DPS, MPI, underlying event and identified hadrons

(and many thanks to C. Loizides, A. Morsch, J.F. Grosse-Oethringhaus, J. Hollar, G. Veres, K. Mueller, V. Belyaev, D. Volyanskyy, S. Glazov from the LHC experiments)
Outline

Multi-parton interactions (MPI) and DPS
  • increasingly important at LHC
  • results on Double Parton Scattering
  • studying MPI with correlations

Underlying event (UE)
  • LHC approaches so far keeping an eye on MPI

Identified hadrons
  • highlights and puzzles
  • particle production and multiplicity

Summary and outlook

DISCLAIMER: a selection of topics with some emphasis on more recent results, not a comprehensive summary
The simple picture: “One hard scattering between two partons, the spectator partons contribute to the underlying event”

- But the probability of other partons in each nucleons to also undergo additional scatterings (MPI) is not zero..
- Increasing $\sqrt{s}$ → access low-$x$ → increase parton density → MPI probability
- @LHC ‘MPI-off’ is just not an option
- ‘Soft’ MPI (semi-hard second interaction) required by underlying event studies and many other observables.

$O(\text{some GeV})$

- But large $p_T$/mass are possible with second interaction (‘hard’ MPI -> DPS)?

$O(\text{some tens of GeV})$

Important for LHC: DPS can create critical background to exclusive physics channels under study!
Double Parton Scattering at the LHC

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Channel</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>$Z + C$</td>
<td>JHEP 04 (2014) 91</td>
</tr>
<tr>
<td>CMS</td>
<td>$W + 2$ jets</td>
<td>JHEP 03 (2014) 032</td>
</tr>
</tbody>
</table>

\[ \sigma_{\text{eff}} = C \frac{\sigma_A \cdot \sigma_B}{\sigma_{\text{DPS}}^{A+B}} \]

- Clean tag
- Increase probability to observe DPS
- Large cross section

C = 1/4 for A=B identical and non self-conjugate
C = 1 for A\neq B and either A or B self-conjugate
C = 1/2 otherwise

M.H. Seymour and A. Siódmok, arXiv:1308.6749

ATLAS analysis includes both e and $\mu$, CMS $\mu$ only
In general fit $f_{\text{DPS}}$ with:

$$(1 - f_{\text{DPS}}) \cdot B + f_{\text{DPS}} \cdot S$$

and then use:

$$\sigma_{\text{eff}} = \frac{N_{W+0j}'}{f_{\text{DPS}} \cdot N_{W+2j}'} \cdot \sigma_{2j}'$$
Double Parton Scattering: $\sigma_{\text{eff}}$

\[
f_{\text{DPS}} = 0.076 \pm 0.013 \text{(stat.)} \pm 0.018 \text{(syst.) (ATLAS)}
\]
\[
f_{\text{DPS}} = 0.055 \pm 0.002 \text{(stat.)} \pm 0.014 \text{(syst.) (CMS)}
\]

\[
\sigma_{\text{eff}} = 15 \pm 3 \text{ (stat)} +5/-3 \text{ (syst) mb (ATLAS)}
\]
\[
\sigma_{\text{eff}} = 20.7 \pm 0.8 \text{ (stat) } \pm 6.6 \text{ (syst) mb (CMS)}
\]

- ATLAS and CMS results consistent
- hard to draw conclusions on $\sqrt{s}$ dependence (but RUN2 could tell us more)

D0 arXiv:1402.1550
first measurement with heavy flavor jets in the final state
towards cleaner DPS channels
Charm production at LHC & DPS

LHCb:
PLB 707 (2012) 52 \( J/\psi J/\psi \)
JHEP 06 (2012) 141: \( J/\psi \) C and CC
(C=open charm hadrons)
JHEP 4(2014) 91 \( Z+\)open charm meson

Early LHCb result on double \( J/\psi \), where
contribution from DPS can be significant, is
however consistent with predictions without
including DPS

\[
\sigma_{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb}
\]

\[
\frac{\sigma_{J/\psi J/\psi}}{\sigma_{J/\psi}} = (5.0 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4}
\]

For future studies it will be important to study channels where one of the two mechanisms
is dominant.

