The LHC Physics Environment

Talk 2: Extrapolations from the Tevatron to RHIC and the LHC

Rick Field
University of Florida

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

- 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 it.

The “underlying event” is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!
Start with the perturbative Drell-Yan muon pair production and add initial-state gluon radiation (in the leading log approximation or modified leading log approximation).

The “underlying event” consists of the “beam-beam remnants” and from particles arising from soft or semi-soft multiple parton interactions (MPI).

Of course the outgoing colored partons fragment into hadron “jet” and inevitably “underlying event” observables receive contributions from initial-state radiation.
Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and form the charged particle density, $dN_{chg}/d\eta d\phi$, and the charged scalar $p_T$ sum density, $dP_{T\text{sum}}/d\eta d\phi$. 

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

$\Delta \eta \Delta \phi = 4\pi = 12.6$  
$dN_{chg}/d\eta d\phi = 3/4\pi = 0.24$  
$dP_{T\text{sum}}/d\eta d\phi = 3/4\pi \text{ GeV/c} = 0.24 \text{ GeV/c}$
Shows the charged particle density in the "transverse" region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) at 1.96 TeV as defined by PTmax, PT(chgJet#1), and PT(jet#1) from PYTHIA Tune A at the particle level (i.e. generator level).
The cut-off $P_T^0$ that regulates the 2-to-2 scattering divergence is $1/(PT^2+P_{T0}^2)^{1/2}$.

$P_T^0$ and $P_{T0}$ are determined by the reference energy $E_0$. The probability of the MPI producing two gluons or quark-antiquark pairs is determined by the double-Gaussian parameter PARP(83). The fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter is $0.5$.

The hard-scattering cut-off $P_T^0$ is $1,000$ GeV/c for $W = 1.8$ TeV. The probability of the MPI producing two gluons either as described by PARP(85) or as a closed gluon loop is $0.66$. The remaining fraction consists of quark-antiquark pairs.

The parameter PARP(67) is 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.

The table shows the default values for the multiple parton interaction parameters.

- **Parameter**
  - PARP(83)
  - PARP(84)
  - PARP(85)
  - PARP(86)
  - PARP(89)
  - PARP(82)
  - PARP(90)
  - PARP(67)

- **Default**
  - 0.5
  - 0.2
  - 0.33
  - 0.66
  - 1 TeV
  - 1.9 GeV/c
  - 0.16
  - 1.0

- **Description**
  - Double-Gaussian: Fraction of total hadronic matter within PARP(84)
  - Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter.
  - Probability that the MPI produces two gluons with color connections to the “nearest neighbors.”
  - 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.
  - Determines the reference energy $E_0$.
  - The cut-off $P_T^0$ that regulates the 2-to-2 scattering divergence is $1/(PT^2+P_{T0}^2)^{1/2}$.
  - Determines the energy dependence of the cut-off $P_T^0$ as follows $P_T^0(E_{cm}) = P_T^0(E_{cm}/E_0)^{1/2}$ with $\epsilon = PARP(90)$.
  - 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.

The tuning of PYTHIA involves adjusting these parameters to match experimental data. For example, the reference point for the CM energy $W$ at $1.8$ TeV is determined by comparing with $630$ GeV data.
The cut-off $P_{T0}$ that regulates the 2-to-2 scattering divergence $1/P_{T0}^4 \rightarrow 1/(P_{T0}^2 + P_{T0}^2)^2$ is 1.9 GeV/c.

**PARP(67)**
- 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.

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<td>0.2</td>
<td>Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter</td>
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<tr>
<td>PARP(85)</td>
<td>0.33</td>
<td>Primarily determines two gluons with different nearest neighbors.</td>
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<tr>
<td>PARP(86)</td>
<td>0.66</td>
<td>Probability of 0 or 1 gluon production decreases as described by closed color string model.</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 parameter $P_{T0}$ that regulates the 2-to-2 scattering divergence $1/P_{T0}^4 \rightarrow 1/(P_{T0}^2 + P_{T0}^2)^2$</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>

**Tuning PYTHIA:**

- **Hard-Scattering Cut-Off $P_{T0}$**
  - Determines the energy dependence of the MPI!
  - Affects the amount of initial-state radiation!
  - Tunes PYTHIA:

**Multiple Parton Interaction Parameters**

- **Color String**
  - Take $E_0 = 1.8$ TeV
  - Determine by comparing with 630 GeV data!
“Transverse” Cones vs “Transverse” Regions

- Sum the $P_T$ of charged particles in two cones of radius 0.7 at the same $\eta$ as the leading jet but with $|\Delta \Phi| = 90^\circ$.
- Plot the cone with the maximum and minimum $P_{T,\text{sum}}$ versus the $E_T$ of the leading (calorimeter) jet.

