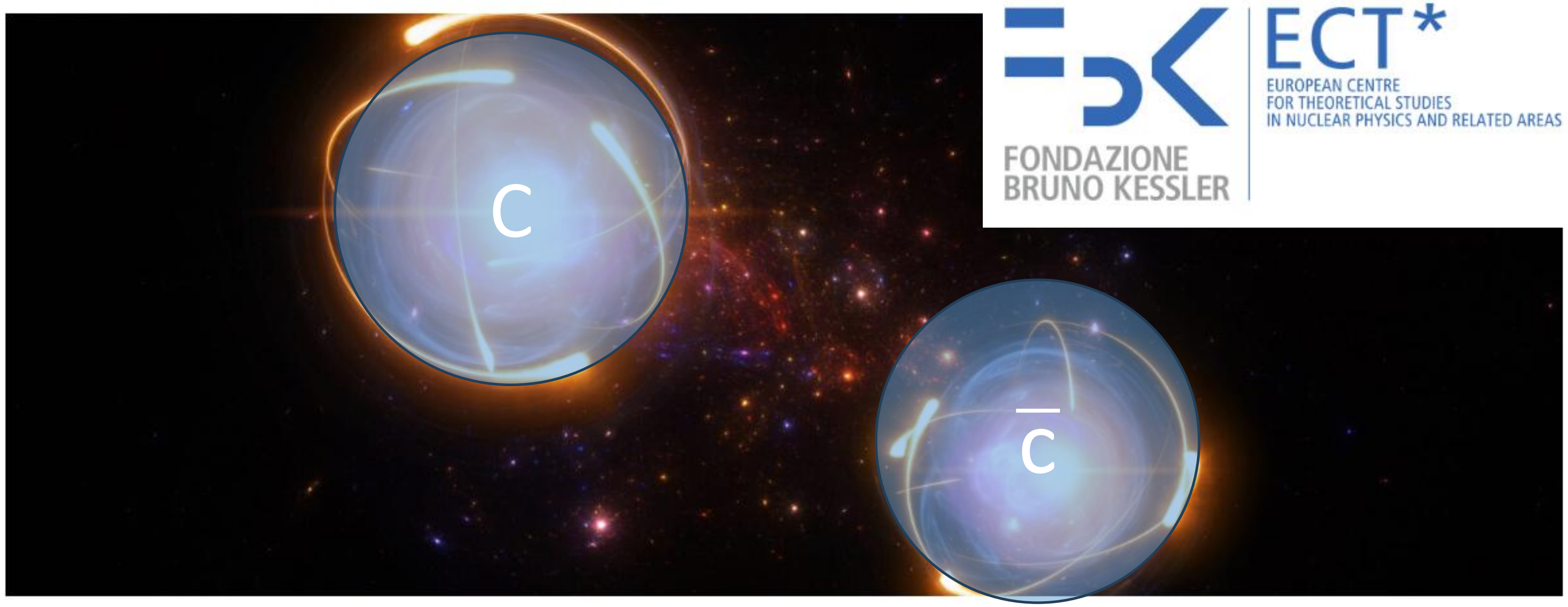
Quarkonium: an overview, with prospects for new fixed-target measurements

E. Scomparin
INFN Torino (Italy)

PENETRATING PROBES OF HOT HIGH-MU_B MATTER: THEORY MEETS EXPERIMENT



FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

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Istituto Nazionale di Fisica Nucleare

TECHNISCHE UNIVERSITÄT DARMSTADT

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21 July 2025 — 25 July 2025

Plan

- Charmonium: the first **"hard probe"** to be accessed experimentally

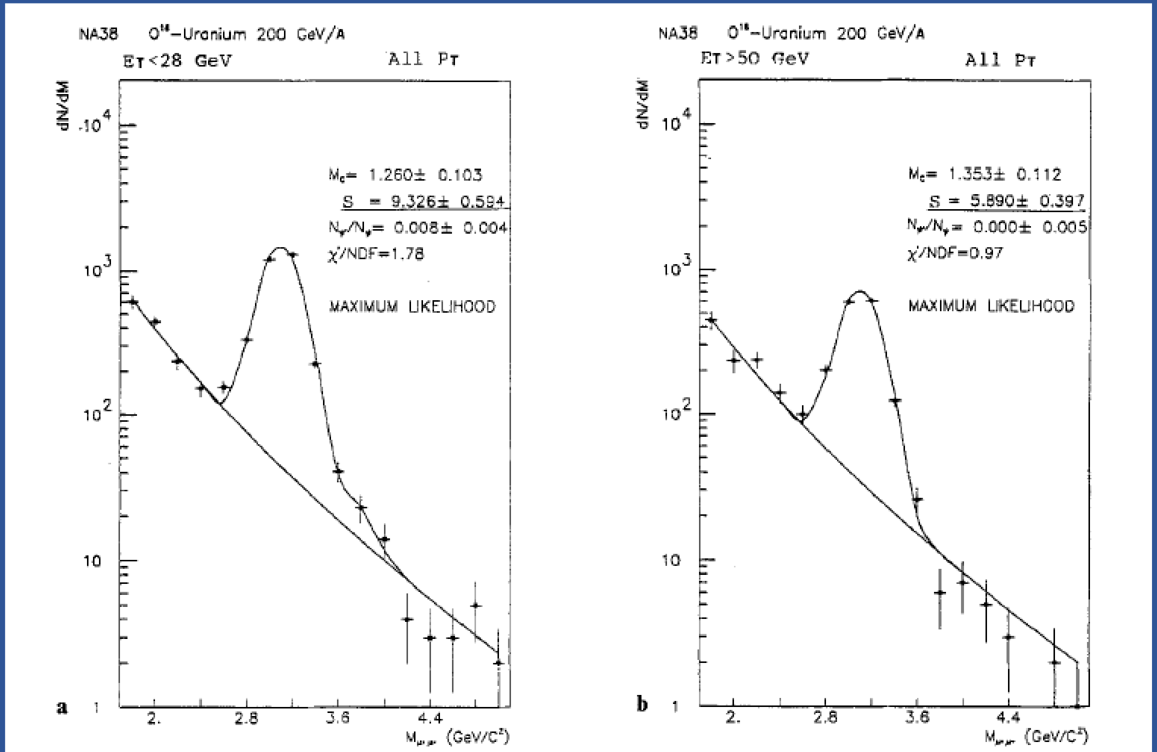
- **What do we (already) know** in the high-μ_B domain ?
  - Reviewing (top) SPS energy results: NA50/NA60 experiments
  - The importance of CNM effects

- What have we learned at **collider energies ?**
  - Milestones from RHIC/LHC programs

- How can we extend our knowledge to even higher μ_B ?
  - **Plans for CBM and NA60+/DiCE**

The beginning of the story

- "If high-energy heavy ion collisions lead to the formation of a quark-gluon plasma, then **color screening prevents cc binding** in the deconfined interior of the interaction region" (Matsui, Satz, 1986)



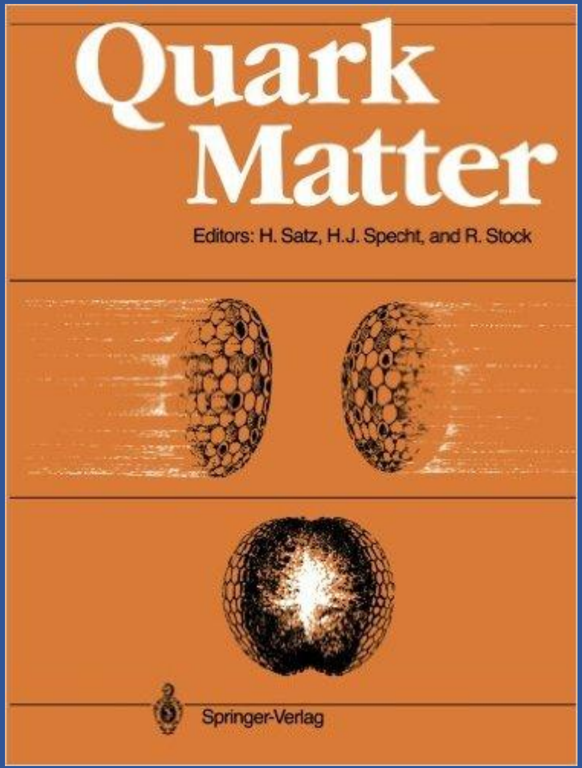
First evidence for J/ψ suppression
in nuclear collisions!

Quark Matter 87

- NA38, O-U collisions at the **CERN SPS**
- 200 GeV/nucleon (lab system! $\sqrt{s_{NN}}$=19.4 GeV)

Abstract. The dimuon production in 200 GeV/nucleon oxygen-uranium interactions is studied by the NA38 Collaboration. The production of *J/Ψ*, correlated with the transverse energy *ET*, is investigated and compared to the continuum, as a function of the dimuon mass *M* and transverse momentum *PT*. A value of 0.64±0.06 is found for the ratio (*Ψ*/Continuum at high *ET*)/(*Ψ*/Continuum at low *ET*), from which the *J/Ψ* relative suppression can be extracted. This suppression is enhanced at low *PT*.

Early feedback from the community



From the QM87 summary talk

The most provocative observation, reported by NA 38 [13], was that J/ψ production seems to be suppressed by $\sim 30\%$ in high E_T events. The second provocative

3 Puzzles

3.1 J/Psi suppression

$$N_\psi/N_c = \begin{cases} 9.3 \pm 0.6 & \text{for } E_T < 28 \text{ GeV} \\ 5.9 \pm 0.4 & \text{for } E_T > 50 \text{ GeV.} \end{cases} \quad (10)$$

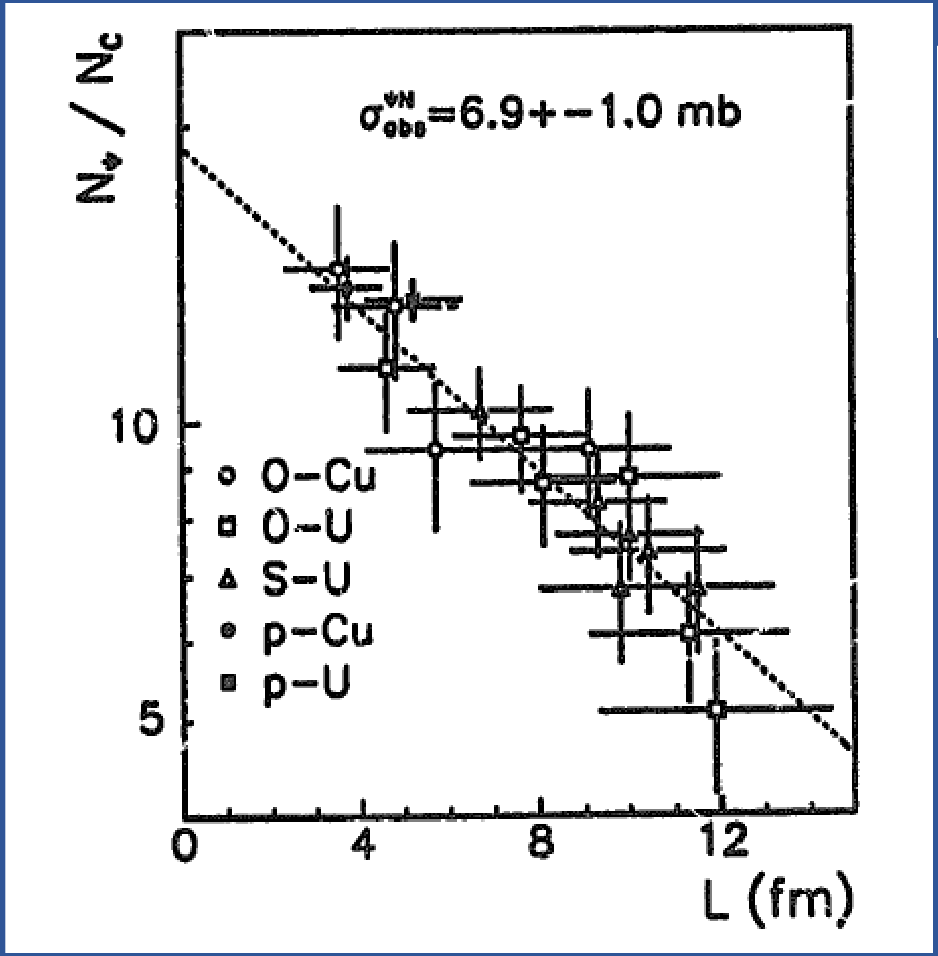
This 30% reduction of ψ production caused the most controversy at Quark Matter '87.

There are naturally several caveats that need further consideration. First, there is the problem of prov-

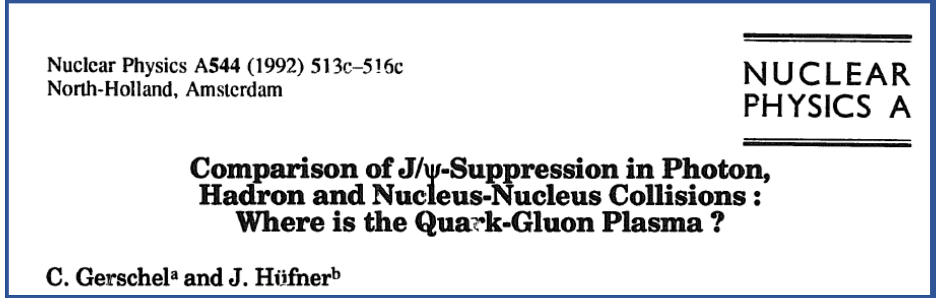
- Can competing sources of J/ψ dissociation involving hadronic interactions (with cold nuclear matter and/or hadronic medium) reproduce the observations ?

A **signature of deconfinement**,
or just a **generic signature** for dense matter formation?

Hot vs cold nuclear matter effects



C. Gerschel et al., PLB207 (1988)253



Nuclear Physics A544 (1992) 513c–516c
North-Holland, Amsterdam

NUCLEAR PHYSICS A

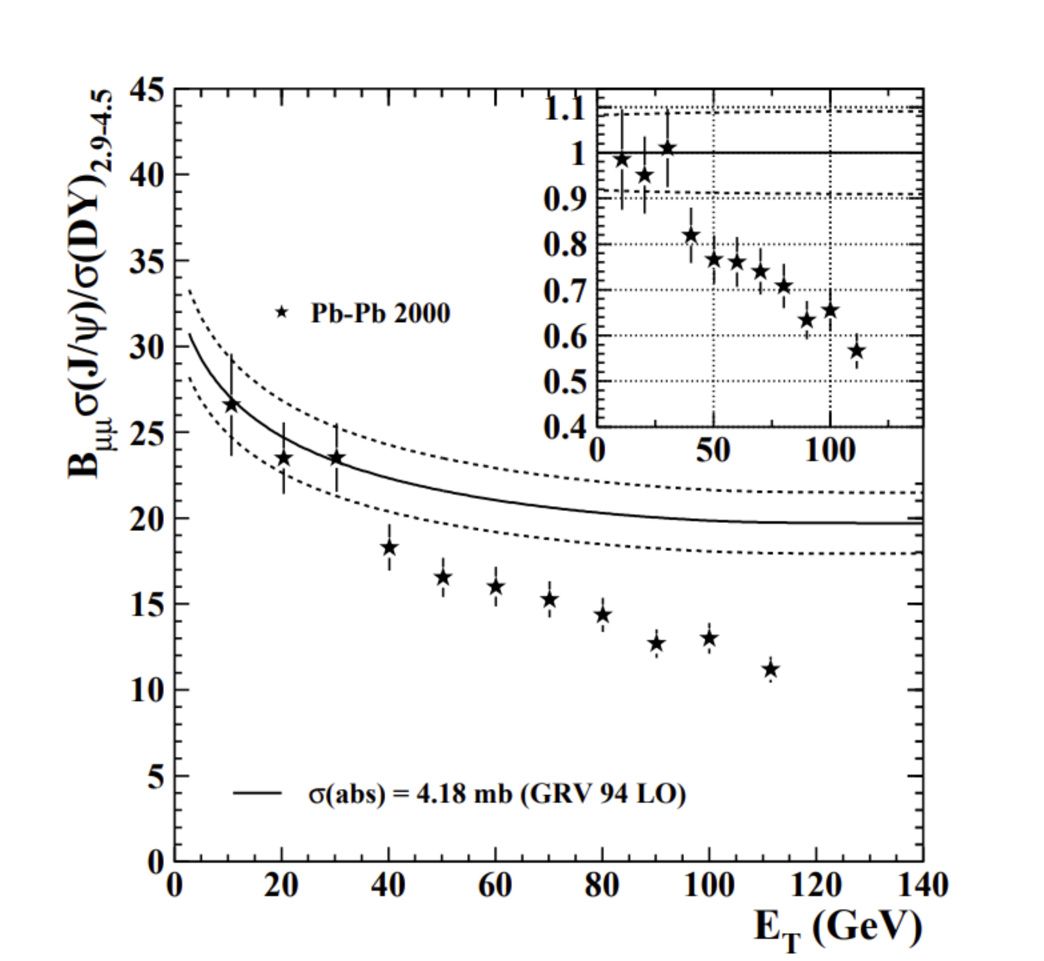
Comparison of J/ψ-Suppression in Photon, Hadron and Nucleus-Nucleus Collisions : Where is the Quark-Gluon Plasma ?

C. Gerschel[a] and J. Hüfner[b]

p-A collision results **imply significant dissociation cross sections in CNM**

→ Crucial ingredient in the interpretation of the data
→ Stimulated an intense experimental program at both CERN and FNAL

From light to heavy ions



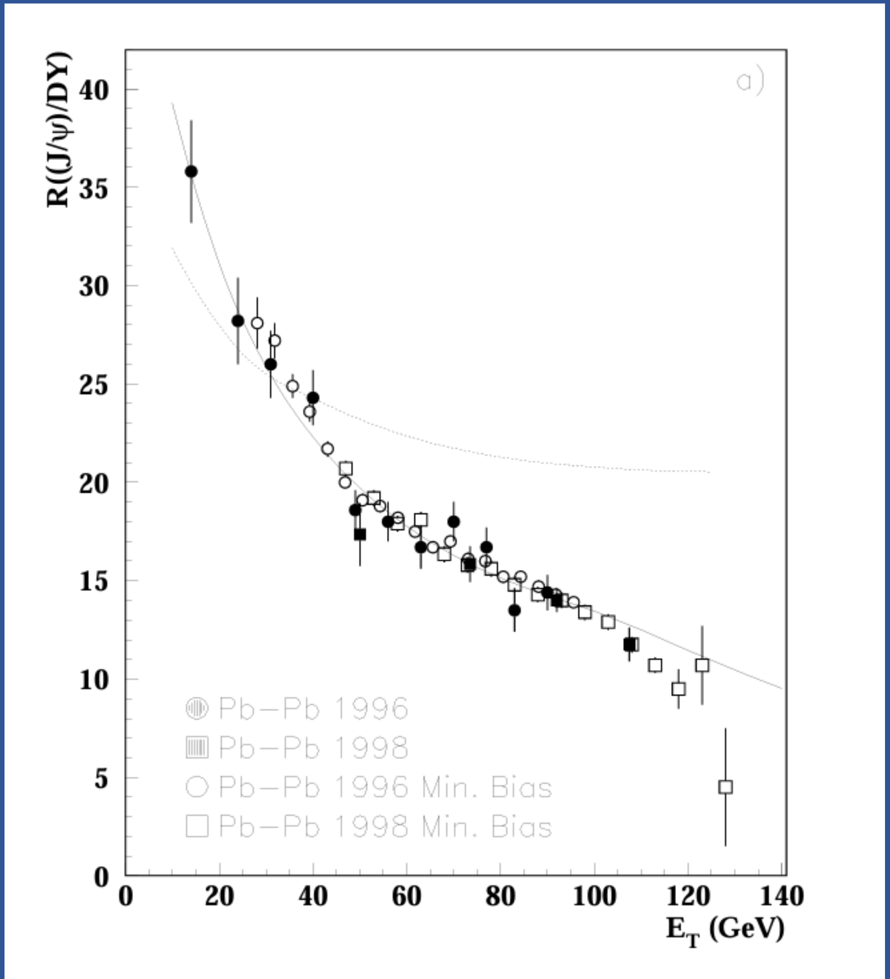
"…Our analysis shows that peripheral Pb-Pb interactions, with impact parameter b > 8.5 fm, exhibit a J/ψ production yield in agreement with the normal nuclear absorption pattern, with σ_{abs} = 4.18 mb, derived from an extensive study of p-A collisions. **For smaller impact parameter values we observe a departure from the normal absorption curve, followed by a persisting decrease up to the most central Pb-Pb collisions** ".

