New Results on Initial State and Quarkonia with ALICE

University of Bari &
INFN, section of Bari

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For the ALICE Collaboration

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INFN Istituto Nazionale di Fisica Nucleare

ALICE

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Outline

- **Motivations**
- **Quarkonium reconstruction with ALICE**
- **Results from p-Pb collisions (J/ψ , ψ(2S) , ϒ(1S))**
- **Conclusions**

Nuclear effects on quarkonium production

At LHC energies, several mechanisms can affect **quarkonium production in nuclear medium** besides QGP:

Cold Nuclear Matter effects (CNM)

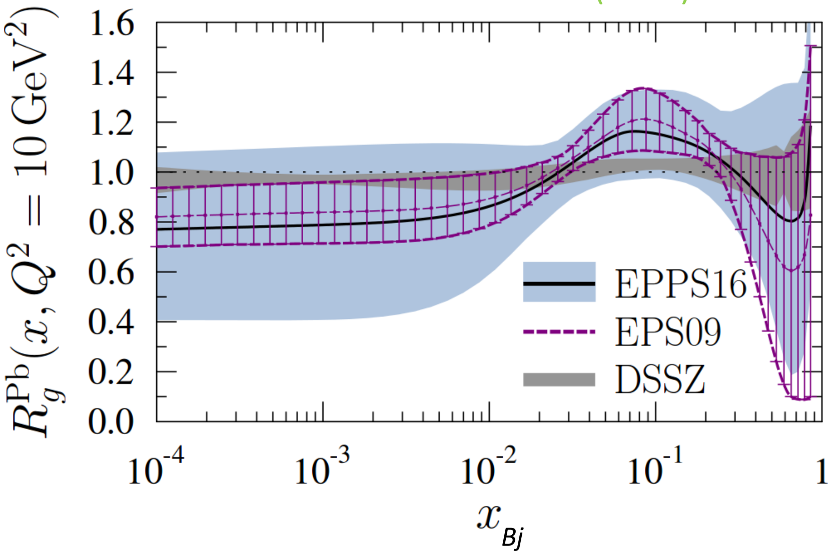
initial state

- **modification of PDF in nuclear target**
  gluon shadowing/anti-shadowing in nPDFs
  (JHEP **0904** (2009) 065)
- **gluon saturation effects at low x_{Bj}**
  Color Glass Condensate framework
  (PRD **92** (2015) 071901)

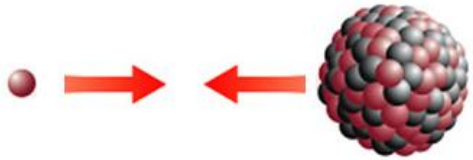
final state

- **partonic energy loss**
  also with initial/final state radiation interference (JHEP **1303** (2013) 122)
- **absorption/break-up in nuclear medium**
  (NPA 700 (2002) 539)
- **Interaction with co-moving hadron gas**
  (JPCS **422** (2013) 012018)

EPJC (2017) 77:163



$$R_g^A = \frac{g\ PDF\ in\ bound\ nucleus}{g\ PDF\ in\ free\ nucleon}$$



p-A collisions

crucial **tool to disentangle different CNM effects** and interpret Pb-Pb results

R_{pA}: evaluating nuclear effects

Nuclear modification factor allows evaluation of nuclear effects on quarkonium production in p-A collisions

$$R_{\mathrm{pA}} = \frac{N_{\mathrm{pA}}^{Q\bar{Q}}}{\langle T_{\mathrm{pA}} \rangle \cdot \sigma_{\mathrm{pp}}^{Q\bar{Q}}}$$

measured **quarkonium yield in p-A**

$$\langle T_{\mathrm{pA}} \rangle = \frac{\langle N_{\mathrm{coll}} \rangle}{\sigma_{\mathrm{pp}}^{inel}}$$

nuclear thickness function
∝ binary pp collision in pA

reference cross section in **pp** in the same energy/kinematic domain

$R_{pA} = 1$ ⟹ no deviation from a superposition of elementary pp collisions

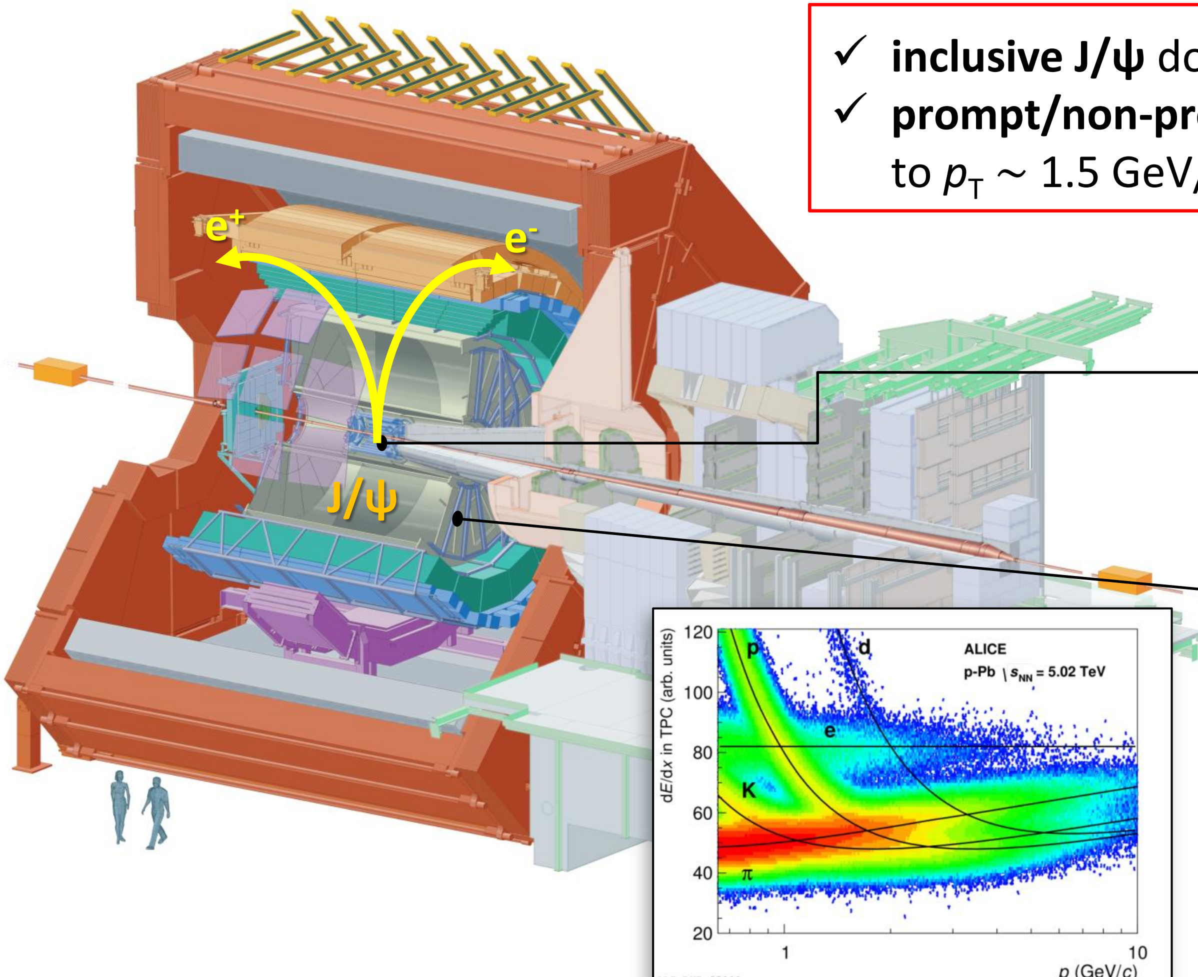
$R_{pA} \neq 1$ ⟹ **modifications due to nuclear medium**

Quarkonia reconstruction with ALICE: mid-rapidity

at mid-y : reconstruction via **e^+e^- decay channel** in Central Barrel

Central Barrel **acceptance**: $|\eta_{\mathrm{lab}}| < 0.9$

- ✓ **inclusive J/ψ** down to **zero p_T**
- ✓ **prompt/non-prompt J/ψ** separation down to $p_T \sim 1.5$ GeV/c



main sub-systems used

Inner Tracking System (ITS)
vertexing,
tracking

Time Projection Chamber (TPC)
tracking
electron PID via **d*E*/dx**

V0 , ZDC:
triggering
centrality estimation

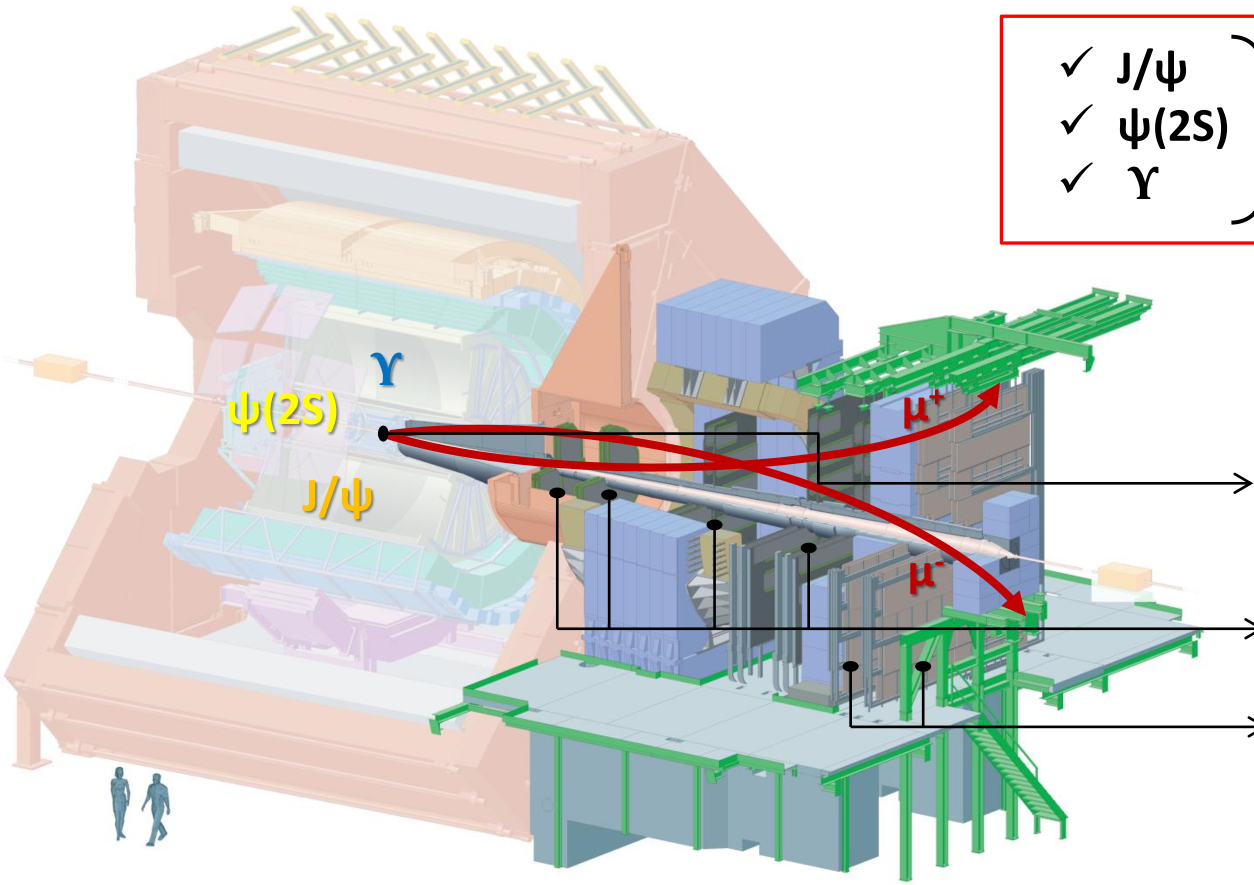
Quarkonia reconstruction with ALICE: fwd-rapidity

