Early QCD Measurements at the LHC

Rick Field
University of Florida

Outline of Talk

- The inelastic non-diffractive cross section.
- What is the “underlying event”?
- The QCD Monte-Carlo Model tunes.
- The Pythia MPI energy scaling parameter PARP(90).
- Extrapolations from the Tevatron to RHIC and the LHC.
- The “underlying event” at STAR.
- Min-Bias and the “underlying event”.
- The “underlying event” in Drell-Yan production.
- LHC predictions!
- Summary & Conclusions.
Outline of Talk

1. The inelastic cross section
2. What is the “underlying event”?
3. The QCD Monte-Carlo model tunes
4. The Pythia MPI energy scaling parameter PARP(90)
5. Extrapolations from the Tevatron to RHIC
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8. The “underlying event” in Drell-Yan production
9. LHC predictions!
10. Summary & Conclusions.

Amplitude Analysis of the Reaction $K^-p \rightarrow \pi^-Y^*(1385)$$\dagger$

M. Aguilar-Benitez, S. U. Chung, R. L. Eisner, and R. D. Field
Brookhaven National Laboratory, Upton, New York 11973
(Received 19 June 1972)

We present a model-independent amplitude analysis of the reaction $K^-p \rightarrow \pi^-Y^*(1385)$ at 3.9 and 4.6 GeV/c incident momenta. By observing the two-step decay of the $Y^*(1385)$ we determine the magnitudes and two relative phases of the four independent transversity amplitudes which describe the reaction. These amplitudes are found to be in rough agreement with the predictions of the naive quark model; however, the predictions do not hold exactly.
Proton-Proton Collisions

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

- Elastic Scattering
- Single Diffraction
- Double Diffraction

The "hard core" component contains both "hard" and "soft" collisions.

"Soft" Hard Core (no hard scattering)

"Hard" Hard Core (hard scattering)
The inelastic non-diffractive cross section versus center-of-mass energy from PYTHIA ($\times 1.2$).

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

$\sigma_{\text{HC}}$ varies slowly. Only a 13% increase between 7 TeV ($\approx 58$ mb) and 14 TeV ($\approx 66$ mb).

Linear on a log scale!
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 the “underlying event”.

The “underlying event” is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!
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, $\Delta \eta \times \Delta \phi = 2 \times 120^\circ = 4\pi/3$.
**PYTHIA 6.206 Defaults**

**PYTHIA default parameters**

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**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)

**MPI constant probability scattering**

- Pythia 6.206 (default) MSTP(82)=1 PARP(81) = 1.9 GeV/c CDF Data data uncorrected theory corrected

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LHC@BNL Workshop
February 8, 2010

Rick Field – Florida/CDF/CMS
The cut-off $P_{T0}$ that regulates the 2-to-2 scattering divergence is

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

1.9 GeV/c

**PARP(82)**

A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of PARP(67) the more initial-state radiation.

1.0

**PARP(67)**

Determine by comparing with 630 GeV data!

1.8 TeV

**PARP(90)**

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

0.16

**PARP(84)**

Determines the energy dependence of the MPI!

0.2

**PARP(83)**

Determines the reference energy $E_0$.

0.5

**PARP(85)**

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

0.33

**PARP(86)**

Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter

0.66

**PARP(89)**

Determines the energy dependence of the MPI as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^\varepsilon$ with $\varepsilon = PARP(90)$

1 TeV

0.25 (Set A))

Tuning PYTHIA:

- Multiple Parton Interaction Parameters
- Hard Core
- Color String
- Double-Gaussian
- Determines the energy dependence of the MPI!
“Transverse” Cones vs “Transverse” Regions

Transverse Cone: \( \pi(0.7)^2 = 0.49\pi \)

Transverse Region: \( 2\pi/3 = 0.67\pi \)

→ 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 \( P_{T_{sum}} \) versus the \( E_T \) of the leading (calorimeter) jet.

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

“Cone Analysis” (Tano, Kovacs, Huston, Bhatti)

- Sum the $p_T$ of charged particles ($p_T > 0.4$ 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 $P_T$ sum versus the $E_T$ of the leading (calorimeter) jet.

