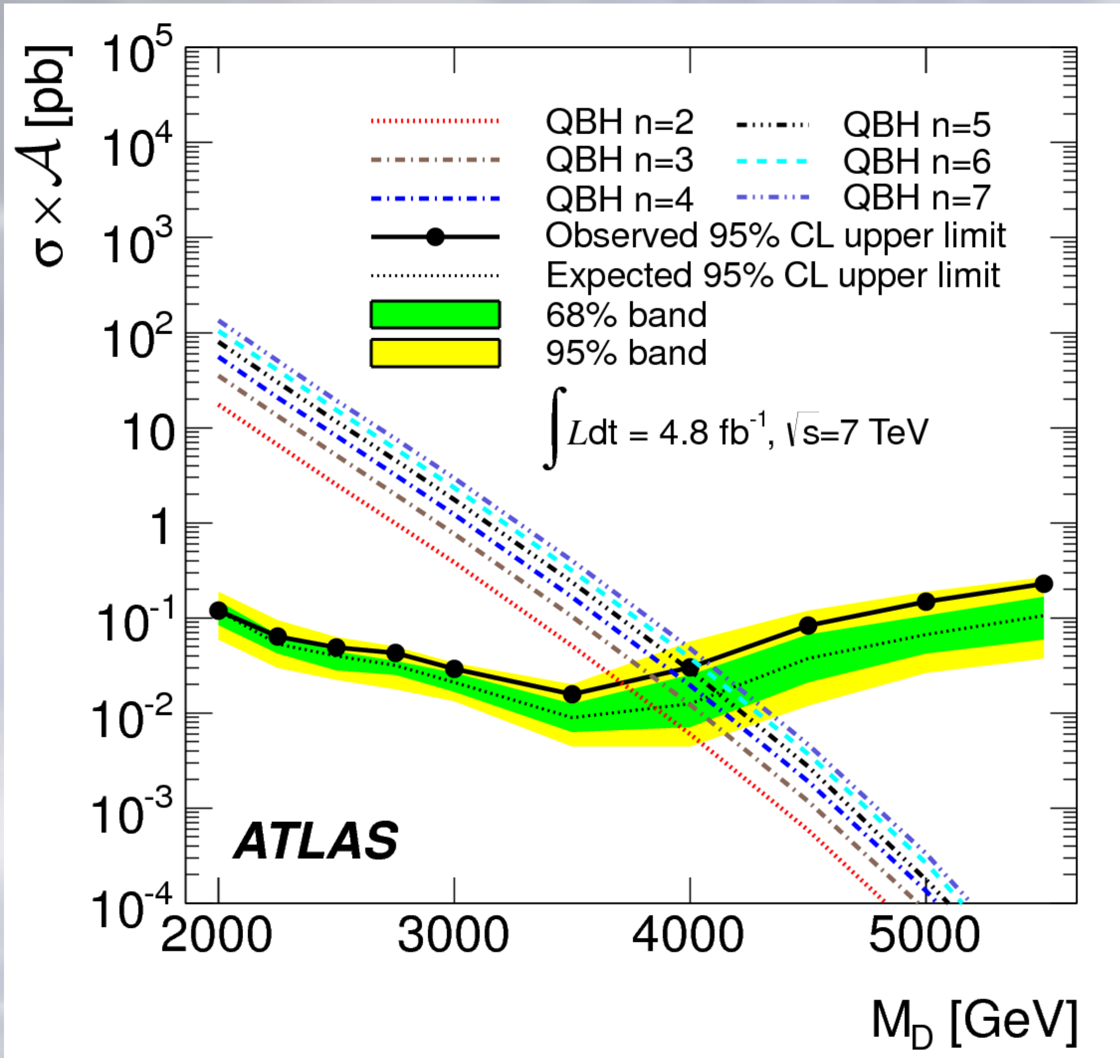
Meade-Randall QBHs excluded at 95% CL for M_D < 3.67 TeV (n=6)

Update analysis for 8 TeV data & 13 fb^{-1} data set

Include angular information for better discrimination

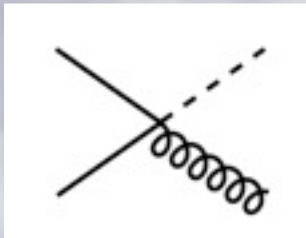




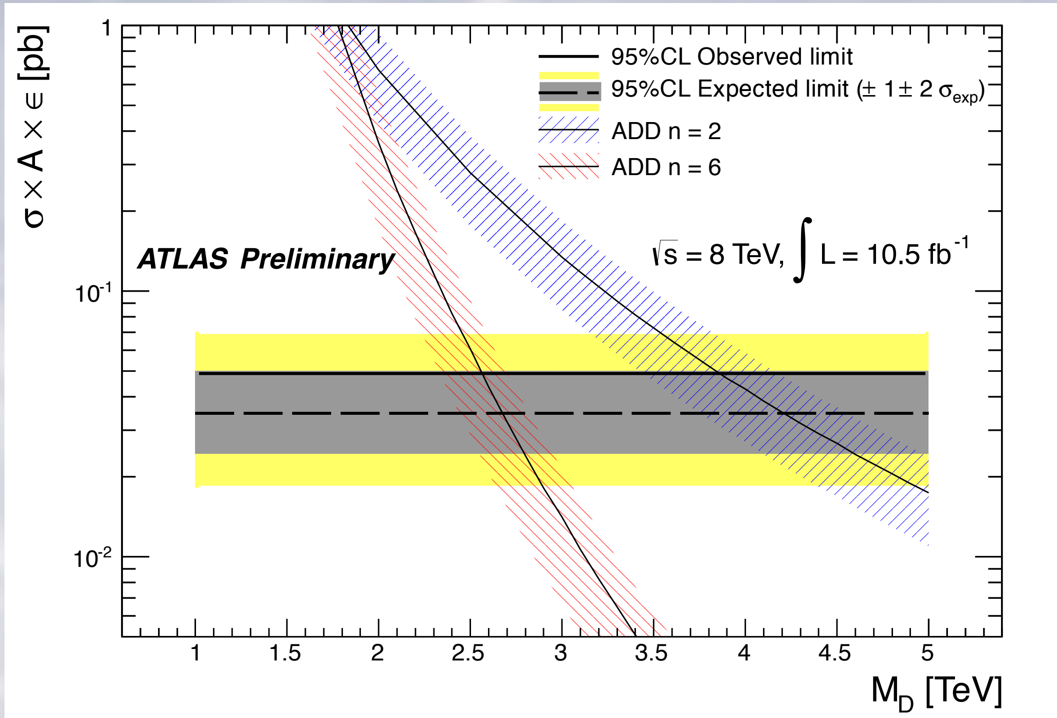


M_D < 4.03 TeV excluded for n=6

Search for ADD gravitons produced moving off SM brane
In this case gravitons not observed
Signature is SM particle: jet + $\not{E}_T$

