Experimental aspects of quarkonia production and suppression in cold and hot nuclear matter

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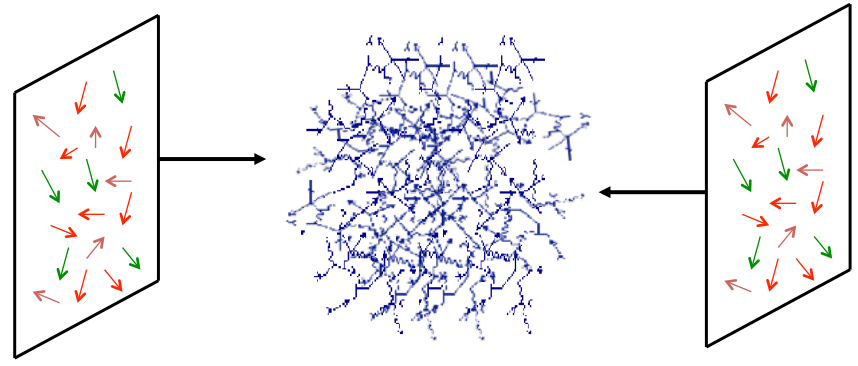
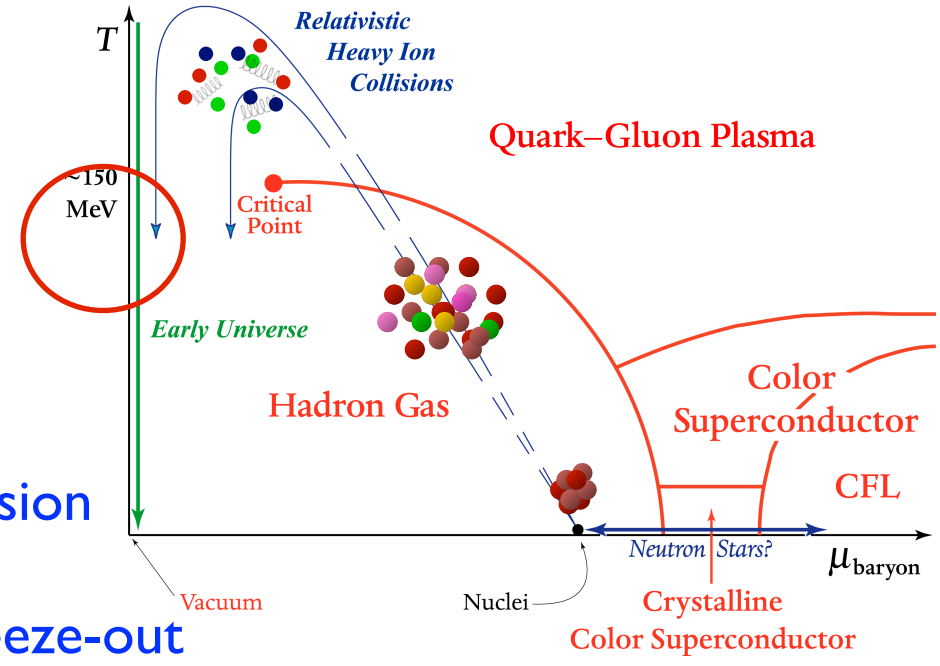
Forming the QGP in heavy ion collisions

