LHC Heavy Ion Physics
Lecture 6: Quarkonia and Heavy Quarks

HUGS 2015

Bolek Wyslouch
Techniques to study the plasma

Radiation of hadrons

Azimuthal asymmetry and radial expansion

Energy loss by quarks, gluons and other particles

Suppression of quarkonia
Production and suppression of quarkonia

• Bound states of heavy quarks produced inside plasma are being used as an indicator of plasma temperature and density

• Comparison of production of quarkonia between ion-ion, proton-ion and proton-proton collisions show several interesting effects that can be interpreted in terms of plasma properties
  – $J/\psi$, $\psi'$ suppression and recombination
  – Properties of $\Upsilon$ family
Quarkonia as a tool to probe the QGP

Different states have different binding energies
Loosely bound states “melt” first!

Successive suppression of individual states provides a “thermometer” of the QGP
Flavor dependence of parton energy loss

- From QCD:
  - Color charge:
    \[ E_{\text{loss}} \text{ in gluons} > E_{\text{loss}} \text{ in quarks} \]
  - Kinematics: “Dead cone effect”:
    \[ E_{\text{loss}} \text{ in quarks} > E_{\text{loss}} \text{ in heavy quarks} \]
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\[ c \rightarrow D^* \]

\[ b \rightarrow B (\rightarrow l\nu D^*) \]

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PLB 512 (2001) 30-48

EPJC 16 (2000) 597-611

\[ \langle x_E(D^*) \rangle_{cc} = 0.4878 \pm 0.0046 \pm 0.0061 \]
\[ \langle x_B^{\text{wd}} \rangle = 0.7163 \pm 0.0061 \text{ (stat)} \pm 0.0056 \text{ (syst)} \]

**b \rightarrow B** harder than **c \rightarrow D** harder than **q/g \rightarrow h**
Flavor dependence of parton energy loss

• From QCD
  • Color charge:
    \[ E_{\text{loss}} \text{ in gluons} > E_{\text{loss}} \text{ in quarks} \]
  • Kinematics: “Dead cone effect”:
    \[ E_{\text{loss}} \text{ in quarks} > E_{\text{loss}} \text{ in heavy quarks} \]

Heavy Quark vs. Light Quark:
Changing the ratio of collisional and radiative energy loss
→ Determination of the elastic energy loss coefficient (\( \hat{\sigma} \))

Heavy flavor jet and hadron analyses cover a wide kinematics range
→ Suppression of induced radiation at low \( p_T \) and the disappearance of this effect at high \( p_T \)
Quarkonia production at LHC

Charmonium production

- Inclusive J/ψ
- B→J/ψ
- Prompt J/ψ
- Direct J/ψ
- ψ',χc→J/ψ

CMS - $\sqrt{s} = 7$ TeV
$L = 37$ pb$^{-1}$

JHEP 1202 (2012) 011
Charmonium production

- Inclusive $J/\psi$
- $B \to J/\psi$
- Prompt $J/\psi$
- Direct $J/\psi$
- $\psi', \chi_c \to J/\psi$

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<table>
<thead>
<tr>
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<tr>
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<td>$B \to J/\psi$</td>
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<td>PRL</td>
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Bottomonium production

- Prompt $\Upsilon(1S)$
- Direct $\Upsilon(1S)$
- $\Upsilon(2S,3S), \chi_b \to \Upsilon(1S)$

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- $L = 37$ pb$^{-1}$
- JHEP 1202 (2012) 011
- CDF, PRL 84 (2000) 2094
Charmonium production

Inclusive J/Ψ

B→J/Ψ

Prompt J/Ψ

Direct J/Ψ

ψ', χc→J/Ψ

Stopping / scattering power of QGP

Temperature / Screening length

Bottomium production

Prompt Υ(1S)

Direct Υ(1S)

Direct Υ(1S)

Y(2S,3S), Xb...→Υ(1S)

CDF, PRL 84 (2000) 2094

CMS - √s = 7 TeV

L = 37 pb⁻¹

JHEP 1202 (2012) 011

CDF, PRL 84 (2000) 2094

J/Ψ; |y| < 0.9

J/Ψ; 0.9 < |y| < 1.2

ψ (2S); |y| < 1.2

Direct 51%

Y(2S)+Y(3S) 11%

Xb(2P) 11%

Xb(1P) 27%
Leptons from heavy quarks

Primary vertex

Secondary vertex

$\mu^+$

$\mu^-$

$K^+$

Sample $O(10\%)$ of b cross-section
Leptons from heavy quarks

Dileptons channel sample $O(0.1\%)$ of $b$ cross-section
Leptons from heavy quarks

