Recent CMS heavy flavor and quarkonia measurements in HI collisions

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See Javier M. Blanco, Chad Flores and Ta-Wei Wang presentations at QM2017 for more details!
Why heavy flavour and quarkonia in HI?
... i guess you know it by now :(
Open heavy flavours
D and B meson production cross sections well described by NLO calculations:

→ D meson upper edge of FONLL calculations
→ B meson consistent with central values of FONLL at higher $p_T$

slightly higher for $p_T < 15$ GeV
B meson production in pPb collisions

FONLL $R_{pA}$ fully compatible with unity

No sizeable modification as a function of rapidity

PRL 116 (2016) 032301
D⁰ meson R_{AA} at 5.02 TeV

D⁰ R_{AA} measured from 2 to 100 GeV/c at central rapidity in 0-100%

→ ~300 MB events recorded for low pₜ analysis
→ Dedicated triggers designed to perform full track reconstruction at HLT and to reconstruct and identify D⁰ meson events at HLT
Several models describe the data within uncertainties:

- hints at low $p_T$ that collisional energy loss is non negligible
- pure collisional models can describe the $R_{AA}$ up to high $p_T$ (??)
- shadowing improve description of the data at low $p_T$
Strong suppression observed for non prompt J/$\psi$ in PbPb collisions

Clear suppression as a function of $p_T$

2.76 TeV and 5.02 TeV results well consistent within uncertainties

CMS non prompt 1.6<$|y|<$2.4

CMS non prompt $|y|<$2.4

ATLAS non prompt $|y|<$2.9

CMS B$^+$ meson measurement in PbPb

CMS B$^+$ production in PbPb at central rapidity $|y|<2.4$

Strong suppression ($R_{AA}\sim0.4$) observed in 0-100% PbPb collision for $p_T>7$ GeV/c

Well described by theoretical calculations that include radiative energy loss
Flavour dependence at 5.02 TeV

charged particle, D meson, B meson $R_{AA}$ are consistent within uncertainties!

charged particle
D meson
B meson
non prompt J/$\psi$

Charged particle, D meson, B meson $R_{AA}$ are consistent within uncertainties!
Flavour dependence at 5.02 TeV

However!
B $R_{AA}$ and D $R_{AA}$ measured in different rapidities!
→ measurements in the same rapidity with more statistics needed to draw a firm conclusions
→ non prompt $J/\psi$ to be measured at 5 TeV

Charged particle, D meson, B meson $R_{AA}$ are consistent within uncertainties!

$\sqrt{s_{NN}} = 2.76$ TeV

$6.5 < p_T < 30$ GeV/c
Cent. 0-100%

non prompt $J/\psi$

arXiv:1610.00613
Significant difference when we compared at low $p_T$ in the same rapidity region D meson and non prompt $J/\psi$ → models explain the difference in the $R_{AA}$ as due to a different $E_{\text{loss}}$ for charm and beauty quarks
Flavour dependence at higher $p_T$

Same suppression for b-jets and inclusive jets at high $p_T$

- Mass difference negligible at high $p_T$
- Large contribution of gluon splitting processes? In GSP case, we are not measuring the b-quark $E_{\text{loss}}$ but to some “fat” gluon $E_{\text{loss}}$
Flavour dependence at higher $p_T$

**NLO process: Gluon splitting**
→ dominant at low opening angles

Same suppression for b-jets and inclusive jets at high $p_T$

Mass difference negligible at high $p_T$

Large contribution of gluon splitting processes? In GSP case, we are not measuring the $b$-quark $E_{\text{loss}}$ but to some “fat” gluon $E_{\text{loss}}$
Di-b-jet measurement in PbPb at 5.02 TeV

→ In back-to-back events $b\bar{b}$ production via gluon splitting processes is negligible.

$x_J \sim 1$ => $p_T,1 > p_T,2$

$x_J < 1$

$x_J = p_{T,2} / p_{T,1}$ distributions of di-b-jets significantly modified in central PbPb collisions!
Di-b-jet measurement in PbPb at 5.02 TeV

There is no significant difference in the suppression of inclusive and b-jets even after excluding the contribution of gluon splitting processes.

$x_J = \frac{p_{T,2}}{p_{T,1}}$

Same average asymmetry observed for inclusive jets!

