Soft QCD and Underlying Event at CDF

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Outline

➡ Event Shapes
  o What are they and why?
  o How to measure?
  o Latest results

➡ Underlying Event
  o Why UE?
  o Latest measurements in Z boson events
In most general terms event shapes measure geometric properties of the energy flow in QCD final states.

Similar to jet finding algorithms which characterize the topology of an event (approach fails to capture the continuous nature of the variability of events)

In contrast, an event shape encodes in a continuous fashion particular aspects of how energy is distributed in an event.

Free of arbitrariness associated with the jet definition (i.e. cone or cluster)
Why ES?

Studies of event shapes allow to probe:
- Fixed order pQCD (measurement of the $\alpha_s$)
- Soft gluon resummations (details of fragmentation)
- Soft QCD (hadronization models)

Studied extensively at LEP but by far less at hadron colliders
Presence of the underlying event casts some doubts as to whether event shapes at hadron colliders can be used to study hadronization effects or even pQCD.
Proposed Observables

The event shapes observables chosen for this study are defined as linear sums over the transverse momentum of all particles in the final state.

\[ \tau \equiv 1 - \max_{n_T} \frac{\sum |\vec{n}_T \cdot \vec{p}_\perp|}{\sum |\vec{p}_\perp|} \]

\[ T_{\text{min}} \equiv \frac{\sum |\vec{n}_m \cdot \vec{p}_\perp|}{\sum |\vec{p}_\perp|} \]

where \( \vec{n}_m \cdot \vec{n}_T = 0 \)

Other proposed observables (Broadening, Hemisphere masses, etc..) were found to be very sensitive to detector mismeasurements in the forward region.
Theory imposes a significant constrain – observable must be **GLOBAL** (i.e. sensitive to emissions in all directions)
This is in direct conflict with the experimental reality where the detector has limited coverage in the forward region

**Indirectly Global Event Shapes**
Define ES in the reduced central region

Introduce Recoil Term defined in the same central region but sensitive to the emissions outside

Add on the event-by-event basis **I.G.O. = ES + Recoil**

- Studies revealed small correlation b/w ES and Recoil
- Best shot of comparing with theory is to measure as much of an event as possible
- Effect of limited coverage $|\eta| < 3.5$ is negligible
Role of the Underlying Event

NLO+CAESAR(NLL) ➔ Pythia 6.216 w/o MPI ➔ Pythia Tune A ➔ Hadronization

Underlying Event significantly changes means and shapes of the distributions

C. Mesropian & S. Jindariani

DIS 2009, Madrid, Spain
Treatment of the Underlying Event

Can we subtract contribution of the UE on average from our measurement? - begin by separating event into hard and soft components:

\[
\tau \approx \frac{\sum |q_{\text{hard}}^{|q_{\text{hard}}|}}{\sum |q_{\text{hard}}| + \sum |q_{\text{UE}}|} - \max \frac{\sum |q_{\text{hard}}^{|q_{\text{hard}}|}| \cos \phi}{\sum |q_{\text{hard}}| + \sum |q_{\text{UE}}|} + \frac{\sum |q_{\text{UE}}|}{\sum |q_{\text{hard}}| + \sum |q_{\text{UE}}|}
\]

\[
T_{\text{min}} = \frac{\sum |q_{\text{hard}}^{|q_{\text{hard}}|}| \sin \phi}{\sum |q_{\text{hard}}| + \sum |q_{\text{UE}}|} + \frac{\sum |q_{\text{UE}}|}{\sum |q_{\text{hard}}| + \sum |q_{\text{UE}}|}
\]

- introduce a new observable

\[
C(\langle \tau \rangle, \langle T_{\text{min}} \rangle) \equiv (\alpha \langle \tau \rangle - \beta \langle T_{\text{min}} \rangle) \cdot \gamma_{MC}
\]

which is independent of the UE part

where \(\alpha = 1 - 2/\pi, \quad \beta = 2/\pi, \) and

\[
\gamma_{MC} \equiv \frac{\sum |q_{\text{hard}}|}{\sum |q_{\text{hard}}| + \sum |q_{\text{UE}}|}
\]
Treatment of the Underlying Event

(NLO+CAESAR) vs Tune A

Converges well
Instrumentation Effects

Instrumentation effects studied individually:

a) B-field on charged particles

b) Calorimeter resolution

c) Calorimeter granularity

\[ \Delta \eta = 0.1, \quad \Delta \Phi = 15^\circ \quad \text{Central} \]

\[ \Delta \eta = 0.2 - 0.6, \quad \Delta \Phi = 15^\circ \quad \text{Forward} \]
Results

Look at the $\tau$ and $T_{\text{min}}$ first…
Results

And now at our observable...

After accounting for the effect of calorimeter granularity observe excellent agreement between Data and Theory.
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.
Dividing up the Central Region

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

We define –

- $|\Delta \phi| < 60^\circ$ as **Toward**
- $60^\circ < |\Delta \phi| < 120^\circ$ as **Transverse**
- $|\Delta \phi| > 120^\circ$ as **Away**
Z-Boson Production at the Tevatron

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

\[ qg \rightarrow Zq, \quad q\bar{q} \rightarrow Zg, \quad \bar{q}g \rightarrow Z\bar{q} \]

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

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<td>$\sigma(Z \rightarrow l^+l^-)$</td>
<td>$254.9\pm3.3({\text{stat}})\pm4.6({\text{sys}})\pm15.2({\text{lum}})$</td>
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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

no FSR!
exclude leptons
“towards” = “Trans”
Charged Transverse Momentum Sum

- Charged Transverse Region: $p_T$ Sum Density: $dp_T/\eta d\phi$
- CDF Run 2 Preliminary: $L \sim 2.7 \text{ fb}^{-1}$
- $p_T > 0.5 \text{ GeV/c}$ and $|\eta| < 1$
- $70 < M_{\ell\ell} < 110 \text{ GeV/c}^2$

Z Boson Direction

"Towards" and "Away"

- "Transverse" Direction

Transverse Momentum of Lepton Pair or Leading Jet (GeV/c)

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

CDF Run 2 Preliminary: Data corrected for jet energy resolution and detector effects.
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

Large $N_{\text{chg}}$ implies high $p_T$ jets (i.e. hard 2→2 scattering). Without MPI the only way to get large $N_{\text{chg}}$ is to have a very hard 2→2 scattering.
Mean $p_T$ vs Charged Multiplicity

$P_T(Z) < 10$ GeV/c

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.
Mean $p_T$ vs Charged Multiplicity

CDF Run 2 Preliminary
data corrected
generator level theory

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

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

No MPI

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

Initial-State Radiation

Final-State Radiation
Conclusions

- First look at Event Shapes in Run II, certainly first comparison to theoretical results

- Great agreement between Data and Theory for the introduced observable

- CDF tunes A and AW describe data quite well

- Still a lot can be done on both ends – theoretical and experimental…
# Pythia Tunes

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ES Results (zoomed)
“Newer” Tunes
(From H. Hoeth, MPI@LHC 2008)

Data/MC comparisons show the features and problems of different generators and tunings.

C. Mesropian & S. Jindariani
Drell-Yan Process

Charged particles with: $p_T > 0.5$ GeV/c and $|\eta| < 1$

Using events with the lepton pair invariant mass in the Z region: $70 < M(\ell\ell) < 110$ GeV/c$^2$