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
In last ~150 years physics has developed enormously
Three major pillars of modern physics have emerged

- general relativity $2 \times 10^{-5}$ Cassini photon time delay close to sun
- thermodynamics $1 \times 10^{-7}$ WMAP precision of CMB fluctuations to 1%
- quantum mechanics $1 \times 10^{-12}$ 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:
\[ \lambda = \frac{1}{E} \]

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

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

Thus objects warp space-time around themselves \( \Rightarrow \) 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

\( M_P \sim 10^{19} \text{ GeV} \) \( (\Rightarrow \text{hierarchy problem}) \)

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

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

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

\[
r = \frac{2M}{M^2_p} = r_s \quad \text{the Schwarzschild radius}
\]

Schwarzschild radius is soln of GR in case of non-rotating uncharged BHs

First solution to GR discovered 1 month after Einstein's publication
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 \( r_h \)

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 \( r_S = 1 \text{cm} \)

Rotating Kerr solution published 1963

A more generic solution was found for charged rotating black holes

Charged rotating BH

Kerr-Newmann solution published 1965
Jump to particle physics...

The Standard Model is fantastically successful

...
61 'fundamental' particles in the SM! (including anti-particles)
The Standard Model

<table>
<thead>
<tr>
<th>Perl</th>
<th>Gross</th>
<th>Rubbia</th>
<th>van der Meer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reines</td>
<td>Lederman</td>
<td>Gell-man</td>
<td>Cronin</td>
</tr>
<tr>
<td>Steinberger</td>
<td>Feynman</td>
<td>Glashow</td>
<td>Taylor</td>
</tr>
<tr>
<td>Hofstadter</td>
<td>Schwinger</td>
<td>Higgs</td>
<td>Veltman</td>
</tr>
<tr>
<td>Politzer</td>
<td>Ting</td>
<td>Alvarez</td>
<td>Fitch</td>
</tr>
<tr>
<td>Schwarz</td>
<td>Richter</td>
<td>Weinberg</td>
<td>Yang</td>
</tr>
<tr>
<td>Wilczek</td>
<td>Salam</td>
<td>Lee</td>
<td>t’Hooft</td>
</tr>
</tbody>
</table>

29 Nobel prizes awarded for the Standard Model

1 more yet to come?
The lagrangian...

Welcome to the Standard Model of particle physics!
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

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

Two gas clouds collide
Clouds slow down
Dark matter passes through

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

(Actually SM can account for only 1000th of this asymmetry)
Dark energy acts to accelerate the expansion of the universe
i.e. repulsive gravity

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

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

\[ e^- + e^- \rightarrow \gamma + e^- + e^- + e^- + \cdots \]

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

All these and more diagrams are required to calculate $g-2$ 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
Precise measurements at low energy are sensitive to Higgs loops.

Loop corrections to $Z/W$ scattering reactions:

Measurements at energy $E < M_H$ are logarithmically sensitive to $M_H$

- Confront data & theory: $\chi^2$ test
- Indicates light SM Higgs!
- But large margin of error...

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

$\Rightarrow$ our loop calculations are correct

---

Indirect sensitivity to Higgs mass:

- Exact measurements at low energy are sensitive to Higgs loops.
- Loop corrections to $Z/W$ scattering reactions:

$\Delta \alpha_{\text{had}}^{(5)} = 0.02750 \pm 0.00033$

- July 2011:

- Measurements at energy $E < M_H$ are logarithmically sensitive to $M_H$
- Confront data & theory: $\chi^2$ test
- Indicates light SM Higgs!
- But large margin of error...

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

$\Rightarrow$ our loop calculations are correct
Why is gravity $\sim 10^{33}$ weaker than EW interactions?
Why is Higgs mass ($\sim 100$ 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” \[ m^2_H = m^2_0 + \Delta m^2_H \]

since Higgs is scalar field we get:
for top: \[ \Delta m^2_H = -\frac{6}{16\pi^2} g_t^2 \Lambda^2 \] (g is Yukawa coupling)
for EW bosons: \[ \Delta m^2_H = +\frac{1}{16\pi^2} g^2 \Lambda^2 \]
for Higgs: \[ \Delta m^2_H = +\frac{1}{16\pi^2} \lambda^2 \Lambda^2 \] (\(\lambda\) is Higgs self-coupling)

\[ m^2_H = m^2_0 + \frac{1}{16\pi^2} \left(-6g_t^2 + g^2 + \lambda^2\right) \Lambda^2 - \ldots \text{new physics} \ldots \]

