Heavy quarks and Quarkonia probes of the QGP in CMS

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on behalf of the CMS Collaboration
Heavy quarks produced in high energy pp collisions can be used to test pQCD calculation

In heavy ion collisions, they interact with the created hot and dense medium

Combined with light quarks, they allow the study of flavor dependence of in-medium interaction

pPb data can help us to understand initial state modification of heavy quark production and cold nuclear matter effects

CMS measurements:
- In PbPb collisions: b-jets and B $\rightarrow$ J/$\psi$
- In pPb collisions: b-jets and exclusive b-meson production
**b-jets in pPb and PbPb collisions**

- **In PbPb collisions:** Clear suppression of b-jets as a function of collision centrality
- **In pPb collisions:** Result is consistent with a small Cronin enhancement
- **b-Jet R_{AA}** is heavily suppressed compared to R_{pA} indicative of strong in-medium effects
In PbPb collisions at 2.76 TeV, b-quark energy loss was also measured via non-prompt J/ψ.

The suppression of beauty is different at low $p_T$ compared to high $p_T$ charged hadrons → Mass effect (?)
Exclusive B mesons

- B-meson reconstructed by combination of
  - $J/\psi$ (decayed dimuon)
  - tracks (charged pion or kaon)
- Kinematic range covered
  - $p_T$: $10 - 60$ GeV/c
  - rapidity: $|y_{CM}| < 1.93$

$B^0$ Decay Vertex

$B^0$:
- $m = 3.10$ GeV/c$^2$
- $c\tau = 456$ µm
- Primary Collision Vertex

$B_0$:
- $m = 0.89$ GeV/c$^2$
- Primary Collision Vertex

$B^+$ Decay Vertex

$B^+$:
- $m = 3.10$ GeV/c$^2$
- $c\tau = 492$ µm
- Primary Collision Vertex

$B_S$ Decay Vertex

$B_S$:
- $m = 1.02$ GeV/c$^2$
- $c\tau = 456$ µm
- Primary Collision Vertex
Differential cross-section in pPb

\[
\frac{d\sigma^B}{dp_T}|_{|y_{CM}|<1.93} = \frac{1}{2\Delta y \Delta p_T} \frac{N^B}{(Acc \times \epsilon) \cdot BR \cdot L_{int}}.
\]

✓ pp reference: FONLL expectation is used
✓ agreement with CDF and CMS(ATLAS) data
✓ calculated in [link](http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html)
Nuclear modification factor: $R_{pA}^{\text{FONLL}}$

\[ R_{pA}^{\text{FONLL}}(p_T) = \frac{\frac{d\sigma}{dp_T} pPb}{A \times \left( \frac{d\sigma^{\text{FONLL}}}{dp_T} pp \right)} \]

$|y_{\text{CM}}| < 1.93$

✓ $R_{pA}^{\text{FONLL}}$ is compatible with unity within given uncertainties for three B-mesons
Rapidity dependence

\[ R_{FB} = \frac{N_{\text{corr forward}}}{N_{\text{corr backward}}} \]

Rapidity dependence of B⁺ production

Forward-Backward ratio \( R_{FB} \) is unity within large uncertainties

CMS Preliminary

\[ p+Pb \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ L_{\text{int}} = 34.8 \text{ nb}^{-1} \]

\[ \frac{d\sigma}{dy_{CM}} \text{(pb GeV}^{-1}\text{.c}) \]

\[ 10<p_T<60 \text{ GeV/c} \]
Quarkonia in CMS

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

$\psi(2S)$

$J/\psi$

$\rho, \omega, \phi$

$\Upsilon(1,2,3S)$

$L_{\text{int}}(\text{PbPb}) = 147 \mu b^{-1}$

$p_T^\mu > 4$ GeV/c

$m_{\mu\mu}$ (GeV/c$^2$)
Physics motivation: Quarkonia in PbPb

✓ **Quarkonia as a probe of deconfinement via colour screening**
  ✓ If $\lambda_D(T) < r$ → screening
    → melting of the bound state
    → yields suppressed
  ✓ *Matsui and Satz, PLB 178 (1986) 416*

✓ **Sequential suppression of the quarkonium states**
  ✓ Screening at different T for different states → sequential melting
  ✓ *Digal, Petreczky, Satz, PRD 64 (2001) 0940150*

