Beauty production with ALICE

The 8th Asian Triangle Heavy-Ion Conference

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on behalf of ALICE Collaboration
Goal of ALICE experiment: quark-gluon plasma (QGP)

- Investigate a nuclear matter at extreme conditions of temperature and energy density
  - quark-gluon plasma: deconfined state of matter
  - lattice QCD predicts \( T_c \approx 150 \text{ MeV} \)\(^1\) and \( \varepsilon_c \approx 0.5 \text{ GeV} \cdot \text{fm}^{-3} \)\(^2\)

\(^{1}\)”S. Borsányi et al. JHEP 09 (2010) 073


- QGP can be produced in ultra relativistic heavy-ion collisions
Why heavy quarks are important

Heavy quarks (charm and beauty): produced in initial hard scattering processes

In heavy-ion collisions
- Interact with medium constituents via collisional and radiative processes
- Evaluated by nuclear modification factor ($R_{AA}$)
  - Mass dependence of the in-medium energy loss
  - Hadronization mechanism in the medium

\[ R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \]

In pp collisions,
- Test of pQCD calculations at the LHC energies

\[ \sigma^{\text{hard}}_{AB \rightarrow h} = \text{PDF}(x_a, Q^2) \text{PDF}(x_b, Q^2) \otimes \sigma^{\text{hard}}_{ab \rightarrow c}(x_a, x_b, Q^2) \otimes D_{c \rightarrow h}(z_q, Q^2) \] factorization theorem

- Reference for measuring nuclear modifications

In p+Pb collisions,
- Cold Nuclear Matter (CNM) effects
A Large Ion Collider Experiment (ALICE)

Central barrel coverage: $|\eta| < 0.9$
0.5 T magnetic field parallel to the beam axis

THE ALICE DETECTOR

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. FMD
17. AD
18. ZDC
19. ACORDE

Beauty production

non-prompt

$D^0 \rightarrow K^-\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$
$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$

semi-leptonic

$B(\rightarrow D) \rightarrow e\nu_eX$

b-tagged jets

Event trigger: V0
Vertexer & Tracker: ITS, TPC
Particle identification: TPC, TOF, EMCal
Cross section of $D^0$ mesons in pp collisions

Compared with FONLL

FONLL

- $f(b \rightarrow Hb)$ FFs from $c^+c^-$ and PYTHIA8 to describe $H_b \rightarrow D + X$ decays
- Describe the non-prompt $D^0$ and $D_s$ measurements within uncertainties

GM-VFNS for non-prompt $D$ mesons

- “single-” and “two-” step approach $b \rightarrow D + X / b \rightarrow B \rightarrow D$
- Predictions tend to underestimate the data at low and intermediate $p_T$
- Indication of an importance of terms of the factorization approach

Compared with GM-VFNS

D mesons : JHEP 05 (2021) 220

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Ratio of D mesons in pp collisions

**D⁺/D⁰ ratios**
- $\rho_T$-independent in the measured $\rho_T$ range
- Compatible with the FONLL predictions for prompt and non-prompt cases

**D⁺/(D⁰+D⁺)**
- Flat in $\rho_T$ and higher for non-prompt D mesons due to substantial $B_s$-decay contribution
Fragmentation fraction of beauty quarks in pp collisions

**FFs of beauty quarks, \( f_s/(f_u+f_d) \)**

- Obtained from constant fit to \( \text{D}_s/(\text{D}^0+\text{D}^+) \)
- Additional correction to account for
  - Non-prompt \( \text{D}_s \) originating from \( \text{B}^0, \text{B}^+ \)
  - Non-prompt \( \text{D}^0 \) and \( \text{D}^+ \) originating from \( \text{B}_s \)
- Compatible with previous measurements and PYTHIA8

\[
\left( \frac{f_s}{f_u+f_d} \right)_{\text{beauty}} = 0.127 \pm 0.036(\text{stat}) \pm 0.012(\text{syst})
\]
$R_{AA}$ Ratio of D mesons in 0—10% Pb—Pb collisions

