Jet Properties in Pb-Pb collisions at ALICE

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Outline

• Introduction
• Jets in heavy-ion collisions
• Strangeness production in jets
• Jet shapes
• Summary
Introduction
in heavy-ion collisions at ultra-relativistic energies, a quasi macroscopic fireball of hot, strongly interacting matter in local thermal equilibrium is created.

- lattice QCD predicts phase transition to deconfined, chirally symmetric matter.

- energy density from the lattice: rapid increase around $T_C$, indicating increase of degrees of freedom (pion gas $\rightarrow$ quarks and gluons).

- $T_C = 154 \pm 9$ MeV
  $E_C = 340 \pm 45$ MeV/fm$^3$
QCD matter at LHC

• direct photons:
  prompt photons from hard scattering
  + thermal radiation from QCD matter

• low-$p_T$ inverse slope parameter:
  $T_{\text{eff}} = 297 \pm 12^{\text{stat.}} \pm 42^{\text{syst.}} \text{ MeV/c}$

• indicates initial temperature way above $T_C$

Partons in heavy-ion collisions

- hard partons are produced early and traverse the hot and dense QGP

- expect enhanced parton energy loss, (mostly) due to medium-induced gluon radiation: ‘jet quenching’

- jet: ‘collimated bunch of hadrons’

- the best available experimental equivalent to quarks and gluons

- ‘vacuum’ expectation calculable by pQCD: ‘calibrated probe of QGP’
Parton fragmentation

- initial hard scattering: high-\(p_T\) partons with high virtuality
- virtuality evolution through parton shower
- hadronisation at a scale (\(O(\Lambda_{QCD})\))
- jets probe the medium at a variety of scales and are sensitive to its properties (energy density, \(\hat{q}\), mean free path, coupling ... )
Hadrons in heavy-ion collisions

• high- $p_T$ hadrons ‘proxy’ for jet

• jet quenching for charged hadrons, Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

\[
R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N_{ch}}{d\eta dp_T} \frac{d^2\sigma_{pp}}{d\eta dp_T}
\]

![Graph showing $R_{AA}$ vs $p_T$ for ALICE Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV charged particles, $|\eta| < 0.8$.]

ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV charged particles, $|\eta| < 0.8$

- 0-5%
- 70-80%
Identified hadrons in heavy-ion collisions

- baryons / meson $R_{AA}$ a probe of gluon / quark energy loss?
- would expect stronger radiative energy loss for gluons than for quarks
  - subtle cancellations?
  - hadron observable biased towards hard fragmentation?

- study jets to improve our understanding of parton energy loss:
  - PID in reconstructed jets mitigates fragmentation biases
  - enhanced sensitivity to medium effects measuring soft particles in jets

- note: medium effects likely strongest at scales of ~ medium Temperature
  
  B. Mueller, hep-ph/1010.4258)
• full jets: assess full parton energy

• charged (tracking) jets:
  - full azimuthal coverage
  - measures parton energy deposited into charged fragments
  - good definition of jet axis: well suited for fragmentation, jet structure, PID …

• charged particle tracking:
  - Inner Tracking System (ITS)
  - Time Projection Chamber
  - full azimuth, $|\eta| < 0.9$
  - $p_T > 150$ MeV/c

• EMCal:
  - neutral particles
  - $\Delta\phi = 107^\circ$, $|\eta| < 0.7$
  - cluster $E_T > 300$ MeV
Underlying event in heavy-ion collisions

- jet reconstruction in heavy-ion collisions: high underlying event background not related to hard scattering
- background is dominant at low jet and constituent $p_T$
- background fluctuations are important

Jet area $\approx 0.5 \ (R = 0.4)$
Strangeness Production in Jets
Strange hadron reconstruction

- neutral strange particles reconstructed via decay topology (‘$V^0$’):
  
  \[ K_S^0 \rightarrow \pi^+ + \pi^- \ (69.2\%) \]
  \[ \Lambda \rightarrow p + \pi^- \ (63.9\%) \]

- signal extraction from invariant mass distributions
Strangeness production in nuclear collisions

• Baryon / Meson ratio enhanced in Pb-Pb and p-Pb collisions
  - collective effects ?
  - parton recombination ?
  - jet fragmentation ?

