



Quarkonium production in pp and p-Pb collisions with ALICE at the LHC

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for the ALICE Collaboration

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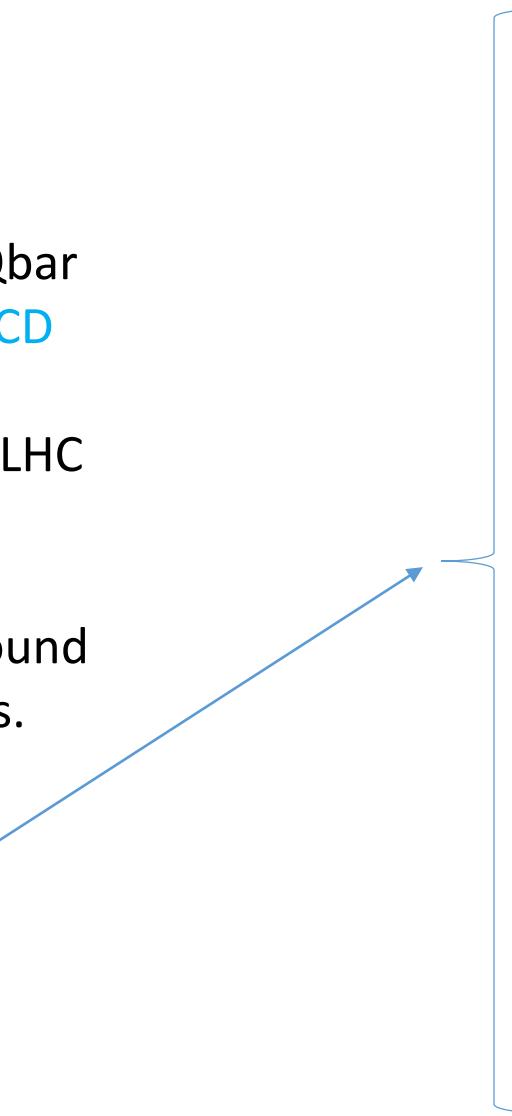
Outline

- Motivation(s)
- Quarkonium detection in ALICE
- Results
 - production in pp collisions
 - production and nuclear modifications in p-Pb collisions
 - production as a function of event multiplicity
- Conclusions

Motivations

Production in pp collisions

- Bound states of **heavy quarks**
- Mass scale is hard enough for Q-Qbar production to be described by **pQCD**
- gluon fusion process dominant at LHC
→ sensitivity to **gluon PDFs**
- **Hadronisation** into a colourless bound state is a **non perturbative** process.
- Three main **production models**



Color Evaporation Model (CEM):

production cross section of a given quarkonium state proportional to the Q-Qbar cross section, integrated between the mass of the state and twice the mass of the D or B meson. Proportionality factor is independent of y , p_T and v_s

Color Singlet model (CSM):

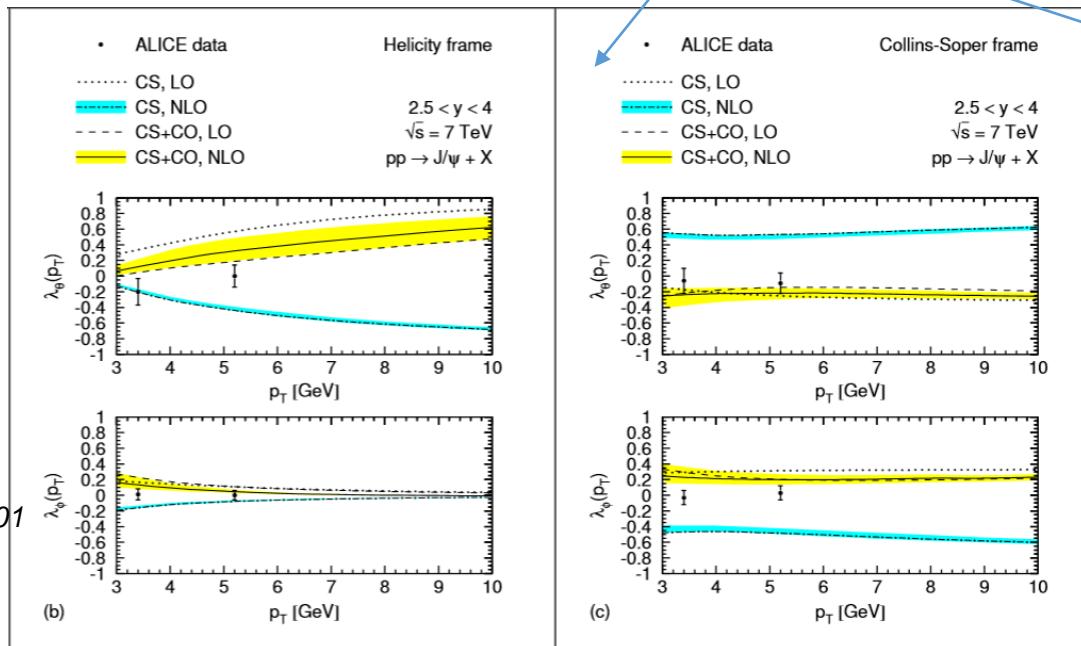
pQCD is used to describe the Q-Qbar production with the same quantum numbers (CS) as the final-state meson.

Non-Relativistic QCD (NRQCD):

both Color Singlet and Color Octet state of the Q-Qbar pairs contribute. The relative contribution of the states is parametrized using a finite set of universal long distance matrix elements (LDME), fitted to a subset of the data (e.g. Tevatron)

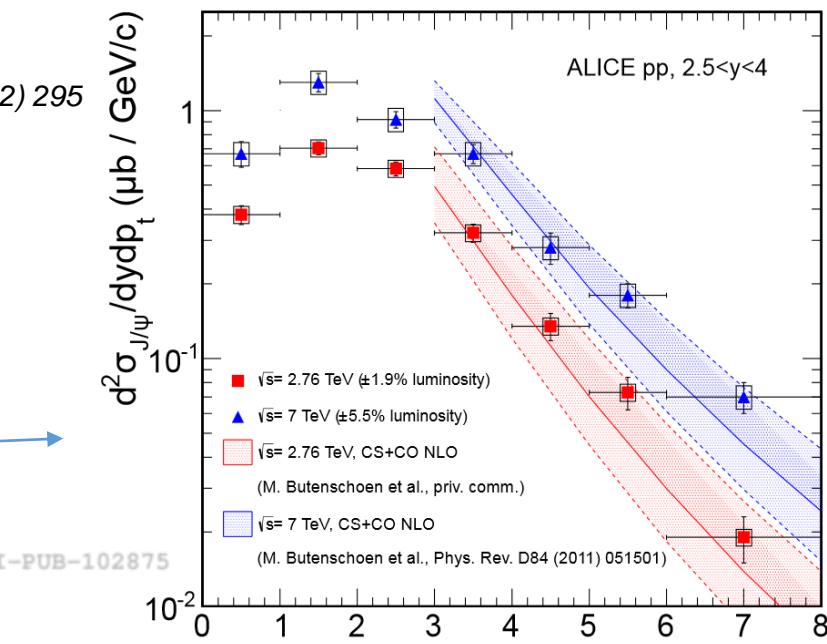
Production in pp collisions

- Non Relativistic QCD was able to reproduce quarkonium yields at Tevatron energies, but not polarisation
- NNLO corrections have «revived» the Color Singlet Model
- Colour Singlet and NRQCD-based models in agreement with LHC RUN-I data at 2.76 and 7 TeV within large uncertainties

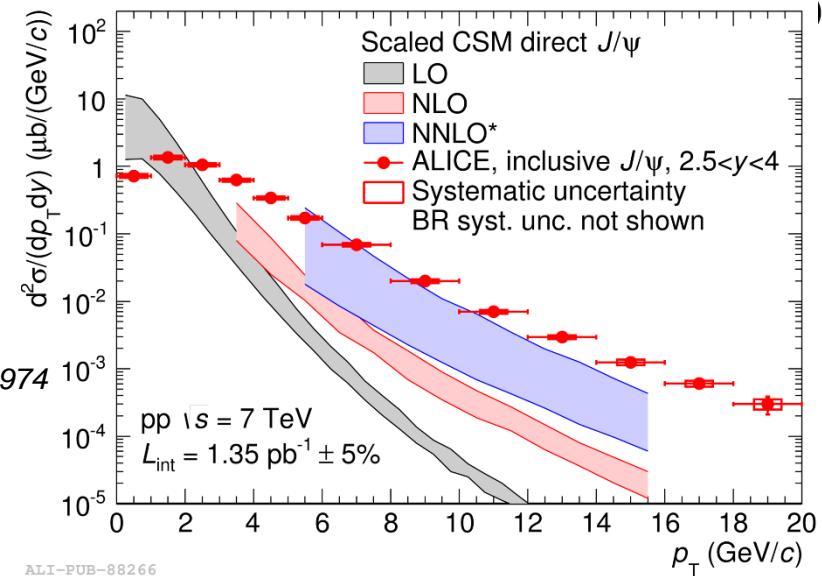


ALICE,
PLB 718 (2012) 295

ALI-PUB-102875



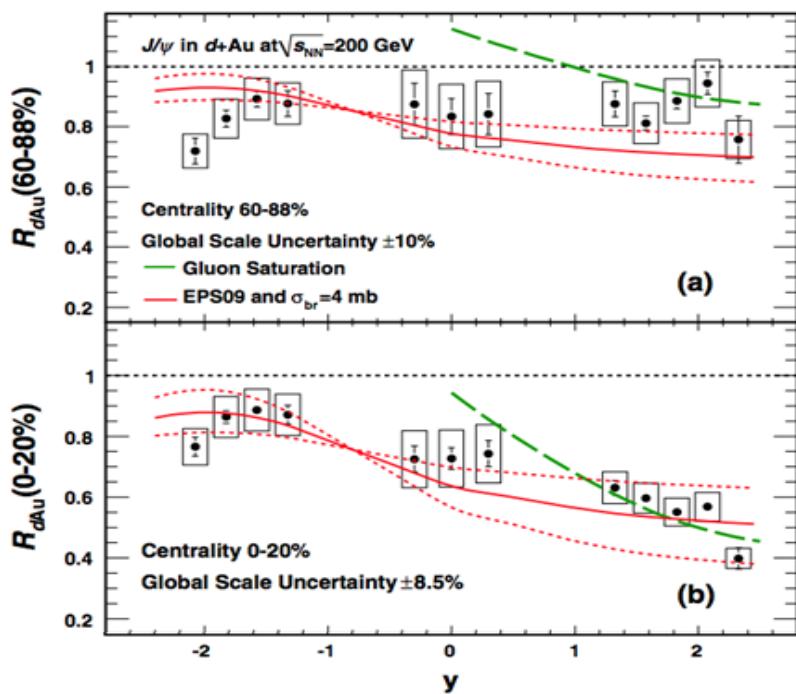
ALICE,
EPJC 74 (2014) 2974



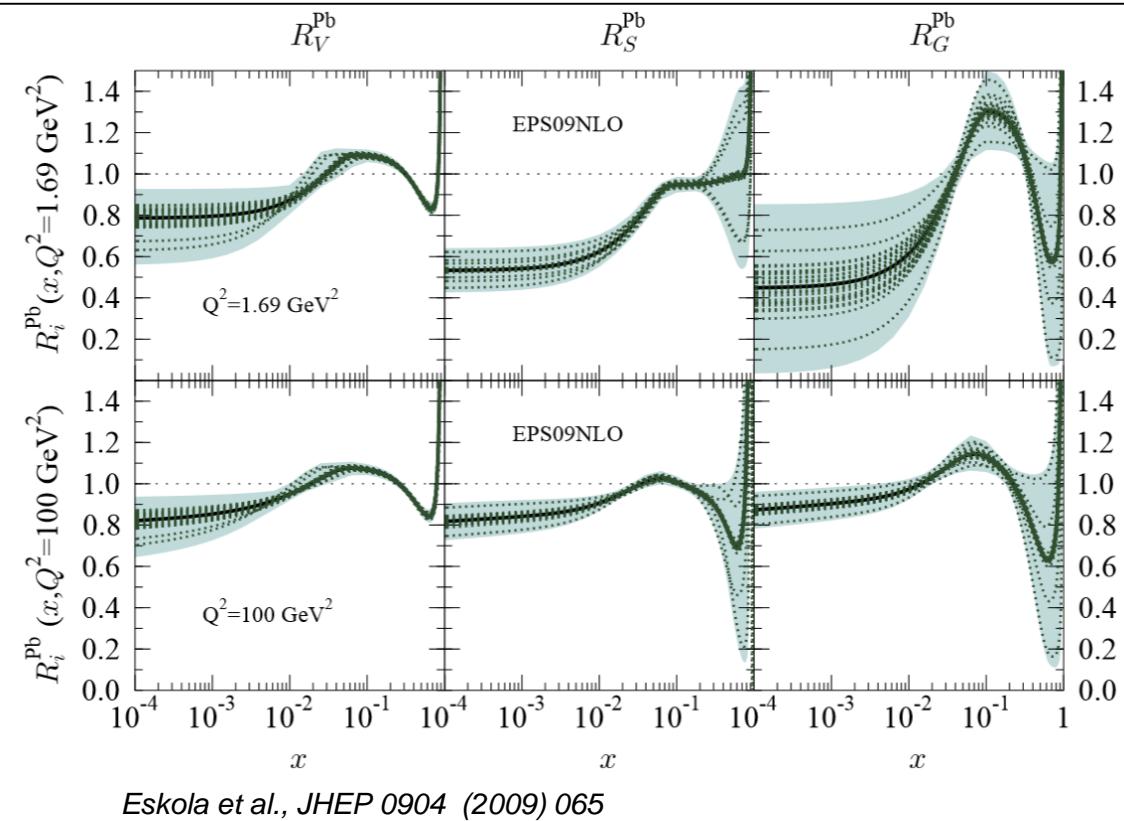
Production in p-Pb collisions

p-Pb collisions give access to the study of cold nuclear matter effects:

- nuclear PDFs (shadowing + anti-shadowing)
- gluon saturation, Colour Glass Condensate
- energy loss
- nuclear absorption and break-up
- interaction with comovers
- collective effects?



PHENIX, PRL 107 (2011) 142301

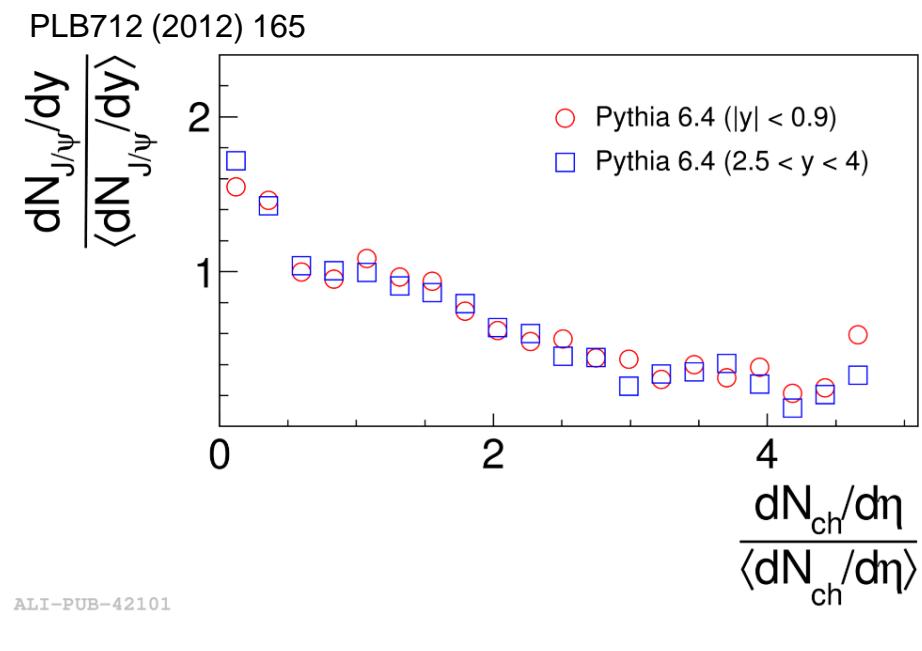
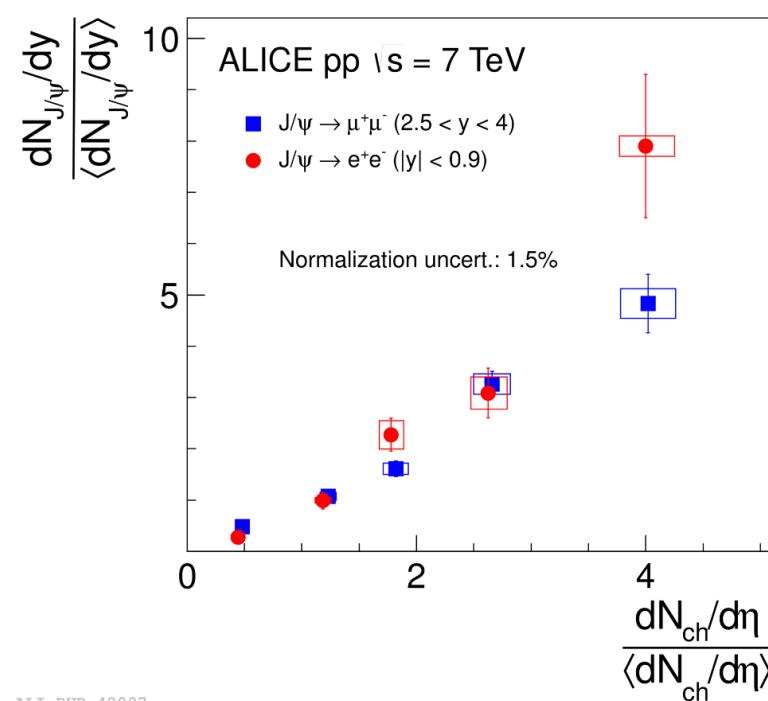


- Reference for Pb-Pb studies
→ are nuclear modifications observed in Pb-Pb collisions due to Quark Gluon Plasma?

