Beauty Production with ALICE at the LHC

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Motivation

- **Beauty quarks** produced in hard scattering processes in the initial stages of the collisions, before the formation of the QGP.
  - $\tau_b \sim 0.02 < \tau_c \sim 0.07 < \tau_{\text{QGP}} \sim 0.1-1 \text{ fm/c}$
  - Production well controlled and calculable with pQCD $\rightarrow$ **Calibrated probe.**

- Undergoes elastic (collisional) and inelastic (radiational) collisions $\rightarrow$ **sensitive to transport properties of QGP.**

- **Lose less energy in QGP compared to light and charm quarks.**
  - Color charge effects: $\Delta E_{\text{gluons}} > \Delta E_{\text{quarks}}$ due to stronger coupling.
  - Mass effects: $M_{\text{gluons}} < M_{u,d,s} < M_c < M_b$ $\rightarrow$ $\Delta E_{\text{gluons}} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

- Collectivity in QGP.

- Not created or destroyed in the medium $\rightarrow$ **identity is preserved** in the medium, thus tagged up to hadronization.

- **pp collisions:** test pQCD calculations at LHC energies.

- **p-Pb collisions:** isolate initial state and cold nuclear matter effects.
Beauty measurements with ALICE

Central barrel coverage: $|\eta| < 0.9$
Muon spectrometer coverage: $-4 < \eta < -2.5$

Beauty measurements:
- Beauty-decay electrons ($b\to e$)
- Beauty-decay $D^0$ ($b\to D^0 \to K^-\pi^+$) \{non-prompt $D^0$\}
- Beauty-decay $J/\Psi$ ($b\to J/\Psi \to e^+e^-$) \{non-prompt $J/\Psi$\}
- $b$-tagged jets

**Inner Tracker System**
- Trigger
- Primary vertex reconstruction
- Event topology
- Tracking
- PID

**Time of Flight**
- PID

**Electromagnetic Calorimeter**
- Trigger and PID

**Time Projection Chamber**
- Tracking and PID

**VZERO**
- Trigger and event topology

**ZDC**
- Trigger and event topology
**Analysis Procedure**

**Beauty-decay electrons (b → e)**

- Beauty hadrons have longer lifetime than charm and other electron sources.
  - Larger distance of closest approach ($d_0$) w.r.t primary vertex

![Graph](attachment:image.png)

- Monte-Carlo templates of b→e, c→e and other sources
  - Fitted to data to separate different sources.

beauty hadrons $\tau \sim 500 \, \mu m/c$

charm hadrons $\tau < 300 \, \mu m/c$
Analysis Procedure

**Beauty-decay D⁰ (b→D⁰ (→ K⁻π⁺))**

- Reconstruct b→D⁰ using invariant mass of secondary vertices displaced from primary vertex (due to longer lifetime of B decays).
- Use boosted decision trees (BDT) to optimize topological cuts
  - Enhance b→D⁰ fraction and reduce combinatorial background.
- Beauty fraction of the raw yield is obtained by template fit of the BDT cut value.

\[
\frac{d^2\sigma_{b\rightarrow D^0}}{dp_T d\eta} = \frac{f_{b\rightarrow D^0} \times N_{raw}}{\Delta p_T \Delta y BR^{D^0\rightarrow K\pi}(Acc \times \epsilon)_{b\rightarrow D^0}}
\]
Analysis Procedure

Beauty-decay J/ψ (b → J/ψ(→ e⁺e⁻))

- Reconstruct J/ψ through their decay channel J/ψ → e⁺e⁻.
- Fraction of non-prompt J/ψ (b → J/ψ) relies on pseudo-proper decay length (x) from the primary vertex.
- Perform un-binned likelihood fit of 2D distributions of invariant mass mₑₑ- and x on both signal and background.

\[
\begin{align*}
\chi &= \frac{L_p}{c m_{J/\Psi}} \\
\frac{L_p}{c m_{J/\Psi}} &= \frac{p_T}{p_T}
\end{align*}
\]

Fraction of b → J/ψ

\[
f_B = \frac{N_{h_B \rightarrow J/\Psi}}{N_{h_B \rightarrow J/\Psi} + N_{\text{prompt } J/\Psi}}
\]
Analysis Procedure

b-Tagged Jets

- Select jets containing displaced secondary vertex (SV) or minimum \(N\) tracks with large impact parameter.
- Jets reconstructed with Anti-\(k_T\) algorithm, \(R = 0.4\)
- Apply topological cuts to increase b-jet fraction
  - Method 1: Significance of the SV displacement - \(SL_{xy} = L_{xy}/\sigma_{L_{xy}} > \alpha\)
  - Method 2: Minimum no. of tracks in a jet with \(d_{xy} > d_{xy}^{\text{threshold}}\)
- Fraction of b-jets (Purity) obtained using Monte-Carlo templates fit to data.

