Results on Jet Spectra and Structure from ALICE

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Outline

- **Jet reconstruction** in ALICE
- **Jet spectra** pp at $\sqrt{s} = 2.76$ TeV
  - Reference for Pb-Pb
- **Charged jet yield suppression** in Pb-Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV
  - $R_{\text{AA}}(p_T^\text{Jet})$ using Pythia reference
  - Resolution parameters $R$ dependence
- **Hadron-Jet correlations**
  - Modification of conditional yields and their $R$ dependence
- **Isolated $\gamma$-hadron correlations**
- **Conclusions**
Jet Reconstruction in ALICE

Energy and direction of neutral particles

**EMCal**: Pb-scintillator sampling calorimeter which covers:

\[|\eta| < 0.7, \ 80^\circ < \phi < 180^\circ\]

- 11520 towers with each covers
  \[\Delta\eta \times \Delta\phi \sim 0.014 \times 0.014\]

4-momenta of charged particles

**Tracking**: \(|\eta| < 0.9, \ 0 < \phi < 360^\circ\)

**TPC**: gas detector

**ITS**: silicon detector

Charged constituents

Neutral constituents

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Jet Finder and Inputs

- **Anti-$k_T$ Algorithm from FastJet** package
  - Resolution parameter $R = 0.2, 0.3, 0.4$
  - Area cut $A > 0.1$-0.4 avoids extremes
  - Jet vector from boost invariant $p_T$ recombination scheme

- **Charged Jets**
  - Input: tracks with $p_T > 150$ MeV/c
  - Advantage: full azimuth ($\phi$) coverage

- **Fully reconstructed jets**
  - Input
    - Tracks with $p_T > 150$ MeV/c
    - EMCAL clusters $E_T^{\text{clus}} > 150$ MeV after correction for energy from charged particles
    - Jet required to be fully contained in EMCAL acceptance
  - Advantages: trigger capability, higher $p_{T,\text{Jet}}$ reach, unbiased fragmentation

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* distances are computed with

\[
D_{ij} = \min \left( p_{T,i}^2, p_{T,j}^2 \right) \frac{\Delta R_{ij}^2}{R^2};
\]

\[
D_i = p_{T,i}^2
\]

\[
k_T(\text{anti } k_T): p = 1 (-1)
\]

Compute all $D_{ij}, D_i, d = \min (D_{ij}, D_i)$

if $d = D_{ij}$: combine $i$ with $j$
if $d = D_i$: $i$ is final state jet
Jet Reconstruction
Corrections

- **Jet-by-Jet**
  - Charged particle energy correction for EMCAL clusters
    \[ E_{\text{clus}}^{\text{corr}} = E_{\text{clus}}^{\text{raw}} - \sum p^{\text{matched}}, \quad E_{\text{clus}}^{\text{corr}} > 0 \]
  - Pb-Pb: Underlying event (UE) energy correction
    \[ p_{T,\text{Jet}} = p_{T}^{\text{rec}} - p_{T}^{\text{UE}} \]

- **Jet spectrum corrections: bin-by bin or unfolding**
  - Corrections for unmeasured neutral energy (n, K\(_{L}^0\)) and related fluctuations of the jet energy scale (JES)
  - Tracking inefficiency and corresponding fluctuations
  - Pb-Pb: Smearing due to UE energy fluctuations
Jets in pp at $\sqrt{s} = 2.76$ TeV

- **JES uncertainty:** 4%
  - Missing neutral energy
  - Tracking efficiency
  - Energy double counting (charged particle correction)
- **Jet $p_T$ resolution 20%**
  - Event-by-event fluctuations of JES
  - Track $\Delta p_T / p_T = 40$ GeV/c: 4%
  - EMCAL resolution at $E = 40$ GeV: 3%
- **Effects of efficiency and resolution on jet spectrum are corrected bin by bin.**

- Good agreement with NLO pQCD + hadronization and Pythia8
- Important reference for Pb-Pb analysis
Jets in pp at $\sqrt{s} = 2.76$ TeV:
Jet shape information by varying $R$

anti $k_T : R = 0.4$

$d^2\sigma/dp_T d\eta$ (mb c/GeV)

Good agreement with NLO pQCD and Pythia8
Increase of $\sigma(R=0.2)/\sigma(R=0.4)$: Higher $p_T$ jets are more collimated
Jets in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

