Discovering New Physics with Early LHC Data

Greg Landsberg

OleMiss Physics Colloquium

April 8, 2008
Outline

- Astro-Particle Physics
- The Standard Model
- Beyond the Standard Model
- The Machine, the Detectors
- Searches for New Physics with early LHC Data*
- Conclusions

*) Chose to focus on a few characteristic examples, rather than being too inclusive
Astro-Particle Physics

• Last decade emphasized remarkable connection between the astrophysics and particle physics:
  – Searches for dark matter
  – QFT connections to early universe and inflation
  – Black hole thermodynamics
  – The “landscape” of string theory

• The more we study these seemingly different subjects, the more connections we discover
  – Physics at the very large distances may be inherently connected to the physics at the shortest ones

• More similarities:
  – Microscopes vs. telescopes
  – Large international collaborations
  – Complicated detectors

• We are (hopefully!) doing the things via two complementary
Microscopes vs. Telescopes

\[ \delta r \sim \frac{1}{E} \]

\[ \Delta \theta = 1.22 \frac{\lambda}{D} \]
Spectacular Launches

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Deep Fields

Quantum vacuum texture

Hubble Deep Field Survey
Unification

• Physics is about unification of seemingly different phenomena:
  – XVIIth century – Newton: Force that makes an apple to fall from the tree is the same force that keeps the Moon orbiting around the Earth
  – XIXth century – Faraday & Maxwell: Electricity and Magnetism are two manifestations of the common electromagnetic (EM) force
  – XXth century – Glashow, Salam, Weinberg: EM and weak force are two manifestations of the common electroweak force
  – XXIth century – Grand Unification of all Forces?

• Unification is the key to the scientific method – reductionism
1960-ies: Glashow, Salam, Weinberg, t’Hooft, …
- EM interactions (Faraday, Maxwell, Feynman, …)
- Weak interactions (Fermi, Cabibbo, …)
- Unified electroweak interaction: SU(2)_L × U(1)_EM
- Symmetry is spontaneously broken to give mass to W/Z and leave photons massless
- Particles acquire masses by interacting with the Higgs field

Energy
0
B or E Field

Energy
0
Higgs Field

Electroweak Symmetry Breaking

\[ \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow{\text{LSB}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}; \]

\[ \nu \equiv \text{vev} = 246 \text{ GeV} \]

4 degrees of freedom → W\(^\pm\), Z\(^0\), h\(^0\)
The Higgs Mechanism

A particle acquiring mass:

[After D. Miller]
The Higgs Mechanism

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A particle acquiring mass:

Self-coupling of the Higgs:

[After D. Miller]
The Higgs Mechanism

A particle acquiring mass:

Self-coupling of the Higgs:

[After D. Miller]
Standard Model Components

**Fermions:**

\[
\begin{pmatrix}
\nu_i \\
l^-_i
\end{pmatrix}_L \quad \begin{pmatrix}
u_i \\
d'_i
\end{pmatrix}_L \quad \begin{pmatrix}
u_i \\
l^-_i
\end{pmatrix}_R \quad \begin{pmatrix}
u_i \\
d'_i
\end{pmatrix}_R
\]

**Left-handed fields** are SU(2) doublets; **right-handed fields** are SU(2) singlets. Hence: C, P violation

**Bosons:**

\[
\tilde{A} = \begin{pmatrix}
A_1 \\
A_2 \\
A_3
\end{pmatrix}, \quad B, \quad \begin{pmatrix}
\gamma = B\cos\theta_w + A_3\sin\theta_w \\
Z = -B\sin\theta_w + A_3\cos\theta_w \\
W^\pm = \frac{1}{\sqrt{2}}(A_1 \pm iA_2)
\end{pmatrix}
\]

\[
M_w = \frac{1}{2\sin\theta_w} \text{ ev} \quad \text{Weinberg angle}
\]

\[
M_Z = M_w / \cos\theta_w
\]

**Standard Model Parameters:**

Fine structure constant \( \alpha = e^2/4\pi = 1/137.03599911(46) \) [QHE] (at Z-pole \( \alpha \approx 1/128 \) and depends on the renormalization scheme)

Fermi constant \( G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^2 \) [muon lifetime]

\( M_Z = 91.1876(21) \text{ GeV} \) [LEP 1 Z line-shape measurements]
We Live in Precision Times...

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>0</th>
<th>O^meas</th>
<th>0</th>
<th>O^fit</th>
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<th>σ^meas</th>
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<th>σ^fit</th>
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<tbody>
<tr>
<td>Δα^had^_{0}(m_Z)</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
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<td>2.4952 ± 0.0023</td>
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<td>σ^had [nb]</td>
<td>41.540 ± 0.037</td>
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<td>R_b</td>
<td>20.767 ± 0.205</td>
<td>20.744</td>
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<td>A^b</td>
<td>0.01714 ± 0.00095</td>
<td>0.01645</td>
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<tr>
<td>A^l (Pν)</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
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<td>R_b</td>
<td>0.21629 ± 0.00066</td>
<td>0.21586</td>
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<td>R_b</td>
<td>0.1721 ± 0.0030</td>
<td>0.1722</td>
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<tr>
<td>A^b</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
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<td>A^l (ν)</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
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<tr>
<td>m_W [GeV]</td>
<td>80.398 ± 0.025</td>
<td>80.374</td>
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<td>Γ_W [GeV]</td>
<td>2.140 ± 0.060</td>
<td>2.091</td>
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<tr>
<td>m_t [GeV]</td>
<td>170.9 ± 1.8</td>
<td>171.3</td>
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We Still Have Things to Do...
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The only Higgs observed in Nature
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The only stop decay observed in Nature
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The only dark matter observed in Nature
We Still Have Things to Do...

