Latest quarkonium measurements in heavy-ion collisions with ALICE

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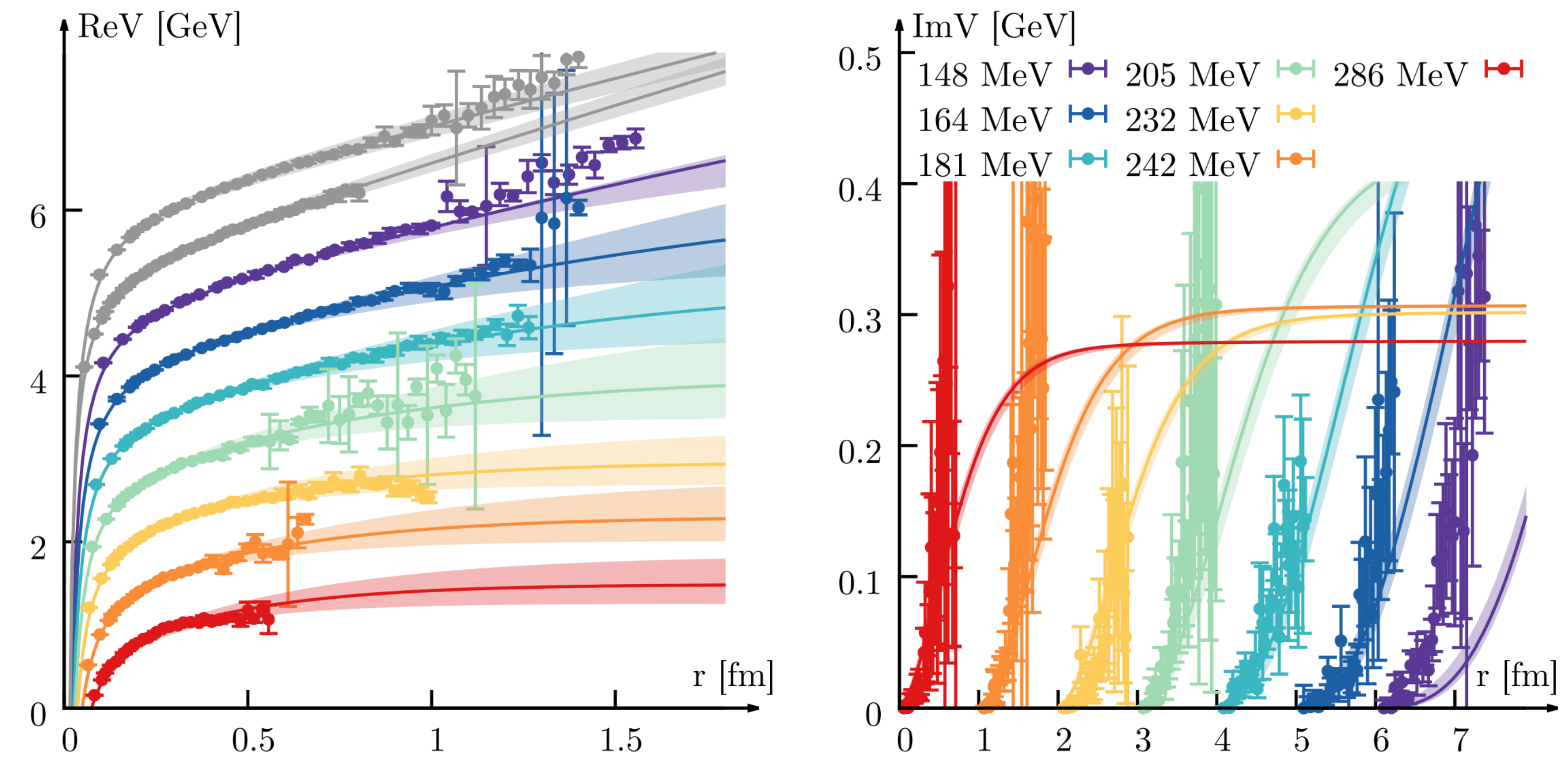
Subatech

Introduction

Physics motivation

Quarkonia are sensitive probes to study **QCD properties in Quark-Gluon Plasma**

- modification of heavy-quark potential ☛
- medium interactions and coupling
- collectivity effects



☛ complex heavy-quark potential from pNRQCD lattice computations [arxiv:1906.00035]

Experimental challenges

- relatively low production cross-sections
- production sources (charmonia from B decays, feed-down of excited states)
- presence of cold nuclear matter effects

Full Run 2 data (Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV)

- better precision (Υ suppression, multi-differential J/ψ R_{AA}, …)
- **first measurements** in heavy-ion collisions

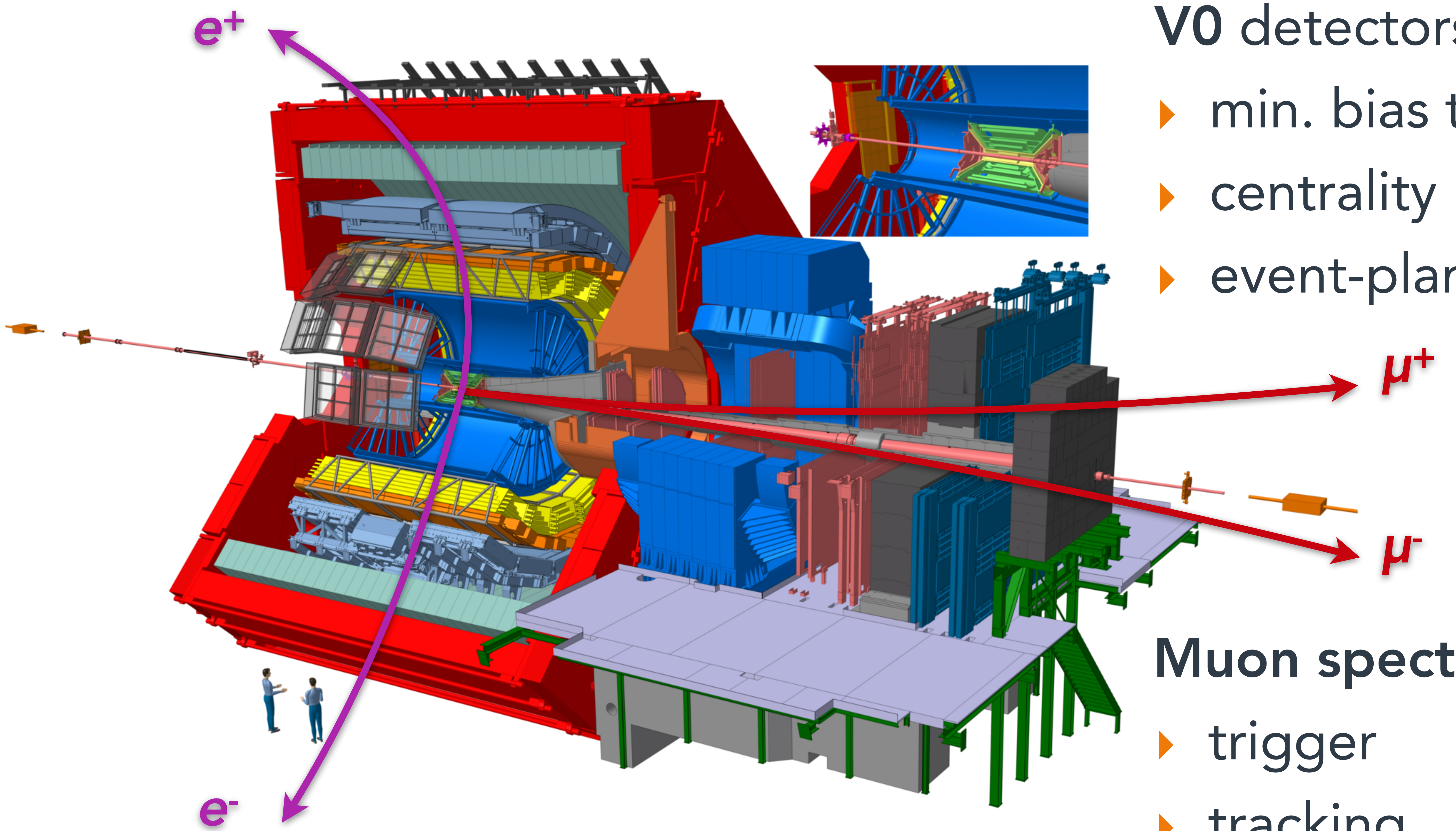
A Large Ion Collider Experiment

ALICE

Time Projection Chamber
- tracking
- particle identification

Inner Tracking System
- vertexing
- tracking

V0 detectors
- min. bias trigger
- centrality
- event-plane



Muon spectrometer
- trigger
- tracking

Measurement of quarkonia **down to p_T = 0**

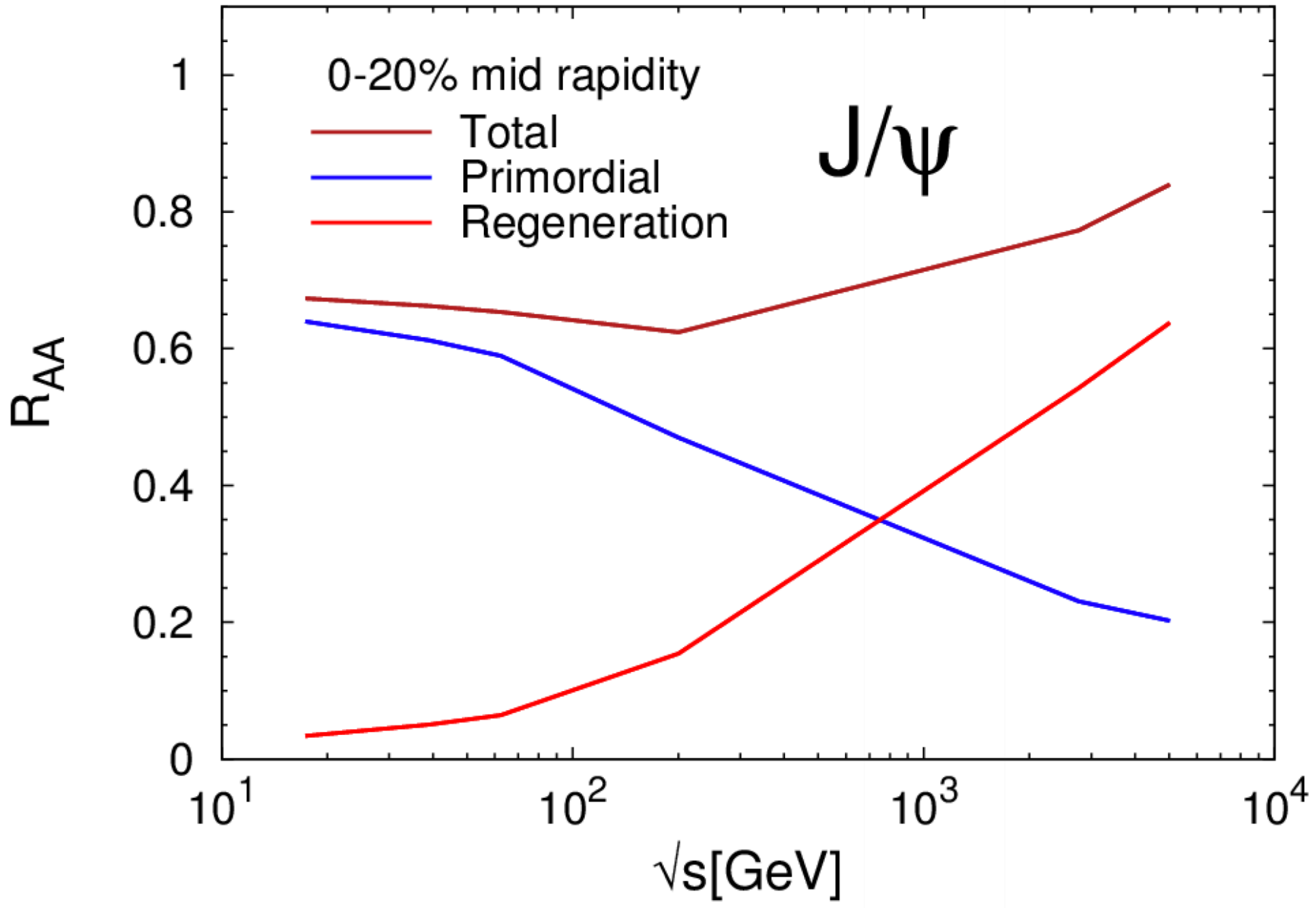
- at mid-rapidity ($|y| < 0.9$) with TPC and ITS
  $J/\psi \rightarrow e^+ e^-$
- at forward rapidity ($2.5 < y < 4$) in dimuon decay channel with the muon spectrometer
  J/ψ, $\psi(2S)$, $\Upsilon(nS)$

Nuclear modification factor

Motivations

Study quarkonium production mechanisms in heavy-ion collisions

- dissociation by color screening in the QGP phase [PLB 178 (1986) 416]
- sequential suppression of the different bound states [PRD 64 (2001) 094015]
- (re)combination of thermalized quarks in QGP [PRC 65 (2001) 054905] or at hadronization stage [PLB 490 (2000) 196]
  - ☛ significant enhancement for charmonium
  - ☛ *unlikely* for bottomonium



Observable

$R_{AA} \equiv$ yield in AA / N_{coll} x yield in pp

- $R_{AA} < 1$ = suppression
- $R_{AA} > 1$ = enhancement

Phenomenological models

Transport

Path-length dependent dissociation and recombination, including shadowing and feed-downs.

- **TM1** or TAMU (X. Du and R. Rapp)
- **TM2** (K. Zhou, N. Xu, P. Zhuang)

Hydro-dynamics or BBJS (P. P. Bhaduri, N. Borghini, A. Jaiswal, B. Krouppa, M. Strickland)

Suppression from the modification of heavy-quark potential in a 3+1D expanding medium.
No CNM effect nor regeneration are considered.

