ALICE Measurements in \( p\text{-}Pb \) Collisions

Charged Particle Multiplicity

Centrality Determination

and implications for Binary Scaling

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on behalf of the ALICE Collaboration

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Physics Motivations

nPDF in centrality classes

Many initial state effects are expected to vary as a function of the impact parameter or the number of collisions.

ALICE, arXiv:1210.4520

I. Helenius, K. Eskola, H. Honkanen and C. Salgado, HP2012

ALICE has measured min bias $R_{pA}$

Average p-Pb overlap function $< T_{pA} >$ determined by total (geometric) p-A cross-section:

$$\langle N_{\text{coll}} \rangle = 208 \frac{\sigma_{pN}}{\sigma_{pA}} = 6.9$$

with

$\sigma_{pN} = 70$ mb

$\sigma_{ppb} = 2100$ mb

$$\langle T_{pPb} \rangle = \frac{\langle N_{\text{coll}} \rangle}{\sigma_{pN}} = \frac{208}{2100} \text{ mb}^{-1} = 0.098 \text{ mb}^{-1}$$

p-A nuclear modifications: incoherent superposition of p-N collisions?

1) how many collisions ($N_{\text{coll}}$)?

2) what is the bias?
Detectors used for Centrality

MID-RAPIDITY

- TPC+ITS Tracks $|\eta| < 0.9$

VZERO Scintillators

<table>
<thead>
<tr>
<th>$z = 340 \text{ cm}$</th>
<th>$2.8 &lt; \eta &lt; 5.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z = -90 \text{ cm}$</td>
<td>$-3.7 &lt; \eta &lt; -1.7$</td>
</tr>
</tbody>
</table>

2 layers Si Pixel

$|\eta| < 2 ; |\eta| < 1.4$

ZERO-DEGREE

Quartz-Fiber “Spaghetti” Zero Degree Calorimeters

$z = \pm 112.5 \text{ m}$

ZDC sensitive to slow nucleons

Nucleus fragmentation model:
- Black nucleons: evaporation
- Grey nucleons: knock-out

Particle production modeled by Negative Binomial Distribution

Pb-fragmentation more relevant at forward rapidity

Centrality Estimators:
- CL1: Clusters in 2$^{nd}$ Pixel Layer
- V0M: VZERO-A+C Multiplicity
- V0A: VZERO-A Multiplicity
- ZNA: ZDC-A Neutron Energy
1. Ncoll
1.a Glauber + NBD
1.b Glauber + SNM
1.a Glauber + NBD Fit

- Same procedure as for Pb-Pb (ALICE, arXiv:1301.4361)
- Centrality classes: Multiplicity distribution sliced into percentiles of cross-section
- Obtain $P(N_{part})$ from Glauber Monte Carlo
  - $N_{part}$ is equal to number of ancestors

Glauber MC Parameters

$$
\rho(r) = \rho_0 \frac{1}{1 + \exp \left( \frac{r - R}{a} \right)}
$$

- $R = 6.62 \pm 0.06$ fm
- $a = 0.546 \pm 0.01$ fm
- Minimum NN distance: $0.4\pm0.4$ fm
- pN Cross-section: $\sigma_{pN} = 70 \pm 5$ mb
- Proton radius: $R_p = 0.6 \pm 0.2$ fm

- For each ancestor obtain multiplicity from Negative Binomial Distribution (NBD) iterated to fit NBD parameters
- Obtain $<N_{\text{coll}}>$ for each centrality class
1.a Results from Glauber+NBD

- \( <N_{\text{coll}} > \) similar for different estimators
- Systematic error estimated by varying Glauber MC parameters.
- MC closure test performed with HIJING
1.b Slow Nucleon Model

- Features of $N_{ch} \sim$ independent of $E_{projectile}$ (1GeV → 1 TeV)

- **Slow nucleons** emission dictated by collision geometry → Maxwell-Boltzmann (independent statistical emission) classified from emulsion experiments
  - Gray: soft nucleons knocked out by wounded nucleons
  - Black: low energy target fragments from de-excitation, evaporation

