Talk 1: What We Have Learned at the Tevatron

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Outline of Talk

► The old days of “Feynman-Field Phenomenology”.

► Review what we learned about “min-bias”, the “underlying event”, and “event topologies” in Run 1 at CDF.

► Review the CDF Run 2 “underlying event” studies in high transverse momentum jet production and in “Drell-Yan” production.

► Describe the QCD Monte-Carlo models that are used to simulate hadron-hadron collisions.

► Examine some extrapolations from the Tevatron to the LHC.
From 7 GeV/c $\pi^0$'s to 600 GeV/c Jets. The early days of trying to understand and simulate hadron-hadron collisions.
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 (no hard scattering) and the outgoing particles continue in roughly the same direction as initial proton and antiproton.

Occasionally there is 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-Quark Black-Box Model

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

FF1 1977

No gluons!

Quark Fragmentation Functions
determined from e+e- annihilations

Quark-Quark Cross-Section
Unknown! Determined from hadron-hadron collisions.
Quark-Quark Black-Box Model

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

FF1 1977

Quark Fragmentation Functions
determined from e^+e^- annihilations

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

**Predict**
particle ratios

**FF1 1977**

- **Predict** increase with increasing CM energy $W$
- Predict overall event topology (FFF1 paper 1977)

The “underlying event” (Beam-Beam Remnants)!

- **7 GeV/c $\pi^0$’s!**
Quark-Quark Black-Box Model

**Predict**
particle ratios

**FF1 1977**
Predict increase with increasing CM energy W

When Jim Cronin’s group at the University of Chicago measured these ratios and we knew we were on the right track!

7 GeV/c π°’s!

The “underlying event” (Beam-Beam Remnants)!

overall event topology (FFF1 paper 1977)
QCD Approach: Quarks & Gluons

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

FFF2 1978

TABLE 1. Cross sections for the various constituent quark-quark, quark-gluon, and gluon-gluon subprocesses. The differential cross section is given by d^2σ/dt dx, where d^2σ/dt is the effective coupling given by Eq. (3.1).
QCD Approach: Quarks & Gluons

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

Parton Distribution Functions
Q^2 dependence predicted 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.”

Quark & Gluon Cross-Sections
Calculated from QCD

FFF2 1978
High $P_T$ Jets

Feynman, Field, & Fox (1978)

CDF (2006)

Feynman quote from FFF

“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.”
- 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 quark 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 it. The “underlying event” is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!
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.
Proton-AntiProton Collisions at the Tevatron

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

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

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

“Inelastic Non-Diffractive Component”

The 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)

“Soft” Hard Core (no hard scattering)

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

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Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and form the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, and the charged scalar $p_T$ sum density, $dP_{\text{sum}}/d\eta d\phi$. 

\[
\Delta \eta \Delta \phi = 4\pi = 12.6
\]

\[
dN_{\text{chg}}/d\eta d\phi = 3/4\pi = 0.24
\]

\[
dP_{\text{sum}}/d\eta d\phi = 3/4\pi \text{ GeV/c} = 0.24 \text{ GeV/c}
\]
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 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 $p_T$).

There are about 0.25 charged particles per unit $\eta$-$\phi$ in “Min-Bias” collisions at 1.96 TeV ($|\eta| < 1$, $p_T > 0.5$ GeV/c).
Use the maximum $p_T$ charged particle in the event, $PT_{\text{max}}$, to define a direction and look at the the “associated” density, $dN_{\text{chg}}/d\eta d\phi$, in "min-bias" collisions ($p_T > 0.5$ GeV/c, $|\eta| < 1$).

Shows the data on the $\Delta\phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{\text{max}}$) relative to $PT_{\text{max}}$ (rotated to 180°) for “min-bias” events. Also shown is the average charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for "min-bias" events.
Use the maximum $p_T$ charged particle in the event, $p_{T\text{max}}$, to define a direction and look at the “associated” density, $dN_{\text{chg}}/d\eta d\phi$, in "min-bias" collisions ($p_T > 0.5 \text{ GeV/c, } |\eta| < 1$).

It is more probable to find a particle accompanying $p_{T\text{max}}$ than it is to find a particle in the central region!

