Minimum bias and underlying event studies at CDF

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Outlook

- Definition of terms
  - Minimum-bias
  - Underlying event
- The structure of minimum-bias
- Underlying event measurements at CDF
  - Evolution with jet $p_T$
  - Drell-Yan events
- Minimum-bias measurements at CDF
"Minimum-bias" is the name of a trigger
- trigger implementation → data sample
- selects events proportionally to their cross-section

\[ \sigma_{\text{tot}} = \sigma_{\text{inel}} + \sigma_{\text{sd}} + \sigma_{\text{dd}} + \sigma_{\text{el}} \]

**Definition:**

\[ \sigma_{\text{tot}} \]

### Minimum-bias

- Usually refers to \( \sigma_{\text{inel}} \)

**Definition:**

\[ \sigma_{\text{tot}} \]

### Underlying Event

- Defined event-by-event: all but 2→2 hard scatter (jets)

**Definition:**

\[ \sigma_{\text{tot}} \]

MB is background to high Lum (pile-up of events)

UE is background to high \( p_T \) observables (jets…)

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Structure of MB

- At CDF minbias is mostly (but not only) soft:
- Jet structure (RunI)
- Has an underlying event → transverse region
- Study evolution of UE with $Q^2$

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At CDF minbias is mostly (but not only) soft
Jet structure (RunI)
Has an underlying event → transverse region
Study evolution of UE with $Q^2$ ($p_T$ of jet)
Higher $Q^2$ → harder UE
The Underlying Event

UE =
- BBR (beam-beam remnants)
- FSR, ISR (gluon radiation)
- MPI (>2 parton interactions)

Different regions are sensitive to different processes:
MIN to BBR+MPI
MAX to BBR+MPI +radiations

Data corrected to particle level
Tracks $p_T > 0.5$ GeV/c
$|\eta| < 1.0$
Jets in $|\eta| < 2.0$

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Event topologies:
- Leading jet
- Back-to-back jets (suppress 3\textsuperscript{rd} jet)
- Drell-Yan

Drell-Yan:
less gluon radiation
easier reconstruct.

\[ \mathcal{L} = ee, \mu\mu \]
\[ p_T > 20 \text{ GeV/c} \]
\[ |\eta| < 1 \]
\[ 70 < M_{\text{pair}} < 110 \text{ GeV} \]
\[ |\eta_{\text{pair}}| < 6 \]
**UE in Drell-Yan events**

Event topologies:
- Leading jet
- Back-to-back jets (suppress 3rd jet)
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**Drell-Yan:**
less gluon radiation
easier reconstruct.

\[ ll = ee, \mu\mu \]
\[ p_T > 20 \text{ GeV/c} \]
\[ |\eta| < 1 \]
\[ 70 < M_{\text{pair}} < 110 \text{ GeV} \]
\[ |\eta_{\text{pair}}| < 6 \]
Toward and MIN are the most sensitive to UE (BBR and MPI)

Define a new “DIF” region: DIF = MAX – MIN sensitive to radiation similar in Jets and DY
UE in Drell-Yan events

Systematic study to tune MonteCarlo models:

\[ \begin{align*}
\text{OBS} & \quad \times \\
\text{MC} & \quad \times \\
\text{Event} & \quad 3
\end{align*} \]

Tuning uses all combinations. Not possible to show all!

Compare to simulation: MPI best to fit the data
Minimum-Bias measurements

- Here we see all models at work together
- Need to input the correct mixing of soft/hard
- Hard to find a model that fits all observables at the same time
  - Uncertainties from:
    - Parton PDFs
    - Gluon radiation
    - MPI models
  - predictions for LHC

CDF measurements:
- trigger efficiency = f(N_{ch})
- event pile-up (<N_{pp}>~1.7)
- 506 pb^{-1}
- track p_T > 0.4 GeV/c
- |η| < 1
MB: charged multiplicity

\[ \sigma_{\text{MB}} = \sigma_{\text{inel}} + \sigma_{\text{sd}} + \sigma_{dd} + \sigma_{el} \]

- **Compare to Pythia**
- **Extrapolate to LHC**
- **Trigger inefficiency**
- **Diffractive bkg subtraction**

