Université Claude Bernard Lyon 1

Υ production and polarization in pp collisions with ALICE at the LHC

Yanchun Ding[1,2]

Central China Normal University[1]

Institut de Physique des Deux Infinis de Lyon[2]

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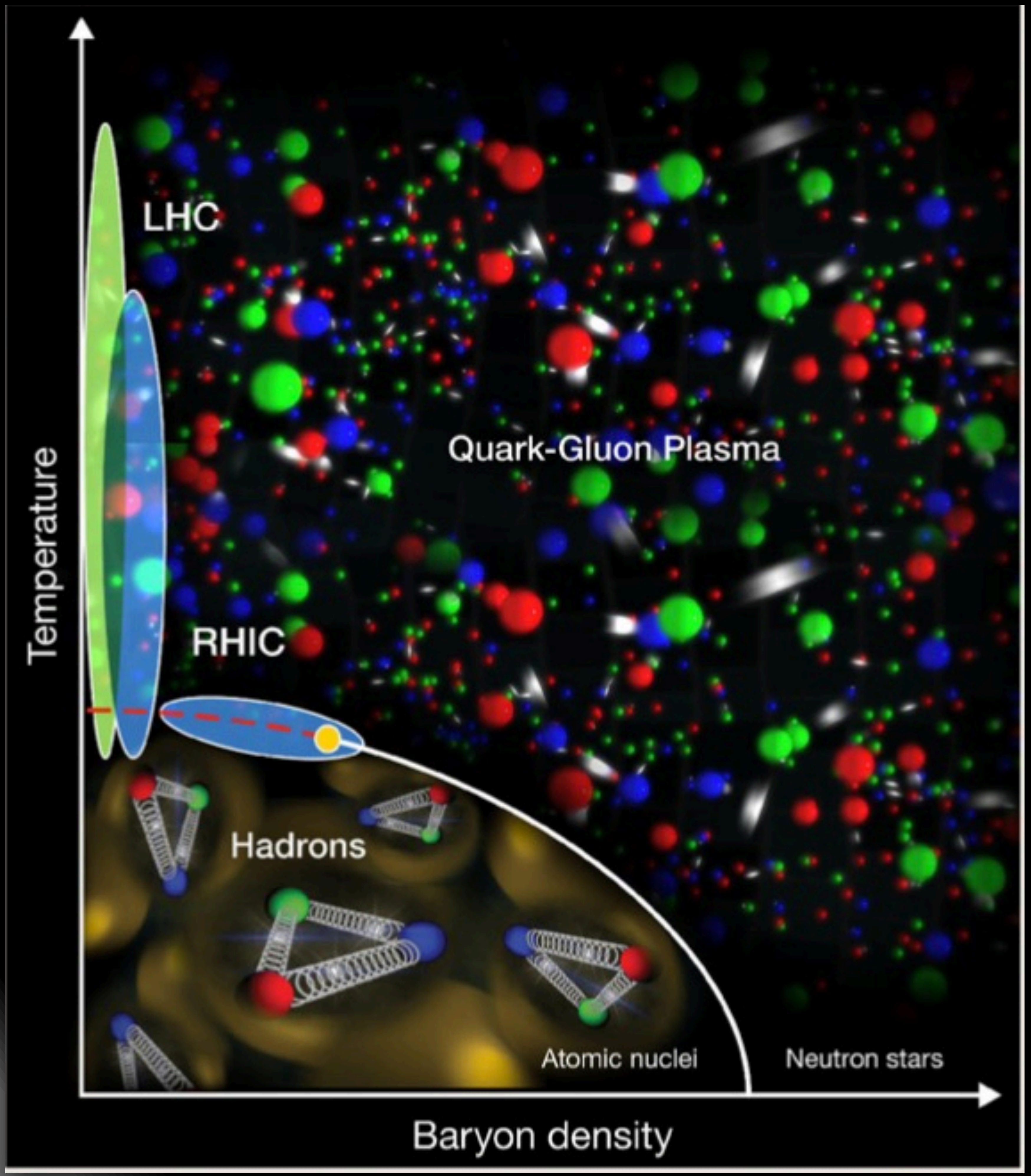
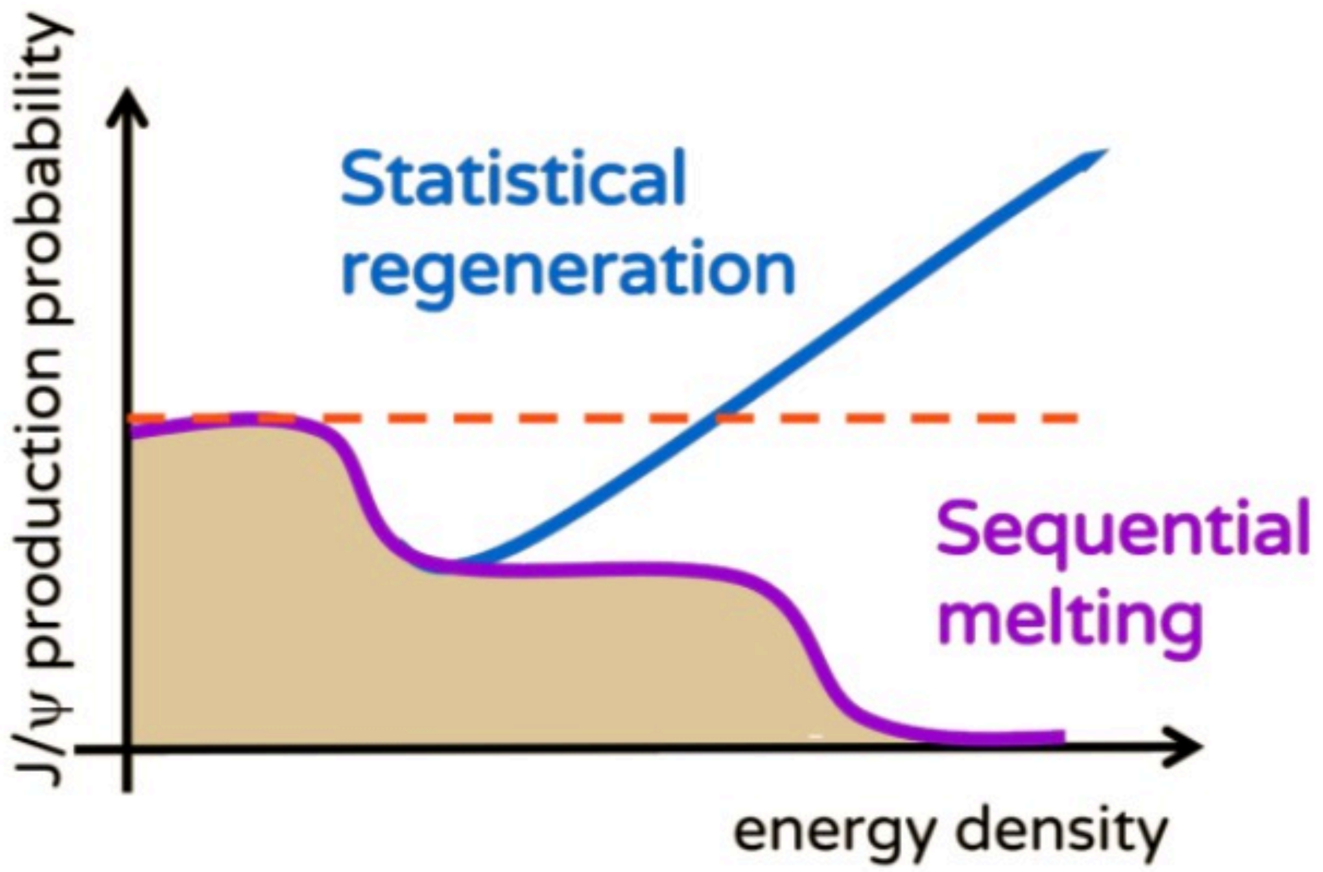
Introduction: QGP physics with ALICE



- **Quark-gluon plasma (QGP)** is a deconfined state of hadronic matter which can form at high temperatures and/or net baryonic densities
- ALICE at the LHC observes QGP produced in ultra-relativistic collisions of heavy ions
- Direct observation of QGP is impossible due to the short life of the deconfined phase
- QGP is studied indirectly by means of a number of probes
  - The suppression of high p_{T} particles and jets
  - The enhancement of strange and multi–strange particles
  - Signatures of a collective motion of the medium
  - …

Introduction: quarkonium as a probe of QGP

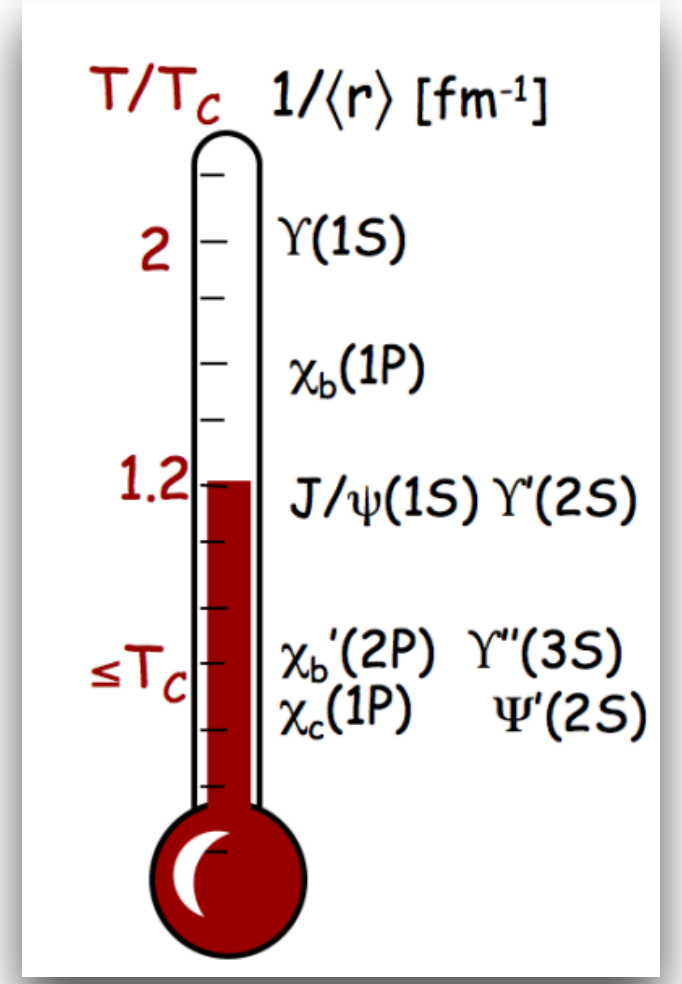
- Quarkonium: bound state of a **heavy quark and its corresponding antiquark**
  - Heavy quarks (charm and bottom): produced at the early stages of the heavy-ion collisions
- Quarkonium production inside the QGP
  - **Color screening** and dissociations (**sequential melting**) vs **regeneration** mechanisms
  - **Parton energy loss** (collisional vs radiative processes)



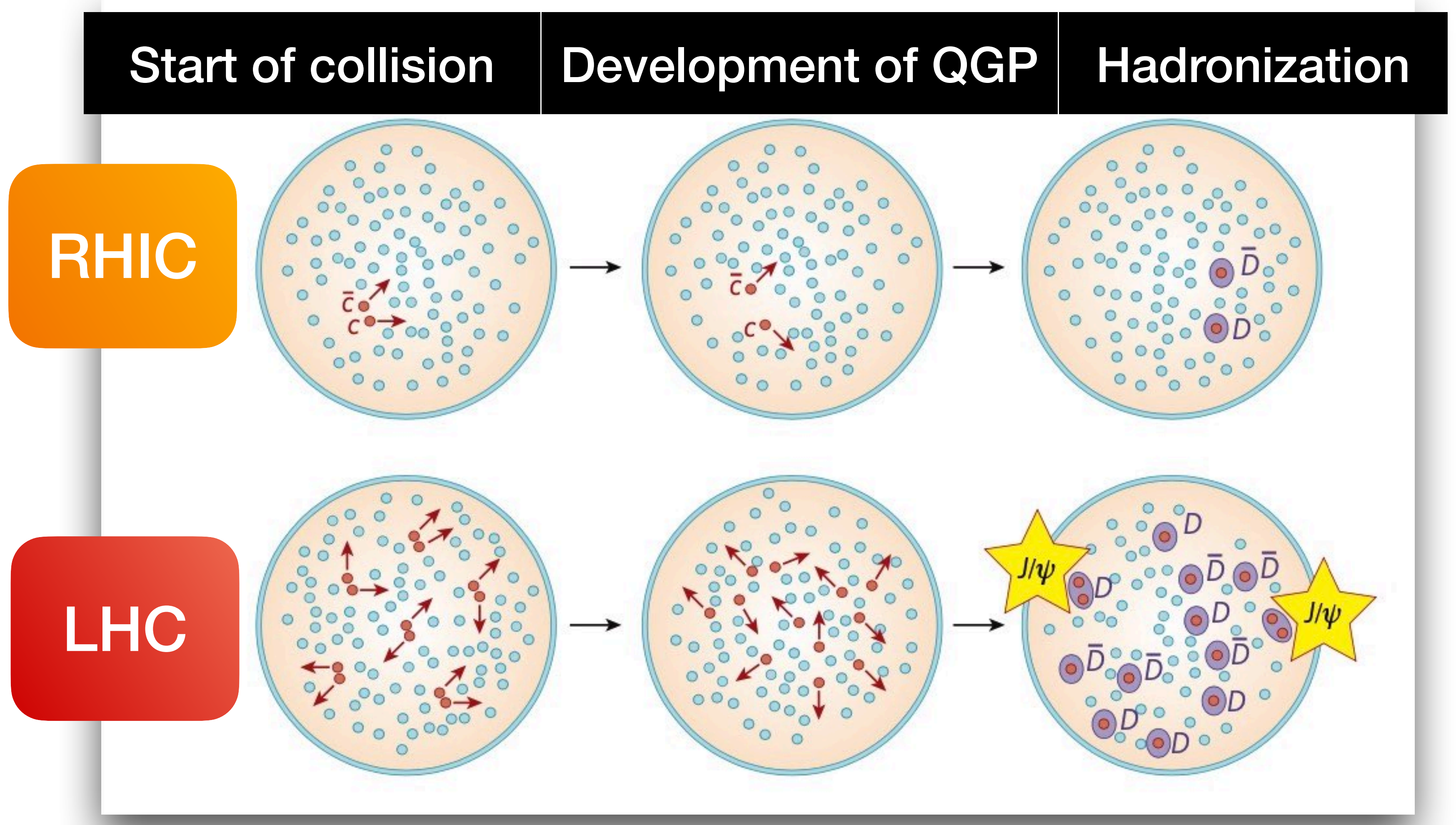
state	J/ψ	χ_c	$\psi(2S)$
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
r_0(fm)	0.25	0.36	0.45

state	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_0(fm)	0.28	0.56	0.78

Thermometer of the QGP



Eur. Phys. J, C61, 2009



Nature 448, 302-309 (2007)

Introduction: quarkonium in small collision systems

- **Small collision systems (pp and p-Pb collisions): no (or very tiny) QGP effect is expected**

- **Measurements in pp collisions:**
  - Provide a baseline for the measurement in p-Pb and Pb—Pb collisions
  - Study of quarkonium production mechanisms: both perturbative (i.e. heavy-quark pair formation) and non-perturbative (quarkonium state formation) QCD processes involved
    - ↳ Measurements of quarkonium production in pp allows to constrain QCD based models

- **Measurements in p-Pb collisions:**
  - Investigate cold nuclear matter (CNM) effects (shadowing, coherent parton energy loss,…)
    - ↳ Help the interpretation of the measurements in Pb—Pb collisions

- **Measurements in high-multiplicity pp/p-Pb collisions:**
  - Study the role of ***multiparton interactions*** (MPIs)
  - Observe possible ***collective-like*** effects

Introduction: quarkonium in small collision systems

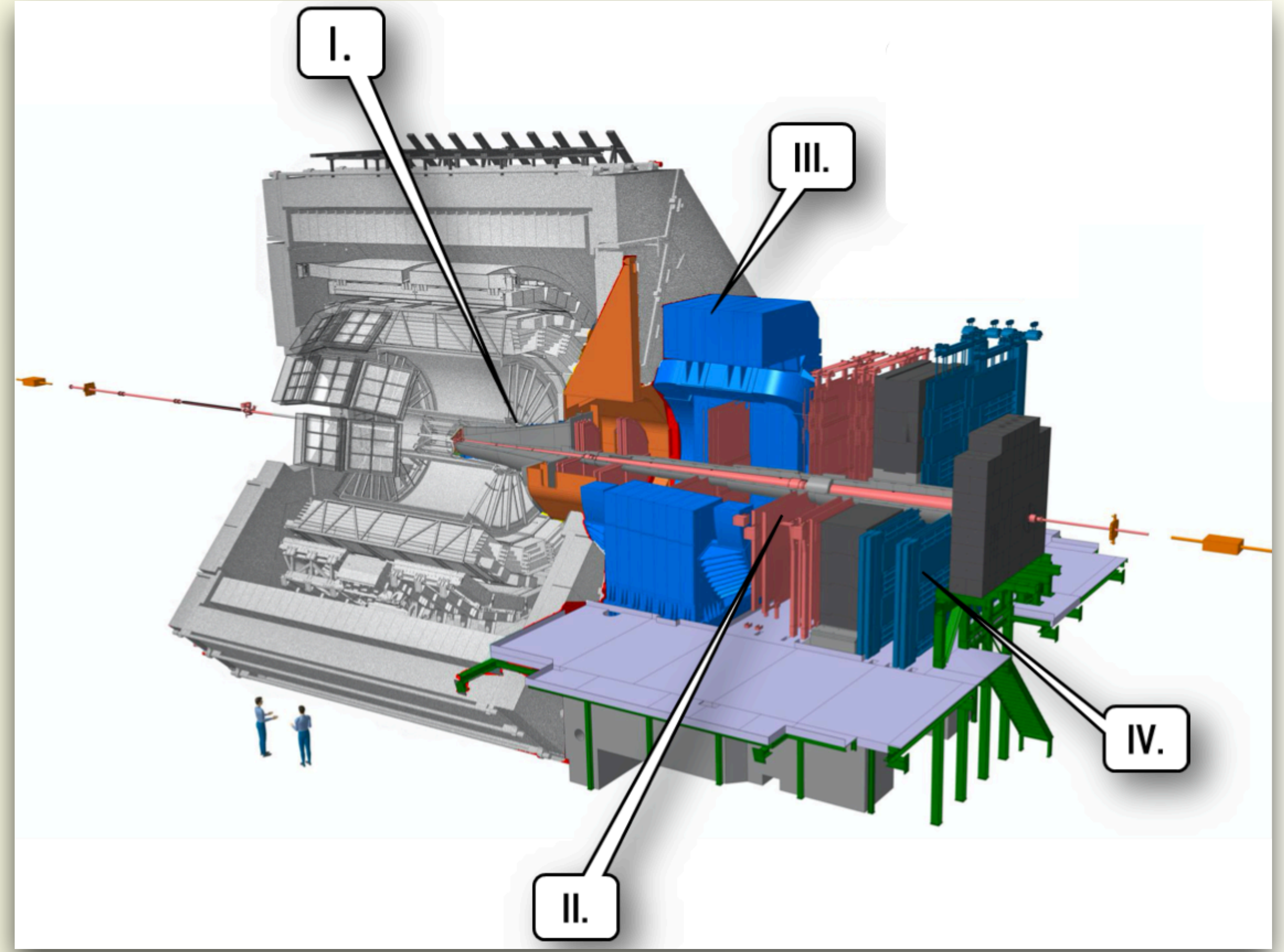
- Small collision systems (pp and p-Pb collisions): no (or very tiny) QGP effect is expected
- Measurements
  - Provide a b
  - Study of qu ... ion) and non-perturb
    - ↳ Measure
- Measurements
  - Investigate
    - ↳ Help the

In this presentation:

- **Multiplicity dependence of Υ production in pp collisions**
  - *Understand the particle production mechanisms (MPI)*
  - *Collective effects in high multiplicity pp collisions?*
- **$\Upsilon(1S)$ polarization in pp collisions**
  - *Help to understand the particle production mechanisms*
  - *Constrain the model predictions*

- Measurements in high-multiplicity pp/p-Pb collisions:
  - Study the role of *multiparton interactions* (MPIs)
  - Observe possible *collective-like* effects

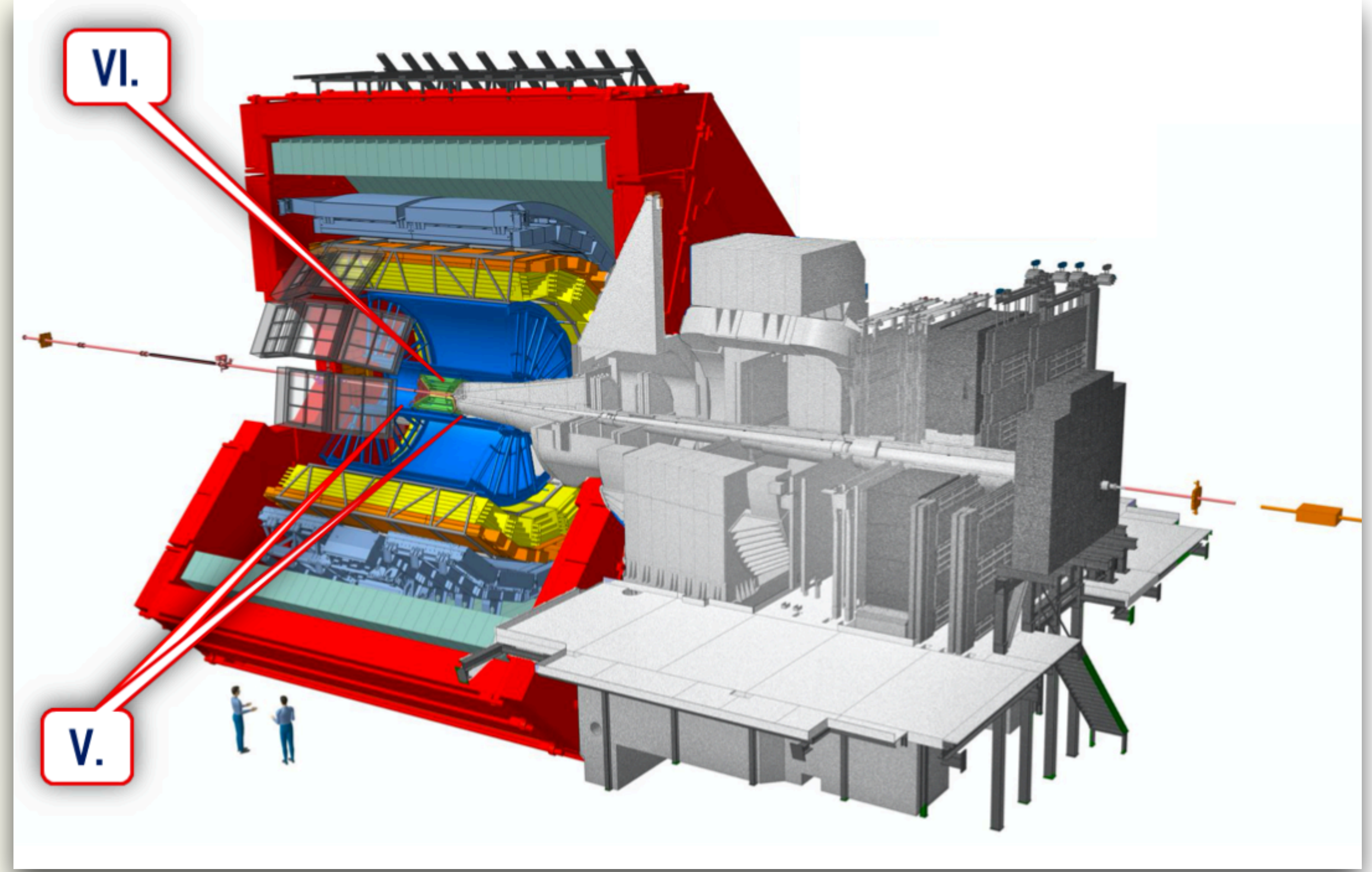
A Large Ion Collider Experiment



- A dedicated heavy-ion experiment at the LHC
  - **Muon Spectrometer** $(-4 < \eta < -2.5)$
    - I. Absorbers: efficiently dump π, K and low-momentum muons
    - II. Tracking system + III. Dipole magnet: muon track reconstruction, muon momentum and its electric charge measurement
    - IV. Trigger system: muon PID and unlike sign dimuon trigger (for the quarkonium analyses)
  - Inclusive quarkonium detection down to $p_{\mathrm{T}} = 0$

A Large Ion Collider Experiment

- A dedicated heavy-ion experiment at the LHC
  - **V. Silicon Pixel Detector** (SPD, the two innermost ITS layers)
    - ↳ Vertex reconstruction
    - ↳ Multiplicity estimation
  - **VI. V0 Detectors** ($-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$)
    - ↳ Event trigger
    - ↳ Event characterization
    - ↳ Background rejection

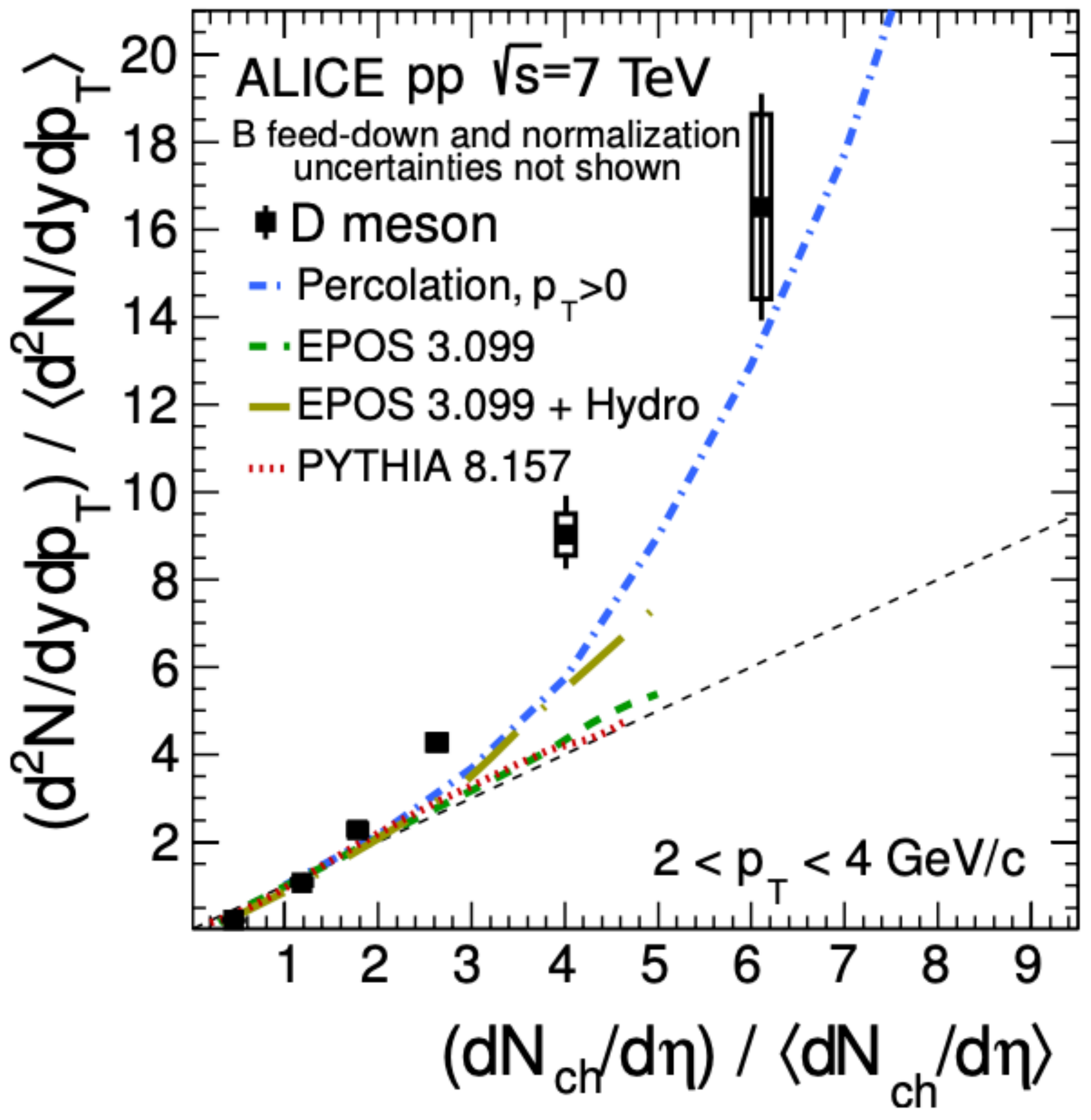


Multiplicity dependence of Υ production in pp collisions

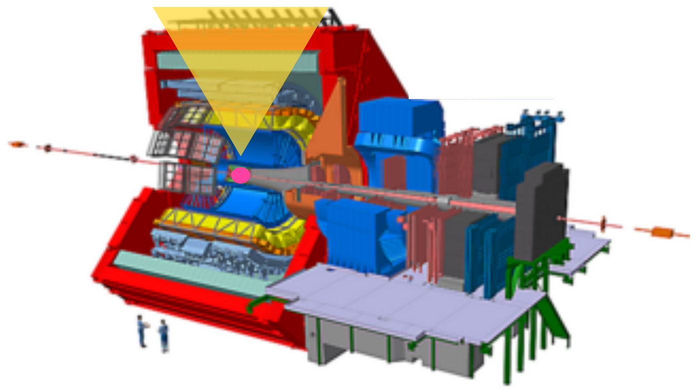
Introduction (I)

