Inclusive ψ(2S) production in p-Pb collisions with ALICE at the LHC

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ALICE

XXIV Quark Matter Darmstadt
May 19-24 2014

Outline

- ψ**(2S) results from the 2013 p-Pb run:**
  - ψ(2S) production as a function of:
    - Rapidity (backward+forward) **FINAL RESULTS arXiv:1405.3796**
    - Transverse momentum **NEW!**
    - Event activity **NEW!**
  - Comparison with J/ψ results and theoretical models

ψ(2S) in p-A collisions

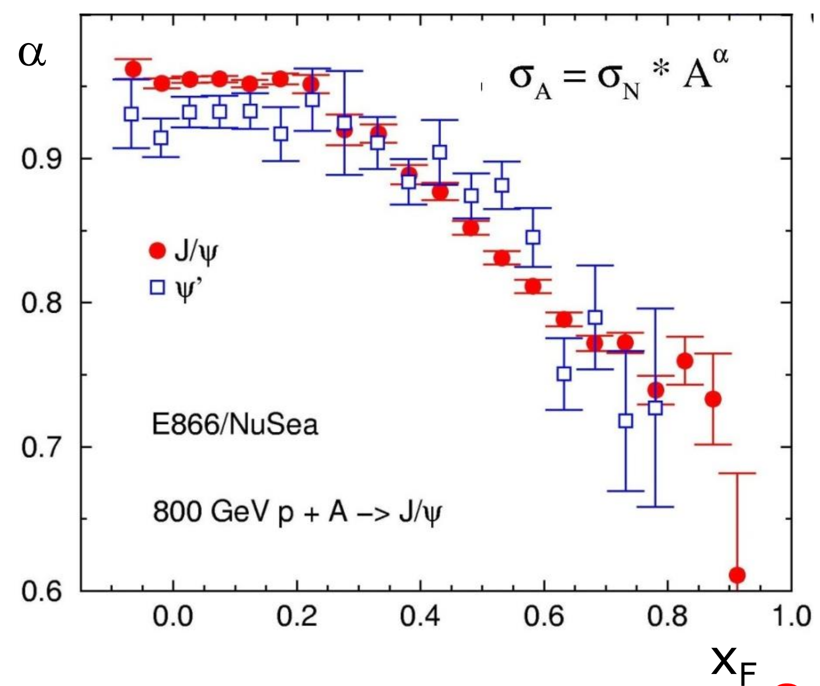
ALICE

- Being a more weakly bound state than the J/ψ, the ψ(2S) is another interesting probe to investigate charmonium behaviour in the medium
  - J/ψ and ψ(2S) significantly affected by cold nuclear matter (CNM) effects as shadowing, energy loss and $c\bar{c}$ break-up

- Low energy ψ(2S) p-A results from NA50, E866 and HERA-B:

mid-*y* (x_F~0):
ψ(2S) suppression stronger than J/ψ one, interpreted in terms of pair break-up
→ charmonium formation time (~0.1fm/c) < crossing time
→ fully formed resonances traversing the nucleus!

forward-*y* (high x_F):
suppression becomes identical
→ formation time > crossing time
→ dominated by energy loss



E866 Collab., PRL 84 (2000) 3256

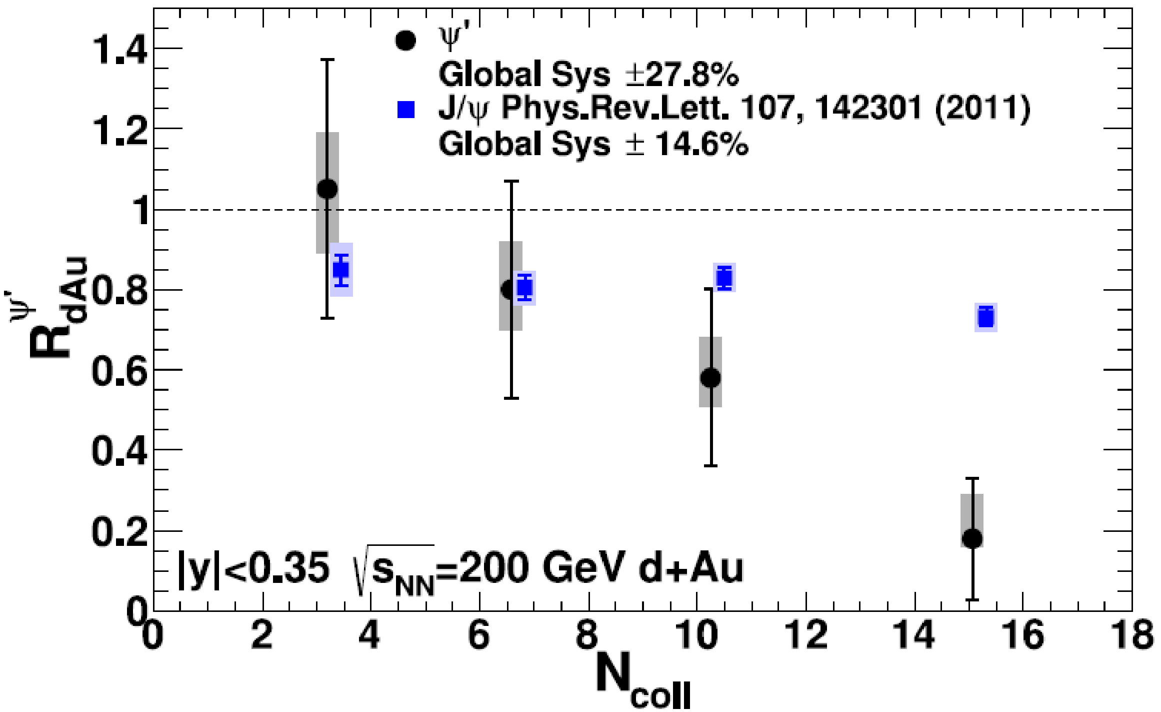
ψ(2S) in d-Au collisions

Being a more weakly bound state, wrt the J/ψ, the ψ(2S) is another interesting probe to investigate charmonium behaviour in the medium

Recently, a ψ(2S) suppression stronger than the J/ψ one, has been observed by PHENIX in mid-*y* d-Au collisions

→ unexpected because, at RHIC, time spent by the $c\bar{c}$ pair in the nucleus should be shorter than charmonium formation time

PHENIX Collab., PRL 111 (2013) 202301

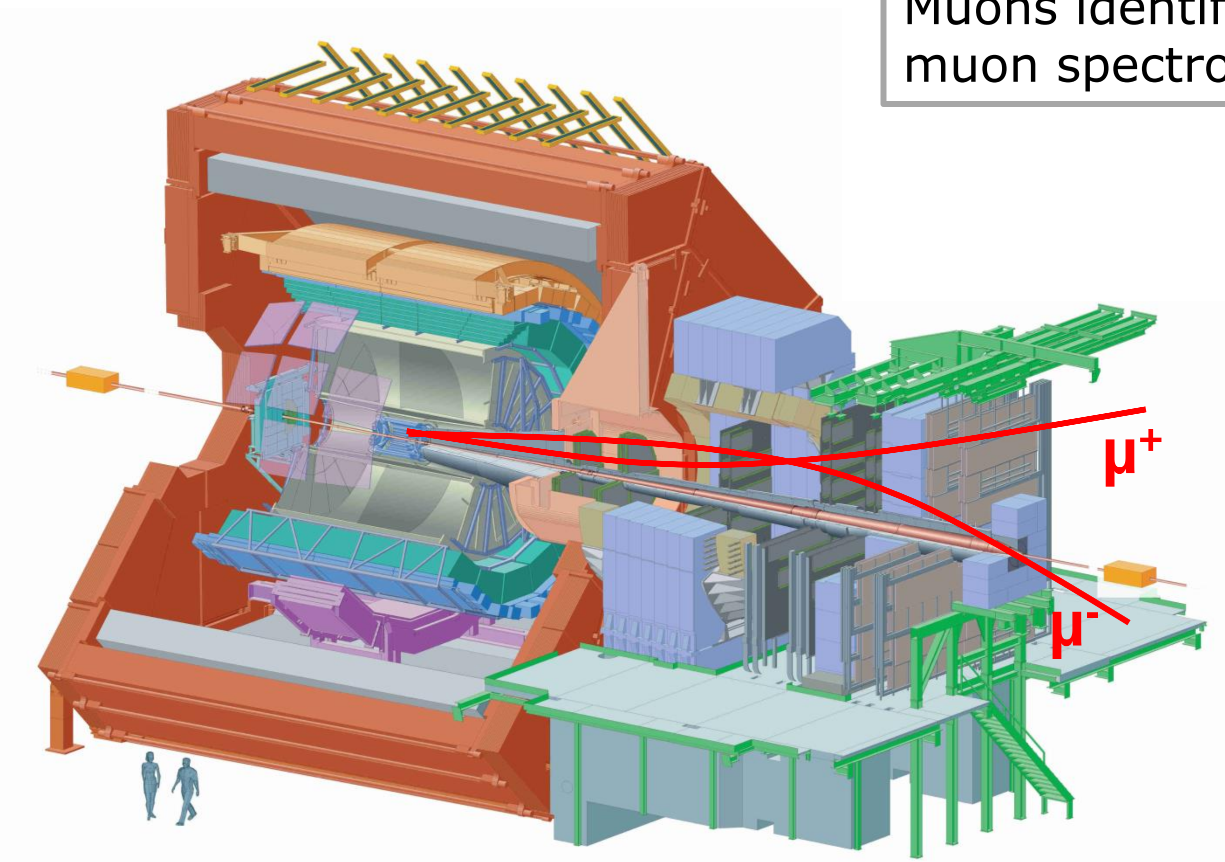


ψ(2S) measurement in ALICE

ALICE results presented in this talk refer to inclusive ψ(2S) production in the $\mu^+\mu^-$ decay channel down to zero p_T

Forward muon arm **J/ψ $\rightarrow \mu^+\mu^-$**
(2.5<y_{LAB}<4)

Muons identified and tracked in the muon spectrometer



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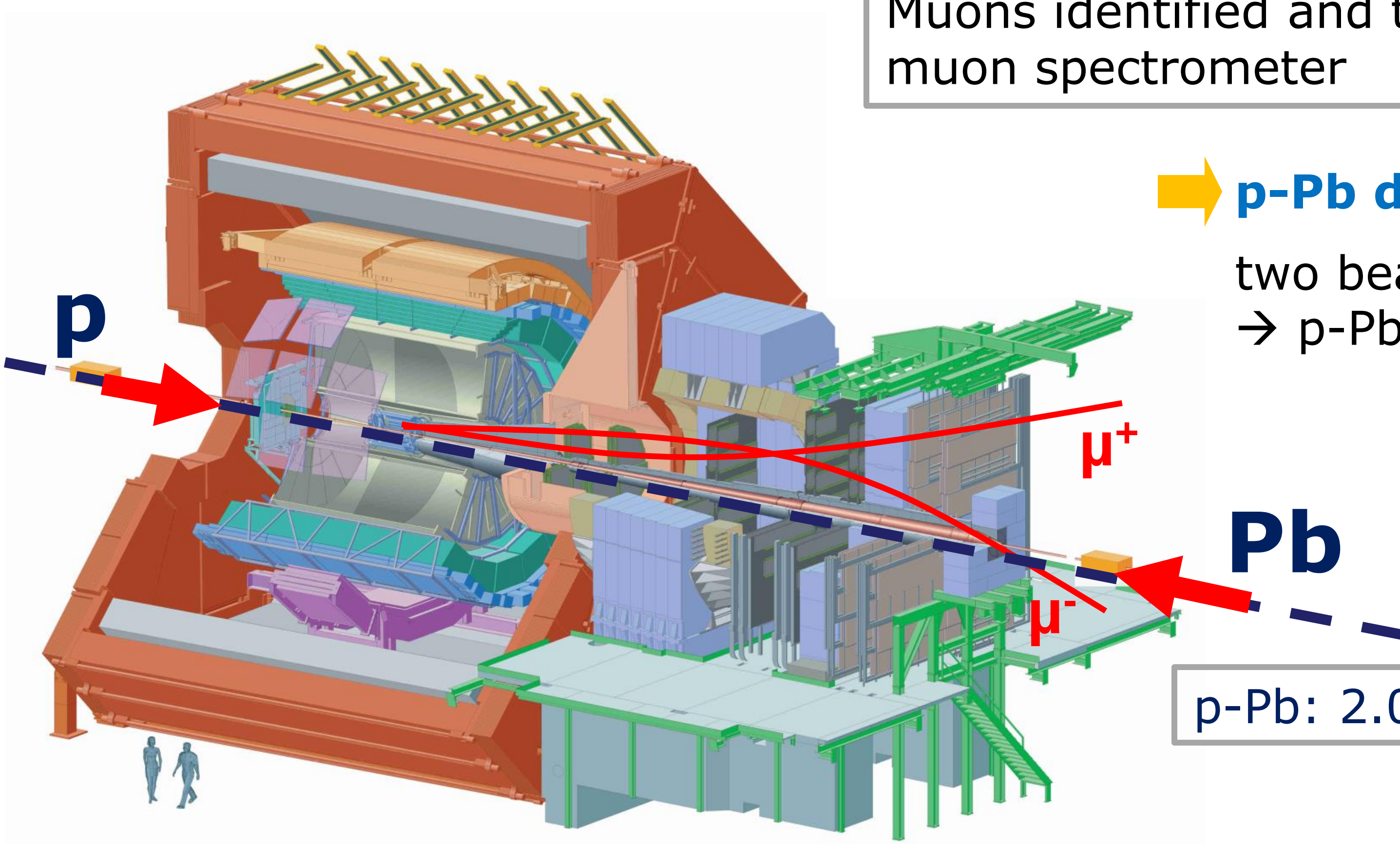

