hard-soft correlations in pA collisions

José Guilherme Milhano
CENTRA-IST (Lisbon) & CERN PH-TH
guilherme.milhano@cern.ch

Correlations and fluctuations, INT, 23rd July 2015
b-dependent nPDFs
:: impact parameter /centrality
pA dijets and nPDFs :: how successful?

- nuclear effects are small within the probed kinematics but essential to describe data

CMS pPb 35 nb⁻¹
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
\( p_{T,1} > 120 \text{ GeV/c} \)
\( p_{T,2} > 30 \text{ GeV/c} \)
\( \Delta \phi_{1,2} > 2\pi/3 \)
All \( E_{T}^{4\text{dijet}} < 5.2 \)

For each rapidity range, the plot shows the jet distribution with statistical and systematic uncertainties. The green band represents a calculation using the EPS09 nuclear parton distribution function set. The shaded gray box indicates the systematic uncertainty on the pPb luminosity. The CMS pPb luminosity is 27.8 nb⁻¹.
• EPS09 successful, others not [note anti-shadowing in EPS]
impact parameter dependence of nPDFs

- impact parameter dependence of nPDFs [1205.5359] cannot account for large ‘centrality’ dependence of dijet $\eta$ distributions
centrality is not impact parameter

- unlike in AA, multiplicity [or activity] not tightly correlated to $N_{\text{part}}$ and $N_{\text{part}}$ not tightly correlated to impact parameter
- ‘centrality’ classes necessarily mix wide range of impact parameters…
- both RHIC and LHC data show hallmarks of ‘centrality’ fuzziness
impact parameter dependence of nPDFs

• impact parameter dependence of nPDFs [1205.5359] cannot account for large ‘centrality’ dependence of dijet $\eta$ distributions

$$\eta_{\text{dijet}} = 2, \quad p_T = 100 \text{ GeV} \implies x_P \sim 0.3 \left( E_p \sim 1.2 \text{ TeV} \right)$$
what is going on?

Physics scenarios

Presence of high-$x_p$ jet is correlated with downward shift in Pb-going $\Sigma E_T$ more jets in peripheral bins, fewer jets in central bins

- Alvioli et al, arxiv:1409.7381:
  - Reduction in size of proton configuration for events when a high-$x$ parton is available for scattering - reduces $N_{\text{coll}}$ and multiplicity

- Armesto et al, arxiv:1502.02986
  - Reduction in CM energy of proton, due to removal of high-$x$ parton - reduces multiplicity and shifts CM rapidity

- Bathe et al, arxiv:1408.3156
  - Reduction in gluon content of projectile proton undergoing a high-$x$ parton-parton scattering - reduces multiplicity

- Kordell & Majumder - previous talk

Each of these can explain aspects of existing data: how do we explore this experimentally?
Event by event matching

\[
\begin{align*}
\sqrt{s_{NN}} &= 2 \sqrt{E_p E_{Pb} (1 - x_p)} \\
\eta_{CM} &= 0.5 \log \left( \frac{E_p (1 - x_p)}{E_{Pb}} \right)
\end{align*}
\]

- The energy that goes in hard scattering from one proton in PYTHIA taken away from proton in HIJING
- \(x_{Pb}\) is not taken into account in HIJING
- Good approximation when \(N_{coll}\) is large and \(x_{Pb}\) is small
**Simple proof of principle**

*Event by event matching*

\[ \sqrt{s_{NN}} = 2 \sqrt{E_p E_{Pb}(1 - x_p)} \]

\[ \eta_{CM} = 0.5 \log \left( \frac{E_p(1 - x_p)}{E_{Pb}} \right) \]

- The energy that goes from proton in HIJING
- \( x_{Pb} \) is not taken into account
- Good approximation

- \( E_{T\text{\,truth}} \): Sum of \( p_T \) of particles at large \( \eta \) from HIJING MB events
- Separate in centrality classes by slicing \( E_{T\text{\,truth}} \) in same fractions as in data
- Scale the \( E_{T\text{\,truth}} \) values with a constant so that the lower bound of highest centrality class in data and MC match (e.g. Scale factor ~ 0.7 for CMS dijet measurement)
- Obtain \( E_{T\text{\,raw}} \) comparable to what is measured by experiment
MB vs dijet events

- Bias towards small impact parameter collisions with higher $E_T$ on both sides.
large dijet energy requirement shifts $E_T$ down

for low $E_T$ [peripheral] events model fails as Pb energy depletion becomes important to calculate activity
η dijet distributions