- The only Higgs observed in Nature
- The only dark matter observed in Nature
- The only stop decay observed in Nature
- A lot of dark energy...
**Puzzle: Where is the Higgs?**

**At the 95% CL:**
- $M_H < 160$ GeV (EW fit)
- $M_H > 114.4$ GeV (direct searches)

Most likely mass is just above the direct exclusion!
Puzzle: Mass and Gravity

- Isaac Newton: the force that makes the apple fall is the same force that keeps the moon going around the Earth!

\[ F = G_N \frac{Mm}{R^2} \]

- Charles Coulomb: opposite electric charges attract!

\[ F = G_C \frac{Qq}{R^2} \]

- Mass is analogous to electric charge?!
- But gravity is \(10^{38} = 100,000,000,000,000,000,000,000,000,000,000,000,000,000\) (hundred trillion trillion trillions!) times weaker than electricity! The hierarchy/naturallness problem: \(M_{Pl} = G_N^{-1/2} = 10^{16}\) TeV \(\gg\) \(M_{EW} \sim 1\) TeV \(\sim 1000\) \(M_p\)
### Standard Model: Beauty & the Beast

#### Beauty…

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Standard Model: Beauty & the Beast

### Beauty... and the Beast

#### RGE evolution

- **Gravitational Force**
- **EM/Hypercharge Force**
- **Weak Force**
- **Strong Force**

#### Inverse Strength vs. RGE evolution

- **Measurement**
  - $\Delta a^{(2)}_{\text{had}}(m_Z)
  - $m_Z$ [GeV]
  - $\Gamma_Z$ [GeV]
  - $a_\text{had}$ [GeV]
  - $R_f$
  - $\Lambda_{\text{fb}}$
  - $\Lambda_{(P_c)}$
  - $R_p$
  - $R_c$
  - $\Lambda_{\text{fb}}$
  - $\Lambda_{\text{fc}}$
  - $\Lambda_{(P)}$
  - $\Lambda_{(\text{SLD})}$
  - $\sin^2\theta_W^{\text{exp}}(Q_e)$
  - $m_W$ [GeV]
  - $\Gamma_W$ [GeV]
  - $m_t$ [GeV]

#### Summary

- $\Delta a^{(2)}_{\text{had}}(m_Z) = 0.02758 \pm 0.00035$
- $m_Z = 91.1875 \pm 0.0021$
- $\Gamma_Z = 2.4952 \pm 0.0023$
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- $\Lambda_{(P)} = 0.923 \pm 0.020$
- $\Lambda_{(P)} = 0.670 \pm 0.027$
- $\Lambda_{(\text{SLD})} = 0.1513 \pm 0.0021$
- $\sin^2\theta_W^{\text{exp}}(Q_e) = 0.2324 \pm 0.0012$
- $m_W = 80.392 \pm 0.029$
- $\Gamma_W = 2.147 \pm 0.060$
- $m_t = 171.4 \pm 2.1$

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Physics beyond the SM may get rid of the beast while preserving SM’s natural beauty!
Naturalness and Triviality

- Higgs mass receives corrections from fermion loops:

\[ \Delta M_H^2 = \frac{\lambda_f^2}{4\pi^2} (\Lambda^2 + M_H^2) + \ldots \]

- The size of corrections is \( \sim \) to the UV cutoff (\( \Lambda \)) squared:

\[ \Delta M_H^2 = \frac{\lambda_f^2}{4\pi^2} (\Lambda^2 + M_H^2) + \ldots \]

- In order for the Higgs mass to be finite, a fine tuning (cancellation) of various loops is required to a precision \( \sim (M_H/\Lambda)^2 \sim 10^{-34} \) for \( \Lambda \sim M_{Pl} \)

- Higgs mass can’t be too light or the potential won’t have a Mexican hat shape and will turn negative at large values.

- For the SM to be valid up to Planck scale, \( M_H > 135 \text{ GeV} \)

- Triviality: if the Higgs mass is too large, the Higgs self-coupling drives the mass to infinity above certain scale.

- If one wants the SM to be correct all the way up to Planck scale, \( 135 < M_H < 175 \text{ GeV} \) is required.

\[ M_H < 160 \text{ GeV @ 95% CL} \]

(Combined EW fit)

\[ M_H > 114.4 \text{ GeV @ 95% CL} \]

(LEP2, up to \( \sqrt{s} = 209 \text{ GeV} \))

- The EW vacuum is absolute minimum

- \( \Delta M_H^2 \) vs. \( \log_{10} \Lambda \) [GeV]

- \( 10^3 \) to \( 10^{19} \) GeV
Large Hierarchies Tend to Collapse...
More Large Hierarchies

Collapse of the Soviet Union

The nineties...
Gravitational Hierarchy Collapse

With thanks to Chris Quigg and the B44 restaurant in San Francisco

• Human Castles in Catalonia
Note: Some Hierarchies are Surprisingly Stable...
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And Keep in Mind...
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- Fine tuning (required to keep a large hierarchy stable) exists in Nature:
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(Food for thought: is it really numerology?)
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• **Alternative:** the *anthropic principle*
  – Properties of the universe are so special because we happen to exist and be able to ask these very questions
  – Is it time to give up science for philosophy? – So far reductionist method worked very well!
• Apart from the hierarchy problem:
  – Standard Model accommodates, but does not explain:
    • EWSB
    • CP-violation
    • Fermion masses
  – It doesn’t provide natural explanation of the:
    • Neutrino masses
    • Cold Dark Matter
Beyond the Standard Model

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  – Standard Model accommodates, but does not explain:
    • EWSB
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• Logical conclusion:
  – Standard model is an effective theory – a low-energy approximation of a more complete theory, which ultimately explains the above phenomena
  – This new theory must take off at a scale of ~1 TeV to avoid significant amount of fine tuning
  – Three classes of solutions:
    • Ensure automatic cancellation of divergencies (SUSY/Little Higgs)
    • Eliminate fundamental scalar and/or introduce intermediate scale \( \Lambda \sim 1 \text{ TeV} \) (Technicolor/Higgsless models)
    • Reduce the highest physics scale to ~1 TeV (Extra Dimensions)
**SuperSymmetry (SUSY)**

- Observation: loop corrections change sign when a fermion is replaced with a boson
  - Solution to the hierarchy problem: for each fermion, introduce a boson with the same Yukawa coupling to the Higgs field and vice versa!
  - Loops cancel and thus quadratic divergencies are (nearly) cured:
    \[ \Delta M_H^2 = \sum_f \frac{\lambda_f^2}{4\pi^2} \left( M_f^2 - M_{\tilde{f}}^2 \right) + \ldots \]
  - High price to pay: double the number of known particles
  - SUSY is clearly broken; masses of superpartners can’t be more than ~ 1 TeV
  - Also need more than one Higgs doublet to cancel anomalies

