Quarkonium production in pp collisions with ALICE

Steffen Weber for the ALICE Collaboration

Overview

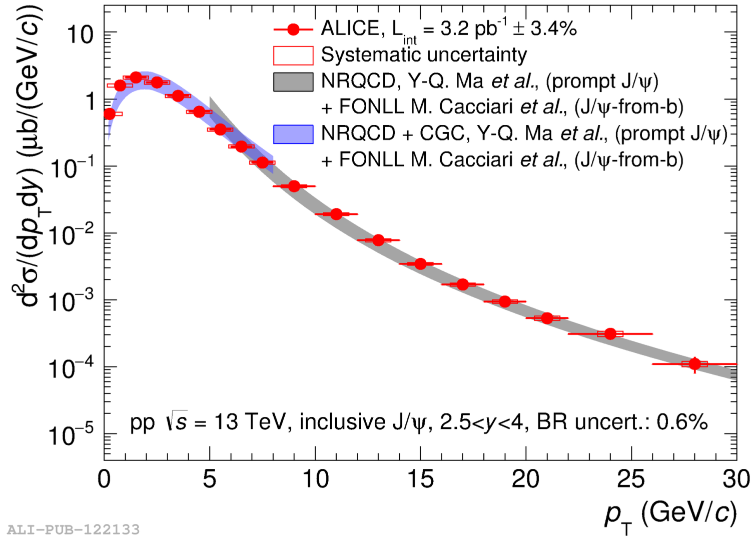
- 45th birthday of the first quarkonium observation this year.
- Prime example of factorization of energy scales in the production
- Since its discovery the understanding of its properties and production mechanisms has greatly improved.
  - **C**olor **E**vaporation **M**odel

    H.Fritzsch: Phys. Lett. B, 67(CALT-68-582):217, 1977
  - **C**olor **S**inglet **M**odel

    R. Baier and R. Rückl: Phys. Lett., 102B:364–370, 1981
  - **N**on**R**elativistic **QCD** (NRQCD)

    G. T. Bodwin, E. Braaten, and G. P. Lepage:
    Phys. Rev., D51:1125–1171, 1995
  - New theoretical developments, e.g. combining NRQCD with **C**olor **G**lass **C**ondensate (GCG+NRQCD)

    Y.-Q. Ma and R. Venugopalan: Phys. Rev. Lett. 113 (2014) 192301



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Open issues / Topics covered in this talk

- Despite success of describing overall J/ψ production in hadronic collisions, polarization puzzle still not solved

  → J/ψ polarization at forward rapidity (8 TeV)

- New observables necessary for a full understanding of the dynamics of quarkonia production in hadronic collisions.

  → J/ψ – hadron correlations at mid-rapidity (13 TeV)

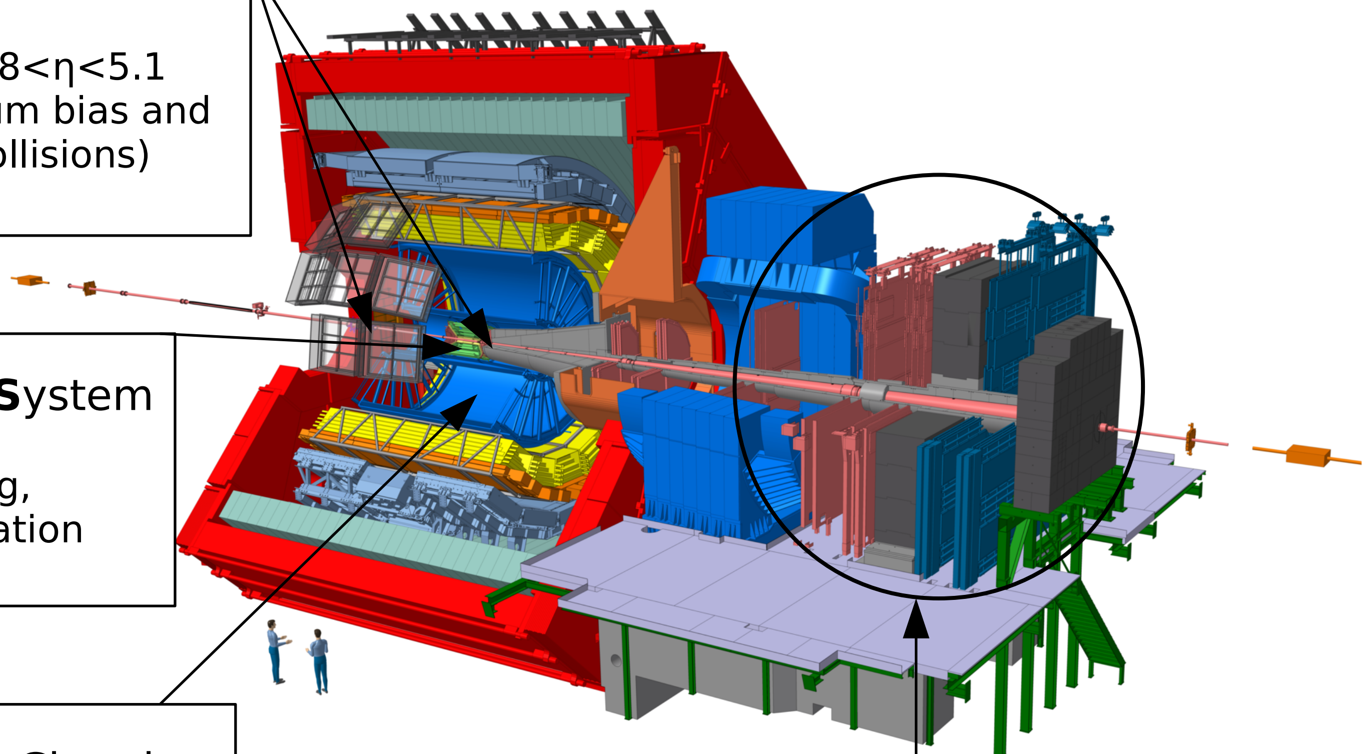
  → Multiplicity dependent quarkonia production (13 TeV)

The ALICE detector system

V0 scintillators
$-3.7<\eta<1.7$ and $2.8<\eta<5.1$
Triggering (minimum bias and high-multiplicity collisions)