Background from UE

- Corrections required due to UE Energy
  - Event-by-event subtraction of the background energy: $A_{\text{Jet}} \rho$
    \[
    \rho = \text{median} \left( \frac{p_{\text{Jet}}^T}{A_{\text{Jet}}} \right) k_T - \text{Algorithm}
    \]
  - Raw spectrum smeared by background energy fluctuations
    - Need to unfold using resolution matrix
  - Jets from background combinatorics (fake jets) at low $p_T^{\text{Jet}}$.
    - Efficiently removed by requiring a $p_T > 5$ GeV/c leading hadron inside jet

In jet with $R=0.4$: $\rho A = 130$ GeV
Background Fluctuations

- In Pb-Pb jet energy resolution limited by background fluctuation within jet area.

- Fluctuations characterized by distribution of
  \[ \delta p_T = (p_T^{\text{rec}} - \rho A_{\text{Jet}}) - p_T^{\text{true}} \]

- Distribution obtained by embedding particles into min. bias event or by placing random cones with areas close to the ones of reconstructed jets.
  - For anti-\(k_T\): \( A \approx \pi R^2 \)
Charged Jet Spectra in Pb-Pb

Normalized yield shows suppression increasing with centrality.

Systematic uncertainties:
- Regularization: 4%
- JES correction: 4-10%

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**Charged Jet $R_{AA}$ wrt Pythia Reference**

- Strong jet suppression: $R_{AA}^{Jet} = 0.2-0.35$ rising with $p_T^{Jet}$
- Low $R_{AA}^{Jet}$ reproduced by JEWEL MC  

K. Zapp et al, Eur.Phys.J. **C69** (2009) 617
Jet suppression similar to inclusive hadron suppression at comparable parton $p_T$

Possible scenario:

- Radiated energy mainly outside jet cone
- Leading particle $p_T$ shifted in proportion to its contribution to the jet energy

\[
\Delta E_{\text{leading}} = z_L \Delta E_{\text{part}}
\]
Possible Redistribution of Energy Between $R=0.2$ and 0.3

- No redistribution of energy within experimental uncertainties
- Ratios consistent with
  - Results from more peripheral collisions
  - Pythia (vacuum fragmentation) and
  - JEWEL MC model calculations

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Jets Tagged by High-$p_T$ Hadron

Requirement of high $p_T$ hadron reduces contribution from combinatorial (fake jets)
Improved stability of unfolding allows to assess lower $p_{T,Jet}^{ch}$
No change of fragmentation within uncertainties except for lowest $p_{T,Jet}^{ch}$ bin.
More details ...

Rosi Reed, Parallel Session 2B
Poster by Marta Verweij
Poster by RongRong Ma
Hadron-Jet Correlations

- Can surface bias of leading hadrons be used to increase jet suppressions and structure modification?
  - **Idea:** Study conditional jet yield requiring a trigger hadron back-to-back with respect to jets
  - If surface bias present the parton producing the jet is biased towards higher in-medium path length
  - **Additional advantages:**
    - Requiring correlated high-$p_T$ hadron tags hard scatterings suppressing the combinatorial (fake jet background)
    - No fragmentation bias on the recoiling jet

See Talk Leticia Cunqueiro, Parallel Session 3B
Hadron-Charged Jet Correlation Analysis

Uncorrected yield per trigger particle

$\Delta \phi (\text{hadron}, \text{jet}) > \pi - 0.6$

Low $p_{T,\text{Jet}}$ dominated by fake jets and uncorrelated BG

High $p_{T,\text{Jet}}$

Clear correlation with trigger $p_T$

Dominated by high $Q^2$ events

How to remove uncorrelated component?

