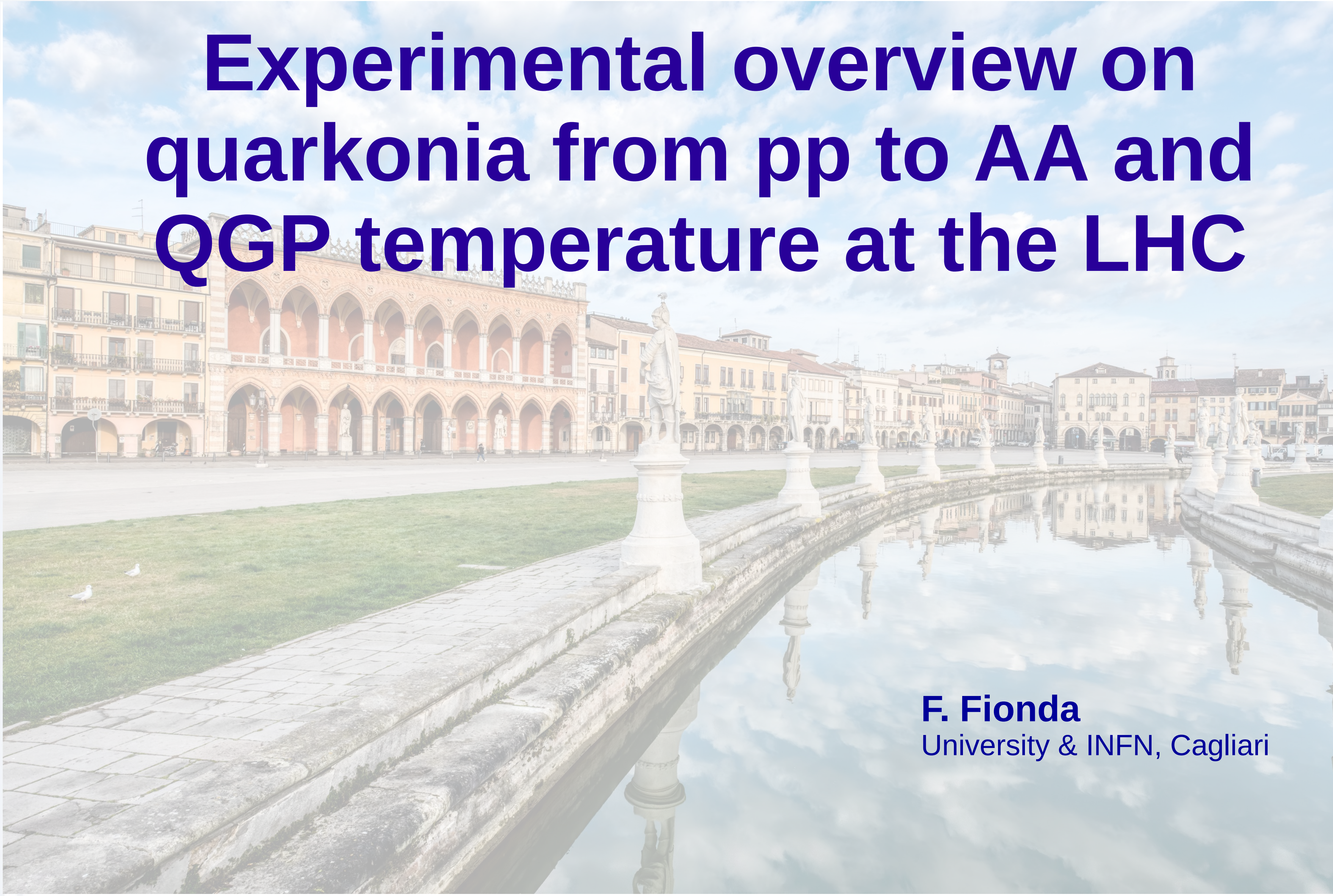


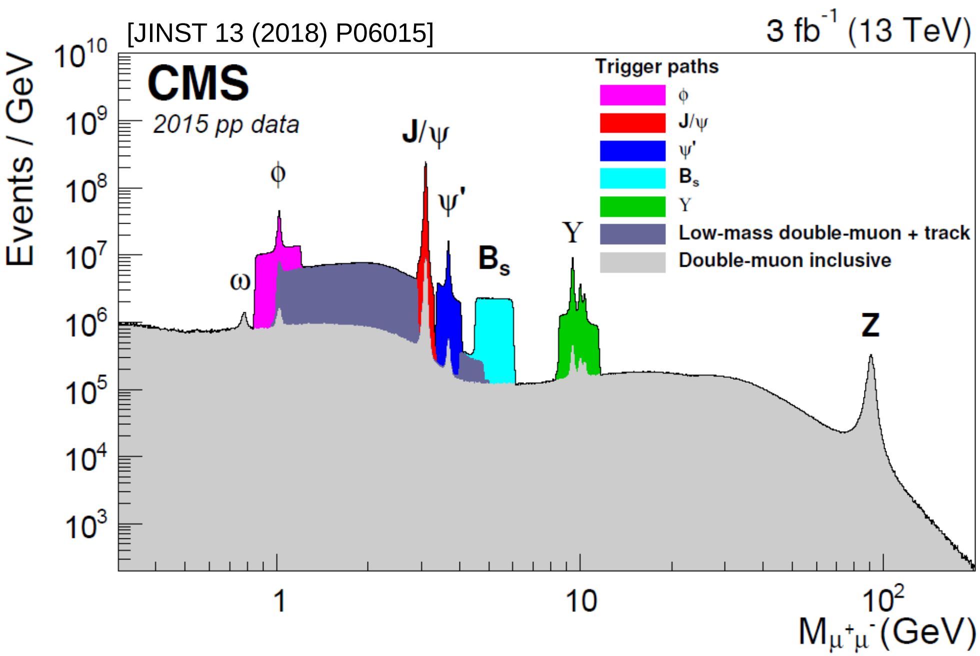
Experimental overview on quarkonia from pp to AA and QGP temperature at the LHC

F. Fionda
University & INFN, Cagliari

Terzo incontro di fisica con ioni pesanti alle alte energie
Padova, Nov. 25-26, 2021

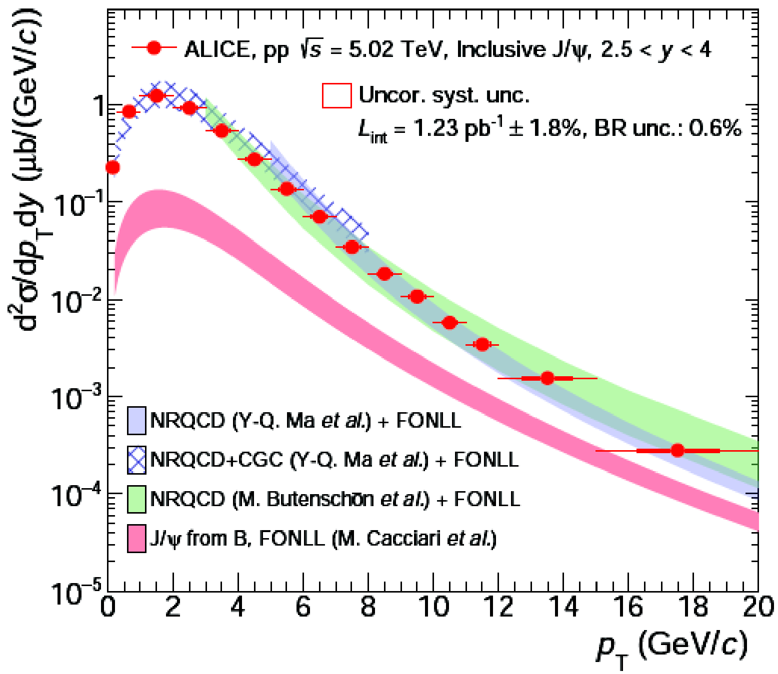
Quarkonia

- **Bound states of $c\bar{c}$ and $b\bar{b}$ quarks** → production in the “vacuum” described in two steps:
  - pQCD (m_c,m_b >> Λ_{QCD}) applicable for computing the $q\bar{q}$ production cross section
  - Hadronization into a “colourless” bound state → non-perturbative process. Three main production models **(+ new recent updates)**:
    - Color Evaporation Model (CEM)
      - **Improved CEM (ICEM)**
    - Color Singlet Model (CSM)
    - Non-Relativistic QCD (NRQCD)
      - **NRQCD + Color Glass Condensate (CGC)**

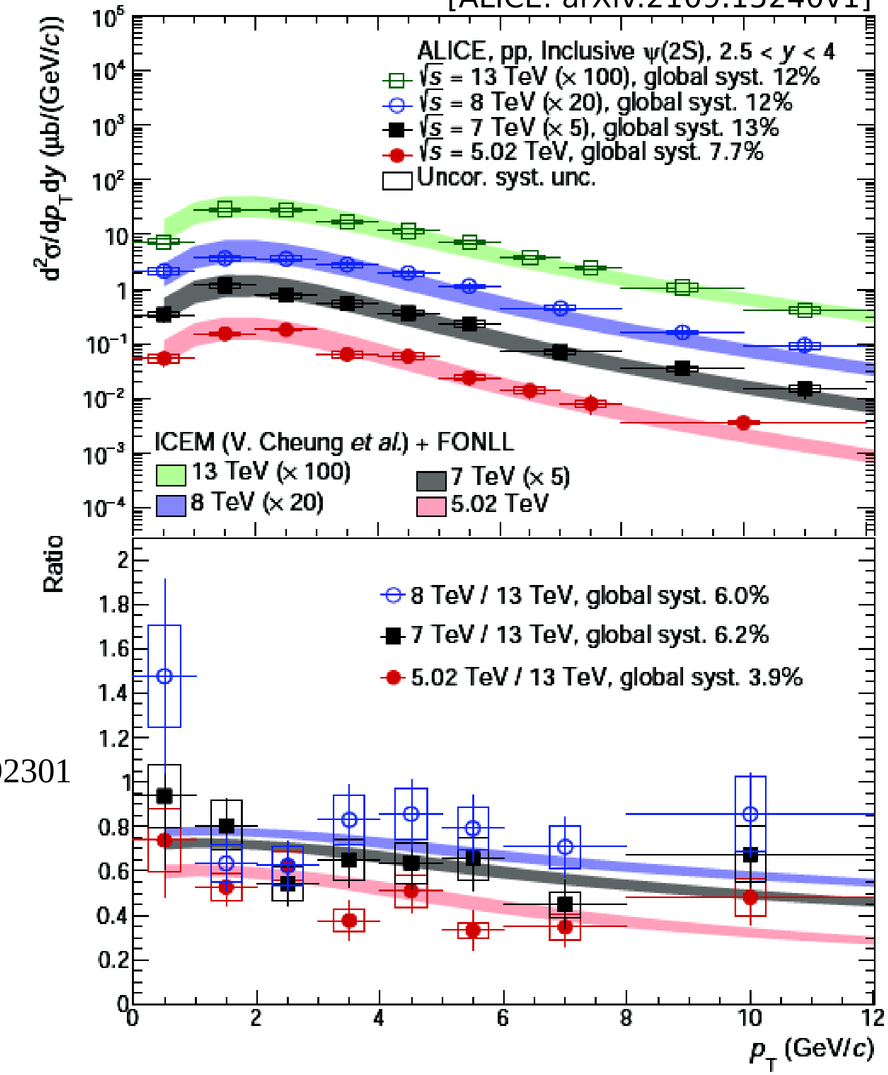


- Existing in a **variety of states** characterized by different masses and binding energies

Quarkonia in pp collisions



[ALICE: arXiv:2109.15240v1]

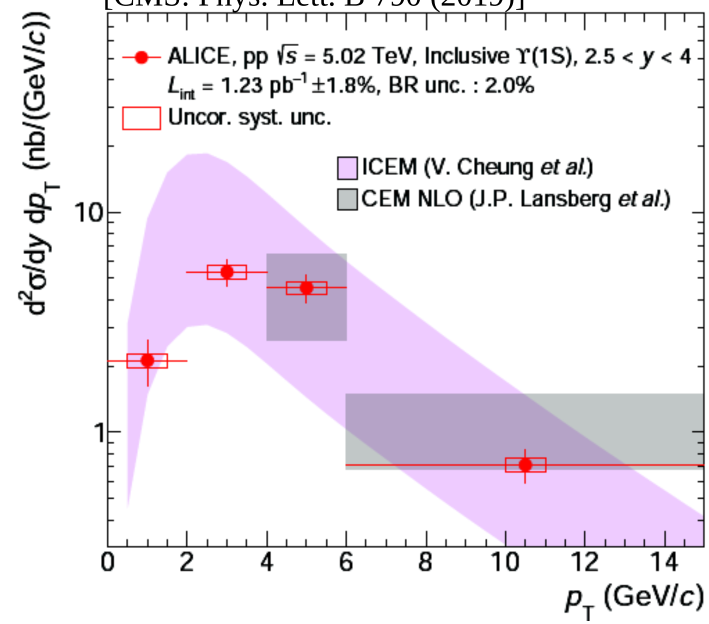


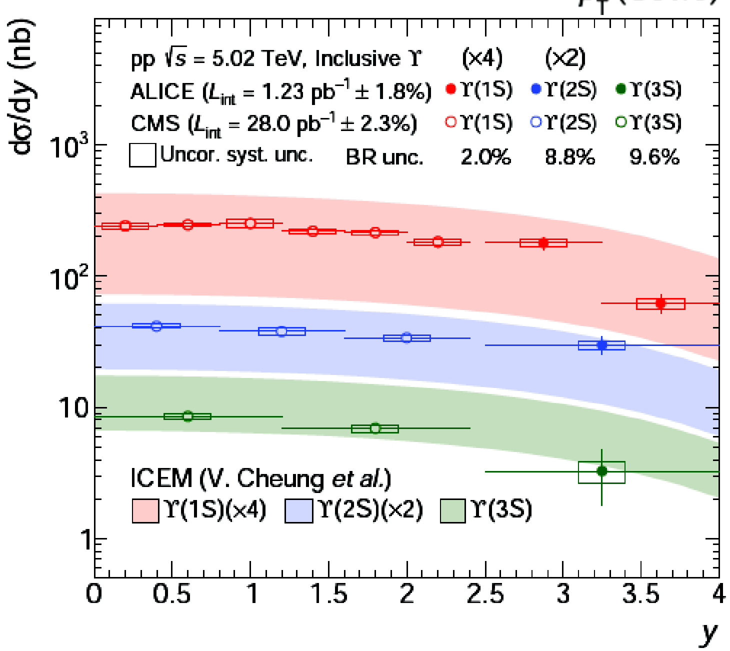
NRQCD (Ma et al): Phys. Rev. Lett. 106 (2011) 042002
NRQCD+CGC (Ma et al): Phys. Rev. Lett. 113 no. 19, (2014) 192301
NRQCD (Butenshon et al): Phys. Rev. Lett. 106 (2011) 022003
ICEM (Cheung, Vogt): Phys. Rev. D 98 no. 11, (2018) 114029
NLO CEM (Lansberg et al): Phys. Lett. B 807 (2020) 135559

- Charmonium cross sections described rather well by NRQCD based models and an improved version of CEM

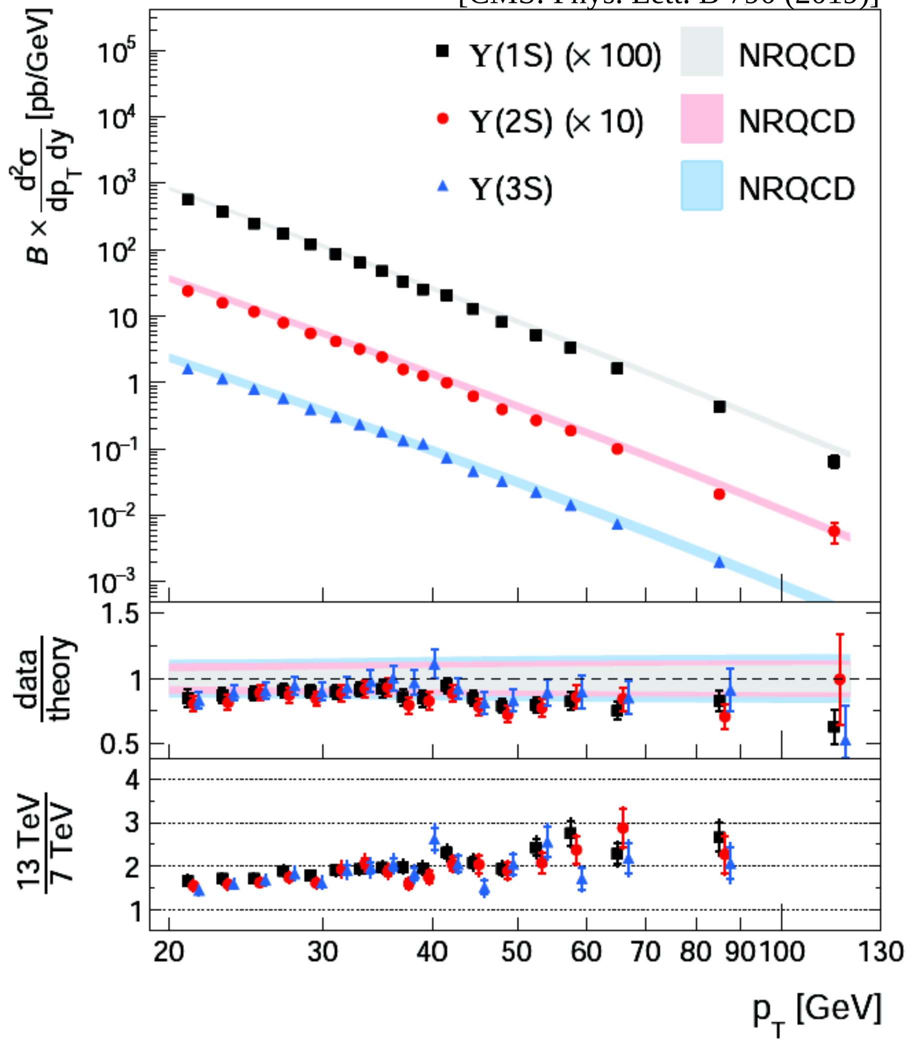
Quarkonia in pp collisions

[ALICE: arXiv:2109.15240v1]
[CMS: Phys. Lett. B 790 (2019)]





[CMS: Phys. Lett. B 790 (2019)]

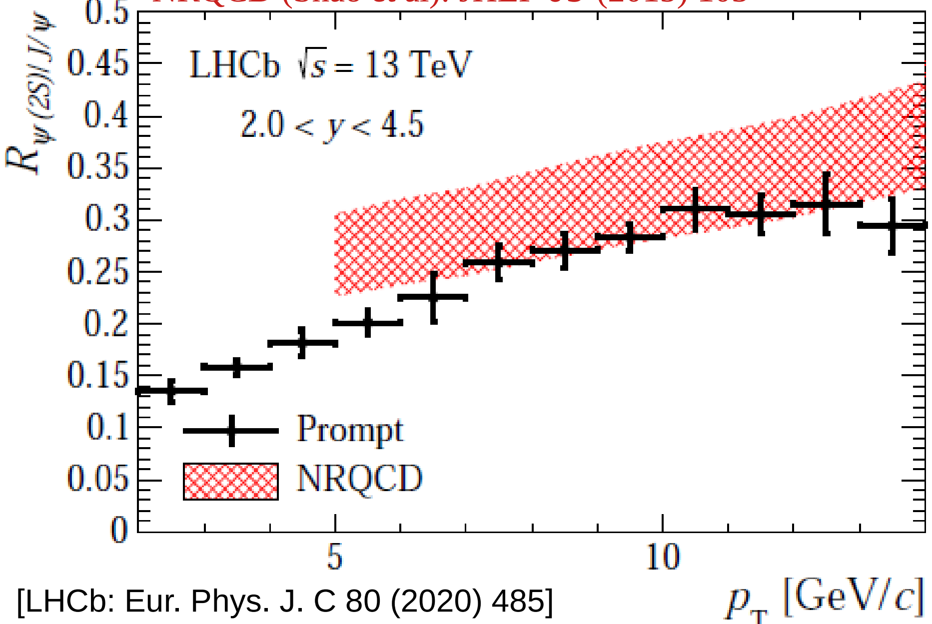


– Similar comments hold for bottonomia, but uncertainties are large

NLO NRQCD (H. Han et al): Phys. Rev. D 94 (2016) 014028
ICEM (Cheung, Vogt): Phys. Rev. D 98 no. 11, (2018) 114029
NLO CEM (Lansberg et al): Phys. Lett. B 807 (2020) 135559