---

*Spring 2008 Physics Colloquium*  
*Greg Landsberg, Searches for New Physics with Early LHC Data*
**SUSY: Gauge Sector**

- Higgses: two complex doublets (8 d.o.f.)
  - One gives masses to down-type, and another one – to up-type quarks
  - Ratio of vacuum expectation values is conventionally called \( \tan \beta \)
  - 3 d.o.f. are “eaten” by massive \( Z, W^\pm \)
  - 5 remaining d.o.f. become physical states: \( h^0, H^0, H^\pm, A^0 \)
  - \( M_H > M_h \) by definition; \( M_h < 135 \text{ GeV} \)
  - \( A \) is a CP-odd Higgs
  - Supersymmetric partners of the two Higgs doublets mix with the partners of SM EWK gauge bosons to give four neutral (neutralinos) and two pairs of charged (charginos) gauginos
  - Gluino remains unmixed
SUSY: Even More Complex

- To describe SUSY breaking, explicit ("soft") terms are added to the Lagrangian: >100 parameters!
- Typically, reduce number of parameters by introducing phenomenological constraints (e.g., no FCNC) and often requiring R-parity conservation

\[ R_p = (-1)^{3B+L+2S} \]

Originated in footnote\(^7\) of classical Farrar-Fayet paper [PL 76B (1978) 575]

- B, L – baryon and lepton numbers; S – spin

```
\text{"Ordinary" particles} \quad +1 \quad R_p \quad \text{SUSY particles} \quad -1
```

P-parity? - Was taken!; Q-parity? - Pardon my French!; hence - R-parity

- \( R_p \)-conservation implies that SUSY particles are produced in pairs
- Consequently, the LSP is stable and serves as an excellent dark matter candidate (and also escapes at colliders)
- Cosmology: LSP is neutral and weakly interacting
**Large Extra Dimensions**

- But: what if there is no other scale, and SM model is correct up to $M_{Pl}$?
  - Give up naturalness: inevitably leads to anthropic reasoning
  - Radically new approach – Arkani-Hamed, Dimopoulos, Dvali (ADD, 1998): maybe the fundamental Planck scale is only $\sim 1$ TeV!!

- Gravity is made strong at a TeV scale due to existence of large (r $\sim 1$mm – 1fm) extra spatial dimensions:
  - SM particles are confined to a 3D “brane”
  - Gravity is the only force that permeates “bulk” space

- What about Newton’s law?

\[
V(\rho) = \frac{1}{M_{Pl}^2} \frac{m_1 m_2}{\rho^{n+1}} \rightarrow \frac{1}{(M_{Pl}^{3+n})^{n+2}} \frac{m_1 m_2}{\rho^{n+1}}
\]

- Ruled out for infinite ED, but does not apply for compact ones:

\[
V(\rho) \approx \frac{1}{(M_{Pl}^{3+n})^{n+2}} \frac{m_1 m_2}{r^n \rho}, \text{ for } \rho \gg r
\]

- Gravity is fundamentally strong force, but we do not feel that as it is diluted by the large volume of the bulk space

\[
G'_{N} = \frac{1}{(M_{Pl}^{3+n})^{2}} = \frac{1}{M_{D}^{2}}; \ M_{D} \sim 1 \text{ TeV}
\]

\[
M_{D}^{n+2} \sim \frac{M_{Pl}^2}{r^n}
\]

- More precisely, from Gauss’s law:

\[
r = \frac{1}{\sqrt{4\pi M_{D}}} \left( \frac{M_{Pl}}{M_{D}} \right)^{2/n} \sim \begin{cases} 
8 \times 10^{12} m, \ n = 1 \\
0.7 mm, \ n = 2 \\
3 nm, \ n = 3 \\
6 \times 10^{-12} m, \ n = 4
\end{cases}
\]

- Amazing as it is, but as of 1998 no one has tested Newton’s law to distances less than $\sim 1$mm!

- Thus, the fundamental Planck scale could be as low as 1 TeV for $n > 1$
Simultaneously, another idea has appeared:

- Explore modification of force behavior in (3+n)-dimensions to achieve low-energy grand unification: Dienes, Dudas, Gherghetta [PL B436, 55 (1998)]

- To achieve that, allow other force carriers (g, γ, W, and Z) to propagate in an extra dimension, which is “longitudinal” to the SM brane and compactified on a “natural” EW scale:
  - $r \sim 1 \text{ TeV}^{-1} \sim 10^{-19} \text{ m}$
Randall-Sundrum Model

- Randall-Sundrum (RS) model [PRL 83, 3370 (1999); PRL 83, 4690 (1999)]
  - One + brane – no low energy effects
  - Two + and – branes – TeV Kaluza-Klein modes of graviton
  - Low energy effects on SM brane are given by $\Lambda_\pi$; for $kr \sim 10$, $\Lambda_\pi \sim 1$ TeV and the hierarchy problem is solved naturally
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**Reduced Planck mass:**

$$\Lambda_\pi = \frac{M_{\text{Pl}}}{r \pi} e^{-kr\pi}$$

**Anti-deSitter space-time metric:**

$$ds^2 = e^{-2kr|\phi|} \eta_{\mu \nu} dx^\mu dx^\nu - r^2 d\phi^2$$

**AdS curvature**

$$k = \text{AdS curvature}$$

**SM brane** ($\phi = \pi$)

**Planck brane** ($\phi = 0$)
The Machine

The LHC
The LHC - Aerial View

CMS

CERN Site

ATLAS

GVA
The LHC

Overall view of the LHC experiments.

Will focus primarily on CMS in this talk
LHC: facts

- Energy: 7 x 7 TeV (will start at 5 x 5 TeV), i.e. 7 times more powerful than the existing machines
- Circumference: 26.7 km
- Number of proton bunches: 2808 x 2808
- Number of protons per bunch: $1.15 \times 10^{11}$
- Magnetic field: 8.3 T
- Luminosity: $10^{34} \text{ cm}^{-2}\text{s}^{-1} = 10^{-2} \text{ pb}^{-1}\text{s}^{-1} = 7 \text{ top pairs/s} = 100 \text{ W(ev)/s}$
- Energy stored in magnets: 10 GJ = A380 at a cruise speed of 700 km/s. Can heat and melt 12 tons of copper!

