Experimental Conference Summary

June 4 - 9, 2012
Physics at LHC -2012
Vancouver, BC

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• At this conference more than 70 experimental talks were given

• I do not attempt to summarize all results in detail and I had to make a selection; I would in no way be capable of giving justice and fair credit to the fantastic amount of work presented during this week (I will also not quote any names of speakers)

• My apologies to those speakers whose results I have omitted. It is not intended as a reflection of the relative importance!
The role of the LHC

1. Explore the TeV mass scale
   - What is the origin of the electroweak symmetry breaking?
     Does the Higgs boson exist?
   - Search for physics Beyond the Standard Model
     (Low energy supersymmetry, other scenarios…,
      
   Look for the “expected”, but we need to be open for surprises
   → perform as many searches (inclusive, exclusive…) for as many final states
      as possible

2. Precise tests of the Standard Model
   - There is much sensitivity to physics beyond the Standard Model in the
     precision area (loop-induced effects, probe energy scales far beyond direct reach)
     → precise measurements, search for rare processes
Ultimate test of the Standard Model:

compare direct prediction of the Higgs boson mass with direct observation
The role of the LHC

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2. Precise tests of the Standard Model

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   → precise measurements, search for rare processes

→ Guidance to theory and Future Experiments
Many theoretical models for physics Beyond the Standard Model
I. The LHC
-a new era in particle physics-

Steve Meyers:

“The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics.”
A few facts to back this up:

- World record on instantaneous luminosity on 22. April 2011: \(4.67 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\) (Tevatron record: \(4.02 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\))

- 2011: collect per day as much int. luminosity as in 2010

- 2012: now regularly above \(6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\), record \(~6.6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)

- Very rapid rise in luminosity

- + good machine stability \(\rightarrow\) high integrated luminosities
Completion of an era: Tevatron

Accelerator Innovations
- First major SC synchrotron
- Industrial production of SC cable (MRI)
- Electron cooling
- New RF manipulation techniques

Detector innovations
- Silicon vertex detectors in hadron environment
- LAr-U238 hadron calorimetry
- Advanced triggering

Analysis Innovations
- Data mining from Petabytes of data
- Use of neural networks, boosted decision trees
- Major impact on LHC planning and developing
  - GRID pioneers

Major discoveries
- Top quark
- B_s mixing
- Precision W and Top mass
- Higgs mass prediction
- Direct Higgs searches
- Ruled out many exotica

The next generation
- Fantastic training ground for next generation
- More than 500 Ph.D.s
- Produced critical personnel for the next steps, especially LHC

But Tevatron is still in the game:
- W mass
- H \rightarrow bb
- B physics
- ...

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II. Detector Performance
Detector performance is impressive:

- Very high number of working channels (> 99% for many sub-systems) in all experiments;
- Data taking efficiency is high (> 94%)
- Impressive reconstruction capabilities for physics objects (e, γ, μ, τ, jets, b-tagging, $E_T^{\text{miss}}$)

Have been optimized to cope with the ever increasing number of pile-up interactions (impressive examples shown here)

An event with 20 reconstructed vertices
(error ellipses are scaled up by a factor of 20 for visibility reasons)
Some performance figures from 2011 data:

**Electron ID efficiency in ATLAS**

**Jet energy scale, E-flow in CMS**
Particle Identification in ALICE and LHCb:

LHCb: Search for $\phi \rightarrow K^+K^-$

Proper time resolution: 45 fs
b-tagging performances in ATLAS and CMS: extremely important for many physics analyses (Higgs, SUSY, SM, ….)

- Reconstruction of the original flavour (B, B*bar) of the reconstructed B meson (important for mixing and CP analyses)

- Performance calibrated from control channels, e.g.

