Quarkonia in heavy-ion collisions at RHIC and LHC

JaeBeom Park, Korea University

— ATHIC 2021 —
Quarkonia in QGP

**J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION**

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If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents cc binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.
Quarkonia color screening

\[ T \ll T_c \]

![Diagram showing quarkonia states and color screening](image)
Quarkonia color screening

$T \ll T_c$  

$T \approx 1.1 T_c$
Quarkonia color screening

$T \ll T_c$

$T \approx 1.1 T_c$

$T \approx 2 T_c$
Quarkonia color screening

Sequential melting by color screening

Quarkonia as thermometer of QGP
Not that simple anymore...
Quarkonia in heavy-ion collisions

- Dynamic screening: Dissociation even for $T_{QGP} < T_{Melting}$
  $\rightarrow$ Imaginary part [JHEP 03 (2007) 054]

[Universe 2019, 5(5), 119]
Quarkonia in heavy-ion collisions

- **Dynamic screening**: Dissociation even for $T_{\text{QGP}} < T_{\text{Melting}}$
  $\rightarrow$ Imaginary part \[ \text{JHEP 03 (2007) 054} \]

- **Recombination**
  - Uncorrelated recombination
  - Correlated recombination

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Universe 2019, 5(5), 119

JHEP 03 (2007) 054
Quarkonia in heavy-ion collisions

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**Feed down contribution**

[Particle Data Group], Prog. Theor. Exp. Phys. 2020, 083C01 (2020)
**Quarkonia in heavy-ion collisions**

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- **Cold Nuclear Matter effect**
  - nPDF, CGC, nuclear absorption, cronin effect, comover breakup,
    [IJMP E 24 (2015) 1530008]

- **Feed down contribution**
  - [[Particle Data Group], Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]
**Puzzle of quarkonium production**

- **Quarkonium production**
  - Perturbative in heavy quark pair
  - Non-perturbative in the evolution to bound state

- **Various hadronization models**: QSM, QEM, NRQCD, ...
  - Tension b/w models and data in low/high $p_T$
  - LO NRQCD transverse polarization at high $p_T$ (not seen in data up to 60 GeV/c) vs NLO CSM longitudinal polarization

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![Image of CMS logo](https://example.com/cms-logo.png)

**CMS**

**Korea University**

**EPJC 78 (2018) 562**

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**Quarkonium production**

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![Graphs and plots](https://example.com/plots.png)

**ALICE inclusive $J/\psi$, 2.5$<y<$4**

- $p_T$ = 13 TeV
- $L_{int} = 3.2 \text{ pb}^{-1} \pm 3.4\%$
- BR uncert.: 0.6\%

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**Helicity**

- **Collins-Soper**
- **NLO CSM**
- **NLO NRQCD**
- **NLO NRQCD2**
Puzzle of quarkonium production

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  - Non-perturbative in the evolution to bound state

- Various hadronization models: QSM, QEM, NRQCD, ...
  - Tension b/w models and data in low/high $p_T$
  - LO NRQCD transverse polarization at high $p_T$ (not seen in data up to 60 GeV/c) vs NLO CSM longitudinal polarization

Production mechanism still unknown since the “November Revolution” in 1974 (47 years)
What have we learned with charmonia?

\[ R_{AA} = \frac{dN_{AA}}{dN_{pp}} \frac{dN_{pp}/d\phi}{dN_{coll}/d\phi} = \frac{\text{"hot/dense QCD medium"}}{\text{"QCD vacuum"}} \]

\[ \frac{dN}{d\phi} \sim v_2 \cos[2(\phi - \Phi_{EP})] \]
Suppression and Recombination of J/ψ

\[ R_{AA}(J/ψ) \]

- ALICE PbPb 2.76 TeV, \( p_T > 0 \) GeV/c
- ALICE PbPb 5.02 TeV, \( p_T > 0 \) GeV/c
- STAR AuAu 0.20 TeV, \( p_T > 0.15 \) GeV/c
- PHENIX AuAu 0.20 TeV, \( p_T > 0 \) GeV/c

LHC

RHIC

[PLB 794 (2014) 314]
[PLB 805 (2020) 135434]
[PLB 797 (2019) 134917]
[PRC 84 (2011) 054913]
[EPJC 78 (2018) 909]
[EPJC 78 (2018) 762]
Suppression and Recombination of $J/\psi$

- Gradual decrease vs $N_{\text{part}}$ in RHIC
- Smaller suppression at LHC!

