What happens when a high energy proton and an antiproton collide?

Most of the time the proton and antiproton ooze through each other and fall apart (i.e. no hard scattering). The outgoing particles continue in roughly the same direction as initial proton and antiproton. A “Min-Bias” collision.

Occasionally there will be a “hard” parton-parton collision resulting in large transverse momentum outgoing partons. Also a “Min-Bias” collision.

The “underlying event” is everything except the two outgoing hard scattered “jets”. It is an unavoidable background to many collider observables.
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Occasionally there will be a “hard” parton-parton collision resulting in large transverse momentum outgoing partons. Also a “Min-Bias” collision.

The “underlying event” is everything except the two outgoing hard scattered “jets”. It is an unavoidable background to many collider observables.
The underlying event in a hard scattering process is a complicated and not very well understood object. It is an interesting region since it probes the interface between perturbative and non-perturbative physics.

There are three CDF analyses which quantitatively study the underlying event and compare with the QCD Monte-Carlo models (2 Run I and 1 Run II).

It is important to model this region well since it is an unavoidable background to all collider observables. Also, we need a good model of “min-bias” collisions.
The Proton-Antiproton Total Cross-Section

Elastic Scattering

Single Diffraction

Double Diffraction

\[ \sigma_{\text{tot}} = \sigma_{\text{EL}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{HC}} \]

1.8 TeV: \(78\text{mb} = 18\text{mb} + 9\text{mb} + (4-7)\text{mb} + (47-44)\text{mb}\)

The "hard core" component contains both "hard" and "soft" collisions.

"Soft" Hard Core (no hard scattering)

"Hard" Hard Core (hard scattering)
The Proton-Antiproton Total Cross-Section

Elastic Scattering

\[ \sigma_{\text{tot}} = \sigma_{\text{EL}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{HC}} \]

1.8 TeV: 78mb = 18mb + 9mb + (4-7)mb + (47-44)mb

The CDF “Min-Bias” trigger picks up most of the “hard core” cross-section plus a small amount of single & double diffraction.

The “hard core” component contains both “hard” and “soft” collisions.

CDF “Min-Bias” trigger
1 charged particle in forward BBC
AND
1 charged particle in backward BBC
The underlying event in a hard scattering process has a “hard” component (particles that arise from initial & final-state radiation and from the outgoing hard scattered partons) and a “soft?” component ("beam-beam remnants").

Clearly? the “underlying event” in a hard scattering process should not look like a “Min-Bias” event because of the “hard” component (i.e. initial & final-state radiation).

However, perhaps “Min-Bias” collisions are a good model for the “beam-beam remnant” component of the “underlying event”.

Are these the same?
The underlying event in a hard scattering process has a "hard" component (particles that arise from initial & final-state radiation and from the outgoing hard scattered partons) and a "soft?" component ("beam-beam remnants").

Clearly, the "underlying event" in a hard scattering process should not look like a "Min-Bias" event because of the "hard" component.

However, perhaps "Min-Bias" collisions are a good model for the "beam-beam remnants" component of the "underlying event".

If we are going to look at "Min-Bias" collisions as a guide to understanding the "beam-beam remnants", then we better study carefully the "Min-Bias" data!

The "beam-beam remnant" component is, however, color connected to the "hard" component so this comparison is (at best) an approximation.
CDF “Min-Bias” Data
Charged Particle Density

Shows CDF “Min-Bias” data on the number of charged particles per unit pseudo-rapidity at 630 and 1,800 GeV. There are about 4.2 charged particles per unit $\eta$ in “Min-Bias” collisions at 1.8 TeV ($|\eta| < 1$, all $P_T$).

Convert to charged particle density, $dN_{\text{chg}}/d\eta d\phi$, by dividing by $2\pi$. There are about 0.67 charged particles per unit $\eta$-$\phi$ in “Min-Bias” collisions at 1.8 TeV ($|\eta| < 1$, all $P_T$).
Shows the center-of-mass energy dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for “Min-Bias” collisions at $\eta = 0$. Also show a log fit (Fit 1) and a $(\log)^2$ fit (Fit 2) to the CDF plus UA5 data.

What should we expect for the LHC?

$<dN_{\text{chg}}/d\eta d\phi> = 0.51$
$\eta = 0$ 630 GeV

24% increase

$<dN_{\text{chg}}/d\eta d\phi> = 0.63$
$\eta = 0$ 1.8 TeV

LHC?
Shows the center-of-mass energy dependence of the charged particle density, \( \frac{dN_{\text{chg}}}{d\eta d\phi} \), for “Min-Bias” collisions compared with the HERWIG “Soft” Min-Bias Monte-Carlo model. Note: there is no “hard” scattering in HERWIG “Soft” Min-Bias.

