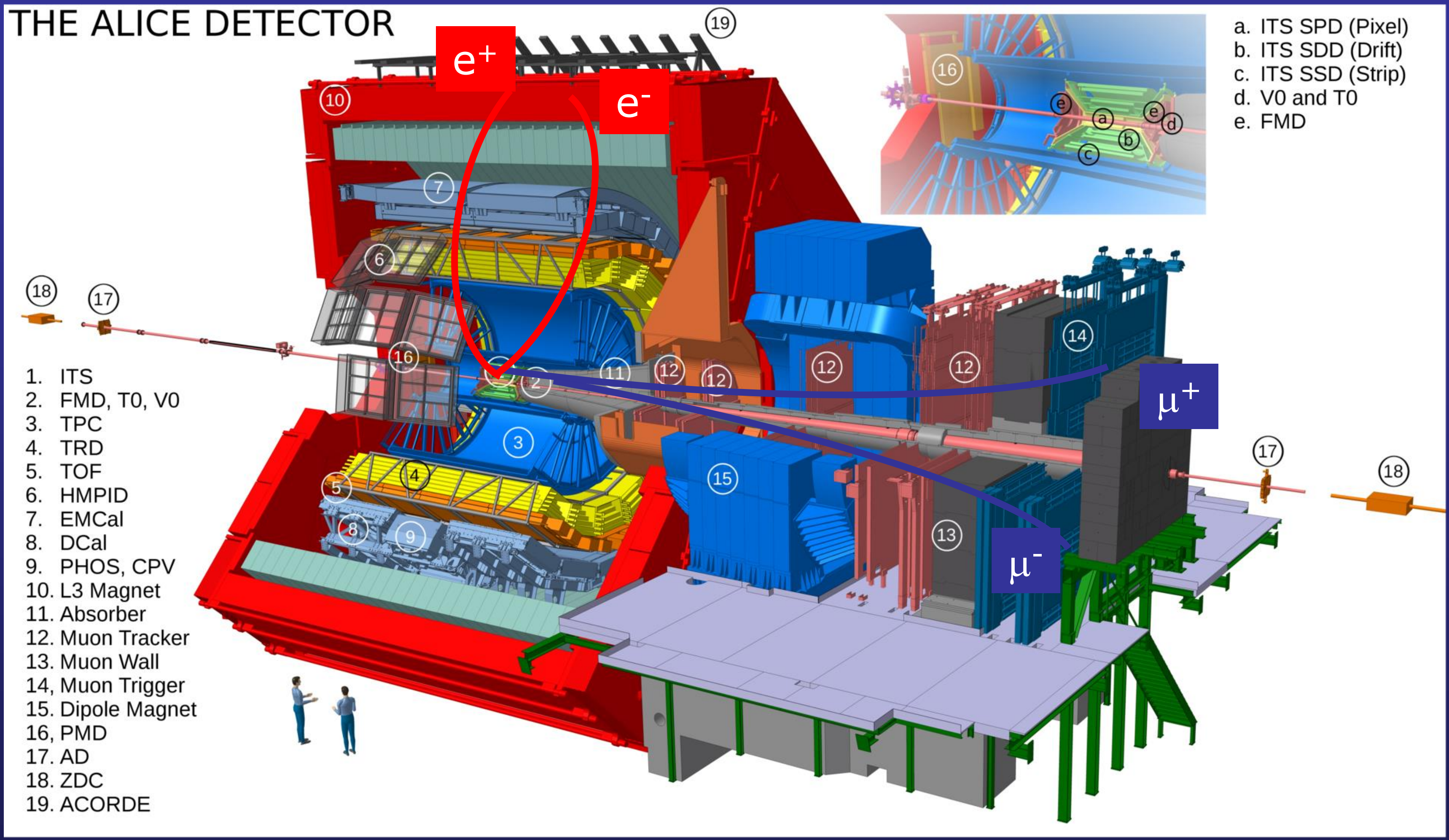
Quarkonium results from ALICE

E. Scomparin (INFN Torino, Italy)
for the ALICE Collaboration

- From LHC run 1 to run 2 → new results at top LHC energy
- From pp to p-Pb to Pb-Pb → new observables and highlights

Workshop on Heavy Flavor Production in High Energy Collisions
Oct. 30 - Nov. 1, 2017,
LBNL, USA

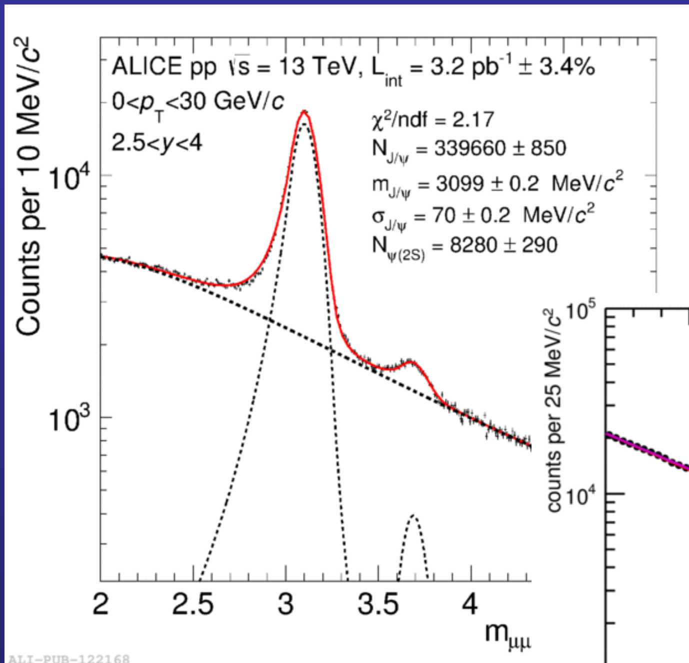
Measuring quarkonium in ALICE



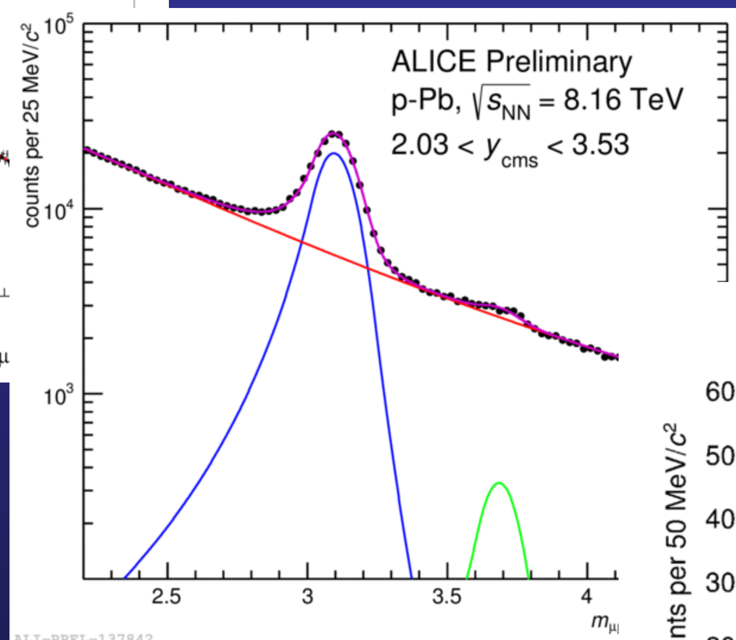
- **Central barrel** : dielectrons, $|y|<0.9$, $p_T>0$ (unique for charmonia!)
- **Forward muon arm** : dimuons, $2.5<y<4$, $p_T>0$ (muon trigger)

Forward-y charmonium: : $\mu^+\mu^-$ spectra

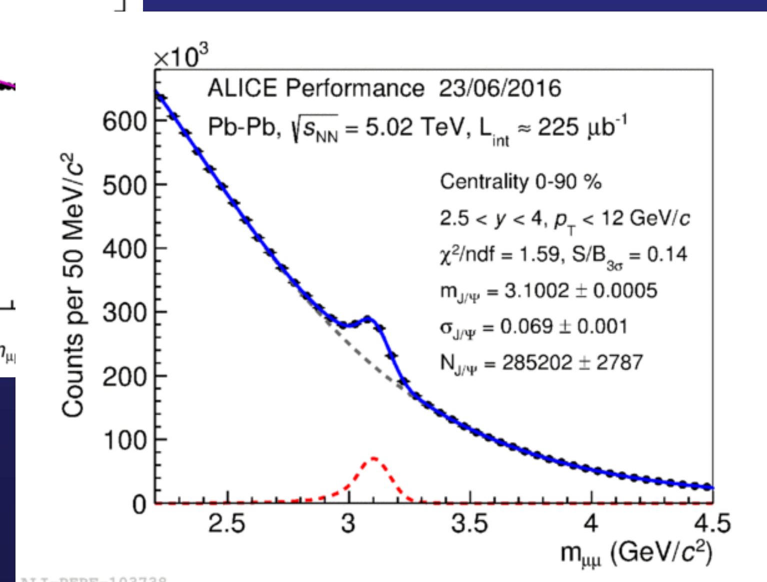
pp



p-Pb



Pb-Pb

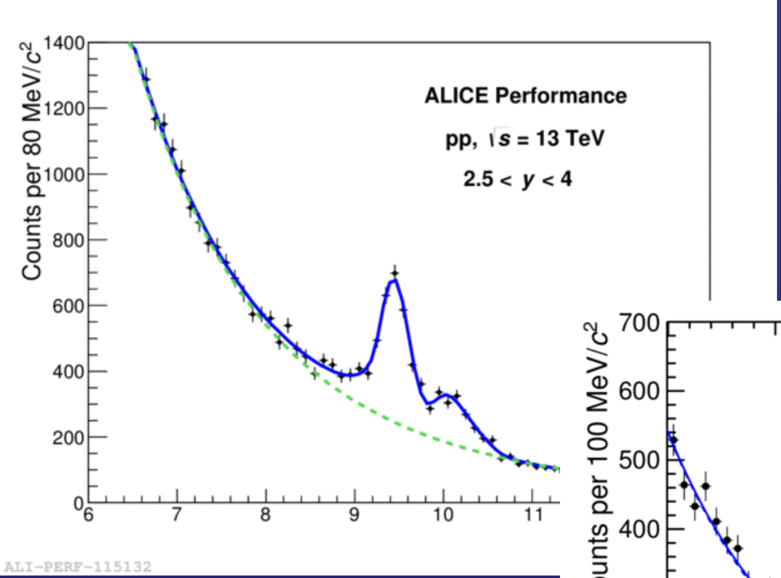


Muon ID based on track matching between muon tracking and muon triggering system

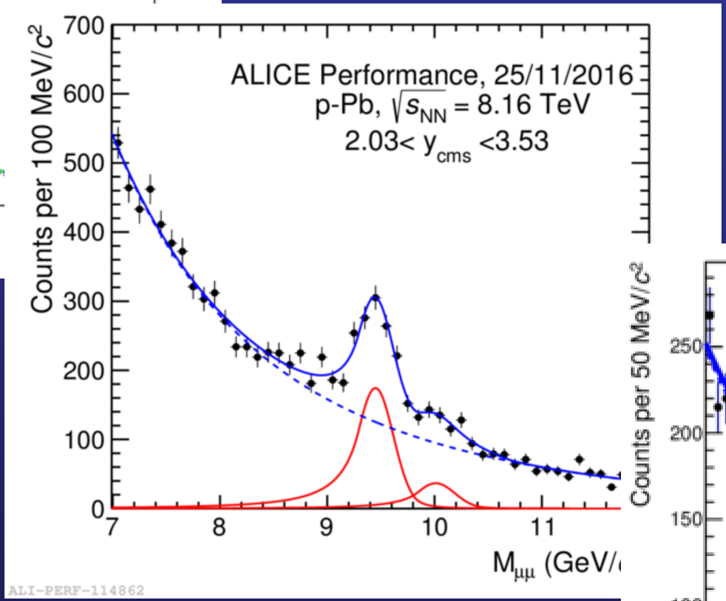
- J/ψ, ~70 MeV resolution from pp to Pb-Pb
- ψ(2S), S/B becomes unfavorable in Pb-Pb

Forward-y bottomonium: $\mu^+\mu^-$ spectra

pp

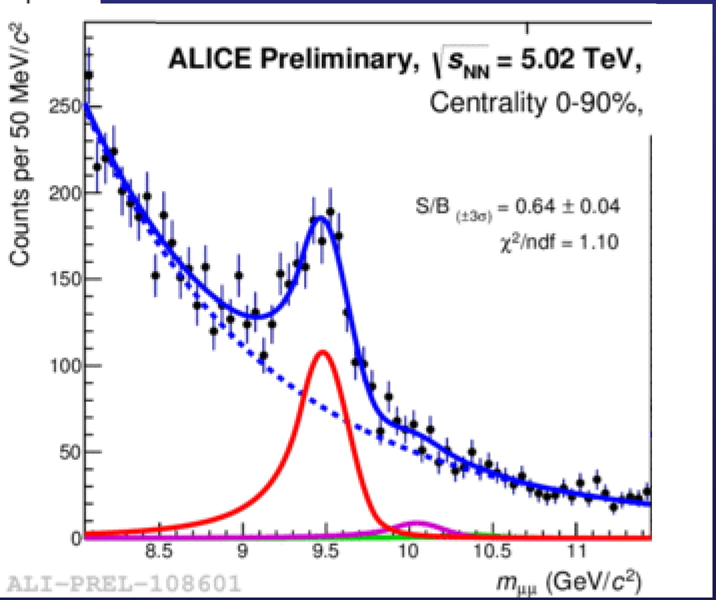


p-Pb



Muon ID based on track matching between muon tracking and muon triggering system

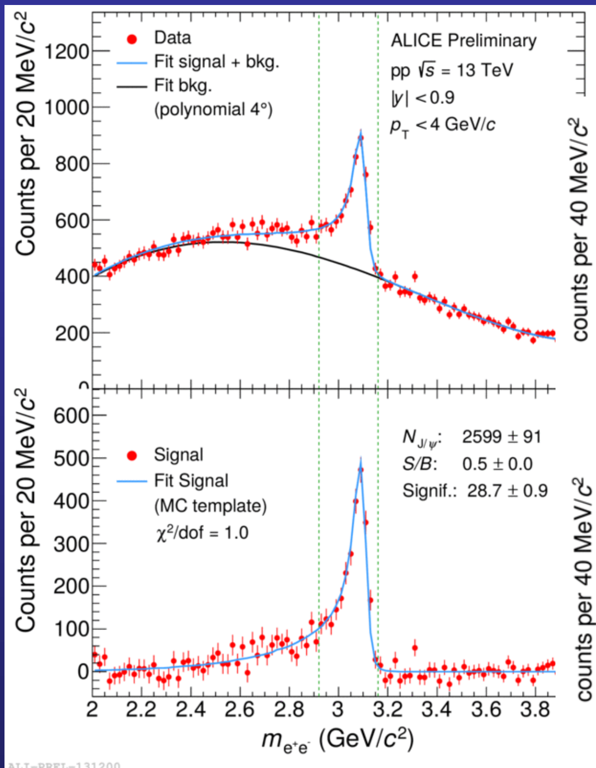
Pb-Pb



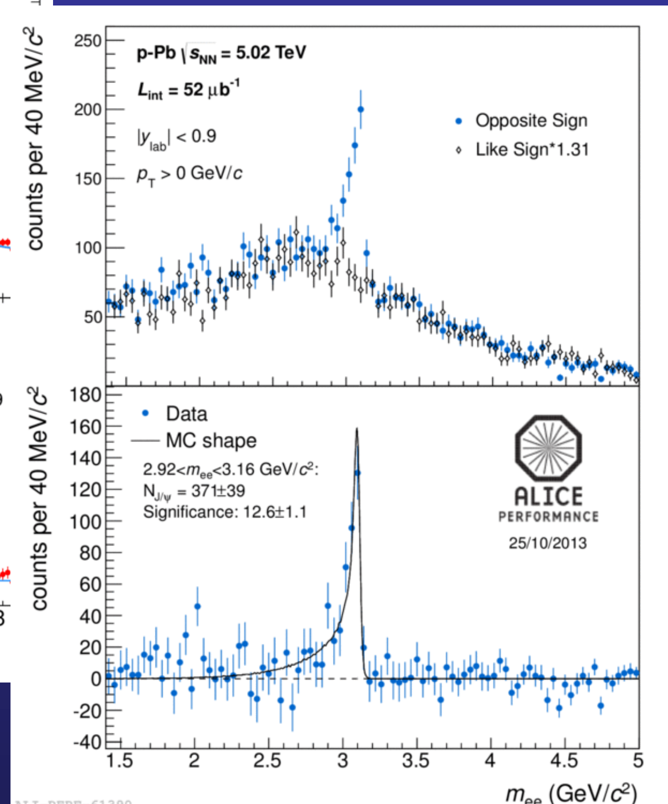
- ❑ Good S/B for Υ(1S), up to Pb-Pb
- ❑ Measurements are still statistics-limited for Υ(2S) and (in particular) Υ(3S)

Mid-y charmonium: e^+e^- spectra

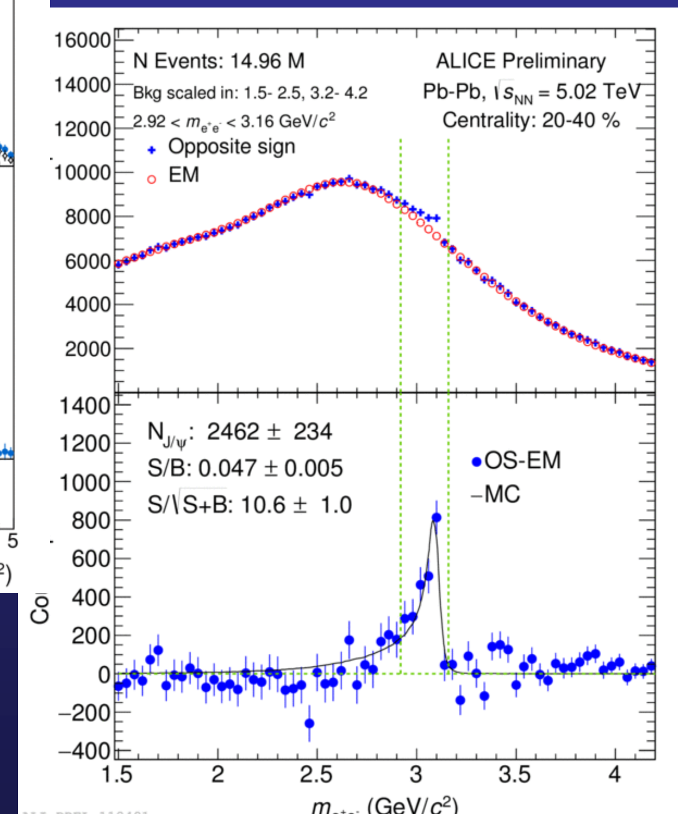
pp



p-Pb



Pb-Pb



Electron ID based on TPC dE/dx

- With respect to dimuon measurement
  - Better mass resolution
  - Worse S/B in Pb-Pb
  - Only J/ψ results for the time being

Data taking and luminosities

Run 1 (2009 – 2013)

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV	L =26 μb^{-1} (MB) L =69 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L =51 μb^{-1} (MB) L_{pPb} = 5nb^{-1} (dimuon) L_{Pbp} = 5.8 nb^{-1}(dimuon)
pp, $\sqrt{s}$ = 0.9, 2.76, 7, 8 TeV	$L_{pp}^{2.76TeV}$ = 1.1 nb^{-1} (MB) $L_{pp}^{2.76TeV}$ = 19.9 nb^{-1} (dimuon)

Run 2 (2015 – 2018)

Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L = 19 μb^{-1} (MB) L = 225 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ =5.02 TeV	L = 0.4 nb^{-1} (MB)
p-Pb, $\sqrt{s_{NN}}$ =8.16 TeV	L_{pPb} = 8.7 nb^{-1} (dimuon) L_{Pbp} = 12.9 nb^{-1} (dimuon)
pp, $\sqrt{s}$ = 5.02, 13 TeV	$L_{pp}^{5.02TeV}$ = 106 nb^{-1} (dimuon)