**CDF RunII Preliminary**

Minimum Bias
- \(|\eta| \leq 1\)
- \(p_T \geq 0.4 \text{ GeV/c}\)

Probability (charged multiplicity)

**14 TeV p+p**

Inelastic, Non-Diffractive

- Data / Pythia tune A
- Systematic uncert. on data

\( \sigma_{\text{MB}} = \sigma_{\text{inel}} + \sigma_{\text{sd}} + \sigma_{dd} + \sigma_{el} \)

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Courtesy of P. Skands
**MB**: charged + neutral \( E_T \)

\[
\sigma_{MB} = \sigma_{inel} + \sigma_{sd} + \sigma_{dd} + \sigma_{el}
\]

\[
\frac{d^3\sigma}{\Delta\phi \, \Delta\eta \, dE_T} = \frac{N_{ev} / (\varepsilon \times A)}{\text{Lum} \, \Delta\phi \, \Delta\eta \, dE_T}
\]

\[\sum E_T \text{ from CAL} \]

Reasonable agreement with Pythia TuneA
Conclusions

- **CDF has a very large and complete set of measurements both of minimum-bias and underlying event**

- More measurements hopefully are on the way
  - Final state correlations
  - Heavy flavors in MB (lower $p_T$ now accessible)

- Fundamental to extrapolate MC models to LHC energies…
  - ..but also to evaluate backgrounds to high $p_T$

- Still we’re not able to model and accommodate all soft(er) components, but CDF has greatly contributed at least in clarifying the topic of soft interactions
Backup slides
Table 1.1. Observables examined in this analysis as they are defined at the particle level and the detector level. Charged tracks are considered good if they pass the track selection criterion given in Section III(5). The mean charged-particle $<p_T>$ is constructed on an event-by-event basis and then averaged over the events. For the average $p_T$ and the $P_{T\text{max}}$, we require that there is at least one charged particle present. Particles are considered stable if $\tau > 10$ mm ($K_\pi, \Lambda, \Sigma, \Xi,$ and $\Omega$ are kept stable).

<table>
<thead>
<tr>
<th>Observable</th>
<th>Particle Level</th>
<th>Detector level</th>
</tr>
</thead>
<tbody>
<tr>
<td>dN/d$\eta$d$\phi$</td>
<td>Number of stable charged particles per unit $\eta$-$\phi$ \newline ($p_T &gt; 0.5$ GeV/c, $</td>
<td>\eta</td>
</tr>
<tr>
<td>dPT/d$\eta$d$\phi$</td>
<td>Scalar $p_T$ sum of stable charged particles per unit $\eta$-$\phi$ \newline ($p_T &gt; 0.5$ GeV/c, $</td>
<td>\eta</td>
</tr>
<tr>
<td>$&lt;p_T&gt;$</td>
<td>Average $p_T$ of stable charged particles \newline ($p_T &gt; 0.5$ GeV/c, $</td>
<td>\eta</td>
</tr>
<tr>
<td>$P_{T\text{max}}$</td>
<td>Maximum $p_T$ stable charged particle \newline ($p_T &gt; 0.5$ GeV/c, $</td>
<td>\eta</td>
</tr>
<tr>
<td>Jet</td>
<td>MidPoint algorithm $R = 0.7$ $f_{\text{merge}} = 0.75$ applied to stable particles</td>
<td>MidPoint algorithm $R = 0.7$ $f_{\text{merge}} = 0.75$ applied to calorimeter cells</td>
</tr>
</tbody>
</table>
## Pythia tunes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Tune A</th>
<th>Tune AW</th>
<th>Tune DW</th>
<th>Tune DWT</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF</td>
<td>Parton Distribution Functions</td>
<td>CTEQ5L</td>
<td>CTEQ5L</td>
<td>CTEQ5L</td>
<td>CTEQ5L</td>
<td>CTEQ5L</td>
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<tr>
<td>MSTP(81)</td>
<td>MPI On</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>MSTP(82)</td>
<td>Double Gaussian Matter Distribution</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>4</td>
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<tr>
<td>PARP(82)</td>
<td>MPI Cut-Off</td>
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<td>2.0</td>
<td>1.9</td>
<td>1.9409</td>
<td>1.8</td>
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<tr>
<td>PARP(83)</td>
<td>Fraction of matter within core</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>PARP(84)</td>
<td>Core Radius</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
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<tr>
<td>PARP(85)</td>
<td>Color Connections</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>PARP(86)</td>
<td>Color Connections</td>
<td>0.95</td>
<td>0.95</td>
<td>1.0</td>
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<td>0.66</td>
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<td>PARP(89)</td>
<td>Reference Energy</td>
<td>1800</td>
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<td>1960</td>
<td>1000</td>
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<td>PARP(90)</td>
<td>MPI Energy Dependence</td>
<td>0.25</td>
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<td>0.25</td>
<td>0.16</td>
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<tr>
<td>PARP(62)</td>
<td>Initial-state radiation Cut-Off</td>
<td>1.0</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.0</td>
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<tr>
<td>PARP(64)</td>
<td>Soft Initial-State Radiation Scale</td>
<td>1.0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>1.0</td>
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<tr>
<td>PARP(67)</td>
<td>Hard Initial-State Radiation Scale</td>
<td>4.0</td>
<td>4.0</td>
<td>2.5</td>
<td>2.5</td>
<td>1.0</td>
</tr>
<tr>
<td>MSTP(91)</td>
<td>Gaussian Intrinsic $k_T$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PARP(91)</td>
<td>Intrinsic Gaussian Width, $\sigma$</td>
<td>1.0</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>1.0</td>
</tr>
<tr>
<td>PARP(93)</td>
<td>Intrinsic $k_T$ Upper Cut-Off</td>
<td>5.0</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

