Heavy Flavor jets in ALICE

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NPI CAS
Introduction

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2
Quark Gluon Plasma (QGP) is created in heavy-ion collisions
Introduction

Quark Gluon Plasma (QGP) is created in heavy-ion collisions

Signatures of QGP:

- **Collective flow:** QGP acts like nearly-perfect liquid
- **Jet quenching:** QGP slows penetrating patrons
- ...

Quark Gluon Plasma (QGP) is created in heavy-ion collisions
Jets

**Jet** – a collimated spray of hadrons, created during hadronization of quark or gluon after hard scattering, defined via algorithm
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Features of heavy-flavor quarks:

- **Large mass** → it can be created only in initial hard scatterings. Its production rate can be calculated from pQCD
- **Long lifetime** → it survives through the whole evolution of QGP
- **Smaller energy loss** by radiative process for quarks with higher mass (Dead-cone effect)

\[ \Delta E_{g}^{\text{rad}} > \Delta E_{u,s,d}^{\text{rad}} > \Delta E_{c}^{\text{rad}} > \Delta E_{b}^{\text{rad}} \]


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Fraction of the jet momentum carried by the tagged meson along axis direction

$$z_{||} = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{tagged}}}{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{jet}}}$$

- In pp, constrains models
- In AA collisions, enables to study medium-induced modification of collinear fragmentation for HF quarks

D.P. Anderle et al., D*±-jets, pp, 7 TeV. [PRD 96 (2017) 034028]
Nuclear modification factor compares particle yield in HI and binary scaled pp collisions

\[ R_{AA} = \frac{d N_{AA}}{d p_T} / \langle N_{coll} \rangle \cdot \frac{d N_{pp}}{d p_T} \]

In pA collision system:
- If \( R_{pA} \neq 1 \) → presence of CNM effects

In AA collision system:
- If \( R_{AA} < 1 \) at intermediate-high \( p_T \) → indication of final state effects (in medium energy loss)

ALICE is focused on low-\( p_T \) sector

ALICE experiment

**V0**
- Scintillator array for triggering
- Estimation of centrality

**Time Projection Chamber**
- Track reconstruction
- Particle identification via dE/dx

**Inner Tracking System**
- Track reconstruction
- Primary and secondary vertex reconstruction

**EMCal**
- Triggering and reconstrunition of high-$p_T$ jets
- Measurements of high-$p_T$ $e^\pm$ and $\gamma$

- Impact param. res. < 70 $\mu$m at 1 GeV/c
- $|\eta_{\text{track}}| < 0.9$
- Full azimuth
- 0.5 T solenoid

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D⁰ - tagged jets in pp at √s = 7 TeV: Analysis overview

1) D⁰ - meson selection

- Hadronic decay channel:
  \[ D⁰ \rightarrow K⁻ π^+ , \text{BR} = 3.89\% \]
  \[ \bar{D}⁰ \rightarrow K^+ π⁻ \]

- D⁰ decay vertex is reconstructed from a pair of tracks with opposite charge
  - \(|\eta_{\text{track}}| < 0.8\)
  - \(p_{T,\text{track}} > 0.3\) GeV/c

- PID selection: TPC dE/dx, TOF
- Topological cuts
  - Sum of D⁰ daughter momenta points to the PV
  - Geometrical selections

ALICE, to be published in JHEP
D⁰ - tagged jets in pp at √s = 7 TeV:
Analysis overview

1) D⁰ - meson selection

2) Jet reconstruction and D⁰-meson tagging

- Before jet reconstruction π and K daughters are removed and replaced by the mother D⁰
- Charged tracks
- |η| < 0.8
- FASTJET Anti-\( k_T \) jet finding algorithm with jet radius \( R = 0.4 \)
- \( p_{T,jet}^{ch} > 5 \) GeV/c, \( p_{T,D} > 3 \) GeV/c
- Only one D⁰ candidate per one jet
D⁰ - tagged jets in pp at $\sqrt{s} = 7$ TeV: 
Analysis overview

1) D⁰ - meson selection

2) Jet reconstruction and D⁰-meson tagging

3) D⁰-meson tagged jet yield extraction

- For each $D⁰ p_T$ bin, K and $\pi$ invariant mass spectrum was fitted with a sum of background, reflection template and signal shapes

- D⁰-jet candidates were corrected for background by means of side-band method
D⁰ - tagged jets in pp at √s = 7 TeV: Analysis overview

1) D⁰ - meson selection

2) Jet reconstruction and D⁰-meson tagging

3) D⁰-meson tagged jet yield extraction

4) Corrections
   - Efficiency of the track reconstruction and of the topological cuts (PYTHIA6 Perugia 2011)
   - B Feed-down contribution (PYTHIA6 + POWHEG)
   - Unfolded for detector effects
   - Cross-section calculated with formula:

\[
\frac{d^2\sigma}{dp_{T,jet}^{ch} d\eta_{jet}}(p_{T,jet}^{ch}) = \frac{1}{\mathcal{L}} \frac{1}{BR} \frac{N(p_{T,jet}^{ch})}{\Delta \eta_{jet} \Delta p_{T,jet}^{ch}}
\]

