Quarkonium production as a function of charged-particle multiplicity with ALICE: A probe for MPI in pp and p-Pb collisions

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MPI@LHC2023, 20th Nov 23
University of Manchester

Outline

I: Physics motivation for the study of multiple parton interaction (MPI) in small systems

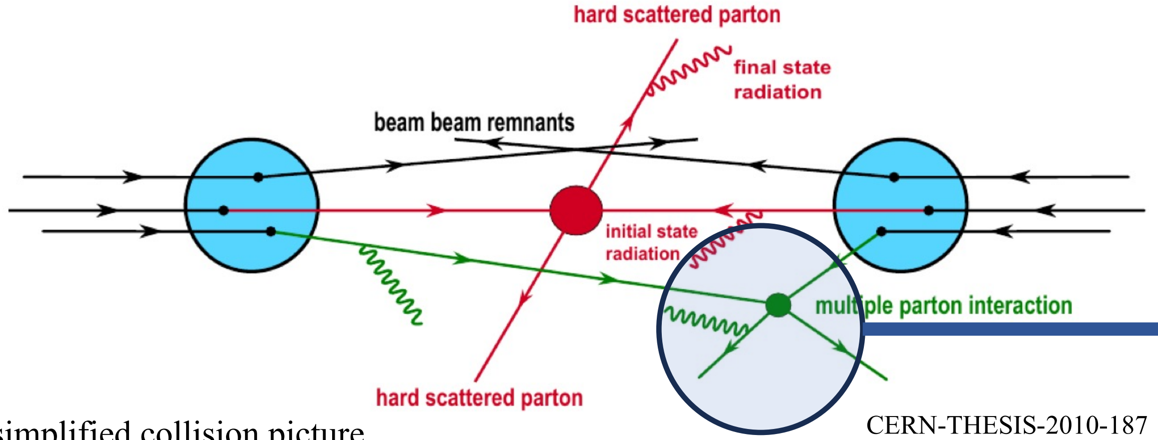
II: Multiplicity-dependent measurements of quarkonium production

III: Prospects for the first multiplicity-differential J/ψ polarization measurement at midrapidity with Run3 data

IV: Conclusions and outlook

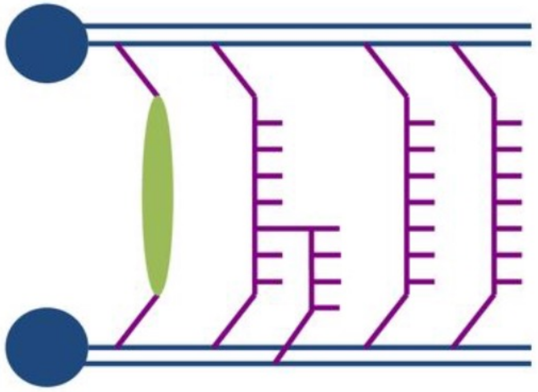
I. Physics motivation for the study of MPI in small systems

I.1 Why we need multiple parton interaction



A simplified collision picture

CERN-THESIS-2010-187



One schematic representation of MPI by parton ladders within **Gribov-Regge** approach

- **In pp collisions**
  - **Many parton scatterings occur with ISR (Initial State Radiation) and FSR (Final State Radiation)**
  - **Underlying events**: **MPI in soft regime** + BBR (Beam-Beam Remnants)
- **Multiple parton interaction occurs in both soft (low p_{T}) and hard (high p_{T}) regime,**
  - In soft regime, hadronic activity is enhanced
  - In hard regime, **DPS (Double Parton Scattering)** is dominant

- **In the MPI picture, number of elementary interactions is directly connected to the multiplicity, MPI needed for full description of pp collisions:**
  - Violation of **KNO** (Koba-Nielson-Oleson)-**scaling** at high $\sqrt{s}$: **soft-MPI**
  - Description of **inclusive quarkonium production** at high $\sqrt{s}$: **hard-MPI**

I.2 How to study MPI in pp and p-A collisions

-A full description of pp and p-A collisions at a high multiplicity regime requires a clear understanding of MPI, which connects soft and hard physics. Various experimental measurements have been performed with **LHC** by different collaborations. Some of the relevant ones from **ALICE** are listed below:

- **Quarkonium production as a function of charged-particle multiplicity**
  - Inclusive: Prompt + Non-prompt from b-hadron decays

Will be discussed in this talk

- **Underlying event measurements**

  See talk of Feng Fan on Thu. 23/11

- **Quarkonium associated production measurements**

  See talk of Ida Storehaug on Tue. 21/11

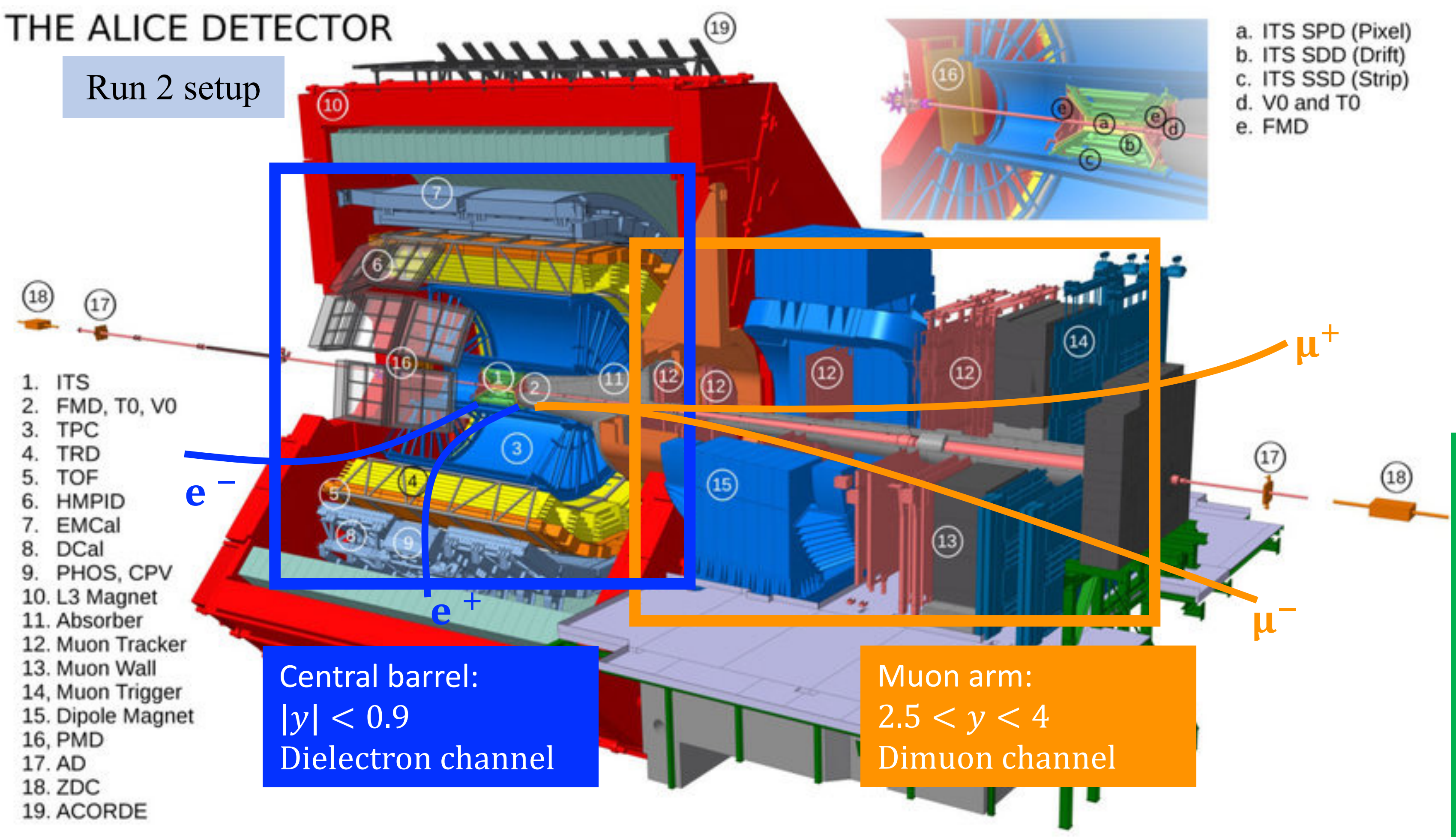
- **Collectivity measurements**

  See talks of Yoshini Bailung and Ida Storehaug on Tue. 21/11

- **Event-by-event hadron correlation measurements**

  See talk of Ante Bilandzic on Tue. 22/11

Experimental setup of ALICE



ALICE Run 3 upgrades:

- A new, high-resolution, low material **Inner Tracking System (ITS)**
- An upgrade of the **Time Projection Chamber (TPC)**
- A new **Muon Forward Tracker (MFT)**
- A new **Central Trigger Processor (CTP)**
- A new **Fast Interaction Trigger (FIT):**
  - **V0 replaced by FV0**
  - **T0 replaced by FT0**
  - **FMD and AD replaced by FDD**
- **New continuous readout and trigger system for data taking**

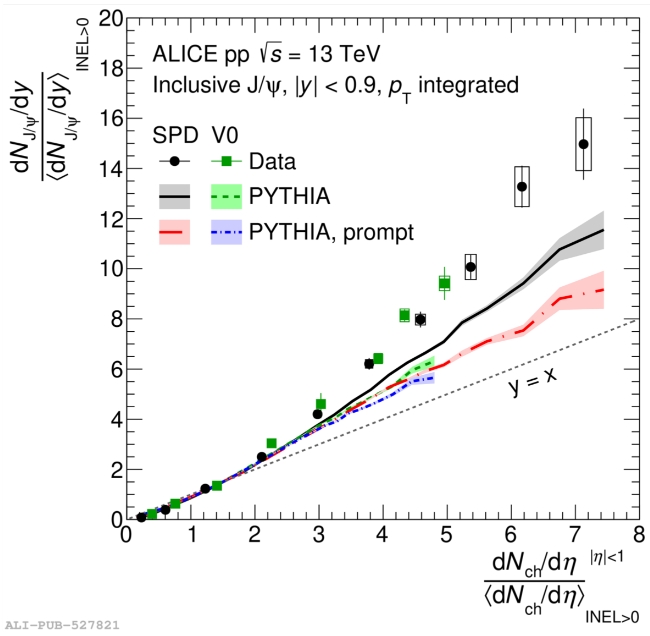
- **Charged-particle multiplicity** are estimated in central barrel with
  - **ITS, V0 (Run 2)**
  - **ITS, ITS+TPC, FIT, MFT (Run 3)**
- For **quarkonium reconstruction**:
  - **At midrapidity: inclusive, prompt, non-prompt (Run 2&3)**
  - **At forward rapidity: inclusive (Run 2), and prompt/non-prompt separation with MFT (Run 3)**

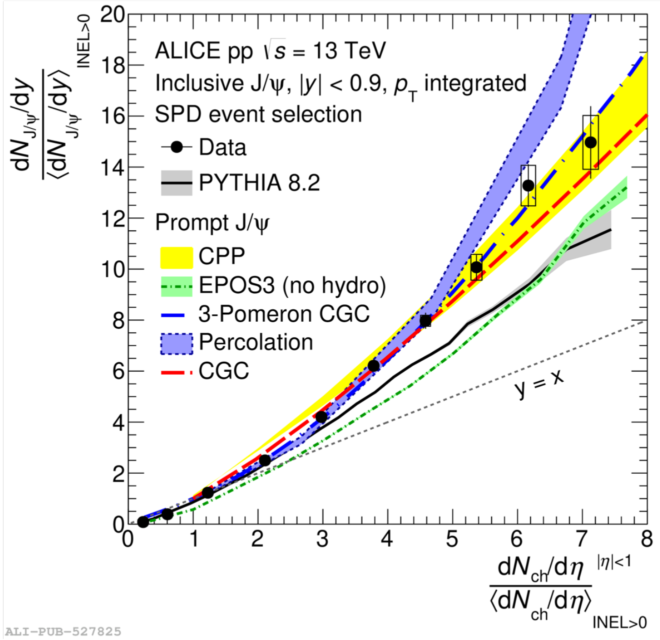
II. Multiplicity-dependent measurements of quarkonium production

J/ψ yield at midrapidity vs. multiplicity in pp collisions

p_T integrated J/ψ yields

Phys. Lett. B 810 (2020) 135758



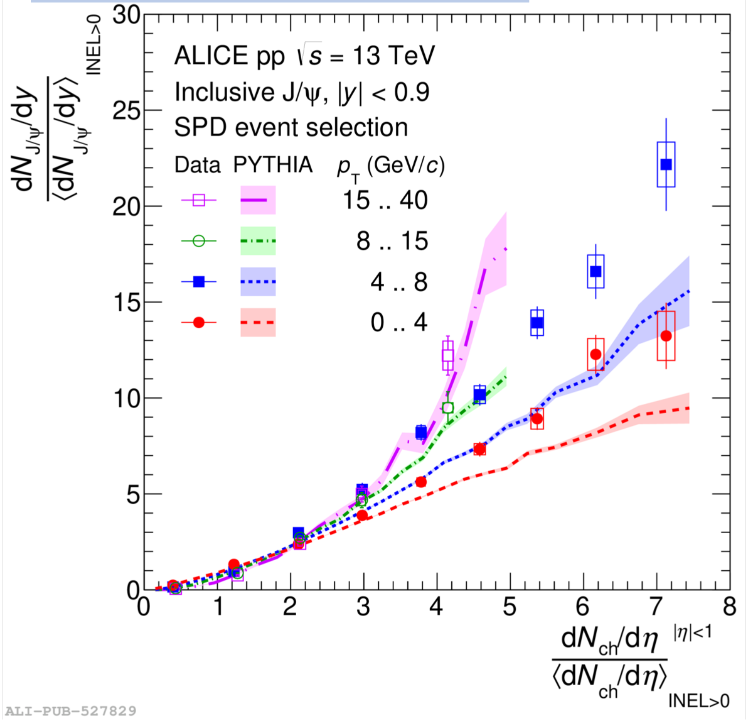


- **Faster than linear increase of J/ψ self-normalized yield with multiplicity** and **enhancement is qualitatively described by several model calculations**
- PYTHIA underpredicts data at high multiplicity
- Except PYTHIA 8.2, all other models are without non-prompt component

PYTHIA 8.2: Eur. Phys. J. C79 no. 1, (2019) 36
EPOS3: Phys. Rev. C89 no. 6, (2014) 064903
Percolation: Rev. C86 (2012) 034903
CPP: Phys. Rev. D88 no. 11, (2013) 116002
3-Pomeron CGC: Eur. Phys. J. C 80 no. 6, (2020) 560
CGC: Phys. Rev. D98 no. 7, (2018) 074025

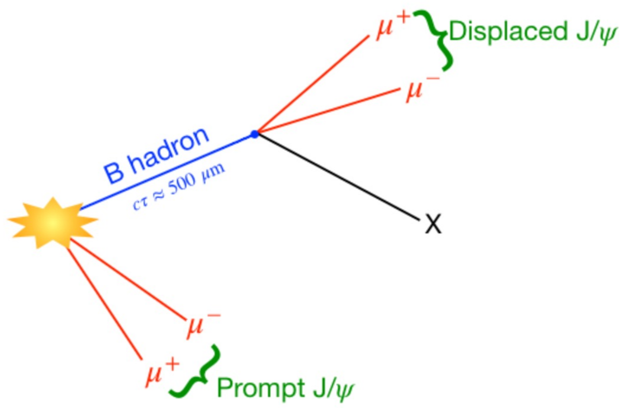
p_T differential J/ψ yields

Phys. Lett. B 810 (2020) 135758



- Inclusive yield shows different dependence on multiplicity in different p_T intervals
- **PYTHIA 8.2 which includes MPI describes qualitatively the p_T dependence**
  - Higher enhancement for higher p_T