at forward-y : reconstruction via $\mu^+\mu^-$ **decay channel** in Muon Arm

Muon Arm **acceptance**: $-4.0 < \eta_{lab} < -2.5$

- ✓ J/ψ
- ✓ ψ(2S)
- ✓ ϒ

} **inclusively** down to **zero** p_T



main sub-systems used

Silicon Pixel Detector (SPD)
vertexing

Muon Chambers (MCH)
tracking

Muon Trigger (MTR)
triggering

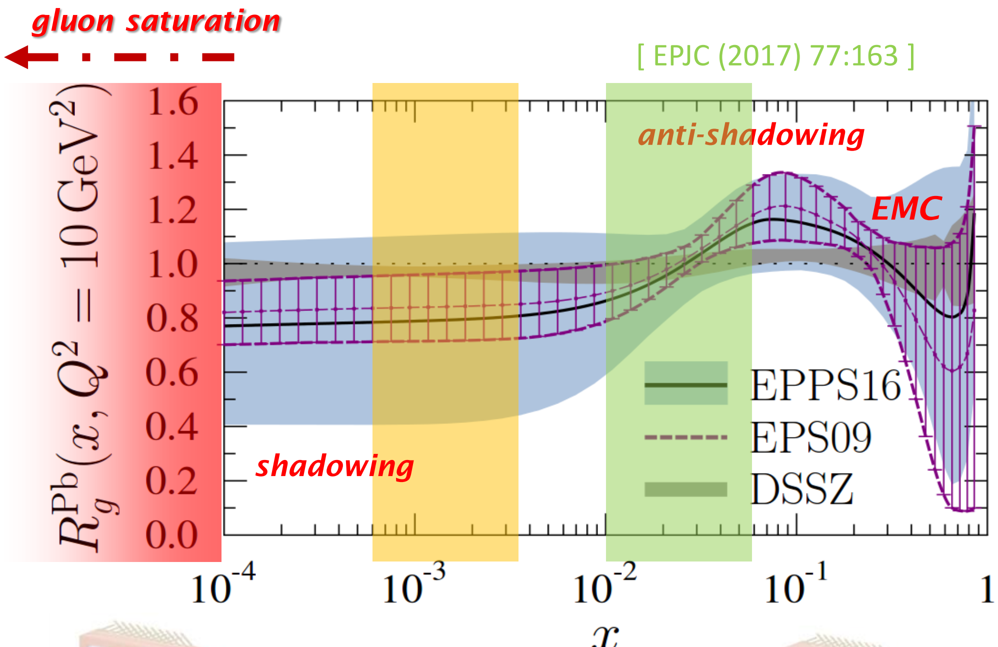
V0 , ZDC:
triggering,
centrality estimation

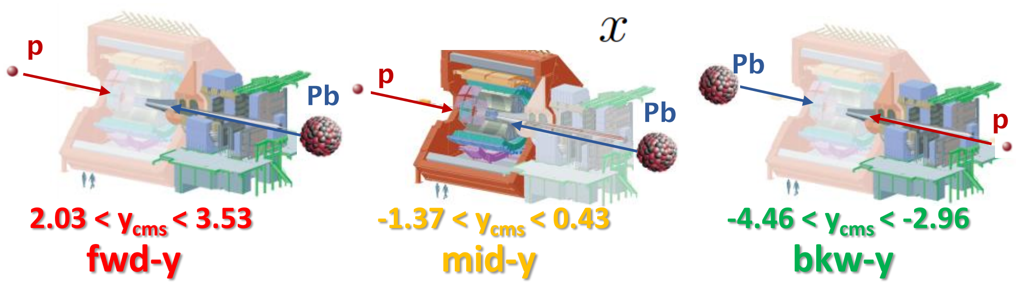
ALICE kinematic coverage in p-Pb collisions

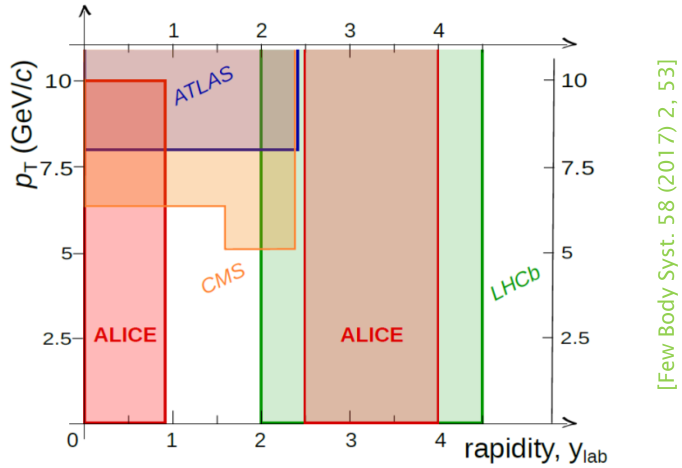
Unique ALICE acceptance at the LHC:

→ access to **low p_T J/ψ** measurement **at mid-y**: complementary to ATLAS and CMS

→ access to kinematic **regions in the domain of CNM effects**







Different **rapidities** & **Bjorken-x** values probed e.g. for J/ψ :

Run1, $\sqrt{s_{NN}}$ = 5.02 TeV

Barrel: $-1.37 < y_{cms} < 0.43$ & $6 \cdot 10^{-4} < x_{Pb} < 3 \cdot 10^{-3}$

Muon Arm → 2 beam configurations

p-Pb: $2.03 < y_{cms} < 3.53$ & $2 \cdot 10^{-5} < x_{Pb} < 8 \cdot 10^{-5}$

Pb-p: $-4.46 < y_{cms} < -2.96$ & $1 \cdot 10^{-2} < x_{Pb} < 5 \cdot 10^{-2}$

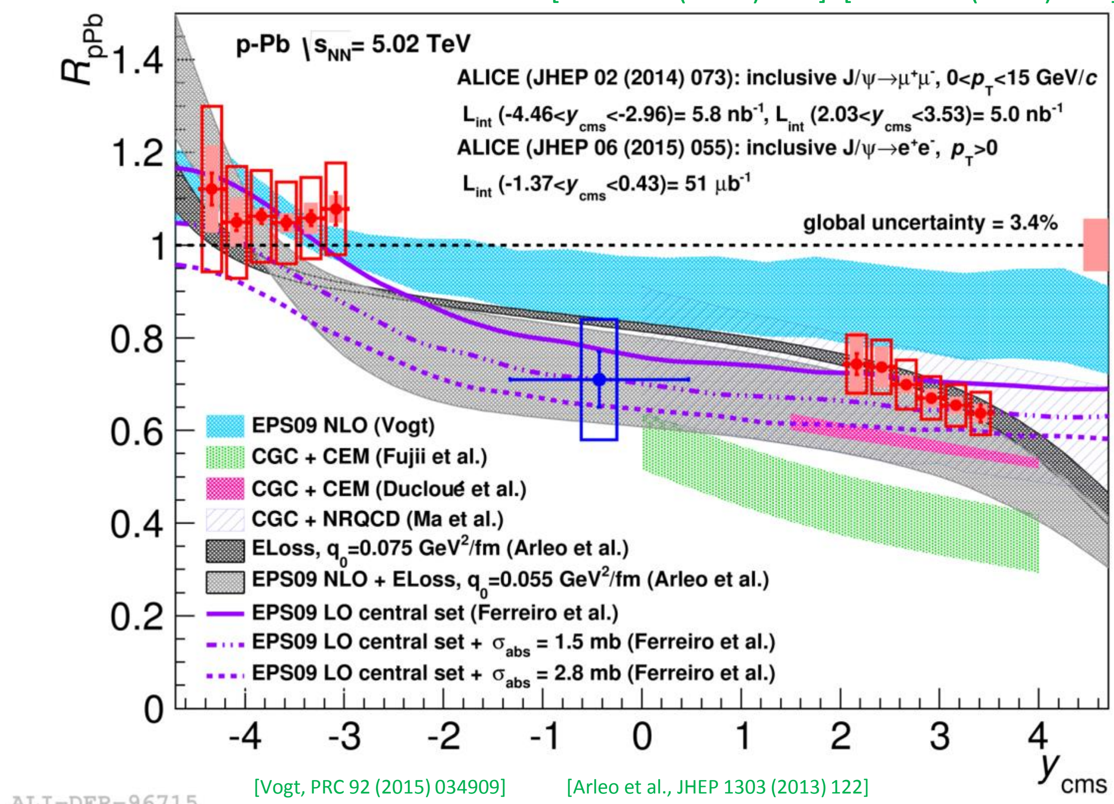
Run2

slightly smaller x values probed at $\sqrt{s_{NN}}$ **= 8.16 TeV**

J/ψ results at $\sqrt{s_{NN}}$ = 5.02 TeV: R_{pPb} vs y

- Measurements of J/ψ R_{pPb} indicate a significant **suppression** at **forward rapidities** with respect to pp collisions. Measurements at backward rapidity are compatible with no modifications from CNM