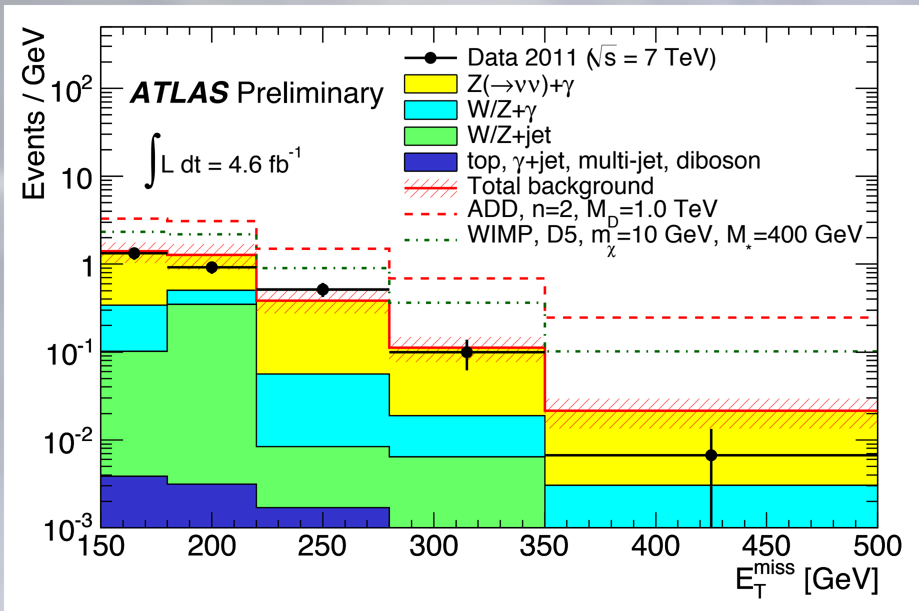


Models predict tower of gravitons
due to compactified extra dimensions



95% CL limits on ADD model using LO signal cross sections						
n extra-dimensions	95% CL observed limit on M_D [TeV]			95% CL expected limit on M_D [TeV]		
	+1σ(theory)	Nominal	−1σ(theory)	+1σ	Nominal	−1σ
2	+0.32	3.88	−0.42	−0.36	4.24	+0.39
3	+0.21	3.16	−0.29	−0.24	3.39	+0.46
4	+0.16	2.84	−0.27	−0.16	3.00	+0.20
5	+0.16	2.65	−0.27	−0.13	2.78	+0.15
6	+0.13	2.58	−0.23	−0.11	2.69	+0.11

Graviton / Large Extra Dimension Searches



Similarly - look for photon + $\not{E}_T$

select events with:

$\not{E}_T$ > 150 GeV

Photon p_T > 150 GeV

both well separated in detector

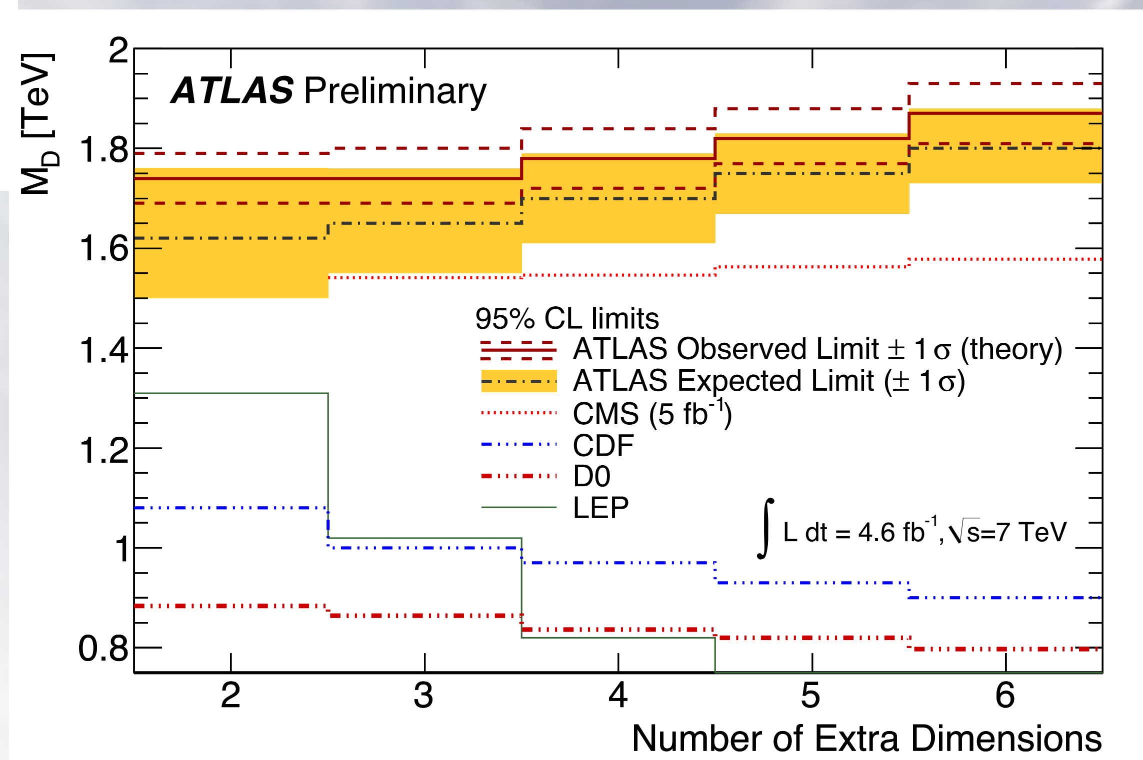
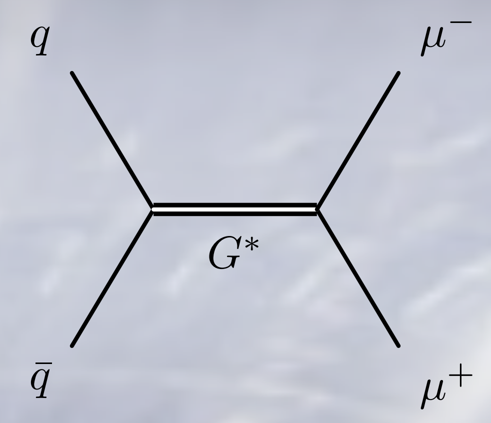