Study difference between signal recoil spectrum and a reference:

$\Delta_{\text{recoil}}(p_{T,\text{Jet}}^{\text{ch}}) = \frac{1}{N_{\text{trig}}} \frac{d N}{d p_{T,\text{Jet}}^{\text{ch}}} \bigg|_{p_{T,\text{ref}}^{\text{min}}, p_{T,\text{ref}}^{\text{max}}} - \frac{1}{N_{\text{trig}, \text{ref}}} \frac{d N}{d p_{T,\text{Jet}}^{\text{ch}}} \bigg|_{p_{T,\text{ref}}^{\text{min}}, p_{T,\text{ref}}^{\text{max}}}$

$\Delta_{\text{recoil}} = p_{T,\text{Jet}}^{\text{ch}} - \rho A_{\text{Jet}}^{\text{rec}}$ [GeV/c]

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Difference Recoil Spectra

Difference of semi-inclusive recoil jet yields

\[ \Delta I_{AA}(p_{T,\text{Jet}}^{\text{ch}}) = \frac{\Delta \text{Pb-Pb} - \Delta \text{Pb-Pb}}{\Delta \text{pp}} \]

Correlated uncertainties:
- Flow bias on background induced by hadron trigger
- Tracking efficiency uncertainty
- Reference distribution scaling factor

Shape uncertainty (from unfolding):
- \( p_T^{\text{min}} \) cut variations, feed in/out
- Regularization: \( \beta \) variations and difference to Bayesian result

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$\Delta I_{AA}$ using Pythia Reference

Ratio of conditional yield close to unity: $\Delta I_{AA} = 0.75$

Strong h-Jet pair suppression $R_{AA}^{h} \Delta I_{AA} \approx 0.25 \times 0.75 = 0.2$

However, two competing effects are possible:

Recoil jet suppression: $\Delta I_{AA}$ decreases

Trigger parton energy loss: $\Delta I_{AA}$ increases since at the same $p_{T}^{\text{trig}}$ : $Q_{\text{Pb-Pb}}^{2} > Q_{pp}^{2}$
Comparison to Di-Hadron Correlations

Qualitatively and quantitatively similar behavior in di-hadron correlations at lower $Q^2$.

PhysRevLett.108.092301
arXiv:1110.0121v2 [nucl-ex]

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Model Comparisons

YaJEM [T. Renk, Phys. Rev. C 80 (2009) 044904]

JEWEL [K. Zapp et al Eur.Phys.J.C69 (2009) 617]

Preliminary: unexplored systematics
Isolated Photon Hadron Correlations in pp at $\sqrt{s} = 7$ TeV

$\gamma$  Quark Fragmentation

Isolated photon

$x_E = -\frac{p_T^h}{p_T^\gamma} \cos \Delta \Phi$

$p_T^\gamma \approx p_T^{\text{parton}}$

$x_E \approx z = \frac{p_T^h}{p_T^{\text{parton}}}$

Isolation criterion:
No particle with $p_T > 0.5$ GeV in cone $R=0.4$
$x_E = -\frac{p_T^h}{p_T^\gamma} \cos \Delta \Phi$

**Isolated $\pi^0$**

```
pp, $\sqrt{s} = 7$ TeV

- 8 GeV/c < $p_T^{\pi^0}$ < 12 GeV/c
- 12 GeV/c < $p_T^{\pi^0}$ < 16 GeV/c ($\times 10^3$)
- 16 GeV/c < $p_T^{\pi^0}$ < 25 GeV/c ($\times 10^2$)
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**Isolated $\gamma$**