One of the milestones of the QGP announcement At CERN in February 2000

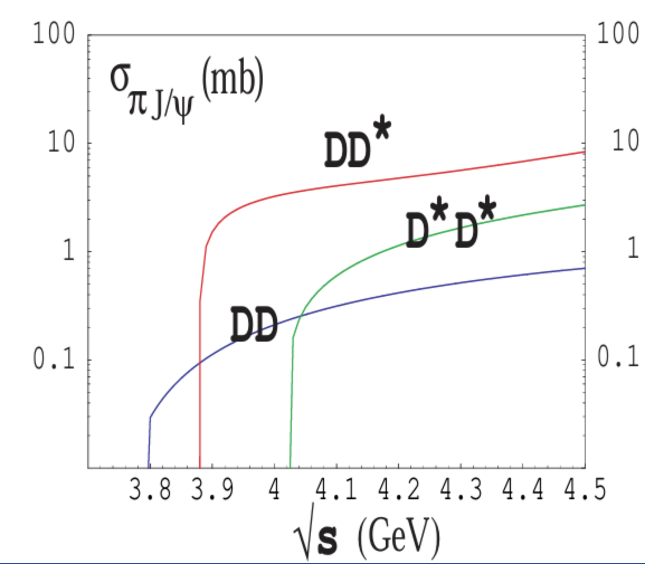
NA50, Eur.Phys.J.C39 (2005) 335

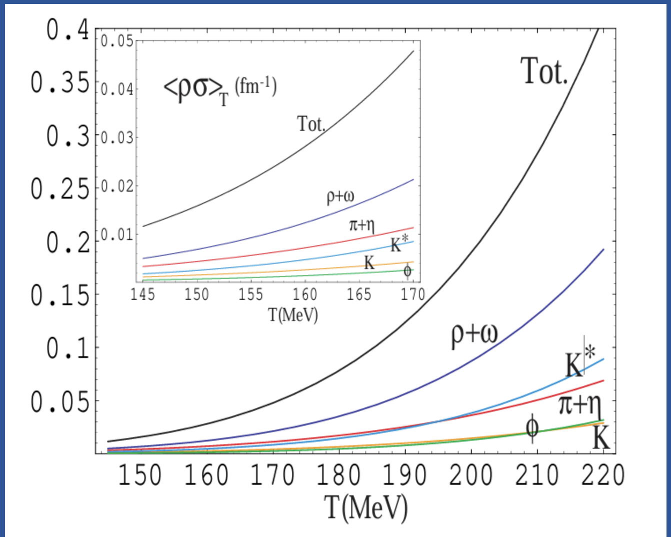
The "comover" saga

Armesto et al., NPA 698 (2002) 583-586

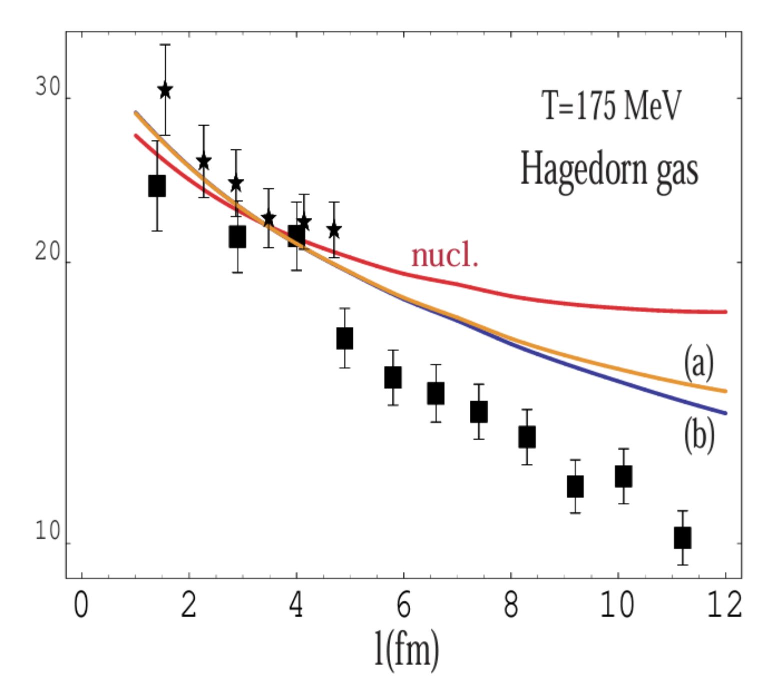


NA50 data reproduced with σ_{co}= 1 mb (~free parameter)



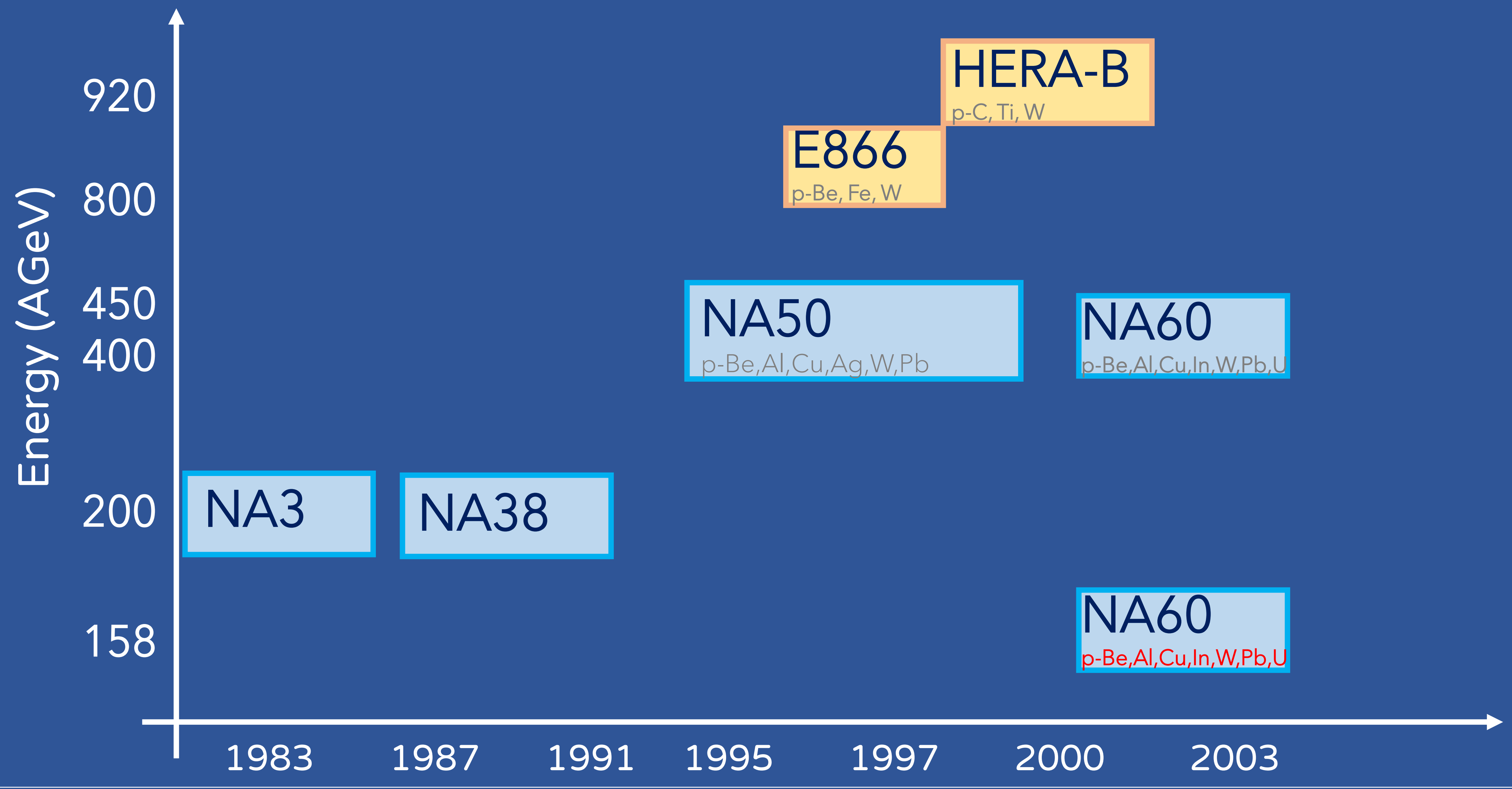


L. Maiani et al., Nucl.Phys. A748 (2005) 209-225

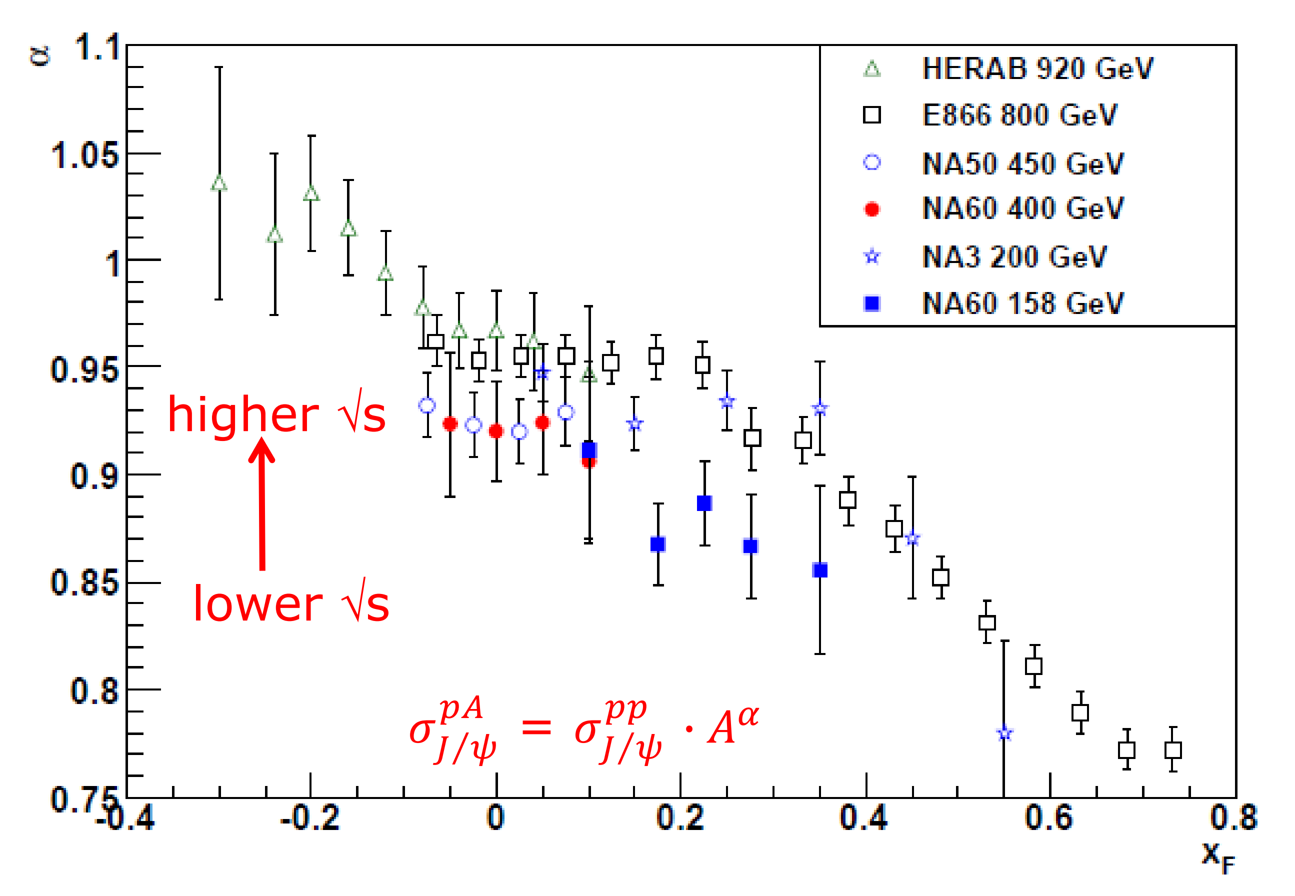


Microscopic approaches showed that **absorption by comovers may not suffice** to reproduce the observations

Initial state and CNM effects at fixed target



p-A results at fixed target: a complex environment



NA60 Coll., Phys. Lett. B 706 (2012) 263-367

J/ψ yield in pA is modified with respect to pp, with a significant kinematic dependence

- **α strongly decreases with x_F**
- **for a fixed x_F, stronger CNM at lower √s**

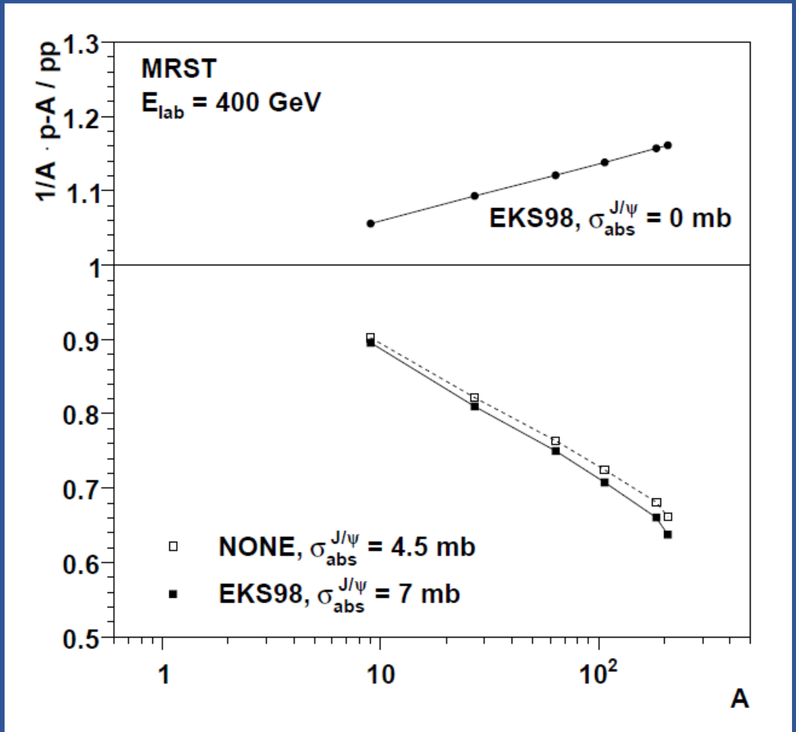
Superposition of several effects

⇩

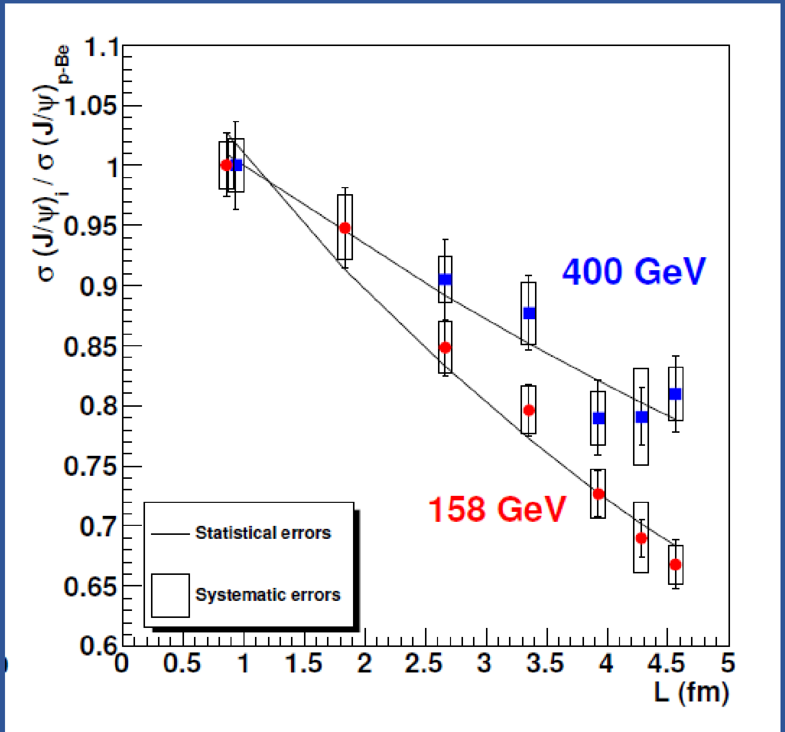
Shadowing
Nuclear break-up
Energy loss (at large x_F)

No consistent theory description over the whole x_F range

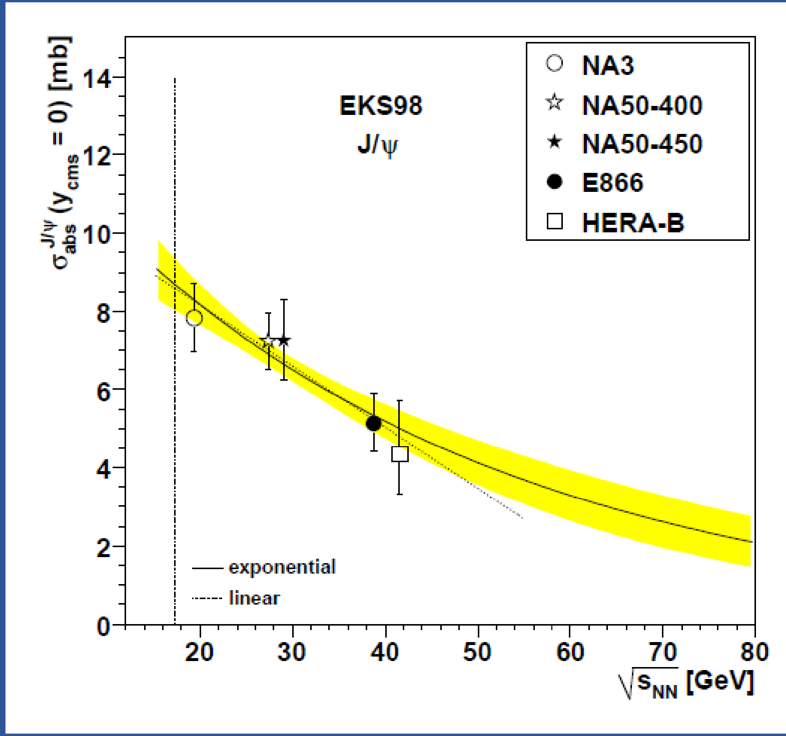
Attempting a parameterization of CNM



NA60, Phys.Lett.B 706 (2012) 263



Lourenco, Vogt, Woehri, JHEP 0902:014,2009



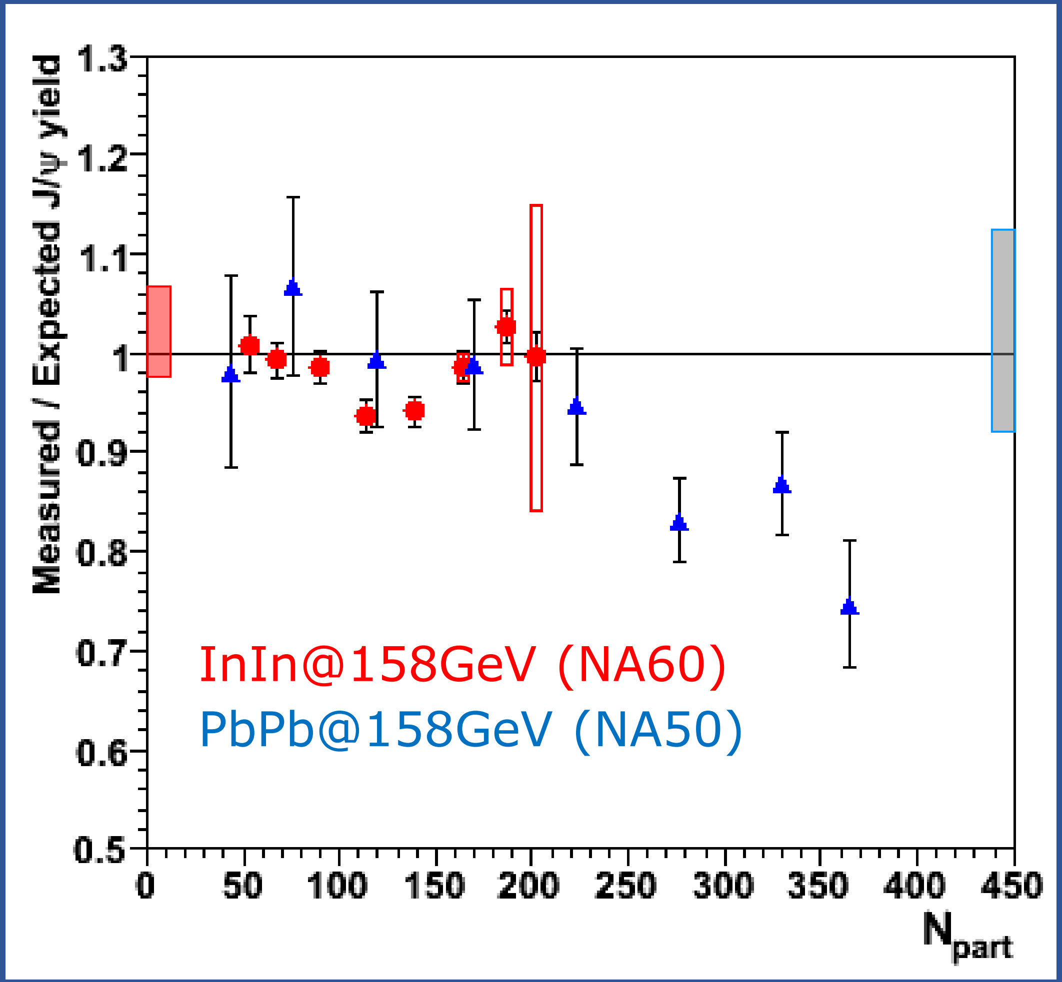
"Competition" between (anti)shadowing and nuclear break-up