Non-prompt J/ψ

J/ψ+1(2) tracks decay channels sample $O(0.01\%)$ of b cross-section
Leptons from heavy quarks

Non-prompt J/ψ

Secondary vertex

Primary vertex

Exclusive B meson decays

b-jet reconstruction
b-tagged jet sample $O(100\%)$ of b cross-section and ~70-90% of the b quark energy
Leptons from heavy quarks

Non-prompt $J/\psi$

Exclusive $B$ meson decays

Requirement: flexible trigger system, muon / electron detection, secondary vertex reconstruction, jet reconstruction
CMS Detector

**Inner tracker:** charged particles, vertex, isolation

**EM and Hadron calorimeters:** photons, isolation, jet reco

- Tracker $|\eta| < 2.5$
- ECAL $|\eta| < 3.0$
- HCAL $|\eta| < 5.2$
- Muon $|\eta| < 2.4$

**Track impact parameter resolution:**
- $100 \mu m$ @ 1 GeV/c
- $20 \mu m$ @ 20 GeV/c
Quarkonia production: Dimuons

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV
$\Upsilon(1, 2, 3S)$

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

$p_T^\mu > 4$ GeV/c

$m_{\mu\mu}$ (GeV/c$^2$)
Prompt and non-prompt $J/\psi$

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

$L_{\text{int}} = 7.28 \mu$b$^{-1}$

Cent. 0-100%, $|y| < 2.4$

$6.5 < p_T < 30$ GeV/c

$\sigma = 34$ MeV/c$^2$

Events / (0.02 GeV/c$^2$)

**Inclusive $J/\psi$**

**$B \rightarrow J/\psi$**

**Prompt $J/\psi$**

**Direct $J/\psi$**

$\psi', \chi_c \rightarrow J/\psi$

CMS PAS HIN-12-014
J/ψ $R_{AA}$ vs. centrality in PbPb collisions

CMS: Prompt J/ψ
- $|y|<2.4$ and $p_T > 6.5$ GeV/c

ALICE: inclusive J/ψ
- $|y|<0.9$ and $p_T > 0$
- $2.5<|y|<4.0$ and $p_T > 0$
- Includes $\sim 10\%$ non-prompt J/ψ from b decays
CMS observed non-zero prompt J/ψ v₂ in PbPb collisions
At high pₜ: related to path length dependent energy loss
Smaller than inclusive hadron v₂
Double ratio \( \frac{\frac{\psi(2S)}{J/\psi}_{PbPb}}{\frac{\psi(2S)}{J/\psi}_{pp}} > 1 \)

→ \( \psi(2S) \) is less suppressed compared to \( J/\psi \) in central PbPb collisions

PRL 113 (2014) 262301
Quarkonia production: Dimuons

CMS Preliminary

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

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

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

$p_T^\mu > 4 \text{ GeV/c}$

$m_{\mu\mu} (\text{GeV/c}^2)$
0-100% $R_{AA}$ ($\Upsilon(3S)$) $<$ 0.1 (at 95% C.L)
Sequential suppression of the three states in order of their binding energy
0-100% $R_{AA}$ ($Y(3S)$) <0.1 (at 95% C.L)
Sequential suppression of the three states in order of their binding energy
Suppression of the five quarkonia in PbPb collisions

The suppression of 5 quarkonia was observed in PbPb

- Well-ordered with binding energy: Quarkonia melt in quark matter
- Caveat: Including feed-down, recombination ...
Upsilon resonances in pp, pPb, and PbPb collisions.

Double ratios in pPb are larger than in PbPb, indicating final state effects in PbPb.

JHEP 04 (2014) 103
Y(2S)/Y(1S) ratios as a function of event activities

Vs. forward calorimeter transverse energy

Vs. mid-rapidity track multiplicity

Y(2S)/Y(1S) ratio decreases as a function of event activity!