[JHEP 12 (2014) 073] [JHEP 06 (2015) 055]



[Vogt, PRC 92 (2015) 034909] [Arleo et al., JHEP 1303 (2013) 122]
[Fujii et al., NPA 915 (2013) 1] [Ducloué et al., PRD 91 (2015) 114005]
[Ma et al., PRD 92 (2015) 071901] [Ferreiro et al., PRC 88 (2013) 047901]

model comparison

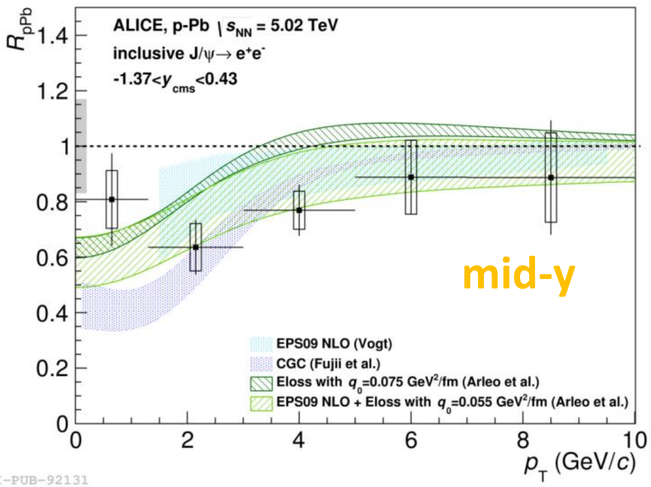
- Fair agreement with CEM+EPS09 nPDF **shadowing** predictions, also with moderate final-state absorption
- Fair agreement with **coherent E-Loss** models with or without shadowing
- Early **CGC** implementations clearly underestimate data at fwd-*y*. Better agreement with more recent calculations

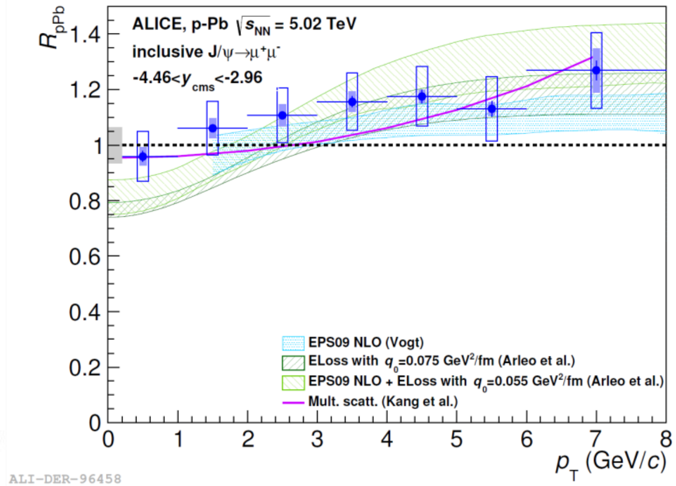
Hard to discriminate between models related to different CNM effects + production models

J/ψ results at $\sqrt{s_{NN}}$ = 5.02 TeV : R_{pPb} vs p_T

- size of CNM effects on J/ψ tends to decrease with increasing p_T

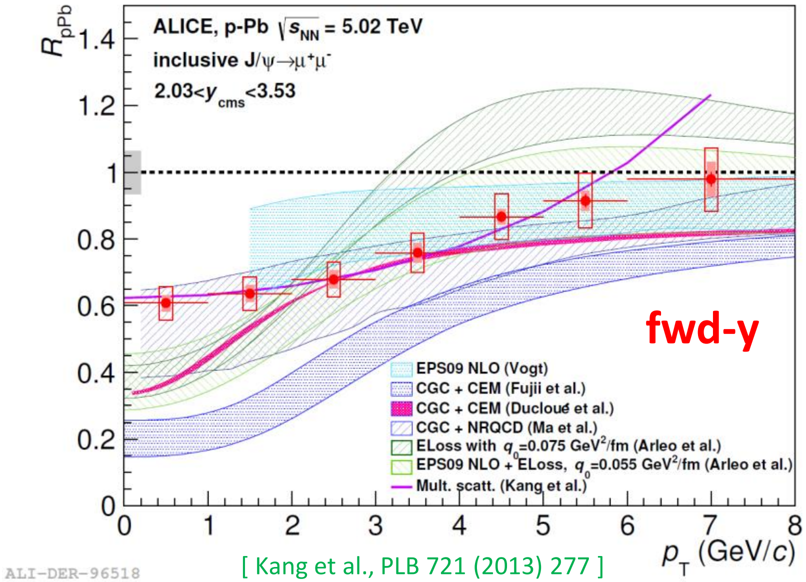
[JHEP 06 (2015) 055]





Mid & Bkw rapidity:

- Fair agreement with **ELoss with shadowing**
- Steeper trend for **pure ELoss** scenarios
- parton **multiple scattering** plausible



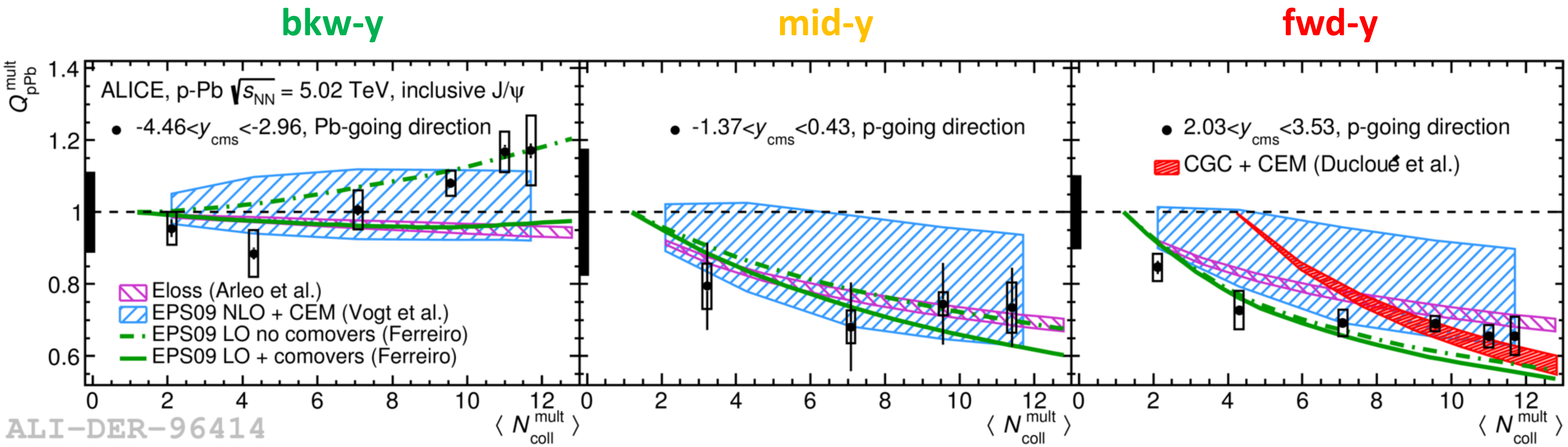
[Kang et al., PLB 721 (2013) 277]

Forward rapidity:

- Fair agreement with **E-loss+shadowing** models for p_T > 1-2 GeV/c while tensions at low p_T
- good description from recent **CGC+NRQCD** calculations within uncertainties
- Steeper trend in **pure E-Loss** and **multiple scattering** scenarios

J/ψ results at $\sqrt{s_{NN}}$ = 5.02 TeV : Q_{pPb} vs event activity

- Measured **nuclear modification factor Q_{pPb}** as a function of the event activity (*) **centrality estimator**



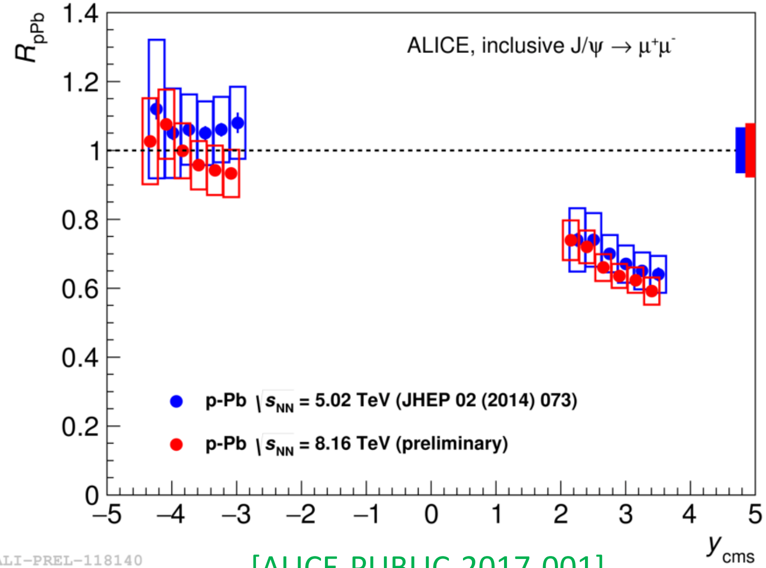
[JHEP 11 (2015) 127]

- Suppression effects tend to be enhanced with increasing centrality at forward *y*
  - Overall agreement with predictions from **E-Loss** and **EPS09 shadowing** with/without **comovers**
  - **CGC + CEM** calculations tend to overestimate data in peripheral collisions at forward *y*

(*) energy deposited in ZDC by neutrons from Pb remnants is used to derive the $\langle N^{mult}_{coll} \rangle$ centrality estimator

J/ψ results at $\sqrt{s_{NN}}$ = 8.16 TeV : R_{pPb} vs y and p_T

Preliminary results from **2016 sample** at increased **energy** and **luminosity**

