Characterization of underlying event in CMS experiment at LHC

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On behalf of CMS collaboration
Hard collision and UE
Underlying event in hadronic collisions

Underlying event (UE): everything in single particle collision except the hard process of interest (may be hard or soft).

Components of UE:
- Initial and final state radiations (assuming only the leading order process is studied in the experiment!)
- Beam-beam remnants
- Multiple parton interactions

Charged multiplicity in minimum bias events at UA5, Tevatron experiments could be explained better by introducing the concept of multi-parton interaction along with parton shower + hadronization.

UE is essentially semi-hard interaction, with typical scale $\sim 1-2$ GeV (to be compared with soft interaction scale of $\Lambda_{QCD} \sim 0.2$ GeV)

- needs phenomenological models for description
- parameters in the models need adjustments
- **TUNING** of monte carlo event generators
Importance of UE in future

Any hard scatter process is essentially embedded with UE
→ we need to have good idea of the activity for events at similar energy.

In many interesting weak processes hard jets are not anticipated in the central region of the detector, eg.,
1. Search for Higgs produced in Vector Boson Fusion decaying to leptons
2. Vector boson scattering

→ Jet veto efficiency is highly sensitive to the model of UE
→ Minijets can also arise from uncorrelated multi-parton interactions

![Diagram]

Isolation criteria of leptons, photon crucially depends on the activity in the environment they are in.

• It also acts as reference to hard p-p and heavy ion collisions.
When two protons collide, the number of interactions ($<n>$) depends on the impact parameter ($b$) hence the matter distribution inside hadrons is introduced. Small $b$ → hard scatter, more interactions, ie, larger $<n>$ → more activity from underlying event than minimum bias process.

$$\sigma_{\text{hard}}(p_{\perp \text{min}}) = \int_{p_{\perp \text{min}}} \frac{d\sigma_{\text{hard}}(p_{\perp})}{dp_{\perp}} dp_{\perp}$$

$p_{T,\text{min}}$ is adjusted to fit experimental data.

UE inversely proportional to $p_{T,\text{min}}$
Multiple interaction parameters in Pythia

Extrapolation from lower energy

\[ p_{T_0} = \text{PARP}(82) \left( \frac{\sqrt{s}}{\sqrt{s_0}} \right)^{\text{PARP}(90)} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTP(81)</td>
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</tr>
<tr>
<td>MSTP(82)</td>
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<tr>
<td>PARP(82)</td>
<td>1.8</td>
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<tr>
<td>PARP(84)</td>
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<td>PARP(89)</td>
<td>1.0</td>
</tr>
<tr>
<td>PARP(90)</td>
<td>0.16</td>
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</tbody>
</table>

- MSTP(81)=1: multiple interactions
- MSTP(82)=4: complex scenario + double Gaussian matter distribution
- PARP(82)=1.8: \( p_{t_{\text{min}}} \) parameter
- PARP(84)=0.5: core radius: 50% of the hadronic radius
- PARP(89)=1.0: energy scale (TeV) used to calculate \( p_{t_{\text{min}}} \)
- PARP(90)=0.16: power of the energy dependence of \( p_{t_{\text{min}}} \)

<table>
<thead>
<tr>
<th>TUNE</th>
<th>PARP(82)(GeV/c)</th>
<th>PARP(89)(TeV)</th>
<th>PARP(90)</th>
<th>PDF</th>
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<td>CTEQ6L</td>
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</tbody>
</table>

Current CMS TuneZ2*: 1.927 1.8 0.225 CTEQ6L
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.

- study topological variation of activity in terms of sensitive variables:
  
  1. density of charged particle multiplicity: $\frac{d^2 N}{d \eta \ d(\Delta \phi)}$
  2. density of scalar $p_T$ sum: $\frac{d(\Sigma p_T)}{d \eta \ d(\Delta \phi)}$
  3. average transverse momentum: $\frac{< \Sigma p_T>}{<N_{ch}>}$

- Angular regions defined wrt the hard object:
  1. Away ($|\Delta \phi| > 120^\circ$): hard-scattering component which balances the leading object
     - away region will have effects of radiation
  2. Transverse ($60^\circ < |\Delta \phi| < 120^\circ$): best suited for UE studies
  3. Towards ($|\Delta \phi| < 60^\circ$): can be suitable, as in case of Drell-Yan process, once the hard scattering component is completely removed by ignoring the leptons
CMS efforts for understanding UE

