LHC Experience and Prospects

Computing in High Energy Physics 2012

May 21, 2012
New York City

Joe Incandela
UC Santa Barbara/CERN

8 TeV event with 16 jets
April 5, 2012
The Standard Model

Confirmed to below 1% uncertainty by 100’s of precision measurements

- $\Delta\alpha^{(\text{had})}(m_Z)$: $0.02758 \pm 0.00035$
- $m_Z$ [GeV]: $91.1875 \pm 0.0021$
- $\Gamma_Z$ [GeV]: $2.4952 \pm 0.0023$
- $\sigma^0_{\text{had}}$ [nb]: $41.540 \pm 0.037$
- $R_l$: $20.767 \pm 0.025$
- $A^0_{\text{tb}}$: $0.01714 \pm 0.00095$
- $A_{\text{l}}(P)$: $0.1465 \pm 0.0032$
- $R_b$: $0.21629 \pm 0.00066$
- $A_{\text{fb}}$: $0.0992 \pm 0.0016$
- $A_{\text{c}}$: $0.0707 \pm 0.0035$
- $A_{\text{b}}$: $0.923 \pm 0.020$
- $\sin^2 \theta_{\text{eff}}$: $0.2324 \pm 0.0012$
- $m_W$ [GeV]: $80.399 \pm 0.023$
- $\Gamma_W$ [GeV]: $2.085 \pm 0.042$
- $m_t$ [GeV]: $173.3 \pm 1.1$

July 2010
Where we stood last summer

- July 2011
  - $M_t = 173.2 \pm 0.9 \text{ GeV}$
  - $M_W = 80.399 \pm 0.023 \text{ GeV}$
  - $M_H = 89^{+35}_{-26} \text{ GeV (68\% CL)}$
  - Between the red diagonals

- $M_H < 185 \text{ GeV (95\% CL)}$
  - But we don’t assume it’s not above 185 without a direct search…
The Higgs mass:

- SM particles affect the Higgs mass. Corrections are huge
  - $\Lambda$ could be $10^{19}$ times the mass of the proton (Planck scale)
  - A.K.A. The Hierarchy problem

$$m_n^2 = (m_n^2)_0 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2.$$
- Partner particles
  - Need same couplings $\lambda$
  - Partners (especially 3\textsuperscript{rd} generation) with not too big masses
- A much smaller term is all that’s left
  - It too becomes large if the new partners are very very heavy
- SUSY is the most appealing source of partners

\[
m^2_n = (m^2_n)_0 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \ldots
\approx (m^2_n)_0 + \frac{1}{16\pi^2} (m^2_{\tilde{f}} - m^2_f) \ln(\Lambda / m_{\tilde{f}}),
\]
We now know that only ~5% of the energy in the universe is ordinary matter (remember $E=mc^2$).

- 25% is dark matter
  - SUSY theories can happily predict this amount

- There are other possibilities but SUSY is a favorite
  - Provides great dark matter candidates
    - (e.g. Neutralino or Gravitino)
  - Leads to remarkable unification of field strengths
  - And it fixes the Higgs mass problem
The absence of any hint of SUSY at LEP, the Tevatron, or LHC accelerators (so far) coupled with results from cosmology and astrophysics experiments, has motivated alternative models. These are characterized by new particles (like SUSY) or new spatial dimensions:

- Little Higgs (with T Parity)
- Universal extra dimensions (with KK parity)
- Strong dynamics
- Extra dimensions (large or warped)
- Hidden Valleys
- Split SUSY
- …

If you don’t exactly know what you’re looking for, a Large Hadron Collider (LHC) is the great tool to use!
Incredible performance! Both pp and Pb-Pb

Stellar performance of the LHC enabled all experiments to produce significant physics results in the first 3 years or operation.
Having gained confidence in 2011 operations:

The LHC has increased energy to 4 TeV beams, tighter collimation and $\beta^*=0.6$ to allow much higher instantaneous luminosity $L$ and much more $\int Ldt$ (More on this later…)
Having gained confidence in core operations:
And it continues to perform extraordinarily well!

Many thanks to Steve and all the incredibly talented staff involved!

And much more $\int L dt$ (More on this later...)
Reasonable to expect that the luminosity estimate is fairly conservative ($\beta^*=0.6$ m may be possible, many other improvements, etc.)