- **p-Pb data taking:**

two beam configurations
→ p-Pb and Pb-p

p-Pb: 2.03<y_{CMS}<3.53

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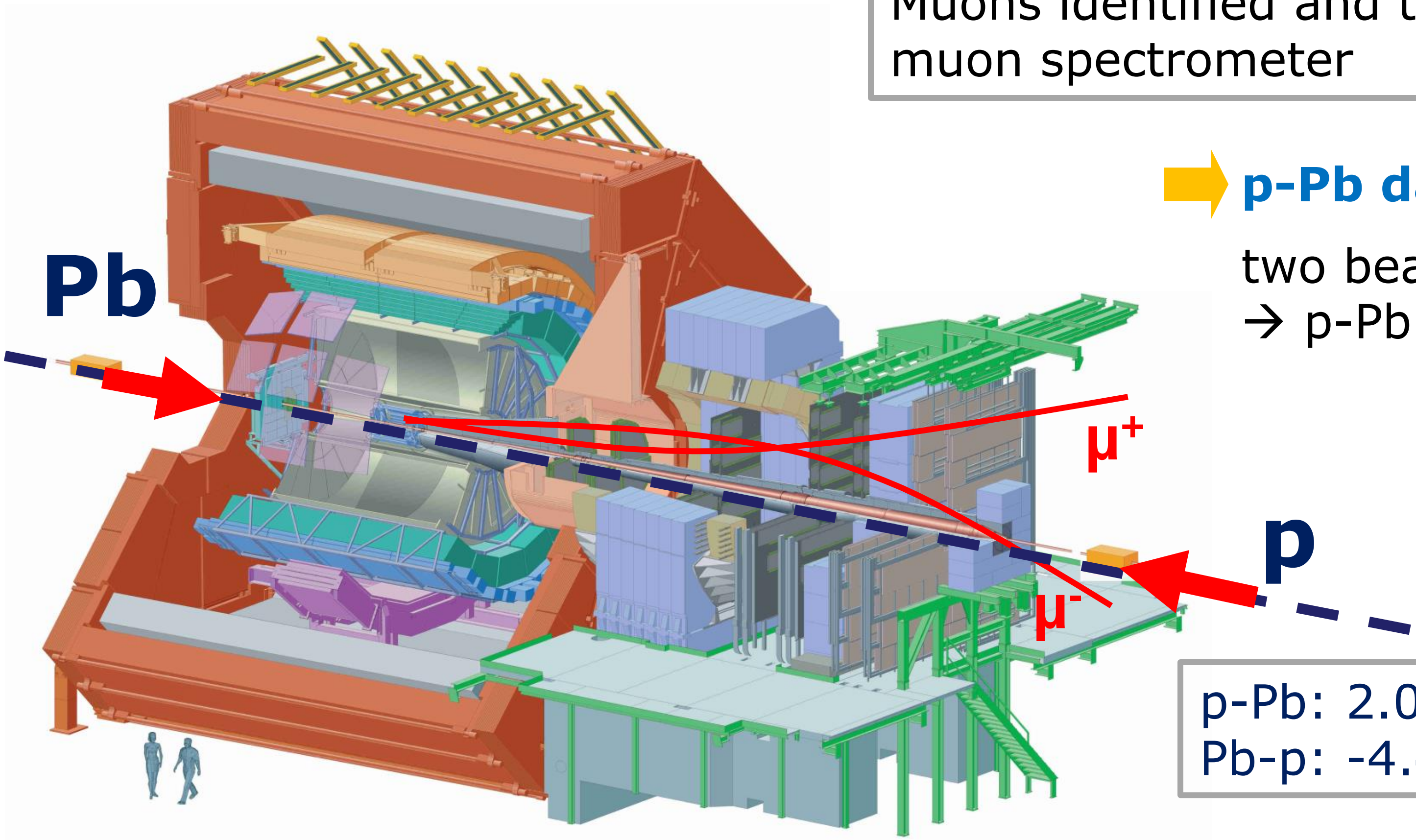


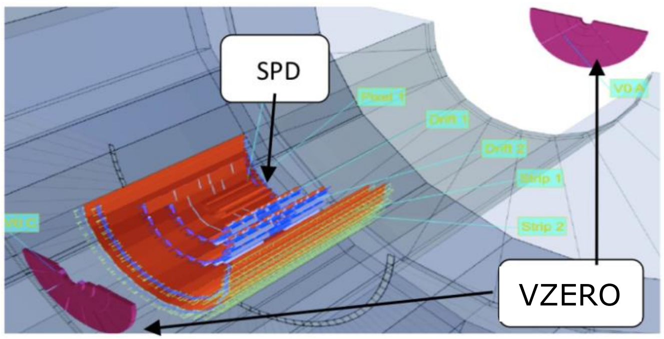
- **p-Pb data taking:**

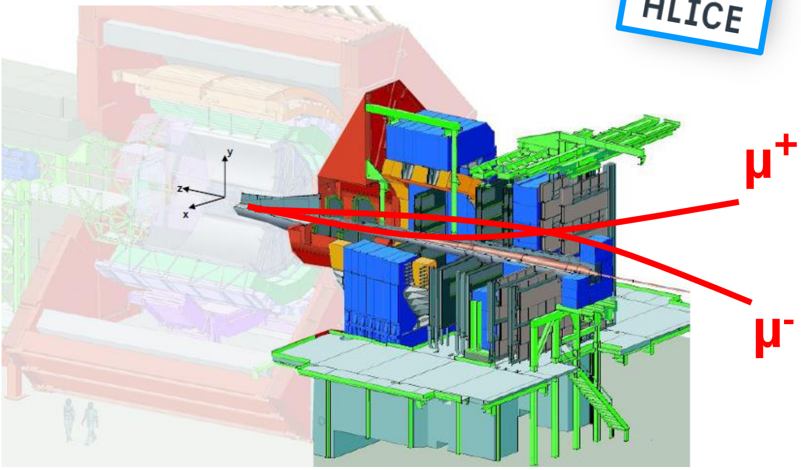
two beam configurations
→ p-Pb and Pb-p

p-Pb: $2.03<y_{CMS}<3.53$
Pb-p: $-4.46<y_{CMS}<-2.96$

Event and track selection

Event selection:
- Rejection of beam gas and EM interactions (VZERO and ZDC)
- SPD used for vertex determination





Muon track selection:
- Muon tracking-trigger matching
- $-4<\eta_\mu<-2.5$
- $17.6<R_{abs}<89$ cm
  (R_{abs}= track radial position at the absorber end)
- $2.5<y^{\mu\mu}_{LAB}<4$
- cut on the transverse distance between vertex and μ tracks

Trigger:
- Dimuon trigger: coincidence of a minimum bias (MB) interaction with two opposite sign muon tracks in the Muon Spectrometer trigger chambers

Event activity:
- ZDC (ZN) energy classes

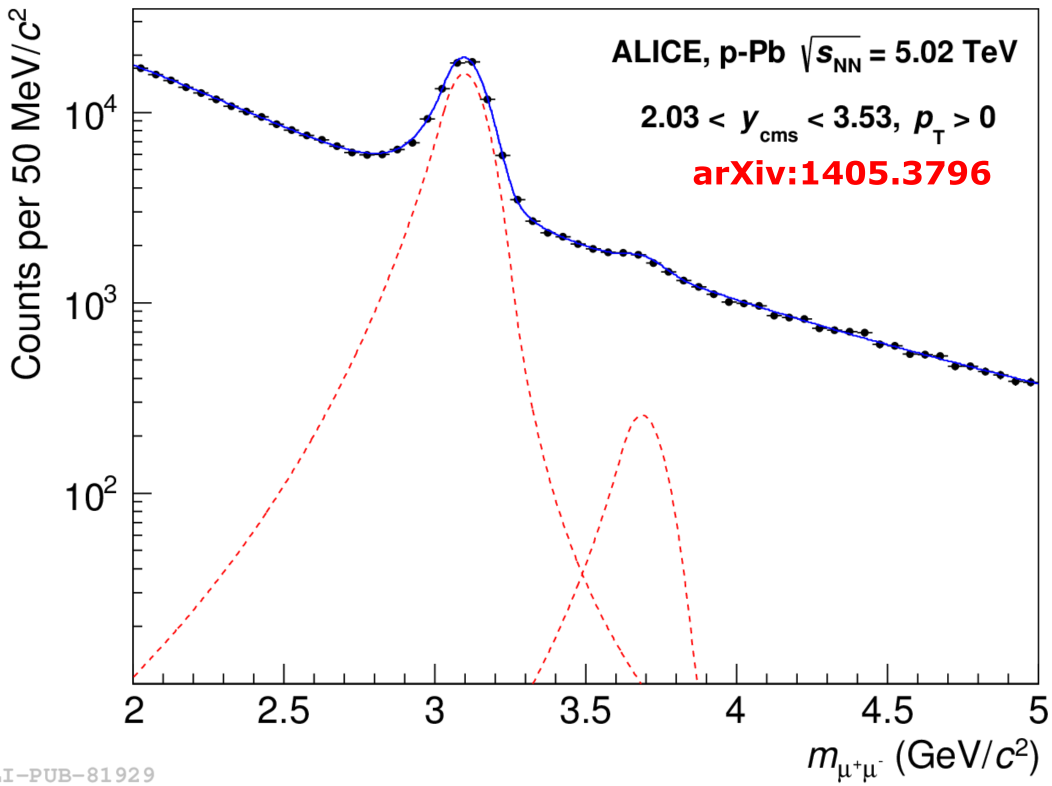
A. Toia's talk

$\psi(2S) \to \mu^+\mu^-$ signal

- Charmonium yields extracted fitting the opposite sign dimuon invariant mass spectrum with a superposition of signal and background shapes:

- **Signal:**
  shapes described by an extended Crystal Ball function or other pseudo-Gaussian phenomenological shapes

- **Background:**
  several functions tested, as a variable width Gaussian or combinations of exponential x polynomial functions



- Total number of $\psi(2S)$:

forward-y → $N_{pPb}(\psi(2S))$ = 1069 ± 130(stat) ± 102(syst)

backward-y → $N_{Pbp}(\psi(2S))$ = 697 ± 111(stat) ± 65(syst)