PLB 794 (2014) 314
PLB 805 (2020) 135434
PLB 797 (2019) 134917
PRC 84 (2011) 054912
EPJC 78 (2018) 509
EPJC 78 (2018) 762
Suppression and Recombination of $J/\psi$

- Gradual decrease vs $N_{\text{part}}$ in RHIC
- Smaller suppression at LHC!
- $R_{AA}\text{(RHIC)} \approx R_{AA}\text{(LHC)}$ at high-$p_T$

**Graph:**
- ALICE PbPb 2.76 TeV, $p_T > 0$ GeV/c
- ALICE PbPb 5.02 TeV, $p_T > 0$ GeV/c
- STAR AuAu 0.20 TeV, $p_T > 0.15$ GeV/c
- PHENIX AuAu 0.20 TeV, $p_T > 0$ GeV/c
- CMS PbPb 5.02 TeV, $p_T > 6.5$ GeV/c
- ATLAS PbPb 5.02 TeV, $p_T > 9$ GeV/c

**References:**
- [PLB 794 (2014) 314]
- [PLB 805 (2020) 135434]
- [PLB 797 (2019) 134917]
- [PRC 84 (2011) 054912]
- [EPJC 78 (2018) 509]
- [EPJC 78 (2018) 762]
Suppression and Recombination of J/ψ

Recombination at low-\(p_T\)!

ALICE PbPb 2.76 TeV, \(p_T > 0\) GeV/c
ALICE PbPb 5.02 TeV, \(p_T > 0\) GeV/c
STAR AuAu 0.20 TeV, \(p_T > 0.15\) GeV/c
PHENIX AuAu 0.20 TeV, \(p_T > 6.5\) GeV/c
CMS PbPb 5.02 TeV, \(p_T > 9\) GeV/c
ATLAS PbPb 5.02 TeV, \(p_T > 0\) GeV/c

LHC

RHIC

\[ R_{AA}(J/ψ) \]

\[ ψ(J/ψ)(AA) R > 0.5 \]

\[ ψ(J/ψ)(AA) R > 0 \]

\[ ψ(J/ψ)(AA) R > 1.5 \]

\[ ψ(J/ψ)(AA) R > 2 \]

\[ ψ(J/ψ)(AA) R > 2.5 \]

\[ ψ(J/ψ)(AA) R > 3 \]

\[ ψ(J/ψ)(AA) R > 3.5 \]

\[ ψ(J/ψ)(AA) R > 4 \]

\[ ψ(J/ψ)(AA) R > 4.5 \]

\[ ψ(J/ψ)(AA) R > 5 \]

\[ ψ(J/ψ)(AA) R > 5.5 \]

\[ ψ(J/ψ)(AA) R > 6 \]

\[ ψ(J/ψ)(AA) R > 6.5 \]

\[ ψ(J/ψ)(AA) R > 7 \]

\[ ψ(J/ψ)(AA) R > 7.5 \]

\[ ψ(J/ψ)(AA) R > 8 \]

\[ ψ(J/ψ)(AA) R > 8.5 \]

\[ ψ(J/ψ)(AA) R > 9 \]

\[ ψ(J/ψ)(AA) R > 9.5 \]

\[ ψ(J/ψ)(AA) R > 10 \]

\[ ψ(J/ψ)(AA) R > 10.5 \]

\[ ψ(J/ψ)(AA) R > 11 \]

\[ ψ(J/ψ)(AA) R > 11.5 \]

\[ ψ(J/ψ)(AA) R > 12 \]

\[ ψ(J/ψ)(AA) R > 12.5 \]

\[ ψ(J/ψ)(AA) R > 13 \]

\[ ψ(J/ψ)(AA) R > 13.5 \]

\[ ψ(J/ψ)(AA) R > 14 \]

\[ ψ(J/ψ)(AA) R > 14.5 \]

\[ ψ(J/ψ)(AA) R > 15 \]

\[ ψ(J/ψ)(AA) R > 15.5 \]

\[ ψ(J/ψ)(AA) R > 16 \]

\[ ψ(J/ψ)(AA) R > 16.5 \]

\[ ψ(J/ψ)(AA) R > 17 \]

\[ ψ(J/ψ)(AA) R > 17.5 \]

\[ ψ(J/ψ)(AA) R > 18 \]