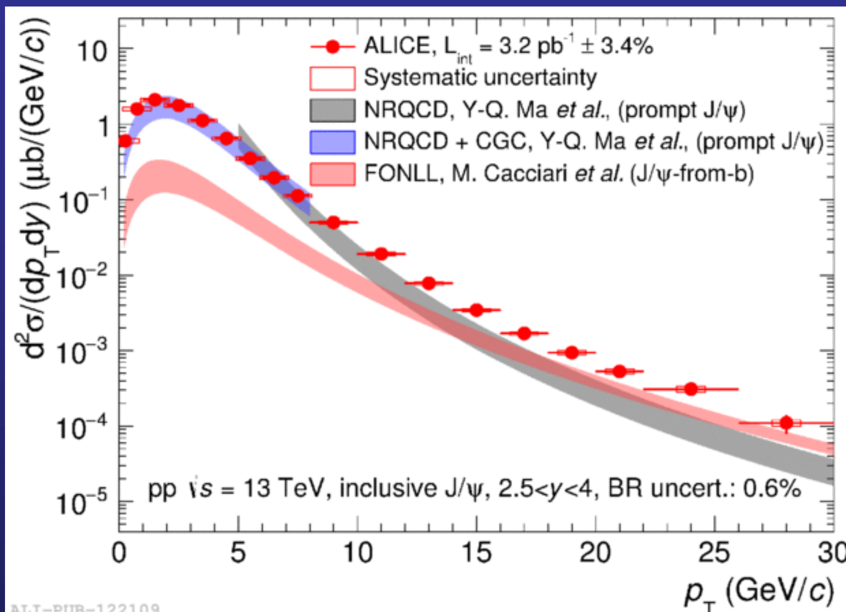
Focus of this talk

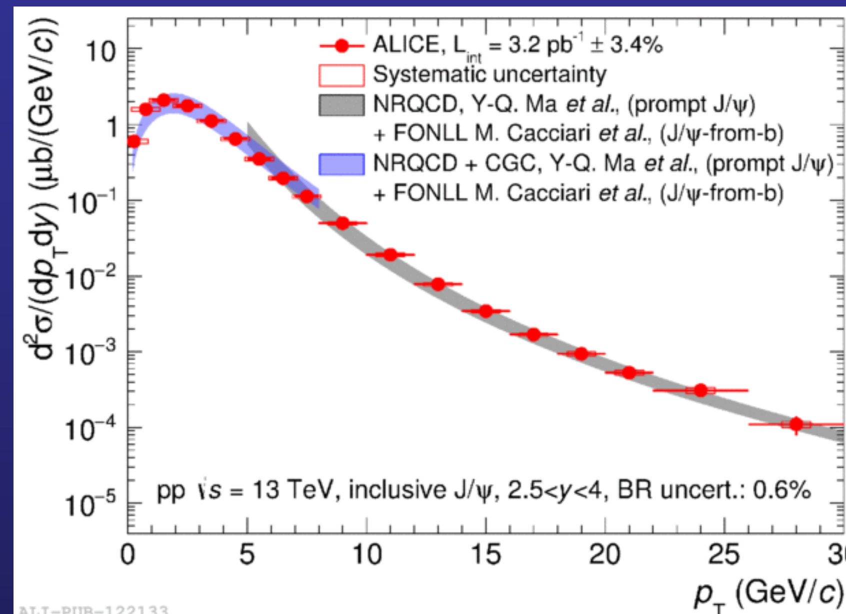
Charmonia

pp collisions: from tests of QCD…

- Twofold aspect
  - QCD studies, comparison to models
  - Reference for hot medium effects seen in AA collisions

NRQCD: Ma, Wang and Chao, PRL 106 (2011) 042002
NRQCD+CGC: Ma and Venugopalan, PRL 113 (2014) 192301
FONLL: Cacciari et al., JHEP 1210 (2012) 137



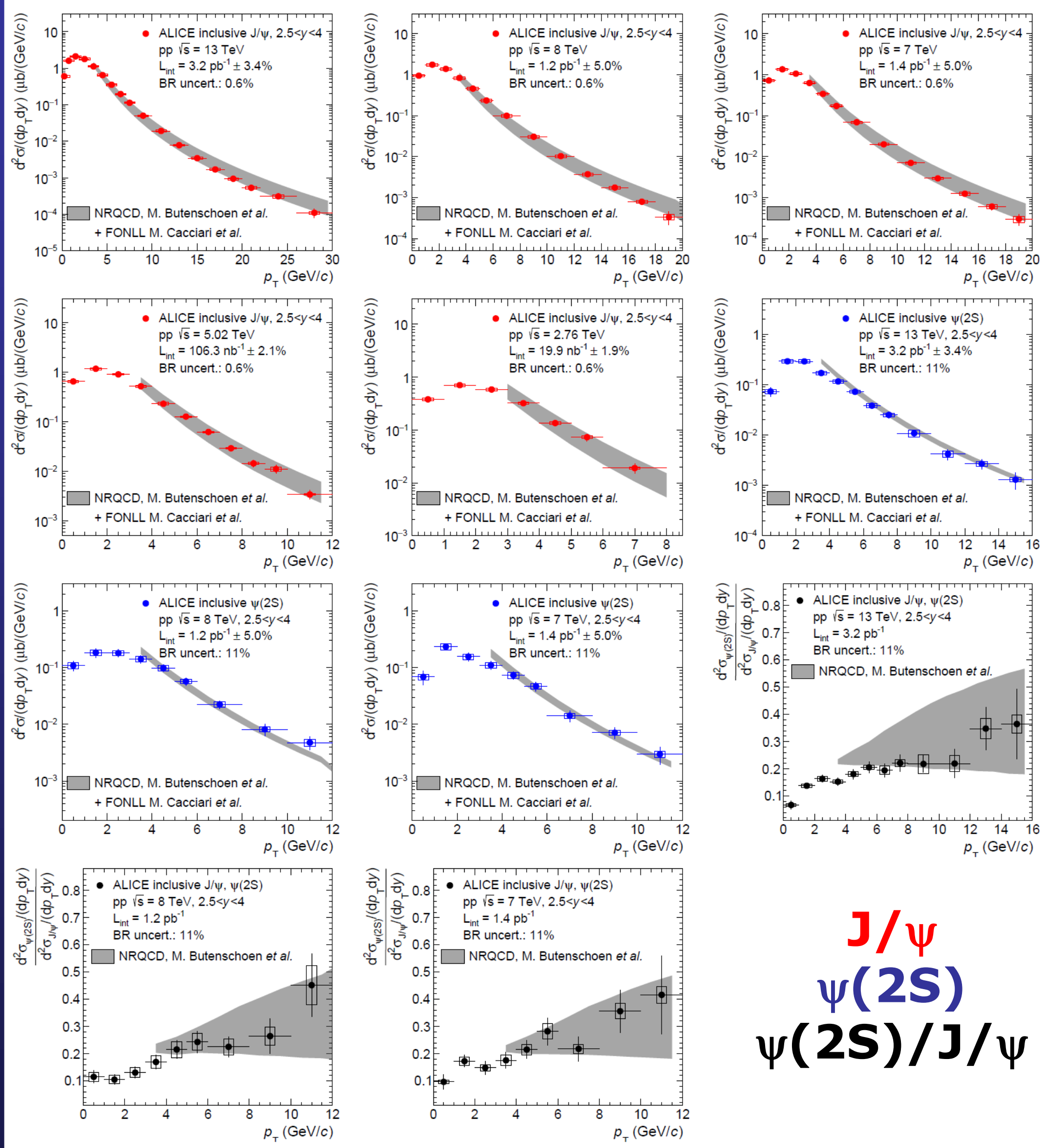


ALICE, EPJC 77 (2017) 392

- Models properly account for higher mass resonance decays
- **Low p_T: NRQCD coupled to a CGC description of the proton reproduces data (b-decay contribution small)**
- **High p_T: non-prompt J/ψ is sizable, taken into account via FONLL**

pp collisions: from tests of QCD…

ALICE, EPJC 77 (2017) 392



J/ψ
ψ(2S)
ψ(2S)/J/ψ

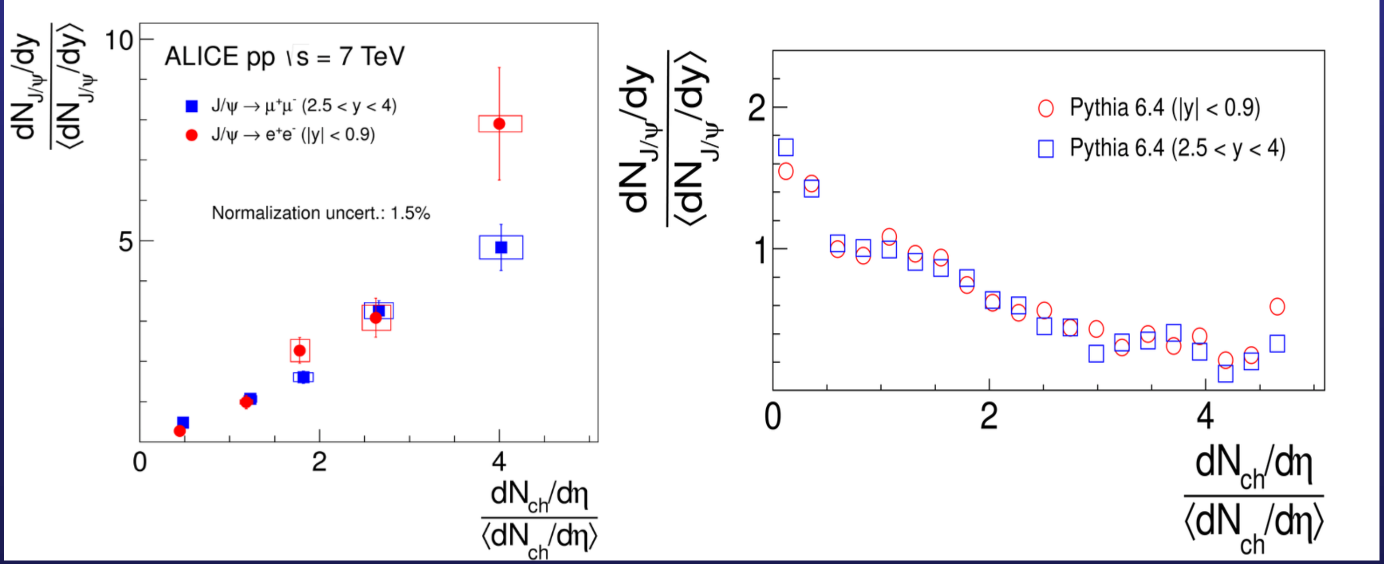
- Extensive data-theory comparisons performed at all energies available at the LHC so far
- **Good agreement between the models and the data** is observed for all measured cross sections, for both J/ψ and ψ(2S)

M. Butenschoen and B. A. Kniehl, PRL 106 (2011) 022003

…to more differential observables

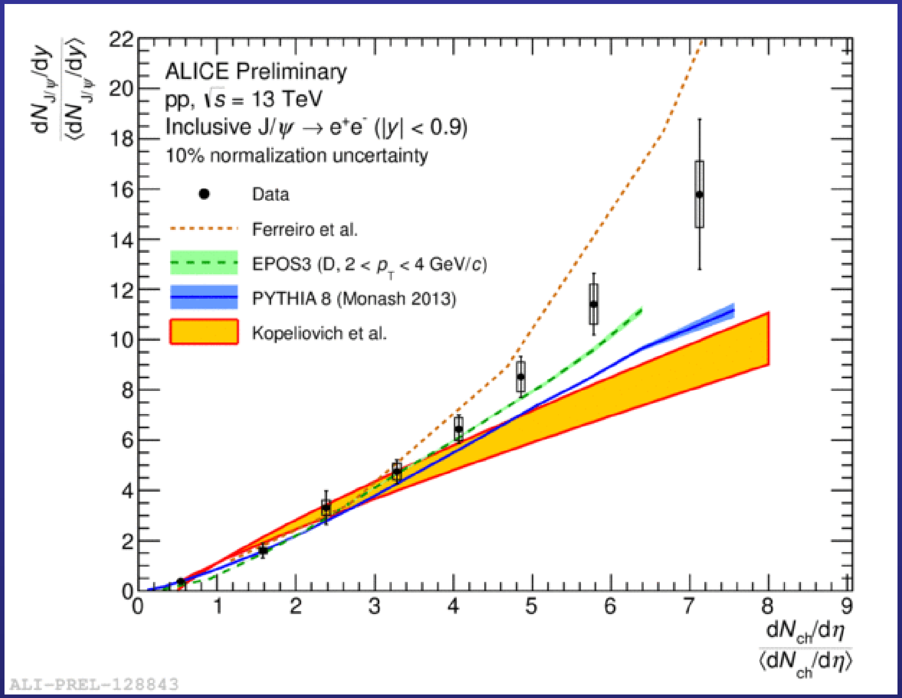
- Charmonium production from hard initial processes → no strong correlation with event activity expected
- Data at 7 TeV suggest (stronger than) linear increase
- PYTHIA 6.4.25 (Perugia 2011) calculations with J/ψ produced only in hard processes (NRQCD) do not reproduce the trend
- **Clearly suggests importance of other physical processes**, e.g. multi-parton interactions, percolation effects, color reconnection…

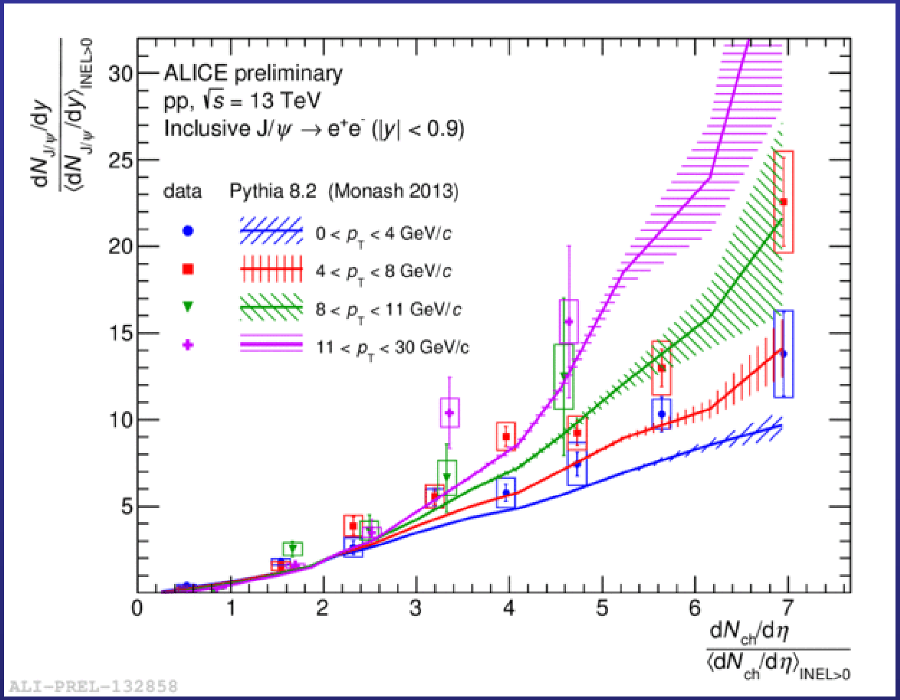
ALICE, PLB 712 (2012) 165



- Effect also seen in D-meson production (ALICE, JHEP 09 (2015) 148)

...to more differential observables

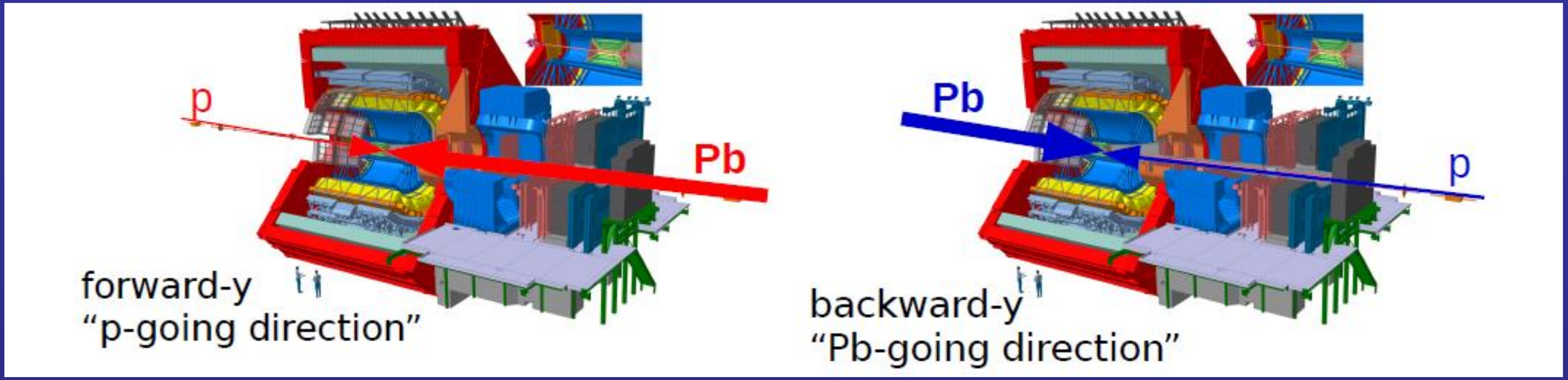


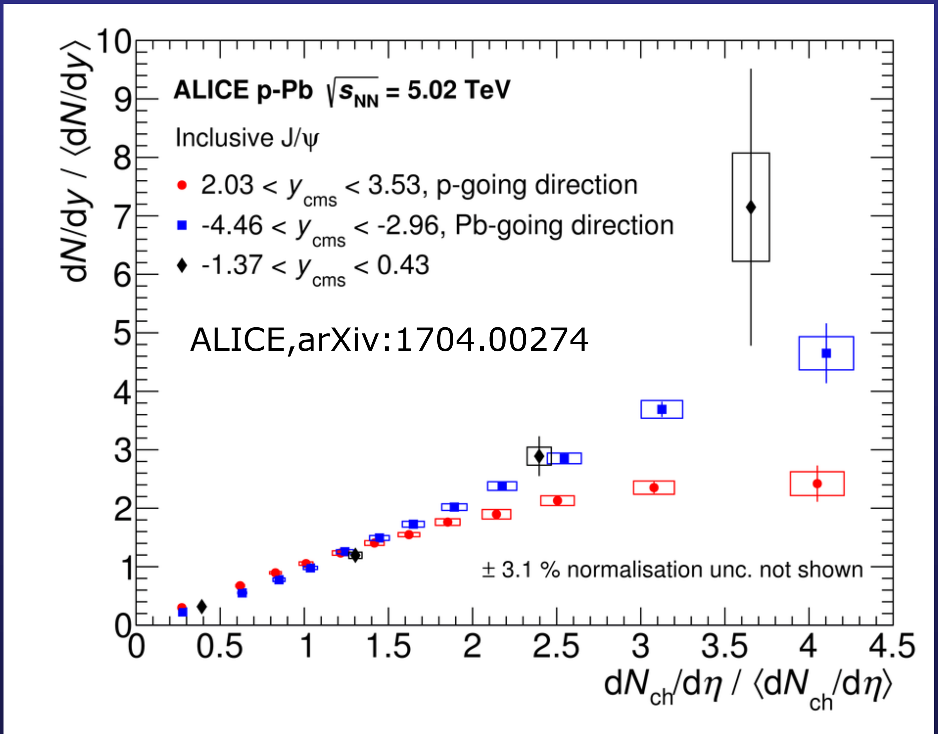


Ferreiro, Pajares, PRC86 (2012) 034903; EPOS3, Werner et al., Phys.Rept.350 (2001) 93; PYTHIA8, Sjostrand et al., Comput.Phys.Commun.178(2008)852; Kopeliovich et al., PRD88 (2013) 116002

- $dN_{ch}/d\eta/\langle dN_{ch}/d\eta \rangle$ almost doubled wrt run 1, higher p_T reach (30 GeV/c)
- **Qualitative agreement with models** assuming
  - Multi-parton effects in J/ψ production (PYTHIA8, EPOS3 w/ hydro)
  - Contributions of higher Fock-states (Kopeliovich et al.)
  - Soft particle saturation (Ferreiro: percolation, PYTHIA8: color reconnection)

