Jet Production with Vector Bosons and Heavy Flavor at the Tevatron

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Results from CDF & D0 Collaborations

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http://flickr.com/photos/72926532@N00
Outline

• Underlying Event Studies

• Z/W+jets Production

• Experimental Techniques
  ▪ b-Jet Identification

• bb Production

• Z+b Production

• W+b/W+c Production

• Final Remarks
High pT QCD Physics at 2 TeV

Big step forward in Run II
• Larger statistics
• Increased pT range
• Measurements in wide rapidity region
• Improvements in jet algorithms
• Inclusion of non-pQCD contributions

W/Z + Jets major background to many measurements and searches
Non-pQCD Contributions

- Non-pQCD contributions
- Underlying Event (remnant-remnant interactions)
- Fragmentation into hadrons

Underlying Event and Fragmentation contributions must be considered before comparing to NLO QCD predictions (only way to perform a fair comparison)

Precise measurements at low Pt require good modeling of the non-pQCD terms

Dedicated measurements are needed to validate the Monte Carlo modeling
Underlying Event Studies

Goal: improve understanding and modeling of high energy collider events

Define 3 regions in an event, based on the leading jet
- “toward”
- “away”
- “transverse”

“transverse” region → very sensitive to underlying event

Study (in all regions)
- charged particle density
- $p_T$ sum density
- $E_T$ sum density
Underlying Event in Drell-Yan and Jet Production

→ charged pT sum density

Comparison of the three regions in DY:

- “away” region: pT density increases with lepton pair pT
- “transverse”, “toward” regions: pT density flat with lepton pair pT

Comparison of “transverse” region between jets and DY

- Similar trend in both
- Tuned PYTHIA describes data
Jet shapes

- PYTHIA Tune A describes the data (enhanced ISR + MPI tuning)
- PYTHIA default too narrow
- MPI are important at low Pt
- HERWIG too narrow at low Pt

We know how to model the UE at 2 TeV for QCD jet processes
Soft radiation in Z+jet(s)

- Implementation of proper modeling of UE still needed in new W/Z+Jet(s) Monte Carlos...very important
- Pythia tune A: good agreement
$Z/\gamma^*(-\rightarrow ee)+\text{jet(s)}$

Clean and allows to validate $Z\rightarrow \nu\bar{\nu}+\text{jets}$ bkg.

Good agreement with NLO pQCD predictions including non-pQCD corrections.
$Z/\gamma^* (\rightarrow ee) + \text{jet(s)}$

- Test pQCD predictions and event generators
- Jets: $p_T > 20 \text{ GeV}$, $|y|<2.5$, $R=0.5$
- Electrons: $E_T > 25 \text{ GeV}$, $65 < M_{ee} < 115 \text{ GeV}$