HERWIG “Soft” Min-Bias contains no hard parton-parton interactions and describes fairly well the charged particle density, \( \frac{dN_{\text{chg}}}{d\eta d\phi} \), in “Min-Bias” collisions.

HERWIG “Soft” Min-Bias predicts a 45% rise in \( \frac{dN_{\text{chg}}}{d\eta d\phi} \) at \( \eta = 0 \) in going from the Tevatron (1.8 TeV) to the LHC (14 TeV). 4 charged particles per unit \( \eta \) becomes 6.
Shows the energy dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for “Min-Bias” collisions compared with HERWIG “Soft” Min-Bias.

Shows the $P_T$ dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi dP_T$, for “Min-Bias” collisions at 1.8 TeV collisions compared with HERWIG “Soft” Min-Bias.

HERWIG “Soft” Min-Bias does not describe the “Min-Bias” data! The “Min-Bias” data contains a lot of “hard” parton-parton collisions which results in many more particles at large $P_T$ than are produces by any “soft” model.
CDF “Min-Bias” Data

PT Dependence

"Tano Analysis" (Tano, Kovacs, Huston, Bhatti)

Shows the energy dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi dP_T$, for "Min-Bias" collisions compared with HERWIG "Soft" Min-Bias.

- Shows the $P_T$ dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi dP_T$, for "Min-Bias" collisions at 1.8 TeV collisions compared with HERWIG "Soft" Min-Bias.

- HERWIG "Soft" Min-Bias does not describe the "Min-Bias" data! The "Min-Bias" data contains a lot of "hard" parton-parton collisions which results in many more particles at large $P_T$ than are produces by any "soft" model.
HERWIG “hard” QCD with $P_T^{(hard)} > 3$ GeV/c describes well the high $P_T$ tail but produces too many charged particles overall. Not all of the “Min-Bias” collisions have a hard scattering with $P_T^{(hard)} > 3$ GeV/c!

HERWIG “soft” Min-Bias does not fit the “Min-Bias” data!
Min-Bias: Combining “Hard” and “Soft” Collisions

HERWIG “hard” QCD with $P_T(hard) > 3$ GeV/c describes well the high $P_T$ tail but produces too many charged particles overall. Not all of the “Min-Bias” collisions have a hard scattering with $P_T(hard) > 3$ GeV/c!

One cannot run the HERWIG “hard” QCD Monte-Carlo with $P_T(hard) < 3$ GeV/c because the perturbative 2-to-2 cross-sections diverge like $1/P_T(hard)^4$?

No easy way to “mix” HERWIG “hard” with HERWIG “soft”.

HERWIG diverges!

HERWIG “soft” Min-Bias does not fit the “Min-Bias” data!

PYTHIA cuts off the divergence. Can run $P_T(hard)>0$!
PYTHIA regulates the perturbative 2-to-2 parton-parton cross sections with cut-off parameters which allow one to run with $P_T(\text{hard}) > 0$. One can simulate both “hard” and “soft” collisions in one program.

The relative amount of “hard” versus “soft” depends on the cut-off and can be tuned.

This PYTHIA fit predicts that 12% of all “Min-Bias” events are a result of a hard 2-to-2 parton-parton scattering with $P_T(\text{hard}) > 5$ GeV/c (1% with $P_T(\text{hard}) > 10$ GeV/c)! 

PYTHIA Min-Bias

“Soft” + ”Hard”

PYTHIA 6.206 Set A

CDF Min-Bias Data

1.8 TeV $|\eta|<1$

12% of “Min-Bias” events have $P_T(\text{hard}) > 5$ GeV/c!

1% of “Min-Bias” events have $P_T(\text{hard}) > 10$ GeV/c!
Look at charged particle correlations in the azimuthal angle $\Delta \phi$ relative to the leading charged particle jet.

- Define $|\Delta \phi| < 60^\circ$ as “Toward”, $60^\circ < |\Delta \phi| < 120^\circ$ as “Transverse”, and $|\Delta \phi| > 120^\circ$ as “Away”.
- 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 the charged particle density in the “transverse” region!
Data on the average charge particle density (P_T > 0.5 GeV, |η| < 1) in the “transverse” (60<|Δφ|<120°) region as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the <dN_{chg}/dηdφ> in a 1 GeV bin. The solid (open) points are the Min-Bias (JET20) data. The errors on the (uncorrected) data include both statistical and correlated systematic uncertainties.
Data on the average charge scalar PT$_{\text{sum}}$ density (P$_T$ > 0.5 GeV, |$\eta$| < 1) in the “transverse” ($60 < |\Delta \phi| < 120^\circ$) region as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the $<dP_{\text{sum}}/d\eta d\phi>$ in a 1 GeV bin. The solid (open) points are the Min-Bias (JET20) data. The errors on the (uncorrected) data include both statistical and correlated systematic uncertainties.
Define “MAX” and “MIN” to be the maximum and minimum charge particle density of the two “transverse” regions $60^\circ < \Delta \phi < 120^\circ$ $(60^\circ < -\Delta \phi < 120^\circ)$ on an event by event basis. The overall “transverse” region is the sum of the “MAX” and “MIN”.

