QCD Studies at the Tevatron

Results from the CDF and DØ Collaborations

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DESY Seminar, June 24, 2008
Fermilab Tevatron - Run II

- 36x36 bunches
- bunch crossing 396ns
- Run II started in March 2001
- Peak Luminosity: $2.85 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$
- Run II delivered: $>4.2$ fb$^{-1}$

Run II Goal: 8 fb$^{-1}$ end of FY2010
Run II Detectors

- Silicon tracking detectors
- Central Outer Tracker (drift chambers, COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding

Multi-Purpose Detectors:
- Tracking
- Calorimeter
- Muon System

New in D0 for Run IIb: Innermost “Layer 0” Silicon
Hadron-Hadron Collisions

proton

anti-proton

two high-energetic hadrons
Hadron-Hadron Collisions

partons inside the hadrons: parton density functions (PDFs)

proton → two high-energetic hadrons

anti-proton
Hadron-Hadron Collisions

- high $p_T$
- inclusive jets ($p_T$, $y$)
- dijets ($M_{jj}$, $y'$)
- $\gamma$, di-$\gamma$, $\gamma +$ jet
- $(Z^0, W^\pm) +$ jet
- top + anti-top

proton \hspace{2cm} \text{hard interaction} \hspace{2cm} \text{anti-proton}

outgoing parton(s) (quark, gluon, $\gamma$, $Z^0$, $W^\pm$)
Hadron-Hadron Collisions

soft radiation
final-state radiation
internal jet structure

proton

outgoing parton(s)

anti-proton

initial-state radiation
di-photon $q_T$
dijet azimuthal decorrelation
Hadron-Hadron Collisions

hard radiation
\[ \gamma + n\text{-jet} \quad (Z^0, W^\pm) + n\text{-jet} \]
multi-jet production

proton

outgoing parton(s)

outgoing parton(s)

anti-proton
Hadron-Hadron Collisions

hadronization, fragmentation

fragmentation functions
hadronization corrections

proton

anti-proton

outgoing parton(s)

outgoing parton(s)
Hadron-Hadron Collisions

multi-parton interactions
underlying event

proton

anti-proton

outgoing parton(s)
Hadron-Hadron Collisions

hadron-hadron physics

proton

anti-proton

outgoing parton(s)

hard process (2 or more partons)
ISR/FSR
hadronization / fragmentation
underlying event
Outline

- Jet Production
- Jets beyond 2→2
- Photon Production
- Vectorboson + Jets
- Heavy Flavor Jets
- W-Asymmetry

Not shown:
- Diffractive Results
- Underlying Event Studies
Jets

PDFs
QCD vs. “New Physics”?
Parton-, Hadron-, Detector- “Jets”

- Use Jet Definition to relate Observables defined on Partons, Particles, Detector

- Direct Observation: Energy Deposits / Tracks

- Stable Particles (=True Observable)

- Idealized: Parton-Jets
  
  no Observable (color confinement)
  
  only quantity to be predicted in pQCD

IR- and Collinear safe jet algorithms:
- TeV4LHC workshop
- Les Houches 2007 workshop
From Particle to Parton Level

- Measure cross section for \( pp \rightarrow \text{Jets} \) (on “Particle-Level”) Corrected for Experimental Effects (Efficiencies, Resolution, …)

Use Models to Study Effects of Non-Perturbative Processes (PYTHIA, HERWIG)
- Hadronization Correction
- Underlying Event Correction

CDF Study for cone \( R=0.7 \) for central Jet Cross Section

→ Apply this correction to the pQCD calculation → to be used for future MSTW/CTEQ PDF results → First time consistent theoretical treatment of jet data in PDF fits

New in Run II !!!
Inclusive Jet Production

- Run II: Increased x5 at $p_T=600\text{GeV}$ → sensitive to “New Physics”: Quark Compositeness, Extra Dimensions, ...(?)... 
- Theory @NLO is reliable (10%) → sensitivity to PDFs → unique: high-x gluon
Inclusive Jet Cross Section

Steeply falling $p_T$ spectrum:
1% error in jet energy calibration $\rightarrow$ 5—10% (10—25%)
central (forward) x-section

Benefit from
• Seven times more luminosity than in Run I
• Increased high $p_T$ cross section due to increased Run II cm energy
• Seven years of hard work on jet energy calibration

$\rightarrow$ Result with largest rapidity coverage and highest precision!

submitted to PRL [arXiv:0802.2400 [hep-ex]]
Inclusive Jet Cross Section

submitted to PRL arXiv:/0802.2400 [hep-ex]

