Hadronic Final States Working Group

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Jet Physics
in Run 2 at CDF

Outline of Talk

- Constructing Jets in Run 2 at CDF (MidPoint and $K_T$ Algorithms).
- New from CDF: The b-Jet Inclusive Cross Section.
- Understanding and Modeling the “Underlying Event” in Run 2 at CDF.
The TeVatron delivered more than 350 pb⁻¹ in 2004!

CDF has ~600 pb⁻¹ on tape!

~800 pb⁻¹ delivered
CDF-QCD Group

Learn more about how nature works. Compare with theory and work to provide information that will lead to improved Monte-Carlo models and structure functions. Our contributions will benefit to the colliders of the future!

Some CDF-QCD Group Analyses!

- **Jet Cross Sections and Correlations**: Jet Clu, MidPoint, $K_T$ algorithms.
- **DiJet Mass Distributions**: $\Delta \phi$ distribution, compositness.
- **Heavy Flavor Jets**: $b$-jet and $b$-$\bar{b}$ jet cross sections and correlations.
- **Z and W Bosons plus Jets**: including $b$-jets.
- **Jets Fragmentation**: jet shapes, momentum distributions, two-particle correlations.
- **Underlying Event Studies**: charged particles and energy for jet, jet+jet, $\gamma$+jet, $Z$+jet.
- **Pile-Up Studies**: modeling of pile-up.

Important for the LHC!
Experimental Jets: The study of “real” jets requires a “jet algorithm” and the different algorithms correspond to different observables and give different results!

Experimental Jets: The study of “real” jets requires a good understanding of the calorimeter response!

Experimental Jets: To compare with NLO parton level (and measure structure functions) requires a good understanding of the “underlying event”!
Cone Algorithms

CDF JetClu Cone Algorithm:
- Detector dependent algorithm (CDF Run 1 legacy).
- Cluster together calorimeter towers by their “angular” proximity in (η, φ) space.
- Merged if common E_T is more than 75% of smallest jet.
- Not infrared safe at the parton level.
- To compare with NLO at the parton level one must introduce and ad hoc parameter R_{sep} (R' = R_{sep} \times R).

MidPoint Cone Algorithm:
- Define a list of seeds using CAL towers with E_T > 1 GeV.
- Also put seed in a the midpoint (η-φ) for each pair of proto-jets separated by less than 2R and iterate for stable jets.
- Merging/Splitting (f_{merge} = 50\%, 70\%).
- Results in improved infrared stability and can be compared with NLO parton-level calculations, but still needs the ad hoc R_{sep} parameter.
- Not all towers end up in a “jet”.
- Use two R values (R/2 for finding stable cones, R for calculating jet properties).
**K_T Algorithm**

**k_T Algorithm:**
- Cluster together calorimeter towers by their k_T proximity.
- Infrared and collinear safe at all orders of pQCD.
- No splitting and merging.
- No ad hoc R_sep parameter necessary to compare with parton level.
- Every parton, particle, or tower is assigned to a “jet”.
- No biases from seed towers.
- Favored algorithm in e^+e^- annihilations!

\[
d_i = p_{T,i}^2 \\
 d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \left( (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \right) / D^2 \\
\text{Find the minimum of all } d_i \text{ and } d_{ij}.
\]

**Will the K_T algorithm be effective in the collider environment where there is an “underlying event”??**

**CDF Run 2**

Only towers with E_T > 0.5 GeV are shown.

Raw Jet E_T = 533 GeV

Raw Jet E_T = 618 GeV
Calorimeter Jets:
- We measure “jets” at the “hadron level” in the calorimeter.
- We certainly want to correct the “jets” for the detector resolution and efficiency.
- Also, we must correct the “jets” for “pile-up”.
- Must correct what we measure back to the true “particle level” jets!

Particle Level Jets:
- Do we want to make further model dependent corrections?
- Do we want to try and subtract the “underlying event” from the “particle level” jets.
- This cannot really be done, but if you trust the Monte-Carlo models modeling of the “underlying event” you can try and do it by using the Monte-Carlo models.

