COST THOR Working Group I & II
GDRI Meeting

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Instituto Superior Técnico, Universidade de Lisboa

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for the ALICE Collaboration

ALICE Lyon group @ IPNL

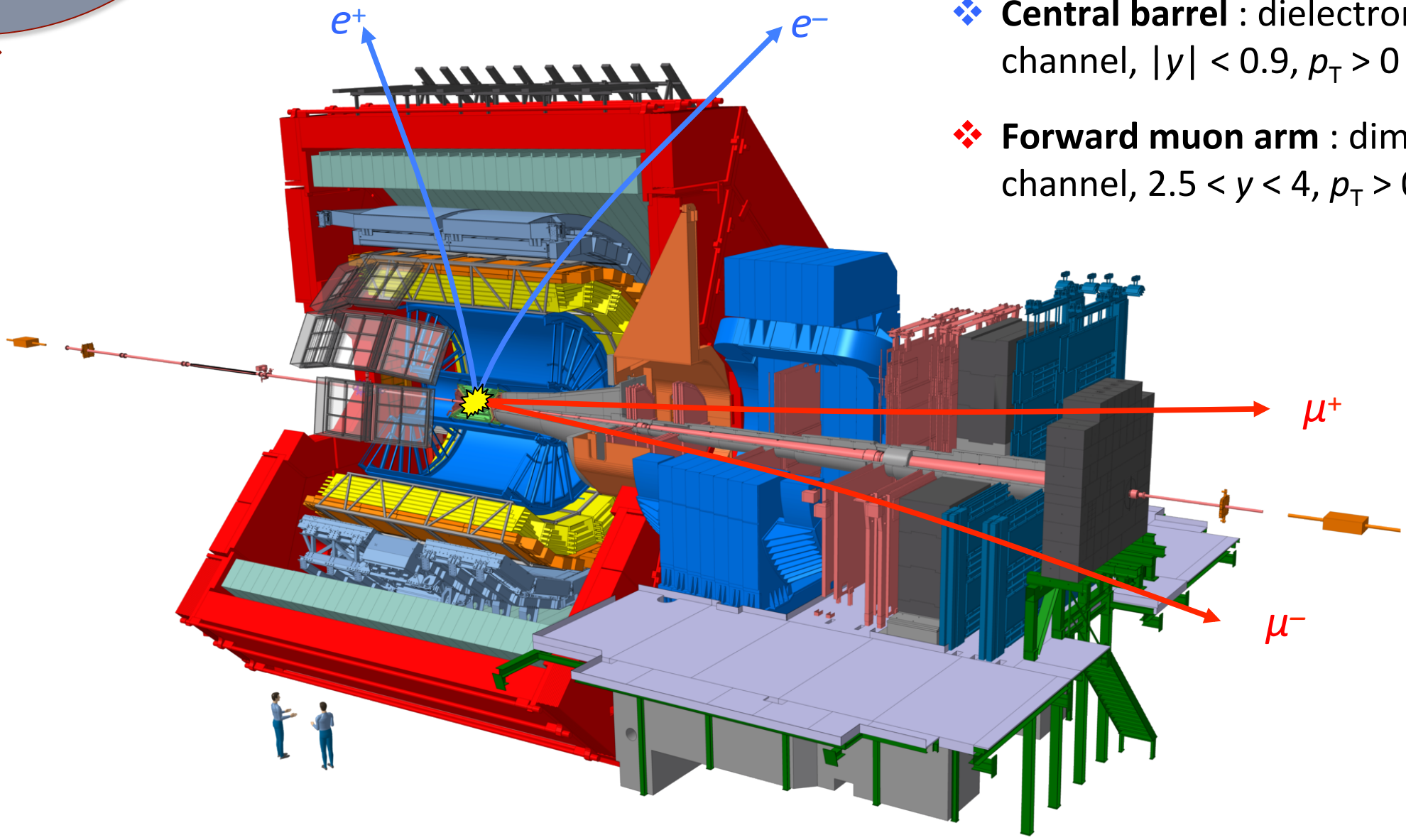
Recent ALICE Charmonium Results

Outline

- **Signal extraction of charmonium in ALICE**
- **Results in pp collisions:** test for QCD, study of multiplicity-dependent effects
- **Results in p-Pb collisions:** initial- vs final-state effects in charmonia suppression, indications for non-zero v_2
- **Results in A-A collisions:** suppression vs regeneration, large v_2 values challenging the available models

[Mainly based on the material presented at the QM18 Conference]

Measuring Charmonium in ALICE



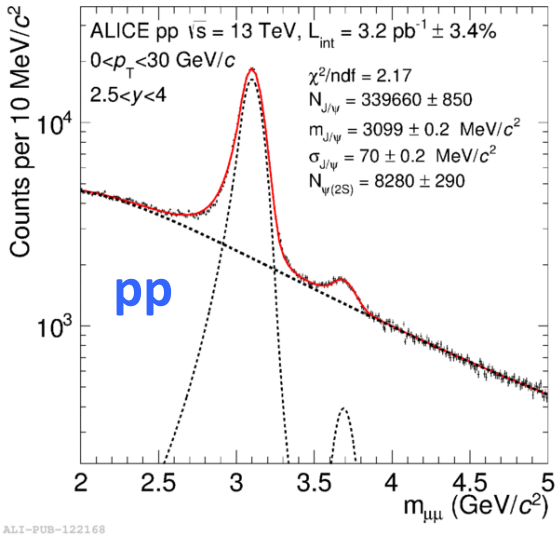
- **Central barrel** : dielectron channel, $|y| < 0.9$, $p_T > 0$
- **Forward muon arm** : dimuon channel, $2.5 < y < 4$, $p_T > 0$

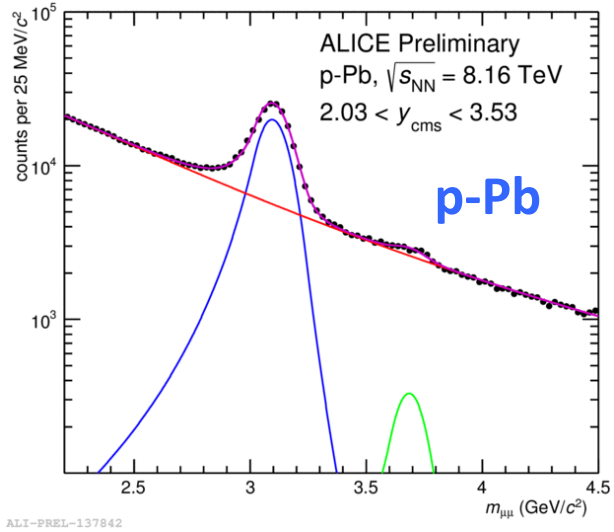
Measuring Charmonium: Forward Rapidity

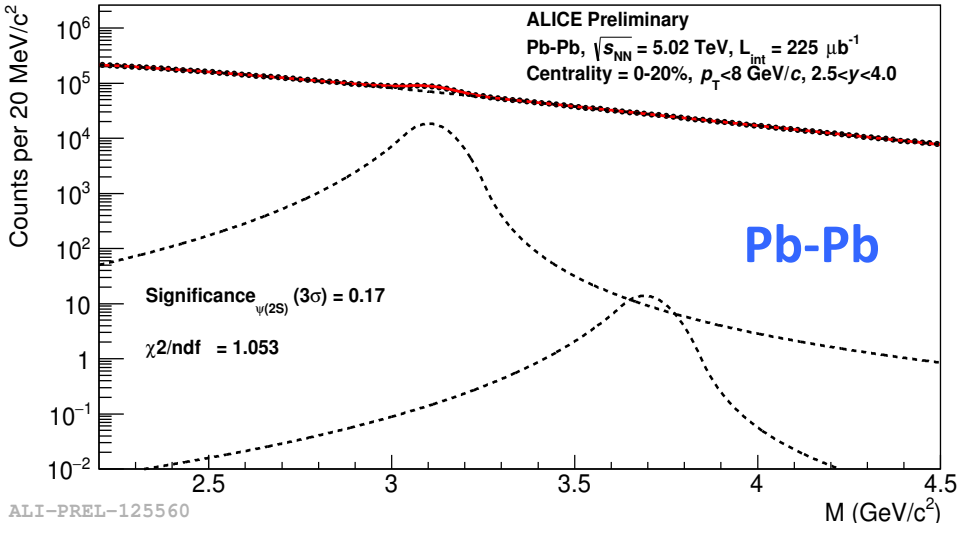
- **Muon identification** is based on the matching between the muon tracking and muon trigger information. No vertex detector: large combinatorial background in Pb-Pb collisions, no prompt/displaced separation

- **J/ψ mass resolution:** ≈ 70 MeV/c^2 from pp to Pb-Pb collisions

- **Very small S/B for the observation of ψ(2S) in Pb-Pb collisions**

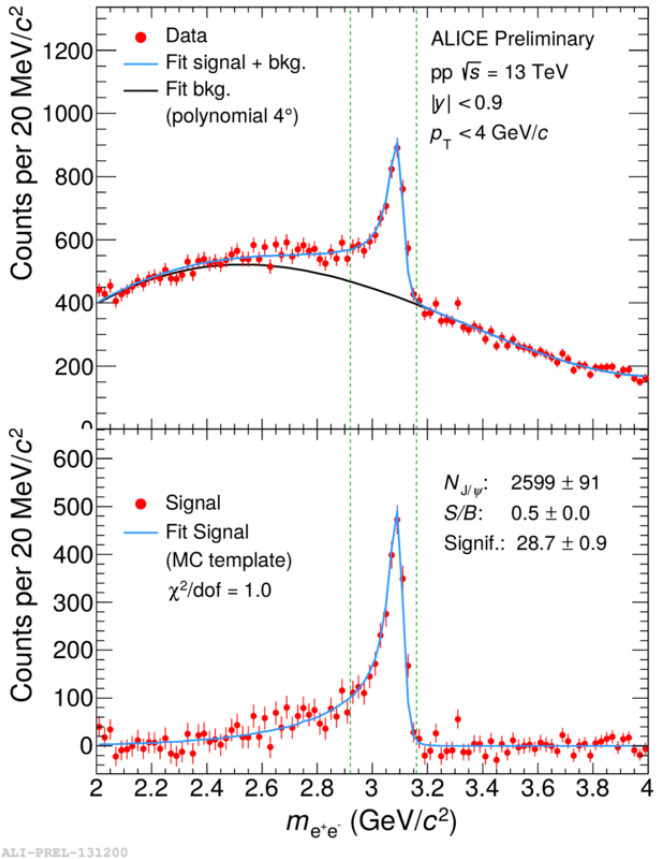


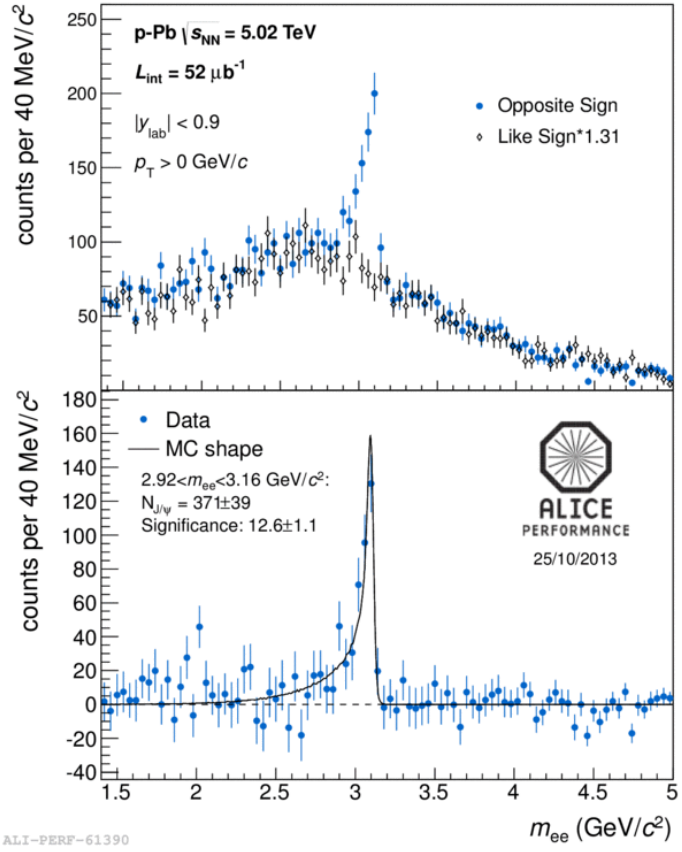


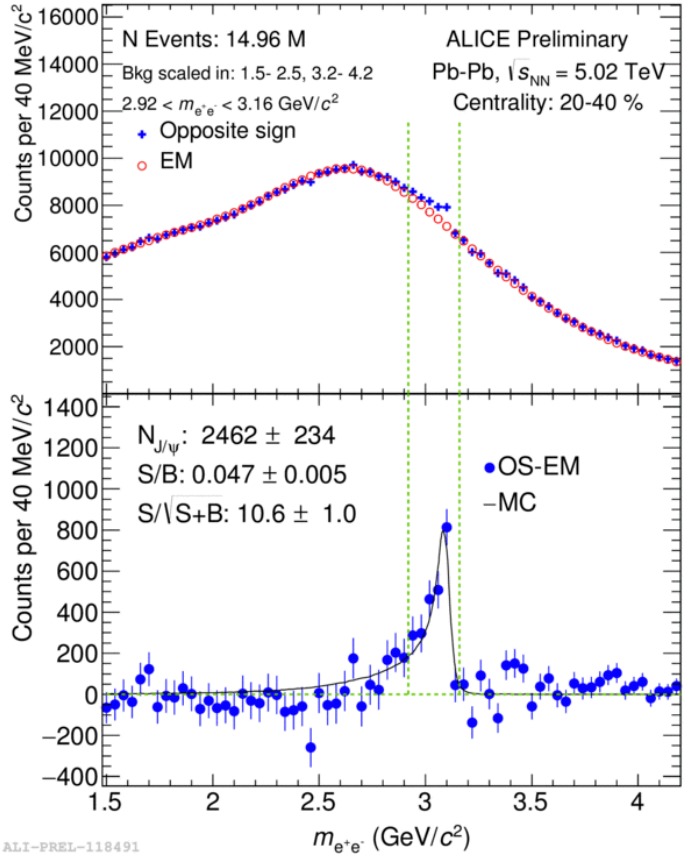


Measuring Charmonium: Mid-Rapidity

- **Electron identification** mainly based on the d*E*/d*x* measurement in the TPC
- **w.r.t. dimuon channel:** better mass resolution + possibility to separate prompt/ displaced contributions, but **worse S/B**

