SEP 3-9
HOUSTON, TEXAS
Quark Matter 2023
The 30th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

Quarkonia as probes of initial and final states in small systems with ALICE

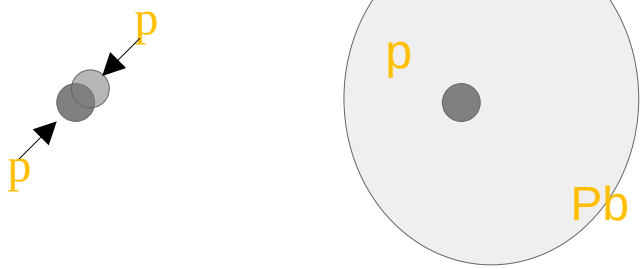
Subikash Choudhury on behalf of the **ALICE Collaboration**
Saha Institute of Nuclear Physics

Quarkonia across different systems

Small systems

Reference system test for QCD

Cold nuclear matter effects R_{pPb}

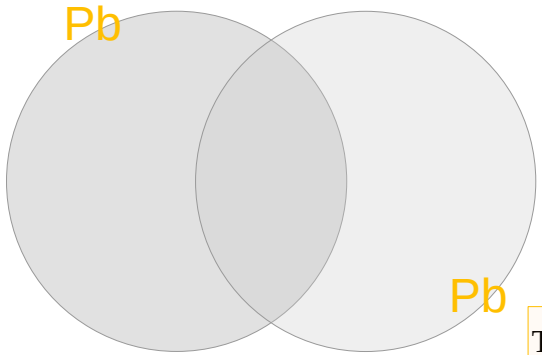


Provide insights on multiparton interactions (MPI) via multiplicity dependent studies of quarkonia production + associated quarkonium production

Large systems

Talks by Afnan Shatat & Luca Micheletti 05/09/2023, 14:50

Probes initial stages of collision photoproduction + polarization vs. event plane measurements



Talk by Xiaozhi Bai 05/09/2023, 8:30

Accessing medium properties measuring suppression/regeneration and collectivity (R_{AA} & v_2)

Heavy quark energy loss via prompt and non-prompt J/ψ measurement

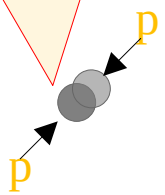
Quarkonia across different systems

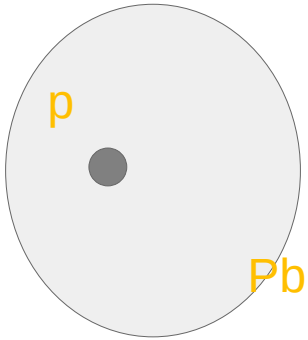
Small systems

Reference system test for QCD

Cold nuclear matter effects R_{pPb}

Focus of this talk
Quarkonium production in pp collisions





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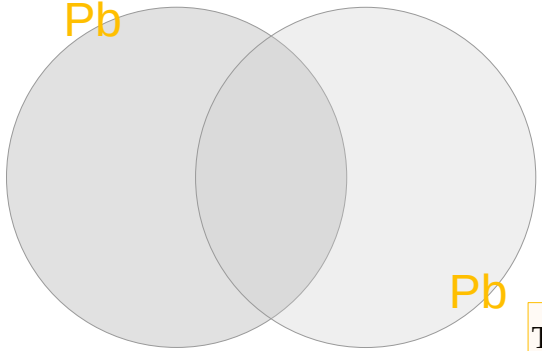

Talk by Xiaozhi Bai
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Accessing medium properties measuring suppression/regeneration and collectivity (R_{AA} & v_2)
Heavy quark energy loss via prompt and non-prompt J/ψ measurement

A Large Ion Collider Experiment (Run 2)

Quarkonium reconstruction in ALICE

V0
Triggering
Background rejection
Multiplicity estimation

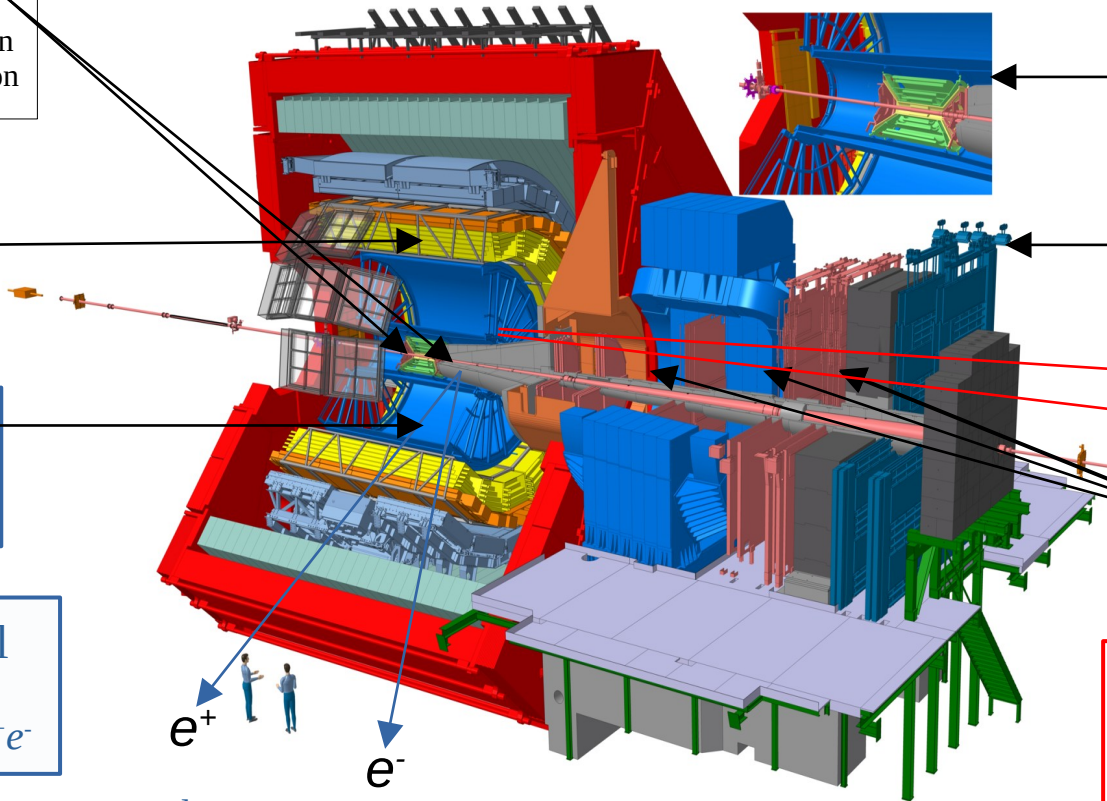
ITS
Vertexing
Tracking
Event selection
Multiplicity Estimation

TRD
Electron ID
Triggering

MTR
Muon trigger

TPC
Tracking
PID via dE/dx

MCH
Muon tracking



Central barrel
$|y_{ee}| < 0.9$
$J/\psi, \psi(2S) \rightarrow e^+e^-$

Inclusive quarkonia + prompt and non-prompt separation

Muon arm
$2.5 < y_{\mu\mu} < 4.0$
$J/\psi, \psi(2S), \Upsilon(nS) \rightarrow \mu^+\mu^-$

Inclusive quarkonia

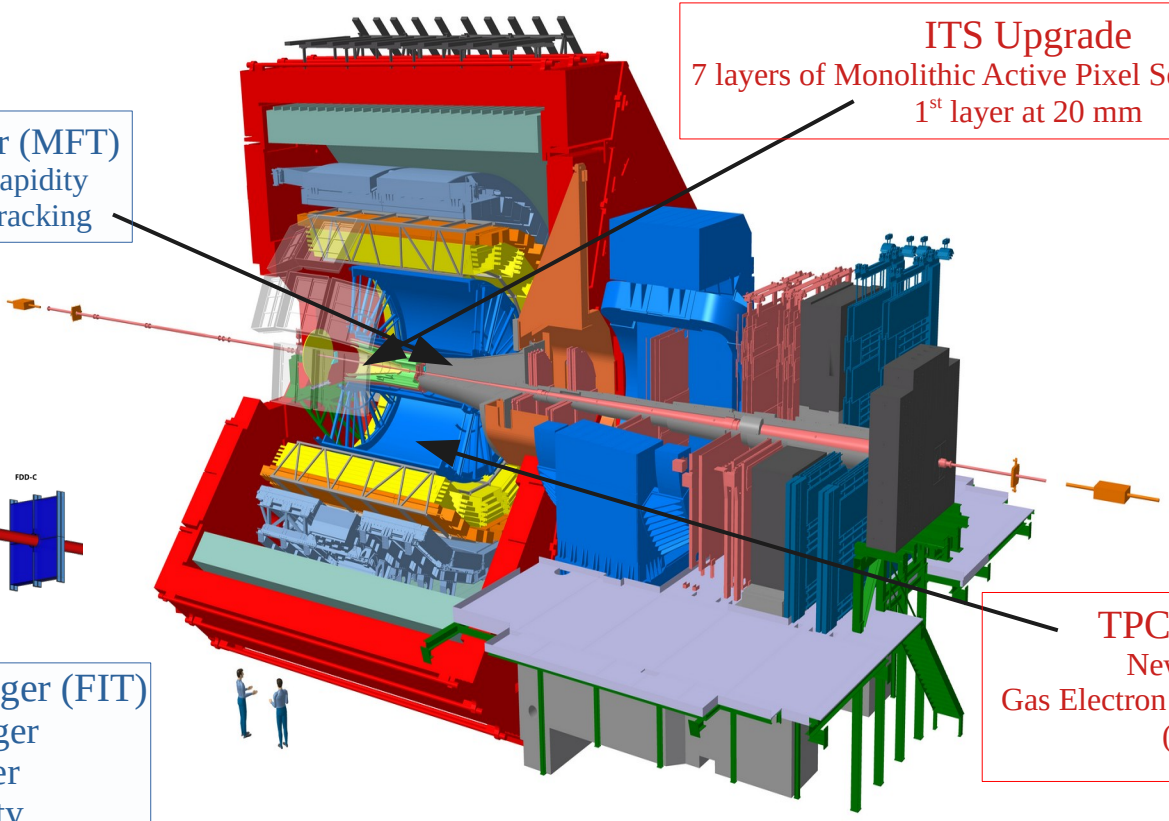
A Large Ion Collider Experiment (Run 3)