From Steve Myers
We envisage 2 break-points

First Break-point

Check if we are on track to produce sufficient integrated luminosity for the Higgs

If needed we can delay the start of LS1 by up to 2 months

From Steve Myers
LHCb

Probing the heavy flavor sector
- To understand CP violation
- Find indirect evidence of new physics
- To discover new particles
- To observe the rarest decays
LHCb: Recent results, 2011 data

B(Bs→μμ) < 4.5 \times 10^{-9} at 95% CL

B_{SM} \sim 3 \times 10^{-9}

Probes SUSY, other New Physics: MSSM: BR - \tan^{6} \beta

B_s \rightarrow \mu \mu

CPV in D \rightarrow KK, \pi \pi

AFB Precision probe of SM, sensitive to new RH currents

Take differences in measured asymmetries to cancel systs

LHCb 3.5\sigma from SM

CPV phase in decay amplitude (\phi_{SM} \sim 0.0) from fit to decay times of \textit{B}_{s}^{0} \bar{B}_{s}^{0}
LHCb: More results

\( B_s \to K^+K^- \)

\( \Delta m_s \) 1\textsuperscript{st} time meas. in charmless decays
Accesses CKM angle \( \gamma \) in penguins

- LHCb measurements constrain many SUSY models particularly at high \( \tan \beta \).
- Complementary to direct searches by ATLAS and CMS

Allowed region from \( B_s \to \mu\mu \) and \( \phi_s \)

\( B_{SM} \sim 10^{-7} \)

Highly suppressed B, D decays with \( \gamma \) dependent interference

\( B^\pm \to [\pi^\pm K]_D K^\mp \)
New particles discovered at LHC: LHCb

First observation of $B^+ \to \pi^+ \mu^+ \mu^-$

- This is the first observation of a $b \to d l l$ transition
- LHCb(1.0 fb$^{-1}$): $B^+ \to \pi^+ \mu^+ \mu^-$: $25.3^{+6.7}_{-6.4}$ signal events
  - 5.2σ excess above background
- The measurement is consistent with the SM prediction

$B(B^+ \to \pi^+ \mu^+ \mu^-) = (2.4 \pm 0.6{\text{(stat)}} \pm 0.2{\text{(syst)}}) \times 10^{-8}$ [preliminary]

The rarest B decay ever observed
LHCb: 2012 data taking startup

- Data-taking ~90% efficiency
  - Successful test vertical collision scheme
    - Symmetric with magnet swaps (25 ns)
  - Test HLT deferred trigger
  - Better S/B at 8 TeV + improved HLT + more CPU $\rightarrow +20$-$30\%$ mainly had. Decays

- $\sqrt{s} = 8$ TeV ($\sigma_{\text{pp}}$ up 15%)
- $L \sim 4 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- Target $\geq 1.5$ fb$^{-1}$

- HLT-online reconstructed $D^0 \rightarrow 2$-body: same S/B, increased yield (amount under study)
LHCb: 2012 data taking startup

- Data-taking ~90% efficiency
- Successful test vertical collision scheme
  - Symmetric with magnet swaps (25 ns)
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Very good prospects for “world record” measurements

\[ \sqrt{s} = 8 \text{ TeV} \] (\( \sigma_{\text{fb}} \) up 15%)

\[ L \sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]

Target \( \geq 1.5 \text{ fb}^{-1} \)

HLT-online reconstructed \( D^0 \rightarrow 2\text{-body} \): same S/B, increased yield (amount under study)
ALICE

• Probing the early state of the Universe: Quark Gluon Plasma
  • Elliptic Flow
  • Hadron suppression
  • Dissolved/Recombined Charmonium
  • ...

Pb-Pb event in ALICE

Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
ALICE in 2011

Additional EM Calorimetry

\[ \Lambda \rightarrow p\pi^- \]

Low $p_T$ tracking

Particle ID

$K^0 \rightarrow \pi^+\pi^-$
QGP explosive expansion generates $u, d, s$ mass ordering of elliptic flow

Charm flows as well: $c$ quark thermalization in QGP
QGP tomography with high $p_T$ partons:

$$E_{\text{loss}}^g > E_{\text{loss}}^q > E_{\text{loss}}^Q?$$

- pQCD dictates that gluons will lose more energy than quarks in the QGP
  - For heavy quarks, there’s an additional kinematic factor (dead cone effect), which suppresses gluon emission

- Interaction of Quarkonia with QGP
  - $J/\Psi$ less suppressed in denser QGP
  - Recombination?
- pp @ 8 TeV 5 pb\(^{-1}\) baseline MB sample at new \(\sqrt{s}\)
  - High multiplicity trigger: Charm in high multiplicity events
  - Jets (EMCAL) and photons (EMCAL/PHOS)
  - Electrons: High \(p_T\) with TRD, HF@high \(p_T\), electrons for quarkonia

- pPb/Pbp @ 4 TeV 30 nb\(^{-1}\)
  - Separation of initial and final state effects in PbPb
  - Measurements: parton saturation & shadowing
    - Heavy flavor, Quarkonia, Jet rates, Direct photons, Dell-Yan cross sections
ATLAS & CMS
Re-discovery of the Standard Model

- [uū], [dd], [sś]
- [cć], [bś]

~1960, 1974, 1978

CMS Preliminary
\[ \sqrt{s} = 7 \text{ TeV}, \quad L_{\text{int}} = 40 \text{ pb}^{-1} \]

