Studying the Energy Dependence of the Underlying Event at the Tevatron and the LHC

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Outline

- Early studies the underlying event (UE) at CDF and PYTHIA Tune A.
- The CDF Tevatron PYTHIA 6.2 UE tunes (Tune A, B, D, AW, DW, D6, DWT, D6T).
- My 113 UE presentations (2000-2016) and LHC predictions.
- Early days of UE@MB at CMS and the LHC PYTHIA 6.4 tunes (AMBT1, Z1, Z2, Z2*).
- LPCC MB&UE Working group and the “common plots”.
- UE@CMS at 13 TeV.
- CMS “Physics Comparisons & Generator Tunes” group and CMS PYTHIA 8 UE Tunes.
- The Tevatron Energy Scan. Mapping out the energy dependence of the UE, Tevatron to the LHC.
The Inelastic Non-Diffractive Cross-Section

Proton + Proton + Proton + …

“Semi-hard” parton-parton collision ($p_T < \approx 2$ GeV/c)

Majority of “min-bias” events!

Multiple-parton interactions (MPI)!
The Inelastic Non-Diffractive Cross-Section

Occasionally one of the parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

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Select inelastic non-diffractive events that contain a hard scattering

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The "underlying-event" (UE)!

Hard parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

Given that you have one hard scattering it is more probable to have MPI! Hence, the UE has more activity than "min-bias".

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"Semi-hard" parton-parton collision ($p_T < \approx 2$ GeV/c)

Multiple-parton interactions (MPI)!

$\frac{1}{p_T^4} \rightarrow \frac{1}{(p_T^2 + p_{T0}^2)^2}$

$p_{T0}(E_{cm}) = p_{T0,Ref} \times (E_{cm}/E_{cm,Ref})^{ecmPow}$
Start with the perturbative 2-to-2 (or sometimes 2-to-3) parton-parton scattering and add initial and final-state gluon radiation (in the leading log approximation or modified leading log approximation).

The “underlying event” consists of the “beam-beam remnants” and from particles arising from soft or semi-soft multiple parton interactions (MPI).

Of course the outgoing colored partons fragment into hadron “jet” and inevitably “underlying event” observables receive contributions from initial and final-state radiation.
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Of course the outgoing colored partons fragment into hadron “jet” and inevitably “underlying event” observables receive contributions from the “underlying event”. The “underlying event” is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!
Look at charged particle correlations in the azimuthal angle $\Delta \phi$ relative to a leading object (i.e. CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF $P_T\text{min} = 0.5 \text{ GeV/c}$ $\eta_{\text{cut}} = 1.0$ or 0.8.

Define $|\Delta \phi| < 60^\circ$ as “Toward”, $60^\circ < |\Delta \phi| < 120^\circ$ as overall “Transverse”, and $|\Delta \phi| > 120^\circ$ as “Away”.

All three regions have the same area in $\eta-\phi$ space, $\Delta \eta \times \Delta \phi = 2\eta_{\text{cut}} \times 120^\circ = 2\eta_{\text{cut}} \times 2\pi/3$. Construct densities by dividing by the area in $\eta-\phi$ space.
Traditional Approach

**Charged Particle Δφ Correlations**

- **Traditional Approach**

Look at charged particle correlations in the azimuthal angle $\Delta \phi$ relative to a leading object (i.e. CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF PTmin = 0.5 GeV/c $\eta_{cut} = 1.0$ or 0.8.

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All three regions have the same area in $\eta$-φ space, $\Delta \eta \times \Delta \phi = 2\eta_{cut} \times 120^\circ = 2\eta_{cut} \times 2\pi/3$. Construct densities by dividing by the area in $\eta$-φ space.
**UE Observables**

- **“transMAX” and “transMIN” Charged Particle Density:** Number of charged particles ($p_T > P_T_{min}$, $|\eta| < \eta_{cut}$) in the the maximum (minimum) of the two “transverse” regions as defined by the leading charged particle, $P_T_{max}$, divided by the area in $\eta$-$\phi$ space, $2\eta_{cut} \times 2\pi/6$, averaged over all events with at least one particle with $p_T > P_T_{min}$, $|\eta| < \eta_{cut}$.

- **“transMAX” and “transMIN” Charged PTsum Density:** Scalar $p_T$ sum of charged particles ($p_T > P_T_{min}$, $|\eta| < \eta_{cut}$) in the the maximum (minimum) of the two “transverse” regions as defined by the leading charged particle, $P_T_{max}$, divided by the area in $\eta$-$\phi$ space, $2\eta_{cut} \times 2\pi/6$, averaged over all events with at least one particle with $p_T > P_T_{min}$, $|\eta| < \eta_{cut}$.

**Note:** The overall “transverse” density is equal to the average of the “transMAX” and “TransMIN” densities. The “TransDIF” Density is the “transMAX” Density minus the “transMIN” Density.

\[
\text{“Transverse” Density} = \text{“transAVE” Density} = (\text{“transMAX” Density} + \text{“transMIN” Density})/2
\]

\[
\text{“TransDIF” Density} = \text{“transMAX” Density} - \text{“transMIN” Density}
\]
The “toward” region contains the leading “jet”, while the “away” region, on the average, contains the “away-side” “jet”. The “transverse” region is perpendicular to the plane of the hard 2-to-2 scattering and is very sensitive to the “underlying event”. For events with large initial or final-state radiation the “transMAX” region defined contains the third jet while both the “transMAX” and “transMIN” regions receive contributions from the MPI and beam-beam remnants. Thus, the “transMIN” region is very sensitive to the multiple parton interactions (MPI) and beam-beam remnants (BBR), while the “transMAX” minus the “transMIN” (i.e. “transDIF”) is very sensitive to initial-state radiation (ISR) and final-state radiation (FSR).

“TransMIN” density more sensitive to MPI & BBR.

“TransDIF” density more sensitive to ISR & FSR.
The “toward” region contains the leading “jet”, while the “away” region, on the average, contains the “away-side” “jet”. The “transverse” region is perpendicular to the plane of the hard 2-to-2 scattering and is very sensitive to the “underlying event”. For events with large initial or final-state radiation the “transMAX” region defined contains the third jet while both the “transMAX” and “transMIN” regions receive contributions from the MPI and beam-beam remnants. Thus, the “transMIN” region is very sensitive to the multiple parton interactions (MPI) and beam-beam remnants (BBR), while the “transMAX” minus the “transMIN” (i.e. “transDIF”) is very sensitive to initial-state radiation (ISR) and final-state radiation (FSR).

