FINAL STATE MULTIPLICITY AND PARTICLE CORRELATION IN SMALL SYSTEMS

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Final state variables and particle correlation results will be shown and discussed under a Multiple Parton Interaction (MPI) interpretation.

- **Final state multiplicity**
  - Pseudorapidity and Transverse-momentum distributions of charged particles
  - Hadronic Event Shape
  - Forward Energy Measurement

- **Particle correlation**
  - Long-Range Near-Side Two particle angular correlation results at 13 TeV
    - Collectivity of strange hadrons
    - MPI as a way to understand LRNS
Measurements of particle yields and kinematic distributions are essential in exploiting the energy regimes of particle collisions at the LHC.

- **Charged particle pseudorapidity distribution:**
  \[
  \frac{1}{N_{\text{events}}} \frac{dN_{\text{ch}}}{d\eta} = \frac{C_{T2} \Sigma_{M} \Sigma_{pT} N_{\text{tracks}}(M,pT,\eta) \omega_{\text{tracks}}(M,pT,\eta) \omega_{\text{event}}(M,nT_{2})}{\Delta\eta \Sigma_{M} N_{\text{evt}}(M) \omega_{\text{event}}(M,nT_{2})}
  \]
  where \( \omega_{\text{tracks}} \) and \( \omega_{\text{events}} \) are correction factors and \( C_{T2} \) accounts for the track reconstruction efficiency.

- **Charged particle pT distribution:**
  \[
  \frac{1}{N_{\text{events}}} \frac{dN_{\text{ch}}}{dpT_{\text{leading}}} = \frac{\Sigma_{\eta} N_{\text{tracks}}(\eta,pT_{\text{leading}}) \cdot C(pT_{\text{leading}}) \cdot C_{T2}(pT_{\text{leading}})}{N_{\text{events}} \cdot \Delta pT_{\text{leading}}}
  \]
  where \( C \) is the correction to stable particle level.

Studies on pseudorapidity and transverse momentum distributions led to the formulation of MPI theories in order to explain the disagreement data-MC.

From the 8 TeV analysis: interesting study on a wide pseudorapidity spectrum triggered by TOTEM.

Tunes based on Underlying Event variables do the best job in describing data (Gunnellini’s talk).

Comparison data-MC shows that models tuned on MPI observables better describe data.
The energy evolution of $dN_{ch}/d\eta$ is fitted using a power law function and compared with the PYTHIA8 and EPOS LHC MC predictions. Both the models globally reproduce the collision-energy dependence.

Energy dependence of pseudorapidity and $p_T$

As expected $\langle p_T \rangle$ values are quite independent of center of mass energy (shown in log scale).

Multiplicity dependence of $p_T$

$\langle p_T \rangle$ values seem strongly correlated to the multiplicity rather than $\sqrt{s}$.

Higher multiplicity events = higher MPI events
Tranverse thrust: $\tau_\perp = 1 - \max_{\eta_T} \frac{\sum_i |p_{T,i} \cdot \eta_T|}{\sum_i p_{T,i}}$.

$\tau_\perp = 0$ for perfectly balanced two-jet events and $\tau_\perp = (1-2/\pi)$ in isotropic multijet events.

Sphericity: $S = \frac{3}{2} (\lambda_2 + \lambda_3)$ and Transverse Sphericity: $S_\perp = \frac{2\lambda_2}{\lambda_1 + \lambda_2}$ where $\lambda_1$, $\lambda_2$ and $\lambda_3$ are the normalized eigenvalues ($\lambda_1 < \lambda_2 < \lambda_3$) of the momentum tensor.

Events with a large number of MPI are expected to appear with a spherical shape, especially for high multiplicity.

- Transverse thrust describe an higher isotropic contribution than expected in jet events
- Sphericity is higher in high-pT (and high multiplicity) events than expected
- Data/MC disagreement at large $\Sigma pT$
FORWARD ENERGY SPECTRUM

**8 TeV**

JHEP 11 (2011) 148

Pseudorapidity region 3.15 < |\(\eta|\) < 4.9

Energy measured with the hadronic forward (HF) calorimeters

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**13 TeV**

CMS PAS FSQ-16-002

The energy is measured using CASTOR which covers the region -6.6 < \(\eta\) < -5.2

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**8 TeV**

- Energy flow increases with pseudorapidity
- The average of energy flow is significantly higher in high multiplicity events
- Models without MPI fail the data description
- Models show a better consistency in low multiplicities events

