Review of electroweak physics at hadron colliders

Frank Petriello

DPF 2011
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Review of electroweak physics at hadron colliders

Outline

- Will begin with a review of the variety of important measurements with $W/Z(\gamma)$ final states
- Will focus on recent LHC and Tevatron results, and theoretical issues associated with them
- Emphasis on impact of QCD on analyses, the status of theoretical knowledge and tools, and some examples of the tricky interplay between QCD and experimental cuts
W, Z at the LHC circa 2010

- W, Z candidate events feature prominently in talks
- A few sparsely populated $p_{T,W}$ and $M_T$ distributions
W, Z at the LHC now

- Detailed measurements of W, Z properties
- Already improving PDFs, a first $\sin^2\theta_W$ determination
Why are we interested?

- Residual theory error from uncalculated terms at the percent level
- Experimental systematics at the percent level, high statistics
- Permits precision measurements in a hadronic environment

\[
\frac{d^2 \sigma}{dM/dY} \text{ [pb/GeV]}
\]

Anastasiou, Dixon, Melnikov, FP 2003

CMS, EPS 2011
Luminosity and PDFs

- Use to remove luminosity error from processes with similar initial states
- Use in PDF extractions; control over differential distributions crucial

\[ \frac{N_{pp\rightarrow WW}}{N_{pp\rightarrow Z}} = \frac{\sigma_{q\bar{q}\rightarrow WW}}{\sigma_{q\bar{q}\rightarrow Z}} \frac{PDF(x_1, x_2, Q^2)}{PDF(x_1, x_2, Q^2)} \]

\[ \Delta l_{pp} = 0! \]

Normalization process

T. Shears
Fundamental parameters

- Most precise determination of $M_W$ from Tevatron
- Check on LEP $\sin^2\theta_W$ measurement; also complete determination of angular properties of $Z$ decay (Collins-Soper moments), other QCD properties
Background to new physics

• Diboson, V+jet major backgrounds to both high and low mass Higgs
• High mass tail needed for heavy resonance searches; interference with SM possibly a useful diagnostic tool
Inclusive cross sections

- **Known through NNLO in QCD** van Neerven et al. 1991; Harlander, Kilgore 2001
- **NLO EW corrections known** Baur, Brein, Hollik, Keller Wackeroth; Dittmaier, Kramer; Carloni Calame et al., 1998-2006

\[
\begin{align*}
W \rightarrow e\nu & \quad 1.418 \pm 0.008_{\text{stat}} \pm 0.036_{\text{syst}} \\
W \rightarrow \mu\nu & \quad 1.423 \pm 0.008_{\text{stat}} \pm 0.036_{\text{syst}} \\
W \rightarrow l\nu \quad \text{(combined)} & \quad 1.421 \pm 0.006_{\text{stat}} \pm 0.033_{\text{syst}}
\end{align*}
\]

\[
R_{+/-} = \frac{\sigma(p p \rightarrow W^+ X) \times BF(W^+ \rightarrow \ell^+\nu)}{\sigma(p p \rightarrow W^- X) \times BF(W^- \rightarrow \ell^-\bar{\nu})} = 1.421 \pm 0.006 \text{ (stat.)} \pm 0.014 \text{ (syst.)} \pm 0.030 \text{ (th.)}
\]

\[
\frac{\sigma(pp \rightarrow W^+X) \times BF(W^+ \rightarrow \ell^+\nu) }{ \sigma(pp \rightarrow ZX) \times BF(Z \rightarrow \ell^+\ell^-) } = 0.975 \pm 0.007 \text{ (stat.)} \pm 0.007 \text{ (syst.)} \pm 0.018 \text{ (th.)} \pm 0.039 \text{ (lumi.) nb.}
\]

\[
\frac{\sigma(pp \rightarrow W^+X) \times BF(W^+ \rightarrow \ell^+\nu) }{ \sigma(pp \rightarrow W^-X) \times BF(W^- \rightarrow \ell^-\bar{\nu}) } = 6.04 \pm 0.02 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \pm 0.08 \text{ (th.)} \pm 0.24 \text{ (lumi.) nb;}
\]