- Energy stored in a single beam: 360MJ = 90 kg of TNT = 8 liters of gas = 15 kg of chocolate
LHC: Niagara worth of Data!

- ATLAS will produce 320 MB/s
- CMS will produce 220 MB/s
- LHCb will produce 50 MB/s
- ALICE will produce 100 MB/s

CD stack with 1 year LHC data! (~20 Km)

Sounding balloon (30 km)

Concorde (15 km)

Mont-Blanc (4.8 km)
Cooldown Status

- [http://lhc.web.cern.ch/lhc](http://lhc.web.cern.ch/lhc)
The LHC Operation Stages

- First 14 TeV Collisions: ~Summer/Fall 2008
- Effective ATLAS/CMS running time/year: ~1000 hours ~ $4 \times 10^6$ s ~ $4 \times 10^{39}$ cm$^{-2} = 4 \times 10^{15}$ b$^{-1} = 4$ fb$^{-1}$ @ $10^{33}$ cm$^{-2}$s$^{-1}$
- Expected luminosity: ~10-100 pb$^{-1}$ in 2008 (@10 TeV); a few fb$^{-1}$ in 2009

<table>
<thead>
<tr>
<th>2008</th>
<th>Hardware commissioning 7TeV</th>
<th>Machine checkout 7TeV</th>
<th>Beam commissioning 7TeV</th>
<th>43 bunch operation</th>
<th>75ns ops</th>
<th>25ns ops I</th>
<th>Shutdown</th>
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<td></td>
<td>No beam</td>
<td>Beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L ~ 1-5 x $10^{32}$ cm$^{-2}$s$^{-1}$</td>
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<th>2009</th>
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<th>Machine checkout 7TeV</th>
<th>Beam setup</th>
<th>L ~ 1-? x $10^{33}$cm$^{-2}$s$^{-1}$</th>
<th>25ns ops I</th>
<th>Shutdown</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>No beam</td>
<td>Beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Detectors
CMS in January

220 m² of Silicon!
CMS Explained

A 100 MP digital camera, which takes 40 million frames/sec!
Detector Concept

- Nearly $4\pi$, hermetic, redundant, Russian-doll design

And Missing Transverse Energy ($M_{ET}$) for anything, which does not interact or interacts weakly
Why $\mathcal{M}_{\mathcal{T}}$ is Tough?

• Fake $\mathcal{M}_{\mathcal{T}}$ appears naturally in multijet events, which have enormous rate at the LHC

• Jets tend to fluctuate wildly:
  – Large shower fluctuation
  – Fluctuations in the $e/h$ energy ratio
  – Non-linear calorimeter response
  – Non-compensation (i.e., $e/h \neq 1$)

• Instrumental effects:
  – Dead or “hot” calorimeter cells
  – Cosmic ray bremsstrahlung
  – Poorly instrumented area of the detector

• Consequently, it will be a challenge to use in early LHC running

• Nevertheless, $\mathcal{M}_{\mathcal{T}}$ is one of the most prominent signatures for new physics and thus must be pursued

• Raw $\mathcal{M}_{\mathcal{T}}$ spectrum at the Tevatron and that after thorough clean-up
Trigger
Triggering at Hadron Colliders

- $e^+e^-$ colliders: low total cross section, low rates
  - Trigger pretty much on everything, perhaps with the exception of very forward processes (low-angle Bhabha)

- Hadron colliders: enormous cross section, unattainable rates
  - Trigger is very selective
  - Only small fraction of collisions is written to tape
  - Additional complications due to pile-up

- LHC:
  - $\sigma_{\text{tot}} = 110 \text{ mb}$, $\sigma_{\text{in}} \sim 70 \text{ mb}$
  - $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} = 10 \text{ nb}^{-1}\text{s}^{-1}$
  - 25 ns bunch crossing
  - Total rate: $\sim 10^9 \text{ s}^{-1}$ or $\sim 20$/crossing

- Tevatron:
  - 1.5 smaller cross section; 50 times lower luminosity; 16 times longer crossing time: $\sim 4$/crossing

[Block, Halzen, hep-ph/0510238]

$LHC: \sigma_{\text{tot}} = 107.3 \pm 1.2 \text{ mb}$

[PDG]
More Trigger Challenges

• LHC Physics Demands
  – EWSB in SM (Higgs, W, Z)
  • Lepton/photons $E_T \sim 50$ GeV
  • High rate (10 Hz of top events and 200 Hz of $W(l\nu)$ events!)
  – TeV scale supersymmetry, UED
  • Multiple leptons, jets and LSPs (missing $E_T$), $E_T < 100$ GeV

• QCD Background
  – Jet $E_T \sim 250$ GeV, rate $\sim 1$ kHz
  – Jet fluctuations $\Rightarrow$ electron BG
  – Decays of $p, K, B \Rightarrow$ muon BG

• Technical challenges
  – 40 MHz input $\Rightarrow$ fast processing
  – 100 Hz output $\Rightarrow$ physics selection
  – $10^9$ events per year $\Rightarrow$ $\leq 10^2$ Higgs events

• Benchmark: $\sigma = 100$ pb $\rightarrow$ 1 Hz
• Must reduce 2.5-40 MHz of input interactions to 50-100 Hz
  – Do it in steps/successive approximations: “Trigger Levels”

“Traditional”: 3 physical levels, ATLAS

CMS: 2 physical levels

x400 rejection

x1000 rejection
Example 1: SUSY in Jets + $M_{E_T}$
Strong Production, Complicated Events

\[
\begin{align*}
\tilde{g} &\rightarrow \tilde{t}_1^+ \tilde{t}_1^- \\
&\rightarrow W^- + \tilde{b} \\
&\rightarrow s + \chi_2^0 + h \\
&\rightarrow u_L + \chi_2^0 + h
\end{align*}
\]

\[
\begin{align*}
\text{Jet4, } E_T &= 113 \text{ GeV} \\
\text{Jet5, } E_T &= 70 \text{ GeV} \\
\text{Jet3, } E_T &= 536 \text{ GeV} \\
\text{Jet1, } E_T &= 206 \text{ GeV} \\
\text{Jet2, } E_T &= 320 \text{ GeV}
\end{align*}
\]

\[
\begin{align*}
\text{m_{miss}} \\
E_T &= 380 \text{ GeV}
\end{align*}
\]

\[
\begin{align*}
m_{\tilde{g}} &= 1256 \text{ GeV} \\
m_{\tilde{t}_1} &= 1450 \text{ GeV} \\
m_{\chi_2^0} &= 1026 \text{ GeV} \\
m_{\chi_2^0} &= 410 \text{ GeV} \\
m_{\chi_1^0} &= 214 \text{ GeV} \\
m_h &= 119 \text{ GeV}
\end{align*}
\]
Possibility for an Early Discovery

