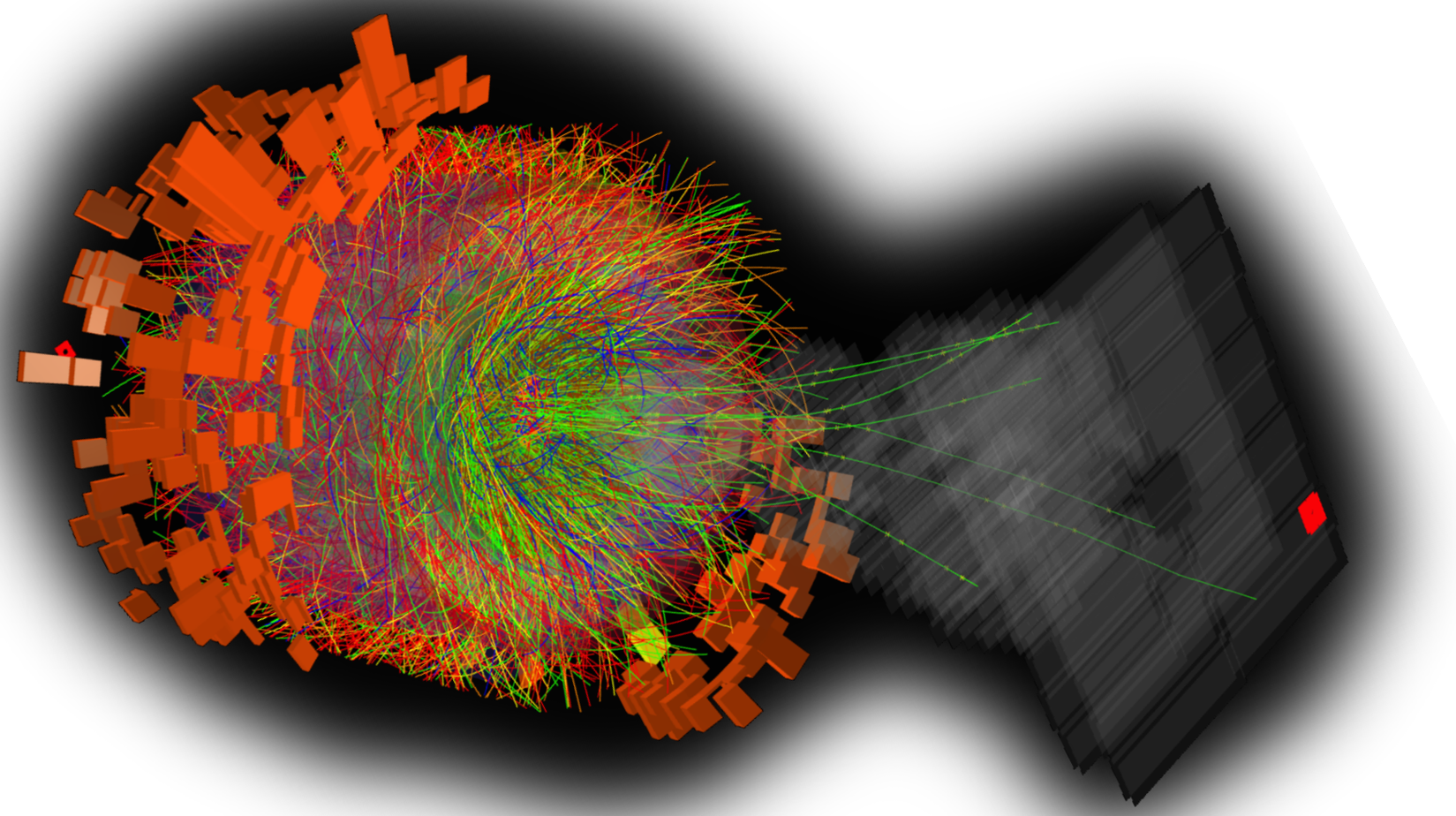
ALICE

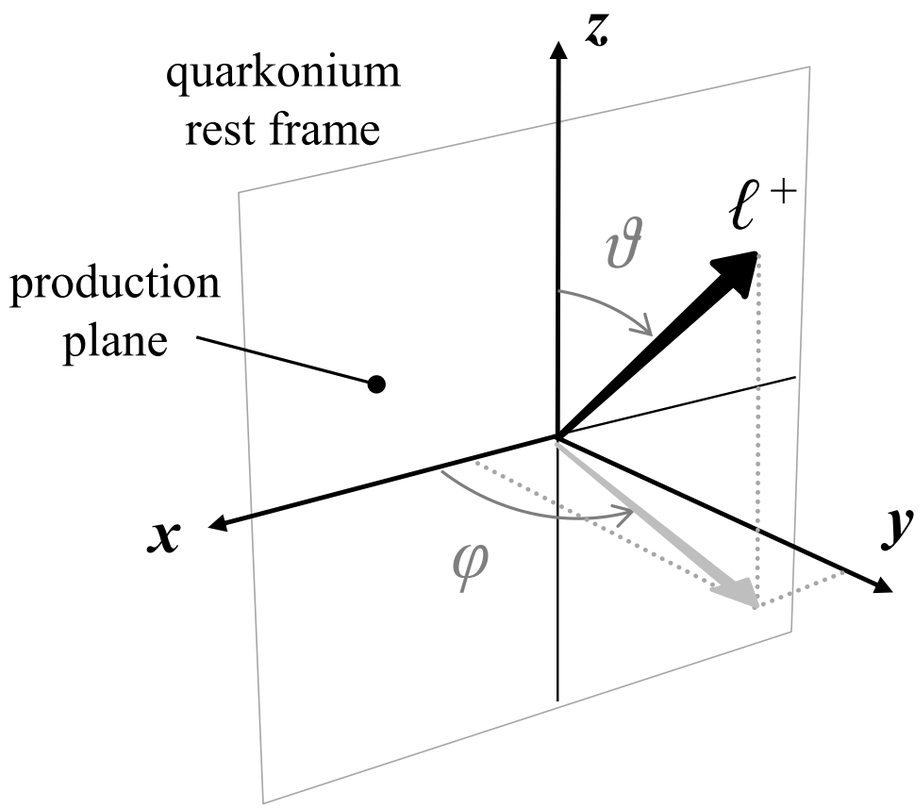
Quarkonium polarisation in pp and Pb-Pb collisions



Andrea FERRERO - CEA/IRFU and CERN
for the ALICE collaboration

Hard Probes 2023, March 30th 2023

Introduction to vector meson polarisation



Polarisation: alignement of the particle's spin along a reference direction

Total angular momentum:

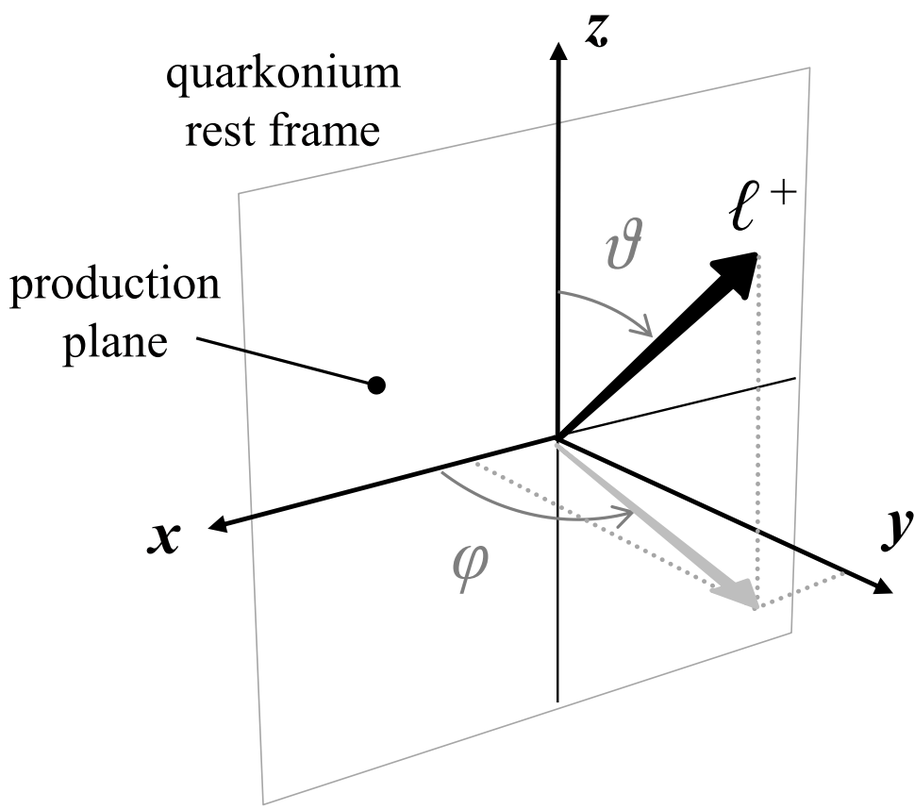
$$|V;J,J_z> = b_{+1}|1,+1> + b_0|1,0> + b_{-1}|1,-1>$$

Angular distribution in di-lepton decays:

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

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

Introduction to vector meson polarisation



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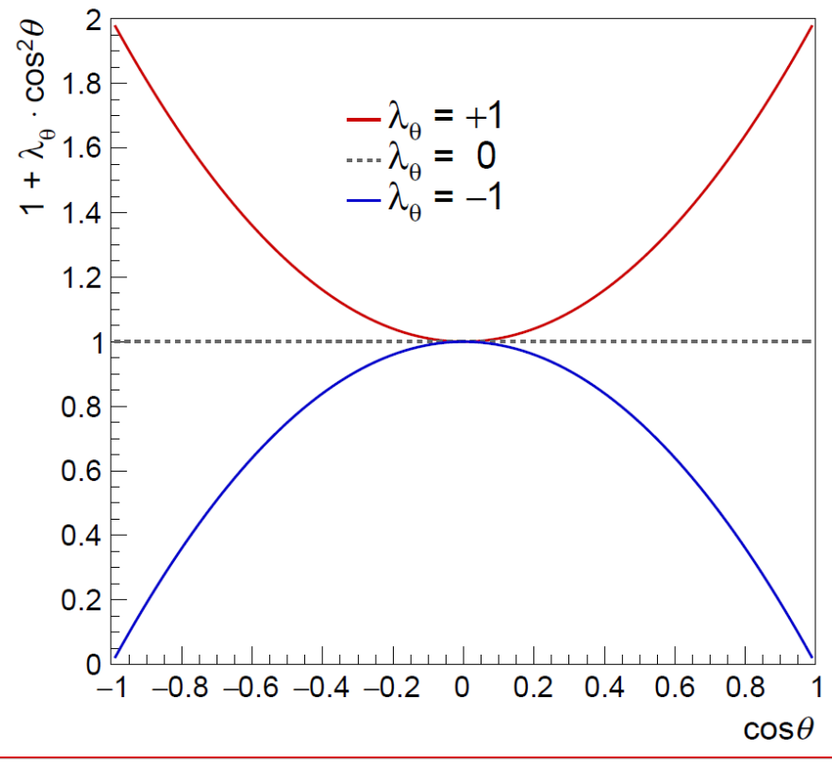


"transverse" polarisation ($\lambda_\theta = +1$, $J_z = +/-1$)

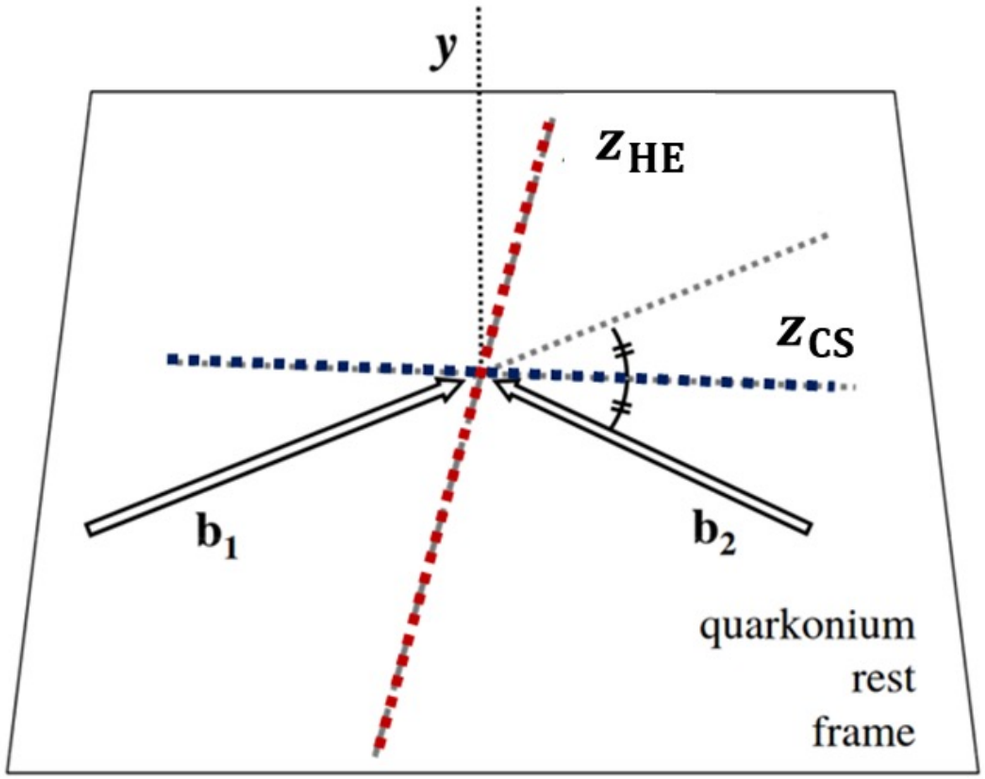
No polarisation

"longitudinal" polarisation ($\lambda_\theta = -1$, $J_z = 0$)

Quarkonium polarisation in pp and Pb-Pb collisions

Motivation: polarisation provides information complementary to differential cross-section measurements

—> Additional contraints to the description of quarkonium production mechanism in hadronic collisions



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

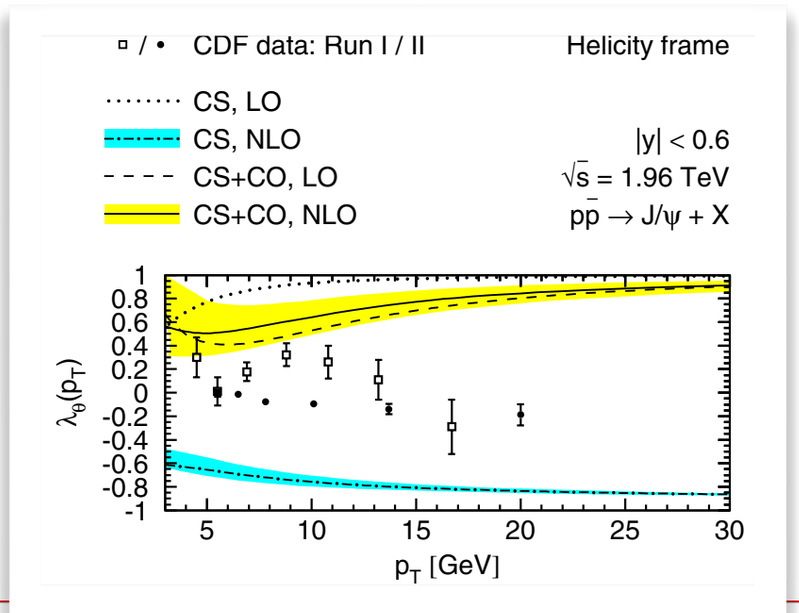
Choice of the reference polarisation directions:

- **Helicity (HE)**: quarkonium direction in the center-of-mass of the colliding beams
- **Collins-Soper (CS)**: bisector of the angle between the colliding beams in the quarkonium rest frame
- HE and CS perpendicular in the limit $p_T \gg |p_L|$

Before LHC results: different theoretical predictions at NLO

- NRQCD —> $\lambda_\theta > 0$
- Color Singlet Model —> $\lambda_\theta < 0$

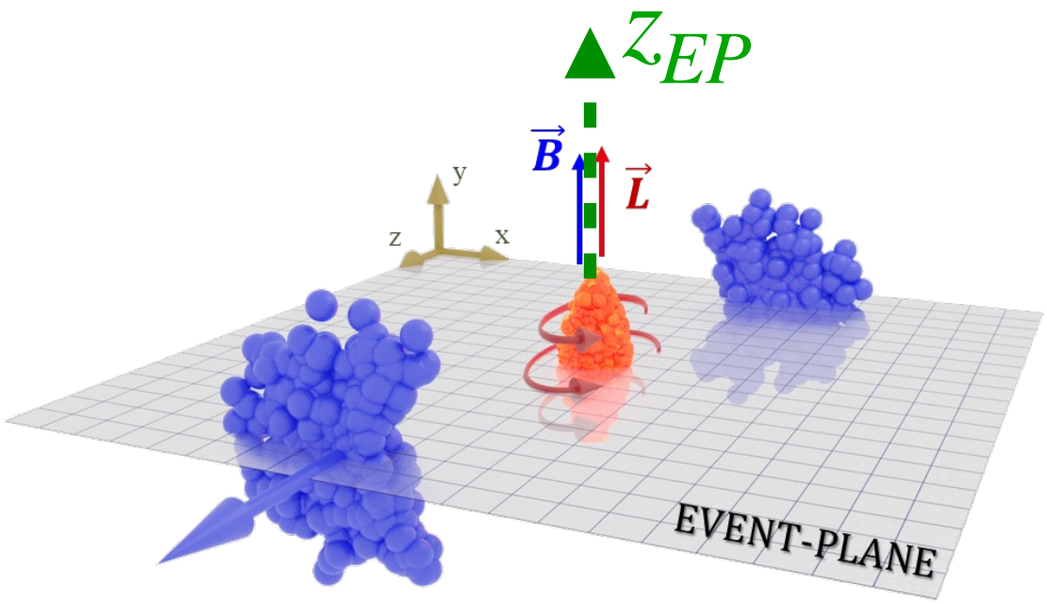
Phys. Rev. Lett. 108, 172002, Butenschoen et al.