- PYTHIA+HIJING
- $x_p$ matched
- CMS

$(dN/d\eta_{\text{dijet}})/(dN/d\eta_{\text{dijet}})_{\text{All}}$

- 100 - 26.9 %
- 16.3 - 26.9 %
- 9.3 - 16.3 %
- 2.5 - 9.3 %
- 2.5 - 0 %
\[ R_{p\text{Pb}} [ATLAS] :: \eta \text{ inclusive} \]

NOTE: ‘centrality’ determination from only Pb side
\( R_{\text{pPb}} \) [ATLAS] :: \( \eta \) inclusive

NOTE: ‘centrality’ determination from only Pb side
\( R_{pPb} \) [ATLAS] :: \( \eta \) inclusive

- \( N_{\text{coll}} \) from ATLAS [model dependent] :: don’t add to unity
- self-consistent determination of \( N_{\text{coll}} \) [events that pass the cuts in in the model] adds to unity

NOTE: ‘centrality’ determination from only Pb side
$R_{pPb}$ [ATLAS] :: ‘central’

- **excellent overall description** $[N_{\text{coll}} \text{ from ATLAS}]$
- **deviations on Pb side** :: same model limitation as before
deviations due to neglecting of nPDF effects [anti-shadowing]

proton PDFs used for both proton and nucleon from Pb
\( R_{pPb} \) [ATLAS] :: ‘peripheral’

- **not good**

outside ‘model’ applicability \([N_{\text{coll}} \text{ peaks at 1, } x_{pPb} \text{ becomes important}]\)
physics scenarios and implementation

high-x parton in proton
physics scenarios and implementation

- high-x parton in proton
  - Bzdak, Skokov, Bathe
  - Alvioli, Cole, Frankfurt, Perepelitsa, Strikman
- smaller proton
- depleted proton energy for UE
  - Armesto, Gulhan, Milhano
  - Kordell, Majumder

- fewer other partons [gluons]
physics scenarios and implementation

- high-x parton in proton
- fewer other partons [gluons]
- smaller proton
- depleted proton energy for UE
physics scenarios and implementation

- high-x parton in proton
- fewer other partons [gluons]
- smaller proton
- depleted proton energy for UE

alternative phrasings of same physics
physics scenarios and implementation

high-x parton in proton

fewer other partons [gluons]

smaller proton

depleted proton energy for UE

alternative phrasings of same physics

implementations [and physical effects] are not independent, rather they should be equivalent even if phrased rather orthogonally
physics scenarios and implementation

- high-x parton in proton
- smaller proton
- depleted proton energy for UE

alternative phrasings of same physics

implementations [and physical effects] are not independent, rather they should be equivalent even if phrased rather orthogonally

• formal equivalence not straightforward to show [possibly a spurious exercise]
• implementations SHOULD NOT, CANNOT be combined :: results should be compared
jet $R_{pA}$ / hadron $R_{pA}$ / jet FFs
jet $R_{pA}$ / hadron $R_{pA}$ / jet FFs
what is going on?

**Figure 1:**
- CMS pPb data for charged particle yield at √s = 5.02 TeV, L = 35 nb⁻¹.
- NPLO (nPDF=EPS09, FF=fDSS), y=0
- CMS h_{1/2} = 1
- ALICE h_{1/2} = 0.3

**Figure 2:**
- ATLAS: 1412.4092
- -0.3 < y* < +0.3
- RpPb
- 40 100 1000
- p_{T} (GeV/c)

**Figure 3:**
- ATLAS Preliminary
- p+Pb L_{int} = 25 nb⁻¹
- √s_{NN} = 5.02 TeV
- 0-90%

**Figure 4:**
- ALICE p-Pb √s_{NN} = 5.02 TeV
- Charged jets, anti-k_{T}, ∥η∥ < 0.5
- Reference: Scaled pp jets 7 TeV

**Figure 5:**
- Resolution parameter R = 0.2
- Resolution parameter R = 0.4
what is going on?

Charged hadron $R_{pPb}$

- Low $p_T$ (<2 GeV/c) particle production dominated by softer scattering
- Mid $p_T$ (2-5 GeV/c) range $R_{pPb}$ is ≈1
- High $p_T$ rise beyond theoretical explanation

$\sqrt{s_{\text{NN}}} = 5.02$ TeV, $L = 35$ nb$^{-1}$

CMS EPJC 72 (2012) 1945
Paukkunen arxiv.org:1408.4657
ALICE EurPhysJ C74 (2014) 3054

ALICE-CMS differences primarily from pp reference
what is going on?