Parton Level Jets:
- Do we want to use our data to try and extrapolate back to the parton level?
- This also cannot really be done, but again if you trust the Monte-Carlo models you can try and do it by using the Monte-Carlo models.

The “underlying event” consists of hard initial & final-state radiation plus the “beam-beam remnants” and possible multiple parton interactions.
Jet Corrections

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**Parton Level Jets:**
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Data at the “hadron level”!

NLO parton level theory corrected to the “hadron level”!

Correction factors applied to NLO theory!
Data at the “hadron level”!

NLO parton level theory corrected to the “hadron level”!

Theory and experiment agree very well! The KT algorithm works fine at the collider! (see the talk by Regis Lefèvre)

Correction factors applied to NLO theory!
Extract fraction of b-tagged jets from data using the shape of the mass of the secondary vertex as discriminating quantity (bin-by-bin as a function of jet $p_T$).

Construct the invariant mass of particles pointing back to the secondary vertex!
The data are compared with PYTHIA (tune A)! Data/PYA ∼ 1.4
Comparison with MC@NLO coming soon!
The “Underlying Event” in Run 2 at CDF

The “underlying event” consists of hard initial & final-state radiation plus the “beam-beam remnants” and possible multiple parton interactions.

CDF Run 2 results

- Two Classes of Events: “Leading Jet” and “Back-to-Back”.
- Two “Transverse” regions: “transMAX”, “transMIN”, “transDIF”.
- PT_{max} and PT_{maxT} distributions and averages.
- \( \Delta \phi \) Distributions: “Density” and “Associated Density”.
- \( <p_T> \) versus charged multiplicity: “min-bias” and the “transverse” region.
- Correlations between the two “transverse” regions: “trans1” vs “trans2”.
The “Transverse” Regions as defined by the Leading Jet

Jet #1 Direction

Charged Particle $\Delta \phi$ Correlations

$p_T > 0.5$ GeV/c $|\eta| < 1$

Jet #1 Direction

- Look at charged particle correlations in the azimuthal angle $\Delta \phi$ relative to the leading calorimeter jet (JetClu R = 0.7, $|\eta| < 2$).
- Define $|\Delta \phi| < 60^\circ$ as “Toward”, $60^\circ < -\Delta \phi < 120^\circ$ and $60^\circ < \Delta \phi < 120^\circ$ as “Transverse 1” and “Transverse 2”, and $|\Delta \phi| > 120^\circ$ as “Away”. Each of the two “transverse” regions have area $\Delta \eta \Delta \phi = 2 \times 60^\circ = 4\pi/6$. The overall “transverse” region is the sum of the two transverse regions ($\Delta \eta \Delta \phi = 2 \times 120^\circ = 4\pi/3$).
Plot shows the “Transverse” charged particle density versus $P_T$(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).
Look at the “transverse” region as defined by the leading jet (JetClu R = 0.7, |η| < 2) or by the leading two jets (JetClu R = 0.7, |η| < 2). “Back-to-Back” events are selected to have at least two jets with Jet#1 and Jet#2 nearly “back-to-back” (Δφ₁₂ > 150°) with almost equal transverse energies (E_T(jet#2)/E_T(jet#1) > 0.8) and E_T(jet#3) < 15 GeV.

Shows the Δφ dependence of the charged particle density, dN_{chg}/dηdφ, for charged particles in the range p_T > 0.5 GeV/c and |η| < 1 relative to jet#1 (rotated to 270°) for 30 < E_T(jet#1) < 70 GeV for “Leading Jet” and “Back-to-Back” events.
Use the leading jet to define MAX and MIN “transverse” regions on an event-by-event basis with MAX (MIN) having the largest (smallest) charged PTsum density.

Shows the “transMIN” charged PTsum density, $dP_{T \text{sum}}/d\eta d\phi$, for $p_T > 0.5$ GeV/c, $|\eta| < 1$ versus $E_T(jet#1)$ for “Leading Jet” and “Back-to-Back” events.
“Transverse” PTsum Density
PYTHIA Tune A vs HERWIG

Jet #1 Direction

Jet #2 Direction

NOW LOOK IN DETAIL AT “BACK-TO-BACK” EVENTS IN THE REGION 30 < E_T(jet#1) < 70 GeV!