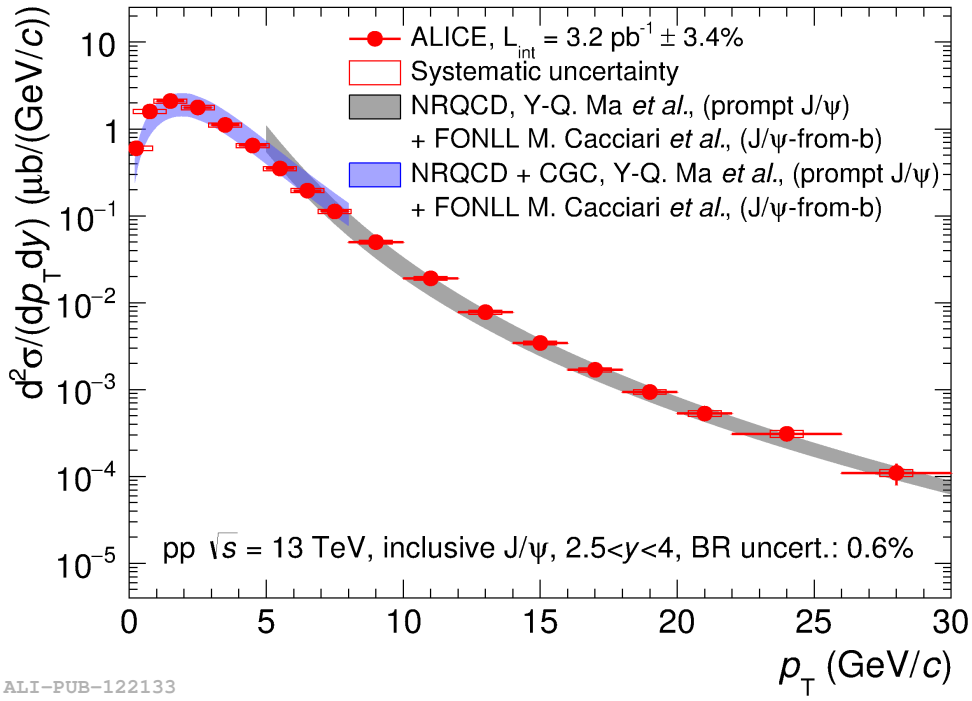






pp Collisions

J/ψ Production: p_T spectra at $\sqrt{s}$ = 13 TeV



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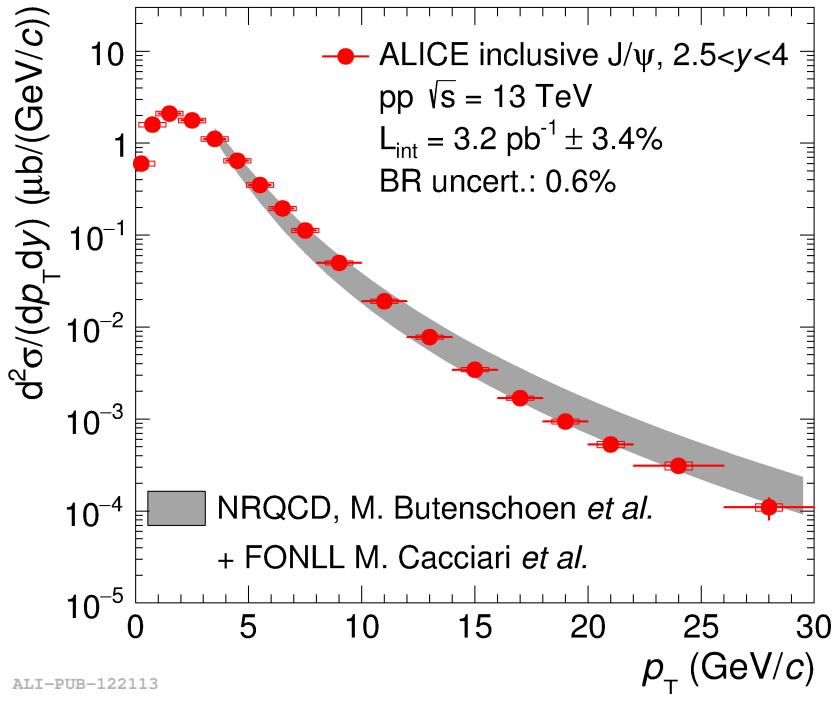
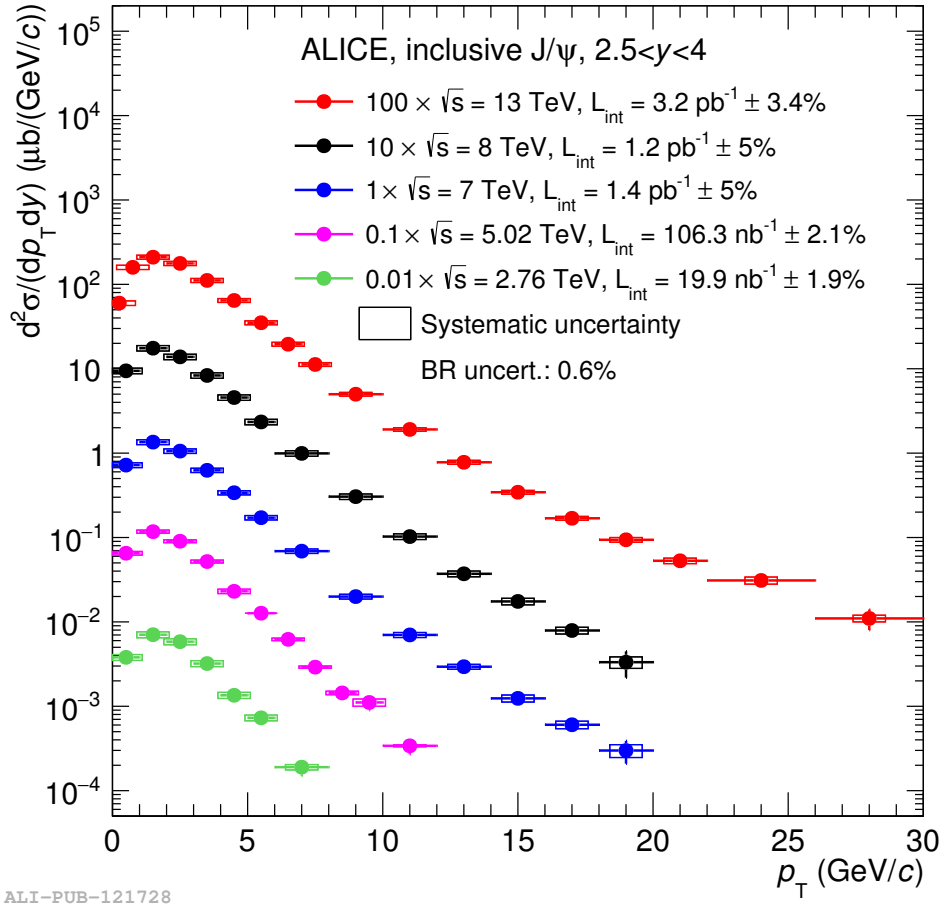


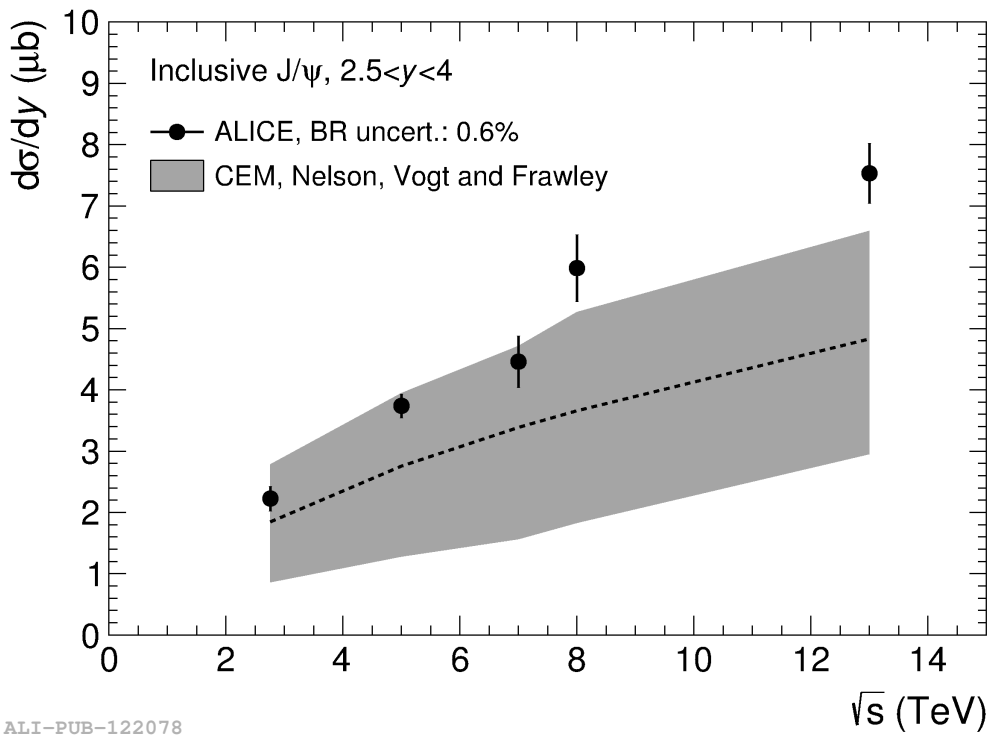
- Non-prompt J/ψ added via FONLL to the NRQCD (data correspond to inclusive J/ψ)
- **Low p_T:** NRQCD coupled to a CGC description of the proton reproduces data (b-decay contribution small)
- **High-p_T:** the two NRQCD calculations differ in the set of LDME, the p_T at which fits are performed and the considered datasets. Fair agreement with both calculations

J/ψ Production: Energy Dependence

- **Cross section measured for five different energies**, with increasing luminosity and p_T-reach
- **Spectra become harder with increasing energy**



- p_T-integrated cross section vs energy sits on the **upper side of a CEM calculation**



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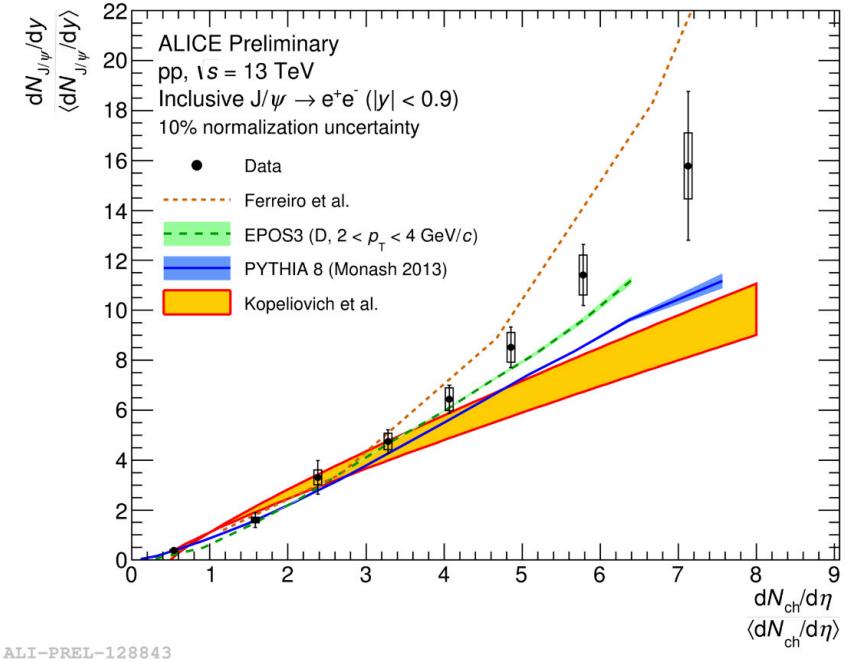
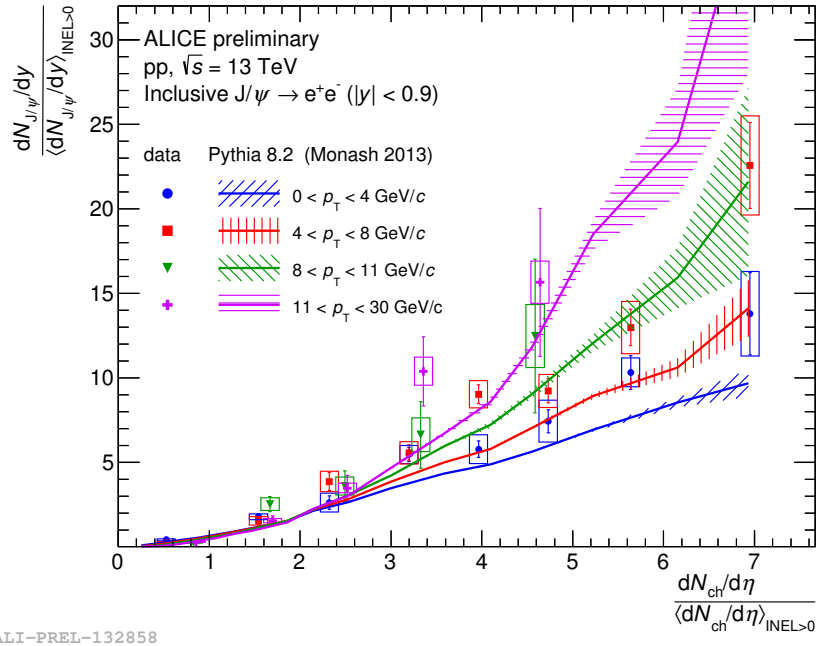
J/ψ Production: Multiplicity Dependence