- **NLO** pQCD large improvement over LO

- Event Generators:
  - Pythia “$p_T$ ordered” better description
  - Sherpa: harder than data
  - Alpgen+Pythia: too low, but right shape

```latex
hep-ex/0903.1748
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$Z/\gamma^*(\rightarrow \mu\mu) + \text{jet(s)}$  

- Data described by NLO pQCD
- PYTHIA and ALPGEN below the data (consistent with LO prediction)
- SHERPA in between LO and NLO predictions (better at large Pt)
W+jet(s) Production

Good agreement with pQCD NLO calculation (includes non-pQCD effects)

At low $P_T$, Monte Carlo needs a better modeling of UE (ALPGEN+PYTHIA)

x 10 more cross section than Z+jets
But requires to control QCD and Top bkgs.

hep-ex/0711,4044
Vector Boson + HF Jets

Important for physics program at Tevatron

- For QCD
  - Test perturbative QCD predictions
  - $W/Z(\gamma)$ direct probe of hard scattering dynamics
  - Sensitive to PDFs HF content

- Understand Background
  - $W/Z+HF$ production is bkgd for: $t\bar{t}$bar, single top, and searches like Higgs, SUSY...
  - Challenging to accurately simulate need to validate data
b-Jet Identification

Lifetime taggers:
- Most common b-tagging technique exploits long lifetime of b-hadrons
- Secondary vertex:
  → Select tracks in jet
  → Identify displaced tracks (not from primary vertex)
  → Make secondary vertex with displaced tracks
  → If large transverse displacement ($L_{xy}$) jet is b-tagged

Soft Lepton Taggers:
- Identify soft leptons inside jets (~20% semi-leptonic branching fraction)

Need to characterize tagger: efficiency and mistag rate (light flavor tags)
b-Jet Identification (cont'd)

Lifetime tagger, different operating points:

- **Loose**: optimized for efficiency (e.g. double tagged analyses)
- **Tight**: optimized for purity (e.g. top cross section)
- **Ultra-tight**: very high purity (reduce mistags)
Dijet Production (bb)

Gluon Splitting
Small DR

Direct Production
Large DR

Measure phi correlation to get insight on contribution of LO and NLO terms.

Secondary vertex mass used to separate bottom from (uds + c) contributions.
Dijet Production ($b\bar{b}$)

2 jets with $ET > 35 \ (32) \ GeV$ and $|y| < 1.2$

NLO prediction closest to the data
Inclusive Z+b

Test of background for Higgs / SUSY

Considering both electron and muon channels and jets with Et > 20 GeV and |\eta| < 1.5

Measurements in agreement with predictions (large uncertainties in both data and theory)
No complete NLO prediction in the Z+bb case translates into a large scale dependence
Also large variations between PYTHIA and ALPGEN

$$\frac{\sigma(Z+b)}{\sigma(Z+\text{jets})} = 2.08 \pm 0.33 \pm 0.34(\%)$$

MCFM:1.8% ($Q^2 = M_Z^2 + P_{T,Z}^2$) ; 2.2% ($Q^2 = <P_{T,Jet}^2>$)

hep-ex/0812.4458
**W+b-jets production**

- $W \rightarrow l \nu$ ($l=e,\mu$) selection:
  - $e$: $E_T > 20$ GeV, $|\eta| < 1.1$
  - $\mu$: $p_T > 20$ GeV/c, $|\eta| < 1.0$
  - $\nu$: Missing $E_T$, MET $> 25$ GeV

- 1 or 2 jets in final state

- **b-Jet selection:**
  - Cone algorithm, R= 0.4
  - $E_T > 20$ GeV, $|\eta| < 2.0$
  - b-identification: “ultratight”

- **W+b-jets cross section:**

$\sigma_{W+bjets} \cdot Br = \frac{N_{b-tags} \cdot f_{bjets} - N_{bjets}^{bkg}}{L \times A \times \varepsilon}$

- $N_{b-tags}$: number of b – tags
- $f_{bjets}$: b – jet purity in b - tag sample
- $N_{bjets}^{bkg}$: number of tagged b – jets not from $W+b\bar{b}$
W+b-jets production

\[ \sigma_{W+bjets} \cdot Br = \frac{N_{b-tags} \cdot f^{bjets} - N^{bjets}_{bkg}}{L \times A \times \varepsilon} \]

- **Major b-jets bkgd. (S/B ~ 3/1):**
  - ttbar (40% of total bkgd)
  - single top (30%)
  - Fake W (15%)
  - WZ (5%)

- **Measurement:**
  \[ \sigma \cdot BR = 2.74 \pm 0.27 \text{(stat)} \pm 0.42 \text{(syst)} \text{ pb} \]
  \[ (p_T^{e\mu}>20 \text{ GeV/c}, |\eta^{e\mu}|<1.1, p_T^{\nu}>25 \text{ GeV}, E_T^{bjet}>20 \text{ GeV}, |\eta^{bjet}|<2.0) \]

- **Alpgen (LO) prediction:**
  \[ \sigma \cdot BR = 0.78 \text{ pb} \]

The measurement x3.5 larger than the Alpgen prediction. Waiting for other theoretical predictions (MCFM NLO etc.)
**Motivation:**
- Probe $s$-content of proton at high $Q^2$
  - $g+s \sim 0.9$, $g+d \sim 0.1$.
- Important BG for top quark studies, searches for Higgs, stop...

**Strategy:**
- $W \rightarrow l+\nu$ selected by high $p_T$ $e,\mu + \text{MET}$
- Charm-jet identified by the soft lepton tagging (SLT) algorithm.
- Utilize charge correlation between $W$ lepton and SLT lepton.
  - $W+c$ production: opposite sign (OS)
  - In $W+bb(cc)$, same sign (SS) $\sim$ OS.

**$W+$ Single $c$ Production**

$$\sigma_{W+c} \times Br(W \rightarrow l\nu) = \frac{N_{\text{measured}}^{OS-SS} - N_{\text{bkg}}^{OS-SS}}{L \times A \times \epsilon}$$

- **Main OS-SS backgrounds**
  - Fake $W$
  - $W+$light jets
  - Drell-Yan
$W+$ Single $c$

Production

- DØ uses both $e$ and muon soft leptons
  For jets with $P_T > 20$ GeV, $|\eta| < 2.5$
- Measure the ratio $\sigma_{W+c}/\sigma_{W+jets}$
  Many systematic uncertainties cancel.

\[ \sigma_{Wc} \times Br(W \rightarrow l\nu) = 9.8\, (stat.) \pm 2.8^{+1.4}_{-1.6}\, (syst.) \, pb \]
\[ NLO: 11.0^{+1.4}_{-3.0} \, pb \, (p_{Tc} > 20 \, GeV/c, \, |\eta_c| < 1.5) \]

In good agreement

\[ \frac{\sigma_{W+c}}{\sigma_{W+jets}} = 0.074 \pm 0.019\, (stat.)^{+0.012}_{-0.014}\, (syst.) \]

LO (Alpgen+Pythia): $0.044 \pm 0.003$

In reasonable agreement
Final Notes

• Proper Modeling of the Underlying Event

• Z/W+jet(s): good agreement with predictions, results test background estimations in searches for new physics

• Good understanding of Vector Boson and HF jets production critical for Tevatron and LHC
  ▪ First Z/W+HF measurements start challenging large theoretical uncertainties
  ▪ W+charm well described by recent NLO predictions
  ▪ W+bottom does not agree well with predictions

• Tevatron promises ~8 fb⁻¹ by End 2009 (further improvements likely)

• First LHC physics data by End 2009 ....

"Just checking."