Quarkonia in heavy ion collisions at the LHC

Yongsun Kim (Sejong University)

HaPhy-CENuM joint workshop
The future of lattice studies in Korea

Universe, Whanki Kim (1913-1973)

Before starting my presentation

- The goal of this talk is to introduce recent LHC results and provide inputs to lattice-QCD society
  - Debye screening
  - Gluon-induced energy loss
  - nPDF

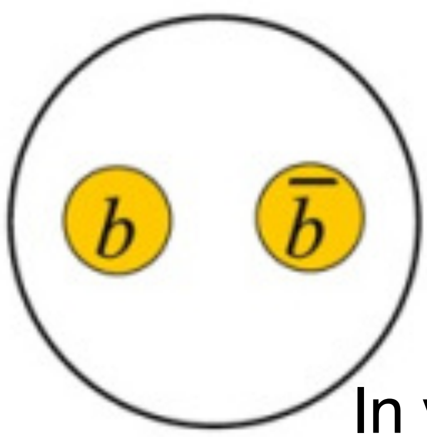
- In addition, it will be great if you can give me some input to connect the theoretical modeling and experimental observables

- For those you are not familiar with heavy ion nomenclature and convention, please ask me. Any pop-up questions will be welcome

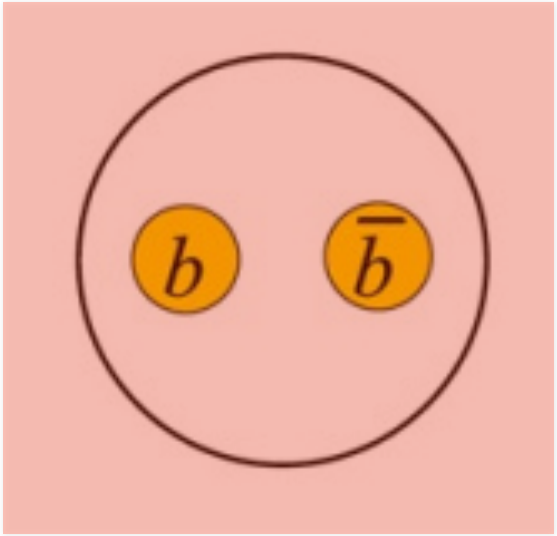
Outline

- **Review the results on quarkonia in PbPb and pPb collisions**
  - Will focus on CMS results
  - Sequential suppression of upsilon at 2.76 and 5.02 TeV
  - Cold nuclear matter effect at 5.02 and 8.16 TeV
  - Similar measurements for J/psi

- **Experimental observables**
  - We compare

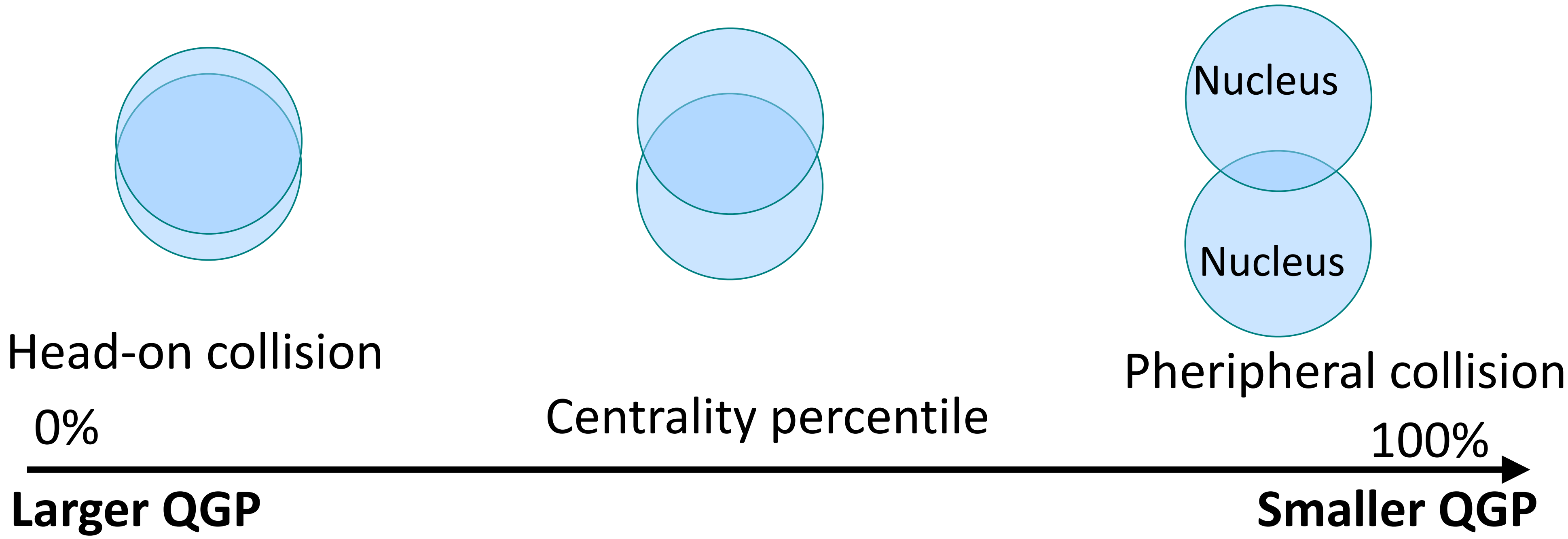


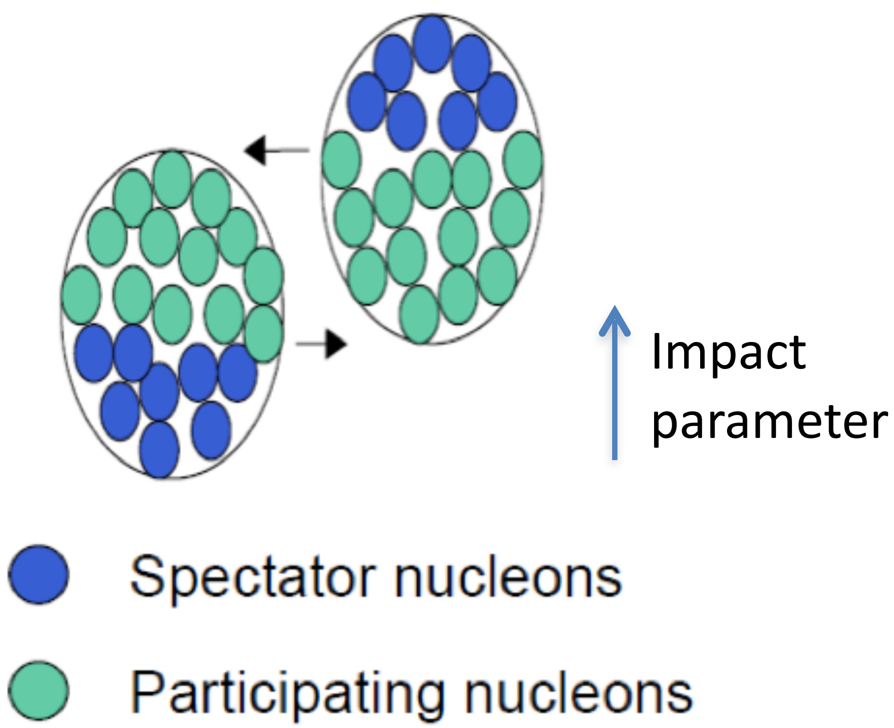
In vacuum
pp collision



In medium
PbPb, pPb

Control observable : Centrality





N_{part} = 25

N_{coll} = 51

Thermal property of (e.g. temperature, density) of the outcome matter depends on the impact parameter.

Glauber model

- N_{part} : number of participating nucleons
- N_{coll} : number of binary nucleon-nuclean collisions

Soft scattering scales by N_{part}

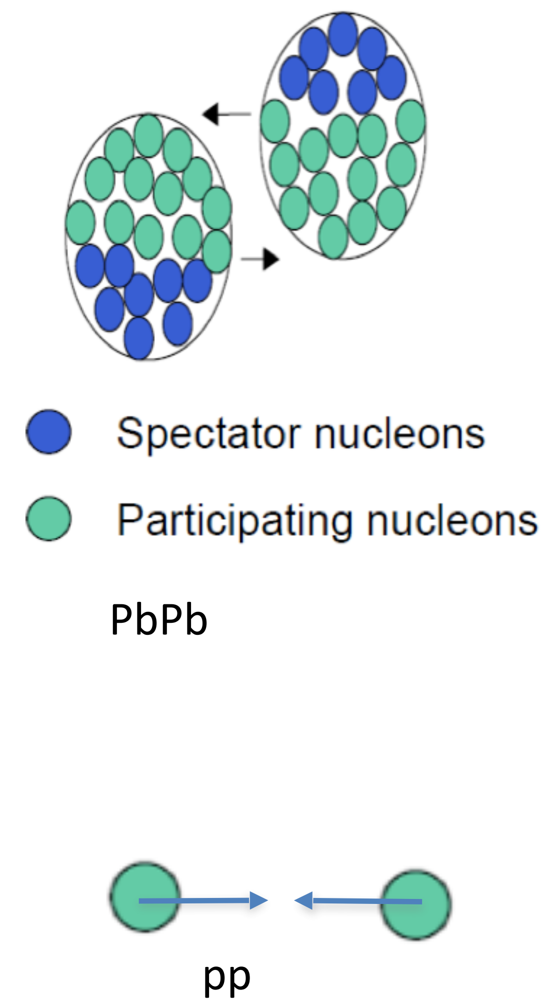
Hard scattering scales by N_{coll}

Observables : R_{AA}

- Modification is quantified by comparing the yield to pp data

- R_{AA} is the ratio of cross-section in PbPb to pp

- Proper normalization for hard probe is N_{coll}

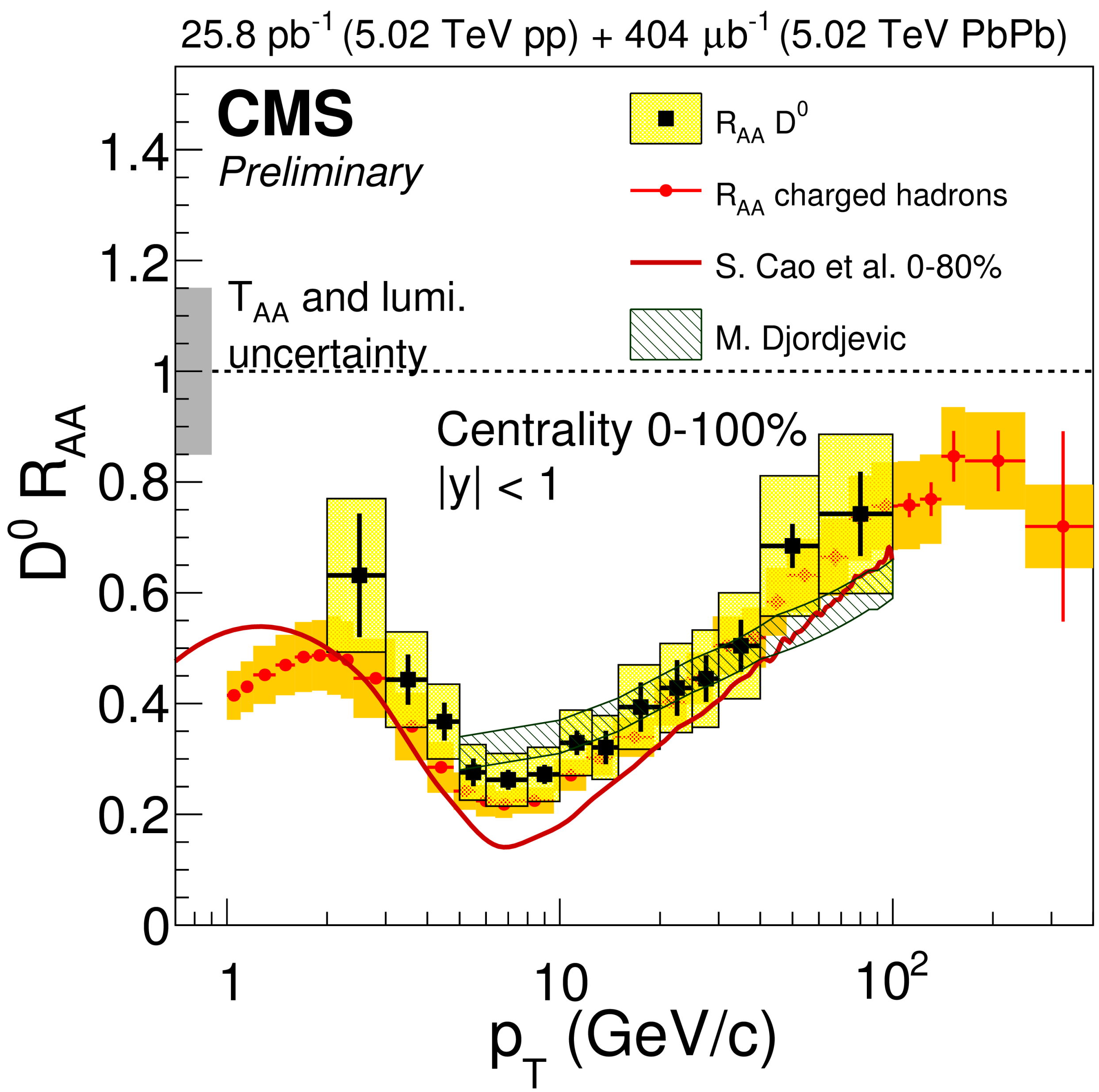


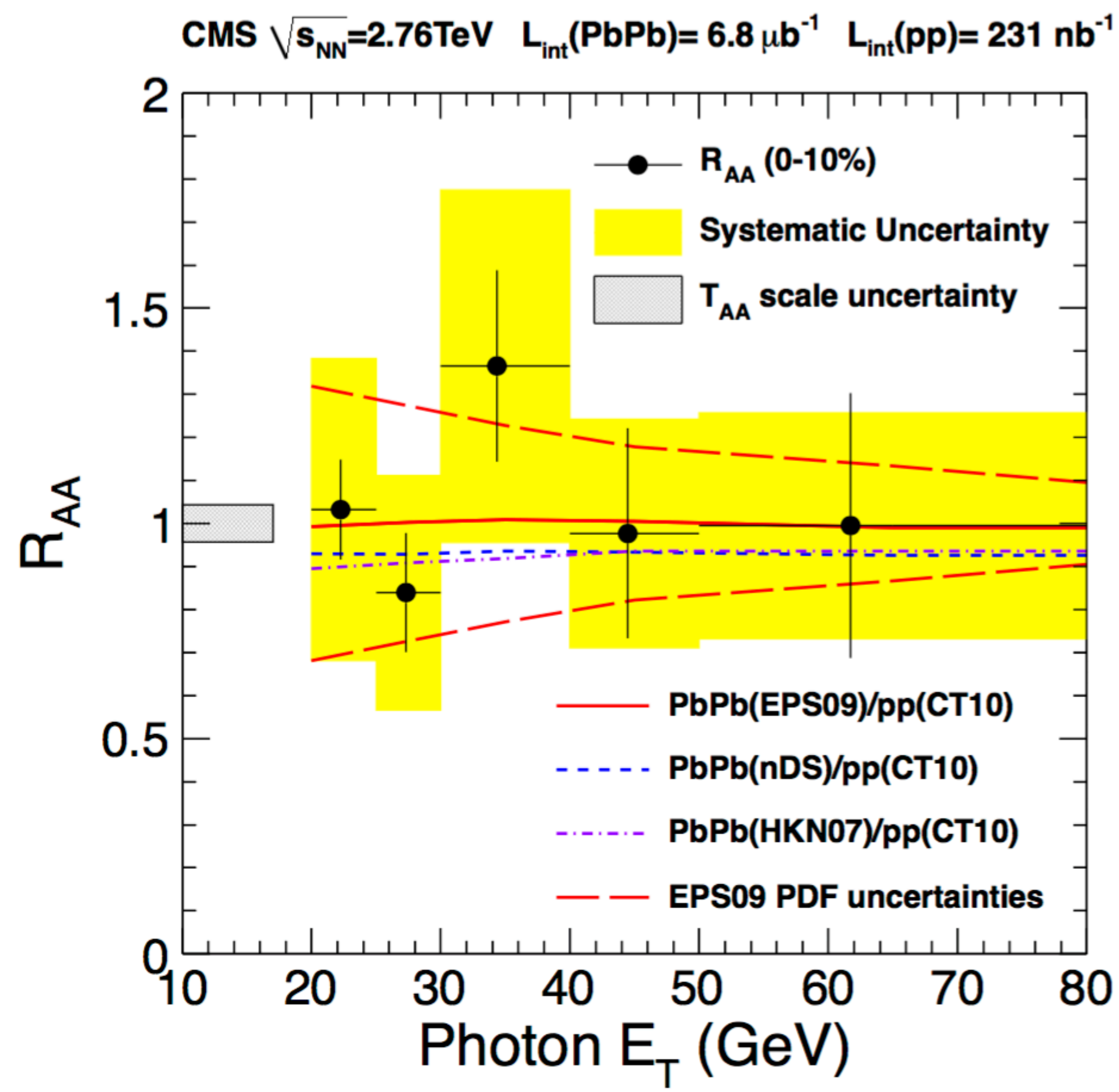
$$R_{AA} = \frac{d^2 N_{AA} / dp_T d\eta}{\langle T_{AA} \rangle d^2\sigma_{pp} / dp_T d\eta}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

$$\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{pp}^{inel}$$

Examples





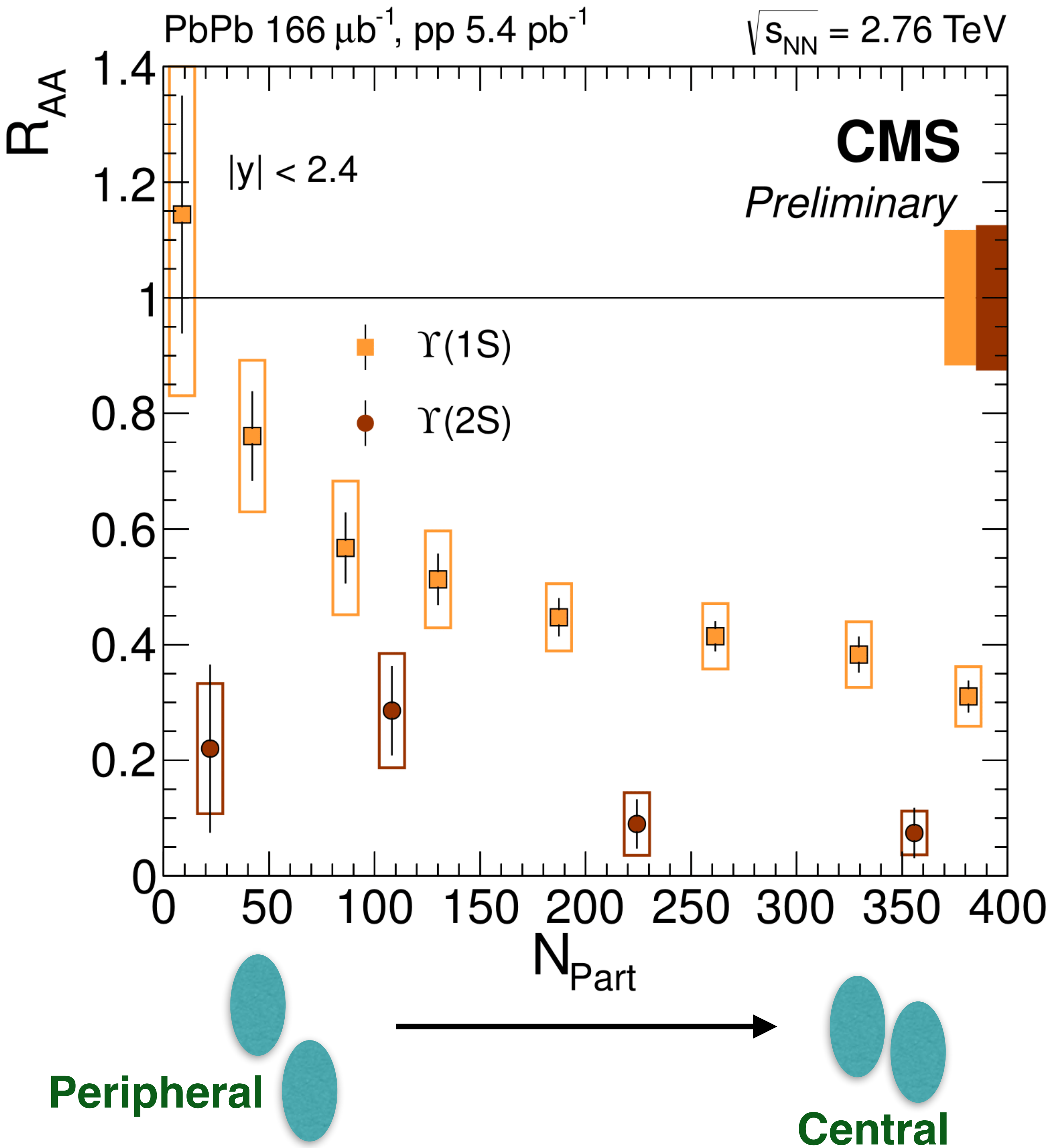
Inclusive charged particles

$R_{AA} < 1$ (suppression)

Direct photons

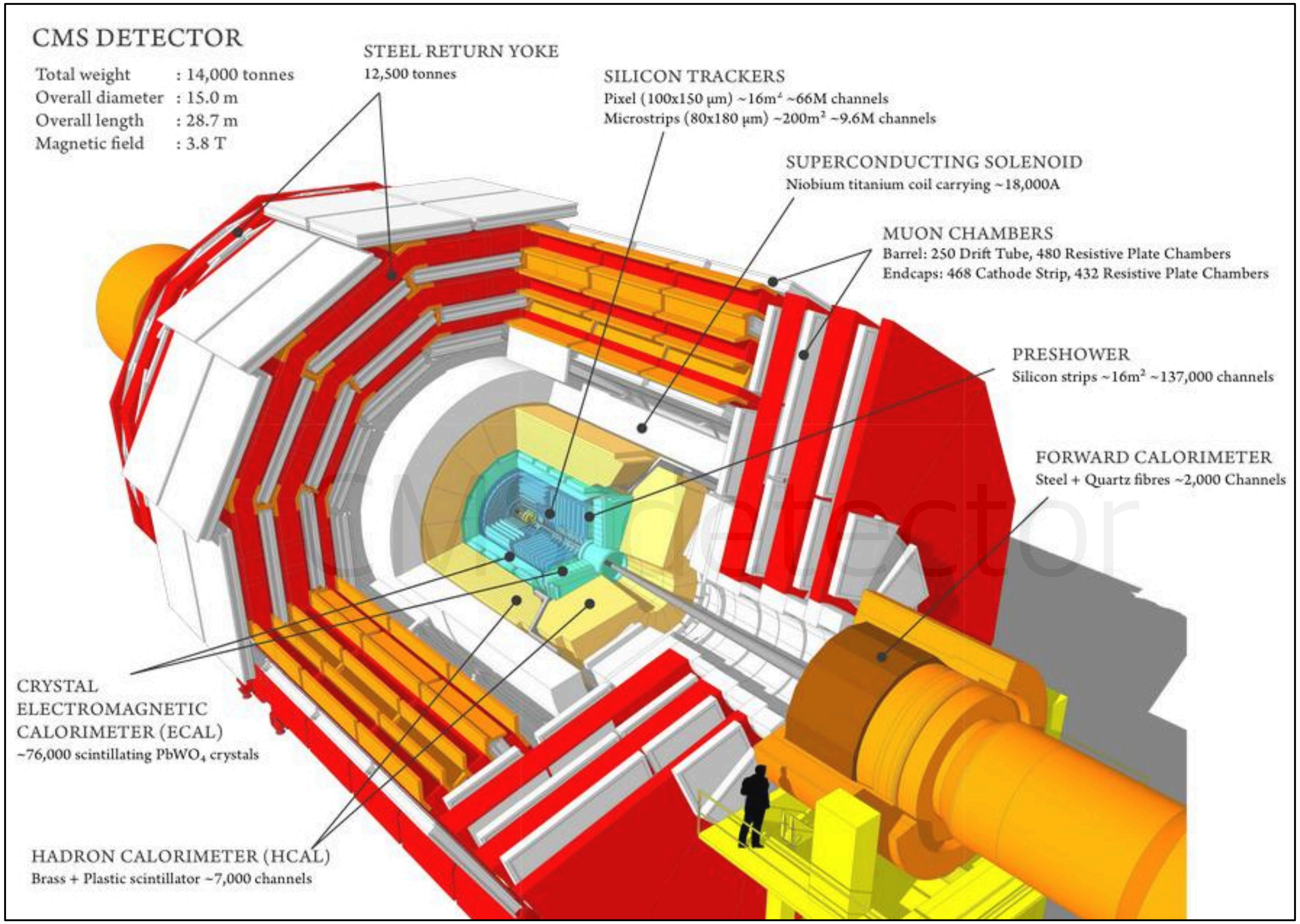
$R_{AA} = 1$ (No medium effect)

Examples



PbPb 166 μb-1, pp 5.4 pb-1
√sNN = 2.76 TeV
RAA
|y| < 2.4
CMS
Preliminary
ϒ(1S)
ϒ(2S)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 50 100 150 200 250 300 350 400
NPart
Peripheral
Central

CMS detector



Large coverage of trackers and calorimeters

- Muons are tracked by muon system (RPC, CSC, DT) and inner silicon pixels and strips
- Upsilons are reconstructed via di-muon decays => Efficient for higher p_T

1. Bottomonia

Sequential melting - Y(nS) is THE best probe

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

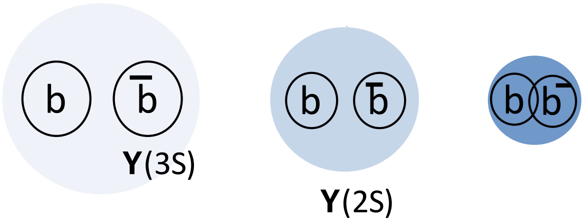
T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

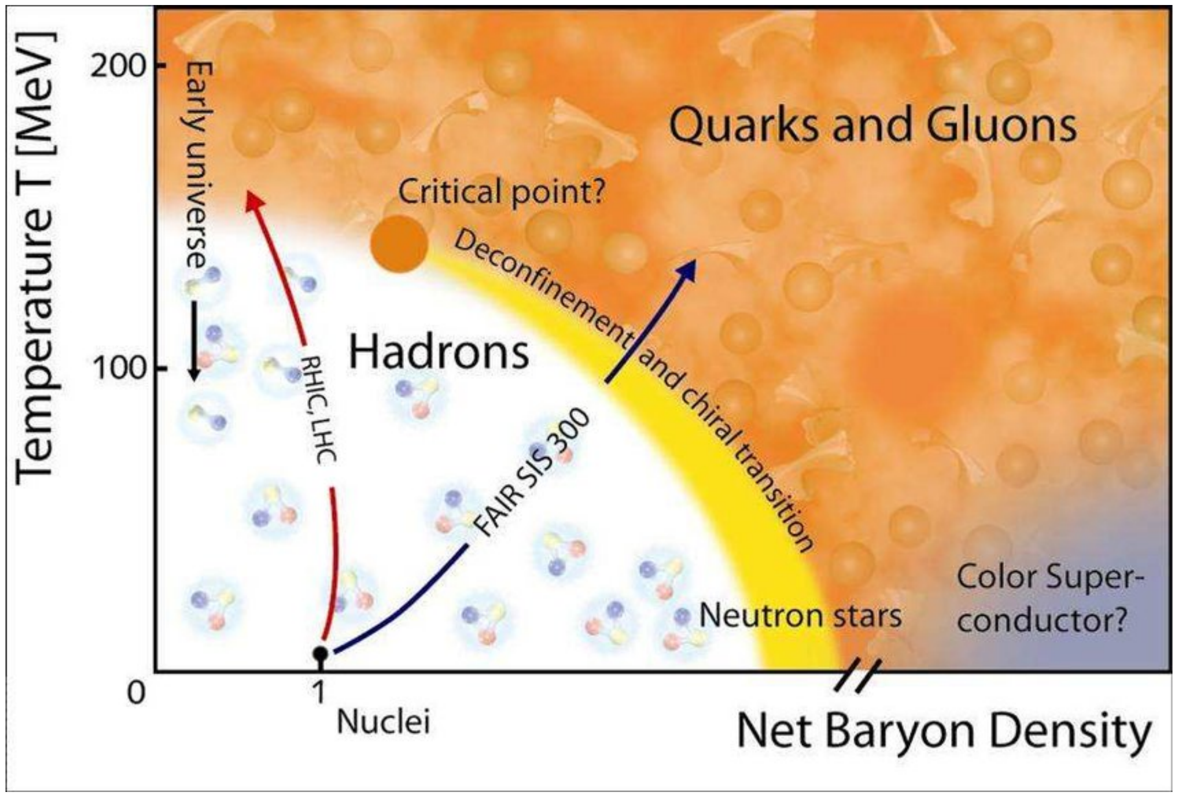
and

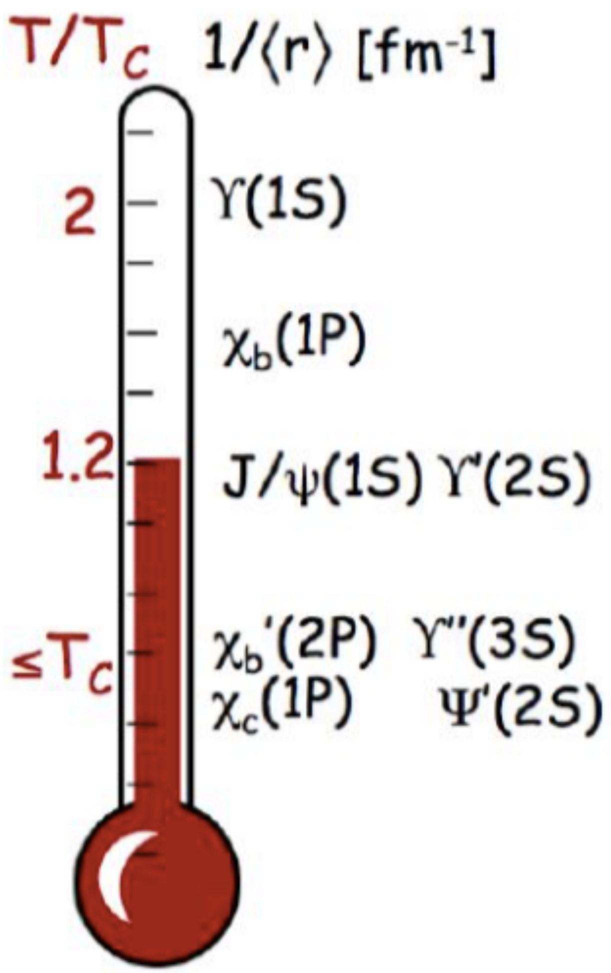
H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

- **Y(nS)** brothers were expected to provide evidence for color charge screening that sequentially increases w.r.t. binding energy

Sequential melting - Υ(nS) is THE best probe







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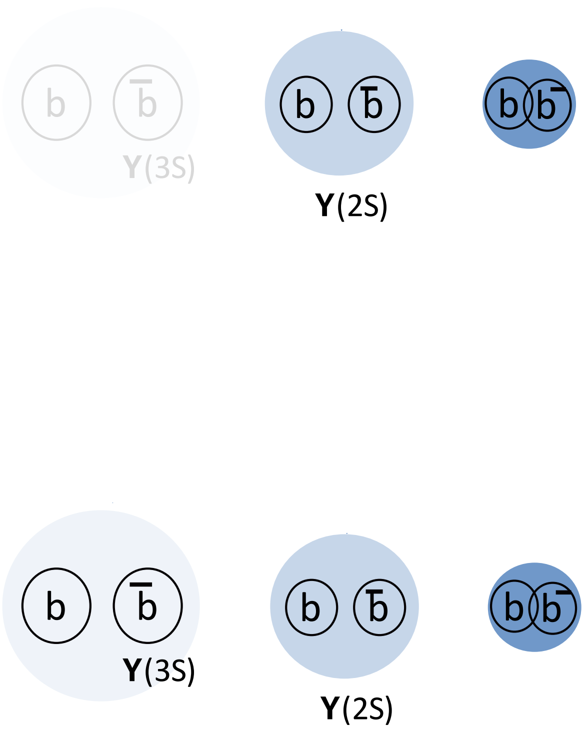