"Associated" densities do not include $p_{T\text{max}}$!
Shows the data on the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{\text{max}}$) relative to $PT_{\text{max}}$ (rotated to 180°) for “min-bias” events with $PT_{\text{max}} > 0.5$, 1.0, and 2.0 GeV/c.

Shows “jet structure” in “min-bias” collisions (i.e. the “birth” of the leading two jets!).

Rapid rise in the particle density in the “transverse” region as $PT_{\text{max}}$ increases!
Min-Bias “Associated” Charged Particle Density

Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{\text{max}}$) relative to $PT_{\text{max}}$ (rotated to 180$^\circ$) for “min-bias” events at 1.96 TeV with $PT_{\text{max}} > 0.5$, 1.0, 2.0, 5.0, and 10.0 GeV/c from PYTHIA Tune A (generator level).

Shows the “associated” charged particle density in the “toward”, “away” and “transverse” regions 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 1.96 TeV from PYTHIA Tune A (generator level).
Min-Bias “Associated” Charged Particle Density

![Graph showing associated charged particle density](image)

- Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{max}$) relative to $PT_{max}$ (rotated to 180°) for “min-bias” events at 1.96 TeV with $PT_{max}$ > 0.5, 1.0, 2.0, 5.0, and 10.0 GeV/c from PYTHIA Tune A (generator level).

- Shows the “associated” charged particle density in the “toward”, “away” and “transverse” regions as a function of $PT_{max}$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{max}$) for “min-bias” events at 1.96 TeV from PYTHIA Tune A (generator level).
Min-Bias “Associated” Charged Particle Density

- Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{chq}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{max}$) relative to $PT_{max}$ (rotated to 180°) for “min-bias” events at 1.96 TeV with $PT_{max} > 0.5, 1.0, 2.0, 5.0, \text{and } 10.0$ GeV/c from PYTHIA Tune A (generator level).

- Shows the “associated” charged particle density in the “toward”, “away” and “transverse” regions as a function of $PT_{max}$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{max}$) for “min-bias” events at 1.96 TeV from PYTHIA Tune A (generator level).
“Transverse” Charged Density

Shows the charged particle density in the “transverse” region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) at 1.96 TeV as defined by PTmax, PT(chgjet#1), and PT(jet#1) from PYTHIA Tune A at the particle level (i.e. generator level).
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, $\Delta \eta \times \Delta \phi = 2 \times 120^\circ = 4\pi/3$. 

"Transverse" region very sensitive to the "underlying event"!
Compares 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 $p_T$. 
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 average "transverse" charge particle density (|η|<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**

**“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).

- 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

HERWIG has the too steep of a $P_T$ dependence of the “beam-beam remnant” component of the “underlying event”!

CDF Data
data uncorrected
theory corrected

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

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

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

→ 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 $P_T$. 

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**MPI: Multiple Parton Interactions**

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, $P_T(\text{hard})$ (constant cross section or varying with impact parameter).
- One can adjust the color connections and flavor of the MPI (singlet or nearest neighbor, $q$-$q\bar{q}$ or glue-glue).
- Also, one can adjust how the probability of a MPI depends on $P_T(\text{hard})$ (single or double Gaussian matter distribution).
MPI: Multiple Parton Interactions

MPI: Additional 2-to-2 parton-parton scatterings within a single proton-antiproton collision.

Pile-Up

Pile-Up: More than one proton-antiproton collision in the beam crossing.

Overlap

Overlap: An experimental timing issue where a proton-antiproton collision from the next beam crossing gets included in the proton-antiproton collision from the current beam crossing because the next crossing happened before the event could be read out.
The cut-off $P_{T0}$ that regulates the 2-to-2 scattering divergence $\frac{1}{P_{T0}^2 + P_{T0}^2}$

$1.9 \text{ GeV/c}$

$\text{PARP(82)}$

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.

$1.0$

$\text{PARP(67)}$

Determine by comparing with 630 GeV data!

$1.0$

$\text{PARP(67)}$

Determines the energy dependence of the MPI!

$0.16$

$\text{PARP(83)}$

Determines the energy dependence of the cut-off $P_{T0}$ as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^\epsilon$ with $\epsilon = \text{PARP(90)}$

$0.2$

$\text{PARP(84)}$

Determines the reference energy $E_0$..