Shows the average charged PTsum density, dPTsum/dηdφ, in the “transverse” region (p_T > 0.5 GeV/c, |η| < 1) versus E_T(jet#1) for “Leading Jet” and “Back-to-Back” events.

Compares the (uncorrected) data with PYTHIA Tune A and HERWIG after CDFSIM.
Charged PTsum Density
PYTHIA Tune A vs HERWIG

HERWIG (without multiple parton interactions) does not produce enough PTsum in the “transverse” region for $30 < E_T(jet#1) < 70$ GeV!
(left) Shows the Run 2 data on the $\Delta\phi$ dependence of the charged scalar PTsum density ($|\eta|<1$, $p_T>0.5$ GeV/c) relative to the leading jet for $30 < E_T(jet#1) < 70$ GeV/c compared with PYTHIA Tune A (after CDFSIM).

(right) Shows the generator level predictions of PYTHIA Tune A and a tuned version of JIMMY ($PT_{min}=1.8$ GeV/c) for the $\Delta\phi$ dependence of the charged scalar PTsum density ($|\eta|<1$, $p_T>0.5$ GeV/c) relative to the leading jet for $PT(jet#1) > 30$ GeV/c. The tuned JIMMY and PYTHIA Tune A agree in the “transverse” region.

(right) For JIMMY the contributions from the multiple parton interactions (MPI), initial-state radiation (ISR), and the 2-to-2 hard scattering plus final-state radiation (2-to-2+FSR) are shown.
(left) Shows the generator level predictions of JIMMY (MPI, $PT_{\text{min}}=1.8$ GeV/c) and HERWIG (BBR) for the $\Delta\phi$ dependence of the charged scalar $PT$sum density ($|\eta|<1$, $p_T>0.5$ GeV/c) relative to the leading jet for $PT(jet#1) > 30$ GeV/c.

(right) Shows the generator level predictions of JIMMY (MPI, $PT_{\text{min}}=1.8$ GeV/c) and HERWIG (BBR) for the $\Delta\phi$ dependence of the scalar $ET$sum density ($|\eta|<1$, $p_T>0$ GeV/c) relative to the leading jet for $PT(jet#1) > 30$ GeV/c.

The “multiple-parton interaction” (MPI) contribution from JIMMY is about a factor of two larger than the “Beam-Beam Remnant” (BBR) contribution from HERWIG. The JIMMY program replaces the HERWIG BBR is its MPI.
(left) Shows the generator level predictions of PYTHIA Tune A and JIMMY (PT_{min} =1.8 GeV/c) for the $\Delta \phi$ dependence of the charged scalar PTsum density ($|\eta|<1$, $p_T>0.5$ GeV/c) relative to the leading jet with $P_T$(jet#1) > 30 GeV/c. JIMMY and PYTHIA Tune A agree in the “transverse” region.

(right) Shows the generator level predictions of PYTHIA Tune A and JIMMY (PT_{min} =1.8 GeV/c) for the $\Delta \phi$ dependence of the scalar ETsum density ($|\eta|<1$, $p_T>0$) relative to the leading jet for $P_T$(jet#1) > 30 GeV/c.

The tuned JIMMY produces a lot more ETsum ($p_T>0$) in the “transverse” region than does PYTHIA Tune A!
Tuned JIMMY versus PYTHIA Tune A

(left) Shows the generator level predictions of PYTHIA Tune A and JIMMY (PT_{min}=1.8 GeV/c) for the Δφ dependence of the charged PTsum density (|η|<1, pT>0.5 GeV/c) relative to the leading jet with P_T(jet#1)>30 GeV/c. JIMMY and PYTHIA Tune A agree in the “transverse” region.

(right) Shows the generator level predictions of PYTHIA Tune A and JIMMY (PT_{min}=1.8 GeV/c) for the Δφ dependence of the scalar ETsum density (|η|<1, pT>0) relative to the leading jet for P_T(jet#1)>30 GeV/c.

The tuned JIMMY produces a lot more ETsum (p_T>0) in the “transverse” region than does PYTHIA Tune A!

The next step is to study the energy in the “transverse region”. We will have results on this soon!