Measurement of the Underlying Event at Tevatron

Deepak Kar

TU Dresden / University of Florida
(On behalf of the CDF Collaboration)
Inclusive photon – non pQCD corr

- Theory is corrected for the non-pQCD effect of the UNDERLYING EVENT
- This correction is estimated using two PTHIA samples with different tunes of the underlying event (see talk of Deepak Kar this afternoon)
- The mean of the two samples is taken as a correction

\[ C_{ue} = 9\% \text{ (constant with } p_{T}^{\gamma}) \]

Jet shapes

- Measurement of the average integrated (or differential) energy flow inside jets.
- Jet shape measurements can be used to test the showering models in the MC generator.
- Can be used to tune the underlying event models.
- Can be used to distinguish gluon-originated jets from quark jets.

Non-pQCD Contributions

- Non-pQCD contributions
- Underlying Event
- Fragmentation into hadrons

Underlying Event and Fragmentation contributions must be considered before comparing to NLO QCD predictions

Summary

- Boson + jets: important background to many measurements and searches
- Wide range of CDF and D0 measurements available – fully corrected for detector effects

Flavor-inclusive:

\[ p_{T}(\text{jet}) \]

- Good agreement data \(\rightarrow\) NLO pQCD for both experiments
- ALPGEN / SHERPA:
  - Reasonable shapes, uncertain normalizations
  - Agreement with data after tuning \(\alpha_s\) and \(\Lambda\)

\[ p_{T}(Z) \text{ / angles / angular correlations} \]

- Varying agreement between models and data
- \(\Delta p_{T}(Z, \text{jet}) \& p_{T}(Z)\): sensitive to underlying event and soft emissions – tuning needed

Dedicated measurements are needed to validate the Monte Carlo modeling

Carolina Deluca

Konstantinos Kousouris

M. Martínez-Pérez

Henrik Nilsen
Motivation:

- Need to be able to simulate “ordinary” QCD and “Standard Model” events at the collider.

- Finding “new” physics requires a good understanding of the “old” Physics (Not only to have a good model of the hard scattering part of the process but also of “underlying event”).
TeVatron

Fermilab's ACCELERATOR CHAIN

Collider Run II Integrated Luminosity

Weekly Integrated Luminosity (pb⁻¹)

Run Integrated Luminosity

Deepak Kar
Collider Detector at Fermilab (CDF)
The Underlying Event (UE)

Everything except the two outgoing hard scattered components. Beam-beam remnants (BBR), multiple parton interactions (MPI) …
From an experimental point of view, on an event by event basis, it is impossible to separate these two components.
So what is the problem with the Underlying Event?

- The process of interest at hadron colliders are mostly the hard scattering events.
- These hard scattering events are contaminated by the underlying event.
- The underlying event is an **unavoidable** background to most collider observables.
- Increasing luminosity implies more hadronic collisions – which also complicates things. *(pile-up)*
- The underlying event is not well understood since **non-perturbative physics** is involved.
Measuring it is important in ...

- Precision measurements of hard interactions where soft effects need to be subtracted.

- Jet cross-section, missing energy, isolation cuts, top mass ...

- QCD Monte-Carlo tuning.

*Higher the precision, higher the accuracy of physics measurements.*
PYTHIA

For underlying event studies, the only tool we have is to compare the data and the predictions from various Monte Carlo event generators, i.e. PYTHIA.

PYTHIA has "knobs" which can be tuned to obtain an optimal description of the data.

