Outline of Talk

⇒ **The Past:** Feynman-Field Fenomenology (1973-1980).

7 GeV $\pi^0$'s to 400 GeV “jets”

⇒ **The Present:** Studying “Min-Bias” and the “Underlying Event” at CDF.


Many people have contributed to our understanding of hadron-hadron collisions! I will say a few words about Feynman’s influence on the field.

My 1st graduate student!

Feynman-Field Fenomenology

1973-1980

What happens when two hadrons collide at high energy?

Most of the time the hadrons 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 large transverse momentum meson. Question: Where did it come from?

We assumed it came from quark-quark elastic scattering, but we did not know how to calculate it!

“Black-Box Model”
What happens when two hadrons collide at high energy?

Most of the time the hadrons 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 large transverse momentum meson. Question: Where did it come from?

We assumed it came from quark-quark elastic scattering, but we did not know how to calculate it!

Feynman quote from FF1:

“The model we shall choose is not a popular one, so that we will not duplicate too much of the work of others who are similarly analyzing various models (e.g. constituent interchange model, multiperipheral models, etc.). We shall assume that the high $P_T$ particles arise from direct hard collisions between constituent quarks in the incoming particles, which fragment or cascade down into several hadrons.”

“Black-Box Model”
Quark Distribution Functions
determined from deep-inelastic lepton-hadron collisions

Quark Fragmentation Functions
determined from e⁺e⁻ annihilations.

Quark-Quark Cross-Section
Unknown! Determined from hadron-hadron collisions.

FF1 1977 (preQCD)

No gluons!
Fermilab Wine & Cheese  
October 4, 2002

Quark-Distribution Functions  
determined from deep-inelastic  
lepton-hadron collisions

Quark-Quark Cross-Section  
Unknown! Determined from  
hadron-hadron collisions.

Feynman quote from FF1:  
“Because of the incomplete knowledge of  
our functions some things can be predicted  
with more certainty than others. Those  
experimental results that are not well  
predicted can be “used up” to determine  
these functions in greater detail to permit  
better predictions of further experiments.  
Our papers will be a bit long because we  
wish to discuss this interplay in detail.”

No gluons!

Quark-Quark Black-Box Model

FF1 1977 (preQCD)

Quark Fragmentation Functions  
determined from e⁺e⁻ annihilations

Rick Field - Florida/CDF
Quark-Quark
Black-Box Model

FF1 1977 (preQCD)

Predict particle ratios

Predict increase with increasing CM energy W

Predict overall event topology (FFF1 paper 1977)
Telegram from Feynman

July 1976

SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE
FY

SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE
FEYNMAN
Letter from Feynman

July 1976

Feynman
ECOLE D'ETE
DE PHYSIQUE THEORIQUE
F - 74310 LES HOCHES

Prof. Rick Field
High Energy Physics
California Institute of Technology
1201 California St.
PASADENA, CALIF. 91100
ETATS UNIS
July 22, 1976

Dear Rick,

If you got my telegram you know how

unreservedly I am by what I learned from Bronie and

from your letter (which I got). We must proceed with

all speed to write it up and I will come in to see

you next week.

Before I left, you gave me a figure for

... which works out...
It is fun!

It is fun.
Because mail here is blocked up in France, try a telegram. Here's address:
ECOLE D'ETE DE PHYSIC
F-74310 LES HOUCHE

just read the number for A in $2\pi/2 = A/sqrt{2}$. Instead it is for $8\pi^2$ say B is 2700 mb, whatever. Just a few words.

Onward,

Dick Feynman.
\[
\int_0^1 \frac{d\bar{z}}{1-\bar{z}} \ln f(\bar{z}) = \left( \int_0^1 \frac{d\bar{z}}{1-\bar{z}} \ln \frac{f(\bar{z})}{F(\bar{z})} \right) + \int_0^1 \frac{d\bar{z}}{1-\bar{z}} \ln f(\bar{z})
\]

\[\text{approximate if } \bar{z} \text{ is not near} \]

\[
\int_0^\infty \frac{dx}{x} \ln \frac{f(x)}{F(x)}
\]
QCD Approach
Quarks & Gluons

Parton Distribution Functions
Q^2 dependence predicted from QCD

Quark & Gluon Fragmentation Functions
Q^2 dependence predicted from QCD

Quark & Gluon Cross-Sections
Calculated from QCD

FFF2 1978

Fermilab Wine & Cheese
October 4, 2002

Rick Field - Florida/CDF

Page 14
Quark & Gluon Fragmentation Functions
Q^2 dependence predicted from QCD

Parton Distribution Functions
Q^2 dependence predicted from QCD

Quark & Gluon Cross-Sections
Calculated from QCD

Feynman quote from FFF2:
“We investigate whether the present experimental behavior of mesons with large transverse momentum in hadron-hadron collisions is consistent with the theory of quantum-chromodynamics (QCD) with asymptotic freedom, at least as the theory is now partially understood.”
QCD Approach
Quarks & Gluons

Feynman quote from FFF2:
“At the time of this writing, there is still no sharp quantitative test of QCD. An important test will come in connection with the phenomena of high $P_T$ discussed here.”

