Forward rapidity ψ(2S) production in pp p-Pb and Pb-Pb collisions with ALICE

Hot Quarks 2014

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(*On behalf of the ALICE collaboration)

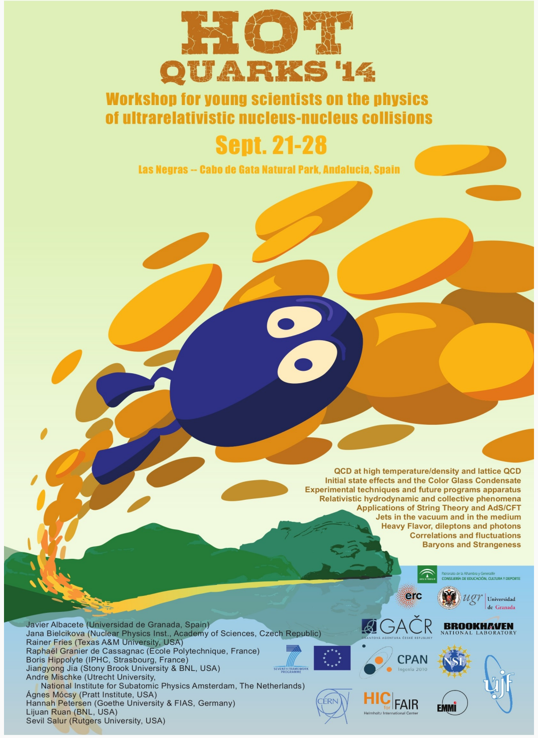
PART 1

Brief introduction on charmonia,

ALICE detector, data taking conditions, mass spectra

PART 2

Results in pp, p-Pb and Pb-Pb collisions



Charmonia: a brief introduction

Charmonia are bound states of **charm-anticharm** heavy quarks

CHARMONIUM PROPERTIES:

- Smaller than light hadrons, different E_b ($E_b^{J/\psi}$~0.6 GeV, $E_b^{\psi(2S)}$~0.05 GeV)
- Reconstructed via their dilepton decay:

$$B.R.\ J/\psi \rightarrow \mu^+\mu^- = (5.93 \pm 0.06)\cdot 10^{-2}$$

$$B.R.\ \psi(2S) \rightarrow \mu^+\mu^- = (7.8 \pm 0.9)\cdot 10^{-3}$$

Sensitive to the medium created in the collisions

CHARMONIUM PRODUCTION MECHANISMS:

- Production via hard scattering of gluons
- Decay from higher charmonium states

} "**prompt**" production

- Decay from b-mesons ("b-decay")

} "**non-prompt**" production

Prompt + non-prompt = Inclusive production

ALICE results presented in this talk refer to ψ(2S) inclusive production

J/ψ results (see J. Martin's talk) will be shown as reference for ψ(2S)

Charmonia in the medium

pp collisions: reference processes

- **Reference collision system:** to understand p-A and A-A collisions
- **Charmonium production mechanisms:** NRQCD, CEM, etc.

p-A collisions: Cold nuclear matter effects (CNM)

- **Initial/final state:** shadowing, energy loss, nuclear absorption (nuclear absorption should be negligible at the LHC energies)

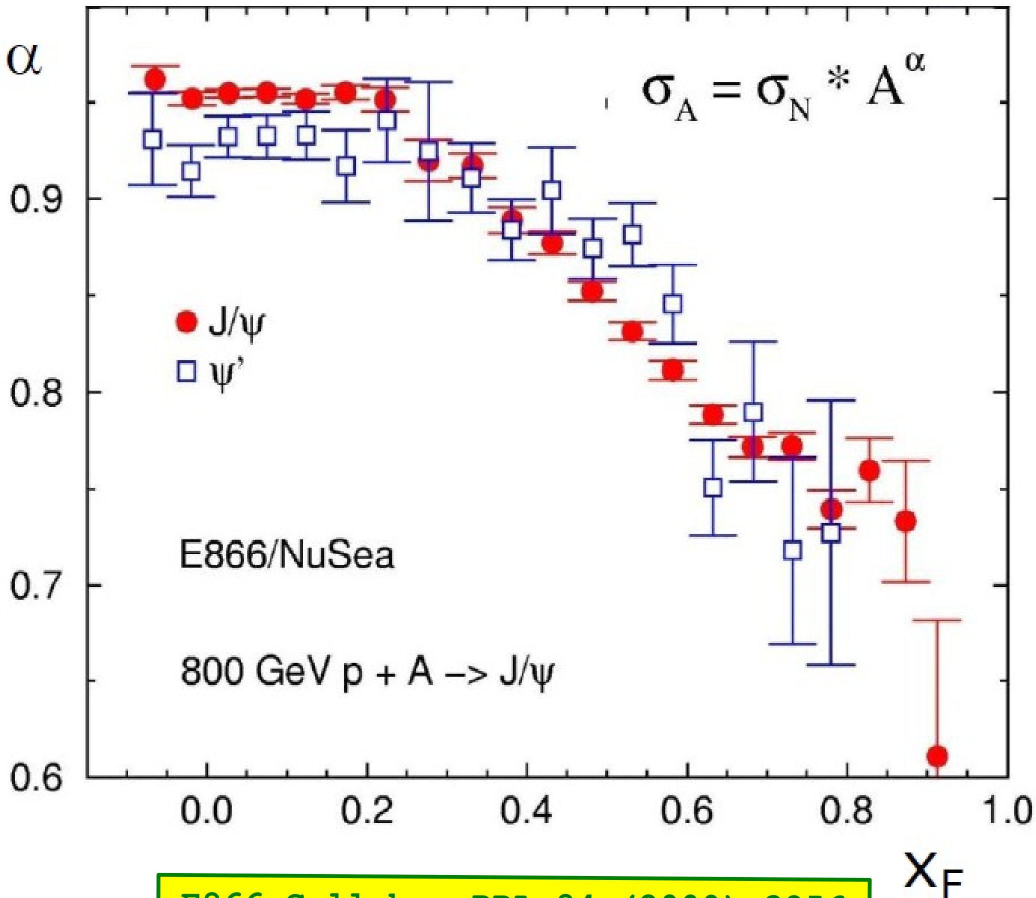
A-A collisions: Hot (and Cold) nuclear matter effects

- **Color screening:** suppression of quarkonium states (high color density in a QGP)
- **Recombination:** at (LHC) high collision-energies $c\bar{c}$ pairs are produced abundantly and the recombination probability is $\propto N^2_{c\bar{c}}$
- **CNM:** also present in A-A collisions

Why the study of the ψ(2S) is so interesting?

The **ψ(2S)** is drawing more and more attention for different reasons:

- → The ψ(2S) is more weakly bound than the J/ψ
- → The ψ(2S) yield is less affected by higher charmonia decays compared to the J/ψ
- → Interesting results already at lower energies in p-A (NA50, E866, HERA-B)



E866 Collab., PRL 84 (2000) 3256

X_F~0 (central rapidity)

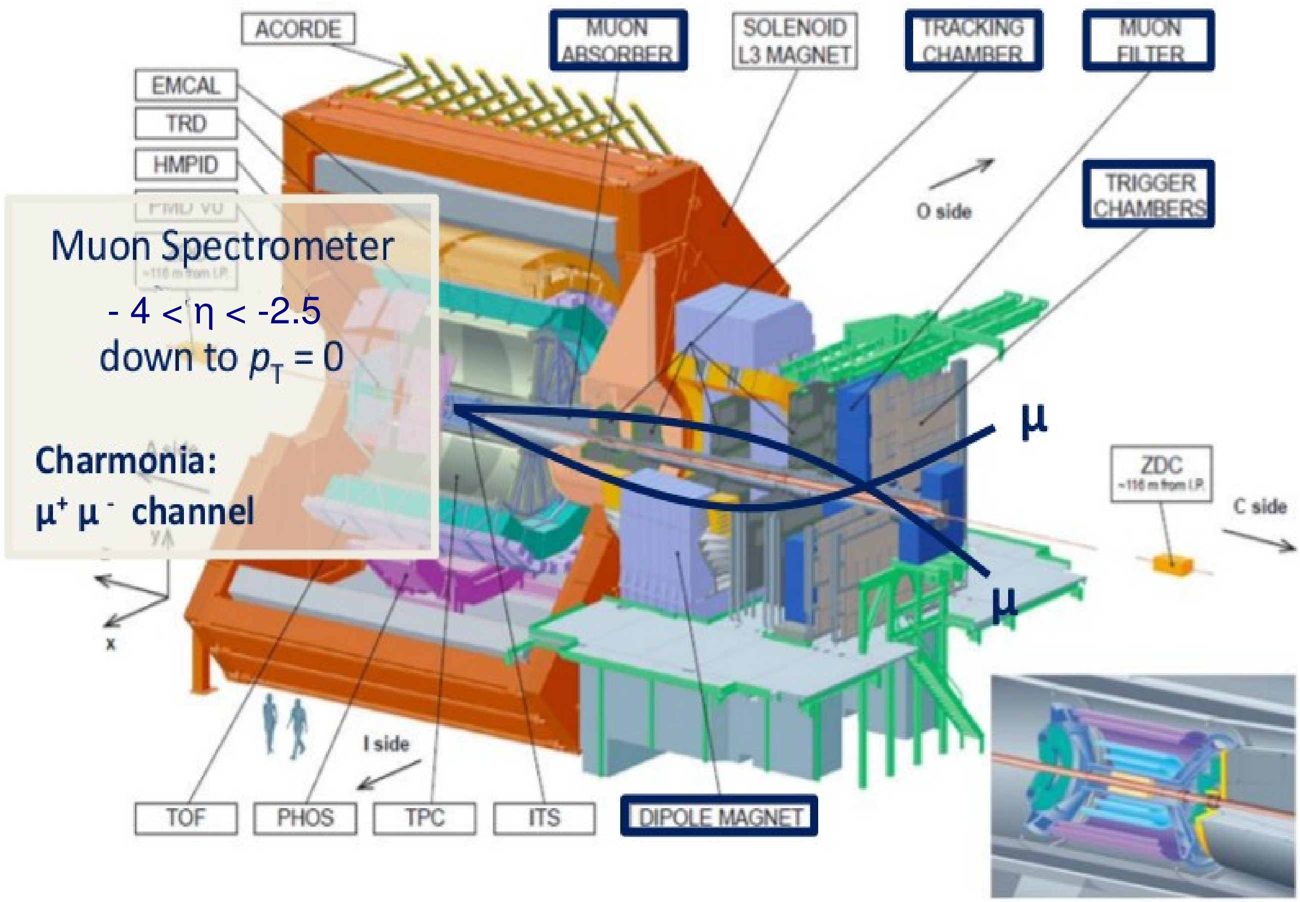
- → the ψ(2S) is slightly more suppressed with respect to the J/ψ
- → the time spent by the $c\bar{c}$ state in the nuclear medium is larger than the resonance formation time $\tau_c > \tau_f$ (~0.1 fm/c)

$X_F \gtrsim 0.2$ (forward rapidity)

- → $\tau_c < \tau_f$: the influence of the nuclear matter on the pre-hadronic state is independent of the particular resonance being produced

The ALICE detector

Charmonia can be detected with ALICE in the $\mu^+\mu^-$ decay channel



Forward muon spectrometer: $\psi(2S) \rightarrow \mu^+\mu^-$

Muons identified and tracked in the muon spectrometer (10 planes of tracking chambers, 2 stations of trigger chambers, absorber system, dipole magnet)

Data samples

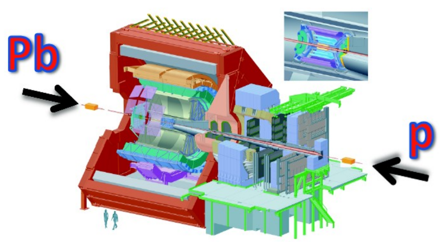
pp collisions

2011 data sample, $\sqrt{s}$ = 7 TeV, L_{int} = 1.35±0.07 pb^{-1}

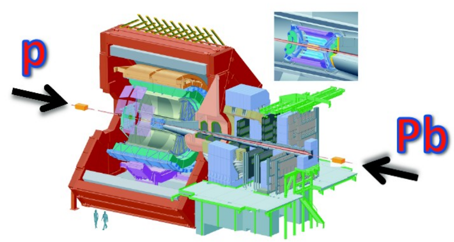
p-Pb collisions

2013 data sample, $\sqrt{s_{NN}}$ = 5.02 TeV

Beam energy asymmetry (E_p=4 TeV,E_{Pb}=1.58 A·TeV, A=208) causes a shift in rapidity: two y_{cms} ranges studied, inverting the LHC beams direction



backward
($-4.46<y_{cms}<-2.96$)



forward
($2.03<y_{cms}<3.53$)