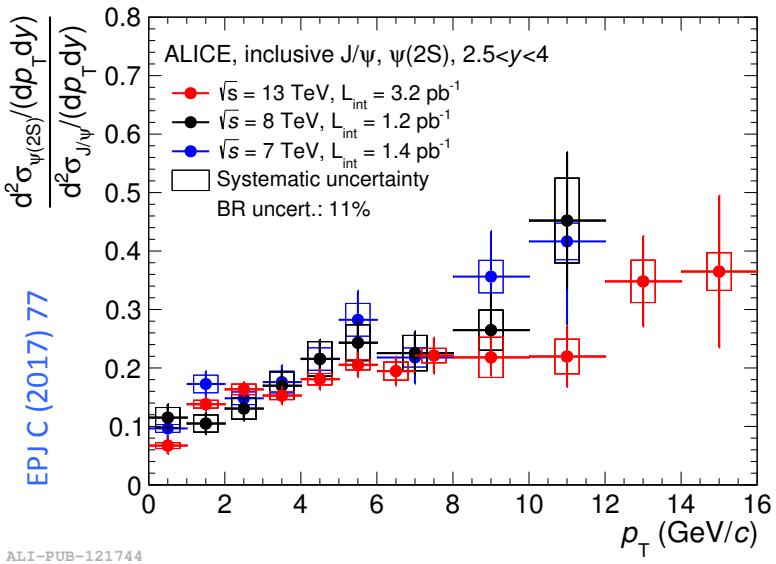


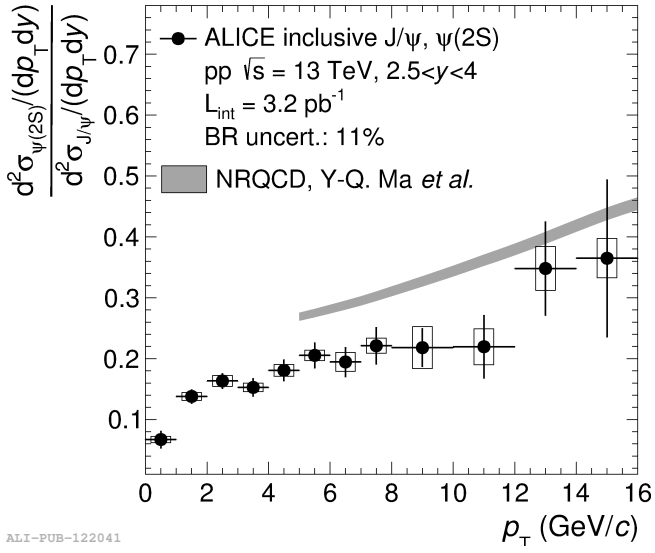


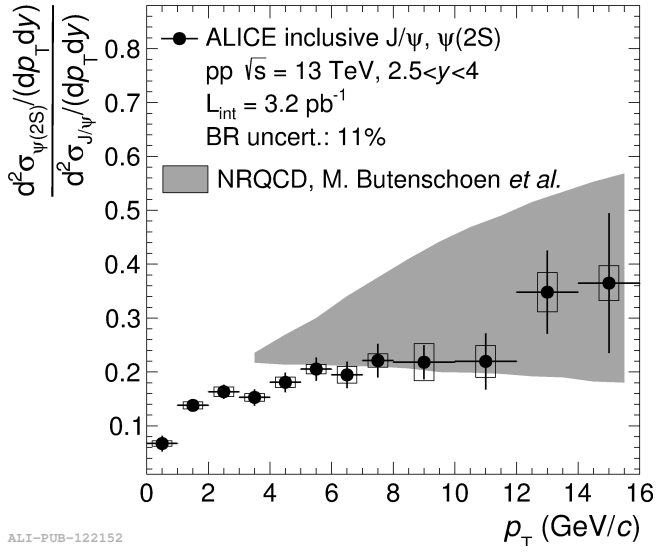
- **$dN_{ch}/d\eta/\langle dN_{ch}/d\eta\rangle$ almost doubled w.r.t. Run1, and higher p_T reach (30 GeV/c)**
- **Faster-than-linear increase of J/ψ yield with multiplicity** qualitatively described by models assuming:
  - Multi-parton effects in J/ψ production (PYTHIA8, EPOS3 with hydro)
  - Contributions of higher Fock-states (Kopeliovichet al.)
  - Soft particle saturation (Ferreiro: percolation, PYTHIA8: color reconnection)
- **Multiplicity dependence steeper at high p_T?** (reproduced by PYTHIA8 with MPI)

ψ(2S) Production

- The ψ(2S)/(J/ψ) ratio allows to **cancel some of the systematic uncertainties** both in the measurements and the theoretical predictions
- **No evidence for energy dependence of ψ(2S)/(J/ψ) ratio**
- The FONLL+NRQCD summation for the displaced charmonium production is not performed for the ψ(2S)/(J/ψ) cross section ratios (but the effect almost cancels out between numerator and denominator)
- **Tensions between data and theory where uncertainties are small enough**



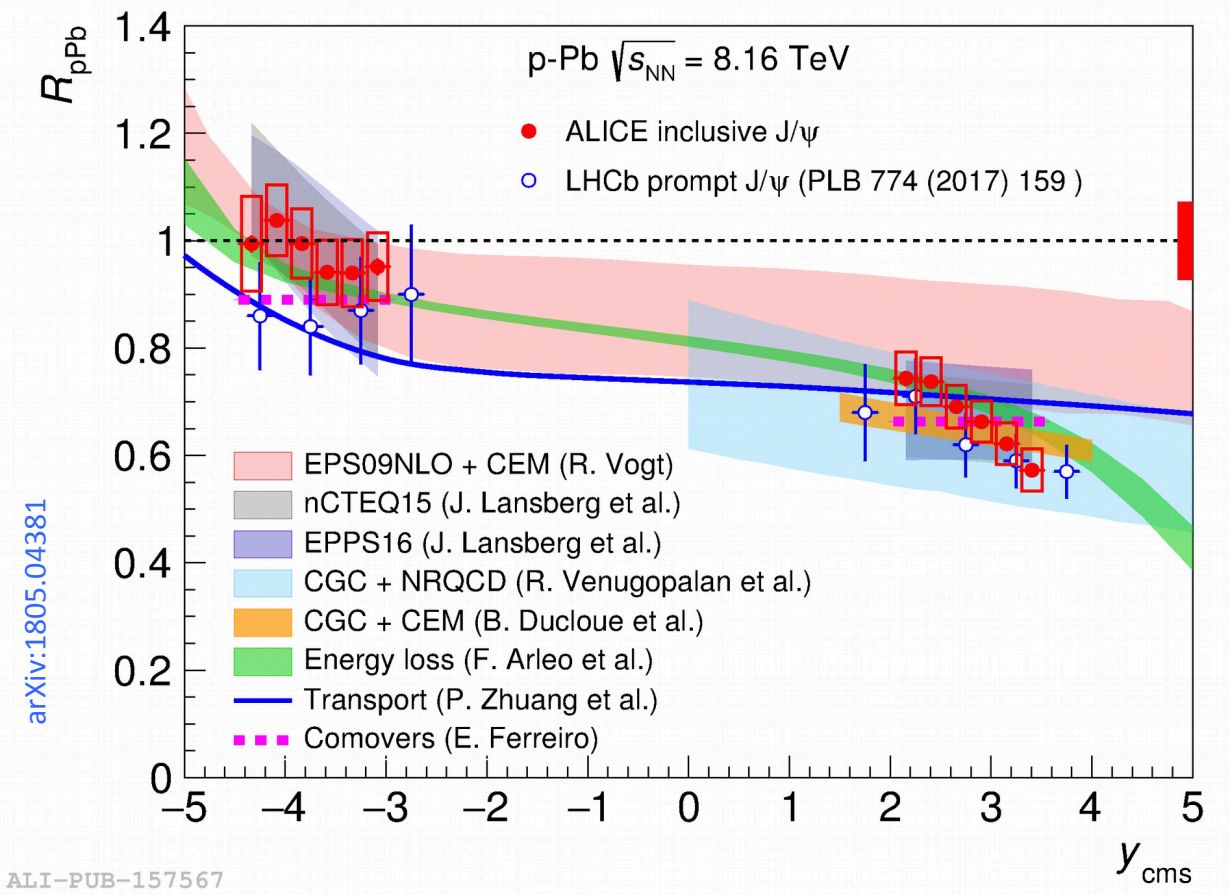




p-Pb Collisions

J/ψ R_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV

- Stronger suppression is observed at **forward rapidity**, while R_{pPb} is compatible with unity at **backward rapidity**
- Results are compatible with LHCb results (prompt J/ψ) at the same energy

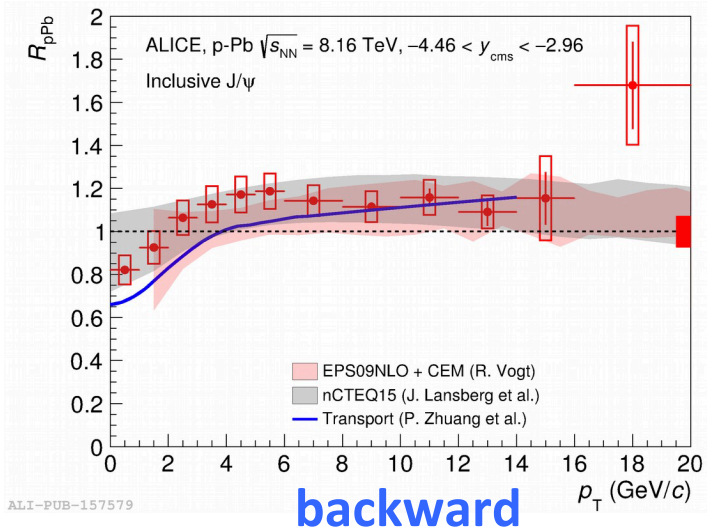


- Models based on different shadowing implementations, CGC, energy loss, transport models and comovers **fairly describe the data (as at $\sqrt{s_{NN}}$ = 5.02 TeV)**
- **Theoretical uncertainties still prevent a more quantitative comparison**

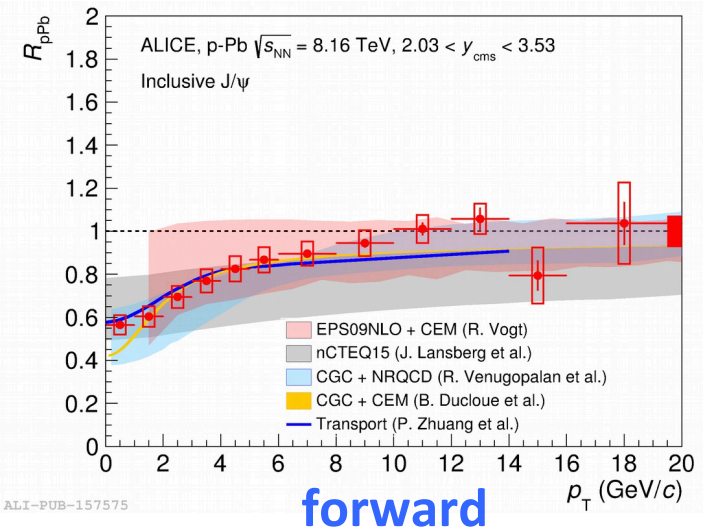
J/ψ R_{pPb} and Q_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV (Fwd & Bwd *y*)

arXiv:1805.04381

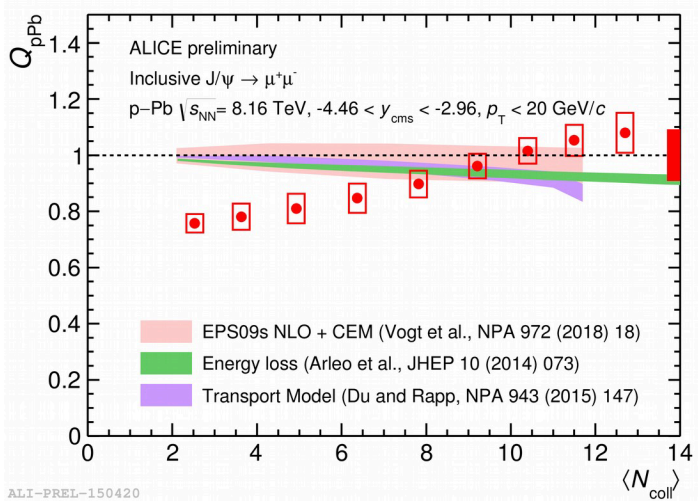
- **R_{pPb} shows a p_T dependence**, with an increase from low to high p_T at both forward and backward rapidity
- Q_{pPb} shows a reduction from peripheral to central collisions at **forward rapidity**, while trend is the opposite at **backward rapidity**

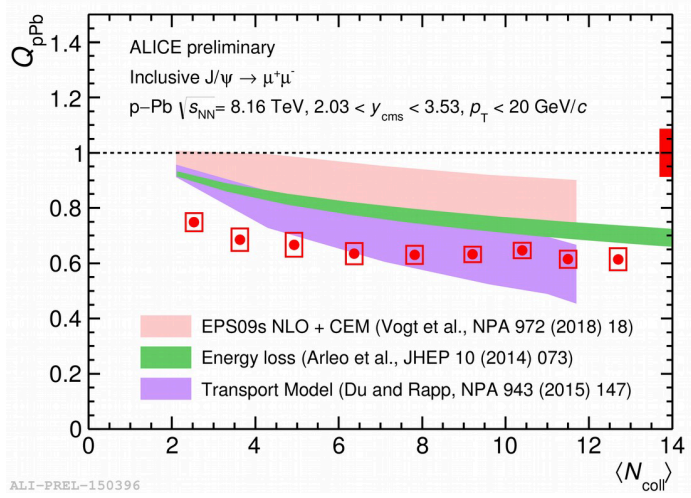


backward



forward





- **The models fail to describe simultaneously all aspects of J/ψ suppression (rapidity, p_T and centrality)**

J/ψ R_{pPb} and Q_{pPb} at $\sqrt{s_{NN}}$ = 5.02 TeV (Mid-Rapidity)

- Run2 results: larger date sample (factor 5) w.r.t. Run1 measurements
  - **R_{pPb} increases with p_T**
- **No centrality dependence of Q_{pPb} is observed**
- Theoretical models based on shadowing and/or energy loss, CGC and comovers are in **fair agreement with the data**

