What happens when a proton and an antiproton collide with a center-of-mass energy of 2 TeV?

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.

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

The “underlying event” is everything except the two outgoing hard scattered “jets”. It is an unavoidable background to many collider observables.
Studying the “Underlying Event” at CDF

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 two CDF analyses which quantitatively study the underlying event and compare with the QCD Monte-Carlo models.

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 (zero-bias) collisions.
Evolution of Charged Jets

"Underlying Event"

Charged Particle $\Delta \phi$ Correlations

$P_T > 0.5$ GeV/c $|\eta| < 1$

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, $\Delta \eta \times \Delta \phi = 2 \times 120^\circ = 4\pi/3$. 
Data on the average number of “toward” ($|\Delta\phi|<60^\circ$), “transverse” ($60^\circ<|\Delta\phi|<120^\circ$), and “away” ($|\Delta\phi|>120^\circ$) charged particles ($P_T > 0.5$ GeV, $|\eta| < 1$, including jet#1) as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the $<N_{chg}>$ 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.
"Transverse" P_T Distribution

Comparison of the "transverse" \langle N_{ch}\rangle versus P_T(charged jet#1) with the P_T distribution of the "transverse" \langle N_{ch}\rangle. The integral of dN_{ch}/dP_T is the "transverse" \langle N_{ch}\rangle. Shows how the "transverse" \langle N_{ch}\rangle is distributed in P_T.
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).

However the “soft” component is color connected to the “hard” component so this separation is (at best) an approximation.

For ISAJET (no color flow) the “soft” and “hard” components are completely independent and the model for the beam-beam remnant component is the same as for min-bias (“cut pomeron”) but with a larger \(p_T\).

HERWIG breaks the color connection with a soft q-qbar pair and then models the beam-beam remnant component the same as HERWIG min-bias (cluster decay).
Plot shows the “transverse” $\langle N_{\text{ch}} \rangle$ vs $P_T(\text{chgjet#1})$ compared to the QCD hard scattering predictions of ISAJET 7.32 (default parameters with $P_T(\text{hard})>3$ 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).
Plot shows the “transverse” \(<N_{\text{chg}}>/vs P_T(\text{chgjet#1})\) compared to the QCD hard scattering predictions of HERWIG 5.9 (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).
Data on the “transverse” $<N_{ch_g}>$ versus $P_T(\text{charged jet#1})$ and the $P_T$ distribution of the “transverse” $<N_{ch_g}>$, $dN_{ch_g}/dP_T$, compared with the QCD Monte-Carlo predictions of HERWIG 5.9 (default parameters with with $P_T(\text{hard}) > 3 \text{ GeV/c}$). The integral of $dN_{ch_g}/dP_T$ is the “transverse” $<N_{ch_g}>$. 

$P_T(\text{charged jet#1}) > 5 \text{ GeV/c} \quad \Rightarrow \quad \text{“Transverse” } <N_{ch_g}> = 1.7$ 

$P_T(\text{charged jet#1}) > 30 \text{ GeV/c} \quad \Rightarrow \quad \text{“Transverse” } <N_{ch_g}> = 2.2$
PYTHIA models the “soft” component of the underlying event with color string fragmentation, but in addition includes a contribution arising from multiple parton interactions (MPI) in which one interaction is hard and the other is “semi-hard”.

The probability that a hard scattering events also contains a semi-hard multiple parton interaction can be varied but adjusting the cut-off for the MPI.

One can also adjust whether the probability of a MPI depends on the $P_T$ of the hard scattering, $P_T$(hard) (constant cross section or varying with impact parameter).

One can adjust the color connections and flavor of the MPI (singlet or nearest neighbor, q-qbar or glue-glue).

Also, one can adjust how the probability of a MPI depends on $P_T$(hard) (single or double Gaussian matter distribution).
Pythia uses multiple parton interactions to enhance the underlying event.