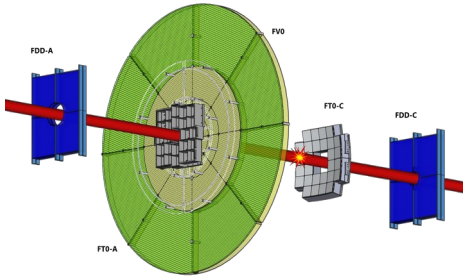
Upgrades and new detectors

ALICE

ITS Upgrade
7 layers of Monolithic Active Pixel Sensors (MAPS)
1st layer at 20 mm

New Muon Forward Tracker (MFT)
5 layers of MAPS at forward rapidity
Forward vertexing and muon tracking

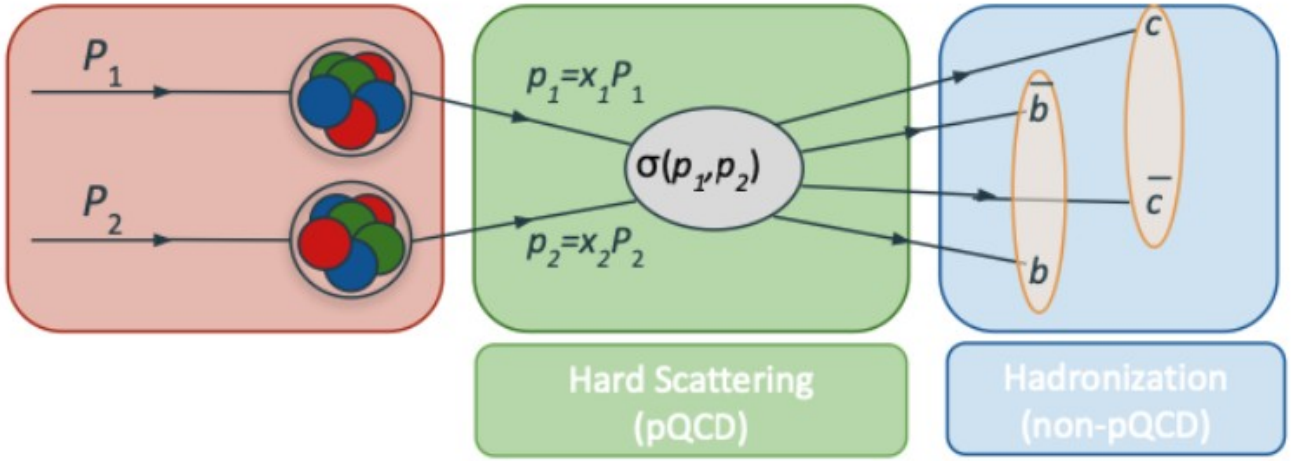




New Fast Interaction Trigger (FIT)
Fast interaction trigger
Online luminometer
Forward multiplicity

TPC Upgrade
New readout
Gas Electron Multiplier detector (GEM)

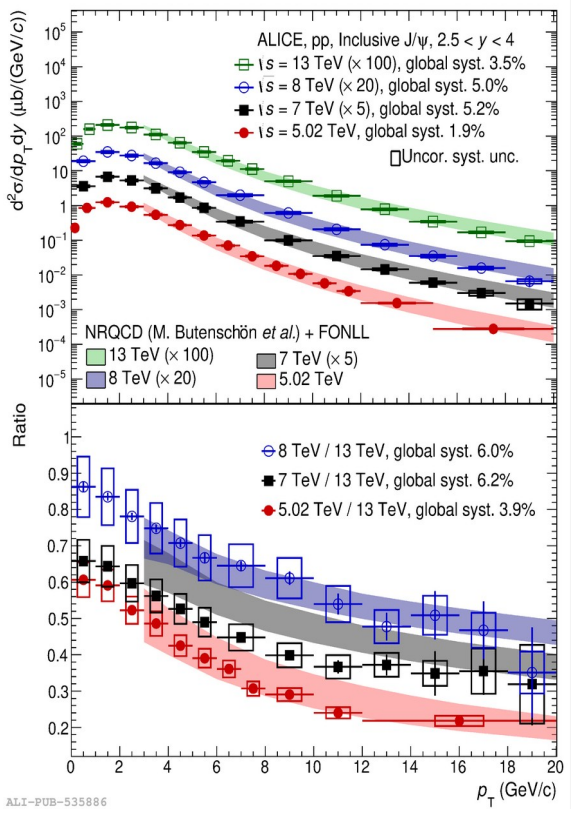
Quarkonium production in small systems

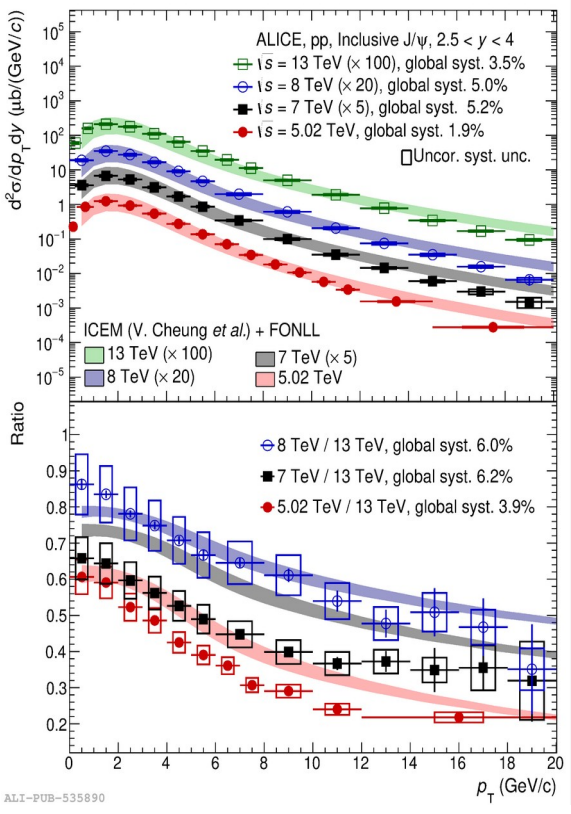


Probing fundamental mechanisms of quarkonium production with small systems

J/ψ production at forward rapidity

- Eur. Phys. J. C 83 (2023) 61

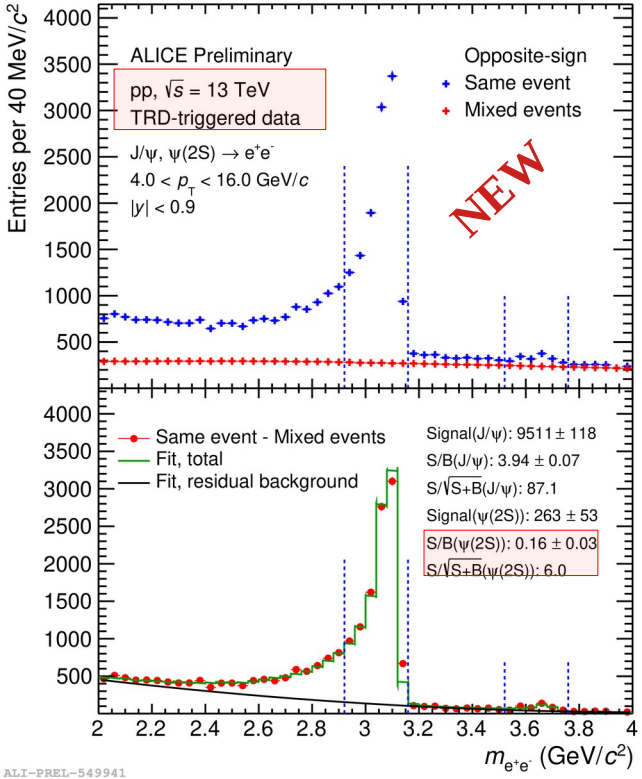




- Comprehensive J/ψ cross section measurements in ALICE
  - Precise p_T and y differential cross sections measured at $\sqrt{s}$ = 13, 8, 7 and 5.02 TeV
- Cross sections well described by NRQCD and ICEM models
- Further insight from cross section ratios among energies and excited-to-ground ($\psi(2S)$ / J/ψ) state cross section ratios
  - Partial cancellation of experimental uncertainties
  - Better constraints on models

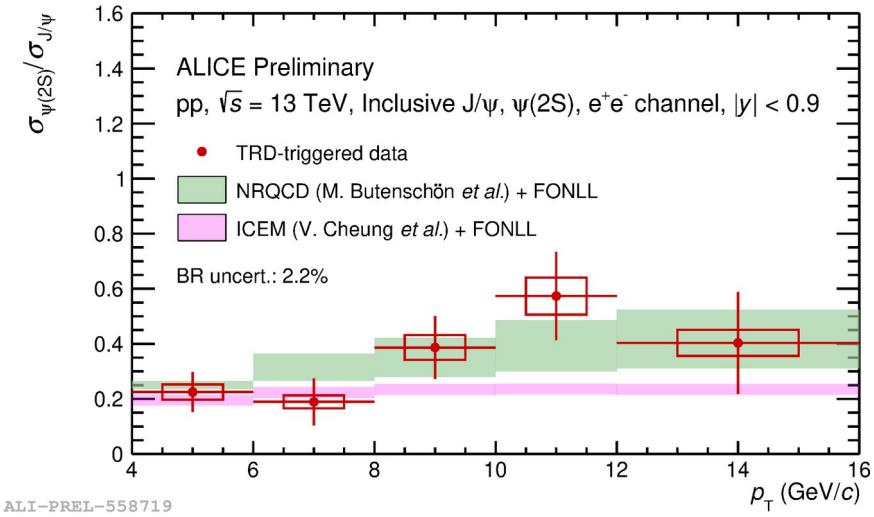
- M. Butenschon et al, Phys. Rev. Lett. 106 (2011) 022003 (Non Relativistic QCD)
- M. Cacciari et al, JHEP 10 (2012) 137 (FONLL)
- V. Cheung et al, Phys. Rev. D (2018) 114029 (Improved Colour Evaporation Model)

First ψ(2S) measurement in ALICE at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV



J/ψ and ψ(2S) signal extraction

- TRD-triggered data enable first ever ψ(2S) measurement in ALICE at midrapidity in Run 2
- ψ(2S) signal significance > 5



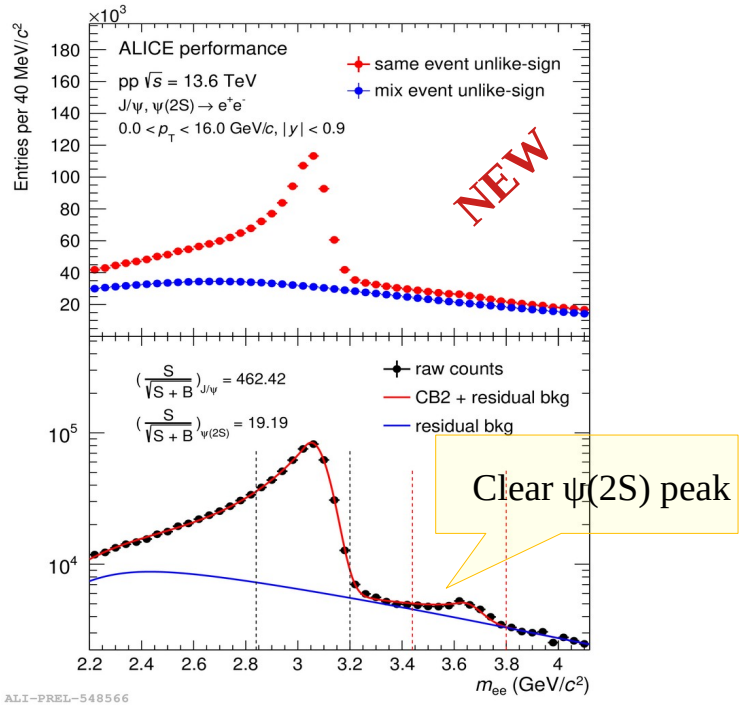
Run 2 measurement of ψ(2S) / J/ψ ratios at midrapidity

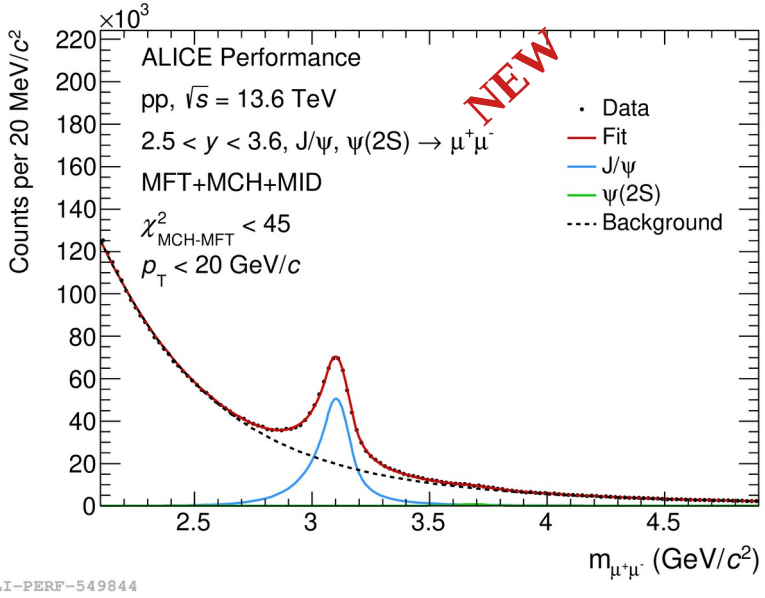
- Moderate p_T dependence in the measured range within the uncertainties
- All model calculations are compatible with data but experimental uncertainties are still large to further constrain models

Poster 465: Jinjoo Seo
05/09/2023

- M. Butenschon et al, Phys. Rev. Lett. 106 (2011) 022003 (NRQCD)
- V. Cheung et al, Phys. Rev. D (2018) 114029 (ICEM)

First measurement of J/ψ, $\psi(2S)$ in pp collisions at $\sqrt{s}$ = 13.6 TeV

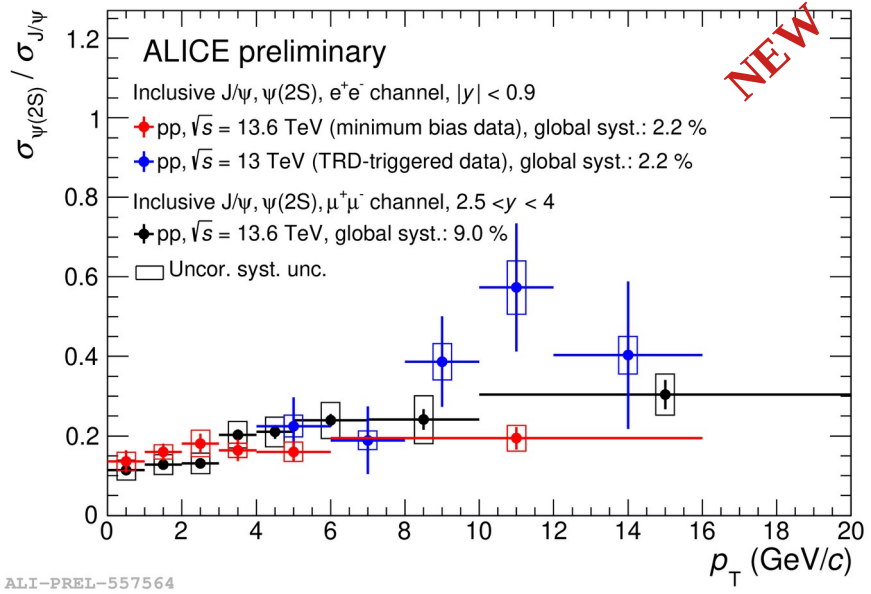


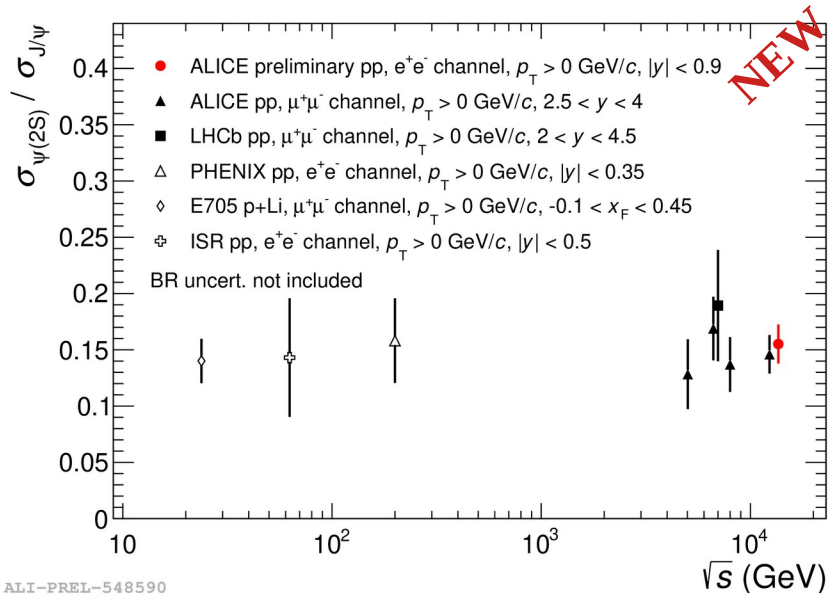


J/ψ and $\psi(2S)$ signal extraction at mid and forward rapidity from Run 3 data

- First Run 3 measurement of J/ψ and $\psi(2S)$ at mid and forward rapidity down to zero p_T
- First ever $\psi(2S)$ measurement at midrapidity in ALICE from minimum bias data
- Very good significance

$\sqrt{s}$ and p_T dependence of $\psi(2S)$ / J/ψ in pp collisions





$\psi(2S)$ / J/ψ ratios from Run 3 & Run 2 data at midrapidity

- Run 3 and Run 2 results at midrapidity are consistent within uncertainties
- First ever measurement of ψ(2S) down to zero p_T at midrapidity
- Similar trend at mid and forward rapidity

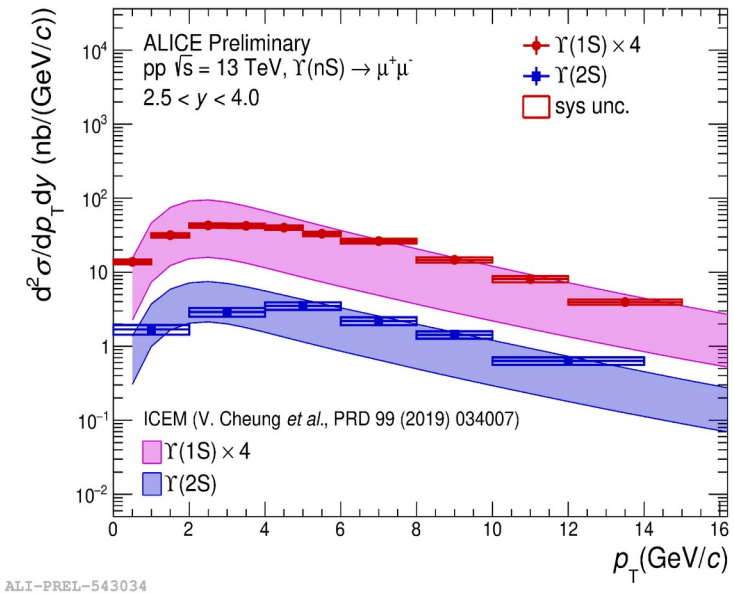
$\sqrt{s}$ dependence of $\psi(2S)$ / J/ψ ratio

