Suppression and elliptic flow of bottomonia in heavy ion collisions at CMS

Jared Jay

UCDAVIS

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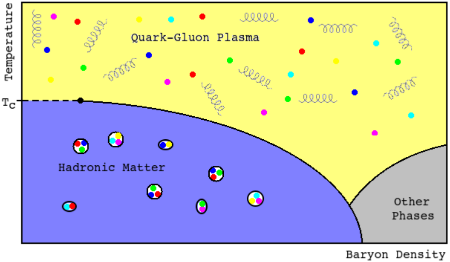
Outline

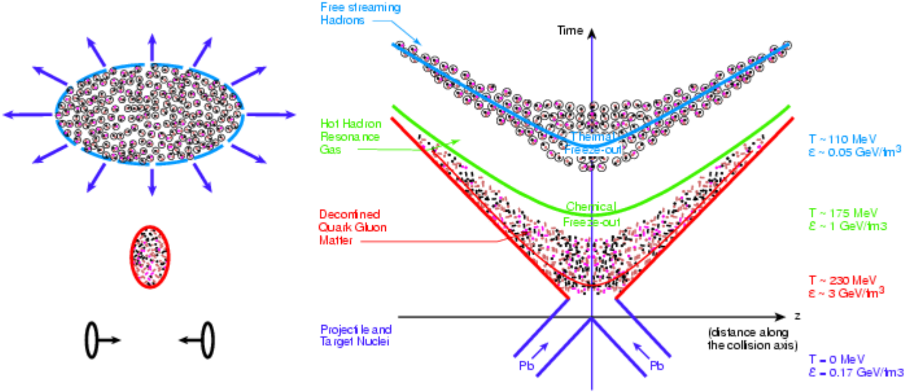
The Quark-Gluon Plasma

- Our research seeks to narrow down the QCD equation of state, and study the properties of the QGP phase, including:
  - Initial-state temperature
  - Viscosity
  - Density
  - etc.
- We can create the QGP by colliding heavy ions (like Pb) at high energies at the LHC.

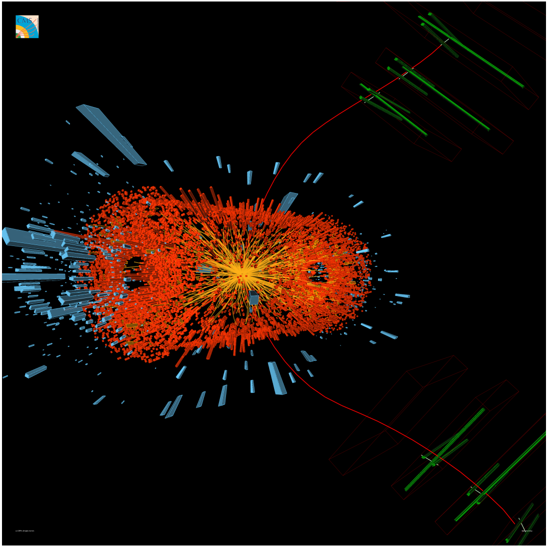
QCD Phase Diagram



Evolution of a heavy-ion collision



The CMS Detector



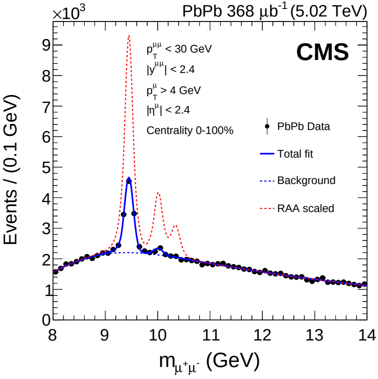
Quarkonia Suppression

Why use heavy quarkonia ($c\bar{c}$ and $b\bar{b}$)?

- Di-muon decay channel. $\rightarrow$Easy for CMS to detect
- Made of colored objects. $\rightarrow$Interact with the QGP
- High mass (especially Υ) compared to the QGP temperatures means production is dominated by the initial hard scatterings. $\rightarrow$Good probe of initial state
- Υ has 3 states which melt at different temperatures. $\rightarrow$We can observe sequential suppression

Quarkonia Suppression

- Heavy quarkonia yields are observed to be suppressed in PbPb compared to pp.
- The ratio of the Υ yield observed in PbPb compared to what we would expect from a superposition of pp collisions is called the Nuclear Modification Factor, R_{AA}.
- In the case of pPb: R_{pA}



(Sirunyan, Albert M et al., arXiv:1805.09215, 2018)

