Overview of Heavy-Flavour measurements in ALICE

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on behalf of the ALICE collaboration
The Quark-Gluon Plasma

- Particle colliders probe the high temperature region of the QCD phase diagram

- Ultra-relativistic heavy-ion collisions result in the creation of a Quark-Gluon Plasma (QGP)

- In this presentation we give an overview of heavy-flavour measurements of ALICE:
  - Open heavy-flavour
  - Quarkonia
  - Heavy-flavour jets

Collision systems

**proton - proton**
- Reference for studies of p-Pb and Pb-Pb collisions
- Determine particle production and test pQCD predictions

**p-Pb**
- Cold-nuclear-matter effects
- Test of collective effects

**Pb-Pb**
- In medium energy loss
- In medium hadronization
- Recombination effects
Open heavy-flavour

Physics Motivation

- Heavy quarks are created early during the collision so they experience the full evolution of the medium.
- The quarks lose energy when they move through the created medium.
  - Collisional
  - Radiative
- Energy loss is expected to depend on:
  - Particle path length and QGP density
  - Colour charge (Casimir factor)
  - Quark mass (dead cone effect)
- Heavy quarks are expected to be affected by the collective motion of the medium.
- Provides insight in medium transport properties.
**ALICE**

**Inner tracker system**
- Tracking
- Primary vertex reconstruction
- Particle identification

**Time of Flight**
- Particle identification

**Electromagnetic calorimeter**
- Particle identification

**Time projection chamber**
- Tracking
- Particle identification

**Muon spectrometer**
- Tracking
- Muon identification

**Central barrel:** $-0.9 < \eta < 0.9$
**Muon spectrometer:** $-4 < \eta < -2.5$
Open heavy-flavour

- Full hadronic reconstruction of heavy-flavour mesons and baryons down to low $p_T$

$D_s^+$ for $\Lambda_c^+$ reconstruction.

$D^0$ down to $p_T = 0$ GeV/$c$ for $\Lambda_c^+$ in Pb-Pb collisions.

Pb-Pb collisions.
Strong discrimination between models from 0 to 1 GeV/c for central Pb-Pb collisions

Models without shadowing overestimate low $p_T$

Suppression decreases moving to peripheral collisions

Most models show a good agreement with data

Test the validity of models by comparing data and models for energy loss and flow at the same time

Accurate modeling of data requires combination of collisional + radiative energy loss, coalescence, cold-nuclear-matter effects, and medium evolution
Open heavy-flavour

Beauty quark energy loss

- Prompt and non-prompt D^0 show different suppression at intermediate $p_T$
- Models with different energy loss for charm and beauty are compatible with data for the ratio of prompt over non-prompt D^0

Indication of flavour dependent energy loss
ALICE provides a detailed picture of the nuclear modification factor for multiple particle species

- $R_{AA}$ hierarchy consistent with expected energy loss for different partons:
  \[ \Delta E_{\text{loss}}(g) > \Delta E_{\text{loss}}(u, d) > \Delta E_{\text{loss}}(c) > \Delta E_{\text{loss}}(b) \]

- Strange D mesons and charm $\Lambda$ baryons show a hint of lower suppression, compared to non-strange D mesons, that may point at recombination effects

- Data for $D_s$ is consistent with models that show an enhancement due to hadronization via recombination
Enhancement of $\Lambda_c / D^0$ ratio compared to ee and ep collider measurements

Results favor models that use both coalescence and fragmentation

Hint of an enhancement in Pb–Pb vs pp collisions in the intermediate $p_T$ region — need more data to conclude
Check the multiplicity dependence of the $\Lambda_c / D^0$ ratio for a more detailed study of the enhancement
Smooth increase from pp to p-Pb to Pb-Pb
Even for low multiplicity pp events the $\Lambda_c / D^0$ ratio remains higher than ee, ep measurements
Indication of recombination which already occurs in pp
PYTHIA including colour reconnection results in a good agreement with data
Quarkonium

