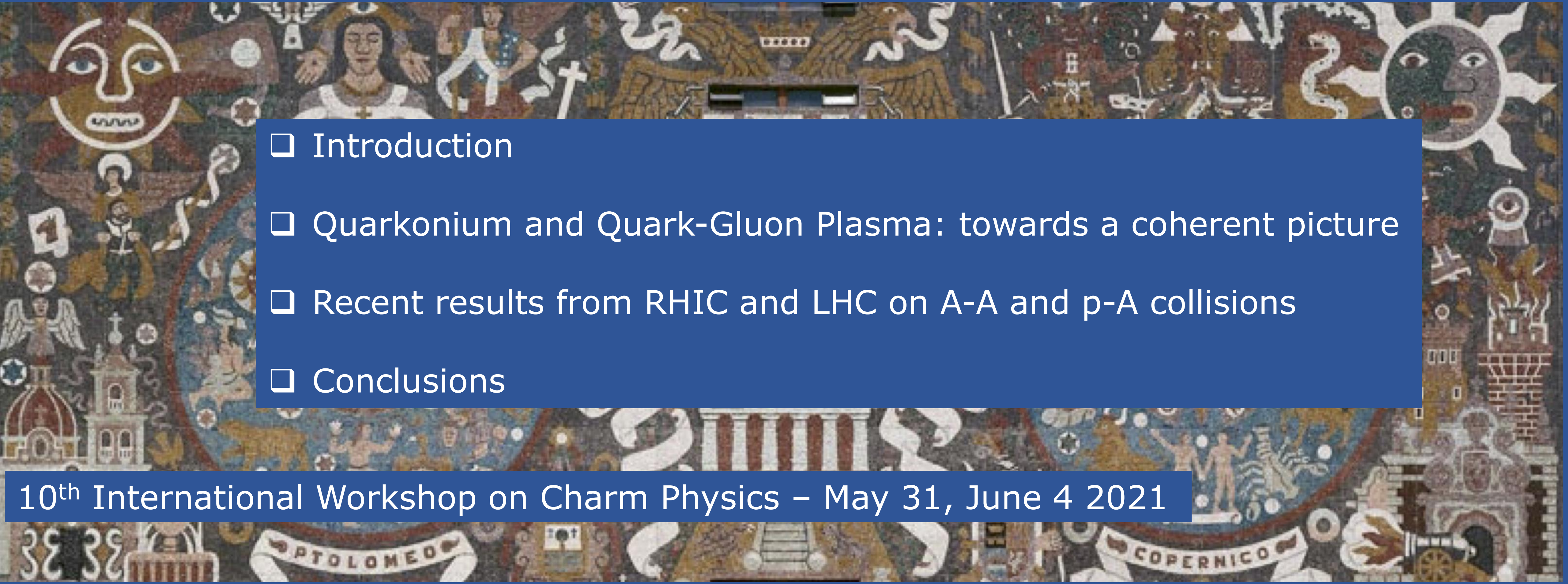
Charmonium "in media": an experimental overview

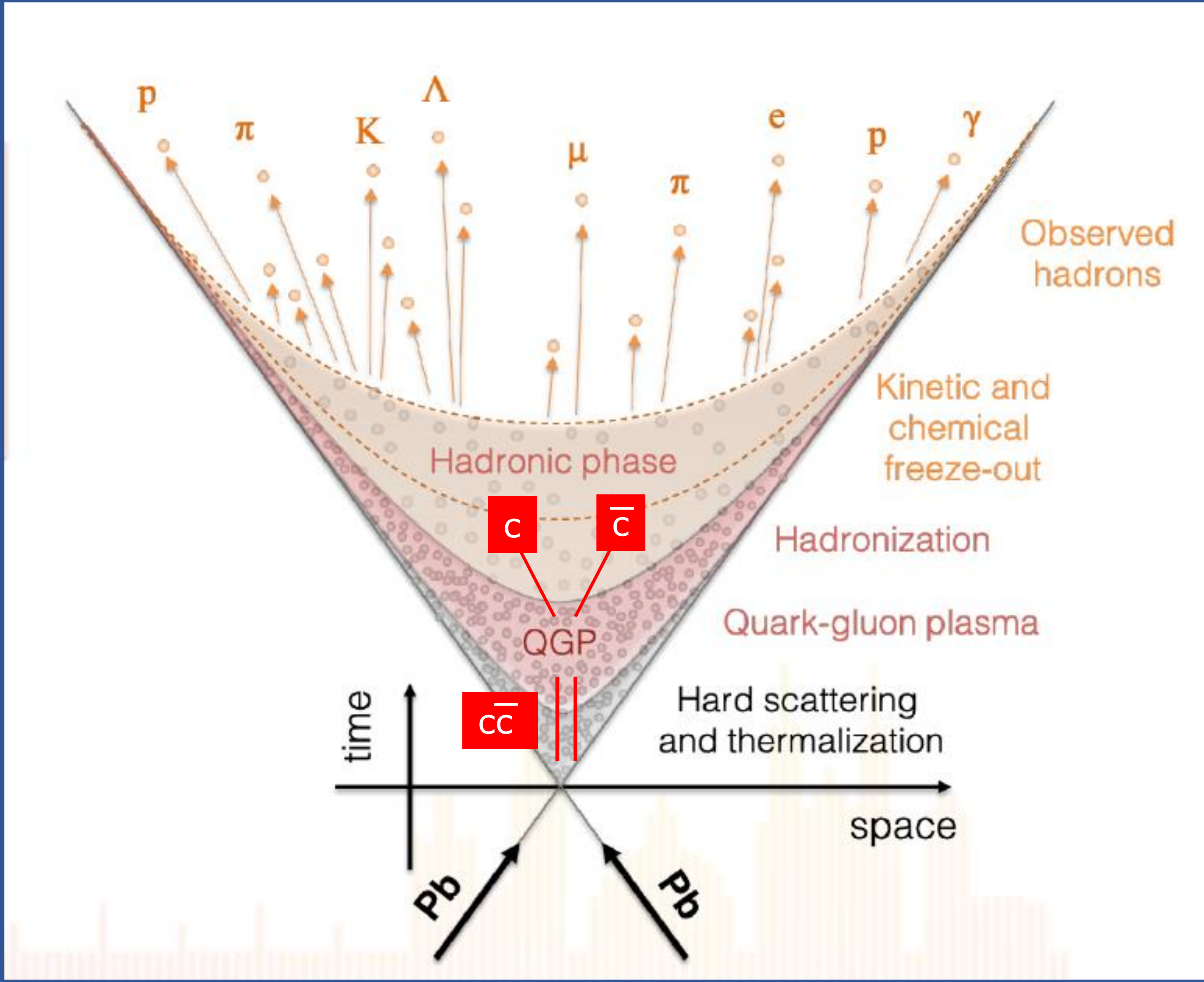
E. Scomparin – INFN Torino (Italy)



- ❑ Introduction
- ❑ Quarkonium and Quark-Gluon Plasma: towards a coherent picture
- ❑ Recent results from RHIC and LHC on A-A and p-A collisions
- ❑ Conclusions

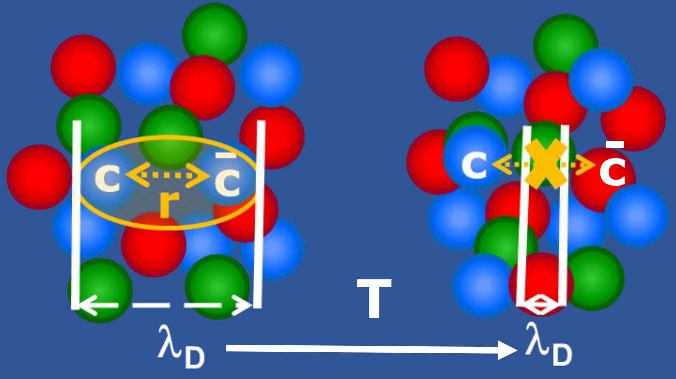
10th International Workshop on Charm Physics – May 31, June 4 2021

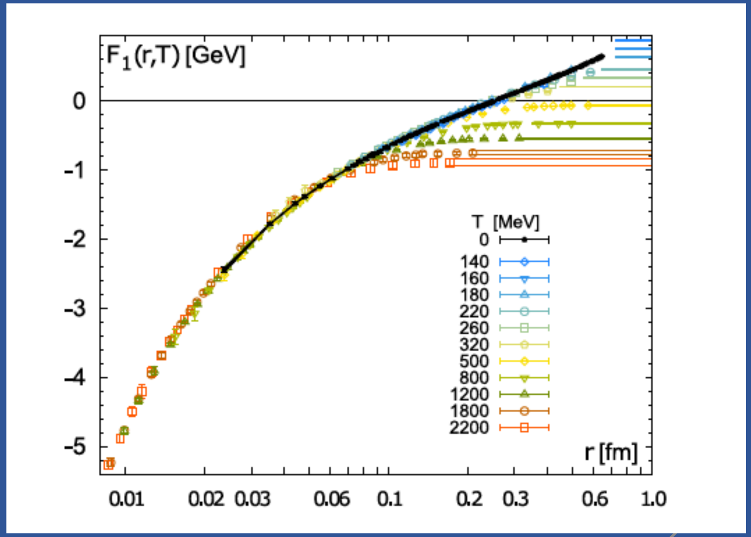
Quarkonium as a probe



- Produced in the **early stages** of the collision
- **Dissociated** in the QGP medium (color screening)

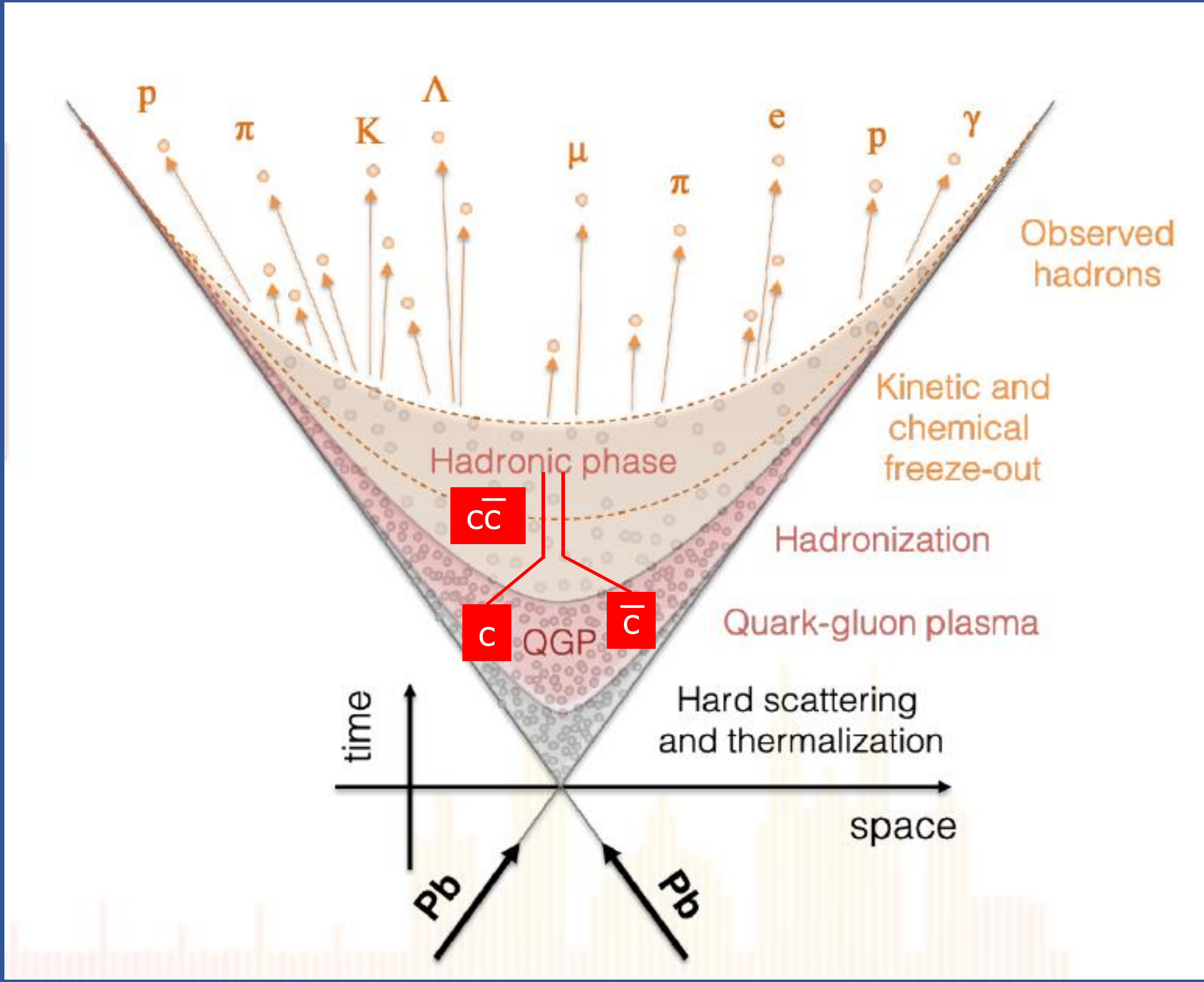
T. Matsui and H. Satz, PLB178 (1986) 416





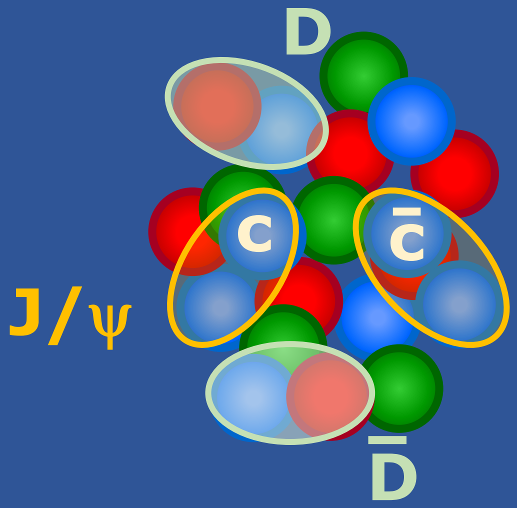
A. Bazavov et al., PRD98(2018) 054511

Quarkonium as a probe



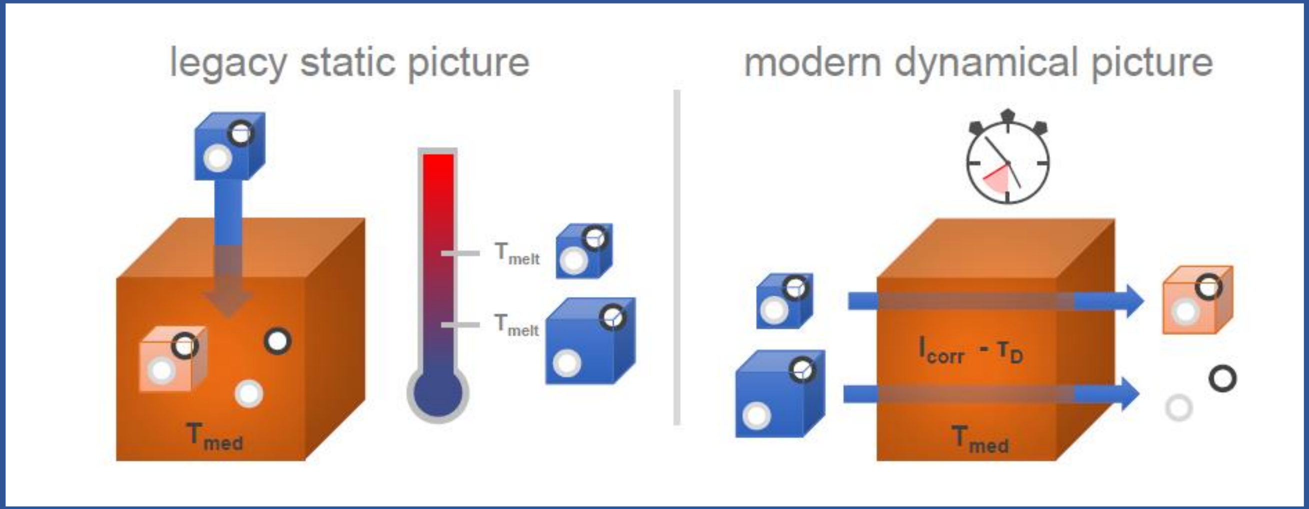
- ❑ Produced in the **early stages** of the collision
- ❑ **Regenerated** in the QGP and at hadronization

P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196
Thews, Schroedter and Rafelski, PRC63 054905 (2001)



Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~115

Quarkonium as a probe



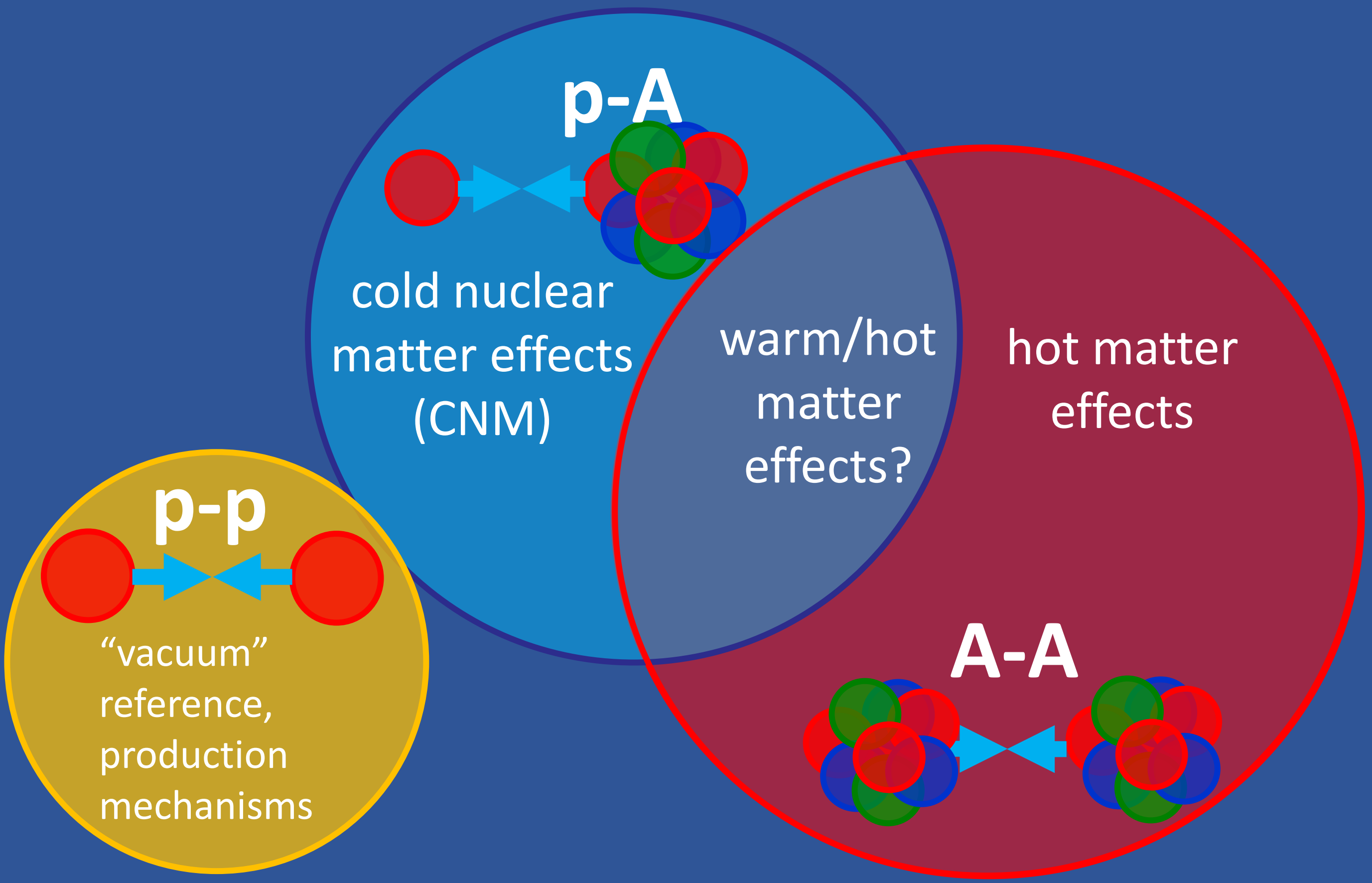
from
A. Rothkopf, Phys.Rep. 858(2020) 1

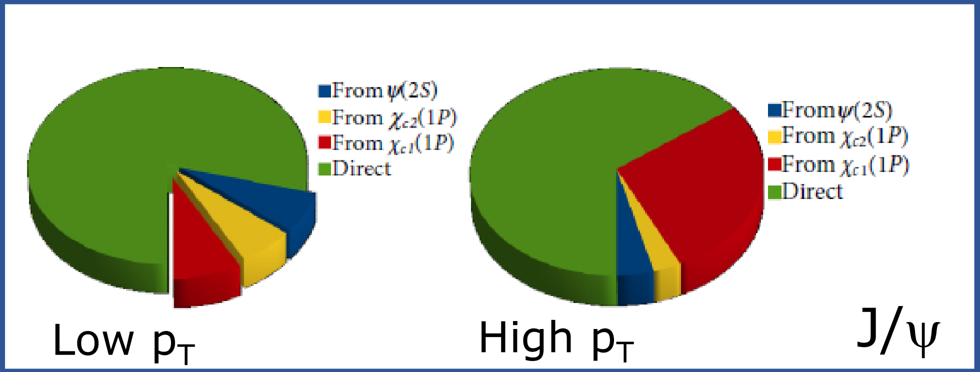
- Although the **"screening+recombination"** static picture is conceptually simple and attractive, a realistic description implies a sophisticate theoretical treatment (cfr. Ralf talk)

- **Dynamical picture**: interplay of how strongly the medium interferes with the binding at any instant, as well as time spent in the medium, determines the survival of the quarkonium state

Impressive advances on theory side but the availability of data for various colliding systems and energy remains a must!

Collision systems





from J.P. Lansberg, Phys. Rep. 889 (2020) 1

Hot matter effects can selectively affect the various quarkonium states

⬇

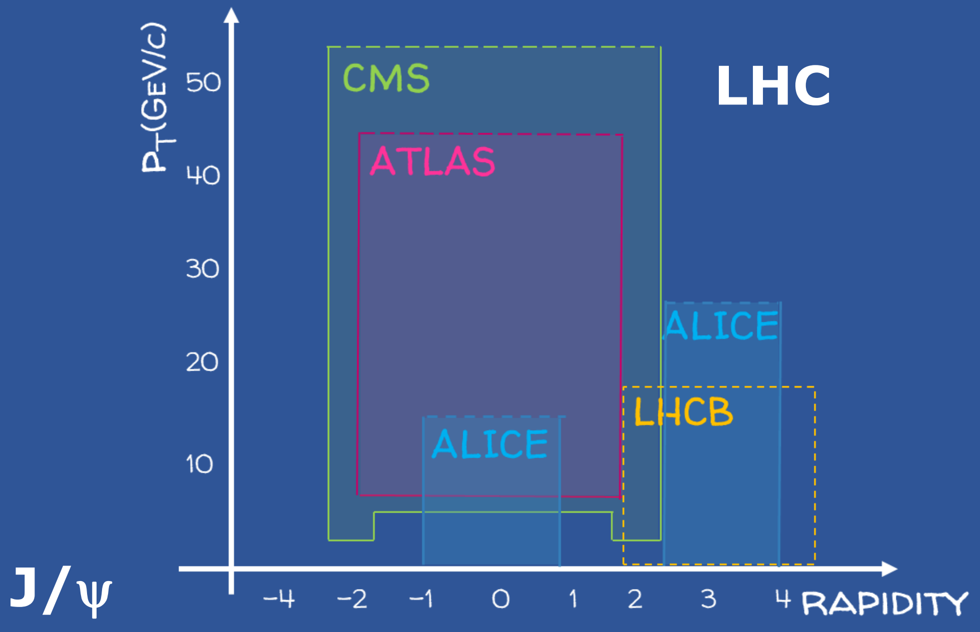
A quantitative understanding of A-A results requires the knowledge of **feed-down** fractions towards ground states (J/ψ, $\Upsilon(1S)$ in particular)

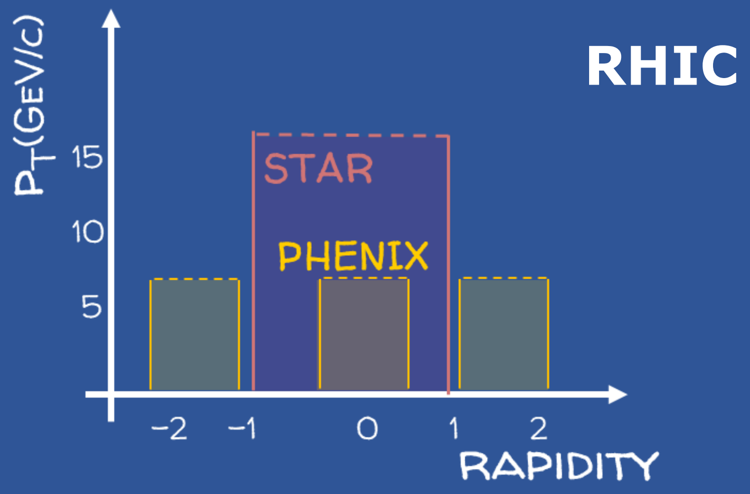
⬇

Accurate data now available at LHC energy

- CNM: nuclear shadowing, color glass condensate, parton energy loss, resonance break-up
- Hot matter effects: suppression vs re-generation
- "Warm" matter effects: hadronic resonance gas

Quarkonium in p-A, AA: RHIC and LHC measurements



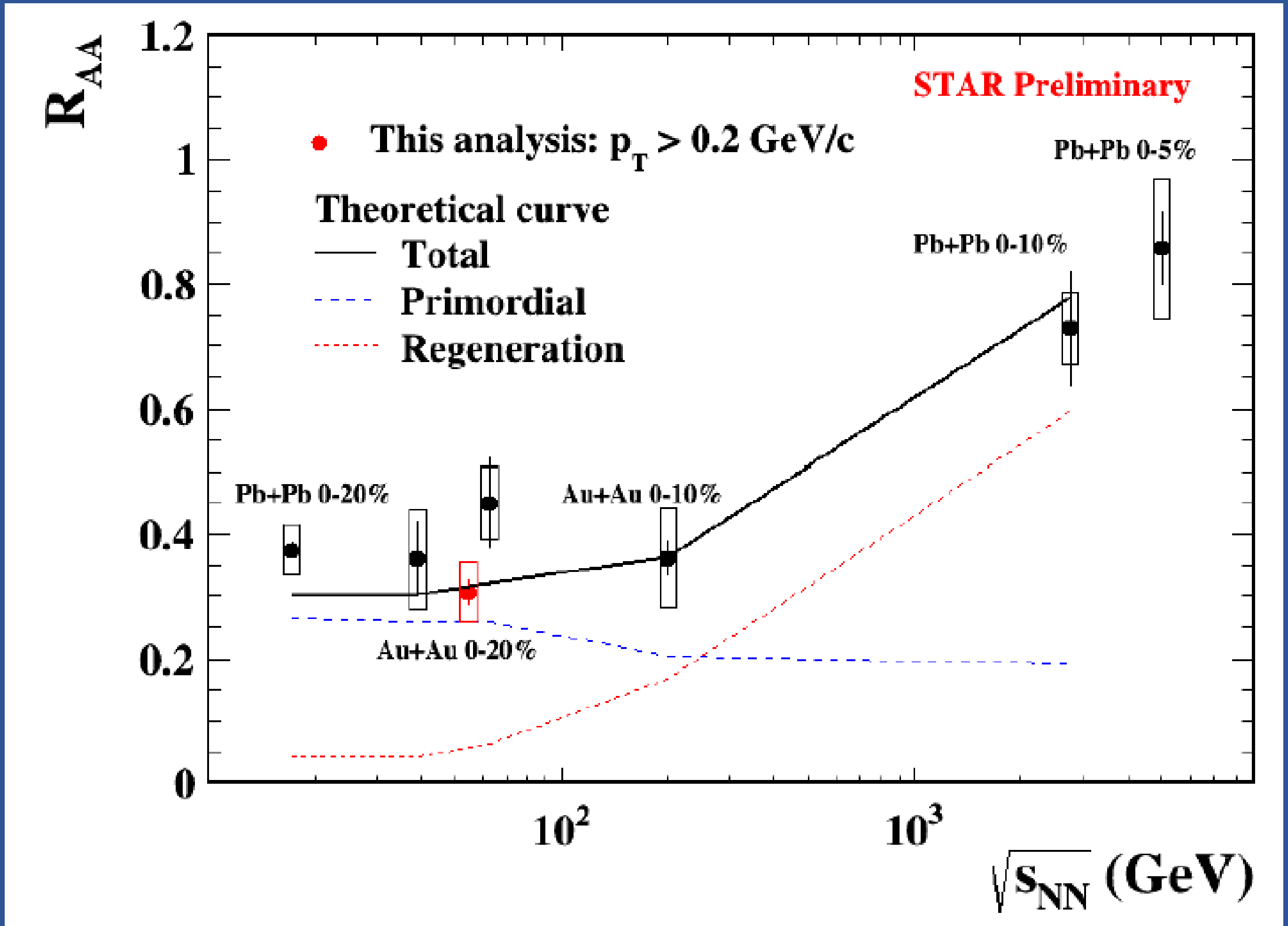


Collider	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	Data taking
RHIC	PHENIX STAR	Au-Au, Cu-Cu, Cu-Au, U-U	200, 193, 62, 54, 39	2000-2020
		p-A, d-Au	200	
		pp	200-500	
LHC	ALICE ATLAS CMS LHCb	Pb-Pb	2760 5020	2010/2011 2015/2018
		p-Pb	5020 8160	2013 2016
		pp	2760, 5020, 7000, 8000, 13000	2010-2018

Good complementarity between experiments
→ Wide **rapidity** coverage
→ Impressive range in $\sqrt{s_{NN}}$

A-A results: charmonium (and bottomonium)

Charmonium: from low to high energy

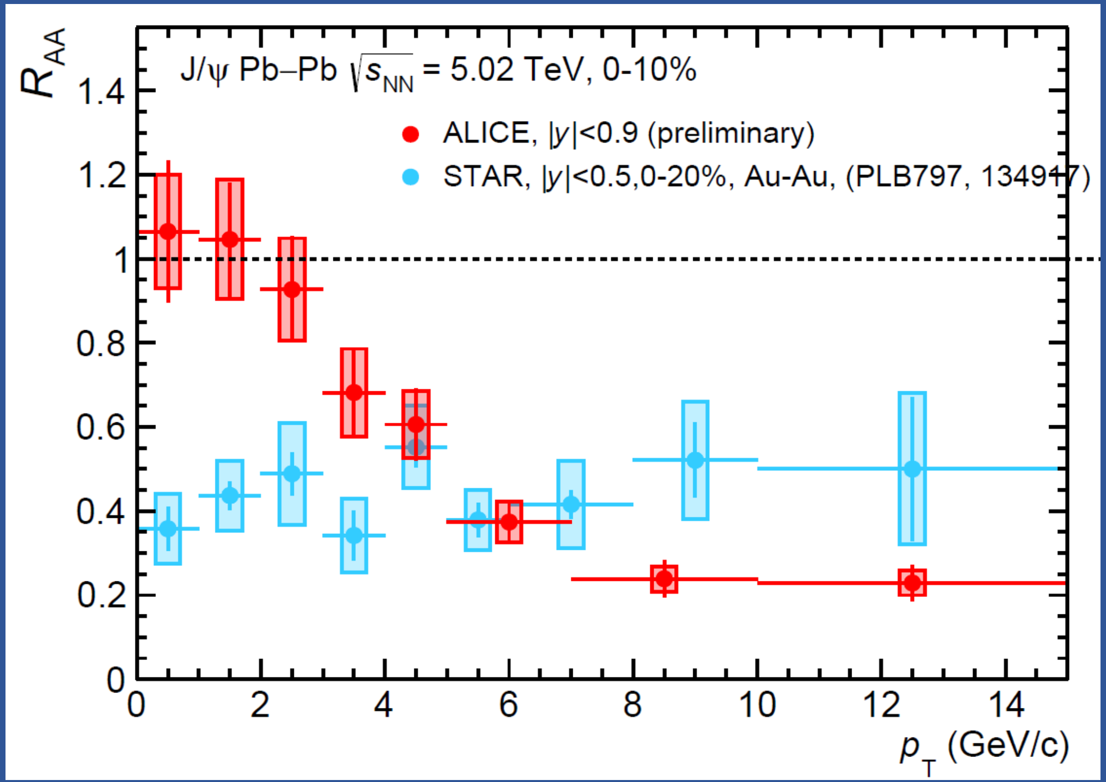


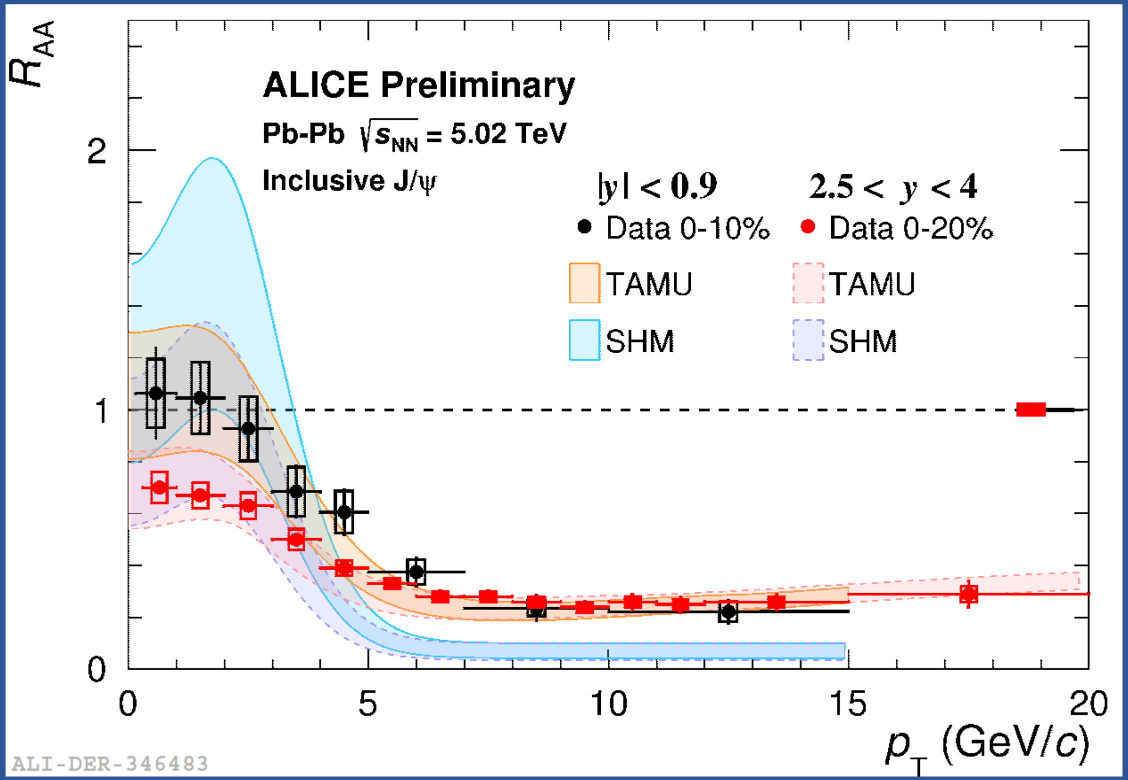
$$R_{AA}^{J/} = \frac{dN_{AA}^{J/\psi}}{N_{coll} dN_{pp}^{J/\psi}}$$

