Outlook and Perspectives After a Year of LHC

DIS2011, April 15, 2011

John Campbell, Fermilab
Preamble

Apologies ...

This is a theorist’s viewpoint.
Focus on LHC results.
Personal bias: high-$p_T$ phenomenology.

Outline:

Highlights from the first year of the LHC.
Open issues and perspectives.
Sociology

* arXiv submissions: ALICE, ATLAS, CMS, LHCb /month.
Highlights
Top pairs

*LHC now earning its “top factory” moniker.*

![Graph showing top pair production cross-sections compared to theoretical predictions.](image-url)
... and also a bottom factory

First steps to understanding bottom production at these energies and rapidities.
Weak cross sections

* Useful gauge of experimental sensitivity, principal backgrounds to many searches.

nb: decays into single flavor of leptons assumed
Speaking of weak: single top

ATLAS Preliminary @ $\sqrt{s}=7\text{TeV}$

\[ \int L = 35 \text{ pb}^{-1} \]

**Data**

- t-channel
- W+prod.
- s-channel
top pairs
W + heavy flavor
W + jets
Dibosons
Z + jets
Multijets

Lepton flavour and charge

- $\mu^+$
- $e^+$
- $e^-$
- $\mu^-$

Theorist: “I almost fell out of my seat when I saw this.”

**CMS Preliminary, $\sqrt{s}=7\text{ TeV}, L=35.9\text{ pb}^{-1}$**

- 2D, $\mu$ channel
- $104.1 \pm 50.9$

- 2D, e channel
- $154.2 \pm 73.1$

- BDT, $\mu$ channel
- $89.8 \pm 40.4$

- BDT, e channel
- $59.2 \pm 37.8$

- 2D, e+$\mu$ channel
- $124.2 \pm 48.1$

- BDT, e+$\mu$ channel
- $78.7 \pm 29.5$

- CMS combination
- $83.6 \pm 30.0$

Outlook and Perspectives After a Year of LHC - John Campbell
The SM @ LHC Year One

- Drell-Yan
- Dibosons, photons
- W, Z+ jets
- Heavy flavor

![Graph showing CMS preliminary results with ratios and uncertainties for various processes.]

36 pb$^{-1}$ at $\sqrt{s} = 7$ TeV
Usual “backwards-compatible” mSUGRA limits.

far beyond both LEP and Tevatron exclusion ranges.

Open question: how to do better?
Beyond mSUGRA

Pick a simplified model: explore regions away from mSUGRA.

- Limits vanish when squark, LSP masses are degenerate.
- Relies on SUSY-NLO cross sections from Prospino.
- but allows interpretation in other models with the same decay modes.
- Is this the best we can do?
- need new ideas, theory input.
Electroweak precision

* Lepton charge asym: $W^+$ and $W^-$ not same.

* Sensitive to up, down quark PDFs @ small $x$.

* At present, exp. errors are of the same order ($\sim 10\%$) as:
  
  * uncertainty of NLO
  
  * difference between current PDF fits.

* First constraints coming soon (NNPDF/HERAPDF).
Forward leptons too ...

* Even smaller $x$ and extending HERA reach to high $Q^2$.

\[ A_W(\mu) \quad W^{+/−} \text{ asymmetry for muons} \]
Higher orders

- Impressive agreement between data and state-of-the-art pQCD (NNLO ME’s and PDF evolution).
High multiplicities

\[ \frac{d\sigma}{dp_T} \text{ [pb/GeV]} \]

\[ \int L dt = 33 \text{ pb}^{-1} \]

W+1 jets

W+2 jets, x10^{-1}

W+3 jets, x10^{-2}

W+4 jets, x10^{-3}

W+3j NLO

ATLAS-CONF-2011-060

Data 2010, \sqrt{s}=7 \text{ TeV}

ALPGEN

SHERPA

BLACKHAT-SHERPA

MCFM

ATLAS Preliminary
Higher orders + PS

Combination of NLO and parton shower highly desirable: just now becoming more available.

CMS preliminary

$36 \text{ pb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$

$1/\sigma \frac{d\sigma}{dp_T} \left[ \text{[GeV/c]}^{-1} \right]$

$|\eta_\mu| < 2.1, p_{T,\mu} > 20 \text{ GeV/c}$

data

POWHEG @ NLO

CMS-PAS-EWK-10-010
Higgs search via WW

- WW cross section established at LHC.
- Can now move beyond measurement and use it as an understood background in Higgs search.
Background estimation

- Measure WW background in control region, propagate to signal using theory.

\[ g \rightarrow g \rightarrow W^- W^+ \]

- Glue-glue, formally higher order but large effectively LO

\[ W^- W^+ \]

- "Normal" production known to NLO

\[ \text{fraction of events from gg} \]

\[ \text{dilepton invariant mass, } M \text{ [GeV]} \]
Open issue: scale dependence @ high multiplicity

* What values of $\mu_R$ and $\mu_F$ to choose?

inclusive production

production @ non-zero $p_T$

in association w/ many jets

M (heavy particle mass)

$M, p_T(M), \sqrt{M^2 + p_T(M)^2}$

$M, p_T(M), p_T^i, \sum_i p_T^i, \ldots$

* Can only understand via comparison with data

* resummation of large logs, NLO + parton shower, ...?
Discrepancies and Outlook
What’s wrong with b-quarks?

Simple question: what’s rate of W and a b-quark?