\[ ψ(J/ψ)(AA) R > 18.5 \]

\[ ψ(J/ψ)(AA) R > 19 \]

\[ ψ(J/ψ)(AA) R > 19.5 \]

\[ ψ(J/ψ)(AA) R > 20 \]

\[ ψ(J/ψ)(AA) R > 20.5 \]

\[ ψ(J/ψ)(AA) R > 21 \]

\[ ψ(J/ψ)(AA) R > 21.5 \]

\[ ψ(J/ψ)(AA) R > 22 \]

\[ ψ(J/ψ)(AA) R > 22.5 \]

\[ ψ(J/ψ)(AA) R > 23 \]

\[ ψ(J/ψ)(AA) R > 23.5 \]

\[ ψ(J/ψ)(AA) R > 24 \]

\[ ψ(J/ψ)(AA) R > 24.5 \]

\[ ψ(J/ψ)(AA) R > 25 \]

\[ ψ(J/ψ)(AA) R > 25.5 \]

\[ ψ(J/ψ)(AA) R > 26 \]

\[ ψ(J/ψ)(AA) R > 26.5 \]

\[ ψ(J/ψ)(AA) R > 27 \]

\[ ψ(J/ψ)(AA) R > 27.5 \]

\[ ψ(J/ψ)(AA) R > 28 \]

\[ ψ(J/ψ)(AA) R > 28.5 \]

\[ ψ(J/ψ)(AA) R > 29 \]

\[ ψ(J/ψ)(AA) R > 29.5 \]

\[ ψ(J/ψ)(AA) R > 30 \]

\[ ψ(J/ψ)(AA) R > 30.5 \]

\[ ψ(J/ψ)(AA) R > 31 \]

\[ ψ(J/ψ)(AA) R > 31.5 \]

\[ ψ(J/ψ)(AA) R > 32 \]

\[ ψ(J/ψ)(AA) R > 32.5 \]

\[ ψ(J/ψ)(AA) R > 33 \]

\[ ψ(J/ψ)(AA) R > 33.5 \]

\[ ψ(J/ψ)(AA) R > 34 \]

\[ ψ(J/ψ)(AA) R > 34.5 \]

\[ ψ(J/ψ)(AA) R > 35 \]

\[ ψ(J/ψ)(AA) R > 35.5 \]

\[ ψ(J/ψ)(AA) R > 36 \]

\[ ψ(J/ψ)(AA) R > 36.5 \]

\[ ψ(J/ψ)(AA) R > 37 \]

\[ ψ(J/ψ)(AA) R > 37.5 \]

\[ ψ(J/ψ)(AA) R > 38 \]

\[ ψ(J/ψ)(AA) R > 38.5 \]

\[ ψ(J/ψ)(AA) R > 39 \]

\[ ψ(J/ψ)(AA) R > 39.5 \]

\[ ψ(J/ψ)(AA) R > 40 \]
Suppression and Recombination of J/ψ

- **ATLAS**
  - Prompt J/ψ, 5.02 TeV, 1 < |y| < 2, 0 - 60%
  - Inclusive J/ψ, 5.02 TeV, 2.5 < y < 4, 20 - 40%
  - Prompt J/ψ, 2.76 TeV, 1.6 < |y| < 2.4, 10 - 60%
  - Prompt J/ψ, 2.76 TeV, |y| < 2.4, 10 - 60%

- **LHC**
  - ALICE, Prompt J/ψ, 5.02 TeV, 0 - 60%
  - CMS, Prompt J/ψ, 5.02 TeV, 2.5 < y < 4, 20 - 40%
  - ATLAS, Prompt J/ψ, 5.02 TeV, 0 - 60%

- **RHIC**
  - STAR, AuAu 0.20 TeV, 0 - 20%
  - PHENIX, AuAu 0.20 TeV, 0 - 20%

- Large $v_2$ at low-$p_T$ due recombination!
- Recombination at low-$p_T$!
Successful work on theory side including recombination-like processes
Deeper look at $R_{AA}$ & $v_2$

Still problems to describe $R_{AA}$ and $v_2$ at the same time (Not only for quarkonia..)
Deeper look at $R_{AA}$ & $v_2$

- **B fraction** $\sim 30\%$ @ $p_T = 8$ GeV/c
  - different $v_2^{\text{beauty}}$ vs $v_2^{\text{charm}}$ $\rightarrow$ need to separate prompt / nonprompt $J/\psi$

