Review of the QCD Monte-Carlo Tunes

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Outline of Talk

- Review some of what we have learned about “min-bias” and the “underlying event” in Run 1 at CDF.

- Review the various PYTHIA “underlying event” QCD Monte-Carlo Model tunes.

- Show some things I do not understand about the CDF data.

- Show some extrapolations to the LHC.
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.
QCD Monte-Carlo Models: High Transverse Momentum Jets

- 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).

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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).

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Proton-AntiProton Collisions at the Tevatron

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.
Proton-AntiProton Collisions at the Tevatron

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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

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

“Hard” Hard Core (hard scattering)

“Soft” Hard Core (no hard scattering)

Beam-Beam Counters
\[ 3.2 < |\eta| < 5.9 \]
Study the charged particles ($p_T > 0.5 \text{ GeV/c, } |\eta| < 1$) and form the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, and the charged scalar $p_T$ sum density, $dP_{\text{sum}}/d\eta d\phi$. 

Charged Particles $

\begin{align*}
\phi & \quad 2\pi \\
\downarrow & \\
\eta & \quad -1 \quad +1 \\
\end{align*}

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

3 charged particles

3 GeV/c PTsum

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

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

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
          & CDF Run 2 “Min-Bias” & Average & Average Density per unit $\eta \phi$ \\
\hline
Nchg       & Number of Charged Particles ($p_T > 0.5 \text{ GeV/c, } |\eta| < 1$) & $3.17 +/- 0.31$ & $0.252 +/- 0.025$ \\
\hline
PTsum (GeV/c) & Scalar $p_T$ sum of Charged Particles ($p_T > 0.5 \text{ GeV/c, } |\eta| < 1$) & $2.97 +/- 0.23$ & $0.236 +/- 0.018$ \\
\hline
\end{tabular}
\end{table}
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 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 $p_T$).

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).
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, $\Delta \eta \times \Delta \phi = 2 \times 120^\circ = 4\pi/3$. 

CDF Run 1: Evolution of Charged Jets

“Underlying Event”
Compared the average “transverse” charge particle density with the average “Min-Bias” charge particle density (|η|<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.
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.
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 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).
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 uses a modified leading-log parton shower-model which does agrees better with the data!
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”!

**“Transverse” Charged Particle Density**

CDF Data
- data uncorrected
- theory corrected

1.8 TeV \(|\eta|<1 \ P_T>0.5 \text{ GeV/c} \)

\( PT(\text{hard}) > 3 \text{ GeV/c} \)

\( PT(\text{charged jet#1}) > 5 \text{ GeV/c} \)

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

**“Remnants”**

**“Hard”**

Herwig CTEQ5L

**“Transverse” Charged Particle Density**

- Total
- Herwig 6.4 CTEQ5L

- \( PT(chgjet#1) > 5 \text{ GeV/c} \)

- \( 1.8 \text{ TeV} \ |\eta|<1 \ P_T>0.5 \text{ GeV} \)

- \( PT(hard) > 3 \text{ GeV/c} \)

**“Hard” Remnants**

Herwig \( P_T(chgjet#1) > 30 \text{ GeV/c} \)

“Transverse” \( <dN_{chg}/d\eta d\phi> = 0.51 \)

Herwig \( P_T(chgjet#1) > 5 \text{ GeV/c} \)

\( <dN_{chg}/d\eta d\phi> = 0.40 \)

**Comparisons**

- Compares the average “transverse” charge particle density (\(|\eta|<1, P_T>0.5 \text{ GeV} \)) versus \( P_T(\text{charged jet#1}) \) 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 \( P_T(\text{hard})>3 \text{ GeV/c} \)). Shows how the “transverse” charge particle density is distributed in \( P_T \).
PYTHIA models the “soft” component of the underlying event with color string fragmentation, but in addition includes a contribution arising from multiple parton interactions (MPI) in which one interaction is hard and the other is “semi-hard”.