$L_{int}^{forward}$ = 5.01±0.19 nb^{-1}

$L_{int}^{backward}$ = 5.81±0.18 nb^{-1}

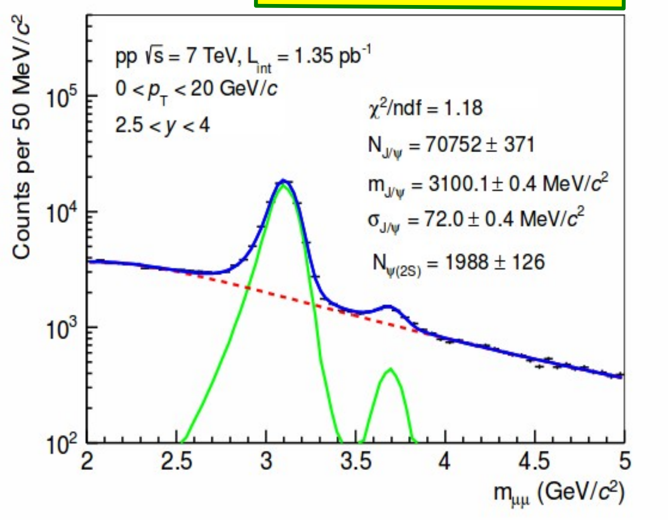
Pb-Pb collisions

2011 data sample, $\sqrt{s_{NN}}$ = 2.76 TeV, L_{int} = 68.8±0.9 μb^{-1}

ψ(2S) signal extraction: examples

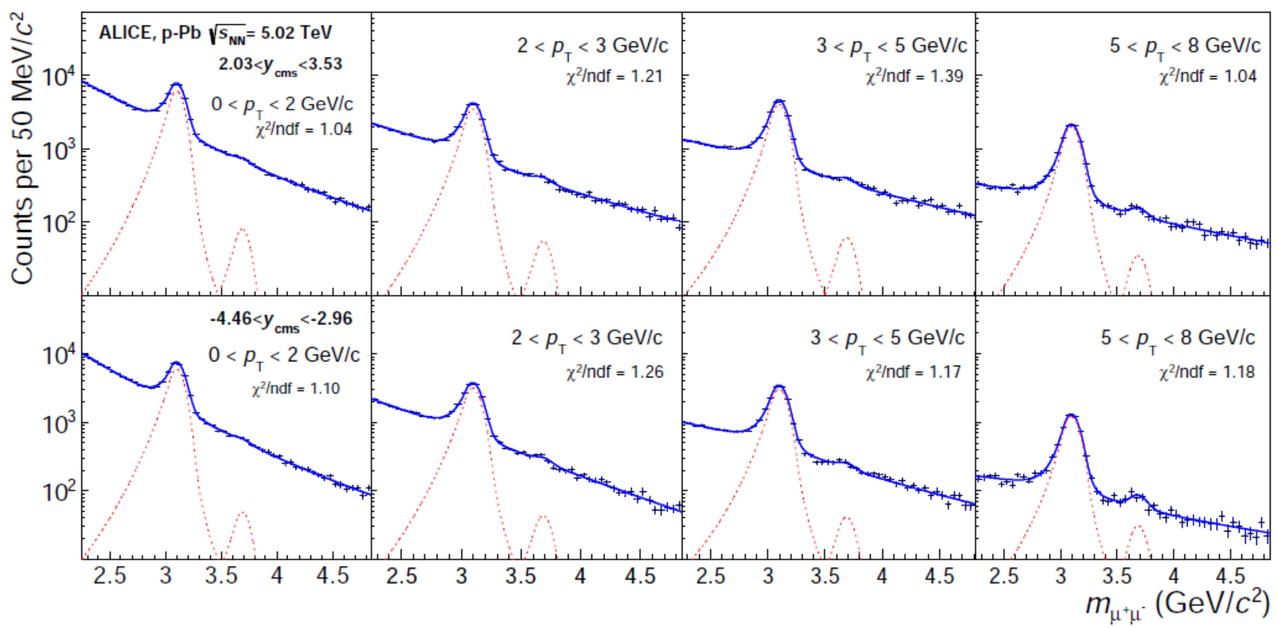
pp

Eur. Phys. J. C (2014) 74:2974

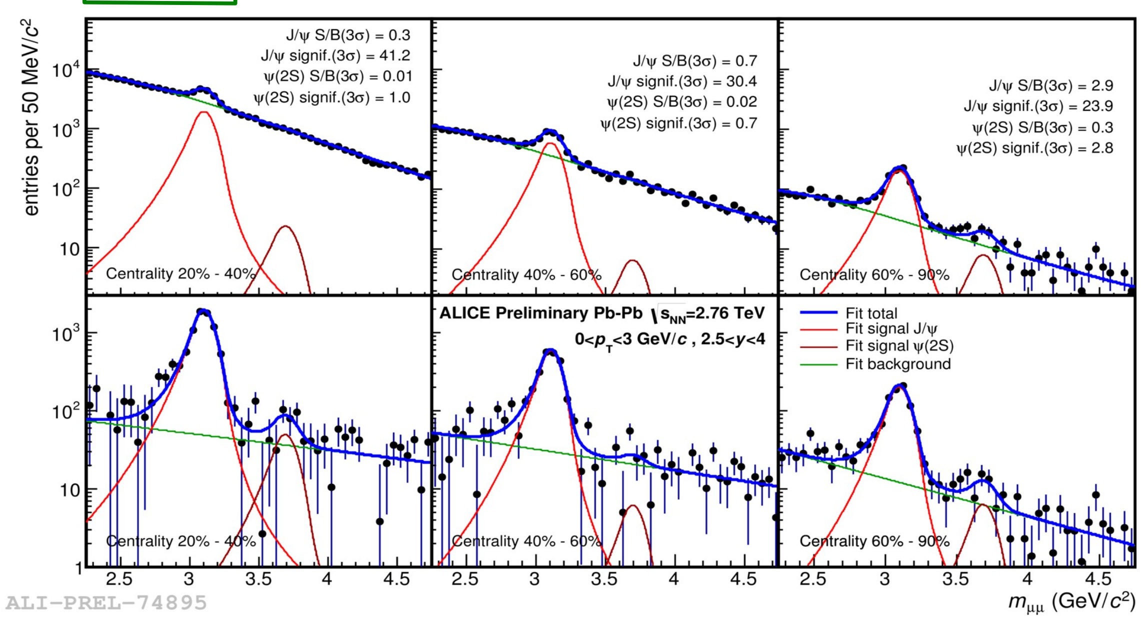


p-Pb

arXiv:1405.3796



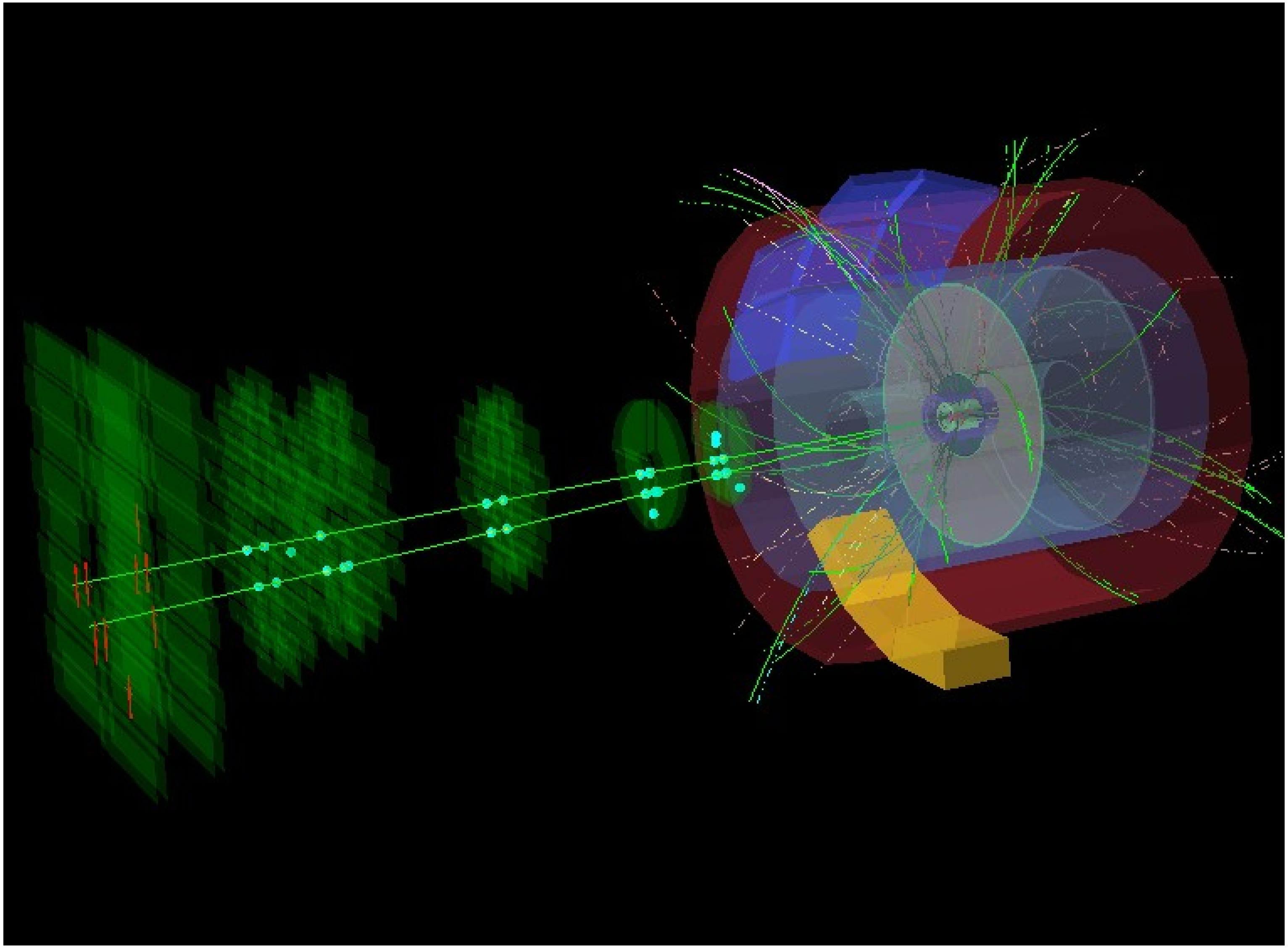
Pb-Pb



- → Sizeable statistics in pp and p-Pb collisions allows for differential studies
- → In Pb-Pb collisions the signal extraction is very difficult because of the limited statistics and low S/B ratio

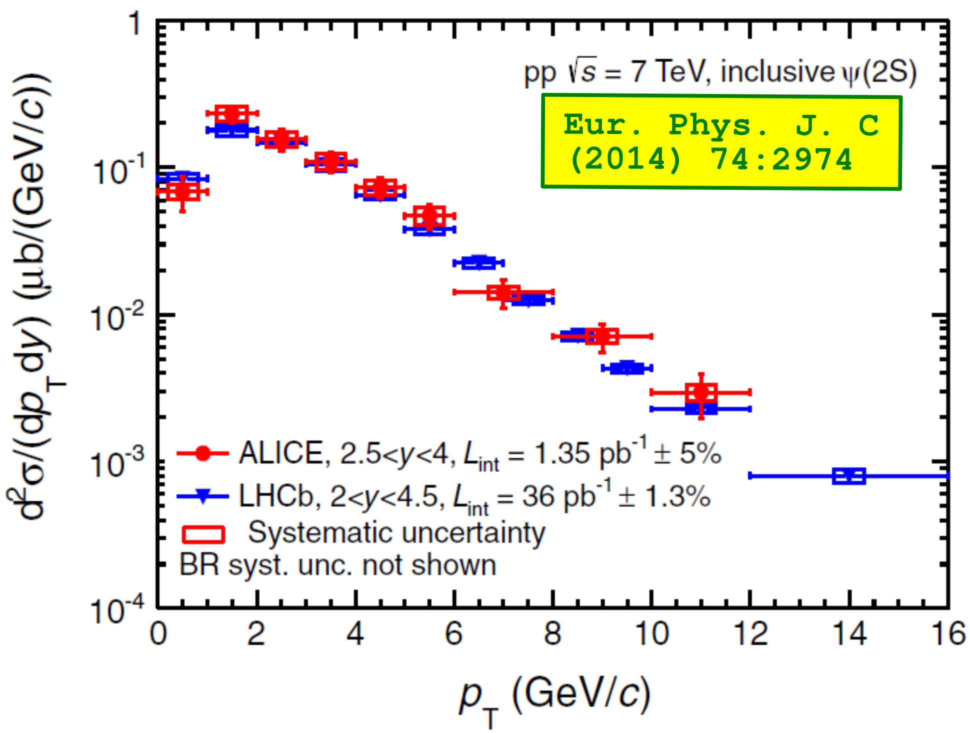
Collision System	Signal extraction systematic (in percent)
p-p	7.5 - 11
p-Pb	8 - 11.9
Pb-p	8.6 - 12.7
Pb-Pb	14 - 45

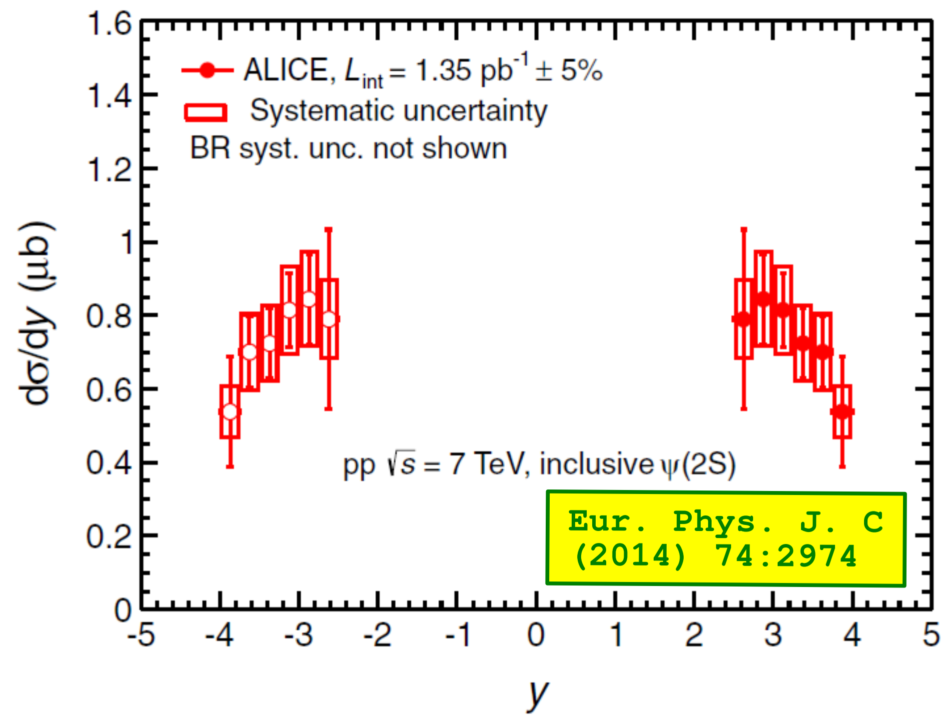
pp collisions



An event in p-p collision, reconstructed with the ALICE detector

ψ(2S) differential cross section in pp





→ The ψ(2S) production cross section, in pp collisions, have been studied in p_T and y intervals:

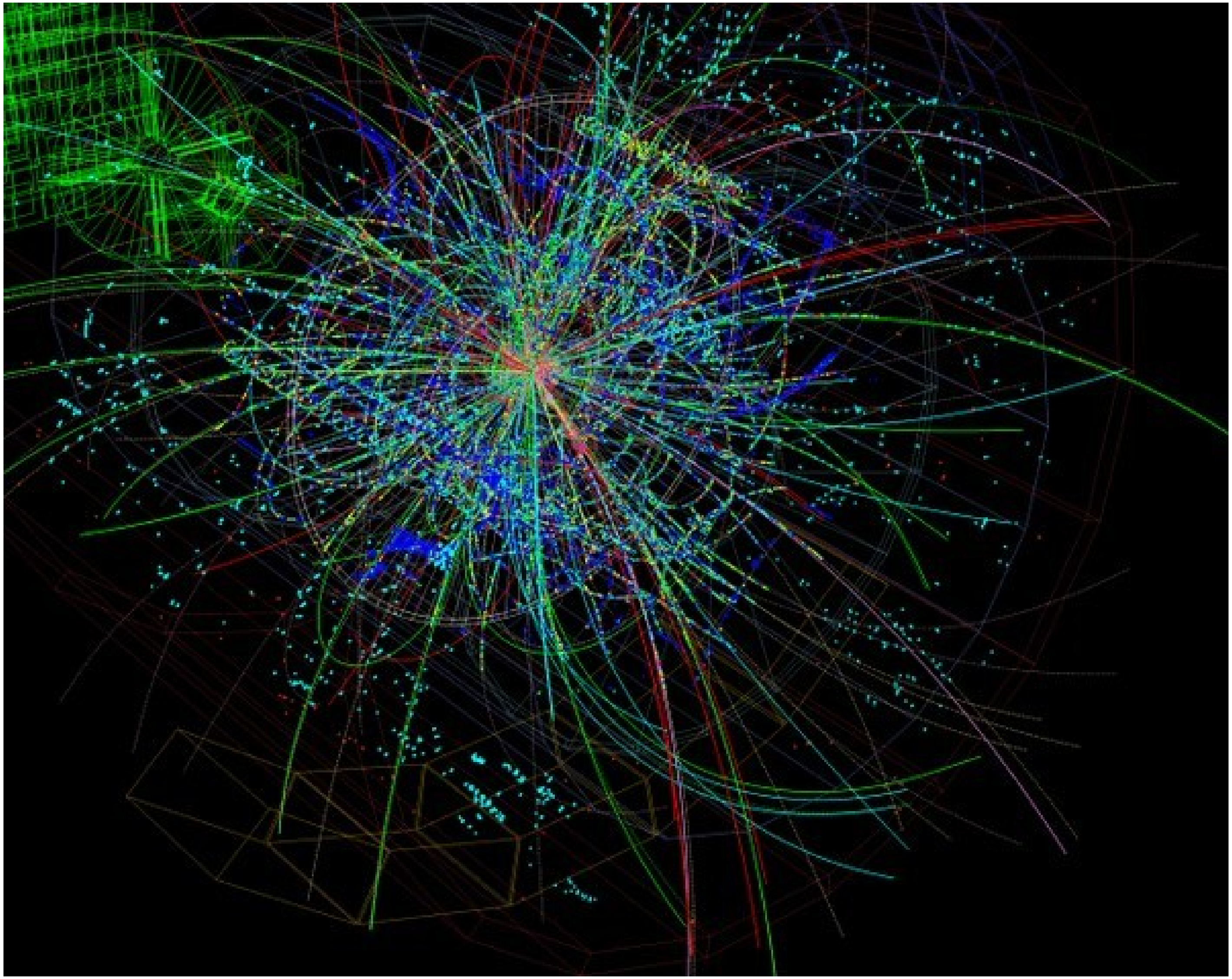
$$\sigma = \frac{1}{L_{\mathrm{int}}} \frac{N}{\mathrm{BR}_{\mu^+\mu^-} \times \langle A\varepsilon \rangle}$$

