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 $\sqrt{s}$

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)

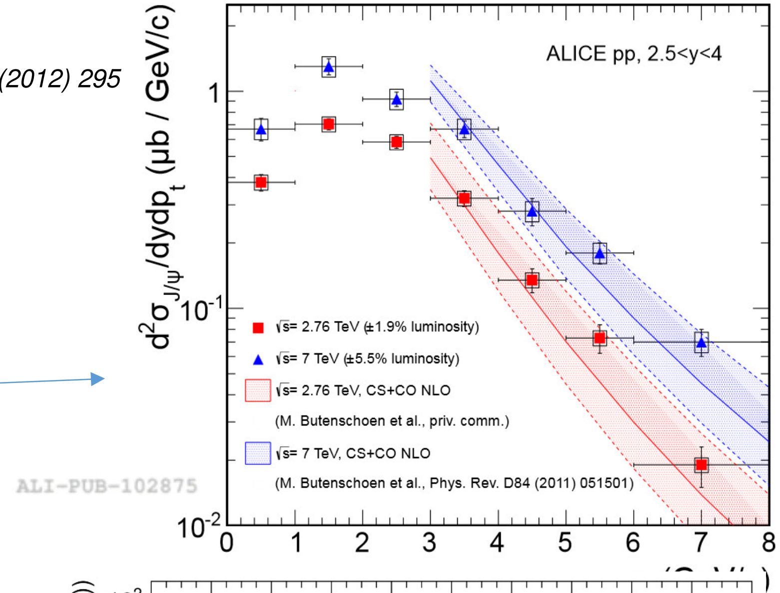
Production in pp collisions

→ Non Relativistic QCD was able to reproduce quarkonium yields at Tevatron energies, but not polarisation

→ NNLO corrections have «revived» the Color Singlet Model

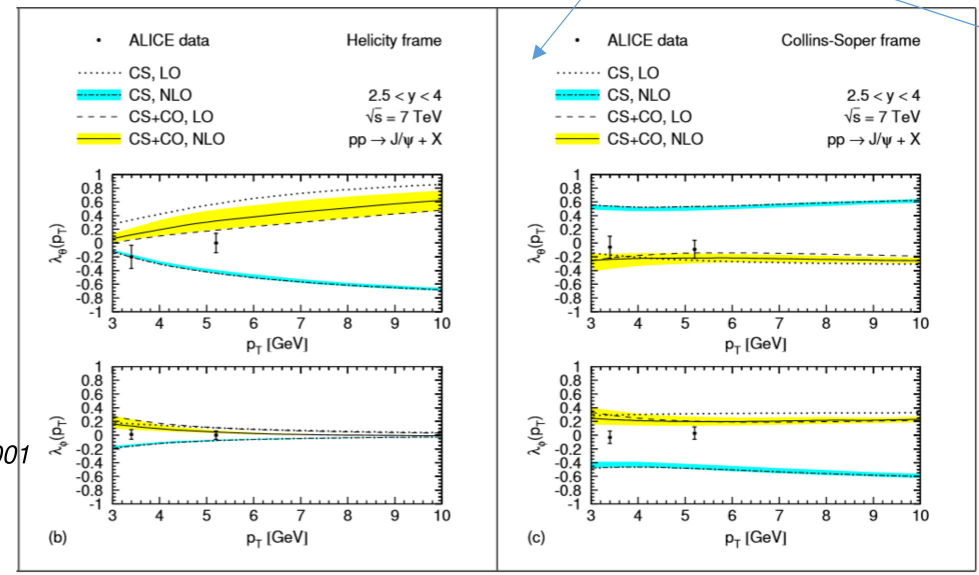
→ Colour Singlet and NRQCD-based models in agreement with LHC RUN-I data at 2.76 and 7 TeV within large uncertainties

ALICE, PLB 718 (2012) 295

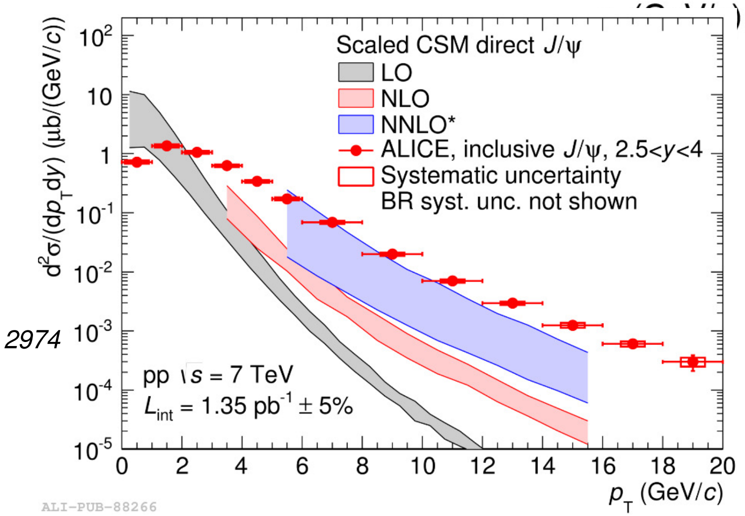


Butenschoen et al., arXiv 1201.3862

ALICE, PRL 108 (2012) 082001



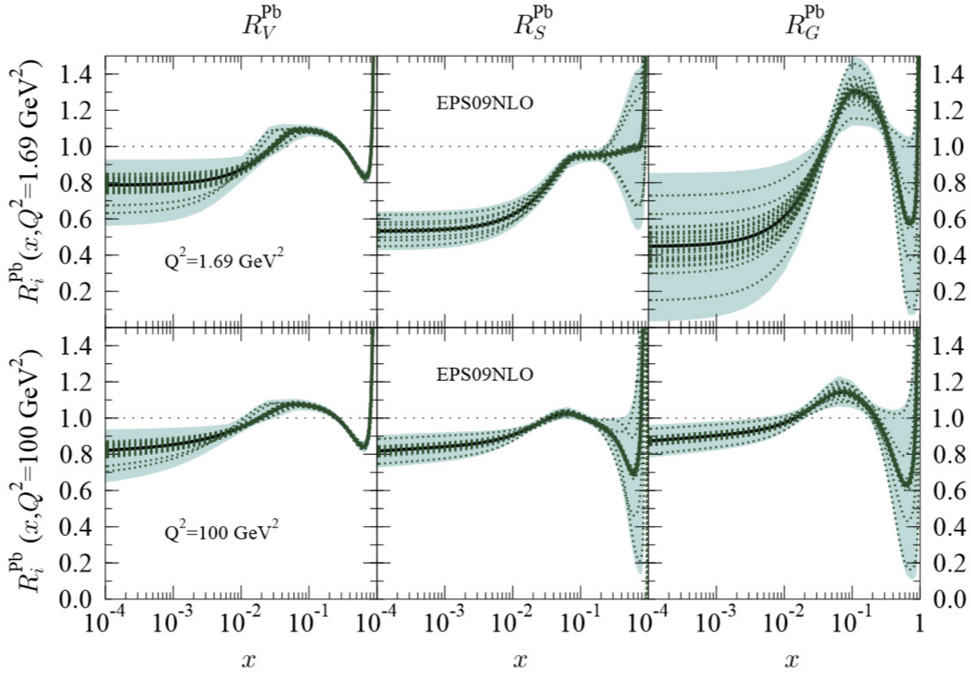
ALICE, EPJC 74 (2014) 2974



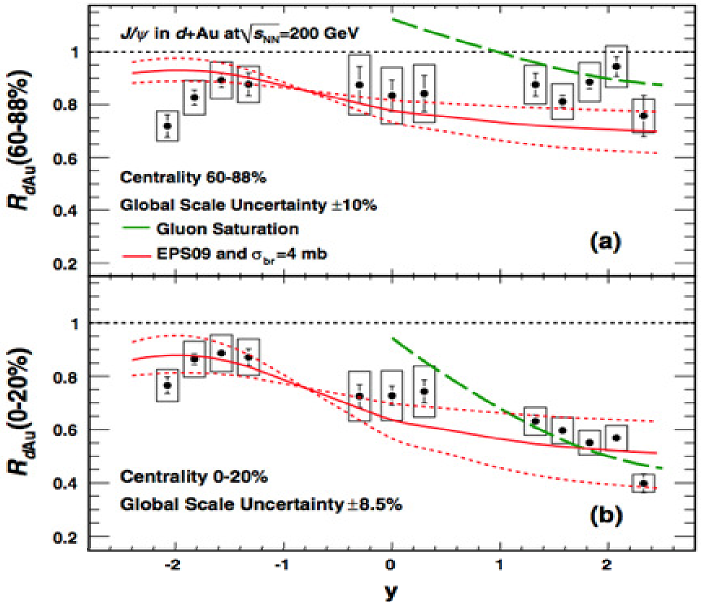
Production in p-Pb collisions

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?



Eskola et al., JHEP 0904 (2009) 065



PHENIX, PRL 107 (2011) 142301

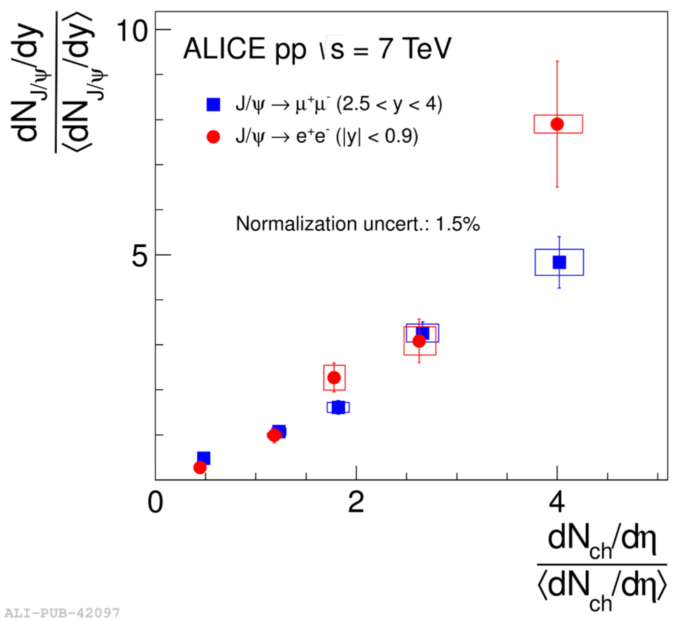
- Reference for Pb-Pb studies

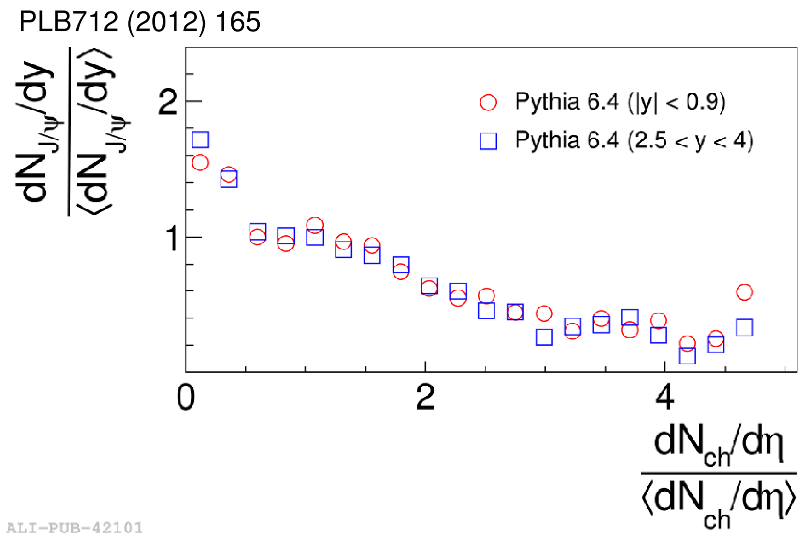
  → are nuclear modifications observed in Pb-Pb collisions due to Quark Gluon Plasma?

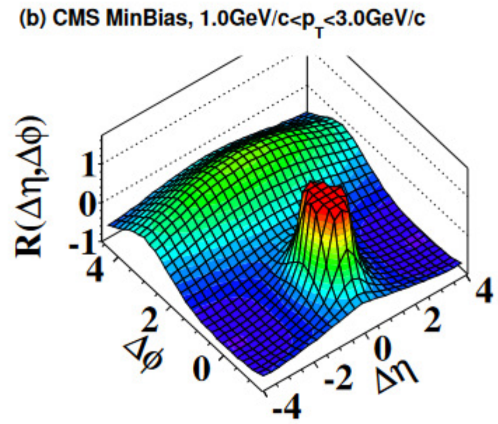
Production as a function of multiplicity

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

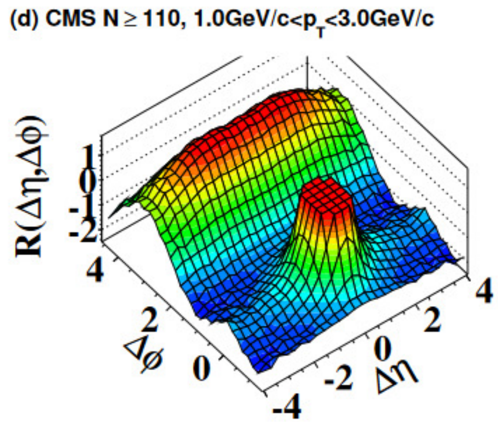
- Run-I: yield increases with mult., not predicted by evt generators
- role of multi-parton interactions (MPI)?







