2022 Joint Workshop of FKPPL and TYL/FJPPL
16-18 May 2022

Nantes

FKPPL laureate of the Yong Researcher

Isabelle Ripp-Baudot (IPHC, France)
David Sarramia (LPC Clermont, France)

Local organisation:
Guillaume Batigne (Subatech, France)

JaeBeom Park (Korea University / CENuM)

Self-introduction

@ QM 2019 (Wuhan)

JaeBeom Park

- Ph.D @ Korea University in 2020
- Member of LAMPS (LEPS) Collaboration at RAON (SPring8) before joining CMS
- 2015 - Present : Member of CMS Collaboration at LHC
  - 2020 - Present : Leader of Dilepton Heavy Ion Physics Group
  - 2020 - Present : Liaison of CMS HI in Quarkonium Working Grou

Selected analyses for today

- Bottomonium production & azimuthal anisotropy in PbPb and pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and $\sqrt{s_{NN}}$ = 8.16 Te

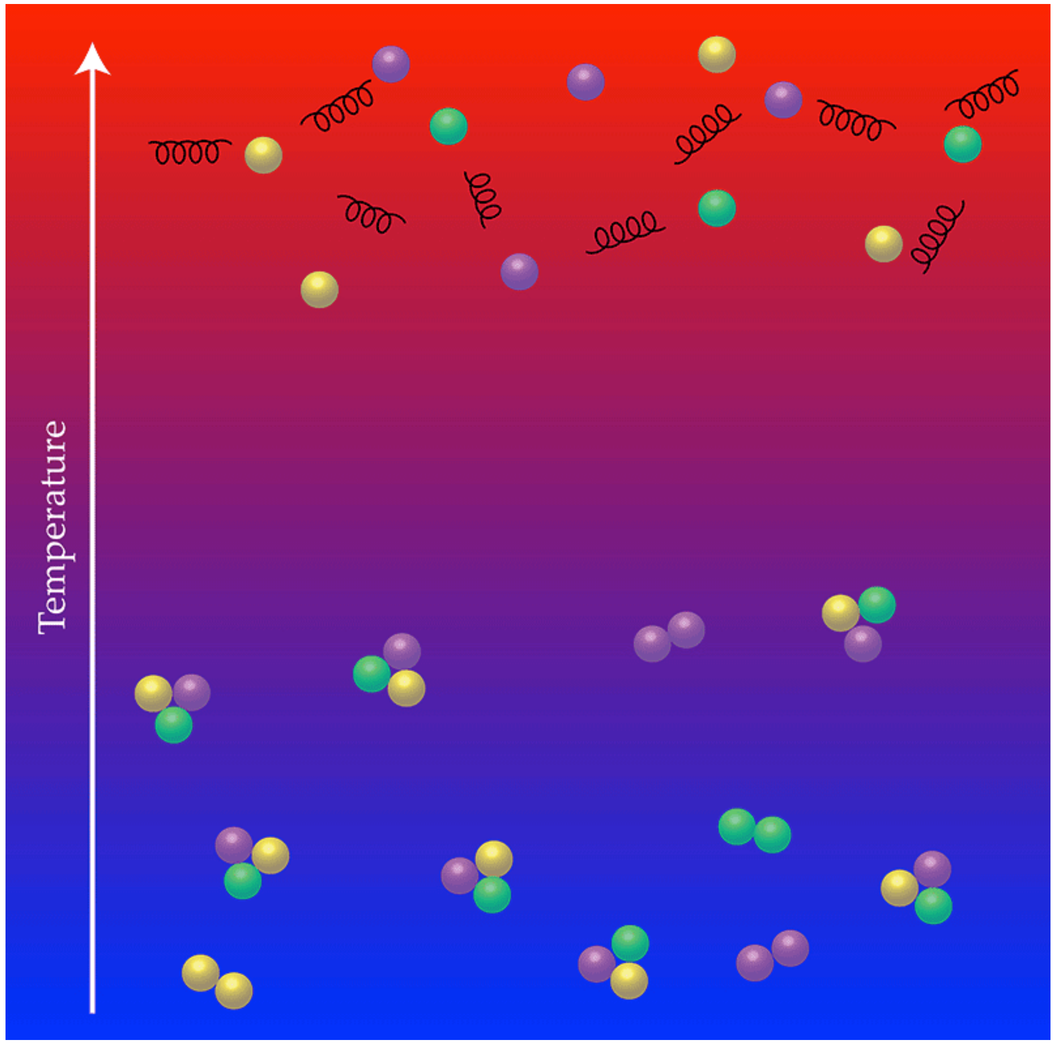
[PLB 790 (2019) 270] [PLB 819 (2021) 136385] [arXiv:2202.11807] [CMS-PAS-HIN-21-001] [CMS-PAS-HIN-21-007]

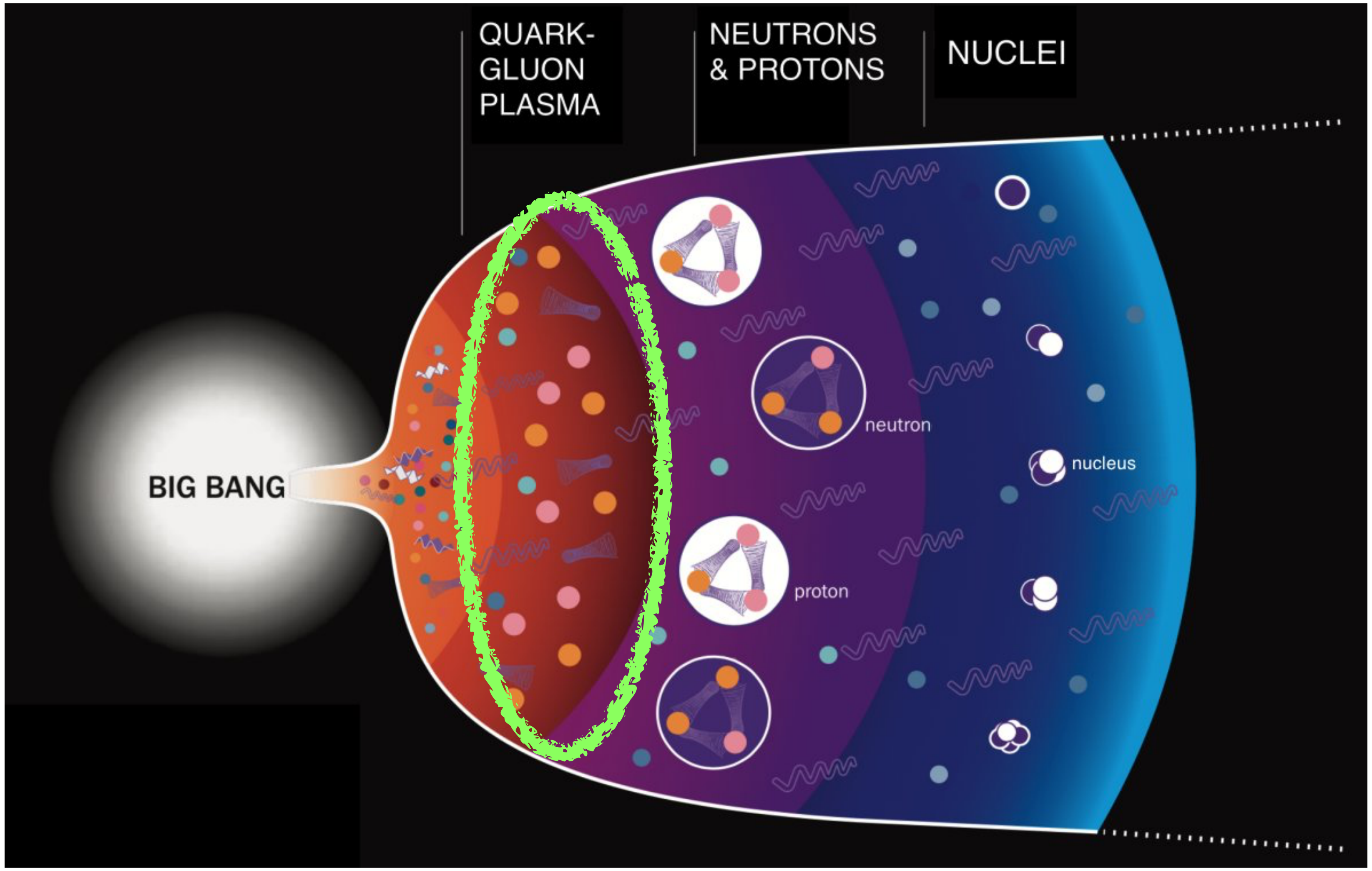
- Charmonium flow measurements in PbPb collisions $\sqrt{s_{NN}}$ = 5.02 TeV

[CMS-PAS-HIN-21-008]

Quark-Gluon Plasma (QGP)

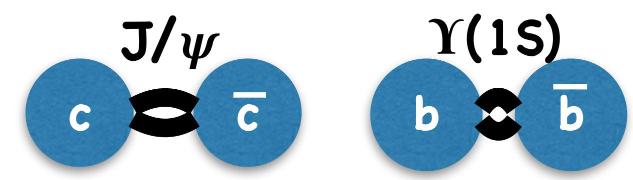
Quark-gluon plasma (QGP) : Strongly interacting *matter* of deconfined quarks and gluons



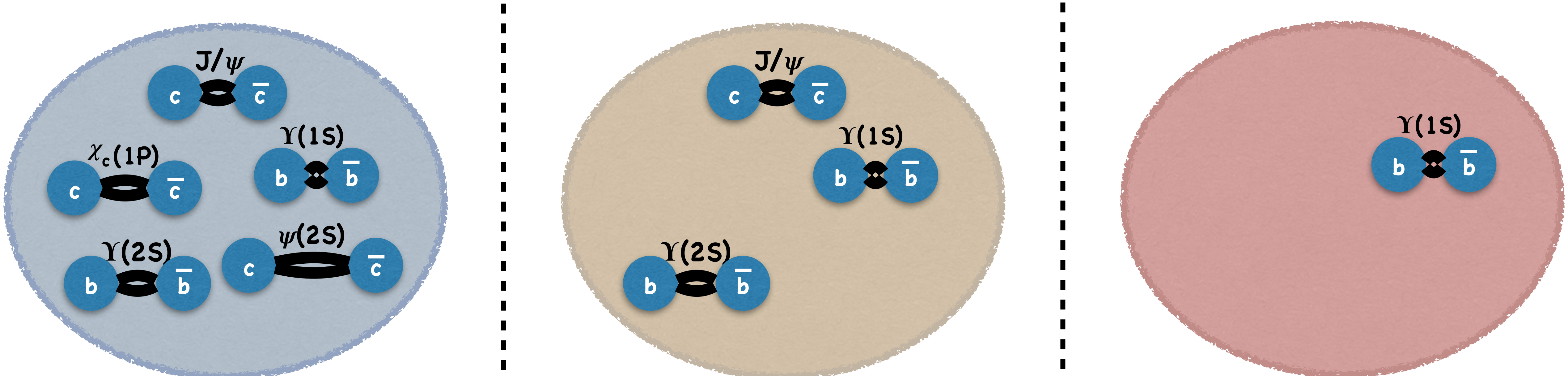


Quarkonia : Bound states of quark and its anti-quark

— Powerful tool to study thermal properties of QGP



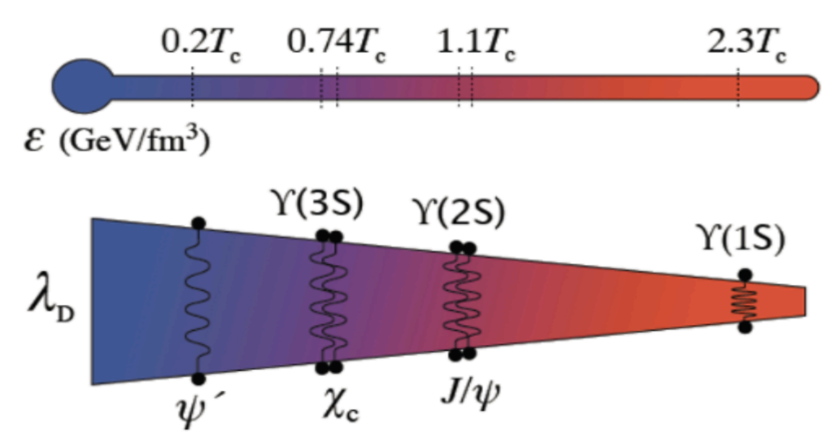
$T << T_c$	$T \approx 1.1T_c$	$T \approx 2T_c$



T. Matsui, H. Satz [PLB 178 (1986) 416] S. Digal, P. Petreczky, H. Satz [PRD 64 (2001) 094015]

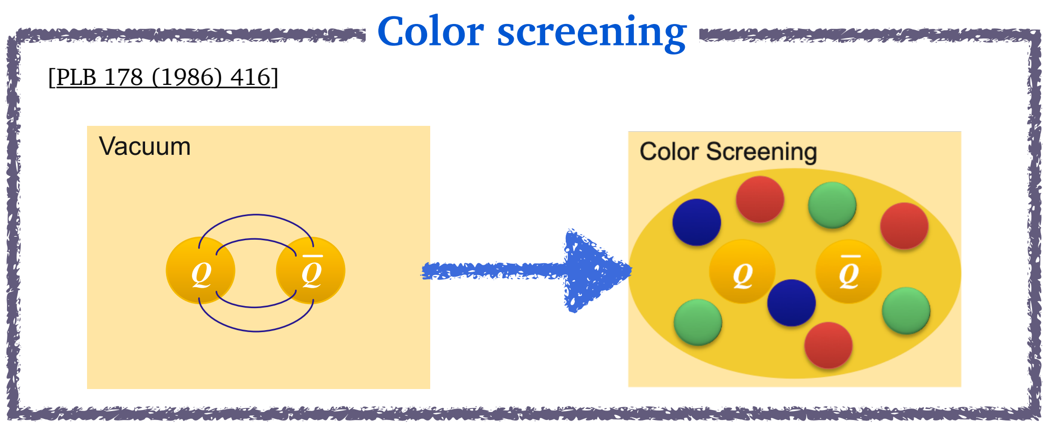
Sequential melting by color screening

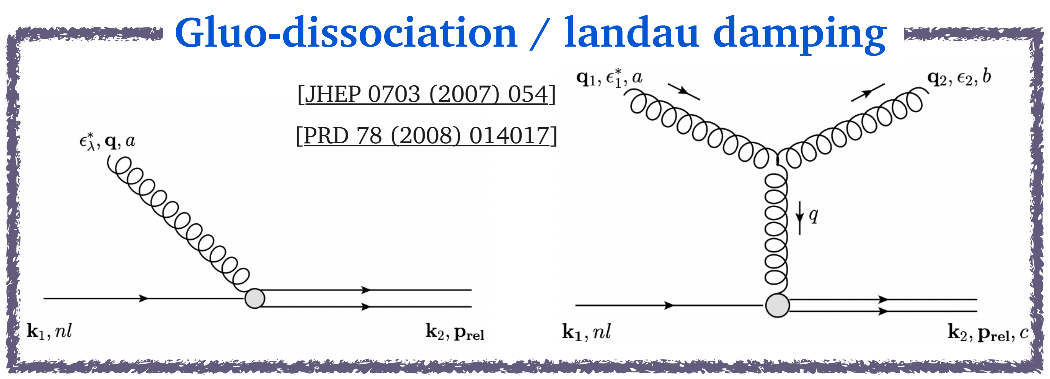
→ Quarkonia as thermometer of QGP



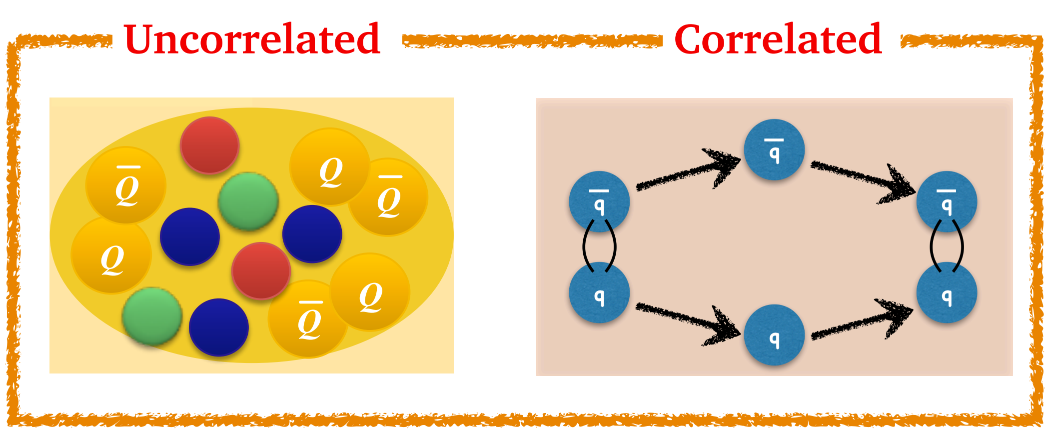
Quarkonia as tools : Probe in-medium effects

- **Suppression in nuclear collisions**
  - Static color screening : Debye screening
  - Interactions with partons
    : Gluo-dissociation & Landau-damping





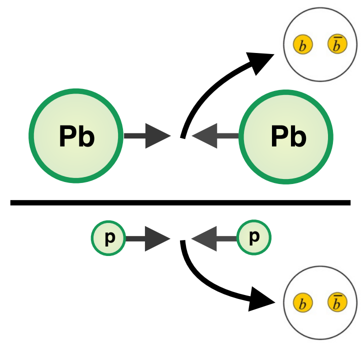
- **Recombination (Regeneration)**
  - Uncorrelated (off-diagonal) recombination
  - Correlated (diagonal) recombination



Experimental probe : R_{AA}, Flow

- **Nuclear modification factor**

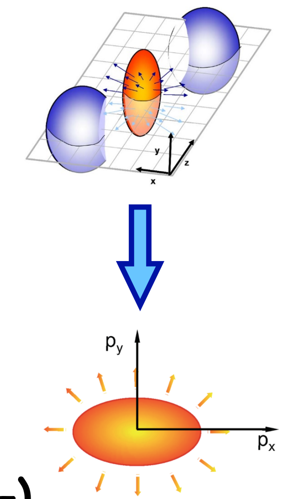
$$R_{AA} = \frac{dN_{AA}\,/\,dp_T\,dy}{\langle N_{coll}\rangle\, dN_{pp}\,/\,dp_T\,dy} = \frac{\text{"hot/dense QCD medium"}}{\text{"QCD vacuum"}}$$



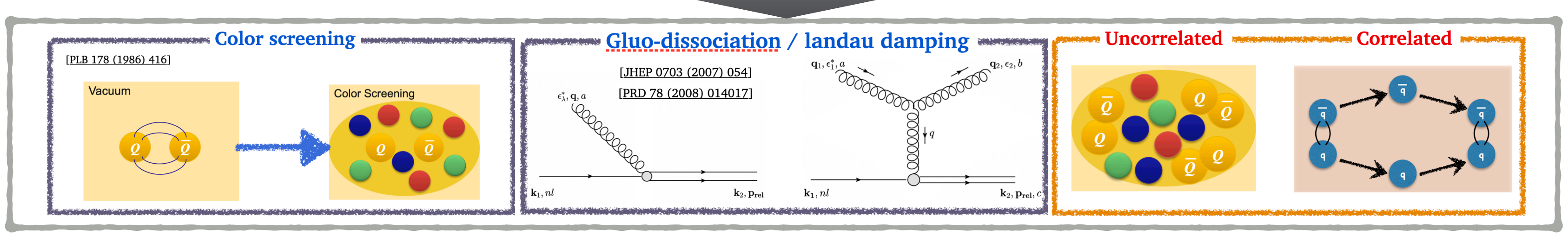
▶ **Quantification of nuclear effects**
- > 1 : enhancement
- = 1 : no modification
- < 1 : suppression

- **Elliptic flow (v_2)**

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n\, cos n(\phi - \Phi_n)$$



▶ **Collectivity (low-p_T)**
Path-length E. loss (high-p_T)



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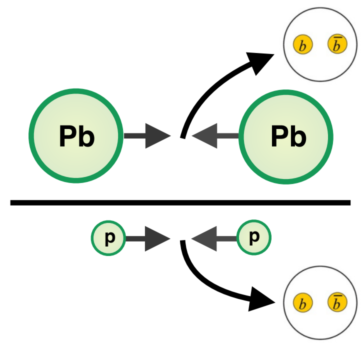

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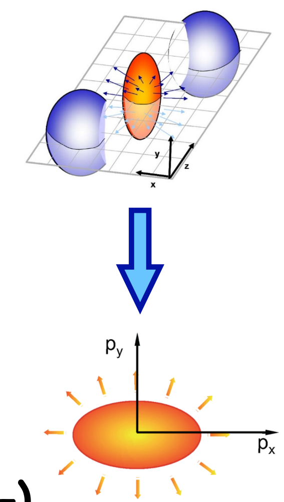

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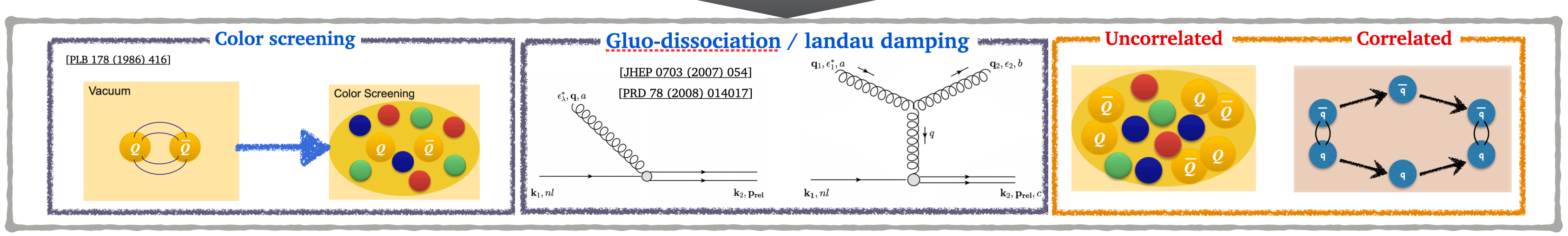
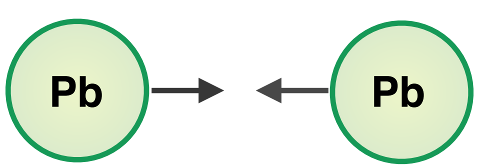
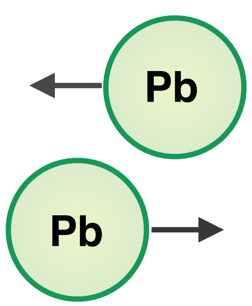


- **Centrality** (Degree of nuclear overlap) : fraction of total nucleus-nucleus cross-section

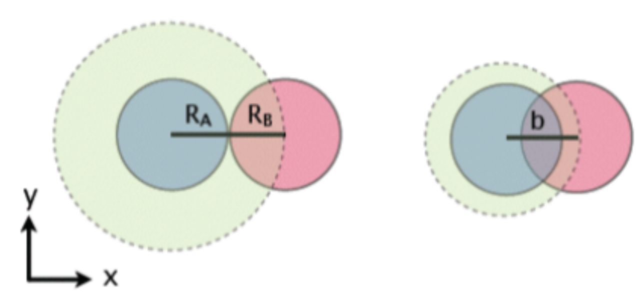


Central (0%)



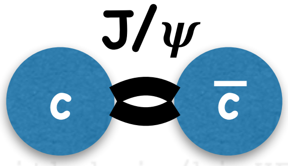
Peripheral (100%)