\[
\sigma_{SPS}^{J/\psi \Upsilon} < \sigma_{SPS}^{\Upsilon \Upsilon} < \sigma_{SPS}^{J/\psi J/\psi}
\]

\[
\sigma_{DPS}^{\Upsilon \Upsilon} < \sigma_{DPS}^{J/\psi \Upsilon} < \sigma_{DPS}^{J/\psi J/\psi}
\]

\[
\left( \frac{\sigma_{DPS}}{\sigma_{SPS}} \right)^{J/\psi \Upsilon} \approx 35
\]

Prediction from Berezhnoy et al, PRD 84(2011) 094203 (not including DPS)

For future studies it will be important to study channels where one of the two mechanisms
is dominant.

\[
\sigma_{SPS}^{pp\rightarrow J/\psi J/\psi X} \approx 4 \text{ nb}
\]

\[
\sigma_{DPS}^{pp\rightarrow J/\psi J/\psi X} \approx 2 \text{ nb}
\]

A. Novoselov
arXiv:1106.2184
DPS: $J/\psi$ and open charm

$S_\sigma > 8 \sigma$ if not indicated!

$p_T^{J/\psi} < 12 \text{ GeV/c}$

$3 < p_T^{C} < 12 \text{ GeV/c}$

$5 \sigma$

first observation of $J/\psi$ C events in hadron production

$8 \sigma$

CC/CC ratio relatively large (10-15% with respect to $10^{-4} \sigma^{J/\psi J/\psi}/\sigma^{J/\psi}$)

$8 \sigma$

absence of azimuthal or rapidity correlations provides support for DPS hypothesis for $J/\psi$ C and CC events

$5 \sigma$

$2.5 \sigma$
Agreement with Tevatron result (and now CMS/ATLAS) using J/ψ C sample

$\sigma_{\text{eff}}$ values for CC agreement also reasonable but higher values

For CC events observation of rapidity and azimuthal correlations support gluon splitting explanation
Prompt Double J/\psi at CMS

CMS PAS: BPH-11-021

Analysis presented at MPI@2013

Complementarity with LHCb measurement (|y|<2.2 and higher p_T)

\( \sigma \) as a function of \( \Delta y \) between J/\psi pair is sensitive to DPS

R. Maciula and A. Szczurek, PRD 87(2013) 074039
Z + open charm

First measurement at LHC (ATLAS/CMS observed W+charm)
Combined 5.1σ significance

- SPS + DPS within expectations for Z + D^0
- below expectations for Z + D^+

$L = 1 \text{ fb}^{-1}$

Z in di-muon channel
usual cuts for D mesons

assuming CDF $\sigma_{\text{eff}}$

$LHCb, JHEP 4(2014) 91$

important to look now at differential distributions with more statistics
Many papers in recent years include DPS contribution in single mesons production fits of experimental results from ALICE/CMS/ATLAS/LHCb.

DPS contribution similar to SPS being comparable at run2. This holds true even taking into account saturation.

RUN2 promising for DPS and b production.
MPI at harder scale: c and b vs multiplicity

- relative yields measured vs relative charged particle density
- results with D mesons from ALICE similar to the previous one about J/ψ (PLB 712(2012) 165)
- similar analysis published now by CMS with Υ
- for pp linear increase with multiplicity can be interpreted as MPI happening at harder scale

pPb / PbPb results discussed in E. Scomparin talk
DPS (and MPI) not only in pp

DPS in pPb and PbPb


• long-waited smoking gun for DPS (like-sign W pair) could be seen in pPb (estimated 10 DPS events with $\mathcal{L}=2$ pb$^{-1}$)
• PbPb events have also sizeable fraction of double $J/\psi$ due to DPS (estimated 240 events per unit of rapidity with $\mathcal{L}=1$ nb$^{-1}$)
• pPb DPS study suggested as a mean to filter out longitudinal correlations (B. Blok et al, EPJ C 73 (2013) 2433)

D. d’Enterria and A. Snigirev, PLB 727 (2013) 157

up to 35% in most central
MPI and correlation studies: pp and pPb

two particle azimuthal correlations in pp and pPb

→ new observable (uncorrelated seeds) constructed to study contribution of MPI to particle production

- \( N_{\text{unc. seeds}} \) increases with \( N_{\text{charged}} \) but evidence of \( N_{\text{MPI}} \) saturation in pp
- in pPb number of uncorrelated seeds increases linearly with multiplicity at midrapidity (no evidence of saturation)

All tunes describes qualitatively the increase pattern (with PHOJET underestimating the data points)
Underlying event studies

A non-exhaustive list:

<table>
<thead>
<tr>
<th>Exp</th>
<th>√s (TeV)</th>
<th>Approach/leading object/observables</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>0.9, 7</td>
<td>“traditional”/track</td>
<td>PRD 83 (2011) 112001</td>
</tr>
<tr>
<td>CMS</td>
<td>7</td>
<td>“traditional”/track</td>
<td>JHEP 1109 (2011) 109</td>
</tr>
<tr>
<td>ATLAS</td>
<td>0.9, 7</td>
<td>Inc. neutral/charged part. flow</td>
<td>EPJ C71 (2011) 1636</td>
</tr>
<tr>
<td>ALICE</td>
<td>0.9, 7</td>
<td>“traditional”/track</td>
<td>JHEP 1207 (2012) 116</td>
</tr>
<tr>
<td>CMS</td>
<td>7</td>
<td>UE in DY events: as a function of Mµµ</td>
<td>EPJ C72 (2012) 2080</td>
</tr>
<tr>
<td>ATLAS</td>
<td>7</td>
<td>“traditional”/jet/ dependency on the R of the jet</td>
<td>PRD 86 (2012) 072004</td>
</tr>
<tr>
<td>ATLAS</td>
<td>7</td>
<td>Includes transMIN/MAX/DIFF</td>
<td>ATLAS-CONF-2012-164</td>
</tr>
<tr>
<td>CMS</td>
<td>0.9, 7</td>
<td>Jet area/median approach</td>
<td>JHEP 1208 (2012) 130</td>
</tr>
<tr>
<td>LHCb</td>
<td>7</td>
<td>Forw. charged particle mult./density</td>
<td>EPJ C72 (2012) 1947</td>
</tr>
<tr>
<td>LHCb</td>
<td>7</td>
<td>Forw. energy</td>
<td>EPJ C73 (2013) 2421</td>
</tr>
<tr>
<td>CMS</td>
<td>0.9, 2.76, 7</td>
<td>Forward energy density ratio</td>
<td>JHEP 1304 (2013) 072</td>
</tr>
<tr>
<td>CMS</td>
<td>7</td>
<td>Neutral strange production (K⁺/Λ)</td>
<td>PRD 88 (2013) 052001</td>
</tr>
<tr>
<td>CMS</td>
<td>7</td>
<td>Charged mult. for intrajet and UE particles</td>
<td>EPJC 73 (2013) 2674</td>
</tr>
<tr>
<td>CMS</td>
<td>7</td>
<td>UE in t-bar events</td>
<td>CMS PAS TOP-13-007</td>
</tr>
<tr>
<td>LHCb</td>
<td>7</td>
<td>Forward p_T distr.</td>
<td>arXiv:1402.4430</td>
</tr>
</tbody>
</table>

- A rich combination of papers/analyses/approaches so far, still evolving
- UE made of particles that arise from BBR and the MPI that accompany the hard scattering

Forward results in S. Tourneur talk

“From a certain point of view, there is no such thing as an UE in a hadron-hadron collision. There is only an event and one cannot determine where a given particle in the event originated” (R. Field)
The “traditional” approach

- first bunch of LHC results with track with highest $p_T$ as leading object
- increasing activity in UE was a prediction of models with MPI
- increase of hadron activity at different $\sqrt{s}$ supports MPI description

predictions (and observables) firmly based on seminal work at Tevatron

R. Field, ARNPS 62 (2012) 453
Refining the traditional approach

- DY events: test UE universality
- cut on $p_T^{\mu\mu}$ limits ISR presence and “select” MPI
- independence of UE from $M_{\mu\mu}$ indicates MPI constant down to 40 GeV
- [ transMAX/MIN/DIF observables (help separation of MPI from ISR/FSR) studied by ATLAS (ATLAS-CONF-2012-164) at LHC and CMS (PAS-GEN-14-001) ]

- jet as leading object
- study UE activity as a function of R parameter to define the jet
  → study the interplay between pQCD and soft QCD in MC models
- Pythia 6 LHC-based tunes (as Z1) able to reproduce the pattern seen in the data
UE: subtracting the jets

- different approach presented by CMS
- define UE subtracting jets ($p_T^{\text{min}} > 5\text{ GeV/c}$) and considering everything else as UE (removal of intrajet particles)
- study as a function of multiplicity
- UE behaviour not predicted by HERWIG, PYTHIA predicts harder spectra, failure of prediction not including MPI (more visible for intrajet and all particles)

increase with $N_{ch}$ expected by increase of semi-hard scatterings
UE: adding observables and event categories