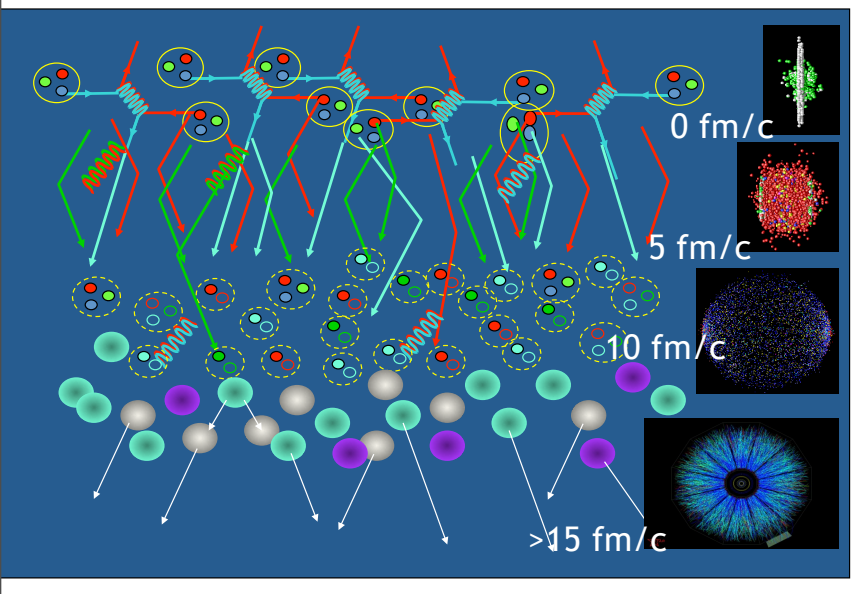
RHIC: $\gamma \sim 100$, $\tau_{crossing} \sim 0.3$ fm/c
LHC: $\gamma \sim 2700$, $\tau_{crossing} \sim 0.001$ fm/c

10,000 virtual gluons, quarks and antiquarks are made physical in the laboratory





Time evolution



initial state

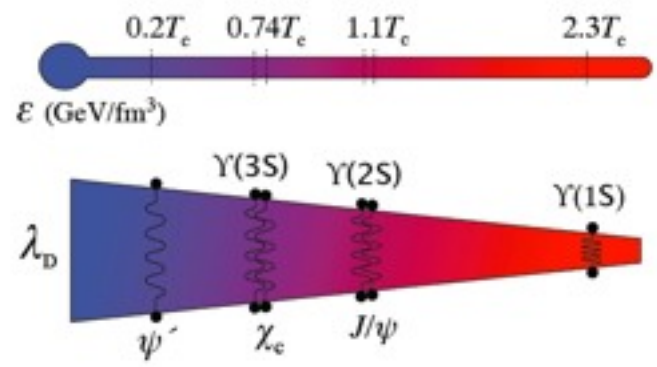
QGP expansion

chemical freeze-out

thermal freeze-out

Heavy quarkonia in nuclear collisions

Heavy quarkonia become unbound at different temperatures in the QGP, depending on radius - sensitive to physics at different length scales (e.g. color screening).



By observing the suppression of different quarkonia states at different temperatures we can directly observe the effects of Debye screening.

But the modification of heavy quarkonia yields in nuclear collisions is caused by an interplay of:

- Energy density in the medium - Debye screening effects
- Coalescence of heavy quarks at hadronization
- Cold nuclear matter effects - production in a heavy nucleus

All of these are significant contributors, and to study the effects of color screening on quarkonia bound states we need to understand the role played by all three of these effects.

History

The CERN SPS program (Pb beam program began 1994)
Experiments: NA38, NA50, NA60
PbPb collisions at $\sqrt{s_{NN}}$ = 17.3 GeV
- initial T ~ 1.5 T_C

pPb collisions for studying cold nuclear matter effects

The RHIC program (began in 2000)
Experiments: PHENIX, STAR
AuAu collisions at up to $\sqrt{s_{NN}}$ = 200 GeV
- initial T ~ 2 T_C

dAu collisions for studying cold nuclear matter effects

The LHC heavy ion program (began in 2010)
Experiments: ALICE, CMS, ATLAS, LHCB
PbPb collisions at up to $\sqrt{s_{NN}}$ = 5.5 TeV
- initial T ~ 2.7 T_C

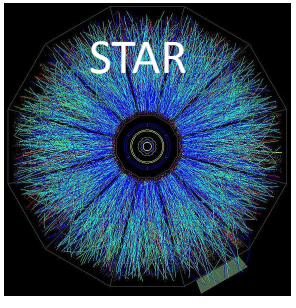
pPb collisions for studying cold nuclear matter effects