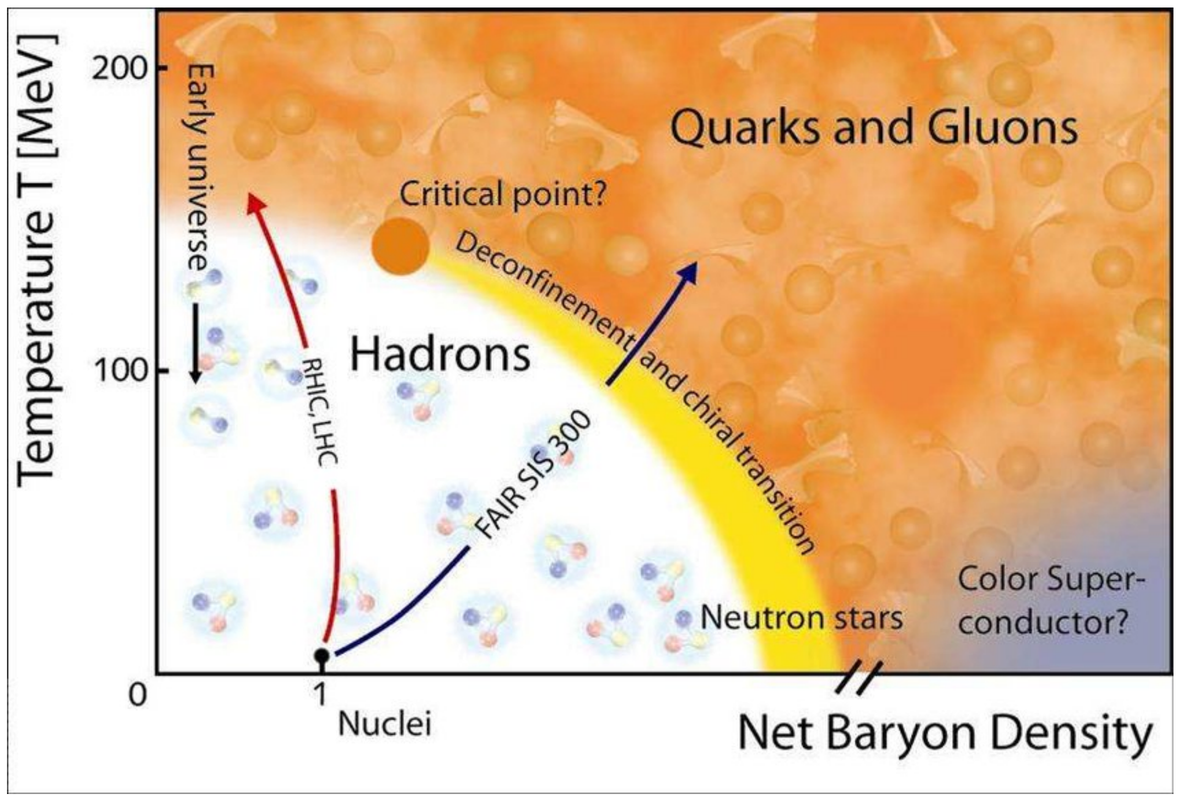

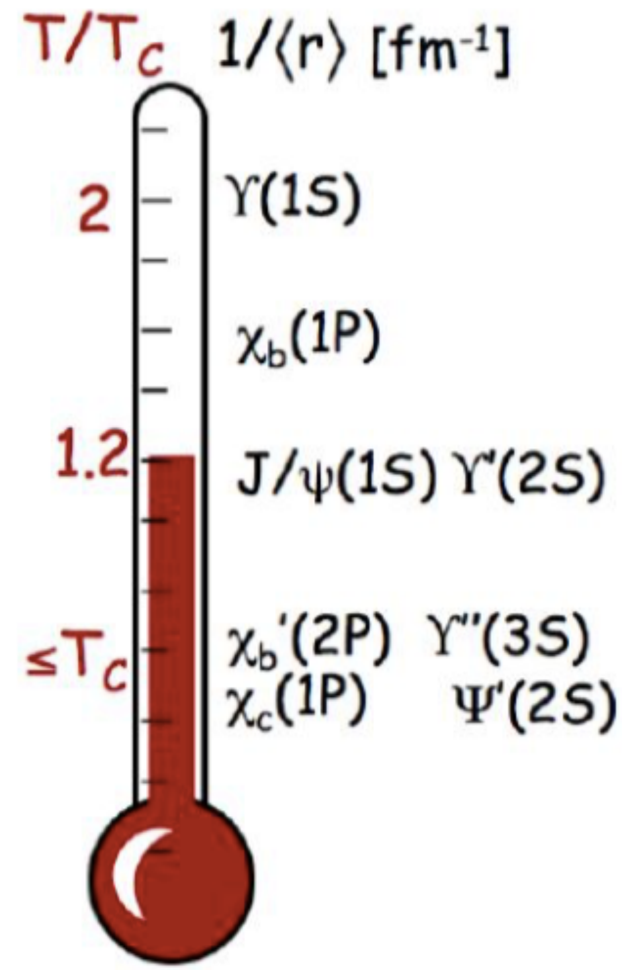

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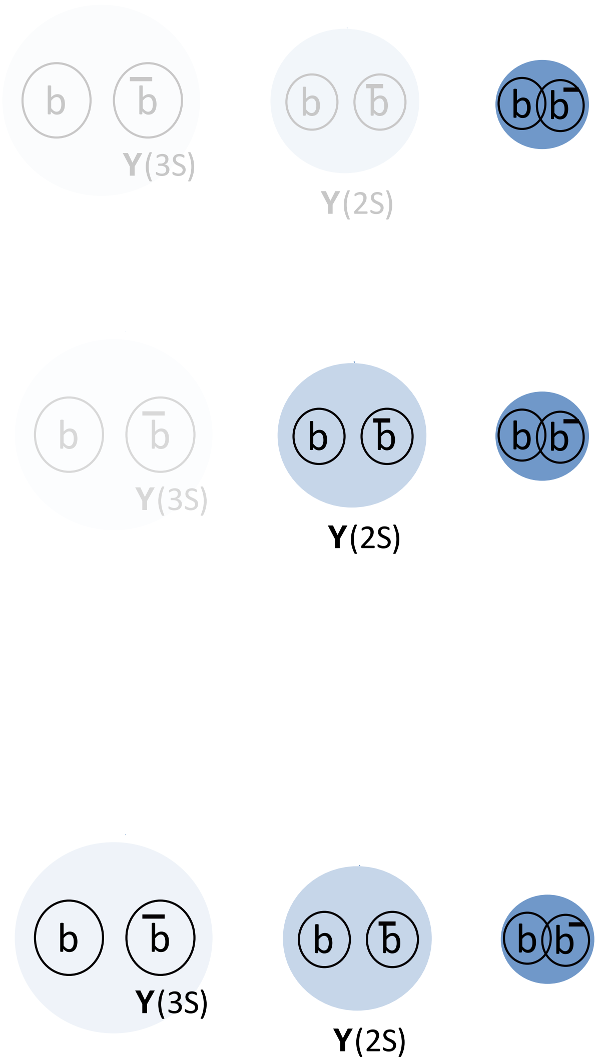

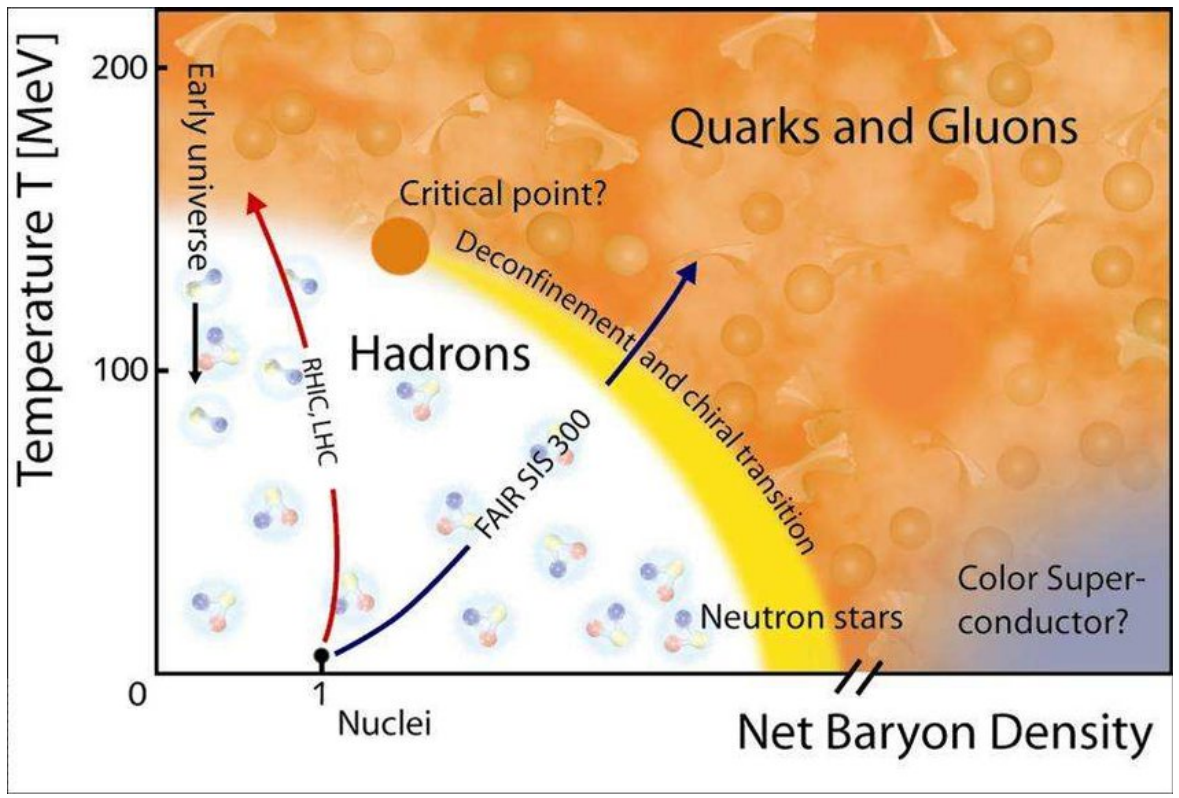

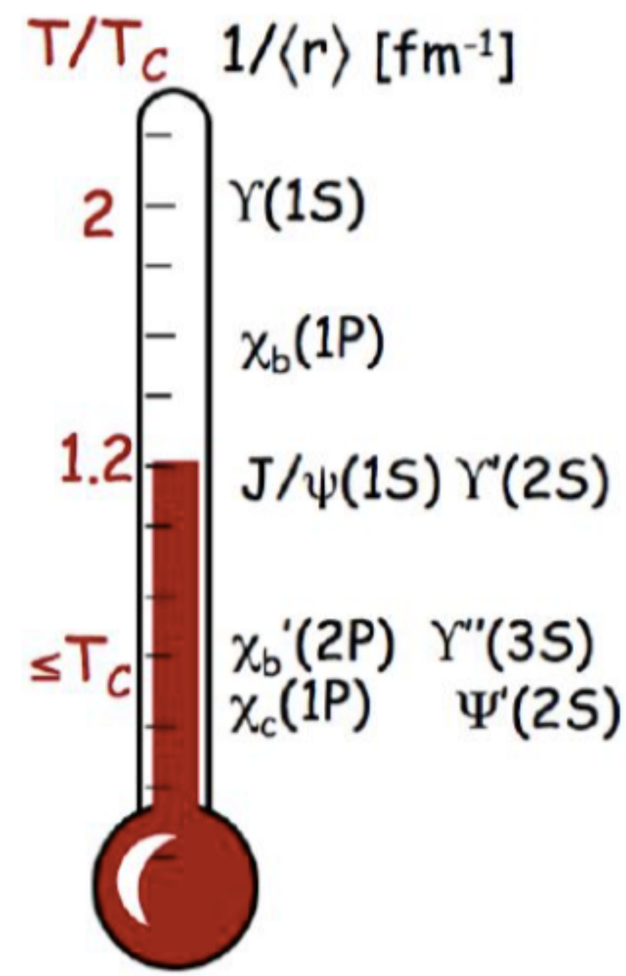

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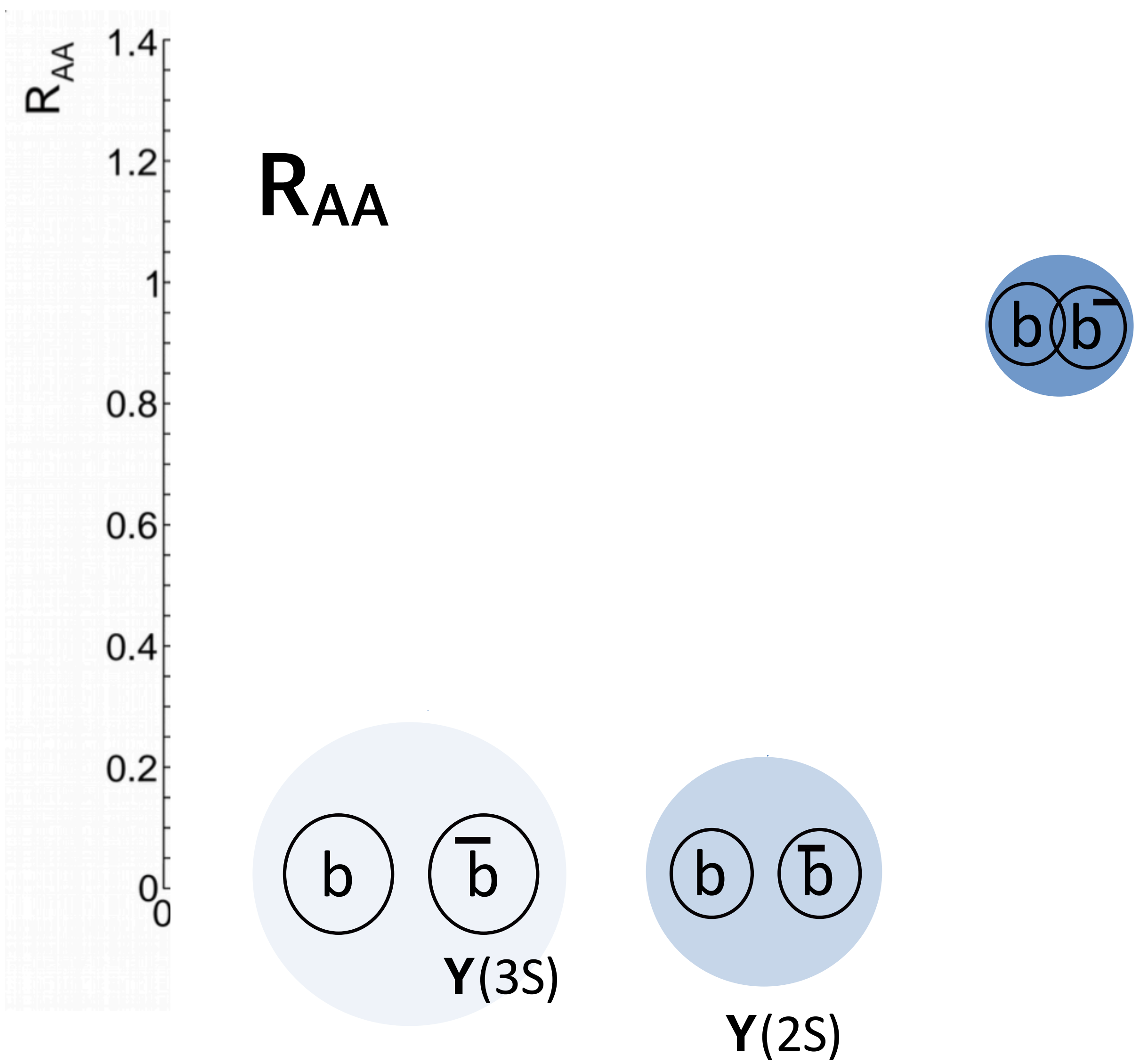
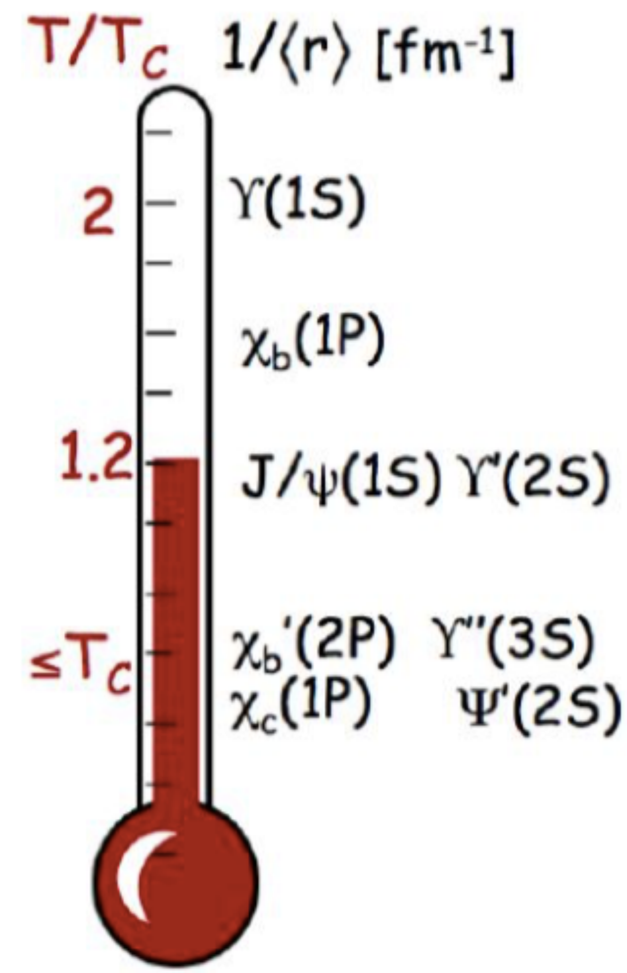




- **Υ(nS)** brothers were expected to provide evidence for color charge screening that sequentially increases w.r.t. binding energy

Upsilon states in Heavy ion collision

- Suppression of excited $\Upsilon(nS)$ in PbPb at 2.76 TeV
  [PRL 107 (2011) 052302]
- Quarkonium production in PbPb collisions at 2.76 TeV
  [JHEP 1205 (2012) 063]
- Observation of $\Upsilon(nS)$ suppression at 2.76 TeV
  [PRL 109 (2012) 222301]
- Suppression of $\Upsilon(nS)$ in PbPb at 2.76 TeV
  [PLB 770, 357(2017)]
- 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
  [PRL 120 (2018) 142301]
- Nuclear modification of $\Upsilon(nS)$ in PbPb at 5.02 TeV
  [PLB 790 (2019) 270]

2011-2013

PbPb : $\sqrt{s_{NN}}$ = 2.76 TeV, L = 166 μb^{-1}

pPb : $\sqrt{s_{NN}}$ = 5.02 TeV, L = 34.6 nb^{-1}

pp : $\sqrt{s_{NN}}$ = 2.76 TeV, L = 5.4 pb^{-1}

Run1

↓

Run2

2015

PbPb : $\sqrt{s_{NN}}$ = 5.02 TeV, L = 368 μb^{-1}

pp : $\sqrt{s_{NN}}$ = 5.02 TeV, L = 28 pb^{-1}

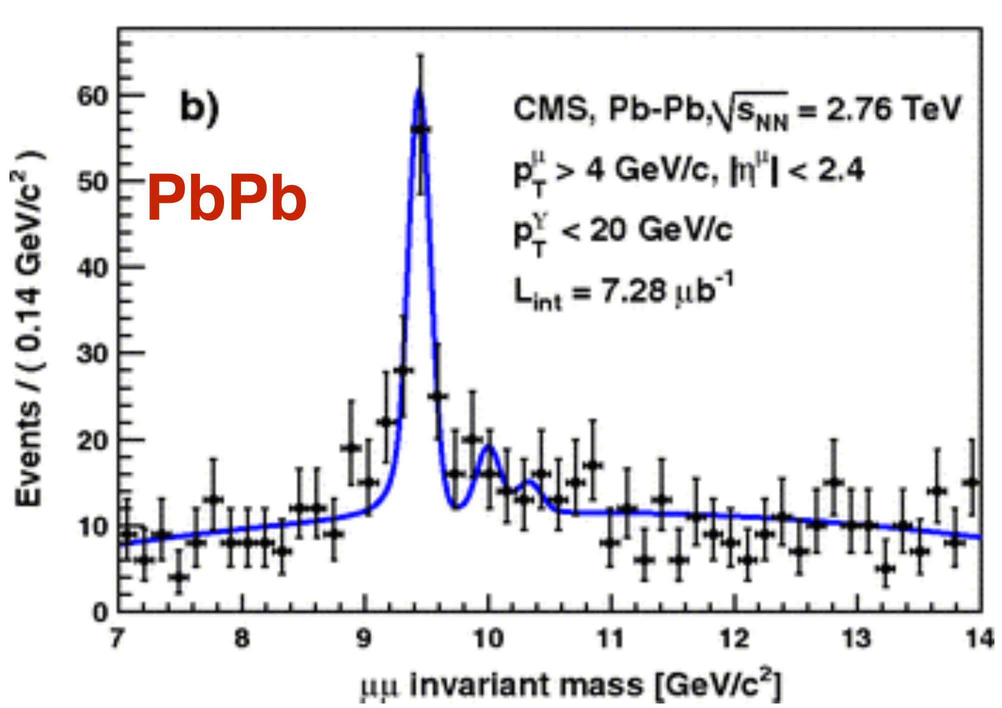
New data 2017-2018 PbPb : $\sqrt{s_{NN}}$ = 5.02 TeV, L ~ 1.6 nb^{-1} , pp : $\sqrt{s_{NN}}$ = 5.02 TeV, L ~ 300 pb^{-1}

Upsilon states in Heavy ion collision

- **Suspension of excited Υ(nS) in PbPb at 2.76 TeV**

  [PRL 107 (2011)]

From the first PbPb run at 2.76 TeV in Dec. 2010, we observed that excited state of upsilons were unusually smaller than the ground state.



Upsilon states in Heavy ion collision

- **Suppression of excited Υ(nS) in PbPb at 2.76 TeV**

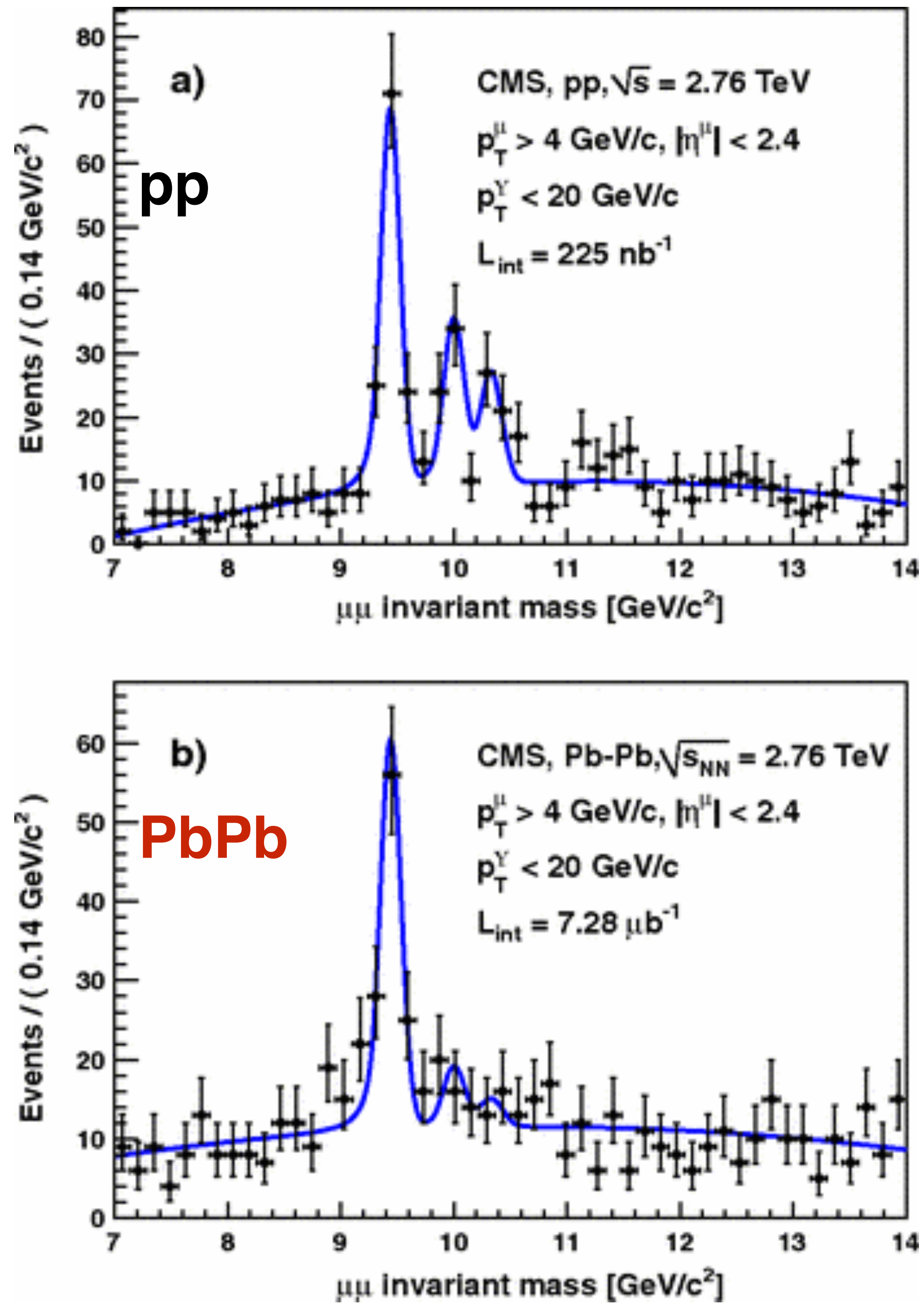
  [PRL 107 (2011)]

3 months later, we took the pp data at the same center-of-mass energy, and we confirmed that the ratio of Y(nS) are different for pp and PbPb

The observation led us to measure the double ratio

$$\frac{R_{AA} \text{ of } \mathbf{Y}(nS)}{R_{AA} \text{ of } \mathbf{Y}(1S)}$$

- Precision measurement for very few corrections beyond signal counting
- Isolates the final state effects from production mechanism
- Used 7.3 μb^{-1}

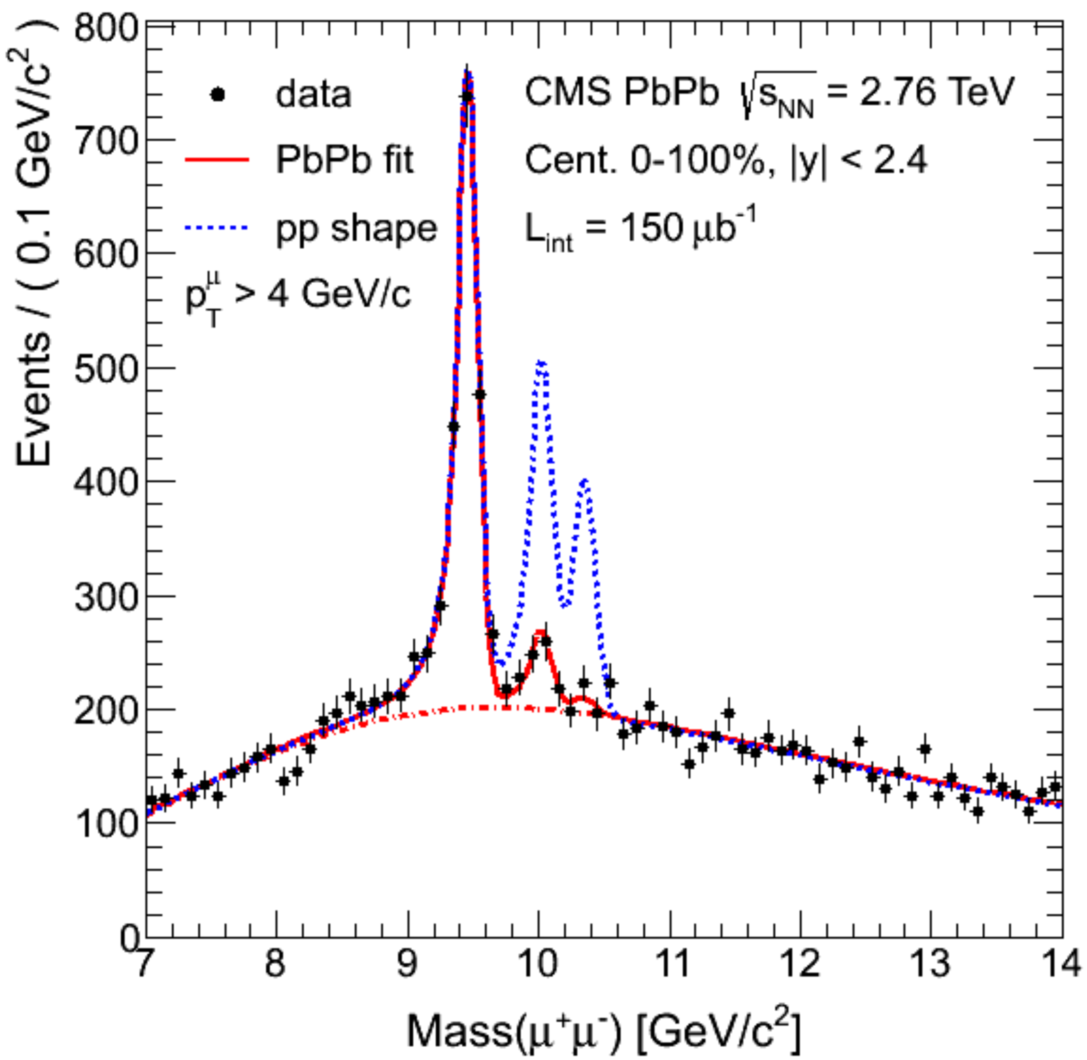


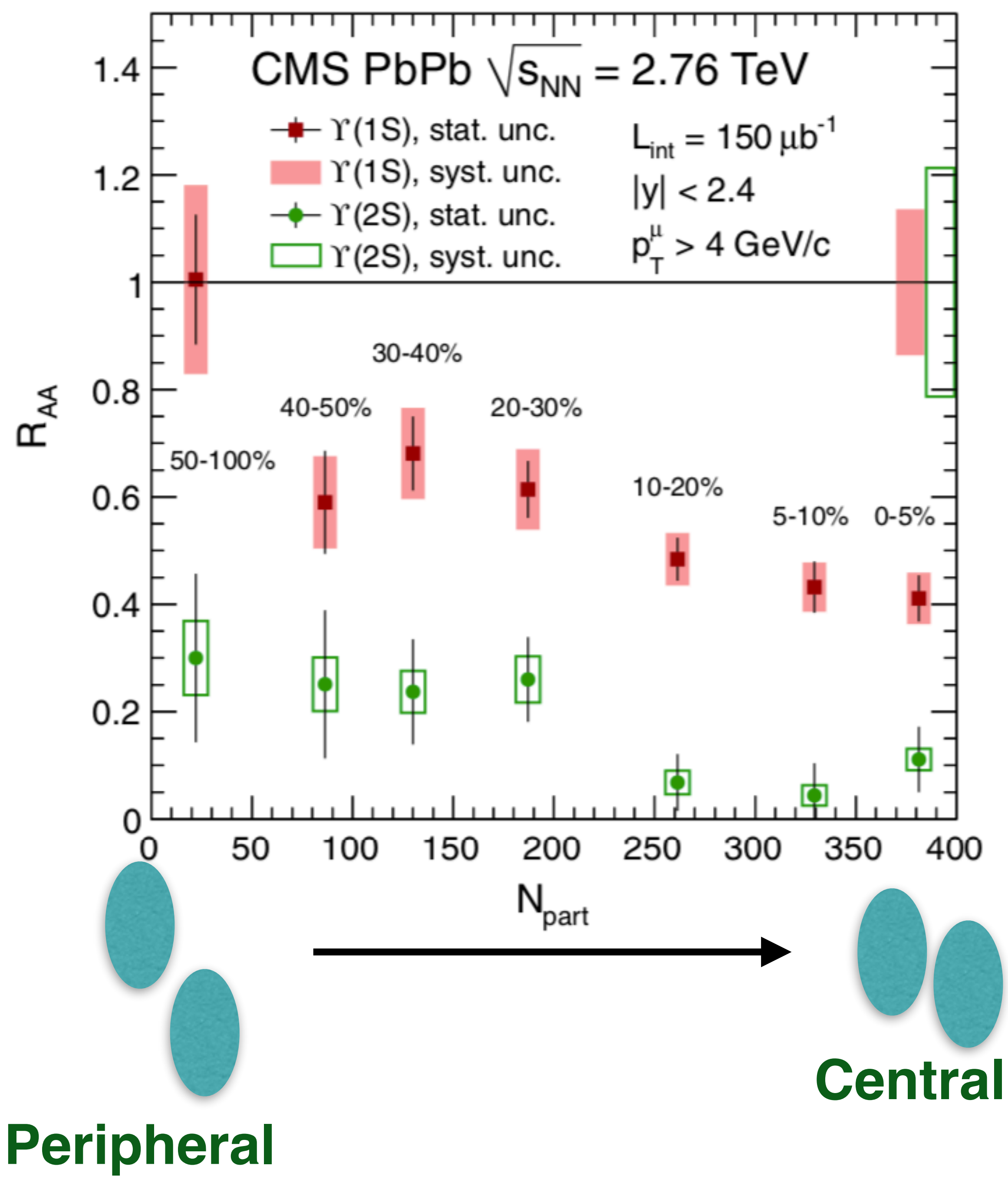
Upsilon states in Heavy ion collision

In the following year, we got 20 times more data

- **Observation of ϒ(nS) suppression at 2.76 TeV**

  [PRL 109 (2012) 222301]

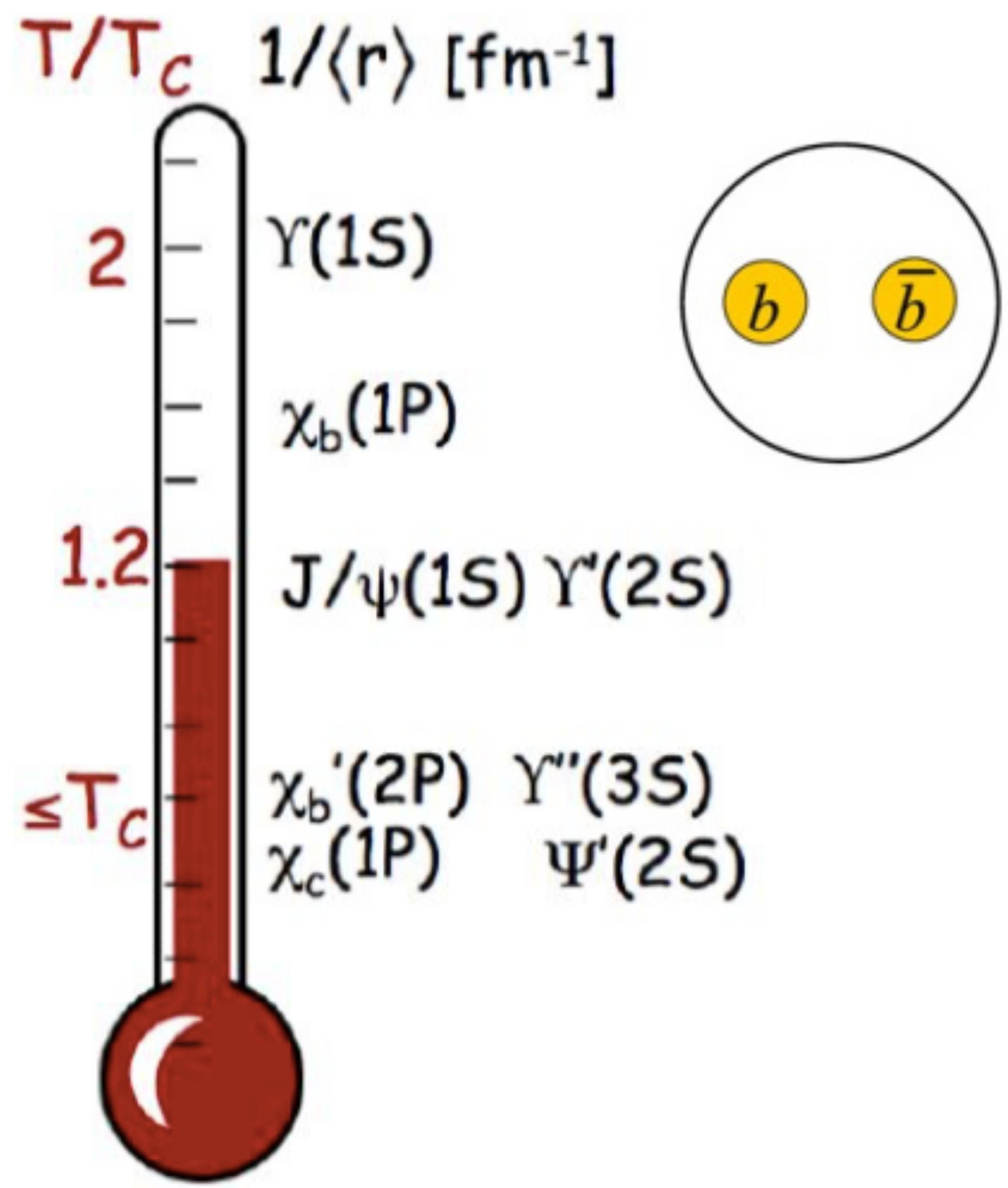




- First measurement of R_{AA} vs centrality
- Not enough statistics for Y(3S) measurement