- complementarity to DY due to high FSR expected by b jets
- good agreement with simulation especially at low tt $p_T$
- CMS is testing different tuning varying factorization/renorm scale, CR and MPI in these events

- s underestimation seen in MB is in UE
- similar trends with respect to charged particles (plateau at 10 GeV/$c$) and for baryon/meson
- consistent with MPI activity depending on impact parameter
- hadronization and MPI decoupled

**$K^0_s$ and $\Lambda$**

- use PID for UE studies
Refining UE studies with jets

- Use transMAX/MIN
- Less activity in transMIN increasing jet energy
- Use only di-jet events
- Almost constant UE activity!
MPI, DPS and underlying event

Four jets analysis revisited in terms of MPI/DPS

CMS, $\sqrt{s} = 7$ TeV, $L = 36$ pb$^{-1}$, pp $\rightarrow 4j+X$

CMS, $\sqrt{s} = 7$ TeV, $L = 36$ pb$^{-1}$, pp $\rightarrow 4j+X$

<table>
<thead>
<tr>
<th>Tune</th>
<th>$\sigma_{\text{eff}}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tune 4C</td>
<td>30.3</td>
</tr>
<tr>
<td>CUETP8S1-CTEQ6L1</td>
<td>27.8 $^{+1.2}_{-1.3}$</td>
</tr>
<tr>
<td>CUETP8S1-HERAPDF1.5LO</td>
<td>29.1 $^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>CDPSTP8S1-4j</td>
<td>21.3 $^{+1.6}_{-1.9}$</td>
</tr>
<tr>
<td>CDPSTP8S2-4j</td>
<td>19.0 $^{+1.9}_{-1.3}$</td>
</tr>
</tbody>
</table>

- UE tunes include Fermilab data
- DPS tunes cross-checked against UE: indication of some tension in the simultaneous description of softer and harder MPI
- A HERWIG++ tune with DPS+UE: arXiv:1307.5014 (M.H. Seymour and A. Siódmok)

MPI off doesn’t describe data: need of additional contributions

Contribution from SPS can be improved

UE tuning needed before DPS can be extracted
Identified hadrons: some highlights & puzzles


**Baryon/meson ratio**

not well described by PYTHIA

PYTHIA 8 4C with CR helps to describe $p/\pi$ ratio up to 4 GeV/c, but CR helps less at LHCb rapidities for $p/K$, especially at very low $p_T$

A. Ortiz et al., PRL 111 (2013) 042001
Recent result from ATLAS on $\phi$ favours EPOS LHC (which has ‘collective’ hadronization via flow), PYTHIA 6 DW (pre-LHC tune CDF tuned + virtuality-ordered parton shower) while more recent PYTHIA 6 or 8 tunes are disfavoured.

- ALICE noted better agreement with HIJING/BB for $\Omega/\phi$ ratio in pp, but this doesn’t fit PbPb data
- soft particles produced via string fragmentation in HIJING/BB and string tension influences strangeness yield
Particle production and multiplicity (I)

PYTHIA with color reconnection enabled gives better description of data:

- In pPb EPOS describes data where others fail, but has different trend at low $p_T$. A pure superposition Glauber model sits similar with DPMJET, HIJING, AMPT.
- Same study from CMS with identified particles and larger multiplicities.

(let’s leave PbPb for the heavy ions session)
Particle production and multiplicity (II)

- Particle production strongly correlated to multiplicity (more than collision system or center-of-mass energy)
- Yields similar in pp pPb

More to come in the heavy ions session!
Particle production and event multiplicity (III)

ALICE, PLB 728 (2014) 25

The evolution of ratios differs but it has the same scaling at fixed $p_T$ values as a function of $dN_{ch}/d\eta$.

The same for $\Lambda/K^0_s$, where pp is also shown.

(and $\Lambda/K^0_s$ ratio overestimated by HIJING/BB model with increased string tension (which works for $\Omega/\phi$))

More to come in the heavy ions session!
Summary and outlook

- Increased comprehension of the role played by MPI at LHC energies seen through different studies/approaches (DPS, correlations, UE).
- Processes directly sensitive to DPS now measured at LHC. Contribution from DPS generally brings predictions closer to measurements. More observables expected in run2.
- Specific UE measurements in different categories of events are emerging further constraining models and tunes. Attempts to dovetail MPI, DPS and UE description in MC tunes all together on-going.
- Strangeness and baryon/meson ratio remain areas where we need to improve predictions/understanding of mechanisms.
- From identified hadrons (and charged hadrons observables) we have a pattern of indications pointing to a better data agreement with MC predictions when we add some ‘collectivity’ like CR or hydro (EPOS LHC). We observe particle production features more correlated with event multiplicity than collision system.

