

# JET PHYSICS IN RUN 2 AT CDF

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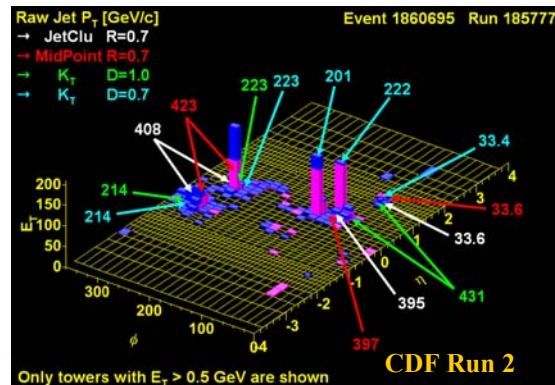
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**Abstract:** New CDF Run 2 results on the inclusive jet cross section ( $K_T$  algorithm) and the b-jet cross section (MidPoint algorithm) are presented and compared with theory. We also study the “underlying event” by using the direction of the leading jet to isolate regions of  $\eta$ - $\phi$  space that are very sensitive to the “beam-beam” remnants and to multiple parton interactions.

**Keywords:** QCD, Jets, Hadron Collider.

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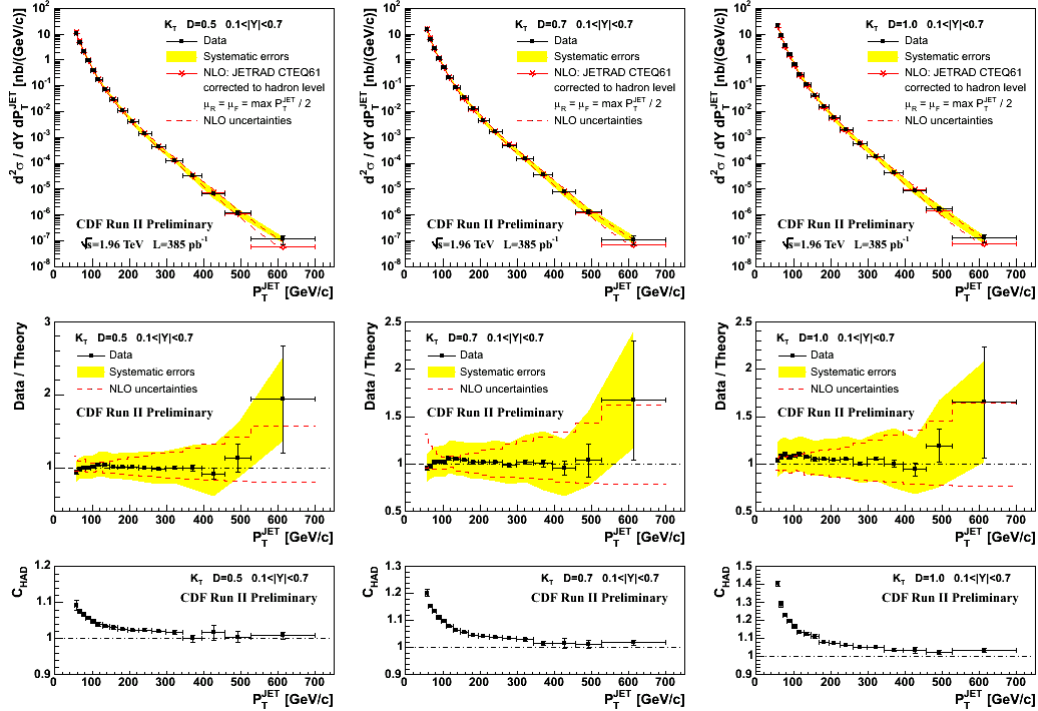
The study of proton-antiproton collisions in Run 2 at CDF is teaching us a lot about how QCD works. Comparing data with theory will lead to improved QCD Monte-Carlo models and to more precise parton distribution functions. In the CDF-QCD group we are studying the inclusive jet cross section using both the MidPoint cone algorithm and the  $K_T$  algorithm [1]. We are studying heavy flavor jets (*i.e.* b-jets) and jets produced in association with photons, W bosons, and Z bosons. We are studying jet fragmentation (jet shapes, momentum distributions, two-particle correlations) and we are making good progress in understanding and modeling the “underlying event” in hard scattering processes. Here I will only be able to show a little bit of what we have learned.



