Inclusive charged jet spectra in pp and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with ALICE

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Outline

• Introduction
  - Jet
  - Physics motivation
• ALICE experiment
• Results: Inclusive charged jet spectra measurements
• Summary and outlook
• Collimated spray of hadrons originated from hard scattered partons at the initial stage of collision
Physics motivations

- **pp collisions**
  - Good test of pQCD calculations and MC generators for high energy physics
  - Reference for heavy ion collisions

- **Pb-Pb collisions**
  - Jets are well established probe for Quark-Gluon-Plasma (QGP) properties
    - QGP lifetime in heavy ion collisions is very short ($\sim 10^{-23}$)
      - Self produced probes, like jets, allows to access QGP properties
    - Jets are produced at an very early stage of collision
      - entire QGP evolution can be proved
  - Jets are modified while traversing the QGP
    - **Jet quenching effect**
      - QGP properties can be probed by evaluating the effect (Nuclear modification factor ($R_{AA}$), Jet shape...)

https://www.star.bnl.gov/
ALICE experiment

• Specialized for measurements of heavy ion collisions
• Explores QGP properties

• Minimum bias event triggering and centrality determination
  - V0A,C

• Charged particle tracking
  - Time Projection Chamber (TPC)
  - Inner Tracking System (ITS)

• Neutral components measurement
  - Electro Magnetic Calorimeters
    – EMCAL, DCAL, (PHOS)
ALICE experiment

- Specialized for measurements of heavy ion collisions
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- Minimum bias event triggering and centrality determination
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- Charged particle tracking
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  - Inner Tracking System (ITS)

Charged jets were measured in this analysis with central barrel charged tracking detectors

Acceptance: \[ 0 < \varphi < 2\pi, \ |0.9| < \eta \]
Jet reconstruction

- Signal jets were reconstructed by anti-$k_t$ algorithm
- Background was estimated with jets reconstructed by $k_t$ algorithm (p.12 in this slide)

1) Include all particles in the cluster list.

2) Calculate

\[ d_{ij} = \min(k_{ij}^p, k_{ij}^y) \frac{\Delta y_{ij}^2}{R^2}, \]

\[ d_B = k_B^p, \]

Where, $p=-1$, $\Delta y_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, $k_{ij}, y_i$ and $\phi_i$ are respectively the transverse momentum, rapidity and azimuth of particle $i$. $R$ is radius parameter.

3) Set minimum value of $d_{ij}$ and $d_{ij}$ as $d_{\min}$. If $d_{ij} = d_{\min}$, calculate the sum of four-momentum of cluster $i$ and $j$ which is weighted by energy, then set the cluster $i$ and $j$ as one cluster. If $d_{\min} = d_{ij}$, consider $d_{ij}$ a Jet and then remove $d_{ij}$ from cluster list.

*(p=-1: anti-$k_t$ algorithm, p=1: $k_t$ algorithm)*
Results: pp 5.02 TeV
Differential charged jet cross section
- Detector effects in real data were corrected by the SVD unfolding method with detector response extracted from MC simulation
- Well described by POWHEG NLO calculation within systematic uncertainties

Jet cross section ratio of $R = 0.2$ and $R = 0.4$ jets
- Sensitive to the jet structure
- Indicates stronger jet collimation at higher jet $p_T$
- Well described by POWHEG and PYTHIA
Comparison with pp and p-Pb results

- No significant dependency on collision energy and collision system
Results: Pb-Pb 5.02 TeV
Underlying event in Pb-Pb collisions

- Difficulty on heavy ion collisions
  - Large background (Underlying event, UE) to be subtracted

- Background density
  \[ \rho = \text{median} \left\{ \frac{p_{T,jet}^{k_t}}{A_{i,jet}} \right\} \]
  - Here, \( p_{T,jet}^{k_t} \) are jets reconstructed by \( k_t \) algorithm
  - \( A_{jet} \): jet area
  - Excluding the highest \( p_T \) tow jets

- Background subtraction
  \[ p_{T,jet}^{corr} = p_{T,jet}^{raw} - \rho \cdot A_{jet} \]
**Underlying event in Pb-Pb collisions**

- **Underlying event fluctuation:**
  
  \[ \delta p_T = \sum_{i=1}^{RC} p^\text{track}_T - A \cdot \rho \]