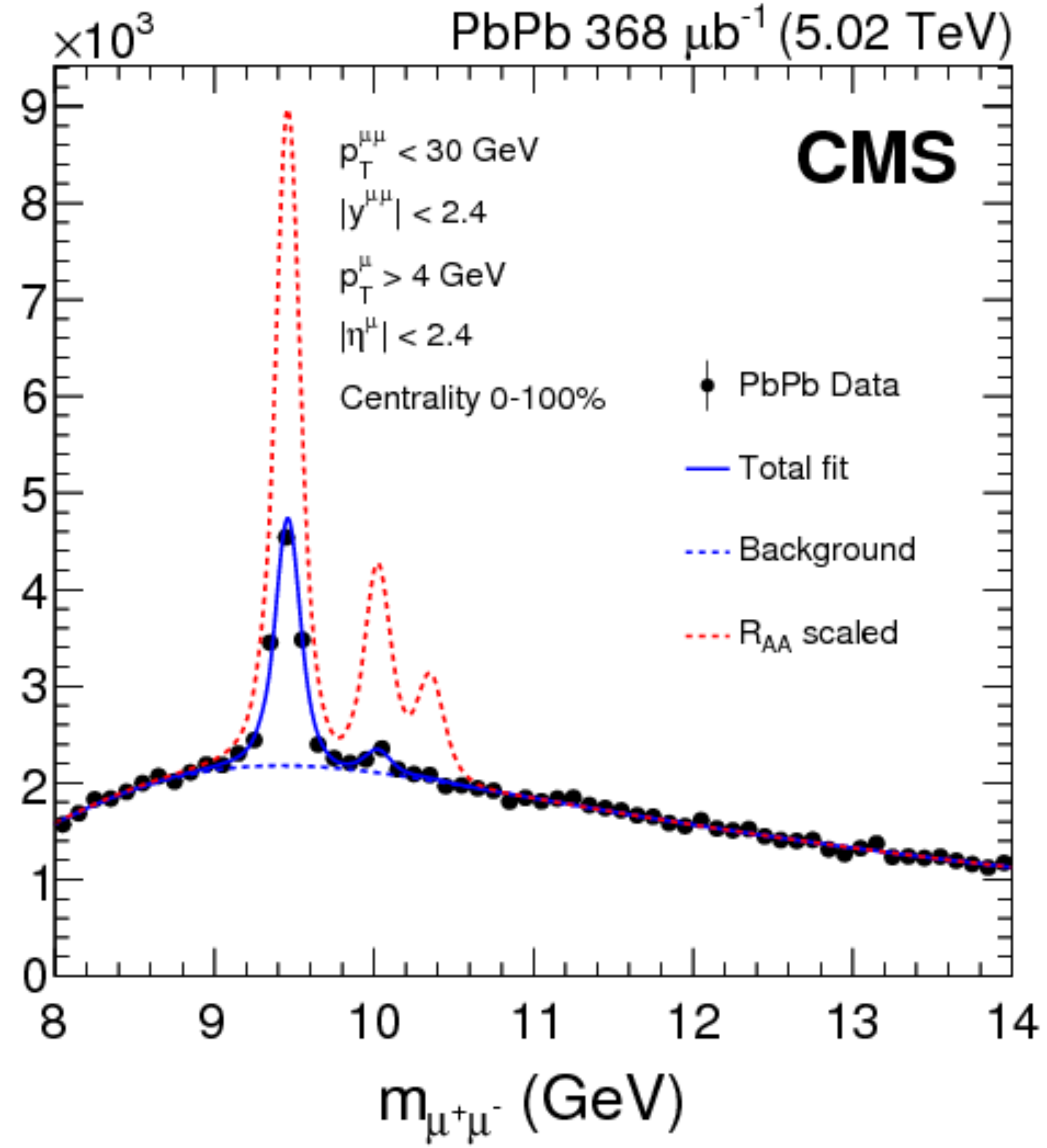
Lessons from Run I data (2010 - 2013)

- Υ(nS) is suppressed by interaction with medium, but not exactly as predicted by the classical sequential melting picture All-or-nothing switch by temperature threshold
- Yet, suppression is higher for more excited states
- Suppression smoothly depends on the centrality
- Results with more statistics and in different collision energy would be useful to comprehend the thermal property of QGP, as a function of space and time



Upsilon results with Run II data (2015 - 2018)

- In 2015 we took the first Run II data with L = 368 ub^{-1}
- This was 50 times higher statistics than the first 2010 data



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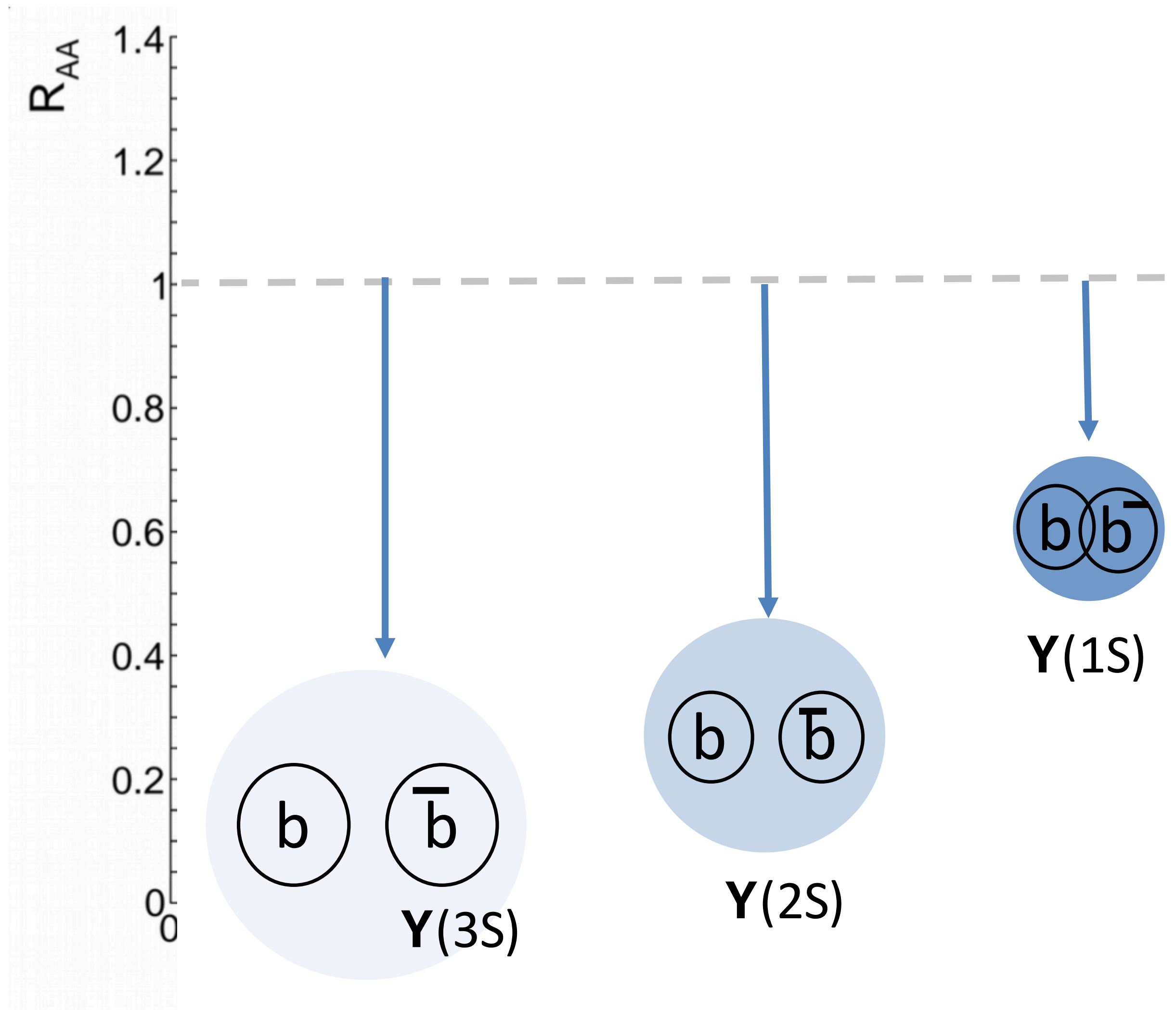
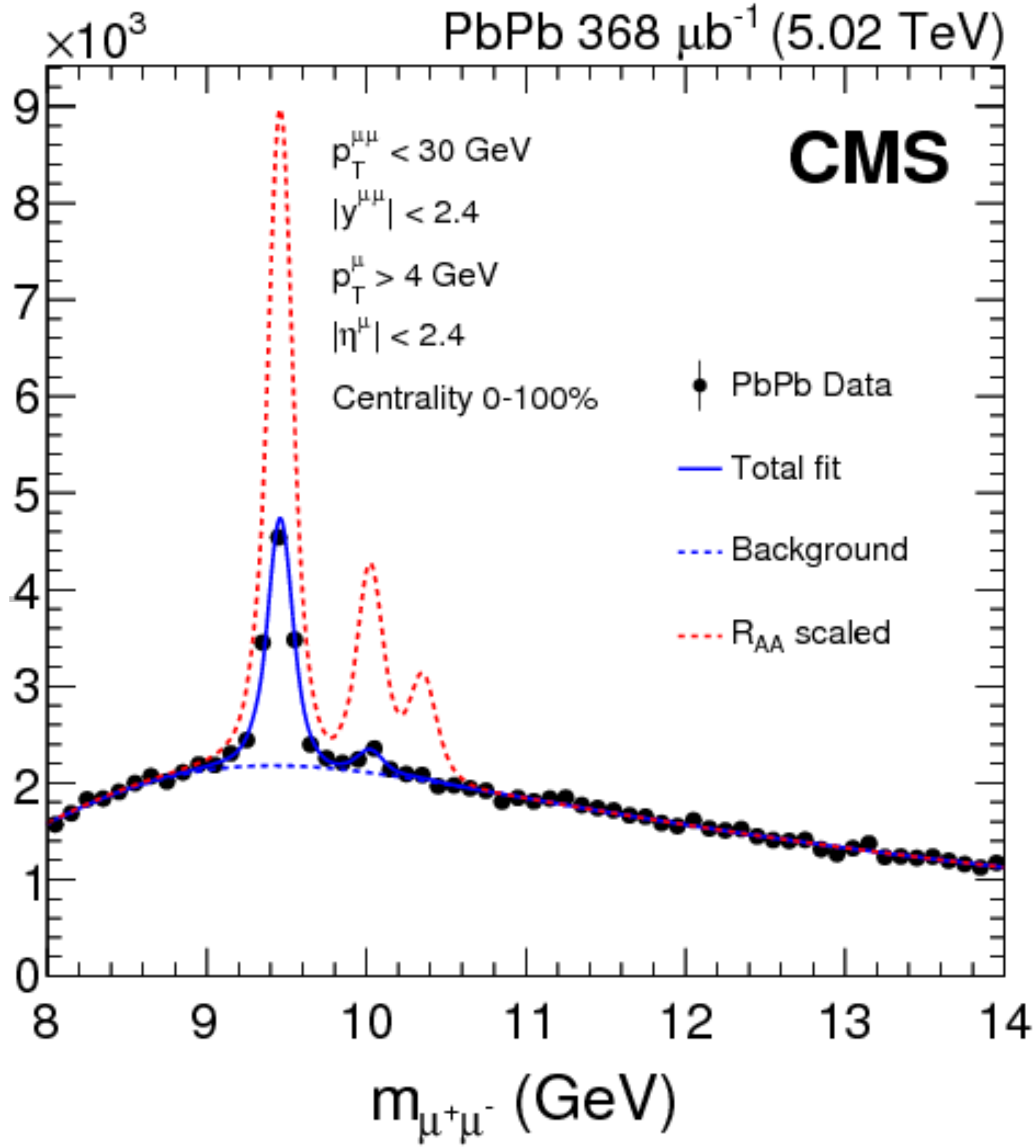
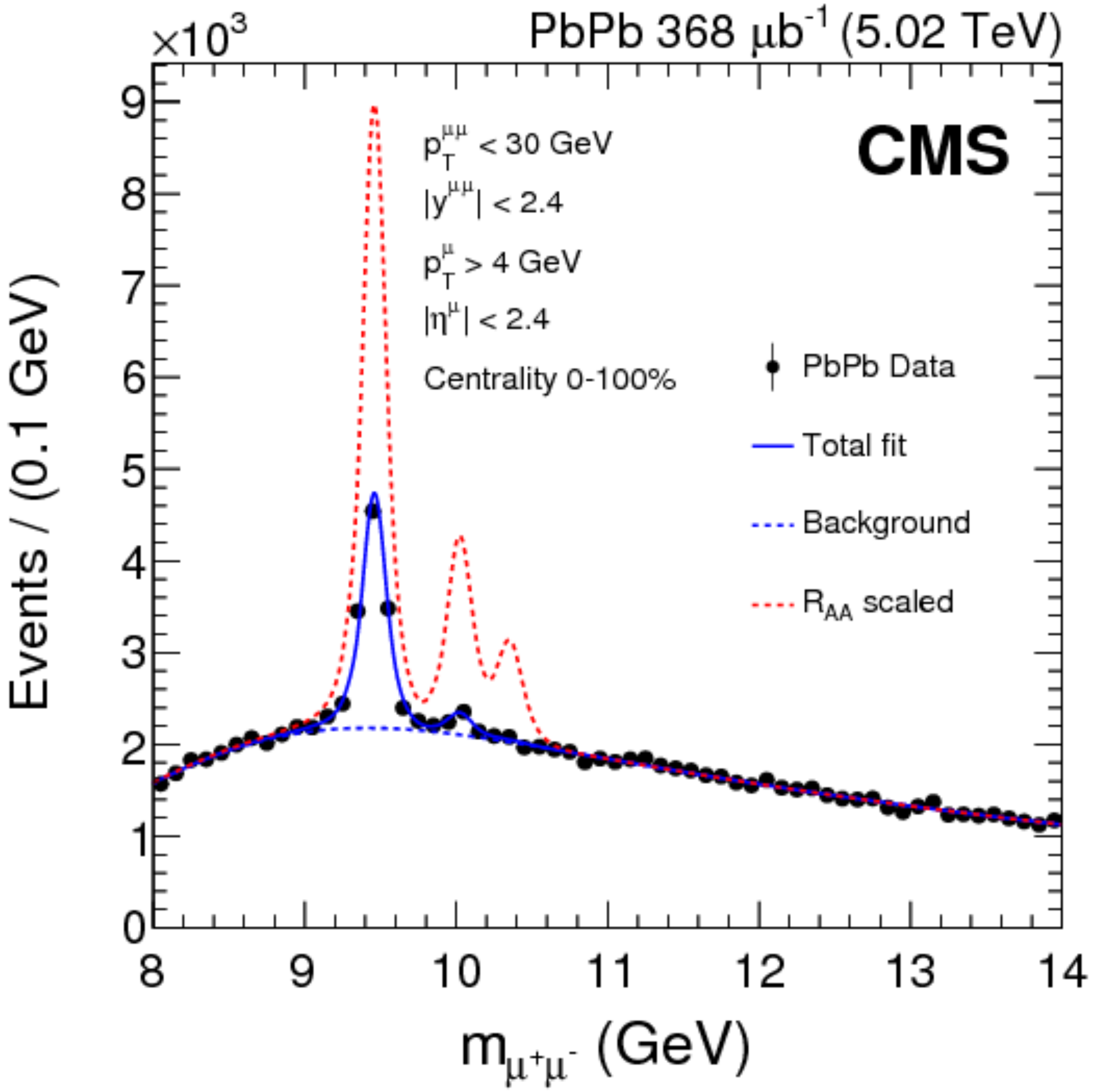


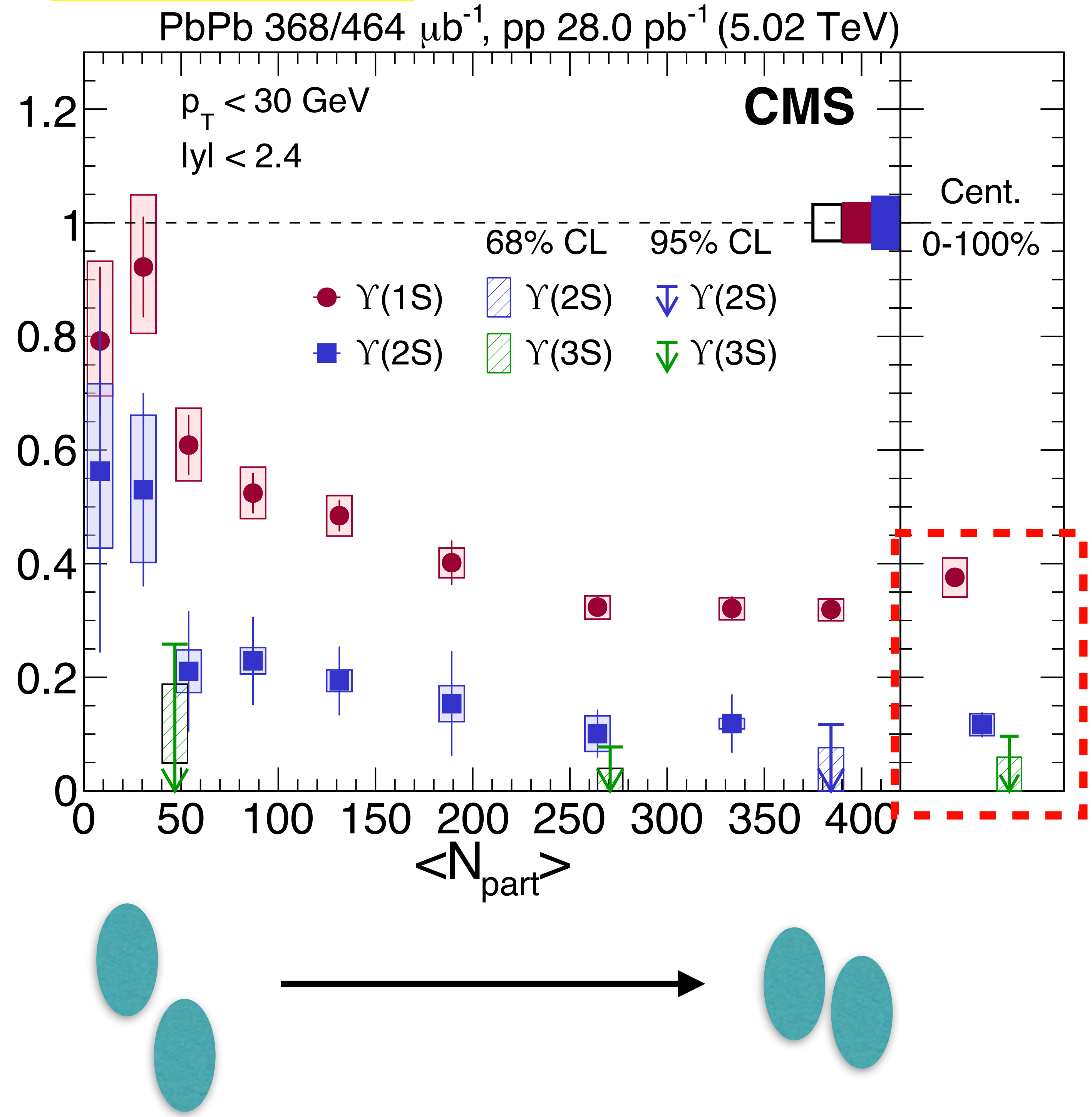


Upsilon results with Run II data (2015 - 2018)

- Nuclear modification measured for all three states



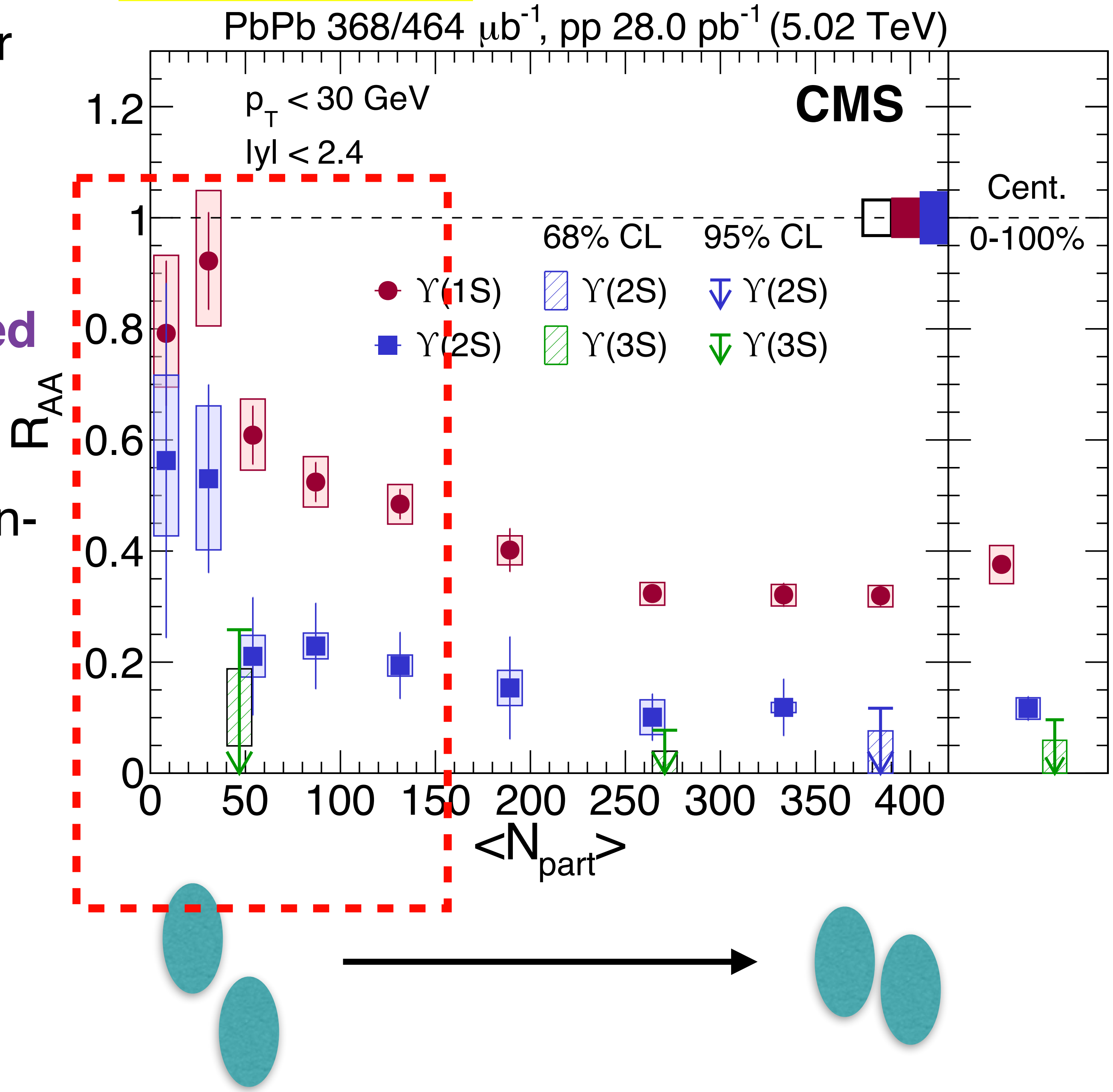
[PLB 790 (2019) 270]



Upsilon results with Run II data (2015 - 2018)

- Nuclear modification measured for all three states
- Dedicated trigger **for un-prescaled peripheral** collision
    - to illuminate the moment of turn-R_{AA} of excited state

[PLB 790 (2019) 270]



Upsilon results with Run II data (2015 - 2018)

- Nuclear modification measured for all three states
- Same ordering of suppression in 2.76 TeV

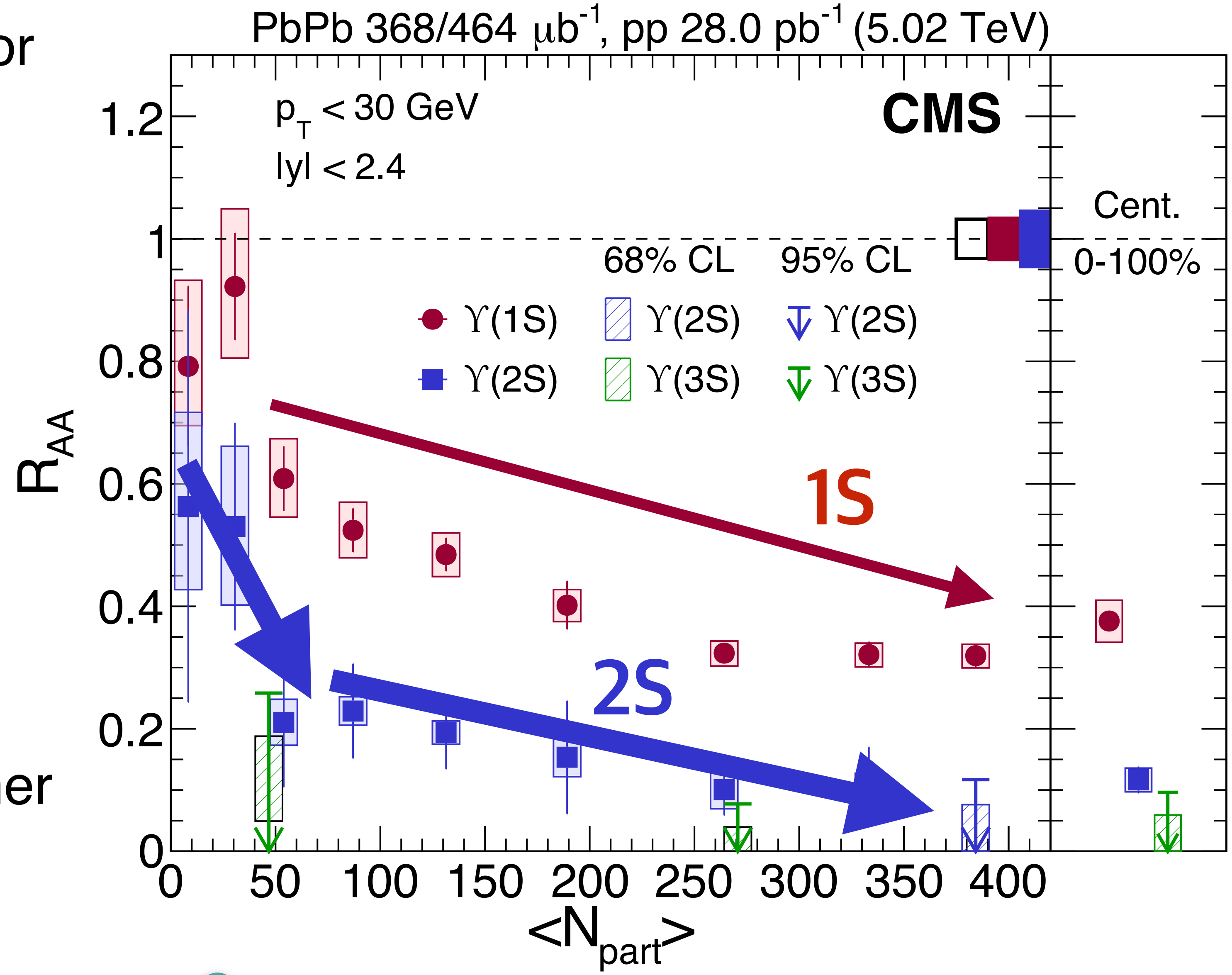
  $R_{AA}(\Upsilon(1S))$: 0.376 ± 0.013 (stat) ± 0.035 (syst)

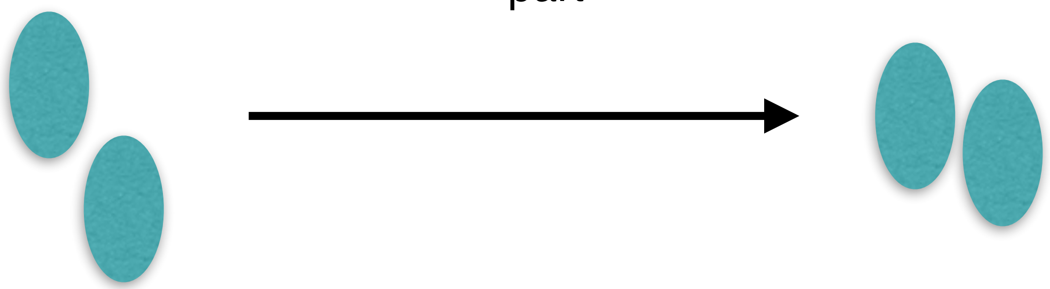
  $R_{AA}(\Upsilon(2S))$: 0.117 ± 0.022 (stat) ± 0.019 (syst)

  $R_{AA}(\Upsilon(3S))$ < 0.096 in 95% C.L.

- R_{AA} Gradually decreases for higher centrality for 1S and 2S
  - Hints for rapid turn-on at very peripheral collision (> 70%)

[PLB 790 (2019) 270]





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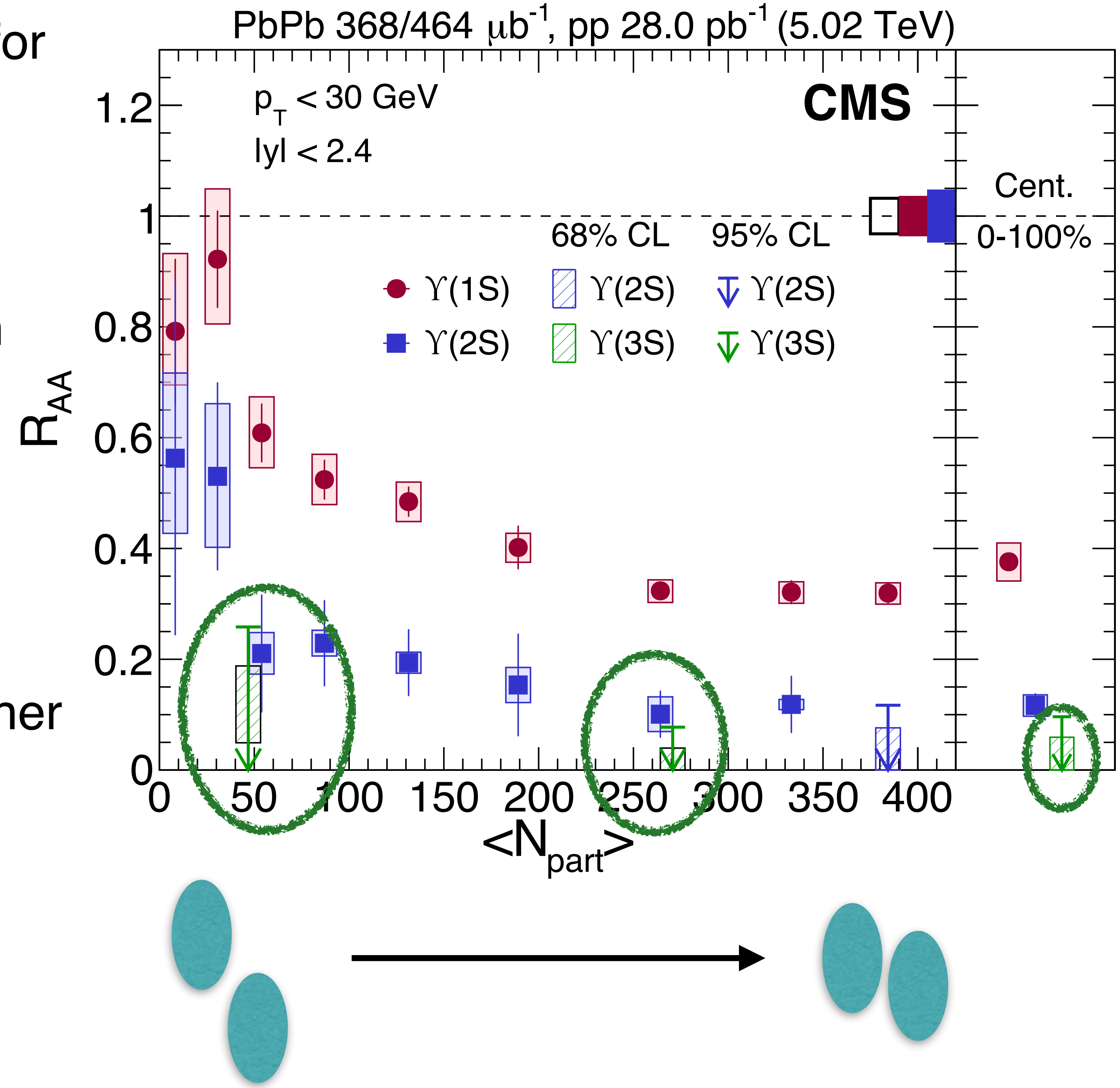
  $R_{AA}(\Upsilon(3S))$ < 0.096 in 95% C.L.