Entirely a PDF error \[\sigma_Z [\text{nb}]\]
W charge asymmetry

- Probes both valence and sea distributions

\[ A_W(y) = \frac{N_{W+}(y) - N_{W-}(y)}{N_{W+}(y) + N_{W-}(y)} \]

\[ A_\ell(\eta) = \frac{N_{\ell+}(\eta) - N_{\ell-}(\eta)}{N_{\ell+}(\eta) + N_{\ell-}(\eta)} \]
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Algebraic expression:

-already entering PDF determinations

From M. Schmitt, LoopFest 2011

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Importance of precision tools I

- Probes both valence and sea distributions

\[ A_W(y) = \frac{N_{W+}(y) - N_{W-}(y)}{N_{W+}(y) + N_{W-}(y)} \]

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\( \mathcal{O}(10\%) \) shape corrections from QCD; not due to PDFs alone

DYNLO: Catani, Cieri, Ferrera, de Florian, Grazzini 2009-10

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Toward collider-only PDFs

• W charge asymmetry just one of many measurements with PDF impact

THE FUTURE: COLLIDER-ONLY PDFS

• LHC can provide us precision information on PDFs

• TOWARDS A “COLLIDER ONLY” HERA+LHC PDF FIT
  (TEVATRON DATA MIGHT BE SUPERFLUOUS)
  - MEDIUM & LARGE $x$ GLUON
    * PROMPT PHOTONS AVAILABLE
    * (PRECISION) JETS IN PROGRESS
  - LIGHT FLAVORS AT MEDIUM @ SMALL $x$, FLAVOR SEPARATION @ SMALL $x$
    * LOW-MASS DRELL-YAN PRELIM.
    * $Z$ RAPIDITY DISTRIBUTIONS PRELIM.
  - STRANGENES & HEAVY FLAVORS
    * STRANGENESS $\Rightarrow W + c$ FUTURE?
    * CHARM $\Rightarrow Z + c, \gamma + c$ FUTURE?
    * BOTTOM $Z + b$ IN PROGRESS

S. Forte, BNL 2011

Let’s look briefly at these
Together these probe $x$ from $10^{-4}$ to $10^{-1}$ with small theoretical errors.
Importance of precision tools II

- Double muon trigger: $p_T^1 > 16$ GeV, $p_T^2 > 7$ GeV
- For $M = [15, 20]$ GeV: NLO $\rightarrow$ LO, NNLO $\rightarrow$ NLO, need a hard jet to generate this configuration
- $\alpha_s(15$ GeV$) \approx 0.17$, K-factor $\approx 1.9$ when going from ‘N’LO $\rightarrow$ ‘N’NLO
- Corrections to POWHEG acceptance of $\approx 1.5-2$

Important to have tools incorporating all our knowledge to catch effects like this.
The forward region

- Forward coverage at LHCb probes complimentary x region to ATLAS, CMS

- Clear potential to discriminate between PDF fits

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from T. Shears
Importance of clever experimenters

- Can also access forward region in CMS (ATLAS)!
- Reconstruction of electrons in forward HCAL allows extension of $Y$ range
- Should lead to improved PDFs and other EW measurements
Combining QCD and EW

• At percent level, combination of QCD and EW corrections essential: $\alpha_s^2 \sim \alpha_{\text{EW}}$

$$\frac{d\sigma}{d\Omega}_{\text{QCD\&EW}} = \left\{ \frac{d\sigma}{d\Omega} \right\}_{\text{QCD}} + \left\{ \frac{d\sigma}{d\Omega} \right\}_{\text{EW}} - \left\{ \frac{d\sigma}{d\Omega} \right\}_{\text{LO}}\right\}_{\text{HERWIG PS}}$$

$$\frac{d\sigma}{d\Omega}_{\text{QCD\&EW}} = \left( 1 + \frac{\left[ d\sigma/d\Omega \right]_{\text{MC@NLO}} - \left[ d\sigma/d\Omega \right]_{\text{HERWIG PS}}} {\left[ d\sigma/d\Omega \right]_{\text{LO/NLO}}} \right) \times \left\{ \frac{d\sigma}{d\Omega} \right\}_{\text{HERWIG PS}},$$