Ongoing multiplicity-dependent prompt/non-prompt J/ψ analysis at midrapidity



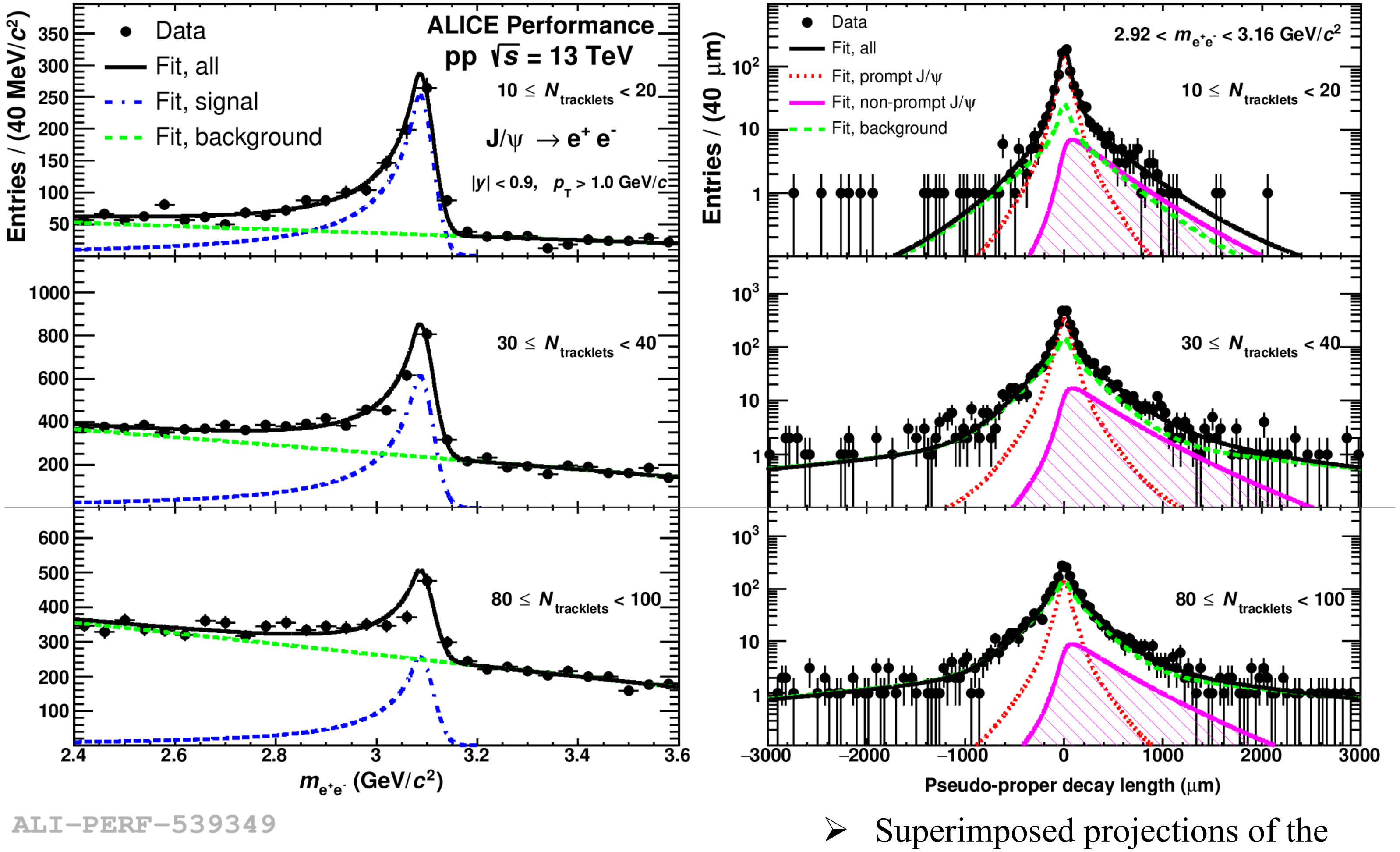
CERN-LHCC-2015-001, A. Technical Design Report for the Muon Forward Tracker. (2015)

- **Pseudoproper decay length variable at midrapidity**

$$x = c \cdot \vec{L} \cdot \vec{p}_{\mathrm{T}} \cdot \frac{m_{\mathrm{J}/\psi}}{p_{\mathrm{T}}}$$

where $\vec{L}$ is the vector pointing from the primary vertex to the J/ψ decay vertex

Eur. Phys. J. C78 (2018) 466

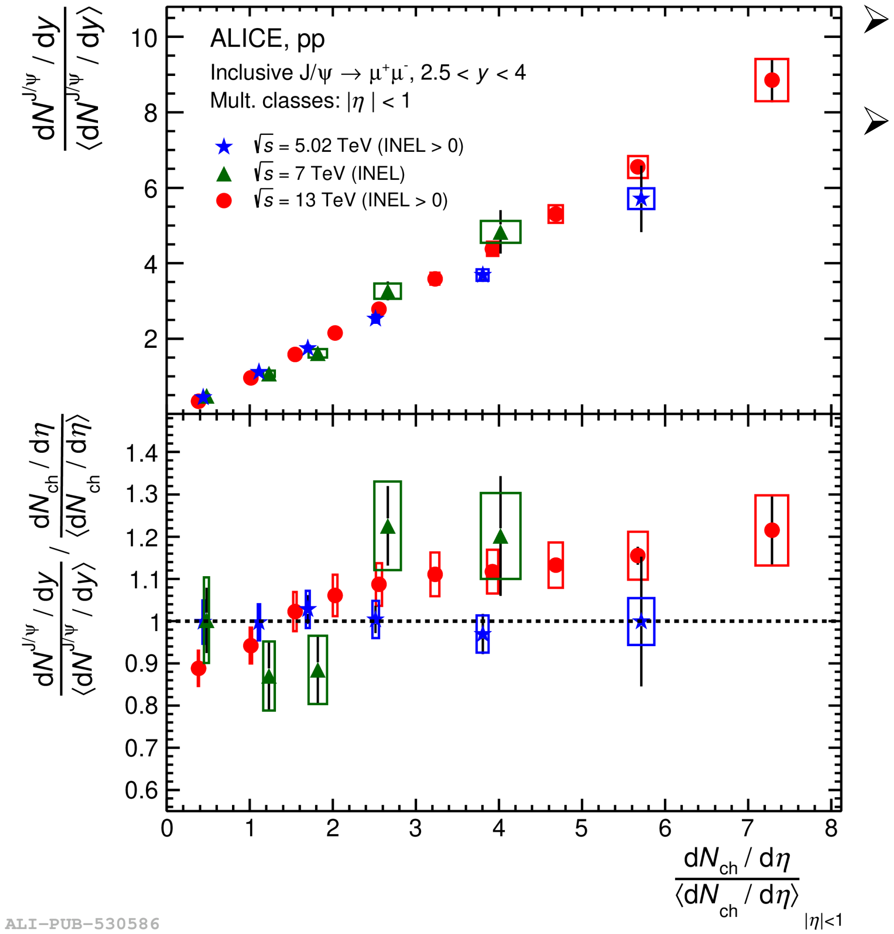


- Superimposed projections of the maximum likelihood fit in 5 multiplicity intervals in pp collisions at 13 TeV