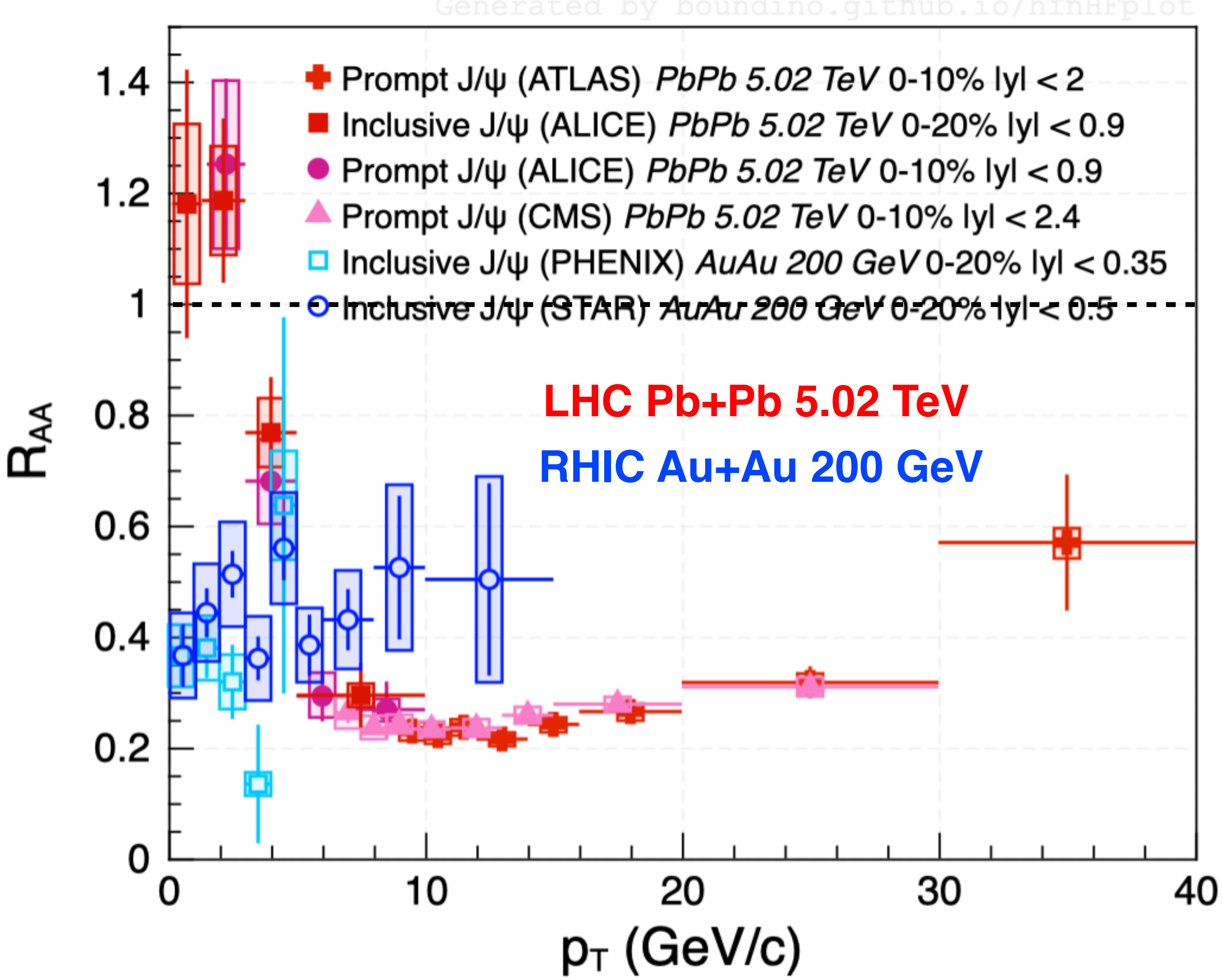
[$\sigma_{geom} \sim \pi(R_A+R_B)^2$] [$\sigma_{reac} \sim \pi b^2$]



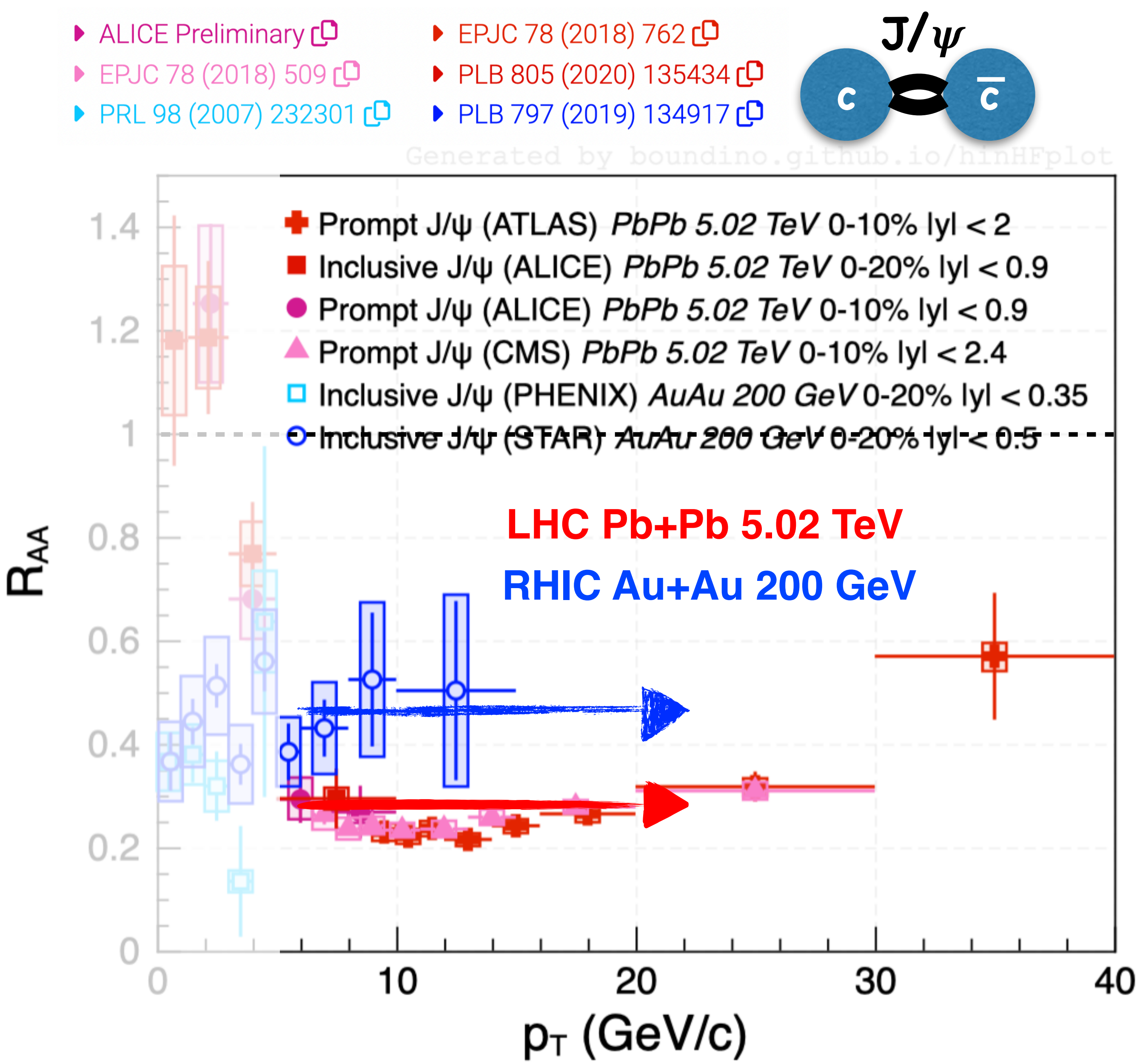
Charmonia in QGP : History

- ALICE Preliminary
- EPJC 78 (2018) 509
- PRL 98 (2007) 232301
- EPJC 78 (2018) 762
- PLB 805 (2020) 135434
- PLB 797 (2019) 134917



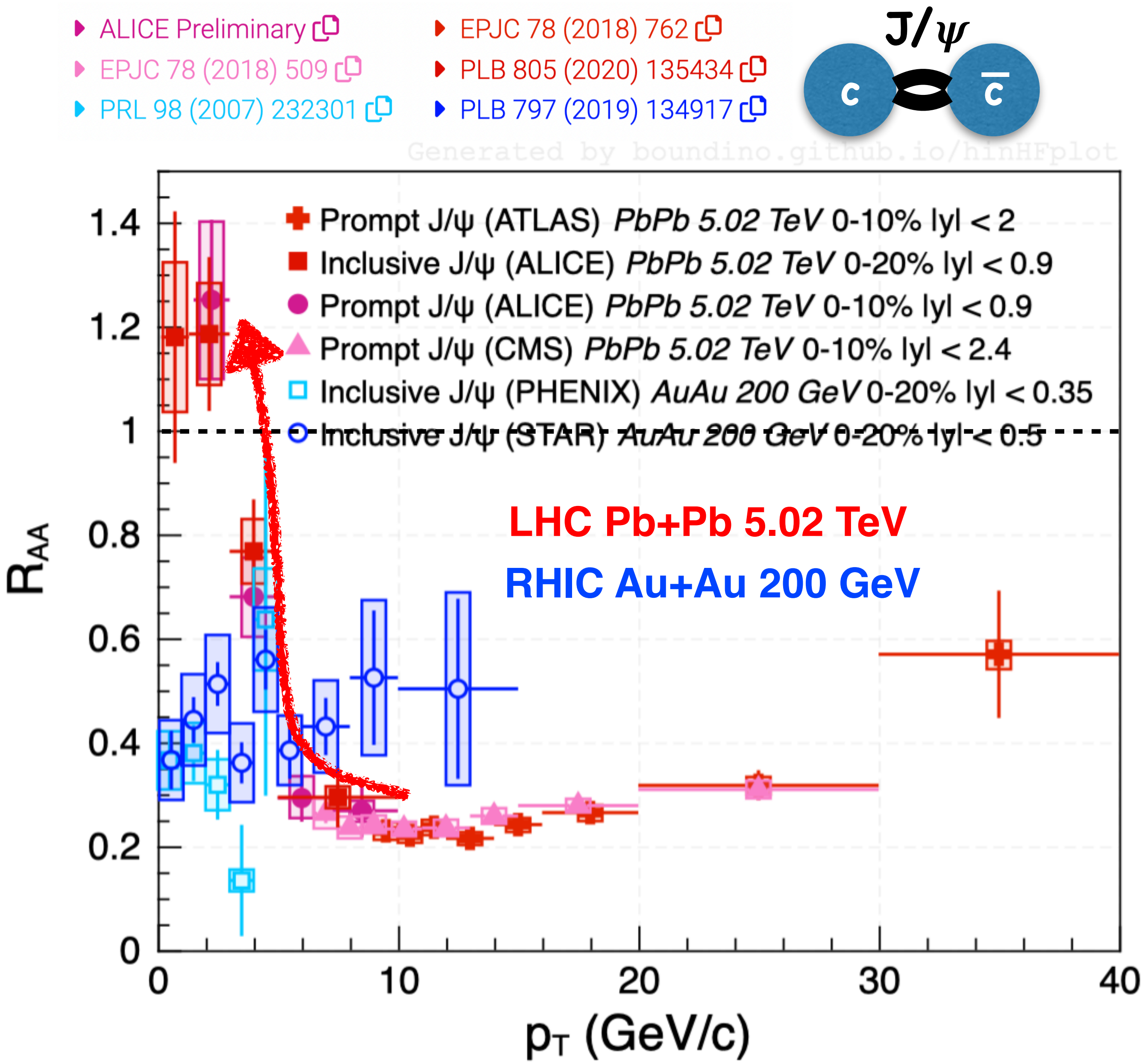


Charmonia in QGP : History



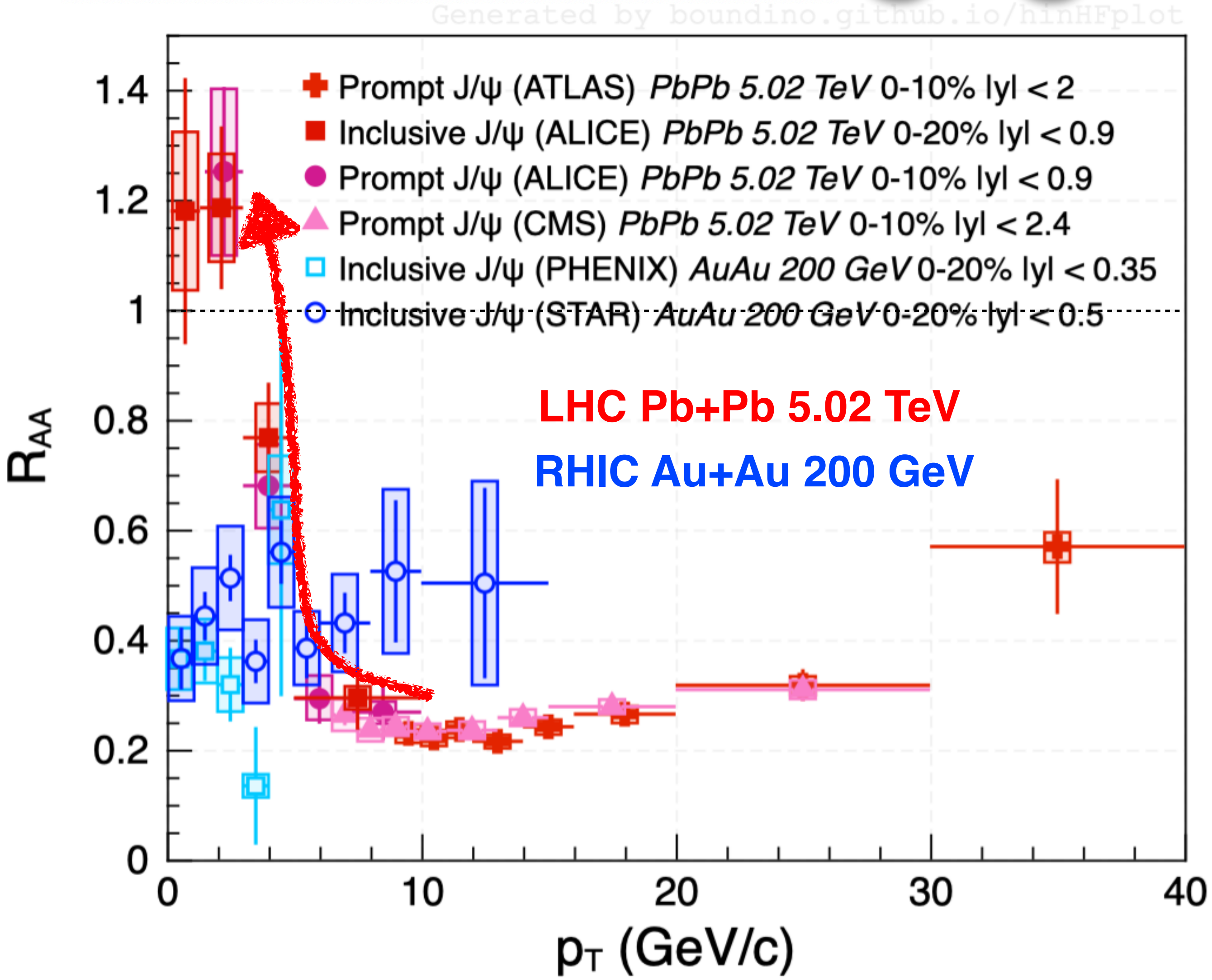
- R_{AA} RHIC > R_{AA} LHC at high-p_T : Higher QGP temperature created in LHC

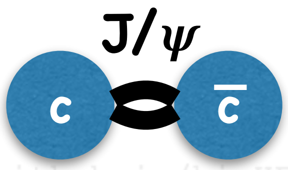
Charmonia in QGP : History

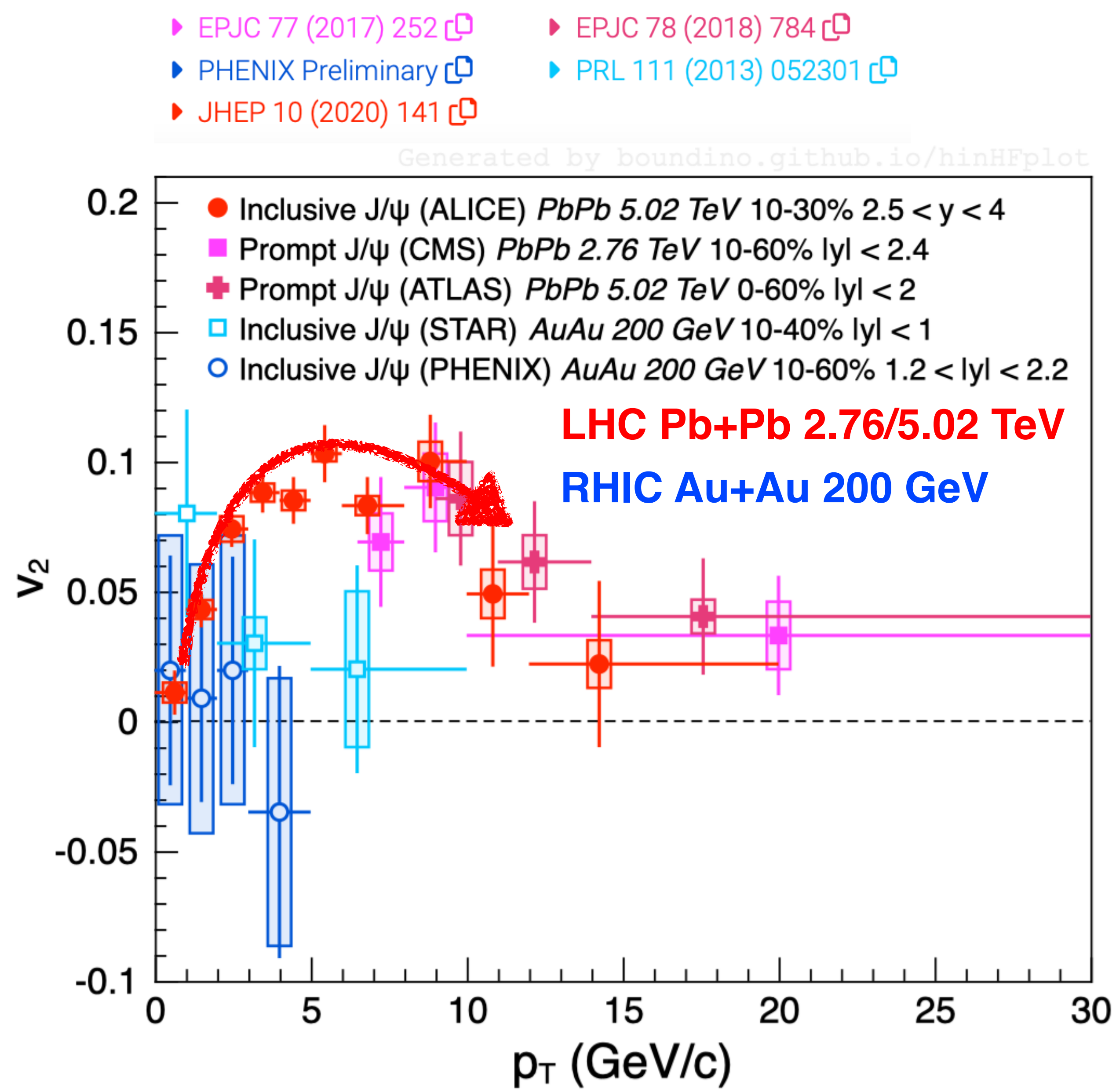


- R_{AA} RHIC > R_{AA} LHC at high-p_T : Higher QGP temperature created in LHC
- Enhancement at low-p_T in LHC energies : Sign of recombination (abundant charm cross section)

Charmonia in QGP : History

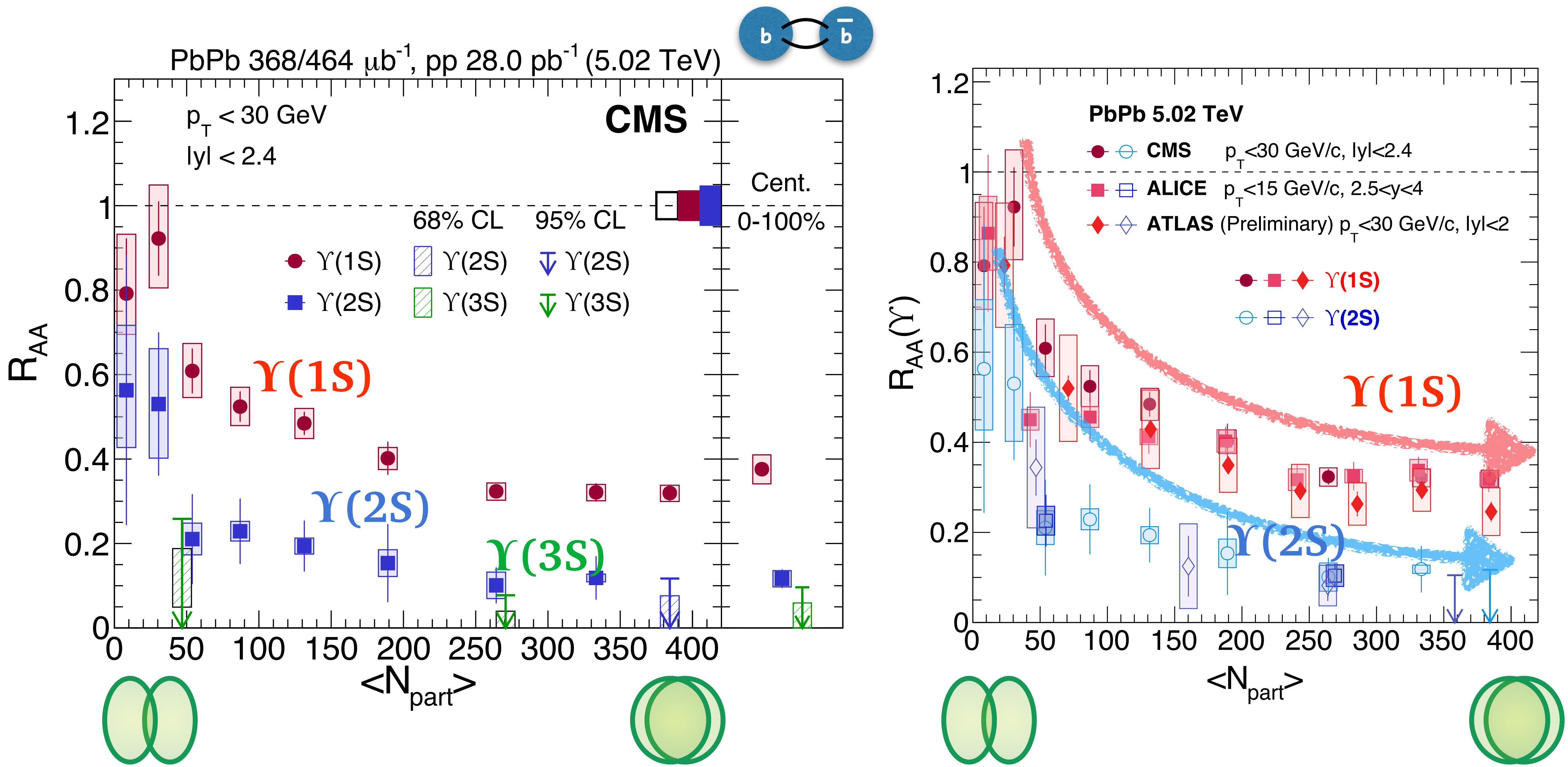






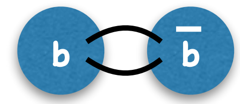
- R_{AA} RHIC > R_{AA} LHC at high-p_T : Higher QGP temperature created in LHC
- Enhancement at low-p_T in LHC energies : Sign of recombination (abundant charm cross section)
- Large v_2 at low-p_T also interpreted as signature of recombination