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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Multiple interactions assuming the same probability, with an abrupt cut-off $P_T_{min}=\text{PARP}(81)$</td>
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<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 $P_{T0}=\text{PARP}(82)$</td>
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<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 $P_{T0}=\text{PARP}(82)$</td>
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Plot shows the “transverse” $<N_{\text{ch}}>$ vs $P_T(\text{charged jet#1})$ compared to the QCD hard scattering predictions of PYTHIA 6.115 (default parameters with $P_T(\text{hard})>3$ GeV/c).

The predictions of PYTHIA are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants including multiple parton interactions); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).
QCD hard scattering predictions of HERWIG 5.9, ISAJET 7.32, and PYTHIA 6.115.

Plot shows the “transverse” \( <N_{\text{chg}} > \) vs \( P_T(\text{charged jet#1}) \) arising from the outgoing jets plus initial and final-state radiation (hard scattering component).

HERWIG and PYTHIA modify the leading-log picture to include “color coherence effects” which leads to “angle ordering” within the parton shower. Angle ordering produces less high \( P_T \) radiation within a parton shower.

DPF2002

Rick Field - Florida/CDF

May 25, 2002
Plot shows “Transverse” $<N_{\text{chg}}>$ versus $P_T(\text{charged jet#1})$ compared to the QCD hard scattering predictions of PYTHIA with $P_T(\text{hard}) > 3$ GeV.

- **PYTHIA 6.115:** GRV94L, MSTP(82)=1, $P_T\text{min}=\text{PARP}(81)=1.4$ GeV/c.
- **PYTHIA 6.125:** GRV94L, MSTP(82)=1, $P_T\text{min}=\text{PARP}(81)=1.9$ GeV/c.
- **PYTHIA 6.115:** GRV94L, MSTP(81)=0, no multiple parton interactions.

**PYTHIA default parameters**

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Constant Probability Scattering

No multiple scattering
 PYTHIA defaults

Multiple Parton Interactions

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Plot shows “Transverse” \( \langle N_{chg} \rangle \) versus PT(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA 6.206 \( (P_T(\text{hard}) > 0) \) 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 “transverse” $<N_{\text{chg}}>$ versus PT(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA with $P_T^{\text{hard}} > 0$ GeV/c.

- PYTHIA 6.115: GRV94L, MSTP(82)=1, $P_T^{\text{min}}=\text{PARP}(81)=1.4$ GeV/c.
- PYTHIA 6.115: CTEQ3L, MSTP(82)=1, $P_T^{\text{min}}=\text{PARP}(81)=1.4$ GeV/c.
- PYTHIA 6.115: CTEQ3L, MSTP(82)=1, $P_T^{\text{min}}=\text{PARP}(81)=0.9$ GeV/c.

Note: Multiple parton interactions depend sensitively on the PDF’s!
Plot shows “transverse” \(<N_{\text{chg}}\) versus PT(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA with \(P_T\text{(hard)} > 0\) GeV/c.

- PYTHIA 6.115: CTEQ4L, MSTP(82)=4, \(P_{T0}=\text{PARP}(82)=1.55\) GeV/c.
- PYTHIA 6.115: CTEQ3L, MSTP(82)=4, \(P_{T0}=\text{PARP}(82)=1.55\) GeV/c.
- PYTHIA 6.115: CTEQ4L, MSTP(82)=4, \(P_{T0}=\text{PARP}(82)=2.4\) GeV/c.
Plot shows “transverse” $<N_{chg}>$ versus $P_T(chgjet#1)$ compared to the QCD hard scattering predictions of PYTHIA with $P_T(hard) > 0$ GeV/c.

- **PYTHIA 6.115**: CTEQ4L, MSTP(82)=3, $P_{T0}=PARP(82)=1.8$ GeV/c.
- **PYTHIA 6.115**: CTEQ4L, MSTP(82)=4, $P_{T0}=PARP(82)=2.4$ GeV/c.

Describes correctly the rise from soft-collisions to hard-collisions!
Plot shows “transverse” \(<N_{\text{chg}}\) versus PT(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA 6.115 and PYTHIA 6.206 (P_T(hard) > 0 GeV/c).