- No significant energy dependence is found

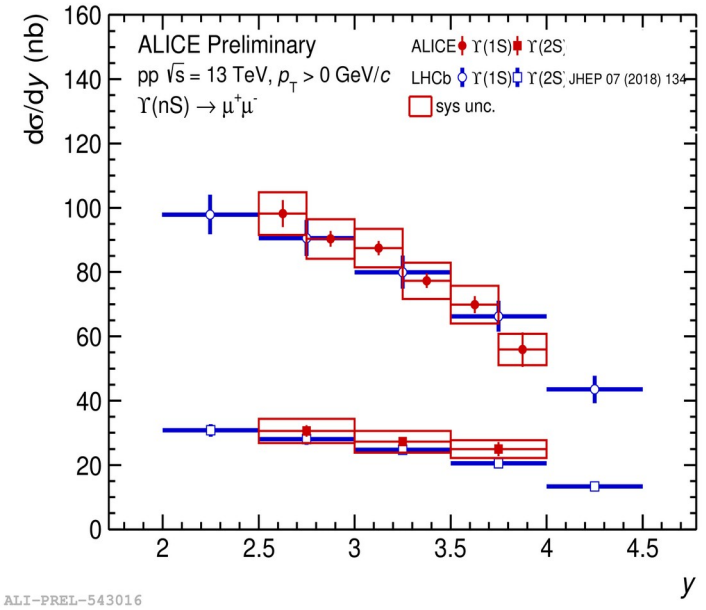
Poster 197: Yuan Zhang
05/09/2023

Υ(nS) cross sections at forward rapidity

Υ(nS) vs p_T



Υ(nS) vs y

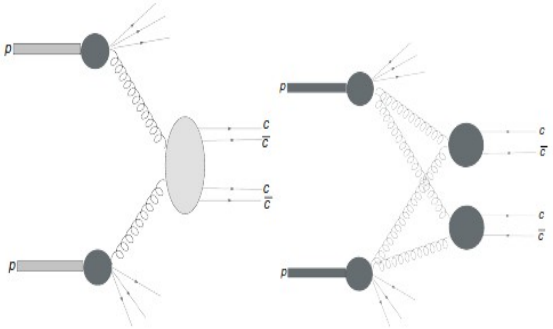


- $\Upsilon(nS)$ differential cross sections measured as a function of p_T and y
- ICEM model calculations agree well with data
- Υ(1S) and Υ(2S) differential cross sections are in good agreement with LHCb data

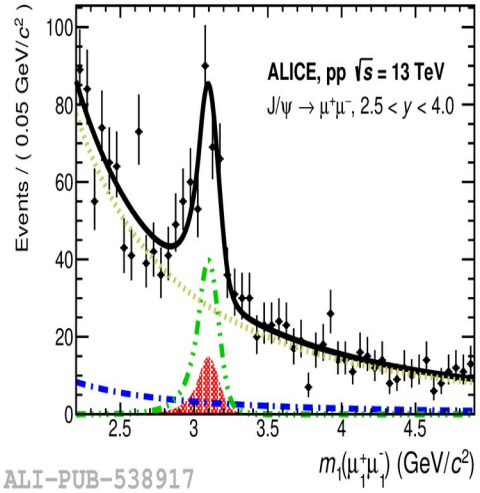
- V. Cheung et al, Phys. Rev. D 99 (2019) 034007 (ICEM)
- R. Aaij et al, JHEP 07 (2018) 134 (LHCb)

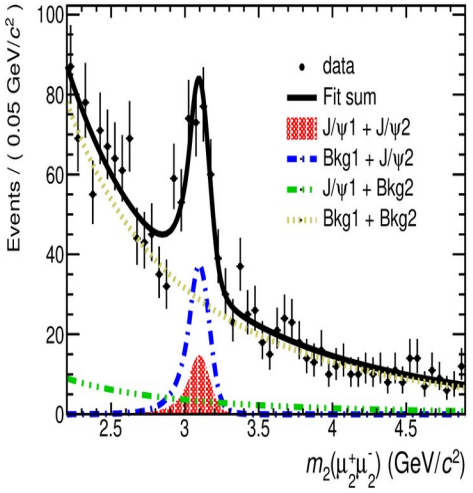
J/ψ pair production in pp collisions at forward rapidity

- AIP Conf. Proc. 1523 (2013) 1



- arXiv: 2303.13431





Important to gain insight on

- J/ψ production mechanism(s)
- Single vs double parton scattering
- Direct access to more than one parton scattering process

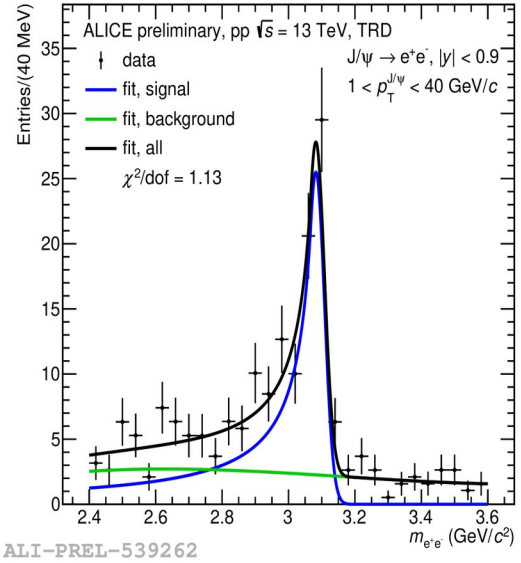
σ(J/ψ, J/ψ)	cross section (nb)
ALICE	10.3±2.3±1.3
LHCb	15.2±1.0±0.9

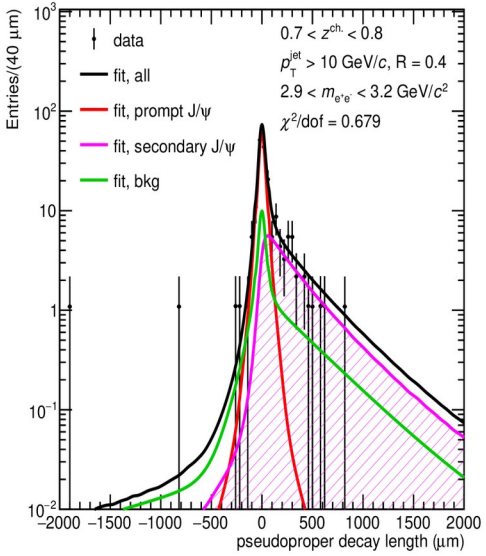
Reasonable agreement between ALICE and LHCb

- Caveats
  - LHCb: prompt J/ψ, ALICE: Inclusive J/ψ
  - Slightly different rapidty range

- R. Aaij et al, JHEP 06 (2017) 047 (LHCb)

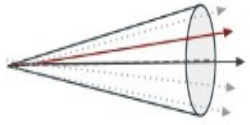
J/ψ production in jets





Jets are tagged in coincidence with J/ψ reconstructed in e^+e^- channel

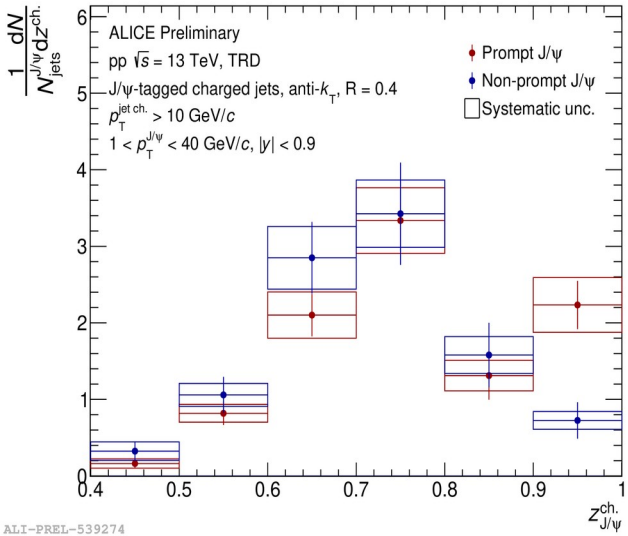
- Separate prompt and non-prompt J/ψ with a template fit to invariant mass and pseudoproper decay length



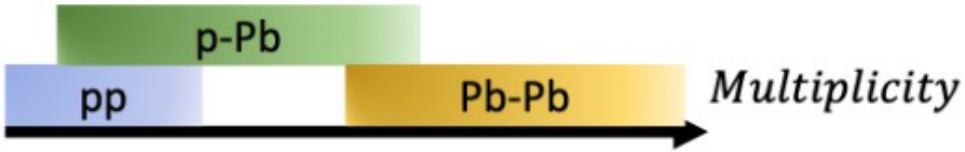
$$z^{ch} = \frac{p_T^{J/\psi}}{p_T^{jet,ch}}$$

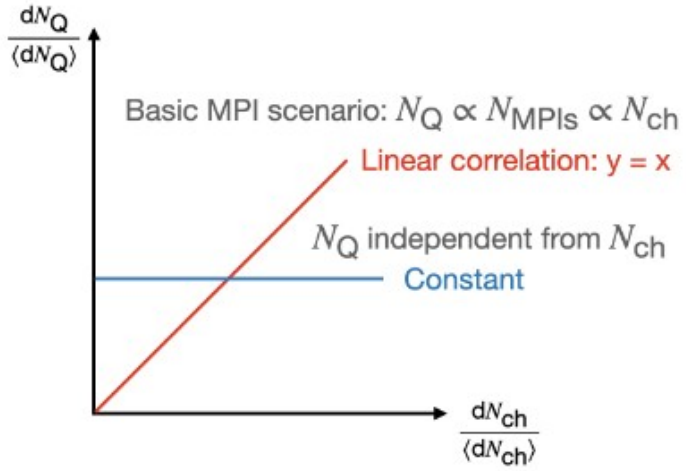
Fragmentation function

- Insights on J/ψ fragmentation interplay with underlying event
- Prompt and non-prompt fragmentation functions are similar within uncertainties



Multiplicity dependence of quarkonium production



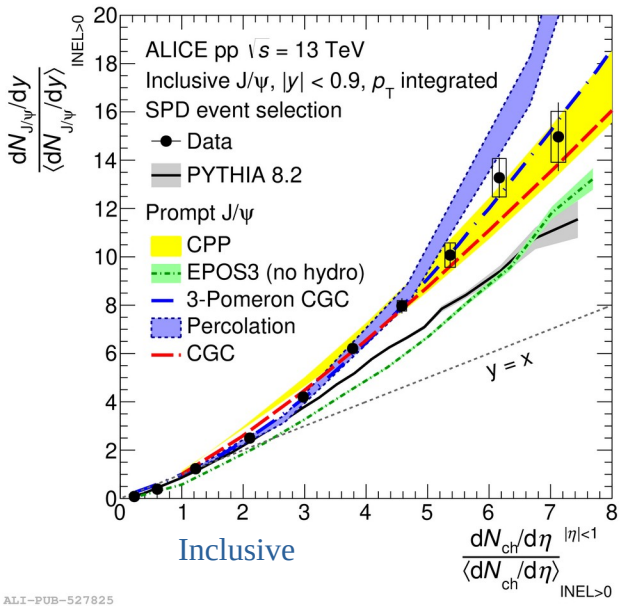


Correlation between quarkonium yields (N_Q) and underlying event (N_{ch})