$\psi(2S) \rightarrow \mu^+\mu^-$ signal

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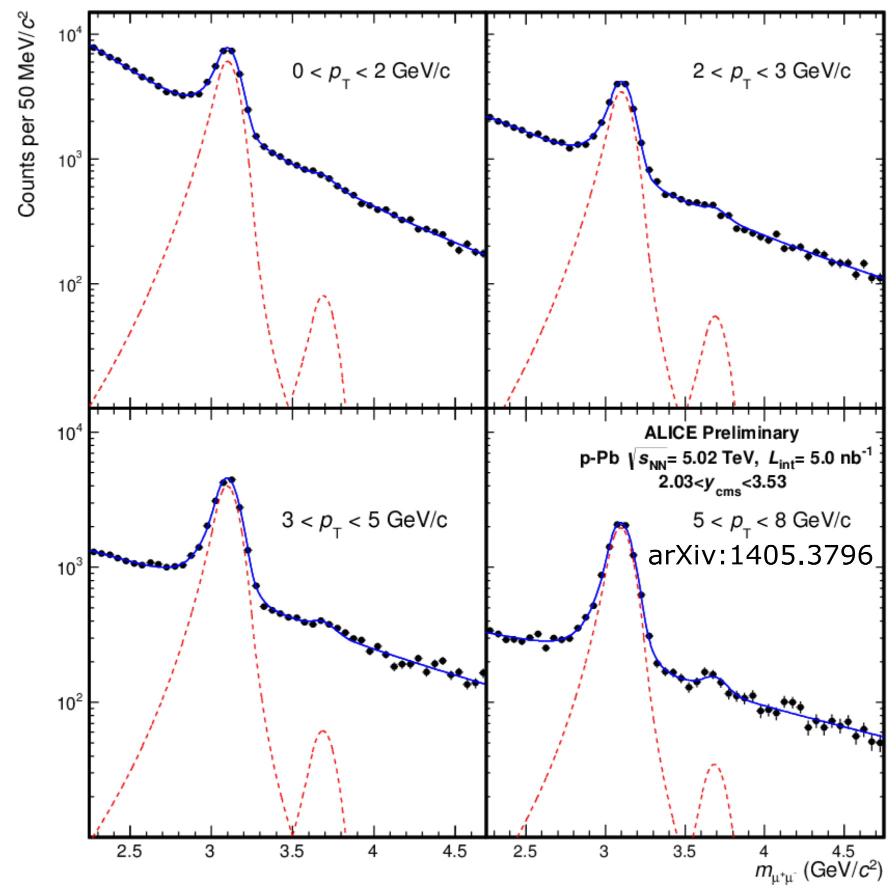


- **Signal:**
  shapes described by an extended Crystal Ball function or other pseudo-Gaussian phenomenological shapes
- **Background:**
  several functions tested, as a variable width Gaussian or combinations of exponential x polynomial functions

- The $\psi(2S)$ statistics allows the yields to be extracted also as a function of p_T or event activity

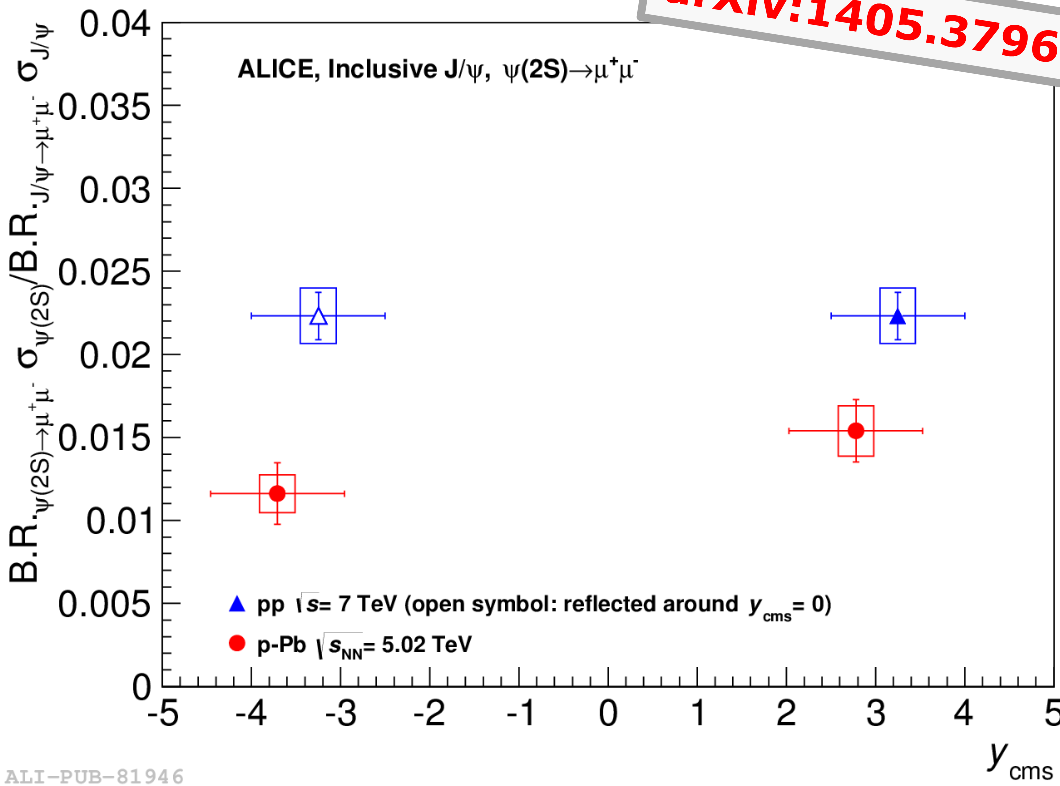
M. Leoncino's poster F-28

$\psi(2S)/J/\psi$

A strong decrease of the $\psi(2S)$ production in p-Pb, relative to J/ψ, is observed with respect to the pp measurement ($2.5<y_{cms}<4$, $\sqrt{s}$=7TeV)

arXiv:1405.3796

B. Paul's poster F-44

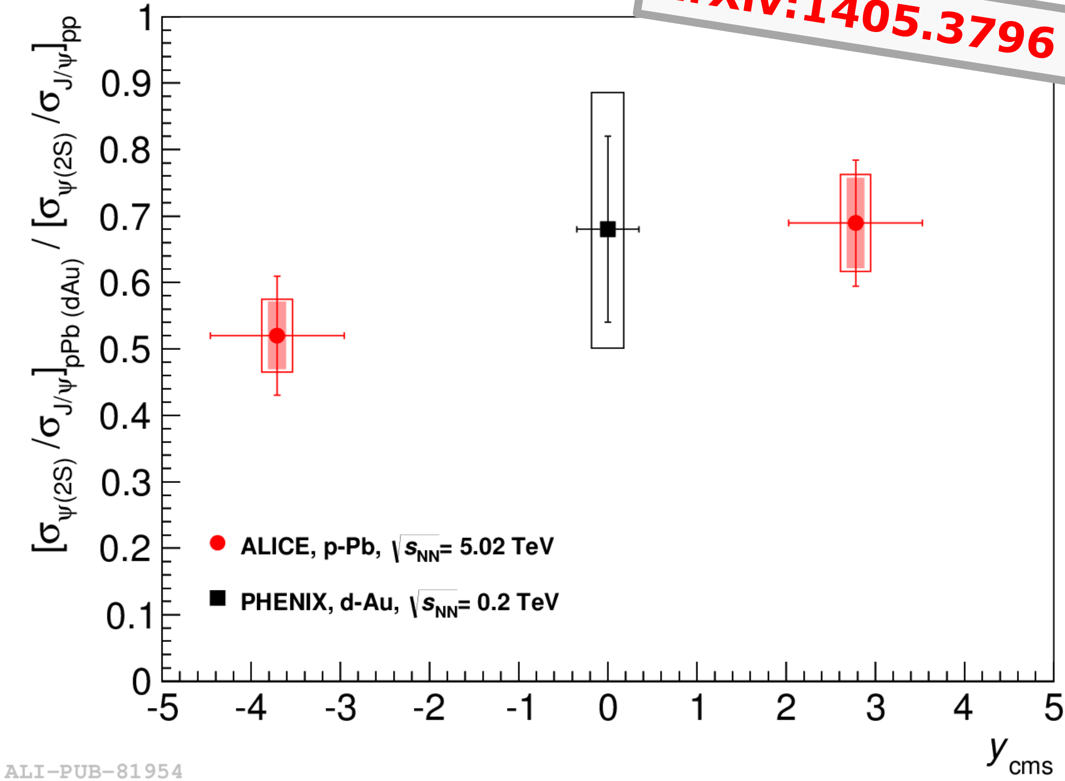


Warning:
different $\sqrt{s}$ and slightly different y range between p-Pb and pp

Compared to pp, the $\psi(2S)$ is more suppressed than the J/ψ to a 2.0σ level at forward-y and 3.2σ at backward-y

ψ(2S)/J/ψ

A strong decrease of the ψ(2S) production in p-Pb, relative to J/ψ, is observed with respect to the pp measurement ($2.5<y_{cms}<4$, $\sqrt{s}$=7TeV)



The double ratio allows a direct comparison of the J/ψ and ψ(2S) production yields between experiments

Similar effect seen by PHENIX in d-Au collisions, at mid-y, at $\sqrt{s_{NN}}$=200 GeV

Line: statistical uncertainty
Shaded box: partially correl. syst. unc.
Open box: uncorrelated syst. uncertainty

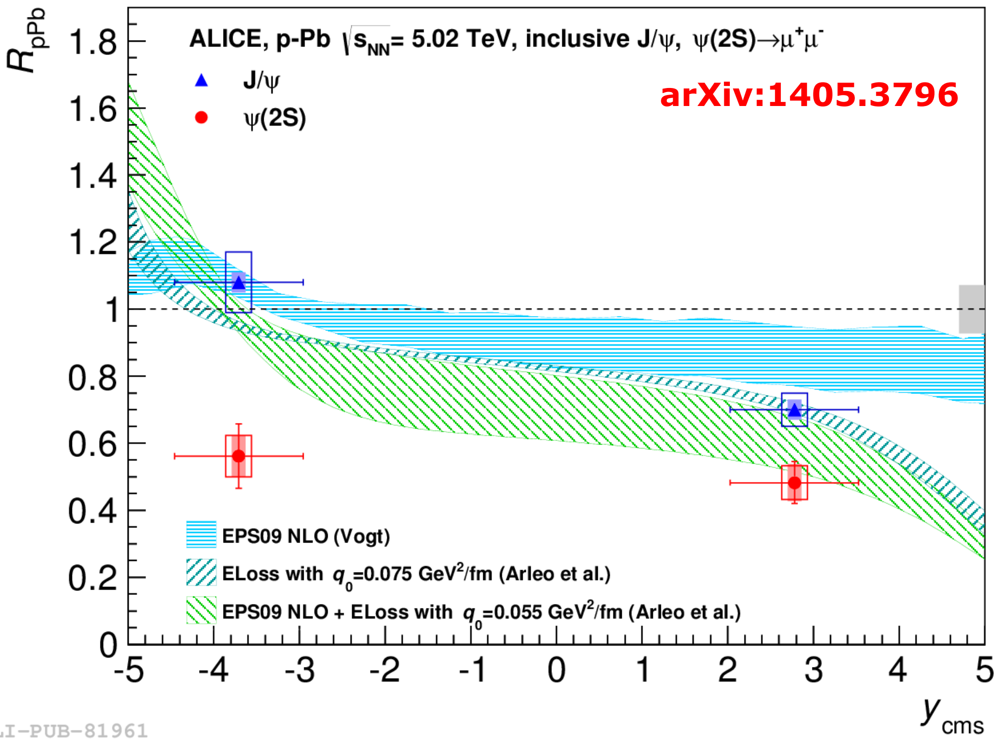
$[\psi(2S)/J/\psi]_{pp}$ variation between ($\sqrt{s}$=7TeV, 2.5<y<4) and ($\sqrt{s}$=5.02TeV, 2.03<y<3.53 or -4.46<y<-2.96) evaluated using CDF and LHCb data (amounts to 8% depending on the assumptions → included in the systematic uncertainty)

$\psi(2S)$ R_{pPb} vs y_{cms}

- The $\psi(2S)$ suppression with respect to binary scaled pp yield can be quantified with the nuclear modification factor

$$R_{pA}^{\psi(2S)} = R_{pA}^{J/\psi} \times \frac{\sigma_{pA}^{\psi(2S)}}{\sigma_{pA}^{J/\psi}} \times \frac{\sigma_{pp}^{J/\psi}}{\sigma_{pp}^{\psi(2S)}}$$

(again, used $\sqrt{s}$=7TeV pp ratio including an 8% systematic uncertainty related to the different kinematics)