Apollo's priestess, Pythia, performing the duty of the oracle
<table>
<thead>
<tr>
<th>PYTHIA UE Parameter</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>MSTP(81)</td>
<td>MPI on/off</td>
</tr>
<tr>
<td>MSTP(82)</td>
<td>3 / 4: resp. single or double gaussian hadronic matter distribution in the p / pbar</td>
</tr>
<tr>
<td>PARP(67)</td>
<td>ISR Max Scale Factor</td>
</tr>
<tr>
<td>PARP(82)</td>
<td>MPI pT cut-off</td>
</tr>
<tr>
<td>PARP(83)</td>
<td>Warm-Core: parp(83)% of matter in radius parp(84)</td>
</tr>
<tr>
<td>PARP(84)</td>
<td>Warm-Core:</td>
</tr>
<tr>
<td>PARP(85)</td>
<td>prob. that an additional interaction in the MPI formalism gives two gluons, with colour connections to NN in momentum space</td>
</tr>
<tr>
<td>PARP(86)</td>
<td>prob. that an additional interaction in the MPI formalism gives two gluons, either as described in PARP(85) or as a closed gluon loop. Remaining fraction is supposed to consist of qqbar pairs.</td>
</tr>
<tr>
<td>PARP(89)</td>
<td>ref. energy scale</td>
</tr>
<tr>
<td>PARP(90)</td>
<td>energy rescaling term for PARP(81-82)~E_{CM}^{\text{parp(90)}}</td>
</tr>
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- PYTHIA uses MPI to enhance the UE.
- Multiple parton interaction more likely in a hard (central) collision.
- ISR Max Scale Factor affects the amount of initial-state radiation.
- Increasing the cut-off decreases the multiple parton interaction.
CDF Run 1 Tune (PYTHIA 6.2 CTEQ5L)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune A</th>
<th>Tune AW</th>
</tr>
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<tbody>
<tr>
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<tr>
<td>PARP(89)</td>
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<td>MSTP(91)</td>
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</tr>
<tr>
<td>PARP(93)</td>
<td>5.0</td>
<td>15.0</td>
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</table>

Both tunes reveal a remarkably good agreement of the data and PYTHIA.
- Charged particles with: $p_T > 0.5$ GeV/c and $|\eta| < 1$
- Using events with the lepton pair invariant mass in the Z region: $70 < M(ll) < 110$ GeV/c$^2$
We define –

- $|\Delta \phi| < 60^\circ$ as **Toward**
- $60^\circ < |\Delta \phi| < 120^\circ$ as **Transverse**
- $|\Delta \phi| > 120^\circ$ as **Away**

Azimuthal angle $\Delta \phi$ relative to the leading calorimeter jet (or the Z-boson)
Z-Boson Production at Tevatron

Single Z Bosons are produced with large $p_T$ via the ordinary QCD sub processes:

$$qg \rightarrow Zq, \overline{q}q \rightarrow Z\overline{q}, \overline{q}g \rightarrow Z\overline{q}$$

They generate additional gluons via bremsstrahlung – resulting in multi-parton final states fragmenting into hadrons and forming away-side jets.

<table>
<thead>
<tr>
<th>$\sigma(Z \rightarrow l^+l^-)$</th>
<th>CDF (pb)</th>
<th>NNLO (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$254.9\pm3.3$(stat)$\pm4.6$(sys)$\pm15.2$(lum)</td>
<td>$252.3\pm5.0$</td>
</tr>
</tbody>
</table>


NNLO Theory: Stirling, Van Neerven
Our Analysis

- The goal of the analysis was to produce data on the **underlying event** that is **corrected** to the particle level so that it can be used to **tune** the QCD Monte-Carlo models without requiring CDF detector simulation (i.e. CDFSIM).

- Also by looking at the measurements sensitive to the underlying event, we would be able to **better constrain** our underlying event models.
Charged Particle Multiplicity

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

CDF Run 2 Preliminary

$p_T > 0.5\text{ GeV/c} \text{ and } |\eta| < 1$

- Drell-Yan PYTHIA Tune AW
- Drell-Yan Data
- Drell-Yan HERWIG
- Leading Jet PYTHIA Tune A
- Leading Jet Data

$70 < M_\perp < 110\text{ GeV/c}^2$

Number of Charged Particles Density

Average Charged Density vs. Transverse Momentum of Lepton Pair or Leading Jet (GeV/c)

Z-boson Direction

$\Delta \phi$

"Toward" vs. "Away"

"Transverse" vs. "Away"

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Charged Transverse Momentum Sum

Transverse Region Charged $p_T$ Sum Density: $dp_T/\,d\eta d\phi$

CDF Run 2 Preliminary

$p_T > 0.5 \text{ GeV/c and } |\eta| < 1$

$70 < M_{ll} < 110 \text{ GeV/c}^2$

Charged PT sum Density: $dPT/\,d\eta d\phi$

Z-boson Direction

``“Toward”``

``“Transverse”``

``“Away”``
"Newer" Tunes
(From H. Hoeth, MPI@LHC 2008)

Data/MC comparisons show the features and problems of different generators and tunings.
Mean $p_T$ vs Charged Multiplicity

$<p_T>$ versus $N_{\text{chg}}$ is a measure of the amount of **hard versus soft** processes contributing and it is **sensitive** to the modeling of the multiple-parton interactions.
Mean $p_T$ vs Charged Multiplicity

CDF Run 2 Preliminary data corrected generator level theory
"Drell-Yan Production" $70 < M(\text{pair}) < 110$ GeV