- The probability that a hard scattering events also contains a semi-hard multiple parton interaction can be varied but adjusting the cut-off for the MPI.
- One can also adjust whether the probability of a MPI depends on the $P_T$ of the hard scattering, $P_T(hard)$ (constant cross section or varying with impact parameter).
- One can adjust the color connections and flavor of the MPI (singlet or nearest neighbor, $q$-$qbar$ or glue-glue).
- Also, one can adjust how the probability of a MPI depends on $P_T(hard)$ (single or double Gaussian matter distribution).
### Tuning PYTHIA: Multiple Parton Interaction Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARP(83)</td>
<td>0.5</td>
<td>Double-Gaussian: Fraction of total hadronic matter within PARP(84)</td>
</tr>
<tr>
<td>PARP(84)</td>
<td>0.2</td>
<td>Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter.</td>
</tr>
<tr>
<td>PARP(85)</td>
<td>0.33</td>
<td>Probability that the MPI produces two gluons with color connections to the “nearest neighbors.”</td>
</tr>
<tr>
<td>PARP(86)</td>
<td>0.66</td>
<td>Probability that the MPI produces two gluons either as described by PARP(85) or as a closed gluon loop. The remaining fraction consists of quark-antiquark pairs.</td>
</tr>
<tr>
<td>PARP(89)</td>
<td>1 TeV</td>
<td>Determines the reference energy $E_0$.</td>
</tr>
<tr>
<td>PARP(90)</td>
<td>0.16</td>
<td>Determines the energy dependence of the cut-off $P_{T0}$ as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^\varepsilon$ with $\varepsilon = PARP(90)$</td>
</tr>
<tr>
<td>PARP(67)</td>
<td>1.0</td>
<td>A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of PARP(67) the more initial-state radiation.</td>
</tr>
</tbody>
</table>

- **Hard Core**
  - Affects the amount of initial-state radiation!

- **Multiple Parton Interaction**
  - Double-Gaussian: Fraction of total hadronic matter within PARP(84)

- **Color String**
  - Probability that the MPI produces two gluons with color connections to the “nearest neighbors.”

- **Hard-Scattering Cut-Off $P_{T0}$**
  - Determined by comparing with 630 GeV data!

- **Reference point at 1.8 TeV**
  - Take $E_0 = 1.8$ TeV

- **PYTHIA 6.206**
  - $\varepsilon = 0.25$ (Set A)
  - $\varepsilon = 0.16$ (default)

- **CM Energy $W$ (GeV)**
  - Reference point at 1.8 TeV

**Oregon Terascale Workshop**  
Rick Field – Florida/CDF/CMS  
February 23, 2009
Plot shows the “Transverse” charged particle density versus $P_T(\text{charged jet#1})$ compared to the QCD hard scattering predictions of PYTHIA 6.206 ($P_T(\text{hard}) > 0$) using the default parameters for multiple parton interactions and CTEQ3L, CTEQ4L, and CTEQ5L.

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

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

- **Parameter**
  - **Tune B**
  - **Tune A**
  - **Parameter**
  - **MSTP(81)**: 1 1
  - **MSTP(82)**: 4 4
  - **PARP(82)**: 1.9 GeV 2.0 GeV
  - **PARP(83)**: 0.5 0.5
  - **PARP(84)**: 0.4 0.4
  - **PARP(85)**: 1.0 0.9
  - **PARP(86)**: 1.0 0.95
  - **PARP(89)**: 1.8 TeV 1.8 TeV
  - **PARP(90)**: 0.25 0.25
  - **PARP(67)**: 1.0 4.0

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

**Old PYTHIA default (more initial-state radiation)**
Run 1 vs Run 2: “Transverse” Charged Particle Density

- Shows the data on the average “transverse” charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) as a function of the transverse momentum of the leading charged particle jet from Run 1.

- Compares the Run 2 data (Min-Bias, JET20, JET50, JET70, JET100) with Run 1. The errors on the (uncorrected) Run 2 data include both statistical and correlated systematic uncertainties.

- Shows the prediction of PYTHIA Tune A at 1.96 TeV after detector simulation (i.e. after CDFSIM).
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- Shows the prediction of PYTHIA Tune A at 1.96 TeV after detector simulation (i.e. after CDFSIM).

PYTHIA Tune A was tuned to fit the “underlying event” in Run 1!
△φ Correlations relative to the leading jet
Charged particles p_T > 0.5 GeV/c |η| < 1
Calorimeter towers E_T > 0.1 GeV |η| < 1

Look at correlations in the azimuthal angle △φ relative to the leading charged particle jet (|η| < 1) or the leading calorimeter jet (|η| < 2).

Define |△φ| < 60° as “Toward”, 60° < |△φ| < 120° as “Transverse”, and |△φ| > 120° as “Away”.

Each of the three regions have area ΔηΔφ = 2×120° = 4π/3.
“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.
Look at the “transverse” region as defined by the leading jet (JetClu R = 0.7, |\eta| < 2) or by the leading two jets (JetClu R = 0.7, |\eta| < 2). “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 (E_T(jet#2)/E_T(jet#1) > 0.8) and with E_T(jet#3) < 15 GeV.