2 types of final states identified to pick up the hard interaction event

a) hadronic final state:
   → analysis based on jets reconstructed from charged tracks
   → event shape

b) Drell-Yan dimuon system with large enough invariant mass: \( m_{l^+l^-} \sim M_Z \)
   → UE is completely extracted by removing the muons from hard scatter

- Confine tracks within \( |\eta| < 2 \) or 2.4 and \( p_T > 0.5 \) or 0.25 GeV/c
- Confine charged track jets \( |\eta| < 1.9, p_T > 5 \) GeV/c

Only a limited flavour of wide range of topics studied:
1) Activities as a function of multiplicity of charged tracks (FSQ-12-022)
2) Comparison of UE activity at different energies (FSQ-12-020)
4) Activities in forward rapidity (FWD-11-003, JHEP 04(2013) 072)
3) Strangeness production (QCD-11-010)
4) Drell-Yan events (QCD-10-040, EPJC 72 (2012) 2080)
5) Using transverse momentum of Z in DY process (SMP-12-025)
Hard and soft particles as a function of particle multiplicity

- Bulk properties of minimum bias events → reasonably described by Pythia.
- However differential distributions does not match data very well. e.g., tail of charged particle multiplicity → incomplete understanding of inelastic scattering?
- Different mechanisms of multiparticle production in p-p collision can be probed via study of jets and UE properties as a function of particle multiplicity.
- Data are not described at all by MPI-off tunes.
- Pythia (semihard MPI modeling) is better than Herwig (softer MPI modeling)
Average charged-particle $p_T$ as a function of multiplicity

MPI has to be accounted for!

Herwig does worse job than Pythia in describing dependence of multiplicity.

With increasing $p_T$ the description of Pythia differs more from that of Herwig.
Comparison of CMS measurements with ALICE

CMS Preliminary $\sqrt{s} = 7$ TeV

$1/\Delta\eta\Delta(\Delta\phi) \langle N_{\phi} \rangle$

+ Data CMS
• Data ALICE charged particles
(p$_T$ > 0.5 GeV/c, $|\eta| < 0.8, 60^\circ < |\Delta\phi| < 120^\circ$)

Leading track $p_T$ [GeV/c]

No difference within uncertainties.

CMS Preliminary $\sqrt{s} = 0.9$ TeV

$1/\Delta\eta\Delta(\Delta\phi) \langle N_{\phi} \rangle$

+ Data CMS
• Data ALICE charged particles
(p$_T$ > 0.5 GeV/c, $|\eta| < 0.8, 60^\circ < |\Delta\phi| < 120^\circ$)

Leading track $p_T$ [GeV/c]
Charged particle activity as a fn. of $\sqrt{s}$

Comparison of measurements with various monte carlo predictions

- get extra constraints for the tuning parameters
- better understanding for the underlying event phenomena.

- Significant increase in the average multiplicity and the scalar sum $p_T$ followed by slower rate of increase due to saturation of MPI
- Activities increase with $\sqrt{s}$

FSQ-12-020
Ratio of energies in the forward direction:
- events with charged particle jet in central region wrt inclusive events
- As a function of central jet $p_T$
- As a function of $\sqrt{s}$

- At lower $\sqrt{s}$, the remnants have lower energy if a hard central object is demanded in the event.
- At higher $\sqrt{s}$, initial steep increase followed by features of saturation
- Transition region reflected in flat spectrum
Strange particle production in UE

Monte carlos underestimate productions of strange particles both in inclusive events and in UE.

For baryons ($\Lambda$) data-MC agreement is worse than for mesons ($K_s$) for all the UE variables.
- UE kinematics is studied as function of invariant mass and transverse momentum of the dimuon system.
- Require small recoil to study UE as a function of energy scale ($M_{\mu\mu}$).
- Around Z resonance, UE dependence on $P_T^{\mu\mu}$ contribution from radiation.

No dependence on energy scale ($M_{\mu\mu}$) as MPI saturates at these scale
- Tunes derived from other analyses describe UE in DY → universality
Use Drell-Yan process further.

Non-zero transverse momentum of $Z$ boson ($q_T$)

a) low $q_T$ region due to UE

b) high $q_T$ region due to higher order corrections.

Present result uses low luminosity data (pile up event $\sim 5$) at 8TeV, $\mathcal{L} \sim 19$ pb$^{-1}$

$\Rightarrow$ poor discriminating power for different models.

