Outline of Talk

- Simulating hadron-hadron collisions: The early days of Feynman-Field Phenomenology.
- The CDF QCD Monte-Carlo Model tunes.
- The CMS QCD Monte-Carlo Model tunes.
- New CDF data from the Tevatron Energy Scan.
- Mapping out the energy dependence: Tevatron to the LHC.
- Summary & Conclusions.
Tevatron Energy Scan: Findings & Surprises

Rick Field
University of Florida

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➤ The CDF QCD Monte-Carlo Model tunes.

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From 7 GeV/c $\pi^0$’s to 1 TeV Jets. The early days of trying to understand and simulate hadron-hadron collisions.
Toward an Understanding of Hadron-Hadron Collisions

Feynman-Field Phenomenology

From 7 GeV/c $\pi^0$'s to 1 TeV Jets. The early days of trying to understand and simulate hadron-hadron collisions.
The Feynman-Field Days

1973-1983


My 1st graduate student!
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”

Parton-Parton Scattering

“Soft” Collision (no large transverse momentum)
Hadron-Hadron Collisions

- What happens when two hadrons collide at high energy?
  - Most of the time the hadrons ooze through each other (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-Quark Cross-Section
Unknown! Determined from hadron-hadron collisions.

Quark Black-Box Model

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

FF1 1977

No gluons!
Quark Distribution Functions
determined from deep-inelastic
lepton-hadron collisions

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

Quark-Quark Black-Box Model

FF1 1977

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!
Predict particle ratios

**FF1 1977**

Predict increase with increasing CM energy $W$

"Beam-Beam Remnants"

Predict overall event topology (FFF1 paper 1977)

7 GeV/c $\pi^0$s!
Telegram from Feynman

July 1976

ICS IPHIINA IISS
IISF FN WUI 19 0249
PMS PASADENA CA
UWA1871 PSX553 310884 A 7290
UWNC CO FRXX 015
CHAMONIXMONTBLANC
RICK FIELD CALTECH
PASADENA/CA

SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE
FEY
NNAH
SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE
FEYNMAN

July 1976
QCD Approach: Quarks & Gluons

Quark & Gluon Cross-Sections
Calculated from QCD

Parton Distribution Functions
Q^2 dependence predicted from QCD

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

Part of the diagram includes a graph with the title "z(x,Q^2) VERSUS x."
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.”
Feynman Talk at Coral Gables (December 1976)

1st transparency

Field & Feynman CALT-68-565
Fox (Brookhaven APS) CALT-68-573

Model

Jet

Proton $\rightarrow$ Jet

Quark-Quark Collision.
But $E^2$ vs. Not $E^4$?

Need: (a) Quark distribution in hadron. (Pion?)
(b) The way quark makes hadron jet.

From experiments with leptons.

Quark-Quark scattering x-section.

Jet

Try to fit all correlation experiments
with no new parameters.

Last transparency

“Feynman-Field Jet Model”

Work in Progress

1. More detailed Calculations
2. Theory of $q \rightarrow$ hadron cascade

Future.

Proton & baryons at high $P_T$.

Single $P_T$ at high $P_T$.

Nuclear targets.

Are we really in trouble from appearance of quark?

Unify Theory to that of main collision at low $P_T$. 
Field-Feynman 1978

Assumed that jets could be analyzed on a “recursive” principle.

Let $f(\eta)d\eta$ be the probability that the rank 1 meson leaves fractional momentum $\eta$ to the remaining cascade, leaving quark “b” with momentum $P_1 = \eta_1 P_0$.

Assume that the mesons originating from quark “b” are distributed in precisely the same way as the mesons which came from quark a (i.e. same function $f(\eta)$), leaving quark “c” with momentum $P_2 = \eta_2 P_1 = \eta_2 \eta_1 P_0$.

Add in flavor dependence by letting $\beta_u =$ probability of producing $u$-$\bar{u}$ pair, $\beta_d =$ probability of producing $d$-$\bar{d}$ pair, etc.

Let $F(z)dz$ be the probability of finding a meson (independent of rank) with fractional momentum $z$ of the original quark “a” within the jet.