  RC: random cone

- **3 methods were tested**
  1) Simply apply random cone without any limitations
  2) RC apart from leading jet (\(\Delta r > 1.0\))
     - can be reduced contributions from signal jets component
      \[ \Delta r = \sqrt{(\eta_{RC} - \eta_{jet})^2 + (\phi_{RC} - \phi_{jet})^2} \]
  3) randomized track(\(\eta, \phi\))
     - to exclude flow effect

In this analysis, 2) was selected as UE fluctuation
Charged jet nuclear modification factor: $R_{AA}$

\[
\frac{d^2\sigma}{dp_Td\eta} = \frac{\langle N_{\text{coll}} \rangle}{\langle T_{AA} \rangle} \frac{1}{N_{\text{evt}}} \frac{dN_{\text{ch jet}}}{dp_Td\eta}
\]

\[
R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{\text{evt}}} \frac{dN_{\text{ch jet}}}{dp_Td\eta}
\]

- Spectra in Pb-Pb collisions are corrected by SVD unfolding with detector (from MC) and background response (from data)
- Strong suppression at central collisions
  - Centrality dependence of the suppression
- Difference of pp reference (POWHEG or Real data)
  - Consistent within uncertainties
$R_{AA}$ comparison with $\sqrt{s_{NN}} = 2.76$ TeV

- Results at $\sqrt{s_{NN}} = 5.02$ TeV are compared with...
  - Full jet $R_{AA}$ in $\sqrt{s_{NN}} = 2.76$ TeV collisions at ALICE ($R=0.2$)
  - Full jet $R_{AA}$ in $\sqrt{s_{NN}} = 2.76$ TeV collisions at ATLAS ($R=0.4$)

- Results at 5.02 TeV is comparable to the results at 2.76 TeV
  - Generally, more denser, hotter and ling time QGP formation is expected at higher $\sqrt{s_{NN}}$
    $\rightarrow$ Stronger suppression $\rightarrow$ decrease the $R_{AA}$
  - More harder (high $p_T$) jet generation is expected at higher $\sqrt{s_{NN}}$
    $\rightarrow$ flatter jet spectrum $\rightarrow$ increase the $R_{AA}$
  - Effect of spectrum flattening is compensated by the stronger jet suppression

24 January 2017
Summary

• First measurements of charged jet spectra and $R_{AA}$ have been performed for LHC Run2 data at ALICE.

• pp collisions
  • Inclusive charged jet differential cross sections are well described by NLO calculation (POWHEG)
  • Jet cross section ratio is well described by POWHEG and PYTHIA
  • Reference for Pb-Pb collisions is established (~60 GeV/c)

• Pb-Pb collisions
  • Larger Underlying Event fluctuation is observed at most central collisions in comparison with peripheral collisions
  • Nuclear modification factor
    - Strong suppression is observed in central collisions
    - Comparable with the results in $\sqrt{s_{NN}} = 2.76$ TeV collisions
    - Effect of spectrum flattening is compensated by the stronger jet suppression
Outlook

• Extend jet $p_T$ reach with more statistics (pp: ~25 % of full statistics, Pb-Pb: ~ few % of full statistics)

• Full jet measurement with calorimeters
  - Allows direct comparison with Run1(2.76 TeV) results
Back up
Data set and event selections: pp

• Data Set
  • Data: LHC15n pass2 lowIR (~25M events)
    MC: LHC15l1b2 (PYTHIA6, pp 5 TeV, Perugia-2011)
    MC: LHC15l1a2 (PYTHIA8, pp 5 TeV, Monash2013)
    MC: LHC16e1 (PYTHIA8, pp 5 TeV, Monash-2013, PtHard production)

• Event selection
  • MB event selection (kINT7, V0A and V0C trigger)
  • \(|VtxZ| < 10\) (cm)
  • Number of tracklets contributing to the primary vertex is at least 2
  • Pileup event cut
  • \(|VtxZ_{track} - VtxZ_{SPD}| < 0.5\) (cm)
  • \(VtxZ_{SPD}\) reconstruction resolution is better than 0.25 (cm) and the dispersion is less than 0.04 *