Multiplicity dependence of D-meson production in pp collisions

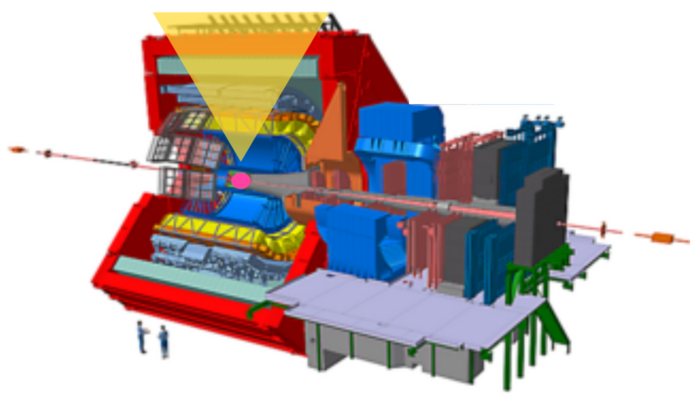
JHEP 09 (2015) 148



D-meson



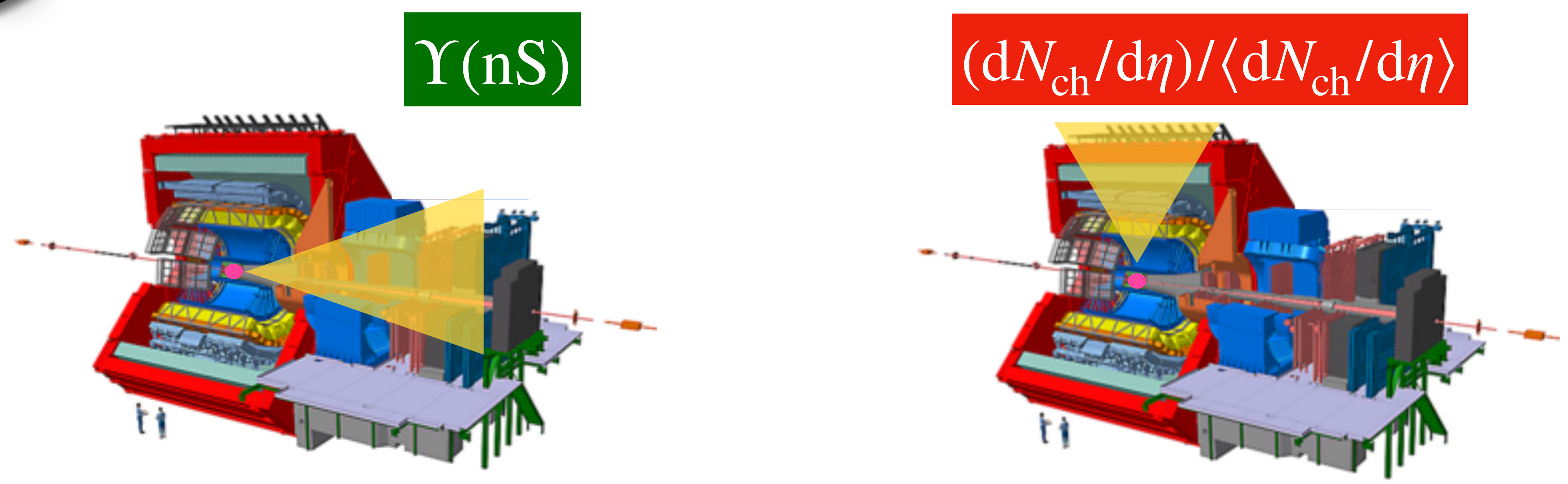
$(dN_{ch}/d\eta)/\langle dN_{ch}/d\eta \rangle$



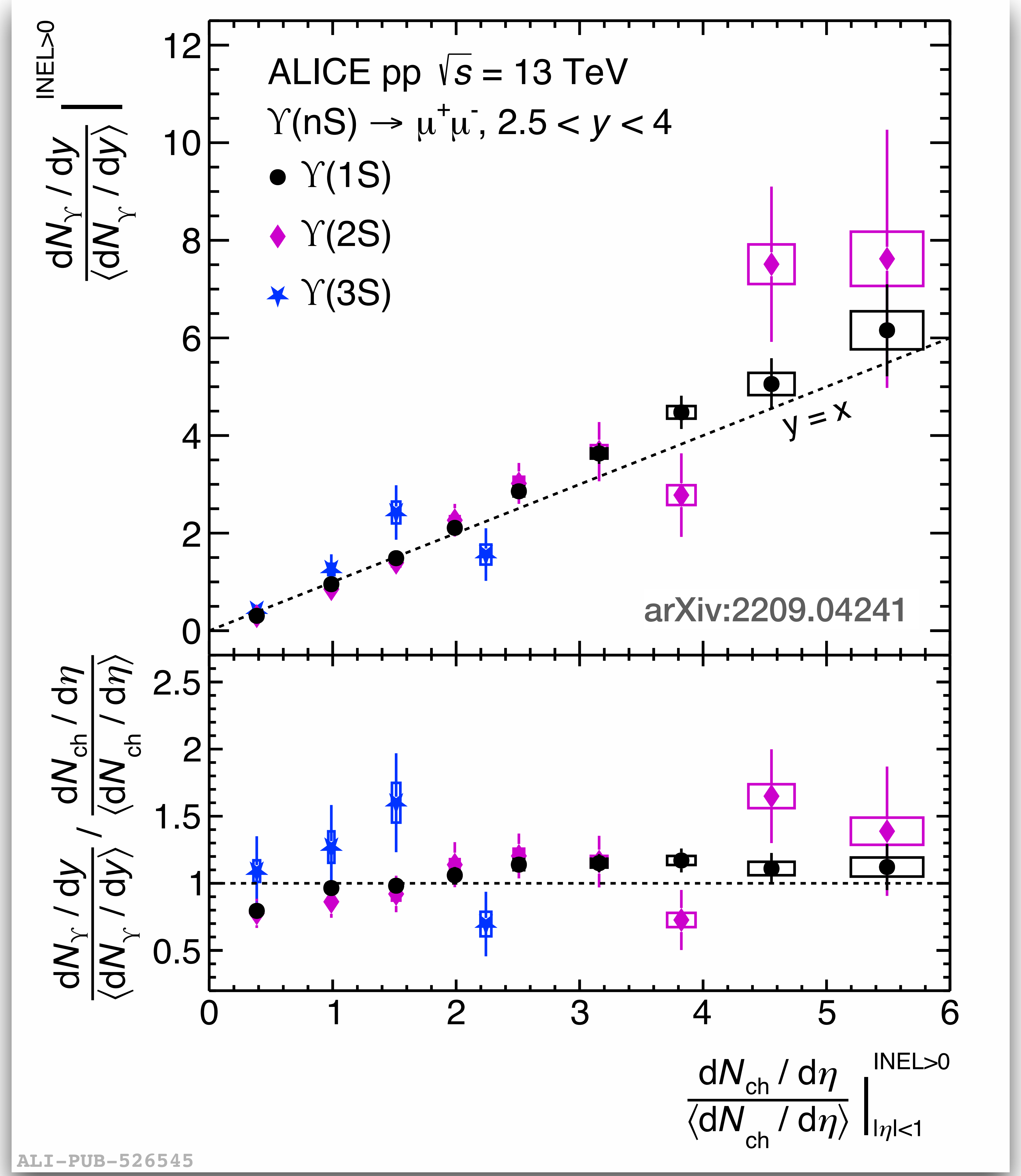
- D-meson self-normalized yields present a **stronger than linear increase** as a function of self-normalized charged-particle multiplicity, both measured at **midrapidity**
- Models, including Percolation and EPOS with hydrodynamical expansion, describe qualitatively the data trend
- Hint of collective effects in high charged-particle multiplicity events?

What about the multiplicity dependence of quarkonium production in small collision system?

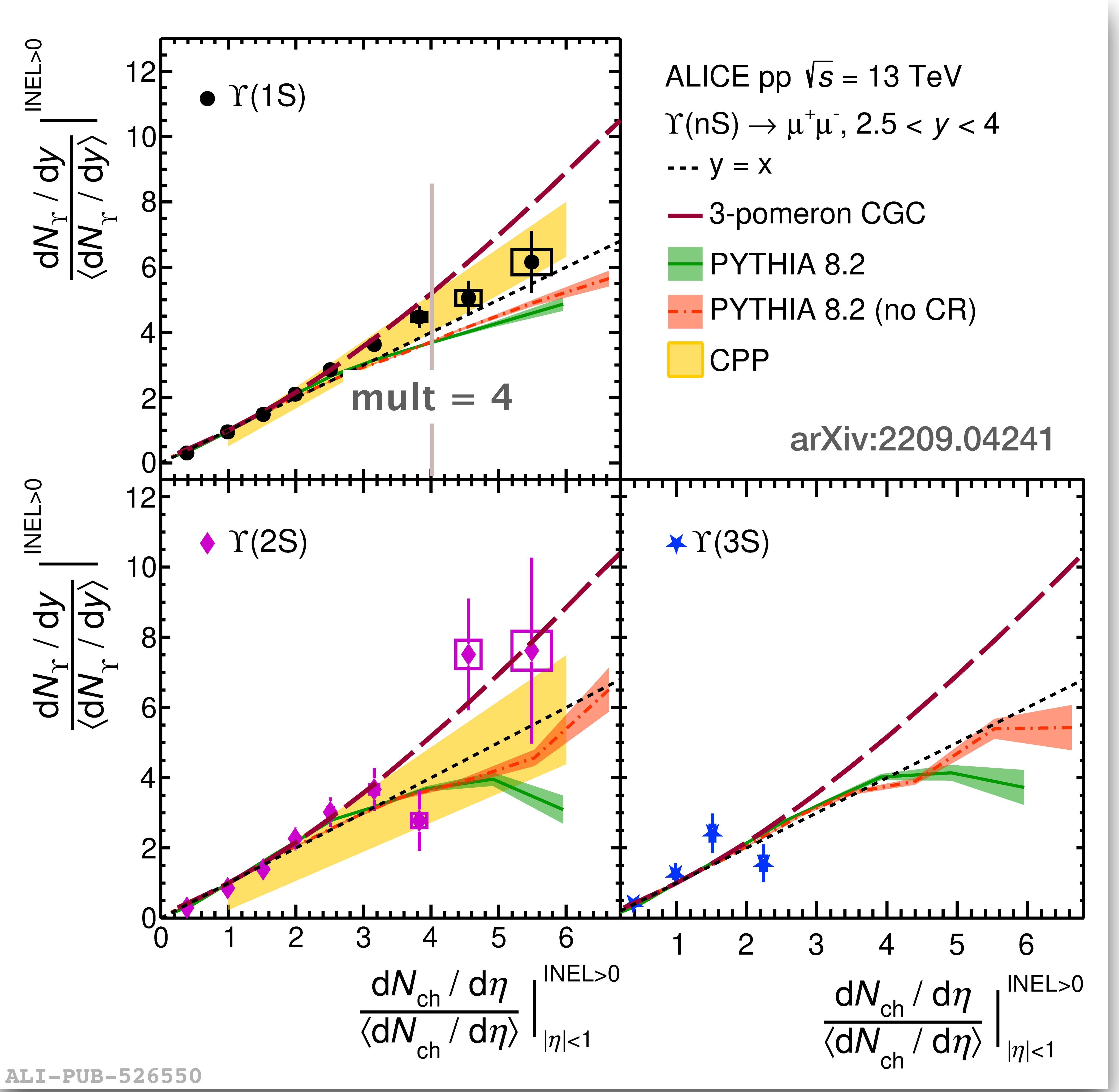
Υ production as a function of multiplicity



- Self-normalized $\Upsilon(1S)$ yield: ***linear increase*** with charged-particle multiplicity within uncertainties
- The linear trend results in a ***flat trend*** of the double ratio of the normalized $\Upsilon(1S)$ yield to the normalized multiplicity
- No firm conclusion can be drawn for the excited states [$\Upsilon(2S)$ and $\Upsilon(3S)$] due to the limited data sample



Υ production as a function of multiplicity

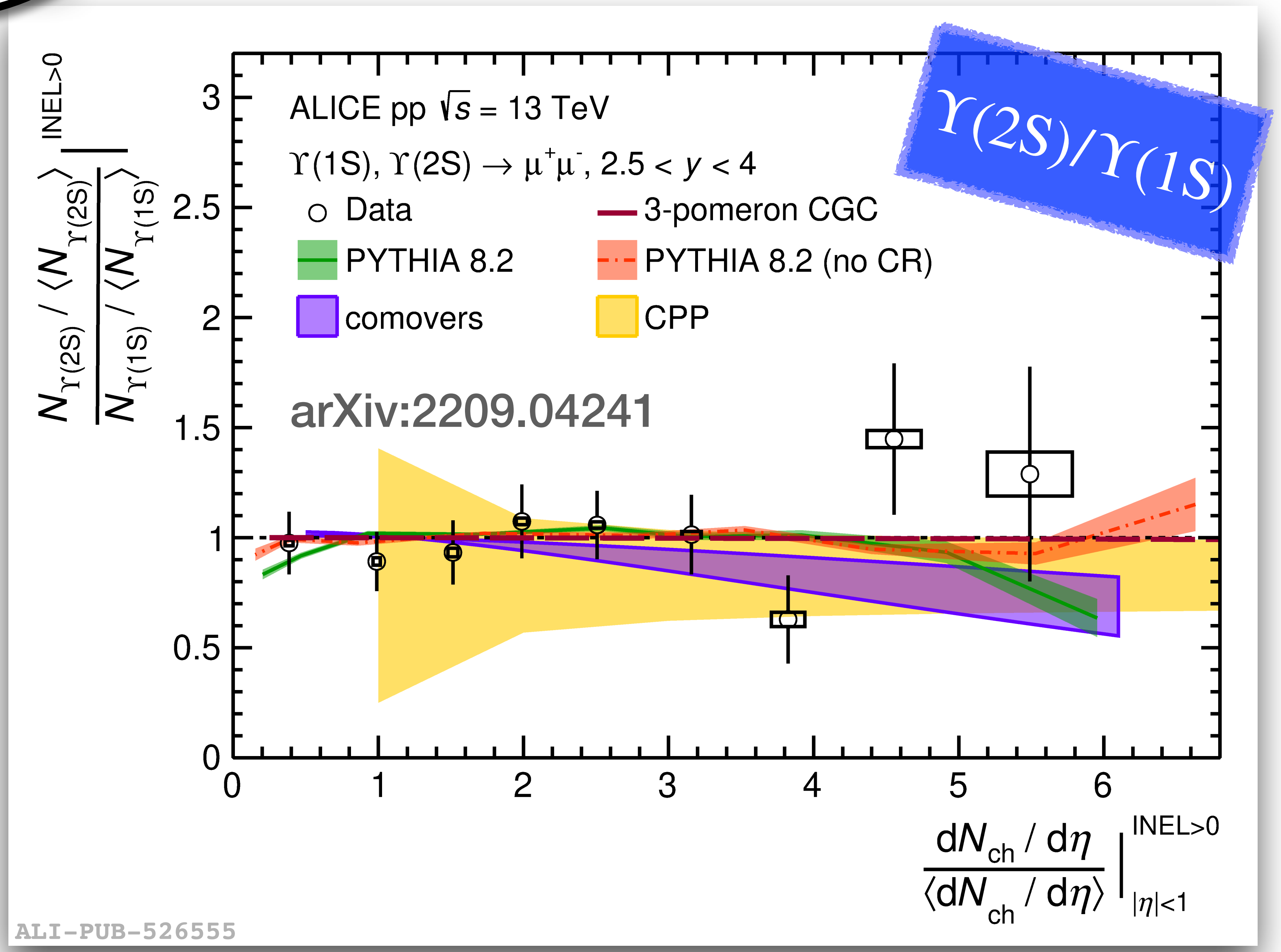


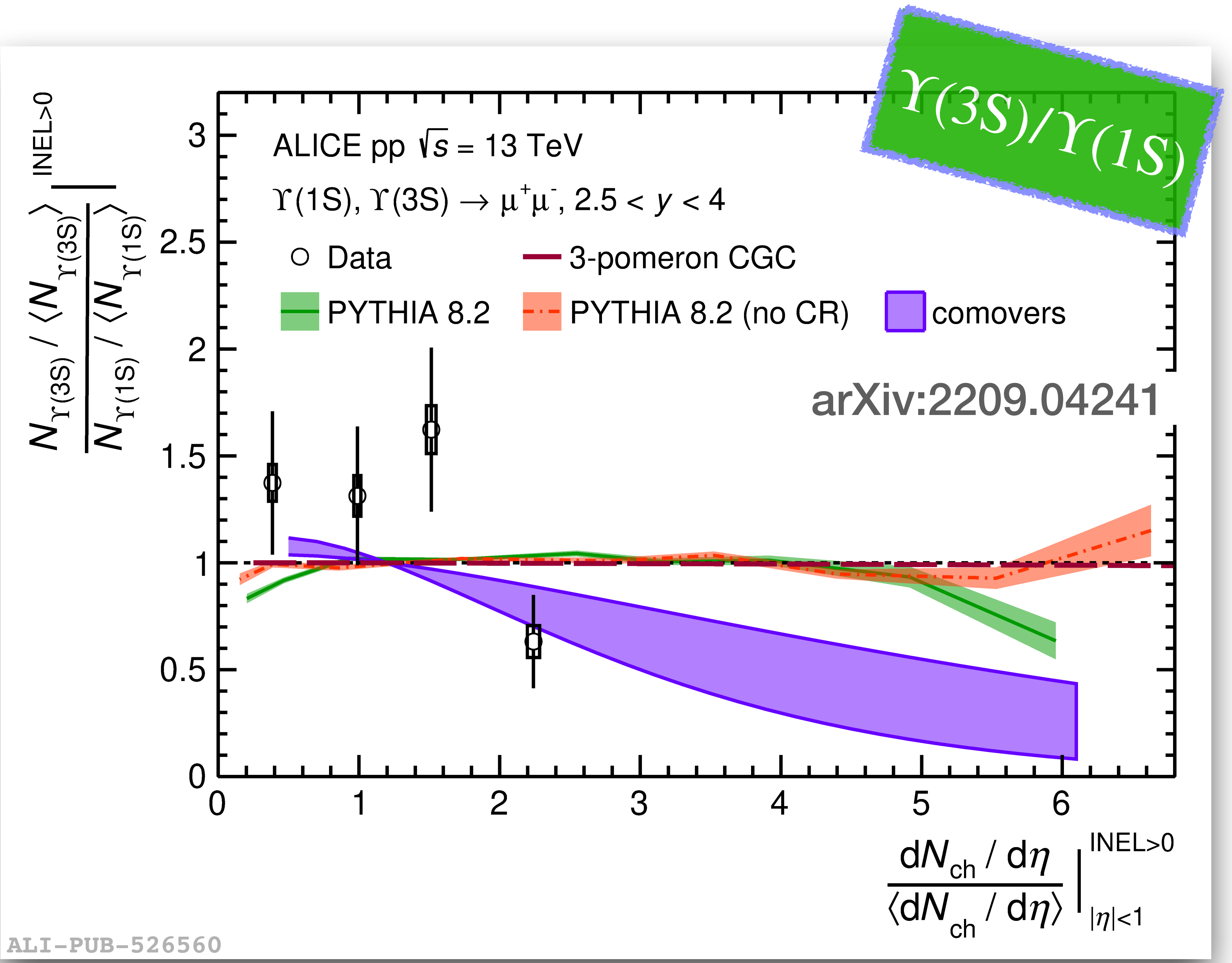
Model comparison

- The linear increase trend is qualitatively reproduced by Coherent Particle Production (CPP) within large uncertainties
- If $dN_{ch}/dy/\langle dN_{ch}/dy \rangle < 4$: the linear increase behavior is qualitatively reproduced by PYTHIA 8.2 (with or without CR), and 3-pomeron CGC approach
- If $dN_{ch}/dy/\langle dN_{ch}/dy \rangle > 4$: the theoretical computations diverge
  - 3-pomeron CGC overestimates the observed trend
  - PYTHIA 8.2 underestimates the data trend

Still lack of predictions for bottomonium studies!

Self-normalized yield ratio as a function of multiplicity

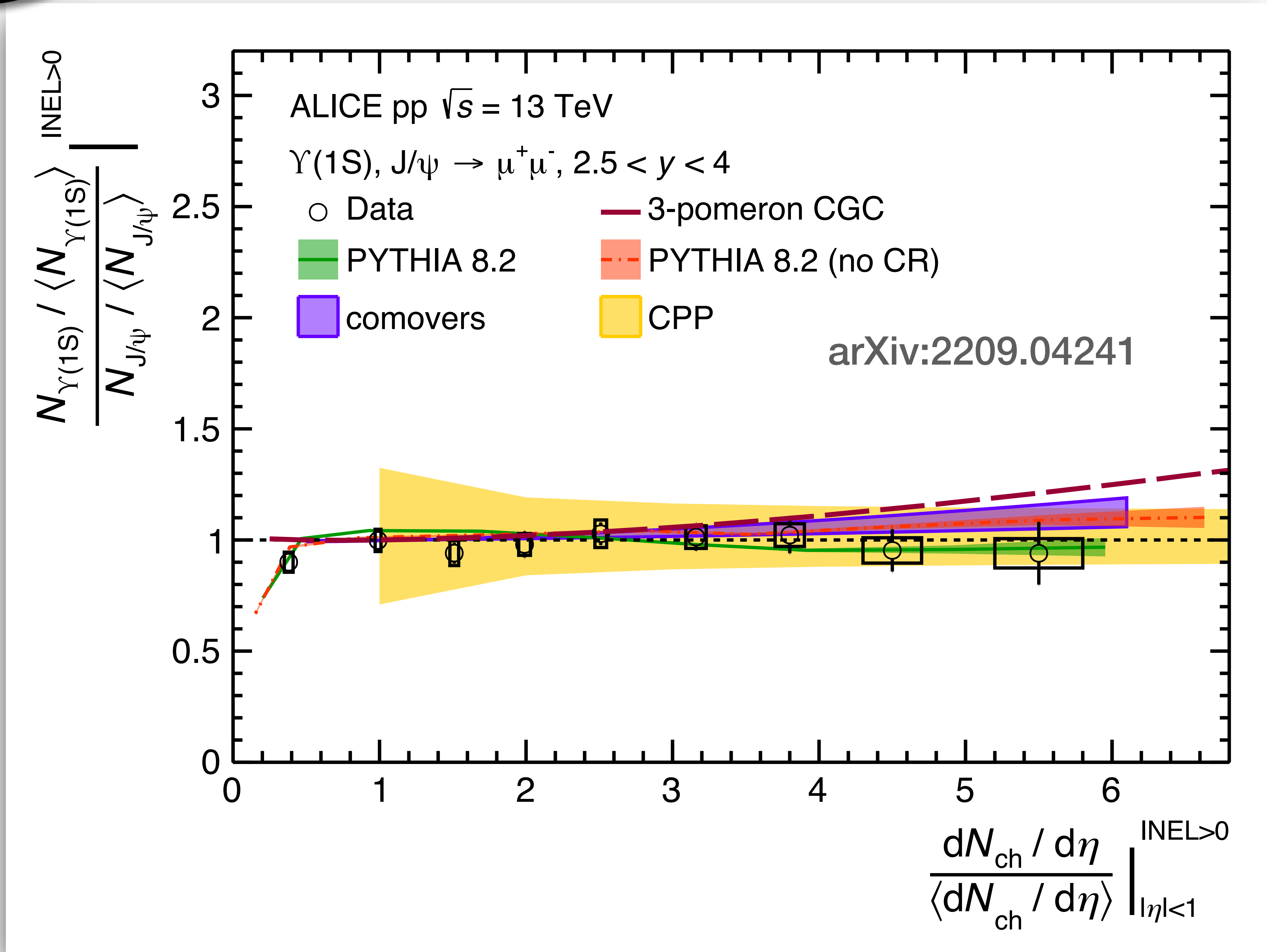


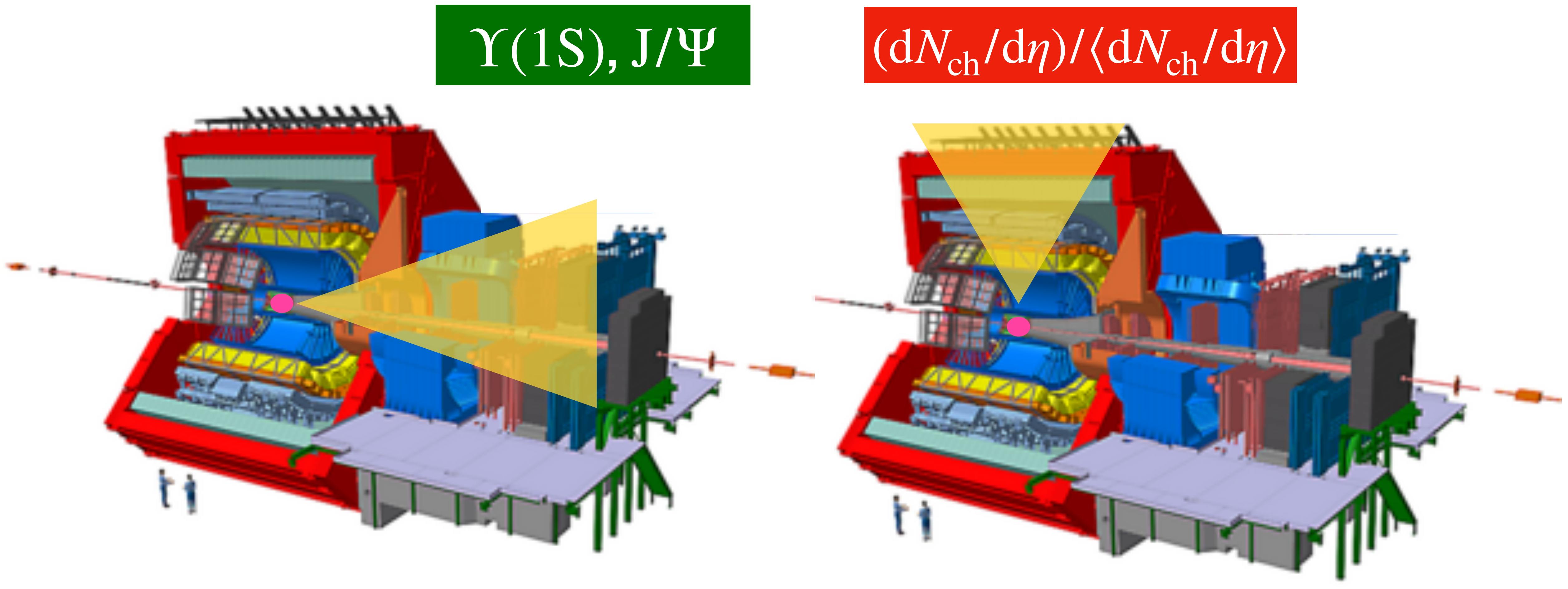


Double ratios (self-normalized signal yield ratios) of Υ(2S)/Υ(1S) and Υ(3S)/Υ(1S):

- Compatible with unity within the large uncertainties
- PYTHIA 8.2, CPP and 3-pomeron CGC calculations show a almost flat trend
- Comovers approach predicts a **dissociation** of the excited states, leading to a **suppression** at high multiplicity, especially for the Υ(3S)