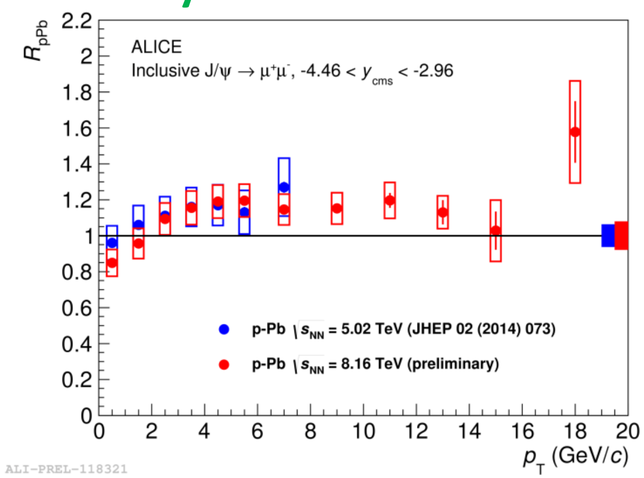


- **8.16 TeV** data show systematically larger suppression, but overall **compatibility** with **5.02 TeV** measurements (slightly different x_{Bj} probed)

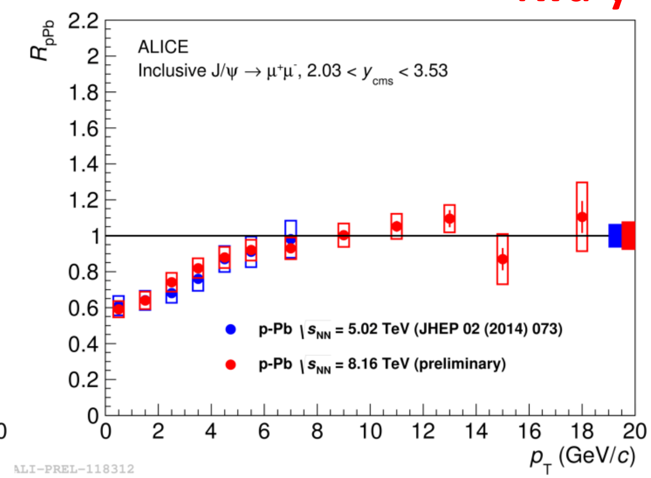
Significant **reduction of uncertainties** and **increased p_T coverage** for R_{pPb} measurements on **Run2** data

[ALICE-PUBLIC-2017-001]

bkw-y



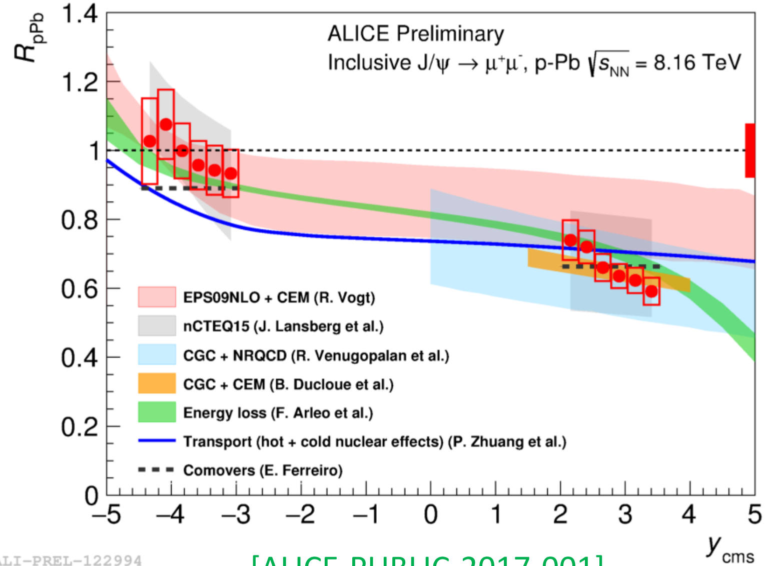
fwd-y



No significant dependence on $\sqrt{s_{NN}}$ for the **suppression** as a function of p_T

J/ψ results at $\sqrt{s_{NN}}$ = 8.16 TeV : R_{pPb} vs y and p_T

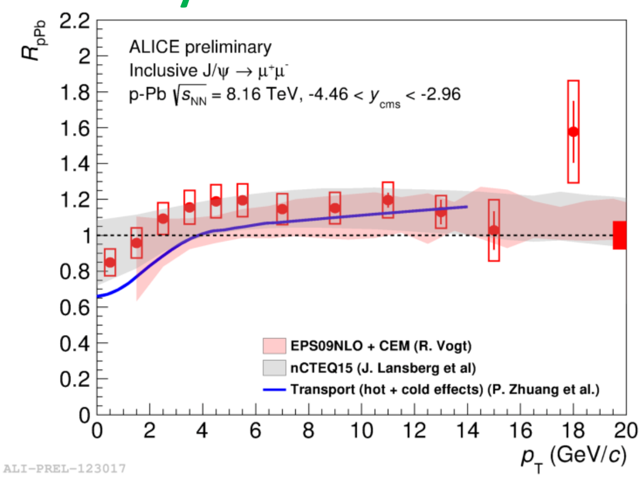
Preliminary results from **2016 sample** at increased **energy** and **luminosity**



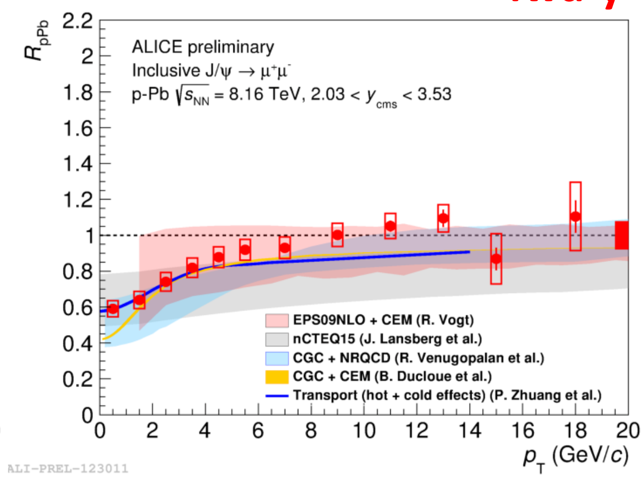
- **data precision** currently **challenging** for most model predictions
- overall good agreement with models based on **shadowing** and/or energy loss, despite large theoretical uncertainties

[ALICE-PUBLIC-2017-001]

bkw-y



fwd-y

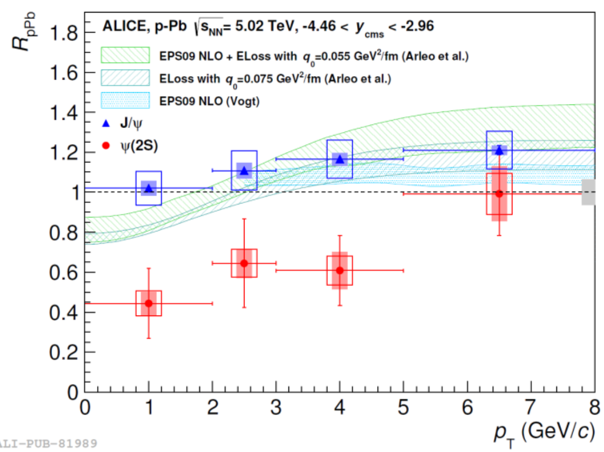


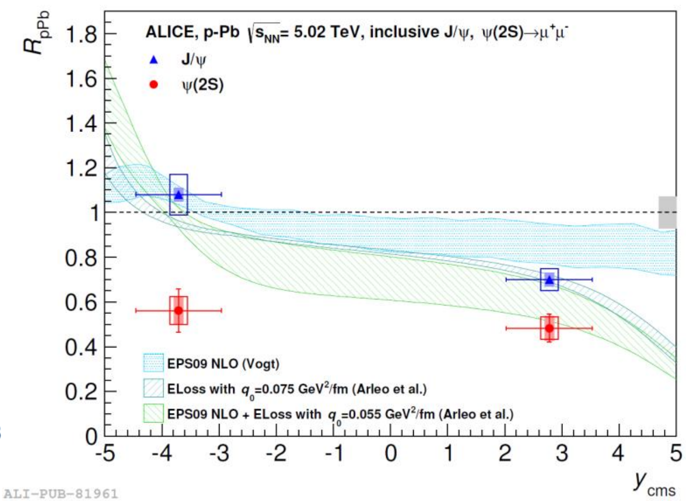
- Good description also from **CGC calculations** at forward rapidity

ψ(2S) results at $\sqrt{s_{NN}}$ = 5.02 TeV : R_{pPb} vs y and p_T

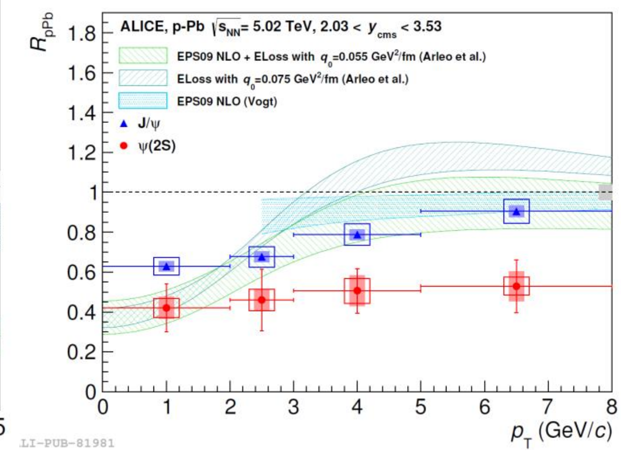
Nuclear modification factor of **ψ(2S)** measured at forward and backward rapidity

bkw-y





fwd-y



[JHEP 12 (2014) 073]

Significantly larger suppression of **ψ(2S)** state compared to **J/ψ** is observed, especially at **backward *y***