Original quark with flavor “a” and momentum $P_0$

Primary Mesons

$\bar{b}\bar{b}$ pair

$c\bar{c}$ pair

Secondary Mesons (after decay)

$\bar{b}k$ $\bar{k}a$

Rank 2

Rank 1

Calculate $F(z)$ from $f(\eta)$ and $\beta_i$!
A Parameterization of the Properties of Jets

Field-Feynman 1978

- Assumed that jets could be analyzed on a “recursive” principle.
- Let $f(\eta)d\eta$ be the probability that the rank 1 meson leaves fractional momentum $\eta$ to the remaining cascade, leaving quark “b” with momentum $P_1 = \eta_1 P_0$.
- Assume that the mesons originating from quark “b” are distributed in precisely the same way as the mesons which came from quark a (i.e. same function $f(\eta)$), leaving quark “c” with momentum $P_2 = \eta_2 P_1 = \eta_2 \eta_1 P_0$.
- Add in flavor dependence by letting $\beta_u =$ probability of producing $u$-ubar pair, $\beta_d =$ probability of producing d-dbar pair, etc.
- Let $F(z)dz$ be the probability of finding a meson (independent of rank) with fractional momentum $z$ of the original quark “a” within the jet.
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

"FF" or “FW” Fragmentation

yesterday:
- ISAJET ("FF" Fragmentation)
- HERWIG ("FW" Fragmentation)
- PYTHIA 6.4

today:
- SHERPA
- PYTHIA 8
- HERWIG++
Feynman, Field, & Fox (1978) Predict large "jet" cross-section

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 from particles arising from soft or semi-soft multiple parton interactions (MPI).

Of course the outgoing colored partons fragment into hadron “jet” and inevitably “underlying event” observables receive contributions from initial and final-state radiation.
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 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!
Proton-Proton Collisions

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

Elastic Scattering

Single Diffraction

Double Diffraction

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

“Soft” Hard Core (no hard scattering)

“Hard” Hard Core (hard scattering)
The Inelastic Non-Diffractive Cross-Section

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

Majority of “min-bias” events!

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

Multiple-parton interactions (MPI)!
Select inelastic non-diffractive events that contain a hard scattering.

The "underlying-event" (UE)!

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

The "underlying-event" (UE)!

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

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

$1/(p_T)^4 \rightarrow 1/(p_T^2+p_{T0}^2)^2$
Model of $\sigma_{\text{ND}}$

Allow leading hard scattering to go to zero $p_T$ with same cut-off as the MPI!

Model of the inelastic non-diffractive cross section!

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

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

Multiple-parton interactions (MPI)!
Fit the “underlying event” in a hard scattering process.

“Underlying Event”

“Min-Bias” (ND)

Predict MB (ND)!

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

Allow primary hard-scattering to go to $p_T = 0$ with same cut-off!
Fit the “underlying event” in a hard scattering process.

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

Allow primary hard-scattering to go to p_T = 0 with same cut-off!

“Min-Bias” (add single & double diffraction)

Predict MB (ND)!

Predict MB (IN)!

“Underlying Event”
## Tuning PYTHIA 6.2: 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(82)</td>
<td>1.9 GeV/c</td>
<td>The cut-off $P_{T0}$ that regulates the 2-to-2 scattering divergence $1/PT^4\to 1/(PT^2+P_{T0}^2)^2$</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*  

*Multiple Parton Interaction*  

*Determines by comparing with 630 GeV data!*  

*Take $E_0 = 1.8$ TeV*  

*Reference point at 1.8 TeV*
The cut-off $\text{PT}_0$ that regulates the 2-to-2 scattering divergence $1/\text{PT}_4 \rightarrow 1/(\text{PT}_2^2+\text{PT}_0^2)^2$.

**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 $\text{PT}_0$ as follows $\text{PT}_0(E_{\text{cm}}) = \text{PT}_0(E_{\text{cm}}/E_0)^\varepsilon$ with $\varepsilon = \text{PARP}(90)$

**PARP(90)**

Determines the reference energy $E_0$.

**PARP(85)**

Determines the energy dependence of the MPI!

**PARP(84)**

Determines the energy dependence of the cut-off $\text{PT}_0$ as follows $\text{PT}_0(E_{\text{cm}}) = \text{PT}_0(E_{\text{cm}}/E_0)^\varepsilon$ with $\varepsilon = \text{PARP}(90)$

**PARP(83)**

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

**PARP(82)**

The cut-off $\text{PT}_0$ that regulates the 2-to-2 scattering divergence $1/\text{PT}_4 \rightarrow 1/(\text{PT}_2^2+\text{PT}_0^2)^2$

**PARP(81)**

Determines the energy dependence of the MPI!
Remember the energy dependence of the “underlying event” activity depends on both the $\varepsilon = \text{PARP}(90)$ and the PDF!
Collider Coordinates

- The z-axis is defined to be the beam axis with the xy-plane being the “transverse” plane.