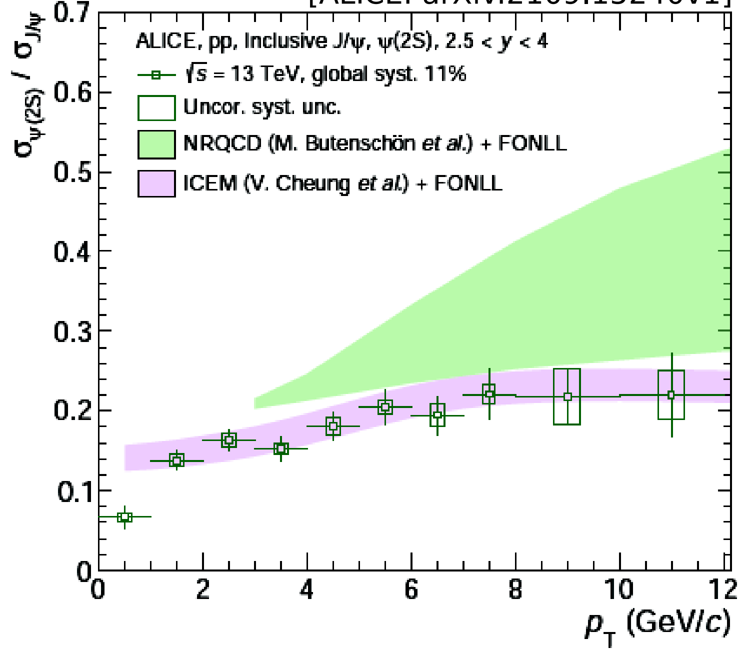
Quarkonia in pp collisions

NRQCD (Shao et al): JHEP 05 (2015) 103

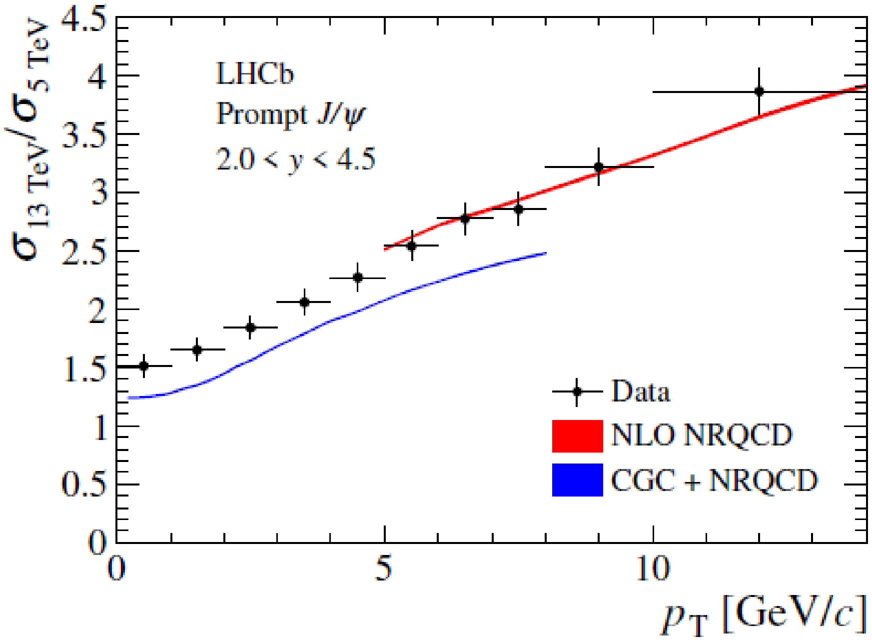


[LHCb: Eur. Phys. J. C 80 (2020) 485]
[LHCb: arXiv:2109.00220]

[ALICE: arXiv:2109.15240v1]



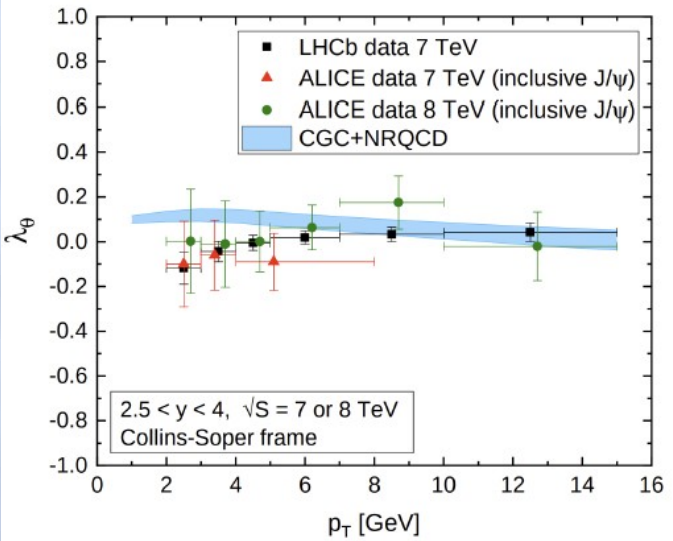
NRQCD (Butenshon et al): Phys. Rev. Lett. 106 (2011) 022003
ICEM (Cheung, Vogt): Phys. Rev. D 98 no. 11, (2018) 114029

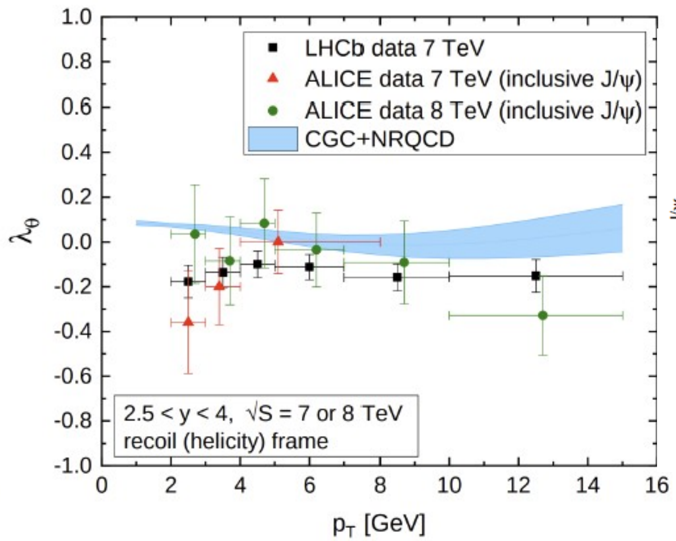


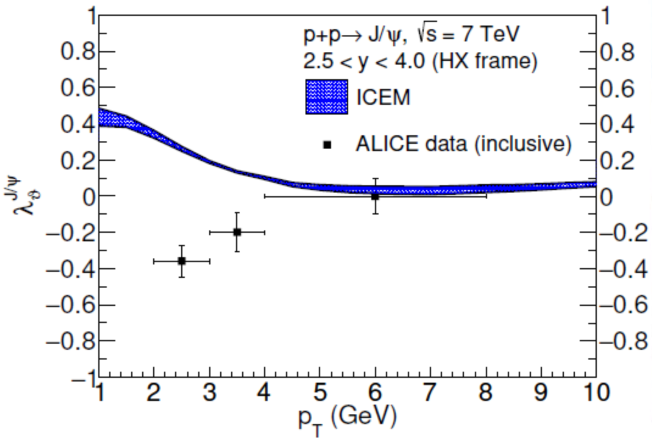
However tensions still present, more visible when studying cross section ratios...

NRQCD+CGC (Ma et al): Phys. Rev. Lett. 113 no. 19, (2014) 192301
NLO NRQCD (Ma et al): Phys. Rev. Lett. 106 (2011) 042002

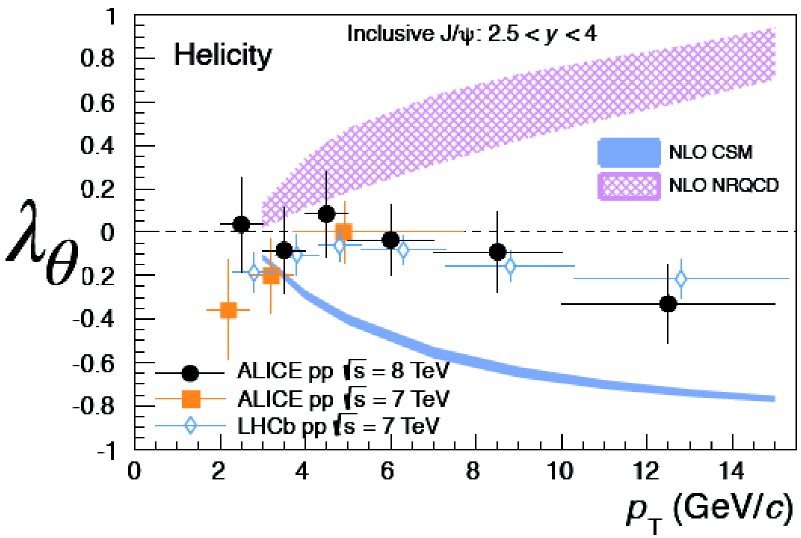
Polarisation in pp collisions







[ALICE: Eur. Phys. J. C (2018) 78]
[ALICE: Phys. Rev. Lett. 108, 082001]
[LHCb: Eur. Phys. J. C 73(11), 2631, (2013)]



However tensions still present, more visible when studying cross section ratios…

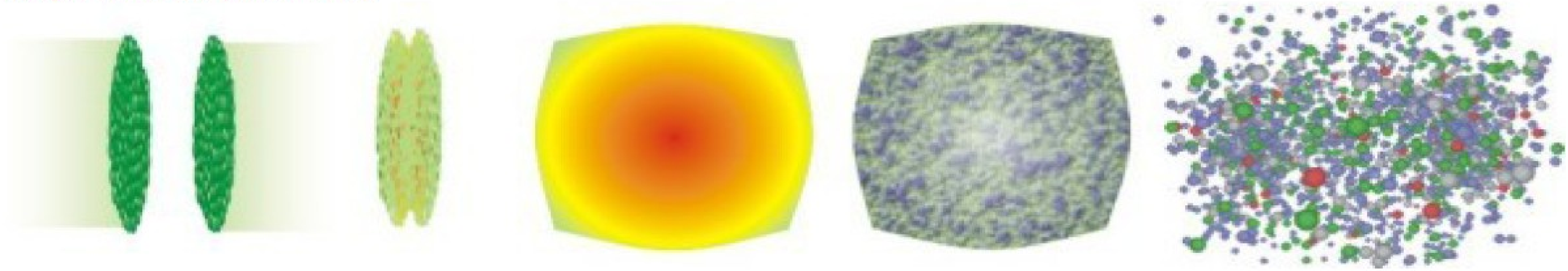
...and polarisation

CSM, NLO NRQCD (M. Butenschoen and B. A. Knieh): Phys.Rev.Lett. 108 (2012) 172002
ICEM (Cheung, Vogt): Phys. Rev. D 98 no. 11, (2018) 114029
NRQCD+CGC: Y.-Q. Ma, T. Stebel and R. Venugopala, JHEP 1812 (2018) 057

Quarkonia in (UR) Heavy Ion collisions

0 | 0.01-1 | 1-10 | ~10 | 10-20 | (fm/c)

Image: S.A.Bass (Duke Univ.)

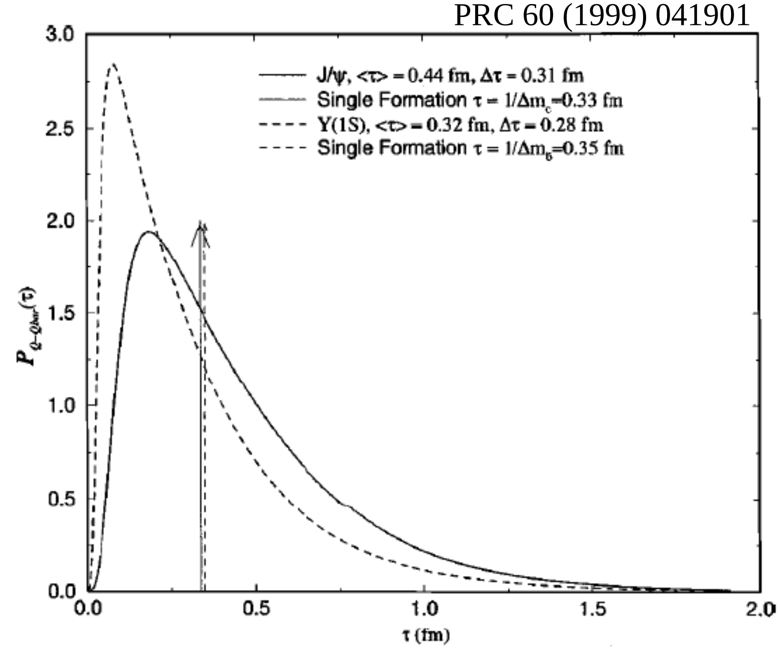


Initial state | Hard partonic collisions | Fireball expansion | Chemical freeze-out | Kinetic freeze-out

Quarkonia as **probe of QGP**:

- Heavy-quark pair produced in initial hard partonic scatterings → **experience the entire collision hystory**
- Formation time of quarkonium state of the order of **0.2 - 2 fm/c** → states may form inside the plasma

PRC 60 (1999) 041901



Quarkonia in (UR) Heavy Ion collisions

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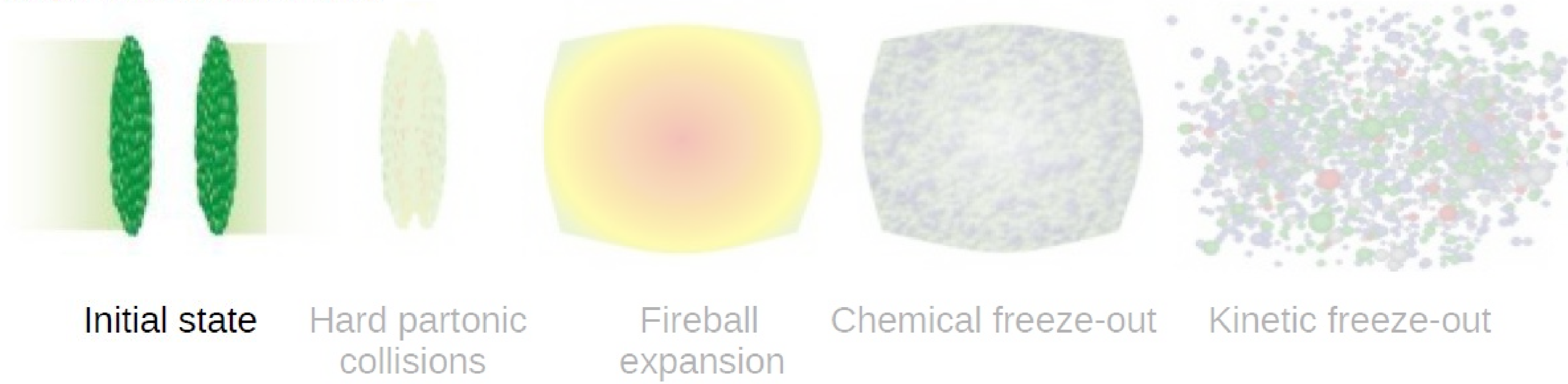
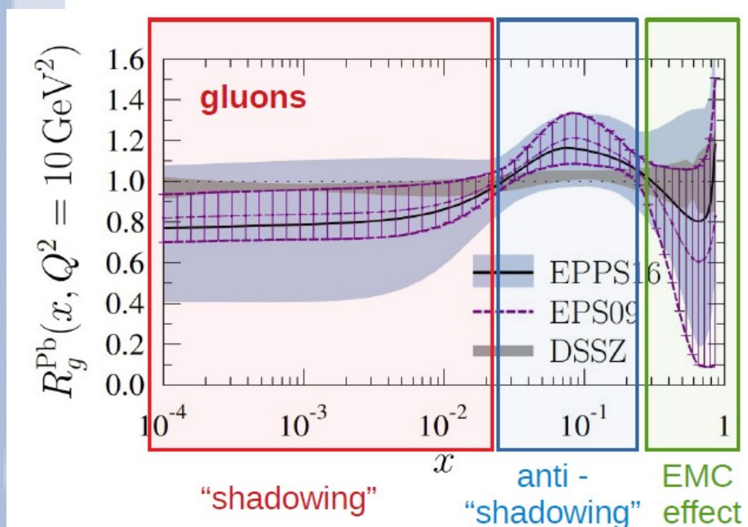


nPDF modification

Eskola et al., EPJC77 (2017) 163



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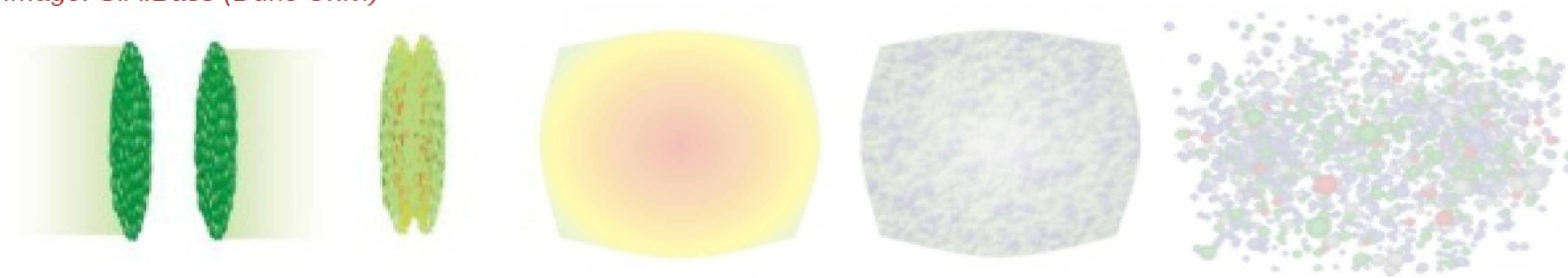

Initial state | Hard partonic collisions | Fireball expansion | Chemical freeze-out | Kinetic freeze-out

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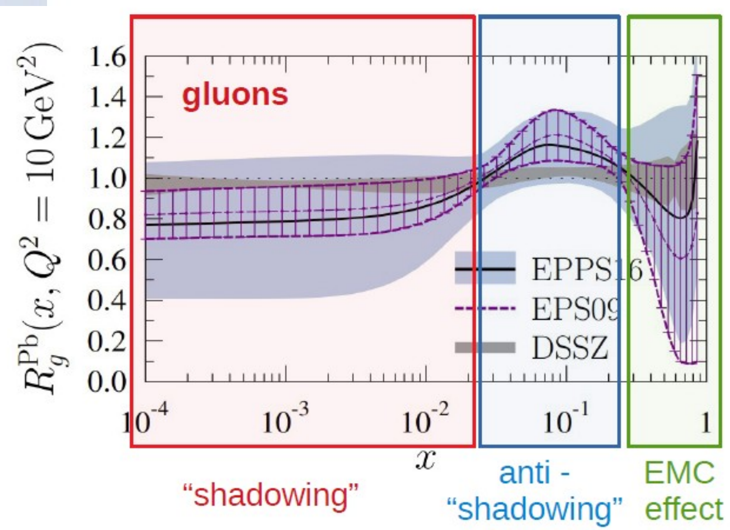
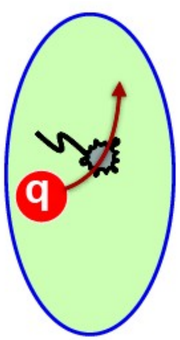
Eskola et al., EPJC77 (2017) 163



Coherent energy loss

F. Arleo, S. Peigne', JHEP 03 (2013) 122.

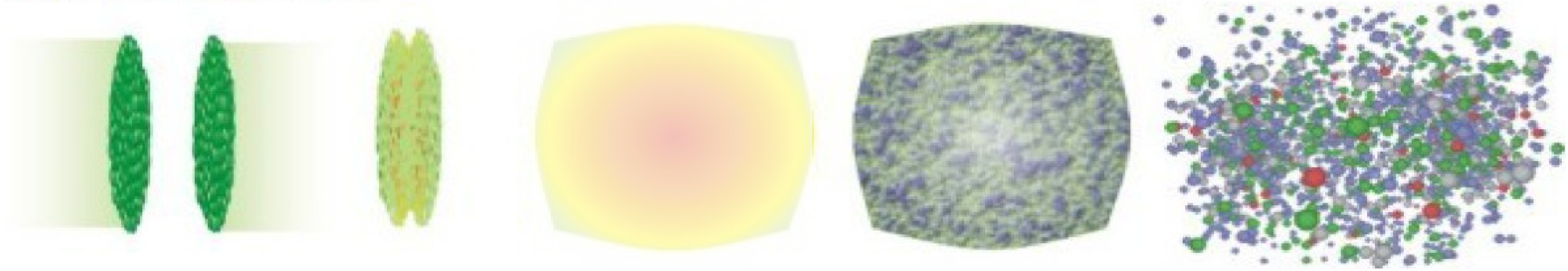


Nuclear medium

Quarkonia in (UR) Heavy Ion collisions

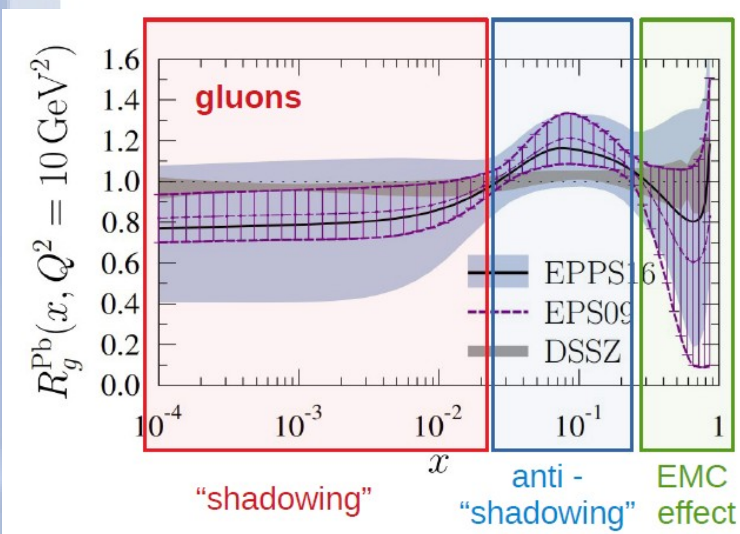
0 0.01-1 1-10 ~10 10-20 (fm/c)

Image: S.A.Bass (Duke Univ.)