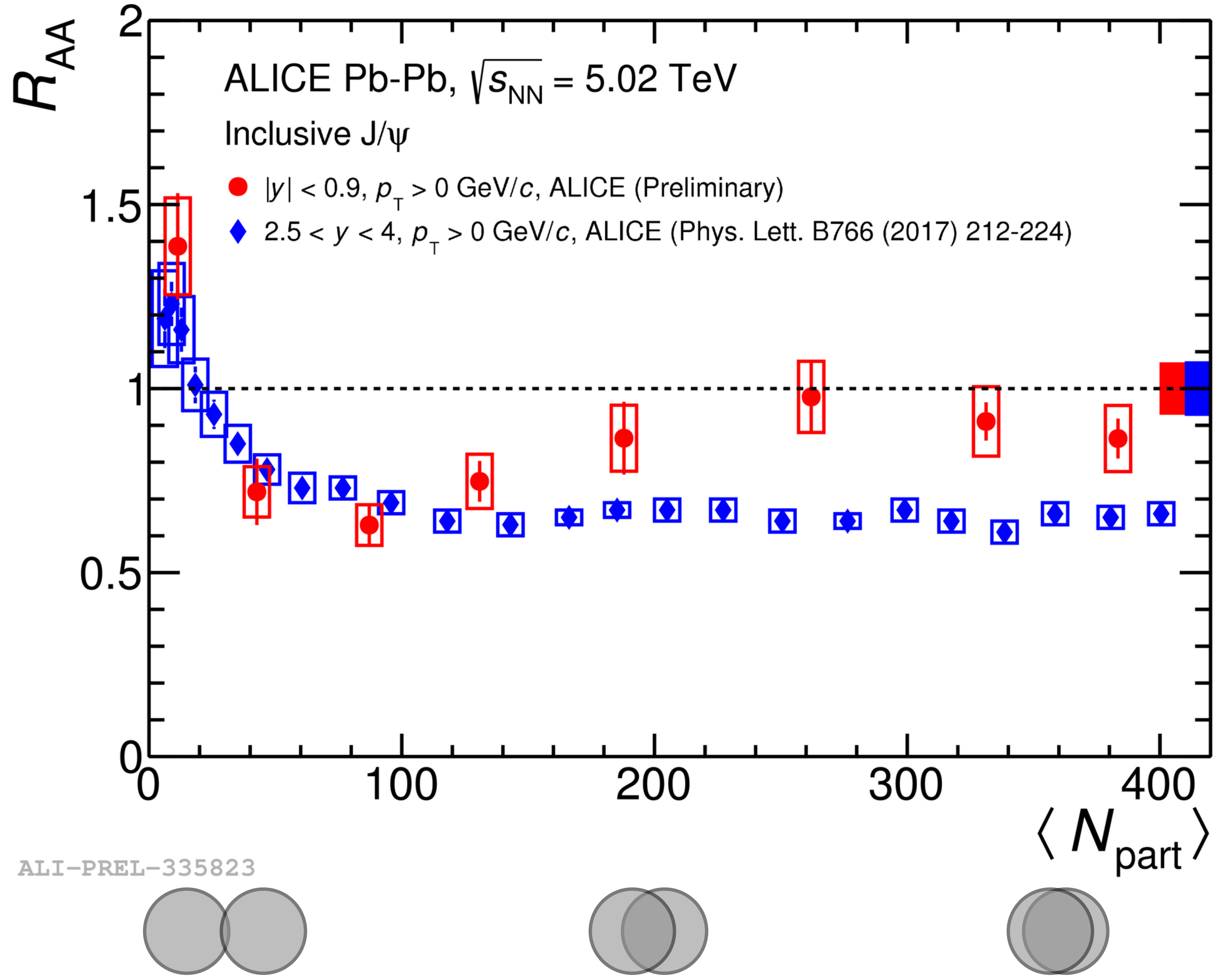
Comovers (E. G. Ferreiro)

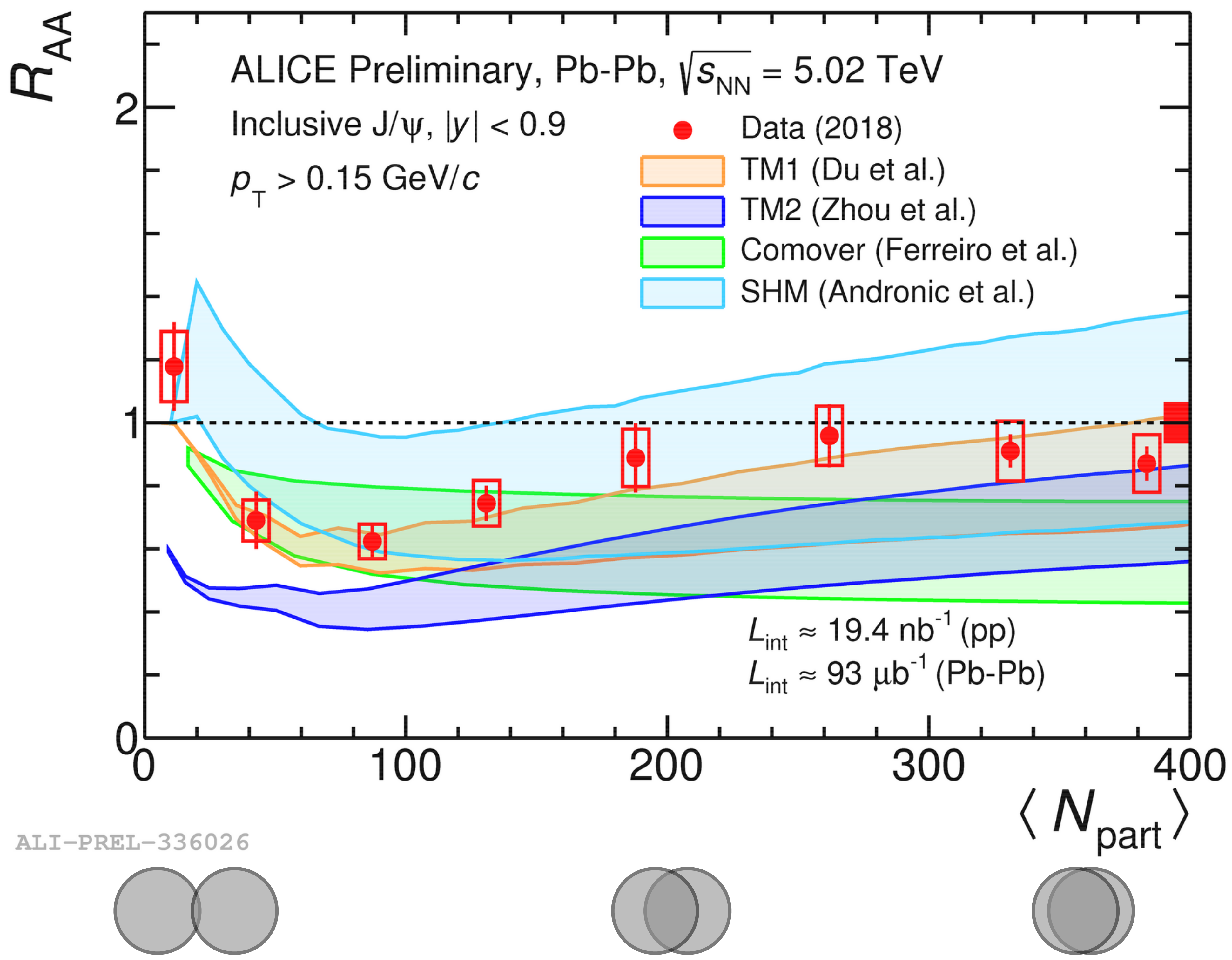
Break-up by interactions with comoving particles. Accounts for shadowing and regeneration.

Statistical hadronization (A. Andronic, P. Braun-Munzinger, J. Stachel)

Particle yield distribution at chemical freeze-out.

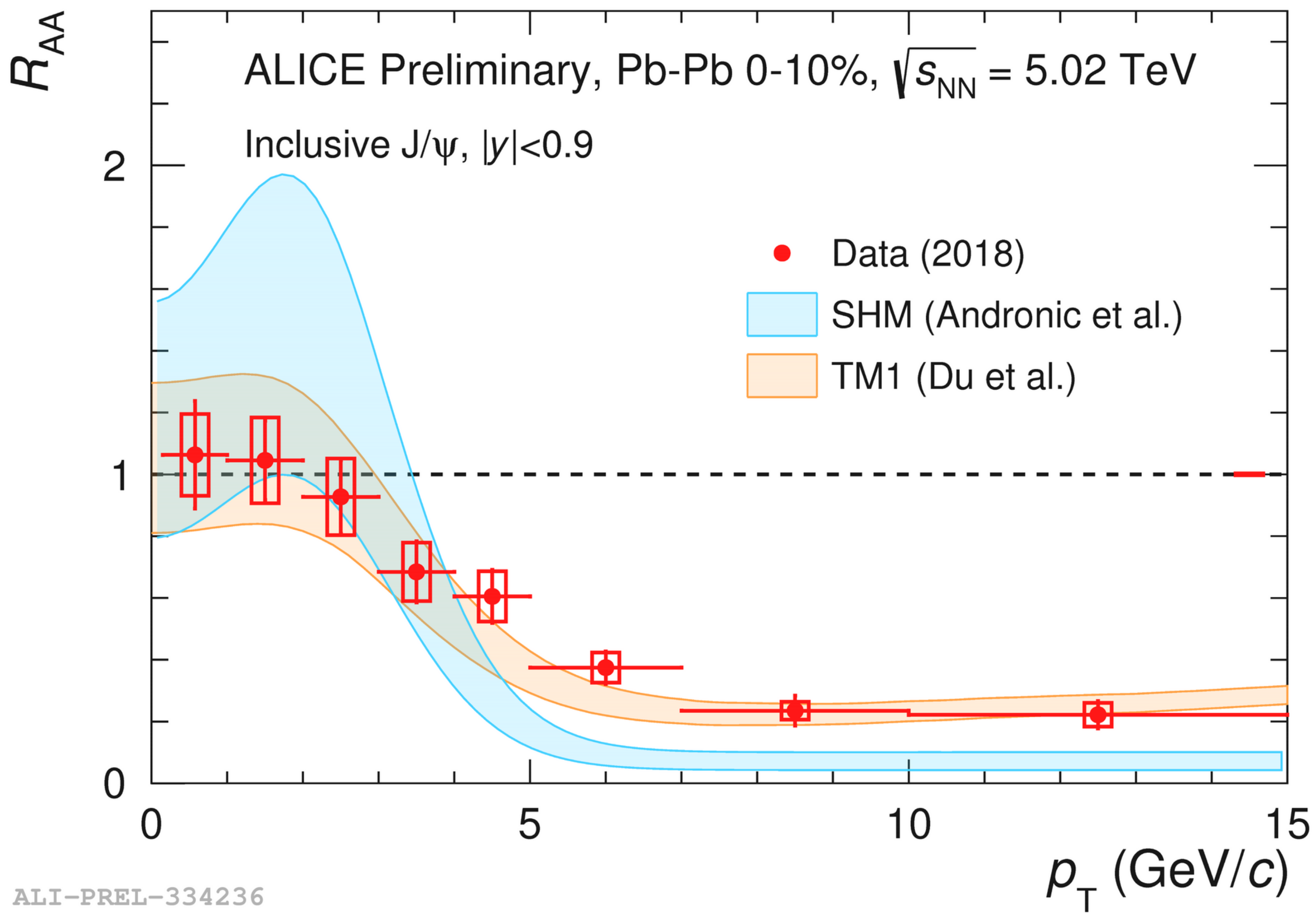
J/ψ R_{AA} vs centrality

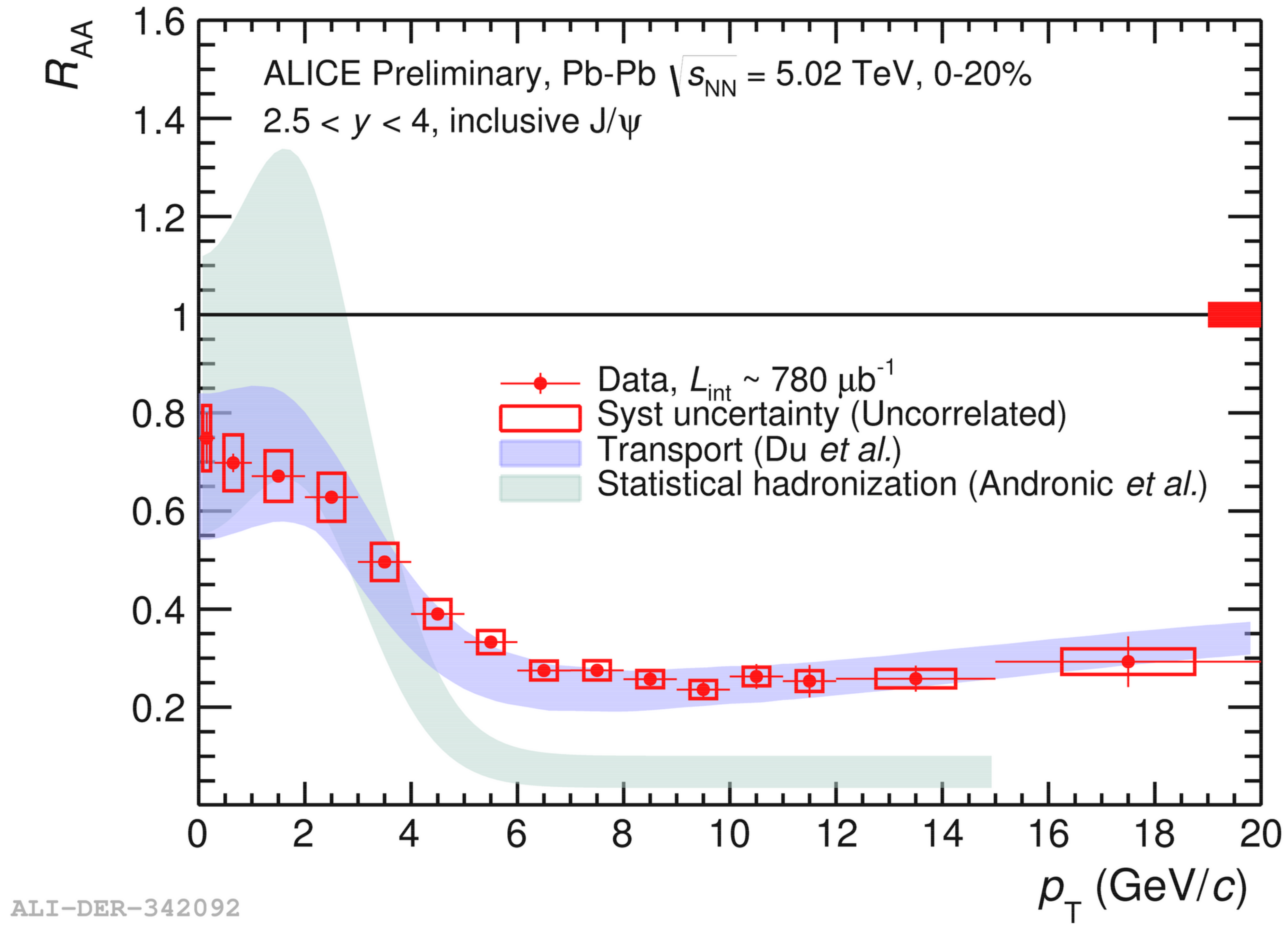




- fast suppression with increasing ⟨N_{part}⟩ until ~50% centrality
- **regeneration** compensates forward suppression, **dominates at mid-rapidity** in more central events
- experimental trend reproduced by the different model predictions, precise measurements needed to constrain models (shadowing factor, $c\bar{c}$ cross-section)

