ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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

Martin Rybář,
for the ATLAS collaboration

Jets in pp , $p+A$ 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 $p+A$ collisions as a reference for $Pb+Pb$ collisions?
 - ◆ How much modification is coming from initial nPDF effects?

$p+p$

$p+A$

$A+A$

Hard Probes in $p+\text{Pb}$ collisions

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

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

- Inclusive jet rate in $p+\text{Pb}$ collisions is only slightly enhanced with respect to pp .
- Consistent with nPDF expectations.

Hard Probes in $p+\text{Pb}$ collisions

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

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

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

Data and MC

Pb + Pb

- Pb+Pb at 2.76 TeV collisions (2011) with integrated luminosity of $140 \mu\text{b}^{-1}$.
- 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 / pp

- 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 Pb+Pb collisions:
 - ◆ $R=0.2, 0.3$, and 0.4 jets.
 - ◆ Jets with $p_T > 100$ GeV ($R=0.4$).
 - ◆ $|\eta| < 2.1$
- Jets in p+Pb and pp collisions:
 - ◆ $R=0.4$ jets.
 - ◆ Six jet p_T bins in region: 45-260 GeV.
 - ◆ $|y^*| < 1.6$

Track reconstruction

$p + Pb / pp$

- Tracks with $p_T > 3.5$ GeV are used in pp and $p+Pb$.
- The cut of $p_T > 2$ GeV is used in $Pb+Pb$.
- Tracking efficiency is parametrized as a function of track p_T and track η .

Fragmentation functions in $p+Pb$

- Fragmentation distribution defined as:

$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{1}{\varepsilon} \frac{\Delta N_{\text{ch}}(z)}{\Delta z}, \text{ where } z = p_{\text{T}}^{\text{ch}} / p_{\text{T}}^{\text{jet}} \cos \Delta R$$

↑
Fragmentation
function (FF)

- To minimize the contribution from the UE only tracks with $p_{\text{T}} > 3.5$ 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:

$$D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{1}{\varepsilon} \frac{\Delta N_{\text{ch}}(p_T)}{\Delta p_T} \quad D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{1}{\varepsilon} \frac{\Delta N_{\text{ch}}(z)}{\Delta z}, \text{ where } z = p_T^{\text{ch}} / p_T^{\text{jet}} \cos \Delta R$$

↑
Spectra of charged
particles in jets

↑
Fragmentation
function

- UE fragmentation distributions were estimated event-by-event using grid of $R=0.4$ cones:

$$D(p_T) = \frac{1}{N_{\text{jet}}(p_T^{\text{jet}})} \frac{1}{\epsilon(p_T, \eta)} \left(\frac{\Delta N_{\text{ch}}(p_T, p_T^{\text{jet}})}{\Delta p_T} - \frac{\Delta N_{\text{ch}}^{\text{UE}}(p_T, p_T^{\text{jet}})}{\Delta p_T} \right)_{\text{jet}}$$

- 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

Pb + Pb

Shaded boxes:
uncorrelated or partially
correlated systematic
uncertainties due to:

- Jet energy scale
- Jet energy resolution
- Track reconstruction
- Unfolding
- Residual MC non-closure

■ $D(z)$ and $D(p_T)$ distributions have similar shape in all centrality bins.

➡ ratios are needed to study centrality dependence:

$$R_{D(z)} \equiv D(z)|_{0-10}/D(z)|_{60-80}$$

$D(z)$ centrality dependence

Pb+Pb

Shaded boxes: uncorrelated or partially correlated systematic errors.

- ➡ ~10% suppression at intermediate z (~ 0.1) and an enhancement at low z .
- ➡ enhancement with significance of 1-2 σ at high z .

$D(p_T)$ centrality dependence

Shaded boxes: uncorrelated or partially correlated systematic errors.

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

Systematic Uncertainties

$p + Pb / pp$

- 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 $p+Pb$

$p + Pb / pp$

- $D(z)$ and distributions have similar shape in pp and $p+Pb$.

➡ ratios are needed to see potential modification: $R_{D(z)} \equiv \frac{D(z)_{pPb}}{D(z)_{pp}}$

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.

Backup

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.

ATLAS inner detector

ATLAS calorimeter

Centrality

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

ATLAS calorimeter

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 $\sigma(\Delta E_T)/E_T = 1/E_T(a \cdot \sqrt{E_T} + b + c \cdot E_T)$ where parameter b is consistent with the result from the fluctuation analysis.
- The performance have been also verified using data overlay with similar results.

Systematic uncertainties on the $R_{D(z)}$

- 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.

Results of Subtraction and Unfolding

- 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, $D(p_T)$ 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!

$\Delta D(z)$

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!

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!