The plot shows the average “MAX” and “MIN” charge particle density versus $P_T$(charged jet#1). The solid (open) points are the Min-Bias (JET20) data. The errors on the (uncorrected) data include both statistical and correlated systematic uncertainties.
Define “MAX” and “MIN” to be the maximum and minimum charge particle density of the two “transverse” regions $60^\circ < \Delta \phi < 120^\circ$ (60°<$\Delta \phi$<120°) on an event by event basis. The overall “transverse” region is the sum of the “MAX” and “MIN”.

The plot shows the average “MAX” and “MIN” charge particle density versus $P_T$ (charged jet#1). The solid (open) points are the Min-Bias (JET20) data. The errors on the (uncorrected) data include both statistical and correlated systematic uncertainties.
Charged Particle Density

“Transverse” $P_T$ Distribution

- Compares the average “transverse” charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T(\text{charged jet#1})$ with the $P_T$ distribution of the “transverse” density, $dN_{\text{chg}}/d\eta d\phi dP_T$.
- Shows how the “transverse” charge particle density is distributed in $P_T$. 

- $P_T(\text{charged jet#1}) > 30$ GeV/c
  - “Transverse” $<dN_{\text{chg}}/d\eta d\phi> = 0.56$

- $P_T(\text{charged jet#1}) > 5$ GeV/c
  - “Transverse” $<dN_{\text{chg}}/d\eta d\phi> = 0.52$
Charged Particle Density

“Transverse” $P_T$ Distribution

Compared the average “transverse” charge particle density with the average “Min-Bias”
charge particle density ($|\eta|<1, P_T>0.5$ GeV). Shows how the “transverse” charge particle
density and the Min-Bias charge particle density is distributed in $P_T$. 

CDF Min-Bias data

$<dN_{chg}/d\eta d\phi> = 0.25$

CDF Preliminary data uncorrected

$1.8$ TeV $|\eta|<1$ $P_T>0.5$ GeV

$P_T(\text{charged jet#1}) > 30$ GeV/c

“Transverse” $<dN_{chg}/d\eta d\phi> = 0.56$

“Transverse” $P_T(\text{chgjet#1}) > 5$ GeV/c

“Transverse” $P_T(\text{chgjet#1}) > 30$ GeV/c

Factor of 2!
Plot shows the “transverse” charged particle density vs $P_T^{(chgjet#1)}$ compared to the QCD hard scattering predictions of HERWIG 6.4 (default parameters with $P_T^{(hard)}>3$ GeV/c).

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").
Plot shows the “min-transverse” charged particle density vs $P_T(\text{hard})$ compared to the QCD hard scattering predictions of HERWIG 6.4 (default parameters with $P_T(\text{hard}) > 3$ GeV/c).

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”).

Equal “hard” and “beam-beam” remnants!
HERWIG 6.4

“Transverse” $P_T$ Distribution

Compares the average “transverse” charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$ (charged jet#1) and the $P_T$ distribution of the “transverse” density, $dN_{chg}/d\eta d\phi dP_T$ with the QCD hard scattering predictions of HERWIG 6.4 (default parameters with $P_T$(hard)>3 GeV/c. Shows how the “transverse” charge particle density is distributed in $P_T$. 

CDF Data

data uncorrected
theory corrected

1.8 TeV $|\eta|<1$ $P_T>0.5$ GeV

Herwig 6.4 CTEQ5L

$P_T$(hard) > 3 GeV/c

$P_T$(hard) > 5 GeV/c

$P_T$(hard) > 30 GeV/c

CDF Data

data uncorrected
theory corrected

1.8 TeV $|\eta|<1$ $P_T>0.5$ GeV

1.8 TeV $|\eta|<1$ $P_T>0.5$ GeV

$P_T$(hard) > 3 GeV/c

$P_T$(hard) > 5 GeV/c

$P_T$(hard) > 30 GeV/c

Herwig 6.4 CTEQ5L

$P_T$(hard) > 3 GeV/c

$P_T$(hard) > 5 GeV/c

$P_T$(hard) > 30 GeV/c

Herwig $P_T$(chgjet#1) > 5 GeV/c 
$<dN_{chg}/d\eta d\phi> = 0.40$

Herwig $P_T$(chgjet#1) > 30 GeV/c
$<dN_{chg}/d\eta d\phi> = 0.51$

Fermilab MC Workshop
Rick Field - Florida/CDF
October 4, 2002
Plot shows the $P_T$ dependence of the “transverse” charged particle density compared to the QCD hard scattering predictions of HERWIG 6.4 (default parameters with $P_T$(hard)>3 GeV/c).

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”).

