Z+Jets results from CDF

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On Behalf of the CDF Collaboration
Motivation

- Test perturbative QCD at high $Q^2$
- Background for rare SM processes (top, diboson) and new Physics searches
- High theoretical uncertainty in $Z + HF$
- Tevatron legacy measurements
Tevatron

- \( p\bar{p} \) collisions at \( \sqrt{s} = 1.96 \) TeV
- Peak instantaneous luminosity 
  \( \sim 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
- \( \sim 10 \text{ fb}^{-1} \) of integrated luminosity available for data analysis
CDF Detector

- Tracking system
  - Silicon detectors
  - Drift chambers COT
- 1.4 T Magnetic field
- Calorimeter
  - Electromagnetic calorimeter
  - Hadronic calorimeter
- Muon detectors
  - Wire chambers
  - Scintillators
- 3 Level Trigger System
  - Level 3 $\rightarrow \sim$ 100 Hz
Z Kinematic region
66 < M_Z < 116 GeV/c^2
E_T > 25 GeV/c, |\eta| < 1

Jets
MIDPOINT R=0.7
p_T > 30 GeV/c, |Y| < 2.1

Z/\gamma^* \rightarrow l^+l^- + jets

Full Tevatron dataset results
\mathcal{L} = 10 fb^{-1}

Z \rightarrow \mu^+\mu^- and Z \rightarrow e^+e^- channels combined
accounting for correlation between uncertainties

Measurement are unfolded back to Particle Level

Data driven backgrounds
- QCD multi-jet
- W + jet
MC backgrounds
- Top
- Diboson
- Z \rightarrow \tau\tau + jets

Total backgrounds between 2%-10%

5% to 15% systematic uncertainties
Jet Energy Scale is the dominant
Z/\gamma^* + jets Theory Predictions

**MCFM and BLACKHAT+SHERPA**
NLO fixed order perturbative QCD
→ reduced scale uncertainty

**ALPGEN+PYTHIA**
Matched LO-ME+PS
→ fundamental tool for Z+jets simulation

**POWHEG+PYTHIA**
Merged NLO+PS
→ good modeling of pQCD and non-pQCD physics

**LOOPSIM+MCFM**
Approximate nNLO
→ best perturbative QCD accuracy

**ArXiv:1103.0914**
NLO QCD x NLO EW perturbative prediction
→ Important corrections at high $p_T$

Comparison with many available theoretical predictions

- Largest theory uncertainty: $\mu_n$ scale variation
- PDF uncertainties: 2%-4%
\[ Z/\gamma^* + \geq 1 \text{ jet leading } p_T^{\text{jet}} \]

CDF Run II Preliminary

\[
\frac{d\sigma}{dp_T^{\text{jet}}} [\text{fb} / \text{GeV/c}] 
\]

- CDF Data \( L = 9.64 \text{ fb}^{-1} \)
- Systematic uncertainties
- NLO LOOPSIM+MCFM
- MSTW2008NNLO PDF

Corrected to hadron level
\[
\mu_0 = \frac{1}{2} \mu_1 = \frac{1}{2} (c_T^2 P_T^2 + P_T^2 + P_T^2) 
\]

**Data / Theory**

- ALPGEN+PYTHIA
  - Matched \( a_s \) Tune P2011
  - \( \Lambda_{\text{QCD}} - \alpha_s^{\text{ew}} \) variations

- POWHEG+PYTHIA
  - Tune Perugia 2011
  - \( \mu = 2\mu_0, \mu = \mu_0/2 \)

- NLO BLACKHAT+SHERPA
  - LO SHERPA (no shower)
  - \( \mu = 2\mu_0, \mu = \mu_0/2 \)

- NLO QCD \(\otimes\) NLO EW

**Good Agreement between data and predictions**

- LOOPSIM+MCFM only 4%-6% scale uncertainty
- NLO EW correction \~5% at high pt \(\rightarrow\) large virtual Sudakov logarithms
\( Z/\gamma^* + \geq 1 \text{ jet } H_T^{\text{jet}} \)

**CDF Run II Preliminary**

- Giant NLO/LO K factor \( \geq 2 \) at high \( H_T^{\text{jet}} = \sum p_T^{\text{jet}} \)
- Significant beyond NLO corrections
- LO-ME+PS (ALPGEN) and NLO+PS (POWHEG) properly model data with large scale uncertainty
- Good modeling of approximate nNLO LOOPSIM with reduced scale uncertainty
$Z/\gamma^* + \geq 1$ jet $p_T^Z$

CDF Run II Preliminary

$NLO$ EW and $NLO$ QCD corrections applied with a factorized ansatz

- NLO EW correction $\sim 5\%$ at high $p_T$
- $\rightarrow$ large virtual Sudakov logarithms
- NLO EW corrections of the same order of approximate nNLO scale uncertainty
$Z/\gamma^* + \geq N \text{ jets}$

CDF Run II Preliminary

- BLACKHAT+SHERPA NLO pQCD for $Z + 3$ jets
- LOOPSIM+MCFM scale variation lower than experimental uncertainty
Measurement of $b$ production Cross Section in association with a Z boson

CDF Run II Preliminary

- Data - 9.13 fb$^{-1}$
- Total Prediction
- light jets
- c jets
- $b$ jets
- QCD bkg.