J/ψ R_{AA} in central events



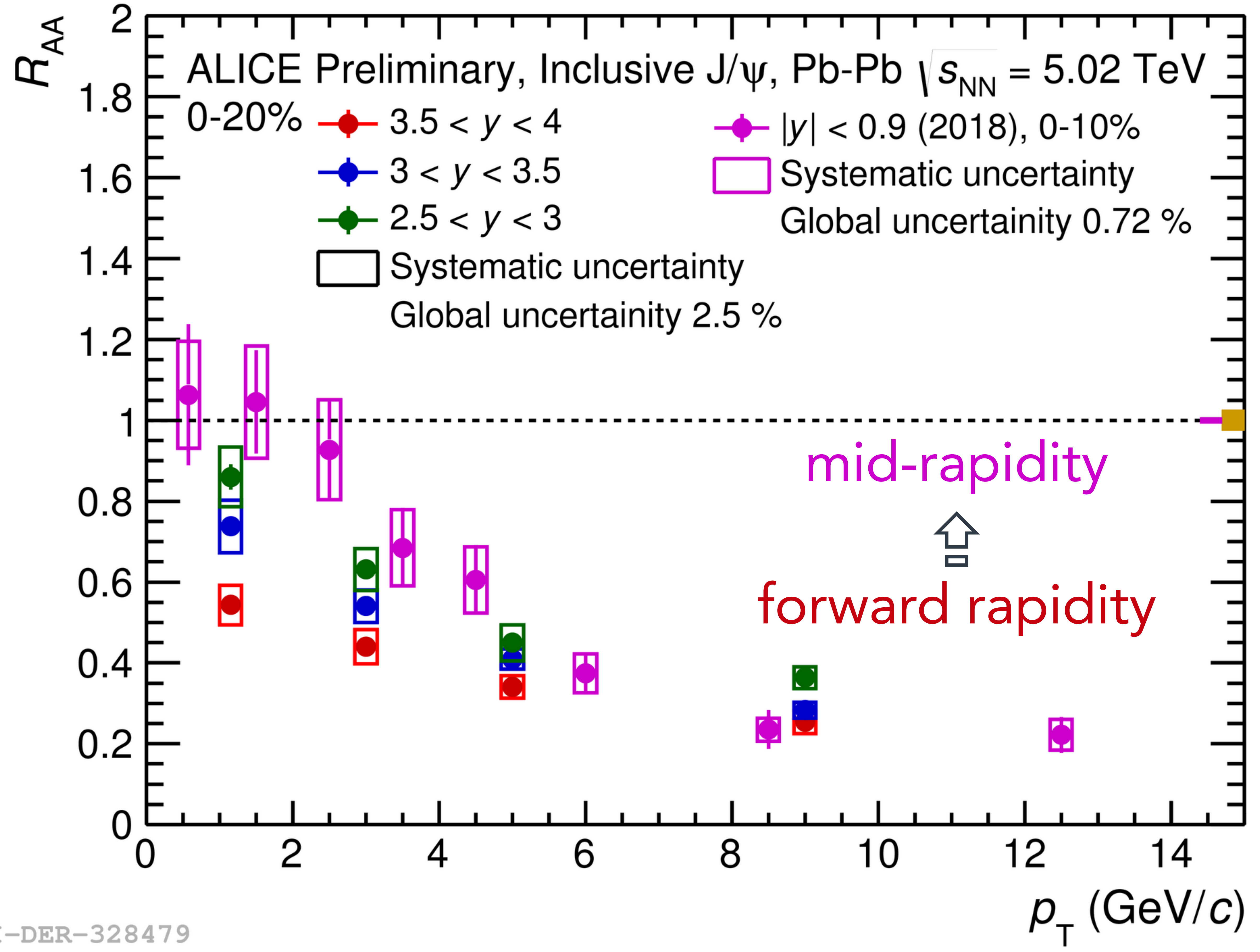


- significant enhancement at low p_T ☛ evidence for **recombination of thermalized charm quarks**
- well described by transport model (TM1) [NPA 943 (2015) 147]
- statistical hadronization model [PLB 797 (2019) 134836] undershoots the data at high p_T

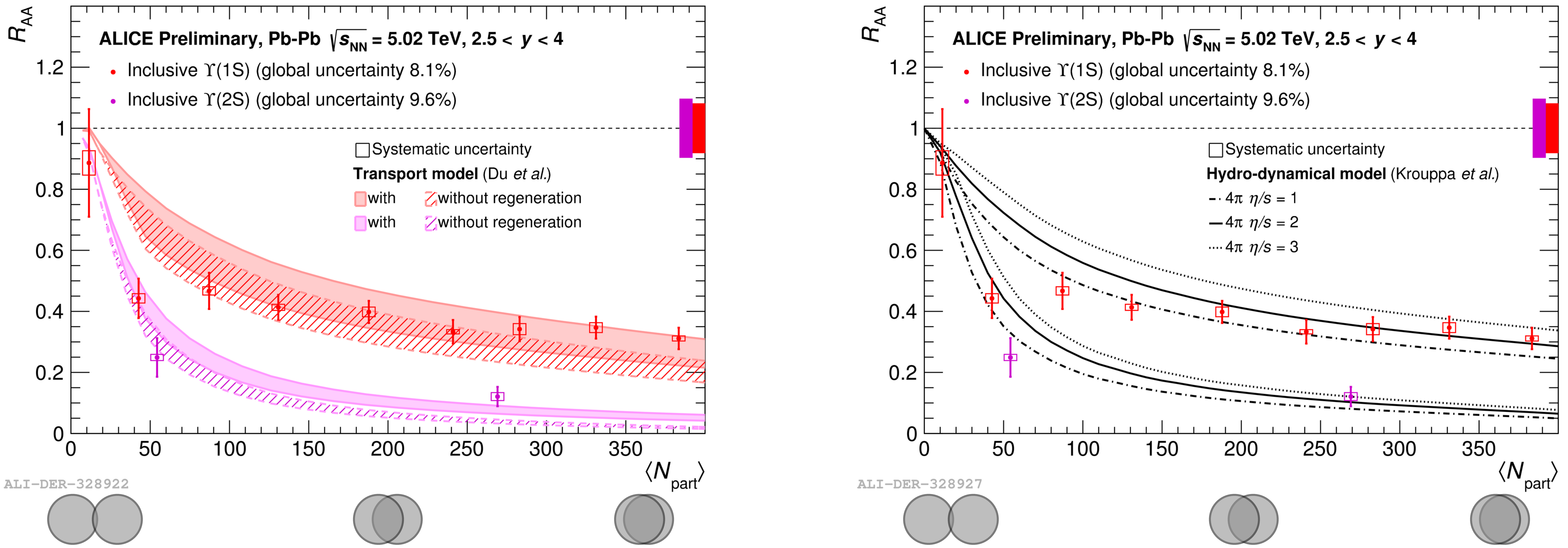
J/ψ R_{AA} in central events

- strong variation of the p_T distribution with y
- **increase of regeneration** component from forward to mid-rapidity

☛ consistent with the **charm density** distribution

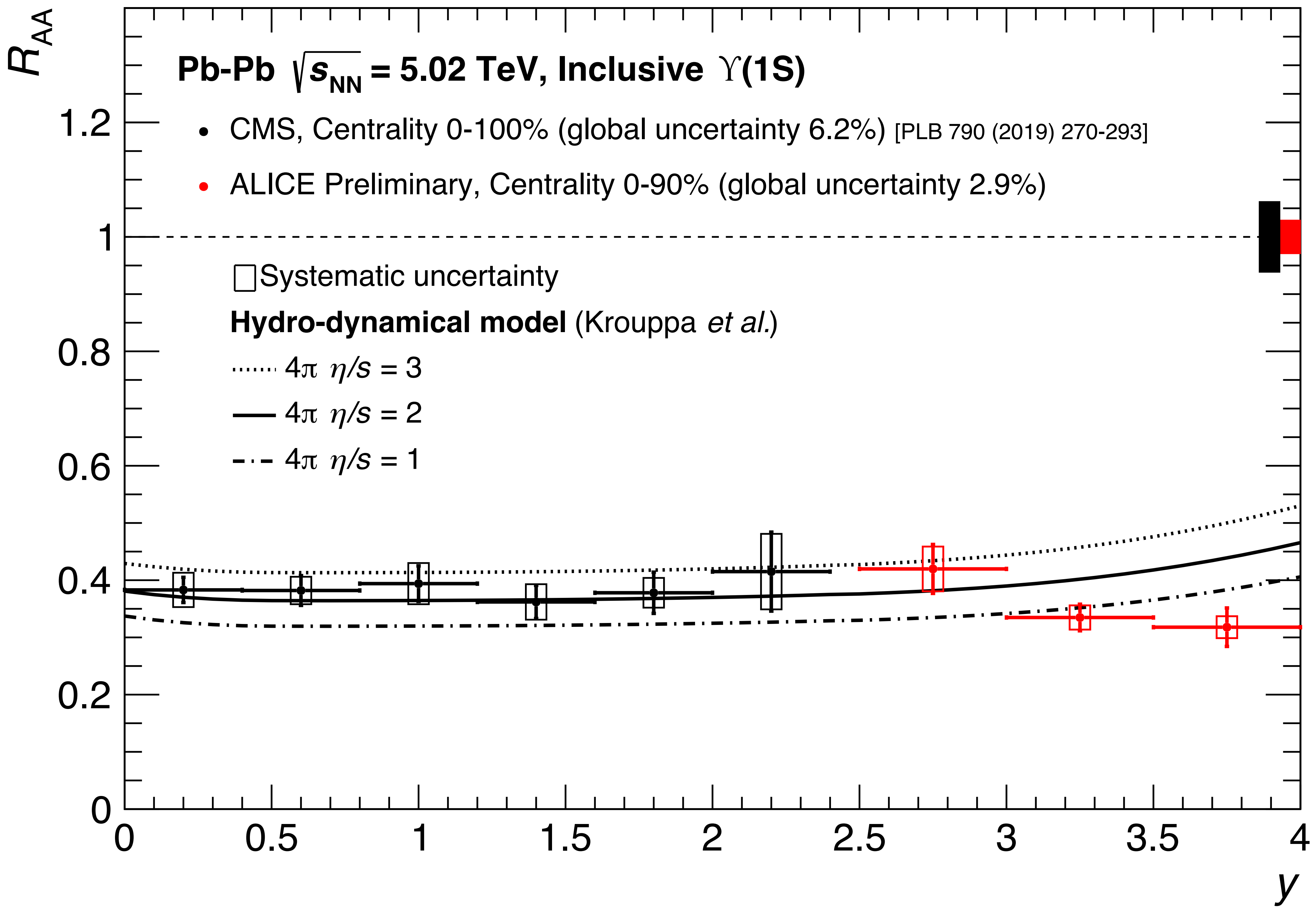


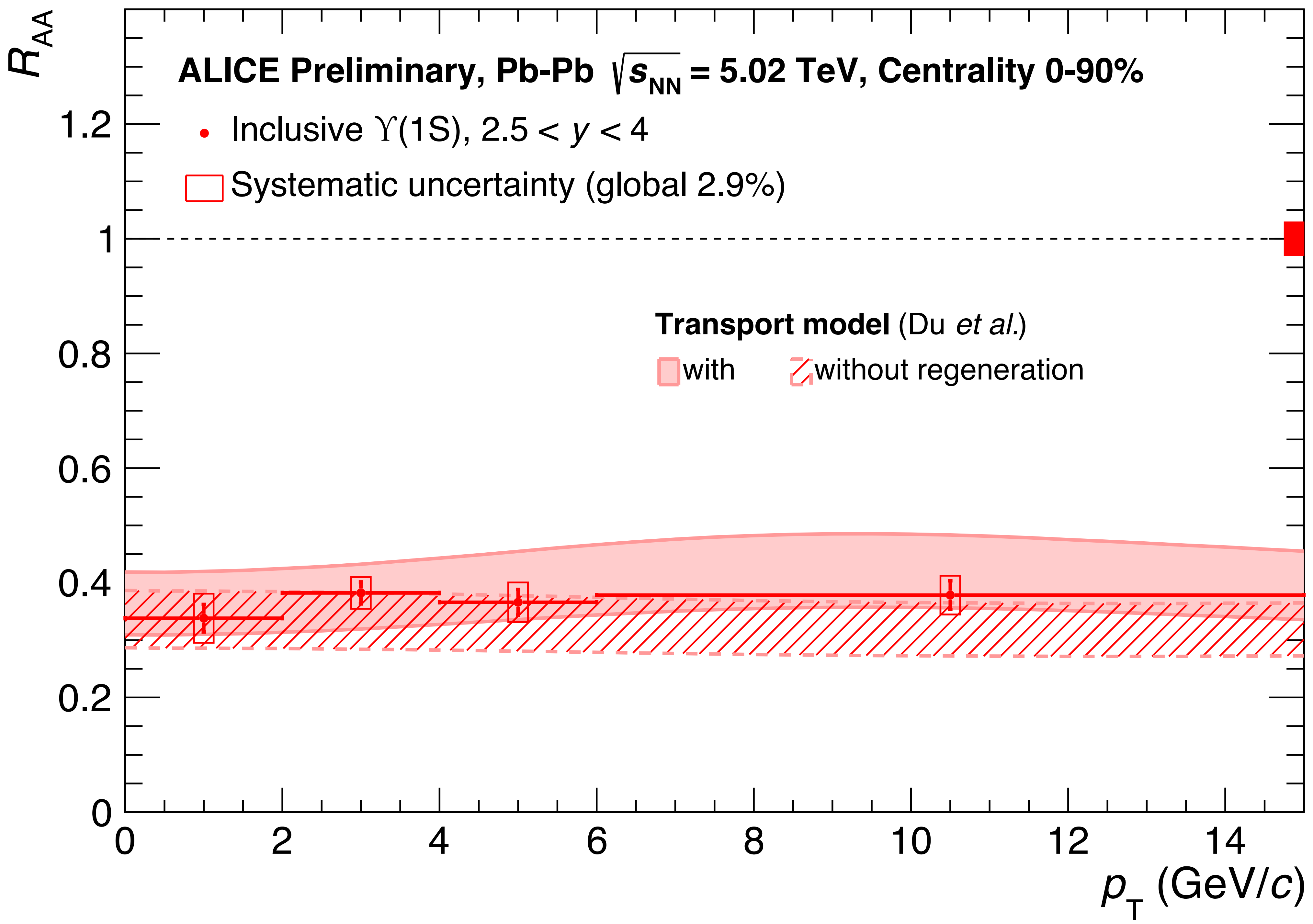
Upsilon R_{AA}



- upsilon suppression increases with centrality, in agreement with models
- **ϒ(2S) more suppressed than ϒ(1S)** ☛ integrated R_{AA} ratio = 0.41 ± 0.09 ± 0.04
- R_{AA}(1S) compatible with 1 in the most peripheral events (70-90% centrality class)
- direct suppression or feed-down from excited states ?