Both HERWIG’s “soft” Min-Bias model and HERWIG’s model for the “beam-beam remnants” do not produce enough high $P_T$ hadrons (i.e. they are both too “soft”).
The CDF “Min-Bias” data describe the “beam-beam” remnants better than HERWIG! But the CDF “Min-Bias” data contain a hard scattering component and hence maybe the “beam-beam remnants” have a hard scattering component (i.e. multiple parton interactions).
Pythia uses multiple parton interactions to enhance the underlying event.

### PYTHIA: Multiple Parton Interaction Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTP(81)</td>
<td>0</td>
<td>Multiple-Parton Scattering off</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Multiple-Parton Scattering on</td>
</tr>
<tr>
<td>MSTP(82)</td>
<td>1</td>
<td>Multiple interactions assuming the same probability, with an abrupt cut-off $P_{T_{min}}=\text{PARP}(81)$</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a single Gaussian matter distribution, with a smooth turn-off $P_{T_0}=\text{PARP}(82)$</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a double Gaussian matter distribution (governed by $\text{PARP}(83)$ and $\text{PARP}(84)$), with a smooth turn-off $P_{T_0}=\text{PARP}(82)$</td>
</tr>
</tbody>
</table>

Same parameter that cuts-off the hard 2-to-2 parton cross sections!

---

Measurements of multiple parton interactions in $p+p$ and $p+\bar{p}$ collisions:

- $\langle n_{\text{jets}}\rangle$ (Jet Multiplicity)
- $\langle n_{\text{muons}}\rangle$ (Muon Multiplicity)
- $\langle n_{\text{charged hadrons}}\rangle$ (Charged Hadron Multiplicity)
- $\langle n_{\text{neutral hadrons}}\rangle$ (Neutral Hadron Multiplicity)

Herwig uses a different approach to model multi-parton interactions.

Hard Core
Pythia uses multiple parton interactions to enhance the underlying event.

Multiple Parton Interactions

Outgoing Parton

Proton

Underlying Event

PT(hard)

- Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a double Gaussian matter distribution (governed by PARP(83) and PARP(84)), with a smooth turn-off $P_{T0} = PARP(82)$
- Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a single Gaussian matter distribution, with a smooth turn-off $P_{T0} = PARP(82)$
- Multiple interactions assuming the same probability, with an abrupt cut-off $P_{Tmin} = PARP(81)$

PYTHIA: Multiple Parton Interaction Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTP(81)</td>
<td>Hard Core</td>
<td>0</td>
</tr>
<tr>
<td>MSTP(82)</td>
<td>Multiple parton interaction more likely in a hard (central) collision!</td>
<td>1</td>
</tr>
</tbody>
</table>

Note that since the same cut-off parameters govern both the primary hard scattering and the secondary MPI interaction, changing the amount of MPI also changes the amount of hard primary scattering in PYTHIA Min-Bias events!
### PYTHIA: Multiple Parton Interaction Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARP(83)</td>
<td>0.5</td>
<td>Double-Gaussian: Fraction of total hadronic matter within PARP(84)</td>
</tr>
<tr>
<td>PARP(84)</td>
<td>0.2</td>
<td>Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter.</td>
</tr>
<tr>
<td>PARP(85)</td>
<td>0.33</td>
<td>Probability that the MPI produces two gluons with color connections to the “nearest neighbors.”</td>
</tr>
<tr>
<td>PARP(86)</td>
<td>0.66</td>
<td>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.</td>
</tr>
<tr>
<td>PARP(89)</td>
<td>1 TeV</td>
<td>Determines the reference energy $E_0$.</td>
</tr>
<tr>
<td>PARP(90)</td>
<td>0.16</td>
<td>Determines the energy dependence of the cut-off $P_{T0}$ as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^{\varepsilon}$ with $\varepsilon = PARP(90)$</td>
</tr>
<tr>
<td>PARP(67)</td>
<td>1.0</td>
<td>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.</td>
</tr>
</tbody>
</table>

**Hard Core**

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

**Color String**: Multiplicon interaction

**Reference point at 1.8 TeV**

**Take $E_0 = 1.8$ TeV**

**Hard-Scattering Cut-Off $P_{T0}$**

$\varepsilon = 0.25$ (Set A)

$\varepsilon = 0.16$ (default)
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.

