A Closer Look at the “Underlying Event” in Run 2: PYTHIA Tune A vs HERWIG

Outline of the Talk

• Look at charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and study the charged particle and $P_T$sum densities in the MAX and MIN “transverse” regions as defined by the leading calorimeter jet (JetClu, $R = 0.7, |\eta| < 2$) for both “leading jet” and “back-to-back” events. Compare with PYTHIA Tune A + CDFSIM with HERWIG + CDFSIM.

• Use the highest $p_T$ particle in the “transverse” region to define “associated” densities and look at “jets structure” in the “underlying event” (i.e. the “transverse” region). Do the particles in the “underlying event” come from “jets”?

• Study correlations between the two “transverse” regions.
A Closer Look at the “Underlying Event” in Run 2: PYTHIA Tune A vs HERWIG

Outline of the Talk

• Look at charged particles (p_T > 0.5 GeV/c, |η| < 1) and study the charged particle and PTsum densities in the MAX and MIN “transverse” regions as defined by the leading calorimeter jet (JetClu, R = 0.7, |η| < 2) for both “leading jet” and “back-to-back” events. Compare with PYTHIA Tune A + CDFSIM with HERWIG + CDFSIM.

• Use the highest pT particle in the “transverse” region to define “associated” densities and look at “jets structure” in the “underlying event” (i.e. the “transverse” region). Do the particles in the “underlying event” come from “jets”?

• Study correlations between the two “transverse” regions.

“Wish list” from the CERN MC Workshop!

With multiple parton interactions!

Without multiple parton interactions!
• Look at the “transverse” region as defined by the leading calorimeter jet (JetClu R = 0.7, |η| < 2).
• Study the charged particles \( (p_T > 0.5 \text{ GeV/c}, |\eta| < 1) \) and form the charged particle density, \( dN_{\text{ch}}/d\eta d\phi \), and the charged scalar \( p_T \) sum density, \( d\text{PTsum}/d\eta d\phi \). Each region “toward”, “away”, and “transverse” region has an area in \( \eta-\phi \) space of \( 4\pi/3 \).
"Transverse" Region: "Leading Jet" vs "Back-to-Back"

- Look at the "transverse" regions 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).

Percent of “Leading Jet” Events that are “Back-to-Back”

<table>
<thead>
<tr>
<th>Range</th>
<th>Data</th>
<th>PY Tune A</th>
<th>HW</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 &lt; $E_T$(jet#1) &lt; 70 GeV</td>
<td>19.9%</td>
<td>17.8%</td>
<td>16.2%</td>
</tr>
<tr>
<td>70 &lt; $E_T$(jet#1) &lt; 95 GeV</td>
<td>28.5%</td>
<td>27.5%</td>
<td>26.2%</td>
</tr>
<tr>
<td>95 &lt; $E_T$(jet#1) &lt; 130 GeV</td>
<td>30.6%</td>
<td>30.4%</td>
<td>29.1%</td>
</tr>
<tr>
<td>130 &lt; $E_T$(jet#1) &lt; 250 GeV</td>
<td>32.7%</td>
<td>33.5%</td>
<td>32.2%</td>
</tr>
</tbody>
</table>

- Look at the “transverse” regions 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, $dN/d\eta d\phi$, 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.
- Also shows charged particle density, $dN/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “min-bias” collisions.

- Shows the $\Delta \phi$ dependence of the charged particle density, $dN/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 for $30 < E_T(jet#1) < 70$ GeV for “leading jet” and “back-to-back” events.
“MAX/MIN Transverse” Charged Particle Densities

- Define the MAX and MIN “transverse” regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density. Each of the two “transverse” regions have an area in $\eta$-$\phi$ space of $4\pi/6$.

- The “transMIN” region is very sensitive to the “beam-beam remnant” and multiple parton interaction components of the “underlying event”.

- The difference, “transMAX” minus “transMIN”, is very sensitive to the “hard scattering” component of the “underlying event” (i.e. hard initial and final-state radiation).
Leading Jet: “MAX & MIN Transverse” Regions

- Use the **leading jet** to define the MAX and MIN “transverse” region on an event-by-event basis with MAX having the largest charged particle density.
- Shows the MAX, MIN, and average (AVE) “transverse” charged particle density \(dN/d\eta d\phi\) for charged particles \((P_T > 0.5 \text{ GeV/c, } |\eta| < 1)\) versus \(E_T(jet\#1)\) compared with PYTHIA Tune A (after CDFSIM).
Leading Jet: “MAX & MIN Transverse” Densities