Differential Υ(1S) R_{AA}





- small rapidity dependence, **flat down to y = 0** with CMS measurement
- opposite trend with respect to hydro-dynamical [Universe 2 (2016)] predictions, *hinting* to additional suppression effects

- no significant dependence with p_T
- current uncertainties (experimental **and** theoretical) do not permit to discriminate the presence of a regeneration component in transport model [PRC 96 (2017) 054901]

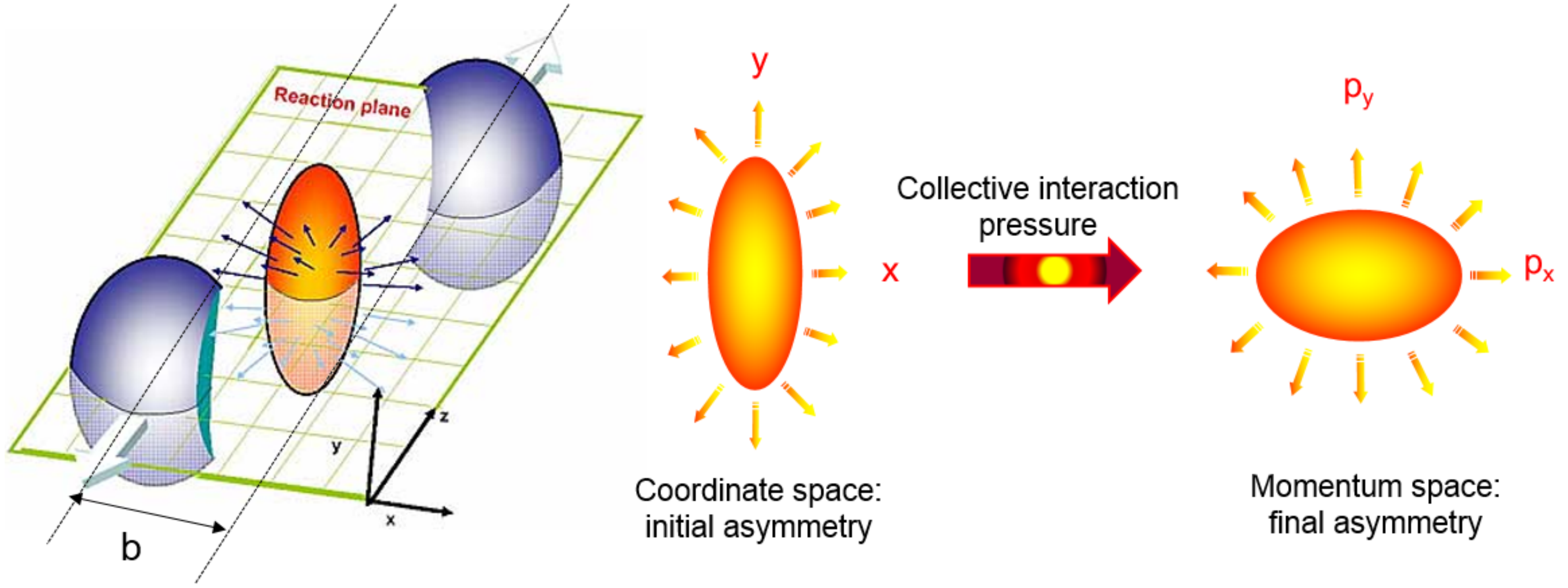
Azimuthal anisotropy

Motivation

Study transport properties of the medium in non-central collisions *via* momentum distribution of the produced particles.

Interests for quarkonia:

- path-length dependent suppression
- heavy-quark transport ☛ thermalization



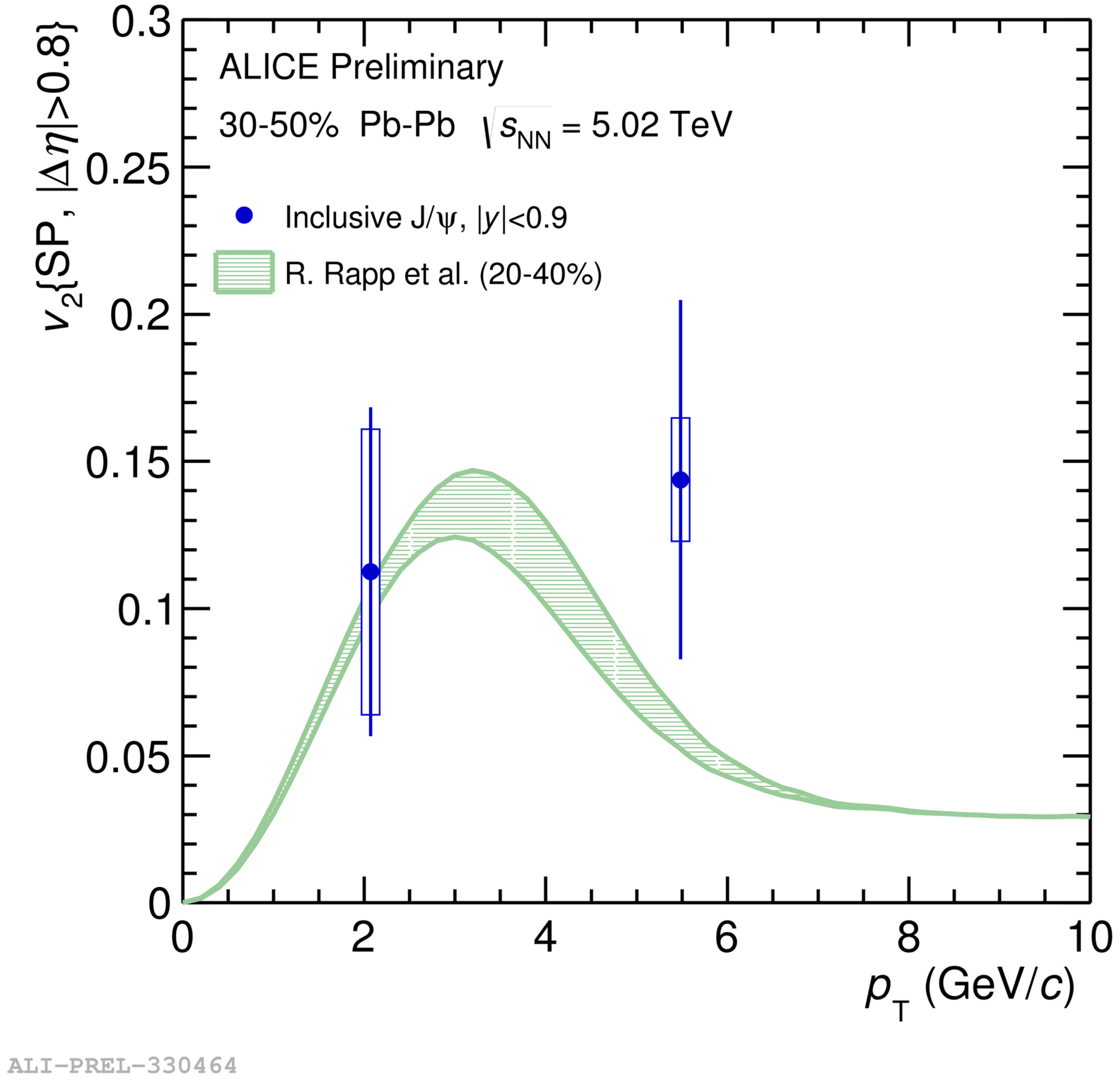
taken from Universe 3 (2017)

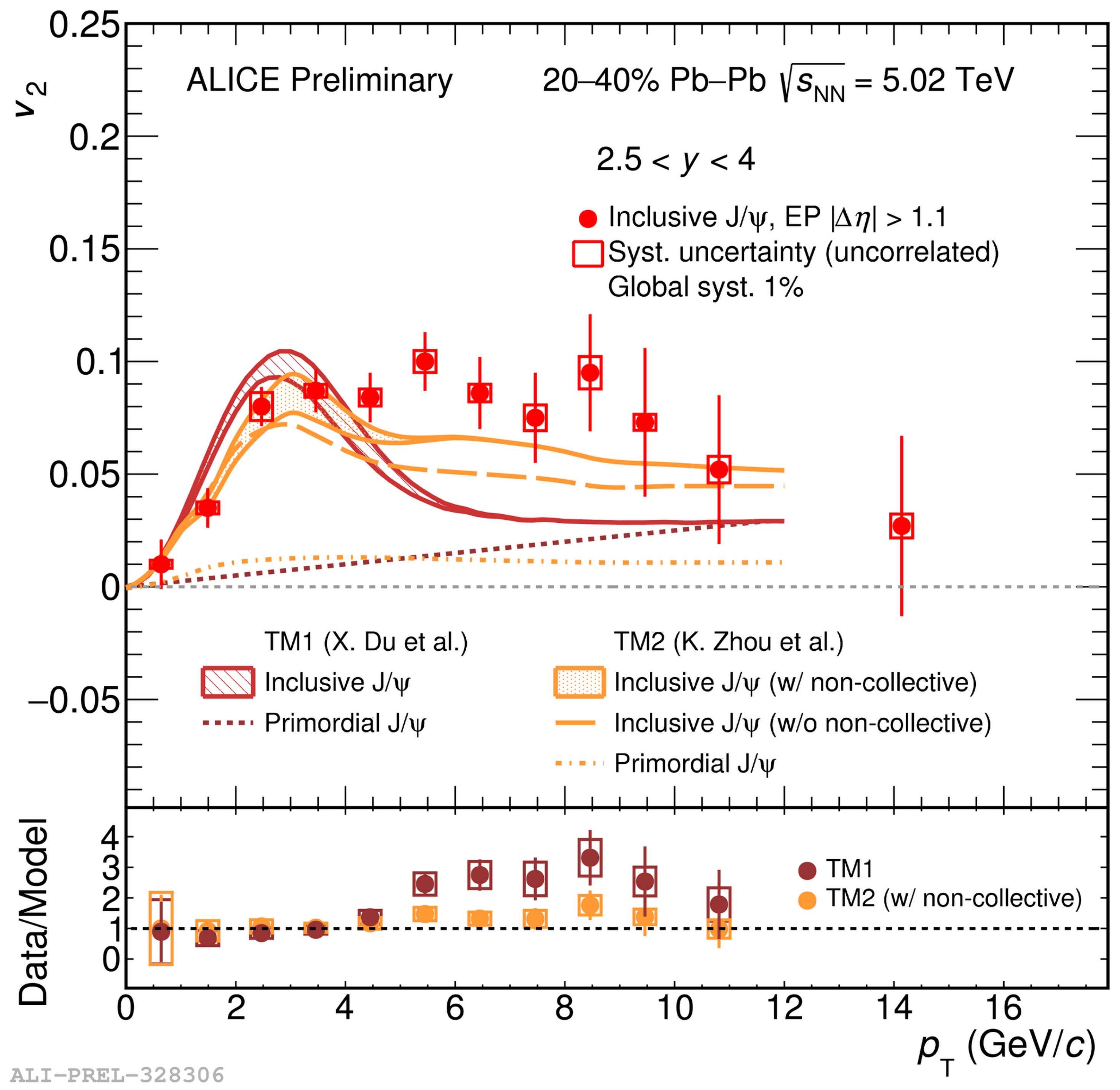
Observable

Harmonic coefficients of the Fourier expansion of the azimuthal particle distribution

v_2 ≡ "elliptic flow"

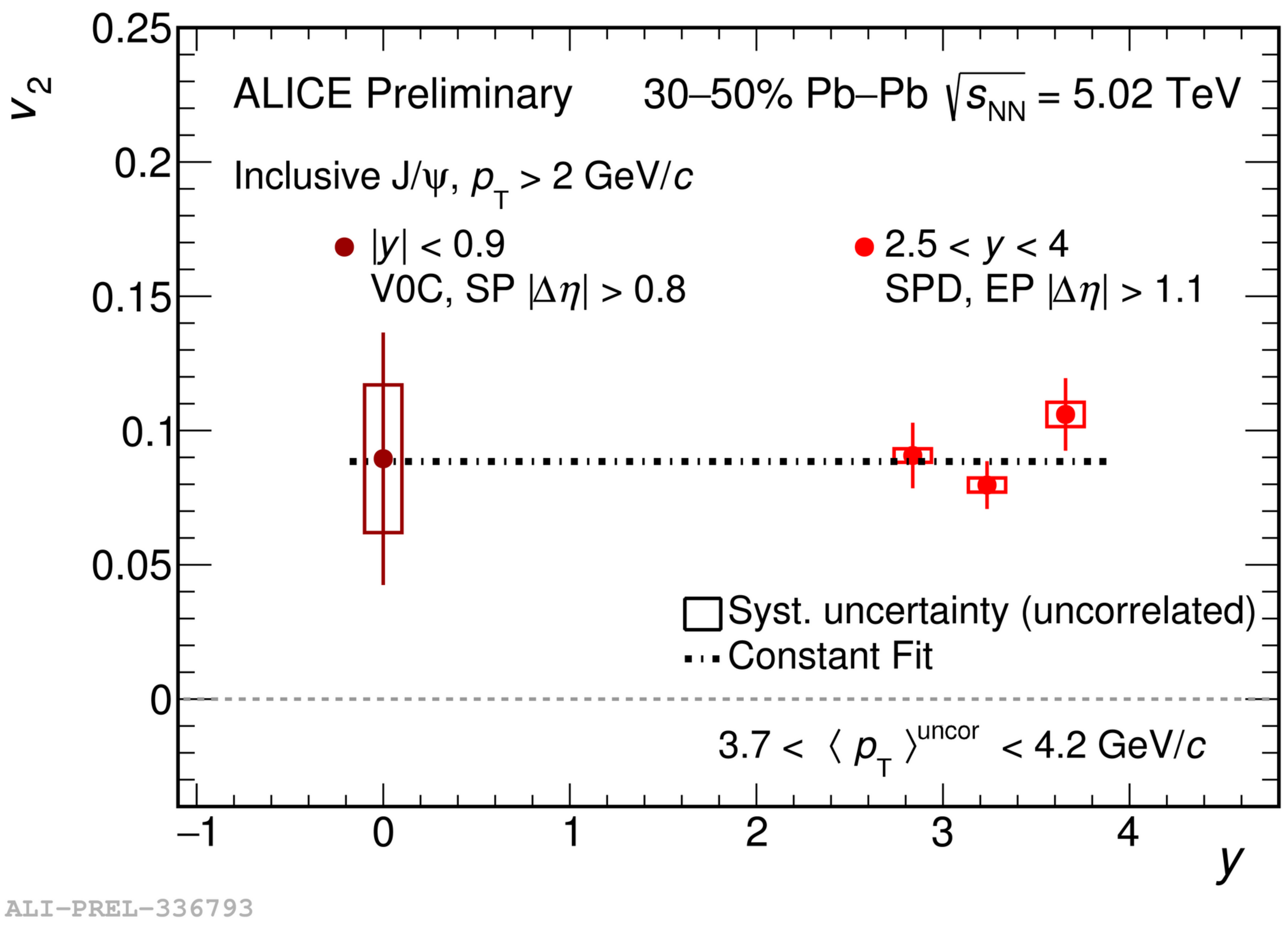
J/ψ elliptic flow





- **positive v_2** at both mid (left) and forward (right) rapidity
- consistent with transport model predictions [NPA 943 (2015) 147, PRC 89 (2014) 054911] at **low p_T ☛ evidence for charm thermalization !**
- deviation from TM1 for intermediate p_T (missing mechanism(s) ?)

