QCD Studies at the Tevatron

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Outline

- Tevatron, CDF and DØ
- Inclusive jet production
- Inclusive photon production
- Boson+jets
- Heavy flavor jets
- Summary

There are many more results, not covered in this talk
Tevatron

*p-pbar* collider at $\sqrt{s} = 1.96$ TeV

- Tevatron has delivered $2.5$ fb$^{-1}$
- CDF and DØ have $\sim 2.0$ fb$^{-1}$ on tape
- Results shown here are using up to $1.1$ fb$^{-1}$

Instantaneous luminosities close to $3E32$

Projections: 4 to 8 fb$^{-1}$ by 2009
CDF and DØ

Both experiments recording data with high **efficiency** (80-90%) and making full use of their capabilities.
Jet Physics at the Tevatron

In Run II:
• Increased $\sqrt{s} \rightarrow$ increase in the jet production cross section
• Increased the $p_T^{\text{jet}}$ range up to 600-700 GeV/c
• Explored the use of new jet algorithms: MidPoint, $k_T$
• Measurements in a wide rapidity region

Measurements of hadronic collisions must take into account:
• Non-pQCD contributions
  • Underlying Event
  • Fragmentation of the partons
**MidPoint** cone algorithm (R=0.7)

Two rapidity regions:
- $|y_{jet}| < 0.4$
- $0.4 < |y_{jet}| < 0.8$

Shape comparison with the pQCD NLO prediction

**DØ Run II preliminary**

- $|y_{jet}| < 0.4$ (x10)
- $0.4 < |y_{jet}| < 0.8$

- $\sqrt{s} = 1.96$ TeV
- $L \sim 0.8$ fb$^{-1}$
- $R_{cone} = 0.7$

- **NLO pQCD**
  - plus threshold corrections (2-loop)
  - Hadronization corrections applied

- CTEQ6.1M $\mu_R = \mu_F = p_T$

- Data scaled to theory for CTEQ6.1M at $p_T = 130$ GeV/c at $|y_{jet}| = 0.4$ to remove luminosity uncertainty

**Figure Details**

- NLO $\mu_R = \mu_F = p_T$, $R_{cone} = 0.7$
- DØ Run II preliminary
- $|y_{jet}| < 0.4$, $L \sim 0.8$ fb$^{-1}$
k_T algorithm (D=0.7) defines jets according to relative k_T between the particles. More natural definition according to QCD radiation mechanism.

- Five rapidity regions up to |y_{jet}| < 2.1
- Compared to pQCD NLO prediction corrected for non-perturbative contributions
- Good agreement in the five rapidity regions

Uncertainties on the data are comparable to the uncertainties on the theoretical prediction.
- Measurement should contribute to increase the PDF knowledge.

CDF has similar results using the MidPoint algorithm
Non-pQCD contributions are understood. Checked with different jet sizes. They are extracted from the MC:

- Dedicated measurements to validate the MC simulation.
Jet Shapes (CDF)

\[ \Psi(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} p_T(0,r) \]

- The observable is sensitive to the fragmentation of the partons.
- Also sensitive to the simulation of the contributions from the underlying event.
- Underlying event and fragmentation are understood in all the \( p_T^{\text{jet}} \) range.

\[ 0 < |Y^{\text{jet}}| < 0.7 \]

\[ 0 < 1 - \Psi(0.3/R) < 0.4 \]

\[ 0 < \Psi(R) < 1 \]

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**k_T** distribution of particle inside jets (CDF)

### Process in the limit of the perturbative calculations:

- **MLLA next-to-leading log** theoretical prediction do not describe large k_T's at low hard scales

- Larger hard scales are better described by the perturbative predictions

**Pythia Tune A** describes well the k_T distribution of the particles even at low scales

774 pb^{-1}

Jet axis

k_T

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Inclusive Photon Cross Section (DØ)

Direct photon production can be used to precisely study QCD dynamics:

- **Cleaner signal**: no definition of “jet” is needed
- Lower $p_T$’s can be accessed
- Sensitive to gluon PDF

Central photons $|y|<0.9$

Photon up to 442 GeV/c of $p_T$

Good agreement with NLO predictions.

With more data (1-2 fb$^{-1}$), $p_T$ range could be expanded and uncertainties can be reduced to level of PDF uncertainties.

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**Boson+jets**

- They are important backgrounds to:
  - **top** production
  - Higgs searches
  - SUSY searches

- Could be used in searches for *compositeness*, *heavy objects* decays, etc.

- Test of **pQCD** at high momentum transfer and **NLO** predictions are available in some cases

- The measurements are also sensitive to **Underlying Events** and **hadronization** modeling.

- Efforts are being made on combining **LO matrix elements** (ME) with different parton multiplicities and matching them with **parton showers** (PS) without double counting the contributions to a given jet multiplicity.
**W+jets (CDF)**

W → eν + jets

Jets reconstructed with CDF Run I cone based algorithm (JetClu)

R = 0.4

E_{T^{jet}} > 15 GeV, |η|_{jet} < 2

Stringent test of pQCD calculations.

