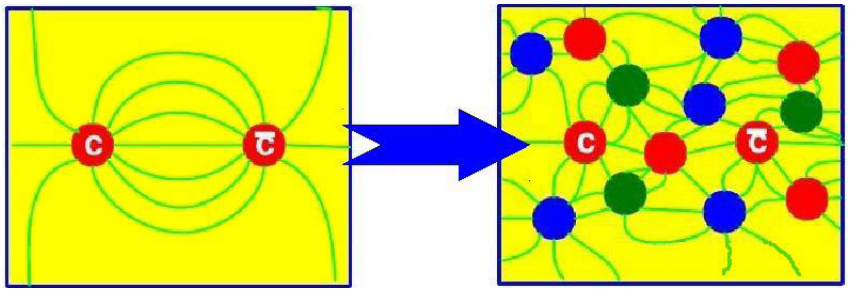
Quarkonium measurements as probe of the QCD medium
-status and outlook-

Ionut-Cristian Arsene
University of Oslo

30/09/2019, Stavanger

Heavy quarkonia in the QGP

- Vacuum potential: $$V_{total} = (-q)\frac{q}{4\pi r} + kr$$



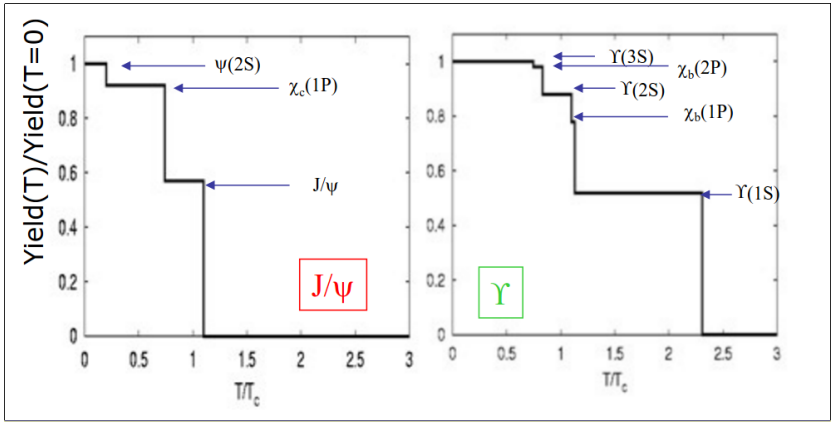
- In a deconfined medium
  - string tension weakened
  - Coulomb potential is Debye screened

- Quarkonium states will be melted if $r > \lambda_D$: *Matsui and Satz, PLB178 (1986) 416*

$$\lambda_D \simeq \frac{1}{T}$$ - Debye screening length

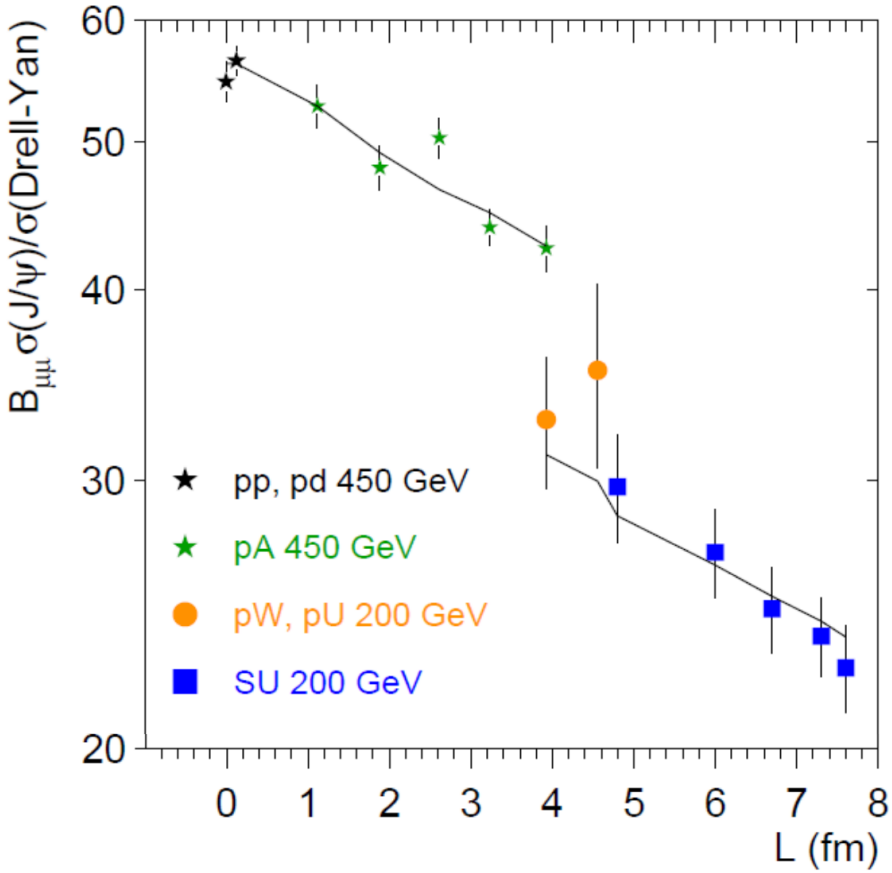
table from H. Satz, J. Phys. G32 (2006) 25

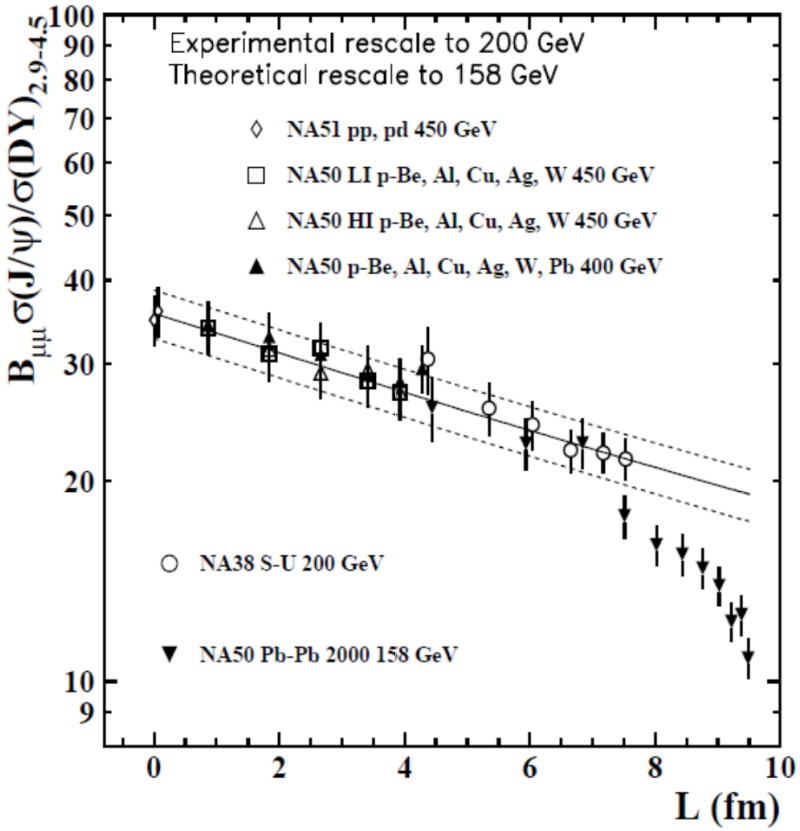
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78



Digal et al., PRD64 (2001) 094015

J/ψ production at the SPS



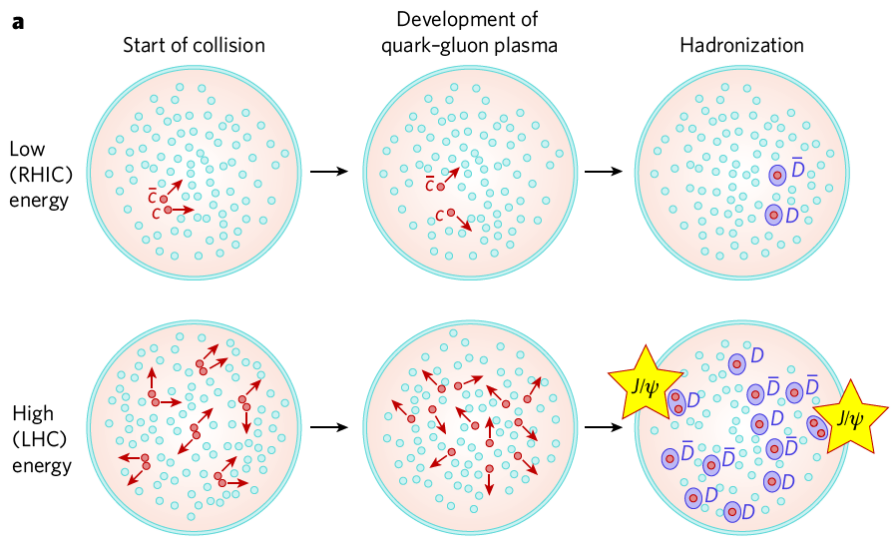


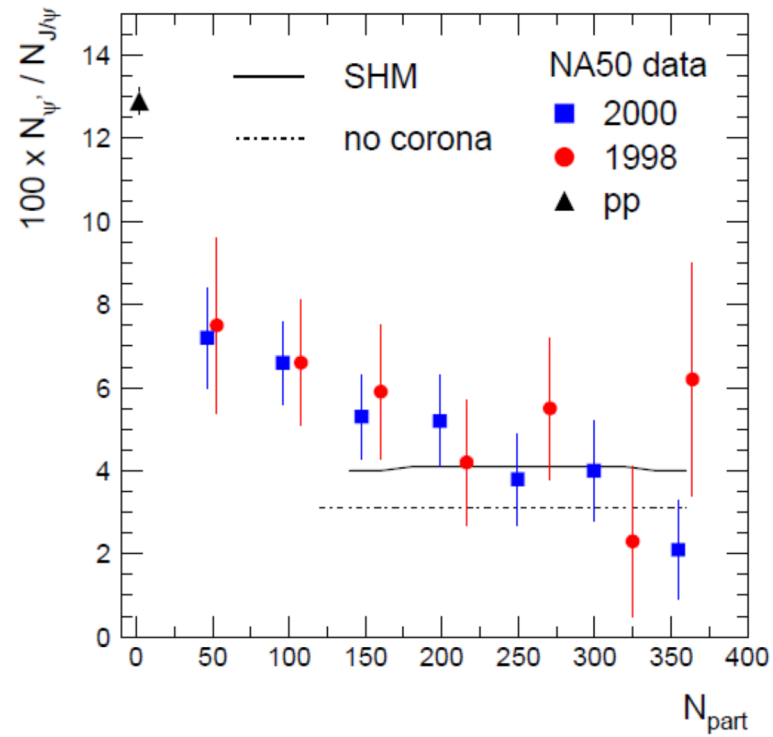
- Suppression pattern in relatively small systems explained by nuclear absorption:
  $\sigma(J/\psi) \sim \exp(-\rho\sigma_{abs}L)$
  C.Gerschel, J.Hufner 1988, A.Capella 1988

- Central PbPb data indicate suppression beyond expectations from nuclear absorption

Statistical hadronization

P.Braun-Munzinger, J.Stachel, PLB490 (2000) 196





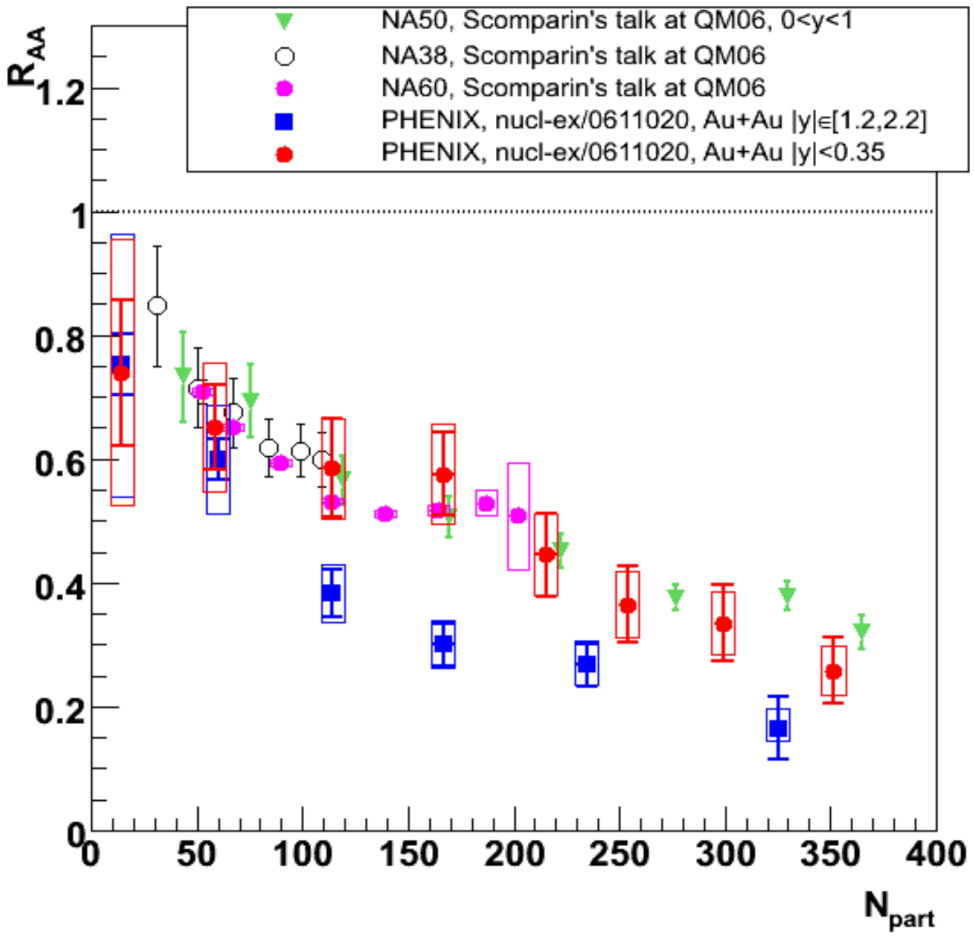
$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V \left(\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}\right) + g_c^2 V \left(\sum_i n_{\psi_i}^{therm}\right) + \ldots$$

- At the LHC energies, large amounts of $c\bar{c}$ pairs are created
- Possible to create charmonium on a statistical basis
  - Assuming charm-quark thermalization and knowing the total $c\bar{c}$ cross-section, all charmed particle yields can be predicted

Microscopic transport models

- Microscopic models developed for the transport of charmonium in QGP
  - CNM effects taken into account to estimate primordial total $c\bar{c}$ cross-section (EPS09 NLO)
  - Quarkonium spectral functions from lattice QCD
  - Ideal hydrodynamics for the fireball evolution
    - QGP phase: ideal gluon gas
    - Hadronic phase: ideal hadron gas
    - Initialization tuned to match charge multiplicities see in Pb-Pb at LHC
  - Boltzmann-type equation for charmonia (J/ψ, χ_c and $\psi(2S)$) with gain and loss terms
- Recently: quantum transport approaches developed using Schrodinger-Langevin or density-matrix formulation
  - Coupling between HQ and plasma, formation time ...

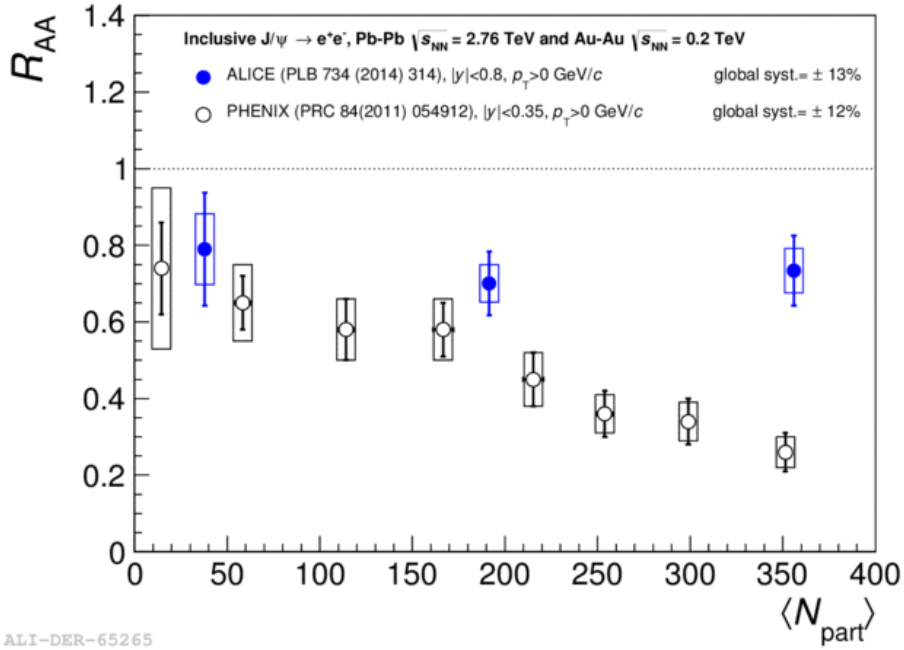
Charmonium at RHIC

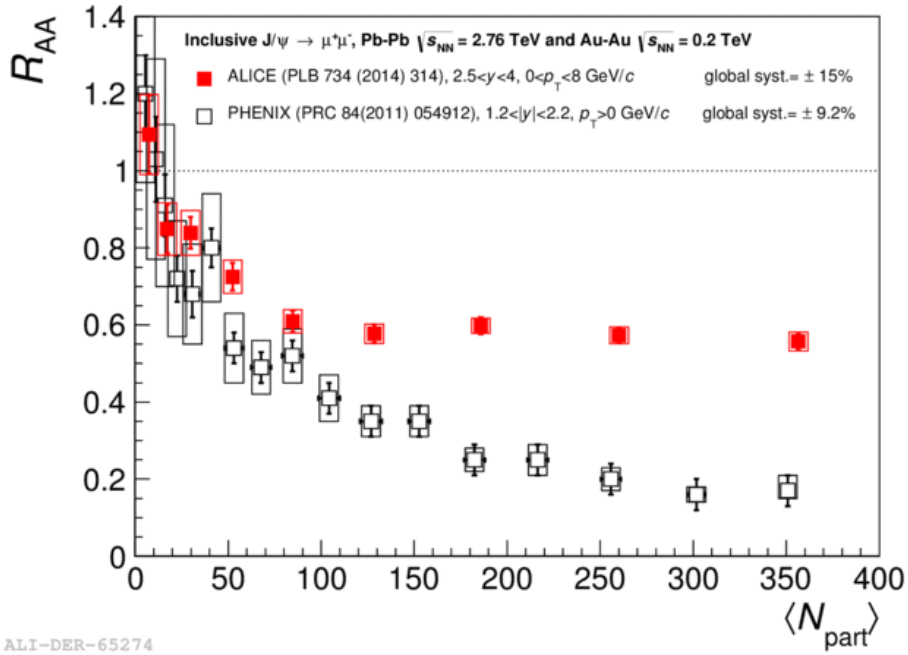


- At mid-rapidity, J/ψ suppression similar at RHIC and SPS energies
- Onset of quarkonium production via recombination

J/ψ suppression vs centrality (2.76 TeV)

ALICE, PLB734 (2014) 314

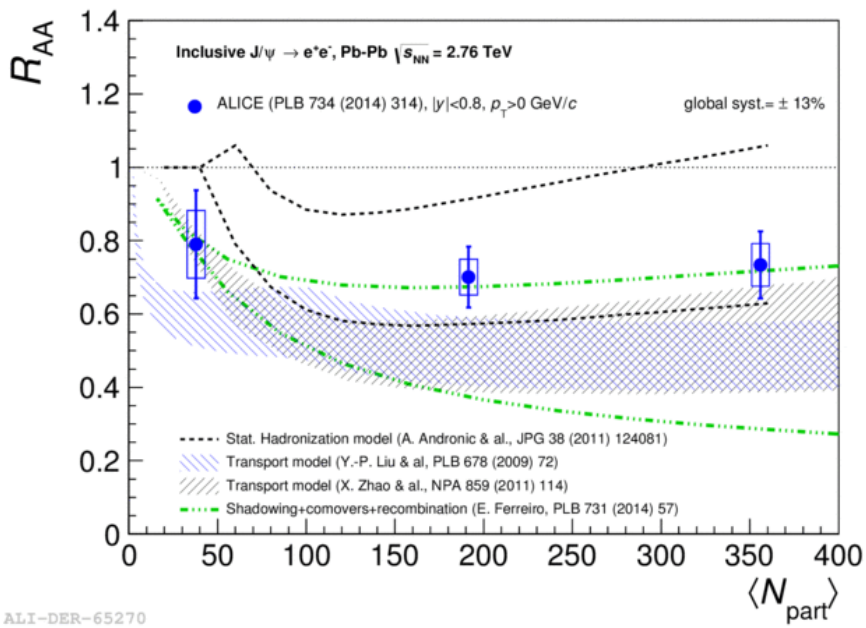


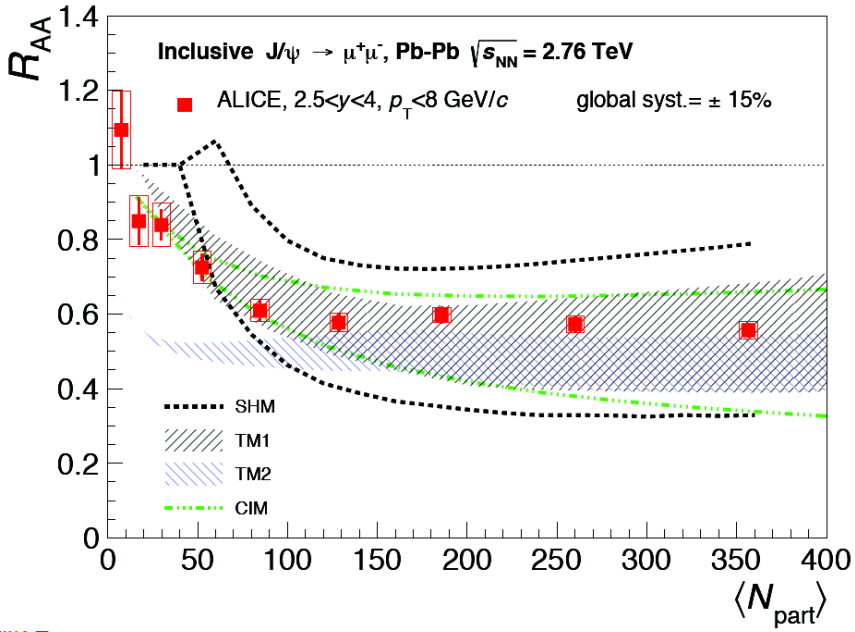


- Much less suppression in central and semi-central collisions wrt to the lower energy measurements
- Indication of a lower suppression at mid-rapidity compared to forward rapidity