(L_{int}= integrated luminosity, BR(ψ(2S)→$\mu^+\mu^-$=0.78±0.09%, Aε=detector acceptance-efficiency)

→ LHCb results, obtained in a slightly different y range, are also shown Results are in a good agreement with ALICE

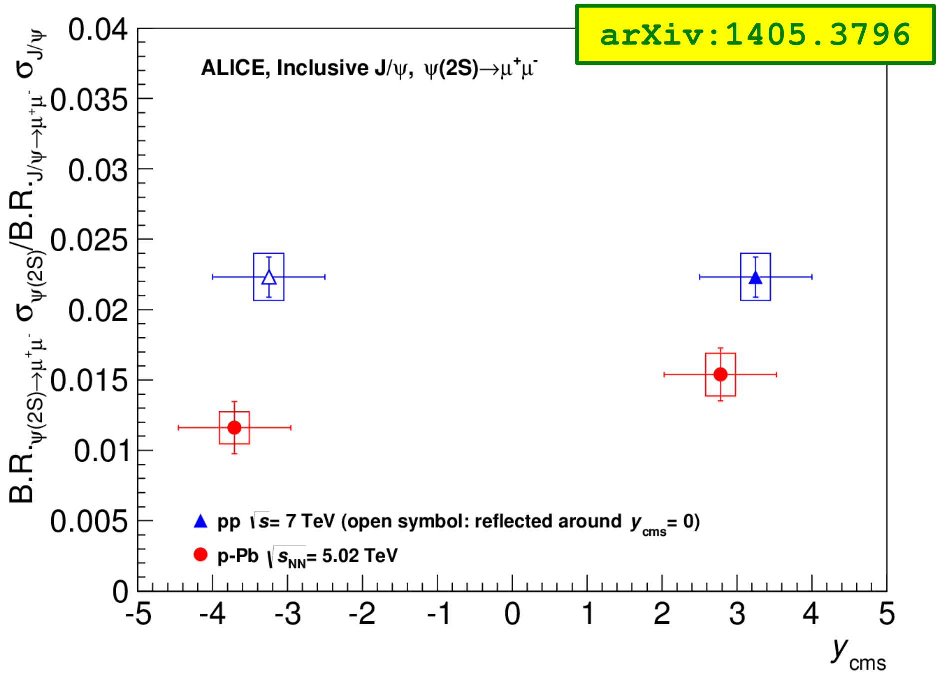
→ pp data useful to build reference for p-Pb and Pb-Pb studies

p–Pb collisions



An event in p-Pb collision, reconstructed with the ALICE detector

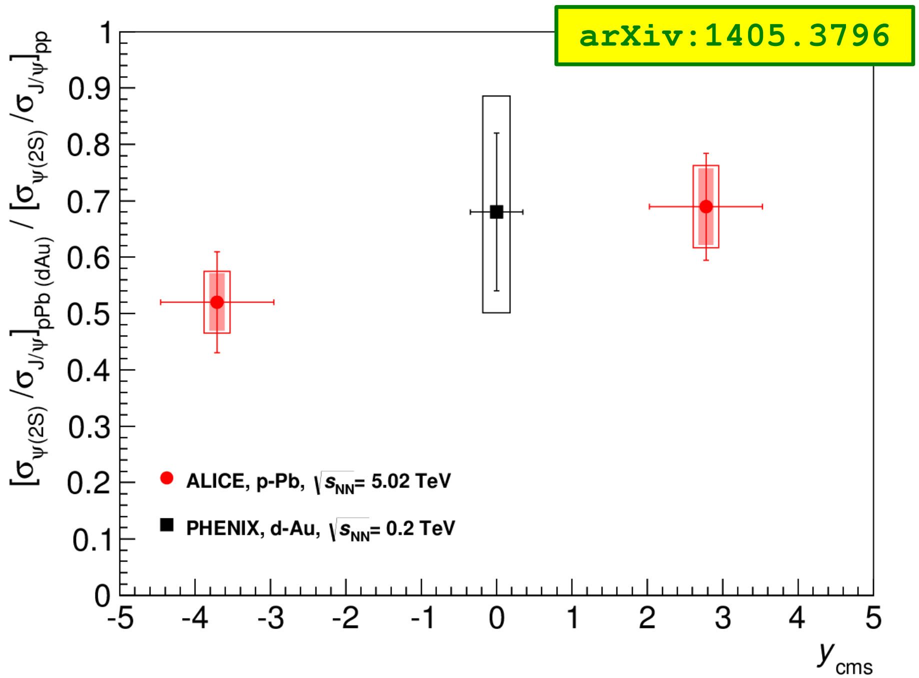
$\psi(2S)/J/\psi$ and $[\psi(2S)/J/\psi]_{pPb}/[\psi(2S)/J/\psi]_{pp}$



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

Stronger* ψ(2S) suppression (compared to the J/ψ) in p-Pb with respect to $\sqrt{s}$=7 TeV pp collisions

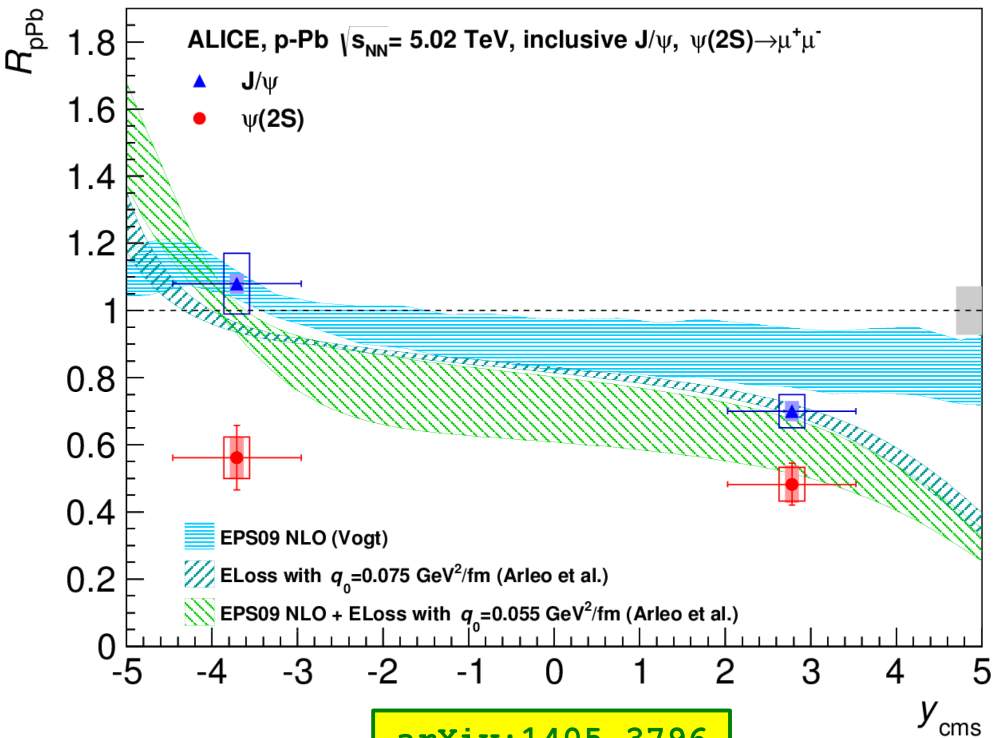
* 2.0 σ-level at forward-y
* 3.2 σ-level at backward-y



$[\psi(2S)/J/\psi]_{pPb}/[\psi(2S))/J/\psi]_{pp}$ double ratio:

PHENIX results in d-Au collisions at $\sqrt{s_{NN}}$=0.2 TeV at midrapidity are qualitatively similar with ALICE measurements

ψ(2S) R_{pPb} as a function of rapidity



arXiv:1405.3796

ψ(2S) nuclear modification factor:

→ Stronger ψ(2S) suppression compared to the J/ψ

→ Same shadowing and coherent energy loss expected for both the J/ψ and the ψ(2S)

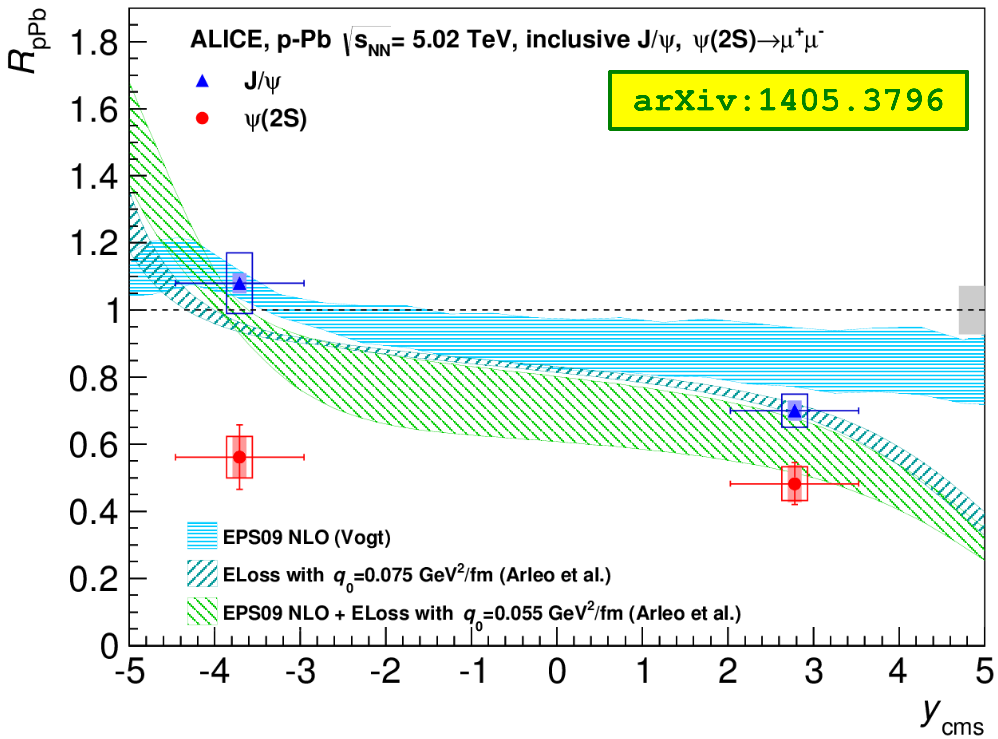
→ Theoretical predictions (based on shadowing and on energy loss) do not describe the observed ψ(2S) suppression

The suppression of ψ(2S) can be quantified using the nuclear modification factor:

$$R_{pA}^{\psi(2S)} = \frac{\sigma_{pA}^{\psi(2S)}}{A_{Pb} \cdot \sigma_{pp}^{\psi(2S)}}$$

Is this effect related to the breakup of the weakly bound ψ(2S) in the nuclear medium?

$\psi(2S)\ R_{pPb}$ as a function of rapidity



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

τ_c and τ_f references:

PRC 87,054910 (2013)

Phys. Rev. Lett. 111 (2013) 202301

<L> = average length of nuclear matter traversed by the $c\bar{c}$ pair

β = $\tanh y_{c\bar{c}}^{rest}$

γ = $E_{c\bar{c}}/m_{c\bar{c}}$

The ψ(2S) breakup is possible if the resonance:

formation time < crossing time

$\tau_f \sim (0.05\text{–}0.15)\,\text{fm}/c < \tau_c$

→ **forward-y:** $\tau_c \sim 10^{-4}$ fm/c

breakup effects are excluded

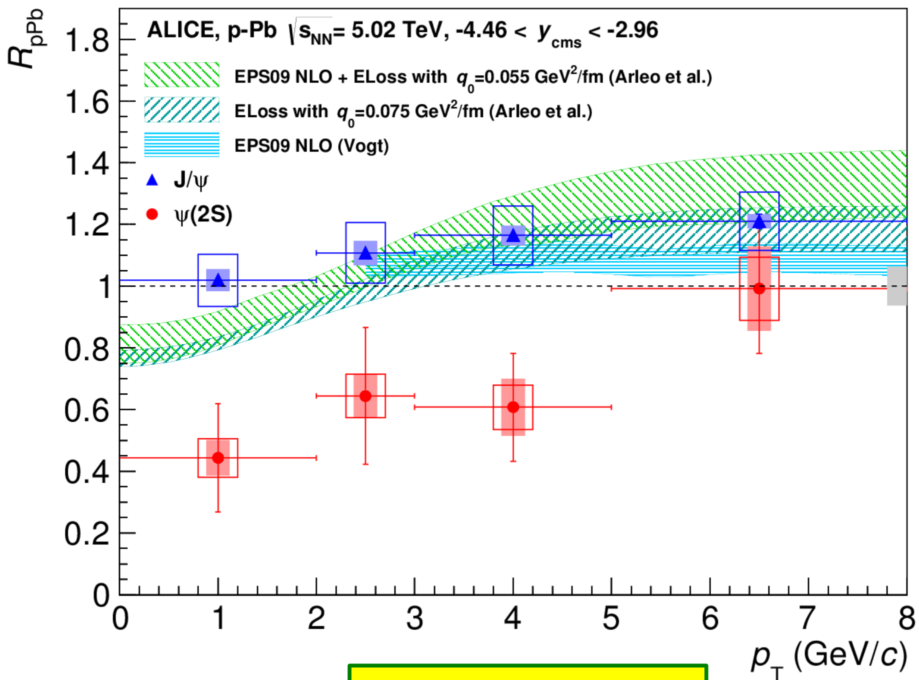
→ **backward-y:** $\tau_c \sim 7\cdot10^{-2}$ fm/c

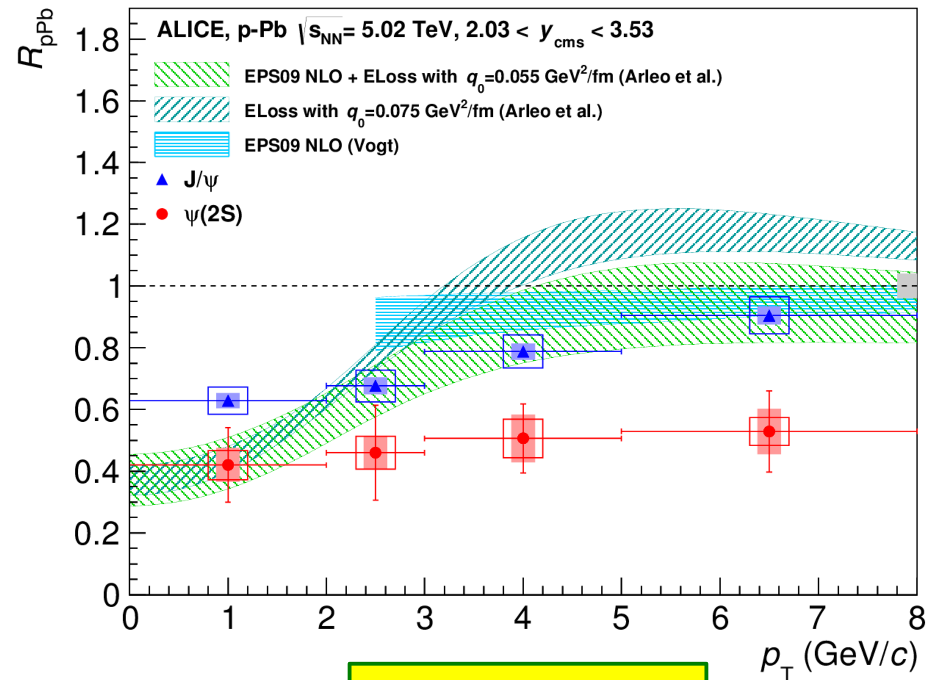
($\tau_f \sim \tau_c$) breakup effects can hardly explain the big difference between J/ψ and ψ(2S) R_{pPb}

Other final state effects are required to describe the stronger ψ(2S) suppression