- Glauber model → distribution of $N_{coll}$

- implemented model used a parameterization of results from low energy experiments
  C. Oppedisano https://edms.cern.ch/document/682801/1
  F. Sikler, hep-ph/0304065

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### SLOW NUCLEONS

<table>
<thead>
<tr>
<th></th>
<th>$\beta$ [c units]</th>
<th>$p$ [MeV/c]</th>
<th>$E_{kin}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Black</strong></td>
<td>0 ÷ 0.25</td>
<td>0 ÷ 250</td>
<td>0 ÷ 30</td>
</tr>
<tr>
<td><strong>Gray</strong></td>
<td>0.25 ÷ 0.70</td>
<td>250 ÷ 1000</td>
<td>30 ÷ 400</td>
</tr>
</tbody>
</table>

saturation in $N_{black}$ vs $N_{gray}$
→ also in ZDC vs $N_{coll}$
1.b Results from Glauber+SNM

- \( N_{\text{coll}} \) from Glauber+SNM and Glauber+NBD similar except for most peripheral
- Despite of saturation, ZNA still able to select for centrality

Reasonable description of spectra except for most peripheral
2. Bias
2.a multiplicity fluctuations
2.b impact parameter
2.c jet-veto
Origin of the Bias in pA

Looser correlation between

$p$-Pb

and impact parameter ($b$) $N_{part}$ multiplicity $N_{part}$ different multiplicity estimators

Fluctuations at the origin of physical bias
2.a Bias in pA

- **2.a** Multiplicity fluctuations sizable → Bias on \( \text{Mult}/N_{part} \) at central and peripheral collisions

- MC models with multi-parton interaction (MPI) include fluctuations of particle sources (hard scatterings) HIJING (X.N. Wang, M. Gyulassy, nucl-th/9502021)

  → bias in mult ~ bias in hard scattering

![Graph showing multiplicity fluctuations and bias in Pb-Pb and pA collisions.](image)

**Toy-MC (Glauber+Pythia)**

- build a Toy-MC by adding a Pythia (pp) event \( N_{\text{coll}} \) (from Glauber pPb calculation) times
- slice it in multiplicity as the real data → centrality classes
2.b,c Bias in pA -- peripheral

- **2.b** Mean nucleon-nucleon impact parameter \(b_{NN}\) increases in peripheral collisions

- Due to MPI mult. fluctuations depend on fluctuations in particle sources (hard scatterings)
  - Mean number of scatterings per event obtained from impact parameter \(b_{NN}\)-dependent proton-nucleon overlap function \(T_N(b_{NN})\)
  
  \[ \rightarrow \text{bias in mult} \sim \text{bias in hard scattering emphasized at peripheral} \]

- **2.c** Jet-veto: multiplicity range in peripheral events represent an effective veto on hard processes
Bias from different estimators

- Different centrality estimators expected to show different deviations from N_{coll} scaling
  - **CL1 (Clusters Pixel Layer 2):** strong bias due to full overlap with tracking region.
    - Additional bias in peripheral event from “Jet veto effect”
    - Jets contribute to the multiplicity and shift events to higher centralities ($p_T$ - dependent)
  - **V0M (V0A+V0C Multiplicity):** reduced bias since outside tracking region
  - **V0A Multiplicity:** reduced bias because of important contribution from Pb fragmentation region.
  - **ZNA:** small bias slow nucleon production independent of hard processes

\[ Q_{pA}(p_T; \text{cent}) = \frac{d N_{pA}^{pA}}{d p_T} \frac{d N_{pp}^{pA}}{d p_T} = \frac{d N_{pA}^{pA}}{d p_T} \frac{d \sigma_{pp}^{pA}}{d p_T} \neq 1 \]

At high $p_T$

In general $N_{coll}$, for a given centrality class can not be used to scale the pp cross-section!
3. Implications for binary scaling
3.a $Q_{pA}$ as biased $R_{pA}$
3.b incoherent superposition of $pN$
3.c un-biased selection?
- $Q_{pPb}$ spread between centrality classes reduces with increasing rapidity gap: CL1→V0M→V0A
- Clear “jet veto bias” in CL1 80-100%
- No (or little?) “jet veto” bias in V0A 80-100% but $Q_{pPb} < 1$
Shapes Only

Cronin-like enhancement at $p_T \sim 3$ GeV increases with centrality

ZNA selects more similar event classes
Mean $Q_{pPb}$ at $p_T > 10$ GeV

p-Pb collisions described as incoherent superposition of nucleon-nucleon
- vs centrality from multiplicity $|\eta| < 1.4$
- only multiplicity bias
- strong deviation from $N_{coll}$-scaling at low and high centralities.