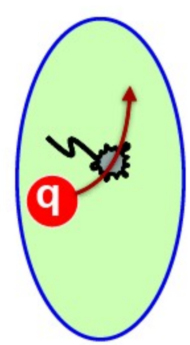
nPDF modification

Eskola et al., EPJC77 (2017) 163



Coherent energy loss

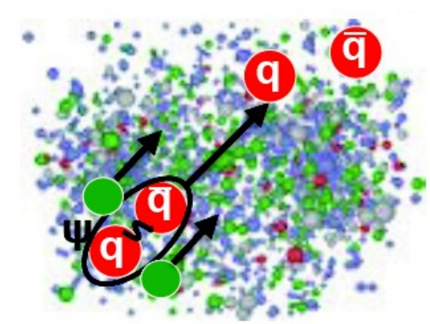
F. Arleo, S. Peigne’, JHEP 03 (2013) 122.



Nuclear medium

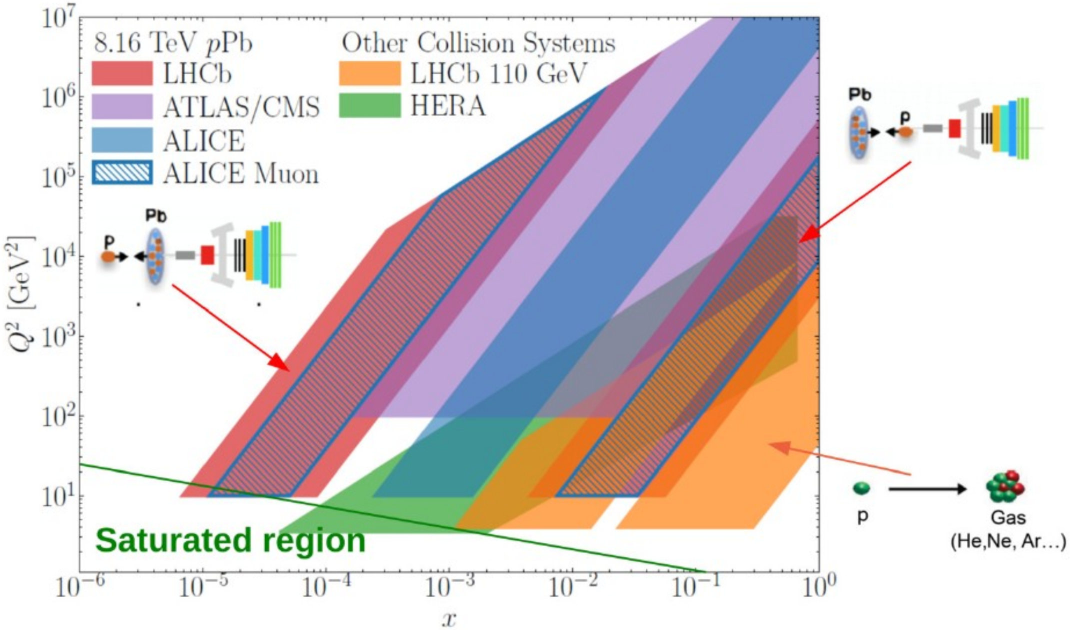
Dissociation with comovers

E. G. Ferreiro, PLB 731 (2014) 57
E. G. Ferreiro and J. P. Lansberg, JHEP 1810 (2018) 094



Hadronic matter

Cold Nuclear Matter (CNM) effects



$$R_{\mathrm{pA}}(y, p_{\mathrm{T}}) = \frac{1}{A} \frac{\mathrm{d}^2\sigma_{\mathrm{pA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}$$

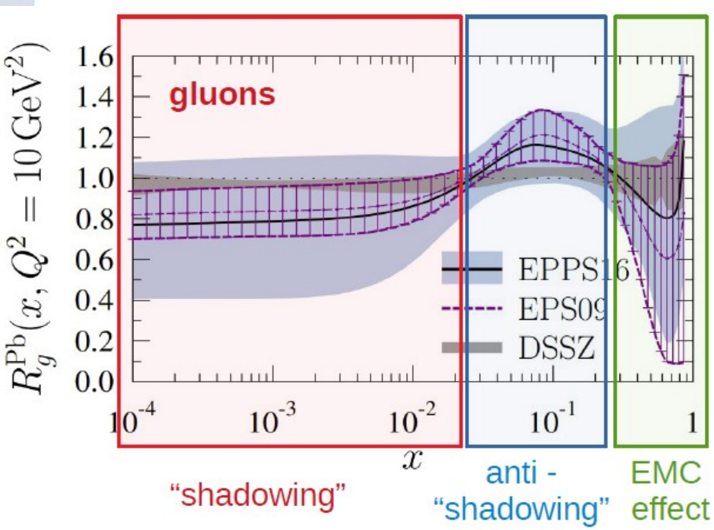
$\mathrm{d}^2\sigma_{\mathrm{pA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}$: cross section in pA

$\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}$: cross section in pp

A: atomic mass number

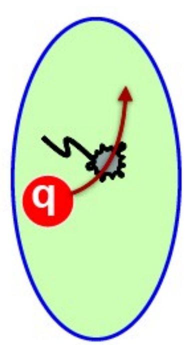
nPDF modification

Eskola et al., EPJC77 (2017) 163



Coherent energy loss

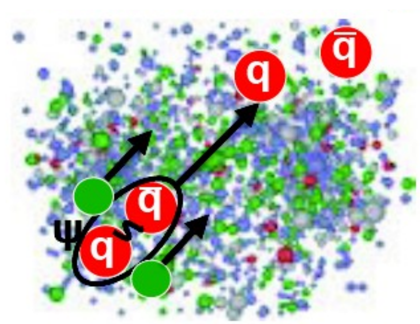
F. Arleo, S. Peigne', JHEP 03 (2013) 122.



Nuclear medium

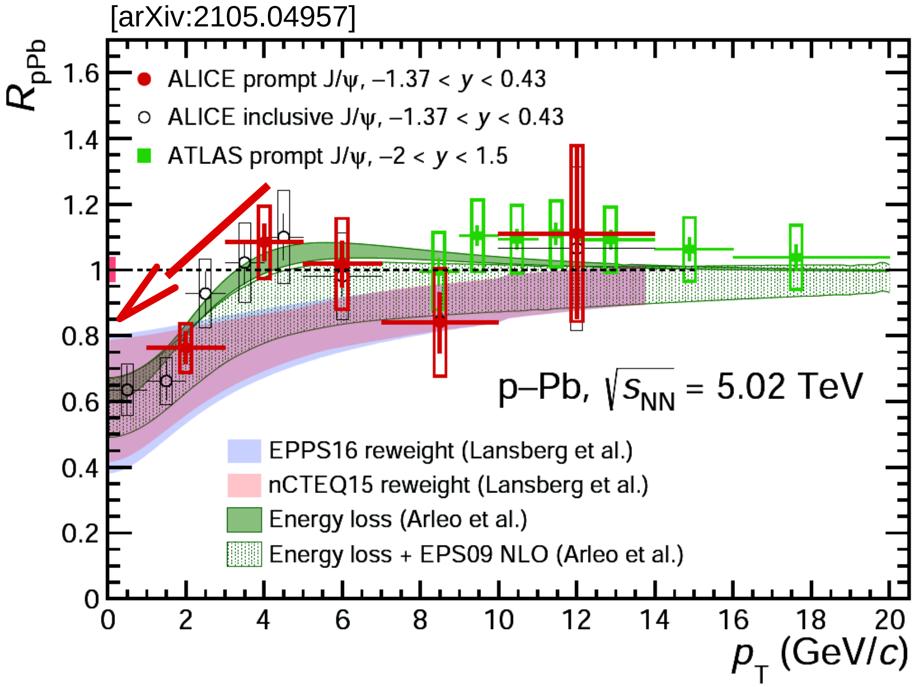
Dissociation with comovers

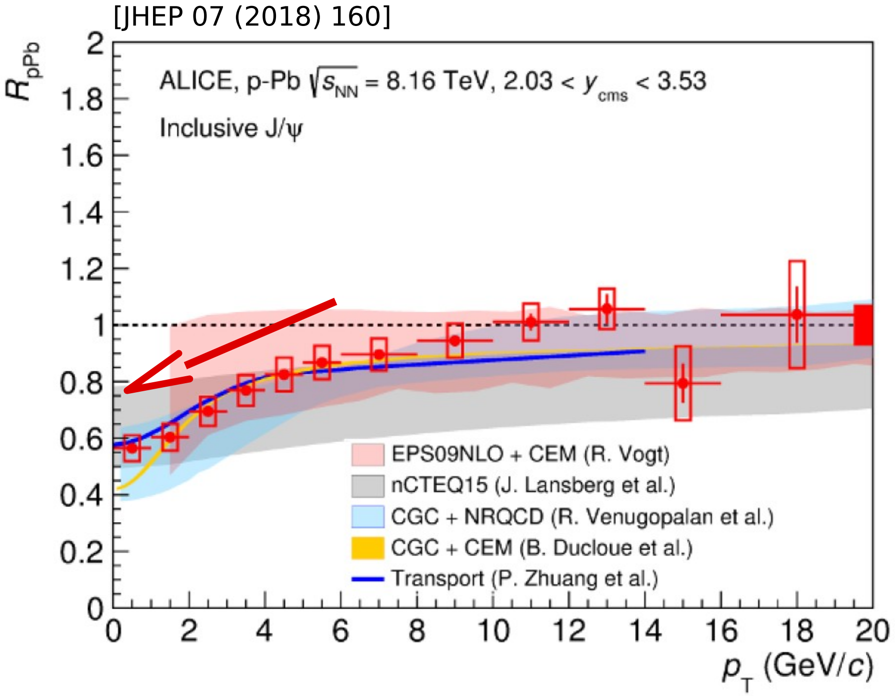
E. G. Ferreiro, PLB 731 (2014) 57
E. G. Ferreiro and J. P. Lansberg, JHEP 1810 (2018) 094



Hadronic matter

J/ψ nuclear modification factor





– J/Ψ production suppressed at low p_T at both midrapidity and forward rapidity

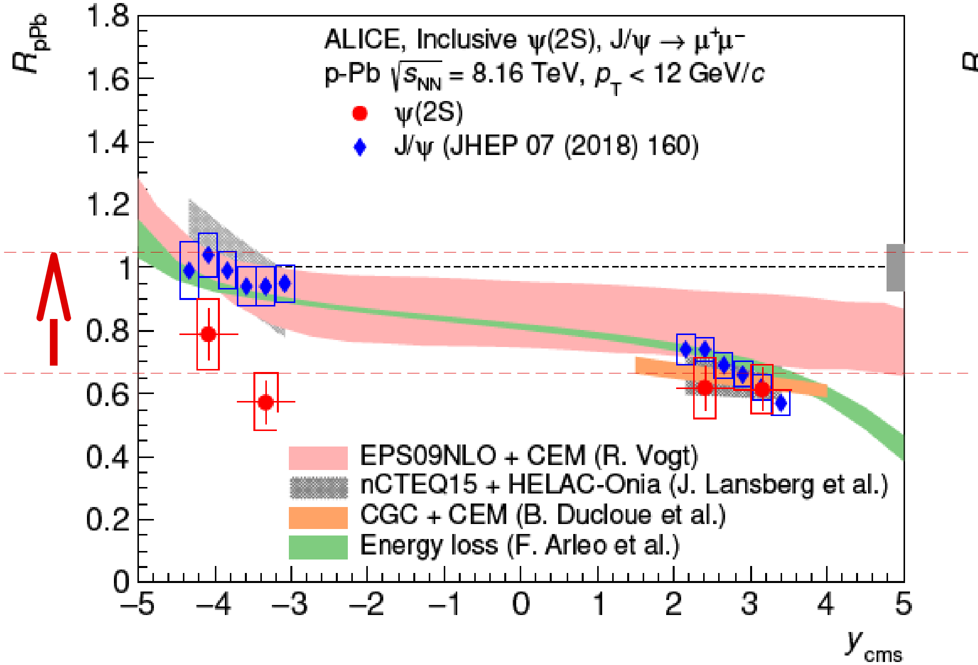
– Models implementing nPDF modifications are able to describe qualitatively the trend at low p_T

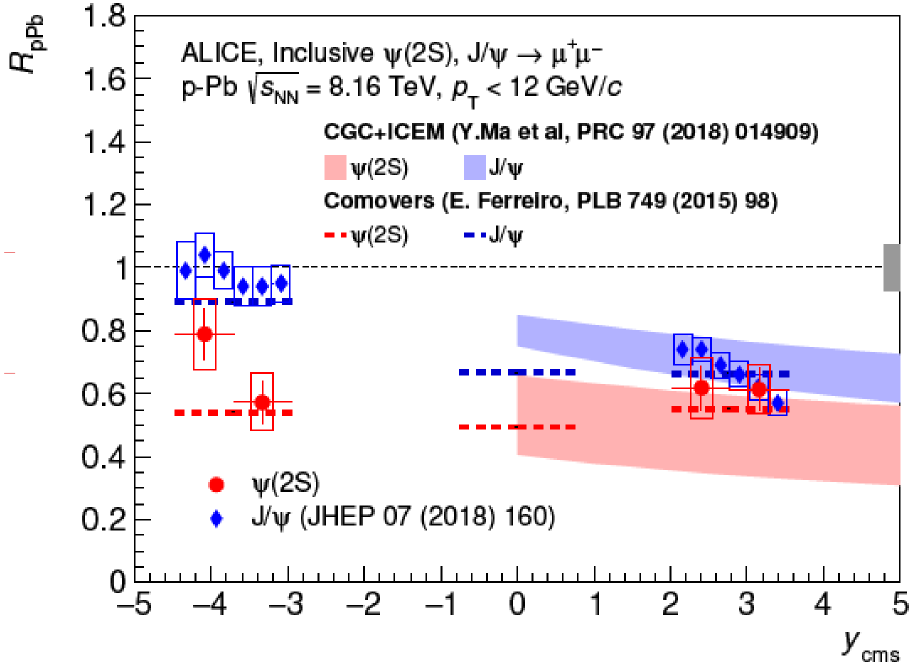
– Model including coherent energy loss also catches the deplation at low p_T at midrapidity

  – larger uncertainties when combined with EPS09NLO nPDFs

J/ψ and ψ(2S) nuclear modification factor

[JHEP 07 (2020) 237]





– larger Ψ(2S) nuclear suppression w.r.t. J/Ψ at backward rapidity

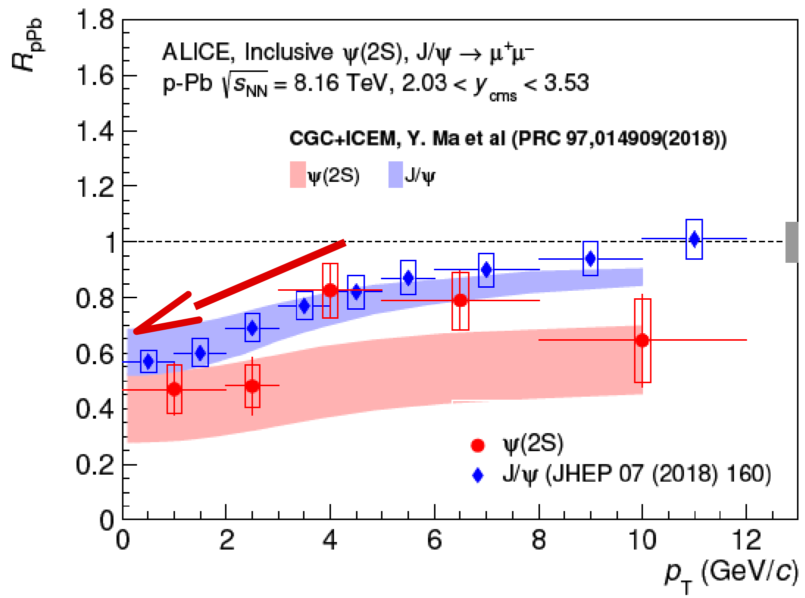
– Calculations implementing initial state CNM effects (CGC or nPDF modifications) and coherent energy loss do not distinguish between charmonium states

– they are able to describe rapidity dependence of R_{pPb} of J/Ψ but fail for Ψ(2S)!