Production as a function of multiplicity

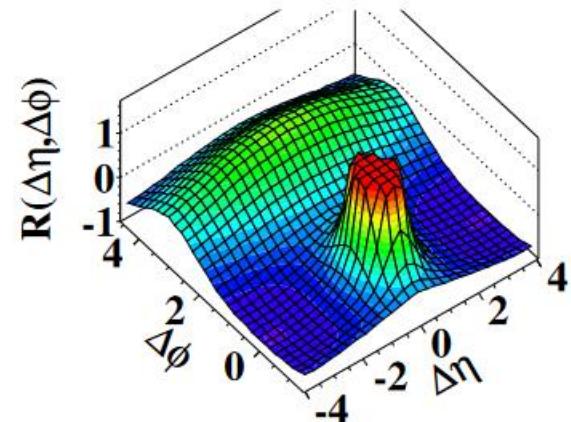
The measurement of quarkonium production as a function of event multiplicity allows one to study the **interplay between hard and soft scale of QCD**

- Run-I: yield increases with mult., not predicted by evt generators
- role of **multi-parton interactions** (MPI)?



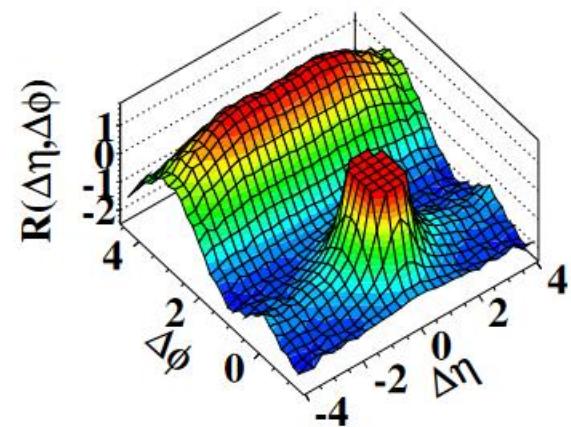
- **collective effects** in high-multiplicity pp and p-Pb collisions?

(b) CMS MinBias, $1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$



CMS, JHEP 2010 (091)

(d) CMS $N \geq 110$, $1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$



Quarkonium detection in ALICE

The ALICE experiment

Central Barrel $|\eta| < 0.9$

Solenoidal magnet

Time Projection Chamber:

- tracking
- PID via dE/dx

Inner Tracking System

(Silicon Pixel, Drift, Strip Detectors)

- vertexing, tracking
- triggering (SPD)

Time Of Flight MRPCs

- PID

T0 (Cherenkov counters)

- luminosity

V0 scintillators

- triggering
- luminosity

Transition Radiation Detector

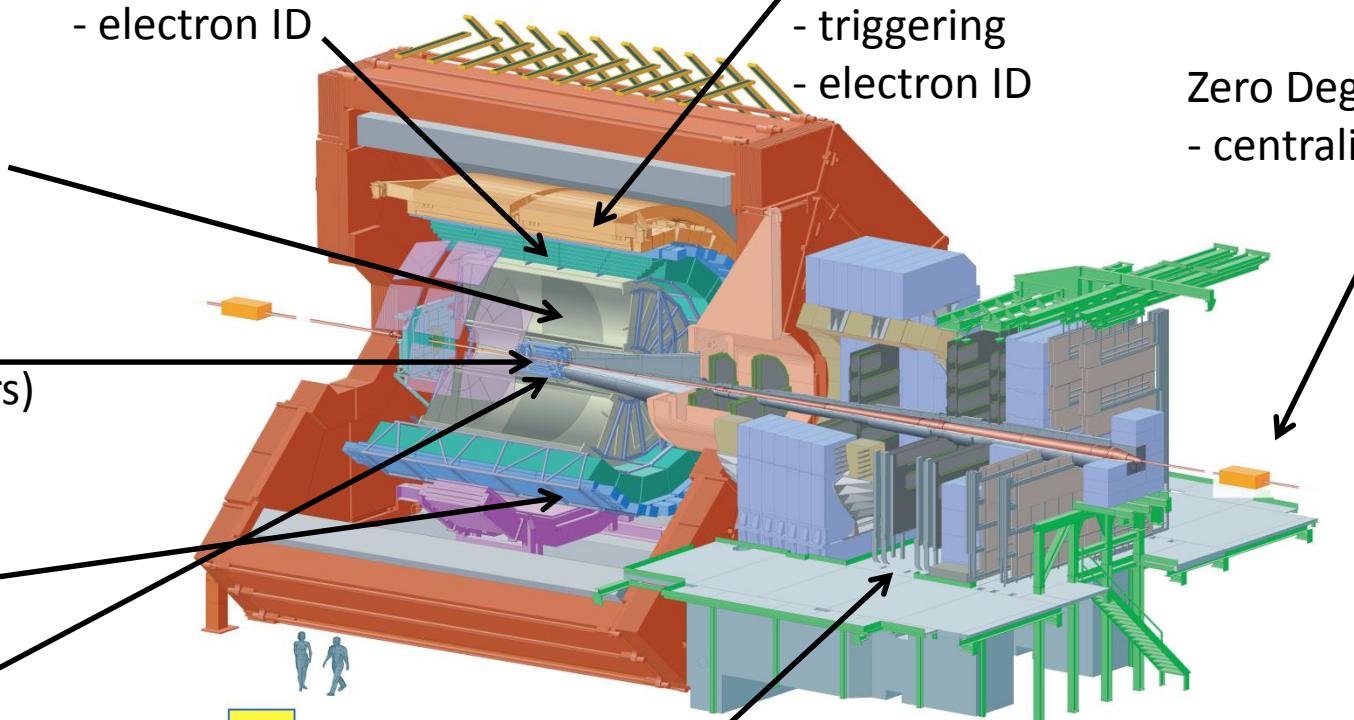
- electron ID

ElectroMagnetic Calorimeter (EMCal)

- triggering
- electron ID

Zero Degree Calorimeters

- centrality in p-Pb



Muon spectrometer $-4 < \eta < -2.5$

Dipole magnet

Front absorber $10 \lambda_l$

10 tracking planes (Cathode Pad Chambers)

4 trigger planes (Resistive Plate Chambers)

Muon filter ($7 \lambda_l$)

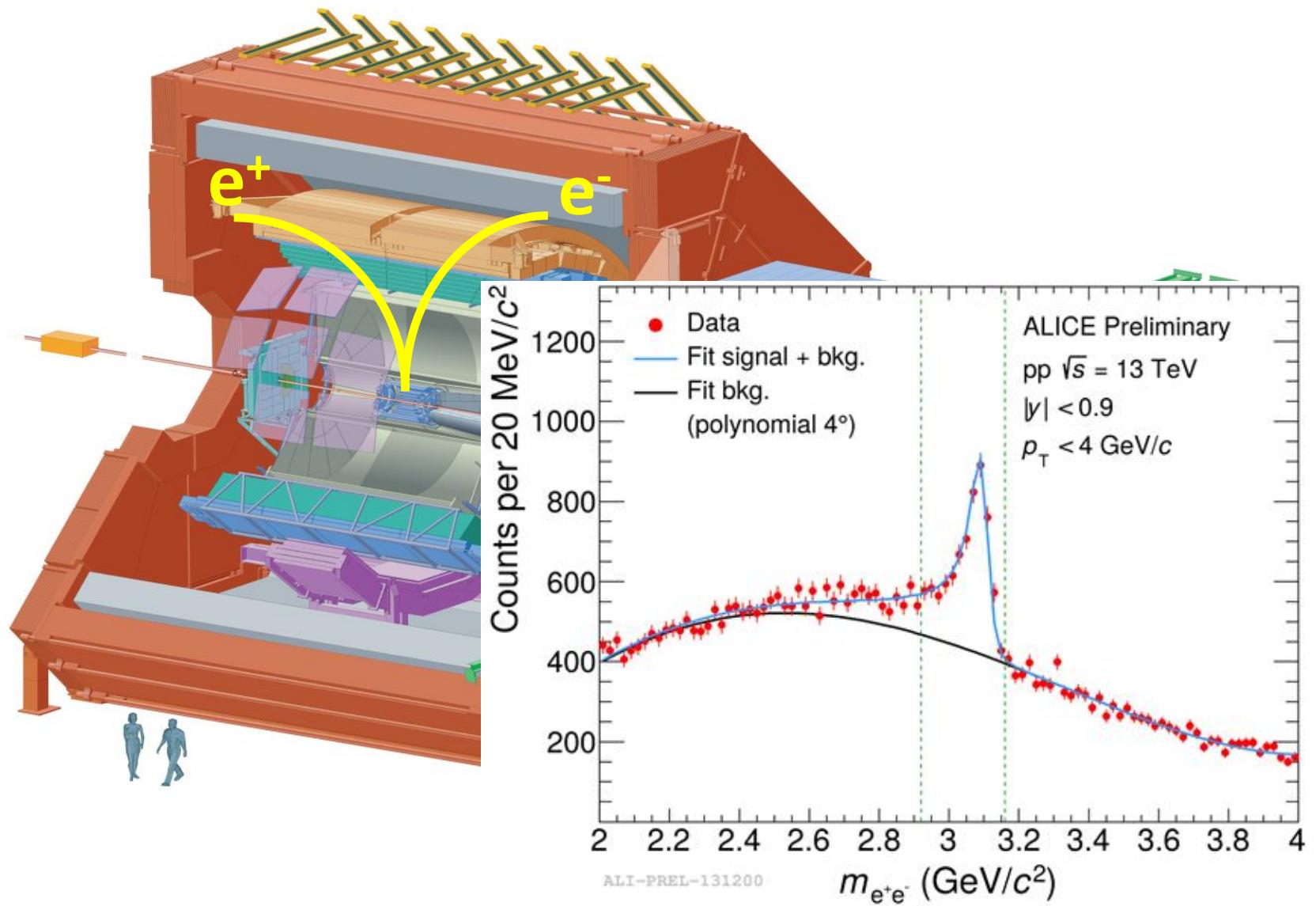
(only detectors involved in quarkonium analyses are discussed here)

Techniques: $J/\psi \rightarrow e^+e^-$ at mid-rapidity

Mid-rapidity

$|y| < 0.9$

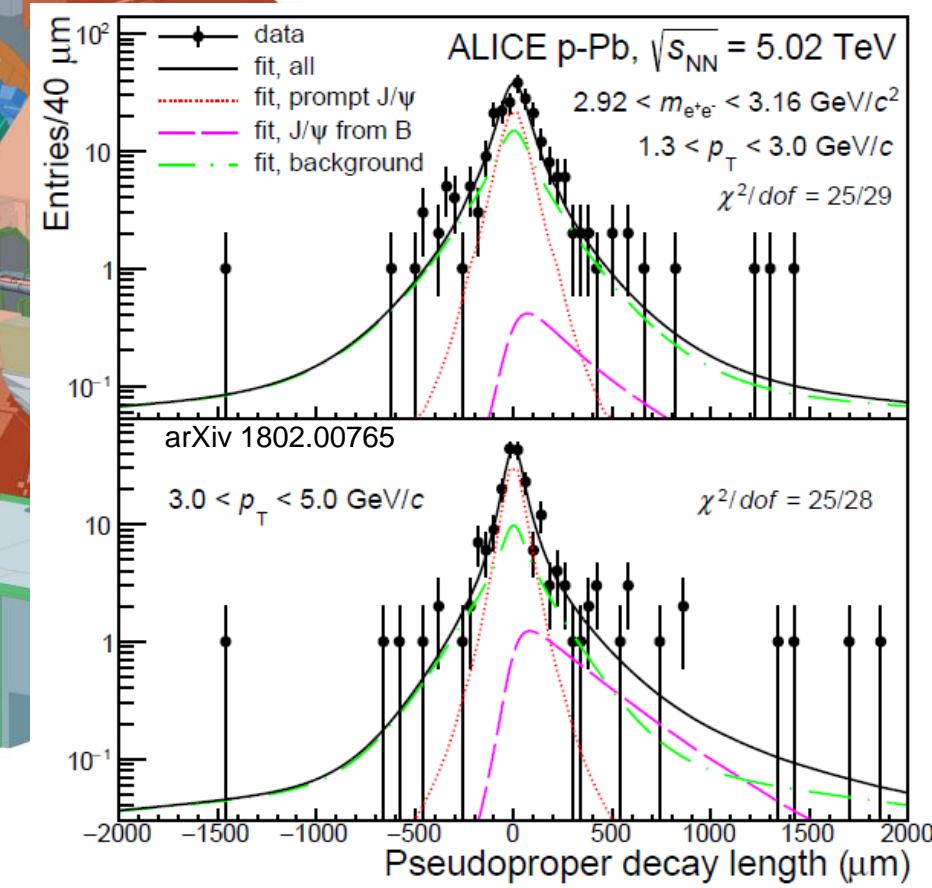
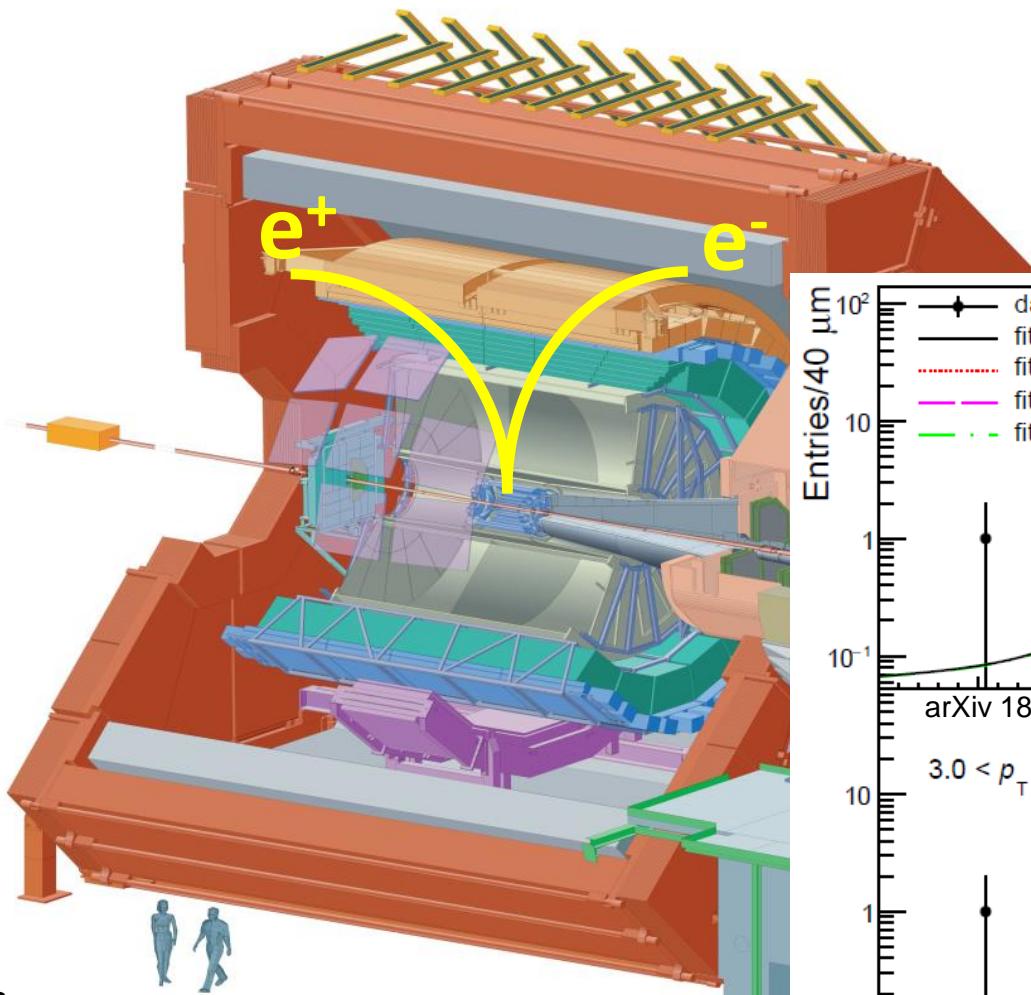
- Invariant mass spectrum of unlike-sign dielectrons
- Minimum-bias- and EMCAL-triggered samples
- Electron identification via dE/dx in the TPC and E/p in EMCAL
- Inclusive analysis:
 - acceptance down to $p_T = 0$



