Quest for New Physics at the Large Hadron Collider

Outline

- Where we started
- Do we understand what we are doing
- Search for the Higgs Boson
- Search for Super Symmetry
- Summary and Outlook

November 19, 2011

Sunanda Banerjee
The Standard Model

- Structure of matter has been studied using high energy collision probing to a scale of $10^{-18}$ m
- Earlier experiments (particularly the experiments done at the LEP and Tevatron) have tested the predictions of the Standard Model to a high level of accuracy
- All measurements agree with the predictions which start with a few unknown parameters

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Standard Model</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{t}$ [GeV]</td>
<td>172.7 ± 2.9 ± 0.6</td>
<td>172.7 ± 2.8</td>
<td>0.0</td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>80.450 ± 0.058</td>
<td>80.376 ± 0.017</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>80.302 ± 0.039</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>$M_Z$ [GeV]</td>
<td>91.1876 ± 0.0021</td>
<td>91.1874 ± 0.0021</td>
<td>0.1</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4968 ± 0.0011</td>
<td>-0.7</td>
</tr>
<tr>
<td>$\Gamma_{\text{had}}$ [GeV]</td>
<td>1.7444 ± 0.0020</td>
<td>1.7434 ± 0.0010</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_{\text{inv}}$ [MeV]</td>
<td>499.0 ± 1.5</td>
<td>501.65 ± 0.11</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma(e^+e^-)$ [MeV]</td>
<td>83.984 ± 0.886</td>
<td>83.996 ± 0.021</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}$ [nb]</td>
<td>41.541 ± 0.037</td>
<td>41.467 ± 0.009</td>
<td>2.0</td>
</tr>
<tr>
<td>$R_e$</td>
<td>20.804 ± 0.050</td>
<td>20.756 ± 0.011</td>
<td>1.0</td>
</tr>
<tr>
<td>$R_p$</td>
<td>20.785 ± 0.033</td>
<td>20.756 ± 0.011</td>
<td>0.9</td>
</tr>
<tr>
<td>$R_\tau$</td>
<td>20.764 ± 0.045</td>
<td>20.801 ± 0.011</td>
<td>-0.8</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.000066</td>
<td>0.21578 ± 0.00010</td>
<td>0.8</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 ± 0.0030</td>
<td>0.17230 ± 0.00004</td>
<td>-0.1</td>
</tr>
<tr>
<td>$A_{F(0,e)}$</td>
<td>0.0145 ± 0.0025</td>
<td>0.01622 ± 0.00025</td>
<td>-0.7</td>
</tr>
<tr>
<td>$A_{F(0,p)}$</td>
<td>0.0169 ± 0.0013</td>
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<td>0.5</td>
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<tr>
<td>$A_{F(0,\gamma)}$</td>
<td>0.0188 ± 0.0017</td>
<td></td>
<td>1.5</td>
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<tr>
<td>$A_{F(0,B)}$</td>
<td>0.1031 ± 0.0008</td>
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<td>-2.4</td>
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<tr>
<td>$A_{F(0,\gamma)}$</td>
<td>0.0767 ± 0.0035</td>
<td>0.0737 ± 0.0006</td>
<td>-0.8</td>
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<tr>
<td>$A_{F(0,\gamma)}$</td>
<td>0.0970 ± 0.0014</td>
<td>0.1032 ± 0.0008</td>
<td>-0.5</td>
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<tr>
<td>$A_{F(0,B)}$</td>
<td>0.0232 ± 0.00012</td>
<td>0.0231 ± 0.00014</td>
<td>0.7</td>
</tr>
<tr>
<td>$A_{F(0,B)}$</td>
<td>0.0238 ± 0.00015</td>
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<td>-1.5</td>
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<tr>
<td>$A_e$</td>
<td>0.15138 ± 0.000216</td>
<td>0.1471 ± 0.0011</td>
<td>2.0</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>0.1494 ± 0.00060</td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>0.1498 ± 0.00049</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>$A_\nu$</td>
<td>0.142 ± 0.0015</td>
<td></td>
<td>-0.3</td>
</tr>
<tr>
<td>$A_\lambda$</td>
<td>0.138 ± 0.0015</td>
<td></td>
<td>-0.7</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>0.136 ± 0.0015</td>
<td></td>
<td>-0.7</td>
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<tr>
<td>$A_\lambda$</td>
<td>0.1439 ± 0.0043</td>
<td></td>
<td>-0.7</td>
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<tr>
<td>$g_{F}^{L}$</td>
<td>0.923 ± 0.020</td>
<td>0.9347 ± 0.0001</td>
<td>-0.6</td>
</tr>
<tr>
<td>$g_{F}^{R}$</td>
<td>0.670 ± 0.027</td>
<td>0.6678 ± 0.0005</td>
<td>0.1</td>
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<tr>
<td>$g_{F}^{C}$</td>
<td>0.895 ± 0.091</td>
<td>0.9356 ± 0.0001</td>
<td>-0.4</td>
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<tr>
<td>$g_{F}^{L}$</td>
<td>0.30005 ± 0.000137</td>
<td>0.30378 ± 0.00021</td>
<td>-2.7</td>
</tr>
<tr>
<td>$g_{F}^{R}$</td>
<td>0.03076 ± 0.000110</td>
<td>0.03006 ± 0.00003</td>
<td>0.6</td>
</tr>
<tr>
<td>$g_{F}^{C}$</td>
<td>-0.040 ± 0.015</td>
<td>-0.0396 ± 0.00003</td>
<td>0.0</td>
</tr>
<tr>
<td>$g_{T}$</td>
<td>-0.507 ± 0.014</td>
<td>-0.5064 ± 0.0001</td>
<td>0.0</td>
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<tr>
<td>$A_{F(L)}$</td>
<td>-1.31 ± 0.17</td>
<td>-1.53 ± 0.02</td>
<td>1.3</td>
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<tr>
<td>$Q_{W}(C_{S})$</td>
<td>-7.26 ± 0.46</td>
<td>-7.31 ± 0.03</td>
<td>1.2</td>
</tr>
<tr>
<td>$Q_{W}(T_{L})$</td>
<td>-116.6 ± 3.7</td>
<td>-116.78 ± 0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>$\Gamma(\tau\rightarrow\tau\nu)$</td>
<td>3.35 ± 0.50 × 10^{-3}</td>
<td>(3.22 ± 0.09) × 10^{-3}</td>
<td>0.3</td>
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<tr>
<td>$\Gamma(\mu\rightarrow\tau\nu)$</td>
<td>451.67 ± 0.82</td>
<td>450.82 ± 0.10</td>
<td>1.5</td>
</tr>
<tr>
<td>$\Gamma(\nu_{\tau}/\nu_{\tau})$</td>
<td>290.89 ± 0.58</td>
<td>291.87 ± 1.76</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