– Ψ(2S) suppression described by models which implement further **interactions in the final state**:

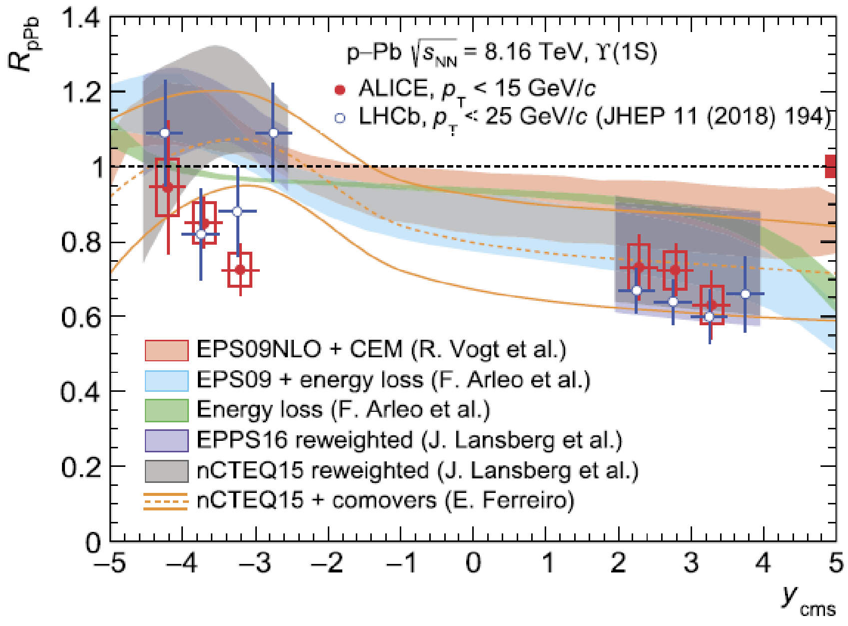
– soft color exhanges during the $c\bar{c}$ hadronization

– interaction with comovers



Υ(1S) production in p-Pb

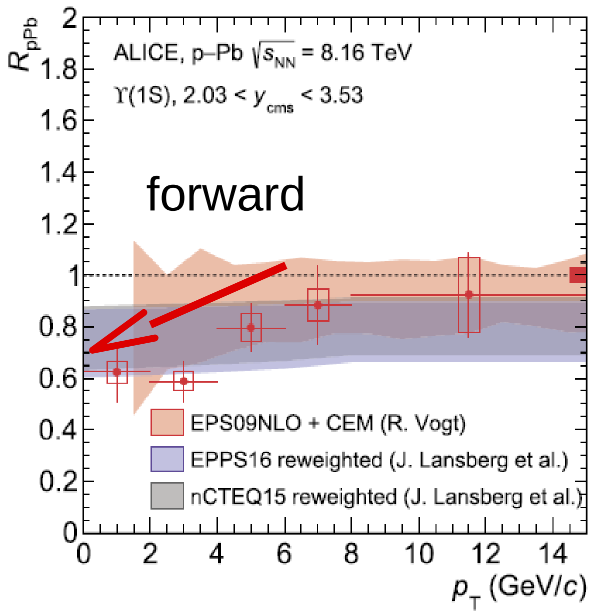
[Phys. Lett. B 806 (2020) 135486]

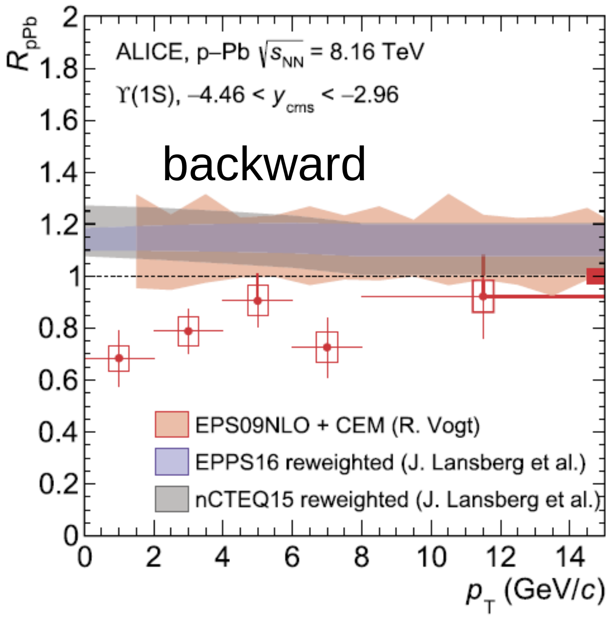


– shadowing calculations fail to predict R_{pPb} at backward rapidity

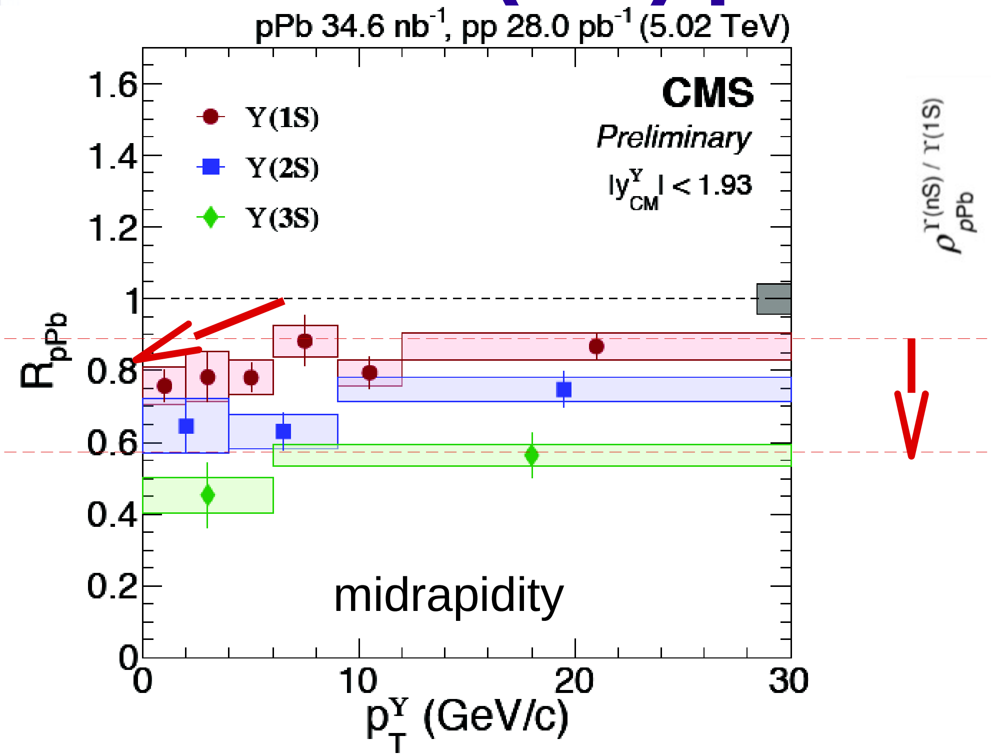
– coherent energy loss catches forward rapidity when EPS09 nuclear shadowing is considered, but fail at backward-y

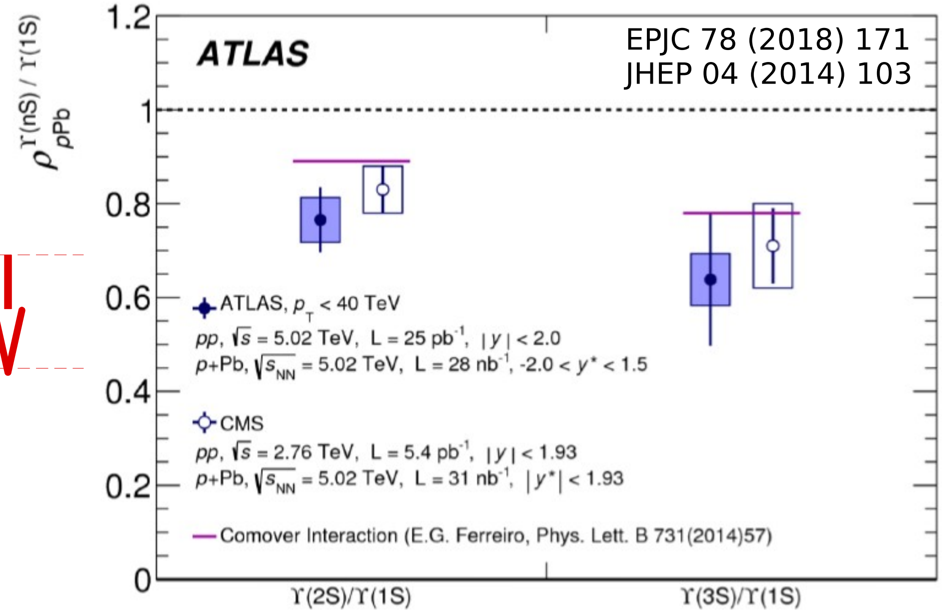
– comovers slightly overestimates data at backward rapidity (but large uncertainty dominated by nPDF)



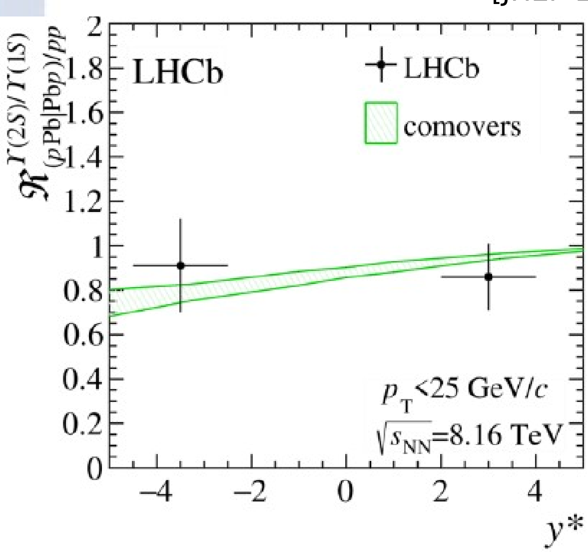


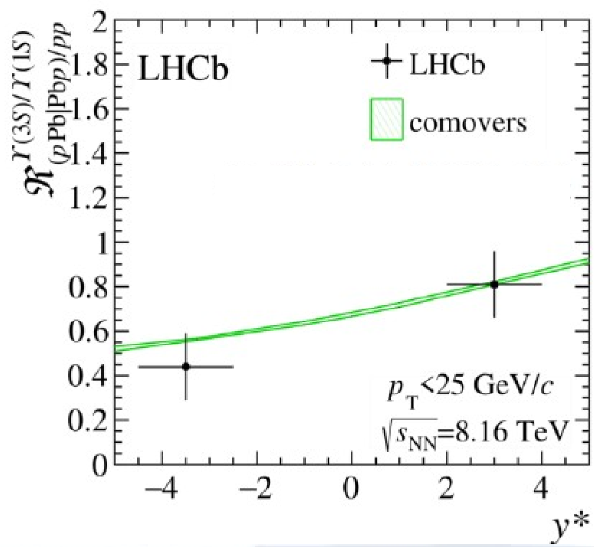
Υ(nS) production in p-Pb





[JHEP 11 (2018) 194]





– higher suppression of excited Υ(nS) states compared to ground state observed at midrapidity by CMS (R_{pPb}(Υ(1S)) > R_{pPb}(Υ(2S)) > R_{pPb}(Υ(3S)))

– in general good agreement with comover model

Take-home notes: Quarkonia in p-Pb collisions

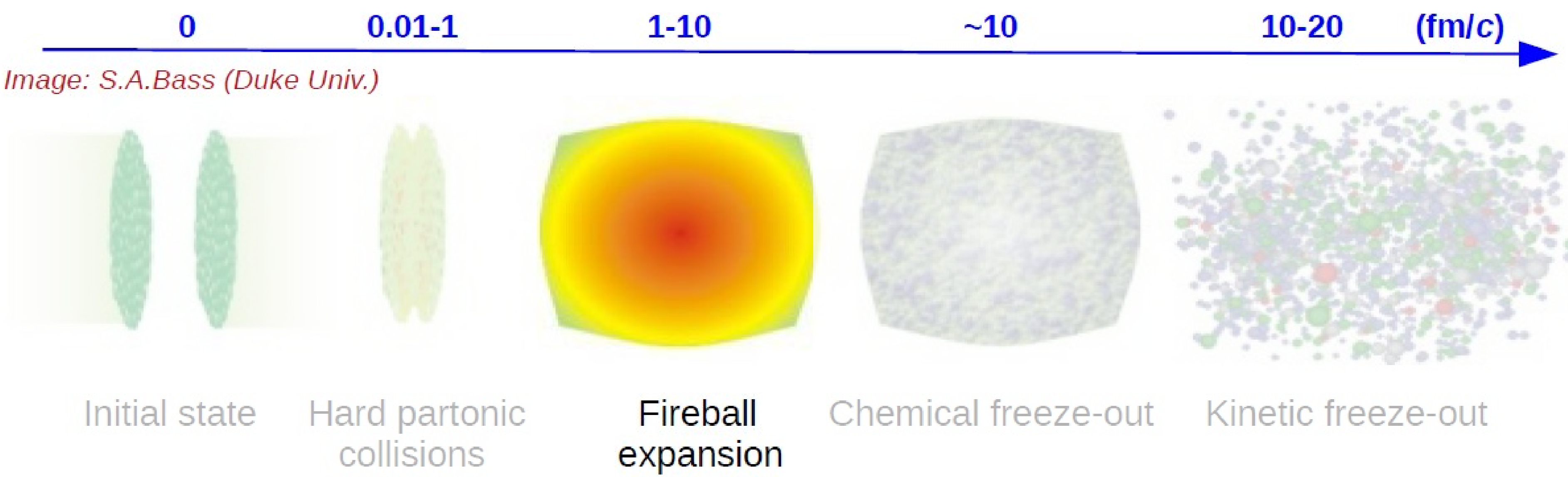
Charmonia:

- J/Ψ suppressed at low p_T; reproduced by models implementing nPDF modifications and coherent energy loss (initial state effects)
- larger Ψ(2S) nuclear suppression w.r.t. J/Ψ at backward rapidity / higher centrality → described by models which implement further interactions in the final state, e.g. comovers

Bottonomia:

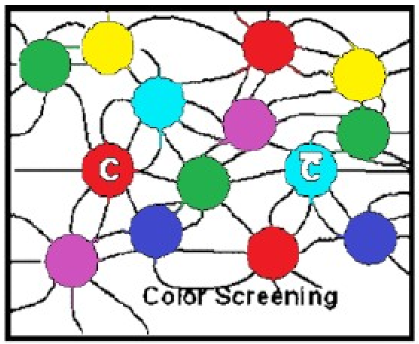
- Increasing suppression for excited states, $R_{pPb}(\Upsilon(1S)) > R_{pPb}(\Upsilon(2S)) > R_{pPb}(\Upsilon(3S))$
- models implementing shadowing and / or coherent energy loss fail to predict R_{pPb} at backward rapidity (also for the ground state)
- in general in good agreement with comovers model

Quarkonia in (UR) Heavy Ion collisions



In-medium dissociation (color Debye screening)

Matui & Satz, Phys.Lett. B178 (1986) 416-422

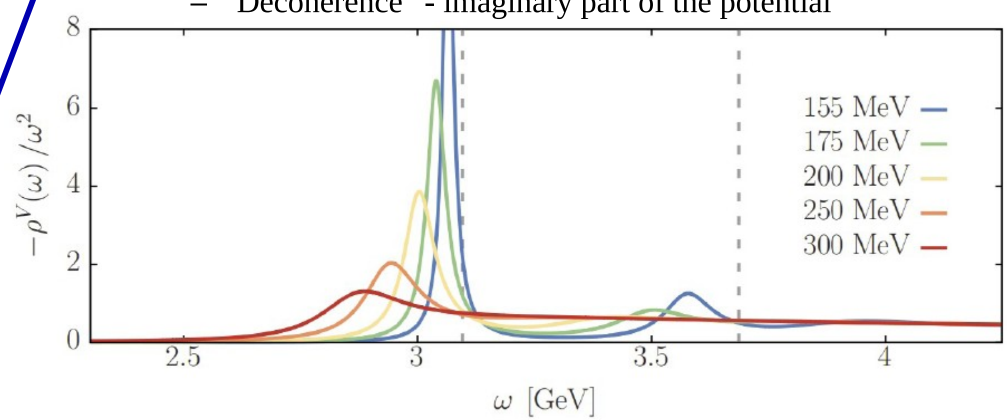


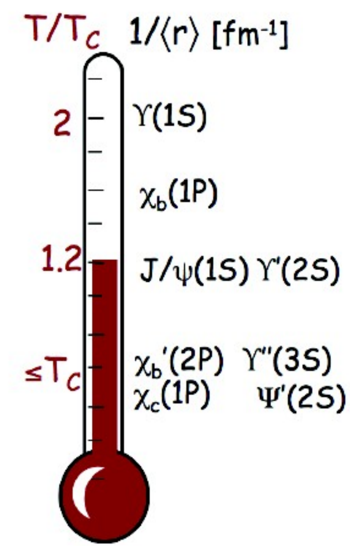
Open quantum system approach

A.Rothkopf, Phys.Rep. 858(2020) 1-117

Quarkonia described in terms of spectral functions modified in a deconfined medium using lattice QCD calculations

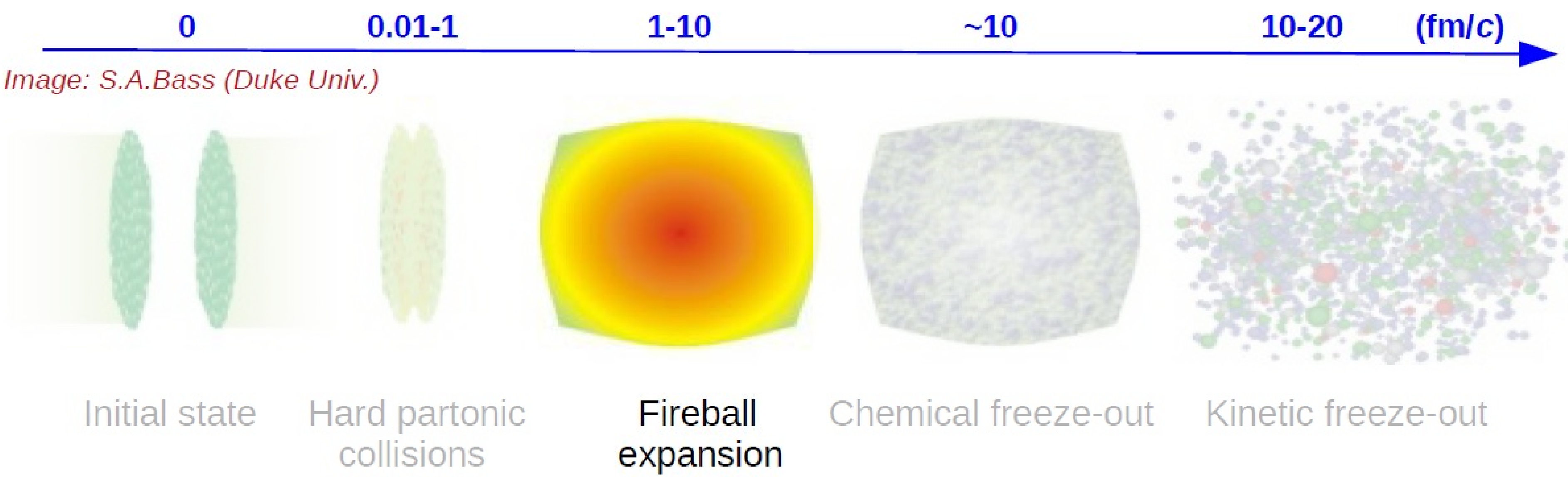
- Debye screening - real part of the potential
- "Decoherence" - imaginary part of the potential





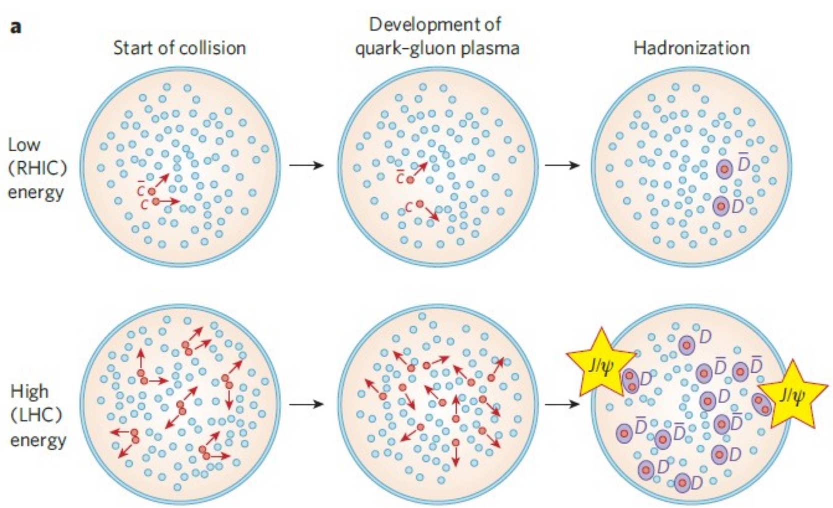
[EPJC 61 (2009) 705]

Quarkonia in (UR) Heavy Ion collisions



Regeneration of quarkonia

Braun-Munzinger and Stachel, PLB 490 (2000) 196
Thews et al., PRC 63 (2001) 054905

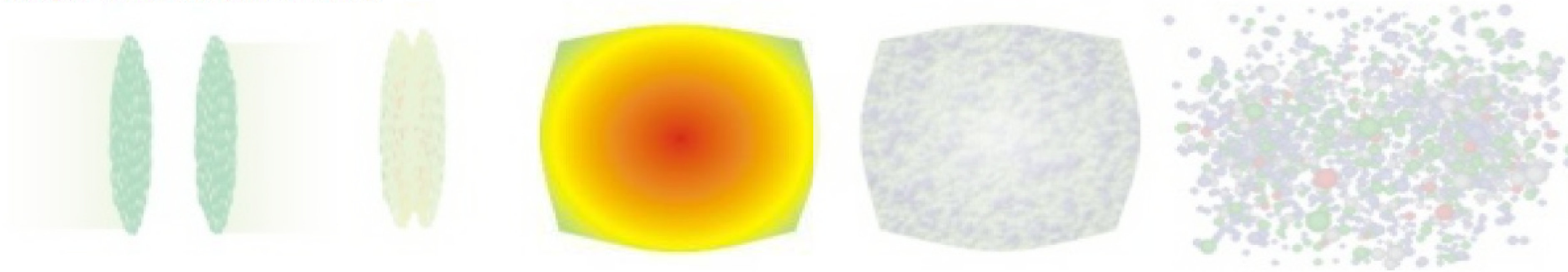


Nature 448 (2007) 302-309

Quarkonia in (UR) Heavy Ion collisions

0 0.01-1 1-10 ~10 10-20 (fm/c)

Image: S.A.Bass (Duke Univ.)