- Note that PYTHIA 6.115 is tuned at 630 GeV with $P_{T0} = 1.4$ GeV and at 1,800 GeV with $P_{T0} = 2.0$ 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 $P_T$ density of $dP_T/d\eta d\phi = 0.16$ GeV/c and 1.4 GeV/c in the MAX cone implies $dP_T/d\eta d\phi = 0.91$ GeV/c (average $P_T$ density of 0.54 GeV/c per unit $\eta$-$\phi$).
Shows the “transverse” charged PT$_{\text{sum}}$ density ($|\eta|<1$, P$_T$>0.4 GeV) versus P$_T$(charged jet#1) at 630 GeV predicted by HERWIG 6.4 (P$_T$(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P$_T$(hard) > 0, CTEQ5L, Set A, $\varepsilon = 0$, $\varepsilon = 0.16$ (default) and $\varepsilon = 0.25$ (preferred)).

Also shown are the PT$_{\text{sum}}$ 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

Rick Field
Fermilab MC Workshop
October 4, 2002!

 Shows the “transverse” charged density (|η|<1, P_T>0.4 GeV) versus P_T(charged jet#1) at 630 GeV predicted by HERWIG 6.4 (P_T(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A, ε = 0, ε = 0.16 (default) and ε = 0.25 (preferred)).

 Also shown are the P_T(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.

 Increasing ε produces less energy dependence for the UE resulting in less UE activity at the LHC!

 Lowering P_T0 at 630 GeV (i.e. increasing ε) increases UE activity resulting in less energy dependence.

 Reference point E_0 = 1.8 TeV
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)).
**CDF Run 1 P_{T}(Z)**

- **Z-Boson Transverse Momentum**
  - 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).

- **UE Parameters**
  - MSTP(81): 1
  - MSTP(82): 4
  - PARP(82): 2.0 GeV
  - PARP(83): 0.5
  - PARP(84): 0.4
  - PARP(85): 0.9
  - PARP(86): 0.95
  - PARP(89): 1.8 TeV
  - PARP(90): 0.25
  - PARP(91): 1.0
  - PARP(92): 4.0
  - MSTP(91): 1
  - PARP(93): 5.0

- **ISR Parameters**
  - MSTP(81): 1
  - MSTP(82): 4
  - PARP(82): 2.0 GeV
  - PARP(83): 0.5
  - PARP(84): 0.4
  - PARP(85): 0.9
  - PARP(86): 0.95
  - PARP(89): 1.8 TeV
  - PARP(90): 0.25
  - PARP(91): 1.0
  - PARP(92): 4.0

- **Intrinsic KT**
  - MSTP(81): 1
  - MSTP(82): 4
  - PARP(82): 2.0 GeV
  - PARP(83): 0.5
  - PARP(84): 0.4
  - PARP(85): 0.9
  - PARP(86): 0.95
  - PARP(89): 1.8 TeV
  - PARP(90): 0.25
  - PARP(91): 1.0
  - PARP(92): 4.0

- **Effective Q cut-off**, below which space-like showers are not evolved.

- The $Q^{2} = k_{T}^{2}$ in $\alpha_{s}$ for space-like showers is scaled by PARP(64)!

**Parameter**

- **Tune A**
- **Tune AW**

- **PARP(62)**: 1.0
- **PARP(64)**: 1.0
- **PARP(67)**: 4.0
- **MSTP(91)**: 1
- **PARP(91)**: 1.0
- **PARP(93)**: 5.0

**Graphical Details**

- Normalized to 1
- 1.8 TeV
- CDF Run 1 published

**Table**

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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).

Data/HERWIG agreement good. Data/NLO 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**

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**Z-Boson Transverse Momentum**

→ 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!**
## PYTHIA 6.2 Tunes

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- **PDF**: CTEQ5L, CTEQ5L, CTEQ6L
- **MSTP(81)**: 1
- **MSTP(82)**: 4
- **PARP(82)**: 2.0 GeV
- **PARP(83)**: 0.5
- **PARP(84)**: 0.4
- **PARP(85)**: 0.9
- **PARP(86)**: 0.95
- **PARP(89)**: 1.8 TeV
- **PARP(90)**: 0.25
- **PARP(62)**: 1.25
- **PARP(64)**: 0.2
- **PARP(67)**: 4.0
- **MSTP(91)**: 1
- **PARP(91)**: 2.1
- **PARP(93)**: 15.0

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

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All use LO $\alpha_s$ with $\Lambda = 192$ MeV!
PYTHIA 6.2 Tunes

There are "old" PYTHIA 6.2 tunes!

These 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)
Dec 2007: Some interesting min-bias distributions for early LHC runs (submitted to the 2007 Las Houches workshop proceedings).