Quarkonia Suppression

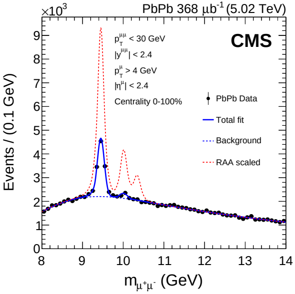
What causes the suppression?
QGP Effects

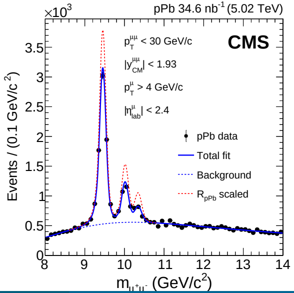
- Color screening.
- Regeneration/Recombination.

Cold nuclear matter (CNM) Effects

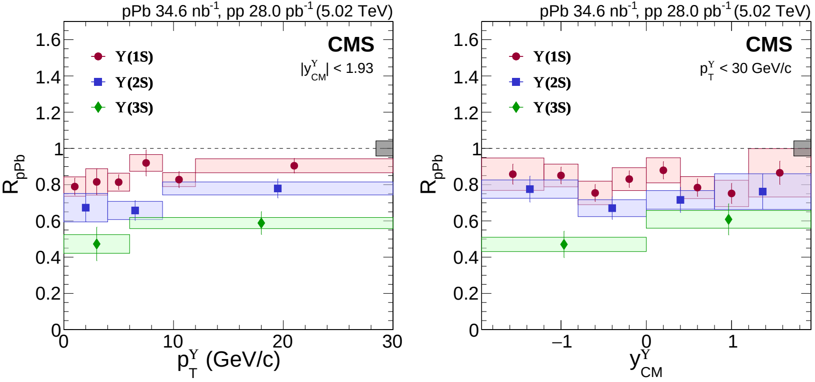
- Shadowing and Anti-shadowing.
- Energy loss.
- Co-movers.

CNM and QGP effects can be separated by comparing PbPb and pPb systems with pp.



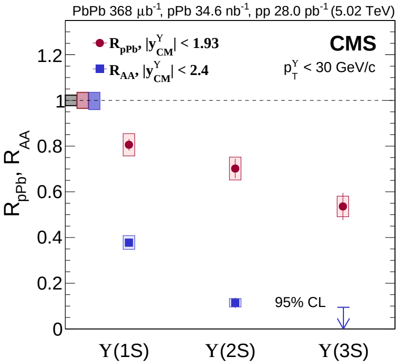


Results: Quarkonia Suppression



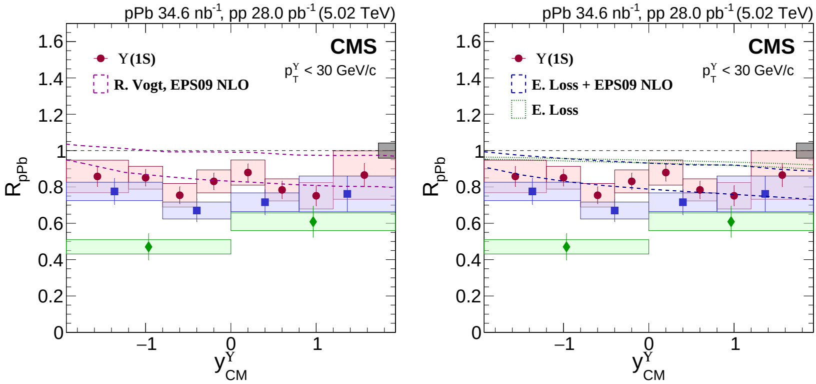
- R_{pPb} tends to increase with p_T.
- Higher states are more suppressed.

Results: Quarkonia Suppression



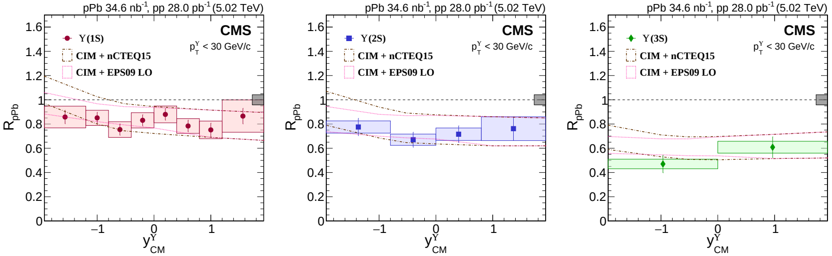
- Suppression is significantly less pronounced than in PbPb for all 3 states, presumably due to the QGP effects in PbPb.
- Higher states are more suppressed.

