Charmonium physics with heavy ions: experimental results

E. Scomparin (INFN-Torino)

Bologna, September 5, 2016

- ❑ A short introduction
  - → 30 years of "J/ψ suppression"
- ❑ Our present knowledge
  - → News from collider experiments (RHIC/LHC)
- ❑ Open points and prospects
  - → Future measurements

VIII International Workshop on Charm Physics

CHARM 2016

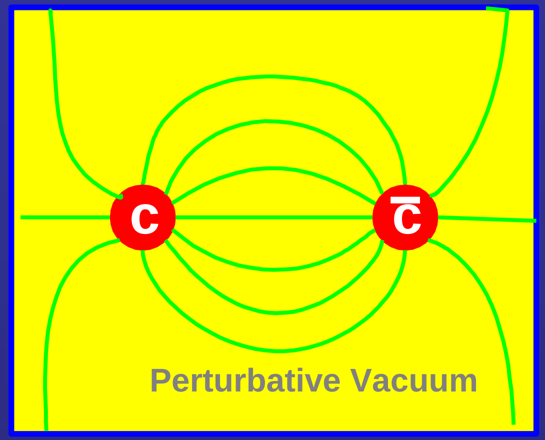
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

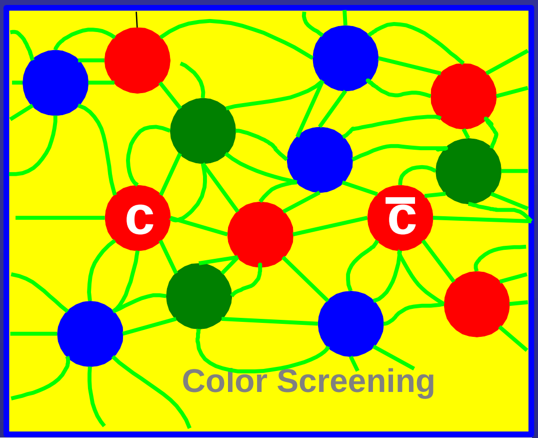
INFN Istituto Nazionale di Fisica Nucleare

Charmonia in heavy-ions: color screening…

Screening of
strong interactions
in a QGP

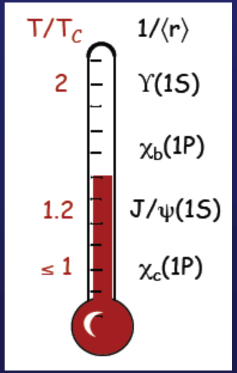
T. Matsui and H. Satz,
PLB178 (1986) 416



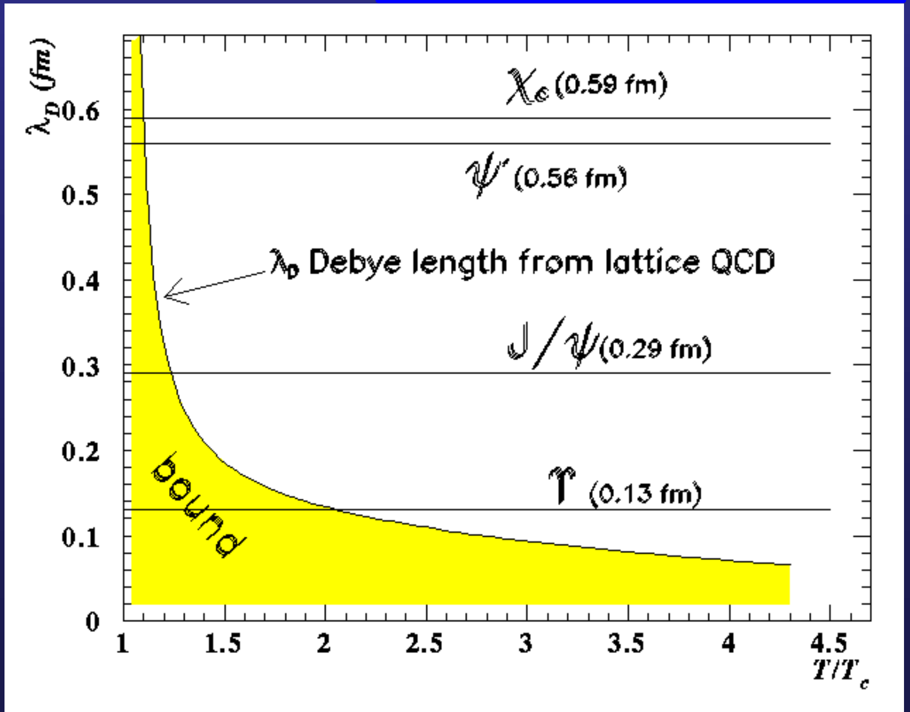


- Screening stronger at high T
- λ_D → maximum size of a bound state, decreases when T increases
- Different states, different sizes

Resonance melting



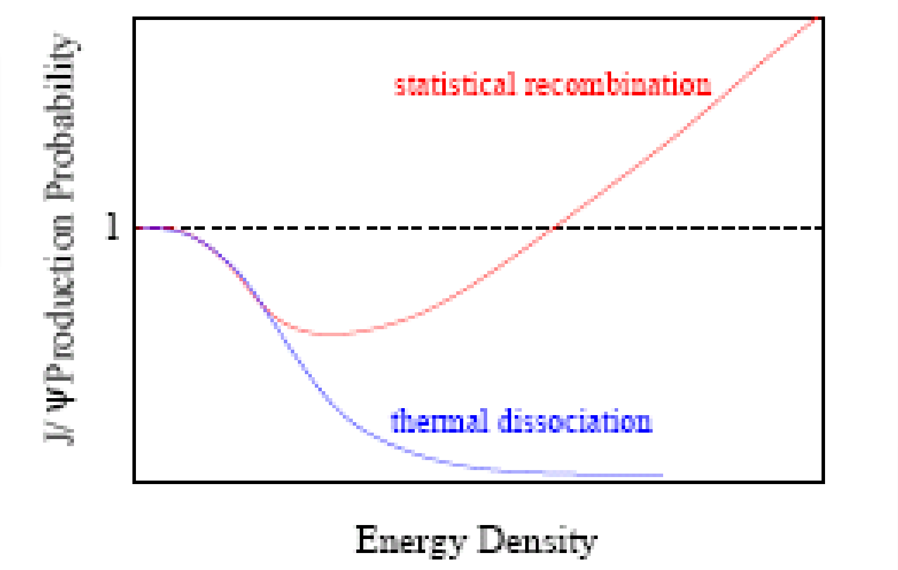
→ QGP thermometer



…and regeneration

At sufficiently high energy, the cc pair multiplicity becomes large

Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76 TeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~85	~115



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

Statistical approach:

- Charmonium fully melted in QGP
- Charmonium produced, together with all other hadrons, at chemical freeze-out, according to statistical weights

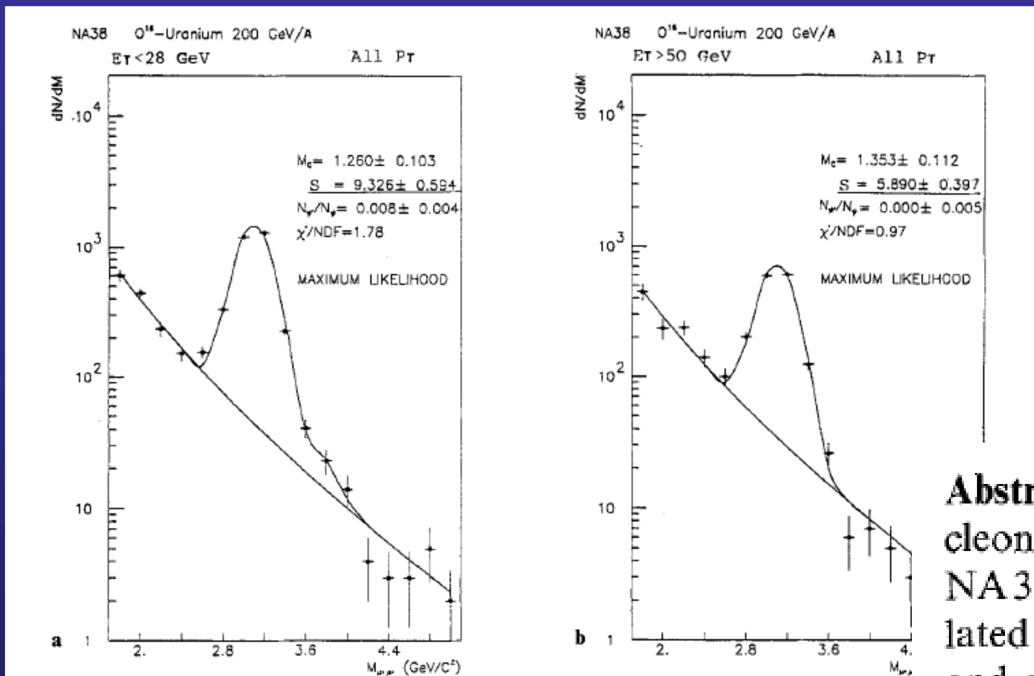
Kinetic recombination:

- Continuous dissociation/regeneration over QGP lifetime

Contrary to the color screening scenario this mechanism can lead to a charmonium enhancement

30 years ago: discovery of J/ψ suppression…

Quark Matter 87, NA38 Collaboration



- Fall 1986
- Oxygen-Uranium collisions at the CERN SPS
- 200 GeV/nucleon (lab system! $\sqrt{s_{NN}}$=19.4 GeV)

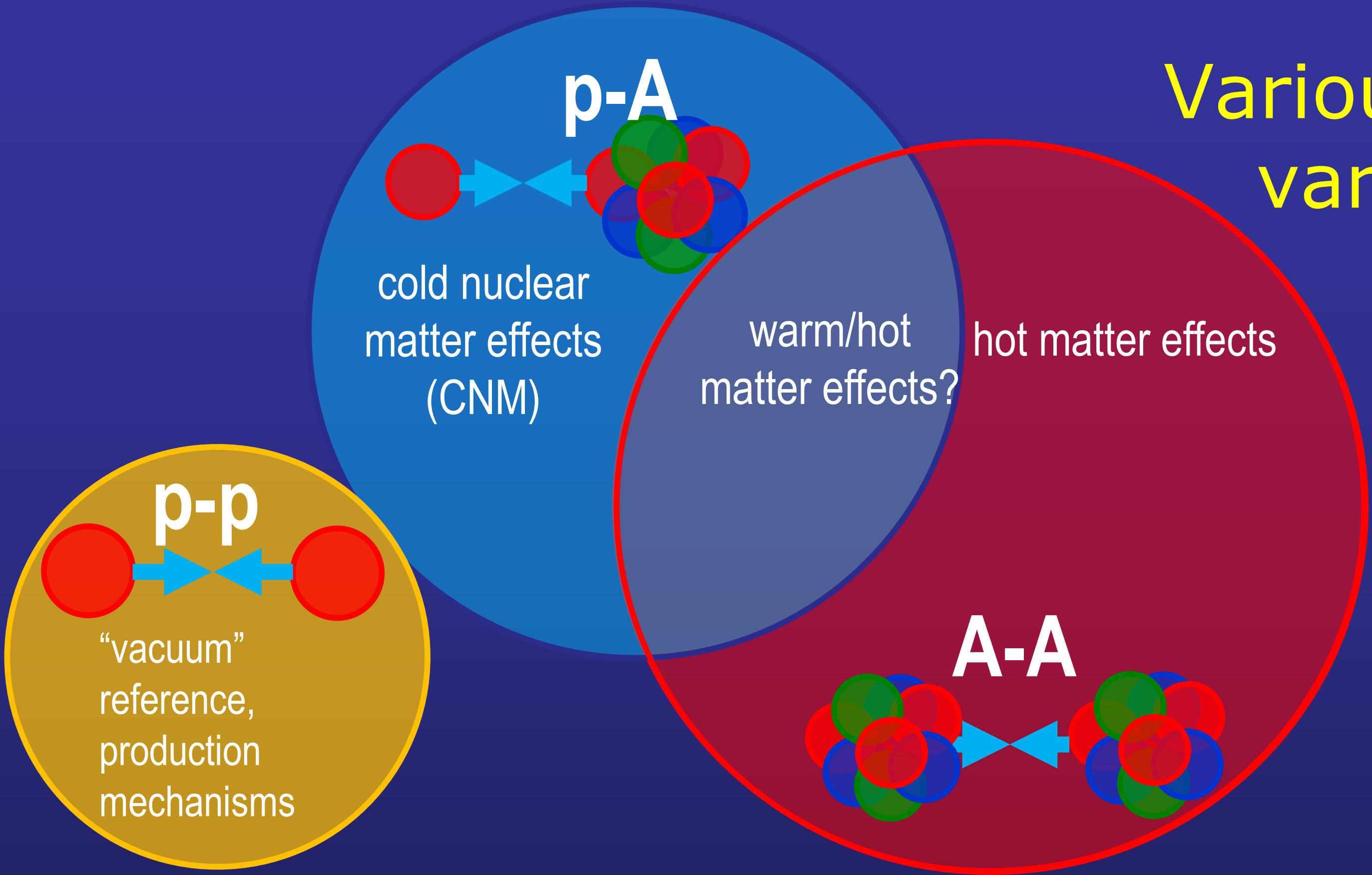
Abstract. The dimuon production in 200 GeV/nucleon oxygen-uranium interactions is studied by the NA38 Collaboration. The production of J/Ψ, correlated with the transverse energy ET, is investigated and compared to the continuum, as a function of the dimuon mass M and transverse momentum PT. A value of 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.

First evidence for J/ψ suppression in nuclear collisions!

Today: a rich and diversified program at hadronic/ion colliders

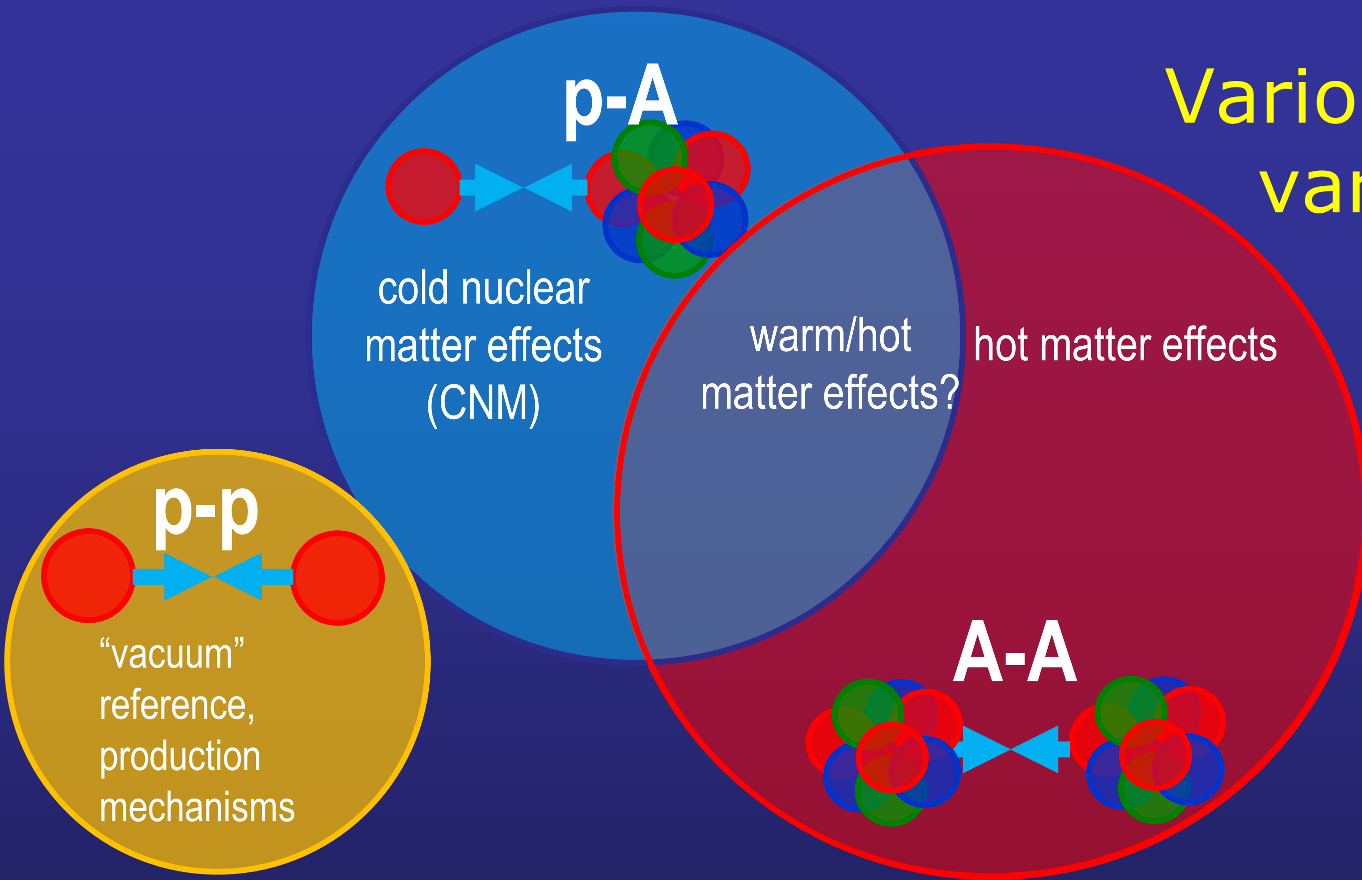
Collider	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	Data taking
RHIC	PHENIX STAR	Au-Au, Cu-Cu, Cu-Au, U-U	200, 193, 62, 39	2000-2016
		p-A, d-Au	200	
		pp	200-500	
LHC	ALICE ATLAS CMS LHCb	Pb-Pb	2760 5020	2010/2011 2015-
		p-Pb	5020 (8000)	2013-(2016)
		pp	2760, 5020, 7000, 8000, 13000	2010-2016

Various systems, various effects



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

Various systems, various effects



Quantify the yield modifications via the nuclear modification factor R_{AA}

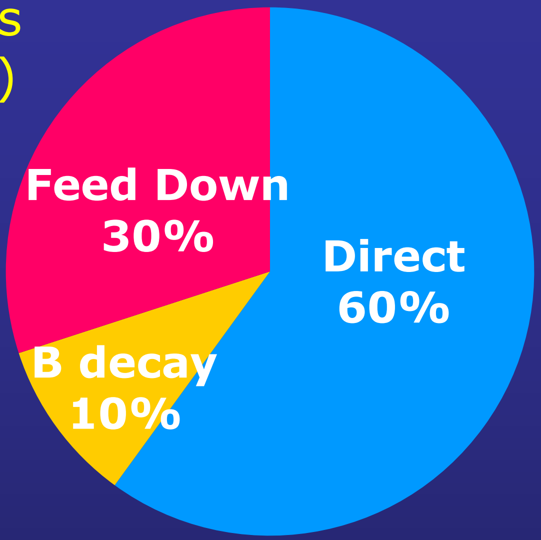
$$R_{AA} = \frac{dN^{P}{}_{AA}}{\langle N_{Coll} \rangle \, dN^{P}{}_{pp}}$$

$R_{AA}<1$ suppression
$R_{AA}>1$ enhancement

Sources of heavy quarkonia

- Quarkonium production can proceed:
  - directly in the interaction of the initial partons
  - via the decay of heavier hadrons (feed-down)

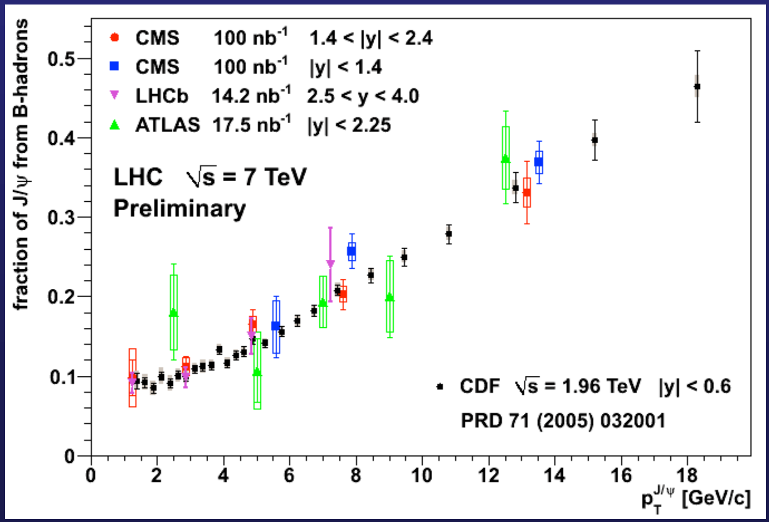
Low p_T J/ψ



- For J/ψ (at CDF/LHC energies) the contributing mechanisms are:

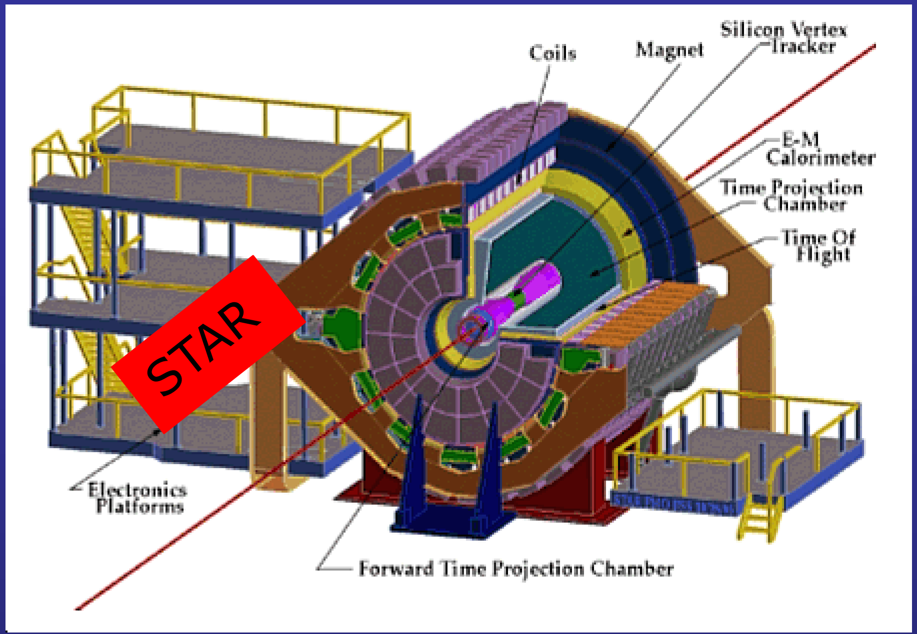
Prompt
- Direct production
- Feed-down from higher charmonium states:
  ~ 8% from ψ(2S), ~25% from χ_c

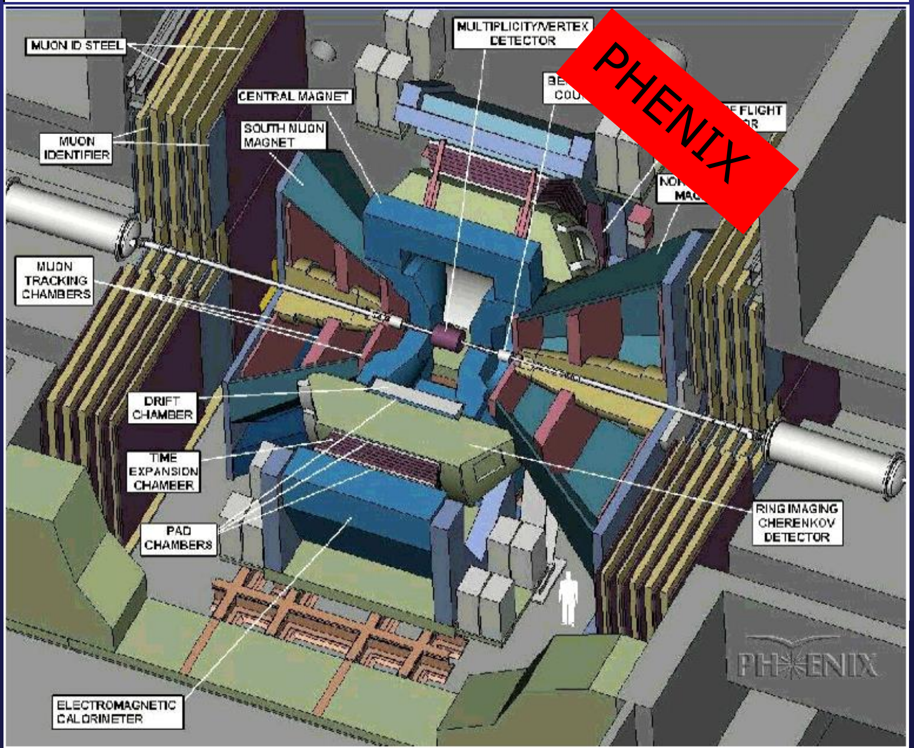
Non-prompt
- B decay
  contribution is p_T dependent
  ~10% at p_T~1.5GeV/c



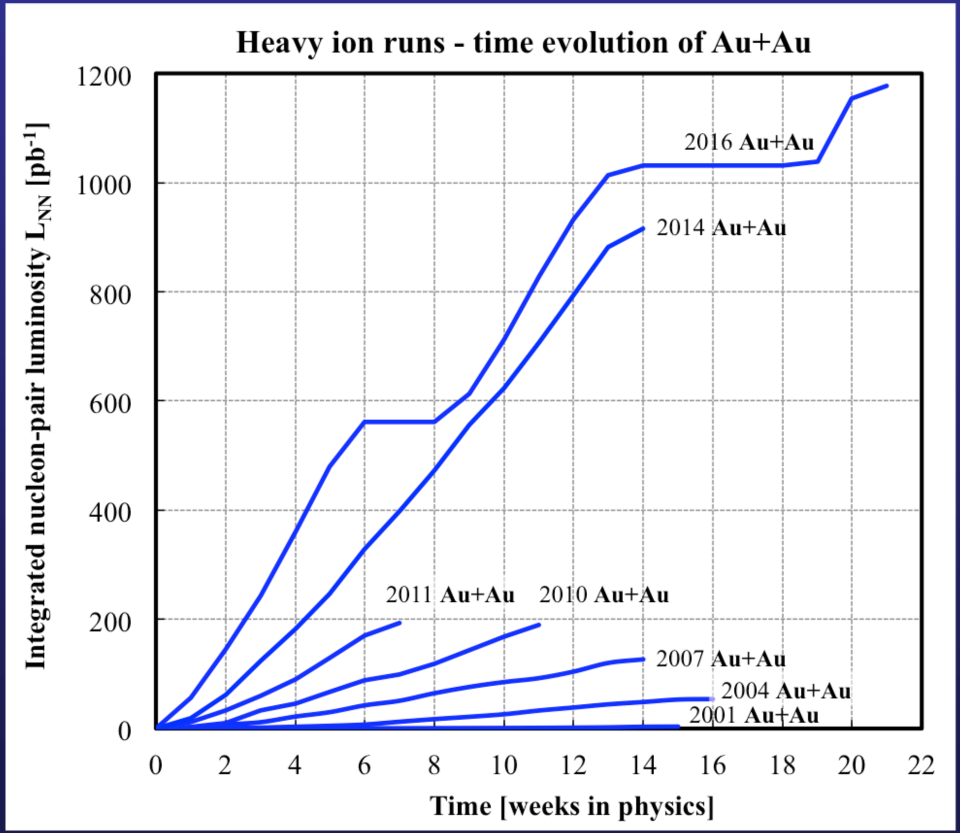
- B-decay component "easier" to separate → displaced production

Quarkonium at RHIC



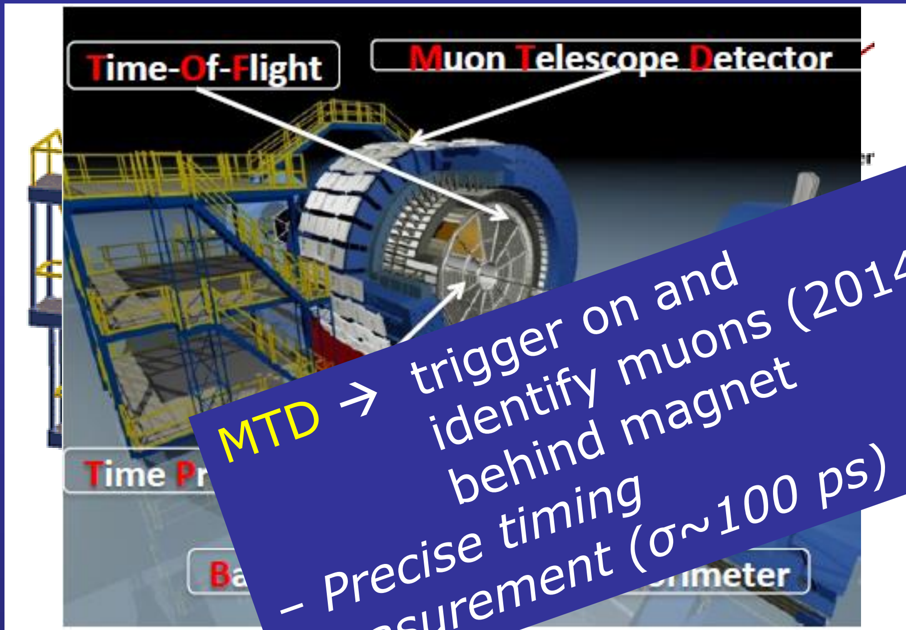


- Kinematic coverage
  - PHENIX $1.2<|y|<2.2$ ($\mu^+\mu^-$), $|y|<0.35$ (e^+e^-)
  - STAR $|y|<1$ (e^+e^-) (recently $|y|<0.5$ $\mu^+\mu^-$)

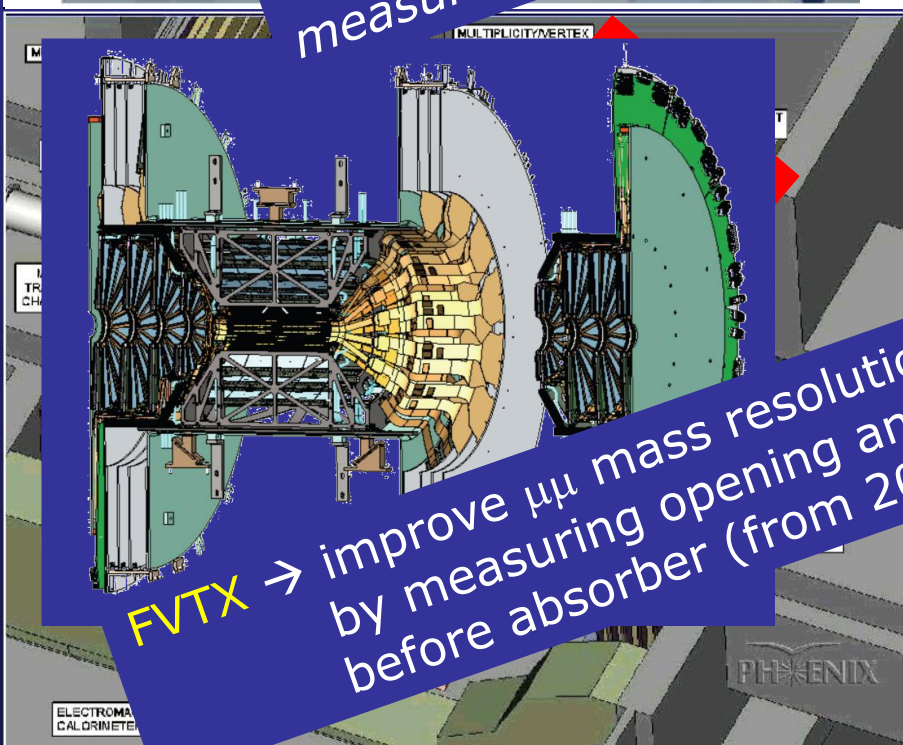


$$L = L_{NN} / (197)^2$$

Quarkonium at RHIC



MTD → trigger on and identify muons (2014) behind magnet – Precise timing measurement (σ~100 ps)



