Azimuthal anisotropy and nuclear modification of Υ states in heavy-ion collisions with the CMS detector

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Motivation

- **Bottomonia**: Bound states of $b$-quark and anti $b$-quark

- Broadening of spectral function with increasing $T$
- Sequential broadening in order of binding energy
- Peak vanish: State melted
  - $\Upsilon(1S)$ survives up to $\sim 250$ MeV
- Produced by hard scattering at early collision stage

[Diagram showing $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonances]
• Quarkonium production in PbPb collisions at 2.76 TeV
  [JHEP 1205 (2012) 063]

• Suppression of excited $\Upsilon(nS)$ in PbPb at 2.76 TeV
  [PRL 107 (2011) 052302]

• Observation of $\Upsilon(nS)$ suppression at 2.76 TeV
  [PRL 109 (2012) 222301]

• Event activity of $\Upsilon(nS)$ in pPb at 5.02 TeV
  [JHEP 04 (2014) 103]

• Suppression of $\Upsilon(nS)$ in PbPb at 5.02 TeV
  [PLB 770, 357(2017)]

• Suppression of $\Upsilon(nS)$ in PbPb at 5.02 TeV
  [PRL 120 (2013) 142301]

• Nuclear modification of $\Upsilon(nS)$ in PbPb at 5.02 TeV
  [PLB 790 (2019) 270]

• RUN 1
PbPb: $\sqrt{s_{NN}} = 2.76$ TeV, $L = 166 \text{ nb}^{-1}$
pPb: $\sqrt{s_{NN}} = 5.02$ TeV, $L = 34.6 \text{ nb}^{-1}$
pp: $\sqrt{s_{NN}} = 5.02$ TeV, $L = 5.4 \text{ pb}^{-1}$

• RUN 2
2011-2013
PbPb: $\sqrt{s_{NN}} = 5.02$ TeV, $L = 368 \text{ pb}^{-1}$
pp: $\sqrt{s_{NN}} = 5.02$ TeV, $L = 28 \text{ pb}^{-1}$
Outline

**Motivation**

- $\Upsilon(nS)$ in pPb at 5 TeV  
  \[ R_{pPb}(p_T, y_{CM}) = \frac{(d^2\sigma/dp_Tdy_{CM})_{pPb}}{A(d^2\sigma/dp_Tdy_{CM})_{pp}} \]

- $\Upsilon$ elliptic flow ($v_2$) in PbPb at 5 TeV  
  \[ R_{FB}(p_T, y_{CM} > 0) = \frac{N_{pPb}(p_T, y_{CM} > 0)}{N_{pPb}(p_T, y_{CM} < 0)} \]

- Collectivity of particle production (low-$p_T$)
- Path length dependence energy loss (high-$p_T$)

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**Cold Nuclear Matter Effect**
- nPDF modification
- Energy loss
- Comover breakup

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**Initial state effects**

**Final state effects**
**Outline**

- **ϒ(nS) in pPb at 5 TeV** [CMS PAS HIN-18-005]
  - \( R_{pPb}(p_T, y_{CM}) = \frac{(d^2\sigma/dp_Tdy_{CM})_{pPb}}{A(d^2\sigma/dp_Tdy_{CM})_{pp}} \)
  - \( R_{FB}(p_T, y_{CM} > 0) = \frac{N_{pPb}(p_T, y_{CM} > 0)}{N_{pPb}(p_T, y_{CM} < 0)} \)

- **Cold Nuclear Matter Effect**
  - nPDF modification
  - Energy loss
  - Comover breakup

- **ϒ** elliptic flow \( (v_2) \) in PbPb at 5 TeV [CMS PAS HIN-19-002]
  - Collectivity of particle production (low-\(p_T\))
  - Path length dependence energy loss (high-\(p_T\))
Y production in pPb collisions

CMS Preliminary

- Y suppressed for all states in all kinematic region
- No significant $p_T$ dependence for all three states
- Larger suppression of $\Upsilon(3S)$ at low-$p_T$ in the Pb-going side
$\Upsilon$ production in pPb collisions