$\psi(2S)\, R_{pPb}$ as a function of p_T

Backward rapidity **Forward rapidity**





arXiv:1405.3796

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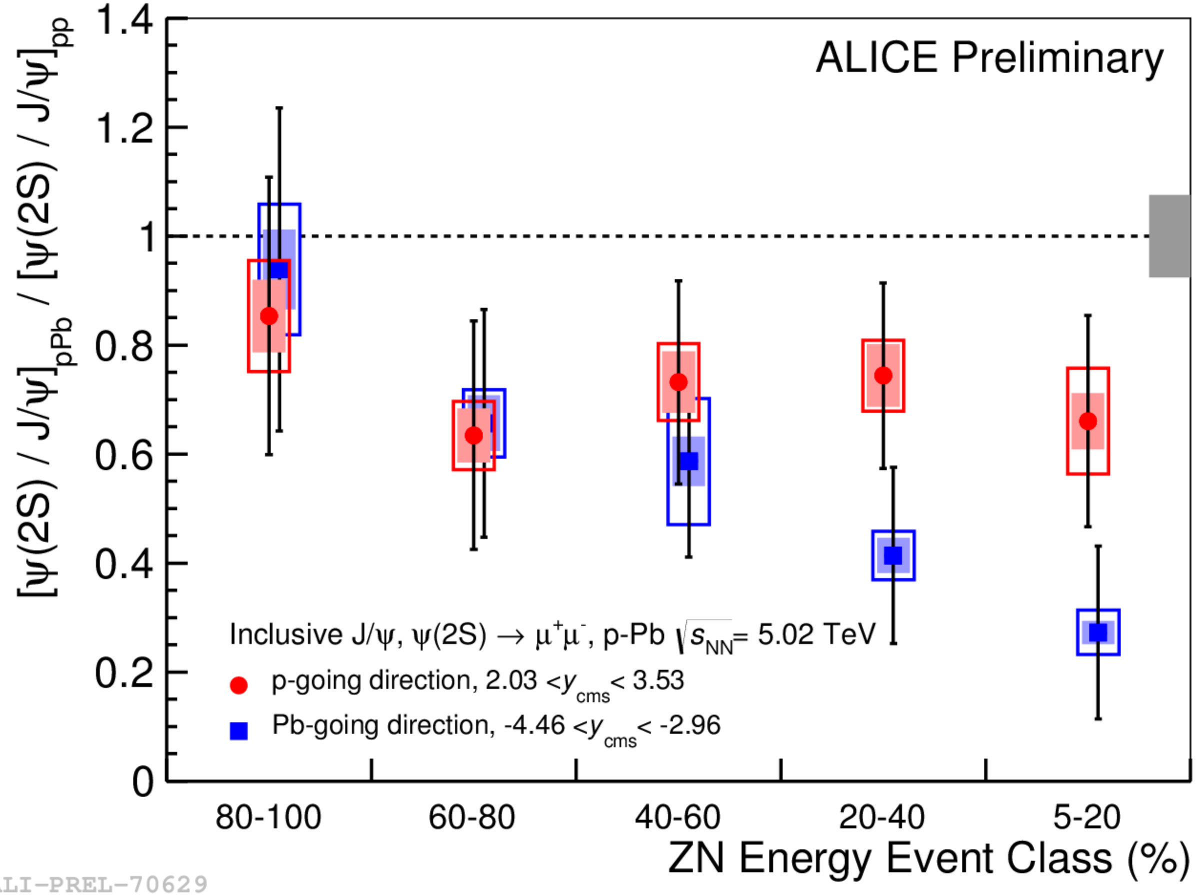
- The high statistics allow to study the $\psi(2S)$ R_{pPb} in p_T bins
- The $\psi(2S)$ is more suppressed than the J/ψ
- Theoretical models do not describe the $\psi(2S)$ suppression

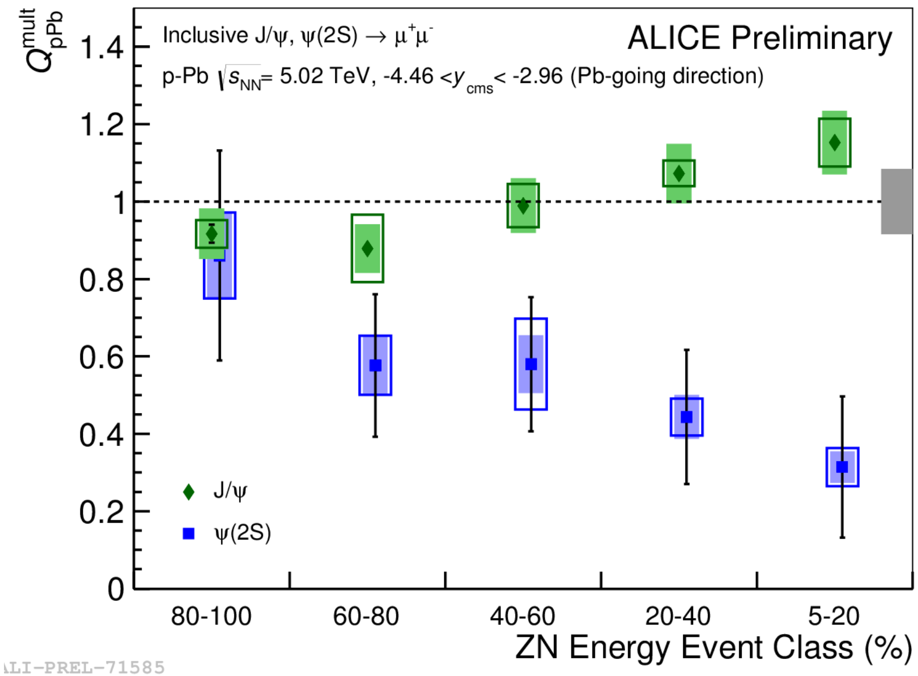
$\psi(2S)/J/\psi|_{pPb}/\psi(2S)/J/\psi|_{pp}$ vs event activity



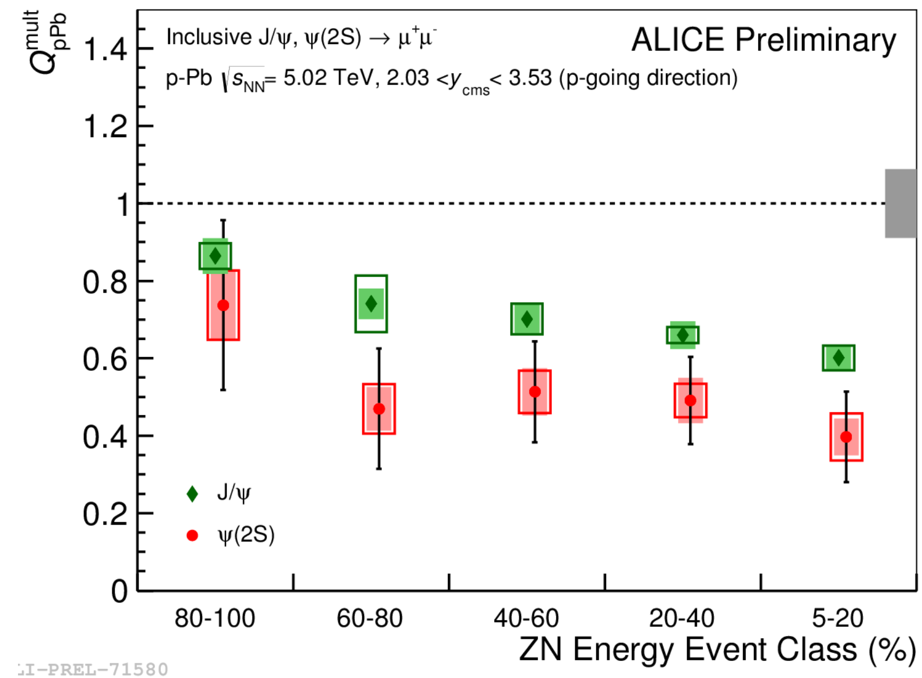
- The $\psi(2S)/J/\psi]_{pPb}/[\psi(2S)/J/\psi]_{pp}$ ratio has also been studied as a function of the event activity
- At backward rapidity the ψ(2S) is more suppressed than the J/ψ for large event activities

ψ(2S) Q_{pPb} vs event activity

Backward rapidity



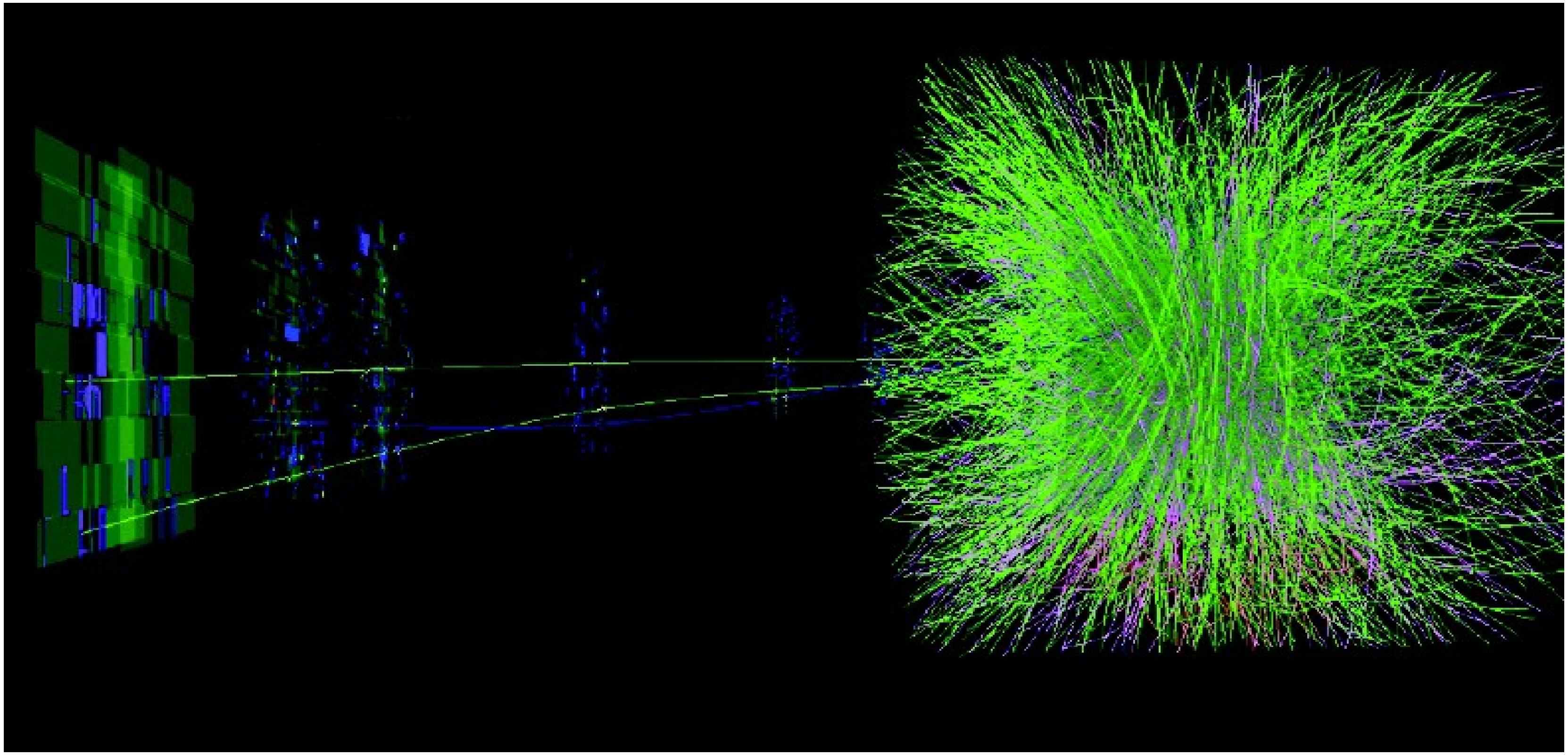
Forward rapidity



$$Q_{pA}{}^{\psi(2S)} = \frac{\sigma_{pA}{}^{\psi(2S)}}{A_{Pb} \cdot \sigma_{pp}^{\psi(2S)}}$$

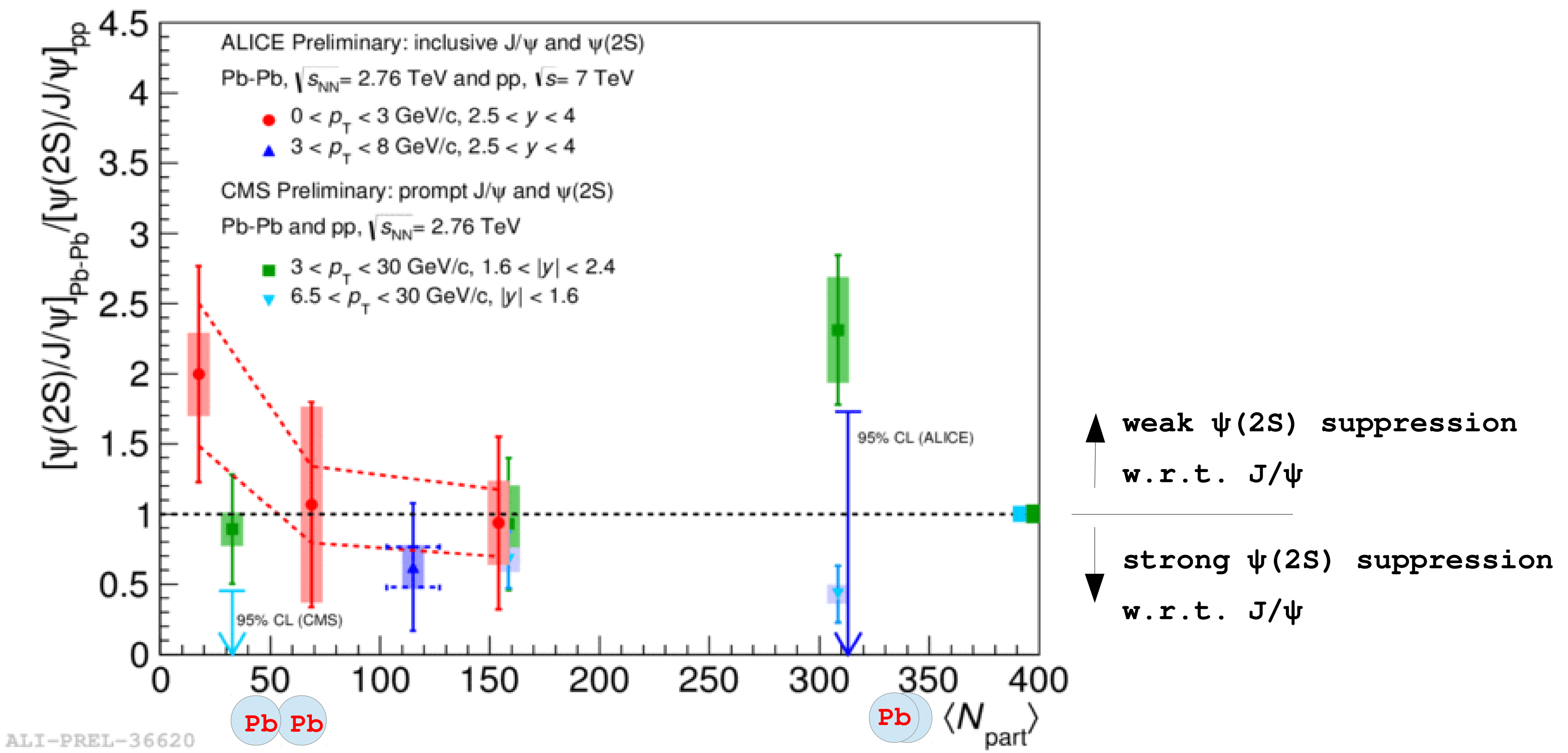
- → Q_{pPb} variable instead of R_{pPb} (possible bias from the centrality estimator), as a function of the event activity
- → At backward rapidity the ψ(2S) and J/ψ Q_{pPb} trends are different: the ψ(2S) Q_{pPb} decreases with increasing event activities
- → At forward rapidity the Q_{pPb} trend is similar for J/ψ and ψ(2S)