Relative J/ψ cross sections
Evidence for **√s-dependence**

$\sigma^{J/\psi}_{abs}$~10 mb at low √s

→ **CNM effects to become dominant in A-A** at sufficiently low collision energy

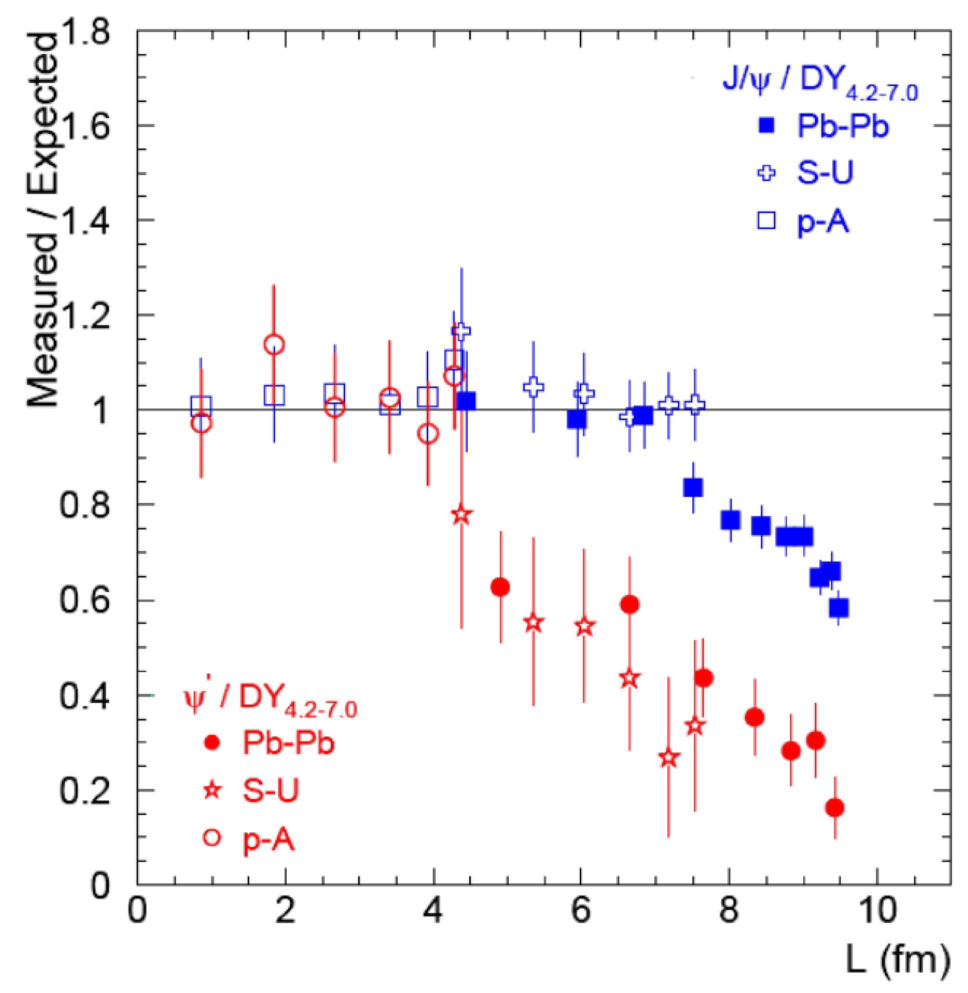
Legacy of SPS experiments



NA50, EPJC39 (2005) 335
NA60, Nucl. Phys. A830 (2009) 345
R.Arnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

- **Measured J/ψ yield, normalized to an extrapolation of CNM effects**, evaluated starting from p-A results **at the same energy**
- **Drell-Yan** reference used to extract NA50 results
- **Suppression** effects beyond CNM reach **~30%** in central Pb-Pb collision
- Qualitatively consistent with **suppression of feed-down** from ψ(2S) (measured) and χ_c (not measured)
- **In-In** result shows **small or no suppression**, with the origin of "wiggle" at intermediate centrality unclear (coupling to X(3872) via DD* proposed in Blaschke et al., NPA927(2014) 1)

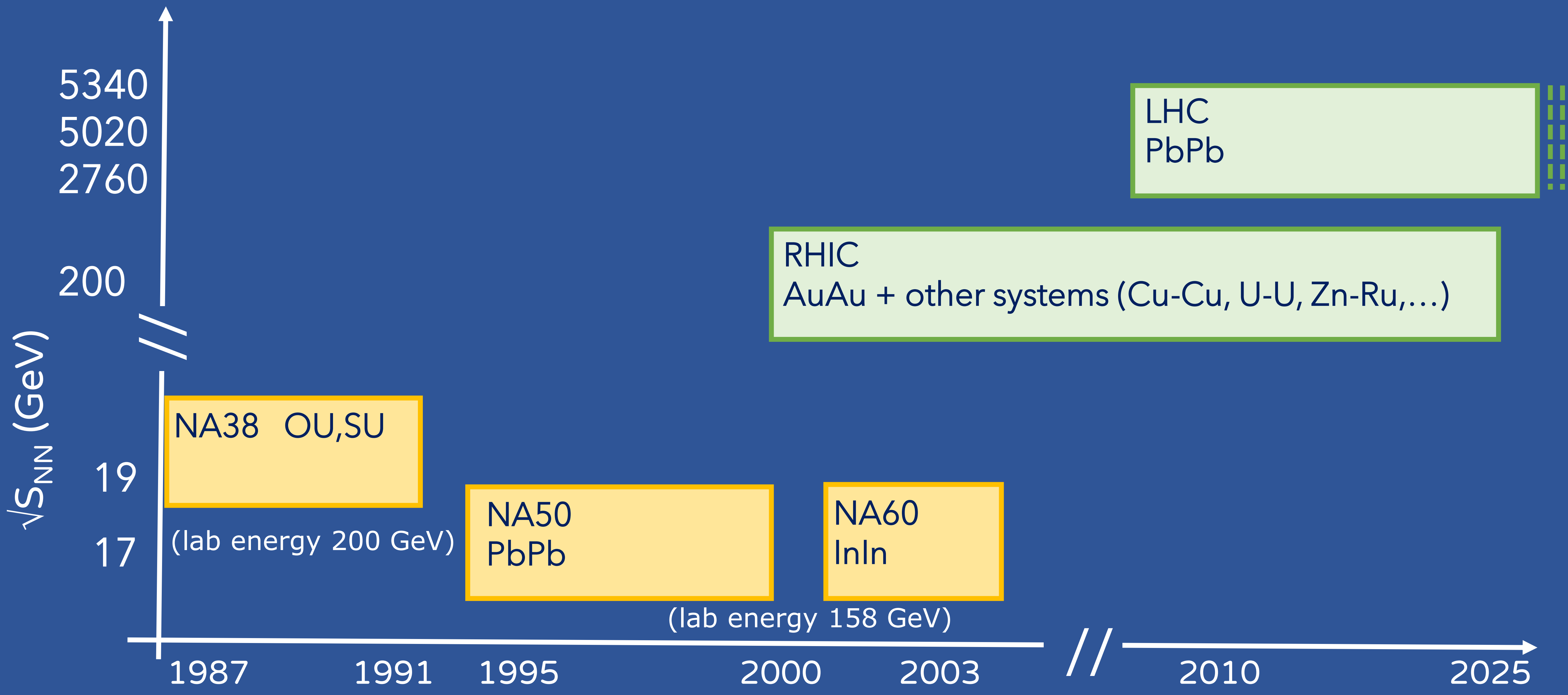
The sequential charmonium suppression



NA50, Eur.Phys.J.C 49 (2007) 559-567

- ❑ With respect to the same reference process
- ❑ Having corrected for respective CNM effects, calibrated with p-A data
- ❑ $\psi(2S)$ suppression effects turn in for more peripheral events in a given collision system
- ❑ The effects are much stronger for $\psi(2S)$ at a given centrality

From fixed-target to collider energies

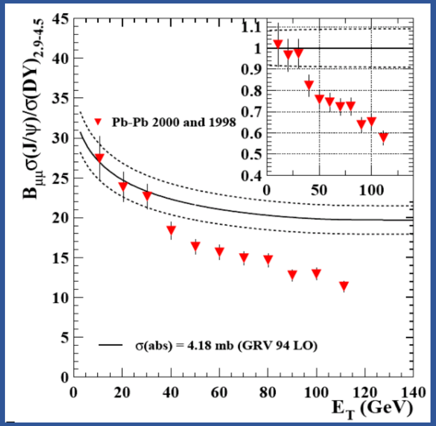


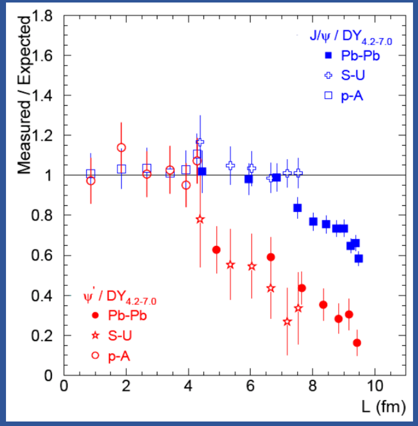
Discoveries and observations

Discovery of **anomalous J/ψ suppression**

Discovery of **sequential charmonium suppression**

SPS





Discoveries and observations

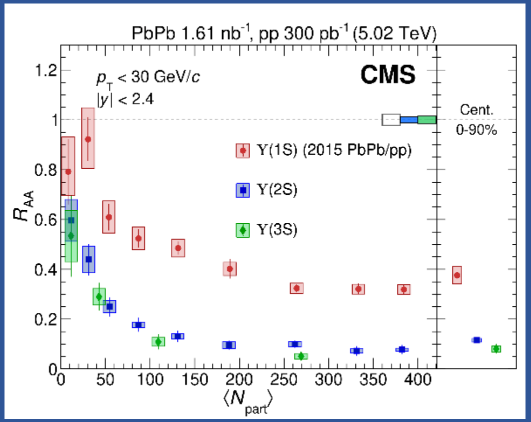
Discovery of **anomalous J/ψ suppression**

Discovery of **sequential charmonium suppression**

SPS

Discovery of **sequential bottomonium suppression**

LHC



Discoveries and observations

Discovery of **anomalous J/ψ suppression**

Discovery of **sequential charmonium suppression**

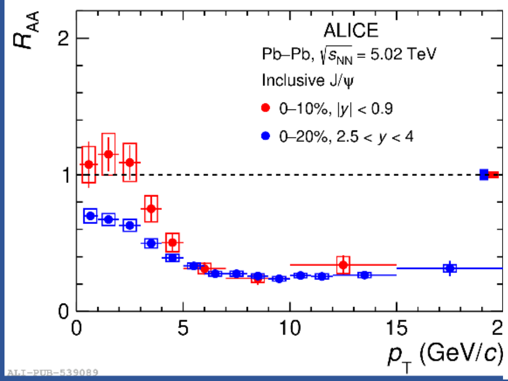
} SPS

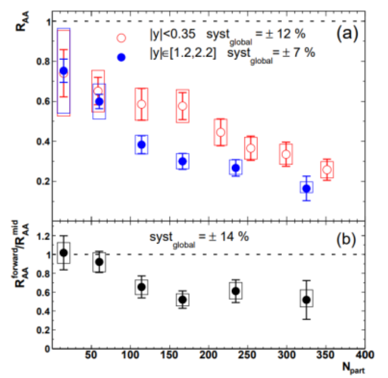
Discovery of **sequential bottomonium suppression**

} LHC

Discovery of **J/ψ regeneration**

} RHIC LHC





Discoveries and observations

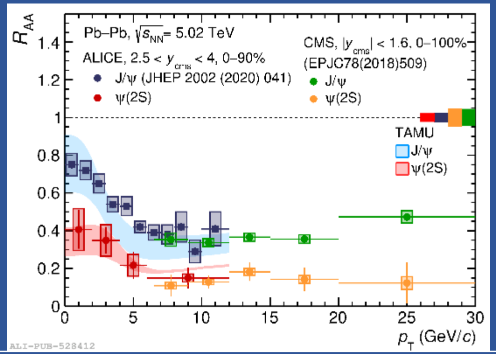
Discovery of **anomalous J/ψ suppression** — SPS

Discovery of **sequential charmonium suppression** — SPS

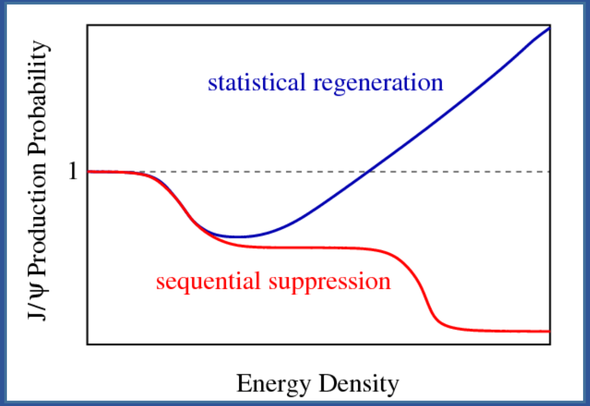
Discovery of **sequential bottomonium suppression** — LHC

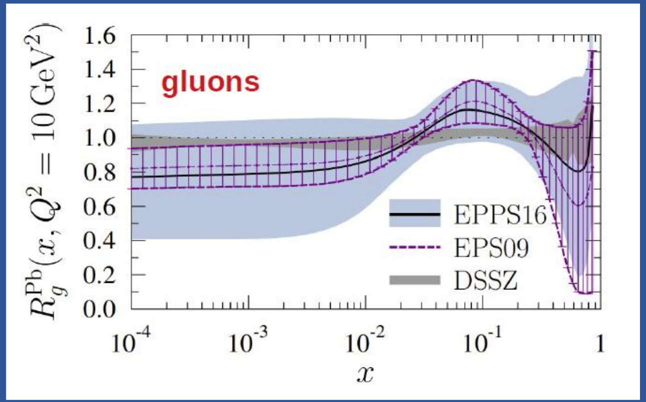
Discovery of **J/ψ regeneration** — RHIC, LHC

Observation of **sequential charmonium regeneration** — LHC



Low vs high energy: charmonia



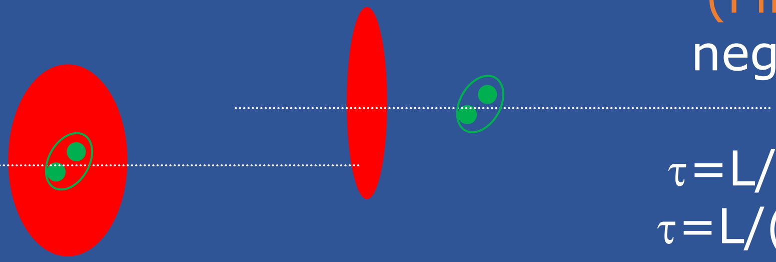


Fixed target (SPS)

Hot matter effects:
suppression effects (if existing) dominate

Initial state effects:
moderate anti-shadowing
$x \sim 10^{-1}$ (y=0)

(Final state) CNM effects:
break-up in nuclear matter can be sizeable
$\tau = L/(\beta_z\gamma) \sim 0.5$ fm/c(y=0)



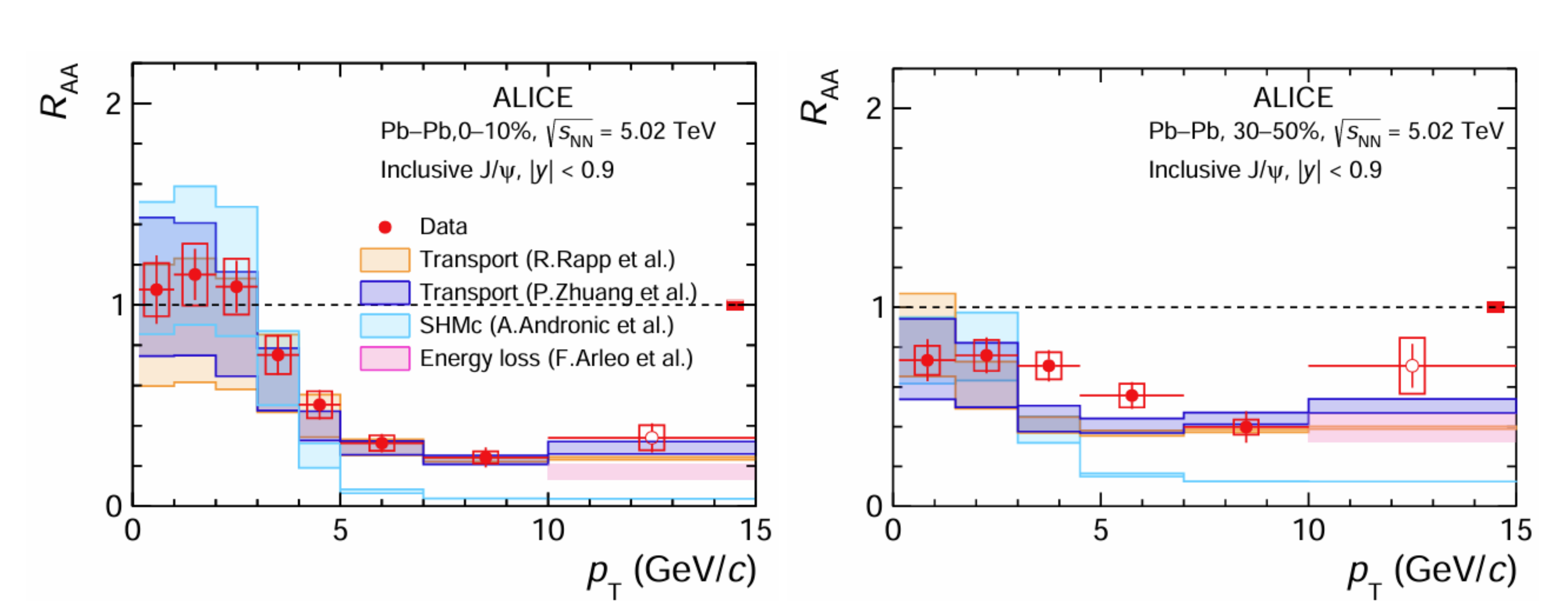
Collider (LHC)

Hot matter effects: regeneration counterbalances (overcomes) suppression

Initial state effects:
shadowing
$x \sim 10^{-5}$ (y~3),
$x \sim 10^{-3}$ (y=0),
$x \sim 10^{-2}$(y~-3)

(Final state) CNM effects:
negligible, extremely short crossing time
$\tau = L/(\beta_z\gamma) \sim 7\ 10^{-5}$ fm/c (y~3)
$\tau = L/(\beta_z\gamma) \sim 4\ 10^{-2}$ fm/c (y~-3)

J/ψ at LHC: (re)generation demonstrated

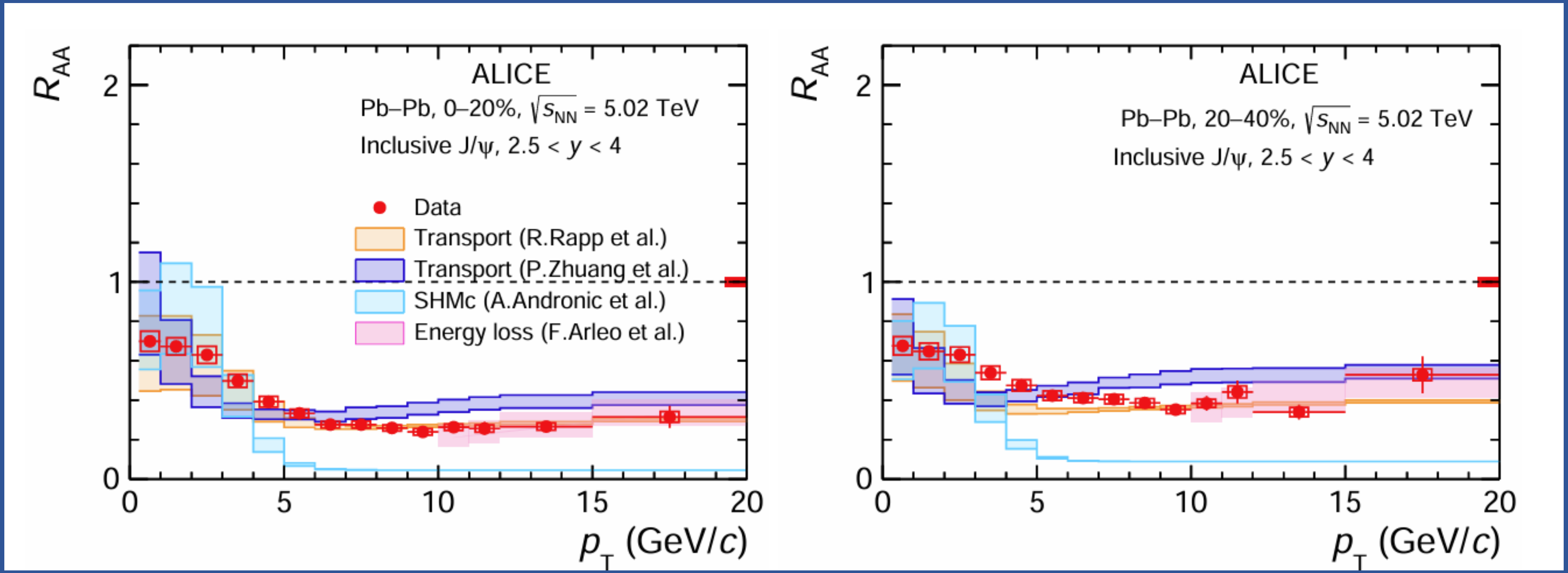


ALICE, Phys. Lett. B 849 (2024) 138451

Mid rapidity

- **Rise of R_{AA}** at low p_T (opposite behaviour with respect to fixed-target)
- In itself, a **proof of deconfinement**
- Models (transport, statistical) reproduce data, **no clear discrimination**
- Shadowing effects + total charm cross section limiting factors for theory uncertainties