✓ **Enhancement via (re)generation of quarkonia, due to the large heavy-quark multiplicity**
  ✓ *Andronic, Braun-Munzinger, Redlich, Stachel, PLB 571(2003) 36*

✓ **Cold Nuclear Matter effects (CNM effects), such as nuclear absorption and gluon shadowing**
J/ψ separation

Inclusive J/ψ

prompt J/ψ

Non-prompt J/ψ
form B decays

Direct J/ψ

Feed-down from
ψ(2S) and χ_c

CMS Preliminary CMS PAS HIN-12-014
PbPb √s_{NN} = 2.76 TeV

N_{J/ψ} = 2424 ± 58
σ = 35 ± 1 MeV/c²

L_{int} = 150 μb⁻¹

|y| < 2.4
6.5 < p_T < 30 GeV/c
Cent. 0-10%

Events / (0.002 GeV/c²)

Events / (0.035 mm)

ℓ_{J/ψ} = L_{xy} \frac{m_{J/ψ}}{p_T}
No significant dependence for $R_{AA}$ vs. rapidity and $p_T$

- $R_{AA}$ vs. centrality:
  - 0-5% factor ~ 5 suppression
  - 60-100% factor ~ 1.4 suppression
Less suppression seen for low $p_T \ J/\psi$ (ALICE) compared to high $p_T \ J/\psi$ (CMS)

Sign of (re)generation for low $p_T \ J/\psi$
Prompt J/ψ Azimuthal Anisotropy

- Low $p_T$ (3-6.5 GeV/c) measured in forward region (1.6<|y|<2.4)
- No strong dependences on centrality, $p_T$, rapidity
At low $p_T$: $v_2$ prompt $J/\psi < v_2$ charged hadrons and $v_2$ $D$ mesons (ALICE)

At high $p_T$: $8 < p_T < 10$ GeV/c: similar $v_2$ for prompt $J/\psi$ and charged hadrons

→ Path-length dependence of partonic energy loss in a deconfined medium?
Double ratio of prompt $\psi(2S)$

- **Double Ratio**
  - $40$-$100\%$ (high $p_T$): upper limit $0.45 \pm 0.13\text{ (stat.)} \pm 0.06\text{ (syst.)}$ with $95\%$ CL.
  - $0$-$20\%$ (low $p_T$): $2.31 \pm 0.55\text{ (stat.)} \pm 0.27\text{ (syst.)}$ with $2.2\sigma$ significance
Sequential suppression of the three states in order of their binding energy

- Clear suppression of $\Upsilon(2S)$
- $\Upsilon(1S)$ suppression consistent with excited state suppression (~50% feed down)
- [0-100%]:
  
  $R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08$ (stat.) $\pm 0.07$ (syst.)
  
  $R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04$ (stat.) $\pm 0.02$ (syst.)
  
  $R_{AA}(\Upsilon(3S)) < 0.1$ (at 95% C.L.)

Sequential suppression of the three states in order of their binding energy
Bottomonia: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ in pPb

Signal extraction same procedure in pp, pPb and PbPb:

- Unbinned maximum log likelihood with 1S, 2S/1S, 3S/1S variables in the fit. For signal: 3 Crystal-Ball functions. For background: errorFunction x exponential (all background parameters free)
$\Upsilon (nS)/\Upsilon (1S)$ decrease with increase of charged-particle multiplicity in both pp and pPb: reflect an influence of the particles on the $\Upsilon$ and/or reflect a different multiplicity associated with the $\Upsilon$ states production.
No significant dependence for PbPb results as function of $N_{\text{tracks}}$ and $E_{T}|\eta|>4$, but we have large uncertainties (more PbPb data needed)
Different $<E_T>$: 3.5 (pp), 14.7 (pPb), 760 GeV(PbPb)

N_{Track}: less coherent behaviour (related to the $Y(nS)/Y(1S)$) variation

pp: multi-parton interaction
Conclusion

Heavy quarks

✓ b-Jet $R_{AA}$ is heavily suppressed compared to $R_{pA}$ indicative of strong in-medium effects

✓ First measurement of exclusive B-mesons, with $R_{pA}$ found compatible with unity

Quarkonia

✓ Non-zero $J/\psi$ $v_2$ (3.8σ significance) in PbPb collisions, and no dependence as a function of $p_T$, rapidity and centrality

✓ Double ratio of $\psi(2S)$: clear difference mid-rapidity (high $p_T$) and forward rapidity (low $p_T$). Mid-rapidity (high $p_T$) : suppressed as predicted by sequential melting, Forward rapidity (low $p_T$) : opposite trend to sequential melting but regeneration?