Pb–Pb collisions



An event in Pb-Pb collision, reconstructed with the ALICE detector

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



→ **ALICE:** limited ψ(2S) statistics does not allow a firm conclusion about the ψ(2S) centrality dependence

→ **CMS** (CMS-HIN-12-007) shows that:

- at **mid-rapidity (6.5<p_T<30 GeV/c)** : the ψ(2S) suppression pattern is in agreement with sequential melting
- at **forward rapidity (3<p_T<30 GeV/c)** : opposite trend to the mid-rapidity (and opposite to expectation from sequential melting)

The ALICE Collaboration has studied the ψ(2S) production in pp, p-Pb and Pb-Pb collisions

The study of the ψ(2S) production cross sections, in pp collisions, is important to perform comparisons with other collision systems

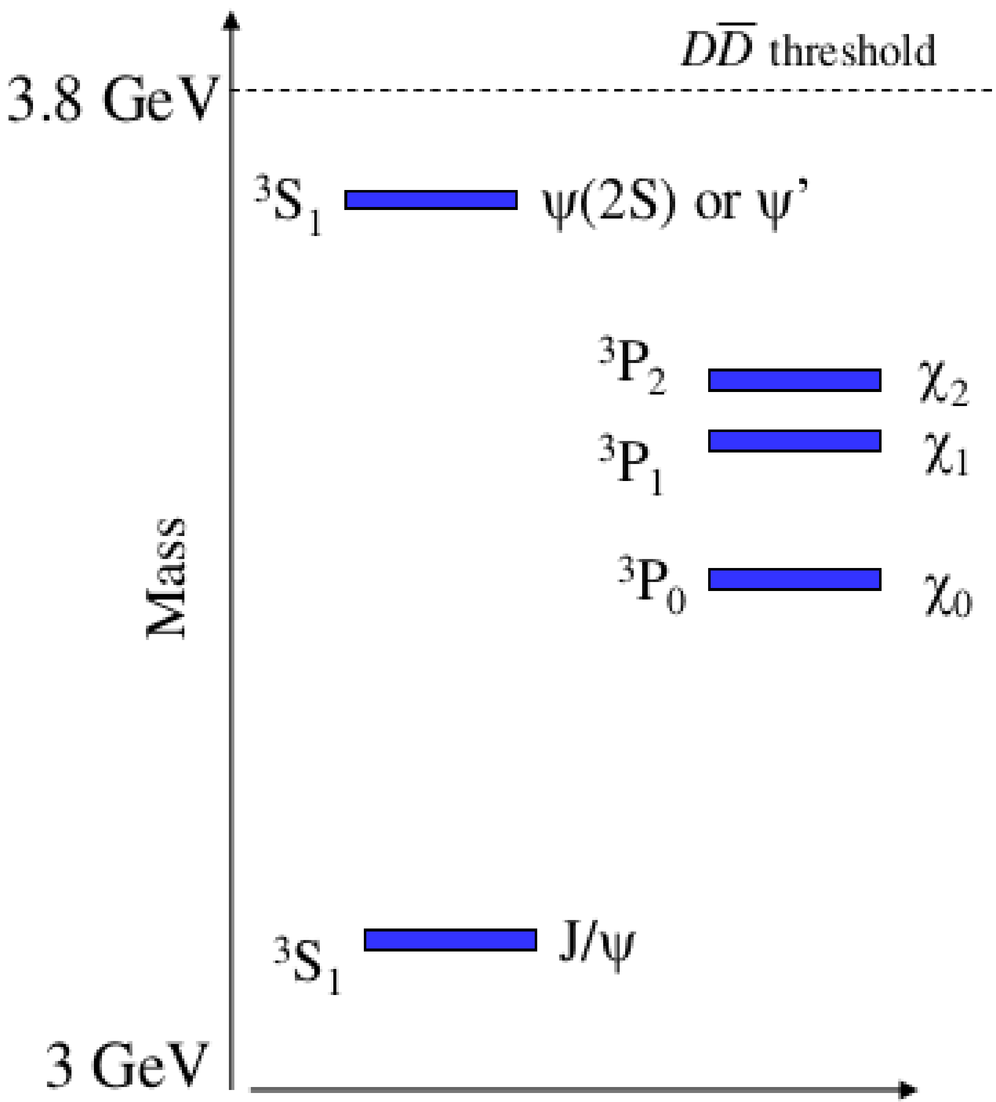
In p-Pb collisions the ψ(2S) is more suppressed with respect to the J/ψ. Theoretical predictions based on shadowing and/or energy loss do not describe data

Limited statistics in Pb-Pb collisions, prevent from firm conclusions on the ψ(2S) behaviour vs centrality


Thanks a lot for
your attention!

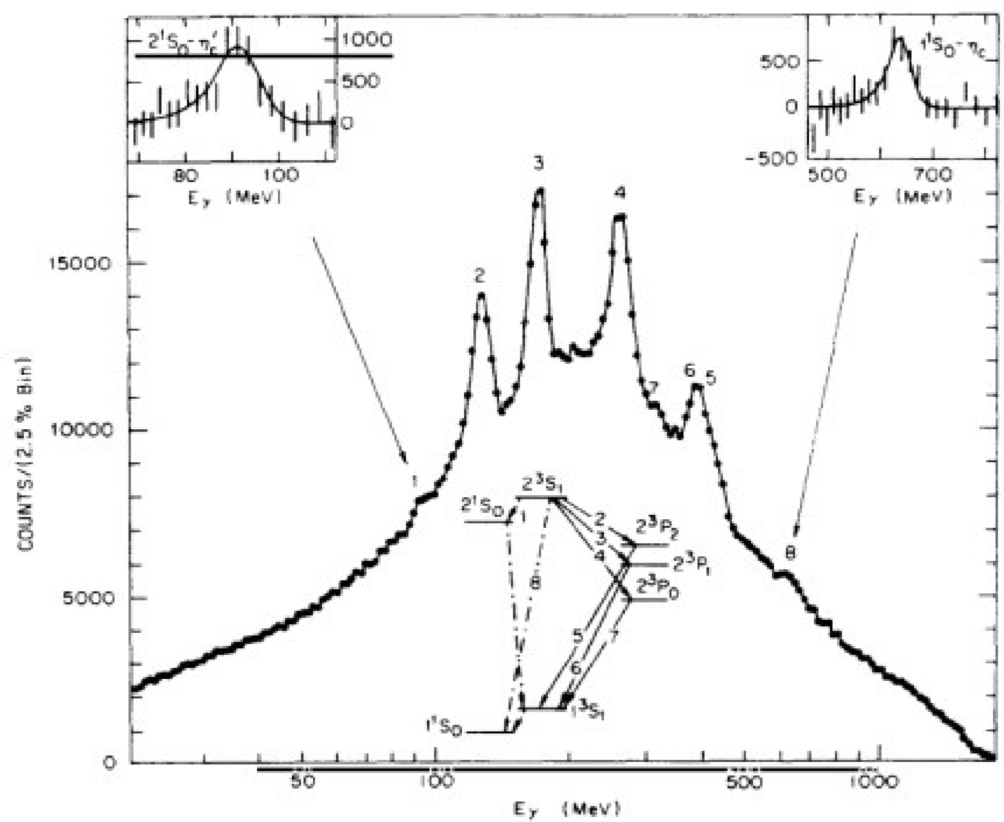
Backup slides

Charmonium family



state	J/ψ	χ_c	ψ(2S)
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
r_o(fm)	0.25	0.36	0.45

Crystal Ball



Charmonium decays

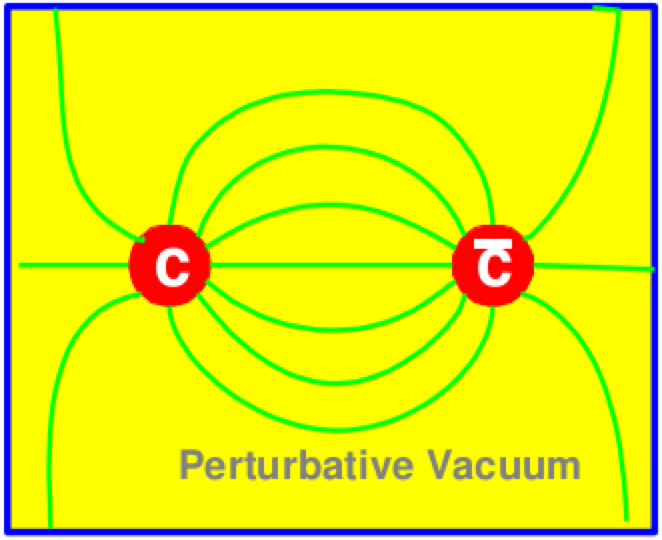
$J/\psi(1S)$ DECAY MODES

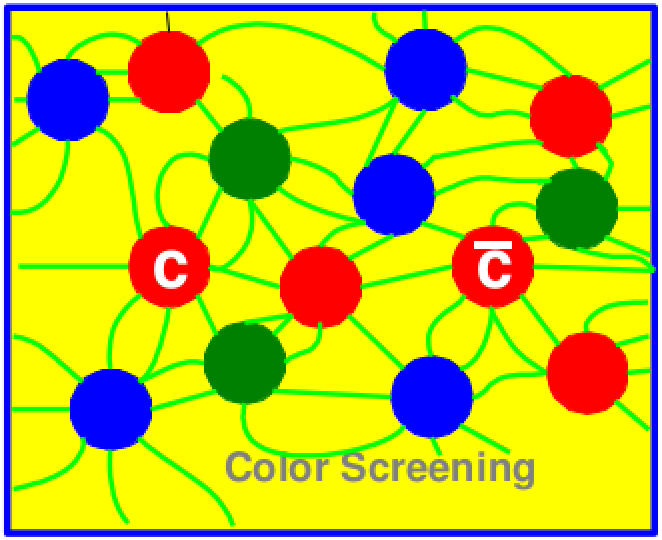
	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons		(87.7 ± 0.5) %	
Γ_2	virtual $\gamma \rightarrow$ hadrons		(13.50 ± 0.30) %	
Γ_3	$g g g$		(64.1 ± 1.0) %	
Γ_4	$\gamma g g$		(8.8 ± 1.1) %	
Γ_5	$e^+ e^-$		(5.94 ± 0.06) %	
Γ_6	$e^+ e^- \gamma$	[a]	$(8.8 \pm 1.4) \times 10^{-3}$	
Γ_7	$\mu^+ \mu^-$		(5.93 ± 0.06) %	

$\psi(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons	(97.85 ± 0.13) %	
Γ_2	virtual $\gamma \rightarrow$ hadrons	(1.73 ± 0.14) %	S=1.5
Γ_3	$g g g$	(10.6 ± 1.6) %	
Γ_4	$\gamma g g$	(1.03 ± 0.29) %	
Γ_5	light hadrons	(15.4 ± 1.5) %	
Γ_6	$e^+ e^-$	$(7.73 \pm 0.17) \times 10^{-3}$	
Γ_7	$\mu^+ \mu^-$	$(7.7 \pm 0.8) \times 10^{-3}$	
Γ_8	$\tau^+ \tau^-$	$(3.0 \pm 0.4) \times 10^{-3}$	

Charmonium suppression in the QGP



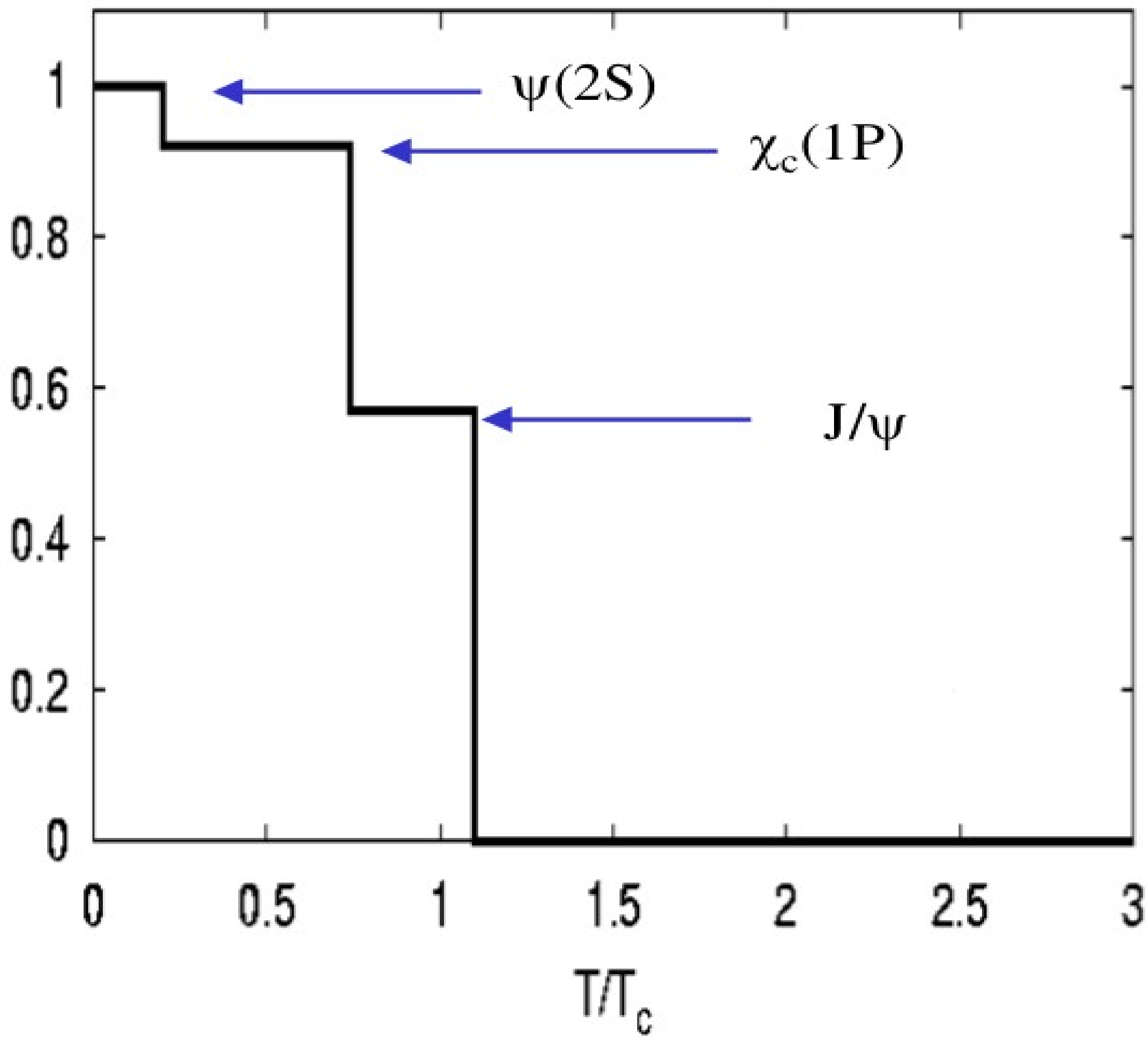


$$V(r) = -\frac{\alpha}{r} + kr \quad \Rightarrow \quad V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

$$\lambda_D(PQCD) = \frac{1}{\sqrt{\left(\frac{N_c}{3} + \frac{N_f}{6}\right) g^2 T}}$$