J/ψ suppression vs centrality (2.76 TeV)

ALICE, PLB734 (2014) 314



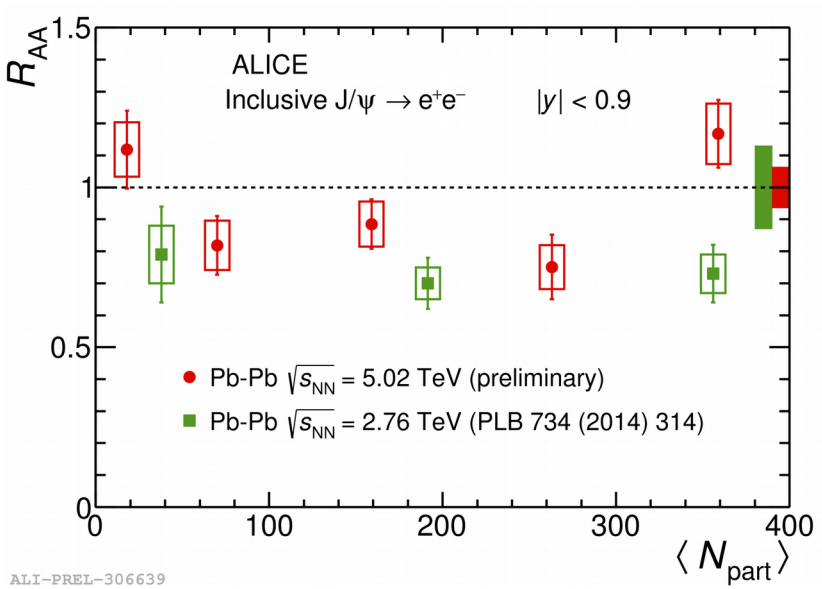


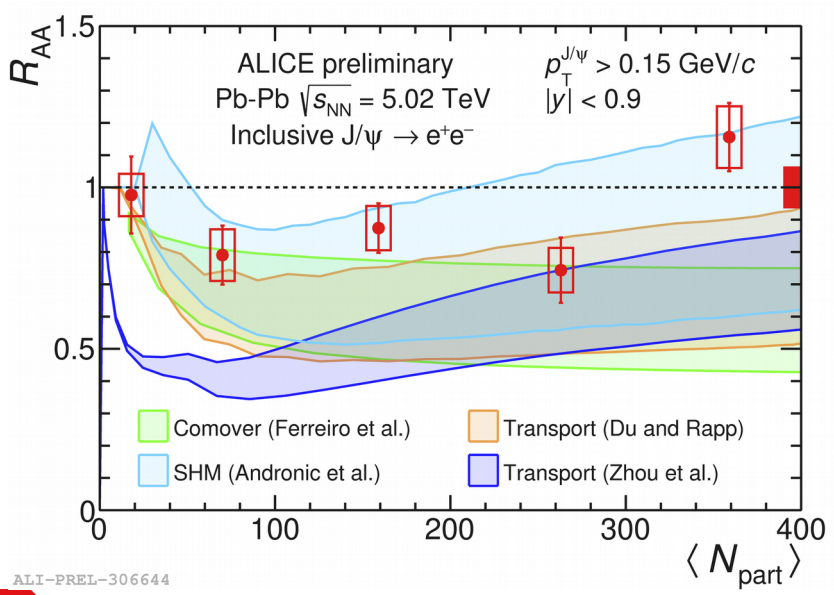
- Models which implement a regeneration component are in agreement with data
- Model uncertainties are dominated by the poor knowledge of the total $c\bar{c}$ cross-section / CNM effects

SHM: A.Andronic et al., JPG38 (2011)12408
TM1: X.Zhao et al.,NPA859 (2011) 114
TM2: Y.-P.Liu et al., PLB578 (2009) 72
CIM: E.Ferreiro, PLB731 (2014) 57

J/ψ R_{AA} in Pb-Pb collisions at 5.02 TeV

ALICE, paper draft in preparation

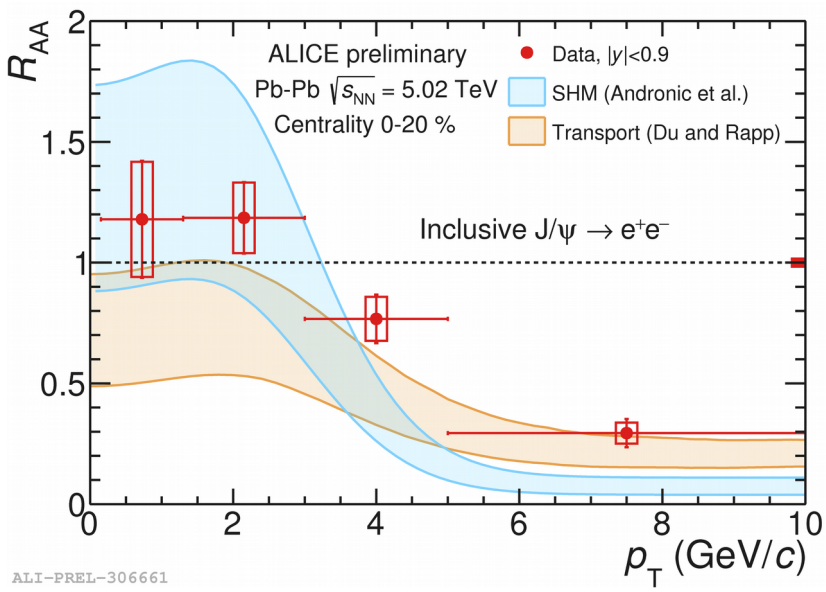


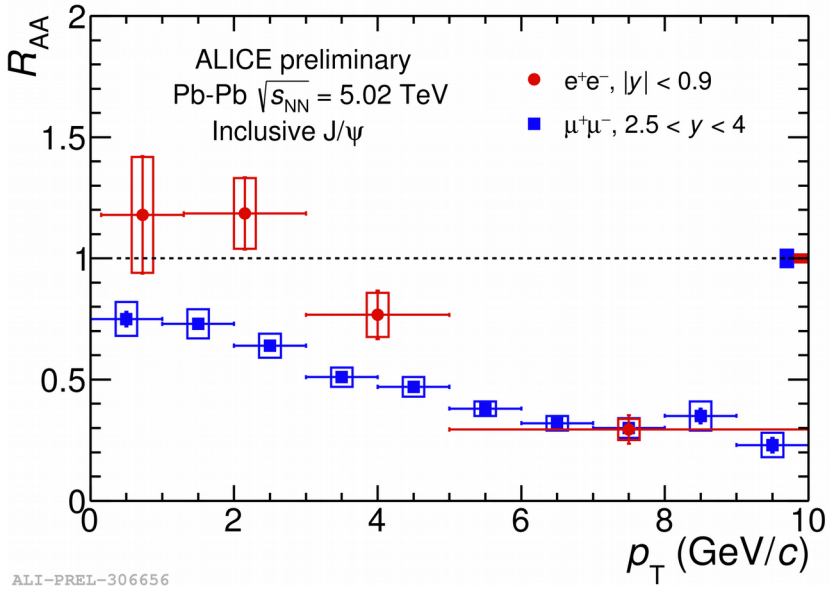


- Analysis done using the 2015 dataset
- Reduced syst uncertainties from the pp reference → measured reference at 5 TeV
- With the current uncertainties, no clear variation of the suppression factor
- Large model uncertainties
- Besides the SHM calculations, all models show tensions with the data

J/ψ R_{AA} in Pb-Pb collisions at 5.02 TeV

ALICE, paper draft in preparation

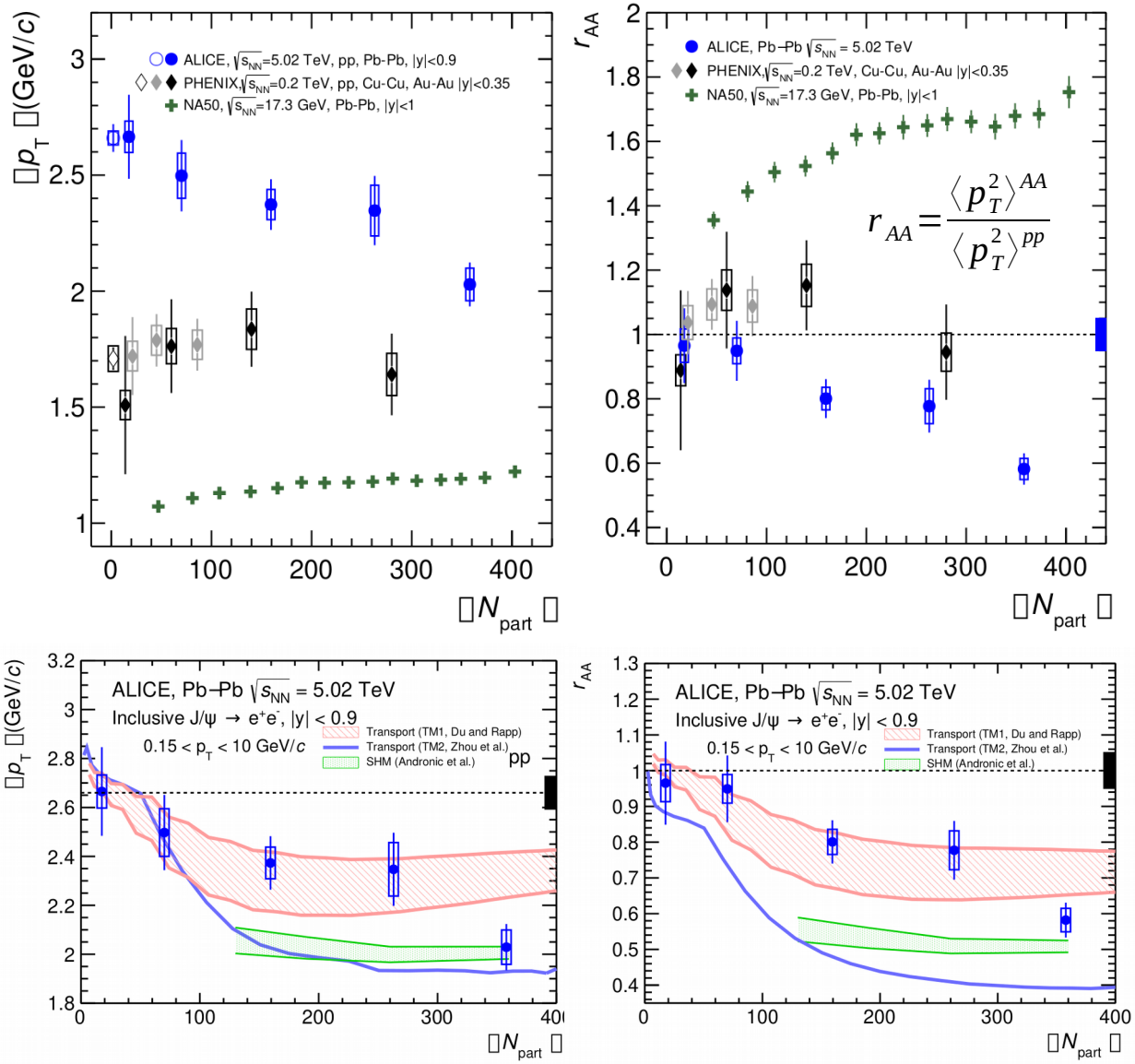




- p_T dependence of the suppression reproduced only qualitatively by models
- SHM uses a blast-wave parameterization of the freeze-out hyper-surface to obtain a p_T spectrum
- Comparison with forward-y results suggests stronger (re)combination effects at mid-y, as expected due to larger σ_{cc}

J/ψ <p_T> in Pb-Pb collisions at 5.02 TeV

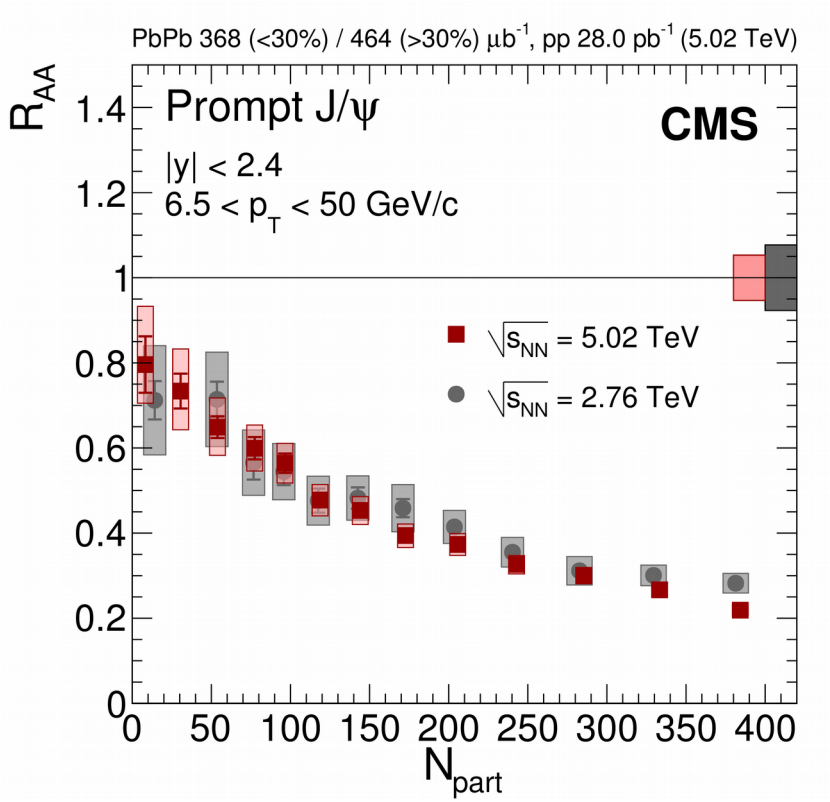
ALICE, paper draft in preparation



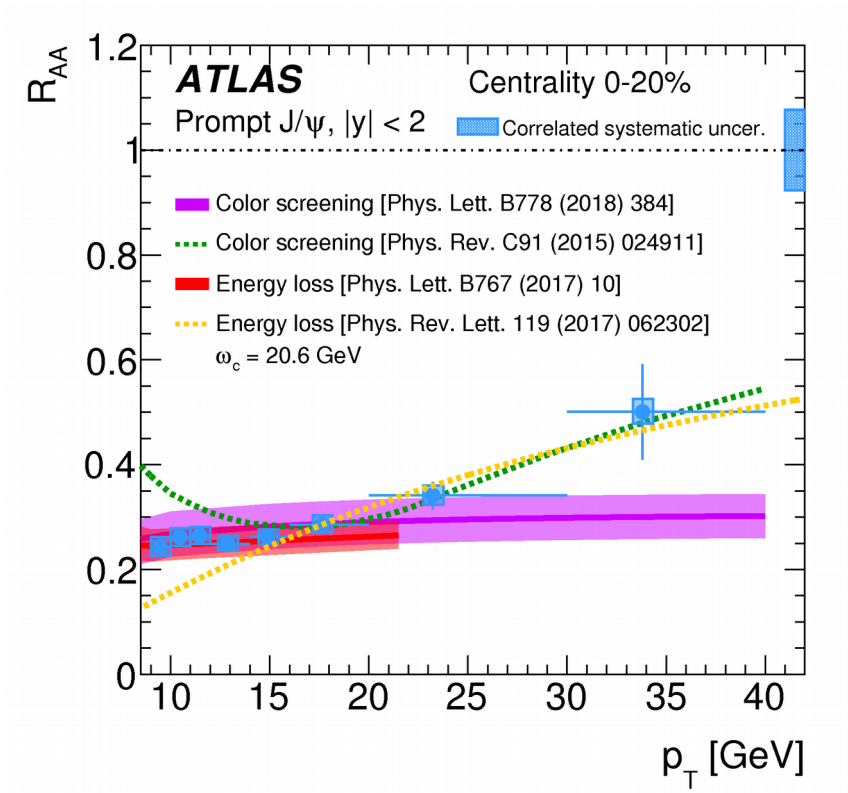
- Very different behaviour of <p_T> and <p_T^2> between SPS, RHIC and LHC
- SPS: Cronin-like increase with centrality
- RHIC: Nearly flat behaviour
- LHC: Drop of both <p_T> and <p_T^2> with centrality
- Drop explained by models via recombination

J/ψ at high p_T

CMS, arXiv: EPJ C78 (2018) 509



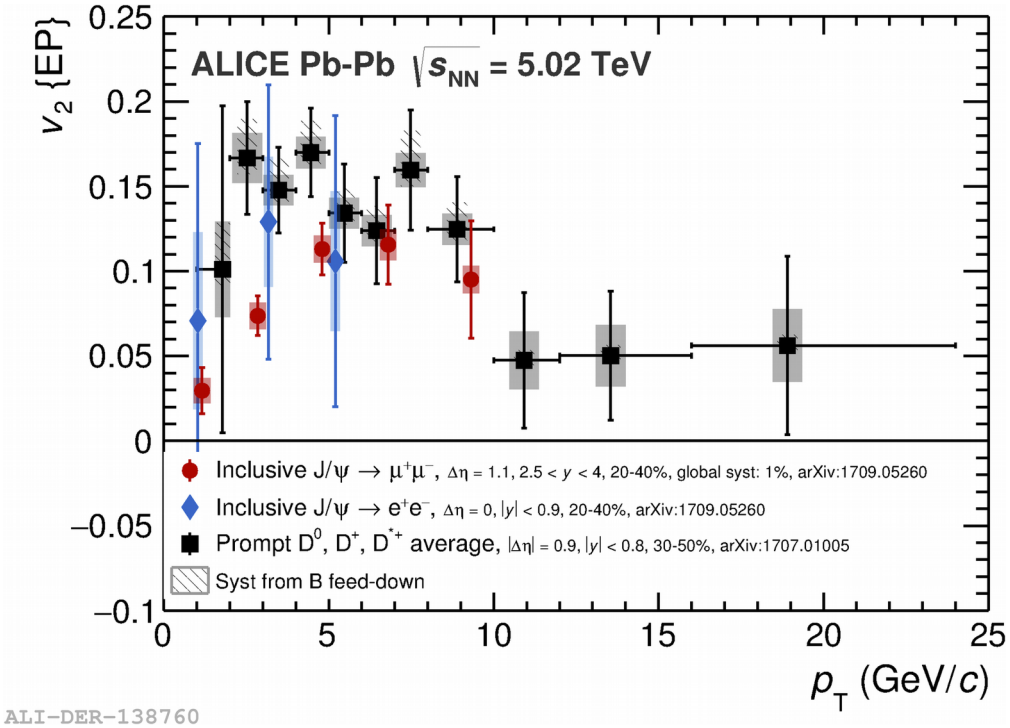
ATLAS, arXiv:1805.04077

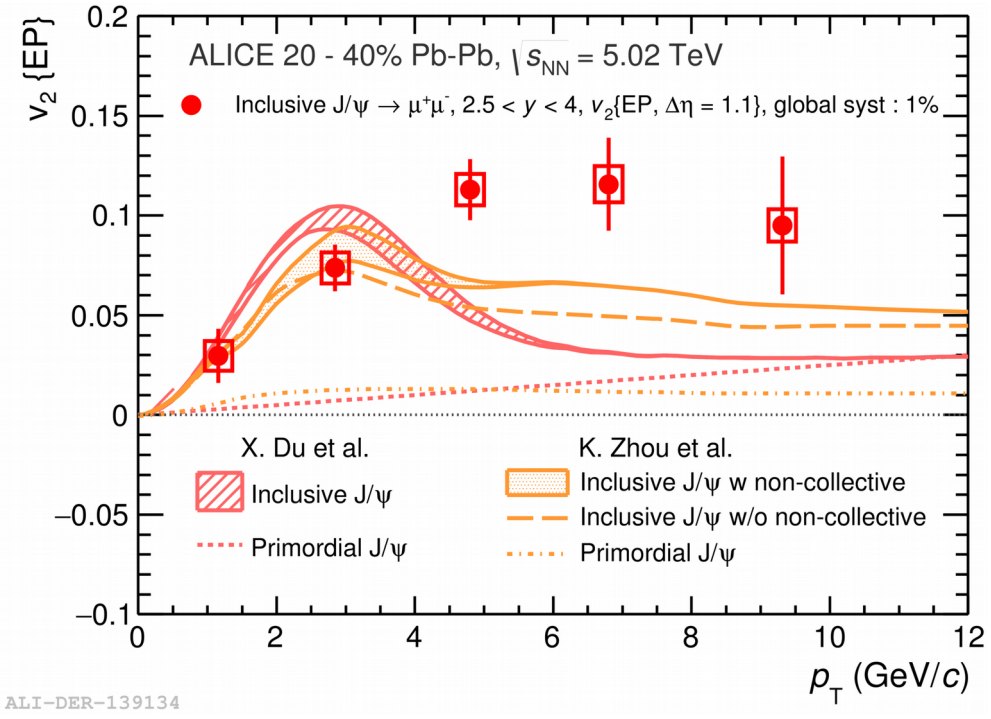


- Suppression grows towards central collisions
- R_{AA} grows towards high p_T
  - Explained in energy loss and color screening models

