Measurements of heavy-flavour hadron production with ALICE at the LHC

Cristiane Jahnke for the ALICE Collaboration
Universidade de São Paulo
Collision systems

● **Pb–Pb collisions:**
  ○ In-medium energy loss
  ○ Colour-charge and quark-mass dependence
  ○ Thermalisation of heavy-quarks in the medium
  ○ Quarkonium dissociation and/or regeneration

● **p–Pb collisions:**
  ○ Cold nuclear matter effects can be studied:
    ■ Nuclear modification of parton densities
      ● Collinear PDFs or saturation description
    ■ Propagation in nucleus and in medium
    ■ Secondary quarkonium interaction

● **pp collisions:**
  ○ Reference for studies with p–Pb collisions and Pb–Pb collisions
  ○ Test of QCD calculations

● **pp and p–Pb collisions:**
  ○ Look for possible collective behaviour in small systems
Why to study heavy quarks?

- Heavy-flavour particles contain charm or beauty quarks:
  - ✔ Quarkonium: $J/\psi$, $\psi(2S)$, $Y(1S)$, $Y(2S)$, $Y(3S)$
  - ✔ Open heavy-flavour: $B$ meson, $D$ meson, $\Lambda_c$, $\Lambda_b$, $\Sigma_c$ and $\Xi_c$

- Charm and beauty are produced (in hard scatterings) in the early stages of the collision:
  - ✔ Large mass ($m_{c,b} \gg \Lambda_{QCD}$)
    - short formation time
    - hard probes, even at low $p_T$

- Charm and beauty can experience the full evolution of the system:
  - ✔ They live much longer than the duration of the quark-gluon plasma (QGP)

- Quarkonium melting as a signature of QGP
  - ✔ Quarkonium destruction in a QGP by Debye screening: melted if $r > \lambda_D$
    (Matsui & Satz, PLB178 (1986) 416)

- Regeneration
How to study heavy quarks?

- Reconstruction via hadronic decays:
  - Prompt and non-prompt D meson reconstruction
    \[
    \Lambda_c^+ \rightarrow p K_s^0
    \]
    \[
    \Lambda_c^+ \rightarrow p K^- \pi^+
    \]

- Semileptonic decays (electrons and muons): branching ratio of the order of 10%:
  - B, D → l + X
  - Separation of electrons from beauty-hadron decays using the impact parameter (long life time of beauty hadrons).
    - At high \( p_T \), it is expected that most of the leptons are from beauty-hadron decays (B).

- Quarkonium via dielectron or dimuon pairs
  - Prompt production
  - B → J/ψ (mid-rapidity)
How to study heavy quarks?

The nuclear modification factor

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

- If \( R_{AA} = 1 \) (at high \( p_T \)): no hot medium effects and no cold nuclear matter effects.
- If \( R_{AA} < 1 \) (at high \( p_T \)): energy loss and/or cold nuclear matter effects.
- Energy loss is expected to depend on the parton colour-charge, parton mass and path length.

\[ \Delta E(\pi^\pm) > \Delta E(D) > \Delta E(B) \quad R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B) \]

Anisotropic flow

\[ E \frac{d^3N}{dp_T^3} = \frac{d^3N}{p_T d\phi dp_T dy} \sum_{n=0}^{\infty} 2v_n \cos[n(\phi - \Phi_R)] \]

- Anisotropic flow is caused by the initial asymmetries in the geometry of the system produced in a non-central collision.
  - Initial spatial anisotropy of the created particles is converted in momentum anisotropy due to the pressure gradients.
- \( v_2 \): indicates collective motion and thermalization
- \( v_3 \): event-by-event fluctuations

Mid-rapidity ($|\eta| < 0.9$):
- ElectroMagnetic Calorimeter
- Time of Flight
- Transition radiation detector
- Time Projection Chamber
- Inner Tracking System

Forward rapidity ($-4 < \eta < -2.5$)
- Muon tracking
Results in Pb–Pb collisions
Strong suppression of open heavy-flavour particles in Pb–Pb collisions

Mass ordering:
- $R_{AA}(\pi) < R_{AA}(D)$ ($p_T < 10$ GeV/$c$)
- $R_{AA}(c\to D) < R_{AA}(b\to D)$ ($4 < p_T < 10$ GeV/$c$)
- Hint of $R_{AA}(c,b\to e) < R_{AA}(b\to e)$ at low $p_T$

$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$
Open heavy-flavour $R_{AA}$

Model comparisons

- Models including collisional (POWLANG, BAMPS el., TAMU) and collisional+radiative energy loss (BAMPS el.+rad., LIDO, PHSD, Catania, MC@sHQ+EPOS2, Djordjevic) can describe the suppression at high $p_T$ (at least qualitatively).
- Models: TAMU, POWLANG, PHSD, MC@sHQ, LIDO and Catania include quark recombination.
Centrality dependence

- Weaker suppression at higher collision energy
  - Effect predicted by regeneration models
- Models including charm-quark regeneration are in good agreement with the data in both mid- and forward-rapidity
  - **TM1** and **TM2**: includes dissociation and regeneration in QGP and hadronic phase
  - **Comovers**: suppression via comovers interactions and includes regeneration
  - **SHM**: charmed particles are generated at chemical freeze-out

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**ALICE, Pb-Pb, √sNN = 5.02 TeV**