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

\[ m^2_H = m^2_0 + \frac{1}{16\pi^2} \left(-6g_t^2 + g^2 + \lambda^2\right) \cdot 10^{38} = (100 \text{ GeV})^2 \]

- 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 $\sim 100$ 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 $\sim 1$ TeV

Introduce large extra spatial dimensions (large $\sim 1$ 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 2\textsuperscript{nd} rank energy-momentum tensor)
ADD Model of Large Extra Dimensions

- All standard model particles are trapped to surface of this hyper-cylinder
- Particles moving in the bulk have quantised wave functions (like 1d potential 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:

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

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

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

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

For $r \gg R$ we recover Newtonian gravity

**Planck scale:**

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

In extra dimensions full scale of gravity $M_D$ is given by

$$M_D^{2+n} = \frac{\hbar c}{G_D} = \frac{M_P^2}{R^n} \quad \text{Thus } M_D \text{ can be } \sim 1 \text{ TeV when } R^n \text{ is large}$$

For $n=1$ and $M_D=1 \text{ TeV}$ then $R \sim 10^{16} \text{ m} \Rightarrow \text{already excluded!}$
Randall-Sundrum Model of Warped Extra Dimensions

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

Two 3-branes connected with 1 extra dimension

Gravitons propagate in the bulk

Extra dimension highly curved with an exponential warp factor

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

\( k = \text{warp factor} \)

models characterised by scale \( k/M_P \)

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

Dark energy is \( \sim 74\% \) of critical density of universe

\[ \Rightarrow \text{density of dark energy } \rho_d \sim 0.0038 \text{ MeV/cm}^3 \]

\[ \Rightarrow \text{distance scale } L_d = 4\sqrt{\frac{\hbar c}{\rho_d}} \sim 85 \mu\text{m} \]

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 \( \sim 1 \) nanoradian twists
(angle subtended by 1 mm at distance of 1000 km)
\[ V(r) = -G \frac{m_1 m_2}{r} \left[ 1 + \alpha \exp\left(-\frac{r}{\lambda}\right) \right] \]

Inverse square law holds for \( \lambda < 56 \, \mu m \)

\[ \Rightarrow \text{extra dims have} \]

\[ R < 44 \, \mu m \, \text{95\% C.L.} \]
Gravity at Large Distances

Reich: Nature 466, 1030 (2010)

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

* The error bars represent the quadrated sum of the individually listed Type A and Type B uncertainties.
In collisions Black Hole forms when impact parameter $< 2r_S$

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

$r_S$ 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 $F = \text{production form factors}$

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

convolute PDFs to get total production cross section

Simple but extremely robust prediction!
\[ \sigma_{BH}(s) = \sum_{a,b} \int \int dx_a \cdot dx_b \cdot f_a(x_a) \cdot f_b(x_b) \cdot \sigma_{BH}(\hat{s}) \]

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

\[ f_a(x_a) = \text{probability to find a parton of flavour } f \text{ with momentum fraction } x_a \]

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 $\Phi$

$\Phi_1 = \frac{N_1}{t}$ and $\Phi_2 = \frac{N_2}{t}$

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 $[\text{cm}^{-2} \text{s}^{-1}]$
no. of particles per unit area per unit time.
Depends only on design of your experiment
$\sigma$ = constant of proportionality
depends on the fundamental physics only!

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

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

$$= \frac{d\sigma}{d\Omega} \cdot N_{inc} \cdot n_A \cdot d\Omega$$
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 $\Rightarrow$ form BH
Energy redistributed as lower momenta thermal emissions

“The end of short distance physics”

Giddings, Thomas: hep-ph/0106219v4
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: $t \sim 10^{33}$y arXiv:0903.0676)
Super Kamiokande

50,000 tons pure water
11,200 photomultipliers
Buried 1000 m deep in mine

Japan

Experiment looks for decays in large volume of water

\[ p \rightarrow e^+ + \gamma \]
\[ p \rightarrow e^+ + \pi^0 \]

(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, 2\textsuperscript{nd} 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...

\[ \frac{\partial S}{\partial E} = \frac{1}{T} \]
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 $T_H$

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

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

Hawking radiation is purely thermal
only depends on $M, Q, J, Col$

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

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:

\[ \psi \xrightarrow{U} \psi' \]

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

\[ U^*U = I \Rightarrow U^{-1} = U^* \]

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 \( \sim 10^{-25} \, \text{s} \)

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
Cross Sections at the LHC

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

parton cross section
\[ F = \text{production form factors} \]

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

Form factors

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

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

\( r_h \) is generalisation of \( r_s \) for spinning BHs

\( b = \text{impact parameter} \)
\( b_{\text{max}} = \text{horizon radius} 2r_h \)

Large \( b \) \(\Rightarrow\) large ang mom states
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 $\sim 1\%$ level
- Nevertheless calcs assume fixed metric...