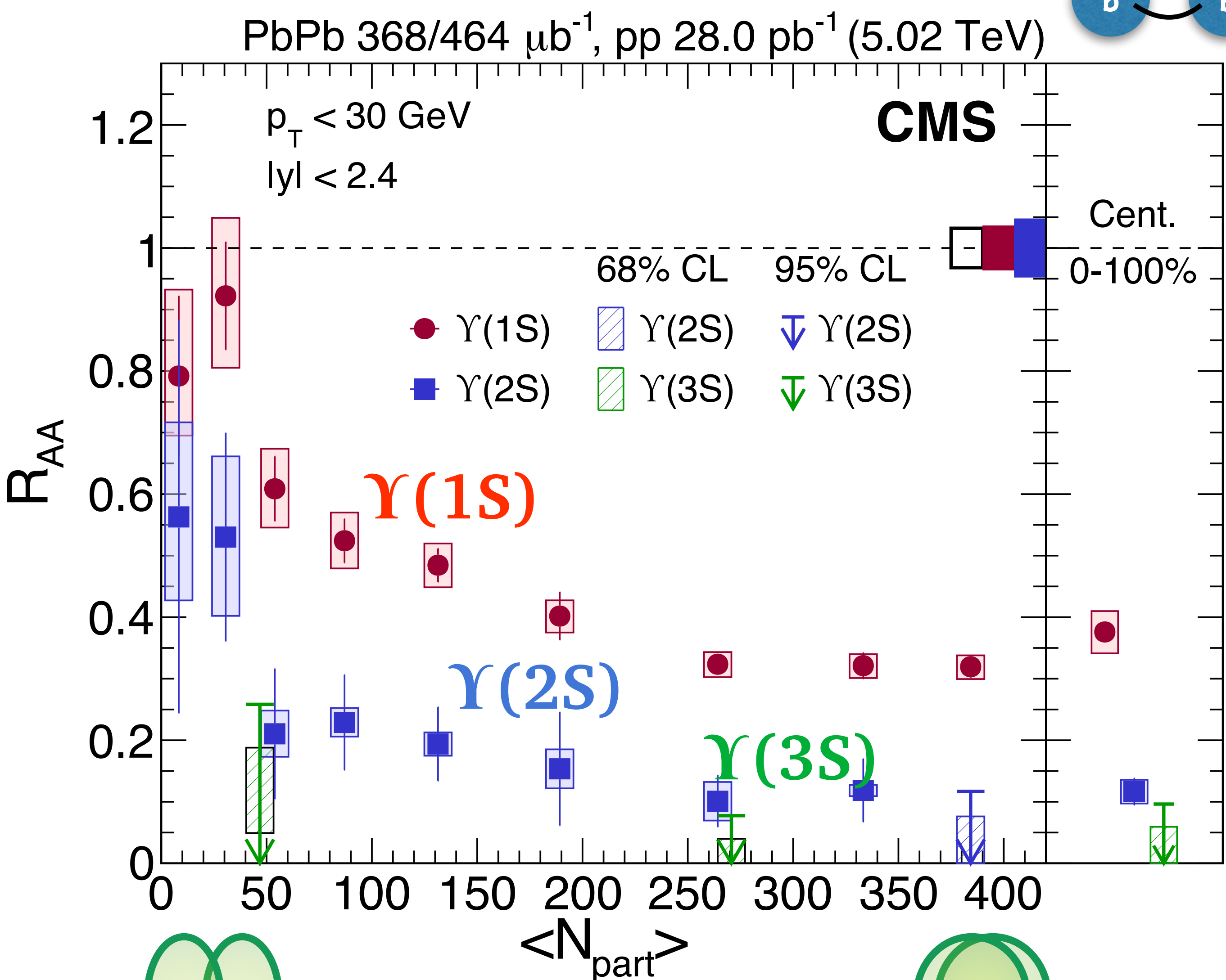
Bottomonia in QGP : History

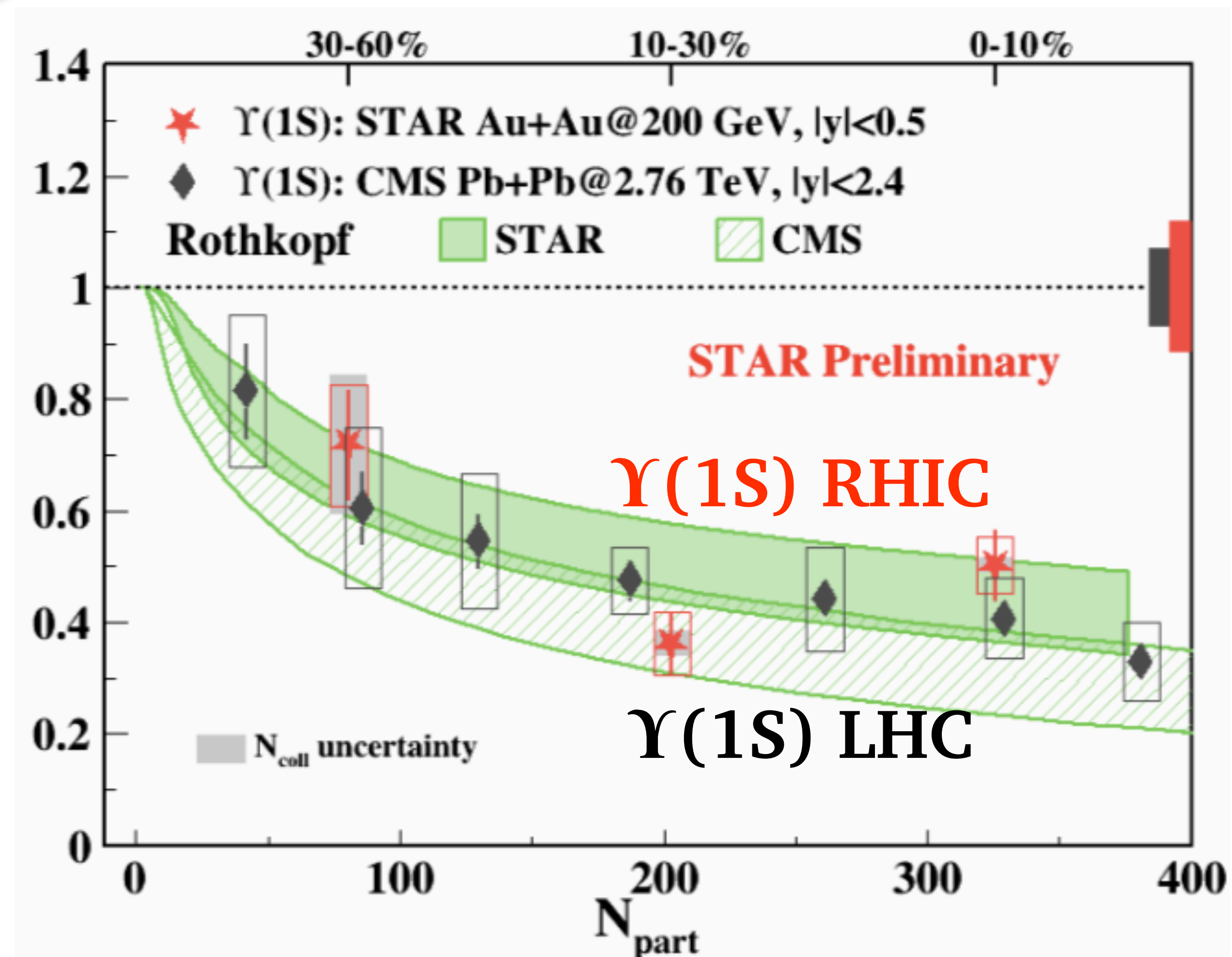


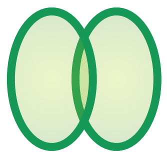
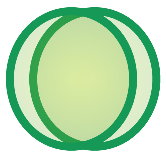
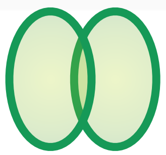
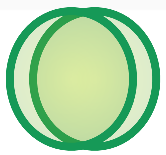
- Sequential suppression! $R_{AA}(\Upsilon(1S))$ > $R_{AA}(\Upsilon(2S))$ >≈ $R_{AA}(\Upsilon(3S))$
- Large suppression of Υ(3S) in all intervals
- Consistent among LHC measurements

Bottomonia in QGP : History



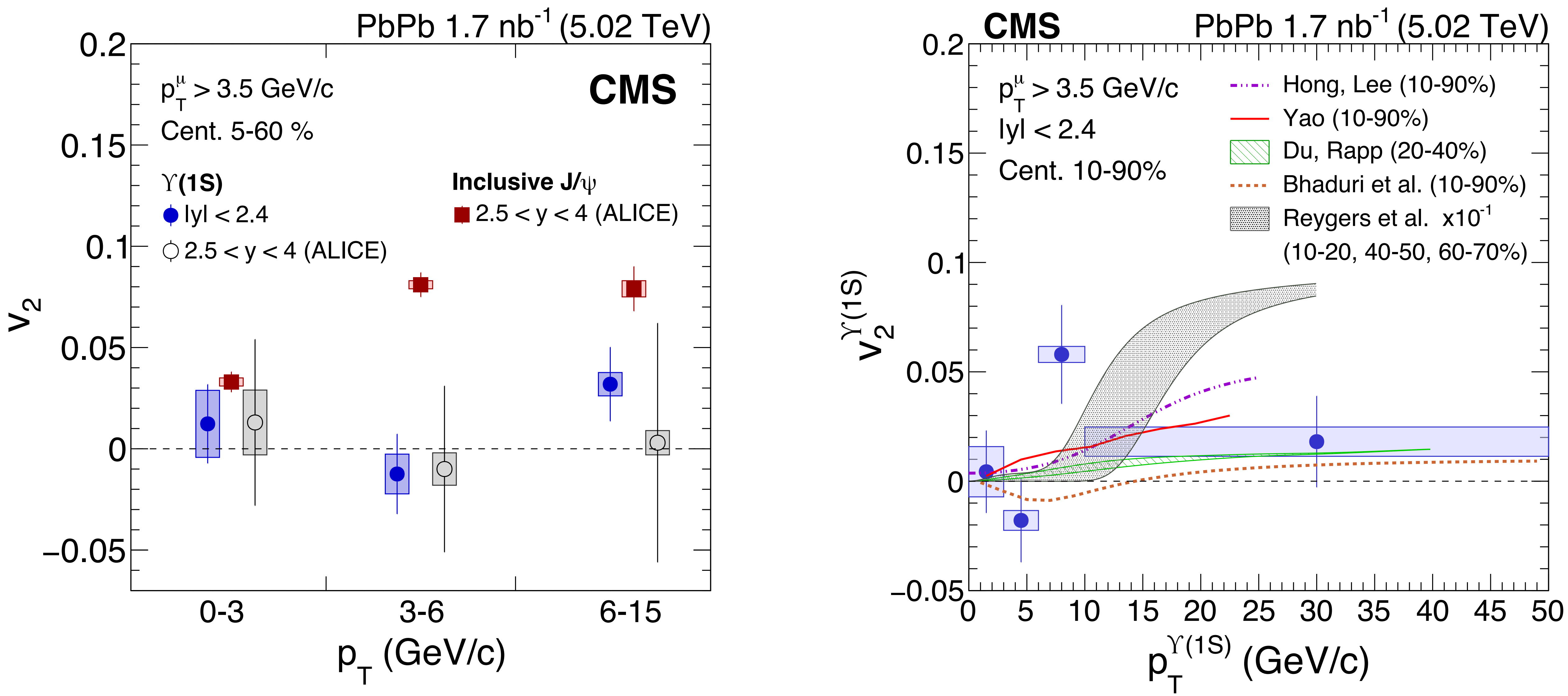




- Sequential suppression! R_{AA}(ϒ(1S)) > R_{AA}(ϒ(2S)) >≈ R_{AA}(ϒ(3S))
- Large suppression of ϒ(3S) in all intervals
- Consistent among LHC measurements <—> Similar suppression at RHIC?

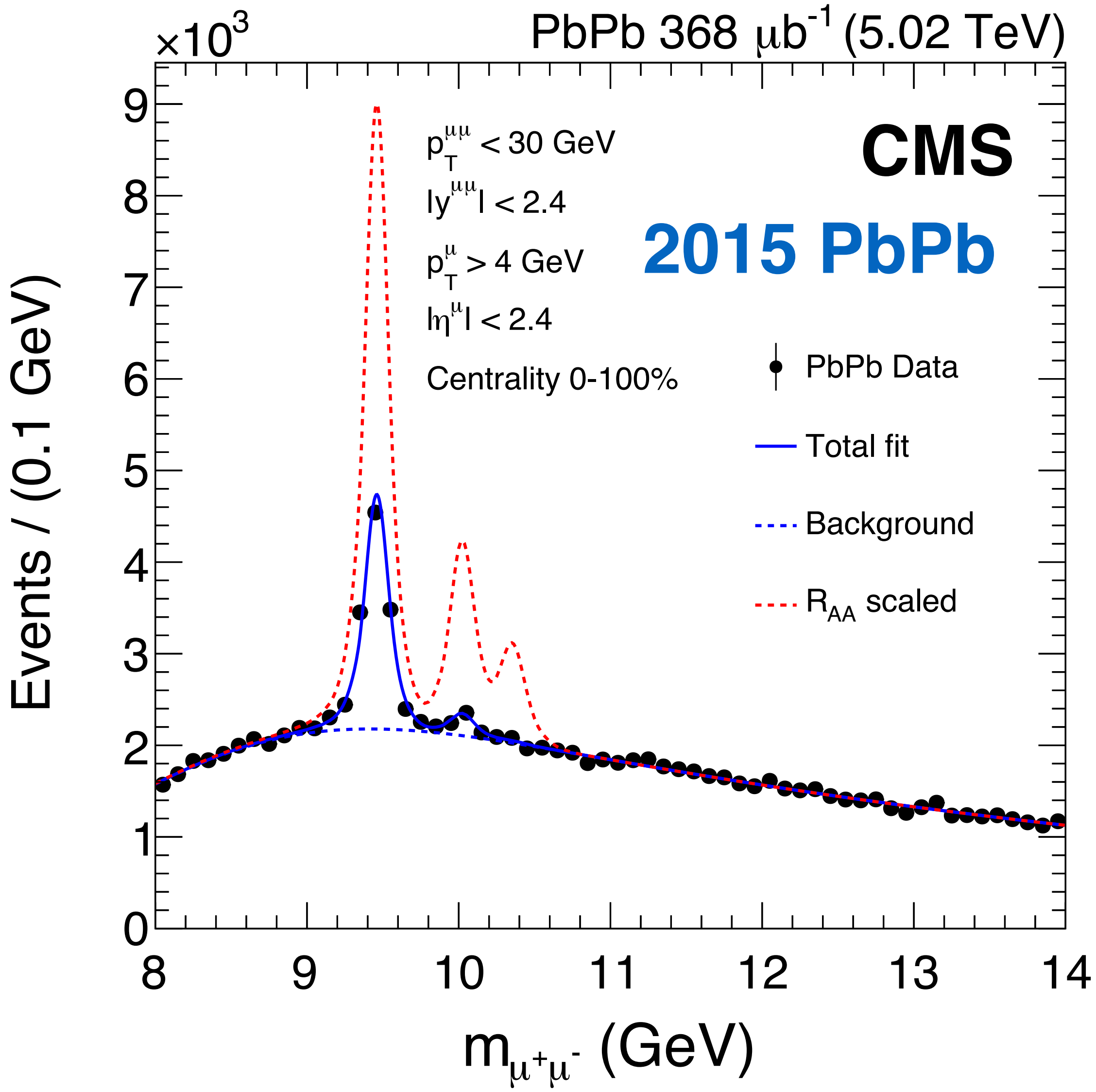
Flow of bottomonia



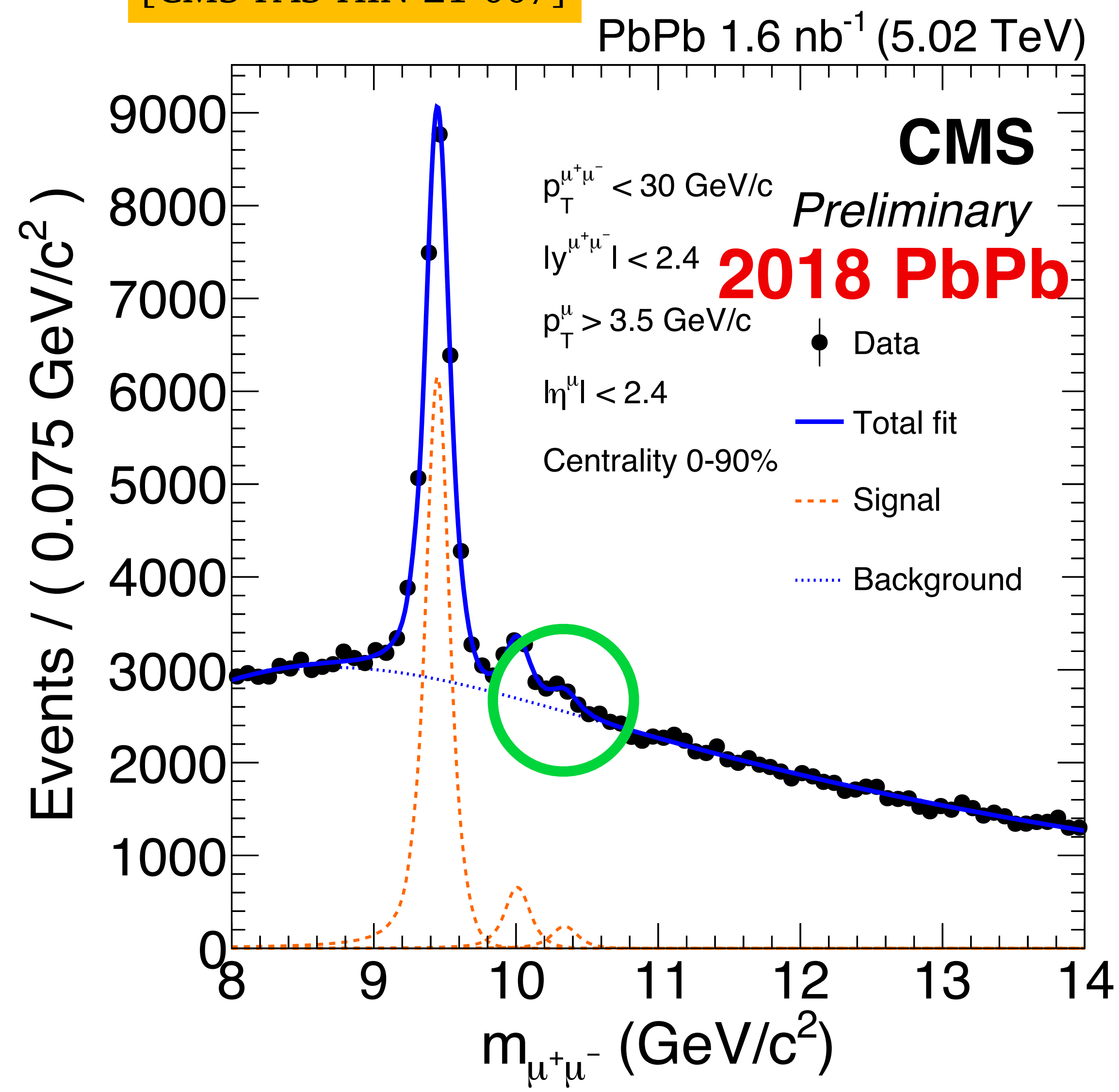
- No elliptic flow signal for Y(1S)
- Much smaller v_2 than J/ψ —> No large collectivity as charm
- Compatible with most models — constraints on Blast-wave model

Observation of Υ(3S) in HIC

[PLB 819 (2021) 136385]

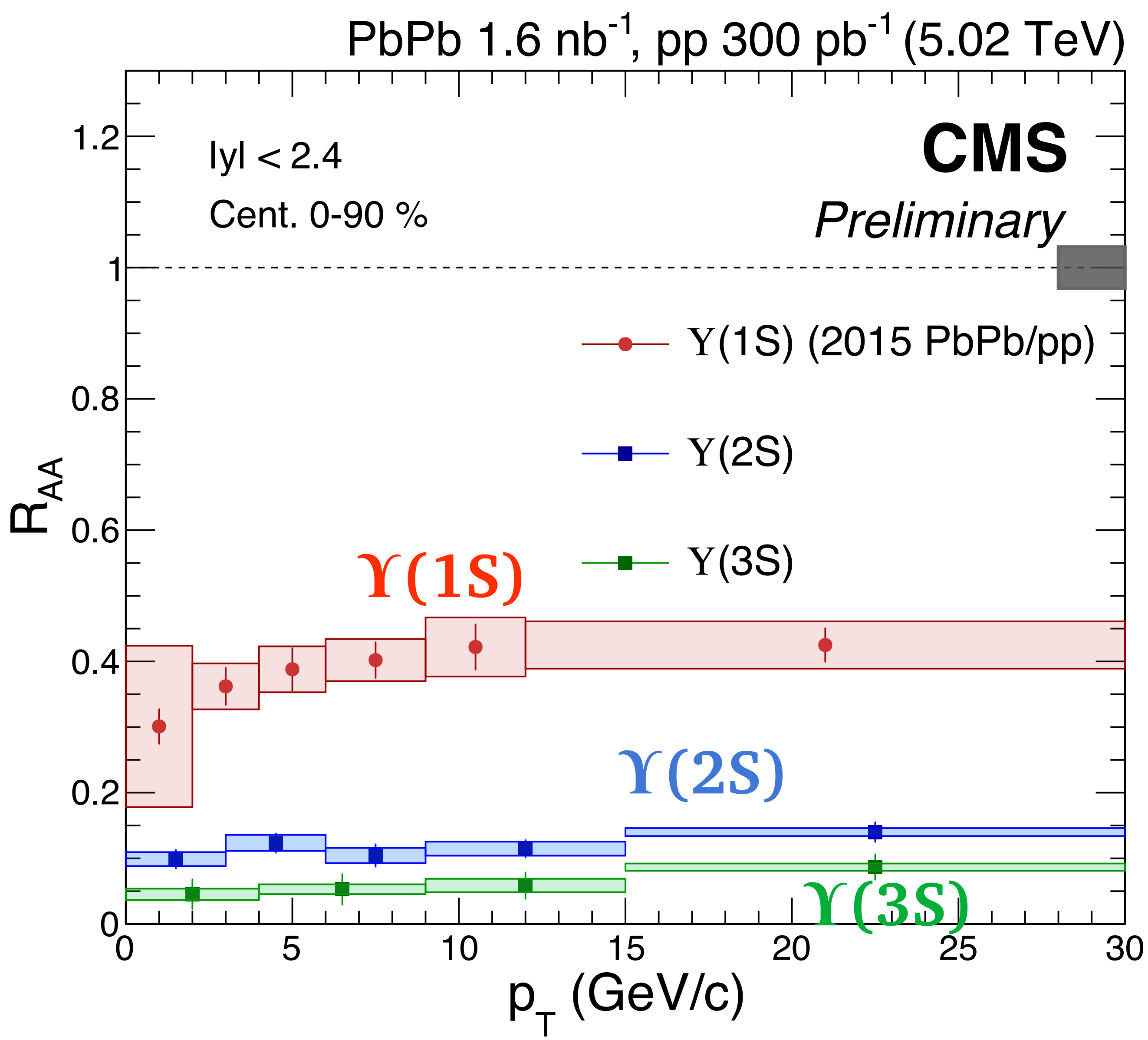


[CMS-PAS-HIN-21-007]



- First observation of Υ(3S) in PbPb collisions : Significance > 5 σ
- Larger dataset & machine-learning based analysis technique (BDT)

Observation of Υ(3S) in HIC

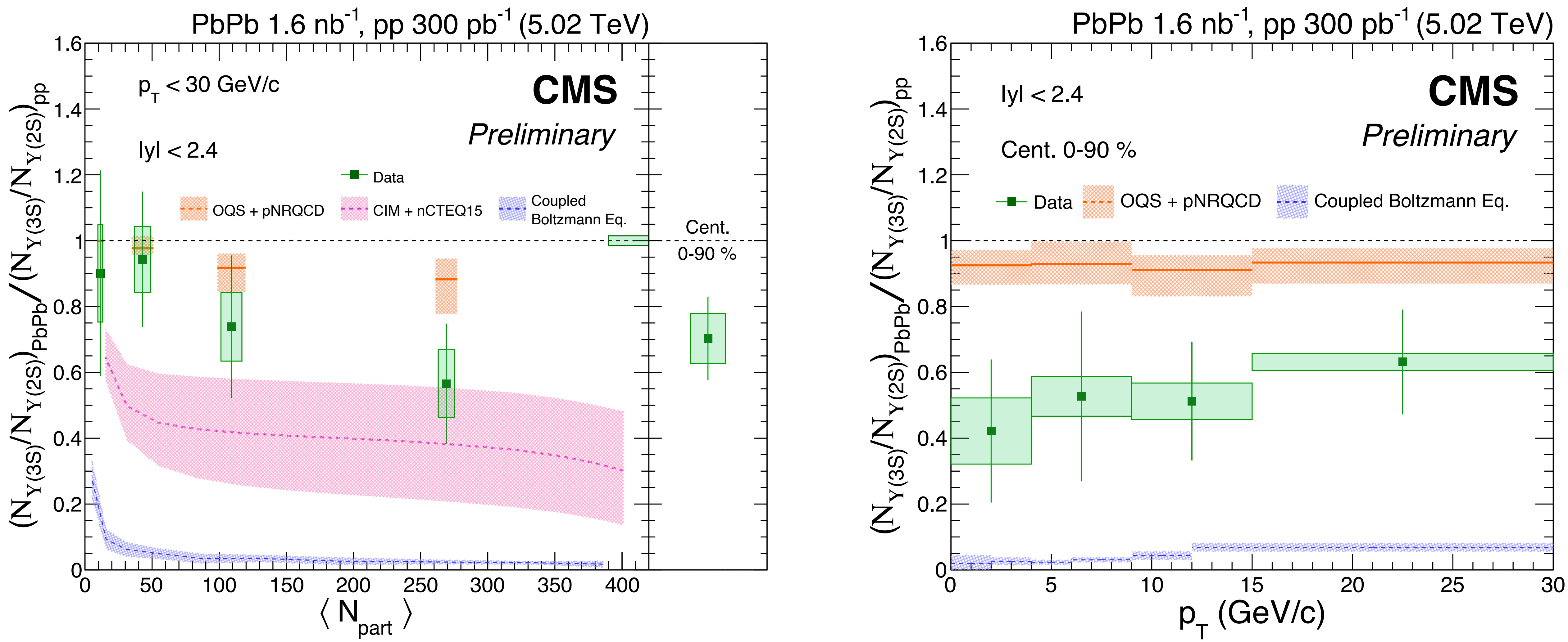


- Reveal of sequential suppression!

