Recent results on heavy flavor and quarkonia from ALICE

E. Scomparin - INFN Torino (Italy) for the ALICE Collaboration
Introduction

- Heavy quarks, a precise tool to study QGP properties and hadronization mechanisms

- Highlights from our menu today:
  - $J/\psi$ production and polarization, $\psi(2S)$ production in Pb-Pb
  - Charm spatial diffusion coefficient from $R_{AA}$ and $\eta_2$ measurements
  - Beauty vs charm energy loss from (non) prompt $D$
  - Hadronization studies via charm baryon production in pp, p-Pb, Pb-Pb
  - ... and much more!

- Some specific features of the ALICE measurements
  - Detection of inclusive charmonium and bottomonium states down to zero $p_T$
  - Open heavy flavor: extended studies of meson AND baryon states over a wide $p_T$ range
Early production (and binding) of heavy quark pairs

T. Matsui and H. Satz, PLB 178(1986) 416
P. Braun-Munzinger and J. Stachel, PLB490(2000) 196
R. Thews et al., PRC63 (2001) 064905
A. Rothkopf, Phys. Rept. 858 (2020) 1
Early production (and binding) of heavy quark pairs
Modification of spectral properties and possible dissociation in the QGP

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Quarkonium

- Early production (and binding) of heavy quark pairs
- Modification of spectral properties and possible dissociation in the QGP
- Recombination effects in the QGP and/or at phase boundary

T. Matsui and H. Satz, PLB 178(1986) 416
P. Braun-Munzinger and J. Stachel, PLB490(2000) 196
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A. Rothkopf, Phys. Rept. 858 (2020) 1
Open heavy flavours

- Heavy quark interactions in the QGP: energy loss and its quark mass dependence, heavy quark diffusion and thermalization

Y. Dokshitzer and D. Kharzeev, PLB 519 (2001) 199
D. Moore and H. Teaney, PRC71 (2005) 064904
Open heavy flavours

- Heavy quark interactions in the QGP: energy loss and its quark mass dependence, heavy quark diffusion and thermalization
- Hadron formation mechanisms and their dependence on the collision system (results from pp to Pb-Pb collisions)

Y. Dokshitzer and D. Kharzeev, PLB 519 (2001) 199
D. Moore and H. Teaney, PRC 71 (2005) 064904
A Large Ion Collider Experiment

- **Quarkonium measurements**
  - Central barrel (ee, $|y|<0.9$)
  - Muon spectrometer ($\mu\mu$, 2.5$<y<4$)
  - Coverage down to zero $p_T$

- **Open heavy flavours**
  - Hadronic measurements ($|y|<0.5$)
    - $D^0 \rightarrow K^- \pi^+$
    - $D^+ \rightarrow K^+ \pi^+ \pi^+$
    - $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$
    - $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
    - $\Lambda_c^+ \rightarrow K_S^0 \ p \rightarrow \pi^+ \pi^- \ p$
    - $\Lambda_c^+ \rightarrow pK^- \pi^+$
    - $\Sigma_c^{0,++} \rightarrow \Lambda_c^+ \pi^-$
    - $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e, \Xi^- \pi^+$
    - $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$
    - $\Omega_c^0 \rightarrow \Omega^- \pi^+$
  - Leptonic measurements ($c,b \rightarrow \ell X$)
    at forward and central $y$

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Heavy flavor and quarkonium results from ALICE

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<table>
<thead>
<tr>
<th>Session</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA – OTH</td>
<td>Measurement of quarkonium production and polarization in pp and Pb-Pb collisions with ALICE (X. Bai, Tue 9 AM)</td>
</tr>
<tr>
<td>PA – BLK</td>
<td>Quarkonia production and elliptic flow in small systems measured with ALICE (R. Sadek, Tue 10 AM)</td>
</tr>
<tr>
<td>PA – HF</td>
<td>( \psi(2S) ) production and nuclear modification factor in nucleus-nucleus collisions with ALICE (H. Hushnud, Tue 10 AM)</td>
</tr>
<tr>
<td>PA –-blk</td>
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</tr>
</tbody>
</table>

More details in

- J/\( \psi \) photoproduction and the production of dileptons via photon-photon interactions in hadronic Pb–Pb collisions measured with ALICE (L. Massacrier, Tue 2.40 PM)

**Quarkonia**
Rise of inclusive $J/\psi$ $R_{AA}$ at low $p_T$, stronger effect at $y=0 \rightarrow$ decisive signature of recombination