Shows the \Delta\phi dependence of the charged particle density, dN_{chg}/d\eta d\phi, for charged particles in the range p_T > 0.5 GeV/c and |\eta| < 1 relative to jet#1 (rotated to 270^\circ) for 30 < E_T(jet#1) < 70 GeV for “Leading Jet” and “Back-to-Back” events.
Shows the $\Delta \phi$ dependence of the charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 (rotated to 270°) for $30 < E_T(\text{jet#1}) < 70$ GeV for “Leading Jet” and “Back-to-Back” events.
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>η</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dPTsum/dηdφ</td>
<td>Scalar p_T sum of charged particles per unit η-φ (p_T &gt; 0.5 GeV/c,</td>
<td>η</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;p_T&gt;</td>
<td>Average p_T of charged particles (p_T &gt; 0.5 GeV/c,</td>
<td>η</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTmax</td>
<td>Maximum p_T charged particle (p_T &gt; 0.5 GeV/c,</td>
<td>η</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>dETsum/dηdφ</td>
<td>Scalar E_T sum of all particles per unit η-φ (all p_T,</td>
<td>η</td>
</tr>
<tr>
<td></td>
<td></td>
<td></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>η</td>
</tr>
</tbody>
</table>
**CDF Run 1 $p_T(Z)$**

 Shows the Run 1 Z-boson $p_T$ distribution ($\langle p_T(Z) \rangle \approx 11.5 \text{ GeV/c}$) compared with PYTHIA Tune A ($\langle p_T(Z) \rangle = 9.7 \text{ GeV/c}$), Tune A25 ($\langle p_T(Z) \rangle = 10.1 \text{ GeV/c}$), and Tune A50 ($\langle p_T(Z) \rangle = 11.2 \text{ GeV/c}$).

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**UE Parameters**

- **PYTHIA 6.2 CTEQ5L**
- **MSTP(81)**: 1, 1, 1
- **MSTP(82)**: 4, 4, 4
- **PARP(82)**: 2.0 GeV, 2.0 GeV, 2.0 GeV
- **PARP(83)**: 0.5, 0.5, 0.5
- **PARP(84)**: 0.4, 0.4, 0.4
- **PARP(85)**: 0.9, 0.9, 0.9
- **PARP(86)**: 0.95, 0.95, 0.95
- **PARP(89)**: 1.8 TeV, 1.8 TeV, 1.8 TeV
- **PARP(90)**: 0.25, 0.25, 0.25
- **PARP(67)**: 4.0, 4.0, 4.0
- **MSTP(91)**: 1, 1, 1
- **PARP(91)**: 1.0, 2.5, 5.0
- **PARP(93)**: 5.0, 15.0, 25.0

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**ISR Parameter**

- **Intensive KT**
Shows 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).

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>
<thead>
<tr>
<th>Parameter</th>
<th>Tune DW</th>
<th>Tune AW</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTP(81)</td>
<td>1</td>
<td>1</td>
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<tr>
<td>MSTP(82)</td>
<td>4</td>
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<td>PARP(82)</td>
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</tr>
<tr>
<td>PARP(83)</td>
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<tr>
<td>PARP(84)</td>
<td>0.4</td>
<td>0.4</td>
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<tr>
<td>PARP(85)</td>
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<tr>
<td>PARP(86)</td>
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<td>0.95</td>
</tr>
<tr>
<td>PARP(89)</td>
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<td>1.8 TeV</td>
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<td>PARP(90)</td>
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<td>PARP(62)</td>
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<td>PARP(64)</td>
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<td>MSTP(91)</td>
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<td>PARP(91)</td>
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<tr>
<td>PARP(93)</td>
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<td>15.0</td>
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**UE Parameters**

- MSTP(81)
- MSTP(82)
- PARP(82)
- PARP(83)
- PARP(84)
- PARP(85)
- PARP(86)
- PARP(89)
- PARP(90)
- PARP(62)
- PARP(64)
- PARP(67)
- MSTP(91)
- PARP(91)
- PARP(93)

**ISR Parameters**

- MSTP(81)
- MSTP(82)
- PARP(82)
- PARP(83)
- PARP(84)
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- PARP(86)
- PARP(89)
- PARP(90)
- PARP(62)
- PARP(64)
- PARP(67)
- MSTP(91)
- PARP(91)
- PARP(93)

