QCD Studies at the Tevatron

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On behalf of the CDF and D0 Collaborations

Les Rencontres de Physique de la Vallee d’Aoste
La Thuile, Aosta Valley, Italy
February 28 - March 6, 2010
Introduction

The Tevatron is the world highest energy “proton-antiproton” collider ....

- Located about 30 miles west of Chicago, IL
  - 1.96 TeV in the C.M.
- Data are continuously recorded with very high efficiency (85-90%)
- The machine and the detectors (CDF and D0) are performing very well
  - Both experiments have collected already > 6 fb-1 on tape
- Measurements are becoming very precise
  - Top quark mass known with precision < 2%
- New analyses are now looking for the needle in the hay stack
  - Low cross section phenomena
  - The search for Higgs
  - Physics beyond the Standard Model

Still, an hadron machine is the perfect place to test QCD!
QCD at Hadron Colliders

Test of the Standard Model (pQCD)
Search for new physics
Inform/check/tune Monte Carlo and theory predictions
The physics objects

**Hadronic jets** are reconstructed using several algorithms: Cone, Midpoint, KT etc..
- From the calorimeter measurement to the parton-level jets, via several corrections
- Currently the jet energy scale is the major source of uncertainty (< 3% over the entire jet energy range)

**Heavy Flavor-jet identification** is implemented via:
- Displaced vertices with $L_{xy}/\sigma$ cut (CDF)
- Vertex mass separation (CDF)
- Vertex properties and displaced track info combined with NN algorithms

**Photons** are selected with stringent isolation criteria to minimize QCD fragmentation effects
In This Talk

• Selected topics
  – Jets and dijet inclusive production
    • PDF’s constraint and measurement of the strong coupling constant
    • Search for quark substructure in dijet angular distribution
    • Search for new particles decaying into dijets
  – Photons final states
    • Inclusive photon cross section
    • Photon + jet(s)
  – Vector bosons + jet(s)
  – The future outlook: TeV vs LHC
Jets

Collimated sprays of particles originating from quark and gluon fragmentation

Jets measurements probes the highest momentum transfer in particle collisions

\[ d\sigma_{\text{jet}} = \sum_a \sum_b f_{a/p}(x_1, \mu_F^2) f_{b/\bar{p}}(x_2, \mu_F^2) \times \hat{\sigma}_{a,b}(p_1, p_2, \alpha_s, Q^2 / \mu_R^2, Q^2 / \mu_F^2) \]

Sensitive to:
- Hard partonic scattering
- strong coupling constant
- proton’s parton content → unique sensitivity to high-x gluon
- dynamics of interaction
  - validity of approximations (NLO, LLA, ...)
  - QCD vs. new physical phenomena
Inclusive Jet Cross Section

Measurements span over 8 order of magnitude in $d\sigma^2/dp_T dy$

Highest $p_T^{\text{jet}} > 600 \text{ GeV/c}$

Jet energy calibration $\pm 1\%$
Inclusive Jet Cross Section

Both CDF and D0 measurements are in very good agreement with NLO predictions:
- Precision now exceeds that of PDF uncertainties
- Data can inform the PDF fits: suggestive of softer gluons at high-x

Data are used in PDF fits:
- included in MSTW2008 PDFs
- at work: forthcoming CTEQ PDFs
Strong Coupling Constant

Measurement uses the $P_T$ dependence of the jet $x$-section
- $\chi^2$ minimization of data/theory points
  - 22/110 points in the inclusive jet cross section used
    - $50 < P_T < 145$ GeV/c,
    - high points excluded to minimize PDF uncertainty correlations
  - NLO+2 loop thresholds corrections
  - MSTW2008NNLO PDF’s


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

Most precise result at hadron-hadron collider

CDF results in Phys. Rev. Lett. 88, 042001
Dijet Mass Spectrum

Old fashion mass bump hunt...

- Choose events with two high-\( p_T \) jets with rapidity less than 1.0. Look for an excess in the dijet mass spectrum for masses above 180 GeV
- Possible signals include excited quarks, \( W' \), \( Z' \), and Randall-Sundrum gravitons
- Find functional form of dijet spectrum in pythia and herwig, fit to data. Look for “bumps” in the data minus fit plot

- No significant resonant structure is observed, so limits are set on various models
- Excludes (at 95% CL) excited quarks from 260-870 GeV, \( W' \) from 280-840 GeV, and \( Z' \) from 320-740 GeV

D0 has also a new result out (arxiv: 1002.4594)
Dijets Angular Distribution

Dijet angular distributions is measured in bins of dijet mass:

- First differential cross section measurement at partonic energies >1 TeV!
- Small experimental and theoretical uncertainties.
- Sensitive to New Physics (95% CL limits)

Consistent with NLO pQCD

Most stringent limits to date!