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Mid-rapidity
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- Minimum-bias- and EMCAL-triggered samples
- Electron identification via dE/dx in the TPC and E/p in EMCAL
- Inclusive analysis:
 - acceptance down to $p_T = 0$
- Prompt-non prompt separation:
 - Simultaneous fit to inv. mass and **pseudo-proper decay length**: separate prompt J/ψ and $B \rightarrow J/\psi$
 - acceptance down to $p_T = 1.3 \text{ GeV}/c$ in p-Pb collisions



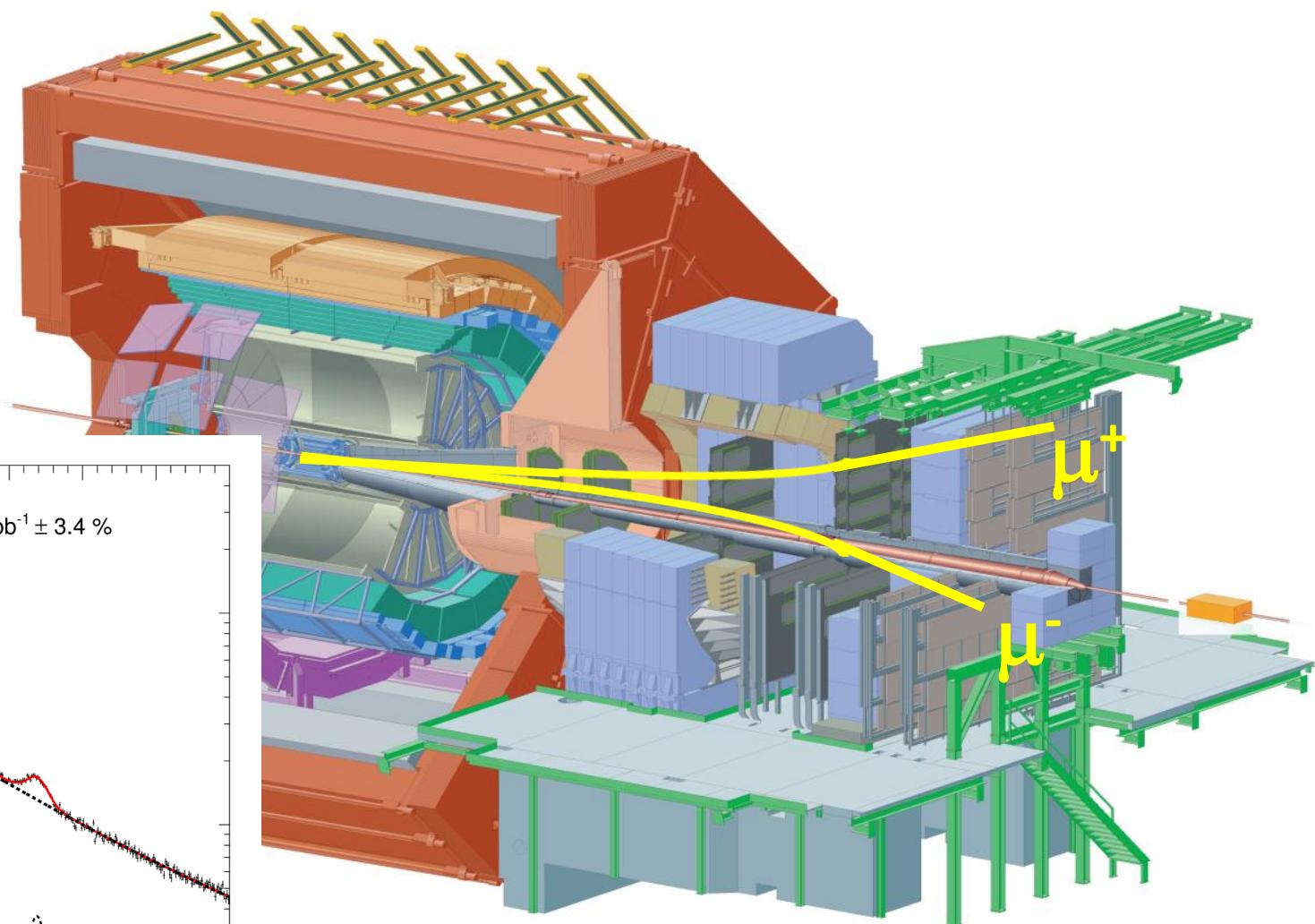
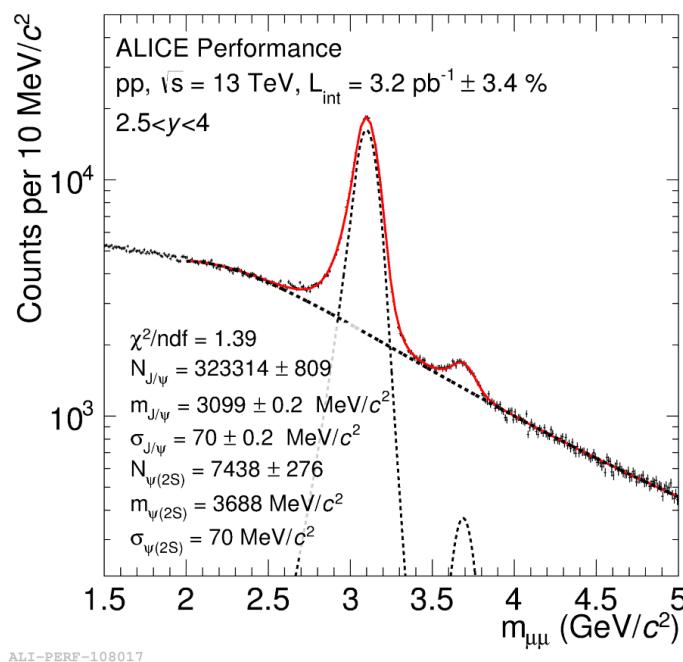
Techniques: Quarkonium $\rightarrow \mu^+\mu^-$ at forward rapidity

Forward rapidity

$2.5 < y < 4$

Invariant mass spectrum
of unlike-sign dimuons

- Di-muon triggered sample
- Matching with trigger chambers (downstream of an iron filter) for muon-ID
- Inclusive analysis, acceptance down to $p_T = 0$ for: J/ψ , $\psi(2S)$



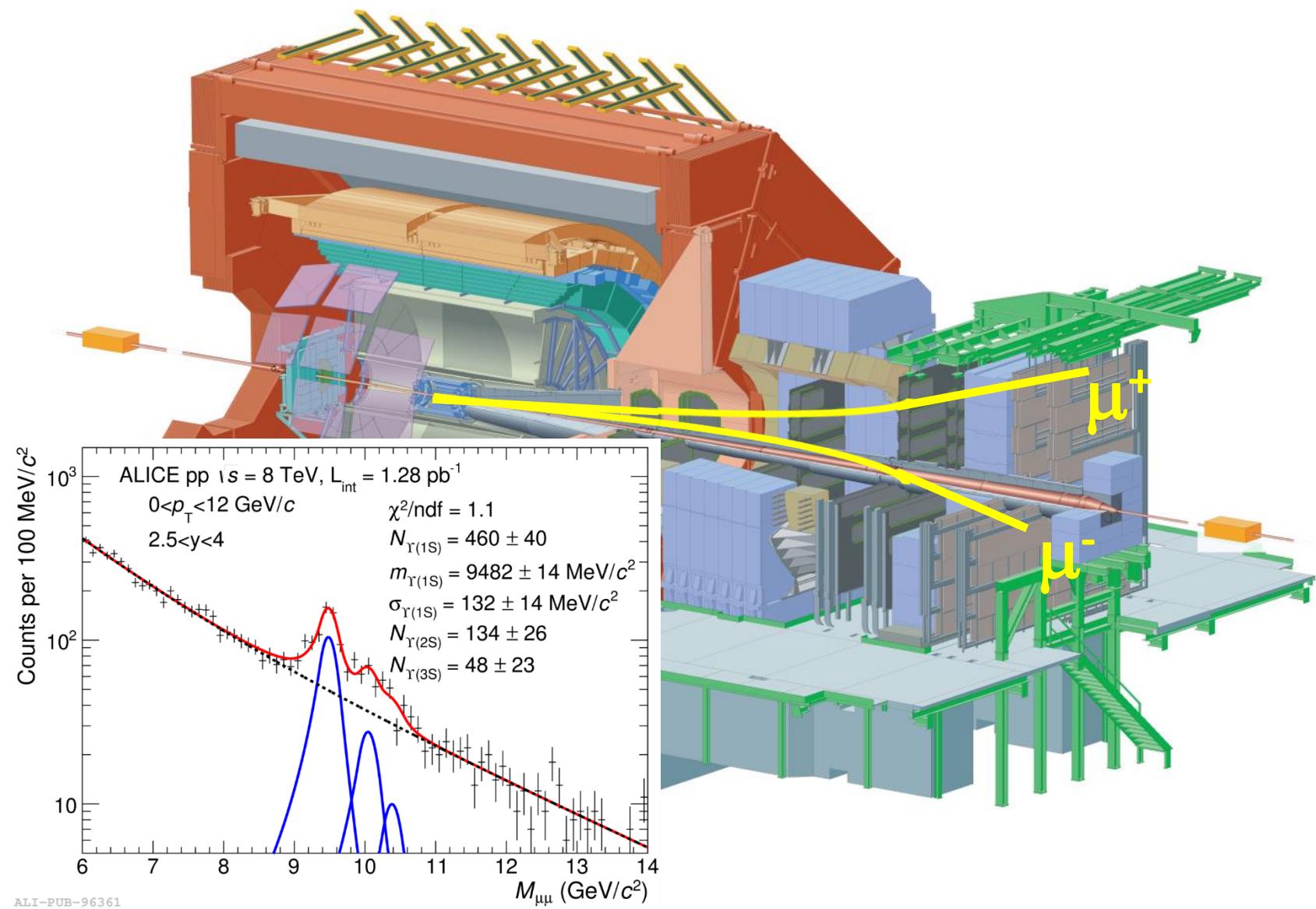
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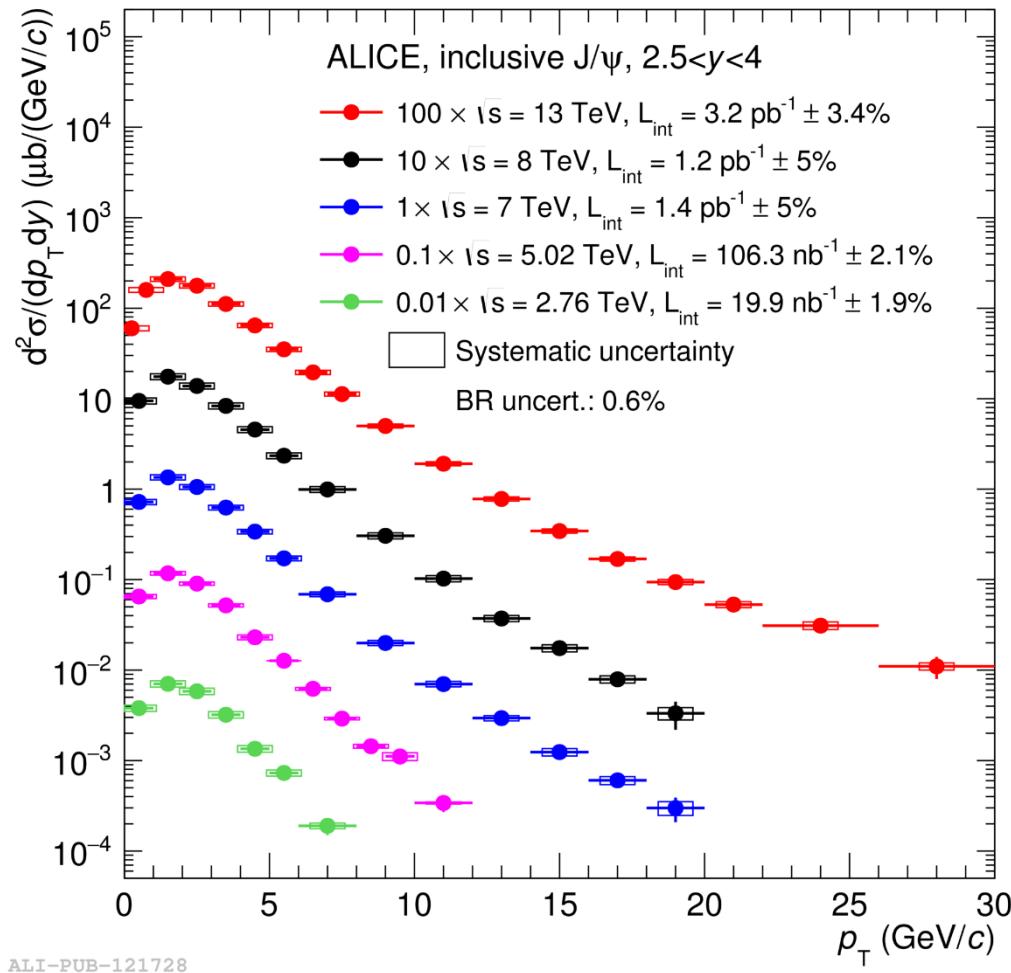
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 J/ψ , $\psi(2S)$
 Υ states



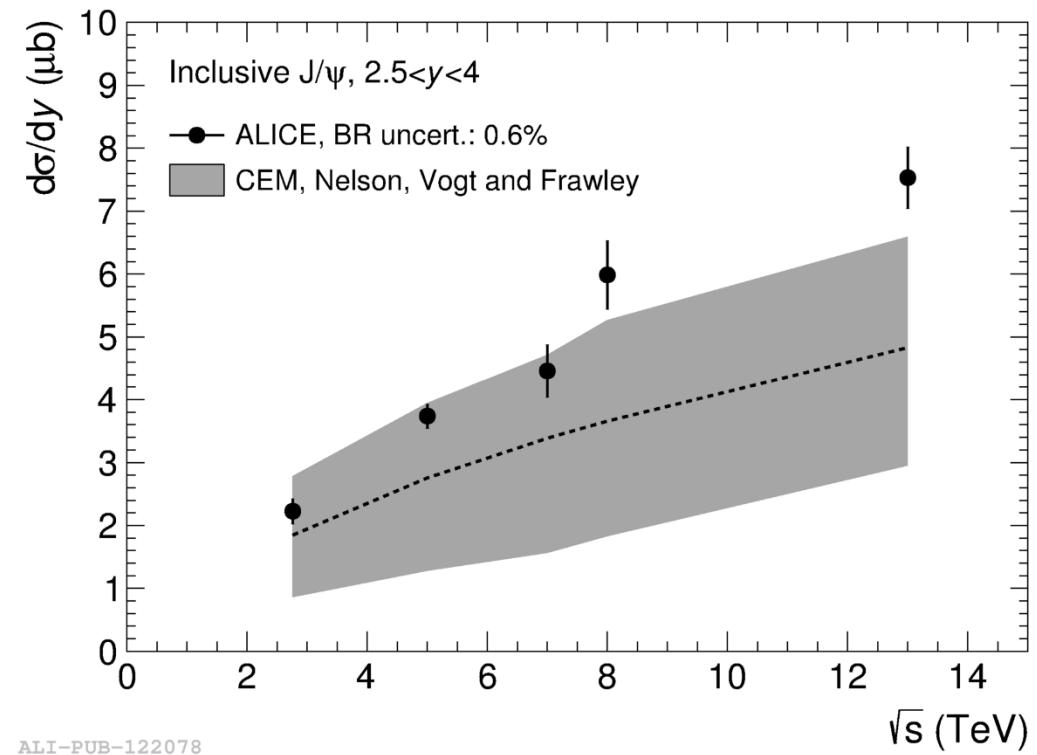
Recent results from pp collisions

Energy dependence of J/ ψ production

Eur. Phys. J. C (2017) 77



- Cross section measured for **five different energies**, with increasing luminosity and p_T -reach
- Spectra become harder with increasing energy