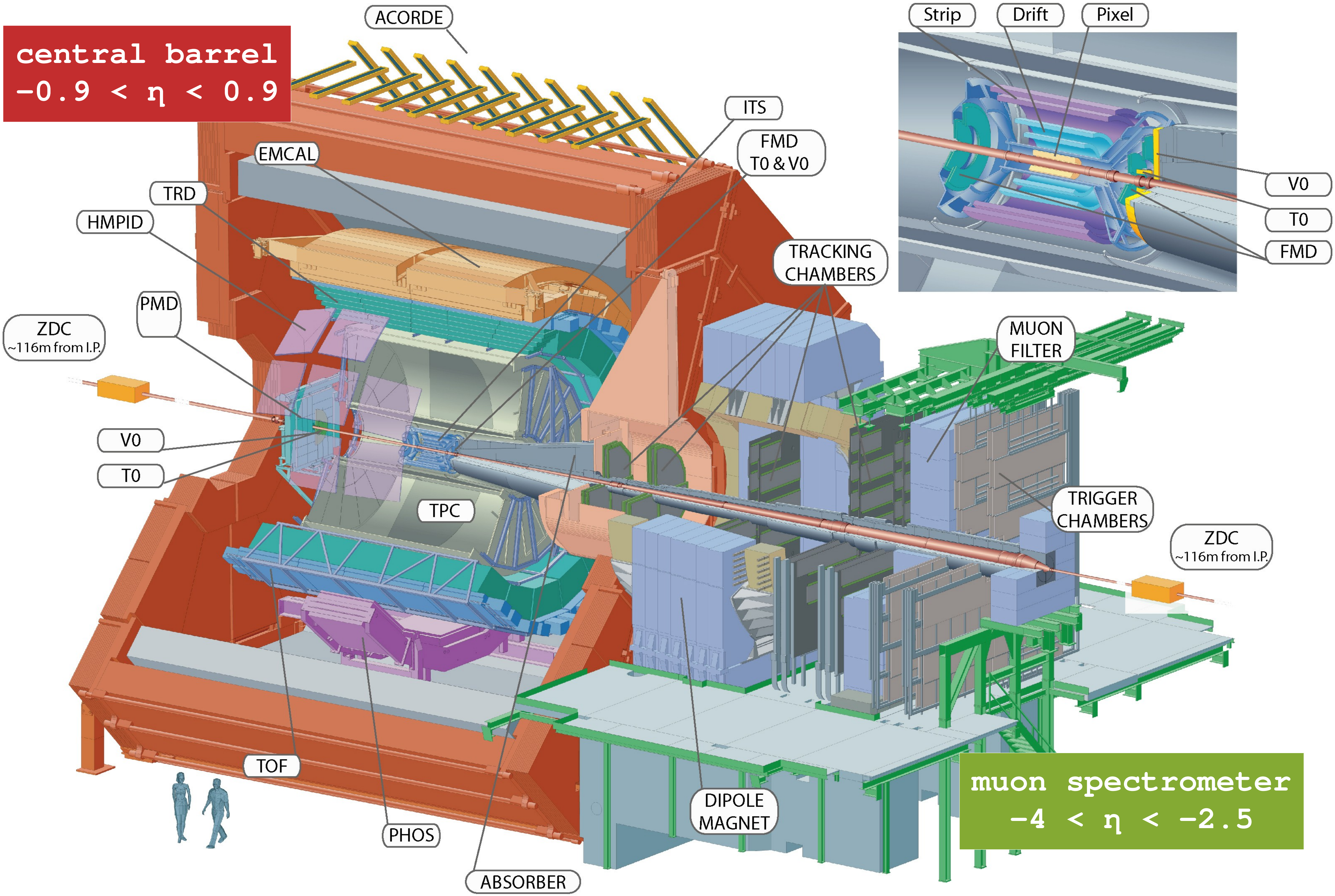
$(g^2 = (\pi/3)\,\alpha)$

Charmonium sequential melting



The ALICE detector

central barrel
$-0.9 < \eta < 0.9$



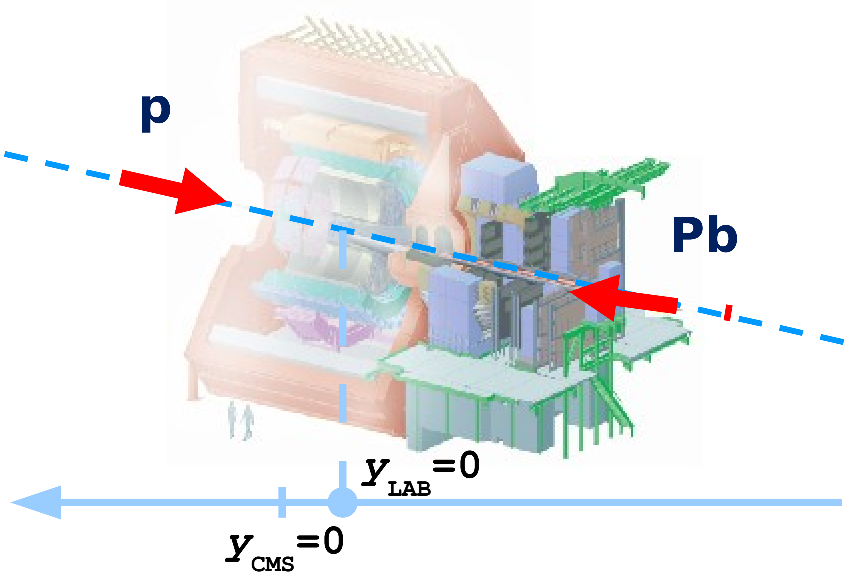
muon spectrometer
$-4 < \eta < -2.5$

2013 p-Pb run

Beam energy asymmetry (E_p=4 TeV, E_{Pb}=1.58 A·TeV) causes a shift in rapidity:

$$|\Delta y_{CMS}| = 0.5 \log (Z_{Pb}A_p/Z_pA_{Pb}) = 0.465$$

p-Pb: proton beam moving towards the muon arm. L_{int} = 5.0 nb^{-1}

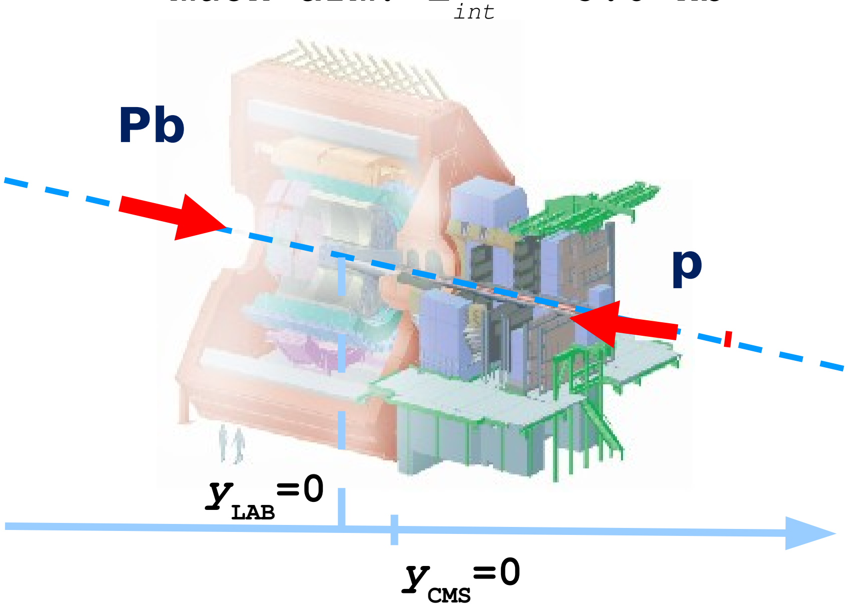


Forward rapidity configuration

(in the centre of mass frame)

$2.03 < y_{CMS} < 3.53$

Pb-p: lead beam moving towards the muon arm. L_{int} = 5.8 nb^{-1}



Backward rapidity configuration

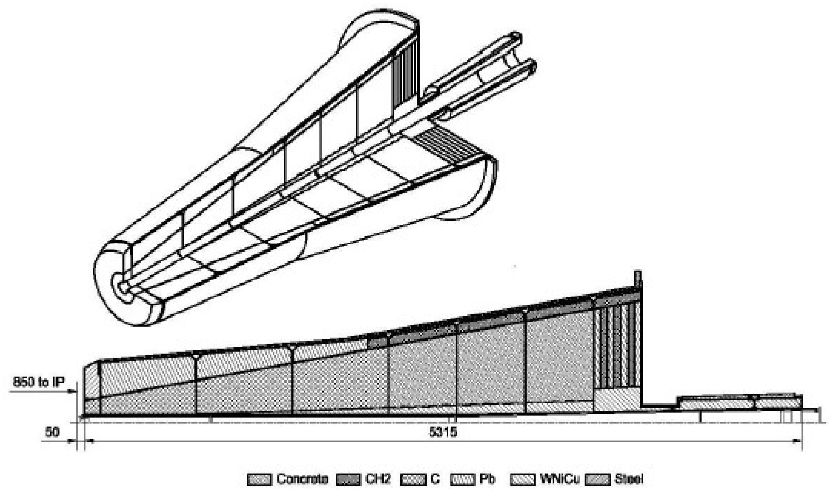
(in the centre of mass frame)

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

Standard selection criteria

The following criteria are applied to remove hadrons escaping (or produced) in the front absorber, muons from pion and kaon decays and fake muon tracks, before performing the signal extraction:

- muon trigger-tracking matching;
- tracks are in the range: $-4 \le \eta_{lab} \le -2.5$
- track radial position at the absorber end is in the range: $17.6 \le R_{abs} \le 89.5$ cm
- dimuon rapidity is in the range: $2.5 \le y_{lab} \le 4$



ψ(2S) signal extraction

1) Fit of the opposite-sign dimuon invariant mass spectra:

→ Signal: extended Crystal Ball and pseudo-Gaussian functions

→ Background: variable width Gaussian and polynomial·exponential functions

→ ψ(2S) position and width are tied to the J/ψ:

$$m_{\psi(2S)} = m_{J/\psi} + (m^{MC}_{\psi(2S)} - m^{MC}_{J/\psi})$$

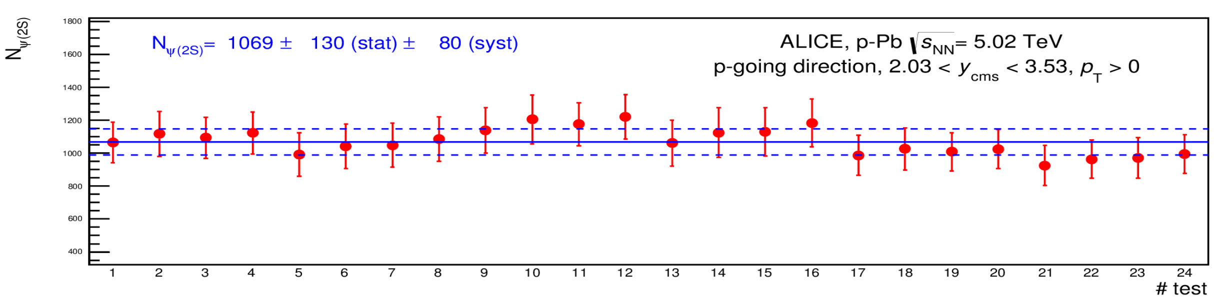
$$\sigma_{\psi(2S)} = \sigma_{J/\psi} \cdot (\sigma^{MC}_{\psi(2S)} / \sigma^{MC}_{J/\psi})$$

2) Systematic uncertainty on the signal extraction:

→ A large number of fits to the invariant mass spectra is performed using various combinations of signal shapes, background shapes, start/end point of the fit range

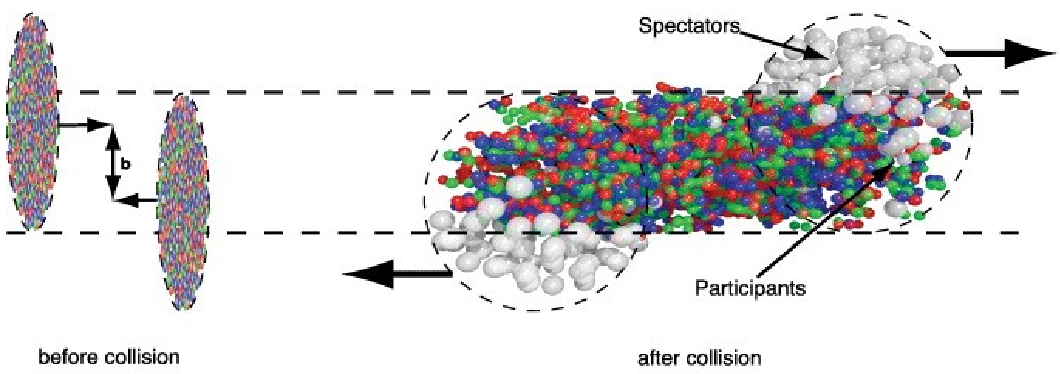
→ Final ψ(2S) yield is obtained as the average of the results of the fits

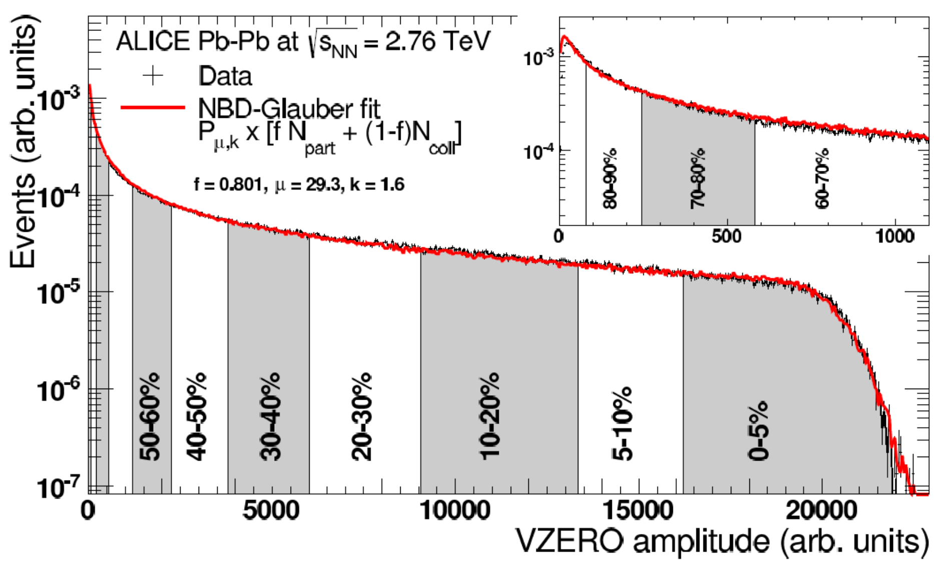
→ Systematic uncertainty on the signal is obtained as the RMS of the distribution

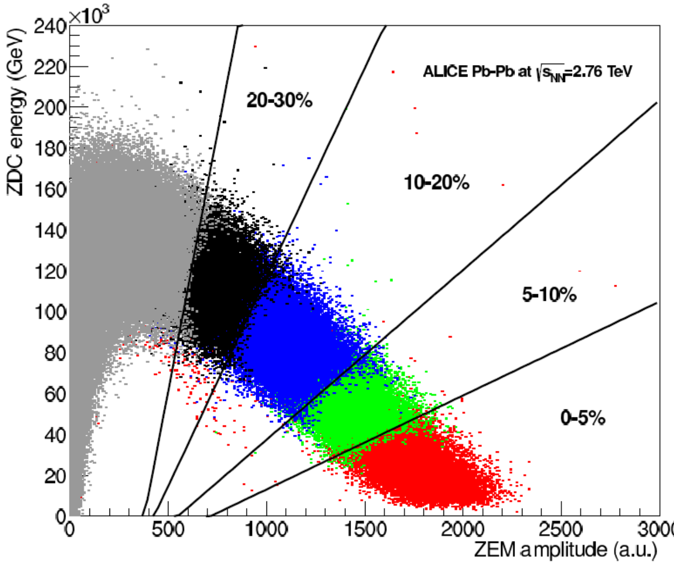


Centrality in Pb-Pb collisions

Phys. Rev. C 88, 044909 (2013)



