Inclusive jet spectra in 2.76 TeV collisions from ALICE

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Jets in Heavy-Ion Collisions

- Jets make an ideal probe of the medium
  - Partons from hard scattering are produced early
  - Propagating parton is modified by the QCD medium
  - Observation of jet quenching indicates modification

- Experimental challenges
  - Need to remove underlying event contribution
  - Jet \( p_T = p_{T \text{ rec}} - \rho A \)
    - \( A \) = Jet area
    - \( \rho \) = Underlying event momentum density
    - \( p_{T \text{ rec}} \) = Jet \( p_T \) from jet finder
ALICE Jets at $\sqrt{s} = 2.76$ TeV

- Inclusive jet cross section in pp $\sqrt{s} = 2.76$ TeV
- Important reference for Pb-Pb measurements
- Test of pQCD calculations
- Minimum-bias: 0.4 nb$^{-1}$
- EMCal trigger: 4x4 towers, 3 GeV threshold: 11 nb$^{-1}$

- Pb-Pb charged jets
  - 15M events from 2010 Pb-Pb run
  - Uniform $\eta$ – $\Phi$ acceptance: $|\eta| < 0.9$ 0$<\Phi<2\pi$
  - Neutral energy missing
Tracking: $|\eta| < 0.9$, $0<\Phi<2\pi$

TPC: gas detector

ITS: silicon detector

Charged constituents

Jets at ALICE
Jets at ALICE

Tracking: $|\eta| < 0.9$, $0 < \Phi < 2\pi$
TPC: gas detector
ITS: silicon detector

Chargedhadronic correction prevents double counting
Neutral constituents

- EMCal is a Pb-scintillator sampling calorimeter which covers:
  - $|\eta| < 0.7$, $1.4 < \phi < \pi$
  - tower $\Delta\eta \sim 0.014, \Delta\phi \sim 0.014$
Jet Reconstruction

- Input to the Jet Finder
  - Assumed to be massless
  - Charged tracks with $p_T > 150$ MeV/c (pp, Pb-Pb)
  - EMCal clusters with $E_T > 150$ MeV after hadronic correction: (pp)
    - $E_{\text{cluster}}^{\text{cor}} = E_{\text{cluster}}^{\text{orig}} - f \sum p^{\text{matched}}$, $E_{\text{cluster}}^{\text{cor}} \geq 0$
  - For pp analysis $f = 100\%$

- Jets reconstructed using FastJet package
  - $R = 0.2, 0.3, 0.4$
  - Anti-$k_T$ for signal jets (pp, Pb-Pb)
  - $k_T$ for $\rho$ calculation (Pb-Pb)
  - EMCal jets: Fiducial cut requires jet fully contained in the EMCal acceptance (pp)
Detector Effects - pp

- **Bin-by-bin technique**
  - Compare simulated the cross sections before and after Detector response
  - Use uncorrected spectrum in data as weighting function

- **Shift of jet energy scale ~ 20-25%**
  - Unmeasured neutrons and K⁰'s: compare proton and kaon spectra to data; PYTHIA vs HERWIG
  - Tracking inefficiency: track quality in data vs simulation
  - 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
Good agreement between data and NLO calculations as well as PYTHIA8 prediction within both experimental and theoretical uncertainties

See Rongrong Ma’s Poster #35
Inclusive pp Cross Section

\[ \frac{d^2 \sigma}{dp_T \, d^2 \Omega} \] (mb c/GeV)

\[ \begin{align*}
\text{anti-}k_T, R=0.2 \\
\text{ALICE pp } \sqrt{s} = 2.76\text{TeV}: L_{\text{int}} = 11 \text{ nb}^{-1}
\end{align*} \]

Correlated systematic uncertainty
Uncorrelated systematic uncertainty

NLO (N. Armesto)
NLO (G. Soyez)
NLO + Hadronization (G. Soyez)
PYTHIA8: points displaced horizontally for visibility

\[ \begin{align*}
\text{anti-}k_T, R=0.4 \\
\text{ALICE pp } \sqrt{s} = 2.76\text{TeV}: L_{\text{int}} = 11 \text{ nb}^{-1}
\end{align*} \]

Correlated systematic uncertainty
Uncorrelated systematic uncertainty

NLO (N. Armesto)
NLO (G. Soyez)
NLO + Hadronization (G. Soyez)
PYTHIA8: points displaced horizontally for visibility
Ratio of Jet Cross Sections
R=0.2/R=0.4

- NLO ratio is equivalent to ratio of cross sections calculated at NNLO
- Good agreement between data and NLO+hadronization\(^{[1]}\) within experimental and theoretical uncertainties

\(^{[1]}\) G. Soyez, Phys.Lett. B698 (2011) 59
Compare the neutral energy fraction (NEF) distribution between data and Detector Level simulation in different jet $p_T$ bins

- **Good agreement within the statistical precision**
Charged Jets in Pb-Pb

- 2 important aspects of the underlying event (UE)
  - Within-event fluctuations
  - Average background

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\[ \rho_{ch} = \text{median}(\frac{p_{T,jet}^{k}}{A^{k_{T,jet}}}) \]