1983

40 pb^{-1} collected in 2010
Expectations and observation

Candidates / 0.025 GeV

Barrel

CMS, 4.9 fb$^{-1}$

$\sqrt{s} = 7$ TeV

$B_d$ expected

1.0 ± 0.4

$B_s$ expected

3.5 ± 0.7

Endcap

CMS, 4.9 fb$^{-1}$

$\sqrt{s} = 7$ TeV

$B_d$ expected

1.0 ± 0.4

$B_s$ expected

2.5 ± 0.6

From 1.5B events on tape

<table>
<thead>
<tr>
<th>Variable</th>
<th>CDF</th>
<th>CMS</th>
<th>Atlas</th>
<th>LHCb</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (fb$^{-1}$)</td>
<td>10</td>
<td>4.9</td>
<td>2.4</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>$\text{Br}(B_d \to \mu^+\mu^-)$ 95% CL ($\times10^{-9}$)</td>
<td>4.6</td>
<td>1.8</td>
<td>1.03</td>
<td>0.10 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>$\text{Br}(B_s \to \mu^+\mu^-)$ 95% CL ($\times10^{-9}$)</td>
<td>31</td>
<td>7.7</td>
<td>22</td>
<td>4.5</td>
<td>3.2 ± 0.2</td>
</tr>
</tbody>
</table>
New particles discovered at LHC: ATLAS

$X_b(3P) \rightarrow \Upsilon(1s,2s) \gamma$

$\int L dt = 4.4 \text{ fb}^{-1}$

$\mu^+ \mu^- \gamma$ Candidates / (25 MeV)

$\chi_b^{(1P)} m = 9.9 \text{ GeV}$ and $\chi_b^{(2P)} m = 10.2 \text{ GeV}$ states clearly visible

New structure at 10.5 GeV

Confirmed with $\Upsilon(2s)$ data and with un-converted photons

Significance $> 6 \sigma$

As theoretically predicted

$m [X_b(3P)] = 10.530 \pm 0.005 \text{ (stat)} \pm 0.009 \text{ (syst)} \text{ GeV}$

$X_b(nP) \rightarrow \Upsilon(1s,2s) \gamma \rightarrow \mu^+ \mu^- \gamma$

$X_b(1P) m = 9.9 \text{ GeV}$ and $X_b(2P) m = 10.2 \text{ GeV}$ states clearly visible

New structure at 10.5 GeV $\rightarrow X_b(3P)$

Confirmed with $\Upsilon(2s)$ data and with un-converted photons

Significance $> 6 \sigma$

As theoretically predicted

PRL.arXiv:1112.5154v4[hep-ex]
New particles discovered at LHC: CMS

$$\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+ \rightarrow \Xi^- J/\psi \pi^+ \rightarrow \Lambda \pi^- \mu^+ \mu^- \pi^+ \rightarrow p^+ \pi^- \mu^+ \mu^- \pi^+$$

$$M(p^+\pi^-) = 1116.7 \text{ MeV}$$
$$M(\Lambda^0\pi^-) = 1315.5 \text{ MeV}$$
$$M(\mu^+\mu^-) = 3117.1 \text{ MeV}$$
$$M(J/\psi\Xi^-) = 5787.8 \text{ MeV}$$
$$Q(J/\psi\Xi^- \pi^+) = 15.7 \text{ MeV}$$

CMS data
- Opposite-sign $p_{T\Xi}$
- Same-sign $p_{T\Xi}$

Signal+background fit
- Background fit

CMS
- Opposite-sign data
- Signal+background fit
- Background

arXiv:1204.5955

CMS
$$\Xi_b^{*0}$$
$\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+ \rightarrow \Xi^- J/\psi \pi^+ \rightarrow \Lambda \pi^- \mu^+ \mu^- \pi^+ \rightarrow p^+ \pi^- \mu^+ \mu^- \pi^+$

$\Xi_b^{*0}$ event with 3 secondary and ~10 primary vertices

$M(p^+\pi^-) = 1116.7 \text{ MeV}$
$M(\Lambda^0\pi^-) = 1315.5 \text{ MeV}$
$M(\mu^+\mu^-) = 3117.1 \text{ MeV}$
$M(J/\psi\Xi^-) = 5787.8 \text{ MeV}$
$Q(J/\psi\Xi^- \pi^+) = 15.7 \text{ MeV}$

New particles discovered at LHC; CMS
Standard Model: Precision Jets, W, and $\gamma^*/Z$