→ **not expected** from **inital-state** interactions with **CNM:**

resonance formation time > **$c\bar{c}$ pair crossing time in CNM** ⇒

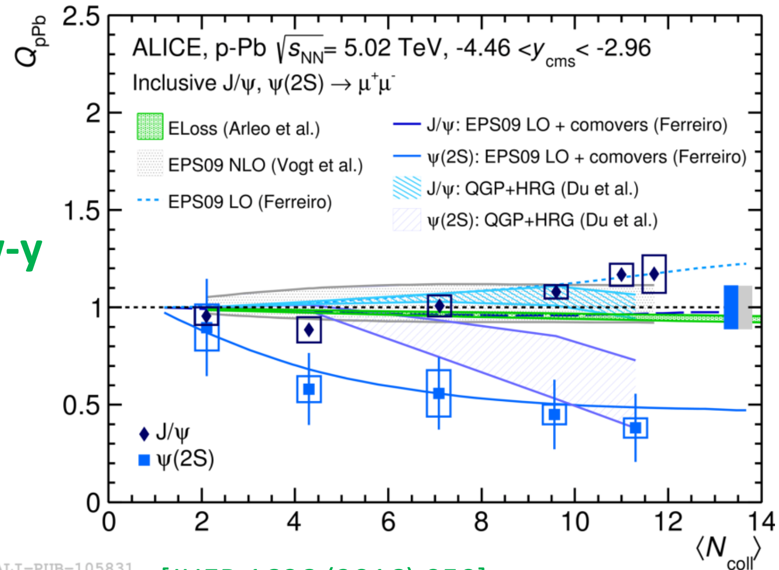
- **negligible ψ(2S)** pair break-up expected
- **shadowing** and **energy loss** do not depend on final-state quantum numbers

other kind of **final-state** interactions with **cold** or **hot** medium needed to explain data

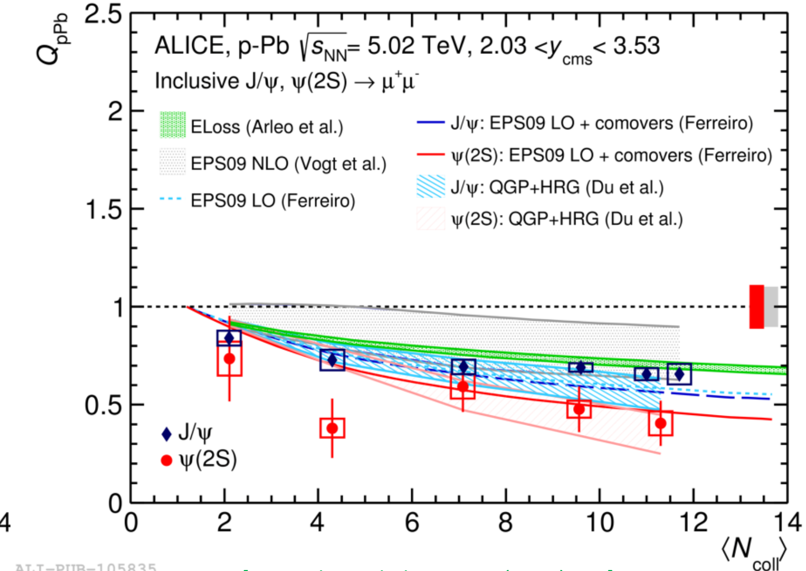
ψ(2S) results at $\sqrt{s_{NN}}$ = 5.02 TeV : Q_{pPb} vs event activity

Measurements as a function of **event activity** allow **different thicknesses** of crossed CNM to be probed

bkw-y



[JHEP 1606 (2016) 050]



fwd-y

[Du et al., Nucl.Phys. A943 (2015) 147]
[Ferriero, Phys.Lett. B749 (2015) 98]

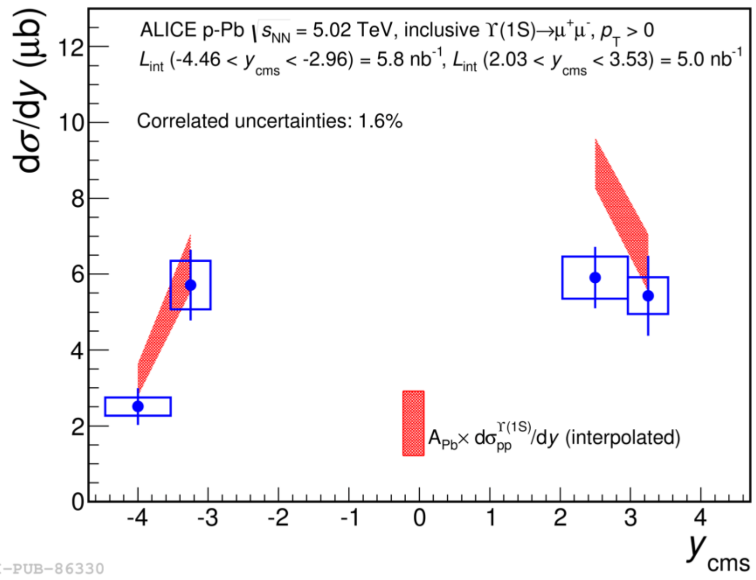
increasing **ψ(2S) suppression** trend towards **more central collisions**

- **shadowing /energy loss** models predict **same degree of suppression for J/ψ and ψ(2S**) and **fail** in reproducing ψ(2S) experimental results

→ models implementing **final-state interactions** with other parton/particles (**co-movers**) or with a *hot* partonic medium (**QGP+HRG**) reproduce the size of the observed suppression

Υ(1S) results at $\sqrt{s_{NN}}$ = 5.02 TeV : R_{pPb} vs y

Measurements of **Υ production** at 5.02 TeV complement charmonium studies of CNM effects

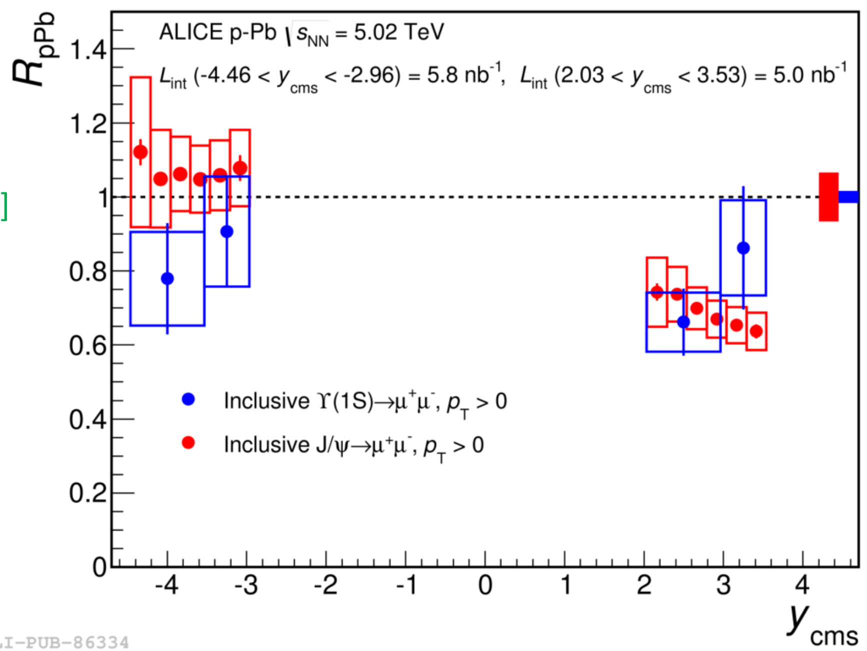


[PLB 740 (2015) 105]

measurements of **Υ(1S)** show **suppression** with respect to binary-scaled pp reference at **forward rapidity**

backward rapidity measurements are compatible with **no modification**

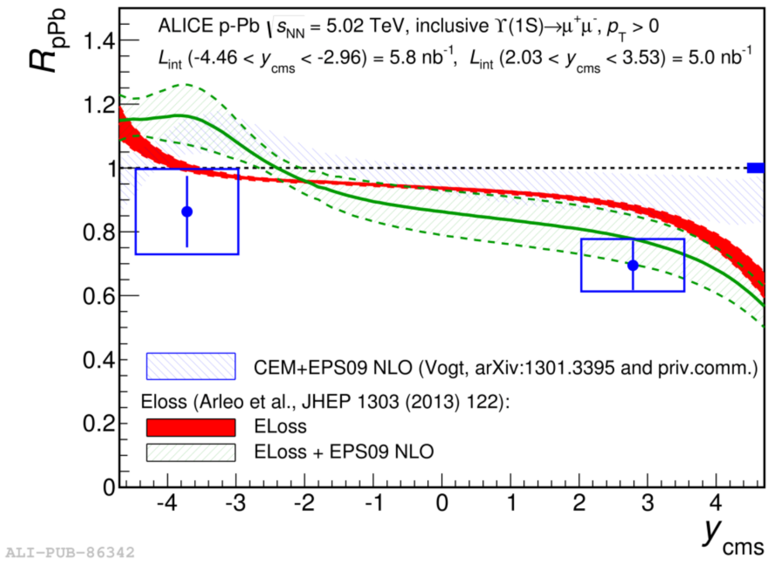
trend of **Υ(1S)** ***R***

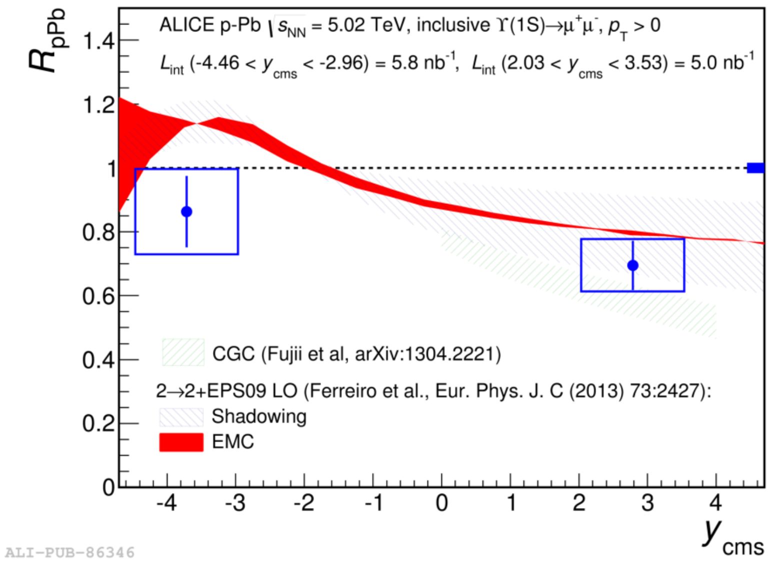


Υ(1S) results at $\sqrt{s_{NN}}$ = 5.02 TeV : R_{pPb} vs y

Measurements can be compared with CNM model predictions

[PLB 740 (2015) 105]