- Indication of less suppression of non-prompt D mesons for $4 < p_T < 8$ GeV/c
- Various theoretical calculations describe the measurements within uncertainties
  - Interplay of heavy quark energy loss and hadronization in the medium

Due to charm quark coalescence

**NEW**

- Indication of less suppression of non-prompt D mesons for $4 < p_T < 8$ GeV/c
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Due to charm quark coalescence
\( R_{AA} \) of non-prompt D mesons in 0—10\% Pb—Pb collisions

- \( R_{AA}(D_s)/R_{AA}(D^0) \) ratio is above unity for \( p_T < 8 \text{ GeV}/c \) at low \( p_T \)
  - \( B_s \) production is enhanced by beauty hadronization via coalescence
- Larger \( R_{AA}(B_s)/R_{AA}(B^+) \) ratio w.r.t non-prompt D meson
  - \( D_s \) from non-strange B meson decays → different decay kinematics

TAMU models describe the observed trend
- Implementing coalescence in transport models

\[ \frac{R_{AA}(B_s)}{R_{AA}(B^+)} \] for non-prompt \( D_s \)
- \( 0-10\% \), \(|y| < 0.5\)
- \( 0-100\% \), \(|y| < 2.4\)

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- \( 0-100\% \), \(|y| < 2.4\)

TAMU: Min He et al, PLB 735 (2014) 445—450
CMS: The CMS Collaboration, PLB 796 (2019) 168—190
$R_{pPb}$ of b-jet in p–Pb collisions

- $R_{pPb}$ of b-jet is unity within uncertainties
- Compatible with POWHEG predictions and CMS measurement in the overlapped region
- In the measured $p_T$ range, no visible CNM effect within uncertainties

$R_{AA}$ of $b \rightarrow e$ in Pb–Pb collisions

- Various transport models describe the data within uncertainties
  - Models include different quark energy loss processes and hadronization mechanisms
- Compare to $c,b \rightarrow e$ $R_{AA}$ at the same collision system

MC@sHQ+EPOS2: M. Nahrgang et al, Phys. Rev. C 89 (2014) 014905
Summary and Outlook

- Beauty production via non-prompt D mesons, b-tagged jets, and beauty-decay electrons
- In pp collisions the measurements are in good agreement with pQCD calculations
- In p—Pb collisions no visible CNM effect for b-jets with the current precision
- In Pb—Pb collisions measured $R_{AA}$ below unity
  - Hint of mass dependent in-medium energy loss
  - Insight into heavy-quark hadronization

Outlook

- Upgrade of the ALICE detector during LS 2
  - Electronics for most ALICE sub-detectors
  - New silicon tracking detector (ITS2 based on MAPS tech.)
- Increase luminosity, tracking resolution and efficiency, etc.
- Measurement of B hadrons via full reconstruction
BACKUP
Non-prompt D mesons

- Reconstruct D mesons using invariant mass and secondary vertex from primary vertex

<table>
<thead>
<tr>
<th></th>
<th>$D^0$</th>
<th>$D^+$</th>
<th>$D_s^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay channel</td>
<td>$\rightarrow K^-\pi^+$</td>
<td>$\rightarrow K^-\pi^+\pi^+$</td>
<td>$\rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$</td>
</tr>
<tr>
<td>Branching ratio</td>
<td>$(3.88 \pm 0.05)%$</td>
<td>$(9.13 \pm 0.19)%$</td>
<td>$(2.24 \pm 0.1)%$</td>
</tr>
<tr>
<td>Decay length (ct)</td>
<td>$123,\mu$m</td>
<td>$312,\mu$m</td>
<td>$150,\mu$m</td>
</tr>
</tbody>
</table>

Example of $D^0$

ALICE
pp, $\sqrt{s} = 5.02$ TeV
$D^0 \rightarrow K^-\pi^+$ and charge conj.
$1 < p_T < 2$ GeV/c