- Larger suppression of $\Upsilon(3S)$ at low-$p_T$ in the Pb-going side
- Similar behavior as prompt $\psi(2S)$
- Hint of final state effect on excited quarkonium states
**Y in pPb with model comparison**

- Different $R_{pPb}$ for each state in comover model (larger size)
- Larger comover effect for higher comover densities: Pb-going direction
- Model predictions are in agreement with data within uncertainties

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**CMS Preliminary**

- **Y(1S)**
  - $p_{T} < 30$ GeV/c
  - $y_{CM}$
  - $R_{pPb}$
  - CMS
  - Comparison with model predictions:
    - CIM + nCTEQ15
    - CIM + EPS09 LO

- **Y(2S)**
  - $p_{T} < 30$ GeV/c
  - $y_{CM}$
  - $R_{pPb}$
  - CMS
  - Comparison with model predictions:
    - CIM + nCTEQ15
    - CIM + EPS09 LO

- **Y(3S)**
  - $p_{T} < 30$ GeV/c
  - $y_{CM}$
  - $R_{pPb}$
  - CMS
  - Comparison with model predictions:
    - CIM + nCTEQ15
    - CIM + EPS09 LO
\( R_{\text{pPb}} \) comparison with other LHC results

- ALICE, ATLAS, LHCb, CMS \( R_{\text{pPb}} \) at 5.02 TeV
- Consistent results within each other

\( R_{\text{pPb}} \) comparison with other LHC results

- ATLAS, \( p+\text{Pb} \), \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV
  - \( \Upsilon(1S) \), \( p_T < 40 \) GeV
  - \( \Upsilon(1S) \), \( p_T < 15 \) GeV
  - \( \Upsilon(1S) \), \( p_T > 0 \) GeV

\( \Upsilon(1S) \) results from various collaborations:
- ATLAS, CMS, LHCb, ALICE

CMS Preliminary

\( R_{\text{pPb}} \) vs. \( y_{\text{CM}} \)

- \( \Upsilon(1S) \) data
- \( \Upsilon(1S) \) comparison with models

- ATLAS, CMS preliminary
- LHCb, ALICE

- \( \Upsilon(1S) \) at 5.02 TeV
- \( p_T \) distributions

- Comover interaction
  - [PLB 740(2015) 105]
  - [EPJC 78(2018) 171]
  - [JHEP 07(2014) 94]
$\Upsilon$ in pPb vs PbPb

- Suppression in ordering of binding energy
  - $R_{pPb}(\Upsilon(1S)) > R_{pPb}(\Upsilon(2S)) > R_{pPb}(\Upsilon(3S))$

- Larger suppression in PbPb than in pPb
  - $R_{pPb}(\Upsilon(nS)) > R_{AA}(\Upsilon(nS))$

PbPb 368 $\mu$b$^{-1}$, pPb 34.6 nb$^{-1}$, pp 28.0 pb$^{-1}$ (5.02 TeV)

CMS Preliminary

$|y_{CM}| < 1.93$
$|y_{pPb}| < 2.4$
$p_T^\Upsilon < 30$ GeV/$c$

95% CL

[HIN-18-005]
[PLB 790 (2019) 270]
PbPb in 2018

**New data 2018**

- PbPb 2018 partial dataset at $\sqrt{s_{NN}} = 5.02$ TeV
- Trigger selections:
  - double muon inclusive
  - $J/\psi$ region
  - $\Upsilon$ + high masses

**PbPb : $\sqrt{s_{NN}} = 5.02$ TeV, $L \sim 1.7$ nb$^{-1}$**

- Event display: Upsilon candidate

- $p_T^{\Upsilon} > 4$ GeV/c

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

- $\Upsilon > 4$ GeV/c

- CMS Preliminary

- ~4.5 more statistics compared to 2015 data

- New first-time measurement in CMS HI: Elliptic flow ($v_2$) of $\Upsilon$
Outline

