Jet Production and Structure in pp, p-Pb and Pb-Pb Collisions Measured by the ALICE Experiment

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Outline

• Motivation

• “Full” (charged + neutral) jets in pp
  • Correction for charged particle contamination
  • Triggering
  • pp jet cross-section and structure

• Jets in Pb-Pb
  • Background
  • Unfolding
  • Cross-section, structure, $R_{AA}$
Jets

- Jets originate from the hard scattering of partons
  - Fragment and hadronize into a spray of particles
- The spray (initial parton) is recovered using jet algorithms
  - Resulting jets depend on algorithm choice and constituent cuts
- Tests of PDFs, fragmentation and pQCD hard scattering
The ALICE detector

EMCal:
Shashlik Pb/organic scintillator sampling electromagnetic calorimeter
$|\eta| < 0.7; \ 1.4 < \Phi < \pi$
$\Delta\eta \sim \Delta\Phi \sim 0.014$

TPC + ITS (silicon) tracking
$|\eta| < 0.9; \ 0 < \Phi < 2\pi$

Charged constituents (tracks)

JET

Neutral constituents (clusters, optional)
Data sets and jet reconstruction

- Data
  - $pp \sqrt{s} = 2.76 \text{ TeV}$
  - $Pb–Pb \sqrt{s_{NN}} = 2.76 \text{ TeV}$
  - $p-Pb \sqrt{s_{NN}} = 5.02 \text{ TeV}$

- Jets
  - Charged tracks (ITS+TPC) and clusters from EMCal (full jets only)
  - Anti-$k_T$ algorithm for signal jets, $k_T$ for background
  - Jets fully contained in acceptance
  - $R = 0.2 – 0.6$
Correction for charged particle contamination

- Charged particles deposit energy in EMCal
- Need to avoid double counting of the momenta
- Tracks are matched to clusters and up to 100% \((f = 1)\) of their momenta is subtracted from the cluster energy

\[
E_{\text{cluster}}^{\text{corr}} = E_{\text{cluster}}^{\text{orig}} - f \cdot \sum E_{\text{track}}
\]

\(E_{\text{cluster}}^{\text{corr}} \geq 0\)
EMCal triggers

- EMCal triggers on integrated energy deposits in a given area
- Triggers are formed by sliding window algorithms of different granularity and steps
  - L0 (600ns), 4x4 towers
  - L1 (~5µs), 4x4 towers without FEE HW borders
  - L1 (~5µs), 32x32 towers, jet trigger
Trigger bias and efficiency in pp

- Trigger selects high-energy jets
- The trigger bias needs to be understood and corrected in the cross-section measurement
- Studied using full MC simulation, good agreement with data
Jet cross-section and structure in pp

- Inclusive jet cross section and structure

\[ R = 0.4 \]

- Good agreement with NLO + hadronization

Jets in medium

- Jets are important probes of the medium that the parton passes through
  - Parton interacts strongly with the medium
  - Parton loses energy due to induced gluon radiation
- Removing the soft background contribution to the jets is an experimental challenge
- p-Pb collisions allow us to probe cold nuclear matter effects

\[
R_{AA} = \frac{\sigma_{pp}^{\text{inel}}}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{AA}}{d p_T d \eta} \frac{d^2 \sigma_{pp}}{d p_T d \eta}
\]
Underlying event

- Event-by-event subtraction
- $\rho_{\text{charged}}$ calculated using $k_T$ jets $p_T/A$
- $\rho_{\text{scaled}}$ is scaled from $\rho_{\text{charged}}$

$\rho_{\text{scaled}} = s_{\text{emc}} \cdot \rho_{\text{charged}} = s_{\text{emc}} \cdot \text{median}(p_T^k / A k_T^\text{jet})$

$s_{\text{emc}}$ scale in between charged and full jets

- Within-event fluctuations determined by
  - Random cones
  - Embedded track with anti-$k_T$ algorithm

\[
\delta^{RC}_{p_T} = p_{T\text{rec}}^{\text{jet}} - \rho \cdot \pi R^2
\]

\[
\delta^{\text{emb}}_{p_T} = p_{T\text{rec}}^{\text{jet}} - \rho \cdot A \cdot A^n - k_T^\text{jet} - p_{T\text{emb probe}}^{\text{med}}
\]

arXiv:1207.2392
Leading particle bias

- Offline requirement of a high-$p_T$ jet constituent
- The bias allows the removal of combinatorial jets, made of soft particles
- 5 GeV/c track required in analysis
Unfolding

- Unfolding used to obtain true jet spectrum
- Bayesian, SVD (Singular Value Decomposition) or $\chi^2$ minimization methods used

$$RM_{\text{detector}} \cdot RM_{\text{bkg}} = RM_{\text{total}}$$

Anti-$k_T$ $R=0.2$

- $p_{T,\text{track}} > 0.15 \text{ GeV/c}$
- $E_{\text{cluster}} > 0.30 \text{ GeV}$
- $p_{T,\text{leading}} > 5 \text{ GeV/c}$