- $\psi(2S)$ suppression is stronger than the J/ψ one and reaches a factor ~2 wrt pp

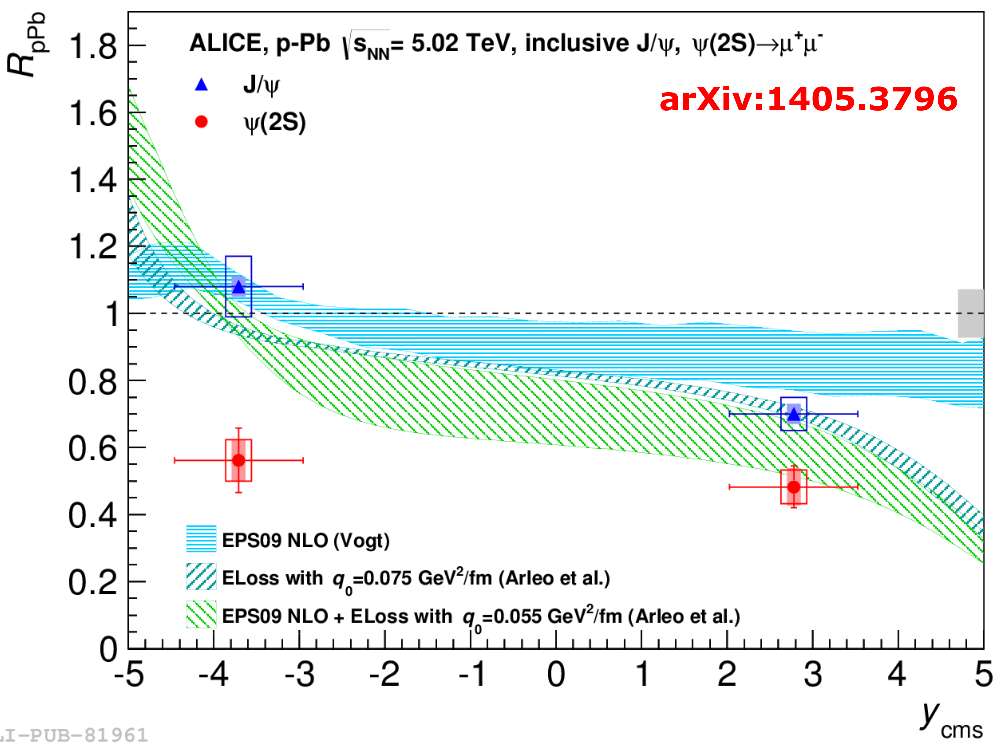
- Same initial state CNM effects (shadowing and coherent energy loss) expected for both J/ψ and $\psi(2S)$

Theoretical predictions in disagreement with $\psi(2S)$ result

Other mechanisms needed to explain $\psi(2S)$ behaviour?

$\psi(2S)$ R_{pPb} vs y_{cms}

- The $\psi(2S)$ suppression with respect to binary scaled pp yield can be quantified with the nuclear modification factor
  - Can the stronger suppression of the weakly bound $\psi(2S)$ be due to break-up of the fully formed resonance in CNM?



possible if formation time (τ_f ~0.05-0.15fm/c) < crossing time (τ_c)

forward-y:
τ_c~10^{-4} fm/c
backward-y:
τ_c~$7\cdot10^{-2}$ fm/c

$$\tau_c = \frac{\langle L \rangle}{(\beta_z \gamma)}$$

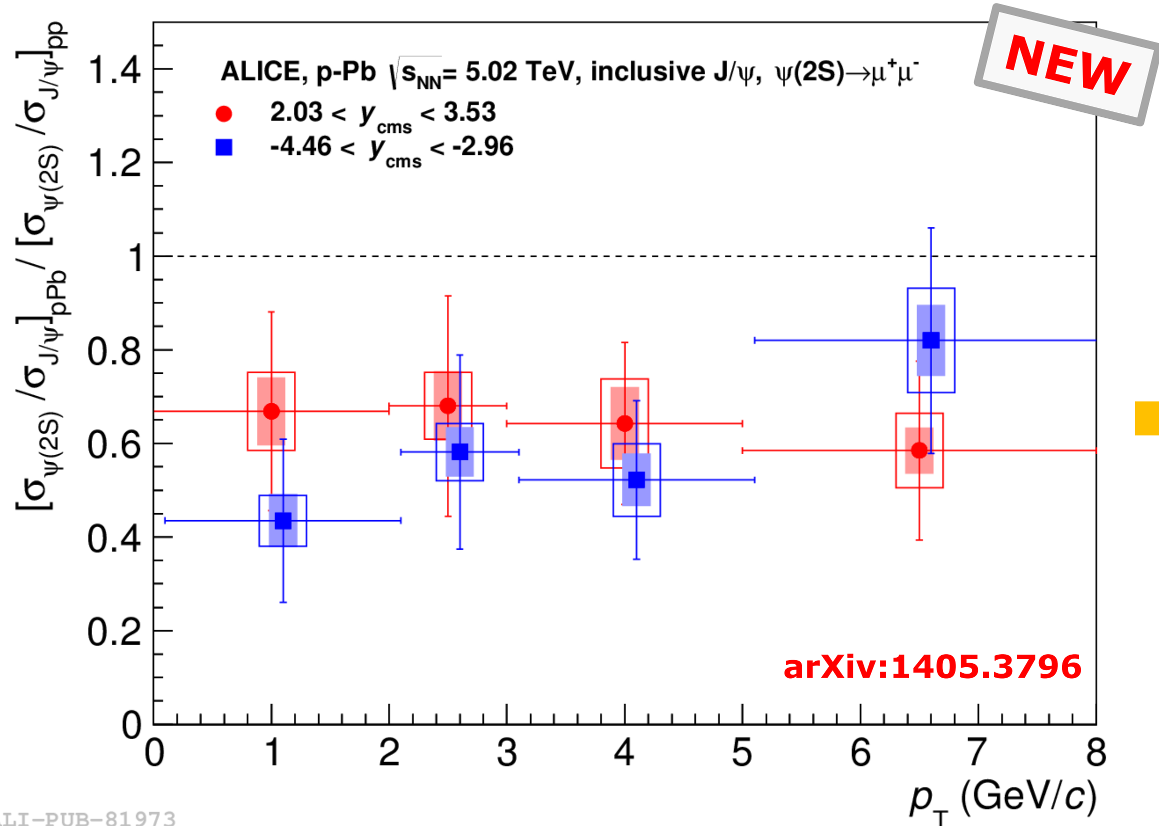
D. McGlinchey, A. Frawley and R.Vogt, PRC 87,054910 (2013)

- break-up effects excluded at forward-y
- at backward-y, since $\tau_f \sim \tau_c$, break-up in CNM can hardly explain the very strong difference between J/ψ and $\psi(2S)$ suppressions

- Final state effects related to the (hadronic) medium created in the p-Pb collisions?

$[\psi(2S)/J/\psi]_{pPb}$ / $[\psi(2S)/J/\psi]_{pp}$ vs p_T

- The sizeable $\psi(2S)$ statistics in p-Pb collisions allows the differential study of $\psi(2S)$ production vs p_T
  - Different p_T correspond to different crossing times, with τ_c decreasing with increasing p_T



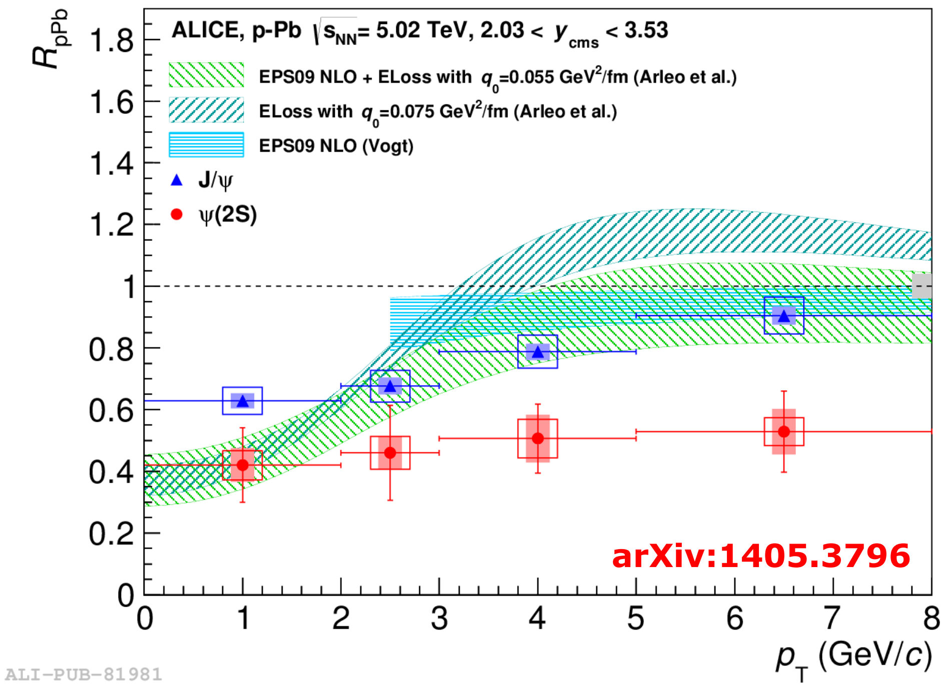
backward-y: τ_c~0.07 (p_T=0) and ~0.03 fm/c (p_T=8 GeV/c)

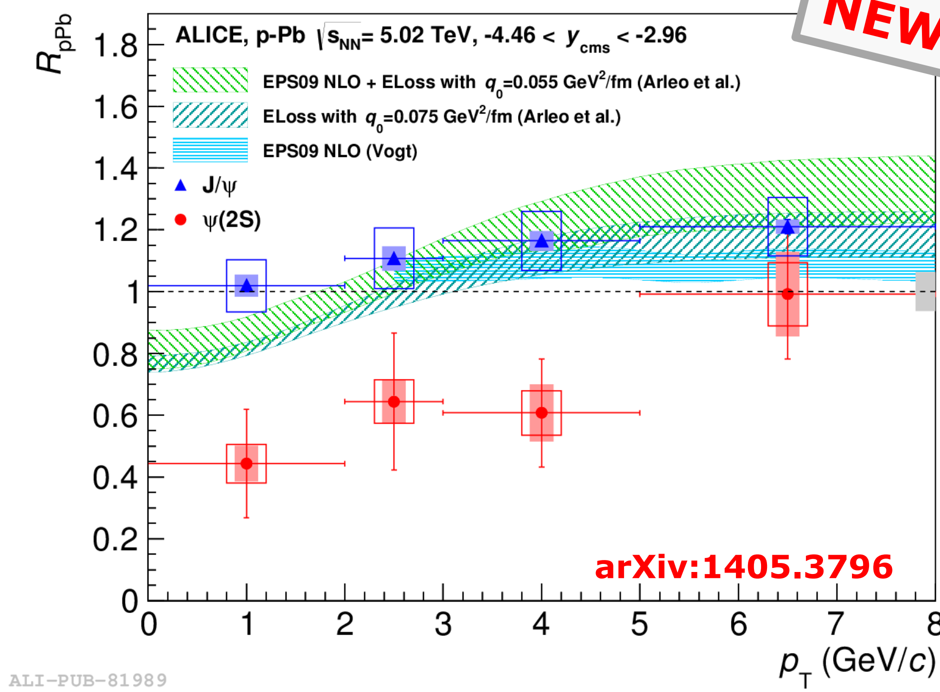
- if $\psi(2S)$ breaks-up in CNM, the effect should be more important at backward-y and low p_T