The Standard Model is a beautiful theory and arguably one that is most precisely tested
Further Experimentation

- Main motivation of building the next generation experiments:
  - Look for the origin of mass – most likely scenario is through spontaneous symmetry breaking → Higgs boson
  - Find candidates for dark matter – Super Symmetry has a natural candidate for dark matter
  - Standard Model is not complete while beyond Standard Model physics is not unique → find a good candidate

- Build the Large Hadron Collider (LHC) and construct experiments there which can take up those challenges
  - Design criteria of an experiment is guided by what we are trying to find
  - Take the example of one such experiment - the Compact Muon Solenoid
Large Hadron Collider
(not to scale)

CMS & ATLAS: General purpose, Higgs, SUSY ? ?
LHC-b: B-Physics, CP-violation
ALICE: Heavy Ion, QGP

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Quest for New Physics at the LHC
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CMS as Higgs Finder

At the LHC search for the SM Higgs boson provides a good benchmark for the performance of a detector

Natural Width

<table>
<thead>
<tr>
<th></th>
<th>0.01</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>GeV</th>
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<tbody>
<tr>
<td>50</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
</tr>
</tbody>
</table>

HIGGS MASS GeV

Lep 190

H → γγ (WH → γγ l) (t ¯tH → γγ l)

H → ZZ* → 4 l

H → ZZ → 2ν + 2μ or 2e

H → WW or ZZ jj → 21 jj

Transparency from the early 90’s
Design Criteria → CMS

Very good muon identification and momentum measurement
High trigger efficiency and measure sign of TeV muons with $dp/p < 10\%$

High energy resolution electromagnetic calorimeter with resolution $\sim 0.5\% @ E_T \sim 50$ GeV

Powerful inner tracking systems
Momentum resolution a factor 10 better than at LEP

Hermetic calorimeter
Good missing $E_T$ resolution
Understanding CMS Detector

- Tracks are reconstructed with great precision
- Momentum resolution as well as energy scale are fantastic

Electrons/photons are identified using shower shapes in ECAL and its performance is well understood.