- Models include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU)
  - Both in agreement with data at low $p_T$

- Effect confirmed when looking at prompt $J/\psi$ production at midrapidity, clear centrality dependence
Inclusive $\psi(2S)$ production in Pb-Pb

- Stronger suppression for $\psi(2S)$ compared to $J/\psi$ → sequential suppression for charmonia?
- Increasing trend of $R_{AA}$ towards low $p_T$ for $\psi(2S)$ → Hint of $\psi(2S)$ production via regeneration
- Compatible with midrapidity CMS results in common $p_T$ range
- $p_T$ dependence of $R_{AA}$ reproduced by TAMU

Centrality dependence of $\psi(2S)/J/\psi$ described by TAMU and slightly underestimated by SHMc

First LHC measurement down to zero $p_T$
Inclusive J/\(\psi\) polarization in Pb-Pb collisions

- Study polarization wrt an axis orthogonal to the event plane, in the collision center of mass frame → orthogonal to \(\mathbf{B}\) and \(\mathbf{L}\).
- Significant spin alignment observed for light vector mesons (\(K^*0\), \(\phi\)) (ALICE, PRL 125 (2020) 012301)
- Centrality dependence → small but significant (3.5\(\sigma\)) polarization in 40-60% and 2\(<p_T<6\) GeV/c
- \(p_T\) dependence → 3.9\(\sigma\) effect for 2\(<p_T<4\) GeV/c, 30-50%

Heavy flavor and quarkonium results from ALICE
Coherent $J/\psi$ production in (semi)peripheral Pb-Pb

- Centrality dependence of $R_{AA}$ in $p_T$ intervals → evidence for coherent production at low $p_T$
- $p_T$ shape and cross sections compatible with a model that includes the effect of the overlap between the nuclei (W. Zha et al., PRC 99 (2019) 061901)

Ratio of coherent cross sections in Pb-Pb collisions with nuclear overlap (PC) over ultraperipheral (UPC) collisions

- No evidence of modification of $\sigma_{PC}$ in semicentral collisions with current experimental precision

ALICE, arXiv:2204.10684
PC: arXiv:2204.10684
UPC: EPJC 81 (2021) 712, PLB 98 (2019) 134926
Quarkonium news from pp collisions

- Strong collective effects on $J/\psi$ already assessed in Pb-Pb
- $p$-Pb: significant flow for $p_T>3$ GeV/c (not explained by transport models)
- $pp$: no significant effect, integrated $v_2$ compatible with zero within 1.5σ

- Self-normalized ratios of $\psi(2S)$ and $J/\psi$ exhibit a similar multiplicity dep. (ratio of ratios is flat)
- Agreement with PYTHIA 8, while comover models predict a suppression effect at large $dN_{ch}/d\eta$, not seen in the data
Open heavy flavours

PA – HF session

More details in

Constraining hadronization processes with charm baryons in pp and p-Pb collisions with ALICE
**J. Seo**, Tue 12.10 PM

Charm production: constraint to transport models and charm diffusion coefficient with ALICE
**M. Völkl**, Tue 11.50 AM

Beauty production in heavy-ion collisions with ALICE at the LHC
**S. Politanò**, Tue 2 PM

Heavy-flavour jet properties and correlations from small to large systems measured by ALICE
**A. Da Silva**, Tue 2.20 PM
Charm quark transport and models

- Most charm-quark transport models able to describe both the $R_{AA}$ and $v_2$
  - Use comparison to understand which physics effects are relevant
  - Use comparison to estimate the spatial diffusion coefficient

ALICE, JHEP 01 (2022) 174
ALICE, PLB 813 (2021) 136054

Charm quark energy loss

Radiative energy loss important to describe intermediate and high $p_T$

$\Rightarrow$ Small impact on low $p_T$ region

Heavy flavor and quarkonium results from ALICE

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ALICE, JHEP 01 (2022) 174
ALICE, PLB 813 (2021) 136054

LIDO: PRC 98, 064901 (2018)
LGR: EPJC 80 (2020) 7, 671

ALI–PUB–501960
Estimating the spatial diffusion coefficient

- Constraining the spatial diffusion coefficient via the data-to-model agreement
  → Using $R_{AA}$ (with $\chi^2/\text{ndf} < 5$) and $v_2$ (with $\chi^2/\text{ndf} < 2$) non-strange D measurements
  → TAMU, MC@sHQ, LIDO, LGR, and Catania “selected”

$1.5 < 2\pi D_s T_c < 4.5$
$\tau_{\text{charm}} \approx 3 - 8 \text{ fm/c}$
Charm vs inclusive jets