ALICE Preliminary
pp, √s = 5.02 TeV

D⁰ → Kπ⁺ and charge conj.
in charged jets, anti-k_T, R = 0.3
|\eta_{lab}^jet| < 0.6

ALI-PREL-309103

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D⁰ - tagged jets in pp at $\sqrt{s} = 7$ TeV: Production cross-section

Fraction of D⁰ jets in inclusive jets:

$$R\left(p_{T,\text{jet}}^{\text{ch}}\right) = \frac{N_{D^0\text{jet}}\left(p_{T,\text{jet}}^{\text{ch}}\right)}{N_{\text{inclusive jet}}\left(p_{T,\text{jet}}^{\text{ch}}\right)}$$

Comparison to models:

- Cross-section: Both versions of PYTHIA overestimate the yield by a factor $\approx 1.5$
- Ratio for D⁰ and inclusive jets: All models describe quite well the ratio of D⁰-meson tagged jets over the inclusive jet production
D⁰ - tagged jets in pp at √s = 7 TeV: D⁰-jet cross section as a function of $z_{||}^{ch}$

- Momentum fraction carried by the D⁰ meson in the direction of the jet axis:

$$z_{||}^{ch} = \frac{p_{ch \ jet} \cdot p_{D^0}}{p_{ch \ jet} \cdot p_{ch \ jet}}$$

$$R(p_{T,jet}^{ch}, z_{||}^{ch}) = \frac{N_{D^0\ jet} (p_{T,jet}^{ch}, z_{||}^{ch})}{N_{inclusive\ jet} (p_{T,jet}^{ch})}$$

- $5 < p_{T,jet}^{ch} < 15$ GeV/c

- Good agreement with Herwig 7 and PYTHIA6/8 generators, POWHEG+ PYTHIA6 simulations
D⁰ - tagged jets in pp at √s = 7 TeV: D⁰ jet cross section as a function of z\_||\_\\text{ch}

- Momentum fraction carried by the D⁰ meson in the direction of the jet axis:

\[ z\_||\_\\text{ch} = \frac{p\_\text{ch jet} \cdot p\_D^0}{p\_\text{ch jet} \cdot p\_\text{ch jet}} \]

\[ R(p\_T\_\text{jet}, z\_||\_\\text{ch}) = \frac{N\_D^0\_\text{jet} (p\_T\_\text{jet}, z\_||\_\\text{ch})}{N\_\text{inclusive jet} (p\_T\_\text{jet})} \]

- 15 < p\_T\_\text{jet} < 30 GeV/c

- Good agreement with PYTHIA6/8 generators, but Herwig7 shows some tension at high z\_||\_\\text{ch}

- POWHEG+ PYTHIA6 simulations for z\_||\_\\text{ch} < 0.9
1) Jet reconstruction

- Charged anti-$k_T$, $R = 0.4$
- $p_T$, constituent $> 0.15$ GeV/c
- $|\eta_{jet}| < 0.9 – R < 0.5$
- $|z_{vtx}| < 10$ cm
- $p_T$ of the jets corrected on the mean underlying event density
1) Jet reconstruction

2) B-Jet candidate selection

- SV constructed out of 3 prongs
- The most displaced SV considered in each event
- Discrimination variables:

  1) Significance of the distance between PV and SV:

     \[ SL_{xy} = L_{xy}/\sigma_{L_{xy}} > 5, 6, 7, 8, 9 \]

  2) Dispersion of the SV \( \sigma_{SV} < 0.02, 0.03, 0.04, 0.05 \) cm

\[ \sigma_{SV} = \sqrt{\sum_{i=1}^{3} d_i^2} \]

\( d_i \) – distance of the closest approach (DCA) of \( i \)-th prong to SV

3) Invariant mass in SV (reserved for purity estimation)
1) Jet reconstruction

2) B-Jet candidate selection

3) Correction on SV tagging efficiency
   - Jet yield estimated based on PYTHIA+EPOS simulation
   - Efficiencies for different b-jet candidates after imposing the default cut:
     \[ \varepsilon_b \approx 35\% , \varepsilon_c \approx 11\% , \varepsilon_{LF} \approx 1\% \]
B jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV: Analysis overview

1) Jet reconstruction

2) B-Jet candidate selection

3) Corrections on efficiency and purity

- Jet yield was corrected on efficiency of SV tagging (estimated with PYTHIA + EPOS)

- Purity of b jets was estimated using the following method:
  - Data-driven template fit method
1) Jet reconstruction

2) B-Jet candidate selection

3) Corrections on efficiency and purity

- Jet yield was corrected on efficiency of SV tagging (estimated with PYTHIA + EPOS)

- Purity of b jets was estimated using the following method:
  - Data-driven template fit method
  - POWHEG + PYTHIA simulation was used to calculate purity for high-\(p_T\) region

\[
P_b = \frac{N_b \varepsilon_b}{N_b \varepsilon_b + N_c \varepsilon_c + N_{LF} \varepsilon_{LF}}
\]

\(N_b, N_c\) – folded POWHEG \(p_T\) spectrum of b and c-jets

\(N_{LF} = \text{RAW} \ p_T\) spectrum of inclusive jets – \(N_b - N_c\)