CMS, JHEP 2010 (091)



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

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

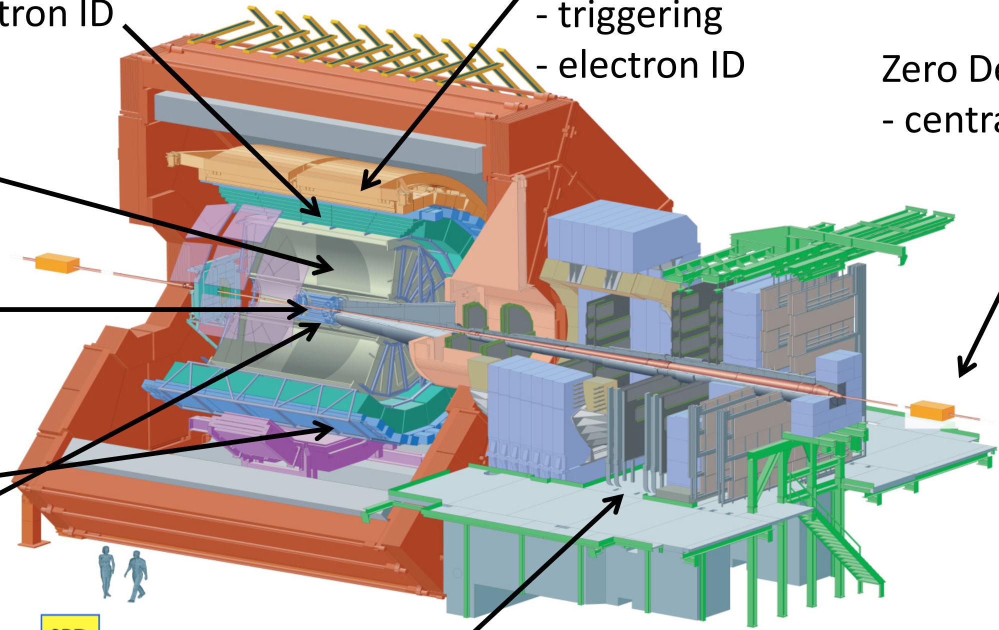
T0 (Cherenkov counters)
- luminosity

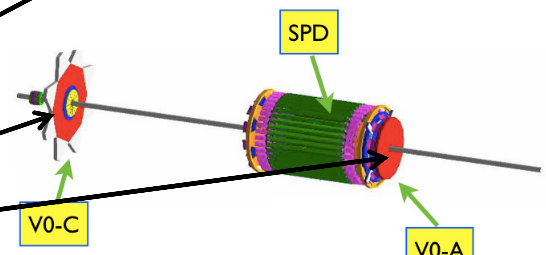
V0 scintillators
- triggering
- luminosity

Transition Radiation Detector
- electron ID

ElectroMagnetic Calorimeter (EMCal)
- triggering
- electron ID

Zero Degree Calorimeters
- centrality in p-Pb





(only detectors involved in quarkonium analyses are discussed here)

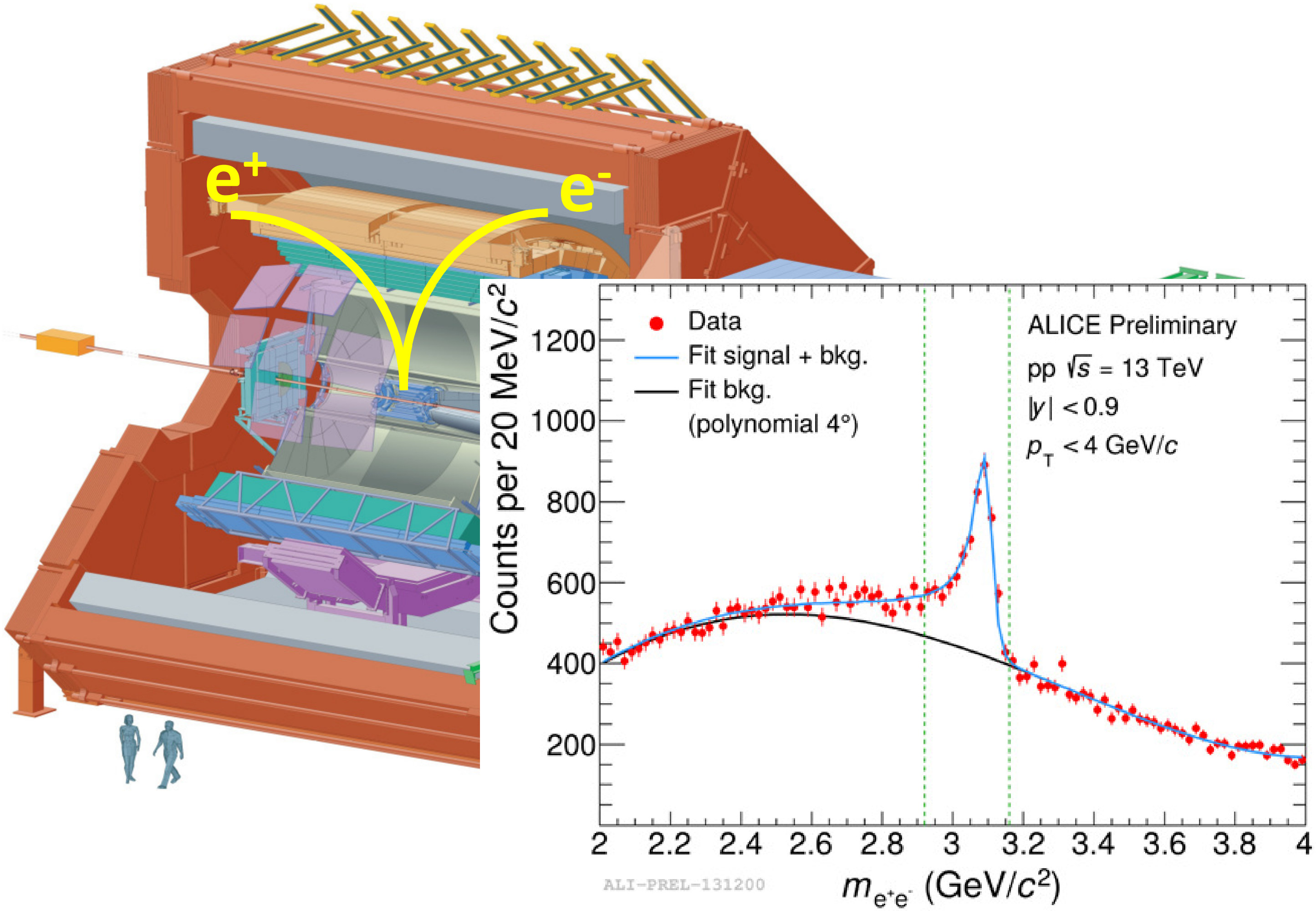
Muon spectrometer $-4 < \eta < -2.5$

Dipole magnet
Front absorber 10 λ_I
10 tracking planes (Cathode Pad Chambers)
4 trigger planes (Resistive Plate Chambers)
Muon filter (7 λ_I)

Techniques: J/ψ → 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 d*E*/d*x* in the TPC and *E*/*p* in EMCal
- Inclusive analysis**:**
  - acceptance down to $p_T = 0$



Techniques: J/ψ → e^+e^- at mid-rapidity

Mid-rapidity
$|y| < 0.9$

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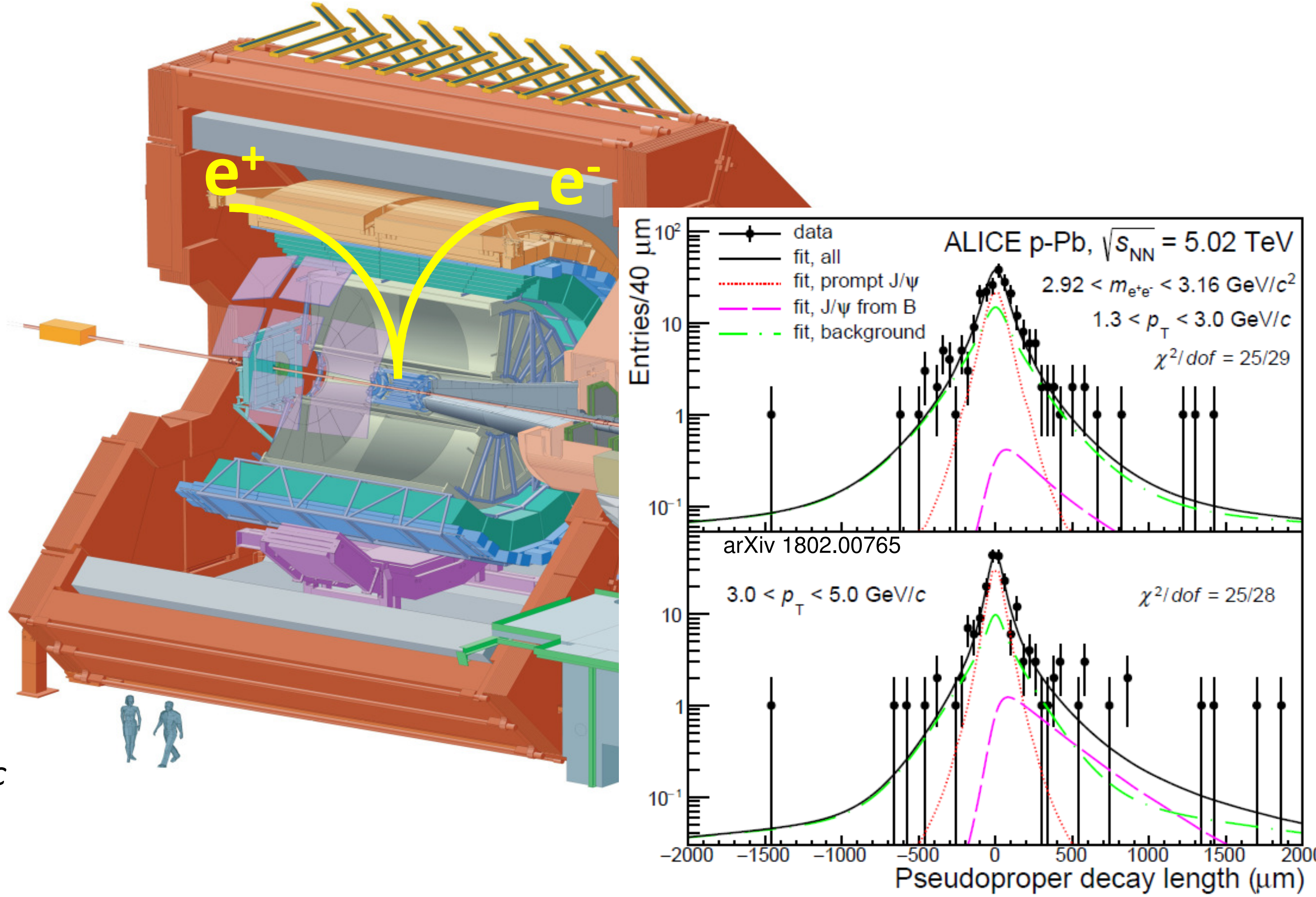
- Electron identification via d*E*/d*x* in the TPC and *E*/*p* in EMCal
- Inclusive analysis:
  - acceptance down to $p_T = 0$
- Prompt-non prompt separation:
  - Simultaneous fit to inv. mass and pseudo-proper decay length: separate prompt J/ψ and B → J/ψ
  - acceptance down to p_T = 1.3 GeV/*c* in p-Pb collisions