CMS-HIN-16-005
D meson $v_2$ at 5.02 TeV in PbPb collisions

$v_2$ and $v_3$ in PbPb collisions at 5.02 TeV in different collision centralities

Significant confirmation of $v_2 > 0$ for $D^0$ at 5.02 TeV:

$v_2$ of $D$ mesons larger than $v_2$ of charged particles

$v_2(0-10%) < v_2(10-30%) \sim v_2(30-50%)$
First observation of $v_3 > 0$ for charm!

$v_3$ for charged particle larger than $D^0$ $v_3$ although not fully significative given current uncertainties
Comparison with models

we need **charm quark diffusion** to describe the magnitude of the D meson $v_2$ (?)
Charmonia and bottomonia
prompt $J/\psi$ in pPb vs $p_T$ at 5 TeV

$1.5 < y_{CM} < 1.93$

arXiv:1702.01462

→ Significant decrease of $R_{pA}$ at low $p_T$ in the forward region as expected in presence of shadowing
prompt $J/\psi$ in pPb vs $p_T$ at 5 TeV

→Significant decrease of $R_{pA}$ at low $p_T$ in the forward region as expected in presence of shadowing

→$R_{pA}>1$ in the full $p_T$ range
prompt $J/\psi$ in pPb vs rapidity at 5 TeV

$R_{pA}$ decreases when going from backward to forward rapidities

Models that include shadowing slightly underestimated the $R_{pA}$ but well reproduce the rapidity-trend
Forward/Backward $J/\psi$ in pPb

Event activity = transverse energy deposited in the Hadron Forward calorimeters

Forward/Backward asymmetry increases when going to “central” events

arXiv:1702.01462
Prompt $\psi(2S)$ in pPb

$R_{pPb}(\psi(2S)) < R_{pPb}(J/\psi)$ at backward rapidity (Pb-going direction)
→ initial state expected to be similar for 1s and 2s states
→ are we observing a different “final state” interaction for the two states?
Prompt charmonia
- J/ψ (arXiv:1610.00613)
  \( p_\perp \in [6.5, 30] \text{ GeV}/c, |y| < 2.4, \text{ Cent. 0-5\%} \)
- \( \psi(2S) \) (PRL 113, 2014)
  \( p_\perp \in [6.5, 30] \text{ GeV}/c, |y| < 1.6 \)

Bottomonia
- \( p_\perp \in [0, 20] \text{ GeV}/c, |y| < 2.4 \)
  (arXiv:1611.01510)
- \( \Upsilon(1S) \)
- \( \Upsilon(2S) \)
- \( \Upsilon(3S) \) 95\% C.L.

This was the state of the art at 2.76 TeV.

What happens when we move to 5.02 TeV and we increase the statistics?
$|y| < 0.9$ ; $9 < p_T < 12$ GeV/c
Cent: 0-100%

$1.6 < |y| < 2.4$ ; $3 < p_T < 30$ GeV/c
Cent: 0-20%

~350/µb collected during 2015 PbPb run!
J/ψ and ψ(2s) double ratio at 5.02 TeV

Central rapidity |y| < 1.6

Larger relative suppression at 5.02 TeV w.r.t. to 2.76 TeV
→ 3σ effect in the centrality integrated sample

arXiv:1611.01438
J/ψ and ψ(2s) double ratio at 5.02 TeV

Forward rapidity $1.6 < |y| < 2.4$

No indication of enhancement of the double ratio in central events at 5.02 TeV

→ Still not understood! No evidence of bugs/problems in the 2.76 at the moment…. 
Still no sign of $\Upsilon(3s)$ even with large statistics sample
Still no sign of $\Upsilon(3s)$ even with large statistics sample

Very high precision measurement of upsilon sequential suppression → compatible with theoretical calculations

CMS PAS HIN-16-008
Evidence of stronger suppression of Y(1S) at 5.02 TeV with respect to 2.76 as expected in case of a hotter and denser medium → difference due to energy very well described by models

CMS PAS HIN-16-008
Summary (I)

- Charm and beauty production well described by pQCD calculations
- pPb compatible with binary scaling → needs for more precise measurements
- Hints of flavour dependence at low $p_T$
- Flavour dependence seems to vanish at higher $p_T$ → precise rapidity dependent measurement needed and higher statistics non prompt J/ψ at 5 TeV
- Evidence of charm flow!
Summary (II)

- Precise measurement of $J/\psi$ in pPb vs rapidity → compatible with shadowing
- $R_{pA}(J/\psi) < \psi(2s)$ → different final state effect?