Self-normalized yield ratio as a function of multiplicity





Double ratio of $\Upsilon(1S)/J/\Psi$:

- Compatible with unity within the current uncertainties
- The model computations are comparable with unity with uncertainties, indicating the **initial- and final-effects** act on $\Upsilon(1S)$ and J/Ψ in a similar way

$\Upsilon(1S)$ polarization in pp collisions

Introduction (II)

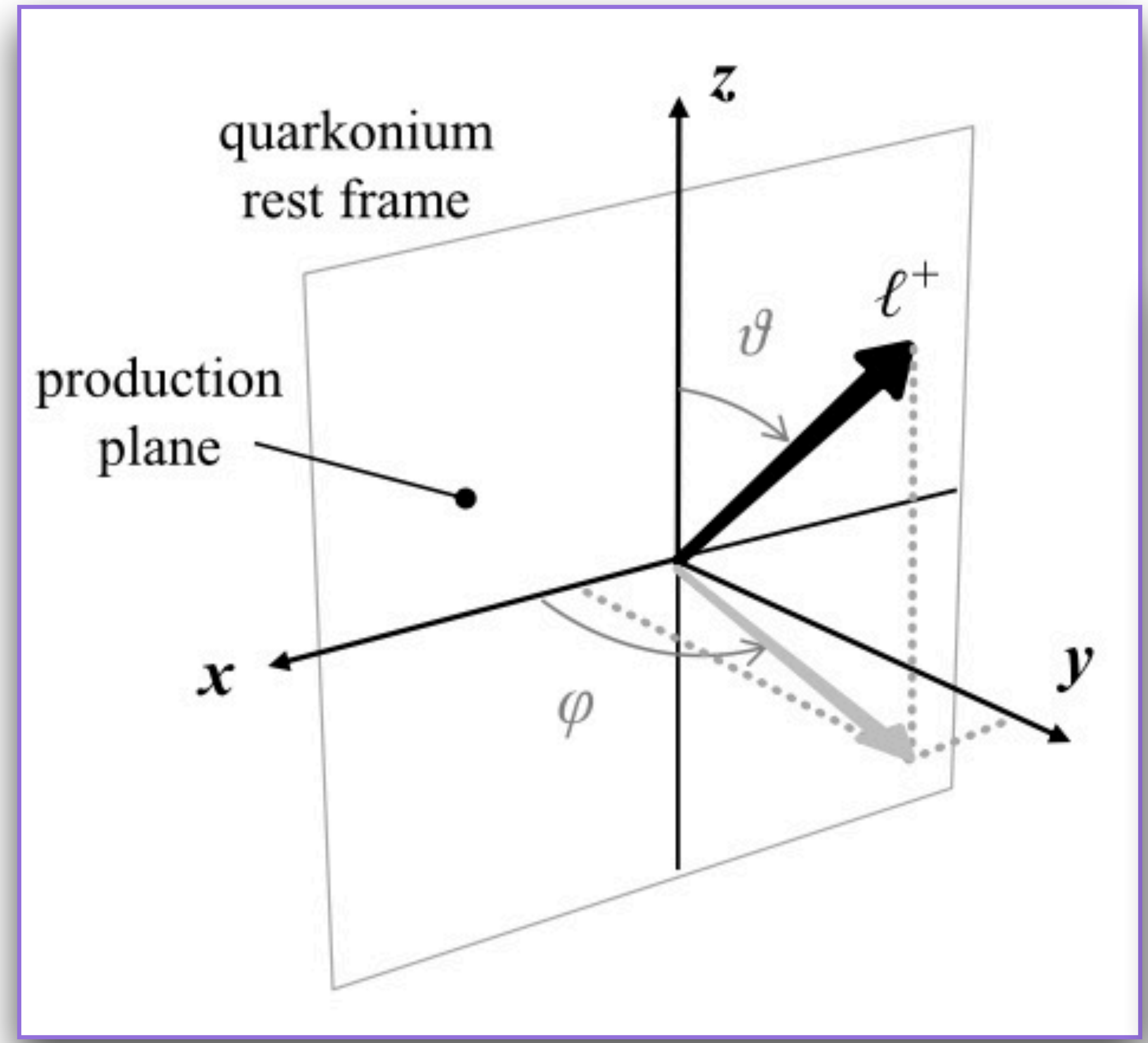
Quarkonium polarization

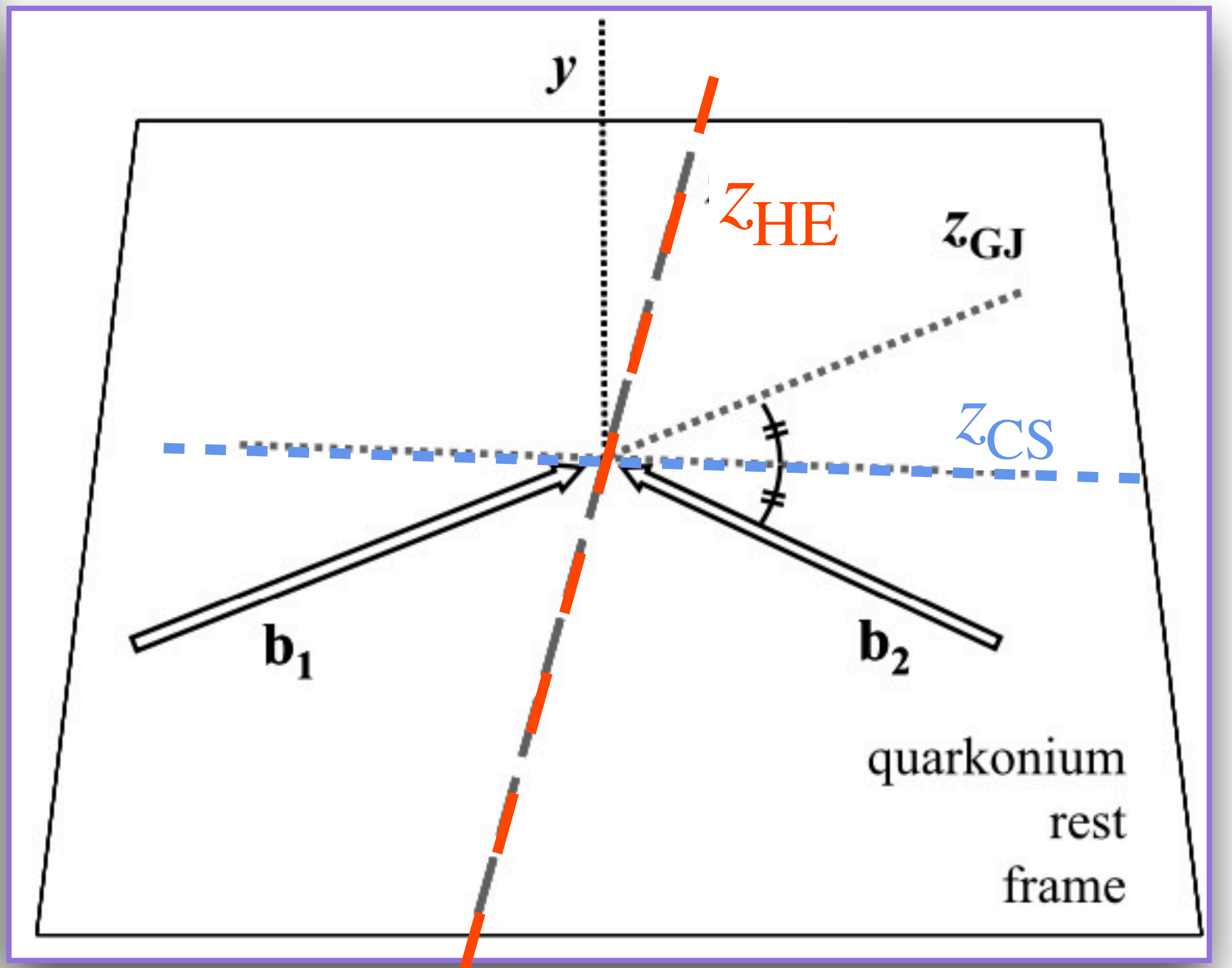
- Related to the particle spin-alignment with respect to a chosen direction
- Measured via anisotropies in the decay products angular distributions

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

→ **obtain λ_θ , λ_φ and $\lambda_{\theta\varphi}$**

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0, 0, 0)$	No polarization
$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (\pm 1, 0, 0)$	Pure transverse (+)/longitudinal (-) polarization





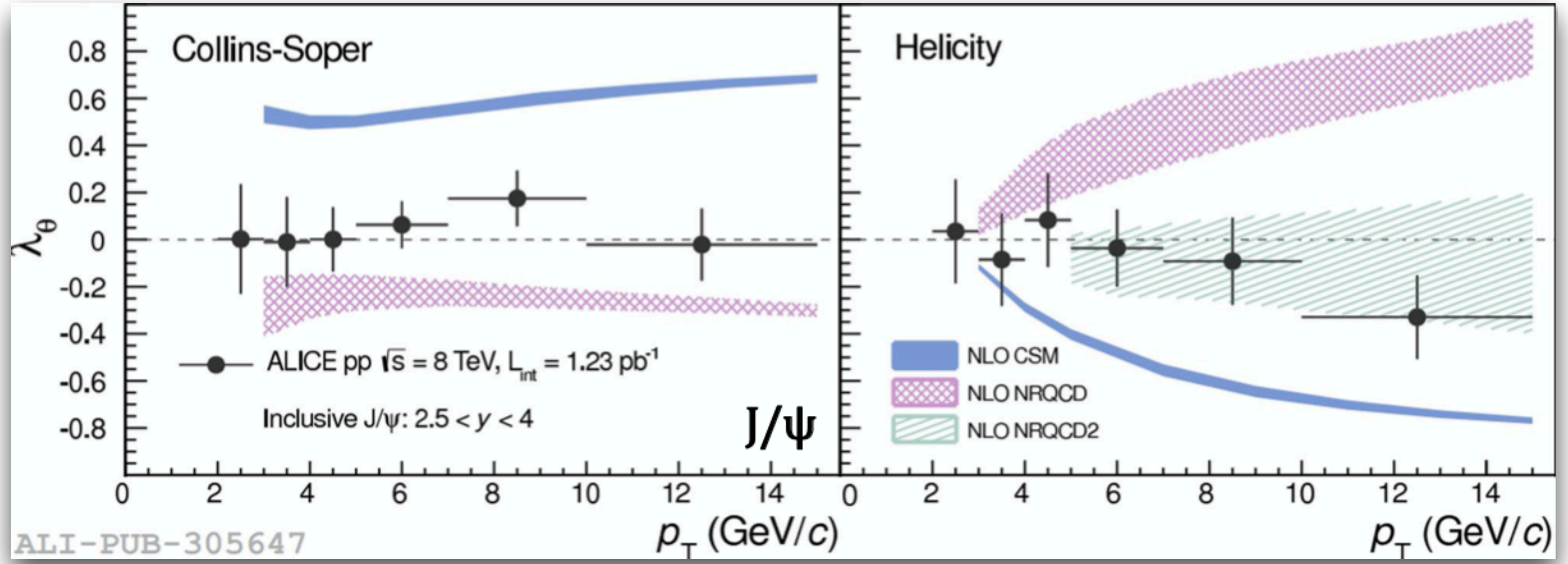
- Reference frames:
  - Helicity (HE): the direction of quarkonium in the center-of-mass frame
  - Collins-Soper (CS): the bisector of the angle between the direction of one beam and the opposite of the other beam in the quarkonium rest frame

Introduction (II)

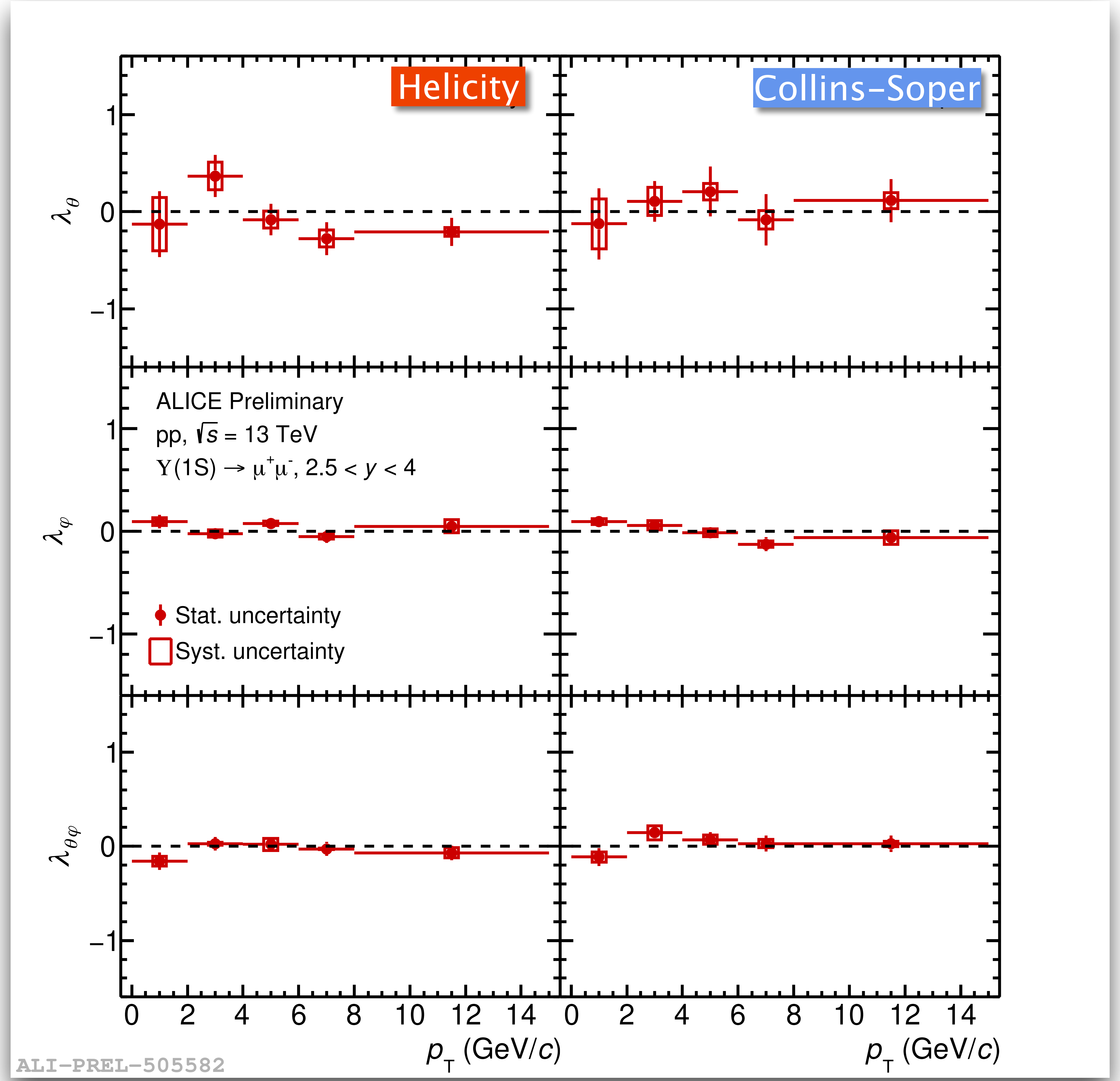
Polarization in pp collisions: **constrain quarkonium production mechanisms**

- No sizeable polarization is observed for the J/ψ polarization measurement in pp collisions
- Theoretical calculations for J/ψ:
  - **NLO NRQCD** —> transverse (longitudinal) polarization in Helicity (Collins-Soper) frame
  - **NLO CSM** —> longitudinal (transverse) polarization in Helicity (Collins-Soper) frame

M. Butenschoen *et al.*, *Phys. Rev. Lett.* 108 (2012) 172002

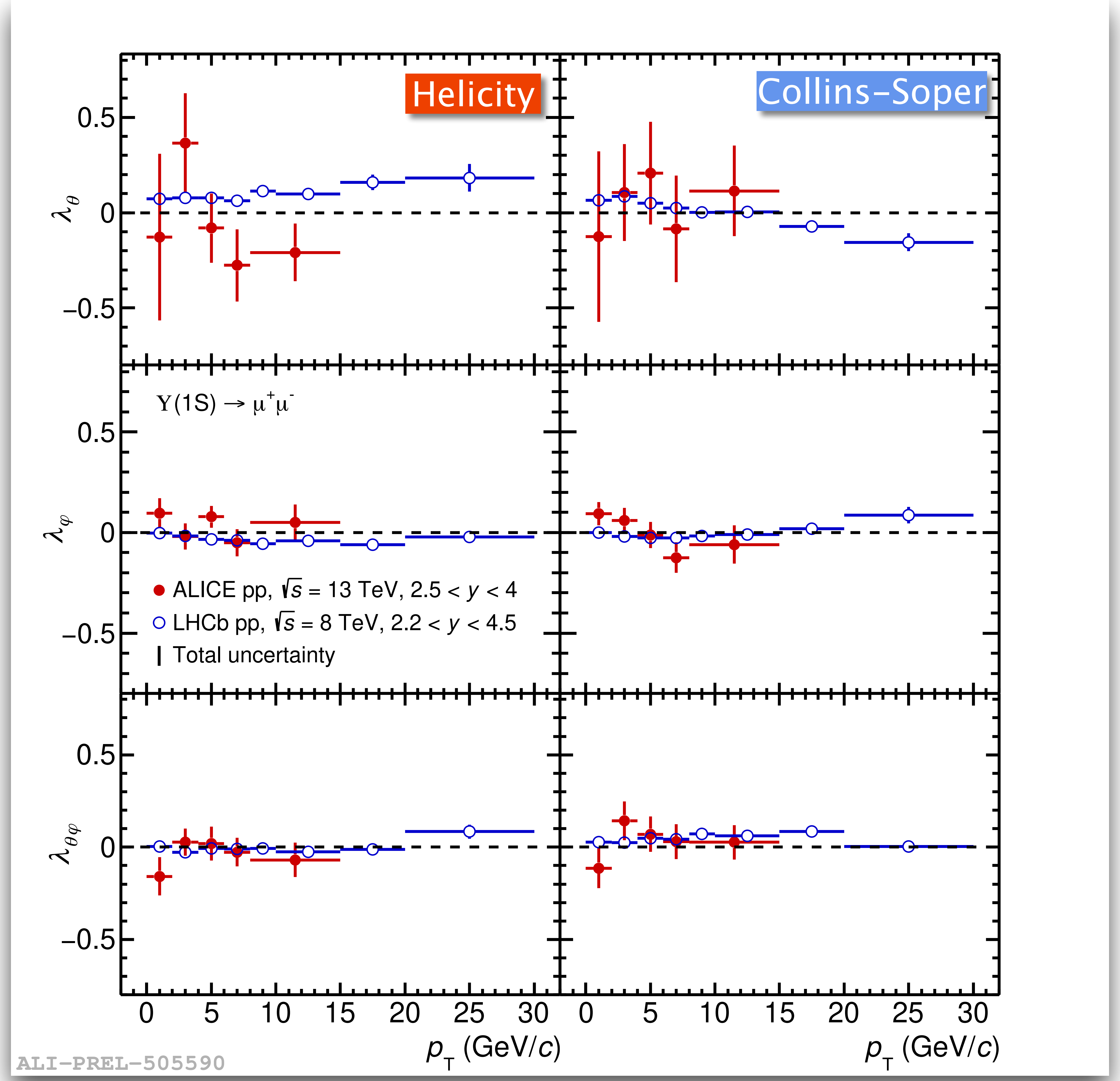


$\Upsilon(1S)$ polarization as a function of transverse momentum



- First ALICE $\Upsilon(1S)$ polarization measurement in pp collisions
  - λ_θ compatible with zero (maximum deviation of 1.5σ *w.r.t* zero) in both **HE** and **CS** frames
  - λ_φ and $\lambda_{\theta\varphi}$ consistent with zero within uncertainties in both frames

Υ(1S) polarization as a function of transverse momentum

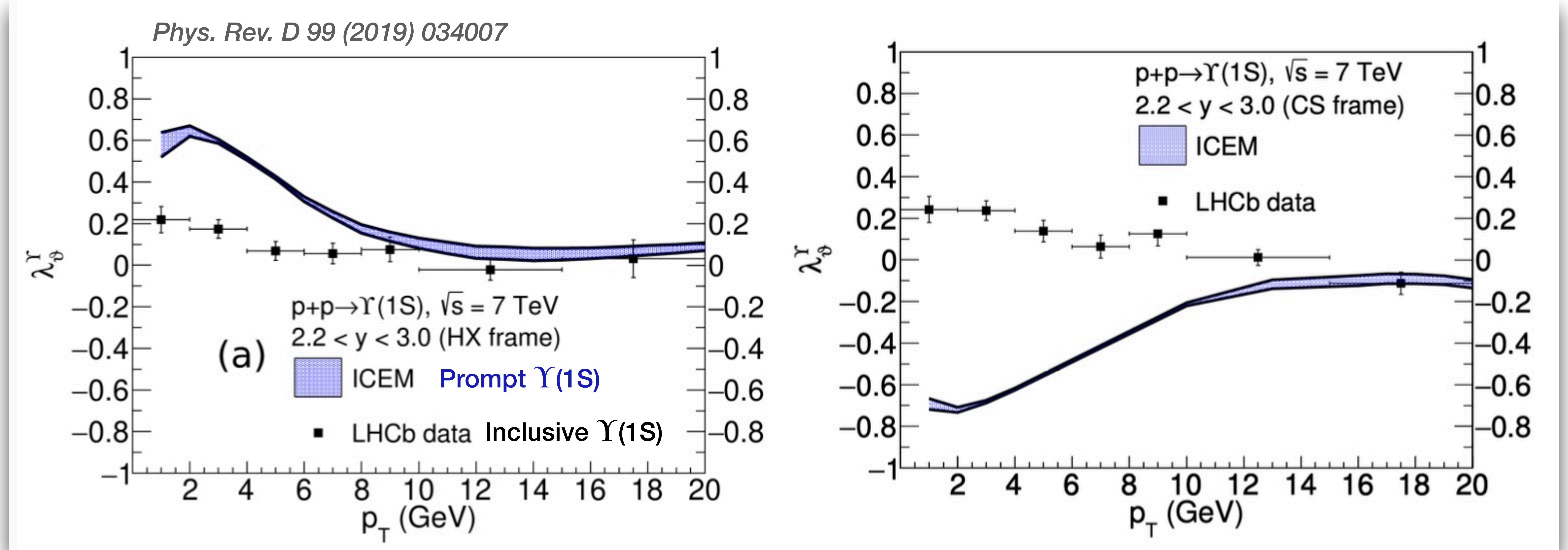


- First ALICE $\Upsilon(1S)$ polarization measurement in pp collisions
  - λ_θ , λ_φ and $\lambda_{\theta\varphi}$ consistent with zero within uncertainties in both **HE** and **CS** frames
  - Good agreement with **LHCb** pp data at $\sqrt{s}$ = 8 TeV, in a similar rapidity range, within the large experimental uncertainties

    LHCb Collaboration, *JHEP* 12 (2017) 110
  - Qualitatively described by **NLO NRQCD** calculations

    M. Butenschoen *et al.*, *Phys. Rev. Lett.* 108 (2012) 172002

Υ(1S) polarization as a function of transverse momentum



- **Improved Color Evaporation Model (ICEM):** using the k_{T} factorization approach
  - At low p_{T}, the polarization is slightly transverse in the HX frame, while it is slightly longitudinal in the CS frame
  - At high p_{T}, unpolarization is expected in both frames —> **consistent with the LHCb data**

Full theoretical description is still missing

LHCb Collaboration, *JHEP* 12 (2017) 110

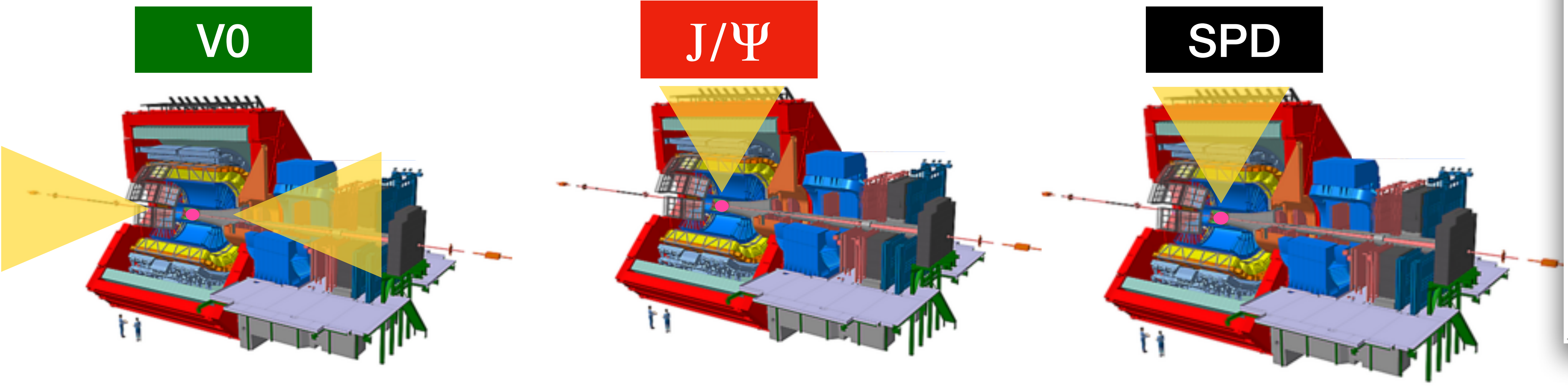
Summary

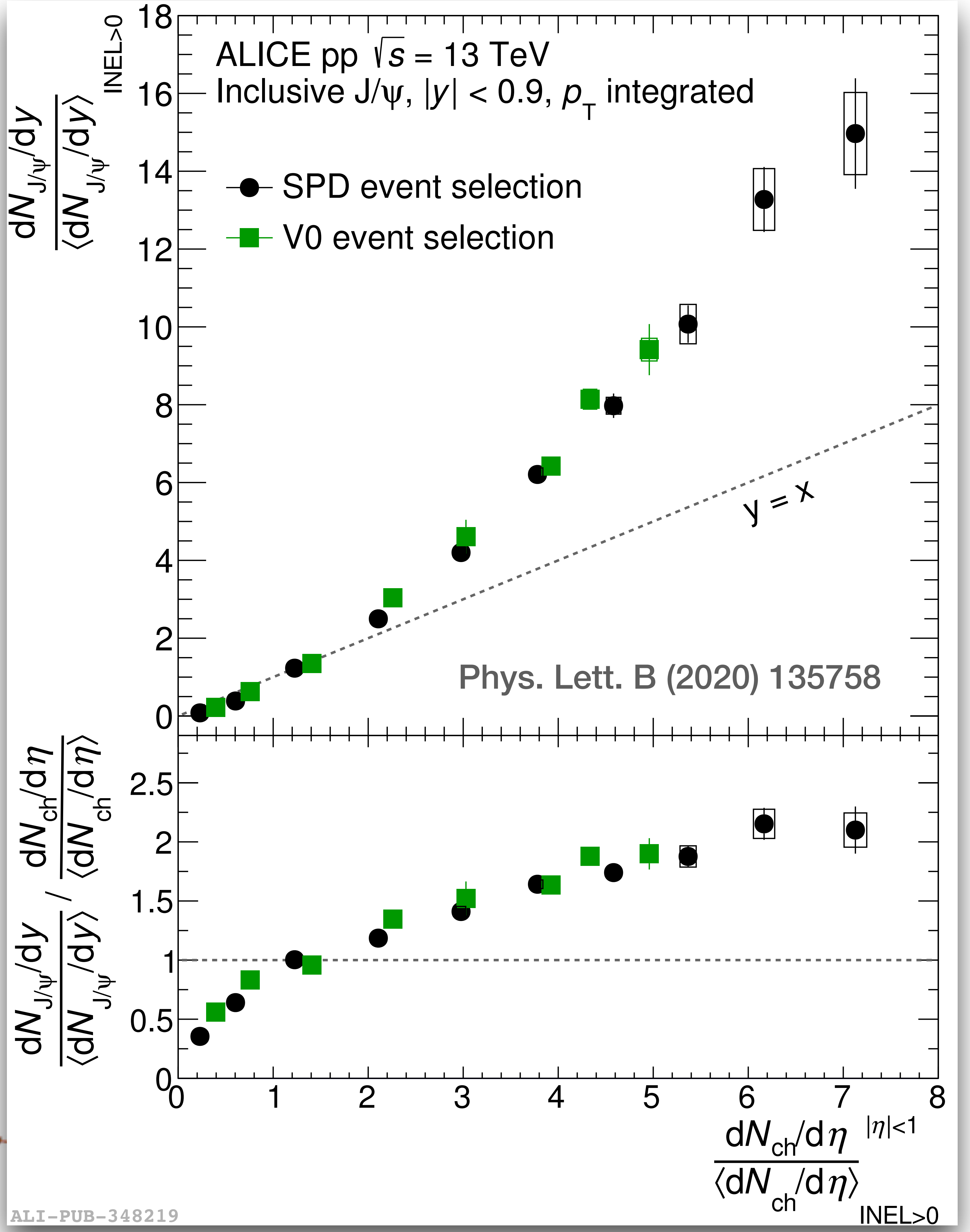
- Multiplicity dependence of Υ production at forward rapidity has been measured with ALICE
  - Self-normalized Υ yield shows a linear increase with increasing multiplicity
  - The results are compared to the model predictions (initial- and/or final-state effects)
- No significant polarization is observed for Υ(1S) in pp collisions