Question: Do you expect the energy dependence of the “transMIN” and “transDIF” densities to be the same? Or do you expect that one of the two densities will increase faster with increasing energy than the other? Which one and why?

“TransMIN” density more sensitive to MPI & BBR.

“TransDIF” density more sensitive to ISR & FSR.
Plot shows average “transverse” charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus $P_T$(charged jet#1) compared to the QCD hard scattering predictions of ISAJET 7.32 (default parameters with $P_T$(hard)>3 GeV/c).

The predictions of ISAJET are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).
 HERWIG 6.4 (without MPI)
“Transverse” Density

Plot shows average “transverse” charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus $P_T$(charged jet#1) compared to the QCD hard scattering predictions of HERWIG 5.9 (default parameters with $P_T$(hard)$>3$ GeV/c without MPI).

The predictions of HERWIG are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).
The cut-off $P_{T0}$ that regulates the 2-to-2 scattering divergence $1/PT^4 ightarrow 1/(PT^2 + P_{T0}^2)^2$

1.9 GeV/c

$P_{T0}$ as follows:

$P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^\varepsilon$ with

$\varepsilon = PARP(90)$

Determined by $PARP(86)$

0.66 Probability that the MPI produces two gluons either as described by $PARP(85)$ or as a closed gluon loop. The remaining fraction consists of quark-antiquark pairs.

$PARP(84)$

0.2 Double-Gaussian: Fraction of the overall hadron radius containing the fraction $PARP(83)$ of the total hadronic matter.

$PARP(83)$

0.5 Double-Gaussian: Fraction of total hadronic matter within $PARP(84)$

$PARP(85)$

0.33 Probability that the MPI produces two gluons with color connections to the “nearest neighbors.”

$PARP(67)$

1.0 A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of $PARP(67)$ the more initial-state radiation.

$PARP(67)$

1.0 Determines the energy dependence of the cut-off $P_{T0}$ as follows:

$P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^\varepsilon$ with

$\varepsilon = PARP(90)$

$PARP(90)$

0.16

$PARP(86)$

0.66

$PARP(85)$

0.33

$PARP(84)$

0.5

$PARP(83)$

0.2

$PARP(82)$

1.9 GeV/c

The cut-off $P_{T0}$ that regulates the 2-to-2 scattering divergence $1/PT^4 ightarrow 1/(PT^2 + P_{T0}^2)^2$

$PARP(89)$

1 TeV

Determines the reference energy $E_0$.

$PARP(89)$

Determines the energy dependence of the cut-off $P_{T0}$ as follows:

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$PARP(83)$

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$PARP(82)$

1.9 GeV/c

The cut-off $P_{T0}$ that regulates the 2-to-2 scattering divergence $1/PT^4 ightarrow 1/(PT^2 + P_{T0}^2)^2$

$PARP(89)$

1 TeV

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The cut-off \( PT_0 \) that regulates the 2-to-2 scattering divergence \( 1/PT_4 \rightarrow 1/(PT_2^2 + PT_0^2) \)

1.9 GeV/c

\( PARP(82) \)

A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of \( PARP(67) \) the more initial-state radiation.

1.0

\( PARP(67) \)

PARP(83)  0.5  Double-Gaussian: Fraction of total hadronic matter within PARP(84)

PARP(84)  0.2  Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter.

PARP(85)  0.33  Produces two gluons with color connections to the nearest neighbors.

PARP(86)  0.66  Probability that one of the gluons either is described as a closed gluon loop, or consists of quark-antiquark pairs.

PARP(89)  1 TeV  Determines the reference energy \( E_0 \).

\( PARP(82) = 0.19 \text{ GeV/c} \)

The cut-off \( PT_0 \) that regulates the 2-to-2 scattering divergence \( 1/PT^4 \rightarrow 1/(PT^2 + PT_0^2)^2 \)

\( PARP(90) = 0.16 \)

Determines the energy dependence of the cut-off \( PT_0 \) as follows \( PT_0(E_{cm}) = PT_0(E_{cm}/E_0)^\varepsilon \) with \( \varepsilon = PARP(90) \)

\( PARP(67) = 1.0 \)

Determines the energy dependence of the MPI!
## PYTHIA 6.206 Defaults

### "Transverse" Charged Particle Density: $dN/d\eta d\phi$

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### Default parameters give very poor description of the “underlying event”!

Plot shows the “Transverse” charged particle density versus $P_T$(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA 6.206 ($P_T$(hard) > 0) using the default parameters for multiple parton interactions and CTEQ3L, CTEQ4L, and CTEQ5L.

Note Change

- PARP(67) = 4.0 (< 6.138)
- PARP(67) = 1.0 (> 6.138)
### Plot shows the “transverse” charged particle density versus $P_T(\text{charged jet#1})$ 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)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Old PYTHIA default (more initial-state radiation)</th>
<th>New PYTHIA default (less initial-state radiation)</th>
</tr>
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<td>PARP(86)</td>
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<td>PARP(89)</td>
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<td>PARP(90)</td>
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<tr>
<td>PARP(67)</td>
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Plot shows the “transverse” charged particle density versus PT(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)).

Plot shows the p_T distribution of the “transverse” charged particle density for PT(chgjet#1) > 5 GeV/c and PT(chgjet#1) > 30 GeV/c.
"Transverse" Charged Densities Energy Dependence

Shows the “transverse” charged $P_{T\text{sum}}$ density ($|\eta|<1$, $P_T>0.4$ GeV) versus $P_T$(charged jet#1) at 630 GeV predicted by HERWIG 6.4 ($P_T$(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set A, $\varepsilon = 0$, $\varepsilon = 0.16$ (default) and $\varepsilon = 0.25$ (preferred)).

Also shown are the $P_{T\text{sum}}$ densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti “transverse” cone analysis at 630 GeV.
"Transverse" Charged Densities Energy Dependence

Shows the “transverse” charged density (|\eta|<1, P_T>0.4 GeV) versus PT(charged jet#1) at 630 GeV predicted by HERWIG 6.4 (P_T(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A, \epsilon = 0, \epsilon = 0.16 (default) and \epsilon = 0.25 (preferred)).

Also shown are the PT_sum densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti “transverse” cone analysis at 630 GeV.

Lowering P_T0 at 630 GeV (i.e. increasing \epsilon) increases UE activity resulting in less energy dependence.

