Min-Bias and the “Underlying Event” in Run II at CDF: The Run 2 analysis gives a more detailed look at the “underlying event” in hard scattering processes and compares the (uncorrected) data with PYTHIA Tune A and HERWIG after CDFSIM.

My graduate student, Alberto Cruz, will take over this analysis and bring it to “publication level” (within the next year!).
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”, $60^\circ < |\Delta \phi| < 120^\circ$ as “Transverse”, and $|\Delta \phi| > 120^\circ$ as “Away”. The “transverse region” is very sensitive to the “underlying event”.

All three regions have the same size in $\eta$-$\phi$ space, $\Delta \eta \times \Delta \phi = 2 \times 120^\circ = 4\pi/3$. 

Look at charged particle density in the “transverse” region!
Particle Densities

Charged Particles
\( p_T > 0.5 \text{ GeV/c} \), \( |\eta| < 1 \)

- Study the charged particles \((p_T > 0.5 \text{ GeV/c}, |\eta| < 1)\) and form the charged particle density, \( dN_{\text{chg}}/d\eta d\phi \), and the charged scalar \( p_T \) sum density, \( dP_{\text{sum}}/d\eta d\phi \).

\[ \Delta \eta \Delta \phi = 4\pi = 12.6 \]

\[ dN_{\text{chg}}/d\eta d\phi = 1/4\pi = 0.08 \]
Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and form the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, and the charged scalar $p_T$ sum density, $dP_{\text{sum}}/d\eta d\phi$.

### Charged Particles

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

<table>
<thead>
<tr>
<th>Observable</th>
<th>Average</th>
<th>Average Density per unit $\eta - \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{chg}}$</td>
<td>3.17 +/- 0.31</td>
<td>0.252 +/- 0.025</td>
</tr>
<tr>
<td>$P_{\text{sum}}$ (GeV/c)</td>
<td>2.97 +/- 0.23</td>
<td>0.236 +/- 0.018</td>
</tr>
</tbody>
</table>

- $\Delta\eta \Delta\phi = 4\pi = 12.6$
- $dN_{\text{chg}}/d\eta d\phi = 3/4\pi = 0.24$

- Divide by $4\pi$
Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the “transverse” region and form the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, and the charged scalar $p_T$ sum density, $dP_{\text{sum}}/d\eta d\phi$. 
Charged Particle Density \( \Delta \phi \) Dependence

Shows the \( \Delta \phi \) dependence of the charged particle density, \( dN_{\text{chg}}/d\eta \, d\phi \), for charged particles in the range \( p_T > 0.5 \) GeV/c and \( |\eta| < 1 \) relative to jet#1 (rotated to 270°) for “leading jet” events \( 30 < E_T(\text{jet#1}) < 70 \) GeV.

Also shows charged particle density, \( dN_{\text{chg}}/d\eta \, d\phi \), for charged particles in the range \( p_T > 0.5 \) GeV/c and \( |\eta| < 1 \) for “min-bias” collisions.
Look at the "transverse" region as defined by the leading jet (JetClu \( R = 0.7, |\eta| < 2 \)) or by the leading two jets (JetClu \( R = 0.7, |\eta| < 2 \)). "Back-to-Back" events are selected to have at least two jets with Jet#1 and Jet#2 nearly "back-to-back" (\( \Delta\phi_{12} > 150^\circ \)) with almost equal transverse energies (\( E_T(jet#2)/E_T(jet#1) > 0.8 \)).

Shows the \( \Delta\phi \) dependence of the charged particle density, \( dN_{chg}/d\eta d\phi \), for charged particles in the range \( p_T > 0.5 \) GeV/c and \( |\eta| < 1 \) relative to jet#1 (rotated to 270\(^\circ\)) for 30 < \( E_T(jet#1) < 70 \) GeV for "Leading Jet" and "Back-to-Back" events.
Shows the $\Delta \phi$ dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 (rotated to 270°) for $30 < E_T(\text{jet#1}) < 70$ GeV for “Leading Jet” and “Back-to-Back” events.
"Transverse" Charge Density
versus $E_T$(jet#1)

Shows the average charged particle density, $dN_{chg}/d\eta d\phi$, in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus $E_T$(jet#1) for "Leading Jet" and "Back-to-Back" events.
"Transverse" Charge Density versus $E_T(jet#1)$

Jet #1 Direction

"Toward" "Transverse" "Away"