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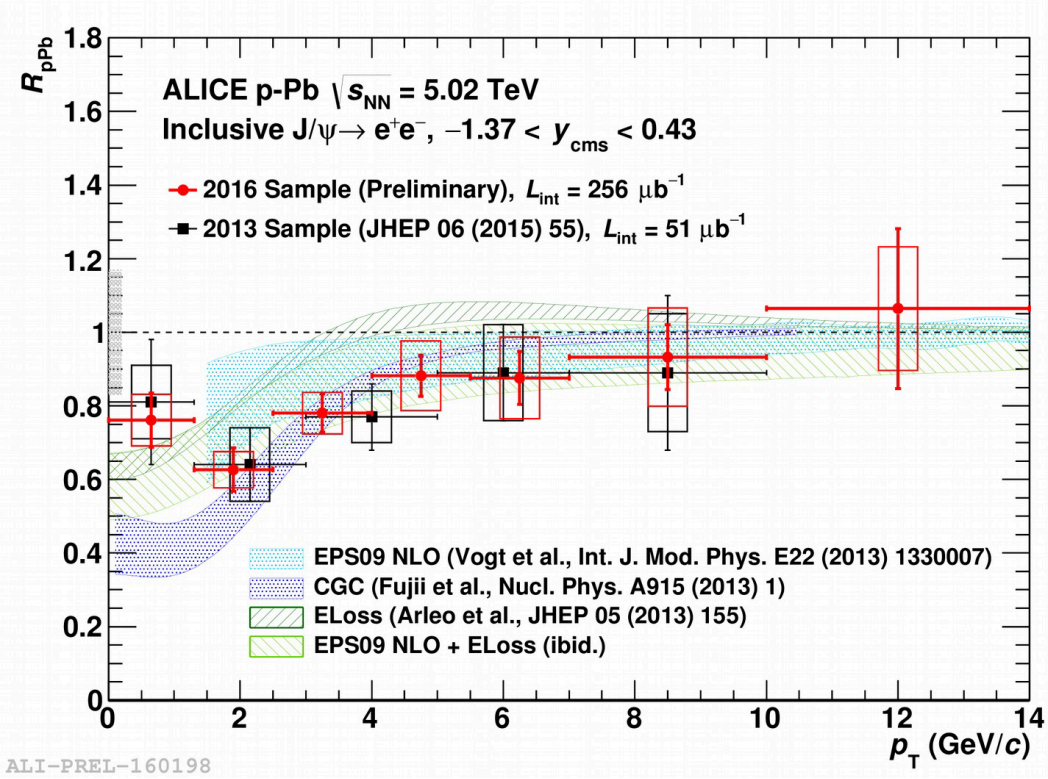
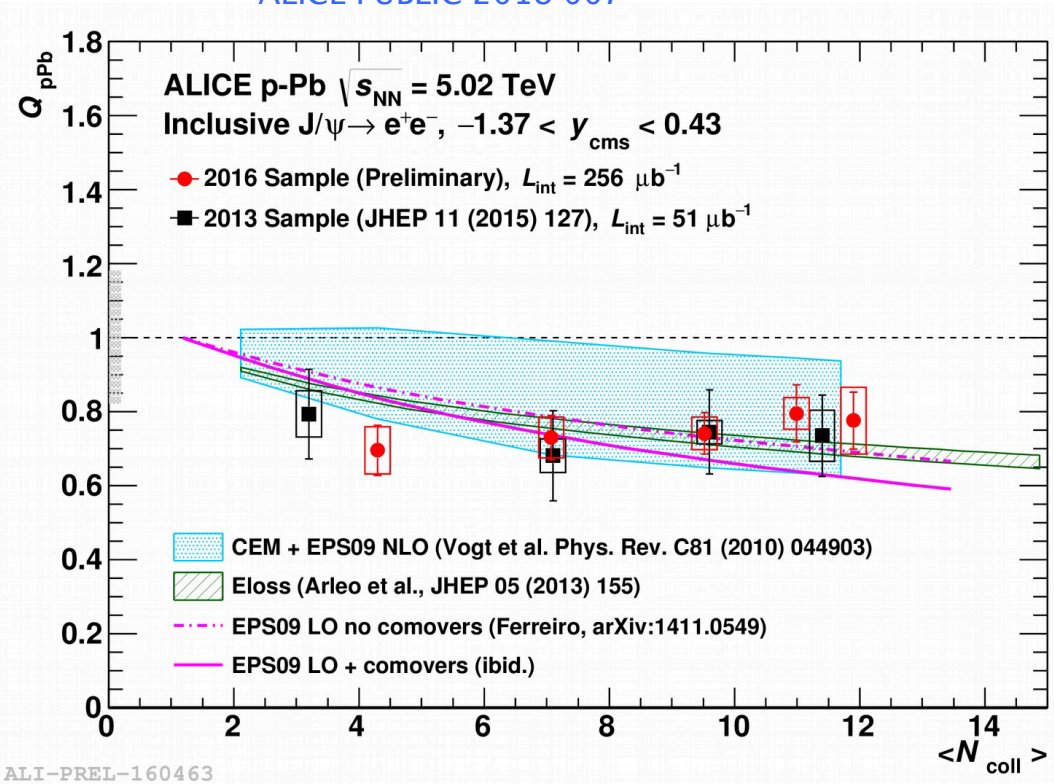
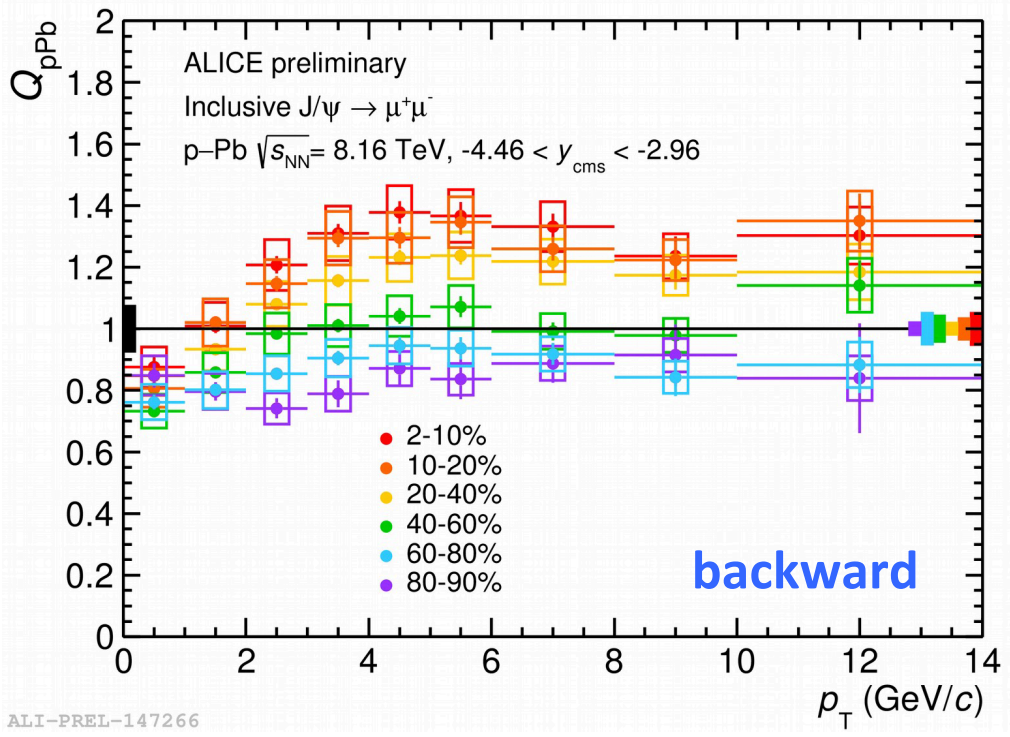
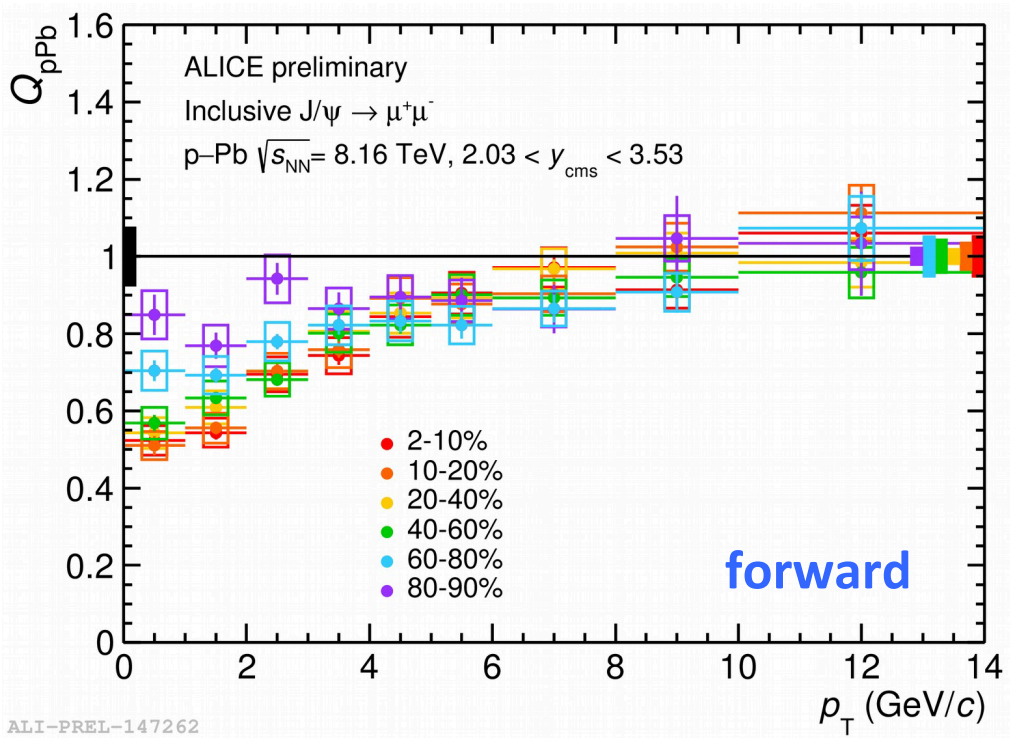




Differential study of J/ψ Q_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV (I)

- **Clear evolution of Q_{pPb} vs p_T in different centrality classes**
- **At backward rapidity**, enhancement in most central collisions for $p_T > 3$ GeV/c
- **At forward rapidity**, stronger suppression at low p_T in most central collisions. Q_{pPb} is compatible with unity for $p_T > 7$ GeV/c within uncertainties for all centralities





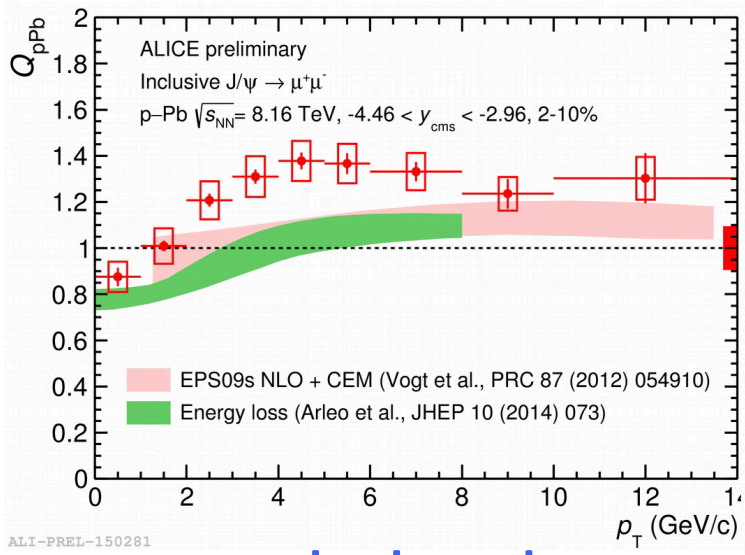
Differential study of J/ψ Q_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV (II)

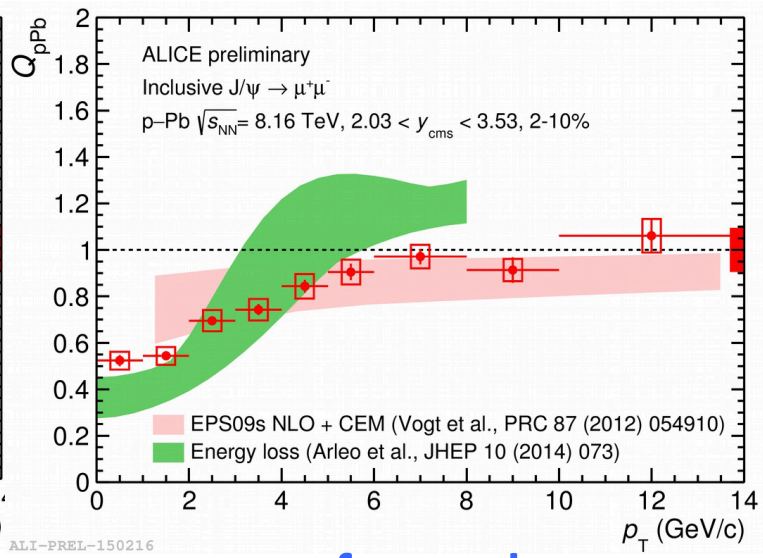
In central collisions:

- Shadowing underestimates the p_T dependence observed in data
- Energy loss predicts an increase of Q_{pPb} with a different steepness than data

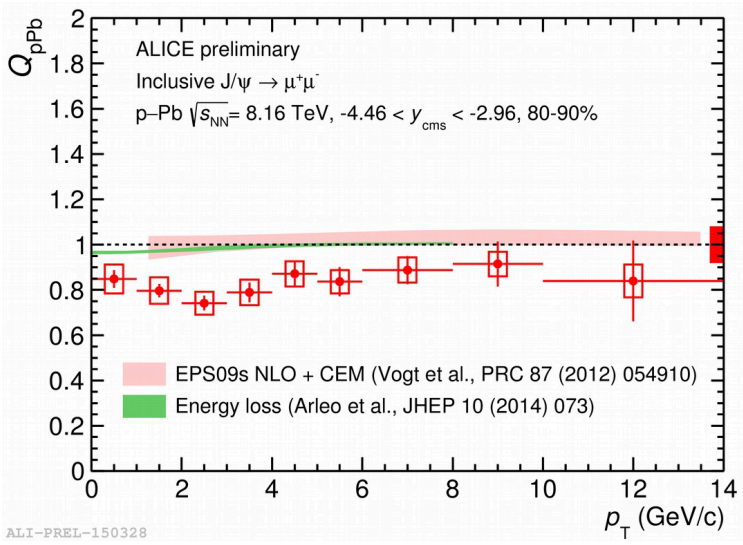
In peripheral collisions:

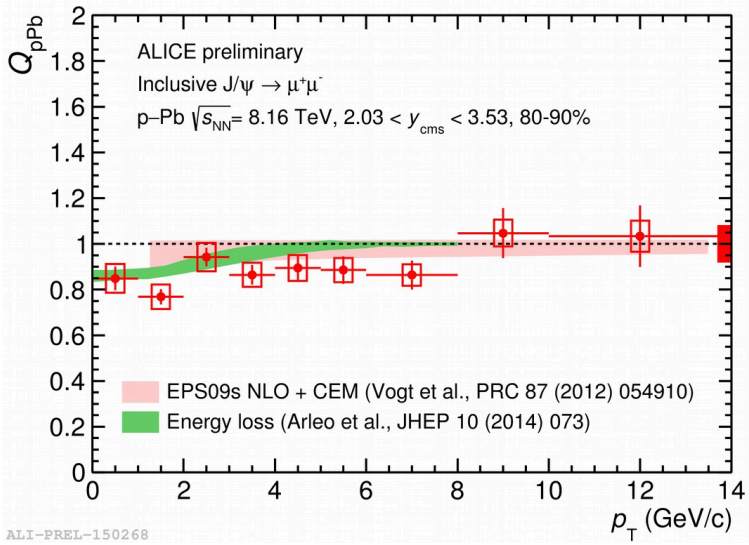
- Both models show no p_T dependence, consistent with data, within uncertainties