Same “S-shape” dependence as seen
- from multiplicity bias (Glauber + NBD fit)
- from Toy-MC (Glauber + Pythia)

Shape flattens with increasing rapidity gap:
CL1 $\rightarrow$ V0M $\rightarrow$ V0A
Comparison with Glauber+Pythia

- Bias at high $p_T$ described by incoherent superposition of pp collisions.
- For most peripheral, good agreement also in low- and intermediate $p_T$ region.
- Strong deviations for all other centrality bins!
Summary

- pA Centrality estimators based on multiplicity measurements in $|\eta| < 5$ induce a bias on the hardness of the pN collisions that can be quantified by the number of hard scatterings per pN collision.
  - Low (high) multiplicity p-Pb → lower (higher) than average number of hard scatterings.
- For "centrality" selected data, for which $<N_{\text{coll}}>$ is not uniquely defined, we introduced $Q_{pPb}$, each biased by the use of the particular estimator for the event ordering.
- To measure nuclear effects in pA: $N_{\text{coll}} \times pp$ is not the proper reference.
  - Include full dynamical bias (incoherent superposition of pN collisions) → Glauber + pp
  - ZDC provides a measurement with minimal (absent?) bias, from which it should be possible to calculate $R_{pPb}$
    - On-going efforts to understand $N_{\text{coll}}$ from Slow Nucleon Model
Extra
Systematic from Glauber

- Nuclear density profile: Woods–Saxon (2pF)
  - Radius = 6.62 ± 0.06 fm
  - Skin depth = 0.546 ± 0.01 fm
  - Intra-nucleon distance = 0.4 ± 0.4 fm
- Cross-section $\sigma_{NN} = 70 \pm 5$ mb
- Proton radius $R_p = 0.6 \pm 0.2$ fm
Slow Nucleon Model

PROTONS

- E910 (p-Au @ 18 GeV/c) fit to $N_{\text{gray}}$ vs. $N_{\text{coll}}$ to determine the average number of gray protons
  
  $$<N_{\text{gray} \, p}> = (c_0 + c_1 \, N_{\text{coll}} + c_2 \, N_{\text{coll}}^2) \left(\frac{A_{\text{pb}}}{A_{\text{Au}}}ight)^{2/3}$$

- COSY (p-Au @ 2.5 GeV) measured the fraction of black over gray protons for the average number of black protons
  
  $$<N_{\text{black} \, p}> = f_{\text{black \, over \, gray}} \times <N_{\text{gray} \, p}>$$
  
  $$\Rightarrow f_{\text{black \, over \, gray}} = 0.65$$

- $N_{\text{gray} \, p}$, $N_{\text{black} \, p}$ extracted from binomial distributions

NEUTRONS

- from COSY: Light Charged Particle (Z<=7)
  
  $$LCP = ( <N_{\text{gray} \, p}> + <N_{\text{black} \, p}> )/\alpha$$
  
  $$\Rightarrow \alpha = 0.585 \text{ (COSY) is left free}$$

  $$<N_{\text{slow} \, n}> = <N_{\text{black} \, n}> + <N_{\text{gray} \, n}> = a + b/(c-LCP)$$
  
  $$\Rightarrow a \text{ (b, c) can be finely tuned}$$

- results from p induced spallation reactions (0.1-10 GeV) for the fraction of black/gray neutrons
  
  $$<N_{\text{black} \, n}> = 0.9 \times <N_{\text{slow} \, n}>$$

- $N_{\text{gray} \, n}$, $N_{\text{black} \, n}$ extracted from binomial distributions
Insigths from Monte Carlo

\[ N_{\text{coll}} \text{ scaling: } \frac{n_{\text{hard}}}{N_{\text{coll}}} = \text{const.} \]

