Quarkonia and heavy flavors: where do we stand? What next?

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Quarkonia → Sensitive to the temperature of QGP

Probing the opacity of QGP → Open heavy quarks
Heavy quark energy loss...

- **Fundamental test** of our understanding of the energy loss mechanism, since $\Delta E$ depends on:
  - Properties of the medium
  - Path length

...but should also **critically depend** on the properties of the parton:
- Casimir factor ($C_R^g = 3$, $C_R^q = 4/3$)
- Quark mass (dead cone effect)

\[
\Delta E_{\text{quark}} < \Delta E_{\text{gluon}} \quad \Delta E_b < \Delta E_c < \Delta E_{\text{light q}}
\]

which should imply

\[R_{AA}^B > R_{AA}^D > R_{AA}^\pi\]

with

\[
R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}}{dp_T} / \frac{dN_{pp}}{dp_T}
\]

S. Wicks, M. Gyulassy, JPG35 (2008) 054001
... and elliptic flow

- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium \( \Rightarrow v_2(b) < v_2(c) \)
- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium \( \Rightarrow \) Transported through the full system evolution
- **Low/intermediate** \( p_T \): collective motion, thermalization
- **High** \( p_T \): path-length dependence of heavy-quark energy loss

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**LHC: unprecedented abundance of heavy quarks**

Opportunity for a deeper understanding of the underlying physics

![Diagram](image.png)
Pb-Pb and p-Pb: results on D-mesons

- $D^0$, $D^+$ and $D^{**}$ $R_{AA}$ agree within uncertainties.

- Strong suppression of prompt D mesons in central collisions → up to a factor of 5 for $p_T \approx 10$ GeV/c.

- Comparison with corresponding results for p-Pb collisions.

- Effect observed in central Pb-Pb due to strong final state effects induced by hot partonic matter.

B. Abelev et al. (ALICE), arXiv:1405.3452.
Pb-Pb and pPb: results on B,D→ muons

- Larger suppression (factor 3-4) in the 10% most central collisions with respect to 40-80% centrality class
- Suppression in the 10% most central Pb-Pb collisions due to a hot matter effect
- No separation of B/D decays

Forward rapidity: 2.5<y<4

B. Abelev et al. (ALICE), PRL109 (2012) 112301
Pb-Pb and pPb: results on B,D→ electrons

- Results available up to $p_T = 18$ GeV/c for central events (EMCAL)
- Clear suppression for central collisions in the studied $p_T$ range
- Stronger suppression for central collisions (hint)
- $R_{pPb}$ compatible with unity within uncertainties
  → Pb-Pb suppression due to final state effects
- No separation D vs B (possible, based on electron impact parameter, but with rather large uncertainties)
Pb-Pb and pPb: results on B,D→ electrons

Central rapidity: |y|<0.6

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Test the **mass ordering** of energy loss

$\Delta E(q,g) > \Delta E(c)$? → Not evident, but...

- Different quark spectrum
- Fragmentation effect

M. Djordjevic, PRL 112, 042302 (2014)
Charm vs beauty

- Comparing direct D results with non-prompt J/ψ
- Similar kinematic range ($\langle p_T \rangle \sim 10$ GeV/c)
- In agreement with expectations $R_{AA}(B) > R_{AA}(D)$
- Comparison with models $\rightarrow$ mass-related effect

- p-Pb results on b $\rightarrow$ small or no effect at backward and forward y
- What about mid-y?
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Direct B in p-Pb (mid-y)

- Use FONLL for pp reference cross section
- $R_{pA}^{FONLL}$ is compatible with unity for all three B-mesons

$$B^+ \rightarrow J/\psi \ K^+$$
$$B^0 \rightarrow J/\psi \ K^*$$
$$B_S \rightarrow J/\psi \ \phi$$

$$\langle p_T \rangle > 10 \ \text{GeV/c}$$
**R_{pPb} & R_{AA} for jets and b jets**

- Discriminating variable → Flight distance of the secondary vertex
- b-jet fraction → template fits to secondary vertex inv. mass distributions
- b-jet $R_{AA}$ is much smaller than $R_{pPb}$ → strong in-medium effects
- No jet modification in p-Pb collisions
- No flavour dependence of the effect

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S. Chatrchyan et al. (CMS), arXiv:1312.4198
D-meson and HFE/HFM $v_2$

- First measurements of charm anisotropy in heavy-ion collisions

- Similar amount of $v_2$ for D-mesons and charged pions
- Similar $v_2$ values for HF decay muons and HF decay electrons (different $y$)
- All channels show positive $v_2$ ($>3 \sigma$ effect)

Information on the initial azimuthal anisotropy transferred to charm quarks
Open charm: model comparisons

- Simultaneous measurement/description of $v_2$ and $R_{AA}$
  - Understanding heavy quark transport coefficient of the medium

- Wealth of theory calculations
  - Main features correctly reproduced
  - Simultaneous comparison with $v_2$ and $R_{AA}$ gives strong constraint to the models \(\rightarrow\) still challenging!