- Sensitive to initial state (MPI) and final state effects

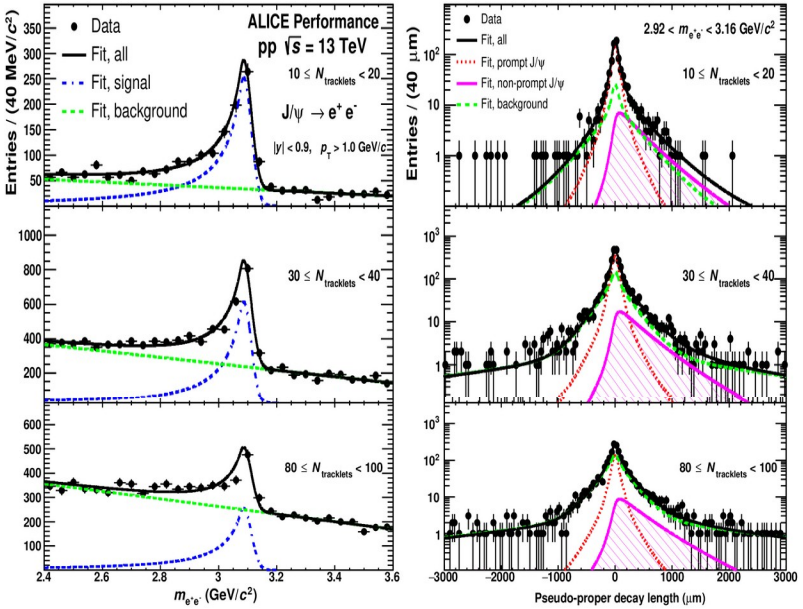
J/ψ production vs. multiplicity at midrapidity

- JHEP 06 (2022) 015



Inclusive

ALI-PUB-527825



ALI-PERF-539349

Self-normalized midrapidity J/ψ yield vs. midrapidity multiplicity

- Exhibits faster than linear increase
- Qualitatively described by most models, best decribed by CGC, 3-Pomeron CGC , CPP model

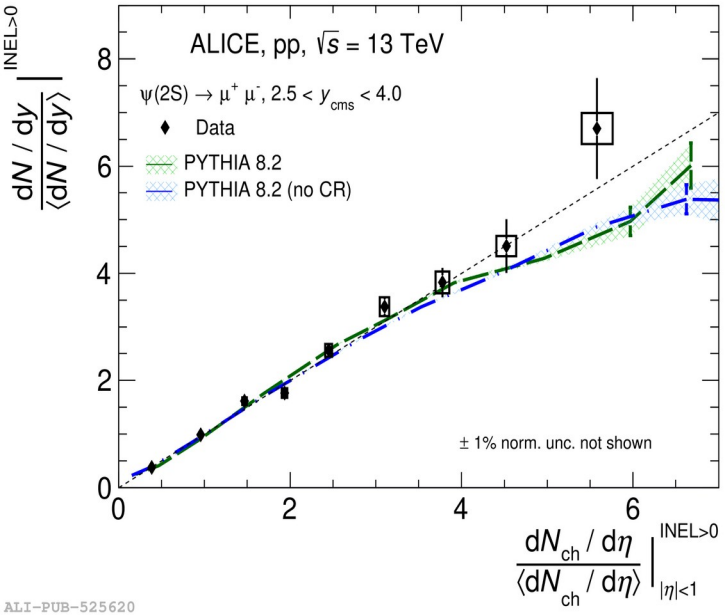
Towards non-prompt J/ψ fraction vs. multiplicity measurement at midrapidity

- Could be a promising tool to discern the origin of non-linear increase of self-normalized inclusive J/ψ yield vs. multiplicity at midrapidity

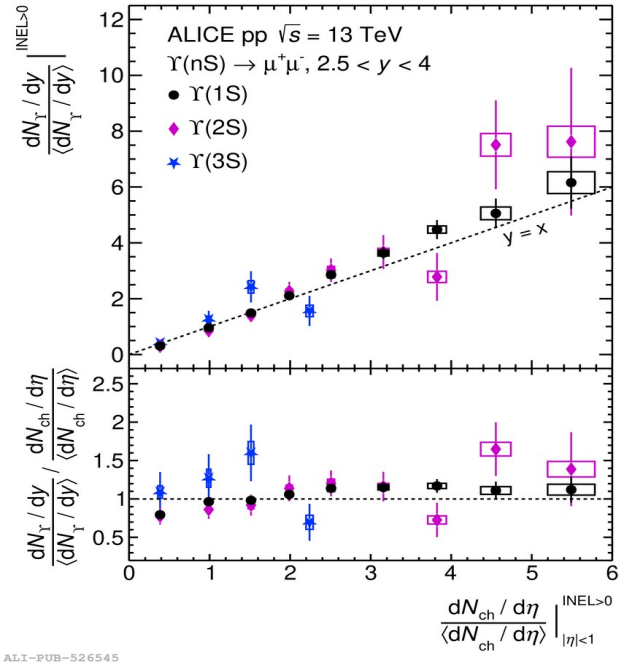
- B.Z. Kopeliovich et al, Phys. Rev. D 101 (2020) 054023 (CPP)
- K. Werner et al, Phys. Rev. C (2014) 064903 (EPOS)
- E. Levin et al, Eur. Phys. J. C 80 (2020) 560 (3 Pomeron CGC)
- E. G. Ferreiro et al, Phys. Rev. C (2012) 034903 (Percolation)
- Y. -Q. Ma et al, Phys. Rev. D 98 (2018) 074025 (CGC)
- T. Sjoestrand et al, Comput. Phys. Commun. 191 (2015) 159 (PYTHIA 8.2)

$\psi(2S), \Upsilon(nS)$ forward rapidity yields vs. multiplicity in pp collisions

- JHEP 06 (2023) 147



- arXiv: 2209.04241



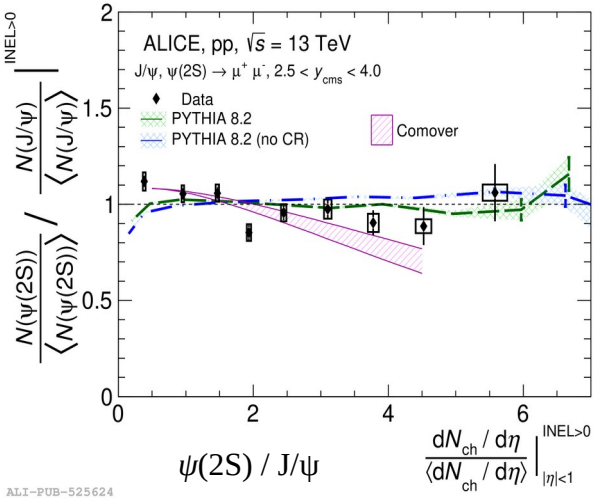
Self-normalised $\psi(2S), \Upsilon(nS)$ yields at forward rapidity exhibit linear increase with multiplicity at midrapidity

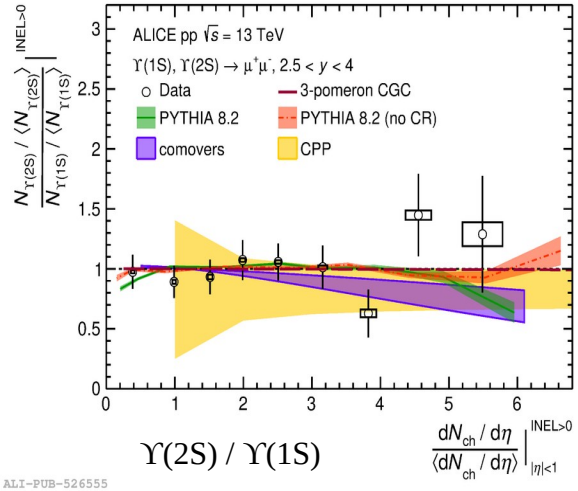
- Similar multiplicity dependence as J/ψ at forward rapidity
- PYTHIA8 w/ and w/o CR can describe self-normalized ψ(2S) yield upto 4 times the average multiplicity at midrapidity

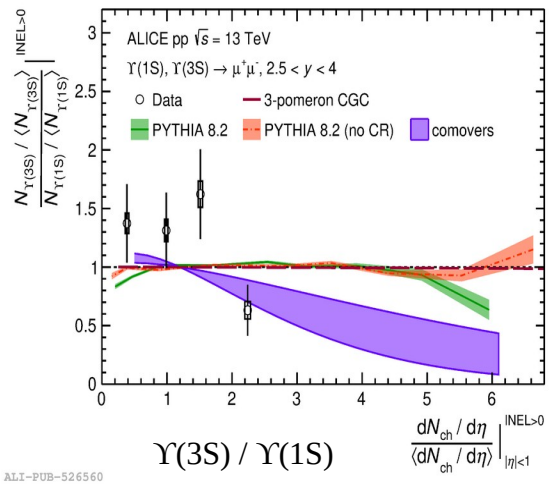
- T. Sjoestrand et al, Comput. Phys. Commun. 191 (2015) 159 (PYTHIA 8.2)

Excited-to-ground state quarkonium ratios at forward rapidity vs. midrapidity multiplicity in pp collisions