\[
dN_{b\text{-jet}}(p_{T,jet}^{ch,reco}) = dN_{rav}(p_{T,jet}^{ch,reco}) \times \frac{P_b}{\epsilon_b} = \frac{N_b \epsilon_b}{N_b \epsilon_b + N_c \epsilon_c + N_{LF} \epsilon_{LF}}
\]

\[
\epsilon_{c,b,LF} = \text{Efficiency from MC}
\]
Results

- **pp collisions**
  - $\sqrt{s} = 5.02, 13$ TeV
  - $b \rightarrow e$ cross-section
  - $b \rightarrow D^0$ (non-prompt $D^0$) cross-section
  - $b \rightarrow J/\Psi$ cross-section
  - $b$-tagged jet cross-section

- **p-Pb collisions**
  - $\sqrt{s_{NN}} = 5.02$ TeV
  - $b \rightarrow J/\Psi$ cross-section
  - $b$-tagged jet cross-section
  - $R_{pPb}$ of $b$-tagged jets

- **Pb-Pb collisions**
  - $\sqrt{s_{NN}} = 5.02$ TeV
  - $R_{AA}$ of $b \rightarrow e$ (2015 data), $b \rightarrow D^0$ (2018 data)
  - $v_2$ of $b \rightarrow e$

*new for QM

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QM 2019
• $b\rightarrow e$ and $b\rightarrow D^0$ cross-section measured in pp at $\sqrt{s} = 5.02$ TeV
  • $b\rightarrow e$: $2 < p_T < 8$ GeV/c
  • $b\rightarrow D^0$: $1 < p_T < 24$ GeV/c

• Measurement described by FONLL calculations within uncertainties $\rightarrow$ lie on the upper edge of FONLL.
• **b→J/Ψ cross-section measured in pp at** $\sqrt{s} = 13$ TeV for $1 < p_T < 13$ GeV/c $\rightarrow$ **described by FONLL.**

• First ALICE measurement of b-tagged jet cross-section measured in pp at $\sqrt{s} = 5.02$ TeV for $5 < p_T < 100$ GeV/c.

• Data well described by different POWHEG +PYTHIA8 simulations within uncertainties (HVQ and Dijet).
• **b-tagged jet cross-section and** $R_{pPb}$ **measured in p-Pb collisions at** $\sqrt{s_{NN}} = 5.02$ TeV **for** $15 < p_T < 90$ GeV/c.

• **Data well described by different POWHEG simulations within uncertainties** (HVQ and Dijet)

• **$R_{pPb}$ consistent with unity within uncertainties in the measured $p_T$ range.**
  • ALICE measurement consistent with CMS in the overlapping $p_T$ range of $50 < p_T < 100$ GeV/c.
Nuclear modification factor measured for $b \rightarrow e$ in 0-10% and 30-50% Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

$R_{AA}$ of $b \rightarrow e$

- Suppression of beauty-decay electrons observed.

- Comparison of $b \rightarrow e$ with $c,b \rightarrow e$
  - Hint of beauty quarks undergoing less energy loss than charm quarks at low $p_T$.
  - At high $p_T$: $b \rightarrow e$ and $b,c \rightarrow e$ overlap as beauty decays dominate at high $p_T$.

- Measurement well described by models that include both collisional and radiative energy loss.

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$R_{AA}$ of $b \rightarrow e$

\[
R_{AA} = \frac{dN_{AA}/dp_T}{<T_{AA}> d\sigma_{pp}/dp_T}
\]

ALICE Preliminary
Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
30–50% centrality

$\bullet$ $R_{AA}$ of $b \rightarrow e$ in 30-50% Pb–Pb collisions.

$\bullet$ Comparison of $b \rightarrow e$ with $c, b \rightarrow e$

$\bullet$ Hint of beauty quarks undergoing less energy loss than charm quarks at low $p_T$.

$\bullet$ $R_{AA}$ (0-10%) < $R_{AA}$ (30-50%) for $4 < p_T < 8$ GeV/c.
\[ R_{AA} = \frac{dN_{AA}/dp_T}{<T_{AA}> \cdot d\sigma_{pp}/dp_T} \]

- **Nuclear modification factor measured for** \( b\to D^0 \) **in 0-10% and 30-50% Pb-Pb collisions at** \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
  
  \( \rightarrow \) **Suppression of** \( b\to D^0 \) **observed.**

- **Comparison of** \( b\to D^0 \) **with prompt** \( D^0 \)
  
  - **Beauty quarks undergoes less energy loss than charm quarks at intermediate** \( p_T \).