Jet #2 Direction

"Toward" "Transverse" "Away"

Charged Particle Density: $dN/d\eta d\phi$

0.1 1.0

0 30 60 90 120 150 180 210 240 270 300 330 360

$\Delta\phi$ (degrees)

95 < $E_T(jet#1)$ < 130 GeV
30 < $E_T(jet#1)$ < 70 GeV
Min-Bias

CDF Preliminary
data uncorrected

Charged Particles ($|\eta|<1.0, PT>0.5$ GeV/c)

Leading Jet
"Transverse" Region
Back-to-Back

Jet #1

Jet #2

"Ave Transverse" Charge Density: $dN/d\eta d\phi$

0.0 0.2 0.4 0.6 0.8 1.0

0 50 100 150 200 250

$E_T(jet#1)$ (GeV)

CDF Run 2 Preliminary
data uncorrected

30-70 GeV 95-130 GeV

1.96 TeV Charged Particles ($|\eta|<1.0, PT>0.5$ GeV/c)

CDF Preliminary
data uncorrected

1.96 TeV

QCD "Blessing"
February 6, 2004

Rick Field - Florida/CDF

Page 10
“Transverse” Charge Density versus $E_T(\text{jet}#1)$

CDF Preliminary data uncorrected

Charged Particles $|\eta|<1.0$, $P_T>0.5$ GeV/c

Very little dependence on $E_T(\text{jet}#1)$ in the “transverse” region for “back-to-back” events!
"Transverse" PTsum Density versus $E_T$(jet#1)

Shows the average charged PTsum density, $dP_T/d\eta d\phi$, in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus $E_T$(jet#1) for "Leading Jet" and "Back-to-Back" events.
“Transverse” PTsum Density versus $E_T$(jet#1)

CDF Run 2 Preliminary data uncorrected

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c)

Jet #1 Direction

Jet #2 Direction

$\Delta \phi$ (degrees)

Charged PTsum Density (GeV/c)

CDF Preliminary data uncorrected

Leading Jet

Back-to-Back

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c)

Jet#1

$\Delta \phi$ (degrees)

Charged PTsum Density (GeV/c)

CDF Preliminary data uncorrected

Leading Jet

Back-to-Back

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c)

Jet#1

$\Delta \phi$ (degrees)

Charged PTsum Density (GeV/c)

CDF Preliminary data uncorrected

Leading Jet

Back-to-Back

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c)

Jet#1

$\Delta \phi$ (degrees)

Charged PTsum Density (GeV/c)

CDF Preliminary data uncorrected

Leading Jet

Back-to-Back

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c)

Jet#1

$\Delta \phi$ (degrees)

Charged PTsum Density (GeV/c)

CDF Preliminary data uncorrected

Leading Jet

Back-to-Back

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c)

Jet#1

$\Delta \phi$ (degrees)

Charged PTsum Density (GeV/c)

CDF Preliminary data uncorrected

Leading Jet

Back-to-Back

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c)

Jet#1

$\Delta \phi$ (degrees)

Charged PTsum Density (GeV/c)

CDF Preliminary data uncorrected

Leading Jet

Back-to-Back

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c)

Jet#1

$\Delta \phi$ (degrees)

Charged PTsum Density (GeV/c)
“Transverse” PTsum Density versus $E_T(\text{jet#1})$

Very little dependence on $E_T(\text{jet#1})$ in the “transverse” region for “back-to-back” events!
"Transverse" Charge Density
PYTHIA Tune A vs HERWIG

Shows the average charged particle density, $dN_{\text{chg}}/d\eta d\phi$, in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) 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.
HERWIG (without multiple parton interactions) produces too few charged particles in the “transverse” region for $30 < E_T^{\text{jet#1}} < 70$ GeV!
**Charged Particle Density**

