Centrality bias from correlations between hard processes and the NN underlying event

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Challenge of centrality-dependent measurements in p+Pb

- It has been noticed by all collaborations that the standard methodology of dividing p+A events into centrality intervals does not easily lead to scaling of hard processes $N_{\text{coll}}$
- ATLAS noticed Z’s not scaling — applied simple “shift” correction based on difference between $E_T$ distributions in Z and non-Z events
- ALICE has systematically characterized biases for different detectors, and modeled them with toy models based on Glauber & PYTHIA

Centrality estimates in p+Pb

We typically perform fits to measured $E_T$ or $N_{ch}$ distributions, assuming a convolution of an underlying $pp$ distribution (modulo non-linear terms) with the Glauber geometry.

We typically do not assume that the $pp$ $E_T$ or $N_{ch}$ distribution depends on the object being measured.
Centrality scaling in pp and p+Pb

Quarkonia production in p+p & p+Pb follow surprisingly linear trends when parametrized by UE activity: interpreted in terms of MPI
Jet yields vs. $E_T$ from PYTHIA

Just to see if such behavior is in PYTHIA, measured yield per event as a function of a forward ET sum: not perfectly linear, but strong correlation.

Primary relationship: $\langle Y_{hard}(E_T) \rangle \propto E_T$. 

Centrality model

- Assume each NN collisions is sampled from a Gamma distribution

\[ P_{NN}(E_T^j) = \Gamma(E_T^j; k, \theta) = \left( \frac{k}{E_T} \right)^{k-1} \exp \left( -\frac{E_T^j}{\theta} \right) / \Gamma(k) \theta^k, \]

- For fixed \( N_{coll} \), sample \( N_{coll} \) times and include contribution from the incident proton

\[ E_T \equiv \left( \sum_{j=1}^{N_{coll}} E_T^j \right) + E_T^{evt(p)} \]

- Full distribution is convolution over \( N_{coll} \) of

\[ P_{N_{coll}}(E_T) = \Gamma(E_T; N_{coll} k, \theta) \oplus \Gamma(E_T; k^{evt}, \theta) \]
Three models: UCM and PCM

- Uncorrelated model (UCM)

\[ Y_j = C, \quad Y_{N_{\text{coll}}}(E_T) = \sum_{j=1}^{N_{\text{coll}}} Y_j = CN_{\text{coll}} \]

- Partially correlated model (PCM)

\[ Y_j = C \left( E_T^j + E_T^{j(p)} \right) / 2k\theta \quad Y_{N_{\text{coll}}}(E_T) = \frac{C}{2k\theta} \sum_{j=1}^{N_{\text{coll}}} \left( E_T^j + E_T^{j(p)} \right) \]

PCM reflects the fact that the \( E_T \) produced by the proton on each nucleon could be different in each collision: however, choose a single \( E_T \) value from the proton for the centrality

\( E_T \) here is a “general” centrality signal: either transverse energy (e.g. ATLAS) or charge (e.g. PHENIX)
Three models: VCM

- Variably correlated model (VCM): integrate out the fluctuations from the proton and one finds:
  \[ Y_j = C \left( \frac{E_T^j}{k\theta + 1} \right) / 2 \]

- The constant weakens the correlation between the yield and the underlying event. Can generalize this to:
  \[ Y_j = C \left( \alpha \frac{E_T^j}{k\theta + (1 - \alpha)} \right) \quad Y_{N\text{coll}}(E_T) = C \left( \alpha \sum_{j=1}^{N_{\text{coll}}} \frac{E_T^j}{k\theta + (1 - \alpha)N_{\text{coll}}} \right) \]

  In this approach, PCM = VCM for \( \alpha = 0.5 \)

We use this to assign a conservative error to the bias factors, by varying \( \alpha \) from 0.25 to 0.75
3 models, illustrated

Fixed $N_{\text{coll}}=5$, and just "$N_{\text{coll}}$" part of centrality observable
Key features of model

• This model does not try and modify the single collision which produces a hard process

• It says that the yield per collision is correlated with the UE
  • Neither that the UE somehow influences the hard process
  • Nor that the hard process increases the UE

