Recent measurements of heavy flavor and jet production at LHC

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Motivation

- **pp collisions:**
  - Test QCD calculations
  - Provide reference for p-Pb and Pb-Pb collisions

- **p-Pb collisions:**
  - Investigate the cold nuclear matter
  - Study the potential collective and energy loss effects

- **Pb-Pb collisions:**
  - Heavy quark energy loss
  - Hadronization mechanisms in presence of a medium
  - Quarkonium dissociation and (re-)generation in the medium
Heavy flavor production in AA collisions

- Heavy quarks produced in hard scattering processes in initial stages of the heavy-ion collisions, experienced the full system evolution
- Beauty and charm quarks production in Pb-Pb collisions, study the mass dependent parton medium interaction
Quarkonium production in AA collisions

- Charm quark ($c$ and $\bar{c}$) production cross section in LHC is larger compared to RHIC energies
- The $J/\psi$ (re-)generation contribution is significantly higher than RHIC


Kluberg, Satz, arXiv:0901.3831
Open heavy flavor production
Open charm and beauty mesons production

- Wide $p_T$ range cross section measured down to $p_T = 0$ for $D^0$ and $D^+$ meson
- NLO pQCD calculations describe cross sections down to low $p_T$
Charm production cross section and fragmentation fractions

- Charm fragmentation is not universal!
- First midrapidity charm production cross section measurement in pp collisions at 5.02 TeV
- Update the charm cross section measurements previously published at 7 and 2.76 TeV \( \rightarrow 40\% \) higher

**Diagram:**

- Comparison of charm production cross sections between various experiments (ALICE, PHENIX, STAR) with theoretical predictions (FONLL, NNLO).

**Legend:**

- ALICE, pp, \( \sqrt{s} = 5.02 \) TeV
- B factories, e\(^+\)e\(^-\), \( \sqrt{s} = 10.5 \) GeV
- LEP, e\(^+\)e\(^-\), \( \sqrt{s} = m_Z \)
- HERA, ep, DIS
- HERA, ep, PHP

**Data Points:**

- \( D^0 \)
- \( D^+ \)
- \( D_s^+ \)
- \( \Lambda_c^+ \)
- \( \Xi_c^0 \)
- \( D^{++} \)
The $\Lambda_c^+/D^0$ ratios increase from pp to central Pb–Pb collisions for $4 < p_T < 8$ GeV/c with a significance of $3.7\sigma$.

The measurements are described by theoretical calculations that include both coalescence and fragmentation.

arXiv:2112.08156
\( \Lambda_c^+ / D^0 \) ratio vs. multiplicity for integrated and intermediate \( p_T \)

- \( p_T \)-integrated ratio compatible with a flat behaviour versus event multiplicity
- Re-distribution of \( p_T \) for baryons and mesons, no modification of overall \( p_T \)-integrated yields
Prompt D-mesons $R_{AA}$ in Pb–Pb collisions

- The average prompt D-mesons $R_{AA}$ compared with different transport model calculations
  - Some of the models only include the collisional energy loss, others coll. + rad.
  - All models include the hadronization via frag.+reco.

- $p_T < 5$ GeV/c sensitive not only to charm-quark interaction with the medium
  - Cold nuclear matter effects
  - Hydrodynamics

TAMU: PRL 124.042301(2020); MC@tHQ+EPOS: PRC 91,014904(2015)
PHSD: PRC 93, 034906(2016); LIDO: PRC 98 064901(2018)
CATANIA: PRC 96 044905(2017); LGR: EPJC 807, 671 (2020)
DAB-MOD: PRC96 064903(2017)
Non-prompt $D^0 R_{AA}$ in Pb–Pb collisions

- $R_{AA}$ (non-prompt $D^0)/ R_{AA}$ (prompt $D^0)$ in Pb–Pb collisions central collisions, larger than unity for $p_T > 5$ GeV/c with significance $3.9\sigma$

- Parton mass-dependent energy loss (dead cone effect), described by the models including the collision and radiative energy loss

LGR: EPJC 807,671(2020)
TAMU: PLB 735,445-450(2014)
CUTJET 3.1: CPC 43,044101(2019)
MC@sHQ+EPOS PRC 89,014905(2015)

arXiv:2202.00815
Direct observation of the dead-cone effect

The first direct measured dead-cone effect via the $D^0$ tagged jet in quantum chromodynamics

This measurement provides insight into the influence of mass effects on jet properties

ALICE: nature 605, 440–446 (2022)
Quarkonium production
First measurement of inclusive J/ψ production at pp 5.02 TeV, $p_T$ down to 0
New measurement consistent with ATLAS and CMS in overlapping $p_T$
The measurements reach $p_T$ to 20 GeV/c at forward rapidity
Prompt and non-prompt $J/\psi$ $R_{AA}$ in $p-$Pb collisions

Significant suppression for prompt $J/\psi$ at $p_T < 3$ GeV/c, the energy loss model can describe the data

No strong $p_T$ dependence for non-prompt $J/\psi$

arXiv:2105.04957
The evidence the regeneration contribution mainly at the central collisions and low $p_T$

The statistical hadronization model can describe the data at low $p_T$, while the transport model agree with data in whole measured $p_T$ ranges.
J/ψ $R_{AA}$ comparison with the models

$R_{AA}$ extended down to $p_T = 1.5$ GeV/$c$ and was compatible with ATLAS and CMS measurements in the overlapping $p_T$ range.