Counts per 8 MeV/$c^2$

D$^0$ flight line

$D^0$ reconstructed momentum

$K$

$\theta^*$

pointing angle $\theta_{\text{pointing}}$

primary vertex

$D^0$ flight line

impact parameters $\sim 100\,\mu$m

$K$

$p_T$

$\pi$

$\rightarrow K^-\pi^+$

$103 \pm 15$

$0.95 \pm 0.01$ (stat.) $\pm 0.03$ (syst.)
Non-prompt D mesons

- **BDT (Boosted Decision Trees)** utilizes geometrical variables from decay topology associated to the primary and secondary vertices
  - Suppress combinatorial background
  - Disentangle non-prompt D mesons from inclusive signals
  - Subtract prompt D mesons by exploiting a min-$\chi^2$ approach with BDT cut variation on the raw yield

**Example of $D^0$**

![Graph showing raw yield and $f_{non-prompt}$ distribution for $D^0$ mesons](image)
**b-tagged jet**

**Two distinct b-jet tagging methods**

1) **Impact Parameter (IP)**: distance of closest approach of jet constituents to primary vertex

2) **Secondary Vertex (SV)**: properties of most displaced 3-prong secondary vertex

**b-jet tagging based on impact parameter**

- Impact parameter significance, $S_{d_{xy}} = \delta \cdot d_{xy} / \sigma_{d_{xy}}$
  - $\delta$: sign of the impact parameter
  - $d_{xy}$: impact parameter in xy-plane
  - $\sigma_{d_{xy}}$: impact parameter resolution

- Sorting $S_{d_{xy}}$ in descending order

- b-jets were tagged with following conditions:
  - Second largest impact parameter significance value
  - $S_{d_{xy}} > S_{d_{xy}}^{min}$ ($S_{d_{xy}}^{min} = 2.5$)
**b-tagged jet**

**Two distinct b-jet tagging methods**

1) **Impact Parameter (IP)**: distance of closest approach of jet constituents to primary vertex

2) **Secondary Vertex (SV)**: properties of the most displaced 3-prong secondary vertex (SV)

**b-jet tagging based on secondary vertex (SV)**

- Reconstruct SV inside the jets from 3-prong jet constituents
- Select for b-jet tagging by considering the most displaced SV
- Dispersion of the reconstructed SV, $\sigma_{SV}$:
  \[ \sigma_{SV} = \sqrt{d_1^2 + d_2^2 + d_3^2} \] where $d_{1,2,3}$ are DCA of three tracks to SV
- Significance of the decay length: $SL_{xy} = L_{xy}/\sigma_{L_{xy}}$
  - $L_{xy}$: distance between PV and SV (decay length)
  - $\sigma_{L_{xy}}$: uncertainty of $L_{xy}$ measurements
- b-jet tagging with $SL_{xy} > 7$ and $\sigma_{SV} > 0.03$ cm
Beauty hadrons via semi-leptonic decays

- Beauty production via beauty-hadron decay electrons
  - Substantial branching ratio: ~10%
- Exploit the track impact parameter distribution
  - Sizable decay length \( (c\tau \approx 400–500 \mu m) \) of beauty hadrons → widest IP distribution
- Statistical extraction of beauty-hadron decay electrons using the impact parameter
  - Maximum likelihood approach, Barlow-Beeston, CPC 77(2) 1993

\[
\log L = \sum_{\text{bin}} \text{data(bin)} \cdot \log \text{fit(bin)} - \text{fit(bin)} \\
+ \sum_{\text{bin}} \sum_{\text{source}} N_{\text{source}}(\text{bin}) \cdot \log A_{\text{source}}(\text{bin}) - A_{\text{source}}(\text{bin}) \\
\text{fit(bin)} = \sum_{\text{source}} p_{\text{source}} \cdot A_{\text{source}}(\text{bin})
\]

Likelihood for weighted sum of expectation values to correspond to data
Likelihood for expectation values to correspond to MC templates
Non-prompt $D_s$ mesons in pp collisions at 5.02 TeV

$|y| < 0.5$

$D$ mesons:
- JHEP 05 (2021) 220

$FONLL$:
- JHEP 05 (1998) 007
- JHEP 03 (2001) 006

$PYTHIA8$:
- JHEP 05 (2006) 026
- CPC 191 (2015) 159—177

$GM$-$VFNS$:
- JHEP 12 (2017) 021
Non-prompt D mesons in pp collisions at 5.02 TeV