- **We still do not have a precise/reliable prompt $J/\psi$ $v_2$ in PbPb!**
  - Large Unc. (CMS), Inclusive only (ALICE), High-$p_T$ only and wide cent. (ATLAS)
  - Collectivity of $J/\psi$ in pp? What about $\psi(2S)$ flow in PbPb? etc.
What about bottomonia?
Bottomonium measurement

$R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$

Large suppression of $\Upsilon(3S)$ in all intervals
Bottomonium measurement

Consistent results among LHC experiments

[PLB 790 (2019) 270]

CMS

PbPb 368/464 \mu b^{-1}, pp 28.0 pb^{-1} (5.02 TeV)

\( p_T < 30 \text{ GeV} \)

\( |y| < 2.4 \)

\( \Upsilon(1S) \)

\( \Upsilon(2S) \)

\( \Upsilon(3S) \)

68\% CL

95\% CL

Cent. 0-100\%

PbPb 5.02 TeV

\( p_T < 30 \text{ GeV/c}, |y|<2.4 \)

\( T_p < 15 \text{ GeV/c}, 2.5<y<4 \)

\( T_p < 30 \text{ GeV/c}, |y|<2 \)

\( (\text{Preliminary}) p_T < 30 \text{ GeV/c}, |y|<2 \)

\( \Upsilon(1S) \)

\( \Upsilon(2S) \)

\( \Upsilon(3S) \)

68\% CL

95\% CL

(1S)

(2S)

(3S)

\[ \text{Consistent results among LHC experiments} \]
Bottomonia : Plenty theory models

- Bottomonia (1S), (2S), and (3S)

- référence: [EPJC (2019) 79:147]
- référence: [PRC 88 044908]
- référence: [PLB 778 (2018) 384]
- référence: [JHEP10(2018) 094]
- référence: [PLB 801 (2020) 135147]
- référence: [Universe 6050061]
- référence: [J. Phys.: Conf. Ser. 779 012041]
- référence: [arXiv:2107.06222]
- référence: [EPJC (2019) 79:147]
RHIC vs LHC

- Expect larger suppression at LHC in theory
- Compatible suppression in data?
Upsilon in sPHENIX

Current dimuon mass plot

\[ Y \rightarrow \mu^+\mu^- \]

2014-2016 data

sPHENIX projection

- Could be resolved with sPHENIX program

\[ Y(\text{ns}) \rightarrow e^+e^- \]

\[ Y(1s) \]

\[ \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \]

p+p, 197 pb\(^{-1}\) signal only

\[ \sigma_{1S} = 83 \pm 1.2 \text{ MeV} \]
Y flow measurement

- Low-\( p_T \): Collectivity of bottom quark?
- High-\( p_T \): Path-length dependence energy loss? (\( p_T \gg m \))

1. **No flow** signal found for \( \Upsilon(1S) \) and \( \Upsilon(2S) \)

2. Much smaller \( v_2 \) than \( J/\psi \)!
   - No large collectivity as charm

3. Still large uncertainties
   - Constraints on Blast-Wave model
Bottomonium flow measurement

- **Y** has much smaller velocity compared to other species
  - Low-$p_T$: $v_Y < v_{QGP}^{flow}$ \(\rightarrow\) Cannot escape QGP
  - Intermediate $p_T$: $v_Y \simeq v_{QGP}^{flow}$ \(\rightarrow\) Long effective travel distance (depending on axis direction) \(\rightarrow\) Even possible negative $v_2$
  - High-$p_T$: $v_Y > v_{QGP}^{flow}$ \(\rightarrow\) Experience initial geometry from fast QGP escape

- **Y** mesons very slow! \(\rightarrow\) Even possible negative $v_2$? (Different effective path-length)
Combined picture

CMS Supplementary

Light

- $h^+$
- $B^+ \mid y \mid < 2.4$
- $(b \to d) D^0$
- $(b \to J/\psi)$

Charm

- $D^0 + \overline{D^0}$
- $1.8 < \mid y \mid < 2.4$
- $\mid y \mid < 2.4$

$R_{AA}$ and lumi. uncert.

$T_{AA}$ and lumi. uncert.