FVTX → improve μμ mass resolution by measuring opening angle before absorber (from 2012)

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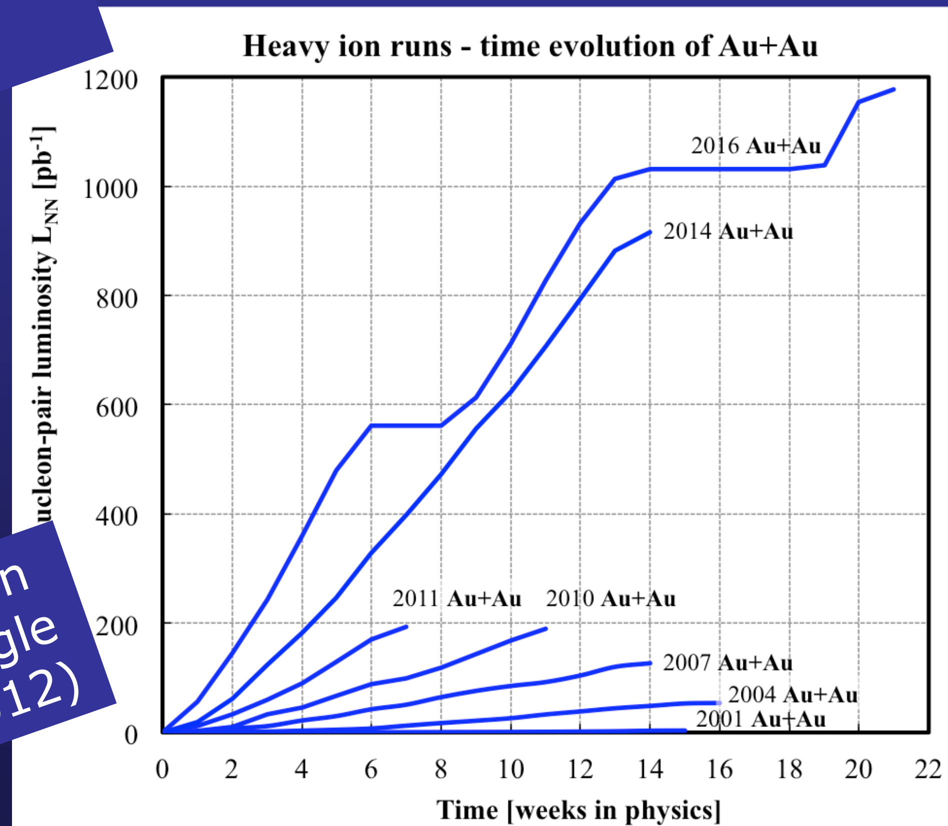
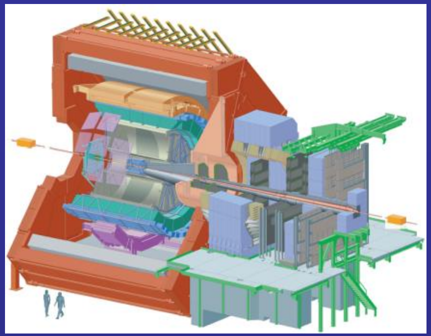
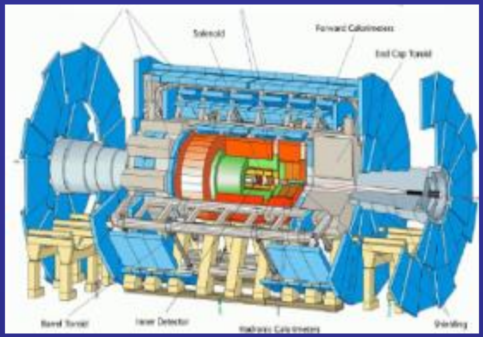
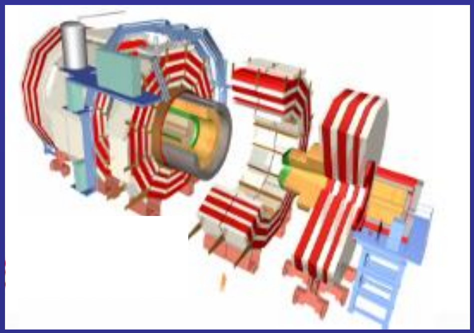
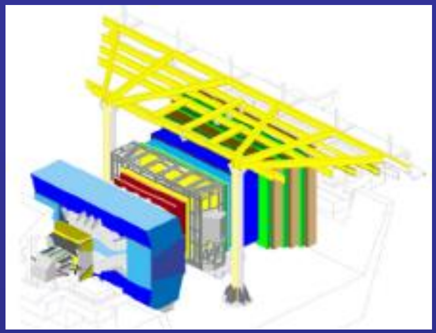


$L = L_{NN} / (197)^2$

Quarkonium at LHC

- ❑ All the four experiments have investigated quarkonium production
  - ❑ Pb-Pb → mainly ALICE + CMS, p-Pb → all the 4 experiments

- ❑ Complementary kinematic ranges → excellent phase space coverage

ALICE → forward-y ($2.5<y<4$, dimuons) and mid-y ($|y|<0.9$, electrons)
LHCb → forward-y ($2<y<4.5$, dimuons)
CMS → mid-y ($|y|<2.4$, dimuons)
ATLAS → mid-y ($|y|<2.25$, dimuons)
(N.B.: y-range refers to symmetric collisions →rapidity shift in p-Pb!)

Data samples Run 1:
- Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV, 2010 (9.7 μb^{-1}) + 2011 (184 μb^{-1})
- p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, 2013 (36 nb^{-1})
- ref. p-p, $\sqrt{s}$ = 2.76 TeV, 2011 (250 nb^{-1}) + 2013 (5.6 pb^{-1})

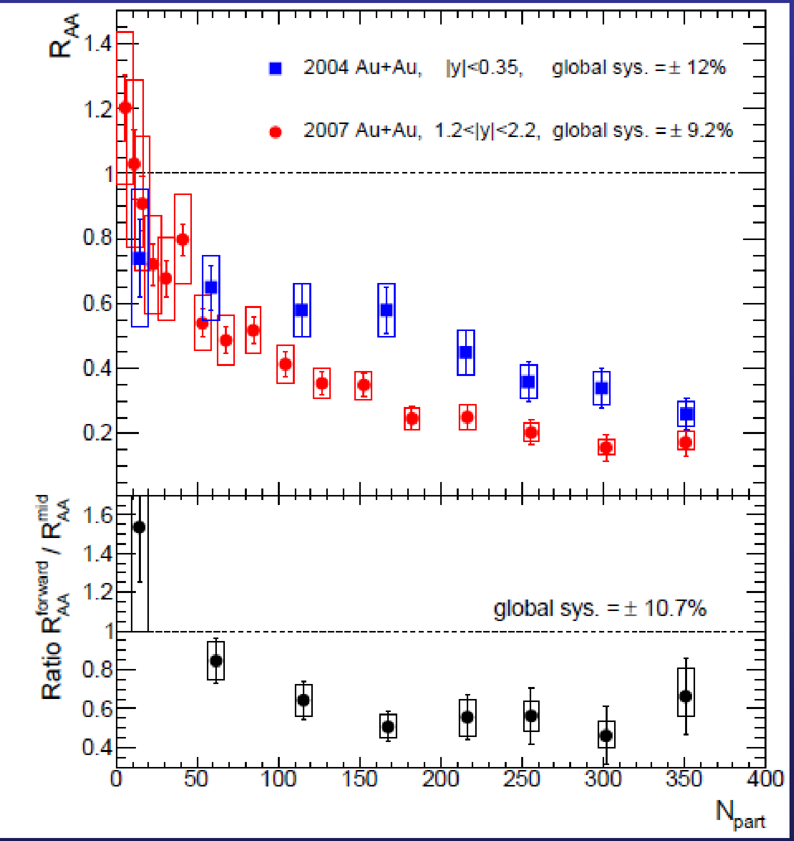
Charmonium results in AA (J/ψ, $\psi(2S)$)

Selected RHIC results: PHENIX

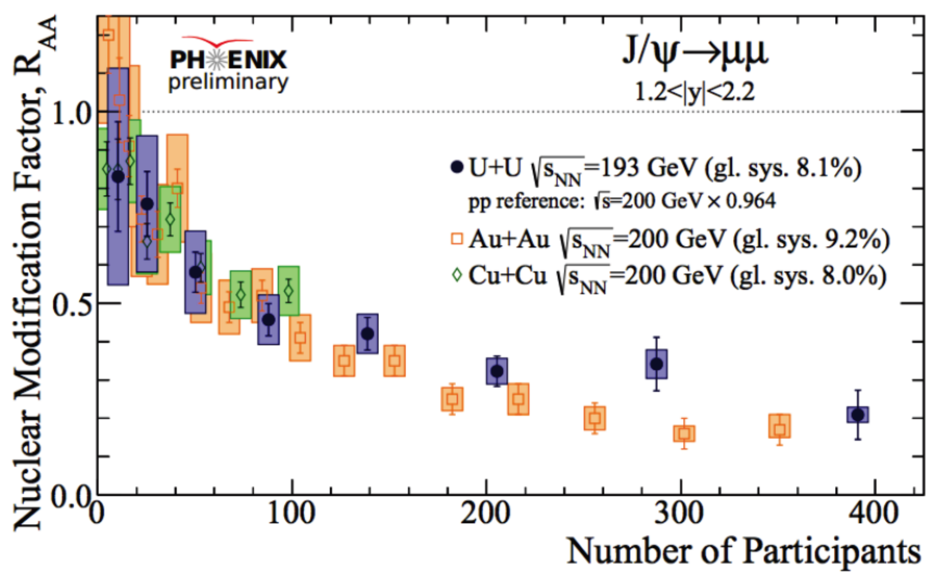
PHENIX, $\sqrt{s_{NN}}$ =200 GeV

A. Adare et al. (PHENIX) PRC84(2011) 054912

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



PHENIX, arXiv:1509.05380



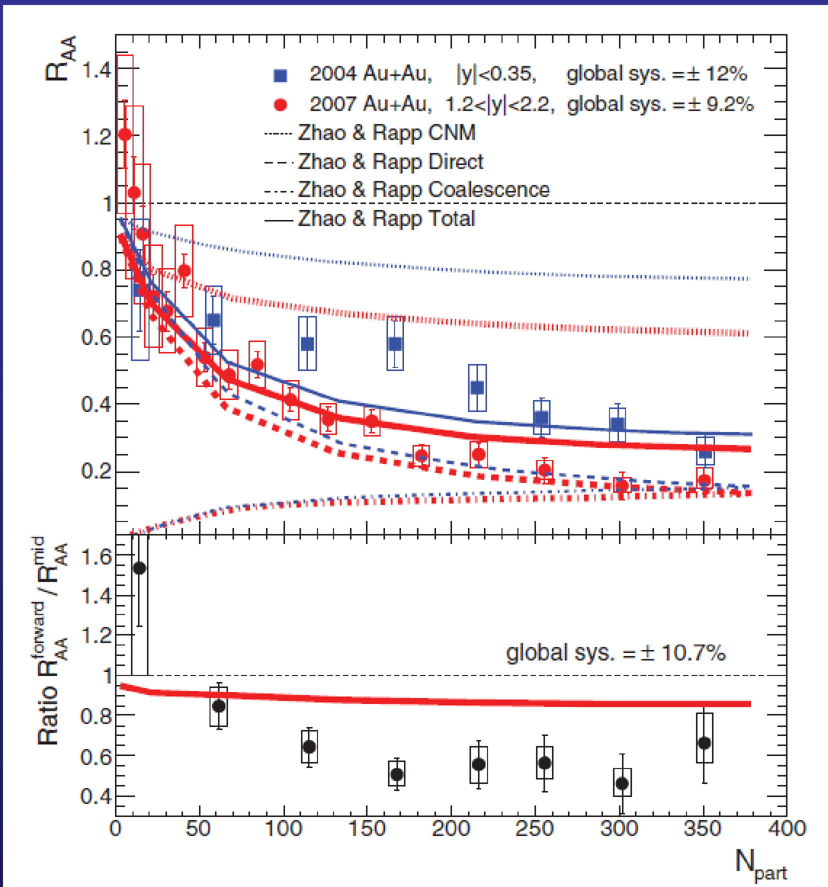
- Various colliding systems studied, up to U-U, similar suppression patterns

- Suppression, with strong rapidity dependence, in Au-Au at $\sqrt{s}$= 200 GeV

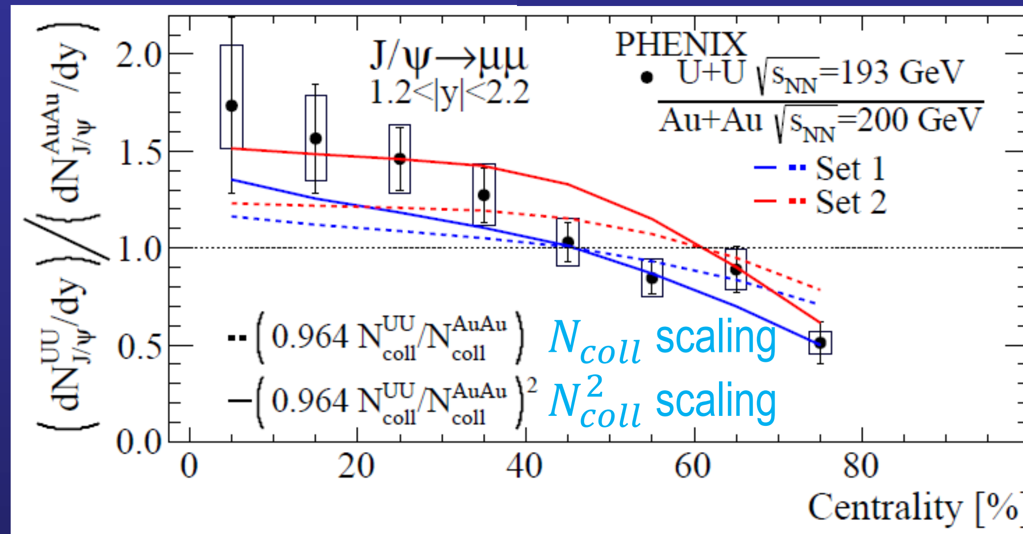
Comparisons with theory

- Smaller suppression at central rapidity in Au-Au suggests the presence of suppression AND recombination effects at RHIC energy
  → Only qualitative agreement with models

PHENIX, arXiv:1509.05380



A. Adare et al. (PHENIX) PRC84(2011) 054912

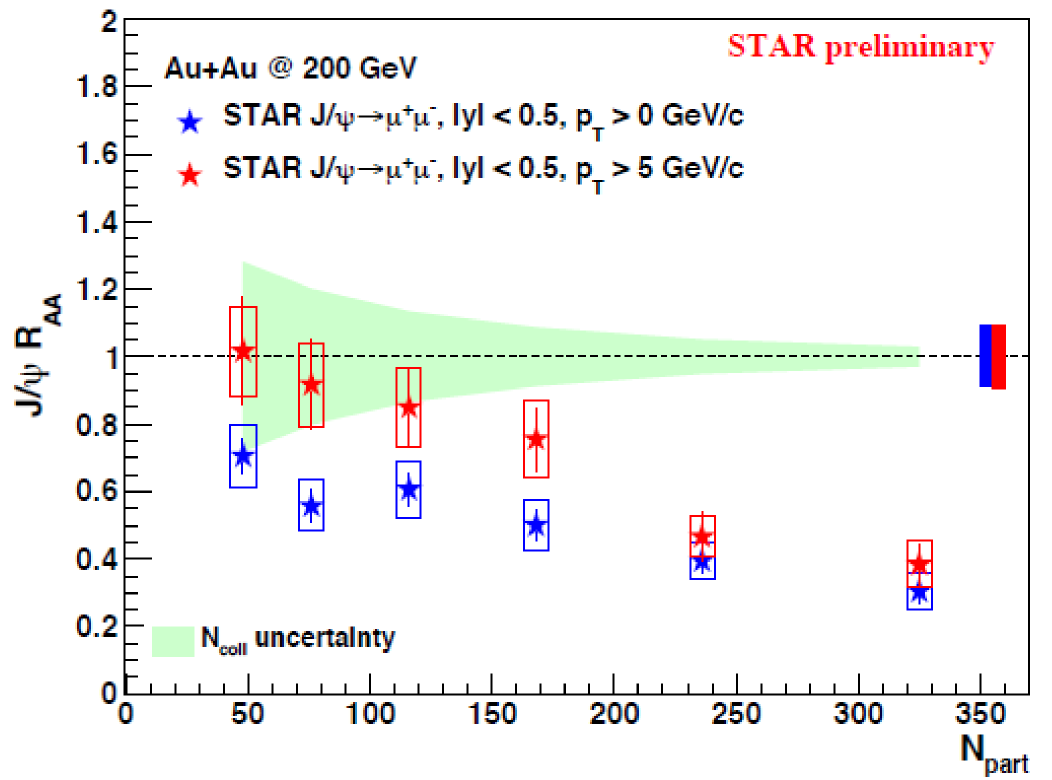


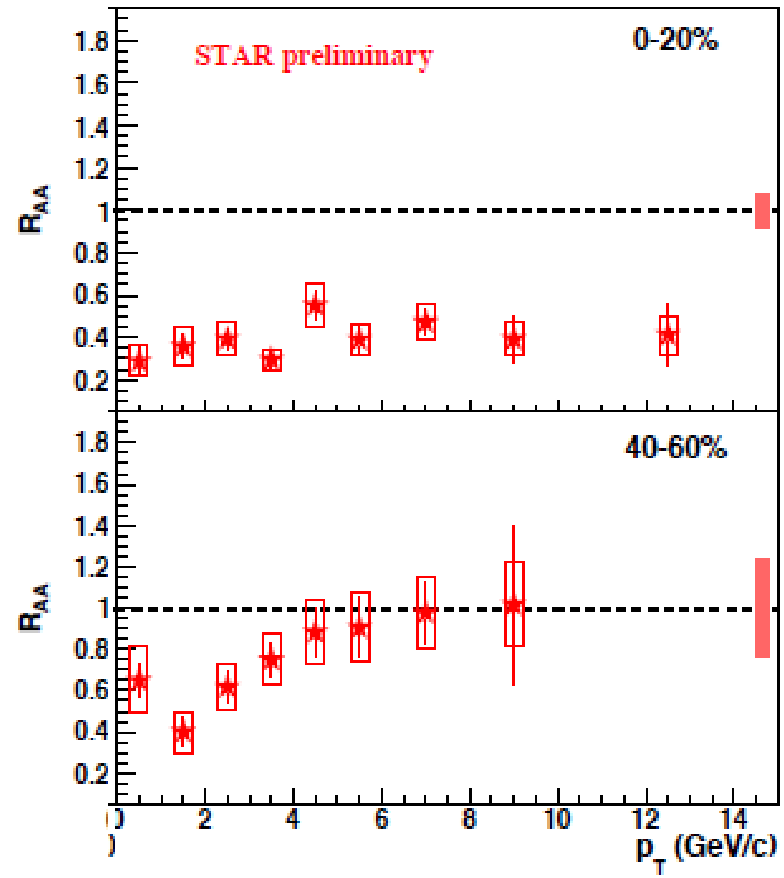
In central U-U wrt Pb-Pb
Expect stronger suppression BUT also stronger recombination due to larger N_{coll}

Results slightly favour N_{coll}^2 scaling
→ (re)combination wins over suppression

Selected RHIC results: STAR

STAR, $\sqrt{s_{NN}}$ =200 GeV



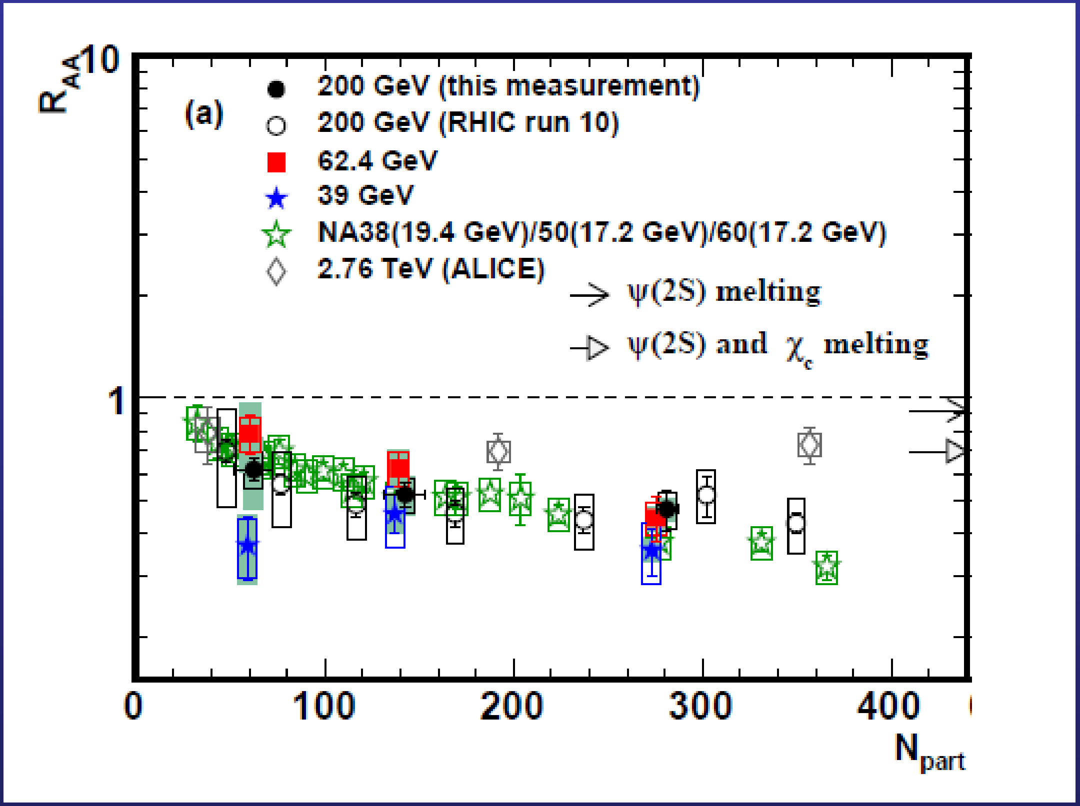


- ❑ Low-p_T , suppression at all centralities
- ❑ High p_T, strong suppression for central events and no suppr. for peripheral

❑ Re-generation expected to enhance low-p_T production → not seen

J/ψ suppression vs $\sqrt{s_{NN}}$

STAR, arXiv:1607.07517



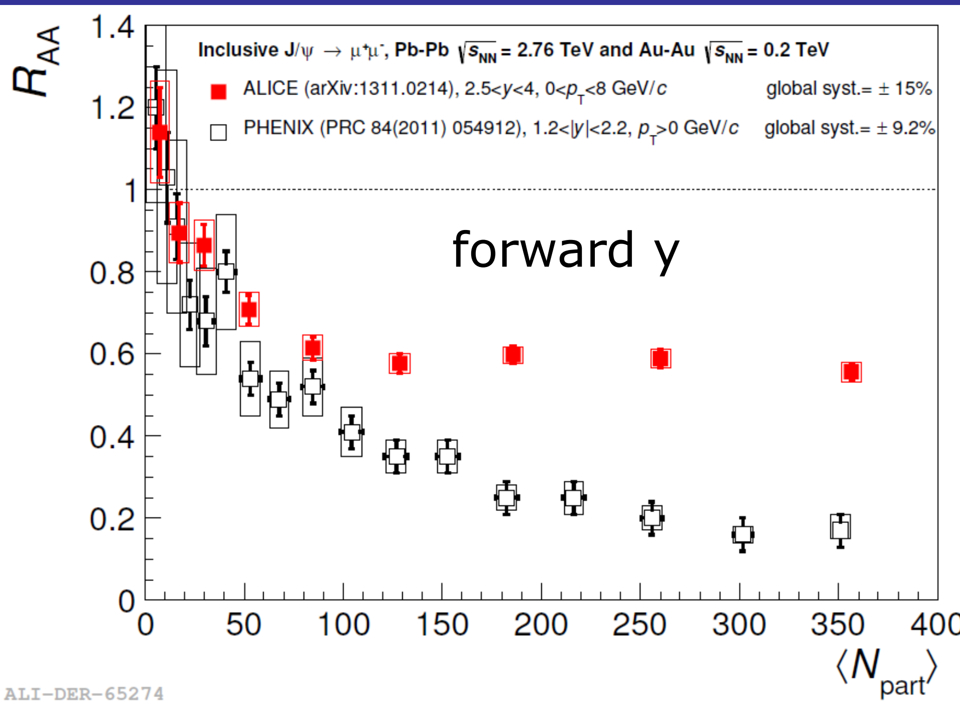
(similar result from PHENIX, at forward rapidity)

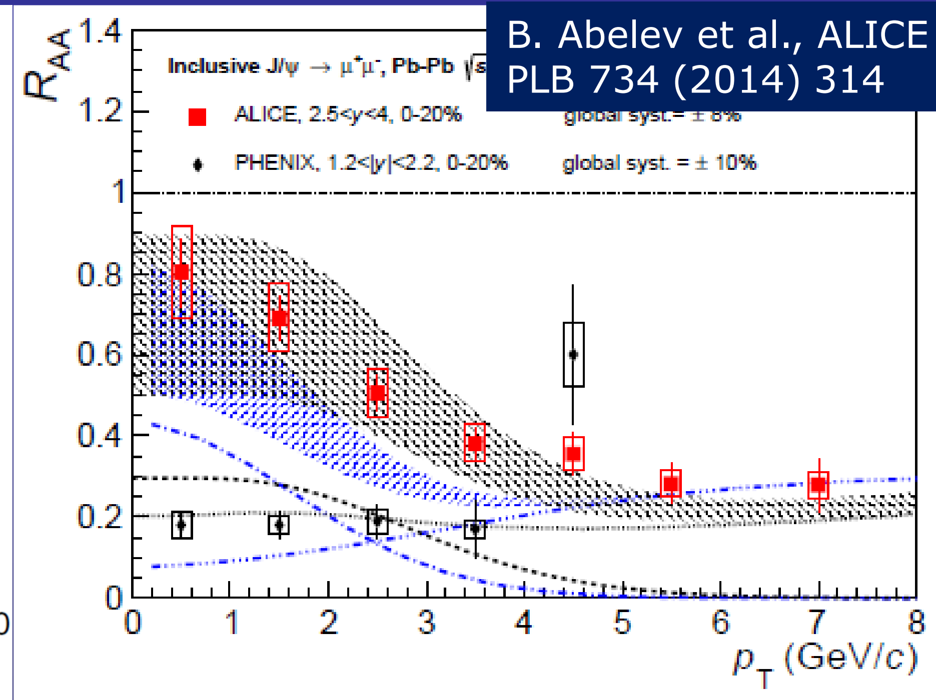
→ No significant $\sqrt{s_{NN}}$-dependence at RHIC energy, from 39 to 200 GeV

- Similar conclusions when including SPS results
- Warning: CNM effects expected to vary, reference pp cross sections obtained through extrapolations

- LHC results show different trend → next slides!