Quarkonium polarisation in pp and Pb-Pb collisions

Motivation: large **magnetic field** ($\vec{B}$) and **angular momentum** ($\vec{L}$) produced in the QGP formation, perpendicular to the **event plane**

—> Might influence the polarisation of quarkonia originating from the early phases of QGP formation



Choice of the reference polarisation directions:

- **Helicity (HE)**: Quarkonium direction in the center-of-mass of the colliding beams
- **Collins-Soper (CS)**: bisector of the angle between the colliding beams in the Quarkonium rest frame
- **Event Plane (EP)**: direction orthogonal to the event plane in the center-of-mass of the colliding beams

Magnetic field $\vec{B}$:

- Huge intensity ($|\vec{B}| \sim 10^{14}$ T)
- Short lived ($\tau \sim 1$ fm/c)

NPA 803 (2008), Kharzeev et al.

Angular momentum $\vec{L}$:

- Highest in semi-central collisions ($b \sim 2$ fm)
- Affects the system evolution up to the freeze-out

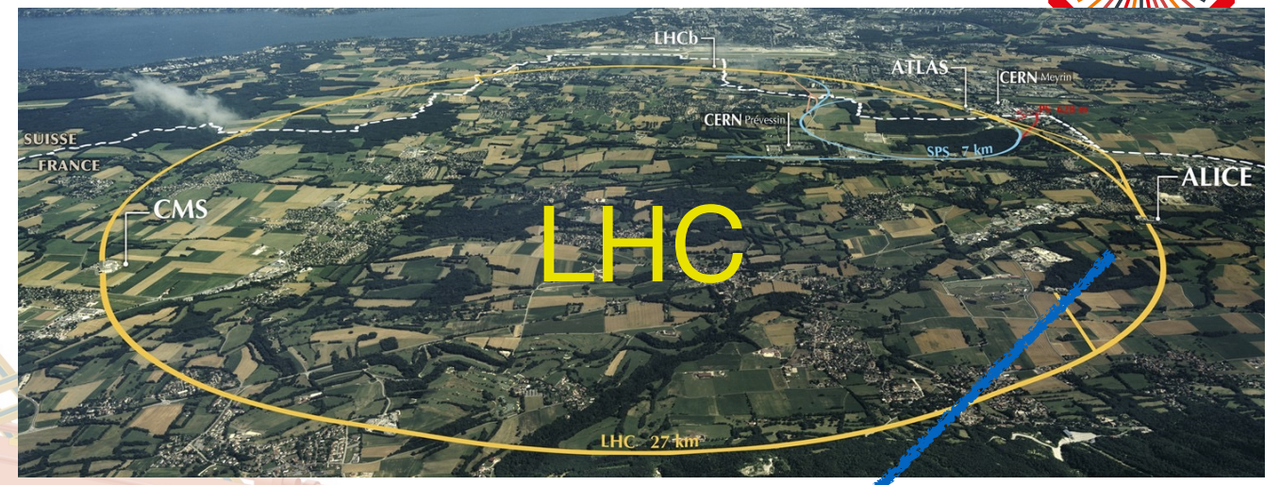
PRC 77 (2008) 024906, Becattini et al.

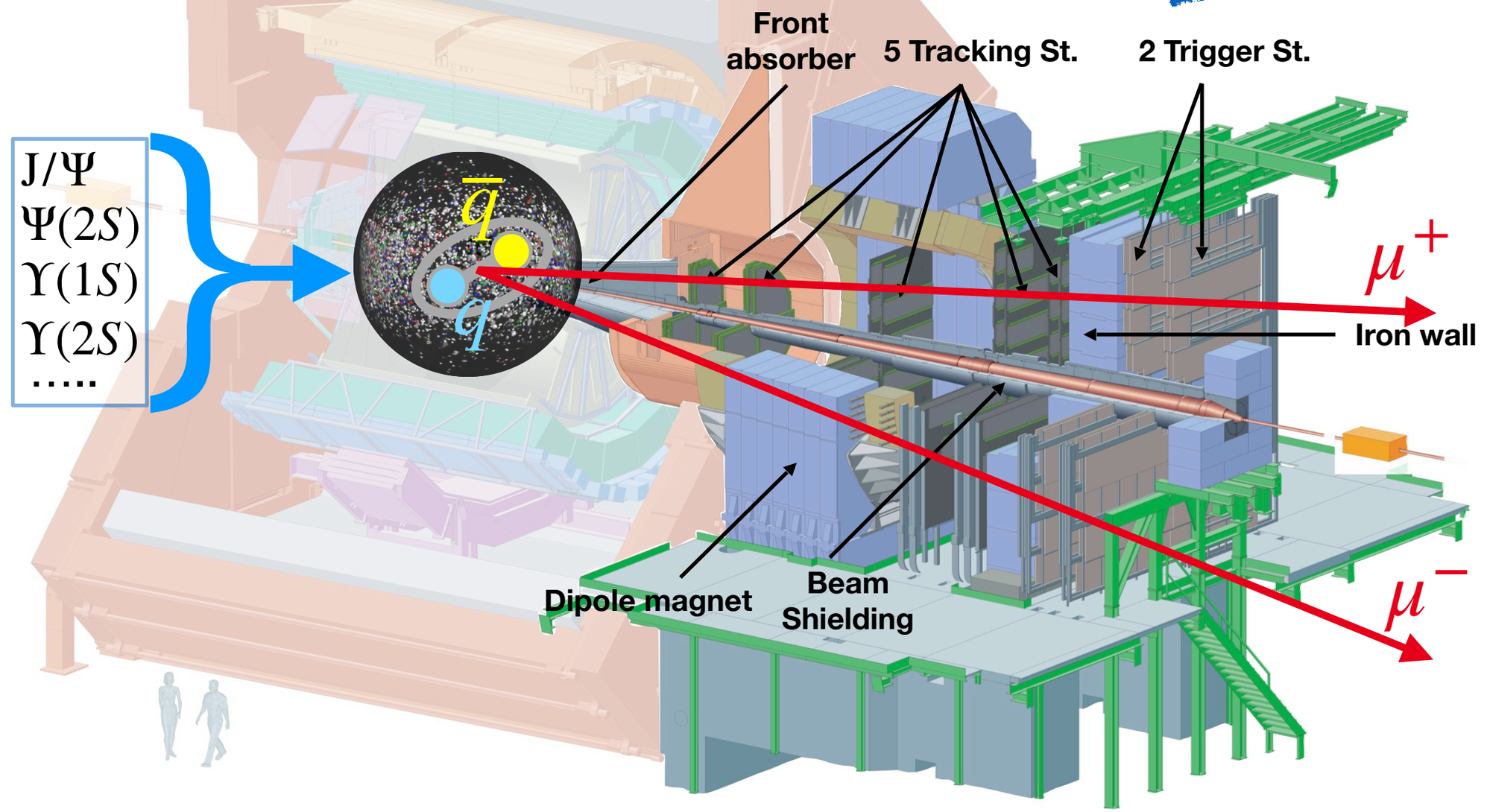
Forward muons detection in ALICE RUN 2

Data sets in this talk (Run 1+2):

- **pp**: $\sqrt{s}$ = 7, 8 and 13 TeV
- **Pb-Pb**: $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