- Suppression at **forward *y*** fairly well described by **EPS09 shadowing** predictions at LO/NLO either with or without E-loss inclusion
- Measurements at **backward *y* disfavour** strong **anti-shadowing** from EPS09 parametrizations

None of the calculations fully describe forward and backward rapidity data
More precise measurements could provide more insight

Summary

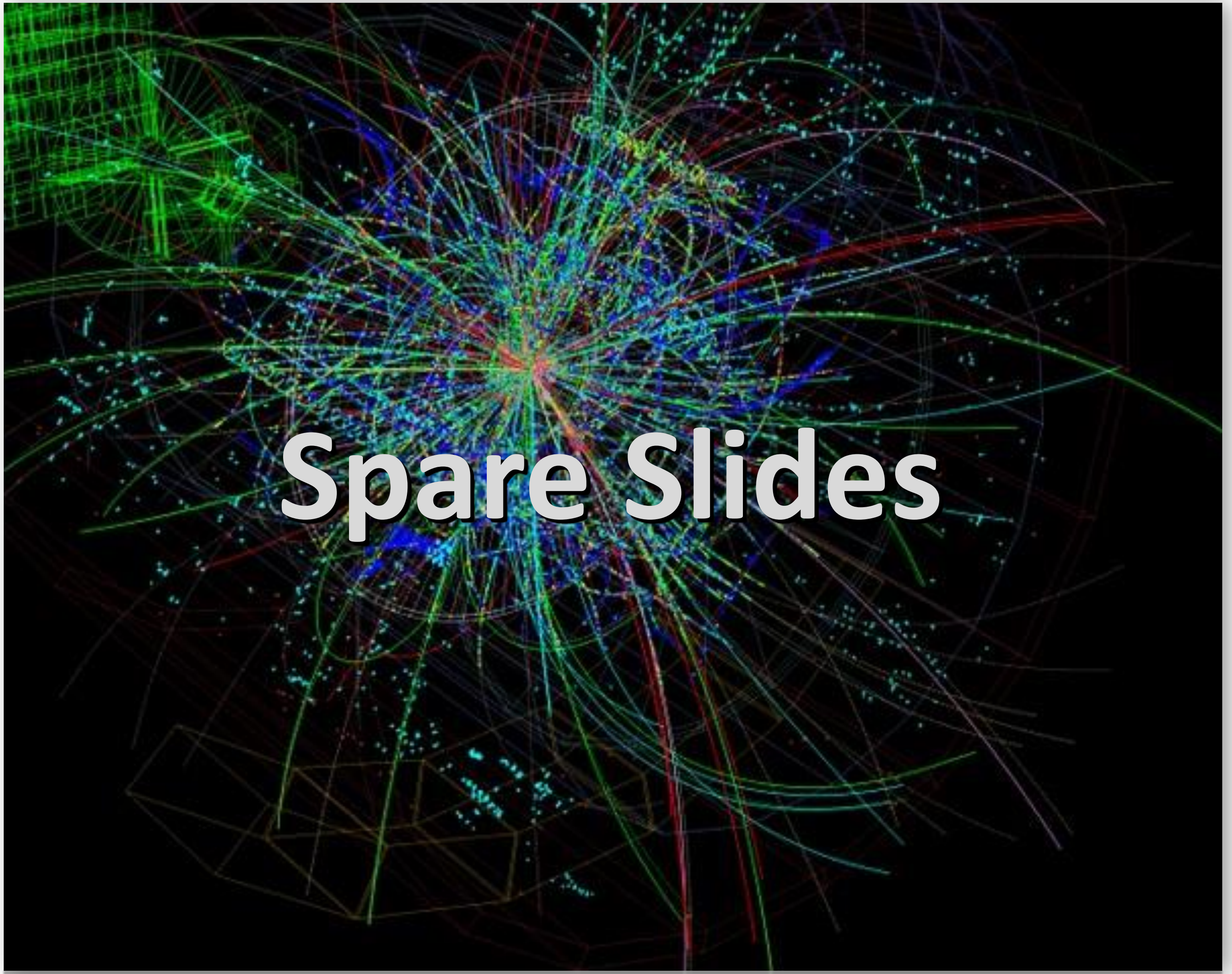
Significant modifications on quarkonium production due to CNM have been measured by ALICE in p-Pb collisions:

- **J/ψ** suppression at forward *y* was observed at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 and $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV:
  - overall good description is provided by models which include gluon shadowing and parton energy loss
  - currently available data precision can help constraining models

- **ψ(2S)** significantly more suppressed than J/ψ at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV:
  - unexpected from initial-state interactions
  - final-state interactions with the nuclear medium could explain the additional suppression

- **ϒ(1S)** suppressed at forward *y* , similiarly as J/ψ at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV
  - compatible with shadowing predictions although measurements at backward rapidity suggest small anti-shadowing contribution

More results still to come from Run2 data!


Spare Slides

p-Pb Measurements and Data Samples

Several analyses carried out on **Run1** data samples..

2013 p-Pb @ 5.02 TeV

mid-y (p-Pb)	$1.37<y_{cms}<0.43$	L_{int} = 51 μb^{-1} (MB)
fwd-y (p-Pb)	$2.03<y_{cms}<3.53$	L_{int} = 5 nb^{-1} (dimuon triggered)
bkw-y (Pb-p)	$-4.46<y_{cms}<-2.96$	L_{int} = 5.8 nb^{-1} (dimuon triggered)

.. and already first J/ψ results from **Run2** samples

2016 p-Pb @ 8.16 TeV

mid-y (p-Pb)	$1.37<y_{cms}<0.43$	L_{int} = 0.4 nb^{-1} (MB)
fwd-y (p-Pb)	$2.03<y_{cms}<3.53$	L_{int} = 8.7 nb^{-1} (dimuon triggered)
bkw-y (Pb-p)	$-4.46<y_{cms}<-2.96$	L_{int} = 12.9 nb^{-1} (dimuon triggered)

Investigated nuclear modifications

J/ψ: vs rapidity, p_T, centrality, multiplicity
[JHEP 12 (2014) 073] [JHEP 06 (2015) 055]
[JHEP 11 (2015) 127] [arXiv:1704.00274]

ψ(2S): vs rapidity, p_T, centrality
[JHEP 12 (2014) 073] [JHEP 1606 (2016) 050]

Υ(1S) vs rapidity [PLB 740 (2015) 105]

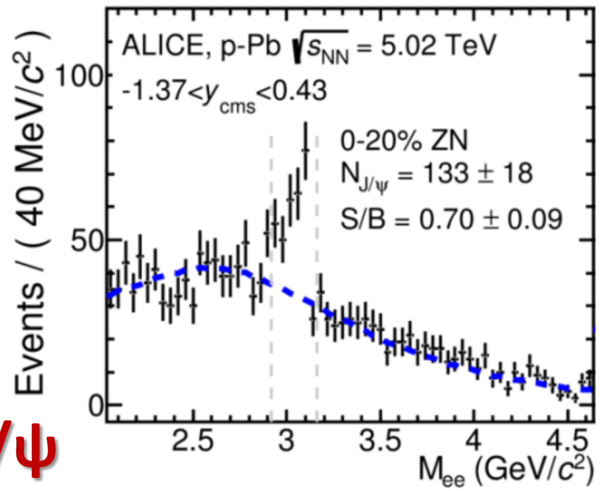
J/ψ: vs rapidity, p_T @ $\sqrt{s_{NN}}$ = 8.16 TeV

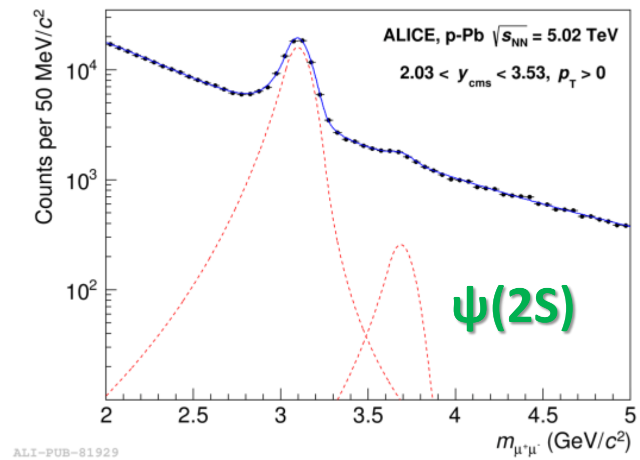
pp reference cross sections for R_{pPb}

from either **energy interpolation** or **measurements** at the corresponding $\sqrt{s_{NN}}$

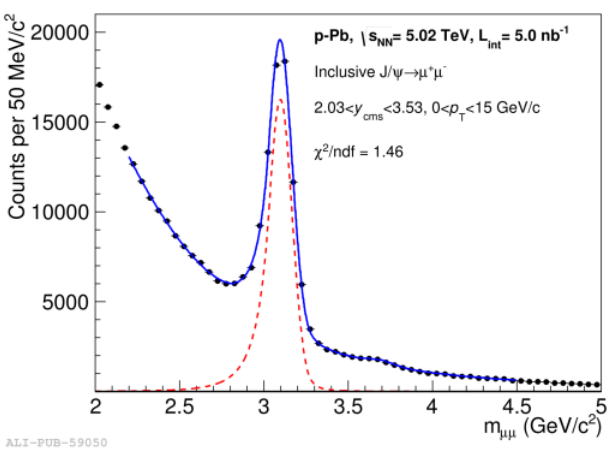
Examples of signal extractions

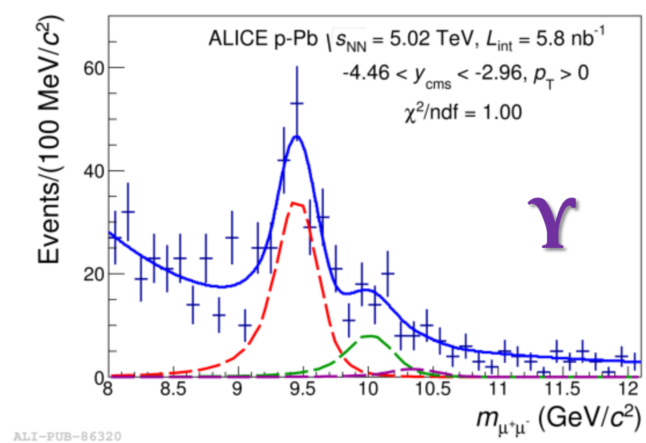
Examples of di-lepton invariant mass distributions from Run1 analyses