Physics Motivation

- At high temperatures colour screening in the QGP results in the suppression of quarkonium production
- Different quarkonium states have different binding energies -> **Sequential melting**
- At higher collision energies $c\bar{c}$ multiplicity increases leading to an enhanced quarkonia production via (re)combination at hadronization or during the QGP phase
J/ψ $R_{AA}$ in Pb-Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV

- Significantly improved precision and $p_T$ reach compared to previous measurements
- Increasing charm-quark density towards mid rapidity -> recombination effects stronger at mid rapidity
Quarkonium

$Y \ R_{AA}$ in Pb-Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV

- Slight bottomonium ($Y$) centrality dependence
- Stronger suppression of $Y(2S)$ compared to $Y(1S)$
• Positive J/ψ $v_2$ in large $p_T$ range at forward rapidity
• Bottomonium $v_2$ consistent with zero -> Need more data to make a conclusive interpretation on the difference between J/ψ and bottomonium $v_2$
Heavy-flavour jets

Physics Motivation

- Jets are produced in hard parton-parton collisions
- Heavy-flavour tagged jets are measured down to low jet $p_T$ (5 GeV/c)
- Provide experimental data for gluon-to-hadron fragmentation functions and gluon PDF at low $x$
- Study the dependencies of energy loss in the QGP -> Jet quenching

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Heavy-flavour jets

\[ Z_{ch}^{\parallel} \] probability density

- Comparison of data to POWHEG for different momenta
- Results for different energies and \( R \) values in backup
- Data is comparable within uncertainty for high \( p_{T,jet} \)
- At low \( p_{T,jet} \) data shows softer fragmentation
Heavy-flavour jets

$\Lambda_c^+$-tagged jets - $z_{\parallel}^{ch}$ probability density

- First measurement of $\Lambda_c^+$ tagged jets at the LHC
- Higher precision measurements expected during next run
Heavy-flavour jets

b-tagged jets

- Results consistent with POWEG
- No cold-nuclear-matter effects observed within uncertainties

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Excited QCD 2020

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Heavy-flavour jets

Heavy-flavour decay lepton tagged jets

- Within uncertainties, no modification of the jet spectra observed in p-Pb
Summary and Conclusion

Large number of heavy flavour results from ALICE:

Open heavy flavour
- Measurements of heavy-flavour decay hadrons to low $p_T$
- Constraining models, can theory predict both $R_{AA}$ and $v_2$?
- Indication of flavour-dependent energy loss
- Hint of strange D mesons and charm $\Lambda$ baryon enhancement in Pb-Pb vs pp
- Indication of $\Lambda_c$ recombination in pp

Quarkonium
- Precise $J/\psi$ measurements
- $J/\psi$ recombination effects stronger at central $y$
- $J/\psi$ and $Y$ $R_{AA}$ and $v_2$ measurements in Pb-Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV
- $Y$ $v_2$ consistent with zero

Heavy-flavour jets
- D-tagged jet measurements consistent with POWHEG with softer fragmentation at low $p_T$
- First measurement of $\Lambda_c^+$ tagged jets at the LHC
- First b-jet measurements in ALICE: results consistent with theory
- Heavy-flavour decay lepton tagged jets show no modification of the jet spectra in p-Pb

Many more measurements are still to come! Exciting future ahead for ALICE!
**D⁰-tagged jets -** \( z^{ch}_{||} \) **probability density**

### Comparison of data to POWHEG for different energies, momenta, and \( R \) values

- Data is comparable within uncertainty for high \( p_{T,\text{jet}} \)
- At low \( p_{T,\text{jet}} \) data shows softer fragmentation

### Formula

\[
z^{ch}_{||} = \frac{\langle p_D \rangle \cdot \langle p_{\text{ch jet}} \rangle}{\langle p_{\text{ch jet}} \rangle \cdot \langle p_{\text{ch jet}} \rangle}
\]