Charged hadron $R_{pPb}$

CMS $pPb \sqrt{s_{NN}} = 5.02$ TeV, $L = 35$ nb$^{-1}$

- Low $p_T (< 2$ GeV/c) particle production dominated by softer scattering
- Mid $p_T (2-5$ GeV/c) range $R_{pPb}$ is $\approx 1$
- High $p_T$ rise beyond theoretical explanation

IS IT ?
what is going on? [vox populi]
what is going on? [vox populi]

[some] data [or scaled reference] is wrong
what is going on? [vox populi]

- [some] data [or scaled reference] is wrong
- personally cannot do anything about it
what is going on? [vox populi]

- [some] data [or scaled reference] is wrong
- personally cannot do anything about it

- [exotic] mechanism in pA produces high-$p_t$ pions [not from a jet]
what is going on? [vox populi]

- [some] data [or scaled reference] is wrong
  - personally cannot do anything about it

- [exotic] mechanism in pA produces high-\(p_T\) pions [not from a jet]
  - such pions would be reconstructed as jets and show up also in jet spectrum

- [standard] physics is being overlooked
at a risk ...
at a risk ...

modification of hadron spectrum without modification of jet spectra can only originate at the hadronization stage
modification of hadron spectrum without modification of jet spectra can only originate at the hadronization stage.

hadronization not under theoretical control but successfully modelled in event generators.
at a risk ...

- modification of hadron spectrum without modification of jet spectra can only originate at the hadronization stage
- hadronization not under theoretical control but successfully modelled in event generators
- colour reconnections are an essential prescription for description of average $p_t$ / low $p_t$ spectrum
modification of hadron spectrum without modification of jet spectra can only originate at the hadronization stage

hadronization not under theoretical control but successfully modelled in event generators

colour reconnections are an essential prescription for description of average $p_t$/low $p_t$ spectrum

colour reconnections :: possibility of colour neutralization involving partons with different colour histories that happen to be close in ($\eta, \phi$) plane
at a risk ...

— modification of hadron spectrum without modification of jet spectra can only originate at the hadronization stage

— hadronization not under theoretical control but successfully modelled in event generators

— colour reconnections are an essential prescription for description of average $p_t$/low $p_t$ spectrum

  colour reconnections :: possibility of colour neutralization involving partons with different colour histories that happen to be close in $(\eta, \phi)$ plane

— no available [validated] pA event generator
Modification of hadron spectrum without modification of jet spectra can only originate at the hadronization stage.

Hadronization not under theoretical control but successfully modelled in event generators.

Colour reconnections are an essential prescription for description of average $p_T$/low $p_T$ spectrum.

Colour reconnections :: possibility of colour neutralization involving partons with different colour histories that happen to be close in $(\eta, \varphi)$ plane.

No available [validated] pA event generator.

At hadronization stage pA and pp differ in magnitude of UE and colour correlations of partons.
Modification of hadron spectrum without modification of jet spectra can only originate at the hadronization stage.

Hadronization not under theoretical control but successfully modelled in event generators.

Colour reconnections are an essential prescription for description of average $p_t$ / low $p_t$ spectrum.

Colour reconnections :: possibility of colour neutralization involving partons with different colour histories that happen to be close in $(\eta, \phi)$ plane.

No available [validated] pA event generator.

Use pp generator with augmented UE [2÷3 times MB pp] and scrambled initial colour correlations.

At hadronization stage pA and pp differ in magnitude of UE and colour correlations of partons.
colour reconnections and high-$p_T$
colour reconnections and high-$p_t$

what do colour reconnections have to do with high-$p_t$?
colour reconnections and high-$p_T$

what do colour reconnections have to do with high-$p_T$?

hadronic multiplicity from colour neutral object dictated by its invariant mass

\[ M_{\text{inv}}^2 = p_T k_T \left[ \cosh (\eta_p - \eta_k) - \cos (\phi_p - \phi_k) \right] \approx p_T k_T R^2 \]
colour reconnections and high-$p_T$

- what do colour reconnections have to do with high-$p_T$?