Initial state | Hard partonic collisions | Fireball expansion | Chemical freeze-out | Kinetic freeze-out

Regeneration of quarkonia

Braun-Munzinger and Stachel, PLB 490 (2000) 196
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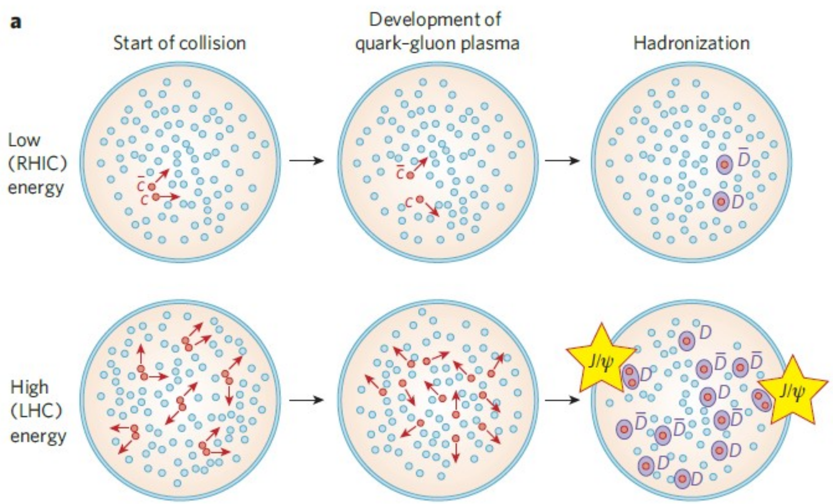
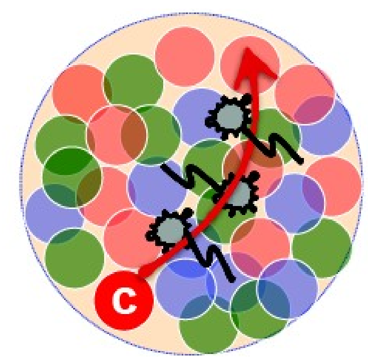


Nature 448 (2007) 302-309

Parton energy loss (at high p_T)

M. Gyulassy and M. Plumer, Phys. Lett. B243 (1990) 432
M. H. Thoma and M. Gyulassy, Nucl. Phys. B351 (1991) 491.



Key Observables

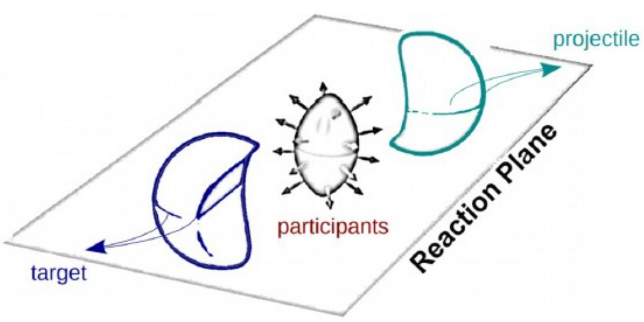
1) $$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

2) $$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cdot \cos[n(\varphi - \Psi_{RP})] \qquad v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

– **Initial spatial anisotropy**:

– pressure gradients convert any initial geometrical anisotropy into an anisotropy in the momentum space

– anisotropy is quantified by the 2^{nd} order coefficient v_2 of the Fourier expansion of the particle azimuthal angle distribution w.r.t. the reaction plane

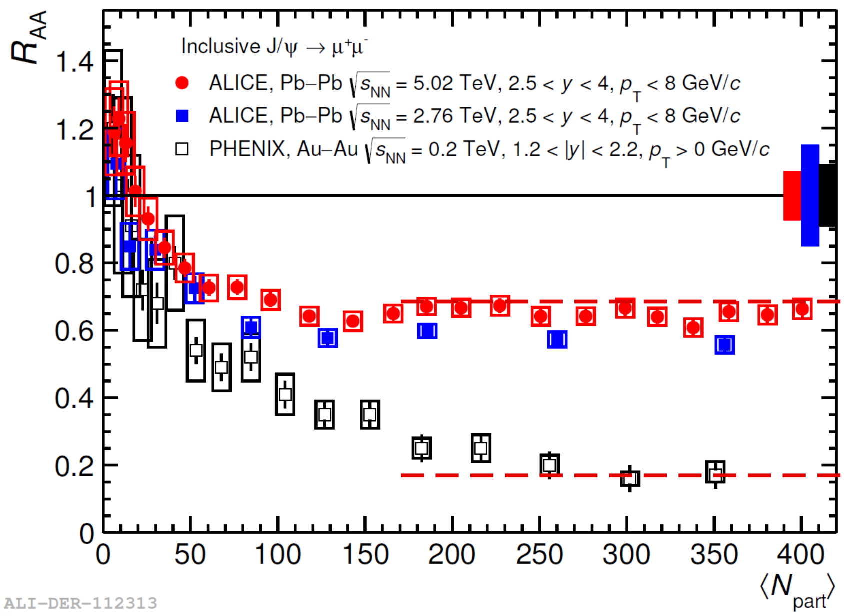


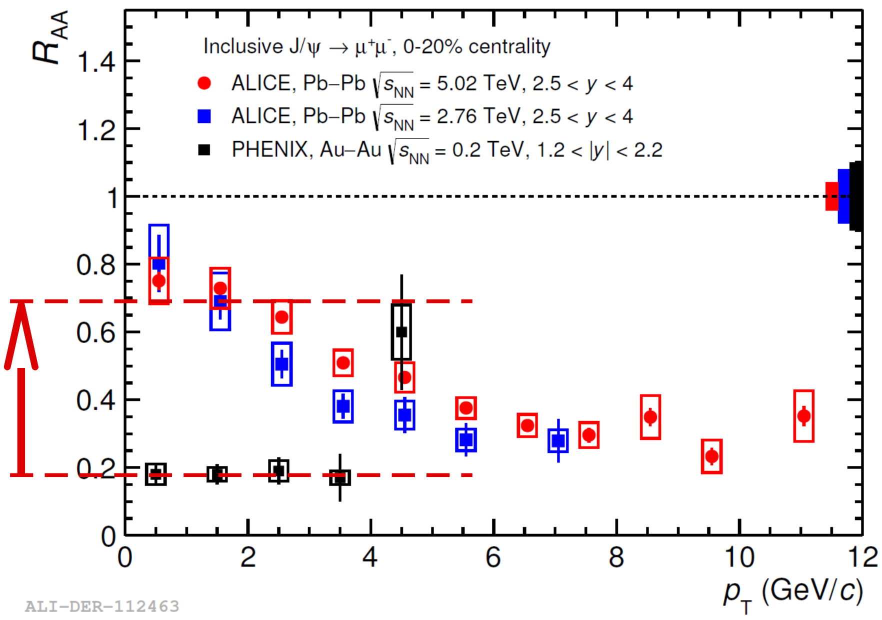
→ **low-p_T: sensitive to bulk QGP properties**

→ **high-p_T: sensitive to the in medium energy loss (path-lenght dependence)**

J/ψ R_{AA}

[PLB 766 (2017) 212]





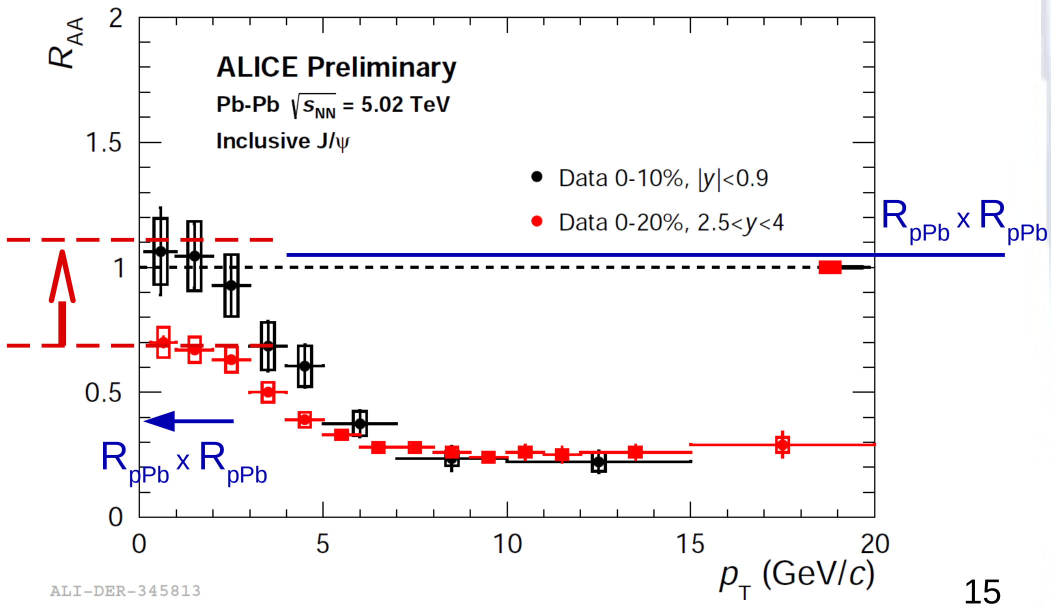
– Similar suppression observed in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV

– Less suppression at LHC energy compared to lower RHIC energy towards more central events

– Weaker suppression at midrapidity compared to forward rapidity at the LHC

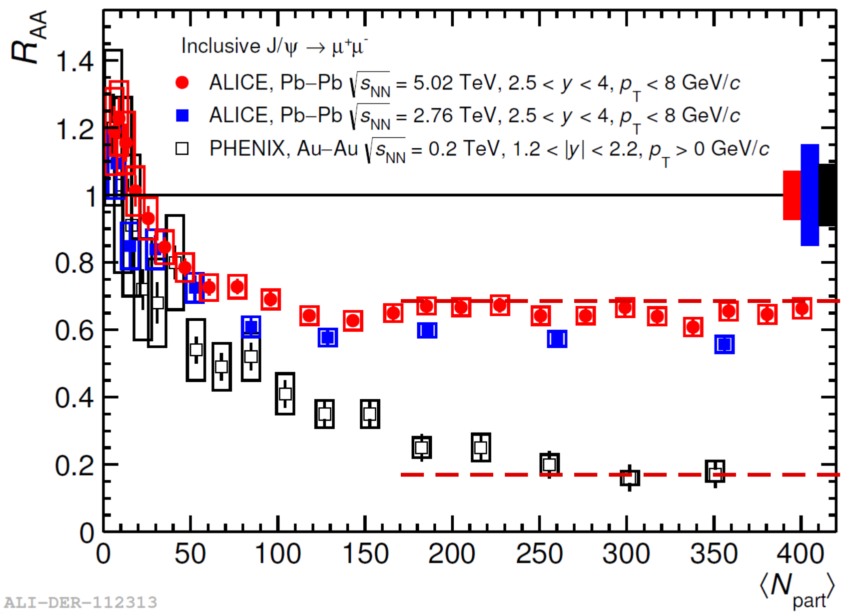
– Comparable suppression at high p_T

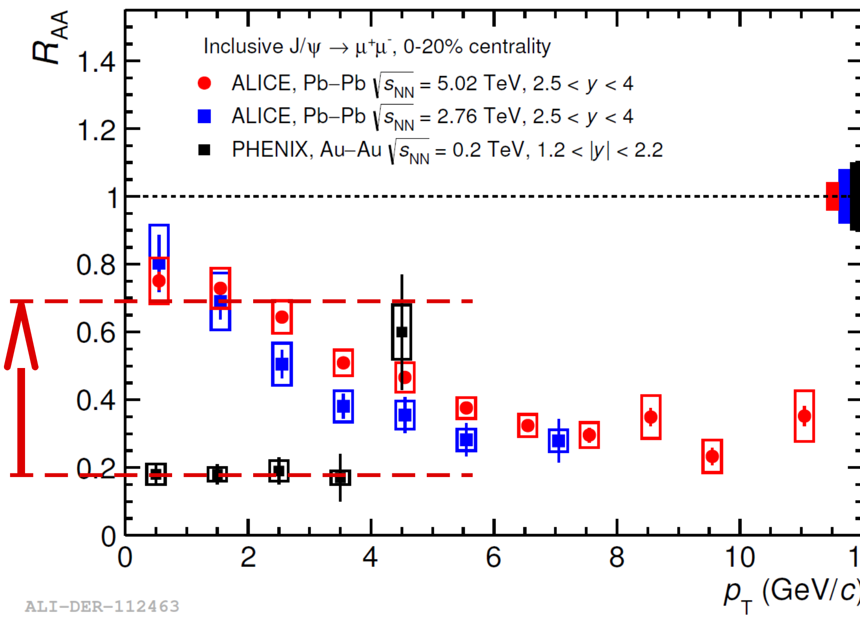
– Increasing R_{AA} towards lower p_T, more pronounced at midrapidity



J/ψ R_{AA}

[PLB 766 (2017) 212]





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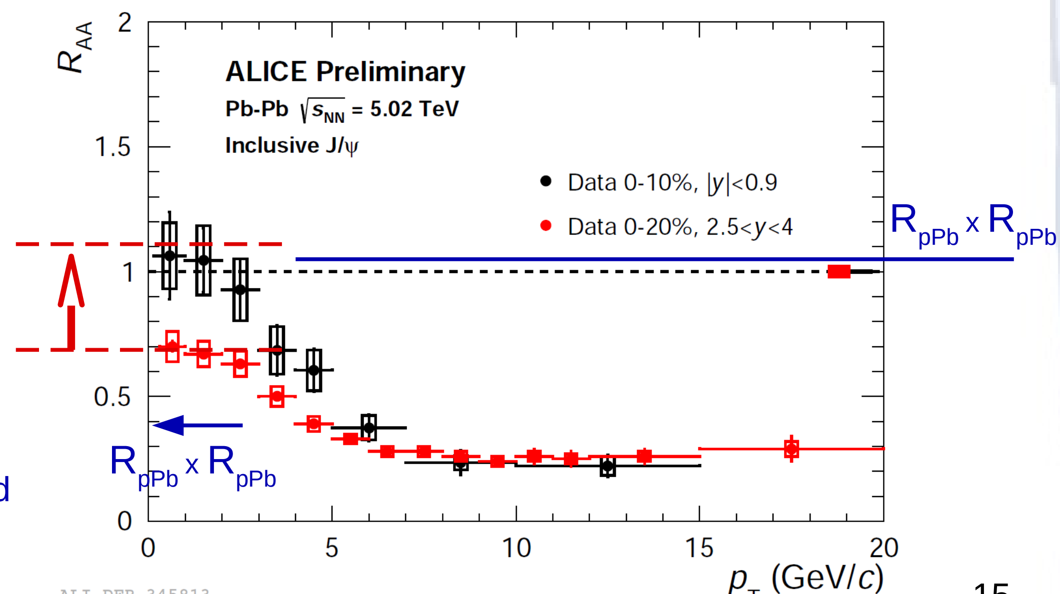
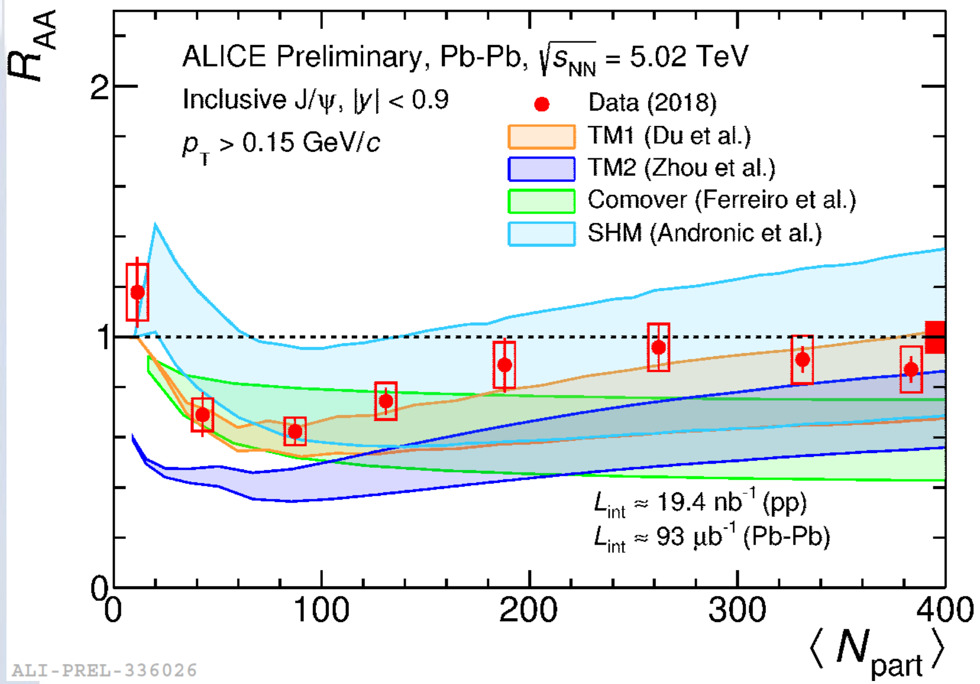
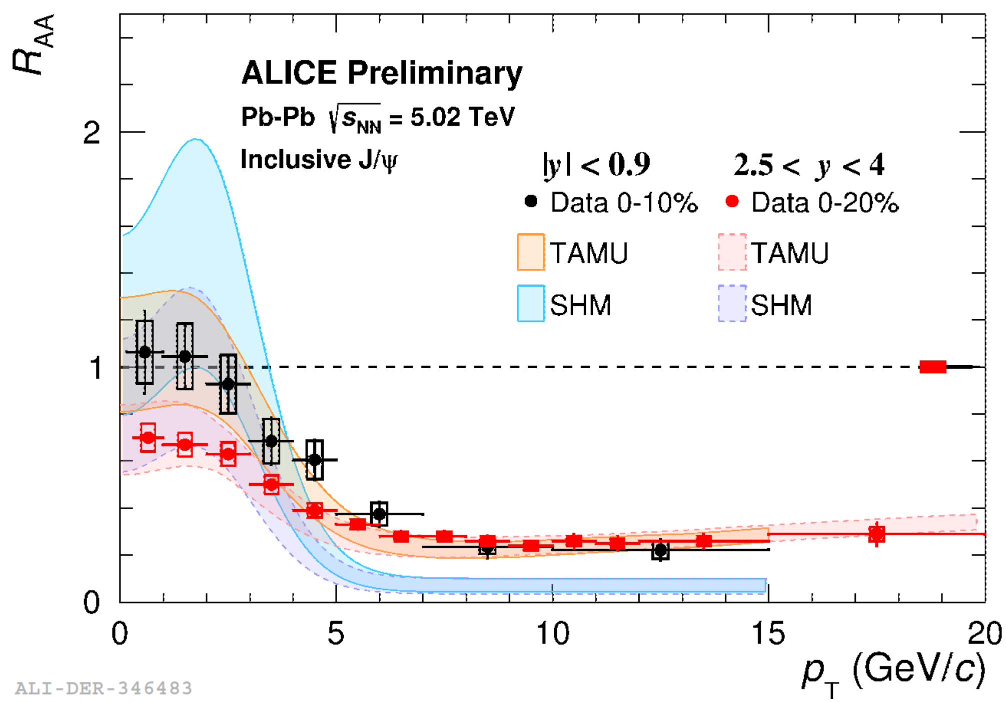


All compatible with a regeneration scenario!