- JHEP 06 (2023) 147
- arXiv: 2209.04241





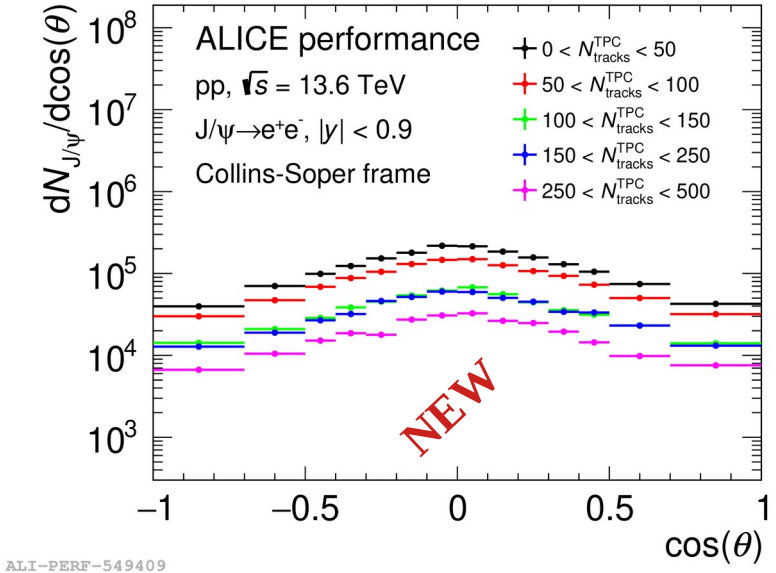


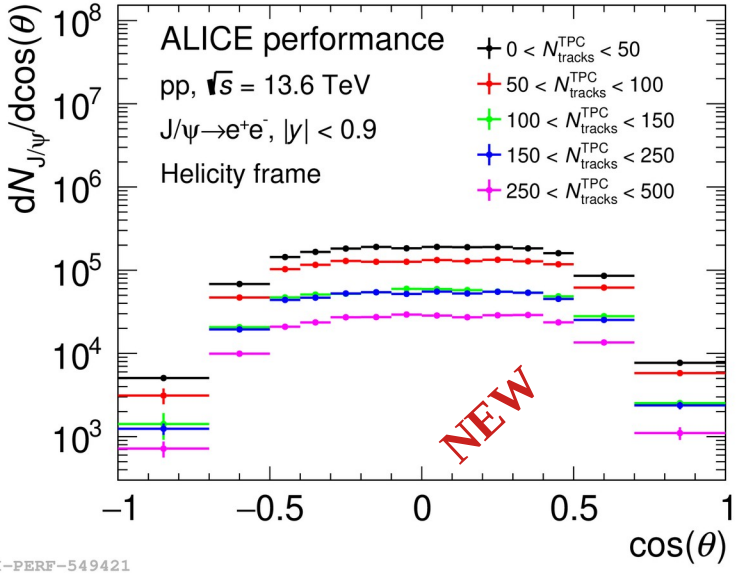
Self-normalized excited-to-ground state ratios vs multiplicity are consistent with unity within uncertainties

- No dependence on binding energy of the excited states
- Models describe multiplicity dependence of excited-to-ground state ratios within uncertainties
- Comover model calculation predicts suppression for ψ(2S), ϒ(2S), ϒ(3S) states due to strong final state interactions
- Large uncertainty in data does not allow any firm conclusion on the presence of final state effects

- B.Z. Kopeliovich et al, Phys. Rev. D 101 (2020) 054023 (CPP)
- E. Levin et al, Eur. Phys. J. C 80 (2020) 560 (3 Pomeron CGC)
- E. G. Ferreiro et al, Phys. Lett. B 749 (2015) 98-103 (Comover)
- T. Sjoestrand et al, Comput. Phys. Commun. 191 (2015) 159 (PYTHIA 8.2)

Multiplicity dependence of J/ψ polarization in pp collisions at $\sqrt{s}$ = 13.6 TeV





Ongoing measurement in ALICE to estimate J/ψ polarization vs. multiplicity at midrapidity

- Polarization measurement is an alternative tool to decipher production mechanism in small systems
- Higher statistics data in Run 3 will allow first polarization measurement and its multplicity dependence at midrapidity

Summary & conclusions

Small collision systems as a probe for quarkonium production mechanisms

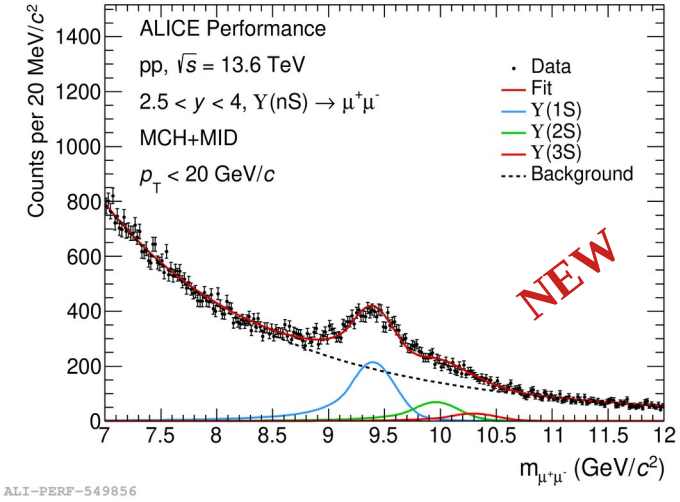
- High statistics Run 3 data allowed first measurement of $\psi(2S)$ and $\psi(2S)$ / J/ψ ratios at midrapidity in pp collisions at $\sqrt{s}$ = 13.6 TeV from minimum bias sample down to zero p_T
- $\psi(2S)$ / J/ψ cross section ratios are found consistent between Run 2 and Run 3 data as well as between mid and forward rapidity
- Inclusive and excited-to-ground state quarkonium cross section ratios at mid and forward rapidity will provide more constraints on the model calculations
- J/ψ pair production provides important insight on MPI, ALICE and LHCb measurements are in good agreement

Multiplicity dependence of quarkonium production as a probe for MPI and final state effects

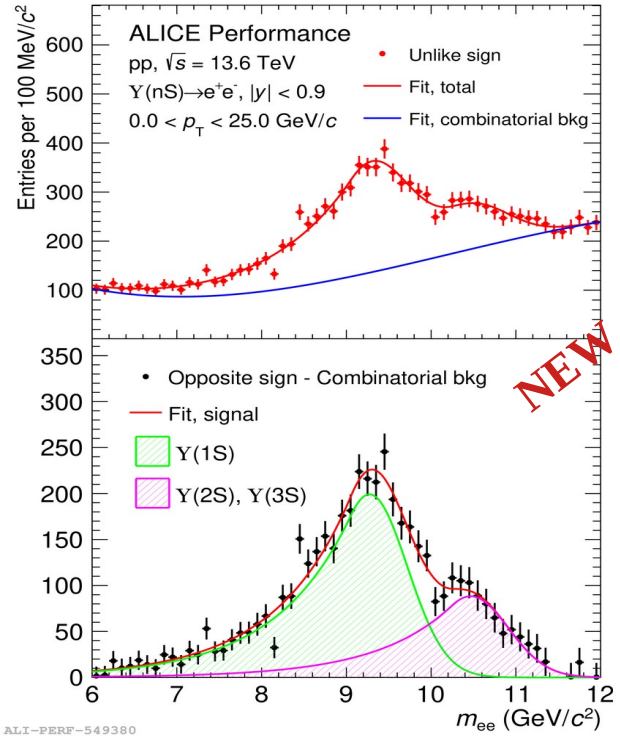
- Multiplicity dependent self-normalized quarkonium yields exhibit linear and faster than linear increase at forward and midrapidity respectively. Similar trend observed for different quarkonium state
- Final state effects could not be inferred firmly given the current uncertainties in data
- New and promising multiplicity dependent polarization measurements are ongoing with Run 3 data

Run3 upgrades and prospects

- ALICE-ITS upgrade will allow more precise measurements of quarkonia at midrapidity as well as cleaner separation of prompt and non-prompt candidate
- ALICE-MFT will allow prompt and non-prompt separation at forward rapidity for the first time in ALICE
- Higher lumonisity will enable higher multiplicity reach



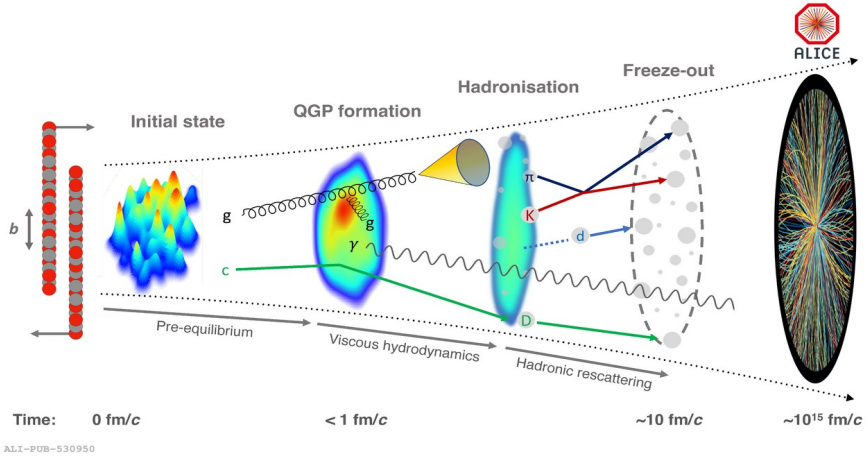
First look to Υ(nS) at mid and forward rapidity from Run 3 data



THANK YOU

Backup slides

Motivation for Quarkonia study



What are Quarkonia ?

- Bound states of heavy quark-antiquark pairs

Why Quarkonia ?