$\Xi^- \rightarrow \Lambda \pi^-$

CMS Preliminary

Yield: 2344.8 ± 58.2
Mean: 1321.92 ± 0.09 MeV/c$^2$
Sigma: 3.24 ± 0.09 MeV/c$^2$
Statistical uncertainties only

PDG Mass:
1321.71 ± 0.07

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Quest for New Physics at the LHC
Jets and Missing $E_T$

Energies of isolated charged particles as well as jets are well modeled in simulation. Detector noise is also well modeled to reproduce MET distributions.
Muons are measured with very high resolution and momentum scale is well matched to reproduce the resonance masses accurately.
The Large Hadron Collider performed magnificently during 2010-11 period. It operated at a centre of mass energy of 7 TeV and during the initial period luminosity used to get doubled every week. There is a dramatic rise in luminosity even during 2011. From April to October, luminosity increased from $2 \times 10^{32}$ to $3.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. CMS collected the delivered luminosity with more than 91% efficiency.
However, .....
Higgs at LHC

- $gg \to H$ is the dominant production mechanism
- Irreducible backgrounds to the processes $H \to WW, ZZ, \gamma\gamma$ due to Standard Model processes
- $S/B$ is better at LHC than at Tevatron except for $VH$ production
Low mass Higgs boson decays dominantly to b-bar, while from 150 GeV onward decay to vector boson pair is dominant. For intermediate and high mass Higgs boson search, vector boson (pair) and ttbar poses irreducible background.
Low Mass Higgs Search: $H \rightarrow \gamma\gamma$

- $\gamma_1 = 86$ GeV
- $\gamma_2 = 56$ GeV

**Signature:** 2 energetic, isolated $\gamma$, narrow mass peak

**Background:** Large & partly irreducible QCD. Measured from $M_{\gamma\gamma}$ sidebands in data

- Data divided in 8 categories depending on $\gamma\gamma$ mass resolution & their $p_T$
- Background shape fitted by 2nd order polynomial constrained to be positive
- Signal shape: Sum of 3 Gaussians, parameters determined from $Z \rightarrow ee$ data
Intermediate Mass Higgs: $H \rightarrow WW$

Signal characteristics:
- Only 2 opposite sign, isolated leptons with small $\Delta \phi$
- Significant Missing $E_T$
- No mass peak, no b-jet, no additional high $p_T$ lepton

Major requirements:
- Lepton $p_T > 10$ GeV, tight ID & Isolation
- Large MET & $Z \rightarrow \mu \mu$, ee veto
- Classification by # of jets ($p_T > 30$ GeV)
- Kinematic discriminants: $M_{ll}$ & $\Delta \Phi (l^+l^-)$
- $M_H$-dependent cut optimization
Higgs Search in $H \rightarrow ZZ \rightarrow 4l$

- **Signal**: 4 isolated lepton from common vertex
- **Fully reconstructed**, Mass resolution $\sim 2$-4 GeV
- **Reducible backgrounds** reduced by isolation & impact parameter requirements – remaining part measured from data.
- **Irreducible background**: $pp \rightarrow ZZ$ continuum. Shape from NLO – rate from data.
- **Event Selection**: Same Flavor, opposite charge, 2 Z-candidates, $M_{4l} > 120$ GeV, impact parameter significance $> 4$

Pair of events observed at three mass bins: 122, 142, 165 GeV

$M_{4\mu} = 201$ GeV

$p_T = 43$ GeV

$p_T = 48$ GeV

$p_T = 26$ GeV

$p_T = 20$ GeV
High Mass Higgs Search

- $H \rightarrow ZZ \rightarrow 2l\ 2\nu$: One H decaying to leptons and other decays in invisible mode: Look for high $p_T$ lepton pair in Z mass window and large missing $E_T$
- $H \rightarrow ZZ \rightarrow 2l\ 2\text{jet}$: Instead of large missing $E_T$, look for 2 jets in Z-mass window

$H \rightarrow ZZ \rightarrow 2l\ 2\nu$ Search

$H \rightarrow ZZ \rightarrow 2l\ 2\text{jet}$ Search
Summary of All Searches

Solid line = Observed limit; Dashed line = Median Expected

CMS Preliminary

95% CL limit on $\sigma/\sigma_{SM}$

Higgs boson mass (GeV/c²)

Combined
$H \rightarrow bb$ (1.1 fb⁻¹)
$H \rightarrow \tau\tau$ (1.1 fb⁻¹)
$H \rightarrow \gamma\gamma$ (1.7 fb⁻¹)
$H \rightarrow WW$ (1.5 fb⁻¹)
$H \rightarrow ZZ \rightarrow 4l$ (1.7 fb⁻¹)
$H \rightarrow ZZ \rightarrow 2l\ 2\tau$ (1.1 fb⁻¹)
$H \rightarrow ZZ \rightarrow 2l\ 2q$ (1.6 fb⁻¹)
$H \rightarrow ZZ \rightarrow 2l\ 2\nu$ (1.6 fb⁻¹)
Combination

95% CL limit on $\sigma/\sigma_{SM}$

CMS Private, $\sqrt{s} = 7$ TeV
Combined, $L_{int} = 1.1-1.7$ fb$^{-1}$

- Observed
- Expected ± $1\sigma$
- Expected ± $2\sigma$

Expected exclusion mass range: 130 – 440 GeV
Observed exclusion mass range: 145-216, 226-288, 310-400 GeV

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Quest for New Physics at the LHC

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SUSY?