• Natural in an MPI scenario where both the hard process and the UE are correlated with the NN overlap
  • Jia, Frankfurt et al
Application to experimental data

Measured hard process yield involves 3 distributions:
- $N_{\text{coll}}$ distribution from Glauber (geometry),
- $E_T$ distribution per collision (centrality model),
- Correlation of yield with underlying UE ($Y$):

$$\mathcal{Y} \left[ Y_{N_{\text{coll}}}(E_T); E_T^{\text{min}}, E_T^{\text{max}} \right] = \sum_{N_{\text{coll}}} \int_{E_T^{\text{min}}}^{E_T^{\text{max}}} dE_T P(N_{\text{coll}}) P_{N_{\text{coll}}}(E_T) Y_{N_{\text{coll}}}(E_T)$$

The modified yield due to correlation is then defined as:

$$\rho = \mathcal{Y} \left[ Y_{N_{\text{coll}}}(E_T) \right] / \mathcal{Y} \left[ CN_{\text{coll}} \right]$$
ATLAS case

- Based on ATLAS centrality bins used in several p+Pb results (multiplicity, jets, Z’s)
- In ATLAS, Gamma function parameters depend on Npart
  - $k(N_{part}) = k_0 + k_1(N_{part} - 2)$
    - $k_0 = 1.39$, $k_1 = 0.425 \rightarrow k_{evt} = 0.965$
  - $\Theta(N_{part}) = 3.41 + 1.3 \ln(N_{part} - 1)$
- Cuts applied exactly as in ATLAS paper

Glauber, $\sigma_{NN}=70$ mb, 10k events per $N_{coll}$
Corrections for ATLAS

- Calculated in PCM for default Glauber, and Glauber-Gribov color fluctuation models (used by ATLAS)
- 10-20% deviations from unity for default Glauber
- Bias factors become smaller with increasing cross section fluctuations
  - Decreasing steepness at high $N_{\text{part}}$

<table>
<thead>
<tr>
<th>centrality</th>
<th>$p+\text{Pb} \ 5.02\ \text{TeV}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\rho$ (default)</td>
</tr>
<tr>
<td>0–10%</td>
<td>1.20 ± 0.10</td>
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<tr>
<td>10–20%</td>
<td>1.06 ± 0.03</td>
</tr>
<tr>
<td>20–30%</td>
<td>1.00 ± 0.01</td>
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<tr>
<td>30–40%</td>
<td>0.96 ± 0.02</td>
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<tr>
<td>40–60%</td>
<td>0.91 ± 0.04</td>
</tr>
<tr>
<td>60–90%</td>
<td>0.82 ± 0.07</td>
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**PHENIX case**

- PHENIX uses charge $Q$ in beam-beam counters (BBC)
  - Assumed to scale linearly with $N_{\text{coll}}$
- NBD has parameters $\mu=3.03$, $\kappa=0.46$
- Bias factors from PCM compared with results from PHENIX (arXiv:1310.4793)
  - Similar in magnitude and consistent within (large) uncertainties

<table>
<thead>
<tr>
<th>centrality</th>
<th>$d+\text{Au} \ 200 \ \text{GeV}$</th>
<th>$1/\text{BF (PHENIX)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20%</td>
<td>$1.15 \pm 0.07$</td>
<td>$1.06 \pm 0.01$</td>
</tr>
<tr>
<td>20–40%</td>
<td>$0.99 \pm 0.01$</td>
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<tr>
<td>60–88%</td>
<td>$0.82 \pm 0.09$</td>
<td>$0.86 \pm 0.06$</td>
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Summary

• We have developed a simple framework for calculating centrality biases in p+Pb/d+Au, based on existing centrality frameworks
• Based on positive (linear) correlation in NN collisions between hard process yield and the centrality observable, which reflects the underlying event activity
• 3 models shown: no correlation, partial correlation, and variable correlation
  • In general, overall level of correlation found to be more important than the stochastic fluctuations.
• Bias factors extracted for ATLAS and PHENIX frameworks
  • However, framework is general and adaptable to other environments