**13 TeV**

- None of the models consistently describe the shape
- PYTHIA8 CUETP8M1 seems to provide best behaviour
- The prediction without MPI is ruled out by the data (and is too steep)
- The data is also very sensitive to the MPI pt cut-off
So far we saw how Multiple Parton Interaction can help in the description of the final state multiplicity variables and hence the understanding of their dynamics.
MULTIPLICITY FOR MPI STUDIES

- Final state multiplicity
  - Pseudorapidity and Transverse-momentum distributions of charged particles
  - Hadronic Event Shape
  - Forward Energy Measurement

- Particle correlation
  - Long-Range Near-Side Two particle angular correlations
    - Strangeness particles production study to access LRNS

So far we saw how Multiple Parton Interaction can help in the description of the final state multiplicity variables and hence the understanding of their dynamics.

Multiplicity plays a key role also in particle correlation, interplay with MPI can help in the results interpretation.
Two-particle angular correlations for charged particles are studied in:

- Short range: $|\Delta \eta| < 2$
- Long range: $2 < |\Delta \eta| < 4.8$

Given:

- Signal function: $S_N(\Delta \eta, \Delta \phi) = \frac{1}{N(N-1)} d^2 N^{\text{sign}} \frac{d^2}{d\Delta \eta d\Delta \phi}$
  charged two-particle pair density in the same events

- Background function: $B_N(\Delta \eta, \Delta \phi) = \frac{1}{N^2} d^2 N^{\text{mixed}} \frac{d^2}{d\Delta \eta d\Delta \phi}$
  distribution of uncorrelated particle pairs from two randomly selected events

Correlation function is defined as:

$$ R(\Delta \eta, \Delta \phi) = \left( \langle N \rangle - 1 \right) \left( \frac{S_N(\Delta \eta, \Delta \phi)}{B_N(\Delta \eta, \Delta \phi)} - 1 \right) \left( \begin{array}{c} \text{bins} \end{array} \right) $$
p-p collisions results at 13 TeV:

For the low-multiplicity sample ($N_{\text{trk, offline}} < 35$), the dominant features is the peak near $(\Delta \eta, \Delta \phi) = (0, 0)$ for pairs of particles originating from the same jet. The elongated structure at $\Delta \phi \approx \pi$ corresponds to pairs of particles from back-to-back jets.
LONG-RANGE NEAR-SIDE TWO-PARTICLE CORRELATIONS

p-p collisions results at 13 TeV:

In high-multiplicity pp events ($N_{\text{trk}}^{\text{offline}} \geq 105$), in addition to these jet-like correlation structures, a “ridge”-like structure is clearly visible at $\Delta \phi \approx 0$, extending over a range of at least 4 units in $|\Delta \eta|$.

Confirmed what was observed at 7 TeV

At lower energy observed in p-A and A-A collisions

No such long-range correlations are predicted by PYTHIA.
LONG-RANGE NEAR-SIDE TWO-PARTICLE CORRELATIONS

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The long-range near-side yields have been measured for p-p, p-Pb and Pb-Pb collisions in CMS.

The ridge-like correlations become significant at a multiplicity value of about 40 in all three systems and exhibit a nearly linear increase for higher value.

For a given multiplicity value the associated yield in pp collision is roughly 10% and 25% of those observed in PbPb and pPb collisions respectively.

There a strong collision system size dependence of the long-range near-side correlations.

Possible interpretations of the “ridge-effect”:
1. Hydrodynamic models
2. Multiple Parton Interaction

Interplay between them??
Strange hadron production and correlations in small colliding systems provide additional insights into the physical origin of the LRNS correlation.

In order to study the “ridge” effect, the jet contribution has to be removed.

Jet shape taken from low multiplicity data assuming it doesn’t depend on multiplicity.
The observed long-range ($|\Delta \eta| > 2$) correlations are quantified in terms of azimuthal anisotropy Fourier harmonics ($v_n$).

The elliptic $v_2$ and triangular $v_3$ flow Fourier harmonics are extracted from long-range two-particle correlations at different values of center of mass energy and for different system size.

**$V_2$:**
- No energy dependence
- Qualitatively similar shape for pp, p-Pb, and Pb-Pb

**$V_3$:**
- No energy dependence
- Values for pp are slightly different from p-Pb and Pb-Pb at higher multiplicity ($N > 60$)
The $v_2$ term is studied as a function of $p_T$ and particle species: **at high multiplicity** a deviation of $v_2$ term among various particle species is observed.