1/σ ∂σ/∂χ_{dijet}

χ_{dijet} = \exp(|y_1 - y_2|)

Limit on Compositeness & LED

- Quark Compositeness Λ > 2.9 TeV
- ADD LED (GRW) M_s > 1.6 TeV
- TeV-1 ED M_c > 1.6 TeV

**Photons**

- **Inclusive photon cross section**

  direct photons emerge unaltered from the hard subprocess
  → direct probe of the hard scattering dynamics
  → sensitive to PDFs (gluon!) ...but only if theory works

Data/pQCD in agreement at high PT

enhancement at low PT

Region where effects of resummation might be higher as well as fragmentation

Not yet sensitive to PDF’s: experimental and theoretical uncertainties still dominate
Photons

-Isolated Photon + jet

-Probe of the gluon pdf and of the dynamics of hard QCD over a wide range of $x$ and $Q^2$

Central  Forward

• NLO predictions do not describe the shape over the full range of $P_T^\gamma$
• Scale variations cannot describe normalization simultaneously for the 4 rapidity ranges
• Measuring ratios reduces some uncertainty, but disagreement still present


Need for an improved and consistent theory description of the process

Photons

- Photons + heavy flavor production


**Sensitive to HF-content of proton Bkgd for many BSMs**

**Photon + b**

- good agreement on all $P_T$ range

**Photon + c**

- agreement only up to $P_T^\gamma < 50$ GeV/c
- increasing disagreement at higher $P_T^\gamma$

Using PDF intrinsic charm improves theory $P_T$ dependence, but data disagreement still remains

**Photon p_T: 30 – 150 GeV/c**

Rapidities: $|y^\gamma| < 1.0$, $|y^{jet}| < 0.8$

CDF has a recently submitted result with similar results for **Photon + b**

arXiv:0912.3453
Vector bosons + jets

Prerequisite for top, Higgs, SUSY, BSM
- major “universal” background

Test of pQCD and various Monte Carlo Models

NLO pQCD calculations are available up to 2(3) jets
Many Monte Carlo tools are available
- LO + Parton shower Monte Carlo (Pythia, Herwig, )
- MC based on tree level matrix element + parton showers, matched to remove double counting: Alpgen, Sherpa, etc..

These calculations and tools need “validation” by experimental measurements
Measure $\sigma$ at hadron level as function of $E_T^{\text{jet}}$ cf. LO, NLO predictions

**NLO**: MCFM ($W + 1$ and $2$ jet available)

**LO**: ME+PS + nonpQCD correction:


Agreement with NLO good.

LO low.

Z+jets

Phys. Rev. Lett 100, 102001 & update

Z\rightarrow ee channel being updated and Z\rightarrow \mu\mu added

CDF Run II Preliminary

New!

Good agreement with NLO (MCFM + CTEQ6M, corrected for UE, fragmentation)
Z+jets angular distributions

- Test of theory predictions (LO and NLO) and Monte Carlo generators
- These measurements test the best predictions for V+jet production at hadron colliders
- These measurements can be used as inputs in tuning event generators
- Sensitive to extra QCD radiation and its modeling ($\Delta\varphi(Z\text{-jet})$, $\Delta\eta(Z\text{-jet})$)
  - Does not require observation of extra jets

Sherpa is chosen as the common denominator for all ratios as it provides the best description of the shape of data in most distributions

**Z+b-jet**

Z+b-jet is an important background to Higgs searches in ZH channel. Z+b-jet is sensitive to the b-content of the proton.

Data are corrected to the hadron level and compared to predictions from PYTHIA, ALPGEN, HERWIG and NLO QCD.

Ratio of cross-section allows for several sources of uncertainties to cancel.