Results: Quarkonia Suppression



- Comparison with predictions based on CNM effects such as shadowing (EPS09 NLO) and energy loss (E. Loss).
- There is good agreement with the $\Upsilon(1S)$ but not the other 2 states.

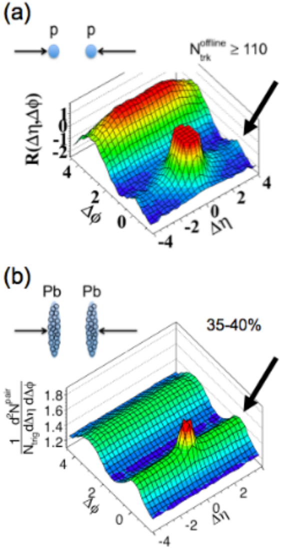
Results: Quarkonia Suppression



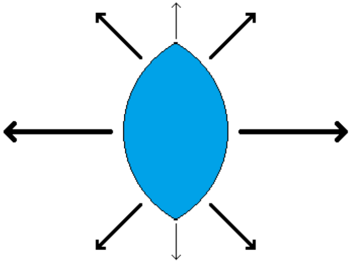
- Comparison with predictions which incorporate sequential suppression via the comover interaction model (CIM) effect.
- These predictions are consistent with data for all three states.

Another way of studying the QGP is through measurements of "elliptic flow".

- Two-particle correlations in PbPb collisions exhibit long-range correlations not seen in pp collisions.
- $\implies$ collective elliptic flow.



Elliptic Flow



$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos(2(\phi - \psi)) + 2v_4\cos(4(\phi - \psi))$$

$$v_n = \langle \cos(n(\phi - \psi)) \rangle$$

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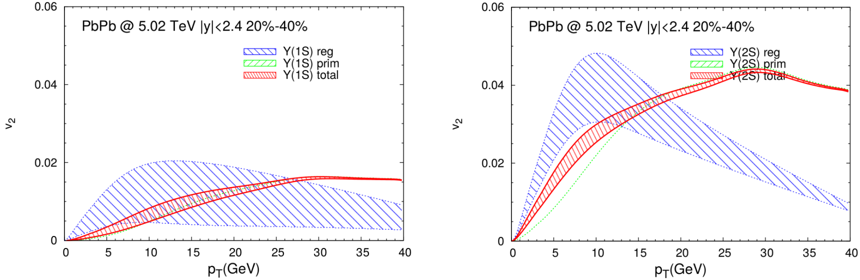
Upsilon v2 Predictions:



Du et al.(2017)Du, Rapp, and He

- The v_2 of Υ's is expected to be very small (< 0.05).
- The v_2 of the $\Upsilon(2S)$ is expected to be about twice as large as the v_2 of the $\Upsilon(1S)$.

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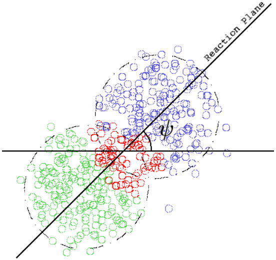
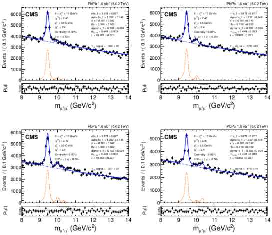
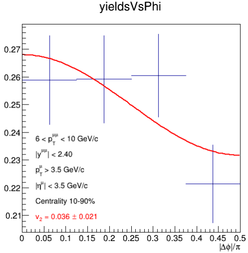
Event-plane method for calculating v_2:







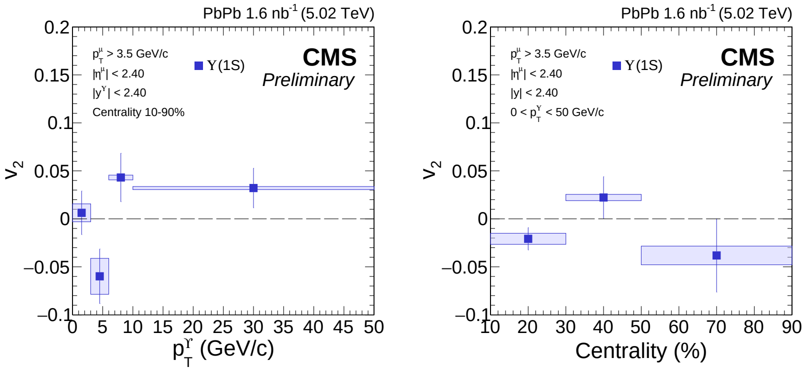
- Determine the event plane for each collision event.
- Fit the invariant mass spectrum in all the kinematic bins.
- Split each bin into 4 $\Delta\phi$ bins and fit them to extract the azimuthal distribution of upsilon yields.
- Fit the distribution $\frac{1}{N^{\Upsilon}_{total}}\frac{dN^{\Upsilon}}{d\phi}$ vs $\Delta\phi$ with the function $1 + 2v_2\cos(2\Delta\phi)$.