Phenomenological suppression of modes that increase $|Q|$ or Colour

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

Gingrich: hep-ph/0609055
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

Monte Carlo Generators

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

lepton brane

split fermion model

0.002 fm

BH is formed on quark brane at pp colliders

BH recoils at each emission
Affects emission spectra
Mostly emits quarks/gluons
Search for deviations from SM cross sections with increasing $m \sqrt{s}$ ...

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

**Pre LHC Constraints**

- **HERA: e-jet**
  - $e^+e^-$
    - LEP: $\gamma + \mathcal{E}_T$
      - $M_D > 1.60$ TeV for $n = 2$ (equiv: $R < 0.19$ mm)
      - $M_D > 0.66$ TeV for $n = 6$ (equiv: $R < 0.05$ nm)
    - CDF: $\gamma/jet + \mathcal{E}_T$
      - $M_D > 1.40$ TeV for $n = 2$
      - $M_D > 0.94$ TeV for $n = 6$
  - **$pp$**
    - D0: $ee, \gamma\gamma, jet-jet$
      - $M_D > 2.16$ TeV for $n = 2$
      - $M_D > 1.31$ TeV for $n = 7$

Variety of limits exclude $\sim 1$ TeV

- LEP: arXiv: hep-ex/0410004
- H1: H1prelim-10-161 (2010)
- D0: Phys. Rev. Lett. 102, 051601 (2009)
Summary of constraints from astrophysical measurements & colliders (2003)
Colliders probe large $n$
Supernovae & neutron stars probe low $n$: nucleon graviton-strahlung $NN \rightarrow NNG$
A graviton flux would cause reduced neutrino flux from supernova
$\rightarrow$ place strong limits on $M_D$ for $n=2,3$


ultra high energy neutrino showers
• deep in atmosphere
• horizontal
BH mediated cross section $\gg$ SM


pre LHC constraints
Potentially very large cross sections predicted
Horizon radius increases with $n \Rightarrow$ cross sections increase with $n$
Factor 10 variation in cross section for $n=1$ to $7$
BlackMax prediction for non-rotating BHs

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

Close to $M_D$ observe jump in $2 \rightarrow 2$ scattering? May be dominant effect

Factor $\sim 10^2$ suppression for $M_D = 1$ to 5 TeV

Dai et al: arXiv 0711.3012

Meade, Randall: arXiv 0808.3017
Cross Sections at the LHC

BlackMax prediction for non-rotating BHs

Dai et al: arXiv 0711.3012

Cross sections vary by \( \sim \) factor 10 for \( n = 1 \rightarrow 7 \)
Factor \( \sim 30 \) suppression for \( M_D = 1 \rightarrow 3 \) 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

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

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

$\langle N \rangle$ falls as $n$ increases
(BH temp increases)

Multiplicity compared to SM
\[ \mathcal{L} = 1 \text{ fb}^{-1} \quad M_{BH} > 5 \text{ TeV} \quad M_D = 1 \text{ TeV} \quad n=2 \]

- \( \Sigma |P_T| > 2.5 \text{ TeV} \)
- lepton \( P_T > 50 \text{ GeV} \)

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, \( \varepsilon = 100\% \)
LHC Signatures

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: $E_T > 500$ 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 $M_{\text{BH}} \gg M_D$ – true thermodynamic objects

Entropy $S = k_B \ln(\Omega)$ \hspace{1cm} $\Omega$=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 \hspace{1cm} $\lambda_C = \frac{h}{M_{\text{BH}} c} < r_s$