J/ψ elliptic flow



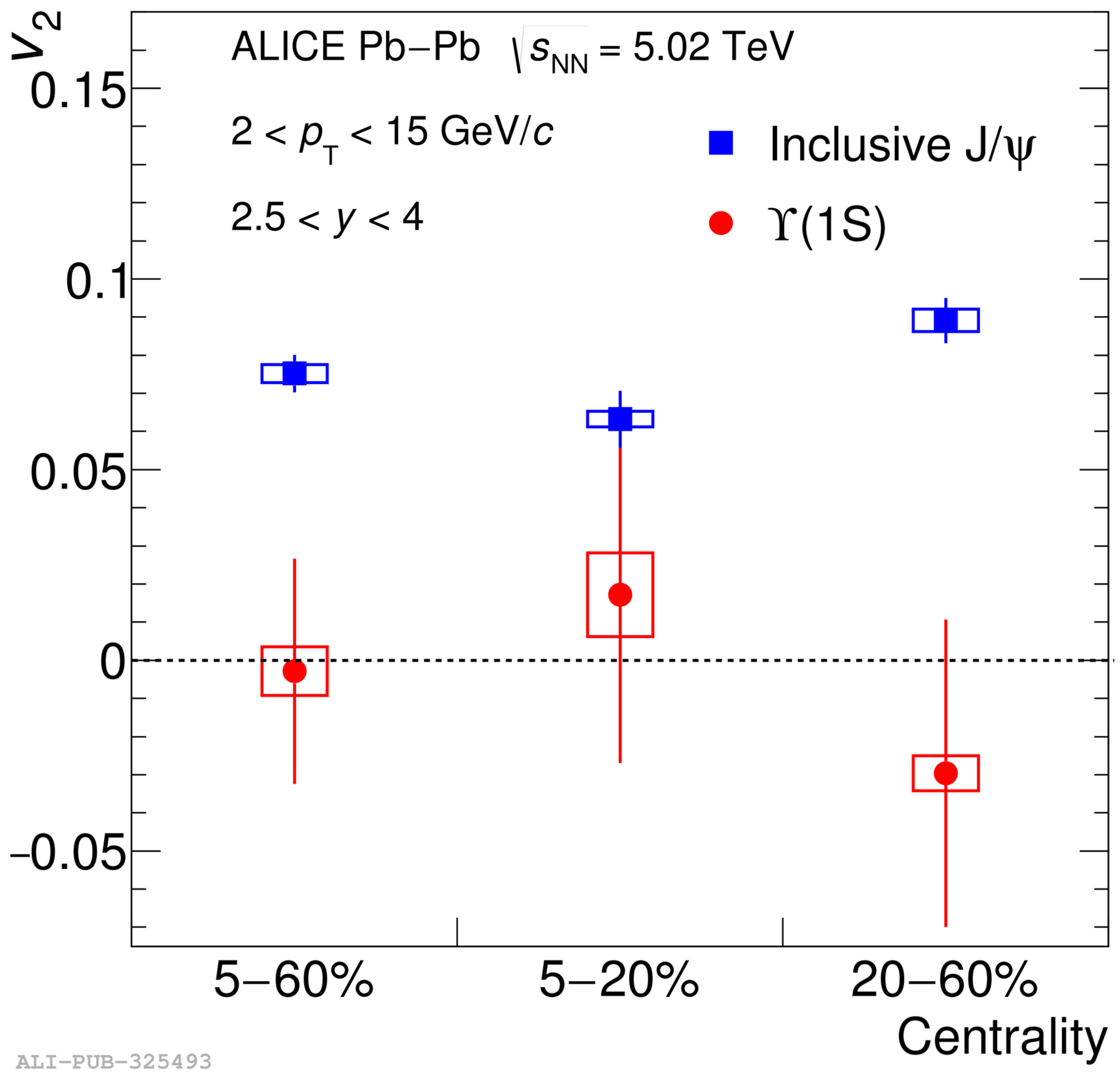
- no significant dependence with rapidity
- **increase of v_2 expected** from models including regeneration (see previous slide) from forward to mid rapidity

☛ need more statistics to conclude !

Υ(1S) elliptic flow [PRL 123 (2019) 192301]

First measurement of Υ(1S) v_2

- **compatible with zero** (a non-zero coefficient is measured for all other hadrons !)
- 2.6σ lower than J/ψ v_2 in $2 < p_T < 15$ GeV/c



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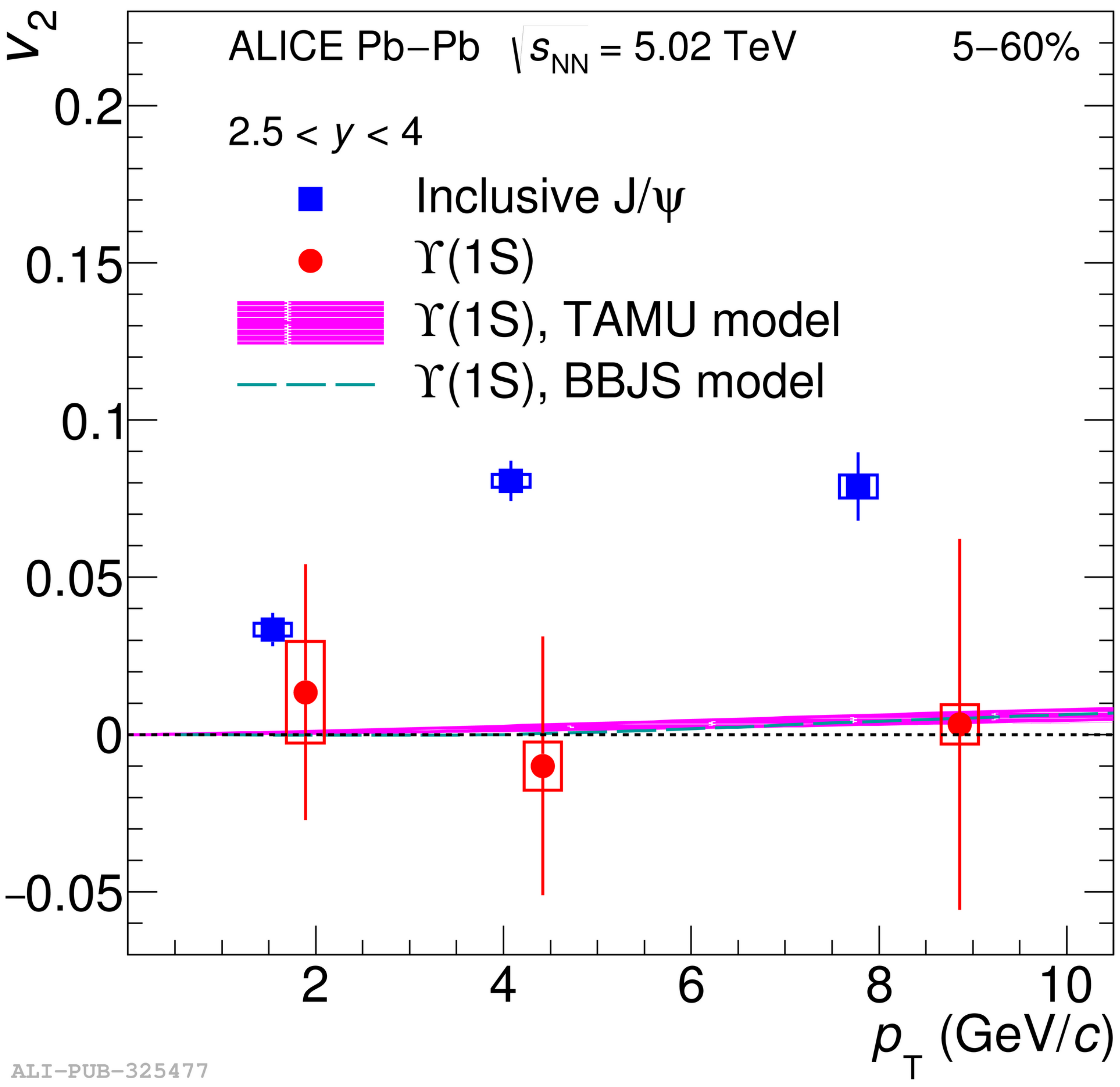
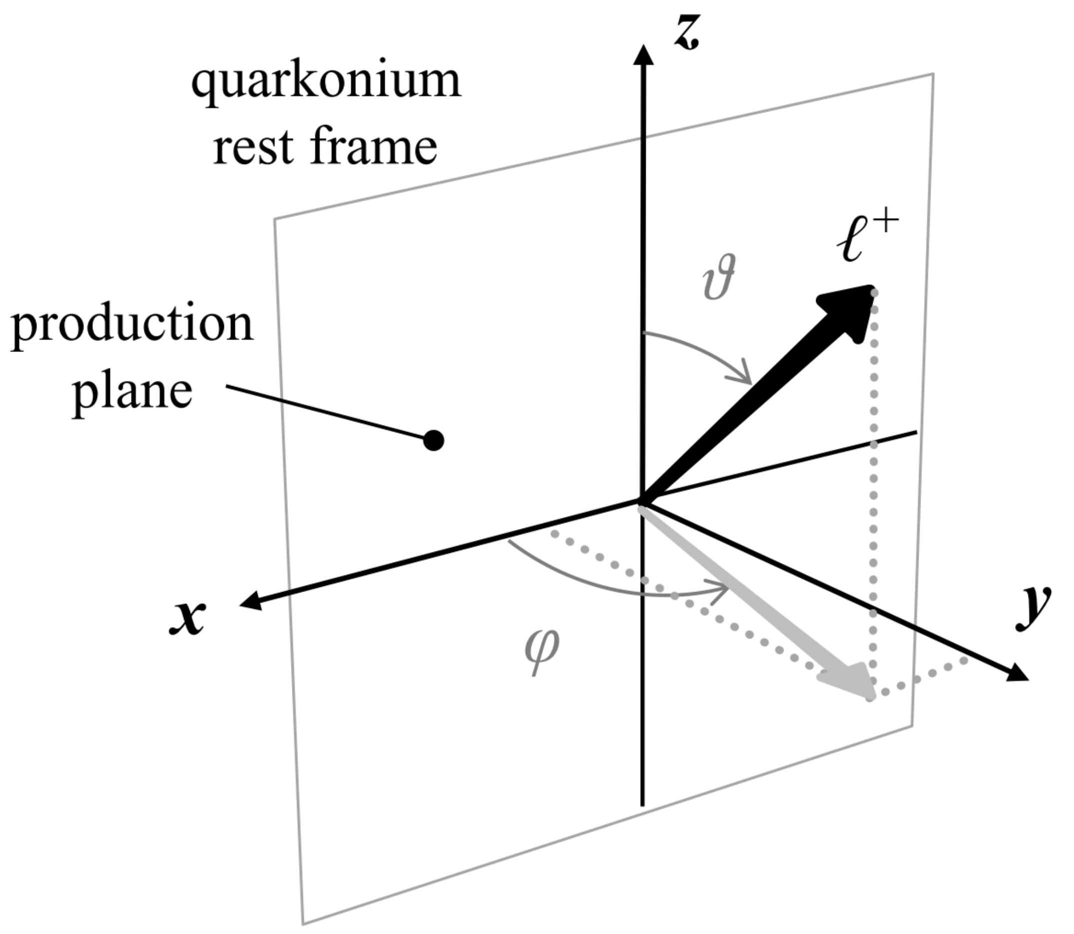
First measurement of Υ(1S) v_2

- **compatible with zero** (a non-zero coefficient is measured for all other hadrons !)
- 2.6σ lower than J/ψ v_2 in $2 < p_T < 15$ GeV/c
- in agreement with the very small values predicted by models including **regeneration** [PRC 96 (2017) 054901] **or not** [PRC 100 (2019) 051901]



Polarization

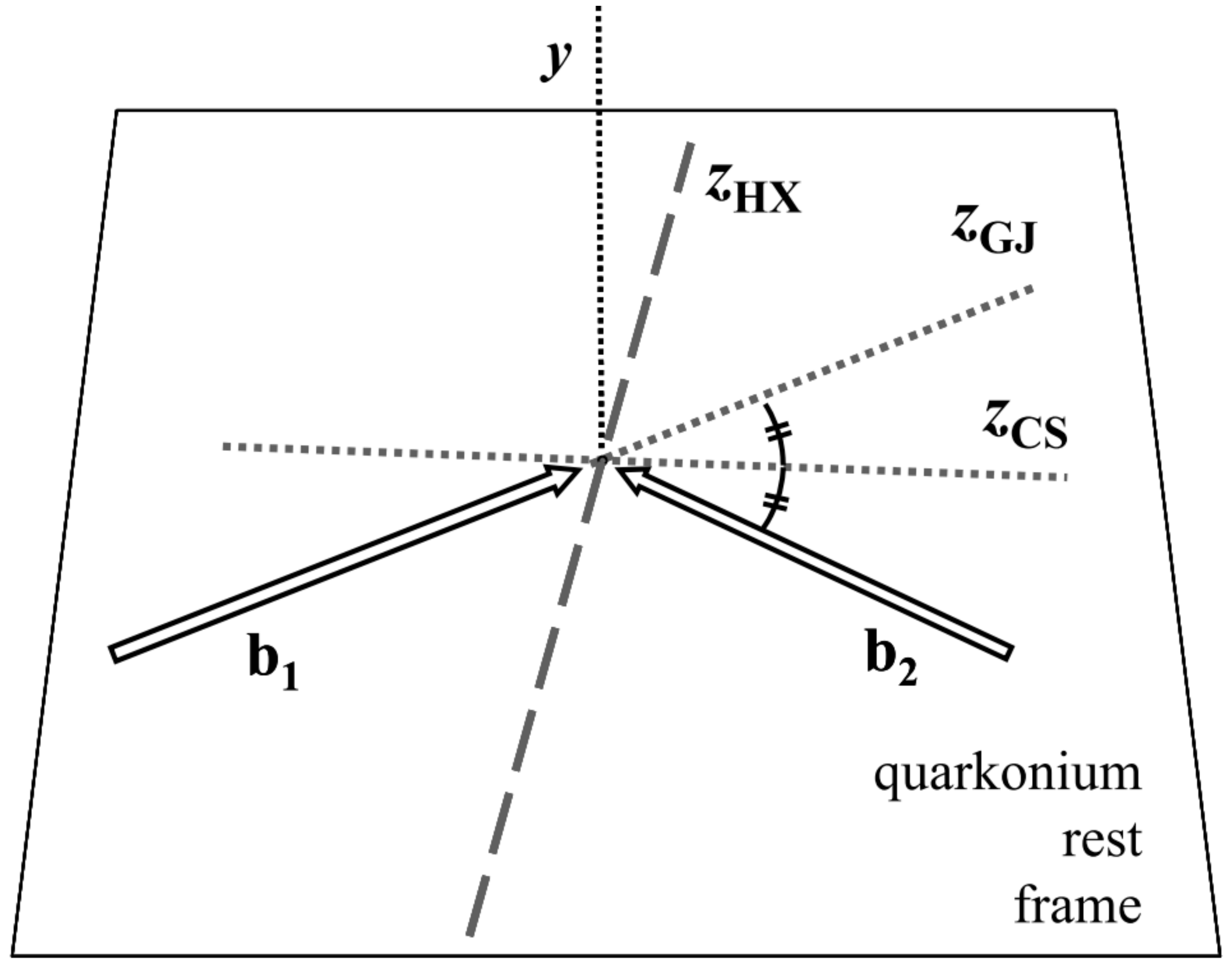


Polarization parameters are extracted from the angular distribution of decay muons in the quarkonium rest frame.