J/ψ at LHC: (re)generation demonstrated

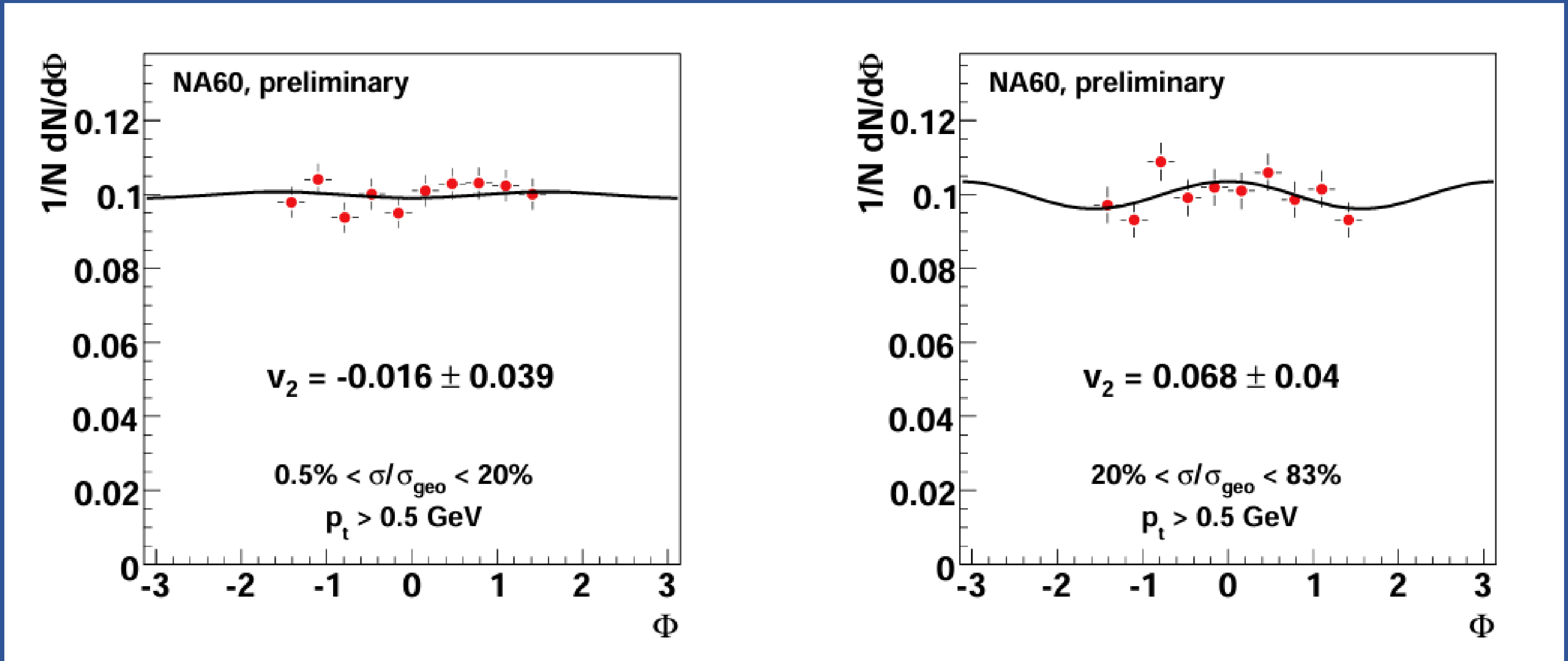


ALICE, Phys. Lett. B 849 (2024) 138451

Forward rapidity

- **Rise of R_{AA}** at low p_T (opposite behaviour with respect to fixed-target)
- In itself, a **proof of deconfinement**
- Models (transport, statistical) reproduce data, **no clear discrimination**
- Shadowing effects + total charm cross section limiting factors for theory uncertainties

J/ψ at ~~LHC~~ SPS: everything flows

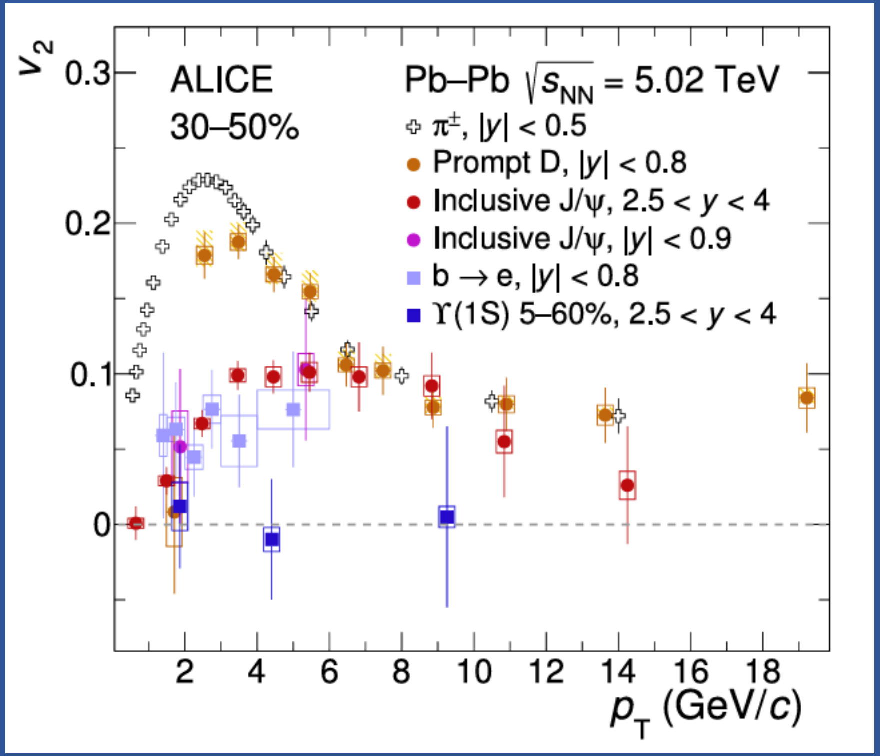


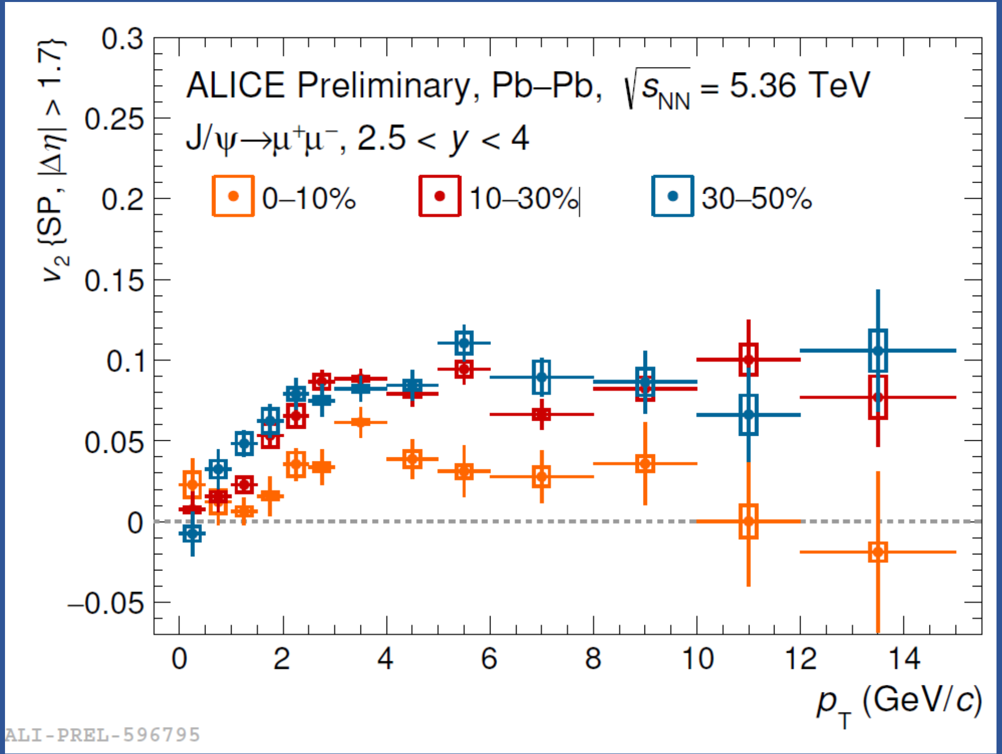
NA60, J.Phys.G32 (2006)S51-S60

Possible indication of charm quark participation to flow already at SPS energy (only 50% of the available statistics, then student left):)

J/ψ at LHC: everything flows

ALICE, Eur. Phys. J. C 84 (2024) 813

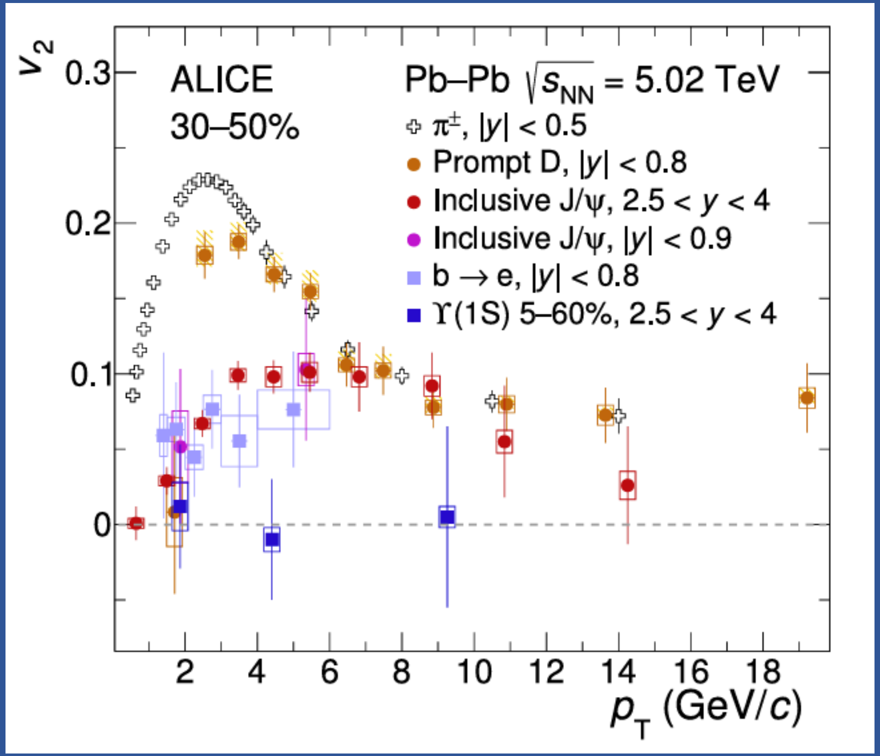


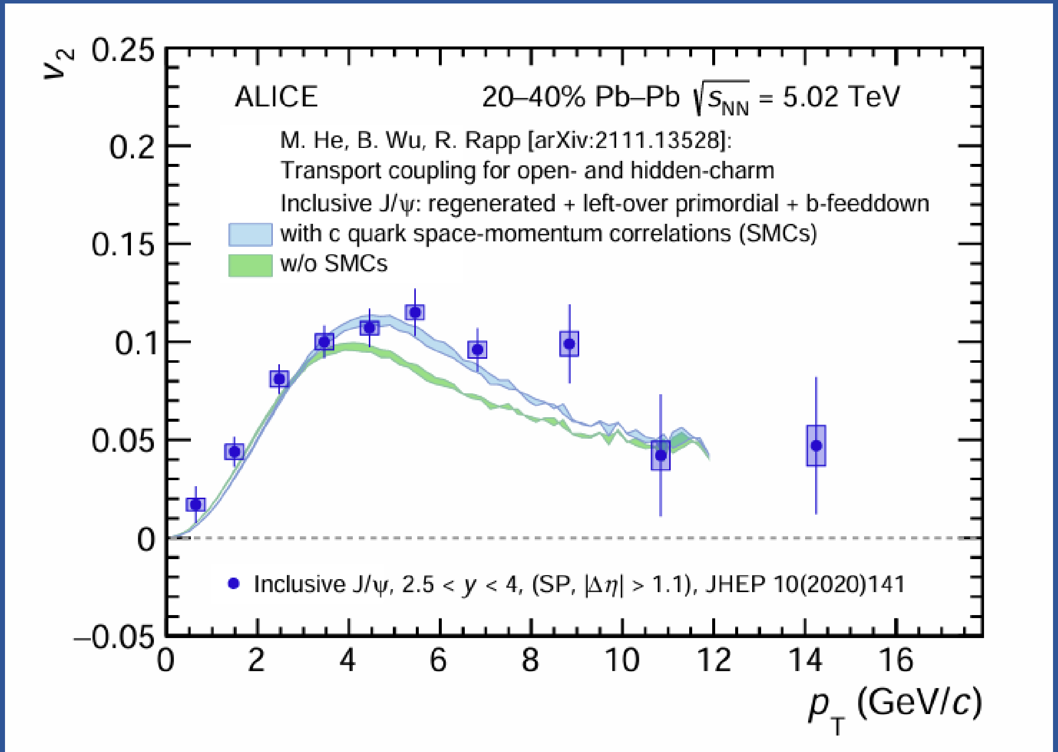


- ❑ Charm quarks (partly) **thermalized**
- ❑ Clear **flavor hierarchy** for both open and hidden production
- ❑ Supports the scenario of J/ψ formation via (re)combination during the late stages of the collision

J/ψ at LHC: everything flows

ALICE, Eur. Phys. J. C 84 (2024) 813

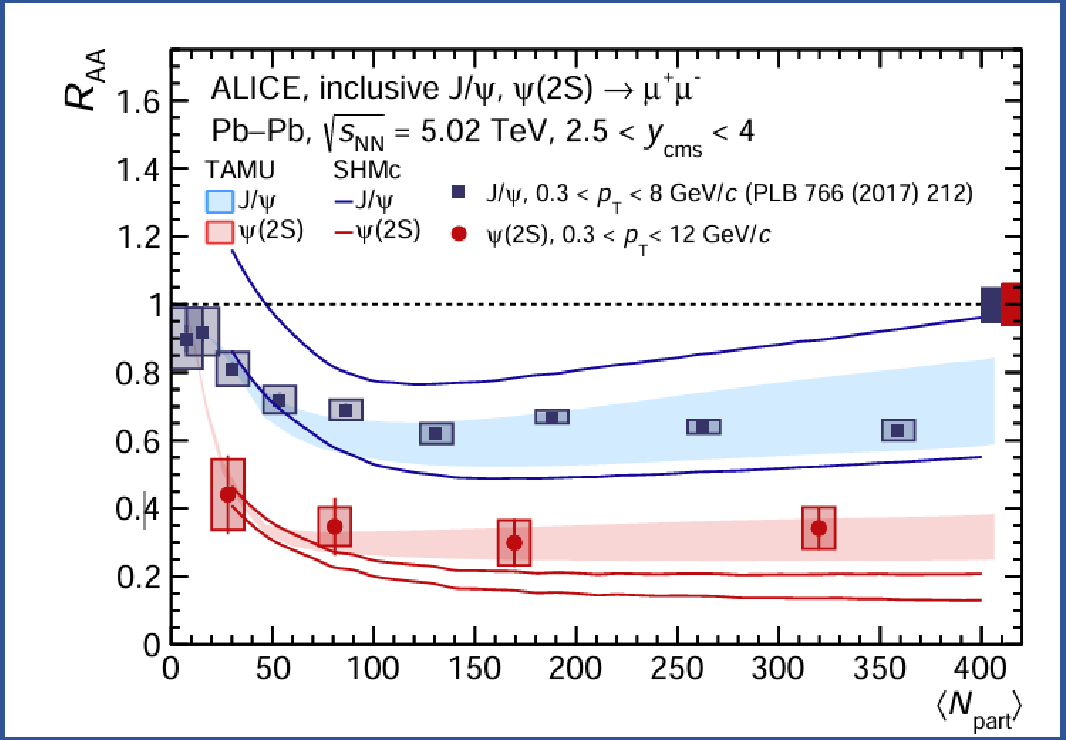


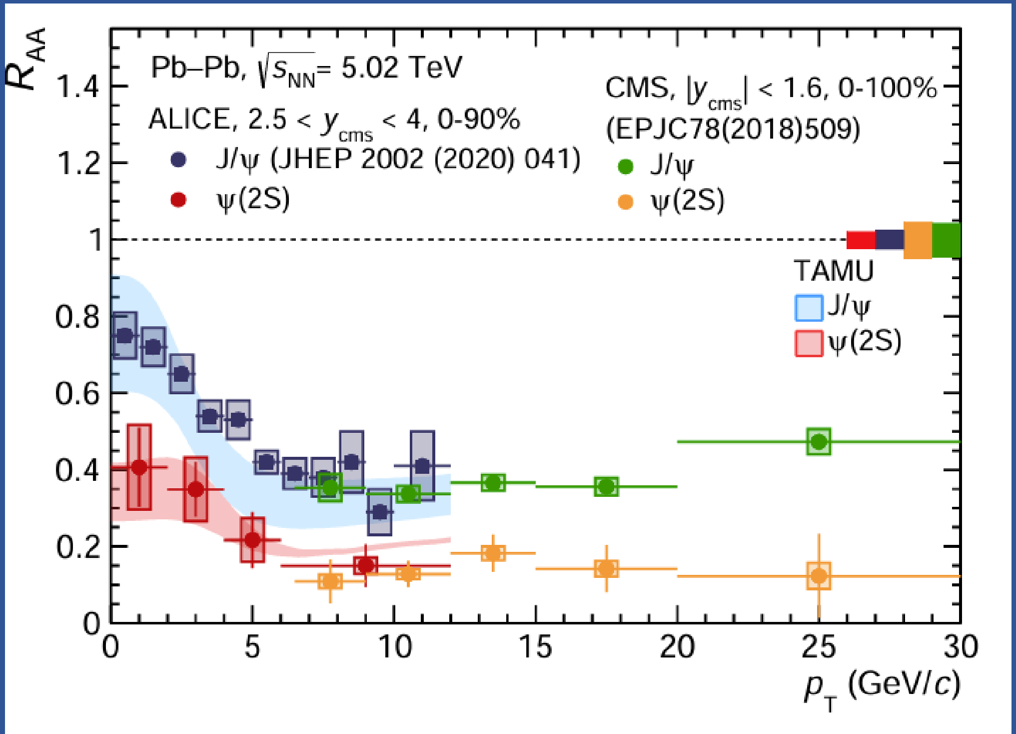


He, Wu and Rapp, Phys.Rev.Lett.128, 162301 (2022)

- Charm quarks (partly) **thermalized**
- Clear **flavor hierarchy** for both open and hidden production
- Supports the scenario of J/ψ formation via (re)combination during the late stages of the collision
- Remarkable **agreement with theory**

ψ(2S) at LHC: sequential (re)generation

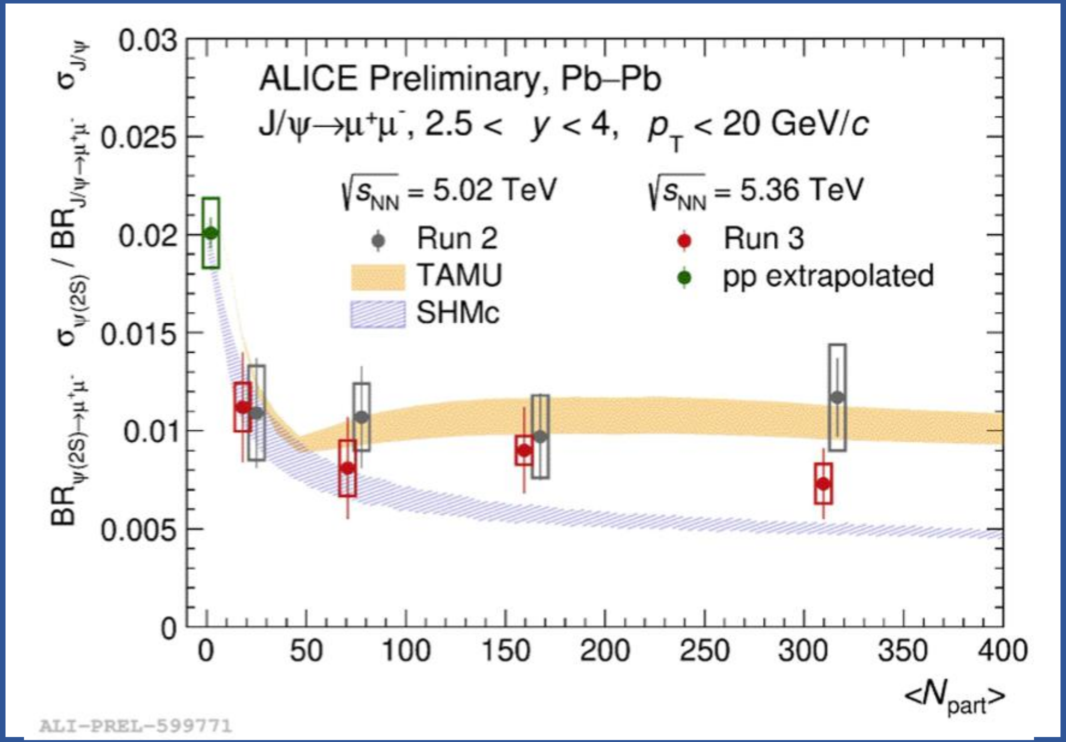


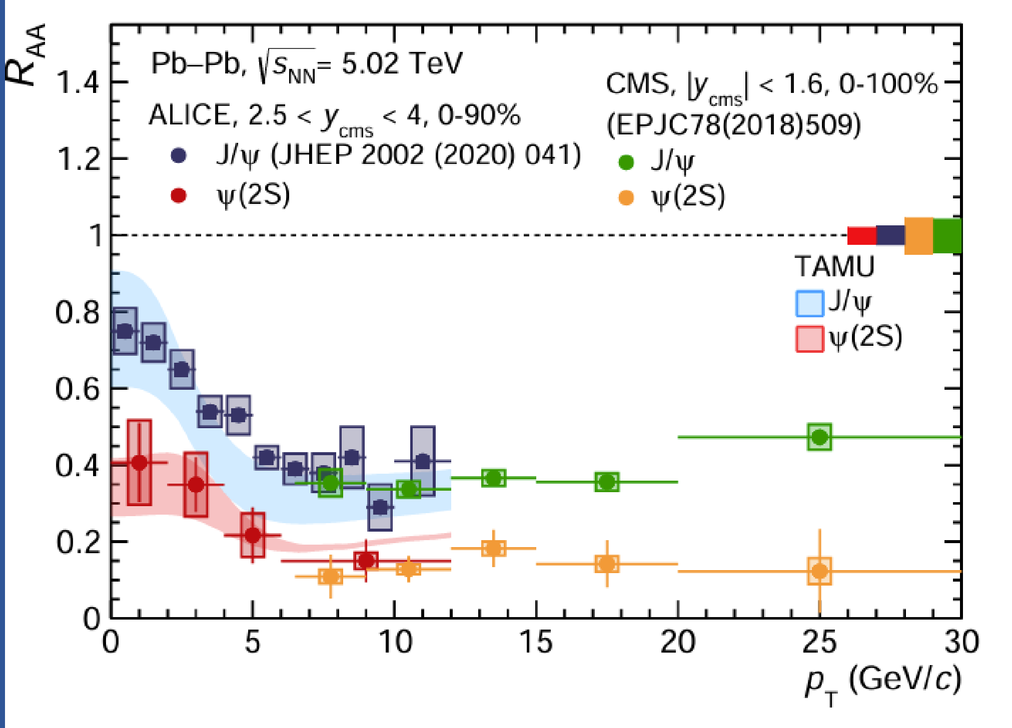


ALICE, Phys. Rev. Lett. 132 (2024) 042301

- **Stronger suppression** for ψ(2S), confirms low-energy observations by NA50
- Indication for a rise of R_{AA} at low p_T , marking **(re)generation**
- Tension with statistical model