$1 \text{ TeV}$

$\text{PARP(89)}$

Reference point at 1.8 TeV

$0.25$ (Set A))

$\text{PARP(82)}$

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

$0.09$ GeV/c

$\text{PARP(80)}$

Affects the amount of initial-state radiation!

$0.66$

$\text{PARP(85)}$

Determines the energy dependence of the MPI!
The cut-off $P_{T0}$ that regulates the 2-to-2 scattering divergence is $1/(P_{T0}^2 + P_{T0}^2)^{1/2}$. 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.

$PARP(67)$

Determines the energy dependence of the cut-off $P_{T0}$ as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)\epsilon$ with $\epsilon = PARP(90)$

$PARP(90)$

Determines the reference energy $E_0$. $1$ TeV

$PARP(89)$

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.

$PARP(85)$

Probability that the MPI produces two gluons with color connections to the "nearest neighbors.

$PARP(84)$

Determines the energy dependence of the MPI! $\epsilon = 0.16$ (default)

$PARP(83)$

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

$PARP(84)$

Determines the overall hadron radius containing the fraction $PARP(83)$ of the total hadronic matter.

$PARP(82)$

$0.25$ (Set A)

Take $E_0 = 1.8$ TeV

Reference point at 1.8 TeV

I will talk more about the energy dependence of MPI tomorrow morning!
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 $P_T$ (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)).
PYTHIA Tune A Min-Bias
“Soft” + ”Hard”

PYTHIA regulates the perturbative 2-to-2 parton-parton cross sections with cut-off parameters which allows one to run with 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 $P_T(\text{hard}) > 10 \text{ GeV/c}$)!
PYTHIA Tune A
LHC Min-Bias Predictions

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

PYTHIA Tune A 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!
Look at correlations in the azimuthal angle $\Delta \phi$ relative to the leading charged particle jet ($|\eta| < 1$) or the leading calorimeter jet ($|\eta| < 2$).

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

Each of the three regions have area $\Delta \eta \Delta \phi = 2 \times 120^\circ = 4\pi/3$. 

Look at the charged particle density, the charged PTsum density and the ETsum density in all 3 regions!
“Leading Jet” events correspond to the leading calorimeter jet (MidPoint $R = 0.7$) in the region $|\eta| < 2$ with no other conditions.

“Inclusive 2-Jet Back-to-Back” events are selected to have at least two jets with Jet#1 and Jet#2 nearly “back-to-back” ($\Delta \phi_{12} > 150^\circ$) with almost equal transverse energies ($P_T(jet#2)/P_T(jet#1) > 0.8$) with no other conditions.

“Exclusive 2-Jet Back-to-Back” events are selected to have at least two jets with Jet#1 and Jet#2 nearly “back-to-back” ($\Delta \phi_{12} > 150^\circ$) with almost equal transverse energies ($P_T(jet#2)/P_T(jet#1) > 0.8$) and $P_T(jet#3) < 15$ GeV/c.

“Leading ChgJet” events correspond to the leading charged particle jet ($R = 0.7$) in the region $|\eta| < 1$ with no other conditions.

“Z-Boson” events are Drell-Yan events with $70 < M(\text{lepton-pair}) < 110$ GeV with no other conditions.
Define the MAX and MIN “transverse” regions ("transMAX" and "transMIN") on an event-by-event basis with MAX (MIN) having the largest (smallest) density. Each of the two “transverse” regions have an area in \( \eta - \phi \) space of \( 4\pi/6 \).

The “transMIN” region is very sensitive to the “beam-beam remnant” and the soft multiple parton interaction components of the “underlying event”.

The difference, “transDIF” ("transMAX” minus “transMIN”), is very sensitive to the “hard scattering” component of the “underlying event” (i.e. hard initial and final-state radiation).

