Multi-Parton and Multi-Nucleon Correlations: Experiment

Andreas Morsch
CERN

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Multi-Parton/Multi-Nucleon Correlations?

- pp, pA, AA: collisions of beams of confined partons

- most of the experimental results are related to Multi-Parton or Multi-Nucleon interaction and their correlations …

Challenging subject for a 20 min talk …

… and the most spectacular results have been already discussed
Focus of this Talk

- Measurements interpreted in the framework of MPI that provide information about
  - correlation between hard and soft particle production
  - the initial state of small systems (pp, p(d)A)
  - final state correlations that might help to understand the origin of collectivity in small systems
- Emphasis is on experimental challenges rather than an exhaustive catalogue of experimental results
Importance of MPI in pp (at LHC)

- Straightforward interpretation of pQCD $\sigma_{2\to2} > \sigma_{\text{tot}}$

Number of $2\to2$ scatterings per event, naïve factorization:

$$\langle n_{2\to2} \rangle = \frac{\sigma_{2\to2}}{\sigma_{\text{tot}}}$$

$$P_n = \frac{\langle n_{2\to2} \rangle^n}{n!} e^{-\langle n_{2\to2} \rangle}$$

$p_T \gg \Lambda_{\text{QCD}}$ for pQCD to be applicable

factorisation breaks for $n_{2\to2}$ large in area $\frac{1}{p_T^2}$

Challenge models based on MPI in this region!

At LHC multiple hard scatterings at perturbative scales

What do we know about the contribution to “bulk (low-$p_T$) particle” production? (event activity = proxy for MPI)
MPI and Charged Particle Multiplicity

- Particle yield from MPI $\propto \sigma_{\text{hard}}/\sigma_{\text{soft}}$ steeply rising with $\sqrt{s}$
  - additional factors $\propto A^{1/3}$ (pA), $\propto A^{4/3}$ (AA)

- Dominance of particle production at LHC?
  - $dN_{\text{ch}}/d\eta$ does not follow this trend
  - hard cross-section must be damped at low $p_T$
  - additional soft processes are important

What about jet like correlations?
Topological Identification of MPI

Di-Hadron Azimuthal Correlations

- “mini-jets” contribution to low-$p_T$ “bulk” particle production
- Multiplicity dependence sensitive to relative contribution of hard-soft processes
- should be the Achilles heel of MPI based models

Quite well described by some of the MC tunes.
Two additional MPI model ingredients

\[ \langle n_{2\rightarrow 2} \rangle = \frac{\sigma_{2\rightarrow 2}}{\sigma_{\text{tot}}} \]

\[ P_n = \frac{\langle n_{2\rightarrow 2} \rangle^n}{n!} e^{-\langle n_{2\rightarrow 2} \rangle} \]

- Impact parameter dependence (needs proton density function)
- Coherence effects between MPIs
  - Color Reconnections (Pythia, Herwig, …)
  - Collective Hadronization (EPOS)
  - Rope Hadronisation (DIPSY)

Factorisation with Poisson Fluctuations not enough
Sensitivity to Impact Parameter Dependence: Charged Particle Multiplicity Distributions

Shape of multiplicity distribution sensitive to impact parameter dependence

\[ P_n = \frac{\langle n \rangle^n}{n!} \exp(-\langle n \rangle) \]

\[ d\sigma_{2\rightarrow2} = db^2 T_p (b_{pp},...) \]
Hallmark of MPI based models:
High $p_T$ objects bias towards smaller $b$ where probability for additional interactions is larger increased UE activity.
Clear discriminating power between different models (tunes)

However, to which extent can we constrain individual mode components:
- exact impact parameter dependence of hard/soft scattering?
- modelling of soft processes?
- confidence intervals for the parameters?

In principle proton density function could be $x$-dependent
- Which measurement would be sensitive to this?

\[
\rho(r, x) \propto \frac{1}{a^3(x)} \exp \left( -\frac{r^2}{a^2(x)} \right)
\]

\[
a(x) = a_0 \left( 1 + a_1 \ln \frac{1}{x} \right)
\]
Probing Coherence Effects

- $N_{\text{ch}}$ dependent measurements inform
- to which extent high-multiplicity events can be understood as incoherent superposition of elementary collisions
- as such sensitive to coherence effects
Probing Coherence Effects

Two component model

- **Ledge Effect**: rise – plateau – rise

1st rise: increased dominance of hard over soft interactions

2nd rise: jet bias (jets contribute to soft particle production $\sim \ln E_{\text{jet}}$)


P. Skands
Pythia: Color Reconnections

Pythia:
Interplay between hard and soft not enough to describe rise
EPOS: Collective Hadronization

\[ \langle p_T \rangle \text{ (GeV)} \]

\[ N_{ch} \]

\[ \text{7000 GeV pp} \] Soft QCD

Average \( p_T \) vs \( N_{ch} \)

- CMS
- Epos (1.99)
- Epos (LHC)

freeze out

collective hadron.

fragm.

primary inter.