Merci

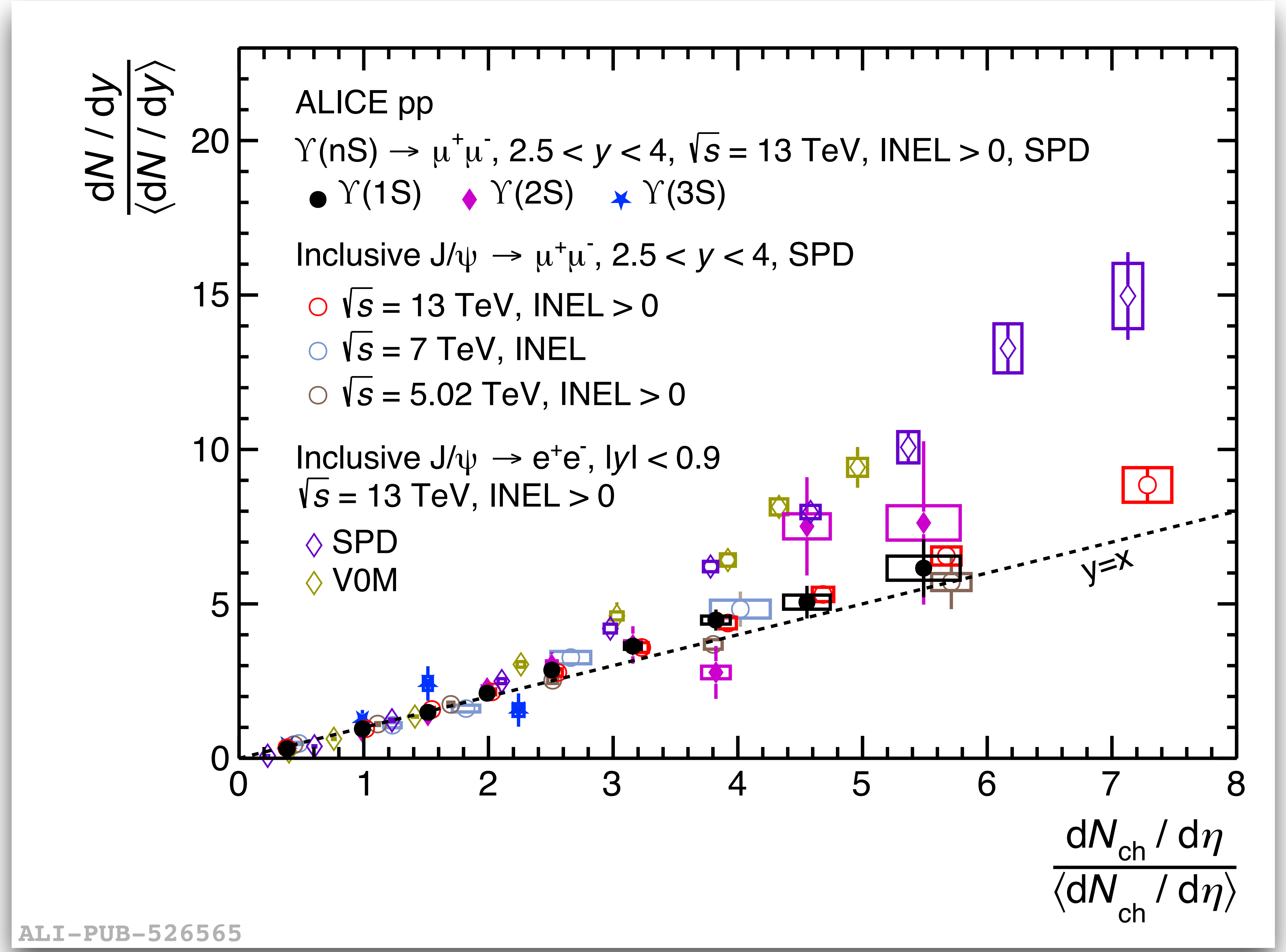
Midrapidity J/Ψ as a function of multiplicity

- J/Ψ measured at the midrapidity as a function of self-normalized multiplicity
  - **Stronger** than linear increase with multiplicity at ***mid- (SPD)*** or ***forward (V0)*** rapidity
  - Unlike what is observed for the J/Ψ measured at the forward rapidity

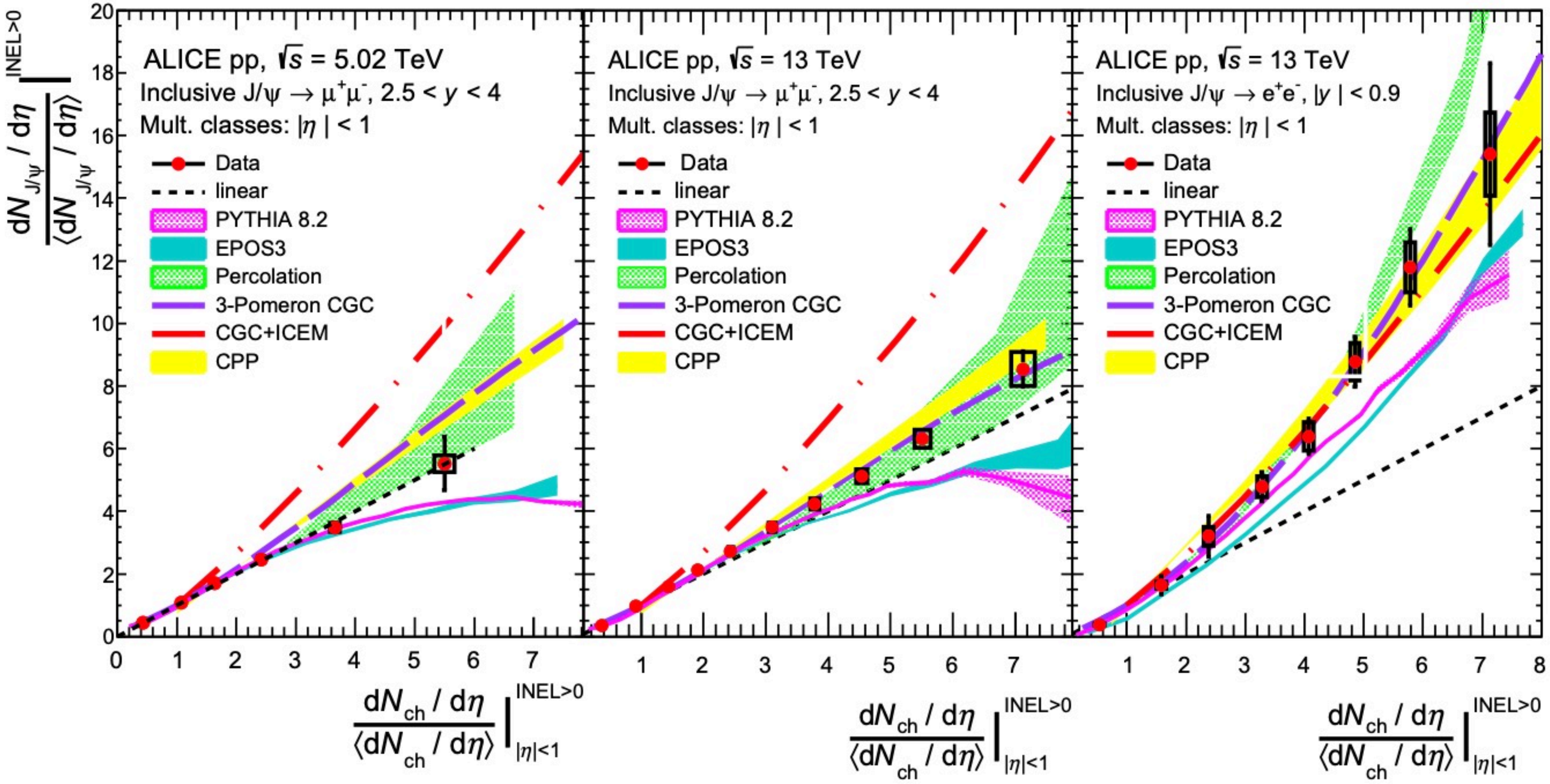




J/ψ production in pp (ALICE)



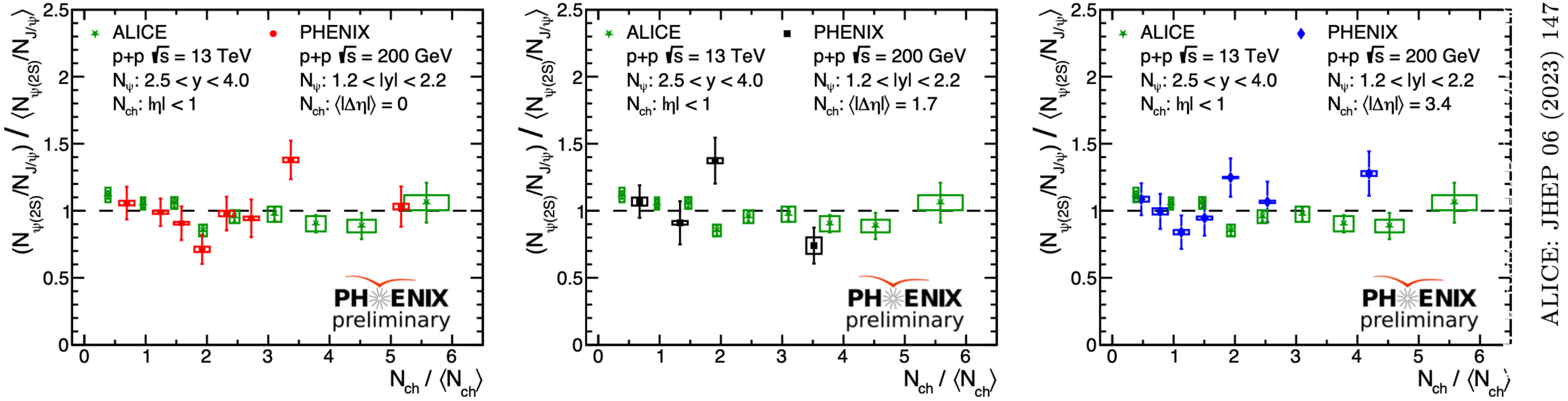
J/ψ production in pp (ALICE)



Percolation model: **color string interaction**s to describe p+p collisions

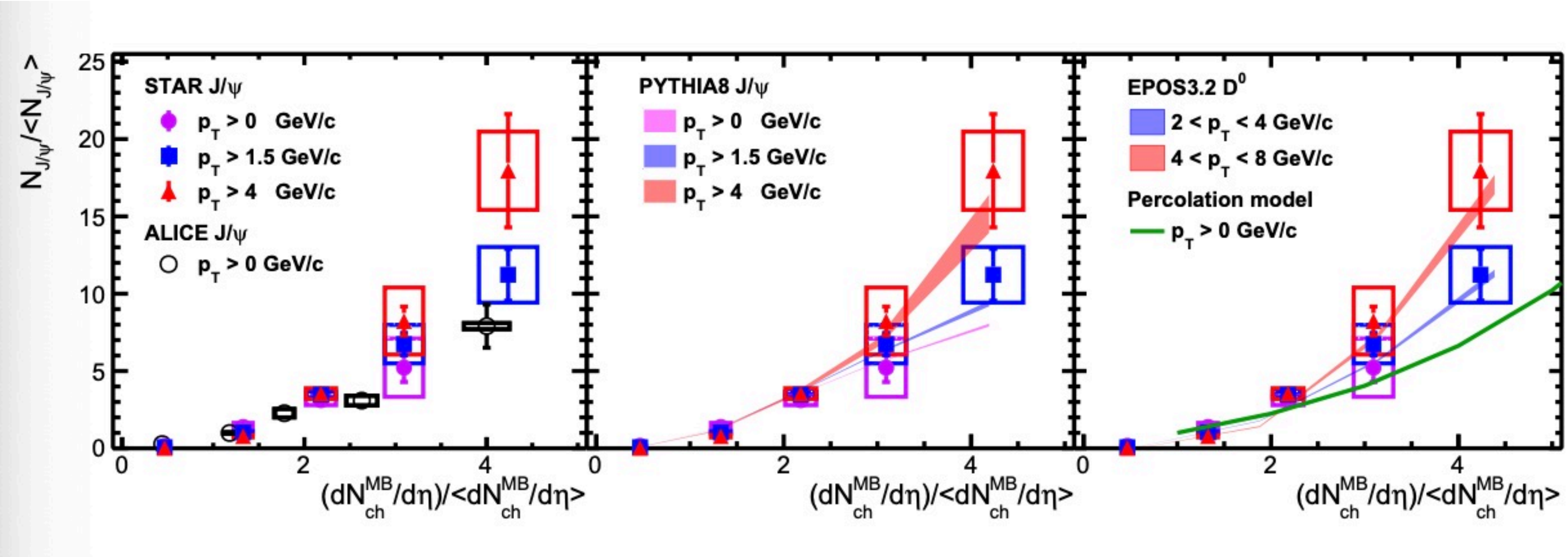
In a high-density environment, the coherence among the sources of the color strings leads to a reduction of their effective number. The total charged-particle multiplicity, which originates from soft sources, is more reduced than heavy-particle production for which the sources have a smaller transverse size

Multiplicity Dependent $\psi(2S)$ to J/ψ



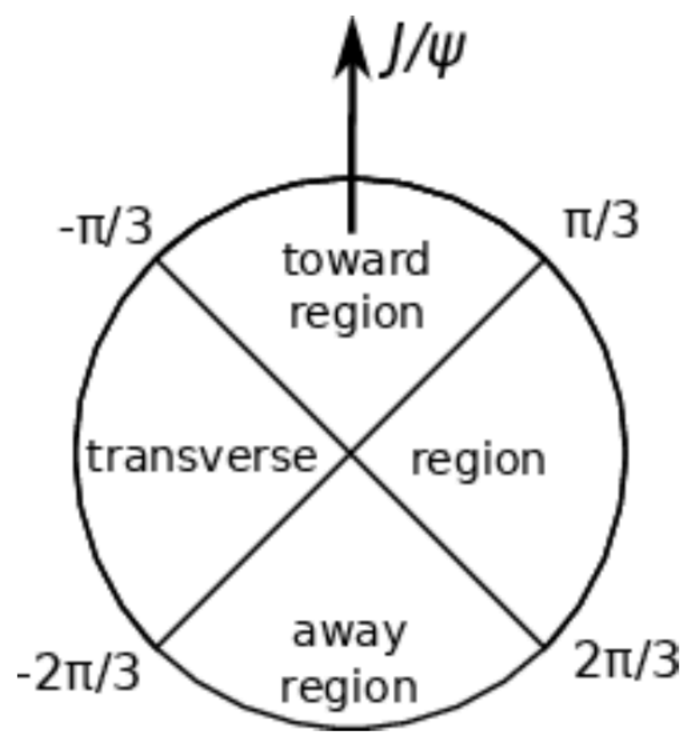
- Multiplicity-dependent studies in small systems provide a testing ground for examining the onset of QGP-like effects
- PHENIX ($\sqrt{s_{NN}}$=200 GeV) and ALICE ($\sqrt{s_{NN}}$=13 TeV) results consistent, with **weak multiplicity dependence more or less consistent with unity**
  - Note that ALICE results have charged particle multiplicity measured at mid-rapidity

J/ψ production in pp (STAR)



Regions of azimuthal angle

Region for each track defined from angle φ between the track and J/ψ candidate



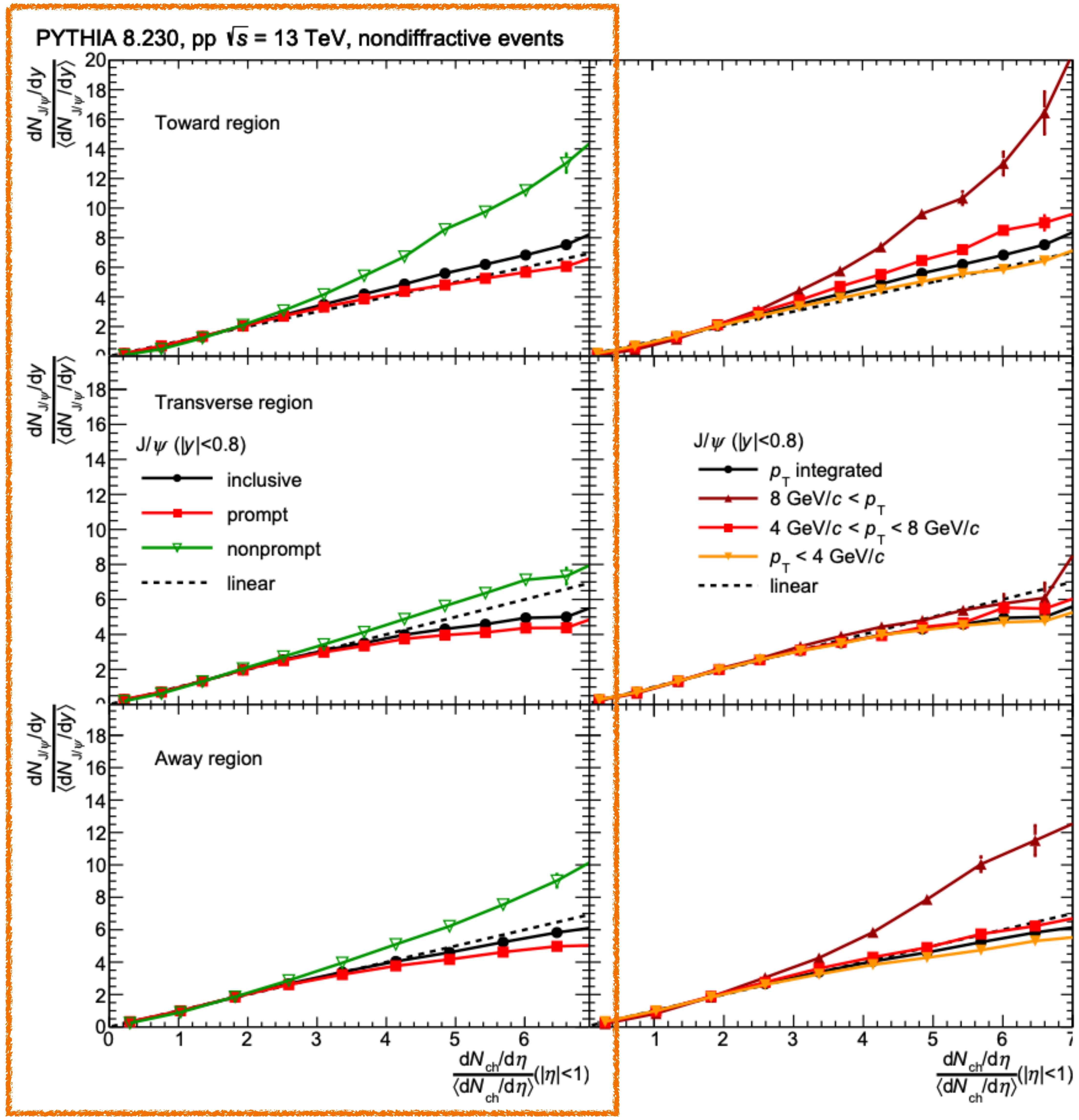
Isolate different effects in different regions:

- **Toward**: particles associated to J/ψ production
- **Transverse**: underlying event
- **Away**: recoil jet

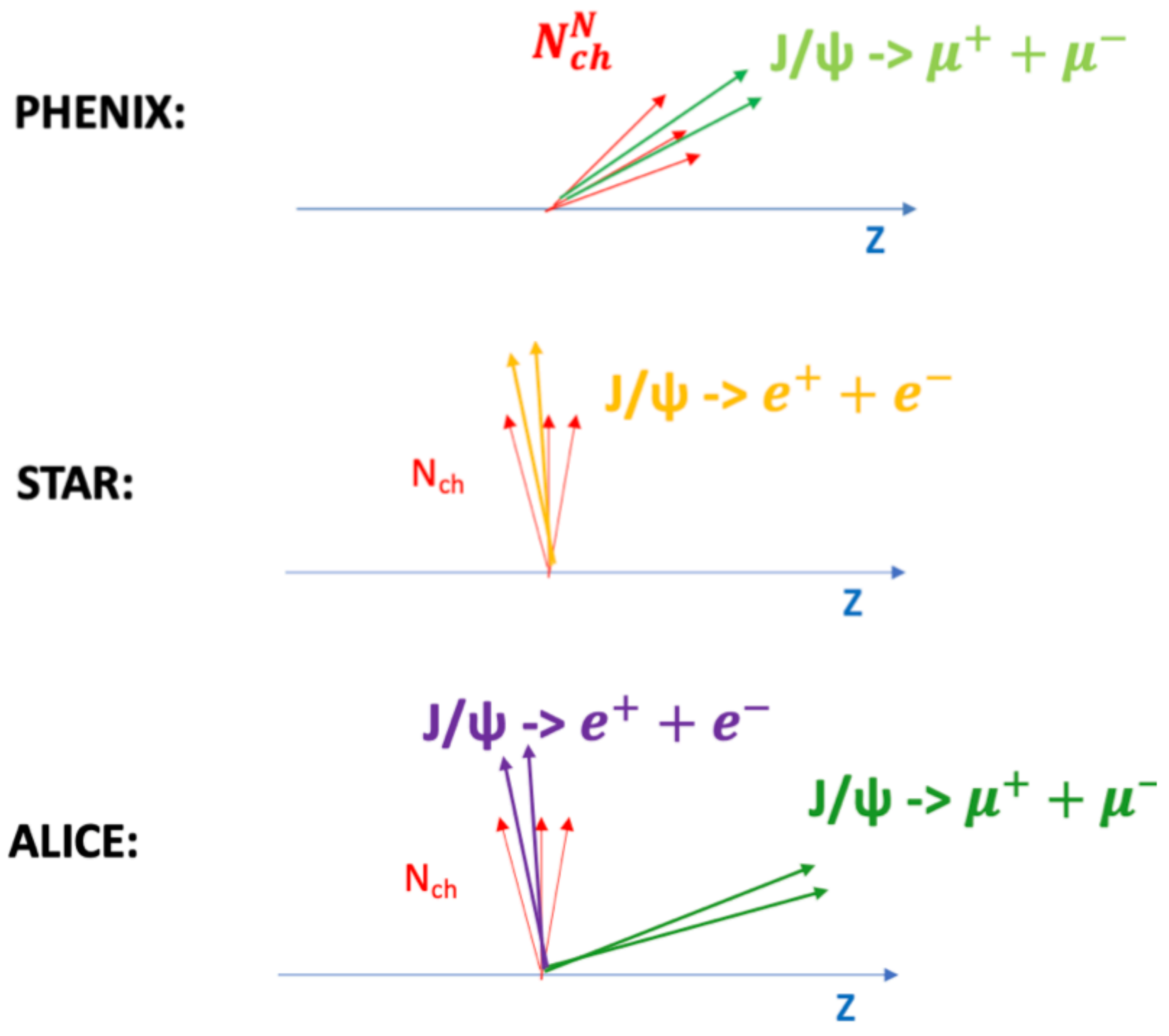
Regions constructed regarding a pair candidate J/ψ and not precisely a J/ψ $\rightarrow$ **Would this influence the results?**

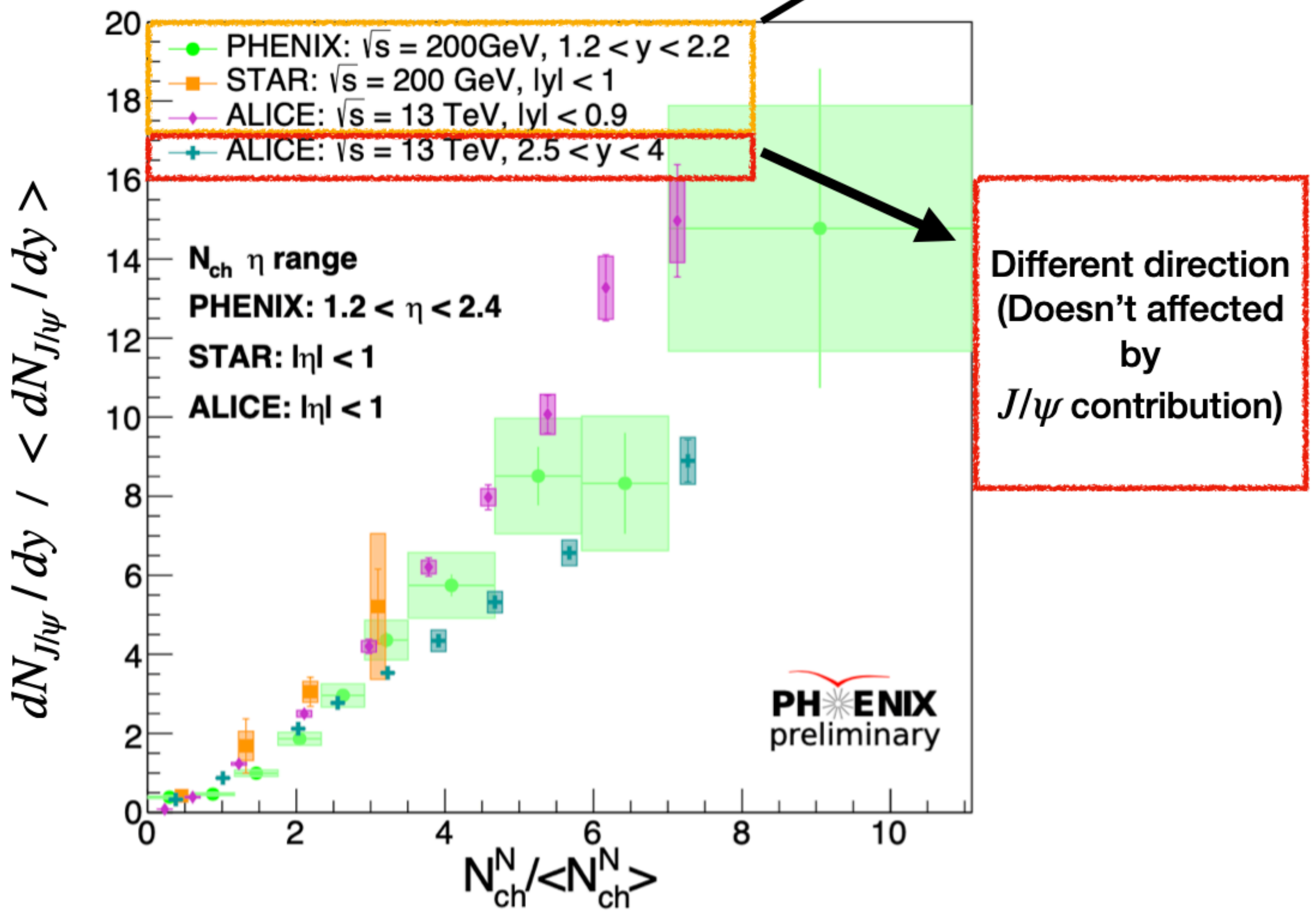
J/ψ production in pp (PYTHIA)

Pythia prediction (only one parsonic interaction activated)
Eur. Phys. J. C 79, 36 (2019)