In all these studies:
- pPb (and PbPb) collisions at LHC could be much more revealing than originally expected
- LHC@14 TeV will be an excellent test opportunity of what we learned during first 5 years of LHC era
Backup
Double Parton Scattering

Single Parton Scattering: usual pQCD factorization

\[ d\sigma^{SPS} = \sum_{i,j} \int D^i(x_1) \cdot D^j(x_2) d\sigma_{(ij\rightarrow abcd)}(x_1, x_2) dx_1 dx_2 \]

Double Parton Scattering formalism


\[ \sigma_4 = \int \frac{d^2 \vec{\Delta}}{(2\pi)^2} \int dx_1 \int dx_2 \int dx_3 \int dx_4 \times D_a(x_1, x_2, p_1^2, p_2^2, \vec{\Delta}) D_b(x_3, x_4, p_1^2, p_2^2, -\vec{\Delta}) \times \left( \frac{d\sigma^{13}}{dt_1} \frac{d\sigma^{24}}{dt_2} \right) dt_1 dt_2 \]

generalized two-parton distributions

\[ \sigma_4 = \frac{\sigma_1 \sigma_2}{\pi R_{int}^2} \frac{1}{\pi R_{int}^2} = \int \frac{d^2 \vec{\Delta}}{(2\pi)^2} \frac{D(x_1, x_2, \vec{\Delta}) D(x_3, x_4, -\vec{\Delta})}{D(x_1) D(x_2) D(x_3) D(x_4)} = \frac{1}{\sigma_{eff}} \]

\( \sigma_{eff} \) measures the size of the partonic core where the flux of short-distance partons is confined

\[ \rightarrow \text{not really a cross section...} \]
\[ \rightarrow \text{proportional to the transversal area of parton overlap} \]
\[ \rightarrow \text{reflects longitudinal correlations of partons} \]
\[ \rightarrow \text{DPS probes hadronic structure!} \]
DPS variables in W+2jets

Both ATLAS and CMS construct templates to fit ‘DPS discriminating variables’

General challenge about how to correctly switch DPS off in MC, choice of a $p_T^{\text{max}}$ scale to separate ‘soft MPI’ from hard DPS

$\Delta^\text{n}_{\text{jets}} = \frac{|\vec{p}_{T}^J_1 + \vec{p}_{T}^J_2|}{|\vec{p}_{T}^J_1| + |\vec{p}_{T}^J_2|}$

$\Delta_{\text{jets}} = |\vec{p}_{T}^J_1 + \vec{p}_{T}^J_2|$
Both ATLAS and CMS construct templates to fit ‘DPS discriminating variables’

\[ \Delta_{\text{rel} \ p_T} \]

same as \( \Delta^{n}_{\text{jets}} \) as ATLAS

azimuthal angle between the W and the di-jet system

back-to-back at L0 in SPS

P. Antonioli
DPS: $J/\psi$ and open charm mesons

$\mathcal{L} = 355 \text{ pb}^{-1}$

- $J/\psi$ identified in di-muon channel
- Double open charm mesons: CC
- CC as control channel

DPS expected dominant over gg but contribution from sea quark can be bigger

Global fit of 2D mass invariant distributions of events with with $J/\psi$ and C, or CC events to establish global yields

$$F(m_i, m_j) \propto N^{S_i \times S_j} \times S_i(m_i) S_j(m_j) + N^{S_i \times B_j} \times S_i(m_i) B_j(m_j) + N^{B_i \times S_j} \times B_i(m_i) S_j(m_j) + N^{B_i \times B_j} \times B_i(m_i) B_j(m_j).$$

di-charm signal

B=combinatorial background
two particle azimuthal correlations in pp and pPb
→ information on parton fragmentation at low $p_T$
→ contribution of MPI to particle production

The basic idea:
1) parton scatterings produced back-to-back in azimuth
   → correlated bundles of particles from different sources
2) at increasing multiplicity, MPI increase
   → number of sources ("uncorrelated seeds") of correlated particles increases

$N_{\text{uncorrelated seeds}} \propto N_{\text{MPI}}$ in PYTHIA