**Inclusive jet and dijets. 2-4% JES. Constrains gluon PDF up to $x=0.6$**

**Differential Drell-Yan cross section: 2.5M $\mu\mu$ pairs tests NNLO PDFs and cross sections**

**W electron charge asymmetry measured to 0.5-1% per bin of 0.1 in $\Delta\eta$. Constrains $u/d$ PDF ratio**

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CMS-PAS-QCD-11-004

CMS-PAS-SMP-12-001

CMS-PAS-EWK-11-007
<table>
<thead>
<tr>
<th>Process</th>
<th>Final state</th>
<th>Measured total cross-section</th>
<th>Theory (NLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>lνlν</td>
<td>$\sigma_{WW}^{tot} = 53.4 \pm 2.1\text{(stat)} \pm 4.5\text{(syst)} \pm 2.1\text{(lumi)} \text{ pb}$</td>
<td>45.1 ± 2.8 pb</td>
</tr>
<tr>
<td>ZZ</td>
<td>4l</td>
<td>$\sigma_{ZZ}^{tot} = 7.2^{+1.1}<em>{-0.9}\text{ (stat)}^{+0.4}</em>{-0.3}\text{ (syst)} \pm 0.3\text{ (lumi)} \text{ pb}$</td>
<td>6.5^{+0.3}_{-0.2} pb</td>
</tr>
<tr>
<td>ZZ</td>
<td>llνν</td>
<td>$\sigma_{ZZ}^{tot} = 5.4^{+1.3}<em>{-1.2}\text{ (stat)}^{+1.4}</em>{-1.0}\text{ (syst.)} \pm 0.2\text{ (lumi.)} \text{ pb}$</td>
<td>6.5^{+0.3}_{-0.2} pb</td>
</tr>
</tbody>
</table>

- Backgrounds to Higgs searches
- Access triple gauge couplings, New Physics
CMS average: $172.6 \pm 0.4 \pm 1.2$ GeV
Tevatron average: $173.2 \pm 0.6 \pm 0.8$ GeV

**Dilepton:** most precise

**TOP-11-015**

**TOP-11-016**

**CMS $\mu+$Jets analysis**

$$m_t = 172.64 \pm 0.57 \text{(stat+JES)} \pm 1.18 \text{(syst)} \text{GeV}$$

$$\text{JES} = 1.004 \pm 0.005 \text{(stat)} \pm 0.012 \text{(syst)}$$
CMS average: $172.6 \pm 0.4 \pm 1.2$ GeV
Tevatron average: $173.2 \pm 0.6 \pm 0.8$ GeV

Cross-check: 44660 events

After applying the calibration, we obtain a top quark mass from 44660 events of $m_t = 172.64 \pm 0.57$ (stat+JES) $\pm 1.18$ (syst) GeV which confirms the result obtained in the main analysis.
As $\int L dt$ grows and more rare processes become accessible
- use them to confirm our understanding of the SM
- to validate detector/physics simulation, objects reconstruction, event selections and analysis techniques

See K. Black’s talk
As $\int L \, dt$ grows and more rare processes become accessible

- use them to confirm our understanding of the SM
- to validate detector/physics simulation, objects reconstruction, event selections and analysis techniques

See K. Black’s talk
Higgs Searches
\[ M_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos \alpha)} \]

- **The challenges**
  - Very large backgrounds
    - Two real and/or fake \( \gamma \)
      - Real \( \gamma \)'s radiated off quarks
      - Neutral pion decaying to collimated pair of \( \gamma \)'s
  - Look for small excess at one mass from \( H \rightarrow \gamma\gamma \)
    - Need excellent \( \gamma \) energy resolution
      - You have to know the point of decay of the Higgs to about 1 cm.

\[ \sigma \approx 40 \text{ fb} \]
Fit observed $\gamma\gamma$ mass distribution with signal + background model:
- Exponential spectrum for background;
- Crystal-ball function to describe the signal

**Observed exclusion:**
113-115 GeV
134.5-136 GeV


Excess at 126.5 GeV with a significance of
2.8$\sigma$ – local
1.5$\sigma$ – global (110-150 GeV)
CMS Update 2: $H \rightarrow \gamma\gamma$ with MVA

- Train MVA on Monte Carlo
  - Use variables independent of $M_H$
  - Categorize on MVA output
    - 4 classes: MVA cut values optimized against expected limit using MC background
    - 5th VBF Dijet class (loose cut MVA)

- Results
  - Best class (class 0)
    - Almost exclusively $p_{T}^{\gamma} > 40$ GeV
  - Second best class (class 1)
    - Predominantly unconverted $\gamma$'s

<table>
<thead>
<tr>
<th>Class</th>
<th>Events/GeV</th>
<th>Data (events/GeV)</th>
<th>SM signal expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.4 (4.4%)</td>
<td>4.5 (1.2%)</td>
<td>19.3 (25.0%)</td>
</tr>
<tr>
<td>1</td>
<td>19.3 (25.0%)</td>
<td>55.1 (14.8%)</td>
<td>81.3 (21.8%)</td>
</tr>
<tr>
<td>2</td>
<td>18.7 (24.2%)</td>
<td>81.3 (21.8%)</td>
<td>229.1 (61.6%)</td>
</tr>
<tr>
<td>3</td>
<td>33.0 (42.8%)</td>
<td>229.1 (61.6%)</td>
<td>2.8 (3.6%)</td>
</tr>
<tr>
<td>Dijet</td>
<td></td>
<td></td>
<td>2.1 (0.6%)</td>
</tr>
</tbody>
</table>

$\sigma_{\text{eff}}$ (GeV) | FWHM/2.35 (GeV)
1.18 | 1.09
1.25 | 1.09
1.64 | 1.43
2.47 | 2.08
1.65 | 1.32