CDF Preliminary
Leading Jet
PYTHIA Tune A 1.96 TeV

"MAX/MIN Transverse" Charge Density: dN/d\eta d\phi

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

ET(jet#1) (GeV)

CDF Preliminary
Leading Jet
HERWIG 1.96 TeV

"MAX/MIN Transverse" Charge Density: dN/d\eta d\phi

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

ET(jet#1) (GeV)

CDF Preliminary
Leading Jet
PYTHIA Tune A 1.96 TeV

"MAX/MIN Transverse" PTsum Density: dPT/d\eta d\phi

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

ET(jet#1) (GeV)

CDF Preliminary
Leading Jet
HERWIG 1.96 TeV

"MAX/MIN Transverse" PTsum Density: dPT/d\eta d\phi

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

ET(jet#1) (GeV)
Leading Jet: “MIN Transverse” Densities

CDF Preliminary data uncorrected
Leading Jet
1.96 TeV

CDF Preliminary data uncorrected
Leading Jet
1.96 TeV

CDF Preliminary data uncorrected
Leading Jet
1.96 TeV

CDF Preliminary data uncorrected
Leading Jet
1.96 TeV

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

Charged Particles ($|\eta|<1.0$, PT>0.5 GeV/c)
Back-to-Back: “MAX & MIN Transverse” Regions

- Use the leading two “back-to-back” jets to define the MAX and MIN “transverse” region on an event-by-event basis with MAX having the largest charged particle density.
- Shows the MAX, MIN, and average (AVE) “transverse” charged particle density $dN/d\eta d\phi$ for charged particles ($P_T > 0.5$ GeV/c, $|\eta| < 1$) versus $E_T(jet#1)$ compared with PYTHIA Tune A (after CDFSIM).
Back-to-Back: “MAX & MIN Transverse” Densities

CDF Preliminary data uncorrected
theory + CDFSIM

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

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

CDF Preliminary data uncorrected
theory + CDFSIM

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

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

CDF Preliminary data uncorrected theory + CDFSIM

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

1.96 TeV

**AVE Transverse** Charge Density: $dN/d\eta d\phi$

**MAX-MIN Transverse** Charge Density: $dN/d\eta d\phi$

**AVE Transverse** PTsum Density: $dP_T/d\eta d\phi$

**MAX-MIN Transverse** PTsum Density: $dP_T/d\eta d\phi$

“MIN Transverse” Charge Density: \( \frac{dN}{d\eta d\phi} \)

CDF Preliminary data uncorrected theory + CDFSIM

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

Min-Bias

Leading Jet

Back-to-Back

ET(jet\#1) (GeV)

“MIN Transverse” Charge Density

CDF Preliminary

1.96 TeV

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

Min-Bias

Leading Jet

Back-to-Back

ET(jet\#1) (GeV)

“MIN Transverse” Charge Density

CDF Preliminary data uncorrected theory + CDFSIM

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

Min-Bias

Leading Jet

Back-to-Back

ET(jet\#1) (GeV)

“MIN Transverse” PTsum Density: \( \frac{dPT}{d\eta d\phi} \)

CDF Preliminary data uncorrected theory + CDFSIM

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

Min-Bias

Leading Jet

Back-to-Back

ET(jet\#1) (GeV)

“MIN Transverse” PTsum Density

CDF Preliminary

1.96 TeV

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

Min-Bias

Leading Jet

Back-to-Back

ET(jet\#1) (GeV)

“MIN Transverse” PTsum Density

CDF Preliminary data uncorrected theory + CDFSIM

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

Min-Bias

Leading Jet

Back-to-Back

ET(jet\#1) (GeV)

• Define PTmaxT on and event-by-event bases to be the highest p_T charged particle (p_T > 0.5 GeV/c, |η| < 1) in the “transverse” region.
• Shows the average PTmaxT versus E_T(jet#1) for “back-to-back” and “leading jet” events.
• Also shows the average maximum p_T charged particle, PTmax, for “min-bias” collisions (p_T > 0.5 GeV/c, |η| < 1).
“Transverse” PTmax: PY Tune A versus HERWIG

- Define PTmaxT on and event-by-event bases to be the highest p_T charged particle (p_T > 0.5 GeV/c, |\eta| < 1) in the “transverse” region.
- Shows the average PTmaxT versus E_T(jet#1) for “back-to-back” and “leading jet” events compared with PYTHIA Tune A and HERWIG after CDFSIM.
Transverse PTmax: “Leading Jet” versus “Back-to-Back”