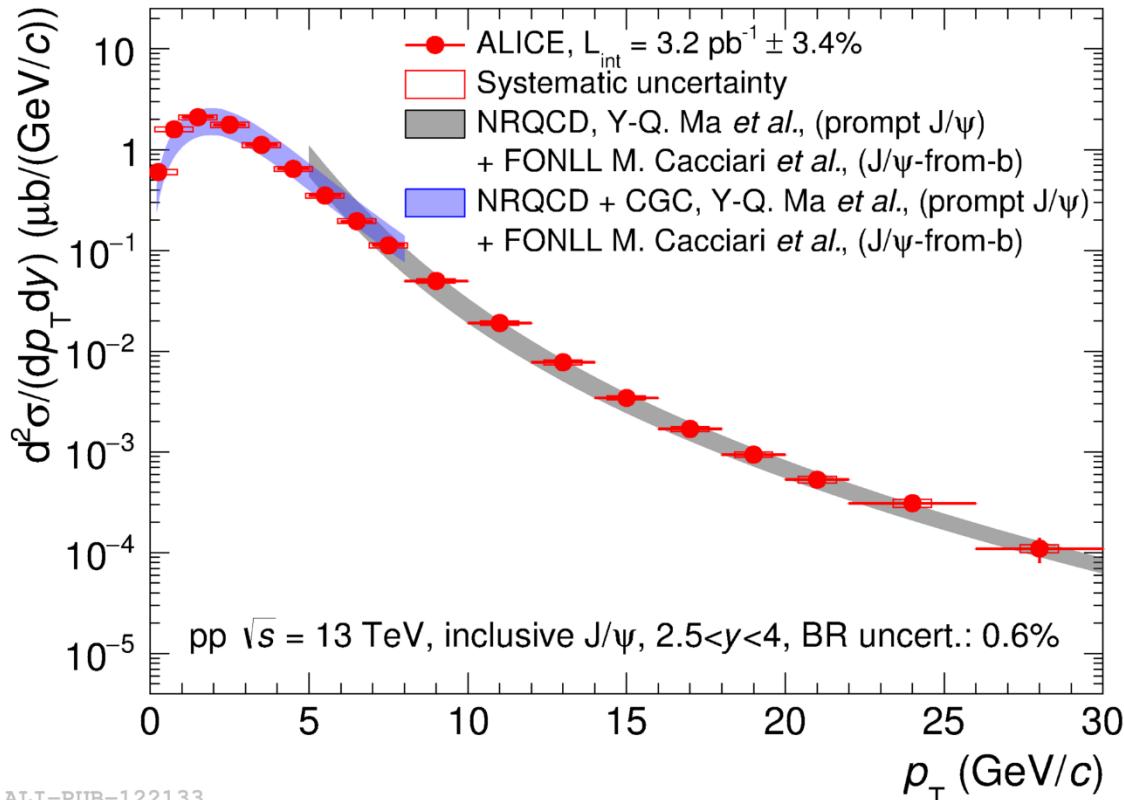


- p_T -integrated **cross section vs energy** sits on the **upper side** of a CEM calculation

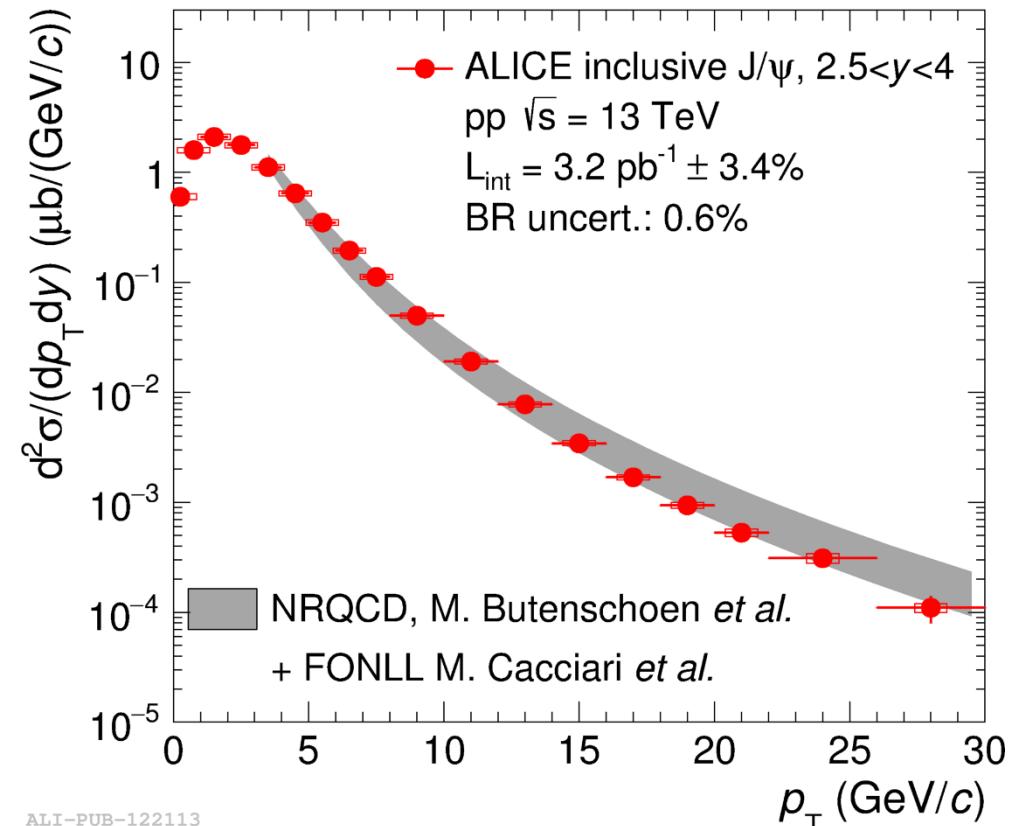
$\sqrt{s} = 2.76 \text{ TeV}$ PLB 718 (2012) 295 $\sqrt{s} = 5.02 \text{ TeV}$ PLB 766 (2017) 212
 $\sqrt{s} = 7 \text{ TeV}$ EPJC 74 (2014) 2974 $\sqrt{s} = 8 \text{ TeV}$ EPJC 76 (2016) 184

Model comparison for J/ ψ (pp 13 TeV)

Eur. Phys. J. C (2017) 77



ALI-PUB-122133

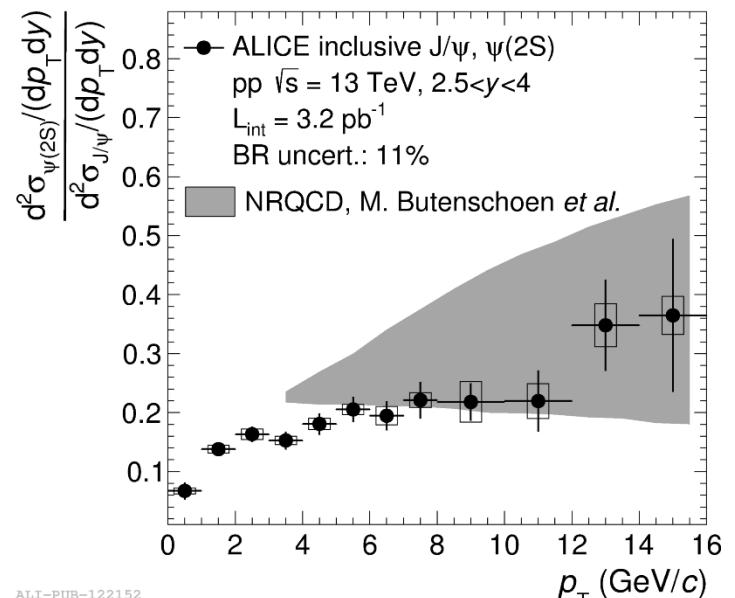
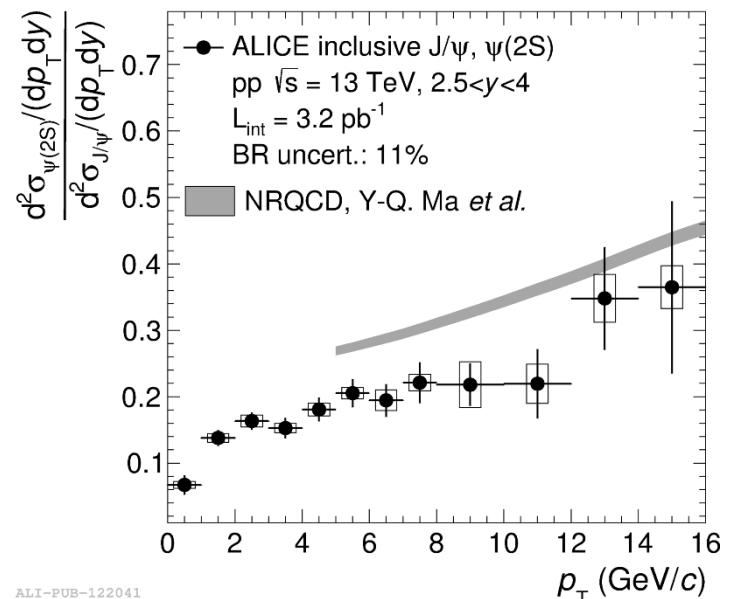
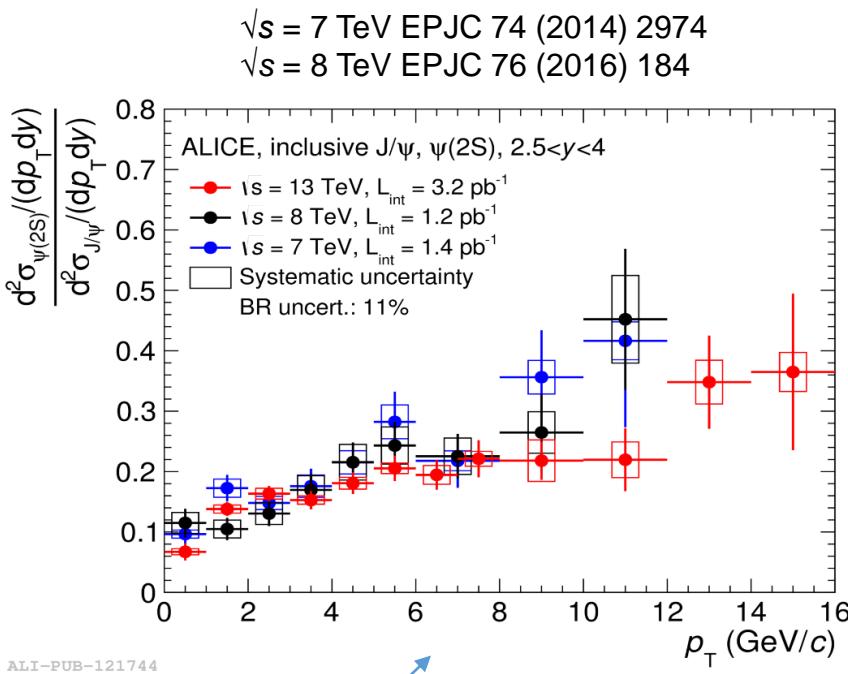
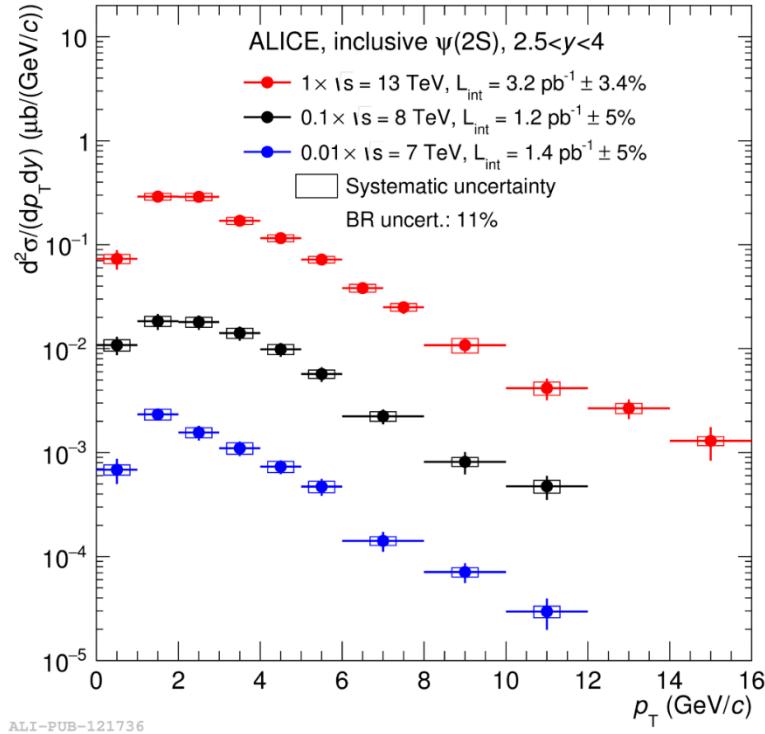


ALI-PUB-122113

- pQCD calculations for non-prompt J/ψ are added to the NRQCD and compared to the inclusive measurement
- The **two NRQCD calculations** differ in the set of LDME that is used, the p_T at which fits are performed and the used datasets
- **CGC calculations** extend the prediction range to $p_T = 0$
- **Fair agreement** with both calculations

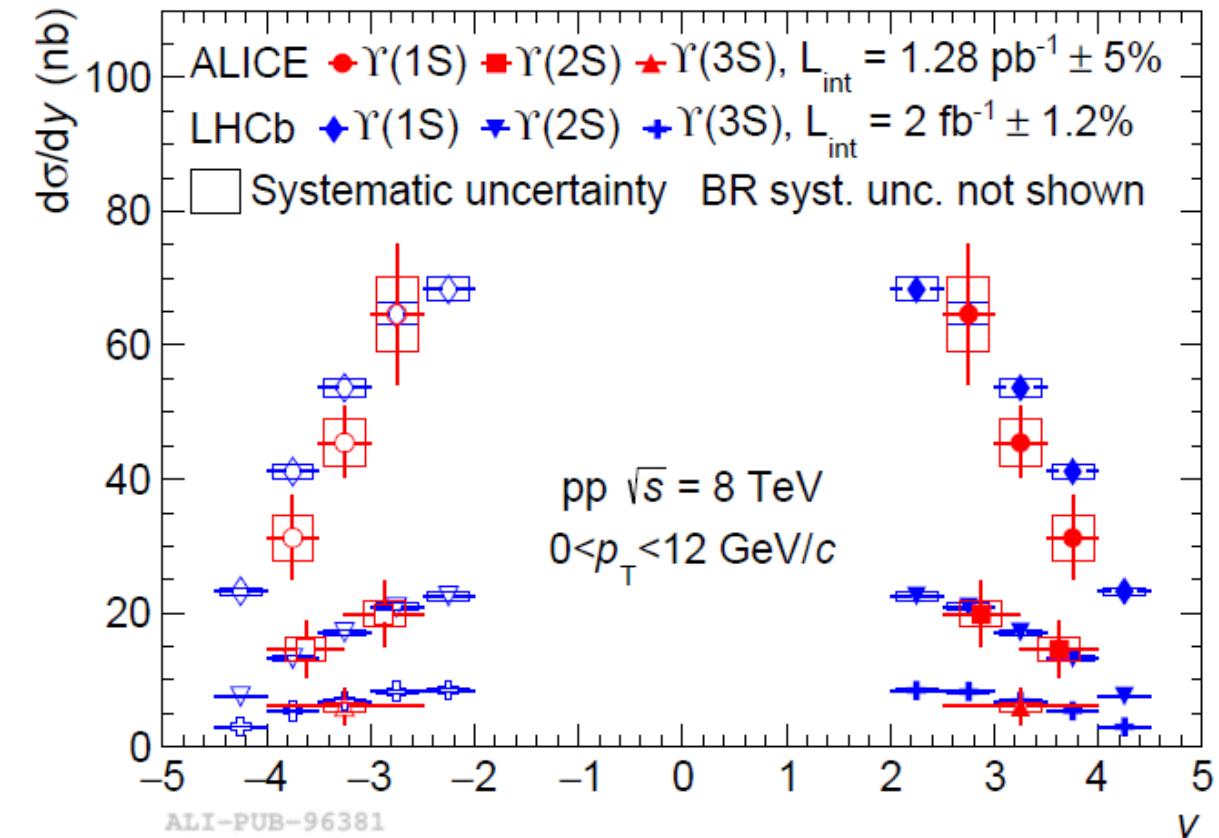
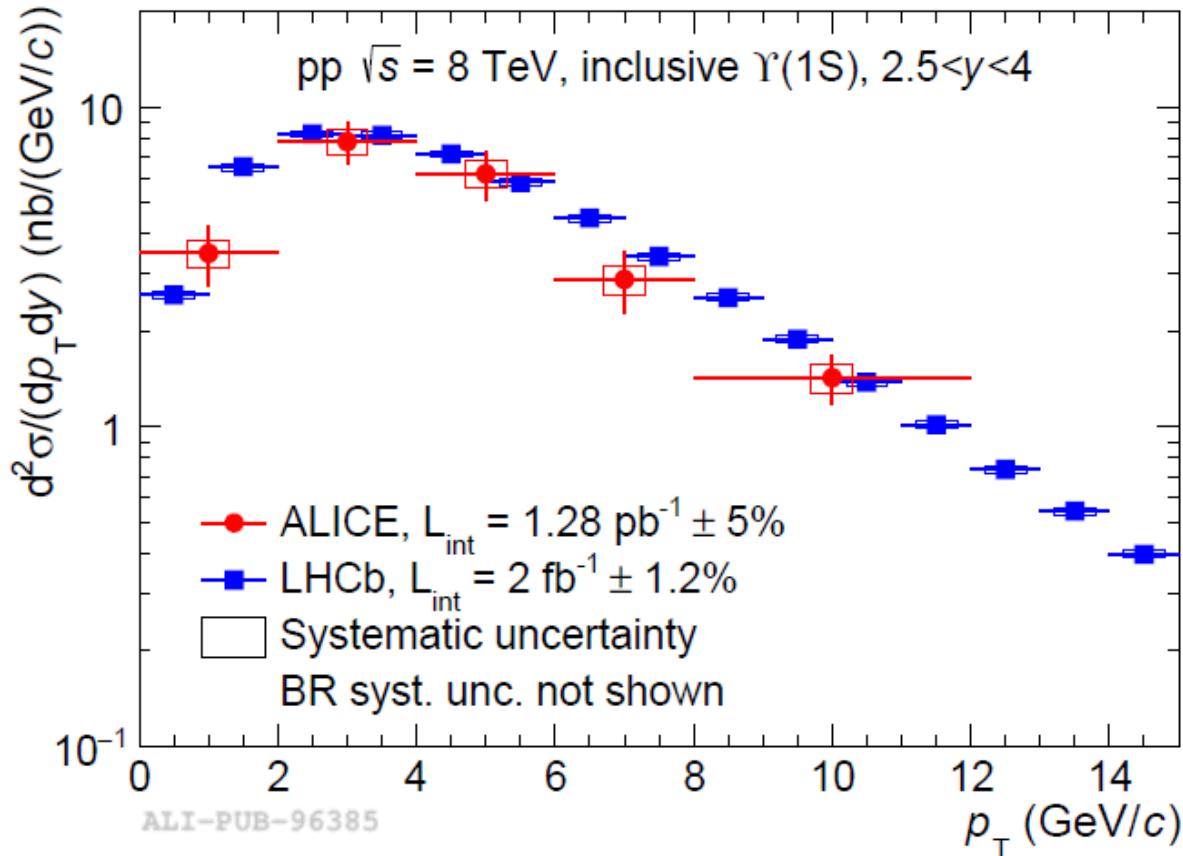
$\psi(2S)$ production

Eur. Phys. J. C (2017) 77



- No evidence for energy dependence of $\psi(2S) / \psi$ ratio
- Some theoretical uncertainties cancel in the $\psi(2S)/\psi$ ratio
- some tension with data for one of the two NRQCD calculations

Bottomonium cross section at $\sqrt{s} = 8$ TeV



- Fair agreement with LHCb results:
($< 1.2 \sigma$ integrated, $< 1.5 \sigma$ differential)
- Run II results ($\sqrt{s} = 13$ TeV) coming soon!