Inclusive J/ψ elliptic flow (v_2)

ALICE, PRL119 (2017) 242301
ALICE PRL 120 (2018) 102301

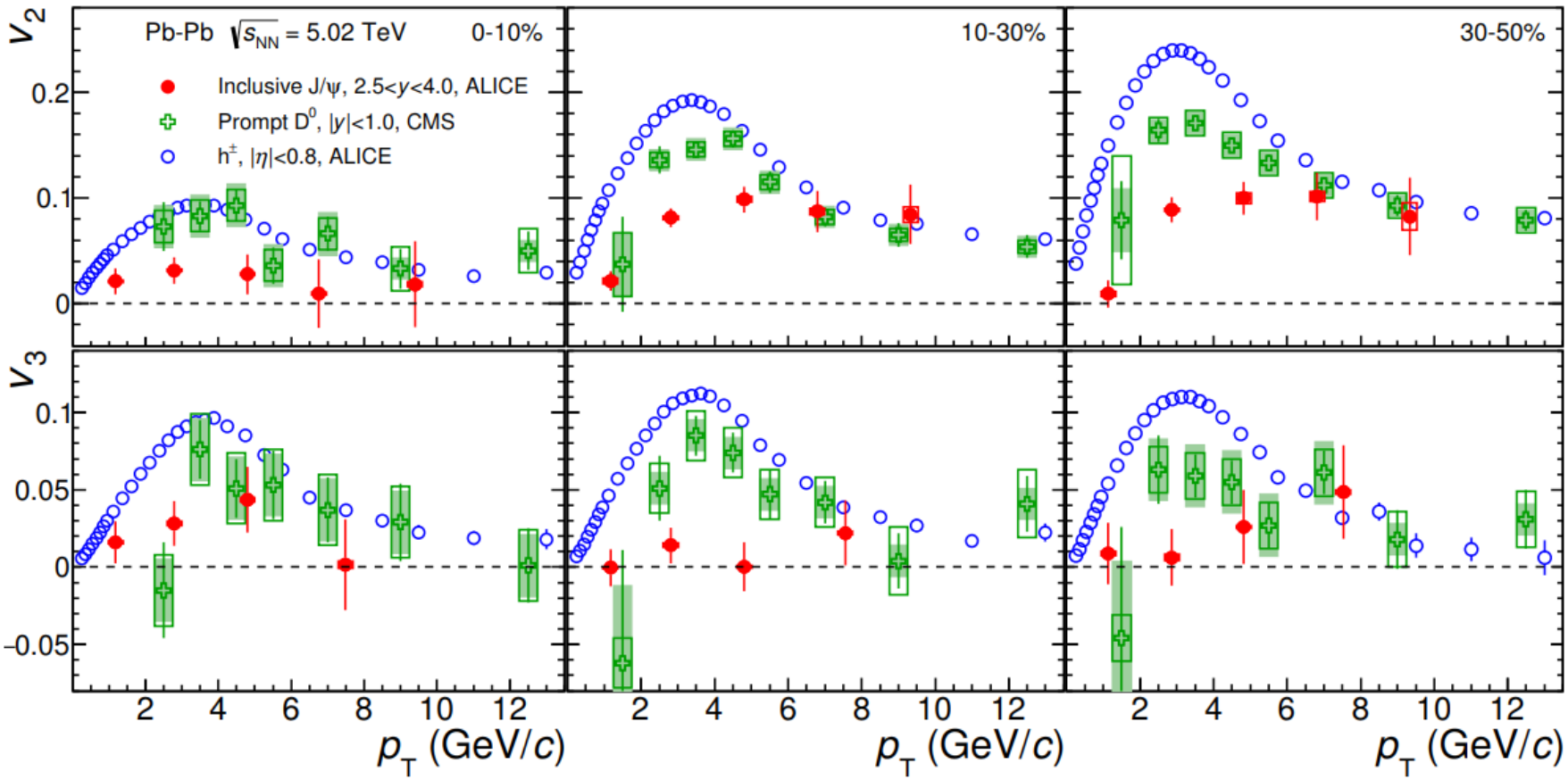




- Significantly large J/ψ v_2 observed at low and intermediate p_T
  - Expected from charm recombination
  - Transport models do not reproduce the v_2 at larger p_T
    - Path length dependent effects stronger than expected?
    - Contribution from higher mass states feed-down ?

J/ψ v_2 and v_3

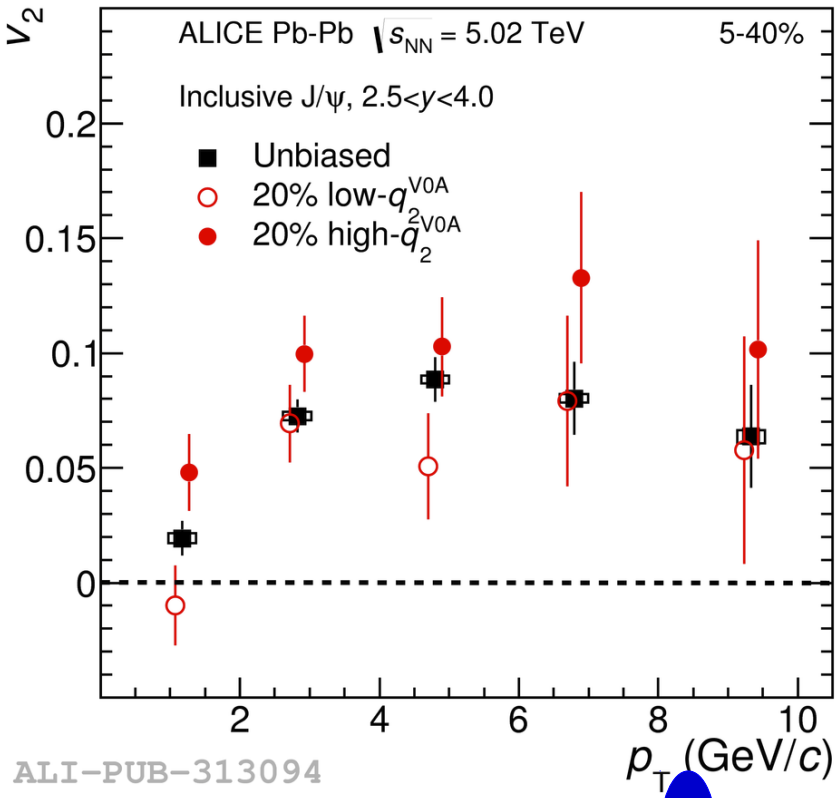
ALICE, arXiv: 1811.09742

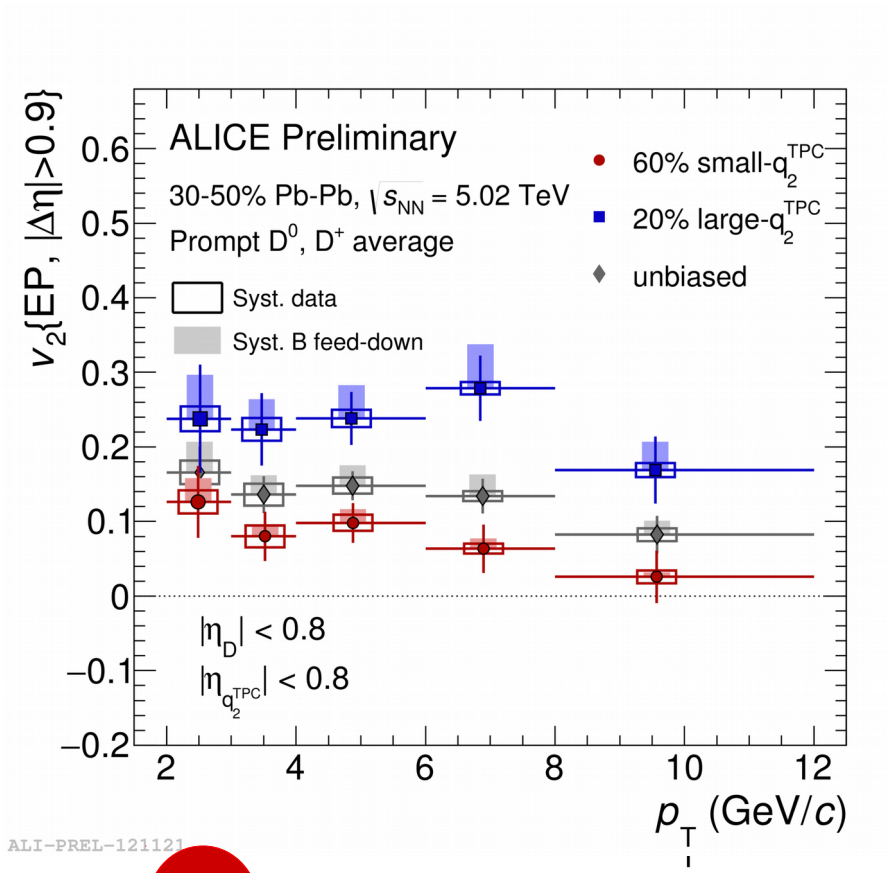


- Triangular flow v_3 sensitive to initial state effects
- v_3 observed for D mesons at all centralities
- Hint of smaller v_3 for J/ψ (except for the 0-10% central collisions)

Event shape engineering

ALICE, arXiv: 1811.09742



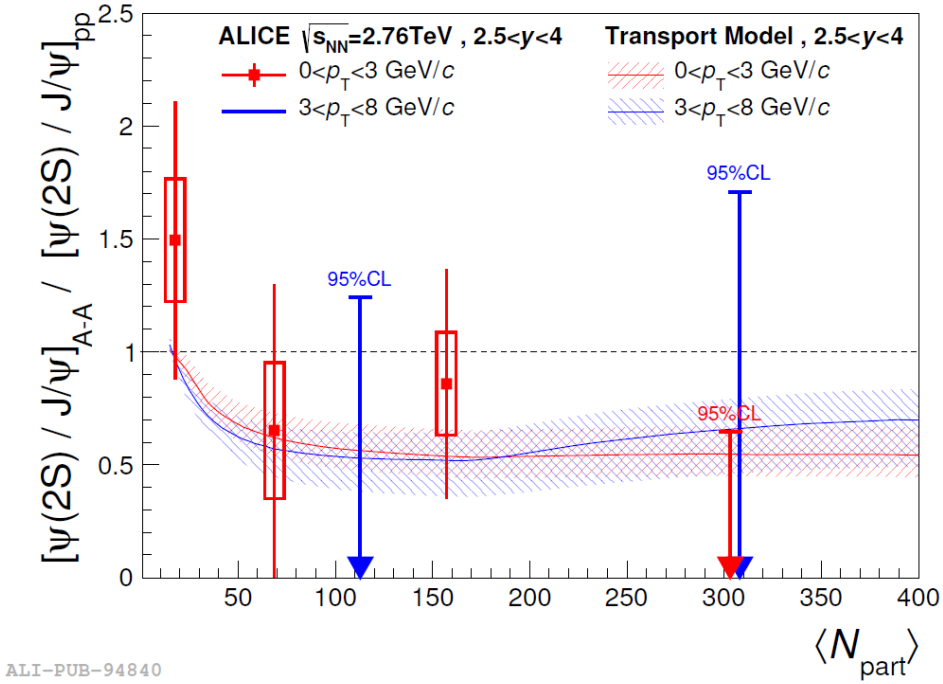


large q_2 small q_2

- Both D-meson and J/ψ elliptic flow sensitive to event shape engineering (ESE)
  - Charm flows with the bulk

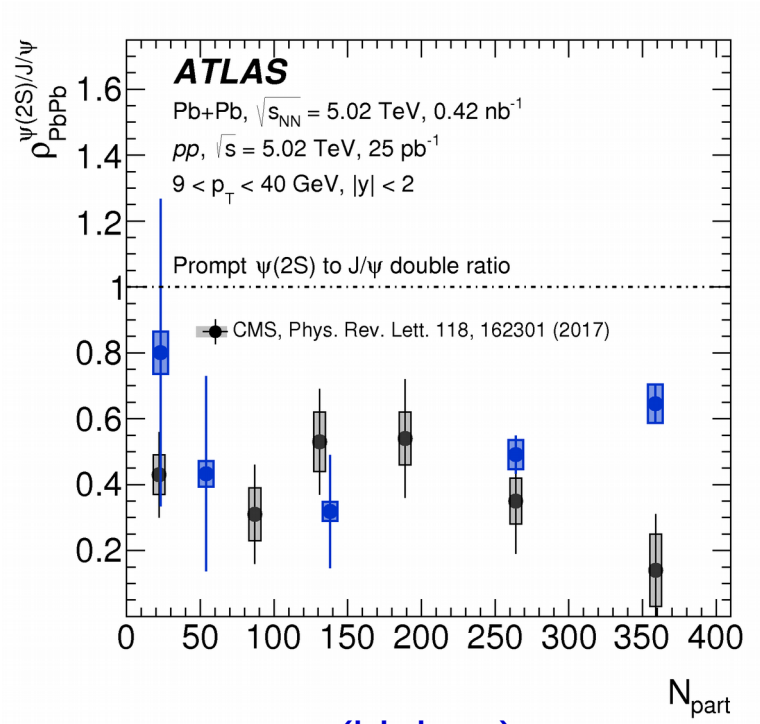
ψ(2S) production in Pb-Pb collisions

ALICE, JHEP 1605 (2016) 179



(low p_T) (intermediate p_T)

CMS, PRL118 (2017) 162301
ATLAS, arXiv: 1805.04077

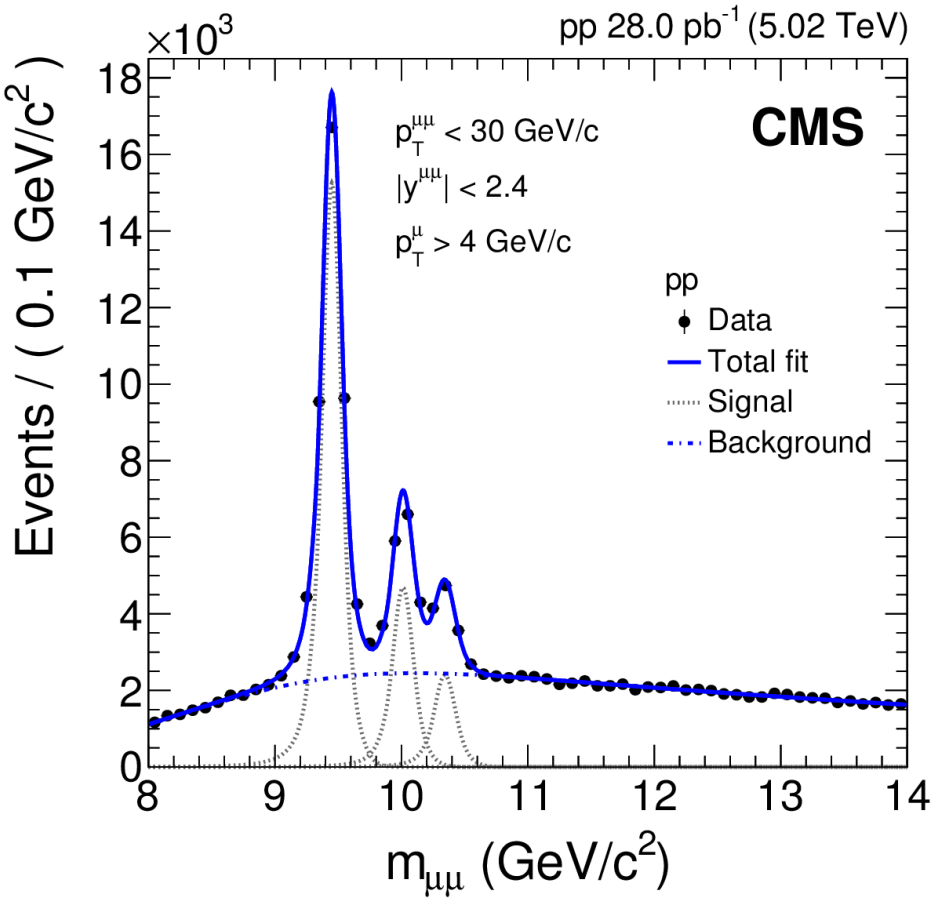


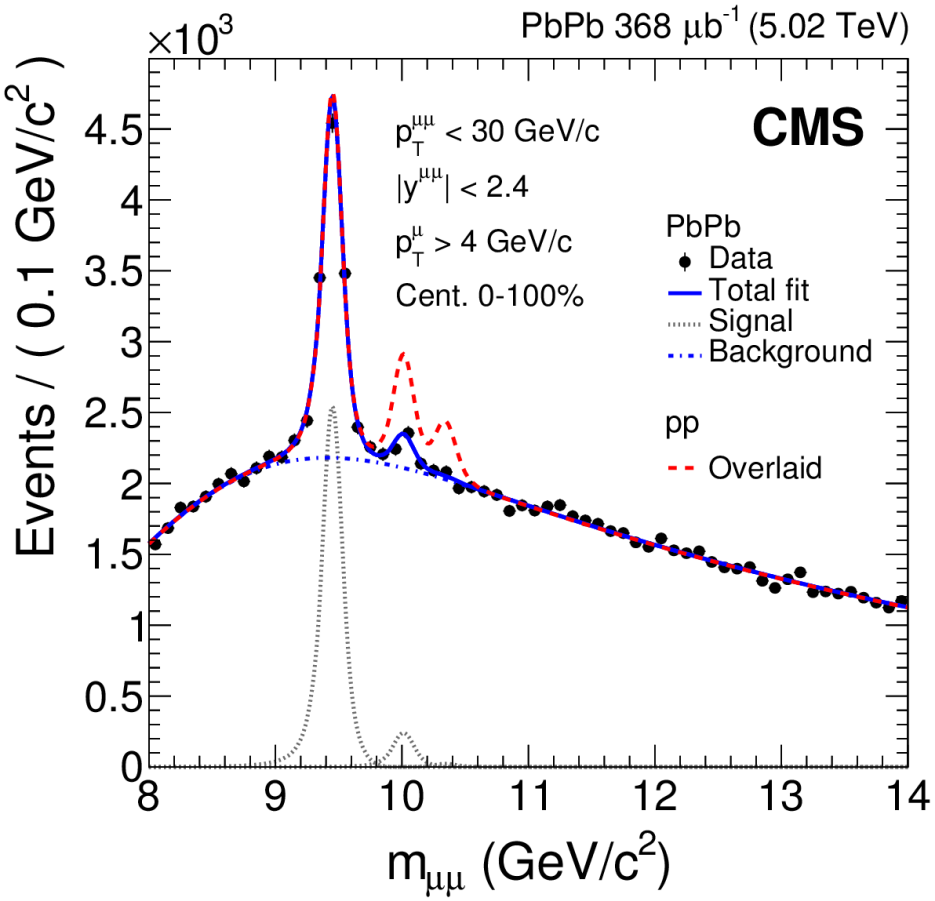
(high p_T)

- ψ(2S): relatively loose binding energy wrt J/ψ
- Difficult measurement in nuclear collisions
- Low and intermediate p_T: large uncertainties with the current data
- High p_T: Indication of a ψ(2S) suppression relative to J/ψ