Analysis of full data set at 8 TeV on-going

$\Rightarrow$ accuracy of measurement will have the potential for discriminating different tunes.
Conclusion

Study of underlying event at LHC is essential
• to understand the soft and semihard interactions in a collision
• to prepare for precision studies as well as for searches

CMS has a vibrant programme to address the relevant issues.

• LHC phase1 data has been extremely useful to understand the underlying event activities.
• Phenomenological models for soft hadronic interactions have been tuned with early data.
• No single modeling of multi-parton interaction in monte carlos is able to describe all features.

Looking forward to operations at LHC(13/14 TeV) to confirm the $\sqrt{s}$-evolution of the semi-hard parton interactions, and improve our understanding of the UE.
backup
HF coverage $|h|<5.2$
Impact parameter resolution along $z \sim 10$ cm
$\delta p_T = 0.7\%$ @ 1 GeV

Data used for multiplicity study collected during low PU operation in 2010 ~ 3.18 /pb
Fraction for events with 2 primary vertices reconstructed as one or which share associated tracks < 0.2%
Negligible contribution from diffractive events.
Mean multiplicity of events ~ 24,
  charged track jet $|h| <1.9$, $p_T > 5$GeV
Eff. For trigger and event selection = 87%, 100% for nch > 10, 30
Jet activity as fn. multiplicity with varying threshold for jet $p_T$
charged multiplicity in minimum bias events at UA5, Tevatron experiments could be explained better by introducing the concept of multi-parton interaction along with parton shower + hadronization.

The descriptions based on lower energy data do not work very well at LHC energies.

No single model of soft interactions in monte carlo is able to describe all features.

→ Lot of studies at LHC underline the importance of understanding the UE processes with much better accuracy.
Spectra of charged particles

CMS-PAS-FSQ-12-014
Properties of charged particles from jets and from UE

Mean transverse momentum of intrajet charged vs. corrected charged-particle multiplicity
Jet $p_T$ density as a function of distance from jet axis
Measurement of minimum bias events in CMS

Tuning of monte carlo generators made the situation better
UE activity in forward region

- Measure energy flow in forward direction $3 < |\eta| < 4.9$ for W/Z events
- Correlation of activity in central region.
- Look for large rapidity gap events
- Presence of diffraction $\Rightarrow$ lepton and gap in the same hemisphere.
Correction for charged tracks

\[ N_{\text{ch}}^{\text{true}}(\eta, p_T) = N_{\text{ch}}^{\text{reco}}(\eta, p_T) \frac{1 - f_{\text{ake}}(\eta, p_T)}{\text{eff}(\eta, p_T)} \]

Dependence of \( p_T \) spectrum on the radius of the jet-defining cones.
Strange particle production in CMS

CMS preliminary $\sqrt{s} = 7$ TeV

Candidates / 3 MeV/c²

$K_S^0$

- Data
- Primary $K_S^0$
- Misidentified
- Other backgrounds

mass [GeV/c²]

$10^5$
$10^4$
$10^3$
$10^2$
$10$
$1$

$0.4$ $0.45$ $0.5$ $0.55$

CMS preliminary $\sqrt{s} = 7$ TeV

Candidates / 1 MeV/c²

$\Lambda + \bar{\Lambda}$

- Data
- Primary $\Lambda + \bar{\Lambda}$
- Cascade decays
- Misidentified
- Other backgrounds

mass [GeV/c²]

$10^4$
$10^3$
$10^2$
$10$
$1$

$1.09$ $1.1$ $1.11$ $1.12$ $1.13$ $1.14$

Uncorrected average production

$10^3 \times 1/\Delta\eta\, d^2\langle N_\gamma, \varphi \rangle/d(\Delta\varphi)$ [deg⁻¹]
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 experimental data and extrapolated at 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 $\hat{p}_{T0}$, etc., and description of matter distribution inside the proton.
Partonic cross-sections

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

- Partonic cross-section

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

- Diverges faster than \(1/p_{\perp \text{min}}^2\)

Interaction rate exceeds total inelastic, non-diffractive cross-section!

- Happens in the perturbative range,
- Above \(\lambda_{\text{QCD}}\)
- More than one 1 interaction per event
- Multiple partonic interaction
- Need modelling \(\Rightarrow\) tuning

Average number of semihard interactions per event >1 for LHC