LHC run-1 results: ALICE (vs PHENIX)



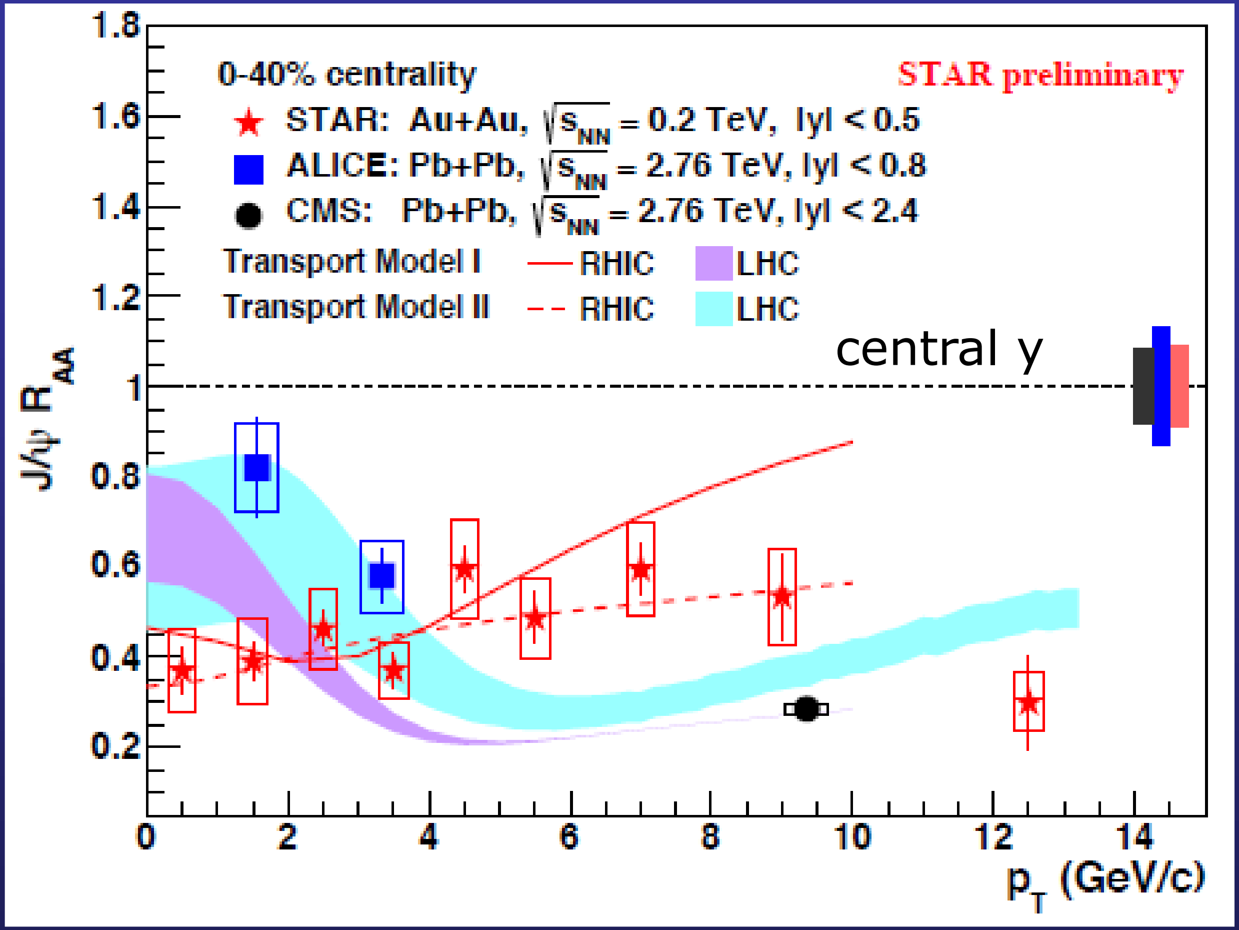


B. Abelev et al., ALICE PLB 734 (2014) 314

- ❑ Compare J/ψ suppression, RHIC ($\sqrt{s_{NN}}$=0.2 TeV) vs LHC ($\sqrt{s_{NN}}$=2.76 TeV)
- ❑ Results vs centrality dominated by low-p_T J/ψ
  - ❑ Systematically larger R_{AA} values for central events at LHC energy
  - ❑ R_{AA} increases at low p_T at LHC energy

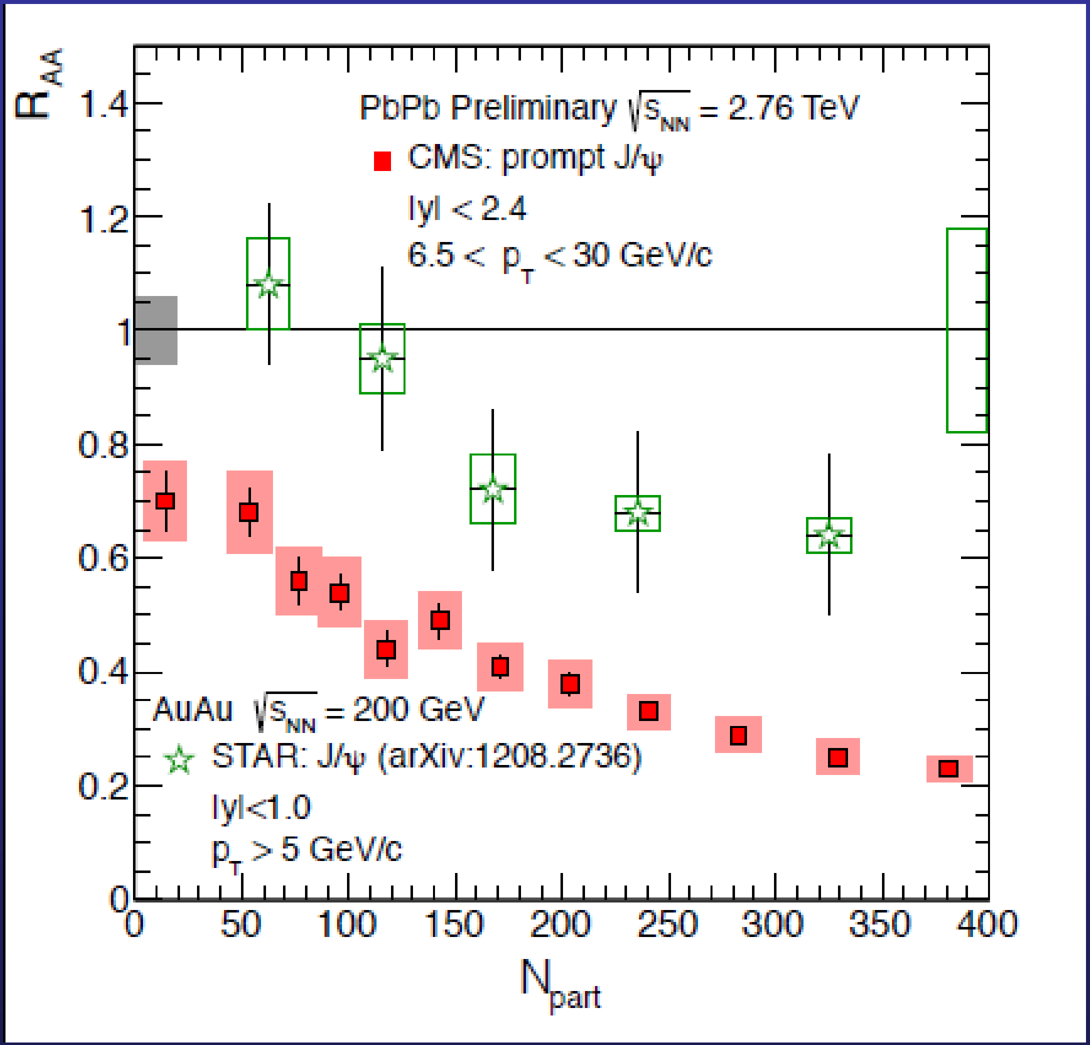
Possible interpretation:
- RHIC energy → suppression effects dominate
- LHC energy → suppression + regeneration

LHC run-1 results: ALICE/CMS (vs STAR)



- Transport models (continuous suppression and regeneration in the QGP) are able to qualitatively reproduce BOTH LHC and RHIC results

CMS run-1 results: prompt J/ψ at high p_T



CMS-PAS HIN-12-2014

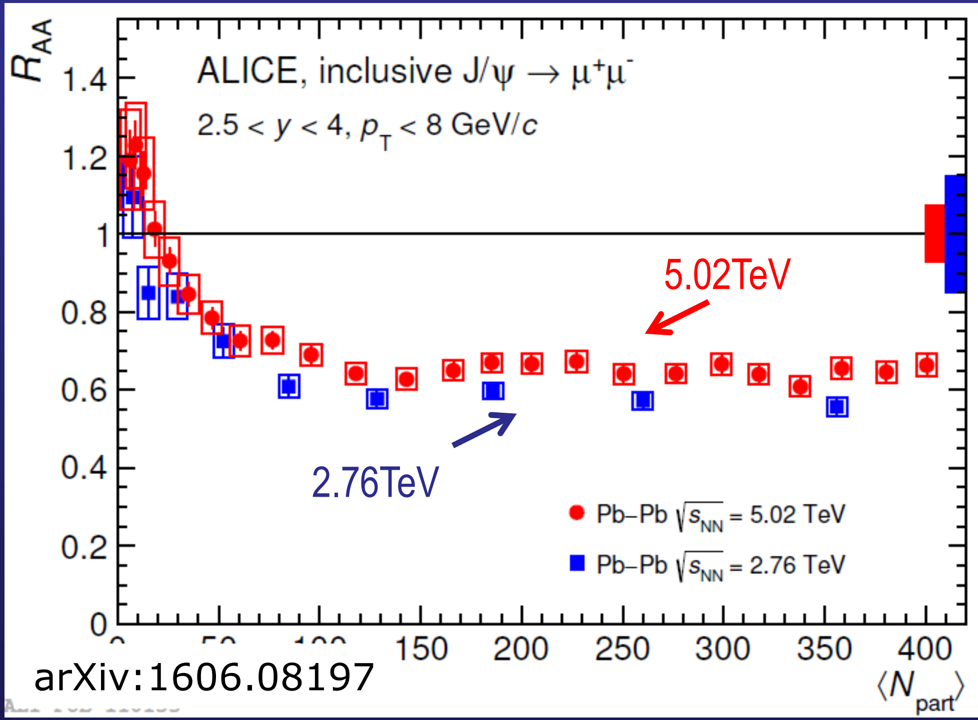
- Striking difference with respect to low p_T results
  - No saturation of the suppression vs centrality
  - High-p_T RHIC results show weaker suppression

- (Re)generation processes expected to be negligible at high p_T

- Larger suppression at the LHC due to higher initial temperature of the QGP

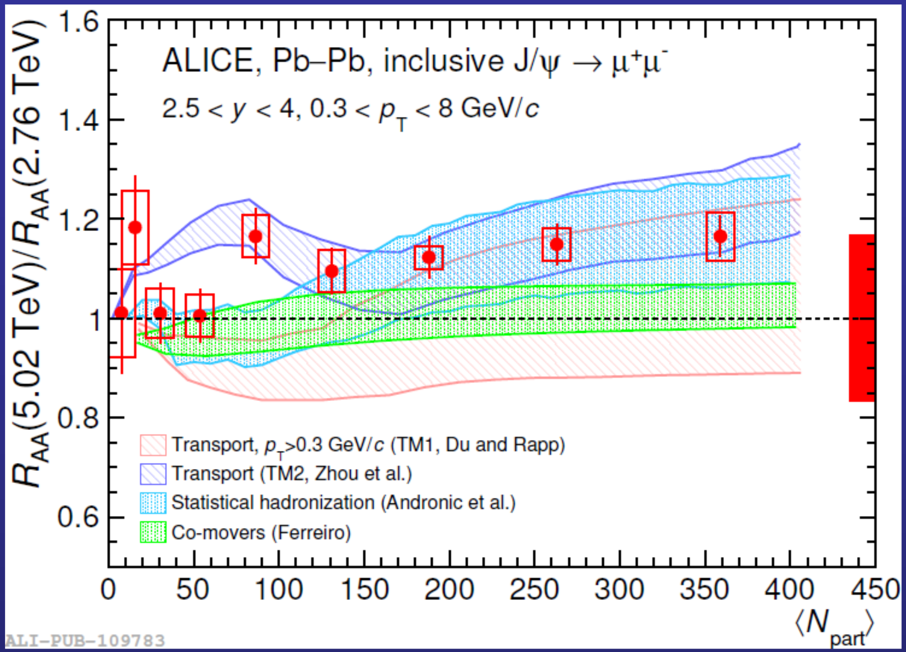
ALICE, recent results from LHC run-2

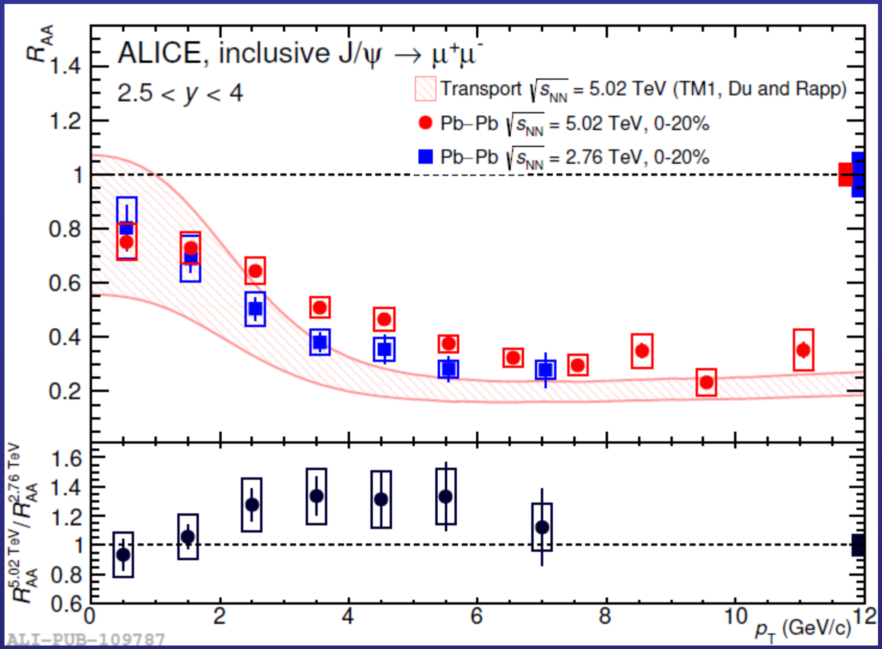
- Pb-Pb collisions @ $\sqrt{s_{NN}}$=5.02TeV
- High statistics Run-2 allows the R_{AA} evaluation in narrow centrality bins



- Similar centrality dependence at the two energies, with an increasing suppression up to N_{part}~100, followed by a plateau
- R_{AA} @ 5.02TeV is ~15% higher than the one at 2.76TeV, even if within uncertainties

Comparison with models





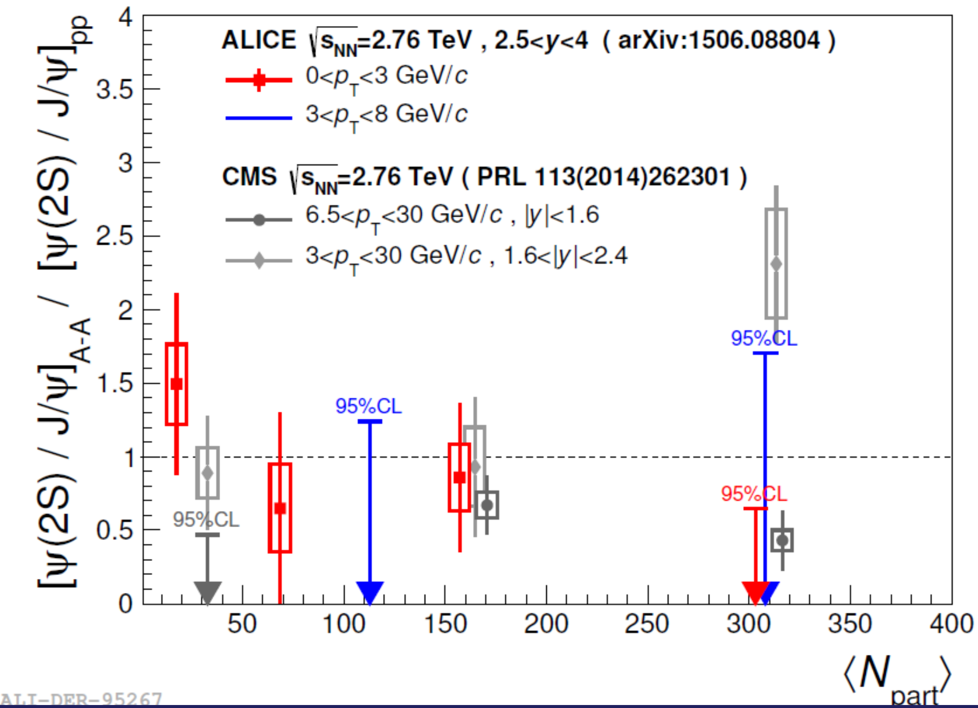
- Theoretical and experimental uncertainties reduced in the R_{AA} double ratio
- Centrality dependence of the R_{AA} ratio is rather flat

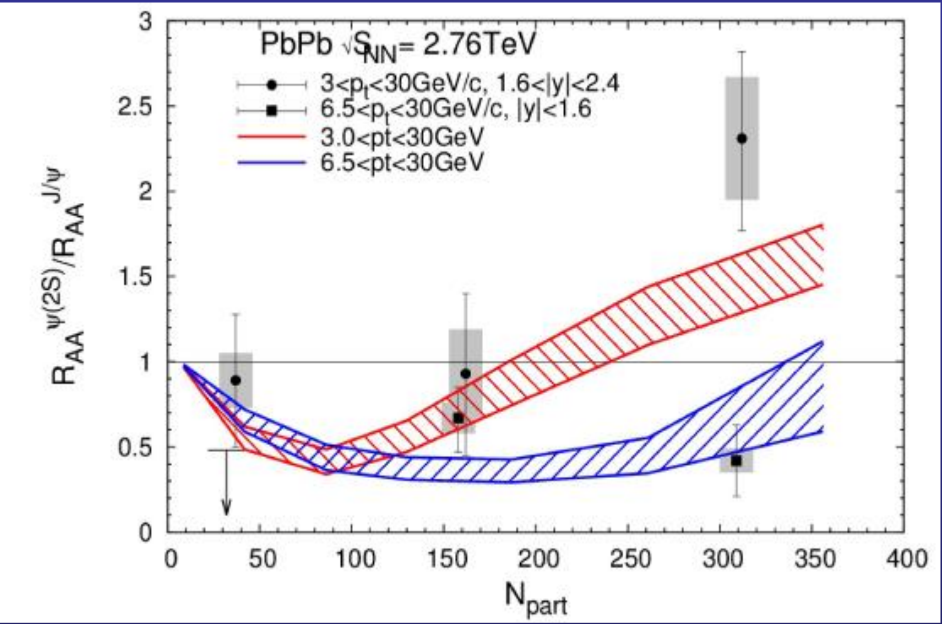
- R_{AA} increases at low p_T, at both energies, as expected in a regeneration scenario
- Hint for an increase of R_{AA}, at 5.02TeV, in 2<p_T<6 GeV/c

→ Also $\sqrt{s_{NN}}$=5.02TeV results support a picture where a combination of J/ψ suppression and (re)combination occurs in the QGP

ψ(2S) in Pb-Pb (run-1): ALICE "vs" CMS

- ψ(2S) production modified in Pb-Pb with a strong kinematic dependence
- CMS → suppression at high p_T, enhancement at intermediate p_T





Du and Rapp arXiv:1504.00670

CMS, PRL113 (2014) 262301
ALICE, arXiv:1506.08804

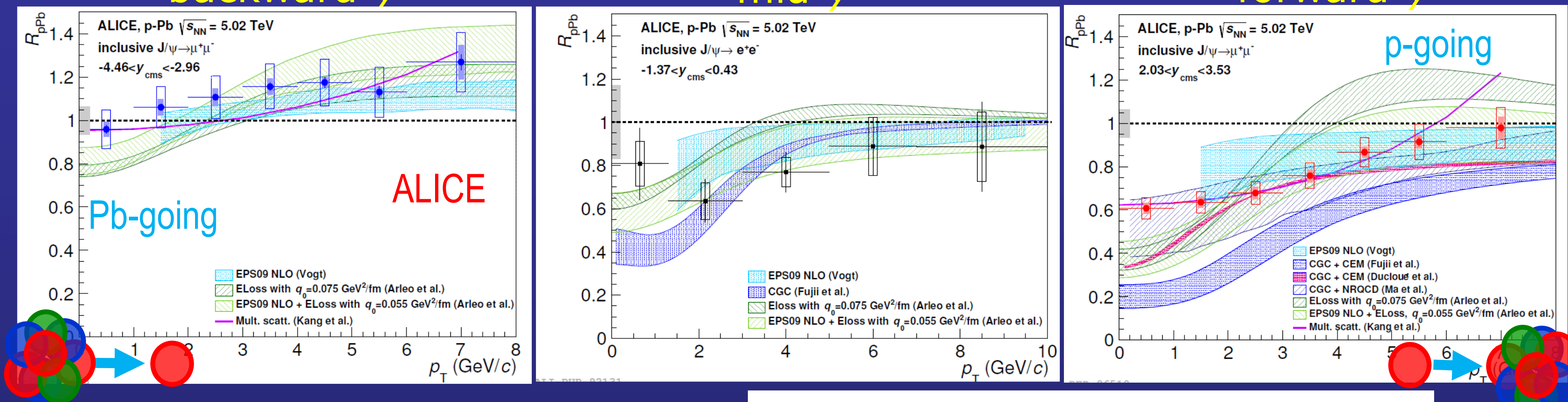
- Possible interpretation (Rapp et al.) → Re-generation for ψ(2S) occurs at later times wrt J/ψ, when a significant radial flow has built up, pushing the re-generated ψ(2S) at a relatively larger p_T

Charmonium results in pA (J/ψ, ψ(2S))

CNM effects are not negligible!

- p-Pb collisions, $\sqrt{s_{NN}}$=5.02 TeV, R_{pPb} vs p_T

backward-y mid-y forward-y

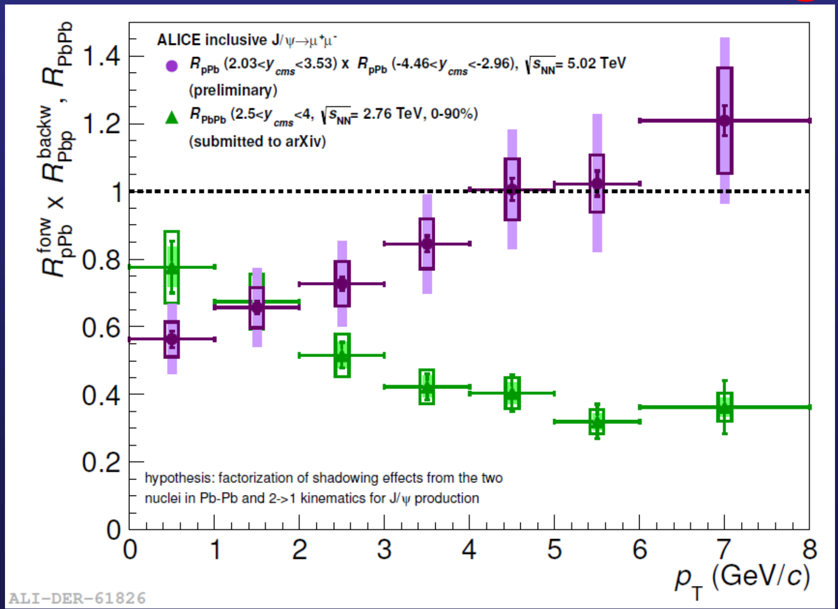


ALICE, JHEP 1506 (2015) 055

- Fair agreement with models (shadowing/CGC + energy loss)

- (Rough) extrapolation of CNM effects to Pb-Pb $R_{PbPb}^{cold}=R_{pPb}\times R_{Pbp}$

→ Evidence for hot matter effects!



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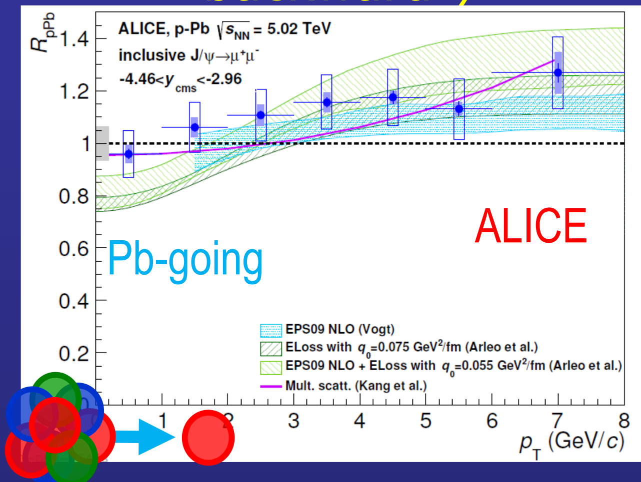
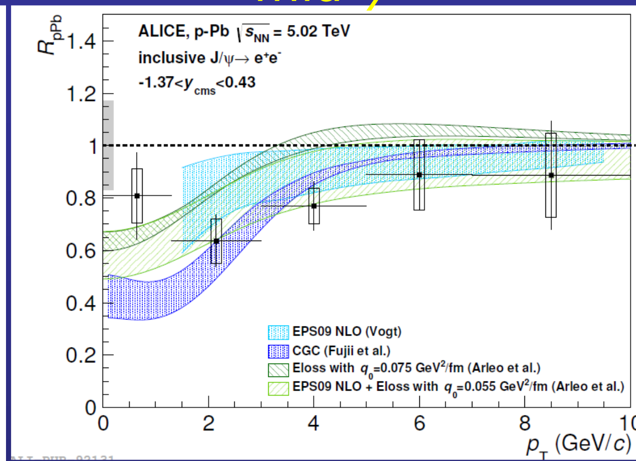
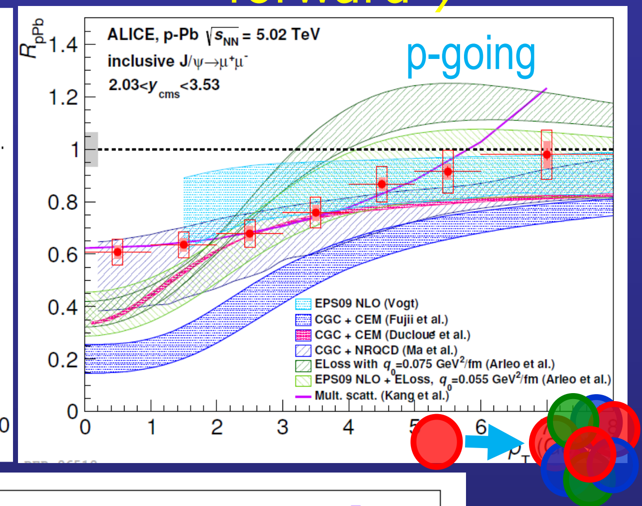
backward-*y*



mid-*y*



forward-*y*



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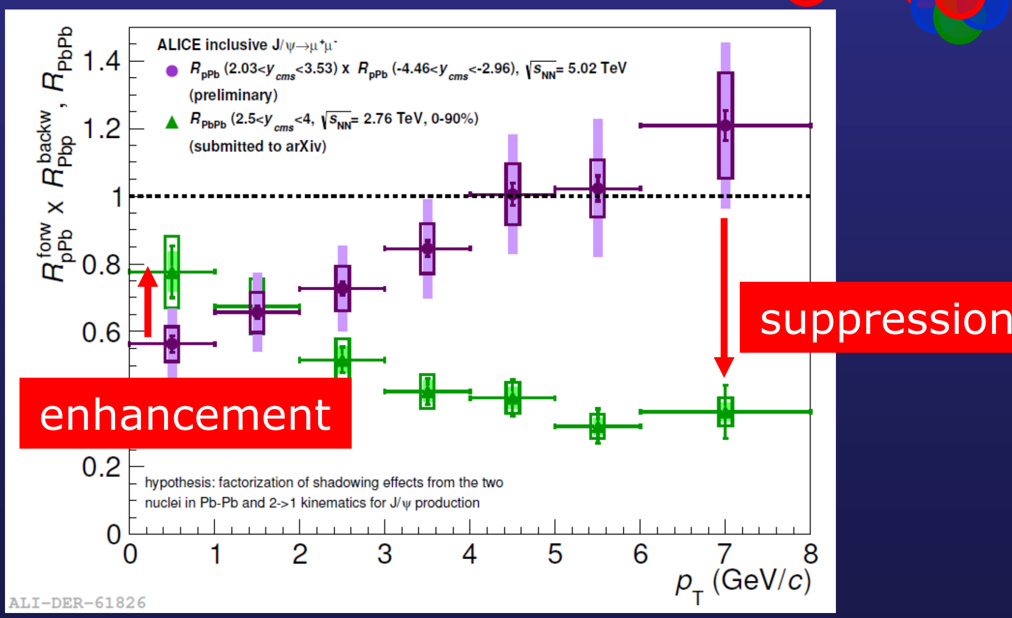
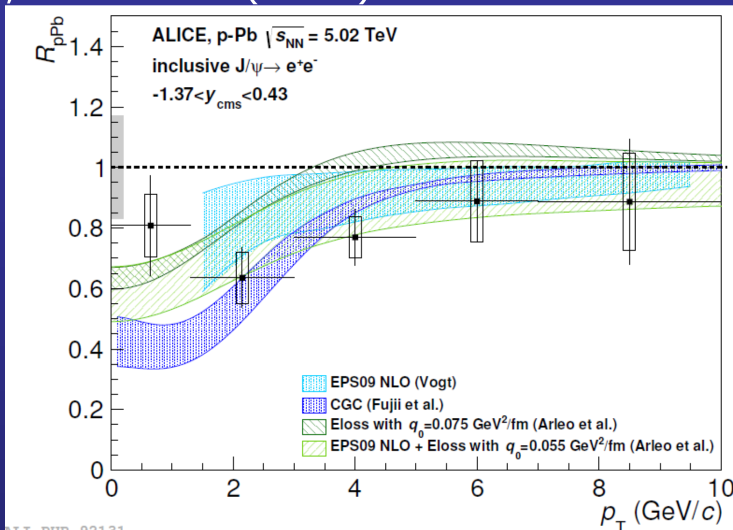


