QCD JET RESULTS FROM THE TEVATRON

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Early Run II QCD jet results from D0 and CDF are presented. Inclusive and dijet cross sections have been measured and underlying events have been studied by two different means. While the results to date are consistent with the standard model both experiments are working hard to spot any deviations that may emerge.

1 Introduction

Hadronic jet production with large transverse momentum ($p_T$) provides useful tests of perturbative QCD (pQCD) calculations. The inclusive jet and dijet cross sections at large $p_T$ or large invariant dijet mass ($M_{jj}$) are directly sensitive to the strong coupling constant ($\alpha_s$) and parton density functions (PDF). Deviations from the theoretical predictions at high $p_T$ or $M_{jj}$, not explained by PDF or $\alpha_s$, may indicate physics beyond the Standard Model.

According to pQCD at lowest order in the strong coupling constant, $\mathcal{O}(\alpha_s^2)$, jets in $\bar{p}p$ collisions are produced in pairs. In this approximation, the jets have identical transverse momenta, $p_T$, and correlated azimuthal angles, $\phi_{\text{jet}}$, with $\Delta\phi_{\text{dijet}} = |\phi_{\text{jet}1} - \phi_{\text{jet}2}| = \pi$. Additional jets can be produced at higher orders. CDF has studied the additional jets directly by measuring event properties in the “transverse” region between the jets. D0 has measured $\Delta\phi_{\text{dijet}}$ decorrelations to examine this physics.

These measurements become all the more interesting now that the Tevatron has entered a new era of luminosity and energy. The center of mass energy of the Tevatron has risen to $\sqrt{s} = 1.96\text{GeV}$ from $\sqrt{s} = 1.8\text{GeV}$ and during the early running the experiments have already accumulated more luminosity that all of Run I. As a consequence the CDF and D0 experiments are now probing length scales on the order of $10^{-19}$m and the discovery of new physics is a tantalizing possibility. To give a sense of the physics reach, CDF has seen an event with $1.3\text{TeV}/c^2$ dijet energy and D0 has seen one at $1.2\text{TeV}/c^2$.

2 Defining Jets

Both experiments used the “Run II cone algorithm” which combines particles within a cone radius $R_{\text{cone}} = 0.7$ in $y$ and $\phi$ around the cone axis. Calorimeter towers were combined into jets in the “$E$-scheme” (adding the four-vectors). The jet finding procedure was iterated until a stable solution was reached. The four-vector of every tower was used as a seed in the first stage
of the iterative procedure. The algorithm was re-run using the midpoints between pairs of jets identified in the first stage as additional seeds (the second stage makes the procedure infrared safe). Jets with overlapping cones were merged if the overlap area contained more than 50% of the $p_T$ from the lower $p_T$ jet, otherwise the particles in the overlap region are assigned to the nearest jet.

3 Single Jet Cross Sections

To measure the jet cross section both experiments used events that were triggered by an inclusive jet trigger based on energy deposited in the calorimeter towers. Data selection was based on run quality, event properties and jet quality criteria. Data were corrected for the jet energy scale, selection efficiencies, and for migration due to the $p_T$ resolution. The jet energy scale was determined by minimizing the missing transverse energy in photon plus jet events.

D0 has presented a measurement of the inclusive jet cross section based on a sample corresponding to an integrated luminosity of $\mathcal{L} = 143pb^{-1}$. Figure 1 shows the jet cross section as a function of $p_T$ in three rapidity regions. To compare to theory, D0 has used the program JETRAD\(^2\). The CTEQ6M\(^2\) parameterization of the PDF was used and $\alpha_s(M_Z) = 0.118$. The renormalization and factorization scales were set to half the leading jet $p_T$, $\mu_R = \mu_f = 0.5 p_T^{max}$. Figure 1 also shows the results of this comparison. The data are in good agreement with theory, given the large systematic errors.

Similarly CDF has presented a measurement of the inclusive jet cross section based on a sample corresponding to $\mathcal{L} = 177pb^{-1}$ in the rapidity range $0.1 < |y_{jet}| < 0.7$. Figure 2 compares the corrected cross section to the pQCD calculations of Ellis, Kunst and Soper\(^3\).

4 Dijet Cross Sections

In addition D0 has reported the dijet cross section in the central rapidity region as shown in figure 3. Also presented is a comparison of the dijet cross section to a next to leading order
Figure 3: On the left is the dijet cross section as a function of dijet mass. The plot on the right is a comparison of the dijet cross section as a function of dijet mass to theory.

Figure 4: Comparison of the dijet cross section as a function of dijet mass to models.

pQCD calculation using the same calculation as for the single jet cross section.