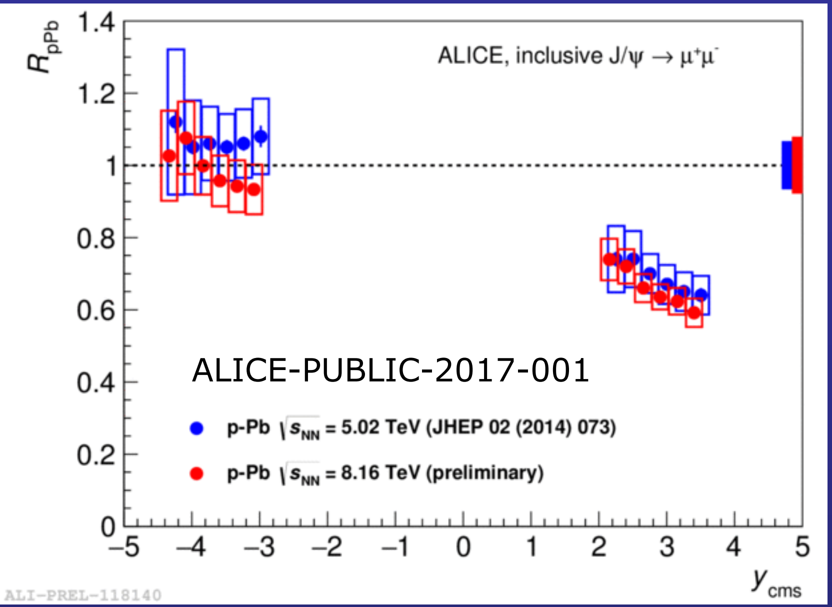
Moving to p-Pb collisions…



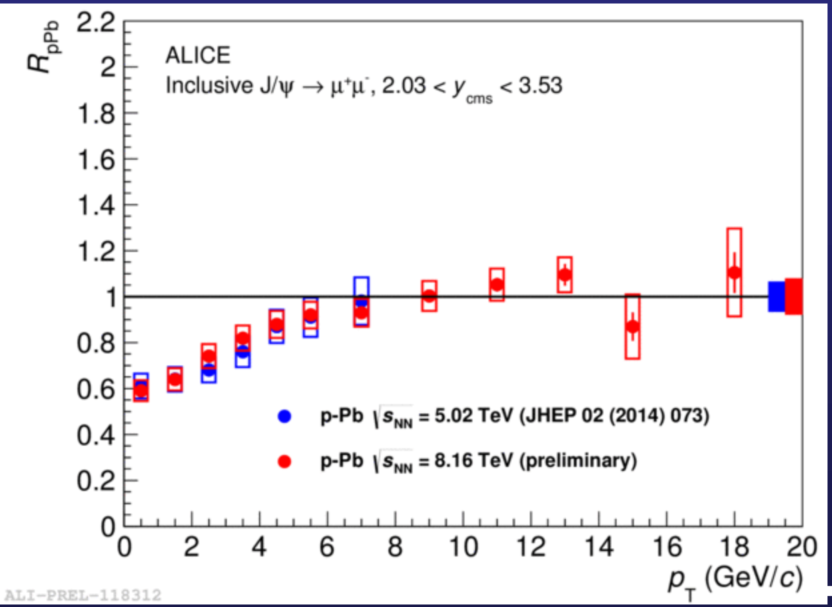


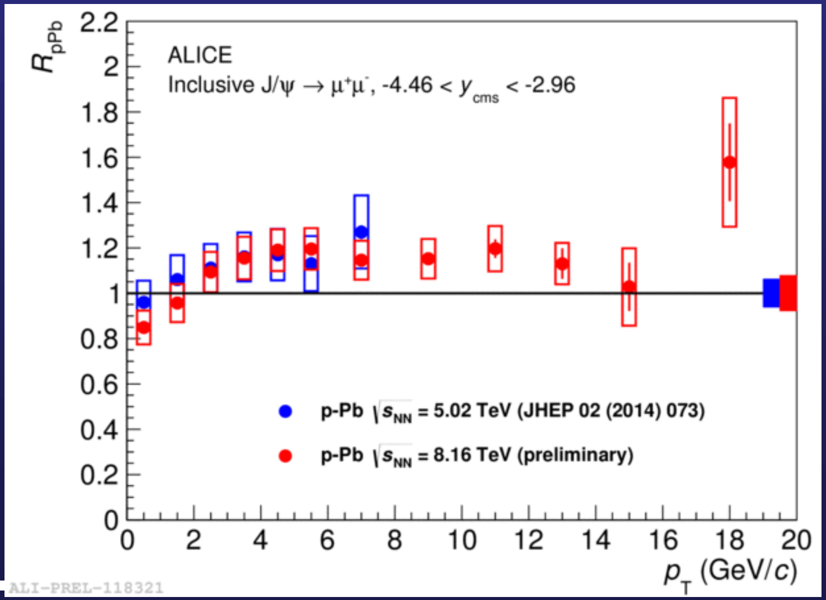
- ❑ Multiplicity dependent measurement → study of very high multiplicity p-Pb events (1% most central events)
- ❑ Increase of the relative J/ψ yield with $dN_{ch}/d\eta$ / ⟨ $dN_{ch}/d\eta$ ⟩
- ❑ **Mid- and backward y: behaviour similar to pp**
- ❑ **p-going direction: saturation at high multiplicities** (Bjorken-x range in the domain of shadowing / saturation)

p-Pb collisions: J/ψ results at $\sqrt{s_{NN}}$ =8.16 TeV

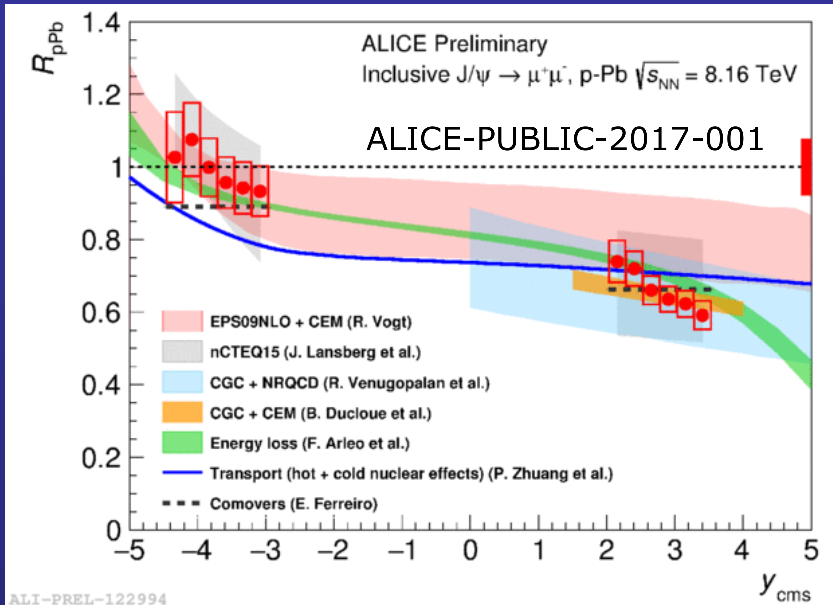


- ❑ Clear **J/ψ suppression at forward y, R_{pPb} compatible with unity at backward y**
- ❑ R_{pPb} at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV are compatible (slightly different x_F range)
- ❑ p_T coverage extended to 20 GeV/c
- ❑ R_{pPb} increases with p_T at forward y
- ❑ Weaker dependence at backward y





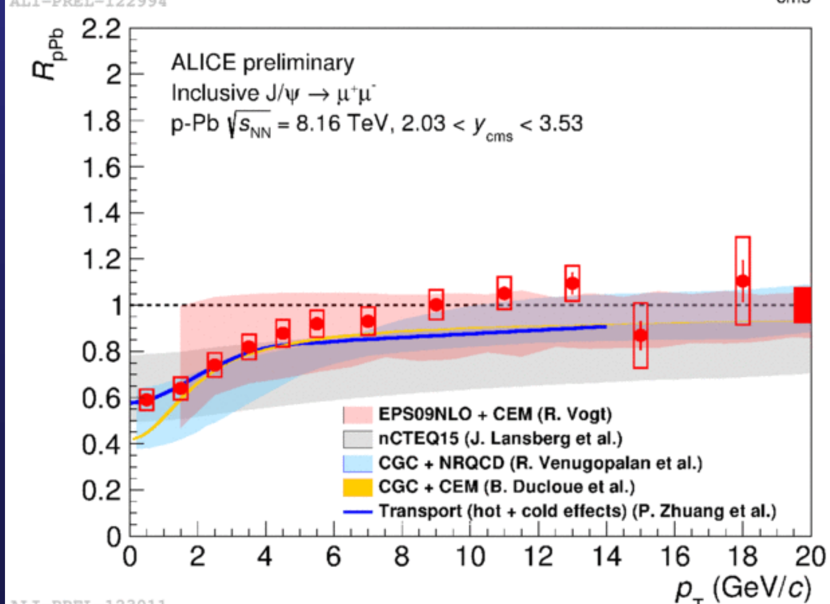
p-Pb collisions: J/ψ results at $\sqrt{s_{NN}}$ =8.16 TeV

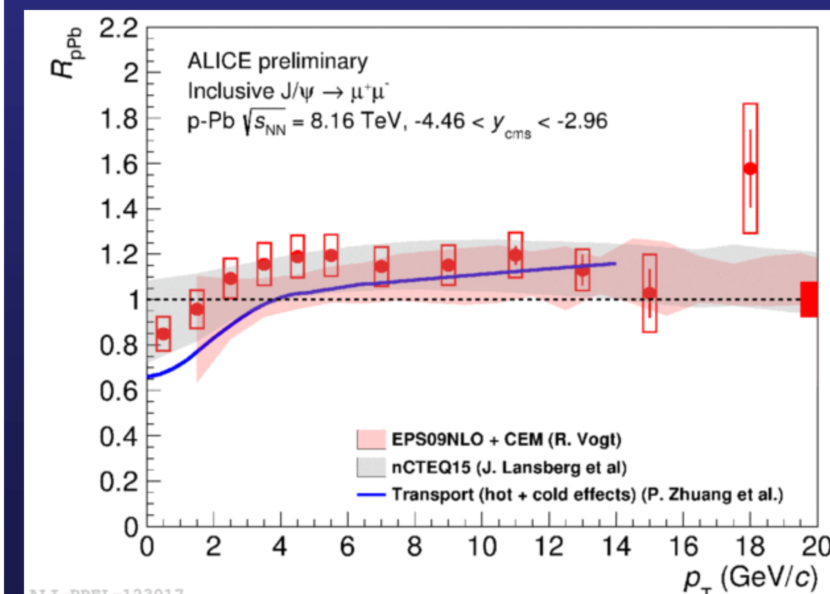


- **Good agreement** between data and models based on shadowing and/or energy loss, as at $\sqrt{s_{NN}}$ = 5.02 TeV

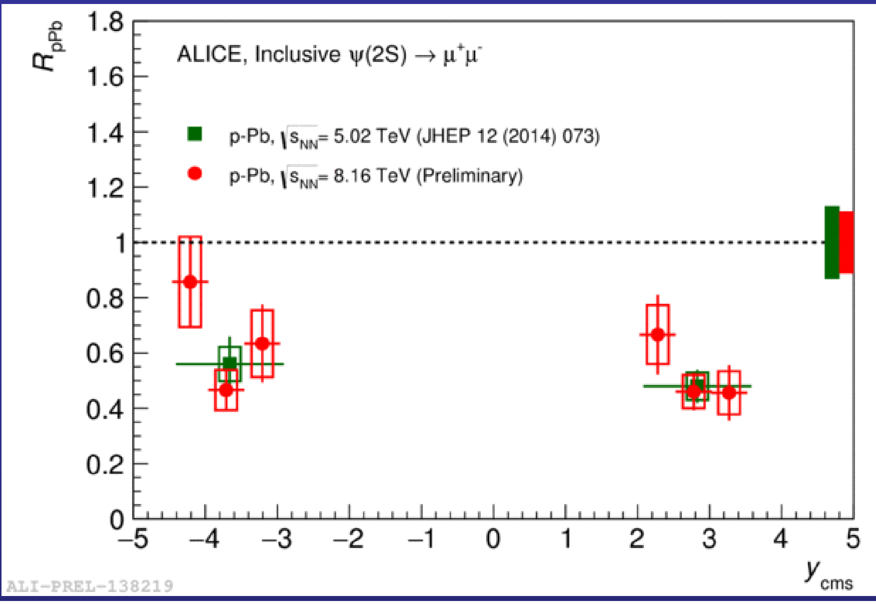
- Theoretical uncertainties still prevent a more quantitative comparison

Ducloue et al., PRD91(2015) 114005
Lansberg et al., EPJC77(2017) 1
Ma et al., PRD92 (2015) 071901
Chen et al., PLB765 (2017) 323
F. Arleo, R. Vogt in arXiv:1707.09973

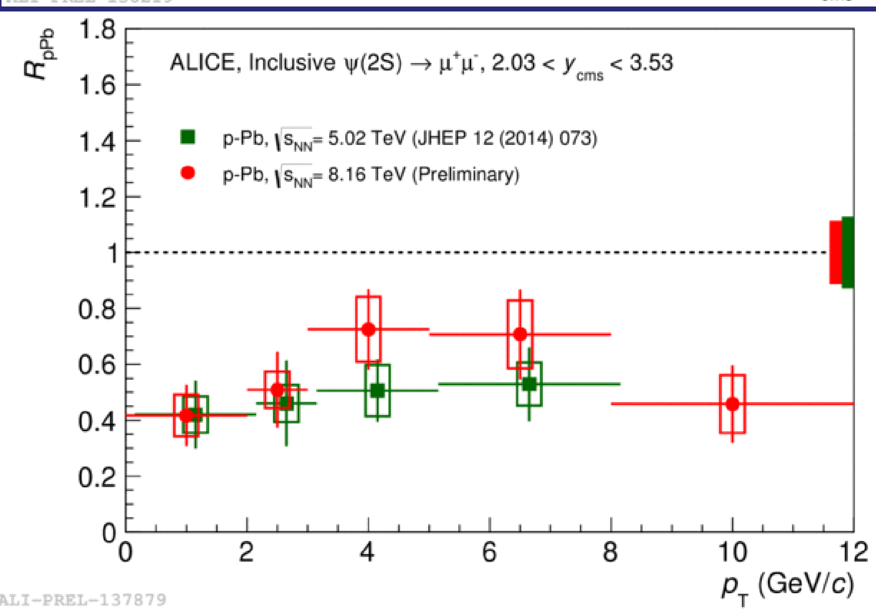


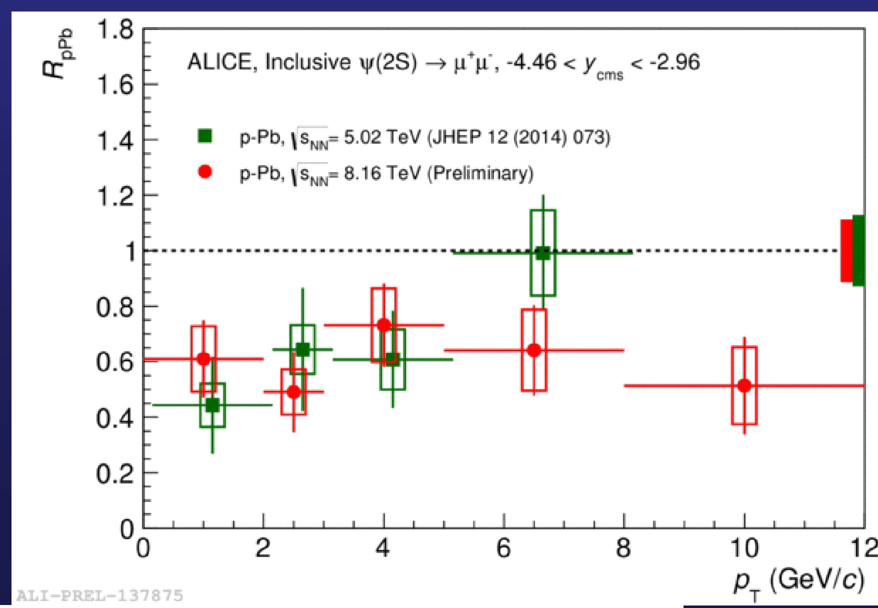


p-Pb collisions: $\psi(2S)$ results at $\sqrt{s_{NN}}$ =8.16 TeV

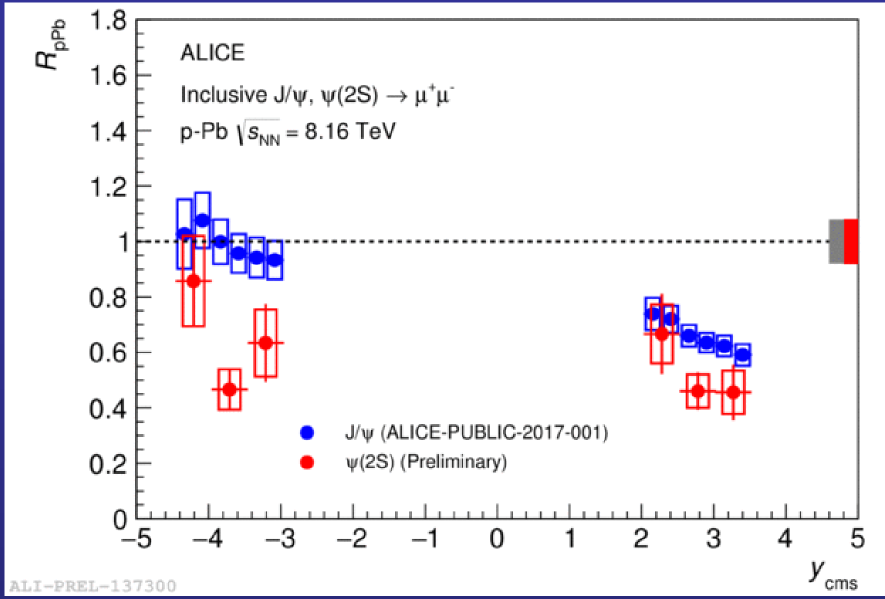


- **Strong suppression of $\psi(2S)$ at BOTH forward and backward y**
- Effect also seen at $\sqrt{s_{NN}}$ = 5.02 TeV
- No sizeable $\sqrt{s_{NN}}$ dependence, both in y and p_T

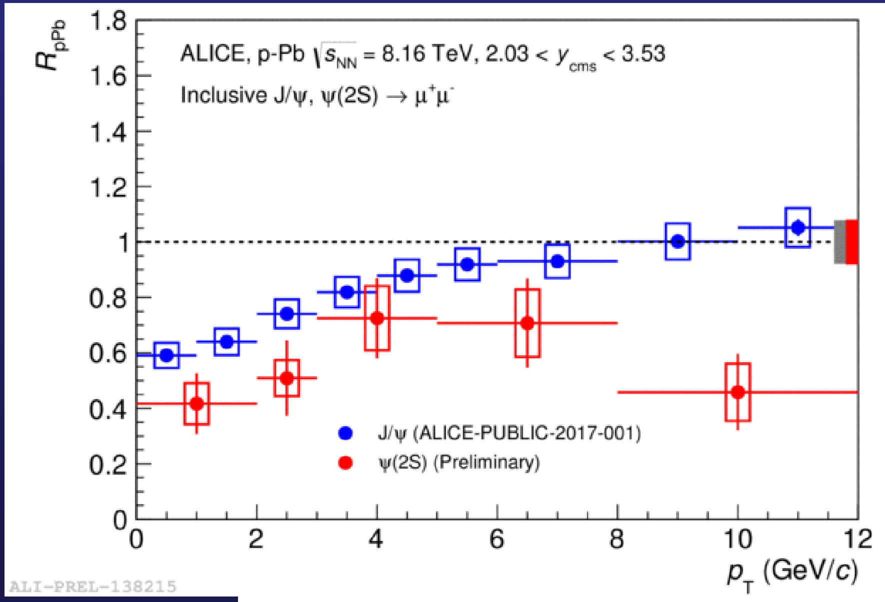


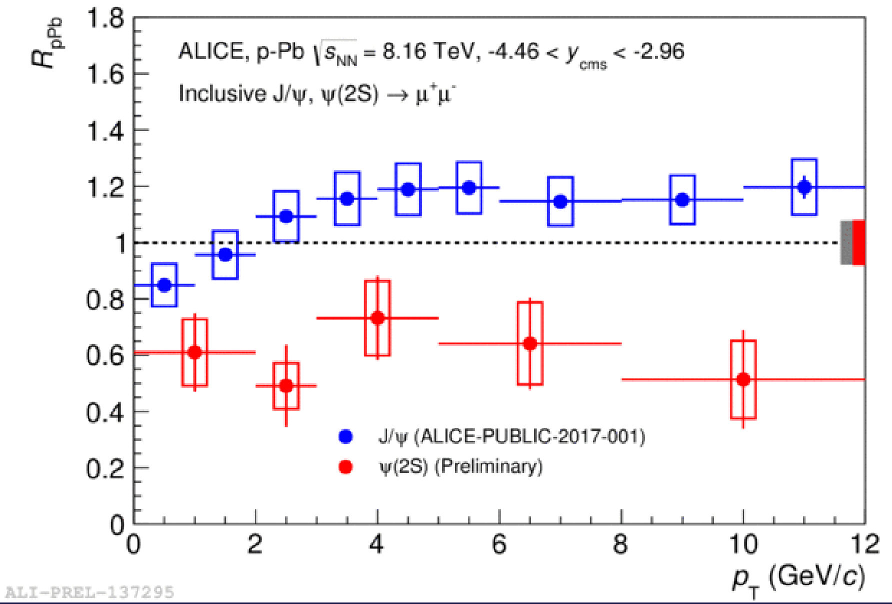


p-Pb collisions: J/ψ vs ψ(2S) at $\sqrt{s_{NN}}$ =8.16 TeV

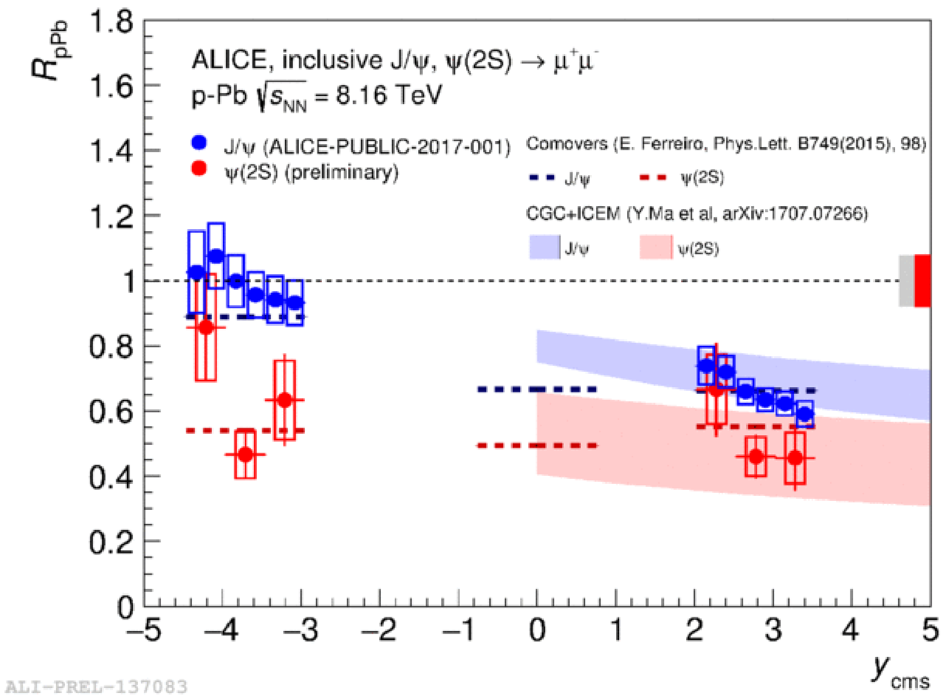


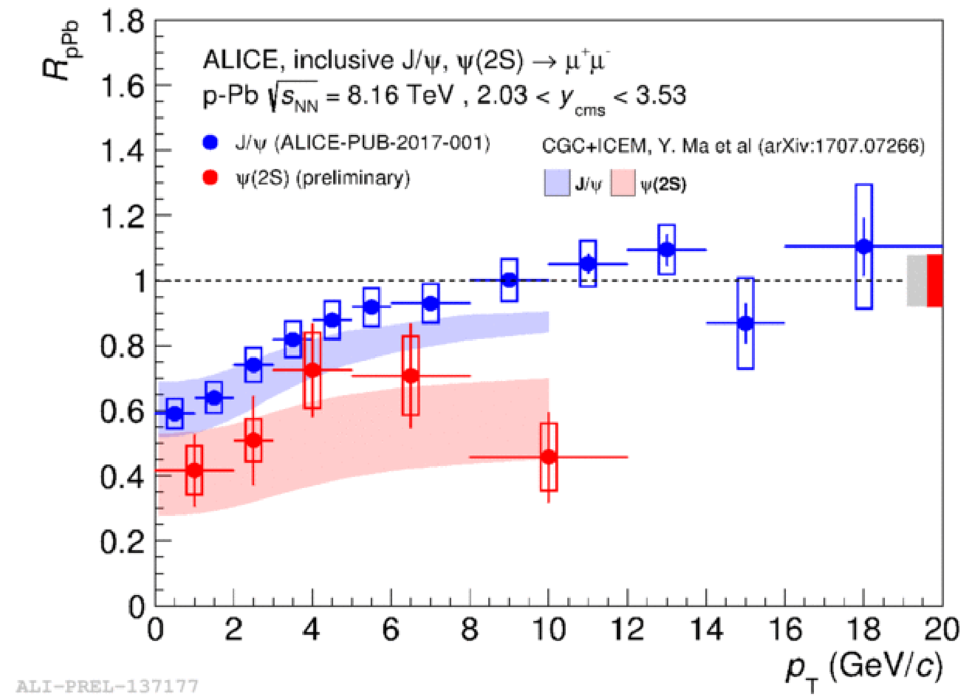
- **Lower R_{pPb} for ψ(2S) compared to J/ψ**
- Effect more evident at backward y, stronger influence of the final state?
- **Formation time > crossing time**
  → need final-state effects on ψ(2S)
  - Hadron gas (comovers model) ?
  - QGP droplet ?