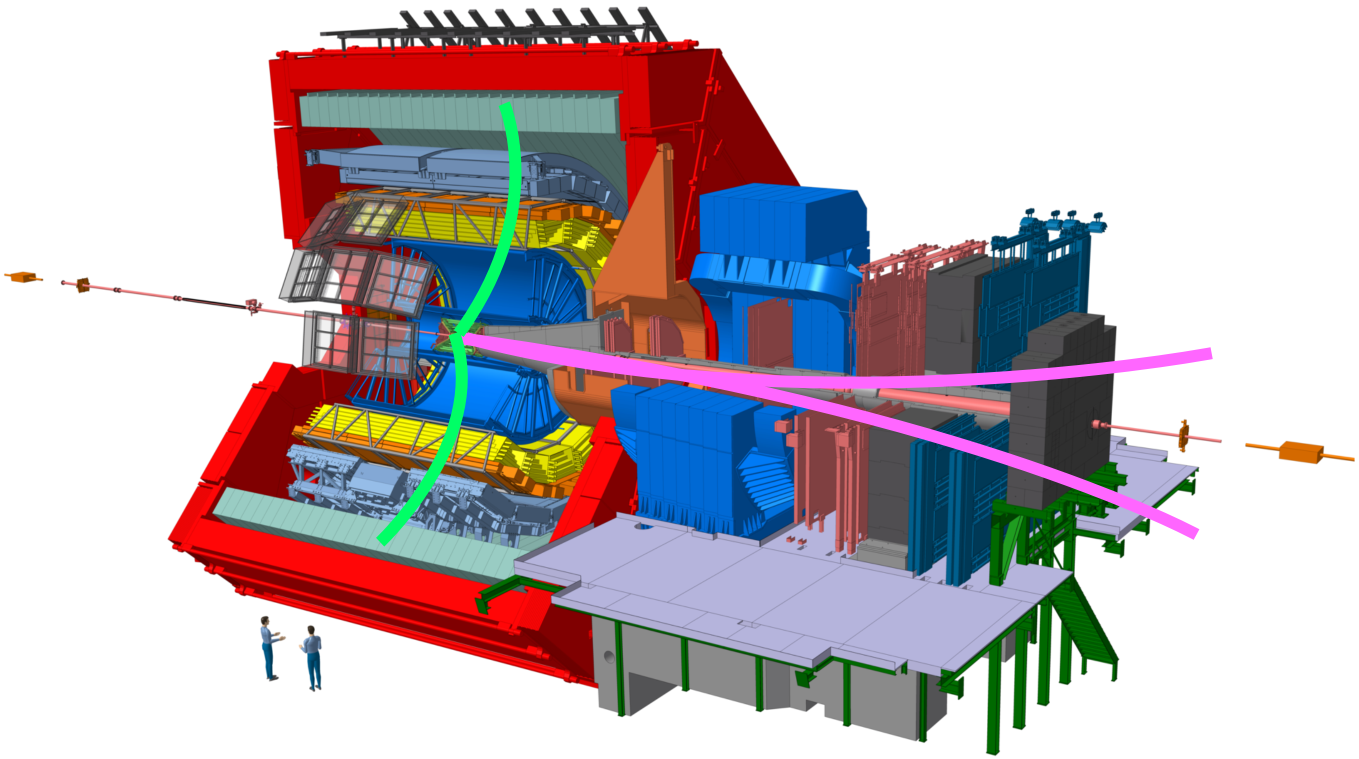
Inner **T**racking **S**ystem
$|\eta|<0.9$
Vertexing, tracking, multiplicity estimation

Time **P**rojection **C**hamber
$|\eta|<0.9$
Tracking, particle identification



MUON arm
$-4<\eta<-2.5$
Tracking chambers behind hadron absorber
Dipole magnet for momentum determination
Muon trigger system for identification and triggering