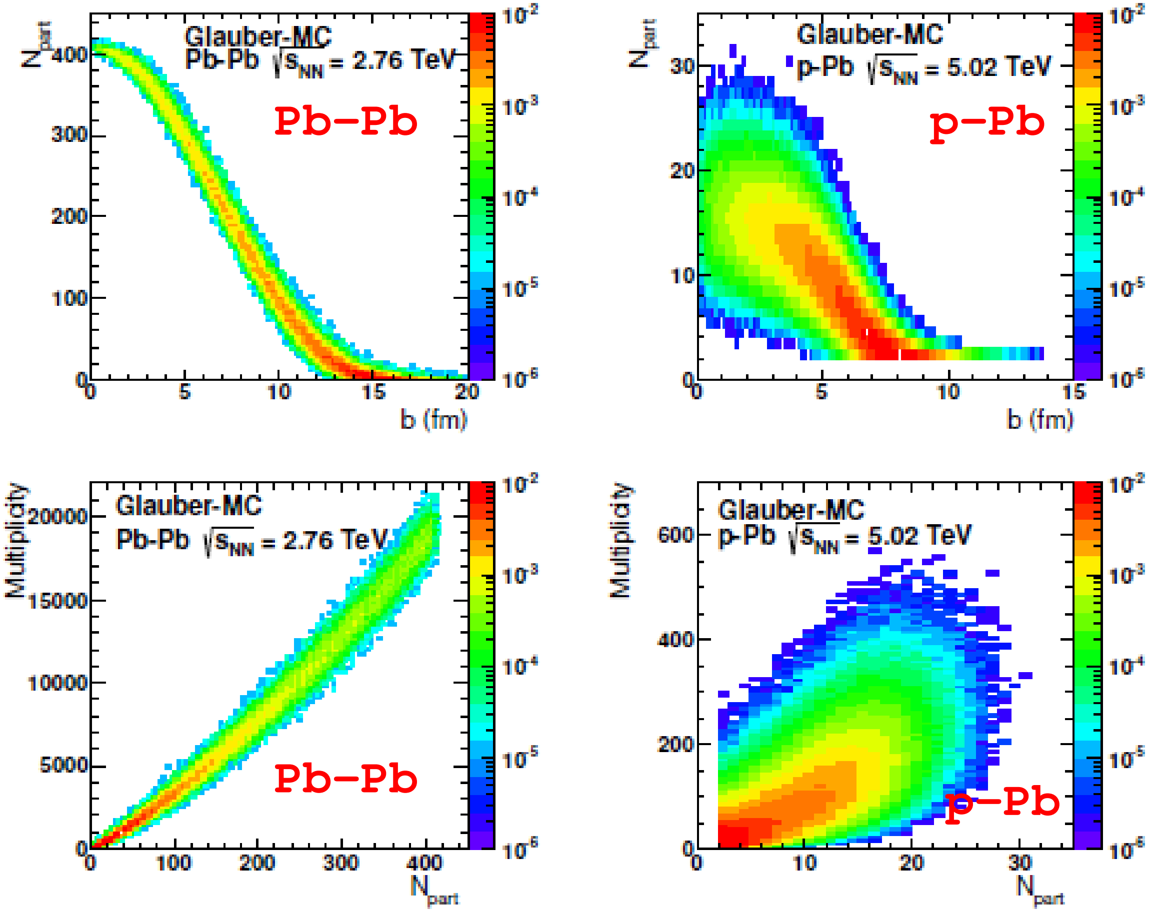




→ VZERO amplitude and Glauber model used to determine centrality percentiles (0-90%)

→ Alternative definition based on ZDC+ZEM (0-30%)

Centrality in p–Pb collisions (1)



Missing correlation between N_{part} and impact parameter (b) in p–Pb collisions

Missing correlation between N_{part} and multiplicity in p–Pb collisions

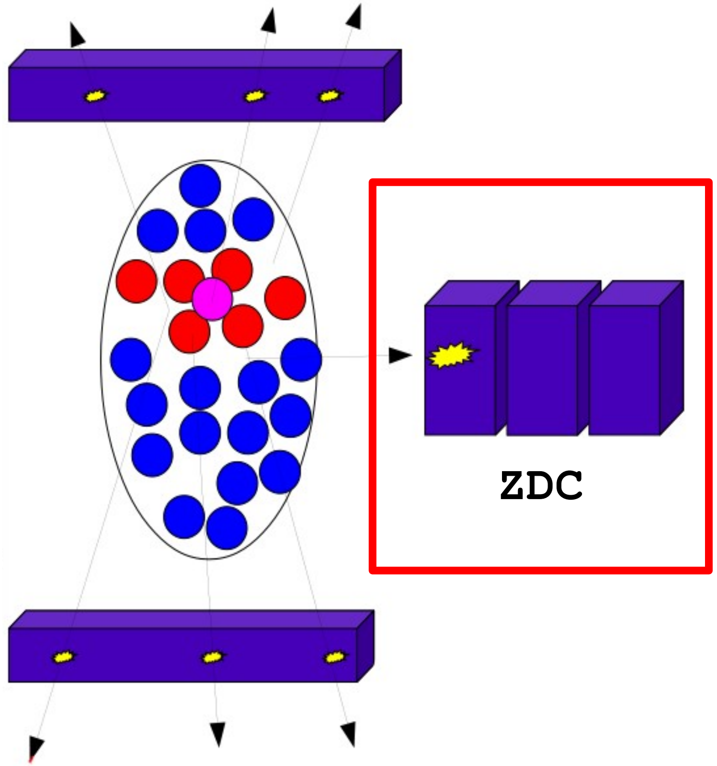
→ Bias when using estimators based on multiplicity (VZERO-A amplitude)

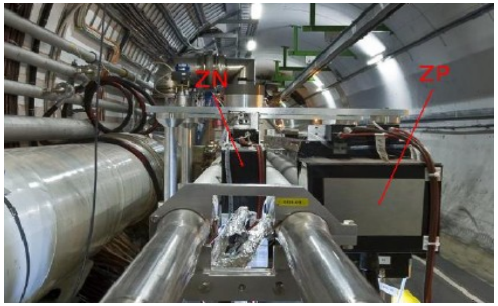
→ The range of multiplicities used to select the centrality in p–Pb collisions is of similar magnitude as the fluctuations

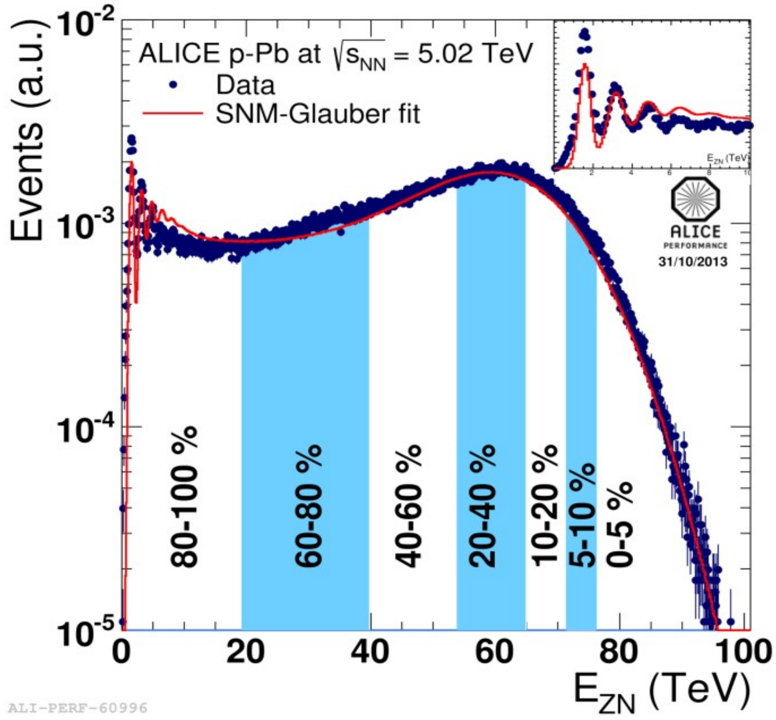
→ Centrality selection based on multiplicity may select a biased sample of nucleon–nucleon collisions

A.Toia's talk QM14

Centrality in p-Pb collisions (2)



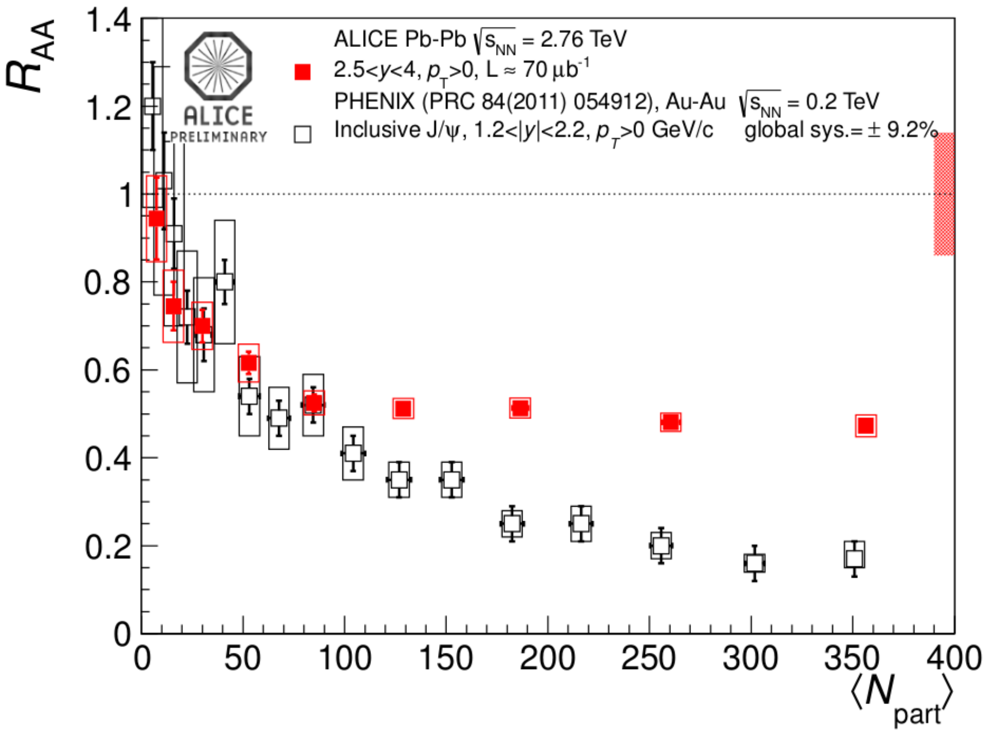


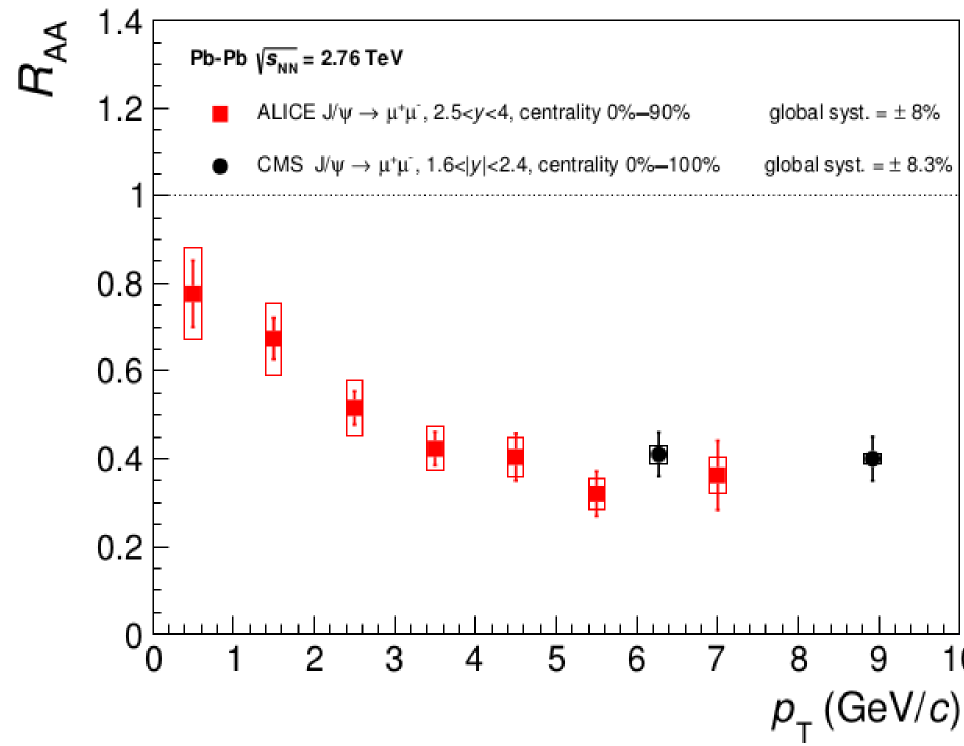


- Zero Degree Calorimeters detect slow nucleons, which are monotonically related to N_{coll} (and can be used as centrality estimator)
- “Black” nucleons: $\beta < 0.25$, “gray” nucleons: $0.25 < \beta < 0.7$
- ZDC provide centrality estimation ~without biases, because of the large η-separation fromt the central part of ALICE
- Glauber + Slow Nuclear Model for Zero-Degree Energy

A.Toia's talk QM14

J/ψ in Pb-Pb





→ Lower energy data from **PHENIX** show an increasing suppression moving towards more central collisions

→ **ALICE** results indicate a saturation of the suppression

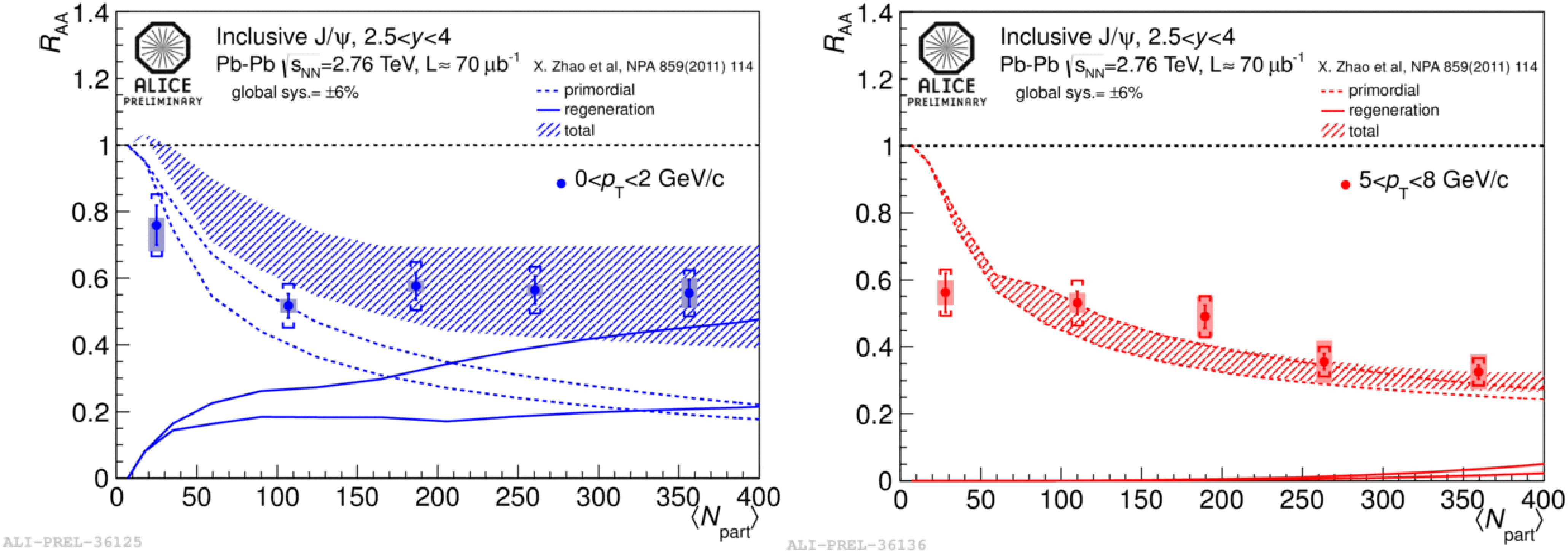
→ Clear evidence for a **smaller suppression at LHC with respect to RHIC** energy in central collisions

→ **Smaller suppression at low p_T**

Suppression pattern consistent with recombination picture!