Table 1: Upper limits on M_D at the 95% confidence limit.

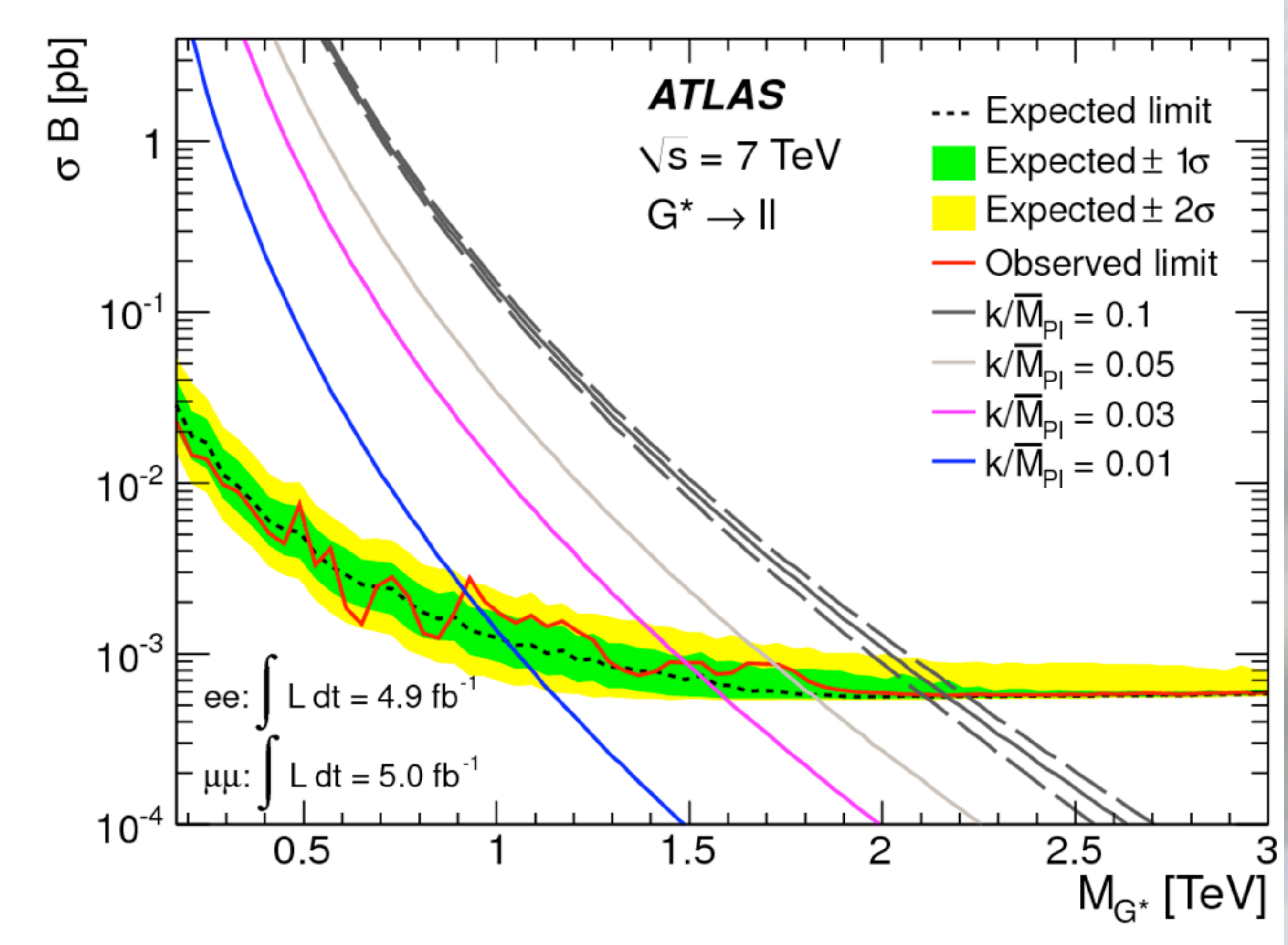
n	M_D [TeV]						
				Mono-photon		Mono-jet	
	LEP	CDF	DØ	ATLAS	CMS	ATLAS	CMS
2	1.60	1.40	0.884	1.93		**4.17**	4.08
3	1.20	1.15	0.864	1.83	1.73	**3.32**	3.24
4	0.94	1.04	0.836	1.86	1.67	**2.89**	2.81
5	0.77	0.98	0.820	1.89	1.84	**2.66**	2.52
6	0.66	0.94	0.797		1.64	**2.51**	2.38
7			**0.797**				
8			**0.778**				

