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

Outline of the Talk

- Look at charged particles \((p_T > 0.5 \text{ GeV}/c, \mid \eta \mid < 1)\) and study the charged particle and \(\text{PT}_{\text{sum}}\) densities in the MAX and MIN “transverse” regions as defined by the leading calorimeter jet (JetClu, \(R = 0.7, \mid \eta \mid < 2\)) 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, $|\eta| < 1$) 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.

“Wish list” from the CERN MC Workshop!
• 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 GeV/c, |η| < 1) and form the charged particle density, dN_{ch}/dηdφ, and the charged scalar p_T sum density, dP_{Tsum}/dηdφ. Each region “toward”, “away”, and “transverse” region has an area in η-φ space of 4π/3.
• 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” (Δφ_{12} > 150°) 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 ($P_T > 0.5$ GeV/c, $|\eta| < 1$) versus $E_T(jet#1)$ compared with **PYTHIA Tune A** (after CDFSIM).
Leading Jet: “MAX & MIN Transverse” Densities

“MAX/MIN Transverse” Charge Density: $dN/d\eta d\phi$

CDF Preliminary Leading Jet PYTHIA Tune A 1.96 TeV

“MAX” “AVE” “MIN”

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

ET(jet#1) (GeV)

“MAX/MIN Transverse” PTsum Density: $dPT/d\eta d\phi$

CDF Preliminary Leading Jet HERWIG 1.96 TeV

“MAX” “AVE” “MIN”

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

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

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

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

CDF Preliminary data uncorrected

theory + CDFSIM

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

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

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

CDF Preliminary data uncorrected
theory + CDFSIM

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

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

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

CDF Preliminary data uncorrected theory + CDFSIM
PY Tune A
Leading Jet
HW
Back-to-Back

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

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

CDF Preliminary data uncorrected theory + CDFSIM
PY Tune A
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Back-to-Back

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

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

CDF Preliminary data uncorrected theory + CDFSIM
PY Tune A
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Back-to-Back

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

- Define $PT_{\text{max T}}$ on and event-by-event bases to be the highest $p_T$ charged particle ($p_T > 0.5 \text{ GeV/c, } |\eta| < 1$) in the “transverse” region.
- Shows the average $PT_{\text{max T}}$ versus $E_T(jet#1)$ for “back-to-back” and “leading jet” events.
- Also shows the average maximum $p_T$ charged particle, $PT_{\text{max}}$, for “min-bias” collisions ($p_T > 0.5 \text{ GeV/c, } |\eta| < 1$).
“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, |η| < 1) in the “transverse” region.
- Shows the average PTmaxT versus ET(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 (|η| < 1) with the highest p_T in the “transverse” region, PTmaxT, for “leading jet” and “back-to-back” events and the p_T distribution of the charged particle (|η| < 1) with the highest p_T, PTmax, in “min-bias” collisions.
**Transverse PTmax: PY Tune A versus HERWIG**

- Data on the p_T distribution of the charged particle (|η| < 1) with the highest p_T in the “transverse” region, PTmaxT, 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, \( PT_{\text{max}} \). Define “\( \text{transMAX} \)” to be the “transverse” region that contains \( PT_{\text{max}} \) and “\( \text{transMIN} \)” to be the other “transverse” region.
- Shows the “\( \text{transMAX} \)” and “\( \text{transMIN} \)” associated charged particle density, \( dN/d\eta d\phi \), for charged particles \( (p_T > 0.5\,\text{GeV/c}, |\eta| < 1, \text{not including } PT_{\text{max}}) \) 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” as the “transverse” region that contains PTmaxT and “transMIN” as 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 ET(jet#1) compared with the average “transverse” charged particle density.

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, $P_{T\text{max}}$. Define “transMAX” to be the “transverse” region that contains $P_{T\text{max}}$ 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 $P_{T\text{max}}$) as a function of $E_T(jet\#1)$ compared with the average “transverse” charged particle density.
"Associated" Transverse Densities: PY Tune A vs HERWIG

CDF Preliminary data uncorrected theory + CDFSIM

PYTHIA Tune A 1.96 TeV

HERWIG

Leading Jet

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

PTmaxT > 2 GeV/c

PTmaxT > 0.5 GeV/c

PTmaxT not included

CDF Preliminary

Charged Particle Density

ET(jet#1) (GeV)

0 50 100 150 200 250
"Associated" Transverse Densities: PY Tune A vs HERWIG

CDF Preliminary
PYTHIA Tune A 1.96 TeV
Leading Jet
PTmaxT > 2 GeV/c
PTmaxT > 0.5 GeV/c
Charged Particles (|\eta|<1.0, PT>0.5 GeV/c)

CDF Preliminary
HERWIG 1.96 TeV
Leading Jet
PTmaxT > 2 GeV/c
PTmaxT > 0.5 GeV/c
Charged Particles (|\eta|<1.0, PT>0.5 GeV/c)

CDF Preliminary
PYTHIA Tune A 1.96 TeV
Leading Jet
PTmaxT > 2 GeV/c
PTmaxT > 0.5 GeV/c
Charged Particles (|\eta|<1.0, PT>0.5 GeV/c)

CDF Preliminary
HERWIG 1.96 TeV
Leading Jet
PTmaxT > 2 GeV/c
PTmaxT > 0.5 GeV/c
Charged Particles (|\eta|<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 of 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”.

![Diagram showing different jet directions and average $P_T$ versus charged multiplicity](image-url)
$<P_T>$ versus Nchg: PY Tune A versus HERWIG
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

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

1.96 TeV

Leading Jet

30 < ET(jet#1) < 70 GeV

PY Tune A

HW

Leading Jet

130 < ET(jet#1) < 250 GeV

PY Tune A

HW

CDF Preliminary data uncorrected theory + CDFSIM

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” \( (p_T > 0.5 \text{ GeV/c}, |\eta| < 1) \) for the range \( 30 < E_T(\text{jet#1}) < 70 \text{ GeV} \) compared with PYTHIA Tune A (after CDFSIM).
Back-to-Back: “Transverse 1” versus “Transverse 2”
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, $PT_{maxT}$. 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 $PT_{maxT}$ (not including $PT_{maxT}$) 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 $PT_{maxT}$ 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.