- \( \theta_{cm} \) is the center-of-mass scattering angle and \( \phi \) is the azimuthal angle. The “transverse” momentum of a particle is given by \( P_T = P \cos(\theta_{cm}) \).

- Use \( \eta \) and \( \phi \) to determine the direction of an outgoing particle, where \( \eta \) is the “pseudo-rapidity” defined by \( \eta = -\log(\tan(\theta_{cm}/2)) \).

<table>
<thead>
<tr>
<th>( \eta )</th>
<th>( \theta_{cm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>90°</td>
</tr>
<tr>
<td>1</td>
<td>40°</td>
</tr>
<tr>
<td>2</td>
<td>15°</td>
</tr>
<tr>
<td>3</td>
<td>6°</td>
</tr>
<tr>
<td>4</td>
<td>2°</td>
</tr>
</tbody>
</table>
Look at charged particle correlations in the azimuthal angle $\Delta \phi$ relative to a leading object (*i.e.* CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF $P_T > P_T^{\text{min}}$ $|\eta| < \eta_{\text{cut}}$.

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

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

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 area in $\eta$-$\phi$ space, $\Delta \eta \times \Delta \phi = 2\eta_{cut} \times 120^\circ = 2\eta_{cut} \times 2\pi/3$. Construct densities by dividing by the area in $\eta$-$\phi$ space.
Study the charged particles \( (p_T > 0.5 \text{ GeV/c}, |\eta| < 1) \) and form the charged particle density, \( dN_{\text{ch}g}/d\eta d\phi \), and the charged scalar \( p_T \) sum density, \( dP_{\text{sum}}/d\eta d\phi \).
“Transverse” Charged Particle Density: Number of charged particles \( (p_T > 0.5 \text{ GeV/c}, |\eta| < \eta_{\text{cut}}) \) in the “transverse” region as defined by the leading charged particle, \( P_{T\text{max}} \), divided by the area in \( \eta-\phi \) space, \( 2\eta_{\text{cut}} \times 2\pi/3 \), averaged over all events with at least one particle with \( p_T > 0.5 \text{ GeV/c}, |\eta| < \eta_{\text{cut}} \).

“Transverse” Charged PTsum Density: Scalar \( p_T \) sum of the charged particles \( (p_T > 0.5 \text{ GeV/c}, |\eta| < \eta_{\text{cut}}) \) in the “transverse” region as defined by the leading charged particle, \( P_{T\text{max}} \), divided by the area in \( \eta-\phi \) space, \( 2\eta_{\text{cut}} \times 2\pi/3 \), averaged over all events with at least one particle with \( p_T > 0.5 \text{ GeV/c}, |\eta| < \eta_{\text{cut}} \).

“Transverse” Charged Particle Average \( p_T \): Event-by-event \( <p_T> = \text{PTsum}/N_{\text{chg}} \) for charged particles \( (p_T > 0.5 \text{ GeV/c}, |\eta| < \eta_{\text{cut}}) \) in the “transverse” region as defined by the leading charged particle, \( P_{T\text{max}} \), averaged over all events with at least one particle in the “transverse” region with \( p_T > 0.5 \text{ GeV/c}, |\eta| < \eta_{\text{cut}} \).

Zero “Transverse” Charged Particles: If there are no charged particles in the “transverse” region then \( N_{\text{chg}} \) and \( \text{PTsum} \) are zero and one includes these zeros in the average over all events with at least one particle with \( p_T > 0.5 \text{ GeV/c}, |\eta| < \eta_{\text{cut}} \). However, if there are no charged particles in the “transverse” region then the event is not used in constructing the “transverse” average \( p_T \).
"Transverse" Charged Particle Density: $dN/d\eta d\phi$ vs. $PT(charged \ jet#1)$ (GeV/c)

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

Note Change
PARP(67) = 4.0 (< 6.138)
PARP(67) = 1.0 (> 6.138)

Default parameters give very poor description of the “underlying event”!
**PYTHIA 6.206 Defaults**

**PYTHIA default parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
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<tbody>
<tr>
<td>MSTP(81)</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>MSTP(82)</td>
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<td>PARP(81)</td>
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<tr>
<td>PARP(67)</td>
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</tbody>
</table>