✓ PbPb: sequential suppression of three $\Upsilon$ states at LHC

✓ pPb: $\Upsilon(nS)/<\Upsilon(nS)>$: increase with increasing event activity in pp, pPb and PbPb
Source of peaking background

✓ B⁺
  ✓ lower mass : B⁺ decays J/ψ + resonant meson decayed to kaon + X
  ✓ B⁺ mass : B⁺ decays J/ψ + pion misidentified as kaon

✓ B⁰
  ✓ B decayed to J/ψ + track + track
    ✓ (ex. B⁰→J/ψ K(1270)⁰, B⁺→J/ψ K(1270)⁺)
  ✓ Bₛ⁰→J/ψ φ (K misidentified as π), B⁰→ J/ψ K⁺ π⁻
  ✓ B⁺ decays J/ψ + X

✓ Bₛ⁰
  ✓ no peaking structure
Reconstruction of B meson

- $B^+$ : $J/\psi + 1$ track (kaon)
- $B^0$ : $J/\psi + 2$ tracks (kaon + pion)
- $B_s$ : $J/\psi + 2$ tracks (kaon + kaon)

- Charged tracks and muons are reconstructed within $|\eta| < 2.4$
- Trigger muon $p_T > 3\text{GeV}/c$
- Assigned the mass of kaon or pion to charged track
Reconstruction of B meson

- **B^+**: J/ψ + 1 track (kaon)
- **B^0**: J/ψ + 2 tracks (kaon + pion)
- **B_s**: J/ψ + 2 tracks (kaon + kaon)

Charged tracks and muons are reconstructed within |eta| < 2.4
- Trigger muon p_T > 3GeV/c
- assigned the mass of kaon or pion to charged track
Signal Extraction 1 – B⁺

- **Signal**: double Gaussian

- **Background**
  - Combinatorial background 1st-order polynomial
  - Peaking structure
- \( B^+ \rightarrow J/\psi + \) (decayed to kaon + X)
Signal Extraction 2 – $B^0$

- **Signal**: double Gaussian

- **Background**
  - Combinatorial background 1st-order polynomial
  - Peaking structure
    - $B \rightarrow J/\psi$ track + track
    - $B \rightarrow J/\psi +$ phi meson (Kaon misidentified as pion)

CMS Preliminary  
$pPb \sqrt{s_{NN}} = 5.02$ TeV  
$10 < p_T < 15$ GeV/c  
$L_{int} = 34.8$ nb$^{-1}$
Signal Extraction 2 – $B^0$

Lower mass peak due to $B_s$ background

- Entries / (30 MeV/c)
- $B^0$ meson with incorrect mass
- $m = 3.10 \text{ GeV/c}^2$
- $m = 1.02 \text{ GeV/c}^2$
- $B_s$ Decay Vertex
- $B_s$ meson
- Primary Collision Vertex
- Assumed to be a $K^*$
- Assumed to be a pion

CMS Preliminary $p\bar{p}$ $\sqrt{s} = 5.02 \text{ TeV}$

$10<\not{p}_T<15 \text{ GeV/c}$

$L_{\text{int}} = 34.8 \text{ nb}^{-1}$

$\Phi$ vertex $\gamma = 456 \mu m$

$\mu^+$

$\mu^-$

$K^+$

$K^-$
• **Signal**: double Gaussian

• **Background**
  - Combinatorial background 2\textsuperscript{nd}-order polynomial
  - no peaking background structure

CMS Preliminary $p\text{Pb} \sqrt{s_{NN}} = 5.02$ TeV

$10<p_T^{B}<60$ GeV/c

$L_{\text{int}} = 34.8$ nb$^{-1}$

$B_s^0$
Self-normalized ratios for excited states