5 Underlying Event

In a dijet event the “underlying event” is everything but the two outgoing jets. This could include initial and final state gluon radiation, beam beam interactions, and possible multiple parton interactions. To study the underlying events the CDF experiment defines 3 regions, the “toward region” within $|\Delta \phi| < 60^\circ$ of the leading jet, the “away region” ($|\Delta \phi| > 120^\circ$) and a “transverse region” between the two. They then classify two types of event: “Back to back” events have a second jet with $|\Delta \phi| > 150^\circ$ and $E_T^2/E_T^1 > 0.8$. “Leading jet” events don’t satisfy the back to back criteria. Plots are made of the charge particle density and the transverse “$p_T$ density” to compare to models, as shown in figure 4. In both cases the Herwig Monte Carlo code does a poor job of representing the data. “Tune A” of Pythia was found by matching to Run I data and is found to match the Run II (higher energy) data well.

6 $\Delta \phi$ Decorrelations

According to perturbative QCD (pQCD) at lowest order in the strong coupling constant, $O(\alpha_s^2)$, jets in $\bar{p}p$ collisions are produced in pairs. In this approximation, the jets have identical transverse momenta, $p_T$, and correlated azimuthal angles, $\phi_{jet}$, with $\Delta \phi_{dijet} = |\phi_{jet 1} - \phi_{jet 2}| = \pi$. Additional jets can be produced at higher orders and the two leading jets may be decorrelated with $\Delta \phi_{dijet} < \pi$. The azimuthal decorrelation of the two leading jets is sensitive to additional radiation which manifests itself as additional $p_T$ in an event. Soft additional radiation with $p_T \to 0$ results in $\Delta \phi_{dijet} \to \pi$, whereas values of $\Delta \phi_{dijet} \ll \pi$ are an indication of hard additional radiation. The measurement of the $\Delta \phi_{dijet}$ distribution is thus an ideal testing ground for higher order QCD effects, without the experimental problems associated with reconstructing additional jets.

D0 measured the dijet cross section as a function of $\Delta \phi_{dijet}$, normalized by the inclusive
terms to all orders in $\alpha_s$. The (N)LO predictions at
the requirement that $\Delta\phi$ is defined between the two leading jets. For the NLO prediction
with up to four final-state partons no such restriction is present. The (N)LO predictions at
$\Delta\phi \to \pi$ is dominated by the phase space where the third jet is soft ($p_{T,3} > 0$). The
(N)LO prediction therefore diverges for $\Delta\phi \to \pi$.

The four plots in Fig. 6 show the $\Delta\phi_{dijet}$ distribution, in different regions of $p_{T,1}$, overlaid
by the results of the NLOJET++ NLO and LO pQCD calculations with the CTEQ6.1M PDFs.

The renormalization and factorization scales were set to $\mu_r = \mu_f = 0.5 p_{T,1}$. The limitations
of the LO calculation at low-$\Delta\phi_{dijet}$ (due to phase space) and at high-$\Delta\phi_{dijet}$ (soft limit) are
obvious. Only at highest $p_{T,1}$ they give a fair description of the intermediate $\Delta\phi_{dijet}$ region.
The NLO predictions are in good agreement with the data in almost the whole kinematic range.
These predictions only fail in the extreme regions at high-$\Delta\phi_{dijet}$ and at low-$\Delta\phi_{dijet}$ (below
$\Delta\phi_{dijet} \simeq 2/3\pi$)

The limitations of fixed order pQCD are cured by calculations that resum leading logarithmic
terms to all orders in $\alpha_s$. Monte Carlo event generators with parton shower models, such
as Pythia and Herwig are good approximations to such resummed calculations. Results from Pythia and Herwig are compared to the data in Fig. 7. Also included in Fig. 7 is a Pythia calculation tuned to other $\bar{p}p$ scattering data (“tune A” from R. Field based on data measured by the CDF collaboration). The default versions of Pythia and Herwig provide a better description of the data over the whole range of $\Delta \phi_{dijet}$ than LO pQCD. The description is substantially improved by using tuned Pythia parameters. However, in the intermediate $\Delta \phi_{dijet}$ region the best description of the data is still obtained by NLO pQCD.

7 Conclusions

With the start of Run II of the Tevatron, the CDF and D0 experiments have entered and exciting new regime in hadron collider physics. It will be possible to test QCD at the highest energies thus far obtained. Both experiments have preliminary results. Inclusive and dijet cross sections have been measured and underlying events have been studied by two different means. While the results to date are consistent with the standard model both experiments are working hard to spot any deviations that may emerge.

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