



# Exploring jet profiles in Pb-Pb collisions at 5.02 TeV with the ALICE detector

# Ritsuya Hosokawa for the ALICE collaboration

University of Tsukuba - TCHoU, Japan

Université Grenoble Alpes - LPSC, France

Quark Matter 2018, Venezia, Italy

13-19 May 2018





#### Jets – powerful probes of QGP properties



#### Jet

- Collimated high-momentum particle spray which originate from initial hard scattered partons at the early stage of a collision (Q<sup>2</sup> > 1 (GeV/c)<sup>2</sup>)
- → The most direct experimental access to partons



Di-Jet event candidate in Pb-Pb collisions  $v_{S_{NN}} = 5.02 \text{ TeV} (2015)$ Triggered by the L1-Jet trigger

#### Jets – powerful probes of QGP properties



#### Jet

- Collimated high-momentum particle spray which originate from initial hard scattered partons at the early stage of a collision (Q<sup>2</sup> > 1 (GeV/c)<sup>2</sup>)
- → The most direct experimental access to partons

- What are the advantages?
  - The QGP life time is very short (~10<sup>-23</sup> s)
    - Self produced probes like jets are suitable to probe QGP properties
- The elementary process is well described theoretically, and experimental measurement techniques are also well established

<sup>•</sup> Well calibrated probes



Di-Jet event candidate in Pb-Pb collisions  $v_{S_{NN}} = 5.02$  TeV (2015) Triggered by the L1-Jet trigger

### Jets – powerful probes of QGP properties



Jet
> Collimated high-momentum particle spray which originate from initial hard scattered partons at the early stage of a collision (Q<sup>2</sup> > 1 (GeV/c)<sup>2</sup>)
> The most direct experimental access to partons

What are the goals?

- Partons interact with the medium while traversing it and jet properties (Yield, shape...) will be modified
  - Collisional energy loss
  - Radiative energy loss

Jet quenching



are also well established

Well calibrated probes

Di-Jet event candidate in Pb-Pb collisions  $v_{S_{NN}} = 5.02$  TeV (2015) Triggered by the L1-Jet trigger

## Probing jet suppression rate and jet radial profile

Nuclear modification factor (R<sub>AA</sub>)
Quantifies the jet suppression due to parton interactions with medium

 $R_{\rm AA} = \frac{dN_{\rm jets}^{\rm AA}/dp_{\rm T}}{\langle N_{\rm coll} \rangle dN_{\rm jets}^{\rm pp}/dp_{\rm T}} = \frac{dN_{\rm jets}^{\rm AA}/dp_{\rm T}}{\langle T_{AA} \rangle d\sigma_{\rm jets}^{\rm pp}/dp_{\rm T}}$ 

#### Cross section ratio

Sensitive to the jet radial profile

- Jet collimation/broadening
  - ➢ Collimation
    - ightarrow The ratio will be increased
  - Broadening
    - ightarrow The ratio will be decreased





#### Jet measurement at ALICE



Acceptance:  $0 < \varphi < 2\pi$ ,  $|\eta| < 0.9$ 

2. FMD, T0, V0 3. TPC 4. TRD

5. TOF 6. HMPID 7. EMCal

DCal PHOS, CPV 10. L3 Magne 11. Absorber Muon Tracker 13 Muon Wall

14. Muon Trigger

16. PMD

17. AD 18. ZDC 19. ACORDE

15. Dipole Magnet

### Overview of the analysis

#### ➢ Raw jet spectra

- Event samples: 68 M(Charged jets, 0-80%), 4.5 M(Full jets, 0-10%) Minimum bias events of Pb-Pb at  $\sqrt{s_{NN}} = 5.02$  TeV
- $\blacktriangleright$  Reconstructed by anti- $k_{T}$  algorithm, R=0.2 and 0.3,  $p_{T}$ -scheme
- > Combinatorial backgrounds are suppressed by leading charged track requirement ( $p_T > 5 \text{ GeV}/c$ )

#### Background subtraction

- Event-by-event background density estimation and subtraction
  - Charged jets : JHEP 30 (2014) 013
  - Full jets : Phys. Lett. B 746 (2015) 1

#### Measured spectra are corrected by SVD unfolding method

- Charged jets
  - > Detector response : Pythia8+Geant3 full MC detector simulation
  - Background fluctuation : Random cone method
- ➢ Full jets
  - Embedding pythia events into Pb-Pb data