The overall “transverse” density is the average of the “transMAX” and “transMIN” densities.
Observables at the Particle and Detector Level

<table>
<thead>
<tr>
<th>Observable</th>
<th>Particle Level</th>
<th>Detector Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>dNchg/dηdφ</td>
<td>Number of charged particles per unit η-φ (p_T &gt; 0.5 GeV/c,</td>
<td>Number of “good” charged tracks per unit η-φ (p_T &gt; 0.5 GeV/c,</td>
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<tr>
<td></td>
<td>(</td>
<td>η</td>
</tr>
<tr>
<td>dPTsum/dηdφ</td>
<td>Scalar p_T sum of charged particles per unit η-φ (p_T &gt;</td>
<td>Scalar p_T sum of “good” charged tracks per unit η-φ (p_T &gt;</td>
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<td>0.5 GeV/c,</td>
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<td>η</td>
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<tr>
<td>&lt;p_T&gt;</td>
<td>Average p_T of charged particles (p_T &gt; 0.5 GeV/c,</td>
<td>Average p_T of “good” charged tracks (p_T &gt; 0.5 GeV/c,</td>
</tr>
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<td>(</td>
<td>η</td>
</tr>
<tr>
<td>PTmax</td>
<td>Maximum p_T charged particle (p_T &gt; 0.5 GeV/c,</td>
<td>Maximum p_T “good” charged tracks (p_T &gt; 0.5 GeV/c,</td>
</tr>
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<td></td>
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<td>η</td>
</tr>
<tr>
<td></td>
<td>Require Nchg ≥ 1</td>
<td>Require Nchg ≥ 1</td>
</tr>
<tr>
<td>dETsum/dηdφ</td>
<td>Scalar E_T sum of all particles per unit η-φ (all</td>
<td>Scalar E_T sum of all calorimeter towers per unit η-φ (E_T &gt; 0.1 GeV,</td>
</tr>
<tr>
<td></td>
<td>p_T,</td>
<td>(</td>
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<td></td>
<td>(</td>
<td>η</td>
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<tr>
<td>PTsum/ETsum</td>
<td>Scalar p_T sum of charged particles (p_T &gt; 0.5 GeV/c,</td>
<td>Scalar p_T sum of “good” charged tracks (p_T &gt; 0.5 GeV/c,</td>
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<td>divided by the scalar E_T sum of all particles (all</td>
<td>divided by the scalar E_T sum of calorimeter towers (E_T &gt; 0.1 GeV,</td>
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<td>p_T,</td>
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<td>η</td>
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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)!

**UE Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune A</th>
<th>Tune AW</th>
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<tbody>
<tr>
<td>MSTP(81)</td>
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**ISR Parameters**

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**MSTP**

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 ($R = 0.7, f_{\text{merge}} = 0.5$)
- $\mathcal{L} = 150$ 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→4.0 (i.e. like Tune A, best fit 2.5).
**CDF Run 1 $P_T(Z)$**

**PYTHIA 6.2 CTEQ5L**

<table>
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<tr>
<th>Parameter</th>
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**Z-Boson Transverse Momentum**

- Shows the Run 1 Z-boson $p_T$ distribution ($\langle p_T(Z) \rangle \approx 11.5 \text{ GeV/c}$) compared with **PYTHIA Tune DW**, and **HERWIG**.

- **Tune DW** uses D0’s preferred value of PARP(67)!

- **Tune DW** has a lower value of PARP(67) and slightly more MPI!
## PYTHIA 6.2 Tunes

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

*Tune A energy dependence! (not the default)*

*Uses CTEQ6L*
## PYTHIA 6.2 Tunes

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- **Intrinsic KT**
- **ISR Parameter**
- **UE Parameters**
- **All use LO $\alpha_s$ with $\Lambda = 192$ MeV**
- **ATLAS energy dependence! (PYTHIA default)**
## 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(72) | 1.9409 GeV | 1.8387 TeV | 1.8 GeV
PARP(90) | 0.5 | 0.5
PARP(96) | 0.4 | 0.4
PARP(97) | 1.0 | 1.0
PARP(98) | 1.0 | 1.0
PARP(99) | 1.96 TeV | 1.96 TeV | 1.0 TeV
PARP(100) | 0.16 | 0.16
PARP(101) | 0.2 | 0.2
PARP(102) | 1.25 | 1.25 | 1.0
PARP(103) | 2.1 | 2.1
PARP(104) | 15.0 | 15.0
PARP(105) | 15.0 | 15.0

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

### UE Parameters
- ATLAS energy dependence! (PYTHIA default)

### Tuning Parameters
- Tune A
- Tune AW
- Tune B
- Tune BW
- Tune D
- Tune DW
- Tune D6
- Tune D6T

---

2009 CTEQ Summer School
June 30, 2009

Rick Field – Florida/CDF/CMS

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## PYTHIA 6.2 Tunes

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<th>Parameter</th>
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These are “old” PYTHIA 6.2 tunes! There are new 6.420 tunes by Peter Skands (Tune S320, update of S0) Peter Skands (Tune N324, N0CR) Hendrik Hoeth (Tune P329, “Professor”)

All use LO $\alpha_s$ with $\Lambda = 192$ MeV!
The Energy in the “Underlying Event” in High P_T Jet Production

JIMMY was tuned to fit the energy density in the “transverse” region for “leading jet” events!