Increasing \epsilon produces less energy dependence for the UE resulting in less UE activity at the LHC!

Reference point E_0 = 1.8 TeV
"Transverse" Charged Densities Energy Dependence

Shows the “transverse” charged PTsum density (|\(\eta|<1, P_T>0.4 \text{ GeV}\)) versus 
30 GeV \(|\eta|<1.0 P_T>0.4 \text{ GeV}\) predicted by HERWIG 6.4 (\(P_T\) (hard) > 3 
GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (\(P_T\) (hard) > 0, CTEQ5L, Set A, \(\varepsilon = 0\), \(\varepsilon = 0.16\) (default) and \(\varepsilon = 0.25\) (preferred)).

Also shown are the PTsum densities (0.16 GeV/c and 
0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti "transverse" cone analysis at 630 GeV.

Lowering \(P_{T0}\) at 630 GeV (i.e. increasing \(\varepsilon\)) increases UE activity resulting in less energy dependence.

Increasing \(\varepsilon\) produces less energy dependence for the UE resulting in less UE activity at the LHC!

Rick Field Fermilab MC Workshop 
October 4, 2002!
Start with the perturbative Drell-Yan muon pair production and add initial-state gluon radiation (in the leading log approximation or modified leading log approximation).

The “underlying event” consists of the “beam-beam remnants” and from particles arising from soft or semi-soft multiple parton interactions (MPI).

Of course the outgoing colored partons fragment into hadron “jet” and inevitably “underlying event” observables receive contributions from initial-state radiation.
Shows the Run 1 Z-boson $p_T$ distribution ($<p_T(Z)> \approx 11.5$ GeV/c) compared with
PYTHIA Tune A ($<p_T(Z)> = 9.7$ GeV/c),
Tune A25 ($<p_T(Z)> = 10.1$ GeV/c), and
Tune A50 ($<p_T(Z)> = 11.2$ GeV/c).

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Vary the intrinsic KT!
Shows the Run 1 Z-boson $p_T$ distribution ($<p_T(Z)> \approx 11.5$ GeV/c) compared with PYTHIA Tune A ($<p_T(Z)> = 9.7$ GeV/c), and PYTHIA Tune AW ($<p_T(Z)> = 11.7$ GeV/c).

Effective $Q$ cut-off, below which space-like showers are not evolved.

The $Q^2 = k_T^2$ in $\alpha_s$ for space-like showers is scaled by PARP(64)!
Jet-Jet Correlations (DØ)

Jet#1-Jet#2 $\Delta\phi$ Distribution

- MidPoint Cone Algorithm ($R = 0.7, f_{\text{merge}} = 0.5$)
- $\mathcal{L} = 150 \text{ pb}^{-1}$ (Phys. Rev. Lett. 94 221801 (2005))
- Data/NLO agreement good. Data/HERWIG agreement good.
- Data/PYTHIA agreement good provided PARP(67) $= 1.0 \rightarrow 4.0$ (i.e. like Tune A, best fit 2.5).

$\Delta\phi$ Jet#1-Jet#2
Shows the Run 1 Z-boson $p_T$ distribution ($<p_T(Z)> \approx 11.5$ GeV/c) compared with PYTHIA Tune DW, and HERWIG.
## PYTHIA 6.2 Tunes

All use LO $\alpha_s$ with $\Lambda = 192$ MeV!

### UE Parameters

- **MSTP(81)**: 1, 1, 1
- **MSTP(82)**: 4, 4, 4
- **PARP(82)**: 2.0 GeV, 1.9 GeV, 1.8 GeV
- **PARP(83)**: 0.5, 0.5, 0.5
- **PARP(84)**: 0.4, 0.4, 0.4
- **PARP(85)**: 0.9, 1.0, 1.0
- **PARP(86)**: 0.95, 1.0, 1.0
- **PARP(89)**: 1.8 TeV, 1.8 TeV, 1.8 TeV
- **PARP(90)**: 0.25, 0.25, 0.25
- **PARP(62)**: 1.25, 1.25, 1.25
- **PARP(64)**: 0.2, 0.2, 0.2
- **PARP(67)**: 4.0, 2.5, 2.5
- **MSTP(91)**: 1, 1, 1
- **PARP(91)**: 2.1, 2.1, 2.1
- **PARP(93)**: 15.0, 15.0, 15.0

### ISR Parameter

- **PARP(67)**: 4.0, 2.5, 2.5

### Intrinsic KT

- **MSTP(91)**: 1, 1, 1

### Tune A energy dependence!

- **PARP(67)**: 4.0, 2.5, 2.5

### Uses CTEQ6L

- **PARP(67)**: 4.0, 2.5, 2.5
- **PARP(92)**: 1.8 GeV, 1.8 GeV, 1.8 GeV

### Parameter

- **Intrinsic KT**
- **ISR Parameter**
- **UE Parameters**
### PYTHIA 6.2 Tunes

#### Parameter | Tune DWT | Tune D6T | ATLAS
---|---|---|---
PDF | CTEQ5L | CTEQ6L | CTEQ5L
MSTP(81) | 1 | 1 | 1
MSTP(82) | 4 | 4 | 4
PARP(82) | 1.9409 GeV | 1.8387 GeV | 1.8 GeV
PARP(83) | 0.5 | 0.5 | 0.5
PARP(84) | 0.4 | 0.4 | 0.5
PARP(85) | 1.0 | 1.0 | 0.33
PARP(86) | 1.0 | 1.0 | 0.66
PARP(89) | 1.96 TeV | 1.96 TeV | 1.0 TeV
PARP(90) | 0.16 | 0.16 | 0.16
PARP(62) | 1.25 | 1.25 | 1.0
PARP(64) | 0.2 | 0.2 | 1.0
PARP(67) | 2.5 | 2.5 | 1.0
MSTP(91) | 1 | 1 | 1
PARP(91) | 2.1 | 2.1 | 1.0
PARP(93) | 15.0 | 15.0 | 5.0

**Intrinsic KT**

**ISR Parameter**

**UE Parameters**

---

*All use LO $\alpha_s$ with $\Lambda = 192$ MeV!*

---

*ATLAS energy dependence!*
Early Studies of the UE

Charged Jet Evolution and the Underlying Event in Proton-Antiproton Collisions at 1.8 TeV

Use the CDF “min-bias” data in conjunction with the CDF JET20 data to study the growth and development of “charged particle jets”.

Study a variety of “local” leading charged jet observables and compare with the QCD “hard” scattering Monte-Carlo models of Herwig, Isajet, and Pythia.