- Overall suppression of J/ψ yields in A-A
- Observed R_{AA} due to a combination of suppression and regeneration effects
- **Regeneration** increasingly **counterbalances dissociation at RHIC** energy → constant R_{AA}
- **Regeneration dominates at LHC** energy → R_{AA} close to 1

NA50, PLB, 477 (2000), 28
STAR, PLB 771 (2017) 13 + preliminary @54 GeV
ALICE, PLB 734 (2014), 314
ALICE, PLB 805 (2020) 135434

J/ψ transverse momentum distributions





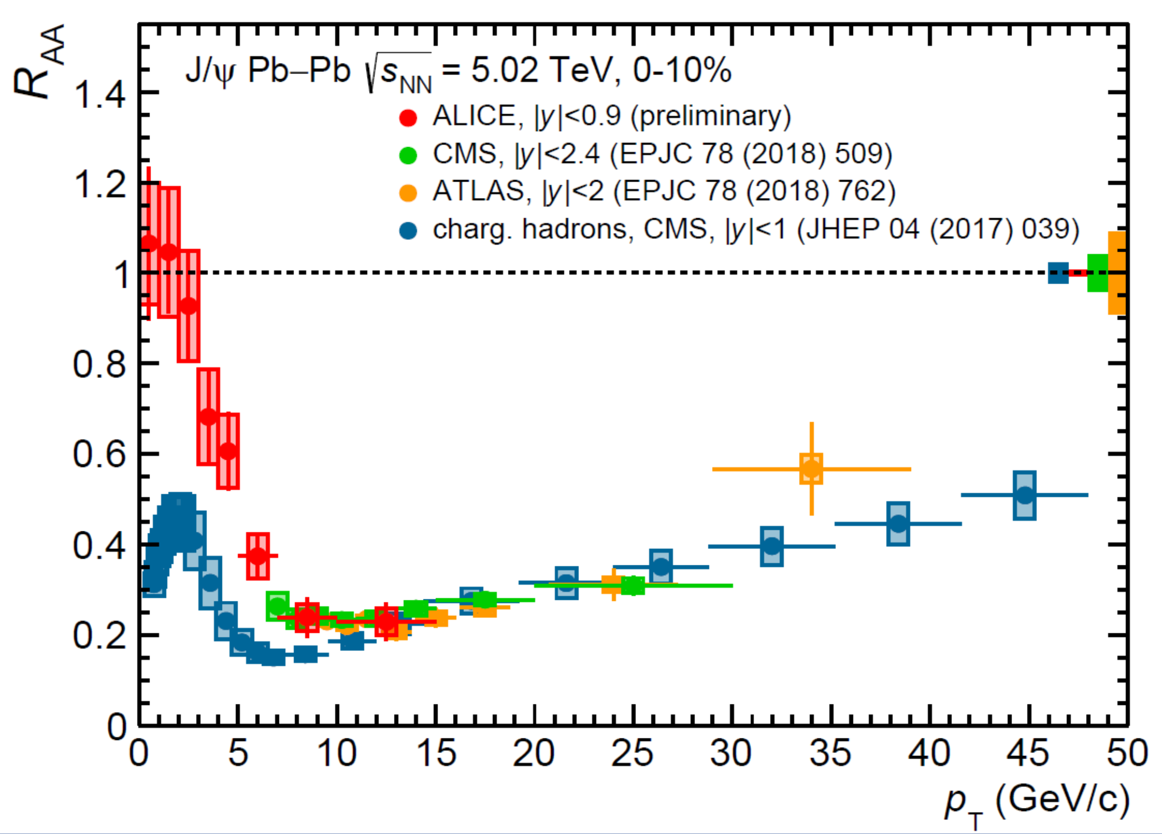
- ❑ **RHIC vs LHC** energy
- ❑ Rise of R_{AA} at low p_T at LHC
  - → **Regeneration** dominant at **low p_T**
  - → **Dissociation** dominant at **high p_T**

- ❑ **y-dependence** at LHC energy
  - → Larger charm multiplicity at **midrapidity**
  - → Hint for **stronger regeneration**

- ❑ Transport and statistical models reproduce this feature

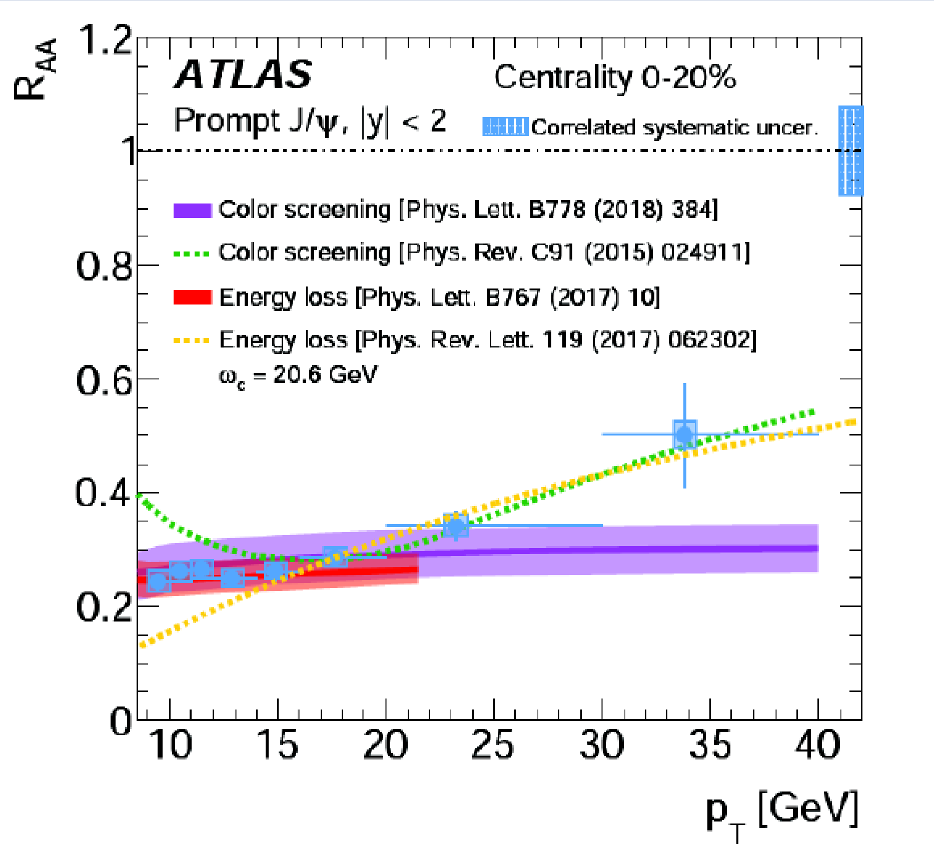
TAMU: Du and Rapp, NPA943(2015) 147
SHM: Andronic et al., PLB797 (2019) 134836

High-p_T J/ψ



- ❑ R_{AA} **rise at very high-p_T** reminiscent of the behaviour observed for most **hadron** species, commonly interpreted in terms of **partonic energy loss**
- ❑ Same effect, or an **interplay of dissociation and energy loss**, possibly at play for charmonia

High-p_T J/ψ



Consistent theory description still missing

- ❑ R_{AA} **rise at very high-p_T** reminiscent of the behaviour observed for most **hadron** species, commonly interpreted in terms of **partonic energy loss**
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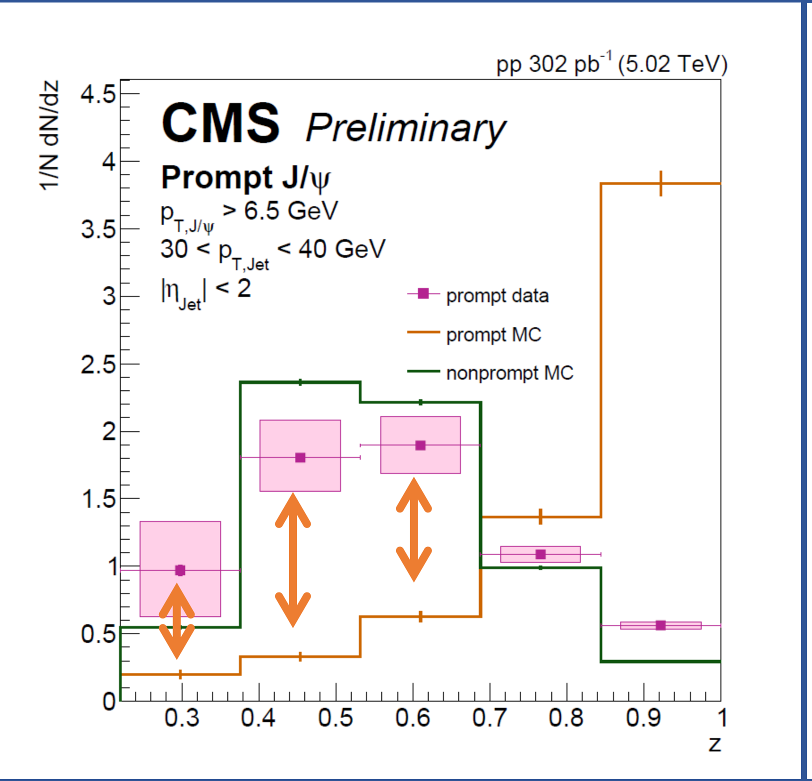
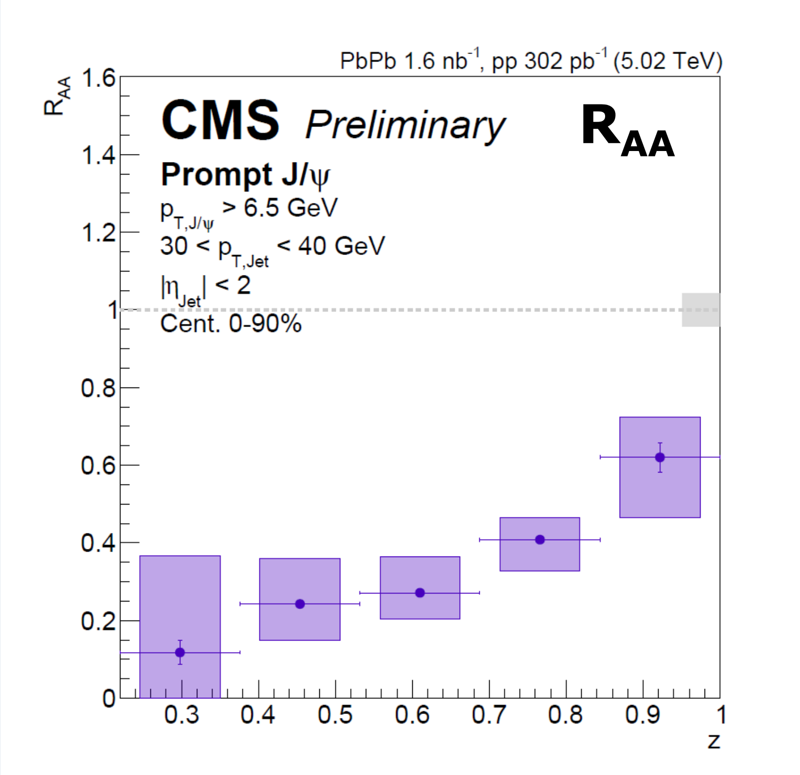
J/ψ production in jets

- Recent developments in the study of **pp collisions** (LHCb, CMS) show that **J/ψ are produced in parton showers** more often than predicted by event generators (PYTHIA), in particular at low z





$z = p_T^{J/\psi} / p_T^{jet}$

- Implies that **J/ψ production** may also occur relatively **late in the collision** history

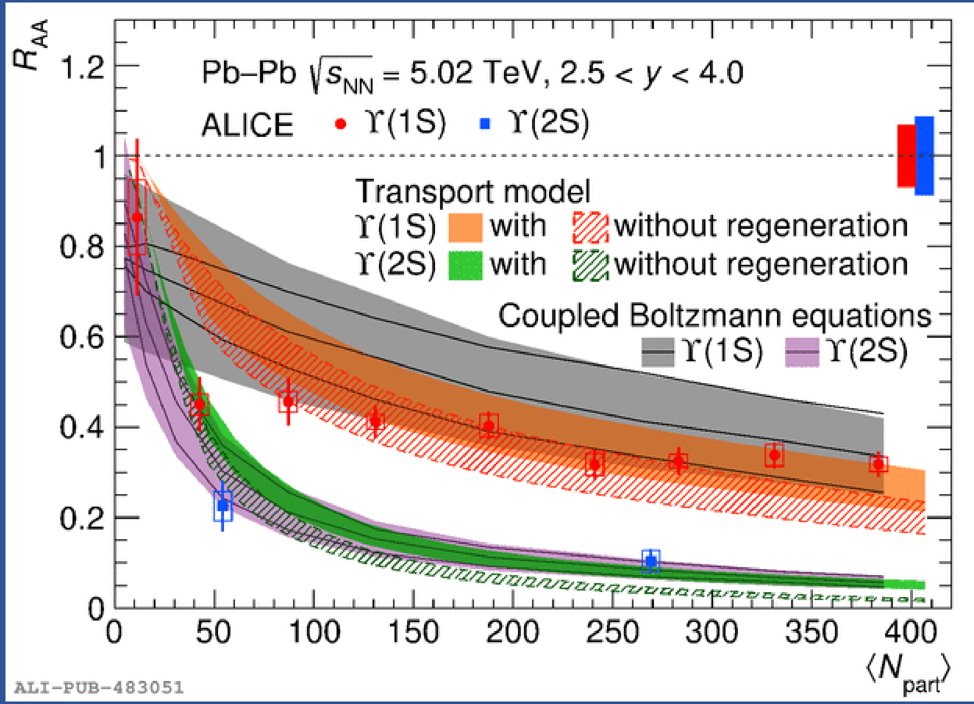
- In those cases QGP "sees" (mainly) the parent hard parton and induces an energy loss

Low z-values → J/ψ produced late in the parton shower → strong(er) energy loss effects

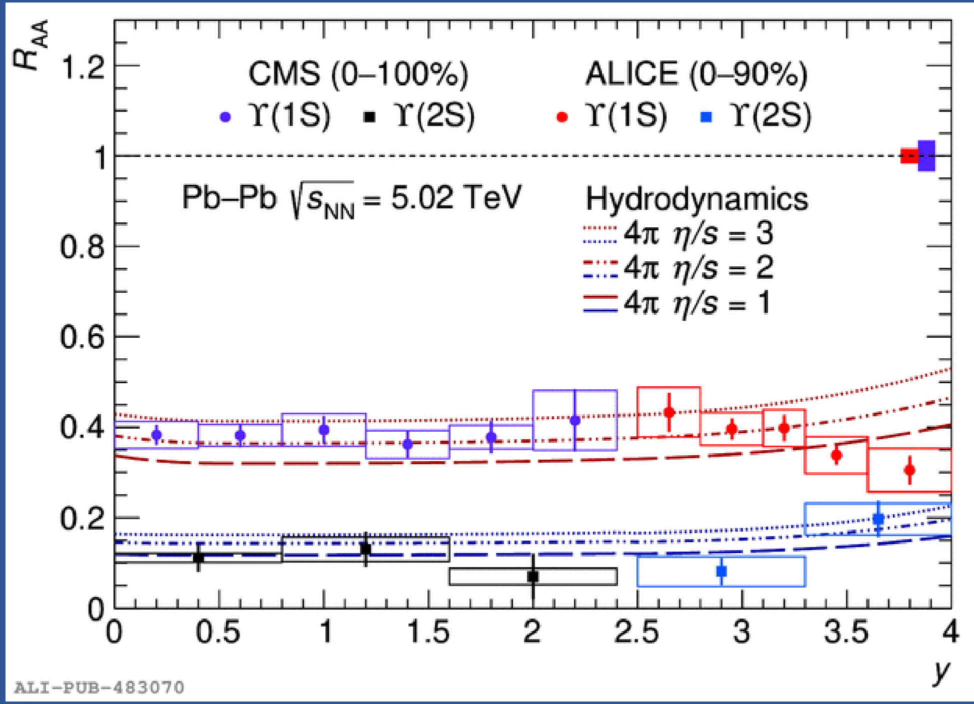
Bottomonium production

- **b-quark** multiplicity much smaller than charm → **recombination effects small**

ALICE, arXiv:2011.05758



CMS, PLB 790 (2019) 270



- Υ(1S) vs Υ(2S): **"sequential" suppression** according to binding energy
- Centrality dependence well reproduced by various theory models
- **Tension** between data and model (anisotropic hydro+transport) **at large y** for Υ(1S)