No clear p_T dependence is observed at y<0, within uncertainties

ψ(2S) R_{pPb} vs p_T

- The p_T-dependence of the R_{pPb} is also investigated





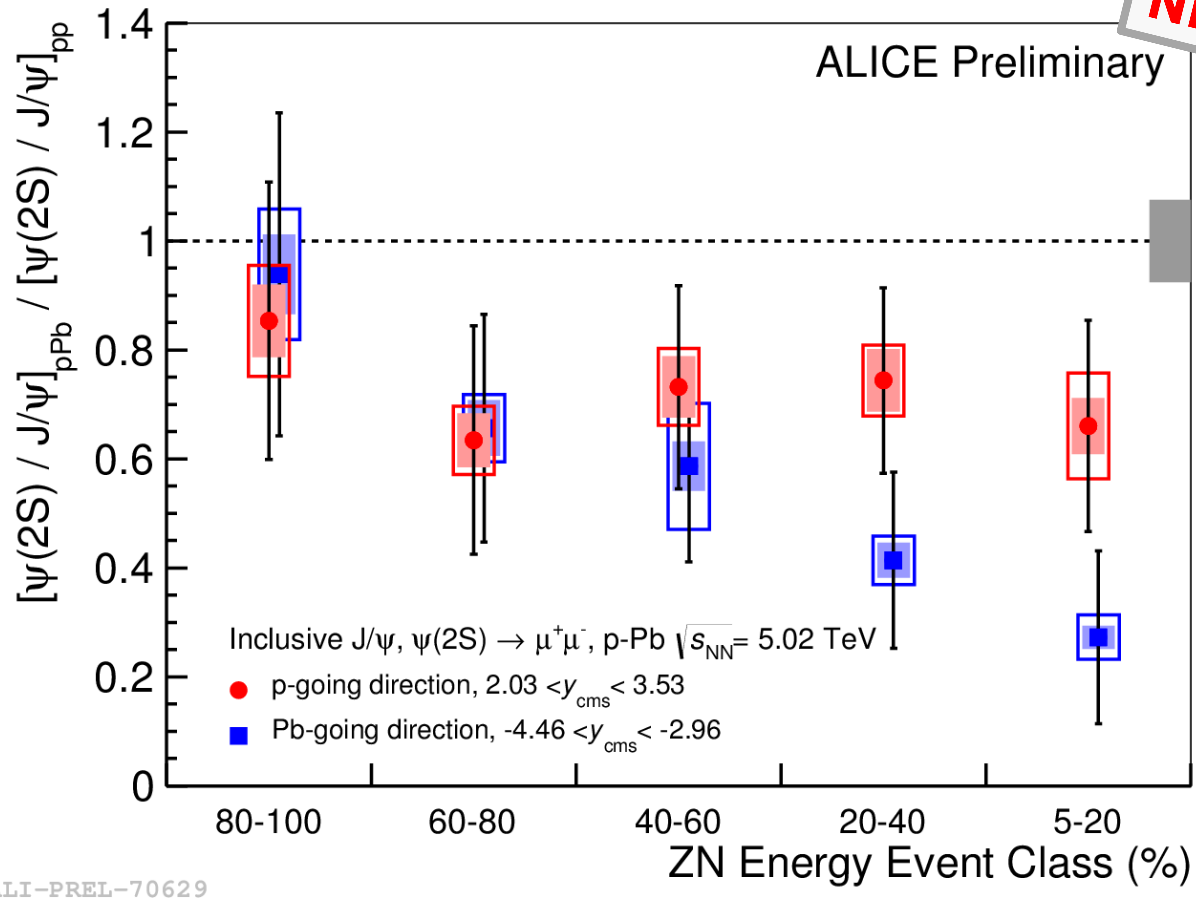
NEW

- As already observed for the p_T-integrated results, ψ(2S) is more suppressed than the J/ψ
- Theoretical models are in fair agreement with the J/ψ, but clearly overestimate the ψ(2S) results

$[\psi(2S)/J/\psi]_{pPb}$ / $[\psi(2S)/J/\psi]_{pp}$ vs event activity

- The p-Pb $\psi(2S)/J/\psi$ ratio, normalized to the pp one, is studied also as a function of the event activity

NEW

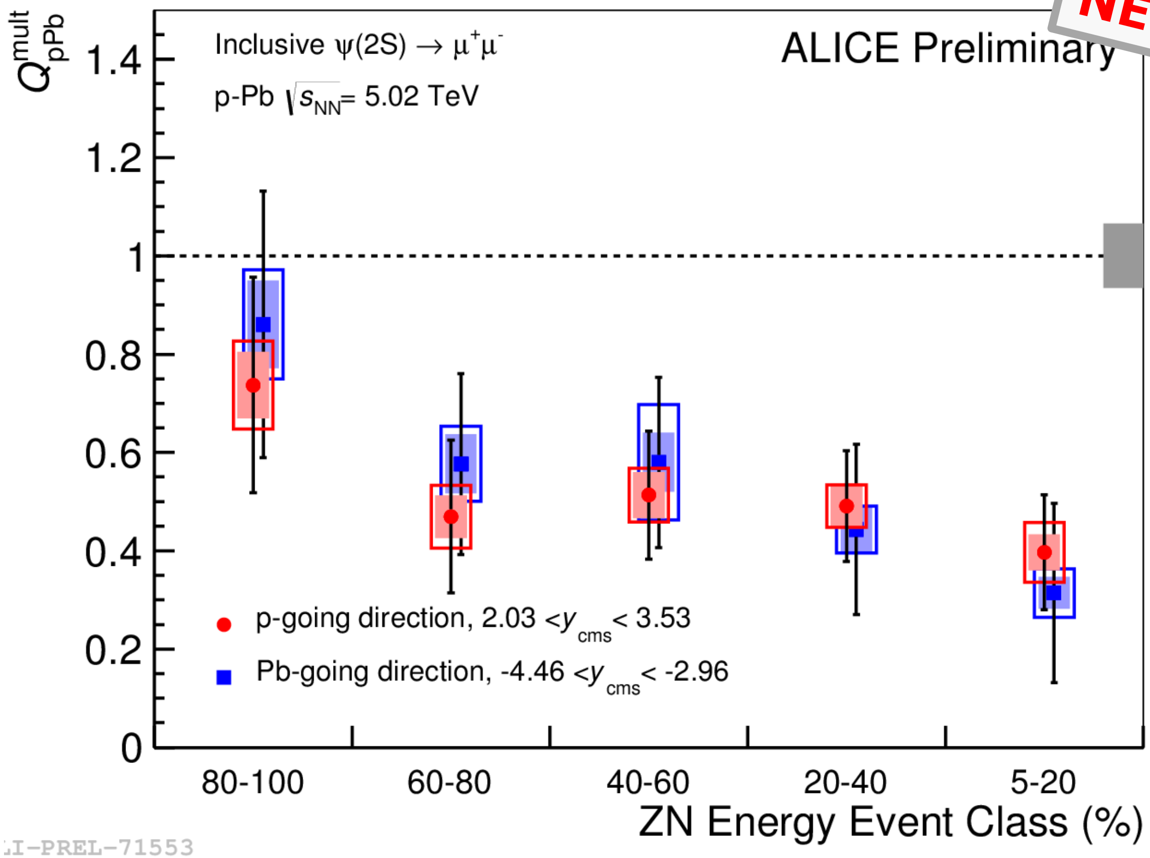


- At backward rapidity $\psi(2S)$ suppression, relative to J/ψ, increases with event activity

ψ(2S) Q_{pPb} vs event activity

- The ψ(2S) Q_{pA} is evaluated as a function of the event activity

NEW



Q_{pA} instead of R_{pA} due to potential bias from the centrality estimator, which are not related to nuclear effects

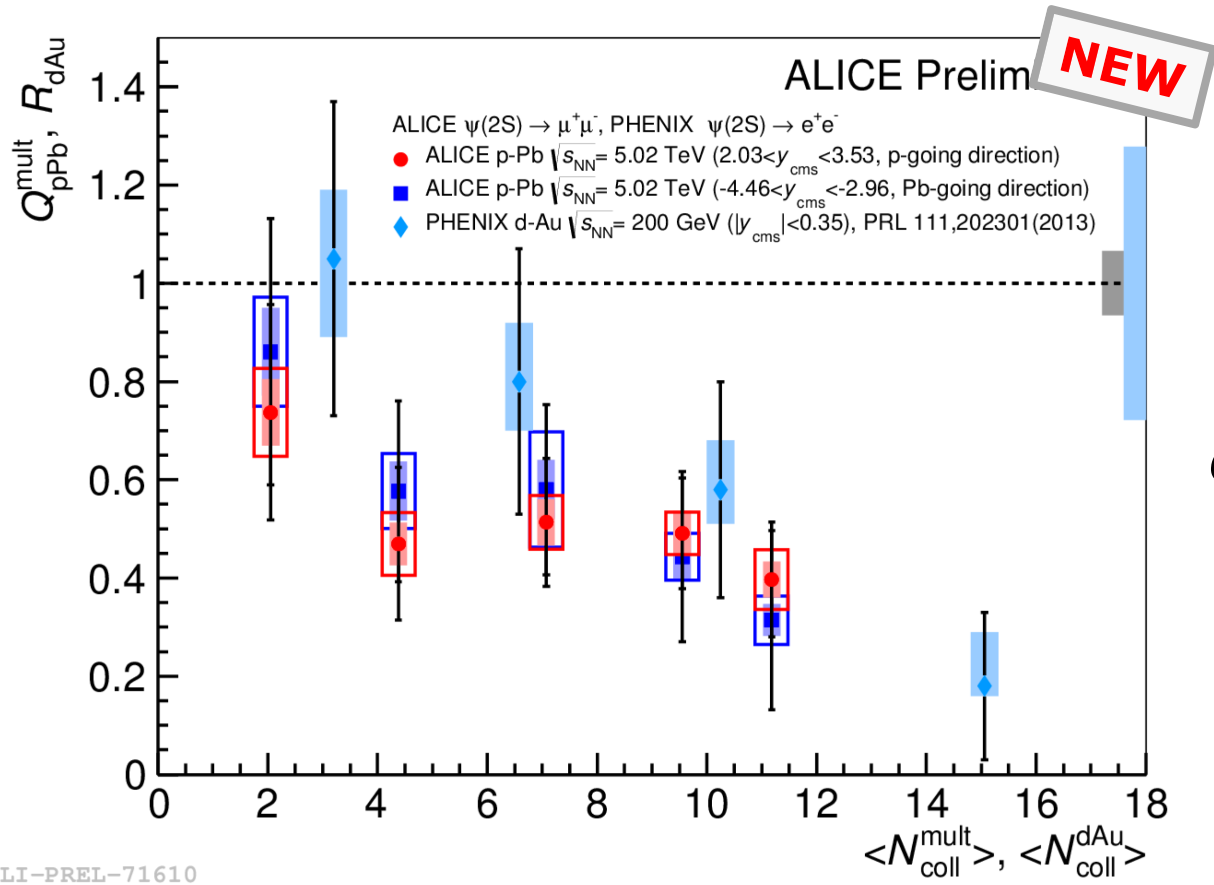
$$Q_{pA}^{\psi(2S)} = Q_{pA}^{J/\psi} \times \frac{\sigma_{pA}^{\psi(2S)}}{\sigma_{pA}^{J/\psi}} \times \frac{\sigma_{pp}^{J/\psi}}{\sigma_{pp}^{\psi(2S)}}$$

with $$Q_{pA}^{J/\psi} = \frac{Y_{pA}^{J/\psi}}{T_{pA}^{mult} \cdot \sigma_{pp}^{J/\psi}}$$

- Clear ψ(2S) suppression, increasing with event activity, both in p-Pb and Pb-p collisions
- Rather similar ψ(2S) suppression at both forward and backward rapidities