"Cone Analysis" (Tano, Kovacs, Huston, Bhatti)
Energy Dependence of the “Underlying Event”

- Sum the \( p_T \) of charged particles (\( p_T > 0.4 \text{ GeV/c} \)) in two cones of radius 0.7 at the same \( \eta \) as the leading jet but with \( |\Delta \phi| = 90^\circ \). Plot the cone with the maximum and minimum \( \text{PT}_{\text{sum}} \) versus the \( E_T \) of the leading (calorimeter) jet.

- Note that PYTHIA 6.115 is tuned at 630 GeV with \( P_{T0} = 1.4 \text{ GeV} \) and at 1,800 GeV with \( P_{T0} = 2.0 \text{ GeV} \). This implies that \( \epsilon = \text{PARP}(90) \) should be around 0.30 instead of the 0.16 (default).

- For the MIN cone 0.25 GeV/c in radius \( R = 0.7 \) implies a \( \text{PT}_{\text{sum}} \) density of \( \frac{d\text{PT}_{\text{sum}}}{d\eta d\phi} = 0.16 \text{ GeV/c} \) and 1.4 GeV/c in the MAX cone implies \( \frac{d\text{PT}_{\text{sum}}}{d\eta d\phi} = 0.91 \text{ GeV/c} \) (average \( \text{PT}_{\text{sum}} \) density of 0.54 GeV/c per unit \( \eta \).-phi).
"Transverse" Charged Densities
Energy Dependence

Shows the “transverse” charged PT\textsubscript{sum} density (|\eta|<1, P\textsubscript{T}>0.4 GeV) versus P\textsubscript{T}(charged jet#1) at 630 GeV predicted by HERWIG 6.4 (P\textsubscript{T}(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P\textsubscript{T}(hard) > 0, CTEQ5L, Set A, \epsilon = 0, \epsilon = 0.16 (default) and \epsilon = 0.25 (preferred)).

Also shown are the PT\textsubscript{sum} densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti “transverse” cone analysis at 630 GeV.
“Transverse” Charged Densities Energy Dependence

Shows the “transverse” charged PT\textsubscript{sum} density (|\eta|<1, P\textsubscript{T}>0.4 GeV) versus P\textsubscript{T}(charged jet\#1) at 630 GeV predicted by HERWIG 6.4 (P\textsubscript{T}\text{\text{hard}} > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P\textsubscript{T}\text{\text{hard}} > 0, CTEQ5L, Set A, \varepsilon = 0, \varepsilon = 0.16 (default) and \varepsilon = 0.25 (preferred)).

Also shown are the PT\textsubscript{sum} densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti “transverse” cone analysis at 630 GeV.

Lowering P\textsubscript{T0} at 630 GeV (i.e. increasing \varepsilon) increases UE activity resulting in less energy dependence. Increasing \varepsilon produces less energy dependence for the UE resulting in less UE activity at the LHC!

Rick Field Fermilab MC Workshop October 4, 2002!
# PYTHIA 6.2 Tunes

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- All use LO $\alpha_s$ with $\Lambda = 192$ MeV!
- Uses CTEQ6L
- Tune A energy dependence! (not the default)

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## PYTHIA 6.2 Tunes

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

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

ATLAS energy dependence! (PYTHIA default)
### PYTHIA 6.2 Tunes

<table>
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<th>Parameter</th>
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**UE Parameters**

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

**ATLAS energy dependence! (PYTHIA default)**

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July 1, 2009

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These are "old" PYTHIA 6.2 tunes!
There are new 6.420 tunes by
Peter Skands (Tune S320, update of S0)
Peter Skands (Tune N324, N0CR)
Hendrik Hoeth (Tune P329, "Professor")
Peter's Pythia Tunes WEBsite

Peter's Pythia Plots
February 2009 @ P. Z. Skands

Navigate these pages by using the menu to the left. More plots will be added, as new tunes become available, and as the available data increases. The default for each topic is a comparison of a small number of tunes to available data (or just to each other if no data exists), but look for links at the top of each page for comparisons with more models.