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

Tunes using O2-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 2 GeV of primordial KT and uses a very small renormalization scale for initial-state radiation (i.e., more SR radiation). It also has complete maximal color correlations. [Oct 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]
- 105: ATLAS-DC2 (“RomA”): 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: D6: Rick Field’s Tune D6 to Tevatron data, using CTEQ6L1 PDF's.
- 110: A-Pro: Tune A with LEP tune from Professor. [Oct 2006]
- 113: D6-Pro: Tune D6 with LEP tune from Professor. [Oct 2008]
- 114: DWT-Pro: Tune DWT with LEP tune from Professor. [Oct 2008]
- 116: ATLAS-DC2-Pro: ATLAS-DC2 with LEP tune from Professor. [Oct 2008]

Tunes intermediate between Q2- and pT-ordered models

- 211: A-PT-Pro: Tune A-PT with LEP tune from Professor. [Oct 2008]
- 228: Perugia A-PT: “Perugia” update of A-PT-Pro, using CTEQ6L1 PDF’s. [Feb 2009]

Tunes using pT-ordered model

- 300: S0: First Sandhoff-Skands Tune of the “new” UE and shower framework, with a smother matter profile than Tune A, 2 GeV of primordial KT, and ‘colour annealing” color reconnections. Uses the default Pythia energy scaling rather than that of Tune A. [Apr 2008]
- 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 2008]
- 304: NOCR: Sandhoff-Skands “best by” without color reconnections. Gives less good agreement with Tevatron data. [Apr 2008]
- 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: “Perugia” update of S0-Pro. [Feb 2008]
- 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 ISR/ISR 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 MRST LO* PDFS. [Feb 2009]
- 326: Perugia 6: Variant of Perugia 0 using CTEQ6L1 PDF’s. [Feb 2009]

http://home.fnal.gov/~skands/leshouches-plots/
### Peter's Pythia Tunes WEBSITE

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**Tunes using O2-ordered models**

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- 107: A-CR variant of Tune A using the Pythia new "color annealing" color reconnection model.
- 108: D/K: Rick Field's Tune D/K to Tevatron data.
- 110: A-Pro: Tune A with LEP tune from Peter.
- 110: D/Pro: Tune D/K with LEP tune from Peter.
- 114: DWT-Pro: tune DWT with LEP tune from Peter
- 115: ATLAS-DC2: tune ATLAS-DC2 with LEP tune from Peter

**Other Tunes**

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- 115: ATLAS-DC2-PRO: ATLAS-DC2 with LEP tune from Peter


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**LHC@BNL Workshop**

**February 8, 2010**

**Rick Field – Florida/CDF/CMS**

**Page 22**
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).
Min-Bias “Associated” Charged Particle Density

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!
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 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.
Use the maximum $p_T$ charged particle in the event, $PT_{max}$, to define a direction and look at the the “associated” density, $dN_{\text{chg}}/d\eta d\phi$, in “min-bias” collisions ($p_T > 0.5$ GeV/c, $|\eta| < 1$).

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

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It is more probable to find a particle accompanying $PT_{max}$ than it is to find a particle in the central region!
Shows the data on the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chgl}}/d\eta d\phi$, for charged particles ($p_T > 0.5 \text{ GeV/c}, |\eta| < 1$, not including $PT_{\text{max}}$) relative to $PT_{\text{max}}$ (rotated to 180°) for “min-bias” events with $PT_{\text{max}} > 0.5, 1.0, \text{ and } 2.0 \text{ GeV/c}$.

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

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

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

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

**Shows the “associated” charged particle density in the “toward”, “away” and “transverse” regions as a function of 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 (generator level).**
Min-Bias “Associated” Charged Particle Density

- 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 with $PT_{\text{max}} > 0.5$ GeV/c and $PT_{\text{max}} > 2.0$ GeV/c compared with PYTHIA Tune A (after CDFSIM).

- PYTHIA Tune A predicts a larger correlation than is seen in the “min-bias” data (i.e. Tune A “min-bias” is a bit too “jetty”).
Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2$, not including $PT_{\text{max}}$) relative to $PT_{\text{max}}$ at 900 GeV with $PT_{\text{max}} > 2.0$ GeV/c from PYTHIA Tune DW, Tune DWPro, and Tune S320 (generator level).
Shows the $\Delta \phi$ dependence of the “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2$, not including $P \text{T}_{\text{max}}$) relative to $P \text{T}_{\text{max}}$ (rotated to 180$^\circ$) at 900 GeV with $P \text{T}_{\text{max}} > 2.0$ GeV/c from PYTHIA Tune DW.

