Searches Beyond the Standard Model at the LHC

Yuri Gershtein
There Must Be New Physics!

- Explain low mass of Higgs (hierarchy problem)
- Explain Dark Matter
  - why shouldn’t it be produced at colliders?
- Explain matter-antimatter imbalance in the Universe
- Explain why Yukawa couplings range more than 11 orders of magnitude from electron neutrino to top quark
- Would be nice to unify gauge forces (and incorporate gravity at some point...)

We also have ideas what this new physics could be - which lead us to believe that there is something new at energies ~ electroweak scale

- we just need to look in the right place...
Money for the operation through high price electricity period are allocated, the length of the run is ~11 months with minimum sensitivity to delays.

Energy is 10 TeV, integrated luminosity ~200 pb$^{-1}$

**Dataset with real discovery potential**
- 10 TeV is 5 times Tevatron’s energy
Event Counts

200 pb\(^{-1}\)
10 TeV

Available during the 2009-2010 Run

New Physics

5/4/2009
Yuri Gershtein (Rutgers) APS 2009 April Meeting
The ATLAS detector
The CMS detector

Total weight: 12'500 T
Overall diameter: 15.0 m
Overall length: 21.5 m
Magnetic field: 4 Tesla
In This Talk...

You’ve heard how great the LHC discovery potential is for many years now – and we keep improving our analysis methods.

What I’ll try to do in this talk is to focus on a few examples of how we think we will be able to prove to ourselves and to the world that we have made a discovery

- topology driven searches
- simple and inclusive methods
- data driven background estimation

“Supersymmetry”
- counting experiments & shapes of distributions
- Jets+MET
- lepton+Jets+MET

“Smoking gun”
- unmistakably sharp features (almost self-calibrating...)
- Z’, W’
- black holes

Detector Commissioning
- we now have real data to work with!
Extra Gauge Bosons

- 2 electrons
  - $p_T > 30$ GeV
  - $|\eta| < 2.5$ & fiducial cuts
  - isolated

- electron
  - $p_T > 50$ GeV
  - $|\eta| < 2.5$
  - isolated
  - MET > 50 GeV
  - $\sum p_T^{\text{leptons}} + \sum E_T^{\text{jets}} > 0.5$
Extra Gauge Bosons

- Not very significant change in reach in 10 vs 14 GeV
  - optimization of running conditions done by physics reach, not $E_{cm}$!

### 5σ discovery reach

<table>
<thead>
<tr>
<th>$Z'$ mass (TeV)</th>
<th>$\sigma(14 \text{ TeV})/\sigma(10\text{ TeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
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</table>

- $Z'_{SSM}$
  - Tevatron's 95%CL' limit
- $Z'_{ij}$
  - $\sqrt{s}=10 \text{ TeV}$
  - $\sqrt{s}=14 \text{ TeV}$

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5/4/2009

Yuri Gershtein (Rutgers) APS 2009 April Meeting
Black Holes

- Models with Large Extra Dimensions (i.e. ADD) Black holes could be produced at the LHC if the $M_{\text{Planck}}$ is $O(1-10 \text{ TeV})$

- They will decay through Hawking’s radiation into a large number of objects democratically

- Identify objects: muons, electrons, photons and jets
- sum up their $|p_T|$ in addition to cut on sum $|p_T|$ require existence of one lepton above 200 GeV or, alternatively, four objects above 200 GeV
SUSY @ LHC

Since superpartners of quarks and gluinos carry color, they are the most abundantly produced SUSY particles at the LHC – small kinematical suppression compared to Tevatron

\[ \tilde{q}\tilde{q} \rightarrow q\tilde{\chi} \quad \bar{q}\tilde{\chi} \quad \text{at least two high } E_T \text{ jets} \]

\[ \tilde{q}\tilde{g} \rightarrow q\tilde{\chi} \quad q\bar{q}\tilde{\chi} \quad \text{at least three high } E_T \text{ jets} \]

\[ \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi} \quad q\bar{q}\tilde{\chi} \quad \text{at least four high } E_T \text{ jets} \]

SUSY events at the LHC, even those with leptons are very jetty. Strategy is to have a grid of analyses:

<table>
<thead>
<tr>
<th></th>
<th>1 jet</th>
<th>2 jet</th>
<th>3 jets</th>
<th>4 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 lepton</td>
<td></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>1 lepton</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>2 lepton</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>3 leptons</td>
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<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>
Jets + Missing Transverse Energy

- Very high probability of new physics
  - if Dark Matter particles are $O(100 \text{ GeV})$ they will be produced by the LHC resulting in missing $E_T$. Since it is hadronic collider association with jets is natural
  - staple Supersymmetry search
- One of the toughest channels: instrumental background
  - Missing $E_T$ is sensitive to all the noise, miscalibration, beam halo and hard to clean up and commission
  - Jets fluctuate and can be catastrophically under-measured in a way that is not reproduced by simulation
  - jet cross-section is humongous even small effects in jet response can look like new physics
Jets + MET