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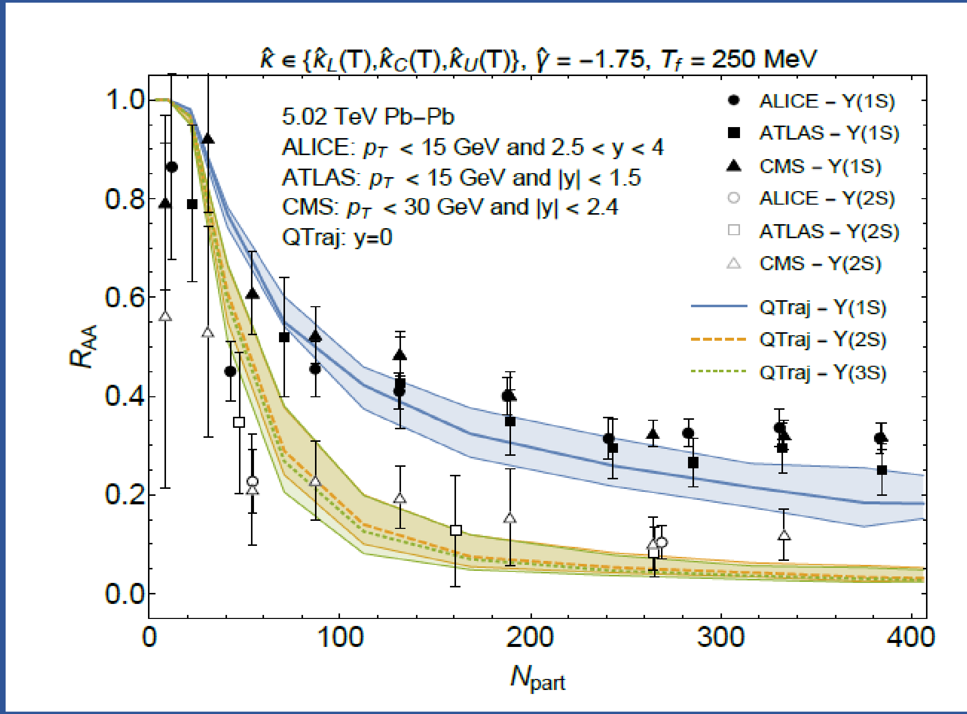
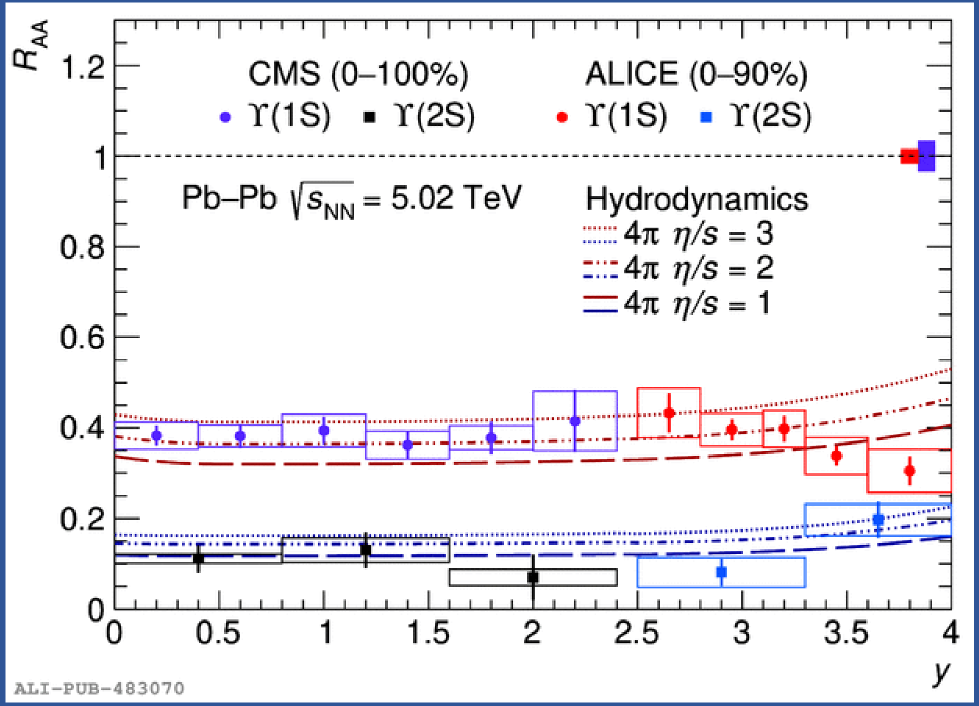
ALICE, arXiv:2011.05758, ATLAS-CONF-2019-054



CMS, PLB 790 (2019) 270



- ❑ ϒ(1S) vs ϒ(2S): **"sequential" suppression** according to binding energy
- ❑ Centrality dependence well reproduced by various theory models (also recent **OQS framework**)
- ❑ **Tension** between data and model (anisotropic hydro+transport) **at large y** for ϒ(1S)

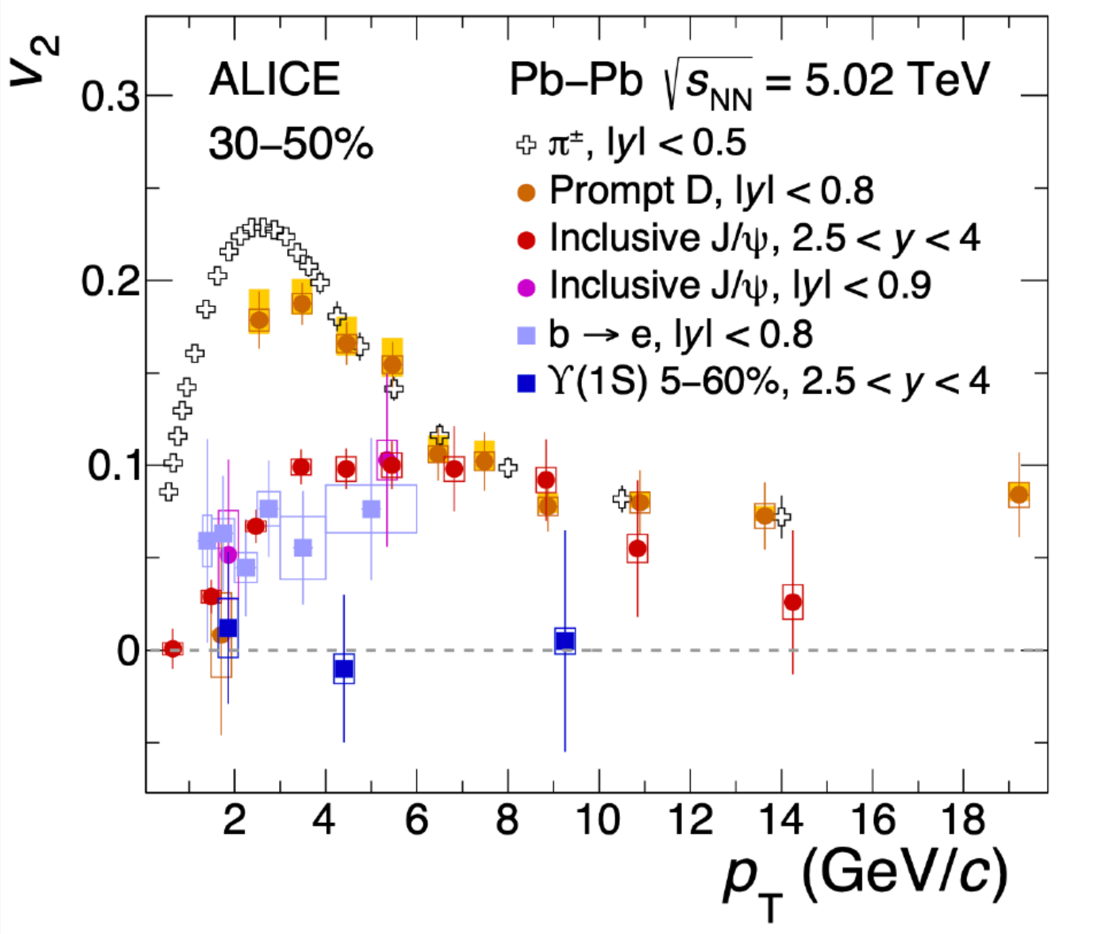
Quarkonium and quark thermalization in QGP

- **Elliptic flow** provides important information on HQ interactions with the medium

$$\frac{dN}{d(\varphi-\Psi_{RP})} = \frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos(2(\varphi-\Psi_{RP}))+....\right)$$

- **Large J/ψ flow** → possibly driven by recombination of thermalized charm quarks

- **No indication of ϒ(1S) flow** → consistent with negligible recombination and/or ϒ(1S) dissociation occurring early in the fireball evolution (high T)



Clear **ordering:**

Low p_T:

$v_2(h) > v_2(D) > v_2(J/\psi) \sim v_2(b) > v_2(\Upsilon)$

High p_T:

$v_2(h) \sim v_2(D) \sim v_2(J/\psi)$

ALICE, arXiv:1805.04390 (hadrons)
ALICE, arXiv:2005.11130 (b→e)
ALICE, arXiv:2005.11131 (prompt D)
ALICE, arXiv:1907.03169 (ϒ(1S))
ALICE, arXiv:2005.14518 (J/ψ)

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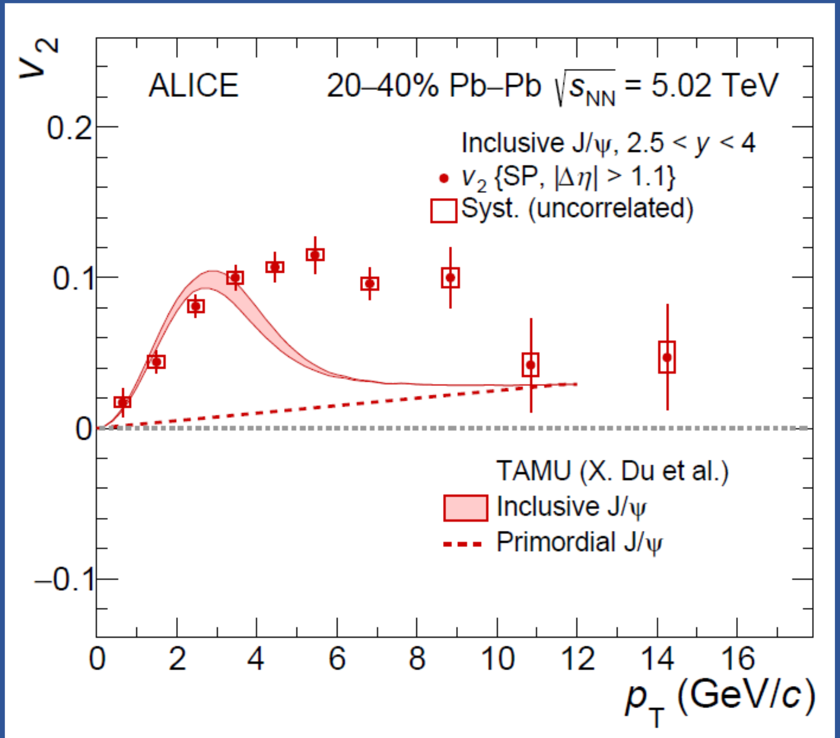
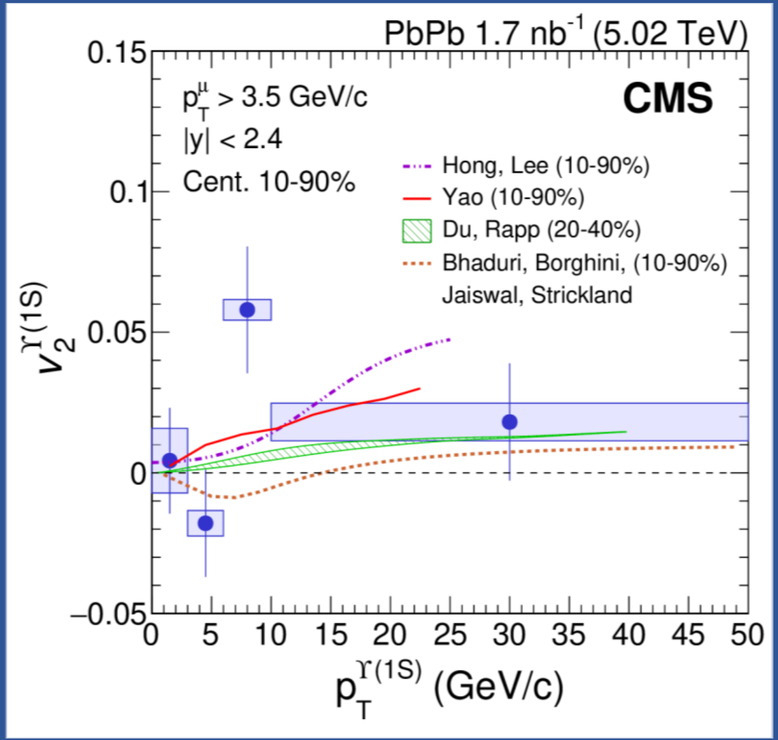


ALICE, arXiv:2005.14518

Du and Rapp, NPA943 (2015) 147
Du, Rapp and He, PRC96 (2017) 054901



CMS, arXiv:2006.07707

Du and Rapp, PRC96(2017)054901
Yao et al., arXiv:2004.06746
Hong and Lee, PLB801 (2020) 135147
Bhaduri et al., PRC100(2019) 051901

- **J/ψ:** v_2 reproduced at low p_T by models including regeneration but intermediate p_T trend is underestimated
- Update on charm quark transport description ongoing → likely leading to better agreement

- **ϒ(1S):** models predict small v_2 at low p_T, in agreement with data
- High(er) accuracy needed to discriminate between models
- High p_T: non-zero v_2 related to pathlength dependence of energy loss (both b and c)

J/ψ polarization

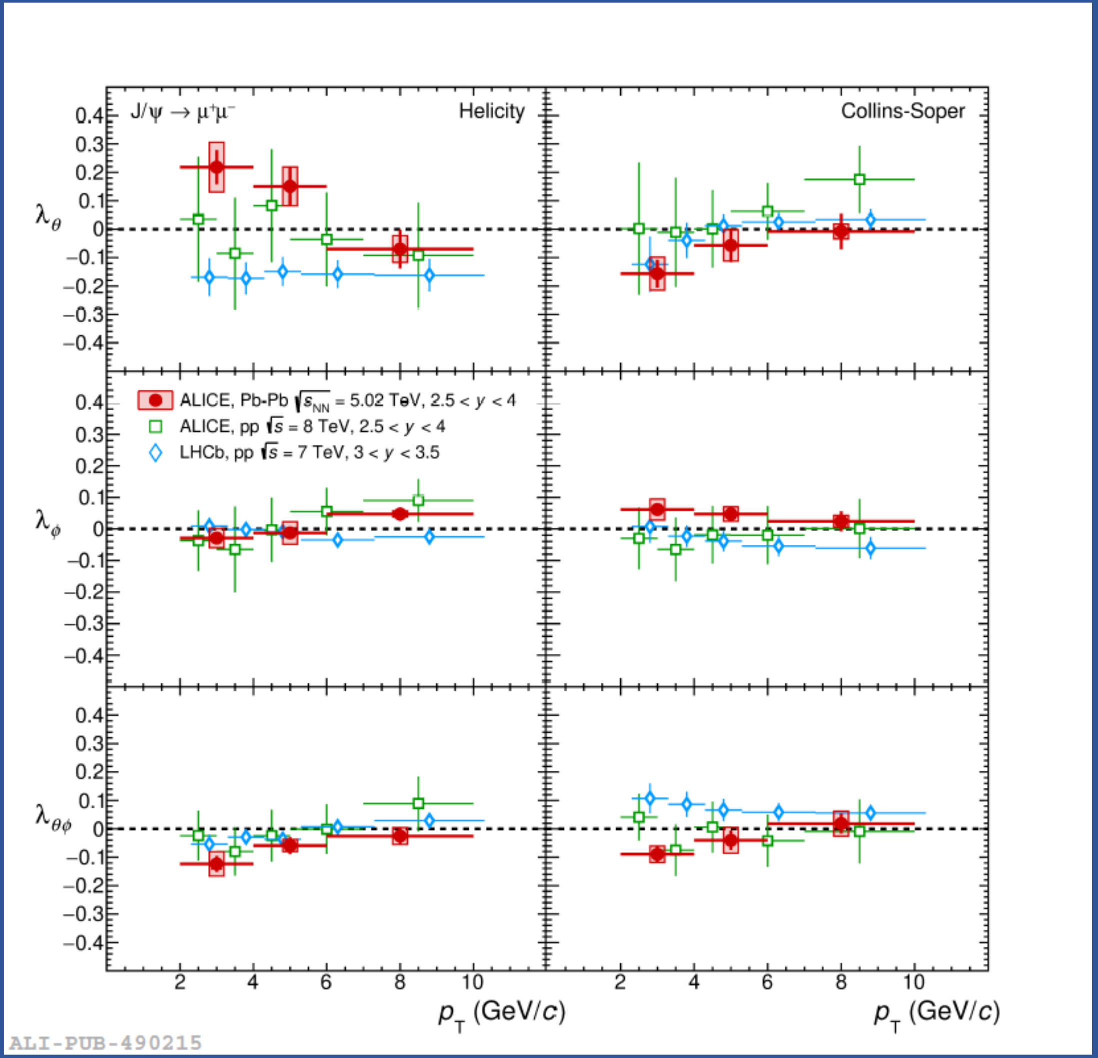
- Measure the **spin orientation** of the particle with respect to a chosen axis

$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta cos^2\theta+\lambda_\phi sin^2\phi+\lambda_{\theta\phi} sin2\theta cos\phi\right)$$

- Polarization axis
  - **Helicity**: quarkonium p_T direction
  - **Collins-Soper:** bisector of angle between beams