- Stronger suppression of $\psi(2s)$ wrt $J/\psi$ at 5.02 TeV!
- Precise measurement of sequential suppression at 5.02 TeV
BACKUP
**heavy quark production mechanism**

**LO process: Flavour Creation (FCR)**
- $b\bar{b}$ produced back-to-back in azimuthal plane and symmetric in $p_T$

**NLO process: Flavour Excitation (FEX)**
- $b\bar{b}$ pairs produced asymmetric in $p_T$ and with a broad opening angle

**NLO process: Gluon splitting (GSP)**
- produced with small opening angles and asymmetric in $p_T$
- $bb$ are not involved in the hard scattering but produced later
Flavour-dependence of radiative energy loss:

- Larger for gluons than for quarks
  - E.g. in BDMPS model \[1\] \( \langle \Delta E \rangle \propto \alpha_s C_R q L^2 \)
  - Dead cone effect: gluon radiation suppressed at small angles for massive quarks

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]

\( \rightarrow \) In-medium energy loss as a consequence of radiative and collisional processes.

\( \rightarrow \) Produced early in the collision, they strongly interact with the deconfined medium

\( \rightarrow \) \( R_{AA}^B > R_{AA}^D > R_{AA}^{\text{light}} (??) \)
Heavy-flavours in pp and pPb collisions

Heavy quarks produced in high $Q^2$ processes at early stages of the collisions

**pp:**
- test of pQCD calculations
- reference for pA and AA measurements

**pPb:**
- test of cold nuclear matter effects
  - PDF modifications
  - saturation
  - final state effects
- collective evolution (hydro?)

Heavy-flavours in PbPb collisions

Heavy quark energy loss in PbPb:
- collisional vs radiative component

Flavour dependence energy loss:
- $\langle \Delta E \rangle \propto \alpha_s C_R q L^2$
- Dead cone effect: gluon radiation suppressed at small angles for massive quarks

Collective behaviour:
- $v_n$ measurements to study collective behaviour of heavy quarks
- charm recombination in medium?
Charmonia in heavy-ion collisions

Charmonia are bound states of \( c\bar{c} \)

\[
\tau_{\text{formation}}^{c\bar{c}} \lesssim \tau_{\text{formation}}^{QGP} < \tau_{\text{life}}^{QGP} < \tau_{\text{quarkonium decay}}
\]

The presence of QGP should affect charmonia production (yield and kinematics)

Less bounded states melts at lower temperature

\[
T_{\text{diss}}^{(1S)} > T_{\text{diss}}^{(2S)} > \ldots
\]

We should observe a hierarchy in the dissociation of different quarkonia states depending on their binding energies
Charmonia are bound states of $\bar{c}c$

$$\tau_{\text{formation}}^{\bar{c}c} \lesssim \tau_{\text{formation}}^{\text{QGP}} < \tau_{\text{life}}^{\text{QGP}} < \tau_{\text{quarkonium decay}}$$

The presence of QGP should affect charmonia production (yield and kinematics).

Less bounded states melts at lower temperature

$$T_{\text{diss}}^{(1S)} > T_{\text{diss}}^{(2S)} > \ldots$$

But life is not that easy, charm (re)combination in the medium is expected to play a significant role at LHC!
Bottomonia, a cleaner probe for the QGP

Y(nS) states are less likely to be created via recombination!
## HF models overview

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<td>fragmentation</td>
<td>QGP transport coefficient fixed at RHIC and LHC (same value)</td>
</tr>
</tbody>
</table>

[1506.03981]
Our experimental tools

- Displayed $J/\psi$ from $B$ decays

Semi-leptonic electrons and muons from c and b quarks

Fully reconstructed D meson decays:
- $D^0 \rightarrow K^- + \pi^+$
- $D^+ \rightarrow K^- + \pi^+ + \pi^+$
- $D^{*+} \rightarrow D^0 + \pi^+$
- $D^{+}_{s} \rightarrow \phi + \pi^+$
Our experimental tools