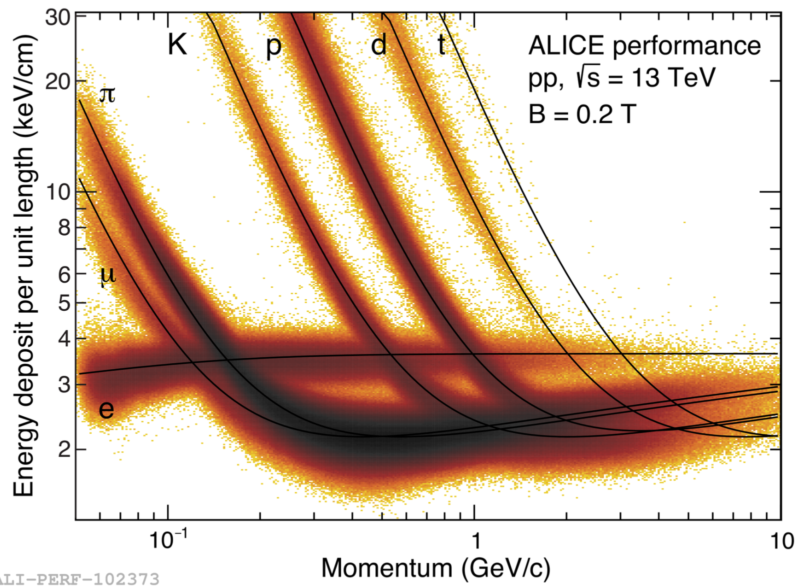
Quarkonium measurements in ALICE



e^+e^- channel
$|y| < 0.9$
$p_T > 0$

$\mu^+\mu^-$ channel
$2.5 < y < 4.0$
$p_T > 0$

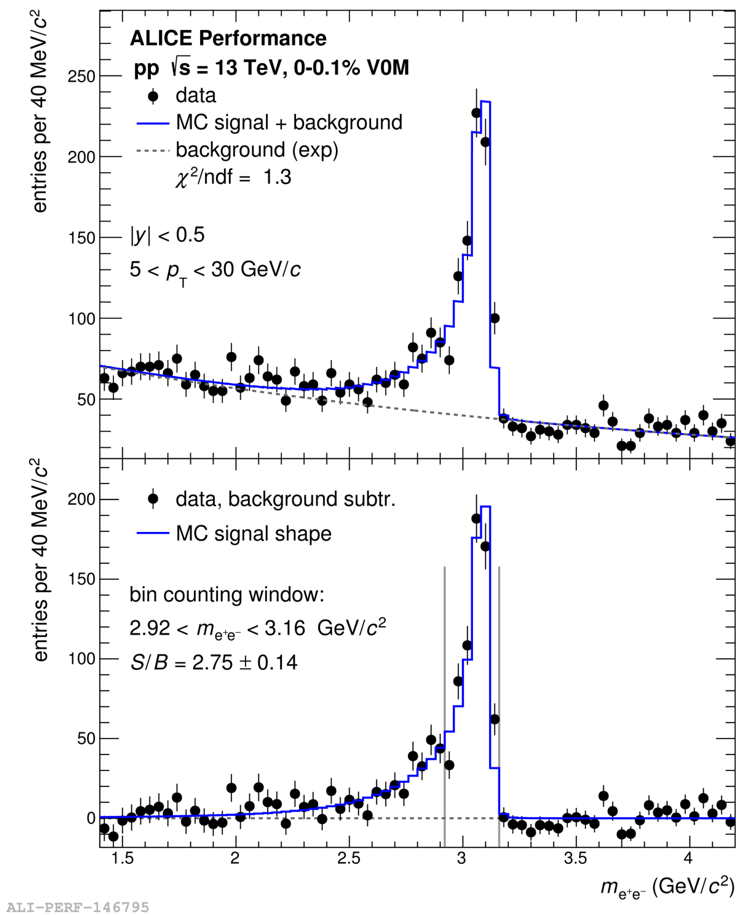
J/ψ in dielectron channel with ALICE



ALICE-PUBLIC-2015-004

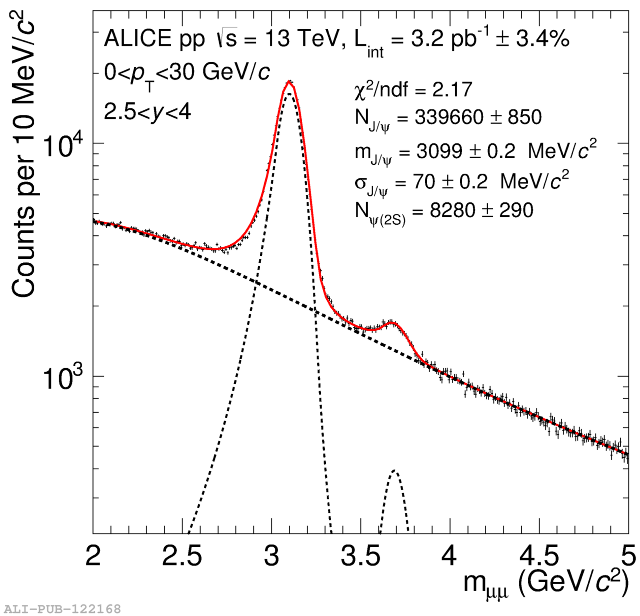
- Primary particle selection based on **I**nner **T**racking **S**ystem (ITS) and **T**ime **P**rojection **C**hamber (TPC)
- Electron identification and hadron rejection with specific energy loss in TPC
- Rejection of conversion electrons with veto on low mass pairs

J/ψ in dielectron channel with ALICE



- Background description techniques used in different analyses
  - Event mixing
  - Like-sign pairs
  - Fitting
- Possibility to distinguish between prompt J/ψ and J/ψ from B meson decay with pseudoproper decay time
- This presentation will focus on inclusive J/ψ though

Quarkonia in dimuon channel with ALICE



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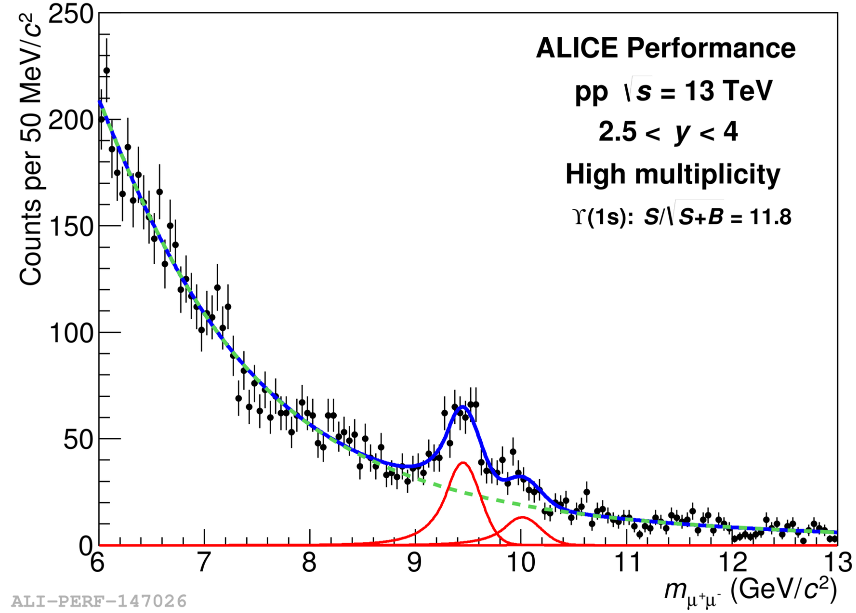


- Muon triggering and identification
- Fitting of signal and background invariant mass distribution
- Charmonia and bottomonia accessible: J/ψ, ψ’, Υ(nS)
- So far, no separation of non-prompt J/ψ possible (inclusive J/ψ only)

J/ψ polarization

Motivation:

- According to NRQCD at leading α_s order, J/ψ production at high p_T is dominated by gluon fragmentation → expect transverse polarization
- Experimentally J/ψ shows weak or no polarization and weak or no p_T dependence.

Recent ALICE measurements:

- First measurements at 8 TeV, extending p_T reach up to 14 GeV/c compared to previous ALICE measurement
- Polarization parameters obtained by fitting 1D angular distributions:

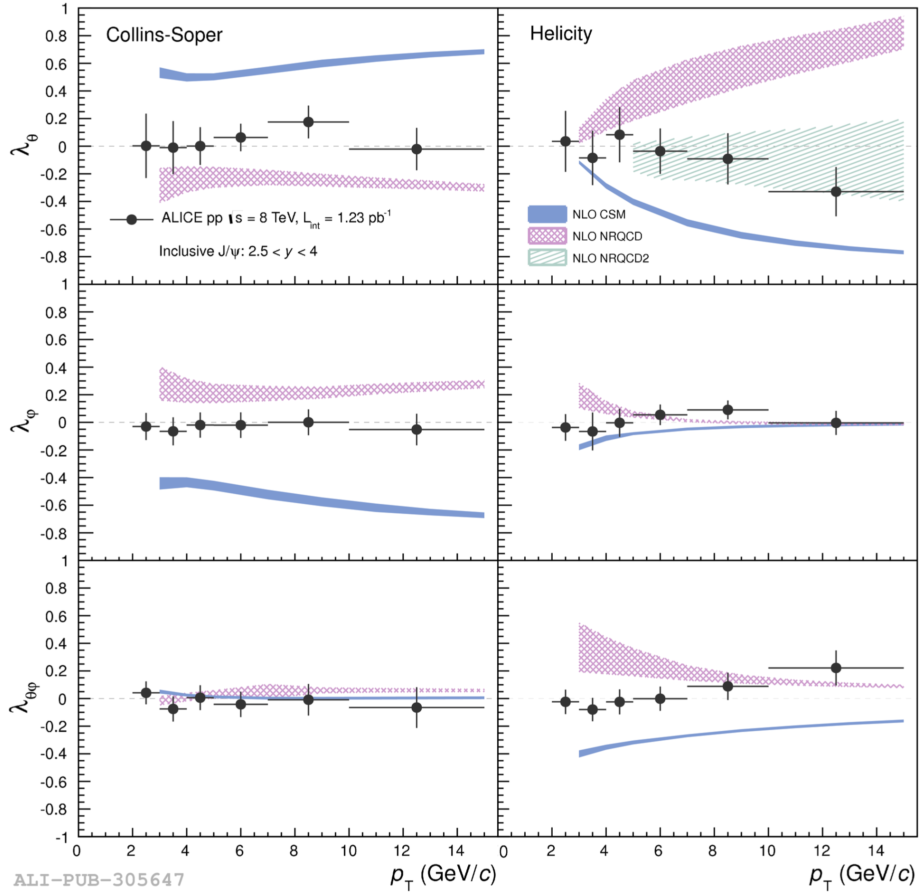
$$W_1(\cos\theta) = \frac{3N}{2(3+\lambda_\theta)}\left[1+\lambda_\theta\cos^2\theta\right]$$

$$W_2(\varphi) = \frac{N}{2\pi}\left[1+\frac{2\lambda_\varphi}{3+\lambda_\theta}\cos(2\varphi)\right]$$

$$W_3(\widetilde{\varphi}) = \frac{N}{2\pi}\left[1+\frac{\sqrt{2}\lambda_{\theta\varphi}}{3+\lambda_\theta}\cos\widetilde{\varphi}\right] \qquad \widetilde{\varphi} = \varphi - \tfrac{3}{4}\pi \text{ for } \cos\theta < 0 \text{ and } \widetilde{\varphi} = \varphi - \tfrac{1}{4}\pi \text{ for } \cos\theta > 0$$