Proj. p

Target p

fraction of particles from core

\[ \frac{p + p |\eta|<2.4}{N_{chrg}} \]

7 TeV

900 GeV
What’s Next?

- Quite unsatisfactory that we cannot get separate effects related to
  - interplay of hard and soft particle production processes
  - jet biases
  - collective / coherence effects

- New observables?

- Absence of multiplicity dependence of $v_2$ (ATLAS) should be contrasted with multiplicity dependence of other observables

![Graph showing $v_2$ vs. multiplicity dependence at different ATLAS settings](image)
Ledge Effect Re-visited

Multiplicity measured in: $|\eta|<0.9$

arXiv:1509.08734v1

2.8 < $\eta$ < 4.1 ∪ -3.7 < $\eta$ < -1.7

- Spectra measured at mid-rapidity,
- hardness multiplicity dependent

- Scaling at high $p_T$, reminiscent of $R_{pA}$
- Informs about $N_{MPI}$
- “Some kind of centrality measure”
Rapidity Separated Measurements

$\Upsilon(1S)$

forward event activity

central event activity
New Ideas

Measurements as a function of the UE activity for fixed jet $p_T$ range

P. Skands, arXiv:1603.0529

$$R_T = \frac{N_{\text{inc}}}{\langle N_{\text{inc}} \rangle}$$

Measurements as a function of event shape (transverse spherocity)

Poster, G Paic

$$S_0 = \frac{\pi^2}{4} \left( \frac{\sum_i |\vec{p}_T^{i} \times \hat{n}|}{\sum_i p_T^{i}} \right)^2$$

$$S_0 = \begin{cases} 
0 & \text{“pencil-like” limit (hard events)} \\
1 & \text{“isotropic” limit (soft events)} 
\end{cases}$$

![Graph showing measurements as a function of the UE activity for fixed jet $p_T$ range.]

![Graph showing measurements as a function of event shape (transverse spherocity).]
pA: Bias on hard processes from soft-hard correlations

- Study of soft-hard correlations and MPI in pp has lead to a better understanding of centrality determination ($N_{\text{coll}}$) in pA.

- Deviation from $N_{\text{coll}}$ scaling if bias on hard processes in binary N-N collisions is not taken into account.
pA: Bias on hard processes from soft-hard correlations

MC


Data driven

DV Perepelitsa, P Steinberg arXiv:1412.0976

Slicing of Multiplicity in $2.8 < \eta < 5.1$

Glauber

Pythia
Low-$p_T$ jet-like correlations in p-Pb

Corrected for contribution from $v_2$

Do collective effects modify di-hadron correlations?

With forward event activity estimators di-hadron correlations level out at high multiplicities

- Despite strong collective effects
- Can this discriminate models?
Correlations between MPIs in the Initial State

- Complete incoherent superposition of MPI relies also on naive pdf factorisation beyond standard QCD factorisation:

\[
\frac{d\sigma^{AA\rightarrow X}}{dp_T} \propto \sum_{n} f_i(x_i^n, Q_{n}^2) \cdot f_j(x_j^n, Q_{n}^2) \cdot \sigma^{ii\rightarrow k}(x_i^n, x_j^n, p_T / z, Q_{n}^2) \cdot D_{k\rightarrow X}(z, Q_{n}^2)
\]

- Draw partons many times from the same pdf
- Must be trivially broken at some level due to energy conservation
  - Taken into account by MC
- Non-trivial correlations between partons
  - in particular between \( x \) of the hardest scattering parton and the proton size

DV Perepelitsa, Tue Parallel Session
N Armesto et al., arXiv:1502.02986
$x_{proj}$ Dependence of Jet Production

DV Perepelitsa, Tue Parallel Session

- Common “initial state” proton-$x$ effect at RHIC and the LHC?
- Minimum Bias Unmodified
  - Centrality Bias?
Can effect be understood as superposition of N-N collisions?

Control measurement:
Forward summed $E_T$ vs projectile (target) $x$

- Contrary to pPb, weak dependence on $x_{proj}$
- Effect in pPb not explained by N-N superposition.
- This is qualitatively expected if kinematic constraints on the proton pdf are responsible for the effect (more scatterings in pPb)
**$N_{\text{ch}}$ Centrality Dependence in AA**

- S-shape reflects hard+soft scaling ($f N_{\text{part}} + (1-f) N_{\text{coll}}$)
- But shape almost energy independent.
  - **Strong $\sqrt{s}$ dependence of the hard component expected**

### 0.2 and 2.76 TeV

- Charged particle density depends only on geometry.

### 2.76 and 5.02 TeV

*arXiv:1512.06104*

*Phys. Rev. Lett. 106(2011)032301*
Questions (instead of summary)

- How to move from MC tuning to extraction of physical parameters for the transverse structure of hadrons (including errors)?

- Can one constrain generalised pdf ($g(x,b)$) and multiparton pdfs?

- How does re-scattering modify (de-correlate) low-$p_T$ jet-like correlations?

- Can “elementary” string interactions explain collective behavior in small systems?