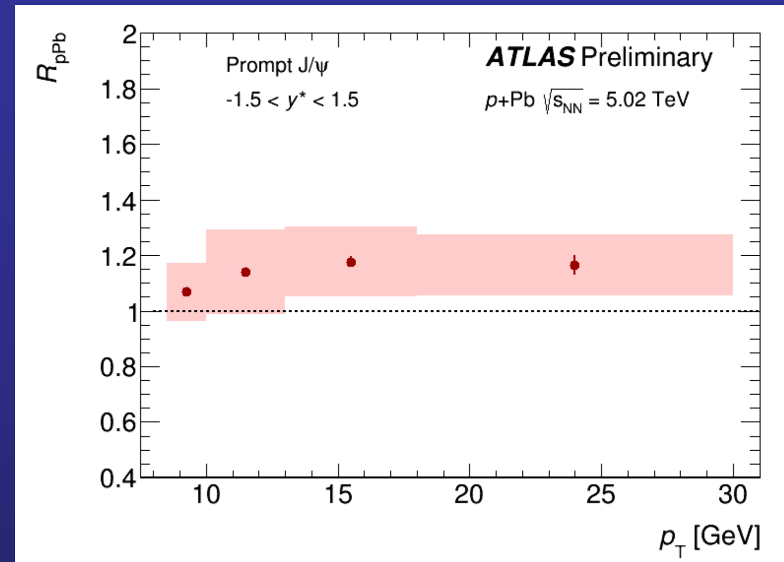
J/ψ R_{pPb}: ATLAS "vs" ALICE "vs" LHCb

- R_{pPb} vs p_T around midrapidity → fair agreement ATLAS vs ALICE

ALICE, JHEP 1506 (2015) 055

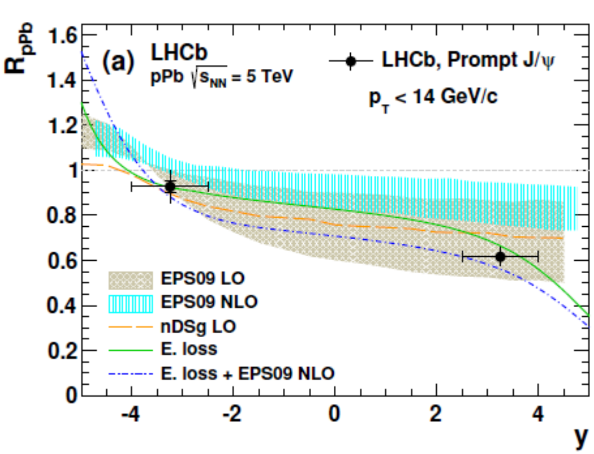
ATLAS-CONF-2015-023

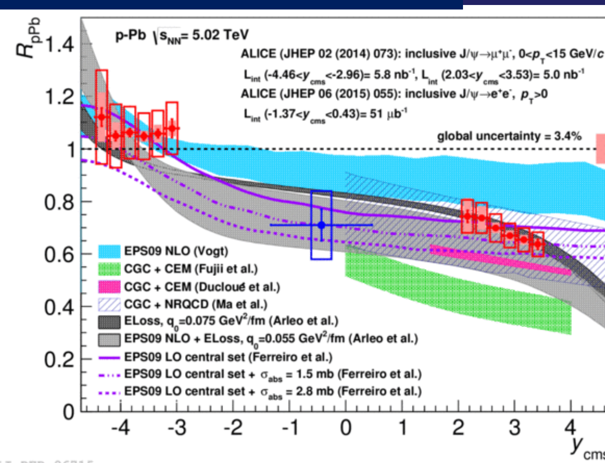


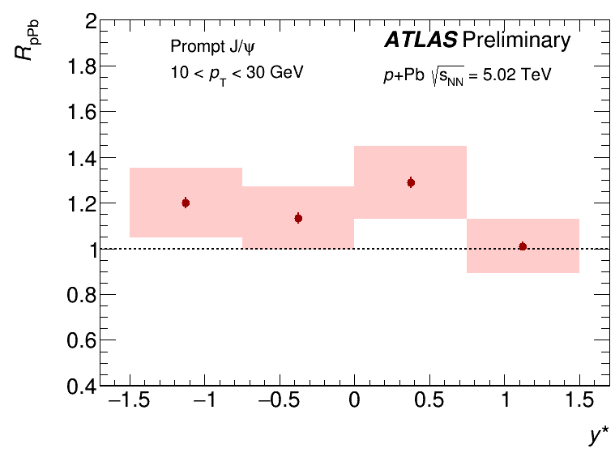


- R_{pPb} vs y → fair agreement ALICE vs LHCb, ATLAS refers to p_T>10 GeV/c

LHCB, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73





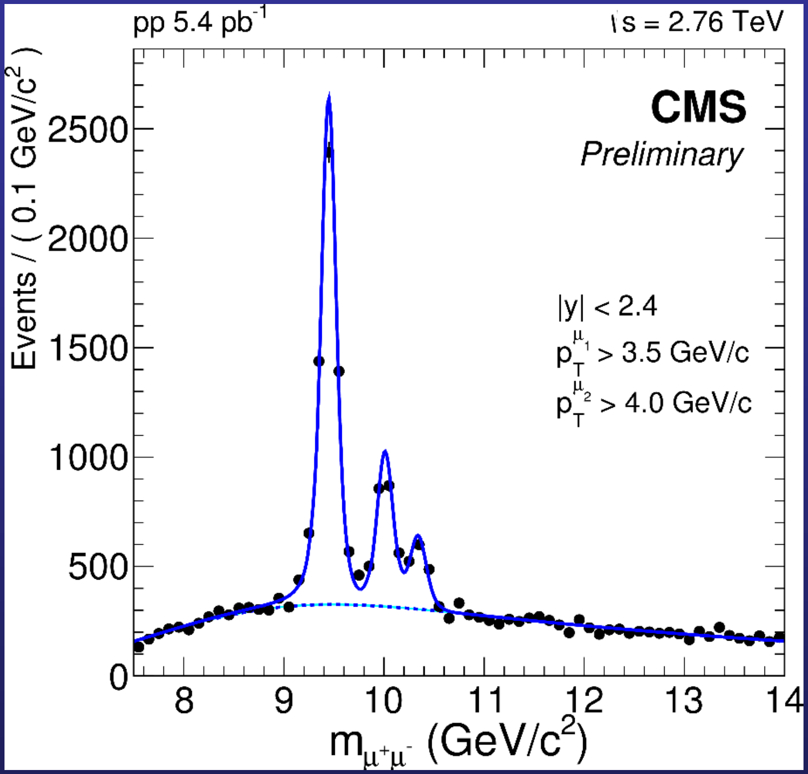


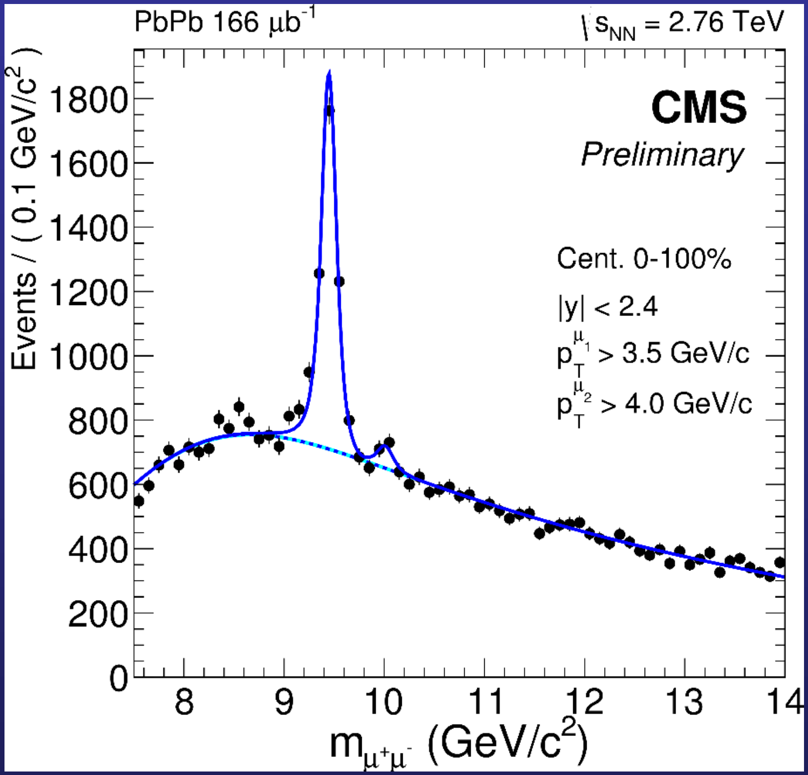
Bottomonium (Υ(1S), Υ(2S), Υ(3S))

(even if this is CHARM2016, these results represent
an important element in the physics picture)

Υ suppression in Pb-Pb collisions

- Relatively low beauty cross section → weak regeneration effects
- Kinematic coverage down to p_T=0 for all LHC experiments





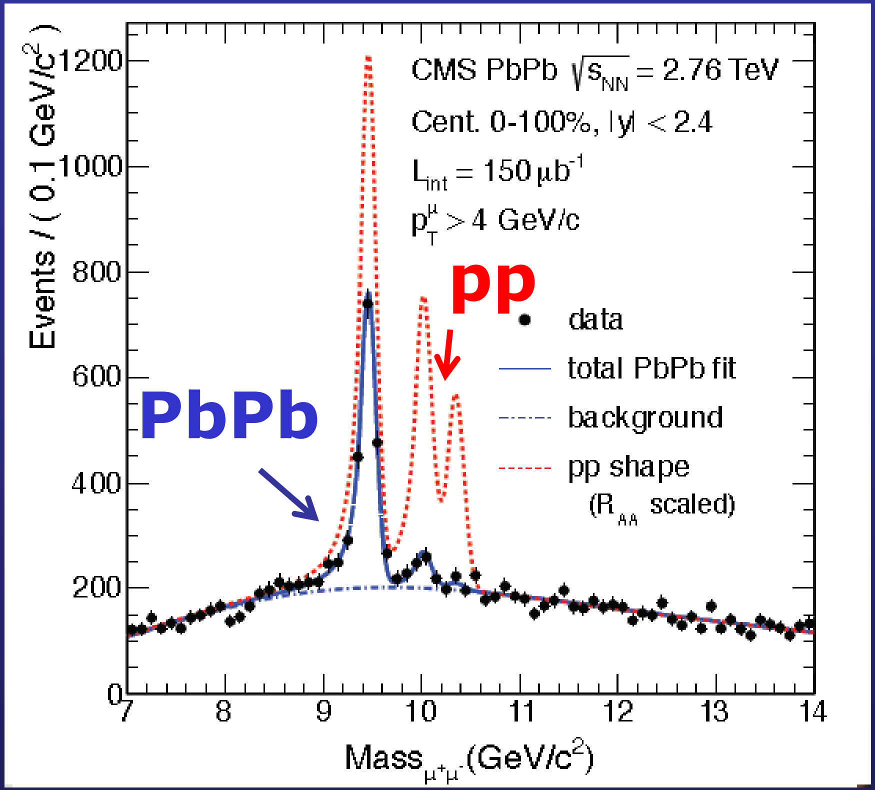
CMS-HIN-15-001

Strong relative suppression of more loosely bound states

$R_{AA}(\Upsilon(1S))$= 0.43±0.03±0.07
$R_{AA}(\Upsilon(2S))$= 0.13±0.03±0.02
$R_{AA}(\Upsilon(3S))$< 0.14 at 95% CL

ϒ suppression in Pb-Pb collisions

- ❑ Relatively low beauty cross section → weak regeneration effects
- ❑ Kinematic coverage down to $p_T=0$ for all LHC experiments



CMS-HIN-15-001

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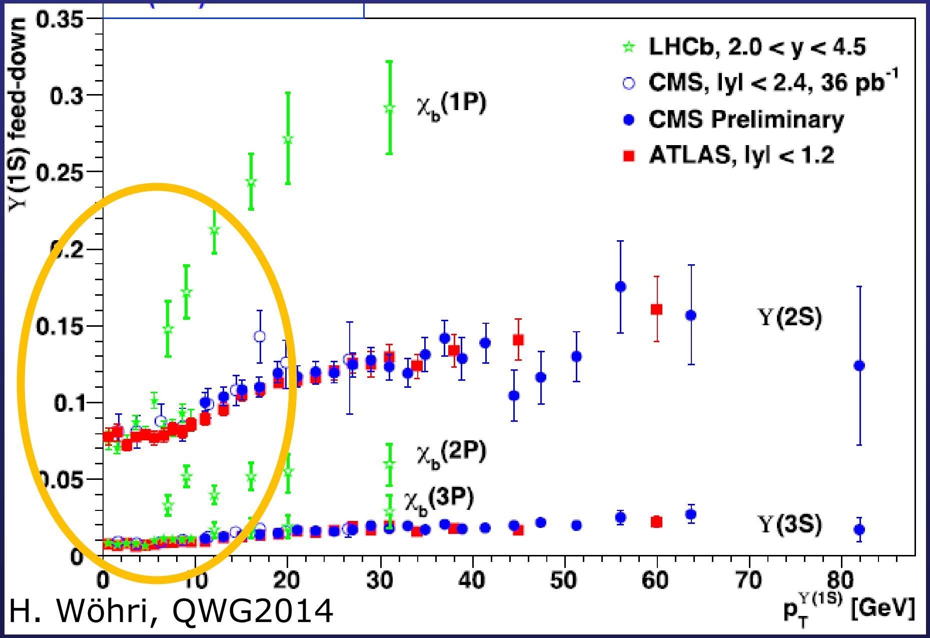
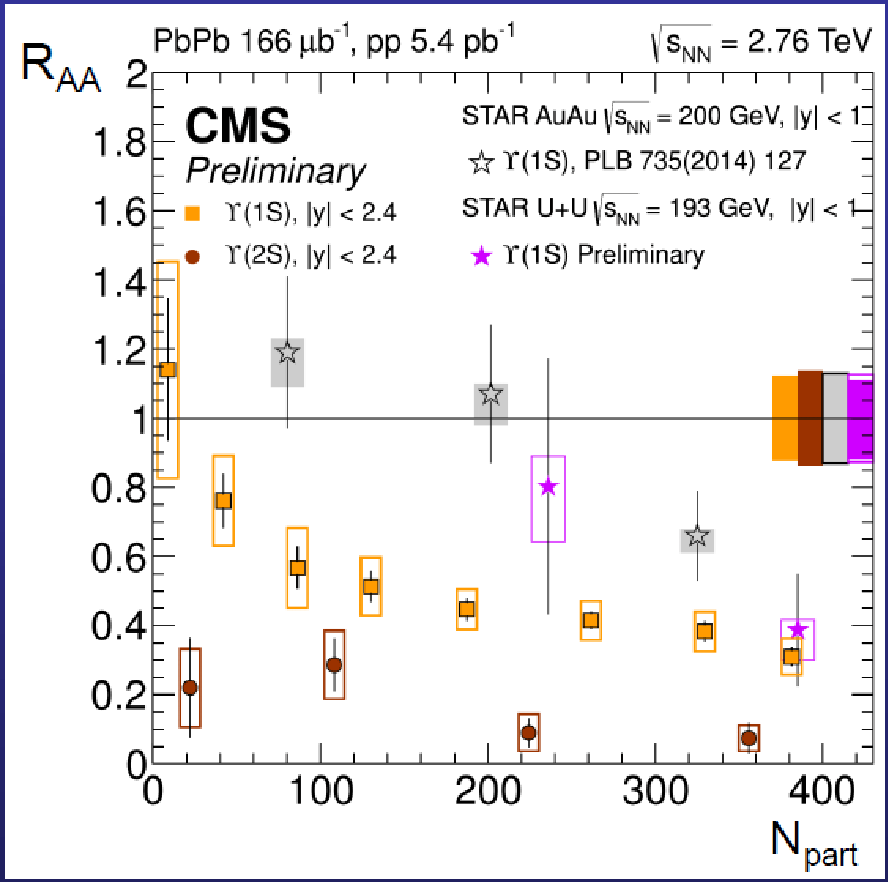
ϒ suppression in Pb-Pb: RHIC and LHC

CMS, PRL109 (2012) 222301 and HIN-15-001
STAR, PLB735 (2014) 127 and preliminary U+U

- ❑ Strong ϒ(1S) suppression
- ❑ Probably dominated by feed-down from excited states, plus CNM effects
- ❑ Similar suppression at RHIC and LHC energy



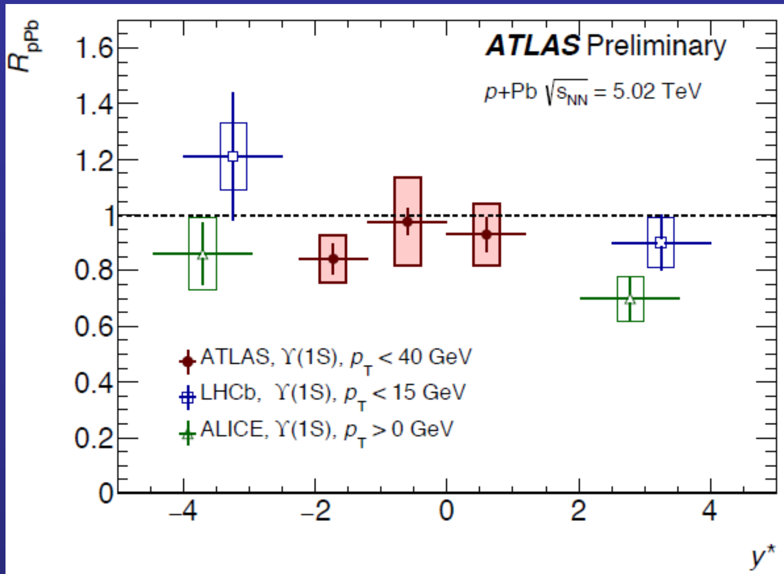
H. Wöhri, QWG2014

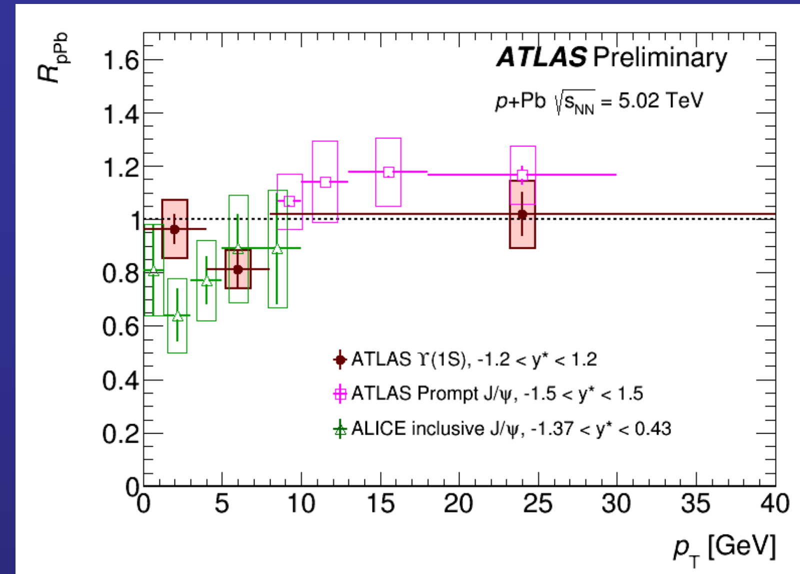


CMS-HIN-15-001

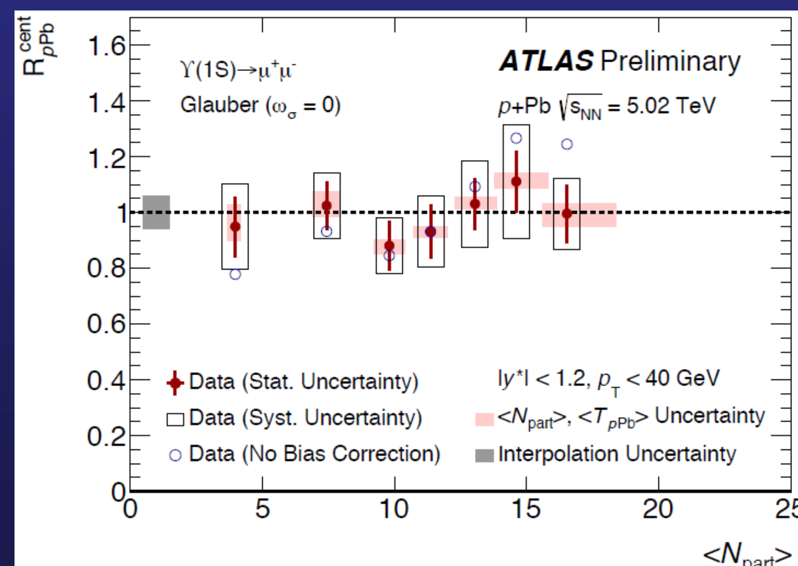
- ❑ ϒ(2S) binding energy similar to that of the J/ψ, but bottomonium suppression much larger
  → recombination effects negligible

Weak CNM effects for bottomonium





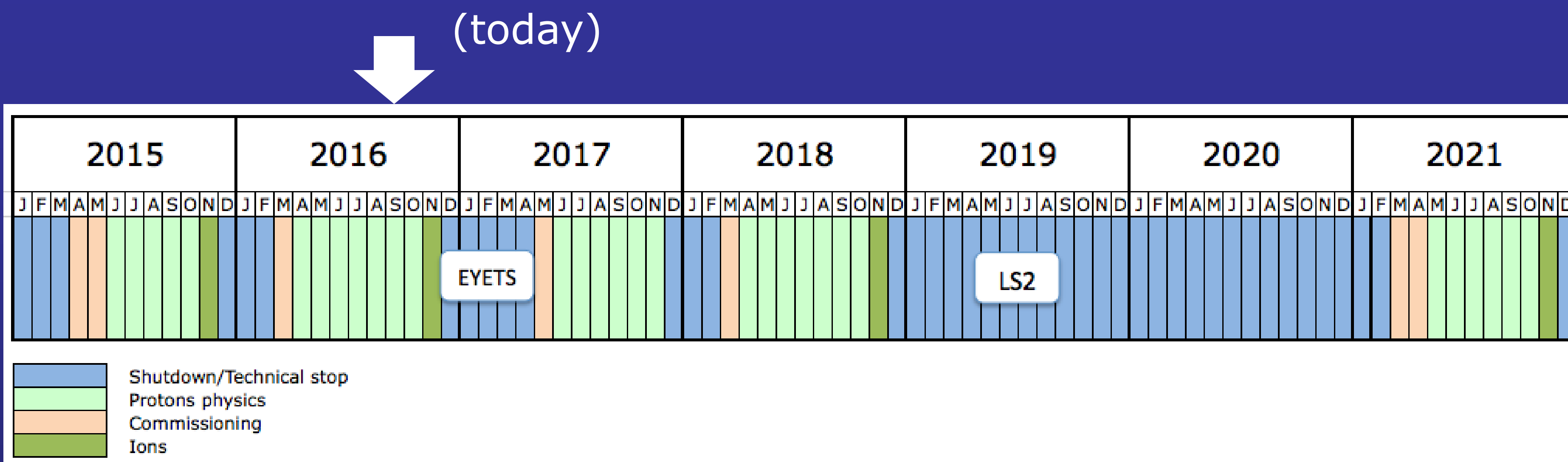
- R_{pPb} close to 1 and with no significant dependence on y, p_T and centrality
- Fair agreement ALICE vs LHCb (within large uncertainties)



ALICE, PLB 740 (2015) 105
ATLAS-CONF-2015-050
LHCb, JHEP 07(2014)094

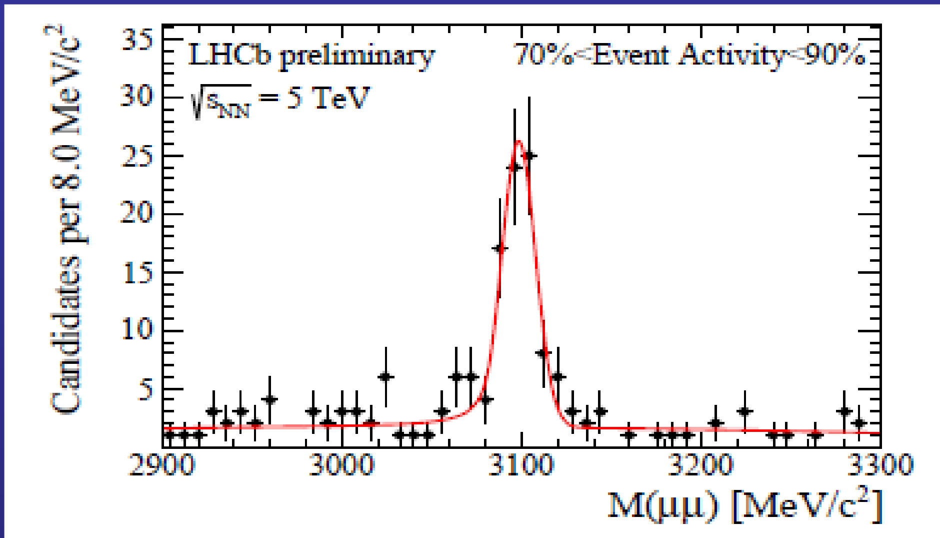
A few prospects

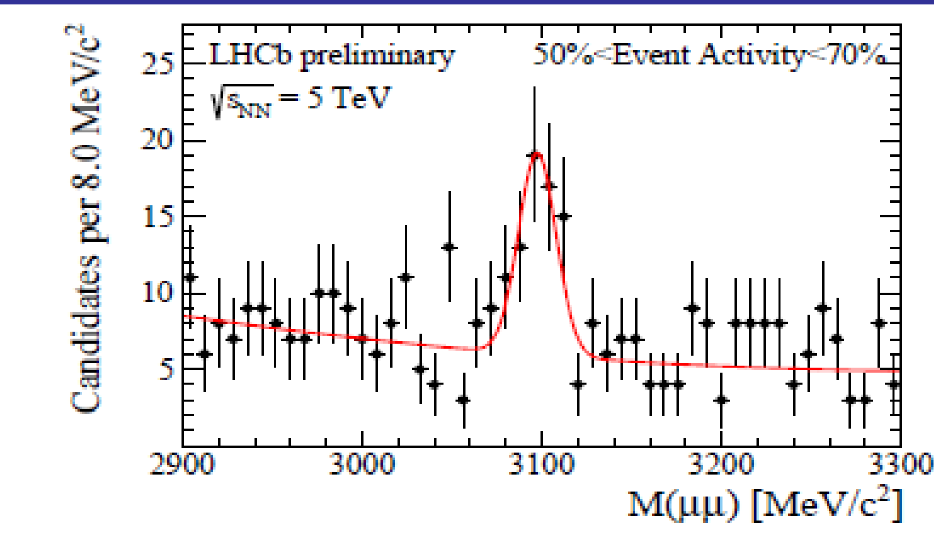
Future of LHC heavy-ion program

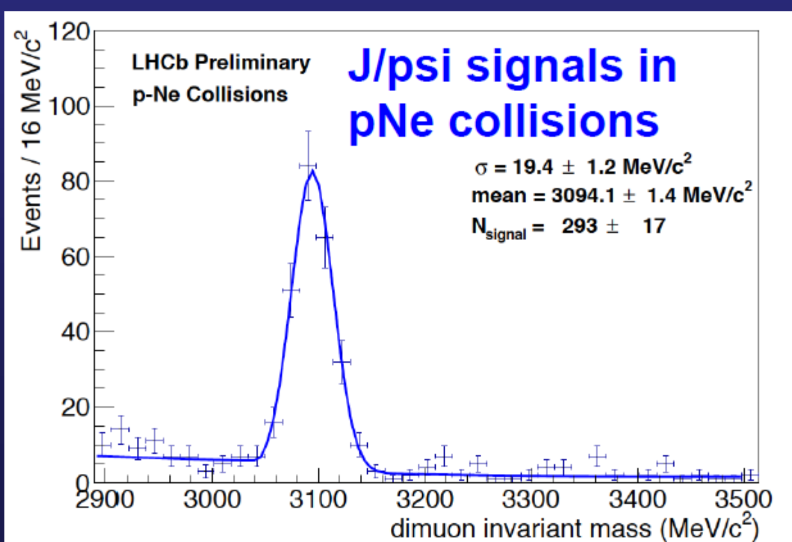


- 2016: p-Pb run, shared between $\sqrt{s_{NN}}$ = 5 TeV and $\sqrt{s_{NN}}$ = 8 TeV
- 2018: Pb-Pb run, maximum available energy, L= 10^{27} cm^{-2} s^{-1}
- LS2: ALICE upgrades apparatus (TPC, ITS) to stand 50 kHz event rate expected for run-3
- 2021-2023: LHC run-3, experiments require L_{int}>10 nb^{-1} for Pb-Pb (compared to L_{int} ~ 1 nb^{-1} for run-2)
  Possibility of accelerating lighter ions under discussion
- 2026-2029: LHC run-4

LHCb – a new actor in PbPb studies

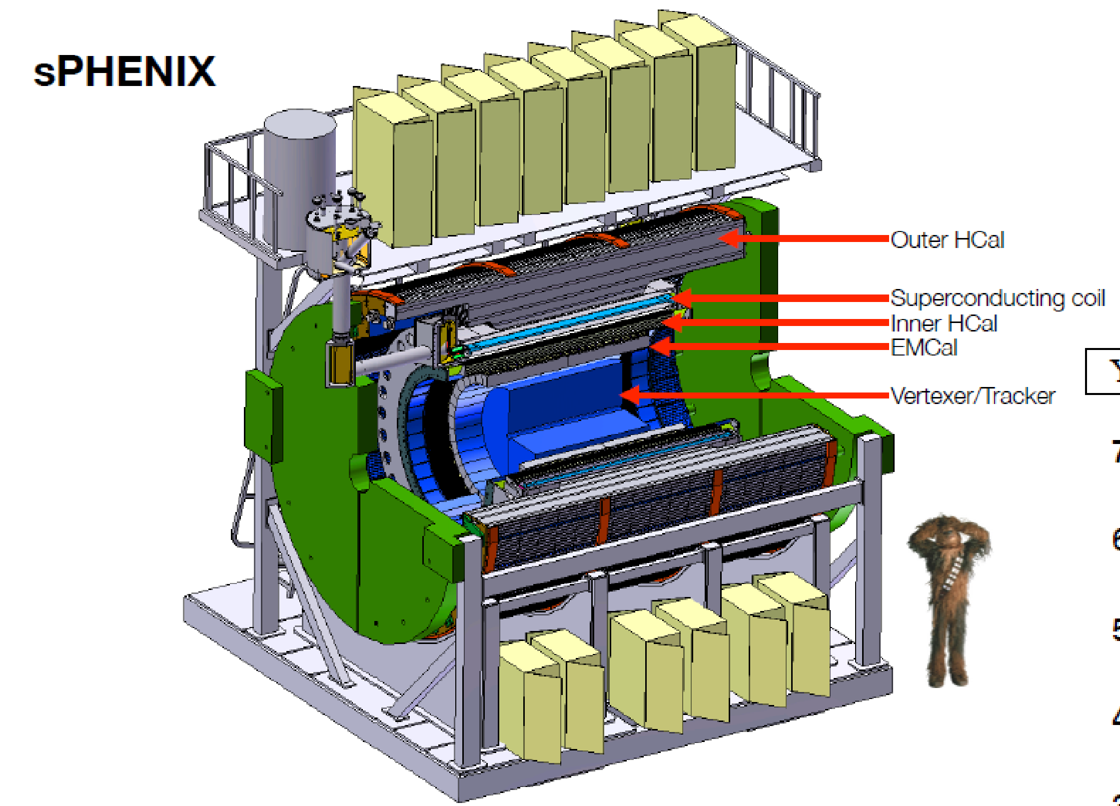




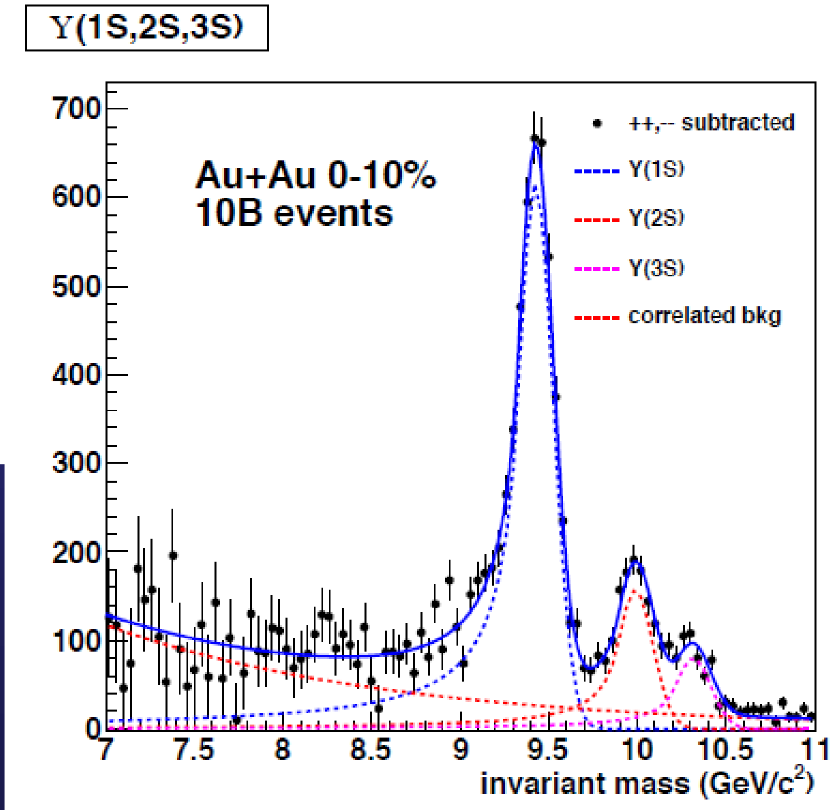


- First PbPb data taking in 2015, result expected for peripheral and semiperipheral collisions
- LHCb SMOG project: p-A beam-gas collisions ($\sqrt{s_{NN}}$=110 GeV) Covers energy between SPS and RHIC

The future of RHIC - sPHENIX



- BaBar 1.5 T superconducting solenoid
- Full em/hadronic calorimetry
- Precision tracking/vertexing



- Physics program
  → Light and HF jets, photons, upsilons and their correlations

Summary/conclusions

- J/ψ (quarkonium) suppression was proposed 30 years ago as an unambiguous signature of QGP formation in HI collisions

- At RHIC ($\sqrt{s_{NN}}$ up to 0.2 TeV) and LHC ($\sqrt{s_{NN}}$=2.76 TeV, now 5 TeV) large samples of data now exist for charmonia (and bottomonia)

- Main results
  - J/ψ suppression, likely related to QGP effects, has been observed
  - The re-generation mechanism has been predicted to be sizeable at both RHIC and LHC
  - Hints for its presence singled out at RHIC (R_{AA} vs y, UU vs PbPb)
  - Re-generation clearly present at LHC energy (R_{AA} vs p_T, flow)
  - Models qualitatively describe the data, but still large uncertainty on some key parameters → open charm cross section
  - CNM effects, dominated at LHC by shadowing/CGC, are sizeable
  - Bottomonium results compatible with sequential suppression in QGP

- New run-2 results eagerly awaited!