Similar trends for non-prompt J/ψ and non-prompt D$^0$ $R_{AA}$ (small difference could arise from the different decay kinematics).

Non-prompt J/ψ $R_{AA}$ described by models implementing collisional and radiative energy loss for $p_T > 5$ GeV/$c$.
Higher suppression was observed for $\psi(2S)$ compared to $J/\psi$.
Increasing trend of $R_{AA}$ towards low $p_T$ for both $J/\psi$ and $\psi(2S)$, hint of $\psi(2S)$ production via (re-)generation!
Centrality and $p_T$ dependence are well reproduced by the TAMU model for both $J/\psi$ and $\psi(2S)$.

ALICE Preliminary, inclusive $J/\psi$, $\psi(2S) \rightarrow \mu^+\mu^-$
Pb–Pb, $\sqrt{s_{\text{NN}}}$ = 5.02 TeV, $2.5 < y_{\text{cm}} < 4$
TAMU

$R_{AA}$ as a function of centrality and $p_T$
$D^0$-to-$J/\psi$ ratio in Pb–Pb collisions

- Sensitive to hadronization mechanisms for open and hidden charm hadrons
- The centrality dependent trend of the $D^0$ to $J/\psi$ ratio can be explained by the increase of charm fugacity towards most central collisions according to SHMc prediction

A. Andronic et al., JHEP07 (2021) 035
J/$\psi$ polarization in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- First measurement of J/$\psi$ polarization in Pb–Pb collisions at LHC

- $\lambda_\theta$ shows a maximum $2\sigma$ deviation w.r.t. zero in HE and CS for $2 < p_T < 4$ GeV/$c$, $3\sigma$ difference w.r.t. LHCb in pp collisions in the HE reference frame

- Different behaviours in Pb-Pb compared to pp collisions due to the suppression/regeneration?

LHCb Collaboration, EPJC 73 (2013) 11
ALICE Collaboration, EPJC 78 (2018) 562
J/$\psi$ polarization in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Collaboration, arXiv:2204.10171

- First measurement of quarkonium polarization w.r.t the event plane
- Significant polarization ($\sim 3.5 \sigma$) observed in semicentral collisions (40-60%) in $2 < p_T < 6$ GeV/$c$
- The deviation reaches ($\sim 3.9 \sigma$) at low $p_T$ ($2 < p_T < 4$ GeV/$c$) in 30-50%
- Interpretation of results requires inputs from theoretical models
LHC experiments

Collision systems
- pp, pPb, Pb-Pb
- pp, pPb, Xe-Xe, Pb-Pb

LHC schedule
- Run 1 2009 - 2013
- Run 2 2015 - 2018
- Run 3 2022 - 2025
- Run 4 2029 - 2032

High luminosity for ions

HL-LHC

Higher luminosities for ions

- ATLAS phase I upgrades
- CMS phase I upgrades
- LHCb upgrade I(a)
- ALICE 2 upgrade

- ATLAS phase II upgrades
- CMS phase II upgrades
- LHCb upgrade Ib
- ALICE 2.1 upgrade

- ALICE 3 upgrade

→ evolution of LHC and the experiments
Heavy flavor transport (Run 3 & 4)

- Precise $R_{AA}$ for c and b mesons
- $v_2$ for charm hadrons
- $v_2$ for beauty hadrons

Measure spatial heavy flavour diffusion coefficient in the QGP

- Precision measurements of $R_{AA}$ and $v_2$ for charm and beauty
- High statistics and improved vertexing detector
Heavy flavor hadronisation (Run 3 & 4)

Constrain hadronisation models
- measurements of baryon/meson ratios, nuclear suppression
- luminosity, vertexing, PID
Quarkonia production (Run 3 & 4)

Understand heavy-quark dynamics in the QGP
- precision measurements of charmonium and bottomonium different states
- luminosity and PID

Precise jet $R_{AA}$ measurement up to high $p_T$ (Run 3 & 4)

Large samples allow us to look at tagged jets, substructure…

- Understand mass and time dependence
- High statistics and new collision systems (OO, pO, also high-multiplicity pp)

Recent measurements of open heavy flavour and quarkonium production at ALICE with LHC are presented

- Non-universal charm hadronisation process
- Mass-dependent energy loss was observed in central Pb-Pb collisions
- $J/\psi$ (re-)generation dominant at low $p_T$
- Significant non-zero polarization observed w.r.t event plane in semicentral at low $p_T$

LHC upgrade program for Run 3 and 4 crucial for heavy flavour and jet measurements
Thanks
Quarkonia production (Run 3 & 4)

\[ \text{Pb-Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV}, \; 2.5 < y < 4.0 \]

- ALICE Upgrade simulation, 10 nb\(^{-1}\)
- Statistical Hadronization Model
- Transport Model (TAMU)

\[ \text{Pb-Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV}, \; |y| < 0.9 \]

- ALICE Upgrade projection, 10 nb\(^{-1}\)
- Statistical Hadronization Model
- Transport Model (TAMU)
Quarkonium polarization

- Constrains quarkonium production mechanism in pp collisions.
- Heavy quark pairs are produced in the earlier stage of AA collision and can experience both the short living $B$ and the $L$ of the rotating medium, can access the spin alignment of w.r.t a chosen axis.

Figures from P. Faccioli et al. EPJ C69 (2010) 657-673