Apr 2009: Full descriptions and parameters of the "Perugia" tunes (submitted to the Perugia MPI workshop proceedings)

The tunes currently available on the plots are (numbered as in PYTUNES):

**Tunes using Q2-ordered model**

- **100: A**: Rick Field's Tune A to Tevatron Underlying-Event Data. Uses the "old" UE and shower models, with a double-gaussian matter profile, 1 GeV of primordial Kt, and near-maximal color correlations. [Oct 2002]

- **103: DW**: Rick Field's Tune DW to Tevatron Underlying-Event and Drell-Yan Data. Similar to Tune A, but has 1 GeV of primordial Kt and uses a very small renormalization scale for initial-state radiation (i.e., more BR radiation). It also has completely maximal color correlations. [Dec 2002]

- **104: DWT**: Variant of DW using the Pythia 6.2 default collider energy scaling (has worse agreement with Tevatron energy scaling quantities than DW). [Apr 2008]

- **106: ATLAS-DC2** ("Roman"): first ATLAS tune of the Q2-ordered showers and old UE framework. Does not give very good agreement with Tevatron min-bias quantities.

- **107: A-CR**: variant of Tune A using the Pythia 6.2 default color connections but with the new "color annealing" color reconnection model applied as an afterburner. Is intended as an example of strong color reconnections. [Mar 2007]

- **108: DE**: Rick Field's Tune DE to Tevatron data, using CTEQ6L1 PDFs.

- **110: A-Pro**: Tune A with LEP tunes from Professor. [Oct 2006]

- **112: DM-Pro**: Tune DMT with LEP tunes from Professor. [Oct 2008]

- **114: DWT-Pro**: Tune DWT with LEP tunes from Professor. [Oct 2008]

- **116: ATLAS-DC2-Pro**: ATLAS-DC2 with LEP tunes from Professor. [Oct 2008]


- **118: DMT-Pro**: Tune DMT with LEP tune from Professor. [Oct 2008]

- **126: NOCR-Pro**: Tune of the Q2-ordered showers and old UE framework made with Professor, an automated tuning tool. [Feb 2009]

**Tunes using pT-ordered model**

- **300: S0**: First Sandhoff-Skands Tune of the "new" UE and shower framework, with a smoother matter profile than Tune A, 2 GeV of primordial Kt, and "colour annealing" color reconstructions. Uses the default Pythia energy scaling rather than that of Tune A. [Apr 2009]

- **303: S0A**: A variant of S0 which is identical to S0 at the Tevatron, but which uses the Tune A energy scaling of the UE activity. [Apr 2006]

- **304: NOCR**: Sandhoff-Skands "best by" without color reconctions. Gives less good agreement with Tevatron data. [Apr 2006]

- **306: ATLAS-CSC**: first ATLAS tune of the pT-ordered showers and new UE framework. Does not give very good agreement with Tevatron min-bias quantities.

- **313: S0A-Pro**: A variant of S0A revamped with a comprehensive return of the fragmentation parameters to LEP data (by the "Professor" tool, hence the name). [Oct 2008]

- **314: NOCR-Pro**: NOCR with LEP tune from Professor. [Oct 2008]

- **320: Perugia 6.1** "Perugia" update of S0-Pro. [Feb 2009]

- **321: Perugia HARD**: Systematically "hard" variant of Perugia 0. [Feb 2009]

- **322: Perugia SOFT**: Systematically "soft" variant of Perugia 0. [Feb 2009]

- **323: Perugia 3**: Variant of Perugia 0 with different HERA/LM balance and different collider energy scaling. [Feb 2009]

- **324: Perugia NOCR**: "Perugia" update of NOCR-Pro. [Feb 2009]

- **325: Perugia X**: Variant of Perugia 0 using MMRST LO* PDFs. [Feb 2009]

- **326: Perugia 6**: Variant of Perugia 0 using CTEQ6L1 PDFs. [Feb 2009]

- **327: Pro-p T**: "Tune of the pT-ordered showers and new UE framework made with Professor, an automated tuning tool. [Feb 2009]

http://home.fnal.gov/~skands/leshouches-plots/
Min-Bias “Associated” Charged Particle Density

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

- Shows the “associated” charged particle density in the “transverse” regions as a function of PTmax for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including PTmax) for “min-bias” events at 0.2 TeV and 14 TeV from PYTHIA Tune DW and Tune DWT at the particle level (i.e. generator level). The STAR data from RHIC favors Tune DW!