Events/GeV = no. of events in a bin of ±10 GeV, centered at 120 GeV, divided by 20 GeV. Resolutions: 120 GeV Higgs
See talks by R. Yoshida, W. Quayle
- MVA's for vertex ID, $\gamma$ and $\gamma\gamma$ ID
- VBF again split off separately
  - Dominates in vicinity of 124-125 GeV

$\sqrt{s} = 7$ TeV $L = 4.76$ fb$^{-1}$

BDT $\geq 0.05$ VBF Tag

Local significance drops
$3.1\sigma \rightarrow 2.9\sigma$
LEE significance
$1.8\sigma \rightarrow 1.6\sigma$ (range 110-150 GeV)

110-111, 117.5-120.5, 128.5-132, 139-140, 146-147 GeV
SM $H \rightarrow \gamma\gamma$ excluded (95% CL)
$H \rightarrow ZZ^* \rightarrow 4\mu, 4e, 2e2\mu$

ATLAS: $H \rightarrow ZZ \rightarrow 4l \rightarrow 4e, 4\mu, 2e2\mu$

Event yield (full search range)

<table>
<thead>
<tr>
<th></th>
<th>$4e$</th>
<th>$2e2\mu$</th>
<th>$4\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>13.4±2.0</td>
<td>29.7±4.5</td>
<td>18.6±2.8</td>
</tr>
<tr>
<td>Signal (130 GeV)</td>
<td>0.43±0.08</td>
<td>1.22±0.21</td>
<td>1.00±0.17</td>
</tr>
<tr>
<td>Data</td>
<td>17</td>
<td>30</td>
<td>24</td>
</tr>
</tbody>
</table>

ATLAS: \( H \rightarrow WW \rightarrow l\nu l\nu \)

Fit the transverse mass distribution to improve the sensitivity

ATLAS-CONF-2012-012

Observed Exclusion: 130-260 GeV
(expected: 127-234 GeV)
Published

Expected exclusion 114.5 - 543 GeV
Observed exclusion 127.5 - 600 GeV
CMS Combination: p-vals, SM consistency

Local p-value  2.8σ
Global p value  0.8σ (110-600 GeV)
Global p-value  2.1σ (110-145 GeV)
Exclusion info
95% CL: 110-117.5, 118.5-122.5, 129-539 Obs)
95% CL: 120-555 GeV (Exp)

Excluded at 99% CL:
130-486 GeV (Obs)

Not excluded:
117.5-118.5, 122.5-129, >539 GeV
The combined signal rate is consistent with the Standard Model expectation of a 126 GeV Higgs boson.
Overview of the 125 GeV region

- Results are not so consistent
  - Tevatron
    - $b\bar{b}$: CDF yes, DØ no
    - WW: CDF no, DØ yes
  - LHC
    - $gg \rightarrow H \rightarrow \gamma\gamma$: CMS not much, ATLAS YES
    - $VV \rightarrow H \rightarrow \gamma\gamma + 2$ jets: CMS yes, ATLAS not much
    - $ZZ^{(*)}$: ATLAS YES, CMS yes
    - $WW^{(*)}$: ATLAS no, CMS a bit
- Or perhaps this is how the Higgs discovery begins
  - First sightings are lucky upward fluctuations...
- Obviously we need (a lot) more data
  - We’re sitting in a very vulnerable position
- Coincidental small excesses at 125 GeV ...
  - We tend to believe something is there because we expect it to be there (given that it’s not anywhere else).
- Hopefully we’ll also see something in other searches
- Up to now, it has been surprisingly quiet…

$Z' \rightarrow ll$ search
1. $M_{\text{top}}$ vs. $M_W$
   - Tevatron $M_W$ Tours de Force!!
     - $m_W = 80385 \pm 15$ MeV (World Ave – Mar 2012)
   - Shifts for SM Higgs expectation

2. Colliders leave little space

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Combined precision Electroweak data

This is the main story of the past year

We eliminated $>450$ GeV of the mass range.
Supersymmetry
Re-optimized/updated for full 2011 Luminosity

0-lepton + 2–6 jets + high MET
0-lepton + 6–9 (multi-)jets + MET
1-lepton + 3,4 jets + high MET

Example: 0-leptons + 2-6 Jets

H_{T} and missing H_{T}

Many all hadronic searches
• with and without b-tags.
Also searches completed with
1, 2, ≥3 leptons
1 and 2 photons
Simple SUSY models are under pressure
- e.g. mSUGRA: \(\tan\beta=10, A_0=0, \mu>0\)
- Limits ~ 1400 GeV for squarks and gluinos

But SUSY is not dead
- A Higgs discovery will mark the true start of the hierarchy problem
- A 115-130 GeV Higgs is “tailor made” for SUSY

“Natural” SUSY models are still plentiful
- More complicated (and interesting)
- More difficult searches for which it is hard to even get the data on tape!
SUSY getting squeezed