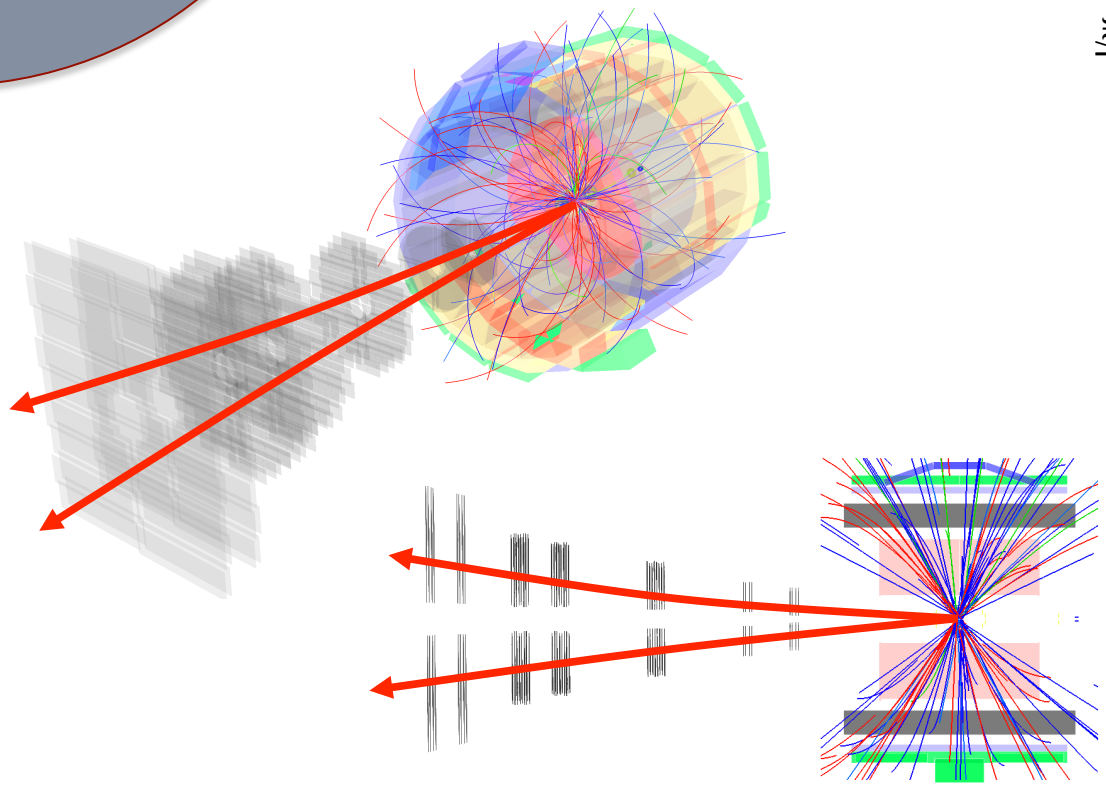


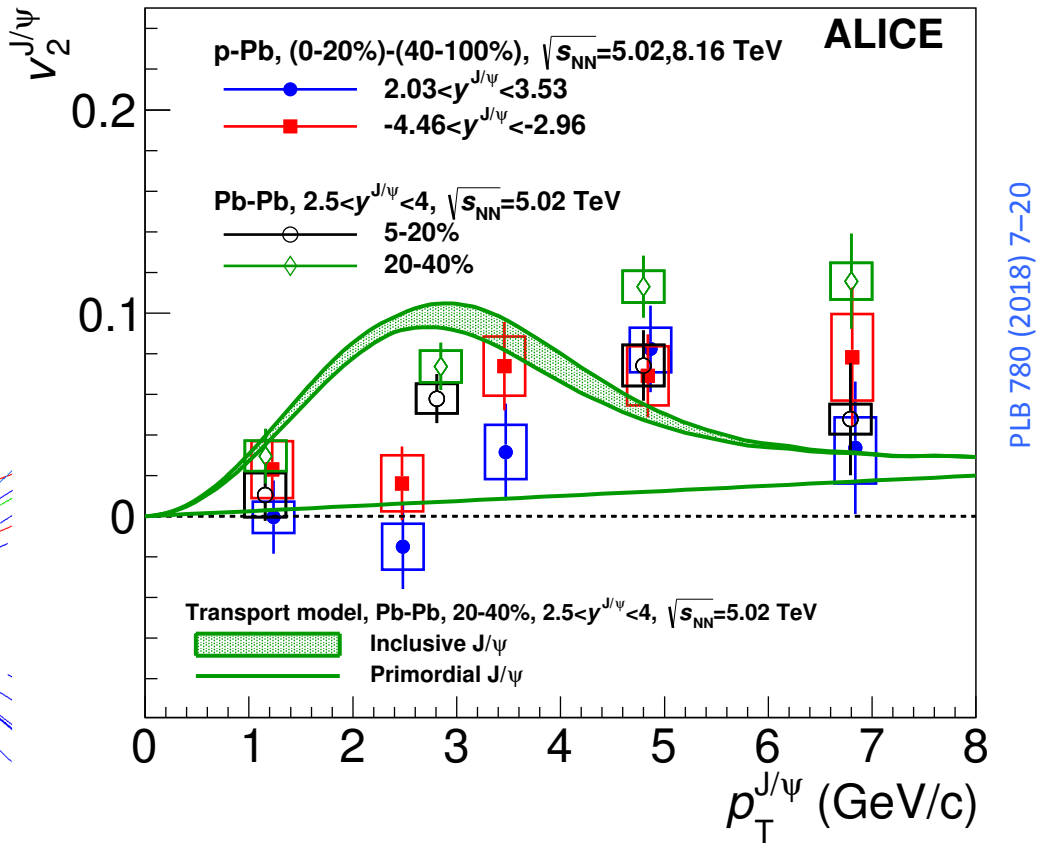
backward **forward**





J/ψ Production: Azimuthal Anisotropy



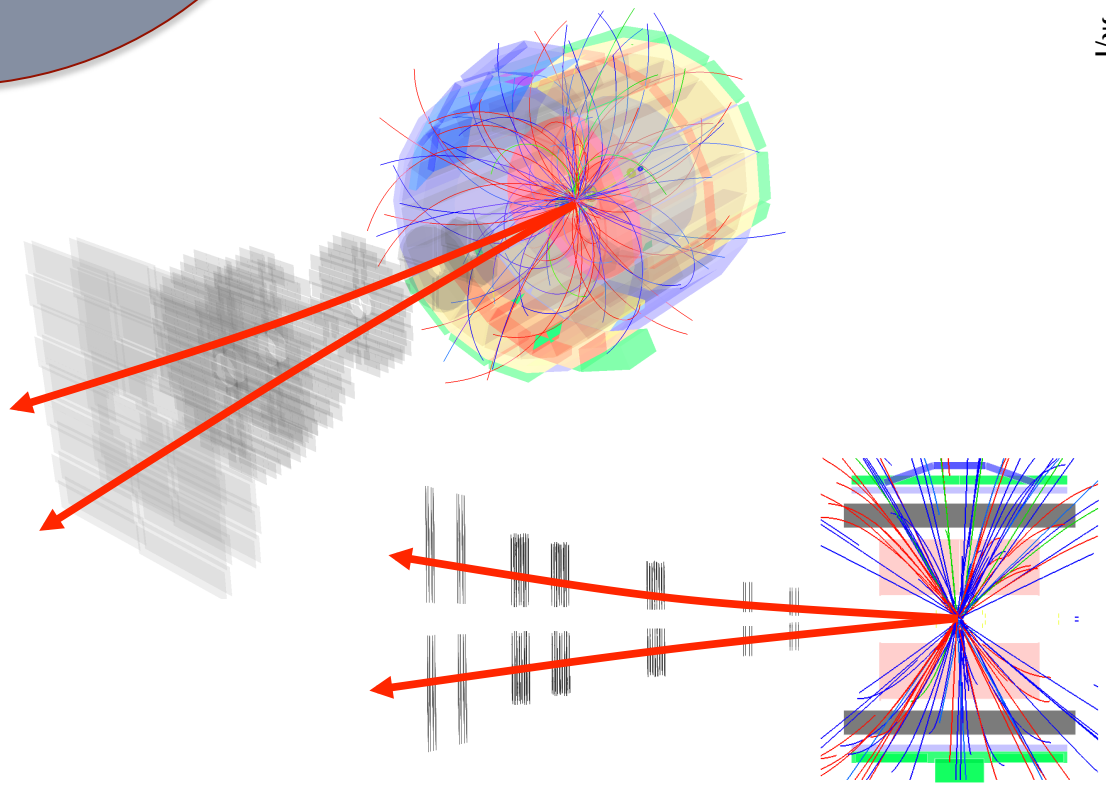


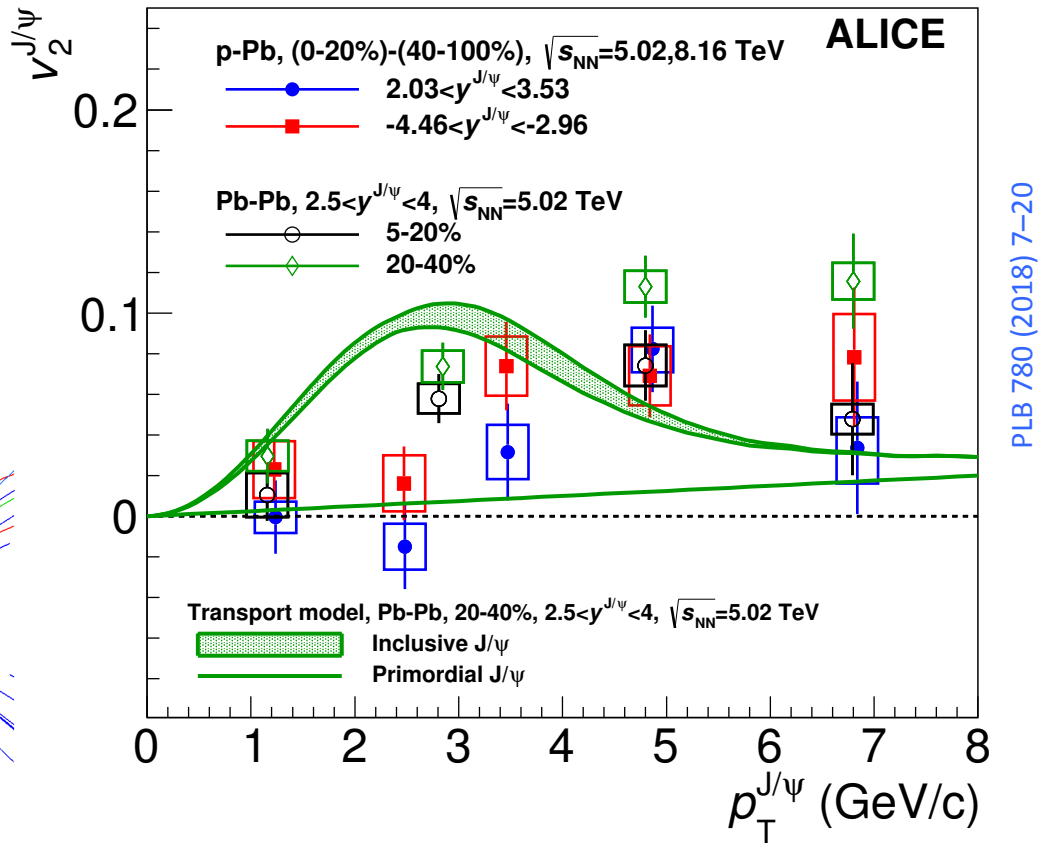
- **Correlations expressed as associated SPD-tracklet yields per dimuon (J/ψ) trigger**
  - 40-100%: clear away-side correlation (jets?)
  - 0-20%: additional enhancement at both near and away sides

Jet correlations eliminated via subtraction

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

J/ψ Production: Azimuthal Anisotropy





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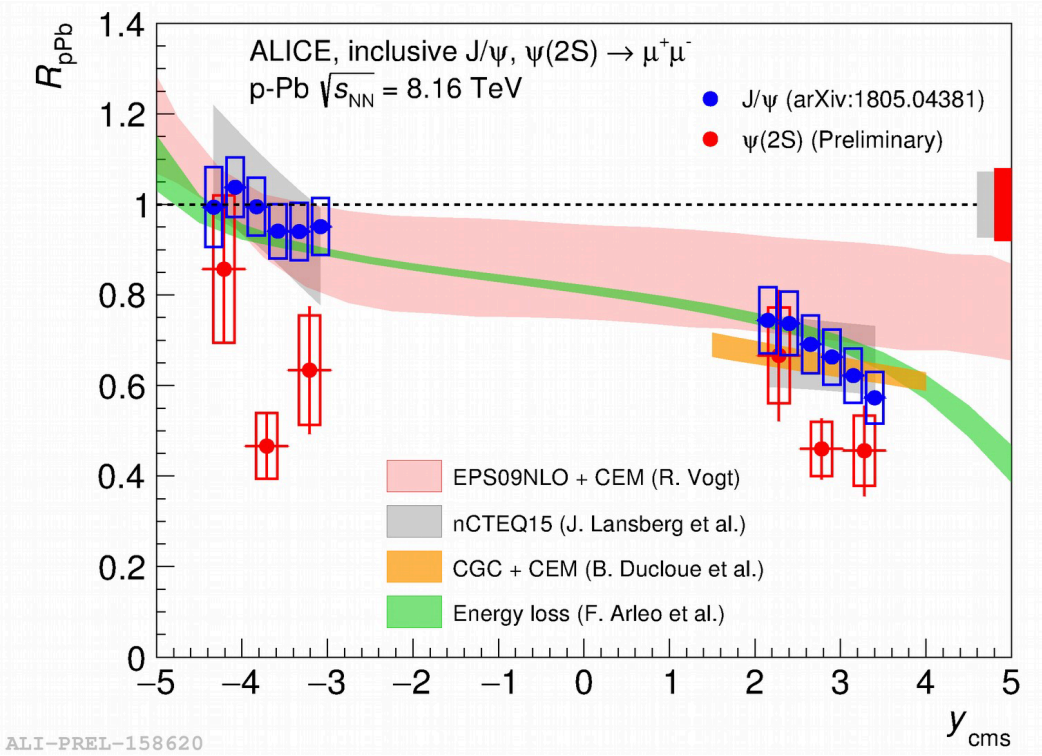
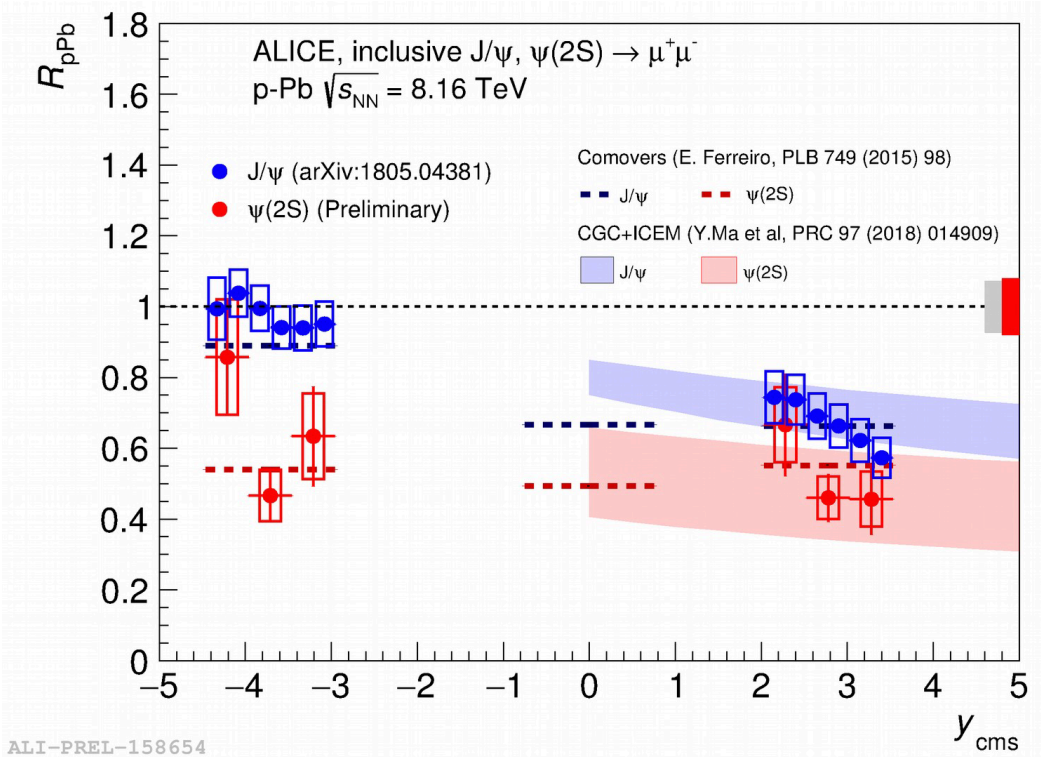
- **Observation of non-zero v_2 in p-Pb collisions for p_T > 3 GeV/c**
- Total significance (forward + backward, 5.02 + 8.16 TeV) ≈ 5σ
- Values are similar as the ones obtained in Pb-Pb collisions: common mechanism at the origin of the J/ψ v_2?