- Data on the $p_T$ distribution of the charged particle ($|\eta| < 1$) with the highest $p_T$ in the “transverse” region, $P_T^{maxT}$, for “leading jet” and “back-to-back” events and the $p_T$ distribution of the charged particle ($|\eta| < 1$) with the highest $p_T$, $P_T^{max}$, in “min-bias” collisions.
Transverse PTmax: PY Tune A versus HERWIG

- Data on the $p_T$ distribution of the charged particle ($|\eta| < 1$) with the highest $p_T$ in the “transverse” region, $\text{PTmax}_T$, for “leading jet” and “back-to-back” events compared with PYTHIA Tune A and HERWIG after CDFSIM.
“Leading Jet”: “Associated” Transverse Densities

- Use the leading jet to define the “transverse” region and look at the maximum $P_T$ charged particle in the “transverse” region, $PT_{maxT}$. Define “transMAX” to be the “transverse” region that contains $PT_{maxT}$ and “transMIN” to be the other “transverse” region.

- Shows the “transMAX” and “transMIN” associated charged particle density, $dN/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{maxT}$) as a function of $E_T$(jet#1) compared with the average “transverse” charged particle density.
“Leading Jet”: “Associated” Transverse Densities

- Use the leading jet to define the “transverse” region and look at the maximum p_T charged particle in the “transverse” region, PTmaxT. Define “transMAX” to be the “transverse” region that contains PTmaxT and “transMIN” to be the other “transverse” region.
- Shows the “transMAX” and “transMIN” associated charged particle density, dN/dηdφ, for charged particles (p_T > 0.5 GeV/c, |η| < 1, not including PTmaxT) as a function of E_T(jet#1) compared with the average “transverse” charged particle density.

“Associated” densities do not include PTmaxT!

It is more probable to find a particle accompanying PTmaxT than it is to find a particle in the “transverse” region!
“Leading Jet”: “Associated” Transverse PTsum Density

- Use the leading jet to define the “transverse” region and look at the maximum $P_T$ charged particle in the “transverse” region, $PT_{maxT}$. Define “transMAX” to be the “transverse” region that contains $PT_{maxT}$ and “transMIN” to be the other “transverse” region.

- Shows the “transMAX” and “transMIN” associated charged PTsum density, $dP_T/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{maxT}$) as a function of $E_T(jet#1)$ compared with the average “transverse” charged particle density.
“Associated” Transverse Densities: PY Tune A vs HERWIG
“Associated” Transverse Densities: PY Tune A vs HERWIG

CDF Preliminary data uncorrected theory + CDFSIM

Leading Jet

PYTHIA Tune A 1.96 TeV
PTmaxT > 2 GeV/c
Charged Particles (|η|<1.0, PT>0.5 GeV/c)

HERWIG 1.96 TeV
PTmaxT > 2 GeV/c
Charged Particles (|η|<1.0, PT>0.5 GeV/c)

CDF Preliminary data uncorrected theory + CDFSIM

Leading Jet

PYTHIA Tune A 1.96 TeV
PTmaxT > 0.5 GeV/c
Charged Particles (|η|<1.0, PT>0.5 GeV/c)

HERWIG 1.96 TeV
PTmaxT > 0.5 GeV/c
Charged Particles (|η|<1.0, PT>0.5 GeV/c)
Average $P_T$ versus the Charged Multiplicity

- Shows Run 2 data on the average transverse momentum as a function of the number particles for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “min-bias” collisions compared with PYTHIA Tune A (after CDFSIM).
“Transverse” Average $P_T$ versus the Charged Multiplicity

- Shows data on the “transverse” $<p_T>$ versus $N_{chg}$ for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “leading jet” and “back-to-back” events compared with “min-bias”.

CDF Preliminary data uncorrected

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

Leading Jet
1.96 TeV

30 < ET(jet#1) < 70 GeV

130 < ET(jet#1) < 250 GeV

Min-Bias

Number of Charged Particles
<P_T> versus Nchg: PY Tune A versus HERWIG

CDF Preliminary data uncorrected theory + CDFSIM

**Leading Jet**

30 < ET(jet#1) < 70 GeV

**Min-Bias**

30 < ET(jet#1) < 250 GeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

PYTHIA Tune A 1.96 TeV

Min-Bias

30 < ET(jet#1) < 70 GeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

HERWIG 1.96 TeV

Min-Bias

30 < ET(jet#1) < 70 GeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

CDF Preliminary data uncorrected theory + CDFSIM

**Leading Jet**

30 < ET(jet#1) < 70 GeV

**Back-to-Back**

30 < ET(jet#1) < 250 GeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)
Leading Jet: “Transverse 1” versus “Transverse 2”