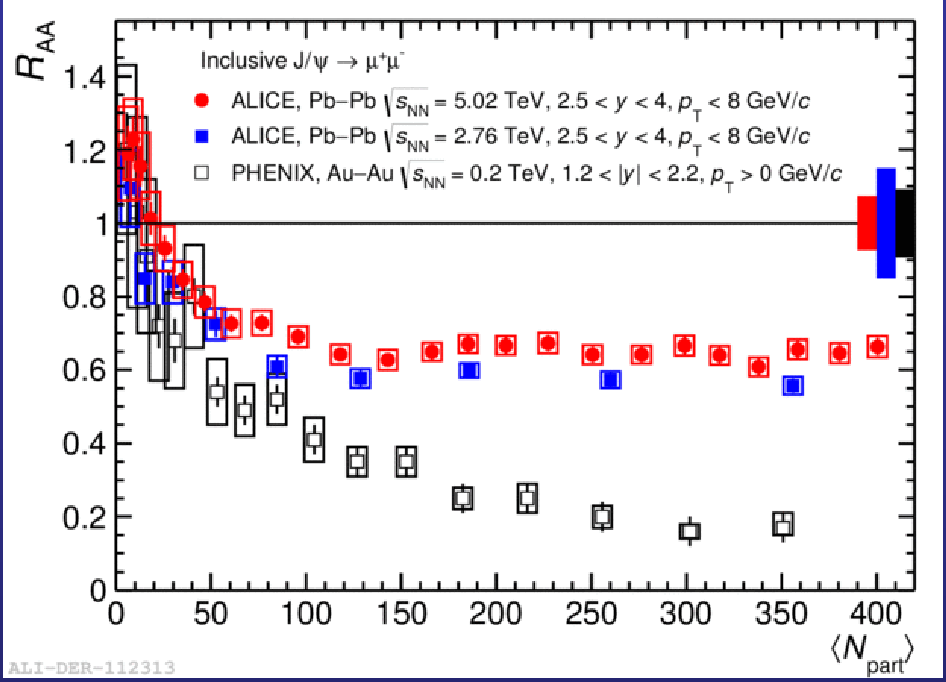
p-Pb collisions: ψ(2S) results at $\sqrt{s_{NN}}$ =8.16 TeV

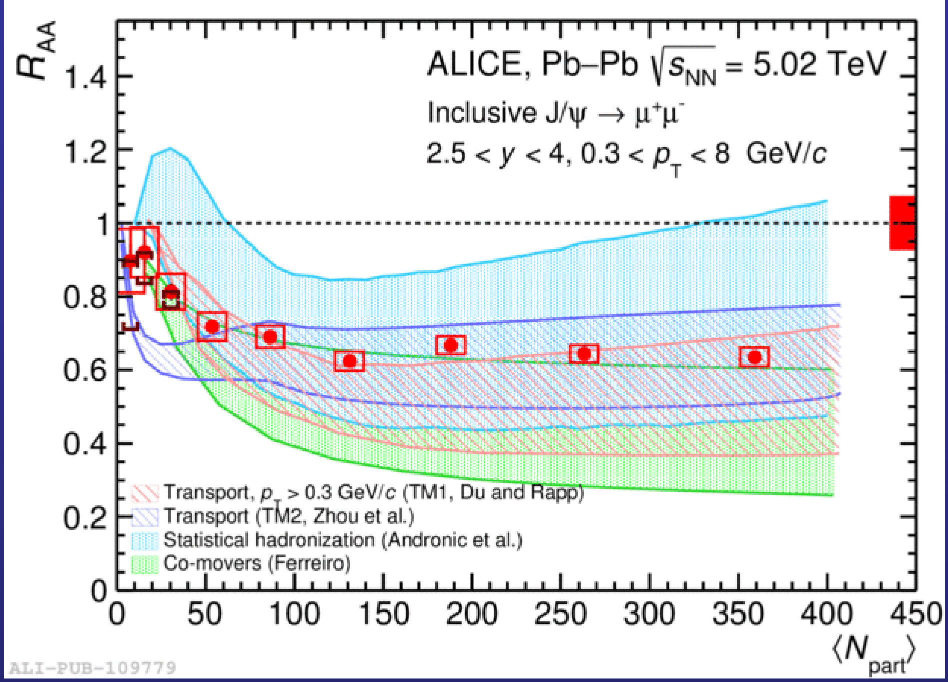




- Comparison with **models including final-state interactions**
- Ma and Venugopalan → soft color exchanges between hadronizing $c\bar{c}$ pair and comoving partons
- Ferreiro → "classical" comover models, break-up cross section tuned on low energy results
- **Fair agreement with data**

Pb-Pb collisions: run-2 results, forward y



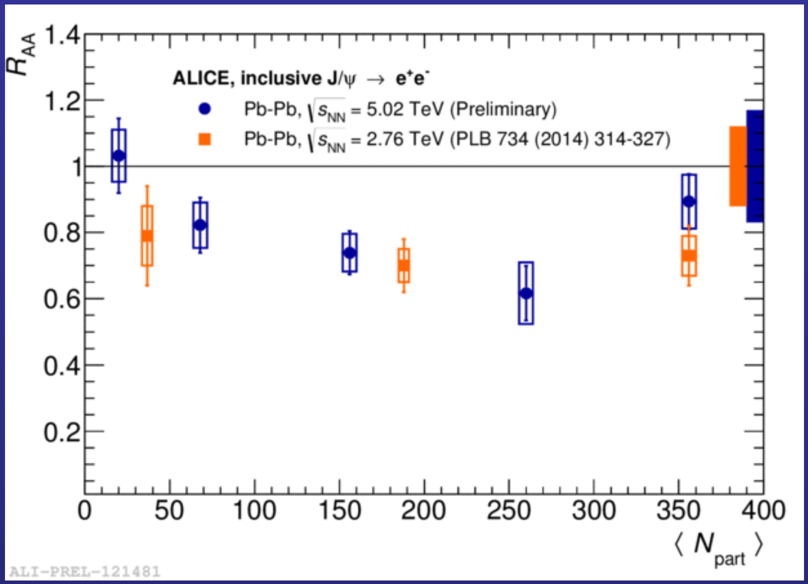


ALICE, PLB 766 (2017) 212

Zhao et al., NPA 859 (2011) 114, Zhou et al., PRC89 (2014) 054911
Ferreiro et al., PLB731 (2014) 57, Andronic et al., NPA904-905 (2013) 535

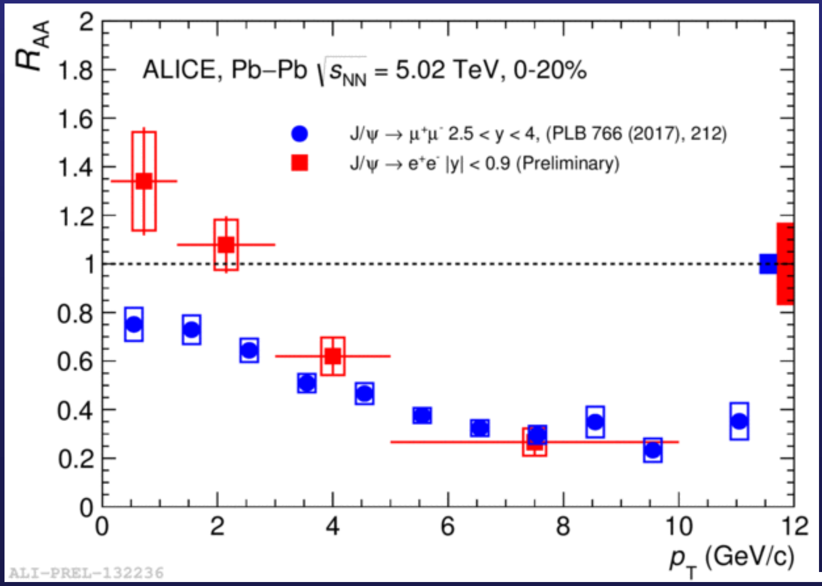
- **No significant centrality dependence beyond $\langle N_{part} \rangle \sim 50$**
- J/ψ suppression at $\sqrt{s_{NN}}$=5.02 TeV confirms observations at $\sqrt{s_{NN}}$=2.76 TeV with an increased precision
- p_T > 0.3 GeV/c to minimize contribution of photo-production when comparing to theory models
- Theoretical uncertainties larger than in the experimental results

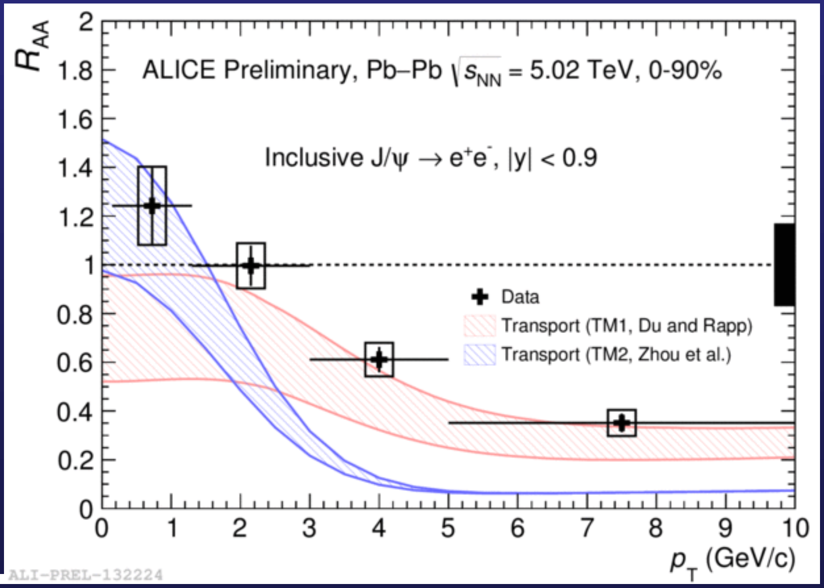
Pb-Pb collisions: run-2 results, mid-y



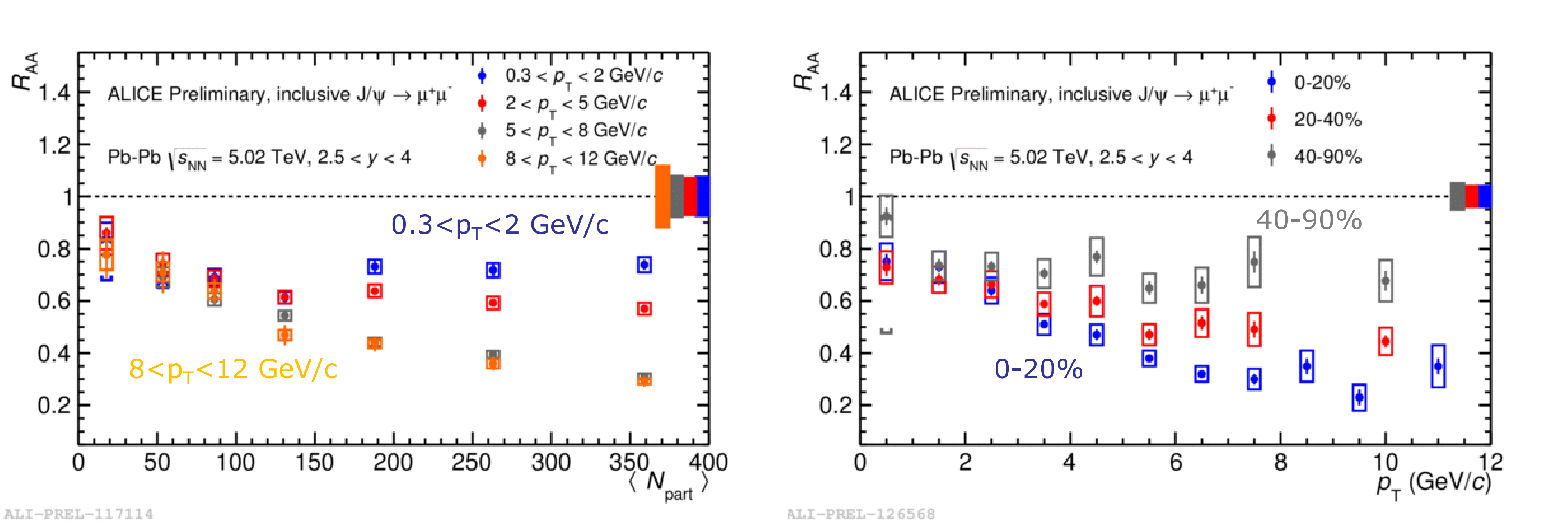
- Compatible results at the two energies
- **Increase at low p_T compared to forward-y measurement**
- Transport models qualitatively describe the data, some tension with TM2

Zhao et al., NPA 859 (2011) 114
Zhou et al., PRC89 (2014) 054911





Multi-differential J/ψ R_{AA} (forward y)



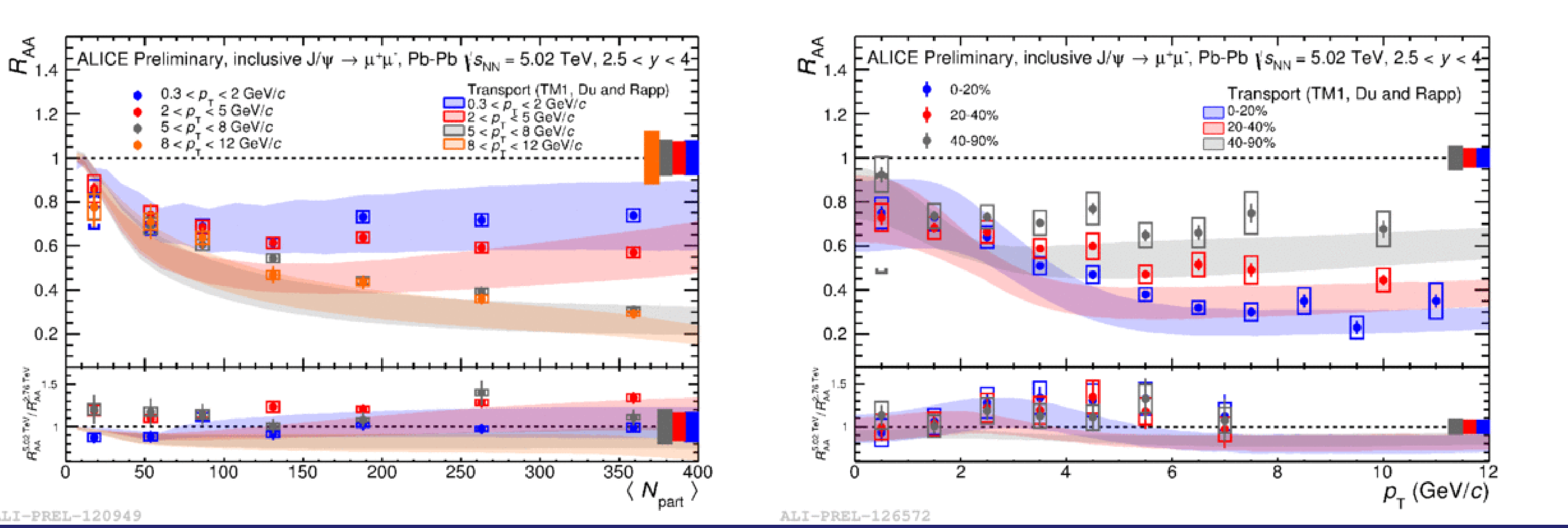
- ❑ R_{AA} vs p_T for different centrality bins (and vice-versa) at $\sqrt{s_{NN}}$=5.02 TeV
- ❑ Striking features observed

  → R_{AA} vs centrality (almost) flat in 0<p_T<2 GeV/c

  → ~80% suppression for central events at p_T~10 GeV/c

Multi-differential J/ψ R_{AA} (forward y)