3. PHENIX Results

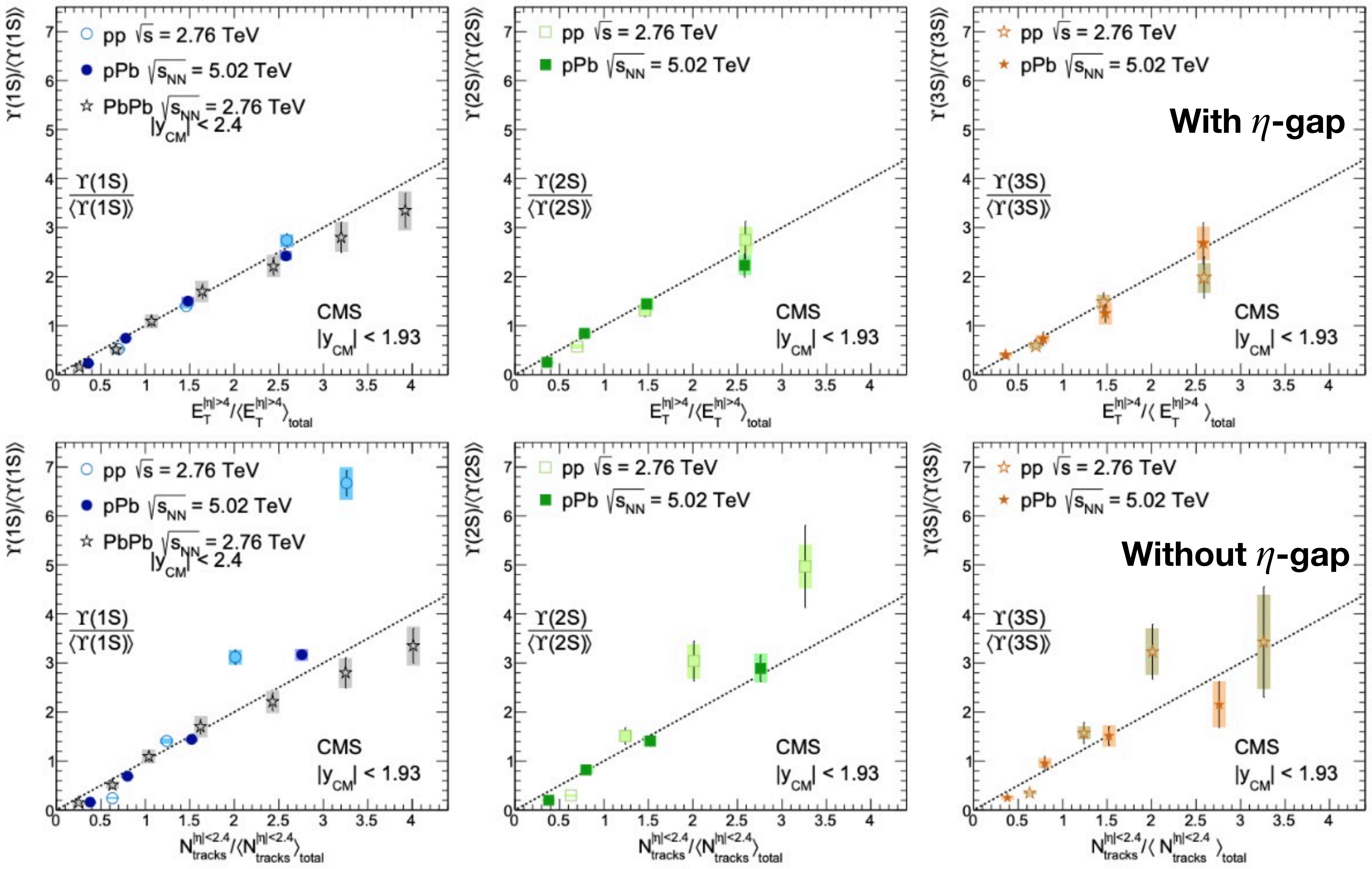




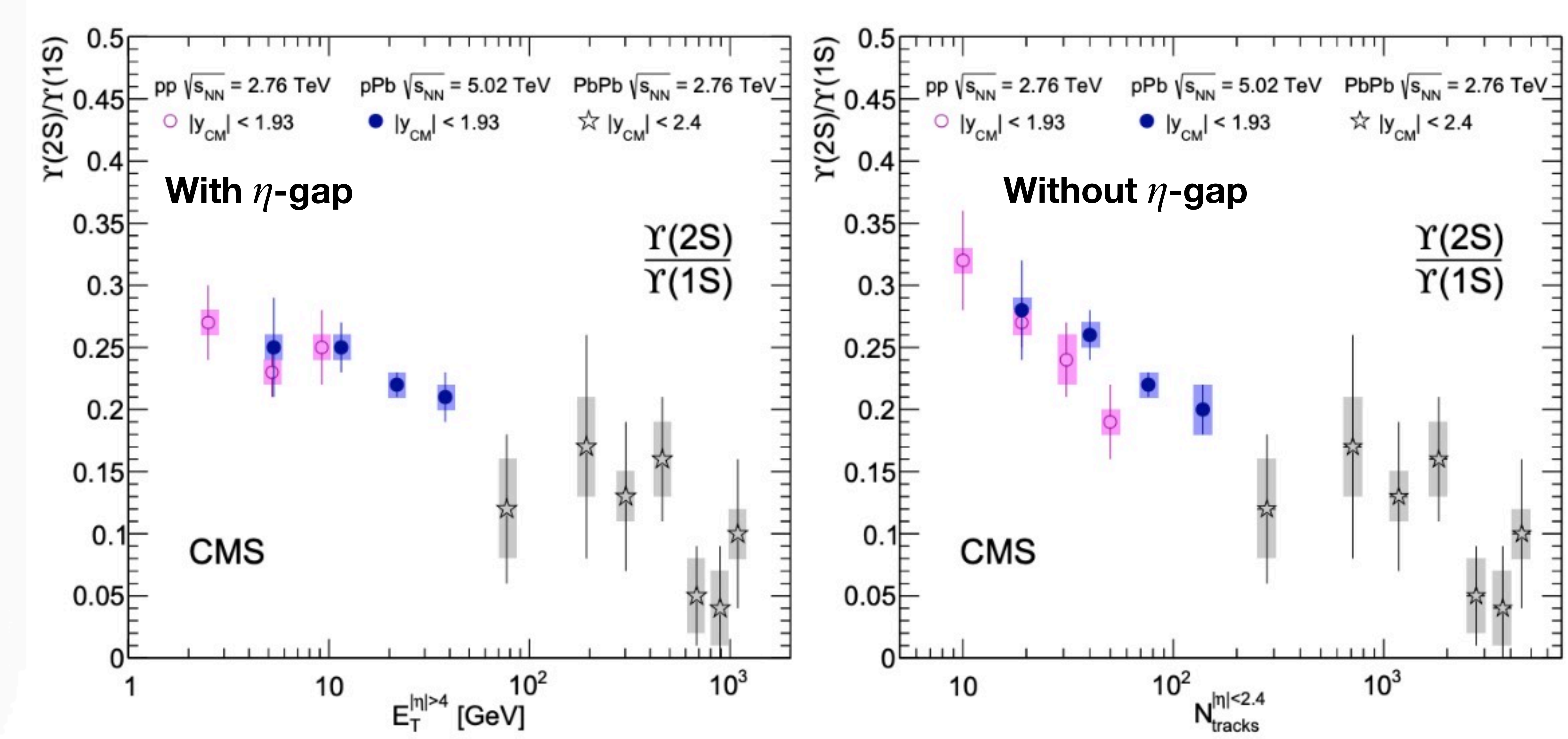
- PHENIX, STAR, ALICE (Measuring multiplicity at the same acceptance with J/ψ)
  → Similar multiplicity dependence despite different center-of-mass energy

J/ψ production in pp (CMS)

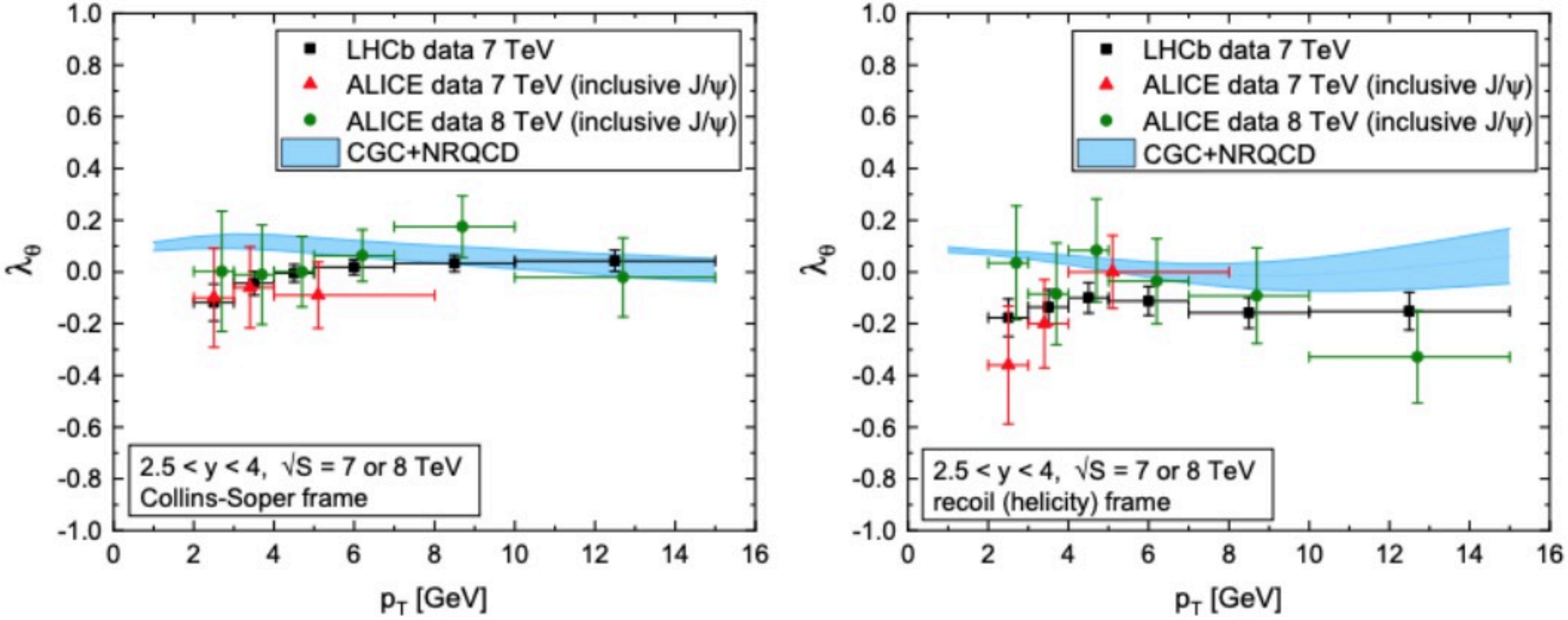
Cross section ratio



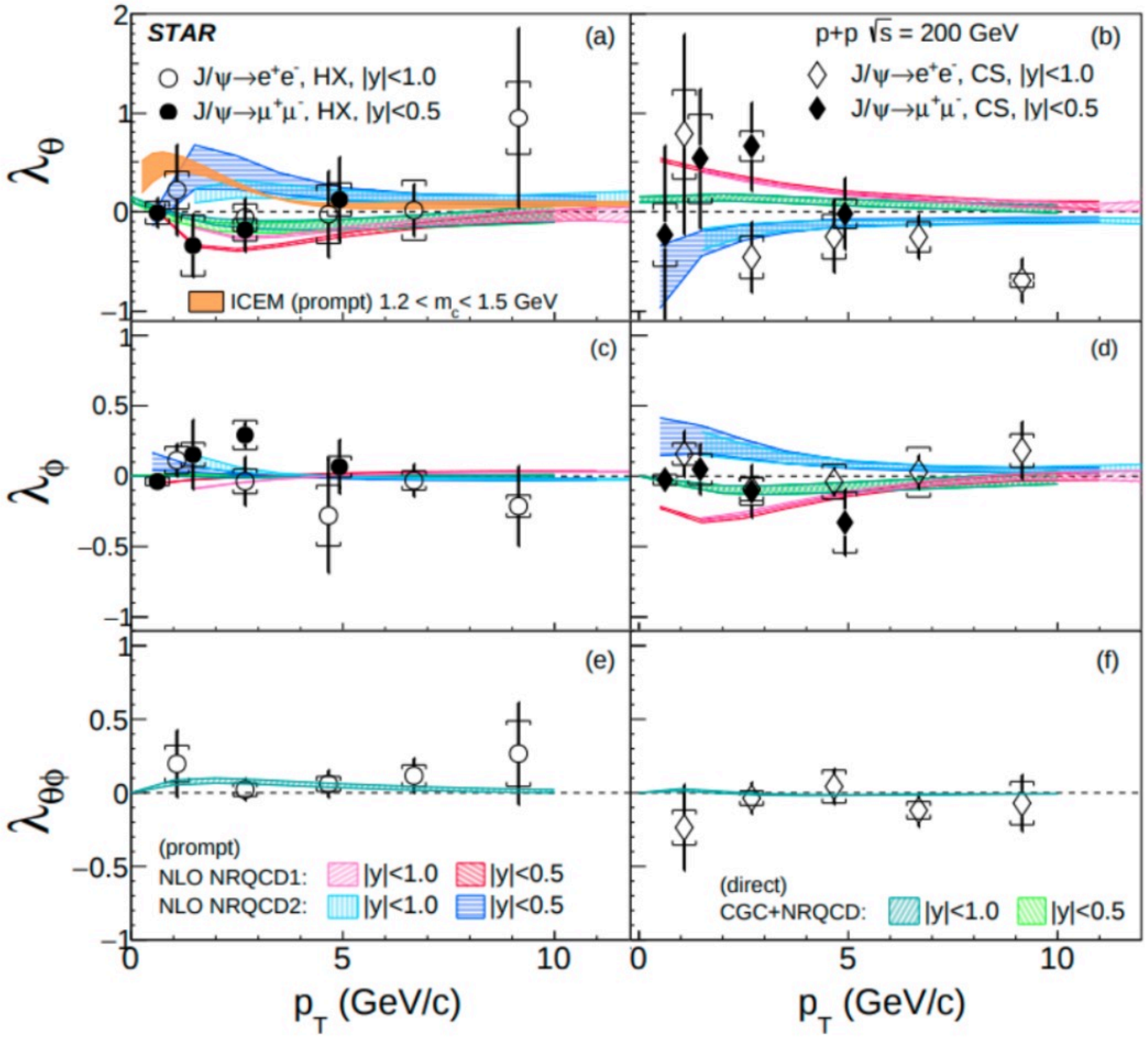
Cross section ratio



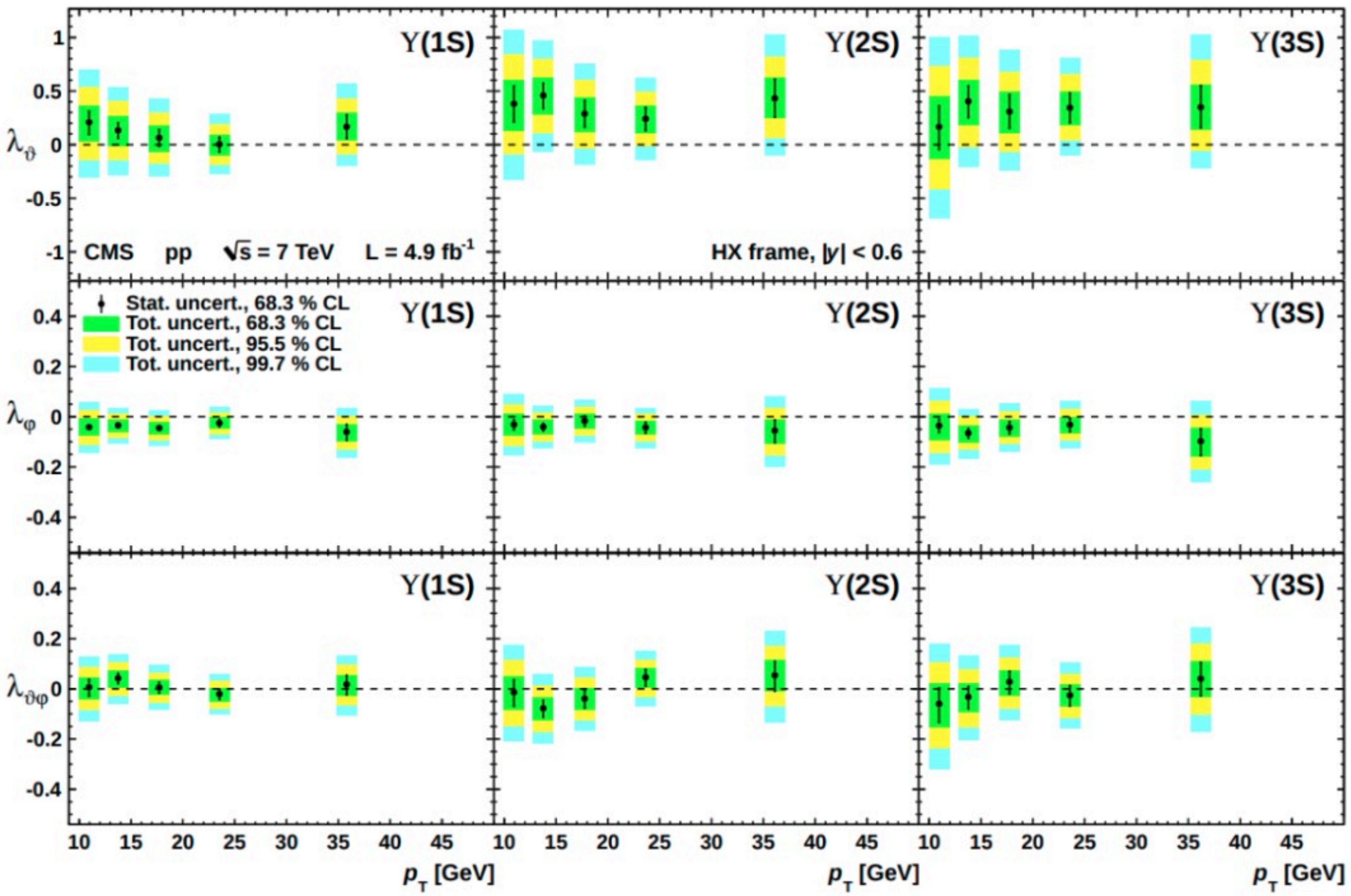
J/ψ polarization in pp



J/ψ polarization in pp (STAR)



Upsilon polarization in pp (CMS)



χ_{c2} production in pp (CMS)

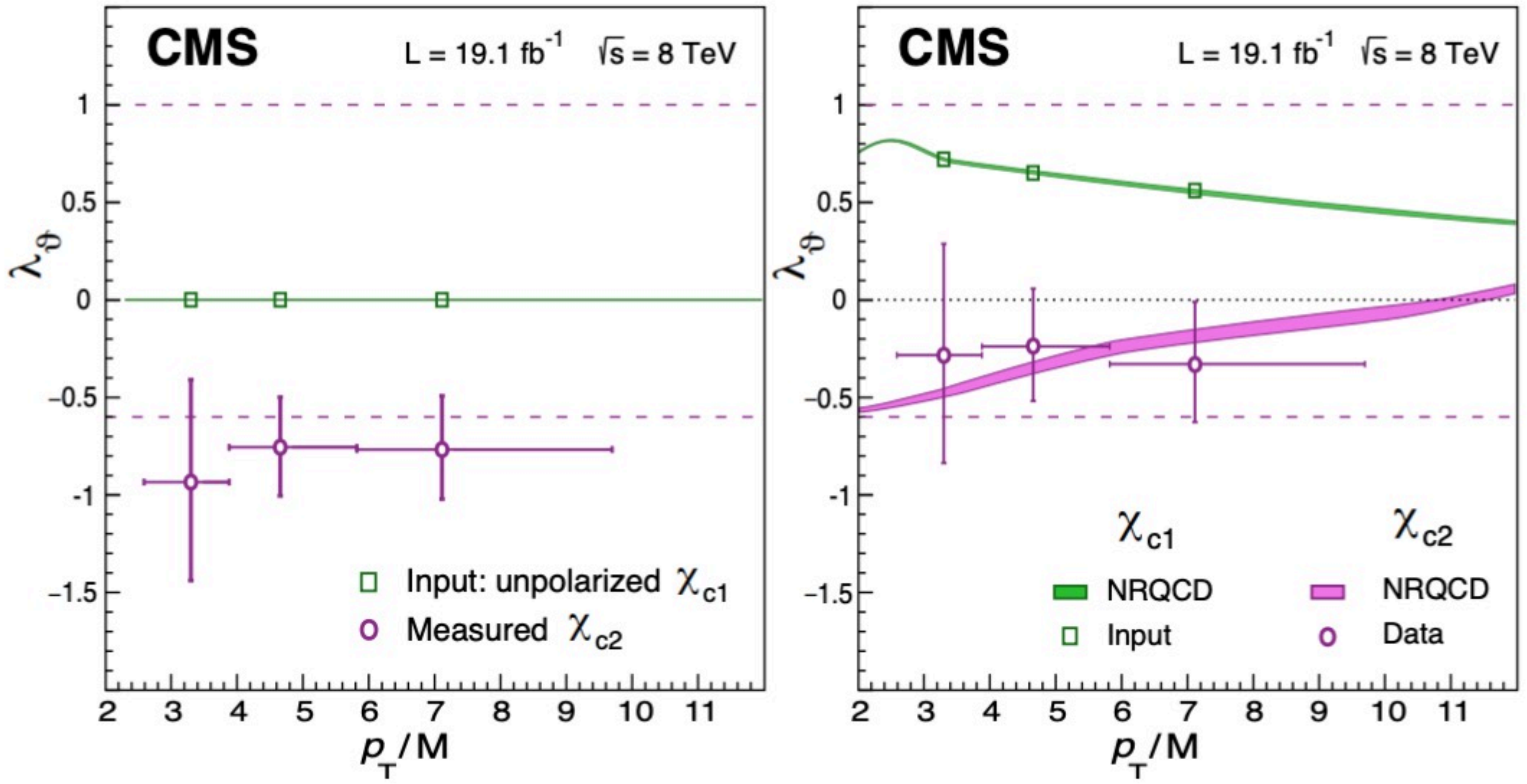
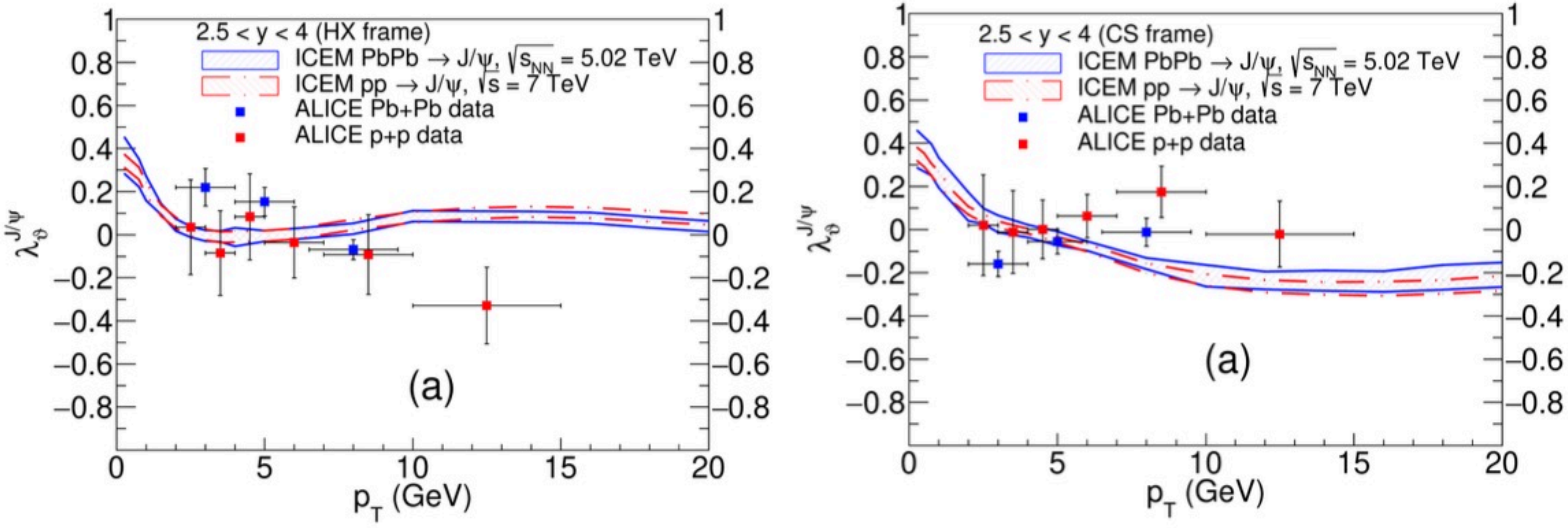


Figure 1.26: The polarization parameter $\lambda_\vartheta^{\chi_{c2}}$ values measured when the $\lambda_\vartheta^{\chi_{c1}}$ values are fixed to the unpolarized (left) or the NRQCD (right) scenarios as a function of p_T/M of the J/ψ [140]. The purple band on the right is the NRQCD prediction for $\lambda_\vartheta^{\chi_{c2}}$ [95].