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

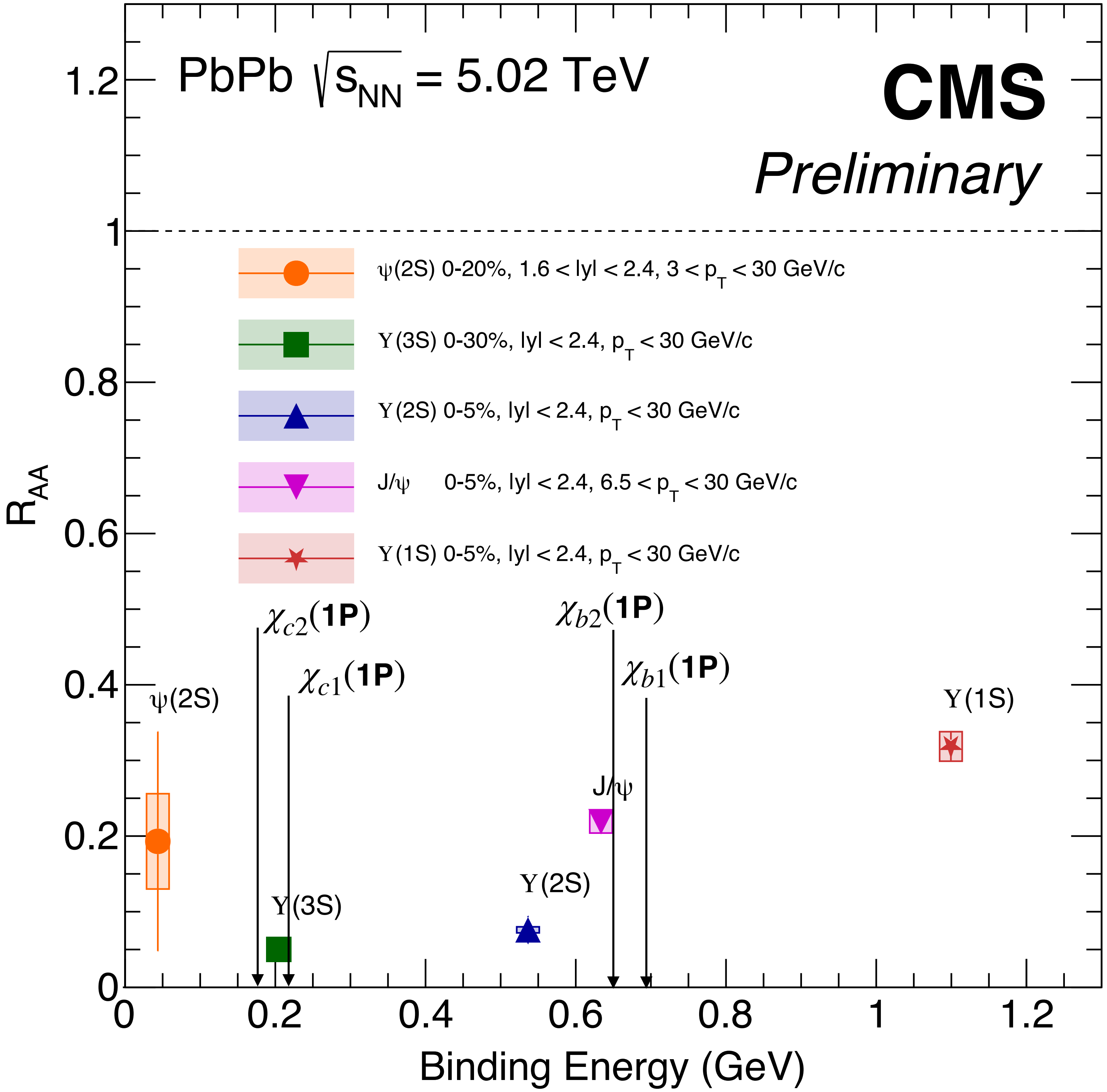
- Larger suppression in all p_T region

Comparison with theory models



- Double ratio of Υ(3S)/Υ(2S) —> Imply relative modification of the two excited states
- Most models fail to describe the measurements

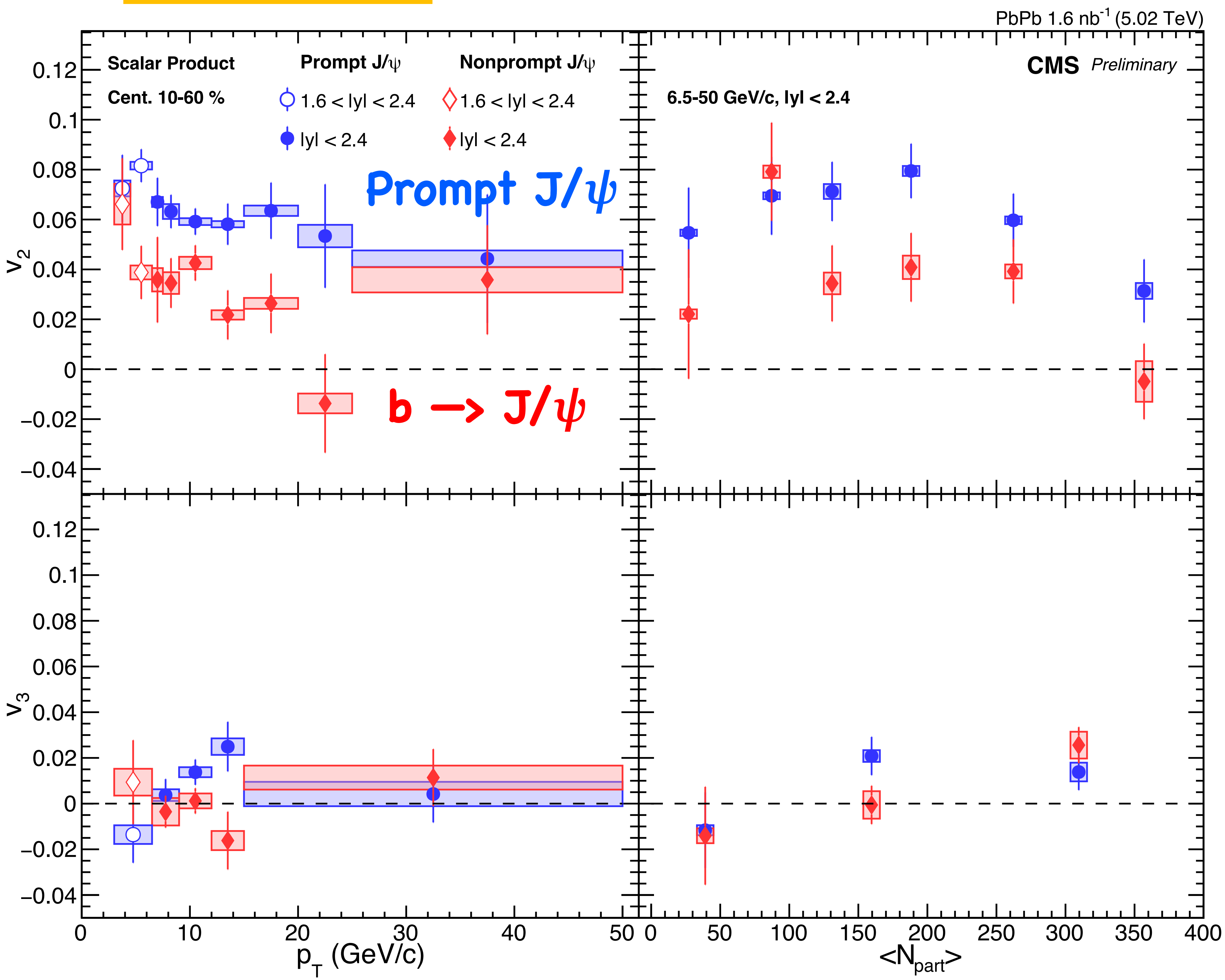
Binding energy picture



- Importance of feed down!
  - ~33% for Υ(1S)
  - ~20-40% for Υ(2S), Υ(3S)
  - Less impact for charmonia
- In-medium effects not directly scale with B.E.?

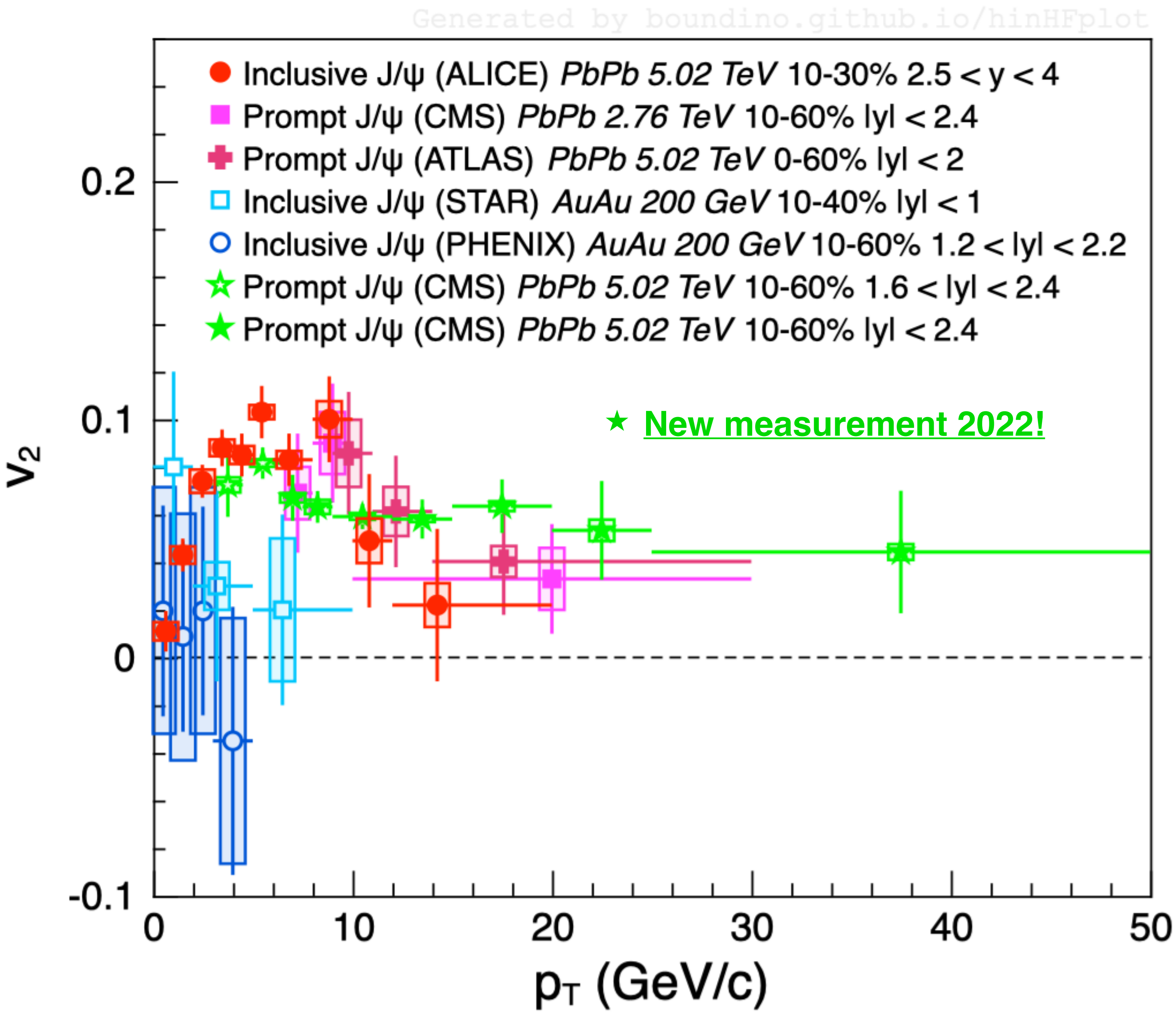
Charmonium flow

[CMS-PAS-HIN-21-008]



- Prompt J/ψ v_2 > b –> J/ψ v_2
- Small v3 for both prompt & b decay J/ψ

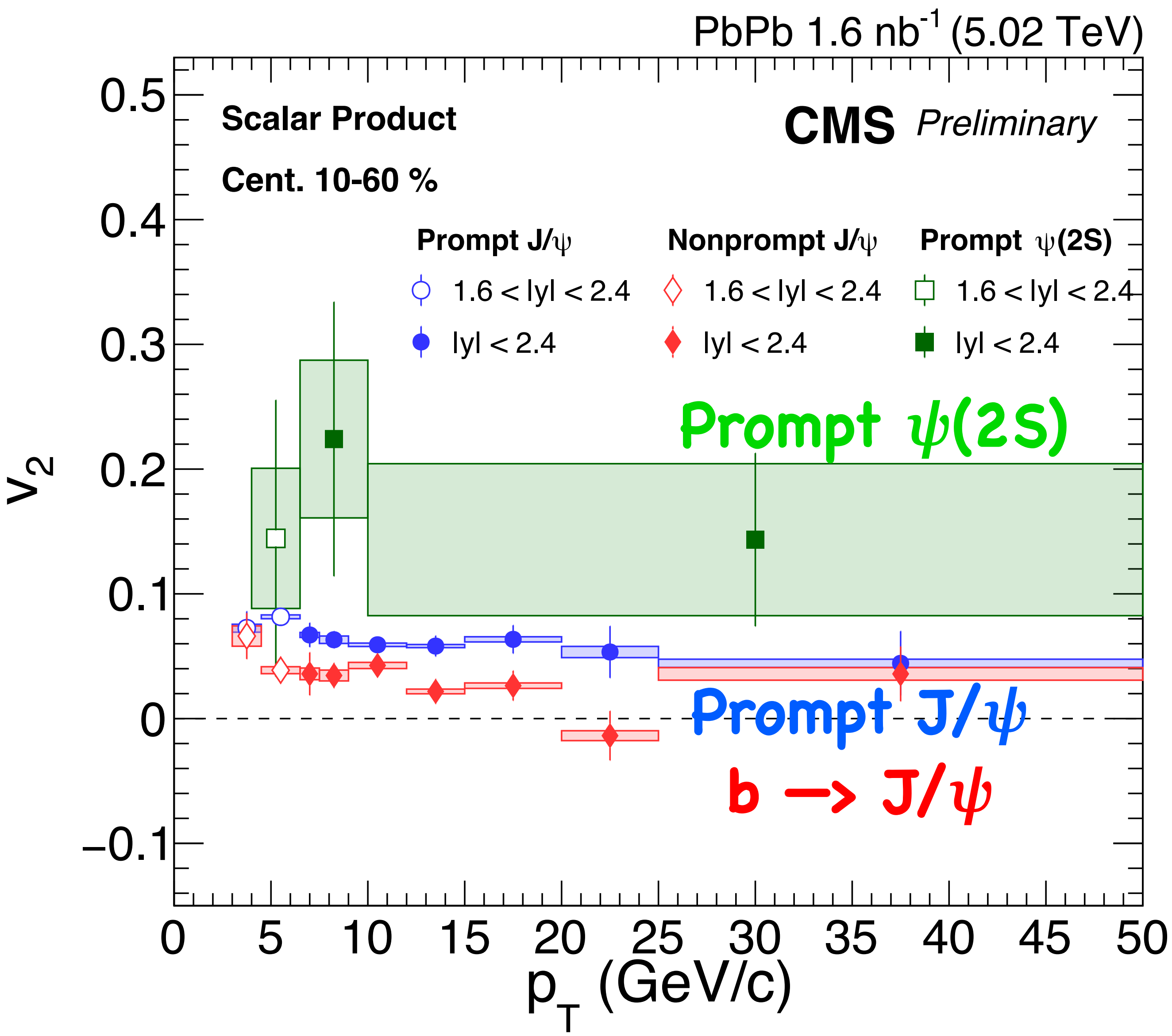
Charmonium flow

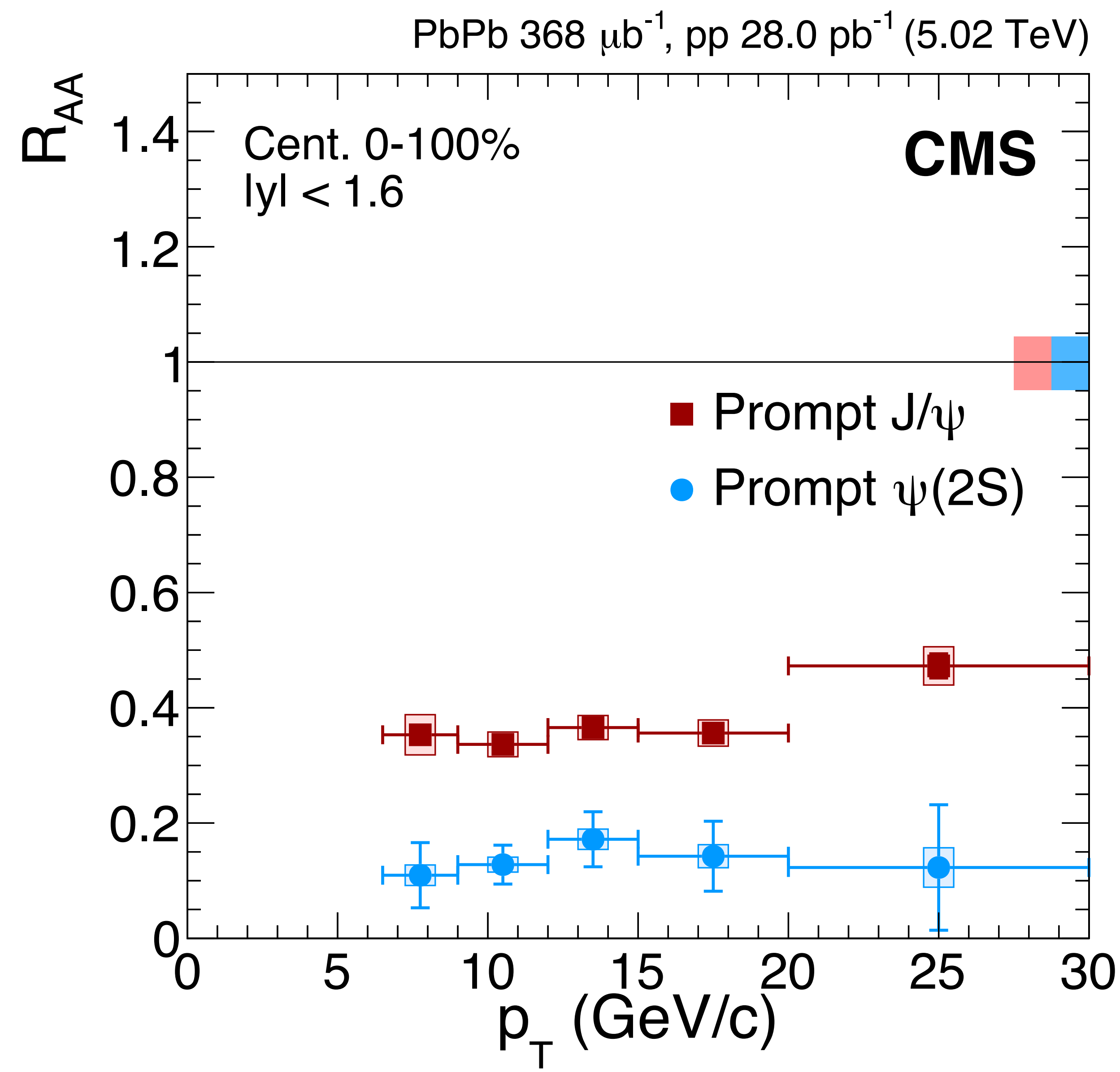


- High precision up to 50 GeV/c

J/ψ vs ψ(2S)

[CMS-PAS-HIN-21-008]

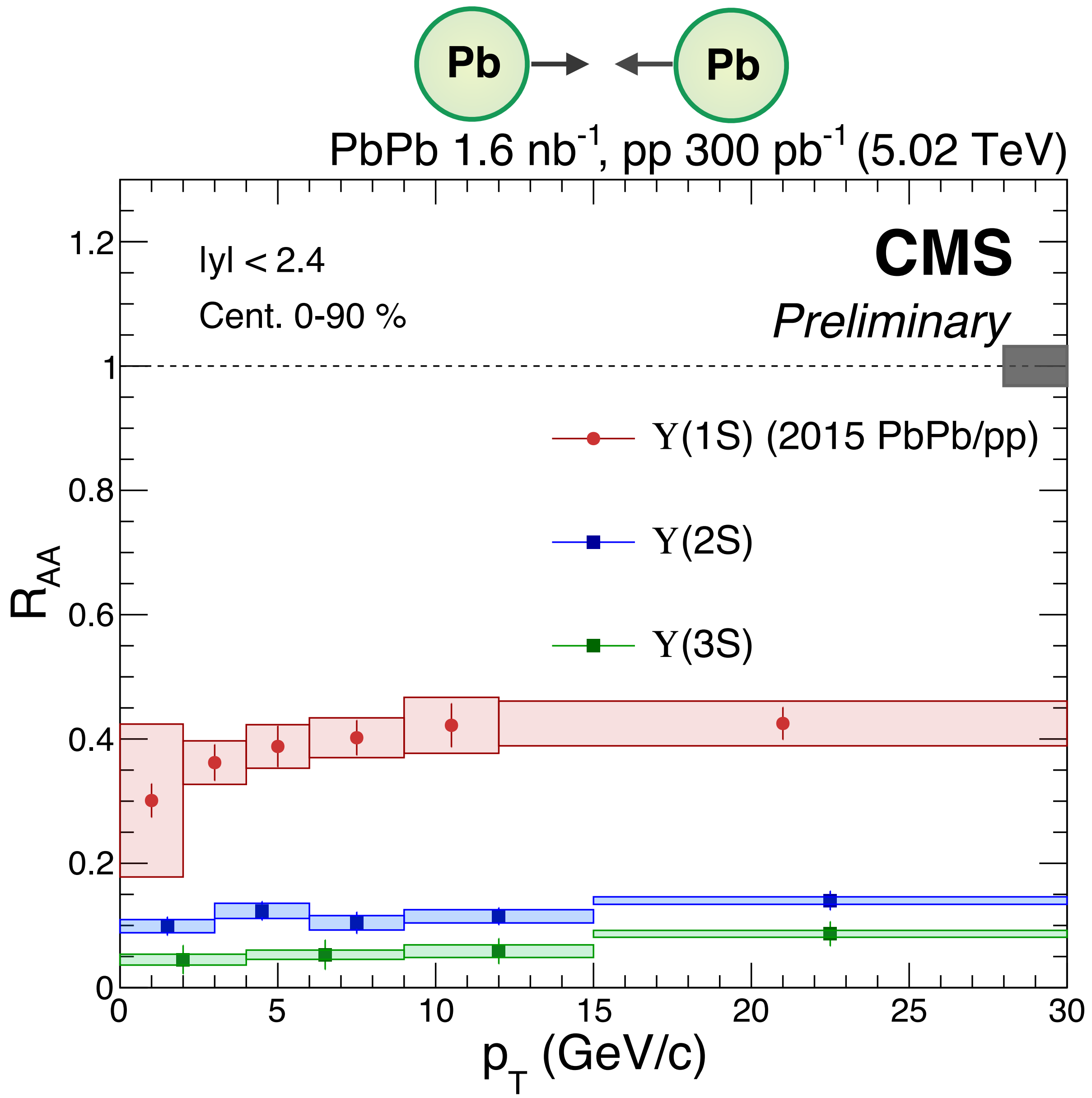




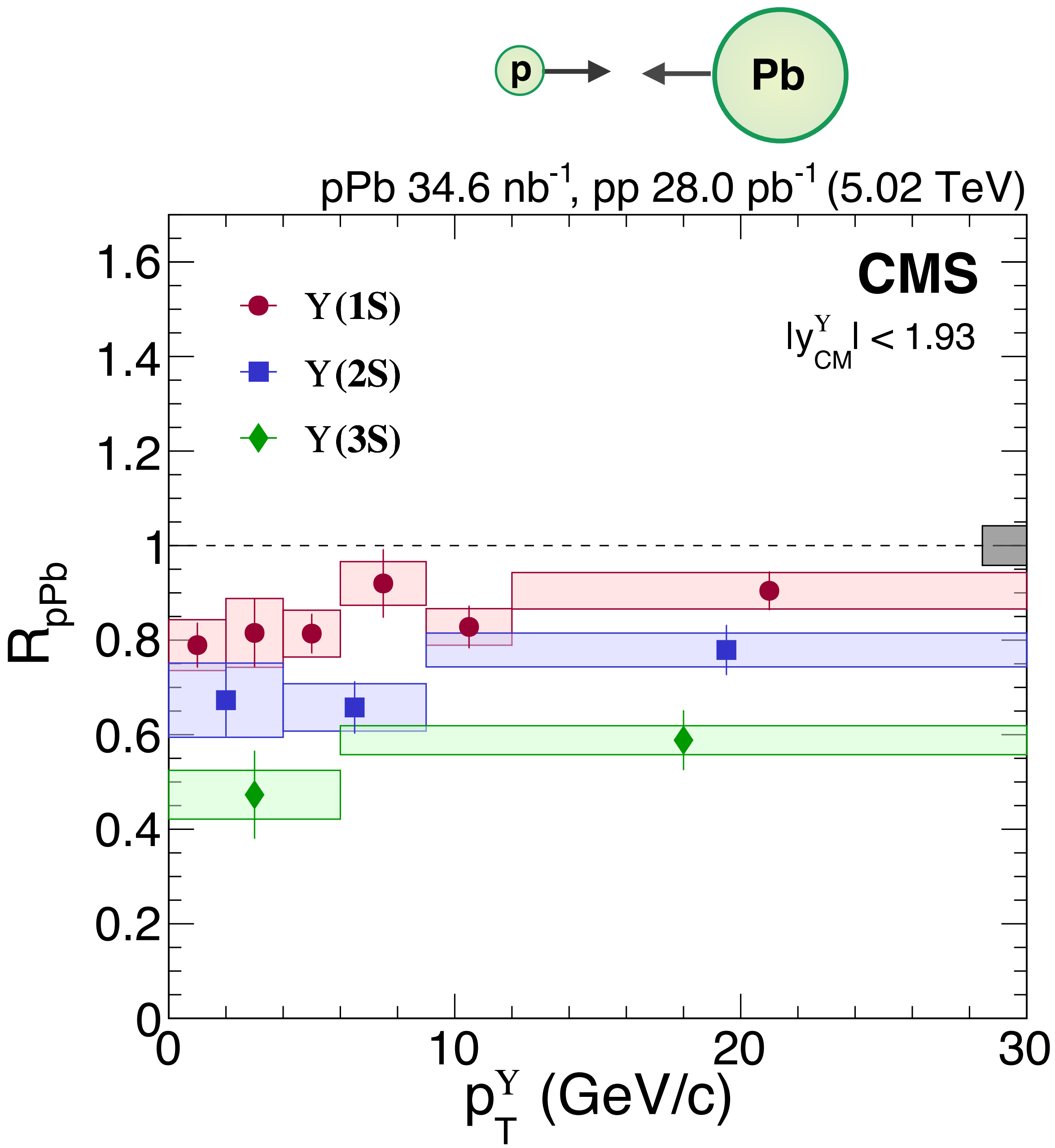
- Larger v_2 observed for ψ(2S)
  : different amount of regeneration? path-length E. loss at high-p_T?
- Reminder : Stronger suppression for ψ(2S) than J/ψ