J/ψ polarization

- Results compatible with no or weak polarization, weak or no p_T dependence
- Disagreement with CSM and NLO NRQCD predictions
- NRQCD prediction assuming cancellation of $^3P_J^{[8]}$ and $^3S_1^{[8]}$ contributions in agreement with data, but large uncertainties, predictions only for high p_T in helicity frame



Data: Eur.Phys.J. C78 (2018) no.7, 562
CSM, NRQCD1: M. Butenschoen, B. A. Kniehl: Phys.Rev.Lett. 108 (2012) 172002
NRQCD2: Kuang-Ta Chao et al.: Phys.Rev.Lett. 108 (2012) 242004

J/ψ polarization

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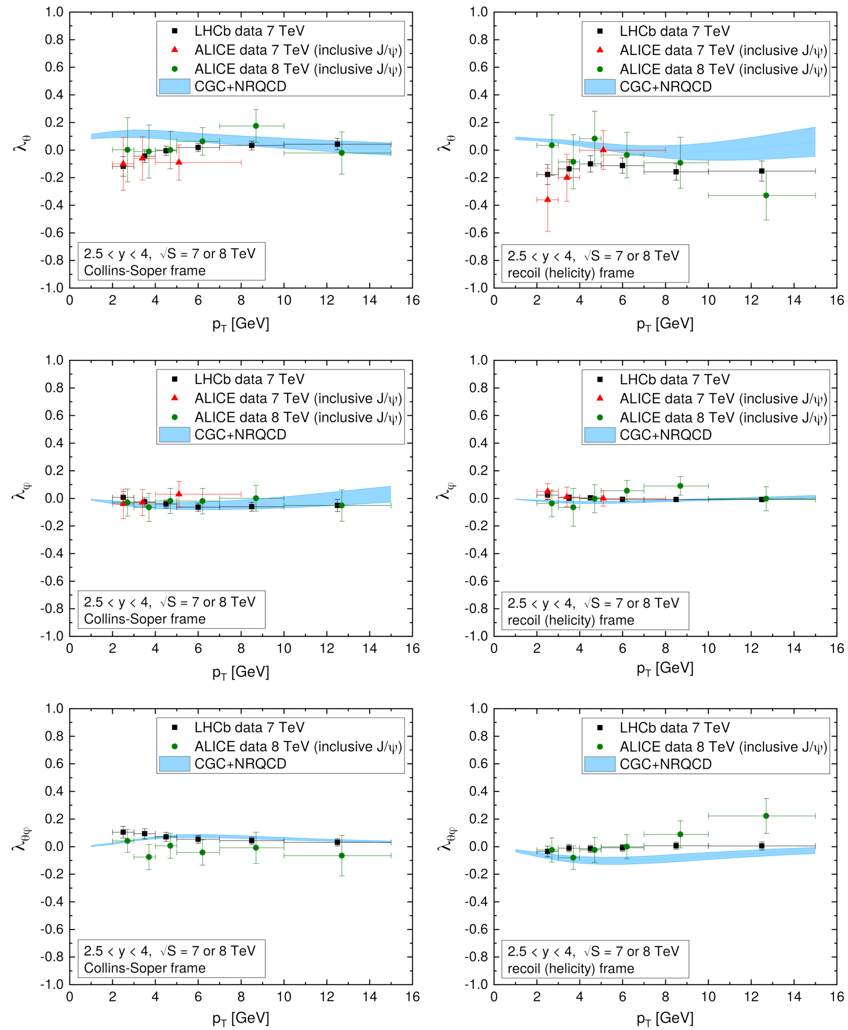
- Results from **C**olor **G**lass **C**ondensate (CGC)+NRQCD model in better agreement with data



Y.-Q. Ma, T. Stebel, R. Venugopalan: JHEP 1812 (2018) 057

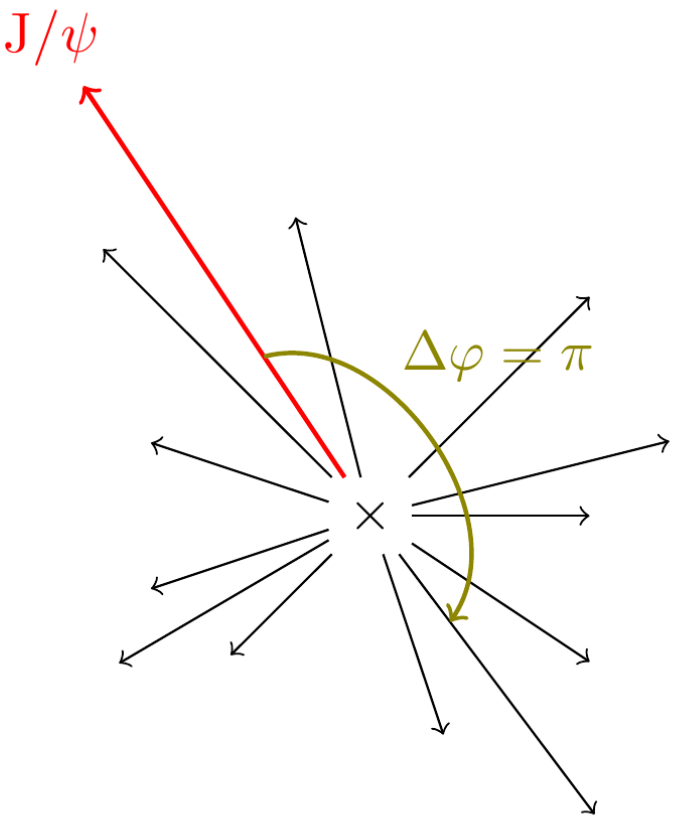
J/ψ – hadron correlations

Motivation:

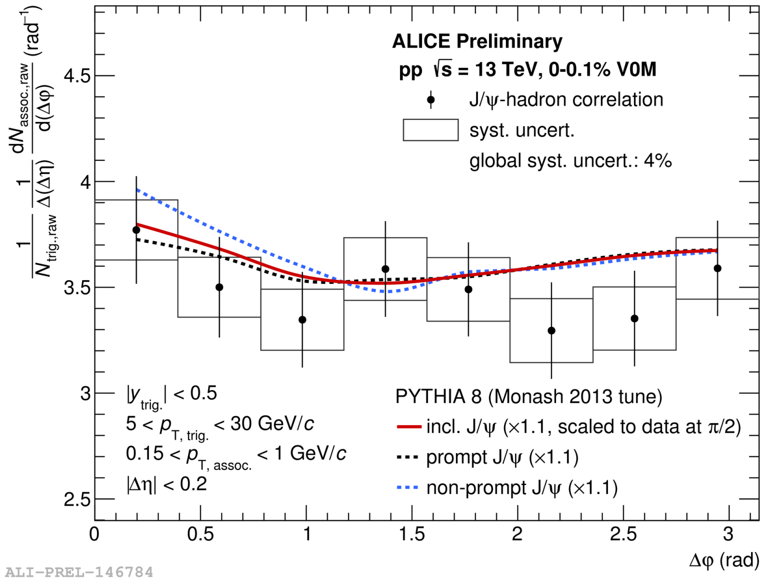
- Models struggle to simultaneously describe all aspects of quarkonium production → go beyond description of production alone, e.g. study correlation with soft particle production.

