Quarkonia:
Experimental Summary

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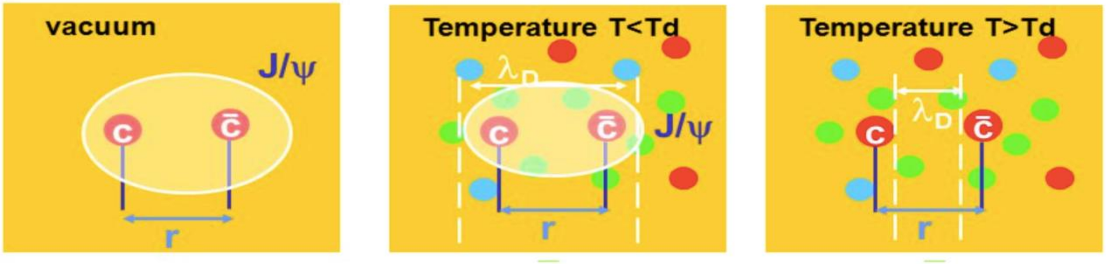
Hard Probes 2018 – Friday, October 5 2018

Motivation

Heavy quarks are created early in the collision,
Quarkonia experience the full evolution of the system

A simple idea: color screening in a QGP of deconfined quark and gluons
→ suppression with respect to vacuum (pp) production

Matsui, Satz, PLB 178 (1986) 416



$$r_{Q\bar{Q}} \propto 1/E_{binding}$$

$$\lambda_D \propto 1/T$$

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But there is more to it:

- In-medium QQbar potential might include an imaginary part corresponding to a damping term
- At low p_T there is a contribution from the recombination of (possibly) thermalized heavy quarks
- Cold nuclear matter effects (shadowing, gluon saturation, energy loss and nuclear breakup) also affect quarkonium production without the presence of a QGP
- As for the pp reference, production mechanism is still debated
- Contribution from excited states must be accounted for
- For charmonium there is also a non-prompt contribution from b-hadrons decay (not discussed in this presentation)

Much richer field than anticipated ~30 years ago

Outline

pp collisions

- differential cross sections, production mechanism
- event activity dependence

Light systems (pA) collisions

- cold nuclear matter effects
- nuclear modification factor, elliptic flow, particle ratios

Heavy ion (AA) collisions

- suppression and recombination
- azimuthal anisotropies

Quarkonium photo-production

- in ultra-peripheral collisions
- in peripheral collisions

proton-proton collisions

J/Ψ cross sections – production mechanism

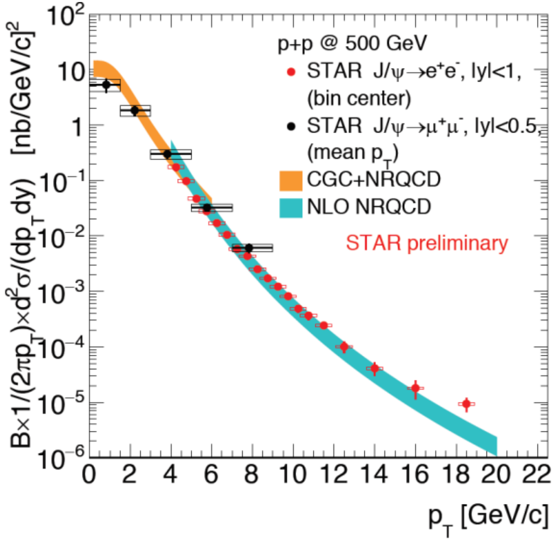
Wed. 9:00 Z. Liu
Wed. 9:20 M. Köhler
Tue. 4:25 S. Tapia

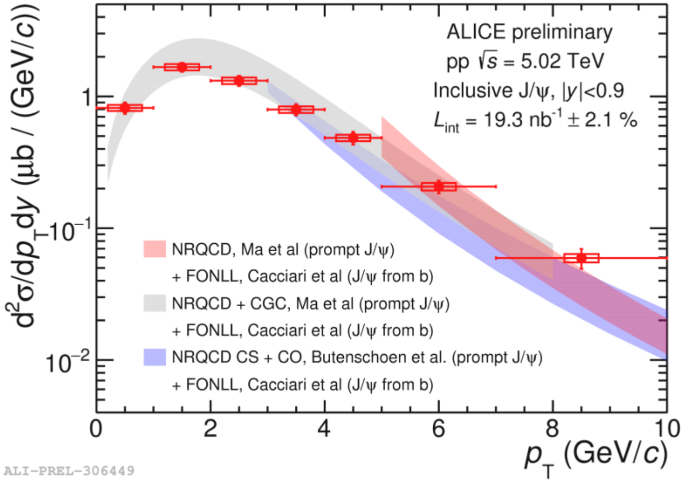
Models include CEM, iCEM, CSM and NRQCD (+CGC)

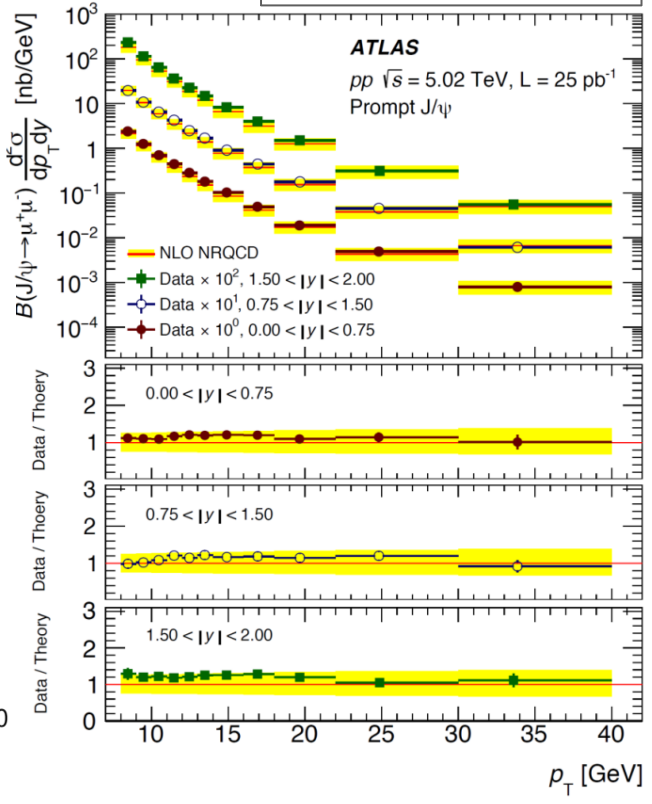
Here NRQCD compared to J/Ψ data at
$\sqrt{s}$ = 500GeV (STAR) and 5 TeV (ALICE, ATLAS)

Good description at both $\sqrt{s}$ down to p_T=0, by coupling to CGC

Issues remain with polarization, other resonances (η_c)





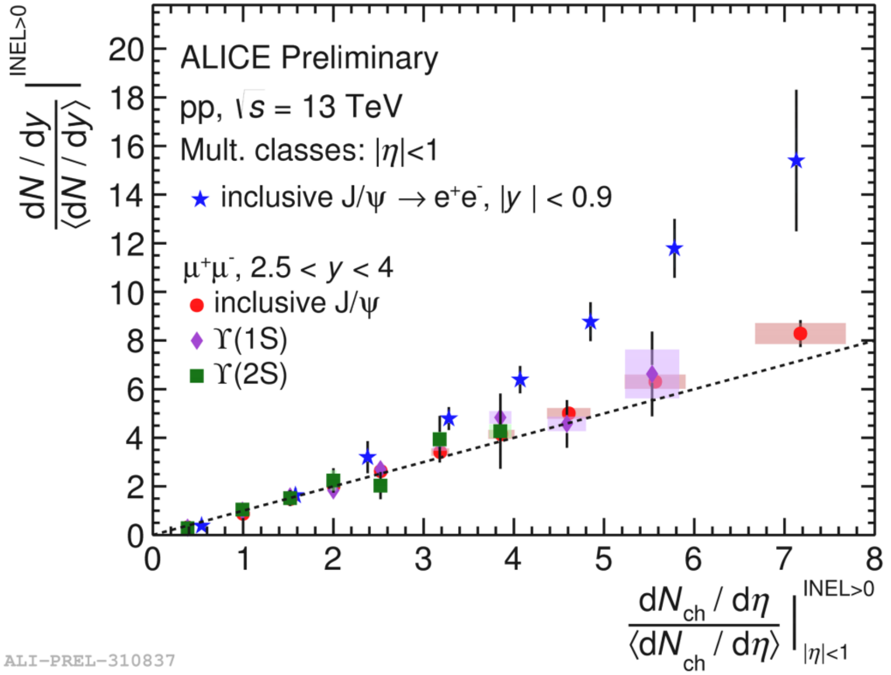


Quarkonium as a function of event activity

Tue. 16:45 D. Takur

Study the role of MPI in quarkonium production

Here event activity measured by number of charged particles at mid rapidity |η|<1



<u>At forward rapidity</u>

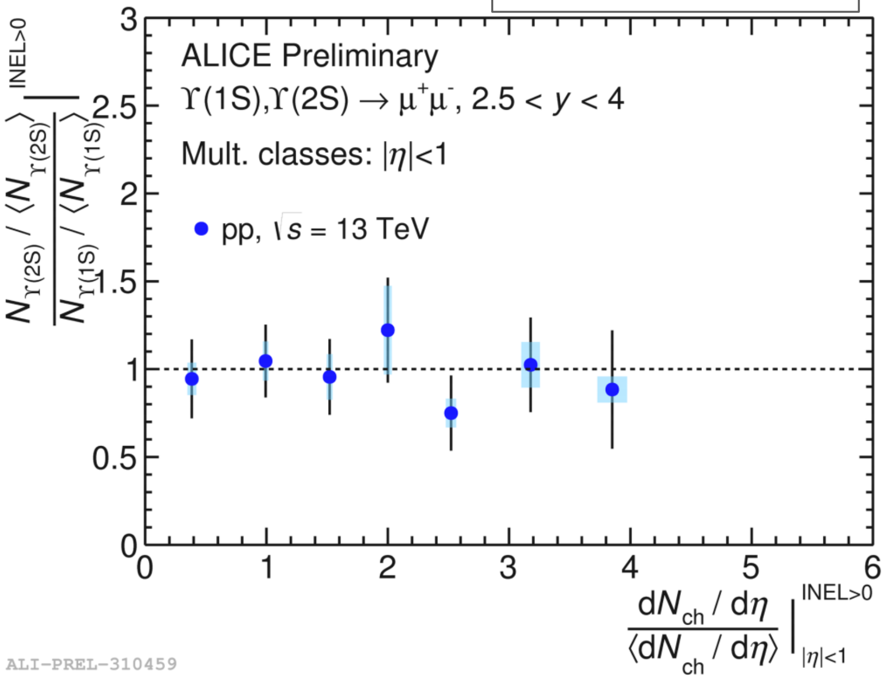
- ~linear increase and no dependence on quarkonium type (J/Ψ, Y(1S) and Y(2S))
- no dependence on √s either (5 TeV result not shown here)