J/ψ yield at forward rapidity vs. multiplicity in pp collisions

p_T integrated J/ψ yields

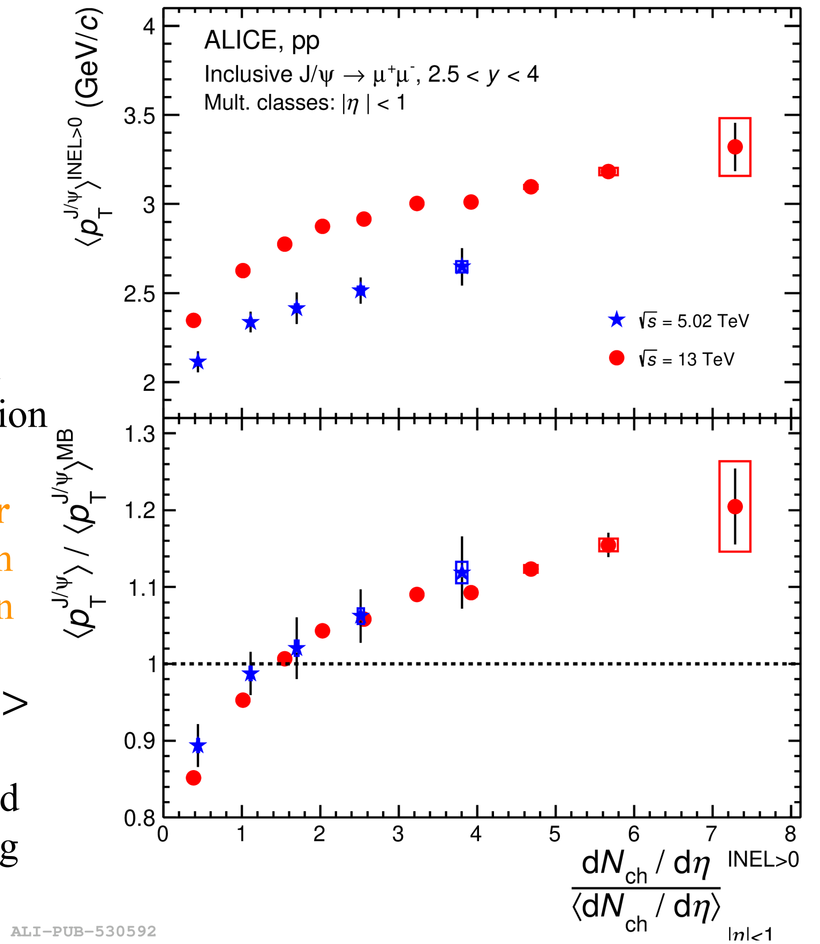
JHEP 06 (2022) 015



- J/ψ yield shows similar **close-to-linear** trend for all √s
- The ratios between self-normalized yields at 5.02 and 7 TeV are **compatible with unity**

$< p_T >$ measurement

JHEP 06 (2022) 015

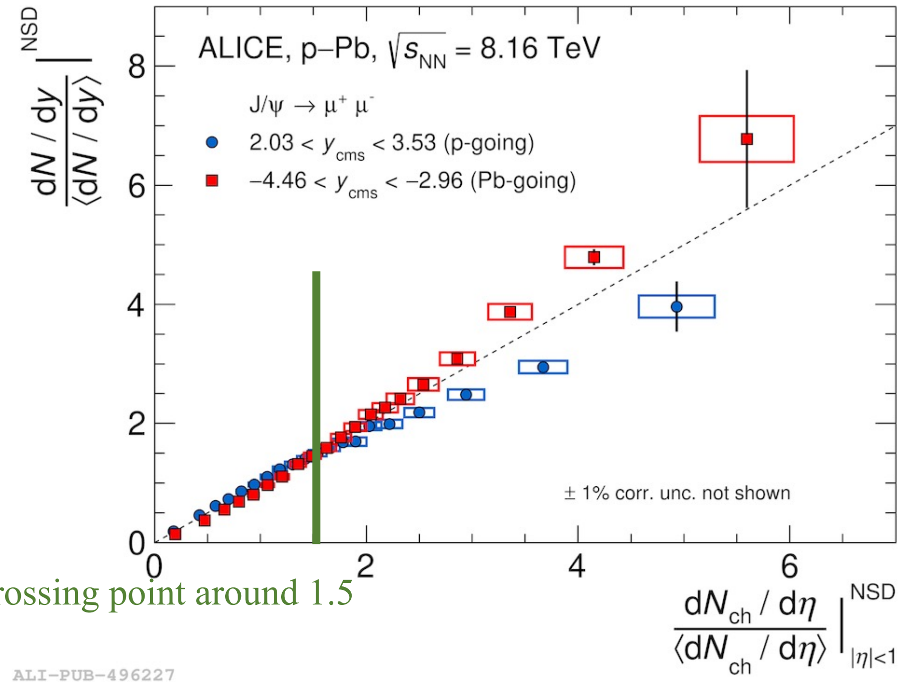


- A possible **saturation** of $< p_T >$ is observed at high multiplicity for both collision energies
- Possibly due to **CR (Color Reconnection)** mechanism or incoherent superposition of MPI
- Increase of absolute $< p_T >$ w.r.t collision energy as expected from the observed hardening of corresponding p_T distributions with increasing √s

J/ψ yield at forward/backward rapidity vs. multiplicity in p-Pb collisions

p_T integrated J/ψ yields

JHEP 2009 (2020) 162

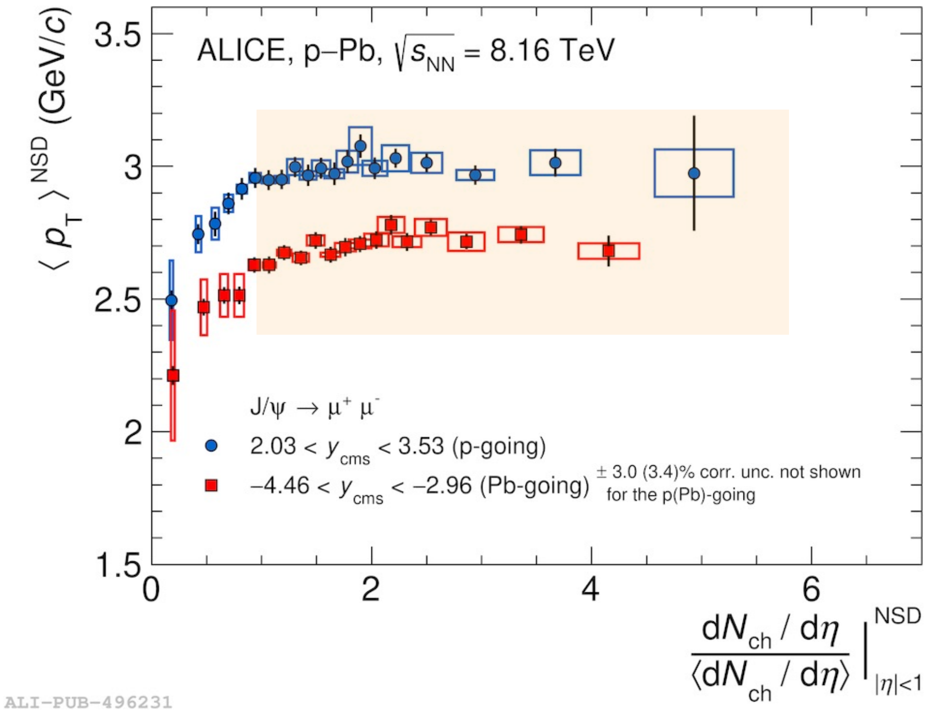


Crossing point around 1.5

- ➢ Backward yield (**faster than linear**) grows faster than forward yield (**slower than linear**)
- ➢ Suppression at forward rapidity described by **CNM (Cold Nuclear Matter) effects** connected with shadowing/saturation domain