Production and decay to leptonic final state
Search for deviations from SM:

$$q\bar{q} \to Z/\gamma^* \to l^+l^-$$



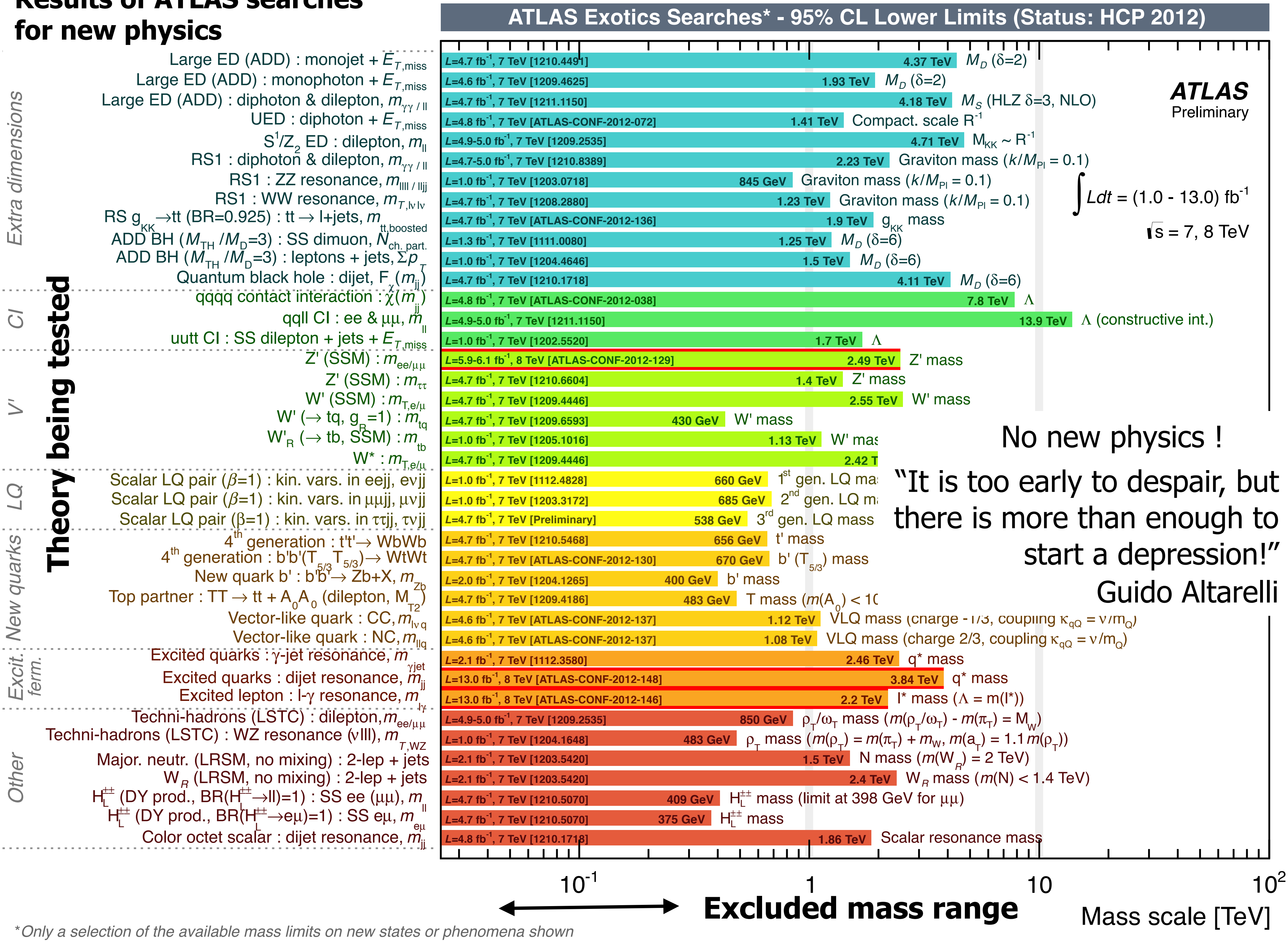
Graviton production



M_{G^*} > 2.15 TeV for k/M_D=0.1 at 95% CL

k = RS warp factor between branes

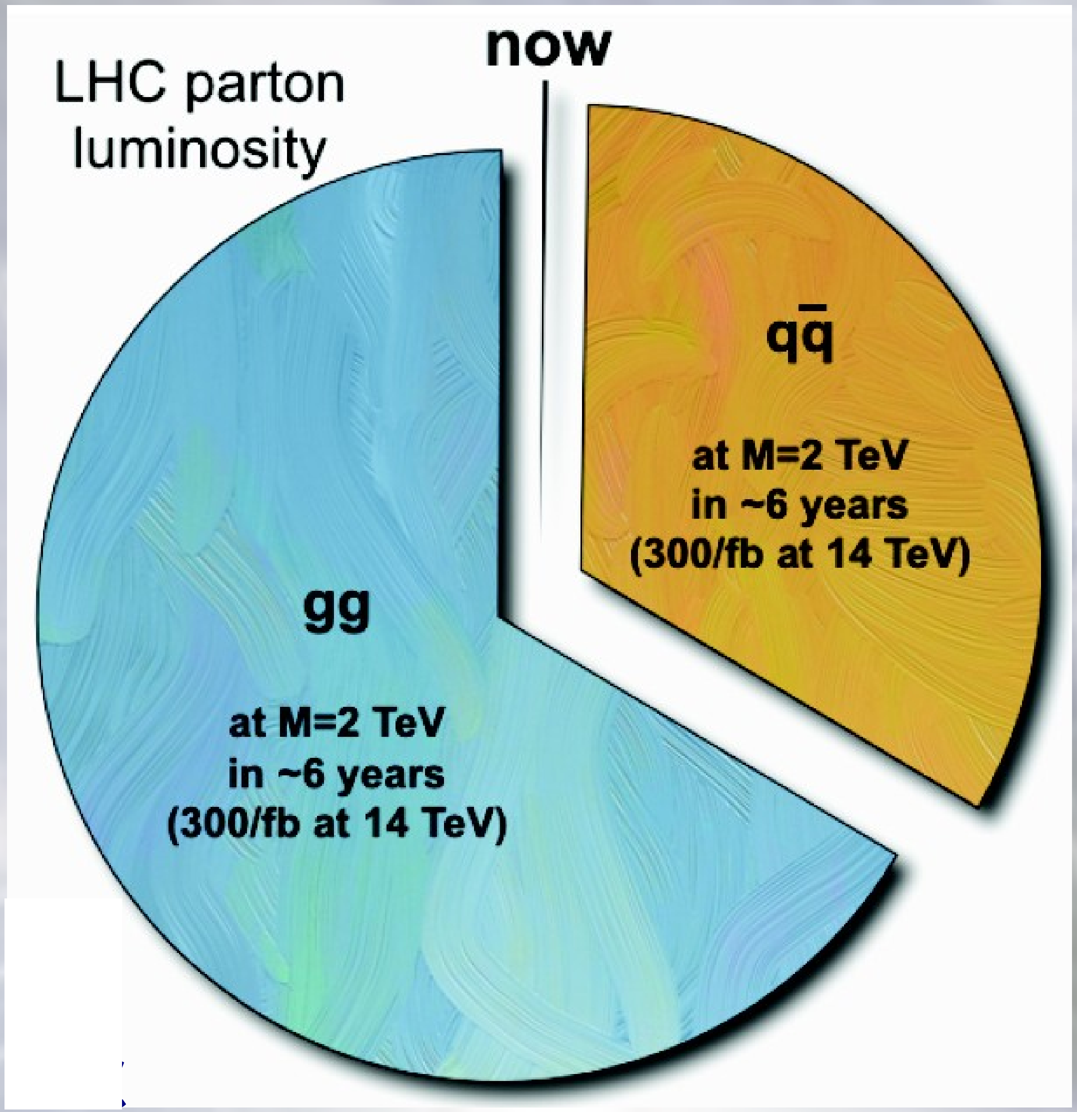
Results of ATLAS searches for new physics