$\sigma_{\text{BH}}$ increases as $\sqrt{\hat{s}}$

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

But proton PDFs fall rapidly with increasing $\hat{s} \Rightarrow \sigma_{\text{BH}}$ 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
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: \( M_{\text{BH}} \sim M_D \) 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 \( \sim 1/M_{\text{BH}} \) ⇒ \( J \sim 1 \)
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
15 different types of QBH in pp collisions depending on initial parton combination

\[ \begin{array}{cccc}
\text{QBH}_{4/3} & \text{QBH}_{8} & \text{QBH}_{15} & \\
\text{QBH}_{3} & \text{QBH}_{6} & \text{QBH}_{15} & \\
\text{QBH}_{2} & \text{QBH}_{6} & \text{QBH}_{10} & \text{QBH}_{27}
\end{array} \]
Quantum Black Holes

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

$\sqrt{s} = 8$ TeV

$\int L \, dt = 13.4$ fb$^{-1}$

Reco $M_{\mu\mu}$

SM processes

Legend

- $\gamma^*/Z \rightarrow \mu\mu$
- Di-Boson
- $t\bar{t}$
- QBH Mth = 1.5 TeV
- QBH Mth = 2.0 TeV
- QBH Mth = 2.5 TeV
- QBH Mth = 3.0 TeV
- QBH Mth = 3.5 TeV
- QBH Mth = 4.0 TeV
- QBH Mth = 4.5 TeV
- QBH Mth = 5.0 TeV

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 $\sim$ TeV and weak coupling

Anchordoqui et.al. arXiv:0808.0497v3

Neutrinos have mass $\Rightarrow$ TeV scale gravity can democratically couple to
   ... left / right handed neutrinos
   ... heavy sterile neutrinos
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

The LHC breaks record for ‘luminosity’
Higher energy → probing particle interactions closer to the big bang

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

At high energy /momentum(Q):
masses $M_W$ & $M_Z$ are small
forces are $\sim$ equal

(increasing energy)
Examples processes at LHC

\[ q\bar{q} \rightarrow \mu^+\mu^- \]
\[ q\bar{q} \rightarrow W^+W^- \]
\[ gg \rightarrow H \rightarrow \gamma\gamma \]

Incoming partons carry momentum fraction \( x \)

Reaction rates depend on flux of incoming partons
\( \Rightarrow \) need a “map” of parton densities in proton

PDFs = parton density functions

4-momentum transfer\(^2 = Q^2 = M^2 \)
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 $x_1=x_2=10^{-1}$

$LHC Kinematics$
Parton Density Functions

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?

\[ e+e \quad e+\mu \quad e+\mu+2b+2v \quad e+2\mu+v \quad \mu+\mu \]
\[ e+j \quad e+\mu+j \quad e+2\tau+2b+3v \quad \mu+j+v \]
\[ 2e+3j \quad 3e+3v+j \quad 2\mu+2\tau+j \quad 2\mu+2b \]
\[ e+\tau+2j \quad e+2\tau+v+j \quad \mu+\tau+2b \quad 2\mu+2j+2v \]
\[ e+2j+v \quad 2e+\tau+2v+2j \quad 2\tau+2b \quad 2b+4j \]
\[ \gamma+e+v \quad \gamma+\mu+v+2j \quad \gamma+\tau+v \quad 2\tau+2j+\nu \]
\[ \gamma+\gamma \quad \gamma+c+\nu \quad \gamma+2e+v \quad 2b+2\nu \]
\[ \gamma+v \quad 2\gamma+2j \quad 2\gamma+2\mu+3j \quad 2b+2\j \]
\[ \gamma+b+2j \quad j+j \quad j+\nu \]
What are we looking for?

- Higgs boson
- spin-2 gravitons $G$
- $\mu+\mu$
- Axigluon
- $e+e$
- $e+\mu$
- $e+\mu+2b+2v$
- $e+2\mu+v$
- $\mu+j+v$
- $e+\mu+j$
- $e+2\tau+2b+3v$
- $b'$
- $\tilde{g}$
- $2\mu+2b$
- $2\mu+2j+2v$
- $2e+3j$
- $t'$
- $3e+3v+j$
- $2\mu+2\tau+j$
- $2\mu+2j+2v$
- W'
- $e+\tau+2j$
- $e+2\tau+v+j$
- $\tau+\tau$
- $Z'$
- $2\tau+2b$
- $2\tau+2j+v$
- $LQ$
- $2b+4j$
- $2b+2v$
- $\tilde{t}_1$
- $e+2j+v$
- $2e+\tau+2v+2j$
- $2\tau+2b$
- $2\tau+2j+v$
- $LQ$
- $\gamma+e+v$
- $\gamma+\mu+v+2j$
- $\gamma+\tau+v$
- SUSY
- $\gamma+2e+v$
- $\gamma+b+2j$
- $\gamma+c+v$
- Coloron
- $\gamma+\gamma$
- $\gamma+\gamma$
- $\gamma+\gamma$
- $\gamma+2j$
- $2\gamma+2j$
- $2\gamma+2\mu+3j$
- $\gamma+2e+2j$
- $E_6$ diquark
- $E_6$ GUT model
- $\chi_1^\pm$
Zombies at the LHC!
The LHC