- Beauty production cross section per rapidity unit at midrapidity as a function of $\sqrt{s}$ described by FONLL and NNLO calculations
- Good agreement with the predictions within uncertainties

From non-prompt D meson measurements

$\frac{d\sigma_{b\bar{b}}}{dy} |y|<0.5 = 34.5 \pm 2.4\text{(stat)}^{+4.7}_{-2.9}\text{(tot. syst)} \mu$b
Non-prompt D mesons in Pb—Pb collisions at 5.02 TeV

First measurements of non-prompt $D^0$ and $D_s$ mesons in Pb—Pb collisions in ALICE
Non-prompt D mesons in Pb—Pb collisions at 5.02 TeV

- $R_{AA}$ of prompt and non-prompt $D^0$ and $D_s$ mesons in 0—10% Pb—Pb collisions at 5.02 TeV
- Provide a hint of mass dependent parton energy loss in the medium: $\Delta E_c > \Delta E_b$
  - Non-prompt $D^0$ $R_{AA}$ > prompt $D^0$ $R_{AA}$ in the intermediate $p_T$
  - Non-prompt $D_s$ > prompt $D^0$ $R_{AA}$ at low $p_T$ region

TAMU : PLB 735 (2014) 445—450
b-jet in pp and pPb collisions at 5.02 TeV

- b-jet production cross section in pp and pPb collisions
- Different methods yield consistent results

![Graphs showing b-jet production cross section](image)

**b-jet**: arXiv:211006104
b-jet production cross section in pp and p—Pb collisions

- Good agreement with POWHEG calculations (based on HF-jet spectra by NLO)
The measured b-jet fraction is consistent with the POWHEG predictions within uncertainties.

Inclusive charged-particle jet cross sections were taken from:

- Phys. Rev. D 100 no.9 (2019) 092004 for pp
- PLB 749 (2015) 68—81 for pPb

\[ b \text{-jet fraction} \]

\[ p_{T, \text{ch jet}} \text{ (GeV/c)} \]

\[ b \text{-jet fraction} \]

\[ p_{T, \text{ch jet}} \text{ (GeV/c)} \]
b-jet in pp and pPb collisions at 5.02 TeV

- Consistent between SV and IP methods for $R_{pPb}$ within uncertainties
- Compatible with POWHEG predictions
  → Insensitive to the CNM effect in pPb collisions

\[
\begin{align*}
\text{ALICE} & \\
p-Pb & \sqrt{s_{NN}} = 5.02 \text{ TeV} \\
\text{Charged b-jets, anti-}k_T, R = 0.4, |\eta_{\text{jet}}| < 0.5
\end{align*}
\]

\[
\begin{align*}
\alpha^{\text{Sys}}_{L_{pPb}} & = 4.37\% \\
\end{align*}
\]

\[
\begin{align*}
\text{POWHEG} & : \text{JHEP 11 (2007) 070} \\
& : \text{JHEP 04 (2011) 081}
\end{align*}
\]
b-jet in pp and pPb collisions at 5.02 TeV

- Both inclusive-jet and b-jet are consistent with unity
  → Mild cold nuclear effect

Cross section of $b \rightarrow e$ in pp collisions

- Cross section of $b \rightarrow e$ in pp collisions
- Compared with FONLL calculation
  - Lying on the upper edge of the prediction
  - Comparable within uncertainties
- Agreement of $b \rightarrow e / b,c \rightarrow e$ with FONLL

\[ \frac{1}{2\pi p_T} \frac{d^2\sigma}{dp_T dy} \]
**b→e in pp and Pb—Pb collisions at 5.02 TeV**

- Comparison of $p_T$-differential yields of $b\rightarrow e$ in pp and Pb—Pb collisions
  - pp reference is scaled by the nuclear thickness function
  - FONLL prediction is used as reference for $p_T > 8$ GeV/c