$\psi(2S)$ Q_{pPb} vs event activity

The $\psi(2S)$ Q_{pA} is evaluated as a function of the event activity



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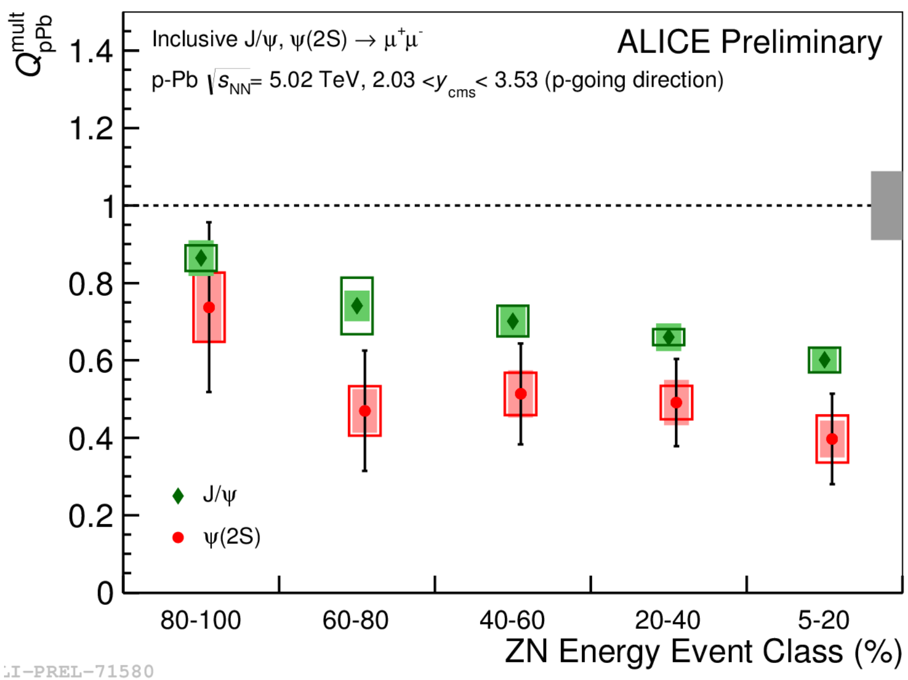
with $$Q_{pA}^{J/\psi} = \frac{Y_{pA}^{J/\psi}}{T_{pA}^{mult} \cdot \sigma_{pp}^{J/\psi}}$$

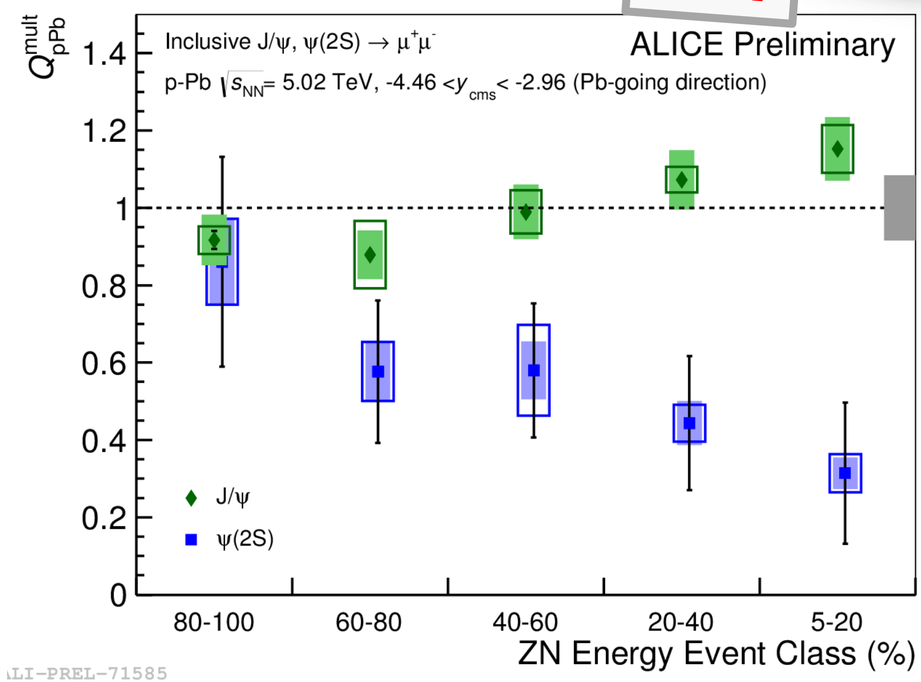
Rather similar $\psi(2S)$ suppression, increasing with N_{coll}, for both ALICE and PHENIX results

J/ψ and ψ(2S) Q_{pPb} vs event activity

NEW

- J/ψ and ψ(2S) Q_{pA} are compared vs event activity





- forward-*y:* J/ψ and ψ(2S) show a similar decreasing pattern vs event activity
- backward-*y:* the J/ψ and ψ(2S) behaviour is different, with the ψ(2S) significantly more suppressed for largest event activity classes

→ Another hint for ψ(2S) suppression in the (hadronic) medium?

J. Martin's talk, I. Lakomov's poster F-26

Conclusions

- Inclusive ψ(2S) production has been measured in p-Pb collisions at $\sqrt{s_{NN}}$=5.02TeV in two y ranges (2.03<y_{cms}<3.53 and -4.46<y_{cms}<-2.96)

- ψ(2S) is significantly more suppressed than the J/ψ in both y regions
  - no p_T dependence of ψ(2S) suppression, with respect to the J/ψ, is observed within uncertainties
  - at backward-y, ψ(2S) suppression shows an increase, with event activity, stronger than J/ψ

- initial state nuclear effects (shadowing, energy loss) alone cannot account for the modification of the ψ(2S) yields

- final state effects, as the resonance break-up with interactions with CNM, are unlikely, because of short $c\bar{c}$ pair crossing time.
  Other final states effects as the $c\bar{c}$ pair interaction with the hadronic medium created in p-Pb collisions should be considered

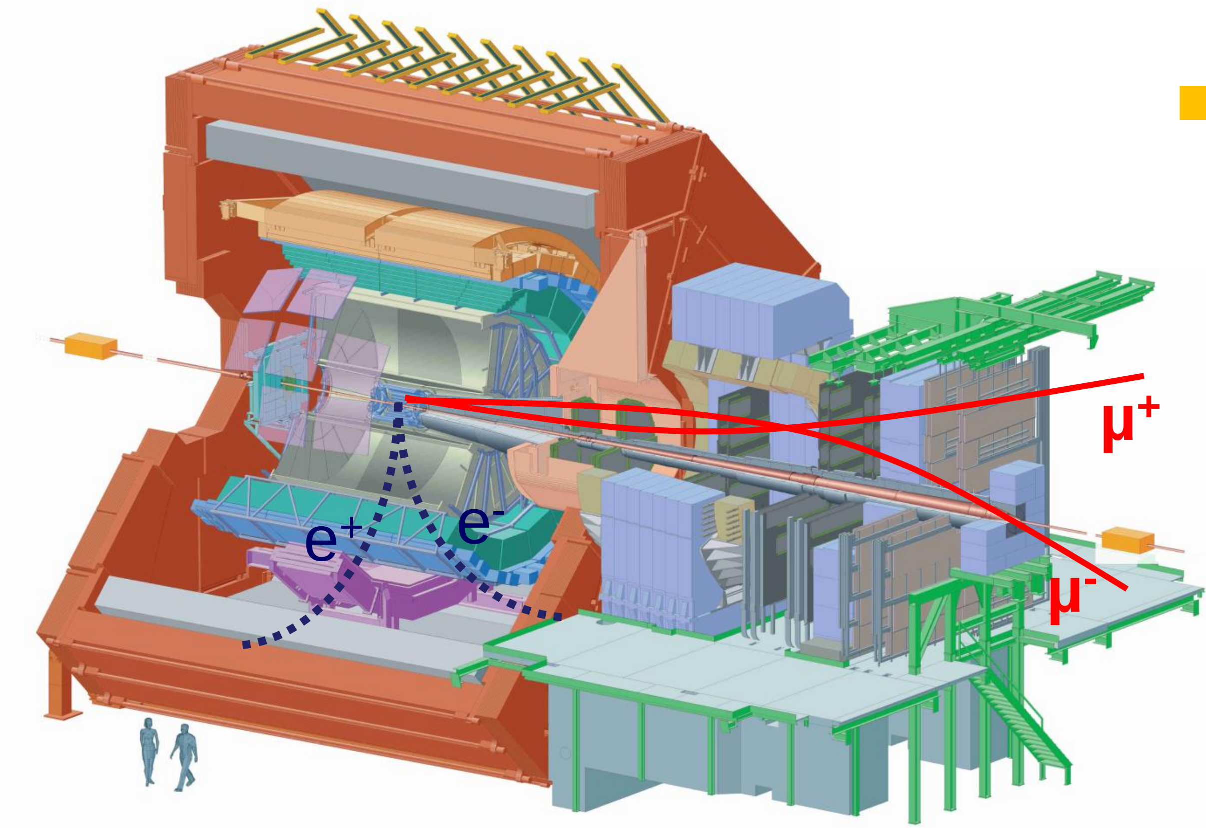
XXIV QUARK MATTER DARMSTADT 2014

Backup

ψ(2S) measurement in ALICE

➡ Quarkonium in ALICE can be measured in two ways:

Central Barrel $J/\psi \rightarrow e^+e^-$	**Forward muon arm** $J/\psi \rightarrow \mu^+\mu^-$
$(\lvert y_{LAB}\rvert<0.9)$	$(2.5<y_{LAB}<4)$
Electrons tracked using ITS and TPC Particle identification: TPC, TOF, TRD	Muons identified and tracked in the muon spectrometer

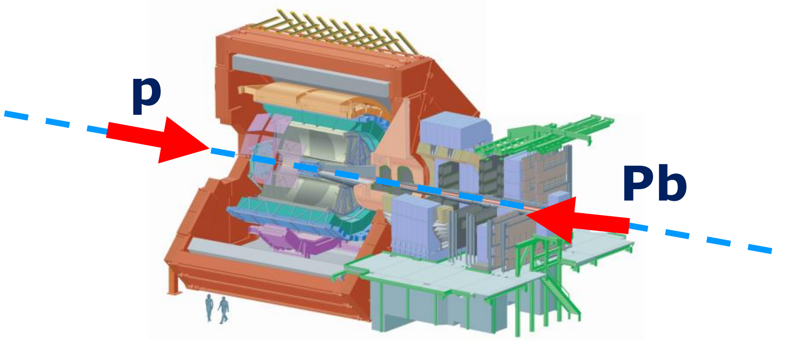


- Acceptance coverage in both y regions down to zero p_T
- ALICE results presented in this talk refer to inclusive ψ(2S) production in the $\mu^+\mu^-$ decay channel

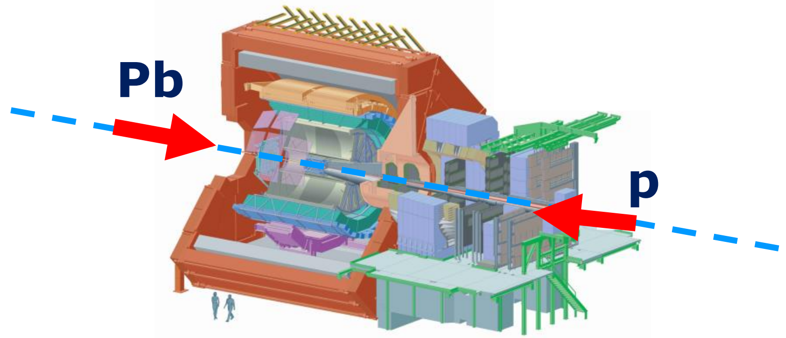
p-Pb collisions at $\sqrt{s_{NN}}$=5.02TeV

- **Beam energy: $\sqrt{s_{NN}}$ = 5.02 TeV**
  Energy asymmetry of the LHC beams (E_p = 4 TeV, E_{Pb}= 1.58 A·TeV)
  → rapidity shift Δy= 0.465 in the proton direction

- **Beam configurations**:
  Data collected with two beam configurations: p-Pb and Pb-p in the range $2.5<y_{LAB}<4$



$2.03<y_{CMS}<3.53$



$-4.46<y_{CMS}<-2.96$

- **Integrated luminosity used for this analysis:**
  p-Pb ($2.03<y_{CMS}<3.53$) = 5.01 ± 0.17 nb^{-1}
  p-Pb ($-4.46<y_{CMS}<-2.96$) ~ 5.81 ± 0.18 nb^{-1}

$A\times\varepsilon$ and systematic uncertainties

Acceptance x efficiency

computed with a pure signal MC simulation assuming unpolarized ψ(2S) production

$\langle$Acc x eff$\rangle_{pPb} \sim 0.270 \pm 0.014$

$\langle$Acc x eff$\rangle_{Pbp} \sim 0.184 \pm 0.013$

Systematic uncertainties

list of all systematic sources related to ψ(2S) analyses (sources may depend on the specific ψ(2S) result under study)