“Transverse” <Densities> vs P_T(jet#1)

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

PT(JIM) = 2.5 GeV/c.

PT(JIM) = 3.25 GeV/c.

“Leading Jet”

CDF Run 2 Preliminary
generator level theory
MidPoint R = 0.7 |η(jet)| < 2
All Particles (|η|<1.0)

“Leading Jet”

CDF Run 2 Preliminary
generator level theory
MidPoint R = 0.7 |η(jet)| < 2
Charged Particles (|η|<1.0, P_T>0.5 GeV/c)
The Energy in the “Underlying Event” in High \( P_T \) Jet Production

The Drell-Yan JIMMY Tune

\[ P_T(JIM) = 3.6 \text{ GeV/c}, \quad JMRAD(73) = 1.8 \]
\[ JMRAD(91) = 1.8 \]

JIMMY was tuned to fit the energy density in the “transverse” region for “leading jet” events!
Data at 1.96 TeV on the density of charged particles, \(dN/d\eta d\phi\), with \(p_T > 0.5\) GeV/c and \(|\eta| < 1\) for “leading jet” events as a function of the leading jet \(p_T\) for the “toward”, “away”, and “transverse” regions. The data are corrected to the particle level (\(\text{with errors that include both the statistical error and the systematic uncertainty}\)) and are compared with PYTHIA Tune A at the particle level (\(\text{i.e. generator level}\)).
Data at 1.96 TeV on the charged particle scalar $p_T$ sum density, $dP_T/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “leading jet” events as a function of the leading jet $p_T$ for the “toward”, “away”, and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune A at the particle level (i.e. generator level).
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Data at 1.96 TeV on the charged scalar PTsum density, dPT/dηdϕ, with \( p_T > 0.5 \) GeV/c and \( |\eta| < 1 \) for “Z-Boson” and “Leading Jet” events as a function of the leading jet \( p_T \) or \( P_T(Z) \) for the “toward”, “away”, and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and Tune A, respectively, at the particle level (i.e. generator level).
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The “TransMAX/MIN” Regions

