Studying the Underlying Event at CDF and the LHC

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Outline of Talk

- Review what we learned about “min-bias” and the “underlying event” in Run 1 at CDF.
- Discuss using Drell-Yan lepton-pair production to study the “underlying event”.
- Explain the various PYTHIA “underlying event” tunes and extrapolations to the LHC.
- “CDF-QCD Data for Theory”: My latest CDF Run 2 project.
- UE&MB@CMS: Plans to measure “min-bias” and the “underlying event” at CMS.
Proton-Antiproton Collisions at the Tevatron

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

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

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

“Soft” Hard Core (no hard scattering)

“Hard” Hard Core (hard scattering)

CDF “Min-Bias” trigger
1 charged particle in forward BBC AND
1 charged particle in backward BBC
The CDF “Min-Bias” trigger picks up most of the “hard core” cross-section plus a small amount of single & double diffraction.

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

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

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

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

“Hard” Hard Core (hard scattering)

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

The “underlying event” is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!
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, $dP_{\text{sum}}/d\eta d\phi$. 

$\Delta \eta \Delta \phi = 4\pi = 12.6$

### Charged Particles

- $p_T > 0.5$ GeV/c $|\eta| < 1$

#### Particle Densities

<table>
<thead>
<tr>
<th>Observable</th>
<th>CDF Run 2 “Min-Bias”</th>
<th>Average</th>
<th>Average Density per unit $\eta \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{chg}}$</td>
<td>Number of Charged Particles ($p_T &gt; 0.5$ GeV/c, $</td>
<td>\eta</td>
<td>&lt; 1$)</td>
</tr>
<tr>
<td>$P_{\text{sum}}$ (GeV/c)</td>
<td>Scalar $p_T$ sum of Charged Particles ($p_T &gt; 0.5$ GeV/c, $</td>
<td>\eta</td>
<td>&lt; 1$)</td>
</tr>
</tbody>
</table>

**Average Density** per unit $\eta \phi$

- $dN_{\text{chg}}/d\eta d\phi = 3/4\pi = 0.24$
- $dP_{\text{sum}}/d\eta d\phi = 3/4\pi$ GeV/c = 0.24 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, $dN_{chg}/d\eta d\phi$, 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 “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$^\circ$) 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, $PT_{\text{max}}$, to define a direction and look at the "associated" density, $dN_{\text{chg}}/d\eta d\phi$, in "min-bias" collisions ($p_T > 0.5$ GeV/c, $|\eta| < 1$).

- Shows 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.

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

"Associated" densities do not include $PT_{\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!).
Look at charged particle correlations in the azimuthal angle $\Delta \phi$ relative to the leading charged particle jet.

- Define $|\Delta \phi| < 60^\circ$ as “Toward”, $60^\circ < |\Delta \phi| < 120^\circ$ as “Transverse”, and $|\Delta \phi| > 120^\circ$ as “Away”.
- All three regions have the same size in $\eta$-$\phi$ space, $\Delta \eta \times \Delta \phi = 2 \times 120^\circ = 4\pi/3$. 

Look at the charged particle density in the “transverse” region!
Compares the average “transverse” charge particle density with the average “Min-Bias” charge particle density ($|\eta|<1, \text{p}_T>0.5 \text{ GeV}$). Shows how the “transverse” charge particle density and the Min-Bias charge particle density is distributed in $\text{p}_T$. 

$<dN_{\text{chg}}/d\eta d\phi> = 0.25$

$<dN_{\text{chg}}/d\eta d\phi> = 0.56$

$\text{p}_T(\text{charged jet#1}) > 30 \text{ GeV/c}$

$\text{p}_T(\text{charged jet#1}) > 5 \text{ GeV/c}$

library腳本
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 \((|\eta|<1, p_T>0.5 \text{ GeV})\) versus \(P_T(\text{charged jet#1})\) compared to the QCD hard scattering predictions of HERWIG 5.9 (default parameters with \(P_T(\text{hard})>3 \text{ GeV/c}\)).

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 $P_T(chgjet#1) > 30$ 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 $p_T$. 
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-qbar 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).
### 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 &quot;nearest neighbors.&quot;</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**
- **Multiple Parton Interaction**
- **Color String**
- **Determine by comparing with 630 GeV data!**
- **Take $E_0 = 1.8$ TeV**
- **Reference point at 1.8 TeV**

This tuning aims to adjust parameters to match experimental data, particularly at various CM energies, focusing on initial-state radiation and MPI effects.
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)).