**PYTHIA Tune A vs HERWIG**

Data - Theory: Charged Particle Density $dN/d\eta d\phi$

<table>
<thead>
<tr>
<th>Data - Theory</th>
<th>Charged Particle Density $dN/d\eta d\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CDF Preliminary</strong></td>
<td>data uncorrected theory + CDFSIM</td>
</tr>
<tr>
<td><strong>Back-to-Back</strong></td>
<td>$30 &lt; \text{ET(jet#1)} &lt; 70 \text{ GeV}$</td>
</tr>
<tr>
<td><strong>PYTHIA Tune A</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Jet#1</strong></td>
<td></td>
</tr>
<tr>
<td><strong>&quot;Transverse&quot; Region</strong></td>
<td></td>
</tr>
<tr>
<td>Charged Particles ($</td>
<td>\eta</td>
</tr>
<tr>
<td>$\Delta \phi$ (degrees)</td>
<td>0 30 60 90 120 150 180 210 240 270 300 330 360</td>
</tr>
<tr>
<td>Data - Theory</td>
<td></td>
</tr>
<tr>
<td><strong>CDF Preliminary</strong></td>
<td>data uncorrected theory + CDFSIM</td>
</tr>
<tr>
<td><strong>Back-to-Back</strong></td>
<td>$30 &lt; \text{ET(jet#1)} &lt; 70 \text{ GeV}$</td>
</tr>
<tr>
<td><strong>HERWIG</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Jet#1</strong></td>
<td></td>
</tr>
<tr>
<td><strong>&quot;Transverse&quot; Region</strong></td>
<td></td>
</tr>
<tr>
<td>Charged Particles ($</td>
<td>\eta</td>
</tr>
<tr>
<td>$\Delta \phi$ (degrees)</td>
<td>0 30 60 90 120 150 180 210 240 270 300 330 360</td>
</tr>
</tbody>
</table>

**Add 0.1 charged particles per unit $\eta$-$\phi$ to HERWIG density, $dN_{\text{chg}}/d\eta d\phi$.**

**This corresponds to $0.1 \times 4\pi = 1.3$ particles in the entire range $p_T > 0.5 \text{ GeV/c}, |\eta| < 1$.**

---

QCD "Blessing"  
February 6, 2004  
Rick Field - Florida/CDF  
Page 17
Shows the average charged PTsum density, \( dP_T/d\eta d\phi \), in the “transverse” region \((p_T > 0.5 \text{ GeV/c, } |\eta| < 1)\) 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

**Charged PTsum Density: dPT/d$$\eta$$d$$\phi$$**

- **Back-to-Back**
- **PY Tune A**

30 < ET(jet#1) < 70 GeV

Charged Particles ($$|\eta|$$<1.0, PT>0.5 GeV/c)

CDF Preliminary
data uncorrected
theory + CDFSIM

**Jets**

Jet#1

"Transverse" Region

**Data - Theory: Charged PTsum Density dPT/d$$\eta$$d$$\phi$$**

CDF Preliminary
data uncorrected
theory + CDFSIM

**Back-to-Back**

30 < ET(jet#1) < 70 GeV

**PYTHIA Tune A**

Herwig (without multiple parton interactions) does not produce enough PTsum in the “transverse” region for 30 < E_T(jet#1) < 70 GeV!
Charged PTsum Density
PYTHIA Tune A vs HERWIG

Data - Theory: Charged PTsum Density $dP_T/d\eta d\phi$

CDF Preliminary
30 < $E_T$(jet#1) < 70 GeV
Back-to-Back

Add 0.2 GeV/c per unit $\eta$-\phi to HERWIG scalar PTsum density, $dP_T{\text{sum}}/d\eta d\phi$.

This corresponds to $0.2 \times 4\pi = 2.5$ GeV/c in the entire range $p_T > 0.5$ GeV/c, $|\eta| < 1$.

308 MeV in $R = 0.7$ cone!

QCD "Blessing"
February 6, 2004

Rick Field - Florida/CDF
Page 20
Now look in detail at “back-to-back” events in the region $95 < E_T(\text{jet#1}) < 130$ GeV!

shows the average charged particle density, $dN_{\text{chg}}/d\eta d\phi$, in the “transverse” region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus $E_T(\text{jet#1})$ for “Leading Jet” and “Back-to-Back” events compared with PYTHIA Tune A and HERWIG after CDFSIM.
Charged Particle Density
PYTHIA Tune A vs HERWIG

HERWIG (without multiple parton interactions) agrees much better in the “transverse” region for 95 < E_T(jet#1) < 130 GeV!
Now look in detail at “back-to-back” events in the region $95 < E_T(\text{jet#1}) < 130$ GeV!

Shows the average charged PTsum density, $dP_T/d\eta d\phi$, in the “transverse” region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus $E_T(\text{jet#1})$ for “Leading Jet” and “Back-to-Back” events compared with PYTHIA Tune A and HERWIG after CDFSIM.
Charged PTsum Density
PYTHIA Tune A vs HERWIG

HERWIG (without multiple parton interactions) agrees much better in the “transverse” region for $95 < E_T^{\text{jet}(#1)} < 130$ GeV!
Use the maximum $p_T$ charged particle in the event, PTmax, to define a direction and look at the the “associated” density, $dN_{\text{chg}}/d\eta d\phi$.