J/ψ R_{AA} - Comparison with models





→ **Models including regeneration mechanism in agreement with data**

– Statistical Hadronization (SHM)
  – All charmonia produced at the QGP phase boundary with thermal weights

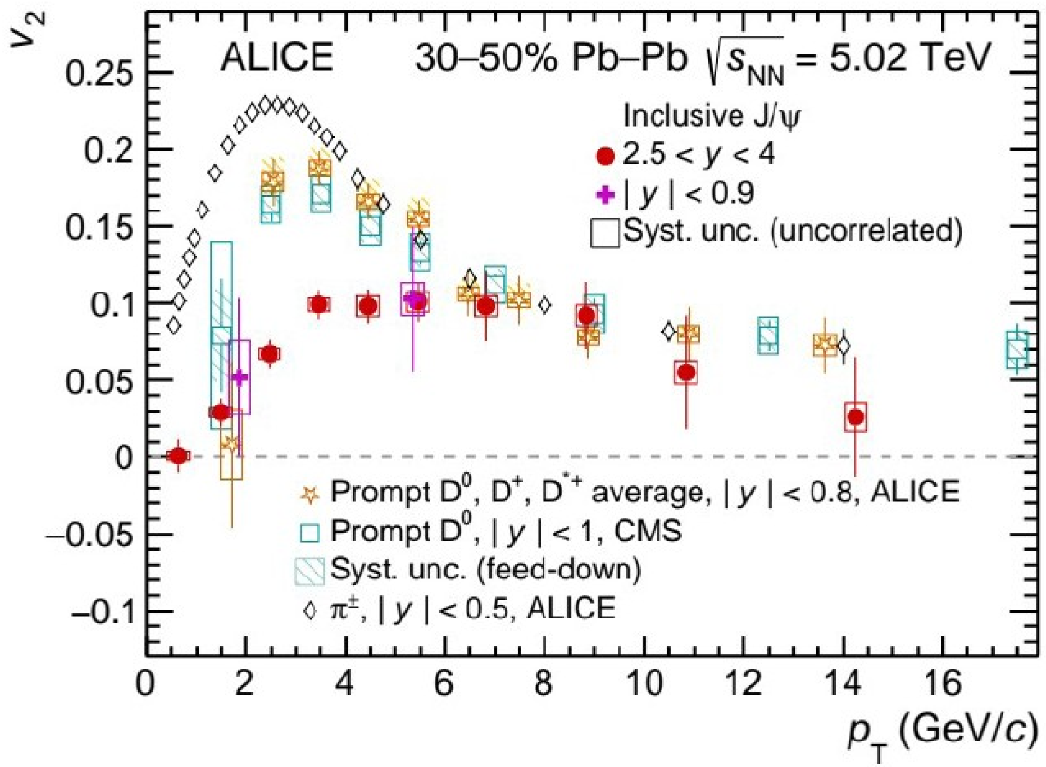
– Transport model (TAMU)
  – Based on rate equation with gain (regeneration) and loss (melting) terms

→ **large uncertainties on the models arise from charm cross sections and poor constrained nPDF**

→ **discriminating between the two pictures is one of the goals of Run3/4**

J/ψ v_2 – comparison to D-mesons and π

JHEP 10 (2020) 141

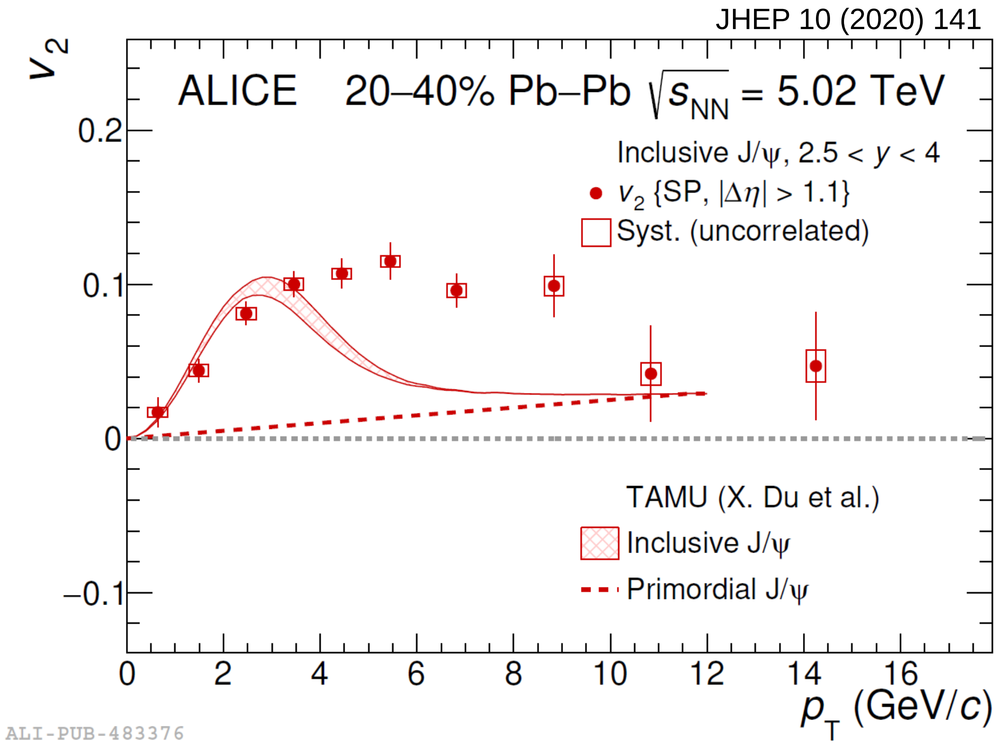


– J/ψ v_2 >0 → consistent with regeneration scenario, considering **charm quarks thermalized** in QGP

– Clear mass hierarchy at low-pT: $v_2(\pi)>v_2(D)>v_2(J/\psi)$

– Specie independent v_2 at high-p_T

J/ψ v_2 – comparison with models



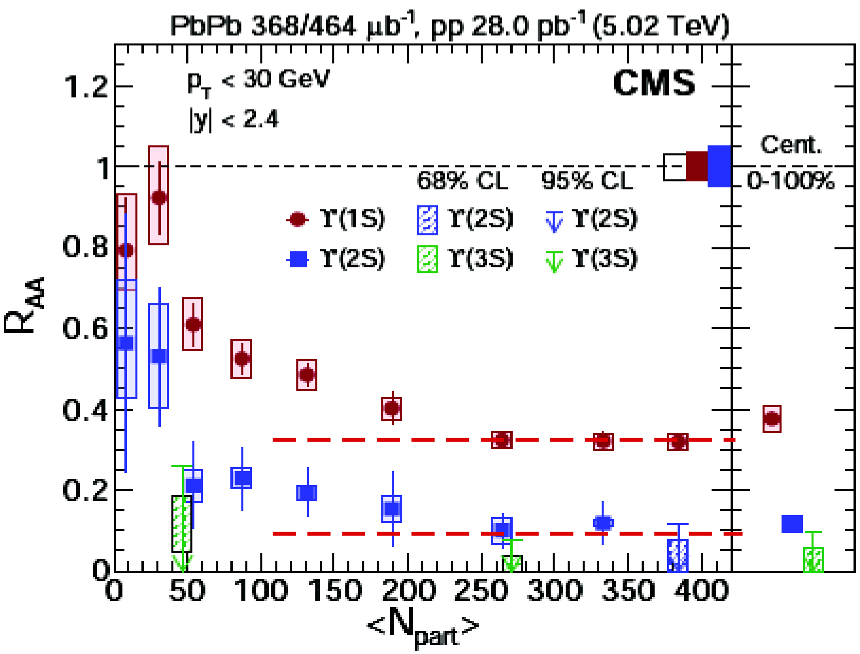
– Low p_T region described by transport model

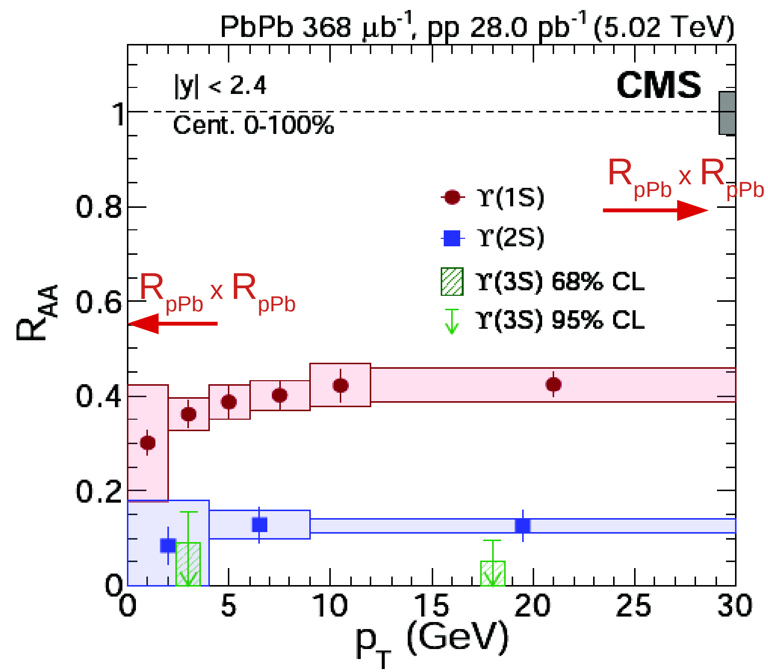
– Larger flow than the one predicted from the model at high-p_T → missing mechanism (e.g. energy loss) and/or underestimated radial flow from the hydrodynamic expansion

[On a side note: nuclear suppression R_{AA} is well reproduced by transport model]

Bottonomium R_{AA}

[Phys. Lett. B 790 (2019) 270]





– Increasing suppression of ϒ(nS) with centrality + saturation of R_{AA} at higher centralities

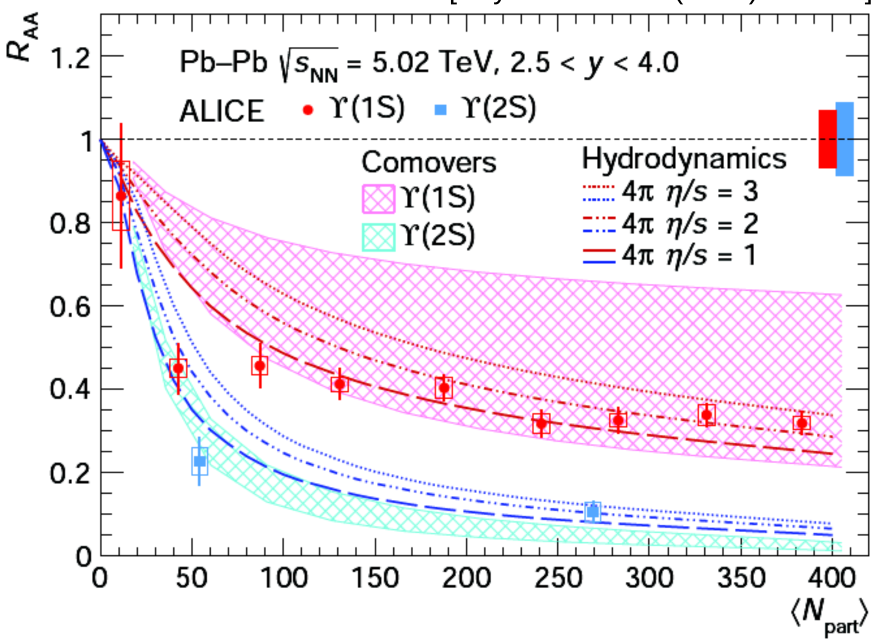
– R_{AA} of ϒ(1S) saturates to ~0.35 (factor ~3 suppression), R_{AA} of ϒ(2S) suppressed by a factor ~10

– compatible with a sequential ordering of the suppression

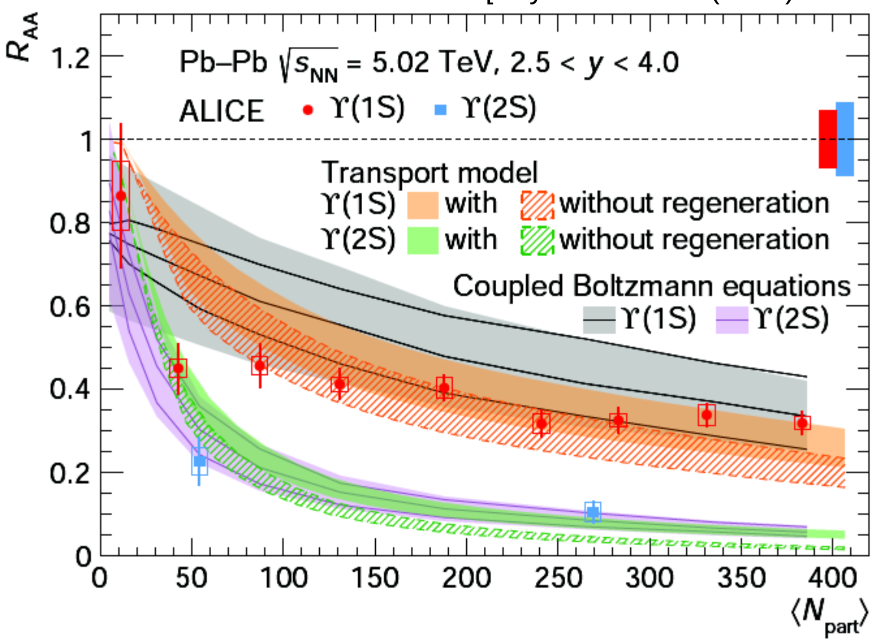
→ difficult to conclude about the effective suppression of the ground state due to the **not well known feeddown contributions**

Bottonomium R_{AA}

[Phys.Lett.B 822 (2021) 136579]



[Phys.Lett.B 822 (2021) 136579]



– Several models reproduce the trends of the data within uncertainties (all include feed-down contributions from higher states):

– **hydrodynamics:** thermal modification of a complex heavy-quark potential inside an anisotropic plasma (no modification of nuclear PDFs / no regeneration included)

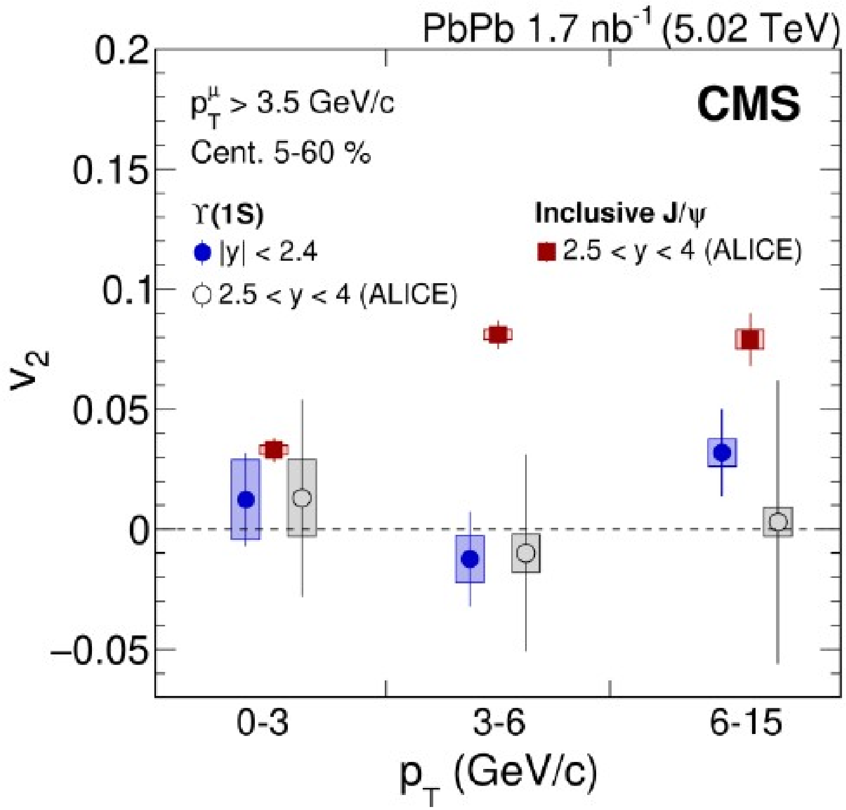
– **transport models:** interplay of dissociation and regeneration mechanisms, modification of nPDF included (available with and without regeneration)

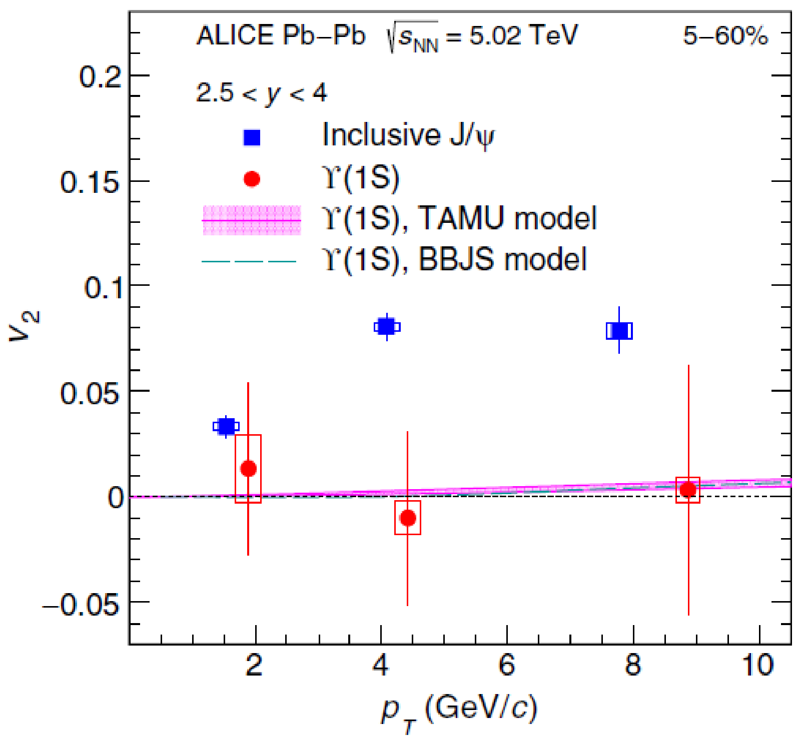
– **comovers:** break-up by interactions with comover particles, nCTEQ15 parametrisation for nPDF

→ **fair agreement also when regeneration is not included**

Υ(1S) v_2

[CMS: Phys. Lett. B 819 (2021) 136385]
[ALICE: Phys. Rev. Lett. 123 (2019) 192301]





– Υ(1S) v_2 compatible with zero and significantly smaller than that of inclusive J/ψ

  – different relative importance of production mechanisms (dissociation vs regeneration) for J/ψ and Υ(1S) ?

– Results compatible within uncertainties with values predicted by theoretical models:

  – regeneration included in TAMU, but it gives no significant contribution to the Υ(1S) v_2

  – only the path-length dependent dissociation implemented in BBJS

Take-home notes: Quarkonia in Pb-Pb collisions

Charmonia:

- Regeneration mechanism essential for describing suppression patterns observed for J/Ψ at the LHC → two competitive models: **statistical hadronization vs transport model**
  - discriminate between the pictures would shed light on **fundamental questions about hadronization** in a deconfined medium
  - precise measurments of **excited states** will help to disentangle between the two pictures
- Significant **non-zero v_2** measured at the LHC for J/Ψ:
  - Consistent with the regeneration scenario, **assuming thermalization of charm quarks in QGP**
  - Clear **mass ordering** observed at low p_T when compared to D mesons and pions
  - **Tension with transport model at intermediate / high p_T** → missing mechanism in models ?