Tevatron: quark-antiquark dominated (90%).

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>ALPGEN</th>
<th>PYTHIA</th>
<th>NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.74 pb ±0.27 (stat) ±0.42 (syst)</td>
<td>0.78 pb</td>
<td>1.10 pb</td>
<td>1.22 pb ±0.14 (scale)</td>
</tr>
</tbody>
</table>

CDF note 9321
W+b-quarks at the LHC

- Floating Wb xsec in background fits (e.g. single top) indicates factor of two over theory - Tevatron & CMS.
- Same issue or not? Gluon contribution is much bigger at the LHC.

More studies essential (but Z seems okay).

Especially important since b-quark is a gateway to NP.
Top asymmetry

Asymmetry in direction that top is produced at NLO:

\[
\text{(rest frame) asym.} = \frac{N(y_{t^t} > 0) - N(y_{t^t} < 0)}{N(y_{t^t} > 0) + N(y_{t^t} < 0)}
\]

1-loop interference

real radiation

parton level prediction: +5.6%

(+10% with jet veto)
Asymmetry vs. theory

*Caveat: NLO is really a LO prediction for the asymmetry (need $d\sigma/dy_t$ @ NNLO for corrections).*
Prospects for the LHC

- Tough challenge at the LHC since glue-glue has no asymmetry, just dilutes sample.  
  
- One idea: use the fact that we have more quarks at large x by defining forward charge asymmetry:

  \[ A_F(y_0) = \frac{N_t(y_0 < |y| < 2.5) - N_{\bar{t}}(y_0 < |y| < 2.5)}{N_t(y_0 < |y| < 2.5) + N_{\bar{t}}(y_0 < |y| < 2.5)} \]

  Hewett, Shelton, Spannowsky, Tait, Takeuchi, 1103.4618

- Further enhance by using moderately boosted tops.

<table>
<thead>
<tr>
<th>( (N_+ + N_-) ), ( (N_+ - N_-) ), ( \Delta N )</th>
<th>( A_{(F,C)10fb^{-1}} )</th>
<th>( \sigma_{10fb^{-1}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM 1.5 &lt;</td>
<td>y</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>Z' 1.5 &lt;</td>
<td>y</td>
<td>&lt; 2.5</td>
</tr>
</tbody>
</table>

signif. @ 7 TeV
10/\text{fb}
The CDF bump

arXiv: 1104.0699

Clarification from DØ in “a few weeks”
The CDF bump

arXiv: 1104.0699

![Graph showing the CDF bump](image)
Explaining the bump

**Proposed explanations:**
- technicolor,
- unusual Z’, new scalar multiplet,
- axial color-octet bosons,
- intrinsic quarks,
- low mass string theory ...

**e.g. technirho.**

Eichten, Lane, Martin, 1104.0976

\[
\rho_T \rightarrow W \pi_T \rightarrow q\bar{q}
\]

\[\rho_T \rightarrow W \pi_T \rightarrow q\bar{q}\]

\[\rho_T \rightarrow W \pi_T \rightarrow q\bar{q}\]

**LHC impact:** hadronic decays complicated;
instead focus on technirho decays into
WZ, Wγ, dilepton final states.
Substructure studies

* Very useful tool for hadronic decays of heavy particles.

* look in boosted (high $p_T$) regions where large QCD backgrounds (jets, $V$+jets, top) are less favoured.

  Butterworth et al. 0802.2470

* Exploit tell-tale signature of jets produced by a heavy object.

* Deconstruct “fat jet” to find two subjets with similar properties.

✔ Big gain in sensitivity over “traditional” methods

✘ Heavy price: lose many events $\rightarrow$ high lum. (10/fb)
Natural boosting

- BSM models often produce Higgs with a natural boost → higher xsec, less $\mathcal{L}$ required.
  Kribs et al. 1006.1656

substructure approach  "traditional" analysis
Flashback

(Long-term outlook)

- It seems clear that performing NLO calculations on a case-by-case basis is not the way of the future.
- An automated approach, combining algebraic and numerical recipes, appears both promising (in terms of physics output) and feasible.
- Perhaps one day we’ll have an ALPGEN@NLO or MadLoop.

2011: Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau
- MadLoop (virtual loops), MadFKS (real radiation).
- Fully-functioning, automatic NLO.

arXiv:1103.0621
Madloop

- Cross-checked with $2\rightarrow 2$, $2\rightarrow 3$ analytic results.
- Limited only by time ~ a few days, hundred CPU farm.
  - maybe not an issue for one-off runs, speed-up soon.
- Very valuable tool even within these confines.
- For example: investigate unforeseen contributions to cross sections and/or subtle interference effects.
Perspectives on one year

✿ Extraordinary progress, spectacular precision tests of the SM already.

✿ Anonymous theorist on a recent conference:

  “The LHC talks were effortless compared to the Tevatron ones.”

  - partly due to the pioneering work at the Tevatron.

✿ Outlook

✿ How can we find NP? “Expect the unexpected”

✿ Plenty of exciting results to come @ 7 TeV, but never too early to think ahead.

✿ are there useful quantities we can measure to help even further beyond 2012, e.g. \( \frac{O(\sqrt{s}^{2012+})}{O(\sqrt{s} = 7 \text{ TeV})} \)?
Outlook

I suspect that this plot is independent of $\sqrt{s}$. 

![Graph: Proceedings of DIS 99](image)