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

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

### Old PYTHIA default (more initial-state radiation)

- Parameter: MSTP(81)
  - Tune B: 4
  - Tune A: 1
- Parameter: MSTP(82)
  - Tune B: 1
  - Tune A: 4
- Parameter: PARP(82)
  - Tune B: 2.0 GeV
  - Tune A: 1.9 GeV
- Parameter: PARP(83)
  - Tune B: 0.4
  - Tune A: 0.5
- Parameter: PARP(84)
  - Tune B: 0.4
  - Tune A: 0.5
- Parameter: PARP(85)
  - Tune B: 0.9
  - Tune A: 1.0
- Parameter: PARP(86)
  - Tune B: 0.95
  - Tune A: 1.0
- Parameter: PARP(89)
  - Tune B: 1.8 TeV
  - Tune A: 1.8 TeV
- Parameter: PARP(90)
  - Tune B: 0.9
  - Tune A: 2.0 GeV
- Parameter: PARP(67)
  - Tune B: 4.0
  - Tune A: 1.0
PYTHIA regulates the perturbative 2-to-2 parton-parton cross sections with cut-off parameters which allows one to run with $P_T^{(hard)} > 0$. One can simulate both "hard" and "soft" collisions in one program.

The relative amount of "hard" versus "soft" depends on the cut-off and can be tuned.

This PYTHIA fit predicts that 12% of all "Min-Bias" events are a result of a hard 2-to-2 parton-parton scattering with $P_T^{(hard)} > 5$ GeV/c (1% with $P_T^{(hard)} > 10$ GeV/c)!
Shows the center-of-mass energy dependence of the charged particle density, \(dN_{\text{chg}}/d\eta d\phi dP_T\), for “Min-Bias” collisions compared with PYTHIA Tune A with \(P_T(\text{hard}) > 0\).

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!
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 and final-state radiation.
Look at the “central” region after removing the lepton-pair.

Study the charged particles \((p_T > 0.5 \text{ GeV/c}, |\eta| < 1)\) and form the charged particle density, \(dN_{\text{ch}}/d\eta d\phi\), and the charged scalar \(p_T\) sum density, \(d\text{PT}_{\text{sum}}/d\eta d\phi\), by dividing by the area in \(\eta-\phi\) space.
CDF Run 1 $P_T(Z)$

**PYTHIA 6.2 CTEQ5L**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune A</th>
<th>Tune A25</th>
<th>Tune A50</th>
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<tr>
<td>MSTP(81)</td>
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<tr>
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* 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), Tune A25 ($<p_T(Z)> = 10.1$ GeV/c), and Tune A50 ($<p_T(Z)> = 11.2$ GeV/c).

* Vary the intrinsic KT!
Show 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) = $1.0 \rightarrow 4.0$ (i.e. like Tune A, best fit 2.5).

$DØ$

- $p_T^{\text{max}} > 180$ GeV ($\times 8000$)
- $130 < p_T^{\text{max}} < 180$ GeV ($\times 400$)
- $100 < p_T^{\text{max}} < 130$ GeV ($\times 20$)
- $75 < p_T^{\text{max}} < 100$ GeV

1/$\sigma_{\text{dijet}}$ vs $\Delta \phi_{\text{dijet}}$

$\Delta \phi_{\text{dijet}}$ (rad)
### CDF Run 1 $p_T(Z)$

**PYTHIA 6.2 CTEQ5L**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune DW</th>
<th>Tune AW</th>
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<tbody>
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**PT Distribution**

- CDF Run 1 Data
- PYTHIA Tune DW
- HERWIG

1.8 TeV
Normalized to 1

- 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!
"Transverse" Charged Particle Density: $dN/d\eta d\phi$

Shows the "transverse" charged particle density, $dN/d\eta d\phi$, versus $P_T(jet#1)$ for "leading jet" events at 1.96 TeV for PYTHIA Tune A, Tune AW, Tune DW, Tune BW, and HERWIG (without MPI).
“Transverse” Nchg Density

Shows the “transverse” charged particle density, \( dN/d\eta d\phi \), versus \( P_T(\text{jet#1}) \) for “leading jet” events at 1.96 TeV for PYTHIA Tune A, Tune AW, Tune DW, Tune BW, and HERWIG (without MPI).

Shows the “transverse” charged particle density, \( dN/d\eta d\phi \), versus \( P_T(\text{jet#1}) \) for “leading jet” events at 1.96 TeV for Tune DW, ATLAS, and HERWIG (without MPI).
"Transverse" PTsum Density

PYTHIA 6.2 CTEQ5L

<table>
<thead>
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<th>Parameter</th>
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Three different amounts of MPI!