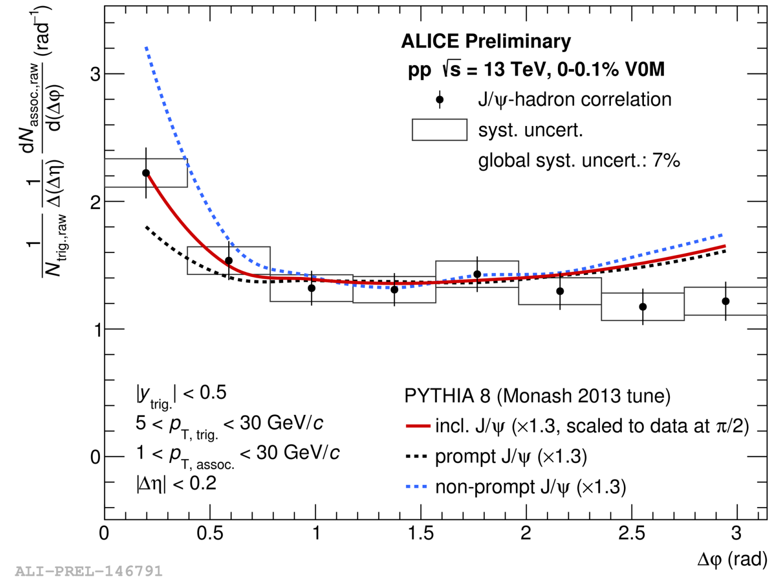
Method:

- Quantify hadronic activity in azimuthal region w.r.t. J/ψ direction
- E.g. activity expected around Δφ=0 from non-prompt decay daughters



J/ψ – hadron correlations





- High multiplicity pp collisions: 0-0.1% highest activity in V0 scintillator.
- Correlation with high p_T (>5 GeV/*c*) inclusive J/ψ at mid-rapidity.
- No significant correlation for low p_T hadrons (<1 GeV/*c*)
- Near-side peak for hadrons with p_T >1 GeV/*c*
- Qualititative agreement with PYTHIA8 prediction. Peak mostly due to non-prompt J/ψ contribution.

Multiplicity dependent quarkonium production

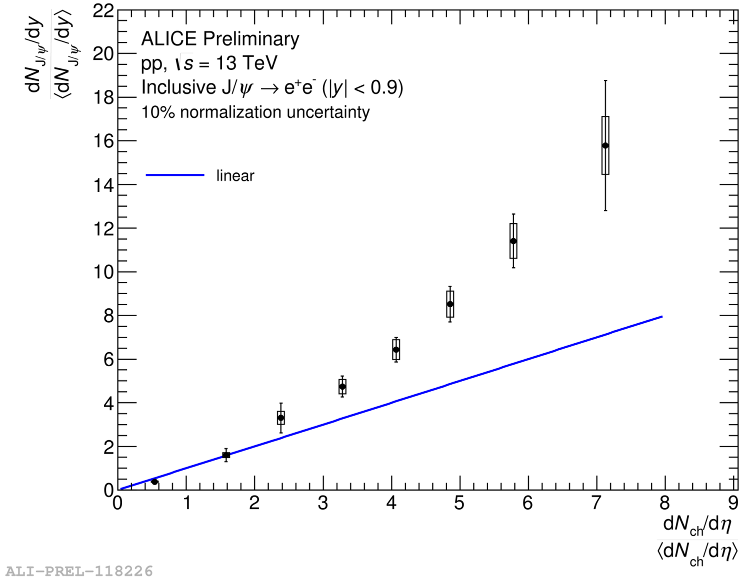
Motivation:

- Correlation of soft and hard processes in hadronic collisions.
- Access to quarkonium production in Multiparton Interactions.
- Novel phenomena at very high particle densities?

Method:

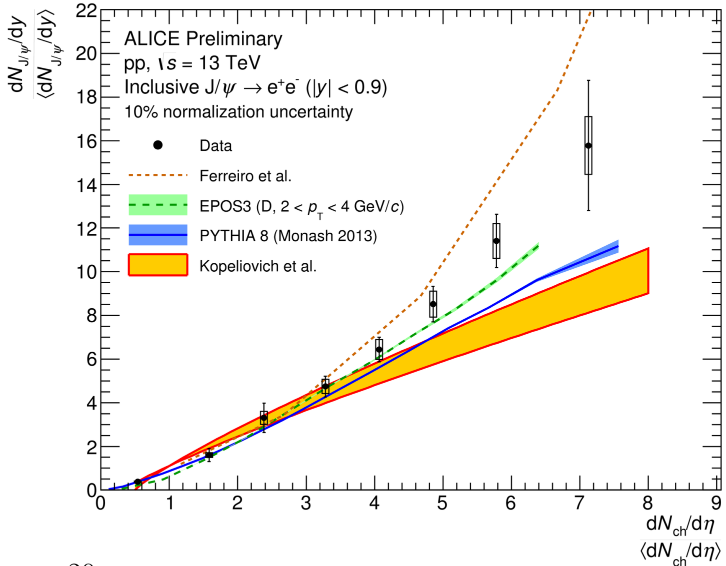
- The multiplicity is estimated with the number of track segments within $|\eta| < 1$ in the ALICE SPD (innermost layers of ITS detector)
- High multiplicities are reached with a dedicated trigger based on high deposited charge required in the ALICE V0 detectors.
- Quarkonia are measured either at the same rapidity (dielectron channel) or with a rapidity gap of at least 1.5 (muon arm)