**Intrensic KT**

- PYTHIA 6.2 CTEQ5L

**Z-Boson Transverse Momentum**

- **CDF Run 1 Data**
- **PYTHIA Tune DW**
- **HERWIG**

- **1.8 TeV**
- **Normalized to 1**

- **PT Distribution 1/N dN/dPT**

- **$Z$-Boson $P_T$ (GeV/c)**

- **0 2 4 6 8 10 12 14 16 18 20**

- **0.00 0.04 0.08 0.12**

**Shows the Run 1 $Z$-boson $p_T$ distribution ($<p_T(Z)> \approx 11.5$ 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!**
Exclusive 3 Jet Final State Challenge

At least 1 Jet ("trigger" jet)
\( (P_T > 40 \text{ GeV/c}, |\eta| < 1.0) \)

Exactly 3 jets
\( (P_T > 20 \text{ GeV/c}, |\eta| < 2.5) \)

Order Jets by \( P_T \)
Jet1 highest \( P_T \), etc.

Bruce Knuteson

CDF Data
PYTHIA Tune A
R(j2,j3)

Khalidoun Makhoul
Georgios Choudalakis
Markus Klute
Conor Henderson
Ray Culbertson
Gene Flanagan
Let $N_{\text{trig}40}$ equal the number of events with at least one jet with $P_T > 40$ GeV and $|\eta| < 1.0$ (this is the “offline” trigger).

Let $N_{3\text{Jexc}20}$ equal the number of events with exactly three jets with $P_T > 20$ GeV/c and $|\eta| < 2.5$ which also have at least one jet with $P_T > 40$ GeV/c and $|\eta| < 1.0$.

Let $N_{3\text{Jexc}Fr} = N_{3\text{Jexc}20}/N_{\text{trig}40}$. The is the fraction of the “offline” trigger events that are exclusive 3-jet events.

The CDF data on $dN/dR(j_2,j_3)$ at 1.96 TeV compared with PYTHIA Tune AW ($\text{PARP}(67)=4$), Tune DW ($\text{PARP}(67)=2.5$), Tune BW ($\text{PARP}(67)=1$).

PARP(67) affects the initial-state radiation which contributes primarily to the region $R(j_2,j_3) > 1.0$. The data have more 3 jet events with small $R(j_2,j_3)$!
Let $N_{\text{trig}40}$ equal the number of events with at least one jet with $P_T > 40$ GeV and $|\eta| < 1.0$ (this is the “offline” trigger).

Let $N_{3\text{Jexc}20}$ equal the number of events with exactly three jets with $P_T > 20$ GeV/c and $|\eta| < 2.5$ which also have at least one jet with $P_T > 40$ GeV/c and $|\eta| < 1.0$.

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The CDF data on $dN/dR(j_2,j_3)$ at 1.96 TeV compared with PYTHIA Tune DW ($\text{PARP}(67)=2.5$) and HERWIG (without MPI).

Final-State radiation contributes to the region $R(j_2,j_3) < 1.0$.

If you ignore the normalization and normalize all the distributions to one then the data prefer Tune BW, but I believe this is misleading.
Let $N_{\text{trig}40}$ equal the number of events with at least one jet with $P_T > 40$ GeV and $|\eta| < 1.0$ (this is the “offline” trigger).

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Final-State radiation contributes to the region $R(j2,j3) < 1.0$.

If you ignore the normalization and normalize all the distributions to one then the data prefer Tune BW, but I believe this is misleading.
Let $N_{\text{trig}40}$ equal the number of events with at least one jet with $P_T > 40$ GeV and $|\eta| < 1.0$ (this is the “offline” trigger).

Let $N_{3J\text{exc}20}$ equal the number of events with exactly three jets with $P_T > 20$ GeV and $|\eta| < 2.5$ which also have at least one jet with $P_T > 40$ GeV/c.

Let $N_{3J\text{exc}Fr} = N_{3J\text{exc}20}/N_{\text{trig}40}$. The is the fraction of the “offline” events that are exclusive 3-jet events.

Final-State Radiation

I do not understand the excess number of events with $R(j_2,j_3) < 1.0$. Perhaps this is related to the “soft energy” problem??

If you ignore the normalization and normalize all the distributions to one then the data prefer Tune BW, but I believe this is misleading.

I will show you a lot more on Thursday!
## PYTHIA 6.2 Tunes

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- **All use LO $\alpha_s$ with $\Lambda = 192$ MeV!**
- **Tune A energy dependence!**
- **Uses CTEQ6L**

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*Oregon Terascale Workshop*  
*February 23, 2009*  
*Rick Field – Florida/CDF/CMS*  
*Page 38*
### PYTHIA 6.2 Tunes

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

UE Parameters

ISR Parameter

Intrinsic KT

ATLAS energy dependence!