- **Pb-Pb vs pp** collisions
  - **Different production process** → regeneration
  - **Suppression of high-mass charmonia** feeding to J/ψ → may change resulting polarization

- **Hint of J/ψ polarization ($\lambda_\theta \neq 0$)** at low p_T
- Significant difference wrt LHCb pp in the same region



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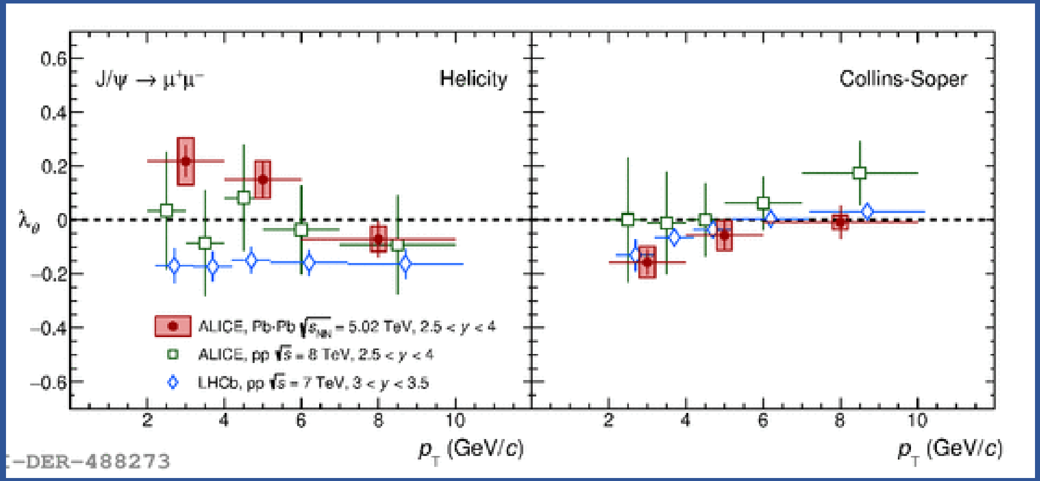

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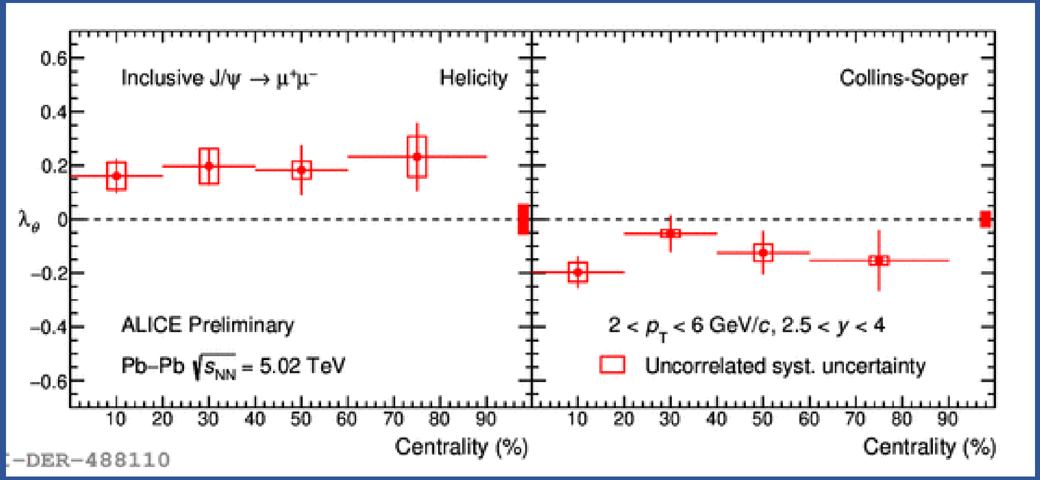


- **Hint of J/ψ polarization ($\lambda_\theta \neq 0$)** at low p_T
- Significant difference wrt LHCb pp in the same region

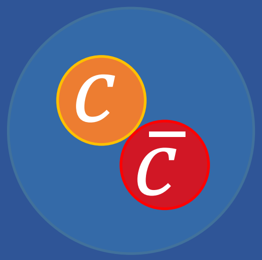
- Weak or no centrality dependence

- Next step: **polarization vs event plane → sensitive to vorticity and/or initial B-field ?**

Other quarkonium-related states

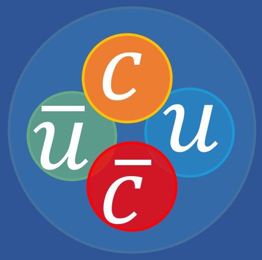
X(3872)

charmonium



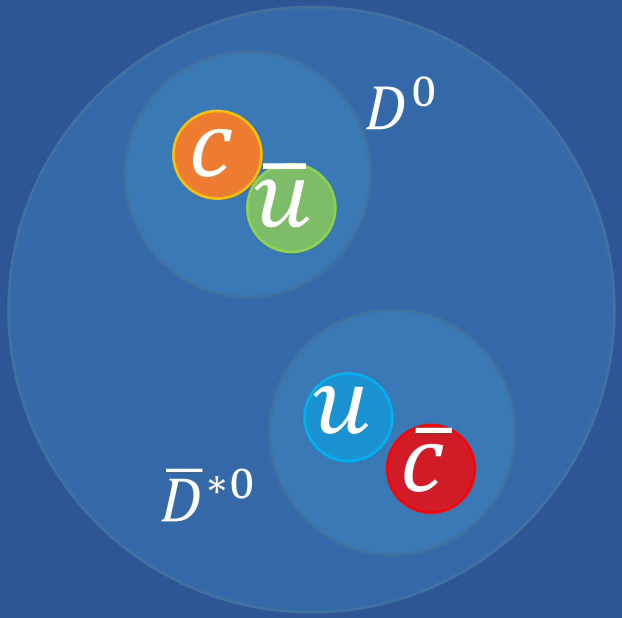
wrong mass predicted with $J^{PC} = 1^{++}$

tetraquark

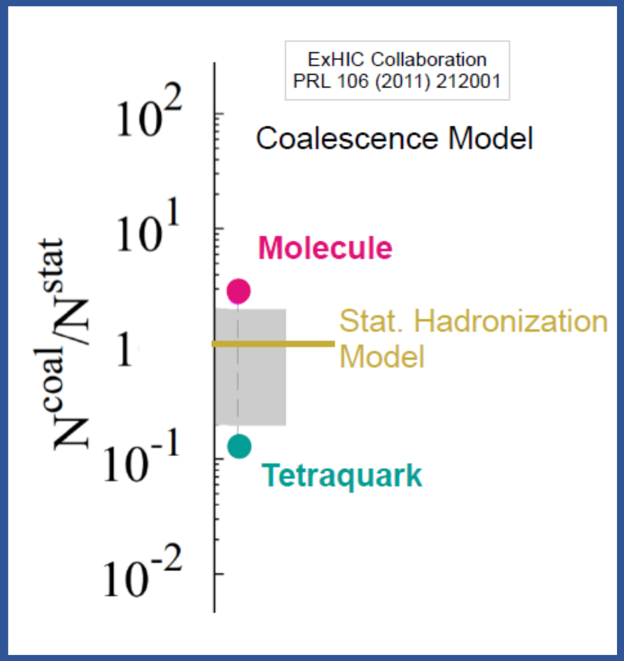


r~0.3fm

D^0-$\bar{D}^{*0}$ molecule



r>5 fm, small binding energy



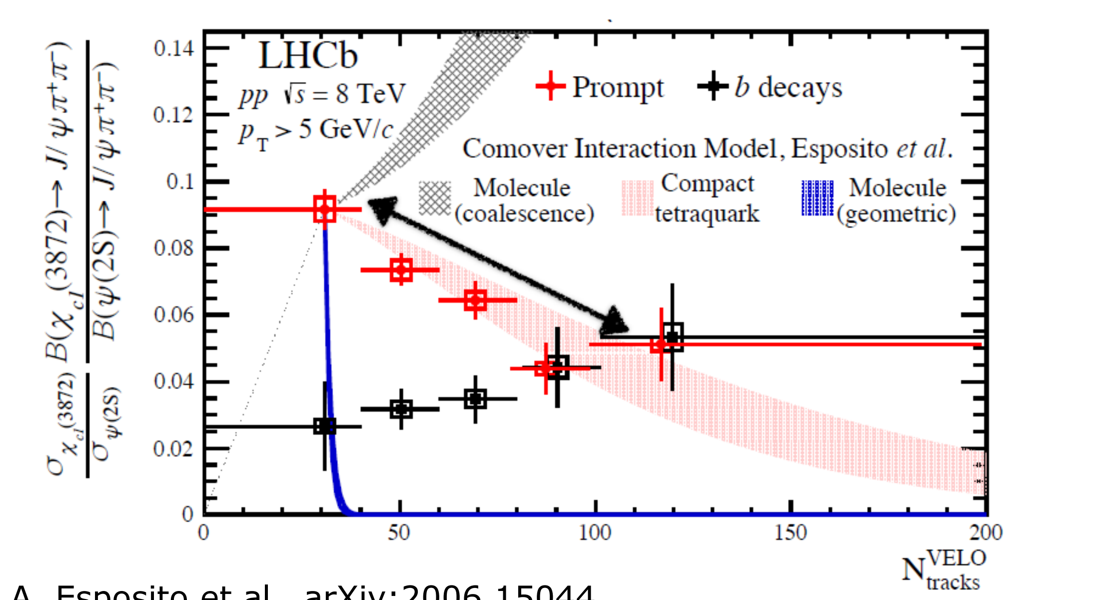
RHIC energy

- Nature of the state **not yet understood!**
- **Production in a QCD medium** might provide insight on its inner structure?
  Coalescence-based models predict in A-A collisions lower yields for a compact multiquark state

X(3872): yield vs multiplicity in pp

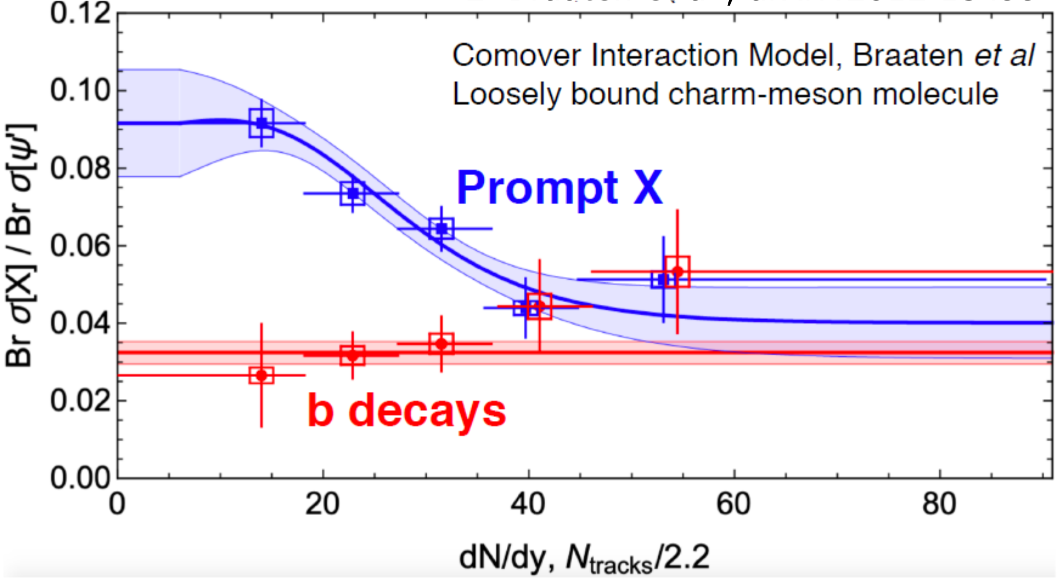
- At the LHC, high-multiplicity pp collisions create a dense hadronic environment
- LHCb studied the **ratio X(3872)/ψ(2S) as a function of hadronic multiplicity**

LHCb, PRL 126 (2021) 092001 (2021)



A. Esposito et al., arXiv:2006.15044

E. Braaten et al., arXiv:2012.13499

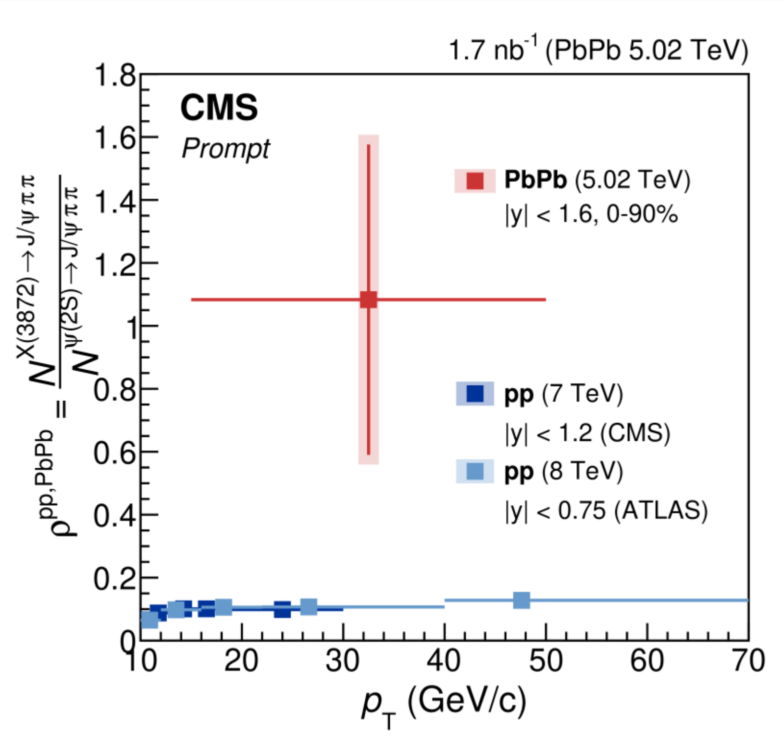


- Data described by comover interaction model assuming X(3872) being a **tetraquark**
  → breakup reaction rate approximated by the geometric cross section

- However, using a different ansatz for CIM can also favour X(3872) being a **molecule**
  → scattering of comoving pions from the charm-meson constituents of X(3872)

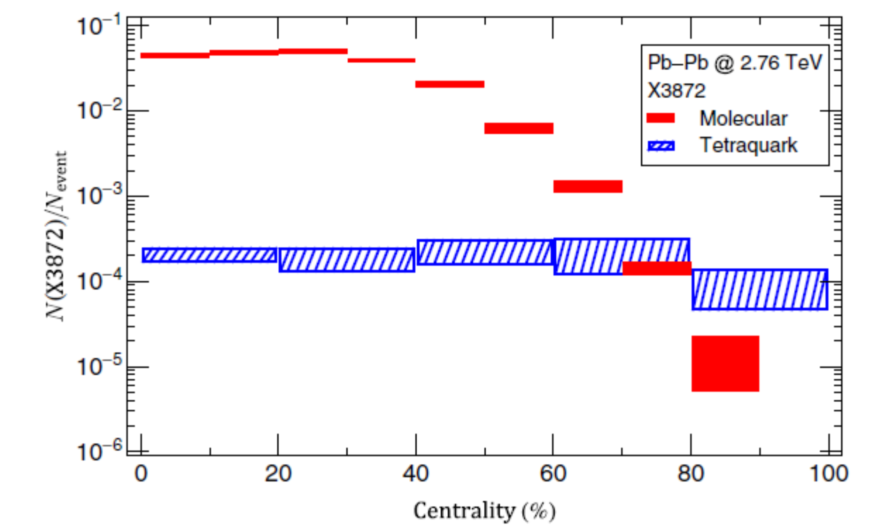
X(3872): first measurement in Pb-Pb

CMS, arXiv:2102.13048

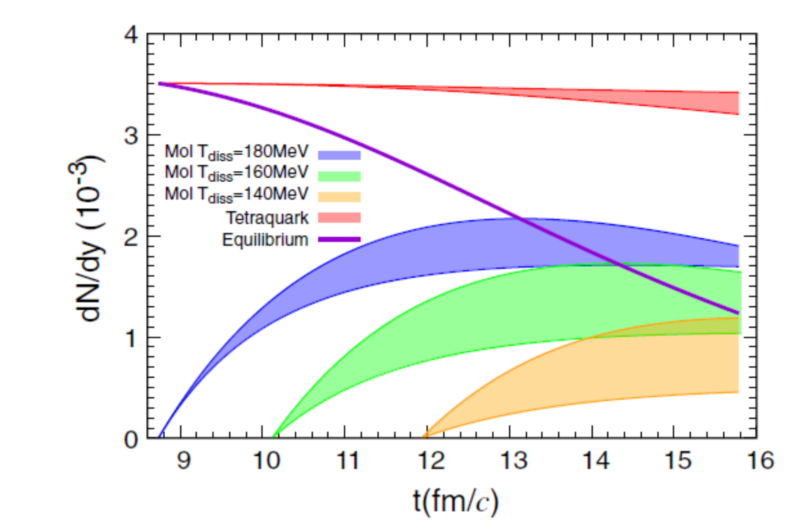


- **Hint of** prompt **X(3872)** to ψ(2S) **enhancement in Pb-Pb**, at very high p_T ($15<p_T<50$ GeV/c)

H. Zhang et al., PRL 126(2021) 012301



B. Wu et al., EPJA 57(2021) 122



- Theory work in progress

  - **Coalescence** model: **much larger yields for molecular option**, with strong centrality dependence (ccbar more likely separated in space at freeze-out)

  - **Transport** model: **moderate difference between yields**, smaller for molecule mainly due to larger reaction rate (yield of molecule freezes out later, when equilibrium limit is smaller)