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

Note Change
PARP(67) = 4.0 ($< 6.138$)
PARP(67) = 1.0 ($> 6.138$)
Plot shows the “Transverse” charged particle density versus $P_T$(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set D (PARP(67)=1) and Set C (PARP(67)=4)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune D</th>
<th>Tune C</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTP(81)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MSTP(82)</td>
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<td>3</td>
</tr>
<tr>
<td>PARP(82)</td>
<td>1.6 GeV</td>
<td>1.7 GeV</td>
</tr>
<tr>
<td>PARP(85)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>PARP(86)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>PARP(89)</td>
<td>1.8 TeV</td>
<td>1.8 TeV</td>
</tr>
<tr>
<td>PARP(90)</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>PARP(67)</td>
<td>1.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Plot shows the “Transverse” charged particle density versus $P_T(chgjet#1)$ compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

**Tuned PYTHIA 6.206**

**PYTHIA 6.206 CTEQ5L**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune B</th>
<th>Tune A</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTP(81)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MSTP(82)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>PARP(82)</td>
<td>1.9 GeV</td>
<td>2.0 GeV</td>
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<tr>
<td>PARP(83)</td>
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<td>0.5</td>
</tr>
<tr>
<td>PARP(84)</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>PARP(85)</td>
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<td>0.9</td>
</tr>
<tr>
<td>PARP(86)</td>
<td>1.0</td>
<td>0.95</td>
</tr>
<tr>
<td>PARP(89)</td>
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<td>1.8 TeV</td>
</tr>
<tr>
<td>PARP(90)</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>PARP(67)</td>
<td>1.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Corrected 11/4/02

Old PYTHIA default (more initial-state radiation)

New PYTHIA default (less initial-state radiation)

PDF Preliminary data uncorrected

theory corrected

CTEQ5L

PYTHIA 6.206 (Set A)

PARP(67)=1

1.8 TeV $|\eta|<1.0$ PT>0.5 GeV

Double Gaussian

"Transverse" Charged Particle Density: $dN/d\eta d\phi$
Plots show CDF data on the charge particle density and the charged PT$_{\text{sum}}$ density in the "transverse" region.

The data are compared with the QCD Monte-Carlo predictions of HERWIG 6.4 (CTEQ5L, P_T(hard) > 3 GeV/c) and two tuned versions of PYTHIA 6.206 (P_T(hard) > 0).
Plots shows CDF data on the charge particle density and the charged $P_T^{\text{sum}}$ density in the MAX/MIN “transverse” region.

The data are compared with the QCD Monte-Carlo predictions of HERWIG 6.4 (CTEQ5L, $P_T^{\text{hard}} > 3$ GeV/c) and two tuned versions of PYTHIA 6.206 ($P_T^{\text{hard}} > 0$).
Compares the average “transverse” charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$(charged jet#1) and the $P_T$ distribution of the “transverse” density, $dN_{chg}/d\eta d\phi dP_T$ with the QCD Monte-Carlo predictions of two tuned versions of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).
"Transverse" Charged Particle Density: $dN/d\eta d\phi$

CDF Preliminary data uncorrected
theory corrected

PYTHIA 6.206 Set A
CTEQ5L

Describes the rise from "Min-Bias" to "underlying event"!

"Transverse" Charged Particle Density

Pythia 6.206 Set A
PDF Min-Bias

CDF Published

"Min-Bias" collision!

Compares the average "transverse" charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$ (charged jet#1) and the $P_T$ distribution of the "transverse" and "Min-Bias" densities with the QCD Monte-Carlo predictions of a tuned version of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set A). Describes "Min-Bias" collisions! Describes the "underlying event"!
Describes the rise from “Min-Bias” to “underlying event”!

CDF Preliminary data uncorrected theory corrected

PYTHIA 6.206 Set A

CTEQ5L

1.8 TeV | |<1 PT>0.5 GeV

CDF Min-Bias

"Transverse" Charged Particle Density: dN/dηdφ

"Transverse" Charged Particle Density

CDF Preliminary

data uncorrected

theory corrected

PYTHIA 6.206 Set A

CTEQ5L

1.8 TeV | |<1.0 PT>0.5 GeV

CDF Min-Bias

"Transverse" PT(chgjet#1) > 0 GeV/c

"Transverse" PT(chgjet#1) > 30 GeV/c

"Transverse" <dNchg/dηdφ> = 0.60

Set A P_T(charged jet#1) > 30 GeV/c

"Transverse" <dNchg/dηdφ> = 0.24

Set A Min-Bias

besides the average “transverse” charge particle density (|η|<1, P_T>0.5 GeV) versus
P_T(charged jet#1) and the P_T distribution of the “transverse” and “Min-Bias” densities with
the QCD Monte-Carlo predictions of a tuned version of PYTHIA 6.206 (P_T(hard) > 0,
CTEQ5L, Set A). Describes “Min-Bias” collisions! Describes the “underlying event”!

Fermilab MC Workshop

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October 4, 2002

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True “Transverse” Particle Density at 1.8 TeV

- Shows the average “transverse” charge particle density ($|\eta|<1$, $P_T>0.5$ GeV, corrected) and the true ($|\eta|<1$, $P_T>0$) “transverse” charged particle density, $dN_{chg}/d\eta d\phi$ predicted by HERWIG 6.4 ($P_T$(hard) > 3 GeV/c, CTEQ5L) and two tuned versions of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set A & Set C).