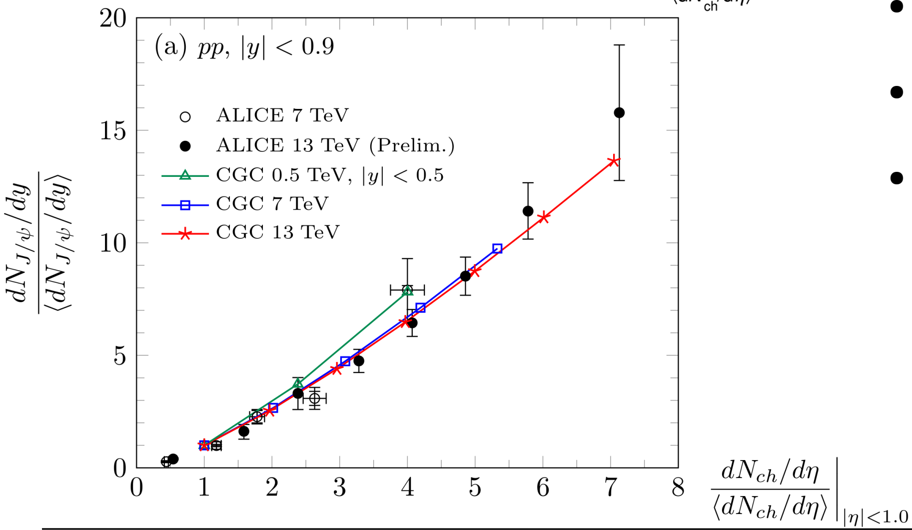
J/ψ at mid-rapidity



- Stronger than linear increase of J/ψ production with multiplicity

Model comparisons

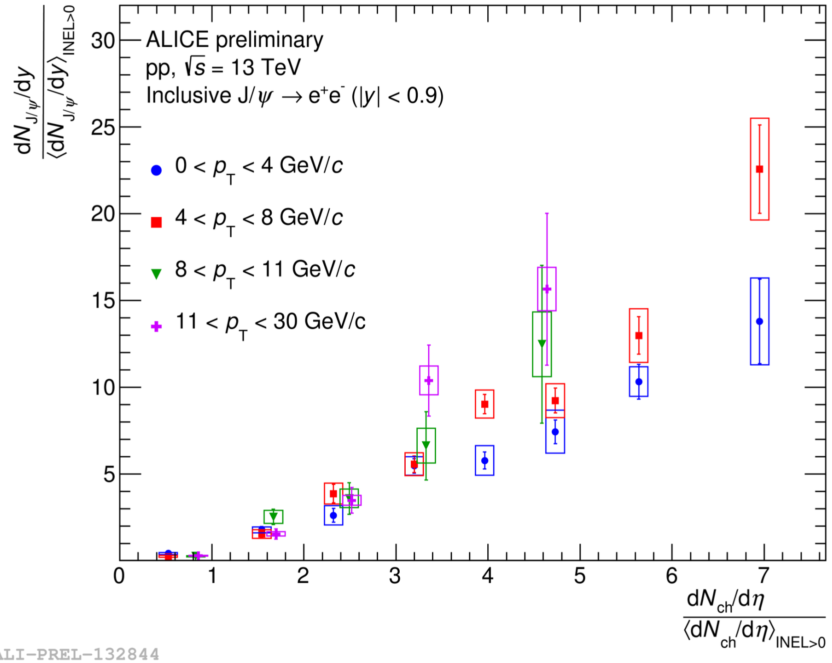




- Stronger than linear increase of J/ψ production with multiplicity
- Various model predictions in qualitative agreement with data.
- Stronger than linear increase attributed to soft particle saturation due to
  - String overlapping (Ferreiro)
  - Higher Fock states (Kopeliovich)
  - Hydrodynamic expansion (EPOS3)
  - CGC saturation effects

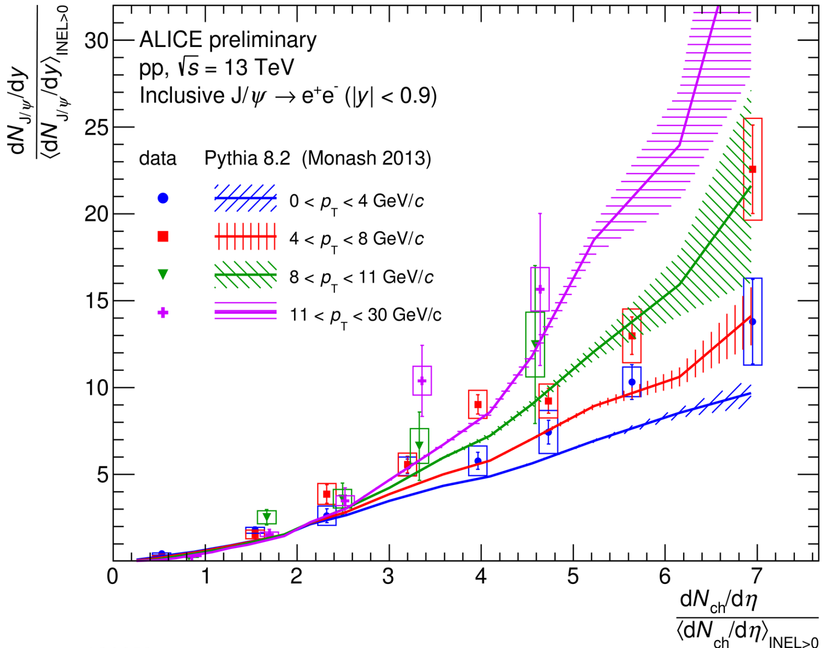
Ferreiro:	Phys.Rev. C86 (2012) 034903
Kopeliovich:	Phys.Rev. D88 (2013) no.11, 116002
CGC:	Phys.Rev. D98 (2018) no.7, 074025

Transverse momentum dependence



- The increase with multiplicity gets stronger at higher p_T

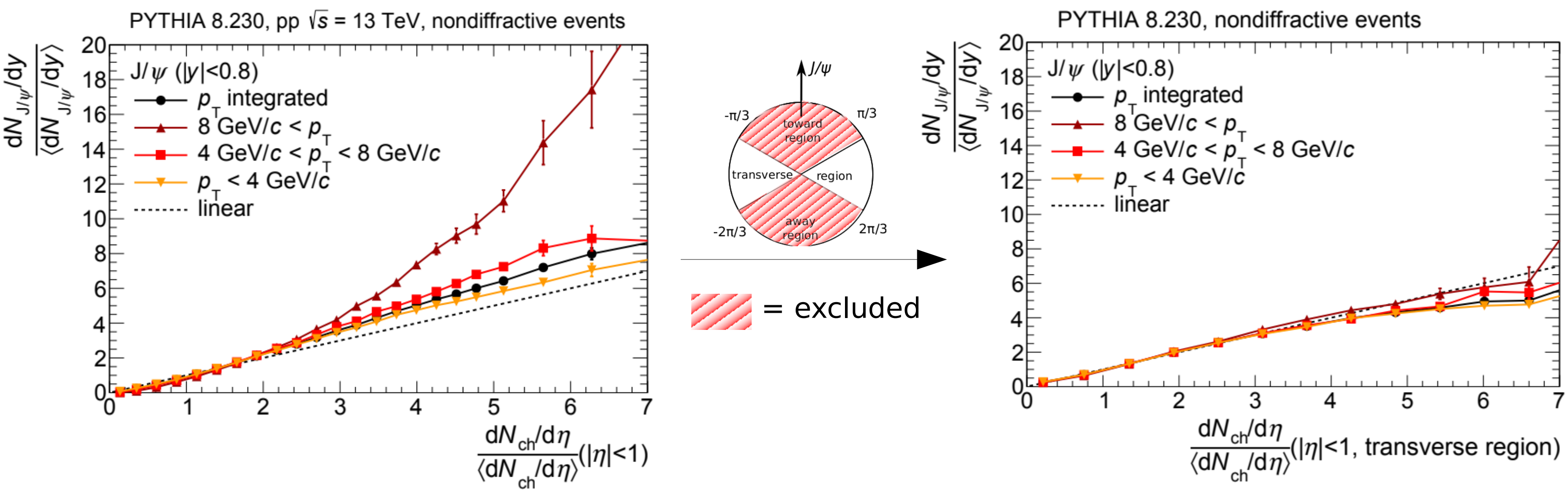
Transverse momentum dependence



ALI-PREL-132858

- The increase with multiplicity gets stronger at higher p_T.
- In qualitative agreement with predictions from PYTHIA8.
- N.B.: Fraction of non-prompt J/ψ increasing with p_T, around ~50% in highest p_T interval.