- R_{AA} Gradually decreases for higher centrality for 1S and 2S

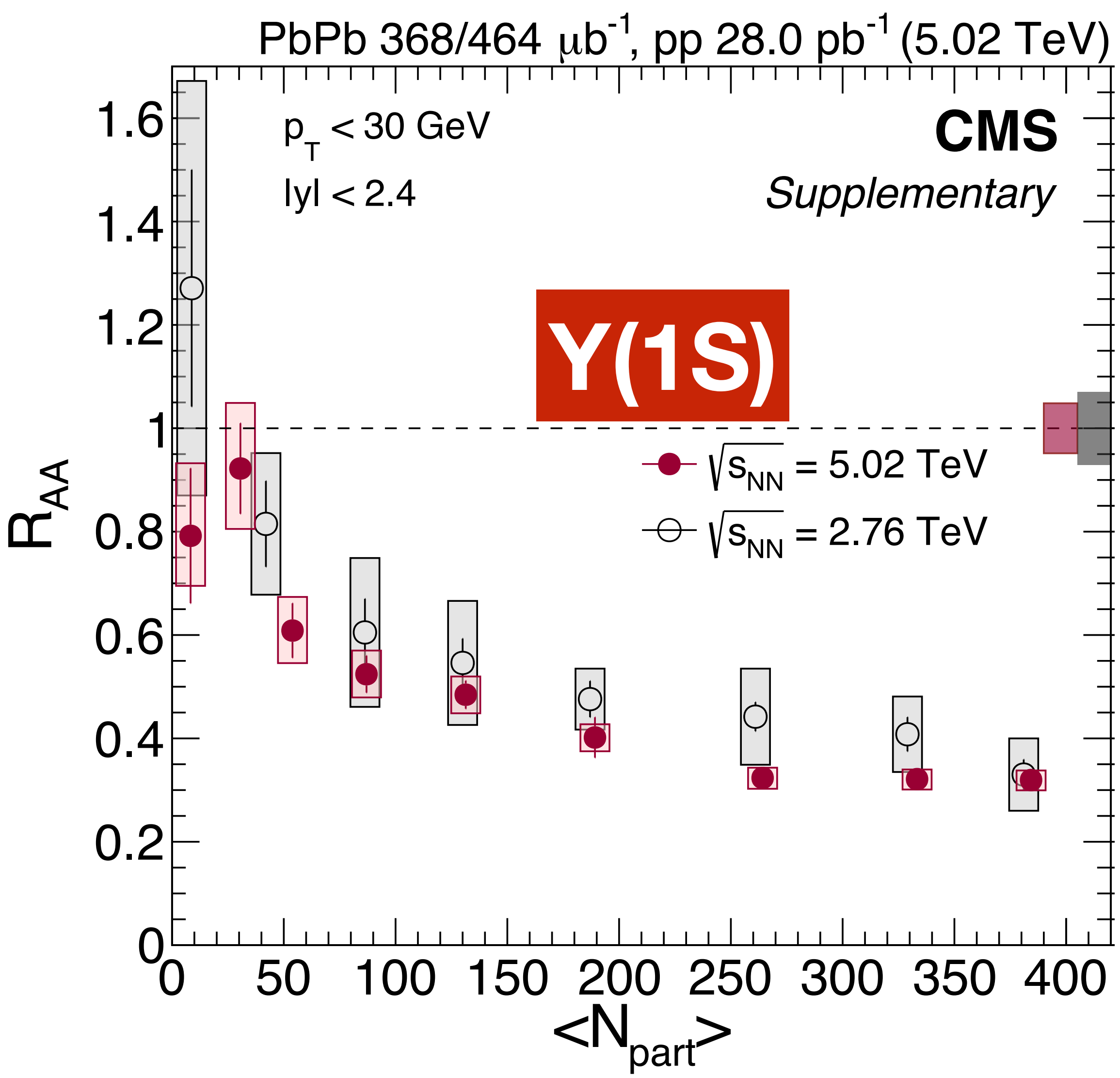
- Strong suppression of 3S

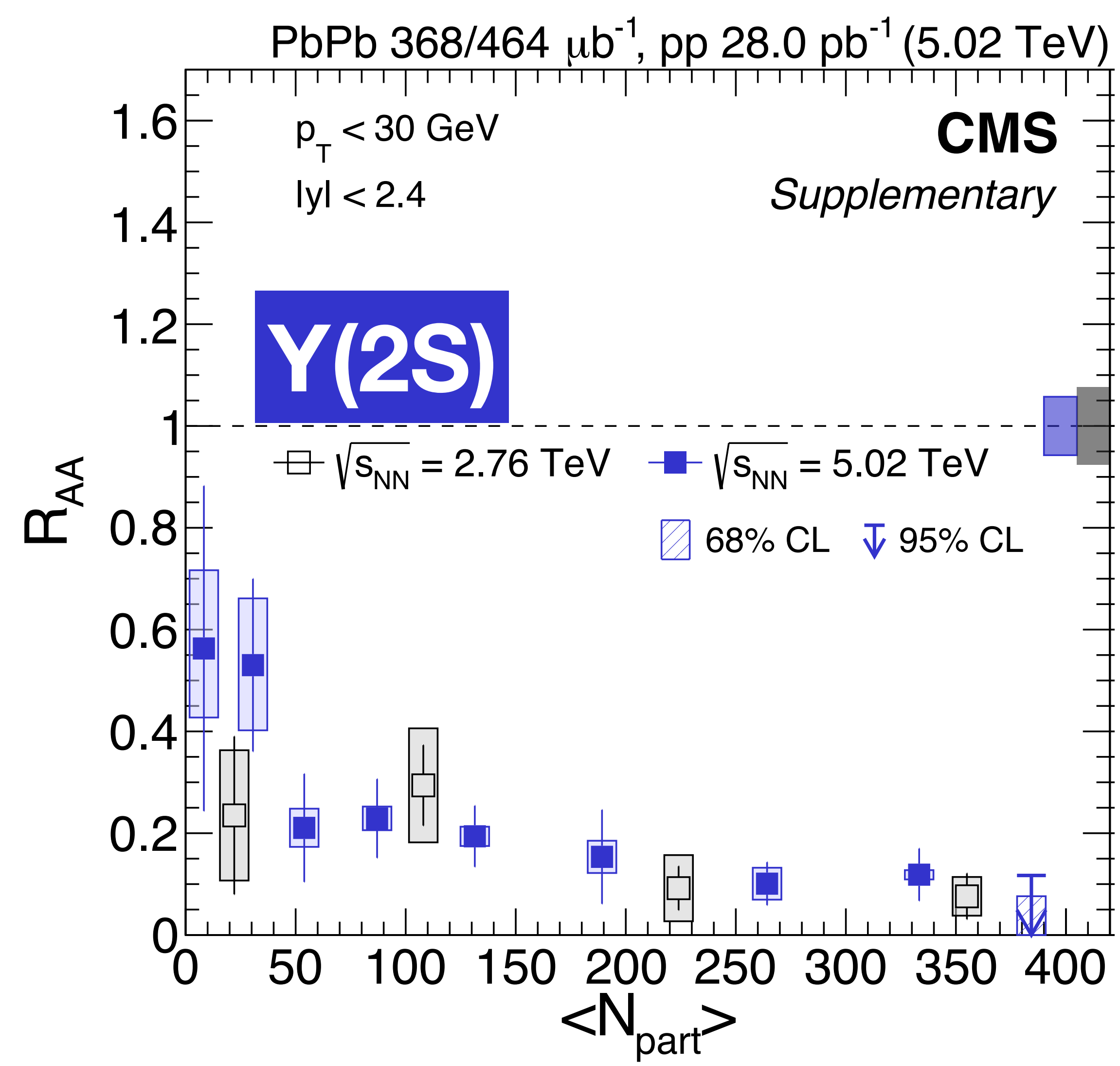
[PLB 790 (2019) 270]



[Comparison with 2.76 TeV] R_{AA} vs centrality

[PLB 790 (2019) 270] [PLB 770, 357(2017)]





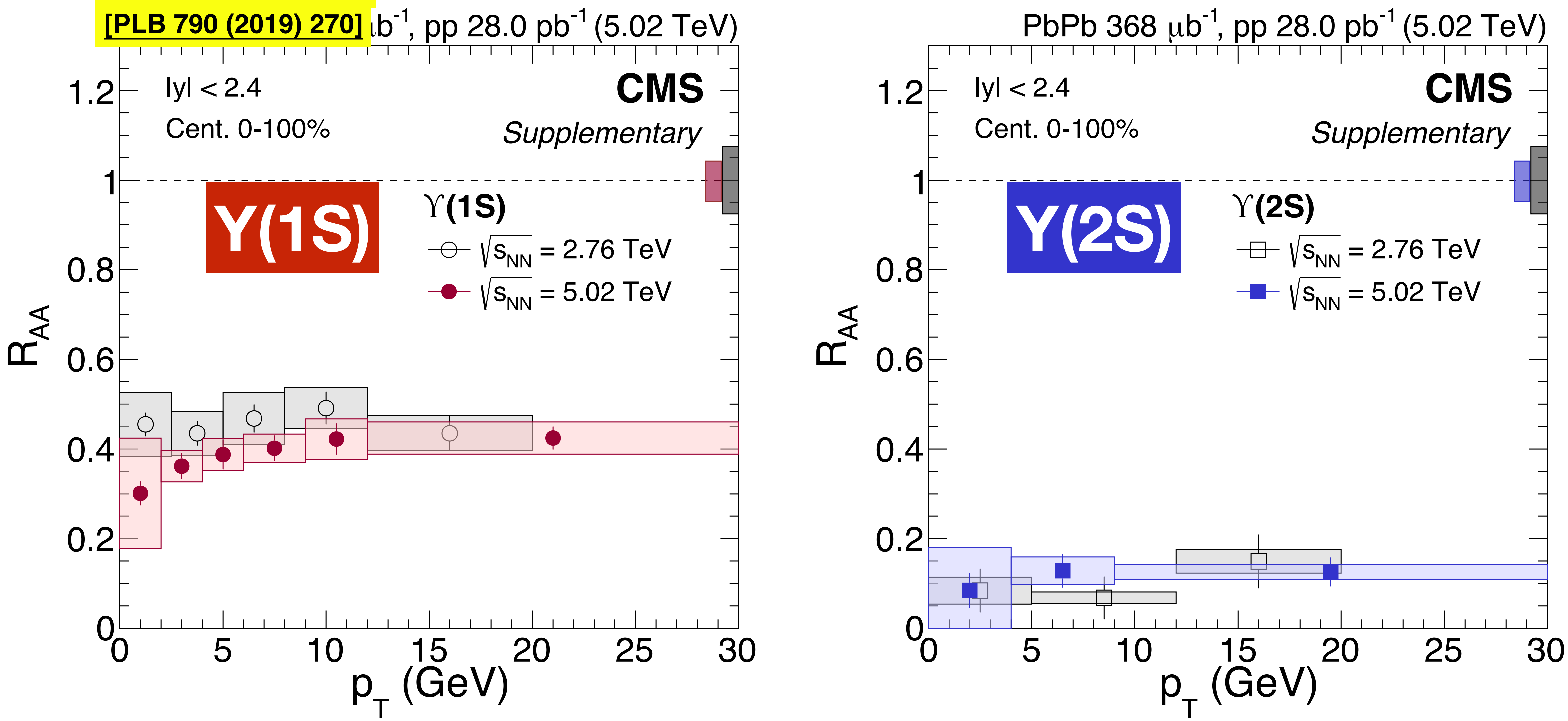
- ϒ(1S)
  - ➡ **R_{AA}(5.02) / R_{AA}(2.76) = 1.2 ± 0.15**
  - ➡ compatible within uncertainties

- ϒ(2S)
  - ➡ Monotonic dependence on centrality is clearer in 5.02 TeV
  - ➡ Similar suppression in both energies

[Comparison with 2.76 TeV] R_{AA} vs p_T

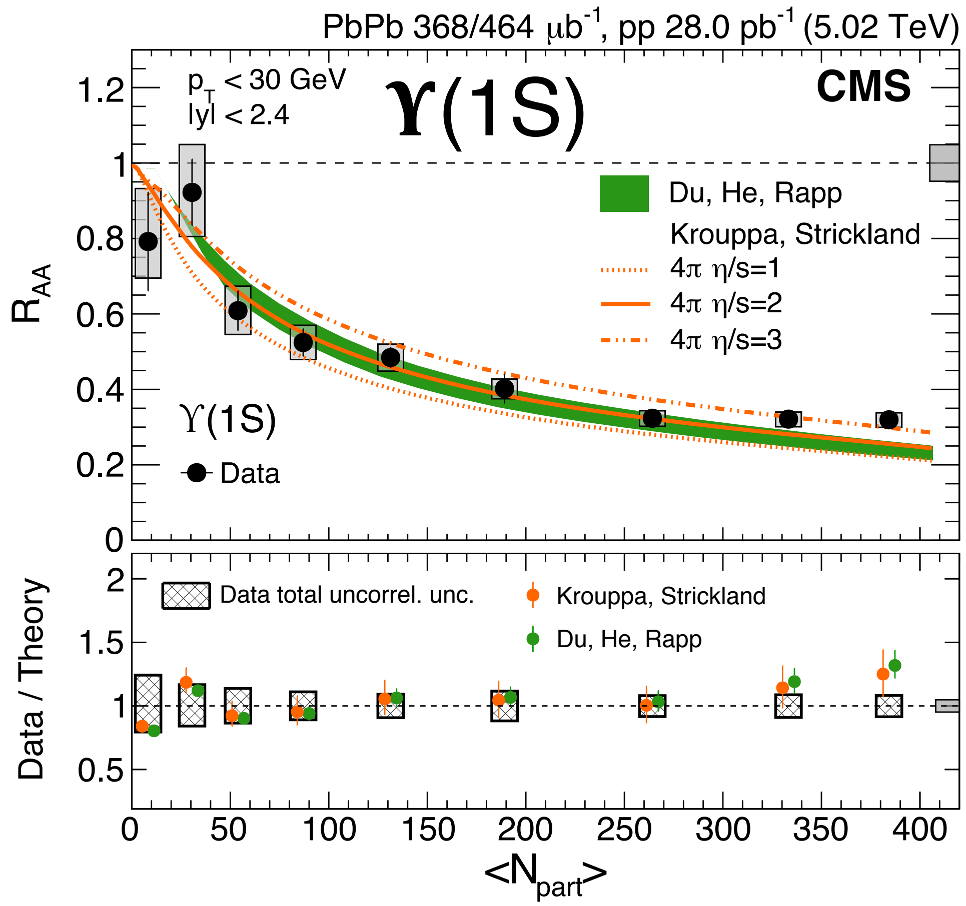
[PLB 770, 357(2017)]

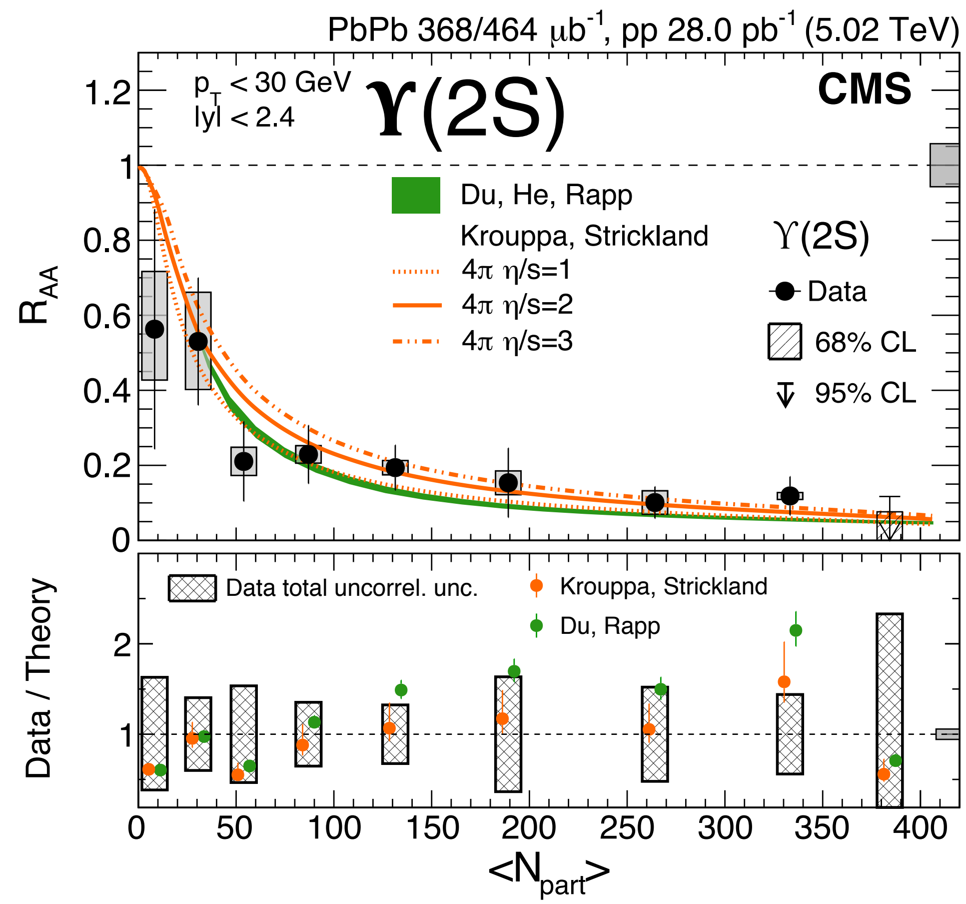
[PLB 790 (2019) 270]



- Extended high-p_T reach by 10 GeV for 5.02 TeV
- No significant p_T dependence for Y(1S) and Y(2S) in both energy
- Compatible suppression for both energies

Comparison with models at 5.02 TeV





<Krouppa & Strickland>

Melting temperature →

- **Υ(1S) : 600 MeV**
- **Υ(2S) : 230 MeV**
- **Υ(3S) : 170 MeV**

Initial temperature →

- **T_0 = {641,632,629} MeV**

- **No regeneration**

***Universe* 2 (2016) 16**

<Du, He & Rapp>

- **Υ(1S) : 500 MeV**
- **Υ(2S) : 240 MeV**
- **Υ(3S) : 190 MeV**

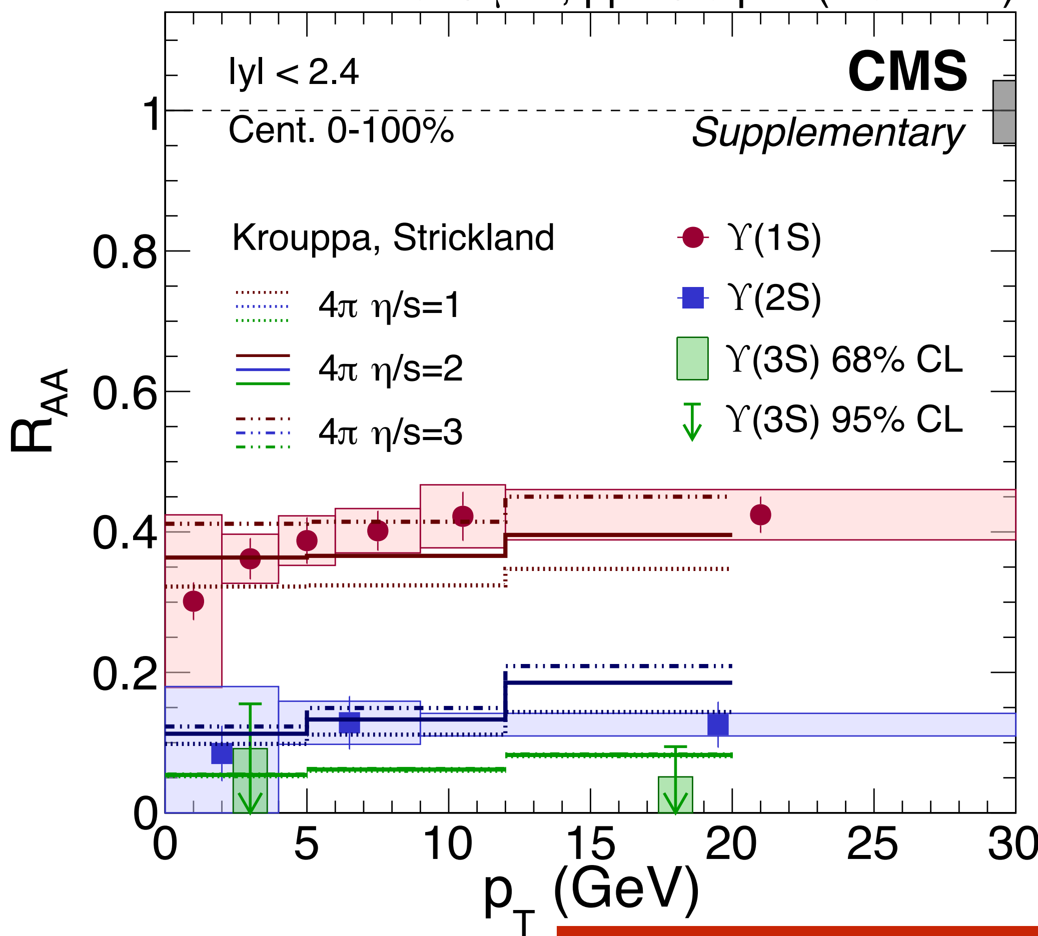
- **T_0= 550 - 800 MeV**

- **Regeneration included**

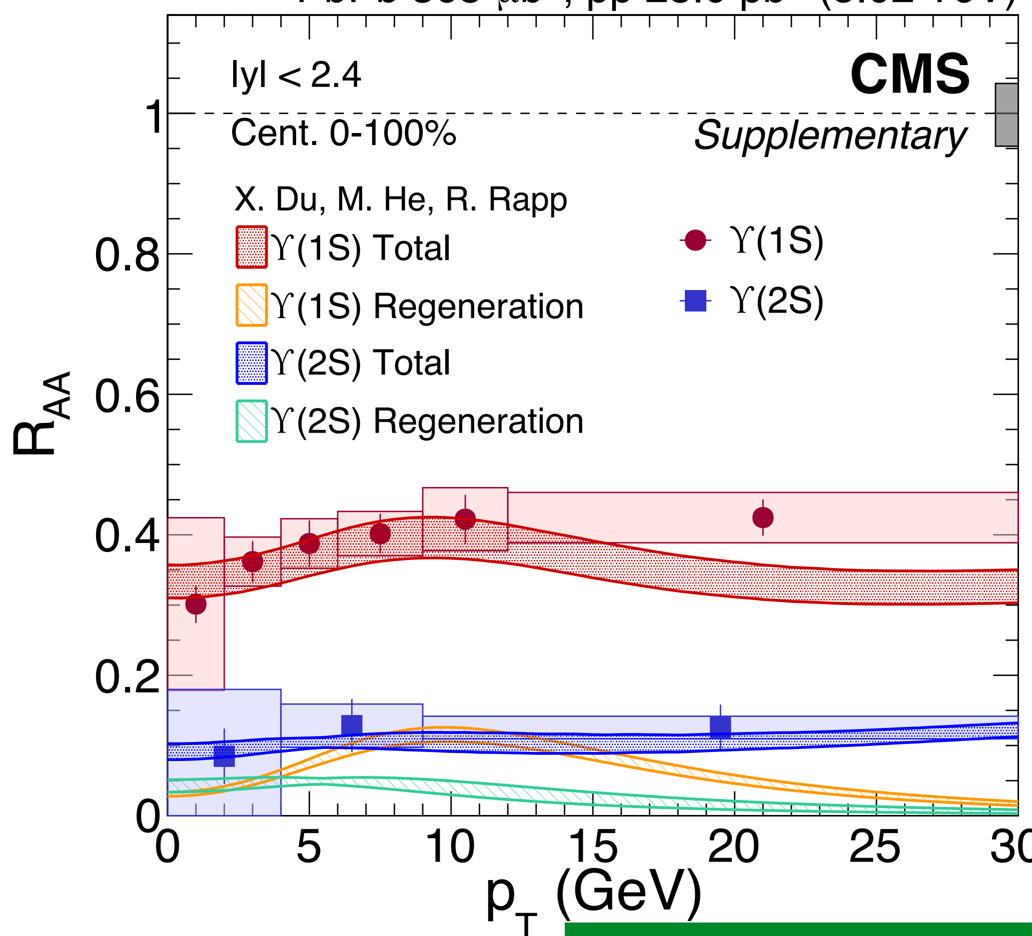
Phys. Rev. C 96, 054901

~67% direct production of Υ(1S) for both model

p_T dependence



Universe 2 (2016) 16



Phys. Rev. C 96, 054901

High speed upsilon can escape QGP
—> Smooth increase R_{AA} for p_T

p_T dependent regeneration competes with suppression
—> Predicts broad bump near p_T =10 GeV

Yet, both models are compatible with data within statistical uncertainty.

Have to check high p_T > 20 GeV —> Need more data

So, does it characterize the HOT medium?

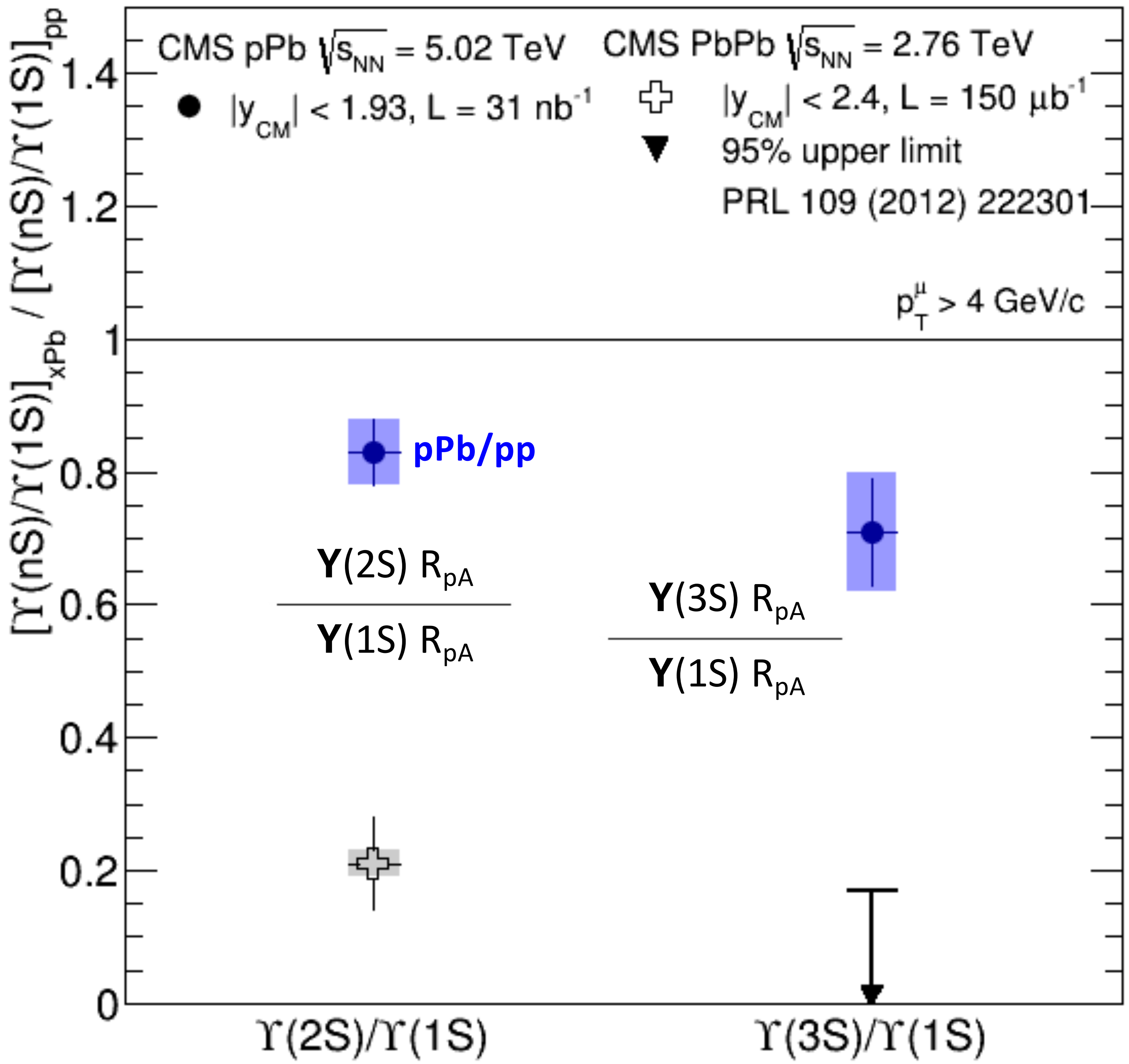
- The answer is “partially correct”
- See what CMS measured in pPb collision at 5.02 TeV

- **Event activity of Υ(nS) in pPb at 5.02 TeV**

  [JHEP 04 (2014) 103]

In 2013, we took pPb data at 5.02 TeV

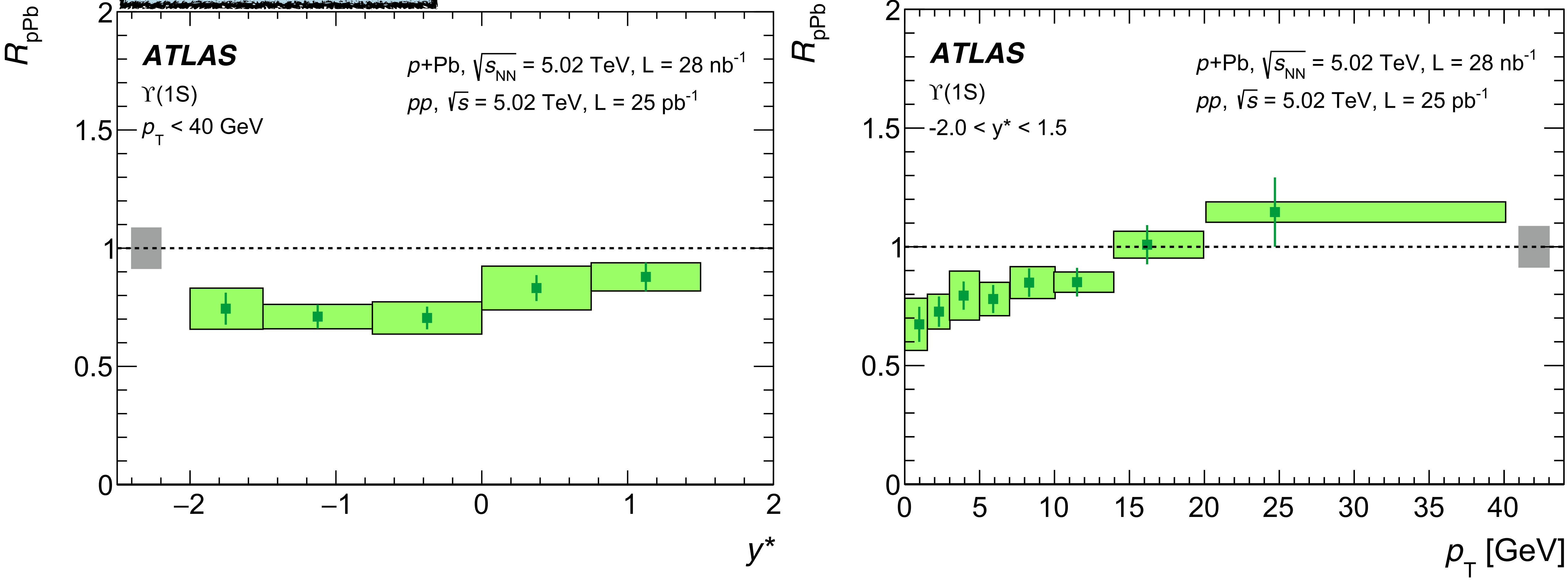
- pPb serves as cold nuclear baseline
- Drop of double ratios observed in pPb less than PbPb but in the analogous manner
- confirmed that large suppression of excited states is primarily due to hot medium (QGP)



So, does it characterize the HOT medium?

- The answer is "partially correct"
- See what ATLAS measured at the same condition

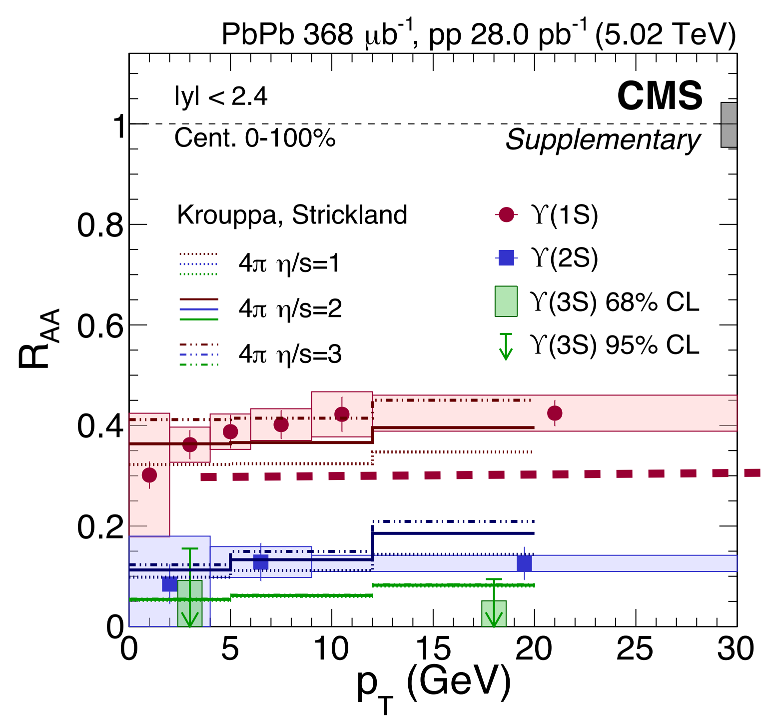
EPJC (2018) 78

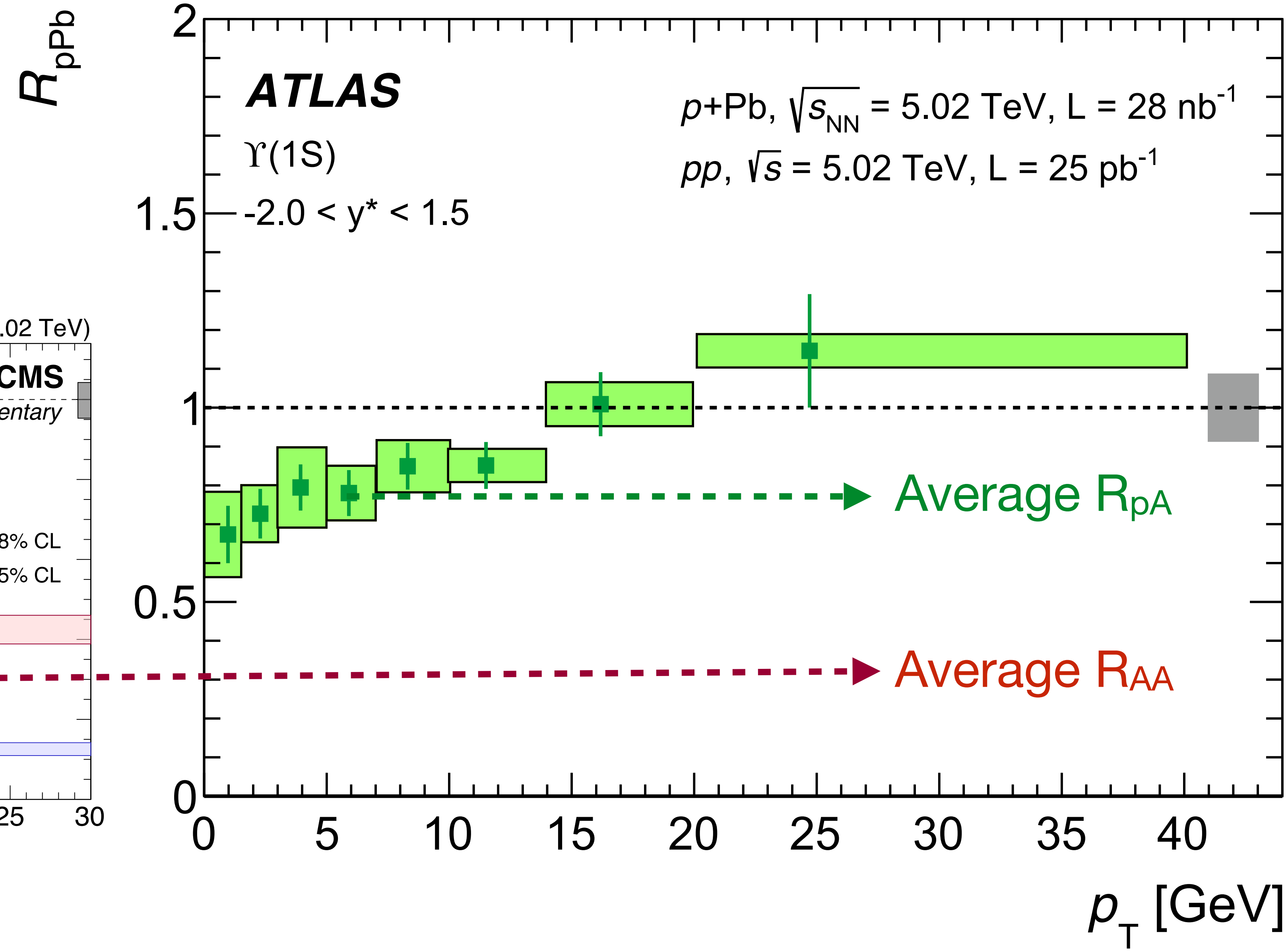


- Average RpPb is 0.8, which means that only cold nuclear matter effect can result in R_{AA} down to 0.64 => Half of the suppression in PbPb attributed to CNM!

So, does it characterize the HOT medium?

- The answer is “Not fully”
- R_{AA} VS R_{pA}





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Elliptic flow of bottomonia

<Krouppa & Strickland>

arXiv1809.06235

We study the role of anisotropic escape in generating the elliptic flow of bottomonia produced in ultrarelativistic heavy-ion collisions. We implement temperature-dependent decay widths for the various bottomonium states, to calculate their survival probability when traversing through the anisotropic hot medium formed in non-central collisions. We employ the recently developed 3+1d quasiparticle anisotropic hydrodynamic simulation to model the space-time evolution of the quark-gluon plasma. We provide a quantitative prediction for transverse momentum dependence of bottomonium elliptic flow and nuclear modification factor for Pb + Pb collisions in $\sqrt{s_{NN}} = 2.76$ TeV at the Large Hadron Collider.