More info

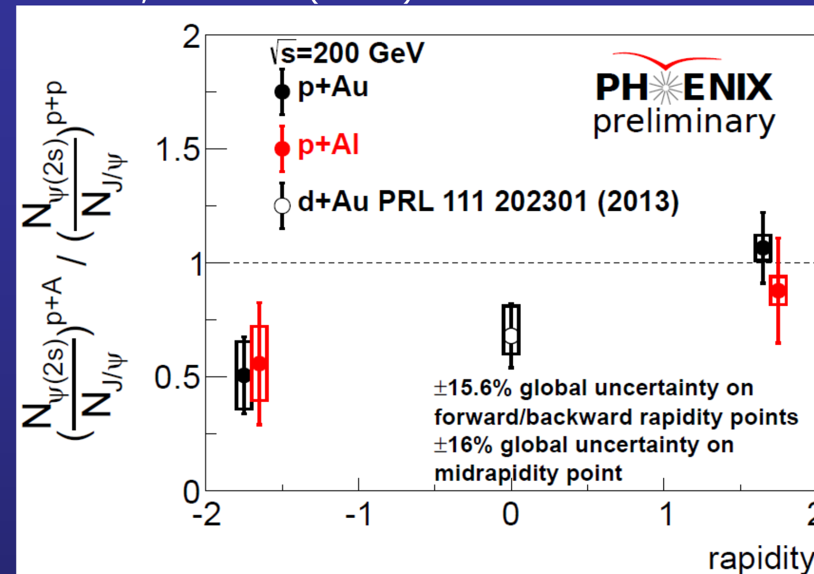
ψ(2S) in p-Pb collisions

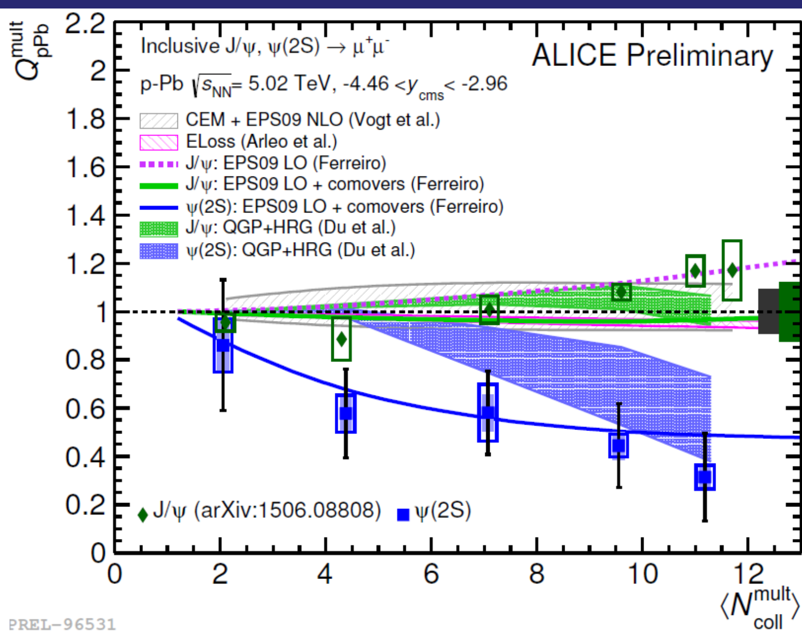
- ψ(2S) suppression is stronger than the J/ψ one at RHIC and LHC

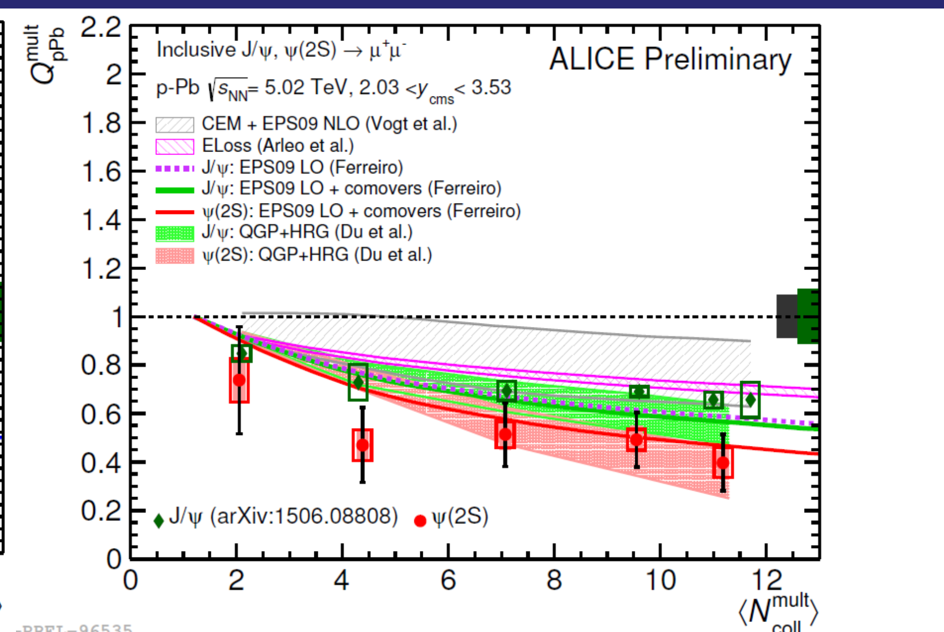
→ shadowing and energy loss, almost identical for J/ψ and ψ(2S), do not account for the different suppression

→ Only QGP+hadron resonance gas (Rapp) or comovers (Ferreiro) models describe the stronger ψ(2S) suppression

ALICE, JHEP 1412(2014)073, LHCb-CONF-2015-005
PHENIX, PRL 111 (2013) 202301



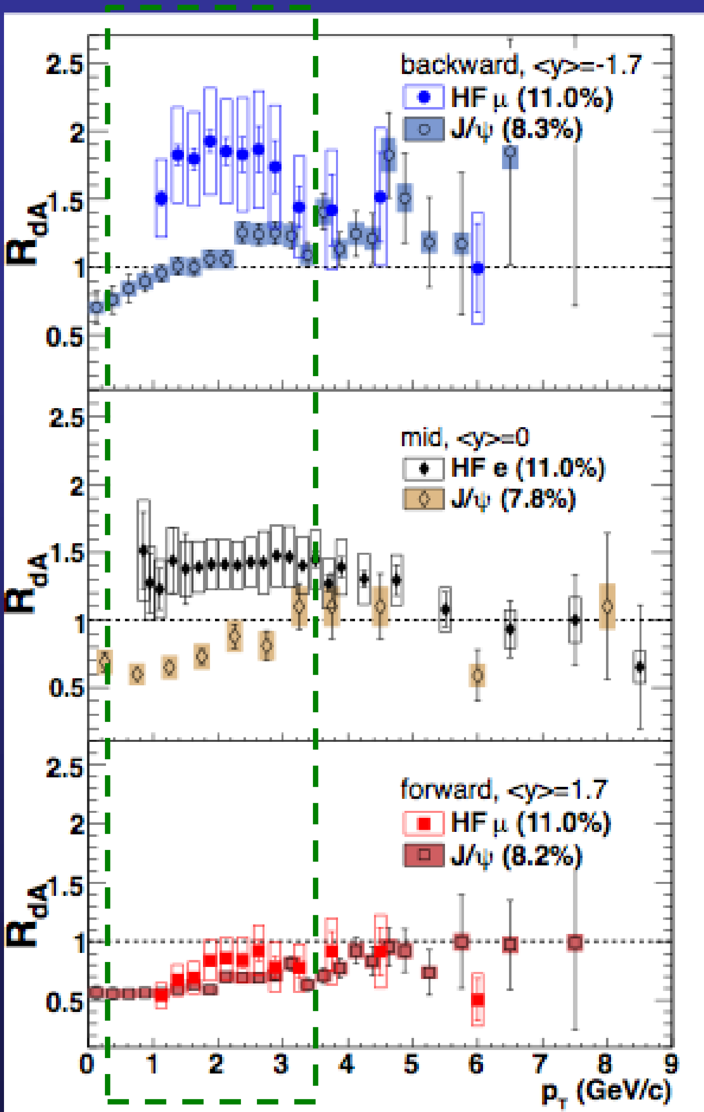




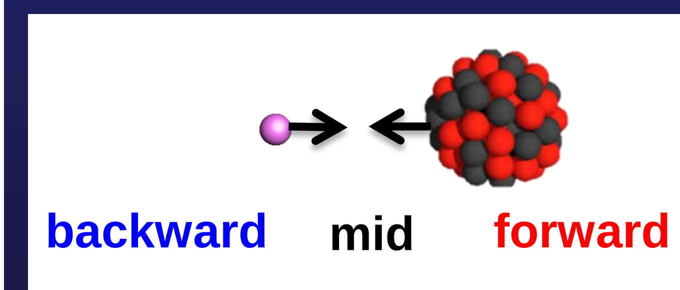
CNM at RHIC energy

PHENIX: PRC 87 034904
PHENIX: PRL 112 252301

d+Au, $\sqrt{s_{NN}}$= 200 GeV

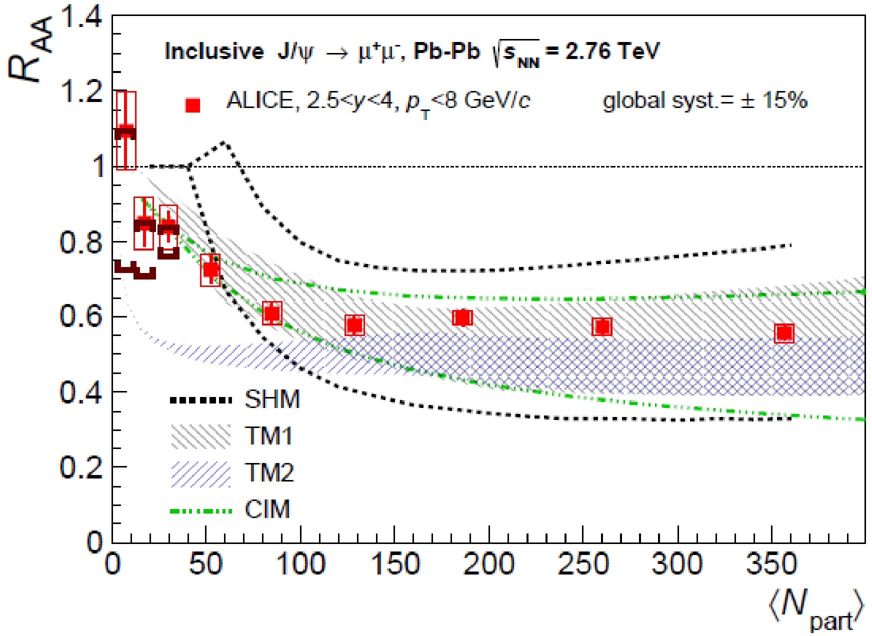


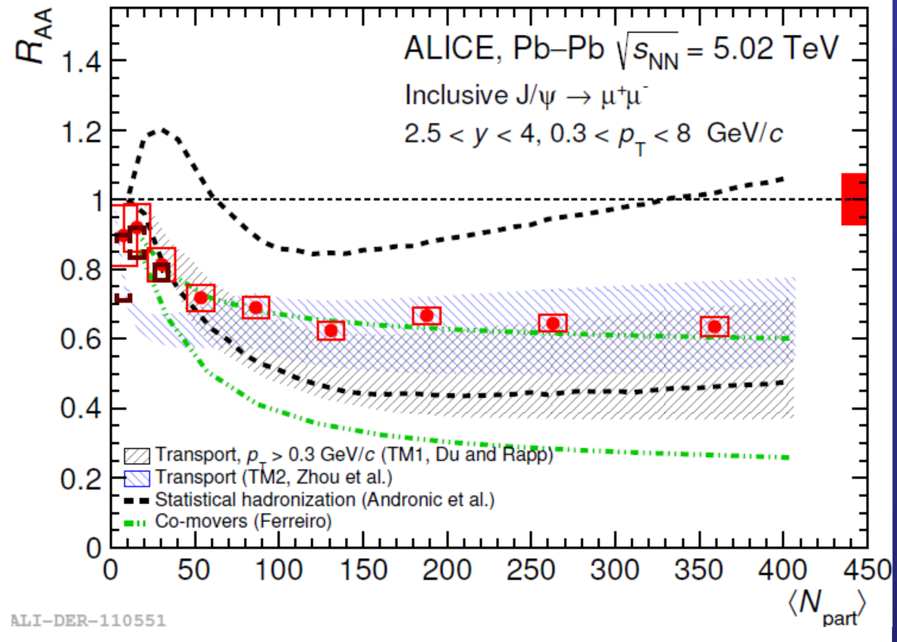
- In the most central collision:
- R_{dAu} of HF muon and J/ψ are still consistent at forward rapidity
- Clearly different at backward rapidity, charm production is enhanced but J/ψ production is significantly suppressed due to nuclear breakup inside dense comovers at backward rapidity
- Contrary to LHC results, J/ψ data allow (need) a contribution from J/ψ breakup in nuclear matter ($\sigma_{J/\psi\text{-}N}$ ~ 4 mb)



Comparison with models

$\sqrt{s_{NN}}$=2.76TeV $\sqrt{s_{NN}}$=5.02TeV





- Compare same theory models at the two energies:

TM1, TM2 (Du et al, Zhou et al): rate equation of suppr./regeneration in QGP
SHM (Andronic et al): J/ψ produced by stat. hadronization at phase boundary
CIM (Ferreiro): suppression by the partonic medium and regeneration

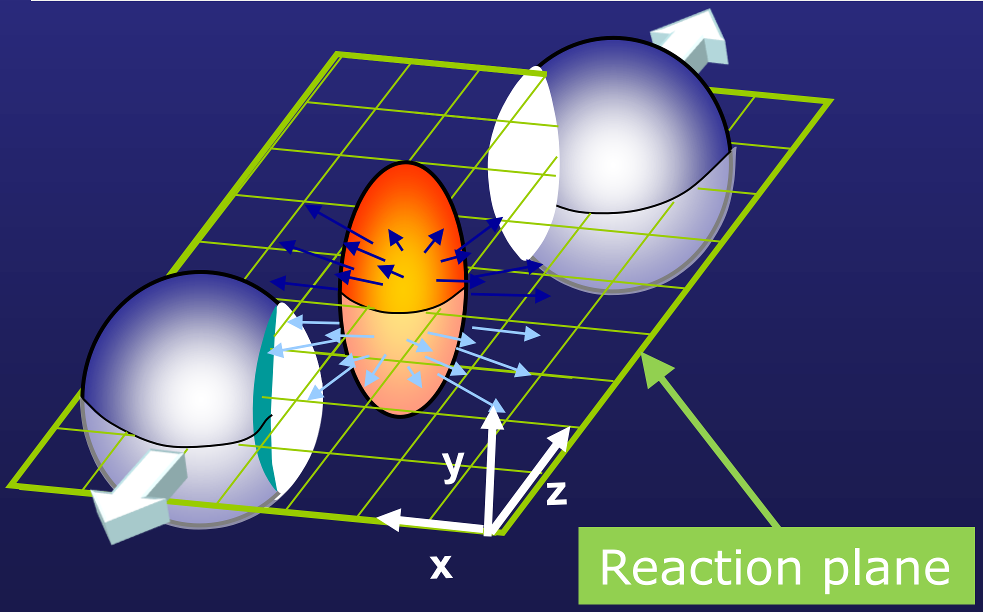
→ Data are compatible with theory models at both energies
→ Still large uncertainties mainly due to the choice of σ_{cc}

Anisotropic transverse flow

- In collisions with b ≠ 0 (non central) the fireball has a geometric anisotropy, with the overlap region being an ellipsoid
- Macroscopically (hydrodynamic description)
  - The pressure gradients, i.e. the forces "pushing" the particles are anisotropic (φ-dependent), and larger in the x-z plane
    → leads to an anisotropic azimuthal distribution of particles

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

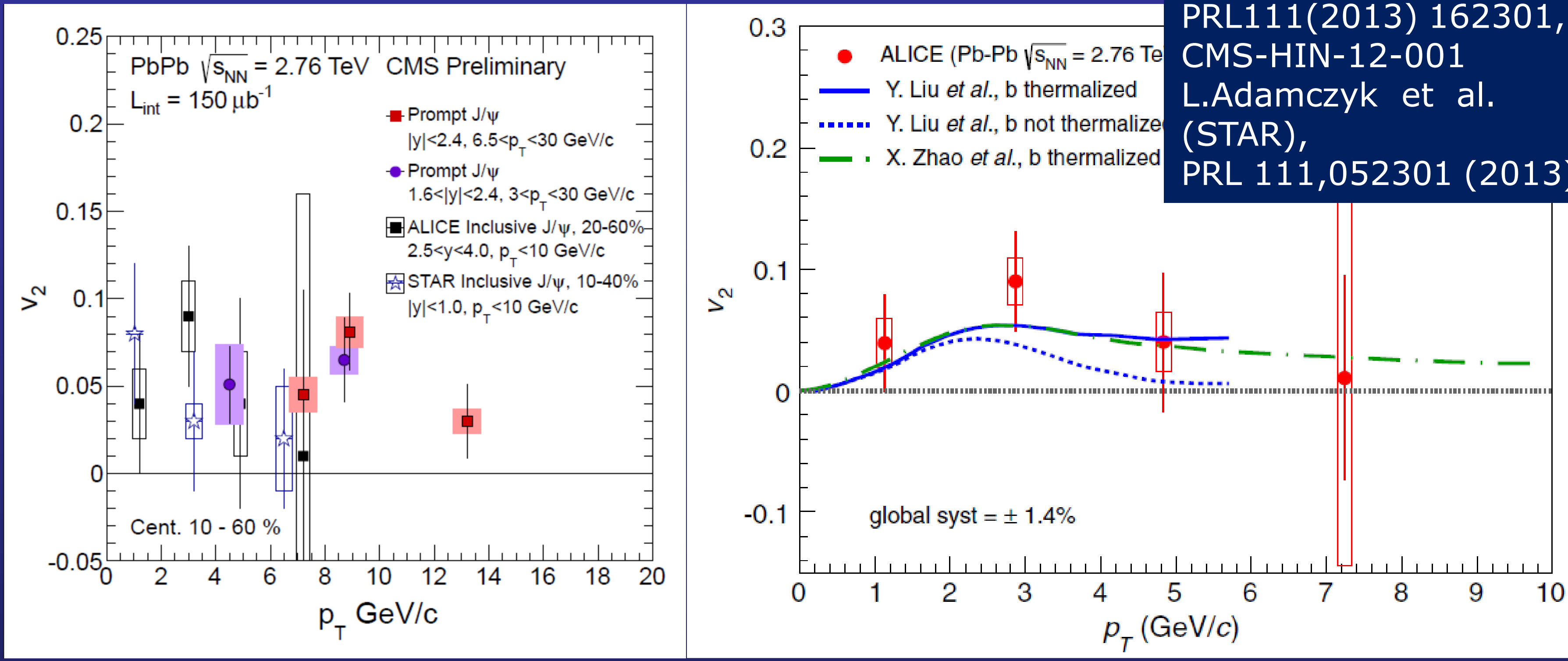
Fourier decomposition of the azimuthal distributions



- Non-zero v_2 observed in HI collisions for produced particles
- Indicates early thermalization of the system
  → observed for D-mesons
  → "Re-generated J/ψ" should inherit charm quark flow

Non-zero v_2 for J/ψ at the LHC (ALICE, CMS)

E.Abbas et al. (ALICE), PRL111(2013) 162301,
CMS-HIN-12-001
L.Adamczyk et al. (STAR),
PRL 111,052301 (2013)



- A significant v_2 signal is observed at LHC but not at RHIC
- v_2 remains significant even in the region where the contribution of (re)generation should be negligible
  → Likely due to path length dependence of energy loss

Anisotropic transverse flow

- Starting from the azimuthal distributions of the produced particles with respect to the reaction plane Ψ_{RP}, one can use a Fourier decomposition and write

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

- The terms in $\sin(\varphi-\Psi_{RP})$ are not present since the particle distributions need to be symmetric with respect to Ψ_{RP}
- The coefficients of the various harmonics describe the deviations with respect to an isotropic distribution
- From the properties of Fourier's series one has

$$v_n=\left\langle\cos\left[n\left(\varphi-\Psi_{RP}\right)\right]\right\rangle$$

On feed-down fractions

- Usually they are not supposed to vary strongly with √s (or y)
- New LHCb pp results could alter the picture inherited by CDF (relative to p_{Υ}>8 GeV/c)

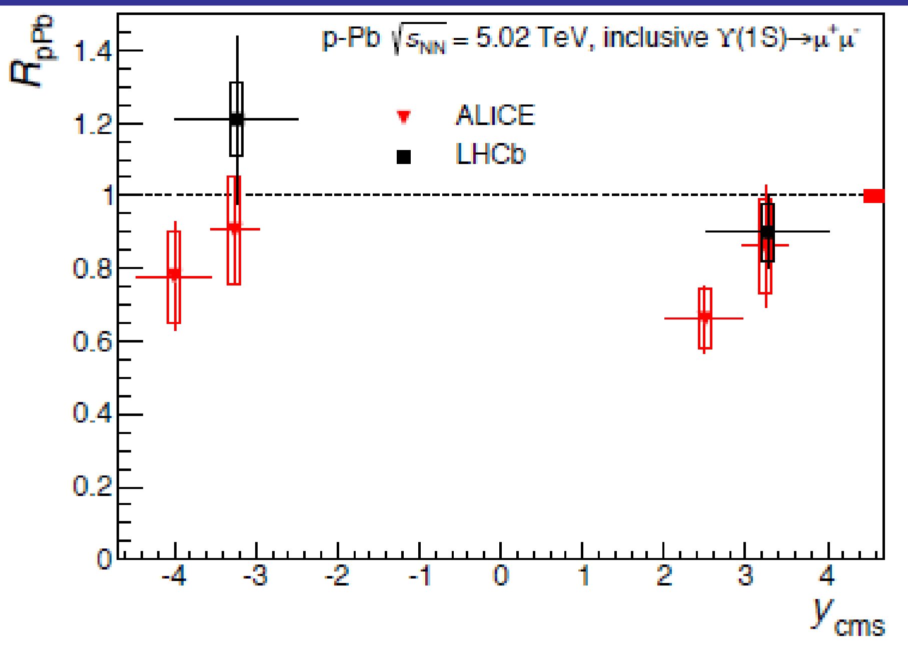
	p_T^{Υ} (GeV/c)	$\mathcal{R}^{\chi_b(1P)}_{\Upsilon(nS)}$	$\mathcal{R}^{\chi_b(2P)}_{\Upsilon(nS)}$
$\Upsilon(1S)$	6–8	$14.8 \pm 1.2 \pm 1.3$	$3.3 \pm 0.6 \pm 0.2$
	8–10	$17.2 \pm 1.0 \pm 1.4$	$5.2 \pm 0.6 \pm 0.3$
	10–14	$21.3 \pm 0.8 \pm 1.4$	$4.0 \pm 0.5 \pm 0.3$
	14–18	$24.4 \pm 1.3 \pm 1.2$	$5.2 \pm 0.8 \pm 0.4$
	18–22	$27.2 \pm 2.1 \pm 2.1$	$5.5 \pm 1.0 ^{+0.4}_{-1.0}$
	22–40	$29.2 \pm 2.5 \pm 1.7$	$6.0 \pm 1.2 ^{+0.4}_{-0.7}$

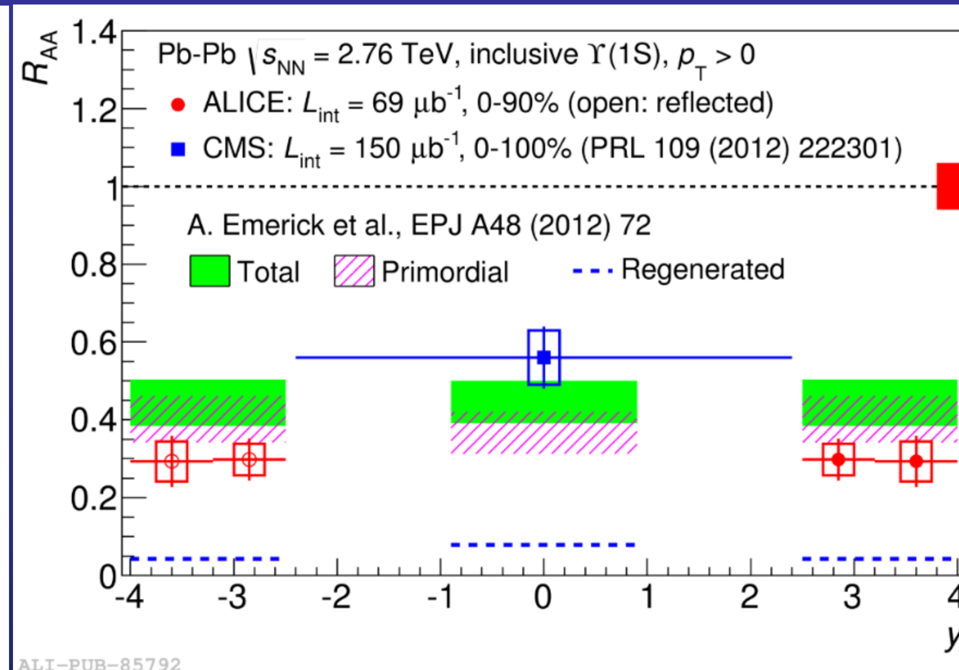
LHCb

We have reconstructed the radiative decays $\chi_b(1P) \to \Upsilon(1S)\gamma$ and $\chi_b(2P) \to \Upsilon(1S)\gamma$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, and measured the fraction of $\Upsilon(1S)$ mesons that originate from these decays. For $\Upsilon(1S)$ mesons with $p_T^{\Upsilon} > 8.0$ GeV/c, the fractions that come from $\chi_b(1P)$ and $\chi_b(2P)$ decays are [27.1 ± 6.9(stat) ± 4.4(syst)]% and [10.5 ± 4.4(stat) ± 1.4(syst)]%, respectively. We have derived the fraction of directly produced $\Upsilon(1S)$ mesons to be [50.9 ± 8.2(stat) ± 9.0(syst)]%.

- At the limit of uncertainties or do we have a problem here ?
- Difficult to reach 50% including 2S and 3S

Can we take CNM into account ?