B. Abelev et al. (ALICE), arXiv:1405.2001
Open charm/beauty: short summary

- **Abundant** heavy flavour production at the LHC
  - Allows for **precision** measurements
- **Can separate charm and beauty** (vertex detectors!)
  - Indication for $R_{AA}^{\text{beauty}} > R_{AA}^{\text{charm}}$
  - $R_{AA}^{\text{beauty}} > R_{AA}^{\text{light}}$ at low $p_T$, effect vanishing at very high $p_T$
  - $R_{AA}^{\text{charm}}$ vs. $R_{AA}^{\text{light}}$ comparison more delicate
- Indication ($3\sigma$) for non-zero charm elliptic flow at low $p_T$
Quarkonia: from color screening...

Screening of strong interactions in a QGP

- Screening stronger at high $T$
- $\lambda_D \rightarrow \text{maximum size}$ of a bound state, decreases when $T$ increases
- Different states, different sizes

Resonance melting

QGP thermometer

T. Matsui and H. Satz, PLB178 (1986) 416

A. Adare et al. (PHENIX), arXiv:1404.2246
...to regeneration (for charmonium!)

At sufficiently high energy, the cc pair multiplicity becomes large.

Statistical approach:
- Charmonium fully melted in QGP
- Charmonium produced, together with all other hadrons, at chemical freeze-out, according to statistical weights

Kinetic recombination:
- Continuous dissociation/regeneration over QGP lifetime

Contrary to the color screening scenario this mechanism can lead to a charmonium enhancement

if supported by data, charmonium looses status as “thermometer” of QGP ...and gains status as a powerful observable for the phase boundary

P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196
Low $p_T$ J/$\psi$: ALICE

- Compare J/$\psi$ suppression, RHIC ($\sqrt{s_{NN}}=0.2$ TeV) vs LHC ($\sqrt{s_{NN}}=2.76$ TeV)
- Results dominated by low-$p_T$ J/$\psi$
  - Stronger centrality dependence at lower energy
  - Systematically larger $R_{AA}$ values for central events in ALICE

Possible interpretation:

- RHIC energy $\rightarrow$ suppression effects dominate
- LHC energy $\rightarrow$ suppression + regeneration

How can this picture be validated?
Charm-quark transverse momentum spectrum peaked at low-$p_T$
Recombination processes expect to mainly enhance low-$p_T$ $J/\psi$
→ Expect smaller suppression for low-$p_T$ $J/\psi$ → observed!

Opposite trend with respect to lower energy experiments
Fair agreement with transport and statistical models (not shown)
Other strong hint for recombination: non-zero $v_2$ for $J/\psi$ (ALICE+CMS)

CNM effects are not negligible!

- Suppression at backward + central rapidity
- No suppression (enhancement?) at forward rapidity
- Fair agreement with models (shadowing + energy loss)
- (Rough) extrapolation of CNM effects to Pb-Pb → evidence for hot matter effects!

R. Aaij et al. (LHCb), JHEP 02(2014) 072
B. Abelev et al. (ALICE), JHEP 02(2014) 073
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Weakly bound charmonia: $\psi(2S)$

ALICE: evidence for **strong suppression** effects in $p_T$-integrated $p$-Pb collisions (compared to $J/\psi$), increasing with the event activity.

CMS: from **enhancement** to strong suppression moving from intermediate ($p_T > 3$ GeV/c) to large ($p_T > 6.5$ GeV/c) transverse momentum.

How can these observations be reconciled?
Suppression: CMS results

More weakly bound states (Γ(2S), Γ(3S)) show strong suppression in Pb-Pb, compared to Γ(1S)

Expected signature for QGP-related suppression

Regeneration effects expected to be negligible for bottomonia

S. Chatrchyan et al. (CMS), PRL 109 (2012) 222301
More weakly bound states ($\Upsilon(2S)$, $\Upsilon(3S)$) show strong suppression in Pb-Pb, compared to $\Upsilon(1S)$

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S. Chatrchyan et al. (CMS), PRL 109 (2012) 222301
First accurate determination of $\Upsilon$ suppression

- Suppression increases with centrality
- First determination of $\Upsilon(2S)$
  - $R_{AA}$: already suppressed in peripheral collisions
- $\Upsilon(1S)$ (see also ALICE)
  - compatible with suppression of bottomonium states decaying to $\Upsilon(1S)$
  → Probably yes, also taking into account the normalization uncertainty