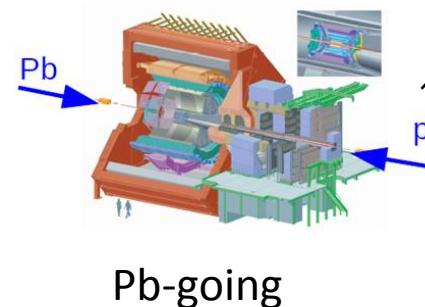
ALICE, EPJC 76 (2016) 184
LHCb, JHEP 1511 (2015) 103

Recent results from p-Pb collisions

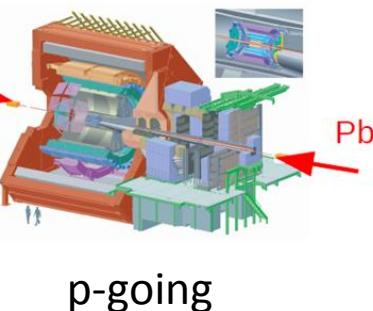
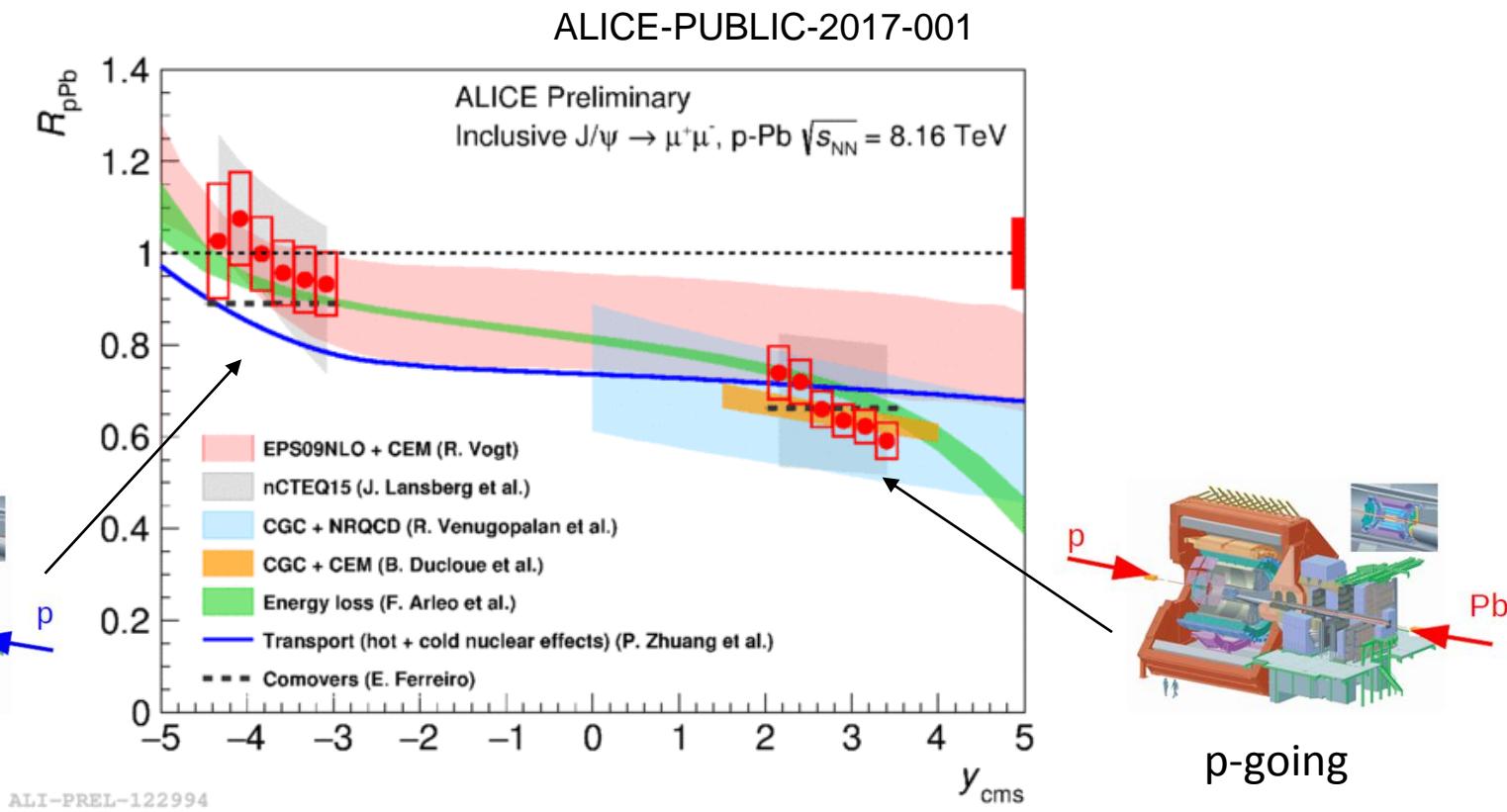
J/ψ nuclear modification factor in Run-II p-Pb ($\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$)

Nuclear modification factor:

$$R_{\text{pPb}} = \frac{\text{Yield per event in p-Pb}}{(\text{Yield per event in pp}) \times \langle N_{\text{collisions}} \rangle}$$



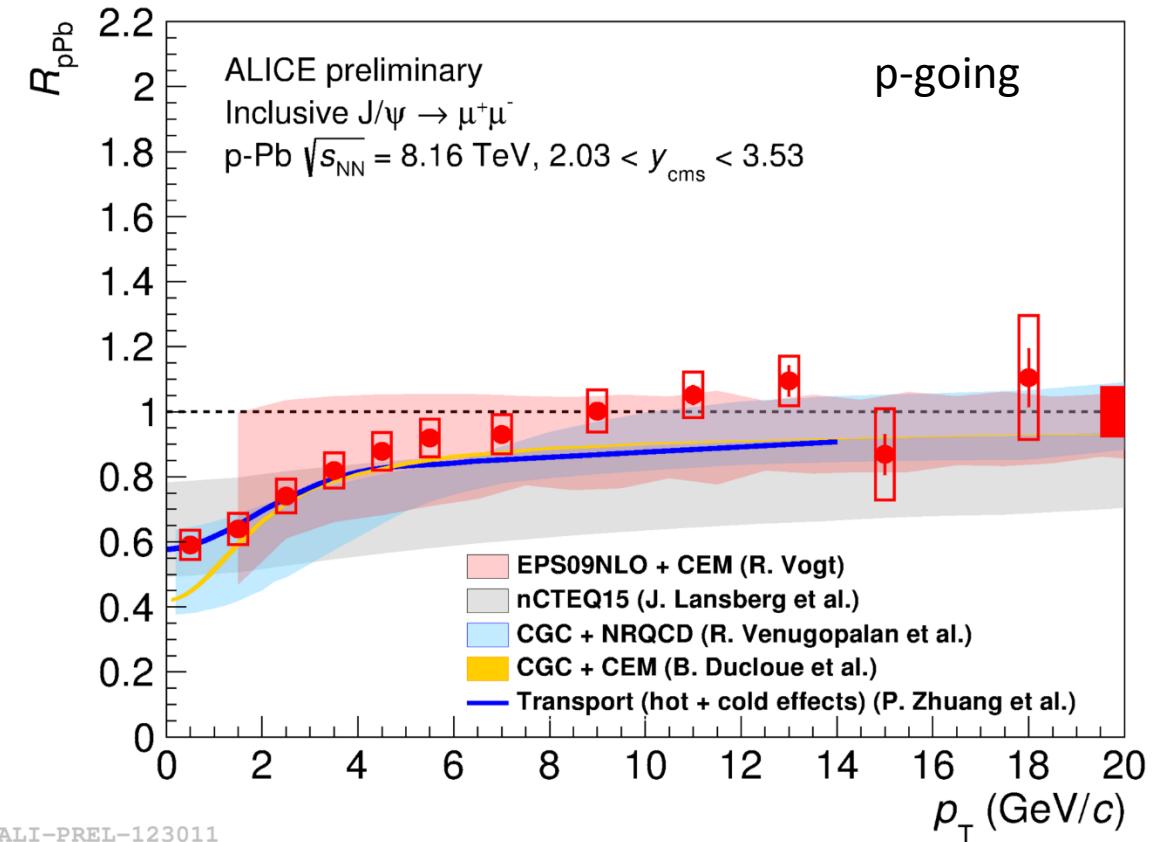
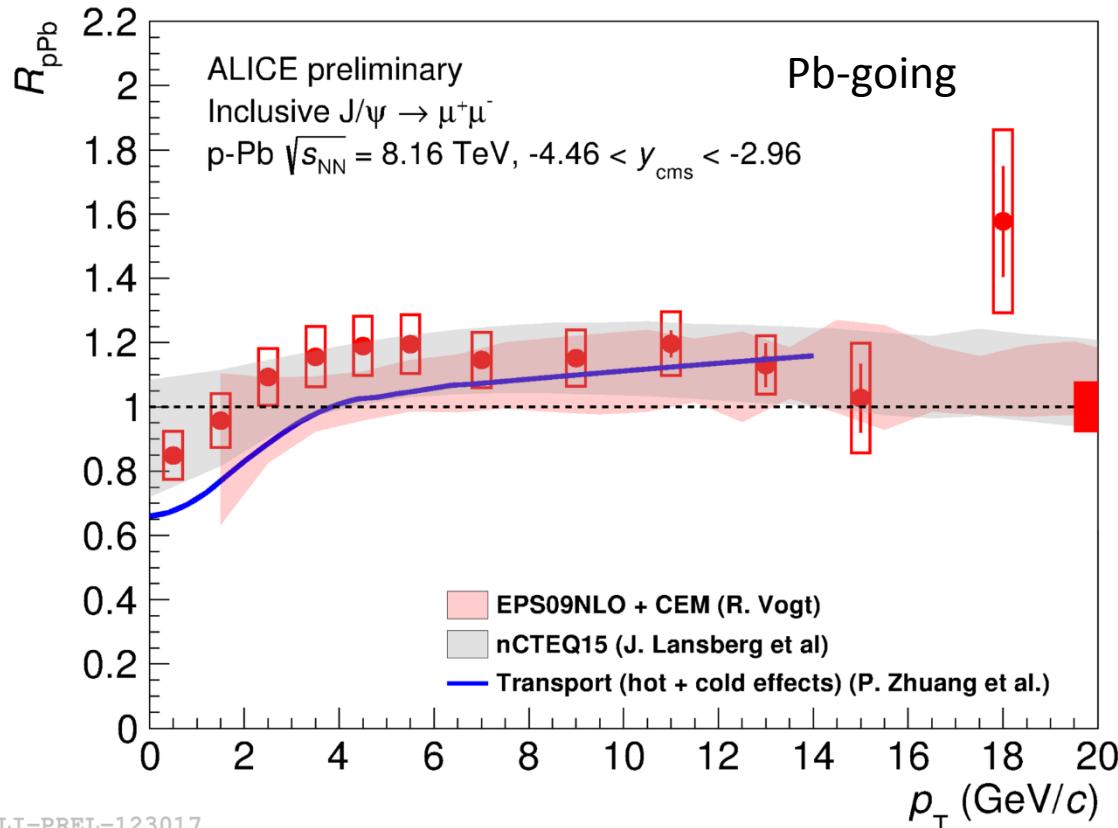
Pb-going



p-going

- Good agreement between data and models based on shadowing and/or energy loss, as observed in Run-I ($\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$)
- Size of theoretical uncertainties (mainly shadowing) still limits a more quantitative comparison

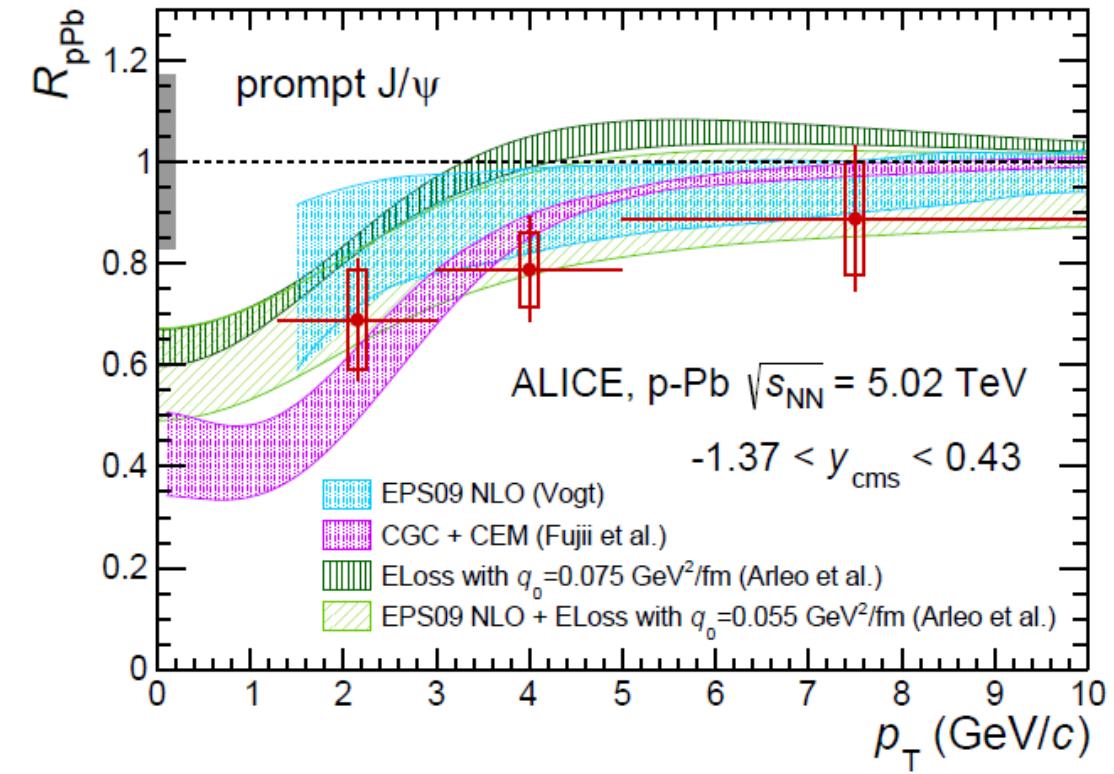
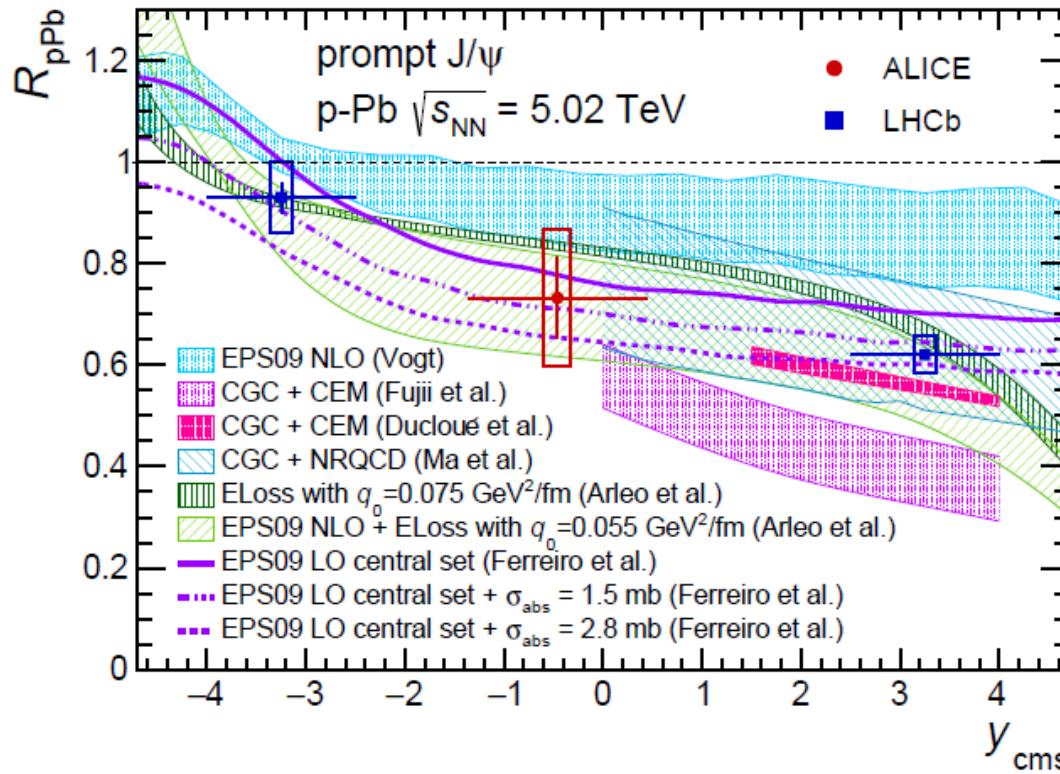
J/ ψ nuclear modification factor vs p_T ($\sqrt{s_{NN}} = 8.16$ TeV)