Study a number of “global” observables, where to fit the observable the QCD Monte-Carlo models have to describe correctly the entire event structure. In particular, examine carefully the “underlying event” in hard-scattering processes.

Compare the “underlying event” in dijet versus Z-boson production.

DPF 2000: My first presentation on the “underlying event”!

First CDF UE Studies
Rick Field Wine & Cheese Talk
October 4, 2002
My First Talk on the UE

DiJet: Charged Multiplicity versus PT(chgjet#1)

The Underlying Event: Summary & Conclusions

- The underlying event is very similar in dijet and the Z-boson production as predicted by the QCD Monte-Carlo models. The “toward” region in Z-boson production is a direct measure of the underlying event.
- The number of charged particles per unit rapidity (height of the “plateau”) is at least twice that observed in “soft” collisions at the same corresponding energy.
- None of the QCD Monte-Carlo models correctly describe the underlying event. Herwig and Pythia 6.125 do not have enough activity in the underlying event. Pythia 6.115 has about the right amount of activity in the underlying event, but as a result produces too much overall multiplicity. Isajet has a lot of activity in the underlying event, but with the wrong dependence on $P_t$(jet#1) or $P_t$(Z).
- None of the Monte-carlo models have the correct $P_t$ dependence of the beam-beam remnant component of the underlying event.

Need to “tune” the QCD MC models!

My first look at the “underlying event plateau”!
Rick’s “underlying event” talks (2000-2016).
Rick’s “underlying event” talks (2000-2016).

18 talks in 2009!
Studying the Underlying Event at CDF and the LHC, seminar presented at the University of California, Berkeley, January 13, 2009.

Toward an Understanding of Hadron-Hadron Collisions: From Feynman-Field to the LHC, research progress meeting (RPM) presented at Lawrence Berkeley Laboratory, University of California, Berkeley, January 15, 2009.


Min-Bias and the Underlying Event, talk presented at the Workshop on Early Physics Opportunities at the LHC, University of California, Berkeley, May 6, 2009.

Min-Bias and the Underlying Event: From RHIC to the LHC, talk presented at the RHIC & AGS Annual Users’ Meeting, Brookhaven National Laboratory, June 2, 2009.
Rick’s UE Talks 2009(1)

- Studying the Underlying Event at CDF and the LHC, seminar presented at the University of California, Berkeley, January 13, 2009.

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Renee Fatemi gave a talk on the "underlying event at STAR!"
At STAR they have measured the “underlying event at $W = 200$ GeV ($|\eta| < 1$, $p_T > 0.2$ GeV) and compared their uncorrected data with PYTHIA Tune A + STAR-SIM.
Conclusions

I. Hadron Collisions at RHIC take place at an order of magnitude smaller \( \sqrt{s} \) than the Tevatron. Nevertheless, jets are observed and reconstructed down to \( p_T = 5 \) GeV and are well described by pQCD.

II. Comparisons between several jetfinders reveal consistent results.

III. Interest in the Underlying Event at RHIC Kinematics is driven by the need for jet energy scale corrections as well as pure physics interests (see talks by M. Lisa and H. Caines).

IV. UE at RHIC appears to be independent of jet \( p_T \) and decoupled from hard interaction.

V. CDF Tune A provides an excellent description of the UE at \( \sqrt{s} = 200 \) GeV (thanks Rick!)

VI. Underlying Event distributions in general smaller than those at CDF. Tower & Track Multiplicities are the exception, but this may be due to the 0.2 (STAR) versus 0.5 GeV (CDF) \( p_T / E_t \) cut-off.

VII. For a cone jet with \( R = 0.7 \) UE contributes 0.5-0.9 GeV.

VIII. Comparison of Leading Jet and Back-to-Back distributions indicate that large angle radiation contributions are small at RHIC energies.
“Transverse” Charge Density

- Shows the “associated” charged particle density in the “transverse” region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |\eta| < 1, not including PTmax) for “min-bias” events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level. 
"Transverse" Charge Density

Shows the “associated” charged particle density in the “transverse” region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, not including PTmax) for “min-bias” events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (i.e. generator level).

RDF Preliminary py Tune DW generator level

0.2 TeV → 1.96 TeV (UE increase ~2.7 times)

0.9 TeV

0.2 TeV

1.96 TeV

Tevatron

RHIC

1.96 TeV → 14 TeV (UE increase ~1.9 times)

LHC

LHC7

LHC10

LHC14

PTmax = 5.25 GeV/c

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

Center-of-Mass Energy (TeV)

Linear scale!
"Transverse" Charge Density

Shows the "associated" charged particle density in the "transverse" region as a function of PT\text{max} for charged particles (p_T > 0.5 GeV/c, |\eta| < 1, not including PT\text{max}) for "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (i.e. generator level).

Log scale!

7 TeV → 14 TeV (UE increase ~20%)

Linear on a log plot!


The LHC Physics Environment: Extrapolations from the Tevatron to RHIC and the LHC, lecture presented at the CTEQ Summer School, Madison, WI, July 1, 2009.

"Min-Bias" and the "Underlying Event": Extrapolations from the Tevatron to RHIC and the LHC, talk presented at the CMS-QCD Group meeting, CERN, August 4, 2009.

Predicting "Min-Bias" and the "Underlying Event" at the LHC, talk presented at the LHC09 Theory Institute: SM & BSM Physics at the LHC, CERN, August 13, 2009.

Predicting "Min-Bias" and the "Underlying Event" at the LHC, talk presented at the Joint Experimental Meeting on Early LHC Measurements, CERN, August 14, 2009.

Toward an Understanding of Hadron-Hadron Collisions: From Feynman-Field to the LHC, seminar presented at Rutgers University, NJ, October 13, 2009.

Predicting "Min-Bias" and the "Underlying Event" at the LHC: The Early Measurements, talk presented at the MB&UE@CMS Workshop, CERN, November 6, 2009.

Predicting "Min-Bias" and the "Underlying Event" at the LHC: Important 900 GeV Measurements, talk presented at the CMS-QCD Group meeting, CERN, November 10, 2009.

Predicting "Min-Bias" and the "Underlying Event" at the LHC, talk presented at Minute Particulars & Hidden Symmetries: Chris Quigg Symposium, Fermilab, December 15, 2009.

Predicting "Min-Bias" and the "Underlying Event" at the LHC, talk presented at Argonne National Laboratory, December 16, 2009.