Three different amounts of ISR!

Shows the “transverse” charged PTsum density, dPT/dηdφ, versus PT(jet#1) for “leading jet” events at 1.96 TeV for PYTHIA Tune A, Tune AW, Tune DW, Tune BW, and HERWIG (without MPI).
"Transverse" PTsum Density

PYTHIA 6.2 CTEQ5L

Three different amounts of MPI!

Shows the "transverse" charged PTsum density, dPT/dηdφ, versus PT(jet#1) for "leading jet" events at 1.96 TeV for PYTHIA Tune A, Tune AW, Tune DW, Tune BW, and HERWIG (without MPI).

Three different amounts of ISR!

Shows the "transverse" charged PTsum density, dPT/dηdφ, versus PT(jet#1) for "leading jet" events at 1.96 TeV for Tune DW, ATLAS, and HERWIG (without MPI).
**PYTHIA 6.2 Tunes**

PYTHIA 6.2 CTEQ5L

<table>
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<tr>
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</table>

**σ(MPI) at 1.96 TeV**

| Tune A | 309.7 mb |
| Tune DW| 351.7 mb |
| Tune DWT| 351.7 mb |
| ATLAS | 324.5 mb |

**σ(MPI) at 14 TeV**

| Tune A | 484.0 mb |
| Tune DW| 549.2 mb |
| Tune DWT| 829.1 mb |
| ATLAS | 768.0 mb |

**"Transverse" Charged Particle Average p_T**

<table>
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<tr>
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<th>Tune DW</th>
<th>Tune DWT</th>
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<td>5.0</td>
<td>15.0</td>
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</table>

- Shows the “transverse” charged average p_T, versus P_T(jet#1) for “leading jet” events at 1.96 TeV for Tune A, DW, ATLAS, and HERWIG (without MPI).

Identical to DW at 1.96 TeV but uses ATLAS extrapolation to the LHC!
"Transverse" Charged Particle Density: $dN/d\eta d\phi$

0.0 0.2 0.4 0.6 0.8 1.0

0 50 100 150 200 250 300 350 400 450

PT(jet#1) (GeV/c)

"Transverse" Charged Particle Average $p_T$

0.7 0.9 1.1 1.3 1.5 1.7

0 50 100 150 200 250 300 350 400 450

PT(jet#1) (GeV/c)

"Leading Jet" (|\eta|<2.0)

Charged Particles (|\eta|<1.0, PT>0.5 GeV/c)

1.96 TeV

CDF Run 2 Preliminary

data corrected to particle level

"Leading Jet"

MidPoint R = 0.7 |\eta(jet#1)| < 2

Identical to DW at 1.96 TeV but uses

ATLAS extrapolation to the LHC!

→ Shows the “transverse” charged average $p_T$, versus $p_T$(jet#1) for “leading jet” events at 1.96 TeV for Tune A, DW, ATLAS, and HERWIG (without MPI).
### PYTHIA 6.2 Tunes

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*Use LO $\alpha_s$ with $\Lambda = 192$ MeV!*
### PYTHIA 6.2 Tunes

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CMS uses Tune DWT and Tune D6T!

- **UE Parameters**
- **ISR Parameter**
- **Intrinsic KT**

*Use LO $\alpha_s$ with $\Lambda = 192$ MeV!*
PYTHIA Tune DW is very similar to Tune A except that it fits the CDF $P_T(Z)$ distribution and it uses the DØ preferred value of PARP(67) = 2.5 (determined from the dijet $\Delta\phi$ distribution).

PYTHIA Tune DWT is identical to Tune DW at 1.96 TeV but uses the ATLAS energy extrapolation to the LHC (i.e. PARP(90) = 0.16).

PYTHIA Tune D6 and D6T are similar to Tune DW and DWT, respectively, but use CTEQ6L (i.e. LHAPDF = 10042).
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).

$\langle p_T(\mu^+\mu^-)\rangle$ is much larger at the LHC!
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). HERWIG (without MPI) is much less active than PY Tune AW (with MPI)!

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

“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).

Charged particle density versus M(pair)

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

Charged particle density versus M(pair)
The goal is to produce data (corrected to the particle level) that can be used by the theorists to tune and improve the QCD Monte-Carlo models that are used to simulate hadron-hadron collisions.