**FIGURE 1.** Shows the transverse energy of calorimeter towers with  $E_T > 0.5$  GeV for an event in the CDF detector. The MidPoint algorithm combines the two clusters into one “jet” with  $p_T = 423$  GeV/c while the  $K_T$  algorithm ( $D = 0.7$ ) finds two “jets” with  $p_T = 223$  GeV/c and 214 GeV/c.

Experimentally we measure “jets” at the detector (*i.e.* calorimeter) level by observing the energy in each calorimeter cell as illustrated in Fig. 1. Of course the “jet” cross section depends on ones choice of jet algorithm. Each jet algorithm is a different observable and comparing the results of different jet algorithm teaches us

about QCD. Most theorists prefer the  $K_T$  algorithm over cone algorithms, however, one must demonstrate that the  $K_T$  algorithm will work in the collider environment where there is an “underlying event”.

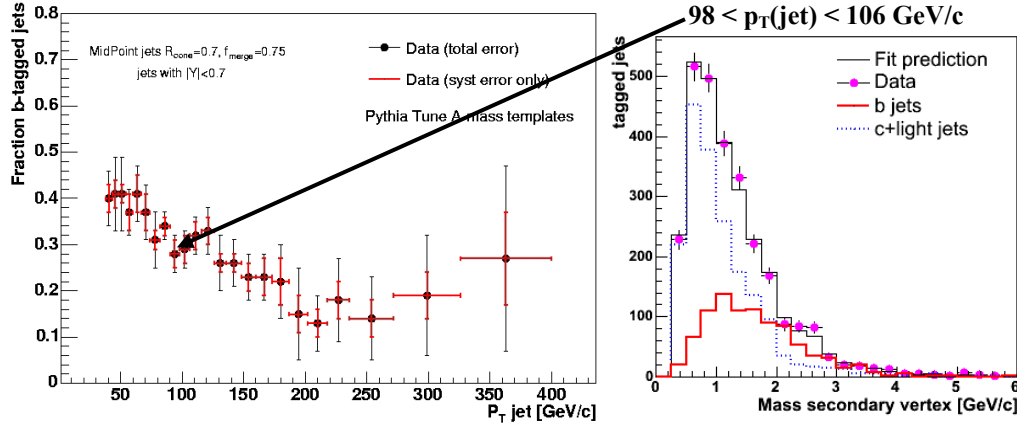


**FIGURE 2.** The CDF Run 2 jet cross section using the  $K_T$  algorithm with  $D = 0.5, 0.7,$  and  $1.0$ . The data have been corrected to the particle level (with an “underlying event”) and the NLO parton level (CTEQ61M) has been corrected for fragmentation and the “underlying event” (with correction factors  $C_{HAD}$ ).