The RHIC and LHC programs are presently running in parallel

Experiments at RHIC

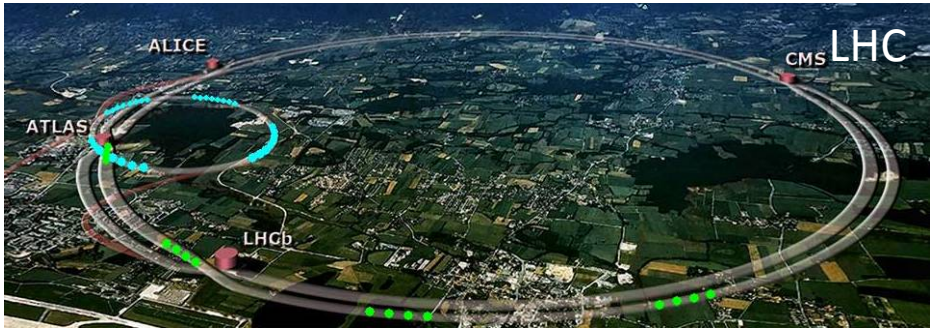
- **PHENIX**
  - dielectrons $|y| < 0.35$
  - dimuons $-2.2 < y < -1.2$, $1.2 < y < 2.4$
  - Good charmonium capability
  - Upsilon mass resolution and rates are poor
    - Proposal to build sPHENIX - excellent Upsilon measurements

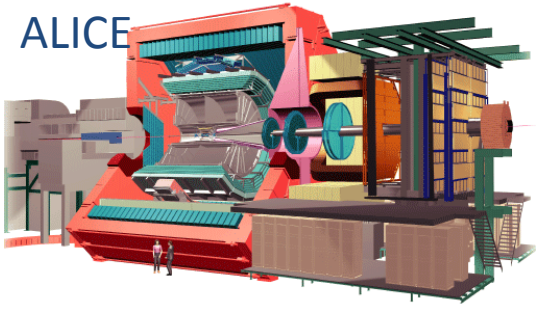
- **STAR**
  - dielectrons in TPC $|y| < 1.0$
  - dimuons in MTD $|y| < 0.5$
  - charmonium capability limited by triggering at low p_T
  - Better resolution and acceptance for Upsilons than PHENIX

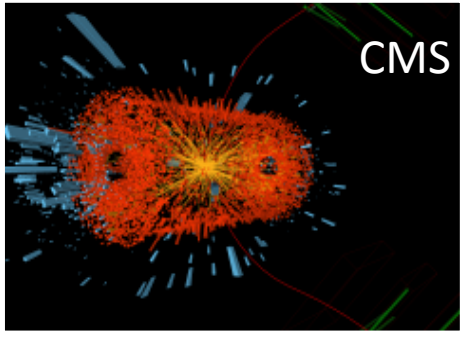


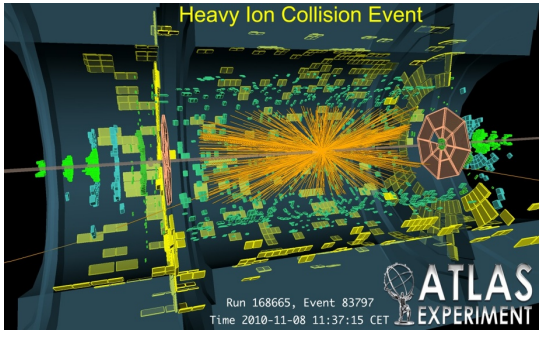
Experiments at LHC

- **ALICE**
  - Dielectrons $|y| < 0.8$
  - Dimuons $2.5 < y < 4.0$
  - Excellent charmonium program
  - Upsilons at forward rapidity
- **CMS**
  - Dimuons $|y| < 2.5$
  - Excellent Upsilon capability
  - Charmonia only at higher p_T
- **ATLAS**
  - Dimuons at midrapidity
  - Upsilon program limited by manpower









Yield modification in nuclear collisions

We characterize the modification of the yield in heavy ion collisions relative to that in pp collisions using the nuclear modification factor:

$$R_{AA} = \frac{dN/dy(AA)}{< N_{coll} > dN/dy(pp)}$$

where $< N_{coll} >$ represents the mean number of nucleon-nucleon collisions in the heavy ion collision.

- The R_{AA} shows **departures** from binary collision scaling

For studying quarkonia modification in the QGP, we want to measure the R_{AA} down to $p_T = 0$

Note that the modification for the J/ψ, for example, is affected by the modification for the ψ' and χ_C , which have significant feed-down branches to the J/ψ (40% combined).