Average $p_T$ versus Nchg

- No MPI

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

Drell-Yan Production (no MPI)
Drell-Yan Production (with MPI)
High $p_T$ Z-Boson Production

Proton AntiProton
Proton AntiProton
Proton AntiProton

Leptron AntiLeptron Leptron AntiLeptron Leptron AntiLeptron

Initial-State Radiation Final-State Radiation

Initial-State Radiation Final-State Radiation

Deepak Kar
Mean $p_T$ vs ChargedMultiplicity

Large $N_{\text{chg}}$ implies high $p_T$ jets (i.e. hard $2 \rightarrow 2$ scattering). Without MPI the only way to get large $N_{\text{chg}}$ is to have a very hard $2 \rightarrow 2$ scattering.
Multiple-parton interactions provides another mechanism for producing large multiplicities that are harder than the beam-beam remnants, but not as hard as the primary Z +jet hard scattering.
Moving Forward to LHC

- The UE measurement plan at the LHC benefits from the solid experience of the CDF studies.

- Predictions on the amount of activity in transverse region at the LHC are based on extrapolations from lower energy data (mostly from the Tevatron).

- All the UE models have to be tested and adjusted at the LHC, in particular we know very little about the energy dependents of MPI in going from the Tevatron to the LHC.
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Few hundred pb\(^{-1}\) integrated luminosity in first year – enough Z’s to look at the UE with Drell-Yan / Z+jets ...
Moving Forward to LHC

Underlying Event much more active at LHC
Conclusions

- Observed excellent agreement with PYTHIA tune AW predictions.
- Close match with leading jet underlying event results – underlying event models (BBR part) independent of hard scattering event?
- By looking at the correlation between $<p_T>$ and charged multiplicity, we can discriminate between different contributing subprocesses.
Backup Material
Proton-AntiProton Collisions at the Tevatron

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

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

“Soft” Hard Core (no hard scattering)

“Hard” Hard Core (hard scattering)
Minimum Bias Event

- Events collected with a trigger that is **not very restrictive** – ideally with totally inclusive trigger.

- In principle contains all types of interactions proportionally to their natural production rate.

At the Tevatron about 1% of min-bias events contain a jet with 10 GeV transverse energy. At the LHC we expect this fraction **increase** by more than a factor of 10.
The Underlying Event in a Hard-Scattering Process is not the same as Min-Bias Events

- The underlying event produces tracks in the detector and energy in the calorimeter, thus affecting the measurement of the hard scattering component.

- Presence of initial and final state radiation.

- Color interactions between the hard scattering and the underlying event might occur.
Tuning PYTHIA

- Need to produce tunes, not of one parameter at a time, but simultaneously for a group of them.

- Given the many PYTHIA parameters to be tuned, it is convenient to divide the task into subtasks.

1. If we assume jet universality, hadronization and final-state parton showers should be tuned to $e^+e^-$ annihilation data, notably from LEP1, since this offers the cleanest environment.

2. With such parameters fixed, hadron collider data should be studied to pin down multiple interactions and other further aspects, such as initial-state radiation.
Bringing PYTHIA in Good Agreement with the Data …

- The initial state radiation had to be adjusted.

- The dependence of the probability of multi-parton (secondary) interactions on the impact parameter had to be smoothed out.

- Probability of di-gluon production in multi-parton secondary interactions had to be substantially enhanced over di-quark production.

- The probability of color connections of products of secondary interactions with $p\bar{p}$-remnants had to be increased.

*Soft QCD phenomena in events with high-ET jets at Tevatron - Andrey Korytov, Eur Phys J C 33, s01, s425–s426 (2004)*
CDF Run 2 Tune (PYTHIA 6.206 CTEQ5L)

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Tune DW</th>
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</tr>
<tr>
<td>PARP(82)</td>
<td>2.0 GeV</td>
<td>1.9 GeV</td>
<td>1.9409 GeV</td>
</tr>
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PYTHIA Tune DW is very similar to Tune A except that it fits the CDF $P_T(Z)$ distribution and it uses the DØ prefered value of PARP(67) = 2.5.
Steps Are:

1. Calculate the observables by Monte Carlo event generator in **particle level** and in (by running through CDFSIM) **detector level**.

2. **Correct** the observables **back to particle level** in real data by calculating the **correction factor** from Monte Carlo.

3. **Compare** with different Monte Carlo event generators (PYTHIA, HERWIG...).
Negligible Background at “Z”