Shows the data on the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including PTmax) relative to PTmax (rotated to 180°) for “min-bias” events. Also shown is the average charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for “min-bias” events.
Min-Bias “Associated”
Charged Particle Density

 رسول Shows the data on the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{max}$) relative to $PT_{max}$ (rotated to 180°) for “min-bias” events with $PT_{max} > 0.5, 1.0, \text{and} 2.0$ GeV/c.
Min-Bias “Associated” Charged Particle Density

- Shows the data on the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including PTmax) relative to PTmax (rotated to 180°) for “min-bias” events with PTmax > 0.5, 1.0, and 2.0 GeV/c.

- Shows “jet structure” in “min-bias” collisions (i.e. the “birth” of the leading two jets!).

QCD "Blessing"  
February 6, 2004  
Rick Field - Florida/CDF  
Page 27
Min-Bias “Associated” Charged Particle Density

Rapid rise in the particle density in the “transverse” region as PTmax increases!

- Shows the data on the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles ($p_T > 0.5 \text{ GeV/c}, |\eta| < 1$, not including PTmax) relative to PTmax (rotated to 180°) for “min-bias” events with PTmax > 0.5, 1.0, and 2.0 GeV/c.

- Shows “jet structure” in “min-bias” collisions (i.e. the “birth” of the leading two jets!).
Use the maximum $p_T$ charged particle in the event, $PT_{max}$, to define a direction and look at the the “associated” PTsum density, $dPT_{sum}/d\eta d\phi$.

Shows the data on the $\Delta\phi$ dependence of the “associated” charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{max}$) relative to $PT_{max}$ (rotated to 180°) for “min-bias” events. Also shown is the average charged particle density, $dPT_{sum}/d\eta d\phi$, for “min-bias” events.
Min-Bias “Associated” Charged PTsum Density

Shows the data on the $\Delta \phi$ dependence of the “associated” charged PTsum density, $dP_{T\text{sum}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $P_{T\text{max}}$) relative to $P_{T\text{max}}$ (rotated to 180°) for “min-bias” events with $P_{T\text{max}} > 0.5$, 1.0, and 2.0 GeV/c.

Ave Min-Bias
0.24 GeV/c per unit $\eta \phi$

QCD "Blessing"  Rick Field - Florida/CDF
February 6, 2004  Page 30
Shows the data on the $\Delta \phi$ dependence of the “associated” charged PTsum density, $d\text{PT}_{\text{sum}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including PTmax*) relative to PTmax (rotated to 180°) for “min-bias” events with PTmax > 0.5, 1.0, and 2.0 GeV/c.

Shows “jet structure” in “min-bias” collisions (*i.e. the “birth” of the leading two jets!*).
Min-Bias “Associated” Charged PTsum Density

Shows the data on the $\Delta\phi$ dependence of the “associated” charged PTsum density, $d\text{PTsum}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $\text{PTmax}$) relative to $\text{PTmax}$ (rotated to 180°) for “min-bias” events with $\text{PTmax} > 0.5$, 1.0, and 2.0 GeV/c.

Shows “jet structure” in “min-bias” collisions (i.e. the “birth” of the leading two jets!).
Min-Bias “Associated” Charged Particle Density

- Shows the data on the $\Delta\phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5 \text{ GeV/c}, |\eta| < 1$, not including $\text{PTmax}$) relative to $\text{PTmax}$ (rotated to 180°) for “min-bias” events with $\text{PTmax} > 0.5 \text{ GeV/c}$ and $\text{PTmax} > 2.0 \text{ GeV/c}$ compared with PYTHIA Tune A (after CDFSIM).

- PYTHIA Tune A predicts a larger correlation than is seen in the “min-bias” data (i.e. Tune A “min-bias” is a bit too “jetty”).
Min-Bias “Associated” Charged PTsum Density

- Shows the data on the $\Delta \phi$ dependence of the “associated” charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{max}$) relative to $PT_{max}$ (rotated to 180$^\circ$) for “min-bias” events with $PT_{max} > 0.5$ GeV/c and $PT_{max} > 2.0$ GeV/c compared with PYTHIA Tune A (after CDFSIM).

