Underlying events in p-p collisions at LHC

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There is lot of *interesting* physics in every collision

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

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

“Soft” Hard Core (no hard scattering)

“Hard” Hard Core (hard scattering)

We are only interested in the HC part of the total cross section! All of my predictions are for HC only!

- Detailed understanding of softer processes \(\Rightarrow\) Discovery in hard, rare processes
- CMS measures (almost) everything beautifully \(\Rightarrow\) excellent physics output!
Recapitulations/Definitions

Minimum Bias events: How do we study in experiments?
• A totally inclusive trigger, without any bias on energy/momentum.
• Typically characterized by low transverse energy, low multiplicity.

• High intensity of beams at LHC → a hard interaction or interesting event is accompanied by multiple soft interaction processes.

• In a triggered event the pileup increases with increasing instantaneous luminosity/beam intensity.

• The minimum bias data at LHC signifies higher hadronic activity than predicted in simulations (pythia etc.).

• Underlying events are related to minimum bias events but they are not equivalent.
Underlying event (UE): everything in single particle collision except the hard process of interest (may be hard or soft).

- any Higgs, SUSY event will contain underlying event
- we need to have good idea of UE for events at similar energy scale.

Components of UE:
- Initial and final state radiations (assuming only LO is studied in the experiment!)
- Beam-beam remnants
- Multiple parton interactions
- Pile up
- Noise

Essentially soft interaction, needs phenomenological models for description.
Hard collision and UE
Why it is important to study underlying events

• In general the hard scattered part of a collision is embedded in the UE.
• While searching for energetic particles produced in the collision, we must have good idea about the ambient activity in the event.

• In many interesting weak processes we do not expect hard jets in central region. eg.: search for Higgs when produced via Vector Boson fusion and decaying through W-pair.
→Jet veto efficiency is highly sensitive to the model of UE.
→Minijets can also arise from uncorrelated multi-parton interactions

• Do not expect any jet in the central region of the detector from hard scattering process.
Partonic cross-sections

\[ \sigma(p_1 + p_2 \rightarrow j_1 + j_2 + X) = f(x_1, \mu^2) \otimes f(x_2, \mu^2) \]
\[ \hat{\sigma}(x_1 p_1 + x_2 p_2 \rightarrow j_1 + j_2) \]

• partonic cross-section diverges with pt
• calculate cross-section as a function of \( p_{\text{min}} \)

\[ \sigma_{\text{hard}}(p_{\perp \text{min}}^2) = \int_{p_{\perp \text{min}}^2} d\sigma_{\text{hard}}(p_{\perp}^2) dp_{\perp}^2 \]

• Diverges as \( 1/p_{\perp \text{min}}^2 \rightarrow 0 \)

• Exceeds total inelastic, non-diffractive cross-section!
⇒ more than one 1 interaction per event
⇒ multiple interaction

\[ \langle n \rangle = \frac{\sigma_{\text{hard}}(p_{\perp \text{min}})}{\sigma_{\text{nd}}} \]

Average number of semihard interactions per event = 5 for LHC, 2 for Tevatron
Evidence of MI from previous experiment

History: charged multiplicity measurement in minimum bias events at UA5 experiments explained better by introduction of MI (alongwith parton shower + hadronization).

Pythia has a model for minimum-bias events with diffraction

CDF has a model for

Minimum-bias events with diffraction

Pythia with full UE

Data from CDF

Pythia without MI

Multiplicity distribution in regions transverse to the jet can be explained by introducing multiple interactions among remnants

Tevatron

**Drell-Yan study at Tevatron**

- $P_t$ of Drell Yan is affected by parton shower BUT also by the underlying events ....
- significant effects
- how to tune the truth?

![Graph showing transverse momentum of hard system](image)

- CDF data
- A
- DW
- APT
- S0

**Tevatron 1800 GeV**

Data from CDF Collaboration, PRL84(2000)845

MC generated with Pythia 6.419β
Multiple interaction in Pythia

To calculate hard scatter cross-section $d\sigma/dp_T^2$
→ introduce a cutoff value:

$$1/\hat{p}_T^4 \rightarrow 1/(\hat{p}_T^2 + \hat{p}_{T0}^2)^2$$

→ evaluate hard scatter cross-section for a given $b$, above threshold which is matched to LHC energies.

$$\hat{p}_{T0}(\sqrt{s}) = \hat{p}_{T0}(\sqrt{s_0}) \cdot (\sqrt{s} / \sqrt{s_0})^\epsilon,$$

Simulation in pythia-8 all interactions simulated in decreasing order of $p_T$. ISR is $p_T$ ordered over all interactions.

Tuning refers to adjustment of values of $\hat{p}_{T0}$, $\epsilon$ etc., and description of matter distribution inside the proton.
When two protons collide, the number of interactions ($<n>$) depends on the impact parameter ($b$). 

$\Rightarrow$ Hence the matter distribution inside hadrons is introduced.

Small $b$ $\Rightarrow$ hard scatter, more interactions, ie, larger $<n>$ $\Rightarrow$ more activity from underlying event than minimum bias process.