- Even with a handful of statistics the reach will be expanded dramatically compared to the Tevatron limits.
Possibility for an Early Discovery

- Even with a handful of statistics the reach will be expanded dramatically compared to the Tevatron limits

\[ \text{DØ, } L=2.1 \text{ fb}^{-1} \]

\[ \tan \beta = 3, A_0 = 0, \mu < 0 \]

\[ \text{no mSUGRA solution} \]

\[ \text{LEP2 } \chi^2 \]

\[ \text{LEP2 } \gamma^2 \]

\[ \text{no mSUGRA solution} \]

\[ \text{CMS} > 0 \]

\[ \frac{1}{2}m \]

\[ \text{LEP} \]

\[ \text{DØ } \]

\[ \text{LSP1} \]

\[ \text{NO EWSB} \]

\[ m_\tau = 120 \text{ GeV} \]

\[ \text{1 fb}^{-1} \]

\[ \text{10 fb}^{-1} \]

\[ \text{jets } \geq 3 + E_T^{\text{miss}} > 600 \text{ GeV} \]

with systematics
SUSY Event Selection

- Focus on low-mass SUSY points
- Jets and ME_T always present; no hit for leptonic branching fraction

<table>
<thead>
<tr>
<th>Point</th>
<th>m_0</th>
<th>m_{1/2}</th>
<th>tan β</th>
<th>sign(µ)</th>
<th>A_0</th>
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<td>60</td>
<td>250</td>
<td>10</td>
<td>+</td>
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<td>35</td>
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<td>300</td>
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<td>-300</td>
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<td>180</td>
<td>850</td>
<td>10</td>
<td>+</td>
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<td>HM2</td>
<td>350</td>
<td>800</td>
<td>35</td>
<td>+</td>
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<tr>
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<td>800</td>
<td>10</td>
<td>+</td>
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<tr>
<td>HM4</td>
<td>1350</td>
<td>600</td>
<td>10</td>
<td>+</td>
<td>0</td>
</tr>
</tbody>
</table>

### Signal Signature

- \( N_1 \geq 3 \), \(|\Delta \eta| < 1.7\)
- \( \delta \phi_{\text{min}}(E_T^\text{miss} - \text{jet}) \geq 0.3 \) rad, \( R1, R2 > 0.5 \) rad,
- \( \delta \phi(E_T^\text{miss} - j(2)) > 20^\circ \)
- QCD rejection
- \( I_{\text{iso}}^{\text{lead \, trk}} = 0 \)
- \( f_{\text{em}}(j(1)), f_{\text{em}}(j(2)) < 0.9 \)
- \( E_{T,j(1)} > 180 \text{ GeV}, E_{T,j(2)} > 110 \text{ GeV} \)
- ILV (I) W/Z/\bar{t}t rejection
- ILV (II), W/Z/t\bar{t} rejection
- \( H_T = E_{T(2)} + E_{T(3)} + E_{T(4)} + E_T^\text{miss} > 500 \text{ GeV} \)
- Signal/background optimisation

SUSY LM1 signal efficiency 13%
A SUSY candidate event:
- Leading jets $ET = 330, 140, 60\ GeV$
- $MET = 360\ GeV$
QCD Background Rejection

- The dominant background is QCD multijet production with fake MEₜ
- Can be effectively reduced by requiring the minimum angular separation between the MEₜ vector and the direction of jet 1 (leading) or jet 2 (subleading)
- Use extrapolation from low MET region to estimate residual background (a la DØ)

90% efficient 15% efficient
Z(νν) + Jets: Estimate from Data

- Use Z(ee) and Z(μμ) + jets for normalization; acceptance corrections via MC
- Necessary since the signal and background shapes are similar
Reach

- Significant reach with as low as $\sim 100 \text{ pb}^{-1}$
Reach

• Significant reach with as low as $\sim 100$ pb$^{-1}$
Other SUSY Channels

- Clearly, a number of channels will be investigated in parallel, including lepton+jets, like- and opposite-sign dileptons, channels with tau’s, and MSSM Higgs searches.
- Sensitivity in all these channels is being reevaluated using most realistic simulation available.
- Previous studies suggest that the best reach is achieved in inclusive channels.
(More) Exotic Models

"Particles, particles, particles."
Example 2:
Extra Dimensions in Space
**Extra Dimensions: a Brief Summary**

**ADD Paradigm:**
- **Pro:** “Eliminates” the hierarchy problem by stating that physics ends at a TeV scale
- Only gravity lives in the “bulk” space
- Size of ED’s (n=2-7) between ~100 μm and ~1 fm
- Black holes at the LHC and in the UHE cosmic rays
- **Con:** Doesn’t explain why ED are so large

**TeV⁻¹ Scenario:**
- **Pro:** Lowers GUT scale by changing the running of couplings
- Only gauge bosons (g/γ/W/Z) “live” in ED’s
- Size of ED’s ~1 TeV⁻¹ or ~10⁻¹⁹ m – i.e., natural EWSB size
- **Con:** Gravity is not in the picture

**RS Model:**
- **Pro:** A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- **Con:** Somewhat disfavored by precision EW fits

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Spring 2008 Physics Colloquium

Greg Landsberg, Searches for New Physics with Early LHC Data
ADD Paradigm:
- Winding modes with energy spacing $\sim 1/r$, i.e. 1 meV – 100 MeV
- Experimentally can’t resolve these modes – they appear as continuous spectrum
- Coupling: $G_N$ per mode; compensated by large number of modes