$\mid y \mid < 1$

Cent. 0-100%

5.02 TeV pp (27.4 pb$^{-1}$) + PbPb (530/404/368 μb$^{-1}$)

$5.02 \text{ TeV pp (27.4 pb}^{-1}) + \text{PbPb (530/404/368 μb}^{-1})$

$R_{AA}$ & $v_2$ converge at high-$p_T$

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Combined picture

Hierarchy of $v_2$ in low-$p_T$ region

$v_2$ of $b$-quark flat?

$Y(1S) \approx 0$
Going to smaller collision systems
Charmonia in pPb

- Agreement with nPDF modification for J/ψ
- Additional suppression for ψ(2S) : hint for comover breakup

ALICE, Inclusive ψ(2S), J/ψ → μ⁺μ⁻
p-Pb |ΔN₂N₂| = 8.16 TeV, pₜ < 12 GeV/c
• ψ(2S)
• J/ψ (JHEP 07 (2018) 160)

ALICE, p-Pb |ΔN₂N₂| = 8.16 TeV, Inclusive J/ψ, ψ(2S) → μ⁺μ⁻
−4.46 < yₜ < −2.96, pₜ < 20 GeV/c
Transport Model (Du and Rapp) ψ J/ψ (2S)
Comovers + EPS09LO (Ferreiro) ψ J/ψ (2S)
EPS09sNLO + CEM (Vogt et al.) ψ J/ψ (2S)
Energy loss (F. Arleo et al.) ψ J/ψ (2S)
Bottomonium in pPb

Similar trend observed in previous charmonia results
**Y pPb at LHC**

1. Sequential suppression: $R_{pPb}(Y(1S)) > R_{pPb}(Y(2S)) > R_{pPb}(Y(3S))$

2. Possible description with comover interaction model
Flow in pPb

CMS

pPb 186 nb⁻¹ (8.16 TeV)

- Still not clear the feature of finite J/ψ $v_2$
- Compatible with prompt D⁰
Getting closer...
**J/ψ in jets**

- **J/ψ produced with much more jet-activity**
- **Fixed order pQCD is not enough to understand J/ψ isolation**
**J/ψ in jets**

- Efforts to describe data with Gluon fragmentation / Fragmentation jet functions
- Better description than LO NRQCD
- $c\bar{c}$ (and $J/\psi$) might not always produced at early stages!

Produced by parton shower
Later time produced
low $z$
**J/ψ in jets**

- Lower z
  - Later produced by parton shower
  - Larger interaction in jet-activity

Larger suppression for more jet-activity surrounding
J/ψ in jets

Rising $R_{AA}$ vs $p_T$ and large $v_2$ at high-$p_T$ of prompt J/ψ

→ Probably connected with jet quenching? → What about Y mesons?
Decrease of \( \frac{Y(nS)}{Y(1S)} \) vs multiplicity in pp -> pPb collisions
**Y in pp w UE study**

- **Decrease of Y(nS)/Y(1S) vs multiplicity in pp -> pPb collisions**

- **No decrease for forward rapidity?**
  - Need further investigations

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**Figure Description**

- The CMS plot shows the ratio of $Y(nS)/Y(1S)$ vs multiplicity for different collision energies: 7 TeV, 5.02 TeV, and 2.76 TeV. The ratio decreases with increasing track multiplicity.

- In ALICE preliminary results, for pp collisions at 13 TeV, the ratio $Y(2S)/Y(1S)$ and $\psi(2S)/J/\psi$ are shown. There is no significant decrease for the ratio in forward rapidity.

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**References**

- [JHEP 11 (2020) 001]
$\Upsilon$ in pp w UE study

$\Upsilon$ / $\Upsilon(1S)$

If $\Upsilon$-particle correlation only
$$\rightarrow$$ Only affect forward region

Decreasing trend for all regions: **Linked with UE!**

- No clear ordering
- Note: $\Upsilon p_T > 7$ GeV/c

[JHEP 11 (2020) 001]
**Y in pp w UE study**

No dependence of $N_{\text{tracks}}$ within cone $\Delta R<0.5$

Different from comover model expectation
(n.b. $p_T>7$ GeV/c / need to compare multiplicity ranges)

Decrease disappears in low-sphericity

Connection with UE for jetty events?

\[
S_T \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2} \quad S^T_{xy} = \frac{1}{\sum_i p_T^i} \sum_i \frac{1}{p_T^i} \left( \begin{array}{c} p_{xi}^2 \\ p_{yi}^2 \end{array} \right)
\]

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New/Exotic results and future prospects
### P-wave state in pPb

![Graph showing data and fits](image)