- Good agreement between data and models based on shadowing and/or energy loss, as observed in Run-I ($\sqrt{s_{NN}} = 5.02$ TeV)
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Prompt J/ ψ nuclear modification factor ($\sqrt{s_{NN}} = 5.02$ TeV)

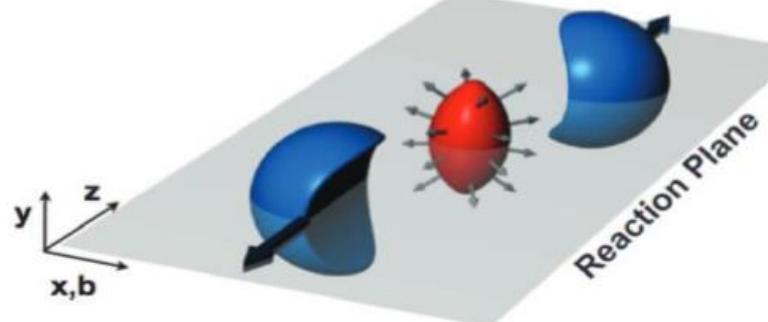
arXiv 1802.00765



- Measurement performed at mid-rapidity with Run-I data
- Indicates suppression at low p_T
- Trends with p_T and y qualitatively reproduced by models including shadowing, gluon saturation, energy loss, nuclear absorption
- Can not discriminate among them with the present uncertainties

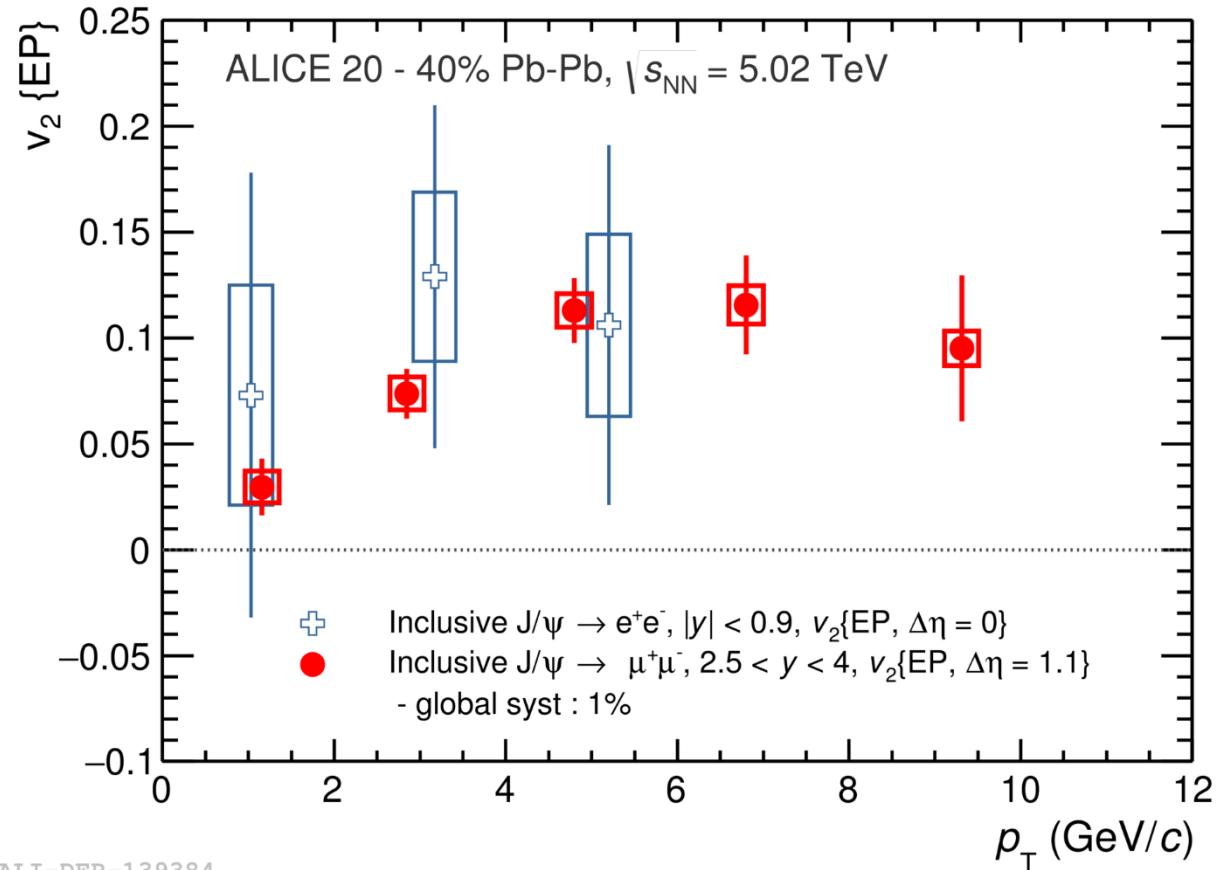
Azimuthal anisotropy (v_2) of J/ ψ production

$$v_2 = \langle \cos 2(\phi_{\text{particle}} - \Psi_{\text{EP}}) \rangle$$

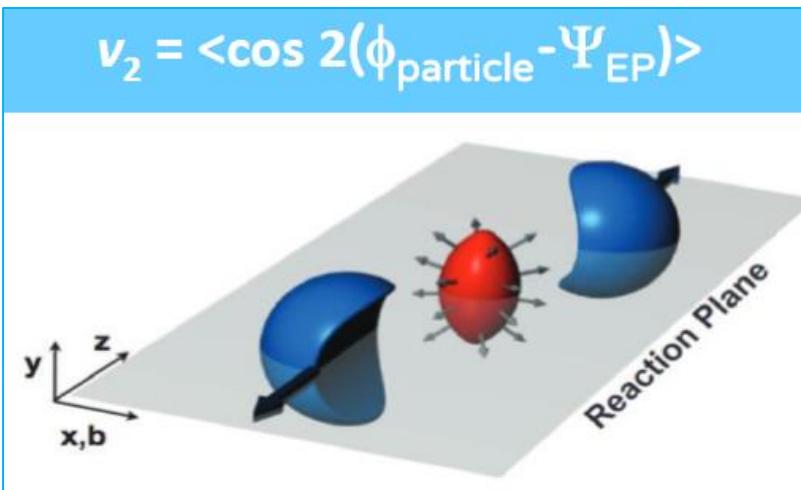


- In a strongly interacting medium, pressure gradients convert any initial **spatial anisotropy** into a **momentum anisotropy**
- Anisotropy is **quantified by the 2nd order coefficient v_2** of the Fourier expansion of the particle azimuthal angle distribution
- In the analysis of Pb-Pb collisions, **non-zero J/ ψ v_2** is regarded as a measure of the charm quark **participation in the collective expansion** of the system

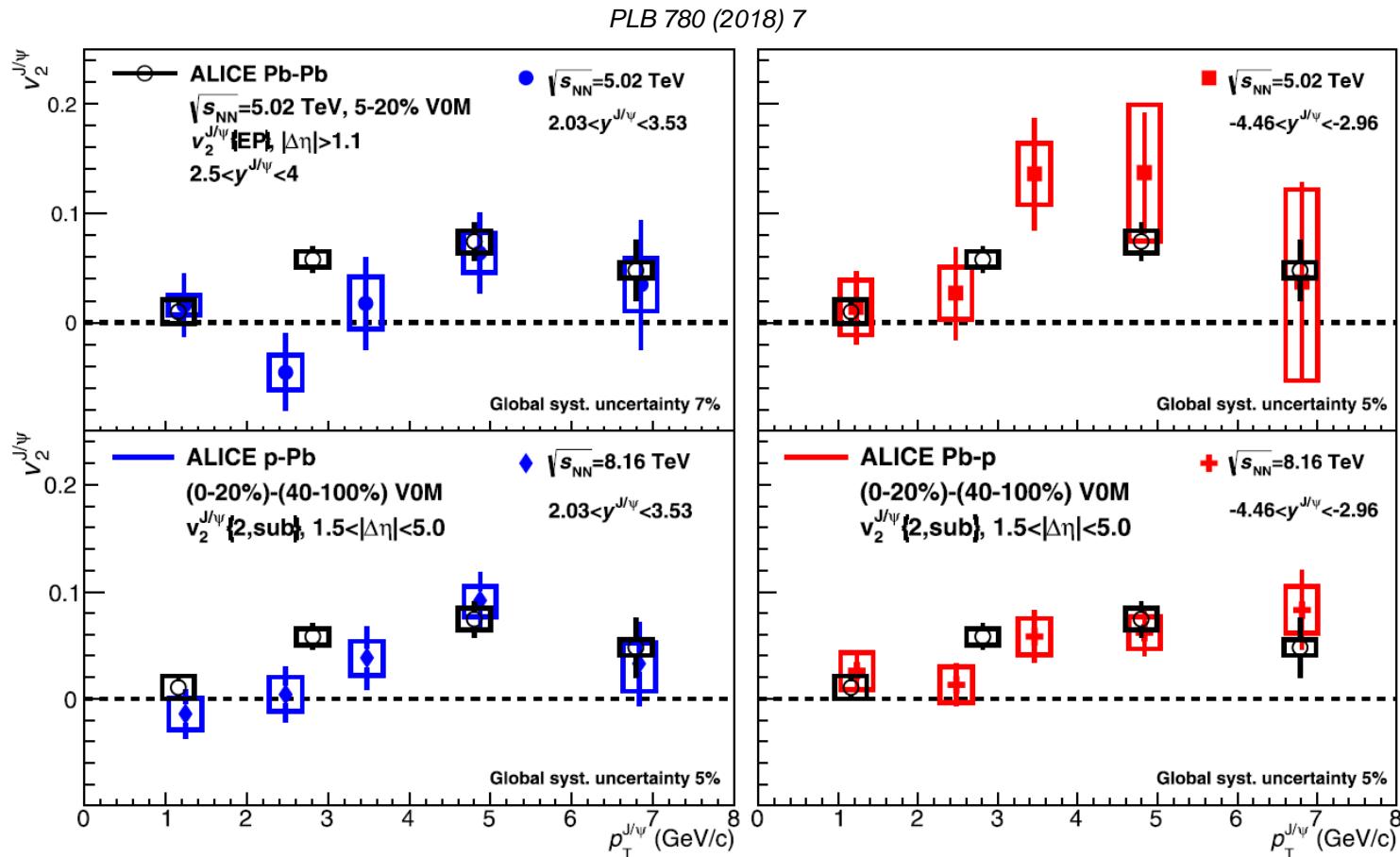
Derived from PRL 119, 242301



Azimuthal anisotropy (v_2) of J/ ψ production in p-Pb

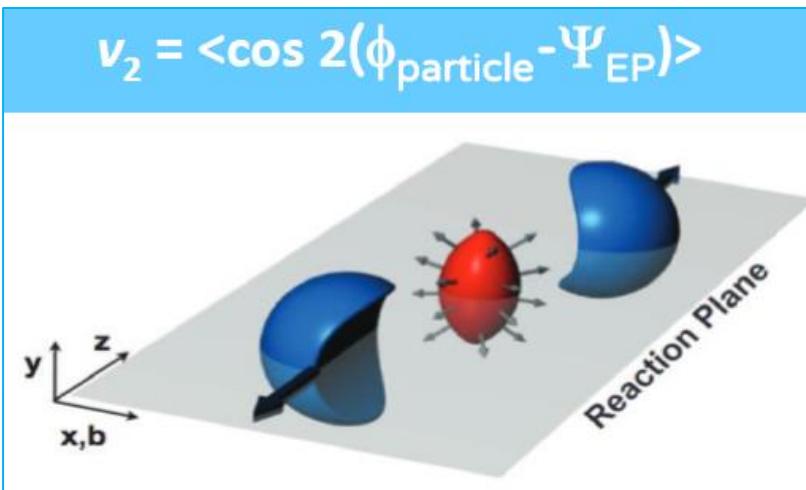


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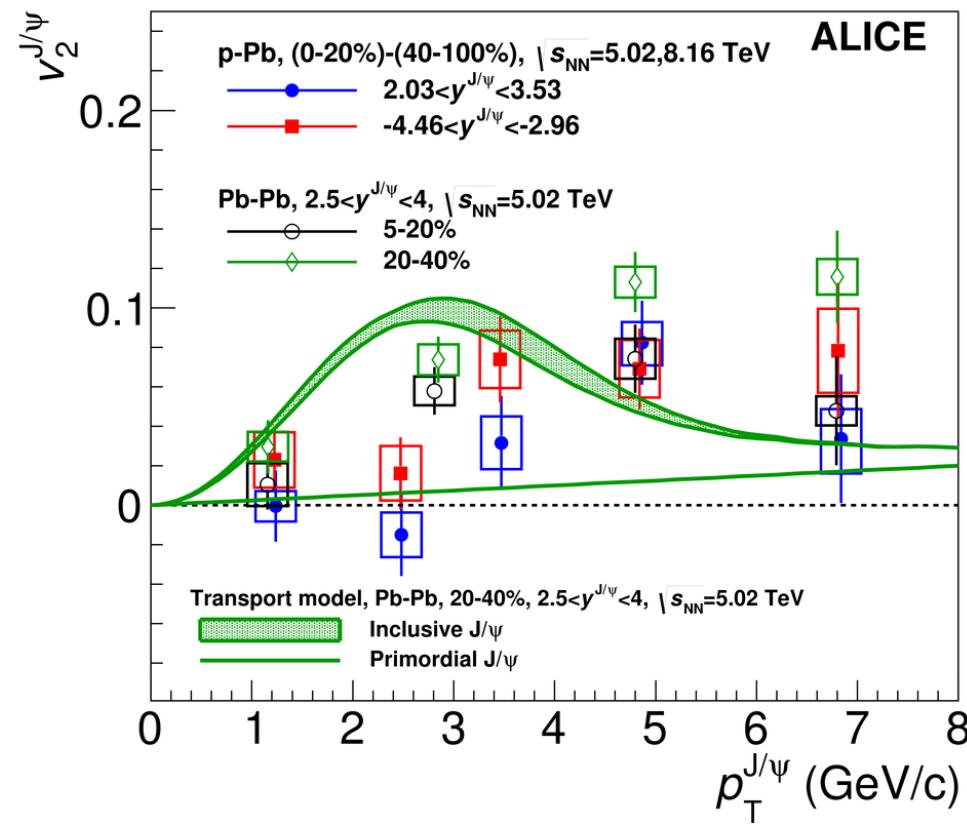
Observation of non-zero v_2 in p-Pb for $p_T > 3$ GeV/c!