- Simple SUSY models are under pressure
  - e.g. mSUGRA: \( \tan \beta = 10, A_0 = 0, \mu > 0 \)
  - Limits ~ 1400 GeV for squarks and gluinos
- But SUSY is not dead
  - A Higgs discovery will mark the true start of the hierarchy problem
  - A 115-130 GeV Higgs is “tailor made” for SUSY
- “Natural” SUSY models are still plentiful
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  - More difficult searches for which it is hard to even get the data on tape!
**ATLAS SUSY Searches** - 95% CL Lower Limits (Status: March 2012)

\[ \int dt = (0.03 - 4.7) \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

**ATLAS Preliminary**

**Similar tables for CMS**

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**Pheno model**
- 0-jet + j's + \( E_{\text{T,miss}} \)
- 1-jet + j's + \( E_{\text{T,miss}} \)
- multi-jets + \( E_{\text{T,miss}} \)

**Gluino med. \( \tilde{\chi}^\pm \to gq \):**
- 1-jet + j's + \( E_{\text{T,miss}} \)
- 2-jet OS + \( E_{\text{T,miss}} \)
- \( \tilde{g} \) mass (large \( m_{\tilde{g}} \))

**GMSB:**
- \( \tilde{\chi} \) + j's + \( E_{\text{T,miss}} \)
- \( \tilde{g} \) mass (\( m(\tilde{g}) < 2 \text{ TeV} \), light \( \tilde{\chi}^0_1 \))
- \( \tilde{g} \) mass (\( m(\tilde{g}) < 2 \text{ TeV} \), light \( \tilde{\chi}^0_1 \))
- \( \tilde{g} \) mass (\( m(\tilde{g}) < 200 \text{ GeV} \), \( m(\tilde{\chi}^\pm) = \frac{1}{2}(m(\tilde{\chi}^0_1) + m(\tilde{g})) \))
- \( \tilde{g} \) mass (\( \tan \beta < 35 \))
- \( \tilde{g} \) mass (\( \tan \beta > 20 \))
- \( \tilde{g} \) mass (\( m(\tilde{\chi}^0_1) > 50 \text{ GeV} \))

**Direct \( \tilde{b} \to \tilde{\chi}_0^+ b \):**
- 2 b-jets + \( E_{\text{T,miss}} \)
- \( \tilde{b} \) mass (\( m(\tilde{\chi}^0_1) < 60 \text{ GeV} \))

**Direct \( \tilde{\tau} \) (GMSB):**
- Z(\( \rightarrow \tau \nu \)) + b-jet + \( E_{\text{T,miss}} \)
- \( \tilde{\tau} \) mass (115 < \( m(\tilde{\chi}^0_1) < 230 \text{ GeV} \))

**Direct gaugino (\( \tilde{\chi}^0_2 \to 3l_1 \tilde{\chi}^0_1 \)):**
- 2-jet SS + \( E_{\text{T,miss}} \)
- \( \tilde{\chi}^0_2 \) mass \( (m(\tilde{\chi}^0_2) < 40 \text{ GeV} \), \( m(\tilde{\chi}^0_1) = m(\tilde{\chi}^0_2) \), \( m(\tilde{\chi}^0_1) = \frac{1}{2}(m(\tilde{\chi}^0_1) + m(\tilde{\chi}^0_1)) \))

**Direct gaugino (\( \tilde{\chi}^0_{2,3} \to 3l_2 \tilde{\chi}^0_1 \)):**
- 3-jet + \( E_{\text{T,miss}} \)
- \( \tilde{\chi}^0_2 \) mass \( (m(\tilde{\chi}^0_2) < 170 \text{ GeV} \), and as above \)
- \( \tilde{\chi}^0_3 \) mass (\( \tau(\tilde{\chi}^0_2) < 2 \text{ ns} \), 90 GeV limit in [0.2, 90] ns)

**Stable massive particles (SMP):**
- R-hadrons
- R-hadrons (Pixel det. only)
- \( \tilde{\tau} \) mass

**AMSBB:**
- \( \tilde{\tau} \) mass
- \( \tilde{\tau} \) mass (\( \lambda_{31} = 0.10, \lambda_{212} = 0.05 \))

**RPV:**
- high-mass \( \tilde{\tau} \)
- \( \tilde{\tau} \) mass (\( c_{\tilde{\tau}_{\text{LPF}} < 15 \text{ mm} \})

**Bilinear RPV:**
- 1-jet + j's + \( E_{\text{T,miss}} \)
- \( \tilde{\tau} \) mass

**MSUGRA/CMSSM - BC1**
- 4-lepton + \( E_{\text{T,miss}} \)
- \( \tilde{g} \) mass (excl. \( m_{\tilde{q}} < 100 \text{ GeV} \), \( m_{\tilde{q}} = 140 \pm 3 \text{ GeV} \))

---

*Only a selection of the available mass limits on new states or phenomena shown*
Exotica
Search for extra dimension signals:
Kaluza-Klein Gravitons in Randall-Sundrum and Arkani-Hamed, Dimopoulos and Dvali models

Accepted by Phys. Lett. B
arXiv:1112.2194v1[hep-ex]
Pair-produced DM particles via monojets & monophotons (ISR)
- Look for “nothing” plus a single radiated photon or jet
- Probing the same effective operators as in direct detection
- High sensitivity to spin-dependent couplings
- Extends direct detection below 5 GeV
  - Interpret also in ADD LED, set limits on Planck Scale vs. EDs

Dark matter has historically been inferred by many astronomical observations, its composition has been the source of speculation.

