Jet fragmentation in p+Pb and Pb+Pb with ATLAS

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Jets in $pp$, $p+Pb$ and $Pb+Pb$ collisions

- Jets provide a powerful tool to probe the medium created in HI collisions and to test the QCD.
- A significant modification of di-jets and suppression of inclusive jet spectra is observed in central HI collisions.
  - Is the energy redistributed to the medium out of the jet cone?
  - Does the energy remain inside the jet but redistributed among fragments?
  - Can we use $p+Pb$ collisions as a reference for $Pb+Pb$ collisions?
  - How much modification is coming from initial nPDF effects?
Hard Probes in $p$+Pb collisions

- Hard probes access the partonic structure of the nucleus.
- $p$+Pb processes are compared to $pp$ by:

$$R_{pPb} = \frac{d^2 N_{Pb}/dy d\rho_T}{\langle T_{Pb} \rangle d^2 \sigma_{pp}/dy d\rho_T}$$

- Inclusive jet rate in $p$+Pb collisions is only slightly enhanced with respect to $pp$.
- Consistent with nPDF expectations.
Hard Probes in $p+Pb$ collisions

- Hard probes access the partonic structure of the nucleus.
- $p+Pb$ processes are compared to $pp$ by:

$$R_{pPb} = \frac{d^2 N_{Pb}/dy dp_T}{\langle T_{Pb} \rangle \ d^2 \sigma_{pp}/dy dp_T}$$

- Enhancement of charged spectra at high $p_T$, suggestive of modification of jet internal structure.

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Data and MC

- Pb+Pb at 2.76 TeV collisions (2011) with integrated luminosity of 140 μb⁻¹.
- Pb+Pb data are compared to MC, where MC PYTHIA 6 di-jet events were embedded into real MB Pb+Pb events.
- Different centrality classes.

- p+Pb at 5.02 TeV collisions (2013) with integrated luminosity of 28 nb⁻¹.
- p+p at 2.76 TeV (2013) with integrated luminosity of 4 pb⁻¹.
- p+Pb and p+p measurements utilize PYTHIA 6 (embedded into real MB p+Pb), PYTHIA 8 and HERWIG++ samples.
Jet Reconstruction and selection

- Reconstruction algorithm anti-$k_t$ with the underlying event (UE) subtraction is used.
- Selected by online high-level jet triggers.
- Jets are required to be isolated.

- Jets in p+Pb and $pp$ collisions:
  - $R=0.2$, $0.3$, and $0.4$ jets.
  - Jets with $p_T > 100$ GeV ($R=0.4$).
  - $|\eta|<2.1$

- Jets in Pb+Pb collisions:
  - $R=0.2$, $0.3$, and $0.4$ jets.
  - Jets with $p_T > 100$ GeV ($R=0.4$).
  - $|\eta|<2.1$
Tracks with $p_T > 3.5$ GeV are used in $pp$ and $p+\text{Pb}$.

The cut of $p_T > 2$ GeV is used in $\text{Pb}+\text{Pb}$.

Tracking efficiency is parametrized as a function of track $p_T$ and track $\eta$. 
Fragmentation functions in $p+Pb$

- Fragmentation distribution defined as:

$$D(z) = \frac{1}{N_{\text{jet}}} \frac{1}{\varepsilon} \frac{\Delta N_{\text{ch}}(z)}{\Delta z},$$

where $z = \frac{p_T^{\text{ch}}}{p_T^{\text{jet}}} \cos \Delta R$.

- To minimize the contribution from the UE only tracks with $p_T > 3.5$ GeV are used.

- 2D Bayesian unfolding in $z$ and jet $p_T$ is used to correct for detector effects.
Fragmentation functions in Pb+Pb

- Fragmentation distribution defined as:
  \[
  D(p_T) \equiv \frac{1}{N_{jet}} \frac{1}{\Delta p_T} \frac{\Delta N_{ch}(p_T)}{\epsilon(p_T, \eta)} \quad D(z) \equiv \frac{1}{N_{jet}} \frac{1}{\Delta z} \frac{\Delta N_{ch}(z)}{\epsilon(z)} , \quad \text{where} \quad z = p_{T}^{ch} / p_{T}^{jet} \cos \Delta R
  \]

- Spectra of charged particles in jets
- Fragmentation function

- UE fragmentation distributions were estimated event-by-event using grid of R=0.4 cones:
  \[
  D(p_T) = \frac{1}{N_{jet}(p_T^{jet})} \frac{1}{\epsilon(p_T, \eta)} \left( \frac{\Delta N_{ch}(p_T, p_T^{jet})}{\Delta p_T} - \frac{\Delta N_{UE}(p_T, p_T^{jet})}{\Delta p_T} \right)_{\text{jet}}
  \]

- Correction of the jet $p_T$ to reduce the effect of the jet up-feeding due to jet energy resolution.
- Distributions are unfolded using SVD in z.
Unfolded fragmentation functions

D(z) and D(p_T) distributions have similar shape in all centrality bins. Ratios are needed to study centrality dependence:

\[ R_{D(z)} \equiv \frac{D(z)|_{0-10}}{D(z)|_{60-80}} \]

Shaded boxes: uncorrelated or partially correlated systematic uncertainties due to:
- Jet energy scale
- Jet energy resolution
- Track reconstruction
- Unfolding
- Residual MC non-closure
$D(z)$ centrality dependence