- 35% more at RHIC means 26% less at the LHC!
Min-Bias “Associated” Charged Particle Density

About a factor of 2.7 increase in the “transverse” region!

 Shows the “associated” charged particle density in the “toward”, “away” and “transverse” regions as a function of PTmax for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including PTmax) for “min-bias” events at 1.96 TeV and at 0.2 TeV from PYTHIA Tune DW at the particle level (i.e. generator level).
Min-Bias “Associated” Charged Particle Density

Showed the “associated” charged particle density in the “toward”, “away” and “transverse” regions as a function of PTmax for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, not including $PT_{max}$) for “min-bias” events at 1.96 TeV and at 14 TeV from PYTHIA Tune DW at the particle level (i.e. generator level).
Min-Bias “Associated” 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, \(|\eta| < 1\), not including PTmax) for “min-bias” events at 0.2 TeV, 1.96 TeV and 14 TeV predicted by PYTHIA Tune DW at the particle level (i.e. generator level).
At STAR they have measured the “underlying event at $W = 200$ GeV ($|\eta| < 1$, $p_T > 0.2$ GeV) and compared their uncorrected data with PYTHIA Tune A + STAR-SIM.
The “Underlying Event” at STAR

Conclusions

I. Hadron Collisions at RHIC take place at an order of magnitude smaller $\sqrt{s}$ than the Tevatron. Nevertheless, jets are observed and reconstructed down to $p_T=5$ GeV and are well described by pQCD.

II. Comparisons between several jetfinders reveal consistent results.

III. Interest in the Underlying Event at RHIC Kinematics is driven by the need for jet energy scale corrections as well as pure physics interests (see talks by M. Lisa and H. Caines).

IV. UE at RHIC appears to be independent of jet $p_T$ and decoupled from hard interaction.

V. CDF Tune A provides an **excellent** description of the UE at $\sqrt{s}=200$ GeV (thanks Rick!)

VI. Underlying Event distributions in general smaller than those at CDF. Tower & Track multiplicities are the exception, but this may be due to the 0.2 (STAR) versus 0.5 GeV (CDF) $p_T/E_t$ cut-off.

VII. For a cone jet with R=0.7 UE contributes 0.5-0.9 GeV.

VIII. Comparison of Leading Jet and Back-to-Back distributions indicate that large angle radiation contributions are small at RHIC energies.
Data on the charged particle scalar $p_T$ sum density, $d\text{PT}/d\eta d\phi$, as a function of the leading jet $p_T$ for the “toward”, “away”, and “transverse” regions compared with PYTHIA Tune A.
The "Underlying Event" at STAR

![Graph showing Charged PTsum Density](image)

- Data on the charged particle scalar $p_T$, sum density, $dP_T/d\eta d\phi$, as a function of the leading jet $p_T$ for the "toward", "away", and "transverse" regions compared with PYTHIA Tune A.
Min-Bias “Associated” 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 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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Min-Bias “Associated” Charged Particle Density

“Transverse” Charged Particle Density: $dN/d\eta d\phi$

0.0 0.4 0.8 1.2 1.6 0 5 10 15 20 25

PTmax (GeV/c)

“Transverse” Charged Density

PY Tune A

Min-Bias 14 TeV

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

RDF Preliminary generator level

PY64 Tune P329

PY64 Tune S320

PY Tune DW

PY Tune DWT

PY ATLAS

Min-Bias 1.96 TeV

Tevatron

LHC

PTmax Direction

Δφ

“Toward”

“Transverse”

“Away”

“Transverse” Charged Particle Density: $dN/d\eta d\phi$

0.0 0.2 0.4 0.6 0.8

0 2 4 6 8 10 12 14 16 18 20

PTmax (GeV/c)

“Transverse” Charged Density

RDF Preliminary generator level

PY Tune A

PY64 Tune P329

PY64 Tune S320

PY64 Tune N324

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

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

If the LHC data are not in the range shown here then we learn new (QCD) physics!