No new physics !

"It is too early to despair, but there is more than enough to start a depression!"

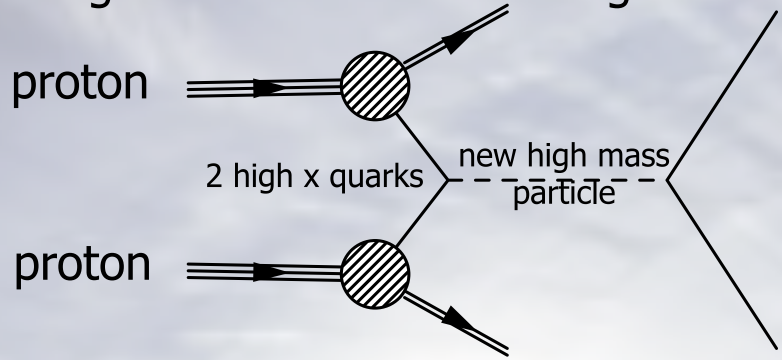
Guido Altarelli

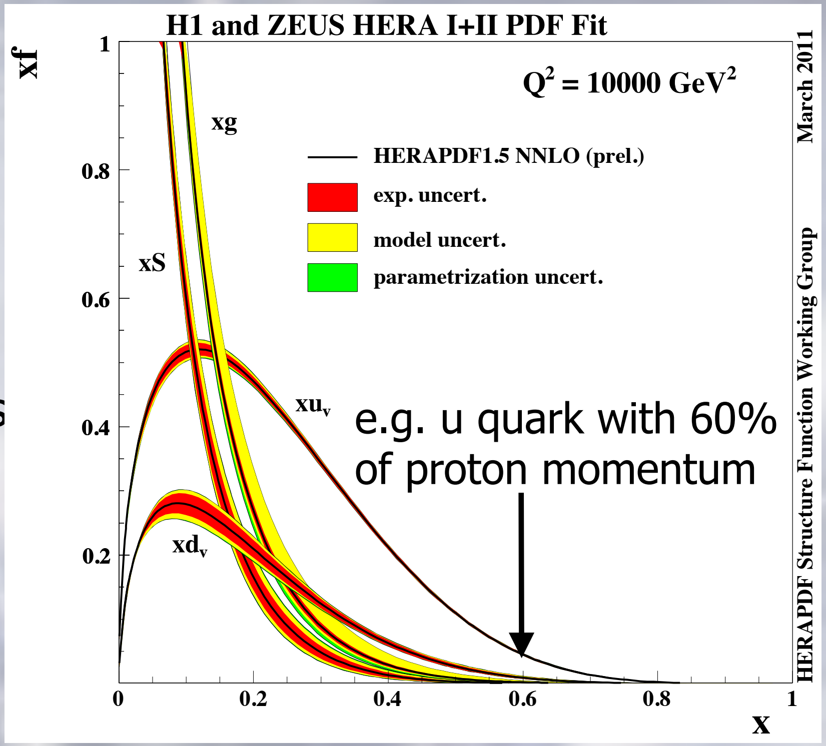


Amount of data taken
compared to what will come ~2020

High luminosity LHC
Project approved & funded
Expect to start operation ~ 2023
super-LHC will provide 10 times more data

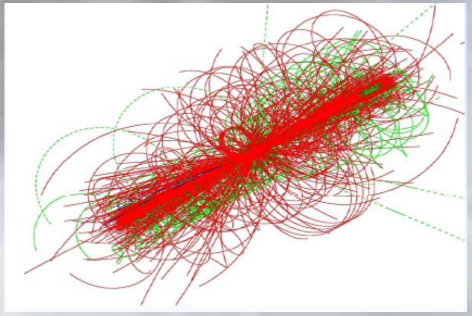
Small probability to collide 2 quarks at very high x
Need high x collisions to form highest mass new particles