- Effective efficiencies 2.1-3.5% (opp. side) and 0.7% – 1.3% (same side) dep. on analysis
Physics Results
Total, elastic and inelastic pp cross sections at 7 TeV

- Domain of the TOTEM experiment
  Detectors in the CMS forward regions

Elastic scattering: $\frac{d\sigma_{el}}{dt}$

$0.36 < |t| < 2.5 \text{ GeV}^2$

$\sqrt{s} = 7 \text{ TeV}$

Total cross section

(four methods give consistent results)

1. (low) Luminosity + Elastic scattering + Optical theorem
   $\sigma_{tot} = 98.3 \pm 2.0 \text{ mb}$

2. (high) Luminosity + Elastic scattering + Optical theorem
   $\sigma_{tot} = 98.2 \pm 2.2 \text{ mb}$

3. (high) Luminosity + Elastic scattering + Inelastic scattering
   $\sigma_{tot} = 98.7 \pm 4.4 \text{ mb}$

4. Elastic scattering + Inelastic scattering + Optical theorem
   $\sigma_{tot} = 97.8 \pm 2.4 \text{ mb}$
The inelastic cross section was also measured by ALICE, ATLAS and CMS; Good agreement among the experiments, within systematic uncertainties

Measurement require the subtraction of diffractive components and acceptance extrapolations;
The associated model dependence (e.g. Donnachie-Landshoff) constitutes the largest systematic uncertainty

ALICE:
$$\sigma_{\text{inel}} = (72.7 \pm 1.1 \text{ (stat)} \pm 5.1 \text{ (model) } \text{ mb})$$

ATLAS:
$$\sigma_{\text{inel}} = (69.1 \pm 2.4 \text{ (stat)} \pm 6.9 \text{ (model) } \text{ mb})$$

CMS:
$$\sigma_{\text{inel}} = (64.5 \pm 1.1 \text{ (stat)} \pm 3.0 \text{ (model) } \text{ mb})$$

TOTEM:
$$\sigma_{\text{inel}} = (73.5 \pm 0.5 \text{ (stat)} \pm 1.8_{-1.3} \text{ (syst) } \text{ mb})$$
Soft Physics and diffraction

- Measurements of soft inelastic collisions and diffractive processes are important for any modeling of the underlying event or pile-up processes.
- LHCb and Totem experiments extend the measurements far into the forward region.
- General behaviour: experiments agree well among each other, however, Monte Carlo models underestimated inclusive particle production;

A Monte Carlo tuning that describes simultaneously all observables is still missing.
Disentangle the various diffractive components by studying rapidity gaps;

Model description needs tuning
Particle production in the extreme forward region

- Single photon and $\pi^0$ spectra, compared to models:

- Important input for astro-particle physics experiments
Hard processes:
Tests of perturbative QCD

- Jet production
- W/Z production
- Production of Top quarks
- Heavy hadrons (Onia and B hadrons)
- Quark-gluon plasma
Double differential cross sections, as function of $p_T$ and rapidity $y$ (full 2010 data set)

- Data are well described by NLO pert. QCD calculations (NLOJet++)
- Experimental systematic uncertainty is dominated by jet energy scale uncertainty
- Theoretical uncertainties: renormalization/ factorization scale, pdfs, $\alpha_s$, ..., uncertainties from non-perturbative effects

somewhat larger deviations in the forward region
Double differential cross sections, as function of $p_T$ and rapidity $y$:
(full 2010 data set)

- Data are well described by NLO pert. QCD calculations (NLOJet++)
- Experimental systematic uncertainty is dominated by jet energy scale uncertainty
- Theoretical uncertainties: renormalization/ factorization scale, pdfs, $\alpha_s$, ..., uncertainties from non-perturbative effects

CMS: include full 2011 data set; comparison up to 2 TeV (central rapidities)
Important for:  
- Test of QCD  
- Search for new resonances decaying into two jets (→ next slide)
In addition to QCD test: Sensitivity to New Physics

- Di-jet mass spectrum provides large sensitivity to new physics
  
  e.g. Resonances decaying into $qq$, excited quarks $q^*$, ....