J/ψ

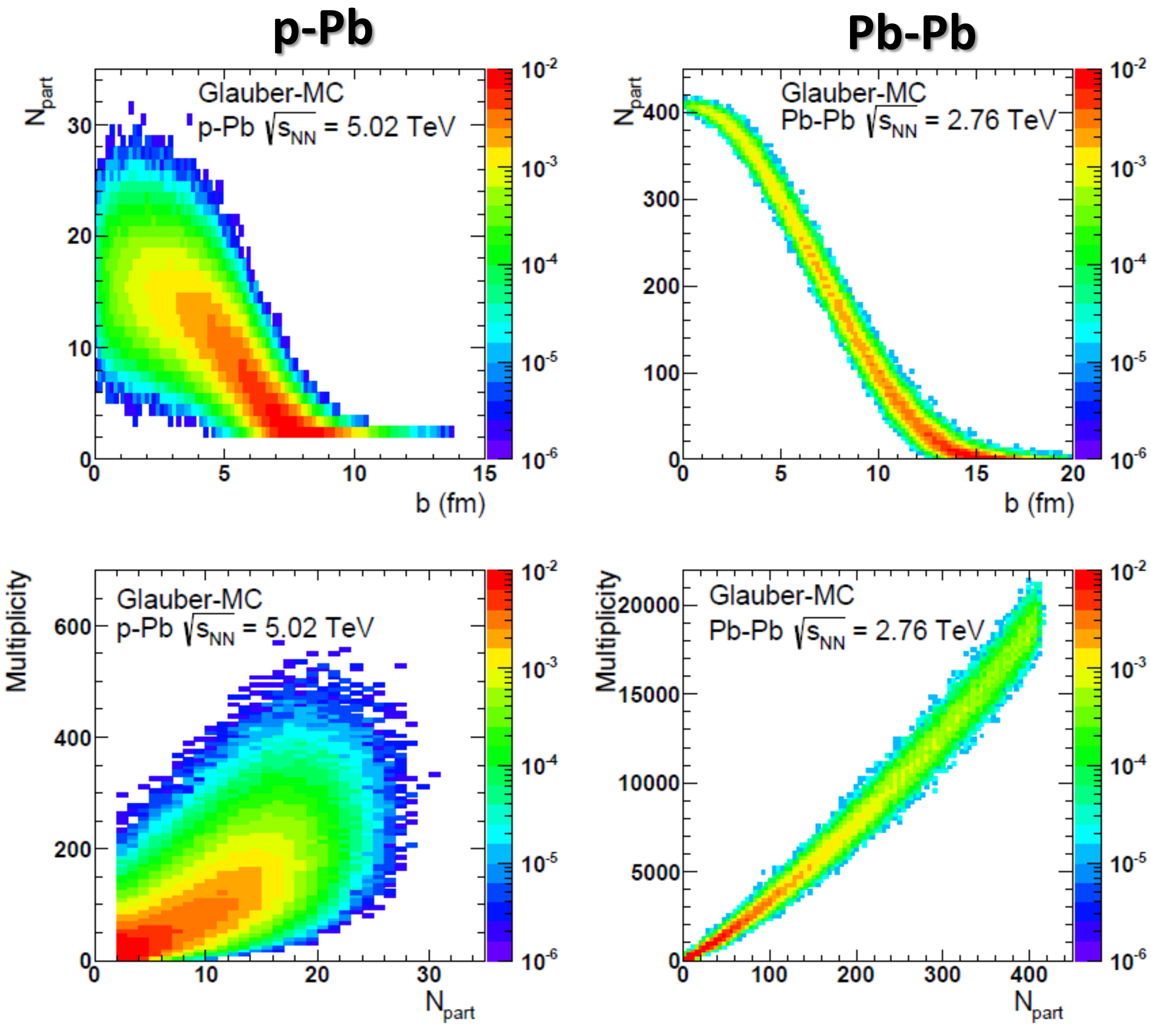




Signal extraction either via **bin-counting** after background subtraction or via simultaneus **fitting** of the signal and background di-lepton invariant mass spectrum

Correlation between centrality estimators in p-Pb

Looser correlation between *N*part vs impact parameter, and Multiplicity vs *N*part **in p-Pb** collisions **impairs centrality evaluation based on charged-particle multiplicity**



Centrality selection based on the **energy** deposited by *slow* nucleons from the **Pb nucleus remnant** minimizes the biases on the centrality estimate

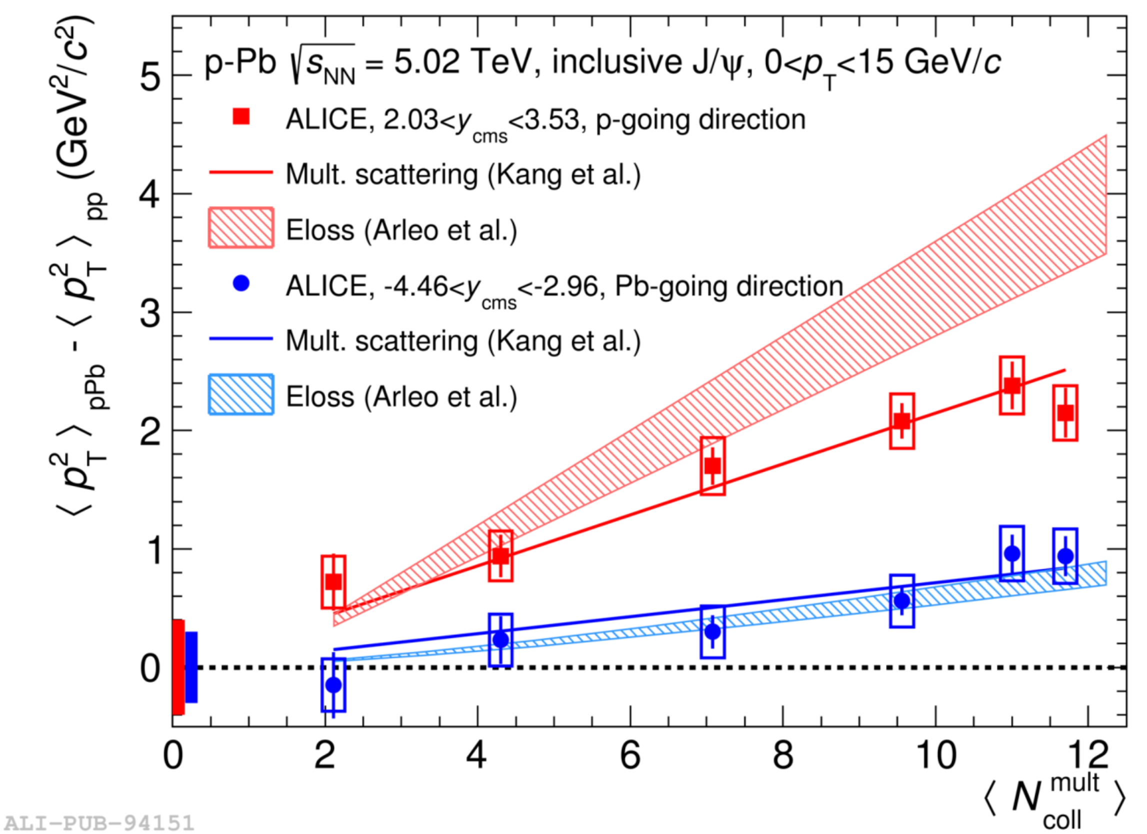
Hybrid method used to derive $\langle T_{\mathrm{pA}} \rangle$ and $\langle N_{\mathrm{coll}} \rangle$ for a given centrality class

[ALICE, PRC **91** (2015) 064905]

J/ψ p_T broadening in p-Pb collisions at 5.02 TeV

Nuclear effects can affect the J/ψ p_T spectrum shape in p-Pb collisions with respect to pp collisions

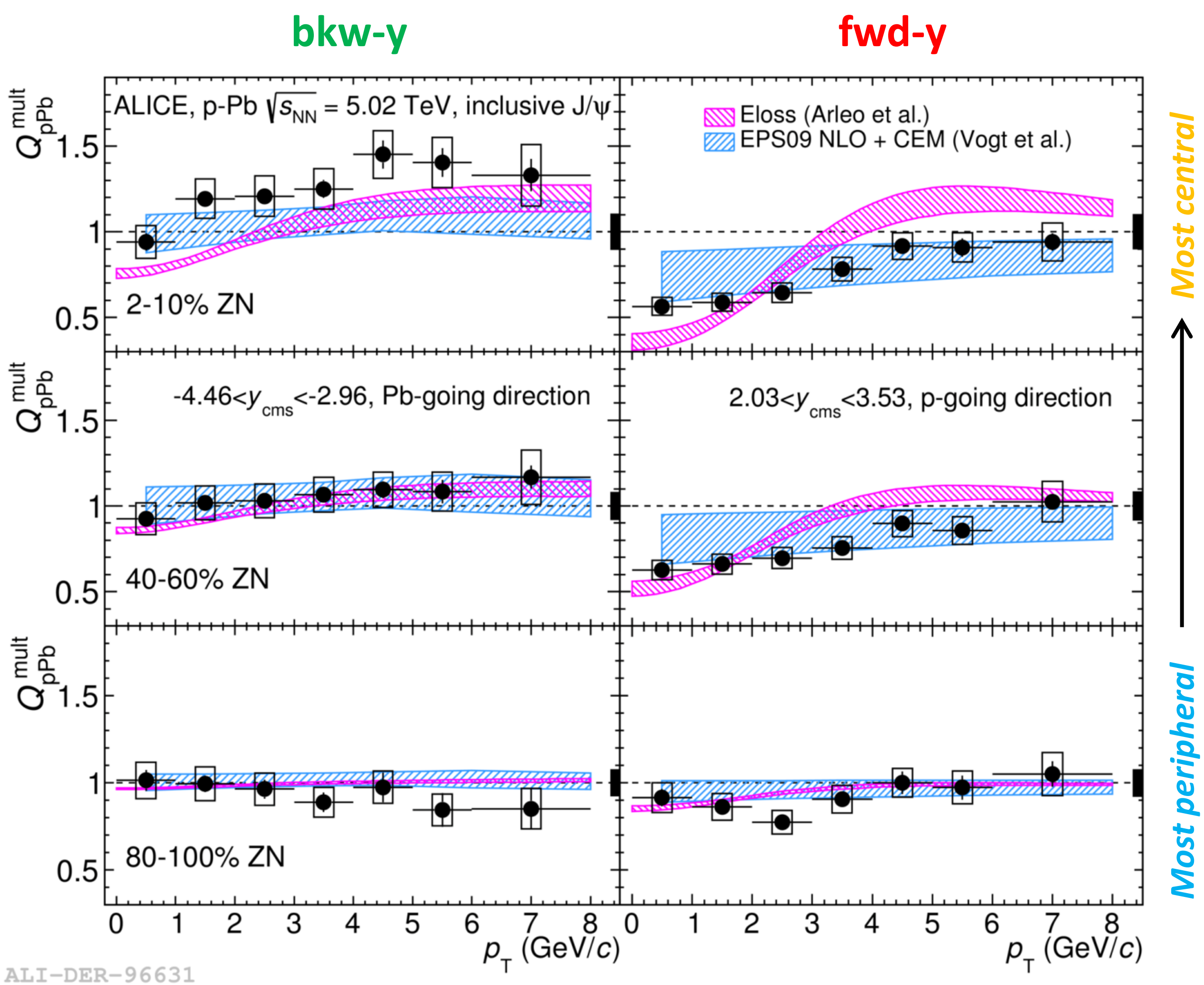
p_T broadening: $\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_{\mathrm{pPb}} - \langle p_T^2\rangle_{\mathrm{pp}}$



