Jet Physics from the Tevatron

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on behalf of the CDF and D0 collaborations
Very wide and varied QCD program
Many interesting results from both CDF and D0

**Hard QCD** - jets, photons, bosons +jets
**Soft QCD** – UE studies, MinBias, diffraction

This talk covers *only jet production* results:
more Tevatron QCD talks:
   Stefano Camarda on “W/Z+jets”

for complete list see:
  http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
  http://www-d0.fnal.gov/Run2Physics/qcd/
Tevatron performing very well:
10.3 fb\(^{-1}\) delivered per experiment
50 pb\(^{-1}\) per week
experiment efficiency \(\sim 90\%\)
peak: \(3.5 \times 10^{32}\) cm\(^{-2}\)s\(^{-1}\)
expecting 12 fb\(^{-1}\) by end of FY11
Test pQCD over 8 orders of magnitude

Precise energy scale:
- 1-2% D0
- 2-3% CDF

Different jet algorithms tested
- Cone algorithm
- \( k_T \) algorithm PRD 75, 092006 (2007)
- extended to forward rapidity \( |\eta| < 2.4 \)
Jet production – Precision regime

PDF input

CDF Data (1.13 fb\(^{-1}\)) / NLO
PDF Uncertainty
MRST 2004 / CTEQ6.1M
Systematic uncertainty
Including hadronization and UE

Midpoint: R=0.7, f_{merge}=0.75

DØ Run II R_{cone} = 0.7
L = 0.70 fb\(^{-1}\)

|y| < 0.4

NLO scale uncertainty

1.2 < |y| < 1.6
Jet production – Precision regime

PDF input

Exp. uncertainties are smaller than theoretical constrain PDF

Midpoint: $R = 0.7$, $f_{\text{merge}} = 0.75$
Jet production – Precision regime

PDF input

Exp. uncertainties are smaller than theoretical constrain PDF
Conclusions from Les Houches QCD 2011:
“Tevatron jet data vital to pin down high-x gluon, giving smaller low-x gluon and therefore larger $\alpha_s$ in the global fit compared to a DIS-only fit.”

Expect Tevatron to dominate high- x gluon PDF for some years
Jet production – Precision regime

\[ \alpha_s(M_Z) = 0.1173^{+0.0041}_{-0.0049} \]

**Historical note:**

CDF Run I  Then  PRL 88:042001, 2002

\[ \alpha_s(M_Z) = 0.1178 \pm 0.0001 \text{(stat)}^{+0.0081}_{-0.0095} \text{(syst)} \]

- Theory: NLO+2-loop threshold corrections
- Significantly improved precision
- Running tested to very high \( Q^2 \) values

Now:

PRD 80, 111107 (2009)

\( \alpha_s(p_T) \) from inclusive jet cross section in hadron-induced processes

- H1
- ZEUS
- DØ

DØ

\[ \alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048} \]

(DØ combined fit)
suppression at LO of the background subprocesses ($J_z=0$ selection rule)

“exclusive channel” → clean signal (no underlying event)
**Dijet Mass Measurements**

**Measurement of dijet mass in six rapidity bins,**

\[ |y|_{\text{max}} = \max(|y_1|, |y_2|) \]

Comparison to NLO pQCD with MSTW2008 and CTEQ6.6M NLO PDFs,

**Study dijet events in |y|<1.0**

NLO pQCD fits to data: \( \chi^2/\text{ndf} = 21/21 \)
Three Jet Mass Cross Section

Differential measurements of 3-jet mass:

\[ p_T^{\text{lead}} > 150 \text{ GeV}, \ p_T^{\text{3rd}} > 40 \text{ GeV}; \ \Delta R_{jj} > 1.4 \]

- Studies Invariant masses > 1 TeV!
- Measurement is done in 3 rapidity and \( p_T \) intervals of 3rd jet.
- Three-jet calculation available @NLO
  Used NLOJET++ with MSTW2008
  Default scale \( \mu = 1/3(p_{T1} + p_{T2} + p_{T3}) \)

NLO non-perturbative corr.: -3%, +6%
Total systematic uncertainty: 20-30%
(dominated by JES, \( p_T \) resolution and lum.)
Many experimental uncertainties cancel in the ratio $R_{3/2}$