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Bottonomia:

- Larger suppression observed for excited bottonium states → compatible with a **sequential ordering of the suppression**
  - Difficult to conclude for the suppression of the ground state due to the **unknown feeddown contributions**
  - Suppression patterns as a function of centrality (and p_T) described fairly well within the uncertainties by transport, hydrodynamics and comover models → **point to no significant contribution from regeneration**
- **ϒ(1S) v_2 compatible with zer**o and much smaller compared to J/Ψ v_2:
  - Consistent with small or negligible contribution from regeneration

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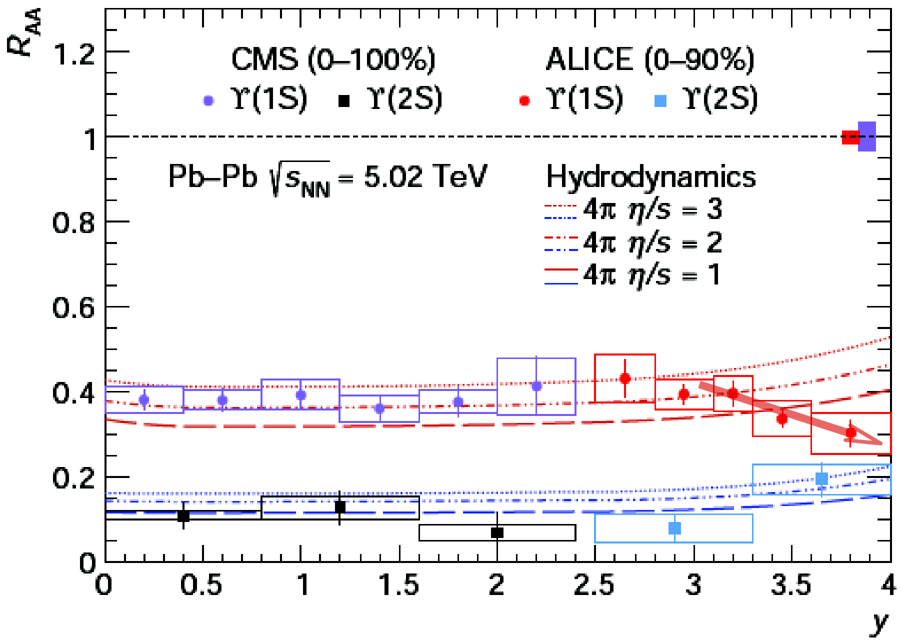
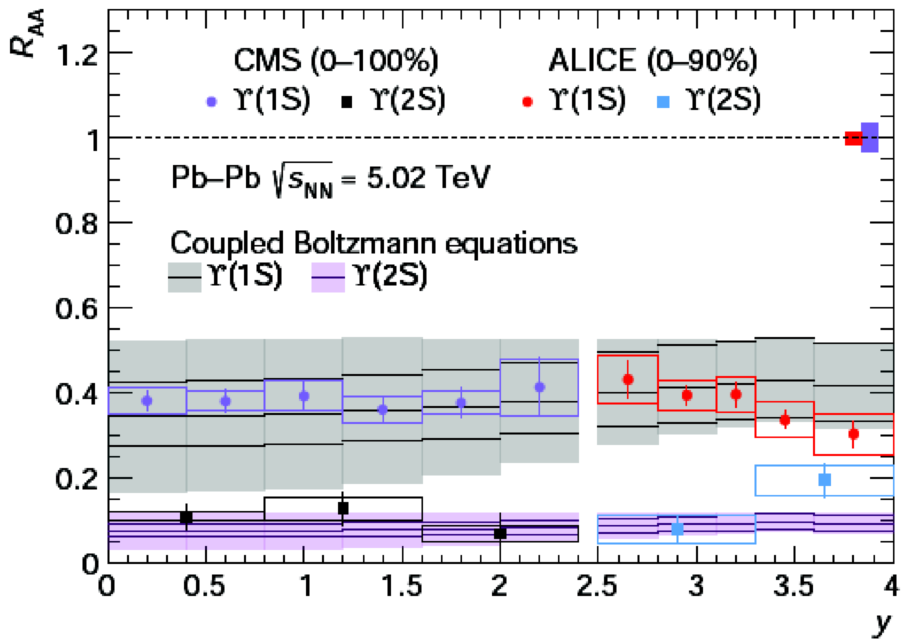
Thank you for your attention!

BACK-UP

Bottonomium R_{AA}

[Phys.Lett.B 822 (2021) 136579]





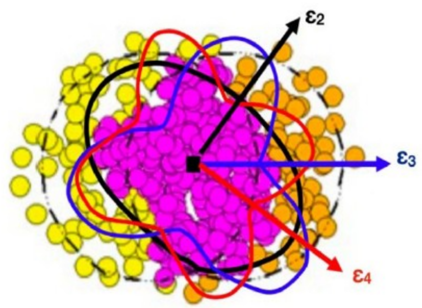
– Constant R_{AA} for Υ(2S) as a function of rapidity in agreement with models within large uncertainties

– Flat R_{AA} as a function of rapidity for Υ(1S) with a dropping from ~0.4 to ~0.3 at forward rapidity

– not reproduced by hydrodynamics (opposite trend) and Coupled Boltzmann equations

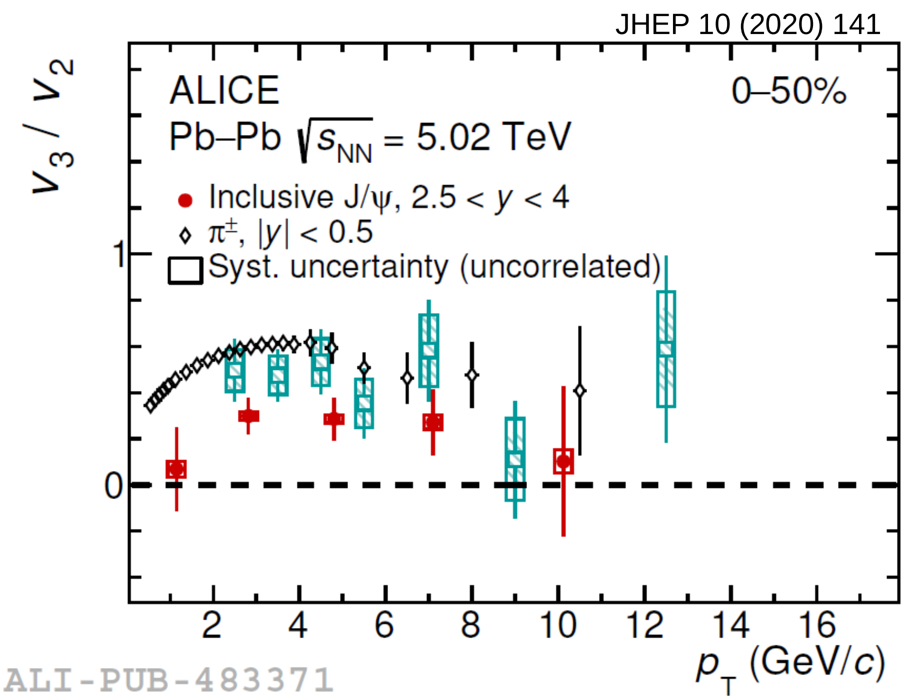
→ **could point to missing mechanism in available models**

J/ψ v_3 / v_2



Decomposed transverse projection of participant region in Fourier series

– Energy density fluctuations in the overlap region → generates triangularity (v_3)



– Similar hierarchy observed for v_3 / v_2 → higher harmonics are damped faster for heavy quarks than for the light ones

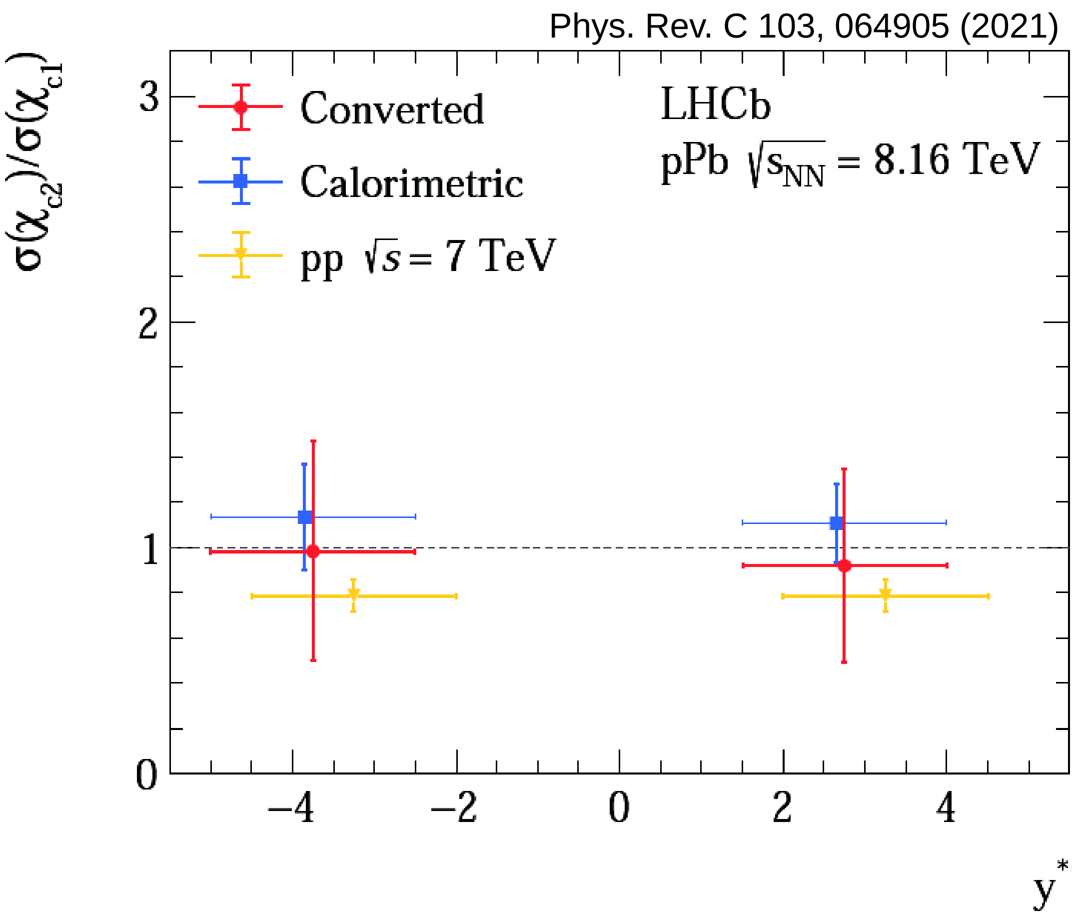
– Nearly species independent for light flavor particles

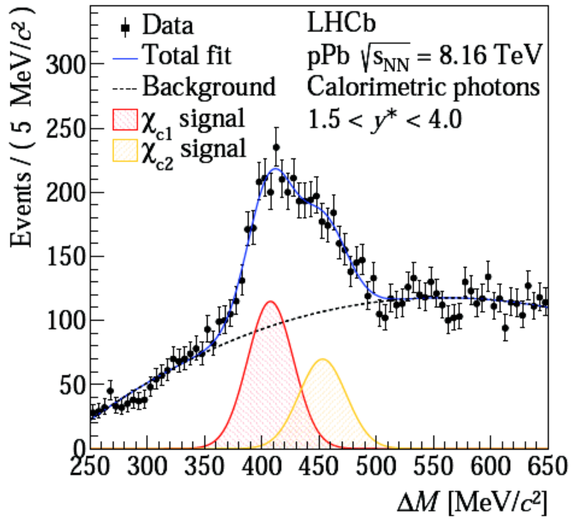
– Heavy-flavour hadrons (both J/ψ and D mesons) deviate from this expectation

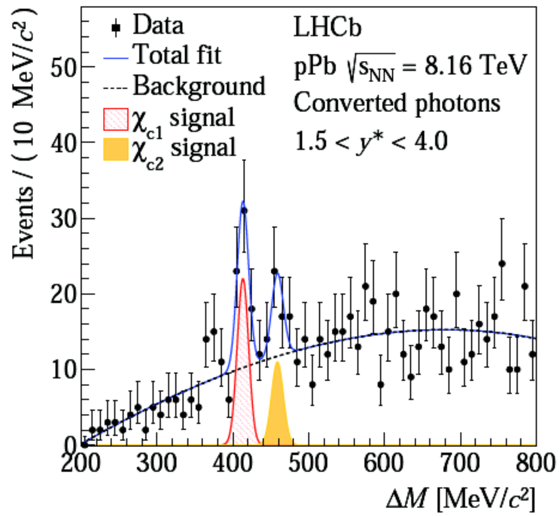
  – Less sensitivity to initial state fluctuations wrt light flavor species

  – Possible consequence of a late or incomplete charm thermalization

χ_c production in p-Pb





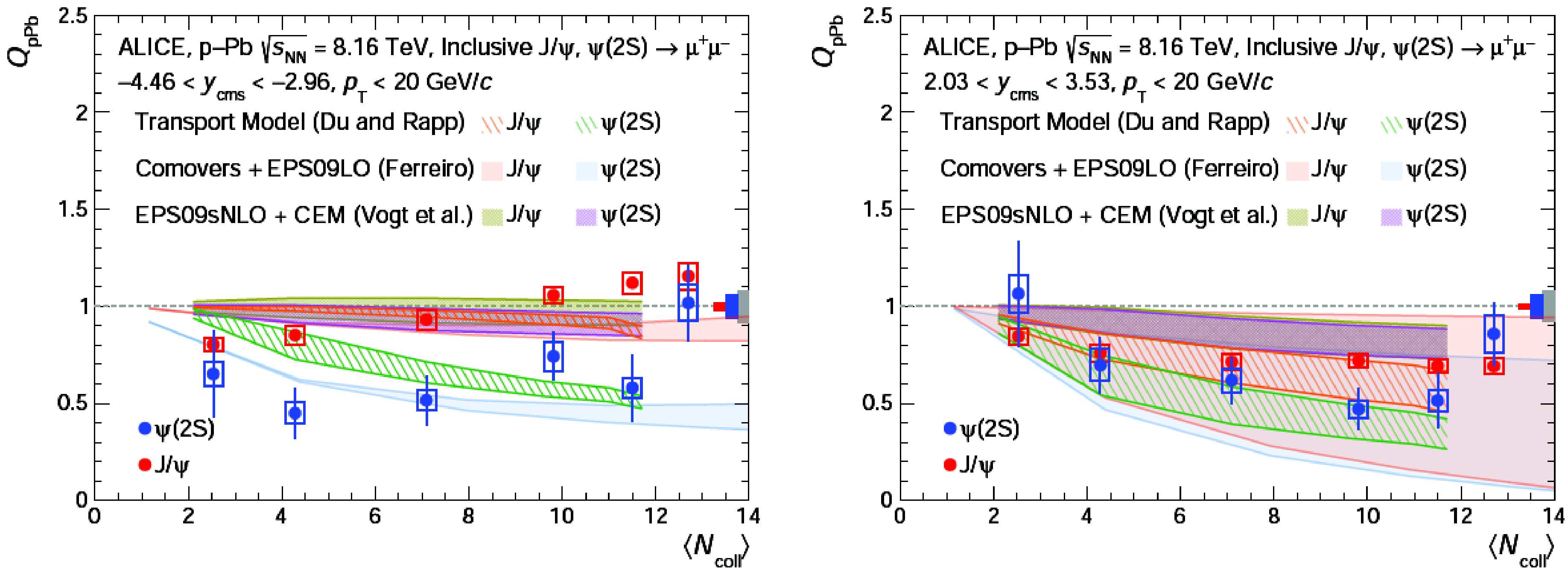


– Prompt $\sigma_{\chi c1}/\sigma_{\chi c2}$ ratio in pPb collisions sensitive to final state effects (similar binding energies for χ_{c1} and χ_{c2})

– consistent with unity and pp within uncertainties at bit forward and mid rapidity → similar CNM effects for the two states

J/ψ and ψ(2S) modification vs centrality

[JHEP 02 (2021) 002]



$$Q_{pPb} = \frac{Y_{\psi}^{pPb}}{\langle T_{pPb} \rangle \times \sigma_{\psi}^{pp}}$$

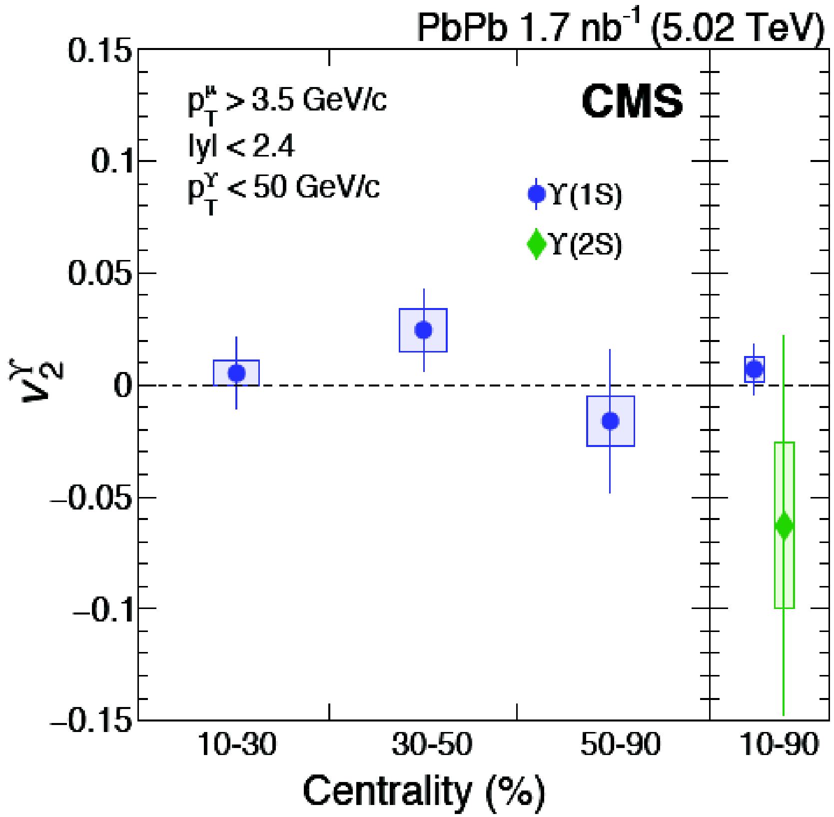
– Models based on nPDF modifications or coherent energy loss (not shown) predict same Q_{pPb} for Ψ(2S) and J/Ψ

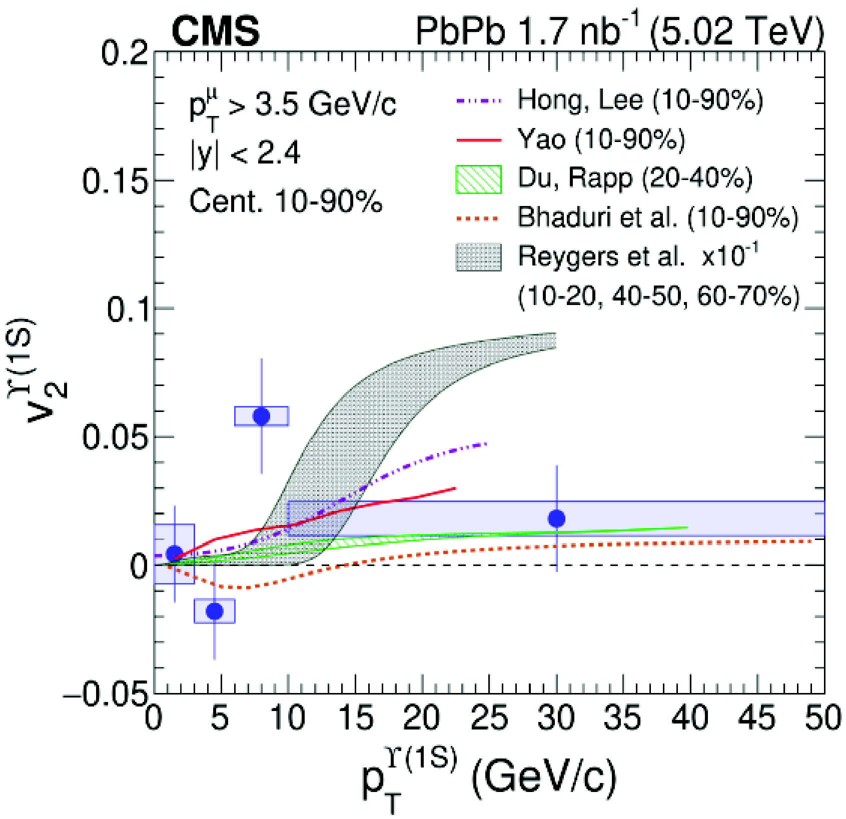
– Only models implementing final state interactions (comovers, transport model) in qualitative agreement with data