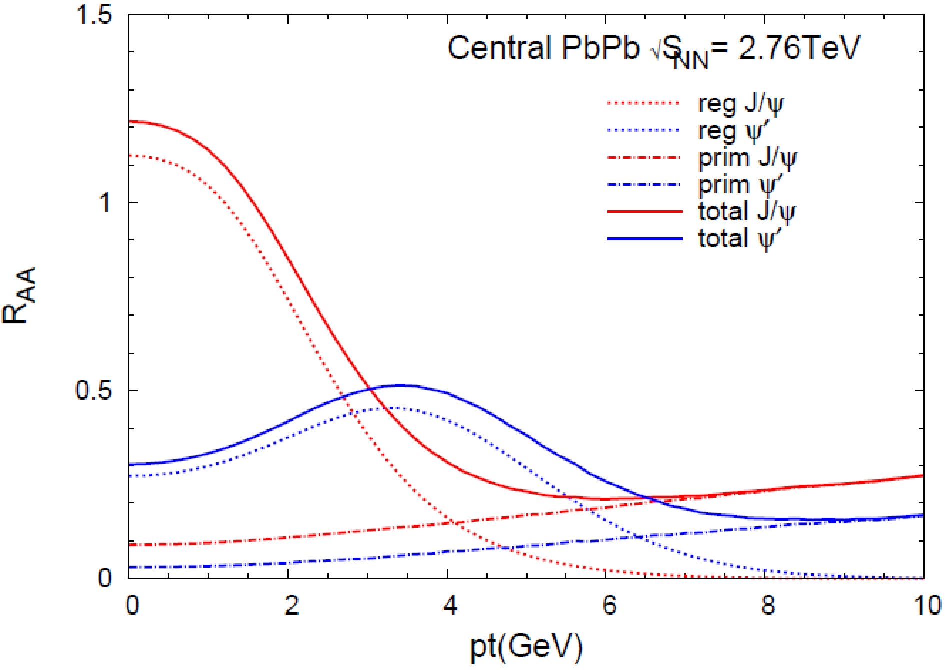
- ❑ Apply the simple $R_{pPb} \times R_{Pbp}$ recipe on ALICE pPb
- ❑ Would give 0.78×0.86 = 0.67 for 3.25<y<4
  0.91×0.66 = 0.60 for 2.5<y<3.25
  (but see also LHCb result)

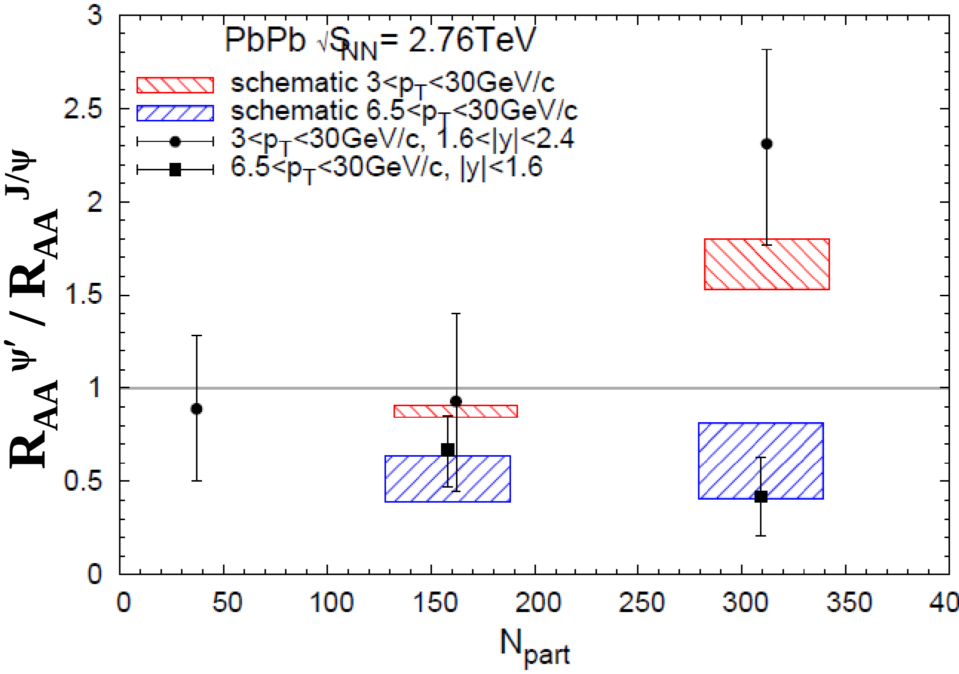
→ ~0.5 "anomalous" suppression at forward-y

- ❑ No results from CMS (for the moment ?)
- ❑ Assuming a "smooth" y-interpolation of CNM

→ ~0.8-0.9 "anomalous" suppression at central-y

Charmonium: the ψ(2S) puzzle

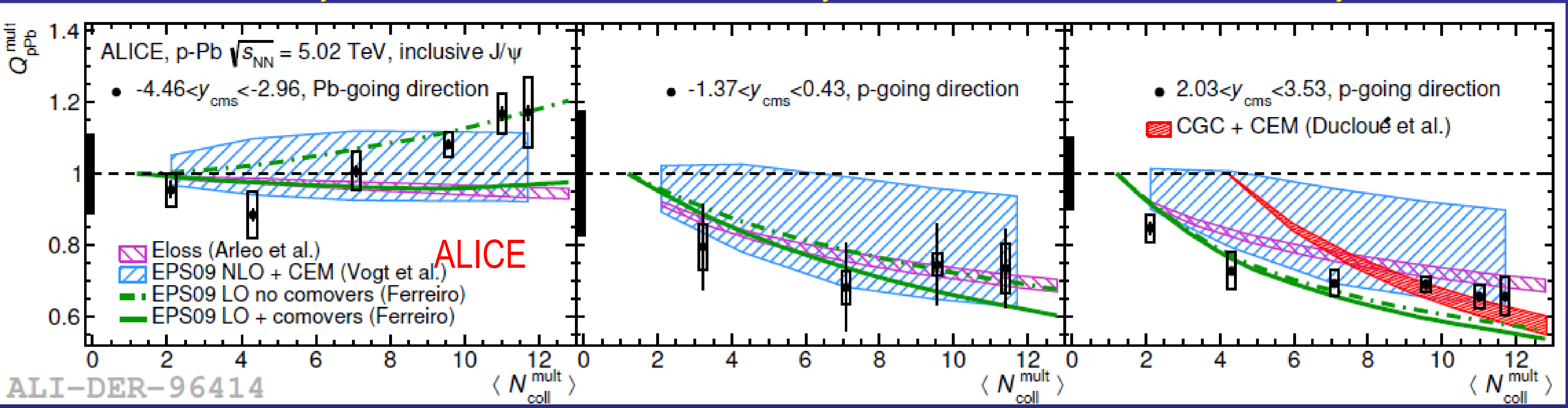




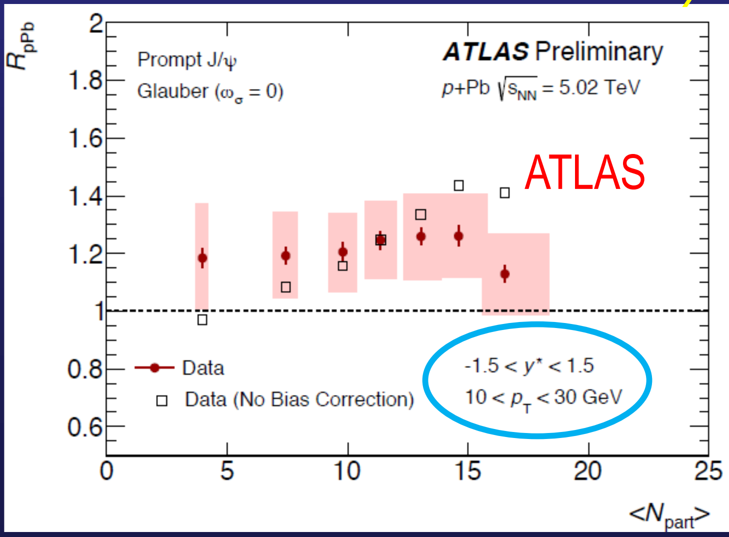
- The regeneration of ψ′ mesons occurs significantly later than for J/ψ's
- Despite a smaller total number of regenerated ψ′, the stronger radial flow at their time of production induces a marked enhancement of their R_{AA} relative to J/ψ's in a momentum range pt ≃ 3-6 GeV/c.

J/ψ R_{pPb}: centrality dependence

backward-y mid-y forward-y



mid-y

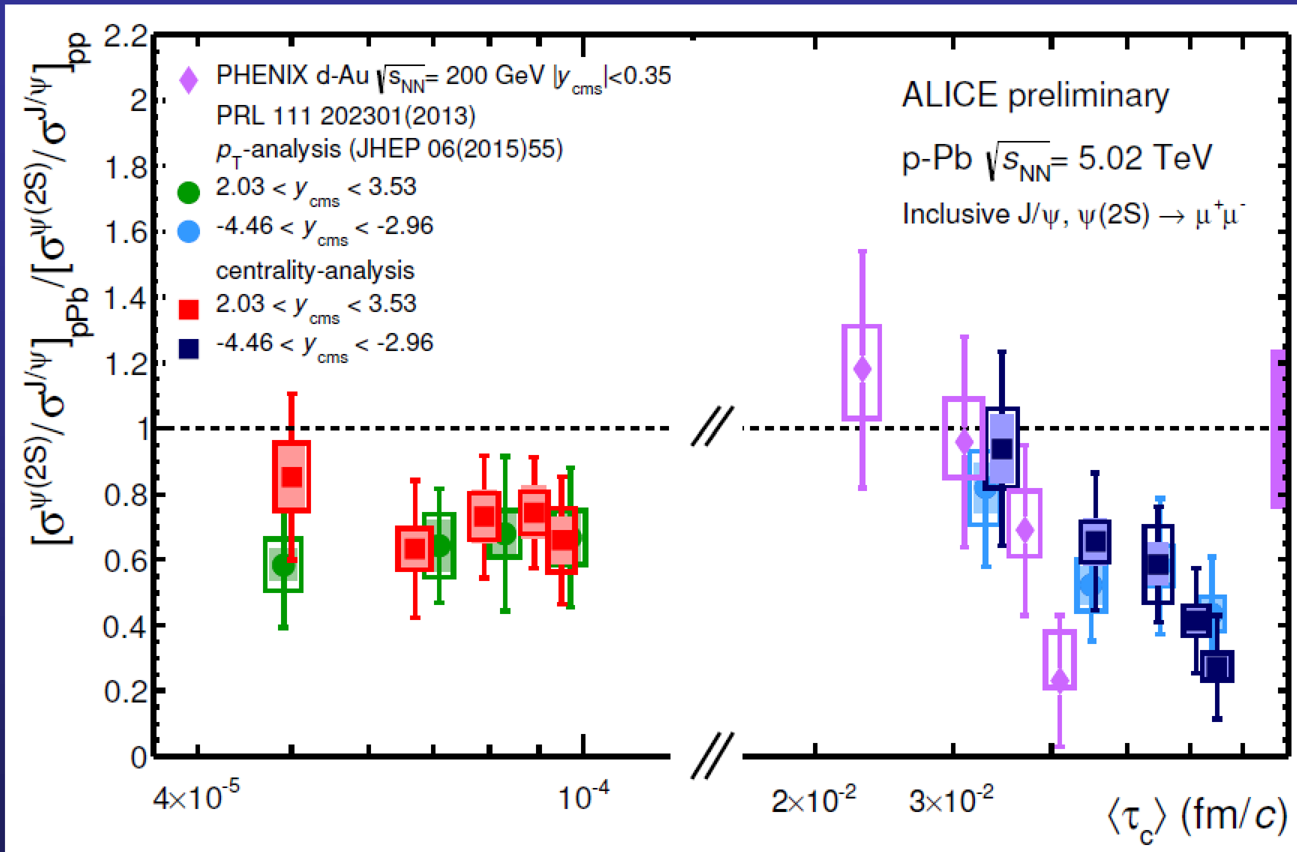


- ❑ ALICE:
- ❑ mid and fw-y: suppression increases with centrality
- ❑ backward-y: hint for increasing Q_{pA} with centrality

- ❑ Shadowing and coherent energy loss models in fair agreement with data

- ❑ ATLAS
- ❑ Flat centrality dependence in the high p_T range

Dependence of suppression on τ_c

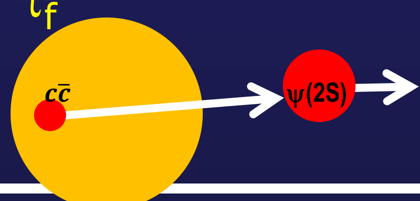


$$\tau_c = \frac{\langle L \rangle}{(\beta_z \gamma)}$$

D. McGlinchey, A. Frawley and R.Vogt, PRC 87,054910 (2013)

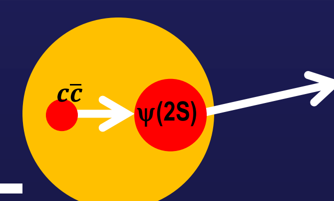
Forward-y: $\tau_c << \tau_f$

interaction with nuclear matter cannot play a role



Backward-y: $\tau_c \lesssim \tau_f$

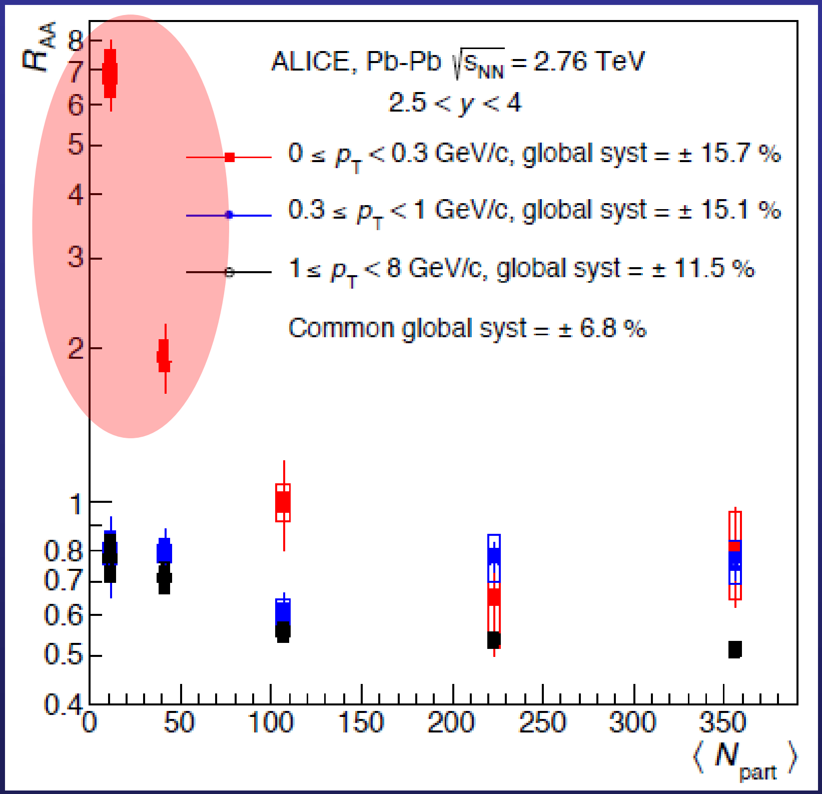
indication of effects related to break-up in the nucleus?



J/ψ at very low p_T

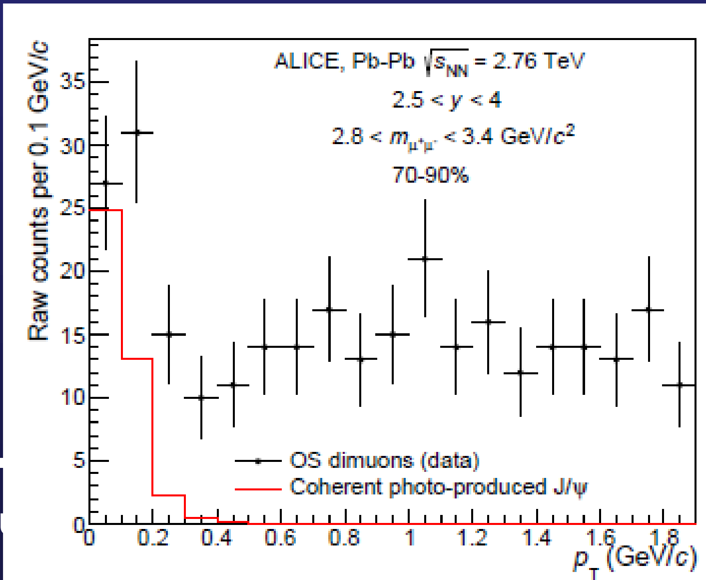
- Strong R_{AA} enhancement in peripheral collisions for $0<p_T<0.3$ GeV/c

ALICE, arXiv:1509.08802

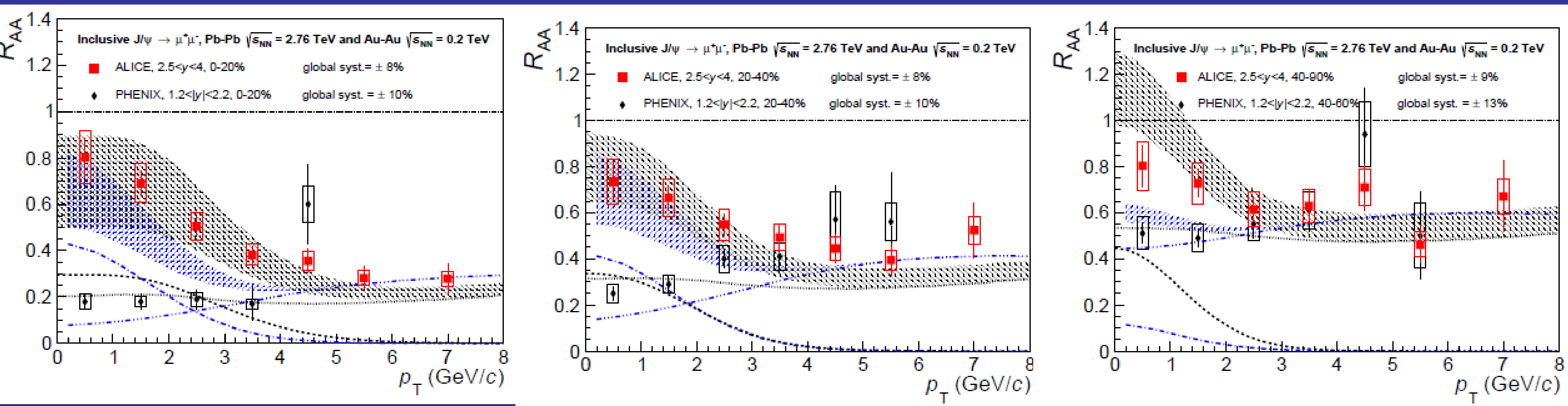


- Significance of the excess is 5.4 (3.4)σ in 70-90% (50-70%)
- Behaviour not predicted by transport models
- Excess might be due to coherent J/ψ photoproduction in PbPb (as measured also in UPC)

If excess is "removed" requiring $p_T^{J/\psi}$>0.3GeV/c
→ ALICE R_{AA} lowers by 20% at maximum
(in the most peripheral bin)



R_{AA} vs p_T



TM1 Zhao et al., Nucl.Phys.A859 (2011) 114

TM2 Zhou et al. Phys.Rev.C89 (2014)054911

ALICE, arXiv:1506.08804

Primordial J/ψ (TM1)
Regenerated J/ψ (TM1)
Primordial J/ψ (TM2)
Regeneration J/ψ (TM2)

- Models provide a fair description of the data, even if with different balance of primordial/regeneration components

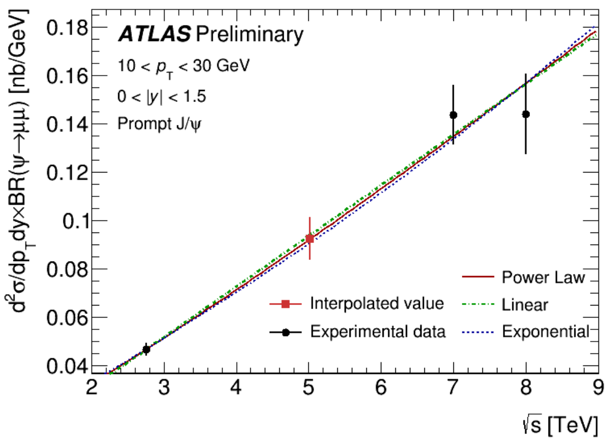
Still rather large theory uncertainties: models will benefit from precise measurement of σ_{cc} and CNM effects

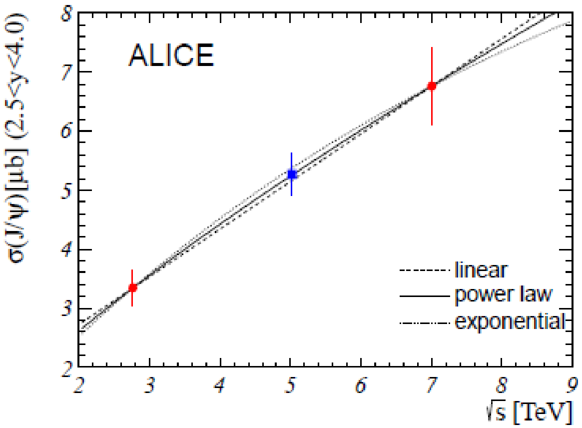
- Opposite trend with respect to lower energy experiments

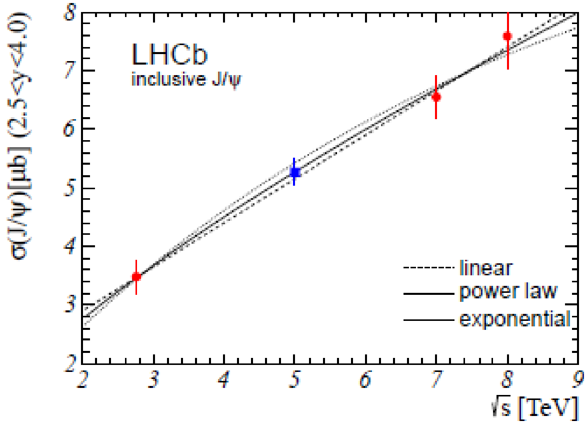
Building a reference σ_{pp} → interpolation

- Simple empirical approach adopted by ALICE, ATLAS and LHCb

CERN-LHCb-CONF-2013-013; ALICE-PUBLIC-2013-002.







Example: ALICE result

$$\sigma_{\mathrm{incl}} = 5.28 \pm 0.40_{\mathrm{exp}} \pm 0.10_{\mathrm{inter}} \pm 0.05_{\mathrm{theo}}\ \mu\mathrm{b} = 5.28 \pm 0.42\ \mu\mathrm{b}\ .$$

inter: spread of interp. with empirical functions
theo: spread of interp. with theory estimates

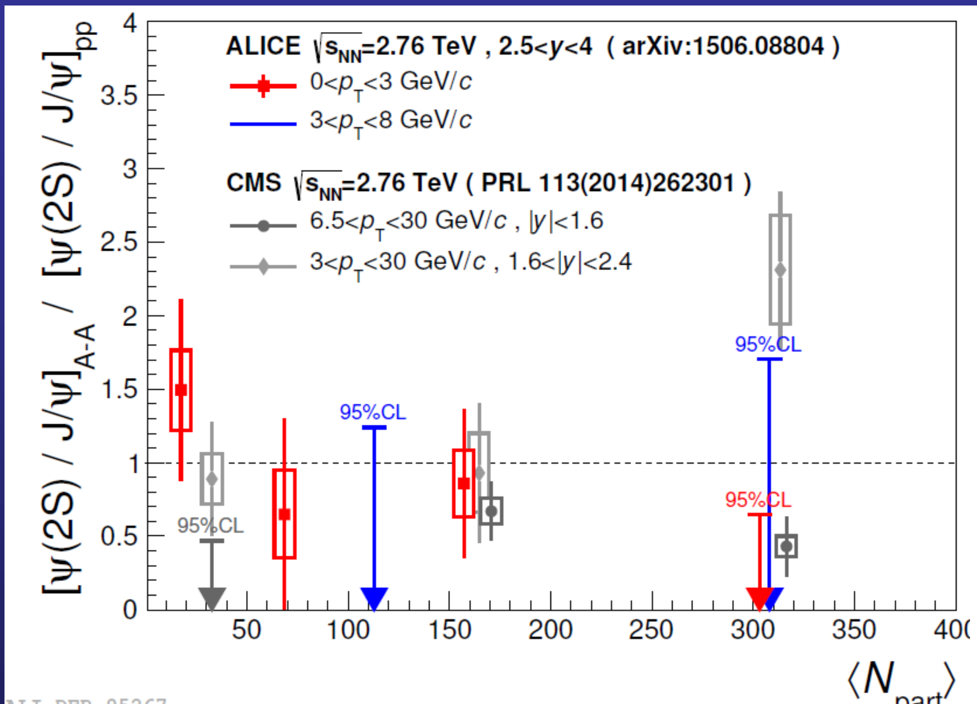
- ψ(2S) → interpolation difficult, small statistics at √s=2.76 TeV
- Ratio ψ(2S) / J/ψ → ALICE uses √s=7 TeV pp values (weak √s-dependence)

$$R_{pA}^{\psi(2S)} = R_{pA}^{J/\psi} \times \frac{\sigma_{pA}^{\psi(2S)}}{\sigma_{pA}^{J/\psi}} \times \frac{\sigma_{pp}^{J/\psi}}{\sigma_{pp}^{\psi(2S)}}$$

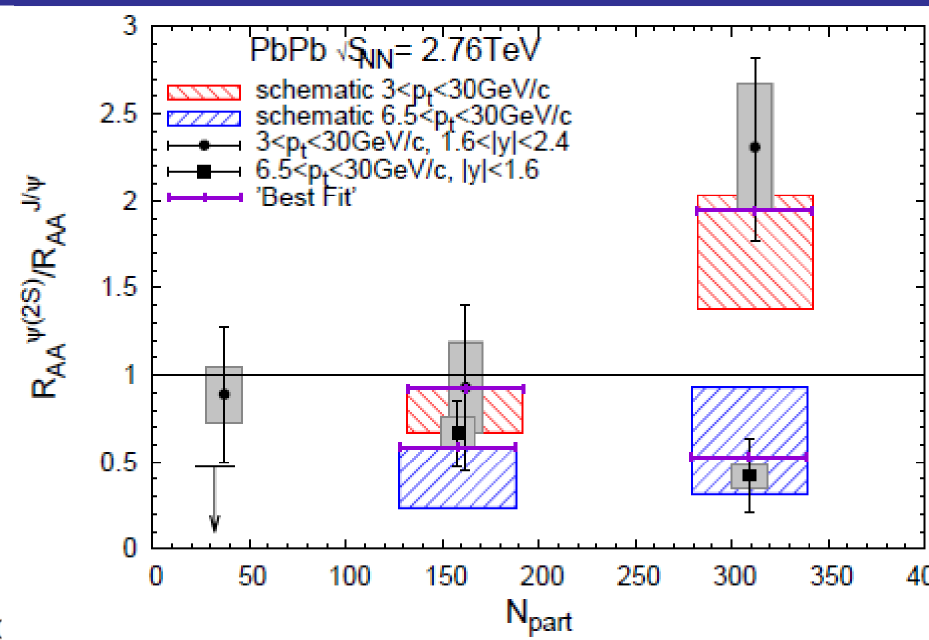
ALICE estimate (conservative)
→ 8% syst. unc. due to different √s
(using CDF/ALICE/LHCb results)

ψ(2S) in Pb-Pb: ALICE "vs" CMS

- ψ(2S) production modified in Pb-Pb with a strong kinematic dependence
- CMS → suppression at high p_T, enhancement at intermediate p_T



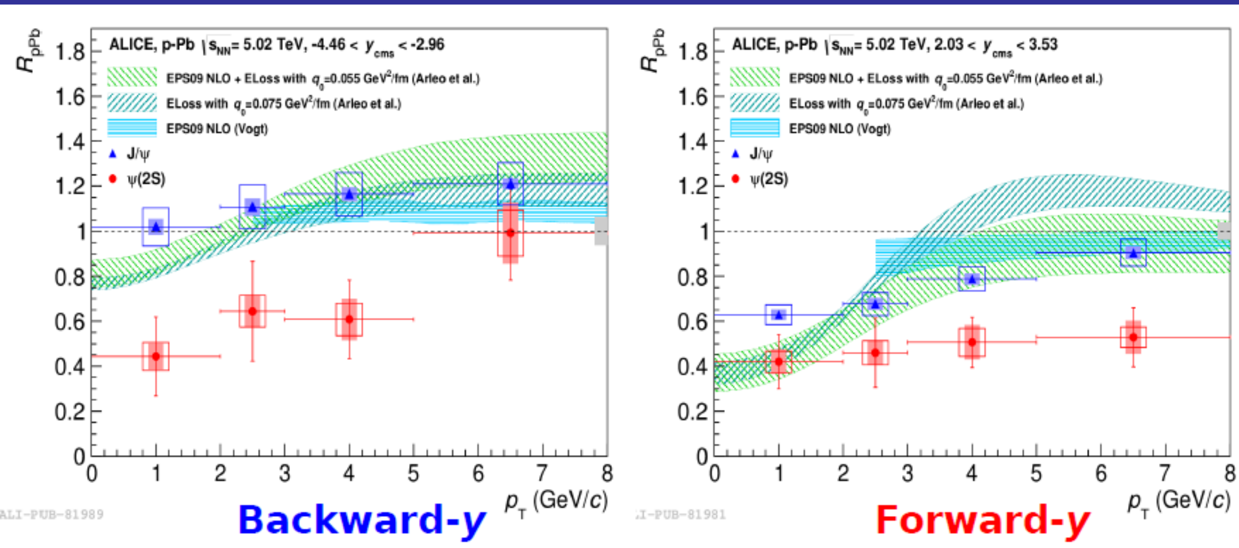
CMS, PRL113 (2014) 262301
ALICE, arXiv:1506.08804



Du and Rapp arXiv:1504.00670

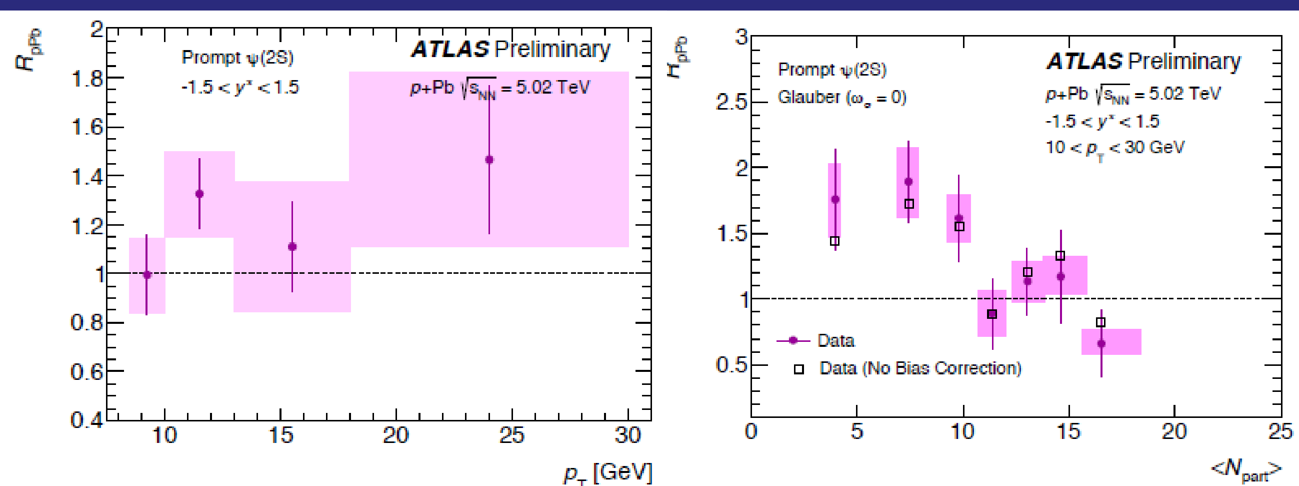
- Possible interpretation (Rapp et al.) → Re-generation for ψ(2S) occurs at later times wrt J/ψ, when a significant radial flow has built up, pushing the re-generated ψ(2S) at a relatively larger p_T
- Small tension, between ALICE and CMS, for central events?