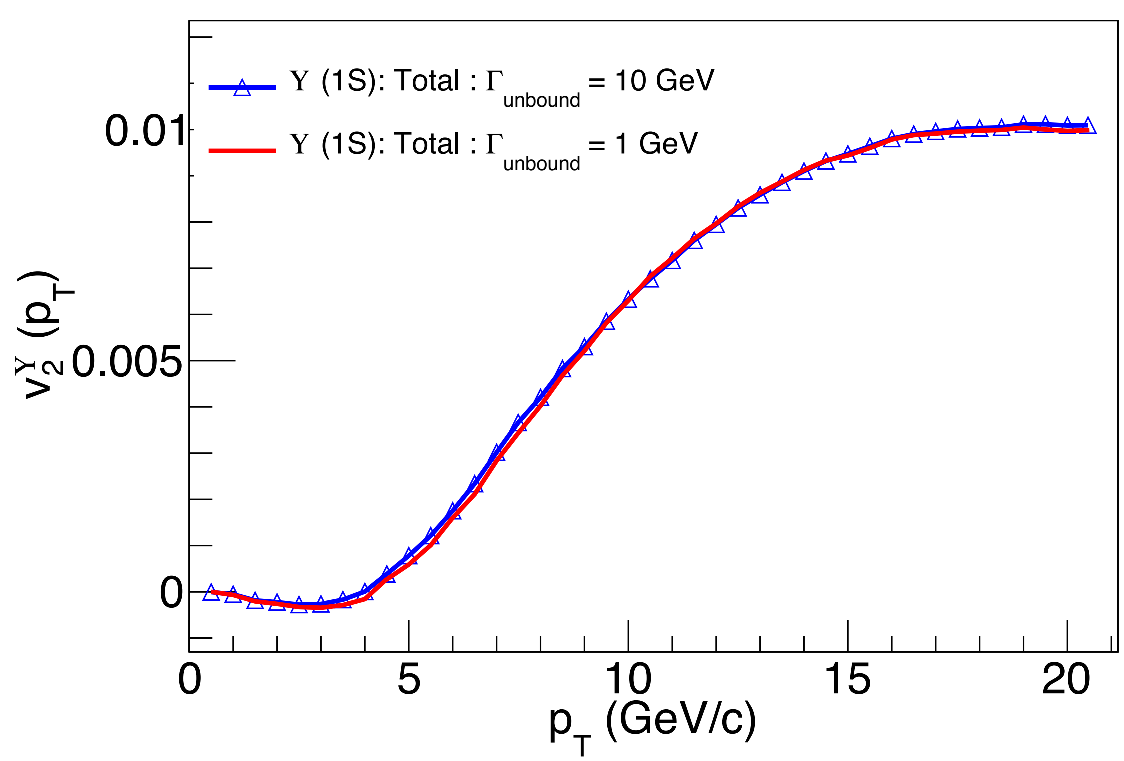
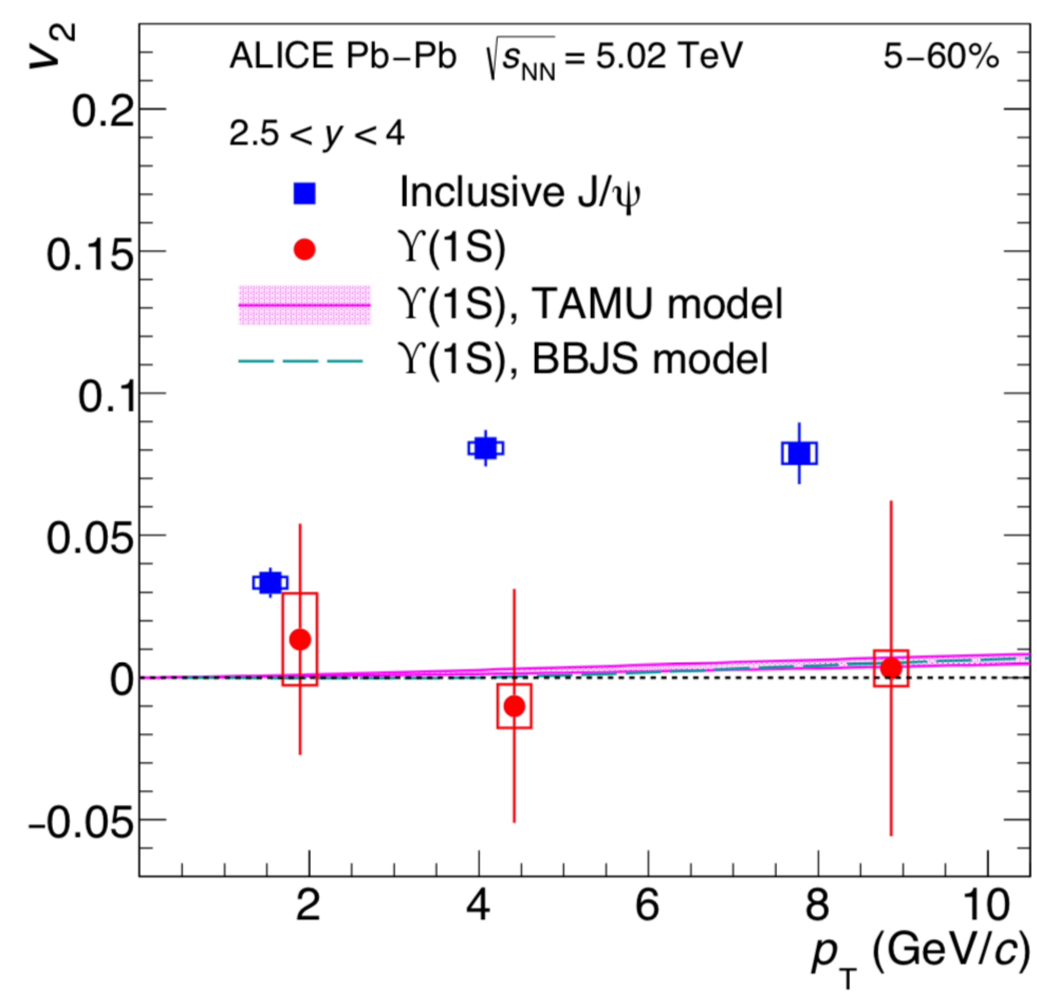
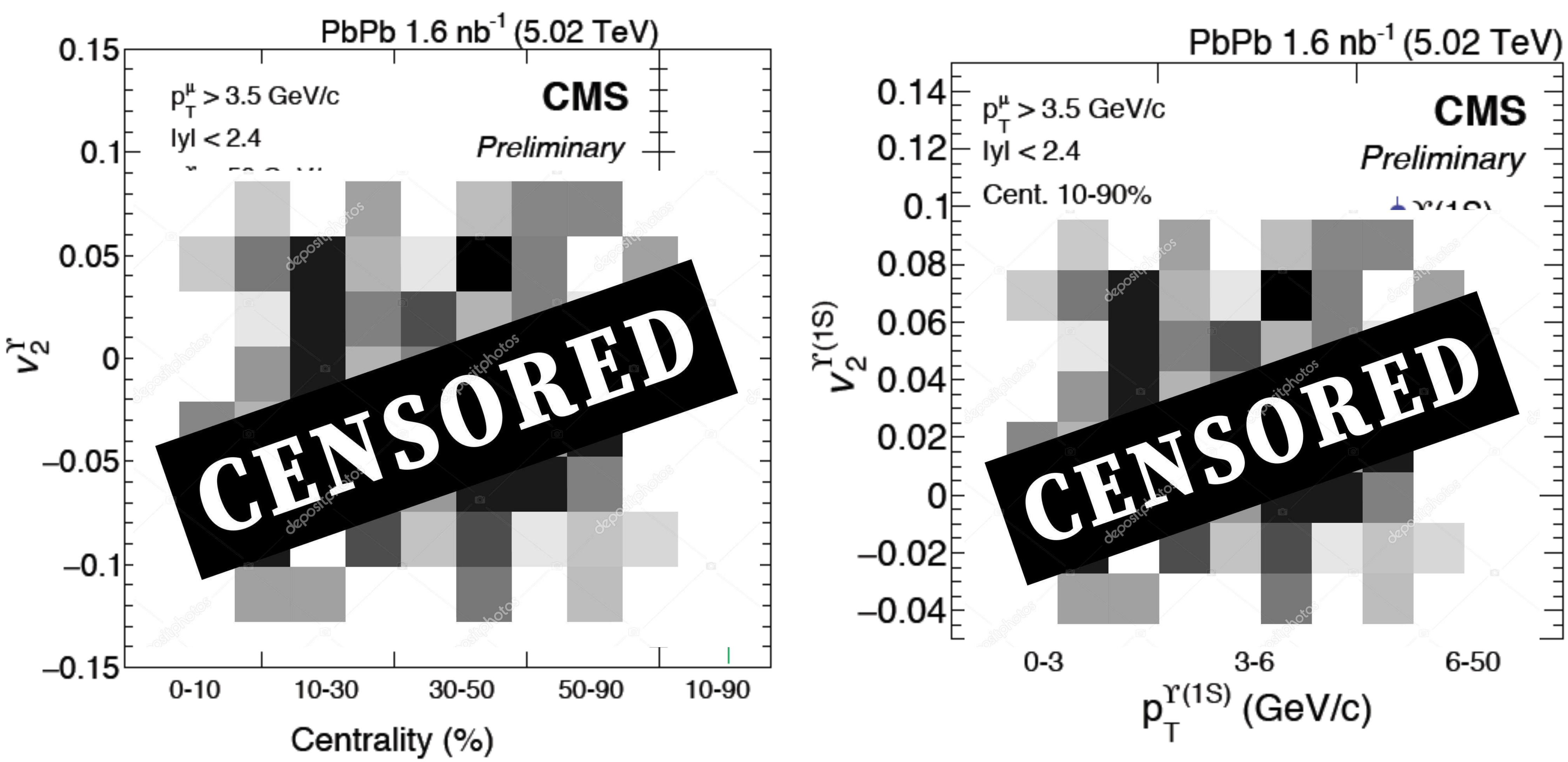


FIG. 4: Transverse momentum dependence of v_2 of $\Upsilon(1S)$ including feed down contributions from higher excited states for Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, for two different values of the decay width of unbound states.



Elliptic flow of bottomonia with CMS

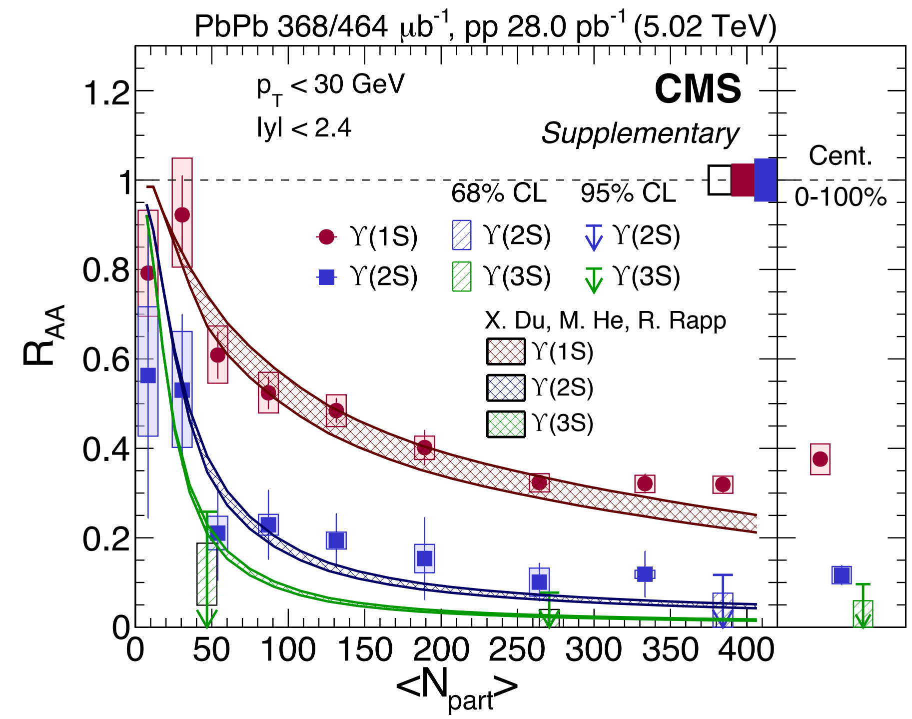


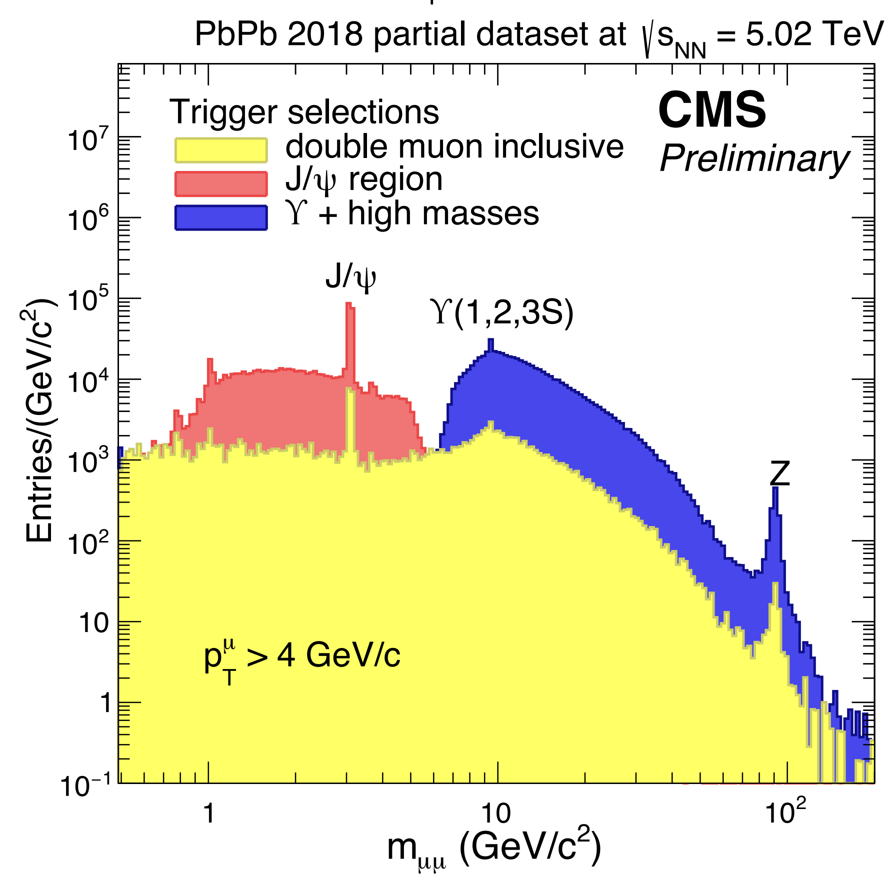
CMS result will be released in the upcoming Quark Matter in November…

- With ~5 more statistics
- Cover wider p_T range
- Rapidity range is complementary
- Also has Y(2S) v_2 result

Remarks and plan for Upsilon analysis

- R_{AA} of Y(1S), Y(2S) and Y(3S) were measured as a function of p_T, rapidity and centrality, improving the previous results at 2.76 TeV
  - Consistent with 2.76 TeV data within uncertainty (Models predicted -16%)
  - Clearer dependence on centrality, yet we need more data for peripheral collisions to find the turn-on curve of R_{AA}
- The Y(3S) peak is not visible yet
- Compatible with both two different models
  - p_T dependence study with higher statistics may help to resolve





2. Charmonia

Outline of charmonia measurement

	Charmonia
PbPb 2.76 TeV 160μb^{-1}	Prompt J/ψ R_{AA} Prompt J/ψ v_2 Prompt ψ(2S) J/ψ in UPC*
pPb 5.02 TeV 35nb^{-1}	J/ψ production

Hot & Cold Nuclear Matter effect

- Debye screening
- Energy loss

Only Cold Nuclear Matter effect

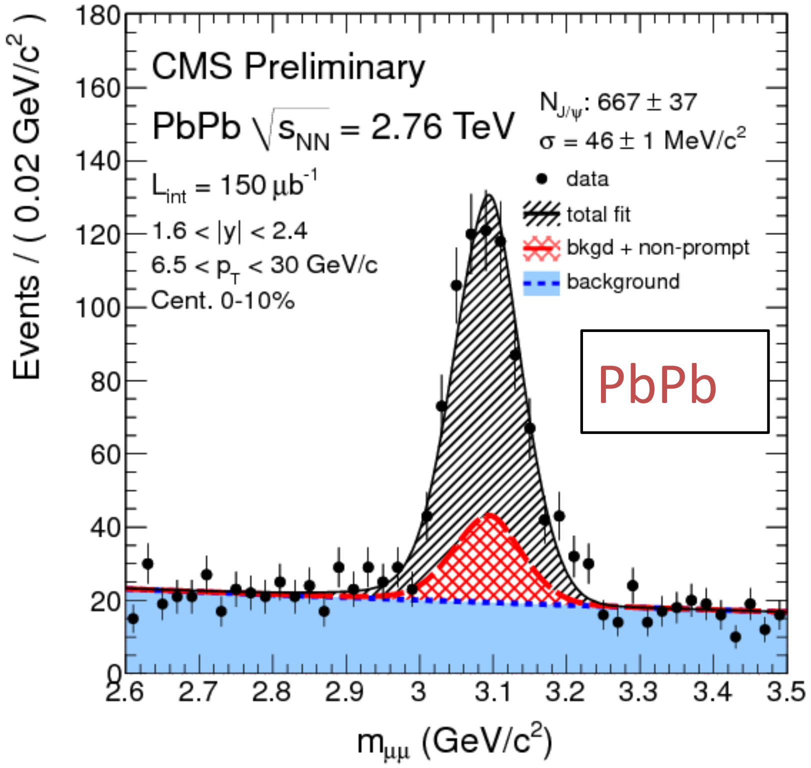
- nPDF
- Energy loss

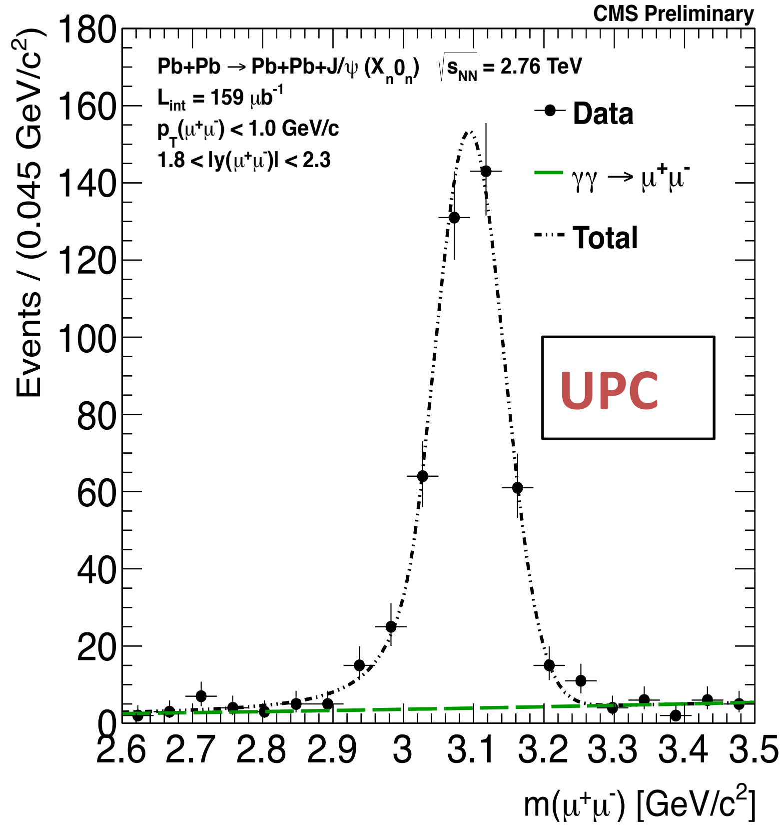
Only nPDF

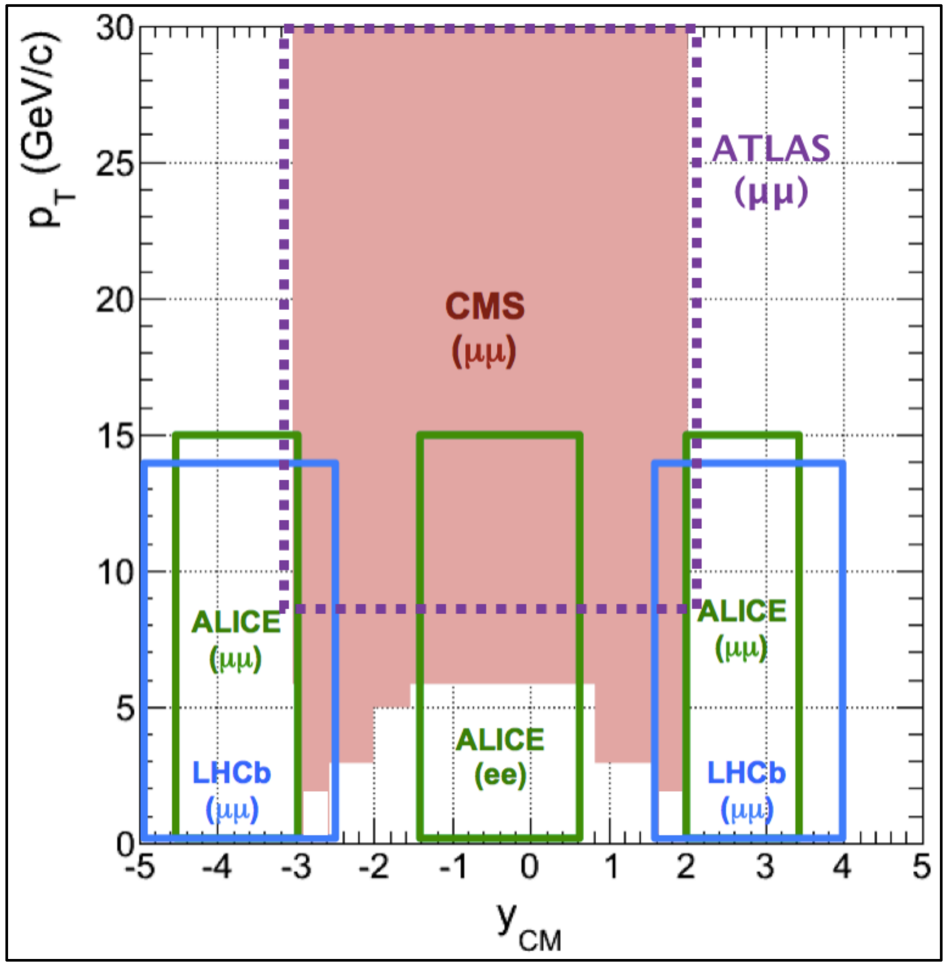
* UPC = ultra-peripheral collision

** Only prompt charmonia discussed in this section

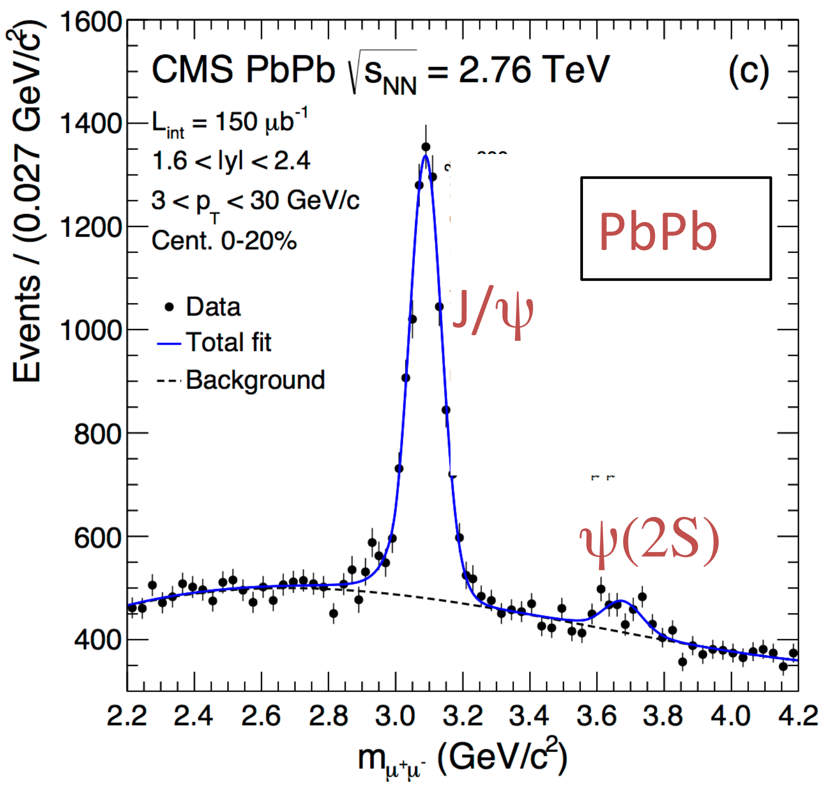
Gallery of J/ψ from LHC experiments

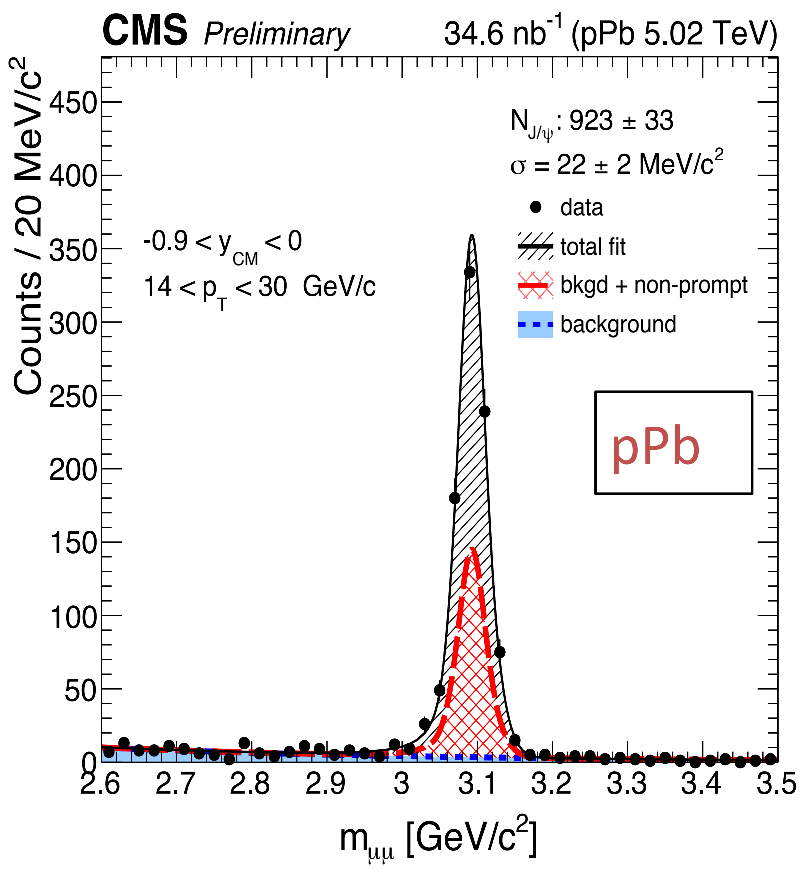




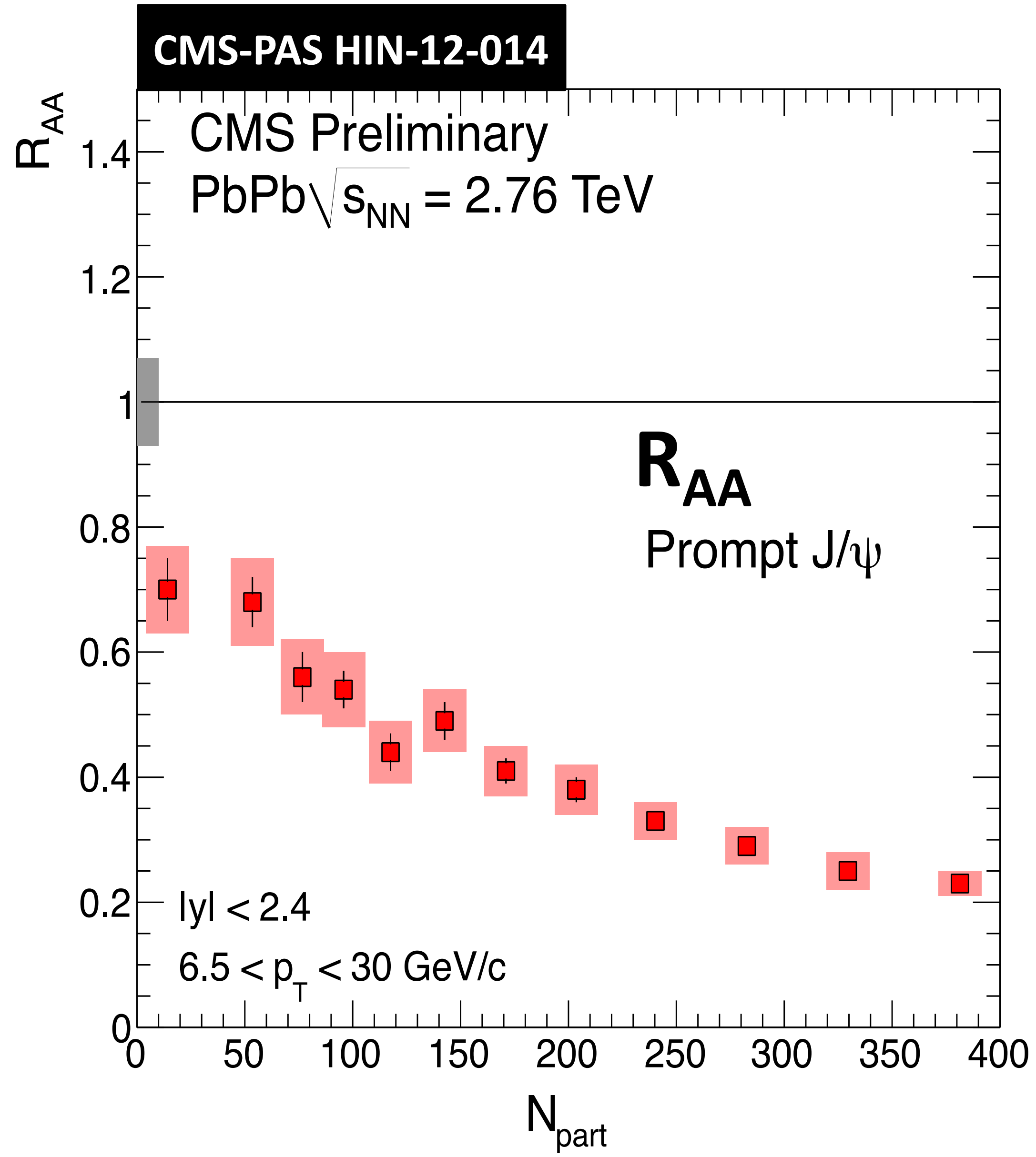


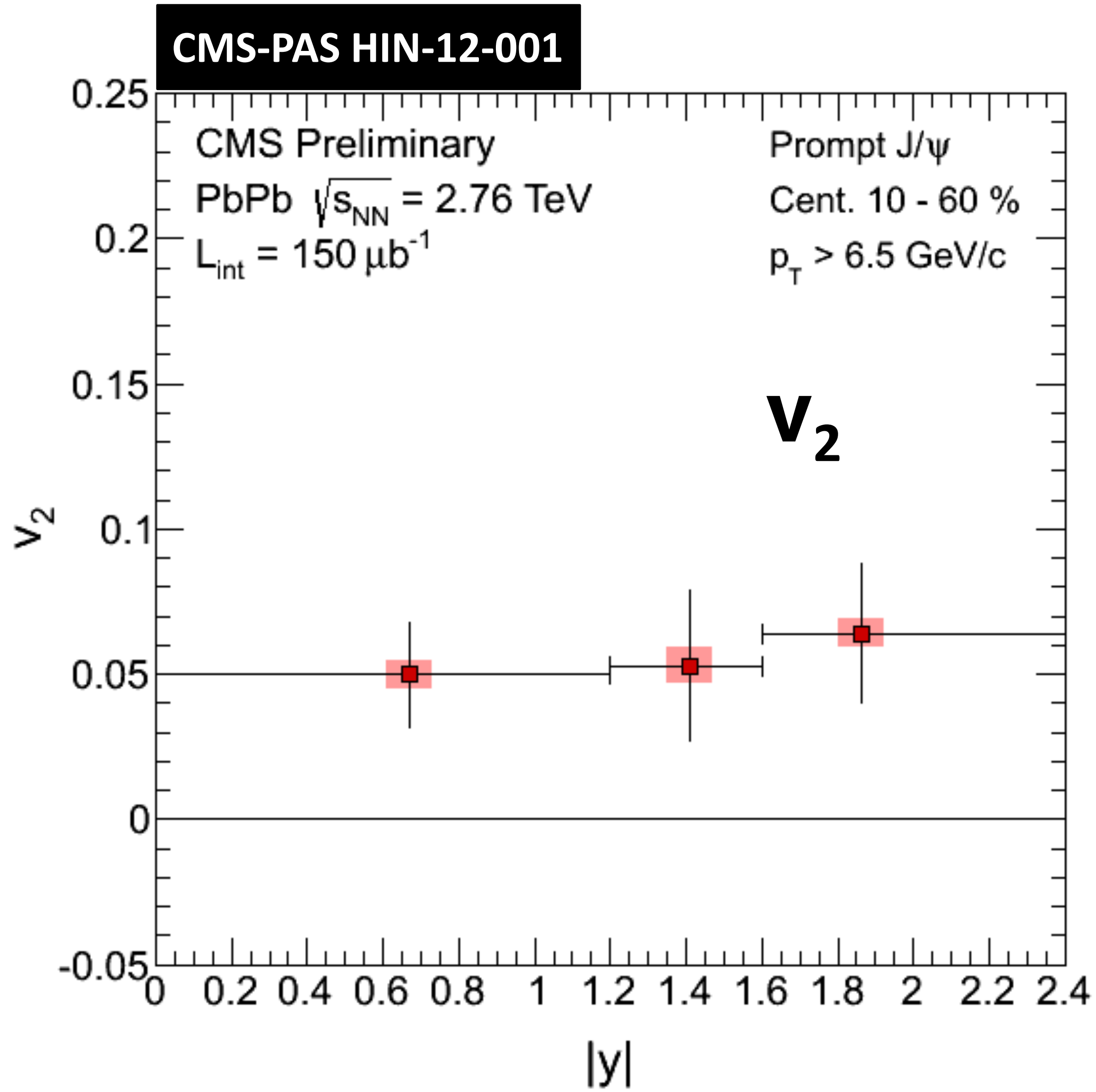
Complmentary coverages of J/ψ in pPb by 4 experiments





Charmonia in PbPb : Ground state (1S)