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



Zhao et al., NPA 859 (2011) 114

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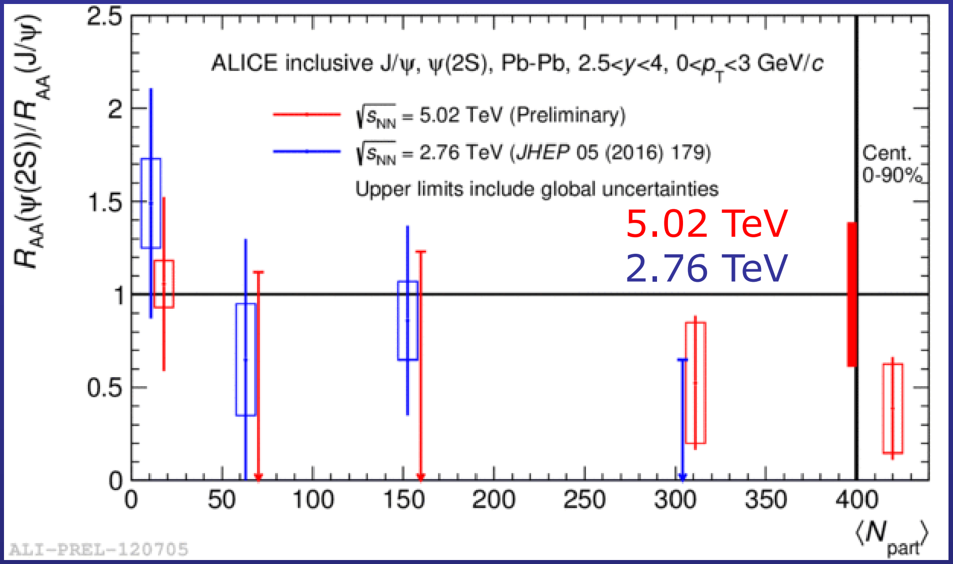
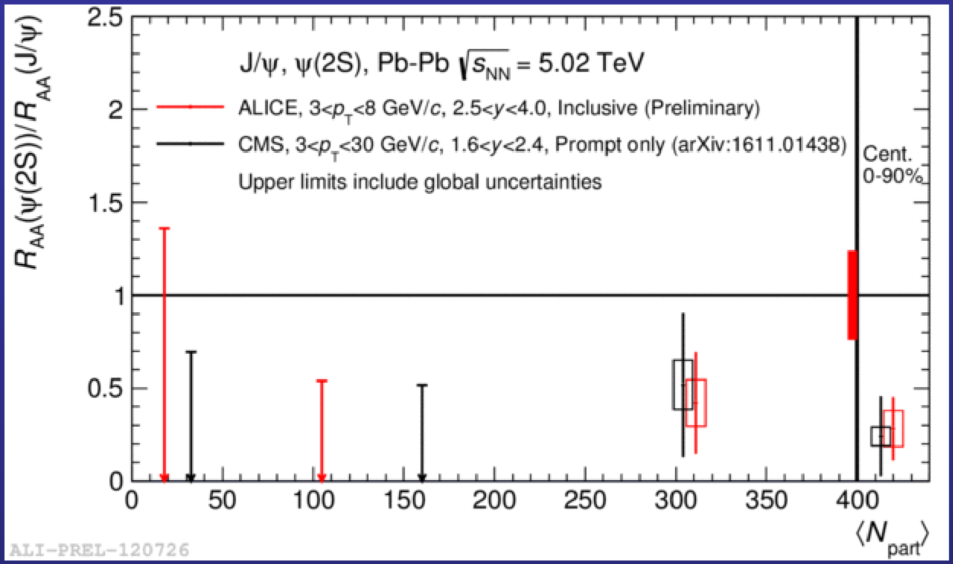
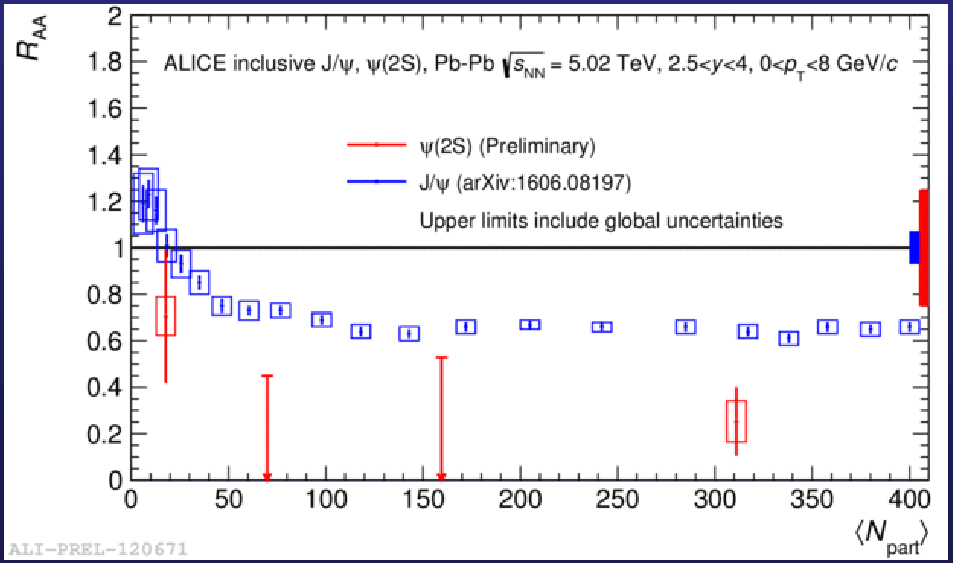
- ❑ Striking features observed
  - **→ R_{AA} vs centrality (almost) flat in $0<p_T<2$ GeV/c**
  - **→ ~80% suppression for central events at p_T~10 GeV/c**
- ❑ Precise results open up the way to precise comparisons with models

Pb-Pb collisions: ψ(2S) results



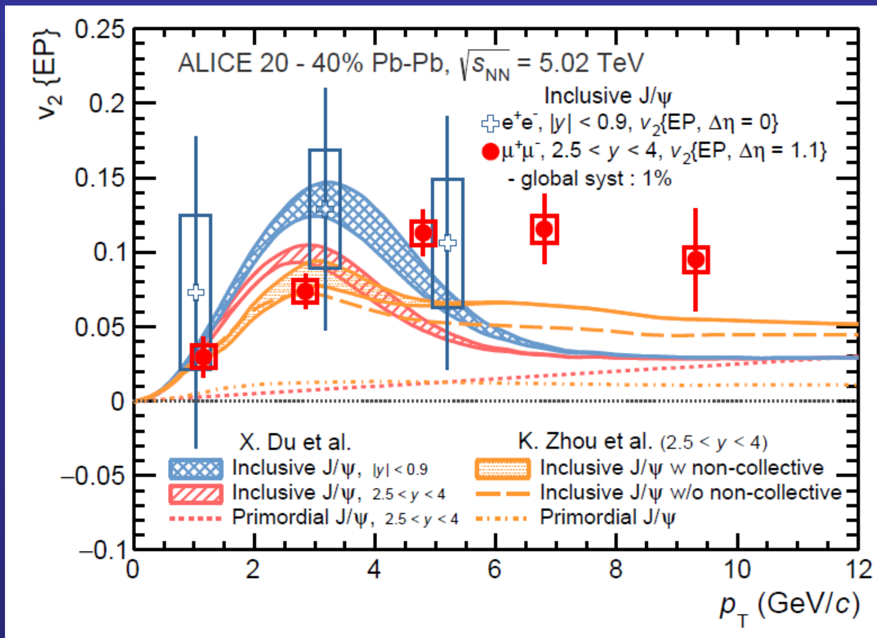


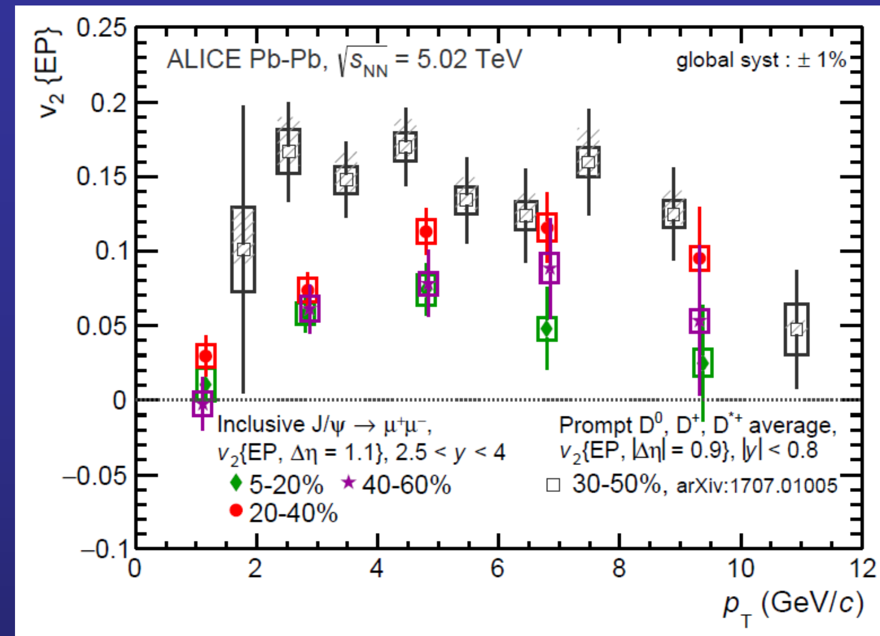


- Uncertainties are rather large (S/B sub-optimal)
- More suppressed than J/ψ
- ALICE $\sqrt{s_{NN}}$=2.76 and 5.02 TeV results are compatible
- **Indications for suppression at low AND intermediate p_T**
- Good agreement with CMS results at $\sqrt{s_{NN}}$=5.02 TeV

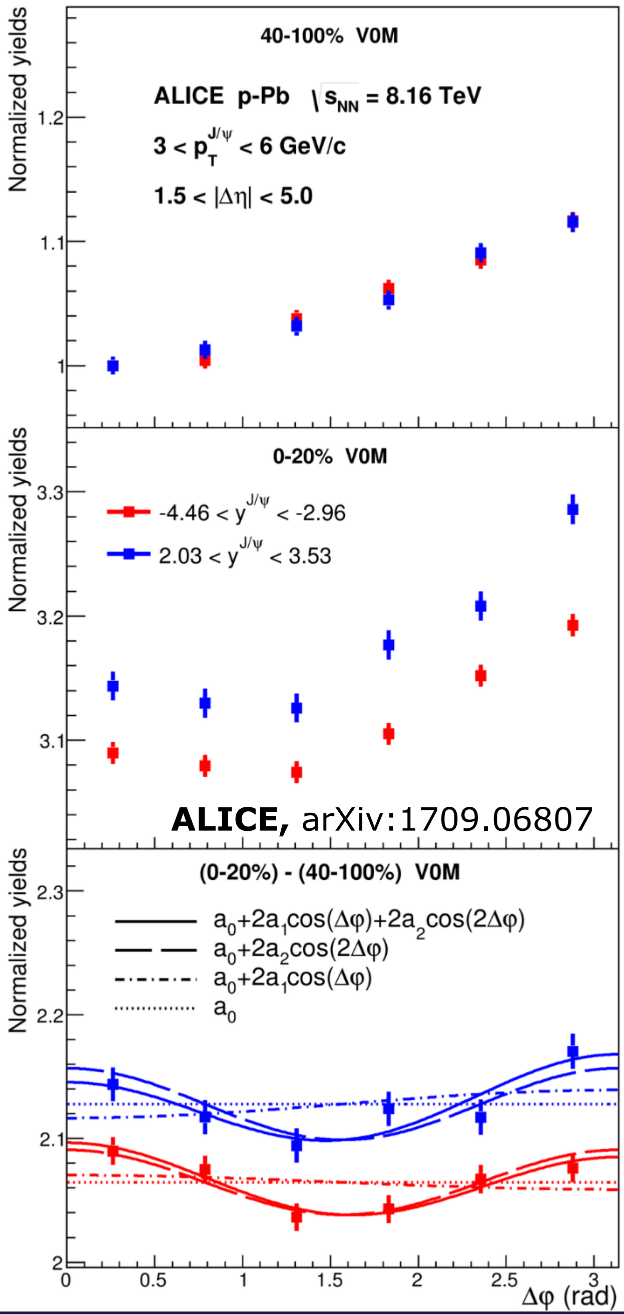
ALICE, arXiv:1709.05260
Zhou et al., PRC89(2014) 054911
Du et al., NPA943 (2015) 147

Pb-Pb collisions: J/ψ v_2



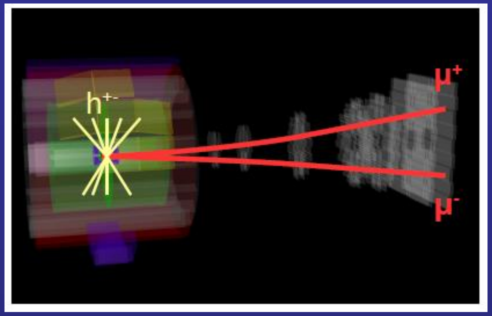


- A clear v_2 signal is observed in various centrality and p_T bins
- Comparison with models
  - **low p_T v_2 reproduced** including a strong J/ψ regeneration component
  - **high p_T v_2 underestimated** (prompt J/ψ from CMS also show $v_2 \neq 0$)
- Comparison with open charm v_2 (different kinematics!)
  - Low-p_T v_2 larger for D mesons
  - **Do J/ψ and D inherit their elliptic flow from thermalized charm quarks ?**



J/ψ v_2 in p-Pb collisions

- Azimuthal correlations between forward/backward J/ψ and mid-rapidity charged particles



- Correlations expressed as associated SPD-tracklet yields per dimuon(J/ψ) trigger

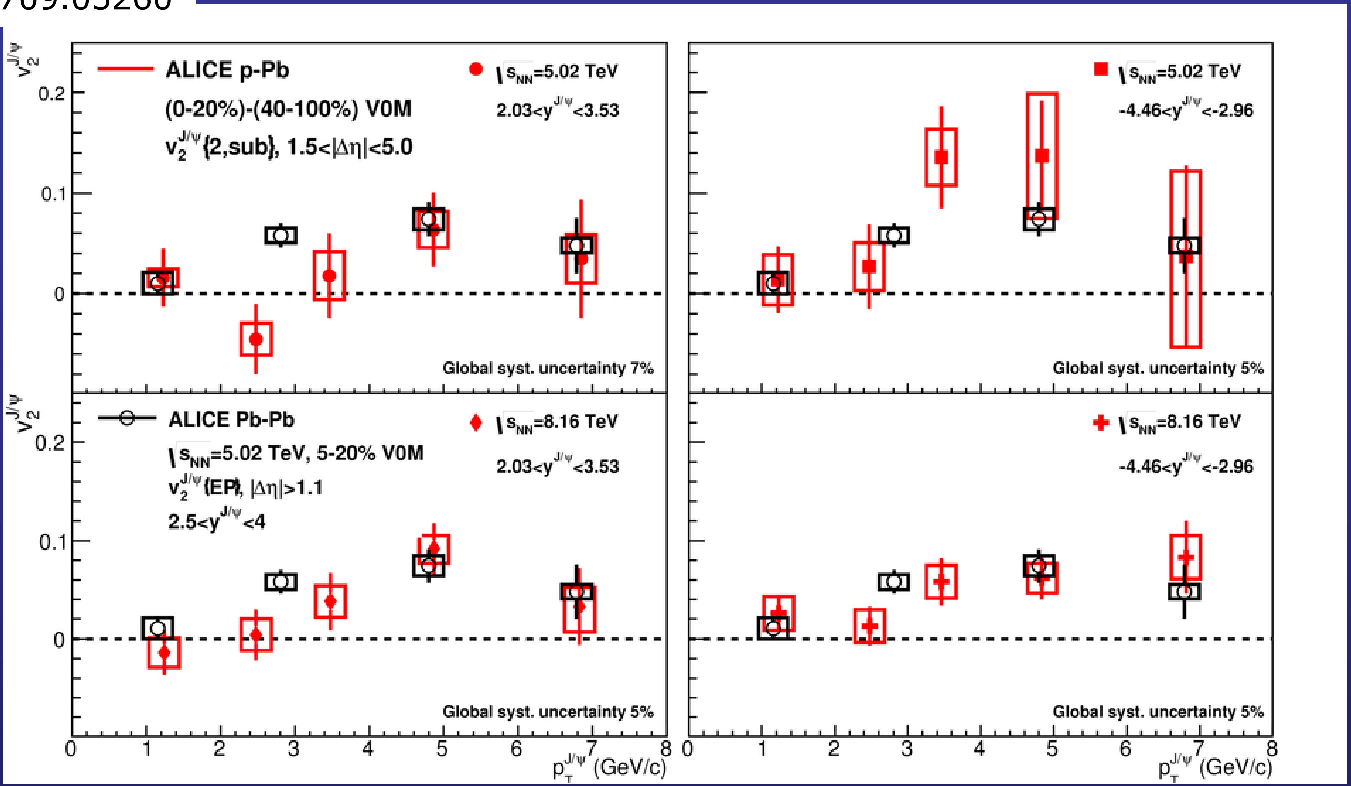
- 40-100%: clear away-side correlation (jets?)
- 0-20%: additional enhancement at both near and away sides

→ Jet correlations eliminated via subtraction

- J/ψ v_2 extracted assuming factorization of J/ψ and tracklet v_2

ALICE, arXiv:1709.06807
ALICE, arXiv:1709.05260

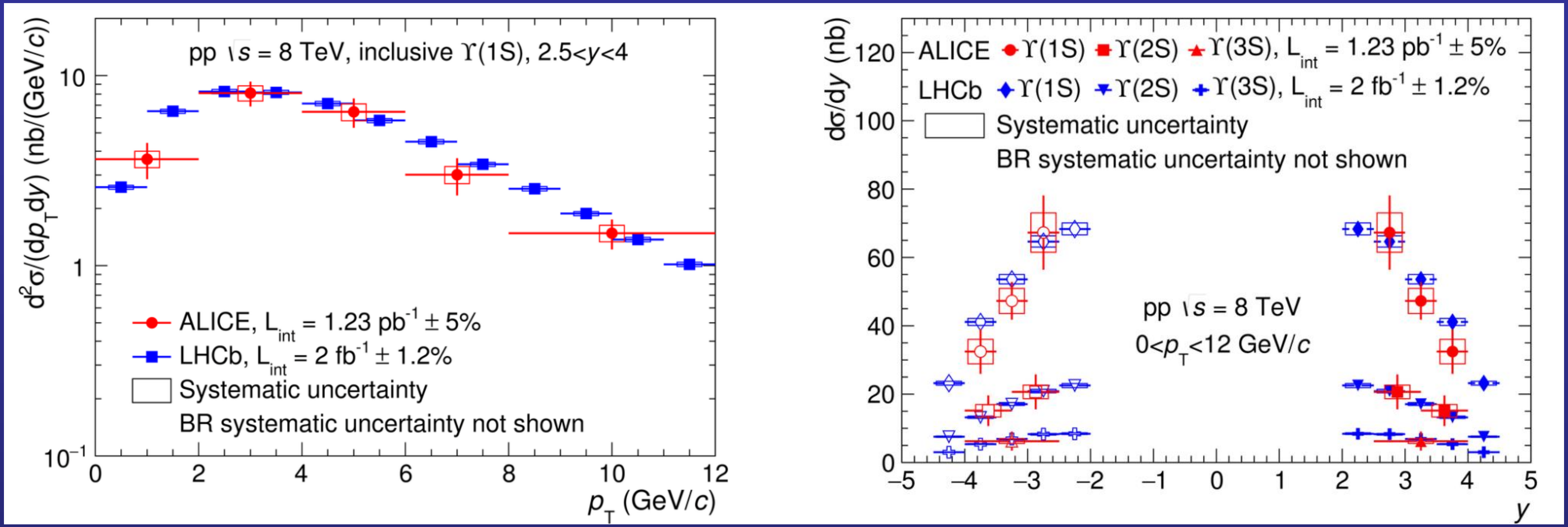
J/ψ v_2 in p-Pb collisions



- **p_T<3 GeV/*c* → v_2 compatible with 0** (in line with expectation of no recombination)
- **3<p_T<6 GeV/*c* → v_2>0**
- Total (forward+backward,5.02+8.16 TeV) significance about 5σ
- Values comparable to the measurements in central Pb-Pb collisions
  → common mechanism at the origin of the J/ψ v_2 ?