<u>At mid rapidity</u>, faster than linear increase

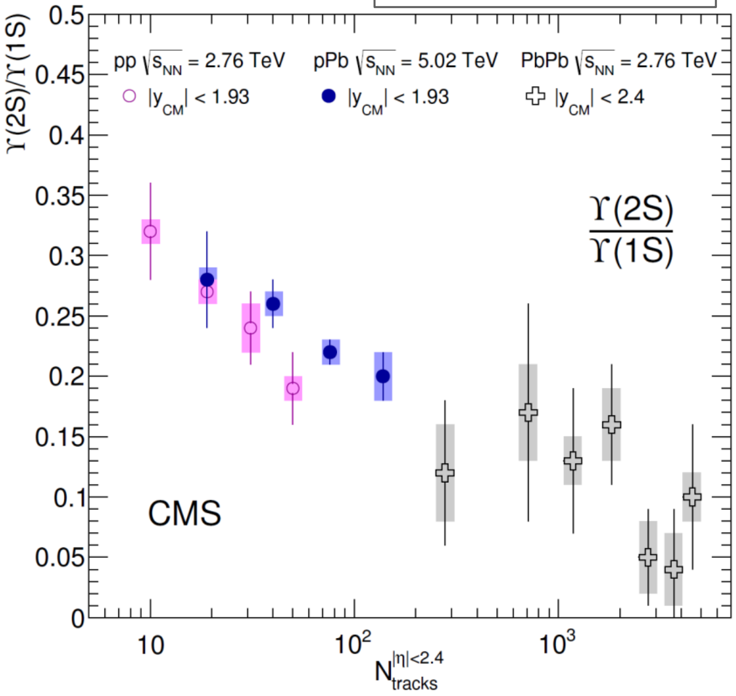
Strong rapidity dependence possibly due to auto-correlations (jets?) when there is no η gap between event activity estimator and the quarkonium

Event activity dependence - particle ratios

Tue. 16:45 D. Takur



Mon. 9:55 Y-J Lee



No event activity dependence on the Y(2S)/Y(1S) ratio, in strong contrast with CMS measurement

Event activity dependence - particle ratios

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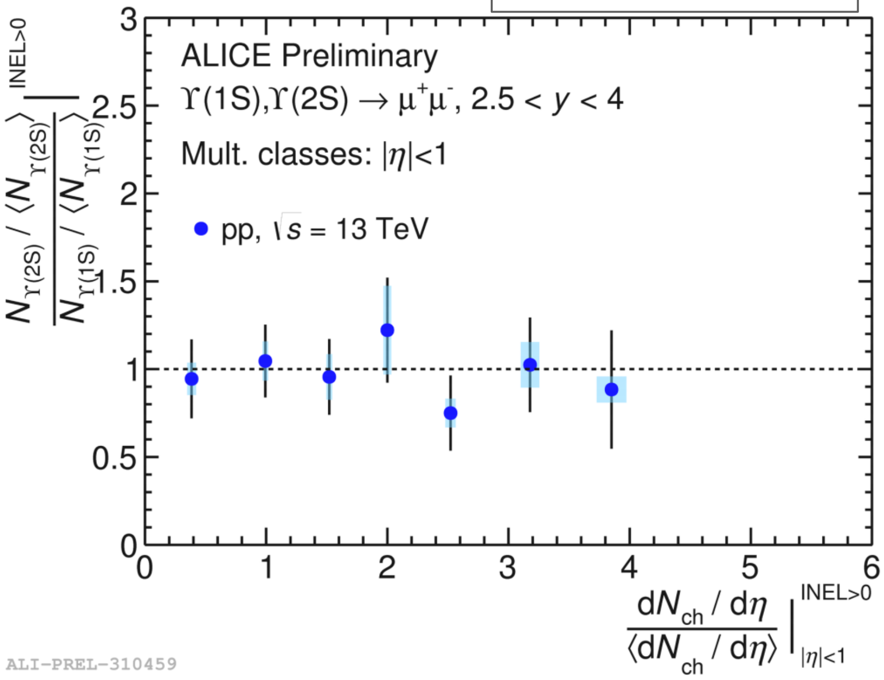

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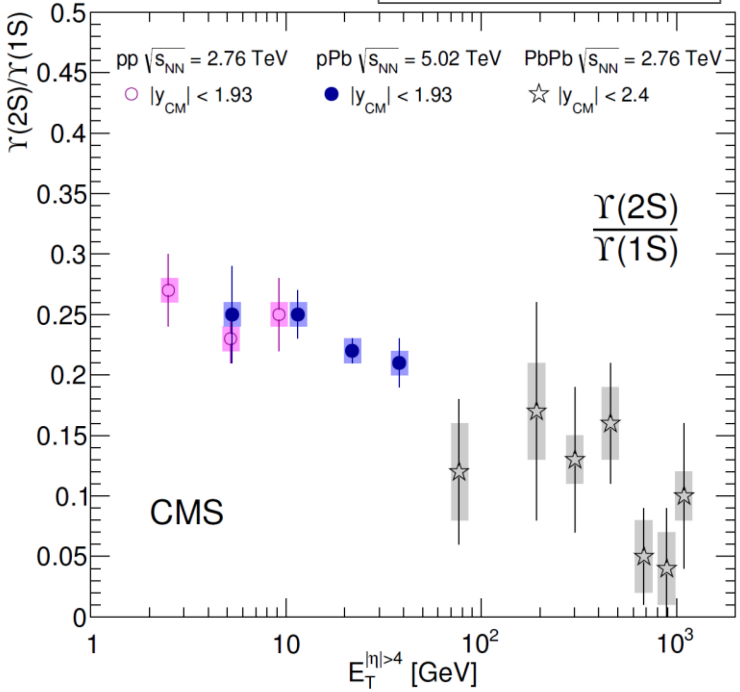


No event activity dependence on the Y(2S)/Y(1S) ratio, in strong contrast with CMS measurement

For CMS, the dependence disappears (in pp) when adding a rapidity gap ← auto correlation

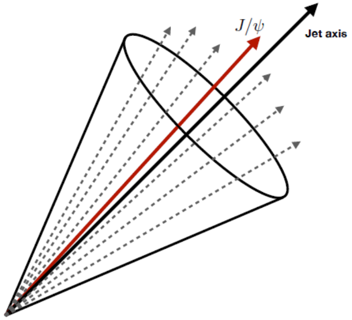
J/Ψ in jets

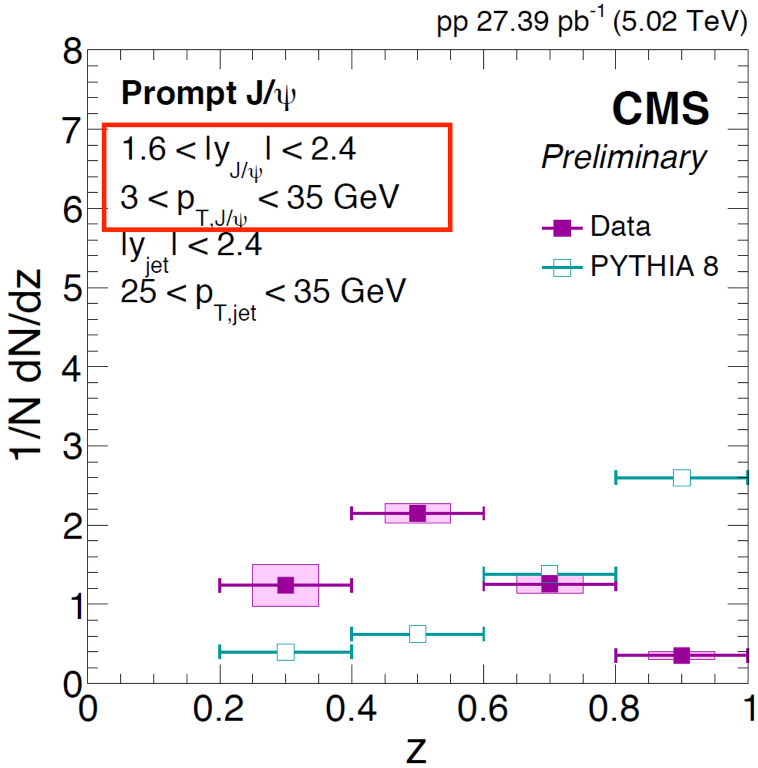
Wed. 10:45 B. Diab

Study particles emitted in a cone centered on the J/Ψ

Define fragmentation function *vs*

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





Results are compared to PYTHIA

J/Ψ are less isolated in data than PYTHIA

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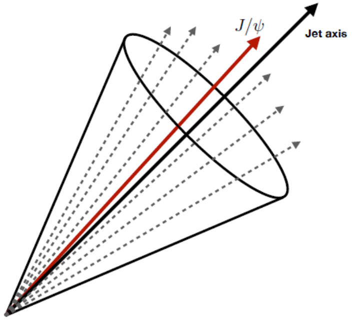
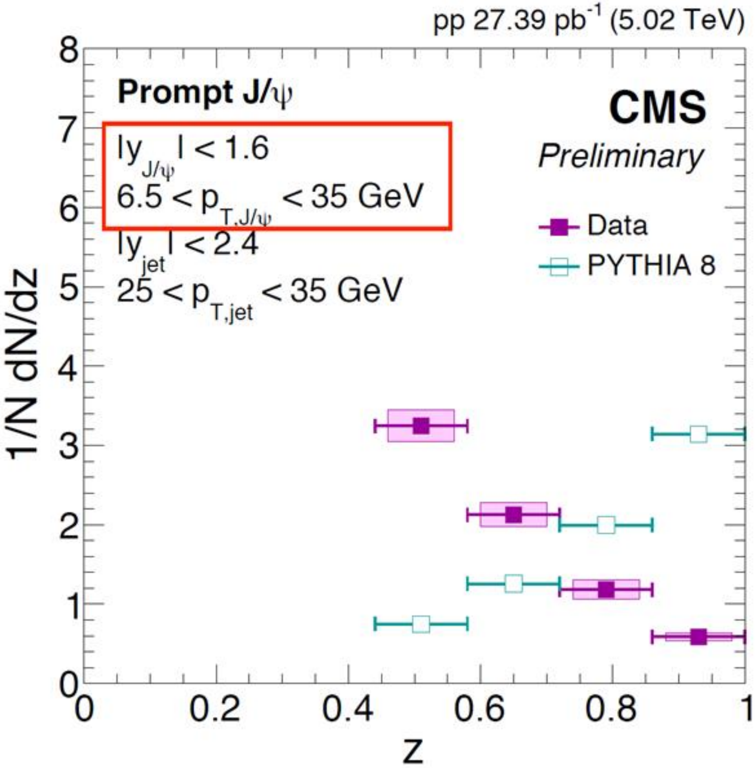




Results are compared to PYTHIA

J/Ψ are less isolated in data than PYTHIA

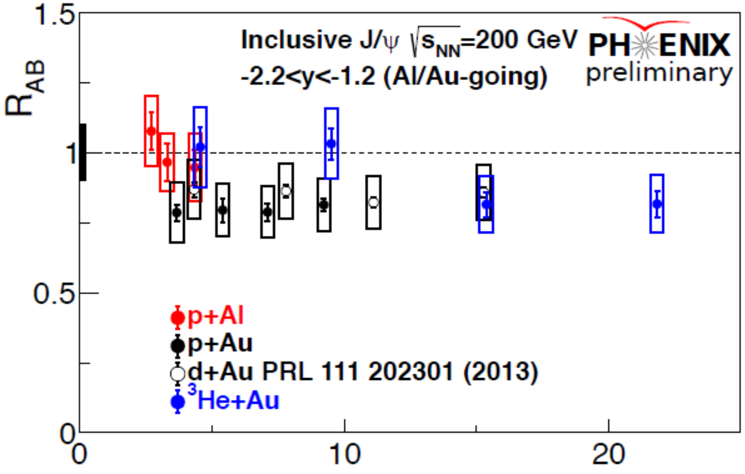
Remains true for high p_T J/Ψs

Light systems (proton-nucleus) collisions

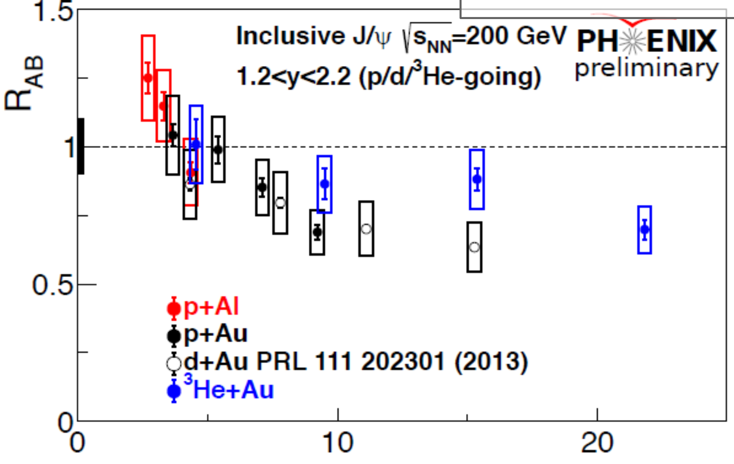
Light systems at RHIC

CNM effects (shadowing, gluon saturation, energy loss, ...) studied by measuring the nuclear modification factor R_{AB} in light systems