18 UE talks in 2009

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18 UE talks in 2009
It is very important to measure BOTH “min-bias” and the “underlying event” at 900 GeV! I hope we get enough events.

Predicting "Min-Bias" and the "Underlying Event" at the LHC: The Early Measurements, talk presented at the MB&UE@CMS Workshop, CERN, November 6, 2009.

Predicting "Min-Bias" and the "Underlying Event" at the LHC: Important 900 GeV Measurements, talk presented at the CMS-QCD Group meeting, CERN, November 10, 2009.

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18 UE talks in 2009
Predicting “Min-Bias” and the “Underlying Event” at the LHC

Outline of Talk

- The inelastic non-diffractive cross section.
- New CDF charged multiplicity distribution and comparisons with the QCD Monte-Carlo tunes.
- Relationship between the “underlying event” in a hard scattering process and “min-bias” collisions.
- “Min-Bias at 900 GeV and 2.2 TeV.
- The “underlying event” at 900 GeV and 7 TeV.
- Summary.

18 UE talks in 2009

Predicting “Min-Bias” and the “Underlying Event” at the LHC: The Early Measurements, talk presented at the MB&UE@CMS Workshop, CERN, November 6, 2009.

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18 UE talks in 2009
Fake data (from MC) at 900 GeV on the “transverse” charged particle density, \(dN/d\eta d\phi\), as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with \(p_T > 0.5\) GeV/c and \(|\eta| < 2\). The fake data (from PYTHIA Tune DW) are generated at the particle level (i.e. generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).
"Transverse" Charged Particle Density: \( \mathrm{d}N/\mathrm{d}\eta \mathrm{d}\phi \)

- RDF Preliminary
- py Tune DW generator level
- \( 7 \text{ TeV} \)
- \( 900 \text{ GeV} \)
- Factor of 2!

Shows the charged particle density in the "transverse" region for charged particles (\( p_T > 0.5 \) GeV/c, \( |\eta| < 2 \)) at 900 GeV and 7 TeV as defined by PTmax from PYTHIA Tune DW and at the particle level (i.e. generator level).

900 GeV → 7 TeV

(UE increase ~ factor of 2)

~0.4 → ~0.8
Measure Min-Bias and the “Underlying Event” at CMS

- The plan involves two phases.
- Phase 1 would be to measure min-bias and the “underlying event” as soon as possible (when the luminosity is low), perhaps during commissioning. We would then tune the QCD Monte-Carlo models for all the other CMS analyses. Phase 1 would be a service to the rest of the collaboration. As the measurements become more reliable we would re-tune the QCD Monte-Carlo models if necessary and begin Phase 2.
- Phase 2 is “physics” and would include comparing the min-bias and “underlying event” measurements at the LHC with the measurements we have done (and are doing now) at CDF and then writing a physics publication.
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Initial Group Members
- Rick Field (Florida)
- Darin Acosta (Florida)
- Paolo Bartalini (Florida)
- Albert De Roeck (CERN)
- Livio Fano’ (INFN/Perugia at CERN)
- Filippo Ambroglini (INFN/Perugia at CERN)
- Khristian Kotov (UF Student, Acosta)

Florida-Perugia-CERN

Perugia, Italy, March 2006
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UF–Perugia–CERN

PTDR Volume 2 Section 3.3.2

Measurement of the Underlying Event in Jet Topologies using Charged Particle and Momentum Densities

F. Ambroglini, L. Fanò
INFN and Università degli Studi di Perugia, Perugia, Italy
F. Bartalini
National Taiwan University, Taipei, Taiwan
R. Field
University of Florida, FL, USA

Abstract

We discuss a study of the "Underlying Event" at CMS (under nominal and start-up conditions) by measuring charged particles and momentum densities. The underlying event is studied by examining charged particles in the "transverse" region in charged particle jet production. The predictions of HERWIG (without multiple parton interactions) and several versions of PYTHIA (with different multiple parton interaction models) are compared and the possibility of discriminating between them is investigated. Exploring QCD dynamics in proton-proton collisions at 14 TeV and the importance of improving and tuning the QCD Monte Carlo models at the LHC start-up are discussed.
The plan involves two phases. Phase 1 would be to measure min-bias and the "underlying event" as soon as possible (when the luminosity is low), perhaps during commissioning. We would then tune the QCD Monte-Carlo models for all the other CMS analyses. Phase 1 would be a service to the rest of the collaboration. As the measurements become more reliable we would re-tune the QCD Monte-Carlo models if necessary and begin Phase 2.

Phase 2 is "physics" and would include comparing the min-bias and "underlying event" measurements at the LHC with the measurements we have done (and are doing now) at CDF and then writing a physics publication.

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- Khristian Kotov (UF Student, Acosta)

QCD contribution to the Joint QCD/HI 2007 paper
Pre-approval talk

Authors:
F. Ambroglini, P. Bartalini
L. Fano’, R. Field

Institutions:
INFN and Universita’ di Perugia
National Taiwan University
University of Florida

Referees:
W. Adam
C. Lourenco
P. Marage
Fake data (from MC) at 900 GeV on the “transverse” charged particle density, \( dN/d\eta d\phi \), as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet\#1) for charged particles with \( p_T > 0.5 \text{ GeV/c} \) and \(|\eta| < 2\). The fake data (from PYTHIA Tune DW) are generated at the particle level \( \text{(i.e. generator level)} \) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).

CMS preliminary data at 900 GeV on the “transverse” charged particle density, \( dN/d\eta d\phi \), as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet\#1) for charged particles with \( p_T > 0.5 \text{ GeV/c} \) and \(|\eta| < 2\). The data are uncorrected and compared with PYTHIA Tune DW after detector simulation (216,215 events in the plot).
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged PTsum density, $dP_T/d\eta d\phi$, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.

ATLAS preliminary data at 900 GeV and 7 TeV on the “transverse” charged PTsum density, $dP_T/d\eta d\phi$, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, $dN/d\eta d\phi$, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.

ATLAS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, $dN/d\eta d\phi$, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.
I am surprised that the Tunes did not do a better job of predicting the behavior of the “underlying event” at 900 GeV and 7 TeV!
I am surprised that the Tunes did as well as they did at predicting the behavior of the “underlying event” at 900 GeV and 7 TeV!
I believed that it was time to move to PYTHIA 6.4 ($p_T$-ordered parton showers and new MPI model)!