- Effect of UE on jets
  - Multiplicity/flow
  - Dependent on R
  - Constituent cut
Detector and Background Effects

- Unfold measured spectrum to obtain true spectrum
  - Effects are combined in response matrix
    - Background \(\rightarrow\) data driven
    - Detector Effects \(\rightarrow\) simulation
  - \(\chi^2\) minimization routine

- Leading track bias removes combinatorial jets
  - Important for charged + neutral Pb-Pb analysis since background fluctuations are larger than in charged only
  - Can cause a fragmentation bias which we can observe in charged only analysis
Charged Jet Spectra in Pb-Pb 0-10%

- Leading track requirement facilitates unfolding to a lower jet $p_T$ compared to inclusive results.
- Does not have a large effect on the spectra with $p_T > 30$ GeV/c.

Marta Verweij’s Poster #34
Jet Structure

- **R=0.2/R=0.3** is consistent with vacuum jets
  - In both central and peripheral collisions!

- Charged Pb-Pb results show consistency with PYTHIA
  - pp shows PYTHIA simulates vacuum fragmentation well

**Graph:**
- Comparison of jet cross-sections with different models and uncertainties.
- ALICE pp $\sqrt{s} = 2.76$ TeV
- Systematic uncertainty
- PYTHIA8
- NLO + Hadronization (G. Soyez)
- NLO (G. Soyez)
- LO (G. Soyez)

**Legend:**
- $\text{p}_T^{\text{charged}}$ (GeV/c)

**Figure:**
- Full Jet Reconstruction
- Ratio of jet cross-sections
- ALICE preliminary results

Rosi Reed - QM 2012
Jet Quenching
Charged Jets in Pb-Pb

JEWEL: (Zapp, Krauss, Wiedemann arXiv:1111.6838)

- Charged jets show suppression with PYTHIA reference ($R_{AA}$) and from peripheral to central ($R_{CP}$).

JEWEL MC: radiative+elastic energy loss
Charged+Neutral Background Determination

\[ \rho_{ch+em} = \text{median}( \frac{p_T^{k_T jet}}{A^{k_T jet}} ) \]

- \( \rho_{ch+em} > \rho_{ch} \)
- \( \sigma_{ch+em} \delta p_T > \sigma_{ch} \delta p_T \)
  - 6.1 vs 4.5 GeV/c

Fluctuation size characterized by \( \delta p_T \)
- Embedded particle
  \[ \delta p_T = p_T^{\text{rec}} - \rho_{ch+em} A^{\text{Anti-k_T}} - p_T^{\text{emb}} \]
- Random Cones
  \[ \delta p_T = p_T^{\text{rec}} - \rho_{ch+em} \pi R^2 \]
Conclusions and Outlook

- Report on fully reconstructed jet cross section for pp $\sqrt{s} = 2.76$ TeV $R = 0.2, 0.4$
- The measured cross sections agree well with theory
- The ratio agrees well with NLO+hadronization
- Important reference

Charged jet analysis in Pb-Pb collisions
- Strong jet suppression in central events
- No signs of modified jet structure observed in ratio $R=0.2/R=0.3$

Charged+neutral background fully characterized in Pb-Pb
Back-up
Unfolding the background

- Need to **unfold** measured jet spectrum to obtain 'real' jet spectrum (Truth)
- Low $p_t$ jets are dominated by random collections of particles → background jets. These appear up to very high $p_t$. 

Toy model G. Barros et al.
Talk Parallel IIB Monday
Unfolding the background

- Need to **unfold** measured jet spectrum to obtain 'real' jet spectrum (Truth)

- Refolded = unfolded jet spectrum smeared with background fluctuations

Assume:

\[
\left. \frac{dN}{dp_T} \right|_{meas} = P(\delta p_T) \otimes \left. \frac{dN}{dp_T} \right|_{jet}
\]

Unfolding done with $\chi^2$ minimization

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

$\chi^2$-term

Regularization/penalty
Unfolding: $p_t$ ranges & systematics

- Measured spectrum: $p_{t,\text{min}} - p_{t,\text{max}}$
  - $p_{t,\text{min}} \sim 5\sigma(\delta p_t)$ → Suppression of background jets. Estimated from various toy model studies
- Feed in from low $p_t$
  - Unfolded starts at $p_t=0$ GeV/c
- Feed in from high $p_t$

Systematic uncertainty from unfolding procedure
'Shape uncertainty'

Main contributions
- Regularization strength
- $p_t$ cut-off in measured spectrum
- Feed in of low $p_t$ bins in unfolded spectrum
Including detector effects

Response matrix includes background fluctuations and detector effects (tracking efficiency and track $p_t$ resolution).
No correction for missing neutral particles

Truth $\rightarrow$ D $\rightarrow$ Measured

$RM_{det}$ $\rightarrow$ $RM_{\delta p_t}$

D=jet spectrum after detector effects

$M = RM_{\delta p_t} \cdot RM_{det} \cdot T$

$p_t^{jet} < 60$ GeV/c:
Dominant correction from background fluctuations