ψ(2S) at LHC: sequential (re)generation

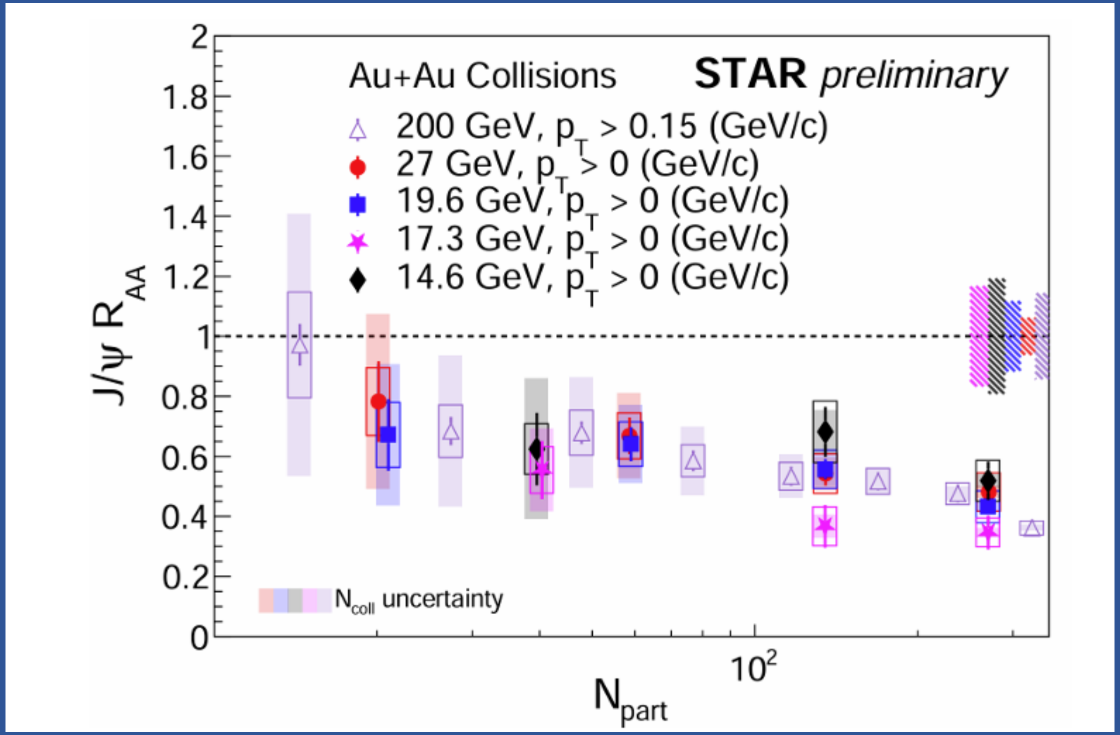


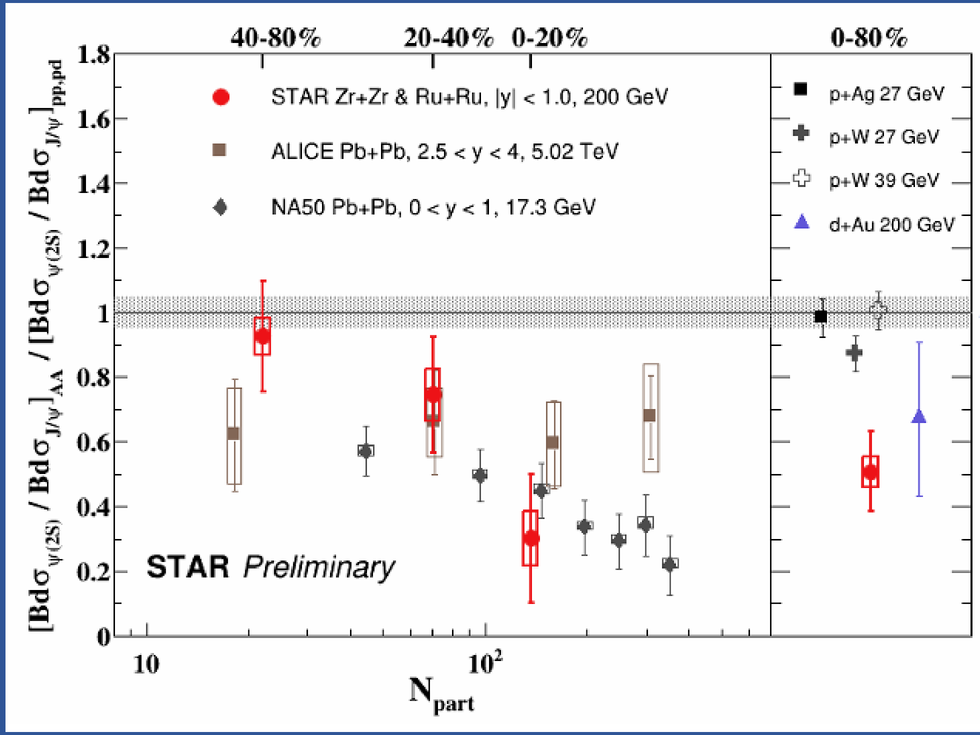


ALICE, Phys. Rev. Lett. 132 (2024) 042301

- ❑ **Stronger suppression** for ψ(2S), confirms low-energy observations by NA50
- ❑ Indication for a rise of R_{AA} at low p_T , marking **(re)generation**
- ❑ Tension with statistical model (less clear with recent preliminary results at $\sqrt{s_{NN}}$=5.36 TeV)

Recent RHIC contributions to the charmonium saga



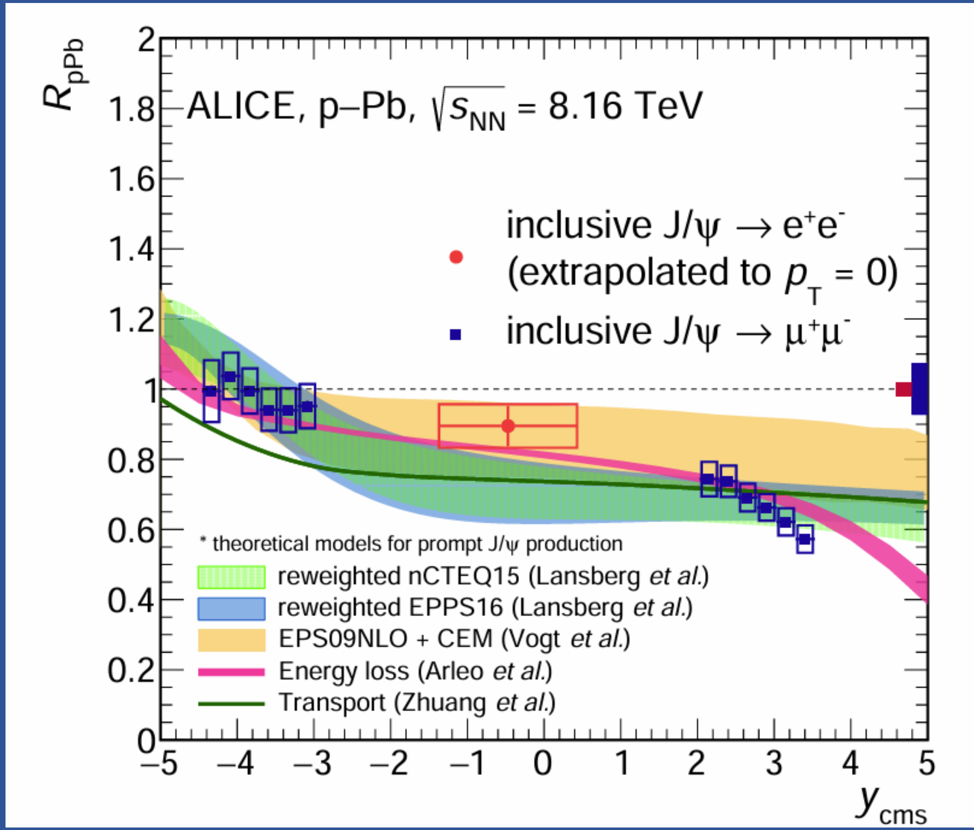


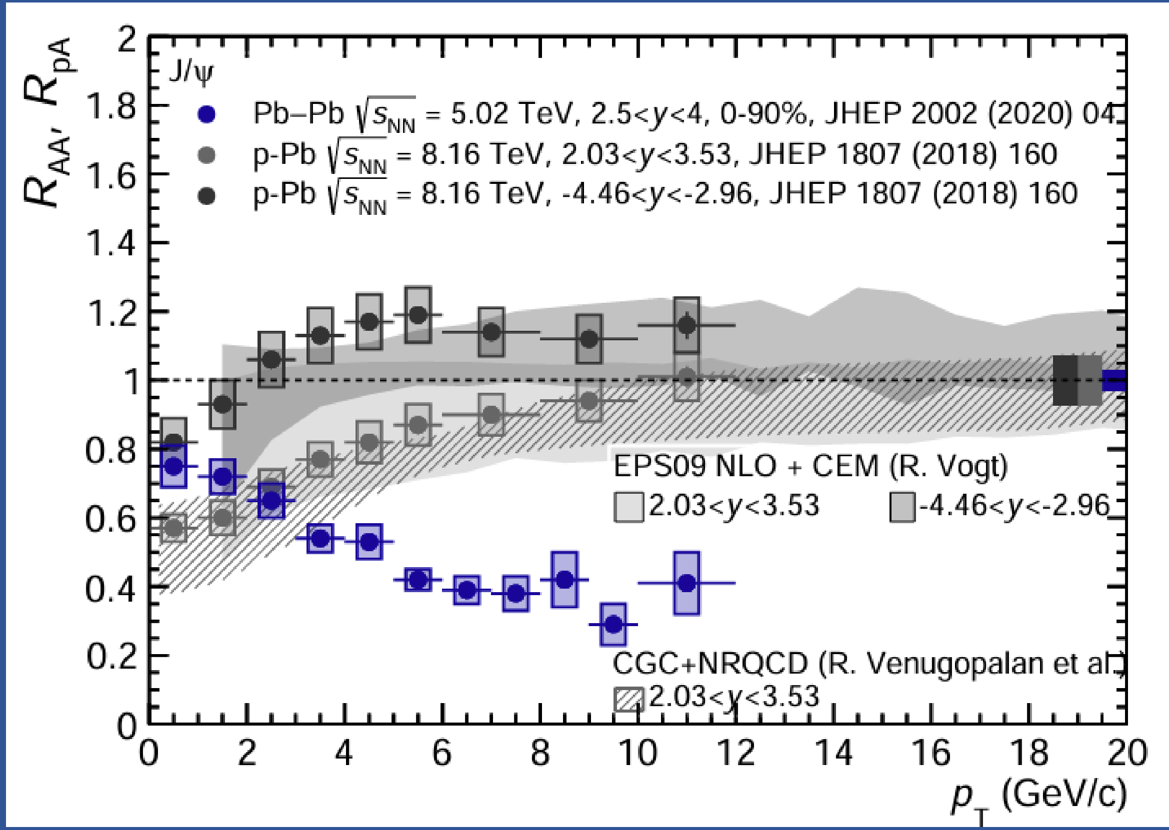
- R_{AA} shows **no significant energy dependence** for similar $<N_{part}>$
- IMO: interesting but a strong physics conclusion requires **calibration of CNM effects**, that likely depend on $\sqrt{s_{NN}}$

- **Stronger suppression** for ψ(2S), confirms SPS and LHC
- Reference obtained as average of measurements in p+p(d) by NA51, ISR and PHENIX

CNM effects at LHC: J/ψ

ALICE, JHEP 07 (2023) 137





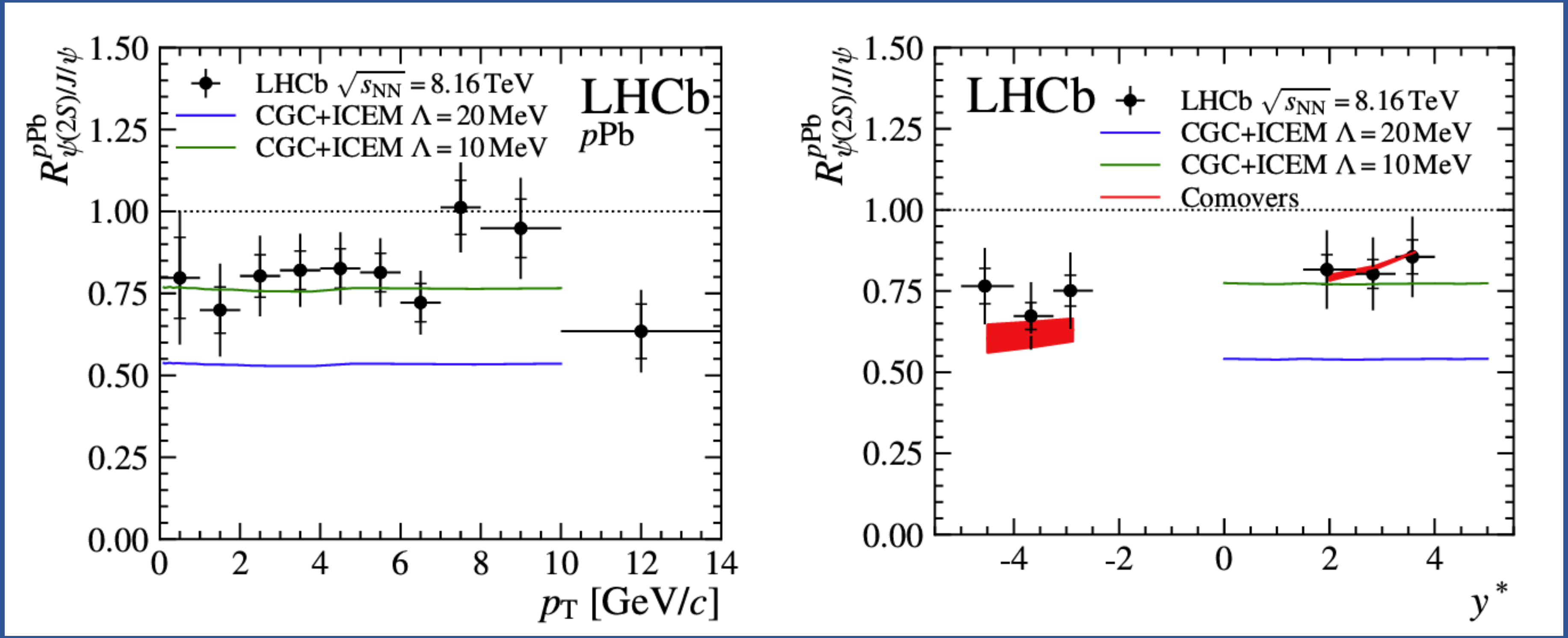
ALICE, Eur. Phys. J. C 84 (2024) 813

- ❑ J/ψ data compatible with **initial state effects** parameterized via nPDF

- ❑ Comparison p-Pb vs Pb-Pb
- ❑ Remaining **low-p_T suppression likely due to CNM effects**

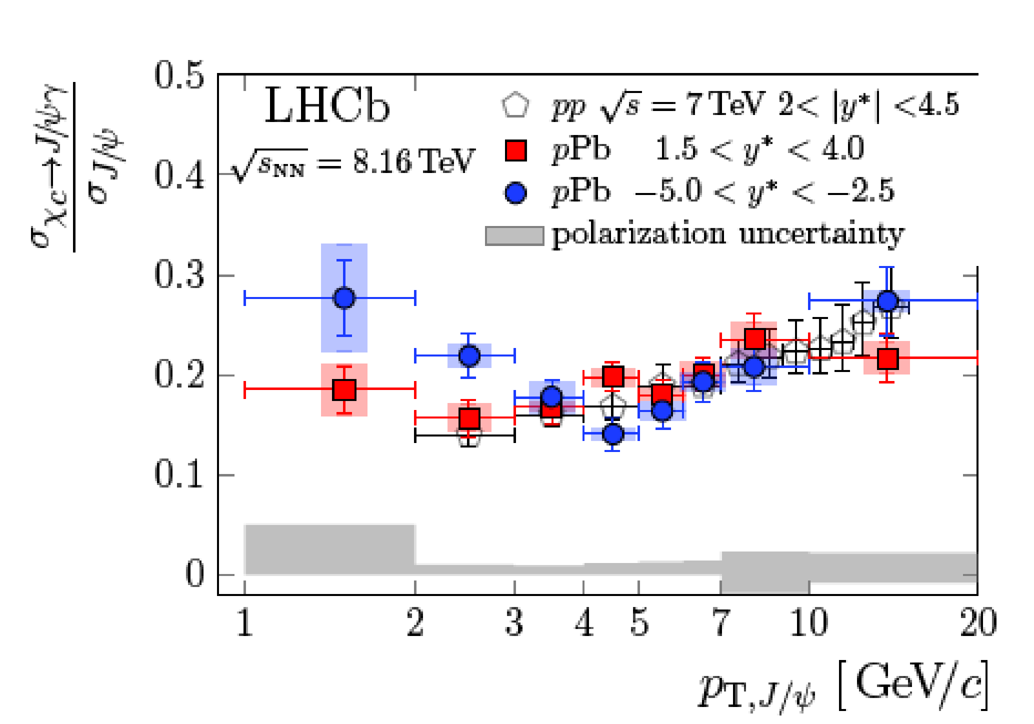
CNM effects at LHC: ψ(2S)

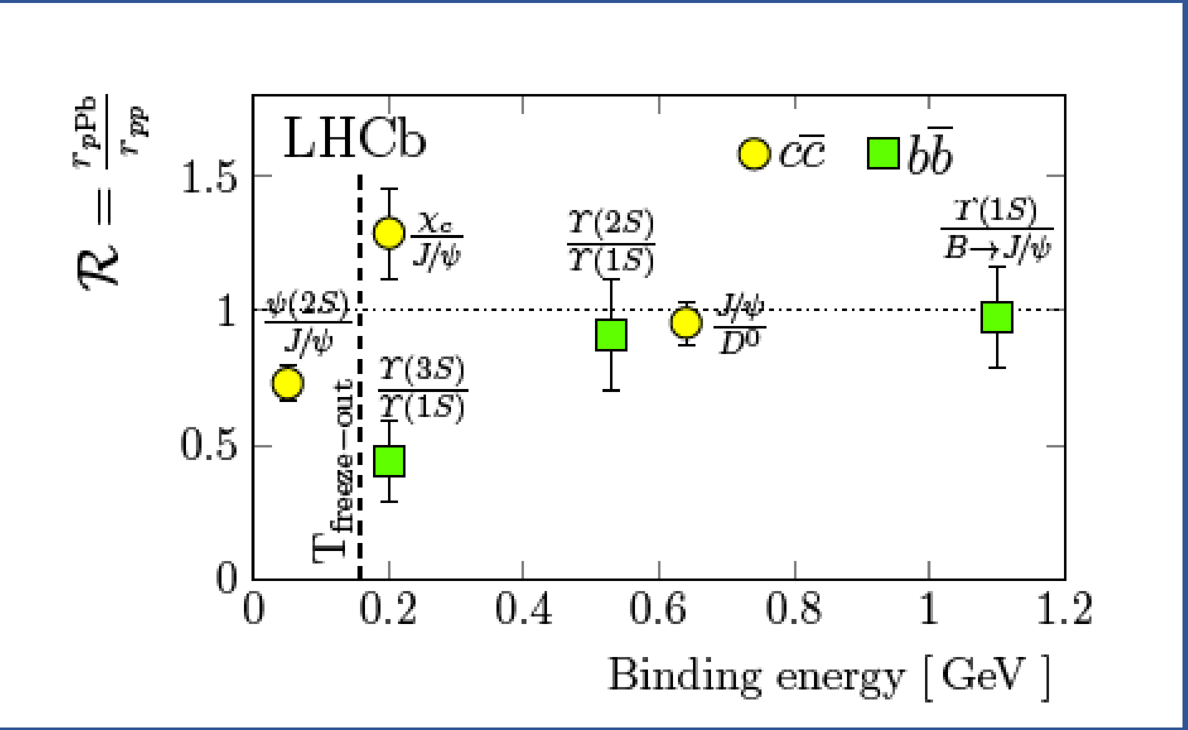
LHCb, JHEP 04 (2024) 111



- **Initial state effects** (shadowing) **cancel out** in the ratio
- Observed extra-suppression for ψ(2S) related to **final state effects** (dense medium ?)
- Was **first observed at RHIC** by PHENIX
- Different origin wrt fixed-target effects, mainly related to dissociation in cold nuclear matter (which is negligible at LHC energies)