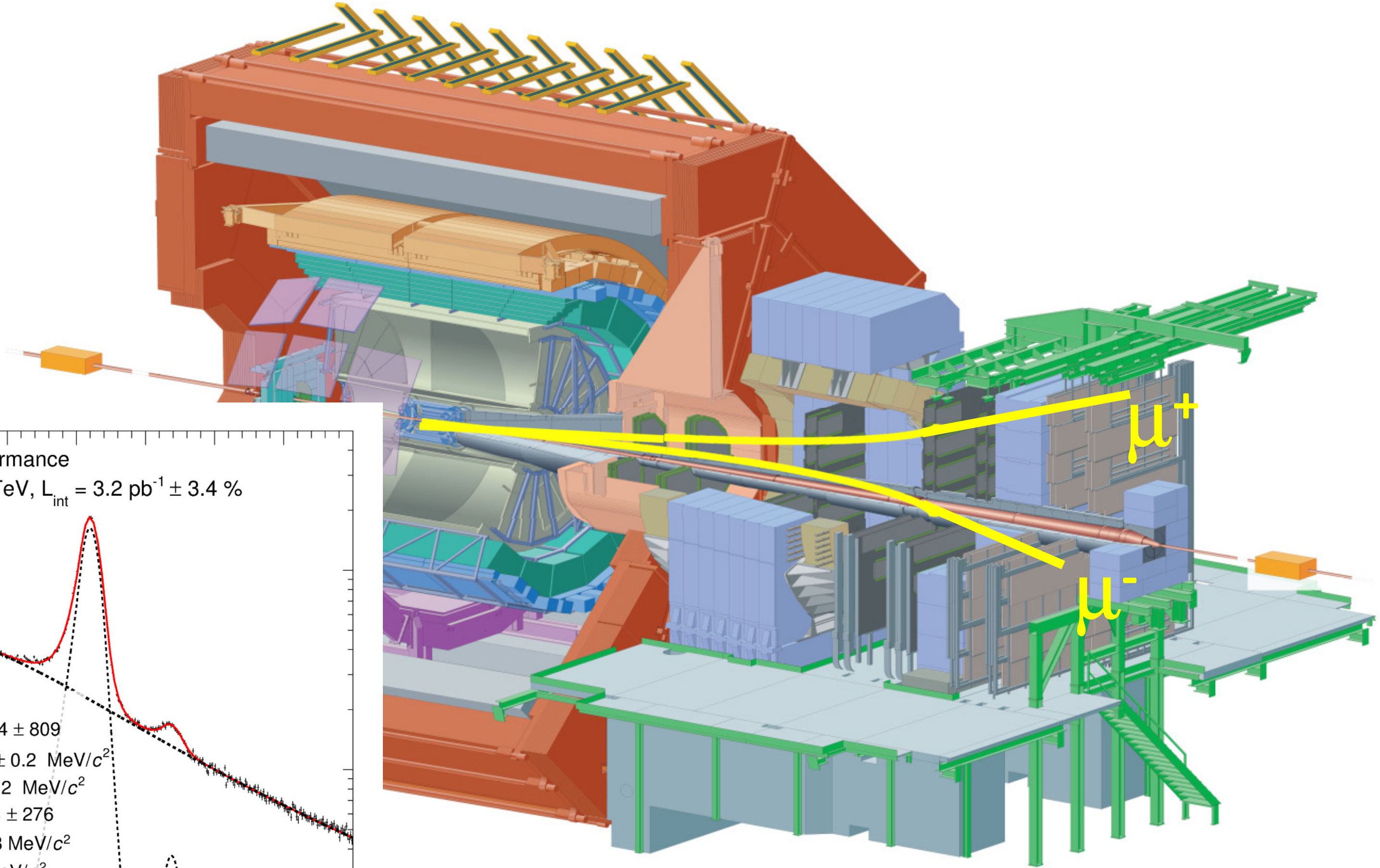


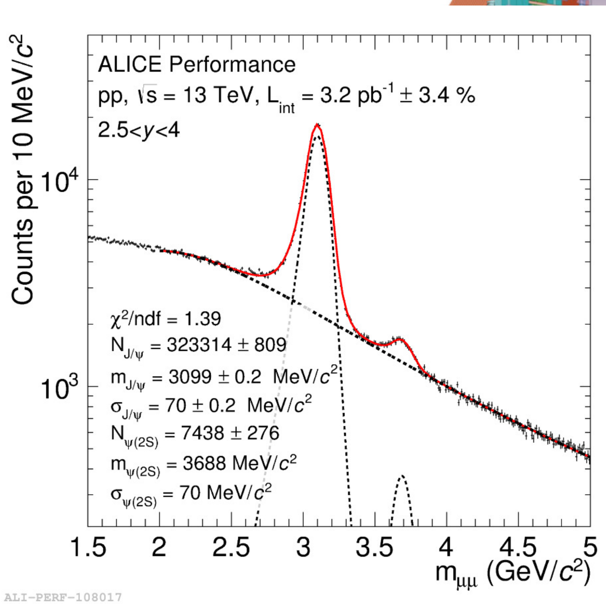
Techniques: Quarkonium → $\mu^+\mu^-$ at forward rapidity

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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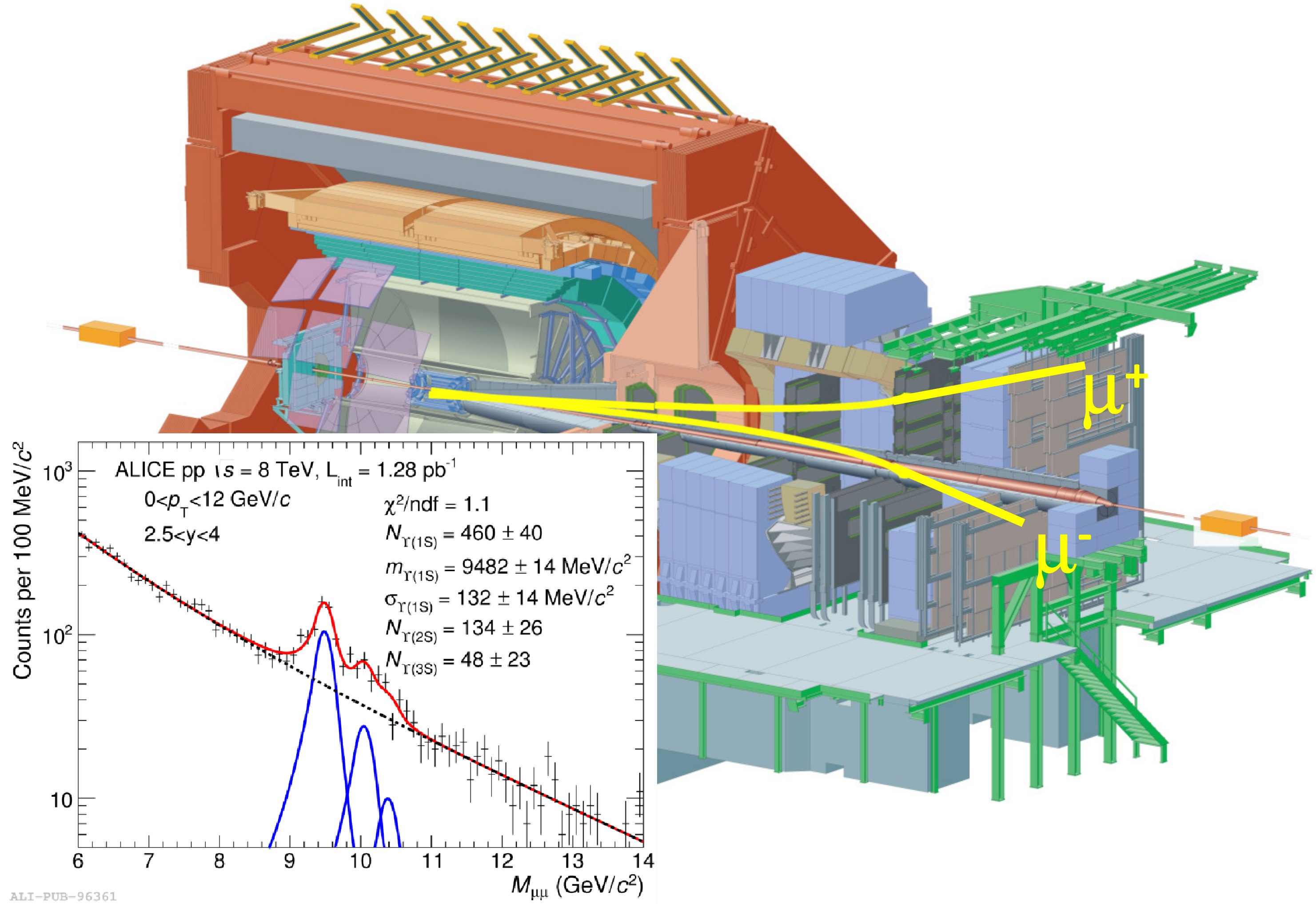
  J/ψ, ψ(2S)

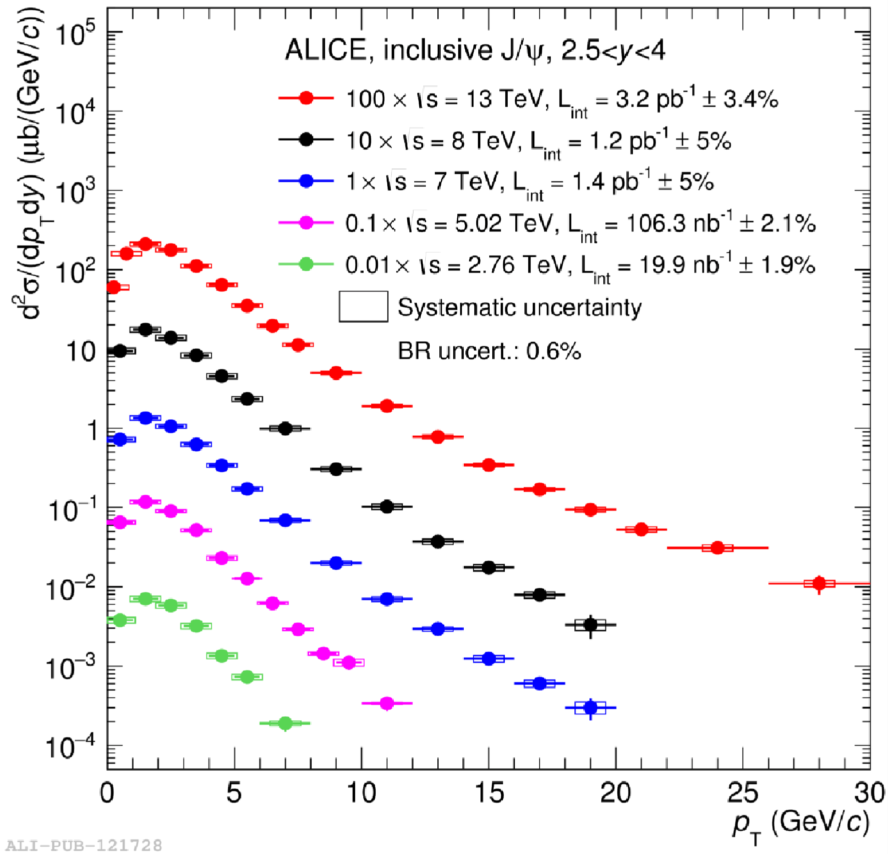
  Υ states



Recent results from pp collisions

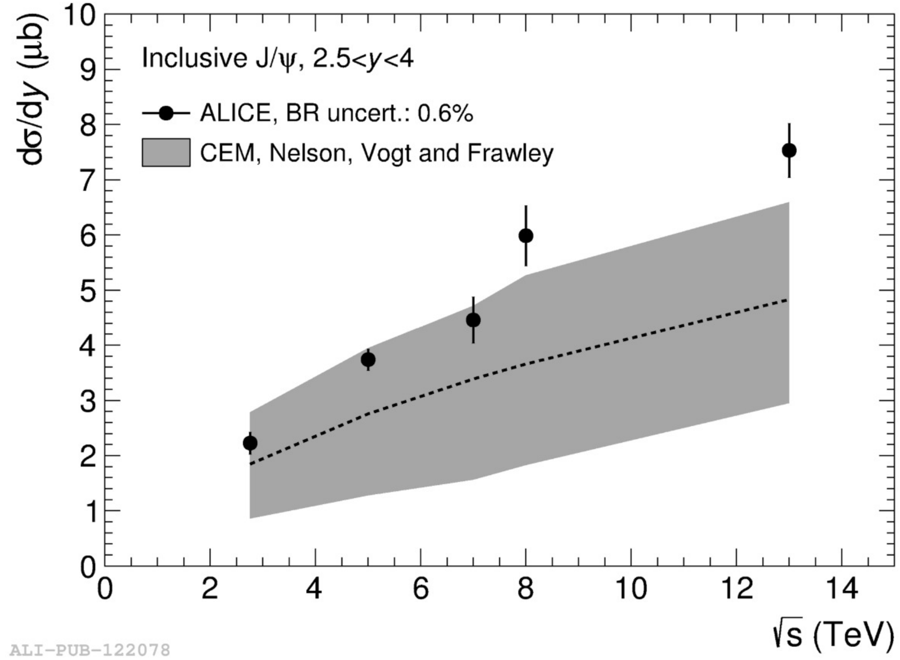
Energy dependence of J/ψ production

Eur. Phys. J. C (2017) 77



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

- 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

Model comparison for J/ψ (pp 13 TeV)