Shows the “associated” charged particle density in the “transverse” region as a function of PTmax for charged particles (pT > 0.5 GeV/c, 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.
Z-Boson: “Towards” Region

- 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 “Z-Boson” events as a function of \( p_T(Z) \) for the “toward” region from PYTHIA Tune AW, Tune DW, Tune S320, and Tune P329 at the particle level (i.e. generator level).

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

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Z-Boson: “Towards” Region

If the LHC data are not in the range shown here then we learn new (QCD) physics!

- Data at 1.96 TeV on the density of charged particles, dN/d(η,φ), with p_T > 0.5 GeV and |η| < 1 for “Z-Boson” events as a function of P_T(Z) for the “toward” region from PYTHIA Tune AW, Tune DW, Tune S320, and Tune P329 at the particle level (i.e. generator level).

- Extrapolations of PYTHIA Tune AW, Tune DW, Tune DWT, Tune S320, and Tune P329, and pyATLAS to the LHC.
Proton-AntiProton Collisions at the Tevatron

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

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

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

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

CDF “Min-Bias” trigger
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

“Soft” Hard Core (no hard scattering)
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 \(P_T(\text{hard}) > 10 \text{ GeV/c}\) which increases to 12% at 14 TeV!
Charged particle (all $p_T$) pseudo-rapidity distribution, $dN_{\text{chg}}/d\eta d\phi$, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.

Charged particle ($p_T>$0.5 GeV/c) pseudo-rapidity distribution, $dN_{\text{chg}}/d\eta d\phi$, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.
Charged particle (all $p_T$) pseudo-rapidity distribution, $dN_{\text{chg}}/d\eta d\phi$, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.

Extrapolations (all $p_T$) of PYTHIA Tune A, Tune DW, Tune S320, Tune P324, and ATLAS to the LHC.
Charged particle (all $p_T$) pseudo-rapidity distribution, $dN_{\text{chg}}/d\eta d\phi$, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.

Extrapolations (all $p_T$) of PYTHIA Tune A, Tune DW, Tune S320, Tune P324, and ATLAS to the LHC.
Charged particle (all p_T) pseudo-rapidity distribution, dN_{chg}/d\eta, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.

Extrapolations (all pT) of PYTHIA Tune A, Tune DW, Tune S320, Tune P324, and ATLAS to the LHC.

If the LHC data are not in the range shown here then we learn new (QCD) physics!
Charged particle ($p_T > 0.5$ GeV/c) pseudo-rapidity distribution, $dN_{\text{chg}}/d\eta d\phi$, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.

Extrapolations ($p_T > 0.5$ GeV/c) of PYTHIA Tune A, Tune DW, Tune S320, Tune P324. and ATLAS to the LHC.
Charged Particle Density: \( dN/d\eta \)

**Charged particle \((p_T > 0.5 \text{ GeV/c})\) pseudo-rapidity distribution, \(dN_{\text{chg}}/d\eta d\phi\), at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.

**Extrapolations \((p_T > 0.5 \text{ GeV/c})\) of PYTHIA Tune A, Tune DW, Tune S320, Tune P324, and ATLAS to the LHC.**
Charged Particle Density: $dN/d\eta$

If the LHC data are not in the range shown here then we learn new (QCD) physics!

- Charged particle ($p_T > 0.5$ GeV/c) transverse-rapidity distribution $dN_{\text{ch}}/d\eta d\phi$, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.

- Extrapolations ($p_T > 0.5$ GeV/c) of HERWIG THIA Tune A, Tune DW, Tune S320, Tune P324, and ATLAS to the LHC.
MPI, Pile-Up, and Overlap

MPI: Multiple Parton Interactions

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

Pile-Up

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

Overlap

- Overlap: An experimental timing issue where a proton-antiproton collision from the next beam crossing gets included in the proton-antiproton collision from the current beam crossing because the next crossing happened before the event could be read out.
The primary vertex is the highest PTsum of charged particles pointing towards it.

Normally one only includes those charged particles which point back to the primary vertex.

The primary vertex is presumably the collision that satisfied the trigger. Maybe not for “min-bias” events?