Bottomonium suppression in Pb-Pb collisions

CMS, arxiv:1805.09215

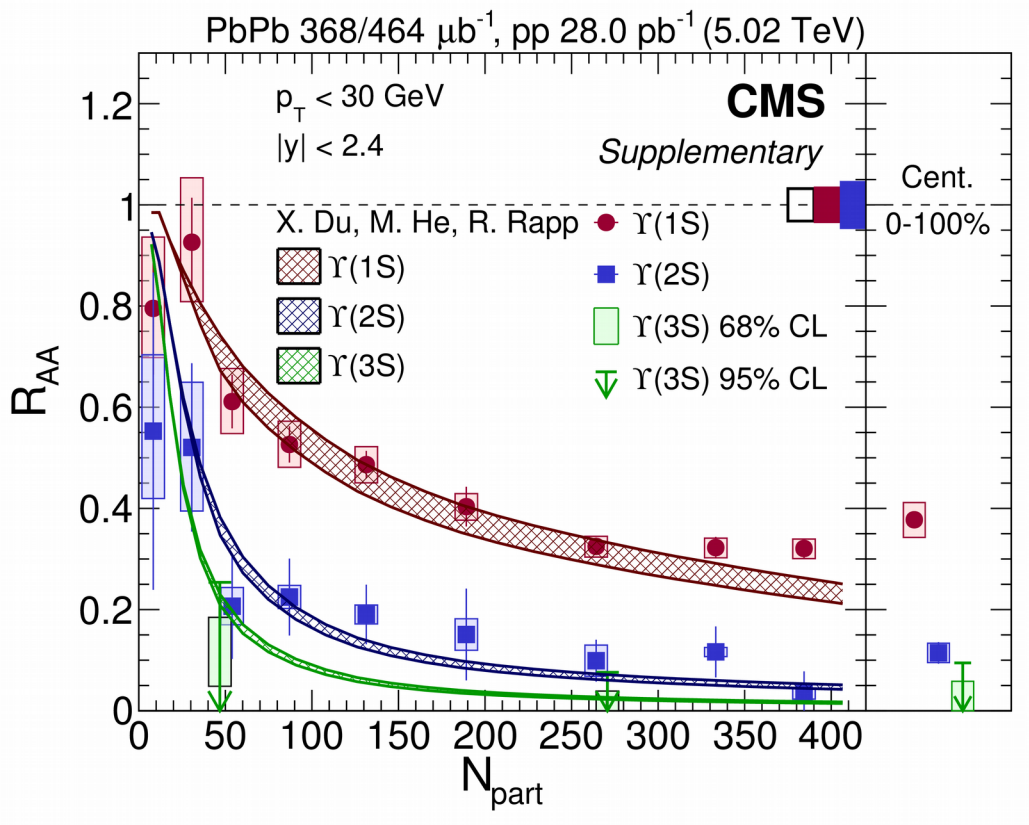




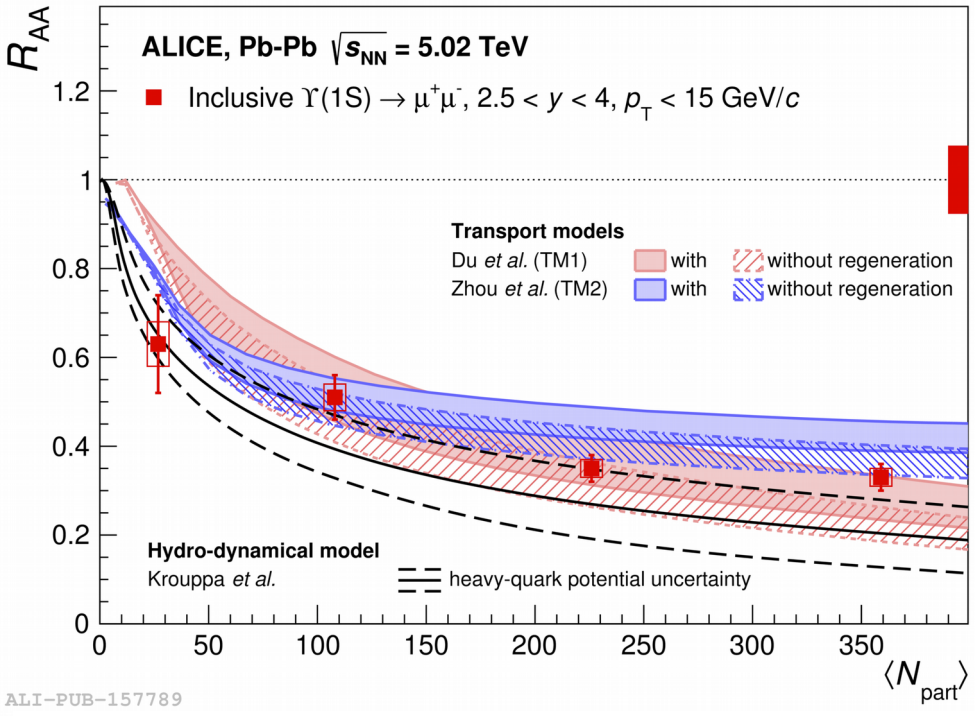
- Bottomonium less affected by recombination
- Clear suppression of the Y(2S) and Y(3S) relative to the ground state observed in Pb-Pb collisions wrt pp collisions

Inclusive Υ production vs centrality

CMS, arxiv:1805.09215



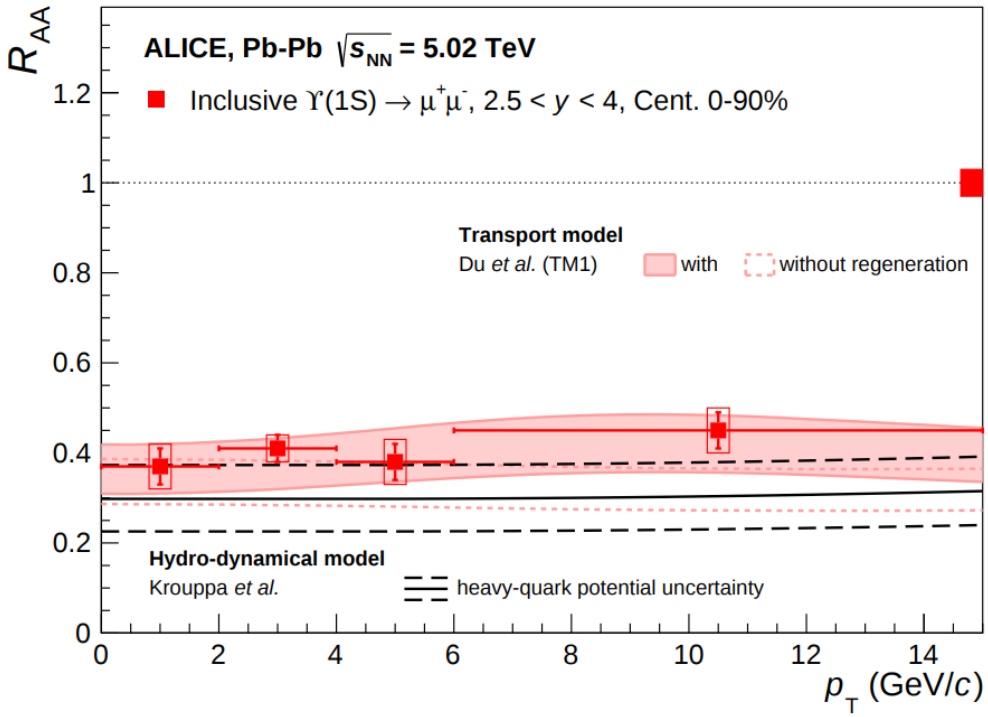
ALICE, arxiv:1805.04387

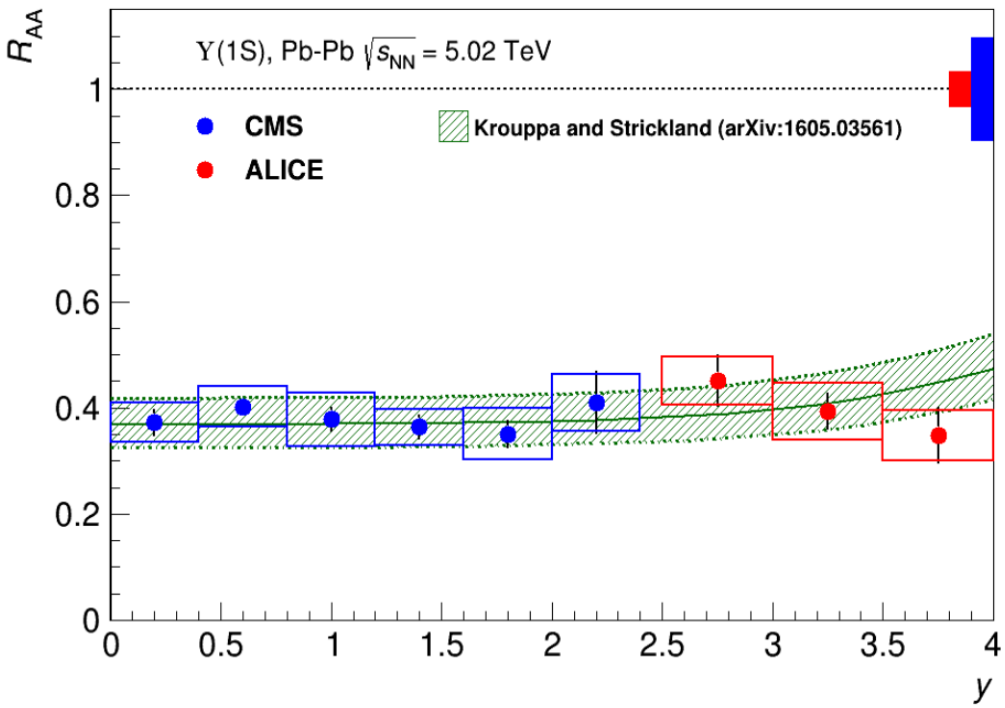


- Increasing suppression towards more central collisions
- Clear indication for sequential melting: $R_{AA}\{\Upsilon(1S)\} > R_{AA}\{\Upsilon(2S)\} > R_{AA}\{\Upsilon(3S)\}$
- Transport model calculations in agreement with data

Υ suppression in Pb-Pb collisions

ALICE, arXiv: 1805.04387

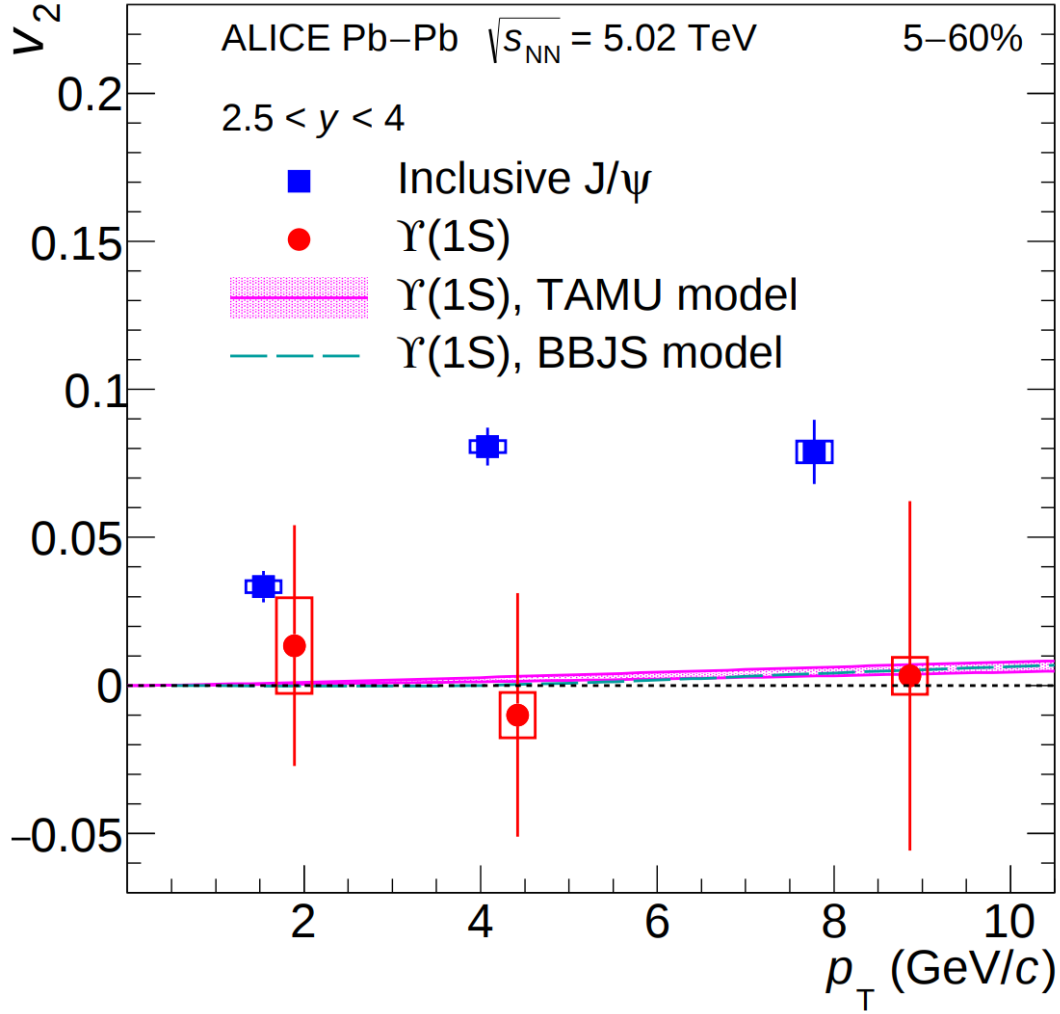




- None or very little p_T and rapidity dependence
- In agreement with model calculations
  - Eventual regeneration effects cannot be established with the current uncertainties

Υ elliptic flow

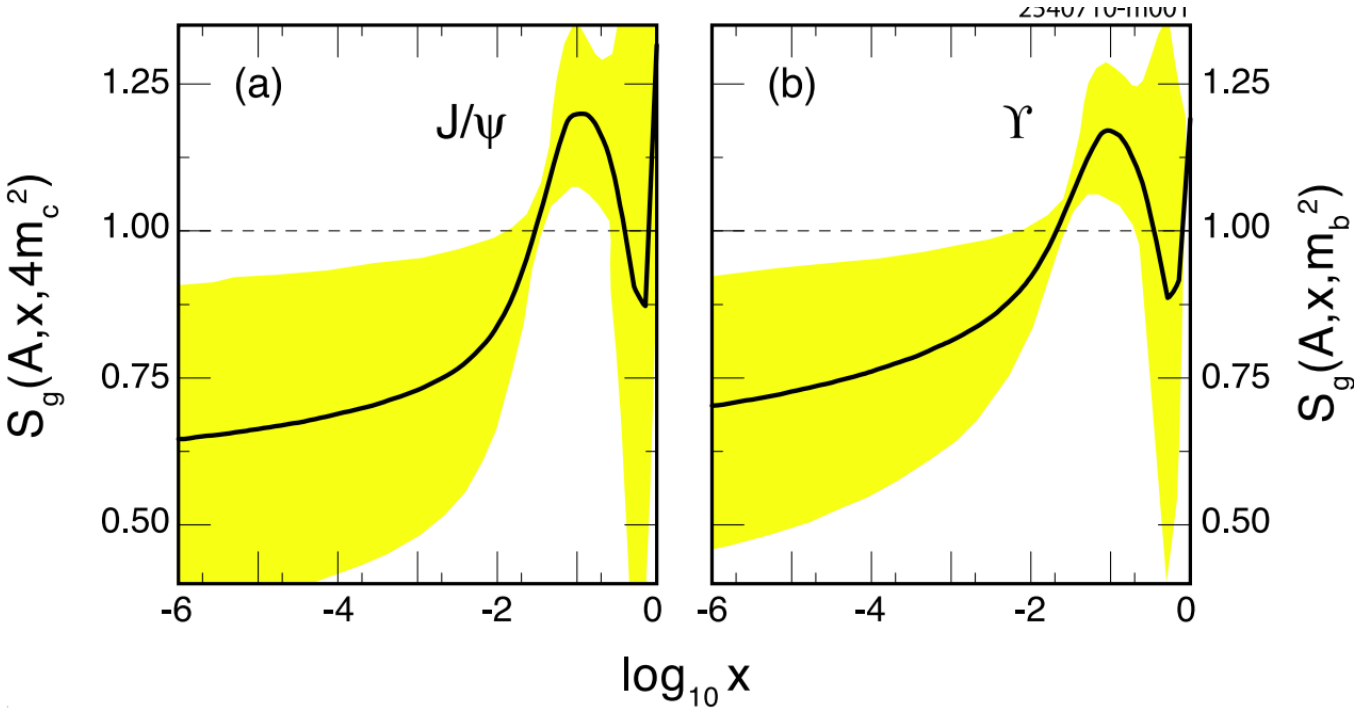
ALICE, arXiv: 1907.03169



- Υ(1S) elliptic flow measurement compatible with no flow, but large stat uncertainties
- Small v_2 expected from transport models, mainly from path length dependent dissociation within QGP

Cold nuclear matter (CNM) effects

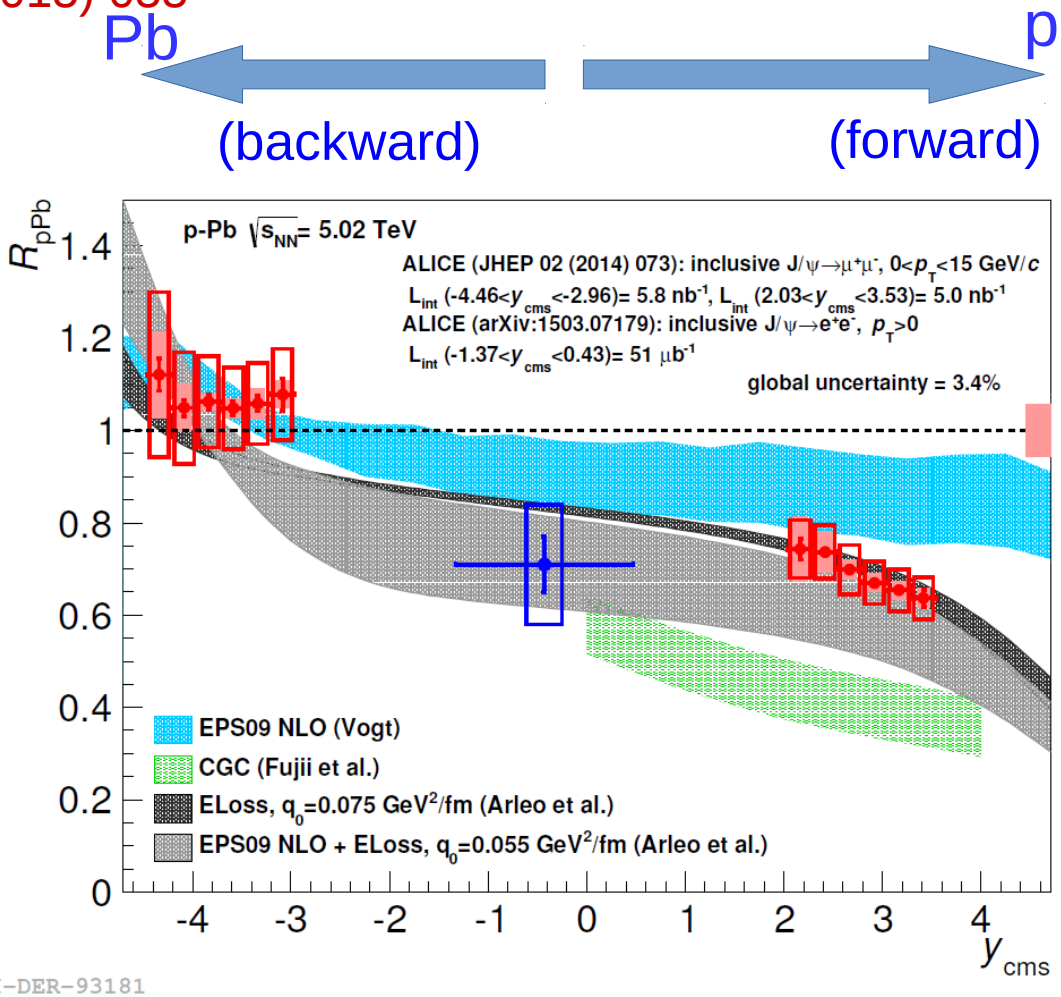
EPS'09



- CNM effects need to be disentangled:
  - modification of the PDFs in nuclear matter (shadowing, CGC), coherent energy loss, comover interaction, Cronin, ...
- Studied usually using proton-nucleus collisions