ψ(2S) R_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV

- **Stronger ψ(2S) suppression observed w.r.t. J/ψ, especially at backward rapidity,** not explained by shadowing and energy loss alone

- **Final-state effects needed:**
  - Soft color exchanges between hadronizing c-cbar and co-moving partons (Ma & Venugopalan)
  - "Classical" comover model, with break-up cross section tuned on low-energy data (Ferreiro)



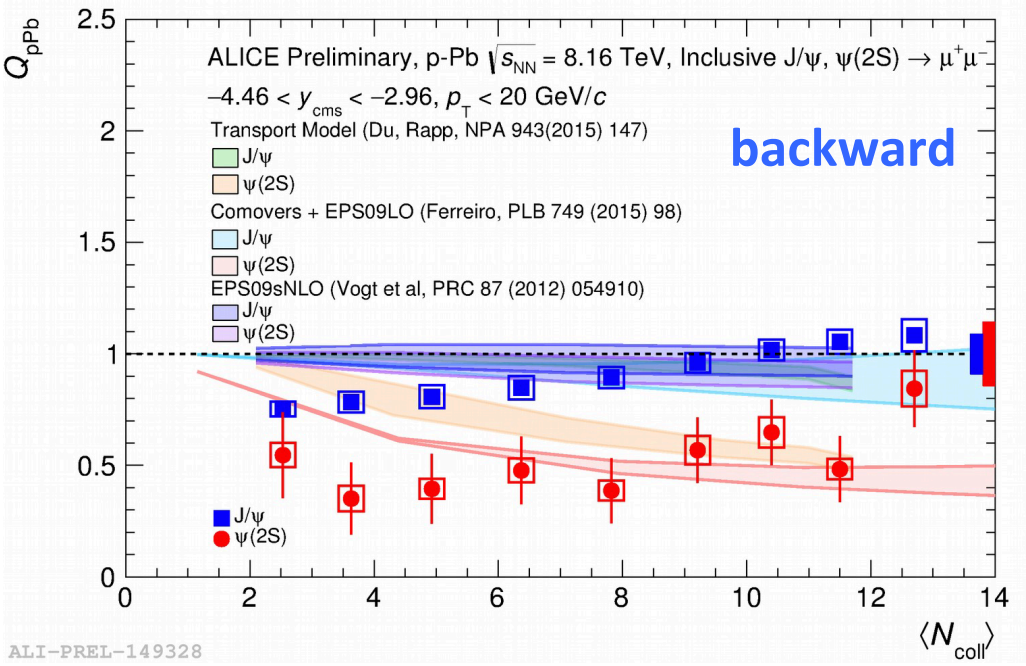


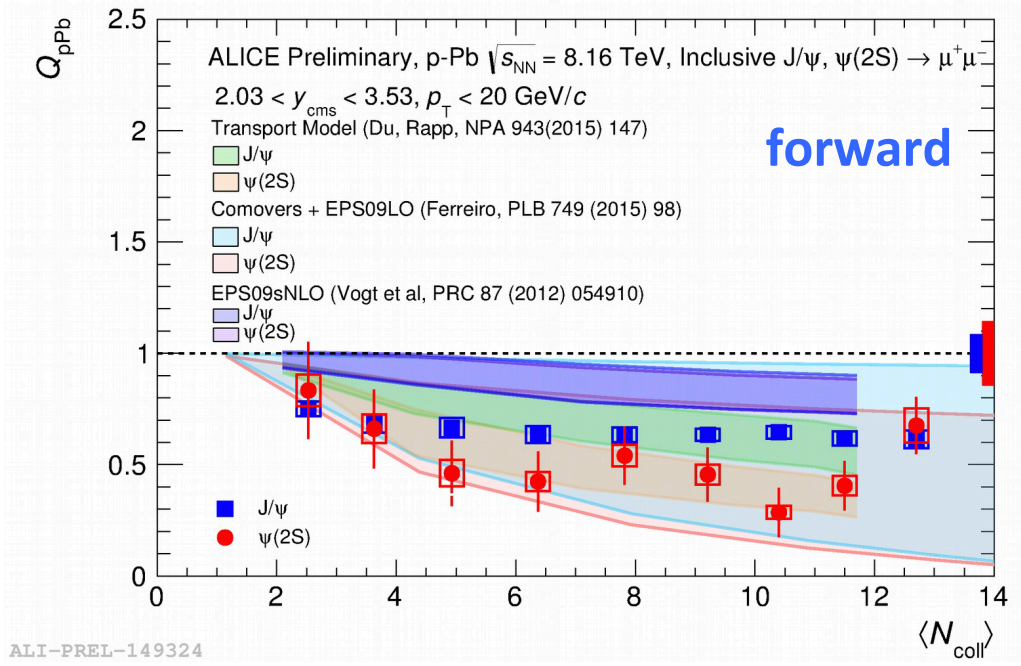
ψ(2S) Q_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV

- **Stronger ψ(2S) suppression observed w.r.t. J/ψ, especially at backward rapidity,** not explained by shadowing and energy loss alone

- **At forward rapidity** the Q_{pPb} of ψ(2S) follows the same trend as J/ψ while at backward rapidity trend is different

- **At backward rapidity**, final-state effects needed to explain the ψ(2S) behavior. Some discrepancies between data and models in peripheral events



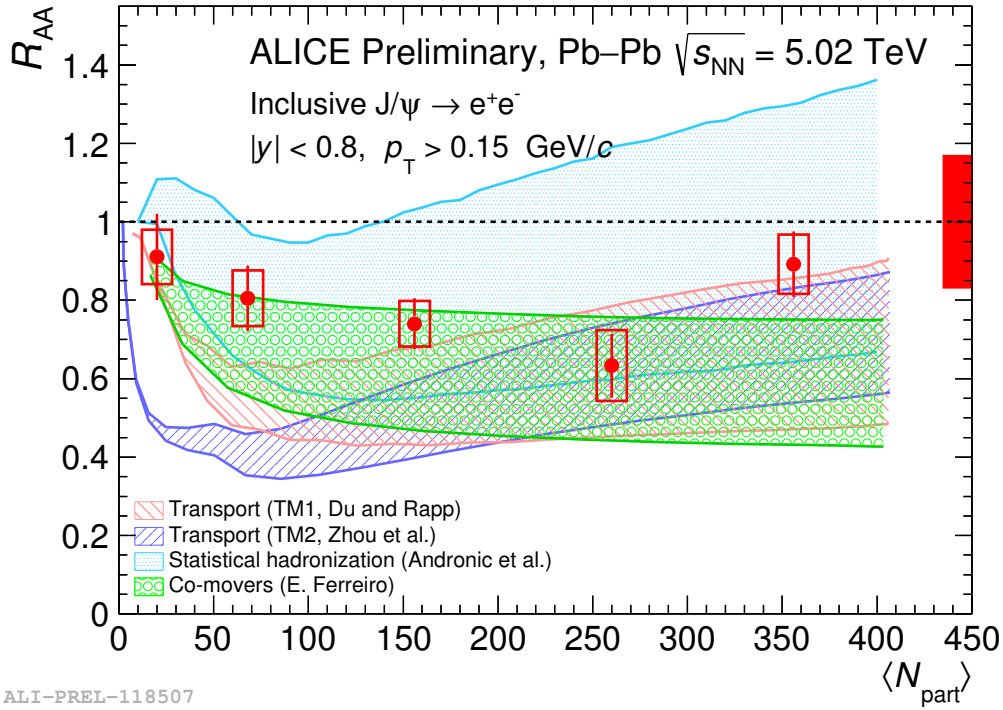


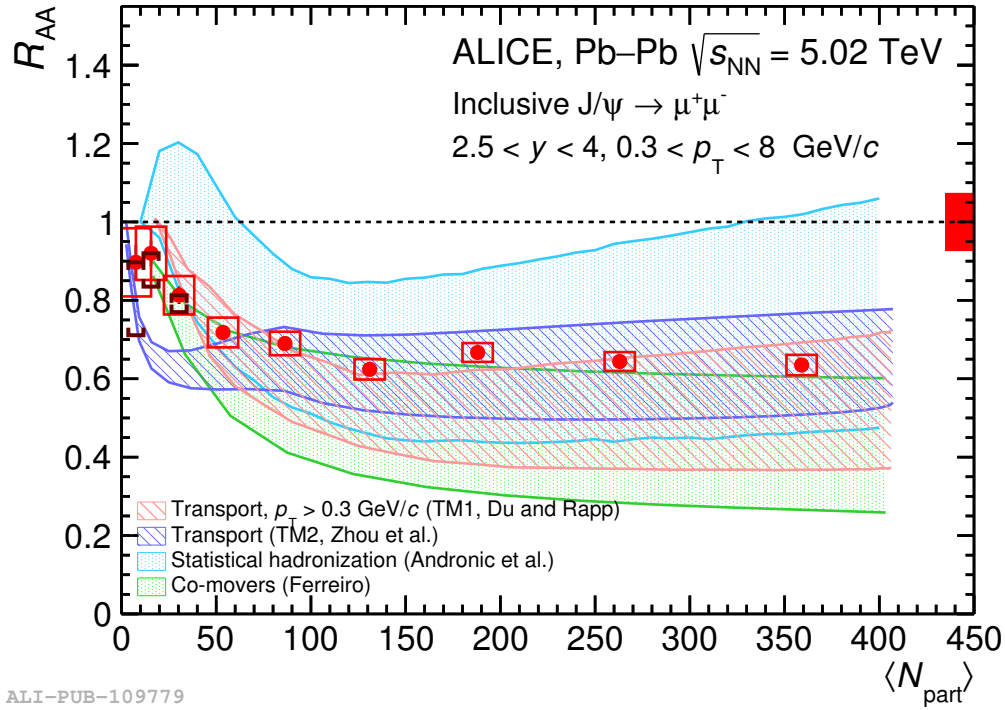
A-A Collisions

J/ψ R_{AA} vs Centrality in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

No significant centrality dependence beyond $\langle N_{part} \rangle \approx 50$

- Results at $\sqrt{s_{NN}}$ = 5.02 TeV confirms observations at 2.76 TeV with improved precision
- $p_T >$ 0.3 GeV/c in the dimuon channel to minimize contribution of photo-production when comparing to theory models
- Interplay between dissociation and recombination. **Theoretical uncertainties larger than the experimental ones: hard to discriminate between models!**





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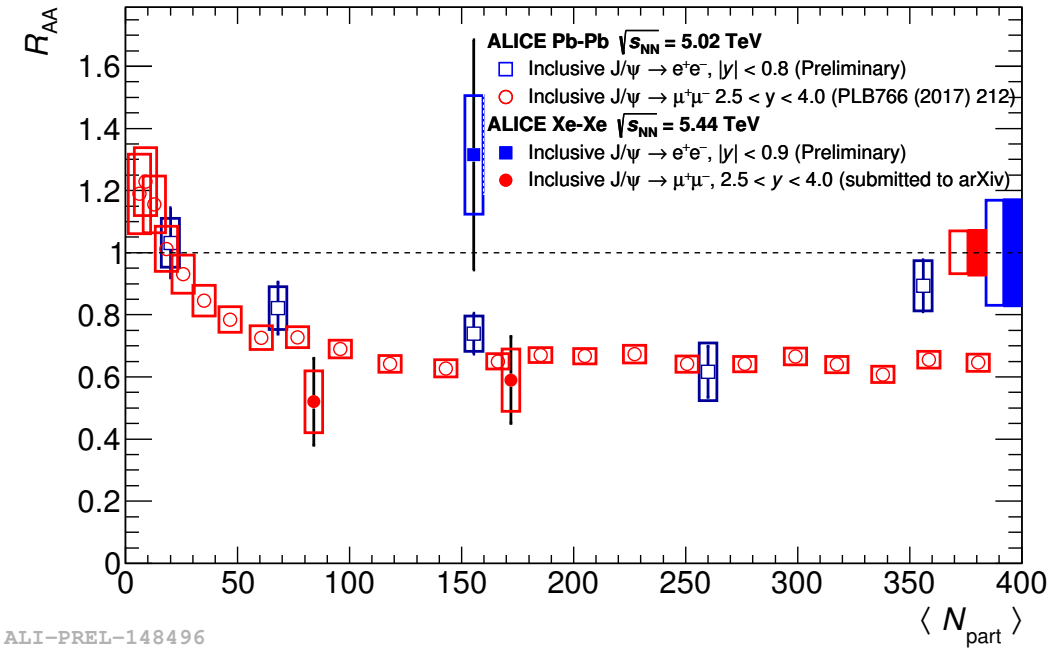
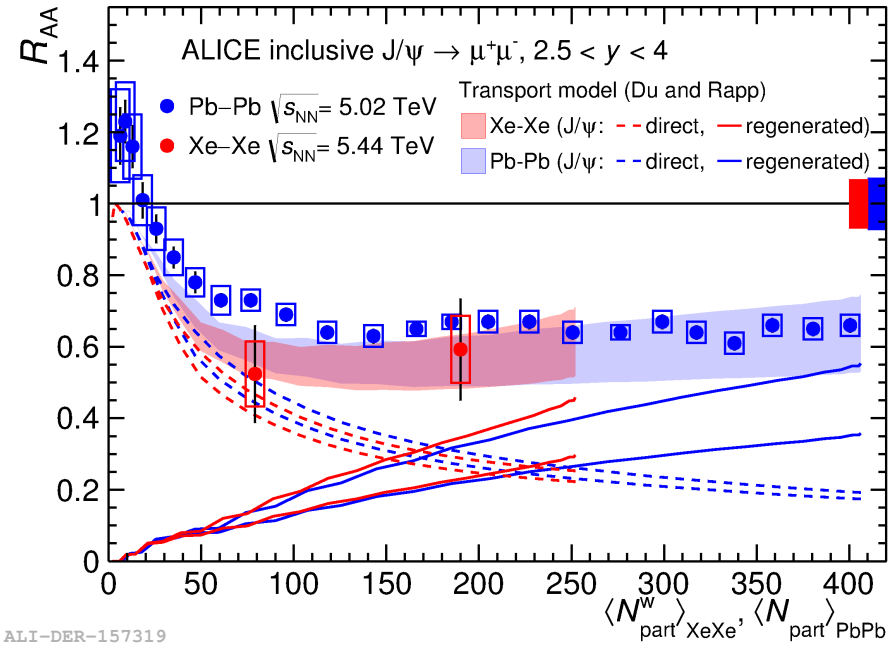
J/ψ R_{AA} vs Centrality in Xe-Xe at $\sqrt{s_{NN}}$ = 5.44 TeV