- $D^0$ meson, $3<p_T<36$ GeV/c
- Charged jets, anti-$k_T$ algorithm with $R=0.3$
- Jet $5<p_T<50$ GeV/c

- Hint of a higher $R_{AA}$ of $D^0$-jets compared to inclusive jets in Pb-Pb
- Comparison sensitive to
  - Difference between quark and gluon energy loss (Casimir colour effect)
  - Mass effects (dead cone)
Suppression of $b \rightarrow D^0$ observed

$R_{AA} b \rightarrow D^0 > R_{AA} c \rightarrow D^0$ at intermediate $p_T$

$R_{AA} (0-10\%) < R_{AA} (30-50\%$)

Theory models that include collisional and radiative eloss describe the data within uncertainties
Ratio non-prompt/prompt $R_{AA}$ for D mesons

- Sensitive to effects that act differently on charm and beauty quarks
- $p_T < 5 \text{ GeV/c}$: difference in shadowing / flow / decay kinematics
- $p_T > 5 \text{ GeV/c}$: $3.9 \sigma$ above unity → beauty quarks undergo less suppression than charm quarks
- Test the double $R_{AA}$ ratio with different LGR configurations
  - The “valley” structure is mainly due to the formation of prompt D-mesons via charm-quark coalescence (iv)
  - The significant enhancement of double ratio at high $p_T$ is related to the mass dependent quark in-medium energy loss (i)
\[ \Lambda_c/D^0: \text{pp collisions} \]

- **Ratios underestimated** at low \( p_T \) by models as PYTHIA 8 Monash, tuned to reproduce \( e^+e^- \) results (\( e^+e^- \) charm fragmentation functions)
- \( \rightarrow \) non-universal fragmentation of charm to hadrons?

- **PYTHIA 8 with updated Colour Reconnection (CR) modelling** J.P. Christiansen, P. Z. Skands: JHEP 1508 (2015) 003
  - CR with SU(3) weights and string length minimization
  - “junction” topology enhances charm baryon production

- **Catania model** V. Minissale, S. Plumari, V. Greco: arXiv:2012.12001
  - Thermalised system of \( u,d,s \) and gluons assumed
  - Mixed hadron formation
    - Fragmentation
    - Coalescence, imposed as only mechanism for \( p \rightarrow 0 \)

- **Statistical Hadronization Model and Relativistic Quark Model (SHM + RQM)**
  - Hadronization driven by statistical weights governed by hadron masses \( (n_i \sim m_i^2 T_H K_2(m_i/T_H)) \) at a hadronization temperature \( T_H \)
  - Strong feed-down from an augmented set of excited charm baryons

| PDG: 5 \( \Lambda_c \), 3 \( \Sigma_c \), 8 \( \Xi_c \), 2 \( \Omega_c \) |
| RQM: additional 18 \( \Lambda_c \), 42 \( \Sigma_c \), 62 \( \Xi_c \), 34 \( \Omega_c \) (not yet measured) |

M. He, R. Rapp, PLB 795 (2019) 117-121
From pp to p-Pb: $\Lambda_c/D^0$ and charm fragmentation fractions

- $\Lambda_c^+/D^0$ enhancement shifted to larger $p_T$ in p-Pb
- **Charm fragmentation fractions** measured including several states in pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV (ALICE, PRD105(2022)L011103)

- For p-Pb: measured for $D^0$ and $\Lambda_c$, extrapolated to zero $p_T$ with POWHEG+PYTHIA for $D^+$ and $D_s^+$, not measured for $\Xi_c$ but evaluated assuming $R_{pPb}(\Lambda_c^+) = R_{pPb}(\Xi_c^+)$

- pp and p-Pb results compatible
- Significant baryon enhancement with respect to $e^+e^-$ and $e^-p$
$\Lambda_c/D^0$: moving across systems, pp, p-Pb, Pb-Pb

- $p_T$-integrated data do not favour an increase of the yield ratio with multiplicity → trend compatible with a constant function.
- Suggests that the increasing trend observed in specific $p_T$ ranges comes from a re-distribution of $p_T$ that acts differently for baryons and mesons.

Increase of the ratio from pp to mid-central and central Pb–Pb collisions for $4 < p_T < 8$ GeV/c → $2.0\sigma$ and $3.7\sigma$ significance respectively.