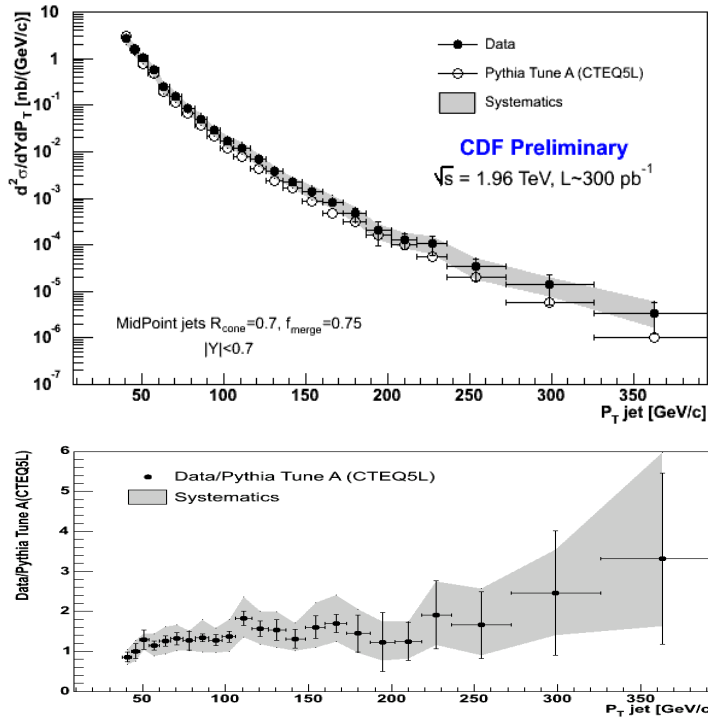
What we measure in the calorimeter must be corrected for detector efficiency which is done by comparing the QCD Monte-Carlo models at the particle (*i.e.* generator level) with the result after detector simulation (*i.e.* CDFSIM). At CDF we correct the data using PYTHIA Tune A [2,3] and use differences between PYTHIA and HERWIG [4] as a measure of the systematic uncertainty in correcting to the particle level. To compare with a NLO parton level theory calculation requires removing the “underlying event” and correcting the data to the parton level. I believe that experimenters should publish what they measure (*i.e.* observables at the particle level with an “underlying event”) and one should correct the NLO parton level theory by adding in the effects of fragmentation and the “underlying event”. Fig. 2 shows the CDF Run 2 jet cross section using the  $K_T$  algorithm. The correction factors for the “underlying event” are large for  $p_T(\text{jet}) < 300$  GeV/c. Nonetheless, the agreement between the theory and data is very good. The highest  $p_T$  bin contains only a few events and the resulting large error makes it consistent with the theory. Within the errors the data and theory agree, however, we will continue to pay close attention to the highest  $p_T$  bins.

We identify b-jets by studying the invariant mass of the charged particles emanating from the secondary vertex which is displaced slightly from the primary interaction vertex due to the long lifetime of the heavy b-quark. As shown in Fig. 3,

the fraction of b-tagged jets is determined by fitting (on a bin-by-bin bases) the secondary vertex invariant mass to templates determined from PYTHIA Tune A. Fig. 4 shows the resulting CDF b-jet inclusive cross section at 1.96 TeV compared with PYTHIA Tune A.



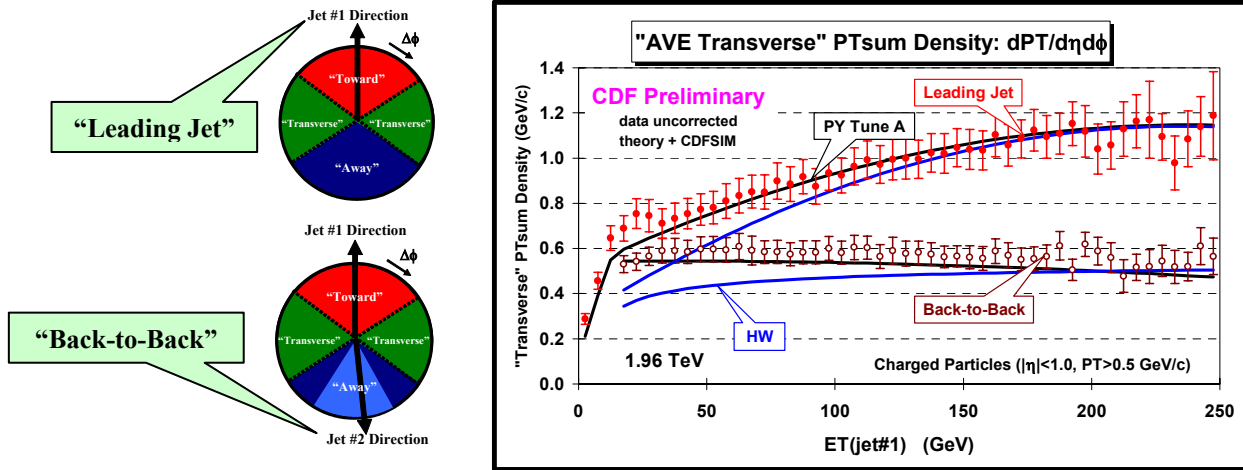
**FIGURE 3.** (left) Shows the fraction of b-tagged jets as a function of the jet  $p_T$ . (right) Shows the fit to the secondary vertex mass for the bin  $98 < p_T(\text{jet}) < 106 \text{ GeV}/c$ .