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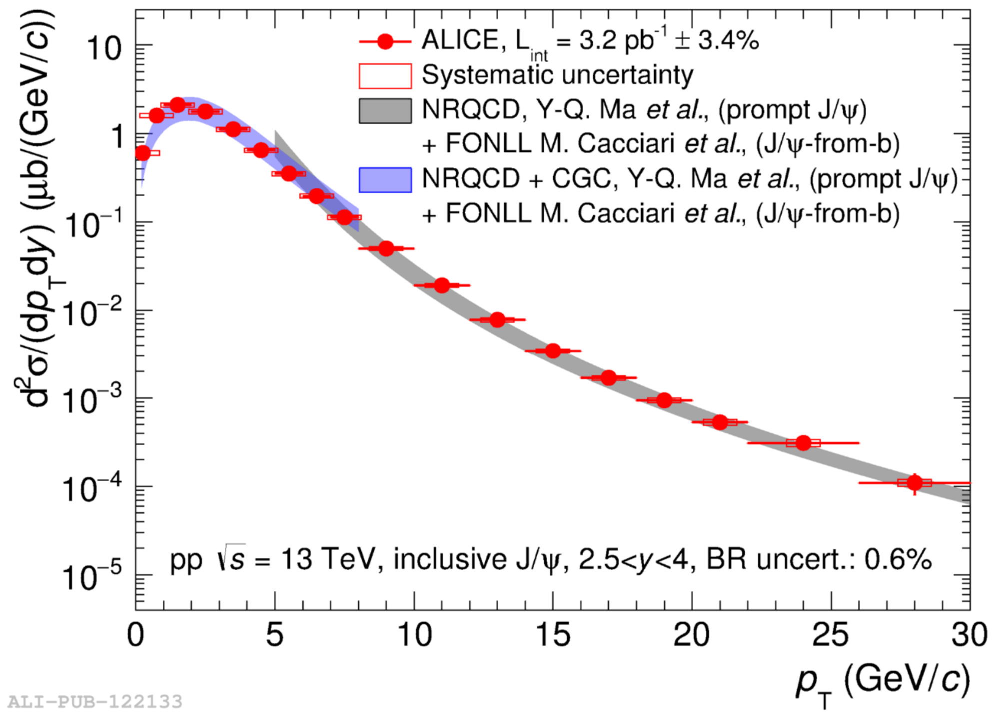
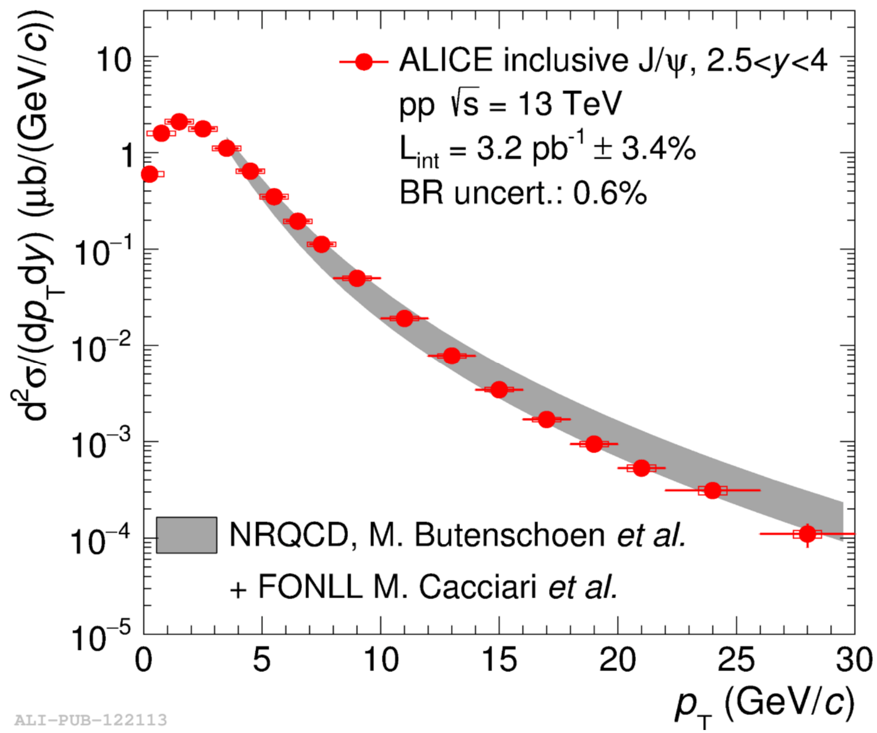
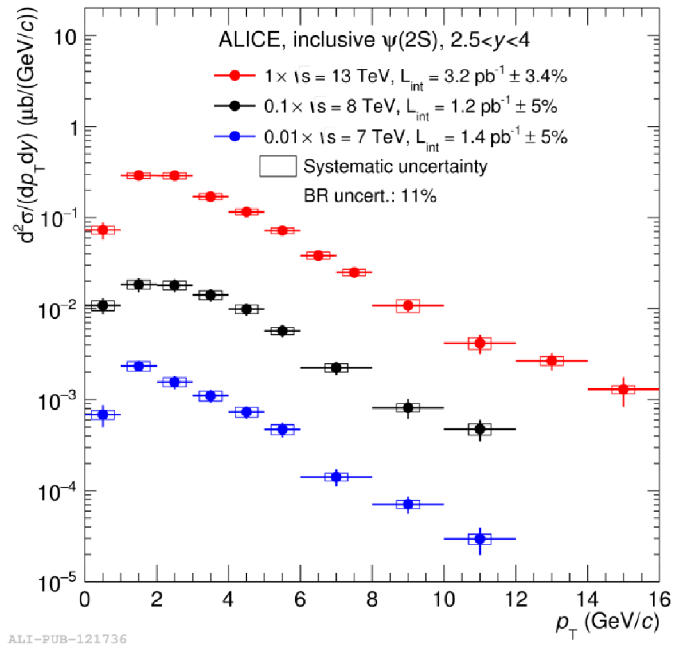




- pQCD calculations for non-prompt J/ψ are added to the NRQCD and compared to the inclusive measurement
- The two NRQCD calculations differ in the set of LDME that is used, the p_T at which fits are performed and the used datasets
- CGC calculations extend the prediction range to $p_T = 0$
- Fair agreement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

ψ(2S) production

Eur. Phys. J. C (2017) 77



$\sqrt{s}$ = 7 TeV EPJC 74 (2014) 2974
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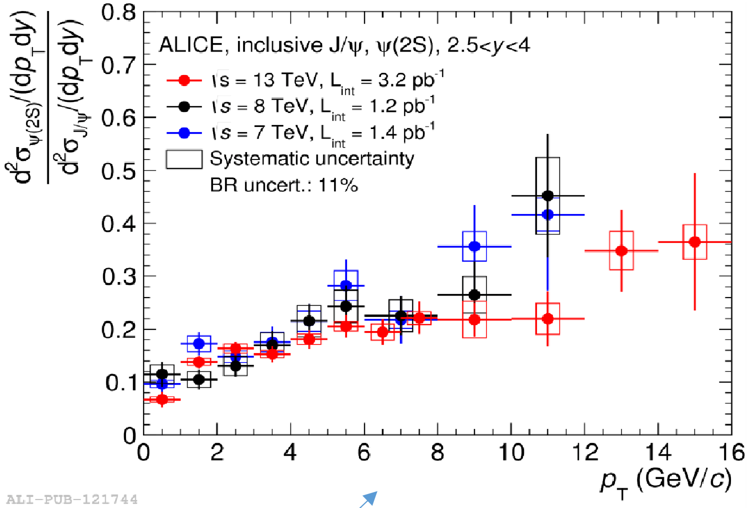
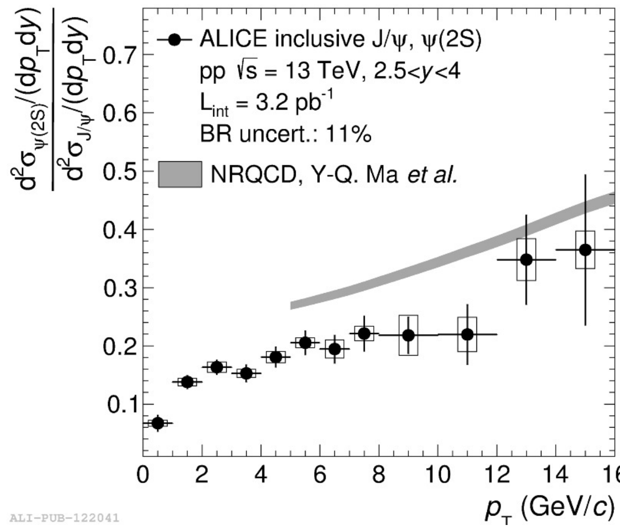
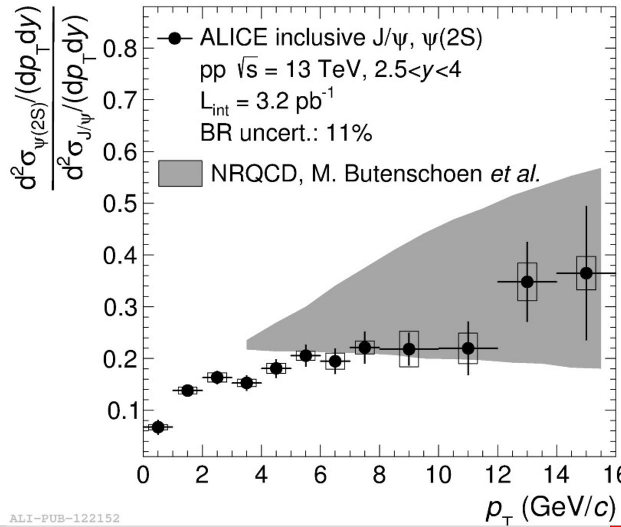
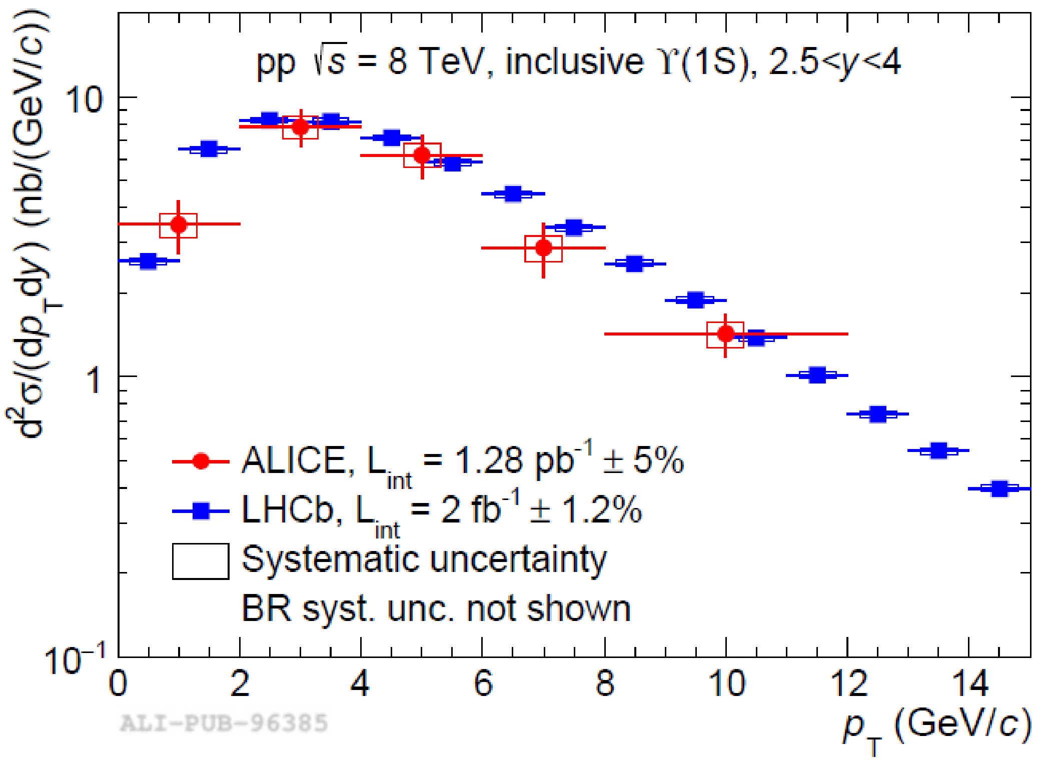


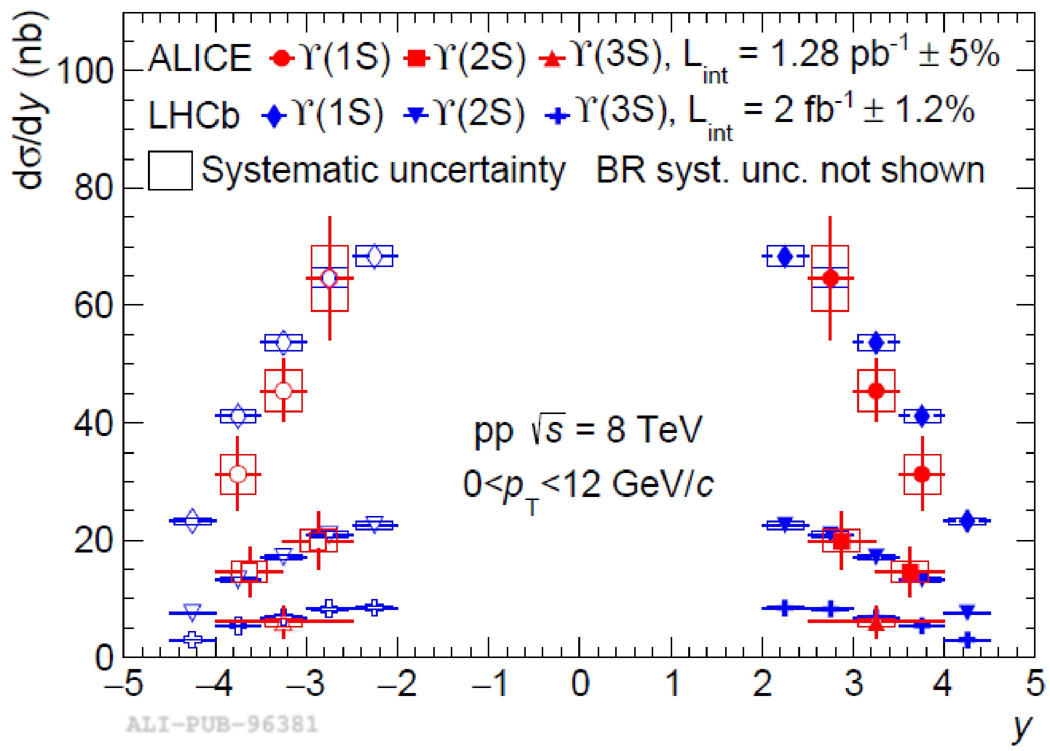




- No evidence for energy dependence of ψ(2S) / ψ ratio
- Some theoretical uncertainties cancel in the ψ(2S)/ψ ratio
  → some tension with data
  for one of the two NRQCD calculations

Bottomonium cross section at √s = 8 TeV





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

- Fair agreement with LHCb results:
(< 1.2 σ integrated, < 1.5 σ differential)

- Run II results (√s = 13 TeV) coming soon!