J/ψ polarization in pp and Pb—Pb (ALICE)



ICEM with the collinear factorization approach for the direct J/ψ component, compared to the inclusive one

No significant difference is observed between the Pb—Pb and pp collisions for the ICEM model

J/ψ polarization in pp and Pb—Pb collisions

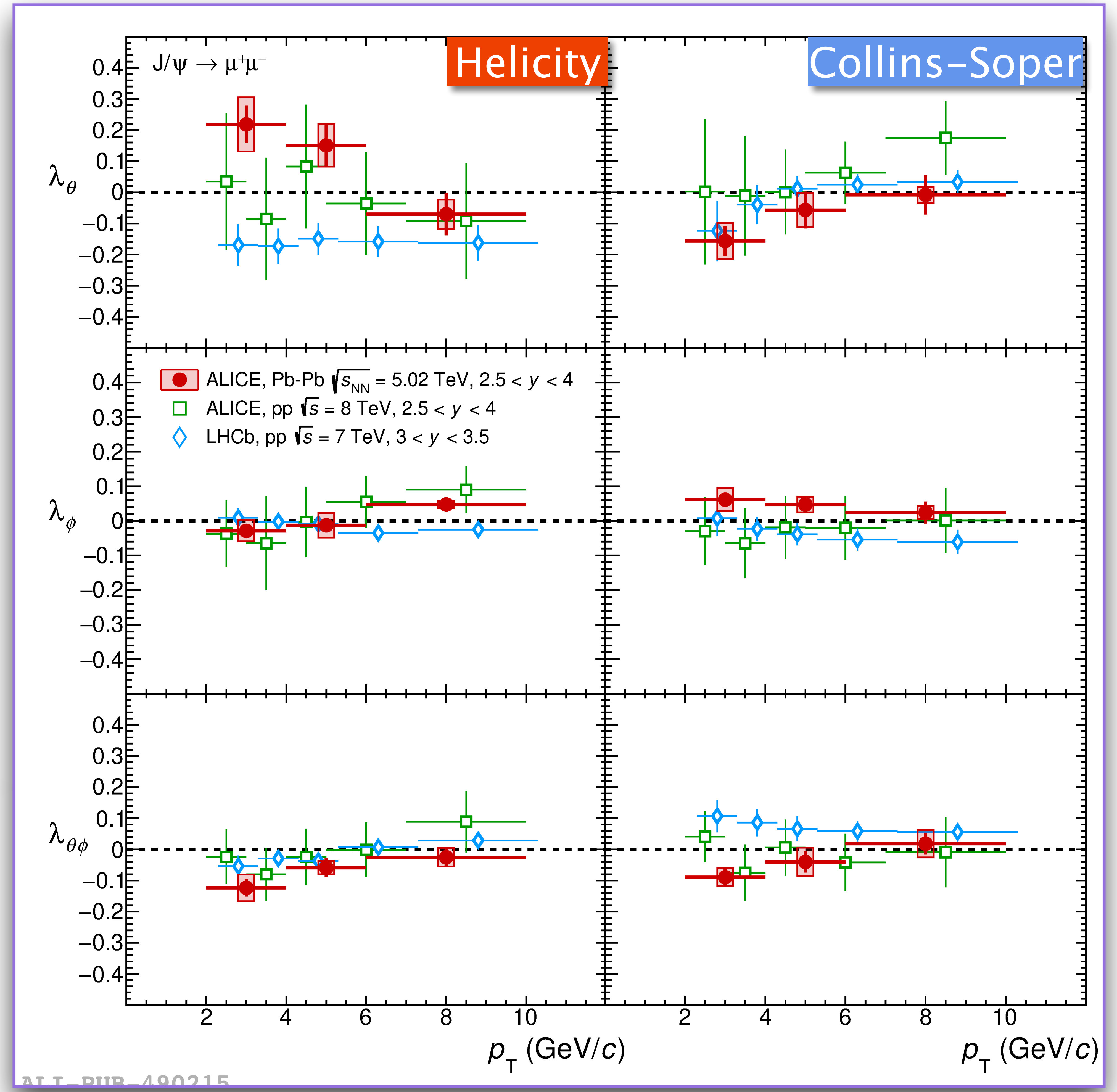
- **ALICE** measured J/ψ polarization in Pb—Pb collisions
  - All polarization parameters are close to zero within uncertainties
    - ↳ λ_θ shows a maximum 2σ deviation w.r.t zero in both **HE** and **CS** frames for $2 < p_{\mathrm{T}} < 4$ GeV/c
  - Compatible with **ALICE** results in **pp** collisions within uncertainties

    EPJC 78 (2018) 562
  - 3σ difference w.r.t **LHCb** in **pp** collisions in **HE** frame

    LHCb Collaboration, *EPJC* 73 (2013) 11

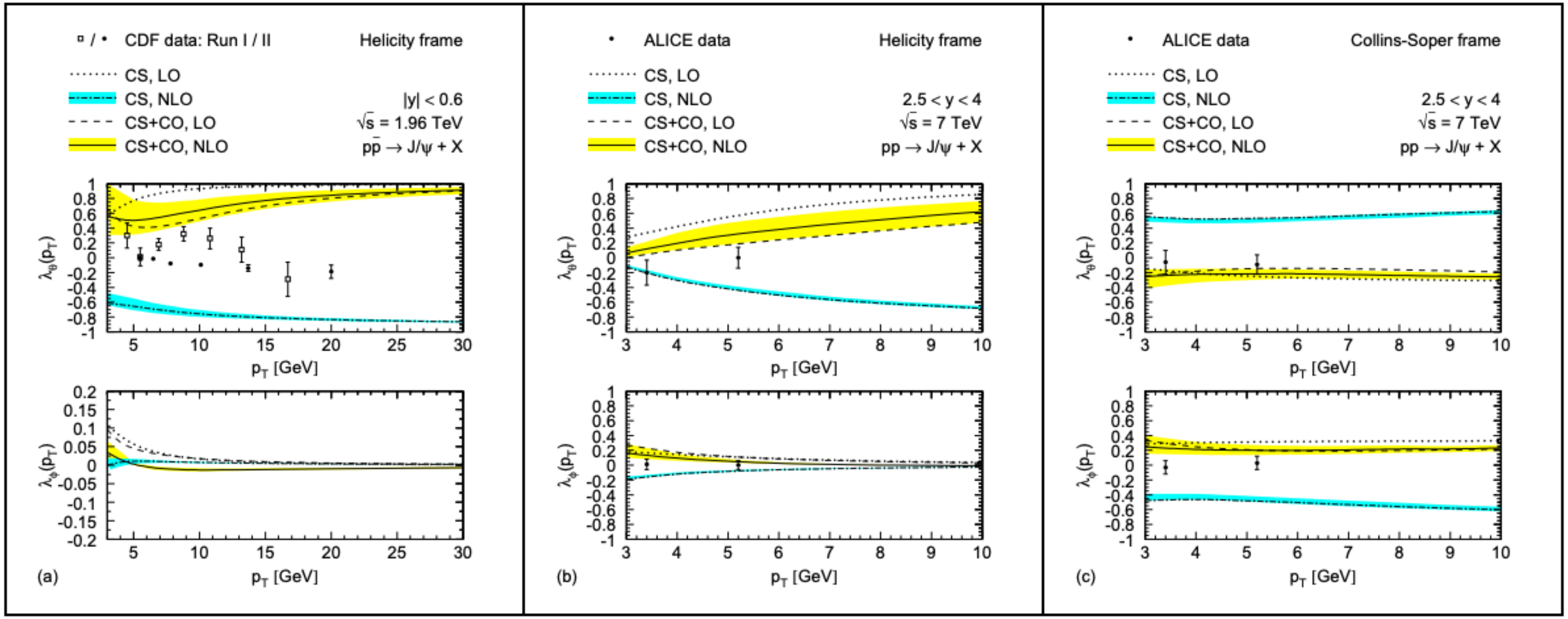
- Difference due to **suppression/regeneration** effects in Pb—Pb w.r.t pp collisions?
- What is the role of the angular momentum ($\vec{L}$) and the magnetic fields ($\vec{B}$)?

Phys. Lett. B 815 (2021) 136146



J/ψ polarization in theory

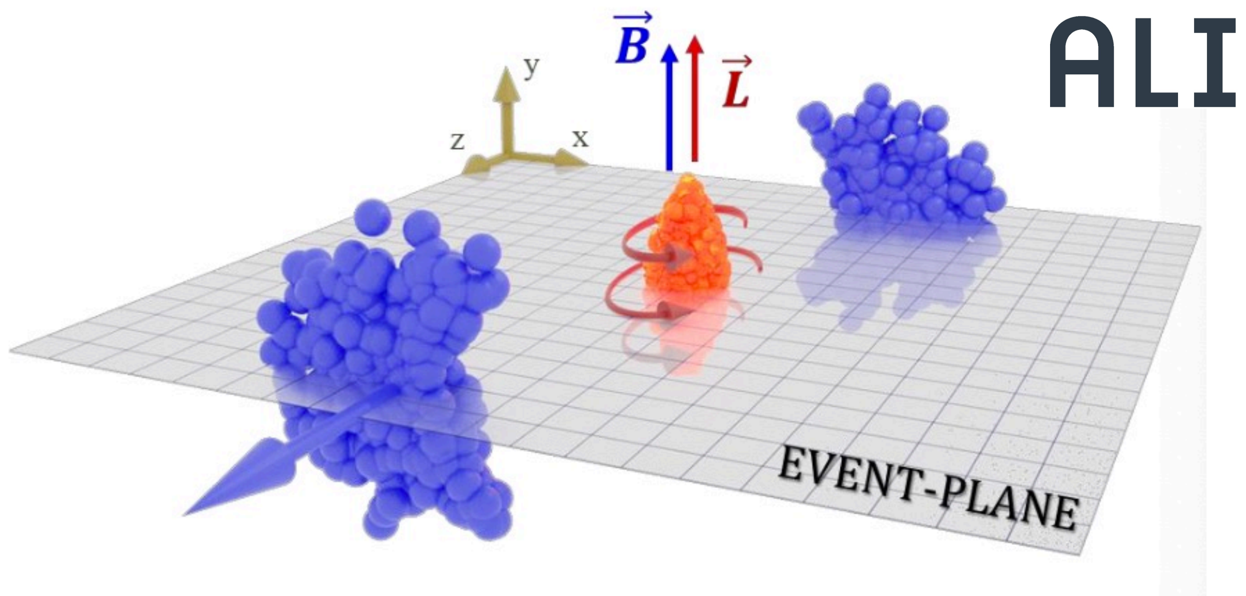
Phys. Rev. Lett. 108 (2012) 172002

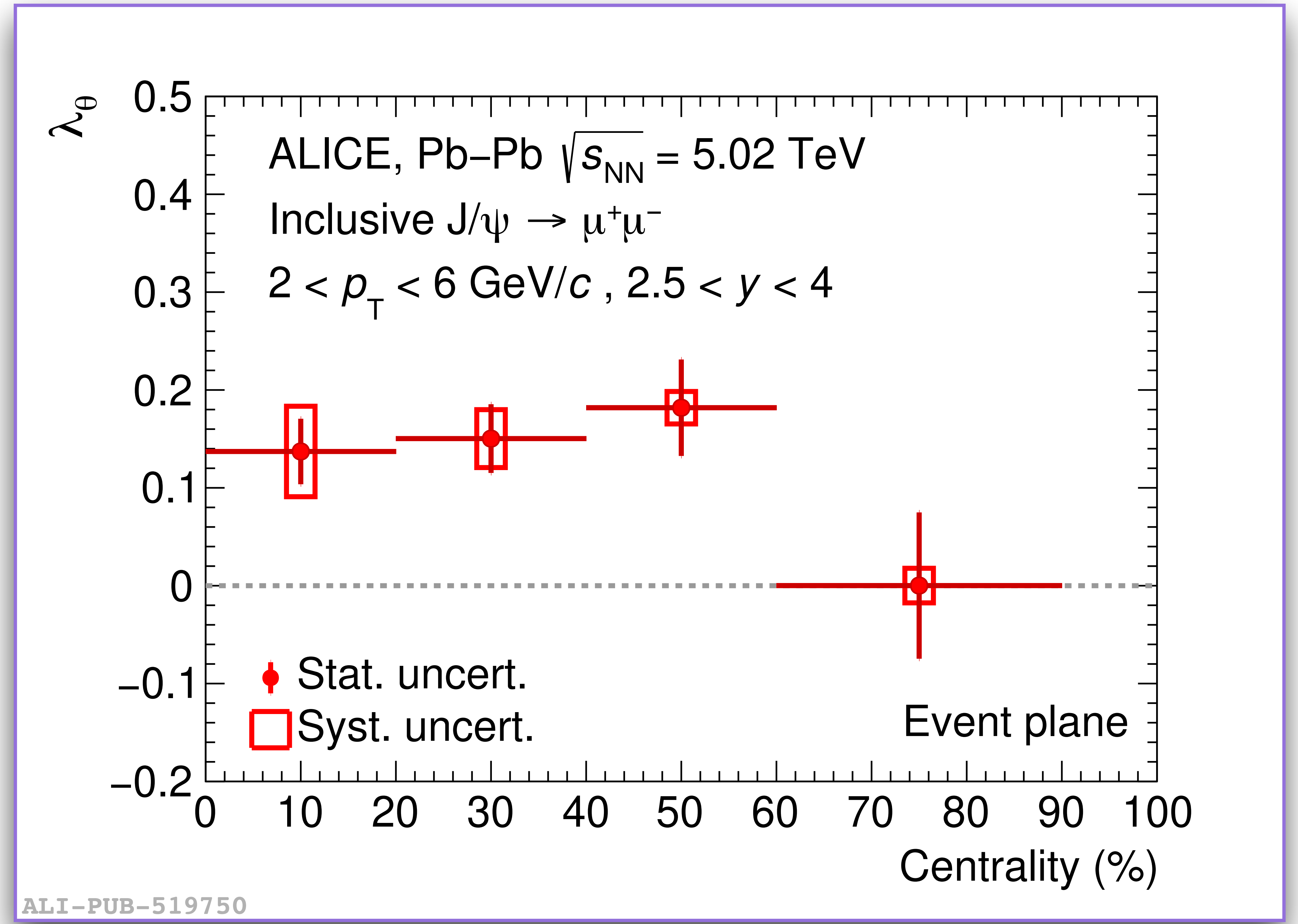


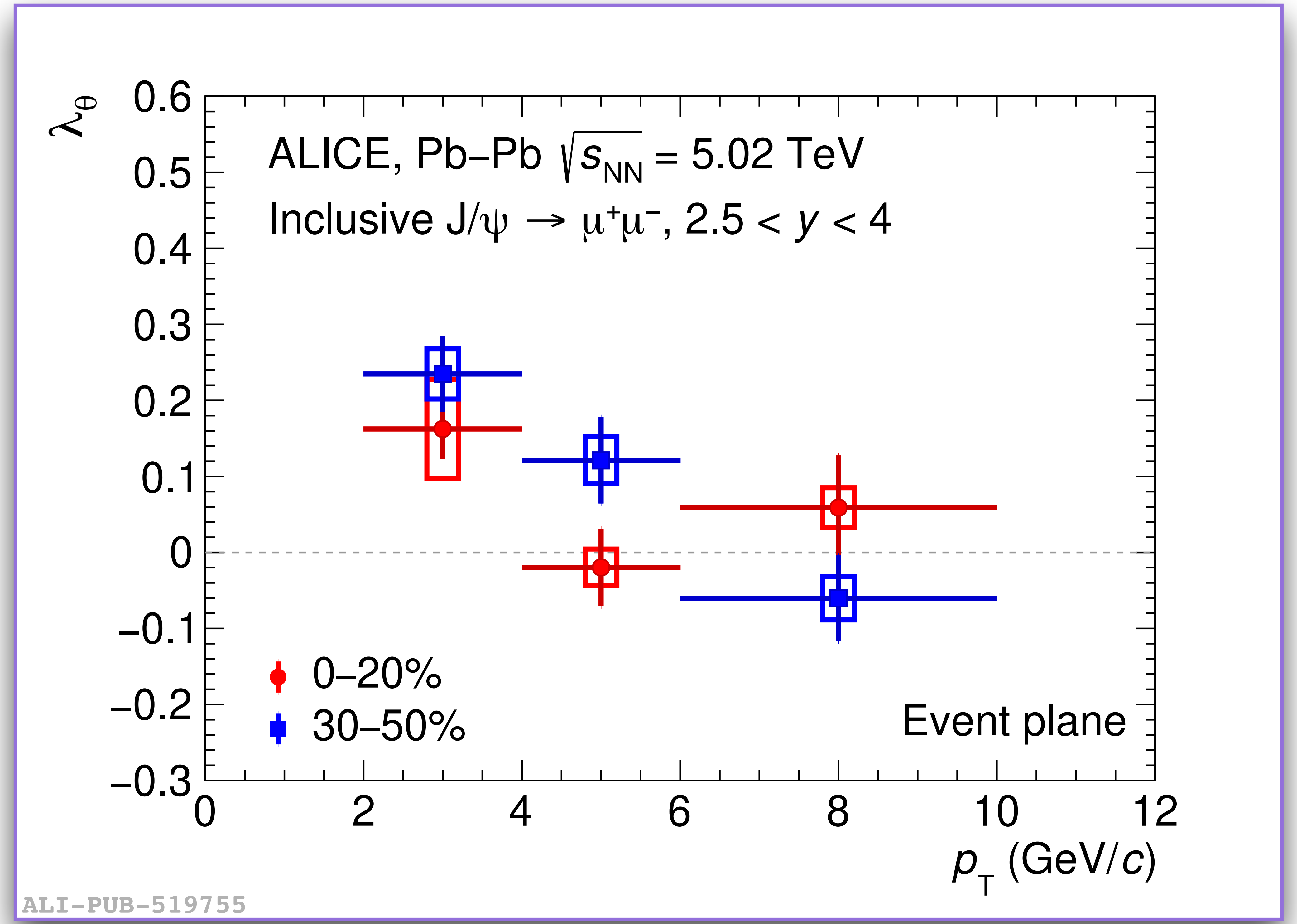
J/ψ polarization in Pb—Pb

Reference frame:

- Event-plane based frame (EP): axis orthogonal to the EP in the collision center-of-mass frame
- EP normal to $\vec{B}$ and $\vec{L}$





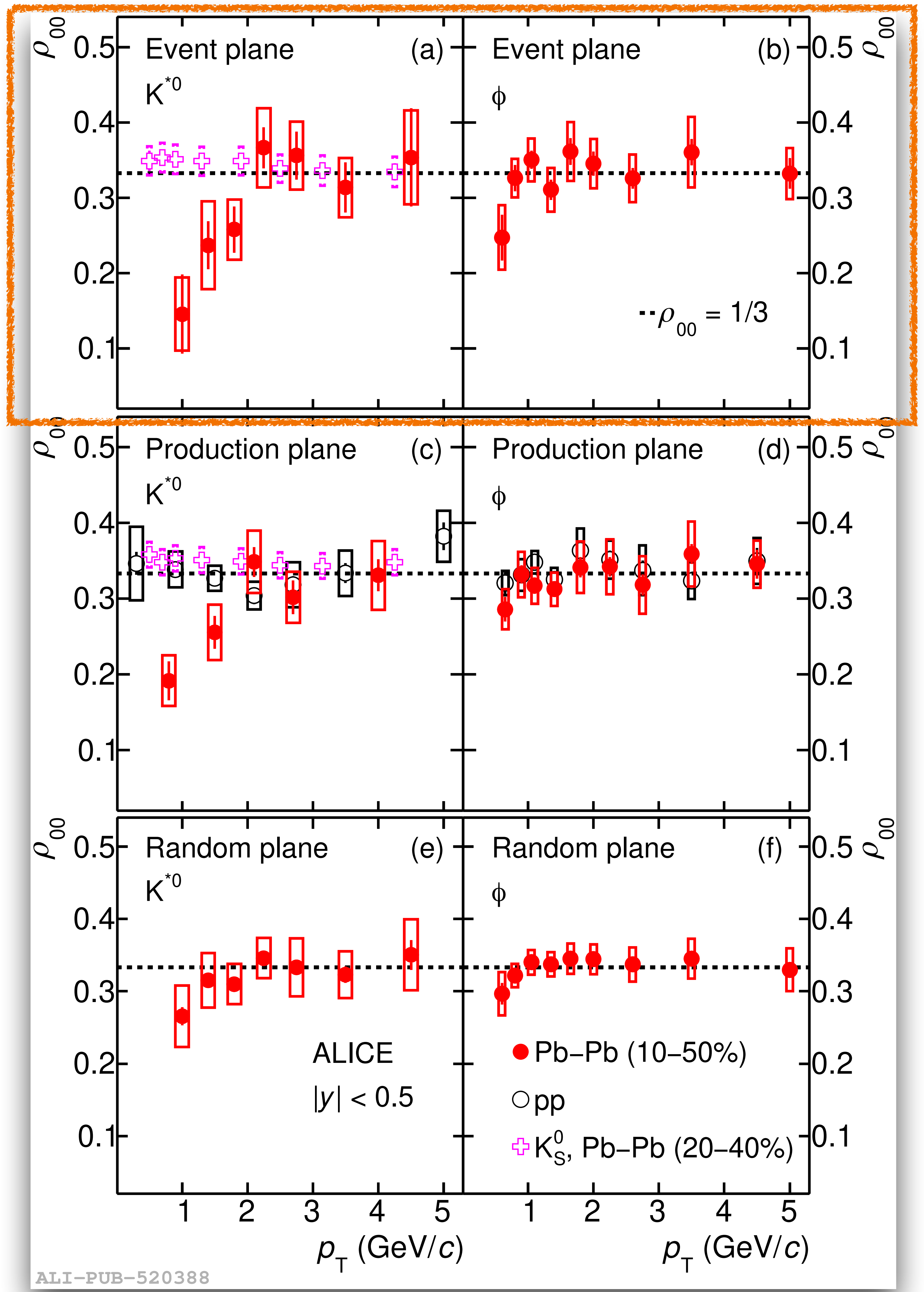


Light flavor hadrons (K^{*0}, Φ) polarization in Pb—Pb

EP

PP

RP



ρ_{00} measurement for light flavor hadrons in Pb—Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in pp collisions at $\sqrt{s}$ = 13 TeV

- p_T dependence
  - $\rho_{00} < 1/3$ for K^{*0} and Φ at low p_T (smaller central value for K^{*0}) in Pb—Pb collisions
  - $\rho_{00} \sim 1/3$ for:
    - $p_T^{K^{*0}} > 2$ GeV/c and $p_T^{\Phi} > 0.8$ GeV/c
    - A random event plane (**RP**)
    - K^{*0} and Φ in pp collisions

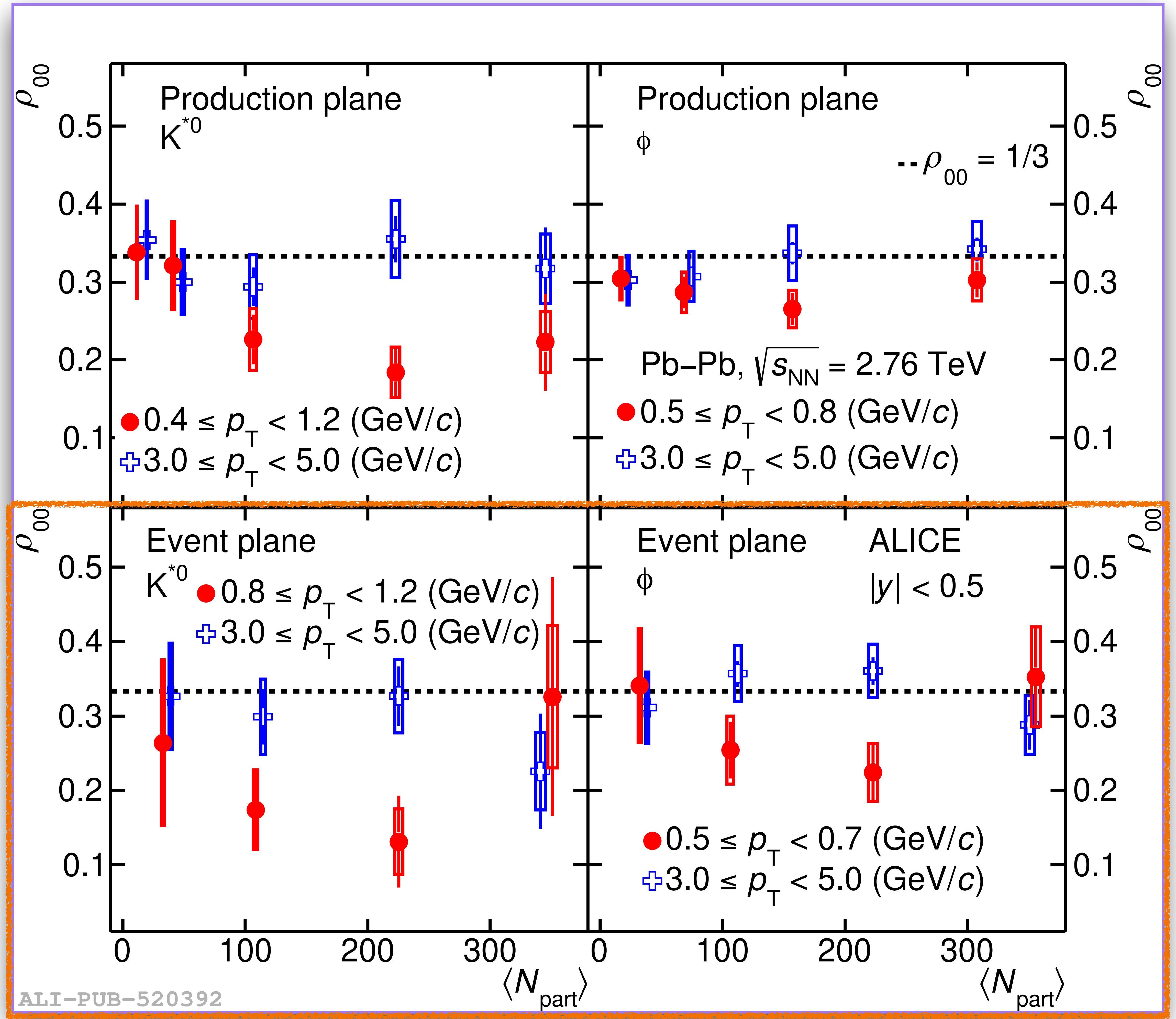
Zero spin hadron K_S^0: no spin alignment is observed

The spin-density matrix element ρ_{00} is determined from the distribution of the angle θ^* between the kaon decay daughter and the quantization axis in the decay rest frame [16],[B],

$$\frac{dN}{d\cos\theta^*} \propto [1-\rho_{00}+\cos^2\theta^*(3\rho_{00}-1)]. \quad (1)$$

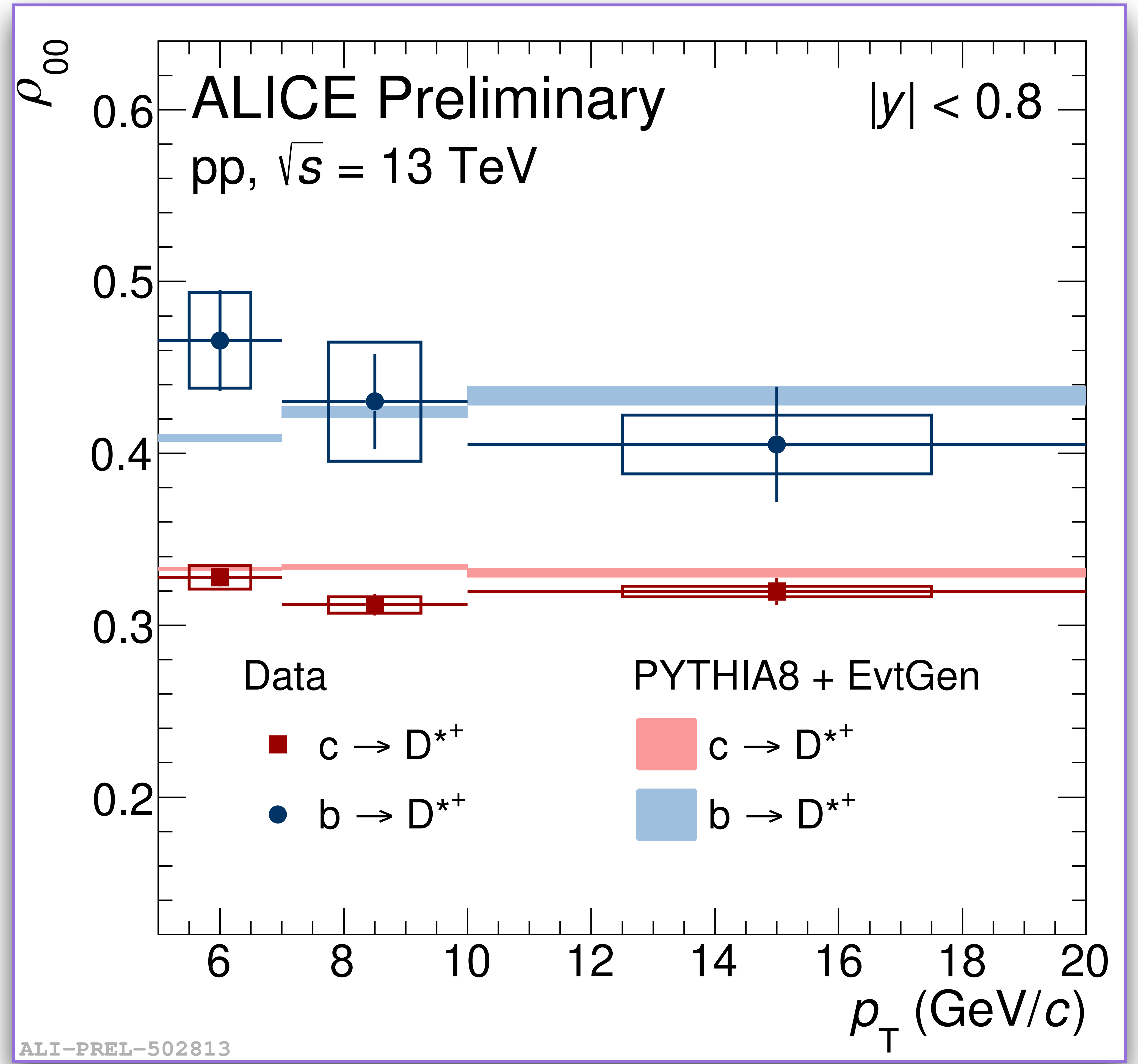
Light flavor hadrons (K^{*0}, Φ) polarization in Pb—Pb

- ρ_{00} measurement for light flavor hadrons in Pb—Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in pp collisions at $\sqrt{s} = 13$ TeV
  - Centrality dependence
    - ρ_{00} deviates w.r.t 1/3 **at low p_T in semi-central collisions**
    - No centrality dependence of ρ_{00} at high p_T