## Charged jet cross section in pp vs POWHEG





#### Measured charged jet cross sections are well described by POWHEG+Pythia8 prediction (NLO pQCD + parton shower, hadronization)

POWHEG-BOX: JHEP 1006 (2010) 043, JHEP 1104 (2011) 081 Pythia8: Comput. Phys.Commun. 191 (2015) 159

### Inclusive charged jet spectra in Pb-Pb 5.02 TeV





- 4 centrality classes (0-10%, 10-30%, 30-50%, 50-80%)
- 2 jet cone radii (R=0.2, 0.3)
- pp reference: POWHEG+Pythia8

#### 13-19 May 2018

- $\succ$   $R_{AA}$  increases for more peripheral events
  - $R_{AA}$  of different cone radius jet are consistent within systematic errors

is observed in central

**Pb-Pb** collisions

> pp data at the same beam energy in ALICE been analyzed

10

## Inclusive charged jet $R_{AA}$ in Pb-Pb 5.02 TeV





# Inclusive charged jet cross section ratios in Pb-Pb 5.02 TeV





Ratios of charged jet cross section between R=0.2 and R=0.3 are measured for each centrality classes

No significant difference with jets in vacuum (POWHEG+PYTHIA8 reference)

> Small difference at low  $p_{T}$  in central collisions  $\rightarrow$  Hints for stronger broadening at low  $p_{T}$ 

## Inclusive full jet spectra in Pb-Pb 5.02 TeV



R = 0.2

R = 0.3



Measured for the most central collisions (0-10%)

- ➤ 2 jet cone radii (R=0.2, 0.3)
- ➢ pp reference: POWHEG+Pythia8

Poster: JET-21, James Mulligan

## Inclusive full jet $R_{AA}$ in Pb-Pb 5.02 TeV



R = 0.2





ALI-PREL-147158

- Full jet nuclear modification factors in the most central collision (0-10%) are measured for R=0.2, 0.3
- Strong jet suppression is observed in central Pb-Pb collisions
- Consistent with charged jet results

13-19 May 2018

Quark Matter 2018

Poster: JET-21, James Mulligan

### Inclusive full jet cross section ratio in Pb-Pb 5.02 TeV





ALI-PREL-147166

- Ratios of full jet cross section between R=0.2 and R=0.3 are measured for the most central collisions (0-10%)
- Consistent with the POWHEG+PYTHIA8 reference at the measured kinematic range

Poster: JET-21, James Mulligan

# Comparison between charged and full jets at 5.02 TeV and 2.76 TeV



#### Full and charged jet R<sub>AA</sub> is consistent



- > Measured  $R_{AA}$  are similar in the two collision energies
  - It suggests effect of flattening of the spectrum in higher collision energy is compensated by stronger jet suppression

> All measurements are consistent within errors

## Comparison with model prediction - Cross section ratio





ALI-PREL-159657

No significant difference with vacuum is predicted by JEWEL for the measured kinematic range

JEWEL predictions agree with data

JEWEL : arXiv:1212.1599, arXiv:1311.0048, parameters for the medium model are taken from arXiv:1707.01539

13-19 May 2018

### Comparison with D<sup>0</sup>-tagged jets





Talk: "Measurements of heavy-flavour correlations and jets with ALICE at the LHC" Barbara Antonina Trzeciak, 15/May

#### Summary and outlook



# ALICE successfully measured charged and full jet spectra in Pb-Pb collisions at Vs<sub>NN</sub> = 5.02 TeV for jet cone radii R=0.2 and 0.3 Large background in heavy-ion collisions is under control

> Nuclear modification factor ( $R_{AA}$ )

Strong jet suppression is observed in central Pb-Pb collisions

- Centrality dependence is observed for charged jets
- ➢ Jet cross section ratio (R=0.2/R=0.3)
  - > Full jets: No significant difference with jets in vacuum at measured  $p_{T}$  range
  - Charged jets: Consistent with no energy redistribution relative to vacuum
    - $\succ$  Hints for stronger broadening at low  $p_{T}$

#### ➢ Prospects

- Nuclear modification factor with measured pp reference
  - Systematics in experimental data points will be reduced
- Improvement of statistical precision with calorimeter triggered data
- $\succ$  Extending the range to higher *R* and lower jet  $p_{T}$
- ALICE jet substructure program to be extended to 5.02 TeV (e.g. Jet mass, radial moment, momentum dispersion)



