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On behalf of the CDF and D0 collaborations

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Introduction

• Mature QCD studies at the Tevatron benefit physics program at the LHC.
  – Challenging measurements, sensitive to (N)NLO as well as non perturbative physics.
  – Mature experiments have had time to think about conditions and detector effects especially in terms of reducing uncertainties. (JES 1-3%, PDF inputs, very precise jets and dijets cross sections.)

• QCD is part of almost any New Physics search.
  – PDFs for background and signal processes.
  – QCD is often a dominant background to Higgs and New Physics searches.
    • e.g. boosted Higgs searches, diphotons for Higgs searches.

• Better understanding of QCD means improved sensitivity to New Physics.
• Collide protons with anti-protons at $\sqrt{s}=1.96\text{TeV}$
• Run II ended September 30th, 2011
  – Delivered $12/\text{fb}$
  – Peak luminosity $4.3\times10^{32}\text{ cm}^{-2}\text{s}^{-1}$
• For comparison, Run I delivered $120/\text{pb}$
Angular Decorrelations in $\gamma +2(3)$ Jet Events

The analysis: $1/fb$

Measuring differential cross sections vs. azimuthal angles in $\gamma +2$ (3) jet events.

$\Delta \phi( \gamma +\text{jet1,jet2})$

In 3 bins of 2$^{nd}$ jet $p_T$:  
(15-20, 20-25, 25-30) GeV

$\Delta S( \gamma +\text{jet1,jet2+jet3})$  
for 2$^{nd}$ jet $p_T$ of 15-30 GeV

Motivation

• Better understanding of non-perturbative QCD.
  – Improve MPI models and constrain existing theories.

• Provides information about proton substructure.
  – Spatial distribution of parton.
  – Possible parton-parton momentum and color correlations.

• Realistic model gives a better handle on background estimation for different analyses.
  – Rare processes
  – Higgs searches

• Differentiation in jet $P_T$ increases sensitivity to MPI models even further.
Angular Decorrelations in $\gamma +2(3)$ Jet Events

- Predictions of Single Parton models do not provide a good description of the data.
- Additional description of Double Parton events is required.
- New PYTHIA MPI models with $P_T$-ordered showers are favored, as well as the SHERPA default ones.
- Fractions of DP events decrease in bins of $P_T$.

Results using $1/fb$
3-jet Mass Cross-sections

The analysis: 0.7/fb


Differential measurement of 3-jet mass:
\( P_T^{\text{lead}} >150\text{GeV}, P_T^{3\text{rd}}>40\text{GeV}, \Delta R_{jj}>1.4 \)

• The measurement is done for 5 scenarios - in 3 rapidity intervals and 3 \( P_T \) intervals of the 3\(^{rd} \) jet (\( P_T \) ordered).
• 3-jet calculations available at NLO.
  – Use fastNLO with MSTW2008
  – Default scale \( \mu=1/3(P_{T1}+P_{T2}+P_{T3}) \)
• NLO non-perturbative correction: vary between (-2,+10)\%.
Motivation:

• Testing QCD at higher orders of $\alpha_s$.
  - Directly sensitive to the pQCD matrix elements of $O(\alpha_s^3)$.
• pQCD calculation available in NLO in $\alpha$.
  - Can be used for precision phenomenology from the experimental data.
• Provides information that can help decorrelate $\alpha$ and PDFs.

Total systematic uncertainties: (20-30)%. Dominated by JES, momentum resolution and luminosity.
Results:

- Perform $X^2$ calculations for different scale choices and $\alpha$ values.
- Best agreement between data MSTW2008NLO for all cases.
  - CT10 and HERAPDFv1.0 PDF sets are in poorer agreement with the data.
The analysis: 4.2/fb  \url{http://arxiv.org/abs/1106.1457}

- Measure the differential cross-section of $W+n$ jets ($n=1,2,3,4$) as a function of the $n$th jet $P_T$.
  - $W$ reconstructed in leptonic channel $W \rightarrow e\nu$

- Results are normalized to the measured inclusive $W+n$-jets cross section.
  - Uncertainties reduced due to cancellation of some systematic uncertainties.

- First inclusion of $W+4$-jets cross-section measurement.

Motivation:

- Fundamental test of $p$QCD, at high momentum scales.
- Dominant background for other measurements.
  - Higgs and NP searches, $tt$ and single top production.
- Large theoretical uncertainties (30%-40%) on $W+HF$ production limits the ability to determine contributions in searches for NP.
  - Precision measurements are crucial to improve these as inputs to such analyses.
W+jets Production

- **W+1jet** agrees with both NLO calculations.
- **W+2 jets**: MCFM significantly below the data.
  - Indicates that the scale uncertainties are larger than what is seen by conventional variations of $\mu$.
- **W+3 jets**: theory smaller than data, but consistent within uncertainties.
- **W+4jets**: consistent with LO, though large uncertainties. No NLO calculation available for Tevatron energies.