• Differences in prescription can reach few % in certain phase-space regions
• First step toward exact $O(\alpha_s \alpha_{\text{EW}})$ to resolve taken Kilgore, Sturm 2011

Balossini, Carloni Calame, Montagna, Moretti, Nicrosini, Piccinini, Treccani, Vicini, 2009
W, Z+jets

• Agreement across all jet bins, large kinematics region between data and multiple tools
• Once anchored at low bins, tools with ME+PS merging describes kinematics for most processes to $\sim 20\%$. 

\[
\frac{\sigma(W + \geq N_{\text{jet}} \text{ jets})}{\sigma(W + \geq N_{\text{jet}} \text{ jets})} \geq 1/\geq 0 \geq 2/\geq 1 \geq 3/\geq 2 \geq 4/\geq 3 \geq 5/\geq 4
\]

Inclusive Jet Multiplicity Ratio

\[
\int \mathcal{L} dt = 33 \text{ pb}^{-1}
\]
W, Z+jets

Enormous progress and too many new NLO tools to properly reference here... GOLEM, BLACKHAT, HELAC/CUTTOOLS,ROCKET, SAMURAI, MCFM, NLOJET+, MADLOOP, VBFNLO, Bredenstein/Denner/Dittmaier/Pozzorini; MADDIPOLE,AUTODIPOLE, MAFKFS+others

here, LO for W+4 jets; there is an NLO result now! BLACKHAT+SHERPA: Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre 2010
**W+b jet**

- Discrepancy for W+1 b-jet observed at CDF; difficult to resolve theoretically

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>ALPGEN</th>
<th>PYTHIA</th>
<th>NLO</th>
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<tbody>
<tr>
<td></td>
<td>$2.74 \text{ pb} \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst)}$</td>
<td>$0.78 \text{ pb}$</td>
<td>$1.10 \text{ pb}$</td>
<td>$1.22 \text{ pb} \pm 0.14 \text{ (scale)}$</td>
</tr>
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Campbell et al. 2008

- Preliminary results agree with NLO to $1.5\sigma$

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

**ATLAS** Preliminary

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

<table>
<thead>
<tr>
<th>$\sigma(W \rightarrow l + \geq 1 \text{ b-jet}) [\text{ pb}]$</th>
<th>$\sigma(W \rightarrow l + \geq 1 \text{ b-jet}) [\text{ pb}]$</th>
</tr>
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- Greatly reduced scale dependence in 5FNS

Caola, Campbell, Febres Cordero, Reina, Wackeroth 2011

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Di-boson production

- All modes have been observed at the LHC

Already providing impressive constraints on triple gauge couplings
Di-photon Higgs background

- Major interest in di-boson production is as background to Higgs

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>$\sigma^{LO}(\gamma\gamma)$ [pb]</th>
<th>$\sigma^{NLO}(\gamma\gamma)$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>35.98(0)</td>
<td>47.0(1)$^{+5%}_{-6%}$</td>
</tr>
</tbody>
</table>

- ‘Staggered’ momentum cuts change $K=1.3 \rightarrow 3$
- At LO, $p_{T1}=p_{T2}$, cut effectively 40 GeV
- Region between 25-40 GeV first opens at NLO, leading to large corrections
- Are the staggered cuts experimentally necessary? They complicate QCD background predictions

from MCFM: Campbell, Ellis, Williams 2011
Conclusions

• After only one year, $W$ and $Z$ physics at the LHC is approaching percent-level... theory/PDF limited already in some results

• Benefit to extensive interactions between theorists and experimenters working in this area; non-trivial interplay between QCD and experimental cuts

• Great progress in theory; $W+3,4$ jets now known at NLO ($W+4$ jets almost unthinkable a few years ago)

• In preparing for this, was struck by the experimental progress from LHC 2010→LHC 2011

• My hope for 2012 talks on EW physics:
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