<table>
<thead>
<tr>
<th></th>
<th>data</th>
<th>Alpgen</th>
<th>Pythia</th>
<th>MCFM (Q^2=m_Z^2+p_T^2)</th>
<th>MCFM (Q^2=\langle p_{T,jet}\rangle^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma(Z+b)) (\sigma(Z))</td>
<td>((3.32 \pm 0.53 \pm 0.42) \times 10^{-3})</td>
<td>(2.1 \times 10^{-3})</td>
<td>(3.5 \times 10^{-3})</td>
<td>(2.3 \times 10^{-3})</td>
<td>(2.8 \times 10^{-3})</td>
</tr>
<tr>
<td>(\sigma(Z+b)) (\sigma(Z+j))</td>
<td>((2.08 \pm 0.33 \pm 0.34) %)</td>
<td>1.5 %</td>
<td>2.2 %</td>
<td>1.8 %</td>
<td>2.2 %</td>
</tr>
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</table>

**PRD 79 052008 (2009)**

Several kinematical distributions show the level of (dis)agreement with theory prediction at LO and NLO.

Awaiting for a complete NLO prediction \((qqbar\rightarrow Zb\bar{b})\)
**W+b-jet**

data-driven measurement of a difficult-to-predict background for single top and Higgs searches.

Jets consistent with the decay of long-lived hadrons are selected by identifying a displaced decay vertex. The invariant mass of the charged particle tracks associated with the vertex is sensitive to the flavor of the decaying hadron and is used to determine the fraction of jets from b-quark production.

**Results:**
in events with $p_T > 20$ GeV/$c$, $|\eta| < 1.1$ electron or muon, a $p_T > 25$ GeV/$c$ neutrino, and 1 or 2 $E_T > 20$ GeV, $|\eta| < 2.0$ jets regardless of species.

**Data:** $\sigma_{b\text{jets}}(W + b \text{jets}) \times BR(W \rightarrow l\nu) = 2.74 \pm 0.27 \pm 0.42$ pb

**LO:** $A_{\text{LPGEN}}: \sigma \cdot BR = 0.78$ pb

**LO factor 3 low** (nb. high scale)
- awaiting NLO comparison.

arXiv:0909.1505v2
(Submitted to PRL)
**W+charm**

s-quark initiated process (dg and bg heavily suppressed)
Charge correlation of the leptons used to identify events
Soft Lepton tagger used to identify charm-jet and NN algorithms

\[
\sigma_{Wc} \cdot BR(W \rightarrow l\nu) = 9.8 \pm 3.2 \text{ pb}
\]

Theory prediction: \(11.0^{+1.4}_{-3.0}\) @NLO (mcfm)

*Phys. Rev. Lett. 100, 091803 (2008)*

A new CDF measurement is in process

\[
\frac{\sigma[W + c - \text{jet}]}{\sigma[W + \text{jets}]} = 0.074 \pm 0.019^{+0.012}_{-0.014}
\]

Theory: \(0.044 \pm 0.003\) Alpgen+Pythia

*Phys. Lett. B 666, 23, July 2008*
Underlying Events and Fragmentation

- The multiplicity distribution of charged particles is measured in inelastic non-diffractive collisions.
- The analysis is part of a systematic and detailed set of measurements of minimum-bias events.
- This data have the highest precision and the largest range extension ever reached in the pseudorapidity range $|\eta| \leq 1$. 

**CDF RunII Preliminary**

Minimum Bias $|\eta| \leq 1$

$P_{t} \geq 0.4 \text{ GeV/c}$

**CDF RunII Preliminary**

Uncertainties

- total
- systematic
- statistical

**CDF RunII Preliminary**

Data / Pythia tuneA

Systematic uncert. on data

Important for MC tunings
- Complement the underlying event study in hard-scattering events
- Actively used for recent MC tunes
Future Outlook: Inclusive Jets

PDF sensitivity:
→ compare jet cross section at fixed $x_T = 2p_T / \sqrt{s}$

Tevatron (ppbar)
>100x higher cross section @ all $x_T$
>200x higher cross section @ $x_T > 0.5$

LHC (pp)
• need more than 2400 fb$^{-1}$ luminosity to improve Tevatron@12 fb$^{-1}$
• more high-x gluon contributions
• but more steeply falling cross sect. at highest $p_T$ (=larger uncertainties)
• Relatively high JES uncertainty in early data impact (5-10% for jets below 1TeV) might seriously limit the physics potential of the data (D. Clements, DIS 2007).