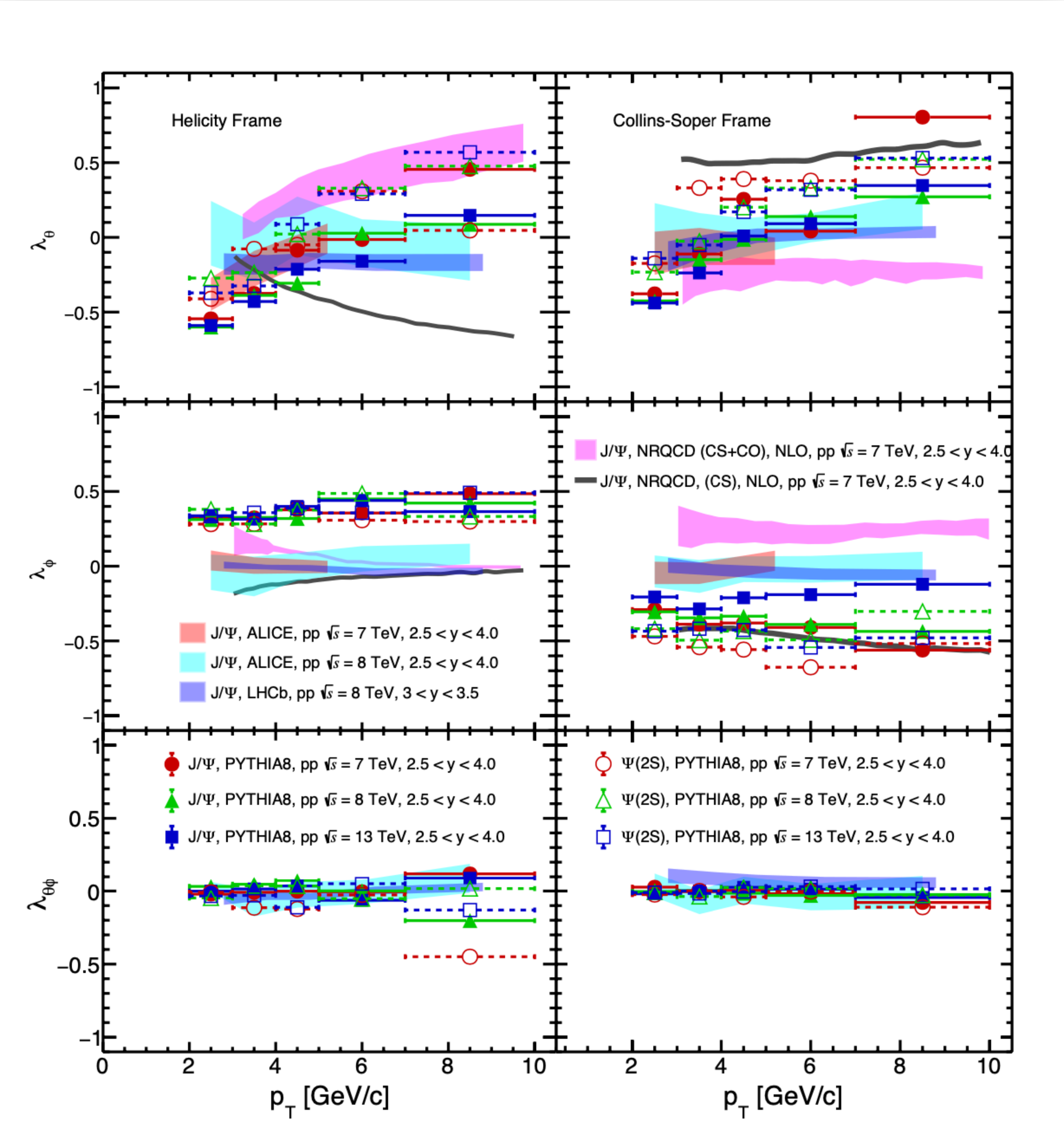
Charm mesons polarization in pp

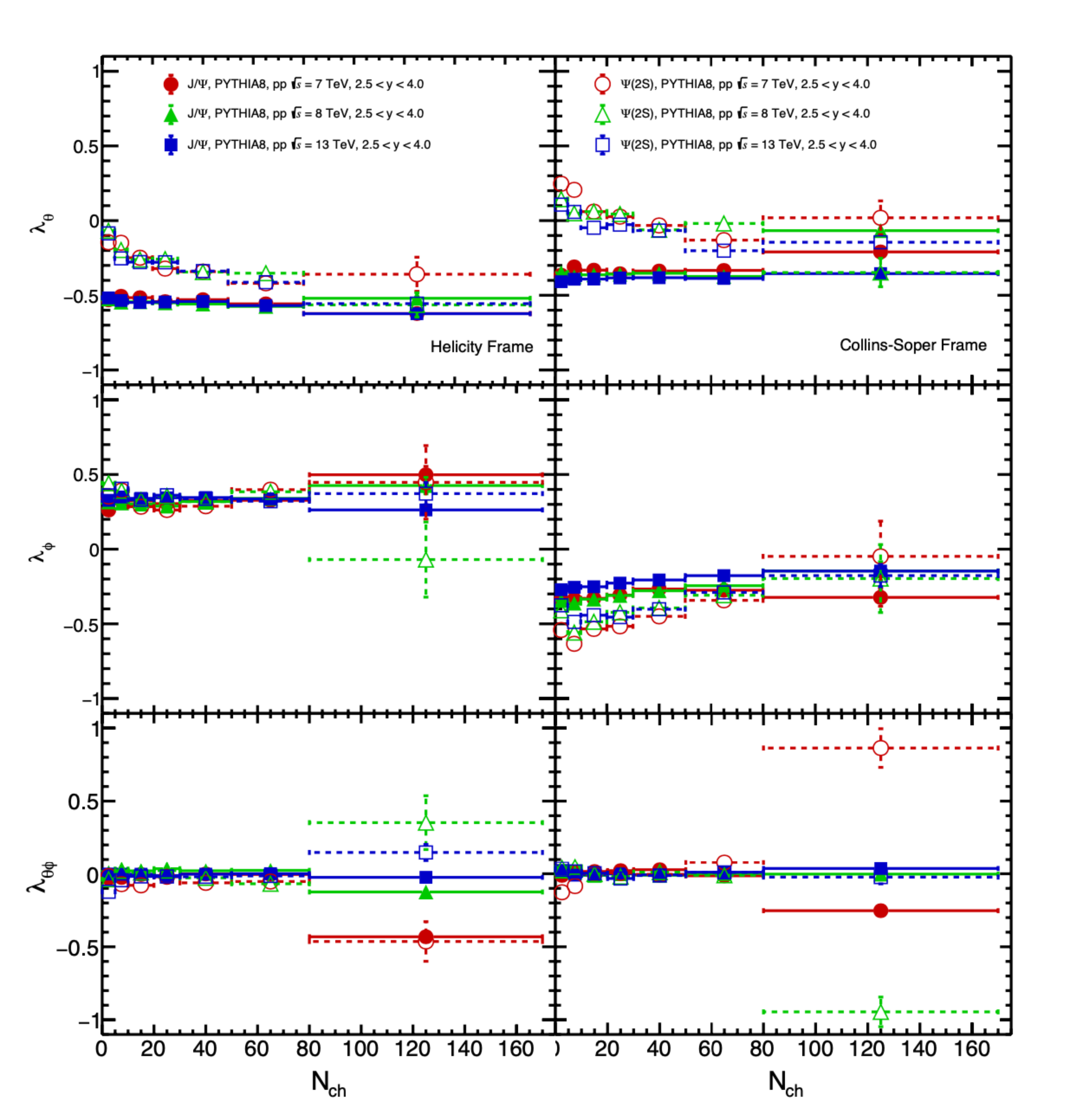
- Charmed vector meson (D^{*+}) polarization crucial to complete the picture in HICs
- D^{*+} polarization in pp collisions at $\sqrt{s}$ = 13 TeV
  - ρ_{00} spin matrix element (1/3 means no polarization)
    - Prompt D^{*+} ($c \rightarrow D^{*+}$) unpolarized
    - Non-zero polarization for non-prompt D^{*+} ($b \rightarrow D^{*+}$)
    - Both well predicted by PYTHIA 8 + EVTGEN



Charm mesons polarization in pp

PYTHIA 8：only considering the direct component

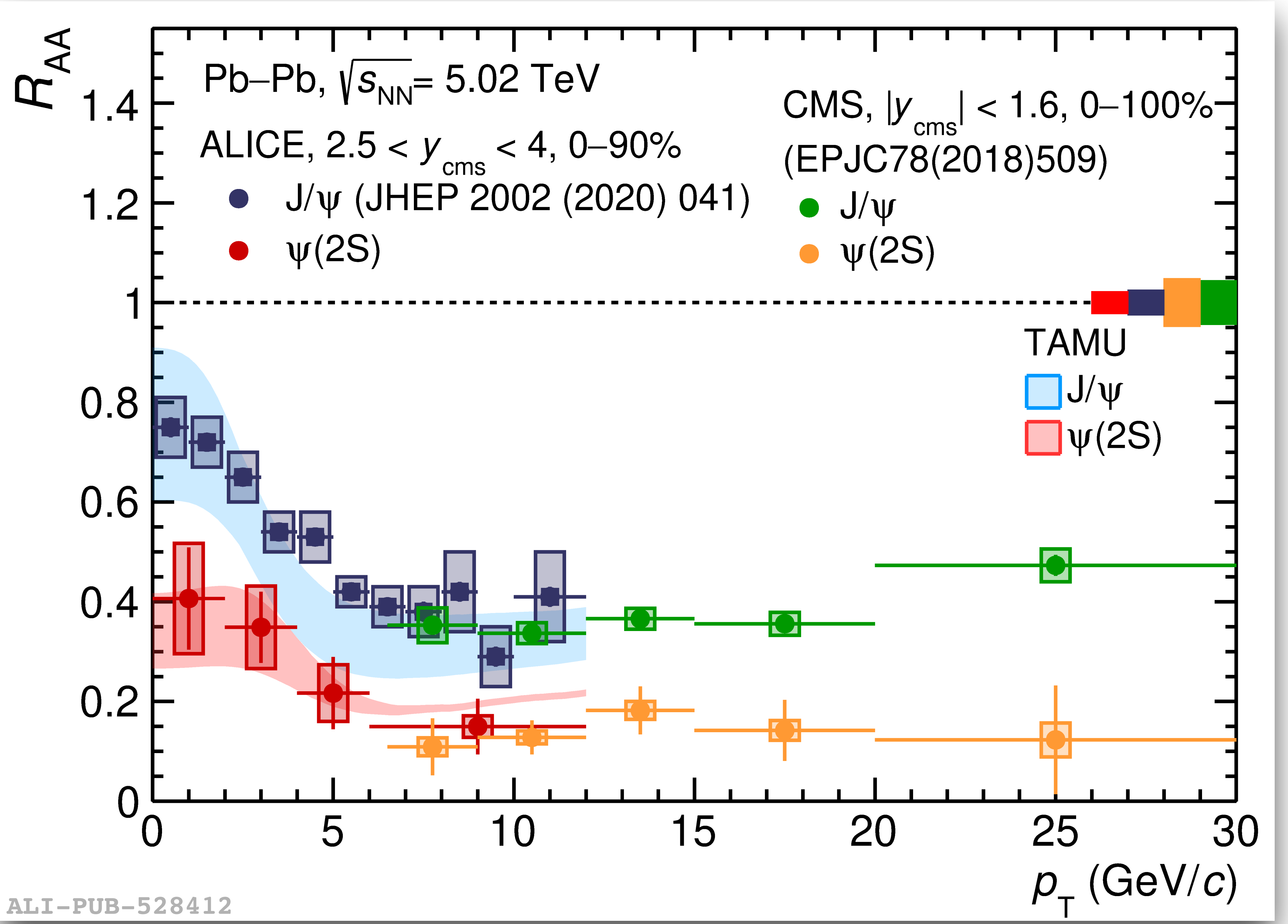


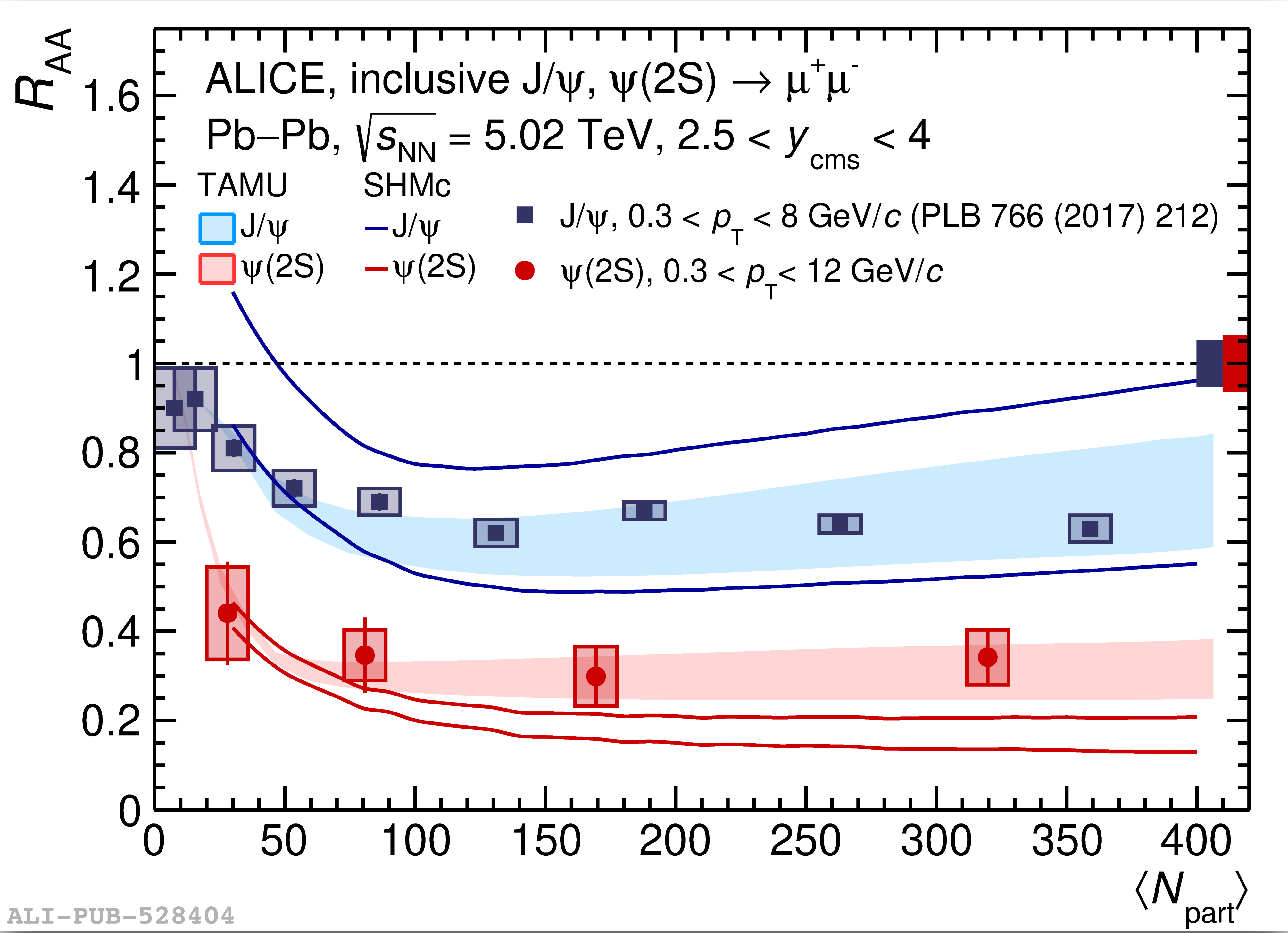


Introduction: quarkonium as a probe of QGP

Charmonia nuclear modification factor R_{AA}

arXiv:2210.08893





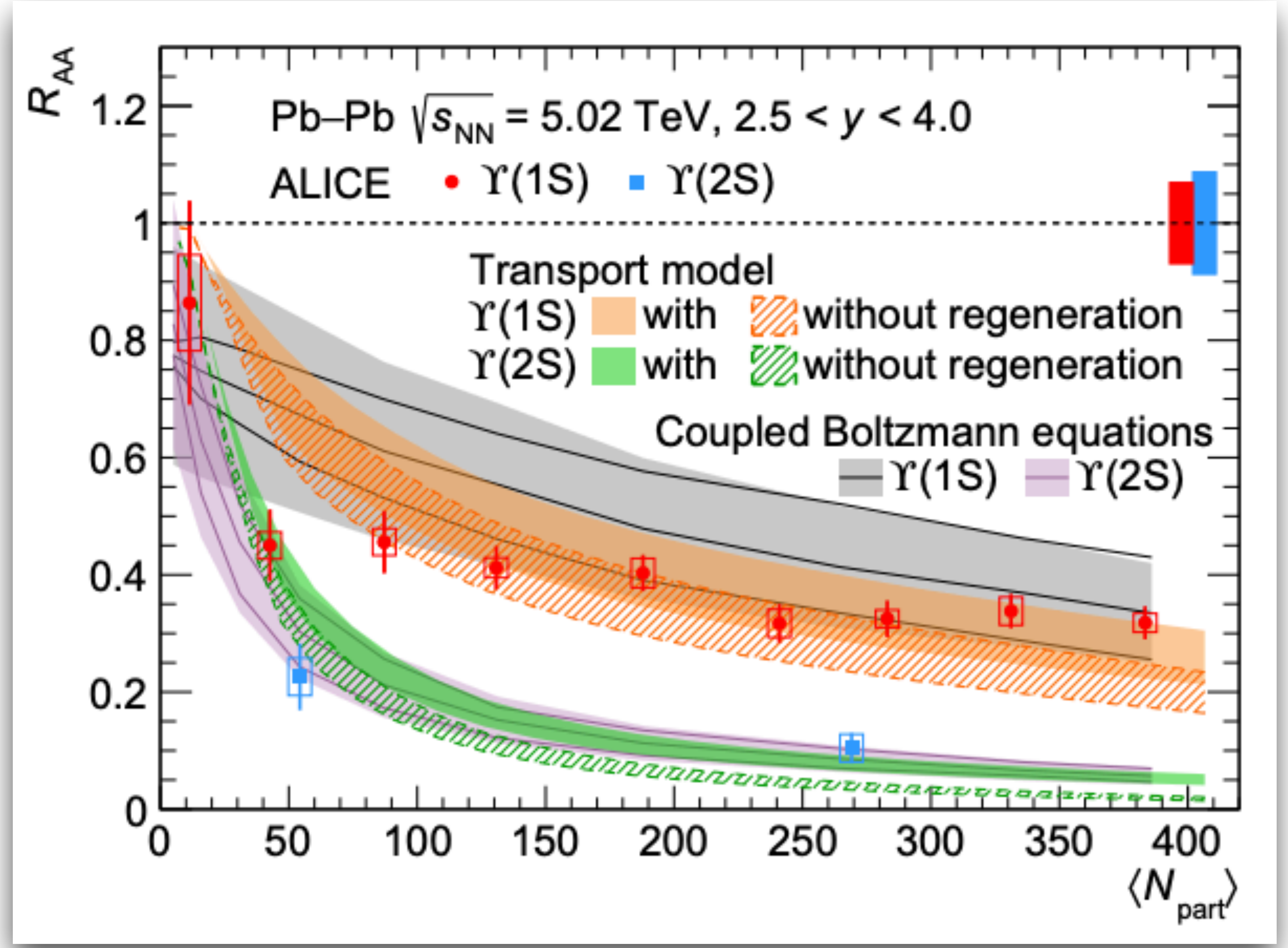
TAMU: *Rapp et al, Nucl. Phys. A943 (2015) 147-158*
SHMc: *Andronic et al, Phys. Lett. B 797 (2019) 134836*

- Transport model (TAMU) is in good agreement with results as a function of p_{T} and centrality
- Statistical hadronization model (SHMc) tends to underestimate $\psi(2S)$ in central collisions
- In SHMc, charmonia are produced (regenerated) from ***deconfined charm quarks*** at the QCD phase boundary whereas TAMU includes ***regeneration*** in the QGP phase

Introduction: quarkonium as a probe of QGP

Bottomonia nuclear modification factor R_{AA}

ALICE Collaboration, *Phys. Lett .B 822 (2021) 136579*



- Stronger suppression for $\Upsilon(2S)$ ***w.r.t*** $\Upsilon(1S)$
- The various calculations (e.g. Transport model w/ or w/o ***regeneration***) reproduce the trend of the data within the corresponding uncertainties
- **Weak regeneration effect expected in the bottom sector**

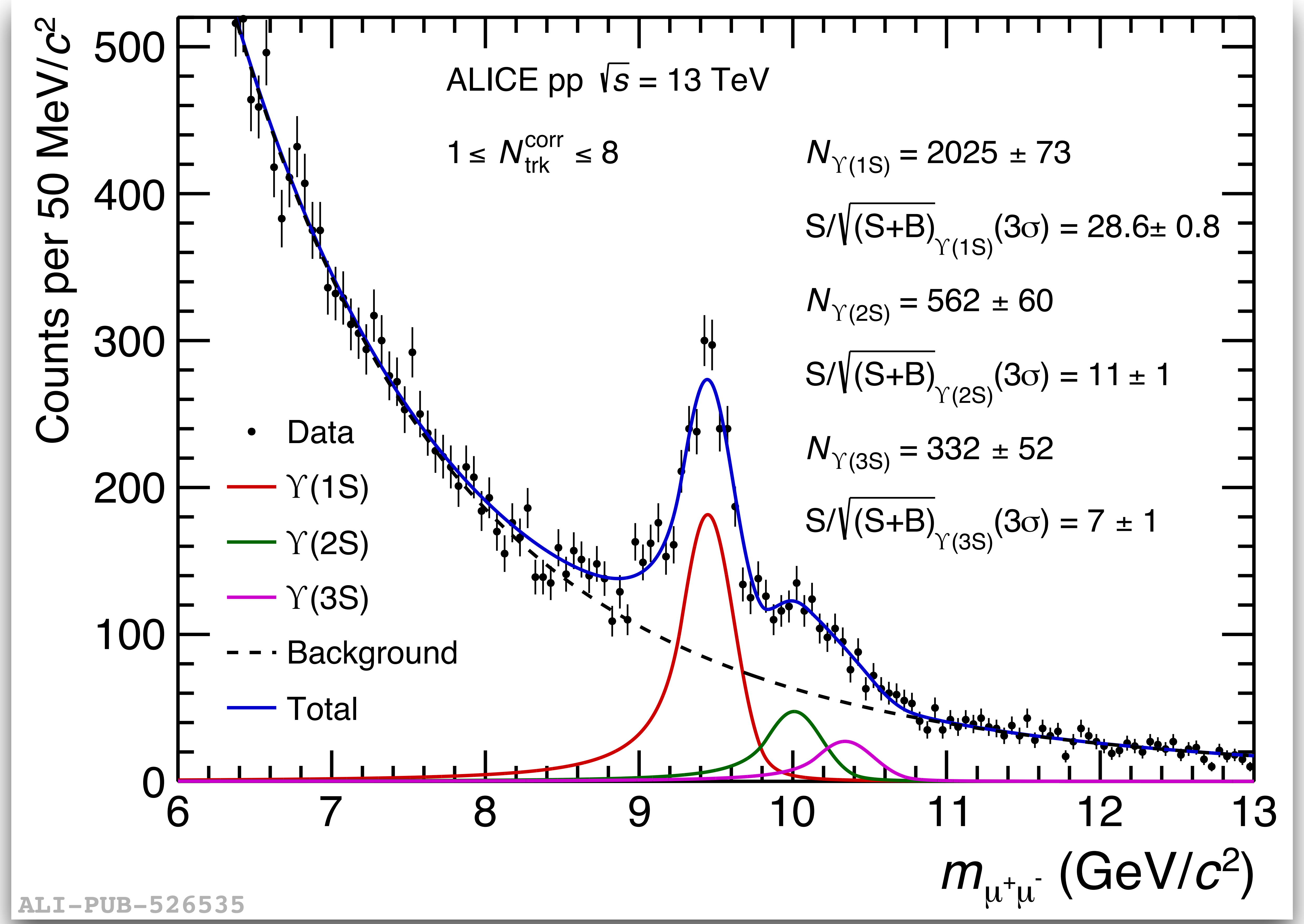
Data sample

- Dataset: collected in 2016, 2017 and 2018 in pp collisions at $\sqrt{s}$ = 13 TeV
- Event selection:
  - Unlike-sign dimuon (CMUL7) trigger and minimum bias (MB) trigger
  - Physics selection with default pileup rejection
  - SPD vertex selection ($N_{\mathrm{contributors}} > 0$, $\sigma_{z_{\mathrm{vtx}}} < 0.25$ cm, $|z_{\mathrm{vtx}}| < 10$ cm)
- In this analysis:
  - The signal Υ is measured at forward rapidity (2.5<y<4.0), the charged-particle multiplicity is measured at central rapidity ($|\eta|$<1)
  - The Υ yield ($\mathrm{d}N_{\Upsilon}/\mathrm{d}y$) and the pseudorapidity charged-particle multiplicity density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$) are both measured for $\mathrm{INEL} > 0$ events

Analysis strategy

Signal extraction

- Υ analysis is performed measuring the number of produced resonances
- After the standard muon and dimuon selections, invariant mass spectra muon pairs are built
- The invariant mass spectra are fitted with a combination of phenomenological functions for peaks and background
- The number of produced resonances is extracted through the integral of the peak



Data sample and analysis strategy

- Data sample: collected in 2016, 2017 and 2018 in pp collisions at $\sqrt{s}$ = 13 TeV, dimuon trigger + quality criteria used to select the events

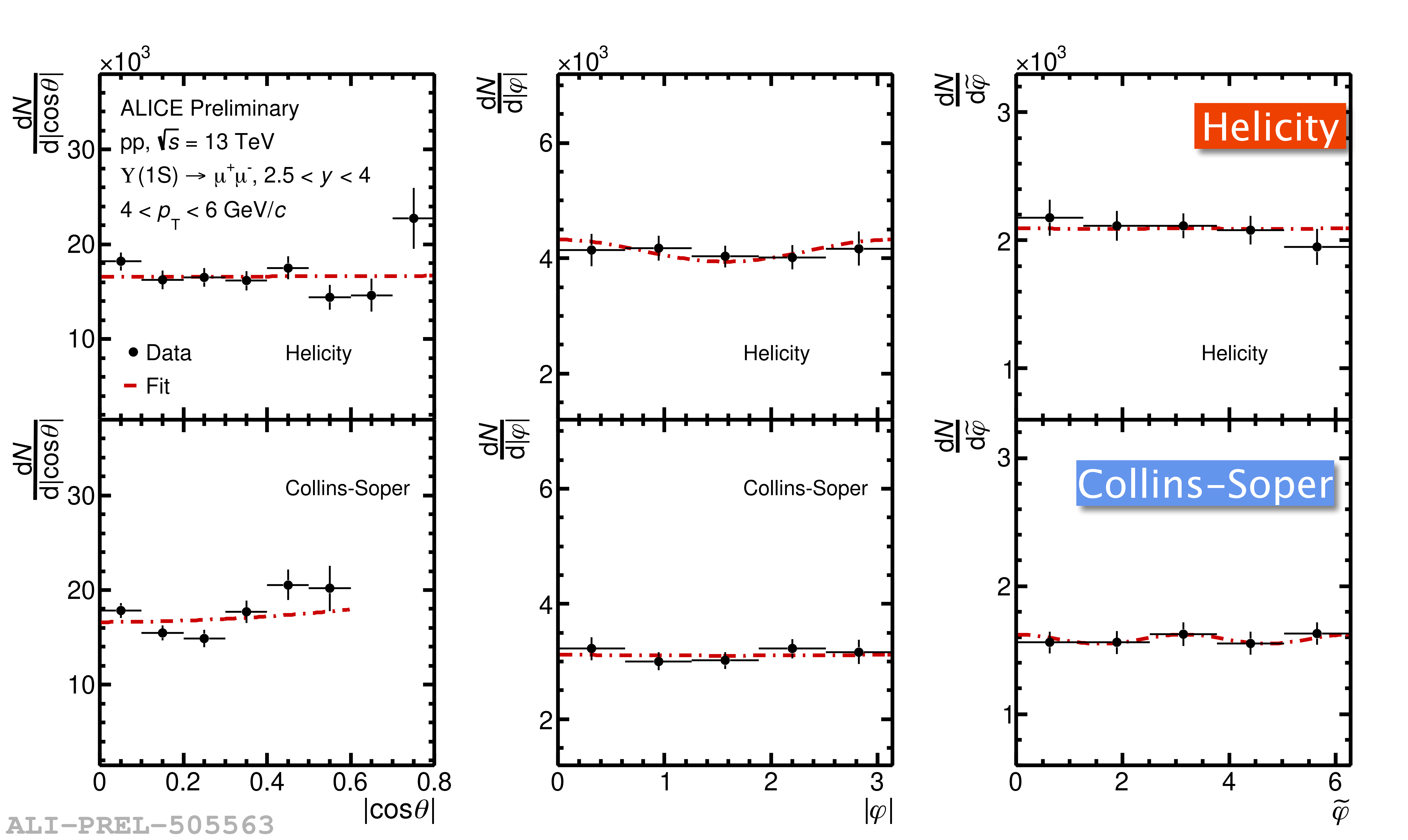
- Analysis procedure:
  - **Signal extraction:** the number of $\Upsilon(1\mathrm{S})$ candidates is obtained via a fit procedure on the dimuon invariant mass distribution in each angular interval considered in the analysis
  - **Acceptance x efficiency correction:** the raw number of $\Upsilon(1\mathrm{S})$ extracted from the fit procedure is corrected for a factor quantifying the geometrical acceptance and reconstruction efficiency effects, estimated via a MC simulation
  - **Polarization parameters determination:** the polarization parameters λ_θ , λ_φ and $\lambda_{\theta\varphi}$ are extracted by fitting the acceptance- and efficiency-corrected angular distributions of $\Upsilon(1\mathrm{S})$, in both the Helicity and Collins-Soper reference frames