At low $p_T$:
- $K_S^0$ is higher than $\Lambda/\bar{\Lambda}$
- the lighter particle species exhibit a stronger azimuthal anisotropy signal
- similar trend observed in A-A and p-Pb collisions

At high $p_T$:
- $\Lambda/\bar{\Lambda}$ higher than $K_S^0$
- Reverse ordering is similar to previous observation in p-Pb and Pb-Pb collisions

**Qualitatively consistent with the hydrodynamic models.**
WHICH ROLE PLAYED BY MPI IN LONG-RANGE NEAR-SIDE CORRELATIONS?

1. For large impact parameter $b$ the MPI tend to lie in the collision plane of the hardest interaction and the final state particles will have similar azimuthal angle $\phi$ (near-side)

2. MPI would require enough interactions to explain the high multiplicity events

3. Incoming partons have very different $x_{bji}$ hence will have interactions in a broad pseudorapidity range $\eta$ (long range)

Adding a modification in PYTHIA6, introducing a correlation between the azimuth of the event plane of individual MPI and the event plane of the hardest interaction

With this modification **PYTHIA shows the ridge structure** for the high-multiplicity moderate $p_T$ events.

**BUT** high multiplicity events are generally central collisions with an impact parameters $b \approx 0$.  

Van Mechelen
arXiv:1203.2048
CONCLUSION

- We can study MPI in two different dynamic regimes, multiplicity studies focus on the soft dynamics and constitute a complementary input on the Underlying Event analysis.

- MPI are unavoidable:
  - Experimental evidences that MPI mechanisms are needed for a complete description of LHC final states
  - To explain the high multiplicity events in the correlation effects

- High multiplicity in the final state plays a key role:
  - Still not completely understood (large deviation MC/Data in high multiplicity)
  - MPI dynamics characterization and the system size dependence
  - Final state correlation, i.e. the «ridge effect» (Hydro? MPI alone? CGC?AMPT?)
THANK YOU FOR THE ATTENTION!
PSEUDORAPIDITY AND TRANSVERSE MOMENTUM DISTRIBUTIONS FOR CHARGED PARTICLES

- Charged particle pseudorapidity distribution:

\[
\frac{1}{N_{\text{events}}} \frac{dN_{\text{ch}}}{d\eta} = \frac{C_{T2} \Sigma M \Sigma pT N_{\text{tracks}}(M, pT, \eta) \omega_{\text{tracks}}(M, pT, \eta) \omega_{\text{event}}(M, n_{T2})}{\Delta \eta \Sigma M N_{\text{evt}}(M) \omega_{\text{event}}(M, n_{T2})}
\]

where \( \omega_{\text{tracks}} \) and \( \omega_{\text{events}} \) are correction factors and \( C_{T2} \) accounts for the track reconstruction efficiency. \( M \) is the track multiplicity.

\[
\omega_{\text{event}}(M, n_{T2}) = \frac{1}{\epsilon_{\text{trig}}(n_{T2}) \epsilon_{\text{PV}}(M)}
\]

\[
\omega_{\text{track}}(M, pT, \eta) = \frac{1 - f_{np}(M, pT, \eta)}{\epsilon_{\text{track}}(M, pT, \eta) (1 + f_{m}(M, pT, \eta))}
\]

\[
f_{np} = \frac{N_{\text{not matched tracks}}(M, pT, \eta)}{N_{\text{reco}}}
\]

- Charged particle pT distribution:

\[
\frac{1}{N_{\text{events}}} \frac{dN_{\text{ch}}}{dpT_{\text{leading}}} = \frac{\Sigma \eta N_{\text{tracks}}(\eta, pT_{\text{leading}}) \cdot C(pT_{\text{leading}}) \cdot C_{T2}(pT_{\text{leading}})}{N_{\text{events}} \cdot \Delta pT_{\text{leading}}}
\]

where \( C \) is the correction to stable particle level.

\[
C(pT_{\text{leading}}) = \frac{\left( \frac{1}{N} \frac{dN_{\text{ch}}}{dpT_{\text{leading}}} \right)_{\text{gen}}}{\left( \frac{1}{N} \frac{dN_{\text{ch}}}{dpT_{\text{leading}}} \right)_{\text{reco}}}
\]
Pseudorapidity and transverse momentum distribution were studied by CMS collaboration at 8 TeV ([Eur. Phys. J. C 74 (2014) 3053](https://link.springer.com/article/10.1140/epjc/s10052-014-2873-x)) with a different trigger:

- Minimum Bias events are triggered by TOTEM T2 telescopes that cover the pseudorapidity region $5.3 < |\eta| < 6.6$ for tracks with $p_T > 40$ MeV.