Enter the χ_c

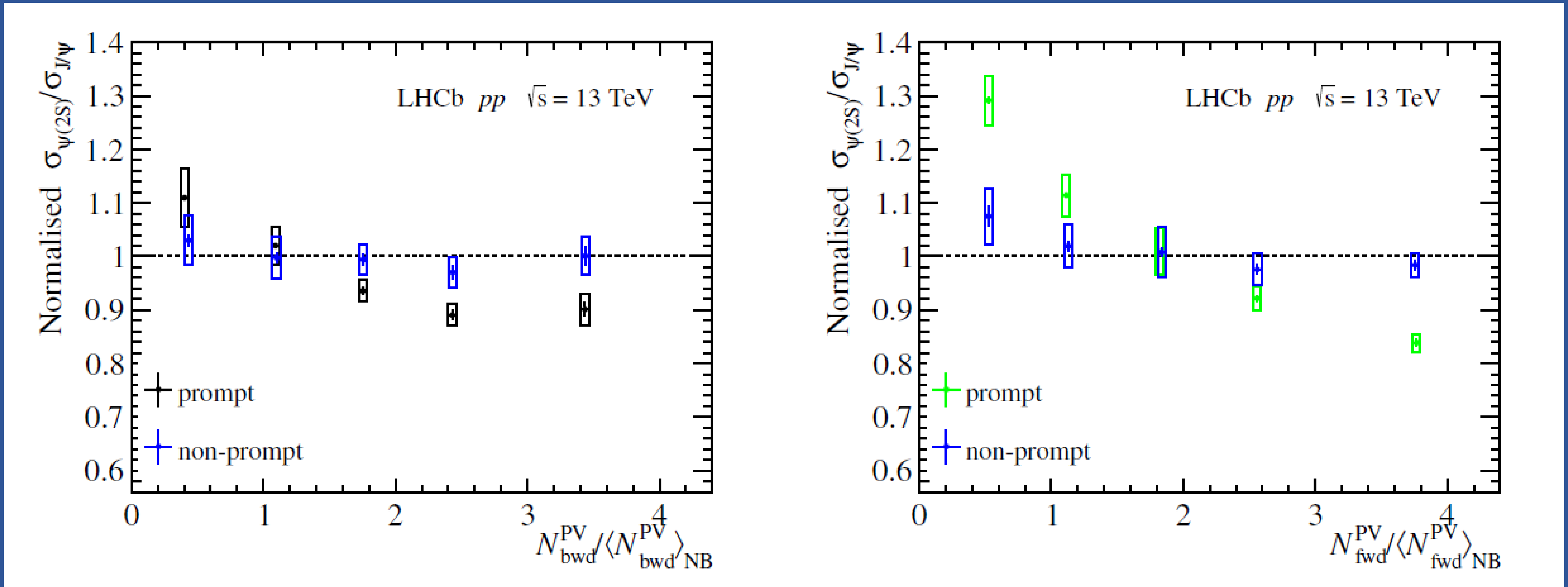




LHCb, Phys. Rev. Lett. 132 (2024) 102302

- **Ratio $\chi_c/J/\psi$ consistent between pp and p-Pb**
- Small excess at negative y due to suppression of **ψ(2S) feedback** contribution ?
- Double ratios p-Pb/pp show suppression only for ψ(2S) (and Υ(3S))

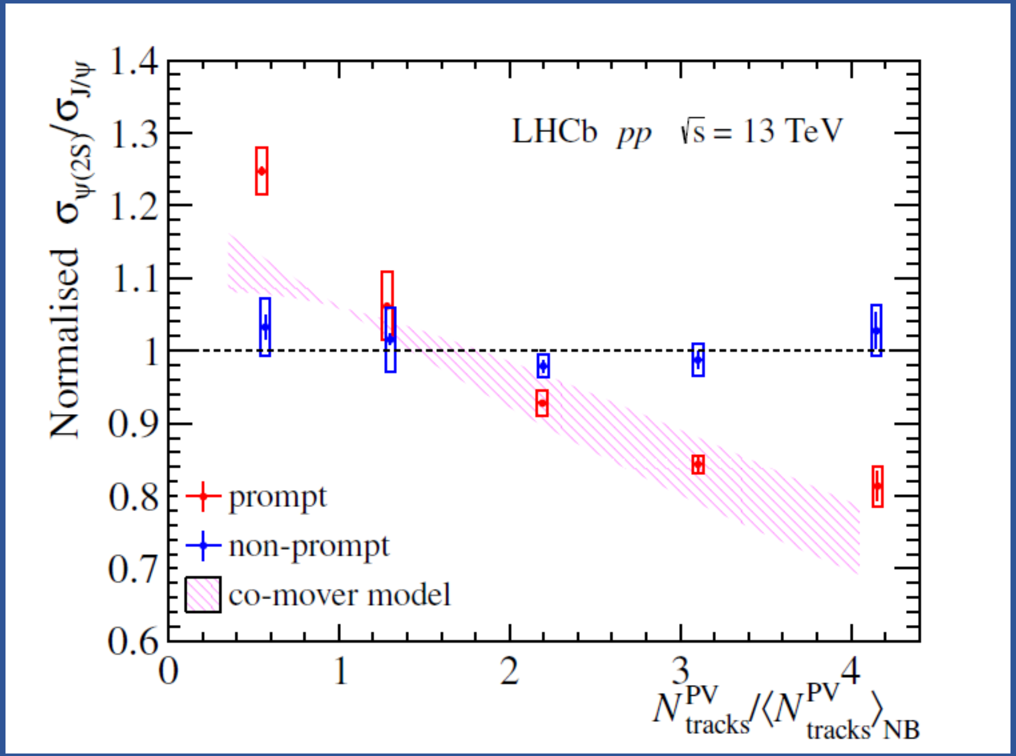
Multiplicity dependence of ψ(2S)/J/ψ



LHCb, JHEP05(2024)243

- **No multiplicity dependence** of ratios for charmonia from **b-decay**
- Visible effect for **prompt production, correlated with multiplicity** in the same y-region

Multiplicity dependence of ψ(2S)/J/ψ

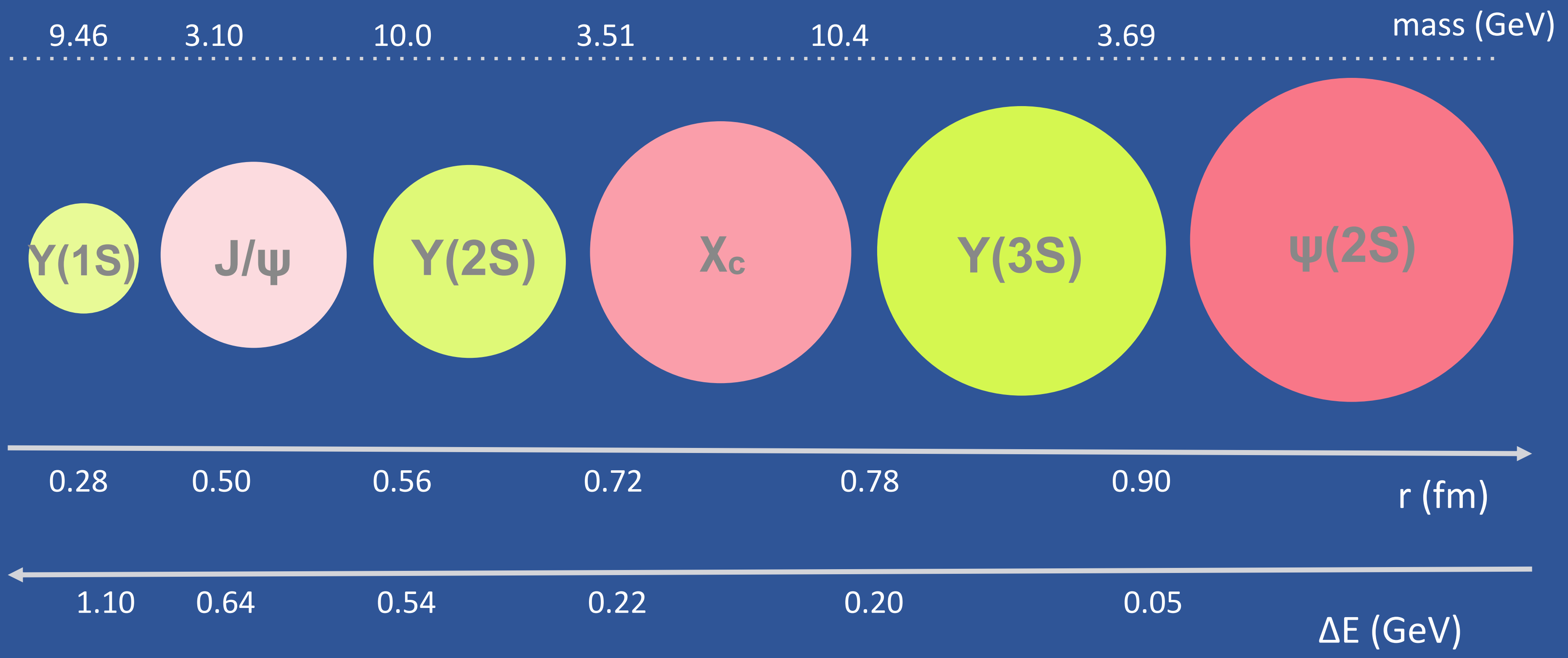


LHCb, JHEP05(2024)243

- **No multiplicity dependence** of ratios for charmonia from **b-decay**
- Visible effect for **prompt production, correlated with multiplicity** in the same y-region
- **Comover approach** well reproduces data, except at very low multiplicity

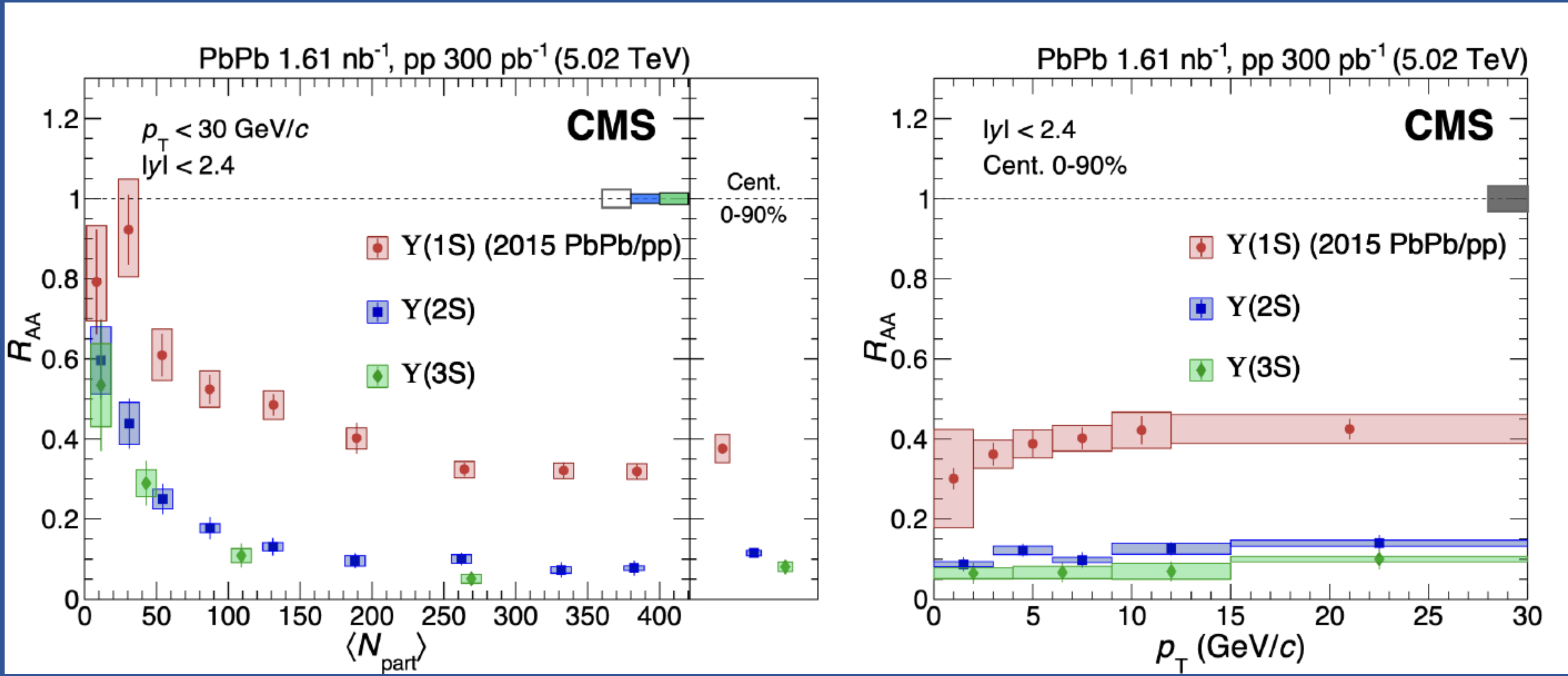
Bottomonium is the new charmonium

- At **collider energies bottomonia** play a similar role to **charmonia at fixed-target**



- Similar **size/binding energy** $\Upsilon(2S) \leftrightarrow J/\psi$, $\Upsilon(3S) \leftrightarrow \psi(2S)$
- (Re)generation effects negligible for bottomonia at LHC and charmonia at SPS

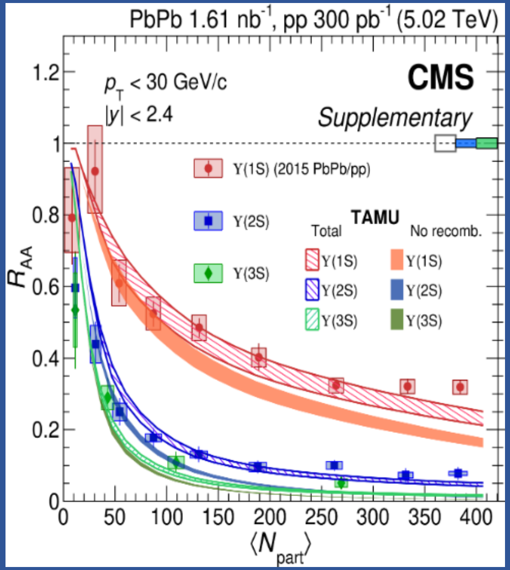
Sequential suppression again



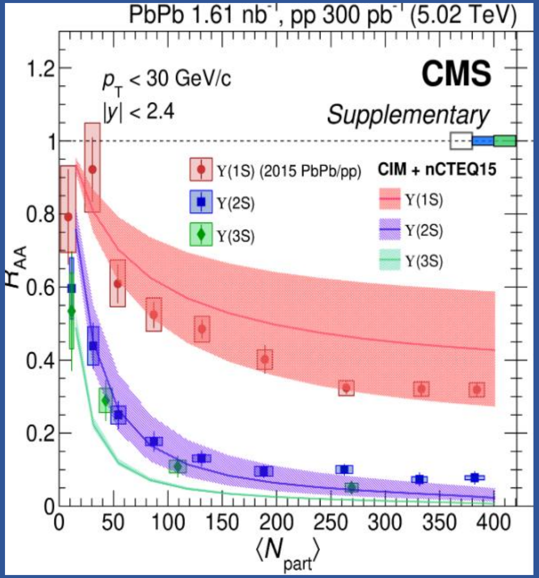
CMS, Phys. Rev. Lett. 133 (2024) 022302

- With the last results on Υ(3S), **the suppression hierarchy** is firmly established experimentally

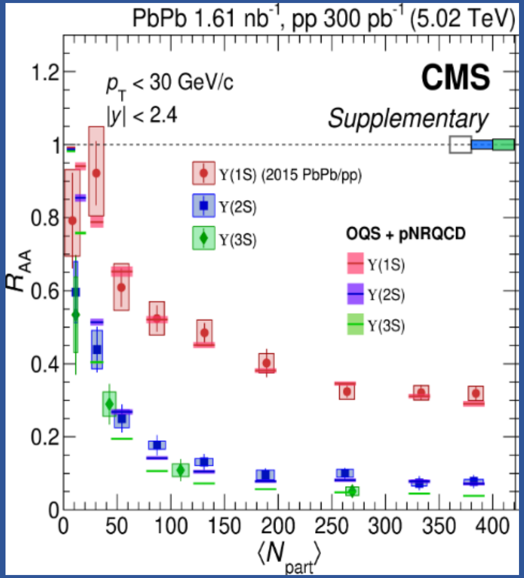
Theory calculations



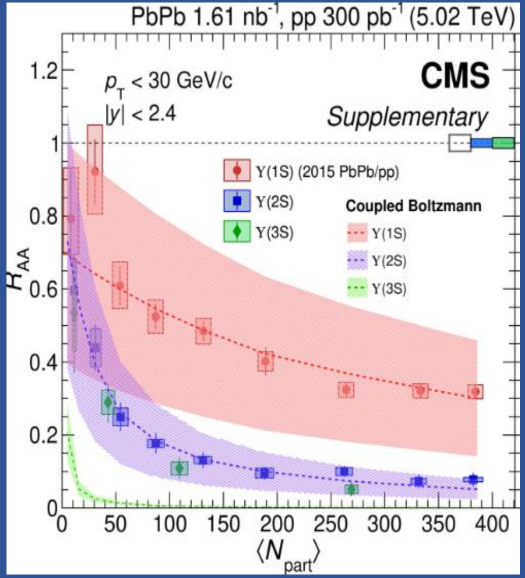
TAMU, PRC 96 (2017) 054901



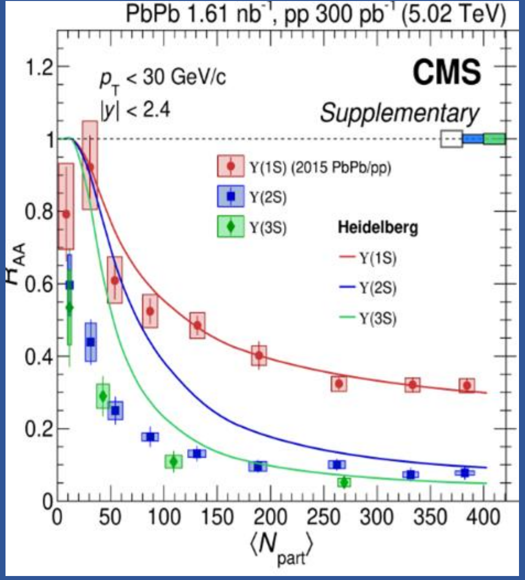
Comovers, JHEP 10 (2018) 094



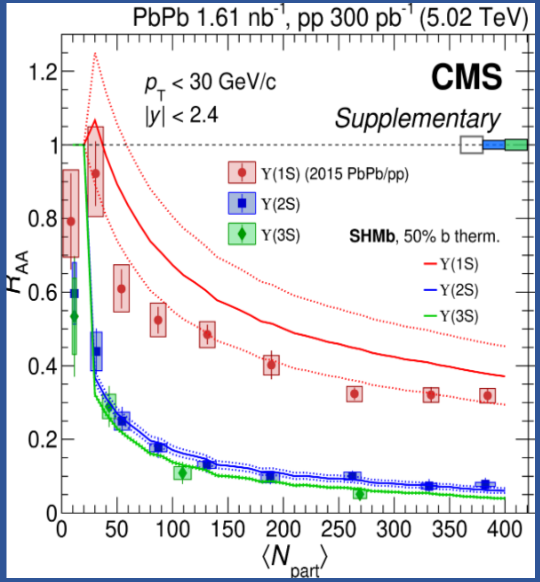
OQS+pNRQCD, PRD 108 (2023) 011502



Coupled Boltzmann,
JHEP01(2021)046



Heidelberg,
IJMPA 35, 2030016 (2020)