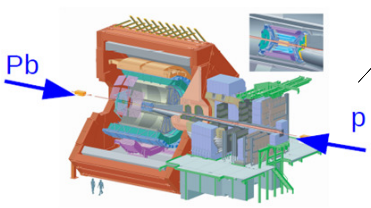
Recent results from p-Pb collisions

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

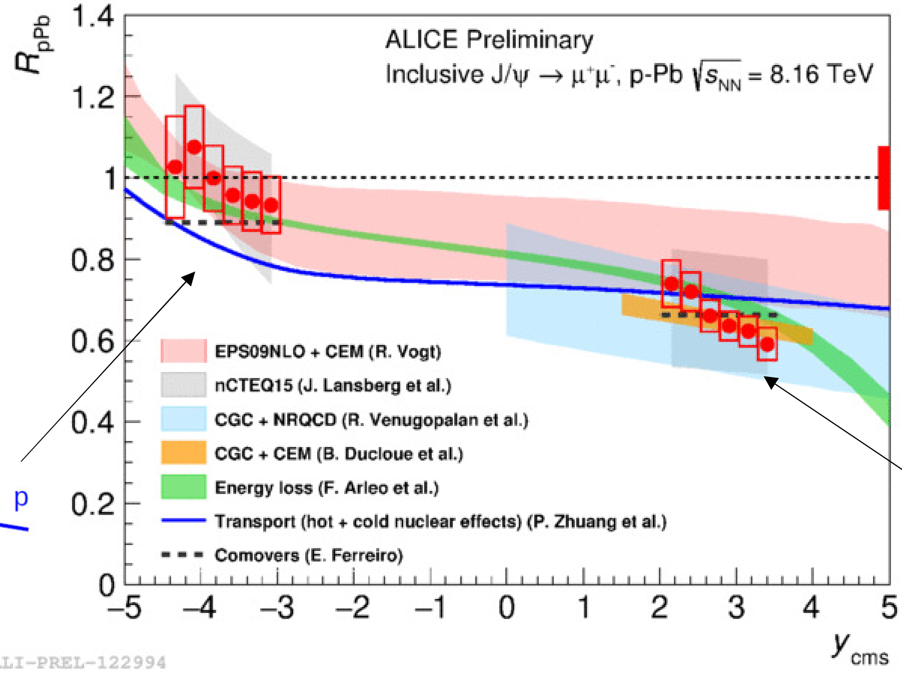
Nuclear modification factor:

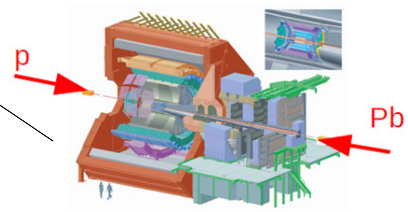
$$R_{pPb} = \frac{\text{Yield per event in p-Pb}}{(\text{Yield per event in pp}) \times \langle N_{collisions} \rangle}$$

ALICE-PUBLIC-2017-001



Pb-going

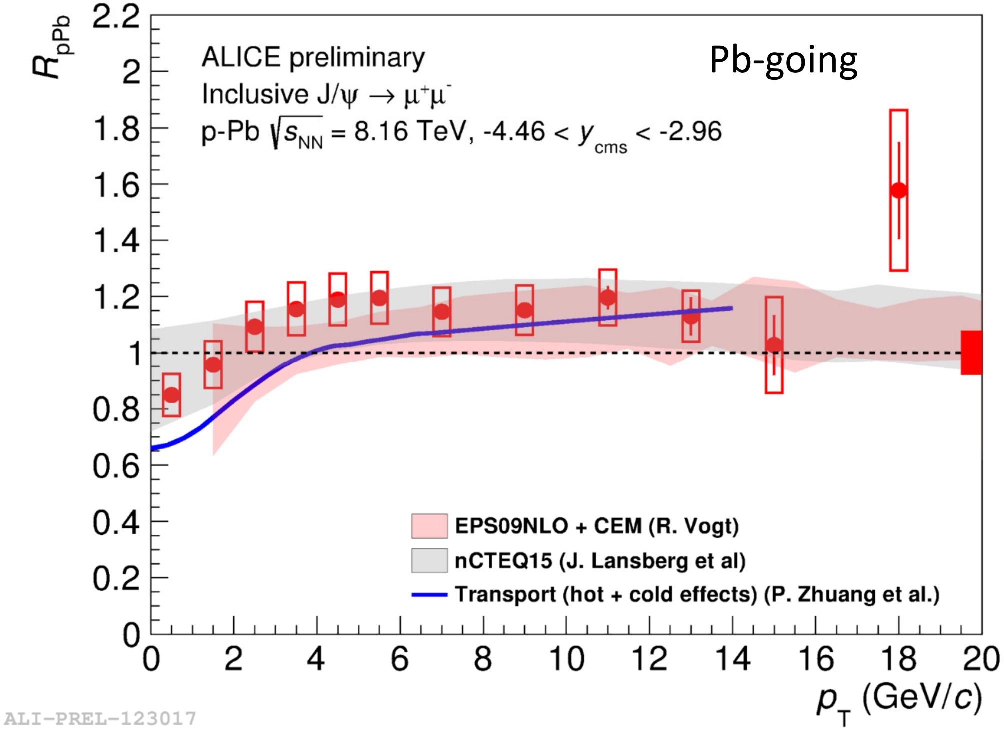


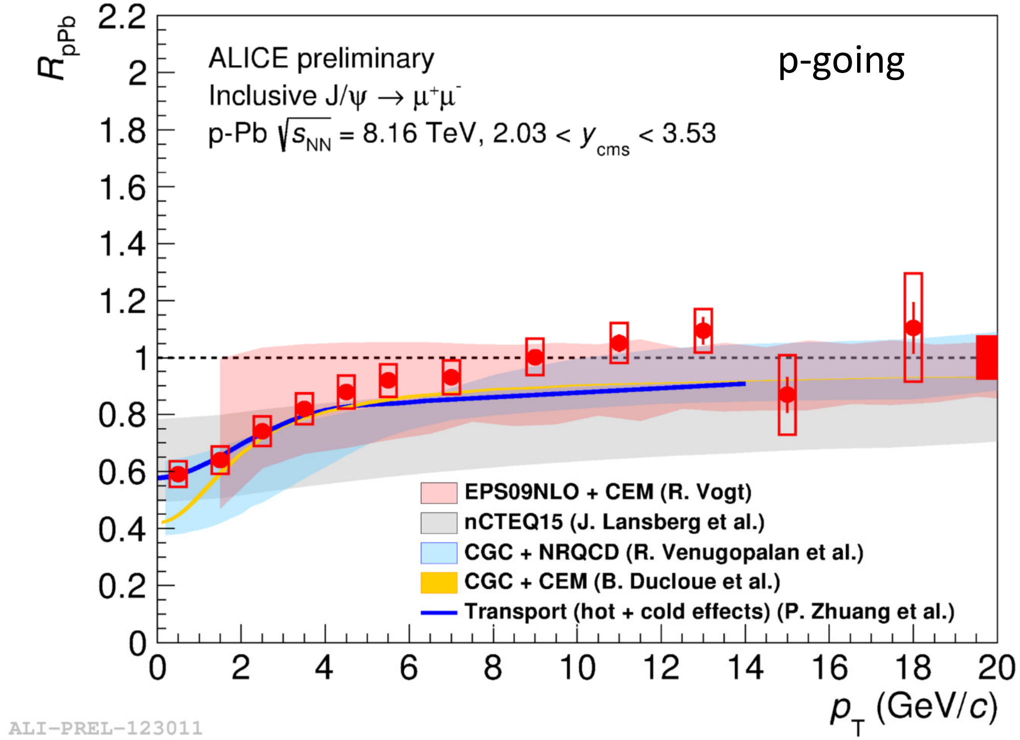


p-going

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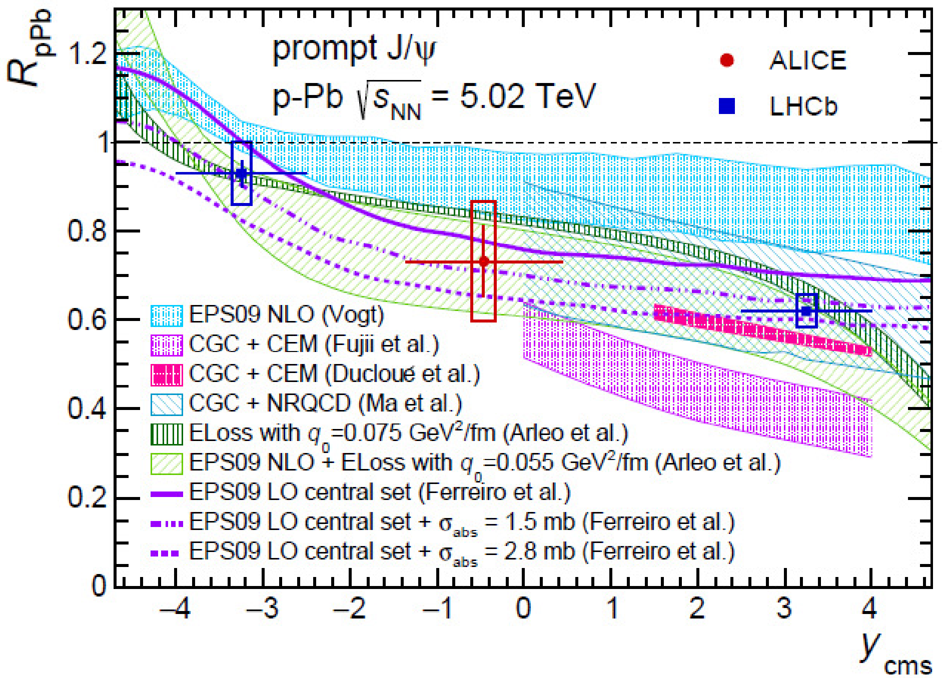
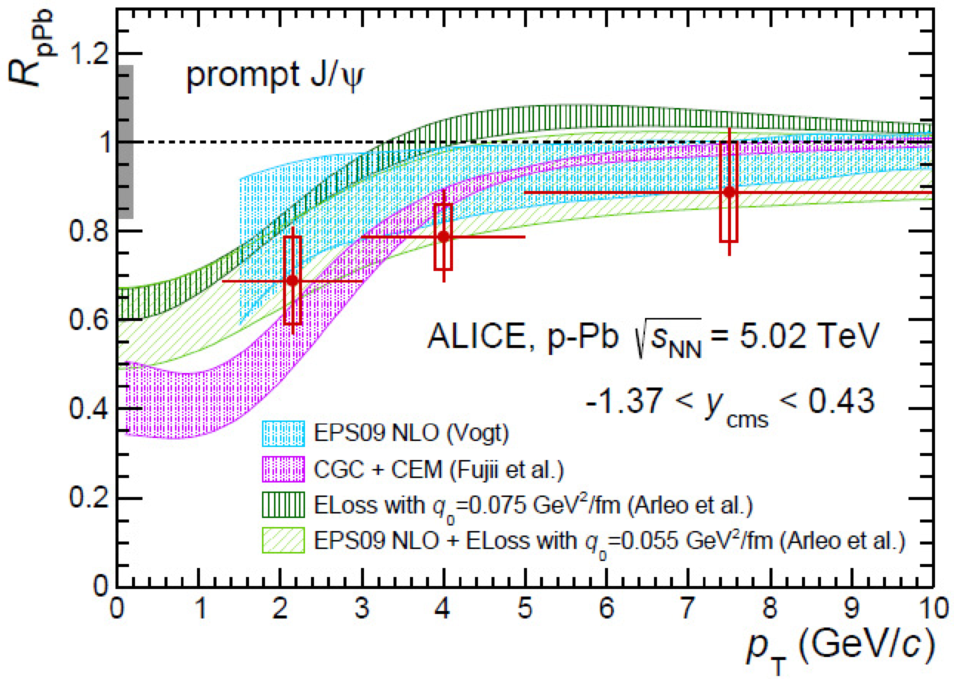
Prompt J/ψ nuclear modification factor ($\sqrt{s_{NN}}$ = 5.02 TeV)

arXiv 1802.00765

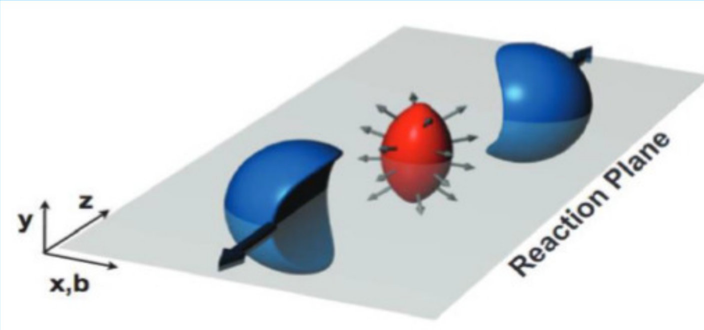




- Measurement performed at mid-rapidity with Run-I data
- Indicates suppression at low p_T
- Trends with p_T and y qualitatively reproduced by models including shadowing, gluon saturation, energy loss, nuclear absorption
- Can not discriminate among them with the present uncertainties