- data are well-described by NLO pQCD
- experimental uncertainties: smaller than PDF uncertainties!!
- data favor lower edge of CTEQ 6.5 PDF uncertainties at high $p_T$
  - shape well described by MRST2004

→ data are used in forthcoming MSTW2008 PDFs  (→ talks at DIS2008)
In 2005: published both central cone and kT jets with 400pb⁻¹
Here: 2007/2006 results with large rapidity coverage for 1fb⁻¹
Inclusive Jets
Cone and kT Algorithms

Interpretations of CDF cone and kT jet results are consistent with D0 cone result.
Inclusive Jets: Tevatron vs. LHC

**PDF sensitivity:**

$\rightarrow$ Compare Jet Cross Section at fixed $x_T = 2p_T / \text{sqrt}(s)$

**Tevatron (ppbar)**

$>100x$ higher cross section @ all $x_T$

$>200x$ higher cross section @ $x_T>0.5$

**LHC (pp)**

- need more than 1600fb-1 luminosity to compete with Tevatron@8fb-1
- more high-x gluon contributions
- but more steeply falling cross sect. at highest $p_T$ (=larger uncertainties)

$\rightarrow$ Tevatron results will dominate high-x gluon for some time ...
Central Dijet Production $|y|<1$
sensitive to new particles
decaying into dijets

CDF Run II Preliminary

$d\sigma / dM_\parallel$ [pb/(GeV/c$^2$)]

- Expectations from NLO pQCD
- Excited quark

$M_\parallel$ [GeV/c$^2$]
Central Dijet Production \(|y| < 1\)
sensitive to new particles decaying into dijets

→ data above \(M_{jj} = 1.2\text{TeV}\!\)
→ All described by NLO pQCD

(see: http://www-cdf.fnal.gov/physics/exotic/r2a/20080214.mjj resonance 1b/)
Jets beyond $2 \rightarrow 2$

- Internal Jet Structure
- Dijet Azimuthal Decorrelation
- Radius Dependence of Jet Cross Sections

Underlying Event Parton Shower Matched Predictions 3-Jet NLO
Internal Jet Structure

Integrated Jet Shape:
Fractional $p_T$ in Subcone vs. $(r/R)$

Sensitive to Soft and Hard Radiation – and UE

Well-Described by (tuned) MCs
Internal Jet Structure

At fixed $r=0.3$ ($38<p_T<400\text{GeV}$)

study $p_T$ dependence of predicted $\Psi (r/R)$ for quark- & gluon-jets

→ significant difference

quark- & gluon-jet mixture in tuned PYTHIA gives good description of data
Jet cross section depends on radius in jet definition
→ Important testing ground

CDF: radius dependence for incl. jets (kT jet algorithm) for D (=radius) parameter
  \(D = 0.5, 0.7, 1.0\)

→ Results for each D value are compared to NLO pQCD calculation + non-pert corr.
→ agreement for all D values

(similar analysis in DIS by ZEUS)

→ ... but effectively only a LO test of radius dependence
→ better: study ratios and compute at true NLO (using 3-jet NLO)
Radius Dependence of Jet Cross Sections @NLO

Ratio of cross sections:
\[ R(D) = \frac{\sigma(D)}{\sigma(D_0)} = 1 + c_1 \alpha_s + c_2 \alpha_s^2 + \mathcal{O}(\alpha_s^3) \]

- Jet cross section at LO \(\rightarrow\) no radius dependence
- Jet cross section at NLO \(\rightarrow\) LO contribution to radius dependence
- Jet cross section at NNLO \(\rightarrow\) NLO contribution to radius dependence

NNLO calculation not available \(\rightarrow\) missing: 2-loop virtual corrections
\(\rightarrow\) but: 2-loop virtual correction don’t depend on radius (2\(\rightarrow\)2 kinematics)
\(\rightarrow\) contributions from 2-loop corrections cancel in difference

Use three-jet NLO calculation to compute difference
\(\rightarrow\) obtain NLO result for ratio:
\[ \left[ \frac{\sigma(D) - \sigma(D_0)}{\sigma(D_0)} \right]_{NLO} + 1 = \left[ \frac{\sigma(D)}{\sigma(D_0)} \right]_{NLO} = R_{NLO}(D) \]

\(\rightarrow\) use for first NLO study of radius dependence of jet cross sections
Radius Dependence of Jet Cross Sections @NLO

Study cross section ratios: (D=1.0/D=0.7) and (D=0.5/D=0.7) and compare with true NLO calculation