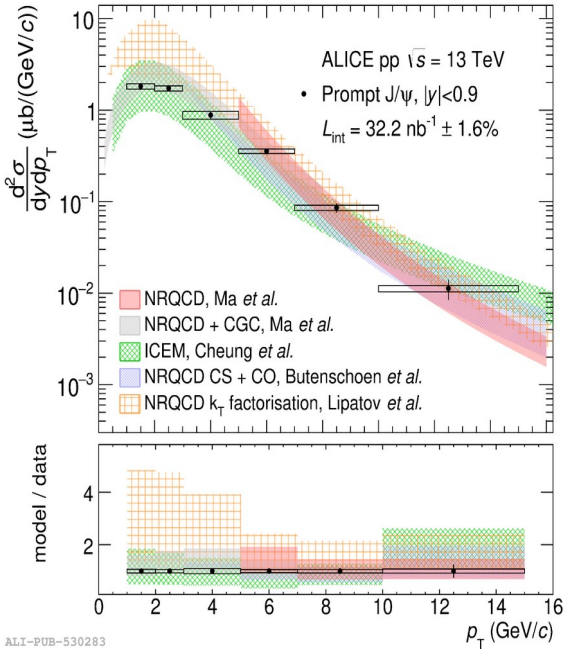
- Hard scale : heavy quarks are produced early from partonic interactions with large momentum transfer ($Q^2 >> \Lambda_{QCD}$)
- Soft scale : binding into colour-neutral final states (J/ψ, ψ(2S) , ϒ(nS), etc)

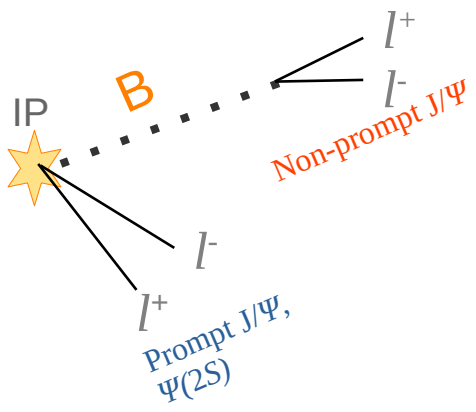
Importance of Quarkonia

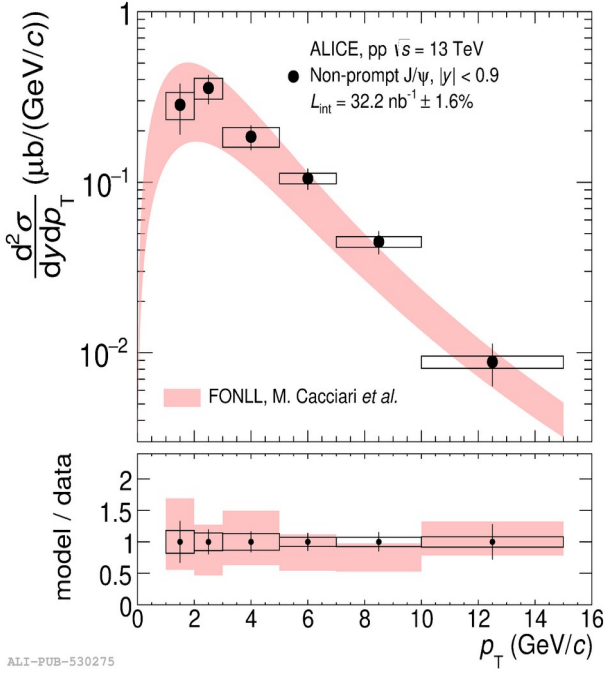
- Sensitive to both perturbative and non-perturbative aspects of QCD
- Production rates are sensitive to Parton Distribution Functions (PDFs) of the incoming proton or nuclei
- Put constrain on models Non-relativistic QCD (NRQCD), Colour Evaporation Model (CEM)

Prompt vs non-prompt J/Ψ production at mid-rapidity

- JHEP 03 (2022) 190







Prompt J/Ψ at 13 TeV

- ICEM and NRQCD+CGC models describe well p_T-differential cross section down to low p_T
- Uncertainties on model calculations limit clear discrimination between models for prompt J/Ψ production

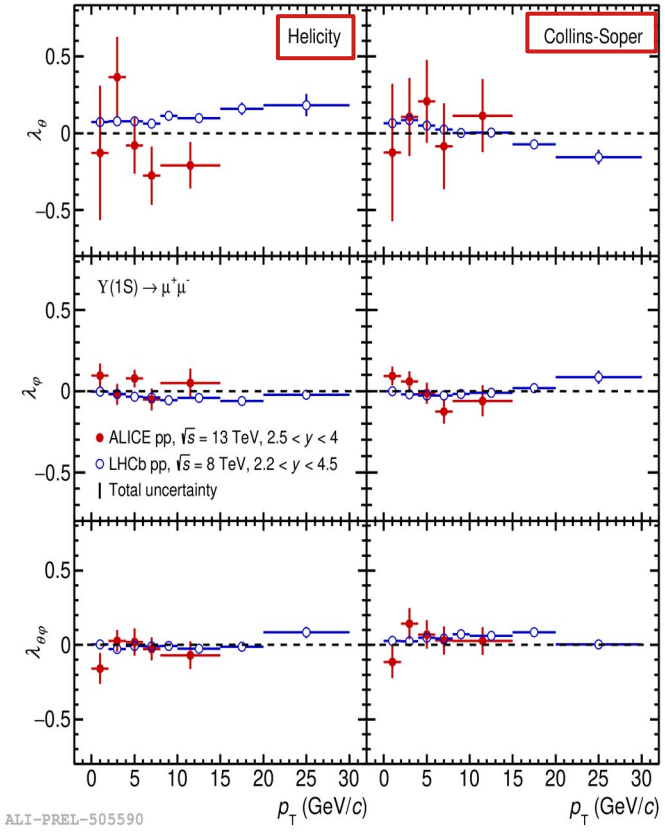
Non-prompt J/Ψ at 13 TeV

- FONLL calculations are in good agreement with data
- Fraction of non-prompt J/Ψ, $f_B = 0.185 \pm 0.015 + 0.014$ (p_T inclusive)

- Phys. Rev. Lett. 106 (2011) 042002 (NRQCD)
- Phys. Rev. Lett. 106 (2011) 022003 (NRQCD CS+CO)
- Phys. Rev. D 100 (2019) 114021 (NRQCD k_T factorization)
- Phys. Rev. Lett. 113 (2014) 192301 (NRQCD+CGC)
- Phys. Rev. D (2018) 114029 (ICEM)
- JHEP 10 (2012) 137 (FONLL)

Υ(1S) polarization in pp collision at $\sqrt{s}$ = 13 TeV

$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta + \dots\right)$$



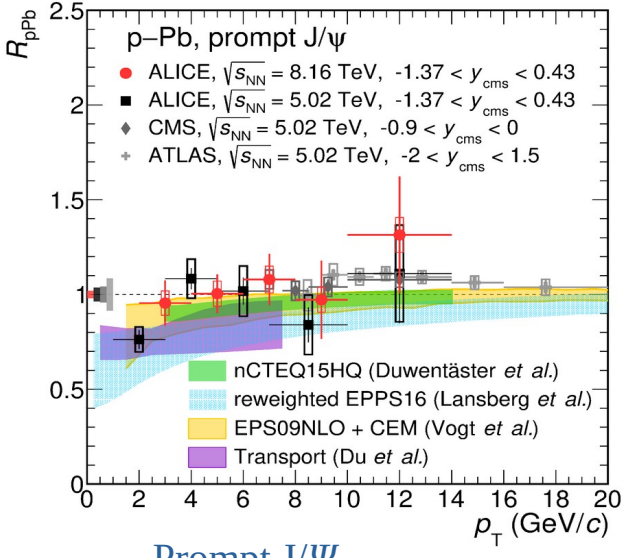
Polarization

- Particle spin alignment along a reference direction
  - Helicity and Collins-Soper plane
- λ_θ → polarization parameter
  - $\lambda_\theta = 0$ → no polarization
- First ALICE measurement of Υ(1S) polarization
- Polarization parameters consistent with zero down to zero p_T and compatible with LHCb measurement at 8 TeV
- Pre-LHC NLO calculations predict finite polarization
  - $\lambda_\theta > 0$ (NRQCD)
  - $\lambda_\theta < 0$ (CSM)

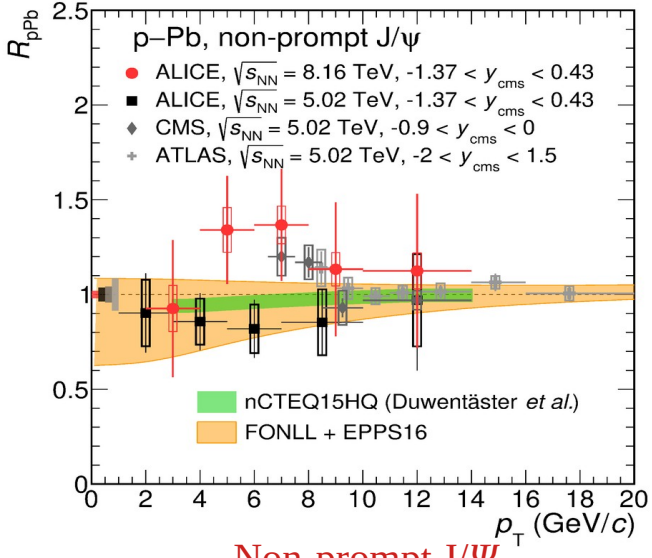
- JHEP 12 (2017) 110
- Phys. Rev. Lett. 108 (2012) 172002