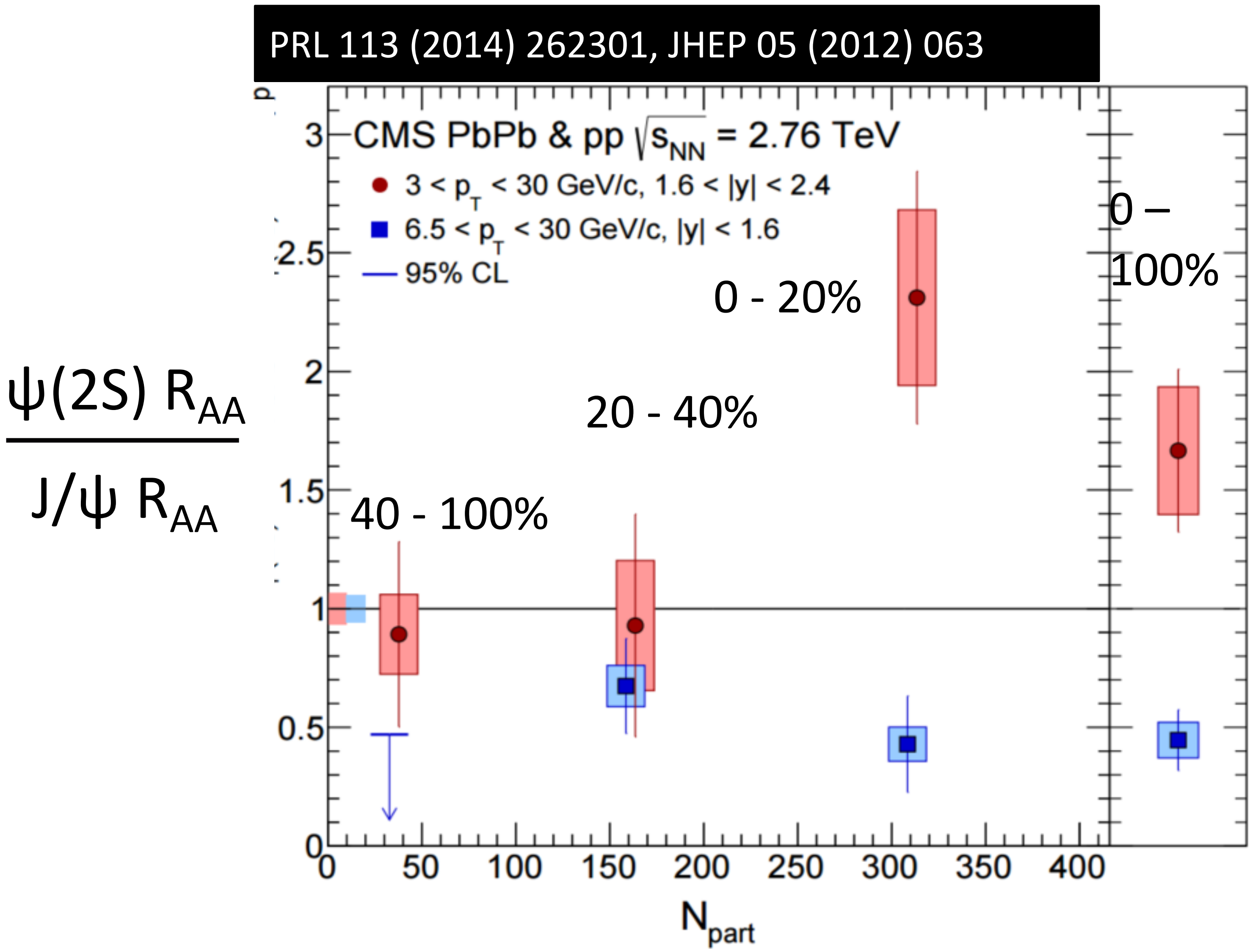


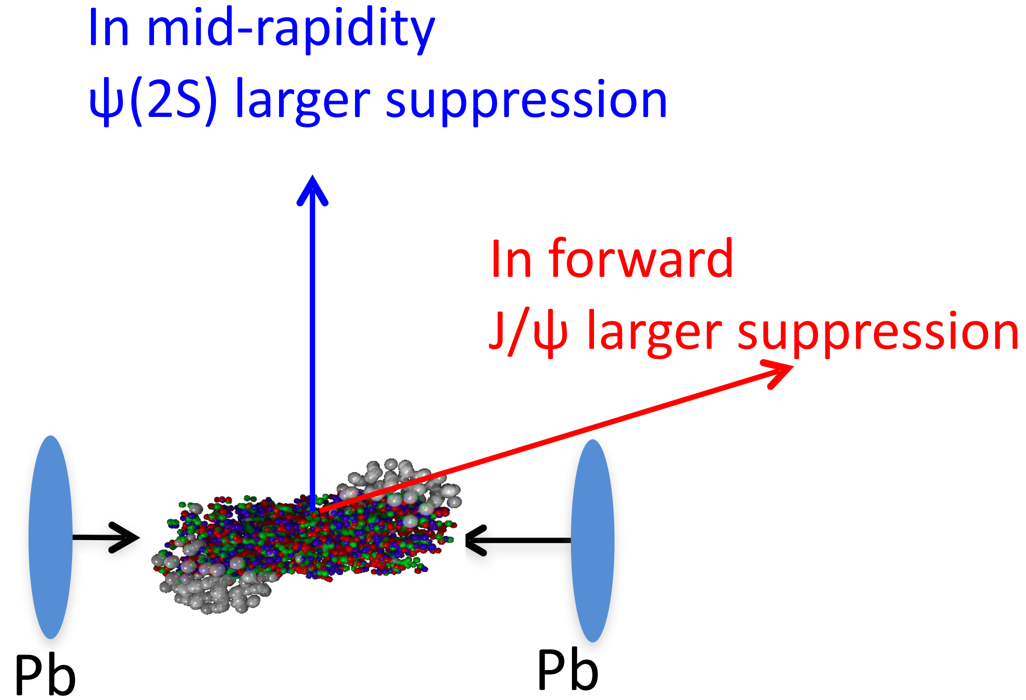


- Suppression has a similar dependence on centrality with Υ(1S)
- Small but clearly finite positive elliptic flow

Charmonia in PbPb : Excited state ψ(2S)

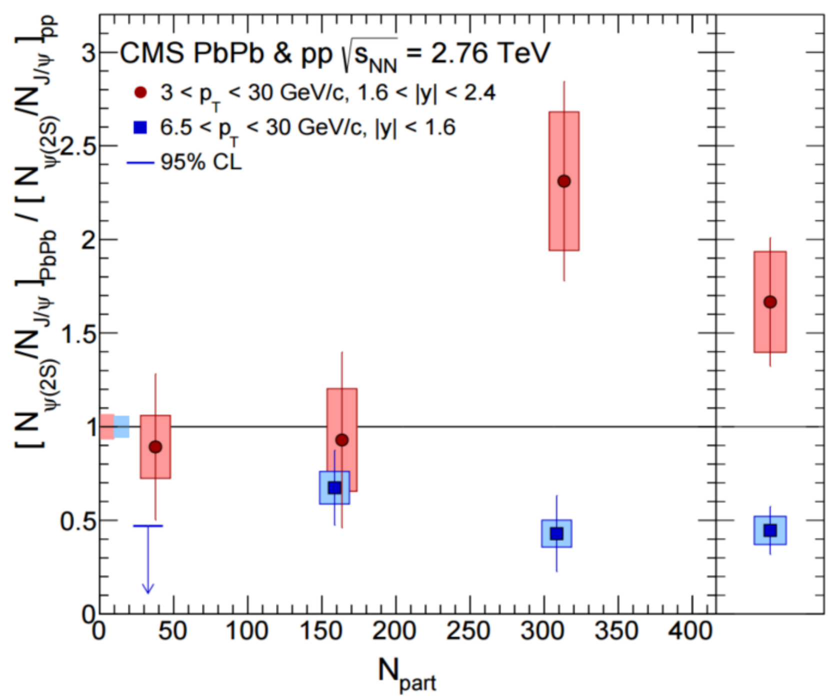
- Compared suppression patterns of J/ψ and ψ(2S) at 2.76 TeV

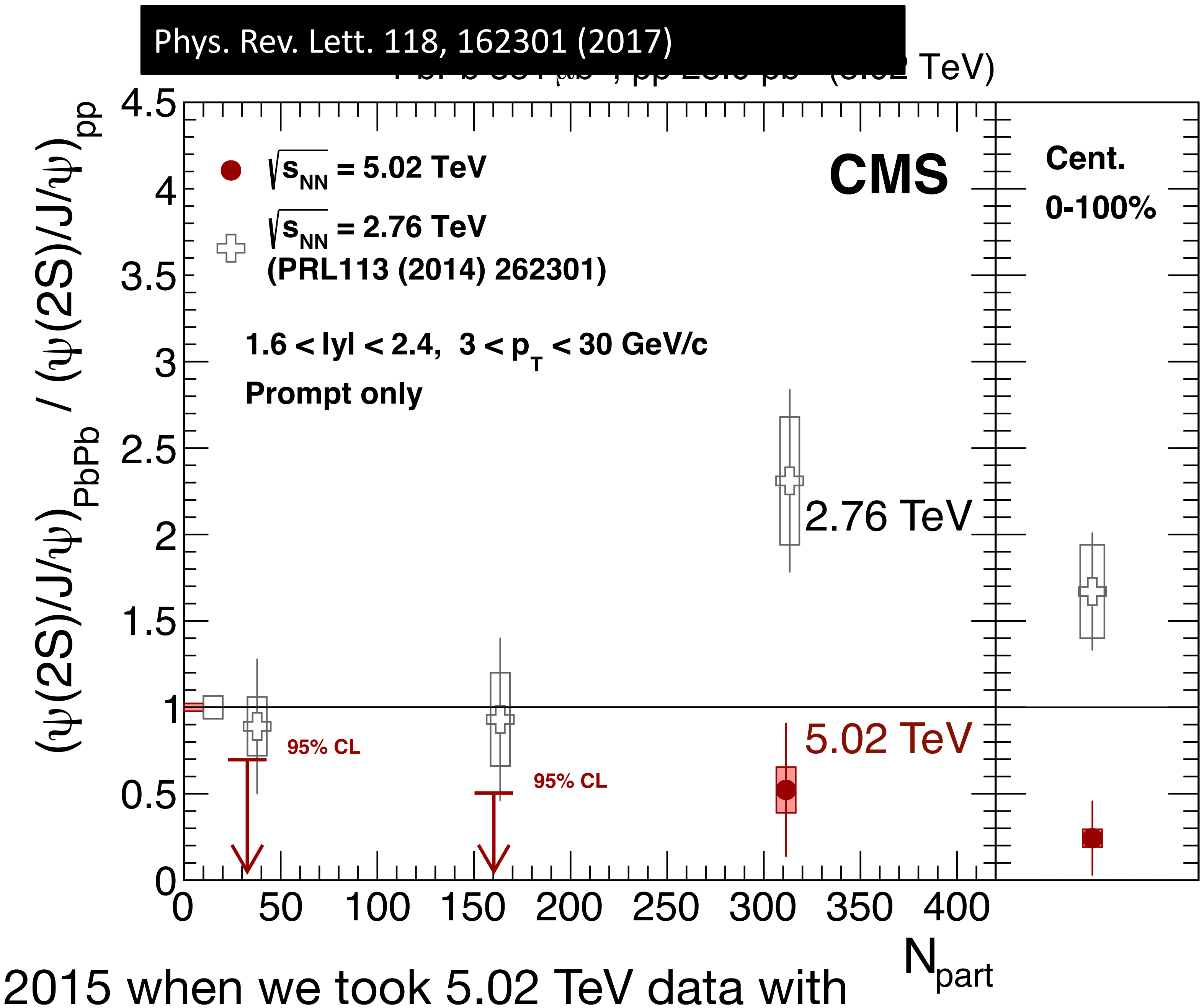




- In naïve sequential suppression picture, excited states are more suppressed than the ground states as observed in Υ(nS) study
- However, ψ(2S) was less suppressed than J/ψ in forward <= Big puzzle at that time

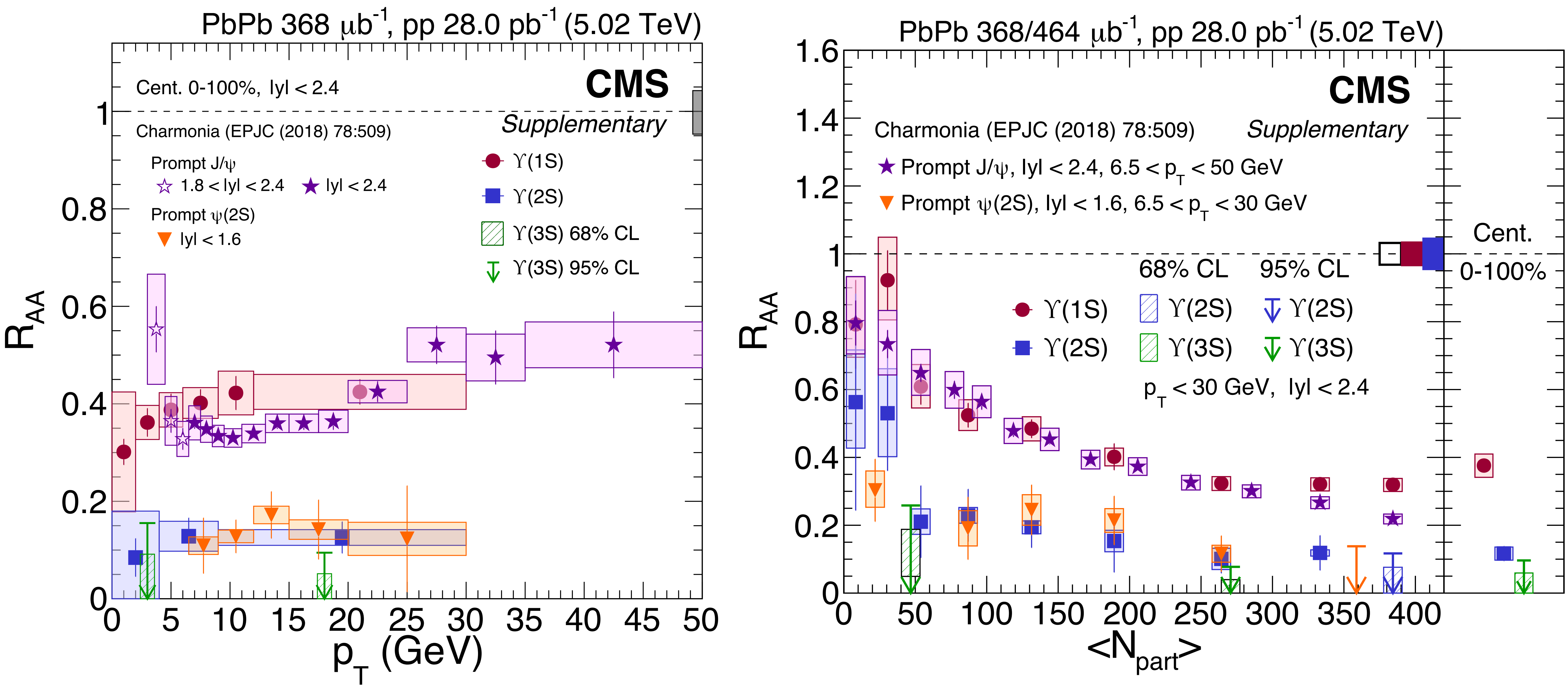
Charmonia in PbPb : Excited state ψ(2S)





- But, there happened a twist in 2015 when we took 5.02 TeV data with higher statistics by factor of 3
- Now, the suppression of ψ(2S) is larger than J/ψ at everywhere

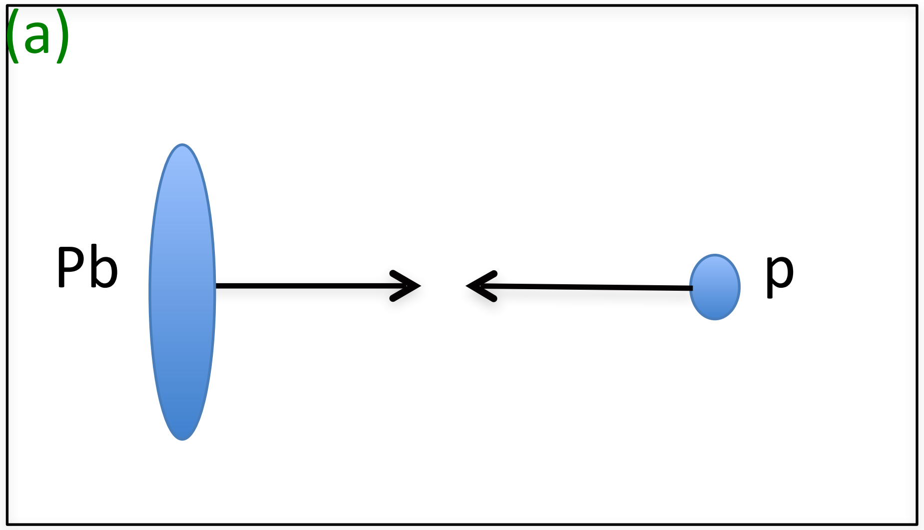
RAA : Charmonia vs Bottomonia



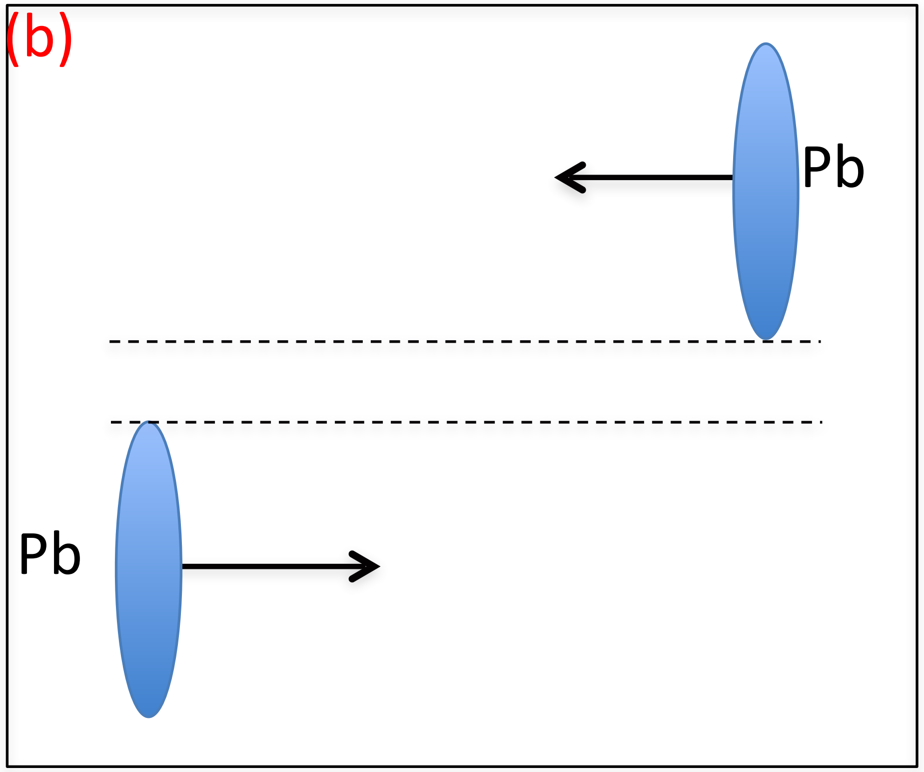
- Very similar behavior between Charmonia and Bottomonia
  - **ϒ**(1S) aligns with J/psi(1S)
  - **ϒ**(2S) aligns with psi(2S)
- Bizarre!
  - Can't say anything before increasing statistics largely

Probing Cold Nuclear Matter effects

- Cold Nuclear Matter effects
  - Modification of PDF
  - Nuclear absorption
  - Energy loss inside nucleus
  - And more

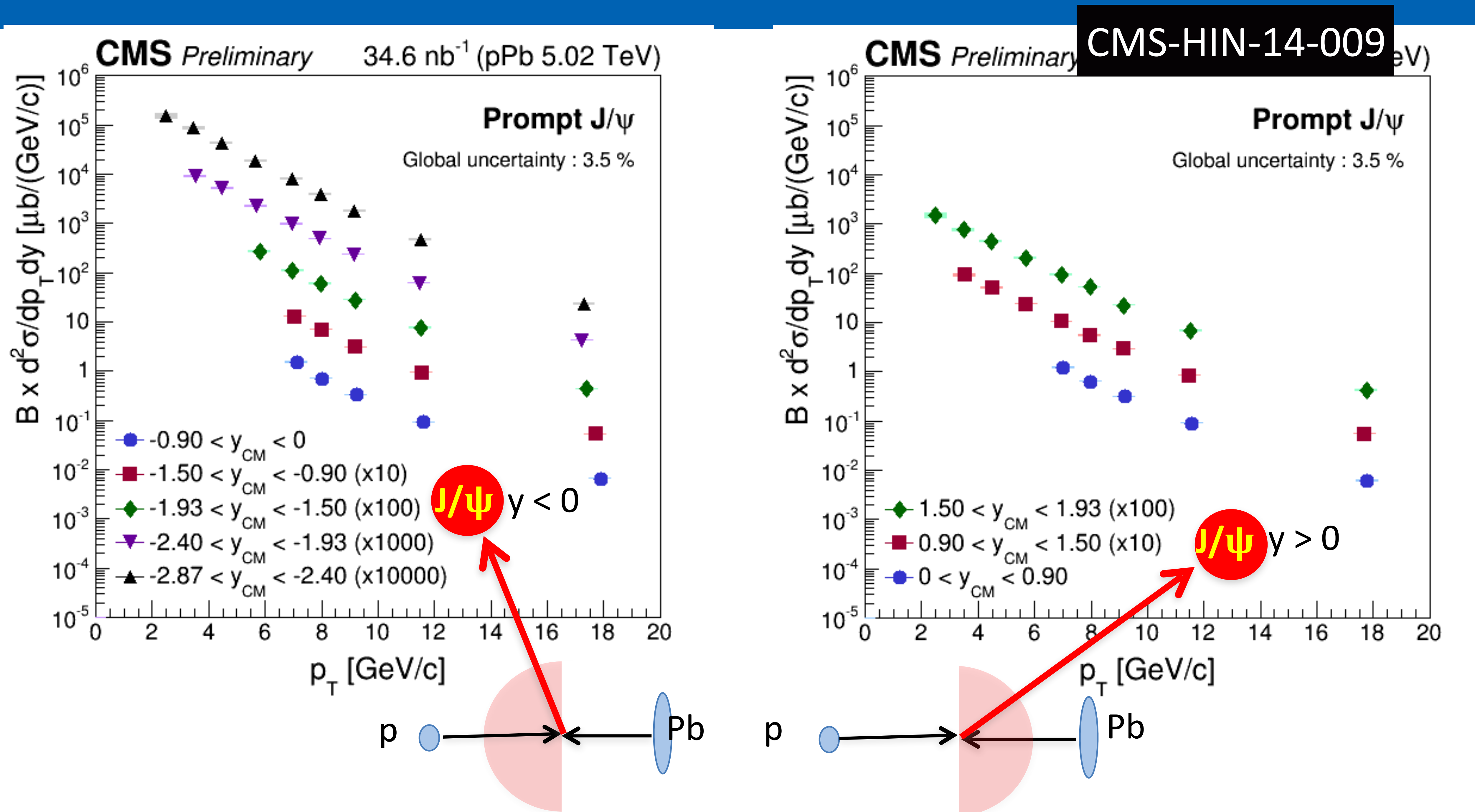


(a) pPb



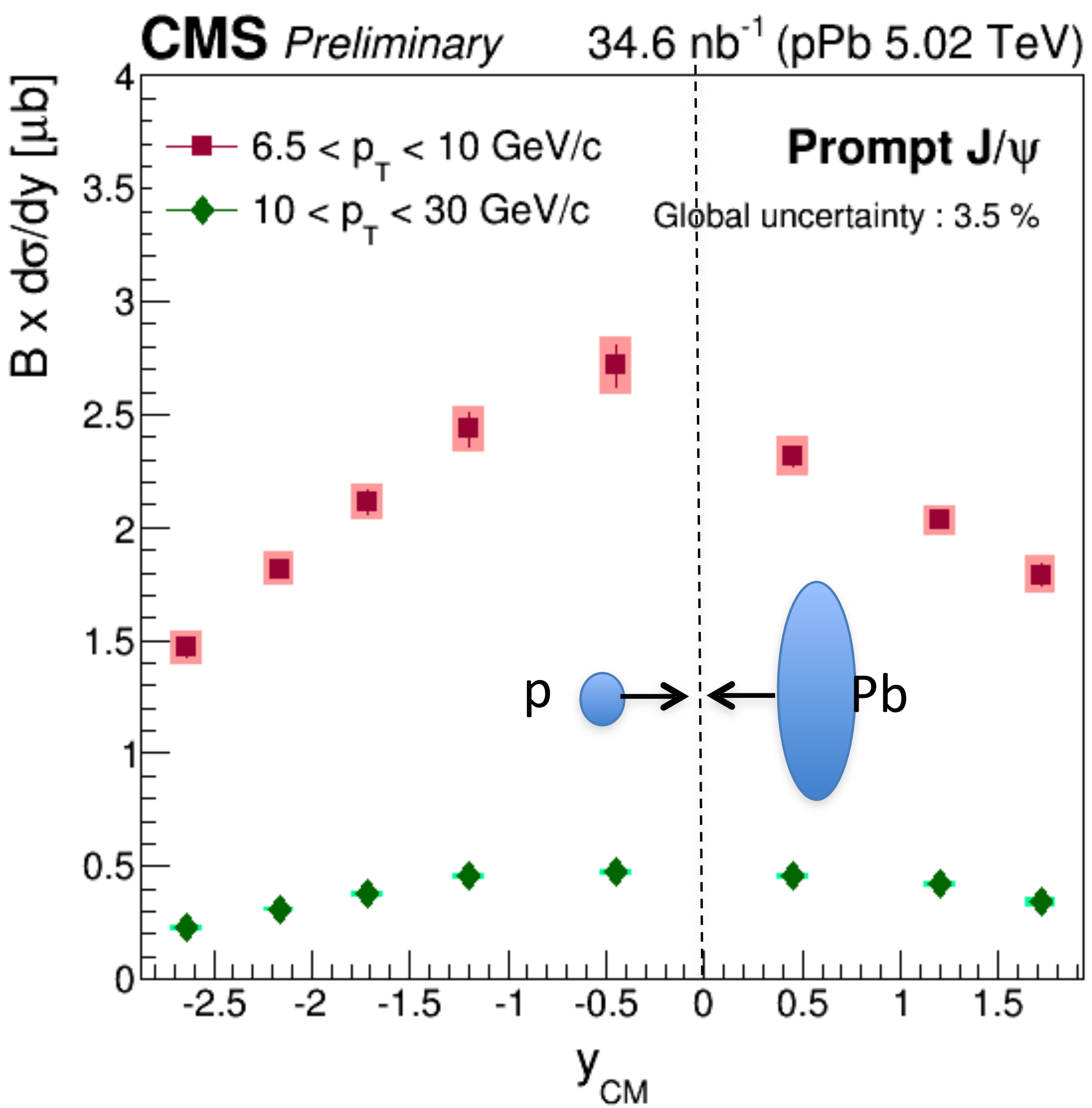
- Charmonia can probe CNM effects via J/ψ production in…
  (a) pPb collisons
  (b) Ultra Peripheral Collisions

J/ψ measured in pPb collision



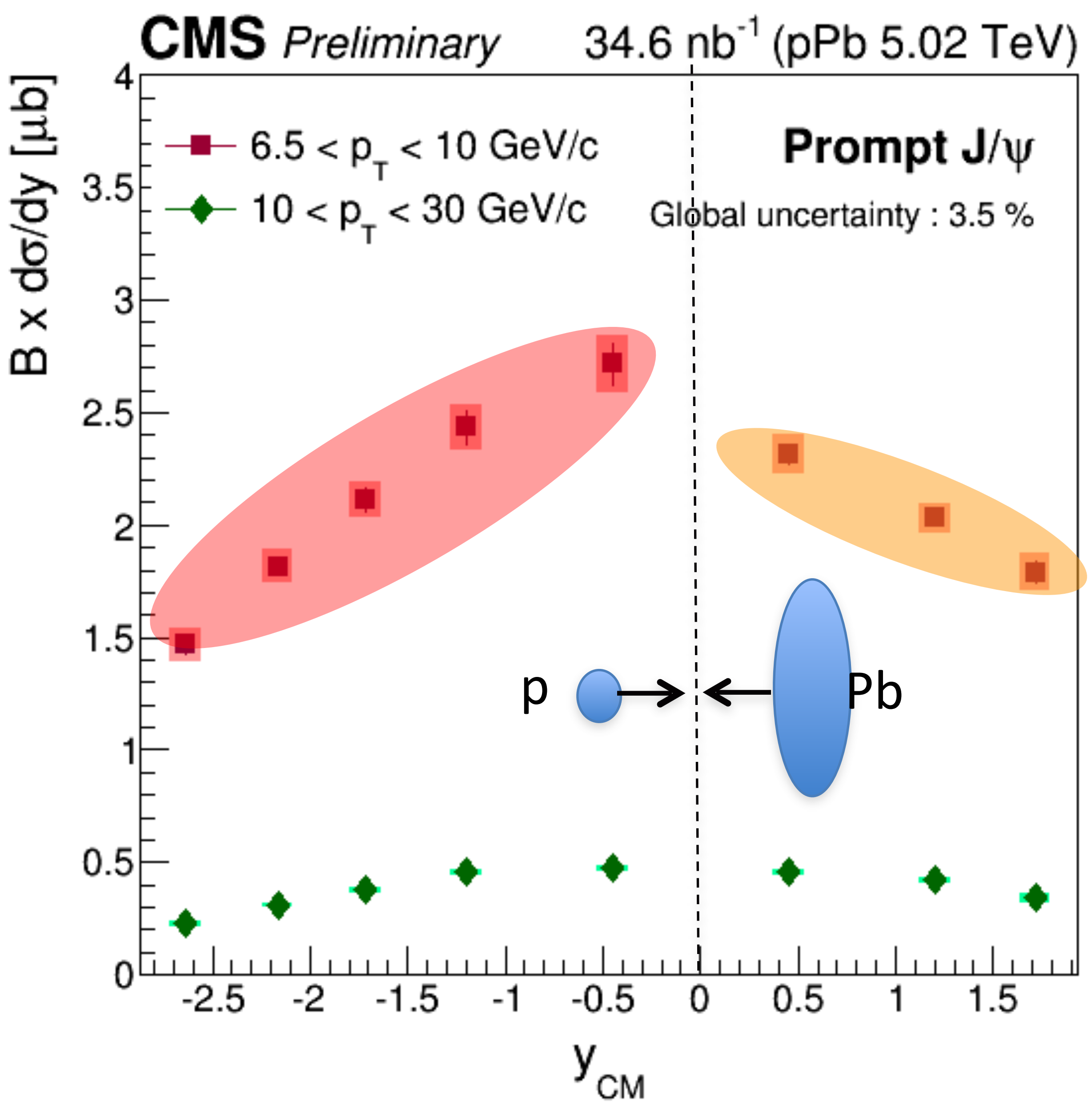
- Double differential cross-section for a wide kinematic range
  - p_T : [2, 30] GeV/c, y_{CM} : [-2.87, 1.93]

Lesson from this measurement



- Cross section as a function of rapidity at
  - Low p_T [6.5, 10] GeV/c
  - High p_T [10, 30] GeV/c

Lesson from this measurement



- Cross section as a function of rapidity at
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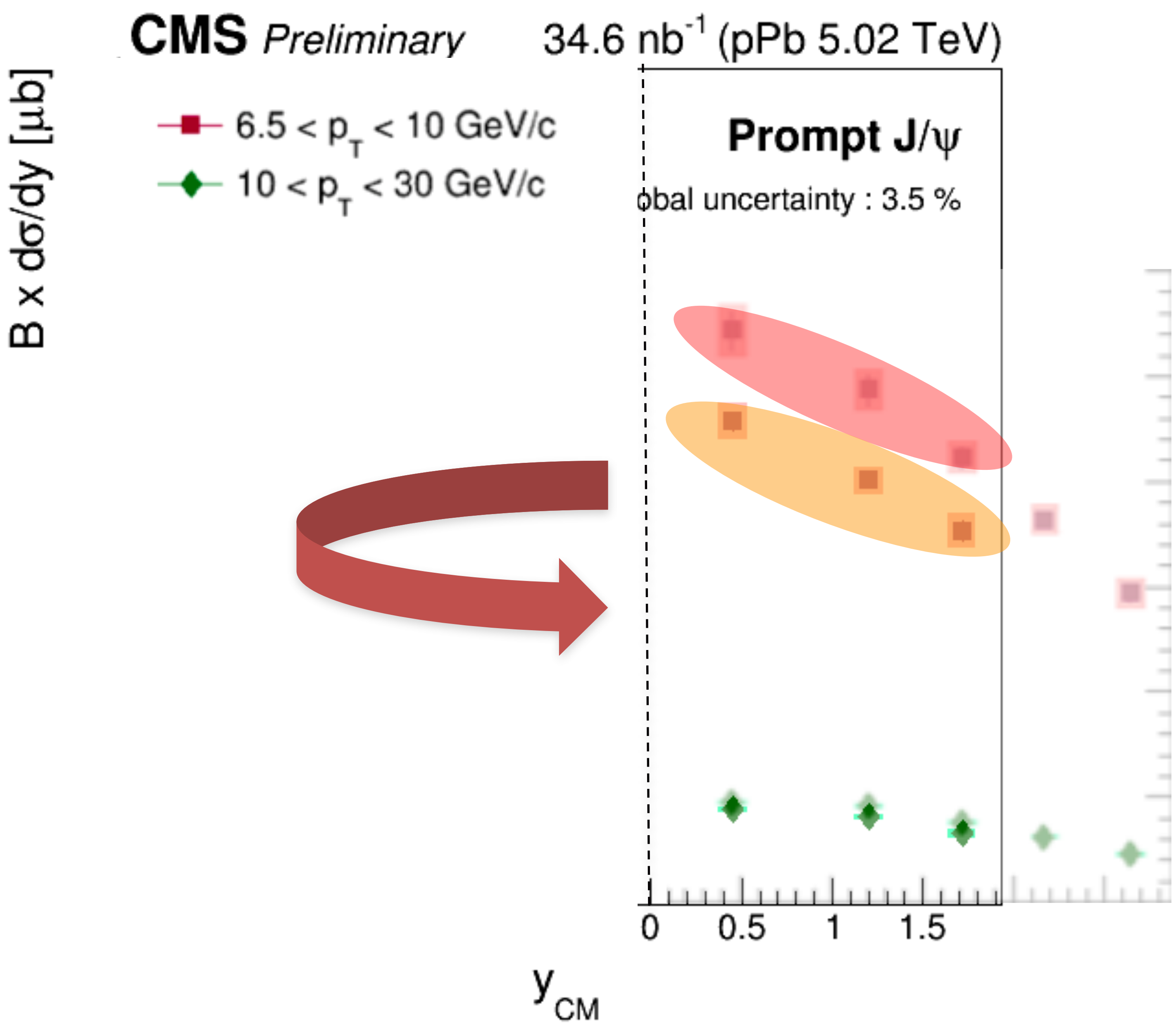
  - High p_T [10, 30] GeV/c

Lesson from this measurement



$$R_{FB}(p_T, y) = \frac{\text{Yield in } (p_T, +y)}{\text{Yield in } (p_T, -y)}$$

- Fold plot around $y_{CM}=0$ ➔ A clear asymmetry at low p_T
- $R_{FB}(|y|)$ = [Yield in +y] / [Yield in –y] for systematic approach