- PYTHIA Tune A predicts a larger correlation than is seen in the “min-bias” data (i.e. Tune A “min-bias” is a bit too “jetty”).

QCD “Blessing”

Rick Field - Florida/CDF

February 6, 2004
Use the leading jet in “back-to-back” events to define the “transverse” region and look at the maximum $p_T$ charged particle in the “transverse” region, $PT_{maxT}$.

Look at the $\Delta \phi$ dependence of the “associated” charged particle and $PT_{sum}$ densities, $dN_{chg}/d\eta d\phi$ and $dPT_{sum}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including $PT_{maxT}$*) relative to $PT_{maxT}$.

Rotate so that $PT_{maxT}$ is at the center of the plot (*i.e.* $180^\circ$).
Look at the $\Delta\phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT\text{max}T$) relative to $PT\text{max}T$ (rotated to $180^\circ$) for $PT\text{max}T > 0.5$ GeV/c, $PT\text{max}T > 1.0$ GeV/c and $PT\text{max}T > 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(\text{jet#1}) < 70$ GeV.

Shows “jet structure” in the “transverse” region (i.e. the “birth” of the 3rd & 4th jet).
Look at the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{maxT}$) relative to $PT_{maxT}$ (rotated to 180°) for $PT_{maxT} > 0.5$ GeV/c, $PT_{maxT} > 1.0$ GeV/c and $PT_{maxT} > 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(jet#1) < 70$ GeV.

Shows “jet structure” in the “transverse” region (i.e. the “birth” of the $3^{rd}$ & $4^{th}$ jet).
Look at the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{\text{maxT}}$) relative to $PT_{\text{maxT}}$ (rotated to $180^\circ$) for $PT_{\text{maxT}} > 0.5$ GeV/c, $PT_{\text{maxT}} > 1.0$ GeV/c and $PT_{\text{maxT}} > 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(\text{jet#1}) < 70$ GeV.

Shows “jet structure” in the “transverse” region (i.e. the “birth” of the 3rd & 4th jet).
Look at the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $\text{PTmaxT}$) relative to PTmaxT (rotated to 180°) for PTmaxT $> 0.5$ GeV/c, PTmaxT $> 1.0$ GeV/c and PTmaxT $> 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(\text{jet#1}) < 70$ GeV.

- Shows “jet structure” in the “transverse” region (i.e. the “birth” of the 3rd & 4th jet).
Look at the $\Delta \phi$ dependence of the “associated” charged particle density, $dPT_{sum}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including $PT_{maxT}$*) relative to $PT_{maxT}$ (rotated to 180°) for $PT_{maxT} > 0.5$ GeV/c, $PT_{maxT} > 1.0$ GeV/c and $PT_{maxT} > 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(jet#1) < 70$ GeV.

Shows “jet structure” in the “transverse” region (*i.e.* the “birth” of the 3rd & 4th jet).
Look at the $\Delta \phi$ dependence of the “associated” charged particle density, $d\text{PT}_{\text{sum}}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $\text{PT}_{\text{maxT}}$) relative to $\text{PT}_{\text{maxT}}$ (rotated to 180°) for $\text{PT}_{\text{maxT}} > 0.5$ GeV/c, $\text{PT}_{\text{maxT}} > 1.0$ GeV/c and $\text{PT}_{\text{maxT}} > 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(\text{jet#1}) < 70$ GeV.

Shows “jet structure” in the “transverse” region (i.e. the “birth” of the 3rd & 4th jet).
Look at the $\Delta \phi$ dependence of the “associated” charged particle density, $dP_{T\text{sum}}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $P_{T\text{max}}$) relative to $P_{T\text{max}}$ (rotated to 180°) for $P_{T\text{max}} > 0.5$ GeV/c, $P_{T\text{max}} > 1.0$ GeV/c and $P_{T\text{max}} > 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(\text{jet#1}) < 70$ GeV.

Shows “jet structure” in the “transverse” region (i.e. the “birth” of the 3rd & 4th jet).
Look at the $\Delta \phi$ dependence of the “associated” charged particle density, $dP_{T\text{sum}}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including $P_{T\text{maxT}}$*) relative to $P_{T\text{maxT}}$ (rotated to 180°) for $P_{T\text{maxT}} > 0.5$ GeV/c, $P_{T\text{maxT}} > 1.0$ GeV/c and $P_{T\text{maxT}} > 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(\text{jet#1}) < 70$ GeV.