→ NLO corrections are <20% for Tevatron
→ most of pT range: dominated by non-pert. corrections
Study cross section ratios: $(D=1.0/D=0.7)$ and $(D=0.5/D=0.7)$ and compare with true NLO calculation

→ NLO corrections are <20% for Tevatron ~60-100% for HERA
→ most of $p_T$ range: dominated by non-pert. corrections
→ HERA data described / Tevatron data not → underlying event???
Dijet Azimuthal Decorrelation

Idea: Dijet Azimuthal Angle is Sensitive to Soft & Hard Emissions:
- Test Parton-Shower
- Test 3-Jet NLO

PRL 94, 221801 (2005)
Dijet Azimuthal Decorrelation

Compare with theory:
- LO has Limitation $>2\pi/3$
- Divergence towards $\pi$

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- NLO is very good – down to π/2
  & better towards π
  ... still: resummation needed

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- PYTHIA is too low in tail ...

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  ... but it can be tuned (tune DW)
  (“tune A” is too high!)
Dijet Azimuthal Decorrelation

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- PYTHIA is too low in tail ...
  ... but it can be tuned (tune DW)
  (“tune A” is too high!)
- SHERPA is great
- ALPGEN looks good – but low efficiency → large stat. fluctuations
Photons

Fixed-Order: NLO (?) Resummation
... PDFs?
Direct Photon Production

Direct Photons come unaltered from the Hard Subprocess
→ Direct Probe of the Hard Scattering Dynamics
→ Sensitivity to PDFs (...but only if we understand theory)

also fragmentation contributions:

suppress by isolation criterion
→ Observable: isolated photons
Isolated Photon Cross Sect.

- \( |y| < 0.9 \)
- \( p_T > 0 \)
- \( L = 326 \text{ pb}^{-1} \)

- data/theory: reasonable agreement over \( 23 < p_T < 300 \text{ GeV} \)
- different shape at low \( p_T \)
- experimental and theory uncertainties > PDF uncertainty

\[ \rightarrow \text{no PDF sensitivity (need improvements in exp. and thy.)} \]
• Measured over $20 < p_T < 170$ GeV
• data/theory $\rightarrow$ consistent with D0 result
Isolated Photon + Jet

investigate source for disagreement in data/theory incl. photon $p_T$ shape:

measure more differential:

- tag **photon and jet**
  → reconstruct full event kinematics

- measure in 4 regions of $y^\gamma / y^{\text{jet}}$
  - photon: central
  - jet: central / forward
  - same side / opposite side

- different PDF sensitivity in different $y^\gamma / y^{\text{jet}}$ regions

→ look at ratios for quantitative statement ...
Isolated Photon + Jet

Observe:

- different shape discrepancies in different $y^\gamma / y^\text{jet}$ regions

Checked that effect is not due to:

- scale choice
- PDF uncertainty/variation
- fragmentation contributions
Isolated Photon + Jet

Study ratios of cross sections in different $y^{\text{jet}}$ regions
- cancelation of correlated uncertainties
- stronger sensitivity to differences in different regions
→ biggest problems for central / forward-opposites

need improved theory
challenge:
→ find out what is missing...
- higher orders?
- resummation?
- ...???
Di-Photon Cross Section

- Pseudorapidity < 0.9
- Photon pT > 13 & 14 GeV


- **DIPHOX**:
  - NLO prompt di-photons
  - NLO fragmentation (1 or 2 \( \gamma \))
  - NNNLO gg \( \rightarrow \gamma\gamma \) corrections

- **ResBos**:
  - NLO prompt di-photons
  - LO fragmentation contribution
  - Resummed initial state gluon radiation (important for qT)

- **PYTHIA** (increased by factor 2)

\[
E_T^{\gamma_1} > 14 \text{ GeV}, \ E_T^{\gamma_2} > 13 \text{ GeV} \\
|\eta^{\gamma_1,\gamma_2}| < 0.9
\]
Di-Photon Cross Section

Additional measurement for \( \Delta \phi \) (gamma-gamma) < \( \pi/2 \) (open markers) compared to DIPHOX

- NLO fragmentation contribution
  - only in DIPHOX
  - \( \rightarrow \) at high qT, low \( \Delta \phi \), low mass

- Resummed initial-state gluon radiation
  - only in ResBos
  - \( \rightarrow \) at low qT

Important:
need combined calculation with NLO fragmentation & initial state resummation
Vector Boson + Jets