**Tune Z1:** I started with the parameters of ATLAS Tune AMBT1, but I changed LO* to CTEQ5L and I varied PARP(82) and PARP(90) to get a very good fit of the CMS UE data at 900 GeV and 7 TeV.

The ATLAS Tune AMBT1 was designed to fit the inelastic data for $N_{ch}$ $\geq$ 6 and to fit the $P_T^{\text{max}}$ UE data with $P_T^{\text{max}}$ $>$ 10 GeV/c. Tune AMBT1 was primarily a min-bias tune, while Tune Z1 was a UE tune!
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune Z1 (R. Field CMS)</th>
<th>Tune AMBT1 (ATLAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parton Distribution Function</td>
<td>CTEQ5L</td>
<td>LO*</td>
</tr>
<tr>
<td>PARP(82) – MPI Cut-off</td>
<td>1.932</td>
<td>2.292</td>
</tr>
<tr>
<td>PARP(89) – Reference energy, E0</td>
<td>1800.0</td>
<td>1800.0</td>
</tr>
<tr>
<td>PARP(90) – MPI Energy Extrapolation</td>
<td>0.275</td>
<td>0.25</td>
</tr>
<tr>
<td>PARP(77) – CR Suppression</td>
<td>1.016</td>
<td>1.016</td>
</tr>
<tr>
<td>PARP(78) – CR Strength</td>
<td>0.538</td>
<td>0.538</td>
</tr>
<tr>
<td>PARP(80) – Probability colored parton from BBR</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>PARP(83) – Matter fraction in core</td>
<td>0.356</td>
<td>0.356</td>
</tr>
<tr>
<td>PARP(84) – Core of matter overlap</td>
<td>0.651</td>
<td>0.651</td>
</tr>
<tr>
<td>PARP(62) – ISR Cut-off</td>
<td>1.025</td>
<td>1.025</td>
</tr>
<tr>
<td>PARP(93) – primordial kT-max</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>MSTP(81) – MPI, ISR, FSR, BBR model</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>MSTP(82) – Double gaussian matter distribution</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MSTP(91) – Gaussian primordial kT</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MSTP(95) – strategy for color reconnection</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Parameters not shown are the PYTHIA 6.4 defaults!
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, \( dN/d\eta d\phi \), as defined by the leading charged particle jet (chgjet\#1) for charged particles with \( p_T > 0.5 \) GeV/c and \( |\eta| < 2.0 \). The data are uncorrected and compared with PYTHIA Tune DW and D6T after detector simulation (SIM).

PYTHIA Tune Z1 is a PYTHIA 6.4 using \( p_T \)-ordered parton showers and the new MPI model!
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune Z1 (R. Field CMS)</th>
<th>Tune Z2 (R. Field CMS)</th>
</tr>
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<tbody>
<tr>
<td>Parton Distribution Function</td>
<td>CTEQ5L</td>
<td>CTEQ6L</td>
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<tr>
<td>PARP(82) – MPI Cut-off</td>
<td>1.932</td>
<td>1.832</td>
</tr>
<tr>
<td>PARP(89) – Reference energy, E0</td>
<td>1800.0</td>
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</table>

My guess!

Reduce PARP(82) by factor of $1.83/1.93 = 0.95$
Everything else the same!
### PYTHIA Tune Z2

<table>
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<tr>
<td>PARP(93) – primordial kT-max</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>MSTP(81) – MPI, ISR, FSR, BBR model</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>MSTP(82) – Double gaussian matter distribution</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MSTP(91) – Gaussian primordial kT</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MSTP(95) – strategy for color reconnection</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

- Reduce PARP(82) by factor of $1.83/1.93 = 0.95$
- Everything else the same!
- PARP(90) same
- For Z1 and Z2!
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, dN/d\(\eta\)d\(\phi\), as defined by the leading charged particle jet (chgjet#1) for charged particles with \(p_T > 0.5\) GeV/c and \(|\eta| < 2.0\). The data are corrected and compared with PYTHIA Tune Z1 at the generator level.

CMS corrected data!

CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged PTsum density, dPT/d\(\eta\)d\(\phi\), as defined by the leading charged particle jet (chgjet#1) for charged particles with \(p_T > 0.5\) GeV/c and \(|\eta| < 2.0\). The data are corrected and compared with PYTHIA Tune Z1 at the generator level.

Very nice agreement!

 CMS corrected data!

Wayne State University
February 17, 2017

Rick Field – Florida/CDF/CMS
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CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, \( dN/d\eta d\phi \), as defined by the leading charged particle jet (chgjet#1) for charged particles with \( p_T > 0.5 \) GeV/c and \(|\eta| < 2.0\). The data are corrected and compared with PYTHIA Tune Z2 at the generator level.

CMS corrected data!

Not good! Bad energy dependence!

CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged PTsum density, \( dP_T/d\eta d\phi \), as defined by the leading charged particle jet (chgjet#1) for charged particles with \( p_T > 0.5 \) GeV/c and \(|\eta| < 2.0\). The data are corrected and compared with PYTHIA Tune Z2 at the generator level.

CMS corrected data!
PYTHIA 6.4 Tune Z2* is an improved version of Tune Z2 constructed to fit the CMS UE data at 900 GeV and 7 TeV.

CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, \( dN/d\eta d\phi \), as defined by the leading charged particle jet (chgjet#1) for charged particles with \( p_T > 0.5 \text{ GeV}/c \) and \( |\eta| < 2.0 \). The data are corrected and compared with PYTHIA Tune Z2 at the generator level.

PYTHIA 6.4 Tune Z2* is an improved version of Tune Z2 constructed to fit the CMS UE data at 900 GeV and 7 TeV.
The LPCC MB&UE Working Group suggested several MB&UE “Common Plots” the all the LHC groups could produce and compare with each other.
UE Common Plots

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

**7 TeV**

RDF Preliminary corrected data

ATLAS (solid blue) ALICE (open black) Charged Particles ($|\eta| < 0.8$, PT > 0.5 GeV/c)

PTmax (GeV/c)

PTsum Density (GeV/c)

900 GeV

RDF Preliminary corrected data

ATLAS (solid blue) ALICE (open black) Charged Particles ($|\eta| < 0.8$, PT > 0.5 GeV/c)

PTmax (GeV/c)
UE Common Plots

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

**7 TeV**
- Charged Particles ($|\eta| < 0.8$, PT > 0.5 GeV/c)
- ATLAS (solid blue)
- ALICE (open black)

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

**7 TeV**
- Charged Particles ($|\eta| < 0.8$, PT > 0.5 GeV/c)
- ATLAS (solid blue)
- ALICE (open black)

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

**900 GeV**
- Charged Particles ($|\eta| < 0.8$, PT > 0.5 GeV/c)
- CMS (solid red)
- ATLAS (solid blue)
- ALICE (open black)
UE Common Plots