- **At forward rapidity:** N(J/ψ) = 241 ± 47 (stat.) ± 26 (syst.).
  R_{AA} results of Xe-Xe and Pb-Pb agree within uncertainties
- **At mid-rapidity:** N(J/ψ) = 340 ± 89 (stat.) ± 14 (syst.)
  R_{AA} of Xe-Xe consistent with unity within large stat. and syst. uncertainties
- **Similar $\sqrt{s_{NN}}$ and $\langle N_{part} \rangle$: similar relative contributions of suppression/regeneration in Pb-Pb and Xe-Xe**



arXiv:1805.04383

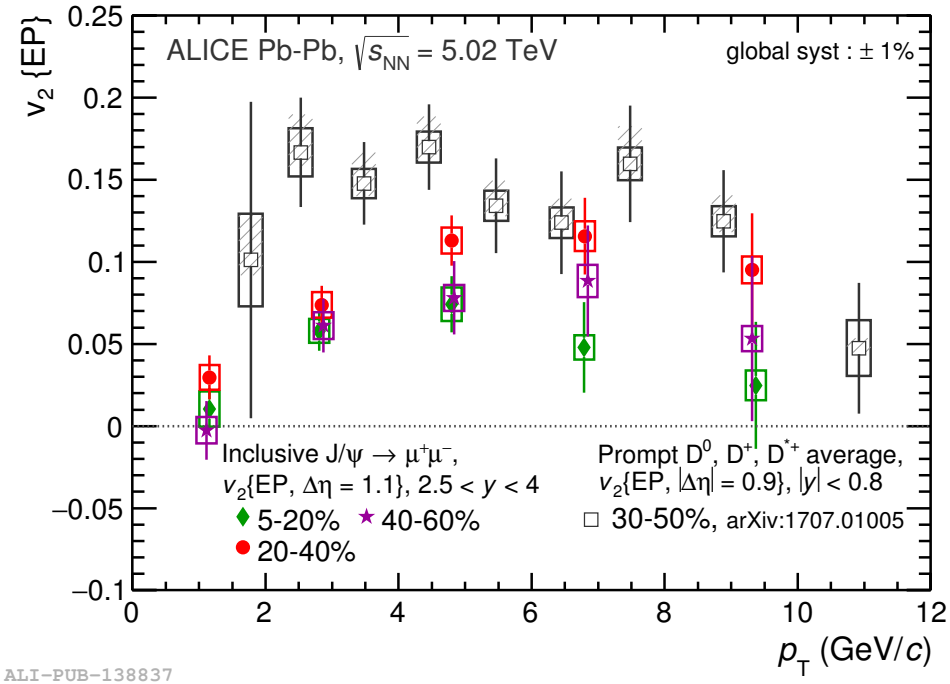


J/ψ elliptic flow in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

- **A clear v_2 signal is observed in various centrality and p_T bins:** forward- and mid-rapidity results agree within uncertainties

- **At low p_T:** models including regeneration agree with the data
- **At high p_T:** the elliptic flow is underestimated by the models

- Large v_2 values for both J/ψ and D mesons: flow inherited from thermalized charm quarks. Low-p_T v_2 larger for D mesons (measured at mid-rapidity)



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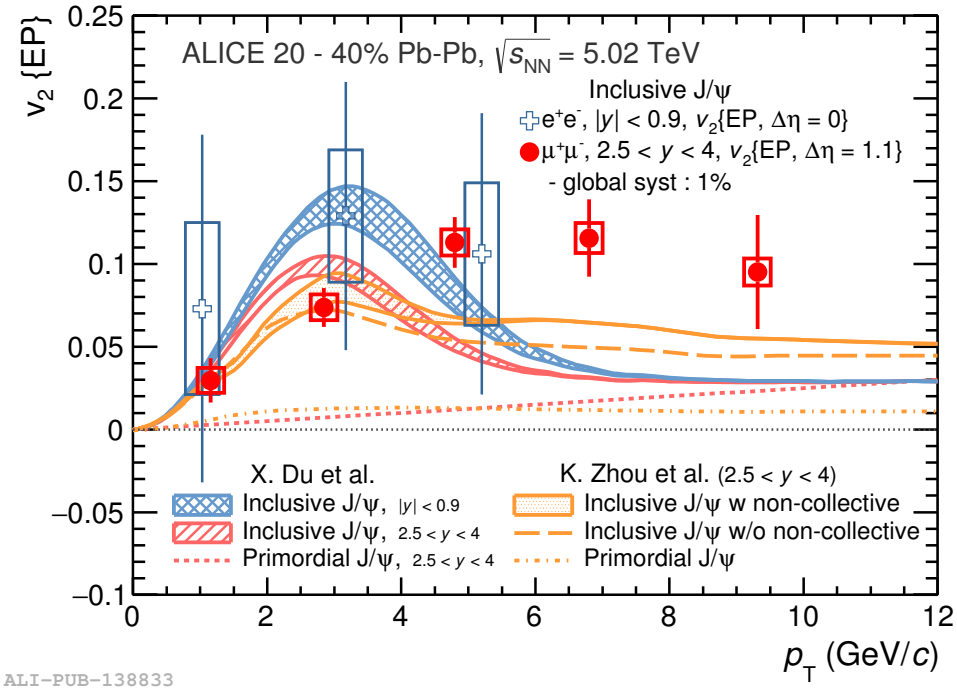
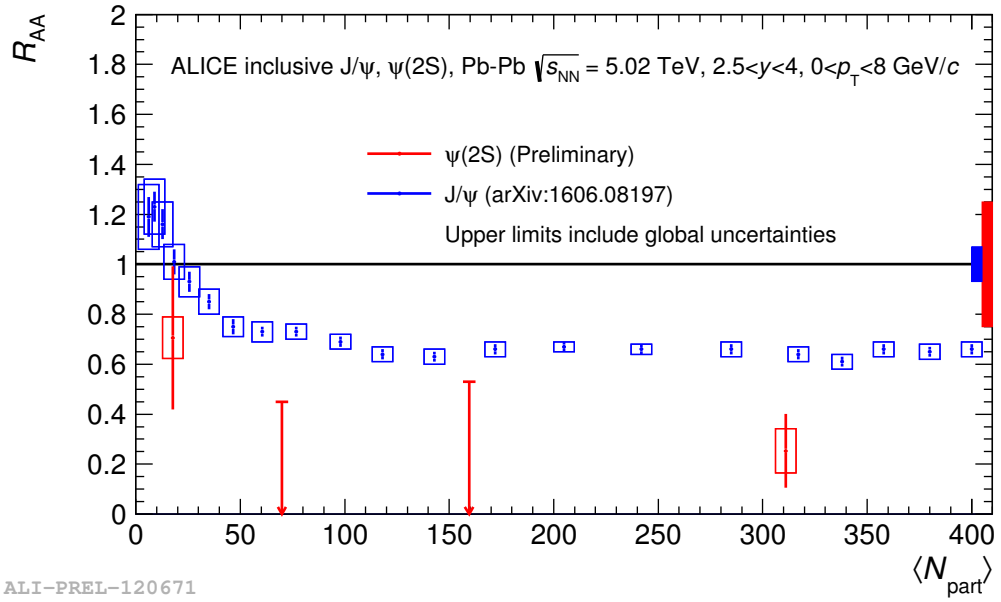
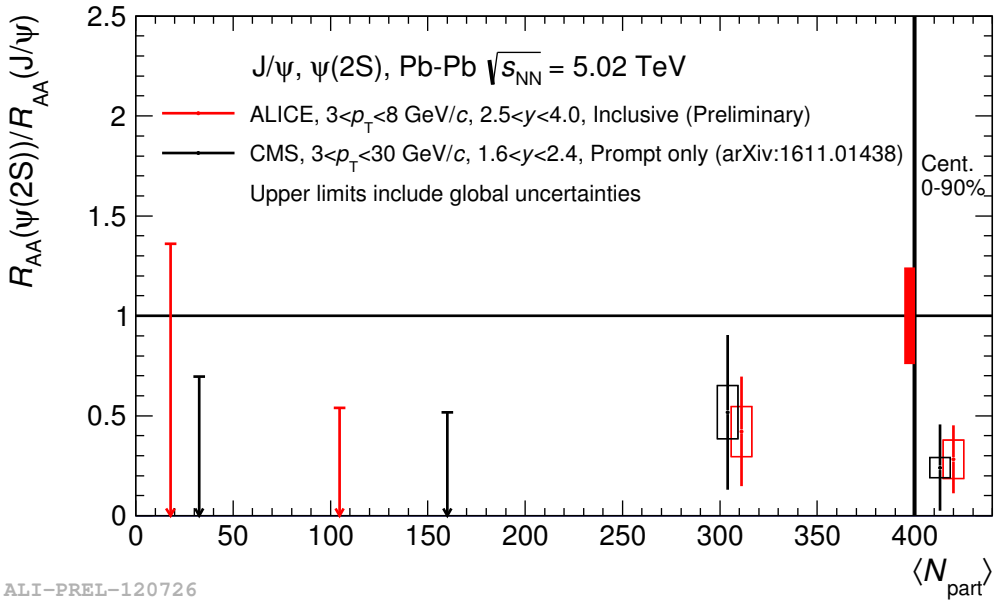
PRL 120 (2018) 102301



ψ(2S) R_{AA} and the ψ(2S)/(J/ψ) Ratio

- ψ(2S) is expected to be more easily dissociated than J/ψ. **ψ(2S)/(J/ψ) should greatly help model discrimination**
- **Indications for suppression at low and intermediate p_T.** For low significance intervals: upper limit at 95% CL.
- Good agreement with CMS results at $\sqrt{s_{NN}}$ = 5.02 TeV (p_T > 3 GeV/c)
- **More statistics and better S/B are needed** → upgrades for LHC run 3





Conclusions

Results in pp collisions:

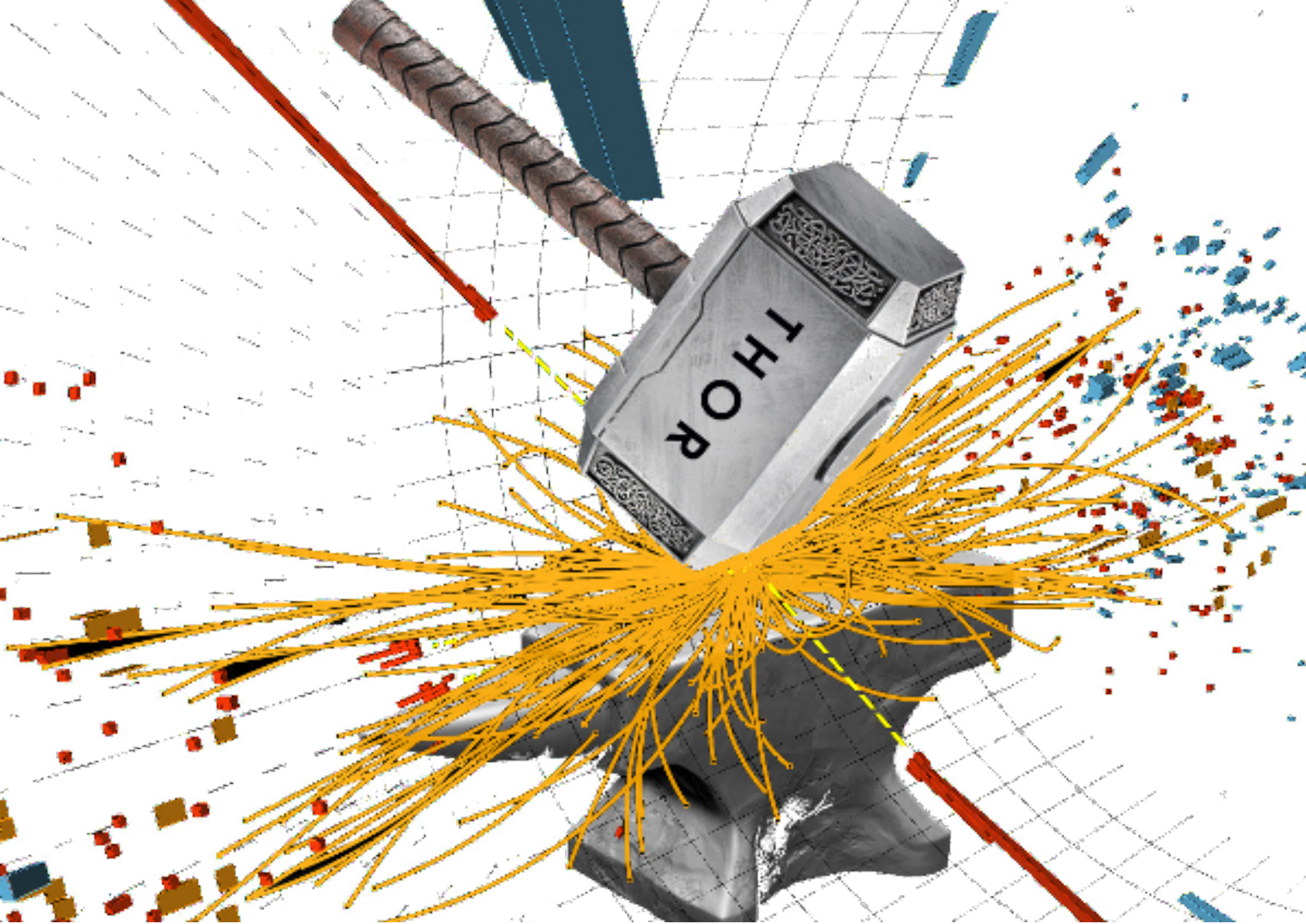
- Well reproduced by NRQCD + FONLL (+CGC description of the proton at low p_T)
- Increasing J/ψ yield as a function of multiplicity: described by models including effects related to multi-parton interactions

Results in p-Pb collisions:

- J/ψ suppression well described by models including shadowing and/or energy loss. ψ(2S) suppression requires final-state effects
- Indication of non-zero J/ψ v_2 in p-Pb collisions: similar origin as in Pb-Pb collisions?