(1) More associated yield with Y(1S)?
(2) Large event size (multiplicity) affects Y states?
(b)-jet Quenching

Leptons from heavy quarks

Primary vertex

Secondary vertex

b-jet reconstruction

Non-prompt J/ψ

Exclusive B meson decays

Leptons from heavy quarks

Primary vertex

Secondary vertex

b-jet reconstruction

Non-prompt J/ψ

Exclusive B meson decays
b-jet Production Mechanisms

Flavor Creation (FCR)  Flavor Excitation (FEX)  Gluon Splitting (GSP)

At NLO:
- Excitation of sea quarks $\rightarrow b(\bar{b}) + $ light dijet, w/ $b(\bar{b})$ at beam rapidity
- Gluon splitting into $b$ and $\bar{b}$ which can be reconstructed as a single jet

LO $b-\bar{b}$ production (FCR) sub-dominant at the LHC

E-loss of split gluons can be different from primary $b$ quarks
Heavy Flavor Jets

• Standard flavor definition used in CMS:
  o If there is a b quark within $\Delta R<0.3$ from jet axis, then it’s a b jet
  o Same for c jets, except b quarks take priority

• HF jet = HF hadron + energy in cone
  • HF hadron need not be fully reconstructed
  • b quark need not be primary (for instance $g \rightarrow b\bar{b}$), although typically assumed for e-loss calculations!
Tagging and Counting b-quark Jets

Select b-tagged jets using “Secondary Vertex Tagger”

b-jet purity:

From template fits to secondary vertex mass distributions using templates from PYTHIA+(HI background) Monte Carlo simulation

CMS HIN-12-003
PRL 113, 132301 (2014)

CMS PAS HIN-14-007
PbPb b-Jet Spectra

- Efficiency corrected and resolution unfolded spectra plotted for both PbPb and pp
- b jets in PbPb is scaled by $T_{AA}$
- Clear indication of b-jet suppression seen

CMS HIN-12-003
PRL 113, 132301 (2014)
• Evidence of b-jet suppression in PbPb collisions
• Suppression favors pQCD model with stronger jet-medium coupling
• Are there cold nuclear effects contributing to the observed suppression?
**pPb b-jet Spectra**

- **b-jet spectra shown for various selections in $\eta_{CM}$**
- **pPb Spectra scaled by $T_{pPb}$ to be compared to PYTHIA reference**
- **Minimal suppression or enhancement is observed**

CMS PAS HIN-14-007
b-jet Fraction and $R_{pPb}$ in pPb Collisions

- Measured b-jet fraction is consistent with PYTHIA prediction
- b-jet $R_{pA}$ is consistent with unity within the quoted systematical uncertainty
- Suppression of b-jet in PbPb collisions is not from initial / cold nuclear effects

CMS PAS HIN-14-004
Three component fit for signal extraction:

- **Signal**
- Combinatorial background from J/ψ-track(s)
- Non-prompt component from other B-meson decays that form peaking structures (e.g. in B⁺ analysis, bkg from B⁰ → J/ψ K⁰*)

Fully reconstructed B meson signal in heavy ion collisions!
Nuclear Modification Factors: \( R_{pA}^{FONLL} \)

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

\( R_{pA}^{FONLL} \) is compatible with unity within given uncertainties for the three B-mesons.

\(|y_{CM}| < 1.93\)

CMS PAS HIN-14-004
b-jets vs. Fully Reconstructed B Mesons

Measurements of nuclear modification factors of b-jet and B mesons are consistent with unity over a wide $p_T$ range.

CMS PAS HIN-14-004

CMS PAS HIN-14-007
Flavor Dependence of Jet Quenching

Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low $p_T$
(However, spectra slope are different)

Pb+Pb
Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low $p_T$

(However, spectra slope are different)

$b$ quark jet (quark jet) ~ inclusive jet (dominated by gluon jets)?

Contribution from gluon splitting?
Summary

• Quarkonia production is strongly affected by the hot plasma. The pattern of suppression depends on the strength of bonding. Work to interpret it as a measure of plasma properties is in progress.

• Jets containing heavy quarks can be clearly identified in collider detectors. The pattern of suppression provides important handle to energy loss calculations.
Summary of the lecture series

• We discussed general ideas behind the goals of the heavy ion physics field: study of hot nuclear matter that existed about 1 microsecond after the Big Bang
• We discussed several different ways in which we try to experimentally characterize the properties of such matter
• We discussed some of the conclusions from the measurements and pointed “things to do”
• We expect new understand coming from the upcoming runs at LHC and RHIC, I hope that these lectures will help you understand the context of the results to come