Different models of UE corresponds to variations in matter distribution.
**MI parameters at LHC**

<table>
<thead>
<tr>
<th>PYTHIA6.214 - tuned</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISUB: 11,12,13,28,53,68, 94,95,96</td>
</tr>
<tr>
<td>MSTP(51)=7</td>
</tr>
<tr>
<td>MSTP(81)=1</td>
</tr>
<tr>
<td>MSTP(82)=4</td>
</tr>
<tr>
<td>PARP(82)=1.8</td>
</tr>
<tr>
<td>PARP(84)=0.5</td>
</tr>
<tr>
<td>PARP(89)=1.0</td>
</tr>
<tr>
<td>PARP(90)=0.16</td>
</tr>
<tr>
<td>QCD 2 → 2 partonic scattering + non-diffractive + double diffractive</td>
</tr>
<tr>
<td>CTEQ5L - selected p.d.f. multiple interactions</td>
</tr>
<tr>
<td>complex scenario + double Gaussian matter distribution</td>
</tr>
<tr>
<td>$p_{t_{\text{min}}}$ parameter</td>
</tr>
<tr>
<td>core radius: 50% of the hadronic radius</td>
</tr>
<tr>
<td>energy scale (TeV) used to calculate $p_{t_{\text{min}}}$</td>
</tr>
<tr>
<td>power of the energy dependence of $p_{t_{\text{min}}}$</td>
</tr>
</tbody>
</table>

CMS tunes: mostly due to R. Field → D6T, DW in Pythia 6
Pythia 6: Virtuality ordered showers
Pythia 8: $p_T$-ordered showers + MCNet/Professor tune from LEP fragmentation data + new model for diffraction
Underlying event in Monte Carlo generator

- **Data**
- **MC**
- **Comparison**

**Understand and tune the detector model**

**Understand pileup, correct data analysis to particle level**

**Understand and tune the collision event model**

**FullSim**

**FastSim**
Measurement of Underlying event

Main observable: hadronic activity as a function of separation in azimuth $\Delta \phi$ between the leading object and any charged track:

1. charged multiplicity density $\left(\frac{dN}{d\eta} \frac{d(\Delta \phi)}{}\right)$ and
2. charged energy density $\frac{d(\Sigma p_T)}{d\eta} \frac{d(\Delta \phi)}{}$

2 types if final states identified to pick up the hard interaction leading object: a) jet reconstructed from charged tracks

b) a dimuon system with large enough invariant mass

In both cases:
• study topological variation of activity of other charged tracks.
• angular regions can be defined which are sensitive to UE
Leading charged-jet defines a direction in the phi plane.

Kinematics measured considering the azimuthal distance of reconstructed charged particles wrt leading object.

Event selection

- triggered
- 1 primary vertex
- $(\pm 10 \text{ cm})$ vertex $z$ window
- vertex n.d.o.f. $> 4$
- leading track-jet, $|\eta| < 2$ and $p_T > 3 \text{ GeV/c}$
- leading track-jet, $|\eta| < 2$ and $p_T > 20 \text{ GeV/c}$
Charged jet analysis results:

Presence of reasonably high energy object in the event → effect of different tunes cannot be discriminated.

Multiplicity with two thresholds for leading track momentum.

Presence of reasonably high energy object in the event → effect of different tunes cannot be discriminated.
Demarcate $\Delta \phi$ regions:

- **towards:** $|\Delta \phi| < 60$
- **transverse:** $60 < |\Delta \phi| < 120$
- **away:** $|\Delta \phi| > 120$

for 2 thresholds of leading track momentum

*Average $\Sigma p_T$*
Activity in transverse region

- Initial sharp increase in multiparton interaction with increasing energy scale, represented by $p_T$ of leading track jet, followed by much slower growth due to MPI saturation above 10-20 GeV/c.

- Saturation effect also observed in Drell-Yan analyses.
$\sqrt{s}$ dependence of UE in transverse region
Growth of UE with $\sqrt{s}$ for leading track momentum greater than 3 GeV/c

Probability densities
Drell-Yan process and underlying events

- Experimentally clean and theoretically well understood process.
- Disentangling the final state muons from the rest is easy.
- There is no QCD final state radiation.
- Comparatively low probability of muons to radiate photons.

- UE kinematics can be studied both as function invariant mass ($M_{\mu\mu}$) and transverse momentum ($P_T^{\mu\mu}$) of di-muon system in the transverse and towards regions.

Consider all charged tracks, other than the muons, with transverse momentum $> 500$ MeV/c, $|\text{pseudorapidity}| < 2$

Select 2 isolated muons, each with transverse momentum $> 20$ GeV/c $\Rightarrow$ calculate dilepton mass and momentum.
Drell-Yan spectrum of di-muon final state
With increasing $P_T^{\mu\mu}$, there is more hadronic activity in the away region to balance the boost of the dimuon system (ISR) $\Rightarrow$ multiplicity increases in away region only while the transverse region is mostly unaffected.