Analysis strategy

- Polarization parameters determination
  - ↳ λ_θ , λ_φ and $\lambda_{\theta\varphi}$ extracted by fitting the $A \times \varepsilon$-corrected $\Upsilon(1S)$ angular distributions in both frames simultaneously

$$\begin{cases} W(\cos\theta) \propto \dfrac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta) \\ W(\varphi) \propto 1 + \dfrac{2\lambda_\varphi}{3+\lambda_\theta}\cos 2\varphi \\ W(\tilde{\varphi}) \propto 1 + \dfrac{\sqrt{2}\lambda_{\theta\varphi}}{3+\lambda_\theta}\cos 2\tilde{\varphi} \end{cases}$$

$$\begin{cases} \tilde{\varphi} = \varphi - 3\pi/4, \ \cos\theta < 0 \\ \tilde{\varphi} = \varphi - \pi/4, \quad \cos\theta > 0 \end{cases}$$



ALICE 2 - LS2 upgrade

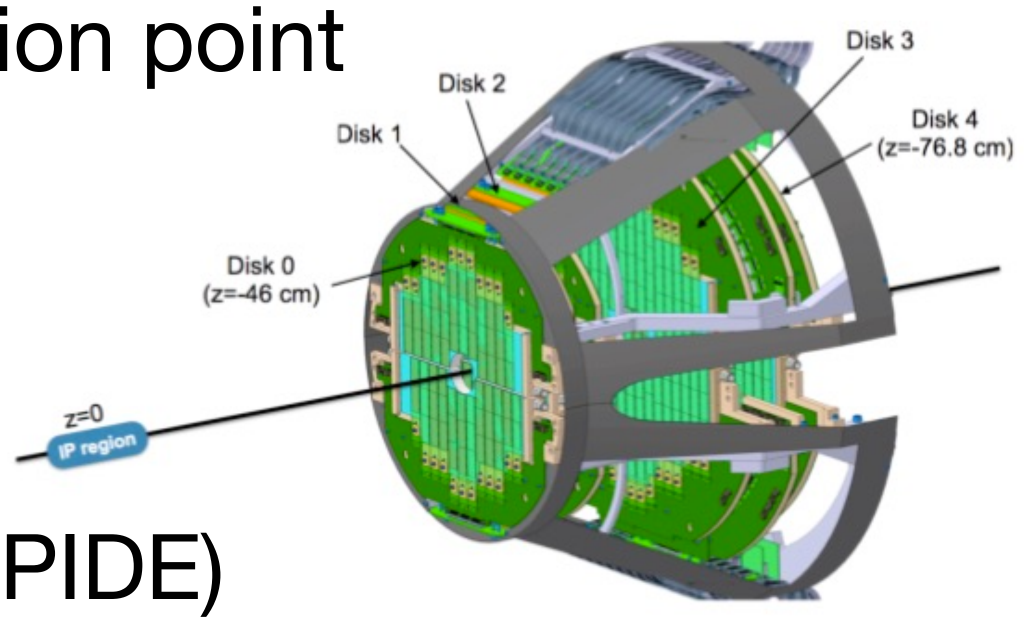
LS: Long Shutdown

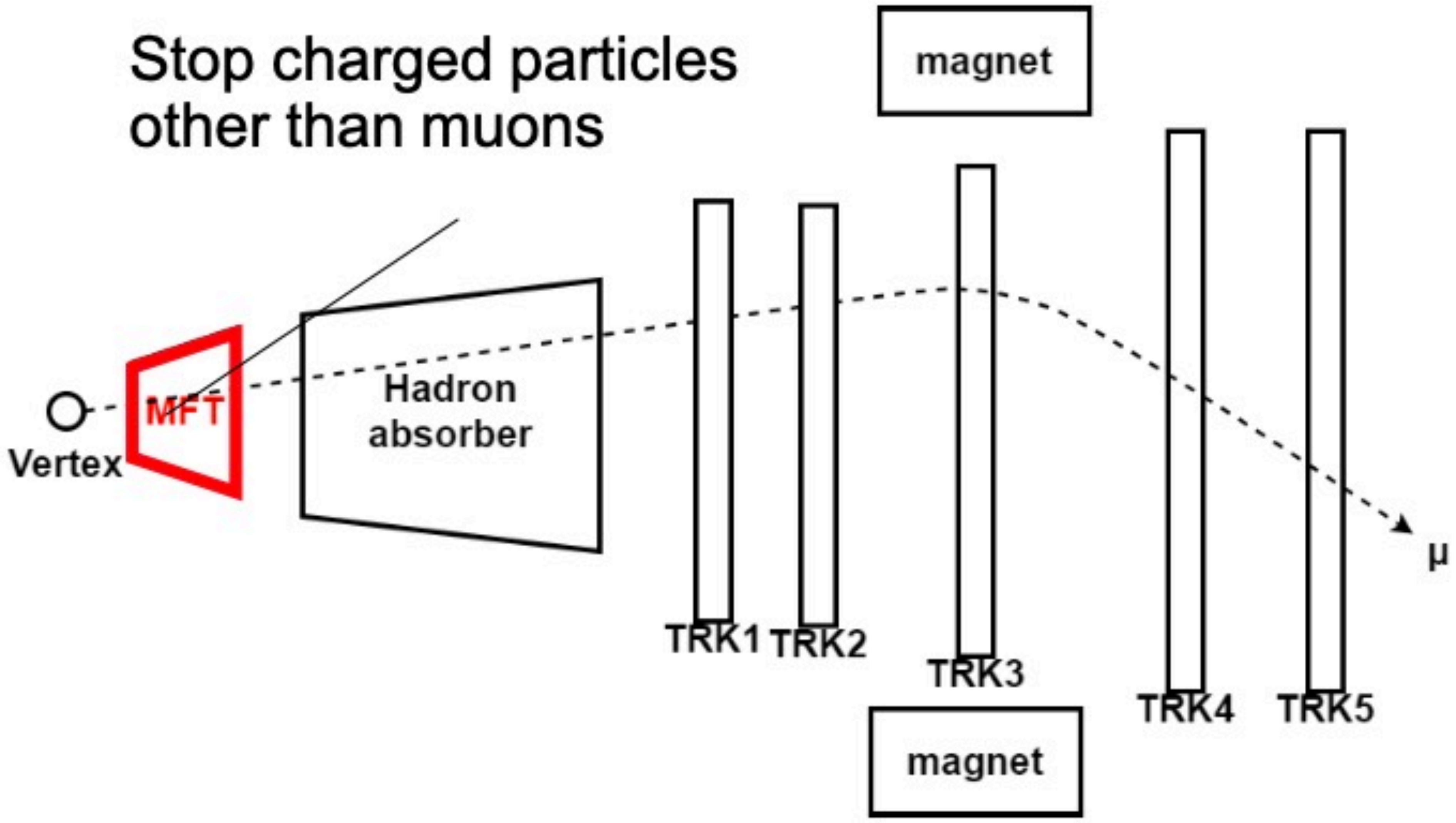
- **Prospects for Run 3:**
  - Significantly higher statistical data sample compared to Run 1 and 2 is expected ($L_{\rm int} = 10\ {\rm nb}^{-1}$ in Pb—Pb, $200\ {\rm nb}^{-1}$ in pp)
- **During the LS2 in 2019 - 2021, all detectors have been upgraded**

ALICE 2 - LS2 upgrade

Muon Forward Tracker (MFT, $2.5 < \eta < 3.6$)

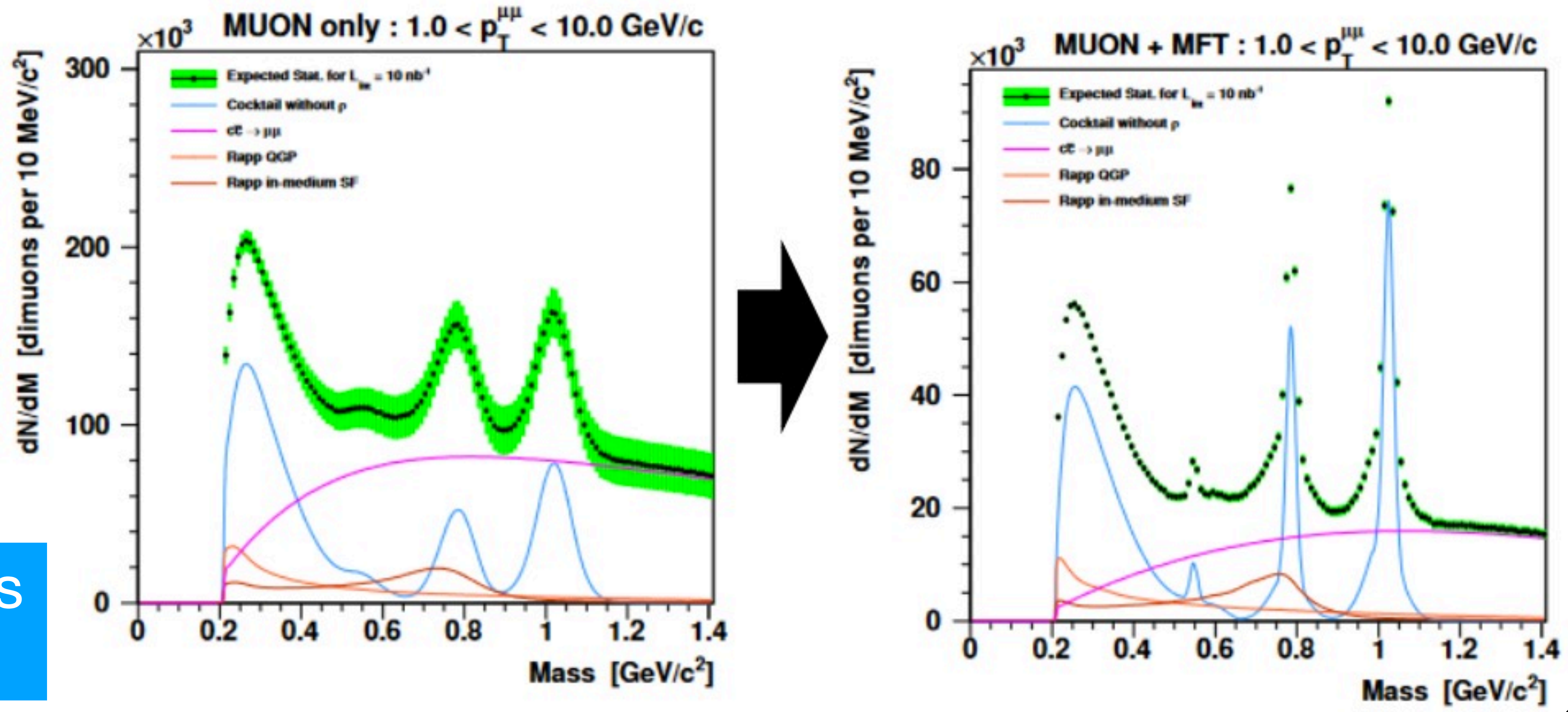
- Installed in the forward area near the interaction point
  - Matching muon track with MFT tracks
  - High-precision vertexing capabilities





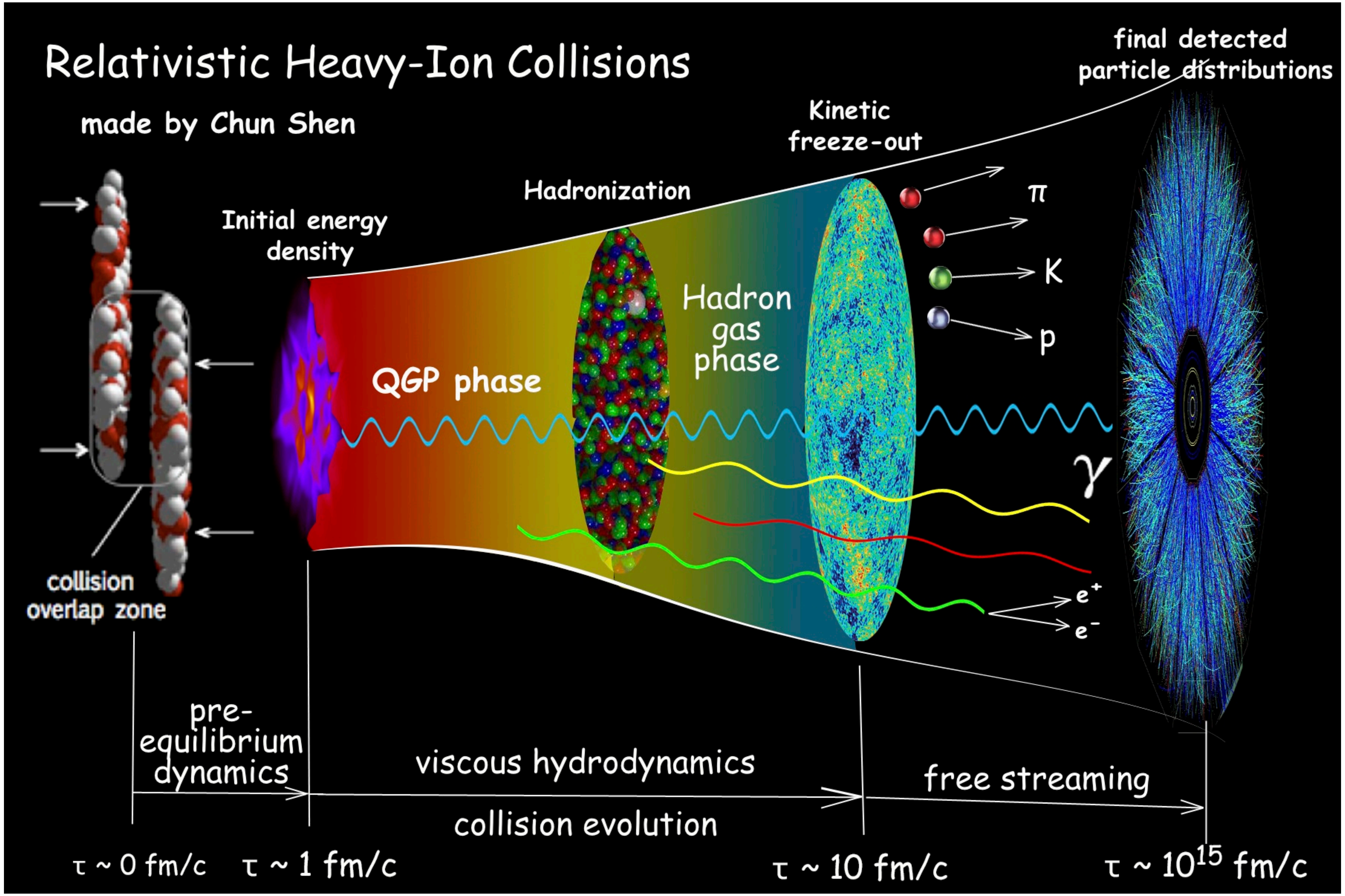
- New silicon chips with MAPS technology (ALPIDE)
  - Pixel size = 27 x 27 μm^2
  - Position resolution ~ 5 μm

- Physics motivations
  - Prompt and non-prompt charmonia disentangling
  - Precise measurement of low-mass dimuon



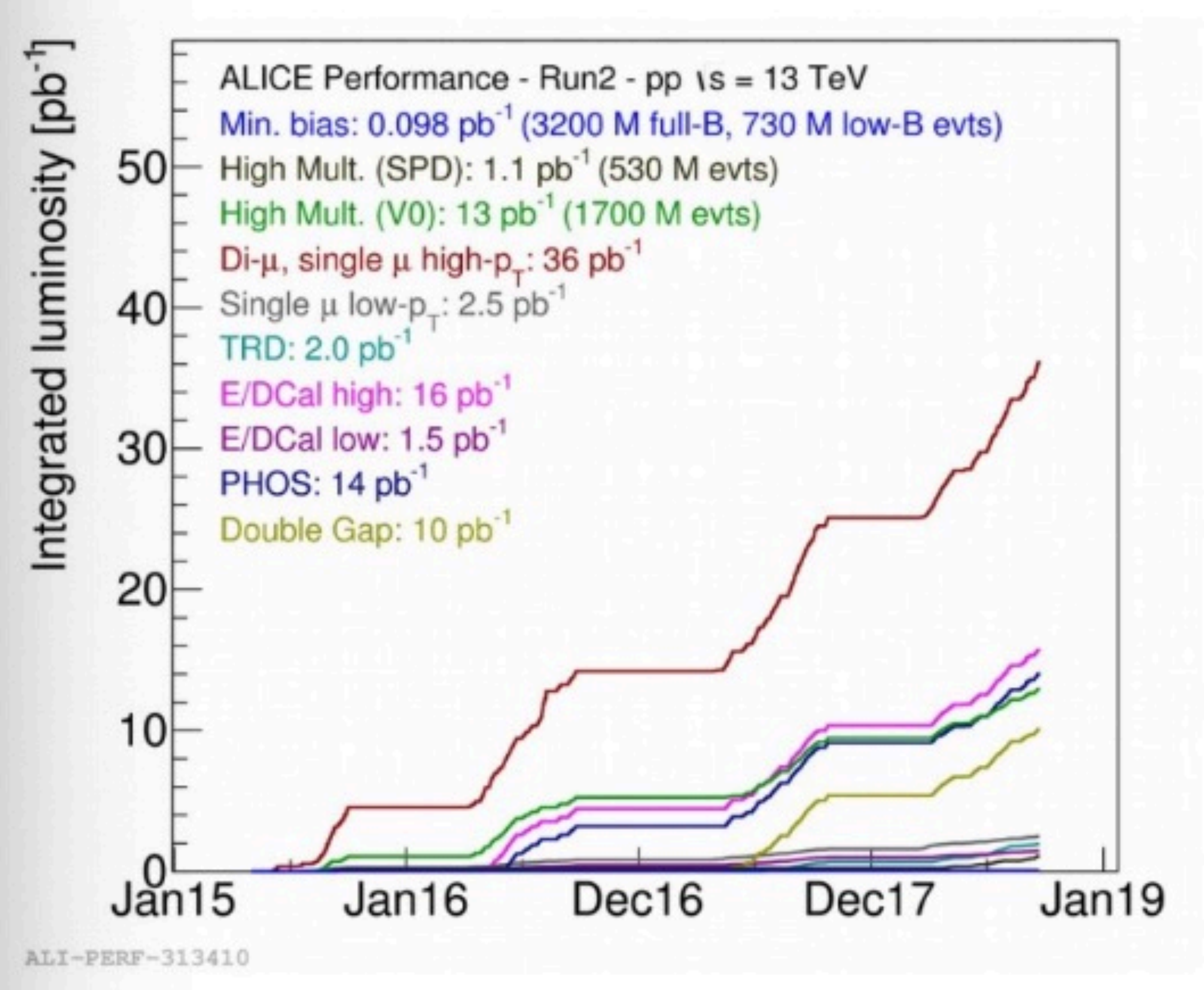
Both Central China Normal University and Institut de Physique des 2 Infinis de Lyon are involved in this MFT project

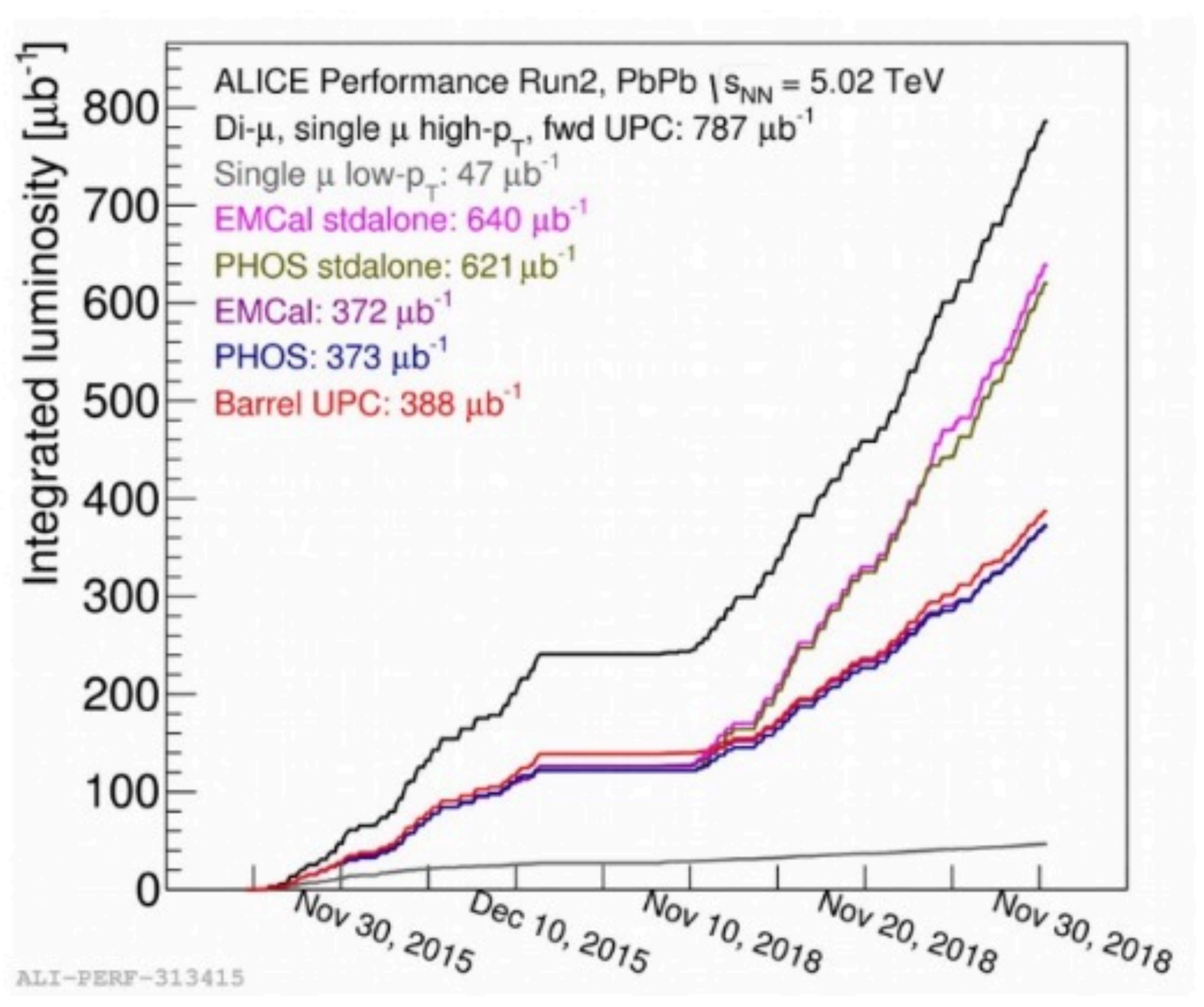
Ultra-relativistic heavy-ion collisions



ALICE data taking history

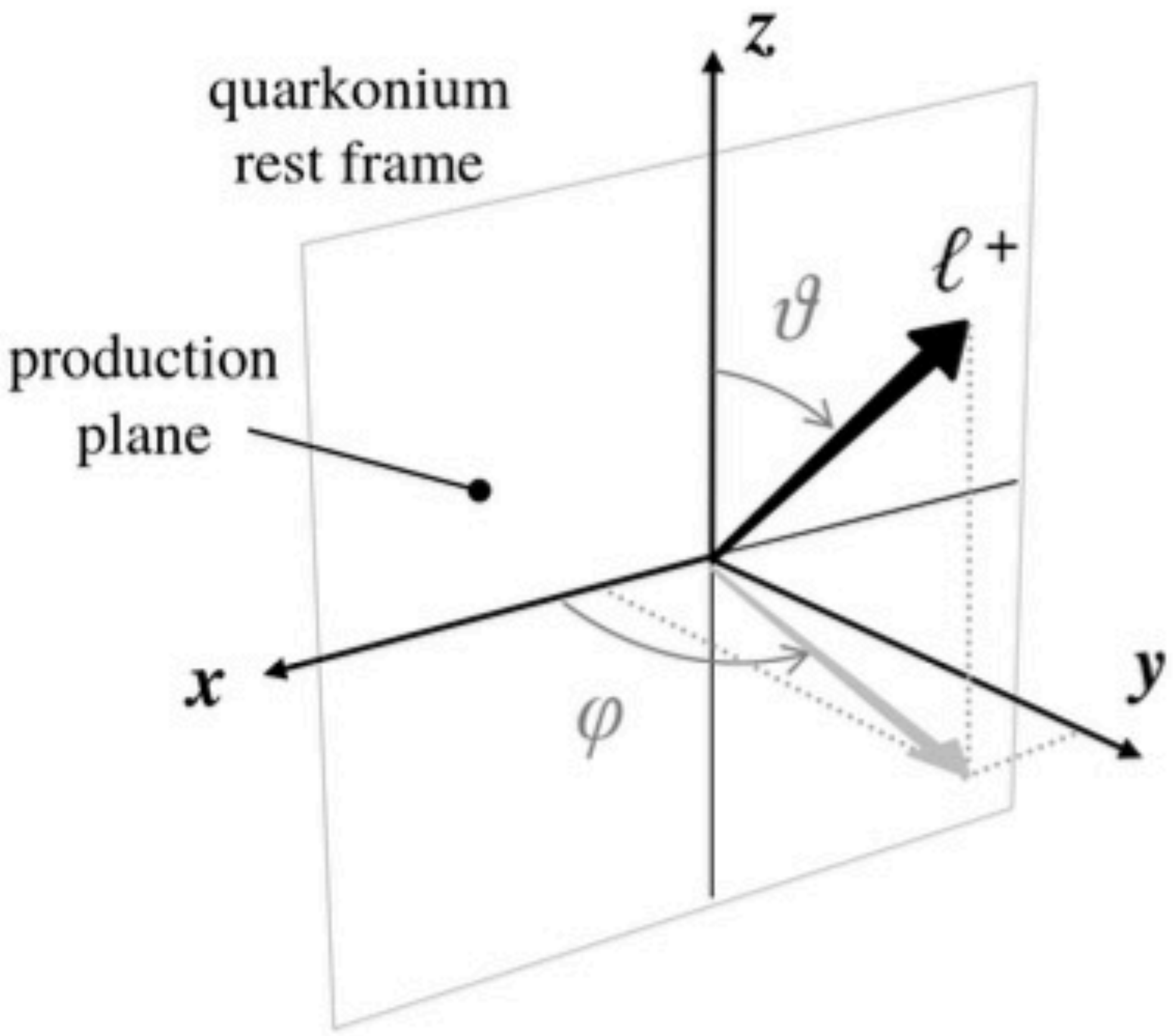
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	Recorded L_{int} (for muon triggers)
Pb–Pb	2010,2011	2.76	~75 μb^{-1}
	2015	5.02	~0.25 nb^{-1}
	2018	5.02	**~0.55 nb^{-1}**
Xe–Xe	2017	5.44	~0.3 μb^{-1}
p–Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}; ~25 nb^{-1}
pp	2009-2013	0.9,2.76,7,8	~200 μb^{-1}; ~100 nb^{-1}; ~1.5 pb^{-1}; ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2018	13	**~36 pb^{-1}**





e.g. J/ψ, Υ(1S) [$J^{PC} = 1^{--}$]

- For a **vector meson** ($\boldsymbol{v}$) the total angular momentum ($\boldsymbol{J}, \boldsymbol{J_z}$) state can be expressed as:



$$|\boldsymbol{v}: \boldsymbol{J}, \boldsymbol{J_z}\rangle = \boldsymbol{b_{+1}}|1,+1\rangle + \boldsymbol{b_0}|1,0\rangle + \boldsymbol{b_{-1}}|1,-1\rangle$$

Spin-alignment ⇔ decay products angular distribution

EPJC 69 (657-673), 2010, Faccioli et al.

Dilepton decay angular distribution

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