- **PYTHIA 6.115**: CTEQ4L, MSTP(82)=4, P_T0=PARP(82)=2.4 GeV/c, PARP(67)=4.0.
- **PYTHIA 6.206**: CTEQ4L, MSTP(82)=4, P_T0=PARP(82)=2.4 GeV/c, PARP(67)=1.0.

PYthia 6.206 not the same as Pythia 6.115 due to PARP(67)!

Governs the amount of large angle initial-state radiation!
PYTHIA 6.206: “Transverse” PTsum vs P_T(chgjet#1)

Plot shows “transverse” $<\text{PT}_{\text{sum}}>$ versus PT(charged jet#1) compared to the QCD hard scattering predictions of PYTHIA 6.115 and PYTHIA 6.206 ($P_T(\text{hard}) > 0$ GeV/c).

- **PYTHIA 6.115**: CTEQ4L, MSTP(82)=4, $P_T0=\text{PARP}(82)=2.4$ GeV/c, $\text{PARP}(67)=4.0$.
- **PYTHIA 6.206**: CTEQ4L, MSTP(82)=4, $P_T0=\text{PARP}(82)=2.4$ GeV/c, $\text{PARP}(67)=1.0$.

Pythia 6.206 not the same as Pythia 6.115 due to PARP(67)!

Governed by $\text{PARP}(67)$.

Pythia 6.206 not the same as Pythia 6.115 due to PARP(67)!

Governed by $\text{PARP}(67)$.
Tuned PYTHIA: “Transverse” $P_T$ Distribution

Data on the “transverse” $<N_{chg}>$ versus $P_T(\text{charged jet#1})$ and the $P_T$ distribution of the “transverse” $<N_{chg}>$, $dN_{chg}/dP_T$, compared with the QCD Monte-Carlo predictions of PYTHIA 6.115 with $P_T(\text{hard}) > 0$ GeV/c, CTEQ4L, MSTP(82)=4, $P_T0=\text{PARP}(82)=2.4$ GeV/c. The integral of $dN_{chg}/dP_T$ is the “transverse” $<N_{chg}>$. 

$P_T(\text{charged jet#1}) > 30$ GeV/c 
“Transverse” $<N_{chg}> = 2.7$

$P_T(\text{charged jet#1}) > 5$ GeV/c 
“Transverse” $<N_{chg}> = 2.3$

Includes Multiple Parton Interactions
Data on the “transverse” $\langle N_{\text{chg}} \rangle$ versus $P_T$ (charged jet#1) and the $P_T$ distribution of the “transverse” $\langle N_{\text{chg}} \rangle$, $dN_{\text{chg}}/dP_T$, compared with the QCD Monte-Carlo predictions of PYTHIA 6.115 (CTEQ4L, MSTP(82)=4, $P_T^0=\text{PARP}(82)=2.4$ GeV/c, PARP(67)=4.0) and PYTHIA 6.206 (CTEQ4L, MSTP(82)=4, $P_T^0=\text{PARP}(82)=2.4$ GeV/c, PARP(67)=1.0).
Combining the two CDF analyses gives a quantitative study of the underlying event from very soft collisions to very hard collisions.

- **ISAJET** (with independent fragmentation) produces too many (soft) particles in the underlying event with the wrong dependence on $P_{T}(\text{jet#1})$. **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 $P_{T} > 0.5 \text{ GeV/c}$.

- **PYTHIA** (with multiple parton interactions) does the best job in describing the underlying event.

- Perhaps the multiple parton interaction approach is correct or maybe we simply need to improve the way the Monte-Carlo models handle the beam-beam remnants (or both!).
The increased activity in the underlying event in a hard scattering over a soft collision cannot be explained by initial-state radiation.

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) describes the underlying event data fairly well. However, there are problems in fitting min-bias events with this approach.

A. Moraes, I. Dawson, and C. Buttar (University of Sheffield) have also been working on tuning PYTHIA 6.2 (CTEQ5L, MSTP(82)=4, PARP(82)=2.2, PARP(67)=1.0?) to fit the underlying event using the CDF data with the goal of extrapolating to the LHC.