```
pp, $\sqrt{s} = 7$ TeV

- 8 GeV/c < $p_T^{\gamma}$ < 25 GeV/c
```

Inverse slope : 7.8 +/- 0.9

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Conclusions

- We observe a strong suppression of the inclusive charged jet yield in central Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV
  - $R_{\text{AA}}^{\text{charged Jet}} = 0.2-0.35$ in the $30 < p_{\text{T, Jet}}^{\text{ch}} < 100$ GeV/c
  - Lower than inclusive hadron $R_{\text{AA}}$ at similar parton $p_{\text{T}}$

- No indication of energy redistribution observed from ratios of jet yields $\sigma(R=0.2)/\sigma(R=0.3)$ within exp. uncertainties.

- Conditional hadron-jet yield suppressed by factor of 0.75 with respect to Pythia reference.
  - Similar to conditional away-side hadron-hadron yields at lower $Q^2$.

- Yield and conditional yield suppression patterns qualitatively and to some extent quantitatively similar for single hadrons and jets.
  - Consistent with interpretation as consequence of energy loss through radiation outside jet cone.

- $\gamma$-hadron measurements ($x_E$) in pp at $\sqrt{s_{\text{NN}}} = 7$ TeV
  - Important step towards Pb-Pb measurement.
Additional Posters

- Measurements of charged particle jet properties in pp collisions at $\sqrt{s} = 7$ TeV (Sidharth Kumar Prasad)
- Jet measurements in proton-proton collisions (Michal Vajzer)
- Jet-Hadron Azimuthal Correlation Measurements in p+p Collisions at $\sqrt{s} = 2.76$TeV and 7TeV (Dosatsu Sakata)
Backup
Jets in pp
Trigger Efficiency

- EMCal Level-0 trigger
  - Used in data-taking to extend the kinematic reach of jet spectrum.
- Bias on the jet population
  - Estimated in simulation via incorporating the EMCal cluster turn-on curves and local inefficiency of the trigger system extracted from data.
Jets in pp
Bin by Bin Corrections

\[
C_{MC}(p_T^{low}, p_T^{high}) = \frac{\int_{p_T^{low}}^{p_T^{high}} d p_T \frac{d F_{\text{measure}}^{\text{unorr}}}{d p_T} \frac{d \sigma_{\text{Particle}}_{MC}^{\text{Detector}}}{d p_T}}{\int_{p_T^{low}}^{p_T^{high}} d p_T \frac{d F_{\text{measure}}^{\text{unorr}}}{d p_T}}
\]
Jets in pp
Underlying Event

Effects of underlying event subtraction on jet spectrum

ALICE pp @ \( \sqrt{s} = 2.76 \text{ TeV} \)
anti-\(k_t\) \( R=0.4 \)

Statistical error only

ALICE
PERFORMANCE
2012-07-20
Event-by-Event Background Subtraction

\[ \rho = \text{median} \left( \frac{p_T^{\text{jet},i}}{A_i^{\text{jet}}} \right) \]

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Charged Jets in PbPb Raw Spectra

$\frac{1}{N_{\text{coll}}} \frac{1}{N_{\text{evts}}} \frac{dN}{dp_T}$ (GeV/c)$^{-1}$

- Inclusive
- Leading track $p_T > 5$ GeV/c
- Leading track $p_T > 10$ GeV/c

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

Charged Jets
Anti-$k_t$ $R = 0.2$
$p_{T,\text{track}} > 0.15$ GeV/c
Jets in Pb-Pb
Unfolding

\[ \chi^2 = \sum_{\text{refolded}} \left( \frac{y_{\text{refolded}} - y_{\text{measured}}}{\sigma_{\text{measured}}} \right)^2 + \beta \sum_{\text{unfolded}} \left( \frac{d^2 \log y_{\text{unfolded}}}{d \log p_T^2} \right)^2 \]

\(\chi^2\)-term

Regularization/penalty
Pb-Pb: Unfolding

- Choice of $p_T$ ranges in unfolding and systematic uncertainties
  - Measured spectrum: Suppression of background jets by $p_{T,\text{meas}} > 5\sigma(\delta p_T)$.
  - Feed in from low $p_T$. Unfolded spectrum starts at $p_T = 0$ GeV/c
  - Regularization strength: systematic uncertainty on extracted jet yield 10% for central events and 4% for peripheral events
  - Jet energy scale correction from detector effects: ~10%
Charged Jets

Anti-$k_T$, $R = 0.2$

$\mathbf{R = 0.2}$

$\mathbf{R = 0.3}$

$\mathbf{p_{T,track} > 0.15 GeV/c}$
Flow bias: high $p_T$ hadron correlated to event and participant plane.
- Background density per unit area below jet is larger.
- Magnitude of bias on inclusive jet spectra depends on $p_T$ of trigger.
- Hadron triggered jet spectra are corrected for the flow bias.
Jet and leading particle energy loss

\[ E_{\text{jet}} \rightarrow E_{\text{jet}} - \Delta E \]

\[ p_{T, \text{leading}} \rightarrow p_{T, \text{leading}} - z_{\text{leading}} \Delta E \]

\[ \frac{p_{T, \text{leading}} - z_{\text{leading}} \Delta E}{E_{\text{jet}} - \Delta E} = \frac{z_{\text{leading}} E_{\text{jet}} - z_{\text{leading}} \Delta E}{E_{\text{jet}} - \Delta E} = z_{\text{leading}} \]