- Supersymmetric partners of SM particles are produced in pair and during decay the lowest mass SUSY object only interacts weakly and leaves the detector undetected giving rise to large missing energy.
- Exact mechanism of production and decays are very much model dependent.

- Topology based searches, not optimized for any particular SUSY model.
- Most searches probe tails of $E_T^{\text{miss}}$ distribution.
- Try to cover as much phase space as possible (e.g. as low lepton $p_T$ as possible).
- Estimate backgrounds from data (data-driven background estimate) to minimize reliance on MC (e.g. for detector (mis)reconstruction effects).
SUSY Searches

<table>
<thead>
<tr>
<th>0-leptons</th>
<th>1-lepton</th>
<th>OSDL</th>
<th>SSDL</th>
<th>≥3 leptons</th>
<th>2-photons</th>
<th>γ+lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets + MET</td>
<td>Single lepton + Jets + MET</td>
<td>Opposite-sign di-lepton + jets + MET</td>
<td>Same-sign di-lepton + jets + MET</td>
<td>Multi-lepton</td>
<td>Di-photon + jet + MET</td>
<td>Photon + lepton + MET</td>
</tr>
</tbody>
</table>

1. Most sensitive search for strongly produced SUSY – very challenging due to large amount & wide range of BG
2. Lepton requirement reduces BG considerably – use topological handles
3. BG due to W significantly reduced – use shape information
4. Natural SUSY signature – very small Standard Model BG
5. Very clean events with low Standard Model BG
6. Many Gauge mediated models predict γ’s in final state – dominated by QCD multijet and γ+jet background
7. Requirement of a lepton reduces Standard Model Background
Inclusive All-Hadronic Search

Signature:
Many jets and large missing transverse energy

- Least model-dependent analysis

Large backgrounds:
- Z+jets with \( Z \rightarrow \nu\nu \) (irreducible)
- W+jets and ttbar with \( W \rightarrow l\nu \) and lost lepton or \( \tau \rightarrow \) hadrons + \( \nu \)
- QCD multijet events with large missing transverse momentum due to:
  - Leptonic decays of heavy flavor hadrons
  - Jet energy mismeasurement
  - Instrumental noise
  - Non-functioning detector components
Event Selection

Baseline selection

- At least 3 jets with $p_T^{\text{jet}} > 50$ GeV and $|\eta| < 2.5$
- $H_T > 350$ GeV
- $H_T^{\text{miss}} > 200$ GeV
- $|\Delta \phi (J_1, J_2, H_T^{\text{miss}})| > 0.5$ and $|\Delta \phi (J_3, H_T^{\text{miss}})| > 0.3$ to veto events where $H_T^{\text{miss}}$ is aligned in transverse plane with one of the 3 leading jets
- Veto on isolated muons and electrons

$$H_T = \sum |p_T^{\text{jet}}|$$

$$H_T^{\text{miss}} = -\sum p_T^{\text{jet}}$$
Search Results

- No excess over estimated background is observed
- Observed and expected 95% CL exclusion limit in the CMSSM $m_0$-$m_{1/2}$ plane using the signal cross sections calculated at NLO
- Contours are the combination of the different selections, such that the shown contours are the envelope with respect to best sensitivity
Results on several analyses on SUSY signals ($\alpha_T$ with and without b-tag, fully hadronic channels, di-photons, SS/OS dileptons, single leptons+MET, photons and MET, lepton spectrum and multi-leptons etc) have been produced.
Summary

- The Large Hadron Collider has started a successful journey to explore new quarters of particle physics.
- Compact Muon Solenoid is utilizing the richness of LHC to look for the elusive Higgs boson.
- Recently SINP has joined this effort and hopes to contribute significantly in this field.
- So far neither CMS nor ATLAS have seen hints of any new physics – not even the Standard Model Higgs boson.
- We are on the verge of getting into something spectacular – either rule out the Standard Model or see some evidence of physics beyond the Standard Model.

Please say tuned.
Back Up
Rediscovering Standard Model
p-value estimates probability of upward background fluctuation as high or higher than the excesses observed in data.