\(\varepsilon_b, \varepsilon_c, \varepsilon_{LF}\) – efficiency of SV tagging for b, c and LF-jets for given \(SL_{xy}\) and \(\sigma_{SV}\)
1) Jet reconstruction

2) B-Jet candidate selection

3) Corrections on efficiency and purity

- Jet yield was corrected on efficiency of SV tagging (estimated with PYTHIA + EPOS)

- Purity of b-jet was estimated using the following method:
  - Data-driven template fit method
  - POWHEG + PYTHIA simulation was used to calculate purity for high-$p_T$ region
  - Purities obtained based on different POWHEG settings were compared with the template fit results.
$B$ jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV: Production cross-section

- $p_T$ spectrum of the b jets was corrected:
  $$\frac{d N_{b-\text{jet}}^{\text{primary}}}{d \ p_T, \text{jet ch}} = \frac{d N_{b-\text{jet candidates}}^{\text{raw}}}{d \ p_T, \text{jet ch}} \times \frac{P_b}{\varepsilon_b}$$

- Jet momentum smearing due to instrumental effects and local background fluctuations was corrected by unfolding

- Result cross section shows good agreement with the model (POWHEG HVQ)
HFe jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV:
Analysis overview

1) HF electrons selection

- $c, b \rightarrow$ semileptonic decay producing $e^{\pm}$
- PID selection: TPC $dE/dx$, EMCal
- $p_{T,e} > 4$ GeV/c
HFe jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV: Analysis overview

1) HF electrons selection

2) Jets reconstruction

- Charged tracks
- FASTJet anti-$k_T$ algorithm
- Jet radius $R = 0.3, 0.4, 0.6$
- $|\eta_{jet}| > 0.9 - R$
- $p_{T,jet}^{ch} > 10$ GeV/c
- Jets with reconstructed electrons
- $p_T$ of the jets corrected on the mean background density
HFe jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV: Analysis overview

1) HF electrons selection

2) Jets reconstruction

3) Corrections
   - Background from photonic $e^\pm$
   - Hadron contamination
   - Reconstruction efficiency
HFe jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV: cross-section

- Measured cross-section shows good agreement with the model (POWHEG+PYTHIA8)

- $R_{pA}$ is compatible with unity. No sign of suppression
Summary

- Measurement of $D^0$-tagged jets in pp at $\sqrt{s} = 7$ TeV:
  - $z^\parallel_{ch}$ cross-section
  - Cross-section of $D^0$ tagged jets production

- Measurement of $b$ – jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV:
  - First results in cross-section of B-jets production

- Measurement of HFe jets in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV:
  - No sign of jet quenching is observed or other medium-induced modification
Backup
B jets in pPb: Physics motivation

pPb collisions:

- Study cold nuclear matter (CNM) effects (nPDF, shadowing, gluon saturation, $k_T$-broadening, energy loss in CNM in the initial and final states)
- Study of the possible collective effects

ALICE wants to study b-jets at lower momenta where CNM effects will be more significant

Was used two independent approaches:

- Most displaced Secondary Vertex (SV)
- Track counting algorithm (IP)
“Gluonsstrahlung” - process of gluon radiation by quarks (or gluons)

“Dead cone” effect – gluon radiation from massive quarks is suppressed at angles $\theta < m/E \rightarrow$ Less E loss inside the medium for heavy quarks expected


Gluonsstrahlung probability

$$\sim \frac{\theta^2}{[\theta^2 + (m/E)^2]^2}$$
Probability of gluon emission

For light quarks:

\[ dP_0 \approx \frac{\alpha_s C_F}{\pi} \frac{d \omega}{\omega} \frac{dk_T^2}{k_T^2} = \frac{\alpha_s C_F}{\pi} \frac{d \omega}{\omega} \frac{d \theta^2}{\theta^2} \]

For heavy quarks:

\[ dP_{HQ} = \frac{\alpha_s C_F}{\pi} \frac{d \omega}{\omega} \frac{k_T^2 dk_T^2}{(k_T^2 + \omega^2 \theta_0^2)^2} = \frac{\alpha_s C_F}{\pi} \frac{d \omega}{\omega} \frac{\theta^2 d \theta^2}{(\theta^2 + \theta_0^2)^2} \]

\[ \theta_0 = \frac{M}{E} \]

Where

- \( \omega \) - Energy,
- \( C_F \) - “color charge”,
- \( k_T \) - transverse momenta
- \( dP_0 \) - Probability to radiate gluon
Probability of gluon emission

For light quarks:

\[ dP_0 \approx \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{dk_T^2}{k_T^2} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2} \]

For heavy quarks:

\[ dP_{HQ} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_T^2 dk_T^2}{(k_T^2 + \omega^2 \theta_0^2)^2} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\theta^2 d\theta^2}{(\theta^2 + \theta_0^2)^2} \]

\[ \theta_0 = \frac{M}{E} \]

Where
\[ \omega \] - Energy, \( C_F \) - “color charge”, \( k_T \) - transverse momenta
\[ dP_0 \] - Probability to radiate gluon