**Comparisons with theory**

**Differential cross sections**

**Graphs**

- [Graph 1](image): 1/$\sigma_W$ vs $p_T$ for different jet multiplicities.
- [Graph 2](image): Ratio of theory to data for leading jet $p_T$.
- [Graph 3](image): Ratio of theory to data for second jet $p_T$.
- [Graph 4](image): Ratio of theory to data for third jet $p_T$.
- [Graph 5](image): Ratio of theory to data for fourth jet $p_T$.
First Observation of W+Single Charm Production

Motivation:

• Production of W+c proceeds at LO through gluon-quark fusion.
  – 90% through sg fusion (PDF suppression but CKM enhancement of dg fusion).

• Measure cross section times leptonic W branching fraction \( \sigma \cdot B(W \rightarrow l \nu) \) for charm parton.

  \[ P_T > 20 \text{ GeV and } |\eta| < 1.5 \]

  – Alpgen LO: \( \sim 7.5 \text{ pb} \)
  – NLO K factor from MCFM: \( 1.5 \pm 0.3 \text{ pb} \) (uncertainty due to ren./fact. scale)
  – Therefore NLO \( \sigma \cdot B(W \rightarrow l \nu) = 11.3 \pm 2.2 \text{ pb} \) for \( p_{Tc} > 20 \text{ GeV and } |\eta_c| < 1.5 \)

• Understand background of low jet multiplicity bins for single top and W+Higgs, as well as control region for top pair production.

• Identify W+charm events among W+H.F events
The analysis:  
http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

- **W boson**: \( 1 \) central lepton (e or \( \mu \) ) with \( P_T > 20 \text{ GeV} \) and \( \text{MET} > 25 \text{ GeV} \) and transverse mass > 20 GeV.
- **1 central jet** \( p_T > 15 \text{ GeV} \) and \( | \eta | < 2.0 \) (JetClu 0.4 cone).
- **Drell-Yan suppression**: \( M_{\mu \mu} \) outside of 8-11 GeV or 70-110 GeV, \( M_{ee} < 45 \) GeV, \( \Delta \Phi_{\text{jet-MET}} > 0.3 \) for \( ee \) case.
- Identify heavy flavor quarks by using soft lepton tagging to find soft electrons or muons embedded in jets.
- \( \geq 1 \) SLTe/\( \mu \): near the jet (\( \Delta R < 0.4 \) for SLTe and \( \Delta R < 0.6 \) for SLT \( \mu \))
- Look for excess of opposite-sign (OS) lepton-pairs over same-sign (SS) lepton pairs.
- **Consider 3 classes of backgrounds:**
  - **W+jet, QCD multijet production**
  - Background estimated from MC

\[
\sigma_\mu = 13.2 \pm 2.3 \text{ (stat)}^{+2.2}_{-1.6} \text{ (syst)}^{+1.2}_{-1.0} \text{ (lumi) pb}
\]
\[
\sigma_e = 14.5 \pm 6.6 \text{ (stat)}^{+4.2}_{-2.5} \text{ (syst)} \pm 1.2 \text{ (lumi) pb}
\]
\[
\sigma_{\text{combined}}^{\text{combined}} = \text{BR}(W \rightarrow l\nu) = 13.3^{+3.3}_{-2.9} \text{ (stat. + syst.)}
\]
Z+b Production

- **The analysis: 7.8/fb**
  
  http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

- Select $Z \rightarrow ee (\mu \mu) + b + X$
  - $66 < M_Z < 116$ GeV
- $E_t(e) > 25$ GeV, at least one central electron.
- Muons are identified with a new ANN separating real Z muons from ones coming from jet fragmentation or from decay in flight.
- Midpoint cone jets with $R=0.7$
- Jet $P_T > 20$ Gev, jet $|\eta| < 1.5$
- $R_{\text{jet-lepron}}>0.7$
- B-tag with secondary vertex.
- Estimate fractions in tagged sample from a maximum likelihood fit to the secondary vertex invariant mass.
  - Templates obtained from ALPGEN.
- **Dominant backgrounds**: top pair production and diboson events.
- **Dominant systematic uncertainties**: b-tag efficiency, light-jet templates for fit, track reconstruction efficiencies.
Z+b Production

\[ \frac{\sigma_{Z+bjets}}{\sigma_{Z}} = 0.293 \pm 0.030^{\text{stat}} \pm 0.036^{\text{syst}} \% \]
\[ \frac{\sigma_{Z+bjets}}{\sigma_{Z+jets}} = 2.31 \pm 0.23^{\text{stat}} \pm 0.32^{\text{syst}} \% \]

- Measured ratios larger than ones from ALPGEN by about 1.6, in agreement with MCFM within uncertainties.
- Results favor predictions with lower renormalization and factorization scales.