Is the pile-up biased?
Is the pile-up the same for all triggers?
Does pile-up conspire to help satisfy your trigger?
How well do we model pile-up?
Show the charged multiplicity distribution ($|\eta| < 2$, all $p_T$) for $N_{\text{pile}} = 1$ (i.e. shows, on the average, what one event looks like). The plot shows the probability of finding 0, 1, 2, ... etc. charged particles. The sum of the points is equal to one. The mean is 24.39 charged particles and $\sigma = 19.7$.

Show the charged particle pseudo-rapidity distribution (all $p_T$) for $N_{\text{pile}} = 1$ (i.e. shows, on the average, what one event looks like). The plot shows the $\langle N_{\text{chg}} \rangle$ in a 0.4 bin (i.e. not divided by bin size). The sum of the points with $|\eta| < 2$ is 24.39.
Pile-Up at the LHC

“Central Limit Theorem”: $\langle N_{\text{chg}} \rangle \sim N_{\text{pile}}, \sigma \sim \sqrt{N_{\text{pile}}}$!

Shows the charged multiplicity distribution $(|\eta| < 2, \text{all } p_T)$ for $N_{\text{pile}} = 10$ (i.e. shows, on the average, what 10 events looks like). The plot shows the probability of finding 0, 10, 20, … etc. charged particles. The sum of the points is equal to one. The mean is 243.9 charged particles and $\sigma = 62.3$. Also shown is the $N_{\text{pile}} = 1$ distribution scaled by a factor of 10 (i.e. $N_{\text{chg}} \rightarrow 10 \times N_{\text{chg}}$).

Shows the charged multiplicity distribution $(|\eta| < 2, \text{all } p_T)$ for $N_{\text{pile}} = 50$ (i.e. shows, on the average, what 50 events looks like). The plot shows the probability of finding 0, 50, 100, … etc. charged particles. The sum of the points is equal to one. The mean is 1219.5 charged particles and $\sigma = 138.9$. Also shown is the $N_{\text{pile}} = 1$ distribution scaled by a factor of 50 (i.e. $N_{\text{chg}} \rightarrow 50 \times N_{\text{chg}}$) and the $N_{\text{pile}} = 10$ distribution scaled by a factor of 5 (i.e. $N_{\text{chg}} \rightarrow 5 \times N_{\text{chg}}$).
Charged multiplicity distribution ($|\eta| < 2$) for $N_{\text{pile}} = 1$ (i.e. shows, on the average, what one event looks like). The plot shows the probability of finding 0, 1, 2, … etc. charged particles. The five curves correspond to $p_T(\text{min}) = 0, 1.0, 2.5, 5.0, \text{ and } 10.0$ GeV/c.

Shows the charged particle pseudo-rapidity distribution for $N_{\text{pile}} = 1$ (i.e. shows, on the average, what one event looks like). The plot shows the $<N_{\text{chg}}>$ in a 0.4 bin (i.e. not divided by bin size). The five curves correspond to $p_T(\text{min}) = 0, 1.0, 2.5, 5.0, \text{ and } 10.0$ GeV/c.
Charged multiplicity distribution ($|\eta| < 2$) for $N_{\text{pile}} = 1$ (i.e. shows, on the average, what one event looks like). The plot shows the probability of finding 0, 1, 2, … etc. charged particles. The five curves correspond to $p_T(\text{min}) = 0, 1.0, 2.5, 5.0$, and $10.0$ GeV/c.

Shows the charged particle pseudo-rapidity distribution for $N_{\text{pile}} = 1$ (i.e. shows, on the average, what one event looks like). The plot shows the $\langle N_{\text{ch}} \rangle$ in a 0.4 bin (i.e. not divided by bin size). The five curves correspond to $p_T(\text{min}) = 0, 1.0, 2.5, 5.0$, and $10.0$ GeV/c.
Shows the charged particle $p_T$ distribution ($|\eta| < 2$) for $N_{pile} = 1$ (i.e. shows, on the average, what one event looks like). The plot shows the $\langle N_{ch} \rangle$ in a 1.0 GeV/c bin (i.e. not divided by bin size). The sum of the points gives 24.39.