Inclusive J/ψ in p-Pb collisions

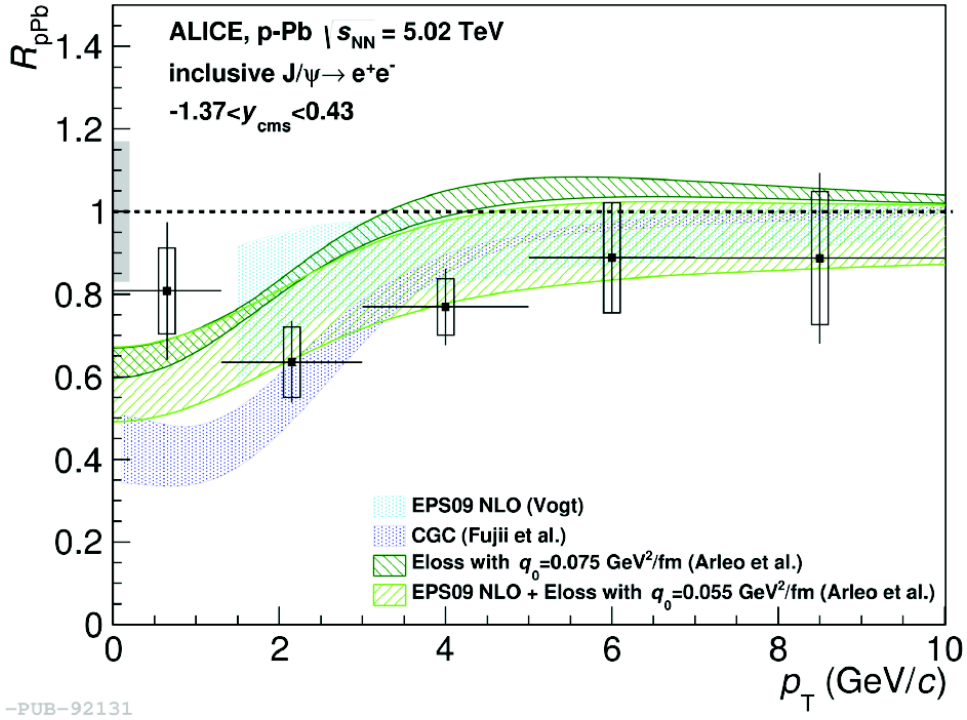
ALICE, JHEP06 (2015) 055

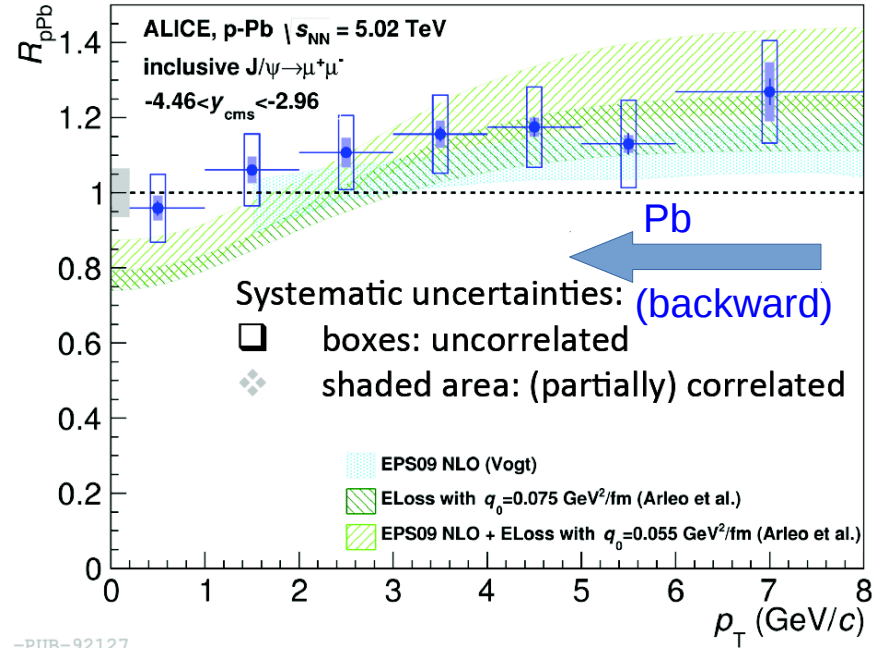


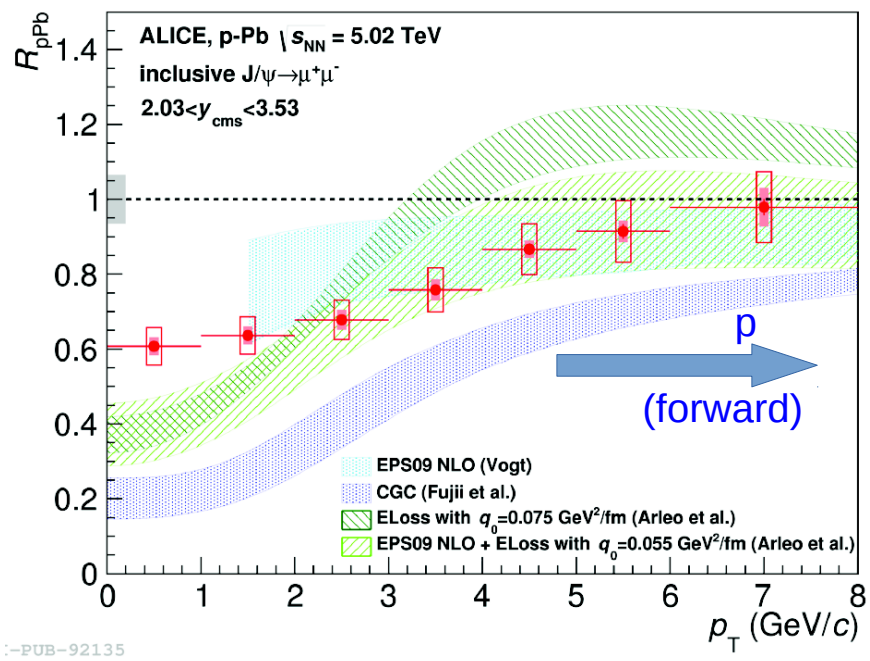
- Mid- and fwd-y:
  - Suppression beyond expectations from pure shadowing at forward rapidity
  - Coherent energy loss models in good agreement to the data

Inclusive J/ψ in p-Pb collisions

ALICE, JHEP06 (2015) 055





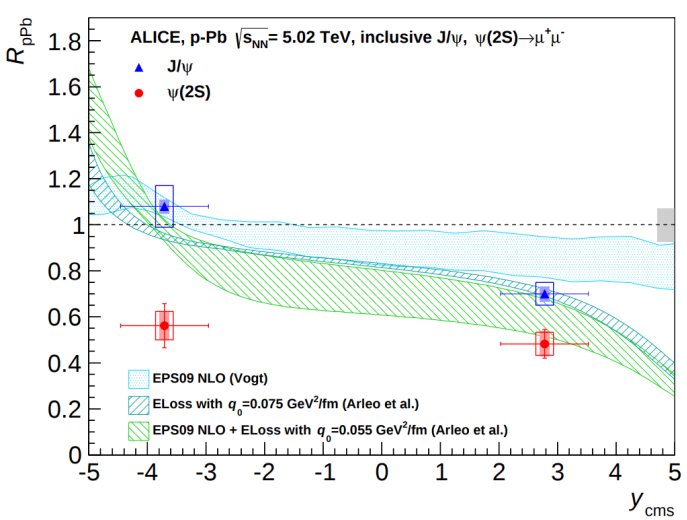


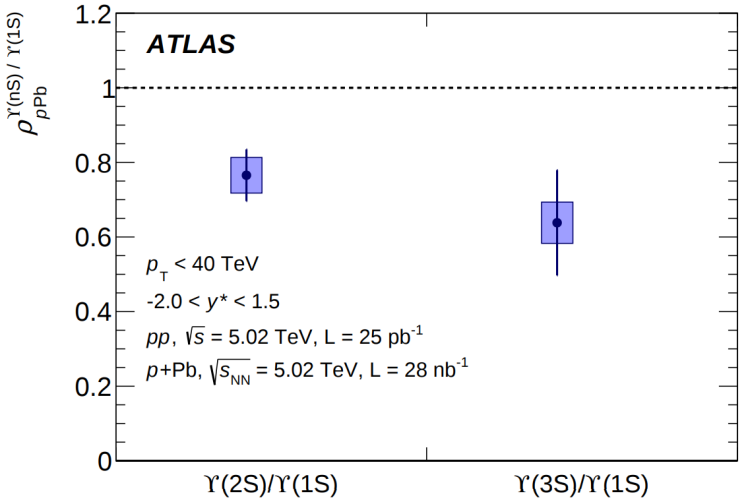
- J/ψ is suppressed at mid- and forward rapidity, except for the highest-p_T region
- Calculations of coherent energy loss w/ or w/o EPS09 shadowing qualitatively predict the data, but overestimate suppression at low p_T

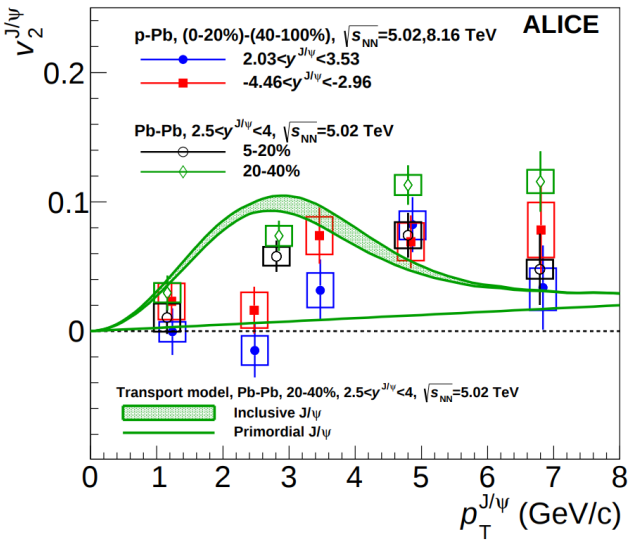
Initial state for quarkonium observables

- Initial state / CNM effects tipically derived from p-Pb collisions, however:

ALICE, JHEP12 (2014) 073



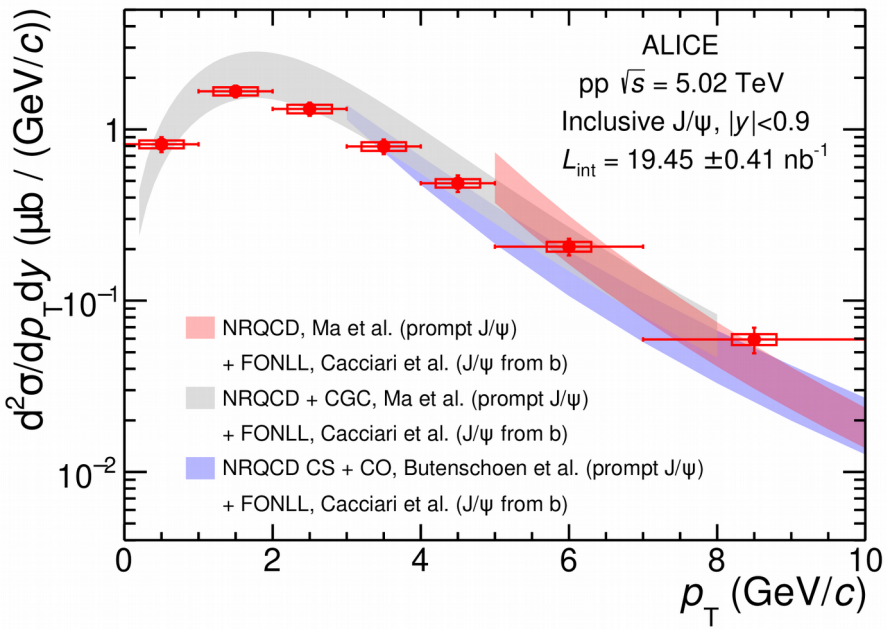


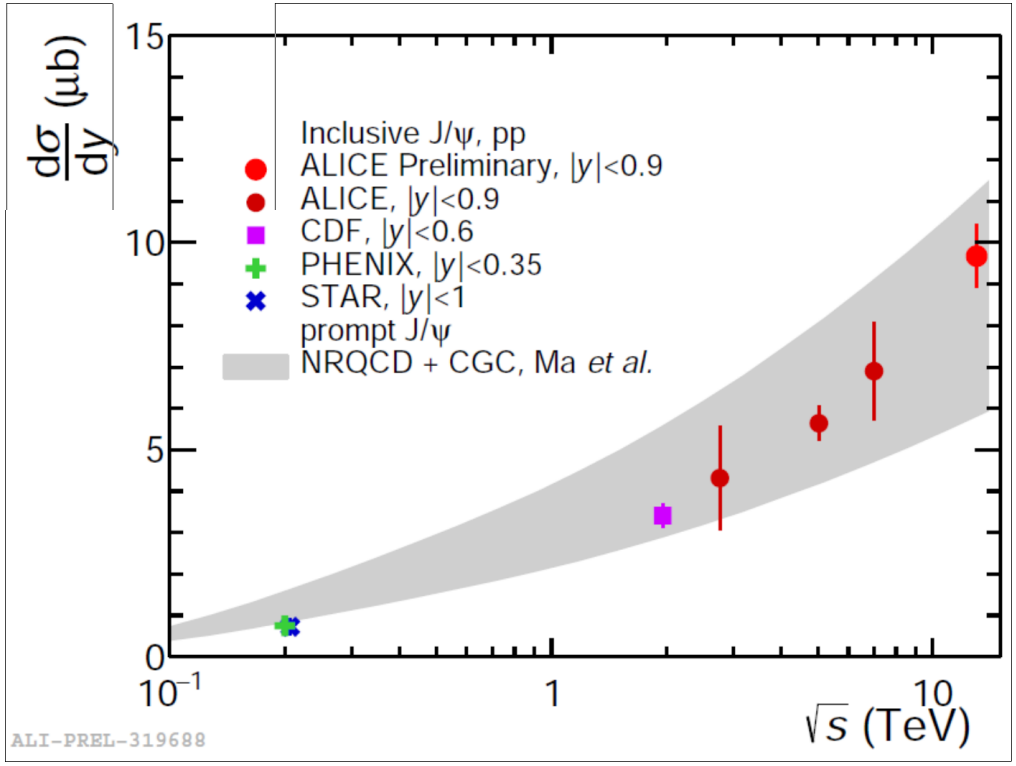


- Higher suppression observed for quarkonium excited states wrt ground states in p-Pb collisions
  - Not expected from nPDF modification or initial state Eloss models
- Long range J/ψ – hadron correlations: hint of collective effects on heavy quarks
- Strong indication that final state effects are present in p-Pb: comovers, QGP droplet?
  - The p-Pb collisions might not be an ideal cold system reference for Pb-Pb observations...

J/ψ production in vacuum

ALICE Collaboration

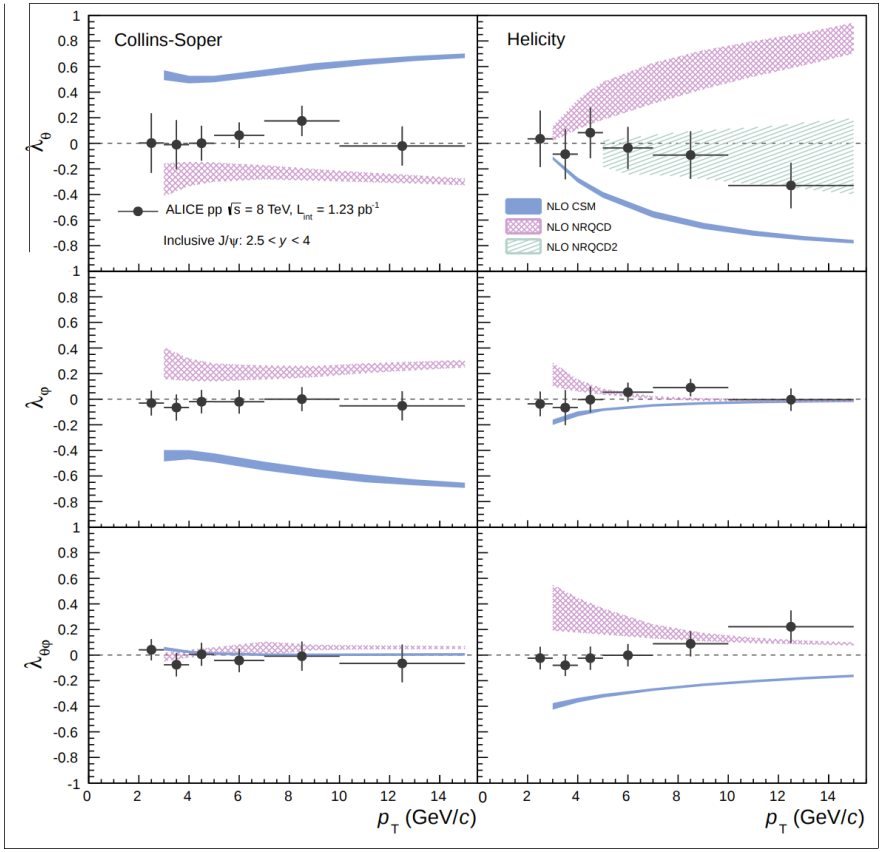


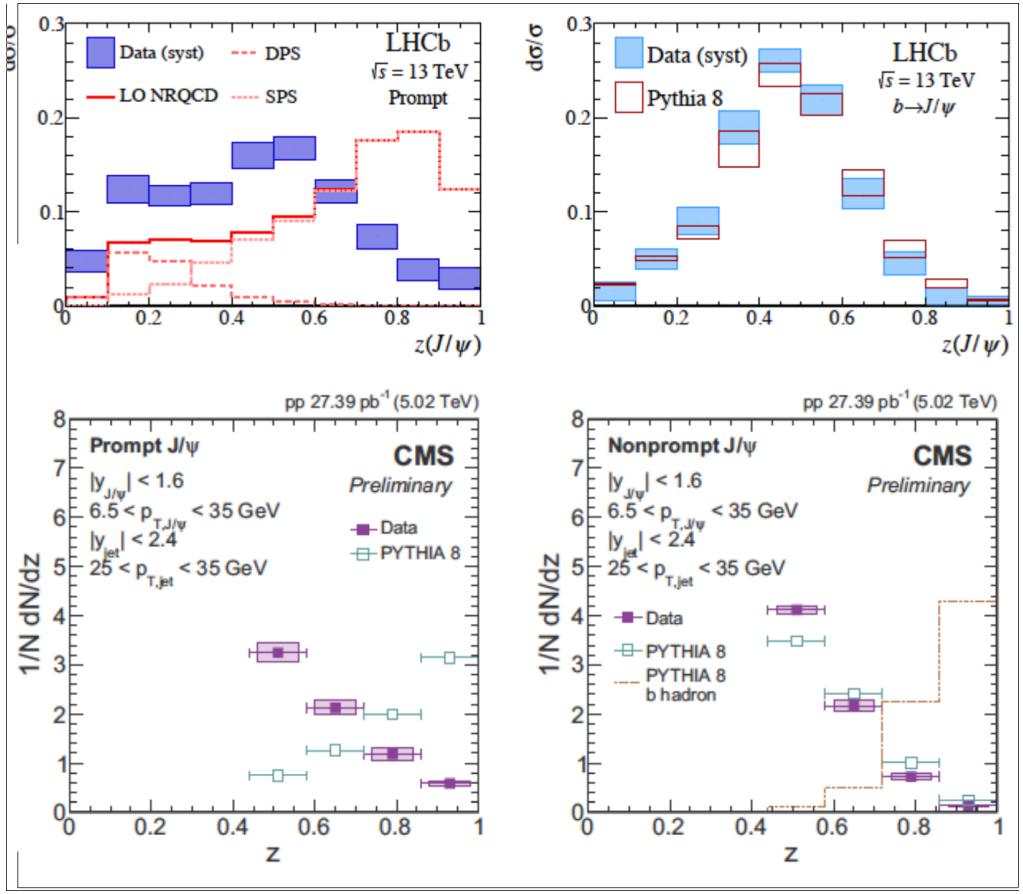


- NRQCD (+CGC): qualitative description of cross-sections
  - Description of both cross-section and polarization still difficult
  - Large uncertainties due to factorization scale, charm quark mass
  - Can some of these uncertainties be reduced using these measurements?