TeV$^{-1}$ Scenario:
- Winding modes with nearly equal energy spacing $\sim 1/r$, i.e. $\sim 1$ TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: $\sim g_w$ per mode

$$M_i = \sqrt{M_0^2 + \frac{i^2}{r^2}}$$

RS Model:
- “Particle in a box” with special AdS metric
- Energy eigenvalues are given by the zeroes of Bessel function $J_1$
- Light modes might be accessible at colliders
- Coupling: $G_N$ for the zero mode; $1/\Lambda^2$ for the others

$$M_0 = 0; \ M_i = M_1 \frac{x_i}{x_1} \approx M_1, 1.83M_1, 2.66M_1, 3.48M_1, \ldots$$
Collider Signatures for Large ED

- Kaluza-Klein gravitons couple to the energy-momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for $G_{KK}$ see:
  - Han, Lykken, Zhang [PRD 59, 105006 (1999)]
  - Giudice, Rattazzi, Wells [NP B544, 3 (1999)]
- Graviton emission: direct sensitivity to the fundamental Planck scale $M_D$
- Virtual effects: sensitive to the ultraviolet cutoff $M_S$, expected to be $\sim M_D$ (and likely $< M_D$)
- The two processes are complementary
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Real Graviton Emission
Monojets at hadron colliders

Single VB at hadron or $e^+e^-$ colliders
Collider Signatures for Large ED

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Real Graviton Emission
Monojets at hadron colliders

Virtual Graviton Effects
Fermion or VB pairs at hadron or $e^+e^-$ colliders
Looking for ED at Colliders

[© 2000, Ferminews]
Looking for ED at Colliders

[© 2000, Ferminews]
Monojets: Tainted History

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY
ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS

AT $\sqrt{s} = 540$ GeV

[PL, 139B, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

Abstract

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.
Monojets: Tainted History

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN pp COLLISIONS

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[PL, 139B, 115 (1984)]

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VOLUME 54, NUMBER 6

PHYSICAL REVIEW LETTERS

11 FEBRUARY 1985

Monojets from Z Decay without Extra Neutrinos or Higgs Particles

Stephen F. King
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 26 November 1984)

The recent discovery of monojets by Arnison et al.\textsuperscript{1} at the CERN $p\bar{p}$ collider has caused ripples of excitement throughout the particle physics world, since they cannot be explained by the minimal standard model.\textsuperscript{2}
Monojets: Tainted History

- These monojets turned out to be due to unaccounted background

- The signature was deemed doomed and nearly forgotten

- It took many years for successful monojet analyses at a hadron collider to be completed (CDF/DØ)
Expectations at the LHC

• Monojets are tough; what about monophotons?
  – CMS simulations only done for 30 fb$^{-1}$ so far, but the luminosity dependence is weak ($\sim L^{1/4}$)

• Virtual graviton exchange offers clean signature, with a huge potential of a quick discovery in dimuon, dielectron, and diphoton channels:
  – Factor of $\sim 3$ gain over the Tevatron/Cosmic Ray limits in just 100 pb$^{-1}$
  – Will also probe compositeness models with similar increase in sensitivity compared to the existing limits

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>$M_D^{max}$ (TeV) LL, 30 fb$^{-1}$</th>
<th>$M_D^{max}$ (TeV) HL, 100 fb$^{-1}$</th>
<th>$M_D^{min}$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7.7</td>
<td>9.1</td>
<td>$\sim 4$</td>
</tr>
<tr>
<td>3</td>
<td>6.2</td>
<td>7.0</td>
<td>$\sim 4.5$</td>
</tr>
<tr>
<td>4</td>
<td>5.2</td>
<td>6.0</td>
<td>$\sim 5$</td>
</tr>
</tbody>
</table>
Black Holes at the LHC?
Black Holes on Demand

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here’s the idea:

Particles collide in three dimensional space, shown below as a flat plane.

As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

NYT, 9/11/01
Black Hole Events

- Detailed studies already started in ATLAS and CMS
  - ATLAS – CHARYBDIS (HERWIG-based generator with an elaborated decay model by Harris/Richardson/Webber)
  - CMS – TRUENOIR, GL/CHARYBDIS/CATFISH (OleMiss)

- The hunt is going on!
Example 3: Kaluza-Klein Resonances/Z’

Found in RS, TeV^{-1} models and in various Z’ models
Randall-Sundrum Model Observables

- Need only two parameters to define the model: $k$ and $r$
- Equivalent set of parameters:
  - The mass of the first KK mode, $M_1$
  - Dimensionless coupling $k/M_{Pl}$, which determines the graviton width
- To avoid fine-tuning and non-perturbative regime, coupling can’t be too large or too small
  - $0.01 \leq k/M_{Pl} \leq 0.10$ is the expected range
- Gravitons are narrow
- Similar observables for $Z_{KK}/g_{KK}$ in TeV$^{-1}$ models

Davoudiasl, Hewett, Rizzo [PRD 63, 075004 (2001)]
Dielectrons: Discovery Channel

- Excellent resolution 5-10%/\sqrt{E, \text{GeV}} (calorimeter based) and detection efficiency
- Low background above \sim 1 \text{ TeV}

<table>
<thead>
<tr>
<th></th>
<th>KK Z</th>
<th>$G, c = 0.01$</th>
<th>$G, c = 0.1$</th>
<th>SSM Z'</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>4.0</td>
<td>6.0</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$M_w$</td>
<td>3.5-4.5</td>
<td>5.0-6.7</td>
<td>1.47-1.52</td>
<td>3.30-3.65</td>
</tr>
<tr>
<td>$N_s$</td>
<td>50.6</td>
<td>1.05</td>
<td>18.8</td>
<td>7.30</td>
</tr>
<tr>
<td>$N_b$</td>
<td>0.13</td>
<td>0.005</td>
<td>4.16</td>
<td>0.121</td>
</tr>
<tr>
<td>$S$</td>
<td>22.5</td>
<td>3.0</td>
<td>6.39</td>
<td>6.83</td>
</tr>
</tbody>
</table>

CMS, 30 fb$^{-1}$

$Z_{\text{KK}}$ production
Dimuons: Confirmation Channel?