Shows “jet structure” in the “transverse” region (i.e. the “birth” of the 3rd & 4th jet).

CDF Preliminary data uncorrected

Back-to-Back $30 < E_T(\text{jet#1}) < 70$ GeV

Jet#1 Region

Jet#2 Region

Charged Particles ($|\eta|<1.0, P_T>0.5$ GeV/c)

$P_{T\text{maxT}}$ not included

$P_{T\text{maxT}} > 2.0$ GeV/c

$P_{T\text{maxT}} > 1.0$ GeV/c

$P_{T\text{maxT}} > 0.5$ GeV/c
Shows the $\Delta\phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{\text{MaxT}}$) relative to $PT_{\text{MaxT}}$ (rotated to $180^\circ$) for $PT_{\text{MaxT}} > 0.5$ GeV/c, $PT_{\text{MaxT}} > 1.0$ GeV/c and $PT_{\text{MaxT}} > 2.0$ GeV/c, for “back-to-back” events with $30 < ET(jet\#1) < 70$ GeV.

Shows $\Delta\phi$ dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) relative to jet$\#1$ (rotated to $270^\circ$) for “back-to-back events” with $30 < ET(jet\#1) < 70$ GeV.
Back-to-Back “Associated” Charged Particle Densities

It is more probable to find a particle accompanying PTmaxT than it is to find a particle in the “transverse” region!

Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) relative to PTmaxT (rotated to 180°) for “back-to-back events” with $30 < ET(jet#1) < 70$ GeV.

It is more probable to find a particle accompanying PTmaxT than it is to find a particle in the “transverse” region!

Shows $\Delta \phi$ dependence of the “transverse” charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for “back-to-back events” with $30 < ET(jet#1) < 70$ GeV.

$\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT not included) relative to PTmaxT (rotated to 270°) for “back-to-back events” with $30 < ET(jet#1) < 70$ GeV.
Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PT_{\text{maxT}}$) relative to $PT_{\text{maxT}}$ (rotated to 180°) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ relative to jet#1 (rotated to 270°) for “back-to-back events” with $30 < E_T(\text{jet#1}) < 70$ GeV.
Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, $\text{PTmaxT} > 2.0$ GeV/c (not including $\text{PTmaxT}$) relative to $\text{PTmaxT}$ (rotated to 180°) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for “back-to-back events” with $30 < E_T(\text{jet#1}) < 70$ GeV.
Jet Topologies

Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, $\text{PT}_{\text{max}} > 2.0$ GeV/c (not including $\text{PT}_{\text{max}}$) relative to $\text{PT}_{\text{max}}$ (rotated to $180^\circ$) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to $270^\circ$) for “back-to-back events” with $30 < E_T(\text{jet#1}) < 70$ GeV.
Jet Topologies

QCD Three Jet Topology

Charged Particle Density: $dN/d\eta d\phi$

CDF Preliminary data uncorrected

30 < $E_T$(jet#1) < 70 GeV
Back-to-Back

Shows the $\Delta\phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, $P_{T\text{max}} > 2.0$ GeV/c (not including $P_{T\text{max}}$) relative to $P_{T\text{max}}$ (rotated to 180°) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for “back-to-back events” with 30 < $E_T$(jet#1) < 70 GeV.

QCD "Blessing"
February 6, 2004
Rick Field - Florida/CDF
Page 49
Jet Topologies

QCD Three Jet Topology

QCD Four Jet Topology

Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, $PT_{\text{max}} > 2.0$ GeV/c (not including $PT_{\text{max}}$) relative to $PT_{\text{max}}$ (rotated to $180^\circ$) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to $270^\circ$) for “back-to-back events” with $30 < E_T(\text{jet}#1) < 70$ GeV.
Jet Topologies

QCD 2-to-4 Scattering

Proton

Underlying Event

AntiProton

Underlying Event

Final-State Radiation

Outgoing Parton

PT(hard)

Initial-State Radiation

QCD "Blessing"
February 6, 2004

180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for “back-to-back events” with $30 < E_T(\text{jet#1}) < 70$ GeV.
Jet Topologies

Multiple Parton Interactions

Proton
Underlying Event
Outgoing Parton
Outgoing Parton
Outgoing Parton
Outgoing Parton
AntiProton
Underlying Event

GeV/c, $|\eta| < 1$, $PT_{\text{max}} > 2.0$ GeV/c (not including $PT_{\text{max}}$) relative to $PT_{\text{max}}$ (rotated to 180°) and the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for “back-to-back events” with $30 < E_T(\text{jet#1}) < 70$ GeV.
Look at the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PT_{\text{max}T}$) relative to $PT_{\text{max}T}$ (rotated to 180°) for $PT_{\text{max}T} > 2.0$ GeV/c for “back-to-back” events with $30 < E_T(\text{jet#1}) < 70$ GeV and $95 < E_T(\text{jet#1}) < 130$ GeV.