- There are roughly 1.4 charged particles per unit $\eta$-$\phi$ ($P_T>0$) in the “transverse” region compared to 0.67 for a typical CDF “Min-Bias” collision (9 charged particles per unit $\eta$ compared to 4).
**True “Transverse” PT$_{\text{sum}}$ Density at 1.8 TeV**

- Shows the average “transverse” charge PT$_{\text{sum}}$ density ($|\eta|<1$, P$_T$>0.5 GeV, corrected) and the true ($|\eta|<1$, P$_T$>0) “transverse” charged PT$_{\text{sum}}$ density, dPT$_{\text{sum}}$/d$\eta$d$\phi$ predicted by HERWIG 6.4 (P$_T$(hard) > 3 GeV/c, CTEQ5L) and two tuned versions of PYTHIA 6.206 (P$_T$(hard) > 0, CTEQ5L, Set A & Set C).

- There is roughly 1 GeV/c per unit $\eta$-$\phi$ (P$_T$ > 0) from charged particles in the “transverse” region for P$_T$(chgjet#1) = 35 GeV/c. Note, however, that the “transverse” charged PT$_{\text{sum}}$ density increases rapidly as P$_T$(chgjet#1) increases.

1.5 GeV/c (charged) in cone of radius R=0.7 at 1.8 TeV
"Transverse" Charged Densities
Energy Dependence

Shows the “transverse” charge particle density and charged PT$_{sum}$ density (|$\eta$|<1, PT>0.5 GeV) versus PT(charged jet#1) at 1.8 TeV and 630 GeV predicted by HERWIG 6.4 (PT(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (PT(hard) > 0, CTEQ5L, Set A, $\varepsilon = 0$ and $\varepsilon = 0.16$ (default)).
"Transverse" Charged Densities
Energy Dependence

shows the "transverse" charged particle density and charged PT sum density (|η|<1, PT>0.5 GeV) versus PT(charged jet#1) at 1.8 TeV and 630 GeV predicted by HERWIG 6.4 (PT(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (PT(hard) > 0, CTEQ5L, Set A, ε = 0 and ε = 0.16 (default)).

A constant PT0 (i.e. ε=0) gives a large cut-off at 630 GeV and less activity in the UE resulting in a large energy dependence.

Lowering PT0 at 630 GeV (i.e. increasing ε) increases UE activity resulting in less energy dependence.

Reference point E0 = 1.8 TeV
"Transverse" Cones vs "Transverse" Regions

- Sum the $P_T$ of charged particles in two cones of radius 0.7 at the same $\eta$ as the leading jet but with $|\Delta \Phi| = 90^\circ$.
- Plot the cone with the maximum and minimum $P_T$ versus the $E_T$ of the leading (calorimeter) jet.

CDF PRELIMINARY

E_T of leading jet (GeV)

$P_T$ (GeV/c)

"Cone Analysis" (Tano, Kovacs, Huston, Bhatti)
Sum the $P_T$ of charged particles ($P_T > 0.4$ GeV/c) in two cones of radius 0.7 at the same $\eta$ as the leading jet but with $|\Delta \phi| = 90^\circ$. Plot the cone with the maximum and minimum $P_T_{\text{sum}}$ versus the $E_T$ of the leading (calorimeter) jet.

Note that PYTHIA 6.115 is tuned at 630 GeV with $P_{T0} = 1.4$ GeV and at 1,800 GeV with $P_{T0} = 2.0$ GeV. This implies that $\varepsilon = \text{PARP}(90)$ should be around 0.3 instead of the 0.16 (default).

For the MIN cone 0.25 GeV/c in radius $R = 0.7$ implies a $P_T_{\text{sum}}$ density of $dP_T_{\text{sum}}/d\eta d\phi = 0.16$ GeV/c and 1.4 GeV/c in the MAX cone implies $dP_T_{\text{sum}}/d\eta d\phi = 0.91$ GeV/c (average $P_T_{\text{sum}}$ density of 0.54 GeV/c per unit $\eta-\phi$).
"Transverse" Charged Densities
Energy Dependence

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

Also shown are the PT\textsubscript{sum} densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano cone analysis at 630 GeV.
Showed the "transverse" charged PT sum density (|η|<1, PT>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, ε = 0, ε = 0.16 (default) and ε = 0.25 (preferred)).

Also shown are the PT_sum densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano cone analysis at 630 GeV.

Increasing ε produces less energy dependence for the UE resulting in less UE activity at the LHC.

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

Reference point E_0 = 1.8 TeV
Tuned PYTHIA (Set A) LHC Predictions

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

**Transverse** Charged PTsum Density: $dPTsum/d\eta d\phi$

- Shows the average “transverse” charge particle and PT$_{\text{sum}}$ density ($|\eta|<1$, $P_T>0$) versus $P_T$ (charged jet#1) predicted by HERWIG 6.4 ($P_T$ (hard) > 3 GeV/c, CTEQ5L), and a tuned versions of PYTHIA 6.206 ($P_T$ (hard) > 0, CTEQ5L, Set A) at 1.8 TeV and 14 TeV.