Results in A-A collisions:

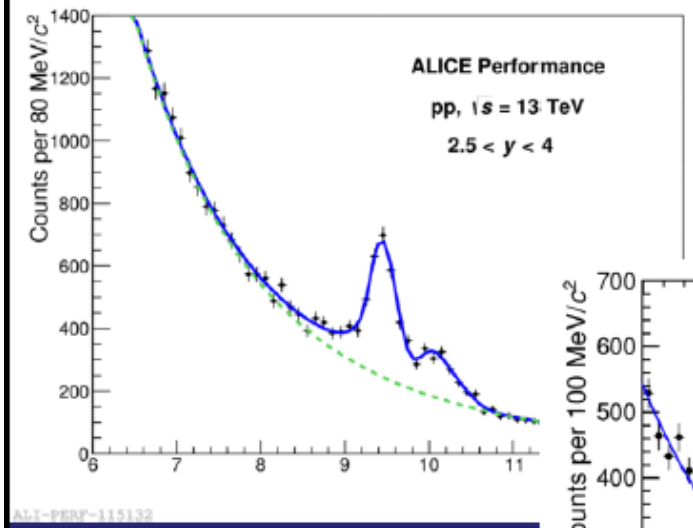
- Competition between suppression and regeneration at the LHC energies
- J/ψ R_{AA} in Xe-Xe and Pb-Pb collisions compatible
- J/ψ elliptic flow agrees with regeneration picture, for $p_T > 5$ GeV/c models significantly undershoot the data at forward rapidity


THOR

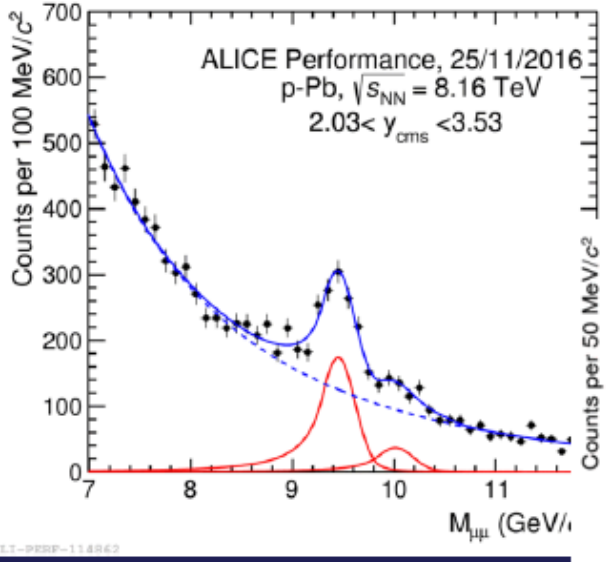
Backup Slides

Measuring Bottomonium in ALICE

pp

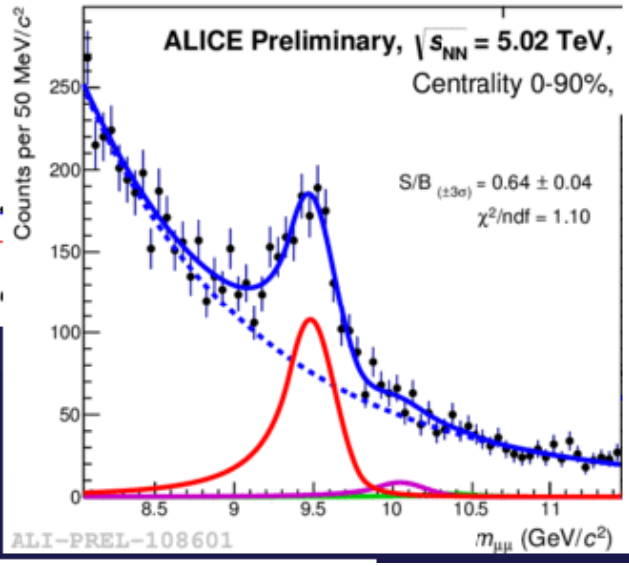


p-Pb



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

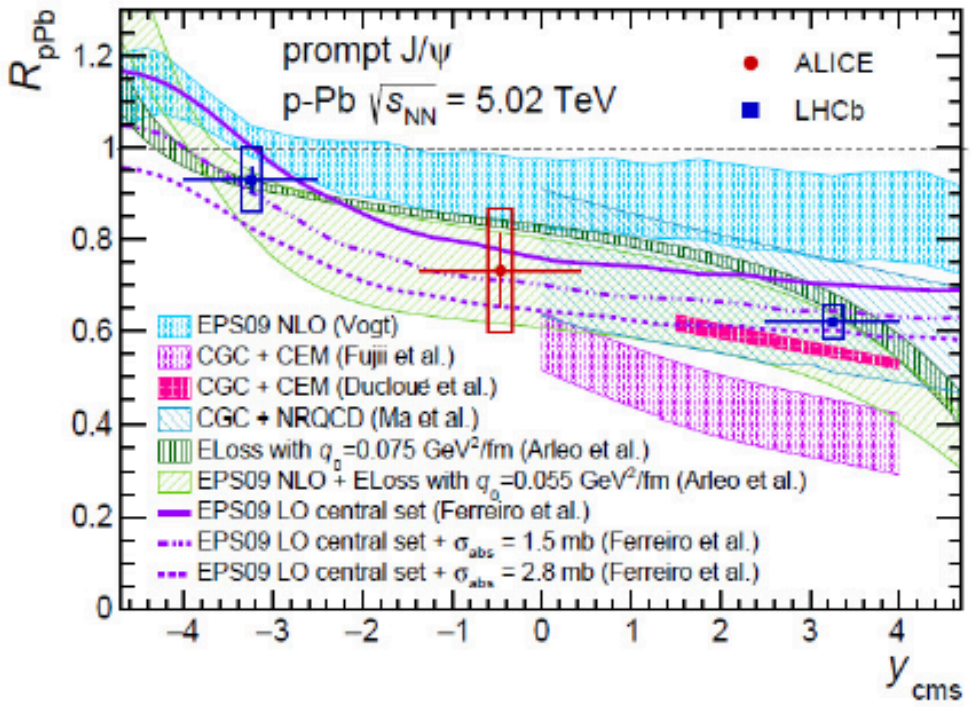
Pb-Pb

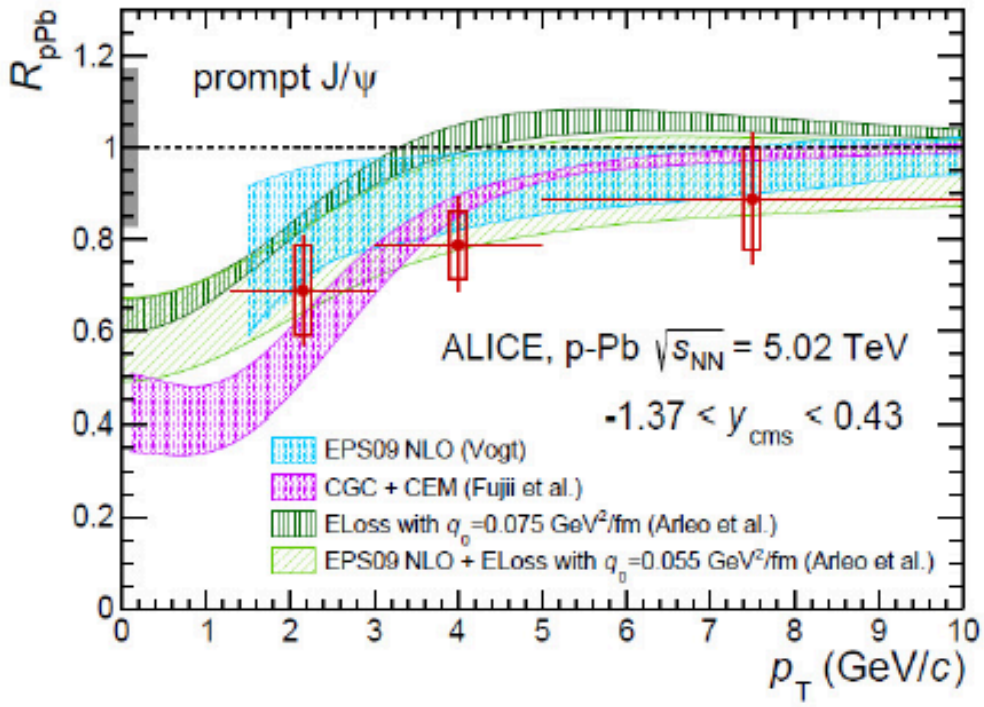


- Good S/B for Υ(1S), up to Pb-Pb
- Measurements are still statistics-limited for Υ(2S) and (in particular) Υ(3S)

J/ψ R_{pPb} at 5.02 TeV (mid-rapidity)

arXiv 1802.00765





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

Data Taking and Luminosities

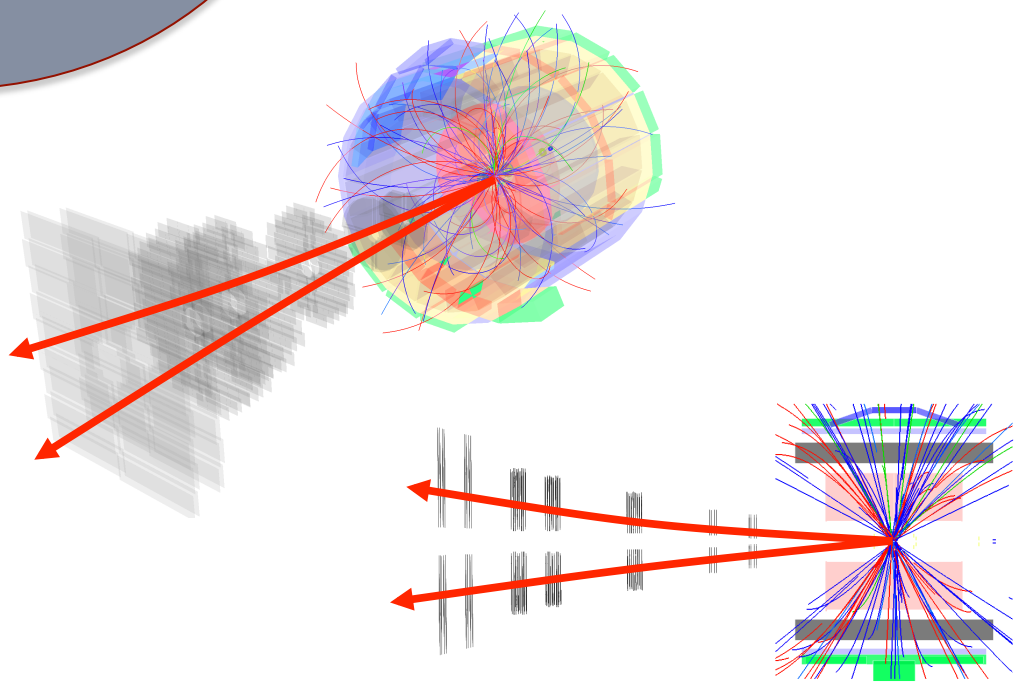
Run1 (2009 – 2013)

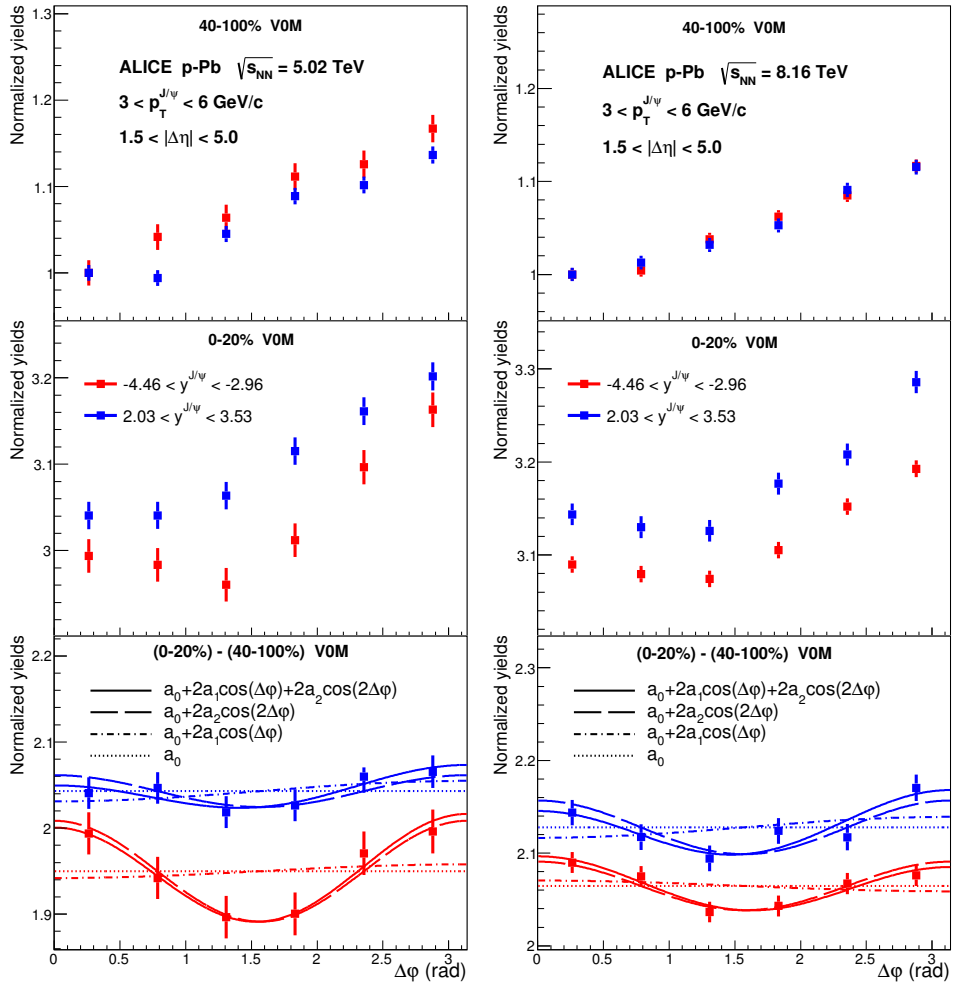
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV	L_{int} = 26 μb^{-1} (MB)
	L_{int} = 69 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L_{int} = 51 μb^{-1} (MB)
	L_{int}(p-Pb) = 5 nb^{-1} (dimuon)
	L_{int}(Pb-p) = 5.8 nb^{-1} (dimuon)
pp, $\sqrt{s}$ = 0.9, 2.76, 7, 8 TeV	L_{int}(2.76 TeV) = 1.1 μb^{-1} (MB)
	L_{int}(2.76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

Run2 (2015 – 2018)

Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L_{int} = 19 μb^{-1} (MB)
	L_{int} = 255 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L_{int} = 0.4 nb^{-1} (MB)
p-Pb, $\sqrt{s_{NN}}$ = 8.16 TeV	L_{int}(p-Pb) = 8.7 nb^{-1} (dimuon)
	L_{int}(Pb-p) = 12.9 nb^{-1} (dimuon)
pp, $\sqrt{s}$ = 5.02, 13 TeV	

J/ψ Production: Azimuthal Anisotropy





- **Correlations expressed as associated SPD-tracklet yields per dimuon (J/ψ) trigger**
  - 40-100%: jet-like away-side correlation
  - 0-20%: additional enhancement at both near and away sides

Jet correlations eliminated via subtraction

J/ψ yield vs event multiplicity in p-Pb collisions

- Multiplicities up to 4 times the average reached
- Increase as in pp, but indication of saturation for p-going J/ψ
- At mid-rapidity, similar increase of J/ψ and D mesons
- Theoretical input needed!