SHMb, arXiv:2209.14562v1

- Large variety of models

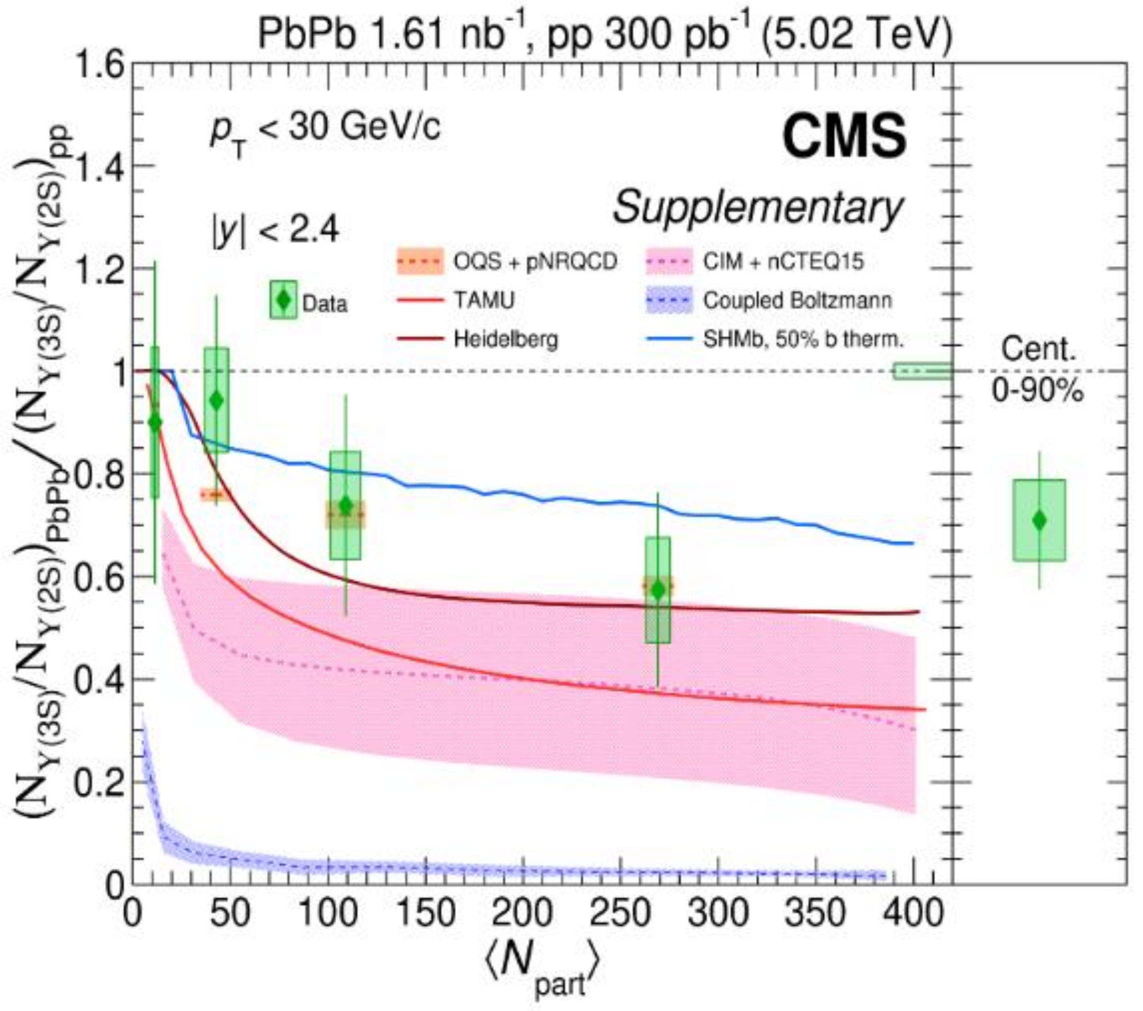
Several approaches can semi-quantitatively reproduce the experimental observations (also the p_T dependence)!

- Look more in details into the excited states

May (again) excited states make a difference ?

$$\frac{[\Upsilon(3S)/\Upsilon(2S)]_{PbPb}}{[\Upsilon(3S)/\Upsilon(2S)]_{pp}}$$

- Stronger suppression for ϒ(3S) compared to ϒ(2S) for more central collisions
- Significant differences among models → these data can put constraints on models, in spite of large uncertainties



CMS, Phys. Rev. Lett. 133 (2024) 022302

What can we expect going back to low energy ?

- Basically, **no data available below top SPS energy**
- Level of suppression observed in central Pb-Pb compatible with **(full) feed-down suppression**
- Can a **threshold** for hot matter effects be observed when lowering collision energy, possibly separately for χ_c and ψ(2S) feed-down ?
- Can such thresholds **be correlated with precise temperature measurements** obtained with an independent observable ?
- Are **there specific μ_B-related effects**, with a quark excess influencing the dissociation process ?
- Can **comover vs QGP** effects be separated when studying the $\sqrt{s}$-dependence of the suppression ?
- Can we understand the mechanisms at play for **dissociation in CNM** ?

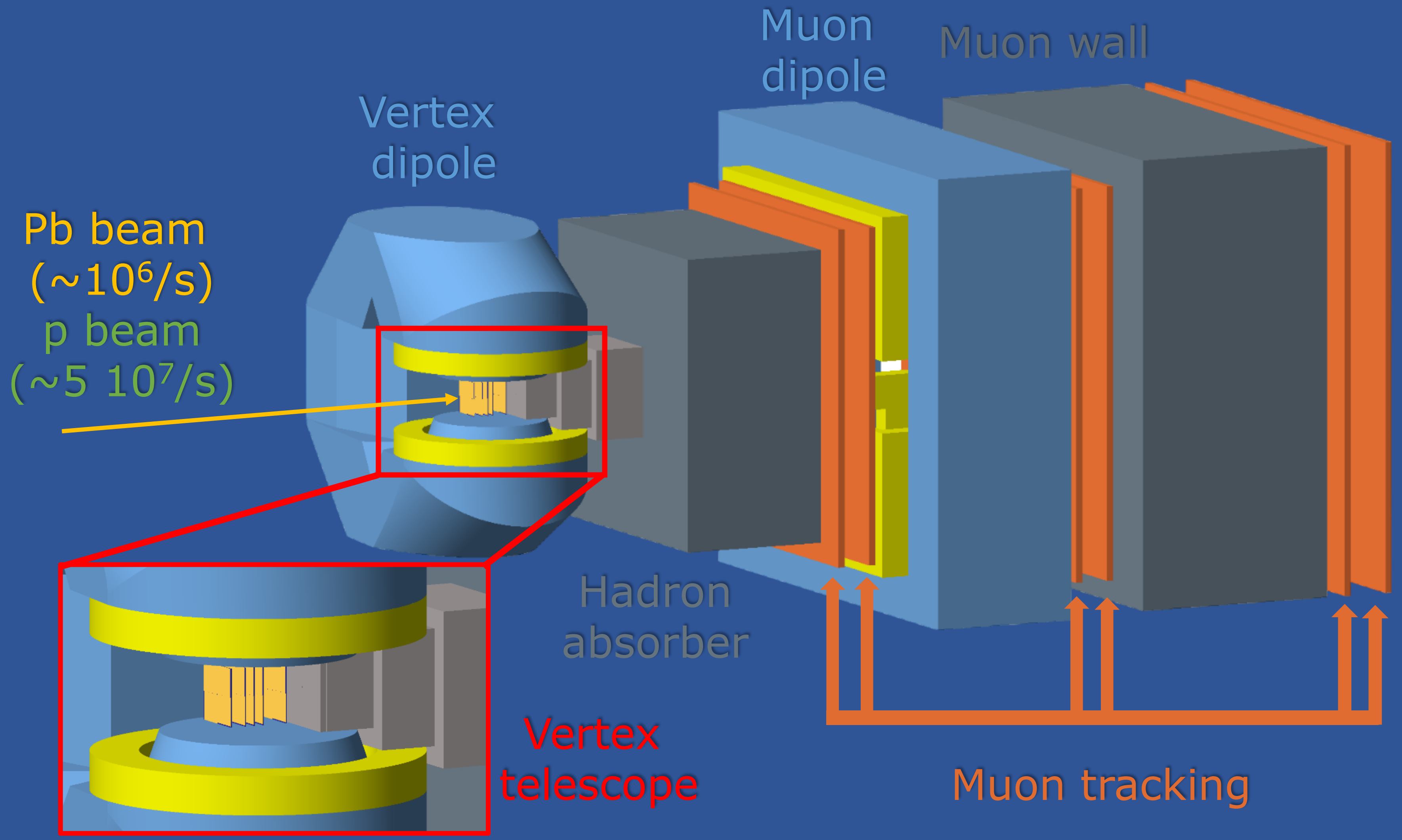
Next slides: looking for charmonia with NA60+/DiCE and CBM

The set-up

Inspired by the **former NA60** detector (2002-2004)

Measurement of **(di)muon** production and hadronic decays of **strange** and **charm** hadrons

SPS **energy scan**: vary z-position of the muon spectrometer and thickness of hadron absorber

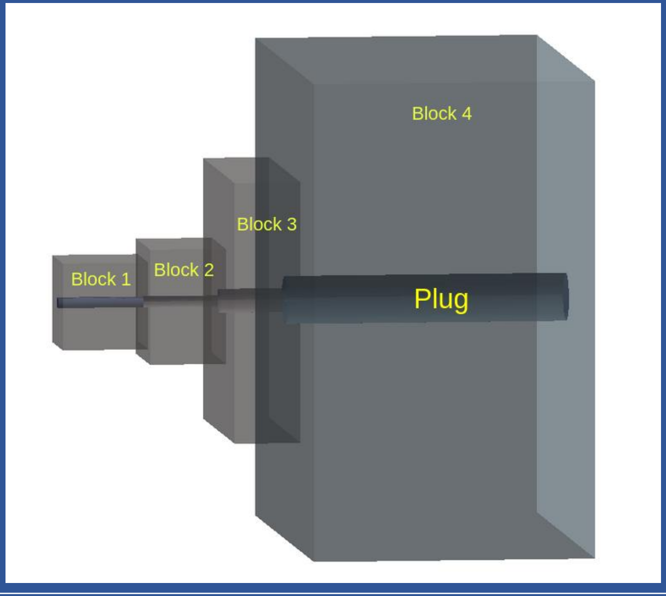


Significant **evolution of the original design** from its inception (EoI, 2019) and from the finalization of the LoI (2023)

High-energy vs low-energy set-up

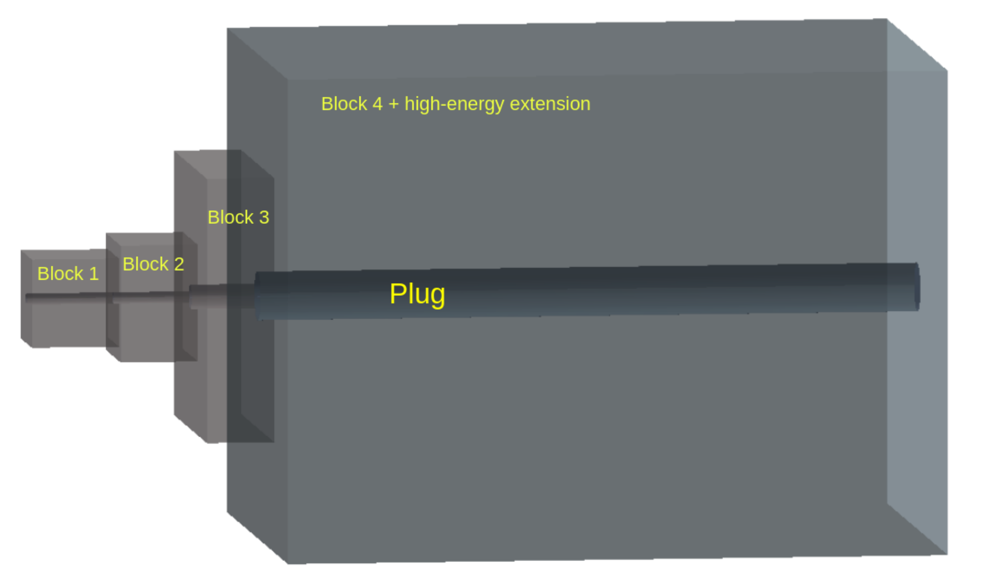
- Differ by **absorber thickness** → should be varied to cope with the increasing charged multiplicity
- FLUKA simulations have shown an **almost linear increase of the residual rate** with collision energy in the muon spectrometer, due to the hadronic showers from
  - Hadrons produced at the target
  - Debris from the dump of the uninteracting Pb beam (or spectator fragents)in the central W plug (interaction probability is ~15%)

- Moving the whole spectrometer downstream also keeps the acceptance coverage approx. constant all along the collision energy range (6<√s<17 GeV)

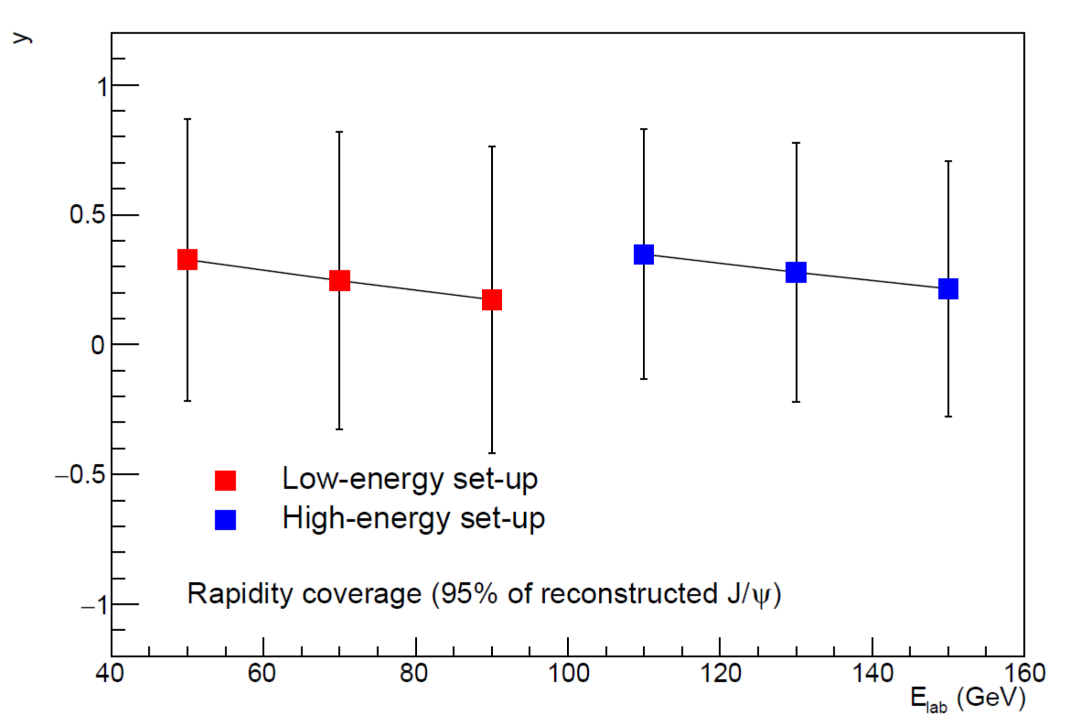


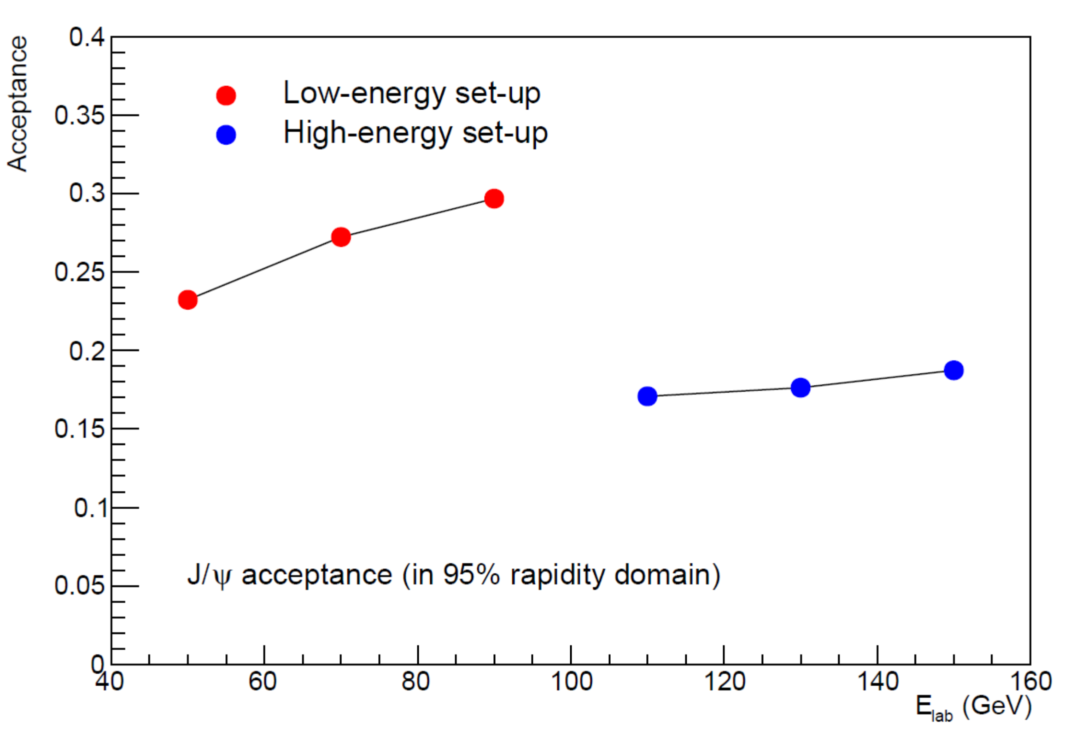
Exact material composition still under study (BeO, Al_2O_3, C)

Both performance and economic aspects to be considered



J/ψ rapidity coverage and acceptance



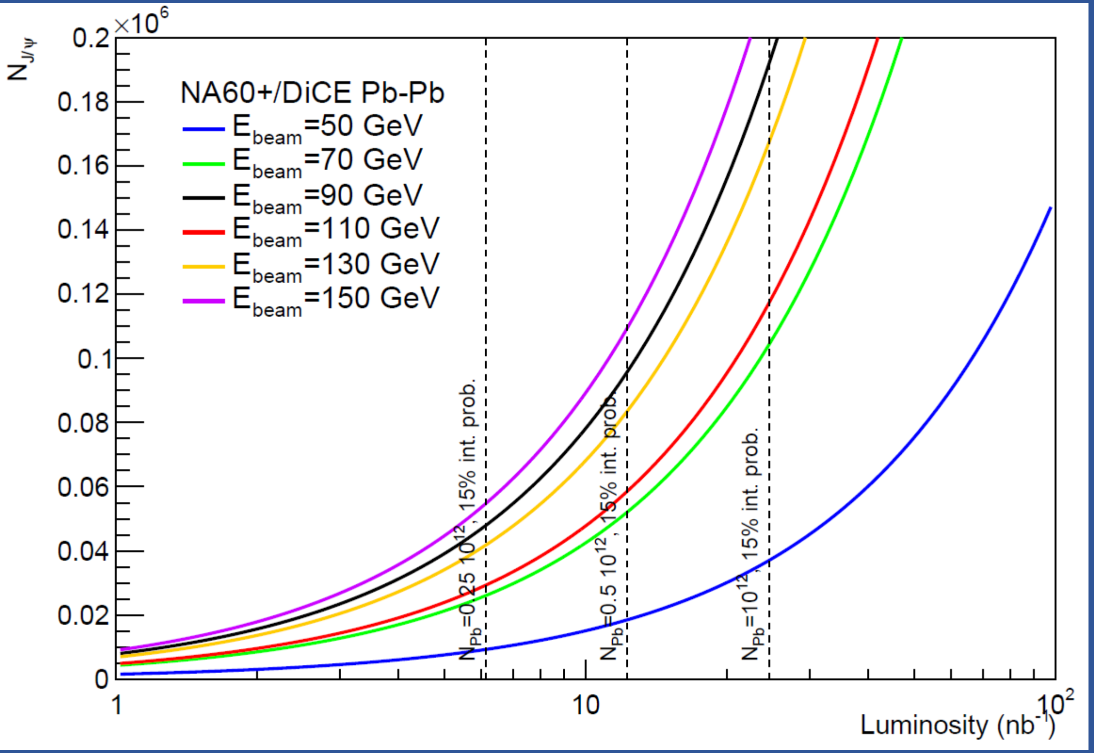


- ❑ Coverage reaches **midrapidity** and is about **1-unit wide**, similar at low and high-energy
- ❑ Acceptance decreases significantly for the high-energy set-up, due to the overall smaller solid angle
- ❑ Still, some room for adjustments in the position of the tracking stations and absorber thickness

Evaluation of expected yields

- **Difficult to have precise estimates** due to
  - Scarce knowledge of the elementary production cross section
  - Unknown CNM and hot matter effects

- The estimates are based on
  1) Empirical parameterization of J/ψ production in pp (from R. Vogt, Phys. Rep. 310 (1999) 197-260)
  2) Assumption of a break-up cross section in CNM $\sigma^{J/\psi\ N}$ =7.6 mb, as measured by NA60 in pA at √s=17 GeV → may be optimistic
  3) Extra 20% suppression due to hot matter effects



- Detailed beam studies have shown that it is realistic to **expect at each energy 0.6 10^{12} Pb on the 15% interaction probability target**