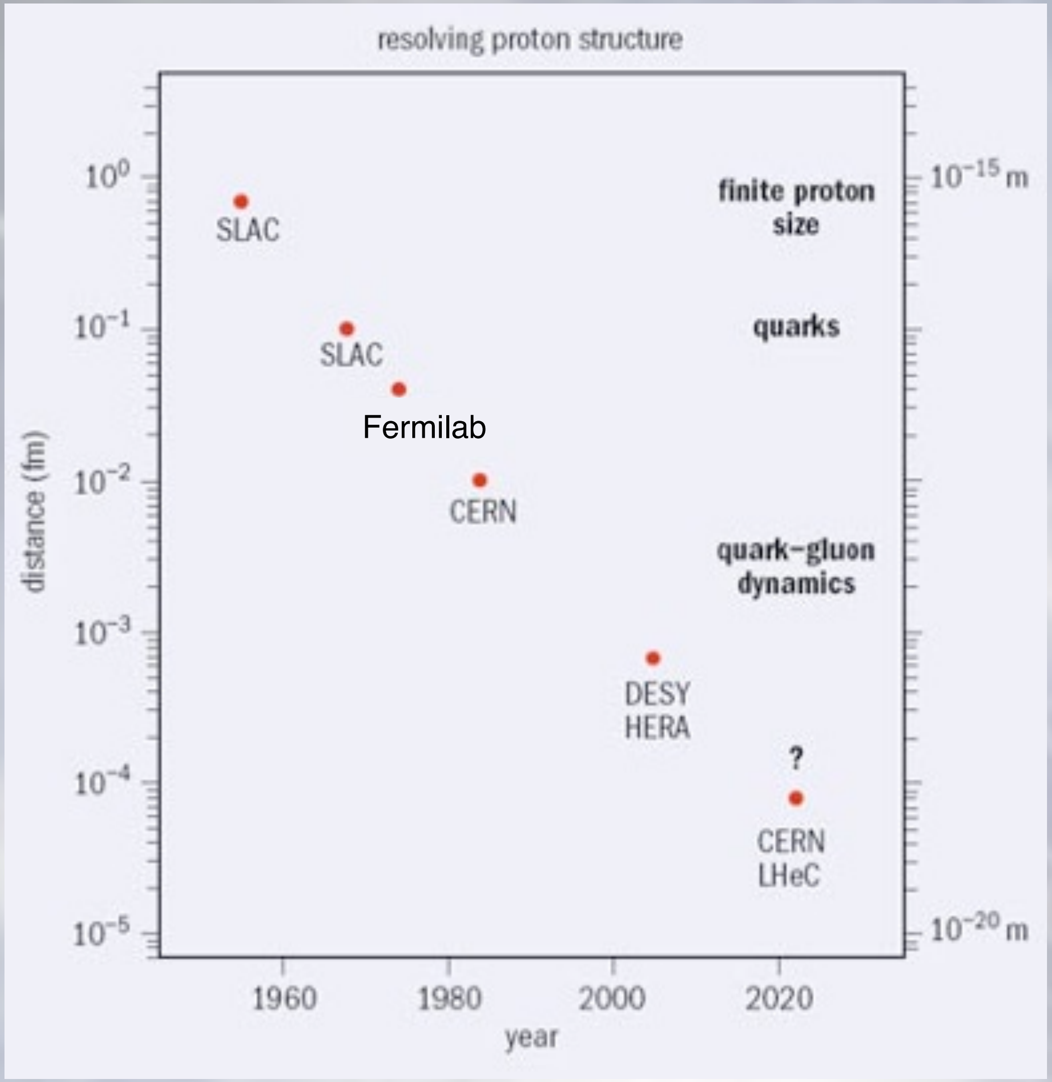


LHC will deteriorate from 10 years high intensity particle flux
Need to be upgrade experiments / magnets
Profit from new technology
At high intensity expect more than 400 simultaneous collisions!

x = fraction of proton's momentum carried by parton



High energy LHC
Under discussion - no firm plans
Double beam energy to 16.5 TeV per beam
Timescale approx. 2030



LHeC

Simultaneous operation of LHC and LHeC

Install electron ring accelerator into LHC tunnel

... or ...

Linear electron accelerator to intersect LHC beam

Electron energy = 60 - 170 GeV

Precision QCD machine

Lower backgrounds

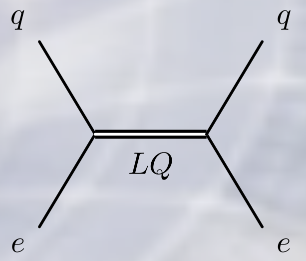
Probe proton structure at highest energy

Constrains proton structure

→ will help LHC discovery potential

Lepto-quark discovery machine

Access LQ quantum numbers



Project at conceptual design phase

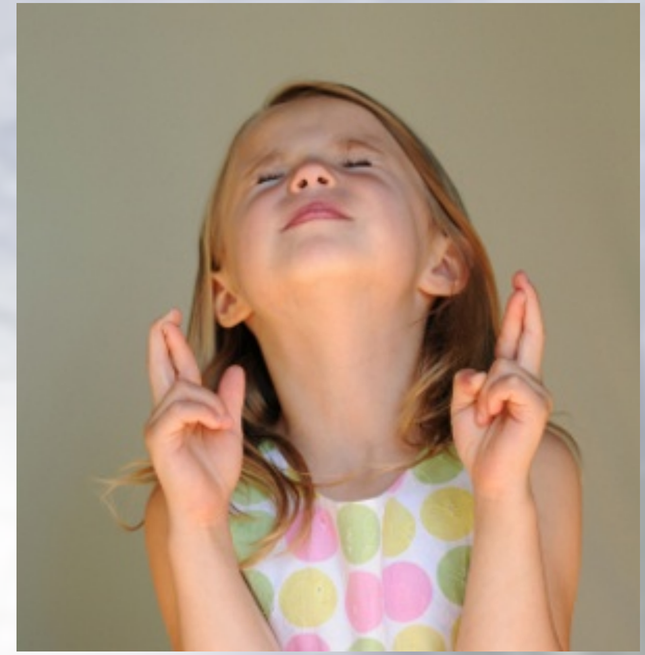
Could start operation with HL-LHC phase 2023

Currently unfunded

- 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



What are the alternatives to the Standard Model?