Outline of the Project

- The “Towards”, “Away”, and “Transverse” regions of \( \eta - \phi \) space.
- Four Jet Topologies.
- The “transMAX”, “transMIN”, and “transDIF” regions.
- Also, study the “underlying event” in Drell-Yan production.
- Over 128 plots to get “blessed” and then to published. So far we have only looked at average quantities. We plan to also produce distributions and flow plots.
- We plan to construct a “CDF-QCD Data for Theory” WEBsite with the “blessed” plots together with tables of the data points and errors so that people can have access to the results.
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 $\Delta\eta \Delta\phi = 2 \times 120^\circ = 4\pi/3$.
“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.
**“Leading Jet” Observables at the Particle and Detector Level**

<table>
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<tr>
<th>Observable</th>
<th>Particle Level</th>
<th>Detector Level</th>
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<td>$dN_{\text{chg}}/d\eta d\phi$</td>
<td>Number of charged particles per unit $\eta-\phi$ ((p_T &gt; 0.5 \text{ GeV/c},</td>
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<td>$dP_T\text{sum}/d\eta d\phi$</td>
<td>Scalar $p_T$ sum of charged particles per unit $\eta-\phi$ ((p_T &gt; 0.5 \text{ GeV/c},</td>
<td>\eta</td>
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<tr>
<td>$&lt;p_T&gt;$</td>
<td>Average $p_T$ of charged particles ((p_T &gt; 0.5 \text{ GeV/c},</td>
<td>\eta</td>
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<tr>
<td>$P_{\text{max}}$</td>
<td>Maximum $p_T$ charged particle ((p_T &gt; 0.5 \text{ GeV/c},</td>
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<tr>
<td>$dE_T\text{sum}/d\eta d\phi$</td>
<td>Scalar $E_T$ sum of all particles per unit $\eta-\phi$ ((\text{all } p_T,</td>
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<td>$P_T\text{sum}/E_T\text{sum}$</td>
<td>Scalar $p_T$ sum of charged particles ((p_T &gt; 0.5 \text{ GeV/c},</td>
<td>\eta</td>
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</table>

Also include the leading jet mass (new)!
Data at 1.96 TeV on the overall number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and the overall scalar $p_T$ sum of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and the overall scalar ET sum of all particles ($|\eta| < 1$) for “leading jet” events as a function of the leading jet $p_T$. 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).
Data at 1.96 TeV on the overall number of charged particles (p_T > 0.5 GeV/c, |\eta| < 1) for “leading jet” events as a function of the leading jet p_T. 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 overall scalar $p_T$ sum of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for “leading jet” events as a function of the leading jet $p_T$. 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 overall scalar ET sum of all particles (|\eta| < 1) for “leading jet” events as a function of the leading jet p_T. 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).
CDF DiJet Event: $M(jj) \approx 1.4$ TeV

$E_{T}^{jet1} = 666$ GeV $E_{T}^{jet2} = 633$ GeV

$E_{sum} = 1,299$ GeV $M(jj) = 1,364$ GeV

CDF Run II Preliminary

Jet Et1 = 666 GeV (corr)
583 GeV (raw)
eta1 = 0.31 (detector)
0.43 (corr z)

Jet Et2 = 633 GeV (corr)
546 GeV (raw)
eta2 = -0.30 (detector)
-0.19 (corr z)

$M(jj)/E_{cm} \approx 70\%!!$
Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with p_T > 0.5 GeV/c and |η| < 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).
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).
Data at 1.96 TeV on the particle scalar $E_T$ sum density, $dE_T/d\eta d\phi$, for $|\eta| < 1$ 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).
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” 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).
Data at 1.96 TeV on the charged 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” 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).
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 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 A and HERWIG (without MPI) at the particle level (i.e. generator level).
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 the “away” 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).
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 "away" 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).
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 \(p_T\) for the “away” region. 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 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 “away” 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).
Data at 1.96 TeV on the charged particle density, 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 “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).
Data at 1.96 TeV on the charged scalar $p_T$ sum 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 $p_T$ 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).
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 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).
Data at 1.96 TeV on the charged particle average $p_T$, 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 “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).
Data at 1.96 TeV on the charged particle maximum $p_T$, 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 “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).
The “Transverse” Region

"Leading Jet""Transverse""Away"

Jet #1 Direction

Δφ

"Toward"

0.1 density corresponds to 0.42 charged particles in the "transverse" region!

→ Shows the Data - Theory for 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 “transverse” region for PYTHIA Tune A and HERWIG (without MPI).
The “Transverse” Region

"Leading Jet"

Jet #1 Direction

Δφ

“Toward”

“Transverse”

“Transverse”

“Away”

"Transverse" Charged PT Sum Density: dPT/dηdφ, with pT > 0.5 GeV/c and |η| < 1 for "leading jet" events as a function of the leading jet pT for the “transverse” region for PYTHIA Tune A and HERWIG (without MPI).