J/ψ production in vacuum

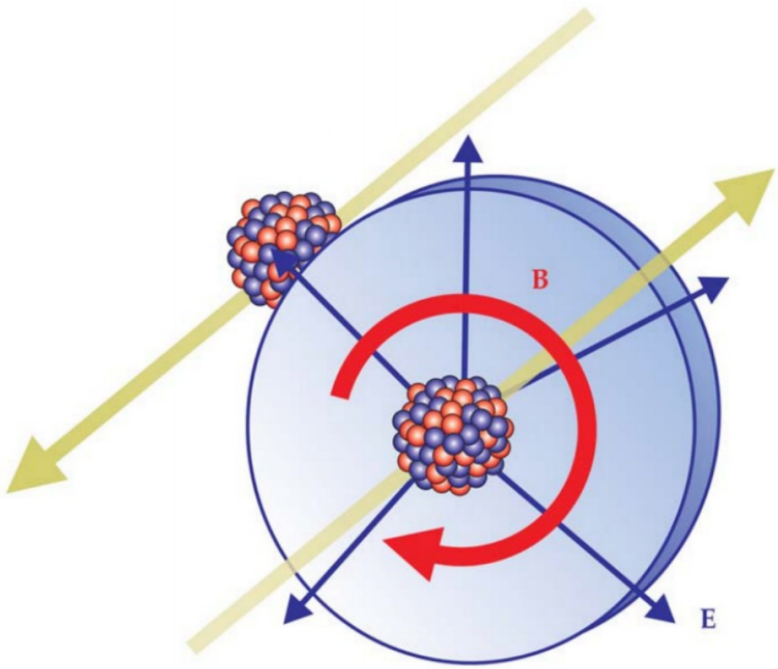
ALICE Collaboration

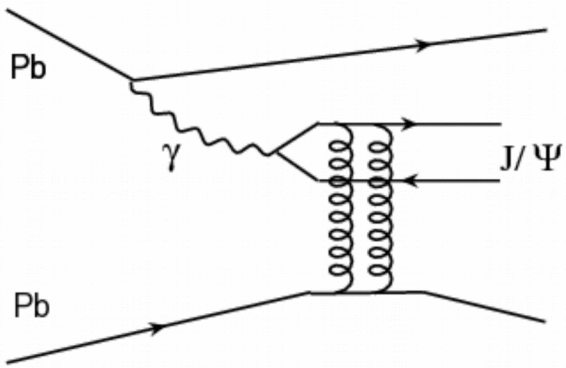




- NRQCD (+CGC): qualitative description of cross-sections
  - Description of both cross-section and polarization still difficult
  - Large uncertainties due to factorization scale, charm quark mass
- Jet fragmentation to J/ψ not well reproduced in pythia

Exclusive vector meson production in ultra-peripheral collisions (UPC)





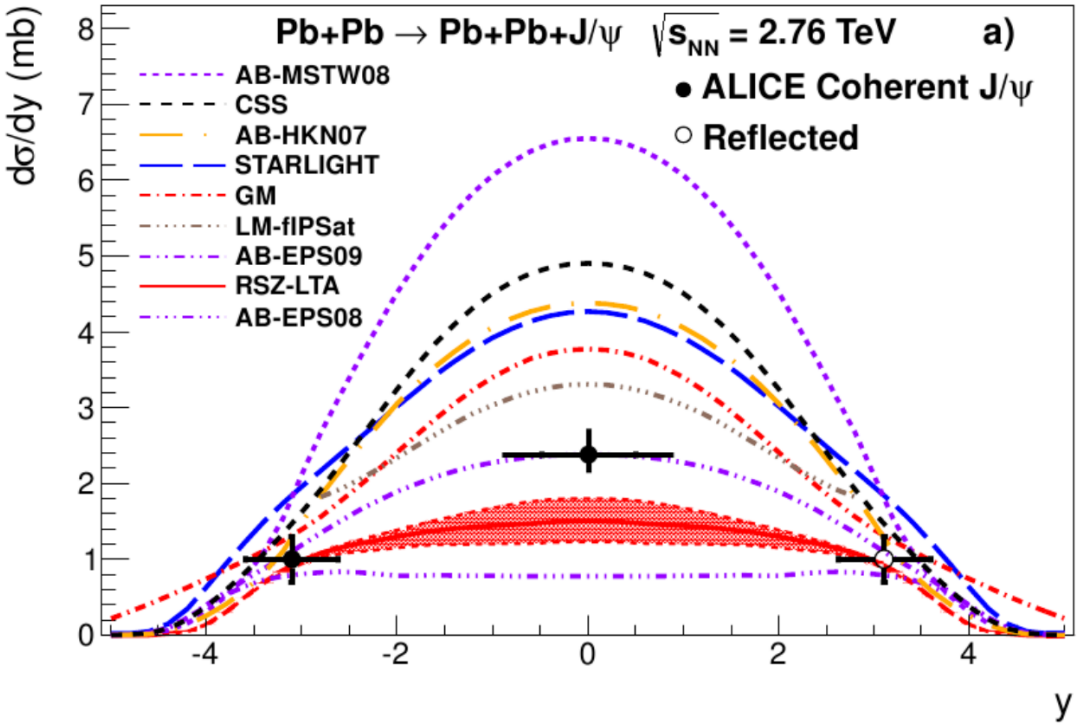
$$\frac{d\sigma}{dt}\Big|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xg\left(x, \frac{M_V^2}{4}\right)\right]^2$$

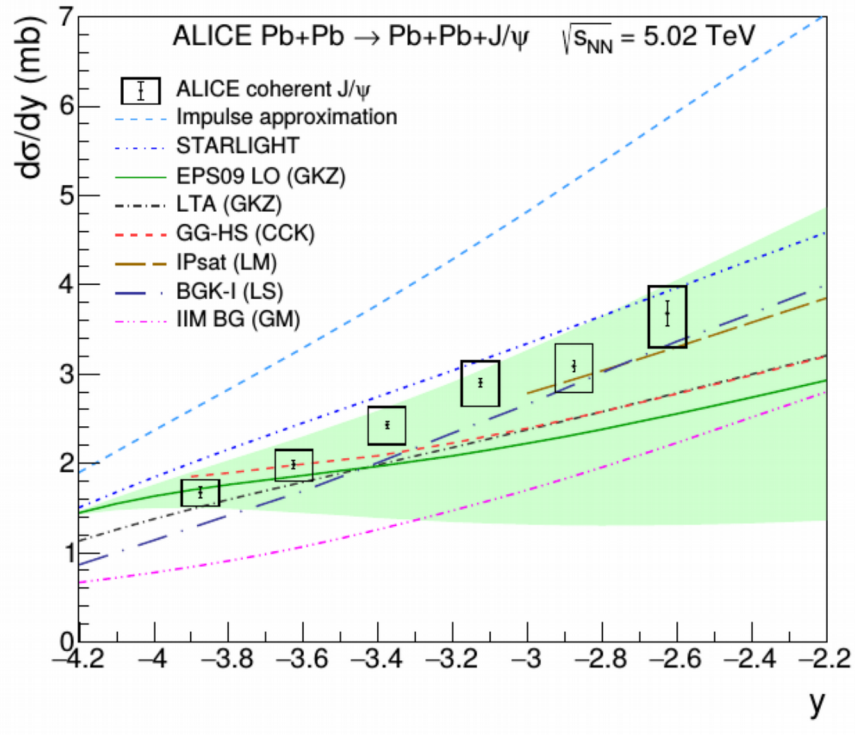
- Collisions between nuclei with b>2R
- Strong interactions are suppressed
- Electro-magnetic fields correspond to a photon flux
  - Study of two-photon and photo-nuclear interactions

- LO: Ryskin 1993
- NLO: work ongoing

(*S.P.Jones et al., J.Phys.G43 (2016) 035002*)

Exclusive vector meson production in ultra-peripheral collisions (UPC)

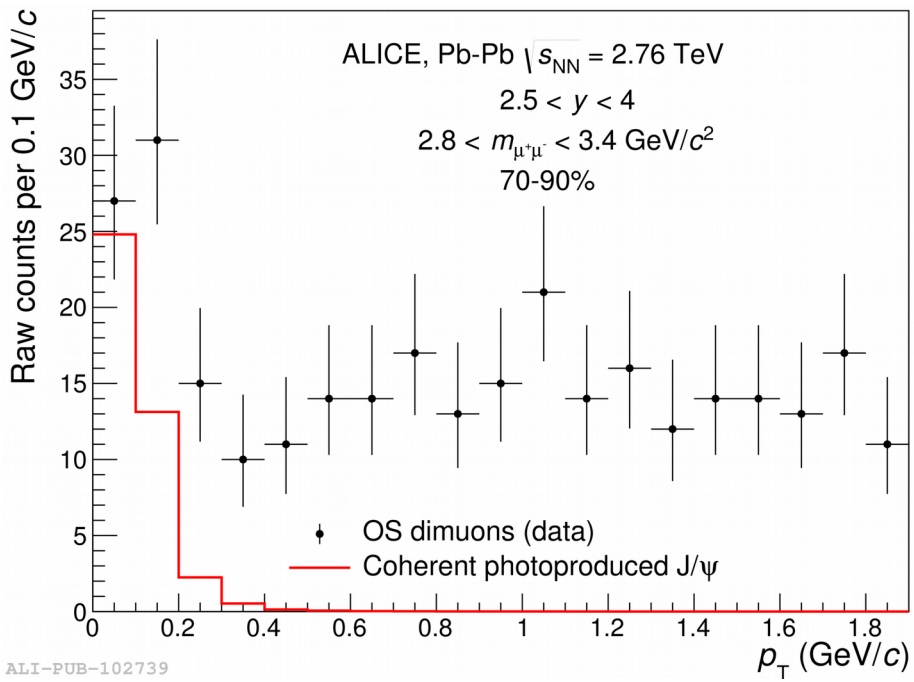


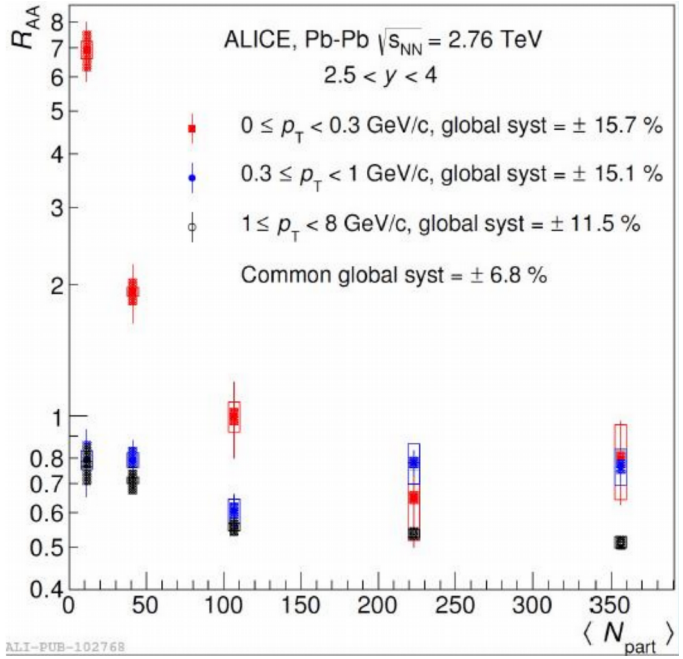


- Measurements consistent with moderate shadowing (EPS09)

J/ψ photo-production in Pb-Pb collisions with b<2R

ALICE, PRL116 (2016)222301

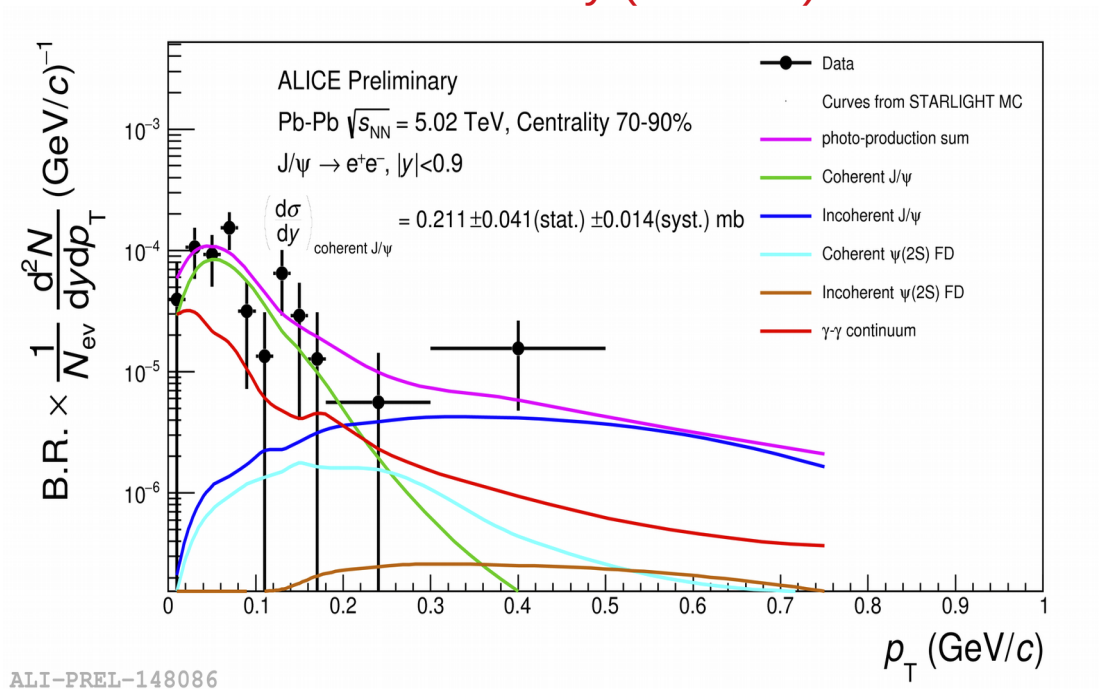


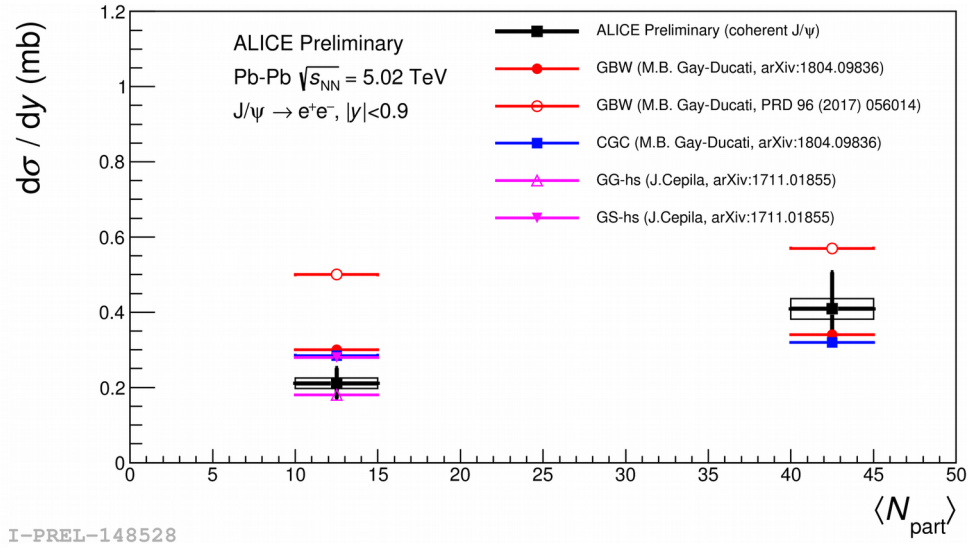


- J/ψ excess observed at very low-p_T (pT<300 MeV) at forward rapidity in peripheral Pb-Pb collisions at 2.76 TeV
- Likely origin: coherent photo-production

J/ψ photo-production in Pb-Pb collisions with b<2R

Mid-y (70-90%)



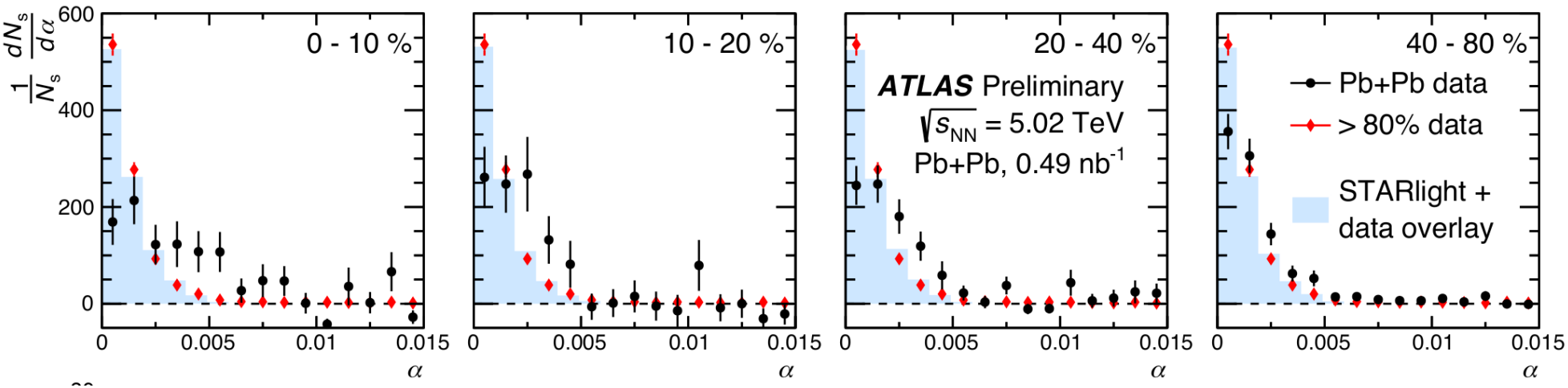


- Excess present also at mid-y using Pb-Pb data (2015) at 5.02 TeV
- Characteristic p_T spectrum for photo-production, as also observed in ultra-peripheral collisions (UPC)
- Unique opportunity for photo-nuclear physics: impact parameter and reaction plane dependent measurements

W. Zha, S.Klein et al., PRC97 (2018) 044910

Di-lepton production in electromagnetic interactions

ATLAS Collaboration, PRL121(2018)212301



$$\alpha = 1 - \frac{\phi^1 - \phi^2}{\pi}$$

- Hadronic physics: novel “probe” of the fireball?
- Acoplanarity of photo-produced di-muon pairs increasing towards central collisions
  - Charged leptons interactions with electric charges in the QGP

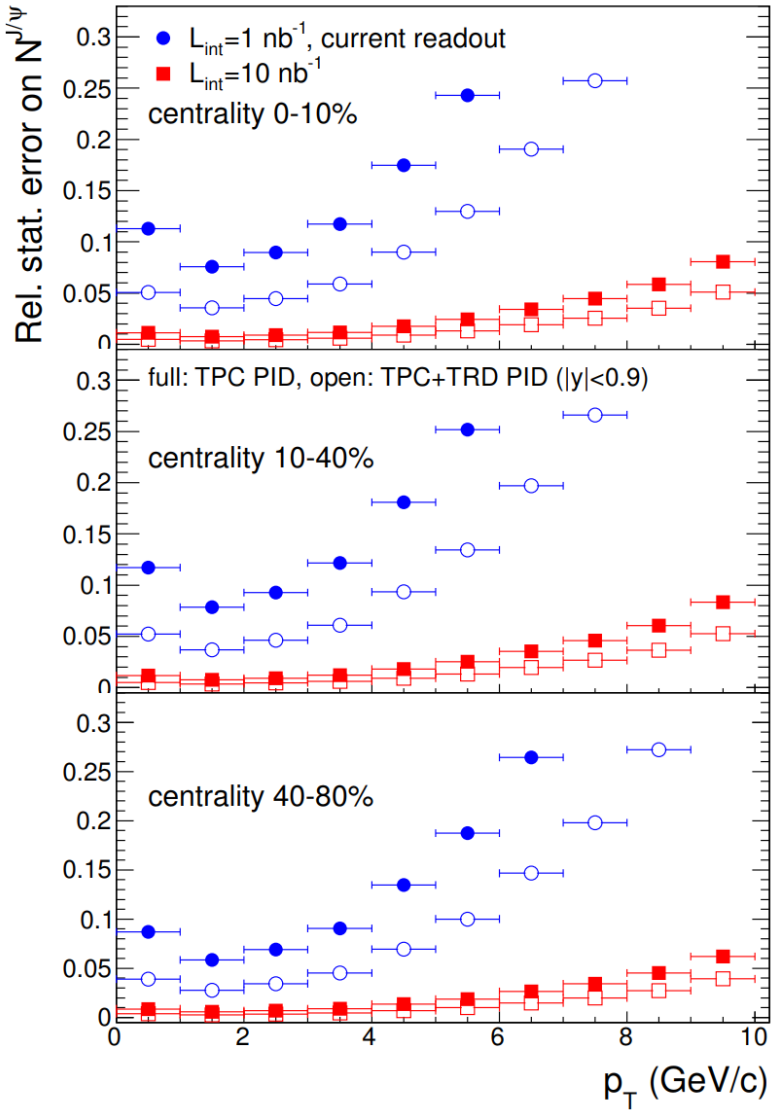
LHC Run3+4 (Pb-Pb)