**Shaded boxes:** *uncorrelated or partially correlated systematic errors.*

- ~10% suppression at intermediate $z$ ($\sim 0.1$) and an enhancement at low $z$.
- Enhancement with significance of 1-2 $\sigma$ at high $z$. 
Shaded boxes: *uncorrelated or partially correlated systematic errors.*

Similar trends observed also in $D(p_T)$ distributions.
Systematic Uncertainties

- Systematic uncertainties due to:
  - Jet Energy Scale
  - Jet Energy Resolution
  - Unfolding
  - Track reconstruction
  - MC non-closure

- The dominant systematic uncertainty on the D(z) is from the jet energy scale.
- Many jet-related systematic uncertainties cancels in the ratio.
- The systematic uncertainty on the reference was estimated as the difference between extrapolation using PYTAHI 6 and HERWIG++
Unfolded fragmentation functions in $pp$ and $p+Pb$

$D(z)$ and distributions have similar shape in $pp$ and $p+Pb$. Ratios are needed to see potential modification: $RD(z) \equiv \frac{D(z)_{p+Pb}}{D(z)_{pp}}$
Reference for $p+$Pb collisions

- No $pp$ data at 5.02 TeV.
- The reference was built by extrapolation of the measured FF at 2.76 TeV $pp$ using PYTHIA 6.

$$D_{pp}(z)_{5.02\text{TeV}} = D_{pp}(z)_{2.76\text{TeV}} \times \frac{D_{\text{PYTHIA6}}(z)_{5.02\text{TeV}}}{D_{\text{PYTHIA6}}(z)_{2.76\text{TeV}}}$$

- The same procedure was repeated using HERWIG++ MC.

*Size of the extrapolation factors.*
$R_{D(z)}$ in different jet $p_T$ intervals

Shaded bands: uncorrelated or partially correlated systematic errors.

**Lines:** the $R_{D(z)}$ evaluated using extrapolation with HERWIG++

- An evidence for an enhancement of $R_{D(z)}$ in the $z$ region 0.3-0.8.
- Correspond to the same range in $p_T$ where the inclusive charged particle spectrum in p+Pb collisions is enhanced.
Conclusions

- We have presented a measurement of fragmentation variables in $pp$, $p$+Pb and Pb+Pb collisions.

- The MC generators show deviations from the $pp$ data of up to approximately 30%.

- The $p$+Pb data was compared to a $pp$ reference, constructed by extrapolating the measured fragmentation functions in 2.76 TeV $pp$ collisions to 5.02 TeV.

- An excess with a maximal magnitude of $\sim$15% is observed in the $p$+Pb fragmentation functions for $0.2 < z < 0.8$.

- Correspond to the same range in transverse momentum where the inclusive charged particle spectrum in $p$+Pb collisions is enhanced.

- Study of jet internal structure in Pb+Pb collisions shows increasing size of modification of fragmentation functions with increasing centrality:
  - $\sim$10% suppression at intermediate $z$ or $p_T$
  - enhancement at low and high $z$.

- Constrains on modelling of the jet response.
The ATLAS Detector

- Large pseudorapidity coverage and full azimuthal acceptance.
- Fine granularity and longitudinal segmentation of ATLAS calorimeter.
- Precise inner detector in a 2T solenoid field.
Centrality

- Characterize centrality by percentile of total cross-section using total $E_T$ measured in Forward Calorimeter ($3.2 < |\eta| < 4.9$).
- Centrality → number of participants $N_{\text{part}}$ and binary collisions $N_{\text{coll}}$ determined with the default Glauber analysis.
Performance of the Jet Reconstruction

- Performance is evaluated using pp hard scattering events from Pythia overlying on top of HIJING MB events without quenching.

- JER is well described by \( \sigma (\Delta E_T)/E_T = 1/E_T (a \sqrt{E_T} + b + cE_T) \)
  where parameter \( b \) is consistent with the result from the fluctuation analysis.

- The performance have been also verified using data overlay with similar results.
Many jet-related systematic uncertainties cancel in the ratio.

The systematic uncertainty on the reference was estimated as the difference between extrapolation using PYTHIA 6 and HERWIG++.

The dominant systematic uncertainty is from the reference.
Performance of the Track Reconstruction

- Performance was evaluated using Pythia particles embedded into HIJING MB events.

- Very good description of detector response by MC.
SVD unfolding was used to correct detector effects and to reduce the effect of statistical fluctuations.

\( D(z) \) unfolding accounts for track momentum and jet energy resolution, \( D(\rho_T) \) for track momentum resolution.
R-dependence of Fragmentation Functions

- Cross-check of possible biases done by measuring the distributions using smaller jet radii with the minimum $p_T$ corresponding to that of R=0.4 jets.
- The cone of 0.4 around the jet axis for track-jet matching was kept.

→ No qualitative or quantitative changes from R=0.4 jets!
$\Delta D(z)$

**ATLAS**

Pb+Pb $\sqrt{s_{NN}}=2.76$ TeV

0.14 nb$^{-1}$

anti-$k_T$ R=0.3

$p_T^{\text{jet}}>92$ GeV

0-10% - 60-80%

- Data
- Systematic Uncertainty
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