Beauty production in heavy-ion collisions with ALICE at the LHC

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Heavy flavours in the QGP

- Quantum chromodynamics calculations on lattice predict phase transition from ordinary nuclear matters to colour-deconfined medium: quark–gluon plasma (QGP)
  - ultrarelativistic heavy-ion collisions
  - high energy-density $\varepsilon > 15$ GeV/fm$^3$

- Heavy flavours (i.e. b and c quarks) produced in hard scattering processes during first stages of the collision
  - $\tau_b < \tau_c < \tau_{QGP} \sim 1$ fm/c
  - probe the full system evolution

Heavy flavours interaction in the QGP

- HF propagate in the QGP with a Brownian motion
  - interact with medium constituents
  - lose energy via elastic collisions and radiative processes
    → in-medium energy-loss mass dependence
  - heavy-quark thermalisation in the QGP?
Heavy flavours hadronisation in the QGP

- **HF hadronisation in the QGP**
  - **Fragmentation** \( (D_{q\rightarrow h}(z_q, Q^2)) \)
    - partons energy-loss traversing QGP modifies \( z_q \) taken by the hadron

- **Coalescence**
  - partons sharing velocity/position recombine into hadrons
Heavy flavours hadronisation in the QGP

- HF hadronisation in the QGP
  - Fragmentation ($D_q \rightarrow h(z_q, Q^2)$)

Beauty measurements in this talk:

**Beauty decay electron** ($b \rightarrow e$)

**Non-prompt D** ($b \rightarrow D^0, D_s^+$) in hadronic decay ($K^-\pi^+, K^+K^-\pi^+$)

- 2015 Pb–Pb 5.02 TeV: $L^{int} \sim 13 \mu b^{-1}$
- 2018 Pb–Pb 5.02 TeV: (0-10%) $L^{int} \sim 130 \mu b^{-1}$
  - (30-50%) $L^{int} \sim 56 \mu b^{-1}$

⇒ partons sharing velocity/position recombine into hadrons
Analysis strategy: beauty-decay electrons

- **Large BR** in semileptonic decay
  \[ b \rightarrow e + X (\sim 10\%) , \ b \rightarrow c \rightarrow e + X (\sim 10\%) \]

- longer lifetime than c-quark and other electron sources
  \[ \tau_b \sim 500 \mu m/c; \ tau_c \sim 60-300 \mu m/c \]
  - larger impact parameter \(d_0\) w.r.t primary vertex

- yield obtained with **template fit on impact parameter distributions**
Analysis strategy: non-prompt D mesons ($D^0, D_s$)

- Large amount of combinatorial background
  - Machine Learning (ML) multiclass classification to enhance $b \to D$ contribution and reject combinatorial background
  - **Signal** from invariant mass fit
  - $b \to D$ fraction obtained via data-driven approach based on ML-based selection variation

**ALICE**

$0-10\% \text{ Pb-Pb, } \sqrt{s_{NN}} = 5.02 \text{ TeV}$

$D_s^+ \to \phi \pi^+ \to K^+ K^- \pi^+ \text{ and charge conj.}$

$4 < p_T < 6 \text{ GeV/c}$

$\mu = (1971 \pm 1) \text{ MeV/c}^2$

$\sigma = 10 \text{ MeV/c}^2$

$S = 789 \pm 73$

$f_{\text{non-prompt}} = 0.73 \pm 0.03 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$

Counts per 8 MeV/c$^2$
b-quark $R_{AA}$ can be studied via leptonic and hadronic decays

ALICE Preliminary
0–10% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV

- $c, b \rightarrow e$
- $b \rightarrow c \rightarrow e$


beauty quark $R_{AA}$ suppression

$\Rightarrow$ Hint of $R_{AA}$ (charm-hadron) < $R_{AA}$ (beauty-hadron) at low $p_T$
Non-prompt $D^0$ nuclear modification factor ($R_{AA}$)

- $R_{AA}$ (non-prompt D) $> R_{AA}$ (prompt D) at intermediate $p_T$
  - integrated $R_{AA}$:
    
    \[ R_{AA}^{\text{prompt}} (0–10\%) = 0.689 \pm 0.054 \]  
    (stat.)$^{+0.104}_{-0.106}$ (syst.)
    
    \[ R_{AA}^{\text{non-prompt}} (0–10\%) = 1.00 \pm 0.10 \]  
    (stat.)$^{+0.15}_{-0.10}$ (syst.)$^{+0.08}_{-0.09}$ (extr.)$^{+0.02}_{-0.02}$ (norm.)
  - compatible within less than 1.5σ
    
    ➞ different shadowing or hadronisation via coalescence?