Shows the average number of charged particle the $P_T$-cut ($|\eta| < 2$) for $N_{pile} = 1$ (i.e. shows, on the average, what one event looks like). The first point corresponds to $\langle N_{ch} \rangle = 24.39$. The fit corresponds to $\langle N_{ch} \rangle = 24.39 \exp(-1.4p_T(\text{min}))$. 
Pile-Up at the LHC

Shows the charged multiplicity distribution ($p_T > 5$ GeV/c, $|\eta| < 2$) for $N_{\text{pile}} = 1$ (i.e. shows, on the average, what one event looks like). The plot shows the probability of finding 0, 1, 2, … etc. charged particles. The plot also shows the “associated multiplicity” distribution (open squares), $\langle \text{AssocNchg} \rangle = \langle \text{Nchg} \rangle - 1$, for events with at least one charged particle with $p_T > 5$ GeV/c (i.e. the overall average multiplicity is $\langle \text{AssocNchg} \rangle + 1$). Note that $\langle \text{AssocNchg} \rangle + 1 = 1.277$ and $\langle \text{Nchg} \rangle = 0.0466$. There are many more particles in events with at least one charged particle with $p_T > 5$ GeV/c, than in an average “min-bias” event. Also, note that the probability of getting an additional particle in an event with at least one charged particle with $p_T > 5$ GeV/c (i.e. AssocNchg = 1 is greater than the probability of getting one particle in a typical “min-bias” event, Nchg = 1).
Shows the probability of finding $N_{\text{ch}} \geq 1$ and $N_{\text{ch}} \geq 2$ ($p_T > 5 \text{ GeV}/c$, $|\eta| < 2$) versus $N_{\text{pile}}$, where $N_{\text{pile}} = 1$ means one event, $N_{\text{pile}} = 10$ means 10 events, etc.. The plot also shows the probability of finding $\text{Assoc}N_{\text{ch}} \geq 1$ (overall multiplicity $\geq 2$) for events with at least one charged particle with $p_T > 5 \text{ GeV}/c$. For $N_{\text{pile}} = 1$ (i.e. one event) there is a strong correlation since $\text{Prob}(\text{Assoc}N_{\text{ch}} \geq 1)$ is much greater than $\text{Prob}(N_{\text{ch}} \geq 2)$. However, this correlation diminishes as $N_{\text{pile}}$ becomes large!

“Central Limit Theorem” strikes again??
Data at 1.96 TeV on the average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.4$ GeV/c, $|\eta| < 1$) for “min-bias” collisions at CDF Run 2. The data are corrected to the particle level and are compared with PYTHIA Tune A at the particle level (i.e. generator level).
Min-Bias: Average PT versus Nchg

- Beam-beam remnants (i.e. soft hard core) produces low multiplicity and small $<p_T>$ with $<p_T>$ independent of the multiplicity.
- Hard scattering (with no MPI) produces large multiplicity and large $<p_T>$.
- Hard scattering (with MPI) produces large multiplicity and medium $<p_T>$.

This observable is sensitive to the MPI tuning!

The CDF “min-bias” trigger picks up most of the “hard core” component!
Data at 1.96 TeV on the average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.4$ GeV/c, $|\eta| < 1$) for “min-bias” collisions at CDF Run 2. The data are corrected to the particle level and are compared with PYTHIA Tune A, Tune DW, and the ATLAS tune at the particle level (i.e. generator level).

Particle level predictions for the average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, excluding the lepton-pair) for for Drell-Yan production (70 < M(pair) < 110 GeV) at CDF Run 2.
Data at 1.96 TeV on the average \( p_T \) of charged particles versus the number of charged particles (\( p_T > 0.4 \text{ GeV}/c, |\eta| < 1 \)) for “min-bias” collisions at CDF Run 2. The data are corrected to the particle level and are compared with PYTHIA Tune A, Tune DW, and the ATLAS tune at the particle level (i.e. generator level).

Particle level predictions for the average \( p_T \) of charged particles versus the number of charged particles (\( p_T > 0.5 \text{ GeV}/c, |\eta| < 1 \), excluding the lepton-pair) for for Drell-Yan production (70 < M(pair) < 110 GeV) at CDF Run 2.
Average PT versus Nchg

- Z-boson production (with low $p_T(Z)$ and no MPI) produces low multiplicity and small $\langle p_T \rangle$.
- High $p_T$ Z-boson production produces large multiplicity and high $\langle p_T \rangle$.
- Z-boson production (with MPI) produces large multiplicity and medium $\langle p_T \rangle$.