Nuclear modification factor, R_{pPb}

- arXiv: 2211.14153



Prompt J/Ψ



Non-prompt J/Ψ

$$R_{pPb} = \frac{d^2\sigma_{pPb}/dydp_T}{A \times d^2\sigma_{pp}/dydp_T}$$

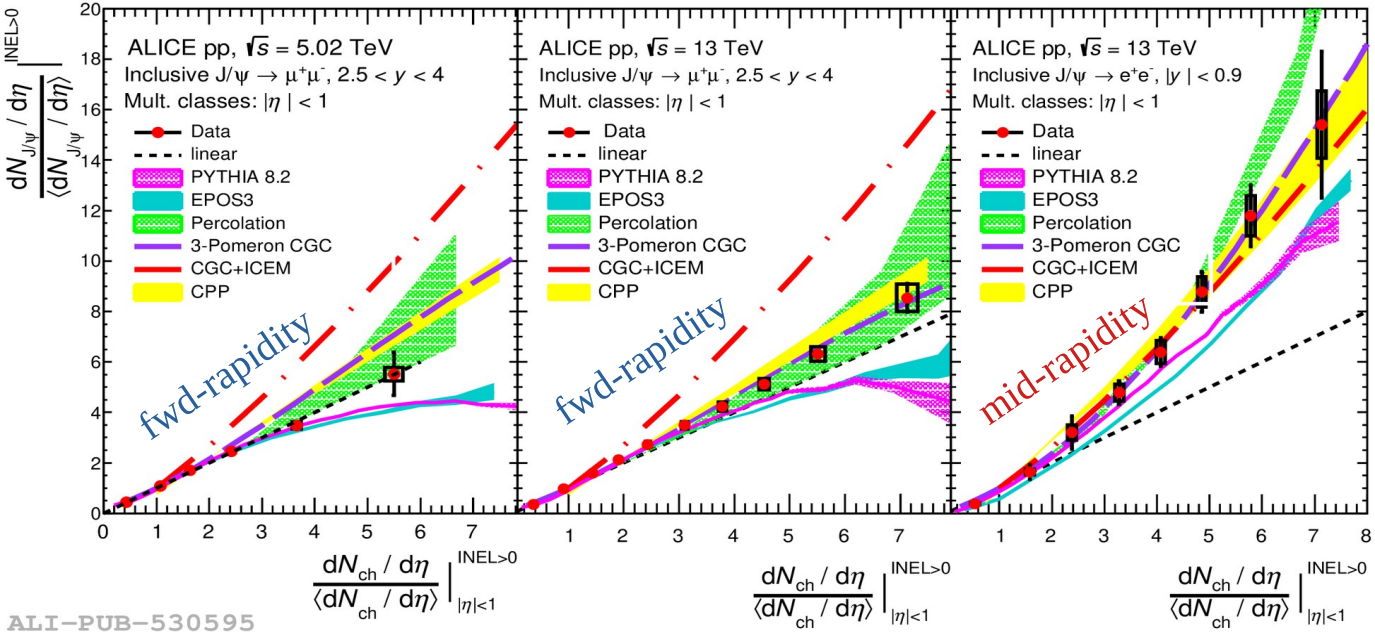
- Phys. Rev. D 105 (2022) 114043 (nCTEQ15HQ)
- Eur. Phys. J. C 77 (2017) 1 (EPPS16)
- IJMPE 22 (2013) 1330007 (EPS09NLO +CEM)
- JHEP 03 (2019) 15 (Transport)
- Eur. Phys. J. C 77 (2017) 163 (FONLL + EPPS16)

Prompt and non-prompt R_{pPb} at √s = 8.16 TeV consistent with unity within uncertainties

- Prompt J/Ψ exhibits a small drop at low p_T
- Cold nuclear matter effects are nominal in the measured kinematic range
- Model calculations invoking modification of nuclear-PDFs is sufficient to reproduce data

J/Ψ production vs multiplicity

- JHEP 06 (2022) 015



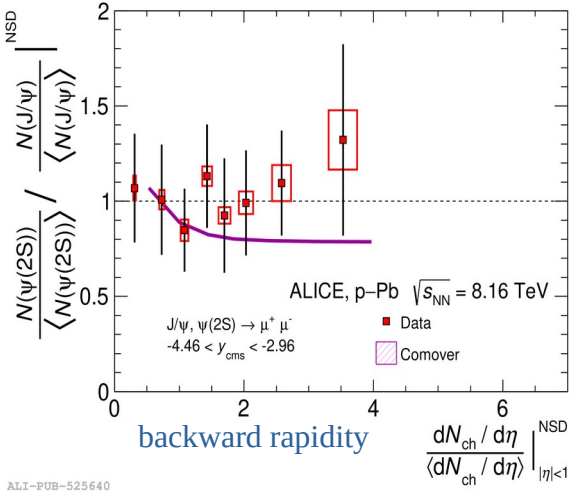
- Phys. Rev. D 101 (2020) 054023 (CPP)
- Eur. Phys. J. C 80 (2020) 560 (3 Pomeron CGC)
- Phys. Rev. C 89 (2014) 064903 (EPOS)
- Phys. Rev. D 98 (2018) 074025 (CGC +ICEM)
- Phys. Rev. C 86 (2012) 034903 (Percolation)
- Comput. Phys. Commun. 191 (2015) 159 (PYTHIA 8.2)

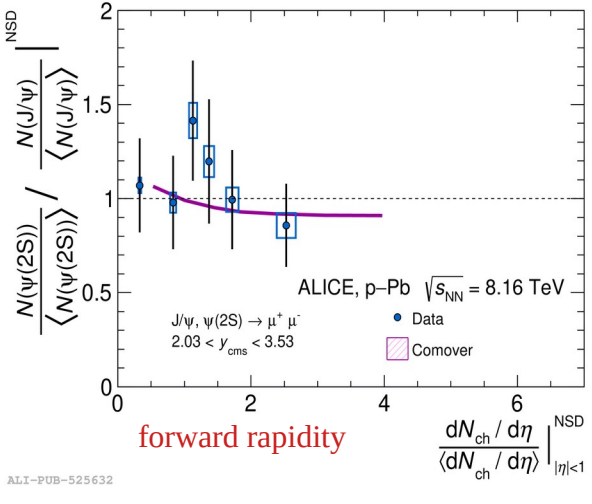
Self normalized J/Ψ yield vs. mid-rapidity multiplicity

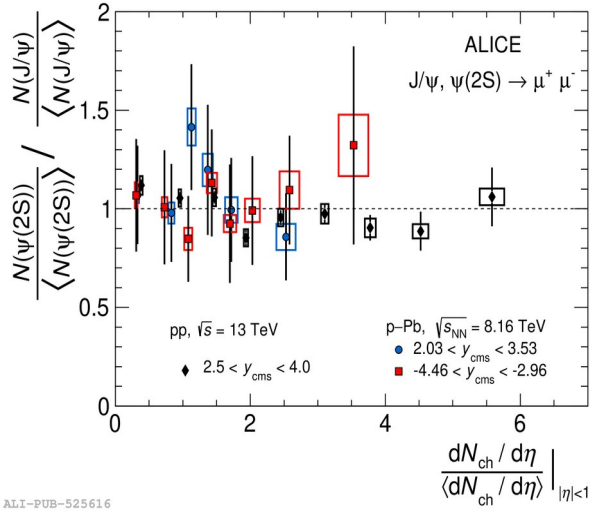
- Forward rapidity : increases linearly and independent of √s, $N_Q \propto N_{MPI}$
- Mid rapidity : increase is faster-than-linear
- Linear increase in forward rapidity is well reproduced by percolation, 3-Pomeron CGC, CPP model
- Faster than linear growth is qualititively reproduced by most models although exact reason remains unclear

Excited-to-ground ($\psi(2S)$ / J/ψ) ratios vs. multiplicity in pp and p–Pb collisions

- arXiv: 2204.10253







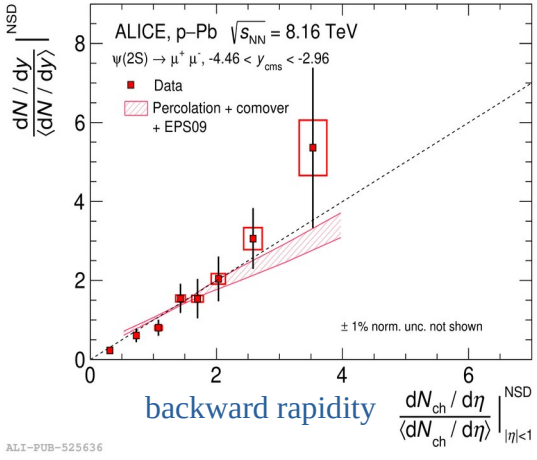
Self normalized excited-to-ground state ratios vs. multiplicity in pp and p–Pb collisions are consistent with unity given the current uncertainties

- Similar multiplicity dependence of J/ψ and ψ(2S) in pp and p–Pb collisions
- Self normalized J/ψ-to-ψ(2S) ratios exhibit similar multiplicity dependence at both rapidity ranges in p–Pb collisions
- Comover model calculation describe the data within uncertainty
- Cold nuclear matter effects can not be distinguished given the current uncertainties in data

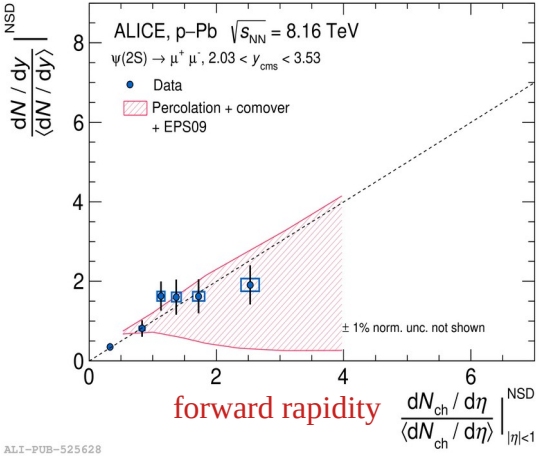
Phys. Lett. B 749 (2015) 98-103 (Comover)

ψ(2S) vs. multiplicity in pp & p–Pb collisions

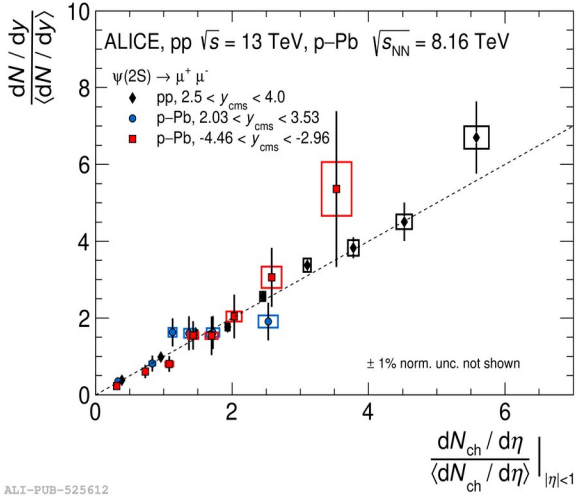
- arXiv: 2204.10253



backward rapidity



forward rapidity



Self-normalized ψ(2S) vs. multiplicity exhibit a linear increase in backward rapidity and seems saturate in forward rapidity at high multiplicity in p–Pb collisions

- Percolation model calculations coupled with comover and EPS09 nPDF describe the data within uncertainty

Similar multiplicity dependence in pp and forward rapidity p–Pb collisions

- Phys. Rev. Lett. 77 (1996) 3736 (Percolation)
- Phys. Lett. B 749 (2015) 98-103 (Comover)
- JHEP 04 (2009) 065 (EPS09)