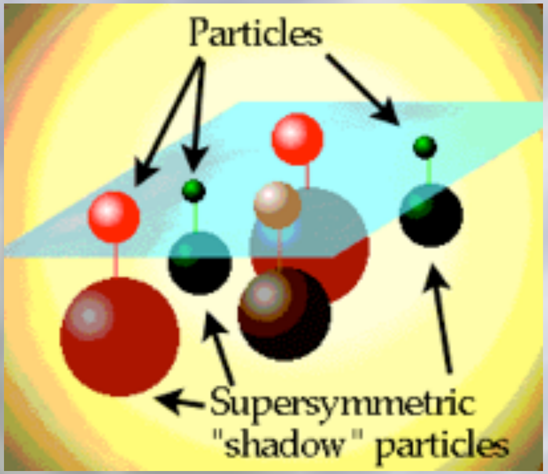
"The LHC opens a door to a new room, but we've got to have a good look around in that new room. The Higgs particle is a very important question but it's far from the only one."

Jon Butterworth

Best bet is Supersymmetry (SUSY)

Theoretically elegant - extends symmetry ideas of the Standard Model
Invokes a symmetry between fermions and bosons
(integer and half integer spin particles)

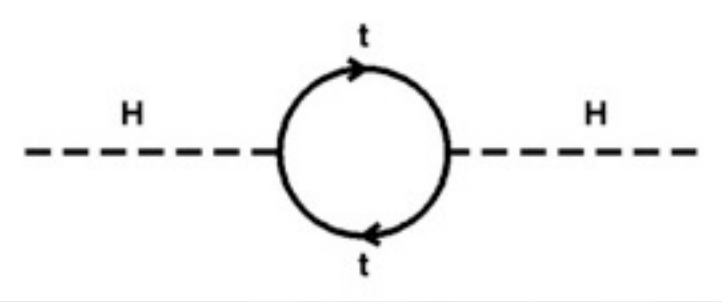
Immediately double number of particles
Each SM particle has a super-partner sparticle



quarks (spin ½)	↔	squarks (spin 0)
leptons (spin ½)	↔	sleptons (spin 0)
photon (spin 1)	↔	photino (spin ½)
W,Z (spin 1)	↔	Wino, Zino (spin ½)
Higgs (spin 0)	↔	Higgsino (spin ½)

None of these has been observed
105 new parameters required by theory - So why bother??

Hierarchy Problem
Why is Higgs mass (~1 TeV) so much smaller than the Planck scale (10^{19} GeV)?
Such calculations need to take account virtual fluctuations



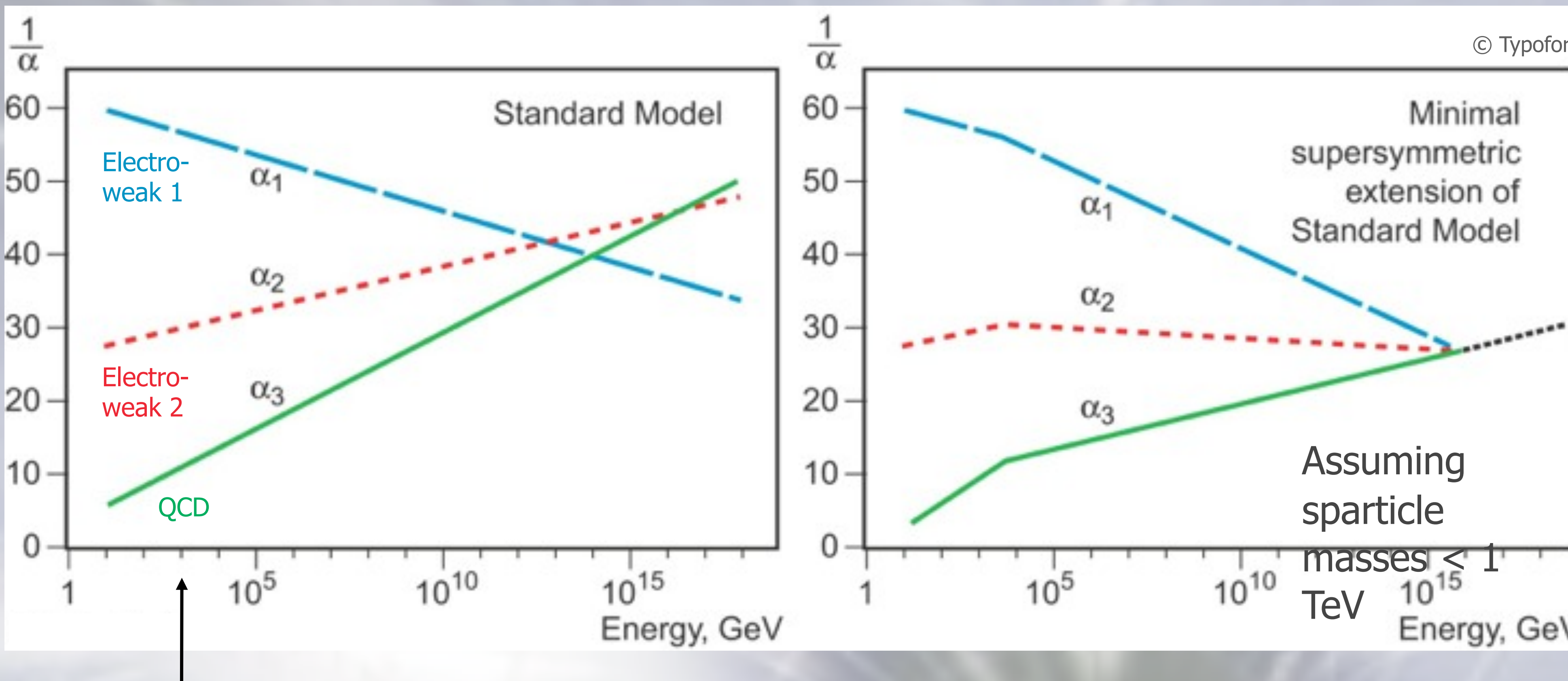
Higgs interacts with all spin ½ particle-antiparticle pairs in the vacuum