Number of hard scatterings per p-N collision
- vs \( N_{\text{coll}} \) (no multiplicity bias here !)
- Deviation from \( N_{\text{coll}} \) scaling
  - at low \( N_{\text{coll}} \): geometry \( b_{NN} \)
  - at high \( N_{\text{coll}} \): energy conservation (break down of factorization)

**p-Pb collisions described as incoherent superposition of nucleon-nucleon**
- vs centrality from multiplicity \(|\eta| < 1.4\)
- only multiplicity bias
- strong deviation from \( N_{\text{coll}} \) -scaling at low and high centralities.
ZNA correlations

ALICE p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

ZN-A Energy (a.u.) vs VZERO-A amplitude (a.u.)

ZP-A Energy (a.u.) vs ZN-A Energy (a.u.)
Detectors used for Centrality

Particle production modeled by Negative Binomial Distribution (NBD)

Nucleus fragmentation model:
- Black nucleons: evaporation
- Grey nucleons: knock-out

(eg. C. Oppedisano
https://edms.cern.ch/document/682801/1
F. Sikler arXiv: 0304.065)
Detectors used for Centrality

Quartz-Fiber “Spaghetti”
Zero Degree Calorimeters

TPC+ITS
Tracks |η| < 0.9

2 layers Si Pixel
|η| < 2 ; |η| < 1.4

Scintillator Hodoscopes

Centrality Estimators:

CL1: Clusters in 2\textsuperscript{nd} Pixel Layer
V0A: VZERO-A Multiplicity
V0M: VZERO-A+C Multiplicity
ZNA: ZN-A Energy

z = 340 cm
2.8 < η < 5.1
z = -90 cm
-3.7 < η < -1.7
Results from Glauber+NBD

Slice in fitted MULT

- \( N_{\text{coll}} \) similar for different estimators
- Systematic error estimated by varying Glauber MC parameters.
- MC closure test performed with HIJING

### Centrality

<table>
<thead>
<tr>
<th>Centrality</th>
<th>( \langle N_{\text{coll}} \rangle ) (CL1)</th>
<th>( \langle N_{\text{coll}} \rangle ) (V0M)</th>
<th>( \langle N_{\text{coll}} \rangle ) (V0A)</th>
<th>Max Diff.</th>
<th>Impact Parameter Slicing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5%</td>
<td>15.4</td>
<td>15.8</td>
<td>14.8</td>
<td>6.8%</td>
<td>14.4</td>
</tr>
<tr>
<td>5 - 10%</td>
<td>13.5</td>
<td>13.7</td>
<td>13.1</td>
<td>4.5%</td>
<td>13.8</td>
</tr>
<tr>
<td>10 - 20%</td>
<td>12.0</td>
<td>12.1</td>
<td>11.7</td>
<td>3.4%</td>
<td>12.7</td>
</tr>
<tr>
<td>20 - 40%</td>
<td>9.3</td>
<td>9.4</td>
<td>9.4</td>
<td>1.1%</td>
<td>10.2</td>
</tr>
<tr>
<td>40 - 60%</td>
<td>6.0</td>
<td>6.1</td>
<td>6.5</td>
<td>6.6%</td>
<td>6.3</td>
</tr>
<tr>
<td>60 - 80%</td>
<td>3.46</td>
<td>3.33</td>
<td>3.85</td>
<td>16%</td>
<td>3.1</td>
</tr>
<tr>
<td>80 - 100%</td>
<td>1.86</td>
<td>1.67</td>
<td>1.94</td>
<td>16%</td>
<td>1.44</td>
</tr>
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Bias in pA

- **2.a** Multiplicity fluctuations sizable
  → Bias on $\text{Mult}/N_{\text{part}}$ at central and peripheral collisions

- **2.b** Mean nucleon-nucleon impact parameter increases in peripheral collisions

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