**FIGURE 4.** (top) Shows the CDF Run 2 b-jet inclusive cross section at 1.96 TeV compared with PYTHIA Tune A. (bottom) Shows the ratio data/theory for PYTHIA Tune A.

Both the inclusive jet cross section and the b-jet cross section depend sensitively on the “underlying event” and we are working to understand and model the “underlying event” in Run 2 at CDF. We study the “underlying event” using the direction of the leading calorimeter jet (JetClu,  $R = 0.7$ ) to isolate regions of  $\eta$ - $\phi$  space that are

sensitive to the “underlying event”. The angle  $\Delta\phi = \phi - \phi_{\text{jet}\#1}$  is the relative azimuthal angle between a charged particle and the direction of jet#1. As illustrated in Fig. 5, the “transverse” region is defined by  $60^\circ < |\Delta\phi| < 120^\circ$  and  $|\eta| < 1$ . The “transverse” region is perpendicular to the plane of the hard 2-to-2 scattering and is therefore very sensitive to the “underlying event”. We restrict ourselves to charged particles in the range  $p_T > 0.5$  GeV/c and  $|\eta| < 1$ , but allow the leading jet that is used to define the “transverse” region to have  $|\eta(\text{jet}\#1)| < 2$ . In our Run 2 analysis we consider two classes of events. We refer to events in which there are no restrictions placed on the second and third highest  $E_T$  jets (jet#2 and jet#3) as “leading jet” events. Events with at least two jets with  $E_T > 15$  GeV where the leading two jets are nearly “back-to-back” ( $|\Delta\phi_{12}| > 150^\circ$ ) with  $E_T(\text{jet}\#2)/E_T(\text{jet}\#1) > 0.8$  and  $E_T(\text{jet}\#3) < 15$  GeV are referred to as “back-to-back” events. “Back-to-back” events are a subset of the “leading jet” events. The idea here is to suppress hard initial and final-state radiation thus increasing the sensitivity of the “transverse” region to the “beam-beam remnant” and the multiple parton scattering component of the “underlying event”.



**FIGURE 5.** Data on the average PTsum density,  $d\text{PT}_{\text{sum}}/d\eta d\phi$ , for charged particles with  $p_T > 0.5$  GeV/c and  $|\eta| < 1$  in the “transverse” region for “leading jet” events and for “back-to-back” events as a function of the leading jet  $E_T$  compared with PYTHIA Tune A and HERWIG at 1.96 TeV after CDFSIM..

Fig. 5 compares PYTHIA Tune A and HERWIG with the “leading jet” and “back-to-back” data on the average PTsum density,  $d\text{PT}_{\text{sum}}/d\eta d\phi$ , in the “transverse” region as a function of the leading jet  $E_T$ . The multiple parton interaction parameters of PYTHIA were adjusted to agree with Run 1 data [2,3]. The “back-to-back” data show a slight decrease in the “transverse” density with increasing  $E_T(\text{jet}\#1)$  which is described well by PYTHIA Tune A (with multiple parton interactions) but not by HERWIG (without multiple parton interactions).

## CONCLUSIONS

We have measured the inclusive jet cross section using the  $K_T$  algorithm. The data agree well with the NLO theory after the theory is corrected for fragmentation effects

and for the “underlying event”. Our results show that the  $K_T$  algorithm works fine at the Tevatron collider, which has implications for the LHC.