\[ \sigma = \text{reaction rate} \]

\[ \sigma = \text{current LHC operating energy} \]

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 \(\mu\)s

Particle physicists measure reaction rates in units of barn: \(1 \text{b} = 10^{-28} \text{ m}^2\)
Exceptional LHC performance

Luminosity \( \mathcal{L} \) = amount of data delivered
Measure of total number of \( pp \) collisions

\[ N_{\text{events}} = \sigma \times \mathcal{L} \]

<table>
<thead>
<tr>
<th>France</th>
<th>Switzerland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgia</td>
<td>Taiwan</td>
</tr>
<tr>
<td>Germany</td>
<td>Turkey</td>
</tr>
<tr>
<td>Greece</td>
<td>UK</td>
</tr>
<tr>
<td>Israel</td>
<td>USA</td>
</tr>
<tr>
<td>Italy</td>
<td>CERN</td>
</tr>
<tr>
<td>Japan</td>
<td>JINR</td>
</tr>
</tbody>
</table>

2900 physicists
174 universities
38 countries
The ATLAS Experiment

Publications

Sustained output of papers ~10 / month

- Performance
- Measurements
- Searches

H discovery paper counted as a measurement

Publication count over time:
- ATLAS
- CMS

Years:
- 2010
- 2011
- 2012

Months:
- April
- June
- August
- October
- December
- February
- April
- June
- August
- October
- December
- March
- May
- July
- September
- November
- January
- March
- May
- July
- September
- November
The power of the WLCG

Running jobs
52 Weeks from Week 01 of 2012 to Week 00 of 2013

100000 jobs

Simulation production
User analysis
Group production/analysis
Data reproc
The ATLAS experiment

- Mass: 7000 tonnes
- Size: 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
Measuring cross-section of a process requires recognising event properties:

- Electromagnetic energy with a charged track
- Electromagnetic energy without track
- Collimated ‘jet’ of particles
- Penetrating charged track
- Missing transverse energy $\xi_T$
- Missing longitudinal energy
- Displaced secondary vertex
- Particle

Electromagnetic energy with a charged track
- $e^+$ or $e^-$
- Photon
- Gluon/quark induced jet
- $\mu^+$ or $\mu^-$
- $\nu$
- Beam remnants
- In-flight decay of 'long lived'

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
Particle Signatures

Decay of a long-lived composite particle

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

\[ K_S^0 \rightarrow \mu^+ \mu^- \]
Production and decay of a W boson particle
### Detector Performance

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

Beam losses thought due to dust particles falling into the beam

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

But potentially a big problem at $E_{\text{beam}} = 7$ 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
Detector Performance

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
**Classical Black Hole Search**

Early LHC result based on $1/5000^{th}$ of the data collected now

ObjectMultiplicity for $\Sigma |P_T| > 300 \text{ GeV}$

- **Jets**: $P_T > 40 \text{ GeV}$, $|\eta| < 2.8$
- **e/γ**: $P_T > 20 \text{ GeV}$, $|\eta| < 2.47/2.37$
- **μ**: $P_T > 20 \text{ GeV}$, $|\eta| < 2.0$
- $E_T$: calorimeter cells, $|\eta| < 4.8$

Large uncertainties:
- MC simulation differences $\sim 26$
- Jet energy scale $\sim 11\%$ & PDFs $\sim 12\%$

Require $\geq 3$ objects

3-jet events dominate

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

$Z / W / t / \tau$ reconstruction not needed

---

Eram Rizvi

Classical to Quantum Gravity Winter School - 16\textsuperscript{th}-18\textsuperscript{th} January 2013
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
Classical Black Hole Search

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

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

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

\[ m_{jj} = 4.69 \text{ TeV!} \]
**Quantum Black Holes**

$$\int L dt = 4.8 \text{ fb}^{-1}, s = 7 \text{ TeV}$$

For $n=6$ models, observed (expected) limit is 4.03 (4.16) TeV using 2011 data.