Shows the $\Delta \phi$ dependence of the “overall” and “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2$, including all particles) relative to the leading charged particle jet (Anti-KT, $d = 0.5$) at 900 GeV with $P \text{T}_{\text{max}} > 2.0$ GeV/c from PYTHIA Tune DW (generator level).
 Shows the $\Delta\phi$ dependence of the “overall” and “associated” charged particle density, $dN_{\text{chg}}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2$, including all particles) relative to the leading charged particle jet (Anti-KT, $d = 0.5$) at 900 GeV with $P_{T\text{max}} > 2.0$ GeV/c from PYTHIA Tune DW (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, |η| < 1, not including PTmax) for “min-bias” events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (i.e. generator level).

RHIC → 0.2 TeV → 1.96 TeV
(UE increase ~2.7 times)

Tevatron → 1.96 TeV → 14 TeV
(UE increase ~1.9 times)

LHC

Linear scale!
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 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (i.e. generator level).

LHC7 → 14 TeV (UE increase ~20%)
Linear on a log plot!
“Transverse” Charge Density

**LHC @ BNL Workshop**  
February 8, 2010

**LHC@BNL Workshop**  
Rick Field – Florida/CDF/CMS  
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- Shows the charged particle density in the “transverse” region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2$) at 900 GeV as defined by PTmax from PYTHIA Tune DW and Tune S320 at the particle level (*i.e.* generator level).
Fake data (from MC) at 900 GeV on the “transverse” charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with p_T > 0.5 GeV/c and |η| < 2. The fake data (from PYTHIA Tune DW) are generated at the particle level (i.e. generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).

Fake data (from MC) at 900 GeV on the “transverse” charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with p_T > 0.5 GeV/c and |η| < 2. The fake data (from PYTHIA Tune DW) are generated at the particle level (i.e. generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).
Data at 1.96 TeV on the charged particle multiplicity \((p_T > 0.4 \text{ GeV/c}, |\eta| < 1)\) for “min-bias” collisions at CDF Run 2.

The data are compared with PYTHIA Tune A and Tune A without multiple parton interactions (pyAnoMPI).
Select inelastic non-diffractive events that contain a hard scattering

Hard parton-parton collisions is hard \((\pt > \approx 2 \text{ GeV/c})\)

The “underlying-event” (UE)!

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

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

Multiple-parton interactions (MPI)!
The Inelastic Non-Diffractive Cross-Section

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

Majority of “min-bias” events!

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

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

**Proton Proton + Proton Proton + ...**

- **Hard parton-parton collisions** is hard ($p_T > \approx 2$ GeV/c)
- The "underlying-event" (UE)!
- Given that you have one hard scattering it is more probable to have MPI! Hence, the UE has more activity than "min-bias".
- "Semi-hard" parton-parton collision ($p_T < \approx 2$ GeV/c)
- Multiple-parton interactions (MPI)!
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!
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.
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 ($70 < M(\text{pair}) < 110$ GeV) at CDF Run 2.
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 $\langle p_T \rangle$. 

**Average PT versus Nchg**

- **Drell-Yan Production (no MPI)**
  - Charged Particles ($|\eta|<1.0$, $PT>0.5$ GeV/c) excluding the lepton-pair

- **Drell-Yan Production (with MPI)**

- **High $p_T$ Z-Boson Production**
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).
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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Remarkably similar behavior! Perhaps indicating that MPI playing an important role in both processes.
Data at 1.96 TeV on the charged particle multiplicity ($p_T > 0.4$ GeV/c, $|\eta| < 1$) for “min-bias” collisions at CDF Run 2.

The data are compared with PYTHIA Tune A and Tune A without multiple parton interactions (pyAnoMPI).

Prediction from PYTHIA Tune A for proton-proton collisions at 900 GeV.
LHC Predictions: 900 GeV

Compares the 900 GeV data with my favorite PYTHIA Tunes (Tune DW and Tune S320 Perugia). Tune DW uses the old $Q^2$-ordered parton shower and the old MPI model. Tune S320 uses the new $p_T$-ordered parton shower and the new MPI model. The numbers in parentheses are the average value of $dN/d\eta$ for the region $|\eta| < 0.6$. 

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LHC Predictions: 900 GeV

Shows the individual HC, DD, and SD predictions of PYTHIA Tune DW and Tune S320 Perugia 0. The numbers in parentheses are the average value of $dN/d\eta$ for the region $|\eta| < 0.6$. I do not trust PYTHIA to model correctly the DD and SD contributions! I would like to know how well these tunes model the HC component. We need to look at observables where only HC contributes!
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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.
Stay tuned! UE studies at 900 GeV coming soon from CMS and ATLAS.

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