- at least 4 jets $E_T > 50$ GeV
  - one with $E_T > 100$ GeV
- MET > 100 GeV
- lepton veto
- sphericity
- for three leading jets $\Delta \phi (\text{jet}, \text{MET}) > 0.2$
Measuring Jet Response

- Measure how often jets are mis-measured
  - Gauss + low energy tail
  - measure gaussian component from $\gamma$+jet balance
  - measure tail from “Mercedes” events

- Take events at low MET and apply the non-Gaussian part of the response to them to predict the high MET tail
Physics Background to Jets+MET

- Irreducible background is coming from Z+jets, where Z decays into neutrinos
  - high order QCD predictions have large uncertainties

- Can be inferred by looking at Z+jets → l+1−+jets but this results in a large statistical error due to smallness of ee & µµ branchings

- Another idea: Z is just a “heavy photon” – at high $Q^2$ the should be little difference between Z+X and $\gamma$+X
  - use $\gamma$+jets events to predict Z+jets
  - works very well, theoretical uncertainties in the ratio of Z to $\gamma$ are small

Other backgrounds from W and top involve lost leptons and are “easily” estimated from lepton+jets+MET samples
Jets+MET without MET

For 2 jets + MET channel can avoid relying on MET altogether by devising clever topological variables

\[ \alpha_T = \frac{E_T^{j2}}{M_T^{j1,j2}} \approx \frac{\sqrt{E_T^{j2} / E_T^{j1}}}{\sqrt{2(1 - \cos \Delta \varphi)}} \]

For perfectly measured QCD di-jets \( \alpha_T = 0.5 \). If one of the jets is undermeasured, \( \alpha_T \) decreases.

- 2 jets, \( E_T^{j1} + E_T^{j2} > 500 \) GeV
- lepton veto
- \( \alpha_T > 0.55 \)

It is possible to generalize \( a_T \) variable to multi-jet case – work is ongoing...


CMS preliminary
Lepton+jets

- Requiring a lepton really helps reducing QCD
- But a new challenge arises: how to deal with W+jets and top backgrounds
  - theoretical prediction has large uncertainties. After years of running at 2 TeV, Tevatron still has to correct W+jets simulation using Z+jets
- Note, that for the largest background sources, W+jets and semi-leptonic top, MET always comes from a single neutrino from W decay creating a sharp jacobian peak
  - use it to normalize the background predictions!

Only guaranteed to work if Variable 1 and 2 are uncorrelated
Lepton+jets

Simulation seems to tell us that MET and $M_T$ are not strongly correlated.

In the absence of signal the method works perfectly.

<table>
<thead>
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<th>$\not{E}_T &gt; 300$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>True BG</td>
<td>$203 \pm 6$</td>
<td>$12.4 \pm 1.6$</td>
</tr>
<tr>
<td>Estimated BG</td>
<td>$190 \pm 8$</td>
<td>$9.4 \pm 0.7$</td>
</tr>
<tr>
<td>Ratio(Est./True)</td>
<td>$0.93 \pm 0.05$</td>
<td>$0.76 \pm 0.11$</td>
</tr>
</tbody>
</table>

The problem is that “background” samples are contaminated with signal – reduced sensitivity...

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<td>$203 \pm 6$</td>
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</tr>
<tr>
<td>Estimated BG</td>
<td>$296 \pm 10$</td>
<td>$33.3 \pm 1.4$</td>
</tr>
<tr>
<td>True BG+SUSY</td>
<td>$653 \pm 8$</td>
<td>$245 \pm 4$</td>
</tr>
</tbody>
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Start-up and Commissioning

It is a large and difficult task to commission detectors like CMS and ATLAS.

But by the time the beam collisions come we will have operated the detectors for almost two years:

- system stabilities and noise measured
- trackers partially aligned
- magnetic fields mapped out with cosmic muons
- billions of events acquired, reconstructed, distributed, re-reconstructed, and compared to detector simulation
- countless problems solved

The start-up is likely to be very different from the Run II Tevatron, where detector and accelerator were brought up ~ simultaneously.
Cosmics Event Example: ATLAS
Cosmics Event Example: CMS
Tracker Alignment

- alignment algorithms work
- achieved precision is already better than considered MC scenario after 10 pb$^{-1}$ of data
data
total stopping power in PbWO4
collision loss
bremsstrahlung

CMS ECAL

Measured stopping power (corrected for containment) of muons in ECAL
Note – the lines are not fits, but absolute predictions

ATLAS muons

consistency of direction in the azimuthal angle between Muon and Inner Tracker - good agreement with MC
One Beam

~2x10^9 protons on collimator
~150 m upstream of CMS

Energies >100 TeV!!

Hundreds of thousands muons/event

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Summary

- LHC operations with two beams will start this year!

- Detectors had more than a year to iron out problems – may be able to produce physics grade results soon after collisions

- Methods for early analysis are improving

Stay tuned!!