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 QGP.
  - $\tau_b \sim 0.02 < \tau_c \sim 0.07 < \tau_{QGP} \sim 0.1-1 \text{ fm/c}$
  - Production well controlled and calculable with pQCD —> **Calibrated probe.**

- Undergoes elastic (collisional) and inelastic (radiational) collisions —> **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: $M_{\text{gluons}} < M_{u,d,s} < M_{c} < M_{b}$ —> $\Delta E_{\text{gluons}} > \Delta E_{u,d,s} > \Delta E_{c} > \Delta E_{b}$

- Collectivity in QGP.

- Not created or destroyed in the medium —> **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 ($b\rightarrow e$)
- Beauty-decay $D^0$ ($b\rightarrow D^0 (\rightarrow K^+\pi^-))$ {non-prompt $D^0$}
- Beauty-decay $J/\Psi$ ($b\rightarrow J/\Psi (\rightarrow e^+e^-))$ {non-prompt $J/\Psi$}
- $b$-tagged jets

Time of Flight
- PID

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

Electromagnetic Calorimeter
- Trigger and PID

VZERO
- Trigger and event topology

Time Projection Chamber
- Tracking and PID

ZDC
- Trigger and event topology
Beauty-decay electrons ($b \rightarrow e$)

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

Monte-Carlo templates of $b \rightarrow e$, $c \rightarrow e$ 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.

\[
f_{b\rightarrow D^0} = \frac{N_b\epsilon_b}{N_c\epsilon_c + N_b\epsilon_b}
\]

\[
d^2\sigma_{b\rightarrow D^0} \over dp_Td\eta = \frac{f_{b\rightarrow D^0} \times N_{raw}}{\Delta p_T\Delta y BR_{D^0\rightarrow K\pi}(Acc \times \epsilon)_{b\rightarrow D^0}}
\]
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 m_{e⁺e⁻} and x on both signal and background.

\[ f_B = \frac{N_{h_B \to J/Ψ}}{N_{h_B \to J/Ψ} + N_{\text{prompt } J/Ψ}} \]

\[ x = \frac{\hat{L} \cdot \vec{p}_T}{c \cdot m_{J/Ψ}} \]

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ALICE Preliminary
\( p\bar{p}, \sqrt{s} = 13 \text{ TeV} \)
\( p_T > 1 \text{ GeV/c} \)

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### 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 $d_{xy} > d_{xy}^{threshold}$
- Fraction of b-jets (Purity) obtained using Monte-Carlo templates fit to data.

#### Displaced SV method

\[
dN_{b\rightarrow jet}(p_{T, jet}^{ch, reco}) = dN_{raw}(p_{T, jet}^{ch, reco}) \times \frac{P_b}{\epsilon_b}
\]

\[
P_b = \frac{N_b \epsilon_b}{N_b \epsilon_b + N_c \epsilon_c + N_{LF} \epsilon_{LF}}
\]

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

- pp collisions
  - $\sqrt{s} = 5.02, 13\ \text{TeV}$
  - $b\rightarrow e$ 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
  - $\sqrt{s_{\text{NN}}} = 5.02\ \text{TeV}$
  - $b\rightarrow J/\Psi$ cross-section
  - $b$-tagged jet cross-section
  - $R_{pPb}$ of $b$-tagged jets

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

*new for QM
b→e & b→D^0 cross-section measured in pp at $\sqrt{s} = 5.02$ TeV

- b→e: $2 < p_T < 8$ GeV/c
- b→D^0: $1 < p_T < 24$ GeV/c

Measurement described by FONLL calculations within uncertainties — 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 → 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.
\( R_{AA} \) of \( b \rightarrow e \)

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

**Nuclear modification factor measured for \( b \rightarrow e \) in 0-10\% and 30-50\% Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV —> 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 $b \rightarrow e$**

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

- $R_{AA}$ of $b \rightarrow e$ in 30-50% Pb-Pb collisions.
- Comparison of $b \rightarrow e$ with $c, b \rightarrow e$
  - Hint of beauty quarks undergoing less energy loss than charm quarks at low $p_T$.
- $R_{AA}$ (0-10%) < $R_{AA}$ (30-50%) for $4 < p_T < 8$ GeV/c.
$R_{AA}$ of $b\to D^0$

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

ALICE Preliminary

Non-prompt $D^0$

Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
0-10%, $|y|<0.5$

Non-prompt $D^0$

0

Prompt $D^0$

0

$0-10%$

$b\to D^0$

Prompt $D^0$

$30-50%$

$b\to D^0$

Prompt $D^0$

- Nuclear modification factor measured for $b\to D^0$ in 0-10% and 30-50% Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV —> 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 $p_T$. 

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

- **Ratio of the $R_{AA}$ of non-prompt to prompt $D^0$**
  - $p_T < 5$ GeV/c: bumpy structure $\rightarrow$ different effects of flow and shadowing on $c$ and $b$ quarks affecting the kinematics?
  - $p_T > 5$ 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.**
\[ v_2 = < \cos[2(\phi - \Psi_2)] > \]

**Non-zero \( v_2 \) for \( b \to e \)**

- Significance of 3.49 \( \sigma \) for \( 1.3 < p_T < 4 \text{ GeV/c} \).
Collective flow

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

\[ v_2 \text{ vs } p_T, \text{ 20-40\% Pb-Pb} \]

\[ v_2 \text{ vs } p_T, \text{ 5-60\% Pb-Pb} \]

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

- Open-beauty \( v_2 > 0 \), while bottomonia \( v_2 \sim 0 \)
  - \( \Upsilon \) \( v_2 \sim 0 \) 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 $b \to e$, $b \to D^0$ and b-tagged jets well described by pQCD calculations (FONLL, POWHEG).

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

- **Pb-Pb collisions:**
  - Beauty quarks undergo 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 $v_2 > 0$?
Back-up
Total cross-section of $b \rightarrow J/\Psi$

$b \rightarrow J/\Psi$ vs $y$

**Non-prompt $J/\Psi$, $p_T > 0$**

- ALICE (preliminary)
- LHCb [JHEP 10, 172 (2015)]
b→J/Ψ in p-Pb

\[ \sigma(p-Pb) = 5.02 \text{ TeV} \]

**b→J/Ψ vs \( p_T \)**

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

**b→J/Ψ vs \( y \)**

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

**\( R_{pPb} \) of b→J/Ψ**

- ALICE, -1.37 < \( y_{\text{cms}} \) < 0.43 (Preliminary)
- CMS, -0.9 < \( y_{\text{cms}} \) < 0 (EPJ C 77 (2017) 269)
- FONLL + EPPS16
$R_{AA}$ of $b \to D^0$

Models describe the data within their uncertainties.
$R_{AA}$ of $b \rightarrow D^0$

**ALICE Preliminary**

Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV

- **Non-prompt $D^0$**
- **Prompt $D^0$**
- CMS $J/\psi$ from b, $|y|<2.4$ 0-10%

**0-10%**

- Non-prompt $D^0$
- Prompt $D^0$
- CMS $J/\psi$ from b, $|y|<2.4$ 0-10%


**30-50%**

- Non-prompt $D^0$
- Prompt $D^0$
- CMS $J/\psi$ from b, $|y|<2.4$ 30-100%