Very little dependence on $E_T(\text{jet#1})$ in the “transverse” region for “back-to-back” events!
Look at the $\Delta \phi$ dependence of the “associated” charged PTsum density, $dPT_{sum}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PT_{maxT}$) relative to $PT_{maxT}$ (rotated to 180°) for $PT_{maxT} > 2.0$ GeV/c for “back-to-back” events with $30 < E_T(jet#1) < 70$ GeV and $95 < E_T(jet#1) < 130$ GeV.

Very little dependence on $E_T(jet#1)$ in the “transverse” region for “back-to-back” events!
Shows the $\Delta \phi$ dependence of the "associated" charged particle density, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PT_{maxT}$) relative to $PT_{maxT}$ (rotated to 180$^\circ$) for $PT_{maxT} > 2.0$ GeV/c, for "back-to-back" events with $30 < E_T(jet#1) < 70$ GeV.

Shows the data on the $\Delta \phi$ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PT_{max}$) relative to $PT_{max}$ (rotated to 180$^\circ$) for "min-bias" events with $PT_{max} > 2.0$ GeV/c.
Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PTmaxT$) relative to $PTmaxT$ (rotated to 180°) for “back-to-back” events with $30 < E_T(jet#1) < 70$ GeV.

Shows the data on the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PTmax$) relative to $PTmax$ (rotated to 180°) for “min-bias” events with $PTmax > 2.0$ GeV/c.
"Back-to-Back" vs "MinBias" "Associated" PTsum Density

Shows the $\Delta \phi$ dependence of the "associated" charged particle density, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PTmaxT$) relative to $PTmaxT$ (rotated to $180^\circ$) for $PTmaxT > 2.0$ GeV/c, for "back-to-back" events with $30 < E_T(jet#1) < 70$ GeV.

Shows the data on the $\Delta \phi$ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PTmax$) relative to $PTmax$ (rotated to $180^\circ$) for "min-bias" events with $PTmax > 2.0$ GeV/c.
Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PTmaxT$) relative to $PTmaxT$ (rotated to $180^\circ$) for $PTmaxT > 2.0$ GeV/c, for “back-to-back” events with $30 < E_T(jet#1) < 70$ GeV.

Shows the data on the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (not including $PTmax$) relative to $PTmax$ (rotated to $180^\circ$) for “min-bias” events with $PTmax > 2.0$ GeV/c.
"Associated" Charge Density
PYTHIA Tune A vs HERWIG

Associated Particle Density: $dN/d\eta d\phi$

CDF Preliminary data uncorrected theory + CDFSIM
Charged Particles ($|\eta|<1.0$, PT > 0.5 GeV/c) PTmaxT not included
Back-to-Back 30 < ET(jet#1) < 70 GeV

PTmaxT > 0.5 GeV/c
PY Tune A

PTmaxT
"Jet#1" Region

Associated Particle Density: $dN/d\eta d\phi$

CDF Preliminary data uncorrected theory + CDFSIM
Charged Particles ($|\eta|<1.0$, PT > 0.5 GeV/c) PTmaxT not included
Back-to-Back 30 < ET(jet#1) < 70 GeV

PTmaxT > 0.5 GeV/c
HERWIG

PTmaxT
"Jet#1" Region

Data - Theory: Associated Particle Density $dN/d\eta d\phi$

CDF Preliminary data uncorrected theory + CDFSIM
Charged Particles ($|\eta|<1.0$, PT > 0.5 GeV/c) PTmaxT not included
Back-to-Back 30 < ET(jet#1) < 70 GeV

PTmaxT
"Jet#1" Region

Data - Theory

CDF Preliminary
HERWIG
Back-to-Back 30 < ET(jet#1) < 70 GeV

PTmaxT
"Jet#1" Region

Data - Theory

CDF Preliminary
HERWIG
Back-to-Back 30 < ET(jet#1) < 70 GeV

PTmaxT
"Jet#1" Region

Data - Theory
"Associated" Charge Density

PYTHIA Tune A vs HERWIG

-associated particles in the direction of PTmaxT!