ALICE, PLB 829 (2022) 137065
ALICE, arXiv:2112.08156
Conclusions

- ALICE Run 1 + 2: several highlights and still investigating exciting topics. Among those:
  - Quarkonium
    - Study of recombination in the charmonium sector, now extended to \( \psi(2S) \)
    - First results on \( J/\psi \) polarization with respect to event plane, small but significant effect
    - Large \( J/\psi \) \( v_2 \) in Pb-Pb, significant signal in p-Pb but no evidence in pp
  - Open heavy flavours
    - Studies on thermalization and energy loss, estimate of crucial QGP parameters \( (D_s) \)
    - Energy loss hierarchy, via charm-jet studies and non-prompt/prompt \( D^0 \) production
    - Detailed studies of charm baryon production, to shed light on anomalous enhancements seen in pp collisions

- LHC Run 3 starting
  - Continuous readout at 50 kHz interaction rate for Pb–Pb collisions
  - Target Pb-Pb integrated luminosity (run 3 + 4) \( \rightarrow L_{\text{int}} \sim 13 \text{ nb}^{-1} \)
  - Improved tracking precision by a factor 3–6 (new Inner Tracker)

- Longer-term plan: ALICE 3
  \( \rightarrow \) Systematic measurements of (multi-)heavy-flavour hadrons

Heavy-ion physics at the LHC with detector upgrades for Runs 3 and 4

S. Porteboeuf, Thu 12.40 PM

Physics program of the ALICE 3 experiment for the LHC Runs 5 and 6

R. Bailhache, Thu 12.05 PM

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Backup
$\Sigma_c^{0,+;++}, \Xi_c^{0,+}, \Omega_c^0$ baryons in pp collisions

- $\Sigma_c'/D^0$ well described by SHM+RQM, Catania and QCM, its enhancement partially accounts for large $\Lambda_c^+/D^0$
- $\Xi_c'/D^0$ significantly underestimated by models, while $\Xi_c'/\Sigma_c$ (not shown) in agreement with Monash (N.B. $D_s^+/D^0 + D^+$ is compatible with expectations from $e^+e^-$, effects above not directly related to s-quark content?)
- $\Omega_c'/D^0$, better agreement with coalescence models, PYTHIA 8 underestimates even with CR-BLC effects (N.B. BR($\Omega_c^0 \rightarrow \Omega^{-}\pi^+$) = (0.51 ± 0.07)% not measured → value from Y. Hsiao et al. EPJC 80, 1066 (2020) used to scale model predictions)

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Heavy flavor and quarkonium results from ALICE

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Reconstructed charm-baryon decays

- $\Lambda^+_c (udc) \rightarrow pK^-\pi^+, pK^0_s$
- $\Sigma^{0,++}_c (ddc, uuc) \rightarrow \Lambda^+_c \pi^-, +$
- $\Xi^0_c (dsc) \rightarrow \Xi^-e^+\nu_e, \Xi^-\pi^+$
- $\Xi^+_c (usc) \rightarrow \Xi^-\pi^+\pi^+$
- $\Omega^0_c (ssc) \rightarrow \Omega^-\pi^+$
A brief detour

- Polarization studies can be extended to other particles containing charm quarks
- First step recently carried out by studying D^{**+} polarization in pp collisions

- Measure spin density matrix $\rho_{00}$

- Deviations from $\rho_{00} = 1/3$ signal a net spin alignment
- Separation of prompt and non-prompt component
- Prompt component unpolarized, while non-prompt component from b-hadron decays exhibit a clear polarization
  - Effect seen and in agreement with PYTHIA 8 + EVTGEN

- Next step: measurements in Pb-Pb collisions, to search for effects related to B and/or L
Charm hadronization in pp: baryons vs mesons

- **Baryon-to-meson ratios underestimated** at low $p_T$ by models such as PYTHIA 8 Monash, tuned to reproduce $e^+e^-$ results ($e^+e^-$ charm fragmentation functions)
- Enhancement with respect to PYTHIA 8 at low $p_T$ also observed in the beauty sector by LHCb
- Points towards **further hadronization mechanisms** → non-universal fragmentation functions
  → Campaign of measurements of various baryon resonances in pp

**Figure 1:** Graphs showing $D^+ / D^0$ and $\Lambda_c^+ / D^0$ ratios against $p_T$ for prompt and non-prompt modes. The data points are compared with models such as FONLL and FONLL + PYTHIA8 Dec., as well as PYTHIA8 Monash, HERWIG 7, and POWHEG. The graph on the right also includes a comparison with LEP average results ($0.113 \pm 0.013 \pm 0.006$).