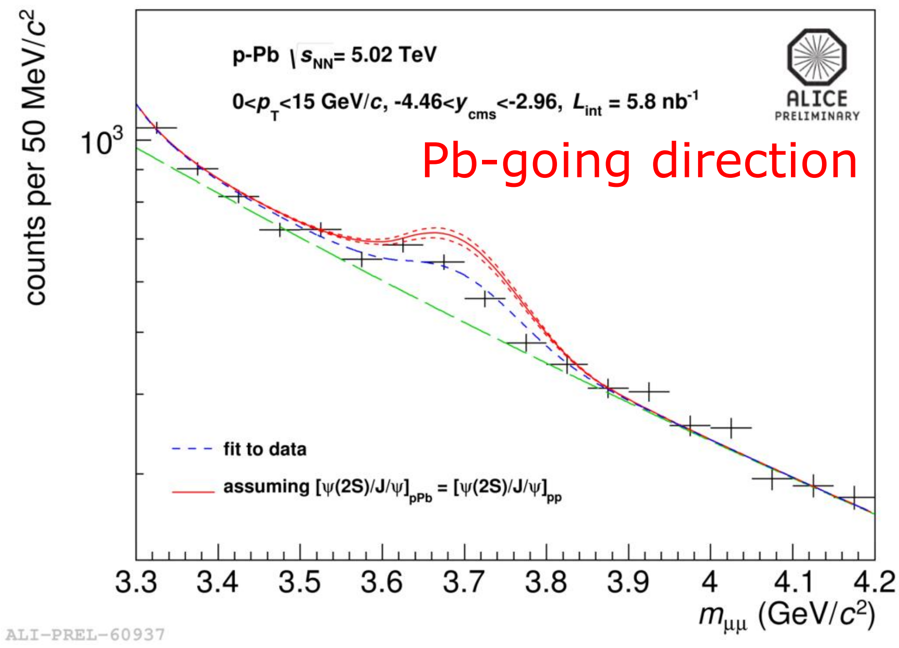
Global uncertainties	
T_{pA} (Glauber)	3.4%
$\sigma_{pp}^{J/\psi}$	7.5%
$\psi(2S)$ / J/ψ $\|_{pp}$	7.5%

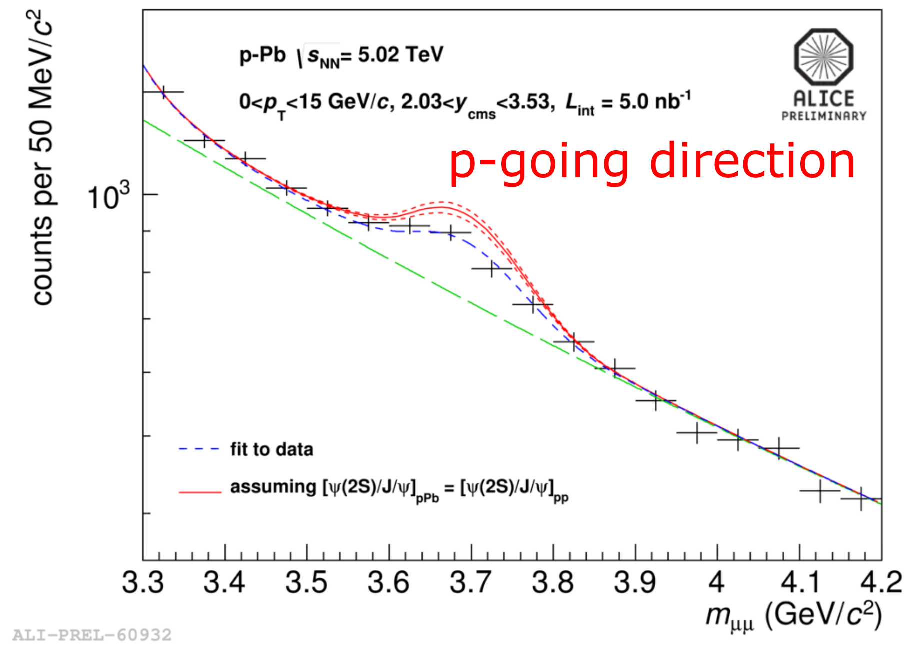
Uncorrelated uncertainties		
	p-Pb	**Pb-p**
J/ψ signal extr.	2%	2%
J/ψ MC input	1.5%	1.5%
ψ(2S) signal extr.	8-14%	9-20%
ψ(2S) MC input	1.5%	2.5%
T_{pA}	3.6(1.5-9.5%)	3.6(1.5-9.5%)
Normalization	1%	1%

Partially Correlated uncertainties		
	p-Pb	**Pb-p**
Pile-up	2%	2%
Muon trigger	2.8%	3.2%
Muon tracking	4%	6%
Muon matching	1%	1%
pp kinematic range cor.	8%	8%

$\psi(2S)/J/\psi$ vs rapidity

A strong decrease of the $\psi(2S)$ production in p-Pb, relative to J/ψ, is observed with respect to the pp measurement ($2.5<y_{cms}<4$, $\sqrt{s}=7$TeV)

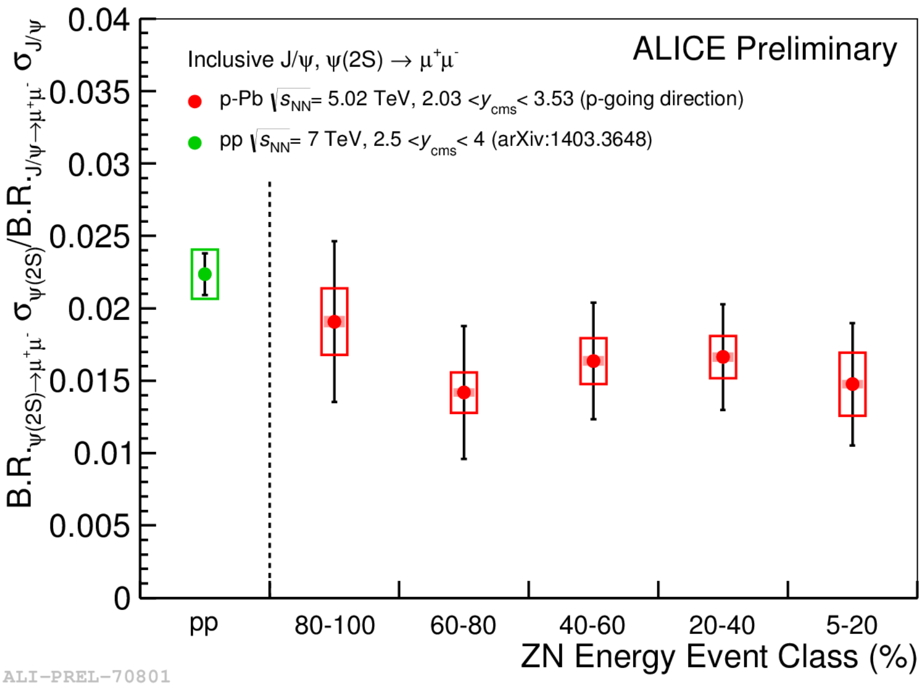


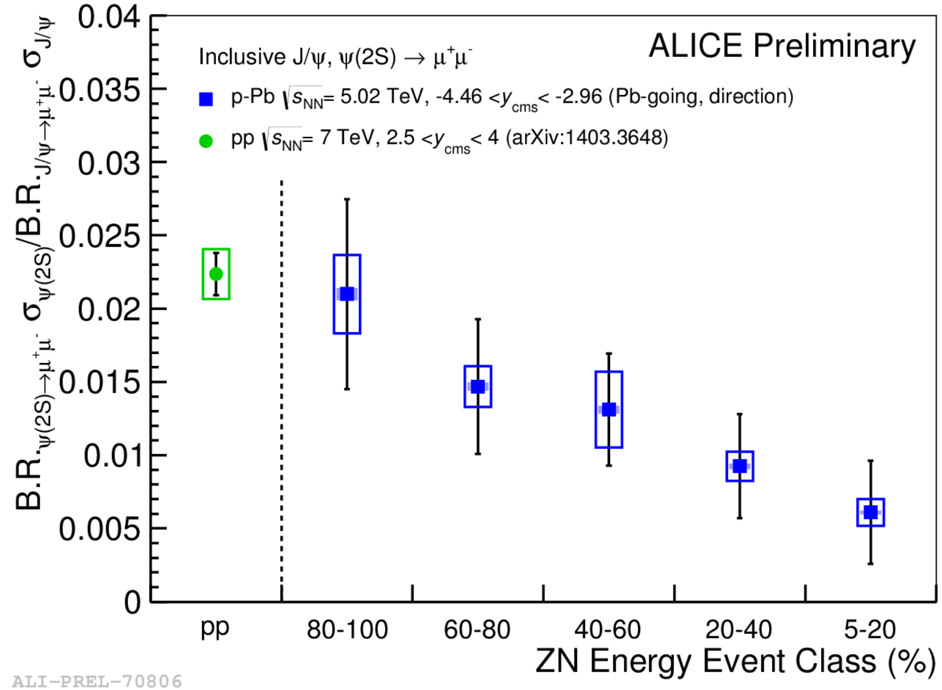


ALICE Coll., arXiv:1403.3648

B. Paul's poster

ψ(2S)/J/ψ vs event activity

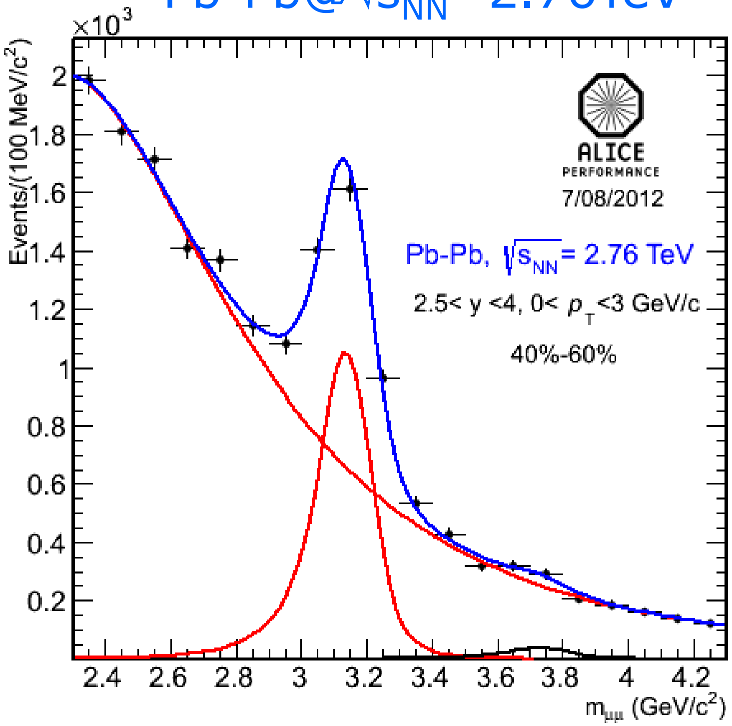




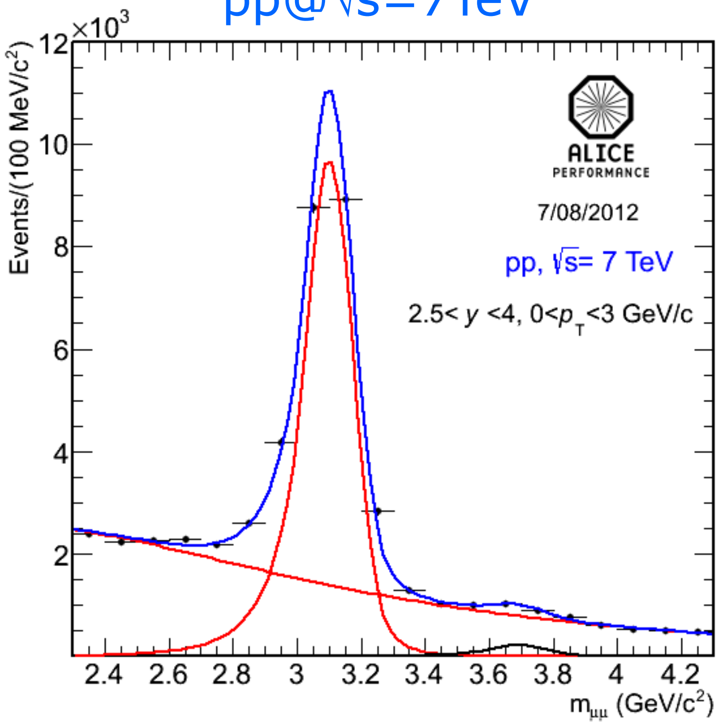
ψ(2S) production in Pb-Pb

- The ψ(2S) yield is compared to the J/ψ one in Pb-Pb and in pp
  - Charmonia yields are extracted fitting the invariant mass spectrum in two p_T bins: $0<p_T<3$ and $3<p_T<8$ GeV/c and, for Pb-Pb, also as a function of centrality