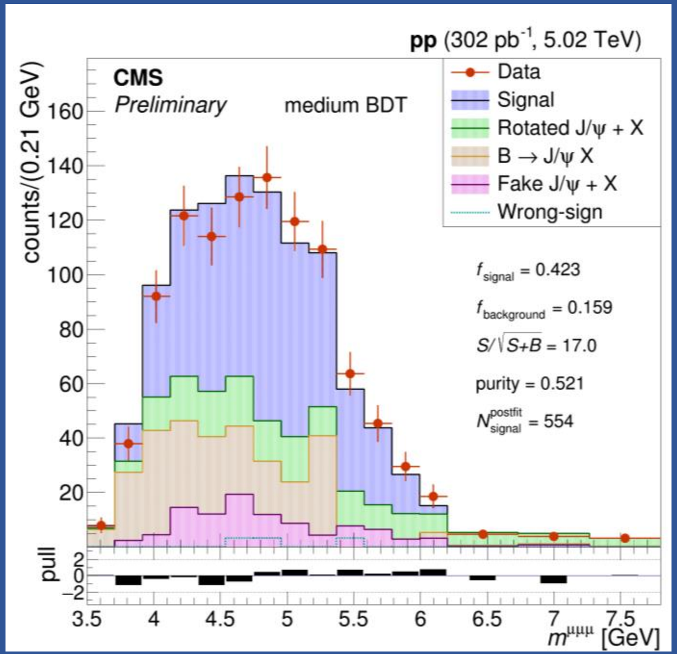
B_c: another probe of QGP

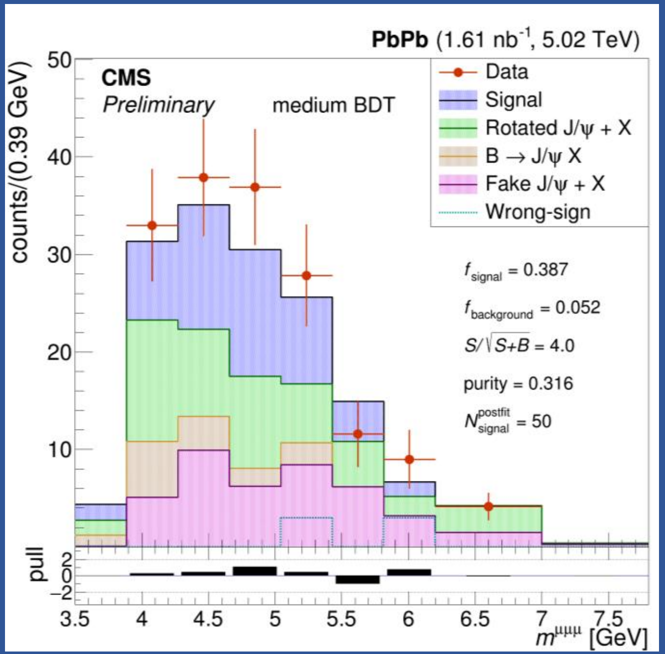
- Binding energy intermediate between J/ψ and Υ(1S), can be dissociated in the QGP
- **Regeneration** effects **could be important** (small σ_{pp}^{Bc}, large charm multiplicity in Pb-Pb)
- Energy loss: study mass and color-charge dependence

- First measurement by CMS in Pb-Pb collisions via **$B_c^+ \rightarrow (J/\psi \rightarrow \mu\mu)\ \mu^+\nu_\mu$**
  (displaced vertex of 3 muons, with OS pair in the J/ψ region)

Needs good understanding of background in $3.2 < M_{\mu\mu} < 6.3$ GeV
→ Use **BDT technique**

CMS-HIN-20-004

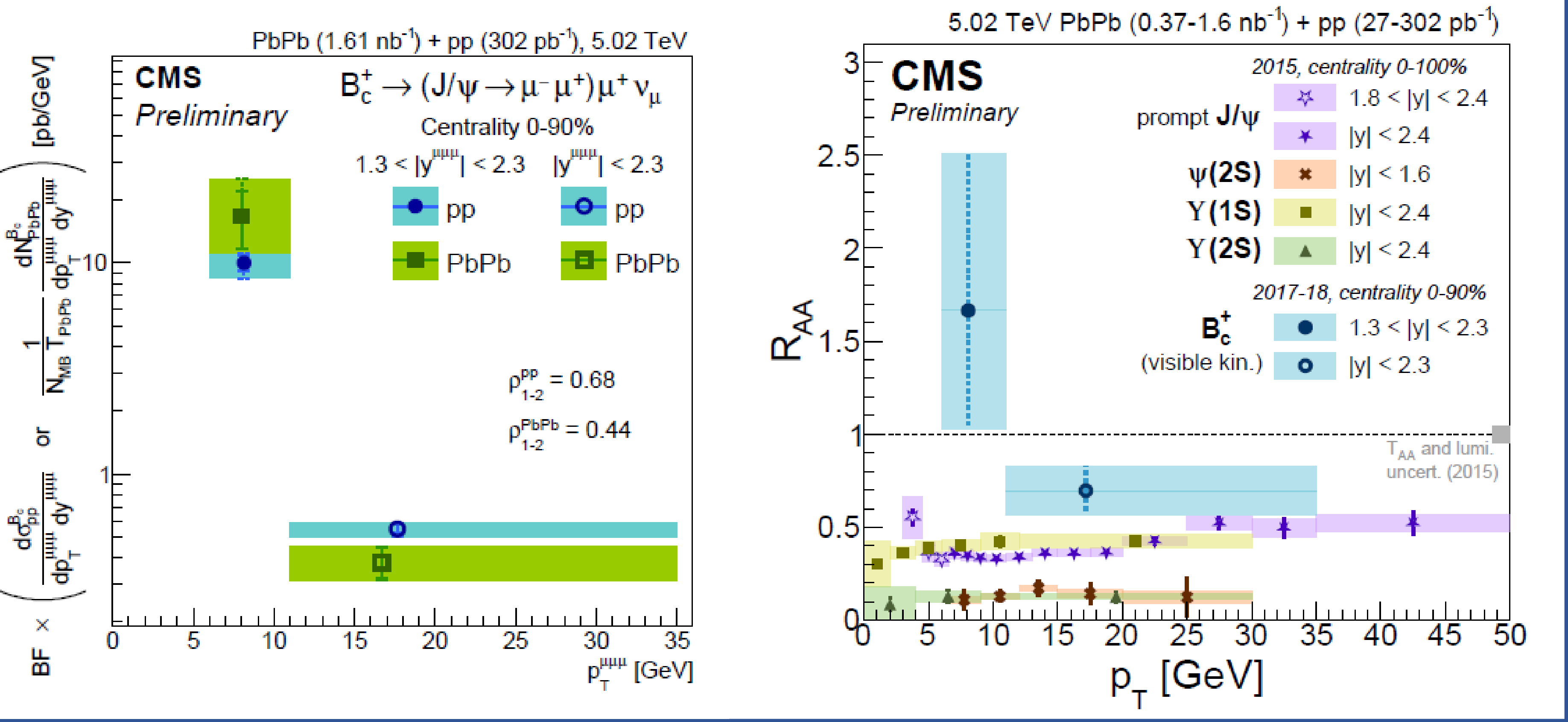




Significance in Pb-Pb well **above 5σ**

Fake J/ψ: OS muons not coming from J/ψ (sidebands)
B decays: B→J/ψ + muon from same vertes (simulation)
Rotated J/ψ: true J/ψ + random muon (rotate J/ψ)

B_c: another probe of QGP



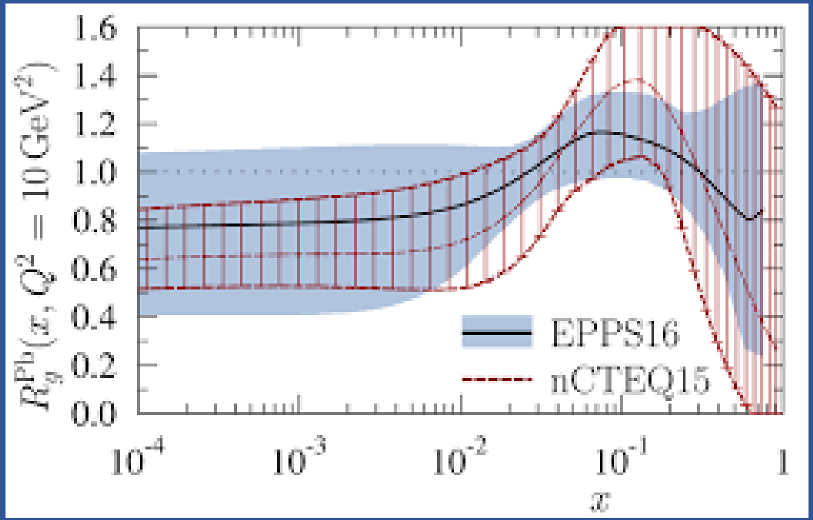
- Reminiscent of **J/ψ behaviour**, but **larger R_{AA}** values
- **High-p_T** region likely sensitive to **energy loss** effects too
- Very promising channel in view of **higher luminosity** data samples

- Cross sections and R_{AA}
  → vs p_T (of the trimuon!)
  → vs centrality (not shown)
- Hint for a p_T dependence
  → from **enhancement to suppression** when increasing p_T (1.6 σ effect)

p-A results: CNM effects and beyond

Cold nuclear matter effects and beyond

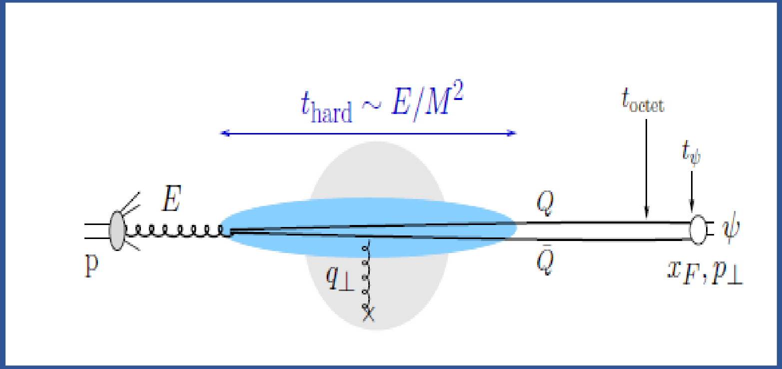
(Anti-)shadowing



$x=(m_T/\sqrt{s})\ e^{-y}$
(2→1 kinematics)

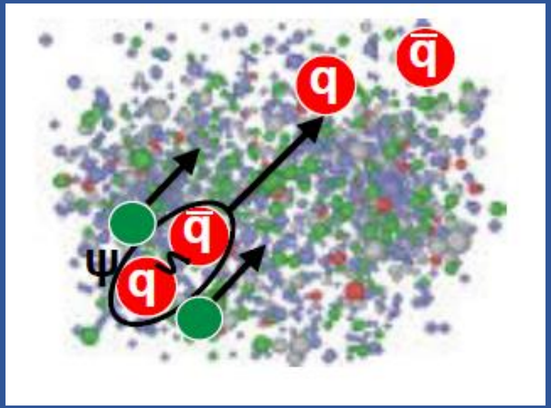
- Values for J/ψ, at $\sqrt{s_{NN}}$=5.02 TeV (ALICE coverage, p-Pb forward y)
- $2.03<y_{cms}<3.53$ → $2{\cdot}10^{-5} < x < 8{\cdot}10^{-5}$
- $-4.46<y_{cms}<-2.96$ → $1{\cdot}10^{-2} < x < 5{\cdot}10^{-2}$

Coherent energy loss



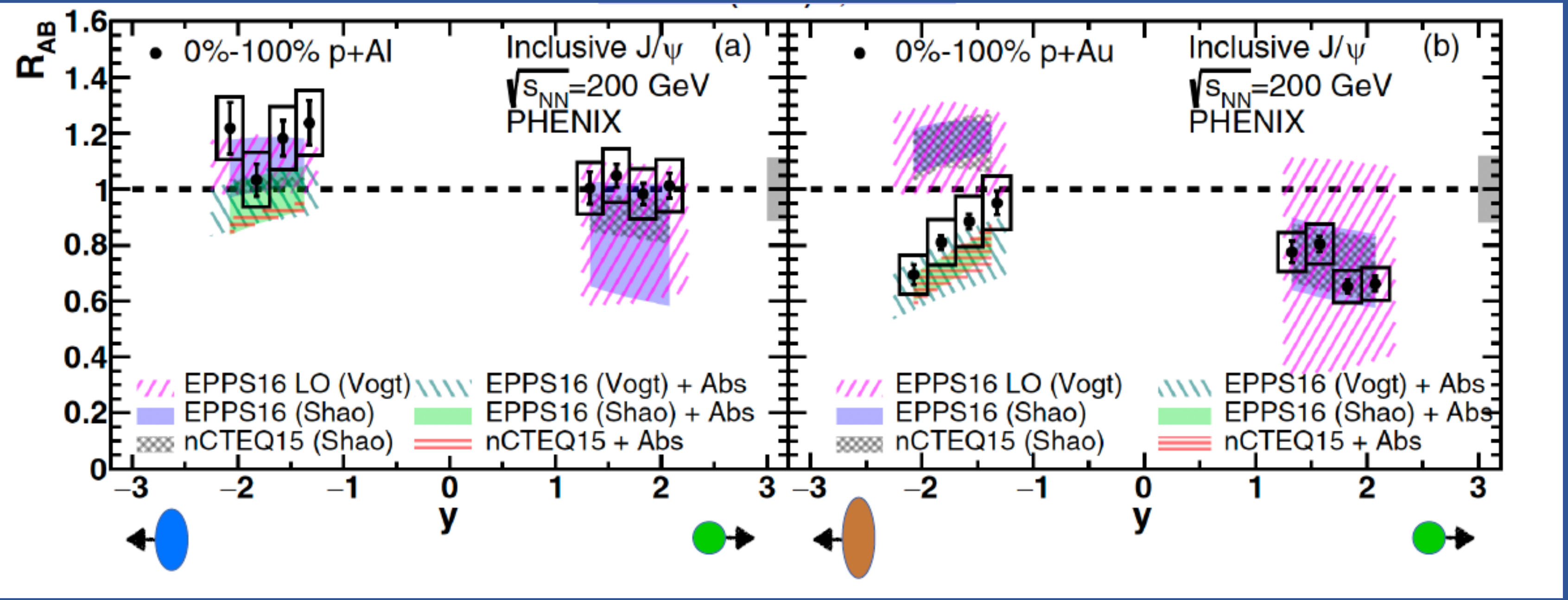
Affects quarkonium kinematics leading to suppression effects, particularly at large x_F

Break-up in nuclear matter or by hadron (parton ?) comovers

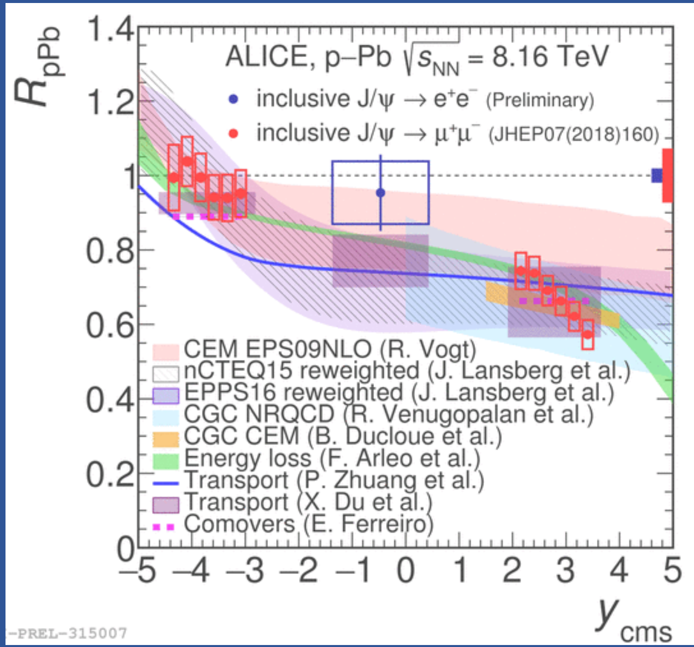


Selectively affects quarkonium states according to their binding energy
→ Look for **QGP-like effects** in small systems!

J/ψ production in p-A: RHIC vs LHC energy



PHENIX, PRC102 (2020) 014902



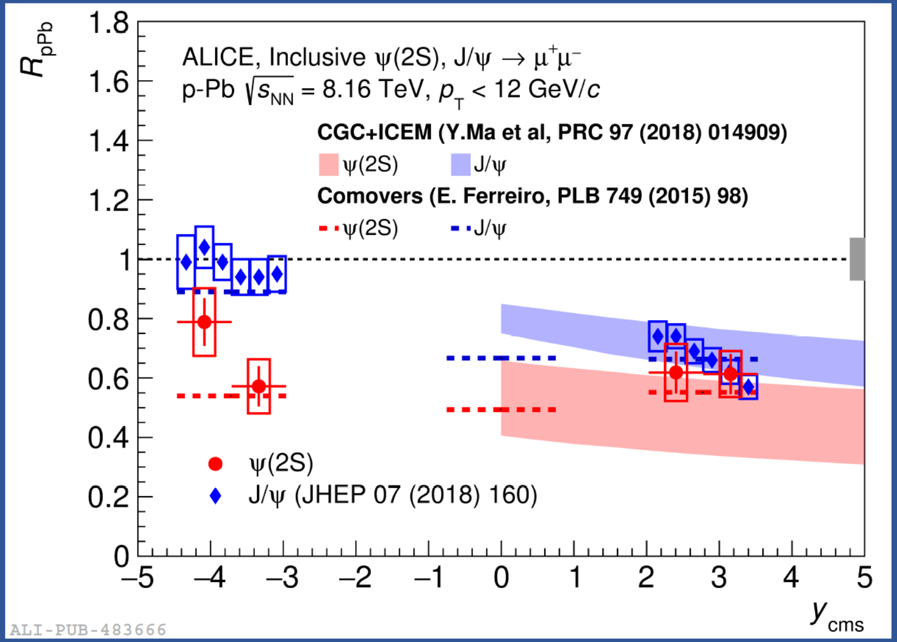
ALICE, JHEP07(2018) 160 + prelim.