Bottomonia

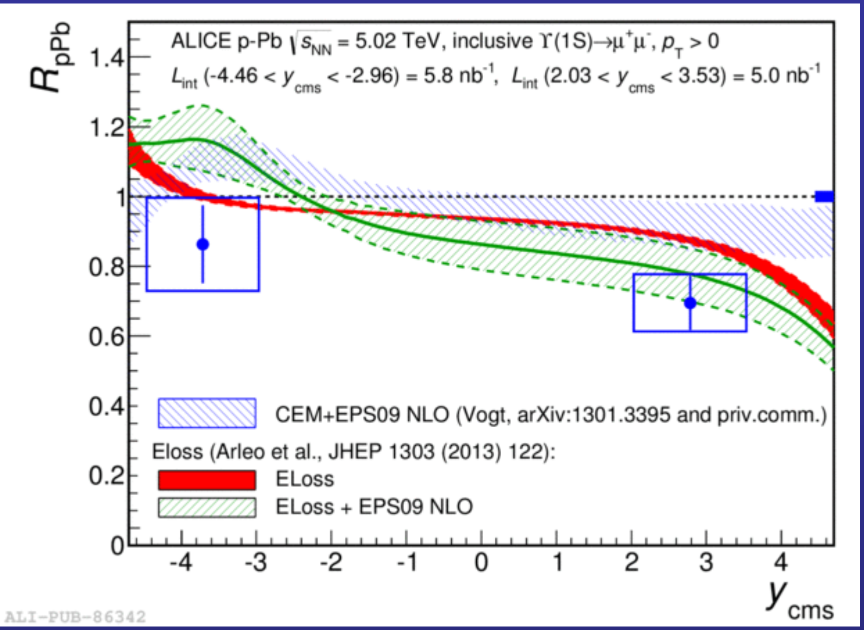
ϒ results in pp: √s = 8 TeV

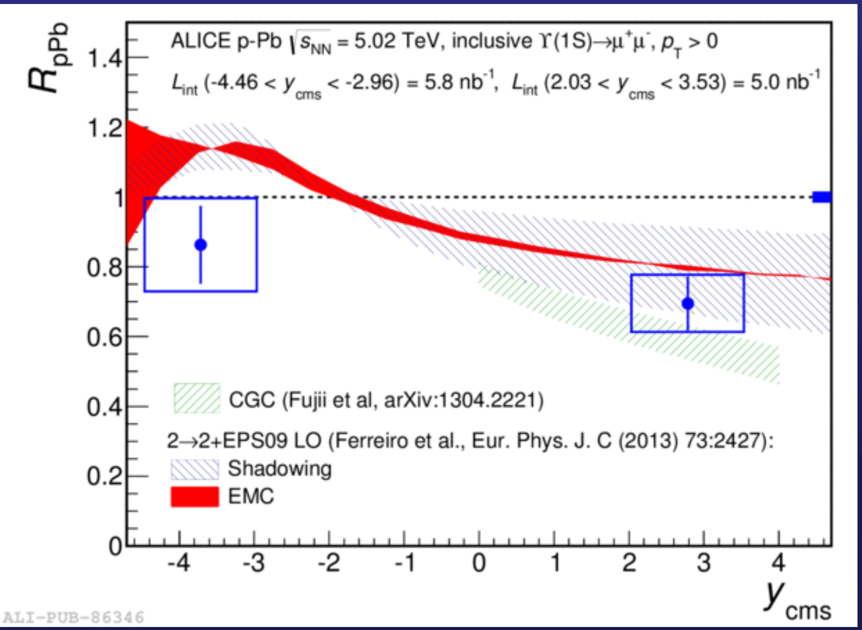


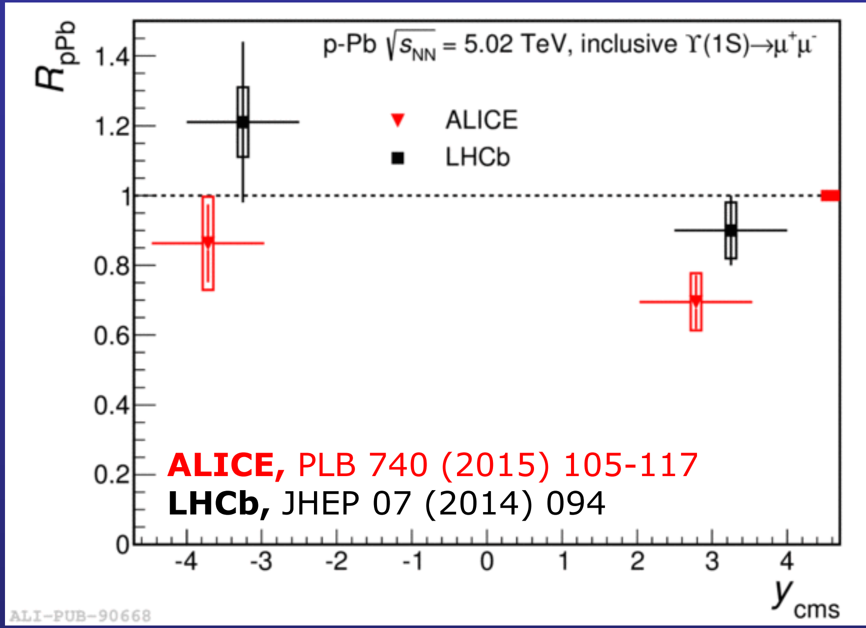
ALICE, EPJC 76 (2016) 184
LHCb, JHEP 11 (2015) 103

- Integrated luminosity enough for a measurement of 1S, 2S and 3S states
- In $2.5<y<4$, $p_T<12$ GeV/c
  - **$\sigma_{\Upsilon(1S)}$ = 71±6(stat)±7(syst) nb**
  - **$\sigma_{\Upsilon(2S)}$ = 26±5(stat)±4(syst) nb**
  - **$\sigma_{\Upsilon(3S)}$ = 9±4(stat)±1(syst) nb**
- Results in agreement with LHCb measurements within 1.2 σ

ϒ results in p-Pb: run 1

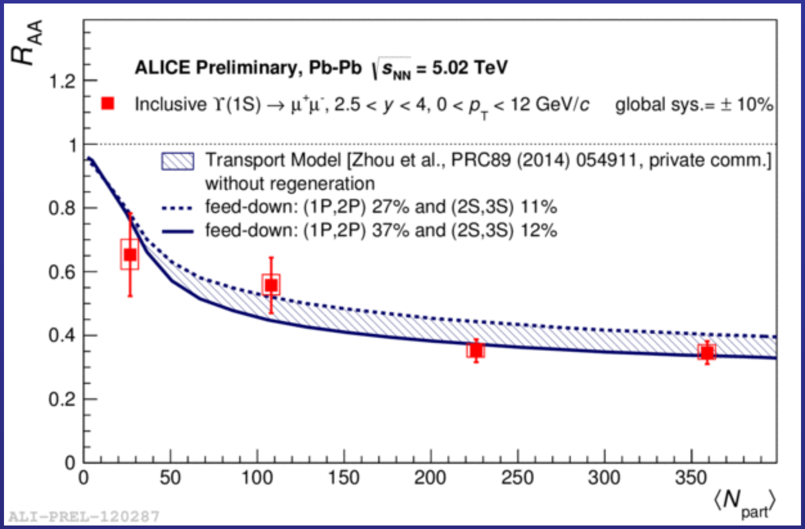






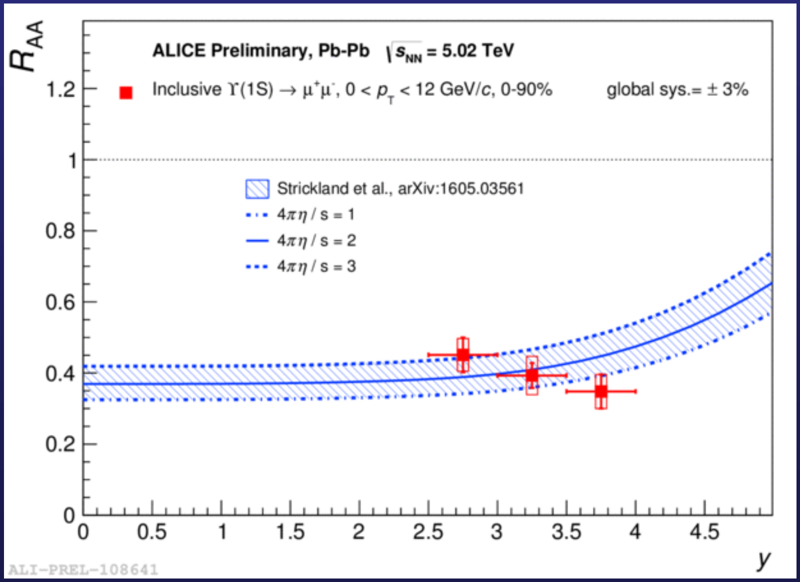
- Model predictions **describe the measured R_{pPb} at forward y** and tend to **underestimate** the suppression at **backward y**
- Compatible within (large) uncertainties with LHCb results
- Run 2 data will be soon available

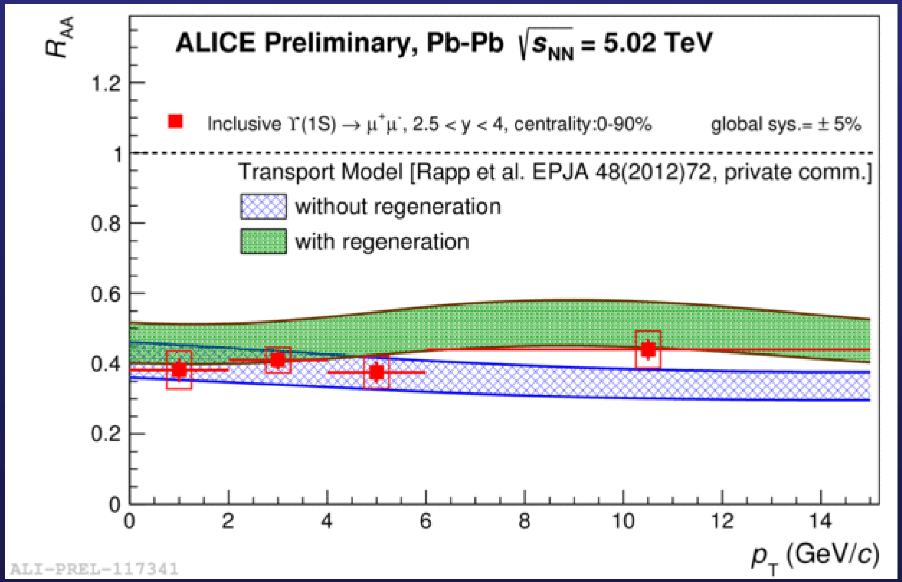
ϒ results in Pb-Pb: run 2



- Transport and anisotropic hydrodynamical models **qualitatively describe** the centrality and p_T–dependence of ϒ(1S) R_{AA}
- Some tension in the y-dependence ?
- **Contribution of regeneration is small**

- **R_{AA} (ϒ(2S))** = 0.26± 0.12 ± 0.06(sys.) **< R_{AA} (ϒ(1S))** = 0.40 ± 0.03 ± 0.04(sys.)



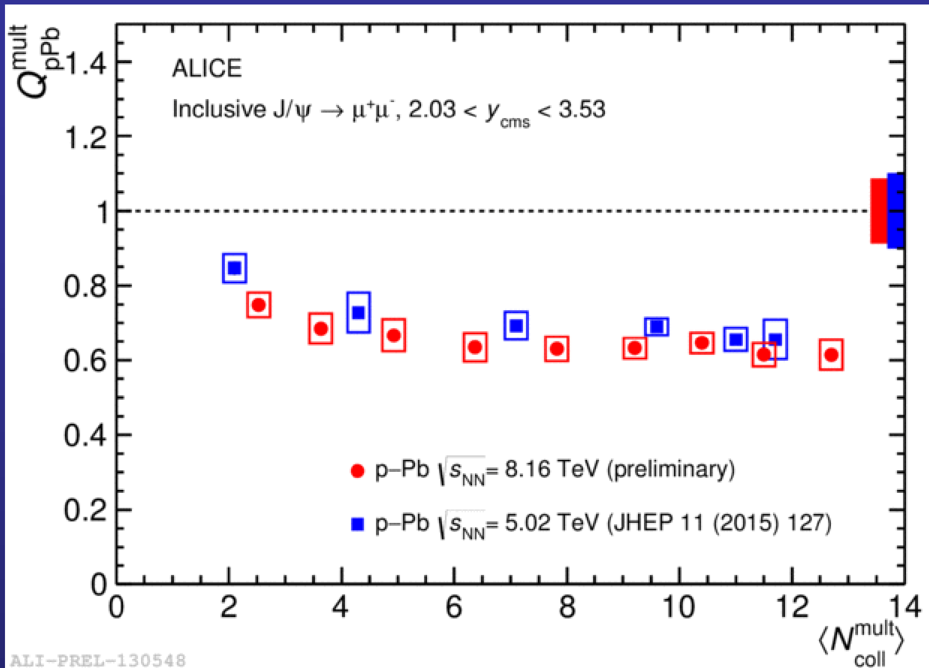


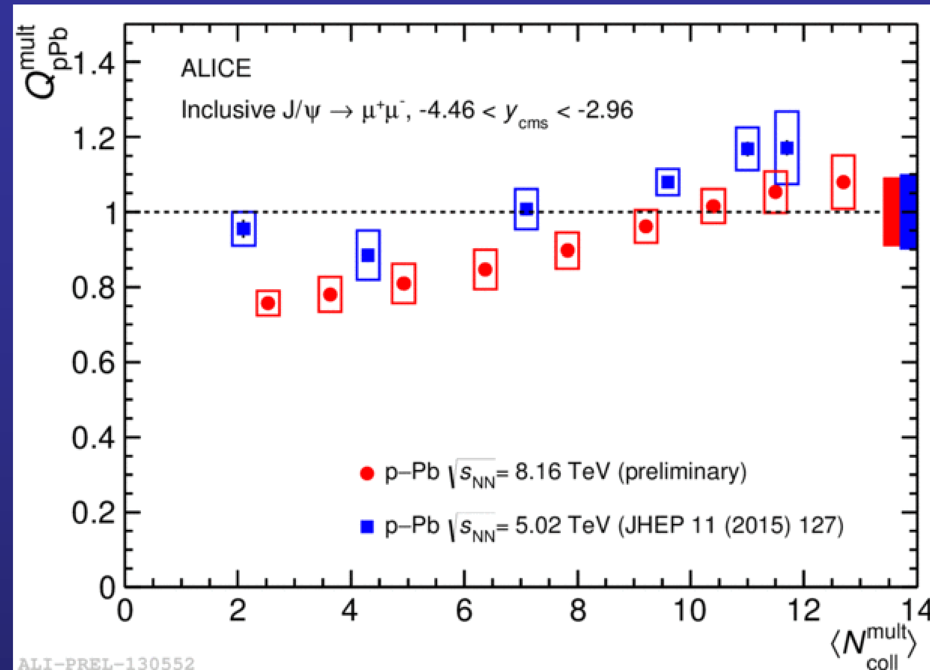
Conclusions

- Bottomonium
  - Pb-Pb results show a **significant suppression of ϒ(1S)**
  - Indication for a **stronger suppression of ϒ(2S)**
  - Good agreement with available theoretical models
  - Forthcoming run 2 p-Pb results → more precise estimate of CNM effects
- Charmonium
- **Significant v_2 for J/ψ observed in BOTH p-Pb and Pb-Pb collisions**
  → common mechanism ?
- Precise **differential results on J/ψ R_{AA}** available
  → stringent comparison to theory
- p-Pb collisions: **evidence for final state effects on ψ(2S)**
- pp collisions: precise results on **multiplicity dependence of J/ψ yield**
  → described by models including effects related to MPI

Backup

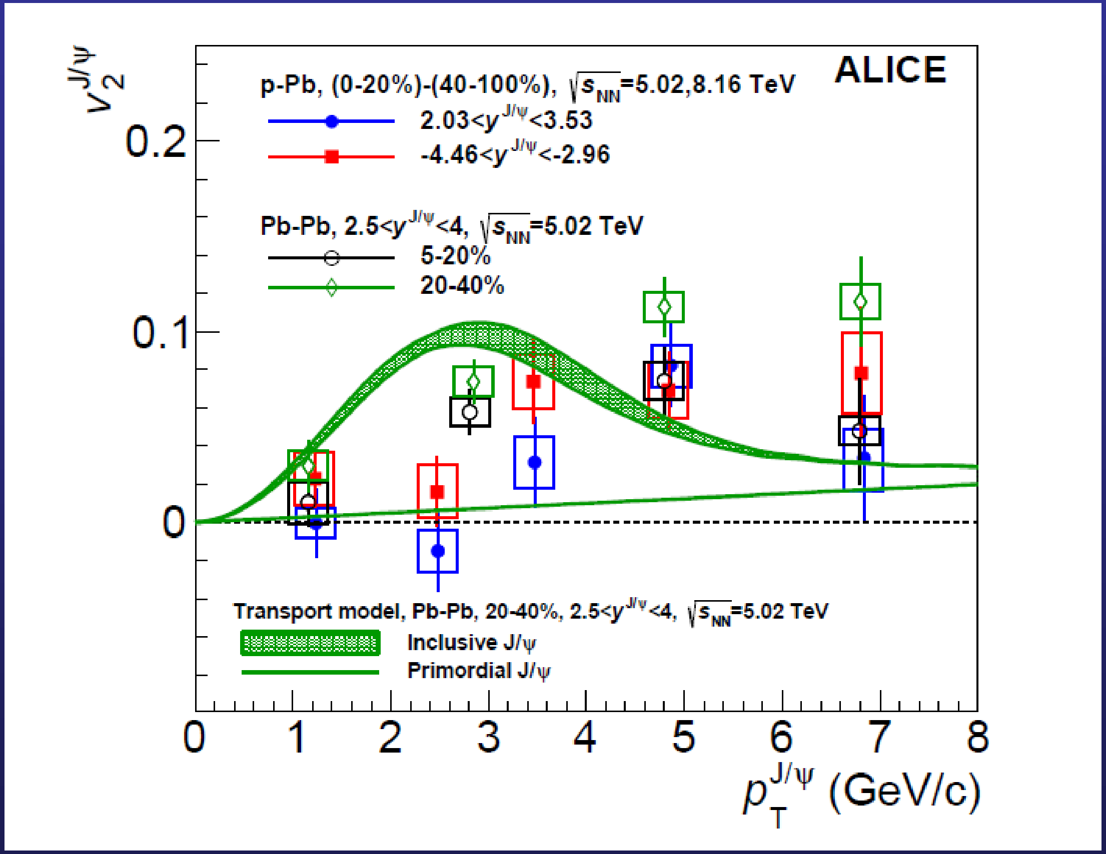
p-Pb collisions: J/ψ results at $\sqrt{s_{NN}}$ =8.16 TeV





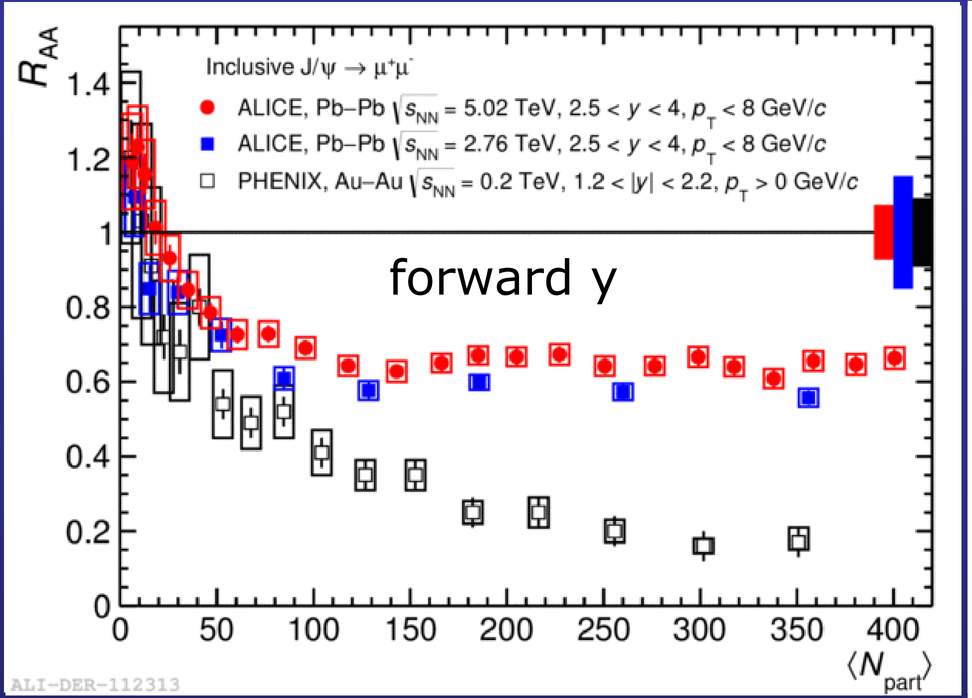
- Centrality dependence of J/ψ nuclear modification factor (Q_{pPb})
- Higher luminosity collected at $\sqrt{s_{NN}}$ = 8.16 TeV allows a finer binning with respect to $\sqrt{s_{NN}}$ = 5.02 TeV
- Similar pattern at both energies, slightly lower values at $\sqrt{s_{NN}}$ = 8.16 TeV but compatible within uncertainties
- **The nuclear modification factor decreases with N_{coll} at forward y while an opposite trend is observed at backward y**

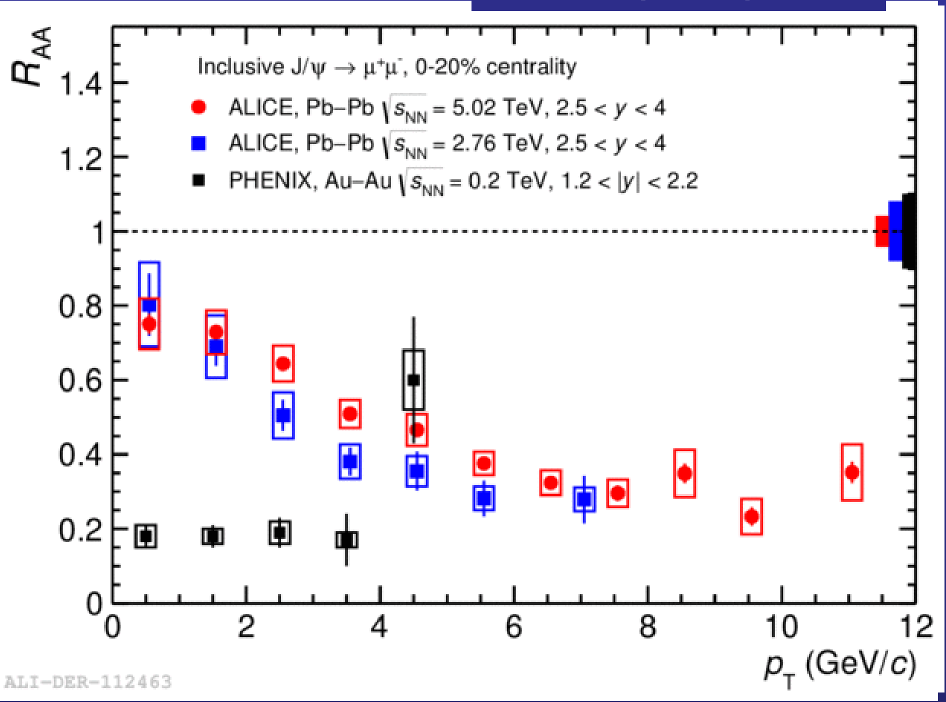
J/ψ v_2 p-Pb: combined energies



Low-p_T J/ψ: ALICE (vs PHENIX)

