LHC:2010-2011: Standard model

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Things have moved fast

- I was amazed that
  - The detectors worked “out of the box”
  - The software worked “out of the box”
  - The data and the simulation agreed amazingly well

- First Collision data taken November 20 2009
- ATLAS, CMS had published by March 15 2010
- First 7 TeV data taken March 30 2010
- First 7 TeV result shown at conferences April 19
- So much for the naysayers who claimed “it will take years to understand the LHC detectors”
Outline

• How much data?
  – Running conditions

• Types of measurements
  – Things we are sure we know (W cross section)
  – Things we might know (Psi cross section)
  – Things we don't care about but need to know (MC tunings)

• Examples of physics

• Next run in 2013: comments

• I know nothing about the heavy ion program
How much data?

- **900 GeV**
  - “million” events
  - Unlikely to be much more
  - “min bias” physics only

- **2.34 TeV**
  - Very small data set
  - Unlikely to be more
  - “min bias” only

- **7 TeV**
  - Today ~ 10 inverse \( \mu \)b
  - Goal 100 inverse pb in 2010, 1 inverse fb in 2011

About 1 nb-1 collected to date:
- ~65 million inelastic events
- Jets to a few 100 GeV
- Handful of W candidates
Summary of expected event rates

- High pt is limited by
  - Luminosity
  - Detector performance
- Low pt is limited by trigger
  - Total output ~200 Hz
  - Prescales apply to cross-sect
  - 10Hz of min bias
  - 10's Hz of jets (staggered thresholds)
  - Inclusive muons pt>4 GeV (?)
  - Trigger prescales now operating

<table>
<thead>
<tr>
<th>Process</th>
<th>Number Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm \rightarrow l^\pm \nu$</td>
<td>4M</td>
</tr>
<tr>
<td>$Z^0 \rightarrow l^+ l^-$</td>
<td>400k</td>
</tr>
<tr>
<td>ttbar $l+jets$</td>
<td>6000</td>
</tr>
<tr>
<td>ttbar dilepton</td>
<td>2500</td>
</tr>
</tbody>
</table>
Running conditions

• Two variables relevant to physics
  – Integrated luminosity
  – Number of interactions per crossing (in-time pile-up)

• Protons per bunch (Nb), number of bunches (M) and $\beta^*$ (beam focusing) are variables
  – Lumin $\sim MN_b^2/\beta^*$

• Total stored energy $\sim$ total current in machine
  – $MN_b$

• Max luminosity for given safety means large $N_b$
Running conditions II

- Published results are from data without pileup

\[ \frac{\text{number-of-coll.}}{\text{BX}} \]

Number of interactions Per crossing for \( \beta^* = 2m \)

\( \sigma_x = \sigma_y = 30 \, \mu m \)

\( \sigma_{MB} = 50 \, \text{mb} \) (just the NSD cross section)
Running conditions III

- This weeks state
  - Testing $10^{11}$ per bunch
  - Have reached $\beta^*=2m$
  - Together would give $10^{30}$ luminosity with 4 bunches

- Pressure to deliver luminosity is likely to result in most data taken with $\sim5$ interactions per crossing
  - Not expected in earlier planning

- Caveat: this is my opinion.
  - LHC operations plans fluid
Clean pile-up events seen

Collision Event at 7 TeV with 2 Pile Up Vertices

Running conditions IV

• Why does this matter?
• Low pt physics
  - All events are the same
  - Must assign all particles to unique vertex
  - Misassignment compromises measurements
  - ATLAS 7 TeV min bias paper vetoed any pileup events (about 0.5%)
    - Data sets may be limited in size
• High pt physics
  - Less impact: mostly on jet resolution
Strong interactions: Low pt

- None of this is calculable
  - “Engineering measurements” vital for future
  - Needed for calibrating luminosity
- Min bias
  - Needed for pile up
  - Measurements: dN/d\(\eta\),
  - SD/DD/ND comments
- Underlying events
  - Jet energy scale
  - Additional low pt jets (tagging and vetoing)
- Needs running without pile-up
- People will move on from this shortly
“Min bias”

• People talk about “min bias”
  – Misnomer
  – Biased (some kind of trigger or event selection)
  – Unbiased (bunch crossing trigger)

• Results can be difficult to compare to MC
  – Bias must be modeled/corrected
  – Correction can depend on MC model
  – Traditionally results are “corrected” to allow comparison with non-diffractive MC
  • Depends on diffractive contributions (SD/DD)
    – Not well modeled or clearly defined
Min bias: measurements I