Pb-Pb@$\sqrt{s_{NN}}$=2.76TeV



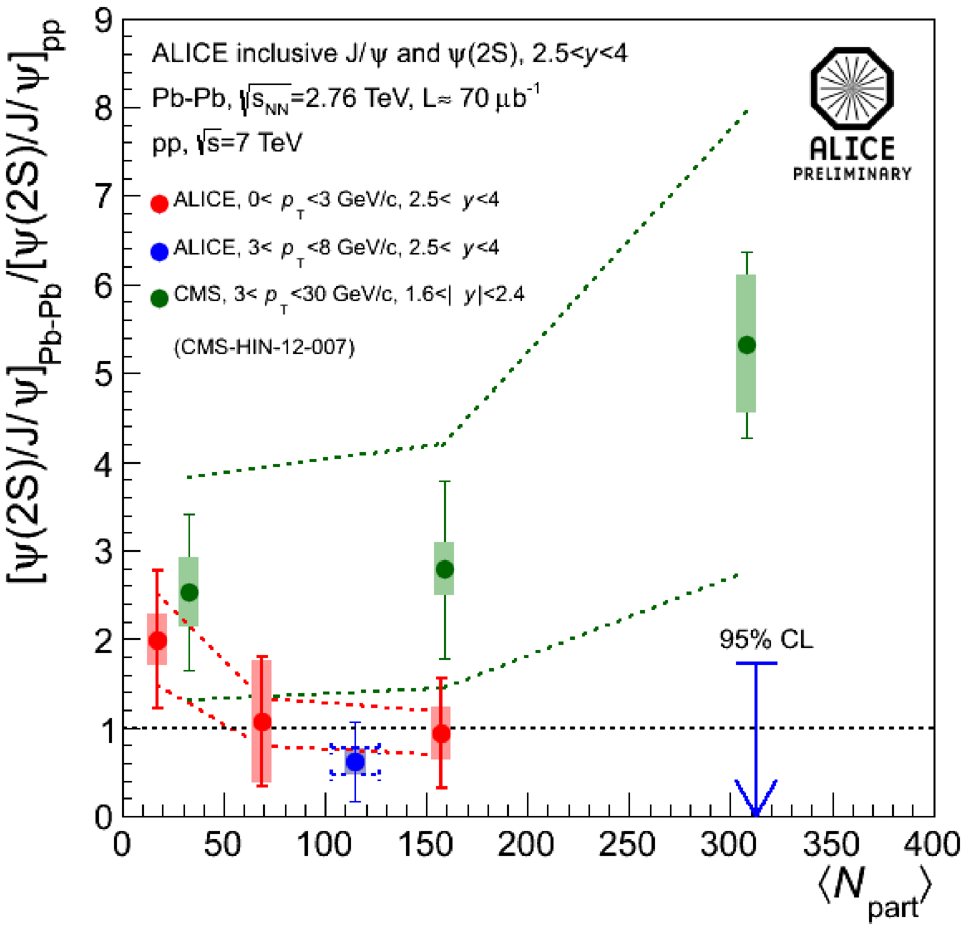
pp@$\sqrt{s}$=7TeV



- Pb-Pb: S/B (at 3 σ around the ψ(2S)) varies between 0.01 and 0.3 from central to peripheral collisions

$[\psi(2S)/J/\psi]_{PbPb}$ / $[\psi(2S)/J/\psi]_{pp}$

- Reference: pp data @$\sqrt{s}$=7TeV (small $\sqrt{s}$- and y-dependence from $[\psi(2S)/J/\psi]_{pp}$ results by CDF, LHCb and CMS taken into account in the syst. uncertainty). (Error on the reference is shown as dashed line)

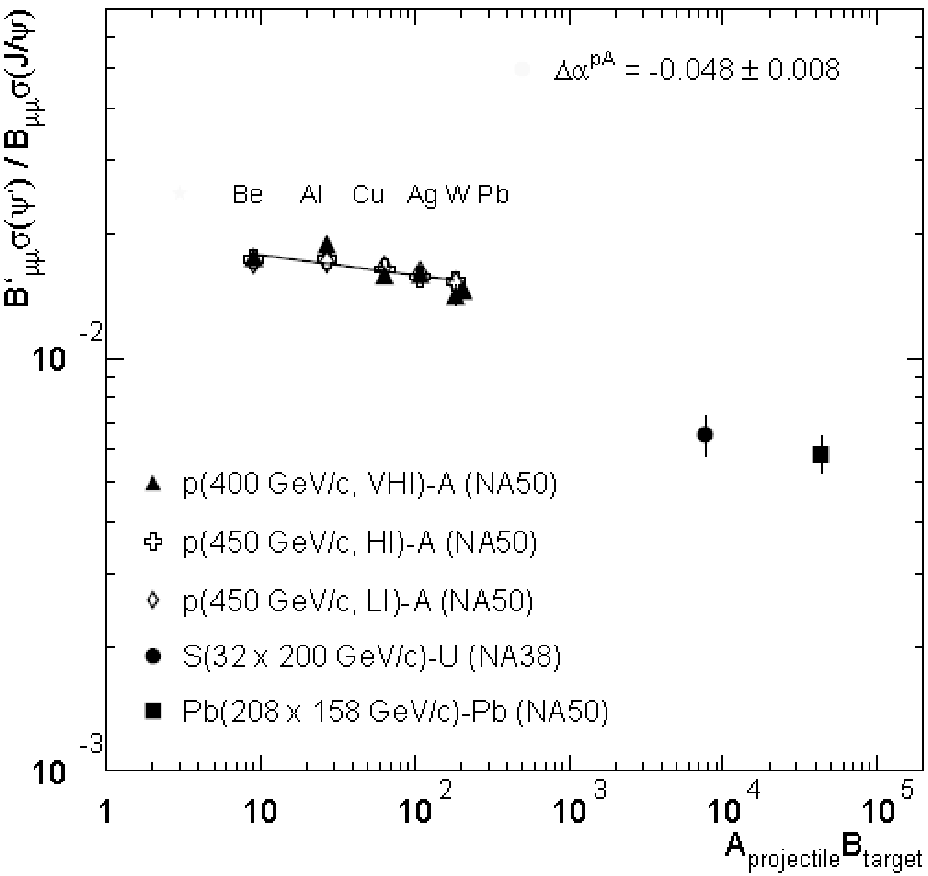


Main systematic uncertainties (some sources cancel out in the double ratio) are the signal extraction and the choice of the MC inputs for acc. calculation

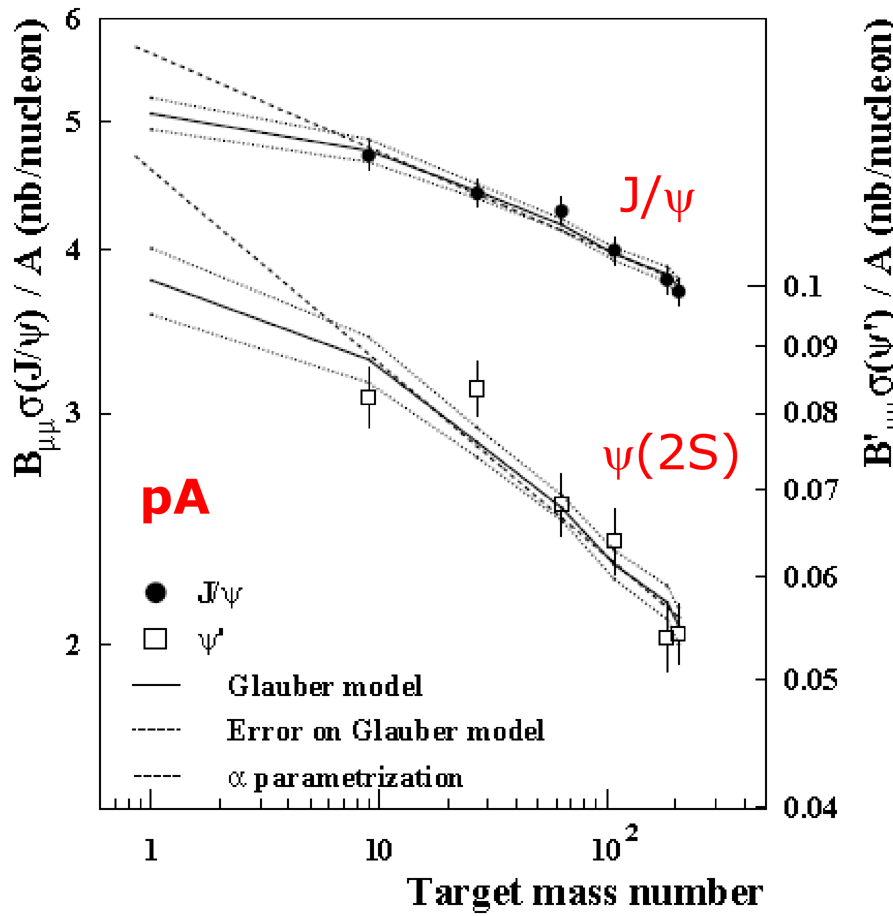
- Large statistics and systematic errors prevent a firm conclusion on the $\psi(2S)$ enhancement or suppression versus centrality

- ALICE result, in central collisions, does not show a large $\psi(2S)$ enhancement

ψ(2S) at SPS



NA50 Collab., Eur. Phys. J. C49 (2007) 559



NA50 Collab., Eur. Phys. J. C48 (2006) 329

ψ(2S) at RHIC

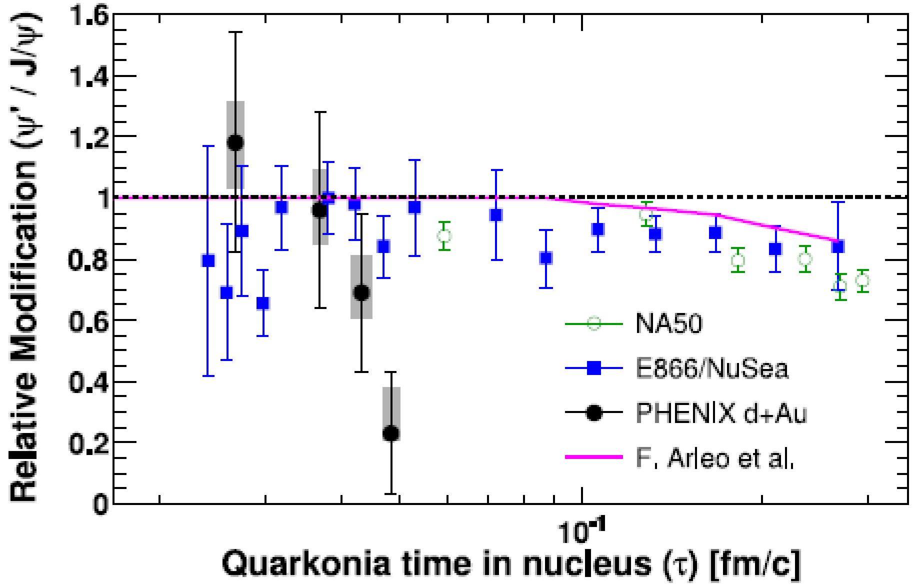


FIG. 5: (Color online) The relative modification of the ψ' to the J/ψ as a function of the proper time spent by the quarkonia (or $c\bar{c}$ precursor) in the nucleus. The data include (open [green] circles) NA50 [16] $p+A$ at 400 GeV/nn, (closed [blue] squares) E866/NuSea [1] $p+A$ at 800 GeV/nn and (closed [black] circles) PHENIX $d+$Au at $\sqrt{s_{NN}} = 200$ GeV which include a global systematic uncertainty of ±24%. The E866/NuSea points are calculated for ψ' and J/ψ modifications in similar rapidity intervals. The curve is a calculation by Arleo *et al.* [3] discussed in the text.