Elliptic Flow

Additional analysis steps:

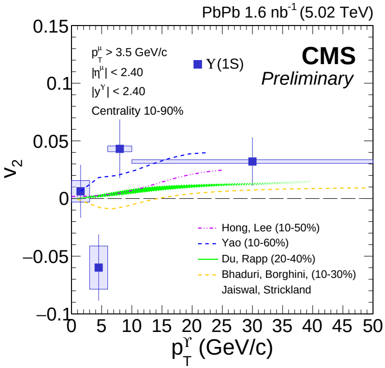
- Re-centering of the event plane
- Flattening of the event plane
- Event-plane resolution correction using the three-sub-event technique
- Acceptance and efficiency corrections

Results: Elliptic Flow



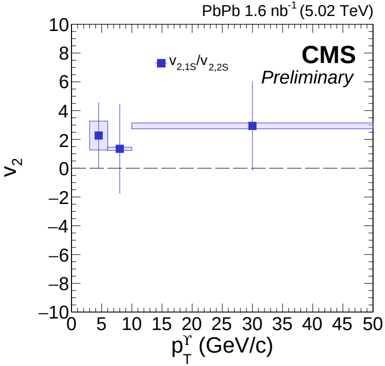
- The elliptic flow is small and consistent with zero.
- This is expected for highly suppressed particles.

Results: Elliptic Flow



- Comparison to theoretical predictions.

Results: Elliptic Flow Ratio



- The ratio of v_2 of the $\Upsilon(2S)$ over v_2 of the $\Upsilon(1S)$ versus p_T hints at a value of about 2.
- Warrants a future study with more data.

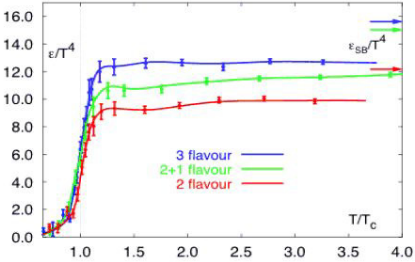
Summary

- The nuclear modification factors R_{AA} and R_{pA} of Υ mesons, measured from PbPb, pPb, and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV at CMS, demonstrate that Υ's are suppressed in heavy ion collisions compared to pp, with significantly more suppression in PbPb compared to pPb.
- Models which incorporate sequential suppression of bottomonia are in better agreement with the data than those which only assume initial-state modification.
- The second-order Fourier coefficients (v2) characterizing the elliptic flow of Υ's in PbPb have been reported, and they are consistent with zero.
- The v_2 of the Υ(2S) appears to be about twice as large as the v_2 of the Υ(1S) versus p_T, in agreement with theoretical predictions, but more data is needed to confirm this.

Backup

The Quark-Gluon Plasma

- At high temperatures and densities, hadronic matter undergoes a phase transition to a state of deconfined quarks and gluons called the quark-gluon plasma (QGP).
- The plot on the right demonstrates this phase transition using calculations from Lattice QCD.



(Altarelli, Guido - arXiv:1303.2842)