Fixed-order: NLO
LO + Parton Shower
Matched Tree-Level + PS
(CKKW/MLM)
Backgrounds to New Physics
Total cross section for jet multiplicity, $n$:

$$\sigma_n = \sigma(W \rightarrow e\nu + \geq n - \text{jet}; E_T^n > 25, |\eta| < 2.0)$$

**JETCLU cone algorithm**

<table>
<thead>
<tr>
<th>CDF II / MLM</th>
<th>MLM uncertainty</th>
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<tbody>
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<td>CDF II / SMPR</td>
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</tr>
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<td>CDF II / MCFM</td>
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</tbody>
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$\frac{\sigma_{Data}}{\sigma_{Theory}}$ vs Inclusive Jet Multiplicity ($n$)

→ NLO predictions look good / questionable: JETCLU & ignore non-pert. corrections
→ matched calc.: up to 40% too low / SMPR: slightly different shape
W + 2 Jets inclusive

Differential jet ET distributions: **Second Jet**

- **CDF II / MCFM**
  - Scale uncertainty
  - PDF uncertainty

- **CDF II / MLM**
  - Scale uncertainty

- **CDF II / SMPR**
  - Scale uncertainty

**“MCFM”:** NLO
No non-pert. corrections applied

**“MLM”:**
ALPGEN (LO) + Herwig (shower) + MLM matching

**“SMPR”:**
MadGraph (LO) + Pythia (shower) + CKKW matching

→ NLO predictions look good / questionable: JETCLU & ignore non-pert. corrections
→ matched calculations: “SMPR” better than “MLM” (under investigation)
\( Z + n \text{ Jets inclusive} \)

\[ Z/\gamma^* \rightarrow e^+e^- \]
- Two \( E_T > 25 \) GeV electrons
- \( 66 < M_{ee} < 116 \) GeV

- **Midpoint Cone algorithm:**
  - \( p_T > 30 \), \(|y| < 2.1\)
  - \( R=0.7\)

**Integrated cross sections for \( n=1,2,3 \)**
Non-pert. corrections: 1.1–1.4

\( \rightarrow \) NLO prediction + non-pert corrections describe data for \( n=1,2 \)
\( \rightarrow \) same deviation from LO for \( n=1,2,3 \) (success, if k-factor is constant)
As for $W$+jets:

→ NLO describe $n$-th jet differential $p_T$ distribution for $n=1,2$

$Z$+2 jet sample would benefit from more statistics
Z + n Jets

- Comparison on Detector-Level: Data vs. PYTHIA and SHERPA

PYTHIA does not describe Higher Jet Multiplicities

SHERPA is pretty good!
Z + 1 Jet inclusive

• Comparison on Detector-Level: Data vs. PYTHIA and SHERPA

PYTHIA does not describe Leading Jet pT Spectrum

SHERPA is pretty good!
Heavy Flavor Jets

Heavy Flavor PDFs
Fixed-Order: NLO
LO + Parton Shower
**W± + single c-jet**

- probe strange quark PDF at rather large $Q^2$
  - PDF fits so far: no direct input on the strange quark density
  - strange quark-PDF errors are small because: $s=(u\text{-sea }+d\text{-sea})/2$
  - this small uncertainty is fake $\rightarrow$ does not reflect true uncertainty

- sensitive to $|V_{cs}|$

- Part of $W+$jets bkgd to top, Higgs searches

Event selection similar to $W+$jets: \( W \rightarrow e/\mu \nu \)

Exploit feature of $W^\pm$ +single c:

$\rightarrow$ Opposite charge of $W$ and semileptonic daughter of charm hadron
$\rightarrow$ almost no charge correlation for backgrounds

Here: First Measurements of $W^\pm+c$
$W^{\pm} + \text{single } c\text{-}jet$


\[
\sigma_{wc} \times \text{BR}(W \rightarrow \ell \nu) = \frac{N_{\text{OS-SS}}^{\text{Tot}} - N_{\text{Bkg}}^{\text{OS-SS}}}{A \cdot L}
\]

\(\sigma \times \text{BR}\)

- **CDF:** for \(p_T^c > 20\) GeV, \(|\eta^c|<1.5\)
  \(9.8 \pm 2.8 \) (stat) +1.4\_1.6 (syst) ± 0.6 (lum) pb
- **NLO prediction (MCFM):**
  \(\sigma \times \text{BR} = 11.0 \pm 1.4 -3.0\) pb

**D0:** measure ratio

\(W+c\text{-jet} / W+\text{jet} \) vs. jet \(p_T\)

\(\rightarrow\) partial cancelation of syst. uncert.