Thu. 12:05 M. Durham



Au,Al going



p, d, ^{3}He going

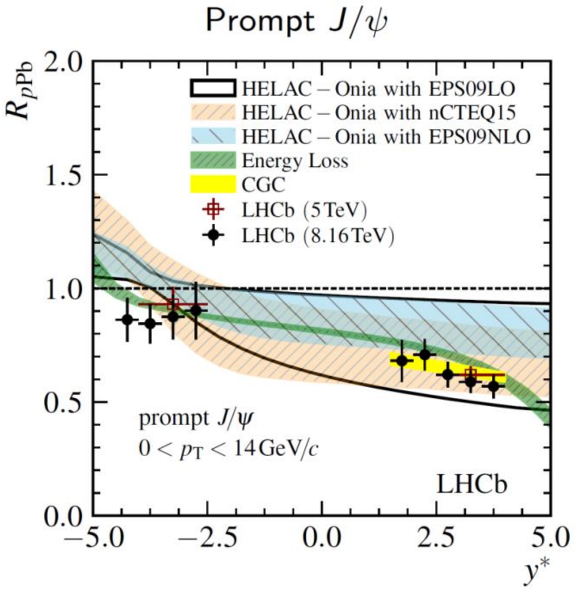
Here at RHIC in p-Al, p-Au, d-Au and ^{3}He-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

in p-Al, R_{AB} ~ 1 and things are consistent with pp

For other systems: forward rapidity suppression consistent with shadowing/gluon saturation. Some amount of suppression also at backward rapidity ← nuclear breakup

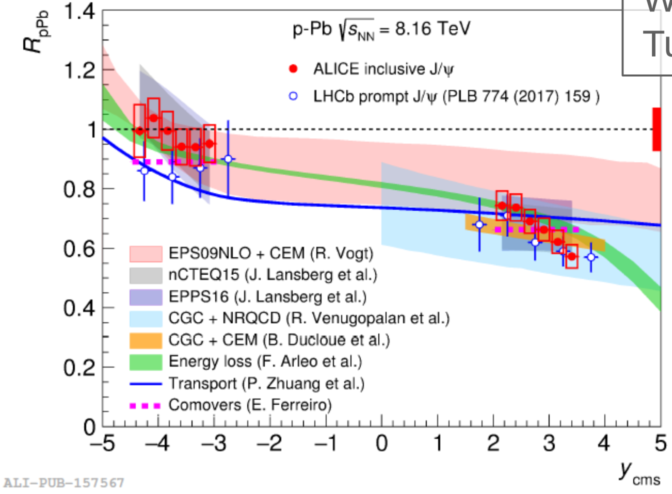
J/Ψ nuclear modification factor *vs* rapidity

Similar CNM effects expected at LHC, except for nuclear breakup, because crossing-time is smaller



inclusive J/Ψ

Wed. 10:00 G. Manca
Tue. 15:40 A. Lardeux



Similar trend as at RHIC for both particles: suppression at y>0 (small x), R_{pPb}~1 at y<0

Models include nPDF, CGC, energy loss

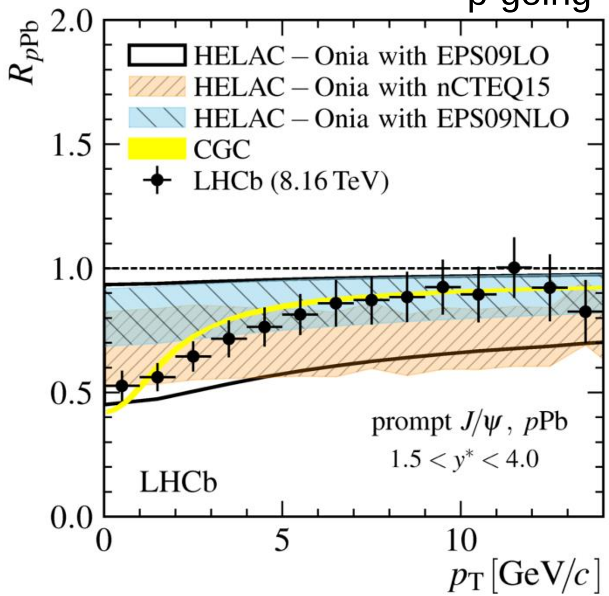
Some also include final state effects (transport models, comover interactions), see later

Overall, good description of the centrality-integrated R_{pPb} *vs* y

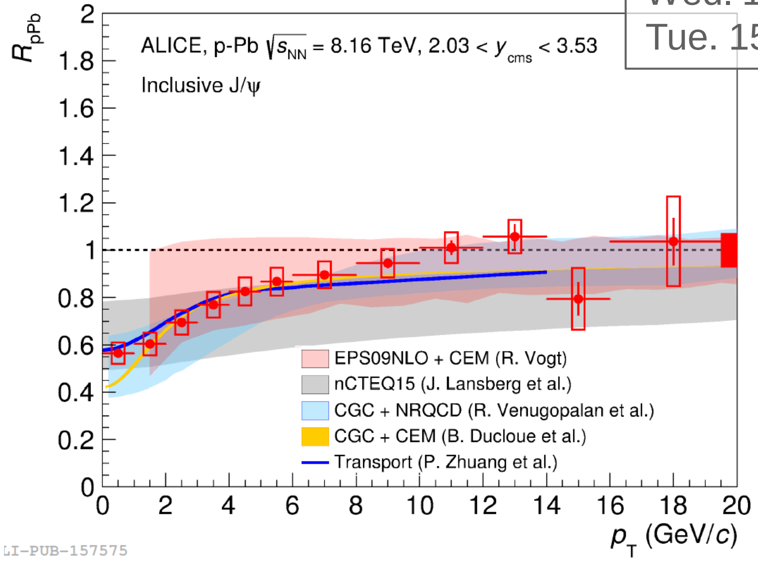
Need more differential measurements to discriminate

J/Ψ nuclear modification factor *vs* p_T

p-going



p-going



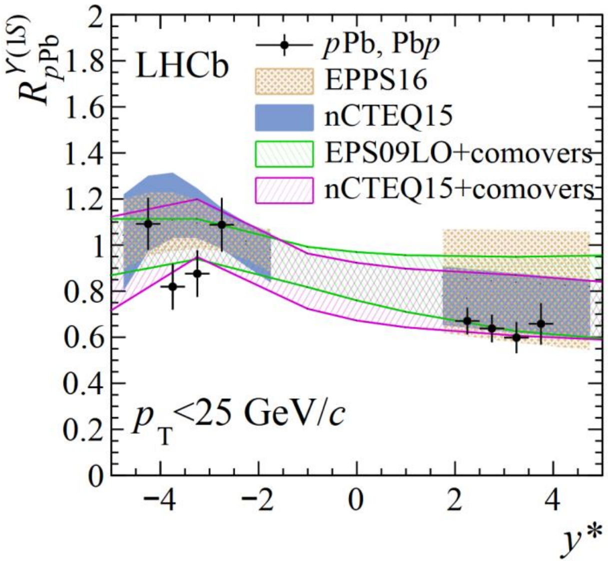
Wed. 10:00 G. Manca
Tue. 15:40 A. Lardeux

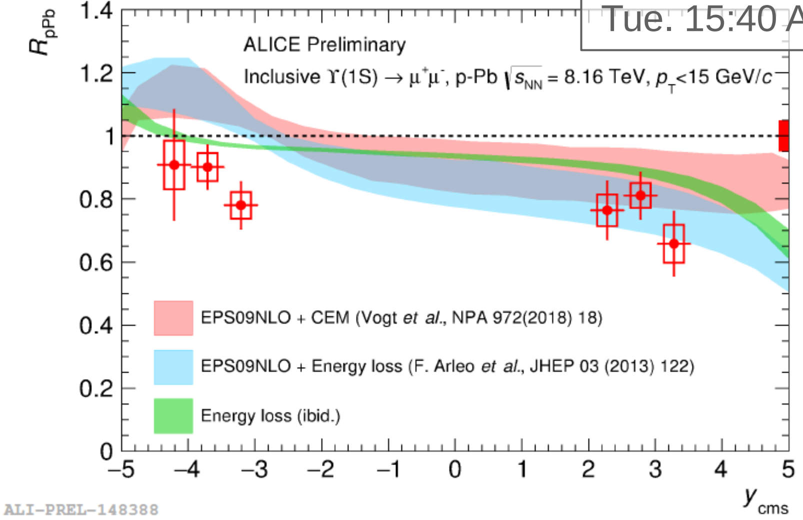
in the p-going direction (small x), suppression is concentrated at low p_T (< 8 GeV/c)

Also well reproduced by models

Υ(1S) nuclear modification factor *vs* y

Wed. 10:00 G. Manca
Tue. 15:40 A. Lardeux



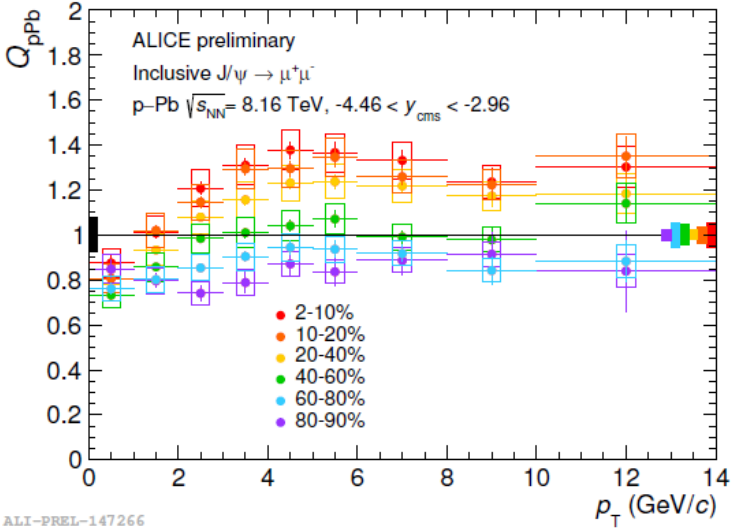


Rapidity dependence is similar between Υ(1S) and J/Ψ with a suppression at forward rapidity, also well reproduced by models