A fits UE  
W fits DY  
DW fits DW+jet $\Delta\phi$
Pythia at LHC

14 TeV p+p Inelastic, Non-Diffractive

Charged Particle Multiplicity ($|\eta|<2.5$, $p_T>0.5$ GeV)

- Perugia 0
- Perugia HARD
- Perugia SOFT
- Perugia 3
- Perugia NOCR
- Perugia LO*
- Perugia 6

Probability Distribution of the Number of Perturbative Interactions

- Perugia 0
- Perugia HARD
- Perugia SOFT
- Perugia 3
- Perugia NOCR
- Perugia LO*
- Perugia 6
Eight possible sources were evaluated:

- Amount of undetected pile-up: 0.5%
- Merging triggers: 1.1%
- Trigger efficiency correction: 4.4%
- Vertex efficiency correction: 0.2% in $N_{ch}<3$
- Diffractive background suppression: 13-0.1% in $N_{ch}<7$
- Dependence on the MC generator up to 22% $f(N_{ch})$
- Usage of dijet MC sample: 2% in 36-43, 4% in $N_{ch}>43$
- Absolute correction of tail: 10% in $N_{ch}>49$

Total systematic: 5 - 34%
Calorimeter Response

Calorimeter response vs. sum $E_T$ [GeV]
Event by event correction $C(N_{ch})$ from MC

Unfold corrected distribution

$$U = \frac{N_{ch}^{GEN}}{N_{ch}^{REC} \times C(N_{ch})}$$

Reweigth MC unitl it follows the data

Unfold again
The main parameter in Pythia ($p_{T\text{min}}$) affects directly (also) the multiplicity of particles:

- Pythia uses only one parameter $p_{T\text{min}}$ to regularize $\sigma_{\text{hard}}$ at low $p_T$ and determine the number of MPI

\[
\sigma_{\text{hard}}(p_{T\text{min}}) = \int \frac{d\sigma}{dp_T^2}
\]

$< N_{\text{parton-parton}} >= \frac{\sigma_{\text{hard}}(p_{T\text{min}})}{\sigma_{\text{inelastic}}}$

- Let $\sigma_{\text{hard}} > \sigma_{\text{tot}}$ and interpret the events in excess as MPI:
- $p_{T\text{min}}$ smaller gives $< N_{\text{parton-parton}} >$ larger $\rightarrow$ larger multiplicities
  - $p_{T\text{min}}$ must be $>0$ to avoid $\sigma_{\text{hard}}$ divergence
  - Experimentally $p_{T\text{min}} \approx 2\text{GeV}$

T. Sjöstrand et al. PRD 36 (1987) 2019