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

**UE Parameters**

- Tune A
- Tune AW
- Tune B
- Tune BW
- Tune D
- Tune DW
- Tune D6
- Tune D6T

*Oregon Terascale Workshop*
*February 23, 2009*
These are “old” PYTHIA 6.2 tunes!

There are new 6.4 tunes by

Arthur Moraes (ATLAS)
Hendrik Hoeth (MCnet)
Peter Skands (Tune S0)

PYTHIA 6.2 Tunes

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

**UE Parameters**

**ISR Parameter**

**Intrinsic KT**

Q$^2$ ordered showers, old MPI!
The Energy in the “Underlying Event” in High P_T Jet Production

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

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

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

Proton
AntiProton

Outgoing Parton

Initial-State Radiation

Final-State Radiation

PT(hard)

PT(JIM) = 2.5 GeV/c.

PT(JIM) = 3.25 GeV/c.

JIMMY: MPI

J. M. Butterworth
J. R. Forshaw
M. H. Seymour

JIMMY was tuned to fit the energy density in the “transverse” region for “leading jet” events!
The Energy in the “Underlying Event” in High $P_T$ Jet Production

The Drell-Yan JIMMY Tune

$PT_{JIM} = 3.6 \text{ GeV/c},$

$JMRAD(73) = 1.8$

$JMRAD(91) = 1.8$

“Transverse” $<\text{Densities}>$ vs $P_T(jet#1)$

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 “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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"Leading Jet" ET sum density, $dE_T/d\eta d\phi$, with $|\eta| < 1$ for "leading jet" events as a function of the leading jet $p_T$ for the "transverse" region for PYTHIA Tune A and HERWIG (without MPI).
Data at 1.96 TeV on the scalar $E_T$ sum density, $dE_T/d\eta d\phi$, with $|\eta| < 1$ for “leading jet” events as a function of the leading jet $p_T$ for “transDIF” = “transMAX”-”transMIN. 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).
The “Transverse” Region

"Transverse" ET sum density: \(dE_T/d\eta d\phi\), with \(|\eta| < 1\) for “leading jet” events as a function of the leading jet \(p_T\) for the “transverse” region for PYTHIA Tune A and HERWIG (without MPI).

- Shows the Data - Theory for the scalar \(E_T\) sum density, \(dE_T/d\eta d\phi\), with \(|\eta| < 1\) for “leading jet” events as a function of the leading jet \(p_T\) for the “transverse” region for PYTHIA Tune A and HERWIG (without MPI).
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"Leading Jet" data at 1.96 TeV on the leading jet invariant mass for "leading jet" events as a function of the leading jet p_{T} 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).

Show the Data - Theory for the leading jet invariant mass for "leading jet" events as a function of the leading jet p_{T} for the "transverse" region for PYTHIA Tune A and HERWIG (without MPI).
The Leading Jet Mass

Shows the Data - Theory for the leading jet invariant mass for “leading jet” events as a function of the leading jet $p_T$ for the “transverse” region for PYTHIA Tune A and HERWIG (without MPI).
The “Underlying Event” in High \( P_T \) Jet Production (LHC)

The “Underlying Event”

Charged particle density in the “Transverse” region versus \( P_T(jet#1) \) at 1.96 TeV for PY Tune AW and HERWIG (without MPI).

Charged particle density in the “Transverse” region versus \( P_T(jet#1) \) at 14 TeV for PY Tune AW and HERWIG (without MPI).

“Underlying event” much more active at the LHC!
Drell-Yan Production (Run 2 vs LHC)

$<p_T(\mu^+\mu^-)>$ is much larger at the LHC!

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

- 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 the lepton-pair invariant mass at 14 TeV for PYTHIA Tune AW and HERWIG (without MPI).

HERWIG (without MPI) is much less active than PY Tune AW (with MPI)!

“Underlying event” much more active at the LHC!
We are making good progress in modeling “min-bias” collisions! I will talk more about this tomorrow.

We are making good progress in understanding and modeling the “underlying event” high transverse momentum jet production and in Drell-Yan production. I will talk much more about this tomorrow.

There are still some things we do not fully understand!

** Soft Underlying Event Energy **  ** Jet Mass **

** R(J2, J3) **

I will talk much more about this on Thursday!

AND we really do not know how to extrapolate to the LHC!