**Plot shows the “Transverse” Charged Particle Density**

- Activity depends on both the cut-off $p_{T0}$ and the PDF!
- Parameter
  - $\text{PARP(67)} = 4.0 (< 6.138)$
  - $\text{PARP(67)} = 1.0 (> 6.138)$

- Default parameters give very poor description of the “underlying event”!
### Table: Parameter Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune B</th>
<th>Tune A</th>
</tr>
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<tbody>
<tr>
<td>MSTP(81)</td>
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<tr>
<td>PARP(82)</td>
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<td>PARP(86)</td>
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<tr>
<td>PARP(67)</td>
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</table>

**Plot:**

The plot shows the "transverse" charged particle density versus $P_T(\text{charged jet#1})$ compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

**CDF Preliminary**
- Data uncorrected
- Theory corrected

**Run 1 Analysis**
- Run 1 PYTHIA Tune A
- Run 1 Analysis

**PYTHIA 6.206 (Set A)**
- PARP(67)=4

**PYTHIA 6.206 (Set B)**
- PARP(67)=1

**CDF Default February 25, 2000!**
- PYTHIA 6.206 CTEQ5L
- CDF Default

**New PYTHIA default**
- (less initial-state radiation)

**Old PYTHIA default**
- (more initial-state radiation)
### PYTHIA 6.2 Tunes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune AW</th>
<th>Tune DW</th>
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<td>2.1</td>
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<tr>
<td>PARP(93)</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

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

*Uses CTEQ6L*

Tune A energy dependence!

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October 16, 2013

Rick Field – Florida/CDF/CMS

Page 39
Transverse Charged Particle Density

Showed the “associated” charged particle density in the “transverse” region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, not including PTmax) for “min-bias” events at 1.96 TeV from PYTHIA Tune A, Tune S320, Tune N324, and Tune P329 at the particle level (i.e. generator level).

Extrapolations of PYTHIA Tune A, Tune DW, Tune DWT, Tune S320, Tune P329, and pyATLAS to the LHC.

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Rick Field – Florida/CDF/CMS
October 16, 2013
If the LHC data are not in the range shown here then we learn new (QCD) physics!

Rick Field October 13, 2009

- Shows the “associated” charged particle density in the “transverse” region as a function of PTmax for charged particles (pT > 0.5 GeV/c, |η| < 1) for “min-bias” events at 1.96 TeV from PYTHIA Tune A, Tune S320, Tune N324, and Tune P329 at the particle level (i.e. generator level).

- Extrapolations of PYTHIA Tune A, Tune DW, Tune DWT, Tune S320, Tune P329, and pyATLAS to the LHC.
"Transverse" Charged Particle Density

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

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

7 TeV → 14 TeV (UE increase ~20%)
Linear on a log plot!

Log scale!
"Transverse" Charge Density

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

**Transverse** Charged Particle Density: dN/dηdφ

**900 GeV → 7 TeV**

(UE increase ~ factor of 2)

~0.4 → ~0.8
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, $dN/d\eta d\phi$, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.

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

Ratio of CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, $dN/d\eta d\phi$, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.
I believe that it is time to move to PYTHIA 6.4 (pT-ordered parton showers and new MPI model)!

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

The ATLAS Tune AMBT1 was designed to fit the inelastic data for Nchg ≥ 6 and to fit the PTmax UE data with PTmax > 10 GeV/c. Tune AMBT1 is primarily a min-bias tune, while Tune Z1 is a UE tune!
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, $dN/d\eta d\phi$, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are uncorrected and compared with PYTHIA Tune DW and D6T after detector simulation (SIM).

Color reconnection suppression. Color reconnection strength.

Tune Z1 (CTEQ5L)
PARP(82) = 1.932
PARP(90) = 0.275
PARP(77) = 1.016
PARP(78) = 0.538

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

Tune Z1 is a PYTHIA 6.4 using $p_T$-ordered parton showers and the new MPI model!
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, dN/dηdφ, as defined by the leading charged particle jet (chgjet#1) for charged particles with p_T > 0.5 GeV/c and |η| < 2.0. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.

CMS corrected data!

Very nice agreement!

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

CMS corrected data!
Just before the shutdown of the Tevatron CDF has collected more than 10M “min-bias” events at several center-of-mass energies!