measurements at $\sqrt{s_{NN}}$ = 5.02 TeV show an **increasing p_T broadening** from peripheral to **central collisions** with **larger** values at **forward rapidity**

- Well described by models including initial and final-state **multiple scattering of partons** with nuclear medium
- Slightly steeper trend predicted by **Energy loss** model calculations

J/ψ Q_{pPb} vs p_T at 5.02 TeV



- Significant enhancement of CNM effects when moving from peripheral to central collisions
- Shadowing from EPS09 in fair agreement with the data
- Steeper trend predicted by pure energy loss model

Estimating CNM effects in Pb-Pb collisions

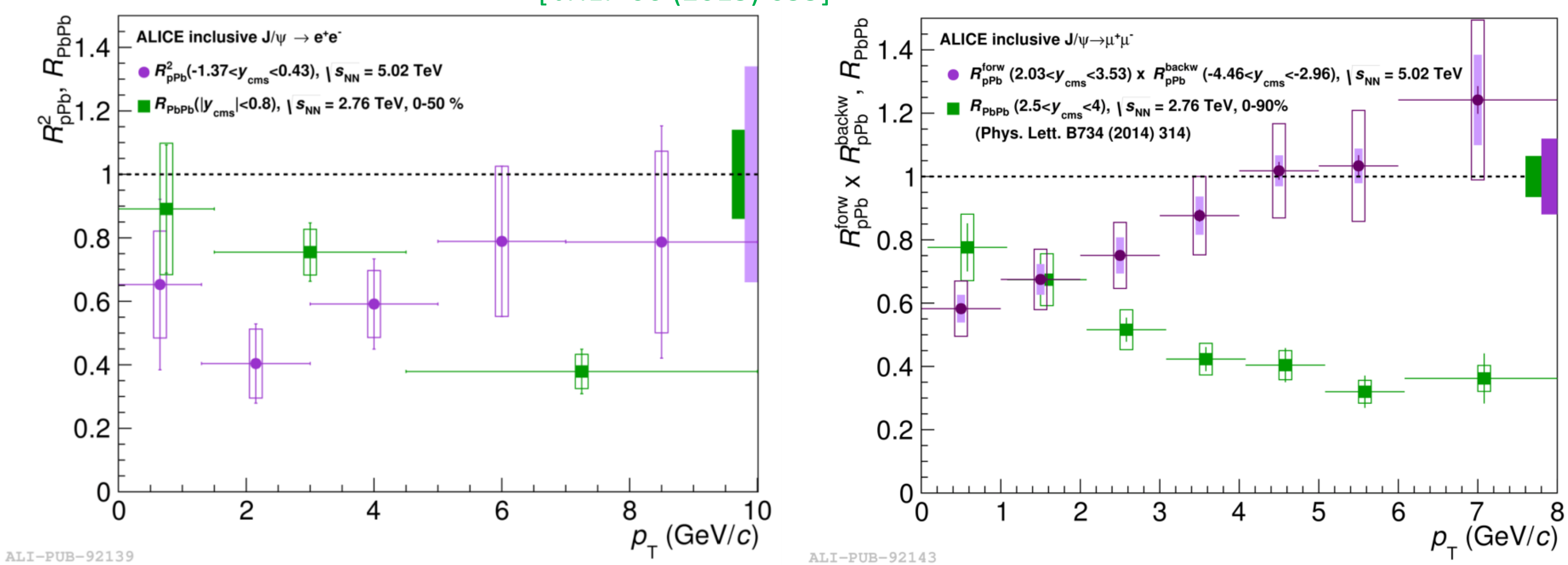
Results of R_{pPb} measurements can be used to **estimate the contribution of CNM effects** to the **nuclear modifications in Pb-Pb** collisions

→ For J/ψ suppression in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV ([PLB **734** (2014) 314–327]):

Assuming factorization of CNM effects on the two Pb nuclei (2→1 kinematics, *shadowing* as main effect):

$\boldsymbol{R_{pPb} \times R_{pPb}}$ ($\boldsymbol{R_{pPb}}^2$) can be used as estimate of CNM effect component and qualitatively compared to $\boldsymbol{R_{AA}}$

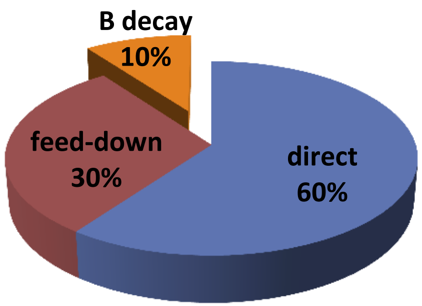
[JHEP 06 (2015) 055]

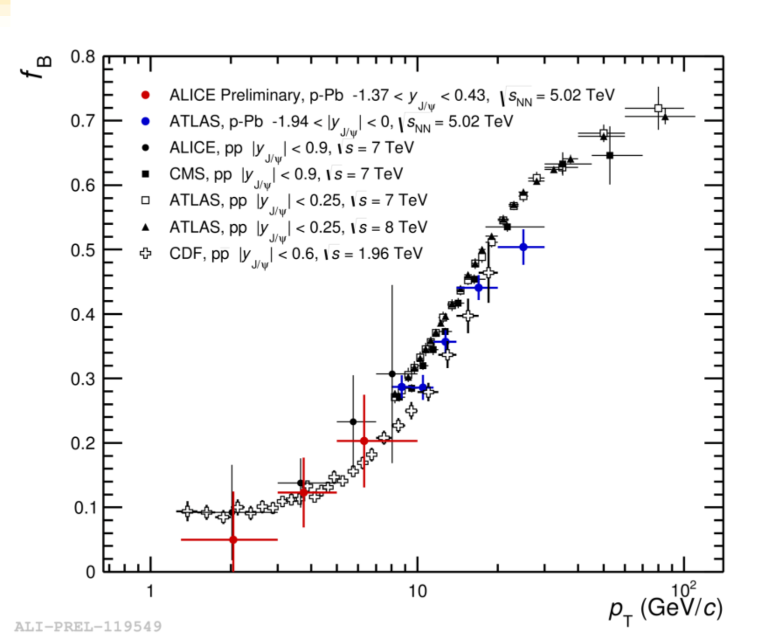


Hint of a smaller suppression at low $\boldsymbol{p_T}$ with respect to extrapolations from CNM
→ *in line* with J/ψ regeneration scenarios in QGP

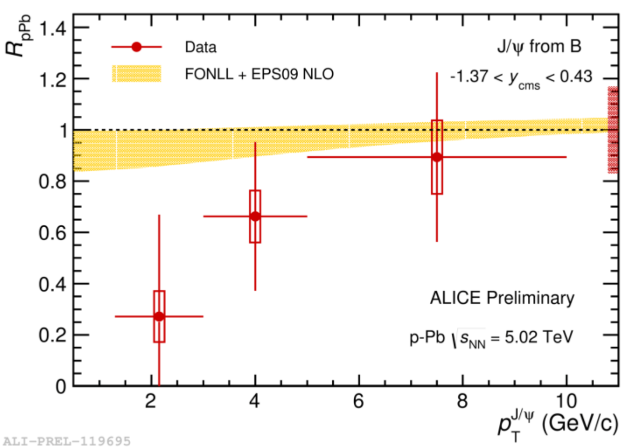
J/ψ from beauty hadrons

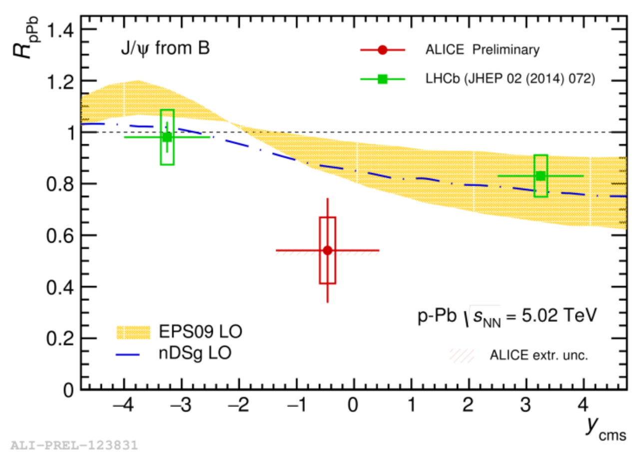
At LHC energies, a significant fraction of the **inclusive J/ψ yield** is made up of non-prompt **J/ψ** from beauty-hadrons decay





ALICE is capable of measuring the fraction f_B of non-prompt J/ψ at mid-rapidity down to p_T = 1.3 GeV/c through likelihood fits of topological observables





Preliminary results available for the nuclear modification factors of **non-prompt J/ψ** at mid-rapidity in p-Pb @ 5.02 TeV from Run1, complementary to LHCb