Fully reconstructed B meson decays:

- $B^+ \rightarrow J/\psi \ K^+ \rightarrow \mu^+ \mu^- \ K^+$
- $B^0 \rightarrow J/\psi \ K^{0*} \rightarrow \mu^+ \mu^- \ K^+ \pi^-$
- $B_s \rightarrow J/\psi \ \phi \rightarrow \mu^+ \mu^- \ K^+ \ K^-$

- tagged c- and b-jets
  - standard jet reconstruction
  - tagging based on the displacement with respect to the primary vertex
B\bar{B} \Delta\phi correlations

**NLO process: Gluon splitting (GSP)**

→ produced with small opening angles and asymmetric in \( p_T \)

\[ \Delta\phi \]

B\bar{B} correlations strongly affected by gluon splitting processes at low \( \Delta\phi \)

Gluon splitting (GS) contribution not well modelled by most of the calculations

→ GS contribution underestimated by models

\[ \Delta\phi(B-\bar{B}) \]

[Image of CMS plot with data points and theoretical curves, labeled JHEP 1103:136,2011]
$R_{pA}$ well described by Cold Nuclear Matter (CNR) models and consistent with unity at high $p_T$!

*Not possible to discriminate between various models with current uncertainties*
$D^0$ meson $R_{pA}$ at 5.02 TeV

LHCb $D^0$ measurement at 5.02 TeV in forward (F) and backward (B) region as a function of transverse momentum and rapidity.

$R_{pA}$ and $R_{FB}$ described by NLO prediction that include EPS09 parametrisation of the nuclear PDFs.
CMS b-jet nuclear modification factor in pPb

CMS b-jet $R_{pA}$ in bins of transverse momentum and pseudo-rapidity

PYTHIA $R_{pA}$ consistent with unity as a function of $p_T$ and pseudo-rapidity

CMS, PLB 754 (2016) 59
Heavy flavour leptons: LHC vs. RHIC

ALICE heavy flavour muons (c,b→μons) in pPb collisions at 5.02 TeV

Models with CNM describe forward/backward rapidity at LHC

forward (shadowing)
backward (anti-shadowing)

PRL112 (2014) 252301
Heavy flavour leptons: LHC vs. RHIC

ALICE heavy flavour muons ($c, b \rightarrow \mu$) in pPb collisions at 5.02 TeV

Models with CNM describe forward/backward rapidity at LHC → Not possible at RHIC!

PHENIX, $c, b \rightarrow \mu$ muons

forward (shadowing)
backward (anti-shadowing)

PRL112 (2014) 252301
D meson $R_{AA}$ in 0-10%

**ALICE $D^0$ $R_{AA}$ $|y|<0.5$ at 2.76 TeV**

Strong suppression at 2.76 TeV:
same suppression for $D^0, D^+, D^{*+}$

**CMS $D^0$ $R_{AA}$ $|y|<1.0$ at 5.02 TeV**

Similar suppression at 5.02 TeV:
Rising trend observed when going to high $p_T$
Several models describe the data within uncertainties:

- **hints at low $p_T$ that collisional energy loss is non negligible**
- **pure collisional models can describe the $R_{AA}$ up to high $p_T$ (??)**
- **shadowing improve description of the data at low $p_T$**
Strong suppression in central PbPb events:

same suppression for $D^0, D^+, D^{*+}$ indicate independence from fragmentation

**ALICE** and **CMS** in good agreement

*Differences at higher $p_T$ due to different pp references*
Strong suppression observed at 5.02 TeV

Rising trend observed when going to high $p_T$

Similar suppression observed at 2.76 and 5.02 TeV by CMS and ALICE

Caveat: different rapidities
According to this model, the difference $R_{AA}$ for non prompt $J/\psi$ and $B$ can be attributed to a difference in the $E_{\text{loss}}$ of charm and beauty quarks.
Flavour dependence of $E_{\text{loss}}$ at 2.76 TeV