**ATLAS Preliminary**
\( p_T > 500 \text{ MeV}, |\eta| < 2.5, n_{ch} \geq 1 \)

\( \sqrt{s} = 7 \text{ TeV} \)

**ATLAS Preliminary**
\( p_T > 500 \text{ MeV}, |\eta| < 2.5, n_{ch} \geq 1 \)

\( \sqrt{s} = 7 \text{ TeV} \)
Evolution from 900 GeV not bad

ATLAS
\( s = 900 \text{ GeV} \)

1/\(N_{\text{ev}}\) \( d^2N_{\text{ch}}/d\eta dp_T\) [GeV^2]

1/\(N_{\text{ev}}\) \( d^2N_{\text{ch}}/d\eta dp_T\) [GeV^2]

Data 2009
PYTHIA ATLAS MC09
PYTHIA ATLAS MC09c
PYTHIA DW
PYTHIA Perugia0
PHOJET

\( p_T > 500 \text{ MeV}, |\eta| < 2.5, n_{\text{ch}} \geq 1 \)

\( p_T > 500 \text{ MeV}, |\eta| < 2.5, n_{\text{ch}} \geq 1 \)

Data Uncertainties
MC / Data

Ratio

Ratio

\( p_T \) [GeV]
Underlying events

Energy flow

Track density
Agreement not bad

- Most preexisting tunings had too few particles and perhaps too slow energy growth
- Existing estimates of pileup effects on new physics signals unlikely to be far off
- Low pt jets emerging from these events are also OK (see later)
  - Impact on tagging and vetoing of jets in new physics signals likely to be reasonable
Other MC tuning measurements

• Detailed particle properties
  – Strangeness fractions
  – Baryon fractions
  – Charm fractions

• Expect these results at pLHC and ICHEP

• A few plots follow
$K_s$ and $\Lambda$
Pi0 and eta

ATLAS preliminary

\[ \sigma_{\text{data}} = 19 \text{ MeV} \]

CMS Preliminary Data \( \sqrt{s} = 7 \text{ TeV} \)

\[ M = 537.37 \pm 0.53 \text{ MeV} \]
\[ \sigma = 6.1 \pm 0.1 \% \]
\[ S/B_{\pm 2\sigma} = 0.34 \]
CMS strangeness
ATLAS charm

D meson

ATLAS Preliminary
\sqrt{s} = 7 \, \text{TeV}

\begin{align*}
\text{Entries / 10 MeV} \\
1.7 & \quad 1.75 & \quad 1.8 & \quad 1.85 & \quad 1.9 & \quad 1.95 & \quad 2 & \quad 2.05 \\
0 & \quad 50 & \quad 100 & \quad 150 & \quad 200 & \quad 250 & \quad 300 & \quad 350 & \quad 400 & \quad 450 & \quad 500 \\
\end{align*}

D-D* mass

ATLAS Preliminary
\sqrt{s} = 7 \, \text{TeV}

\begin{align*}
\text{Entries / 1 MeV} \\
0.14 & \quad 0.145 & \quad 0.15 & \quad 0.155 & \quad 0.16 \\
0 & \quad 50 & \quad 100 & \quad 150 & \quad 200 & \quad 250 & \quad 300 & \quad 350 & \quad 400 & \quad 450 & \quad 500 \\
\end{align*}
Low Pt stuff: final comment

• If you care about this, now is your only chance
• Once we have more interesting data, no one will measure it any more
High pt QCD

• Should be calculable
  – Jet distributions
  – Direct photons
• Verify that detector works
• Check that MC have no bugs
• Validate in regions where predictions may be suspect
  – e.g Multi jet final states
• Extrapolate into new physics regions
Current jets

- Low pt jets emerge nicely from min bias
- Jets up to few hundred GeV seen
- Good agreement with MC: (detector simulation surprisingly good)
- Measured both in calorimeters and tracking
Current measurements

CMS

ATLAS
7 TeV jets
Reach of jets

- 1 inverse pb : 900 GeV
- 100 inverse pb: 1.4 TeV
- 1 inverse fb: 1.7 TeV
- First new physics limit?