"What sets its abundance? Is it a WIMP?" Does it interact with matter apart from gravity? How weak are these interactions?

Direct Detection at Colliders:
- To get a particular WIMP-nucleon cross section we assume that a DM-hadron interaction exists that couple to quarks. Hence a similar interaction can lead to its production at LHC.
  - A similar dark matter pair production could lead to $\pm{\text{MET}}$ final state at the LHC where is radiated from initial state.
Decay into all objects democratically weighted by degrees of freedom
\[ \sum P_T : \text{scalar sum of the } E_T \text{ of the } N \text{ objects in the event} \]

Examples:
- (ATLAS) at least one electron or muon and two or more jets,
- (CMS) any three objects

Sub. to JHEP.
arXiv:1202.6396v1[hep-ex]
Decay into all objects democratically weighted by degrees of freedom

\[ \sum P_T : \text{scalar sum of the } E_T \text{ of the } N \text{ objects in the event} \]

**Examples:** (ATLAS) at least one electron or muon and two or more jets, (CMS) any three objects
A candidate event in CMS with 9 jets and $S_T = 2.6$ TeV
CMS Searches 2011

95% CL Exclusion Limits

Heavy Resonances

- Z' SSM II
- Z' $\psi$ II
- Z', ttbar, hadronic, width=3%
- Z', ttbar, lep+jets, width=3%
- GKK jet+MET $k/M = 0.2$
- GKK jet+MET $k/M = 0.3$
- GKK II $k/M = 0.1$
- GKK $\gamma\gamma$ $k/M = 0.1$
- GKK II $k/M = 0.05$
- GKK $\gamma\gamma$ $k/M = 0.05$
- W' lv, constructive inter.
- W' lv, destructive inter.
- WKK $\mu = 0.05$ TeV
- W' dijet
- WR, MNR < 1.0 TeV
- W'→ WZ
- $\rho_T$, $\pi_T > 700$ GeV

4th Generation

- Mb', b' $\rightarrow$ tW, l+jets
- Mt', t' $\rightarrow$ tZ (100%)
- Mt', t' $\rightarrow$ bW (100%), l+jets
- Mt', t' $\rightarrow$ bW (100%), l+l

Heavy Long-Lived

- gluino, HSCP, gluonball=0.5
- gluino, Stopped Gluino
- stop, HSCP
- stop, Stopped Gluino
- stau, HSCP, GMSB
- hyper-K, hyper-$\rho=1.2$ TeV

Extra Dimension

- LQ1, $\beta=0.5$
- LQ1, $\beta=1.0$
- LQ2, $\beta=0.5$
- LQ2, $\beta=1.0$
- LQ3, $\beta=1.0$

LeptoQuarks

- MBH, rotating, MD=3TeV, nED=2
- MBH, non-rot, MD=3TeV, nED=2
- Quantum BH, MD=3TeV, nED=2
- String Ball, MD=2.1, Ms=1.7, gs=0.4
- String Resonances
- E6 diquarks
- Axigluon/Coloron
- $q^*$, dijet
- $q^*$, dijet pair
- $q^*$, boosted Z
- e*, $\Lambda = 2$ TeV (2010)
- $\mu^*$, $\Lambda = 2$ TeV (2010)
- C.I. $\Lambda$, X analysis, A+ LL/RR
- C.I. $\Lambda$, X analysis, A- LL/RR

Compositeness and Contact Interactions

There’s a similar table for ATLAS
Heavy Ions
Azimuthal Anisotropy

- Fourier coefficients $v_n$ vs. centrality for six $p_T$ ranges
  - From the full FCal event plane method.
  - The shaded bands indicate systematic uncertainties

arXiv:1203.3087
\( \gamma + \text{jet} \) \( p_T \) balance in PbPb: HIN-11-010

- **Transverse momentum ratio:**
  \[ x_{J\gamma} = \frac{p_T^{\text{Jet}}}{p_T^{\gamma}} \text{ vs centrality (N}_{\text{part}}) \]
- **Fraction \( \gamma \) with associated jets:**
  \[ R_{J\gamma} \text{ vs centrality (N}_{\text{part}}) \]

- **2011 Dataset**

  - Full 2011 dataset: Direct measure of parton energy loss in QGP using \( x_{J\gamma} \) and \( R_{J\gamma} \)
  - \( R_{J\gamma} \) in central PbPb collisions is well below PYTHIA + HYDJET
  - Large fraction shifted to \( p_T < 30 \)
Consistent with the SM
- Taking into account nucleon content of colliding nuclei
The 2012 Run

A big year for the LHC (and HEP in general)
What can we expect in 2012?