Data at 1.96 TeV on the density of charged particles, \(dN/d\eta d\phi\), with \(p_T > 0.5\) GeV/c and \(|\eta| < 1\) for “leading jet” events as a function of the leading jet \(p_T\) and for Z-Boson events as a function of \(P_T(Z)\) for “TransDIF” = “transMAX” minus “transMIN” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level (i.e. generator level).
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Data at 1.96 TeV on the density of charged particles, $dN/d\eta d\phi$, with $p_T > 0.5$ GeV$c$ and $|\eta| < 1$ for “leading jet” events as a function of the leading jet $p_T$ and for Z-Boson events as a function of $P_T(Z)$ for “TransDIF” = “transMAX” minus “transMIN” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level (i.e. generator level).
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Data at 1.96 TeV on the charged scalar PTsum density, \( \text{dPT/d} \eta \text{d} \phi \), with \( p_T > 0.5 \text{ GeV/c} \) and \( \eta < 1 \) for “leading jet” events as a function of the leading jet \( p_T \) and for Z-Boson events as a function of \( P_T(Z) \) for “TransDIF” = “transMAX” minus “transMIN” regions. The data are corrected to the particle level (\textit{with errors that include both the statistical error and the systematic uncertainty}) and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level (\textit{i.e.} generator level).
Data at 1.96 TeV on the charged *scalar* PTsum density, $dP_T/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events as a function of the leading jet $p_T$ and for Z-Boson events as a function of $P_T(Z)$ for "TransDIF" = "transMAX" minus "transMIN" regions. The data are corrected to the particle level (*with errors that include both the statistical error and the systematic uncertainty*) and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level (*i.e. generator level*).
Data at 1.96 TeV on the charged scalar PTsum density, $dPT/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "leading jet" events as a function of the leading jet $p_T$ and for Z-Boson events as a function of $P_T(Z)$ for "TransDIF" = "transMAX" minus "transMIN" regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the charged particle average $p_T$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for the “toward” region for “Z-Boson” and the “transverse” region for “Leading Jet” events as a function of the leading jet $p_T$ or $P_T(Z)$. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and Tune A, respectively, at the particle level (i.e. generator level). The Z-Boson data are also compared with PYTHIA Tune DW, the ATLAS tune, and HERWIG (without MPI).
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Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with p_T > 0.5 GeV/c and |η| < 1 for “Z-Boson” events as a function of P_T(Z) for the “toward” and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and HERWIG (without MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the density of charged particles, $dN/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” events as a function of $P_T(Z)$ for the “toward” and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and HERWIG (without MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with \( p_T > 0.5 \text{ GeV/c} \) and \( |\eta| < 1 \) for “Z-Boson” events as a function of \( P_T(Z) \) for the “toward” and “transverse” regions. The data are corrected to the particle level (\textit{with errors that include both the statistical error and the systematic uncertainty}) and are compared with PYTHIA Tune AW and HERWIG (without MPI) at the particle level (\textit{i.e.} generator level).
Data at 1.96 TeV on the charged scalar PTsum density, $dP_T/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” events as a function of $P_T(Z)$ for the “toward” and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and HERWIG (without MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the charged scalar PTsum density, dPT/dηdφ, with p_T > 0.5 GeV/c and |η| < 1 for “Z-Boson” events as a function of P_T(Z) for the “toward” and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and HERWIG (without MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the charged scalar PTsum density, $dP_T/d\eta d\phi$, with $P_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” events as a function of $P_T(Z)$ for the “toward” and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and HERWIG (without MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the charged scalar PTsum density, dPT/dηdφ, with PT > 0.5 GeV/c and |η| < 1 for “Z-Boson” events as a function of PT(Z) for the “toward” and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and HERWIG (without MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the density of charged particles, $dN/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” events as a function of $P_T(Z)$ for the “toward” region. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW, Tune DW, PYTHIA ATLAS Tune, HERWIG (without MPI), and HERWIG (with JIMMY MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the density of charged particles, $dN/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” events as a function of $P_T(Z)$ for the “toward” region. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW, Tune DW, PYTHIA ATLAS Tune, HERWIG (without MPI), and HERWIG (with JIMMY MPI) at the particle level (i.e. generator level).
Data at 1.96 TeV on the the average $p_T$ of charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” events as a function of $P_T(Z)$ for the “toward” region. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW, Tune DW, PYTHIA ATLAS Tune, HERWIG (without MPI), and HERWIG (with JIMMY MPI) at the particle level (i.e. generator level).
Average Lepton-Pair transverse momentum at the Tevatron and the LHC for PYTHIA Tune DW and HERWIG (without MPI).

Shape of the Lepton-Pair $p_T$ distribution at the Z-boson mass at the Tevatron and the LHC for PYTHIA Tune DW and HERWIG (without MPI).
The “Underlying Event” in Drell-Yan Production

**The “Underlying Event”**

- Charged particle density versus the lepton-pair invariant mass at 1.96 TeV for **PYTHIA Tune AW** and **HERWIG (without MPI)**.

**Charged particle density versus M(pair)**

- “Underlying event” much more active at the LHC!

- Charged particle density versus the lepton-pair invariant mass at 14 TeV for **PYTHIA Tune AW** and **HERWIG (without MPI)**.
Data at 1.96 TeV on the density of charged particles, $dN/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Leading Jet” events as a function of $P_T(jet#1)$ for the “transverse” region. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune A, and HERWIG (without MPI) at the particle level (i.e. generator level).
Talk 2: Extrapolations from the Tevatron to RHIC and the LHC

Outline of Talk

- The Pythia MPI energy scaling parameter PARP(90).
- The “underlying event” at STAR. Extrapolations to RHIC.
- LHC predictions for the “underlying event” (hard scattering QCD & Drell-Yan).
- “Min-bias” and “pile-up” at the LHC.
- Correlations: charged particle $\langle p_T \rangle$ versus the charged multiplicity in “min-bias” and Drell-Yan.
- Summary & Conclusions.