< p_T> measurement

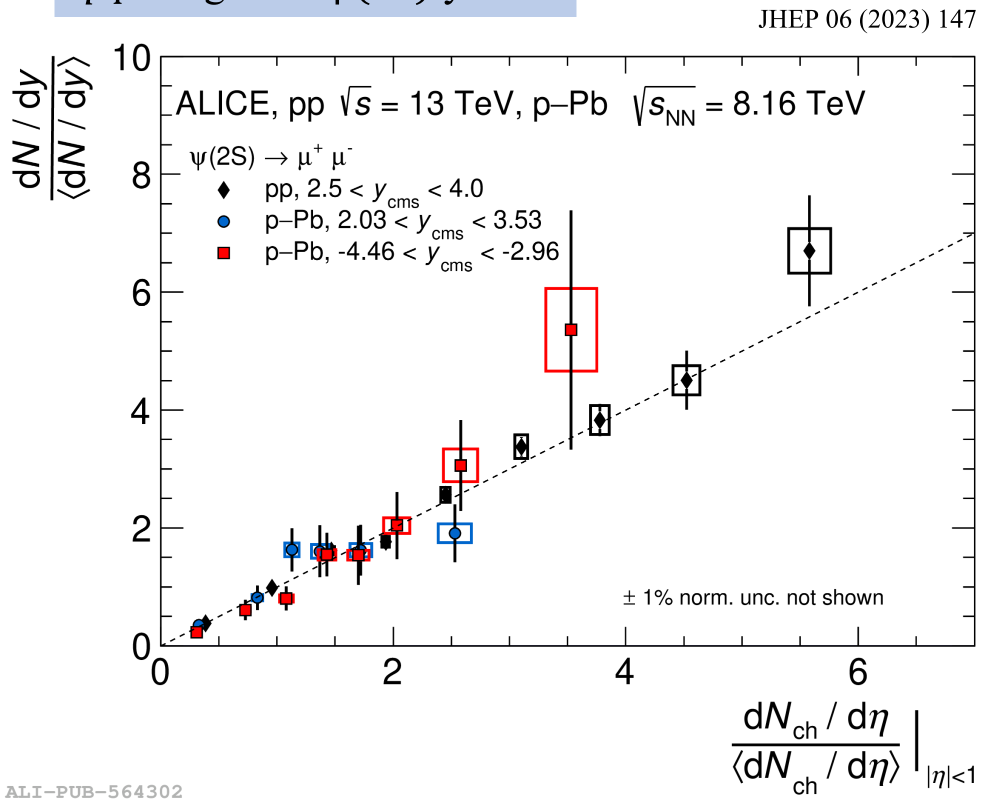
JHEP 2009 (2020) 162

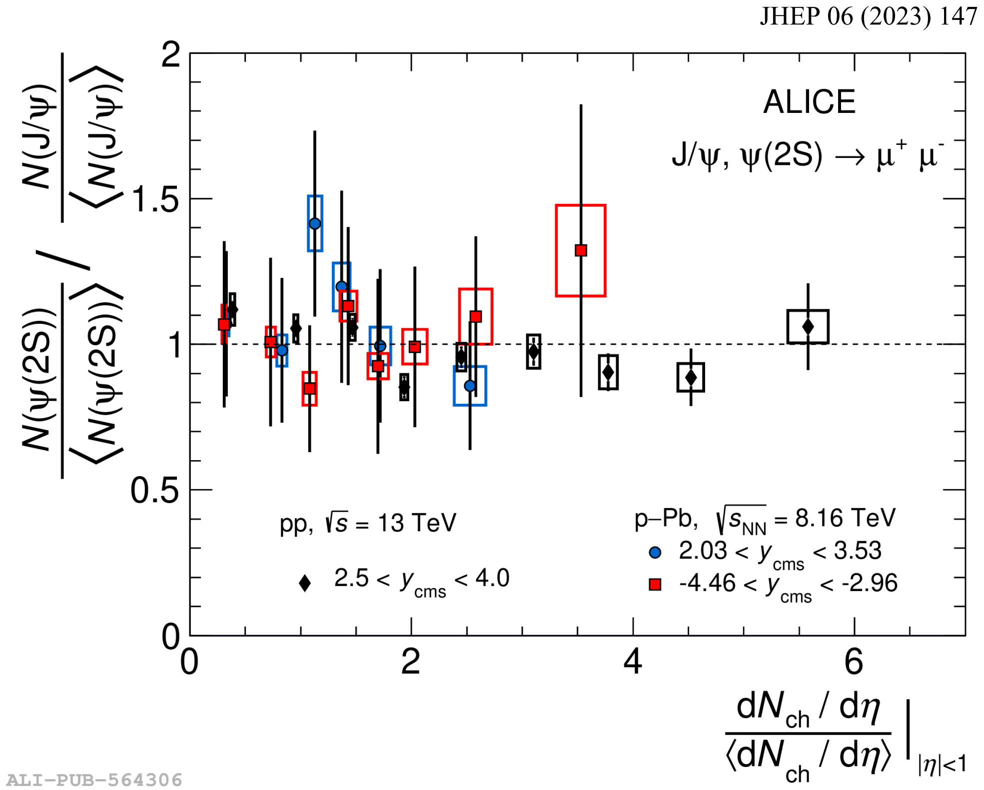


- ➢ **Plateau** is observed at large relative multiplicity
- ➢ High-multiplicity events could be described by: incoherent superposition of multiple parton-parton collisions, **SPS (Single Parton Scattering)** with high energy transfer, or **CR** mechanism

$\psi(2S)$ yield at forward rapidity vs. multiplicity in pp and p-Pb collisions

p_T integrated $\psi(2S)$ yields





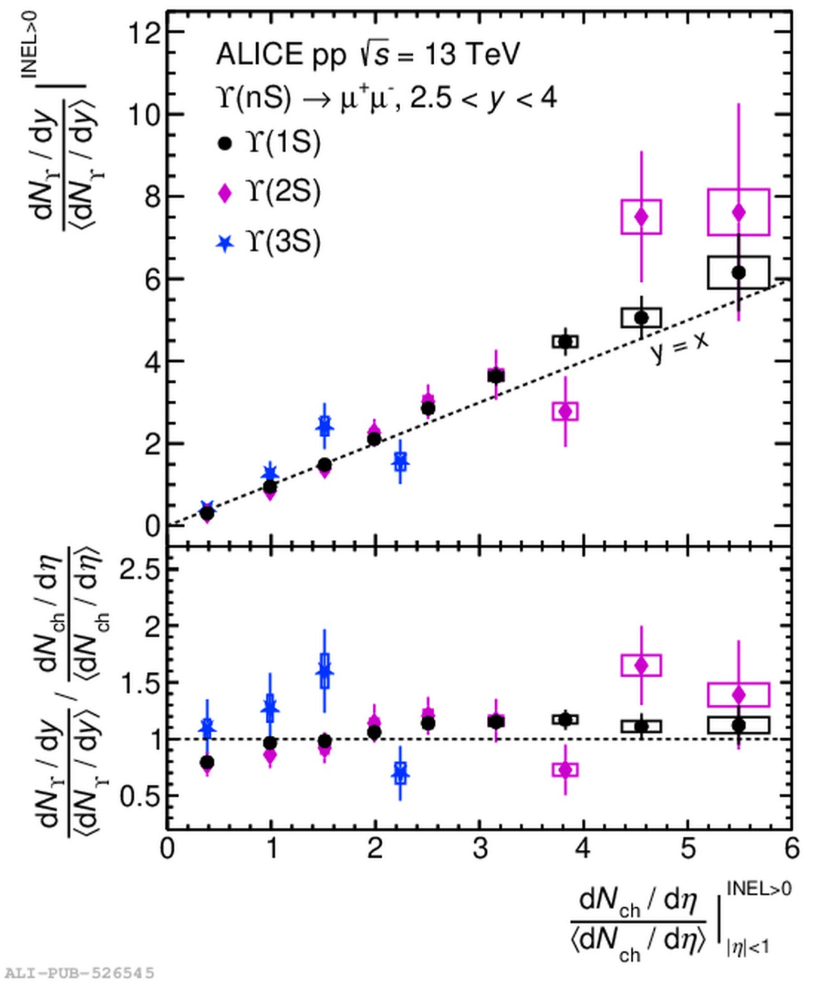
- Similar trend for p-Pb compared to pp collisions
- Forward and backward yields compatible within uncertainties

- Ratio between $\psi(2S)$ and J/ψ yield compatible with unity within uncertainties for both pp and p-Pb
- No evidence for relative $\psi(2S)$ suppression at high multiplicity within current uncertainties