Predict large “jet” cross-section

30 GeV!
CDF Run II DiJet Event
July 2002

Raw $E_T$ values!!

$E_T^{\text{jet1}} = 403$ GeV
$E_T^{\text{jet2}} = 322$ GeV
Monte-Carlo Simulation of Hadron-Hadron Collisions

FF1-FFF1 (1977)  
"Black-Box" Model

F1-FFF2 (1978)  
QCD Approach

FF2 (1978)  
Monte-Carlo simulation of “jets”

FFFW “FieldJet” (1980)  
QCD “leading-log order” simulation of hadron-hadron collisions

the past

today

ISAJET  
("FF" Fragmentation)

HERWIG  
("FW" Fragmentation)

PYTHIA

“FF” or “FW” Fragmentation
Monte-Carlo Simulation of Hadron-Hadron Collisions

F1-FFF1 (1977) ‘Black-Box’ Model

FF2 (1978) Monte-Carlo Simulation of ‘jets’

Monte-Carlo simulation of ‘jets’

F1-FFF2 (1978) QCD Approach

ISAJET
(‘FF’ Fragmentation)

HERWIG
(‘FW’ Fragmentation)

PYTHIA

Feynman quote from FF2:
“The predictions of the model are reasonable enough physically that we expect it may be close enough to reality to be useful in designing future experiments and to serve as a reasonable approximation to compare to data. We do not think of the model as a sound physical theory, ....”

the past
today

“FF” or “FW” Fragmentation
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.
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.
Studying the “Underlying Event” at CDF

The Underlying Event:
- beam-beam remnants
- initial-state radiation
- multiple-parton interactions

- 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.

Run I CDF
“Evolution of Charged Jets”
Rick Field
David Stuart
Rich Haas

Run I CDF
“Cone Analysis”
Valeria Tano
Eve Kovacs
Joey Huston
Anwar Bhatti

Run II CDF
“Jet Shapes & Energy Flow”
Mario Martinez
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: 78mb = 18mb + 9mb + (4-7)mb + (47-44)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

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

Single Diffraction

Double Diffraction

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

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

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

CDF “Min-Bias” trigger
1 charged particle in forward BBC
AND
1 charged particle in backward BBC

“Hard” Hard Core (hard scattering)

Beam-Beam Counters
3.2 < |\( \eta \) | < 5.9

Fermilab Wine & Cheese
October 4, 2002

Rick Field - Florida/CDF
Page 24
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 remnant" 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!

Are these the same?

The "beam-beam remnant" component is, however, color connected to the "hard" component so this comparison is (at best) an approximation.

Maybe not all "soft"!
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, $dN_{chg}/d\eta d\phi$, 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, \( \frac{dN_{\text{chg}}}{d\eta d\phi} \), 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?

\[ \langle \frac{dN_{\text{chg}}}{d\eta d\phi} \rangle = 0.51 \quad \eta = 0 \quad 630 \text{ GeV} \]

\[ \langle \frac{dN_{\text{chg}}}{d\eta d\phi} \rangle = 0.63 \quad \eta = 0 \quad 1.8 \text{ TeV} \]

24% increase
Shows the center-of-mass energy dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, 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, $dN_{\text{chg}}/d\eta d\phi$, in “Min-Bias” collisions.

HERWIG “Soft” Min-Bias predicts a 45% rise in $dN_{\text{chg}}/d\eta d\phi$ 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.
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 \(P_T(\text{hard}) > 3\) 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 \(P_T(\text{hard}) > 3\) GeV/c!

One cannot run the HERWIG “hard” QCD Monte-Carlo with \(P_T(\text{hard}) < 3\) GeV/c because the perturbative 2-to-2 cross-sections diverge like \(1/P_T(\text{hard})^4\)?
PYTHIA regulates the perturbative 2-to-2 parton-parton cross sections with cut-off parameters which allows 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 of 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 regulates the perturbative 2-to-2 parton-parton cross sections with cut-off parameters, which allows 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 $P_T^{\text{hard}} > 5 \text{ GeV/c}$ (1% with $P_T^{\text{hard}} > 10 \text{ GeV/c}$)!
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 \( (P_T > 0.5 \text{ GeV}, |\eta| < 1) \) 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 \( \langle dN_{\text{chg}}/d\eta d\phi \rangle \) 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.
Charged Particle Density

"Transverse" P_T Distribution

Compared to the average "transverse" charge particle density (|\eta|<1, P_T>0.5 GeV) versus P_T(charged jet#1) with the P_T distribution of the "transverse" density, dN_{chg}/d\eta d\phi dP_T. Shows how the "transverse" charge particle density is distributed in P_T.
Charged Particle Density