- 300 GeV 12.1M MB Events
- 900 GeV 54.3M MB Events
“transMAX” and “transMIN” Charged Particle Density: Number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 0.8$) in the the maximum (minimum) of the two “transverse” regions as defined by the leading charged particle, $p_T^{\text{max}}$, divided by the area in $\eta$-$\phi$ space, $2\eta_{\text{cut}} \times 2\pi/6$, averaged over all events with at least one particle with $p_T > 0.5$ GeV/c, $|\eta| < \eta_{\text{cut}}$.

“transMAX” and “transMIN” Charged $p_T$sum Density: Scalar $p_T$ sum of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 0.8$) in the the maximum (minimum) of the two “transverse” regions as defined by the leading charged particle, $p_T^{\text{max}}$, divided by the area in $\eta$-$\phi$ space, $2\eta_{\text{cut}} \times 2\pi/6$, averaged over all events with at least one particle with $p_T > 0.5$ GeV/c, $|\eta| < \eta_{\text{cut}}$.

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

“Transverse” Density = “transAVE” Density = (“transMAX” Density + “transMIN” Density)/2

“TransDIF” Density = “transMAX” Density - “transMIN” Density

$\eta_{\text{cut}} = 0.8$
The “toward” region contains the leading “jet”, while the “away” region, on the average, contains the “away-side” “jet”. The “transverse” region is perpendicular to the plane of the hard 2-to-2 scattering and is very sensitive to the “underlying event”. For events with large initial or final-state radiation the “transMAX” region defined contains the third jet while both the “transMAX” and “transMIN” regions receive contributions from the MPI and beam-beam remnants. Thus, the “transMIN” region is very sensitive to the multiple parton interactions (MPI) and beam-beam remnants (BBR), while the “transMAX” minus the “transMIN” (i.e. “transDIF”) is very sensitive to initial-state radiation (ISR) and final-state radiation (FSR).

“TransMIN” density more sensitive to MPI & BBR.

“TransDIF” density more sensitive to ISR & FSR.

0 ≤ “TransDIF” ≤ 2×”TransAVE”

“TransDIF” = “TransAVE” if “TransMIX” = 3×”TransMIN”
PTmax UE Data

- **CDF PTmax UE Analysis:** “transMAX”, “transMIN”, “transAVE”, and “transDIF” charged particle and PTsum densities \((p_T > 0.5 \text{ GeV/c}, |\eta| < 0.8)\) in proton-antiproton collisions at 300 GeV, 900 GeV, and 1.96 TeV (R. Field analysis).

- **CMS PTmax UE Analysis:** “transMAX”, “transMIN”, “transAVE”, and “transDIF” charged particle and PTsum densities \((p_T > 0.5 \text{ GeV/c}, |\eta| < 0.8)\) in proton-proton collisions at 900 GeV and 7 TeV (M. Zakaria analysis). The “transMAX”, “transMIN”, and “transDIF” are not yet approved so I can only show “transAVE” which is approved.

- **CMS UE Tunes:** PYTHIA 6.4 Tune Z1 (CTEQ5L) and PYTHIA 6.4 Tune Z2* (CTEQ6L). Both were tuned to the CMS leading chgjet “transAVE” UE data at 900 GeV and 7 TeV.
Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the “transMAX” and “transMIN” regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
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The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*. 

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

- **1.96 TeV**
  - CDF Preliminary Corrected Data
  - Generator Level Theory
  - Tune Z2* (solid lines)
  - Tune Z1 (dashed lines)

- **900 GeV**
  - CDF Preliminary Corrected Data
  - Generator Level Theory
  - Tune Z2* (solid lines)
  - Tune Z1 (dashed lines)

- **300 GeV**
  - CDF Preliminary Corrected Data
  - Generator Level Theory
  - Tune Z2* (solid lines)
  - Tune Z1 (dashed lines)
Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged PTsum density in the “transAVE” and “transDIF” regions as defined by the leading charged particle (PTmax) for charged particles with pT > 0.5 GeV/c and |η| < 0.8. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
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Corrected CDF data on the charged particle density in the “transMAX” region as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (log scale).
Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the “transMAX”, and the “transMIN”, regions as defined by the leading charged particle (PTmax) for charged particles with \( p_T > 0.5 \text{ GeV/c} \) and \( |\eta| < 0.8 \) with \( 5 < \text{PTmax} < 6 \text{ GeV/c} \). The data are plotted versus the center-of-mass energy \((\log \text{ scale})\). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.

Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged PTsum density in the “transMAX”, and the “transMIN”, regions as defined by the leading charged particle (PTmax) for charged particles with \( p_T > 0.5 \text{ GeV/c} \) and \( |\eta| < 0.8 \) with \( 5 < \text{PTmax} < 6 \text{ GeV/c} \). The data are plotted versus the center-of-mass energy \((\log \text{ scale})\). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.
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The data are “normalized” by dividing by the corresponding value at 300 GeV.
Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the “transMAX”, and the “transMIN”, regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (log scale). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.

The data are “normalized” by dividing by the corresponding value at 300 GeV.

Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged PTsum density in the “transMAX”, and the “transMIN”, regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (log scale). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.
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Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the “transAVE”, and the “transDIF”, regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PT_{\text{max}} < 6$ GeV/c. The data are plotted versus the center-of-mass energy (log scale). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*. 

The data are “normalized” by dividing by the corresponding value at 300 GeV.
Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV for the charged particle density in the “transMIN”, and “transDIF” regions as defined by the leading charged particle (PTmax) for charged particles with \( p_T > 0.5 \) GeV/c and \( |\eta| < 0.8 \) with \( 5 < \text{PTmax} < 6 \) GeV/c. The data are plotted versus the center-of-mass energy (log scale). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*. The data are “normalized” by dividing by the corresponding value at 300 GeV.

Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV for the charged PTsum density in the “transMIN”, and “transDIF” regions as defined by the leading charged particle (PTmax) for charged particles with \( p_T > 0.5 \) GeV/c and \( |\eta| < 0.8 \) with \( 5 < \text{PTmax} < 6 \) GeV/c. The data are plotted versus the center-of-mass energy (log scale). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.
Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV for the charged particle density in the “transMIN”, and “transDIF” regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (log scale). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.

The data are “normalized” by dividing by the corresponding value at 300 GeV.
The “transMIN” (MPI-BBR component) increases much faster with center-of-mass energy than the “transDIF” (ISR-FSR component)! The data are “normalized” by dividing by the corresponding value at 300 GeV.

The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*. The “transMIN” (MPI-BBR component) increases much faster with center-of-mass energy than the “transDIF” (ISR-FSR component)!

The “transMIN” (MPI-BBR component) increases much faster with center-of-mass energy than the “transDIF” (ISR-FSR component)!
"TransAVE" Charged Particle Density: $dN/d\eta d\phi$

Charged Particle Density

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

RDF Preliminary
Corrected Data
Tune Z2* Generator Level

13 TeV Predicted
7 TeV
1.96 TeV
900 GeV
300 GeV

Tune Z2*

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

PTmax (GeV/c)
"Transverse" Charged PTsum Density: $dPT/d\eta d\phi$

- RDF Preliminary
- Corrected Data
- Tune Z2* Generator Level
- 13 TeV Predicted
- 7 TeV
- 1.96 TeV
- 900 GeV
- 300 GeV

Charged Particles ($|\eta|<0.8$, $PT>0.5$ GeV/c)
• Publications with “underlying event” in the title.
Publications with “underlying event” in the title.


Summary & Conclusions

- The “transverse” density increases faster with center-of-mass energy than the overall density ($N_{\text{ch}} \geq 1$)! However, the “transverse” = “transAVE” region is not a true measure of the energy dependence of MPI since it receives large contributions from ISR and FSR.

- The “transMIN” (MPI-BBR component) increases much faster with center-of-mass energy than the “transDIF” (ISR-FSR component)! Previously we only knew the energy dependence of “transAVE”.

We now have a lot of MB & UE data at 300 GeV, 900 GeV, 1.96 TeV, and 7 TeV! We can study the energy dependence more precisely than ever before!

- Both PYTHIA 6.4 Tune Z1 (CTEQ5L) and PYTHIA 6.4 Tune Z2* (CTEQ6L) go a fairly good job (although not perfect) in describing the energy dependence of the UE!
The “transverse” density increases faster with center-of-mass energy than the overall density (N_{ch} ≥ 1)! However, the “transDIF” region is not a true measure of the energy dependence of MPI since it receives large contributions from ISR.

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

What we are learning should allow for a deeper understanding of MPI which will result in more precise predictions at the future LHC energy of 13 TeV!

Both PYTHIA 6.4 Tune Z1 (CTEQ5L) and PYTHIA 6.4 Tune Z2* (CTEQ6L) go a fairly good job (although not perfect) in describing the energy dependence of the UE.

We now have a lot of MB & UE data at 300 GeV, 900 GeV, 1.96 TeV, and 7 TeV! We can study the energy dependence more precisely than we could before!