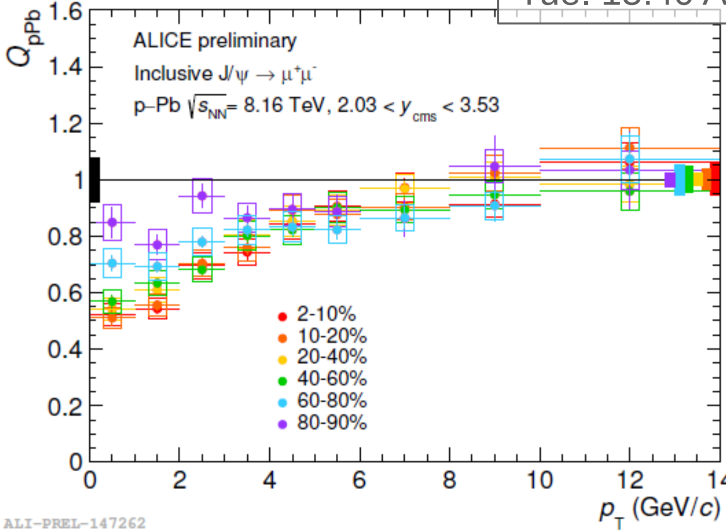
Multi-differential J/Ψ nuclear modification factor

Tue. 15:40 A. Lardeux

Pb-going



p-going



J/Ψ R_{pPb} *vs* p_T for different centralities and two bins of rapidity

Opposite trends seen in both rapidity ranges:

Pb-going (large x): enhancement for central collisions and high p_T

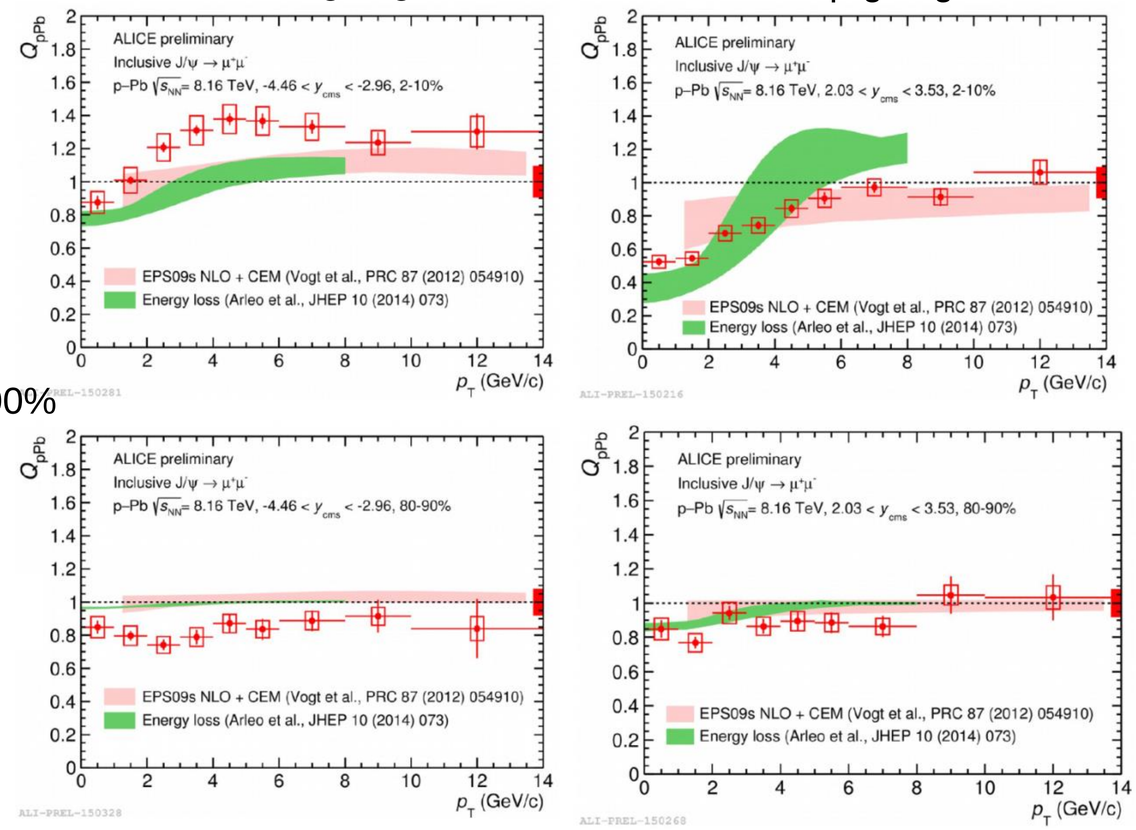
p-going (low x): suppression at low p_T increases for more central collisions

→ strong constrains on models

Multi-differential J/Ψ nuclear modification factor

2-10% Pb-going p-going

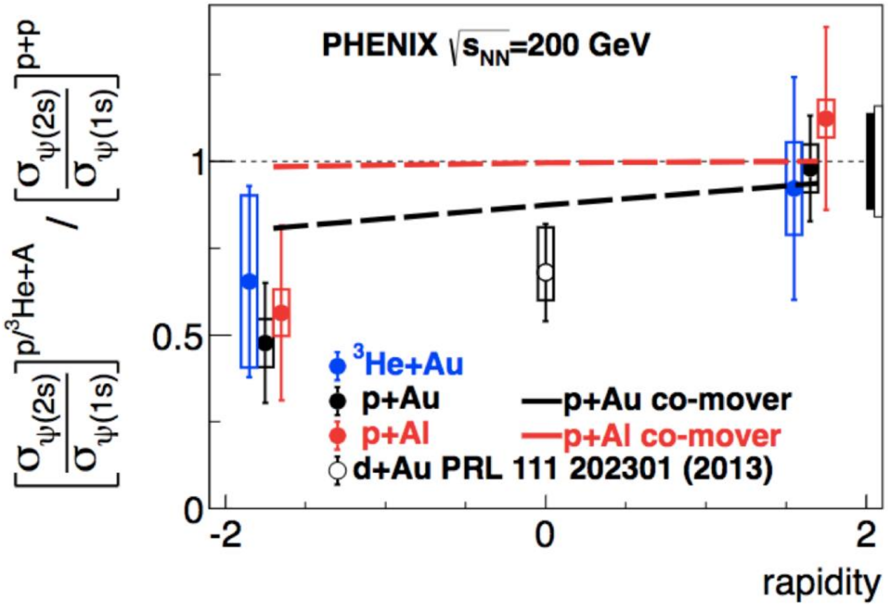
80-100%



Models including nPDF or energy loss are not capable of reproducing these trends, especially for central collisions

Ψ(2S) R_{AB} and Ψ(2S)-to-J/Ψ ratio

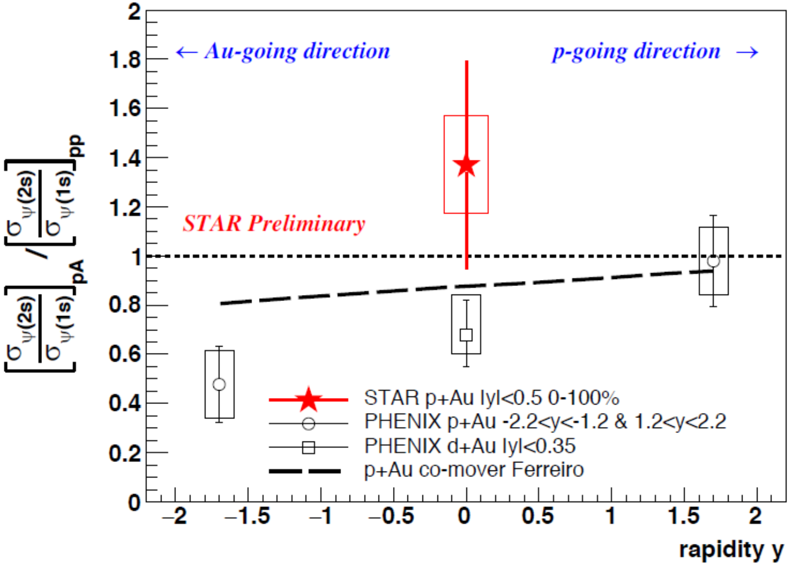
Thu. 12:05 M. Durham



Ψ(2S) is more suppressed than J/Ψ at RHIC

Ψ(2S) R_{AB} and Ψ(2S)-to-J/Ψ ratio

Wed. 9:00 Z. Liu



PHENIX p+Au, PRC 95 (2017) 034904
PHENIX d+Au, PRL 111 (2013) 202301
Co-mover calculation, Ferreiro (2016) private communication
Calculation based on PLB749 (2015) 98-103

Ψ(2S) is more suppressed than J/Ψ at RHIC. New STAR measurement stands out but has large uncertainties

Ψ(2S) R_{AB} and Ψ(2S)-to-J/Ψ ratio

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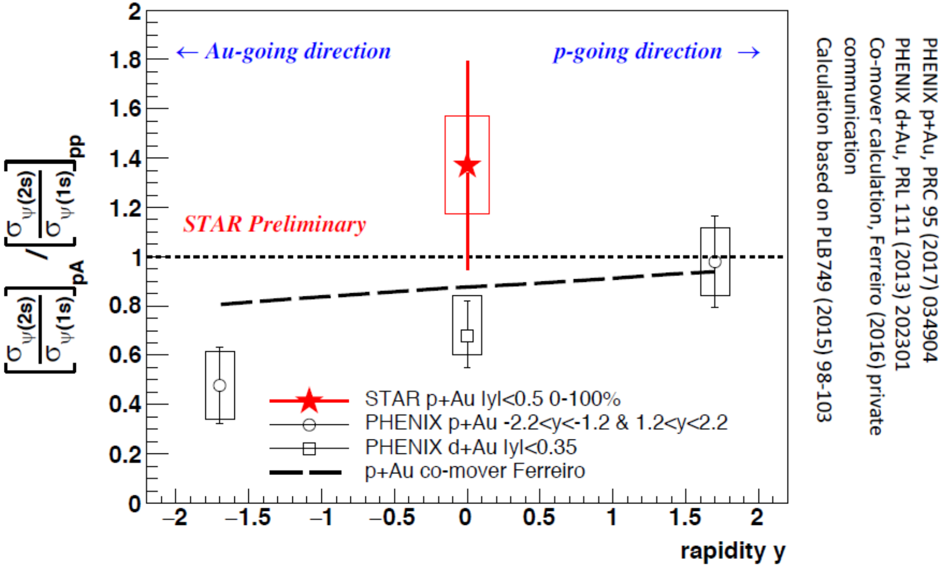
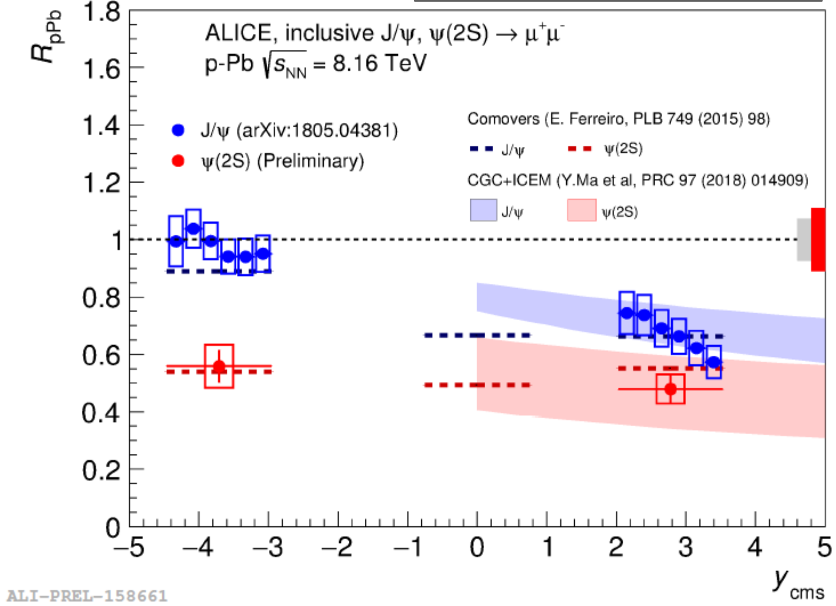