- Measure as a function of two momentum $R_{3/2}(p_{T_{\text{max}}}, p_{T_{\text{min}}}) = P(3\text{rd jet} \mid 2\text{ jets})$:
  - $p_{T_{\text{max}}}$ – leading jet $p_T$ (common between 2- and 3-jet productions)
  - $p_{T_{\text{min}}}$ – scale at which other 1-2 jets resolved

- Excellent agreement to Sherpa 1.1.3 (MSTW2008 LO)
  - Pythia tunes – virtuality-ordered parton showers

A and DW does not describe the $R_{3/2}$ data; Tune BW works
Many experimental uncertainties cancel in the ratio R3/2

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  - $p_{T\text{max}}$ – leading jet $p_T$ (common between 2- and 3-jet productions)
  - $p_{T\text{min}}$ – scale at which other 1-2 jets resolved

- Excellent agreement to Sherpa 1.1.3 (MSTW2008 LO)
  - Pythia tunes Perugia – $p_T$-ordered parton showers don’t work that well
MOTIVATION: Mass of high-pT jets - important property, but only theor. studies:

- High mass:
  - QCD NLO predictions for jet mass
  - Ellis et al, 0712.2447
  - Alemeida, et al. 0810.0934

Such jets form significant background to new physics signals

Examples: high $p_T$ tops, Higgs, neutralino ...

- 4-vector sum over towers in jet
- Each tower is a particle with $m = 0$
- Four vector sum gives $(E, p_x, p_y, p_z)$

Use standard “e-scheme” for mass calculation

CDF Run II Preliminary, $L_{int} = 6\text{fb}^{-1}$

Selection: > 1 jet

$\mathbf{p}_T > 400\text{ GeV/c}$

$0.1 < |\eta| < 0.7$
Jet Substructure
Angularity and Planar Flow

Jet substructure variables that are insensitive to soft radiation at high jet mass:

Angularity:
\[ \tau_a (R, p_T) = \frac{1}{m_J} \sum_{i \in \text{jet}} \omega_i \sin^a \vartheta_i [1 - \cos \vartheta_i]^{1-a} \]

- Emphasizes cone-edge radiation
- For large \( m_{\text{jet}} \), has analytic approximation

Planar flow:
\[ I_{w}^{kl} = \frac{1}{m_{\text{jet}}} \sum_{i} \frac{p_{i,k}}{w_{i}} \frac{p_{i,l}}{w_{i}} ; \]
\[ Pf = \frac{4 \lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)^2} \]

Selection: > 1 jet
\( p_T > 400 \text{ GeV/c} \)
0.1 < |\( \eta \) | < 0.7
anti-top requirements
Understanding of jet identification, JES, and systematics leads (in many cases) to experimental systematic uncertainties smaller than theoretical uncertainties.

Extended measurement to forward rapidities and high pT values improving our knowledge of PDF, particularly high-x gluons measurements of the strong coupling constant.

**Next level of measurements**
- 3 jet studies
- Measurements of jet substructure variables
- Validating phenomenological models for diffraction

**Results shown today use only half of the data sample**

More to come from the QCD program at the Tevatron.
Backup
Jet Measurements

- Unfold measurements to the hadron (particle) level
- Correct parton-level theory for non-perturbative effects (hadronization & UE)
Jet Algorithms

Two main categories of jet algorithms

- **Cone Algorithms**
  - E.g. Midpoint Algo.: Extensive use at Tevatron in Run II (as suggested in Run II workshop in 1999, hep-ex/0005012)
  - Cluster objects based on their proximity in $y(\eta)$-$\phi$ space
  - Identify "stable" cones (kinematic direction = geometric center)
  - Pros: simpler for underlying-event and pileup corrections
  - Cons: infrared-unsafe in high order pQCD & overlapping stable cones.

- **Successive Combination Algorithms**
  - E.g. Kt Algorithm: Extensive use at HERA. A few Tevatron analyses.
  - Cluster objects based on a certain metric. Relative Kt for Kt algorithm.
  - Pros: Infrared-safe in all order of perturbative QCD calculations.
  - Cons: Jet geometry can be complicated. Complex corrections.

A lot of developments in recent years.

- SISCon, Cambridge-Aachen, Anti-Kt, etc.
- Extensively studied in LHC experiments. Will benefit future studies.