Detector Efficiency

PYTHIA pp $\sqrt{s}=2.76$ GeV

(a) $RM_{\text{det}}$ Detector response matrix
(b) $RM_{\text{bkg}}$ Background fluctuation matrix
(c) $RM_{\text{tot}} = RM_{\text{bkg}} \times RM_{\text{det}}$

$Pb-Pb \sqrt{s_{NN}}=2.76$

0-10% Centrality

ALICE PERFORMANCE
15/10/2012
Pb-Pb jets

Full jets

Charged jets

- Leading particle bias, central events 0-10%, R = 0.2
- Charged jets are not corrected for the neutral part
Pb-Pb jet structure

- No significant jet broadening within the uncertainties for charged jet ratio $R_{0.2}/R_{0.3}$
- Good agreement with Pythia + JEWEL
- From inclusive spectra with no leading track bias
Jet vs hadron $R_{AA}$

- Similar $R_{AA}$ value for most central collisions for jets and charged hadrons at high-$p_T \sim 0.4$
Other results...

- See M. Ploskon's talk from Tuesday
- More information $R_{pPb}$ and $R_{CP}$ available ($R_{pPb} \sim 1$)

\[ \begin{align*}
R_{CP} \\
\text{charged (GeV/c)} \\
\end{align*} \]

\[ \begin{align*}
p_{T} \\
PbPb \\
p-Pb
\end{align*} \]
Conclusion

- Charged and full (charged+neutral) jet spectra were analyzed in several collision systems collected by the ALICE experiment

- Jet structure measured in pp collisions is well described with NLO + hadronization model

- Full jet $R_{AA}$ from the 10% most central events is comparable with charged hadrons $R_{AA}$ in high-$p_T$

- Within uncertainties there is no observation of jet broadening between $R = 0.2$ and $0.3$ due to in-cone radiation
Backup
Cold nuclear matter, p-Pb

- Charged jets
- No suppression observed
- Scaled pp 7 TeV spectra used as a reference (slide 26)

\[ N_{5\,\text{TeV}} = N_{7\,\text{TeV}} \cdot \frac{N_{5\,\text{TeVMC}}}{N_{7\,\text{TeVMC}}} \]
p-p jet structure

- Jet collimation increases weakly with $p_T$
- Good agreements with NLO + hadronization within uncertainties

![Graph showing jet structure with $p_{T,\text{jet}}$ vs. $\sigma(R=0.2)/\sigma(R=0.4)$](image)

Geometrical ratio $0.2/0.4 = 0.25$

Detector effects

- Bin-by-bin technique
  - Compare the MC cross-section before and after the detector response
  - Use uncorrected spectrum in data as weighting function
- **Shift of jet energy scale ~ 20-25%**
  - Unmeasured neutrons and $K^0_L$: compare proton and kaon spectra to data; PYTHIA vs HERWIG
  - Tracking inefficiency: track quality in data vs MC
  - Residual hadronic correction for EMCal: data-driven check
  - JES uncertainty ~ 4%
- **Jet energy resolution ~ 18%**
  - Detector resolution: data-driven check + test beam
  - Fluctuations (e-by-e) in correction of jet energy scale
Response matrix

Anti-$k_T$ $R=0.2$

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(a) $\text{RM}_{\text{det}}$ Detector response matrix
(b) $\text{RM}_{\text{bkg}}$ Background fluctuation matrix
(c) $\text{RM}_{\text{tot}} = \text{RM}_{\text{bkg}} \times \text{RM}_{\text{det}}$

Pb-Pb $\sqrt{s_{NN}}=2.76 \text{ TeV}$
0-10% Centrality

Detector Efficiency
PYTHIA pp $\sqrt{s}=2.76 \text{ GeV}$

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Bayesian unfolding

Measured $p_T$ range

Unfolded $p_T$ range

Residual combinatorial jets

Iteration choice
pp reference for pPb

Different scaled references compared to used reference

Ratio

$\frac{y}{x}$

$p_T$ (GeV/c)
pp scaled reference
Background MC

FastJet $k_t$ ($p_t^{\text{min}} = 0.15$ GeV/c)
Fit: $(-3.3 \pm 0.3)$ GeV/c + $(0.0623 \pm 0.0002)$ GeV/c $\times N_{\text{raw input}}$

Pb-Pb $\sqrt{s} = 2.76$ TeV

ALICE JHEP03 (2012) 053, arxiv:1201.2423
Pb-Pb, charged jets

Two jet cone variables: 0.2, 0.3

Strong suppression for central collisions
Pb-Pb, charged jets

Leading particle trigger

Strong suppression for jets. Not dependent on $p_T$
QCD vacuum p-p baseline

- Inclusive jet cross section

R = 0.2

- Good agreement with NLO + hadronization

R = 0.4

\[ d_{ij} = \min\left(k_{Ti}^p, k_{Tj}^p\right) \frac{R_{ij}^2}{R^2} \]

\[ R_{ij}^2 = (\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2 \]

\[ d_{iB} = k_{Ti}^p \]

\[ k_T: p = 2 \quad \text{Anti-} k_T: p = -2 \]