- Use the leading jet to define the two “transverse” regions for “leading jet” events and look at correlations between “transverse 1” and “transverse 2”.
- Shows the average number of charged particles in “transverse 2” versus the number of charged particles in “transverse 1” ($p_T > 0.5$ GeV/$c$, $|\eta| < 1$) for the range $30 < E_T(jet#1) < 70$ GeV compared with PYTHIA Tune A (after CDFSIM) and HERWIG ((after CDFSIM).
Leading Jet: “Transverse 1” versus “Transverse 2”

CDF Preliminary data uncorrected theory + CDFSIM

Leading Jet
30 < ET(jet#1) < 70 GeV

1.96 TeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

CDF Preliminary data uncorrected theory + CDFSIM

Leading Jet
130 < ET(jet#1) < 250 GeV

1.96 TeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)
Back-to-Back: “Transverse 1” versus “Transverse 2”

- Use the leading jet in “back-to-back” events to define the two “transverse” regions and look at correlations between “transverse 1” and “transverse 2”.
- Shows the average number of charged particles in “transverse 2” versus the number of charged particles in “transverse 1” ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for the range $30 < E_T^*(\text{jet#1}) < 70$ GeV compared with PYTHIA Tune A (after CDFSIM).
Back-to-Back: “Transverse 1” versus “Transverse 2”

CDF Preliminary data uncorrected theory + CDFSIM

30 < ET(jet#1) < 70 GeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

PYTHIA Tune A 1.96 TeV

HERWIG 1.96 TeV
Summary & Conclusions

• By selecting events with at least two jets that are nearly back-to-back 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 $E_T(jet#1)$ less than about 150 GeV, which was also observed in our published Run 1 analysis.

• To examine the “jet” structure in the “underlying event” we define “associated” charged particle densities that measure the number of charged particles and scalar $p_T$ sum of charged particles accompanying the maximum $p_T$ charged particle in the “transverse” region, $PT_{\text{maxT}}$. The data show strong correlations. For $E_T(jet#1)$ greater than about 50 GeV there is a higher density of charged particles “associated” with $PT_{\text{maxT}}$ (not including $PT_{\text{maxT}}$) in the “transMAX” region than there is in the average “transverse” region. These correlations indicate “jet” structure in the “underlying event” (i.e. “transverse” region) at $PT_{\text{maxT}}$ values as low as 1.0 GeV/c!
Summary & Conclusions (continued)

• The data show interesting correlations between the two “transverse” regions. The “transMIN” densities rise with PTmaxT which is in the “transMAX” region (i.e. the other “transverse” region). Similarly, the charged multiplicity and the $<p_T>$ in the “transverse 2” region increases with the charged multiplicity in the “transverse 1” region. This might simply be due to high multiplicity in “transverse 1” or high PTmaxT in “transMAX” biasing in favor of a harder over 2-to-2 scattering (i.e. higher $P_T$(hard)) which would result in a higher multiplicity, larger PTsum, and larger $<p_T>$ other “transverse” region. It is possible that the “transverse 1” versus “transverse 2” correlations arises from multiple parton interactions. A large multiplicity in the “transverse 1” region or high PTmaxT in “transMAX” would indicate that a hard collision with small impact parameter has occurred enhancing the probability of multiple parton interactions which would then cause an increased activity in the other “transverse” region. The fact that PYTHIA Tune A (with multiple parton interactions) agrees with the data better than HERWIG (without multiple parton interactions) is very interesting. However, much more work is necessary to actually pinpoint the source of the “transverse 1” versus “transverse 2” correlations.
Summary & Conclusions (continued)

- The data show interesting correlations between the two “transverse” regions. The “transMIN” densities rise with PTmaxT which is in the “transMAX” region (i.e. the other “transverse” region). Similarly, the charged multiplicity and the <pT> in the “transverse” region increases with the charged multiplicity in the “transverse 2” region which might simply be due to high multiplicity in “transverse 1” or high PTmaxT in “transMAX” biasing in favor of a harder over 2-to-2 scattering (i.e. higher P_T(hard)) which would result in a higher multiplicity in “transverse 2” region.

It is possible that the data points for the QCD “blessed” plot area with the data better than HERWIG (without multiple parton interactions) are very interesting. However, much more work is necessary to actually pinpoint the source of the “transverse 1” versus “transverse 2” correlations.

I will create a WEBsite with pdf and eps versions of the figures and with the data points for the QCD “blessed” plot area!