$\psi(2S)$ in p-Pb: p_T dependence



ALICE, JHEP 12 (2014) 073

- ALICE (low p_T) : rather strong suppression, possibly vanishing at backward y and p_T> 5 GeV/c

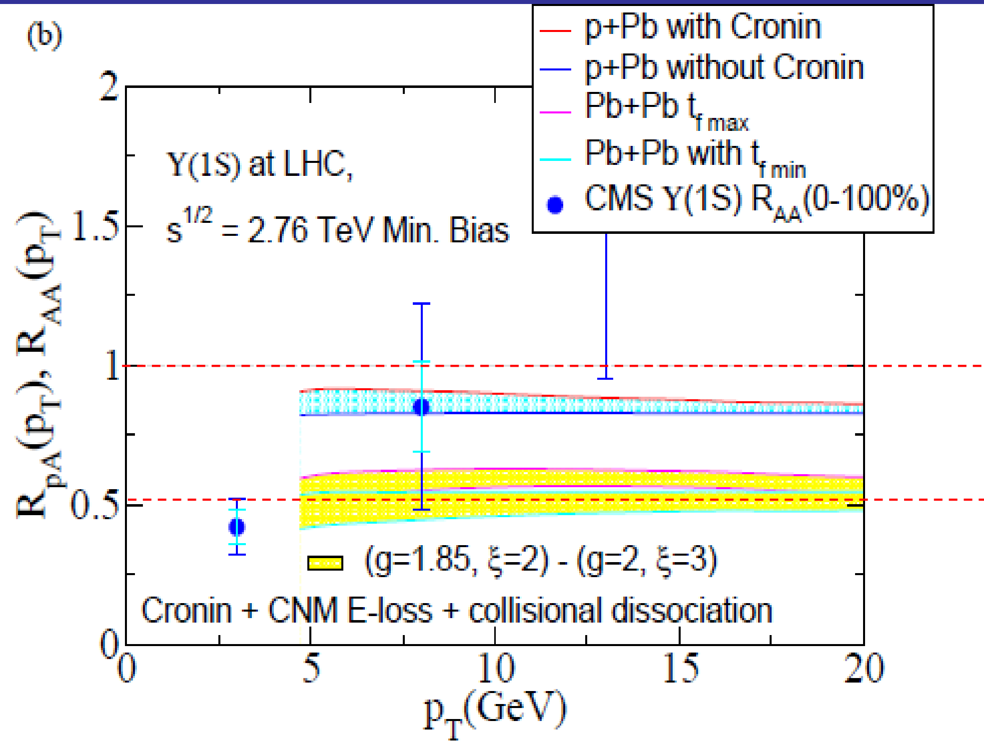


ATLAS-CONF-2015-023

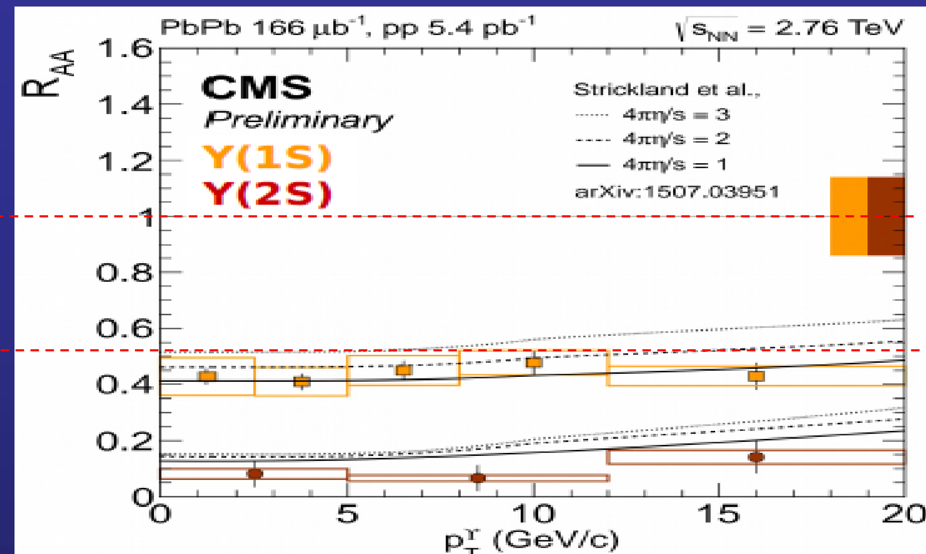
- ATLAS (high p_T) : larger uncertainties, hints for strong enhancement, concentrated in peripheral events

- Possible tension between ALICE and ATLAS results ? Wait for final results

High p_T ϒ: model comparison

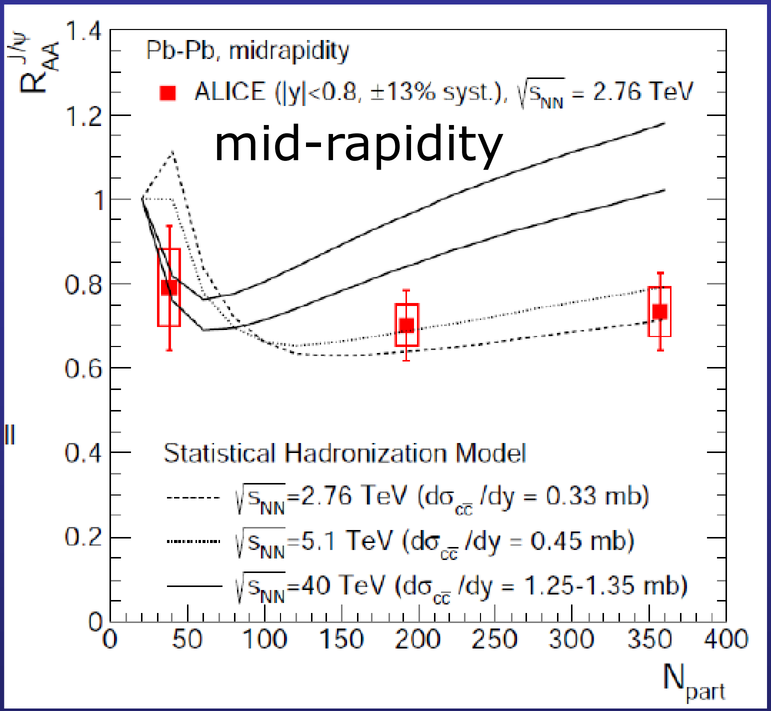


Sharma and Vitev,
Phys. Rev. C 87, 044905 (2013)

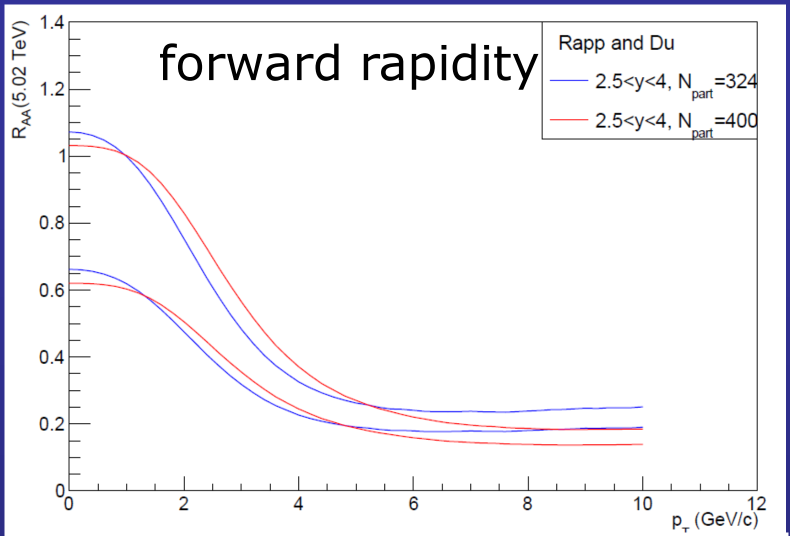


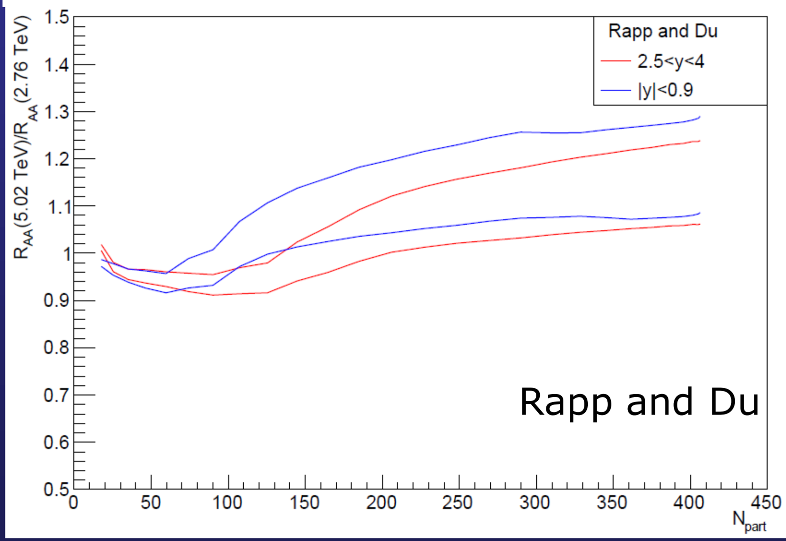
- High p_T ϒ suppression
- Propagation effects through QGP
  - Quenching of the color octet component
  - Collisional dissociation model
- Approximation: initial wave function of the quarkonia well approximated by vacuum wavefunctions in the short period before dissociation
- CNM effects accounted for (shadowing + Cronin)

Some J/ψ predictions for run-2



PBM, Andronic, Redlich and Stachel





- ❑ First predictions for (both statistical and transport models) indicate a moderate increase in R_{AA}, when comparing $\sqrt{s_{NN}}$=5.02 and 2.76 TeV
- ❑ Theoretical uncertainties are larger than the predicted increase
  - → Provide quantities where at least partial cancellation of uncertainties takes place (double ratios of R_{AA})

From run-1 ro run-2

- Charmonium highlight → evidence for a new mechanism which enhances the J/ψ yield, in particular at low p_T, with respect to low-energy experiments

- In addition
  - Indications for J/ψ azimuthal anisotropy (non-zero v_2)
  - Significant final state effects on ψ(2S) in p-Pb, likely related to the (hadronic) medium created in the collision

- Bottomonium highlight → evidence for a stronger suppression of 2S and 3S states compared to 1S. Effect not related to CNM and compatible with sequential suppression of "bottomonium" states

- In addition
  - 1S is also suppressed (~50-60%). Feed-down effect only?
  - y-dependence of 1S suppression to be understood

From run-1 to run-2

- ❑ Prospects for run-2
  → Collect a ~1 order of magnitude larger integrated luminosity

- ❑ High-statistics J/ψ sample
  → Comparison with run-1 AND with theoretical predictions crucial to confirm/quantify our understanding in terms of regeneration
  → more precise v_2 results also needed

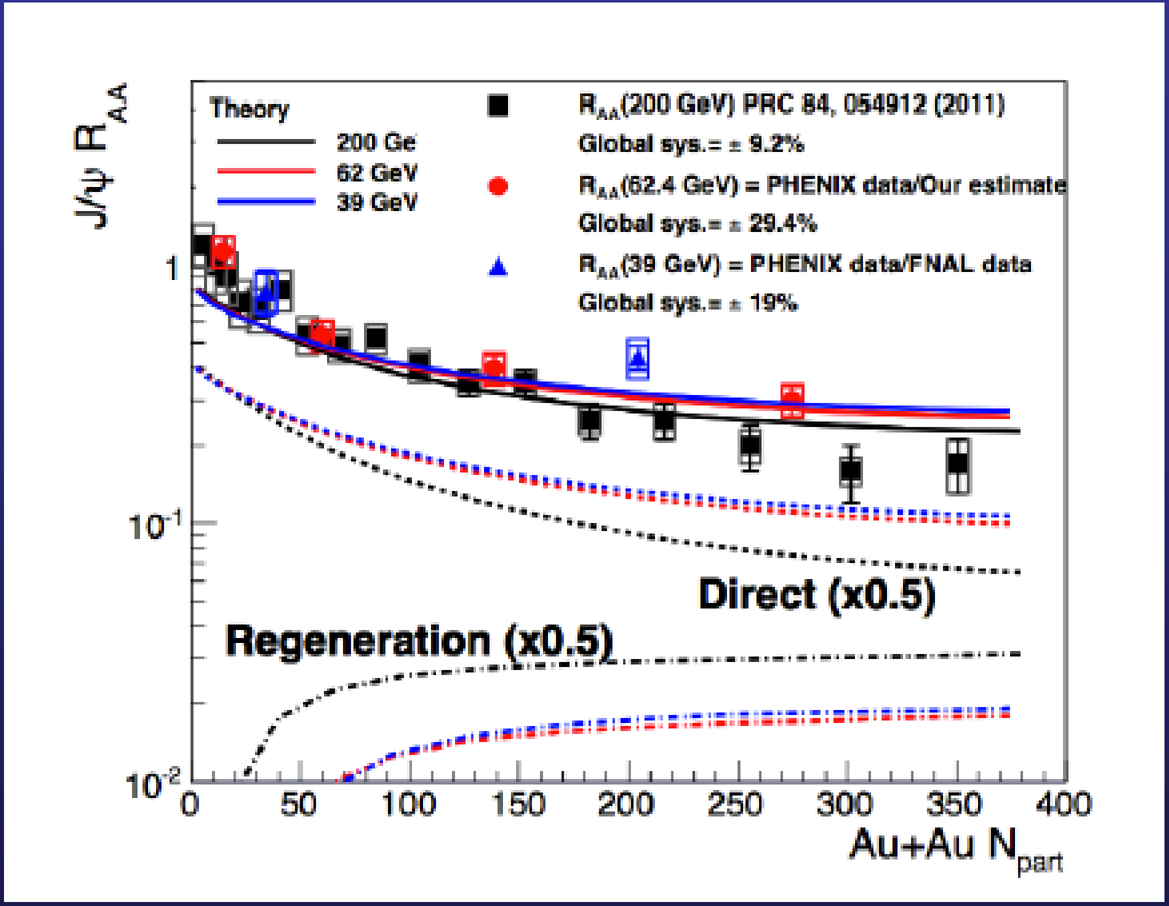
- ❑ Significant $\psi(2S)$ sample
  → Crucial: run-1 results "exploratory" (and interpretation not clear)

- ❑ High-statistics $\Upsilon(1S)$ sample
  → A significant increase in 1S suppression with respect to run-1 might imply that a high-T QGP is formed ("threshold" scenario)

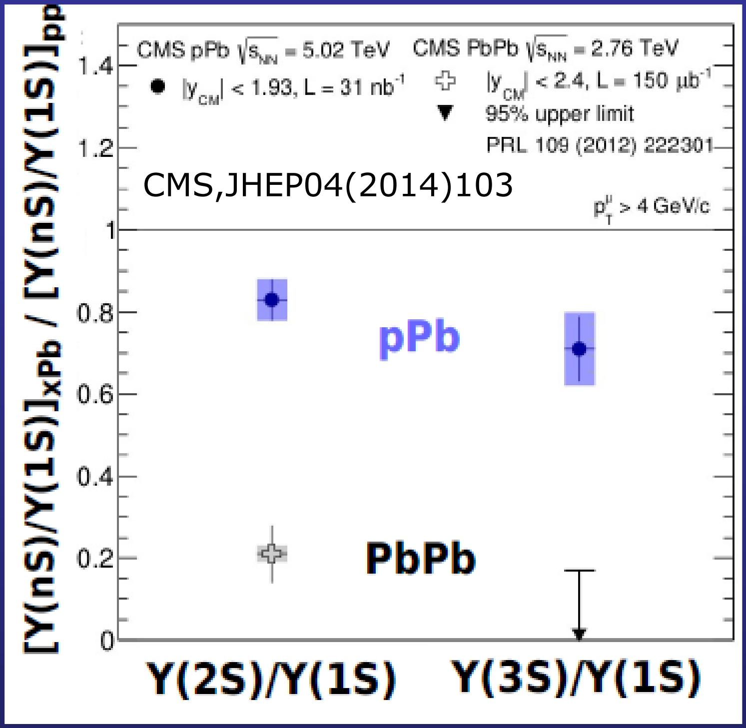
- ❑ Differential $\Upsilon(2S)$ and $\Upsilon(3S)$ results from run-1 are limited by statistics
  → Centrality and p_T-dependent studies important to assess details of sequential suppression

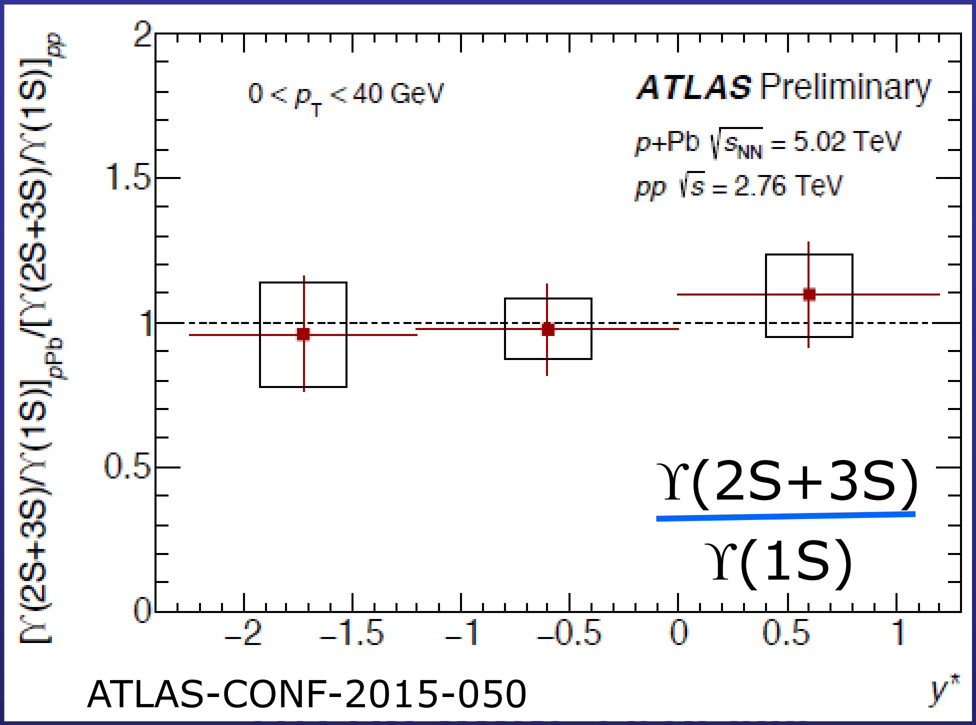
Suppression vs $\sqrt{s_{NN}}$ (RHIC)

- At RHIC 39 GeV, 62 GeV, 200 GeV all show similar suppression



Yield ratios for bottomonium in p-Pb





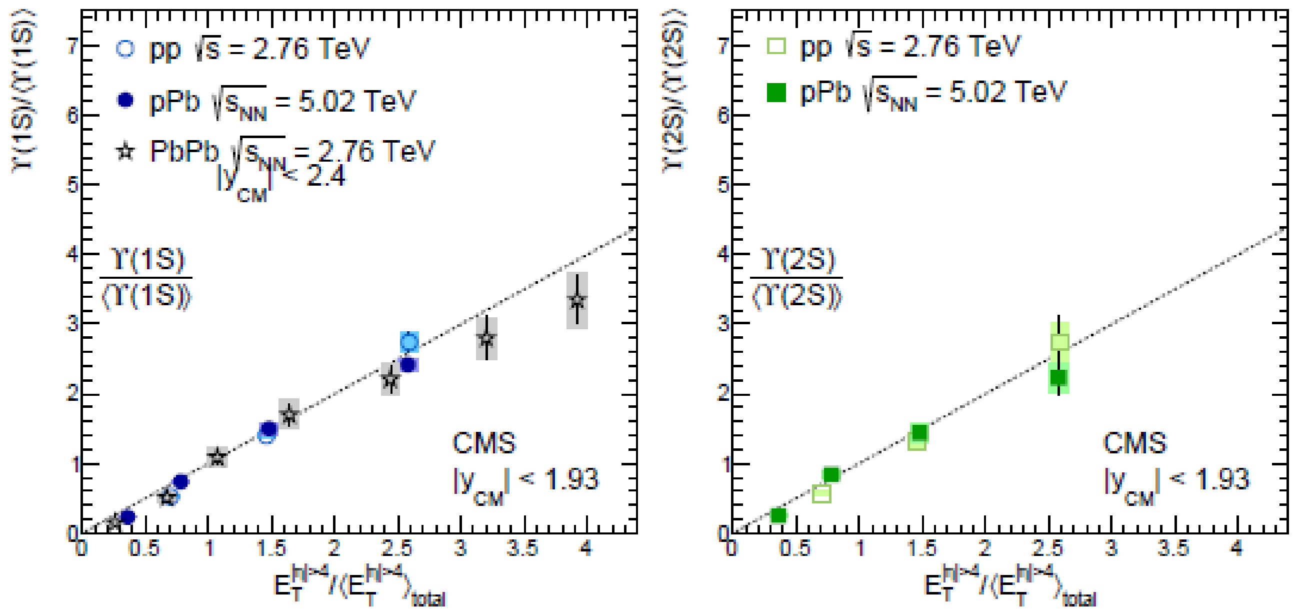
CMS

- Excited states suppressed with respect to $\Upsilon(1S)$
- Initial state effects similar for the various $\Upsilon(ns)$ states
  → Final states effects at play?

ATLAS

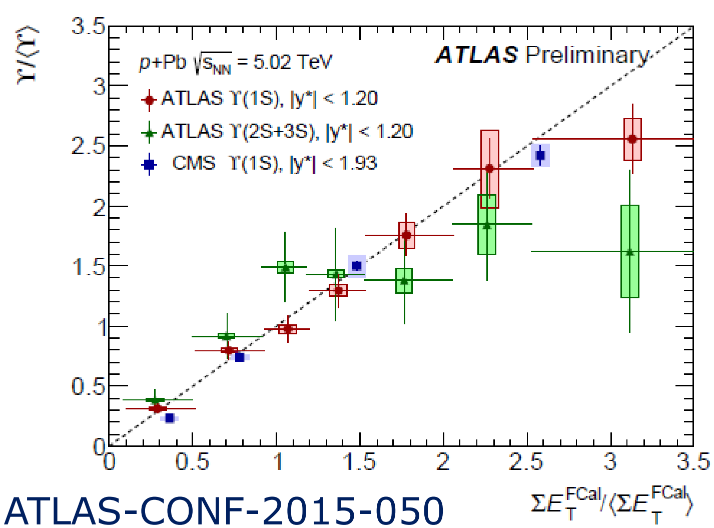
- no strong y (and p_T) dependence
- agreement with CMS within uncertainties

Self-normalized Υ cross sections



Similar behaviour observed for J/ψ (ALICE)
(PLB712 (2012) 165-175)

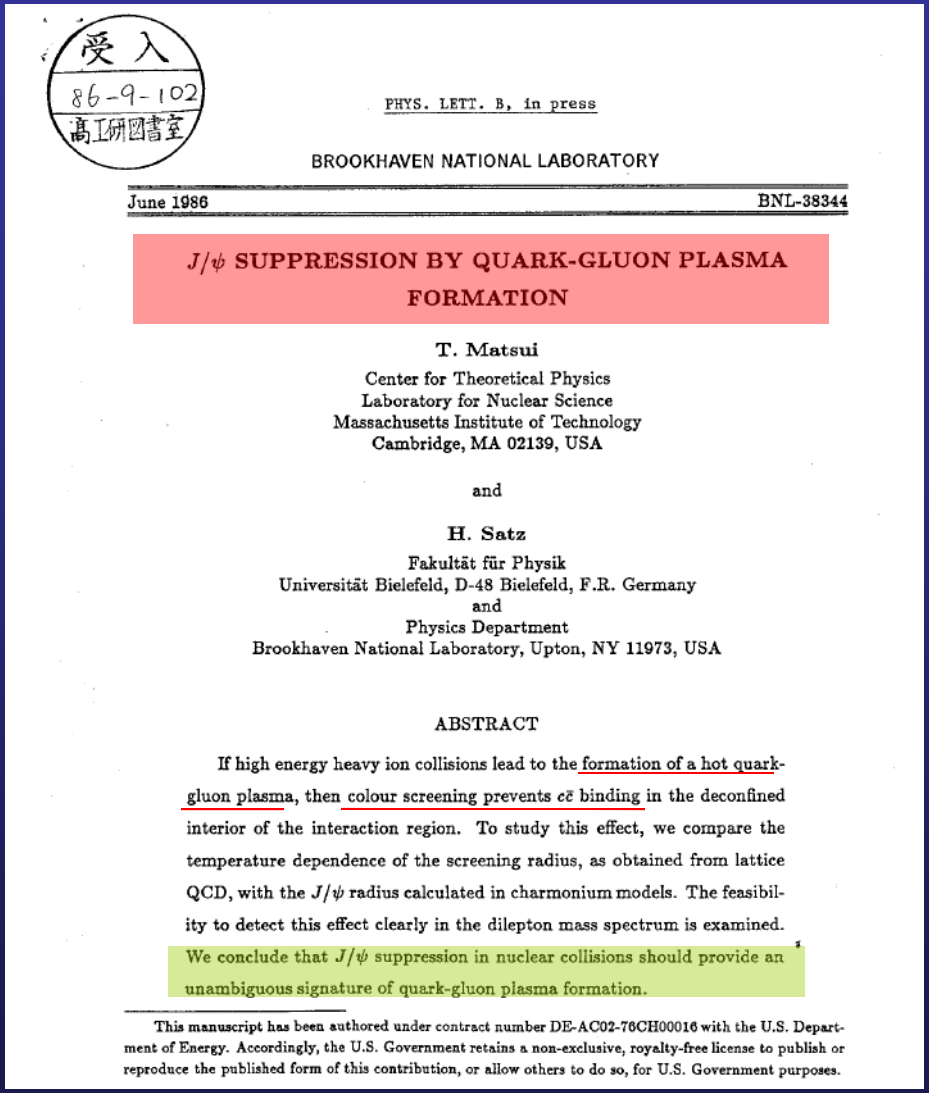
CMS, JHEP 04 (2014) 103



ATLAS-CONF-2015-050

- All the ratios increase with increasing forward transverse energy
- When Pb nuclei are involved
  → Increase partly due to larger number of N-N collisions
- Increase observed also in pp collisions
  → multiple partonic interactions ?

In the beginning…



受入 86-9-102 高エ研図書室

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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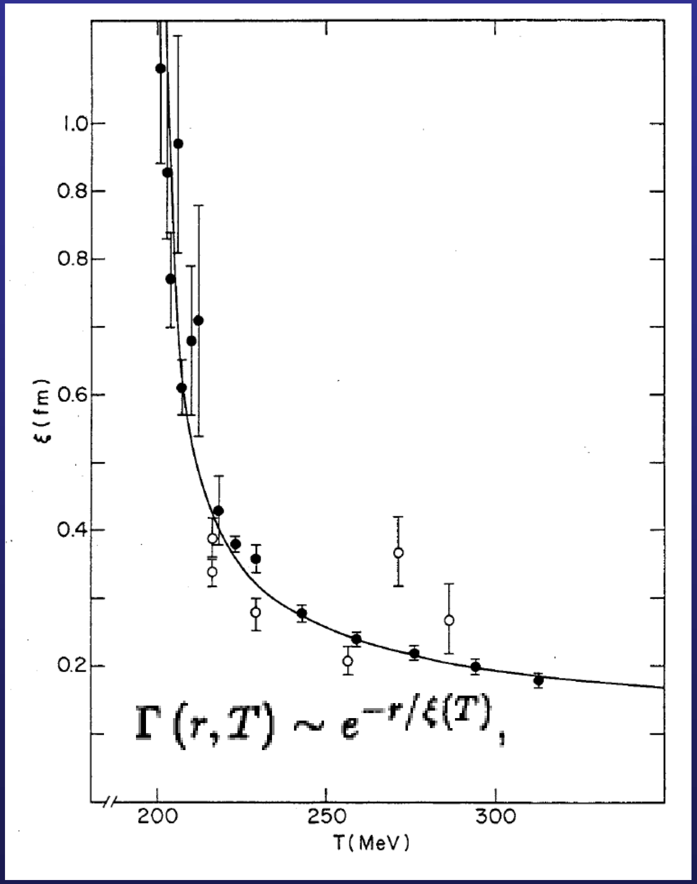
…there was a definite and clear prediction



…and got immediate attention from the (newborn) HI community…

- QM87, from the summary talk of M. Gyulassy

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.

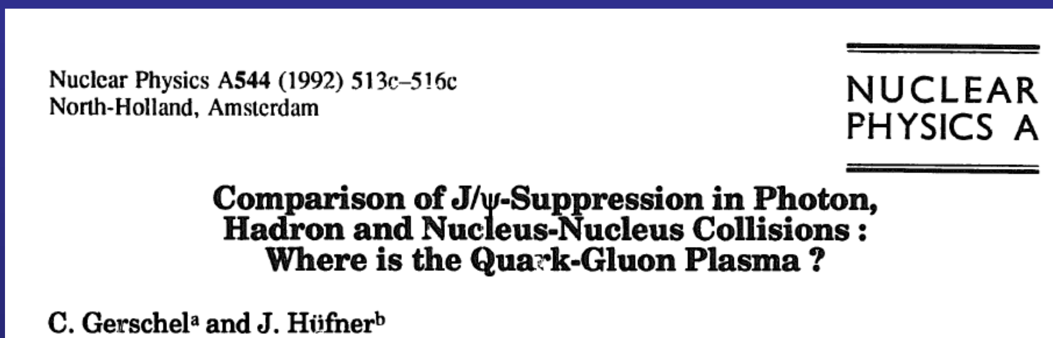
There are naturally several caveats that need further consideration. First, there is the problem of prov-

Competing sources of suppression involving hadronic final state interactions
Dissociation reactions with σ_{diss}~1-2 mb could reproduce the observation

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

…which looked for alternative explanations/mechanisms…

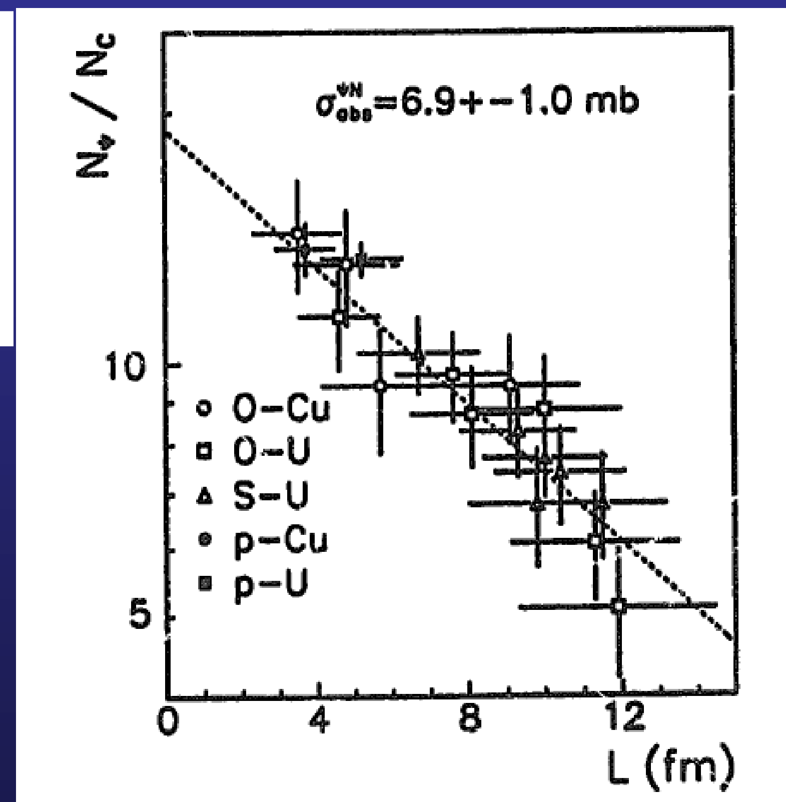
…which included a significant contribution from J/ψ interactions with nucleons (nowadays Cold Nuclear Matter effects, CNM)


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 ?