Rapidity range: 2.5 < y < 4.0



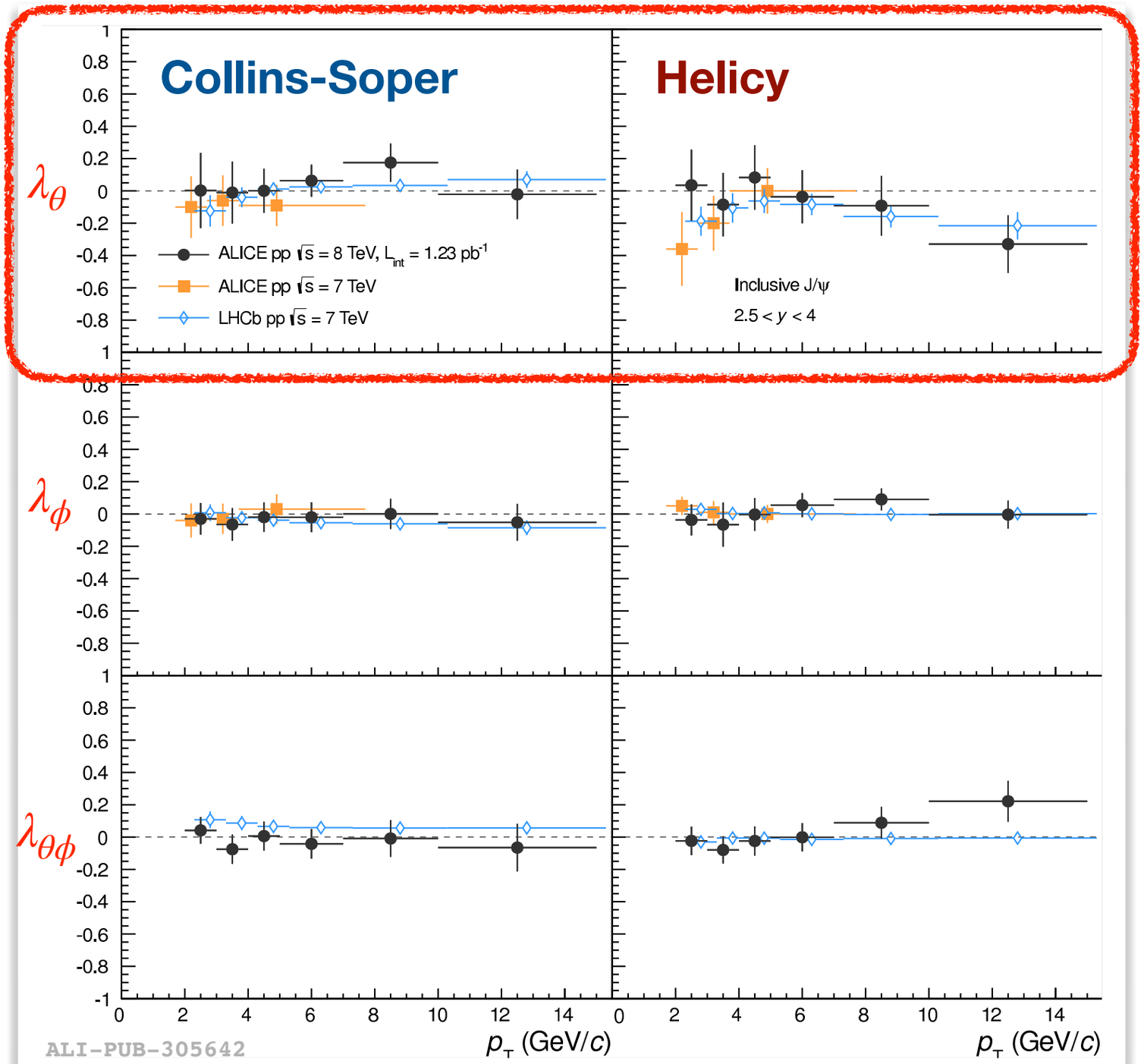


Quarkonium polarisation in pp collisions

Inclusive J/ψ polarisation in pp collisions

Polarisation measured in pp collisions in the **CS** and **HE** frames

No significant polarisation observed by **ALICE** and **LHCb** at forward rapidity



Data samples:

- ALICE $\sqrt{s}$ = 7 TeV (2010)
- ALICE $\sqrt{s}$ = 8 TeV (2012)
- LHCb $\sqrt{s}$ = 7 TeV (2011)

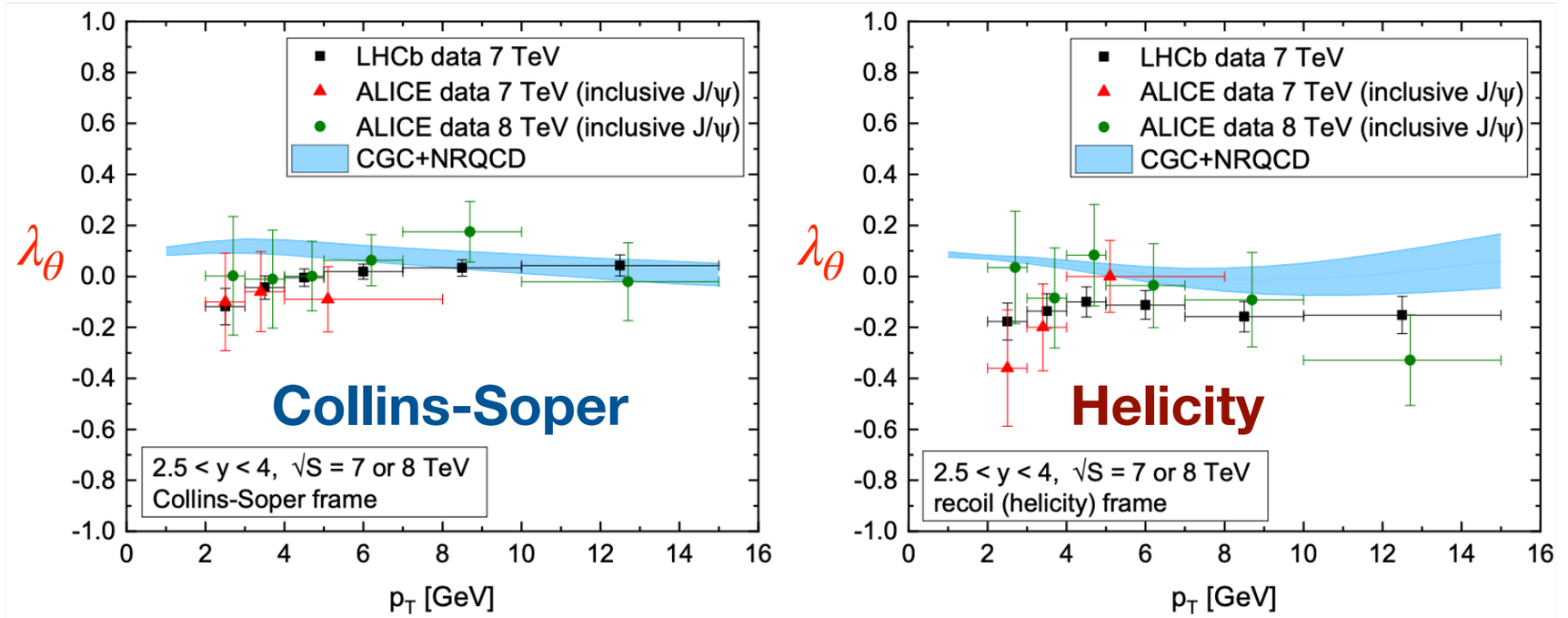
PRL 108 (2012) 082001 EPJC 78 (2018) 562

EPJC 73 (2013) 11

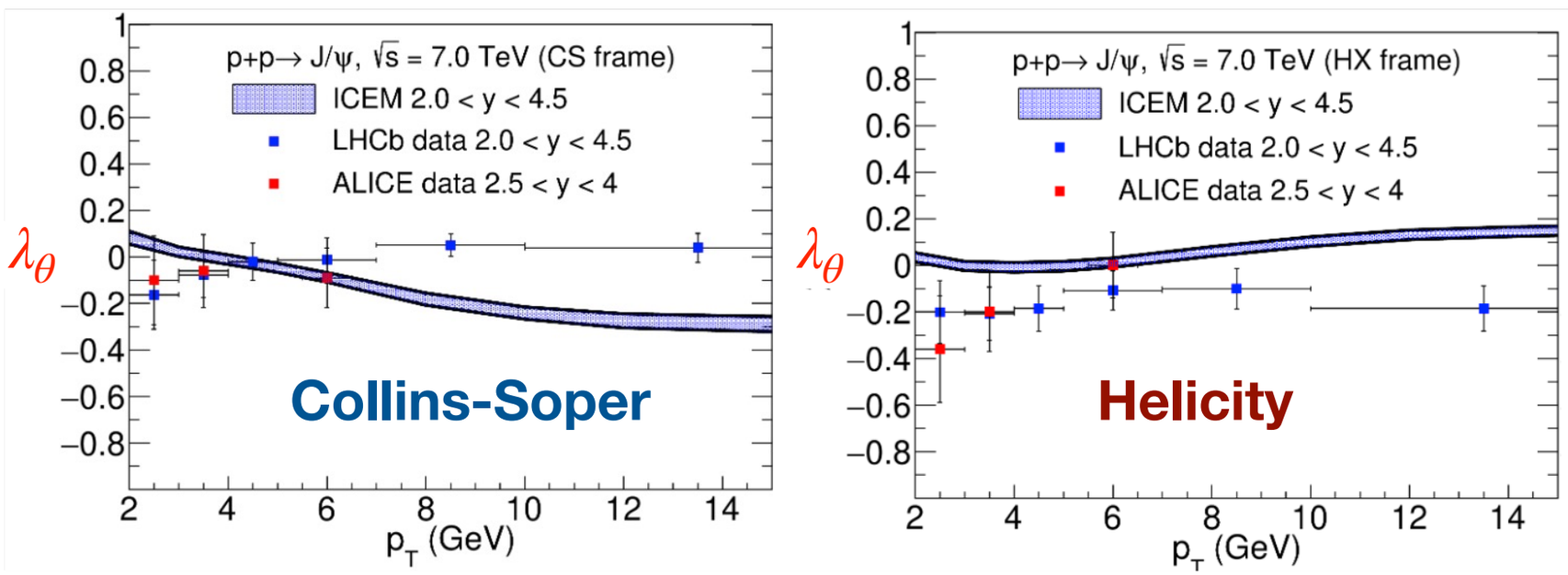
Inclusive J/ψ polarisation in pp collisions

Significant theoretical work to describe the recent results

CGC + NRQCD, JHEP 12 (2018) 057, Yan-Qing Ma et al.