$M_D < 4.03 \text{ TeV}$ 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

<table>
<thead>
<tr>
<th>$n$ extra-dimensions</th>
<th>95% CL observed limit on $M_D$ [TeV] $+1\sigma$(theory)</th>
<th>Nominal</th>
<th>$-1\sigma$(theory)</th>
<th>95% CL expected limit on $M_D$ [TeV] $+1\sigma$</th>
<th>Nominal</th>
<th>$-1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>+0.32</td>
<td>3.88</td>
<td>-0.42</td>
<td>-0.36</td>
<td>4.24</td>
<td>+0.39</td>
</tr>
<tr>
<td>3</td>
<td>+0.21</td>
<td>3.16</td>
<td>-0.29</td>
<td>-0.24</td>
<td>3.39</td>
<td>+0.46</td>
</tr>
<tr>
<td>4</td>
<td>+0.16</td>
<td>2.84</td>
<td>-0.27</td>
<td>-0.16</td>
<td>3.00</td>
<td>+0.20</td>
</tr>
<tr>
<td>5</td>
<td>+0.16</td>
<td>2.65</td>
<td>-0.27</td>
<td>-0.13</td>
<td>2.78</td>
<td>+0.15</td>
</tr>
<tr>
<td>6</td>
<td>+0.13</td>
<td>2.58</td>
<td>-0.23</td>
<td>-0.11</td>
<td>2.69</td>
<td>+0.11</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>$n$</th>
<th>LEP</th>
<th>CDF</th>
<th>DØ</th>
<th>$M_D$ [TeV]</th>
<th>Mono-photon</th>
<th>Mono-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ATLAS</td>
<td>CMS</td>
<td>ATLAS</td>
</tr>
<tr>
<td>2</td>
<td>1.60</td>
<td>1.40</td>
<td>0.884</td>
<td>1.93</td>
<td>4.17</td>
<td>4.08</td>
</tr>
<tr>
<td>3</td>
<td>1.20</td>
<td>1.15</td>
<td>0.864</td>
<td>1.83</td>
<td>3.32</td>
<td>3.24</td>
</tr>
<tr>
<td>4</td>
<td>0.94</td>
<td>1.04</td>
<td>0.836</td>
<td>1.86</td>
<td>2.89</td>
<td>2.81</td>
</tr>
<tr>
<td>5</td>
<td>0.77</td>
<td>0.98</td>
<td>0.820</td>
<td>1.89</td>
<td>2.66</td>
<td>2.52</td>
</tr>
<tr>
<td>6</td>
<td>0.66</td>
<td>0.94</td>
<td>0.797</td>
<td>1.64</td>
<td>2.51</td>
<td>2.38</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>0.797</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>0.778</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Graviton Searches

Production and decay to leptonic final state
Search for deviations from SM:
\[ q\bar{q} \rightarrow Z/\gamma^* \rightarrow l^+ l^- \]

Graviton production

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

\[ k = \text{RS warp factor between branes} \]
**Results of ATLAS searches for new physics**

- Large ED (ADD) : monojet + $E_{T,miss}$
- Large ED (ADD) : monophoton + $E_{T,miss}$
- Large ED (ADD) : diphoton & dilepton, $m_{TT}$
- UED : diphoton + $E_{T,miss}$
- S'/Z' ED : dilepton, $m_h$
- RS1 : diphoton & dilepton, $m_{TT}$
- RS1 : ZZ resonance, $m_{ll}$
- RS1 : WW resonance, $m_{T,T'}$
- RS g -> tt (BR=0.925) : tt -> l+jets, $m_{t,t'}$
- ADD BH ($M_1/M_3=3$) : SS dimuon, $N_{ch,part.}$
- ADD BH ($M_1/M_3=3$) : leptons + jets, $\Sigma P$
- Quantum black hole : dijet, $F(m)$
- qqqq contact interaction : $\chi^2(m)$
- uutt : SS dilepton + jets $+ E_{T,miss}$
- $Z'$ (SSM) : $m_{\ell\ell}$
- $W'$ (SSM) : $m_{\ell\ell}$
- $W^* (\rightarrow t\bar{t}, SS e\mu)$ : $m_{tb}$
- 4th generation : $t\bar{t}$ -> WbWb