CDF Run 2 Preliminary data corrected generator level theory

"Drell-Yan Production" $70 < M(\text{pair}) < 110$ GeV

Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c) excluding the lepton pair

High $p_T$ Z-Boson Production

Drell-Yan

Drell-Yan Production (no MPI)

Drell-Yan Production (with MPI)
Predictions for the average $P_T(Z$-Boson) versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, excluding the lepton-pair) for for Drell-Yan production ($70 < M$(pair) < 110 GeV) at CDF Run 2.

Data on the average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, excluding the lepton-pair) for for Drell-Yan production ($70 < M$(pair) < 110 GeV) at CDF Run 2. The data are corrected to the particle level and are compared with various Monte-Carlo tunes at the particle level (i.e. generator level).
Predictions for the average $P_T(Z\text{-Boson})$ versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, excluding the lepton-pair) for Drell-Yan production ($70 < M\text{(pair)} < 110$ GeV) at CDF Run 2.

Data on the average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, excluding the lepton-pair) for Drell-Yan production ($70 < M\text{(pair)} < 110$ GeV) at CDF Run 2. The data are corrected to the particle level and are compared with various Monte-Carlo tunes at the particle level (i.e. generator level).
Data the average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, excluding the lepton-pair) for Drell-Yan production ($70 < M(\text{pair}) < 110$ GeV, $p_T(\text{pair}) < 10$ GeV/c) at CDF Run 2. The data are corrected to the particle level and are compared with various Monte-Carlo tunes at the particle level (i.e. generator level).
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The average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for “min-bias” collisions at 1.96 TeV from PYTHIA Tune A, Tune DW, Tune S320, Tune N324, and Tune P324.

Extrapolations of PYTHIA Tune A, Tune DW, Tune S320, and Tune P324 to the LHC.
The average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for “min-bias” collisions at 1.96 TeV from PYTHIA Tune A, Tune DW, Tune S320, Tune N324, and Tune P324.

Extrapolations of PYTHIA Tune A, Tune DW, Tune S320, and Tune P324 to the LHC.
I believe because of the STAR analysis we are now in a position to make some predictions at the LHC!

The amount of activity in “min-bias” collisions.

The amount of activity in the “underlying event” in hard scattering events.

The amount of activity in the “underlying event” in Drell-Yan events.
I believe because of the STAR analysis, we are now in a position to make some predictions at the LHC!

→ The amount of activity in “min-bias” collisions.

If the LHC data are not in the range shown here then we learn new (QCD) physics!

→ The amount of activity in hard scattering events.

→ The amount of activity in the “underlying event” in Drell-Yan events.
We are making good progress in understanding and modeling the “underlying event”. RHIC data at 200 GeV are very important!

The new Pythia $p_T$ ordered tunes (py64 S320 and py64 P329) are very similar to Tune A, Tune AW, and Tune DW. At present the new tunes do not fit the data better than Tune AW and Tune DW. However, the new tune are theoretically preferred!

It is clear now that the default value PARP(90) = 0.16 is not correct and the value should be closer to the Tune A value of 0.25.

The new and old PYTHIA tunes are beginning to converge and I believe we are finally in a position to make some legitimate predictions at the LHC!

All tunes with the default value PARP(90) = 0.16 are wrong and are overestimating the activity of min-bias and the underlying event at the LHC! This includes all my “T” tunes and the ATLAS tunes!

Need to measure “Min-Bias” and the “underlying event” at the LHC as soon as possible to see if there is new QCD physics to be learned!
Early LHC Thesis Projects

Thesis 1: Measure $dN_{chg}/d\eta$ and $<p_T>$ versus $N_{chg}$ in “min-bias” collisions.

Thesis 2: Measure the “toward”, “away”, and “transverse” region as a function of $P_{T,max}$ in “min-bias” collisions.

Thesis 3: Measure the “toward”, “away”, and “transverse” region as a function of $P_T(chgjet#1)$.

Thesis 4: Measure the “toward”, “away”, and “transverse” region as a function of $P_T(Z)$ for $Z$-boson production.

Thesis 5: Measure $P_T(Z)$ and $<p_T>$ versus $N_{chg}$ for $Z$-boson production (all $P_T(Z)$, $P_T(Z) < 10$ GeV/c).

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