$$W(\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi)$$

Polarization *z*-axis defined in different reference frames ☛

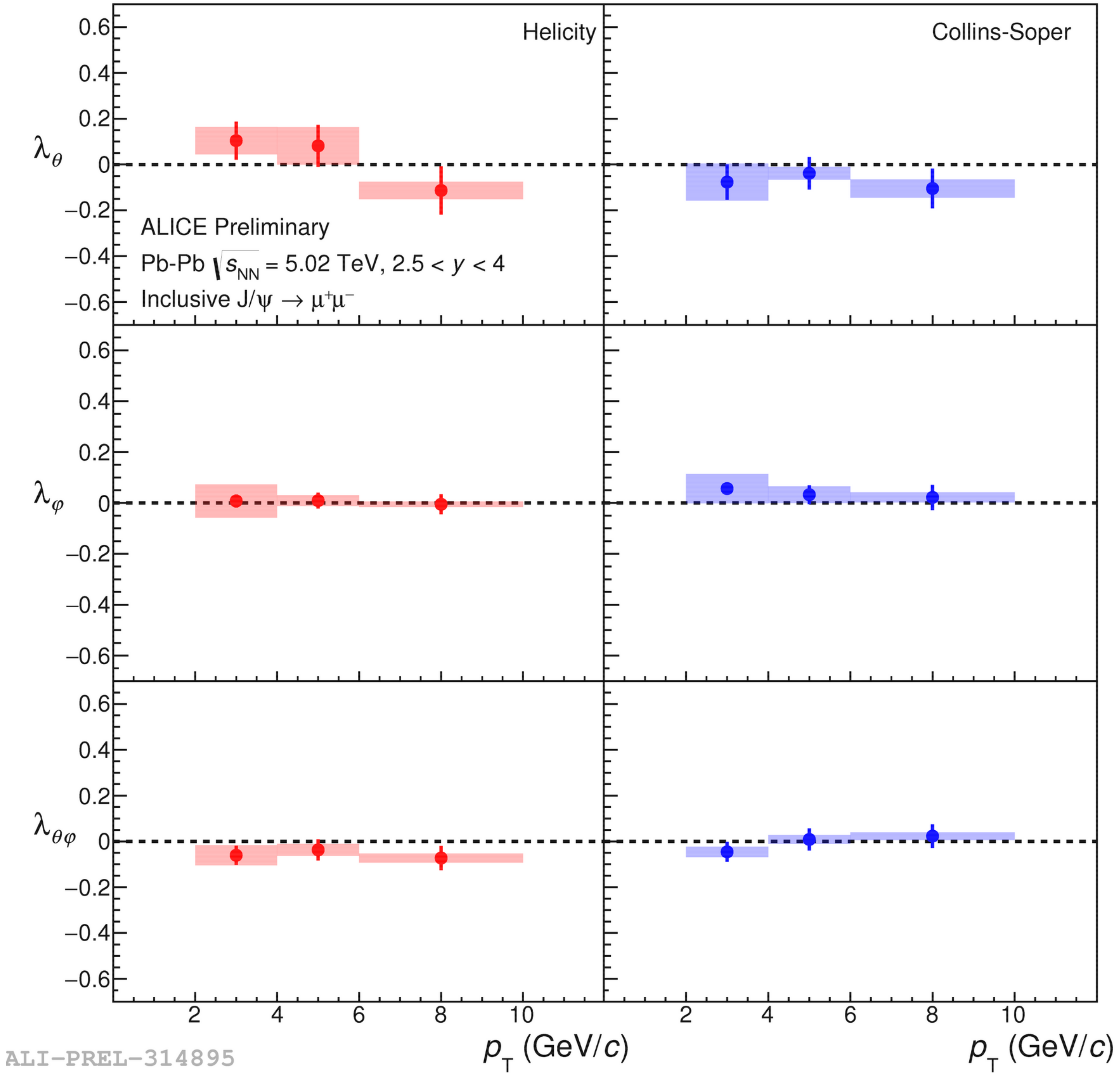
- Collins-Soper (CS)
- Helicity (HX)



Motivation

- observation of a strong magnetic field effect
- any deviation from pp measurements (system dependence, recombination effect)

J/ψ polarization



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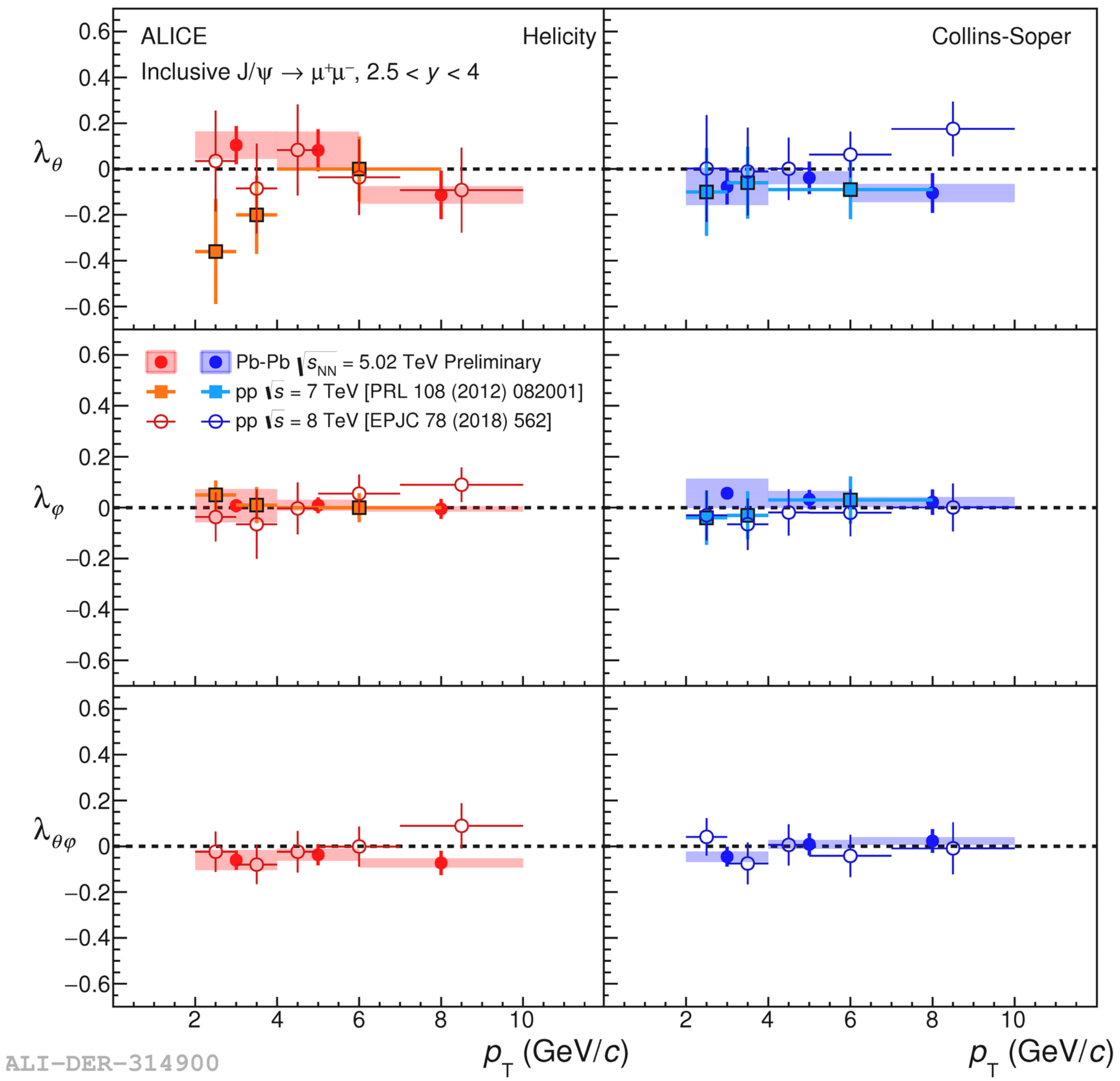
First measurement in A-A collider mode

- parameters **compatible with zero** in both reference frames

J/ψ polarization



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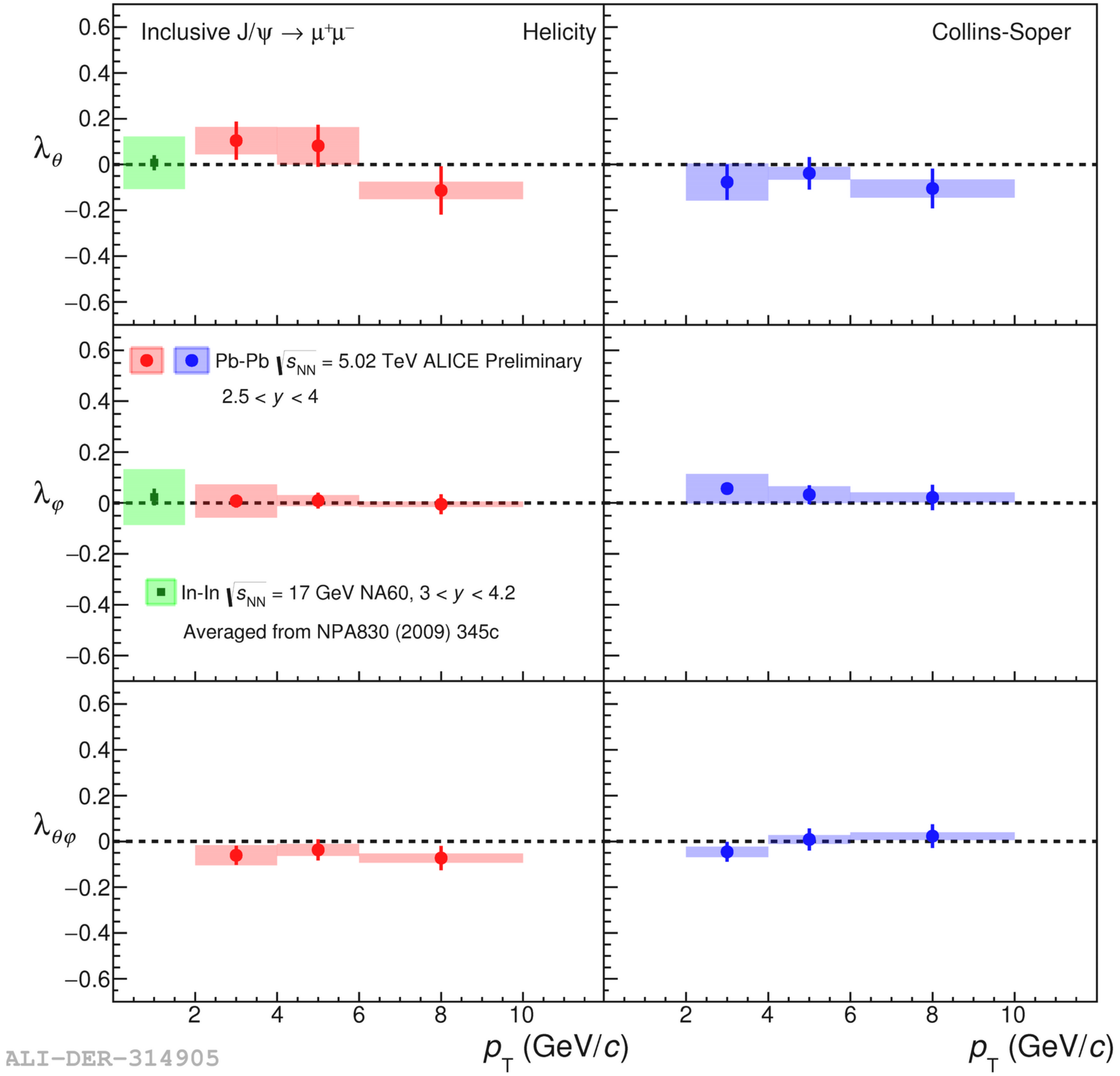
First measurement in A-A collider mode

- parameters **compatible with zero** in both reference frames
- no significant difference with results in pp collisions

J/ψ polarization



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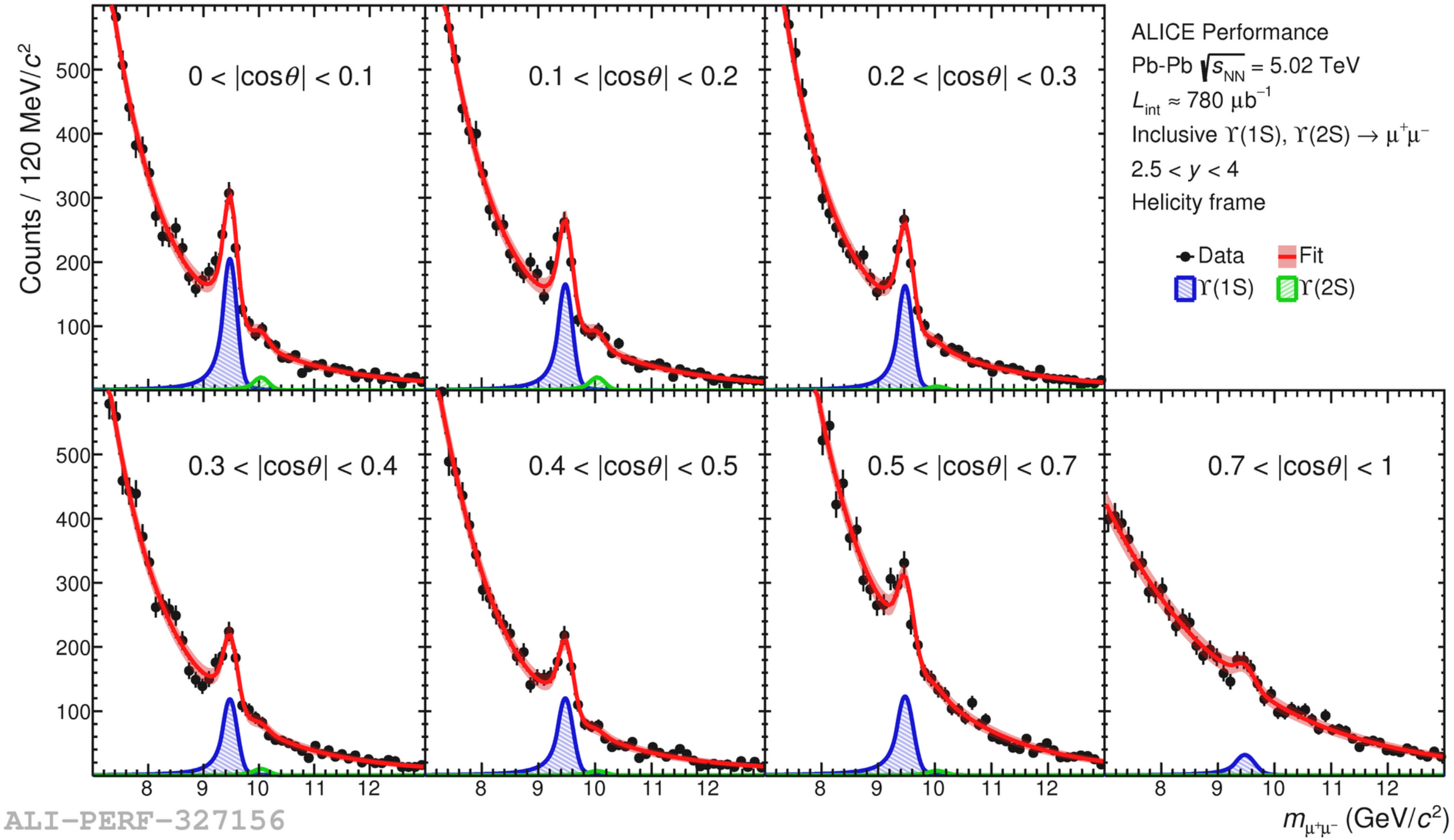
First measurement in A-A collider mode

- parameters **compatible with zero** in both reference frames
- no significant difference with results in pp collisions
- in agreement with the first measurement at SPS

☛ **suggests no J/ψ polarization**

Differential study with 2018 data set on-going.