**Extra dimensions**

- Scalar LQ pair ($j=1$) : kin. vars. in eejj, eejj
- Scalar LQ pair ($j=1$) : kin. vars. in $\mu\mu\mu$, $\mu\mu\mu$
- Scalar LQ pair ($j=1$) : kin. vars. in $\tau\tau\tau$, $\tau\tau\tau$

**V**

- 4th generation : $t\bar{t}$ -> WbWb
- New quark $b^*$ : $b\bar{b}$ -> Zb+X, $m_{b^*}$
- Top partner : $T_T$ -> $t + A_A, (dilepton, M_{T_T})$
- Vector-like quark : $d, m_{T_D}$
- Vector-like quark : $N, m_{T_N}$
- Excited quarks : $y$-jet resonance, $m_{bj}$
- Excited quarks : dijet resonance, $m_t$
- Excited lepton : $l\rightarrow l, m_{l,\gamma}$
- Techni-hadrons (LSTC) : dilepton, $m_{e\mu, e\mu}$

**Other**

- Techni-hadrons (LSTC) : WZ resonance (viii), $m_{T,WZ}$
- Major. neutr. (LRSM, no mixing) : 2-lep + jets
- $W_R$ (LRSM, no mixing) : 2-lep + jets
- $H^{'+}$ (DY prod., $BR(H^{'+}\rightarrow l\ell)=1$) : SS $ee, m_{H^{'}}$
- $H^{'+}$ (DY prod., $BR(H^{'+}\rightarrow e\mu)=1$) : SS $e\mu, m_{H^{'}}$
- Color octet scalar : dijet resonance, $m_{A_4}$

---

**ATLAS Exotics Searches**

- $\int Ldt = (1.0 - 13.0) \text{ fb}^{-1}$
- $\sqrt{s} = 7, 8 \text{ TeV}$

---

No new physics!

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

Guido Altarelli

---

*Only a selection of the available mass limits on new states or phenomena shown*
At 14 TeV the partonic luminosities are much higher than at 7-8 TeV at masses above a few hundred GeV.

We have barely scratched the surface of the exploration of high energies given by the LHC.

Amount of data taken compared to what will come ~2020

LHC parton luminosity

now

$q\bar{q}$

at M=2 TeV in ~6 years
(300/fb at 14 TeV)

$gg$

at M=2 TeV in ~6 years
(300/fb at 14 TeV)
**LHC Plans**

**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!

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

---

**HERAPDF Structure Function Working Group**
H1 and ZEUS HERA I+II PDF Fit

\[ Q^2 = 10000 \text{ GeV}^2 \]

- HERAPDF1.5 NNLO (prel.)
- exp. uncert.
- model uncert.
- parametrization uncert.

\[ x = \text{fraction of proton's momentum carried by parton} \]

\[ x_f = 10000 \text{ GeV}^2 \]

\[ x_u = x \]

\[ x_d = x \]

\[ x_S = x \]

\[ x_g = x \]

---

Eram Rizvi
Classical to Quantum Gravity Winter School - 16\textsuperscript{th}-18\textsuperscript{th} January 2013
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
Supersymmetry

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 $\frac{1}{2}$) ↔ squarks (spin 0)
- leptons (spin $\frac{1}{2}$) ↔ sleptons (spin 0)
- photon (spin 1) ↔ photino (spin $\frac{1}{2}$)
- W,Z (spin 1) ↔ Wino, Zino (spin $\frac{1}{2}$)
- Higgs (spin 0) ↔ Higgsino (spin $\frac{1}{2}$)

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 $\frac{1}{2}$ 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

Incorporating SUSY into extrapolation brings unification below Planck scale!

Current measurements at 1000 GeV
16 orders of magnitude extrapolation!
Involves including all particle loops
New SUSY particles = different loops = different extrapolation

Assuming sparticle masses < 1 TeV

Electro-weak 1
Electro-weak 2
QCD

© Typoform

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

Incorporating SUSY into extrapolation brings unification below Planck scale!

Current measurements at 1000 GeV
16 orders of magnitude extrapolation!
Involves including all particle loops
New SUSY particles = different loops = different extrapolation

Assuming sparticle masses < 1 TeV

Electro-weak 1
Electro-weak 2
QCD

© Typoform
Supersymmetry “died” in December!

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 $\sim 10^{-9}$ !!

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 $(B_s^0 \rightarrow \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$
SM predicts: $(3.54 \pm 0.30) \times 10^{-9}$