**P_T Distribution**

- **Comparing 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 $P_T$.
Plot shows the “transverse” charged particle density vs $P_T(\text{chgjet#1})$ 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”).
HERWIG 6.4
“Transverse” P_T Distribution

Compares 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” density, dN_{chg}/dηdφdP_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.
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 $P_T\text{min}=\text{PARP}(81)$</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 PARP(83) and PARP(84)), with a smooth turn-off $P_{T_0}=\text{PARP}(82)$</td>
</tr>
</tbody>
</table>

Jimmy: MPI  
J. M. Butterworth  
J. R. Forshaw  
M. H. Seymour

Multiple parton interaction more likely in a hard (central) collision!
PYTHIA: Multiple Parton Interaction Parameters

Pythia uses multiple parton interactions to enhance the underlying event. Multiple parton interactions assume a varying impact parameter and a hadronic matter overlap consistent with a double Gaussian matter distribution, with a smooth turn-off $P_{T0}=\text{PARP}(82)$. Multiple interactions assuming a varying impact parameter and a single Gaussian matter distribution, with a smooth turn-off $P_{T0}=\text{PARP}(82)$, also changes the amount of hard primary scattering in PYTHIA Min-Bias events!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTP(81)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>MSTP(82)</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!
## 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)).

<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>
</tr>
<tr>
<td>PARP(83)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PARP(84)</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>PARP(85)</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>PARP(86)</td>
<td>1.0</td>
<td>0.95</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>

Corrected 11/4/02
Tuned PYTHIA 6.206 vs HERWIG 6.4

“Transverse” Densities

Plots shows CDF data on the charge particle density and the charged $P_T^{\text{sum}}$ density in the “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" 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!
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”!

CDF Preliminary data uncorrected theory corrected

Set A Min-Bias
$<dN_{chg}/d\eta d\phi> = 0.24$

Set A $P_T$(charged jet#1) > 30 GeV/c “Transverse” $<dN_{chg}/d\eta d\phi> = 0.60$
Shows the average “transverse” charge particle and PT\textsubscript{sum} density ($|\eta|<1, \text{PT}>0$) versus \text{PT}(charged jet#1) predicted by HERWIG 6.4 ($P_T^{\text{hard}} > 3 \text{ GeV/c}, \text{CTEQ5L}$), and a tuned versions of PYTHIA 6.206 ($P_T^{\text{hard}} > 0, \text{CTEQ5L, Set A}$) 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\textsubscript{sum} per unit $\eta$-\$\phi$ ($P_T > 0$) in the “transverse” region at $P_T$(chrgjet#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 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. 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$_T$(chgjet#1) = 100 GeV/c. Note, however, that the “transverse” charged PT$_{\text{sum}}$ density increases rapidly as P$_T$(chgjet#1) increases.
Tuned PYTHIA (Set A)
LHC Predictions

- Shows the center-of-mass energy dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, 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 $dN_{\text{chg}}/d\eta d\phi$ 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, $dN_{\text{chg}}/d\eta d\phi dP_T$, 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!
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 ($P_T^{(hard)} > 0$).

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 $dN_{\text{chg}}/d\eta d\phi$ 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).
LHC Predictions
Summary & Conclusions

- Both HERWIG and the tuned PYTHIA (Set A) predict a 40-45% rise in \( \frac{dN_{\text{chg}}}{d\eta} \) 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 \( PT(\text{hard}) > 10 \) 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) 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 about a factor of two increase at the LHC in the charged \( PT_{\text{sum}} \) density of the “underlying event” at the same \( PT(\text{jet#1}) \) (the “transverse” charged \( PT_{\text{sum}} \) density increases rapidly as \( PT(\text{jet#1}) \) increases).
Collider Phenomenology
From 7 GeV/c π⁰’s to 400 GeV “Jets”

NLO QCD (2002)
400 GeV “jets”

FF1 (1977)
7 GeV/c π⁰’s
Rick Field (Fermilab “Wine&Cheese”):
“At the time of this writing, there is still no sharp quantitative test of QCD. We believe it is the correct theory of strong interactions because it qualitatively describes an enormous variety and amount of data over many decades of $Q^2$.”

Feynman played an enormous role in our understanding of hadron-hadron collisions and his influence is still being felt!

FF1 (1977)
7 GeV/c $\pi^0$’s

CDF Preliminary

NLO QCD prediction (EKS)
cteq4m $\mu=\sqrt{s}/2$ $R_{sep}=1.3$

Errors Only

Transverse Energy (GeV)

Rick Field - Florida/CDF
Page 58
At the time of this writing, there is still no sharp quantitative test of QCD. We believe it is the correct theory of strong interactions because it qualitatively describes an enormous variety and amount of data over many decades of Q2.

Feynman played an enormous role in our understanding of hadron-hadron collisions and his influence is still being felt!

I enjoyed very much working with Feynman. I was lucky to have the opportunity! Now I am having a great time working on CDF!