• Jets
  • Charged tracks
  • Hybrid track (2011 version)
  • Utilized FastJet package
    FastJet v3.1.3
  • Anti-Kt algorithm
  • Cone radii R=0.2,0.4
  • Fiducial cut
Data set and event selections: Pb-Pb

**Data sets**
- **Pb-Pb data**
  - LHC15o, $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb
  - pass2 low-IR, AOD (3.36M events)
- **MC simulation data**
  - PYTHIA
    - (tracking eff. Jet finding eff. detector RM)
    - LHC16e1
      - (pthard-binned, jet production PYTHIA8), $\sqrt{s} = 5.02$ TeV pp
    - LHC15l1b2
      - (MB, PYTHIA6 Perugia-2011), $\sqrt{s} = 5.02$ TeV pp
  - HIJING (tracking eff.)
    - LHC15k1a1, LHC15k1a2, $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb

**Event Selection**
- kINT7
- $|v_z^{SPD} - v_z^{PRI}| < 0.1$ cm
  - (to avoid UE density mis-estimation)
- $|v_z| < 10$ cm

**Charged track selection**
- Hybrid track selection in which same parameters used with LHC11h.
  - to compensate for inefficiency in SPD
- $|\eta| < 0.9, p_T > 0.15$ GeV/c

**Jet Reconstruction**
- R=0.2, anti-kt algorithm, pt-scheme
- $|\eta| < 0.7$
- Jet Area $> 0.6 \pi R^2$
  - to reduce fake jet contamination at low $p_T$, jet
Figure 1: A sample parton-level event (generated with Herwig) to demonstrate the "ghosts", clustered with four different jets algorithms, illustrating the "active" catchment areas of the resulting hard jets. For \( k_t \) and Cam/Aachen the detailed shapes are in part determined by the specific set of ghosts used, and change when the ghosts are modified.

The above properties of the anti-\( k_t \) algorithm translate into concrete results for various quantitative properties of jets, as we outline below.

2.2 Area-related properties

The most concrete context in which to quantitatively discuss the properties of jet boundaries for different algorithms is in the calculation of jet areas. Two definitions were given for jet areas in [4]: the passive area (\( a \)) which measures a jet's susceptibility to point-like radiation, and the active area (\( A \)) which measures its susceptibility to diffuse radiation. The simplest place to observe the impact of resilience is in the passive area for a jet consisting of a hard particle \( p_1 \) and a soft one \( p_2 \), separated by a \( \Delta \phi \) distance \( \Delta_{12} \). In usual IRC safe jet algorithms (JA), the passive area \( a_{JA,R}(\Delta_{12}) \) is \( \pi R^2 \) when \( \Delta_{12} = 0 \), but changes when \( \Delta_{12} \) is increased. In contrast, since the boundaries of anti-\( k_t \) jets are unaffected by soft radiation.
Charged jet cross section ($R = 0.4$)
The true distribution: \( t(x) \)
The observed distribution: \( o(y) \)

\[
o(y) = \int dx A(x,y) t(x),
\]

\( A(x,y) \) is a response or detector matrix (is usually derived with MC).
Finding \( A^{-1}(x,y) \) is ill-posed problem: very sensitive to small perturbations of the data.

Discrete formulation: \( O[m] = A[m \times n] T[n] \)
\( A_{ji} \) is the probability that given true input in \( i \)-th bin output will be measured in \( j \)-th bin

\textit{RooUnfold} package \textit{arXiv:1105.1160}

Regularization methods
\begin{itemize}
  \item iterative ("Bayesian"), \textit{D’Agostini NIM A 362 (1995) 487}
  \item singular value decomposition (SVD), \textit{H.Hoecker, V.Kartverlishvili, NIM(1996) 469}
\end{itemize}

Non-regularization method
\begin{itemize}
  \item Bin-by-bin method (assumes no migration of events between bins, eg. resolution is much smaller than the bin size and no systematic shifts).
\end{itemize}
Response matrices

Inputs for unfolding by RooUnfold software package (arXiv:1105.1160)

- Input for pp spectrum correction
- Input for Pb-Pb spectrum correction
### Systematic uncertainties: pp

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### Systematic uncertainties: Pb-Pb

#### 0-10 % centrality

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#### 10-30 % centrality

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