Bottomonia in pPb

[CMS-PAS-HIN-21-007]



[arXiv:2202.11807]

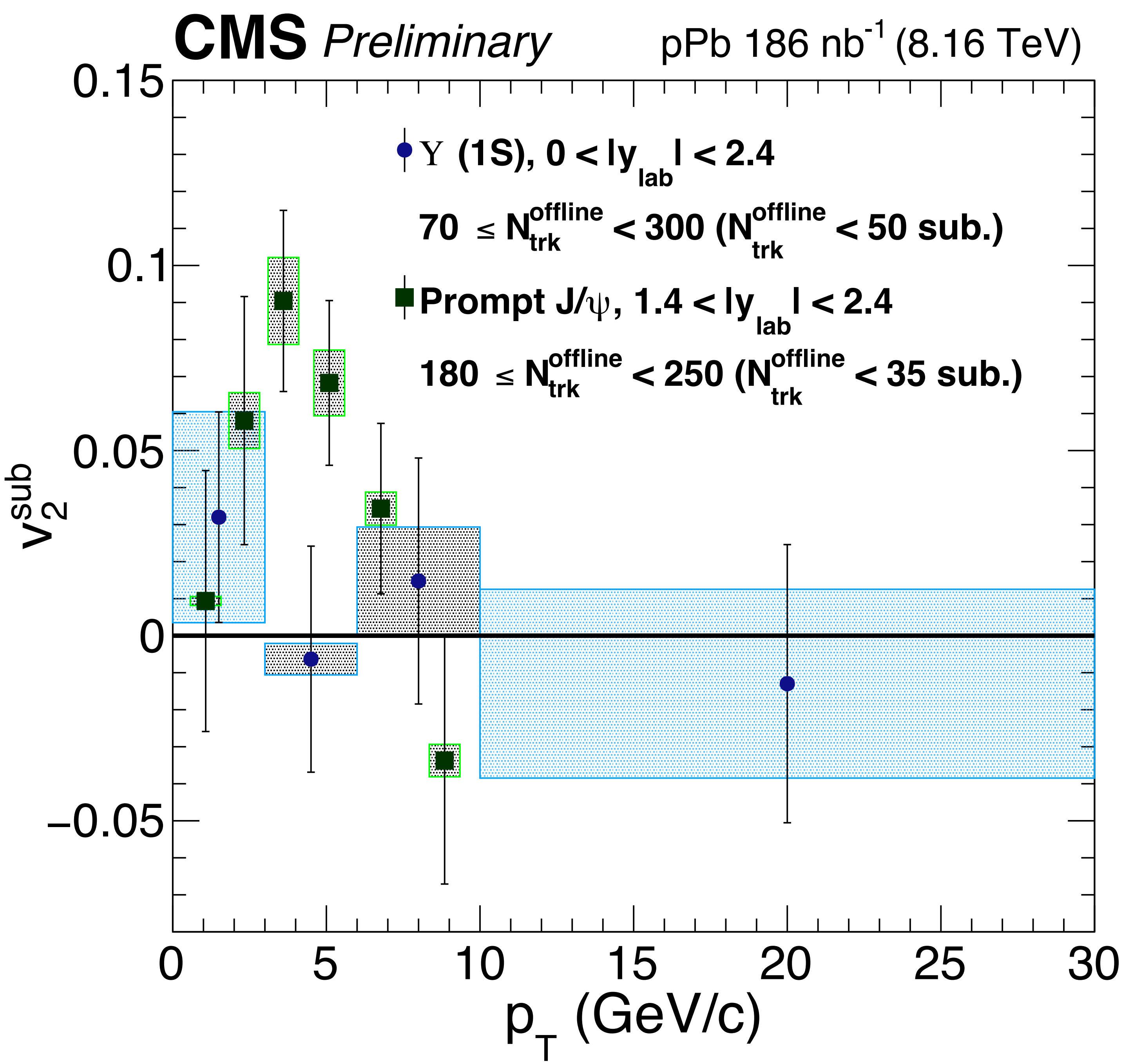


- Smaller suppression in pPb compared to PbPb
- BUT sequential suppression also present in pPb collisions…!

Bottomonium flow in pPb

[CMS-PAS-HIN-21-001]

First Υ v_2 measurement in pPb!



(Recent measurement by ALICE)

pp : Υ(1S) v_2 ?? <—> J/ψ $v_2 \approx 0$

pPb : Υ(1S) $v_2 \approx 0$ <—> J/ψ $v_2 > 0$

PbPb : Υ(1S) $v_2 \approx 0$ <—> J/ψ $v_2 > 0$

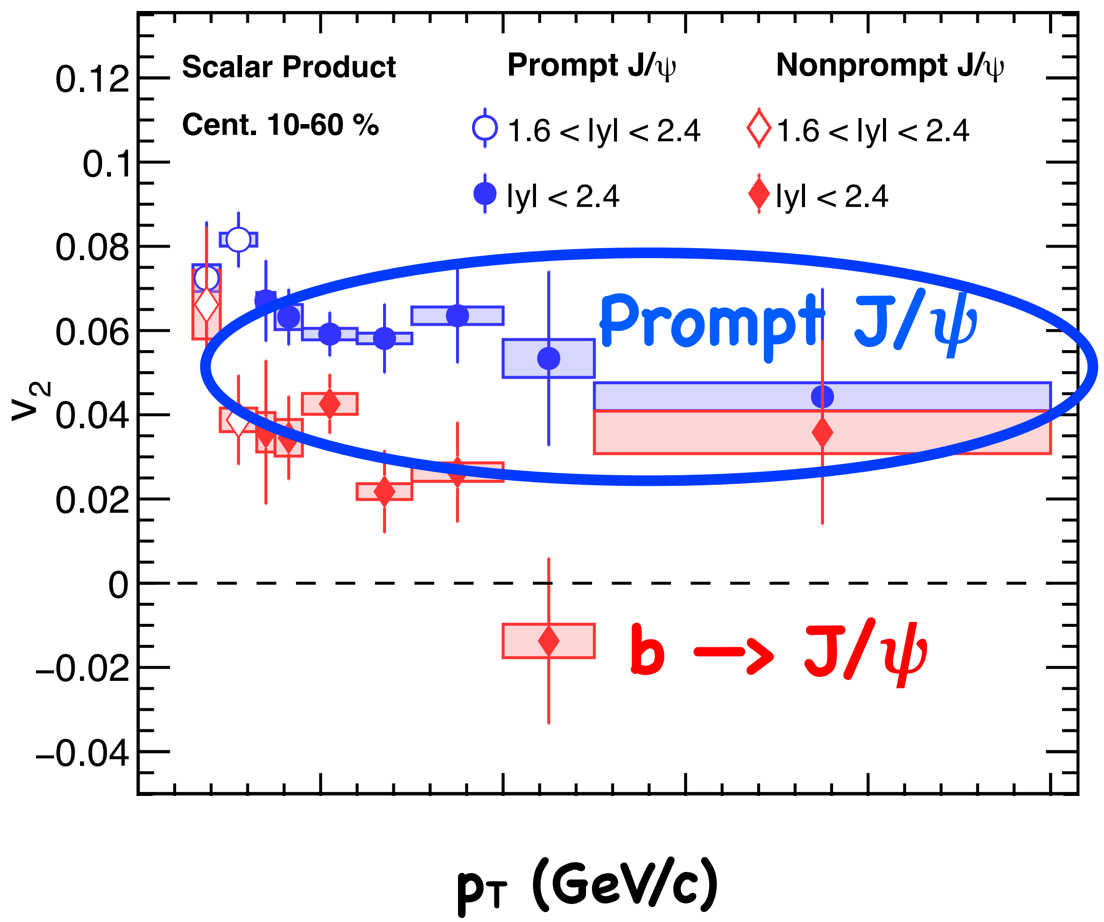
Summary

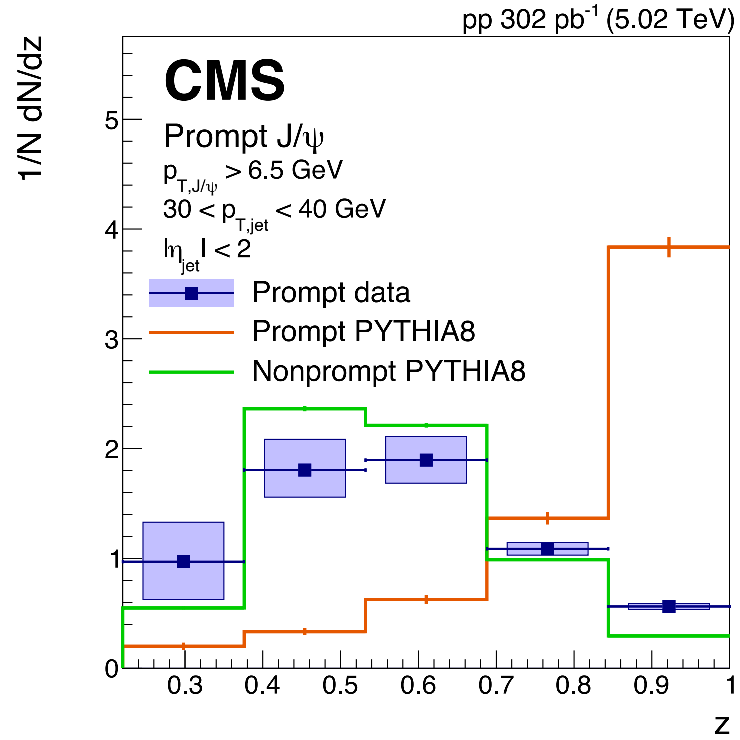
- Quarkonia : Golden probes to study QGP thermal properties
- Huge amount of efforts done in recent years by RHIC & LHC
- Important contributions from CMS results to understand different in-medium effects
- Still many things in a question mark
  — dissociation/recombination, feed-downs, small systems, etc.
- Future analyses needed to further improve our understanding of quarkonium dynamics

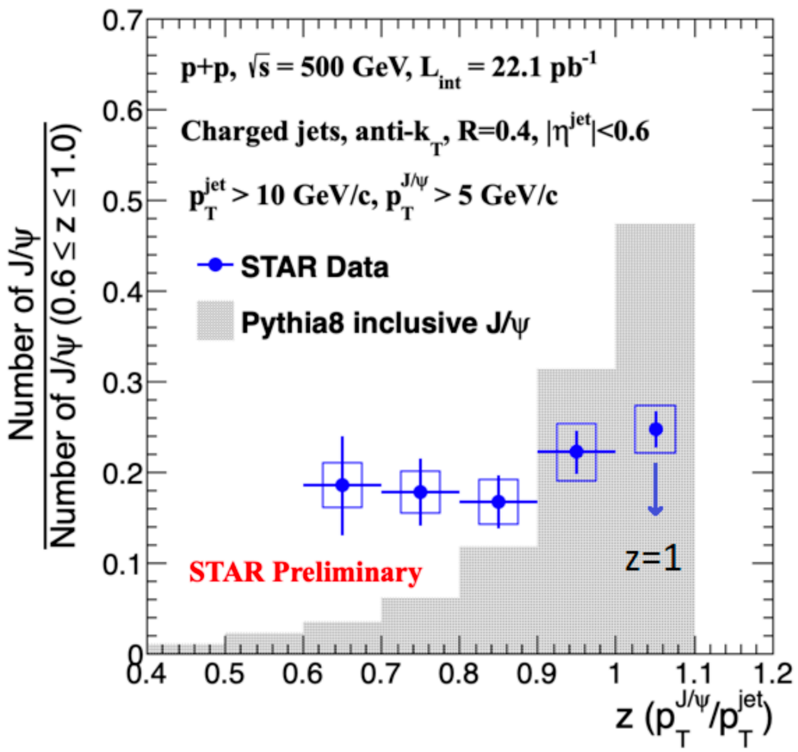
Back-up

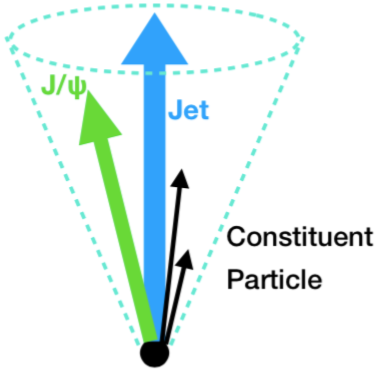
J/ψ jet fragmentation

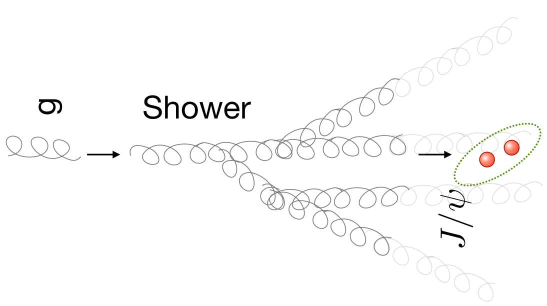
[CMS-PAS-HIN-21-008, QM-link]

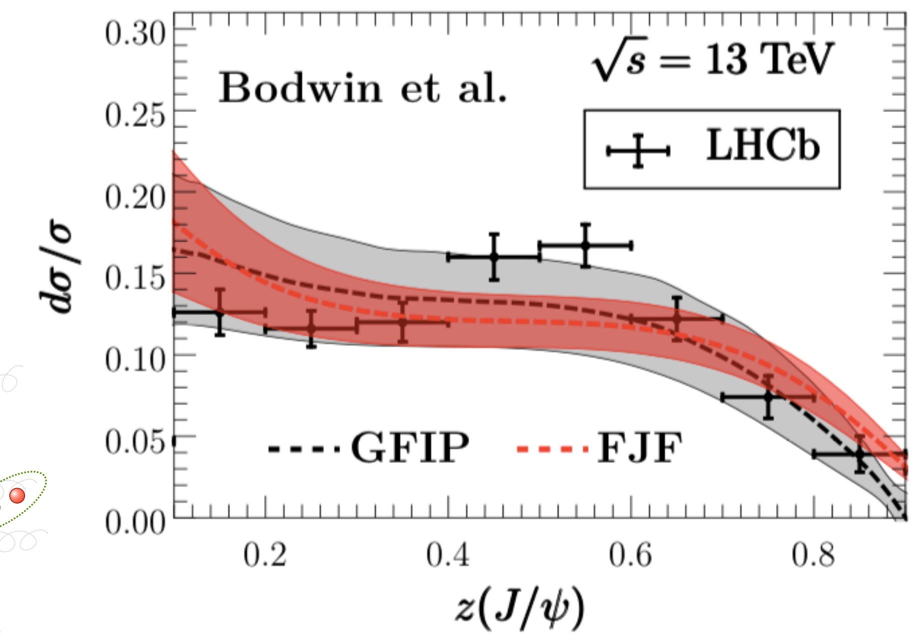








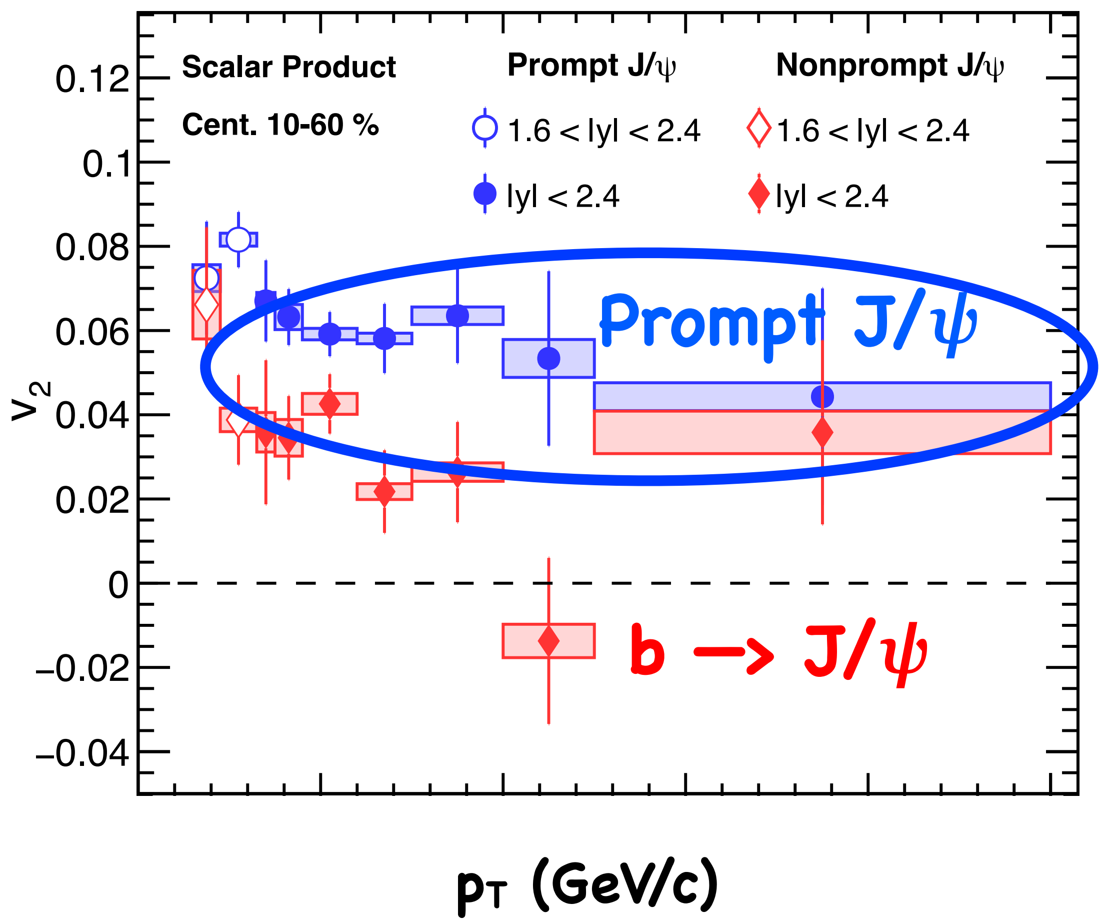


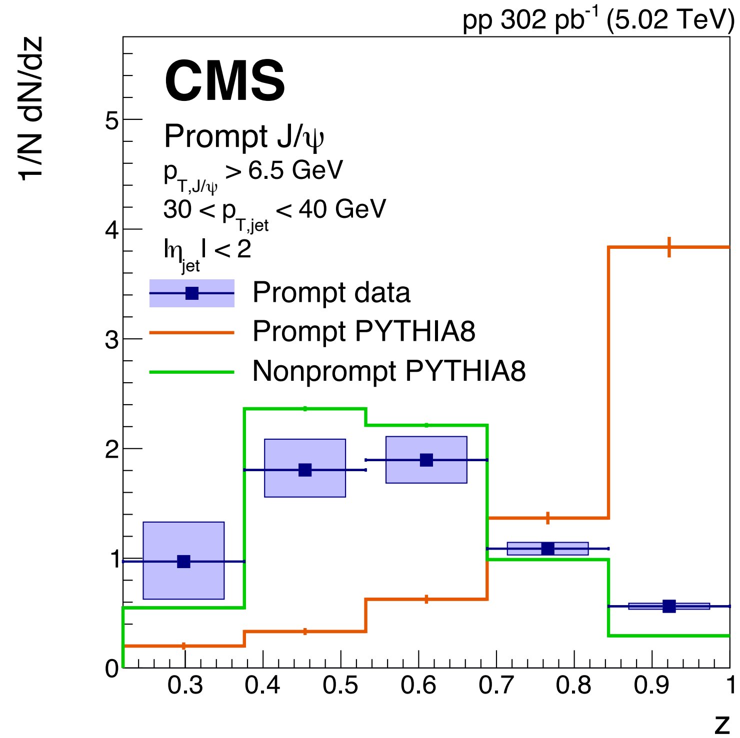


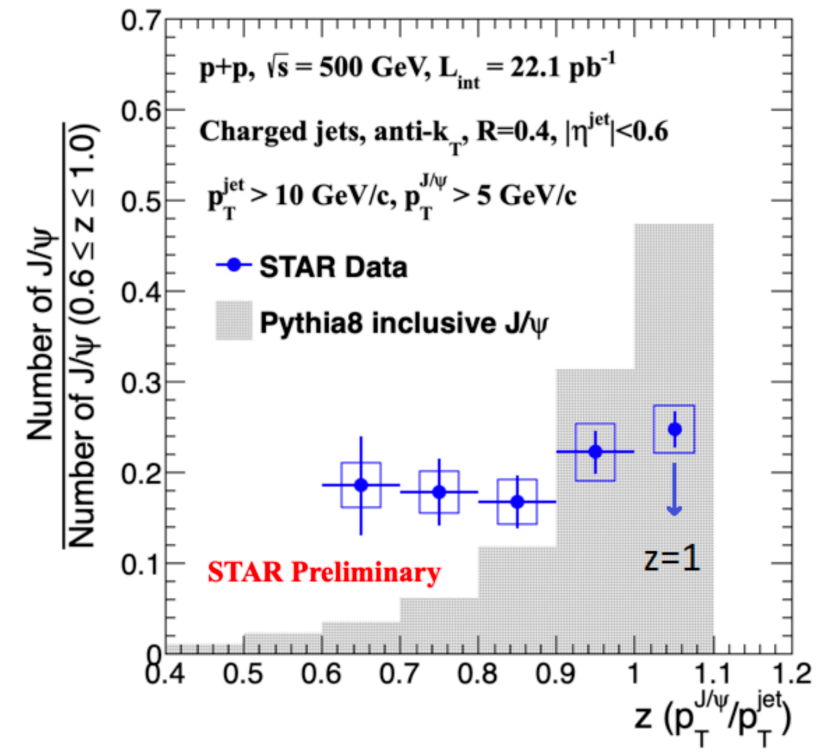
- Large v_2 up to 50 GeV/c
- Large contribution from parton shower

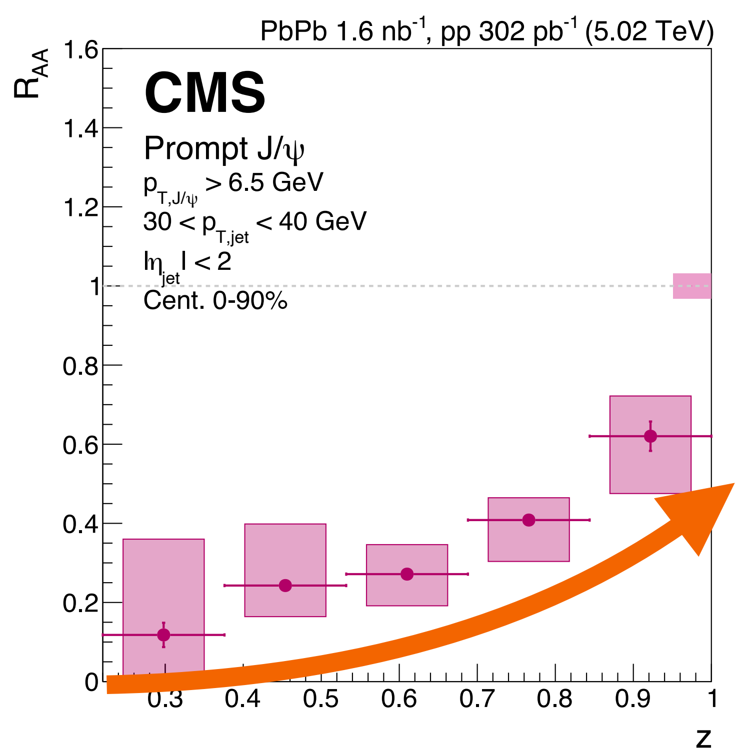
J/ψ jet fragmentation

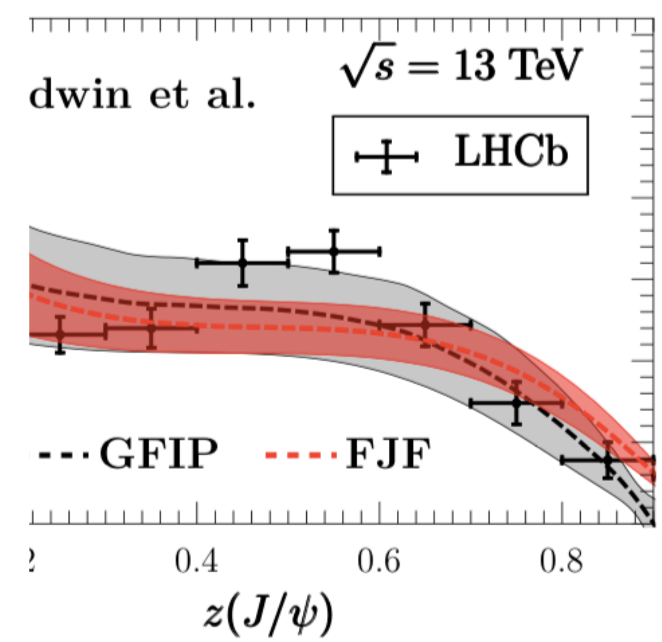
[CMS-PAS-HIN-21-008, QM-link]









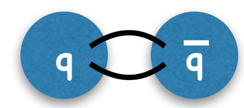


- Large v_2 up to 50 GeV/c
- Large contribution from parton shower
- Less suppression for isolated J/ψ