- **First measurement of chi-states in pPb**
- **Agreement with pp measurements**

**Legend:**
- Data
- Total fit
- Background
- $\chi_1$ signal
- $\chi_2$ signal

- LHCb
- pPb $\sqrt{s_{NN}} = 8.16$ TeV
- Converted photons
- $1.5 < y^* < 4.0$

- Converted
- Calorimetric
- pp $\sqrt{s} = 7$ TeV
Feed down

\[
\mathcal{G}(mL')/\mathcal{G}(nL) \equiv \frac{\sigma(p p \rightarrow \mathcal{G}(mL') + X)}{\sigma(p p \rightarrow \mathcal{G}(nL) + X)} \times \mathcal{B}(\mathcal{G}(mL') \rightarrow \mathcal{G}(nL) + \ldots)
\]

- Feed down calculated by cross section ratios and branching ratio
- Strongly dependent on \(p_T\)

[F. Damas Honex]

Feed-down fractions to \(Y(1S)\), no global uncertainties
$X(3872)$

$\rho^{PbPb} = 1.08 \pm 0.49 \text{ (stat)} \pm 0.52 \text{ (syst)}$
Bc in PbPb

Larger RAA values compared to B+ or D mesons / quarkonia at low-pt

Becomes closer to other species at high-pt
Bc comparison with theory

Transport model including correlated & uncorrelated recombination

Do not include recombination of excited Bc states
Summary

- Significant amount of work done on quarkonium measurements at RHIC and LHC
- Different in-medium effects of charmonia and bottomonia still under investigation
- Interesting results in small systems
  - need to think about how to implement it into AA collisions
- Still many things to be done in the future
  (P-wave, flow in of excited states, in/with jets etc.)
Back-Up
Low-pT excess

- Increase of cross section with collision energy
- Agreement in peripheral collisions
Path length?

CMS Prompt $D_0$

CMS Prompt $J/\psi$

ALICE Prompt $D_0$

CMS Prompt $D_0$

ALICE $J/\psi$

High-$p_T$ region among different species

- Similar velocity
- Similar suppression
- Similar path-length and $v_2$?

What about recombination?
Bottomonium flow measurement

Much smaller $v_2$ than $J/\psi$!
- No large collectivity as charm

• Important to describe $R_{AA}$ & $v_2$ together on $J/\psi$ & $Y$
Charmonia w statistical recomb.

- NCQ extension to D meson
  → Assume $v_2(p_T)$ scales with NCQ

\[ v_2^\psi(p_T) = v_2^J/\psi(2p_T^\psi)/2 \]
\[ v_2^\pi(p_T) = v_2^\pi(2p_T^\pi)/2 \]
\[ v_2^D(p_T) = v_2^q(p_T^q) + v_2^\pi(p_T^\pi) \]

- Agreement with nearly equal $p_T$ fraction
  - Different w statistical recombination model?
Y with event-activity

CMS $4.8 \text{ fb}^{-1} (7 \text{ TeV})$

$|y^{\mu\mu}| < 1.2$

$Y/(2S) / Y(1S)$

$p_T^{\mu\mu} [\text{GeV]}:$
- 20-50
- 15-20
- 11-15
- 9-11
- 7-9
- 5-7
- 0-5

CMS $4.8 \text{ fb}^{-1} (7 \text{ TeV})$

$|y^{\mu\mu}| < 1.2$

$Y/(3S) / Y(1S)$

$p_T^{\mu\mu} [\text{GeV]}:$
- 20-50
- 15-20
- 11-15
- 9-11
- 7-9
- 5-7
- 0-5
Y with event-activity

CMS

$\frac{\Upsilon(2S)}{\Upsilon(1S)}$ vs $E_T^{jets > 4}$ [GeV]

CMS

$\frac{\Upsilon(2S)}{\Upsilon(1S)}$ vs $N_{tracks}$

CMS
Motivation

J/ψ with event-activity

CMS

Prompt J/ψ

Nonprompt J/ψ

CMS

Preliminary

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$\Xi(E_c; z_1) \equiv \frac{N(E_c; z_1)}{\int_{0.3}^{0.8} N(E_c; z) \, dz}$

$\sim 85\%$ of $J/\psi$ are produced within a jet

($E_{J/\psi} > 15$ GeV, $|y_{J/\psi}| < 1$, $E_{jet} > 19$ GeV, $|\eta_{jet}| < 1$)