First look to Υ



Run 2 statistics allow to perform **Υ(1S) polarization measurement** (1D approach only).

Promising performances, stay tuned !

Summary

ALICE measurements of quarkonia are of great interest to study the properties of the deconfined medium produced in heavy-ion collisions at LHC.

J/ψ

- competition of **suppression *vs* regeneration** (dominant at mid-rapidity !)
- **charm thermalization** from v_2 at low p_T
- first polarization measurement in Pb-Pb collisions at LHC is compatible with 0

  ☛ aim to study the centrality dependence (clearer evidence for a magnetic field effect)

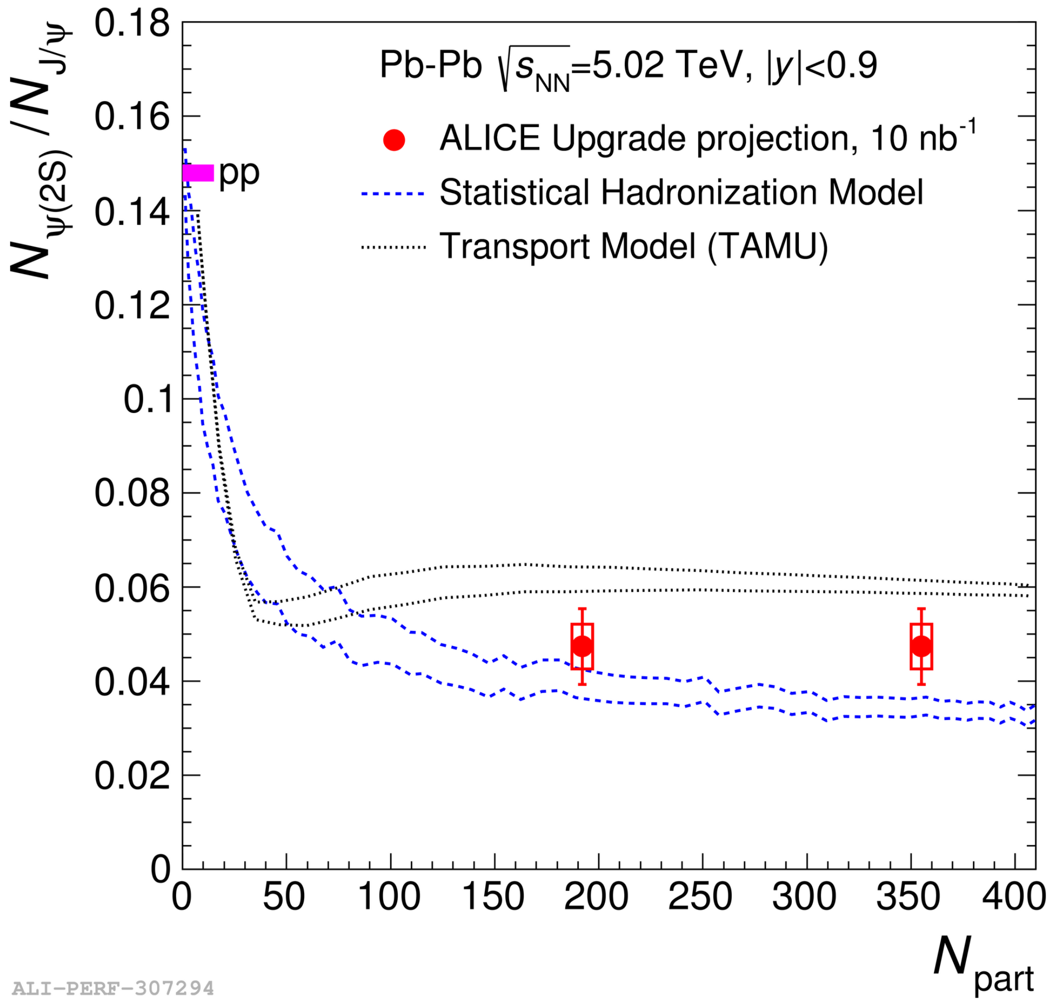
ϒ

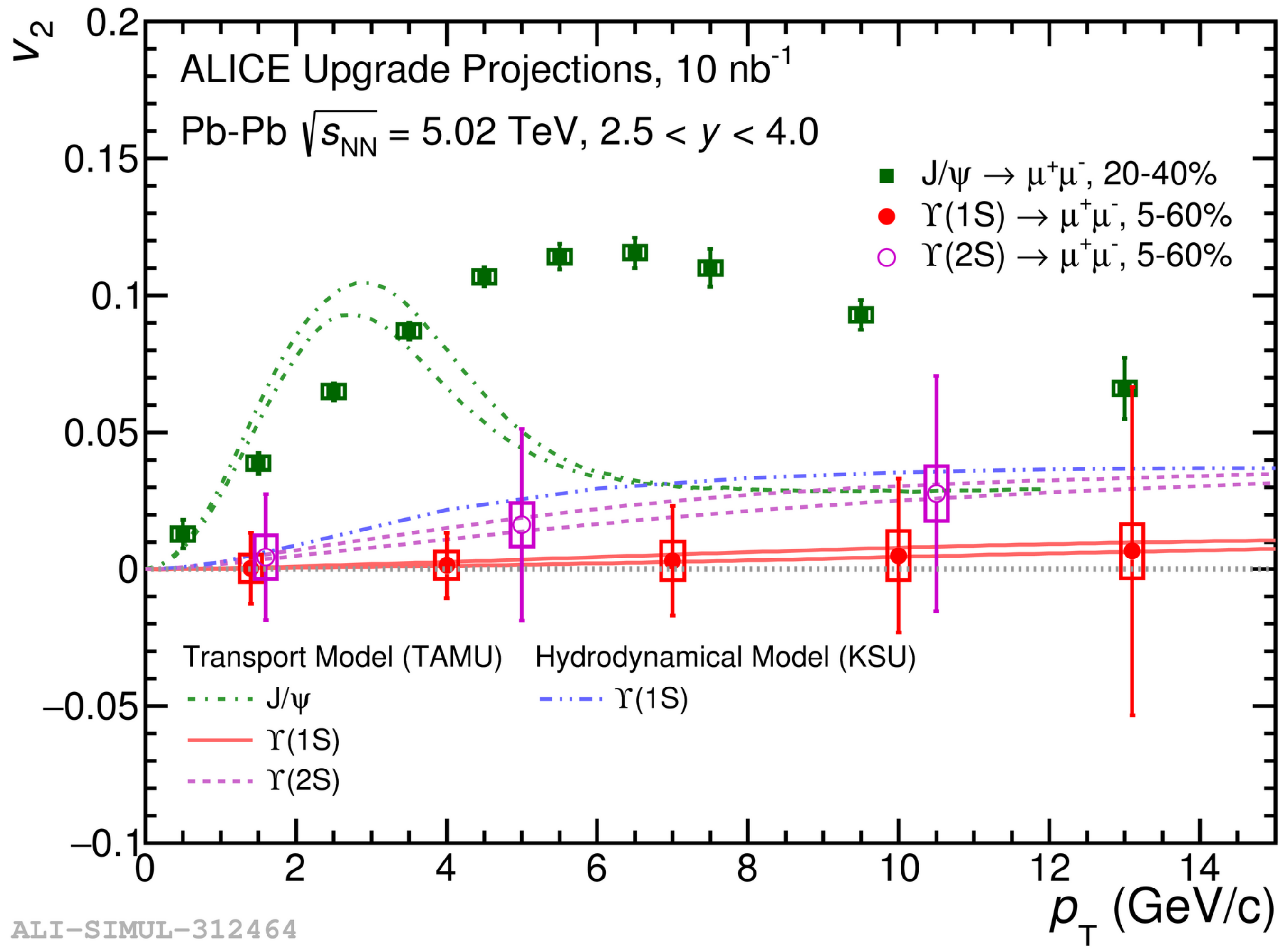
- strong suppression consistent with **sequential melting** scenario
- no sign of regeneration from **first v_2 measurement** and differential ϒ(1S) R_{AA}
- additional suppression effect(s) at forward rapidity ?

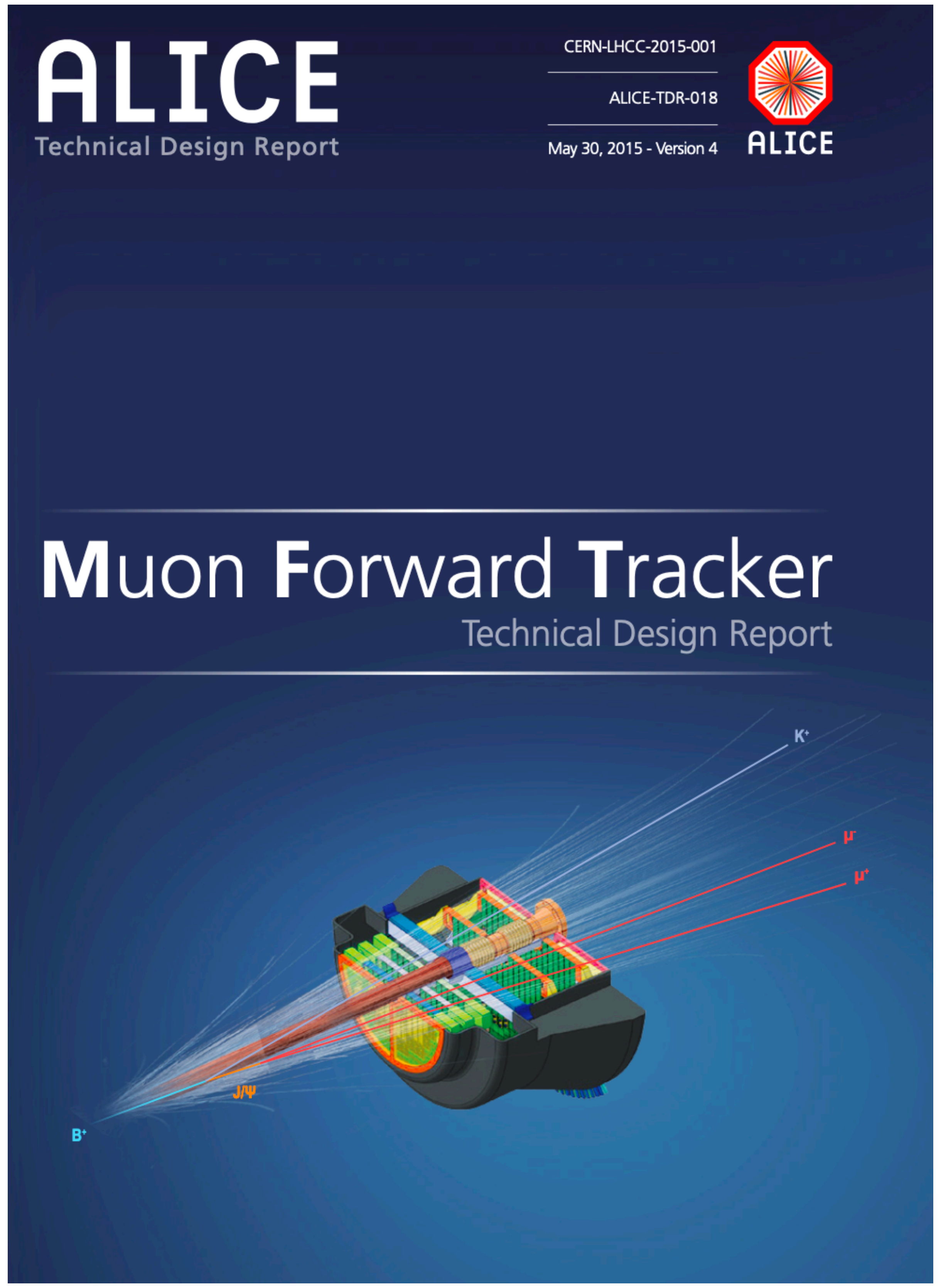
Prospects for Runs 3 & 4

LS2 = major upgrade of ALICE detector

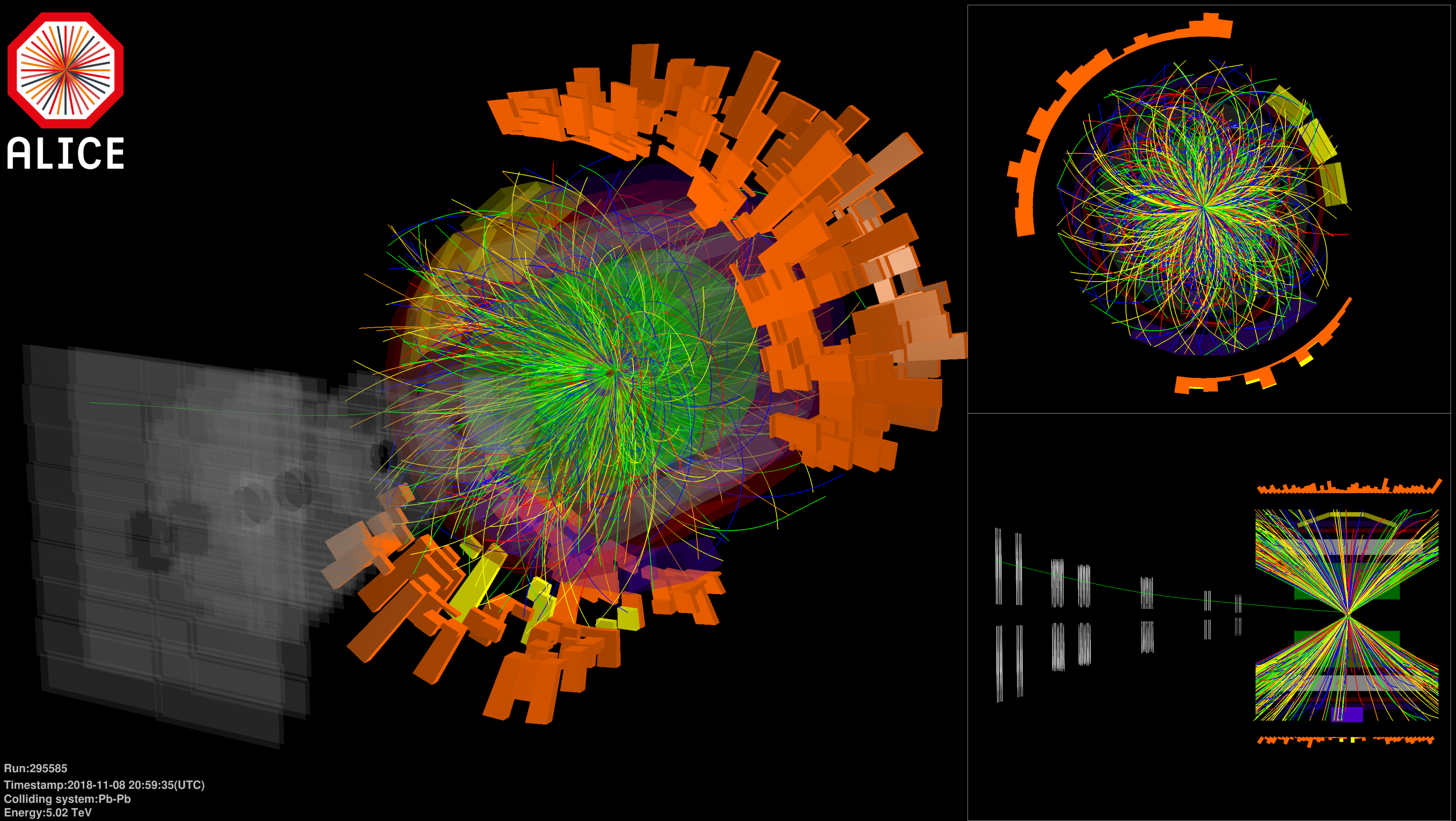
- prompt/non-prompt J/ψ separation by adding a **M**uon **F**orward **T**racker [ALICE-TDR-018]
- from **10** (forward) **to 100** (mid-rapidity) **x Run 2 statistics**
  - ☛ increase significance of excited-states
  - ☛ improve ϒ v_2 measurement
- new observables ? (B_c, ψ(2S) at mid-rapidity)