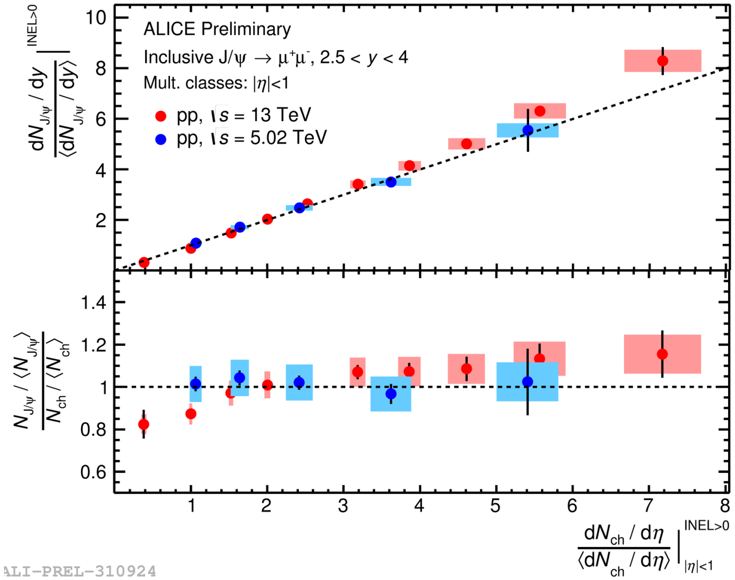
PYTHIA8 study

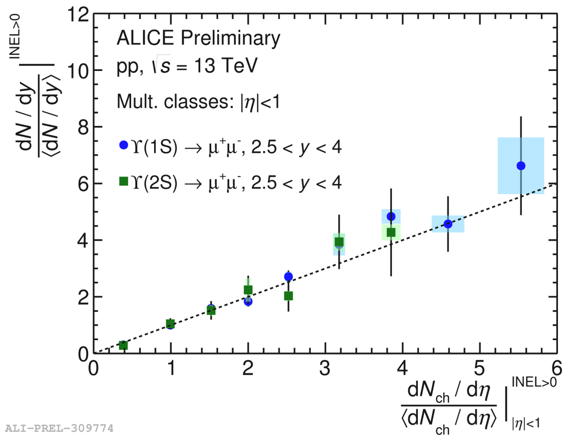


SW, A. Dubla, A. Androic, A. Morsch: Eur.Phys.J. C79 (2019) no.1, 36

- PYTHIA8 simulations attribute the stronger-than-linear increase and the p_T dependence to jet bias effects, mostly from non-prompt J/ψ.
- By restricting the multiplicity estimation to the underlying event region (perpendicular in azimuth to the J/ψ direction) a linear and p_T independent increase is predicted.

Rapidity, flavour dependence





- By comparing J/ψ at forward rapidity with mid-rapidity multiplicity, a rapidity gap can be introduced.
- The observed increase with multiplicity then is approximately linear.
- Comparing collisions at 5 and 13 TeV, no strong energy dependence is observed.
- A similar multiplicity dependence is observed for bottomonium production at forward rapidity.

Summary

- **J/ψ polarization:**

  ALICE results confirm un- or weakly polarized J/ψ at 8 TeV, extending the reach to higher transverse momenta. New theoretical developments → will they solve the polarization puzzle?

- **J/ψ – hadron correlations:**

  Near-side peak observed in qualitative agreement with PYTHIA8 predictions. Potential to give new insights into production mechanisms.

- **Multiplicity dependent quarkonium production:**

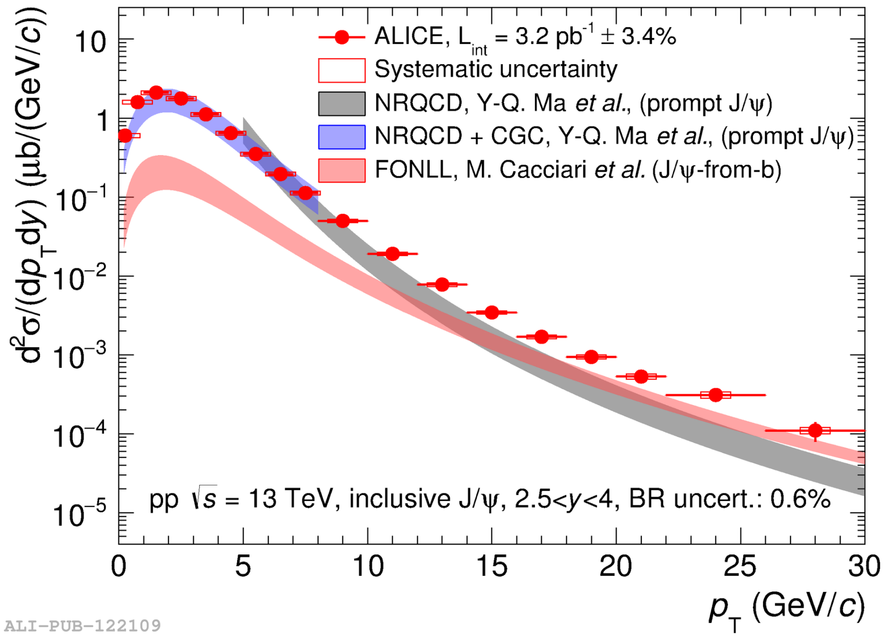
  Stronger-than-linear increase of J/ψ production and mid-rapidity and linear increase of quarkonium production at forward rapidity observed, independent of quarkonium species, but p_{T} dependent.