Improved Color Evaporation Model (ICEM), PRD 104 (2021) 9, Cheung, Vogt



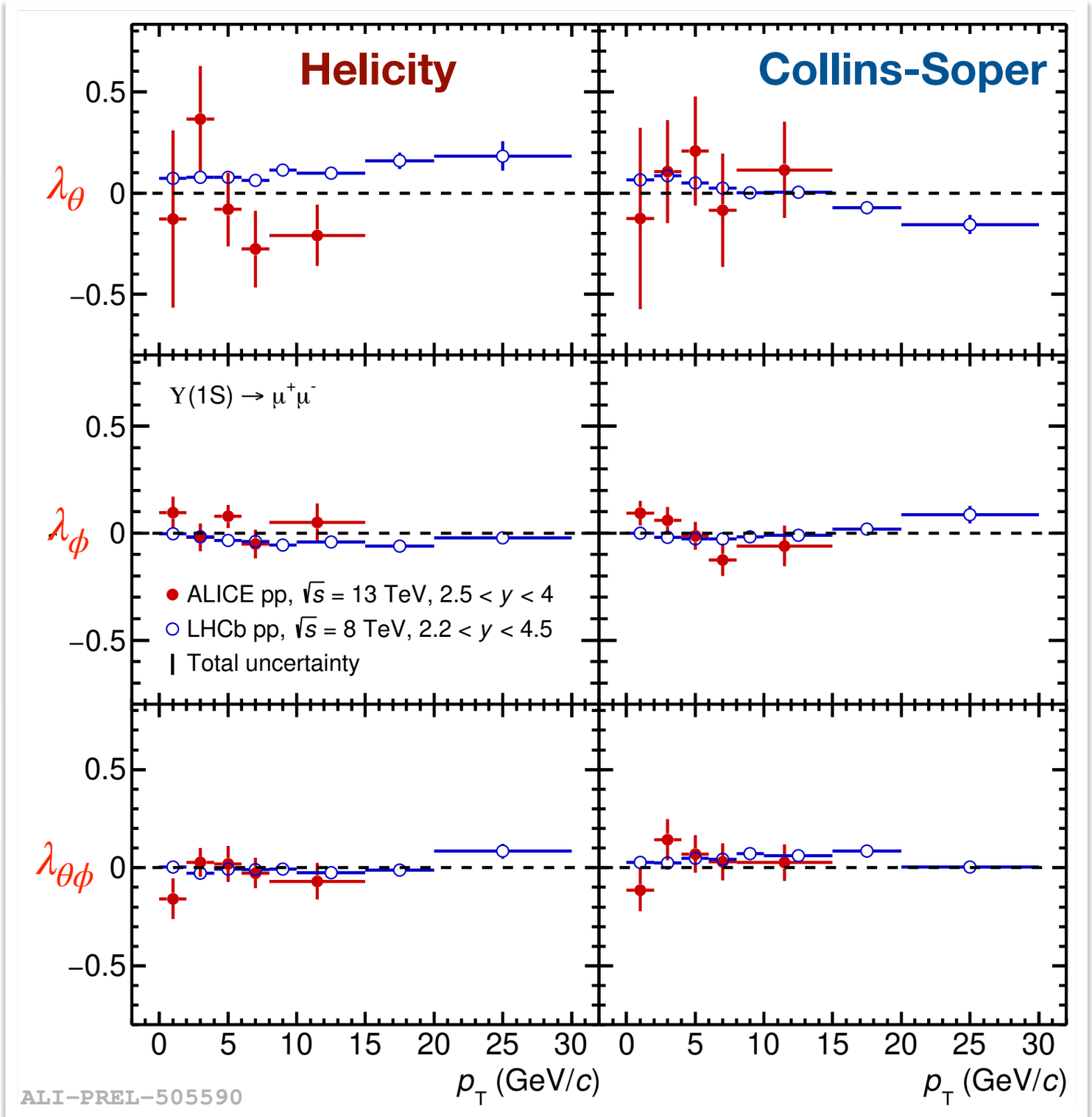
- General agreement between predictions
- zero or small λ_θ predicted in the whole p_T range

PRL 108 (2012) 082001
EPJC 78 (2018) 562

EPJC 73 (2013) 11

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

Recent preliminary measurement of polarisation at $\sqrt{s}$ = 13 TeV from ALICE



- Results compatible with previous LHCb measurements at $\sqrt{s}$ = 8 TeV
- Polarisation evaluated down to ~zero p_T
- All values compatible with zero within uncertainties
- Limited by the statistical precision

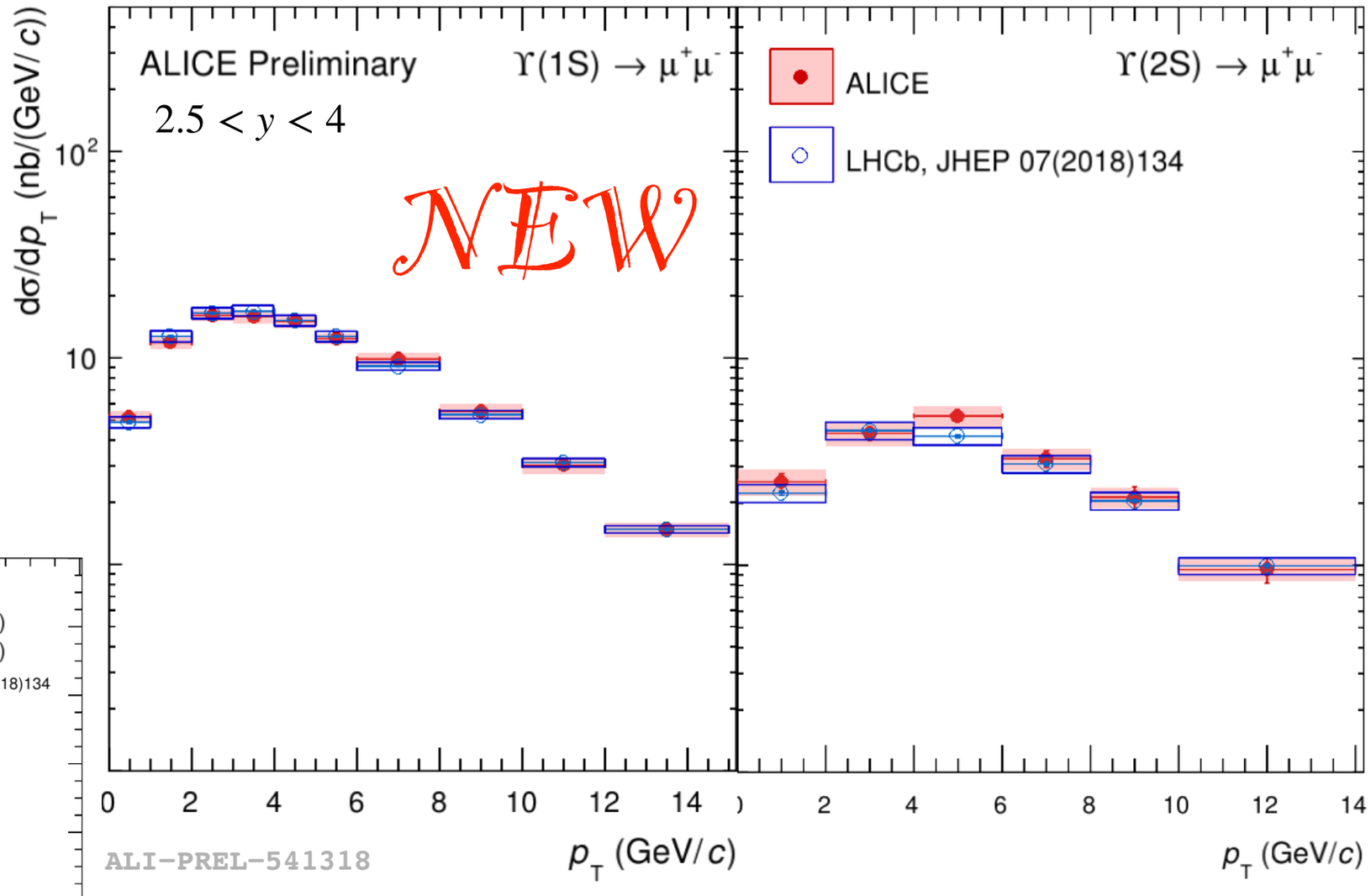
LHCb JHEP 12 (2017) 110,

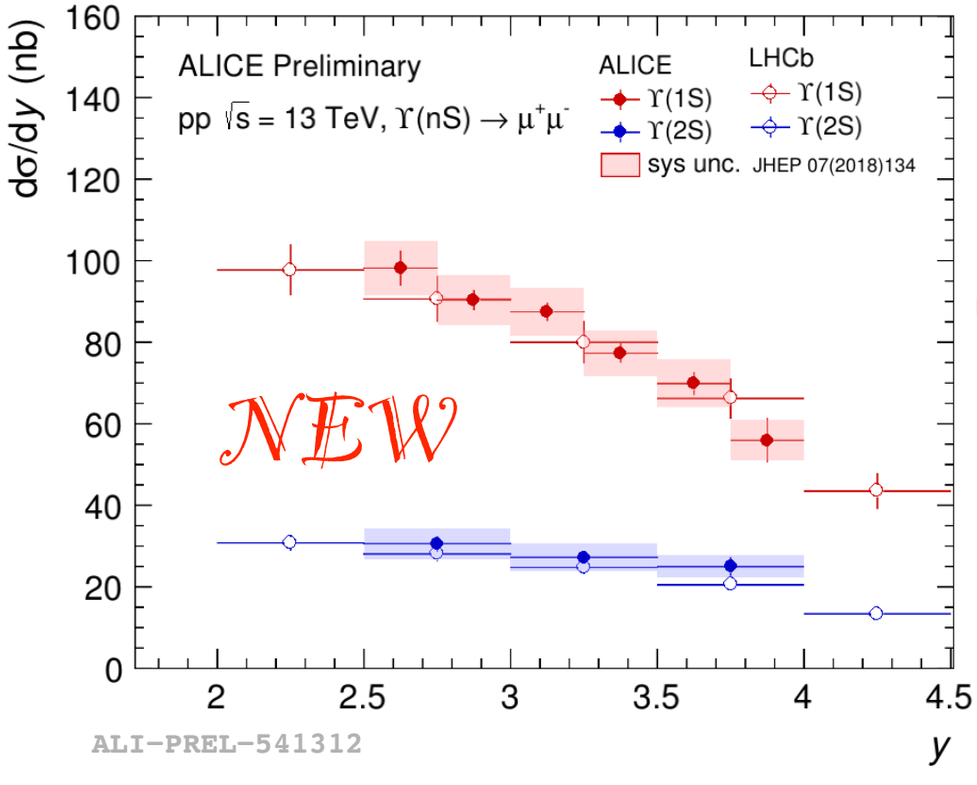
Preliminary

$\Upsilon(nS)$ production cross-section in pp collisions

Preliminary measurement of $\Upsilon(nS)$ production cross-sections at $\sqrt{s}$ = 13 TeV compared to LHCb results