Steve Ellis NLO spectrum

Inclusive Jet Cross Section

\( \sqrt{s} = 7 \text{ TeV}, \text{ kT algorithm, D = 0.7} \)

averaged over \(|\eta| \leq 1\)
Partial list of possible results this summer

• Pt spectrum
• Fragmentation function
• Angular correlation
• Multi-jet events
W and Z

- 25K Z and 250K W per 100 inverse pb
- Properties well predicted by QCD
  - Production rate, pt and rapidity distributions
- Properties less well predicted
  - Associated jet multiplicity
    - Important for new physics
- W and Z will be used for calibration
W/Z masses

- Z is a “standard candle”: LHC cannot improve on LEP
- W mass from CDF/D0 used 500K W's
  - LHC will have more by 2011
  - But dominant issue is systematic errors
    - Often scale with statistics as you get more control events
    - LHC may be able to exploit this
- A very hard measurement
- Is there something more interesting?
W production

- First few events look OK
- PP machine so more W+ than W-
- Expected results
  - Pt and rapidity
  - Rapidity distribution probes PDF's beyond HERA range
W candidates

Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST

\[ p_\text{t}(\mu^-) = 40 \text{ GeV} \]
\[ \eta(\mu^-) = 2.0 \]
\[ E_{\text{T}}^{\text{miss}} = 41 \text{ GeV} \]
\[ M_W = 83 \text{ GeV} \]

W-\(\mu\nu\) candidate in 7 TeV collisions

W-ev candidate in 7 TeV collisions

\[ p_\text{t}(e^+) = 34 \text{ GeV} \]
\[ \eta(e^+) = -0.42 \]
\[ E_{\text{T}}^{\text{miss}} = 26 \text{ GeV} \]
\[ M_W = 57 \text{ GeV} \]
Z candidates

ee

Mu mu

CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

Electrons $p_T = 34.0, 31.9$ GeV/c
Inv. mass = 91.2 GeV/c$^2$
Top physics as samples increase

• Observation this summer
• Cross section at 7 TeV
  – Well predicted by QCD
  – Can only be wrong in the tails
• Single top (hard)
• Top properties
  – Decays and production properties
No data yet: so only MC

- S/B better than Tevatron: Higher energy
- Need at least one lepton
- Need a few inverse fb to get started
- More data than Tevatron (horizontal lines)
  - 100 inverse pb for dileptons
  - 150 inverse pb for single leptons
- Someone will try the full hadronic T-Tbar Yields
Handles to extract top: 1 lepton

- Lepton (isolated) and etmiss distributions (must have a W)
- Many jets
- Presence of b-jets
- Top mass peak
- Same number of + and – leptons in signal not in background (not available at Tevatron)
- Backgrounds
  - W+jets
  - Charm and bottom +jets
  - Junk (fake leptons) +jets
Handles to extract top

More jets better S/B

W peak: less junk Bckg

This W+jets background may not be well predicted

No b-tagging required
Top with more data

- Mass peaks
- Clean up background

This is a 10 TeV simulation
Approx same as 500 inverse Pb at 7 TeV
Single top

- Very hard as t tbar is dominant
- Might be possible with much data
- Cannot be sure now
- Possible MC problems?

![Graph showing experimental sensitivity to cross section as a function of integrated luminosity at different center-of-mass energies. The graph indicates an expected sensitivity of ~1 fb⁻¹ at 7 TeV and 10 TeV.]
B-tagging

- Aids greatly in top and new physics
  - Need to measure tagging efficiency and fakes

- Basic methods
  - Vertexing
  - Muons in jets

- (almost) No b's at 900 GeV
  - Understand fakes from K's
Importance of flavor tagging

ATLAS Preliminary

CMS Preliminary, $\sqrt{s} = 900$ GeV

Looking good
7 TeV plots soon
Charm and bottom

• Production properties may not be well described by “theory”
  – Long history of failed predictions and inadequate measurements
• Inclusive b-jet cross section
  – Needs b-tagging
• Inclusive charm
  – Use D*-D trick
  – Kinematics to remove bottom
• Psi and Upsilon rates: prompt and non prompt
Psi have started to appear

- Must identify muons
- Rates only measurable in restricted kinematic regions
Getting ready for new physics: backgrounds

- Some results come for free out of SM measurements
  - Z prime: SM dilepton mass plot
  - W prime: tail of transverse mass plot
  - Jet compositeness: jet pt distribution
  - Top and W+Jets backgrounds to SUSY

- > 100 inverse pb: New regime

Significant Discovery Potential
- 5σ SUSY discovery above current Tevatron limit with a few 100 pb⁻¹
- Z' → μμ up to ~1.5 TeV
- Higgs discovery highly unlikely: 3σ for ~145 to 180 GeV
Next run in 2013

• Energy will be 13? TeV
  – Redo all the SM measurements with first 100 inverse pb: comparable statistics to current run for top
  – A dedicated no pile-up run may be needed for some studies
  – Then on to new physics
Min bias: what have we learned

- Most previous MC tunings don’t work well
  - More particles than predicted