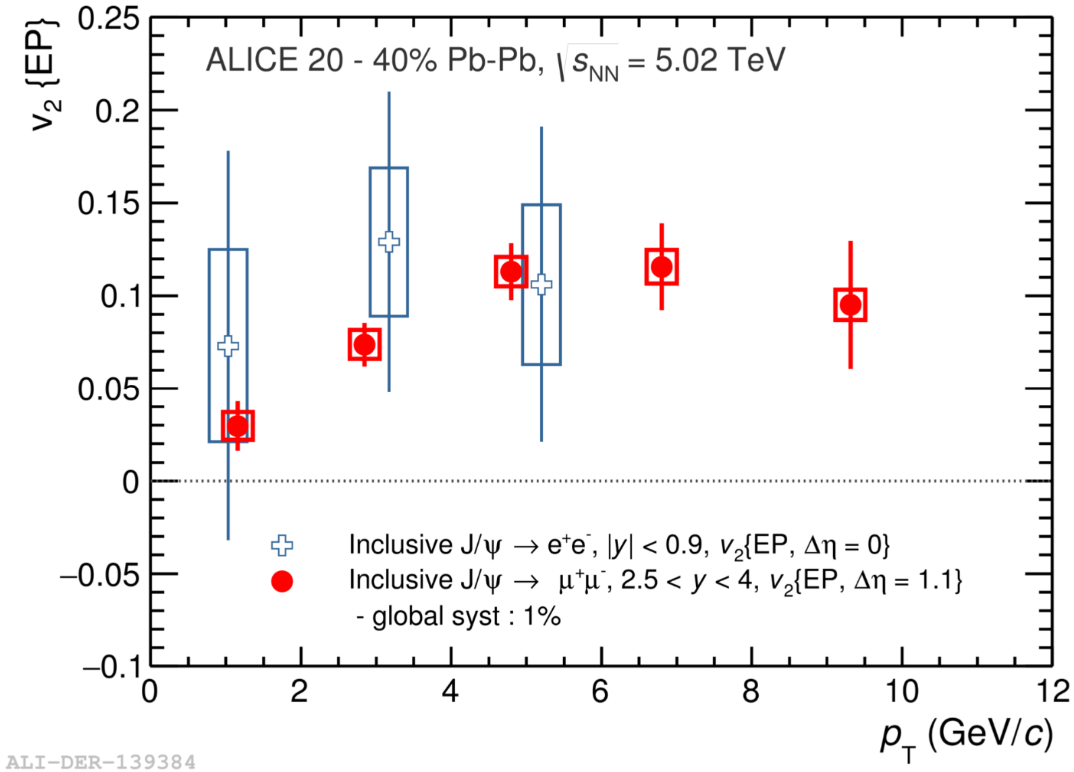
Azimuthal anisotropy (v_2) of J/ψ production

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



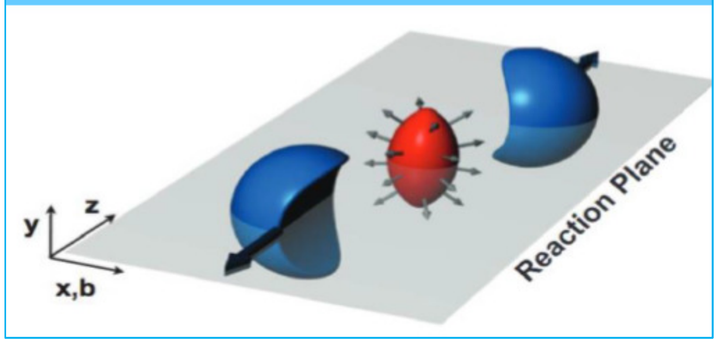
- In a strongly interacting medium, pressure gradients convert any initial spatial anisotropy into a momentum anisotropy
- Anisotropy is quantified by the 2nd order coefficient v_2 of the Fourier expansion of the particle azimuthal angle distribution
- In the analysis of Pb-Pb collisions, non-zero J/ψ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

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



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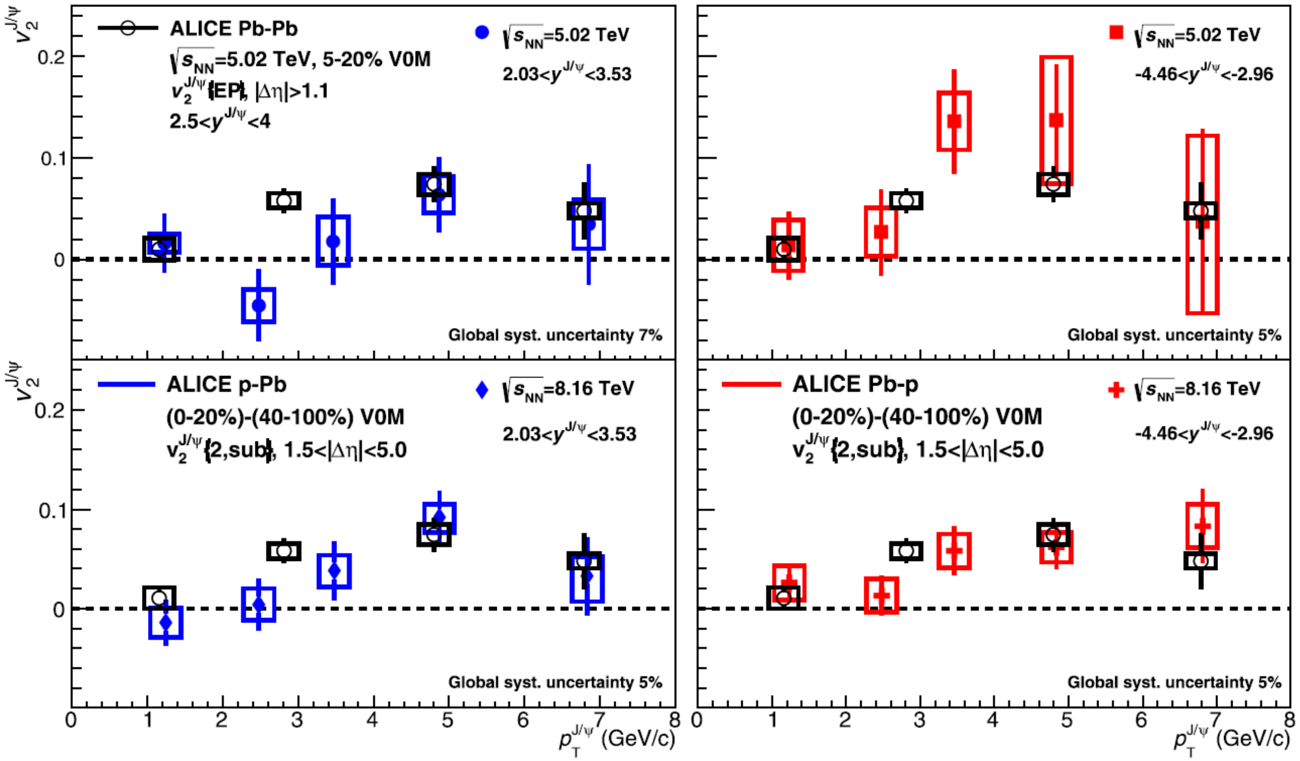
PLB 780 (2018) 7



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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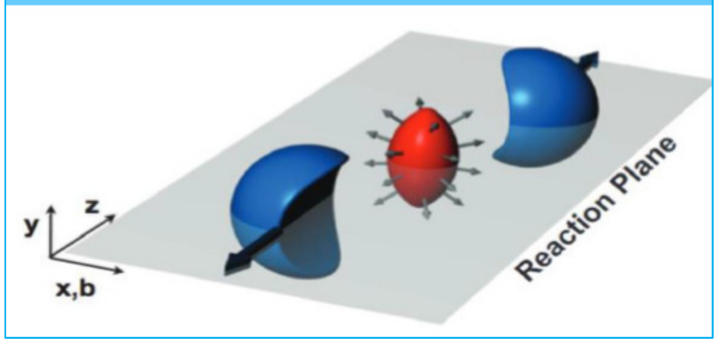

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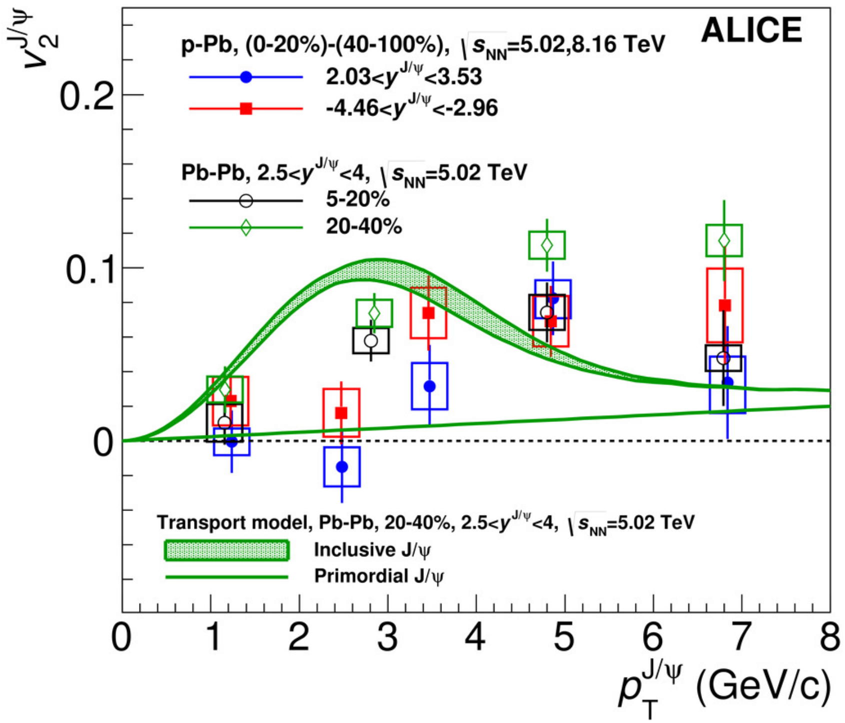


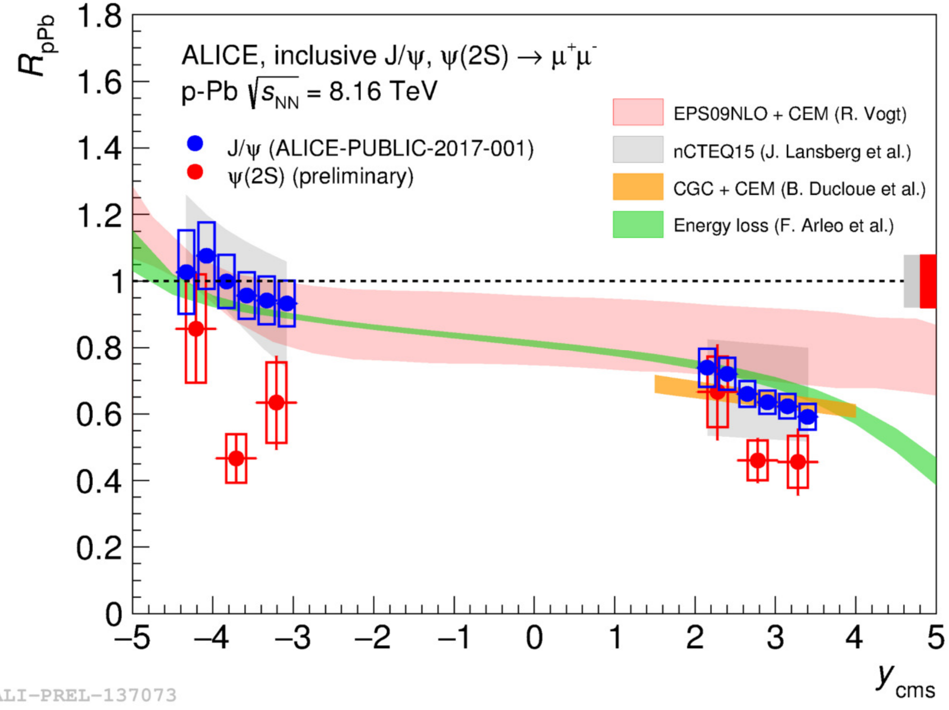
Observation of non-zero v_2 in p-Pb for p_T > 3 GeV/c!