Open beauty: nonprompt $J/\psi$
- $6.5 < p_T < 30$ GeV/c, $|y| < 1.2$

Open charm: prompt D (ALICE)
- $8 < p_T < 16$ GeV/c, $|y| < 0.5$

Light hadrons: $\pi^\pm$ (ALICE)
- $8 < p_T < 16$ GeV/c, $|y| < 0.5$

No change in the physics message when comparing to the final result of non prompt $J/\psi$ $R_{AA}$ from CMS
we need **charm quark diffusion** to describe the magnitude of the D meson $v_2$!
Positive $v_2$ for muons from heavy-flavour decays (b+c) at LHC:

- include the contributions of beauty to $v_2$ that is currently unknown
- $v_2$ of heavy flavour muons < $v_2$ ($D^0$) from ALICE
The $B^+$ $R_{AA}$ at 5.02 TeV and non-prompt $J/\psi$ at 2.76 fully compatible within uncertainties!

**BIG CAVEAT:** different energies!
How do we reconstruct B mesons in CMS?

→ Clean and high statistics sample collected by triggering on muons!
v$_2$ of non prompt J/$\psi$

v$_2$ of non prompt J/$\psi$ in PbPb collisions at 2.76 TeV

\[ \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \]

\[ \text{CMS} \]

\[ \begin{array}{c}
\text{Open beauty: nonprompt J/$\psi$} \\
+ \text{, } 1.6 < |y| < 2.4 \\
\star \text{, } |y| < 2.4 \\
\text{MC@sHQ + EPOS (Cent. 20-60%, } |y| < 1) \\
\text{B (K=0.8)} \\
\text{B (K=1.5)} \\
\text{NP J/$\psi$ (K=0.8)} \\
\text{NP J/$\psi$ (K=1.5)} \\
\end{array} \]

\[ p_T \text{ (GeV/c)} \]

\[ V_2 \]

\[ 0 \quad 0.05 \quad 0.1 \quad 0.15 \quad 0.2 \quad 0.25 \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16 \]

→ Compatible within uncertainties with theoretical calculations

Looking to see the new measurement with Run2 data with higher statistics!

Inclusive $J/\psi$

- **Prompt component:** affected by color screening and regeneration in the QGP
- **Nonprompt component:** reflects $E_{\text{loss}}$ of $b$ quarks in the medium

Separation of components based on **pseudo-proper decay length** ($\ell_{J/\psi}$):

$$\ell_{J/\psi}^{3D} = L_{xy} \cdot \frac{m_{J/\psi}}{p_{\mu\mu}}$$

This talk: prompt charmonia

Ta-Wei Wang’s talk (8th): nonprompt charmonia & full B reconstruction
Two techniques to separate components:

1. **2D fits of dimuon mass and pseudo-proper decay length**

   ![Graphs showing 2D fits of dimuon mass and pseudo-proper decay length](Image)

2. **Rejecting nonprompt using a cut on $\ell J/\psi$**
   (can be used with low stats: $\Psi(2S)$ analyses)

   Correction (from data) to account for remaining nonprompt contamination:
   - Using reverted $\ell J/\psi$ cut
   - MC efficiency of $\ell J/\psi$ cut

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Note: The equations and figures are placeholders. In a real scenario, they would be replaced with appropriate mathematical expressions and graphical representations.
$\psi(2S)/J/\psi$ vs $p_T$

CMS

PbPb 351 $\mu$b$^{-1}$, pp 28.0 pb$^{-1}$ (5.02 TeV)

- $|y| < 1.6$, 0-100%
- $1.6 < |y| < 2.4$, 0-100%

Prompt only

- $R_{AA}(\psi(2S))/R_{AA}(J/\psi) < 1$ in all bins → $\psi(2S)$ is more suppressed than $J/\psi$
- No $p_T$ dependence within uncertainties
- X. Du and R. Rapp: transport model with temperature dependent reaction rates
  → $\psi(2S)$ regenerated later than $J/\psi$ in the fireball evolution?

95% CL where no significant $\psi(2S)$ signal in PbPb
CMS results vs centrality, \( p_T \) and rapidity can help to constrain the model:

- Relative contribution of primordial and regenerated charmonia
- Dissociation and regeneration rates
- Temperatures at which \( J/\psi \) and \( \psi(2S) \) regenerate
- …
Comparison to theoretical calculations

**Strong suppression observed for non prompt J/φ in PbPb collisions**

*Clear suppression as a function of p_T*

**CMS non prompt 1.6<|y|<2.4**

**CMS non prompt |y|<2.4**