We should be able to find the SM Higgs or kill it...
At 5.3E33, heading to 7E33 and beyond (?)

CMS HLT
Peak rate: ~500 Hz @ 5x10^{33} cm^{-1}s^{-1}
Average: ~385 Hz

Prepared for
7 x 10^{33} cm^{-1}s^{-1}
PU~30

~100 ms per event near is our old limit.
Upgraded HLT farm in early May as have other experiments.
Limit now around 170-180 ms
- CMS Studied $<PU> \sim 25$
- No optimizations as of yet. Just re-run 2011 analyses
  - Impact on low mass Higgs
    - $H \rightarrow \gamma \gamma$ sees about 15% equivalent lumi loss
    - Worse (much) for $H \rightarrow \tau \tau, WW$
- No significant impact on precision top physics
- No significant impact on $B_{d/s} \rightarrow \mu \mu$

Pileup independence: $B^\pm \rightarrow J/\psi K^\pm$

- Measure efficiency of all selection criteria in data vs $N_{PV}$
- Photon isolation efficiency (5% relative isolation cut)
- No effect on track isolation (same 5% relative isolation cut)
LHC

Computing challenges
- Tevatron a few years into Run2 vs LHC on year 3

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>50Hz</td>
<td>ATLAS 500 Hz CMS 400 Hz LHCb 2 kHz</td>
</tr>
<tr>
<td>RAW Size</td>
<td>150kB</td>
<td>ATLAS 0.6 MB CMS 0.5 MB</td>
</tr>
<tr>
<td>RECO Size</td>
<td>150kB</td>
<td>ATLAS 1.1 MB CMS 1 MB</td>
</tr>
<tr>
<td>Reco Time</td>
<td>~1-2 seconds (CPU of day)</td>
<td>~10 seconds</td>
</tr>
</tbody>
</table>

Roughly a factor of 10 in the relevant quantities
- CMS and ATLAS detectors read out at 10’s of TB/sec
  - Selective triggers get this down to 0.5 – 1 GB/sec
- Larger events in ALICE lead to even bigger numbers
Reprocessing & Reconstruction Challenges

- High profile analyses like $H \rightarrow \gamma\gamma$ require a precise detector calibration
  - In 2011 every CMS event was reconstructed 3 times on average (as planned)
  - In 2012 the events look more like this

*High PU run October 25, 2011*
- LHC experiments produce up to 3 times as many simulated events as real data events
- This is higher than in previous hadron colliders
The Challenge of Distributed Analysis

- Must make a complicated distributed system accessible to a lot of people – A global computing system at your fingertips

- A lot of things need to go right for this to work
  - Efficiency of completion, user experience, debugging and tracking are still being improved
How do they (you know who you are) do it?
- Distributed computing environments very early
  - Grid concepts evolved and matured at the same time
  - Many concepts were motivated by the desire to make use of resources at the home institutes

Workflows were carried out at the expected location basically from the first day. A major LHC success story.

Distributed Computing was commissioned with the detectors
- Computing has grown exponentially in capacity

<table>
<thead>
<tr>
<th></th>
<th>CMS CERN Resources 2011</th>
<th>CDF CAF Resources 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk</td>
<td>5000TB</td>
<td>500TB</td>
</tr>
<tr>
<td>Tape</td>
<td>21PB</td>
<td>6PB</td>
</tr>
<tr>
<td>CPU Cores</td>
<td>5500</td>
<td>~1000 (?)</td>
</tr>
</tbody>
</table>

- The LHC experiments have 3-4 times more processing capacity away from CERN than at CERN
  - Tevatron had about 1 times
- Experiments have > 10x more capacity
But don’t relax, the upgrades are coming …

- LHC Experiments are moving toward more and more data collected each successive year
  - Each run will have 3x the $\int L dt$ of the previous run
  - With 3-year runs the 1st year of every new run will approximately match the discovery potential of the previously collected data

- Detectors are becoming more granular
  - More channels and more precision

- More complexity
  - Computing challenges get more interesting every year
- CMS studies 14 TeV, 25ns
- 30 interactions/bx
- Out-of-time pile-up
  - preceding 3 bx
  - following 5 bx
Life will not be easier...
Summary

- Lots of 2011 full dataset results and publications underway
- LHC experiments are gearing up for ICHEP and year end
- The SM Higgs story will likely be completed this year
- Searches for new physics continue to expand into more difficult areas and have some new reach with $\sqrt{s}=8$ TeV
- It’s amazing how well it all works, despite the immense challenges!
Computing is the final step in a long journey to realizing the full physics potential of the LHC

Many many thanks to the LHC computing and software groups
  - None of this is possible without you!
The year of the Dragon…
Stay Tuned

http://aliweb.cern.ch/
http://atlas.ch/
http://cms.web.cern.ch/
http://lhcb.web.cern.ch/lhcb/
http://totem.web.cern.ch/Totem/