→ Tevatron results will dominate high-x gluon for some years
Future Outlook: Photons

Some experimental issues (ATLAS)
• Photon mis-identification
  low fake probability but high jet rate
• Large fraction of photons will convert before reaching the calorimeters (70%)
• Photon Purity (very high at the Tevatron)

$P_T^\gamma$ cross-section for $\gamma$+jet events predicted by NLO QCD for Tevatron and LHC kinematic range

• The jet energy scale does not apply to direct photon events so they will have a much smaller uncertainty
• This should allow the differences in the $\eta$ spectrum of different PDF's (~10%) to be observed

# Future Outlook: V+jets

<table>
<thead>
<tr>
<th></th>
<th>Inclusive jets</th>
<th>B-jets</th>
<th>C-jets</th>
</tr>
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<tbody>
<tr>
<td><strong>Z-boson</strong></td>
<td>Agree with MC or theory predictions so far</td>
<td>Discrepancies observed</td>
<td>No planned measurement so far</td>
</tr>
<tr>
<td><strong>W-boson</strong></td>
<td>Agree with MC or theory predictions so far</td>
<td>Discrepancies observed</td>
<td>Update in progress</td>
</tr>
<tr>
<td><strong>Photon</strong></td>
<td>D0 observes discrepancies</td>
<td>D0 results agrees with predictions</td>
<td>D0 observes discrepancies. Provide information about c-pdf’s</td>
</tr>
</tbody>
</table>

- Perform all V+jets analyses with full Run-2 dataset
  - All these processes are backgrounds to New Physics and Higgs
- Great interest in Tevatron measurements from theoretical community
  - They need our detailed results for tuning MC and checking calculations
- It will take considerable time for LHC measurements to compete with Tevatron results
Future Outlook: Soft Physics

First results on Minimum Bias data (CMS) measurements of inclusive charged-hadron transverse-momentum and pseudorapidity distributions

Still very low track $P_T$ compared to the range measured at the Tevatron

\[ \frac{1}{(2\pi P_T^2) N_{\text{coll}}(dN/dp_T)} \]

- Integrate all detector
- Accumulate enough luminosity to be in the cross-section reach
- Tune the simulation appropriately

arXiv:1002.0621

Conclusions

• The Tevatron is providing for precision QCD physics
  – Consistency between CDF and D0 results
• Jet Production (inclusive, dijet mass, dijet angle)
  – Tests pQCD
    • PDF, $\alpha_s$
  – constraints new physics,
• Photons and Photons + (heavy flavor) jets
  – Some disagreement ($\gamma$+jet) and need for more theory feedback
• Vector bosons + jets
  – Very active area, universal background to many other processes
    • W/Z + jets in very good agreement
    • W/Z+ b, W+charm
  – Testing of Monte Carlo tools and schema
• Underlying events and fragmentation studies
  – MC tuning
• Community looks forward to the re-discovery of QCD at LHC
  – But more to come from the Tevatron…
Backup: Peak Lumi

Tevatron Peak Luminosity

Peak Luminosity (1/μb/sec) Max: 347.4 Most Recent: 305.0

Days since October 1

- Fiscal Year 10
- Fiscal Year 09
- Fiscal Year 08
- Fiscal Year 07
- Fiscal Year 06
- Fiscal Year 05
- Fiscal Year 04
- Fiscal Year 03
- Fiscal Year 02
Jet Algorithms: association of objects to cluster based on proximity in space coordinates (cone algorithms) or proximity in momentum space ($K_T$ algorithms)

Comparison between midpoint and $K_T$ results
Backup: Photon + Jets

-Photon + Jet

investigate source for disagreement in data/theory incl. photon pT 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 ...

Need for an improved and consistent theoretical prediction
**Backup: Photons**

**-DiPhotons**

- Signature for very interesting physics processes
- Invariant mass distribution can be measured with good precision
- The direct measurement of the transverse momentum of the $\gamma\gamma$ system ($q_T$) is sensitive to initial state soft gluon radiation

**A window on new physics:** diphoton + X as an example of model independent searches

Nominal high $E_T$ object identification and kinematic selections are used.
The observed event counts is reported as well as SM prediction for various kinematic distributions

The dijet mass spectrum is measured in 6 different rapidity regions. Experimental uncertainties are similar in size to PDF and scale uncertainty, suggesting that the measurement might constraint future theoretical predictions.
Backup: Photon Purity

CDF Run II Preliminary

CDF Data, $L=2.5 \text{ fb}^{-1}$

- **Signal Fraction**
  - $p_T > 30 \text{ GeV/c}$
  - $E_{T\text{iso}} < 2 \text{ GeV}$

- **Systematic Uncertainty**