Azimuthal anisotropy (v_2) of J/ ψ production in p-Pb



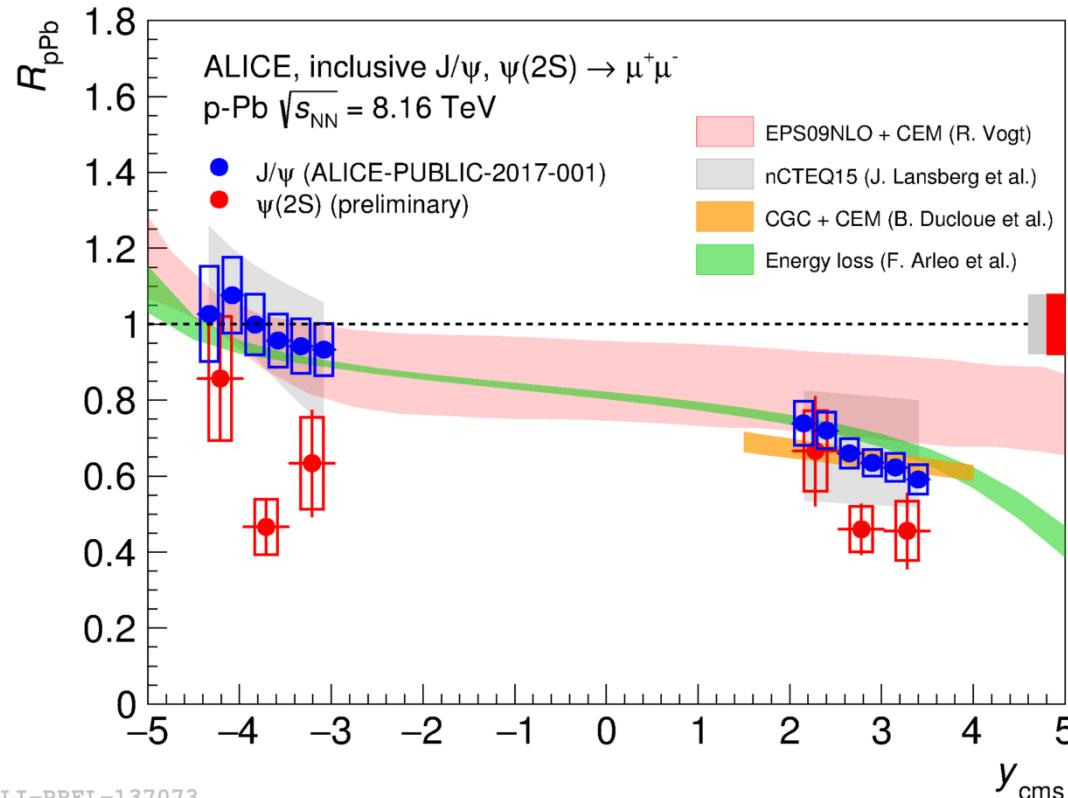
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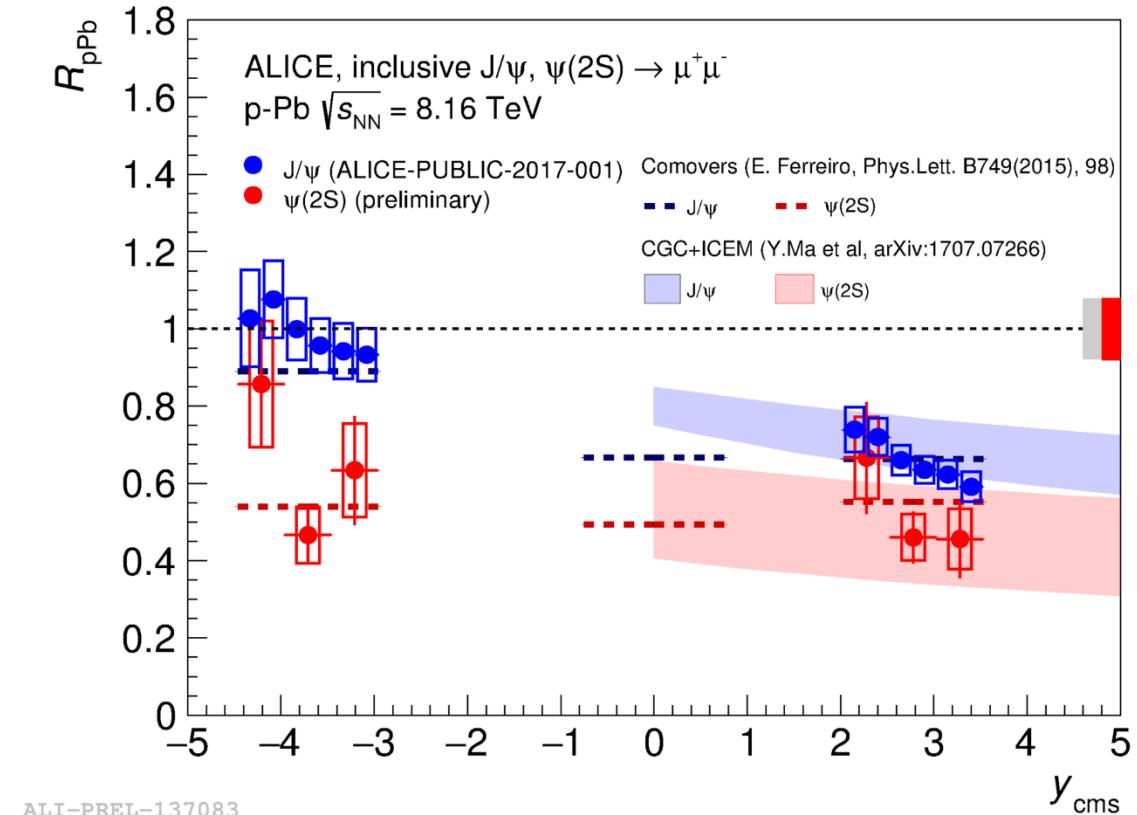
Observation of non-zero v_2 in p-Pb for $p_T > 3$ GeV/c!
 Total significance (forward + backward, 5.02+8.16 TeV) $\sim 5\sigma$
 Values are similar to Pb-Pb:
 common mechanism at the origin of the J/ ψ v_2 ?

$\psi(2S)$ nuclear modification factor ($\sqrt{s_{NN}} = 8.16$ TeV)



ALI-PREL-137073

- Larger suppression of Pb-going $\psi(2S)$ wrt J/ψ
- Shadowing and energy-loss predict similar effects



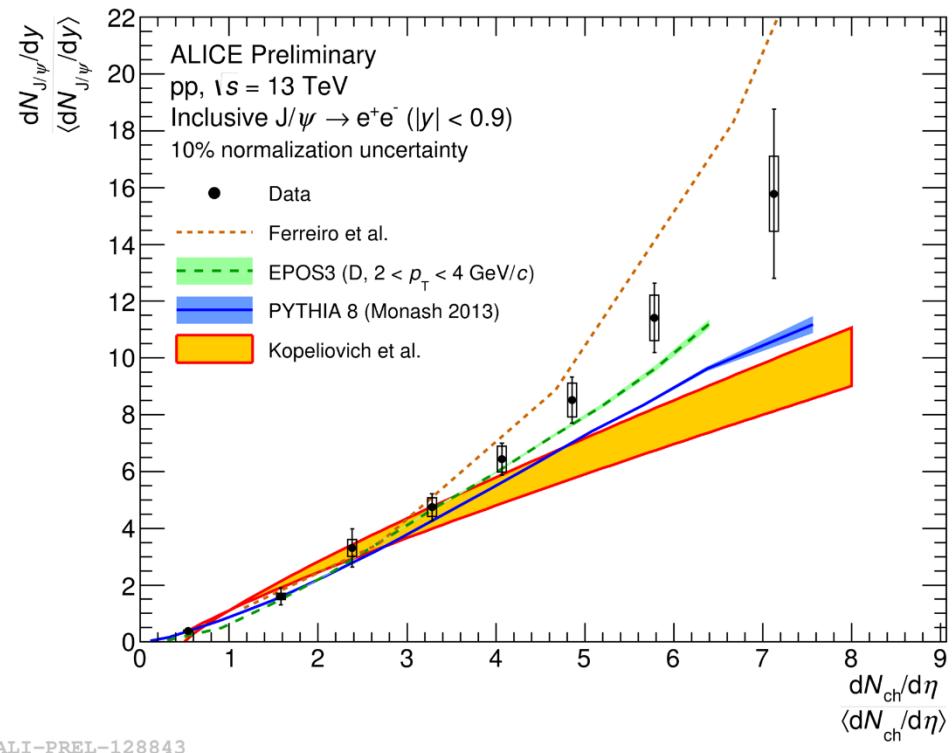
ALI-PREL-137083

Need final state effects!

-
- soft color exchanges between hadronizing c-cbar and co-moving partons (Ma and Venugopalan)
 - “classical” comover model, with break-up cross section tuned on low-energy data (Ferreiro)

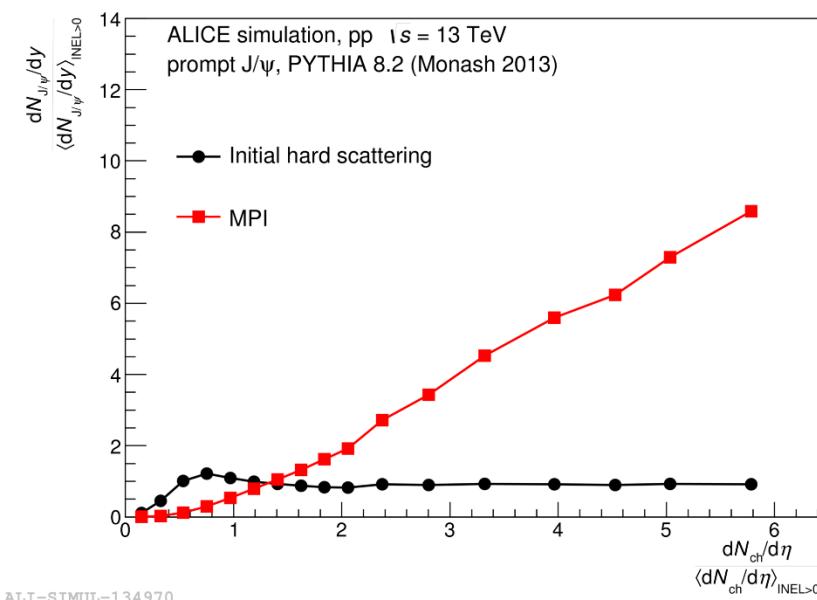
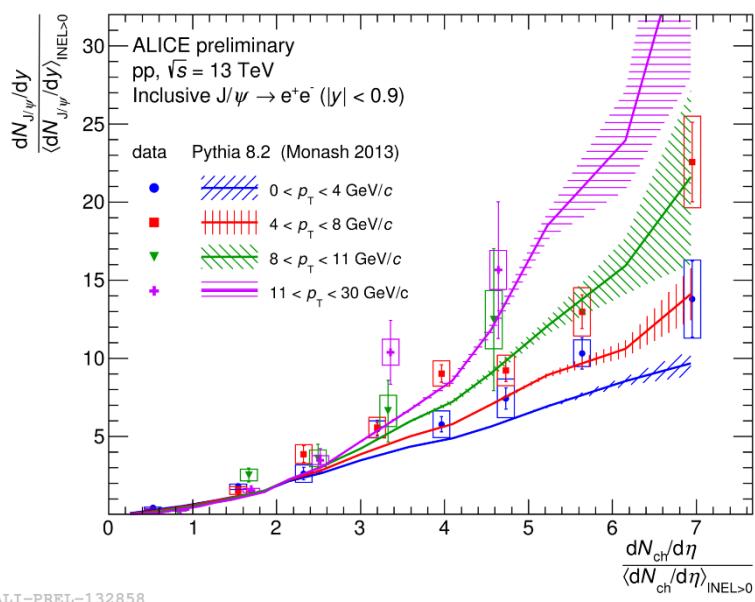
Results on J/ψ production as a function of multiplicity

J/ ψ yield vs event multiplicity in pp collisions ($\sqrt{s} = 13$ TeV)



- Multiplicities up to 7 times the average reached by combining min. bias, high-multiplicity and EMCal triggers
- Results indicate a faster-than-linear increase

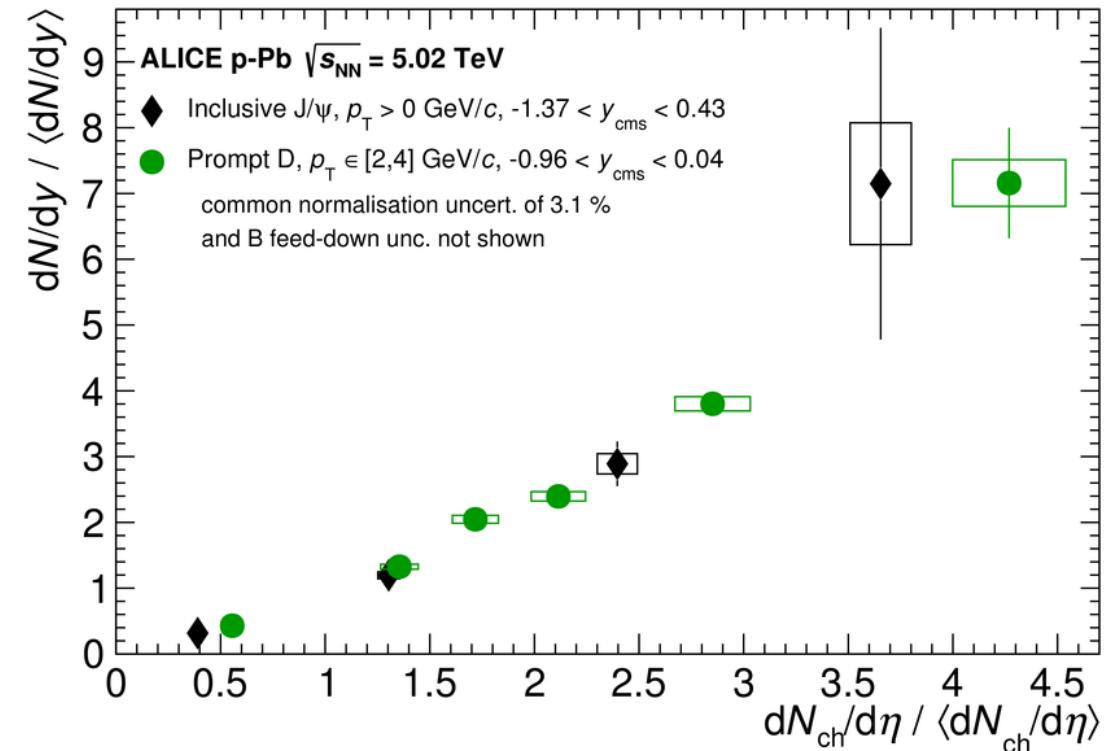
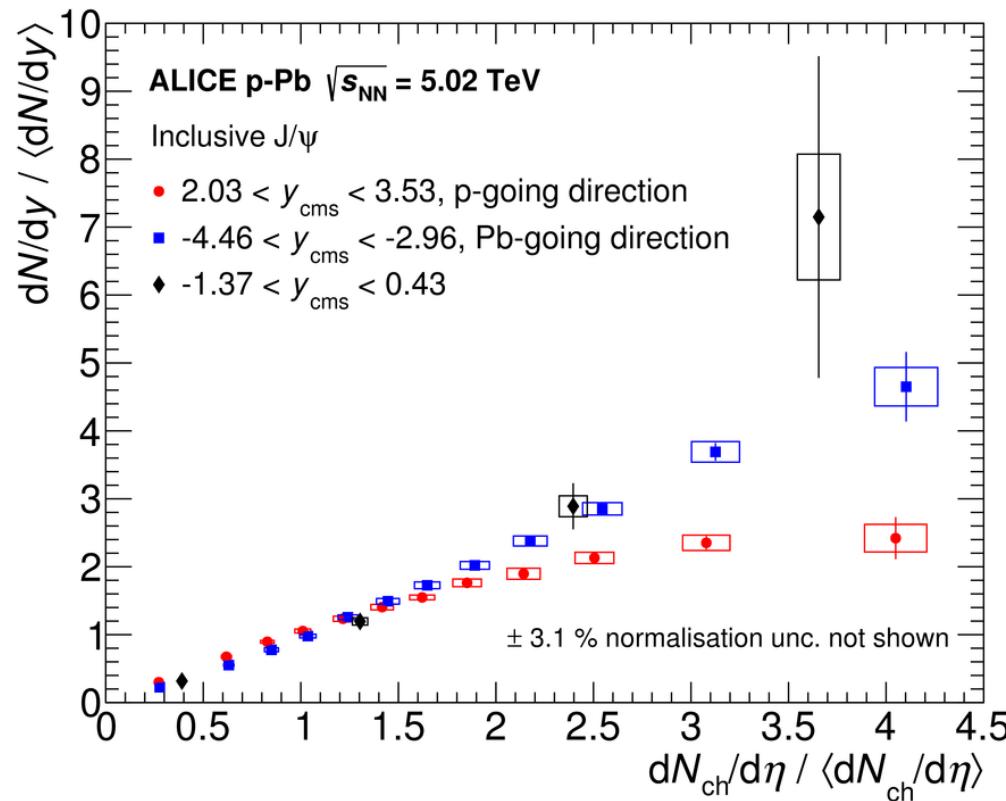
- Increase qualitatively reproduced by models (details in the back-up)
- In particular, adding multi-parton interactions (MPI) in Pythia seems to fix the multiplicity dependence



- Hint that multiplicity dependence is steeper at high p_T
- Reproduced by Pythia with MPI

J/ψ yield vs event multiplicity in p-Pb collisions

PLB 776 (2018) 91



Multiplicities up to 4 times the average reached

Increase as in pp, but indication of saturation for p-going J/ψ

At mid-rapidity, similar increase of J/ψ and D mesons

Theoretical input needed!