- **Differential cross-sections** measured as function of p_{T} and y
- ALICE values compatible with LHCb measurements within uncertainties





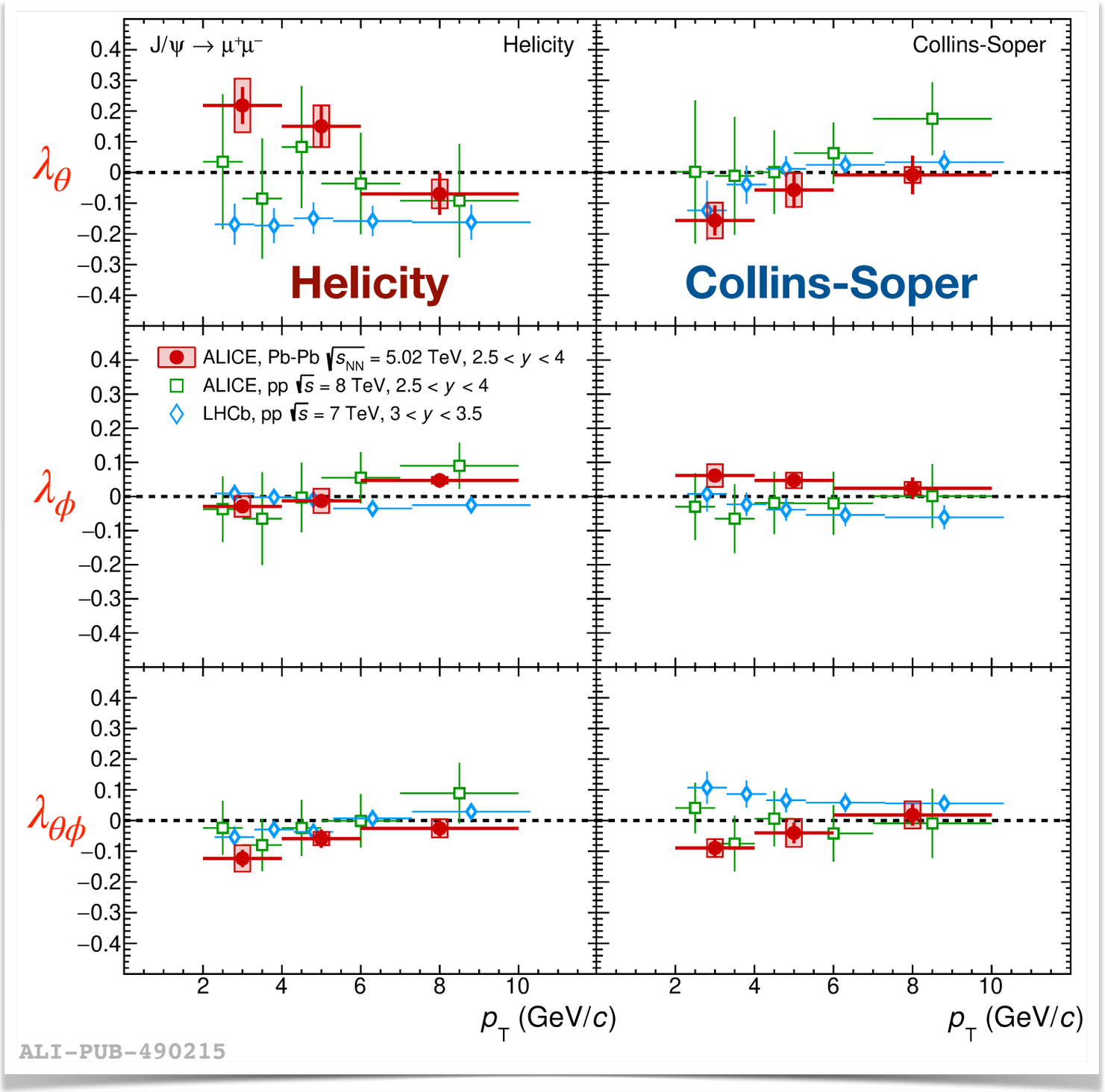
Full RUN 2 pp statistics

Quarkonium polarisation in Pb-Pb collisions

J/ψ polarisation in Pb-Pb collisions

ALICE measurement of J/ψ polarisation in **Pb-Pb collisions** at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

Helicity (**HE**) and Collins-Soper (**CS**) reference frames



- λ_θ shows a 2σ deviation from zero at intermediate p_{T}
  - Present in both **HE** and **CS** frames
  - 3σ deviation from **LHCb** measurement in pp collisions in the **Helicity frame**
- Values compatible with ALICE results in pp collisions within uncertainties
- Can this be explained by **Cold Nuclear Matter** (CNM) effects?

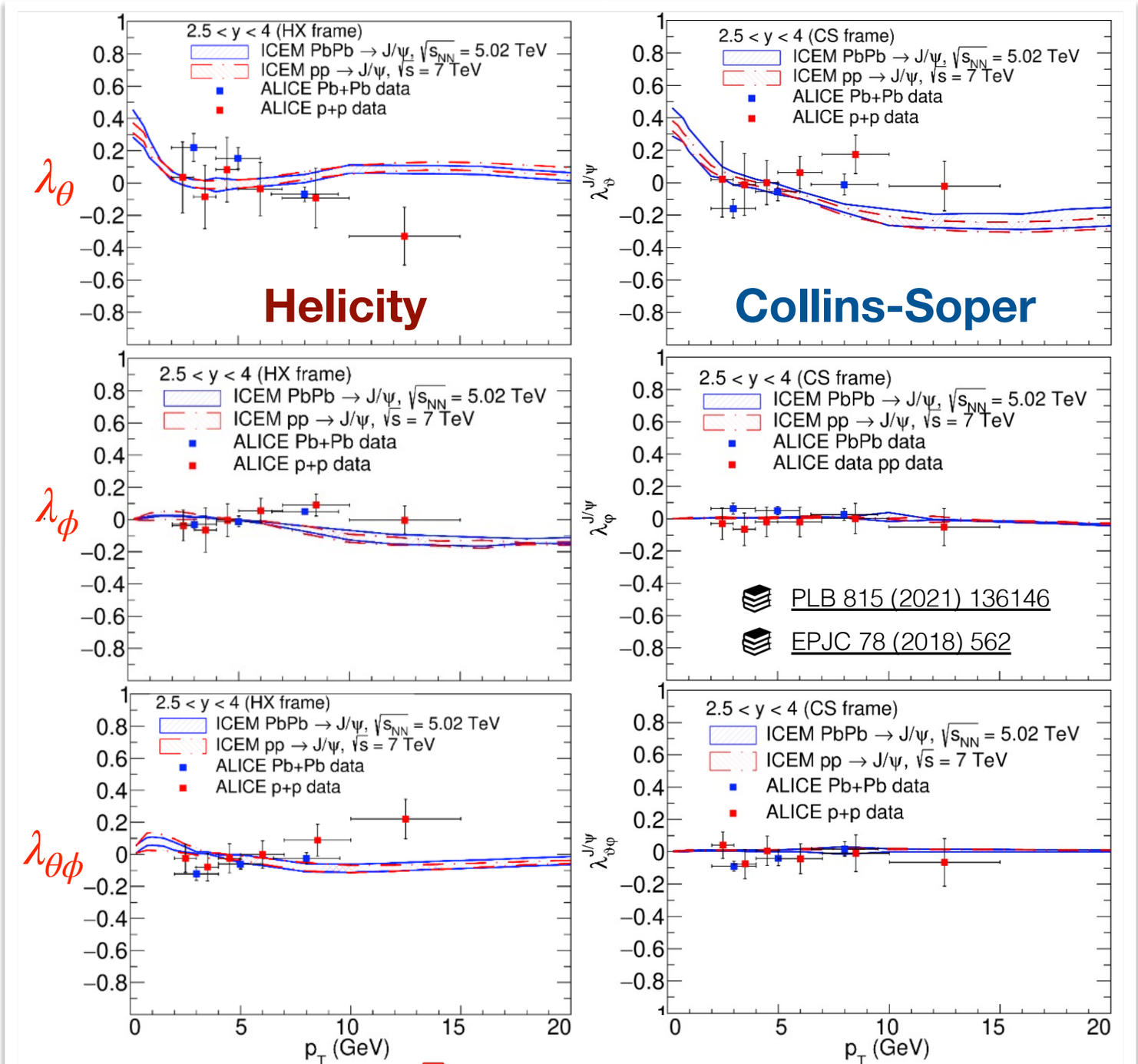
PLB 815 (2021) 136146 EPJC 78 (2018) 562

EPJC 73 (2013) 11

J/ψ polarisation in Pb-Pb collisions

ALICE measurement of J/ψ polarisation in **Pb-Pb collisions** at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