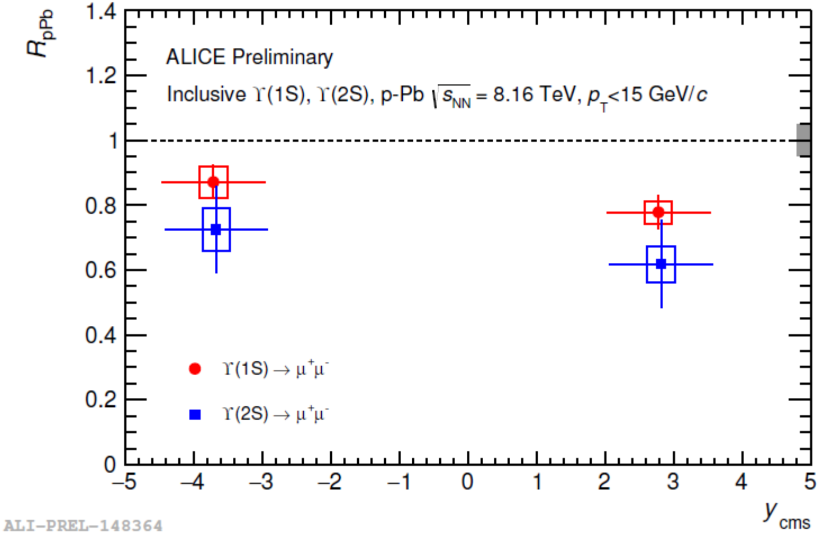


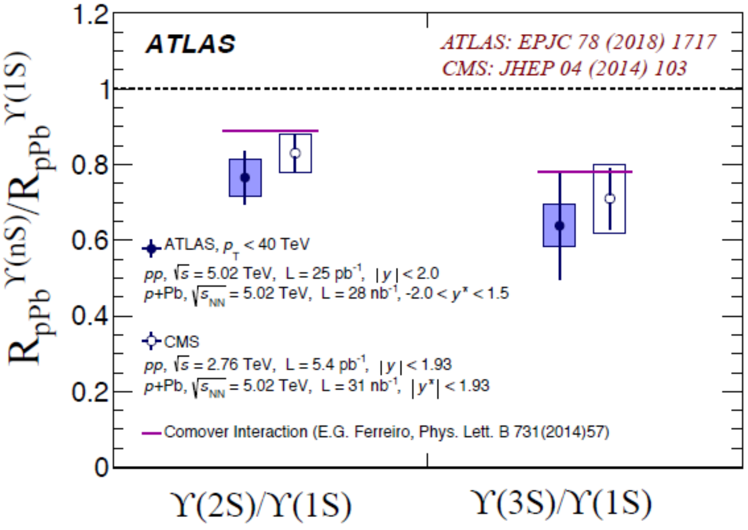
Ψ(2S) is more suppressed than J/Ψ at RHIC. New STAR measurement stands out but has large uncertainties

Ψ(2S) is also more suppressed at LHC

Final state effects? Other approaches also possible (here CGC+ICEM, at small x)

Particle ratios – Υ(ns)/Υ(1S)





LHCb integrated double ratios

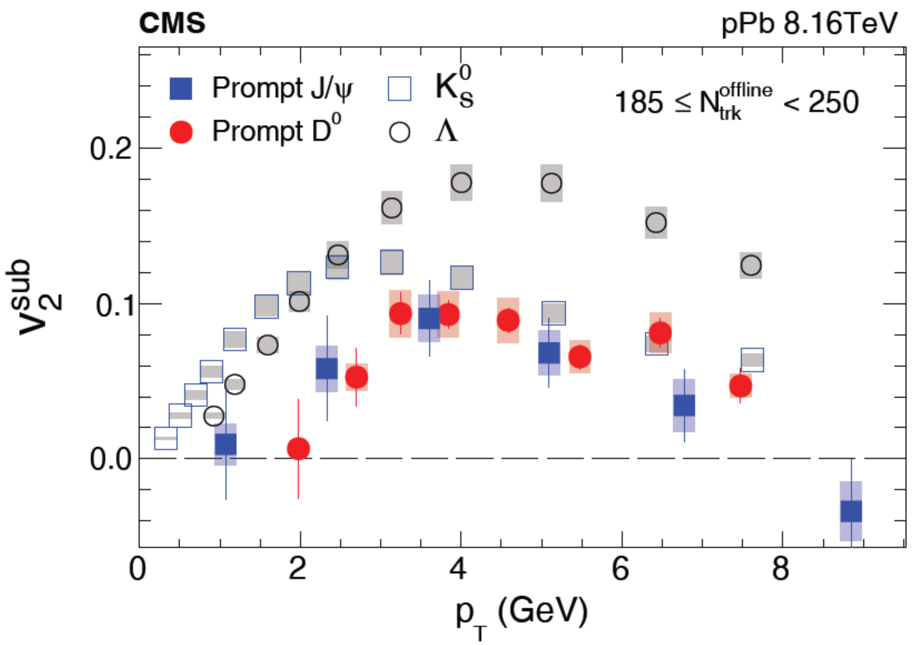
$$R(p\mathrm{Pb}/pp)[\Upsilon(2S)] = 0.86 \pm 0.15$$
$$R(p\mathrm{Pb}/pp)[\Upsilon(3S)] = 0.81 \pm 0.15$$
$$R(\mathrm{Pb}p/pp)[\Upsilon(2S)] = 0.90 \pm 0.21$$
$$R(\mathrm{Pb}p/pp)[\Upsilon(3S)] = 0.44 \pm 0.15$$

Also in the upsilon sector excited states are more suppressed

Tue. 15:40 A. Lardeux
Wed. 10:00 G. Manca

A puzzle: J/Ψ elliptic flow

Wed. 10:45 B. Diab



A significant J/psi elliptic flow v_2 is measured in central pPb collisions, comparable to that of D mesons.

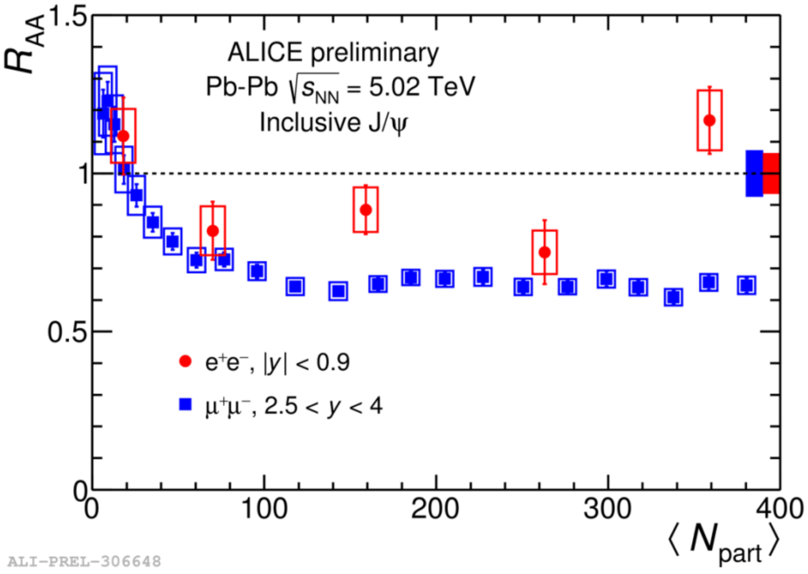
Its origin is debated. Sign of collectivity ? Initial state ? Something else ?

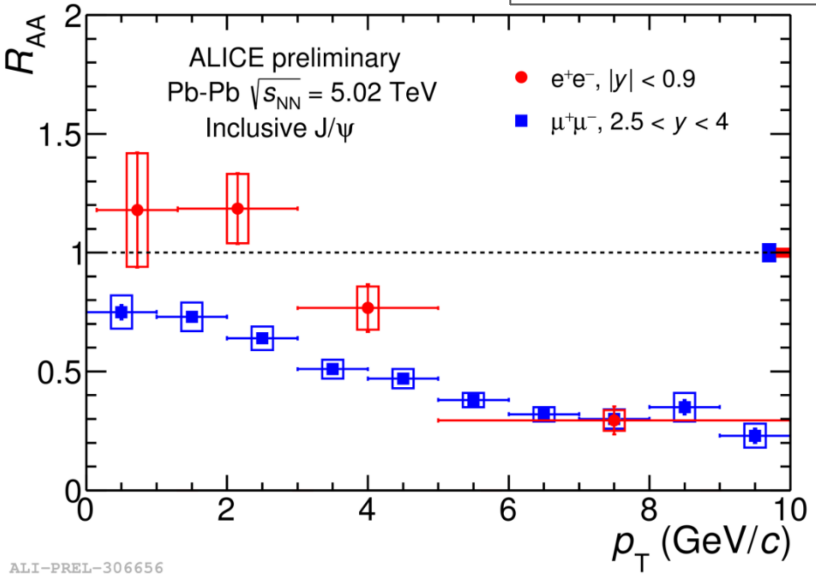
Also measured by ALICE at forward rapidity (see later)

nucleus-nucleus collisions

Low p_T J/Ψ R_{AA}

Wed. 9:20 M. Köhler



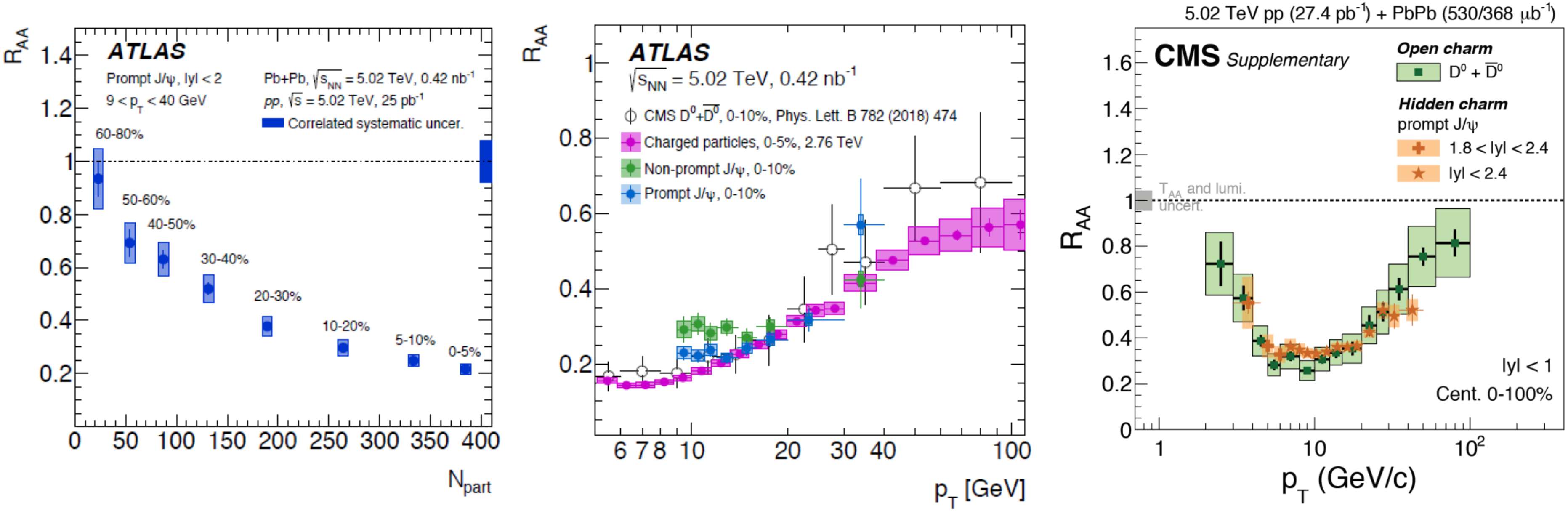


Left: no significant centrality dependence of the J/Ψ R_{AA}
mid-rapidity points are systematically above the forward rapidity