Lesson from this measurement

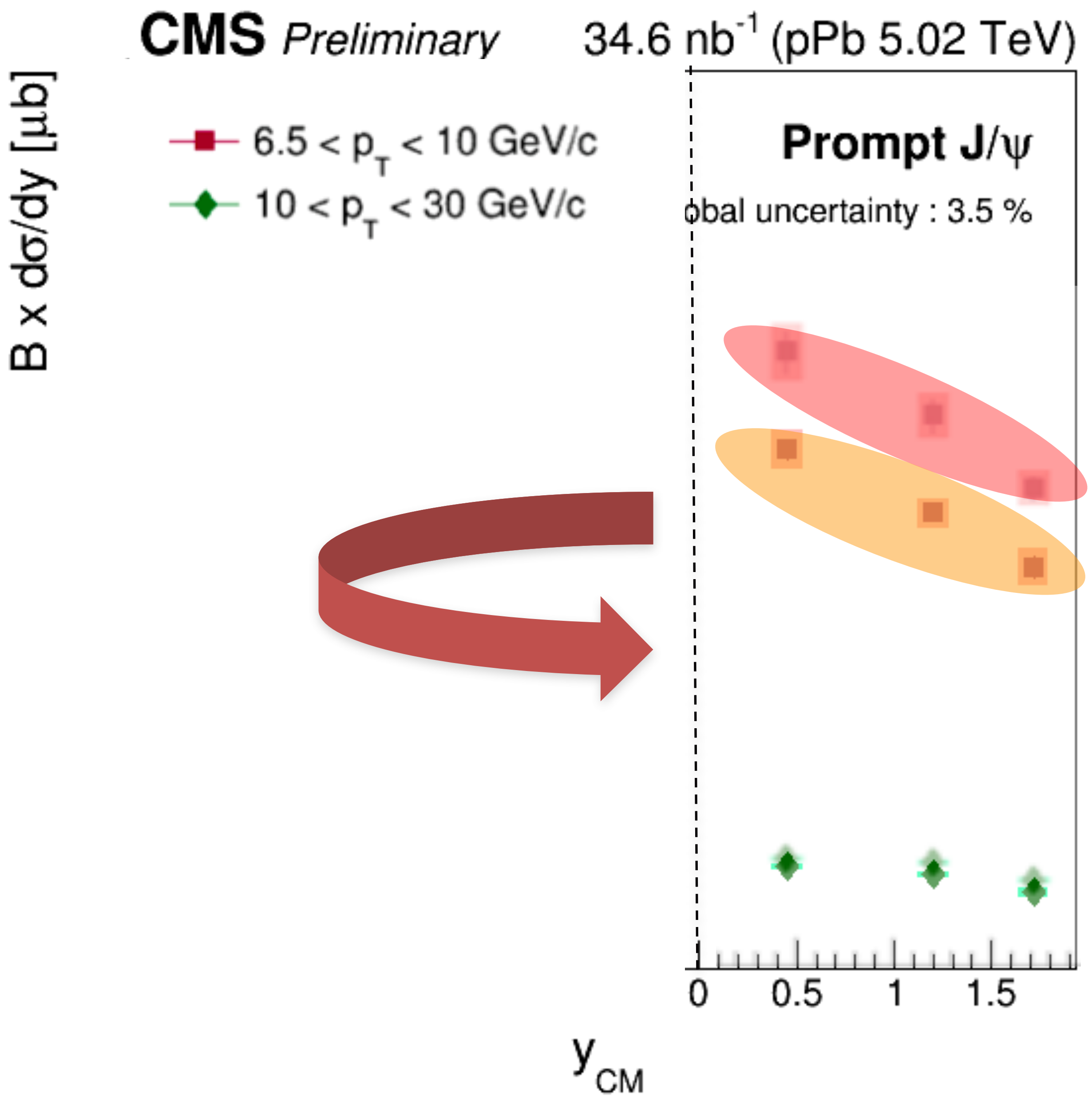
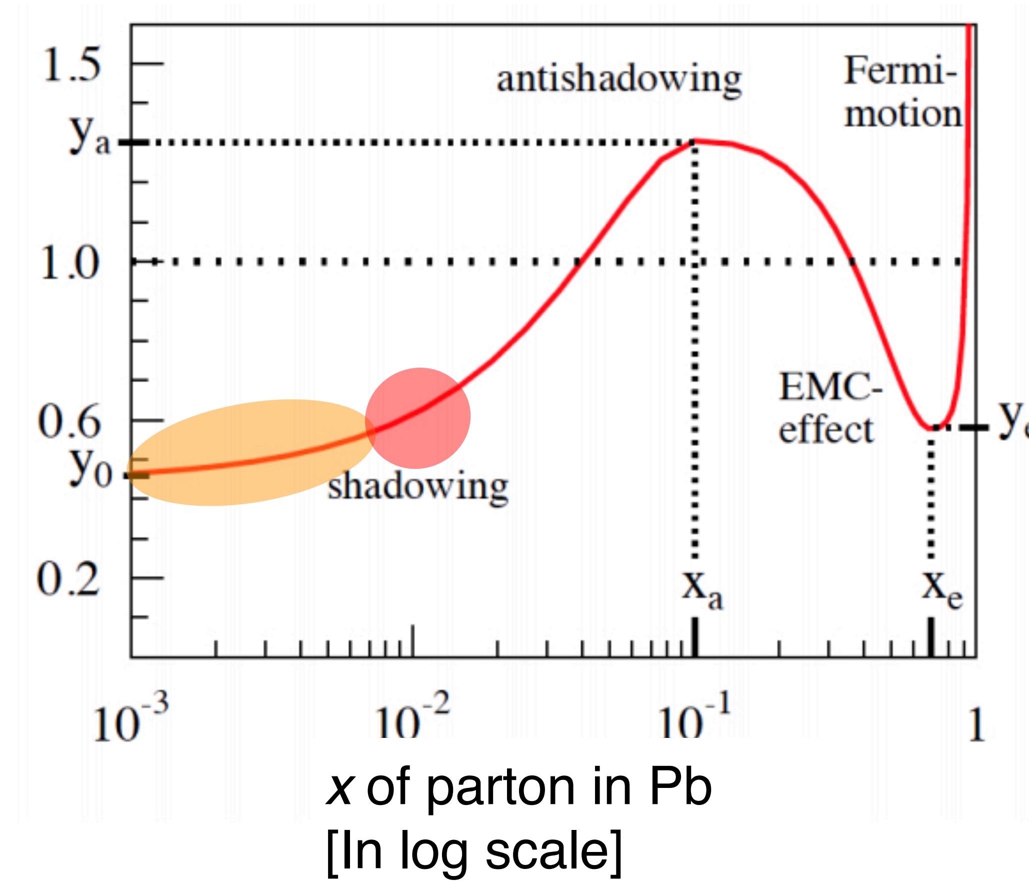
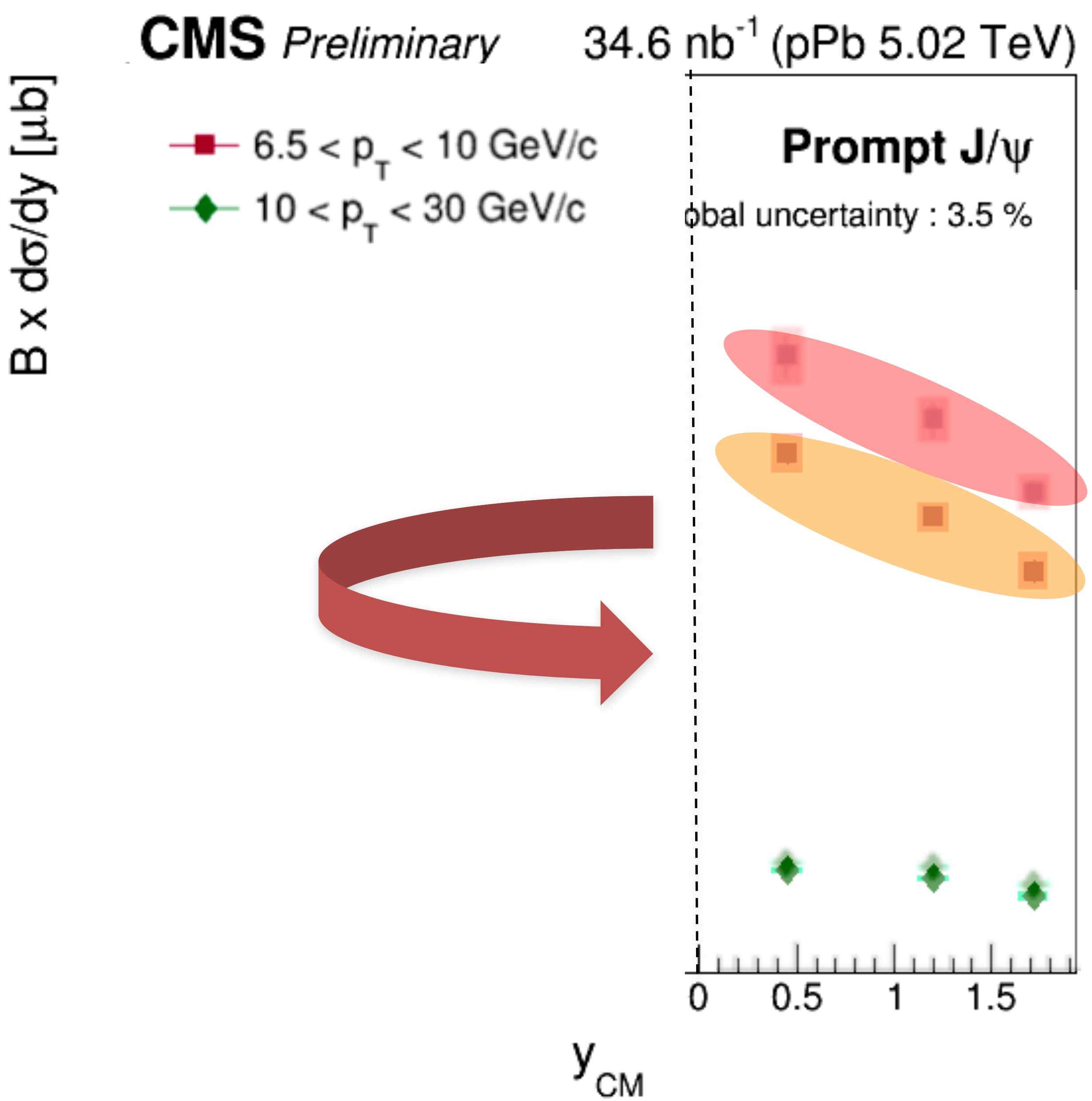


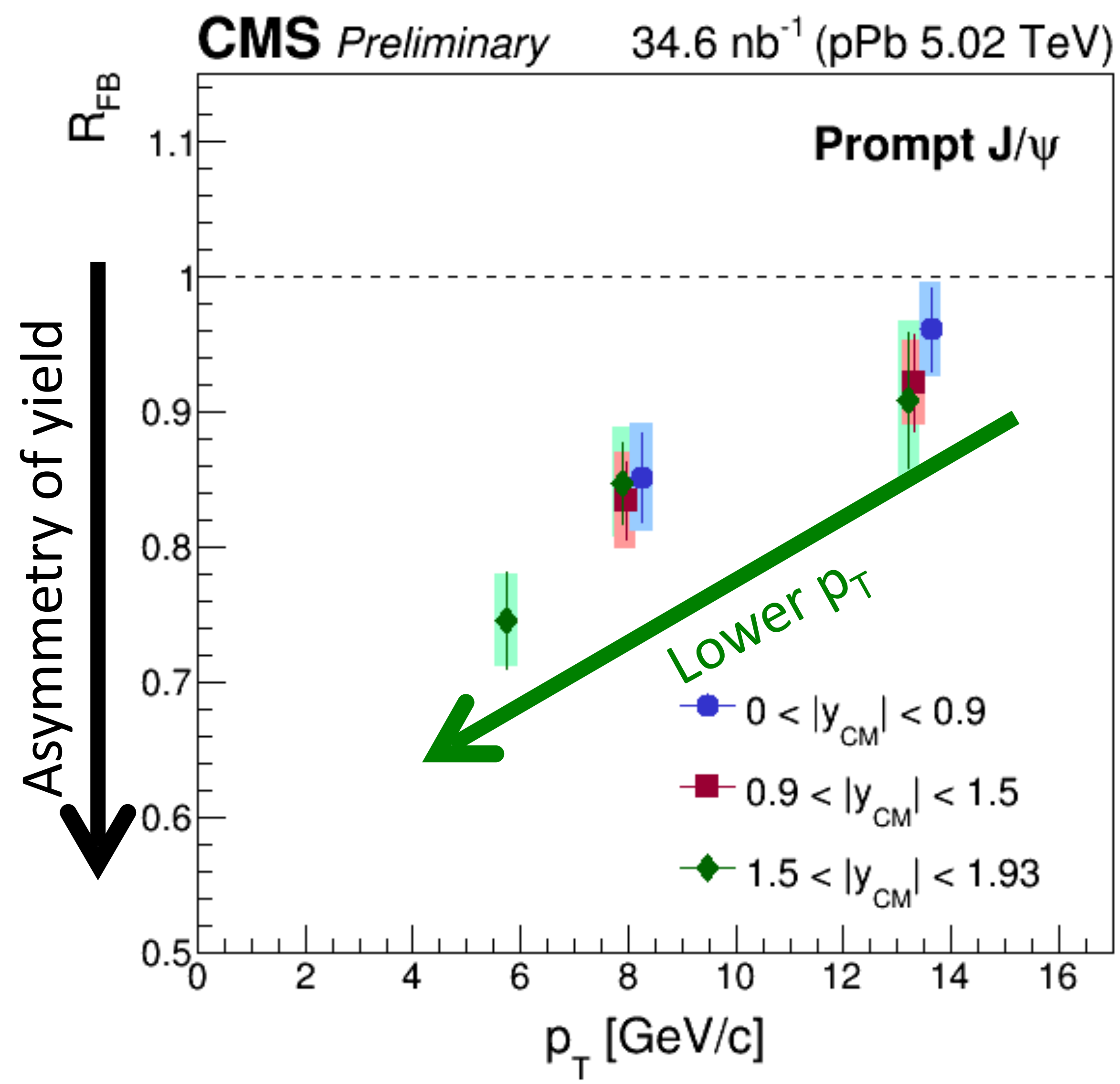
Illustration of nPDF fit
JHEP 0904 (2009) 065



- One may interpret this by nuclear shadowing effect
- But, cold nuclear matter effects are mixture of various initial and final effect. Can we concentrate on initial state effect only?

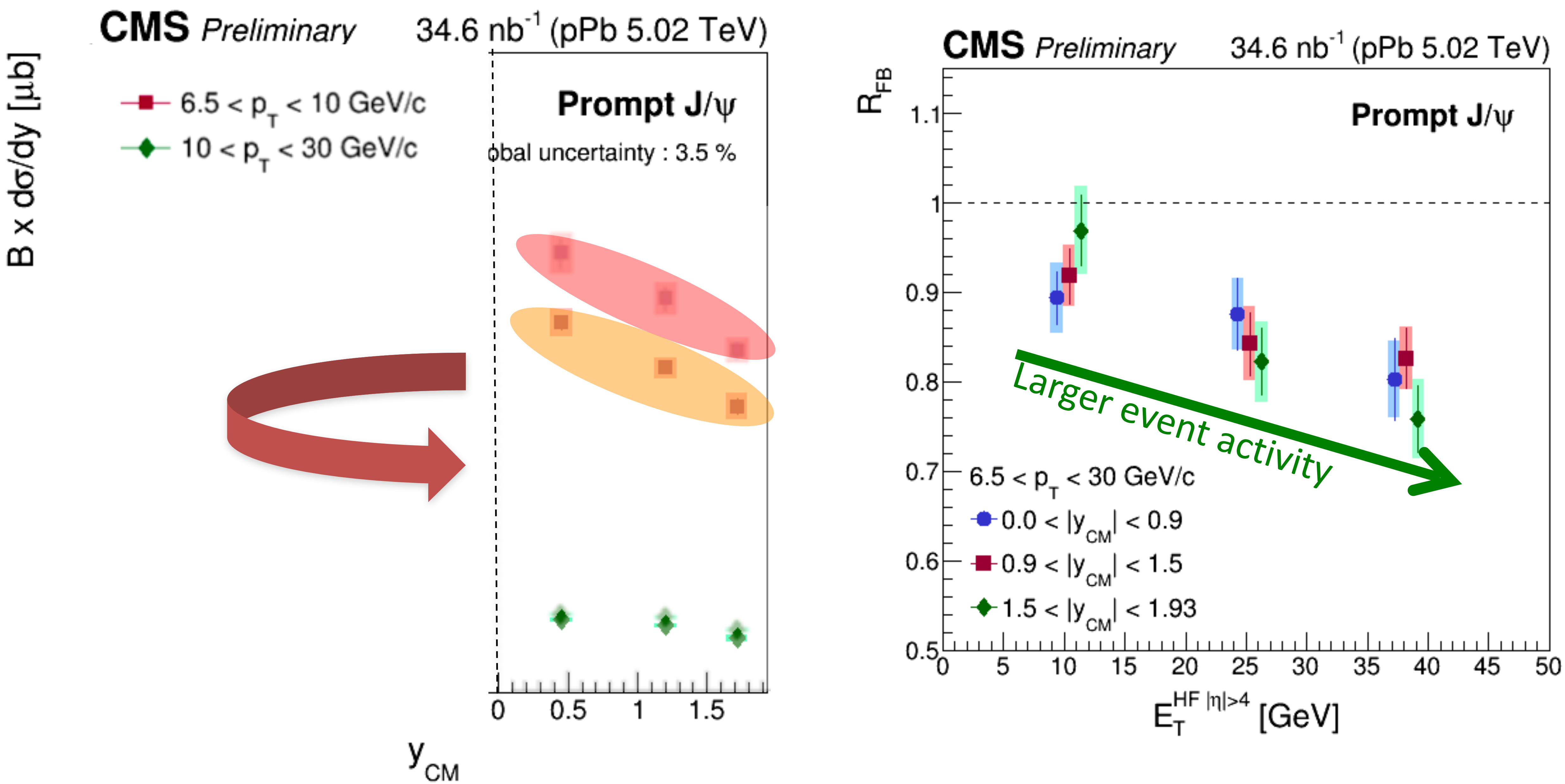
Lesson from this measurement





- Asymmetry is bigger for lower p_T and higher rapidity range

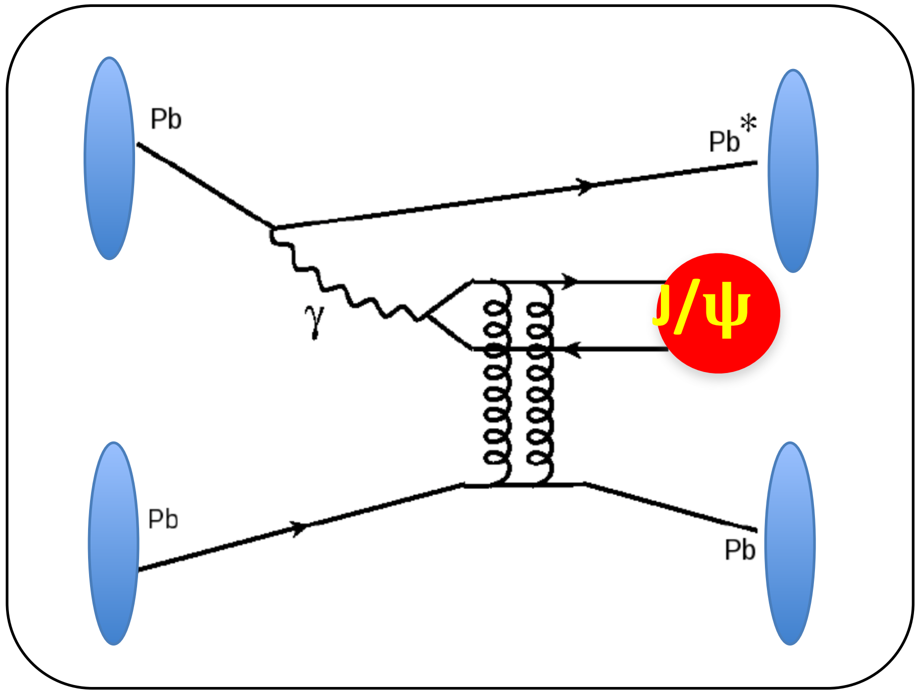
Lesson from this measurement



- Asymmetry is bigger for lower p_T and higher rapidity range
- The effect is enhanced for larger activity events
  - 25% effect in CNM
  - Event activity measured by forward calorimeter 4<|η|<5.2

J/psi in UPC

- J/ψ in UPC can do!



Cross section proportional to (gluon density)^2

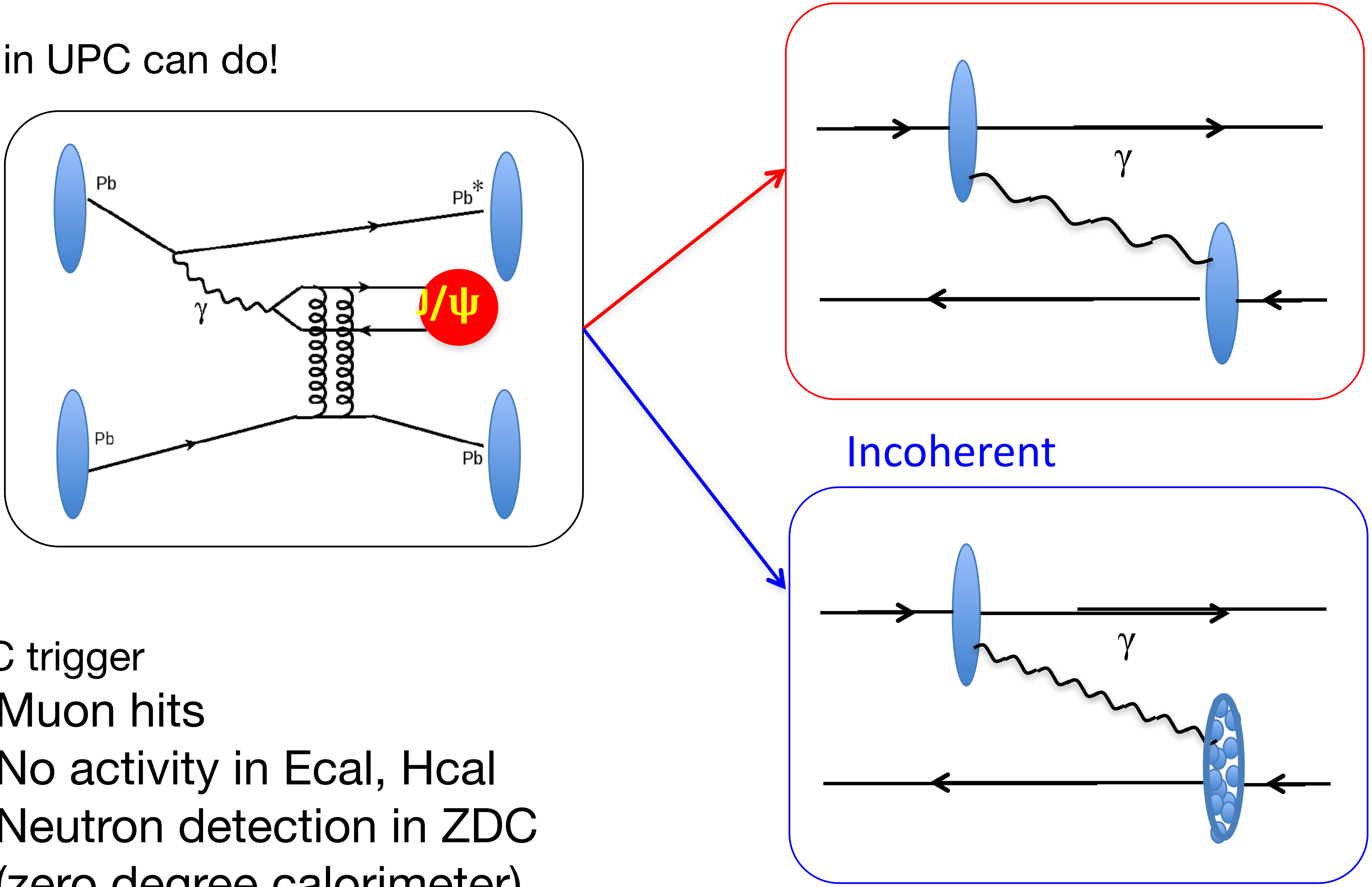
➔ Carries information of nPDF at very low x and low Q^2

- UPC trigger
  - Muon hits
  - No activity in Ecal, Hcal
  - Neutron detection in ZDC (zero degree calorimeter)

J/psi in UPC

- J/ψ in UPC can do!

Coherent



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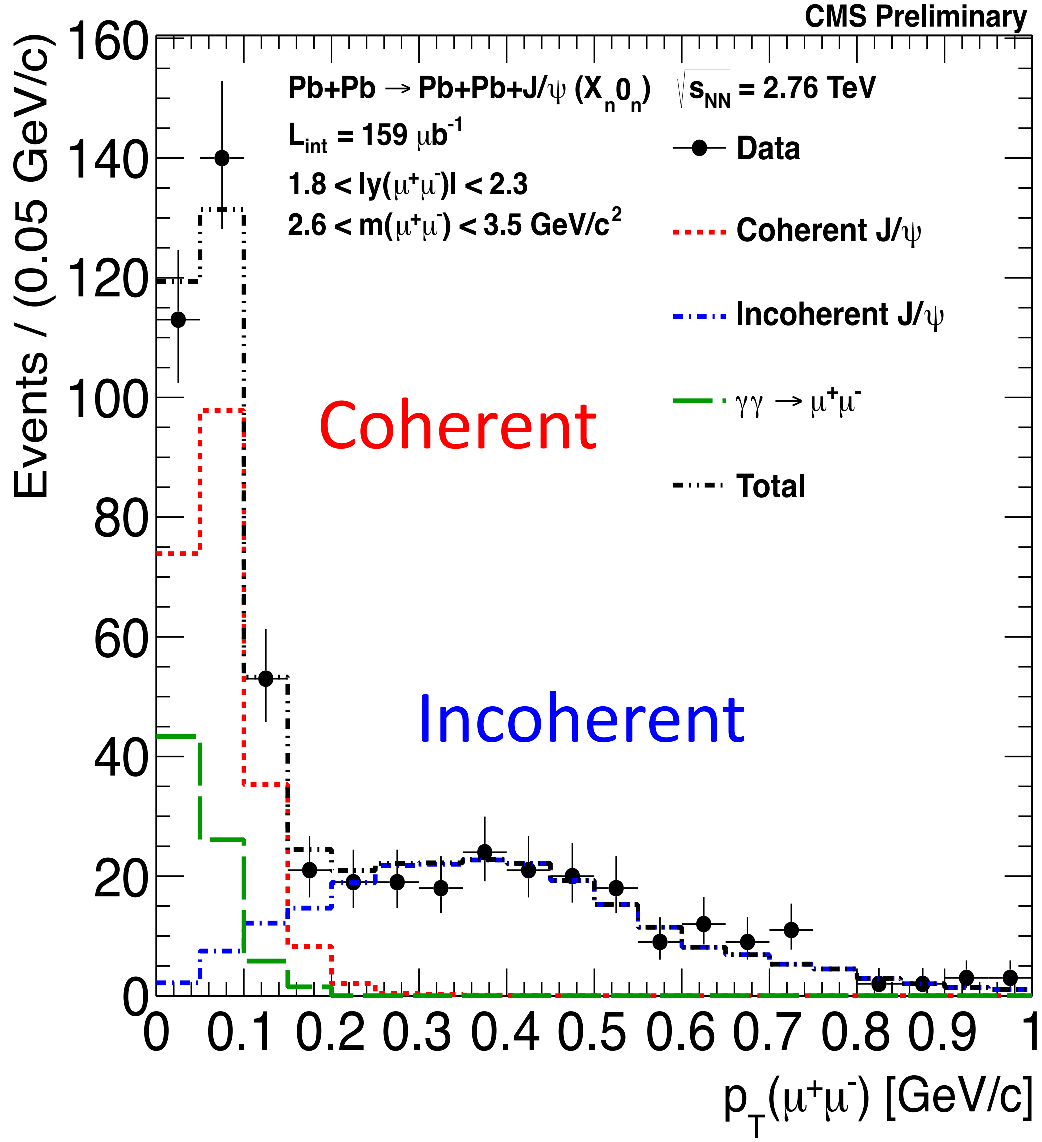
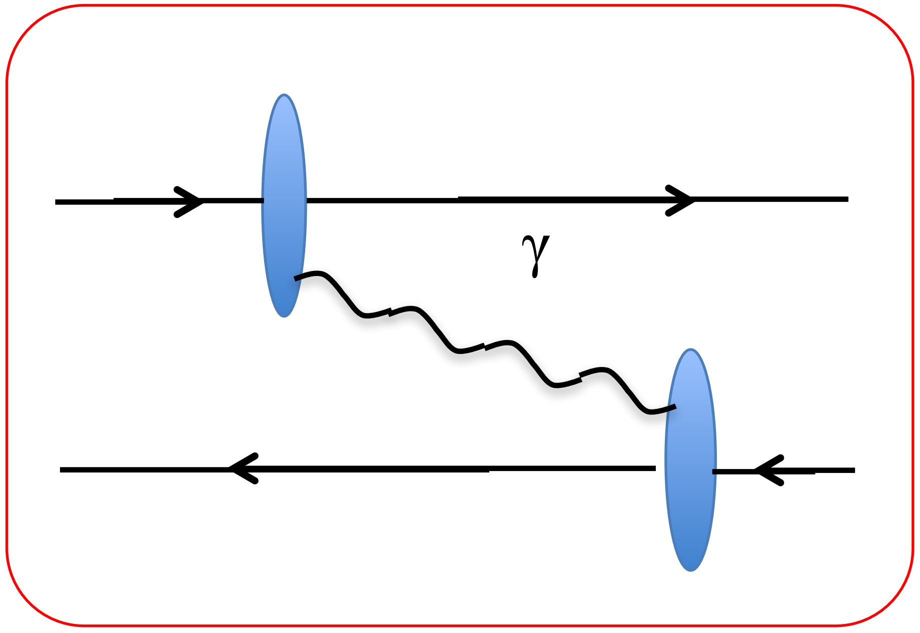
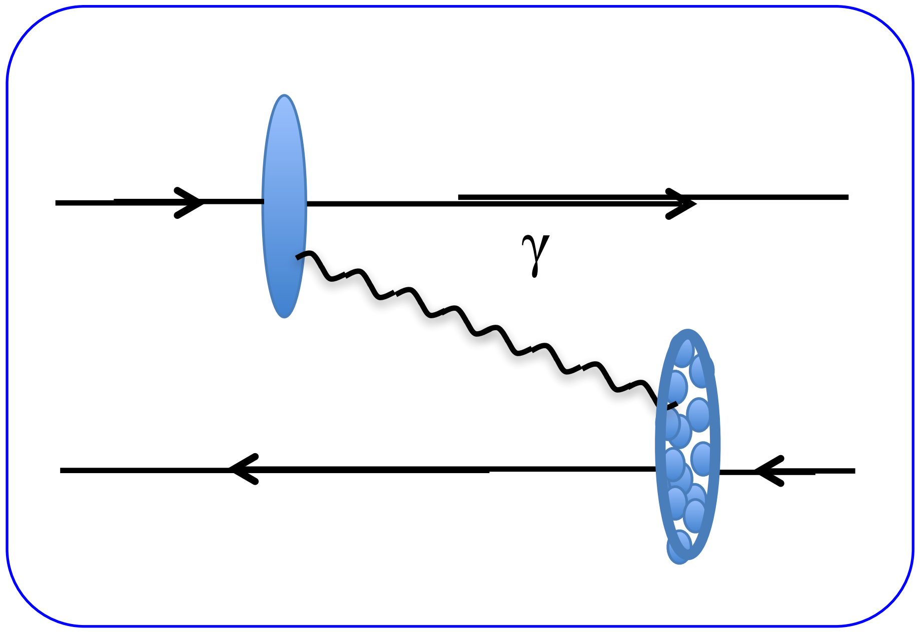
J/psi in UPC



Coherent

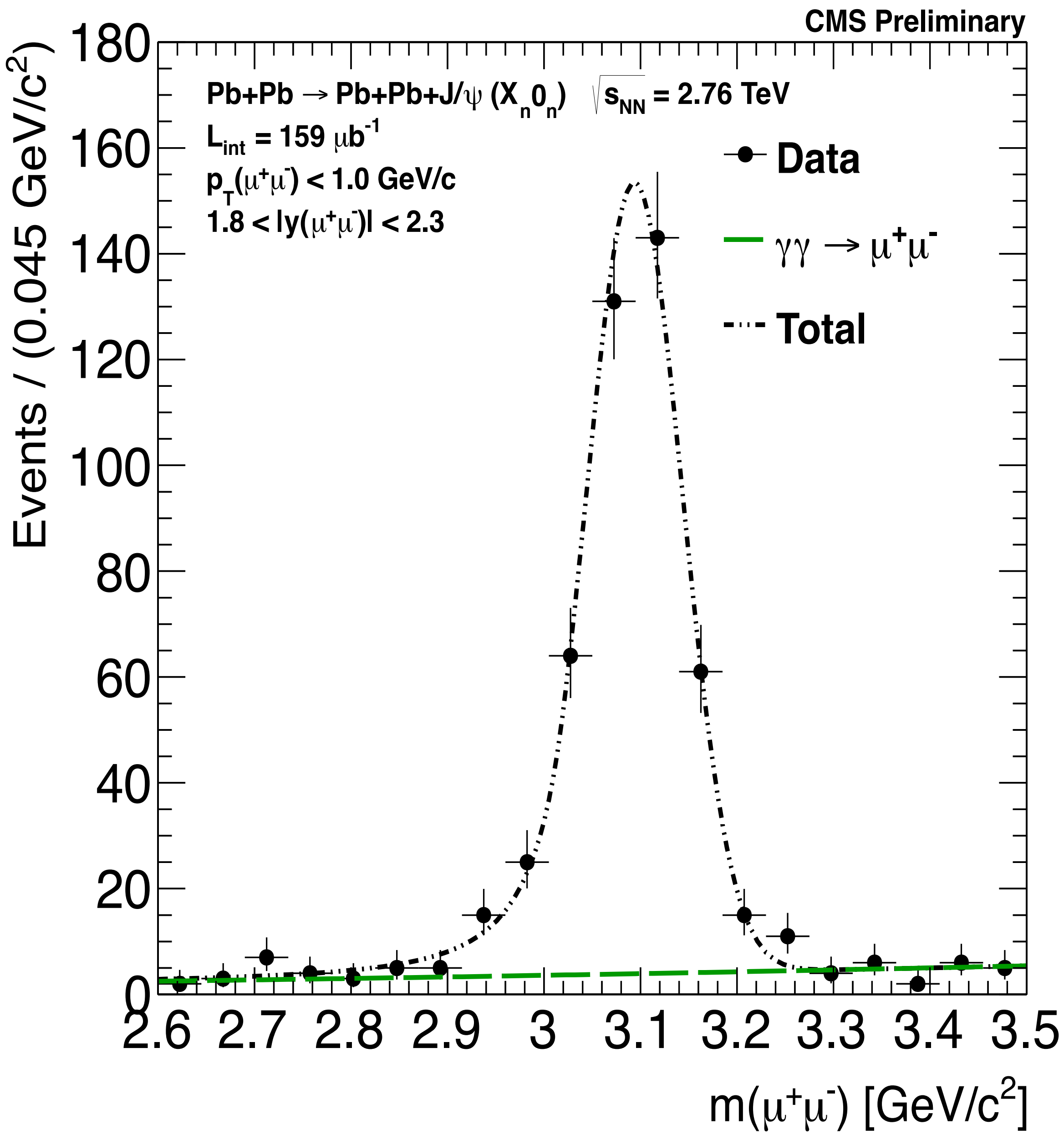


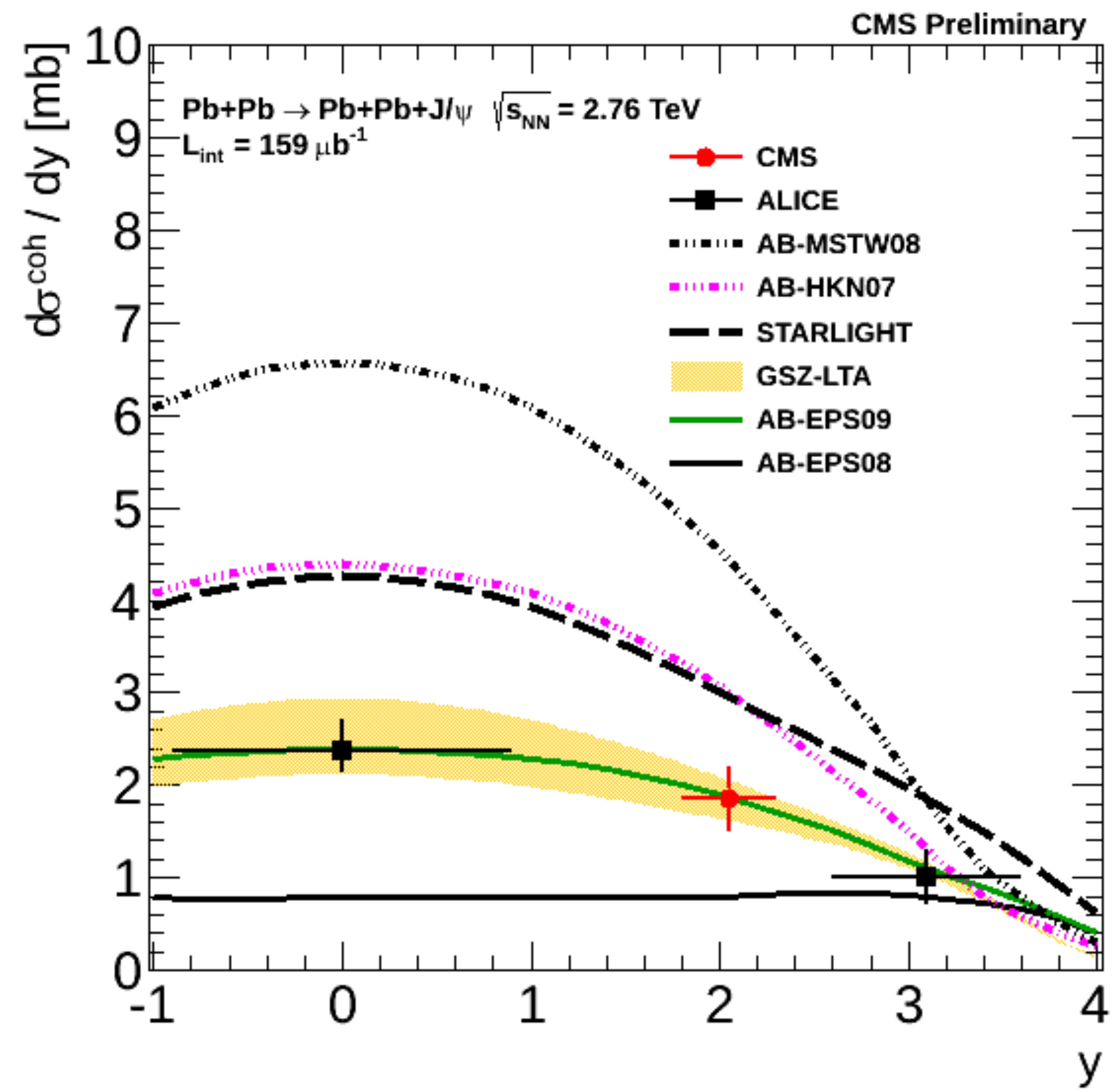
Incoherent



- Coherent J/ψ
  - Dominant for p_T < 150MeV/c
  - Measured p_T up to 1GeV/c and fit using MC template (STARLIGHT)