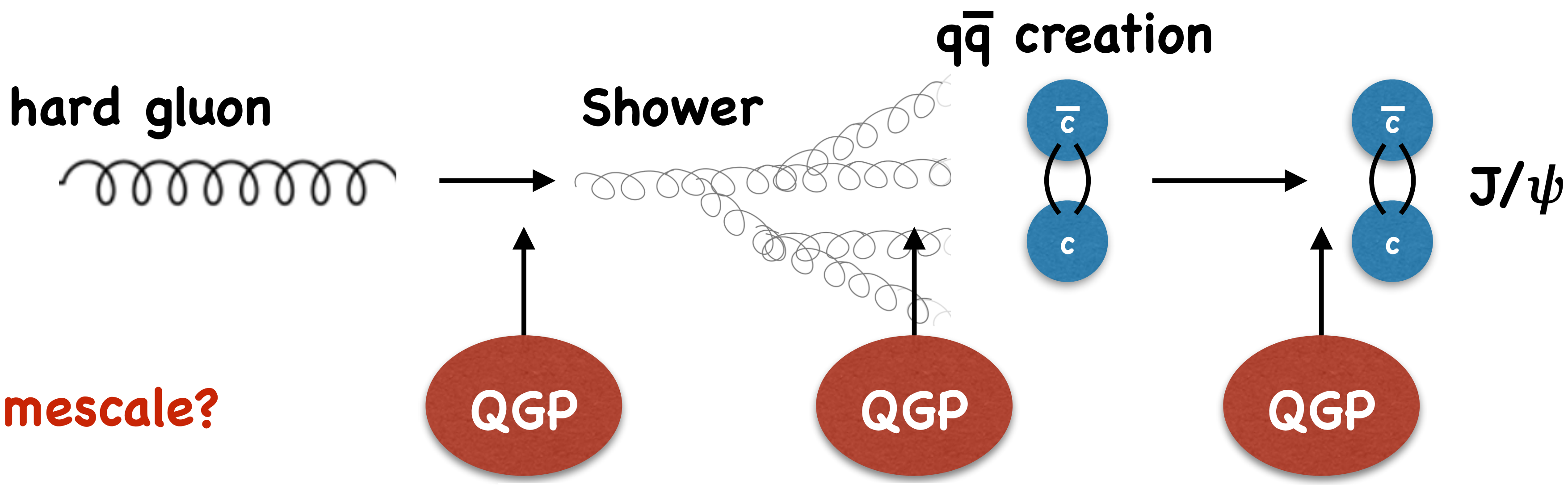
J/ψ creation time at high-p_T

[CMS-PAS-HIN-21-008, QM-link]

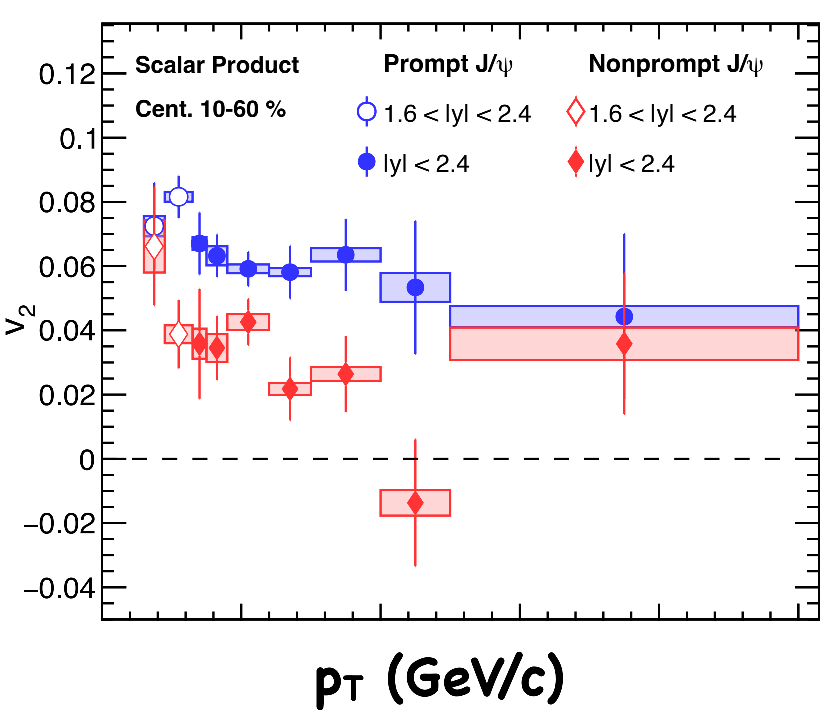
- Traditionally : q-qbar creation time ~ $1/2m_q$

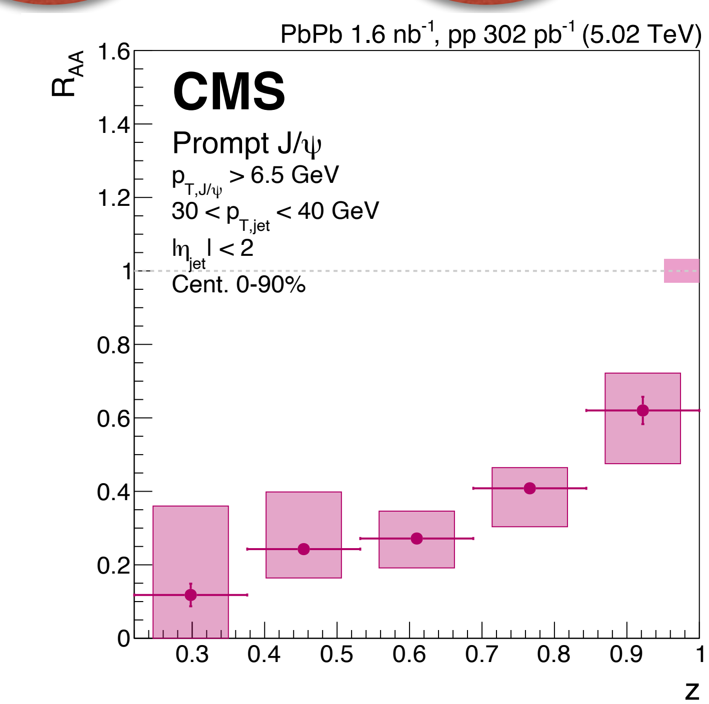


  - Not at high-p_T?



- Timescale?





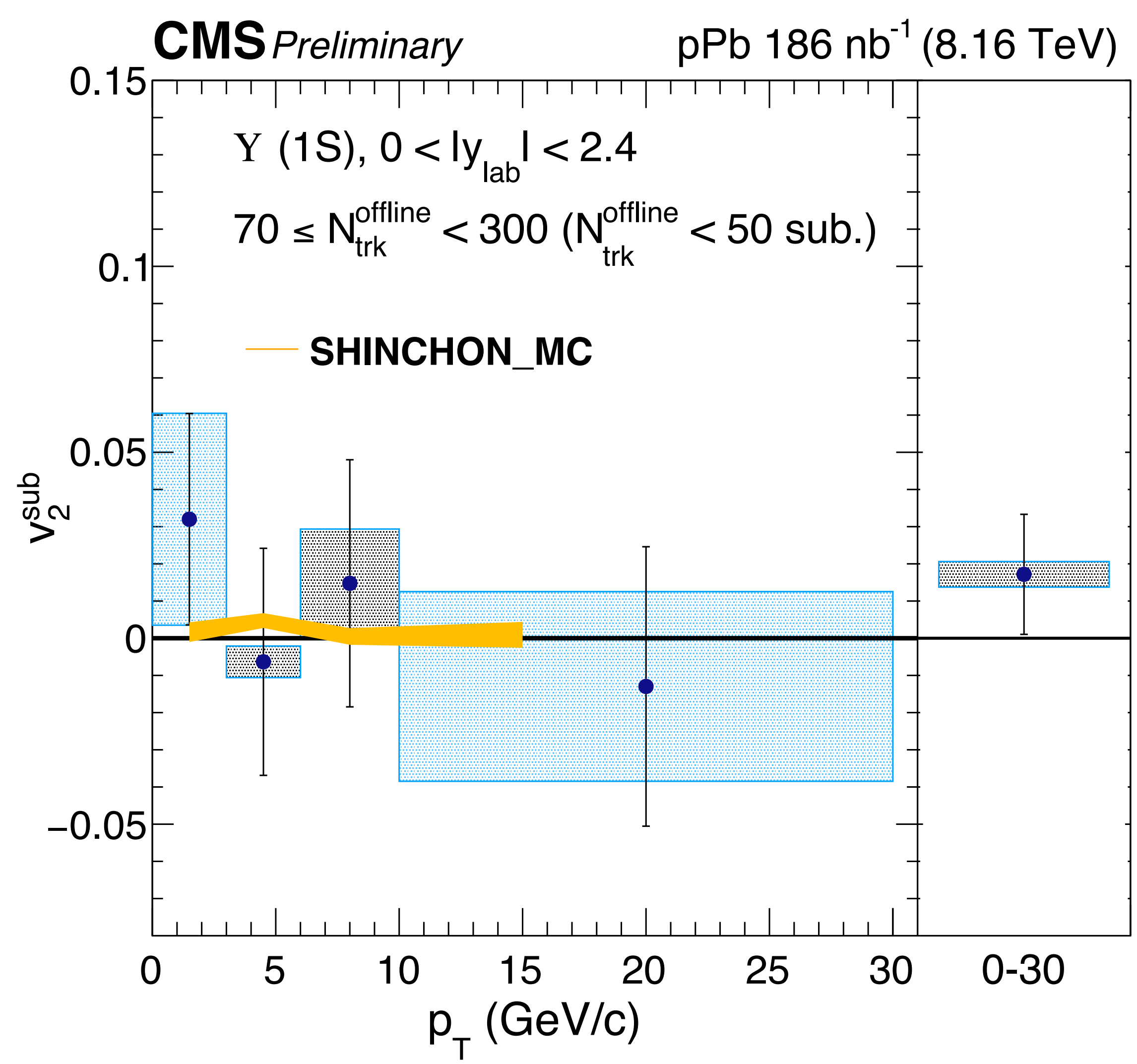
- How to incorporate jet-quenching for charmonium modification?

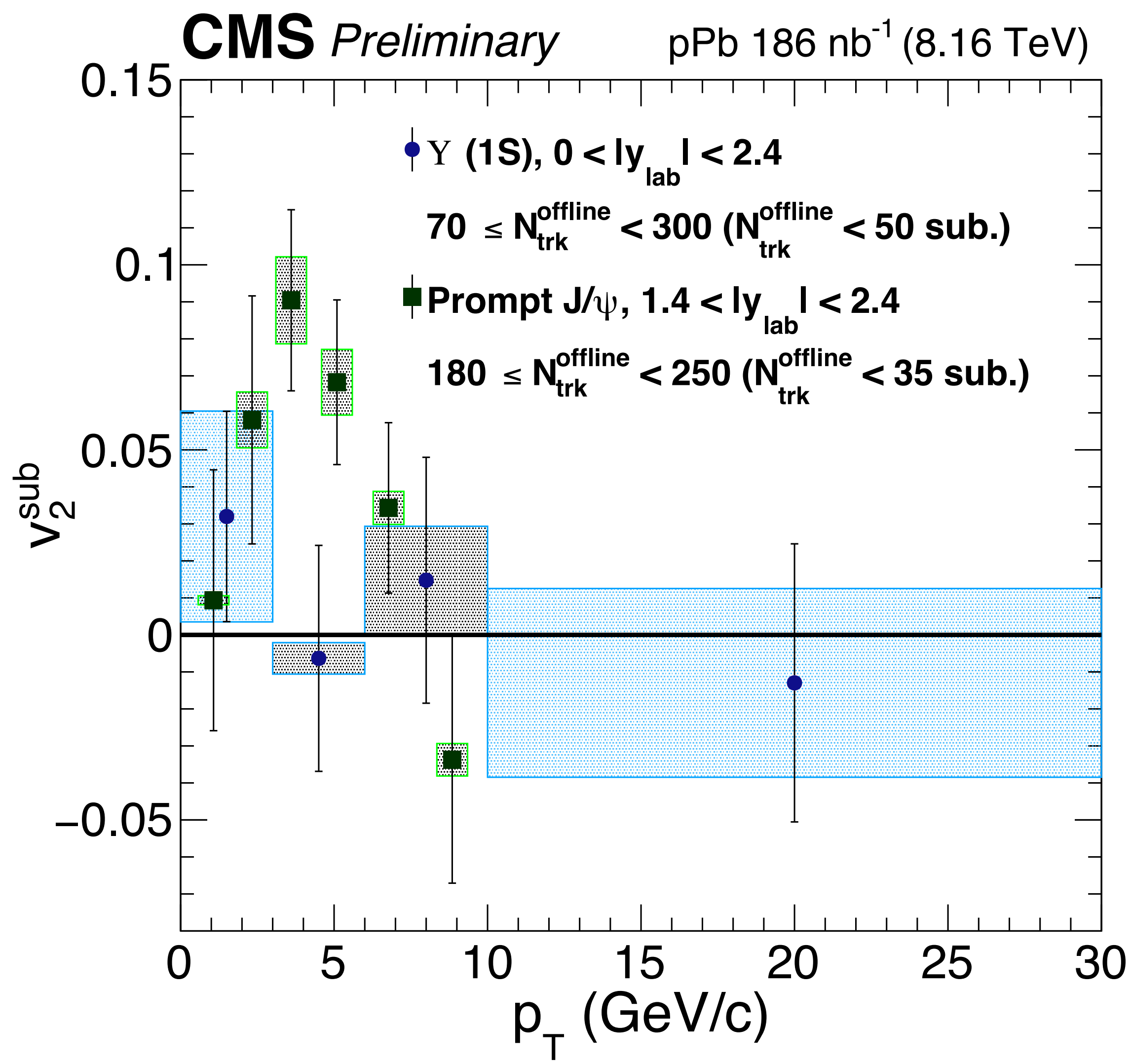
Bottomonia flow

[PLB 801 (2020) 135147]

First measurement!

[CMS-PAS-HIN-21-001, QM-link]



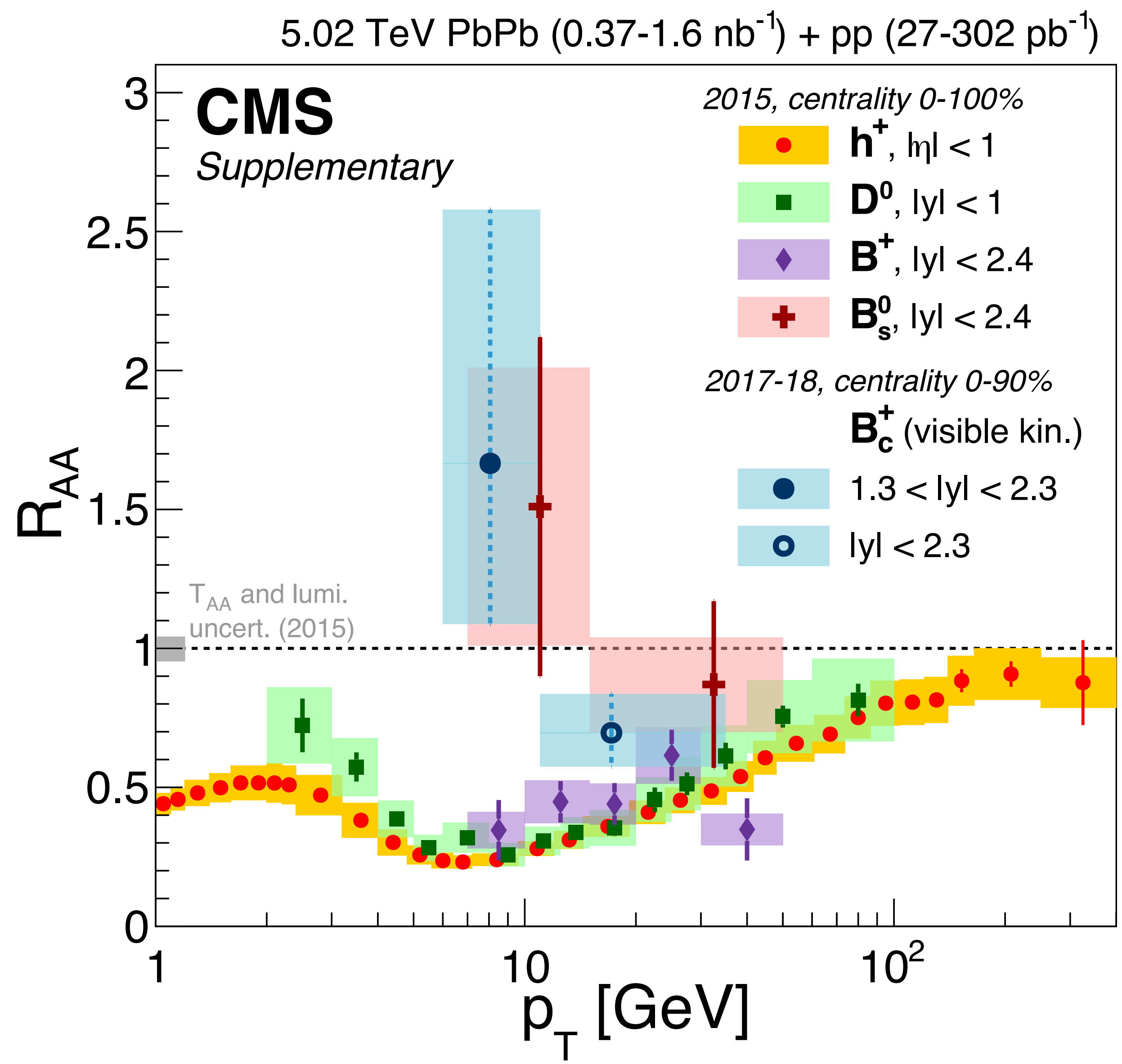


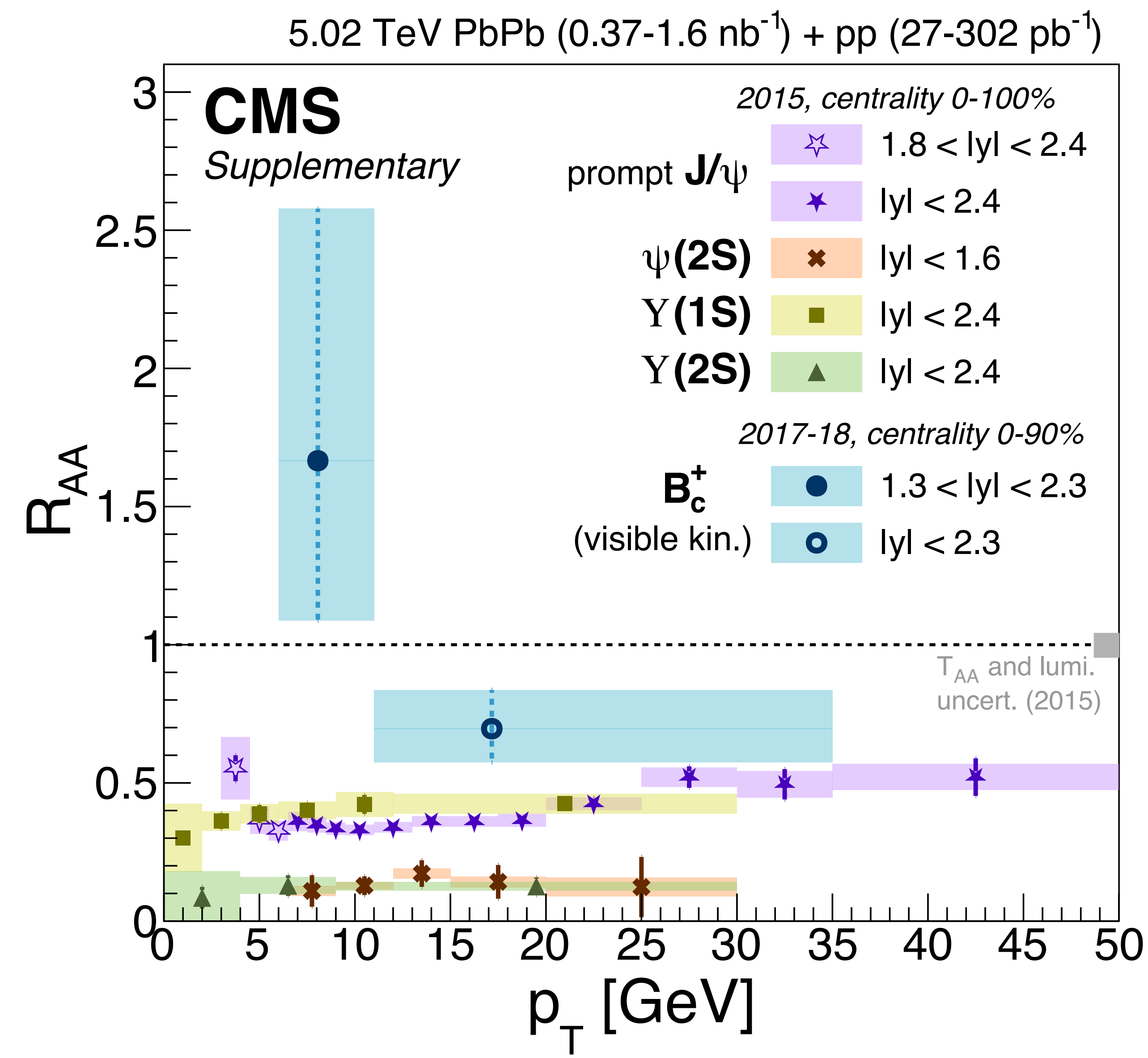
- In agreement with dissociation only picture
  - Thanks to SHINCHON Collaboration!