- Generally worse rapidity coverage, detection efficiency

![Efficiency graph]

- Significantly worse momentum resolution than for electrons

![Mass resolution graphs]

- Nevertheless: generally lower instrumental background may make dimuons a discovery channel along with dielectrons
**Randall-Sundrum Graviton Reach**

- **G → ee with c = 0.01**
  - Significance vs. $M$ (TeV/c^2)
  - Luminosity, fb^{-1}

- **G → ee with c = 0.1**
  - Significance vs. $M$ (TeV/c^2)
  - Luminosity, fb^{-1}

<table>
<thead>
<tr>
<th>Coupling constant c</th>
<th>Estimator</th>
<th>1 fb^{-1}</th>
<th>10 fb^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>$S_{eP}$</td>
<td>0.75</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>$S_{eL}$</td>
<td>0.77</td>
<td>1.21</td>
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<tr>
<td></td>
<td>$S_{L}$</td>
<td>0.78</td>
<td>1.23</td>
</tr>
<tr>
<td>0.02</td>
<td>$S_{eP}$</td>
<td>1.21</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>$S_{eL}$</td>
<td>1.22</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>$S_{L}$</td>
<td>1.22</td>
<td>1.74</td>
</tr>
<tr>
<td>0.05</td>
<td>$S_{eP}$</td>
<td>1.83</td>
<td>2.48</td>
</tr>
<tr>
<td></td>
<td>$S_{eL}$</td>
<td>1.85</td>
<td>2.49</td>
</tr>
<tr>
<td></td>
<td>$S_{L}$</td>
<td>1.85</td>
<td>2.51</td>
</tr>
<tr>
<td>0.1</td>
<td>$S_{eP}$</td>
<td>2.34</td>
<td>3.11</td>
</tr>
<tr>
<td></td>
<td>$S_{eL}$</td>
<td>2.36</td>
<td>3.13</td>
</tr>
<tr>
<td></td>
<td>$S_{L}$</td>
<td>2.36</td>
<td>3.16</td>
</tr>
</tbody>
</table>

**CMS Discovery Limit of Randall-Sundrum Graviton**

- $\mu^+\mu^-$ Channel
- Luminosity, fb^{-1}
- Graviton Mass, GeV/c^2
- Allowed region
KK Excitations of the Z Boson

ATLAS $e^+e^-$

ATLAS $M_c=4$ TeV

ATLAS $M_{\gamma}=4$ TeV

ATLAS $M_{\gamma}=4$ TeV

Drell-Yan

$M_c = 4$ TeV

$M_c = 5$ TeV

$M_c = 6$ TeV

$M_c = 7$ TeV

CMS

$Z$

$\eta$

$E$ (GeV)

Spring 2008 Physics Colloquium

Greg Landsberg, Searches for New Physics with Early LHC Data
KK Reach

- Dramatic reach even with ~1 fb^{-1}
Example 4: The Higgs

The race of two machines
**Tevatron Search Strategy**

- **Low mass Higgs** ($M_H < 135 \text{ GeV}$):
  - $bb$ decay channel
  - Associated $WH/ZH$ production to keep backgrounds under control
  - Final states: $l\nu bb$, $llbb$, $\nu\nu bb$ or $l\nu bb$

- **High mass Higgs** ($M_H > 135 \text{ GeV}$):
  - $WW^{(*)}$ decay channel
  - Production via gluon fusion to maximize cross section
  - Final states: $ll'\nu\nu'$

- **Backgrounds**:
  - $W/Z +$ (heavy quark) jets, dibosons
  - Single and pair top production
  - QCD multijets

- **Analyses**:
  - $l\nu bb$: $1.9 \text{ fb}^{-1}$ CDF + $1.7 \text{ fb}^{-1}$ DØ
  - $llbb$: $1.0 \text{ fb}^{-1}$ CDF + $1.1 \text{ fb}^{-1}$ DØ
  - $\nu\nu bb$: $1.7 \text{ fb}^{-1}$ CDF + $0.9 \text{ fb}^{-1}$ DØ
For $M_H = 115$ GeV, $\sigma^{95}/\sigma^{SM} = 5.1$ (3.3) observed (expected)

Tevatron Run II Preliminary, $L=1.0-2.4$ fb$^{-1}$

- $LEP$ Limit
- Tevatron Expected
- Tevatron Observed
- $\pm 1\sigma$ CDF Exp
- $\pm 2\sigma$ DØ Exp

March 10, 2008
The Race is On!

- Challenge: commissioning detectors simultaneously with search for Higgs
- Early running: gluon fusion production; $\gamma\gamma$, $WW(\rightarrow ll'll')$, $ZZ \rightarrow lll'l'$
- Discovery possible with $\sim 5fb^{-1}$ of well understood data: 2009?

**Graphs:**
- CMS

**Legend:**
- $5fb^{-1}$ enough for $140<m_H<450GeV/c^2$
- 2009?

**Significance**
- CMS, 30 fb$^{-1}$
- discovery with 30fb$^{-1}$ in the full range
The Race is On!

• Challenge: commissioning detectors simultaneously with search for Higgs

• Early running: gluon fusion production; $\gamma\gamma, WW(*) \rightarrow ll'\nu\nu'$, $ZZ \rightarrow lll'l'$

• Discovery possible with $\sim 5\text{fb}^{-1}$ of well understood data: 2009?

---

**Needed $\mathcal{L}dt (\text{fb}^{-1})$ per experiment**

- $\leq 1\text{fb}^{-1}$ for 98% C.L. exclusion
- $\leq 5\text{fb}^{-1}$ for 5$\sigma$ discovery over full allowed mass range

---

**2009?**

---

**Luminosity for 5$\sigma$ discovery, fb$^{-1}$**

- $5\text{fb}^{-1}$ enough for $140 < m_H < 450 \text{ GeV}/c^2$

---

**Spring 2008 Physics Colloquium  Greg Landsberg, Searches for New Physics with Early LHC Data**
The Race is On!

- Challenge: commissioning detectors simultaneously with search for Higgs
- Early running: gluon fusion production; $\gamma\gamma$, $WW^(*) \rightarrow ll'\nu\nu'$, $ZZ \rightarrow ll'l'l$
- Discovery possible with $\sim 5\text{fb}^{-1}$ of well understood data: 2009?