J/psi in UPC

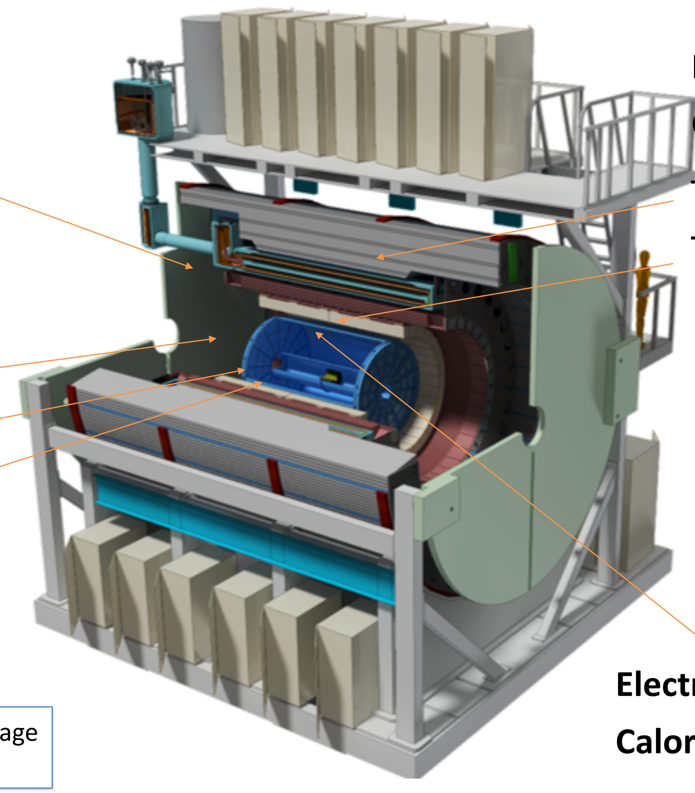




•Accompanied by ALICE data, the CMS results favors moderate nuclear shadowing models (AB-EPS09, GSZ-LTA) at low Q^2

3. Quarkonia study in future

sPHENIX, the state-of-the-arts detector for RHIC



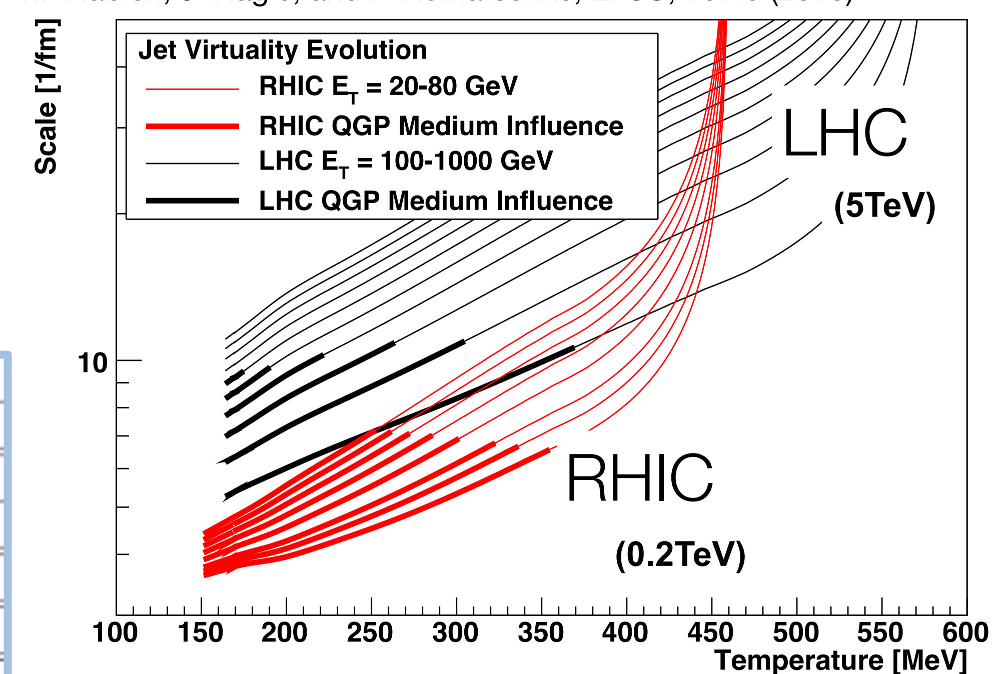
- Full Azimuthal Coverage
- |eta| < 1.1

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

Experiment planed from 2023

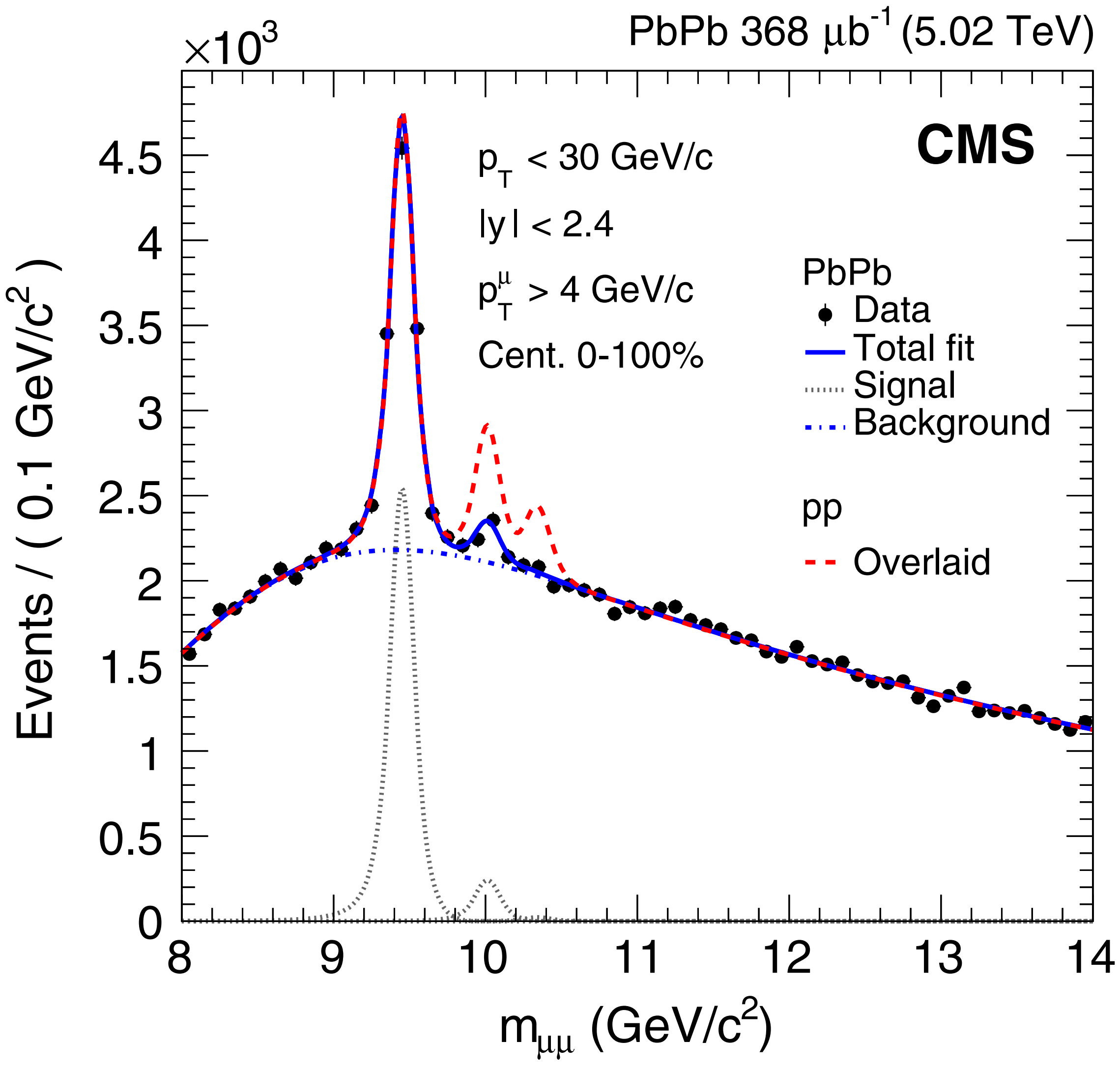
Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

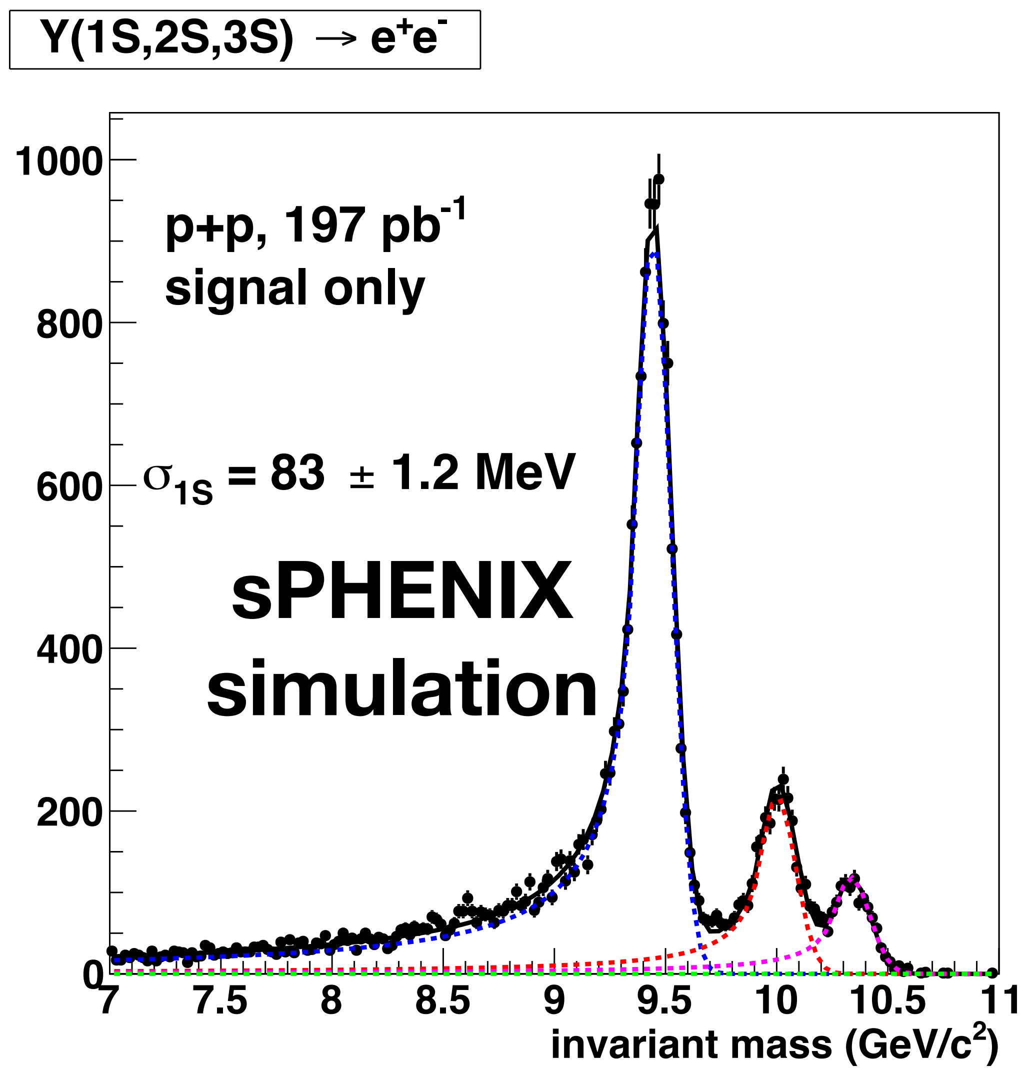
M. Habich, J. Nagle, and P. Romatschke, EPJC, 75:15 (2015)



System evolution

sPHENIX, the state-of-the-arts detector for RHIC



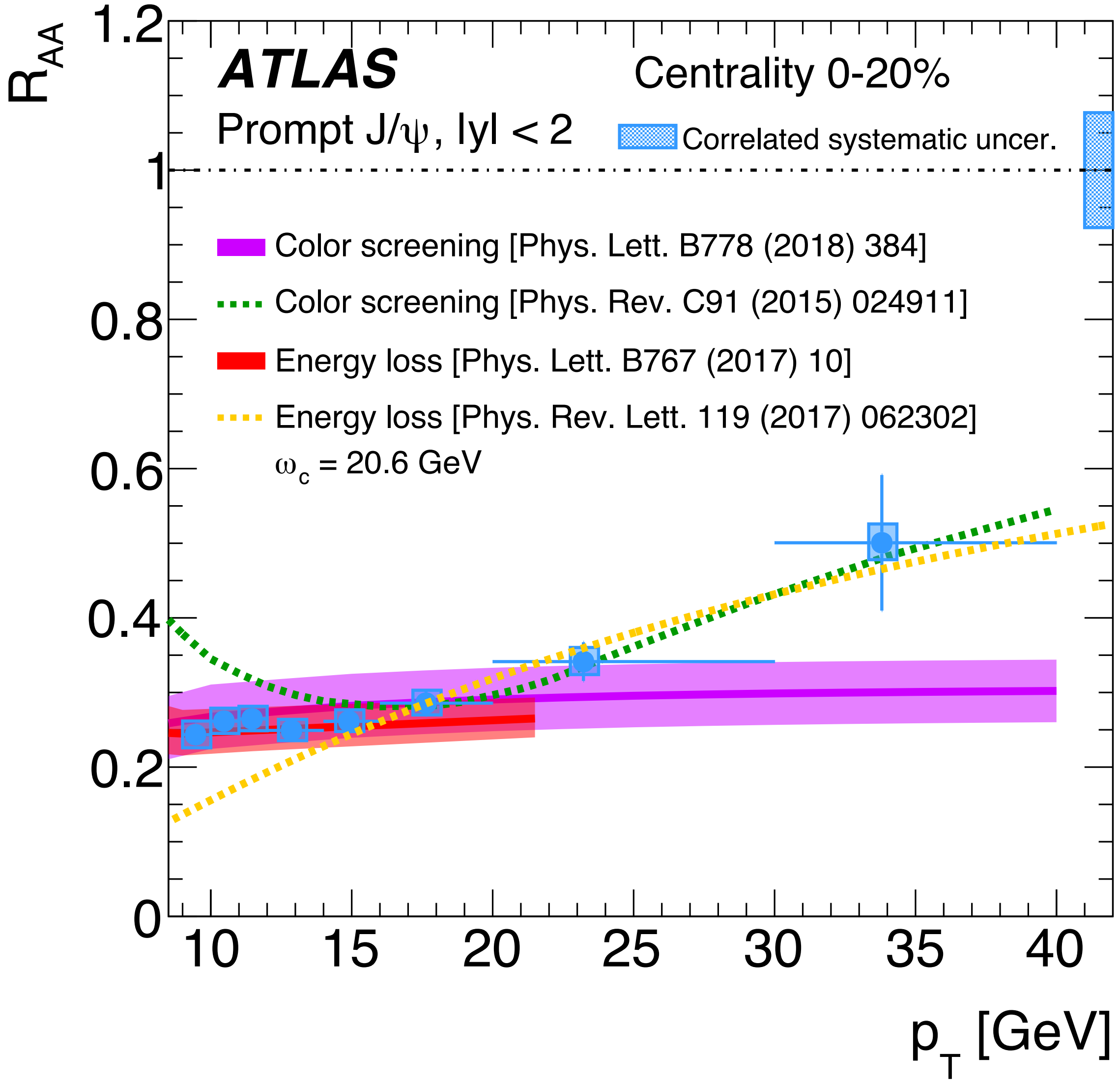


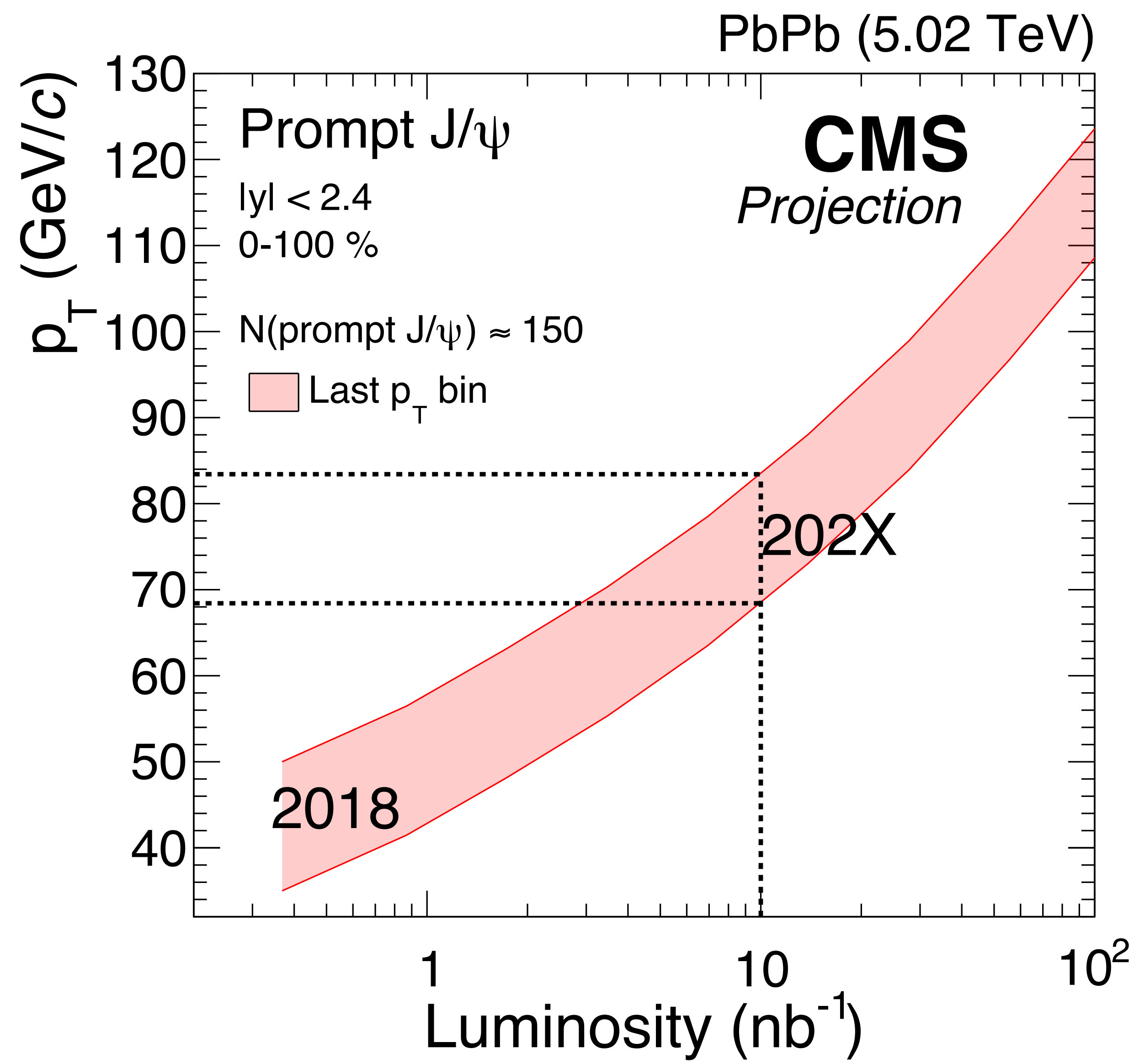
sPHENIX (Simulation) ⟷ **LHC (Data)**

complementary

LHC High-Luminosity Heavy Ion Run

Citius altius fortius! (faster higher stronger)
LHC upgrade will allow the integrated L = 10 nb^{-1}

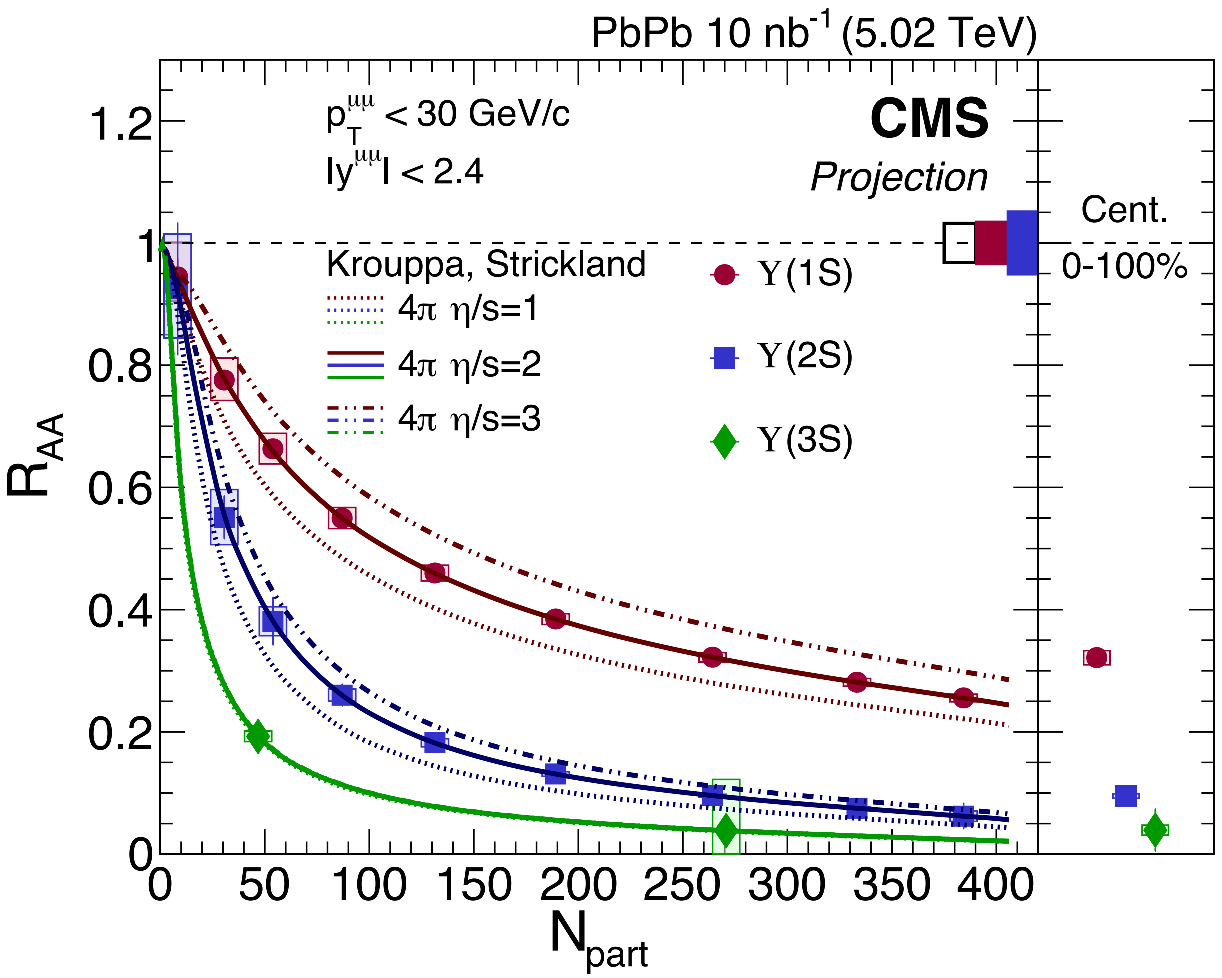


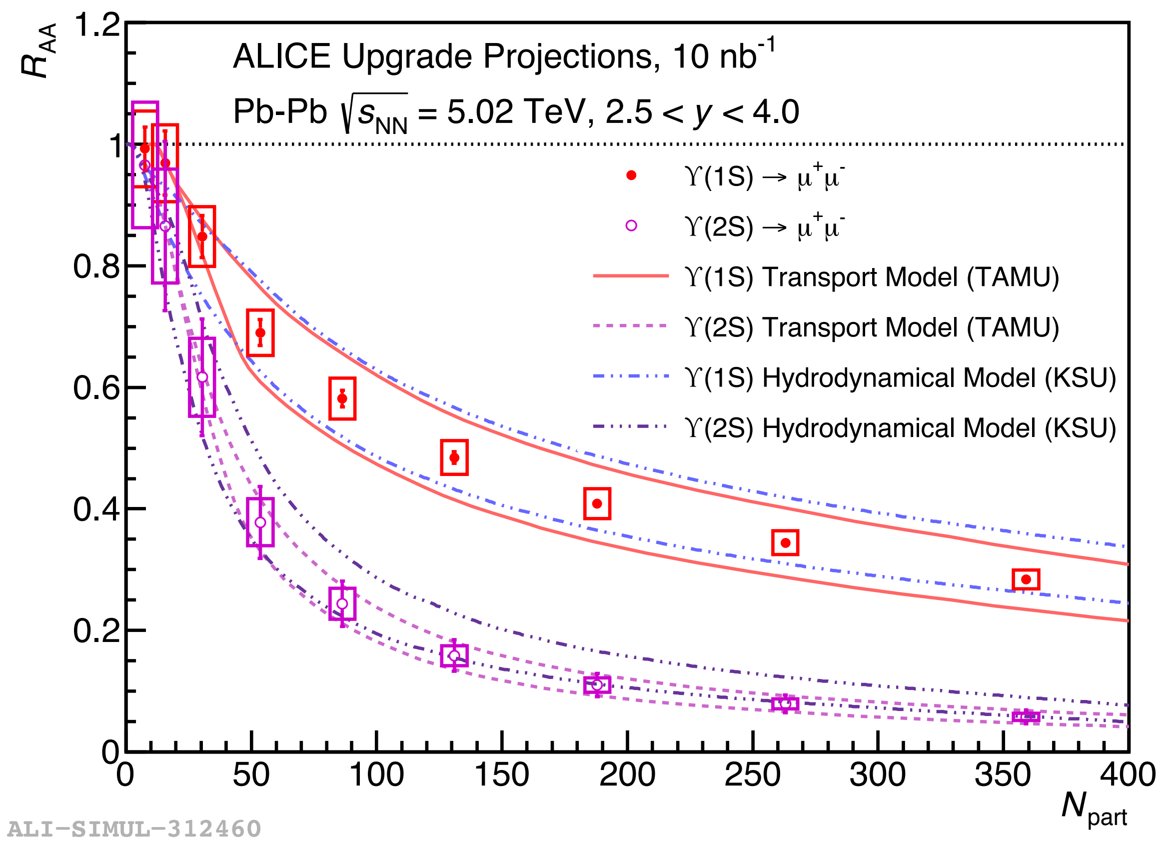


LHC High-Luminosity Heavy Ion Run

Citius altius fortius!

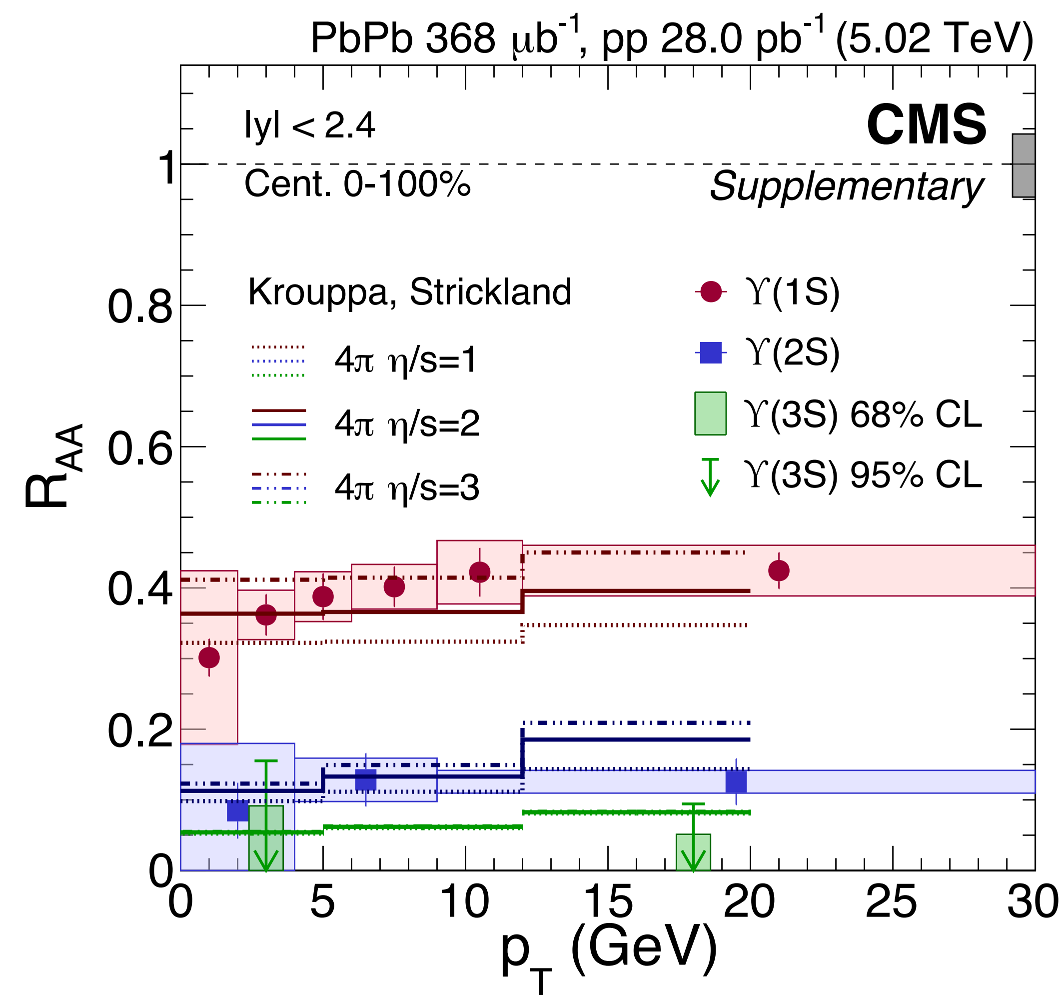
(faster higher stronger)





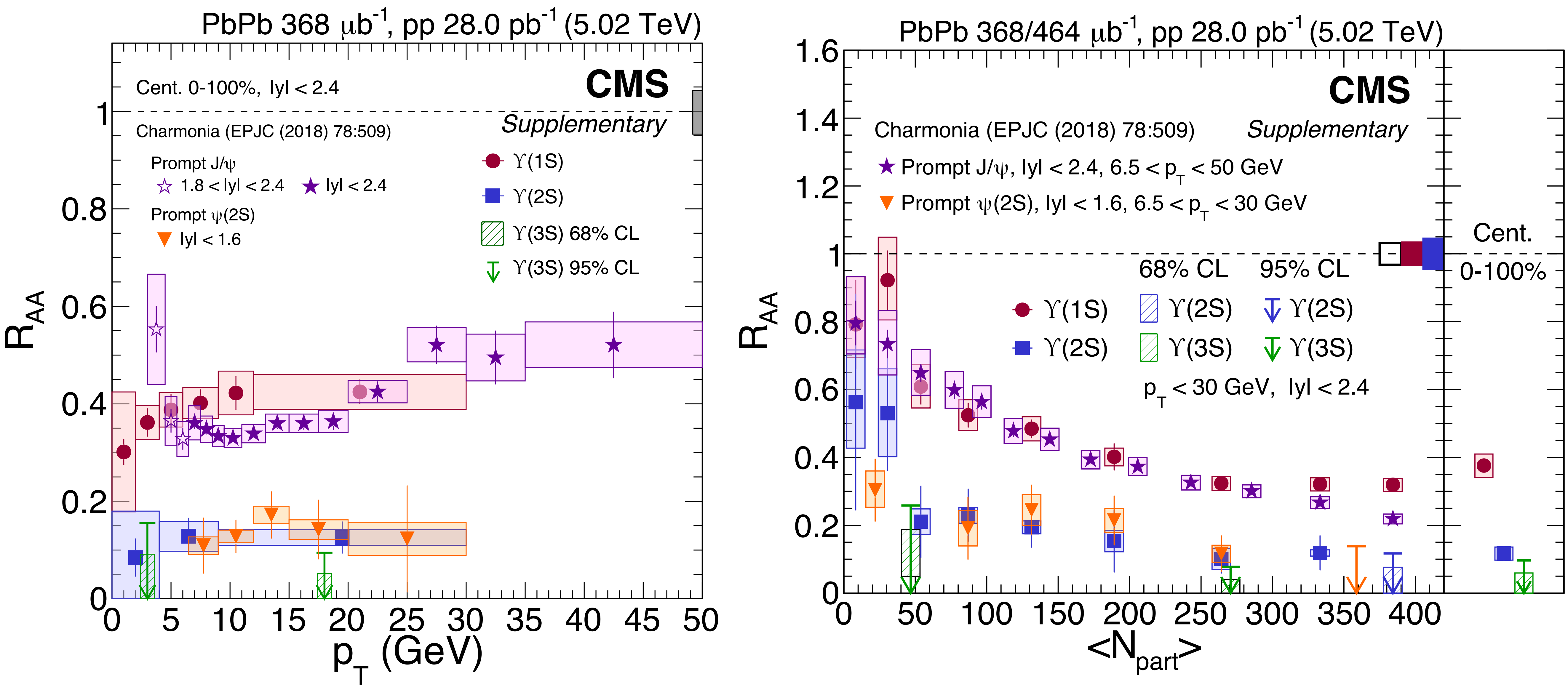
Take home messages

- Y(nS), J/psi and psi(2S) were measured by LHC experiments in wide kinematic ranges
- The precision measurement for quarkonia melting provides strong constraints for hydrodynamics parameters
- Yet, there are still a big room to be revealed at high pT sectors, which requires high luminosity runs
- sPHENIX will be a very exciting experiment to reveal quarkonia melting at lower temperature QGP
- Cold Nuclear matter effect must not be ignored



backup

Comparison with Charmonia results



- Very similar behavior between Charmonia and Bottomonia
  - **ϒ**(1S) aligns with J/psi(1S)
  - **ϒ**(2S) aligns with psi(2S)
- Any geometrical indication?