Total Jets: 1941

- $f_c: 0.47 \pm 0.04$
- $f_b: 0.15 \pm 0.06$

$$\frac{\sigma_{Z\_bjet}}{\sigma_Z} = 0.261 \pm 0.023^{stat} \pm 0.029^{syst} \%$$

$$\frac{\sigma_{Z\_bjet}}{\sigma_{Z\_jet}} = 2.08 \pm 0.18^{stat} \pm 0.27^{syst} \%$$

Main systematic uncertainties due to SecVtx template modeling

To compare with NLO prediction with MCFM:

<table>
<thead>
<tr>
<th>$Q^2 = m_Z^2 + p_{T,Z}^2$</th>
<th>$Q^2 = &lt;p_{T,jet}^2&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\sigma_{Z_bjet}}{\sigma_Z}$</td>
<td>0.23 %</td>
</tr>
<tr>
<td>$\frac{\sigma_{Z_bjet}}{\sigma_{Z_jet}}$</td>
<td>1.8 %</td>
</tr>
</tbody>
</table>
Measurement of b production Cross Section in association with a Z boson

CDF Run II Preliminary

$\frac{1}{\mathcal{L}} \cdot \frac{d\sigma_{Z+\text{jet}}}{dp_T}$ [GeV/c]$^{-1}$

- CDF Data - 9.13 fb$^{-1}$
- Systematic uncertainties
- NLO MCFM $Q^2 = M_Z^2 + p_T^2$
- MSTW 2008 NLO PDF
- Corrected to hadron level

Data/Theory

- NLO MCFM $Q^2 = M_Z^2 + p_T^{2\text{T}}$
- $Q = 2\ Q_0$; $Q = 0.5\ Q_0$
- Syst. unc.
- PDF unc.

Data/Theory

- NLO MCFM $Q^2 = M_Z^2 + p_T^{2\text{T}}$
- $Q = 2\ Q_0$; $Q = 0.5\ Q_0$
- NLO MCFM $Q = p_T^{2\text{T,jet}}$

10$^{-7}$ 10$^{-6}$ 10$^{-5}$ 10$^{-4}$

20 30 40 50 60 70 80 100 $p_T^{\text{jet}}$ [GeV/c]

20 30 40 50 60 70 80 100 $p_T^{\text{jet}}$ [GeV/c]
Measurement of $b$ production Cross Section in association with a $Z$ boson
Summary

- Precise measurements of Z+jets, Z+b-jets with the full Run II dataset
- Tevatron legacy measurements
- General good agreement with state of the art theoretical predictions

More details at:
Backup slides
Z/\gamma^* + jets

ALPGEN LO-ME+PS

$\alpha_s$ "matched" ALPGEN+PYTHIA setting and Tune Perugia 2011
\[ \text{coherence between CKKW } \alpha_s \text{ in ALPGEN and } \lambda_{QCD} \text{ in PYTHIA} \]
\[ \text{Can use NLO (2-loop) PDF} \]

No normalization factor needed
Z/γ* + ≥ 1 jet
POWHEG NLO+PS

- Good modeling of perturbative high $p_T$ (NLO accuracy) and non-perturbative low $p_T$ (PS+hadronization+UE) regions
- POWHEG formula independent of parton shower modeling → lower dependence from PYTHIA Tune
Z/γ* + ≥ 2 jets

- Important final state for Higgs and beyond SM searches → sensitive to new resonances
- Measured cross sections compared to ALPGEN, MCFM and BLACKHAT
- Good modeling within experimental and theoretical uncertainties
Measurement of $b$ production Cross Section in association with a $Z$ boson

Use same framework as $Z$+jets analysis

Add a NN for lepton ID
gain of 30-40% efficiency for $Z$
reconstruction

**Leptons**
- $|\eta| < 1.0$
- $p_T > 20$ GeV/c

**Jets**
- Midpoint algorithm cone 0.7
- $|Y| < 1.5$
- $p_T > 20$ GeV/c

**B-tagging:** 1 or more Tight
SecVtx
Measurement of b production Cross Section in association with a Z boson

Measured the ratio of the b-jet XS with respect to the Z inclusive one and differential XS as a function of the b-jet transverse momentum and rapidity

fit SecVtx mass distribution to find b-fraction