Right: difference is concentrated at low p_T

Consistent with the presence of J/Ψ from charm quark recombination

High p_T J/Ψ R_{AA}

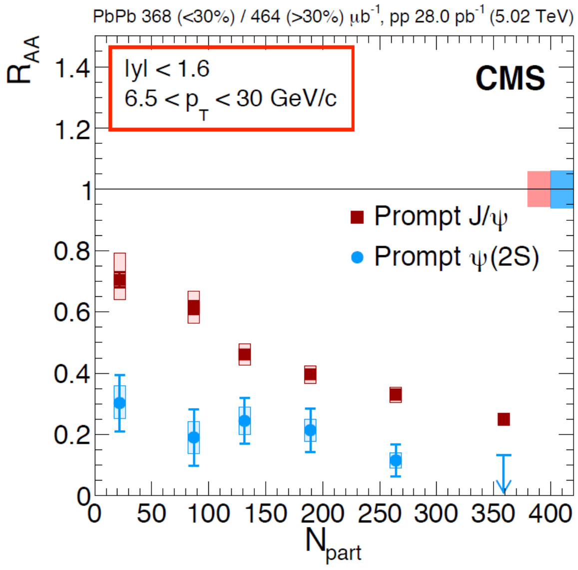


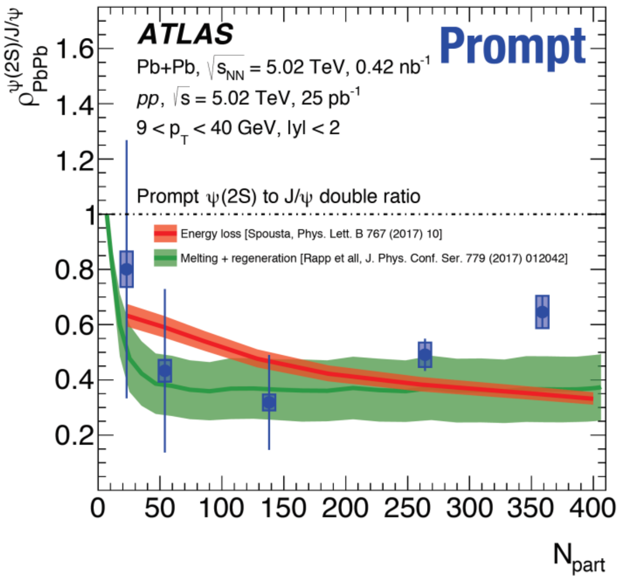
Left: *vs* centrality, in strong contrast to the low p_T result, consistent with J/Ψ suppression

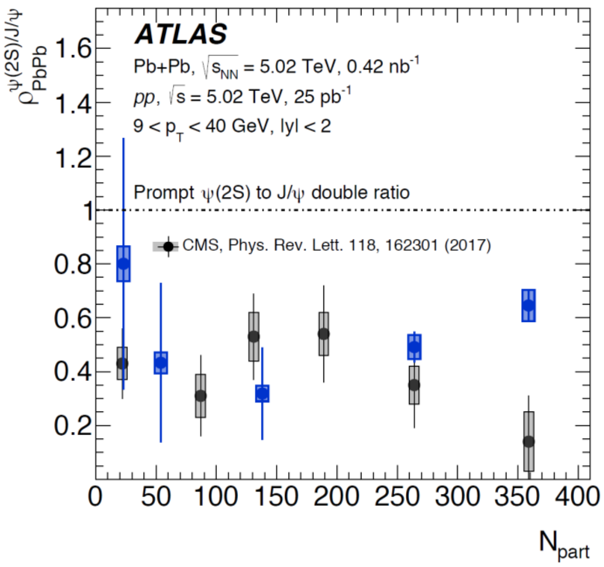
Center and right: *vs* p_T, similar suppression observed at high p_T to that of D mesons and charged hadrons, consistent with in-medium energy loss calculation

Tue. 4:25 S. Tapia
Wed. 10:45 B. Diab

$\Psi(2S)$ R_{AA} and double ratio







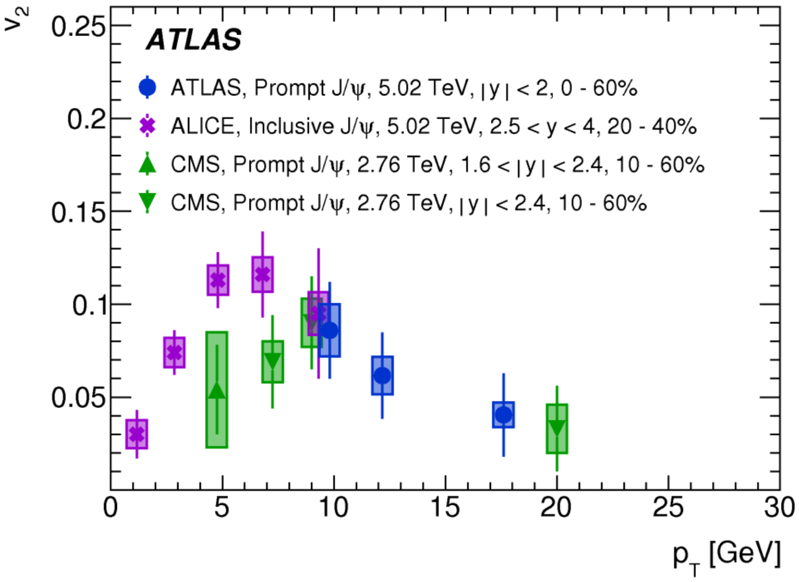
High p_T $\Psi(2S)$ are more suppressed than J/Ψ (also true at low p_T)

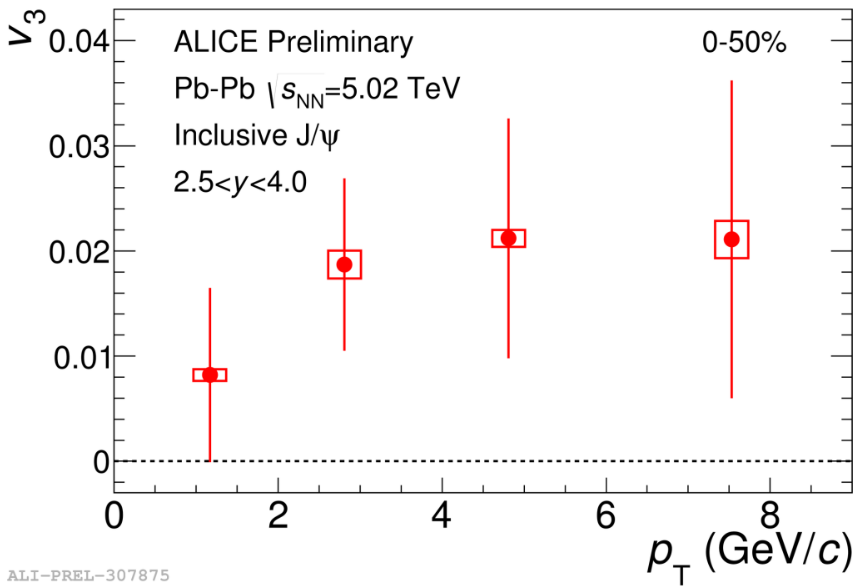
Qualitatively reproduced by transport models and energy loss calculations

Some tension in most central collisions

Tue. 4:25 S. Tapia
Wed. 10:45 B. Diab

J/Ψ azimuthal anisotropies





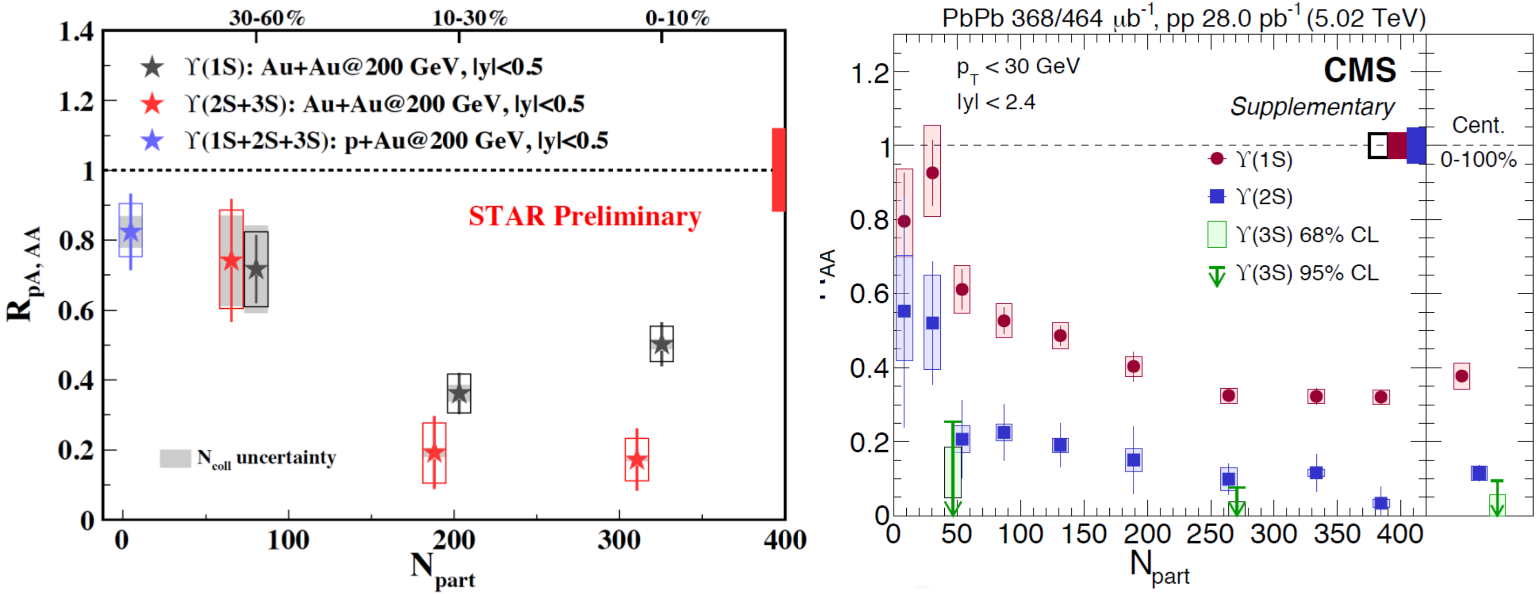
Left: significant J/Ψ elliptic flow v_2 measured by ATLAS CMS and ALICE in Pb-Pb

Right: first evidence of triangular flow v_3 measured by ALICE (significance 3.7σ)

Further confirm the presence of J/Ψ from recombined charm quarks

Tue. 4:25 S. Tapia
Wed. 9:20 M. Köhler

Upsilon R_{AA} – Centrality dependence



Y(nS) R_{AA} *vs* centrality at RHIC (left) and LHC (right)