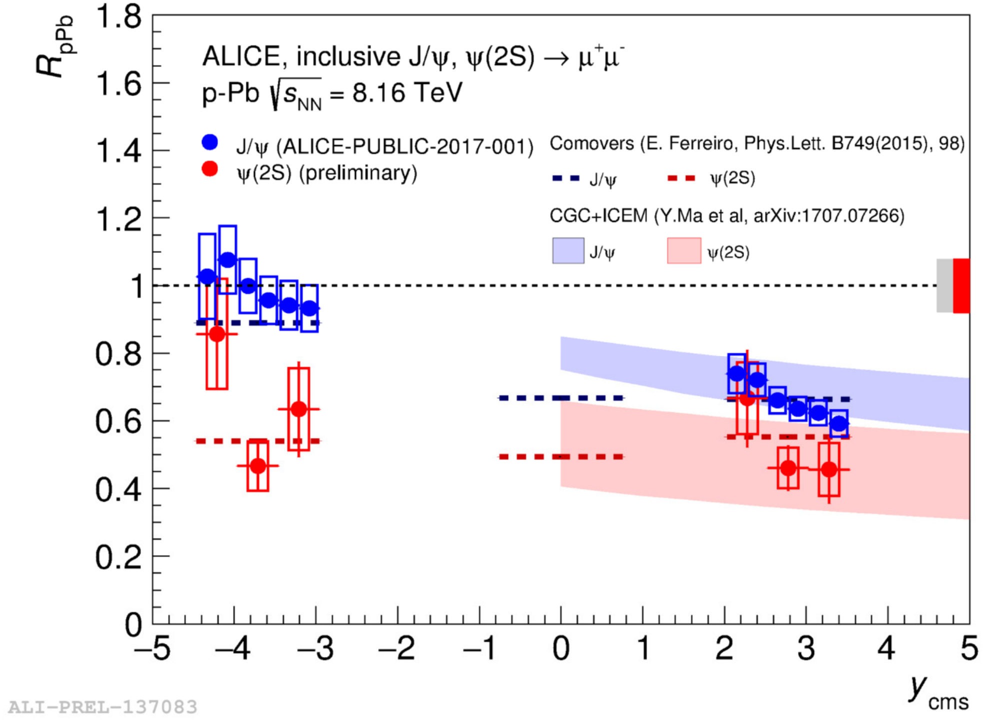
Total significance (forward + backward, 5.02+8.16 TeV) ~5σ

Values are similar to Pb-Pb:

common mechanism at the origin of the J/ψ v_2?

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





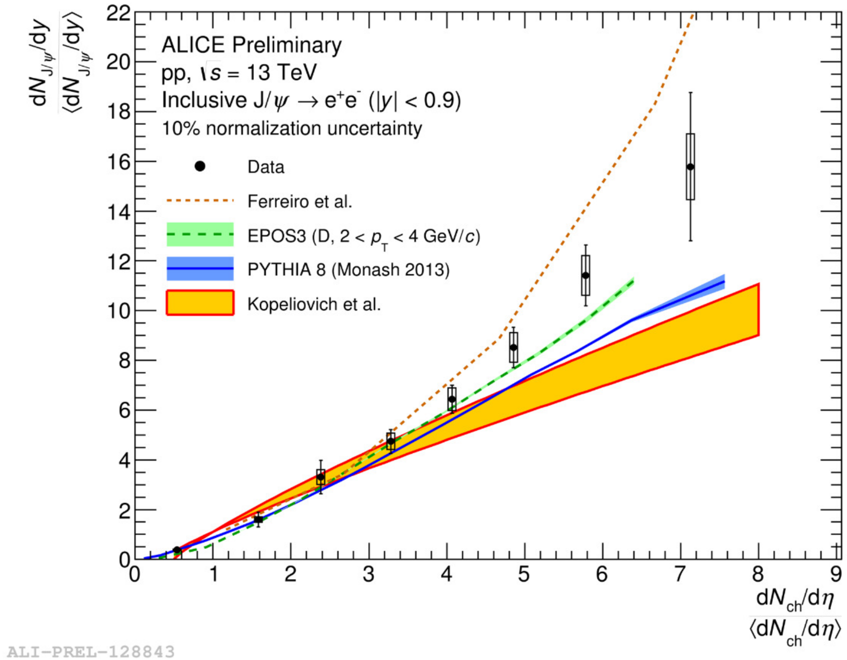
Need final state effects!

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

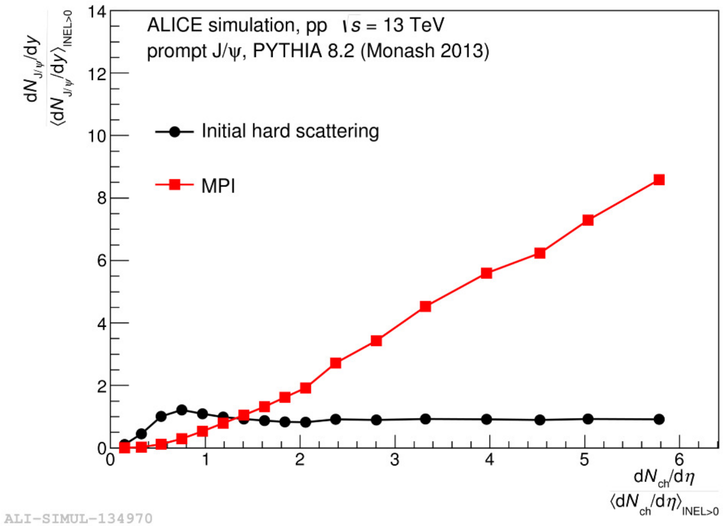
Results on J/ψ production as a function of multiplicity

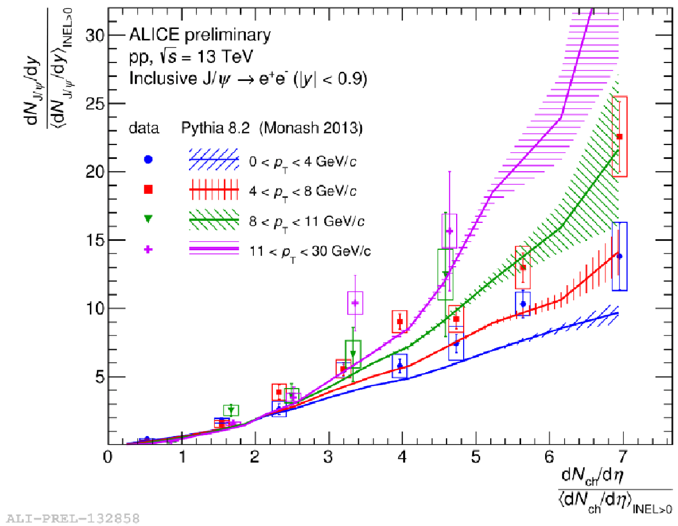
J/ψ yield vs event multiplicity in pp collisions ($\sqrt{s}$ = 13 TeV)



- 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

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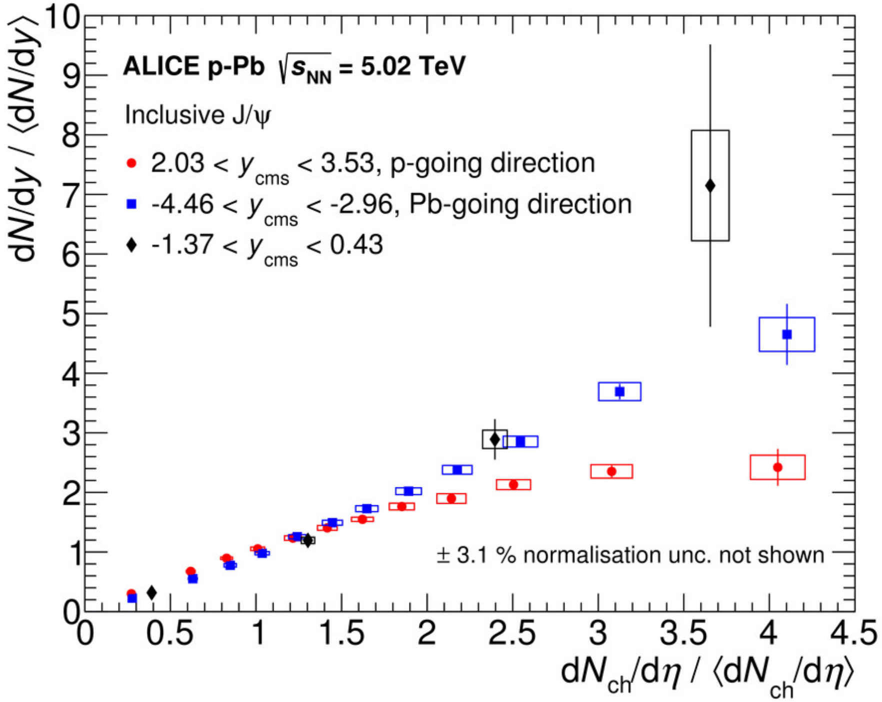
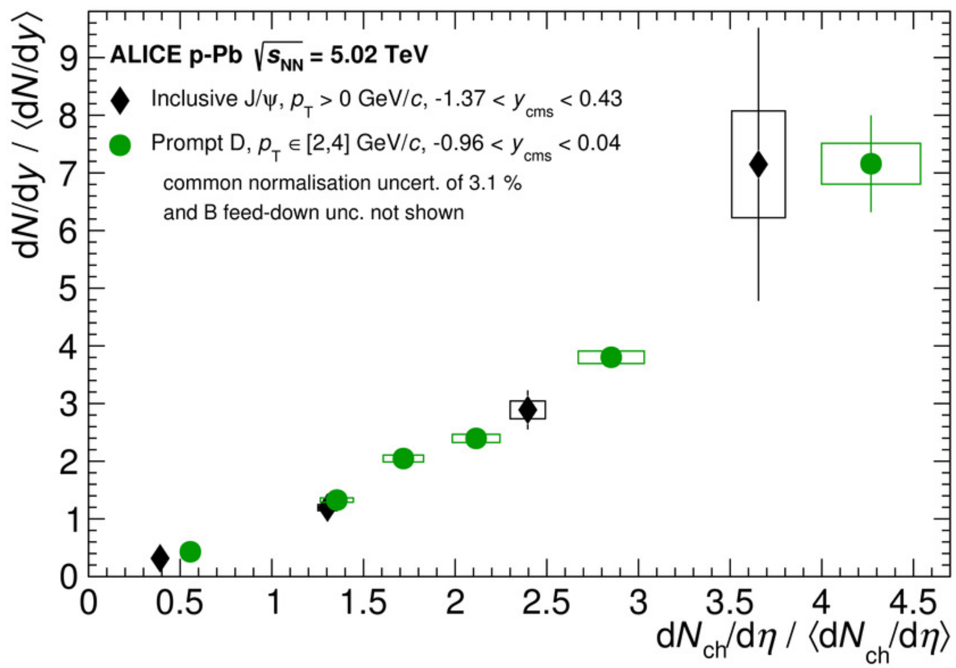




Multiplicities up to 4 times the average reached

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!