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

0–10%, $|y| < 0.5$

- blue: non-prompt $D^0$
  - red: prompt $D^0$
  
open markers: $p_T$ extrapolated pp reference

NEW

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SQM 2022, Busan 14/06/2022
Non-prompt over prompt $D^0 R_{AA}$ ratio

- $R_{AA}$ (non-prompt D) / $R_{AA}$ (prompt D) ratio comparison with models

**Figure Description**

- **Plotted Data and Models**
  - ALICE data for Pb-Pb collisions with $\sqrt{s_{NN}} = 5.02$ TeV, $0-10\%$, $|y| < 0.5$
  - TAMU, LGR, MC@sHQ+EPOS2, CUJET3.1

- **Graph Axes**
  - $p_T$ (GeV/c)
  - $R_{AA}$ (non-prompt) / $R_{AA}$ (prompt)

**New Data Point**

- NEW

**References**

- LGR: EPJC 80, no.7, (2020) 671
- TAMU: PLB 735 (2014) 445-450
- CUJET3.1: JHEP 02(2016) 169
- MC@sHQ+EPOS2: PRC 89 (2014) 014905

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Non-prompt over prompt $D^0 R_{AA}$ ratio

- $R_{AA}$ (non-prompt D) / $R_{AA}$ (prompt D) ratio
- comparison with models
  - both collisional and radiative energy loss mechanisms important to describe data
  - low $p_T$ (< 5 GeV/c): pattern hints difference in shadowing / flow / coalescence
  - high $p_T$ (> 5 GeV/c): $3.9\sigma$ above unity → beauty less suppressed than charm

Data points and model predictions for $R_{AA}$ vs. $p_T$ (GeV/c) are shown, with a focus on the ratio of non-prompt to prompt $D^0$ yield in heavy-ion collisions at a center-of-mass energy of 5.02 TeV. The plot includes contributions from various models and data sets:

- LGR: EPJC 80, no.7, (2020) 671
- TAMU: PLB 735 (2014) 445-450
- MC@sHQ+EPOS2: PRC 89 (2014) 014905

The $p_T$ distribution is divided into two regions:
- Low $p_T$ (< 5 GeV/c): shows a pattern that hints at differences in shadowing, flow, and coalescence mechanisms.
- High $p_T$ (> 5 GeV/c): exhibits a $3.9\sigma$ above unity suppression pattern, indicating that beauty is less suppressed than charm.

Reference:
- S. Politano (PoliTO) stefano.politano@cern.ch
- ALICE EPJC 80 no.12, (2020) 1113
Non-prompt over prompt $D^0 R_{AA}$ ratio

- $R_{AA}$ (non-prompt D) / $R_{AA}$ (prompt D) ratio comparison with models
  - both collisional and radiative energy loss mechanisms important to describe data
  - low $p_T$ (< 5 GeV/c): pattern hints difference in shadowing / flow / coalescence
  - high $p_T$ (> 5 GeV/c): 3.9σ above unity → beauty less suppressed than charm

- Testing LGR ingredients effect
  - “valley” structure $p_T < 5$ GeV/c
    - charm coalescence (iv)
  - enhancement for $p_T > 5$ GeV/c
    - mass dependent quark in-medium energy loss effect (i)
Central collisions (0–10%)

- central values higher w.r.t those of prompt $D_s$,
and non-prompt $D^0 R_{AA}$ for $p_T < 6$ GeV/c, though compatible within uncertainties

→ interplay of different energy loss and recombination btw. charm and beauty
Non-prompt $D_s^-$ $R_{AA}$

- Central collisions (0–10%)
  - central values higher w.r.t those of prompt $D_s^+$ and non-prompt $D^0 R_{AA}$ for $p_T < 6 \text{ GeV/c}$, though compatible within uncertainties
  - interplay of different energy loss and recombination btw. charm and beauty

- Semicentral collisions (30–50%)
  - no sizeable medium-induced effect
Non-prompt $D_s$ $R_{AA}$ ratios

- Non-prompt/prompt $R_{AA} D_s$ and non-prompt $R_{AA} D_s/D^0$ show hint of enhancement
  - $1.6\sigma$ ($1.7\sigma$) at $4 < p_T < 12$ GeV/c in 0–10%
    - $\Rightarrow$ coalescence + strangeness enhancement
  - TAMU qualitatively describes the result in 0–10%
Non-prompt D⁰ v₂

- Non-prompt D⁰ show non-zero v₂
  - 2.7σ significance for 2 < pₜ < 12 GeV/c
  - beauty partially thermalizes in the medium and/or recombines with light quarks
- 3.2σ btw non-prompt D⁰ and prompt non-strange D meson in 2 < pₜ < 8 GeV/c
  - charm and beauty quarks participate differently to collective motion
Beauty elliptic flow $v_2$

- Non-prompt D$^0$ show non-zero $v_2$
  - 2.7σ significance for $2 < p_T < 12$ GeV/c
    - beauty partially thermalizes in the medium and/or recombines with light quarks
  - 3.2σ btw non-prompt D$^0$ and prompt non-strange D meson in $2 < p_T < 8$ GeV/c
    - charm and beauty quarks participate differently to collective motion
- Model describe data within uncertainties
  - compatible $b \rightarrow e$ and non-prompt D$^0$ $v_2$
Constrain of beauty spatial diffusion coefficient