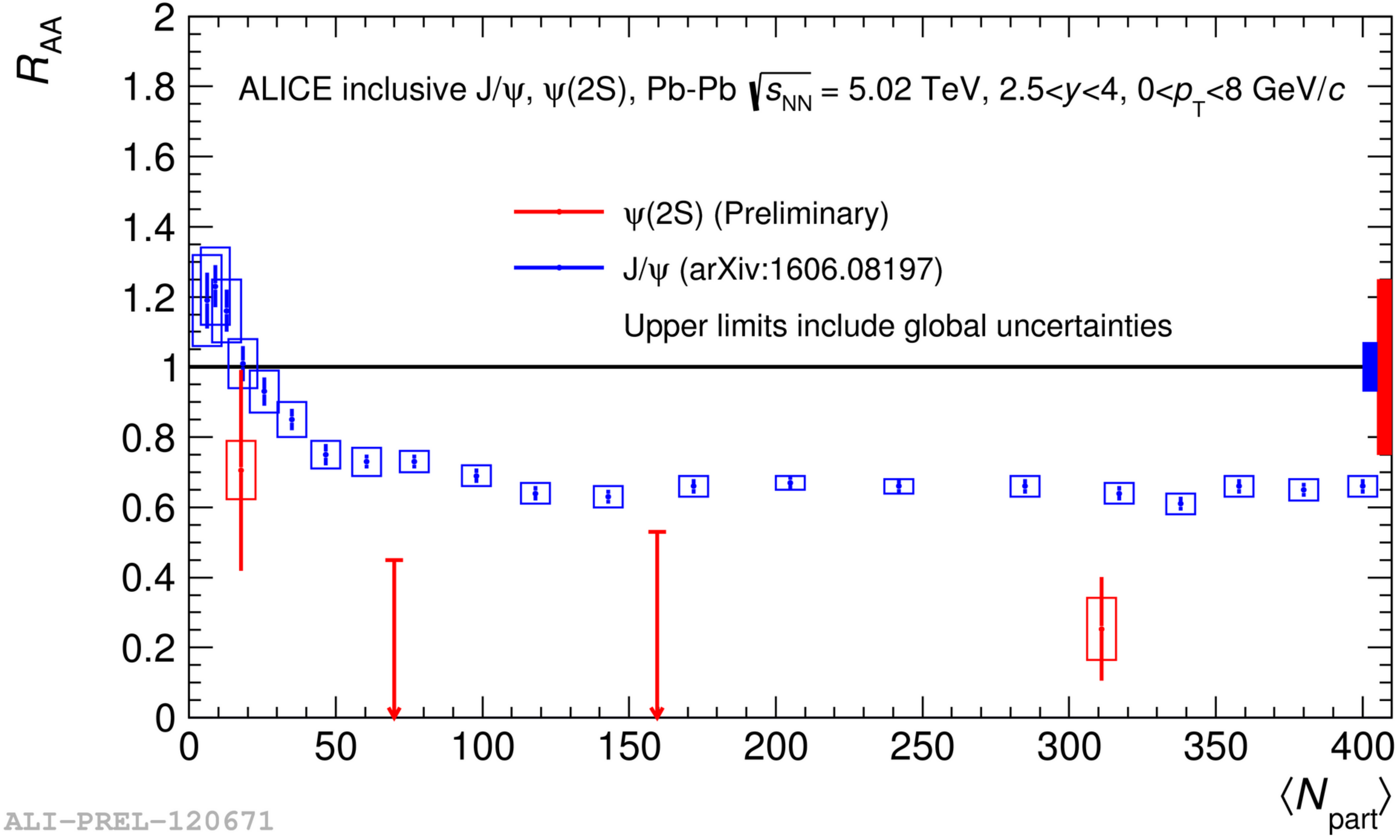




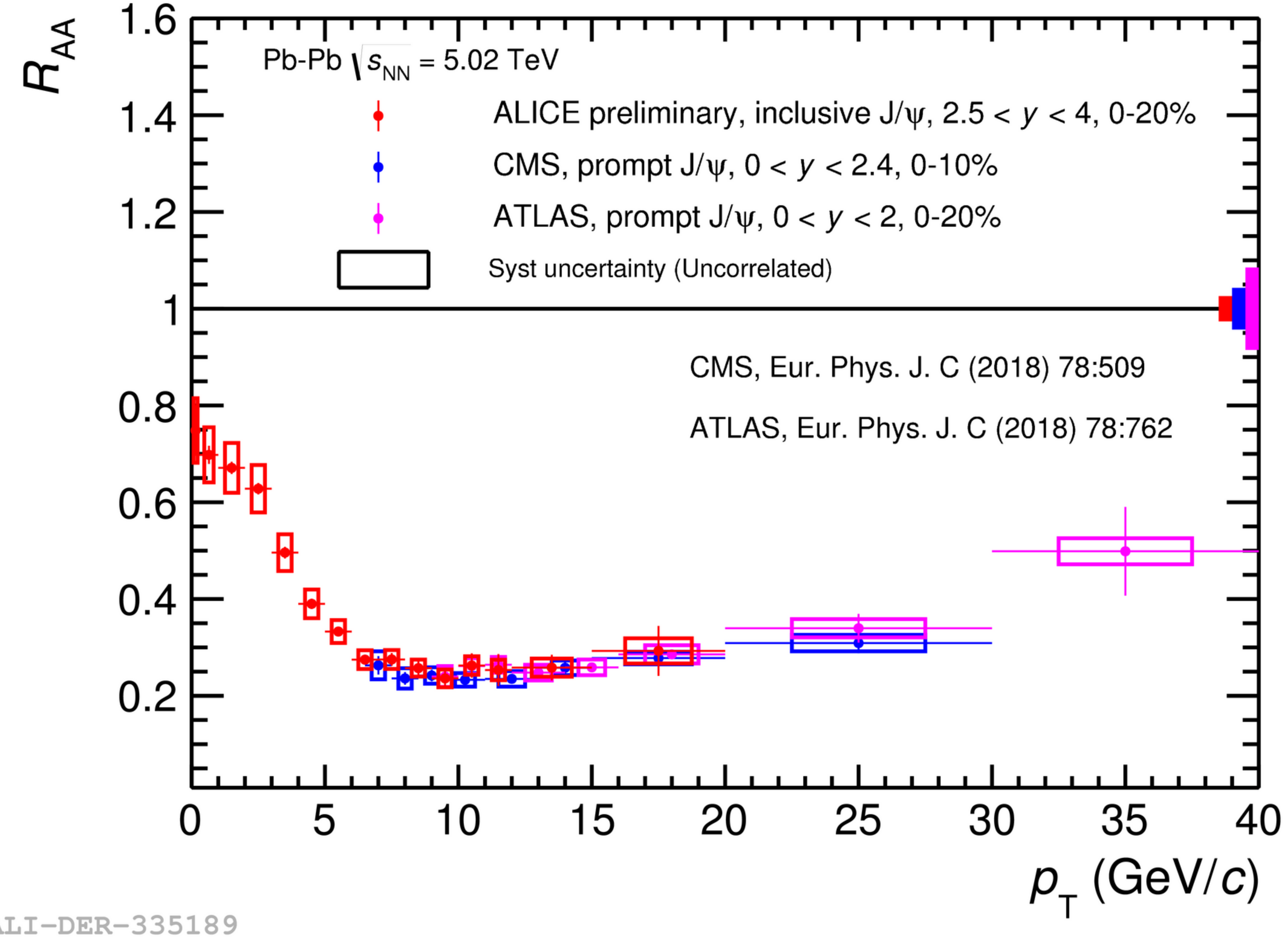
Thanks for your attention !



ψ(2S) (2015 data)



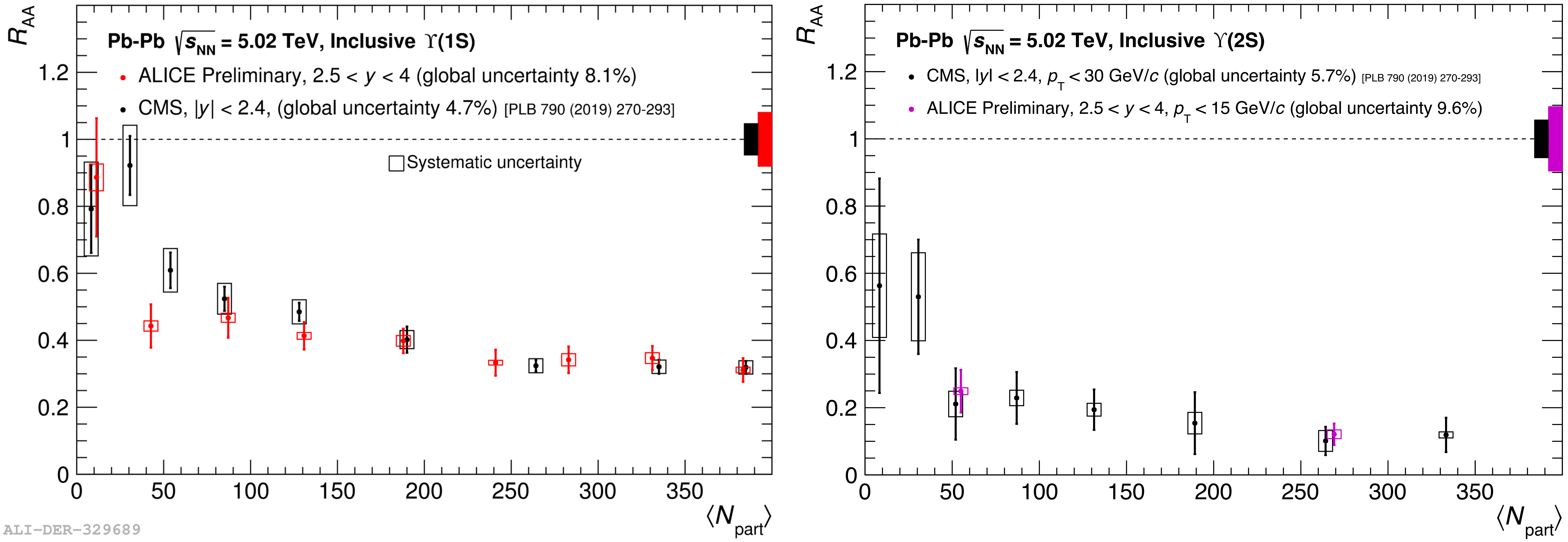
J/ψ R_{AA} vs p_T in central events



Nice overlap between the experiments

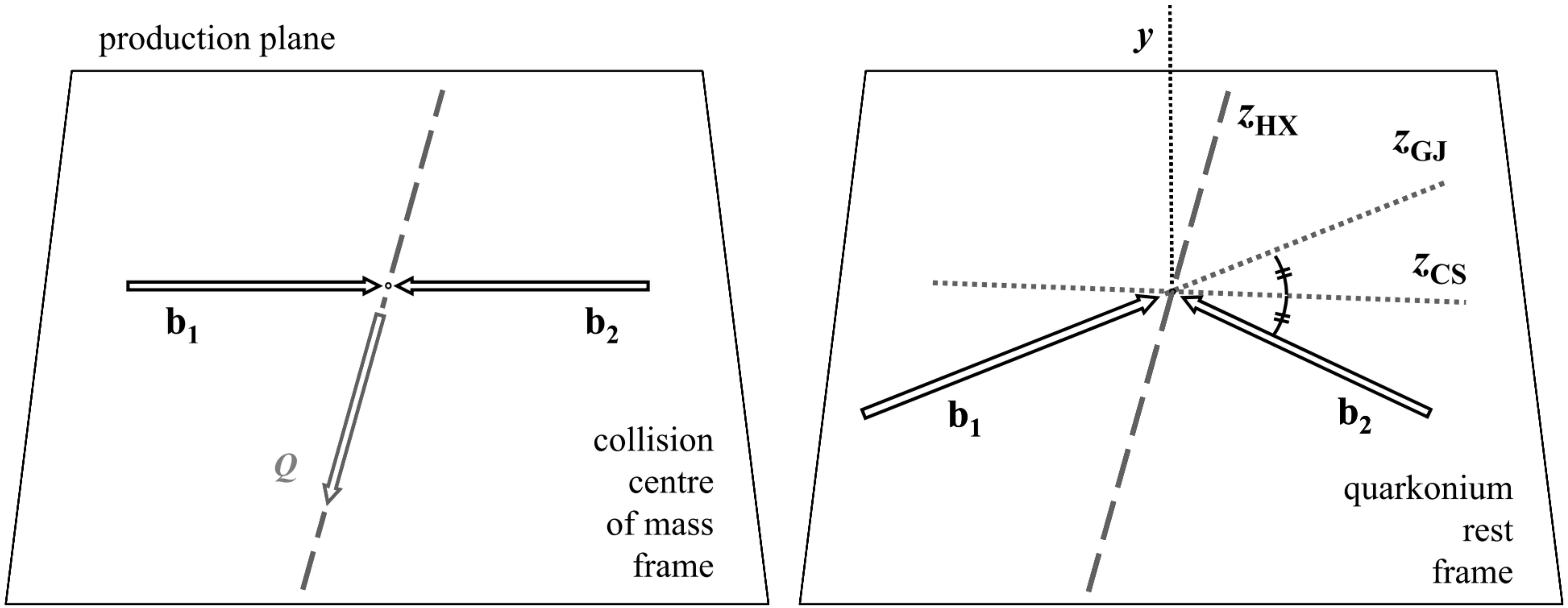
- **significant enhancement at low p_T**, consistent with recombination (ALICE)
- ***suppression plateau*** for intermediate p_T (5-15 GeV/c)
- **increase for p_T > 15 GeV/c**

Υ(nS) R_{AA} compared to CMS



Υ(nS) in Runs 3 & 4

Polarization [EPJC (2010) 69: 657-673]



Polarization *z*-axis defined in different **reference frames**:

- **Collins-Soper** (CS) = bisector of the angle between one beam and the opposite of the other beam
- **Helicity** (HX) = flight direction of the quarkonium in the collision center-of-mass frame

J/ψ polarisation in proton-proton [EPJC 78 (2018) 562]