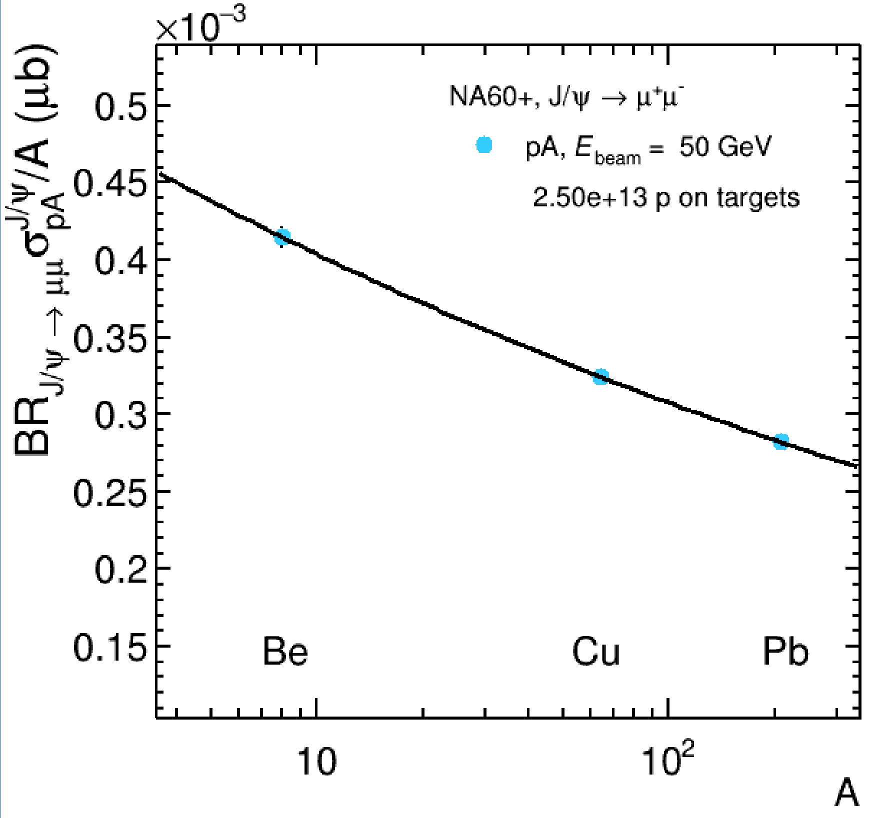
→ leads to an expected statistics **between 10^3 and 10^4 J/ψ** depending on collision energy

Toward performance plots

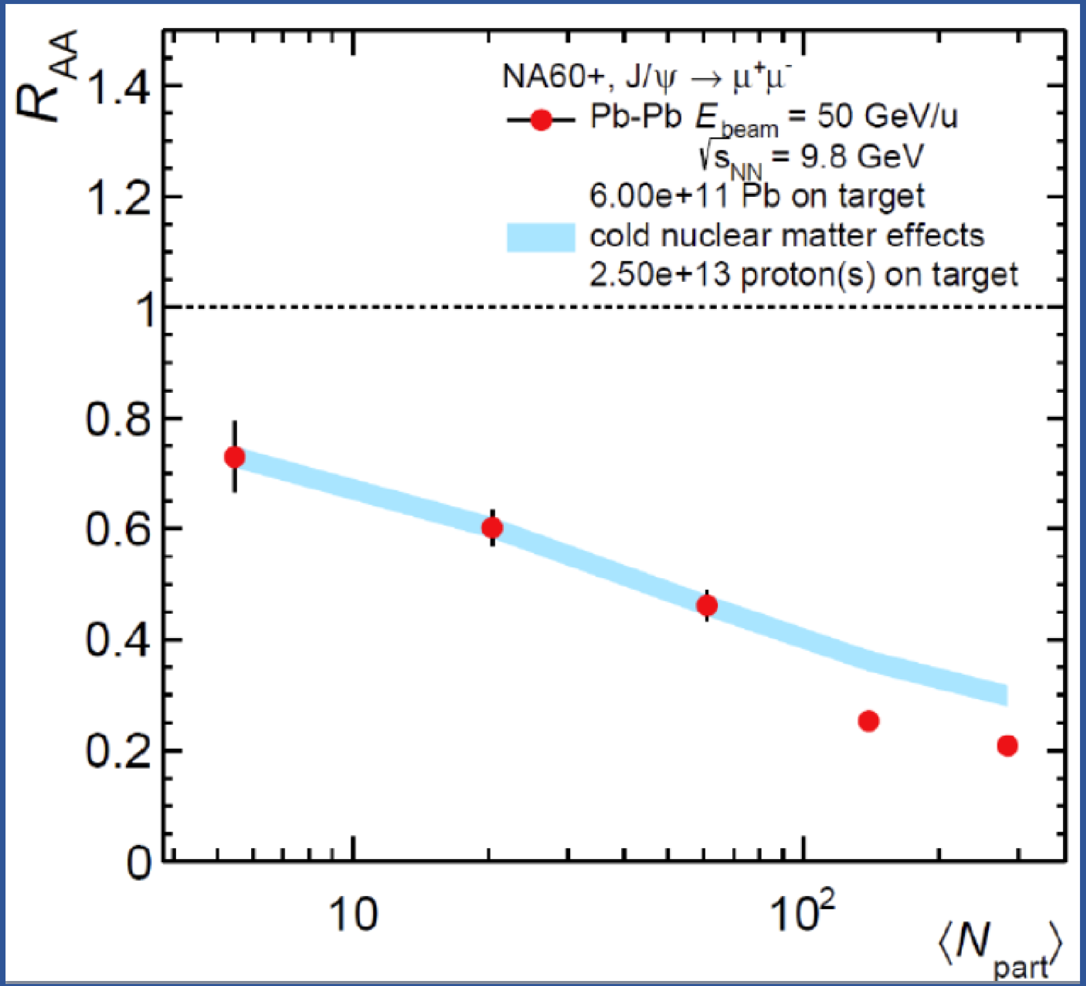
- A **calibration of CNM effects** via pA collisions is mandatory
- Detailed beam studies show that the **required integrated luminosity per N-N collision**, equivalent to the one for Pb-Pb, can be reached by extracting a primary low-energy p beam from the SPS. Non-negligible technical issues currently under study
- An optimized target set-up includes a **12 mm (Be) + 3 mm (Cu) + 3 mm (Pb)** target

- p-A data allow
  - Extrapolation to pp for **R_{AA} calculation**
  - Estimate of $\sigma^{J/\psi\ N}$ at each energy (CNM)

- Assume a S/B at the J/ψ peak identical to the one measured by NA60 at $\sqrt{s_{NN}}$=17 GeV
- Should not depend too much on $\sqrt{s_{NN}}$, dominated by Drell-Yan production
- **Only statistical errors quoted**
  - Should not impact significantly $\sigma^{J/\psi\ N}$, which is given by the slope of the A-dependence
  - May impact the pp extrapolation

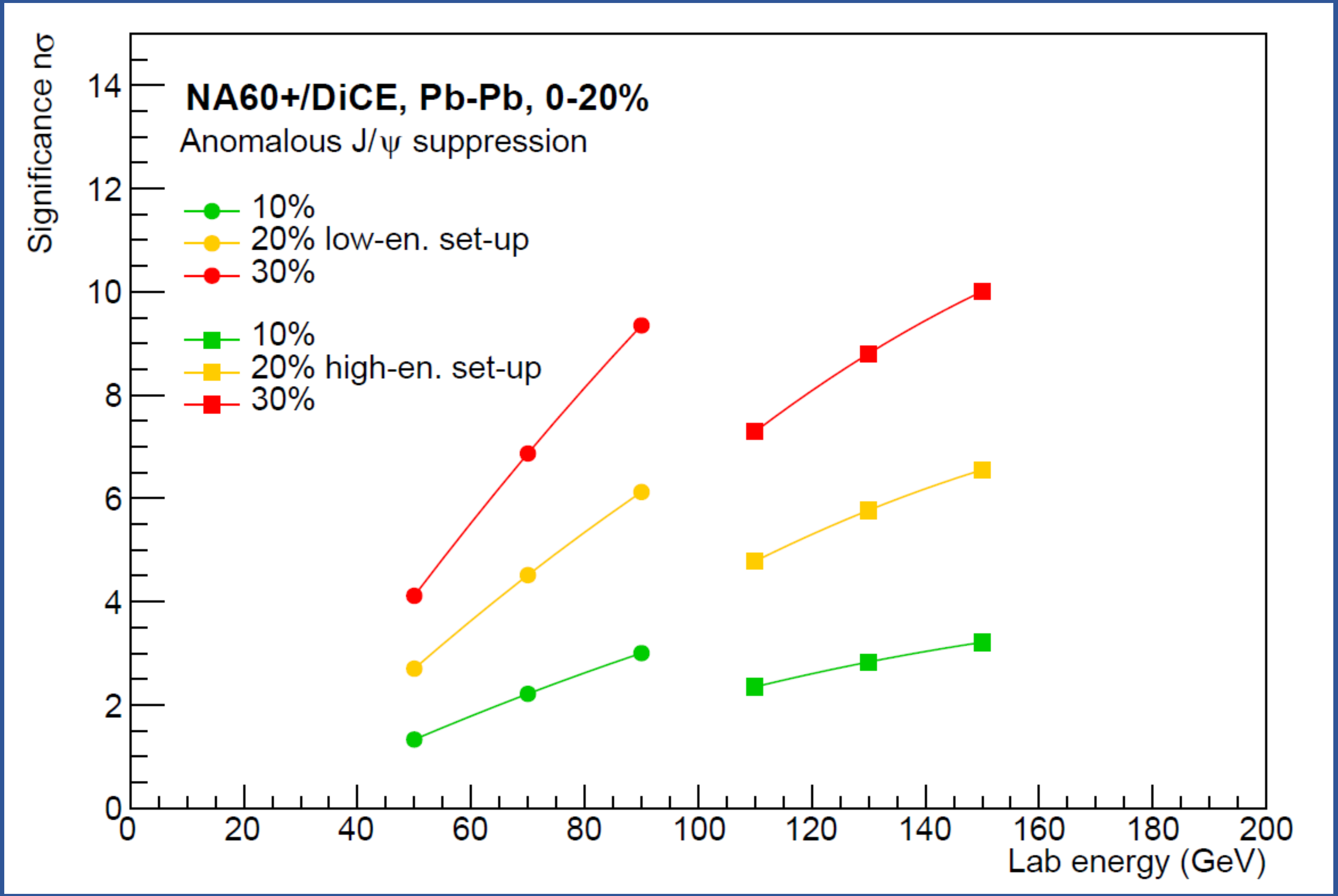


Estimating R_{AA}



- At each collision energy, consider the y-region covering 95% of the acceptance
  - → **slight rapidity shift** when changing energy, but overall small effect
  - → <0.3 y-units from 50 to 150 GeV, using two spectrometer set-ups
- Assume as a test a **20% suppression** beyond CNM effects for central and semi-central collisions
- Only statistical uncertainties included

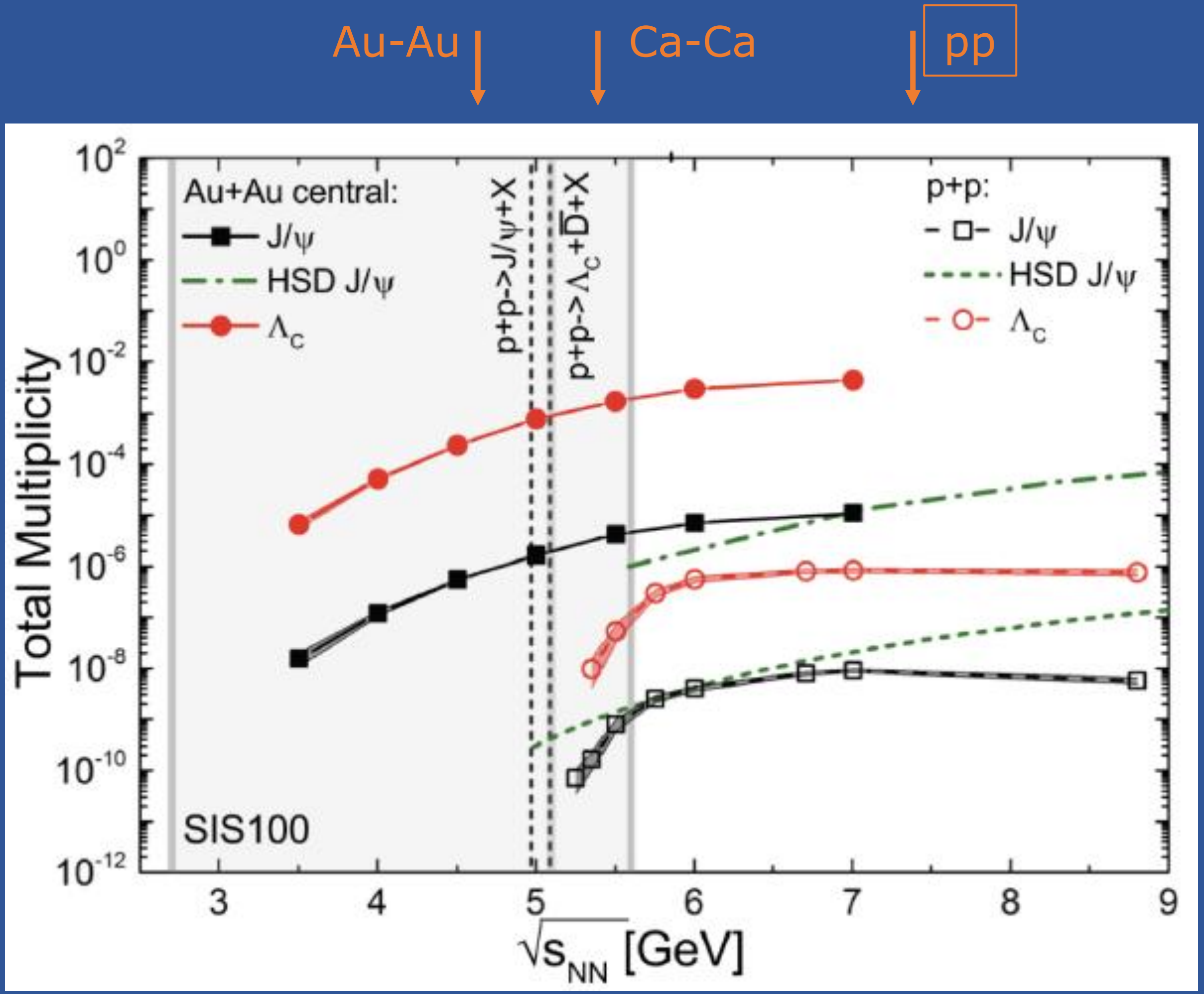
Significance of anomalous suppression signal



- ❑ Assume **suppression level** beyond CNM effects in the range **10-30%**
- ❑ Estimate the significance for the observation of such an effect
- ❑ A **20% effect** can be observed with a **>3σ** significance at all energies
- ❑ Detecting a smaller effect would require a larger integrated luminosity (>1 data period at a given energy)

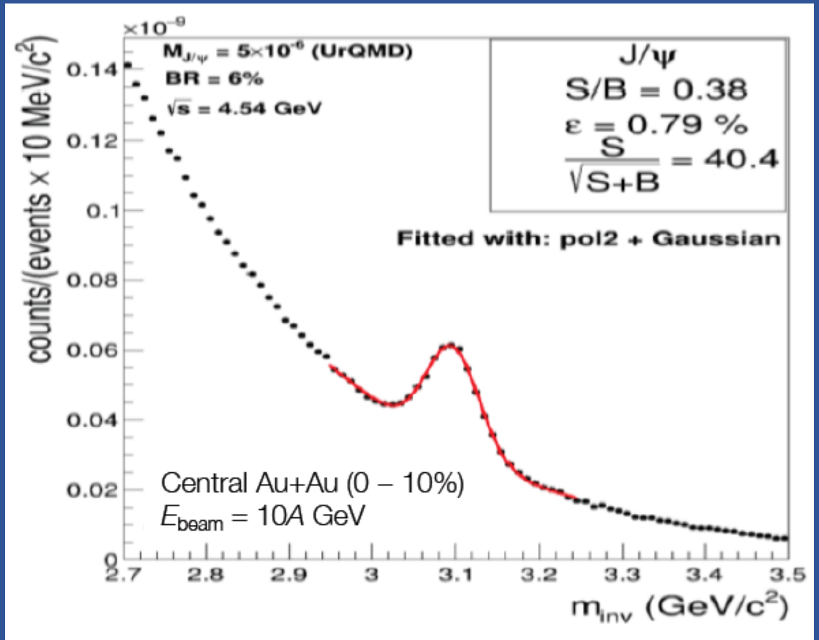
Quarkonium at CBM: threshold production

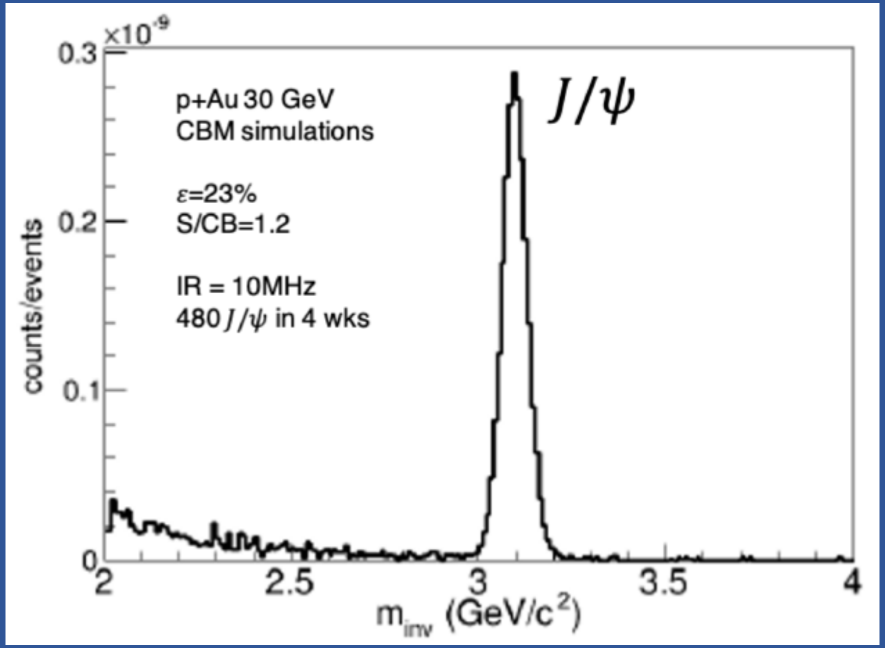
- **Sub-threshold production** (rare but feasible) via multiple collision processes
- Production threshold might be exceeded with SIS100 beam of N=Z nuclei
- Both $\mu^+\mu^-$ and e^+e^- decay channels accessible
- Needs **very large interaction rates** → 10 MHz (>50 times NA60+)
- Beam intensities → 10^9/s A, 10^{11}/s p

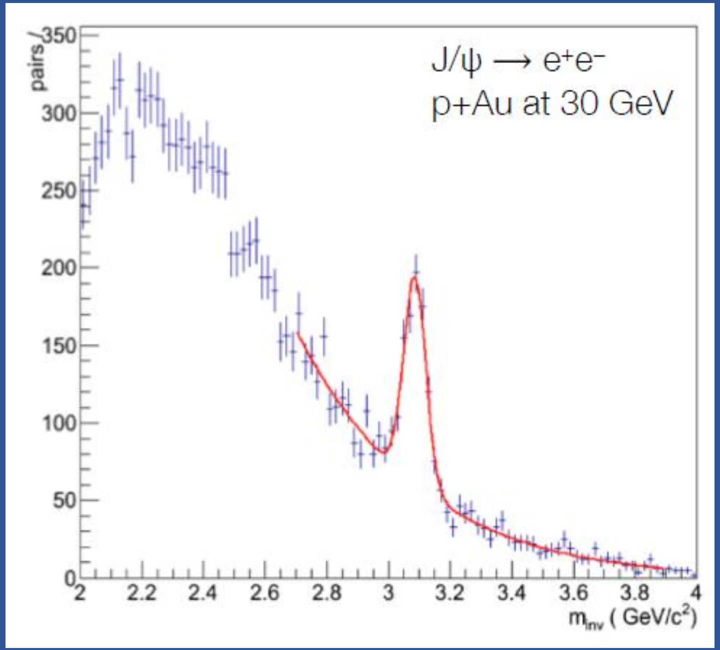


J. Steinheimer et al, Phys. Rev, C95 (2017) 014911

Quarkonium at CBM: physics performance







J/ψ→μμ
AuAu ~30k J/ψ in 4 weeks at 10 MHz interaction rate
pAu ~500 J/ψ in 4 weeks at 10 MHz interaction rate

J/ψ→ee
pAu ~450 J/ψ in 4 weeks
at 10 MHz int. rate

pA → lower statistics, but very clean signal

Conclusions & prospects

- In spite of (thanks to) its long history, quarkonia continue being a very sensitive probe of the medium, from fixed-target to collider energy
- While at collider energies (and at top SPS energy) high-precision data have become available, there is a considerable lack of (i.e. no) information below $\sqrt{s}$=17 GeV
- The main issues for an investigation at low energy are represented by the strongly decreasing cross sections
  → Forthcoming experiments as CBM and NA60+/DiCE, with their 10MHz/0.15MHz foreseen interaction rates are well placed for these studies
- Solid theory predictions are needed now, to provide experiments with a frame for scheduling the more appropriate measurements (collision energy, kinematics, collision systems,…)