• measurement of identified particles in jets helps to constrain hadronisation and energy loss scenarios

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Strangeness in jets

- candidate - jet matching \((V^0\text{ in jet cone})\)
  \[
  \sqrt{(\phi_{V^0} - \phi_{jet, \text{ch}})^2 + (\eta_{V^0} - \eta_{jet, \text{ch}})^2} < R
  \]
  \[
  |\eta_{jet, \text{ch}}|^{\text{max}} < |\eta_{V^0}|^{\text{max}} - R
  \]

- jet \(R = 0.2\), acceptance \(|\eta_{V^0}| < 0.7\)

- candidate - bulk matching: underlying event \(V^0\)

- signal extraction from invariant mass distributions

- correct for efficiency and feed-down

- subtract underlying event from spectra
Underlying event subtraction

- subtract underlying event contribution to $K^0_s$, $\Lambda$ spectra in jets

- various methods with different sensitivity to acceptance, event plane correlations, presence of additional jets, …

- differences used to estimate systematic uncertainty
$(\Lambda + \bar{\Lambda})/2K^0_s$ ratio in jets

- Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV
- jet $R = 0.2$
- $p_T^{\text{jet}} > 10$ GeV/c (20 GeV/c)
- leading constituent bias $p_T^{\text{leading}} > 5$ GeV/c to reject ‘fake’ jets
- no significant jet $p_T^{\text{jet}}$ dependence
- ratio in jets significantly lower than for inclusive case
Comparison to p-Pb

- compare Pb-Pb results to reference from p-Pb collisions at 5.02 TeV: agreement within uncertainties

- ongoing efforts to improve systematics for lowest $K^0_S$, $\Lambda$ $p_T$

**Pb-Pb**

**p-Pb**

- $\sqrt{s_{NN}} = 5.02$ TeV
- 0-100%, V0A Multiplicity Class (Pb-Side)
- $p_{T,jet}^{ch} > 10$ GeV/c, anti-$k_T$
- $|\eta_{jet}| < 0.75$ - $R$, $|\eta_{\gamma^0}| < 0.75$
- inclusive $\Lambda/K^0_S$, ALICE, (0-5 %, $|y_{\gamma^0}| < 0.5$)
- $|\eta_{\gamma^0}| < 0.7$
- anti-$k_T$, $R = 0.2$
- $|\eta_{jet,\gamma^0}| < 0.5$
- $p_T^{leading track} > 5$ GeV/c
- $p_T^{track} > 150$ MeV/c

**ALICE Preliminary**
Jet Shapes
Jet nuclear modification factor

- strong suppression, similar to hadron RAA
  → parton energy not recovered inside jet cone

- increase of suppression with centrality, weak $p_T$ dependence

- JEWEL:
  - microscopic pQCD parton shower + gluon induced emissions

- YaJEM:
  - detailed fireball model
  - parameterisation of radiative and collisional energy loss

- different models reproduce observed jet suppression
  → study jet quenching through more differential measurements

JEWEL: PLB 735 (2014)
YaJEM: PRC 88 (2013) 014905
Jet shapes

- radial moment ‘girth’ g, longitudinal dispersion $p_T D$, difference leading - subleading $p_T$ LeSub

- shapes in pp collisions at 7 TeV:
  - constrain QCD calculations of small-R jets
    ('microjets': M. Dasgupta, F. Dreyer, G. Salam, G. Soyez)
  - validate MC simulations

- shapes in Pb-Pb as IRC safe probe of quenching of low-$p_T$ jets:
  characterise fragment distributions and are sensitive to medium induced changes of intra-jet momentum flow

- ‘event-by-event’ measure, sensitive to fluctuations
Jet shapes as quenching signatures

• compare quarks and gluons: gluon jets broader and softer

• $g$ is $p_T$ weighted width of the jet:
  - broadening (collimation) $\rightarrow$ enhanced (reduced) $g$

• $p_T D$ measures $p_T$ dispersion:
  - less constituents / ‘more democratic’ splitting $\rightarrow$ reduced $p_T D$

• LeSub characterises hardest splitting, insensitive against background
Analysis details