-0.2 0.0 0.2 0.4 0.6

Data - Theory (GeV/c)

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

0.1 density corresponds to 420 MeV/c in the “transverse” region!

Shows the Data - Theory for the charged scalar pT sum density, dPT/dηdφ, with pT > 0.5 GeV/c and |η| < 1 for “leading jet” events as a function of the leading jet pT for the “transverse” region for PYTHIA Tune A and HERWIG (without MPI).
The “Transverse” Region

 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).
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 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.
Data at 1.96 TeV on the density of charged particles, \( dN/d\eta d\phi \), with \( p_T > 0.5 \text{ GeV/c} \) and \( |\eta| < 1 \) for “leading jet” events as a function of the leading jet \( p_T \) for “transDIF” = “transMAX”-”transMIN. 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 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 “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).
Data at 1.96 TeV on the charged 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 “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).
Data at 1.96 TeV on the charged scalar $p_T$ sum 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 $p_T$ 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).
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).
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).
Data at 1.96 TeV on the density of charged particles, $dN/d\eta d\phi$, for $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “leading jet” events as a function of the leading jet $p_T$ for the “transMIN” region. The data are corrected to the particle level (with errors that include both the statistical errors and the systematic uncertainty) and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level (i.e., generator level).

These are the key plots! Tune A does not produce enough activity in the “transMIN” region!
Data at 1.96 TeV on the charged scalar PTsum density, \( \frac{dPT}{d\eta d\phi} \), with \( p_T > 0.5 \text{ GeV/c} \) and \( |\eta| < 1 \) for “leading jet” events as a function of the leading jet \( p_T \) for the “transMIN” 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).

These are the key plots! Tune A does not produce enough activity in the “transMIN” region!
Data at 1.96 TeV on the scalar ETsum density, \( d_{\text{ET}}/d\eta d\phi \), with \( |\eta| < 1 \) for “leading jet” events as a function of the leading jet pT for the “transMIN” 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).

These are the key plots! Tune A does not produce enough activity in the “transMIN” region!
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 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).
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!
“Min-Bias” is not well defined. What you see depends on what you trigger on! Every trigger produces some biases.

We have learned a lot about “Min-Bias” at the Tevatron, but we do not know what to expect at the LHC. This will depend on the Min-Bias Trigger!

We are making good progress in understanding and modeling the “underlying event”. However, we do not yet have a perfect fit to all the features of the CDF “underlying event” data!

Need to measure “Min-Bias” and the “underlying event” at the LHC as soon as possible and tune the Monte-Carlo modles and compare with CDF!
Min-Bias Studies: Charged particle distributions and correlations. Construct “charged particle jets” and look at “mini-jet” structure and the onset of the “underlying event”. (requires only charged tracks)

“Underlying Event” Studies: The “transverse region” in “leading Jet” and “back-to-back” charged particle jet production and the “central region” in Drell-Yan production. (requires charged tracks and muons for Drell-Yan)

Drell-Yan Studies: Transverse momentum distribution of the lepton-pair versus the mass of the lepton-pair, \( <p_T^{\text{pair}}>, <p_T^{2}(\text{pair})>, d\sigma/dp_T(\text{pair}) \) (only requires muons). Event structure for large lepton-pair \( p_T \) (i.e. \( \mu\mu + \text{jets} \), requires muons).
Min-Bias Studies: Charged particle distributions and correlations. Construct “charged particle jets” and look at “mini-jet” structure and the onset of the “underlying event” (as soon as possible!)

Drell-Yan Studies: Transverse momentum distribution of the lepton-pair versus the mass of the lepton-pair, \(<p_T^2(p_{\text{pair}})>, <p_T(p_{\text{pair}})>, d\sigma/dp_T(p_{\text{pair}})\) (only requires muons). Event structure for large lepton-pair \(p_T\) (i.e. \(\mu\mu +\text{jets}, \text{requires muons}\)).

Study charged particles and muons using the CMS detector at the LHC (as soon as possible)!
It is important to produce a lot of plots \textit{(corrected to the particle level)} so that the theorists can tune and improve the QCD Monte-Carlo models. If they improve the “transverse” region they might miss-up the “toward” region etc.. We need to show the whole story!

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There are over 128 plots to get “blessed” and then published. So far we have only looked at average quantities. We plan to also produce distributions and flow plots

I will construct a “CDF-QCD Data for Theory” WEBsite with the “blessed” plots together with tables of the data points and errors so that people can have access to the results.

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