Υ(nS) yield at forward rapidity vs. multiplicity in pp collisions

p_T integrated Υ(nS) yields

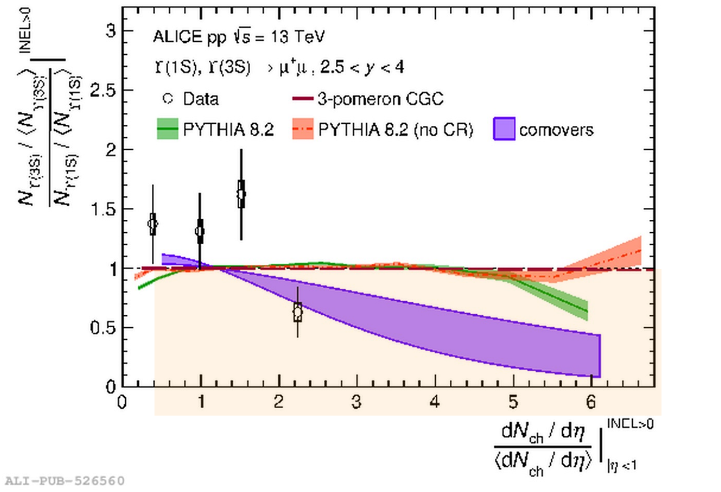
arXiv:2209.04241

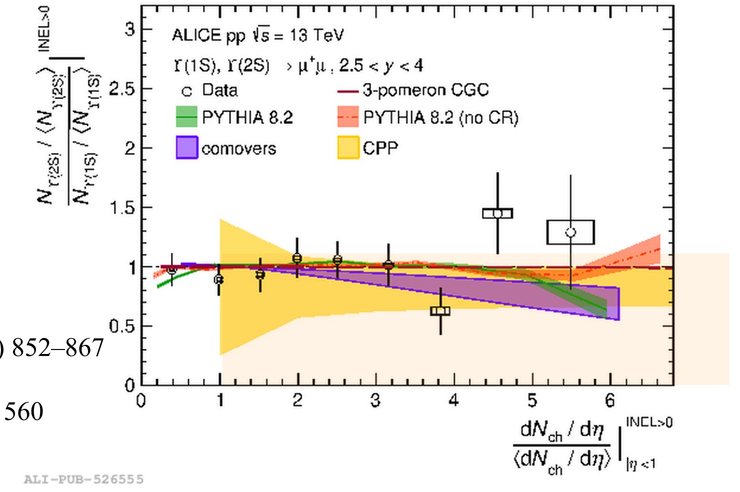


- Trend of Υ(nS) yield compatible with linear increase within uncertainties
- Present measurement not able to confirm the suppression of Υ(2S) and Υ(3S) yield predicted by **comover model**

Model comparison

arXiv:2209.04241





PYTHIA 8.2: Comput. Phys. Commun. 178 (2008) 852–867
CPP: Phys. Rev. D 101 no. 5, (2020) 054023
3-Pomeron CGC: Eur. Phys. J. C 80 no. 6, (2020) 560
Comover: Phys. Lett. B 749 (2015) 98–103

III. Prospects for the first multiplicity-differential J/ψ polarization measurement at midrapidity with Run 3 data

J/ψ polarization at forward rapidity in pp collisions with Run 2 data

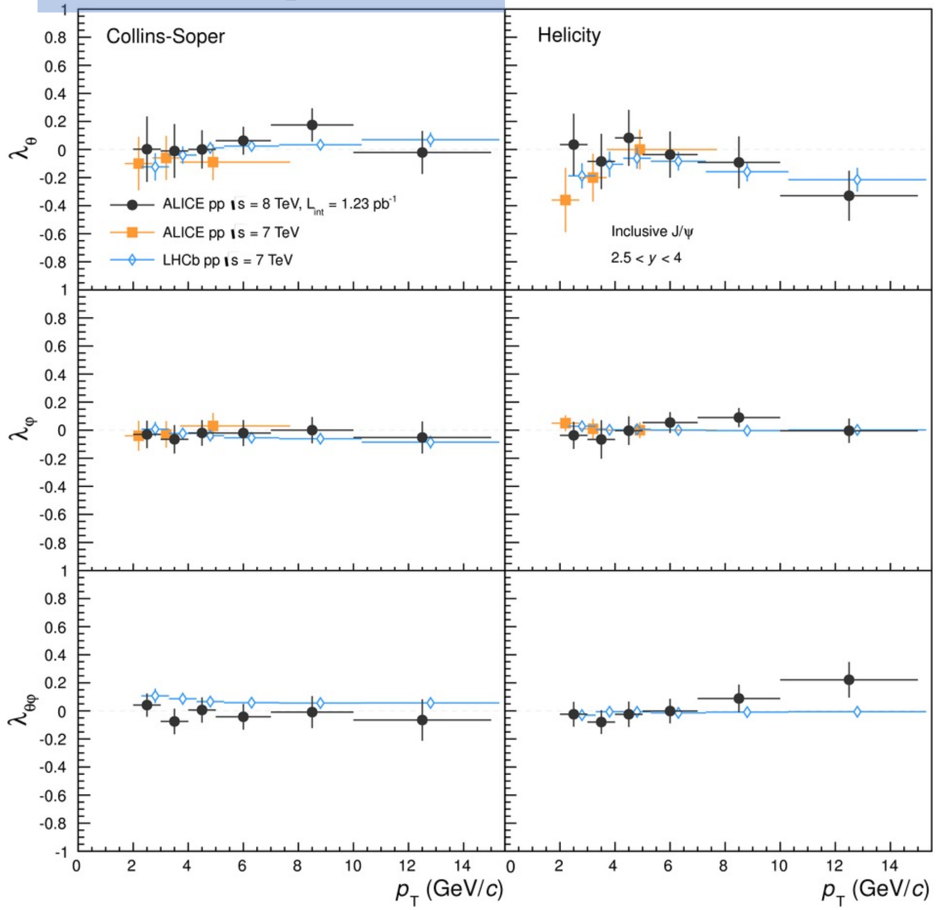
- **Polarization parameters** ($\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$) from study of the angular distribution of the quarkonium dilepton decay (W):

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

- Selected reference axes:
  - **Helicity axis** pointing to quarkonium flight direction in the centre-of-mass of colliding beams
  - **Collins-Soper axis** defined by the direction of the relative velocity of the colliding beams in the quarkonium rest-frame
- p_T dependent polarization states are predicted by NLO calculations

Polarization parameters

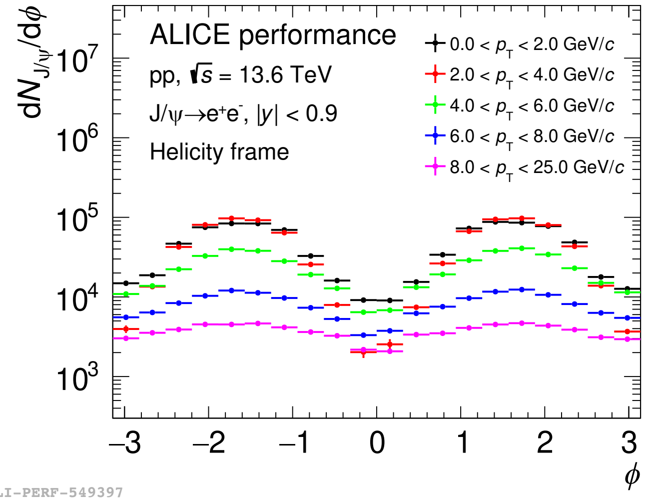
Eur. Phys. J. C 78 (2018) 562



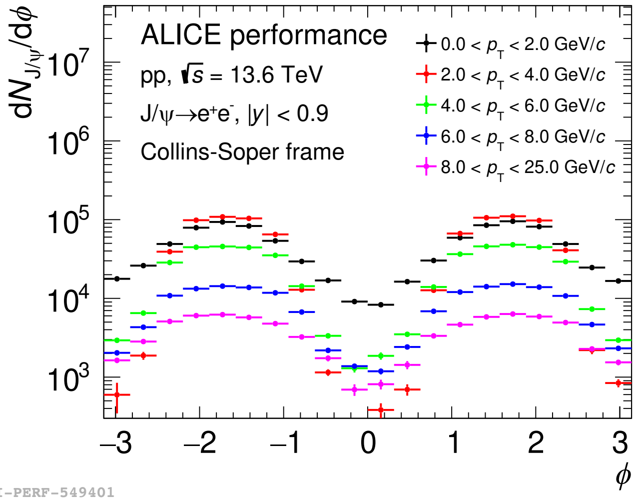
- Polarization compatible with 0 within uncertainties
- No difference in polarization results between ALICE (inclusive) and LHCb (prompt): **no visible effect of J/ψ from b-decays**