– large model uncertainties from nPDF

Υ(nS) v_2 - CMS

[CMS: Phys. Lett. B 819 (2021) 136385]





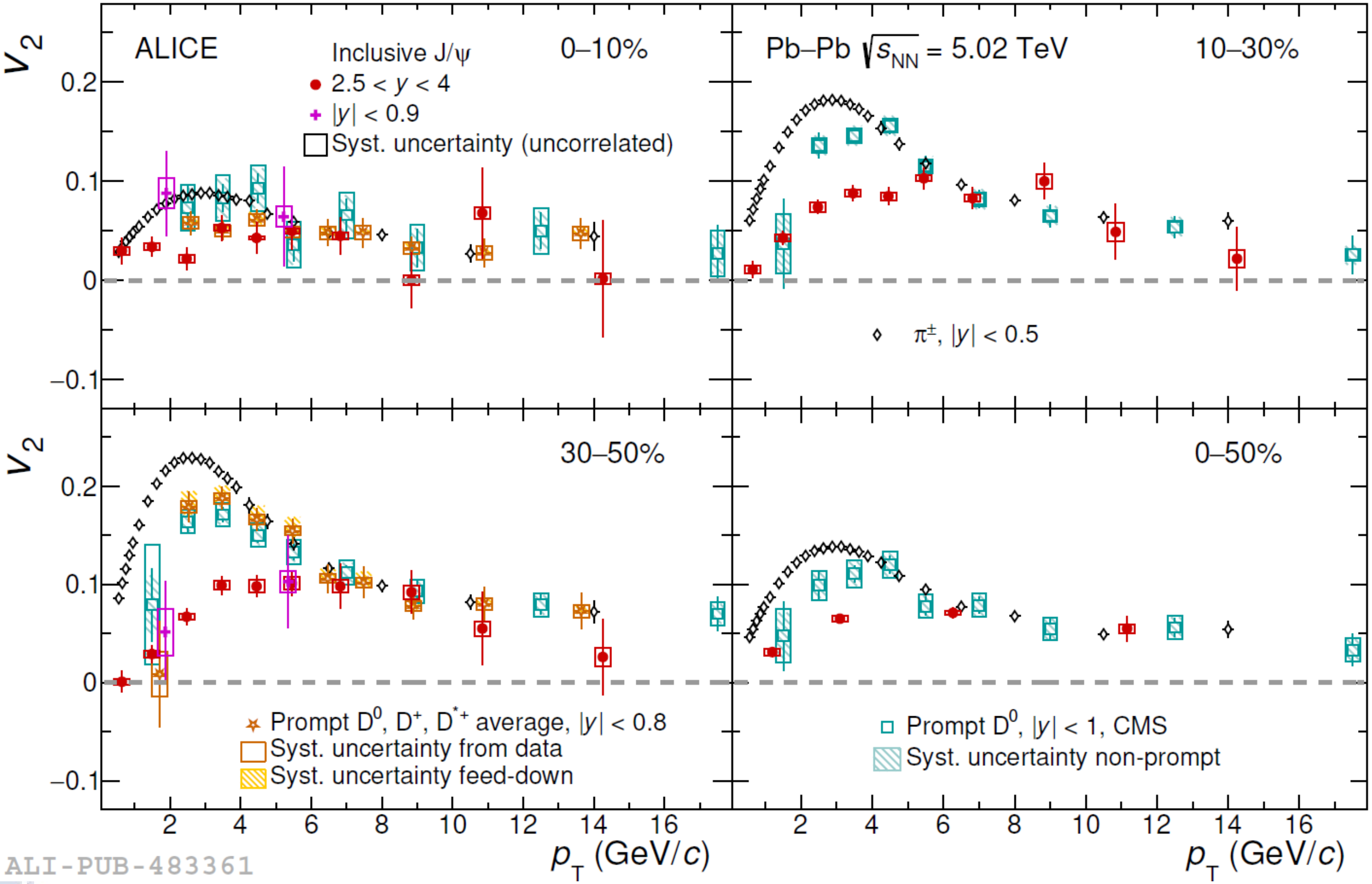
– No significant flow observed for Υ(1S) and Υ(2S)

– Compatible with models at low-p_T, some of the the predict large v_2 at high-p_T

– Large uncertainties → all scenarios still possible

J/ψ v_2 – comparison to D-mesons and π

JHEP 10 (2020) 141



– J/ψ v_2 >0 → consistent with **hydrodynamic flow of charm quarks** in QGP

– J/ψ v_2 grows from central towards semi-central collisions, similarly as lighter particles

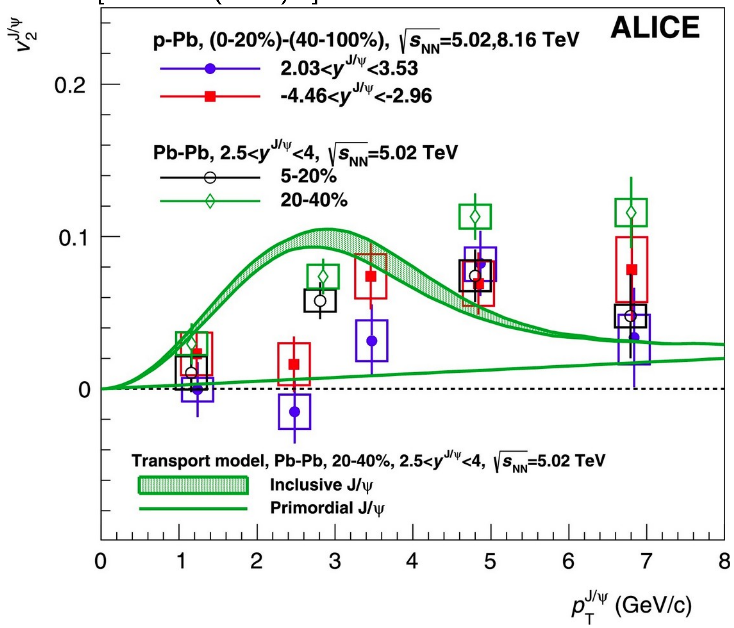
– Clear mass hierarchy at low-pT: v_2(π)>v_2(D)>v_2(J/ψ)

– Specie independent v_2 at high-p_T

J/ψ v_2 in p-Pb collisions

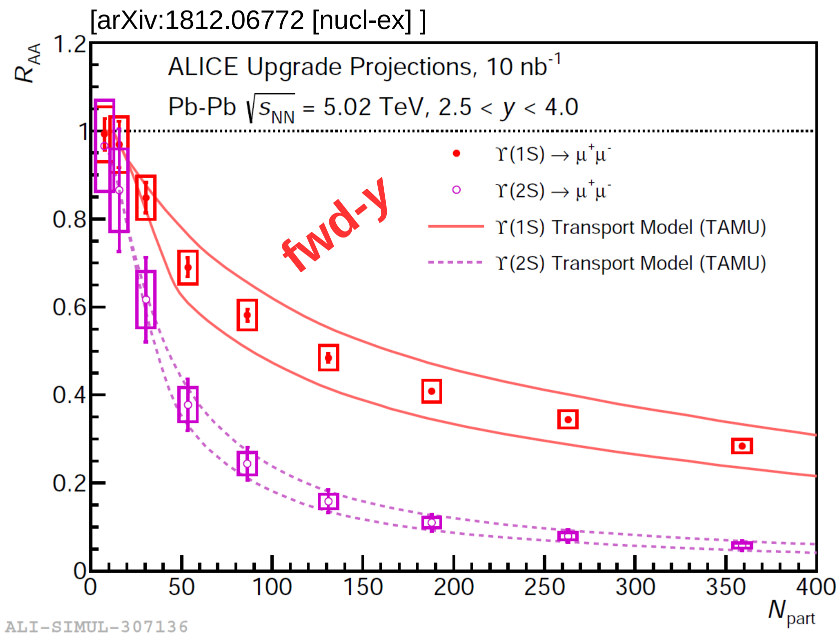
- In heavy-ion collisions **non-zero v_2** indicates the **participation in the collective expansion** of the system
- p-Pb collisions:
  - J/ψ v_2 measured looking at **long-range angular correlations** between backward / forward rapidity J/ψ and charged hadrons produced at mid-rapidity (rapidity gap ~ 1.5)
  - Non-zero v_2 observed for p_T > 3 GeV/c (~5σ significance)
    - Similar v_2 compared to Pb-Pb measurements → very intriguing result: **common underlying mechanism** (besides what's included in current calculations) at the origin of J/ψ v_2?
    - **Initial conditions** ?

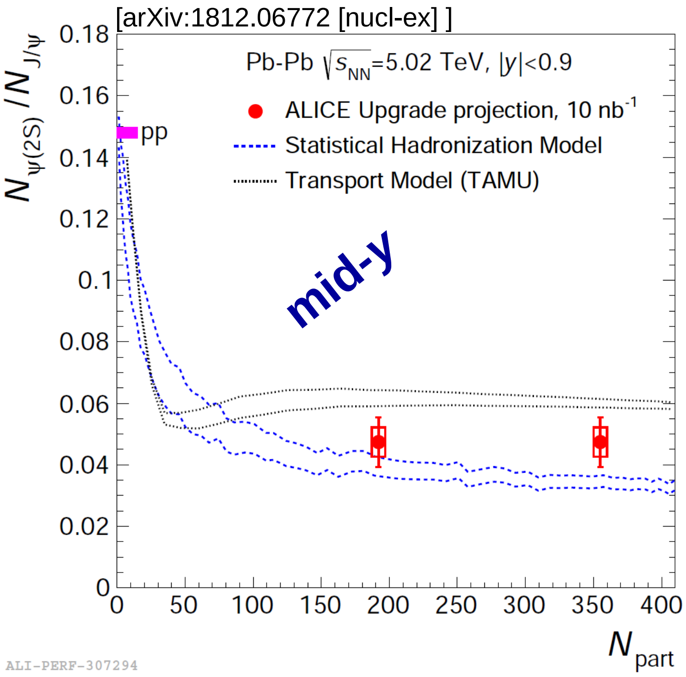
[PLB 780 (2018) 7]



ALICE Perspectives Run 3 / 4

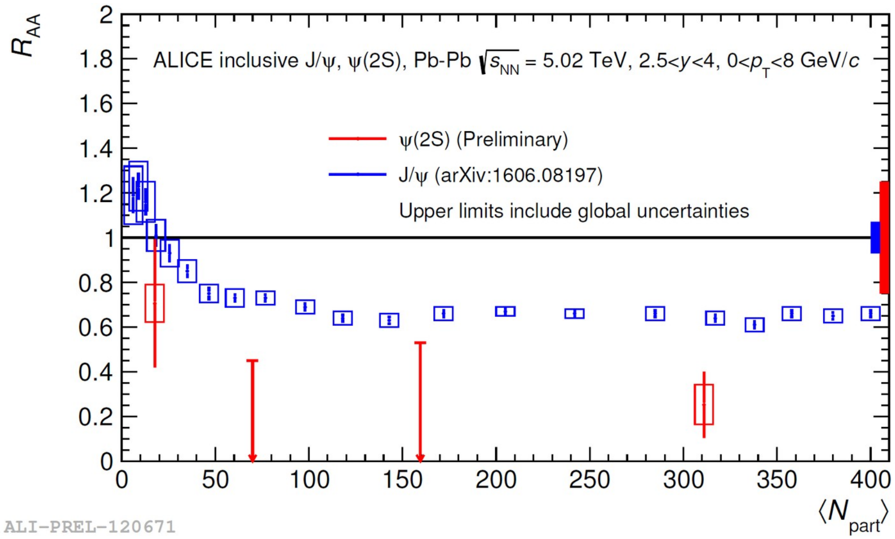
- ALICE Upgrade foreseen for Run III-IV:
  - Continuous readout: high statistics minimum bias sample **(target for Pb-Pb: L_{int} = 10 nb^{-1})** → significant improvement for low p_T quarkonia at mid-rapidity
  - New Muon Forward Tracker (MFT) at forward rapidity → reconstruction of secondary vertices possible

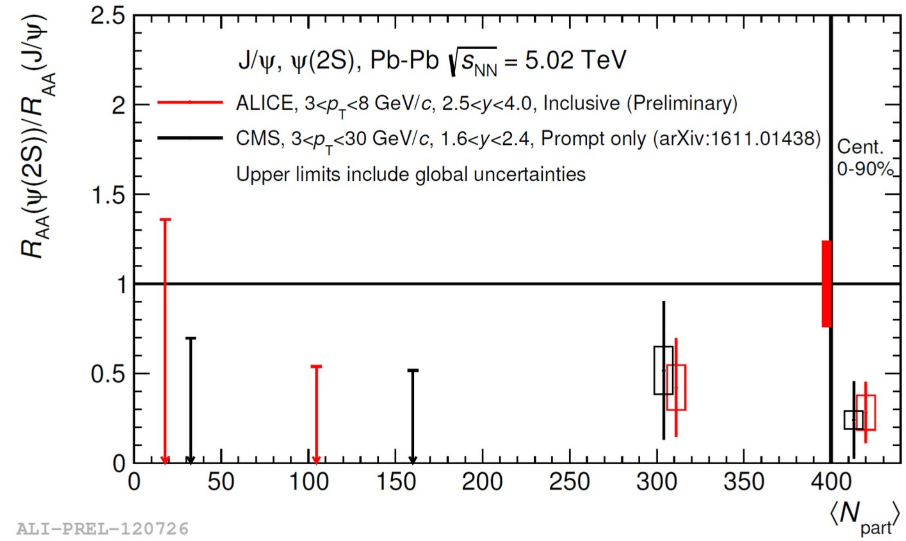


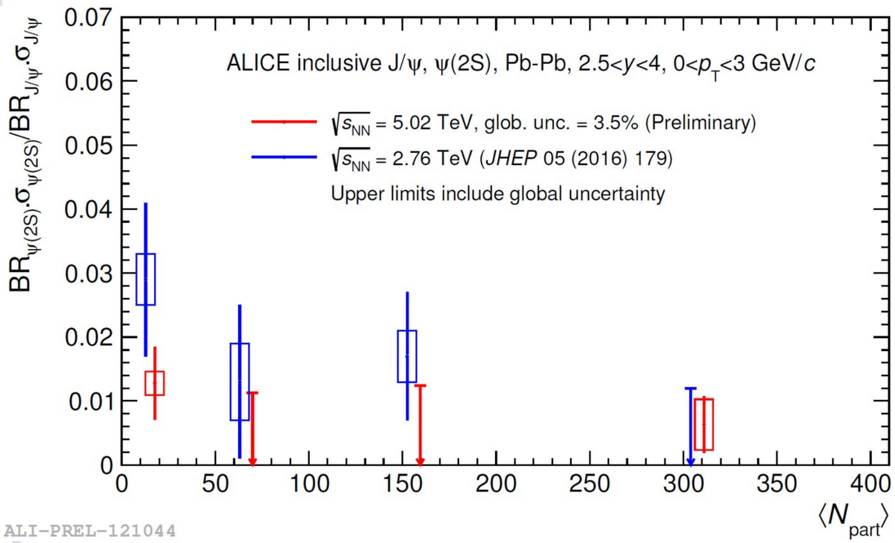


- Improved precision for existing quarkonium measurements down to p_T = 0
- New measurements will become accessible

ψ(2S) in Pb-Pb collisions at 5.02 TeV



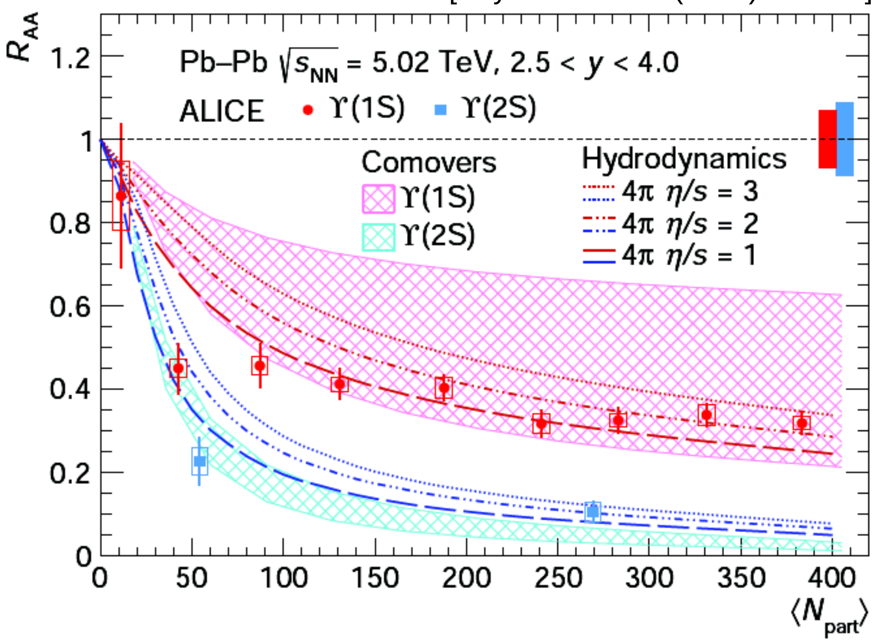




- ✔ ψ(2S) more suppressed than J/ψ towards more central collisions
- ✔ Results compatible with CMS
- ✔ Not possible to conclude due to the large uncertainties → more precise measurements expected thanks to 2018 Pb-Pb data

Bottonomium R_{AA}

[Phys.Lett.B 822 (2021) 136579]



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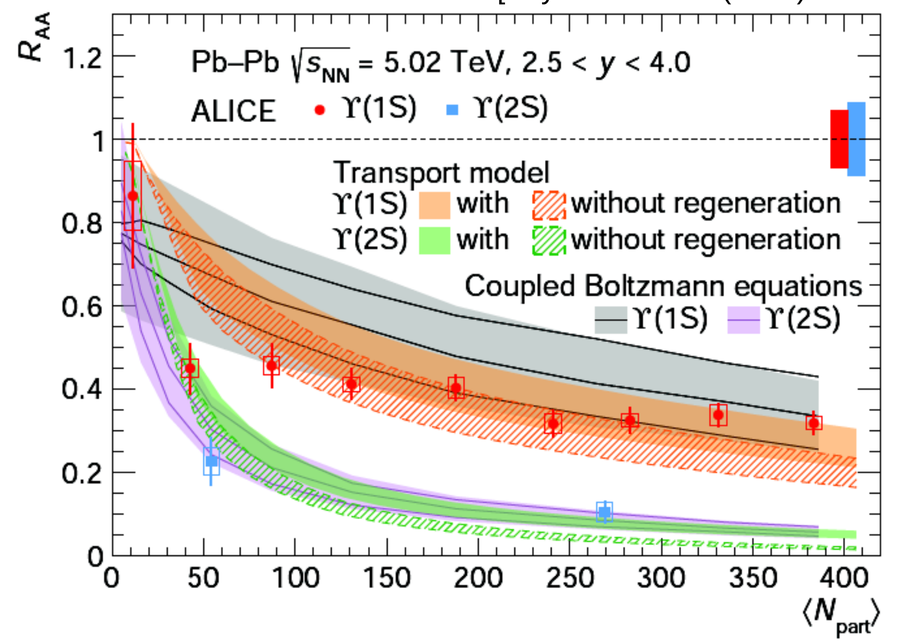

– Comparison of **Y(2S)-to-Y(1S) double ratio** with models:

– tension observed with comovers

– hydro calculations describe the data within uncertainties

– transport model with regeneration component included in better agreement

→ with more precise measurements could serve as a model discriminator

[PRL 120 (2018) 142301]