J.Adam et al, ALICE
PLB766(2017) 212

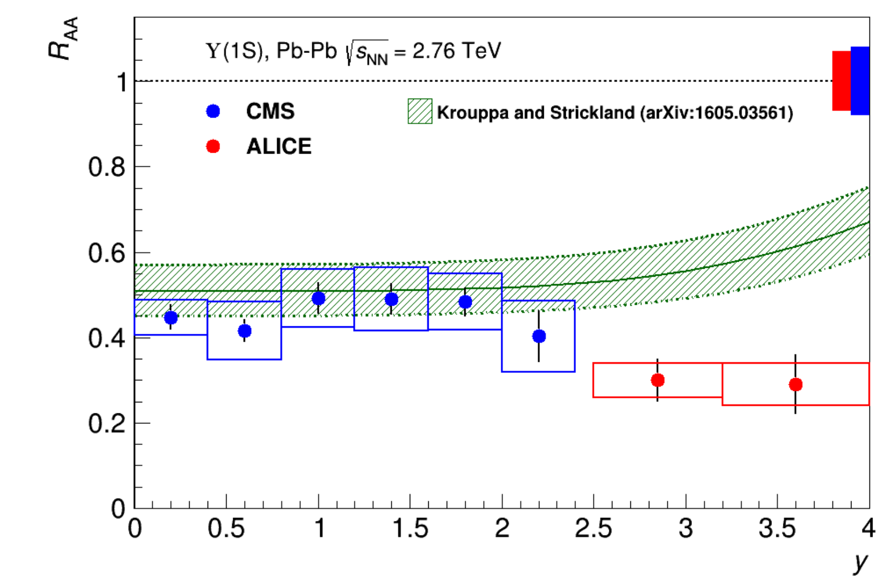


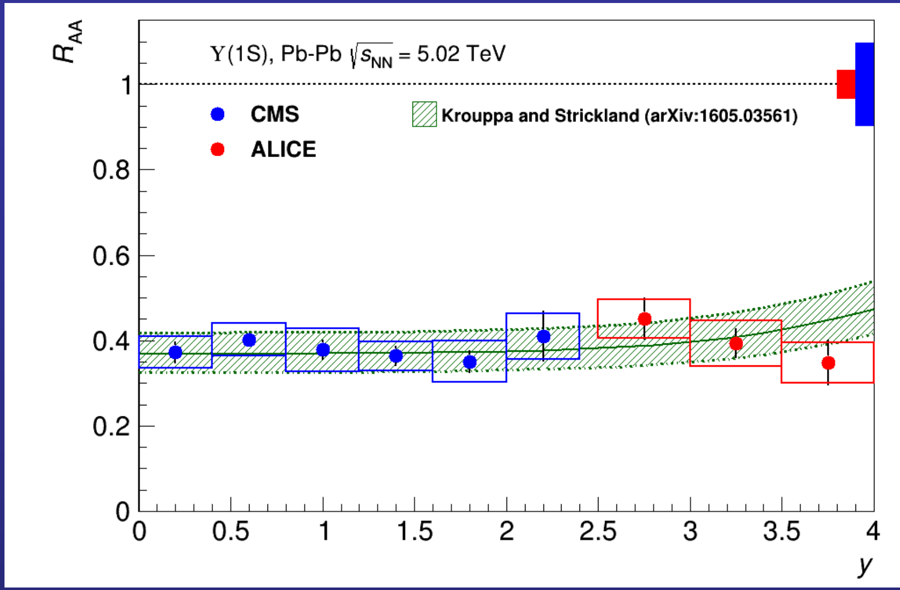


- Results vs centrality dominated by low-p_T J/ψ
  - Systematically **larger R_{AA} values** for **central** events at LHC
  - **R_{AA} increases at low p_T** at LHC
  - **Precise results at $\sqrt{s_{NN}}$=5.02 TeV**, compatible with $\sqrt{s_{NN}}$=2.76 TeV

Possible interpretation:
- **RHIC** energy → **suppression** effects dominate
- **LHC** energy → **suppression + regeneration**

R_{AA} vs y: ALICE and CMS Υ(1S)





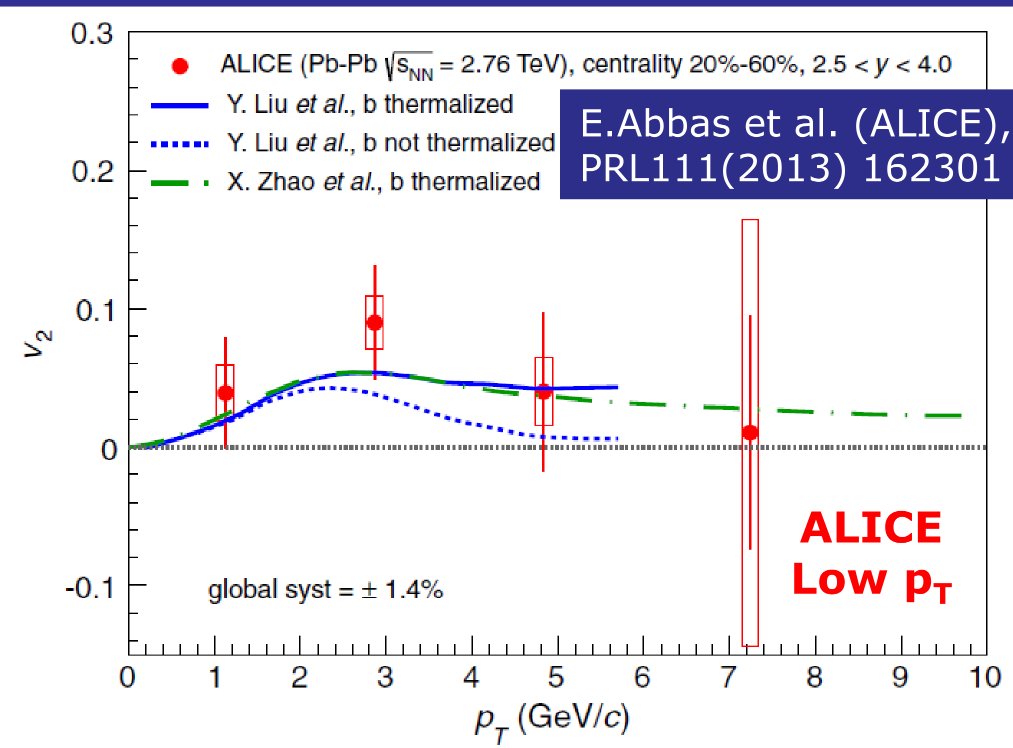
- Suppression **increases** with y at **$\sqrt{s_{NN}}$=2.76 TeV**
- Suppression **constant** vs y at **$\sqrt{s_{NN}}$=5.02 TeV**

- $\sqrt{s_{NN}}$=2.76 TeV: typical features of a **(re)generation pattern,** which seems to vanish at $\sqrt{s_{NN}}$=5.02 TeV

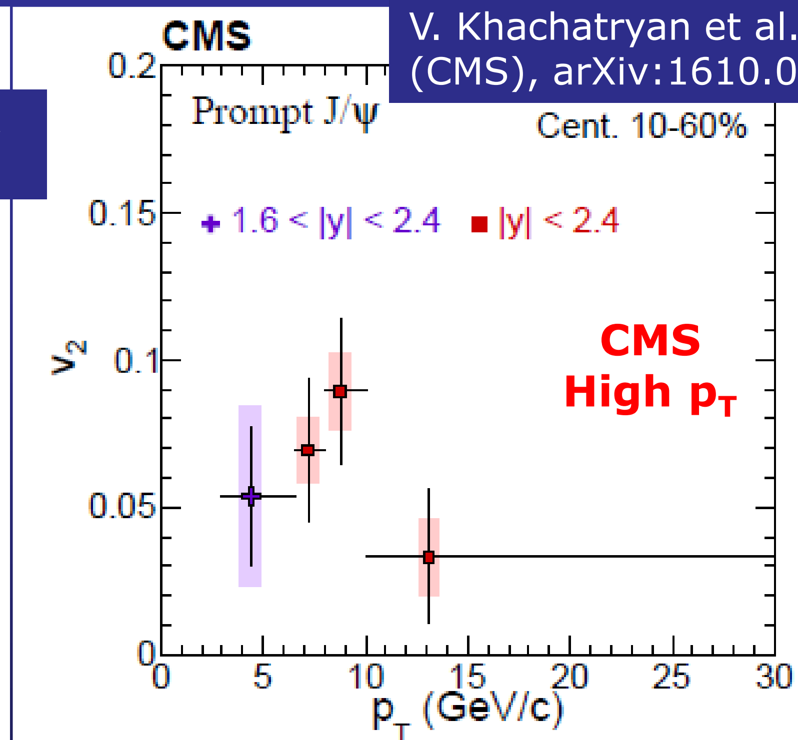
- Systematic uncertainties not negligible
- Can the y-dependence of CNM effects play a role? Not likely

J/ψ v_2

- The contribution of J/ψ from (re)combination could lead to an **elliptic flow** signal at LHC energy → hints observed in run-1 results



E.Abbas et al. (ALICE), PRL111(2013) 162301

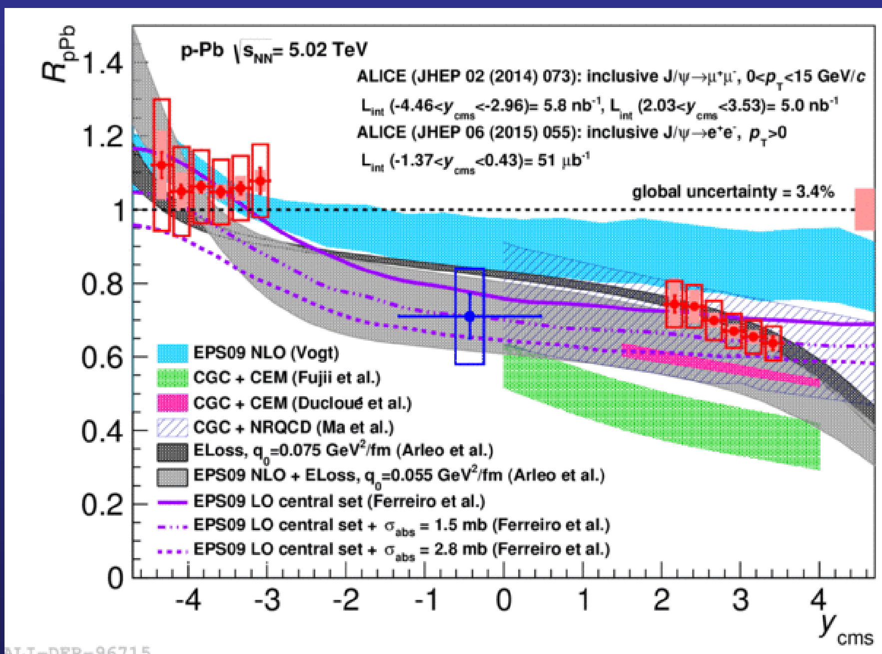


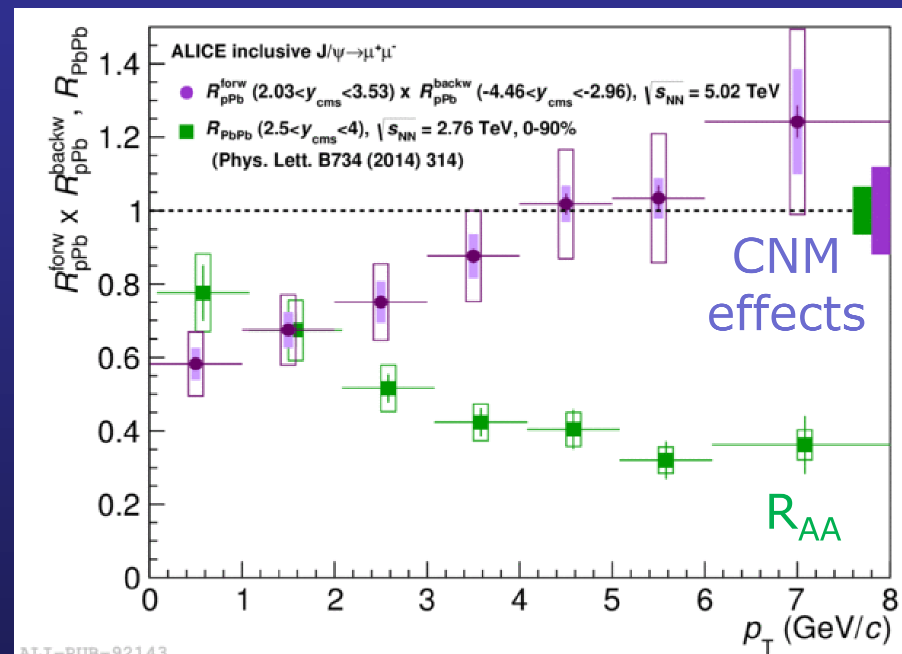
V. Khachatryan et al. (CMS), arXiv:1610.00613

- v_2 remains significant **at large p_T (~10 GeV/c)** where the contribution of (re)generation should be negligible
  → Likely due to **path length dependence of energy loss**

CNM effects - charmonia

- ❑ LHC energy → **Strong CNM effects** observed at **forward-y and low p_T**
- ❑ Can be described via **shadowing + coherent energy loss** and also via a **ColorGlassCondensate** approach

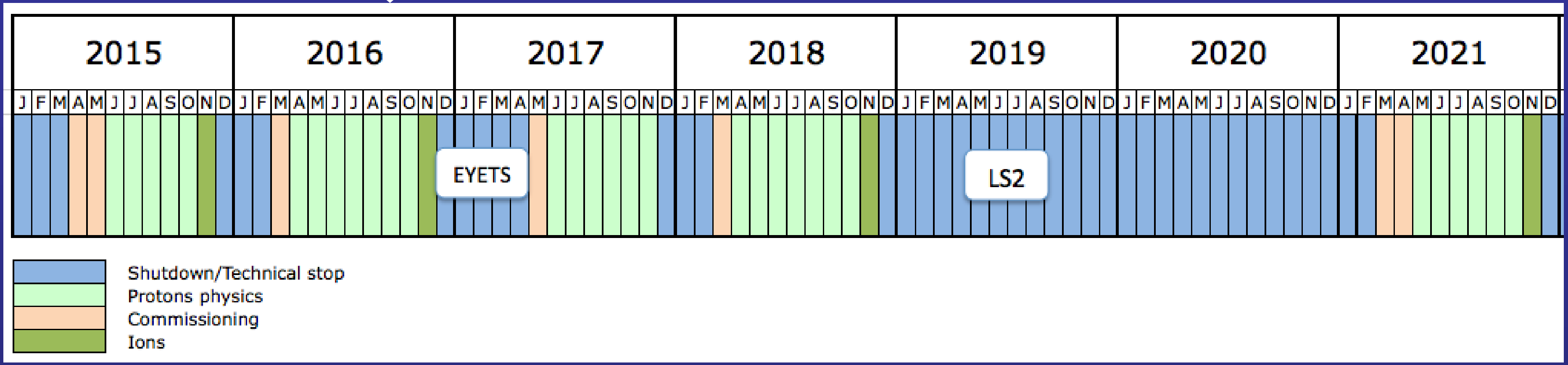




- ❑ Qualitative extrapolations of CNM effects to Pb-Pb imply **strong high p_T suppression** and hints for **J/ψ enhancement at low p_T**

Future of LHC heavy-ion program

(today)



- 2016: p-Pb run, shared between $\sqrt{s_{NN}}$ = 5 TeV and $\sqrt{s_{NN}}$ = 8 TeV
- EYETS: CMS pixel upgrade (for pp luminosity)
- 2018: Pb-Pb run, maximum available energy, L= 10^{27} cm^{-2} s^{-1}
- LS2: ALICE upgrades apparatus (TPC, ITS, MFT) → stand 50 kHz event rate expected for run-3 and improve tracking
  LHCb upgrades tracker → higher granularity, push towards central collisions
  ATLAS new muon small wheel → reduce fake trigger
  CMS muon upgrade → add GEM for p_T resolution, RPC for reducing background (better time resolution), extend coverage to η>2.4
- 2021-2023: LHC run-3, experiments require L_{int}>10 nb^{-1} for Pb-Pb (compared to L_{int} ~ 1 nb^{-1} for run-2)
  Possibility of accelerating lighter ions under discussion
- 2026-2029: LHC run-4

Prospects for quarkonium studies

- Factor ~10 gain in run-3 surely beneficial for ψ(2S), ϒ(2S), ϒ(3S) studies and for all non-R_{AA} analyses (see next slide)
  → Possibility of investigating (very) peripheral collisions

- Possibility of accelerating lighter ions
  - Once considered very useful in the frame of detecting "threshold" effects and/or scaling behaviors for various observables
  - …but we have now extensively seen that threshold effects are not really detectable
  - Asymmetric collisions (see Cu+Au @RHIC) are in principle interesting, but admittedly it is not easy to extract physics out of it

Prospects for quarkonia studies

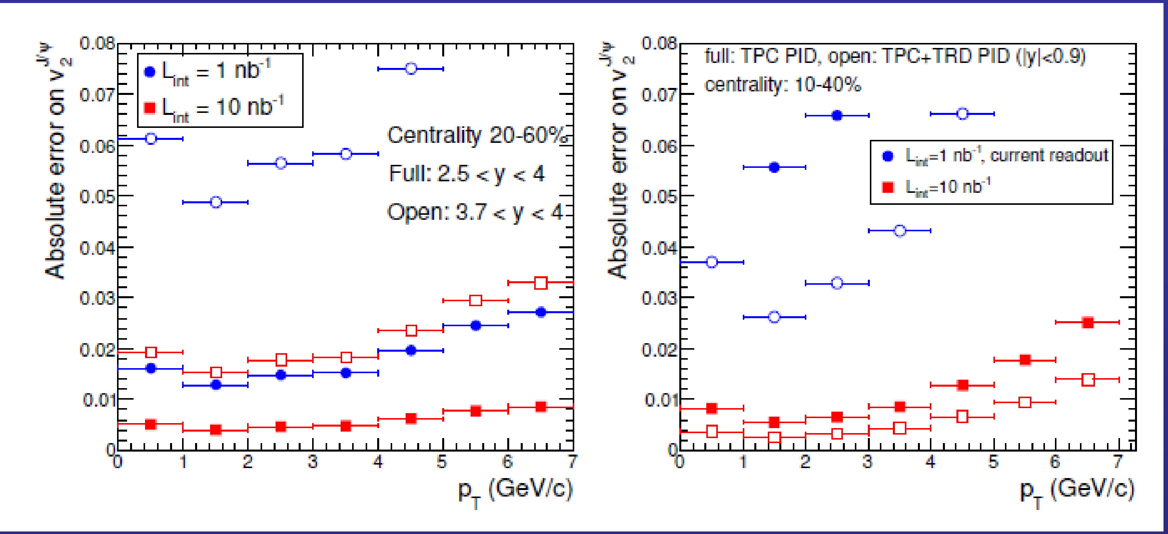
- CMS prospects for run-3 (CMS-PAS-FTR-13-025)

$\sqrt{s_{NN}}$	2.76 TeV	5.5 TeV						
L_{int}	150 μb^{-1}	10 nb^{-1}						
Centrality(%)	0-100	0-100	50-100	60-100	70-100	80-100	90-100	0-100
Signal	p_T-inclusive raw yields							($p_T > 30$ GeV)
$B \to J/\psi$	2 250	300 000	12 400	6 150	2 350	810	215	5500
Prompt J/ψ	9 000	1 200 000	49 500	24 500	9 420	3 240	860	4400
$\psi(2S)$	200	26 600	1 100	547	210	70	20	100
$\Upsilon(1S)$	2 000	266 000	11 000	5 460	2 090	720	191	267
$\Upsilon(2S)$	300	40 000	1650	820	314	108	29	80
$\Upsilon(3S)$	50	6 700	275	137	52	18	5	20

- ALICE prospects for run-3 (Upgrade Letter of Intent)

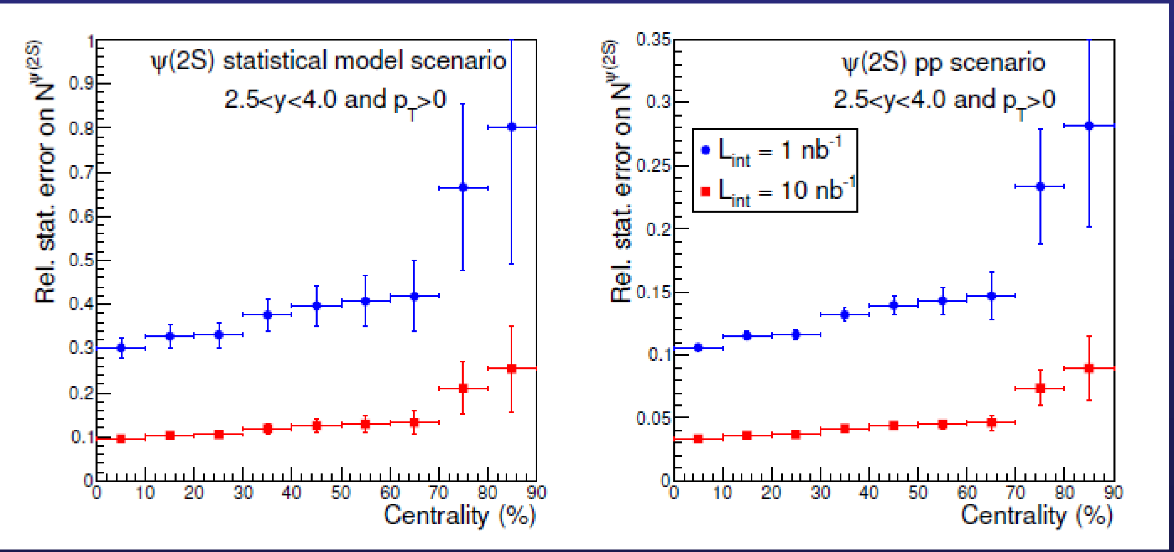
Observable	Approved		Upgrade	
	p_T^{Amin} (GeV/c)	statistical uncertainty	p_T^{Umin} (GeV/c)	statistical uncertainty
Charmonia				
J/ψ R_{AA} (forward rapidity)	0	1 % at 1 GeV/c	0	0.3 % at 1 GeV/c
J/ψ R_{AA} (mid-rapidity)	0	5 % at 1 GeV/c	0	0.5 % at 1 GeV/c
J/ψ elliptic flow ($v_2 = 0.1$)	0	15 % at 2 GeV/c	0	5 % at 2 GeV/c
$\psi(2S)$ yield	0	30 %	0	10 %