"Transverse" Charged Particle Density: \( \frac{dN}{d\eta d\phi} \)

- **7 TeV**
  - CMS (solid red)
  - ATLAS (solid blue)
  - ALICE (open black)
  - Charged Particles \((|\eta| < 0.8, PT > 0.5 \text{ GeV/c})\)

"Transverse" Charged PTsum Density: \( \frac{dPT}{d\eta d\phi} \)

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"Transverse" Charged PTsum Density: \( \frac{dPT}{d\eta d\phi} \)

- **900 GeV**
  - CMS (solid red)
  - ATLAS (solid blue)
  - ALICE (open black)
  - Charged Particles \((|\eta| < 0.8, PT > 0.5 \text{ GeV/c})\)
Just before the shutdown of the Tevatron CDF has collected more than 10M “min-bias” events at several center-of-mass energies!

300 GeV 12.1M MB Events
900 GeV 54.3M MB Events
The goal is to produce data (corrected to the particle level) that can be used by the theorists to tune and improve the QCD Monte-Carlo models that are used to simulate hadron-hadron collisions.

http://arxiv.org/abs/1508.05340
**CDF and CMS data at 900 GeV/c** on the charged particle density in the “transverse” region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.

**CDF and CMS data at 900 GeV/c** on the charged PTsum density in the “transverse” region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
CDF versus CMS

CDF and CMS data at 900 GeV/c on the charged particle density in the “transverse” region as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.

CDF and CMS data at 900 GeV/c on the charged PTsum density in the “transverse” region as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
Physics Comparisons & Generator Tunes

CMS at the LHC
PC&GT

Underlying Event Tunes and Double Parton Scattering
The CMS Collaboration

Abstract

Using the "Rivet" and "Professor" framework, we construct a new PYTHIA 6 tune using the CTEQ6L1 PDF and two new PYTHIA 8 UE tunes (one using CTEQ6L1 and one using the HERAPDF15LD). By simultaneously fitting CDF data from $p\bar{p}$ collisions at 300 GeV, 900 GeV, and 1.96 TeV together with CMS data for $p\bar{p}$ collisions at 7 TeV, we test the Underlying Event (UE) models and constrain their parameters, allowing for more precise predictions at 13 TeV and 14 TeV. The consistency of these new tunes with measurements of double-parton scattering (DPS) is also investigated.

Hannes Jung, Paolo Gunnellini, Rick Field
PYTHIA 6.4 Tune CUETP6S1-CTEQ6L: Start with Tune Z2*-lep and tune to the CDF PTmax “transMAX” and “transMIN” UE data at 300 GeV, 900 GeV, and 1.96 TeV and the CMS PTmax “transMAX” and “transMIN” UE data at 7 TeV.

PYTHIA 6.4 Tune CUETP6S1-HERAPDF1.5LO: Start with Tune Z2*-lep and tune to the CDF PTmax “transMAX” and “transMIN” UE data at 300 GeV, 900 GeV, and 1.96 TeV and the CMS PTmax “transMAX” and “transMIN” UE data at 7 TeV.

PYTHIA 8 Tune CUETP8S1-CTEQ6L: Start with Corke & Sjöstrand Tune 4C and tune to the CDF PTmax “transMAX” and “transMIN” UE data at 900 GeV, and 1.96 TeV and the CMS PTmax “transMAX” and “transMIN” UE data at 7 TeV. Exclude 300 GeV data.

PYTHIA 8 Tune CUETP8S1-HERAPDF1.5LO: Start with Corke & Sjöstrand Tune 4C and tune to the CDF PTmax “transMAX” and “transMIN” UE data at 900 GeV, and 1.96 TeV and the CMS PTmax “transMAX” and “transMIN” UE data at 7 TeV. Exclude 300 GeV data.

PYTHIA 8 Tune CUETP8M1-NNPDF2.3LO: Start with the Skands Monash-NNPDF2.3LO tune and tune to the CDF PTmax “transMAX” and “transMIN” UE data at 900 GeV, and 1.96 TeV and the CMS PTmax “transMAX” and “transMIN” UE data at 7 TeV. Exclude 300 GeV data.

HERWIG++ Tune CUETHS1-CTEQ6L: Start with the Seymour & Siódmok UE-EE-5C tune and tune to the CDF PTmax “transMAX” and “transMIN” UE data at 900 GeV, and 1.96 TeV and the CMS PTmax “transMAX” and “transMIN” UE data at 7 TeV.
CMS data at 7 TeV and CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the “transAVE” region as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8. The data are compared with PYTHIA 6.4 Tune Z2*.

CMS data at 7 TeV and CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the “transAVE” region as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8. The data are compared with PYTHIA 8 Tune CUETP8S1-CTEQ6L (excludes 300 GeV in fit).
Measure the “Underlying Event” at 13 TeV at CMS

Measure the UE observables as defined by the leading charged particle jet, chgjet#1, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$.

Measure the UE observables as defined by the leading charged particle, PTmax, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$ and $|\eta| < 0.8$.

Livio & Rick were part of the CMS Run 1 UE&MB team!
"Tevatron" to the LHC

Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)
Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)
“Tevatron” to the LHC

Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)
Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)
"TransAVE" Charged Particle Density: $dN/d\eta d\phi$

Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)
Particle Density: MAX & MIN

"TransMAX" Charged Particle Density: dN/d\(\eta\) d\(\phi\)

- Tune Z2* (solid lines)
- Tune Z1 (dashed lines)

PTmax (GeV/c)

Charged Particles (|\(\eta\)|<0.8, PT>0.5 GeV/c)

- 300 GeV
- 900 GeV
- 1.96 TeV
- 7 TeV
- 13 TeV

"TransMIN" Charged Particle Density: dN/d\(\eta\) d\(\phi\)

- Tune Z2* (solid lines)
- Tune Z1 (dashed lines)

PTmax (GeV/c)

Charged Particles (|\(\eta\)|<0.8, PT>0.5 GeV/c)

- 300 GeV
- 900 GeV
- 1.96 TeV
- 7 TeV
- 13 TeV
Particle Density: AVE & DIF

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

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

Charged Particle Density

Charged Particles ($|\eta|<0.8$, $PT>0.5$ GeV/c)