pPb : Υ(1S) v2 $\approx$ 0 <—> J/ψ $v_2 > 0$

PbPb : Υ(1S) v2 $\approx$ 0 <—> J/ψ $v_2 > 0$

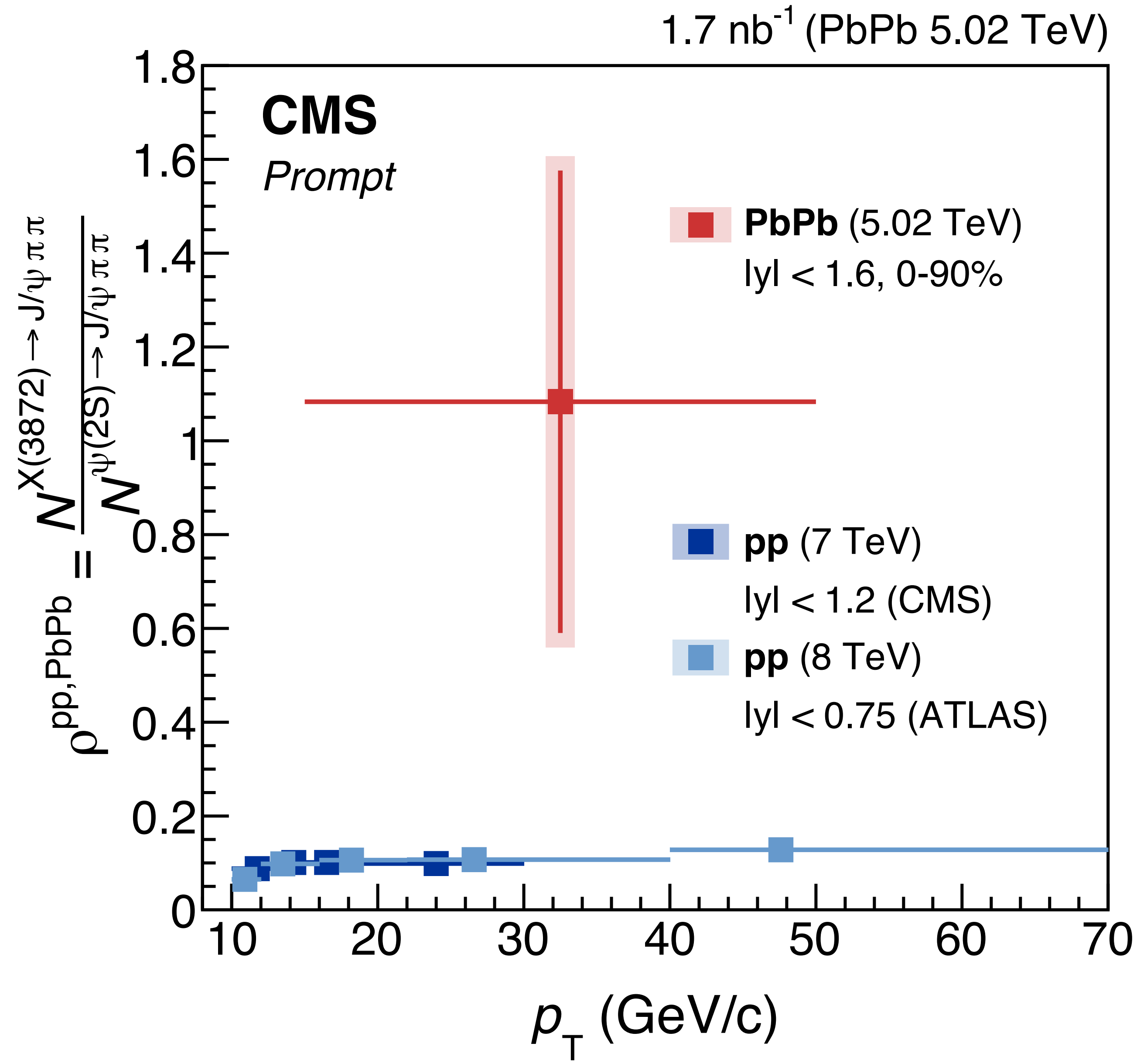
Rare probes : B_c

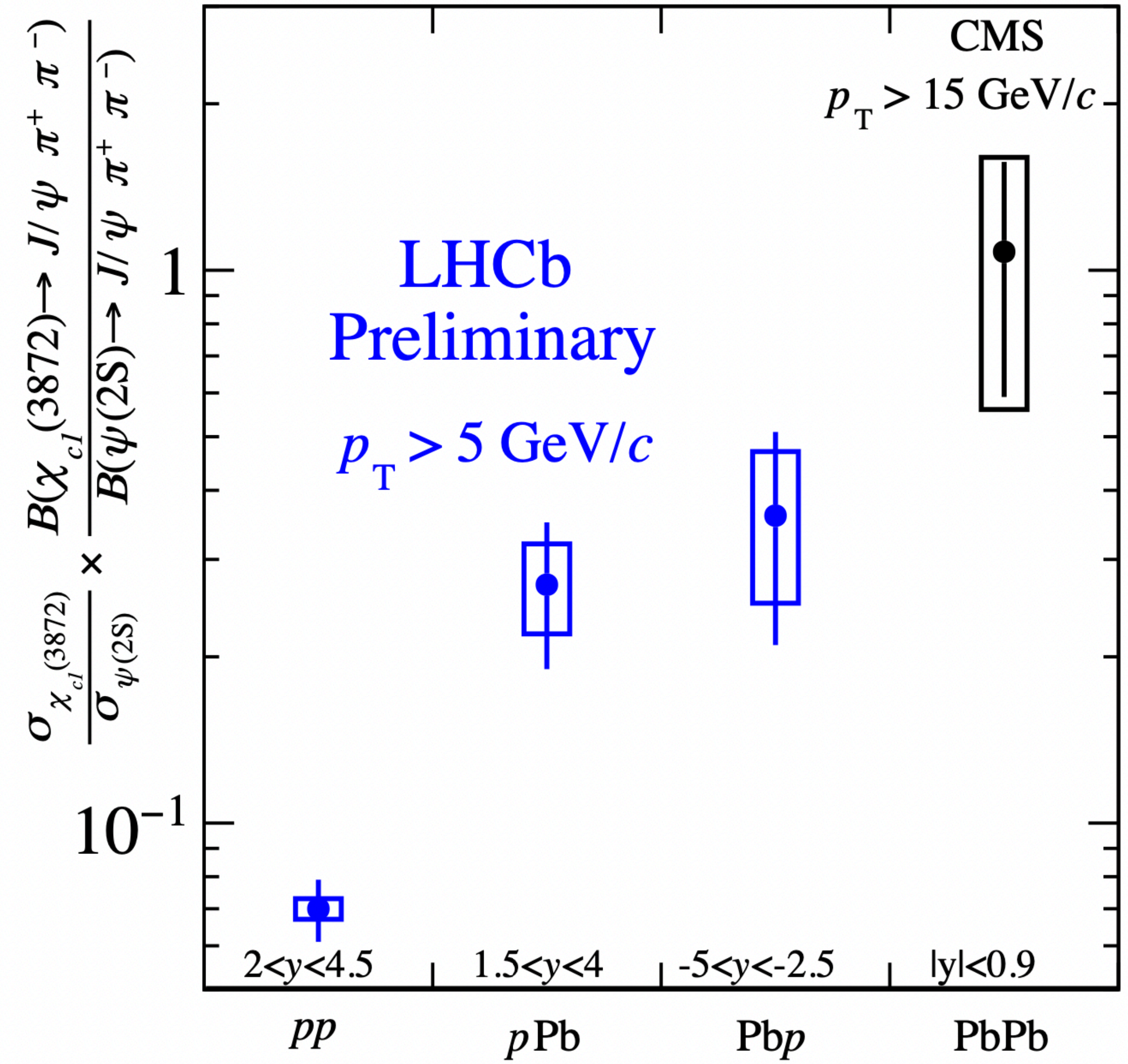




- Novel probe to recombination/dissociation in-medium effects!
- Similar enhancement as B_s at low-p_T

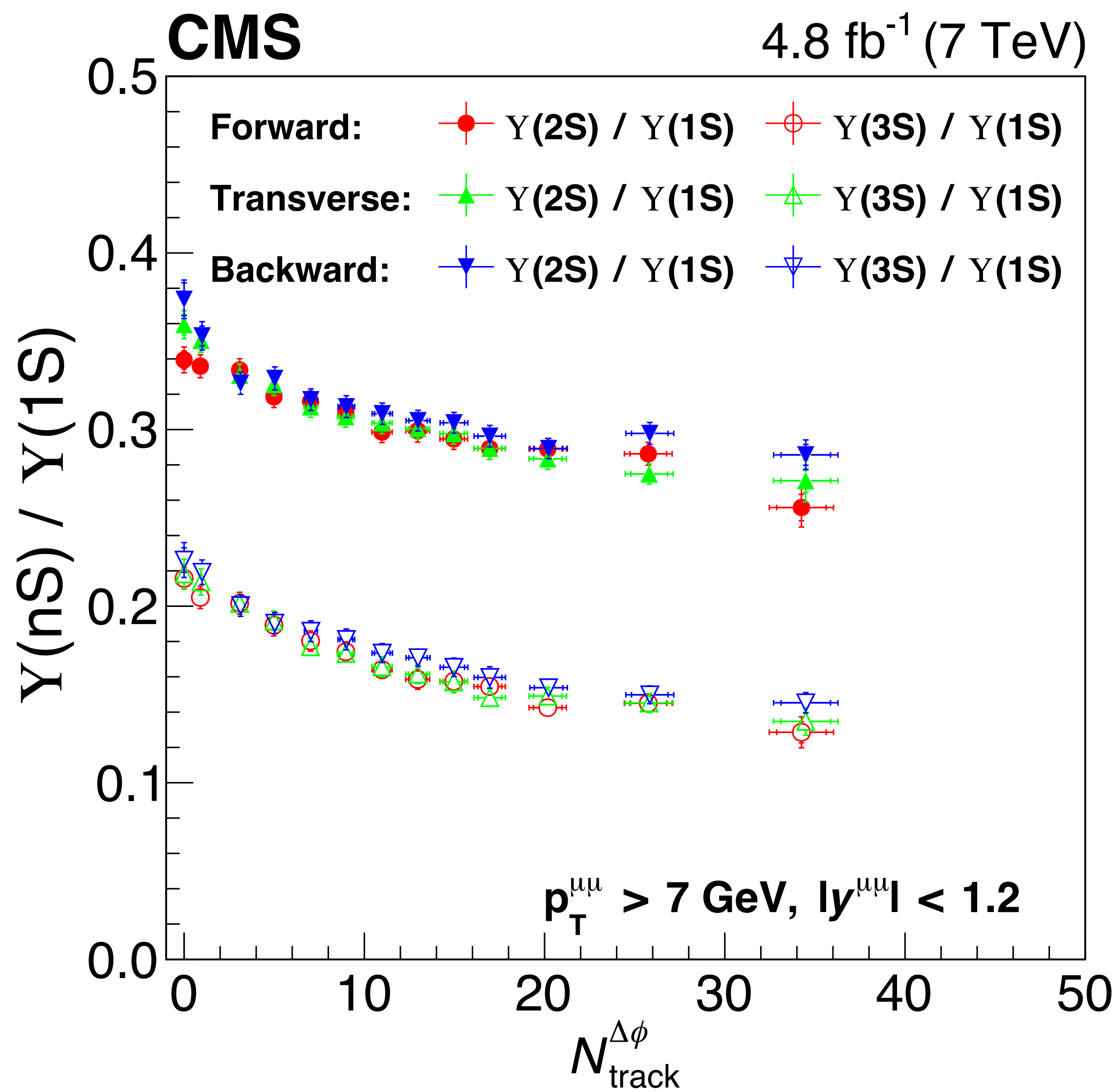
Rare probes : X(3872)

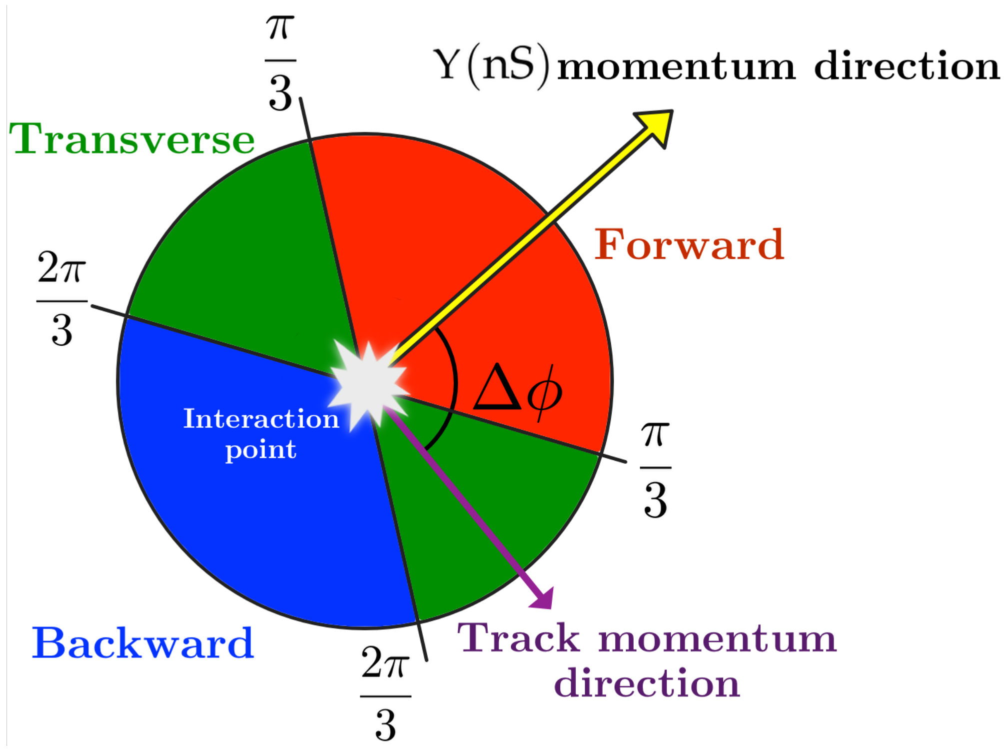




- Different behavior for ψ(2S) : System size dependence?
- ψ(2S) also suppressed in pPb —> No firm conclusion possible

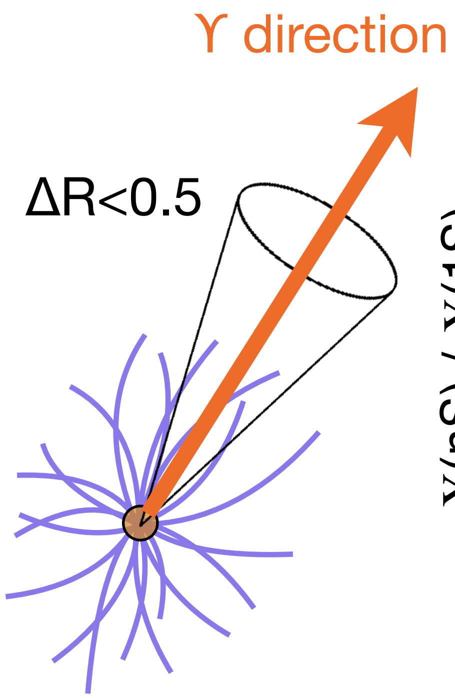
New results in RHIC & LHC

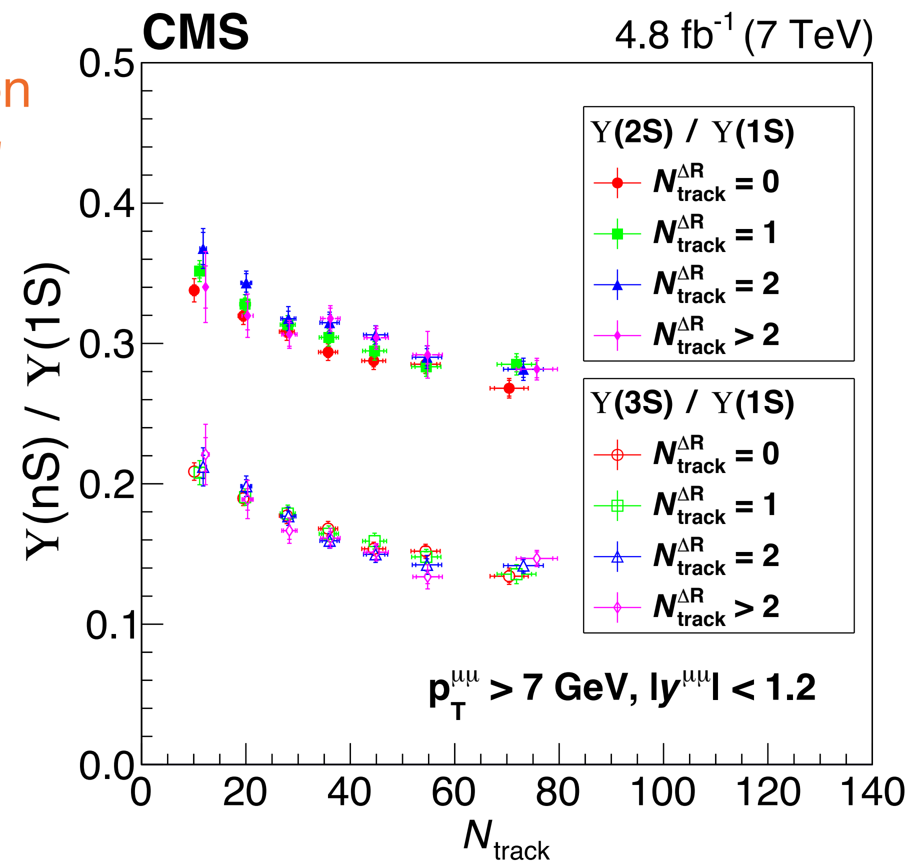




- If only Υ-h correlation exists : Affect only forward region
- Decreasing trend for all regions : Itself implying connection to UE
    - Note : pT > 7 GeV/c

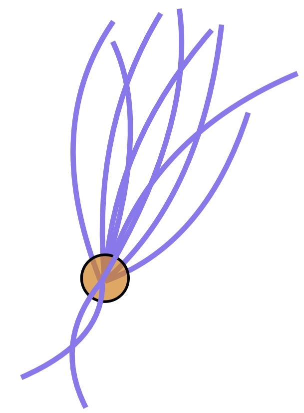
New results in RHIC & LHC



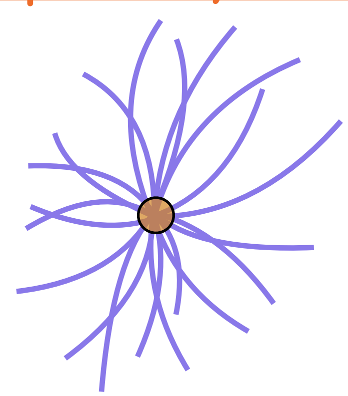


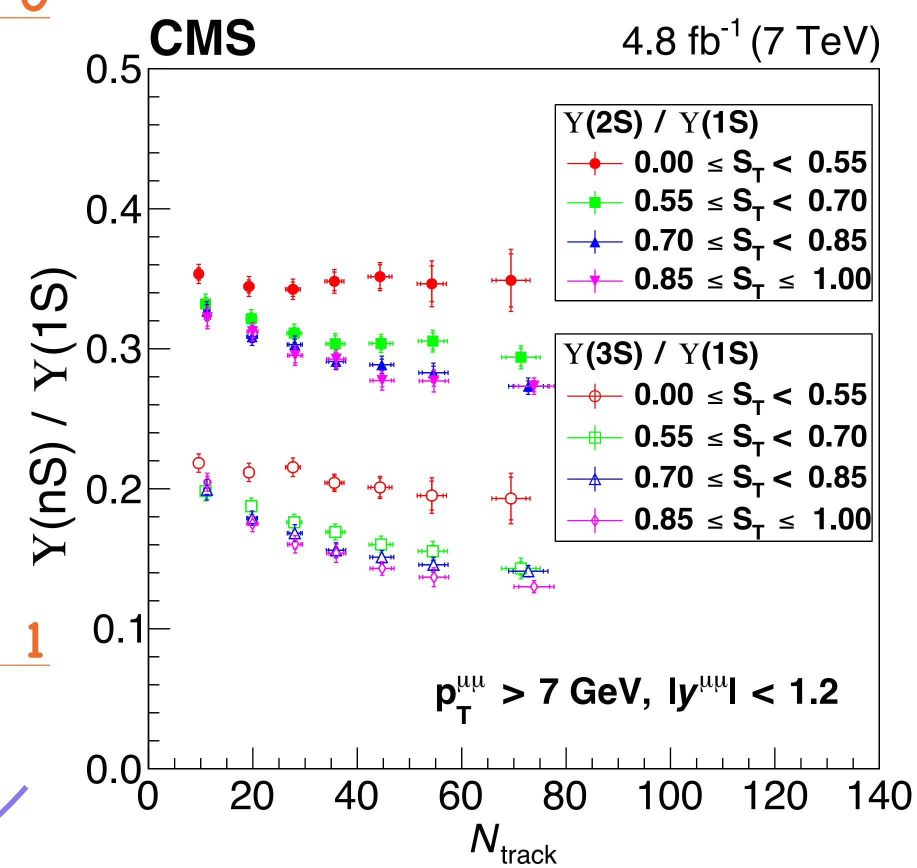
$$S_{\mathrm{T}} \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2} \qquad S^{T}_{xy} = \frac{1}{\sum_i p_{\mathrm{T}i}} \sum_i \frac{1}{p_{\mathrm{T}i}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$

Sphericity —> 0



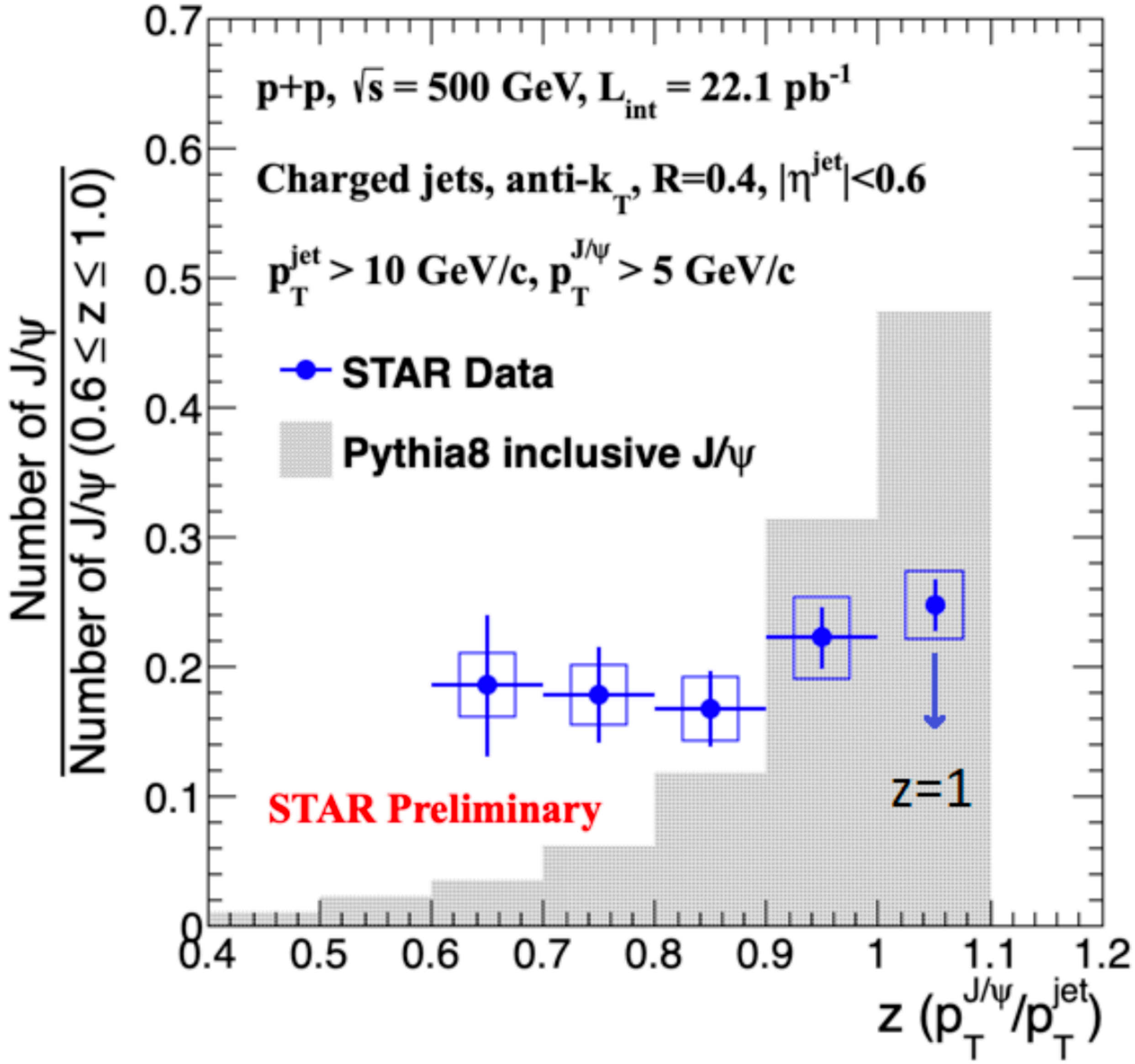
Sphericity —> 1

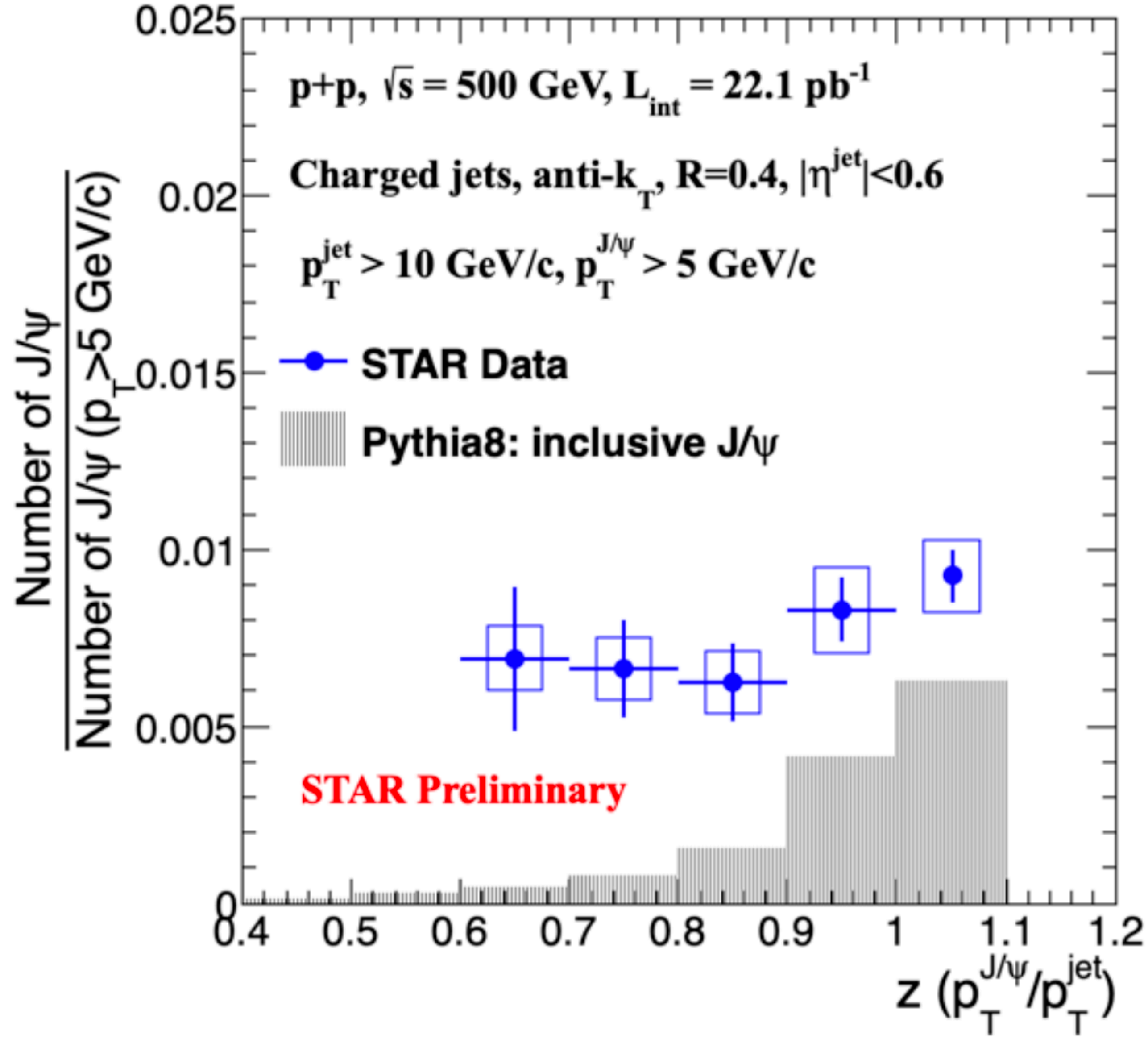




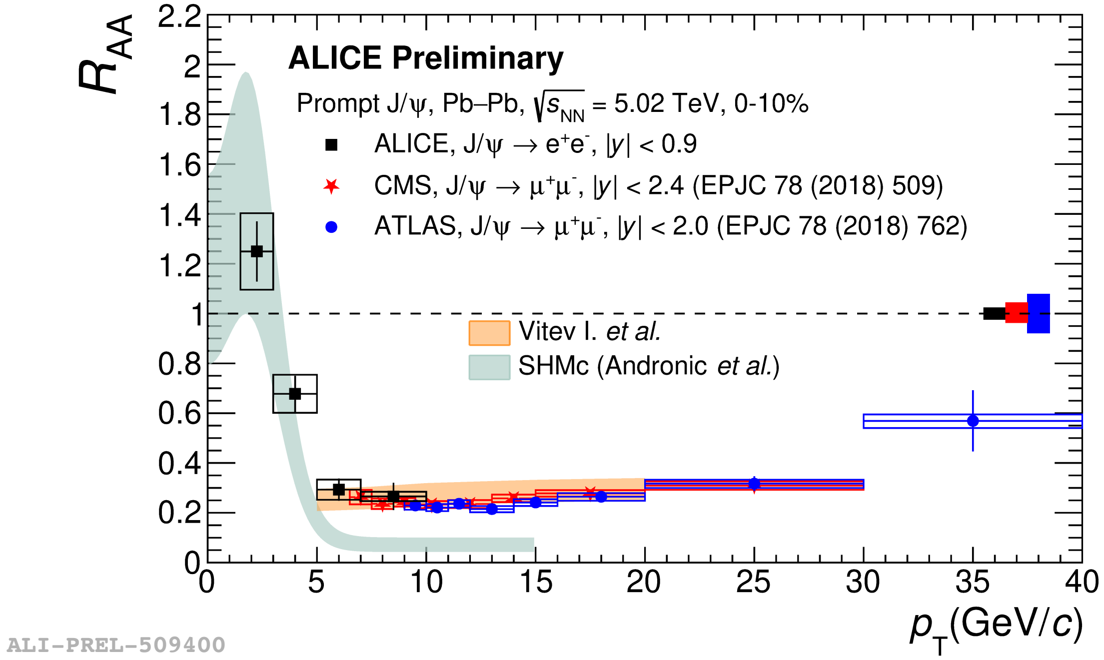
- No dependence of N_{tracks} within cone ΔR<0.5
  - Different from comover model expectation (n.b. p_T>7 GeV/c / need to compare multiplicity ranges)
- Decrease disappears in low-sphericity
  - Connection with UE for jetty events?