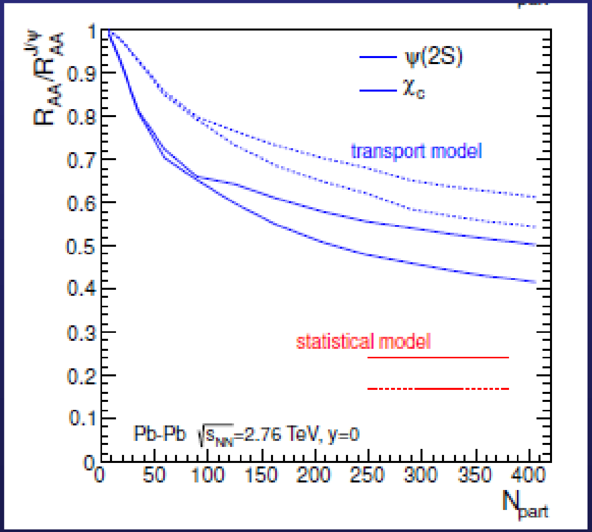
ALICE projected highlights



v_2 measurement for J/ψ at mid- and forward-y

ψ(2S) precision measurement only in run-3

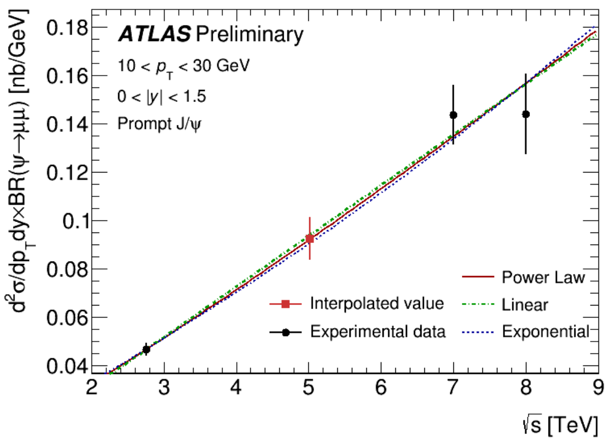


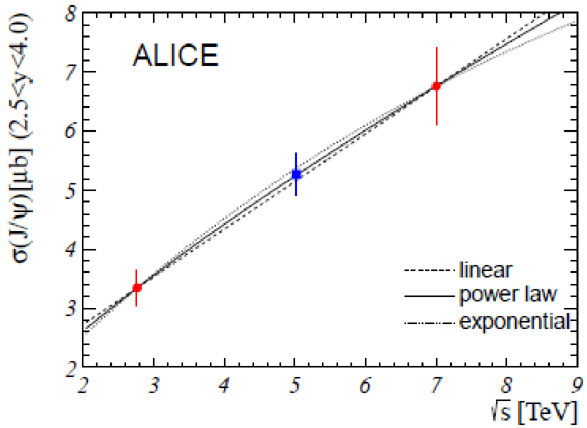


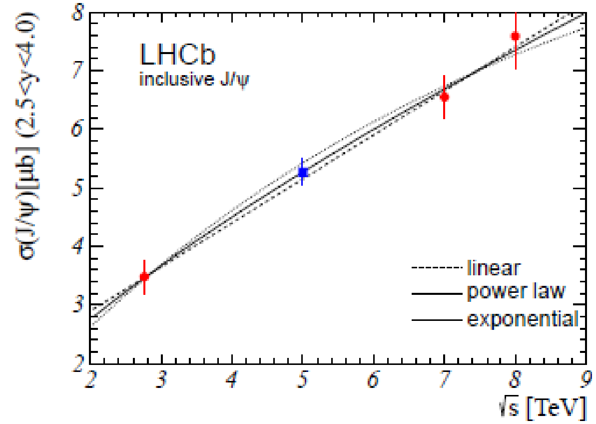
Building a reference σ_{pp} → interpolation

- Simple empirical approach adopted by ALICE, ATLAS and LHCb

CERN-LHCb-CONF-2013-013; ALICE-PUBLIC-2013-002.







Example: ALICE result

$$\sigma_{\rm incl} = 5.28 \pm 0.40_{\rm exp} \pm 0.10_{\rm inter} \pm 0.05_{\rm theo}\ \mu{\rm b} = 5.28 \pm 0.42\ \mu{\rm b}\ .$$

inter: spread of interp. with empirical functions
theo: spread of interp. with theory estimates

- $\psi(2S)$ → interpolation difficult, small statistics at $\sqrt{s}$=2.76 TeV
- Ratio $\psi(2S)$ / J/ψ → ALICE uses $\sqrt{s}$=7 TeV pp values (weak $\sqrt{s}$-dependence)

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

ALICE estimate (conservative)
→ 8% syst. unc. due to different $\sqrt{s}$
(using CDF/ALICE/LHCb results)

J/ψ elliptic flow: analysis technique

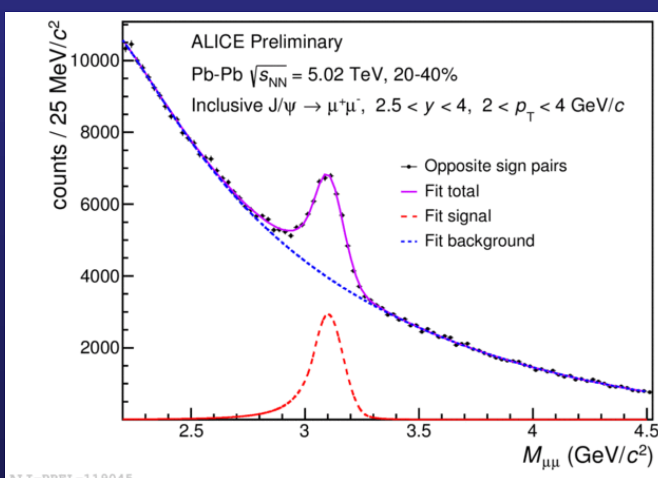
$J/\psi\ v_2 = \langle\cos 2(\phi_{\mu\mu} - \Psi_{EP})\rangle$ is computed using the Event Plane from
- SPD ($\Delta\eta=1.1$) at fw-y
- TPC ($\Delta\eta=0$) at mid-y

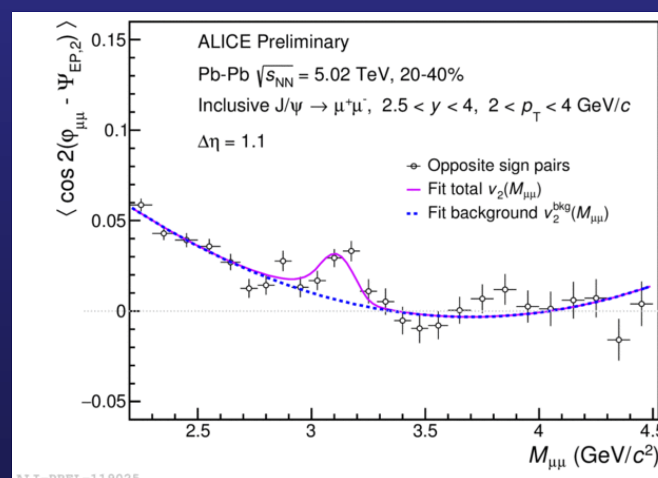
$v_2^{J/\psi}$ is obtained modeling $\langle\cos 2(\phi_{\mu\mu} - \Psi_{EP})\rangle$ vs inv. mass as

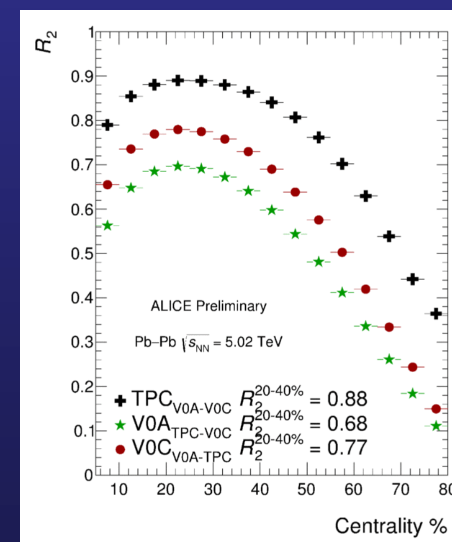
$$v_2(m_{\mu\mu}) = v_2^{J/\psi}\alpha(m_{\mu\mu}) + v_2^{bck}(1 - \alpha(m_{\mu\mu}))$$

- $\alpha(m_{\mu\mu})$ is S/S+B from inv. mass fit
- v_2^{bck} background parametrized by several functions

➡ $v_2 = v_2^{obs}/\sigma_{EP}$

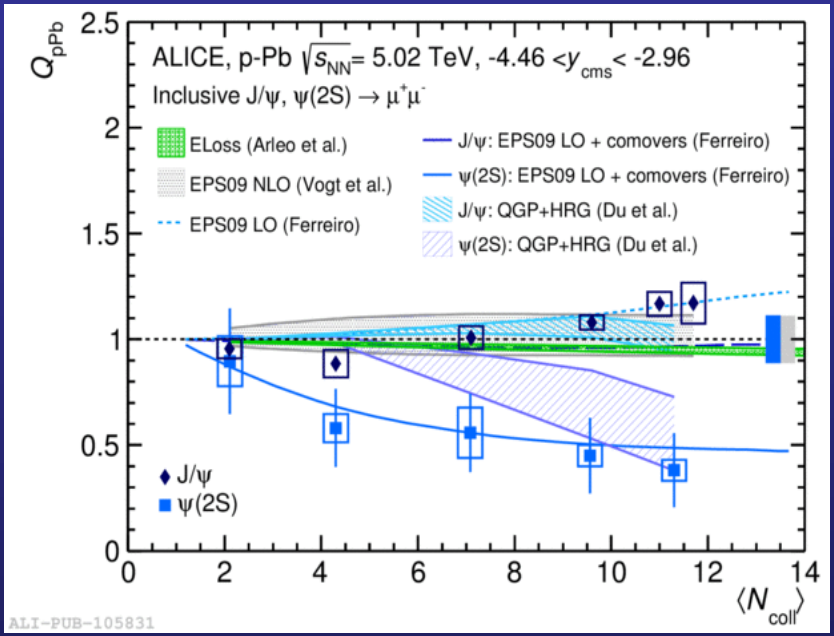


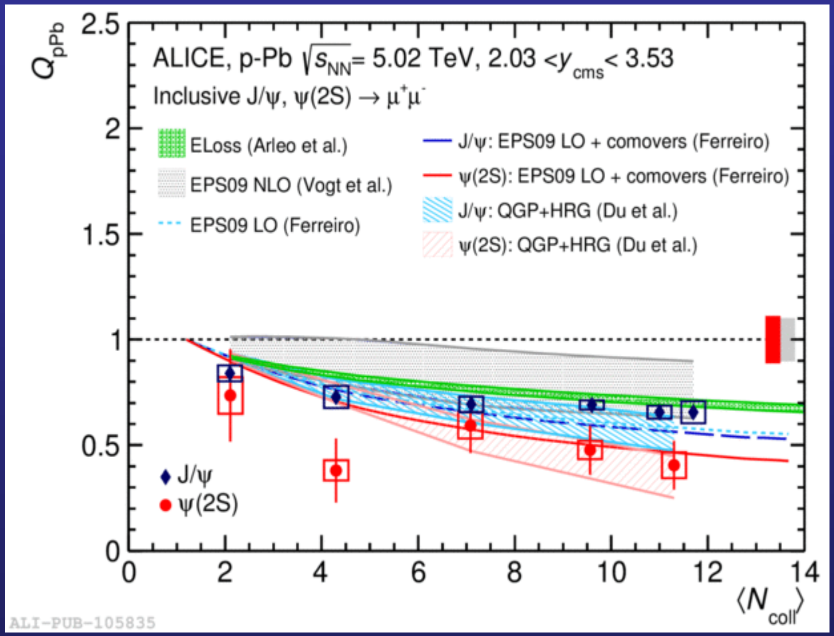




Cold nuclear matter: the ψ(2S)

- In principle should be affected by CNM in the same way as the J/ψ
- Formation times should prevent any "nuclear absorption"
- Shadowing/energy loss cancel, at least at first order

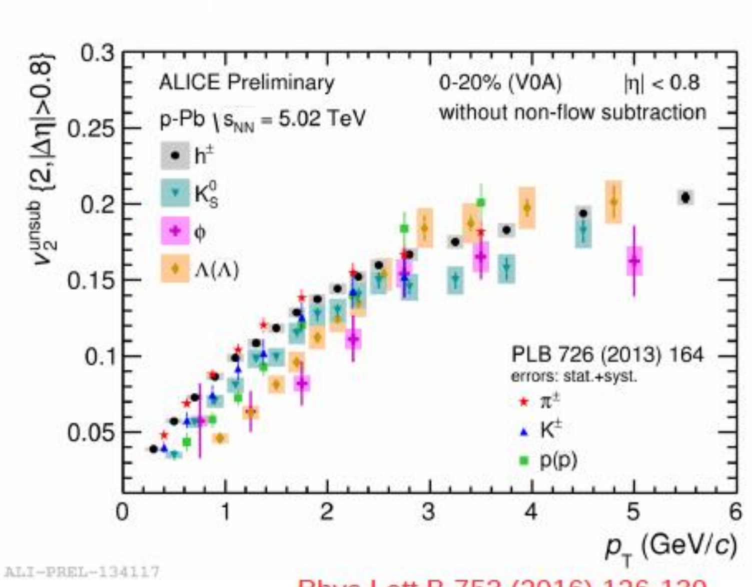




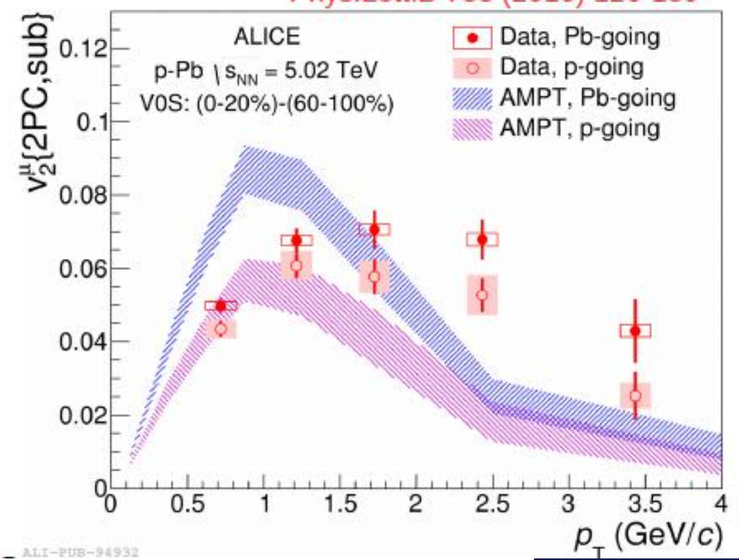
- Results show a (much) stronger ψ(2S) suppression
- Not a "real" surprise, already seen by PHENIX even if with large uncertainties
- Very strong rapidity dependence, compatible with an effect related with the hadronic activity (not so strange, seen the weak binding)

Collectivity in p-Pb

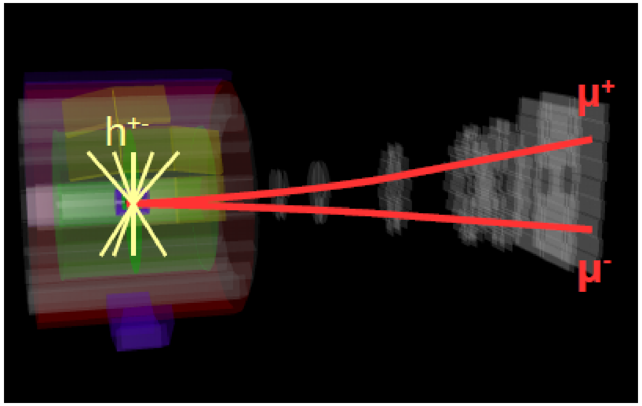
- v_2>0 in two- and multi-particle correlations, clear signs of collectivity
- Mass ordering in $v_2(p_T)$
- Forward/backward muons v_2>0 even at high p_T dominated by heavy-flavour decays



Phys.Lett.B 753 (2016) 126-139



Measurement of J/ψ v_2



- Azimuthal correlations between **forward/backward J/ψ** and **mid-rapidity charged particles**
- Correlations expressed as **associated SPD-tracklet yields per dimuon(J/ψ) trigger**

$$Y^{ij}(M_{\mu\mu}, p_{\rm T}^{\mu\mu}, \Delta\varphi, \Delta\eta) = \frac{1}{N_{\rm trig}^{ij}(M_{\mu\mu}, p_{\rm T}^{\mu\mu})} \frac{SE^{ij}(M_{\mu\mu}, p_{\rm T}^{\mu\mu}, \Delta\varphi, \Delta\eta)}{ME^{ij}(M_{\mu\mu}, p_{\rm T}^{\mu\mu}, \Delta\varphi, \Delta\eta)}$$

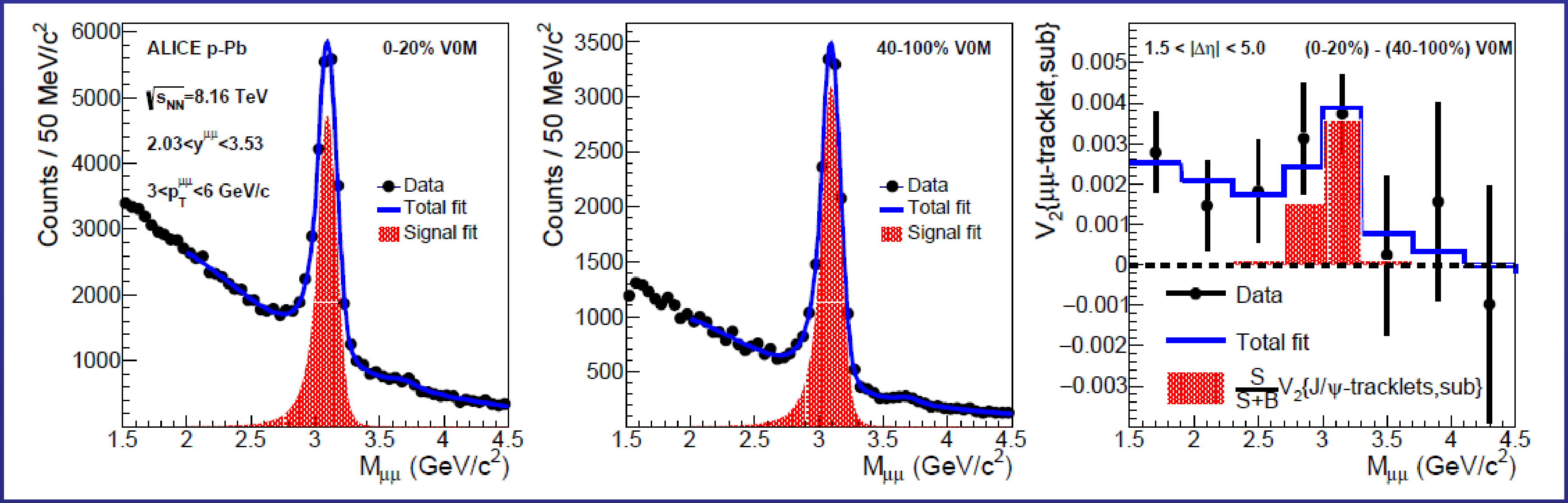
i – event-multiplicity class (V0M)
j – z vertex bin
N_{trig} – # of trigger dimuons

SE – # of associated tracklets from same event
ME – mixed event

- Yields projected on Δφ in **1.5<|Δη|<5.0**
- Yields per J/ψ trigger obtained from fit of yields vs $M_{\mu\mu}$

$$\frac{S}{S+B} Y_{J/\psi} + \frac{B}{S+B} Y_B(M_{\mu\mu})$$

S/B – signal/background from $M_{\mu\mu}$ fit
Y_B – background v_2 (2nd order polynomial)



$$\frac{S}{S+B}V_2\{\mathrm{J}/\psi - \mathrm{tracklet,sub}\} + \frac{B}{S+B}V_2^B\{\mu\mu - \mathrm{tracklet,sub}\}(M_{\mu\mu}),$$