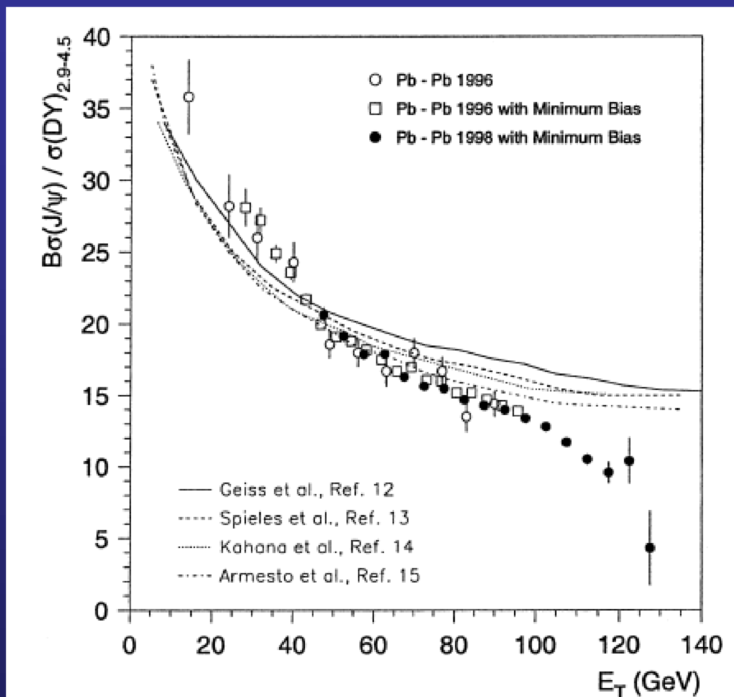
C. Gerschel[a] and J. Hüfner[b]



Triggered an experimental program at SPS energy (with inputs from the FNAL fixed target program too!) on the study of p-A collisions, used as a reference for A-A results

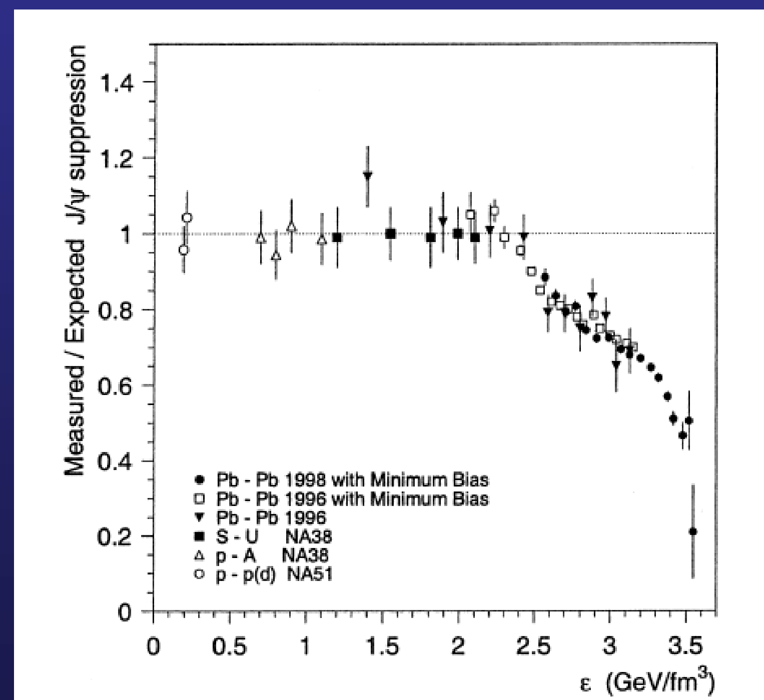
More accurate data allowed more stringent conclusions…

1994-2000: really "heavy" ions in the SPS (Pb-Pb collisions)
February 2000 → "New state of matter created at CERN" press release



Evidence for deconfinement of quarks and gluons
from the J/ψ suppression pattern
measured in Pb-Pb collisions at the CERN-SPS

NA50 Collaboration



- ❑ Clear suppression beyond CNM effects measured by NA50

1) Sharp onset of suppression
2) "Conventional" models found to disagree with data

Still a bit of history….

- The possibility of an enhancement of charmonium production in nuclear collisions was considered from the very beginning!

From T.Matsui QM87 proceedings

> *Q3*. Could J/ψ suppression be compensated at the hadronization stage?
>
> – This is very unlikely from our consideration on the charm production mechanism. One should check, however, both experimentally and theoretically whether there is no anomalous enhancement in the charm production cross section which could lead to large recombination probability of $c\bar{c}$ into J/ψ during the hadronization stage.

(even if, at that time, correctly discarded because of the small open charm cross section at the energies then available)

A comprehensive theoretical description?

- Implementing a realistic quarkonium production in a realistic medium is a considerably difficult task

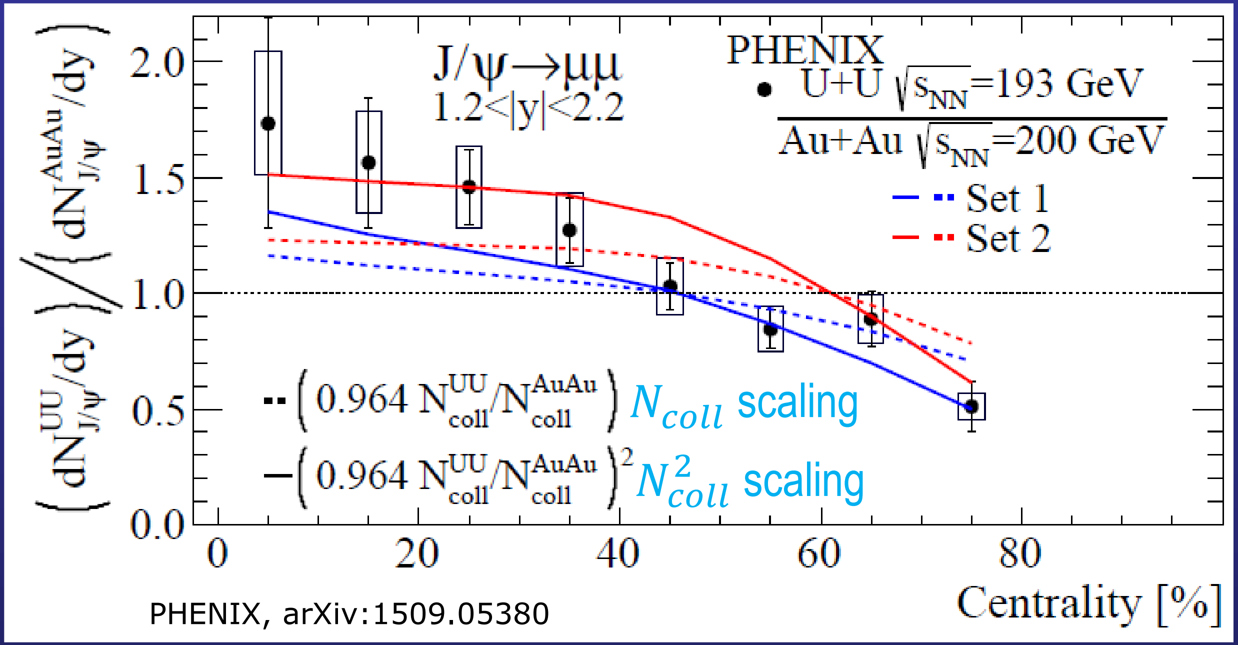
- Some open points
  - In high-energy heavy-ion collisions the QGP thermalization times are very short (~1 fm/c)
    → One should deal with in-medium formation of quarkonium rather than with suppression of already formed states
    → Heavy quark diffusion is relevant for quarkonium production

- Need to determine T_D , $M_\psi(T)$, $\Gamma_\psi(T)$ from QCD calculations (using spectral functions from EFT/LQCD)
- Need to know the fireball evolution from microscopic calulcations
- A precise determination of the total open charm cross section is still lacking

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

Recent RHIC results: U-U!

(re)combination/suppression role investigated comparing U-U and AuAu



PHENIX, arXiv:1509.05380

in central U-U wrt Pb-Pb

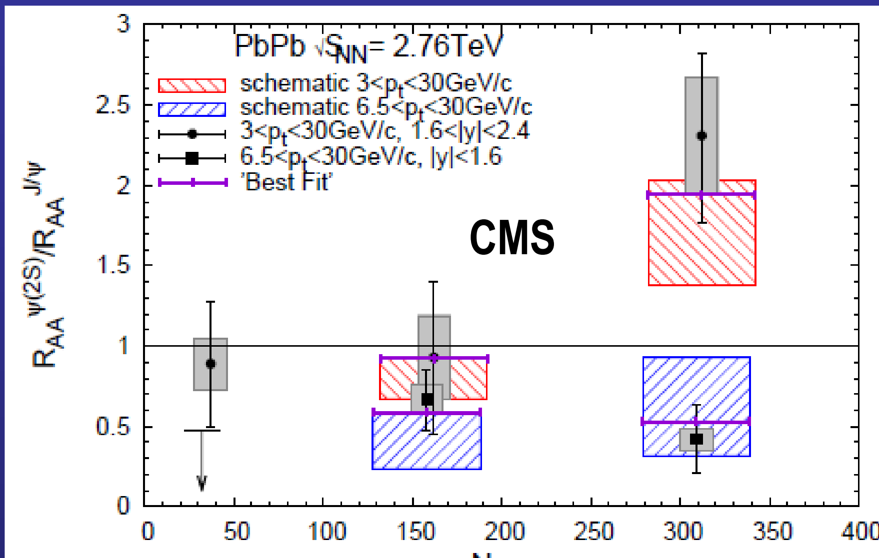
1) stronger suppression due to color screening
ε_{AuAu} ~ 80-85% ε_{UU}

2) J/ψ recombination favoured by 25% larger N_{coll} in UU
$N_{J/\psi}^{stat} \sim N_c^2 \sim N_{coll}^2$

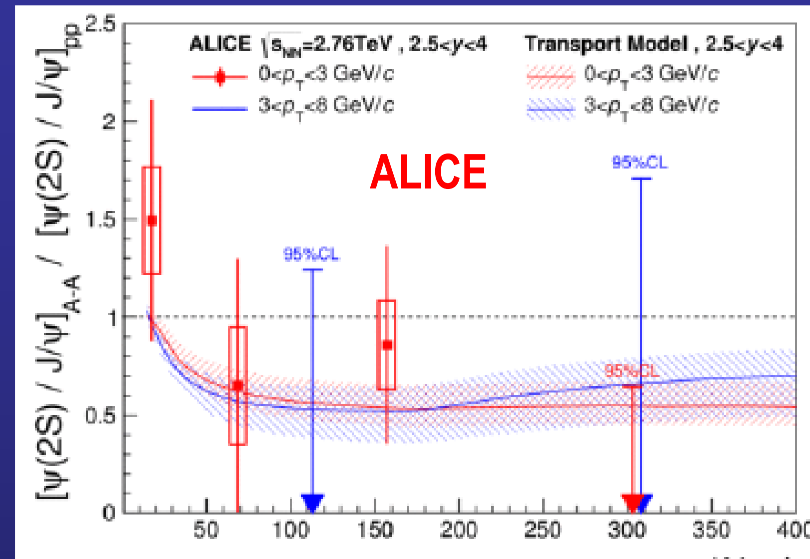
- results slightly favour N_{coll}^2 scaling → (re)combination wins over suppression when going from central U-U to Au-Au collisions
- quantitative comparison depends on the choice of the uranium Woods-Saxon parametrizations

ψ(2S), run-1 results

ψ(2S) production modified in AA with a strong kinematic dependence



Du and Rapp arXiv:1504.00670



Chen et al. PLB726(2013)725

Fw-y, 3<p$_T$<30GeV/c → $R_{AA}^{J/\psi} < R_{AA}^{\psi(2S)}$

→ later ψ(2S) regeneration, when radial flow is stronger, might explain the rise

Mid-y 6.5<p$_T$<30GeV/c → $R_{AA}^{J/\psi} > R_{AA}^{\psi(2S)}$

→ No regeneration, stronger suppression of ψ(2S) wrt J/ψ

CMS, PRL 113(2014) 262301

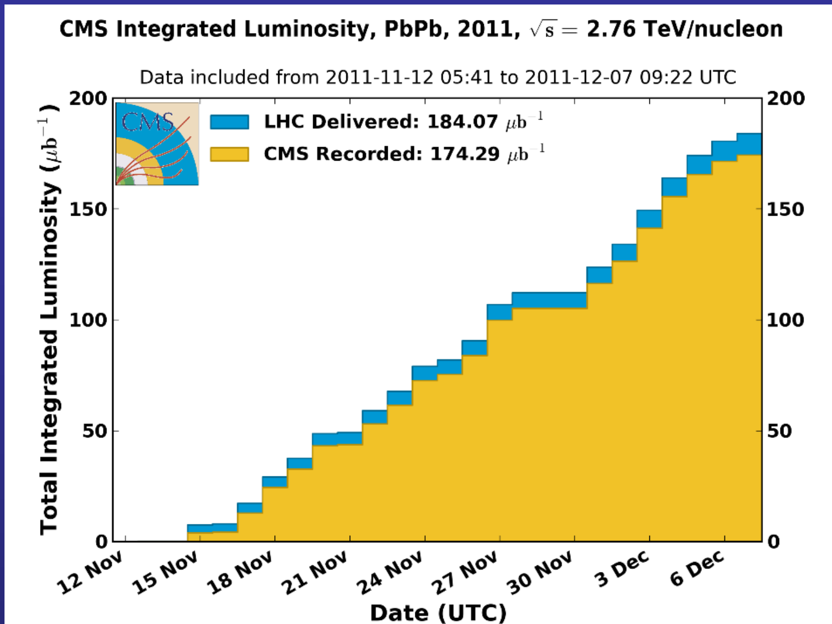
Fw-y, 0<p$_T$<3GeV/c → $R_{AA}^{J/\psi} > R_{AA}^{\psi(2S)}$

→ ALICE trend agrees with transport models and stat. hadronization approach

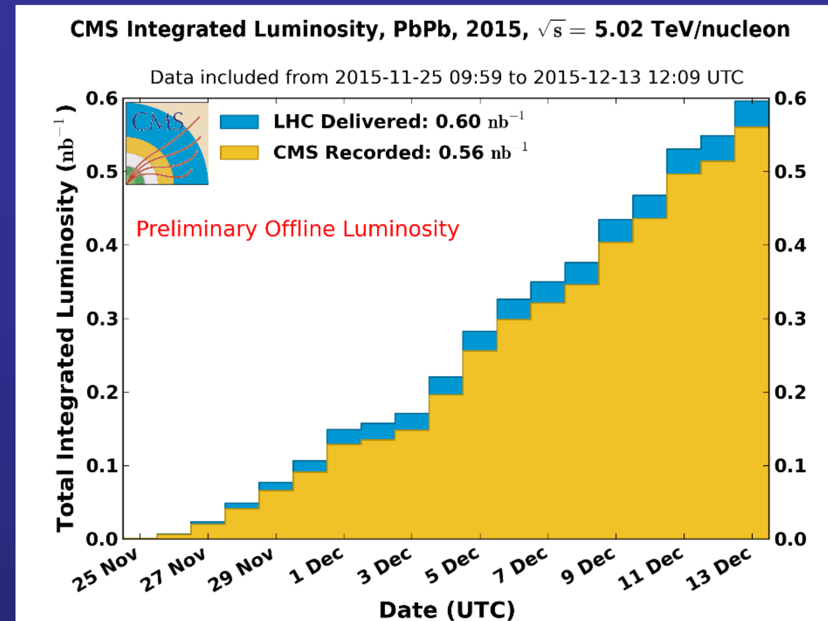
JHEP 05 (2016) 179

Run-2 results eagerly awaited

LHC run-2: Pb-Pb at $\sqrt{s_{NN}}$=5 TeV



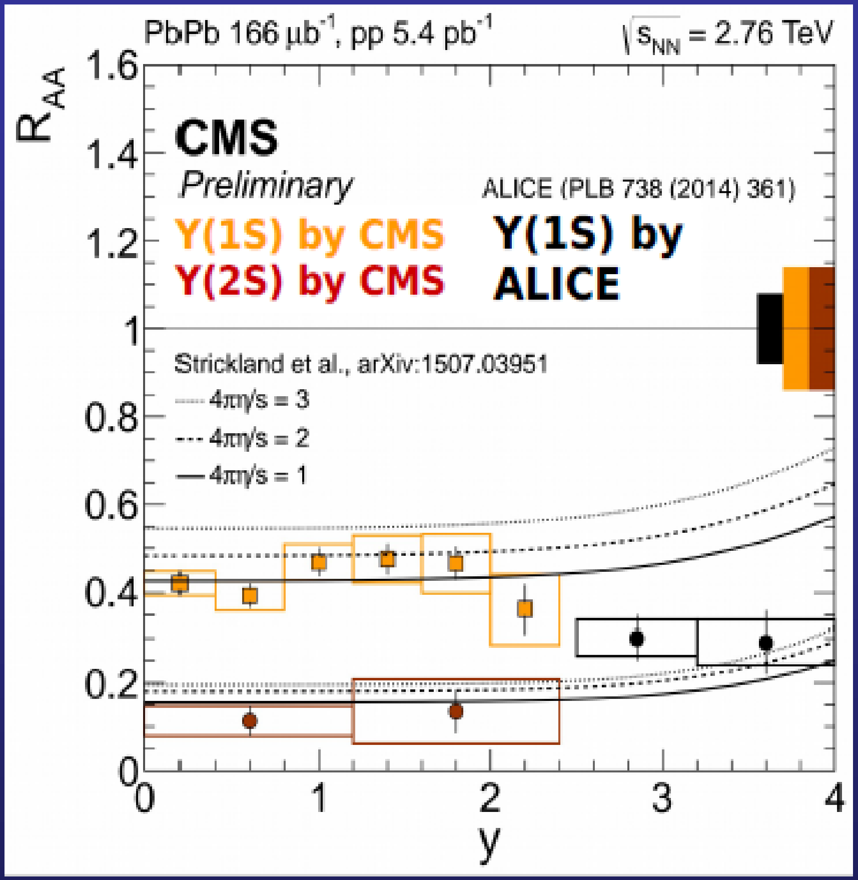
Run 1

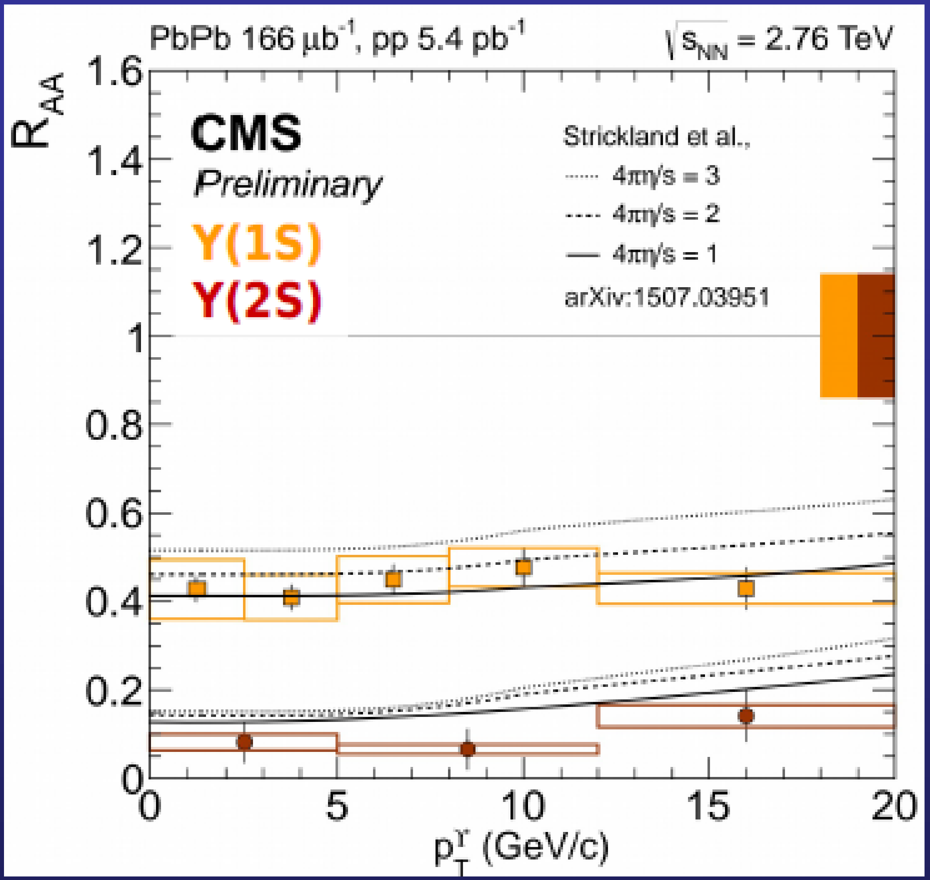


Run 2

- ❑ Integrated luminosity → more than a factor 3 delivered by the LHC with respect to run 1 (2011 Pb-Pb)
- ❑ Short pp run at $\sqrt{s}$ = 5.02 TeV at the beginning of the HI period → L_{int} = 30 pb^{-1} , good reference for BOTH Pb-Pb and p-Pb results
- ❑ Data analysis quickly progressing

R_{AA} vs p_T and y, comparison with models

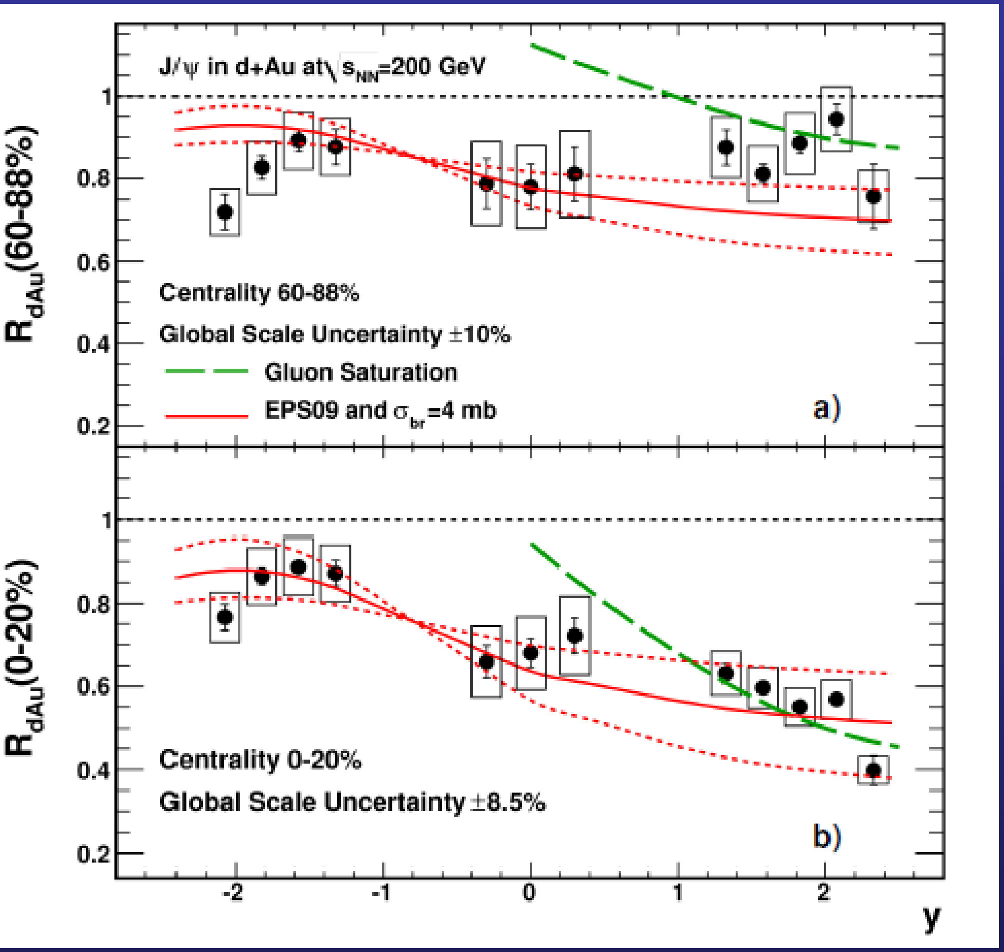




CMS-HIN-15-001

- No significant p_T dependence of R_{AA}
- Hints for a decrease of R_{AA} at large y (comparison ALICE – CMS)
- Could suggest the presence of sizeable recombination effects at mid-rapidity (?)

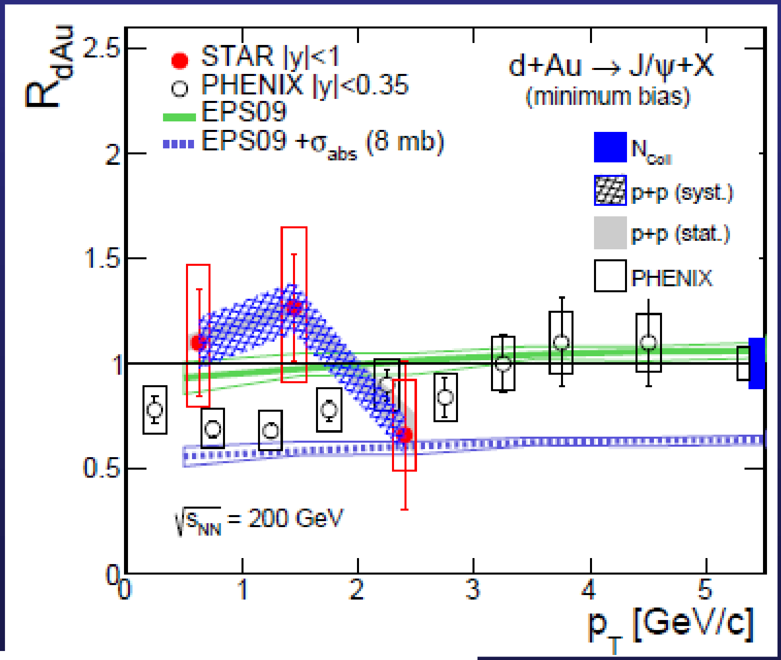
CNM at RHIC energy



PHENIX, PRL107 (2011) 142301

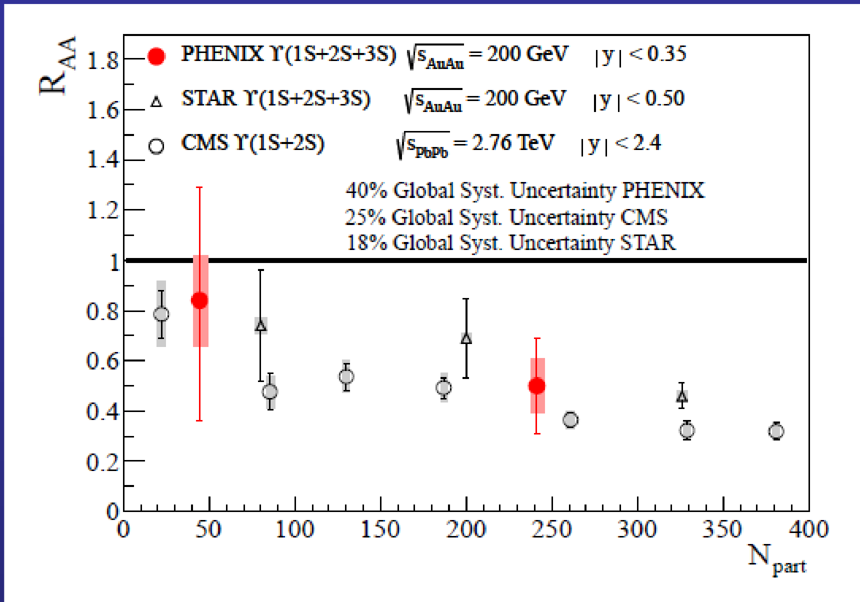
- ❑ Significant CNM effects also at RHIC energy

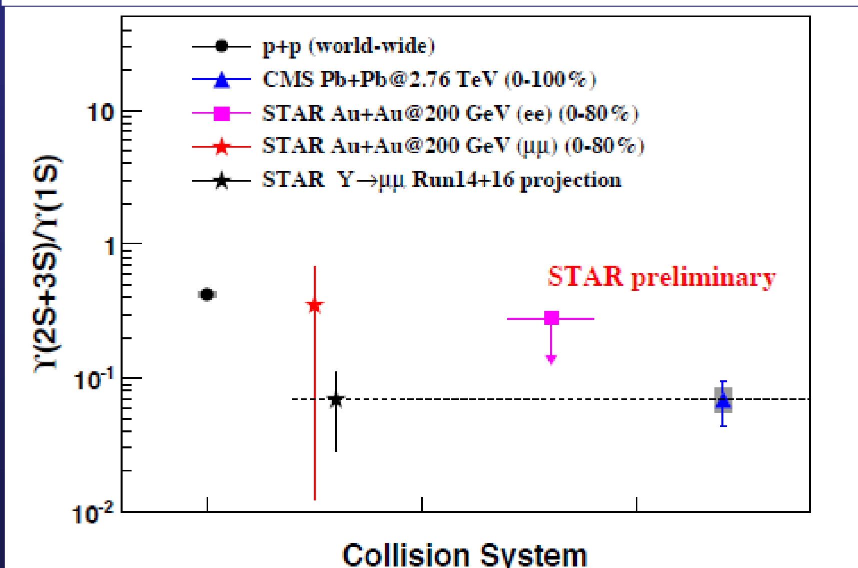
STAR, arXiv:1602.02212



- ❑ Transverse momentum dependence more difficult to reproduce

Bottomonium results at RHIC





- ❑ Both PHENIX/STAR have published results on ϒ
- ❑ Mutual agreement between experiments but still large stat+syst uncertainties

→ Need upgraded detectors and higher luminosity

- ❑ Recent results with the STAR MTD on the ratio excited/ground state
- ❑ Consistent with dielectron measurement within large uncertainties
- ❑ Factor 7 more statistics on this measurement with full Run14+ Run16 data

Summary/conclusions

- In the bottomonium sector
  - CNM effects are present but not strong
  - At LHC, a very strong suppression of Υ(2S) and Υ(3S) states wrt pp was observed, while the tightly bound Υ(1S) yield is reduced by ~50%
  - Compatible with sequential suppression of the states in a QGP
  - Quantitative description still needs refinements
  - RHIC upgrades will bring high quality data also at lower energies

- In the charmonium sector
  - The re-generation mechanism has been predicted to be sizeable at both RHIC and LHC
  - Hints for its presence were singled out at RHIC (R_{AA} vs y, UU vs PbPb)
  - Re-generation clearly present at LHC energy (R_{AA} vs p_T, flow)
  - Models qualitatively describe the data, but still large uncertainty on some key parameters → open charm cross section
  - CNM, dominated by shadowing/CGC, are stronger than in the Υ sector