J/ψ in Pb-Pb comparison to theoretical models

J/ψ R_{AA} as function of the collision centrality in two different p_T bins

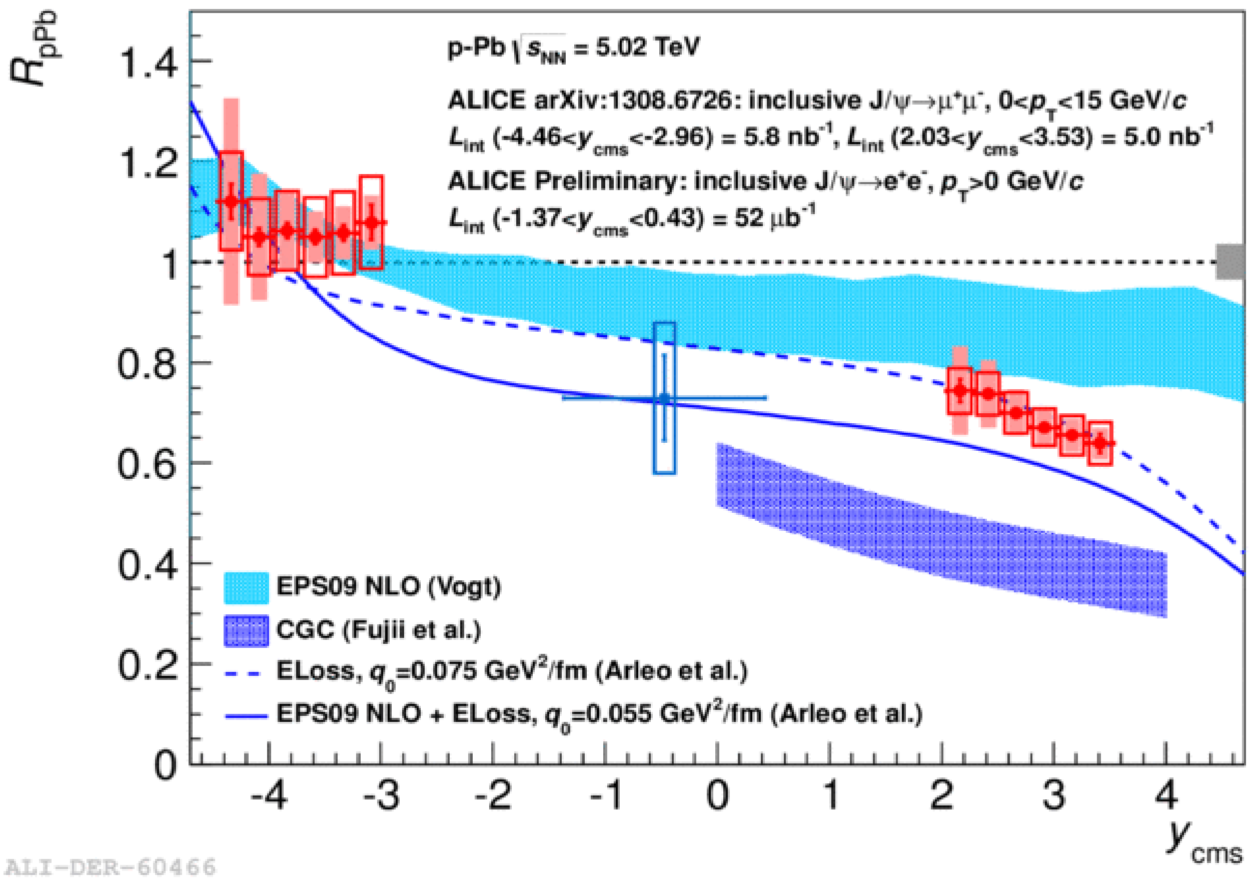


→ The contribution of primordial (dashed) and regeneration(continuous line) component is shown, as well as their sum

→ A larger R_{AA} is observed at low p_T: this behaviour is reasonably described by models including J/ψ produced by recombination (continous line)

J/ψ in p-Pb collisions

The J/ψ R_{pPb} modification factor is compared to theoretical predictions

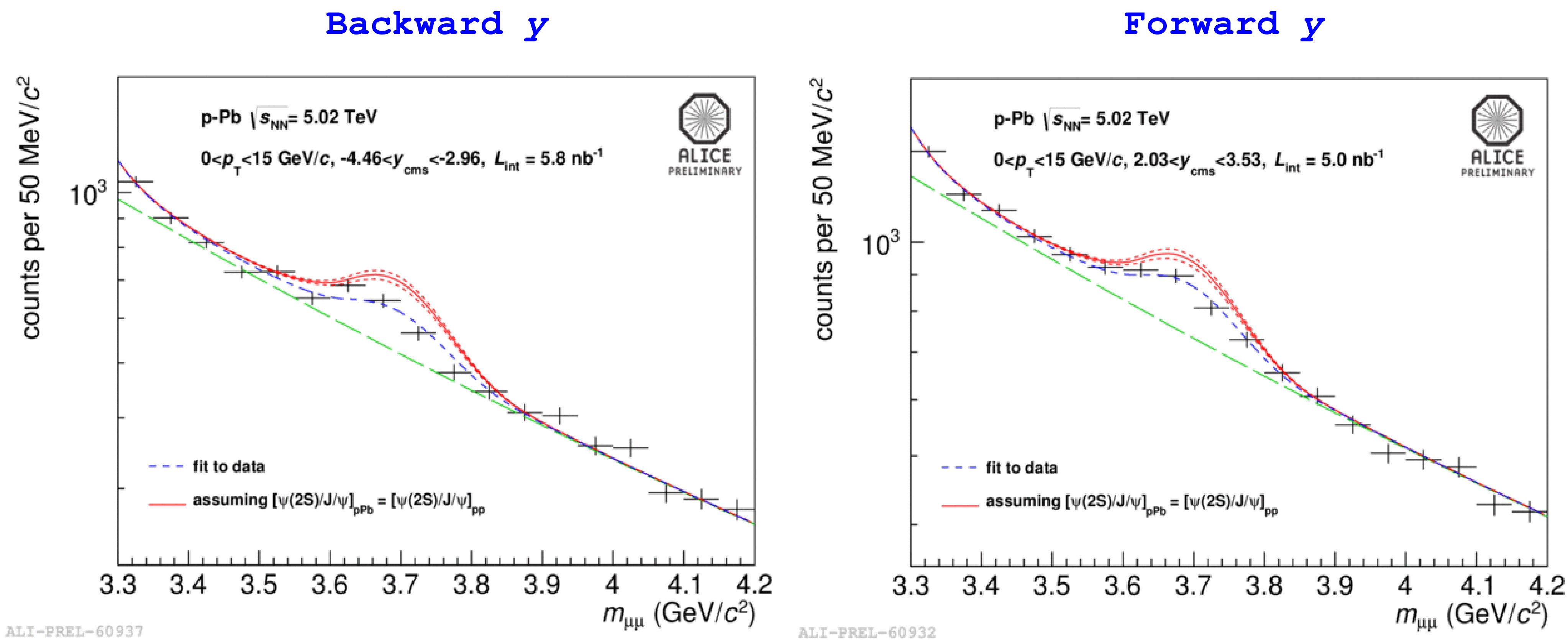


→ **Shadowing model** reproduces well data at backward rapidity, some differences at forward rapidity (arXiv:1301.3395)

→ **Energy loss** models reproduce well data at forward rapidity(arXiv:1212.0434)

→ **Color Glass Condensate** model overestimates the suppression(arXiv:1304.2221)

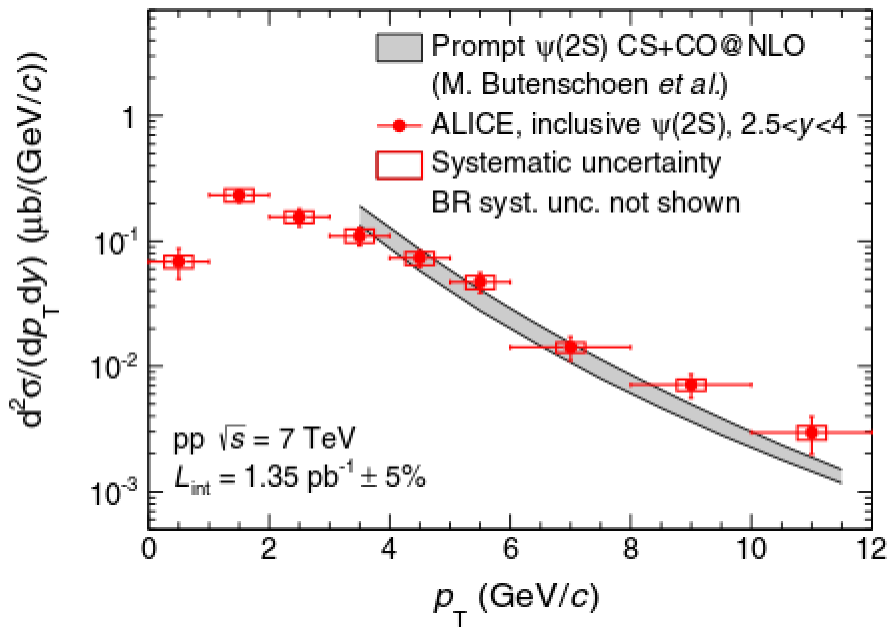
ψ(2S) in p-Pb collisions



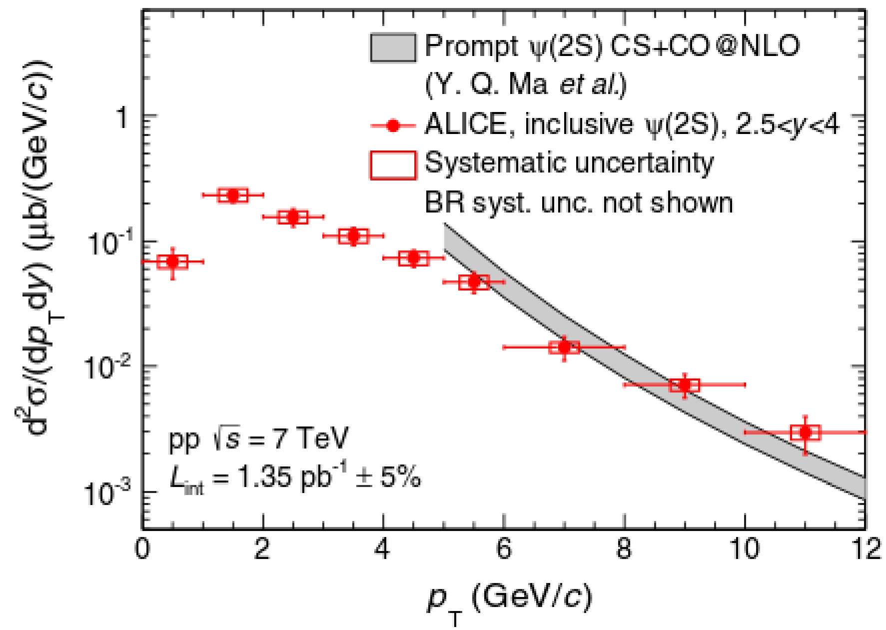
- The p-Pb ψ(2S) yield can be compared with the expected Ψ(2S) yield based on the measured p-p ψ(2S)/J/ψ ratio
- Significant **decrease** of ψ(2S) yield in p-Pb with respect to p-p collisions

ψ(2S) in pp: comparison to models

Eur. Phys. J. C (2014) 74:2974



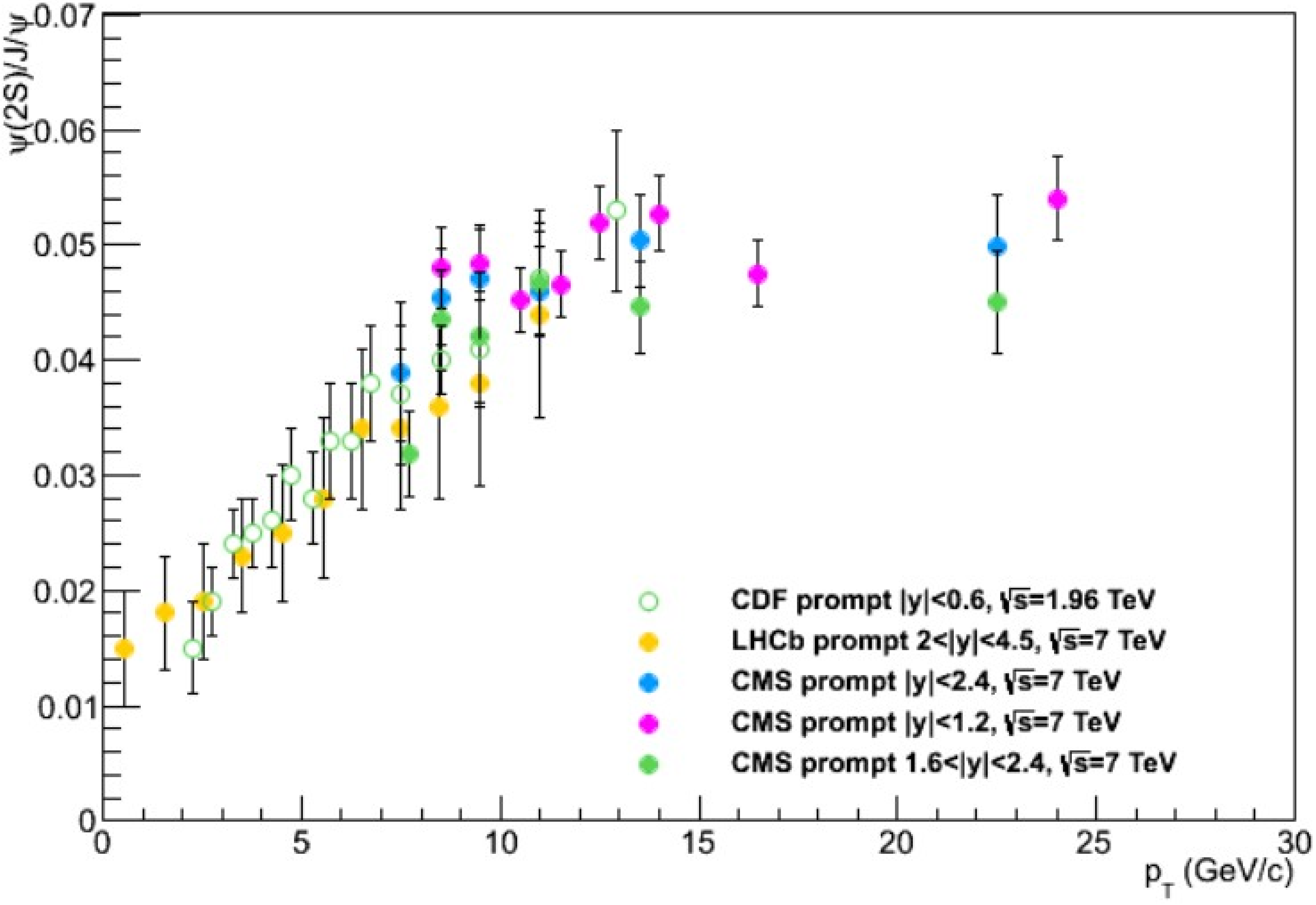
Eur. Phys. J. C (2014) 74:2974



→ comparison the inclusive ψ(2S) differential production cross section to two NRQCD production at NLO (left: arXiv:1105.0820, right: arXiv:1012.1030)

→ both calculations show reasonable agreement with data

ψ(2S)/J/ψ in pp collisions



Quarkonia production mechanisms

- In the **Color-Singlet Model** perturbative QCD is used to model the production of on-shell heavy quark pairs,with the same quantum numbers as the quarkonium into which they hadronize
- In the **Color Evaporation Model**, the production cross section of a given quarkonium state is considered proportional to the cross section of its constituting heavy quark pair, integrated from the sum of the masses of the two heavy quarks to the sum of the masses of the lightest corresponding mesons (D or B)
- In the framework of **Non Relativistic QCD**, contributions to the quarkonium cross section from the heavy-quark pairs produced in a color-octet state are also taken into account, in addition to the color-singlet contributions described above