- \( \Upsilon(nS) \) in \( pPb \) at 5 TeV \(^{\text{[CMS PAS HIN-18-005]}}\)
  - \[ R_{pPb}(p_T,y_{CM}) = \frac{(d^2\sigma/dp_Tdy_{CM})_{pPb}}{(d^2\sigma/dp_Tdy_{CM})_{pp}} \]
  - \[ R_{FB}(p_T,y_{CM} > 0) = \frac{N_{pPb}(p_T,y_{CM} > 0)}{N_{pPb}(p_T,y_{CM} < 0)} \]

Cold Nuclear Matter Effect
- nPDF modification
- Energy loss
- Comover breakup

- \( \Upsilon \) elliptic flow \( (v_2) \) in \( PbPb \) at 5 TeV \(^{\text{[CMS PAS HIN-19-002]}}\)
  - Collectivity of particle production (low-\( p_T \))
  - Path length dependence energy loss (high-\( p_T \))

Initial state effects
Final state effects

\[ \bar{b} - b - \Upsilon \]
Scalar Product (SP) Method

- Large $\eta$ gap applied ($|\Delta \eta|>3.0$) to remove non-flow effects
- Average denominator & numerator of $v_2\{SP\}$ over all events

\[
Q_n = \sum_j w_j e^{i\phi_j}
\]

\[
v_2\{SP\} = \frac{\langle Q_2^*Q_{2A}^* \rangle}{\sqrt{\langle Q_{2A}Q_{2B}^* \rangle \langle Q_{2A}Q_{2C}^* \rangle}}
\]
Elliptic flow ($v_2$) of $\Upsilon$ in PbPb

- Precise $\Upsilon$(1S) $v_2$ measurement: compatible with zero in all centrality intervals
- First measurement of $\Upsilon$(2S) $v_2$
  - provide new input to production mechanism
  - expect different regeneration than $\Upsilon$(1S)

Centrality (%)

$\Upsilon$(1S)

$\Upsilon$(2S)

CMS Preliminary

PbPb 1.7 nb$^{-1}$ (5.02 TeV)

$\Upsilon^0$ > 3.5 GeV
|y| < 2.4
$p_T^\Upsilon$ < 50 GeV

Centrality intervals:
- 0-10
- 10-30
- 30-50
- 50-90
- 90-100

$\Upsilon$(1S) $v_2$ measurement compatible with zero in all centrality intervals

$\Upsilon$(2S) first measurement
- Provide new input to production mechanism
- Expect different regeneration than $\Upsilon$(1S)
Elliptic flow ($v_2$) of $\Upsilon(1S)$ in PbPb

- $p_T$ $v_2$ measured with high precision
- Compatible with zero over all kinematic range
  - Max. $\sim$2.5 standard dev. ($p_T$ 6–10 GeV/c)

[Figure showing elliptic flow ($v_2$) of $\Upsilon(1S)$ in PbPb with CMS Preliminary 1.7 nb$^{-1}$ (5.02 TeV)].
Elliptic flow ($v_2$) of $\Upsilon(1S)$ vs $J/\psi$

- **CMS**
  - Preliminary
  - PbPb 1.7 nb$^{-1}$ (5.02 TeV)
- **Conditions**
  - $p_T^{\Upsilon(1S)} > 3.5$ GeV
  - $|y| < 2.4$
  - Cent. 10-90%

- **Results**
  - ATLAS, Prompt $J/\psi$, 5.02 TeV, $|y| < 2$, 0 - 60%
  - ALICE, Inclusive $J/\psi$, 5.02 TeV, $2.5 < |y| < 4$, 20 - 40%
  - CMS, Prompt $J/\psi$, 2.76 TeV, $1.6 < |y| < 2.4$, 10 - 60%
  - CMS, Prompt $J/\psi$, 2.76 TeV, $|y| < 2.4$, 10 - 60%

- **Additional Information**
  - Contrast result to $J/\psi$ $v_2$
  - Different medium effect of charmonia and bottomonia

[EPJC 78 (2018) 784]
[PRL 119 (2017) 242301]
[EPJC 77 (2018) 252]
Comparison with ALICE

- $0 < |y| < 2.4$ CMS
- $2.5 < |y| < 4.0$ ALICE

- Similar $\Upsilon(1S) v_2$ for both CMS and ALICE results: compatible with zero
- Precise measurement in CMS with high lumi $\sim 1.7$ nb$^{-1}$
- No $|y|$ dependence found over wide rapidity range
Comparison with models

- Theory calculations with different ingredients
- Overall in agreement with data
- Need more data to provide significant input to theory models

Hong, Lee: HTL perturbation theory
- Used diffusion constant

Yao: Boltzmann transport model
- Real-time open heavy quark dist.