The first (coming soon) Run3 J/ψ polarization at midrapidity in pp collisions

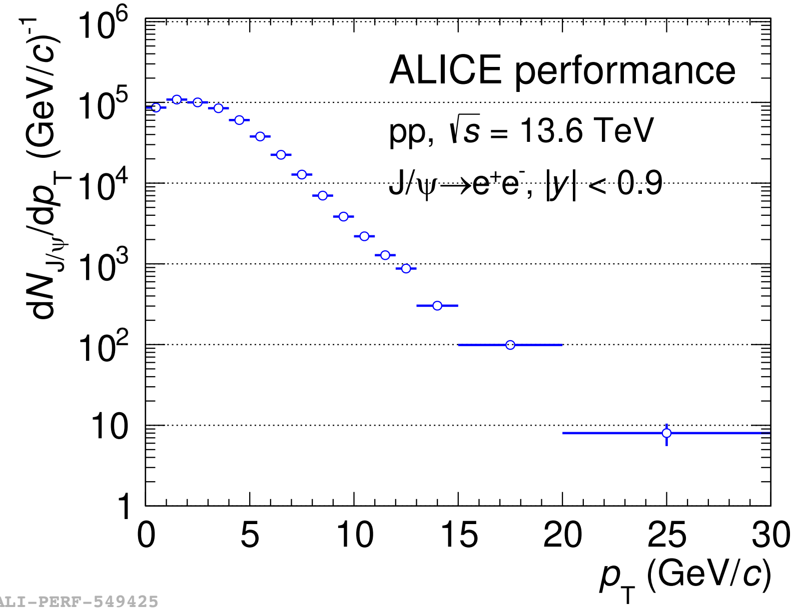
p_T differential J/ψ raw counts



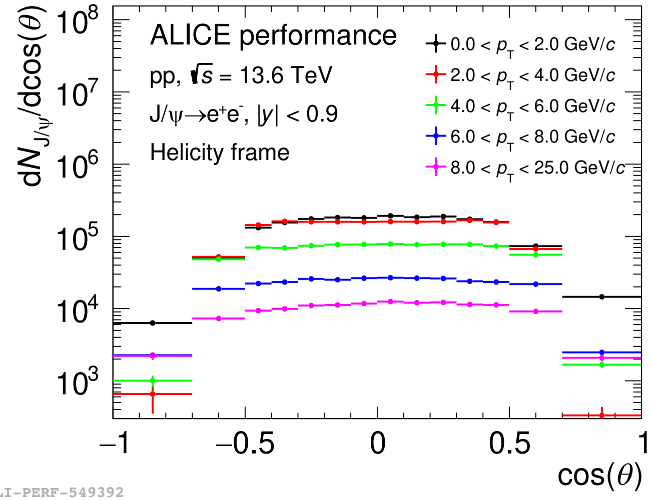
ALI-PERF-549397



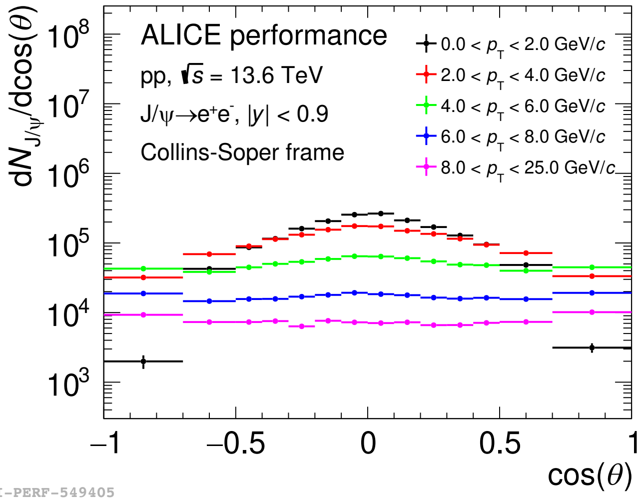
ALI-PERF-549401



ALI-PERF-549425



ALI-PERF-549392

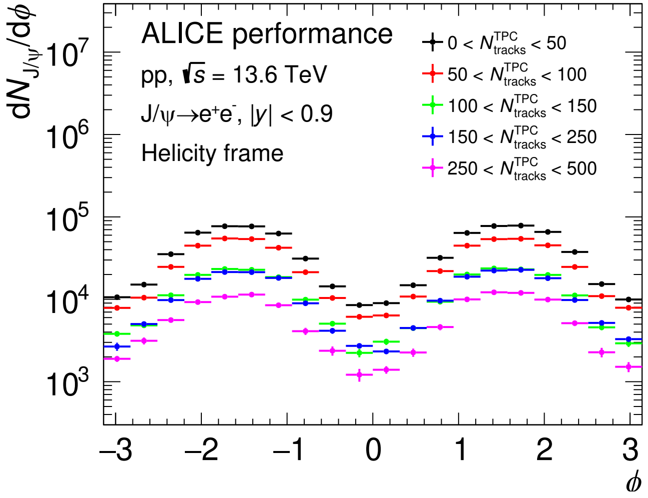


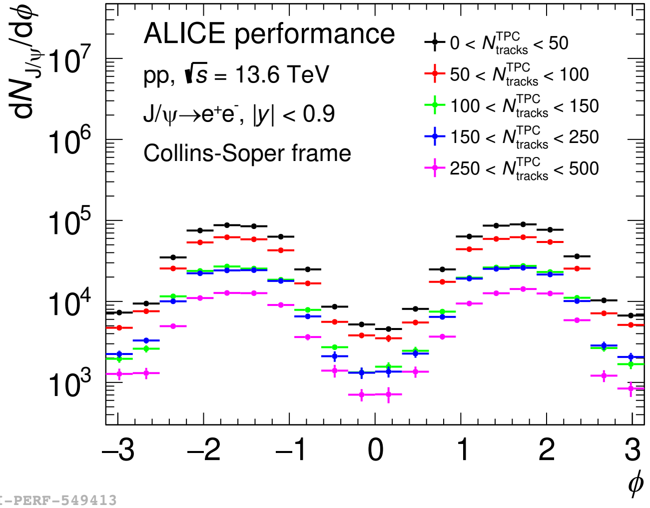
ALI-PERF-549405

- Run 3 provides larger statistics for **multi-differential polarization analysis in p_T/multiplicity bins**
- This will be the first quarkonium polarization analysis at midrapidity

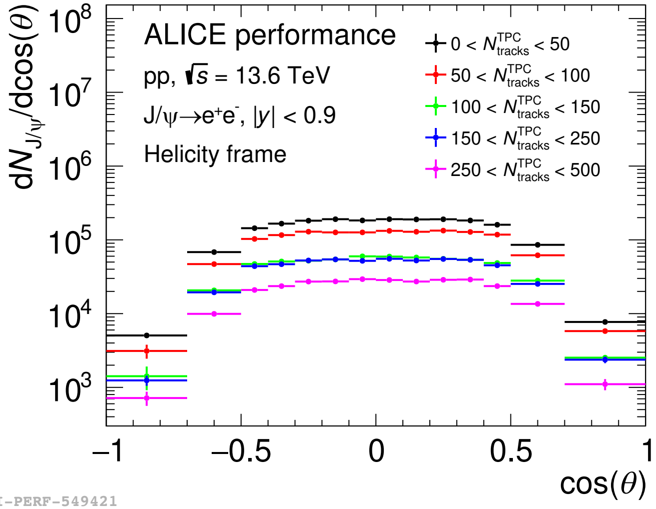
The first (coming soon) Run3 J/ψ polarization at midrapidity in pp collisions