- charged jets from charged particle tracks, $p_{T}^{\text{const}} > 150$ MeV/c in pp MinB at 7 TeV and Pb-Pb 10% central at 2.76 TeV

- $R=0.2$, $40 < p_{T}^{\text{jet}} < 60$ GeV/c, no leading constituent cut

- novel background subtraction methods (Pb-Pb)
  - constituent subtraction (P. Berta et al, JHEP 1406 (2014) 092)

- 2D unfolding to correct for background fluctuations and detector effects
Jet shapes in pp

- fully corrected to charged particle level
- fair agreement with PYTHIA simulations: validates PYTHIA as reference for Pb-Pb
Jet shapes in Pb-Pb

- fully corrected to charged particle level
- $g$ shifted to smaller values compared to PYTHIA reference → indicates more collimated jet core

![Graph showing jet shapes in Pb-Pb](image-url)

ALICE Preliminary

$\sqrt{s_{NN}} = 2.76$ TeV

Anti-$k_T$ charged jets, $R = 0.2$

$40 < p_T^{\text{jet,ch}} < 60$ GeV/c

- ALICE Data
- Shape uncertainty
- Correlated uncertainty
- PYTHIA Perugia 11
• larger $p_T$D in Pb-Pb compared to PYTHIA
  → indicates fewer constituents in quenched jets

• LeSub in Pb-Pb in good agreement with Pb-Pb:
  → hardest splittings likely unaffected
• trends reproduced by JEWEL jet quenching model: collimation through emission of soft particles at large angles
Qualitative discussion

- characterise degree of dispersion and broadening in terms of ‘quark-like’ and ‘gluon-like’

- observed effects favour ‘quark-like’ scenario

- quenching mechanism or change of quark/gluon composition caveat: jet $p_T$ not equal parton $p_T$
Qualitative discussion II

- jet quenching = jet $p_T$ shift + vacuum fragmentation?

- if yes, would expect shapes to agree with vacuum shapes from higher $p_T$ jets

- $g$ agrees qualitatively with this picture, however $p_T D$ does not
Summary

- strangeness production in jets in Pb-Pb collisions
  - significant difference between the $\Lambda/K^0_S$ ratio of inclusive particles and the ratio in charged jets

- measurement of jet shapes
  - characterise modifications of intra-jet momentum flow by QGP
  - results indicate that jet cores in Pb-Pb are narrower and harder and have fewer constituents than PYTHIA pp reference
  - results in qualitative agreement with quark-like fragmentation and described by quenching models like JEWEL
LHC run 2

- increased CMS energy for Pb-Pb collisions from 2.76 → 5.1 TeV
- quenching strength $\hat{q} \sim s \sim \varepsilon^{3/4}$
- expect (modest) increase in $\varepsilon$, $T$ → measure energy density dependence of jet quenching
- note: also a dependence on parton ‘input spectrum’ (increased $R_{AA}$ ???)

ALICE, PRL 105, 252301

Oliver Busch – TGSW 2015/09/30
ALICE in run 2: DCal

• run 2: DCal upgrade
  - significantly extended jet acceptance
  - back-to-back in azimuth (di-jet topology)
Jet structure

- ‘jet structure ratio’ R=0.2 / R=0.3 for charged jets
- sensitive to potential broadening of jet shape
- consistent with PYTHIA pp: no modification observed within small radii (jet core)
Jet reconstruction

• Establish correspondence between detector measurements / final state particles / partons

• two types of jet finder:
  - iterative cone
  - sequential recombination (e.g. anti-k_T)

• resolution parameter R

hep-ph/0802.1189
Uncertainties in the measurement

- **Tracking efficiency** uncertainty of ±4% dominates the Jet Energy Scale uncertainty.
- **Unfolding:**
  - **Regularization** variations of ±3 iterations.
  - **Truncation** of the measured yield at a 10 GeV lower value (10 and 20 GeV/c in pp and Pb-Pb resp.)
  - **Prior:** intrinsic correlation between $p_{T,\text{jet,part}}$ and $\text{shape}_{\text{part}}$ with which response is built.
    - Default is PYTHIA Perugia 0, variation is a smearing of such correlation by 20%.
- **Additional ingredient in Pb-Pb:** background subtraction method variation.

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