Constrain b-quark spatial diffusion coefficient comparing $v_2$ and $R_{AA}$ simultaneously

- More precise measurements of exclusive beauty decay needed
Summary

- Beauty quarks undergo **energy loss in the medium** → important constraint of mass dependence energy loss
- Measurements described by models that include **collisional and radiative energy loss**
- **Strange non-prompt D meson** $R_{AA}$ provides insights into beauty quarks hadronisation via coalescence
- Different non-prompt and prompt $D^0 v_2$
  - different degree of **participation to collective motion** and hadronisation between charm and beauty
- Beauty-strange meson and beauty-baryon production and azimuthal anisotropy measurements in **Run 3**
ADDITIONAL SLIDES
Analysis strategy: beauty-decay electrons

- $v_2$ measured with the Event-Plane (EP) method
  
  - computation of event-plane angle
    \[ \psi_n = \frac{1}{n} \tan^{-1} \left( \frac{Q_{n,y}}{Q_{n,x}} \right) \]
    where
    \[ Q_n = \left( \sum_{k=0}^{N_{\text{tracks}}} \cos(n\varphi_k), \sum_{k=0}^{N_{\text{tracks}}} \sin(n\varphi_k) \right) \]

  - Yield extracted:
    - in-plane ($(7\pi/4, \pi/4] \cup (3\pi/4, 5\pi/4]$)
    - out-of-plane ($(\pi/4, 3\pi/4] \cup (5\pi/4, 7\pi/4]$)

  \[ v_2 = \frac{\pi}{4R_2} \frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}} \]
Analysis strategy: non-prompt D mesons ($D^0$, $D_s$)

- Large amount of combinatorial background

  - Machine Learning (ML) multiclass classification to enhance $b \to D$ contribution and reject combinatorial background

  - **Signal** from invariant mass fit

  - **$b \to D$ fraction** obtained via data-driven approach based on ML-based selection variation

  - $v_2^{\text{non-prompt}}$ obtained by linear fitting of $v_2^{\text{obs.}}$ vs. $f_2^{\text{non-prompt}}$, and extrapolate to $f_2^{\text{non-prompt}} = 1$

**ALICE Preliminary**

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

$D^0 \to K^- \pi^+$ and charge conj.

$3 < p_T < 4$ GeV/c
Data driven method for D meson fraction

- Define $n$ sets of ML-based selections with different prompt and non-prompt D-meson contributions

![Graph showing Acceptance x efficiency vs. ML based selection]

**Non-prompt D**

**Prompt D**

*ALICE Performance*

$pp$, $\sqrt{s} = 5.02$ TeV

$8 < p_T < 10$ GeV/c

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Define \( n \) sets of ML-based selections with different prompt and non-prompt D-meson contributions

For each ML-based selection raw yield and efficiencies are related to the corrected yields of prompt and non-prompt D mesons

\[ \epsilon^i_P \cdot N_P + \epsilon^i_{NP} \cdot N_{NP} = Y^i \]

- overdetermined algebraic system obtained
- solvable in approximated way
- \( f_{NP} \) obtained from the approximated solution

\[ f_{NP}^i = \frac{\epsilon^i_{NP} N_{NP}}{\epsilon^i_{NP} N_{NP} + \epsilon^i_P N_P} \]
D⁰ nuclear modification factor ($R_{AA}$)

- $R_{AA}$ (non-prompt D) > $R_{AA}$ (prompt D)
  - in-medium mass-dependent energy loss
  - dead cone effect: gluon radiation suppressed for small angles ($\theta < m_q/E$)
  - direct observation of dead cone effect with D⁰-tagged jets in pp collisions

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

- 0–10%, $|y| < 0.5$
  - blue: non-prompt D⁰
  - red: prompt D⁰

open markers: $p_T$, extrapolated pp reference

Non-prompt D⁰: arXiv: 2202.00815
Prompt D⁰: JHEP 01 (2022) 174

Antonio Carlos Oliveira Da Silva
14 Jun 2022, 14:20
Time Projection Chamber:
- Track reconstruction
- Particle Identification (PID) via specific energy loss

Time Of Flight detector:
- PID via time-of-flight measurements

Electromagnetic Calorimeter
- PID via energy deposited
- Trigger

Inner Tracking System
- Track reconstruction
- Primary and decay vertices reconstruction

V0 detectors
- Trigger
- Centrality determination
- Event-plane estimation
ALICE in Run 3... and beyond

- ALICE upgrade for LHC Run 3 and 4 crucial for HF
  - increase collected Pb-Pb luminosity by more than one order of magnitude
  - new silicon Inner Tracking System (ITS)
    - Run 3: ITS2 (TDR: CERN-LHCC-2013-024)
    - Run 4: ITS3 (CERN-LHCC-2019-018 ; LHCC-I-034)
    - Run 5: all silicon ultra-light detector (ALICE 3)