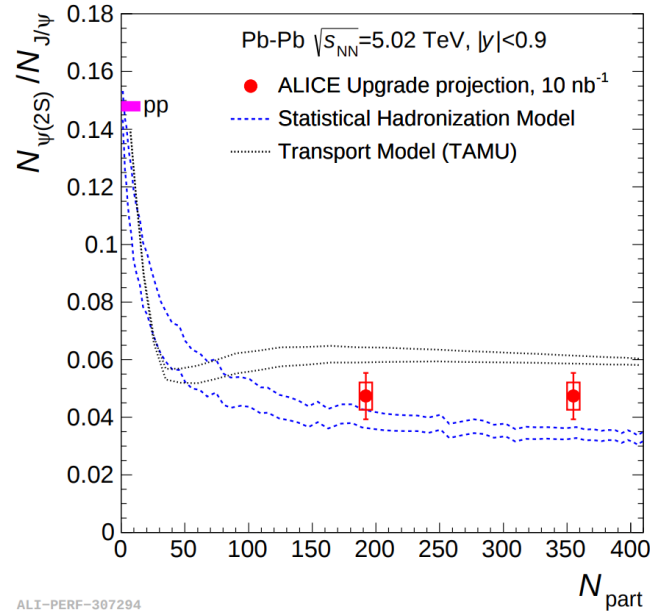
Year	Systems, time, L_{int}	Total per Run (3 and 4)
2021	Pb-Pb, 3 weeks: 2.3/nb pp 5.5, 1 week	Pb-Pb: 6.2/nb p-Pb 8.8: 0.6/pb ATLAS,CMS, 0.3/pb ALICE/LHCb pp 5.5: 3/pb ALICE, 350/pb ATLAS/CMS pp 8.8: 100/pb ATLAS/CMS, 50/pb LHCb, ALICE few/pb O-O: few 100/μb p-O
2022 (extended from 4 to 6 weeks)	p-O + O-O 7 TeV, 1 week (after EYETS?) Pb-Pb, 5 weeks: 3.9/nb	
2023	pp 8.8 TeV, few days p-Pb 8.8 TeV, 3.x weeks	
LS3	ATLAS/CMS upgrades, ALICE: ITS3? FoCal?	
2027	Pb-Pb, 3 weeks 2.3/nb pp 5.5, 1week	Pb-Pb: 6.8/nb p-Pb: 0.6/pb ATLAS,CMS, 0.3/pb ALICE/LHCb pp 5.5: 3/pb ALICE, | 350/pb ATLAS/CMS pp 8.8: 100/pb ATLAS/CMS, 50/pb LHCb, ALICE few/pb
2028 (extended from 4 to 6 weeks)	Pb-Pb, 2 weeks: 1.5/nb p-Pb 8.8 TeV, 3.x weeks pp 8.8 TeV, few days	
2029	Pb-Pb, 4 weeks: 3/nb	

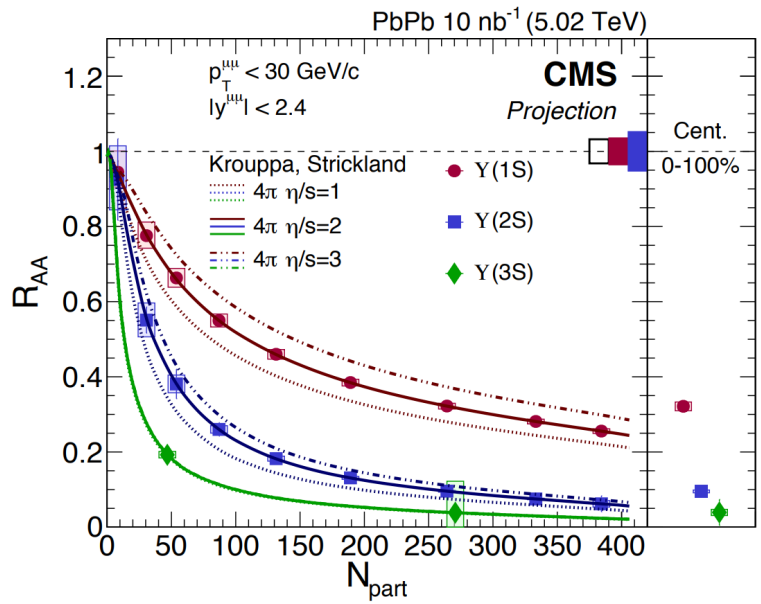
- Pb-Pb (ALICE): ~13 nb^{-1} (> 100x current ALICE lumi at mid-y) !!
- p-Pb (ALICE): ~0.6 pb^{-1}
- Physics projections: *ALICE Collaboration, J.Phys.G41(2014)8,*
  Z.Citron et al., arxiv:1812.06772

Projections for Pb-Pb measurements at mid-y in Run3+4

ALICE Collaboration, J.Phys.G41(2014)8
Z.Citron et al., arxiv:1812.06772

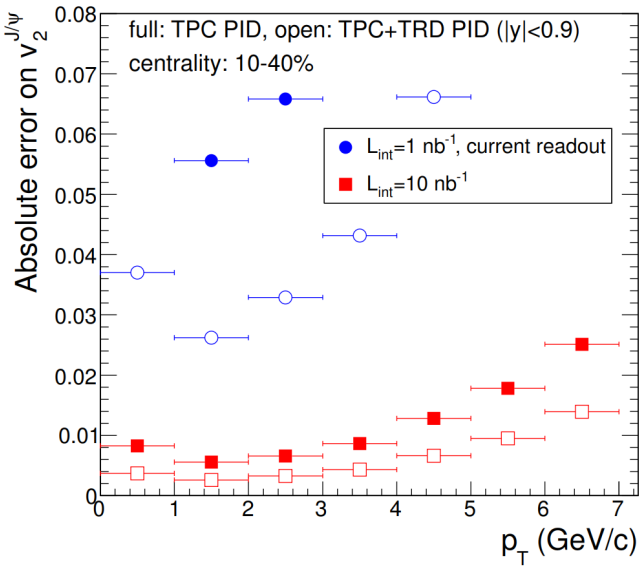


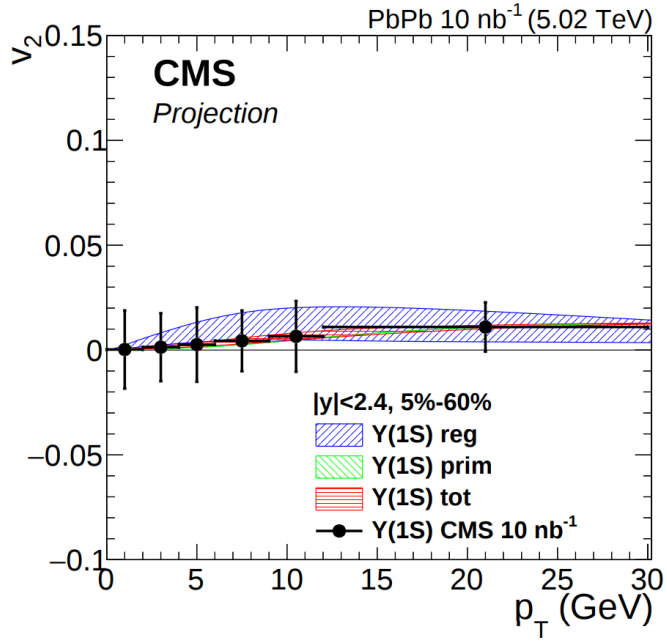


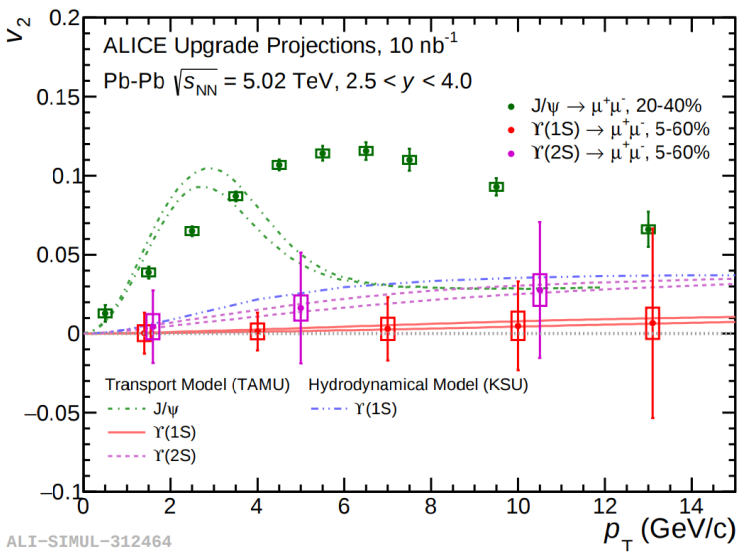


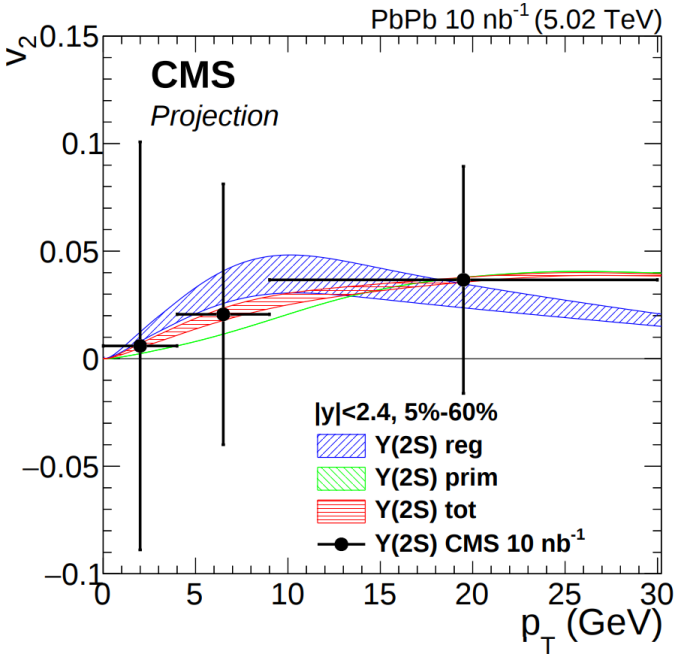
Projections for Pb-Pb measurements at mid-y in Run3+4

ALICE Collaboration, J.Phys.G41(2014)8
Z.Citron et al., arxiv:1812.06772









Projections for pp measurements at 14 TeV (ALICE)

- Ongoing discussions on possibility to have an extensive pp at 14 TeV physics programme enabled by the use of “High-Level Triggering” (HLT)
- Inspected lumi reachable with Central Barrel: 200 pb^{-1}
- Work ongoing for an p_T>0 J/ψ HLT which would produce ~3.0e+7 J/ψ counts
- “Infinite” statistics for looking into J/ψ production mechanisms
  - Prompt / non-prompt cross-sections, polarization
  - J/ψ – hadron correlations
  - J/ψ production in jets
- Higher mass charmonia, bottomonium, exotics
- High multiplicity pp events: study of final state and collective effects
  - excited/gound state ratios, flow-like long range correlations

Summary

- In medium transport properties and bulk properties studied using the R_{AA} and anisotropic flow measurements of quarkonia (and open heavy-flavor mesons)
  - Large hadronization (quark recombination) effects on J/ψ R_{AA}
  - Significant v_2 and ESE dependence suggests charm thermalization
  - Clear mass hierarchy seen for Υ family suppression → sequential melting

- p-Pb puzzles
  - Elliptic flow of J/ψ and D
  - Larger suppression for excited states wrt ground state:
    - ψ(2S) / J/ψ, Υ(2S)/Υ(1S)
  - Strong suggestion of final state effects

- Quarkonium production in pp not yet fully understood in NRQCD
  - Novel approaches needed: J/ψ-hadron correlations, J/ψ production in jets

- J/ψ photo-production Pb-Pb ultra-peripheral collisions possible constrain for gluon nPDF
- Observation of J/ψ and di-lepton photo-production in Pb-Pb collisions with overlap opens novel physics opportunities

Outlook

- Constraining of the initial state:
  - total $Q\overline{Q}$ cross-section in pp collisions
  - J/ψ production mechanisms
  - nuclear PDFs (p-Pb, UPC measurements?)
- Precision measurements
  - Quarkonium R_{AA}, flow harmonics, event shape engineering
- excited states (ψ(2S), χ_c, Υ(3S), …), possibly also exotic states, e.g. X(3872) ?
- Novel observables: jet fragmentation in J/ψ
- Theory: crucial to go beyond statistical and semi-classical transport models in order to make inferences on QGP properties and in-medium QCD force
  - First steps have already been done, e.g.
    - Wave function decoherence via screened potential models + HQ scattering in plasma (*Kajimoto, Akamatsu, Asakawa, Rothkopf, arxiv:1705.03365v2*)
    - Screened thermal potential and formation time effects (*Aronson, Borras, Odegard, Sharma, Vitev, arxiv:1709.02372v2*)
    - Heavy-quark / Quarkonia jets in medium splitting (*Block and Tywoniuk, arxiv:1901.07864*)

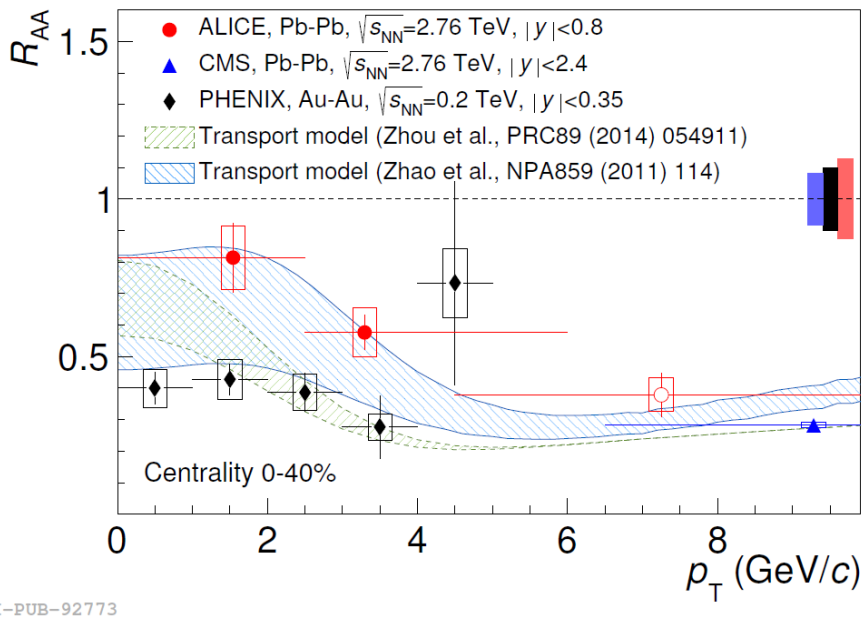
Backup

Plan

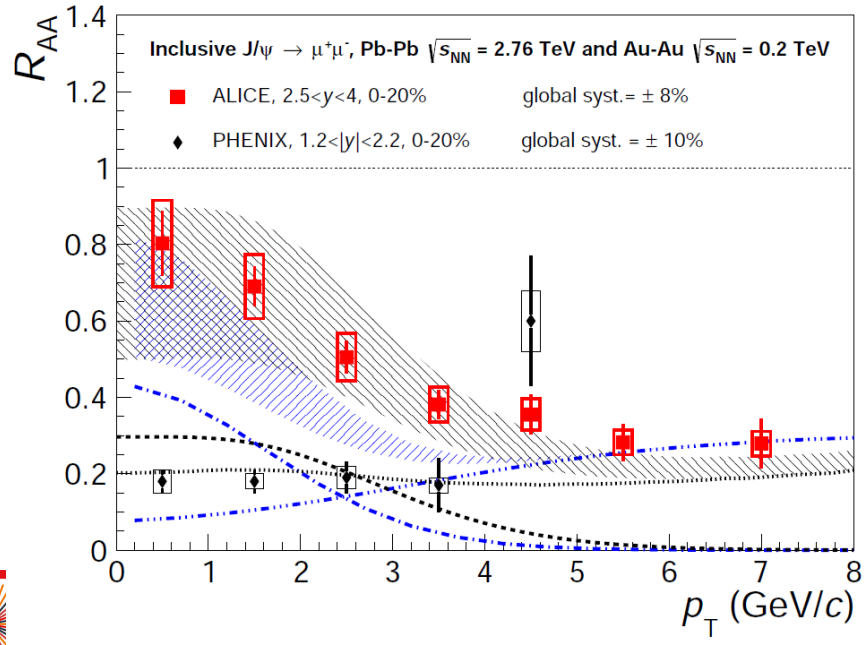
- Charmonium
  - Recombination: problem or not?
- Bottomonium
  - Pros and cons with charmonium:
    - Pro: small regeneration
    - Cons: large feed-down → poorly measured
      - Do we see direct Ups(1S) suppression? Not clear due to large feed-down
- Probe of bulk properties? See latest lattice calculations, SHM
  - Temperature history profile?
  - Thermalization time scale?
  - Viscosity???
  - diffusion
- Probe of micro properties? (transport coef, something else?)
  - Check Ivan Vitev's latest calculations
  - Need to understand suppression pattern in plasma
    - Screening?
    - Dependence on associated production? What happens with quarkonium produced in jets? → jet fragmentation in plasma and vacuum
      - Quarkonia produced in jets → Crucial to understand jet fragmentation in quarkonia → look in pp and p-Pb also?
        - Jets fragmenting in vacuum
        - Jets fragmenting in plasma

J/ψ suppression vs p_T

ALICE, JHEP07 (2015) 051



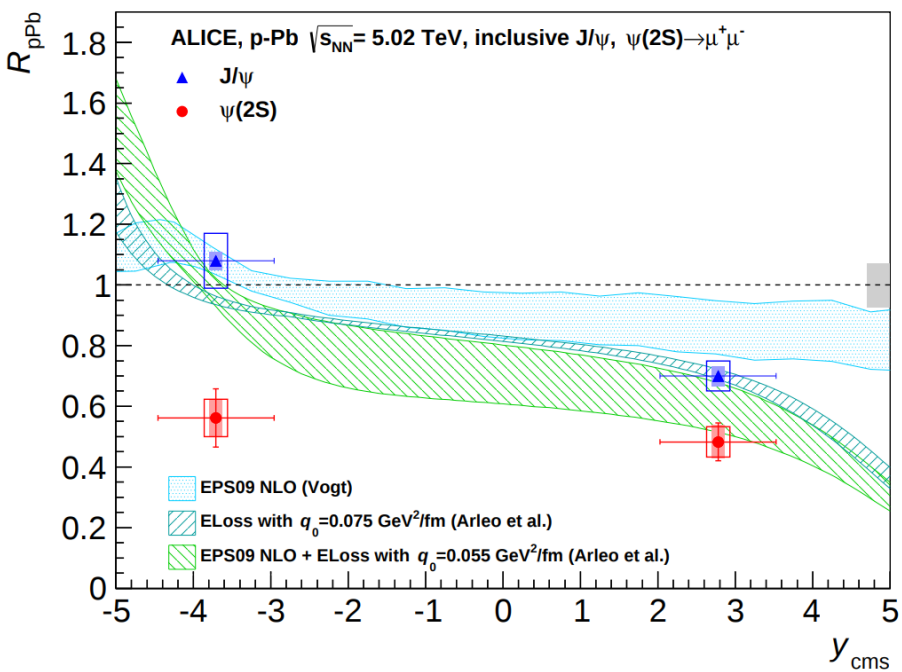
ALI-PUB-92773



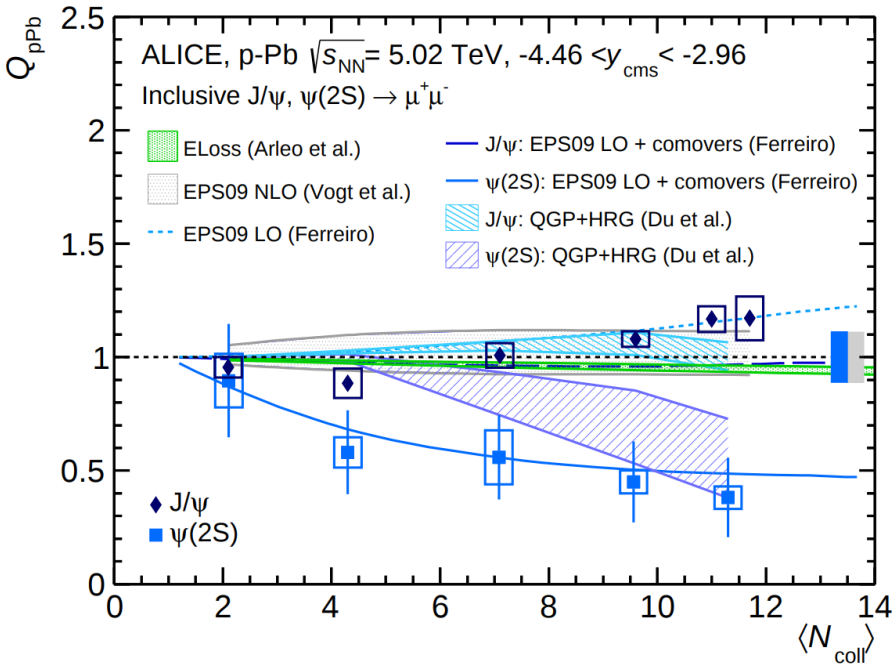
- Low p_T : striking difference between LHC and RHIC
- Quite clear support for (re)generation hypothesis
- Transport model calculations using regeneration describe qualitatively the data