- The measurements was performed for tracks with $p_T > 0.1$ GeV and $p_T > 1$ GeV in two conditions:
  - Inclusive sample with tracks reconstructed in the TOTEM T2 in either hemisphere
  - Sample enhanced in non-single diffractive dissociation events by requiring tracks in T2 both forward and backward hemispheres

- Selection criteria:
  - Rejection of the backgrounds requiring at least one reconstructed primary vertex with at least two tracks and with $|z|<15$ cm around the position of the nominal interaction
  - High purity tracks are selected with $p_T > 0.1$ GeV or $p_T > 1$ GeV and relative transverse momentum uncertainty less than 10% within the pseudorapidity range $|\eta|<2.4$
  - Track-vertex association applied requiring $d_{xy}/\sigma_{xy} < 3$ and $d_z/\sigma_z < 3$
  - For the measurement of the leading-track $p_T$ distribution the threshold for the tracks is 0.4 GeV
CENTRAL MULTIPLICITY ANALYSIS AT 13 TEV

13 TeV results by CMS Collaborations:

- Measurements of $dN_{ch}/d\eta$ in the range $|\eta|< 2$ for inelastic proton-proton collision with 2015 data taken at 0 Tesla during a special low intensity beam configuration.
- $N_{ch}$ is defined to include decay products of particle with decay length $ct < 1$ cm, products of secondary interactions are excluded.
- Data are compared to PYTHIA8 v208 and EPOS LHC (Energy-conserving quantum mechanical multiple scattering approach, based on Parton, Off-shell remnants, and Splitting of parton ladders).

Event selection:

Selection of inelastic collision events:

- Online: a coincidence of signals from both the BPTX devices is required (both proton bunches crossing the IP).
- Offline: at least one reconstructed interaction vertex is required.
MB events are analyzed

The sphericity in data is steadily rising with multiplicity suggesting a more isotropic distribution of tracks in azimuth than the models.

The general agreement between models is better for “soft” events while for the “hard” ones the disagreement is up to ~20% at low and high multiplicity.

Figure 1: Mean transverse sphericity as a function of charged particle multiplicity for pp collisions at $\sqrt{s} = 7$ TeV. The statistical errors are displayed as error bars and the systematic uncertainties as the shaded area. The results are shown for the different event classes: (a) “bulk,” (b) “soft” and (c) “hard.”
0.9 TeV

Event at $\sqrt{s} = 0.9$ Pythia6 D6T without multiple parton interaction completely fails the data description

Energy flow increase with center of mass energy of a factor two or three from 0.9 to 7 TeV
Comparison between 13 TeV (red) and 7 TeV data,
Comparison between CMS data at 7 TeV (CMS-QCD-10-002) and PYTHIA8 in 4 range of pT bins.

Two discrepancies:

- The strength of the away-side correlation is over --or underpredicted for almost all the bins
- PYTHIA8 fails to reproduce the local maximum near $\Delta \phi \approx 0$ in any of the pT or multiplicity bins.

The long range, near side correlation increases in strength with increasing multiplicity and is stronger in the bin $1<pT<2$ GeV
Deeper study on $v_2$ term is done evaluating this variables from simultaneously correlating several (no less than four) particles.

- Suppress the short-range two particle correlations such as jets and resonance decays and as a
- Powerful tool to directly probe the collective nature of the observed azimuthal correlations.

$v_2^2 \approx v_4^2 \approx v_6^2$ in pp collisions (left)

- Qualitatively similar results seen in high multiplicity pp and pPb, as well as peripheral PbPb for $v_2^4$ and $v_2^6$
- The ratio of $v_2^4$ to $v_2^2$ is related to the total number of fluctuating sources in the initial state of a collision.

The comparable magnitudes of $v_2^2$ and $v_2^4$ signals observed in pp collisions may indicate a smaller number of initial fluctuating sources that drive the long-range correlations seen in the final state.

Strong evidence for the collective nature of the long-range correlations observed in pp collisions.