Suppression increases for more central collisions

Excited states are more suppressed than the fundamental

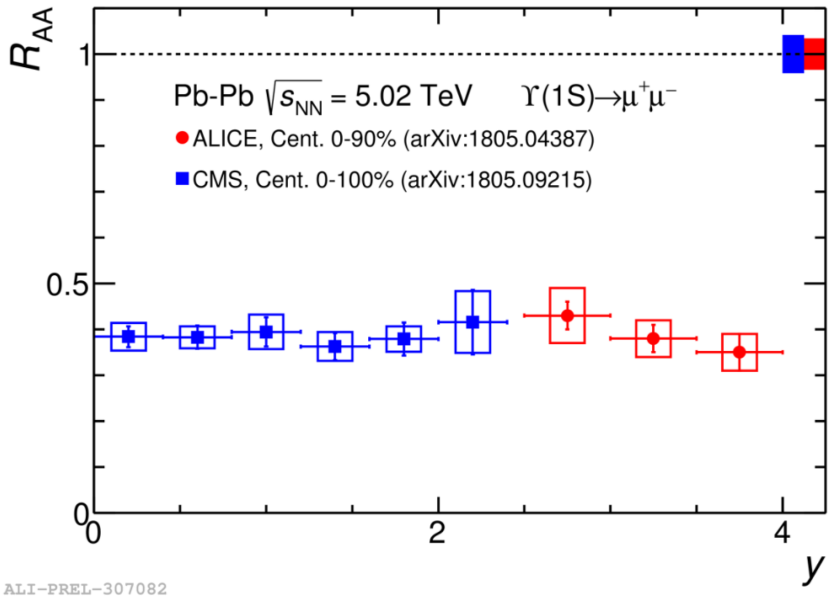
Consistent with sequential melting

Suppression is similar between both energies for both Y(1S) and y(ns)

Wed. 9:00 Z. Liu
Wed. 11:25 J. Park

Υ(1S) R_{AA}, rapidity dependence

Wed. 9:20 M. Köhler



No significant dependence on rapidity over the full range (also true for Y(2S) and Y(3S))

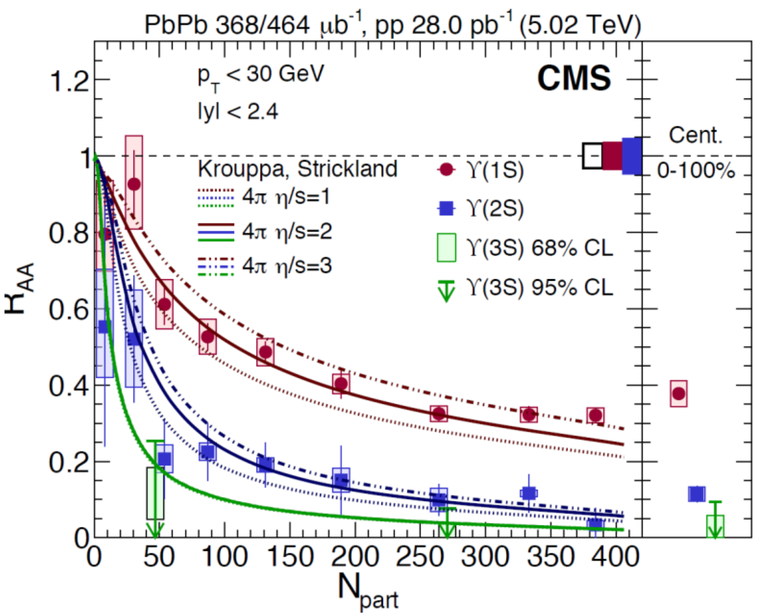
Screening scenari predict a (moderate) increase with rapidity

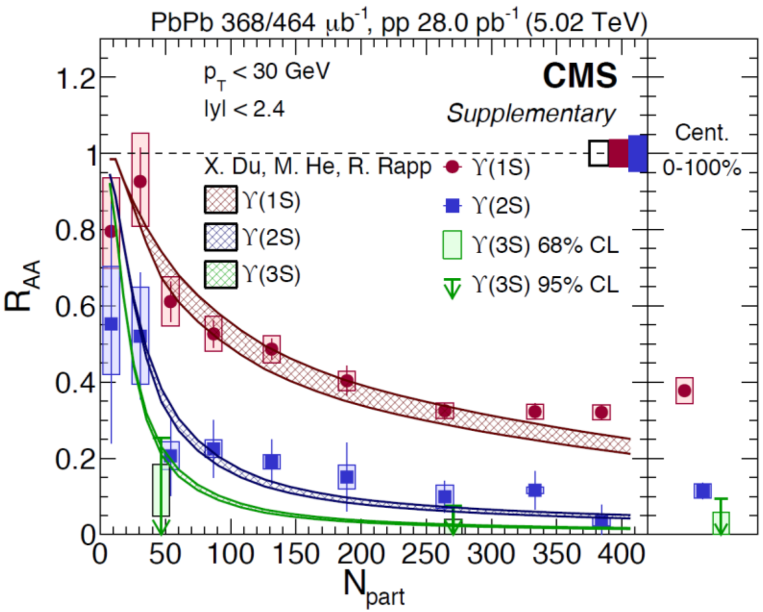
Need CNM and/or some amount of recombination to explain this trend

Comparison to models

Most features presented so far (low p_T J/Ψ recombination, suppression of high-p_T J/Ψ, sequential suppression of Ψ(2S) and Υ(nS)) are reasonably well reproduced by models

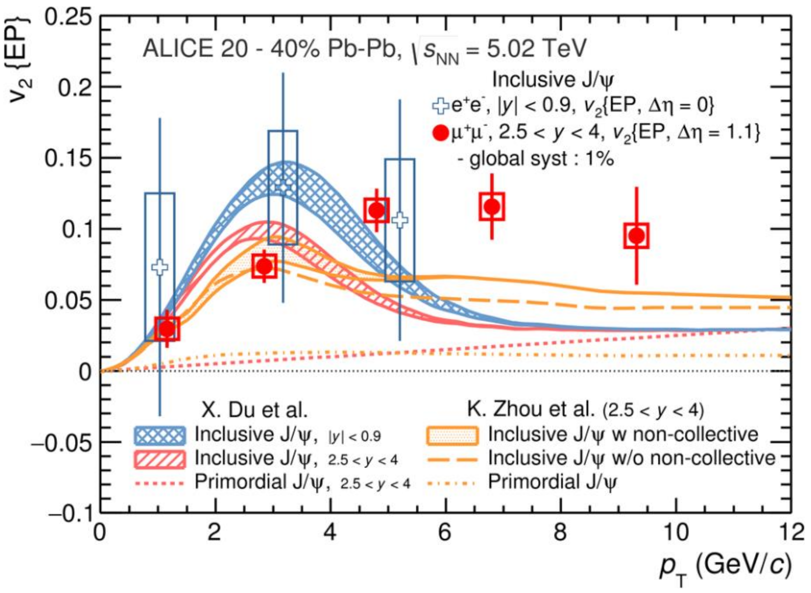
Wed. 11:25 J. Park

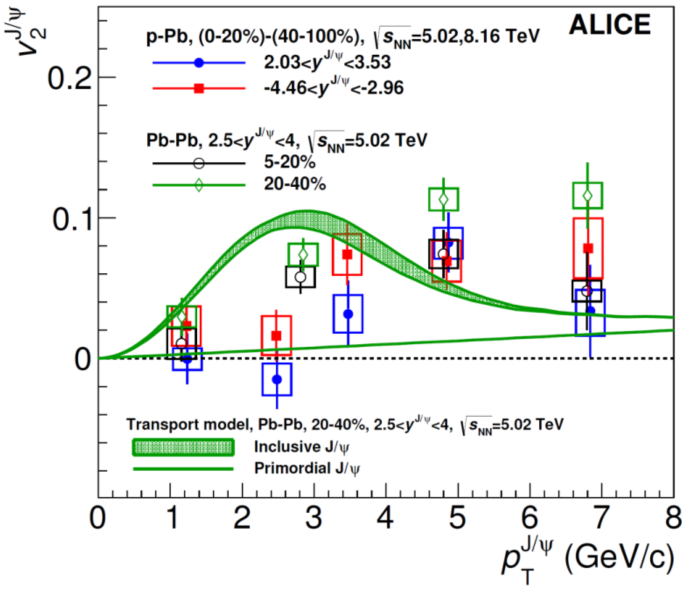




but …

Coming back to J/Ψ elliptic flow





J/Ψ v_2 at moderate p_T (p_T>7 GeV) is not well captured by transport models

It is of the same magnitude as that measured in pPb

Same (unknown) origin ? Initial state ?

Wed. 9:20 M. Köhler
Tue. 15:40 A. Lardeux

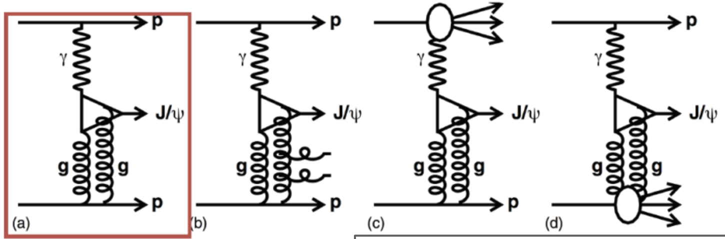
Quarkonium photo-production

Ultra-peripheral collisions in pp and pA

Consider collisions for which $b > R_A + R_B$

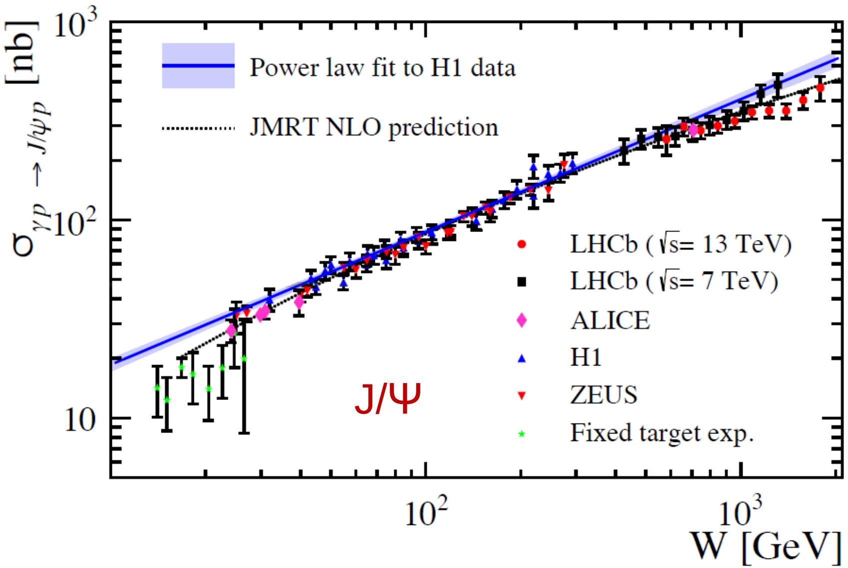
Measure exclusive production of quarkonia