Higgs mass quantum corrections diverge up to 10^{19} GeV
If SM valid upto Planck scale then incredible fine-tuning of cancellations is needed to ensure ~1 TeV Higgs mass
Seems unnatural
Only a problem for the Higgs (only SM particle with spin 0)

New SUSY sparticles (e.g. stop squark) contribute and cancel identically

Higgs interaction with spin 0 sparticle cancels SM quantum corrections above

GUT Unification
Another of SUSY's charms:
Coupling constants extrapolated to Planck scale do not intersect

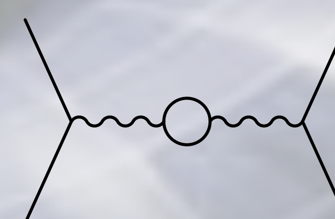


Current measurements at 1000 GeV

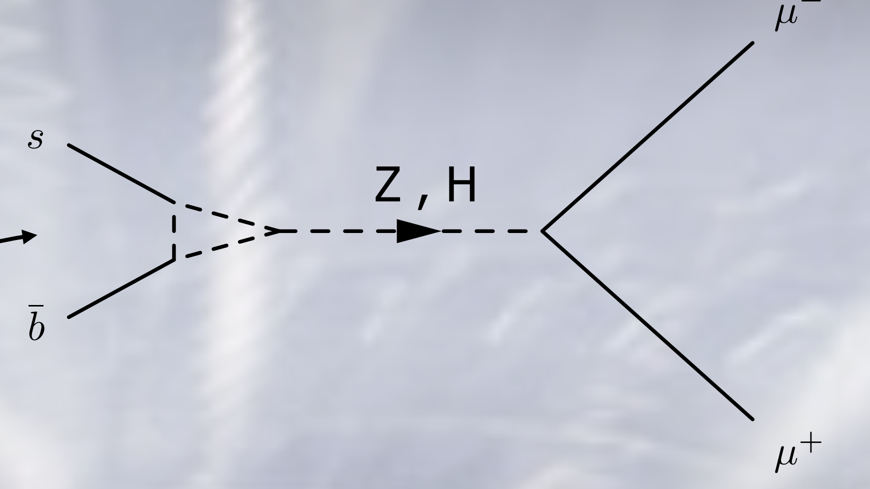
16 orders of magnitude extrapolation!
Involves including all particle loops

New SUSY particles = different loops
= different extrapolation

Incorporating SUSY into extrapolation
brings unification below Planck scale!



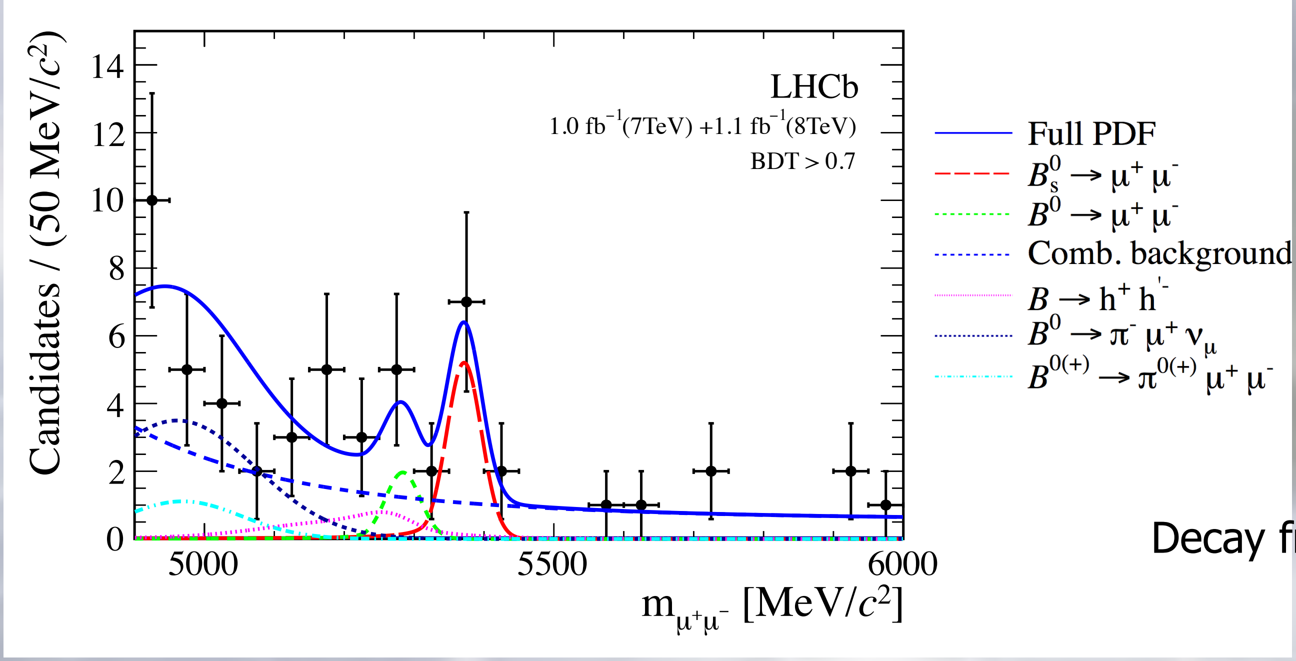
Experiments search for new physics (NP):
look for influence of new heavy particles via quantum loops
Choose a process heavily suppressed by Standard Model
(low contamination from SM background)



New physics quantum loop effects visible if
NP loops are similar size to SM loops

Measure the decay rate of the B_S^0 meson
Decay to $\mu^+\mu^-$ is very suppressed in SM - SM predicts fraction of decays is ~10^{-9} !!

New heavy particles can enter the loops and alter decay rate



On Monday LHCb experiment announced worlds first measurement of this very rare decay rate

Agrees with SM :(

Supersymmetry has few places left to hide!

Decay fraction $(B_s^0 \to \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$

SM predicts: $(3.54 \pm 0.30) \times 10^{-9}$