Important to test ME+PS matching techniques (MLM, CKKW…)

Shape comparison to different LO ME+PS predictions with different matching techniques.
Comparing the prediction of Z+jets done by different MCs:
(p_{T,jet} > 15 \text{ GeV/c})

- **Pythia Z inclusive**
  Jets are created from the PS
  It describes up to the 2\text{nd} jet

- **Sherpa Z+0…3p**
  ME+PS matched for every parton/jet multiplicity
  Describes better higher jet multiplicities.
**Z+jets (CDF)**

Ten times smaller cross section than **W+jets**, but **Z→ee** is a cleaner sample almost background free below the Z mass peak

\[ p_T^{\text{jet}} > 30 \text{ GeV}/c \quad |y^{\text{jet}}| < 2.1 \]

- **Data** corrected to hadron level.
- Good agreement with **NLO predictions** with non-perturbative contributions.

**CDF Run II Preliminary**

- Z\(\rightarrow\)ee + jets
  - 66 < M_{\nu\nu} < 116 \text{ GeV}/c^2
  - E_T > 25 \text{ GeV}, |y| < 1
  - |\eta^{\text{jet}}| < 1.2, |\eta^{Z}| < 2.8
  - p_T^{\text{jet}} > 30 \text{ GeV}/c, |y^{\text{jet}}| < 2.1
  - \Delta R(\phi,|\text{jet}|) > 0.7

- Z\(\rightarrow\)ee + jets
  - Data L = 1.1 fb\(^{-1}\)
  - Systematic uncertainties
  - NLO MCFM CTEQ6.1M
  - Corrected to hadron level
  - \(\mu_0^2 = M_Z^2 + p_T^2(Z)\), \(R_{\text{had}} = 1.3\)
  - \(\mu = 2\mu_0\)
  - \(\mu = \mu_0/2\)
  - PDF uncertainties

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Parton-to-hadron level corrections

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Parton-to-hadron level corrections
**Z+jets (CDF)**

**NLO** predictions up to 2 jets in the final state.

**LO** for 3 jets.

Constant **k-factor**

NLO/LO with the jet multiplicity.

Size of the **non-perturbative** contributions: ~15%
Underlying Events in Z+jets (CDF) 1.1 fb⁻¹

Energy flow

Jet Shapes

CDF Run II Preliminary

Z→ee + jets
66 < M_{ee} < 116 GeV/c²
E_T > 25 GeV, |η_{tow}| < 1
|η_{calo}| < 1 || 1.2 < |η_{calo}| < 2.8
p_T > 30 GeV/c, |y^{jet}| < 2.1
ΔR(e,jet) > 0.7
Calorimeter towers with |y| < 0.7

Statistical uncertainties only

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Data L = 1.1 fb⁻¹

Pythia Tune A

Pythia w/o UE

Pythia Tune DW

Statistical uncertainties only
b-bbar dijet production (CDF)

Provides understanding of the b production mechanisms: direct production, flavor excitation, gluon splitting.

\[ \Delta \phi \] distribution is very sensitive to the soft gluon radiation.

CDF Run II Preliminary

JetClu \( R_{\text{cone}} = 0.4, |\eta| < 1.2 \)
\[ E_{T,1} > 35 \text{ GeV}, E_{T,2} > 32 \text{ GeV} \]
\[ \sqrt{s} = 1.96 \text{ TeV}, L = 260 \text{ pb}^{-1} \]
Z→bb (DØ & CDF)

Challenging due to the very large background from b-bbar production and mis-tagged jets. Important to establish the b energy scale.

300 pb⁻¹

584 pb⁻¹

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Summary

• **Tevatron** and the experiments are performing very well and more than 4 fb\(^{-1}\) of data are expected by 2009.

• **CDF** and **DØ** are carrying out a coherent set of QCD measurements.

• Measurements cover a large range of \(p_T\) and rapidities.

• All these measurements will provide at good basis for the **LHC**.

"Particles, particles, particles."
Backup slides
**Z+jets (CDF)**

Ten times smaller cross section than **W+jets**, but **Z→ee** is a cleaner sample almost background free below the Z mass peak

\[ p_T^{\text{jet}} > 30 \text{ GeV/c} \quad |y^{\text{jet}}| < 2.1 \]

**Data** corrected to hadron level.

Good agreement with **NLO predictions** with **non-perturbative** contributions.

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b-jet Shapes (CDF)

\[ \Psi(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{p_T(0, r)}{p_T(0, R)} \]

First attempts to measure the shapes in heavy flavor jets.

Showing the jet shapes in the data compared to Pythia Tune A and Herwig.

Shape in b jets are sensitive to the b content of the jet (fraction of 1b/2b jets: \( f_{1b} \)).