\(p_T^{\text{lepton}} > 20\) GeV, \(|\eta^\text{jet}|<2.5\)

\[
\frac{\sigma(pp \rightarrow W+c\text{-jet})}{\sigma(pp \rightarrow W+\text{jet})} = 0.071 \pm 0.017
\]

LO prediction: \(0.040 \pm 0.003\) (PDF)
Measure cross section for $W+b$-jet production in events with a high $p_T$ central lepton, high $p_T$ neutrino and 1 or 2 total jets improve background estimate for Higgs search

- $\sim 1000$ tagged jets
- among which $\sim 700$ are consistent with coming from a $b$ quark

**CDF:**

$\sigma_{b\text{-jets}}(W+b\text{-jets}) \times \text{BR}(W \rightarrow l\nu) = 2.74 \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst)} \text{ pb}$

**Default ALPGEN:**

$\sigma \times \text{BR} = 0.78 \text{ pb}$

$\rightarrow$ Difference by factor of 3.5 - under investigation (other predictions?)
- Use $Z \rightarrow ee$ and $\mu\mu$
- jet reconstruction
  - Cone algorithm with $R=0.7$
  - Secondary vertex tags
  - Corrected $E_T > 20$ GeV, $|\eta| < 1.5$

Normalize by inclusive $Z$ cross sect.
→ Helpful to compare to LO and NLO

- PYTHIA good at low ET
- ALPGEN (LO) and MCFM (NLO) undershoot data in several bins
W-Asymmetry

PDFs
W-Asymmetry

\[ A = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W} \approx \frac{d}{u} \]

W decay: longitudinal neutrino momentum not measured → can’t reconstruct W rapidity
Lepton Charge Asymmetry

$W$ decay: longitudinal neutrino momentum not measured → can’t reconstruct $W$ rapidity

V-A structure of $W^{+(-)}$ decay favors backward (forward) charged lepton

$$A_l(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \sim \frac{d(x)}{u(x)}$$

0.3 fb$^{-1}$ DØ measurement

~190,000 $W \rightarrow \mu \nu$ events with $|\eta_\mu| < 2$
Direct Extraction of $A(y_W)$

- determine $p_L \gamma$ by constraining $M_W = 80.4$ GeV → two possible solutions for $y_W$

- Each solution receives a weight probability according to:
  - V-A decay structure
  - $W$ cross-section: $\sigma(y_W)$

- Process iterated since $\sigma(y_W)$ depends on asymmetry


- preliminary CDF measurement (1 fb$^{-1}$) ($\sim$715,000 $W \rightarrow e\nu$ events with $|\eta_e| < 2.8$) → Compared to CTEQ6.1 and MRST2006 PDFs
Summary

• This Presentation: Broad Spectrum of Processes
  Jets, Photons, W-Asymmetry, Vector-Boson + Jets,
  Heavy-Flavor Jets, Jet Production at higher Orders

• Tevatron is more than “the Place to Develop Tools for the LHC”

• “Bread-and-Butter Physics”: Precision Measurements of Fundamental Observables @2TeV

• PDF knowledge (for searches at Tevatron and LHC)
  → Inclusive Jets, W Asymmetry → strong PDF constraints

• Testing QCD at higher orders & transition soft → hard QCD
  Internal jet structure, jet radius dependence, dijet azimuthal
  decorrelation → novel QCD tests and MC tuning

• Differential Measurements of Vectorboson+Jet production
  to test predictions for “New Physics” backgrounds & model tuning

• Provide data to identify theory shortcomings: photons, HF jets

→ Significant improvements with 8fb-1
Backup
W + 1 Jet inclusive

Differential jet ET distributions: **First Jet**

→ NLO predictions look good / questionable: JETCLU & ignore non-pert. corrections
→ matched calculations: don’t describe ET dependence

**“MCFM”**: NLO
No non-pert. corrections applied

**“MLM”**: ALPGEN (LO) + Herwig (shower) + MLM matching

**“SMPR”**: MadGraph (LO) + Pythia (shower) + CKKW matching
W + 3 Jets inclusive

Differential jet ET distributions: Third Jet

→ not computed to NLO
→ matched calculations: "SMPR" better than "MLM" (under investigation)
Isolated Photon + Jet

quark-gluon subprocess fraction in different rapidity regions versus $p_T$
Dedicated silicon vertex trigger data

- Displaced tracks with IP > 120 μm
- Secondary vertex b-tagging algorithm

Fit signal+bkd template to mass distribution of tracks from secondary vertices to extract heavy flavor contribution

Data/theory agreement improves as we go from LO to Herwig or MC@NLO + Jimmy