Most recent D0 result (4.2/fb): \[ \frac{\sigma_{Z+bjets}}{\sigma_{Z+jets}} = 1.93 \pm 0.22^{\text{stat}} \pm 0.15^{\text{syst}} \% \]

PRD83,031105 (2011)
Motivation:

• Test QCD, tune MC – especially wrt parton showering mechanism.
• Considerable LHC program to search for New Physics with boosted objects.
  – $Z'$ to boosted tops, $W/Z+boosted$ Higgs, GMSB+boosted Higgs, etc.

• The analysis: 6/fb  arXiv:1106.5952
• Compare distributions of jet substructure variables with MC predictions and analytical calculations.
• Compare differential jet cross section as a function of jet mass for different algorithms and cone sizes.
Jet Substructure

Selection: ≥1 central jet, $P_T > 400$ GeV. $0.1 < |\eta| < 0.7$, jet $R = 0.4, 0.7, 1.0$

Test two jet Shape variables:

1. **Angularity**
   
   $$\tau_a(R, p_T) = \frac{1}{m_J} \sum_{i \in \text{jet}} \omega_i \sin^a \theta_i \left[ 1 - \cos \theta_i \right]^{1-a} \sim \frac{2^{a-1}}{m_J} \sum_{i \in \text{jet}} \omega_i \theta_i^{2-a}$$

   measures the energy distribution inside the jet sensitive to the degree of symmetry in the energy deposition

   pQCD predicts angularities of high mass jets to have sharp kinematic edges, with give min and max that can be tested on data.

2. **Planar flow**
   
   $$I_{W}^{kl} = \frac{1}{m_J} \sum_{i} w_i p_{i,k} \frac{p_{i,l}}{w_i}$$
   $$Pf = 4 \frac{\det(I_W)}{\text{tr}(I_W)^2} = \frac{4\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)^2}$$

   $\lambda$s are eigenvalues of $I_W$

   Should be close to unity for isotropic depositions of energy, high values when hard gluons are emitted and low values when soft gluon are emitted

   - **Main background**: top pair production
     - Suppress by cut on $P_T$ and mass of second jet and missing $E_T$ in the event
Jet Substructure - Results

- Good Agreement between data and QCD and MC predictions over jet mass range 100-250 GeV.
- Similar results obtain when using the anti-Kt and Midpoint algorithms.
Summary

Public webpages:

CDF: http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
D0: http://www-d0.fnal.gov/Run2Physics/qcd/D0_public_QCD.html

• Several recent Tevatron results are presented:
  – Current level of understanding jet ID, systematics and JES ends up in experimental uncertainties similar or lower than theoretical uncertainties.
  – Precision measurements of fundamental observables are allowed.

• New techniques and larger datasets
  – First observation of $W^+\text{single Charm}$ production.
  – First measurement of its kind – Jet Substructure at the Tevatron ("jetography").

• Tevatron measurements provide important feedback to MC tunning and QCD modeling.
  – Many analyses show importance of NNLO terms and of having better experimental constraints on theories.
The analysis: 4.2/fb  PRD83,031105 (2011)

- Select $Z \rightarrow ee(\mu \mu) + b + X$
  - $70 < M_z < 110$ GeV
- $P_T(e) > 15$ GeV, $P_T(\mu) > 10$ GeV
- Midpoint cone jets with $R = 0.5$
- Jet $P_T > 20$ GeV, jet $|\eta| < 2.5$
- Secondary vertex tagging
  - Apply NN selection to enrich sample with $b$-jets
- Use the long $B$ lifetime to discriminate between $b/c$/light jets
  - Use log-likelihood fit to extract $b$-jet fractions
  - Templates to likelihood fit are taken from MC and corrected to match data for $b$ and $c$ jets. Template for light jets is taken from data.
\( \sigma (Z+b)/ \sigma (Z+\text{jets}) \) Results

- Measurements yield the ratio:
  \( 0.0193 \pm 0.0022 \text{(stat)} \pm 0.0015 \text{(syst)} \)
- Most precise measurement of this fraction
- Consistent with NLO QCD calculations