Helicity (**HE**) and Collins-Soper (**CS**) reference frames, **compared to pp data**



PLB 815 (2021) 136146, EPJC 78 (2018) 562

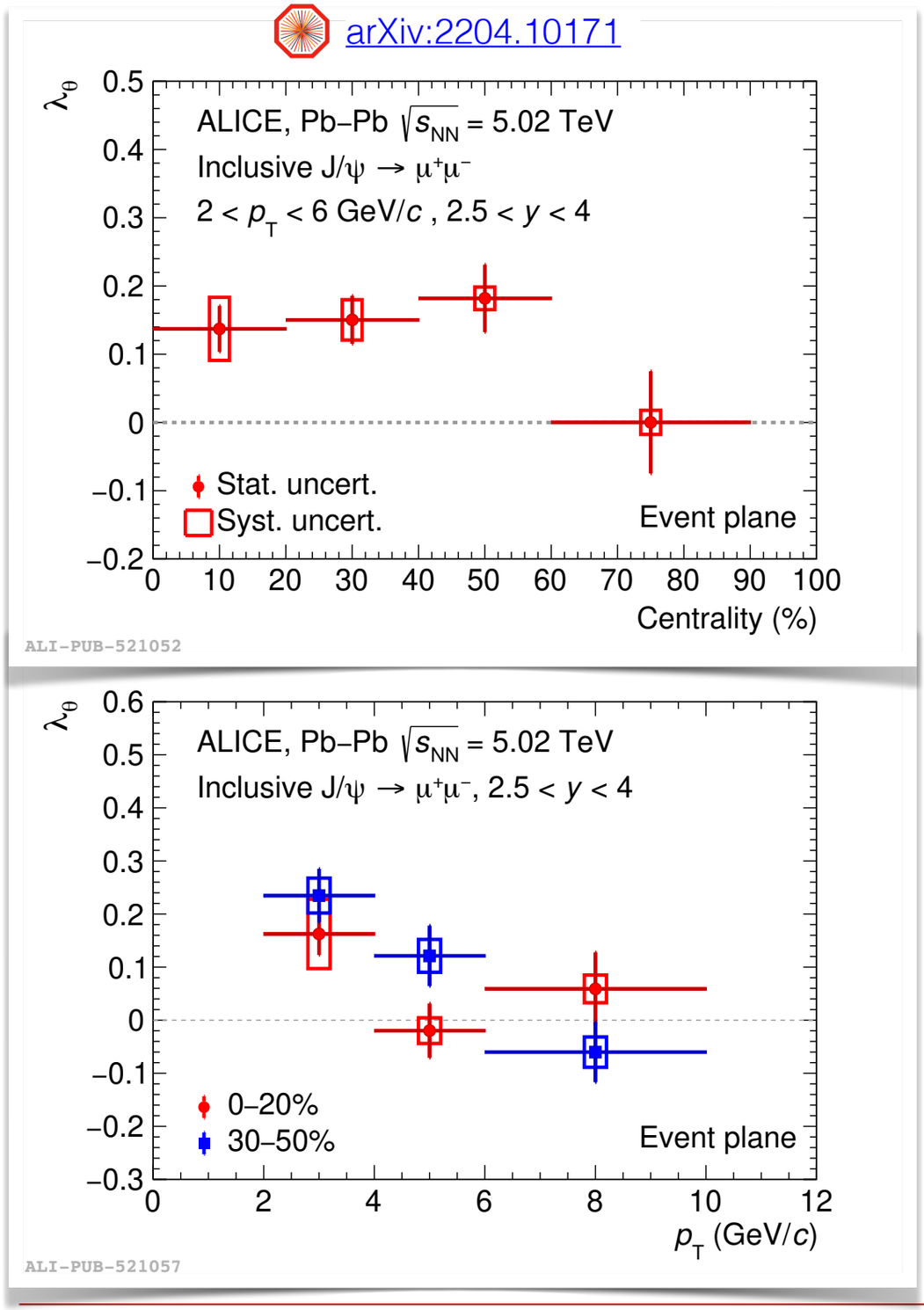
- Improved Color Evaporation Model (ICEM)
  - No Hot Nuclear Matter effects
  - Direct J/ψ only (no feed-down)
  - CNM effects only in Pb-Pb
- Small difference between pp and Pb-Pb collisions
- CNM effects not contributing significantly to the polarisation

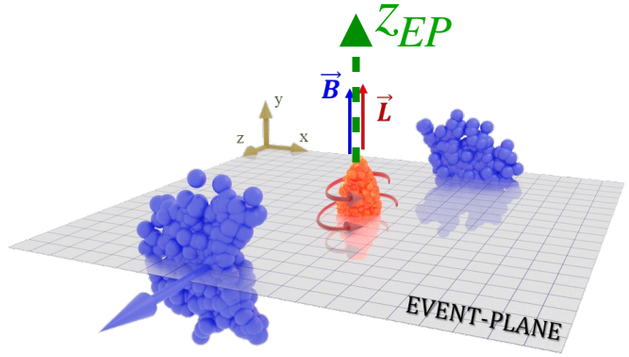
PRC 105, 055202, Cheung, Vogt

J/ψ polarisation in Pb-Pb collisions

ALICE measurement of J/ψ polarisation in **Pb-Pb collisions** at $\sqrt{s_{\rm NN}}$ = 5.02 TeV

First measurement with respect to the Event Plane (**EP**)

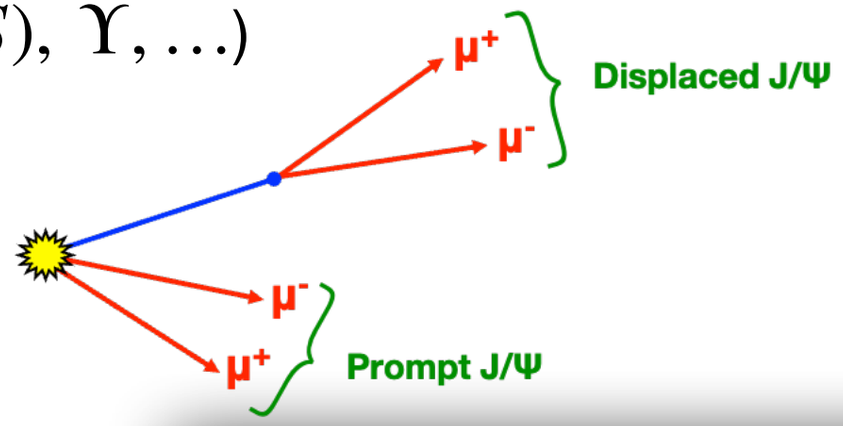




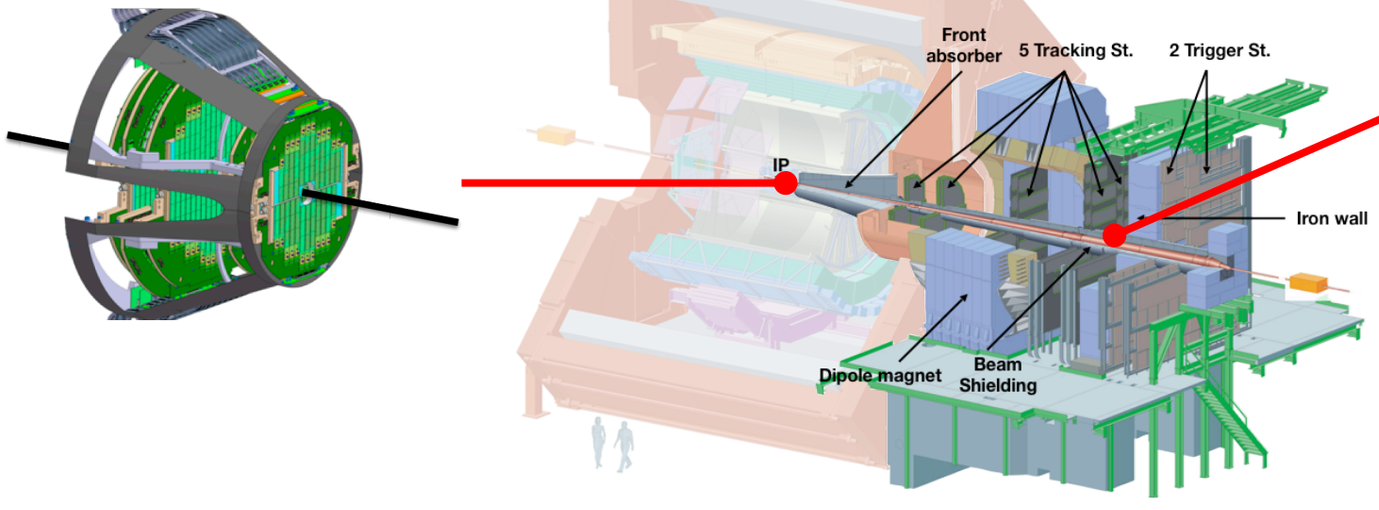
- Small but significant polarisation, particularly in the 40-60% centrality range (3σ effect)
- Effect more pronounced at low transverse momentum (2 < $p_{\rm T}$ < 4 GeV/c)
- Qualitatively in agreement with spin alignment observed for light vector mesons
  PRL 125 (2020) 012301
- Theoretical models needed to distinguish between possible $\vec{B}$ and $\vec{L}$ contributions