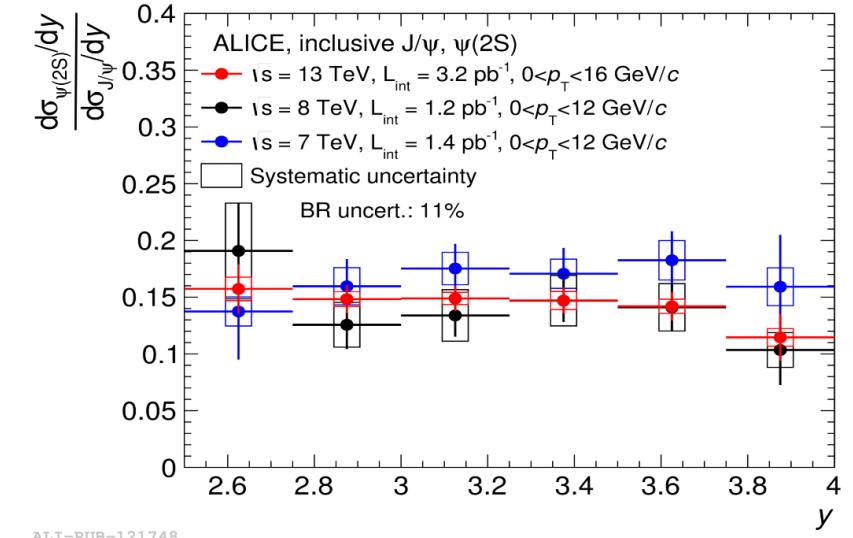
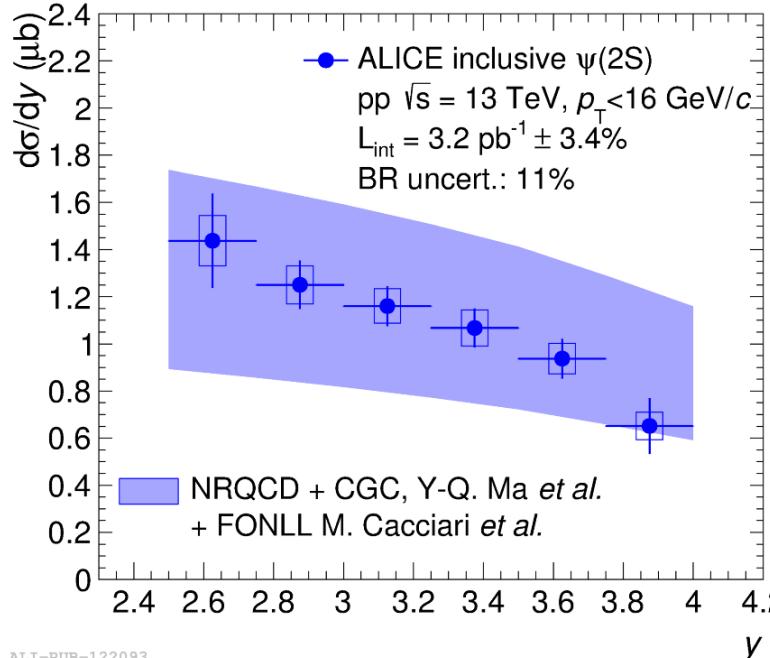
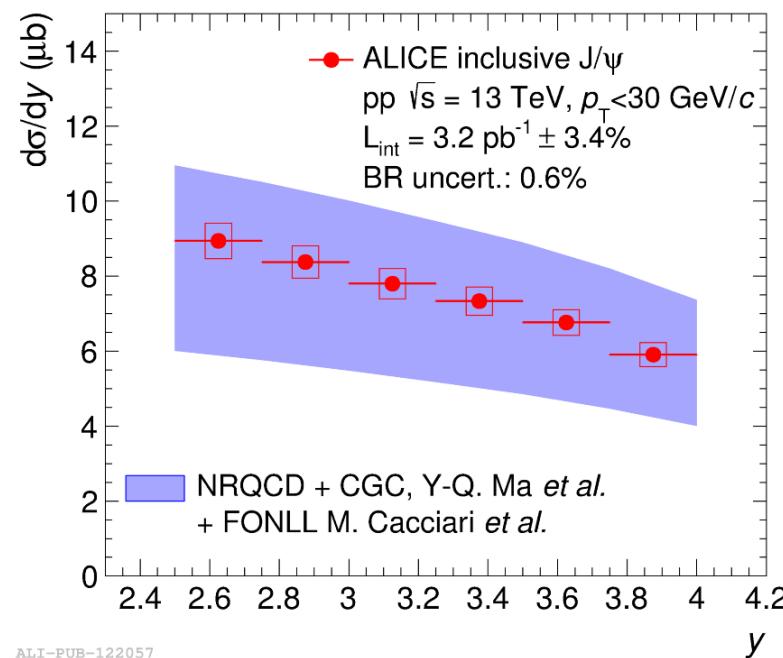
Conclusions

- Results on inclusive charmonium production in pp collisions reproduced by NRQCD + FONLL. CGC description of the proton seems to work well at low- p_T
- J/ψ suppression in p-Pb collisions well described by models including shadowing and/or energy loss. $\psi(2S)$ suppression requires final-state effects
- Intriguing indication of non-zero $J/\psi v_2$ in p-Pb: similar origin of azimuthal anisotropy as in Pb-Pb?
- Increasing J/ψ yield as a function of multiplicity observed in pp and p-Pb collisions. For pp, treatment of multi-parton interactions greatly improves the agreement with particle generators

Back-up

Model comparison for J/ ψ and $\psi(2S)$ (pp 13 TeV)

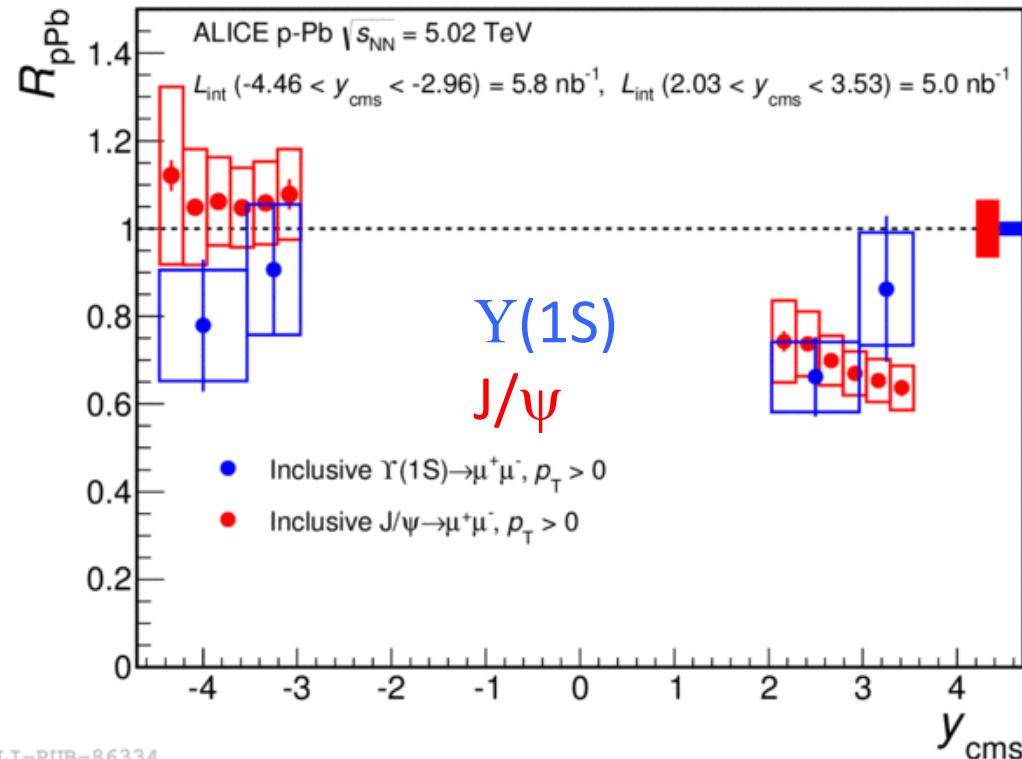
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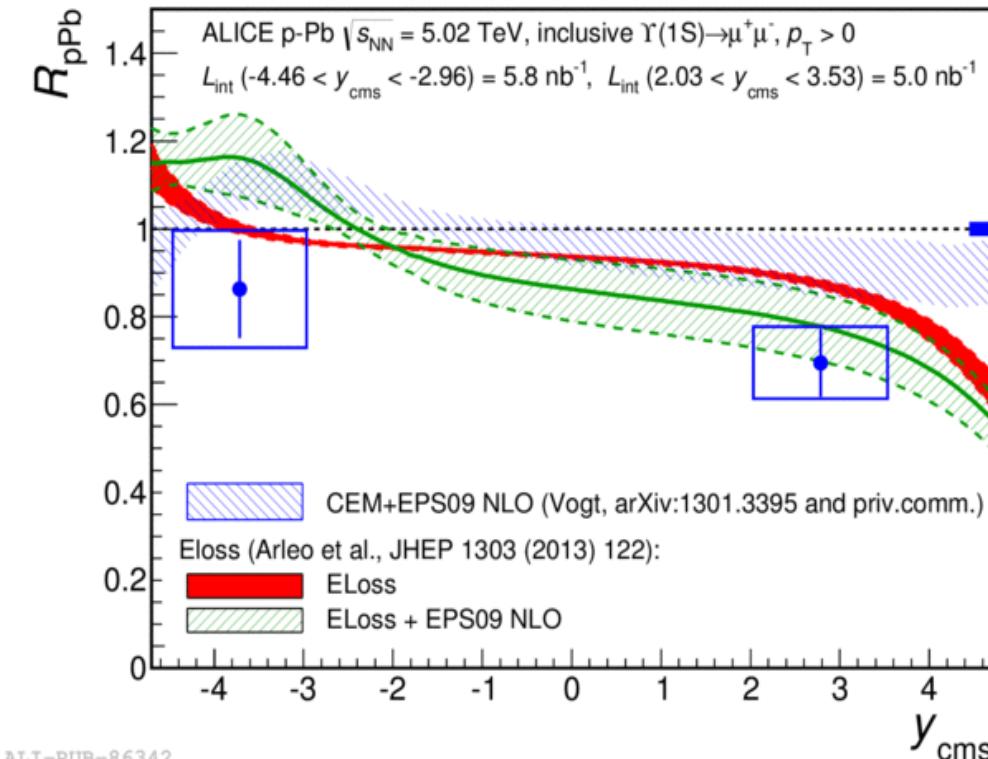
Rapidity dependence is reproduced within uncertainties by CGC+NRQCD+FONLL, for both resonance

$\psi(2S)$ / ψ ratio vs rapidity compatible at the three considered energies

$\Upsilon(1S)$ nuclear modification factor in Run-I p-Pb



ALI-PUB-86334

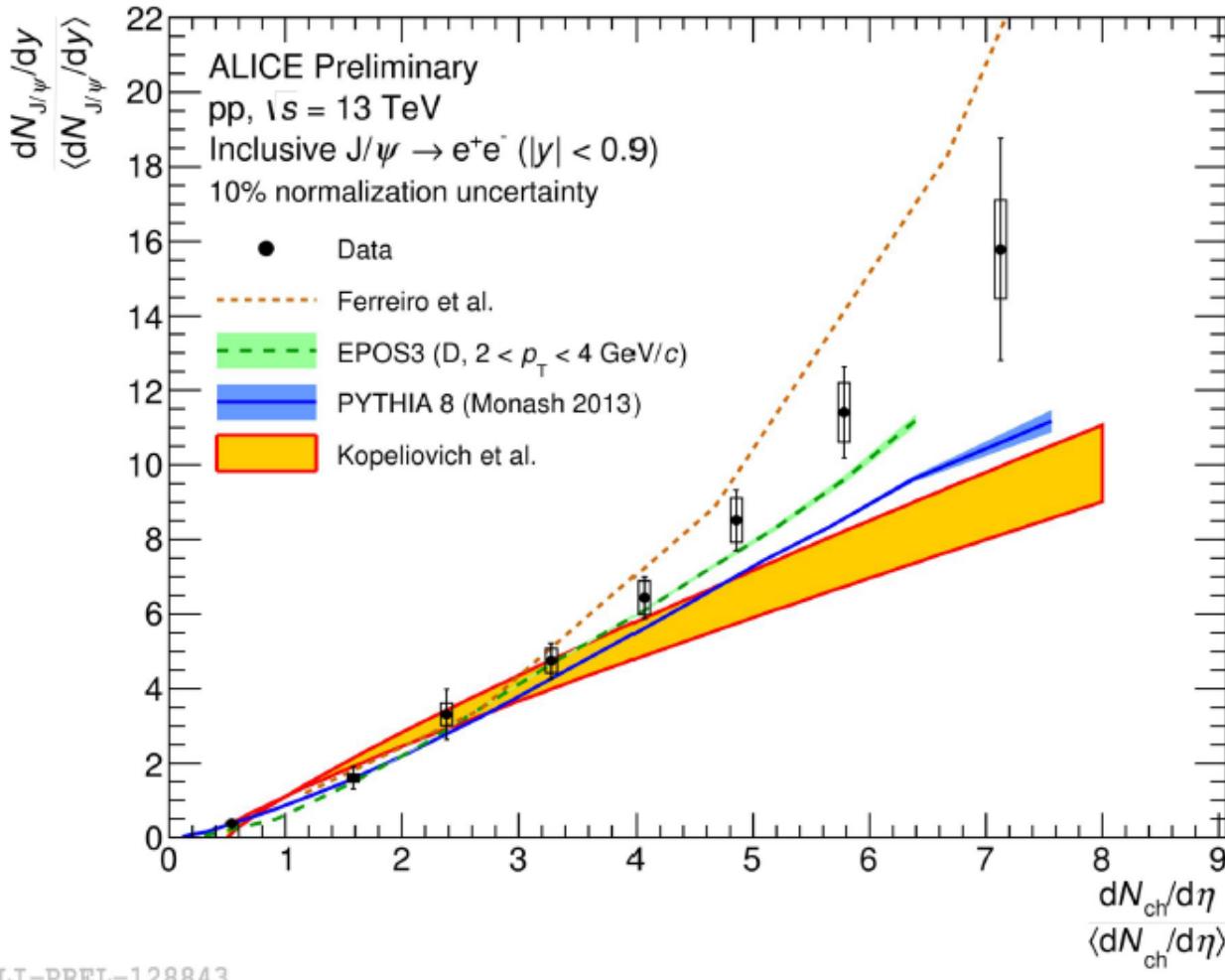


ALI-PUB-86342

- ΥR_{pPb} compatible with J/ψ within uncertainties
- Models including shadowing and energy loss tend to overpredict R_{pPb} at backward rapidity
- $\Upsilon(2S)$ to $\Upsilon(1S)$ ratio compatible with pp within uncertainties
→ no evidence for different CNM effects
(CMS reports a difference at mid-rapidity *JHEP 1404 (2014) 103*)

ALICE PLB 740 (2015) 105

J/ ψ yield vs event multiplicity in pp collisions



Ferreiro et al: Saturation of soft particle production.

(Ferreiro, Pajares, PRC86 (2012) 034903)

EPOS3: MPI and hydrodynamic expansion of the system.

(Werner et al., Phys.Rept.350 (2001) 93)

PYTHIA8: MPI and saturation of soft particle production via color reconnection.

(Sjostrand et al., Comput.Phys.Commun.178(2008)852)

Kopeliovich et al: higher Fock states.

(Kopeliovich et al., PRD88 (2013) 116002)

Motivation: Pb-Pb collisions

- Bound states of heavy quarks, produced in hard collisions and crossing the medium throughout its evolution
- quarkonium **suppression by colour screening** in a deconfined medium was one of the first proposed signatures for Quark-Gluon Plasma (Matsui, Satz 1986)
- excited states expected to be suppressed at lower temperature (sequential suppression) → quarkonia as a «thermometer» of the plasma
- **puzzling results on J/ψ from RHIC experiments:**
 - similar suppression at mid- vs forward rapidity
 - similar suppression at RHIC vs SPS
 - sequential melting in action?
 - **regeneration phenomena** from deconfined heavy quarks in the QGP or at the phase boundary?
- **bottomonium production** accessible at the LHC