- At 14 TeV tuned PYTHIA (Set A) predicts roughly 2.3 charged particles per unit $\eta$-$\phi$ ($P_T > 0$) in the “transverse” region (14 charged particles per unit $\eta$) which is larger than the HERWIG prediction.

- At 14 TeV tuned PYTHIA (Set A) predicts roughly 2 GeV/c charged PT$_{\text{sum}}$ per unit $\eta$-$\phi$ ($P_T > 0$) in the “transverse” region at $P_T$ (chgjet#1) = 40 GeV/c which is a factor of 2 larger than at 1.8 TeV and much larger than the HERWIG prediction.
Shows the average “transverse” charge particle and \( P_T^{\text{sum}} \) density \((|\eta|<1, P_T>0)\) versus \( P_T^{\text{charged jet#1}} \) predicted by HERWIG 6.4 \((P_T^{\text{hard}}>3 \text{ GeV/c}, \text{CTEQ5L})\), and a tuned version of PYTHIA 6.206 \((P_T^{\text{hard}}>0, \text{CTEQ5L}, \text{Set A})\) at 1.8 TeV and 14 TeV. Also shown is the 14 TeV prediction of PYTHIA 6.206 with the default value \( \varepsilon = 0.16 \).

Tuned PYTHIA (Set A) predicts roughly 2.3 charged particles per unit \( \eta-\phi \) \((P_T > 0)\) in the “transverse” region (14 charged particles per unit \( \eta \)) which is larger than the HERWIG prediction and much less than the PYTHIA default prediction.
Tuned PYTHIA (Set A)
LHC Predictions

Shows the average “transverse” charge particle and $P_T^{\text{sum}}$ density ($|\eta|<1, P_T>0$) versus $P_T(\text{charged jet#1})$ predicted by HERWIG 6.4 ($P_T(\text{hard}) > 3$ GeV/c, CTEQ5L), and a tuned versions of PYTHIA 6.206 ($P_T(\text{hard}) > 0$, CTEQ5L, Set A) at 1.8 TeV and 14 TeV. Also shown is the 14 TeV prediction of PYTHIA 6.206 with the default value $\varepsilon = 0.16$.

Tuned PYTHIA (Set A) predicts roughly $2.5$ GeV/c per unit $\eta-\phi$ ($P_T > 0$) from charged particles in the “transverse” region for $P_T(\text{chgjet#1}) = 100$ GeV/c. Note, however, that the “transverse” charged $P_T^{\text{sum}}$ density increases rapidly as $P_T(\text{chgjet#1})$ increases.
† Shows the center-of-mass energy dependence of the charged particle density, \( \frac{dN_{\text{chg}}}{d\eta d\phi} \), for “Min-Bias” collisions compared with the a tuned version of PYTHIA 6.206 (Set A) with \( P_T(\text{hard}) > 0 \).

† PYTHIA was tuned to fit the “underlying event” in hard-scattering processes at 1.8 TeV and 630 GeV.

† PYTHIA (Set A) predicts a 42% rise in \( \frac{dN_{\text{chg}}}{d\eta d\phi} \) at \( \eta = 0 \) in going from the Tevatron (1.8 TeV) to the LHC (14 TeV).
Tuned PYTHIA (Set A) LHC Predictions

Charged Particle Density

12% of “Min-Bias” events have $P_T(\text{hard}) > 10$ GeV/c!

Hard-Scattering in Min-Bias Events

 Shows the center-of-mass energy dependence of the charged particle density, $dN_{\text{ch}}/d\eta d\phi dP_T$, for “Min-Bias” collisions compared with the a tuned version of PYTHIA 6.206 (Set A) with $P_T(\text{hard}) > 0$.

This PYTHIA fit predicts that 1% of all “Min-Bias” events at 1.8 TeV are a result of a hard 2-to-2 parton-parton scattering with $P_T(\text{hard}) > 10$ GeV/c which increases to 12% at 14 TeV!

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October 4, 2002
The “Underlying Event”

Summary & Conclusions

- ISAJET (with independent fragmentation) produces too many (soft) particles in the “underlying event” with the wrong dependence on $P_T(jet#1)$. HERWIG and PYTHIA modify the leading-log picture to include “color coherence effects” which leads to “angle ordering” within the parton shower and do a better job describing the “underlying event”.

- Both ISAJET and HERWIG have the too steep of a $P_T$ dependence of the “beam-beam remnant” component of the “underlying event” and hence do not have enough beam-beam remnants with $P_T > 0.5$ GeV/c.