The CMS Detector

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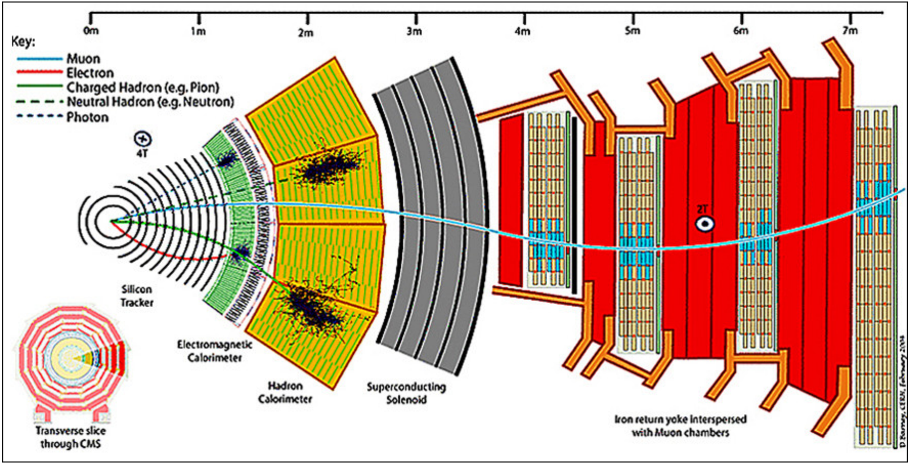
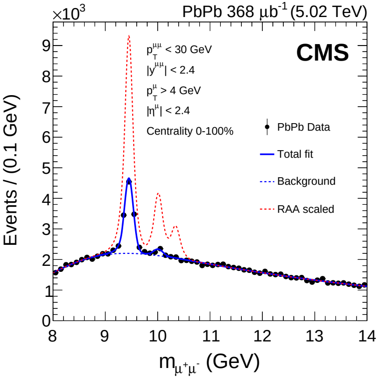


Quarkonia Suppression

- Heavy quarkonia yields are observed to be suppressed in PbPb compared to pp.
- Nuclear Modification Factor:
  $$R_{AA} = \frac{N^{AA}(p_T,y)}{\langle T^{AA}\rangle \sigma^{pp}(p_T,y)}$$
- In the case of pPb:
  $$R_{pA} = \frac{\sigma^{pA}(p_T,y)}{A\sigma^{pp}(p_T,y)}$$

where $\sigma^{pp}(p_T, y) = \frac{N^{pp}/(a \cdot \varepsilon)}{\mathcal{L}_{int}\Delta p_T \Delta y}$.



(Sirunyan, Albert M et al., arXiv:1805.09215, 2018)

Quarkonia Suppression

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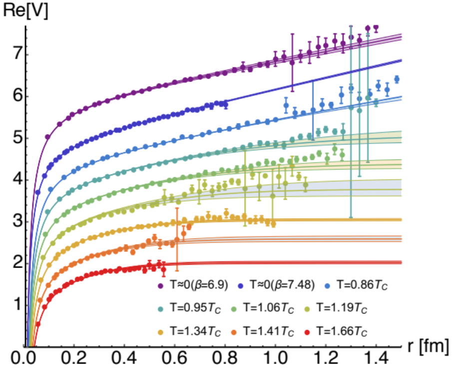

Burnier, Y., Kaczmarek, O. & Rothkopf, A. J. High Energ. Phys. (2015) 2015: 1.

Cold Nuclear Matter (CNM) Effects

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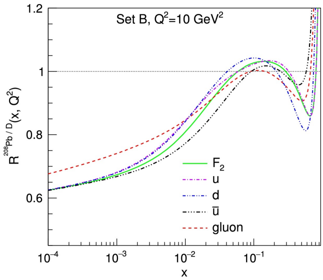
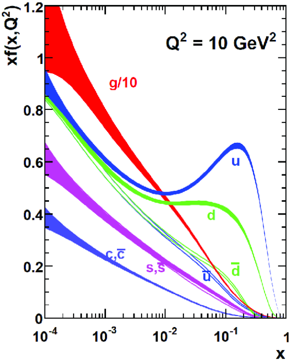


Nuc. Phys. B 920, (Jul 2017) 1-19

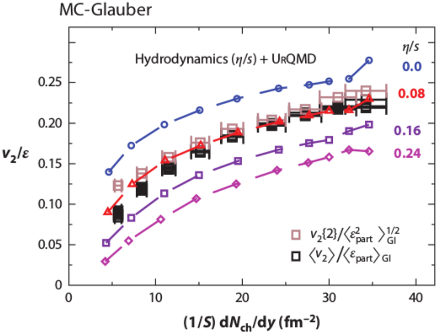


(Ann.Rev.Nucl.Part.Sci. 62 (2012) 337-359)

Elliptic Flow

Elliptic flow predictions come from hydrodynamics simulations. Therefore, measured v_2 tells us about the inputs to those simulations, including:

- viscosity
- equation of state
- speed of sound in medium
- level of thermalization



Song H, et al. Phys. Rev. Lett. 106:192301 (2011)

The Event-plane method:
The reaction plane angle ψ must be determined event by event, using energy deposited in a region of the HF spanning
$-5 < \eta < -3$ $(3 < \eta < 5)$.

$$\Psi_2' = \frac{1}{2}\tan^{-1}\frac{\sum_i w_i \sin(2\phi_i)}{\sum_i w_i \cos(2\phi_i)}$$