**Graphs:**
- CMS Luminosity for $5\sigma$ discovery
- Needed $\mathcal{L}dt$ (fb$^{-1}$) per experiment
- ATLAS + CMS preliminary

**Data:**
- 5fb$^{-1}$ enough
- 10 events 0.5 GeV
- Needed $\mathcal{L}dt$ (fb$^{-1}$) per experiment
- 1 fb$^{-1}$ for 98% C.L. exclusion
- $\leq 5$ fb$^{-1}$ for 5$\sigma$ discovery over full allowed mass range
Challenges

There will be surprises on the way!
Before One Can Succeed in Searches

- Proper detector calibration, alignment, and detailed simulation is required
- Taunting task, which easily takes several years
- Searches typically look for one event in a million; that means that the detector often has to be understood to the $10^{-6}$ level!
- Use calibration samples of well understood nature:
  - Test beams (initial calibration)
  - Cosmic runs (alignment, efficiency)
  - Minbias data (channel-by-channel calibration)
  - “Standard candles” – Z, W, top (efficiency, non-Gaussian tails in resolution, b-tagging)
  - Z(ee) and $\gamma +$ jets (jet energy calibration and resolution)
  - High-p$_T$ dijets (saturation, ME$_T$ resolution and tails)
- Easily a subject for several dedicated lectures; not covered here in detail:
  - See 2006, 2007 Hadron Collider Physics Summer School proceedings for dedicated talks
- Note: while a few spectacular discoveries may happen as early as 2008, most would require two-three years of accelerator running and operating the detectors!
  - Gear up for a long(er) ride!
# Early Discovery Menu from Chez LHC

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass reach</th>
<th>Luminosity (fb⁻¹)</th>
<th>Early Systematic Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Interaction</td>
<td>$\Lambda &lt; 2.8$ TeV</td>
<td>0.01</td>
<td>Jet Eff., Energy Scale</td>
</tr>
<tr>
<td>$Z'$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALRM</td>
<td>$M \sim 1$ TeV</td>
<td>0.01</td>
<td>Alignment</td>
</tr>
<tr>
<td>SSM</td>
<td>$M \sim 1$ TeV</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>LRM</td>
<td>$M \sim 1$ TeV</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>E6, SO(10)</td>
<td>$M \sim 1$ TeV</td>
<td>0.03 – 0.1</td>
<td></td>
</tr>
<tr>
<td>Excited Quark</td>
<td>$M \sim 0.7 – 3.6$ TeV</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>Axigluon or Colouron</td>
<td>$M \sim 0.7 – 3.5$ TeV</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>E6 diquarks</td>
<td>$M \sim 0.7 – 4.0$ TeV</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>Technirho</td>
<td>$M \sim 0.7 – 2.4$ TeV</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>ADD Virtual $G_{KK}$</td>
<td>$M_0 \sim 4.3 - 3$ TeV, $n = 3-6$</td>
<td>0.1</td>
<td>Alignment</td>
</tr>
<tr>
<td></td>
<td>$M_0 \sim 5 - 4$ TeV, $n = 3-6$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ADD Direct $G_{KK}$</td>
<td>$M_0 \sim 1.5-1.0$ TeV, $n = 3-6$</td>
<td>0.1</td>
<td>MET, Jet/photon Scale</td>
</tr>
<tr>
<td>SUSY</td>
<td>$M \sim 1.5 – 1.8$ TeV</td>
<td>1</td>
<td>MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backgrounds</td>
</tr>
<tr>
<td>Jet+MET+0 lepton</td>
<td>$M \sim 0.5$ TeV</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Jet+MET+1 lepton</td>
<td>$M \sim 0.5$ TeV</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Jet+MET+2 leptons</td>
<td>$M \sim 0.5$ TeV</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>mUED</td>
<td>$M \sim 0.3$ TeV</td>
<td>0.01</td>
<td>ibid</td>
</tr>
<tr>
<td>$\text{TeV}^{-1} (Z_{KK}^{(1)})$</td>
<td>$M_{z1} &lt; 5$ TeV</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>RS1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>di-jets</td>
<td>$M_{d1} \sim 0.7 - 0.8$ TeV, $c=0.1$</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>di-muons</td>
<td>$M_{d1} \sim 0.8 - 2.3$ TeV, $c=0.01-0.1$</td>
<td>1</td>
<td>Alignment</td>
</tr>
</tbody>
</table>
LHC Discovery Roadmap

- ADD X-dim@9TeV
- SUSY@3TeV
- Compositeness@40TeV
- H(120GeV)→γγ
- Higgs@200GeV
- SUSY@1TeV
- 10-20 fb⁻¹/yr
- 100 fb⁻¹/yr
- 1000 fb⁻¹/yr

Year:
- 2008
- 2010
- 2012
- 2014
- 2016
- 2018
- 2020

Integrated luminosity (fb⁻¹)
- 0.1
- 1
- 10
- 30
- 100
- 300
- 1000
- 3000

SHUTDOWN
- 200 fb⁻¹/yr

Z'@6TeV
Conclusions
It’s Fun to be a Theorist Today

• Enormous landscape of models
  – Peaks, deserts, valleys, some of which may be hidden!

• Emerging connection of physics at the smallest and largest distances

• Wild West of models; some are pretty imaginative
  – New particles
  – New dimensions
  – New geometries and topologies

• State of the art high-precision calculations at NLO and NNLO

• Improved QCD calculation precision:
  – Important insights from string theory methods (twistor space, AdS/CFT)
  – Greatly improved lattice QCD

• Very powerful MC generators

• Good understanding of PDF and uncertainties

• Interesting attempts to reverse-engineer experimental data
It’s Really a Great Time to be an Experimenter!
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- We have a beautiful picture of the universe, and yet it is strikingly incomplete
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- We have **detailed maps** - theoretical guidance - but let’s not forget that we **may be in the uncharted waters**
- The **future is bright**; no bumps on the road would stop us
- We are **destined to find unknown**, perhaps of a much more puzzling type than any of us could now imagine!
If History is a Guide...

- Let’s recall a tale of a great discovery of five centuries ago: the discovery of the Americas
- Christopher Columbus was an ideal experimenter:
  - He raised funding
  - He ignored theoretical prejudice
  - He was lucky
  - As a result, he has discovered a WHOLE NEW WORLD!
- We have a thing or two to learn from him...
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¡Prospero Año Nuevo 2008: el año de LHC!