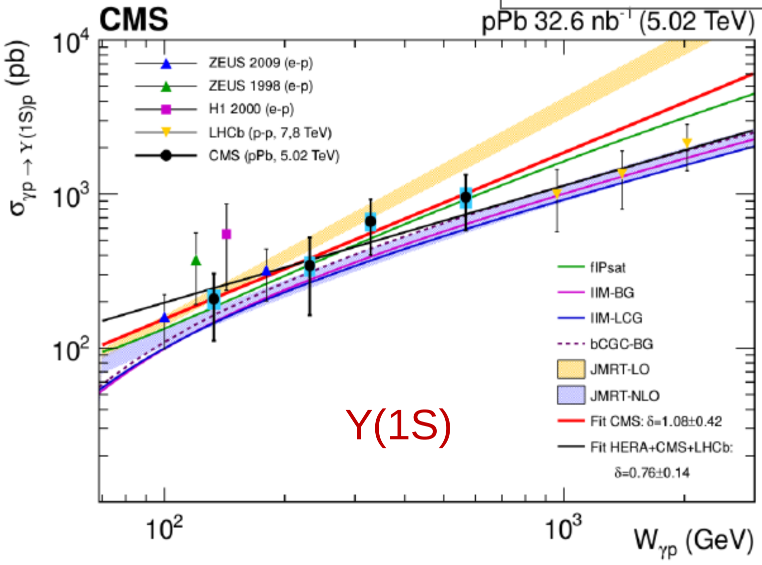
Probe gluon distribution in the target proton with the photons from the projectile nucleus



Tue. 9:00 S. Belin
Tue. 10:00 K. Naskar

W: center of mass energy of the γp system





Ultra-peripheral collisions in AA

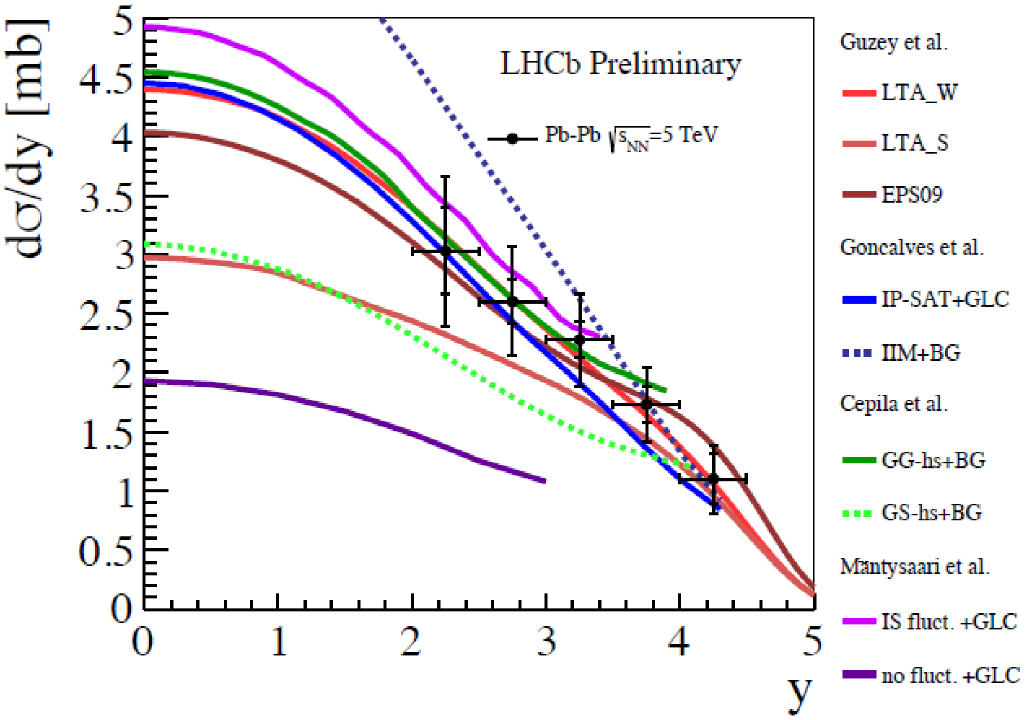
Tue. 9:00 S. Belin

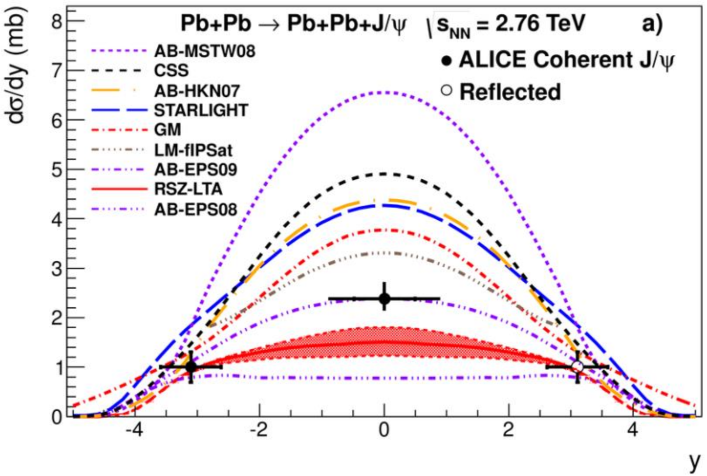
In Pb-Pb, extra complication due to coherent *vs* incoherent production

Measurement is sensible to nPDF or gluon saturation

First LHCb measurement in Pb-Pb

Limited discriminating power at forward rapidity





J/Ψ photo-production in peripheral AA collisions

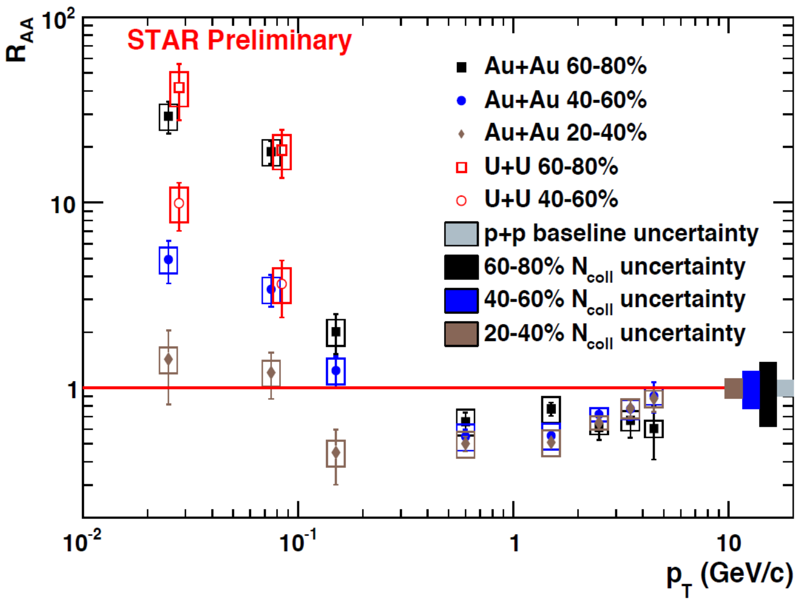
Quarkonium photo-production also happens in (non-ultra) peripheral collisions

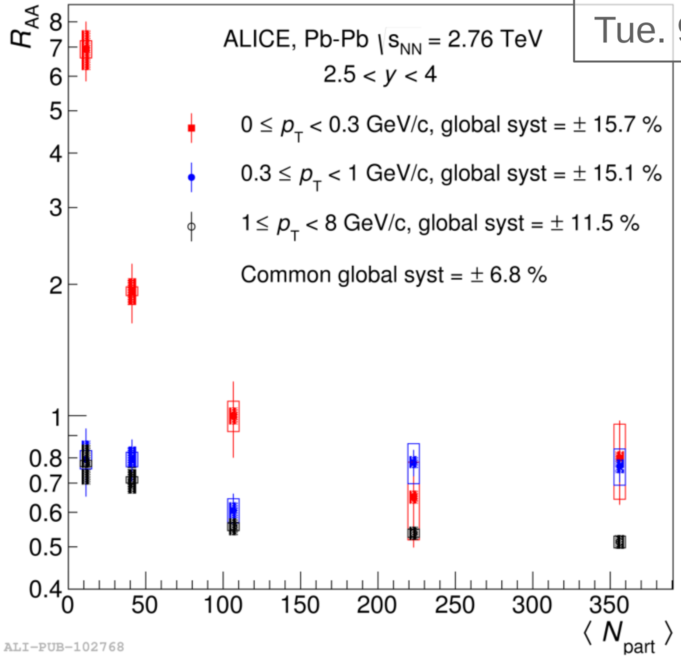
It is characterized by very low p_T

Since the photon flux is very large you expect an excess in low p_T and peripheral collisions

Observed at RHIC and LHC

Tue. 9:20 S. Yang
Tue. 9:40 L. Massacrier





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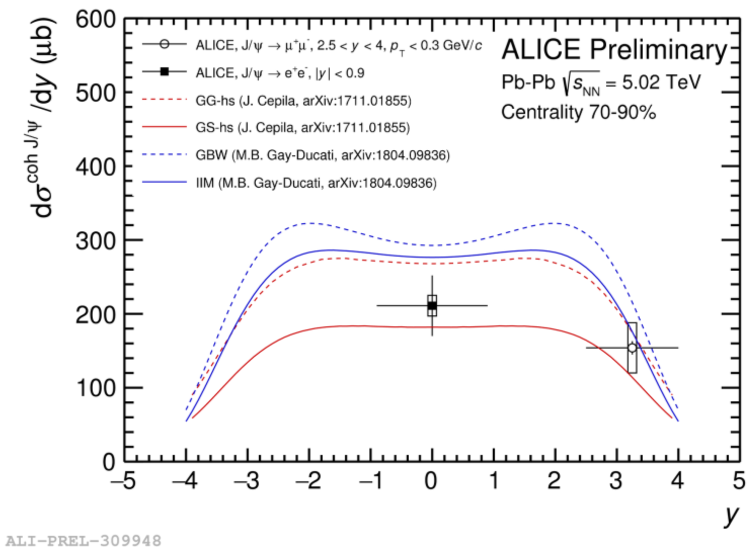
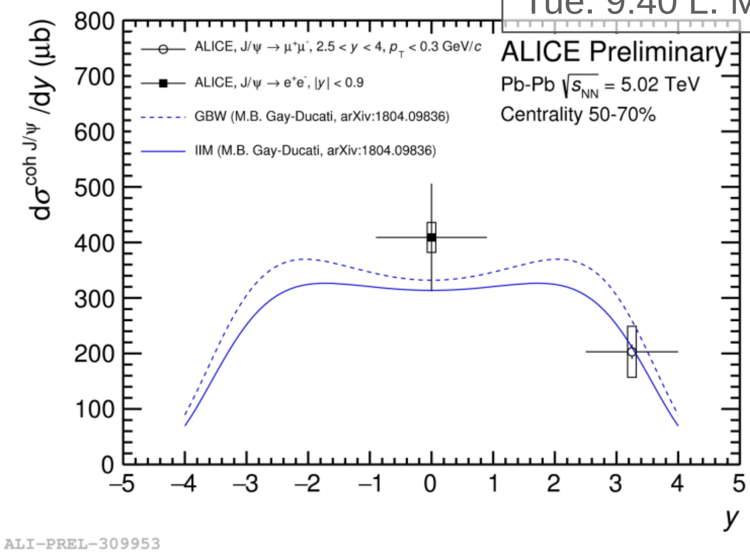
From this one can get a cross section and compare to model.

For models, the challenge is to calculate the photon flux when the nucleus breaks during the collision

Tue. 9:40 L. Massacrier





Summary

After ~30 years, the field is still very rich and active, and there is still a lot to investigate and understand

Selected points to follow up:

- Event activity dependence of quarkonium production. Can we go continuously from pp to pA to AA ?
- Multi-differential R_{AA} measurements in pA
- Azimuthal anisotropies in pA
- High p_T quarkonium R_{AA} in AA, energy loss *vs* screening
- Intermediate to high p_T elliptic flow

Thank you