- Inclusive J/ψ, |y| < 0.9
- \( p_T > 0.15 \text{ GeV/c} \)

**ALICE Preliminary**

\[ \frac{dN_{\text{ch}}}{d\eta} \] at \( \eta = 0 \)

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**ALICE, Pb-Pb, √sNN = 5.02 TeV**

- Inclusive J/ψ → μ⁺μ⁻
- \( 2.5 < y < 4, 0.3 < p_T < 8 \text{ GeV/c} \)

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**ALICE, Pb-Pb, √sNN = 5.02 TeV**

- Inclusive J/ψ, |y| < 0.9
- \( p_T > 0.15 \text{ GeV/c} \)

**ALI-PREL-358983**

**ALI-PREL-336026**

**ALI-PUB-109775**
$p_T$ dependence, mid vs. forward rapidity

- $p_T < 5$ GeV/c: stronger suppression at forward rapidity.
- $p_T > 5$ GeV/c: similar suppression for mid- and forward-rapidities.
- Model uncertainties dominated by total $c\bar{c}$ cross section uncertainty
  - TM1 can describe the data over the whole $p_T$ range for both mid- and forward-rapidities.
  - SHM describes the data qualitatively.
Elliptic flow

- Positive $v_2$ for prompt $D$ mesons, $J/\psi$, $b \rightarrow e$
- $\Upsilon(1S) v_2$ compatible with zero

For $p_T < 3$ GeV/c, a mass ordering can be observed:
$v_2(\Upsilon(1S)) \leq v_2(b \rightarrow e) \sim v_2(J/\psi) < v_2(D) < v_2(\pi)$

For $3 < p_T < 6$ GeV/c: $v_2(J/\psi) < v_2(D) \sim v_2(\pi)$ due to charm quark thermalization

For $p_T > 6$ GeV/c: $v_2(J/\psi) \sim v_2(D) \sim v_2(\pi)$ due to similar path-length dependence of the energy loss

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Triangular flow

- $v_3$ of prompt D mesons, $J/\psi$ and $\pi^\pm$

- For $p_T < 5$ GeV/c:
  - $0 < v_3(J/\psi) \sim v_3(D) < v_3(\pi^\pm)$
  - Indication that charm quarks are sensitive to initial state fluctuations

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Results in $p$–$Pb$ collisions
Prompt J/ψ is consistent with several model predictions:
(EPS09-NLO, CGC+CEM, Energy loss and EPS09 NLO + energy loss)

Non-prompt J/ψ: FONLL + EPPS16 agrees with data and suggests a small shadowing at low \( p_T \)

Theoretical models in good agreement with inclusive J/ψ, despite the very different approaches:
- Shadowing (EP09NLO, nCTEQ15, EPPS16)
- CGC (NRQCD, CEM)
- Energy loss
- Final state effects (Transport, comovers)
**J/ψ vs. ψ(2S) R_{pPb}**

**mid vs. forward rapidity**

- **ψ(2S):** suppression compatible at forward and backward rapidities.
  - Stronger suppression than J/ψ at backward rapidity, whereas compatible at forward rapidity.
  - Secondary interactions proposed as mechanism to explain this effect
Elliptic flow in p–Pb

- Light-flavour particles flows in p–Pb following a mass ordering → collective behaviour in small systems
- What about heavy-flavour?

- Non-zero $v_2$ for electrons and muons from heavy-flavour lepton decays

- $v_2$ of $J/\psi$
  - Consistent with zero for $p_T < 3$ GeV/c
  - $v_2 > 0$ for $p_T > 3$ GeV/c with similar amplitude as measured in semi-central Pb–Pb collisions

- Possible final states effects and collective motion
Results in pp collisions
Open heavy-flavour production vs. multiplicity

- $\Lambda_c^+/D^0$, $\Sigma_c^0/D^0$ and $\Xi_c^0/D^0$
  - Shows a higher value than in $e^+e^-$ collisions
  - Increases from low to high multiplicity ($\Lambda_c^+/D^0$)
  - Modification not captured by standard hadronization models
- No hadronization universality between $e^+e^-$ and pp
- PYTHIA 8 with Color Reconnection: reasonable reproduction for $\Lambda_c^+/D^0$ and $\Sigma_c^0/D^0$ but not $\Xi_c^0/D^0$
- Violation of universal hadronization fractions
J/ψ production vs. multiplicity

Looking for collective behaviour in small systems

- J/ψ self normalized yield
  - Mid-rapidity: increase faster than linear
    - Enhancement qualitatively described by several model calculations
      - PYTHIA8 which includes multi-parton interactions describes qualitatively the $p_T$ dependence
      - Higher enhancement for higher $p_T$
  - Forward-rapidity: shows a linear increase
Conclusions

- **Pb–Pb collisions:**
  - Charm diffusion and energy loss constrained by azimuthal anisotropies and nuclear modification factor of heavy-flavour hadrons
  - Beauty measurements indicate partial thermalisation and weaker energy loss
  - Quarkonium indicating strong regenerated component at late stage

- **pp and p–Pb collisions:**
  - Similar behaviour as in Pb–Pb collisions for hadronization and azimuthal anisotropies;
  - Hint of multi-parton interactions affecting the J/ψ yield.

Thank you for your attention!
Heavy-flavour production in pp collisions

- Prompt J/ψ described by NRQCD calculations
- Non-prompt J/ψ described by FONLL calculations