- The CDF “Min-Bias” data describes the “beam-beam remnants” better than HERWIG does. Adding HERWIG’s initial & final state radiation to the CDF “Min-Bias” data comes close to describing the “underlying event”, but the CDF “Min-Bias” data contain a lot of “hard” scatterings. Thus, maybe the “beam-beam remnants” also contain “hard” scatterings (i.e. multiple parton collisions).
Multiple parton interactions gives a natural way of explaining the increased activity in the “underlying event” in a hard scattering. A hard scattering is more likely to occur when the hard cores overlap and this is also when the probability of a multiple parton interaction is greatest. For a soft grazing collision the probability of a multiple parton interaction is small.

PYTHIA (with varying impact parameter) does a good job fitting the “underlying event” data and also describes fairly well the “Min-Bias” data with the same program \( P_T^{(\text{hard})} > 0 \).

A. Moraes, I. Dawson, and C. Buttar (University of Sheffield) have also been working on tuning PYTHIA to fit the underlying event using the CDF data with the goal of extrapolating to the LHC.

Also check out Jon Butterworth’s JETWEB at http://jetweb.hep.ucl.ac.uk/Results/MI/.
Both HERWIG and the tuned PYTHIA (Set A) predict a 40-45% rise in \( \frac{dN_{\text{chg}}}{d\eta d\phi} \) at \( \eta = 0 \) in going from the Tevatron (1.8 TeV) to the LHC (14 TeV). 4 charged particles per unit \( \eta \) at the Tevatron becomes 6 per unit \( \eta \) at the LHC.

The tuned PYTHIA (Set A) predicts that 1% of all “Min-Bias” events at the Tevatron (1.8 TeV) are the result of a hard 2-to-2 parton-parton scattering with \( P_T(\text{hard}) > 10 \) GeV/c which increases to 12% at LHC (14 TeV)!

For the “underlying event” in hard scattering processes the predictions of HERWIG and the tuned PYTHIA (Set A) differ greatly (factor of 2!). HERWIG predicts a smaller increase in the activity of the “underlying event” in going from the Tevatron to the LHC.

The tuned PYTHIA (Set A) predicts about a factor of two increase at the LHC in the charged \( P_T_{\text{sum}} \) density of the “underlying event” at the same \( P_T(\text{jet#1}) \) (the “transverse” charged \( P_T_{\text{sum}} \) density increases rapidly as \( P_T(\text{jet#1}) \) increases).
Both HERWIG and the tuned PYTHIA (Set A) predict a 40-45% rise in $dN/d\eta$ at $\eta = 0$ in going from the Tevatron (1.8 TeV) to the LHC (14 TeV). 4 charged particles per unit $\eta$ at the Tevatron becomes 6 per unit $\eta$ at the LHC.

The tuned PYTHIA (Set A) predicts that 1% of all “Min-Bias” events at the Tevatron (1.8 TeV) are the result of a hard 2-to-2 parton-parton scattering with $P_T^{(hard)} > 10$ GeV/c which increases to 12% at LHC (14 TeV).

For the “underlying event” in hard scattering processes the predictions of HERWIG and the tuned PYTHIA (Set A) differ greatly (factor of 2!). HERWIG predicts a smaller increase in the activity of the “underlying event” in going from the Tevatron to the LHC.

The tuned PYTHIA (Set A) predicts about a factor of two increase at the LHC in the charged $P_T^{\text{sum}}$ density of the “underlying event” at the same $P_T^{(\text{jet}\#1)}$ (the “transverse” charged $P_T^{\text{sum}}$ density increases rapidly as $P_T^{(\text{jet}\#1)}$ increases).
Both HERWIG and the tuned PYTHIA (Set A) predict a 40-45% rise in $\frac{dN_{\text{ch}}}{d\eta}$ $\phi$ at $\eta = 0$ in going from the Tevatron (1.8 TeV) to the LHC (14 TeV). 4 charged particles per unit $\eta$ at the Tevatron becomes 6 per unit $\eta$ at the LHC.

The tuned PYTHIA (Set A) predicts that 1% of all “Min-Bias” events at the Tevatron (1.8 TeV) are the result of a hard 2-to-2 parton-parton scattering with $P_T(\text{hard}) > 10$ GeV/c which increases to 12% at LHC (14 TeV).

For the “underlying event” in high energy hard scattering events at the LHC the predictions of HERWIG and the tuned PYTHIA (Set A) disagree greatly (factor of 2!). HERWIG predicts a smaller increase in the activity of the underlying event in going from the Tevatron to the LHC.

The tuned PYTHIA (Set A) predicts a factor of two increase at the LHC in the charged $P_T\text{sum}$ density of the “underlying event” at the same $P_T(\text{jet#1})$ (the “transverse” charged $P_T\text{sum}$ density increases rapidly as $P_T(\text{jet#1})$ increases).