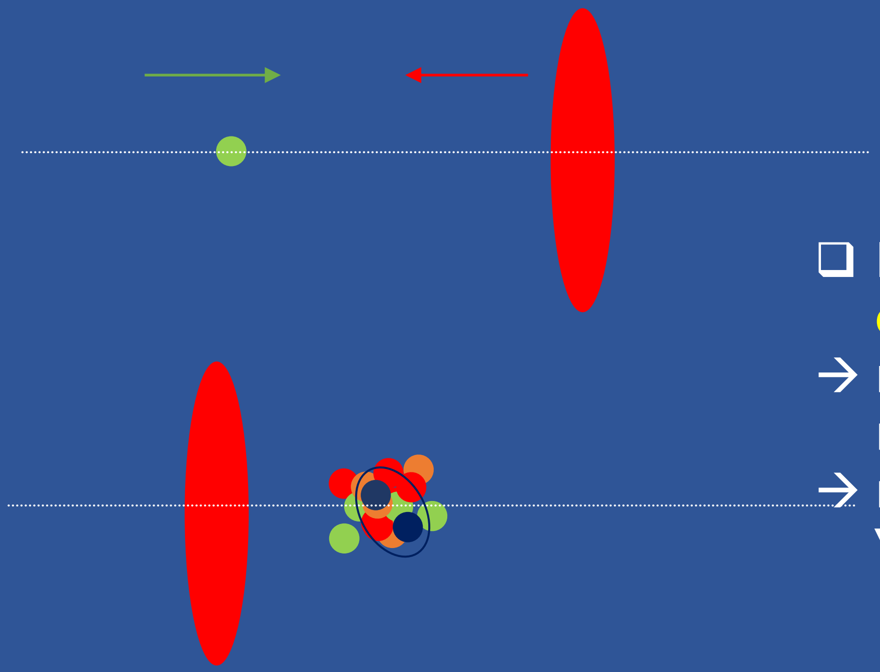
- **RHIC**
  - **p-going** results: significant suppression in p-Au → consistent with **shadowing**
  - **A-going** results: p-Au suppression exceeds shadowing estimates → **nuclear break-up**
  - No significant effects in p-Al (small nucleus)

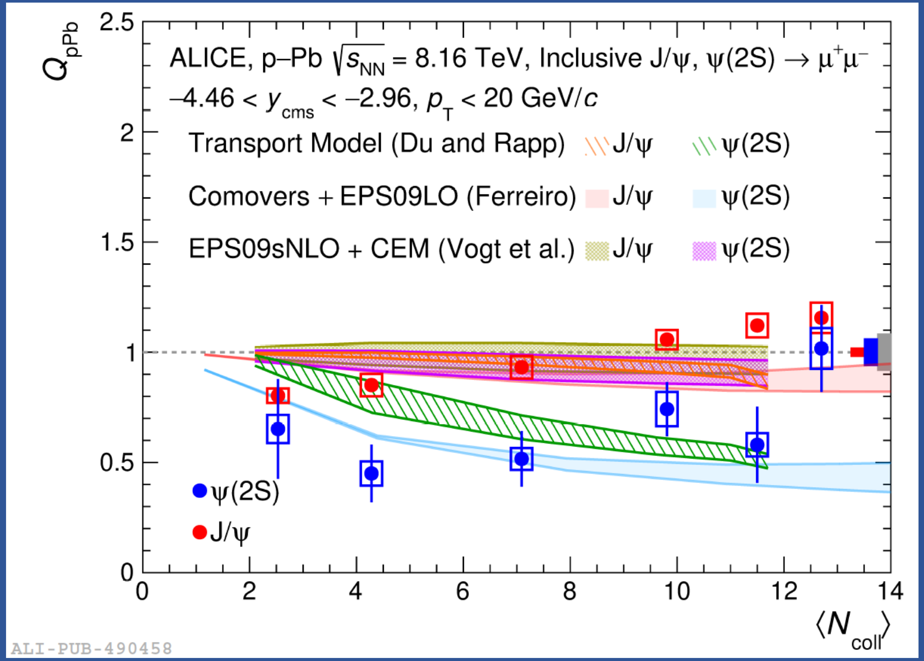
- **LHC**
  - Both p-going and Pb-going results compatible with shadowing → **nuclear break-up negligible**

ALICE, JHEP07 (2020) 237

Weakly bound states: ψ(2S)







- ❑ High energy: ccbar pair forms **outside the nucleus**
- → not dissociated in nuclear matter
- → may interact with the "medium"

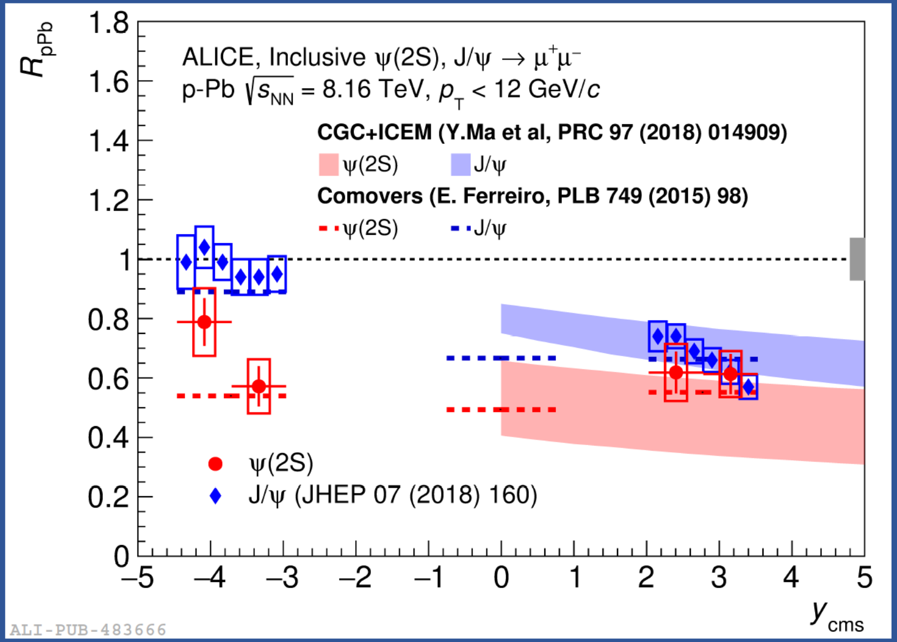
- ❑ Pb-going rapidity → **strong ψ(2S) suppression**
- ❑ Reproduced by models that **include final-state interactions** (pure shadowing not enough)

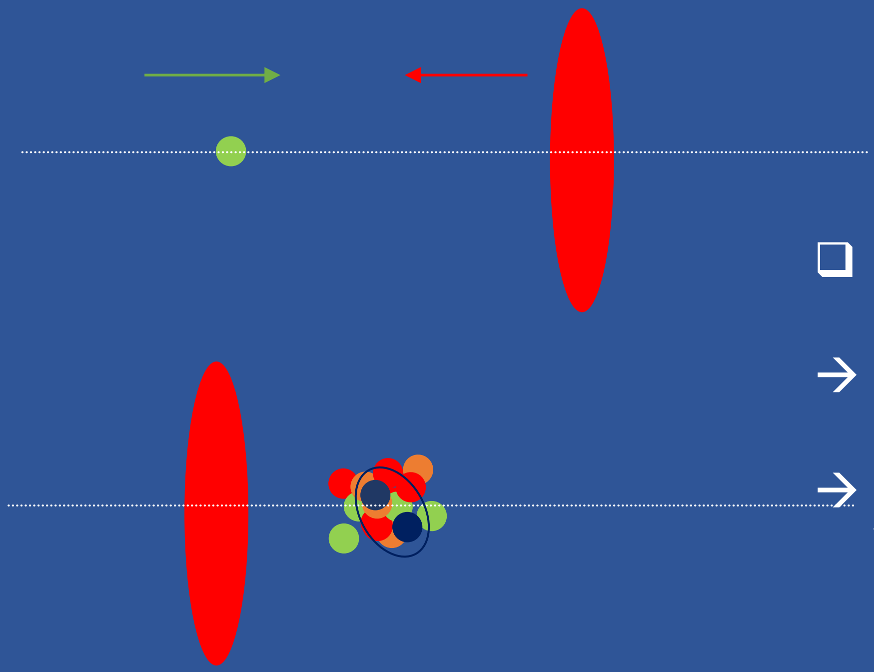
ALICE, JHEP02 (2021) 002

McGlinchey et al., PRC87 (2013) 054910
Du and Rapp, NPA943 (2015) 147
Ferreiro, PLB749 (2015) 98

ALICE, JHEP07 (2020) 237

Weakly bound states: ψ(2S)





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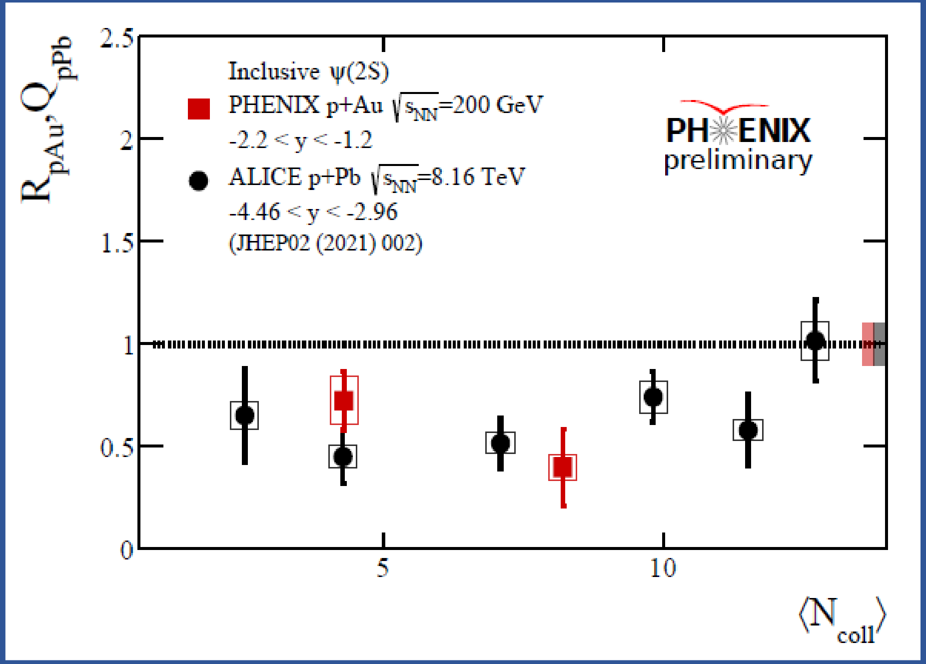


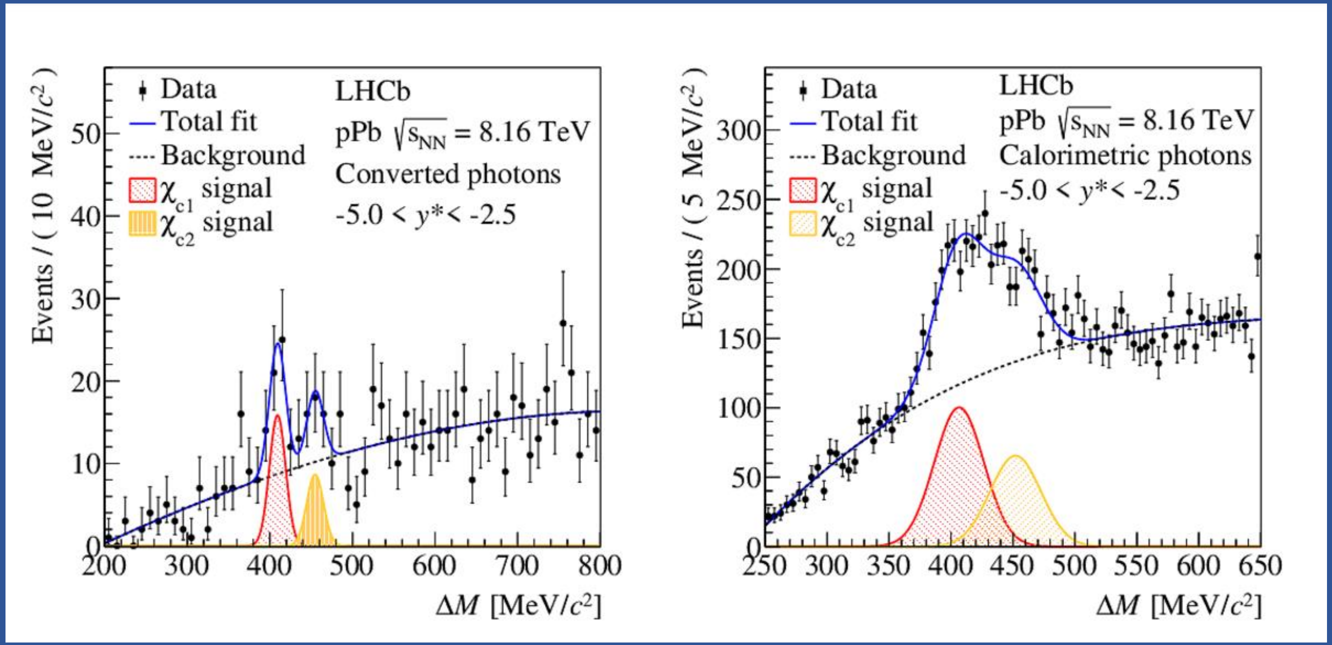
- ❑ Pb-going rapidity → **strong ψ(2S) suppression**
- ❑ Reproduced by models that **include final-state interactions** (pure shadowing not enough)
- ❑ Remarkably similar effect also at **RHIC energy**

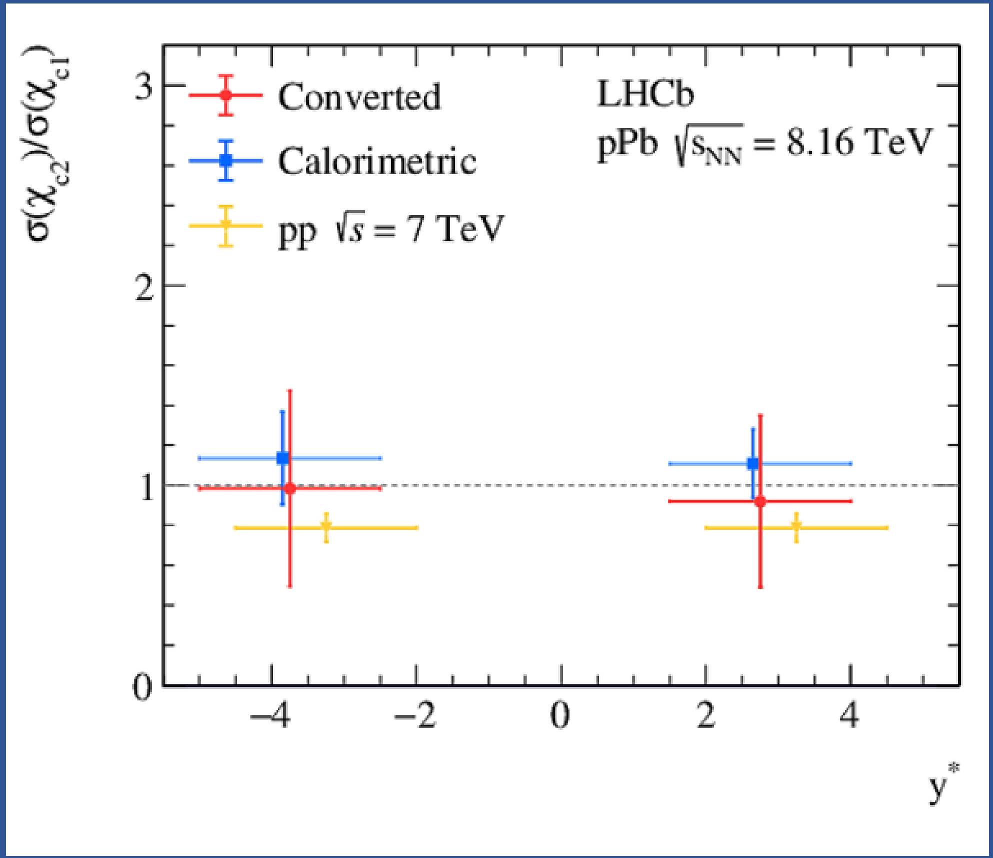
ALICE, JHEP02 (2021) 002

McGlinchey et al., PRC87 (2013) 054910
Du and Rapp, NPA943 (2015) 147
Ferreiro, PLB749 (2015) 98