ALICE muon spectrometer in Run 3

- **Readout electronics upgrade** for higher data rates:
  - Pb-Pb collisions at 50 kHz —> ~10x more statistics (13 nb^{-1} projected Run 3+4)
  - pp collisions at 500 kHz —> ~100x more statistics
  - Enhancement of low statistics signals ($\psi(2S)$, Υ, …)
- **Forward silicon-based tracker** (MFT)
  - Detection of displaced charmonia decays (prompt/non-prompt separation)
  - Better matching with interaction point



MUON Forward Tracker (MFT)



Readout electronics upgrade
« Trigger-less » continuous readout
High rate capabilities

Conclusions and outlook

- ALICE has extensively measured the **quarkonium polarisation** in both **pp** and **Pb-Pb** collisions

- No significant J/ψ and $\Upsilon(1S)$ polarisation observed in pp collisions

- Results compatible with other LHC measurements and recent model predictions

- Interesting dynamics emerging from **Pb-Pb data**:
  - **Hint for non-zero λ_θ values** at intermediate p_{T} in the HE and CS frames
  - Not explained by **Cold Nuclear Matter (CNM)** effects
  - 3σ deviation from zero of λ_θ along the **normal to the event plane**

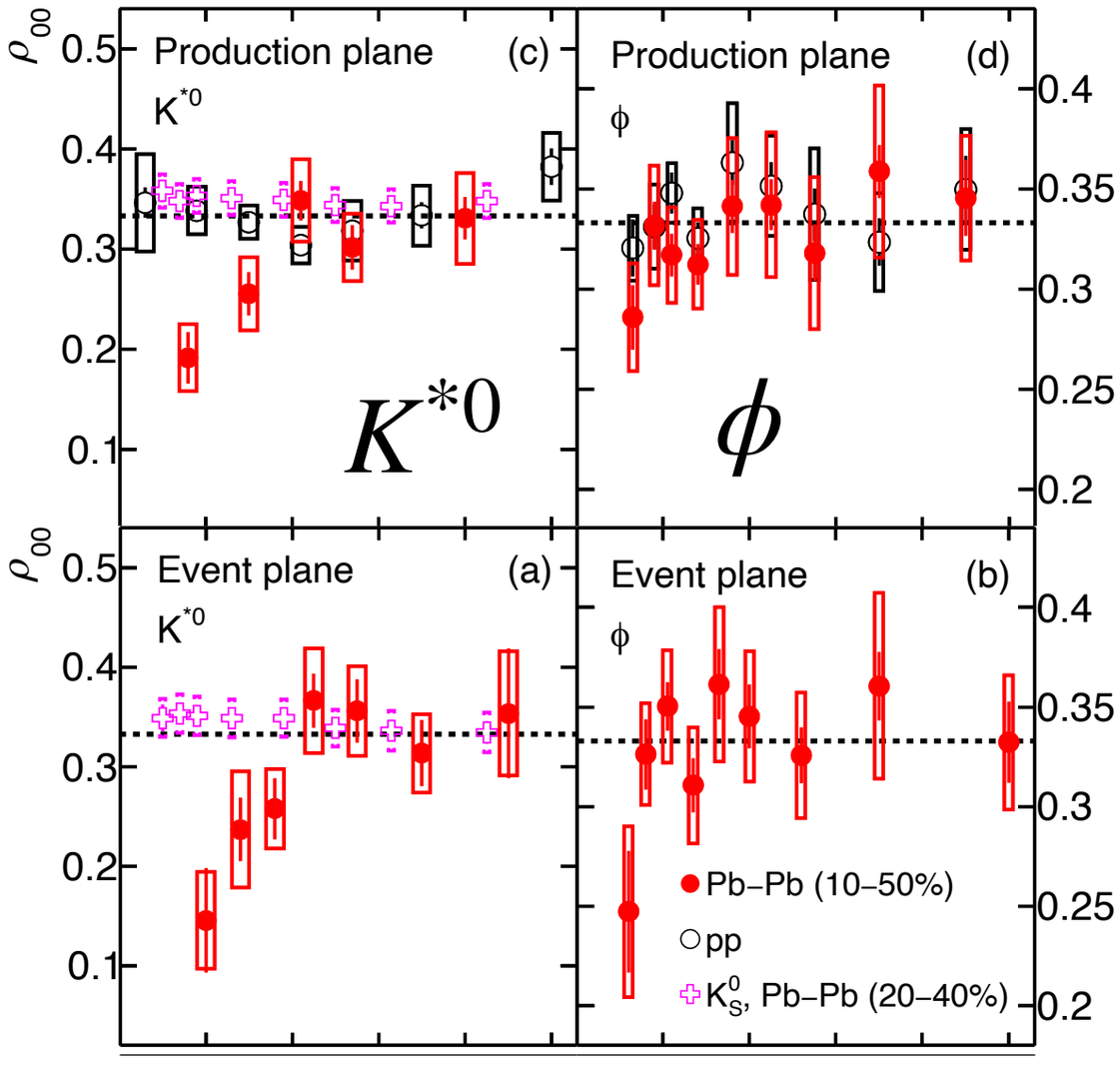
★ *Possible correlation with $\overrightarrow{B}$ and $\overrightarrow{L}$ in the formed QGP*

BAKUP SLIDES

K^{*0} and ϕ polarisation in pp and Pb-Pb collisions

Light vector meson polarisation measurements from ALICE
pp at $\sqrt{s}$ = 13 TeV and Pb-Pb at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV

$\rho^{00} < 0$ for K^{*0} and ϕ <==> $\lambda_\theta > 0$ for charmonia



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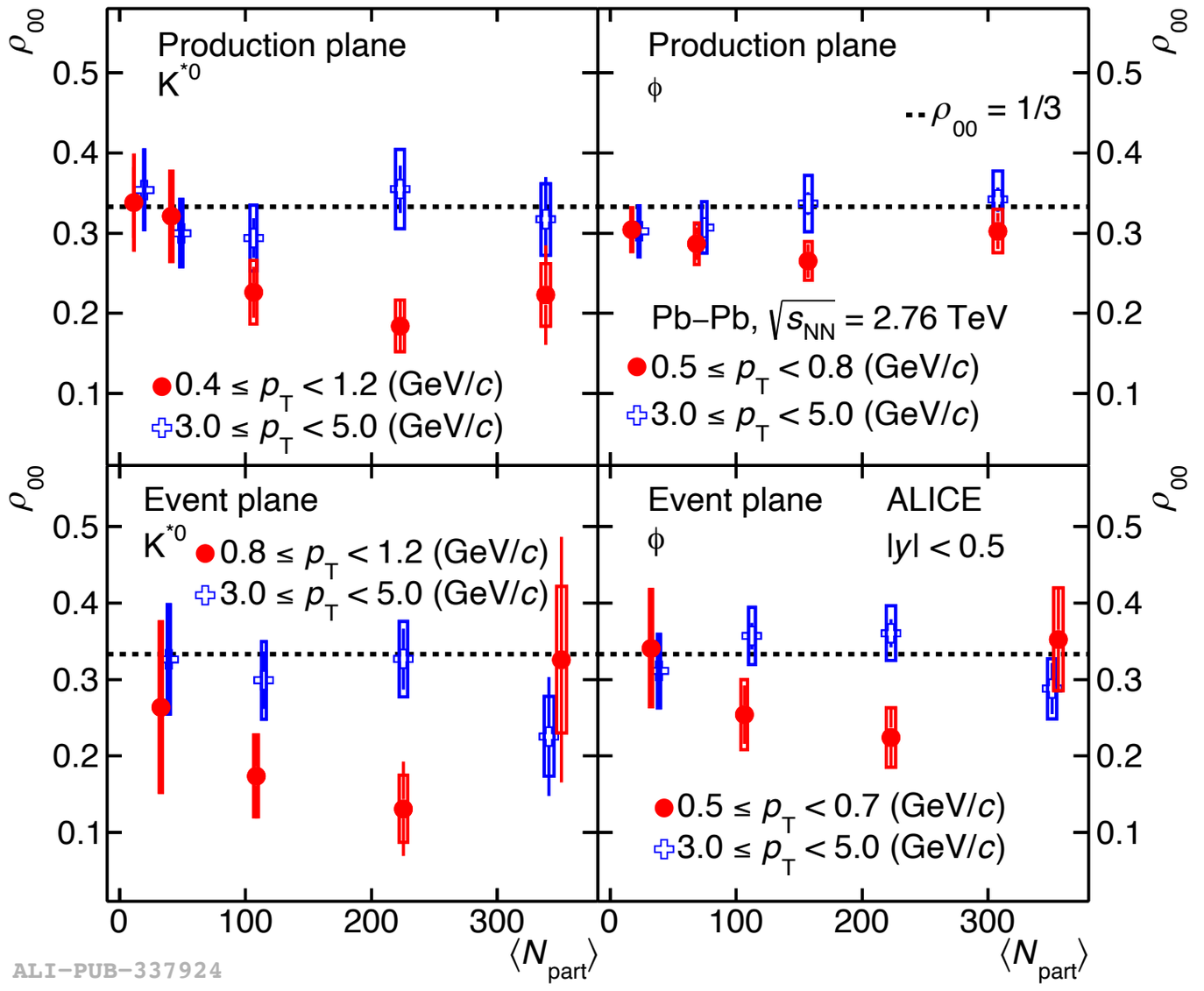

ALI-PUB-337924