And HERWIG (without multiple parton interactions) too few particles in the direction opposite of PTmaxT!
“Associated” PTsum Density
PYTHIA Tune A vs HERWIG

Associated PTsum Density: \( \frac{dPT}{d\eta d\phi} \)

PT\(\text{max} T > 0.5 \) GeV/c

\( \eta \) < 1.0, PT > 0.5 GeV/c

Back-to-Back

30 < ET(jet#1) < 70 GeV

Charged Particles

CDF Preliminary

data uncorrected

theory + CDFSIM

PT\(\text{max} T \) not included

Data - Theory: Associated PTsum Density \( \frac{dPT}{d\eta d\phi} \)

CDF Preliminary

data uncorrected

theory + CDFSIM

PT\(\text{max} T \) not included

QCD "Blessing"

February 6, 2004

Rick Field - Florida/CDF
"Associated" PTsum Density
PYTHIA Tune A vs HERWIG

HERWIG (without multiple parton interactions) does not produce enough "associated" PTsum in the direction of PTmaxT!

And HERWIG (without multiple parton interactions) does not produce enough PTsum in the direction opposite of PTmaxT!
"Associated" Charge Density

PYTHIA Tune A vs HERWIG

Associated Particle Density: \( \frac{dN}{d\eta d\phi} \)

CDF Preliminary

Charged Particles 
\((|\eta|<1.0, \text{PT}>0.5 \text{ GeV/c})\)

Back-to-Back

PTmaxT not included

30 < ET(jet\#1) < 70 GeV

Associated Particle Density: \( \frac{dN}{d\eta d\phi} \)

CDF Preliminary

Charged Particles 
\((|\eta|<1.0, \text{PT}>0.5 \text{ GeV/c})\)

Back-to-Back

PTmaxT not included

30 < ET(jet\#1) < 70 GeV

Data - Theory: Associated Particle Density \( \frac{dN}{d\eta d\phi} \)

CDF Preliminary

Charged Particles 
\((|\eta|<1.0, \text{PT}>0.5 \text{ GeV/c})\)

PTmaxT > 2.0 GeV/c (not included)

PYTHIA Tune A

Back-to-Back

30 < ET(jet\#1) < 70 GeV

Data - Theory: Associated Particle Density \( \frac{dN}{d\eta d\phi} \)

CDF Preliminary

Charged Particles 
\((|\eta|<1.0, \text{PT}>0.5 \text{ GeV/c})\)

PTmaxT > 2.0 GeV/c (not included)

HERWIG

Back-to-Back

30 < ET(jet\#1) < 70 GeV

CDF "Blessing"
February 6, 2004
Rick Field - Florida/CDF
For $\text{PTmaxT} > 2.0 \text{ GeV}$ both PYTHIA and HERWIG produce slightly too many “associated” particles in the direction of $\text{PTmaxT}$!

But HERWIG (without multiple parton interactions) produces too few particles in the direction opposite of $\text{PTmaxT}$!
“Associated” \( PT_{\text{sum}} \) Density

**PYTHIA Tune A vs HERWIG**

**Associated \( PT_{\text{sum}} \) Density: \( \frac{dN}{d\eta d\phi} \)**

- Charged Particles \((\eta<1.0, PT>0.5 \text{ GeV/c})\)
- \( PT_{\text{maxT}} \) not included

**Back-to-Back**
- \( 30 < ET(\text{jet#1}) < 70 \text{ GeV} \)

**Charged Particles**
- \(|\eta|<1.0, PT>0.5 \text{ GeV/c} \)

**Data - Theory: Associated Particle Density \( \frac{dN}{d\eta d\phi} \)**

- \( PT_{\text{maxT}}>2.0 \text{ GeV/c} \)
- PY Tune A
- HERWIG

**CDF Preliminary**
- data uncorrected
- theory + CDFSIM

**PT_{\text{maxT}} \) not included**
- \( \text{Jet#1} \) Region

**QCD “Blessing”**

February 6, 2004
For $PT_{\text{max}} > 2.0$ GeV both PYTHIA and HERWIG produce slightly too much “associated” PTsum in the direction of $PT_{\text{max}}$!

But HERWIG (without multiple parton interactions) produces too few particles in the direction opposite of $PT_{\text{max}}$!