We have also measured the b-jet production cross section at 1.96 TeV. Measurements of the b-jet production at hadron colliders provide an important test of QCD. Past Tevatron measurements of b-quark production indicated a possible “excess” with respect to QCD predictions. However, the b-jet cross is in agreement expectations. The data are about a factor of 1.4 larger than the prediction of PYTHIA Tune A, however, this is to be expected since PYTHIA is a “leading log order” model. One cannot expect it correctly predict the precise amount of “flavor excitation” and “gluon splitting”. We are working on the comparisons with MC@NLO [5].

Both the inclusive jet cross section and the b-jet cross section depend sensitively on the “underlying event”. In Run 2 at CDF we use the direction of the leading calorimeter jet in each event to define the “transverse” regions of  $\eta$ - $\phi$  space that is very sensitive to the “underlying event”. In addition, by selecting events with at least two jets that are nearly back-to-back ( $\Delta\phi_{12} > 150^\circ$ ) and with  $E_T(\text{jet}\#3) < 15$  GeV we are able to look closer at the “beam-beam remnant” and multiple parton interaction components of the “underlying event”. PYTHIA Tune A (with multiple parton interactions) does a good job in describing the “underlying event” (*i.e.* “transverse” regions) for both “leading jet” and “back-to-back” events. HERWIG (without multiple parton interactions) does not have enough activity in the “underlying event” for  $E_T(\text{jet}\#1)$  less than about 150 GeV, which was also observed in our published Run 1 analyses [6].

JIMMY [7] is a model of multiple parton interaction which can be combined with HERWIG or MC@NLO to enhance the “underlying event” thereby improving the agreement with data. We are working on tunes of JIMMY that fit the CDF Run 2 “underlying event” data [8]. We are also studying the energy in the “underlying event”.

## REFERENCES

1. S. D. Ellis and D. E. Soper, Phys. Rev. **D48**, 3160 (1993).
2. T. Sjostrand, Phys. Lett. **157B**, 321 (1985); M. Bengtsson, T. Sjostrand, and M. van Zijl, Z. Phys. **C32**, 67 (1986); T. Sjostrand and M. van Zijl, Phys. Rev. **D36**, 2019 (1987).
3. *Min-Bias and the Underlying Event at the Tevatron and the LHC*, talk by R. Field at the Fermilab ME/MC Tuning Workshop, Fermilab, October 4, 2002. *Toward an Understanding of Hadron Collisions: From Feynman-Field until Now*, talk by R. Field at the Fermilab Joint Theoretical Experimental “Wine & Cheese” Seminar, Fermilab, October 4, 2002.
4. G. Marchesini and B. R. Webber, Nucl. Phys. **B310**, 461 (1988); I. G. Knowles, Nucl. Phys. **B310**, 571 (1988); S. Catani, G. Marchesini, and B. R. Webber, Nucl. Phys. **B349**, 635 (1991).
5. *The MC and NLO 3.1 Event Generator*, Stefano Frixione and Bryan R. Webber, CAVENDISH-HEP-05-09, hep-ph/0506182 (2005). *Matching NLO QCD and Parton Showers in Heavy Flavor Production*, Stefano Frixione, Paolo Nason, and Bryan R. Webber, JHEP 0308:007 (2003).
6. *Charged Jet Evolution and the Underlying Event in Proton-Antiproton Collisions at 1.8 TeV*, The CDF Collaboration (T. Affolder et al.), Phys. Rev. **D65**, 092002 (2002). *The Underlying Event in Hard Interactions at the Tevatron Proton-Antiproton Collider*, CDF Collaboration (D. Acosta et al.), Phys. Rev. **D70**, 072002 (2004).
7. *Multiparton Interactions in Photoproduction at HERA*, J.M. Butterworth, J.R. Forshaw, and M.H. Seymour, Z. Phys. **C7**, 637-646 (1996).
8. *HERWIG, JIMMY, and PYTHIA Tune A*, talk by R. Field at the TeV4LHC Workshop, Fermilab, December 1, 2004.