Is $\Upsilon(1S)$ dissociation threshold still beyond LHC reach? → Run-II

S. Chatrchyan et al. (CMS), PRL 109 (2012) 222301
B. Abelev et al. (ALICE), arXiv:1405.4493
Do not forget CNM...

- In the $\gamma$ sector, the influence of CNM effects is small

- Hints for suppression of $\gamma(1S)$ at forward rapidity?
- (Small) relative suppression of $\gamma(2S)$ and $\gamma(3S)$ wrt $\gamma(1S)$ at mid-rapidity
- Qualitative agreement with models within uncertainties
- CNM cannot account for all of the effect observed in Pb-Pb

S. Chatrchyan et al. (CMS), JHEP 04(2014) 103
Evolution of relative yields: pp, p-Pb, Pb-Pb

- Strong correlation of charmonia/bottomonia/open charm relative yields as a function of quantities related to the hadronic activity in the event.
- Observation related to the role of MPI in pp also in the hard sector.

S. Chatrchyan et al. (CMS), JHEP 04(2014) 103
Charmonia/bottomonia: short summary

- Two main mechanisms at play
  1) Suppression in a deconfined medium
  2) Re-generation (for charmonium only!) at high $\sqrt{s}$
  - can qualitatively explain the main features of the results

- In the charmonium sector
  - $R_{AA} \rightarrow$ weak centrality dependence at all $y$, larger than at RHIC
  - Less suppression at low $p_T$ with respect to high $p_T$
  - CNM effects non-negligible but cannot explain Pb-Pb observations

- In the bottomonium sector
  - Clear ordering of the suppression of the three $\Upsilon$ states with their binding energy $\rightarrow$ as expected from sequential melting
  - $\Upsilon(1S)$ suppression consistent with excited state suppression (50% feed-down)
Conclusions

- Complete set of results from run-I is now available
- Confirm the role of heavy quarks/quarkonia as privileged probes for the study of Quark-Gluon Plasma
  - Open charm/beauty mesons are strongly affected by the medium
    - Energy loss pattern, including mass-related effects, in agreement with calculations
    - Significant $v_2$ confirms the presence of collective effects (low $p_T$) as well as path-length dependence of energy loss (high $p_T$)
  - Charmonia/bottomonia are suppressed in the QGP according to their binding energy
    - Charmonium results show clear effects of re-generation during the QGP-phase and/or at phase boundary
- Many (most) of the heavy-quark/quarkonia related observables would benefit from more data to sharpen the conclusions
  - Run-II at $\sqrt{s_{NN}} \sim 5.1$ TeV, 2015-2017
  - Experiment upgrades, 2018 onwards
Backup
First $B \rightarrow e$ measurement in Pb-Pb

- Analysis based on the study of the electron impact parameter distribution

- Indicates $R_{AA} < 1$ for $p_T > 3$ GeV/c

- $R_{pPb} (b \rightarrow e)$ compatible with unity: b-quark affected by the interaction with the hot medium
Non-zero $v_2$ for $J/\psi$ at the LHC

- The contribution of $J/\psi$ from (re)combination should lead to a significant elliptic flow signal at LHC energy.

- A significant $v_2$ signal is observed by BOTH ALICE and CMS.

- The signal remains visible even in the region where the contribution of (re)generation should be negligible.

- Due to path length dependence of energy loss?

- In contrast to these observations STAR measures $v_2=0$. 

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E. Abbas et al. (ALICE), PRL111(2013) 162301
Charm(ed) and strange: $D_S R_{AA}$

- First measurement of $D_s^+$ in AA collisions
- Expectation: enhancement of the strange/non-strange $D$ meson yield at intermediate $p_T$ if charm hadronizes via recombination in the medium

**Strong $D_s^+$ suppression** (similar as $D^0$, $D^+$ and $D^{*+}$) for $8 < p_T < 12$ GeV/c

- More statistics needed to conclude about the low-$p_T$ region
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\( \Upsilon(1S) \) vs \( y \) and \( p_T \) from CMS+ALICE

- Start to investigate the **kinematic dependence** of the suppression
- Suppression concentrated at **low** \( p_T \)
  - (opposite than for \( J/\psi \), no recombination here!)
- Suppression extends to **large rapidity** (puzzling \( y \)-dependence?)
Results available up to $p_T=18$ GeV/c for central events (EMCAL)

Clear suppression for central collisions in the studied $p_T$ range

Stronger suppression for central collisions (hint)

$R_{pPb}$ compatible with unity within uncertainties

→ Pb-Pb suppression due to final state effects

No separation D vs B (possible, based on electron impact parameter, but with rather large uncertainties)