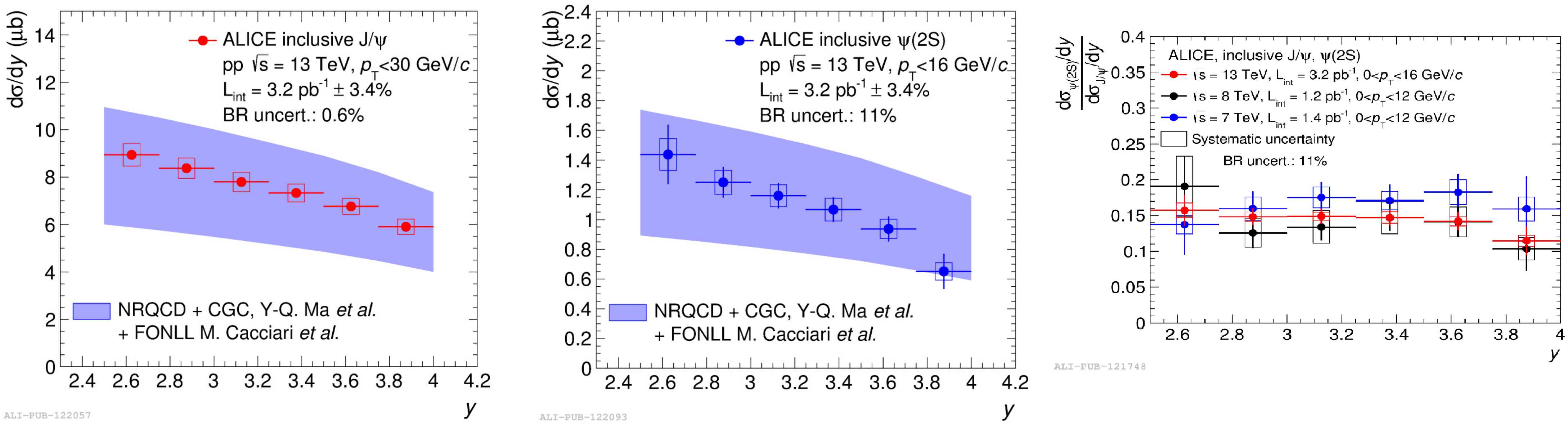
Conclusions

- 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/ψ 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 ψ(2S) (pp 13 TeV)

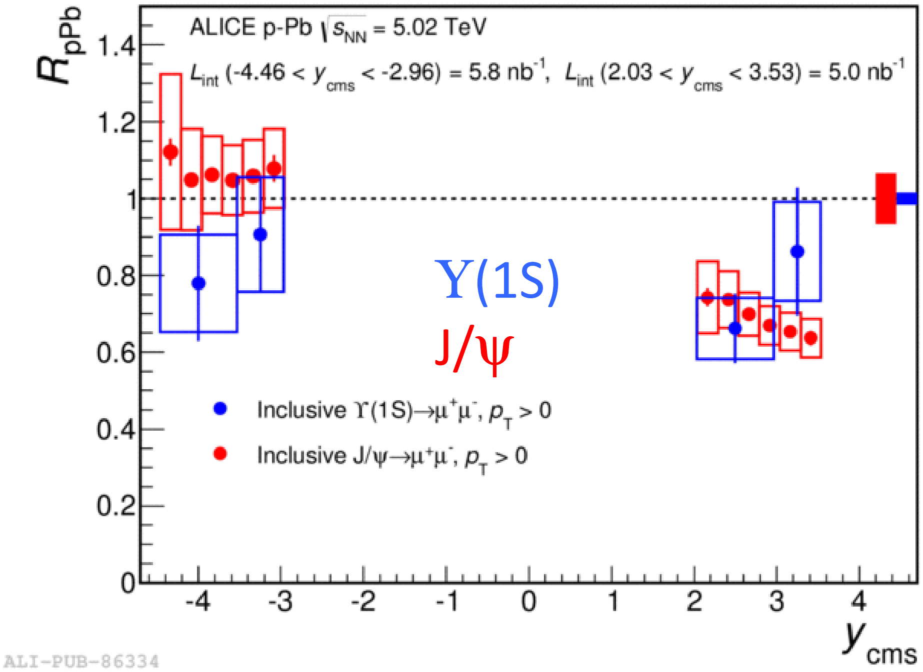
Eur. Phys. J. C (2017) 77

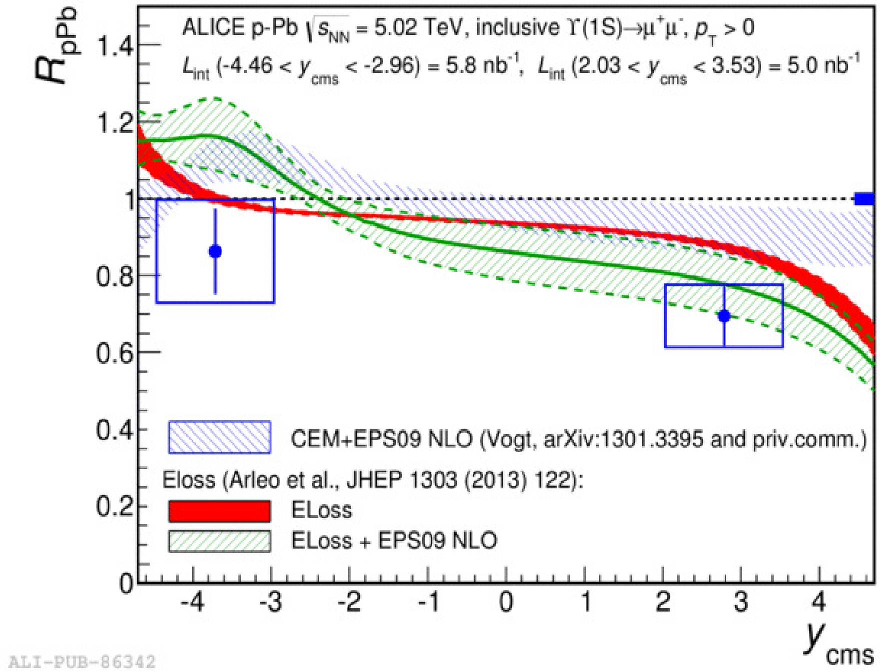


Rapidity dependence is reproduced within uncertainties by CGC+NRQCD+FONLL, for both resonance

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

Υ(1S) nuclear modification factor in Run-I p-Pb



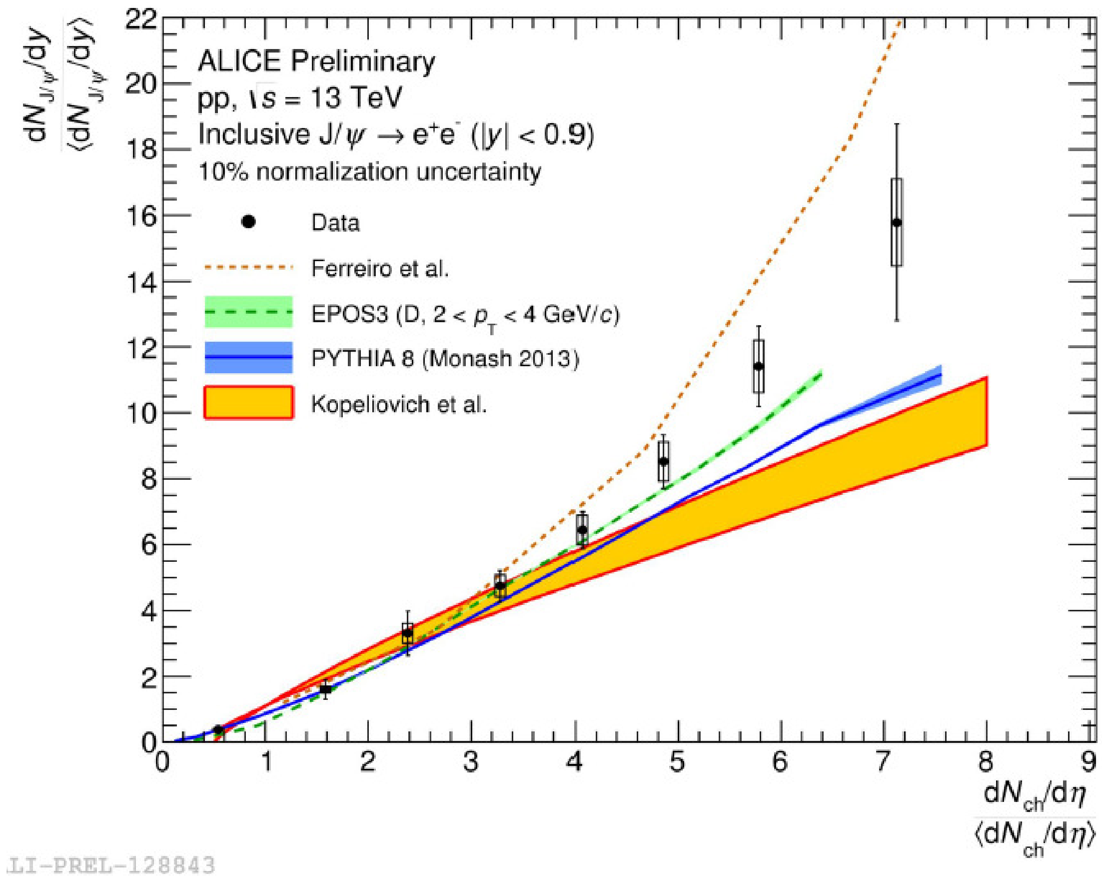


- Υ R_{pPb} **compatible with J/ψ** within uncertainties
- **Models** including shadowing and energy loss tend to **overpredict R_{pPb}** at backward rapidity

- **Υ(2S) to Υ(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)

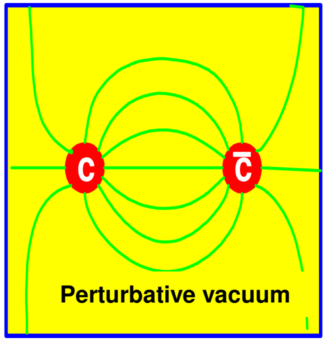
PYTHIA8: MPI and saturation of soft particle production via color reconnection.
(Sjostrand et al.,Comput.Phys.Commun.178(2008)852)

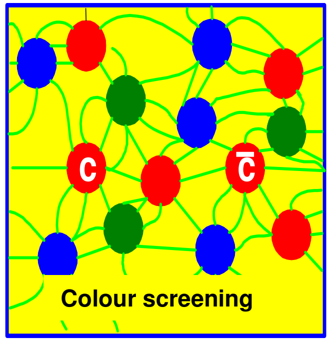
Kopeliovich et al: higher Fock states.
(Kopeliovich et al., PRD88 (2013) 116002)

Motivation: Pb-Pb collisions

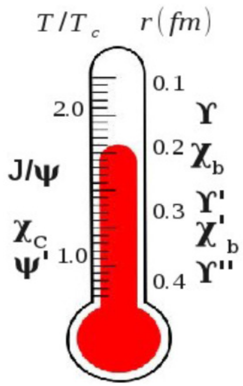
- Bound states of heavy quarks, produced in hard collisions and crossing the medium throughout its evolution

- quarkonium **suppression by colour screening** in a deconfined medium was one of the first proposed signatures for Quark-Gluon Plasma (Matsui, Satz 1986)

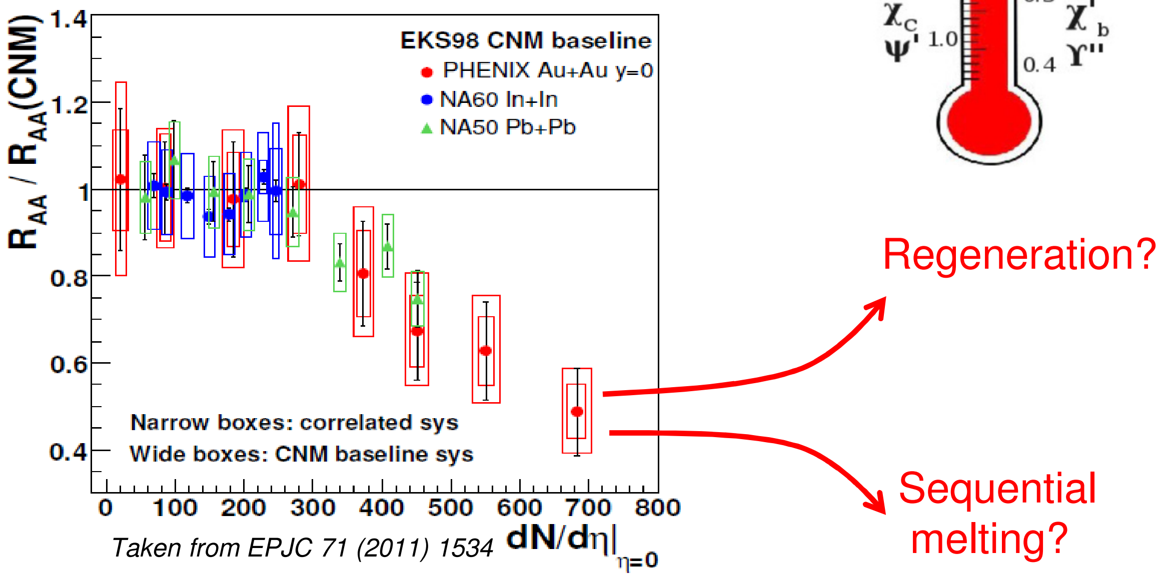




- excited states expected to be suppressed at lower temperature (sequential suppression)
  → quarkonia as a «thermometer» of the plasma



- **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?



Taken from EPJC 71 (2011) 1534

- **bottomonium production** accessible at the LHC