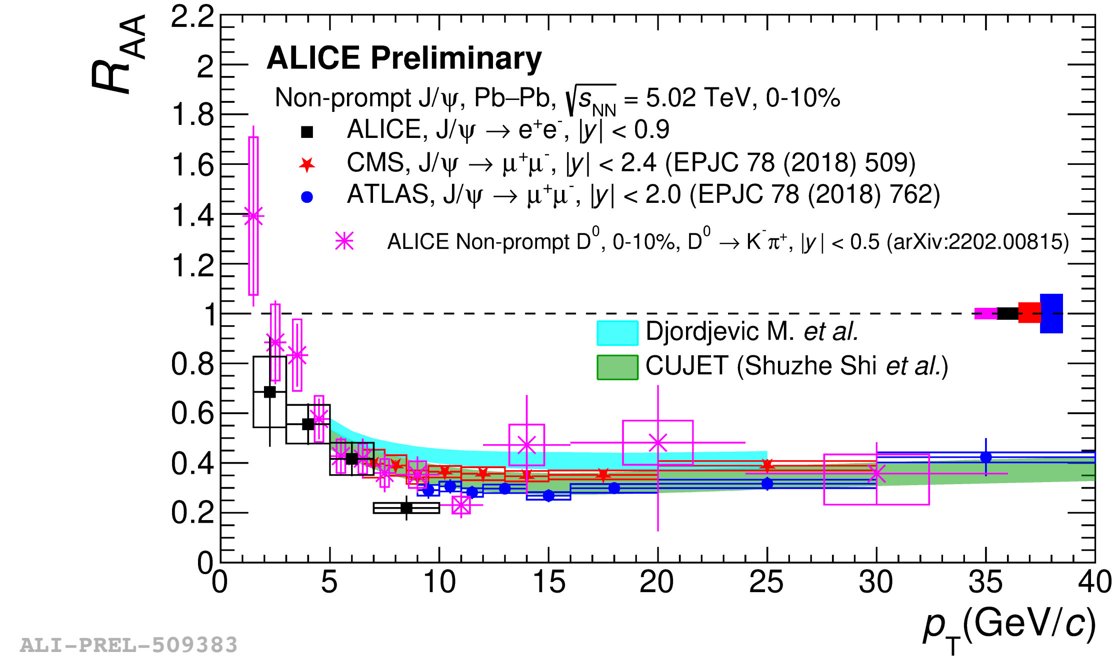
[Poster Session 3 T11_3 L. Kosarzewski]



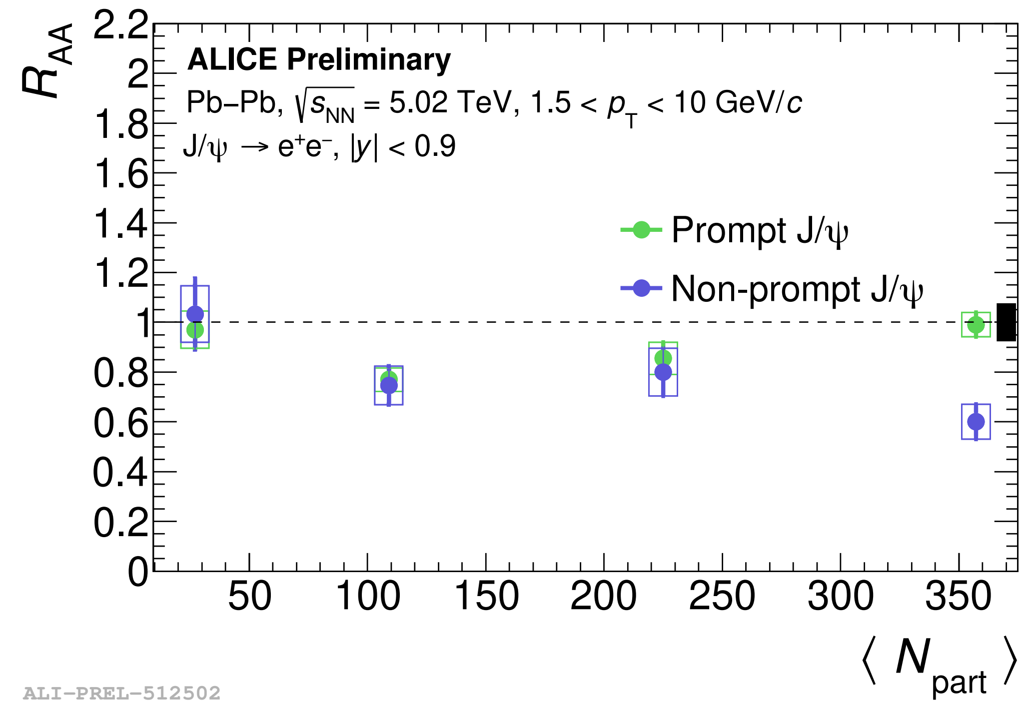


- Less isolated J/ψ production than predicted by PYTHIA8
- Higher J/ψ-in-jets production than PYTHIA8 for p_T > 5 GeV/c

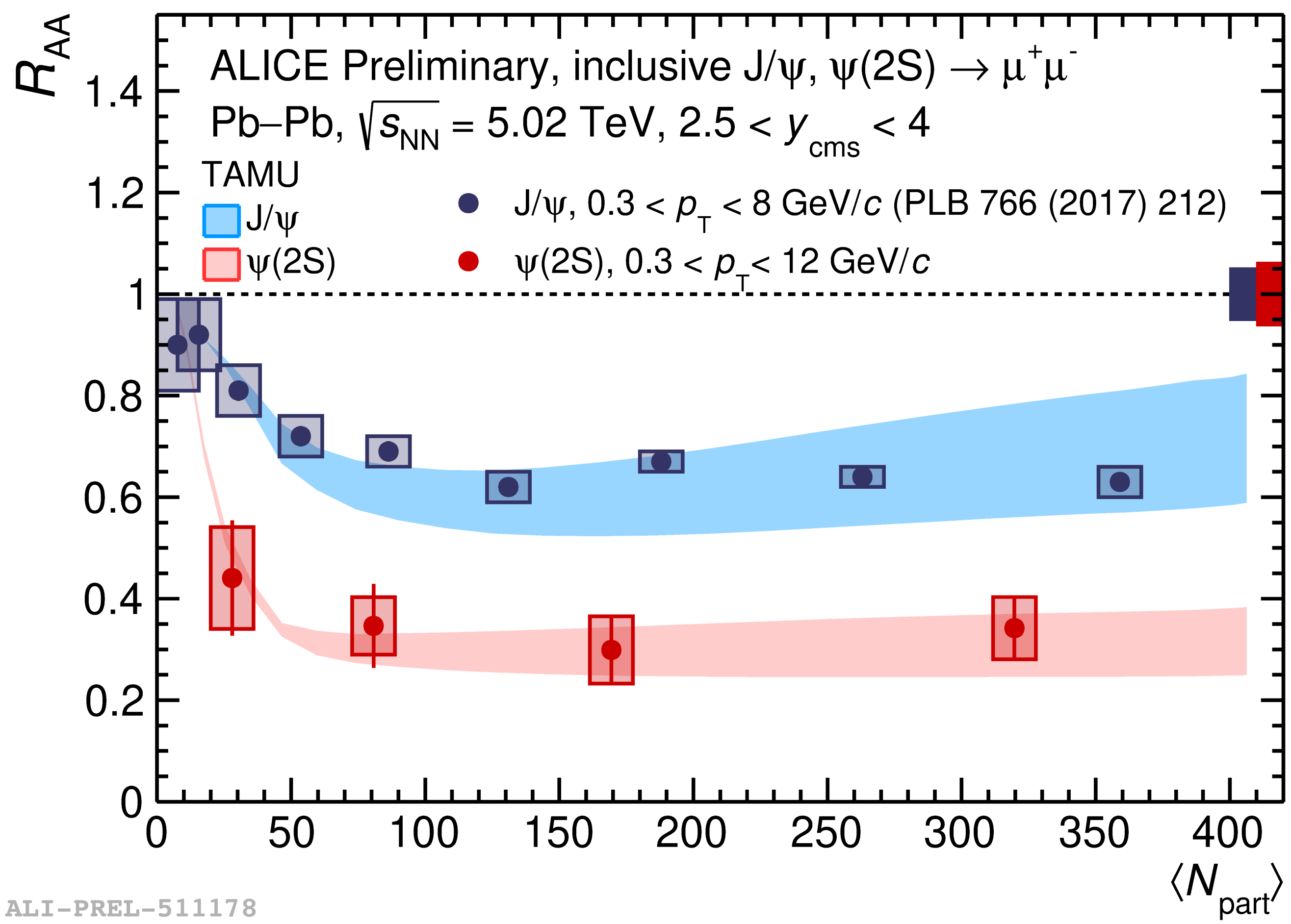


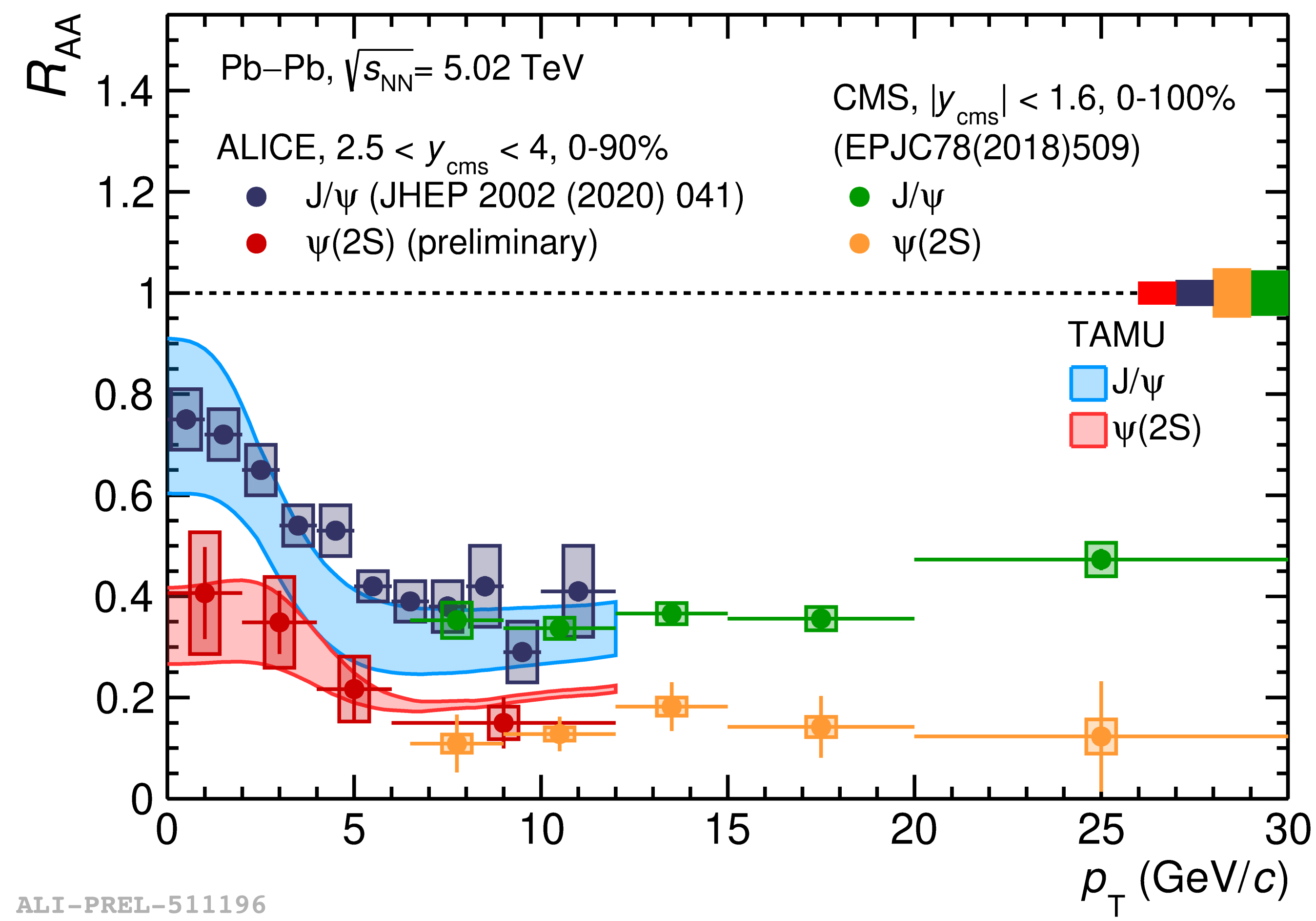


- Prompt & nonprompt J/ψ
  - Clear difference at low-pT and central collisions



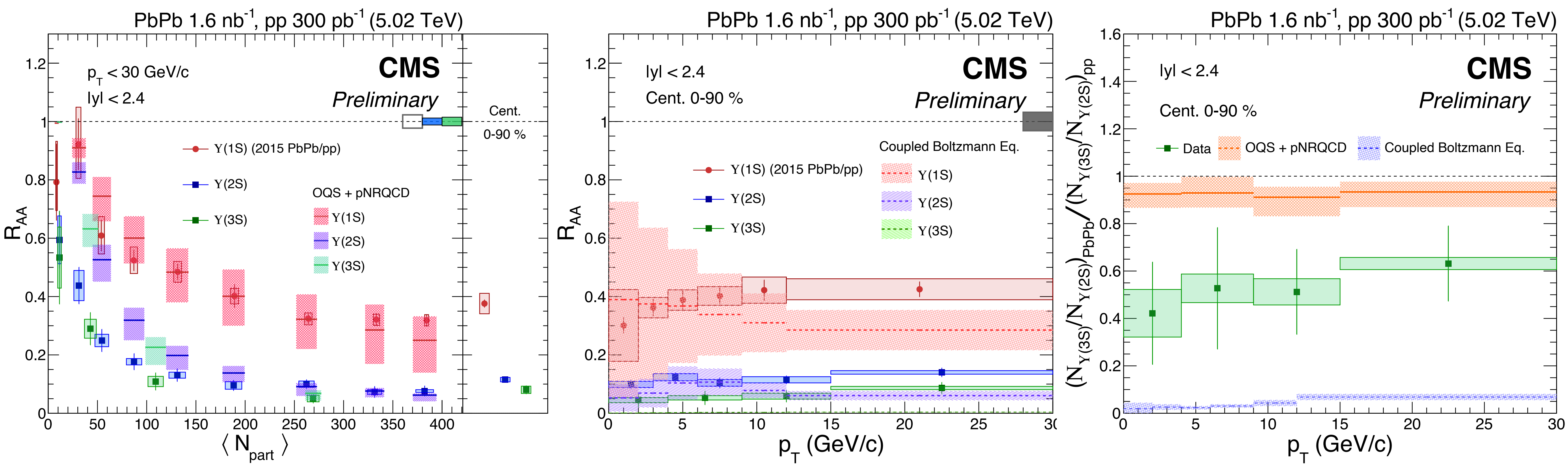
New results in RHIC & LHC





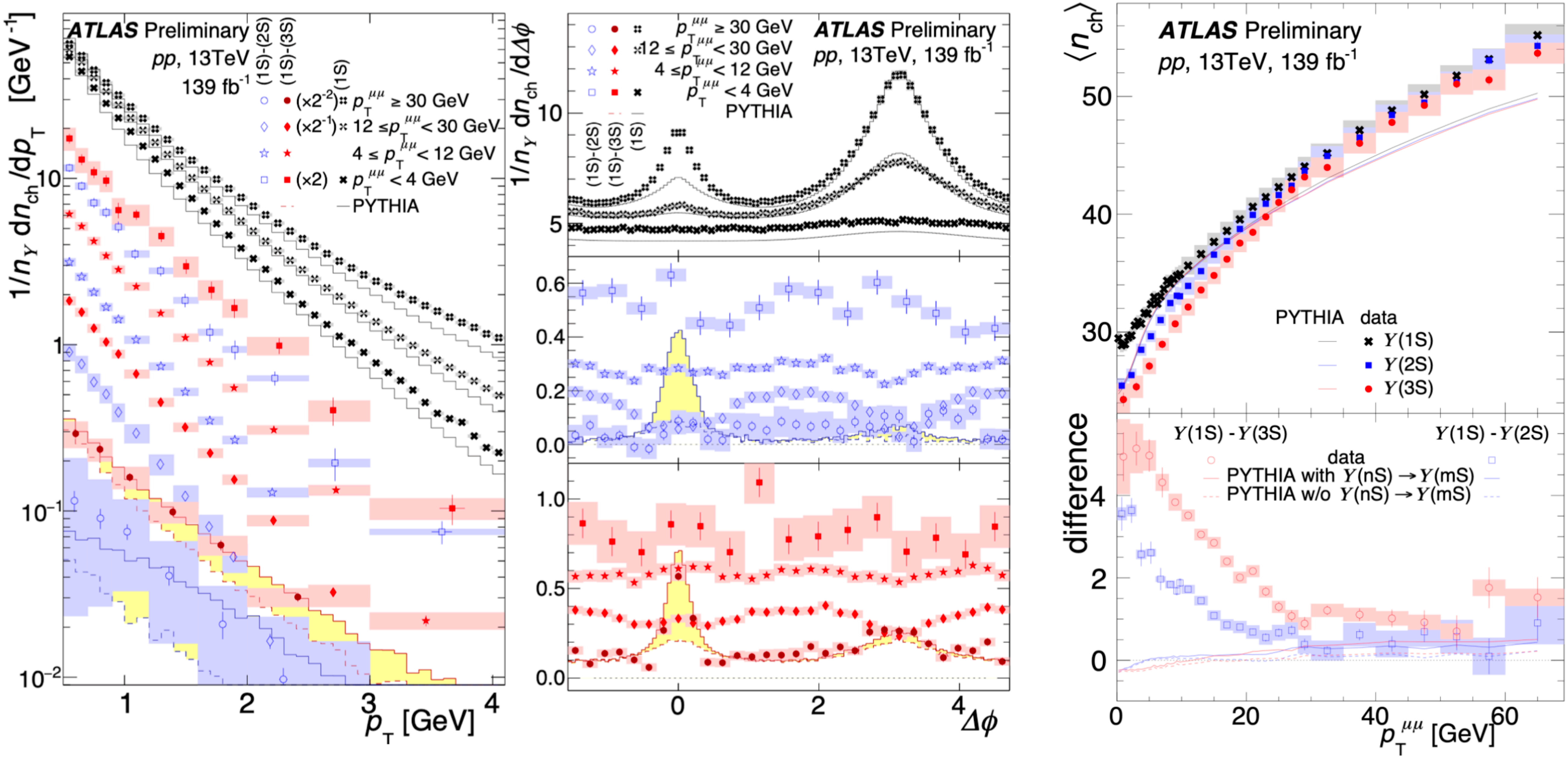
- Larger suppression for the excited state
  - Present also at low-pT down to zero

New results in RHIC & LHC



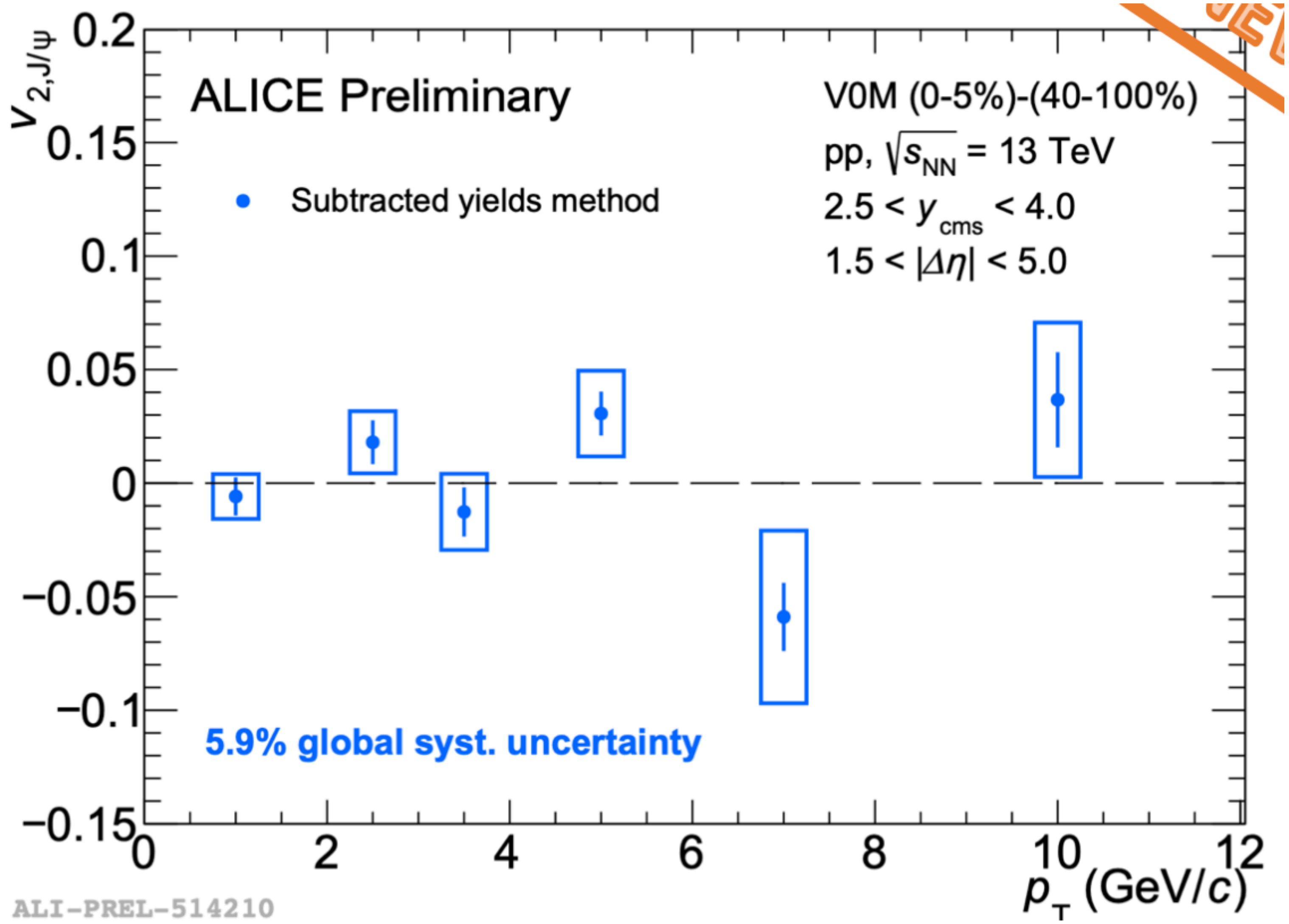
- Tension exist both on pT & centrality dependence
- Description for excited states : Strong constraint to models
  - Amount of 'dissociation' and 'recombination' still not clear

New results in RHIC & LHC



- Difference on Ntrk for each state b/w PYTHIA
  - Connection to sequential suppression?

New results in RHIC & LHC



- No v2 observed so far in pp collisions
  - nonzero v2 observed for D meson and HF charm muon