Between J/ψ and ψ(2S) → χ_c

LHCb, arXiv:2103.07349

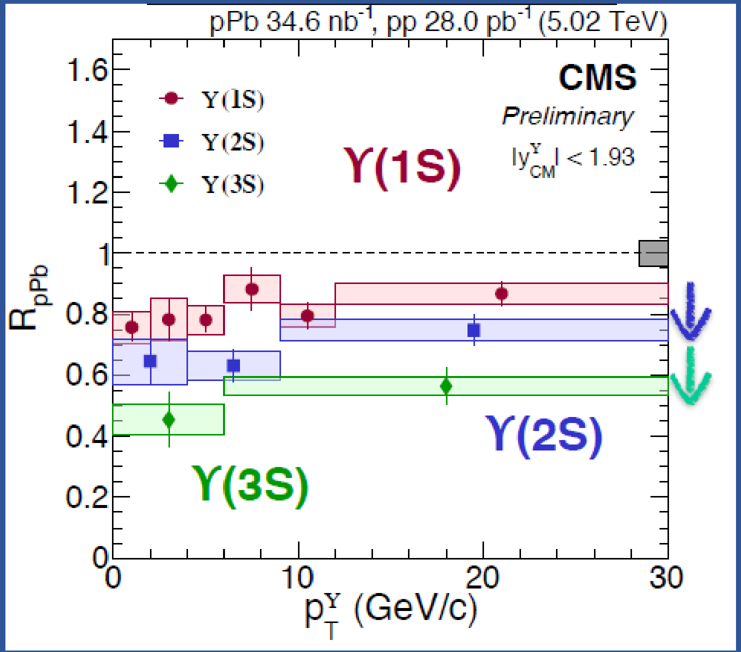


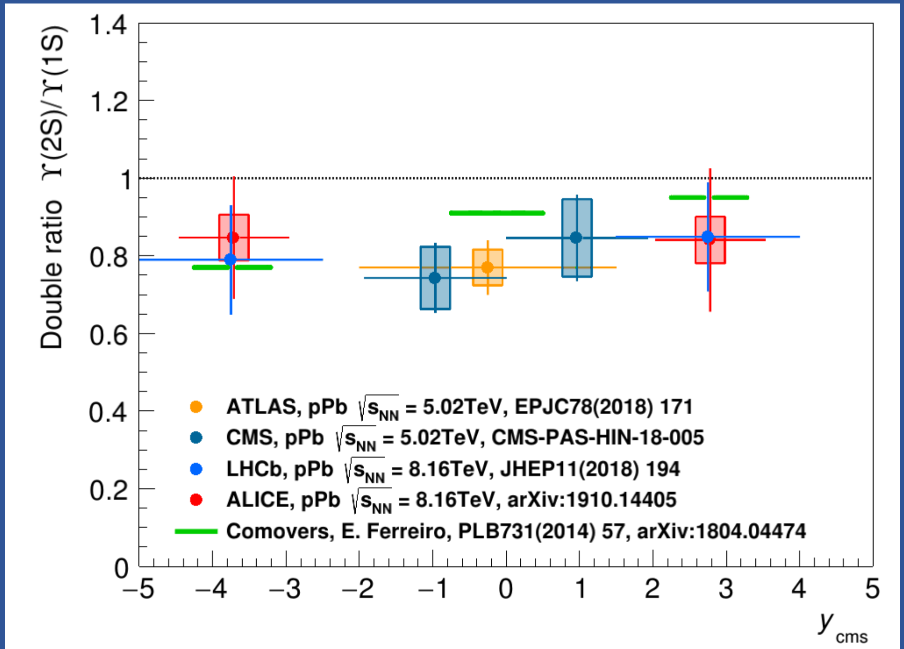


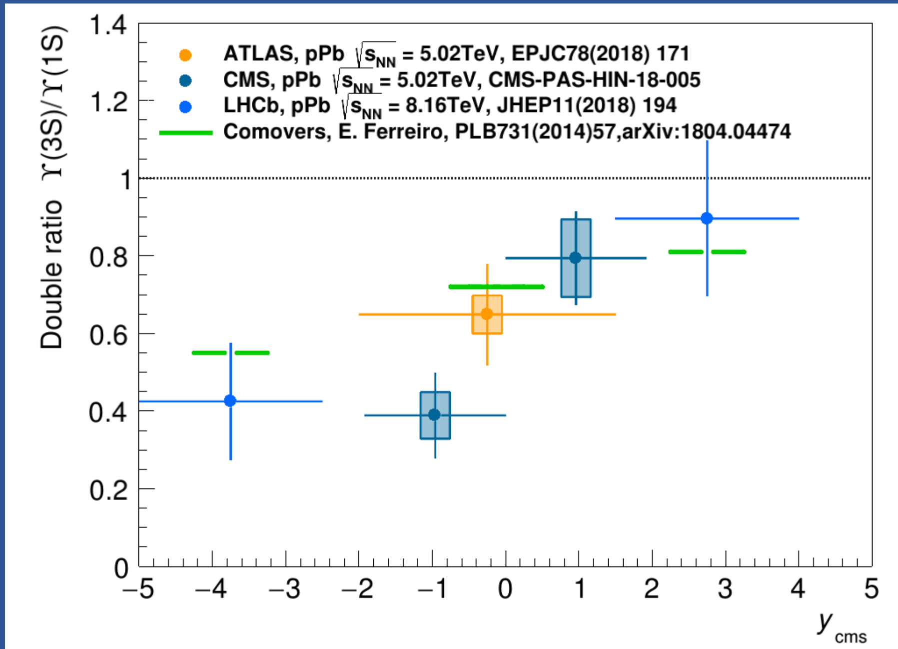
- ❑ Fit of the mass difference distribution M(μμγ)- M(μμ)
- ❑ χ_{c0} signal not visible (small BR to μμγ)
- ❑ Converted photons: better resolution but smaller efficiency

- ❑ Cross section **ratios in pPb compatible with pp** at both forward and backward y
- ❑ **CNM effects affect similarly the two resonances** (similar binding energy)

CNM effects on Υ(nS) states







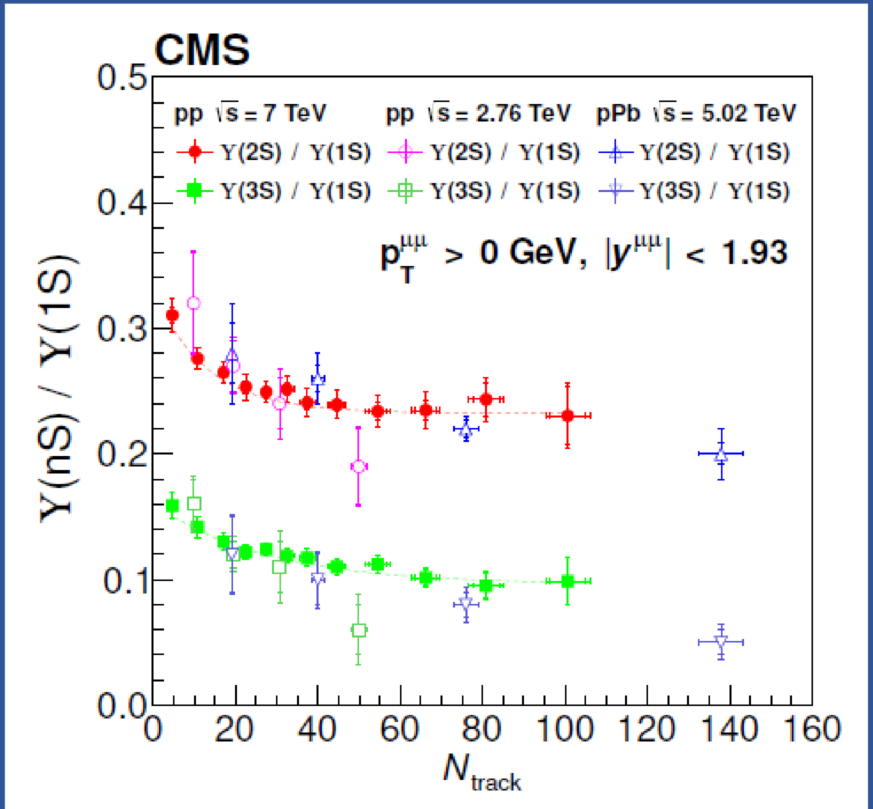
- ❑ All Υ(nS) states show **significant suppression**, increasing from 1S to 2S and 3S
- ❑ Indication of a p_T dependence, with stronger suppression at low p_T
- ❑ Dominated by **shadowing effects for Υ(1S)**, **further suppression for Υ(2S) and Υ(3S)**
- ❑ Good agreement of ratios with comover interaction model, evidence for final state effects on Υ(3S)

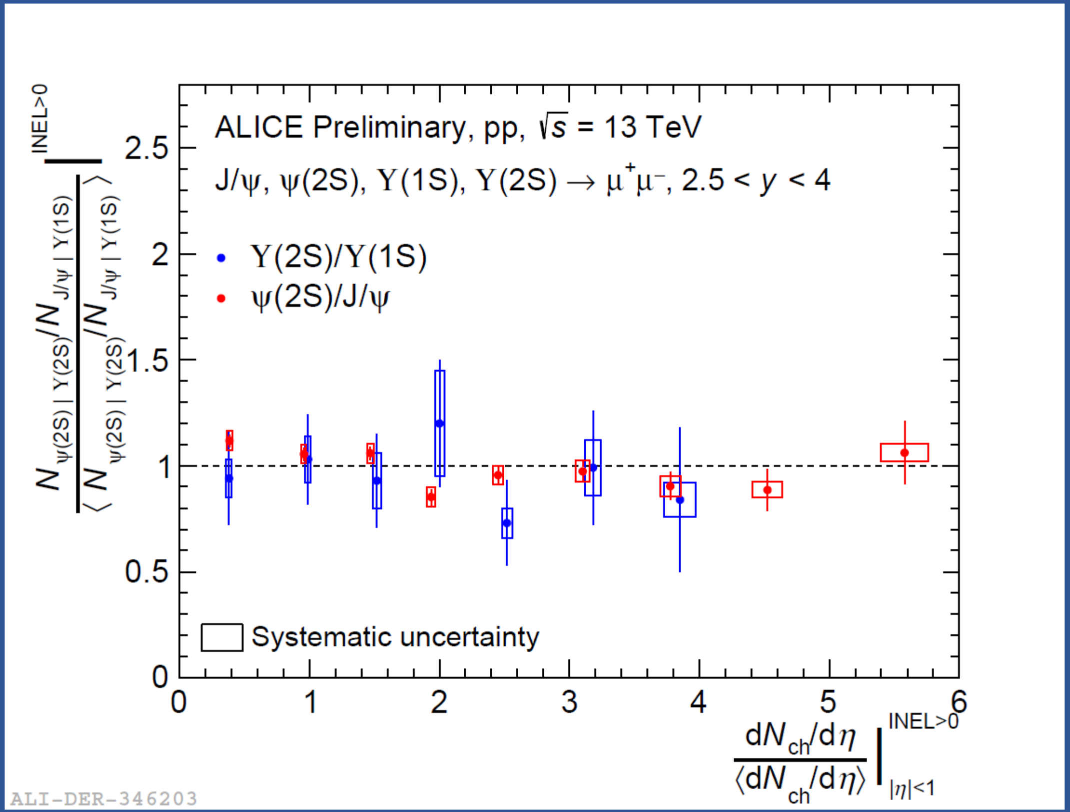
→ Indication for **final state effects** also on **Υ(2S)**, which has a binding energy similar to J/ψ

Intriguing effects in high multiplicity pp

Quarkonium production vs event activity

CMS, JHEP 11 (2020) 001

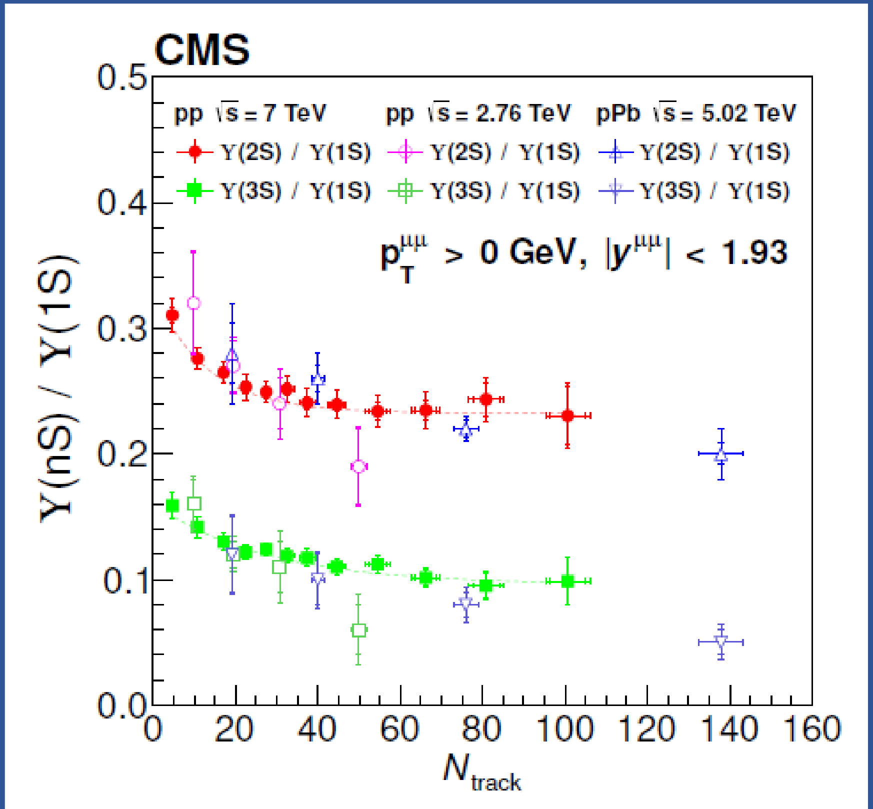


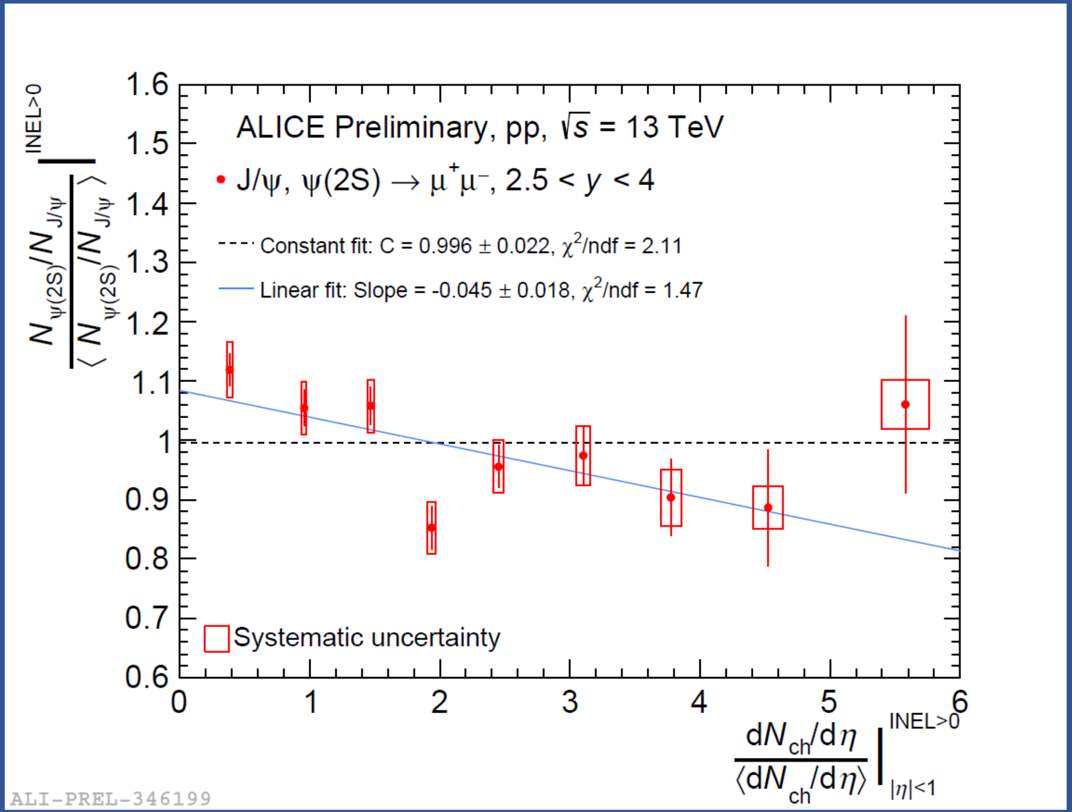


- **Central** rapidity (CMS): suppression of ϒ(2S,3S) wrt ϒ(1S) at large N_{track}
- **Forward** rapidity (ALICE): no effect within uncertainties

Quarkonium production vs event activity

CMS, JHEP 11 (2020) 001





- **Central** rapidity (CMS): suppression of ϒ(2S,3S) wrt ϒ(1S) at large N_{track}
- **Forward** rapidity (ALICE): no effect within uncertainties

- ψ(2S)/J/ψ: **indication for a relative suppression** increasing with $dN_{ch}/d\eta$

Conclusions

- Charmonium and bottomonium states: an invaluable **tool for QGP studies**
- After 20 years of RHIC data and 10 years of LHC data
  - → **coherent picture** emerges from the results
  - → **new and more accurate results** still coming
  - → **excellent prospects** for future (exotica, ψ(2S)+Υ(2S)+Υ(3S) flow,…)

- **Nuclear collisions** (Au-Au, Pb-Pb)
  - **Charmonium: from suppression to regeneration**
    → J/ψ: evidence for deconfinement and thermalization of charm quarks in the QGP
  - **Bottomonium: evidence for sequential suppression**, agreement with models assuming initial temperatures >600 MeV

- **p-A collisions**
  - **Reference** for CNM effects in A-A
  - **Strongly bound** states: suppression dominated by **shadowing**
  - **Weakly bound** states: evidence for further suppression due to **final state effects**

- **pp collisions:** non-trivial effects as a function of event activity