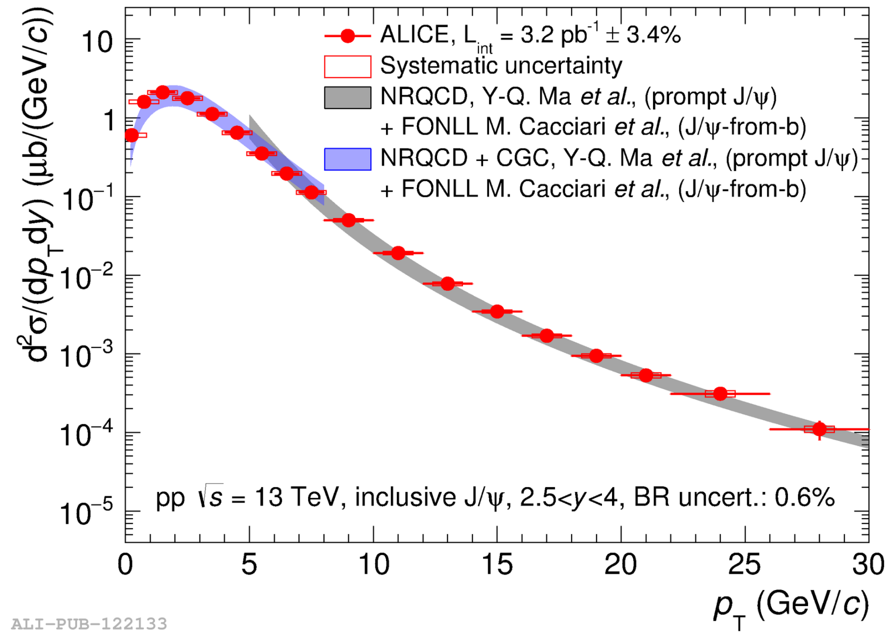
  Various model predictions with different underlying assumptions in qualitative agreement with data. Ample room for improvement in the theoretical understanding of the observations.

Thank you for your attention!

Backup

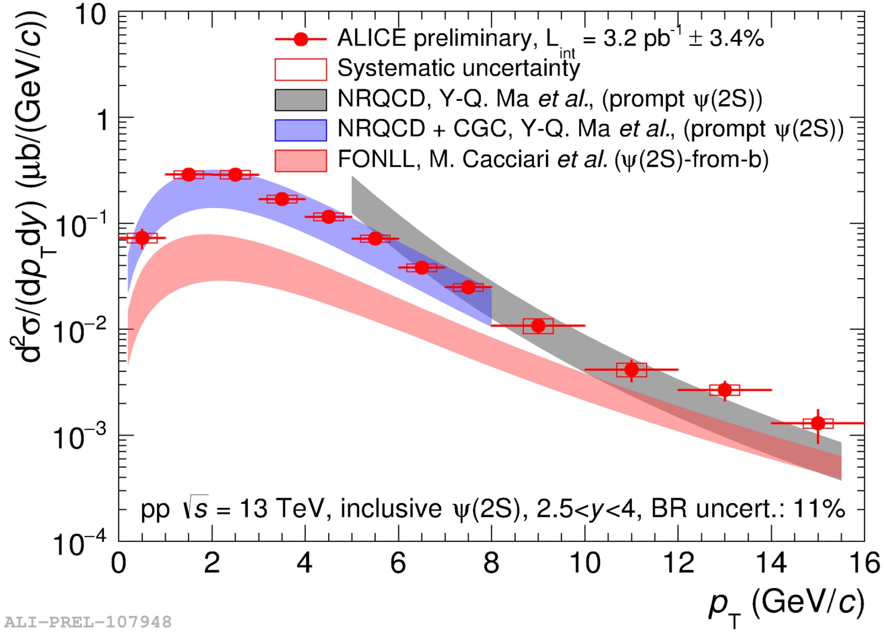
Inclusive J/ψ cross section at forward y

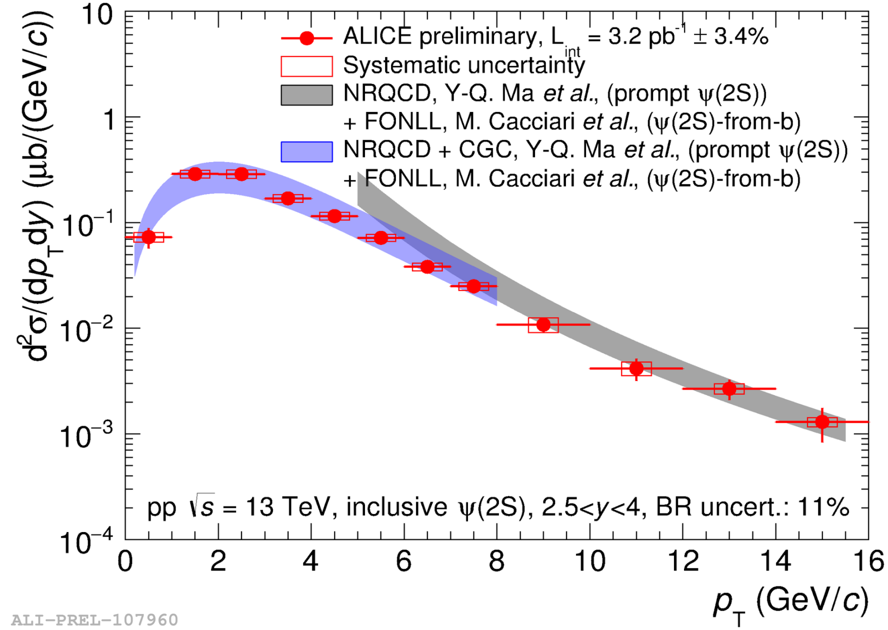




Data:	Eur. Phys. J. C 77 (2017) 392
NRQCD:	Y.-Q. Ma, K. Wang, K.-T. Chao: Phys. Rev. Lett. 106 (2011) 042002
NRQCD+CGC:	Y.-Q. Ma and R. Venugopalan: Phys. Rev. Lett. 113 (2014) 192301
FONLL:	M. Cacciari et al.: J. High Energ. Phys. 1210 (2012) 137

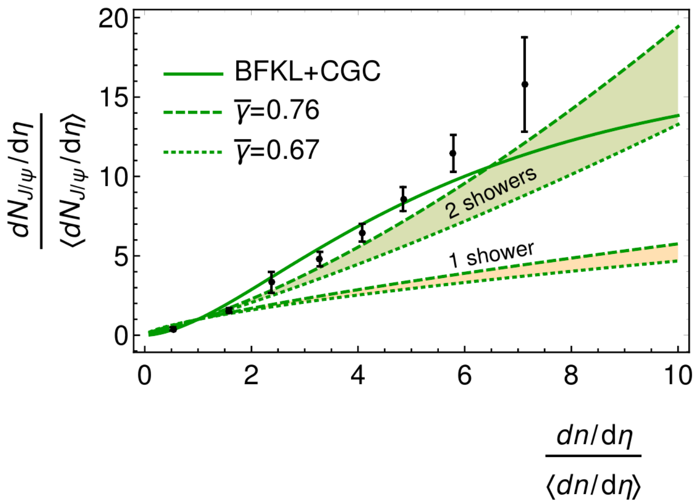
Inclusive ψ’ cross section at forward y





Data:	Eur. Phys. J. C 77 (2017) 392
NRQCD:	Y.-Q. Ma, K. Wang, K.-T. Chao: Phys. Rev. Lett. 106 (2011) 042002
NRQCD+CGC:	Y.-Q. Ma and R. Venugopalan: Phys. Rev. Lett. 113 (2014) 192301
FONLL:	M. Cacciari et al.: J. High Energ. Phys. 1210 (2012) 137

Further model comparisons



E. Levin, M. Siddikov: Eur.Phys.J. C79 (2019) no.5, 376

- Color Glass Condensate model used together with BFKL approach
- Enhancement with multiplicity attributed to three pomeron fusion process