Multiplicity differential J/ψ raw counts

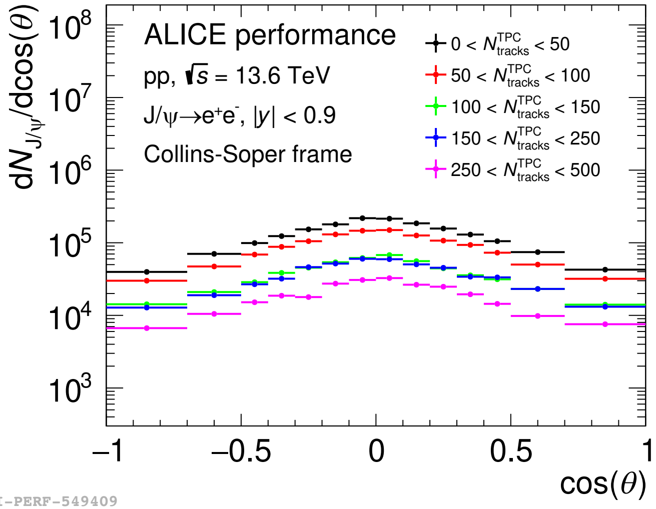




ALI-PERF-549413



ALI-PERF-549421



ALI-PERF-549409

IV. Conclusions and Outlook

IV. Conclusions

- **Multiplicity-dependent quarkonium production measurements:**
  - Large number of recent measurements from ALICE show results sensitive to MPI
  - The **close-to-linear trend** is observed at **forward rapidity**, while at **midrapidity** quarkonia exhibits a **stronger than linear trend**
  - **At midrapidity**, one observed that qualitative features can be extracted from data and understood within uncertainties, but quantitative descriptions by models are so far not conclusive
  - Recent experimental results are very important as input for quarkonium production models

IV. Outlook

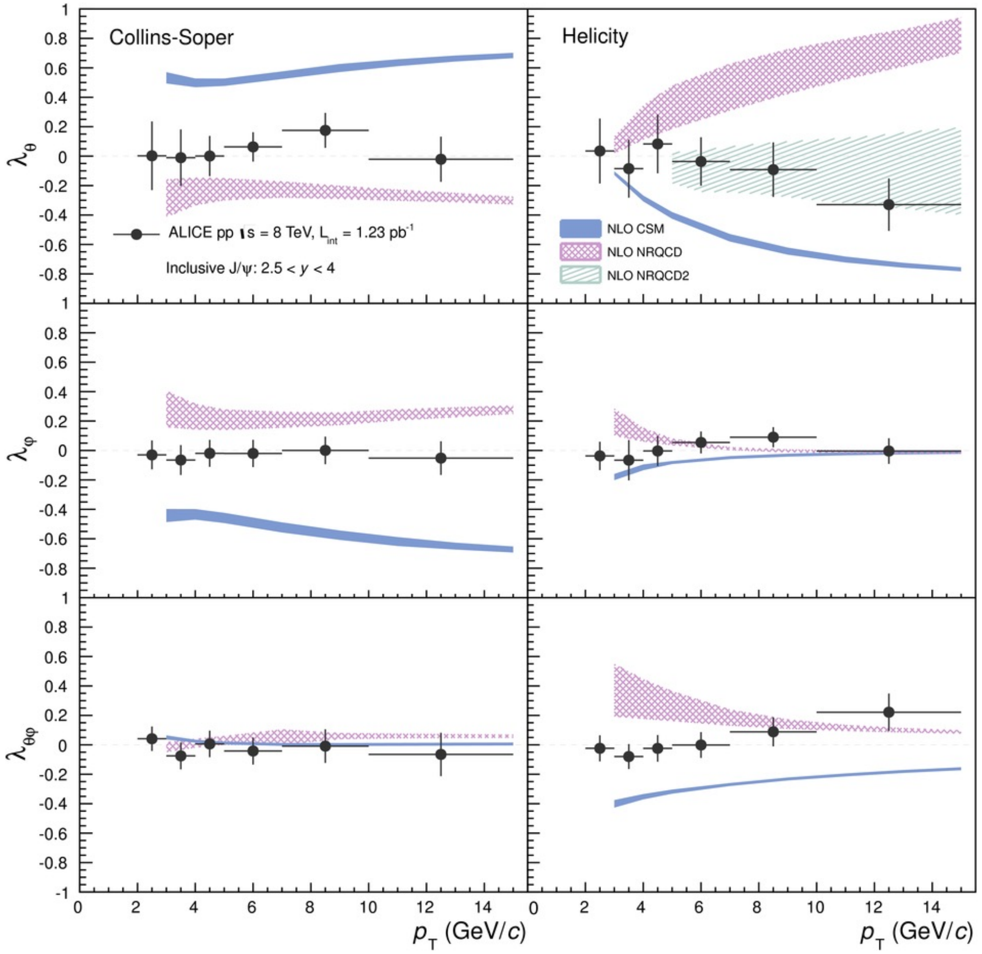
- **Multiplicity-dependent quarkonium production measurements:**
  - New data taken from 2022 to 2023 (Run 3) should provide improved measurements with larger statistics and a separation of non-prompt component also at forward rapidity (with MFT detector)
  - Predictions from some models are yet to be completed with non-prompt calculations
- **Multiplicity-differential quarkonium polarization measurements:**
  - We will soon have the first **Run 3** J/ψ polarization measurement **at midrapidity** in pp collisions at 13.6 TeV with enough statistics to perform multiplicity-differential analysis
  - For the multiplicity-dependent Run 3 measurements: higher multiplicity reach and better precision for prompt/non-prompt J/ψ studies and for excited states to probe final states effect

Backup slides

J/ψ polarization at forward rapidity in pp collisions with Run 2 data

Model comparison

Eur. Phys. J. C 78 (2018) 562

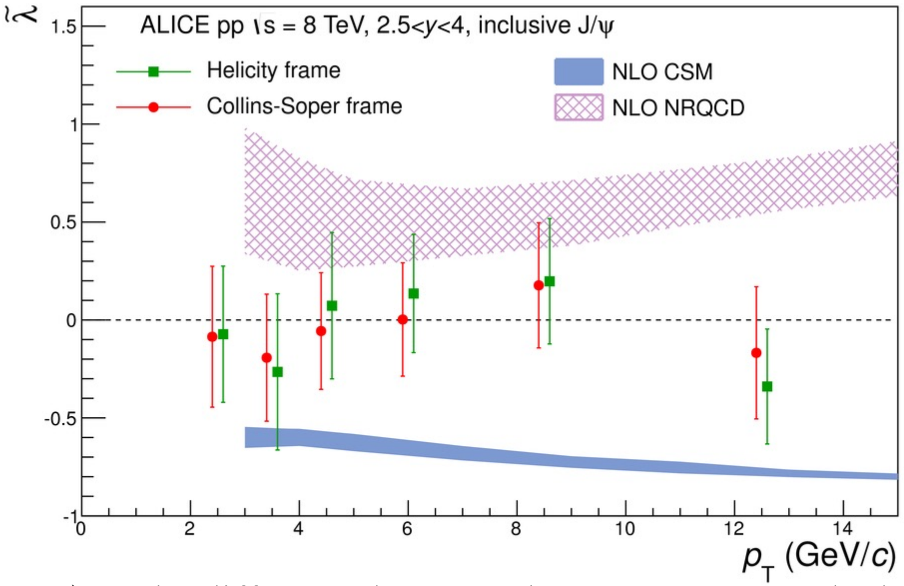


NLO NRQCD: Phys. Rev. Lett. 108 (2012) 172002
NLO NRQCD2: Phys. Rev. Lett. 108 (2012) 242004
NLO CSM: Phys. Rev. Lett. 108 (2012) 172002

Frame-invariant quantity

Eur. Phys. J. C 78 (2018) 562

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi}.$$



- The difference between the two NRQCD calculations originates from the data used to compute the LDMEs
- The **CSM** and **NRQCD calculations** predict an opposite p_T trend for all polarization parameters in the two frames
- **NRQCD including both CS (colour-singlet) and CO (colour-octet) gives a better description except for λ_θ**
- The comparison in frame-invariant quantity shows good agreement in both frames within uncertainties; but model calculations are not yet conclusive