- Search for resonant structures in the di-jet invariant mass spectrum

<table>
<thead>
<tr>
<th>Experiment</th>
<th>L (fb$^{-1}$)</th>
<th>$0.26 &lt; m_{q^*} &lt; 0.87$ TeV</th>
<th>$0.30 &lt; m_{q^*} &lt; 1.26$ TeV</th>
<th>$0.60 &lt; m_{q^*} &lt; 2.64$ TeV</th>
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<tbody>
<tr>
<td>CDF (Tevatron)</td>
<td>1.13</td>
<td></td>
<td></td>
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<tr>
<td>ATLAS (LHC)</td>
<td>0.000315</td>
<td>exclude (95% C.L)</td>
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<tr>
<td></td>
<td>0.036</td>
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Inclusive b and bb-cross sections

Also good agreement found for the more challenging inclusive b and bb di-jet cross sections (limited to central region, tracker acceptance)
Direct $\gamma$ production ($\gamma + \text{jet}$)

In general good agreement, (within uncertainties, dominated by systematics, e.g. $\pi^0$ background, contributions from fragmentation, pdfs, …)

Similar ratios (data / theory) found as function of pseudorapidity in ATLAS and CMS
γ + b jet production at the Tevatron

- NLO calculation describe data well in low \( p_T \) region
- Larger deviations at high \( p_T \) (large NNLO contributions ??)
**QCD in W/Z (+ jet) production**

QCD at work

- Drell-Yan pair production measured over large mass range (normalized to Z peak)
- Clear signals, measurements extend into the forward rapidity region by LHCb
W cross sections at the LHC

- Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, ppbar and as a function of energy)
- Precision is already dominated by systematic uncertainties
- Good agreement as well between experiments
(i) Lepton charge asymmetries

![Graph showing lepton charge asymmetry](image)

(j) Flavour separated W+jet production

![Diagram of flavour separated W+jet production](image)

(iii) Extraction of s/sbar from global fit to ATLAS W/Z differential measurements

![Graph showing ATLAS W/Z differential measurements](image)

e.g. W+c production

\[ r_s = 0.5 \frac{\bar{s}}{d} \]
Jet multiplicities in $W+$jet production

$p_T$ spectrum of leading jet

- Impressive description of jet multiplicities and kinematic properties up to high jet multiplicities

- Impressive progress on NLO calculations for higher jet multiplicity (NLO $W+$5 jet in reach)
W + b jets

- Important background for many studies (Higgs, SUSY, top)
- Measurements at the Tevatron exceed NLO prediction

- Measured by ATLAS using 2010 data sample
  - studied W + 1 jet and W + 2 jets
  - require at least one b-tagged jet

Results from e and µ combined.
Measurements ~1.5σ above NLO prediction, but still consistent within uncertainties

**W→eν + 2 jets**

Distribution of the mass of the particles associated to the secondary vertex for b-tagged jets
Top Quark pair production

Pair production: \(qq\) and \(gg\)-fusion

b-tag multiplicity in 1-jet events ...and... in di-lepton events
Top cross section measurements

- Measurements at the Tevatron and at the LHC are well described by approx. NNLO calculations.
- Precision reached at the Tevatron: 6.4%.
- LHC experiments have already reached a comparable precision (6.2%).
  (large dataset, still potential to reduce the already dominant systematic uncertainties)
Top properties according to expectations, except maybe $A_{FB}$ (Tevatron)

$A_{FB} = \frac{F - B}{F + B} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$

$\Delta y = y_1 - y_\bar{1}$

Needs clarification:

More data, improved theoretical calculations
Charmonium and Bottomonium states

Is this for the LHC?

Yes, all experiments at the Tevatron and LHC have observed these states, measured production cross sections and have even discovered new ones.

- except for ALICE and LHCb-

use \( \mu \mu \) decays and \( \gamma \)-signatures.
Charmonium production:

- Production reasonably well described by NLO QCD calculations
- Simple colour singlet model not adequate
- Similar conclusions for bottomonium states
- Polarization is still not understood, further measurements needed
New heavy meson or baryon states

- First observation by ATLAS: $\chi_b (3P) \rightarrow Y(1S)^+ \gamma$ and $Y(2S)^+ \gamma$
- First observed by CDF in $B^+_c \rightarrow J/\psi \ell \nu$
- Observed in $B^+_c \rightarrow J/\psi \pi (LHCb, ATLAS)$ and $J/\psi \pi\pi\pi (LHCb)$
- Many other states by LHCb ($B_S^{**}, \Lambda_b^0*, ...$)
\[ \Xi_b^{*0} \rightarrow \Xi_b^{-}\pi^+ \rightarrow \Xi^- J/\psi \pi^+ \rightarrow \Lambda\pi^- \mu^+\mu^- \rightarrow p^+\pi^-\mu^+\mu^- \]

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

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