1.96 TeV
300 GeV
900 GeV
7 TeV
13 TeV

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Tune CUETP8S1 (solid lines)
Tune MONASH (dashed lines)
Energy Dependence

"TransAVE" Charged Particle Density: \( \frac{dN}{d\eta d\phi} \)

<table>
<thead>
<tr>
<th>Center-of-Mass Energy (GeV)</th>
<th>Charged Particle Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 GeV (CDF)</td>
<td></td>
</tr>
<tr>
<td>900 GeV (CDF, CMS)</td>
<td></td>
</tr>
<tr>
<td>1.96 TeV (CDF)</td>
<td></td>
</tr>
<tr>
<td>7 TeV (CMS)</td>
<td></td>
</tr>
<tr>
<td>13 TeV (CMS)</td>
<td></td>
</tr>
</tbody>
</table>

Charged Particles (|\( \eta \)|<0.8, \( PT > 0.5 \) GeV/c)

CMS solid dots
CDF solid squares

\( PT_{max} \) (GeV/c)

0 5 10 15 20 25 30

0.0 0.5 1.0 1.5

0.1 1.0 10.0 100.0
Energy Dependence

"Transverse" Charged Particle Density: \( \frac{dN}{d\eta d\phi} \)

- **TransMAX**
  - Tune Z2* (solid lines)
  - Tune Z1 (dashed lines)

- **TransAVE**
  - CMS solid dots
  - CDF solid squares

- **TransDIF**
  - Tune CUETP8S1 (solid lines)
  - Tune MONASH (dashed lines)

- **TransMIN**
  - CMS solid dots
  - CDF solid squares

Center-of-Mass Energy (GeV)

Charge Particle Density

Charged Particles (\( |\eta| < 0.8, PT > 0.5 \text{ GeV/c} \))

5.0 < PTmax < 6.0 GeV/c
The data are “normalized” by dividing by the corresponding value at 900 GeV.
The data are “normalized” by dividing by the corresponding value at 900 GeV.

MIN increases by factor of 6.7

DIF increases by factor of 2.5

MIN increases by factor of 8.7

DIF increases by factor of 3.1
Energy Dependence

"Transverse" Charged Particle Density Ratio

Center-of-Mass Energy (GeV)

Tune Z2* (solid lines)
Tune Z1 (dashed lines)
CMS solid dots
CDF solid squares
5.0 < PTmax < 6.0 GeV/c
Divided by 300 GeV Value

"TransDIF"

"TransMIN"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

The data are “normalized” by dividing by the corresponding value at 900 GeV.
The data are “normalized” by dividing by the corresponding value at 900 GeV.
The data are “normalized” by dividing by the corresponding value at 900 GeV.

The “transMIN” (MPI-BBR component) increases much faster with center-of-mass energy than the “transDIF” (ISR-FSR component)!

Duh!!

Answer to Question
Rick’s UE Graduate Students

- Richard Haas (CDF Ph.D. 2001): The Underlying Event in Hard Scattering Collisions of Proton and Antiproton at 1.8 TeV.

- Alberto Cruz (CDF Ph.D. 2005): Using MAX/MIN Transverse Regions to Study the Underlying Event in Run 2 at the Tevatron.

- Craig Group (CDF Ph.D. 2006): The Inclusive Jet Cross Section in Run 2 at CDF. After receiving his Ph.D Craig helped in Deepak Kar’s UE analyses (2008) and the “Tevatron Energy Scan” UE analysis (2015).


- Mohammed Zakaria (CMS Ph.D. 2013): Measurement of the Underlying Event Activity in Proton-Proton Collisions at the LHC using Leading Tracks at 7 TeV and Comparison with 0.9 TeV.

- Doug Rank (CMS Ph.D. 2016): The Underlying Event via Leading Track and Track Jet at 13 TeV.
A Wonderful Journey

7 GeV/c $\pi^0$s!

Field-Feynman (1977)
A Wonderful Journey

QCD Improved Parton Model

6 GeV/c Jets!

FFF2 (1978)
A Wonderful Journey

QCD Improved Parton Model

"TransAVE" Charged Particle Density: \( dN/d\eta d\phi \)

- 13 TeV (CMS)
- 7 TeV (CMS)
- 1.96 TeV (CDF)
- 900 GeV (CDF, CMS)
- 300 GeV (CDF)

Charged Particles \((|\eta|<0.8, PT>0.5 \text{ GeV/c})\)

PTmax (GeV/c)

Charged Particle Density

- Single \( \pi \) Rate
- Logarithmic scale
- "QCD" prediction

6 GeV/c Jets!

FFF2 (1978)

Proton

PT(hard)

Initial-State Radiation

Final-State Radiation

Underlying Event

Outgoing Parton
A Wonderful Journey

Field-Jet 1978-1985

CDF Tune A 2000-2009

CDF Tune DW 2002-2010

CMS Tune Z2* 2014-Present

CMS Tune Z1 2010-2014

CUETP8S1 2014-Present

CUETP8M1 2014-Present

Proton

Underlying Event

Final-State Radiation

Outgoing Parton

Outgoing Parton

PT(hard)
A Wonderful Journey

QCD Improved Parton Model

Rick & Jimmie Wedding November 24, 1966
Little Chapel of the West, Las Vegas

Field-Feynman (1977)

7 GeV/c $\pi^0$'s!

CDF Tune

1978

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

0.0

0.5

1.0

1.5

0 5 10 15 20 25 30

PT$_{\text{max}}$ (GeV/c)

Charged Particle Density

Charged Particles ($|\eta|<0.8$, PT>0.5 GeV/c)

1.96 TeV (CDF)

300 GeV (CDF)

900 GeV (CDF, CMS)

7 TeV (CMS)

13 TeV (CMS)

Field-Jet 1978-1985

CDF Tune A 2000-2009

CDF Tune DW 2002-2010

CMS Tune Z1 2010-2014

CMS Tune Z2* 2010-Present

CUETP8M1 2014-Present

Rick & Jimmie Celebration November 24, 2016
Little Chapel of the West, Las Vegas

CUETP8M1 2014-Present

Proton

PT(Inc)

PT(hard)

Outgoing Parton

Final-State Radiation

Underlying Event

Proton

Outgoing Parton

Final-State Radiation

CUETP8M1 2014-Present

Rick & Jimmie Wedding November 24, 1966
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Wayne State University
February 17, 2017

Rick Field – Florida/CDF/CMS

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