Du, Rapp: kinetic-rate equation
- T dependent binding energy
- Medium effect from lattice-QCD based EOS

Bhaduri et al: 3+1d aHydro model
- Initial T & $\eta/s$ tuned to LHC data
- No recombination

[arXiv:1909.07696]
[arXiv:1812.02238]
[PRC 96(2017) 054901]
[arXiv:1809.06235]
- All three upsilon states in ordered suppression
  : $R_{pPb}(\Upsilon(1S)) > R_{pPb}(\Upsilon(2S)) > R_{pPb}(\Upsilon(3S))$

- Larger suppression in PbPb compared to pPb
  : $R_{pPb} > R_{AA}$

- Precise measurement of $v_2$ for $\Upsilon(1S)$
  : $v_2 = 0.007 \pm 0.011$ (stat.) $\pm 0.005$ (syst.)

- First measurement of $\Upsilon(2S)$ elliptic flow ($v_2$) in heavy-ion collisions
Thank you
Motivation

- Bottomonia measured in pp, pPb and PbPb covering all phase space at 5.02 TeV
- Smaller suppression in pPb compared to PbPb collisions

pPb vs PbPb
\( \Upsilon \) in \( pPb \)

- \( \Upsilon \) suppressed for all states in all kinematic region
- No significant \( p_T \) and rapidity dependence
Y in pPb

CMS Preliminary

- pPb 34.6 nb⁻¹, pp 28.0 pb⁻¹ (5.02 TeV)

Motivation

- ψ (2S) [EPJC 77, 269 (2017)]
  - 6.5 < p_T < 10 GeV/c

CMS Preliminary

- 6 < p_T < 30 GeV/c

CMS Preliminary

- 10 < p_T < 30 GeV/c

Prompt J/ψ [EPJC 77, 269 (2017)]

- 6 < p_T < 30 GeV/c

CMS

- Prompt J/ψ [EPJC 77, 269 (2017)]
  - 10 < p_T < 30 GeV/c

LHCb

- ψ (2S) [EPJC 77, 269 (2017)]
  - 6.5 < p_T < 10 GeV/c

LHCb comovers

- ψ (2S) [EPJC 77, 269 (2017)]
  - 10 < p_T < 30 GeV/c

LHCb comovers

- ψ (2S) [EPJC 77, 269 (2017)]
  - 6.5 < p_T < 10 GeV/c

LHCb comovers

- ψ (2S) [EPJC 77, 269 (2017)]
  - 10 < p_T < 30 GeV/c

LHCb comovers

- ψ (2S) [EPJC 77, 269 (2017)]
  - 6.5 < p_T < 10 GeV/c

LHCb comovers

- ψ (2S) [EPJC 77, 269 (2017)]
  - 10 < p_T < 30 GeV/c
Bottomonia vs Charmonia

Charmonia (EPJC (2018) 78:509)

- Prompt $J/\psi$, $|y| < 2.4$, $6.5 < p_T < 50$ GeV
- Prompt $\psi(2S)$, $|y| < 1.6$, $6.5 < p_T < 30$ GeV

$p_T < 30$ GeV, $|y| < 2.4$

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

68% CL 95% CL

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

CMS

Supplementary

Cent. 0-100%
Elliptic flow ($v_2$) of $\Upsilon$ in PbPb

- Consistent with zero in central and peripheral collisions in overall $p_T$ range
- Similar behavior for mid-centrality collisions (10-50%) as result in 10-90%
- Hint of non-zero $v_2$ in intermediate $p_T$ 6-10 GeV/c
  - $\sim 2.6\sigma$ including sys. & stat. uncertainty