- **\( R_{AA} \) (0-10%) < \( R_{AA} \) (30-50%) at intermediate** \( p_T \).
$R_{AA}$ of $b \rightarrow D^0$

- Ratio of the $R_{AA}$ of non-prompt to prompt $D^0$
  - $p_T < 5 \text{ GeV/c}$: bumpy structure $\rightarrow$ different effects of flow and shadowing on $c$ and $b$ quarks affecting the kinematics?
  - $p_T > 5 \text{ GeV/c}$: beauty quarks undergo less suppression than charm quarks.

- Theoretical models that include collisional and radiational energy loss describe the data well within uncertainties.
Collective flow

\[ v_2 = \langle \cos[2(\phi - \Psi_2)] \rangle \]

- **Non-zero** \( v_2 \) for \( b \to e \)
  - Significance of 3.49 \( \sigma \) for \( 1.3 < p_T < 4 \) GeV/c.
$v_2 = <\cos[2(\phi - \Psi_2)]>$

**$v_2$ vs $p_T$, 20-40% Pb-Pb**

- **ALICE Preliminary**
- $20-40\%$ Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- $b (\rightarrow c) \rightarrow e$, $|y|<0.8$

**$v_2$ vs $p_T$, 5-60% Pb-Pb**

- **ALICE Pb–Pb** $\sqrt{s_{NN}} = 5.02$ TeV
- $2.5 < y < 4$
- **Inclusive J/$\Psi$**
- **$\Upsilon$(1S)**
- **$\Upsilon$(1S), TAMU model**
- **$\Upsilon$(1S), BBJS model**

- **Non-zero $v_2$ for $b\rightarrow e$**
  - Significance of 3.49 $\sigma$ for $1.3 < p_T < 4$ GeV/$c$.
  - **Model describes the data well at high $p_T$.**

- **Open-beauty $v_2 > 0$, while bottomonia $v_2 \sim 0$**
  - **$Y$ $v_2 \sim 0$ vs. $p_T$ and collisional centralities.**
  - Impact of path-length dependent energy loss and coalescence on $b\rightarrow e$?
Summary & Conclusions

• Beauty production studied in pp, p-Pb and Pb-Pb collisions with the ALICE detector.

• pp collisions:
  • Production cross-section of b->e, b->D⁰ and b-tagged jets well described by pQCD calculations (FONLL, POWHEG).

• p-Pb collisions:
  • Production cross-section of b-tagged jets well by POWHEG simulations.
  • $R_{pPb}$ of b-tagged jets consistent with unity.

• Pb-Pb collisions:
  • Beauty quarks undergoes energy loss $\rightarrow$ less suppression than charm quarks at intermediate $p_T$.
  • Measurements described by models that include collisional and radiative energy loss.
  • Non-zero $v_2$ of beauty-decay electrons $\rightarrow$ beauty $v_2 > 0$?
b→J/Ψ in p-Pb

**b→J/Ψ vs p_T**

- ALICE, -1.37 < y_{CMS} < 0.43 (Preliminary)
- ATLAS, -1.94 < y_{CMS} < 0 (Phys. Rev. C 92 (2015) 034904)
- FONLL + EPPS16
- EPPS16 unc.

**R_{pPb} of b→J/Ψ**

- ALICE, -1.37 < y_{CMS} < 0.43 (Preliminary)
- CMS, -0.9 < y_{CMS} < 0 (EPJ C 77 (2017) 269)
- FONLL + EPPS16

**b→J/Ψ vs y**

- ALICEx extr. unc.

- ALICE (Preliminary)
- LHCb (JHEP 02 (2014) 072)
- FONLL + EPPS16
- EPPS16 unc.

CMS, -0.9 < y_{CMS} < 0 (EPJ C 77 (2017) 269)
$R_{AA}$ of $b \rightarrow D^0$

Models describe the data within their uncertainties.

TAMU: PLB 735 (2014) 445
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: arXiv:1901.04600; 1805.05807
CUJET3: arXiv:1411.3673; 1508.00552; 1804.01915; 1808.05461

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$R_{AA}$ of $b \rightarrow D^0$

**Graph 1:**
- **Title:** ALICE Preliminary
- **Legend:**
  - Non-prompt $D^0$
  - Prompt $D^0$
  - CMS $J/\psi$ from $b$, $|y|<2.4$ 0-10%, $l_y<0.5$
- **Data:**
  - Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
  - 0-10%, $|y|<0.5$

**Graph 2:**
- **Title:** ALICE Preliminary
- **Legend:**
  - Non-prompt $D^0$
  - Prompt $D^0$
  - CMS $J/\psi$ from $b$, $|y|<2.4$ 30-100%, $l_y<0.5$
- **Data:**
  - Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
  - 30-50%, $|y|<0.5$

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