- energy scale of the event: $60 < M^{\mu\mu} < 120$ GeV/c$^2$ $\Rightarrow$ high to be well into MPI saturation region.

- Pythia6 DW and Z1 tunes describe measurement within $\sim 10\%$.
- agreement with Pythia8 tune 4C $\sim 10$-15\%.
Average track pt sum ($\sum p_T$) density as function of $p_T^{\mu\mu}$

Choose dilepton invariant mass range: $M_{\mu\mu} (60,120)$ GeV/c$^2$ \(\Rightarrow\) background level (due to top-pair production mainly) \(\sim 10^{-3}\)

- Increase in average $\sum p_T$ density mainly due to increase in contribution from ISR.
- Pythia8 tune 4C gives the better description at low $p_T^{\mu\mu}$, Pythia6 Z1 describe the measurements within \(\sim 10\%\).
Comparing unfolded data with generator level information
Activites as a fn. of dilepton mass with low boost ($p_T^{\mu\mu} < 10$ GeV/c)

Activity in region of MPI saturation is independent of dilepton mass
In proton-proton collisions, majority are soft, elastic ➔ need phenomenological modeling.

- multiple parton interaction (MPI) and beam-beam remnants (BBR) constitute the underlying events (UE) interleaved with initial state (ISR) and final state radiations (FSR).
  ➔ Excluding the final state particles from the hard scattering part of the collision, everything else contributes collectively as underlying event.

Study of underlying events is crucial to understand well, while preparing for searches.

Early LHC data helps us to understand soft QCD and gives chance to tune phenomenological models for soft hadronic interactions.
Back up
## Systematic uncertainties (%) for observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Trigger</th>
<th>Isolation</th>
<th>Track Sel.</th>
<th>Fake</th>
<th>Pile-up</th>
<th>QCD Model</th>
<th>Bkg. Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/$N_{ev}$ $\Delta^2 \Sigma p_T / \Delta \eta \Delta (\Delta \phi)$ (towards)</td>
<td>0.4 (0.4)</td>
<td>1.0 (1.1)</td>
<td>0.7 (0.8)</td>
<td>0.7 (0.7)</td>
<td>1.0 (1.2)</td>
<td>0.7 (1.5)</td>
<td>1.9 (0.2)</td>
</tr>
<tr>
<td>1/$N_{ev}$ $\Delta^2 \Sigma p_T / \Delta \eta \Delta (\Delta \phi)$ (transverse)</td>
<td>0.4 (0.4)</td>
<td>0.8 (1.3)</td>
<td>0.6 (1.1)</td>
<td>0.7 (0.7)</td>
<td>0.9 (1.2)</td>
<td>0.4 (1.7)</td>
<td>2.0 (0.2)</td>
</tr>
<tr>
<td>1/$N_{ev}$ $\Delta^2 \Sigma p_T / \Delta \eta \Delta (\Delta \phi)$ (away)</td>
<td>0.4 (0.4)</td>
<td>0.6 (0.8)</td>
<td>0.8 (0.8)</td>
<td>0.7 (0.6)</td>
<td>0.6 (1.1)</td>
<td>1.0 (1.4)</td>
<td>0.2 (0.2)</td>
</tr>
<tr>
<td>1/$N_{ev}$ $\Delta^2 N_{chg} / \Delta \eta \Delta (\Delta \phi)$ (towards)</td>
<td>0.4 (0.4)</td>
<td>0.8 (0.9)</td>
<td>0.8 (0.8)</td>
<td>0.9 (0.8)</td>
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<td>0.7 (1.0)</td>
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</table>
Dependence on hard scale

Leading track $p_T > 3$ GeV/c

Leading track $p_T > 20$ GeV/c
\[ p_T \] resolution of tracks:

@ 1 GeV/c: 0.7% at \( \eta = 0 \)

2% at |\( \eta | = 2.5 \)

\[ p_T \] resolution of muons:

ONLY Muon chambers:
8%-15% at 10 GeV/c
20%-40% at 1 TeV/c

WITH Tracker matching:
1%-1.5% at 10 GeV/c
6-17% at 1 TeV/c
Examples of relevant parameter values in Pythia 8/6

MultipleInteractions:coreRadius=0.4', / parp(84)=0.4
MultipleInteractions:ecmPow=0.16', / parp(90)=0.16
MultipleInteractions:pT0Ref=1.8387', / parp(82)=1.8387

MultipleInteractions:coreFraction=0.5', / parp(83)=0.5
MultipleInteractions:coreRadius=0.4', / parp(84)=0.4
'BeamRemnants:primordialKT=on', / mstp(91)=1
'BeamRemnants:primordialKThard=2.1', / parp(91)=2.1
What is the momentum limit?

- Tracker is in principle sensitive to soft tracks
  \( P_T = 400 \text{ MeV} \) - tracks reach end of TRT
  \( P_T = 150 \text{ MeV} \) - tracks reach last SCT layer
  \( P_T = 50 \text{ MeV} \) - tracks reach all Pixel layers

→ Do not need to run with low field