# Thank you for your attention!



# Backup

### Overview of analysis flow



#### Background $p_{T}$ density vs centrality





ALI-PREL-113557

13-19 May 2018





#### **Response matrices**





13-19 May 2018



0 - 10 %	30-40	40-50	50-60	60-70	70-90
	[GeV/c]	[GeV/c]	[GeV/c]	[GeV/c]	[GeV/c]
Method	4.2	4.2	4.2	4.2	4.2
delta-pT	-1.9	-1.2	-0.9	-0.9	-0.9
	5.1	4.1	3.8	2.9	2.2
FlowBias	6.4	5.2	4.6	3.7	3.3
MeasuredPtRange	-3.2	-0.2	-1.2	-2.4	-3.0
	0.1	0.3	2.1	1.6	3.6
UnfoldedPtRange	-0.7	0.0	-0.1	-0.2	-0.4
	0.1	0.3	0.5	0.0	0.3
RegParameter	0.4	1.1	3.3	3.6	5.4
Prior	4.2	5.2	5.2	4.0	1.7
Efficiency	1.5	2.7	5.9	8.1	9.7

## Systematics for full jet spectrum



orrelated uncertainti	elated uncertainties		Relative uncertainty (%) for $p_{\rm T} \in [A, B]$ GeV					
	[40, 50]	[50, 60]	[60, 70]	[70, 80]	[80, 100]	[100, 120]	[120, 140]	
R = 0.2								
Tracking efficiency	5.4	5.8	6.5	7.0	7.6	8.2	8.7	
Input $p_{\rm T}$ range	2.4	0.2	0.8	0.7	0.1	0.4	0.8	
Jet reco efficiency	4	3	2	2	1	1	1	
Track $p_{\rm T}$ resolution	1	1	1	1	1	1	1	
EMCal energy response	4.4	4.4	4.4	4.4	4.4	4.4	4.4	
EMCal hadronic response	4	4	4	4	4	4	4	
Total corr. uncertainty	9.3	8.9	9.1	9.5	9.8	10.2	10.7	
R = 0.3								
Tracking efficiency			9.7	10.6	9.8	8.6	7.3	
Input $p_{\rm T}$ range			1.5	2.3	1.6	0.7	0.5	
Jet reco efficiency	Jet reco efficiency		2	2	1	1	1	
Track $p_{\rm T}$ resolution			1	1	1	1	1	
EMCal energy response			4.4	4.4	4.4	4.4	4.4	
EMCal hadronic response	EMCal hadronic response		4	4	4	4	4	
Total corr. uncertainty	Total corr. uncertainty		11.7	12.6	11.7	10.6	9.5	

#### • Shape uncertainties

e uncertainties		Relative uncertainty (%) for $p_{\rm T} \in [A, B]$ GeV								
	[40, 50]	[50, 60]	[60, 70]	[70, 80]	[80, 100]	[100, 120]	[120, 140]			
R = 0.2										
Unfolding method	9.1	4.0	1.4	2.6	4.4	5.3	8.5			
Reg. parameter	3.9	2.8	1.4	1.2	3.5	5.5	7.1			
Prior	0.6	1.0	1.0	2.2	1.0	2.1	4.7			
Total shape uncertainty	5.7	2.9	1.3	2.1	3.3	4.6	6.9			
R = 0.3										
Unfolding method			17.5	11.1	1.9	9.1	15.1			
Reg. parameter			5.1	1.8	3.5	4.5	4.2			
Prior			2.3	2.4	1.7	0.9	2.7			
Total shape uncertainty			10.6	6.6	2.5	5.9	9.2			

13-19 May 2018



Source	Uncertainty (%)								
Jet $p_{\rm T}$ (GeV/c)	[-10,-5]	[-5,0]	[0,5]	[5,10]	[10,15]	[15,20]	[20,25]	[25,35]	
Raw Yield Extraction	18	16	15	13	13	9	12	13	
POWHEG	21	22	27	21	22	21	27	22	
R <sub>AA</sub>	22	23	28	22	23	22	29	24	
D cuts	5	5	5	5	5	5	5	5	
D Track Res.	2	2	2	2	2	2	2	2	
Source		Uncertainty (%)							
Jet $p_{\rm T}$ (GeV/c)			[3,5]	[5,10]	[10,15]	[15,20]	[20,25]	[25,35]	
Unfolding			5	3	9	15	17	19	
Final Sys. Unc.			37	36	36	39	40	40	