- hadronic multiplicity from colour neutral object dictated by its invariant mass

  high-$p_T$ hadrons originate from low invariant mass clusters/strings where high-$p_T$ parton retains most [or all] of its momentum

\[ M_{\text{inv}}^2 = p_T k_T \left[ \cosh (\eta_p - \eta_k) - \cos (\phi_p - \phi_k) \right] \approx p_T k_T R^2 \]
colour reconnections and high-$p_T$

what do colour reconnections have to do with high-$p_T$?

hadronic multiplicity from colour neutral object dictated by its invariant mass

high-$p_T$ hadrons originate from low invariant mass clusters/strings where high-$p_T$ parton retains most [or all] of its momentum

colour neutralization of high-$p_T$ parton with low-$p_T$ parton from UE favours production of hard hadrons

\[
M_{\text{inv}}^2 = p_T \ k_T \ [\cosh (\eta_p - \eta_k) - \cos (\phi_p - \phi_k)] \approx p_T \ k_T \ R^2
\]

higher invariant mass :: higher multiplicity :: softer

lower invariant mass :: lower multiplicity :: harder
non-decaying clusters [high-$p_t$ hadrons]
non-decaying clusters \([\text{high-}\mathbf{p_{T}} \\text{hadrons}]\)

\[ M_{\text{cut}}^2 > M_{\text{inv}}^2 \approx p_T \, k_T \, R^2 \]

maximum invariant mass for non-decaying cluster
non-decaying clusters [high-\(p_T\) hadrons]

\[
M_{\text{cut}}^2 > M_{\text{inv}}^2 \approx p_T \, k_T \, R^2
\]

maximum invariant mass for non-decaying cluster

probability of soft parton from UE within \(R\) proportional to UE multiplicity

\[
R \sim 1/\sqrt{p_t}
\]
non-decaying clusters [high-$p_T$ hadrons]

\[ M_{\text{cut}}^2 > M_{\text{inv}}^2 \approx p_T k_T R^2 \]

maximum invariant mass for non-decaying cluster

probability of soft parton from UE within R proportional to UE multiplicity

\[ R \sim \frac{1}{\sqrt{p_t}} \]

for fixed UE multiplicity

\[ P_{\text{CR}} \sim \frac{1}{p_t} \]
non-decaying clusters [high-\(p_T\) hadrons]

\[ M_{\text{cut}}^2 > M_{\text{inv}}^2 \approx p_T k_T R^2 \]

maximum invariant mass for non-decaying cluster

probability of soft parton from UE within \(R\) proportional to UE multiplicity

\[ R \sim 1/\sqrt{p_t} \]

for fixed UE multiplicity

\[ P_{\text{CR}} \sim \frac{1}{p_t} \]

effect dies out much slower than other power corrections
generic effect [very difficult to argue away]
generic effect [very difficult to argue away]

does it work?
event generator evidence [SHERPA]

smaller than in data but clear effect :: much more statistics needed
[only very conservative CR considered]
outlook

• origin of ‘centrality’ binning problems pinned down to hard+UE strong correlation
  • strong constraint for hard+UE pA MC :: seems worth the trouble as essential to access impact parameter dependence
  • a laboratory for ‘proton-size’ studies :: no clear path put forward

• $R_{pA}$ meets $R_{pA}$ conundrum may have natural explanation
  • very difficult to argue away
  • violation of universality of FFs :: fundamental physics opportunity
  • can be checked in high multiplicity pp
  • need validated pA MC
backups
correlations detailed
correlation detailed :: different estimators

PYTHIA + HIJING
Matched $x_p$
$\hat{p}_T > 80$ GeV/c

Fractions defined by:

- $E_T^{p} + E_T^{Pb}$
- $E_T^{Pb}$
- $E_T^{p}$

at $4<|\eta|<5$
$N_{coll}$ centrality dependence

Minimum bias HIJING
- - - $x_p$ matched PYTHIA+HIJING

$p_{T}>100$ GeV/c, $|\eta_{jet}|<3$

Centrality definition:
$\Sigma E_T^{p_{T}} [3.2<q<4.9]$
$N_{\text{coll}}$ definitions :: 0-10%

HIJING

same event

ATLAS
N_{coll} definitions :: 20-30%
$N_{\text{coll}}$ definitions :: 60-90%

![Graph showing $R_{pPb}$ as a function of $p_T$ for different $\eta$ ranges.](image)

**HIJING**

**ATLAS**
hard process / UE ['centrality'] correlation
with fixed proton side $E_T$

- same trend and magnitudes in data and MC
- lowest activity [lowest $N_{\text{coll}}$] not described :: over simplistic treatment of Pb
- see recoil of UE [different slope for each $E_T^p$ class]
no CR vs CR [not colour scrambled]