ψ(2S) production in p-Pb collisions

ALICE, JHEP12 (2014) 073



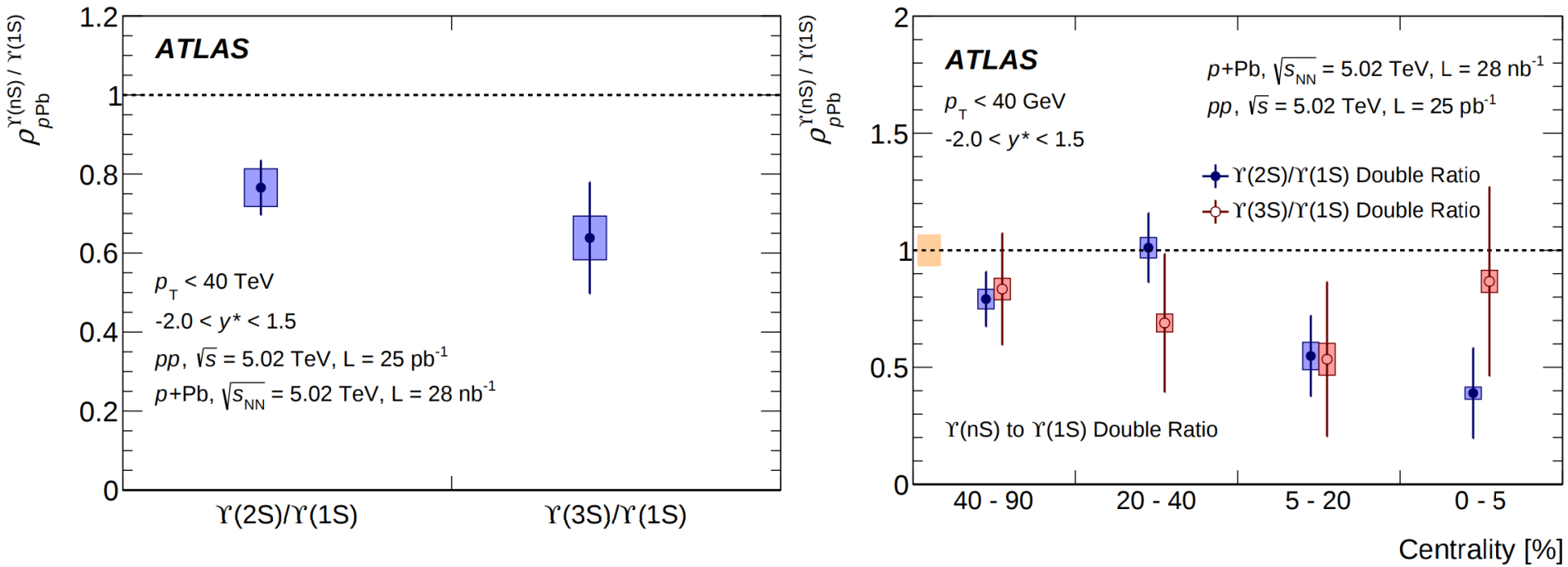
ALICE, JHEP06 (2016) 50



- Higher suppression for ψ(2S) wrt J/ψ in p-Pb collisions
  - Not expected from nPDF modification or initial state Eloss models
- Strong indication that final state effects are present in p-Pb
  - Comover interaction, QGP

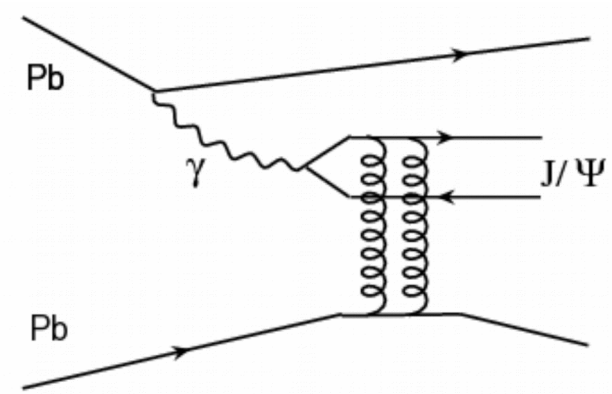
Υ(2S) and Υ(3S) production in p-Pb collisions

ATLAS, EPJC78 (2018) 171



- Excited Υ states are also more suppressed wrt ground state
- *Nota bene*: Υ(2S) binding energy is similar to J/ψ

Vector meson production in electromagnetic interactions

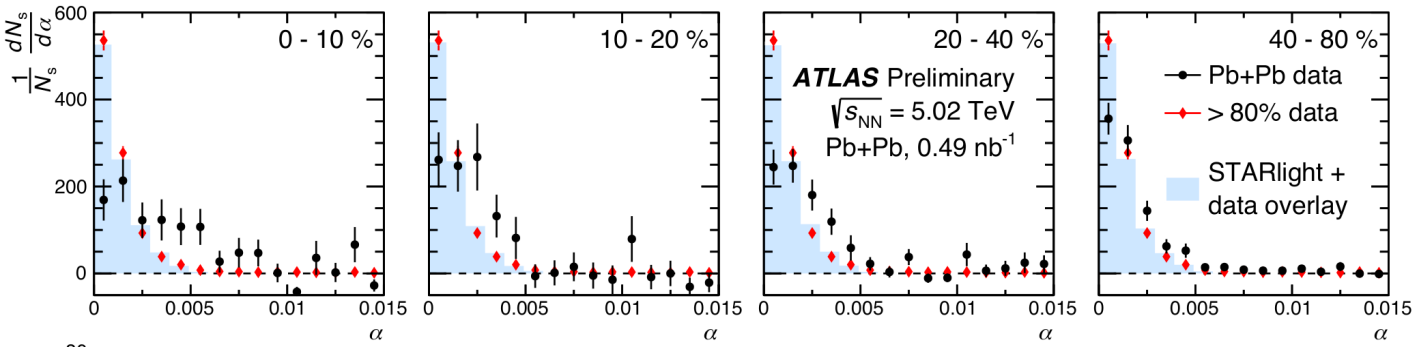


$$\frac{d\sigma}{dy} = k_1 \times \frac{dn}{dk_1} \times \sigma_{\gamma+A_2\to J/\psi+A_2} + k_2 \times \frac{dn}{dk_2} \times \sigma_{\gamma+A_1\to J/\psi+A_1}$$

$$\frac{d\sigma}{dt}\Big|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xg\left(x, \frac{M_V^2}{4}\right)\right]^2$$

- Unique opportunity for photo-nuclear physics: reaction plane dependent measurements
  W. Zha, S.Klein et al., PRC97 (2018) 044910

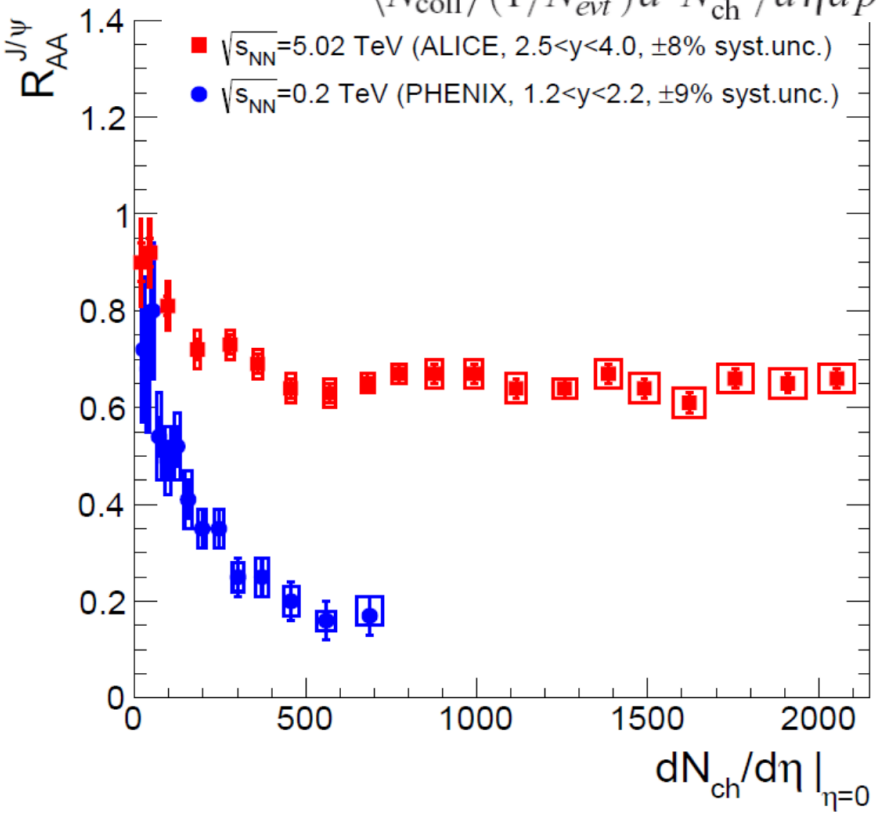
- Hadronic physics: novel "probe" of the fireball?

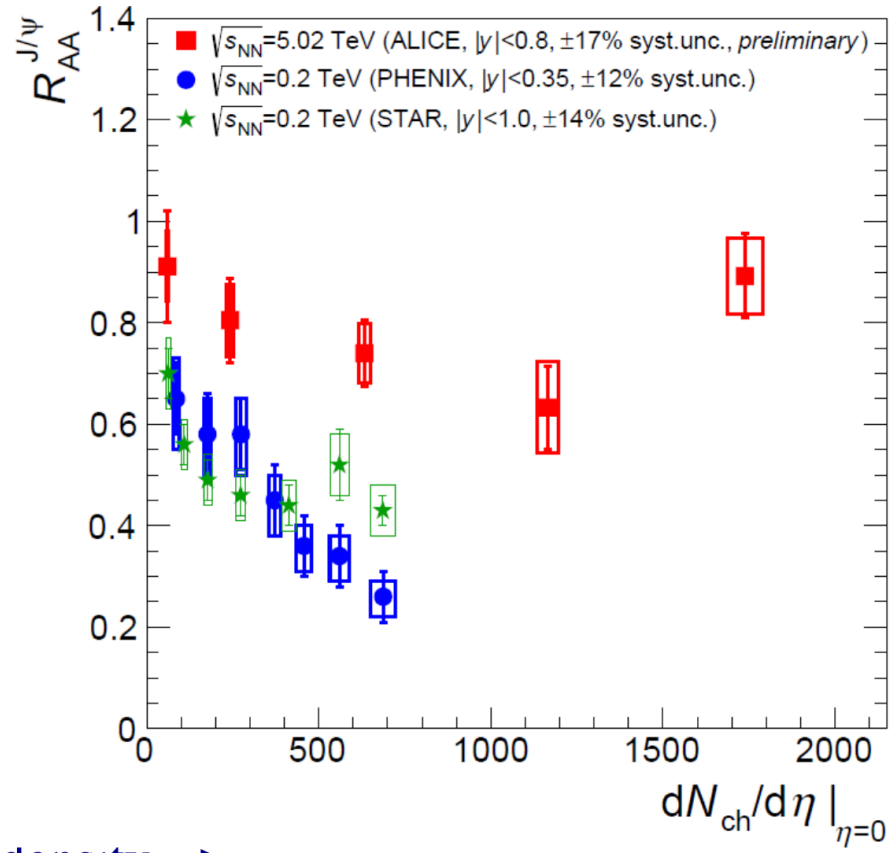


- Sensitivity to nuclear PDFs ?
  - LO: Ryskin 1993,
  - *NLO: S.P.Jones et al., J.Phys.G43 (2016) 035002*

Charmonium at the LHC vs RHIC

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

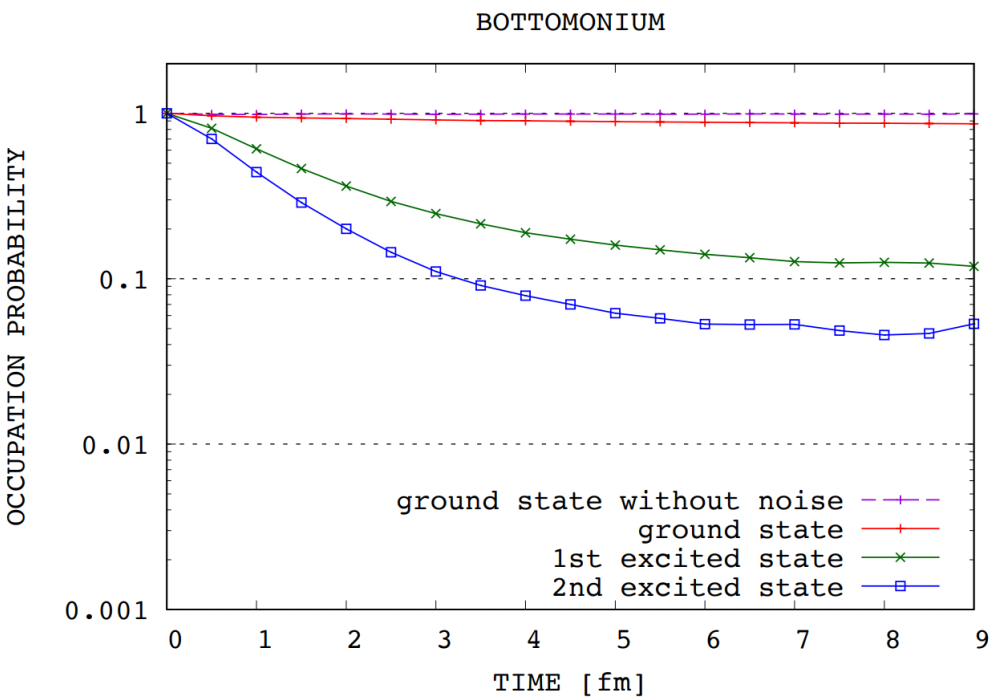


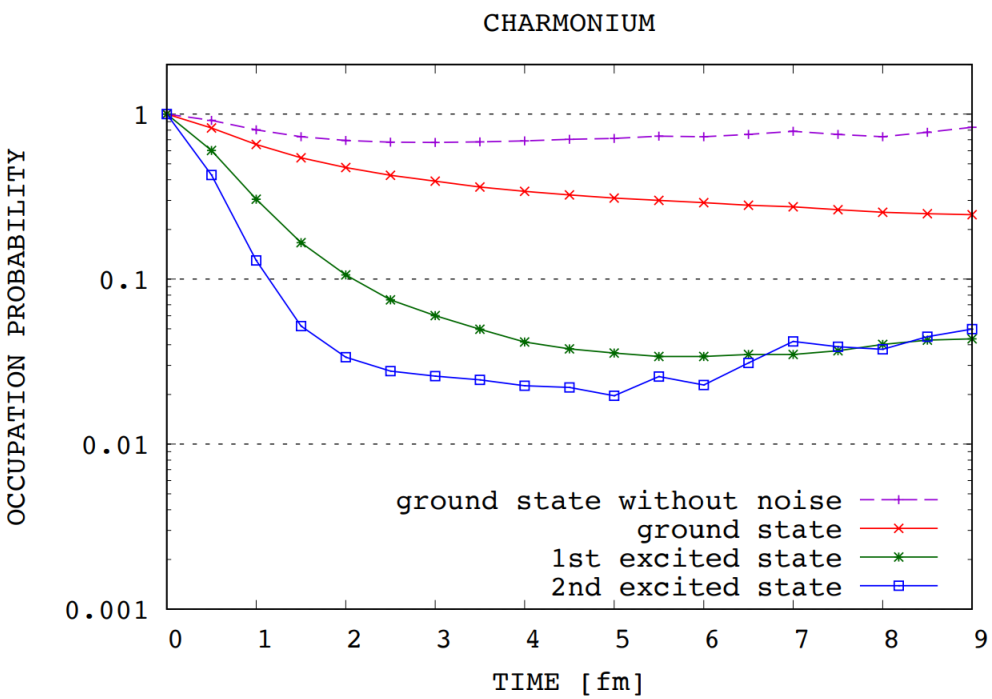


- Sequential melting scenario not observed
  - Rather enhancement with increasing energy density

Quarkonium dissociation by wave function decoherence

Kajimoto, Akamatsu, Asakawa, Rothkopf, arxiv:1705.03365v2

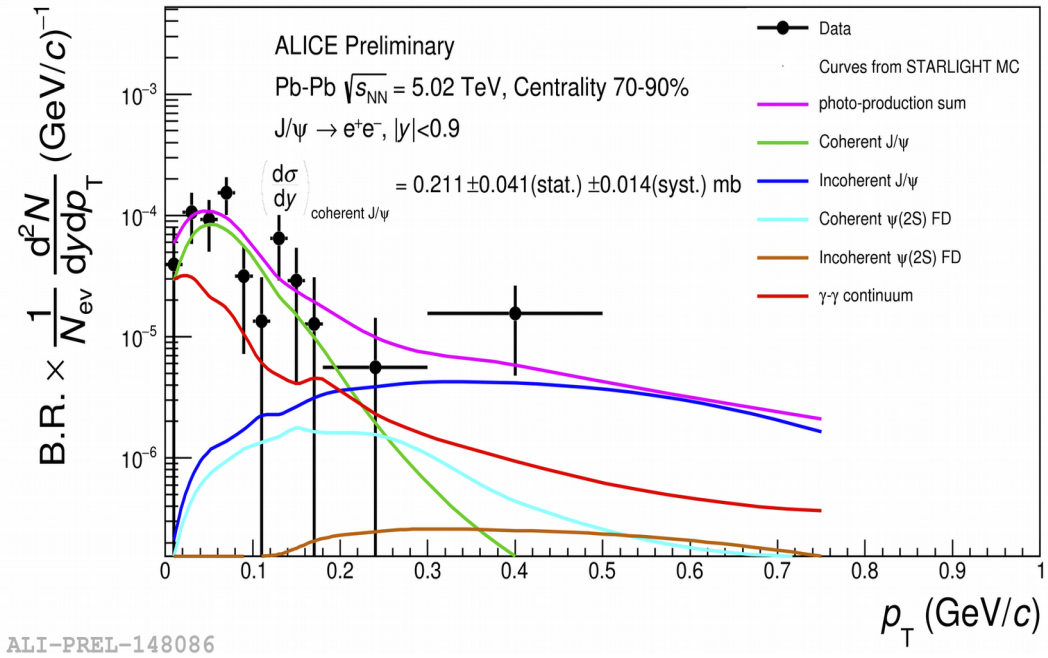




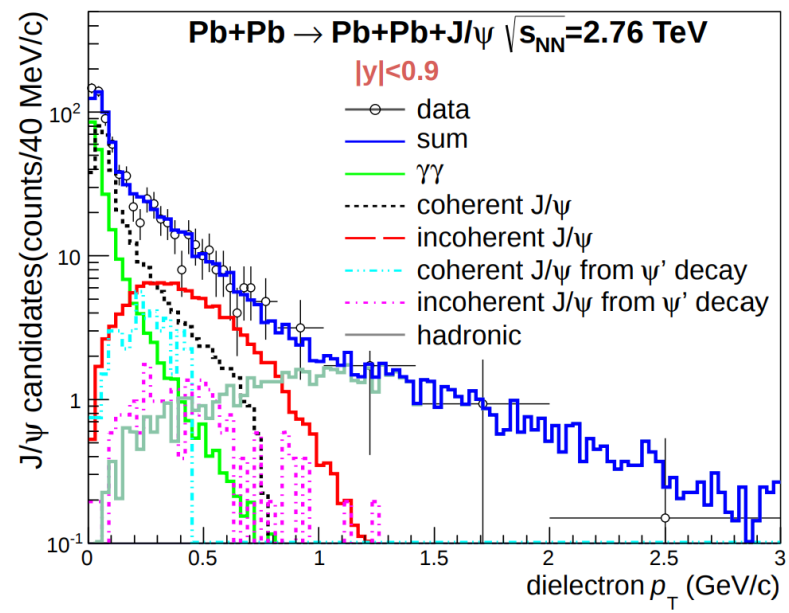
- Improved stochastic potential model including
  - Debye screened potential
  - Noise term (scattering between HQ and medium)

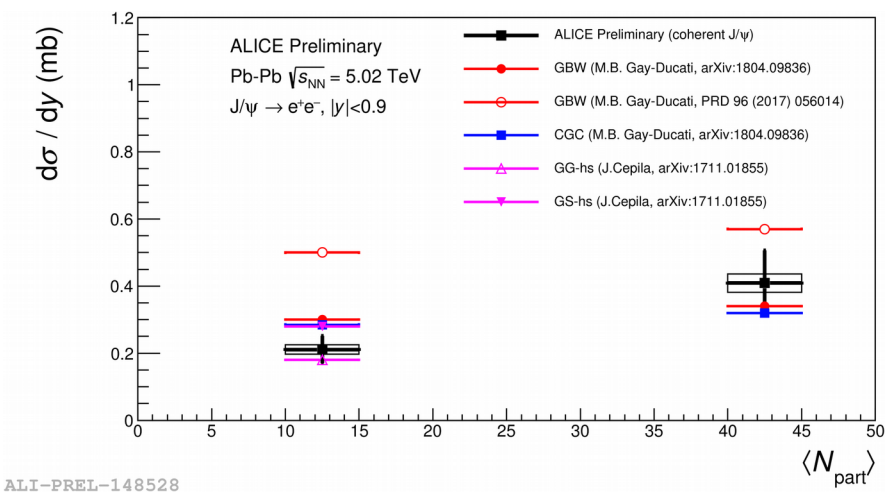
J/ψ photo-production in Pb-Pb collisions with b<2R

Mid-y (70-90%)



(ultra-peripheral)





- Excess present also at mid-y using Pb-Pb data (2015) at 5.02 TeV
- Characteristic p_T spectrum for photo-production, as also observed in ultra-peripheral collisions (UPC)
- Plan to improve these results with 2018 and Run-3+4 data