- There is also (non-prompt) B → J/ψ feed down (up to 25%)

Heavy ion collisions at SPS and RHIC - J/ψ

The first comparison of the measured J/ψ modification in PbPb collisions at the SPS (17.3 GeV/A) and AuAu at RHIC (200 GeV/A) was striking:

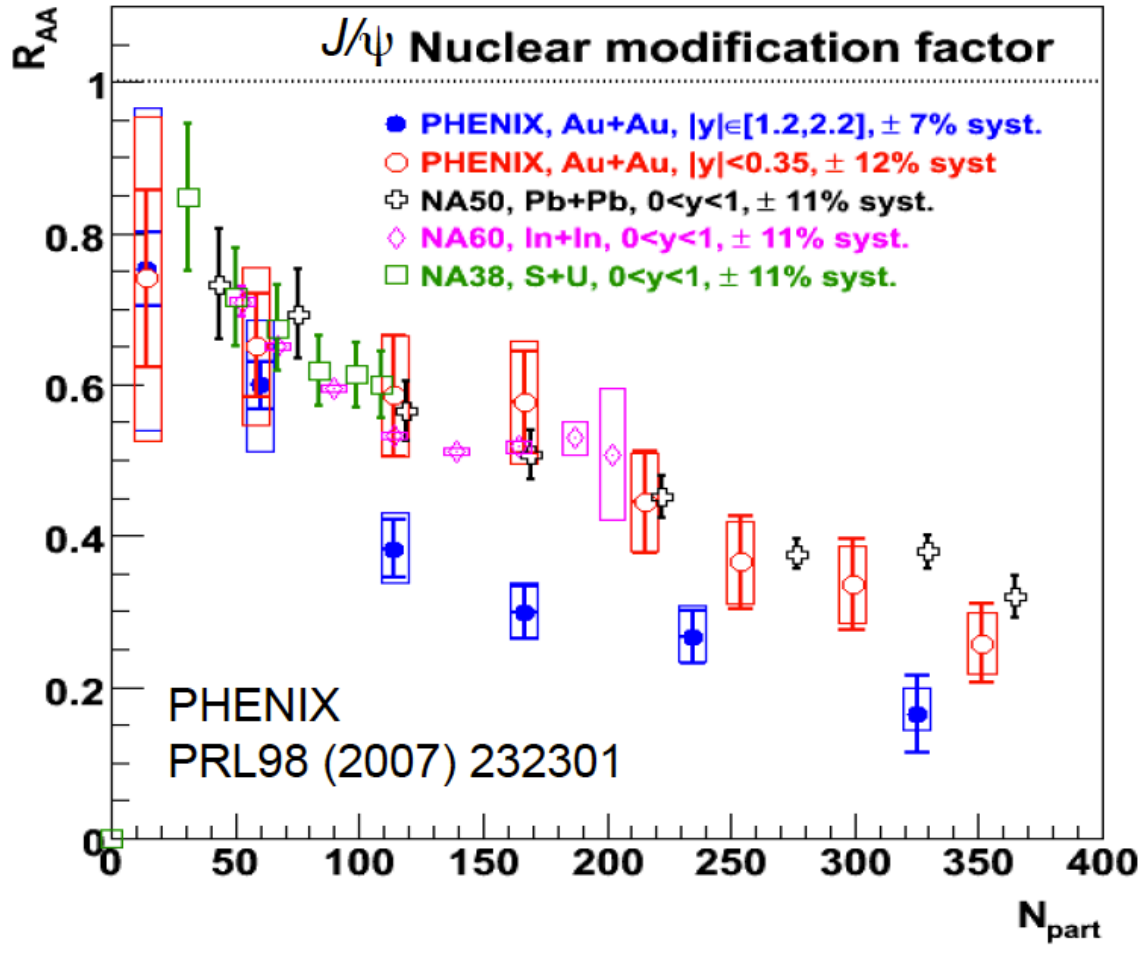
- Strong suppression in all cases
- No obvious pattern with energy density

The suppression at midrapidity at RHIC is similar to that at midrapidity at SPS

- But the energy density is much higher at RHIC

The strongest suppression is for forward rapidity in PHENIX

- But the energy density is (slightly) lower than in midrapidity collisions at RHIC

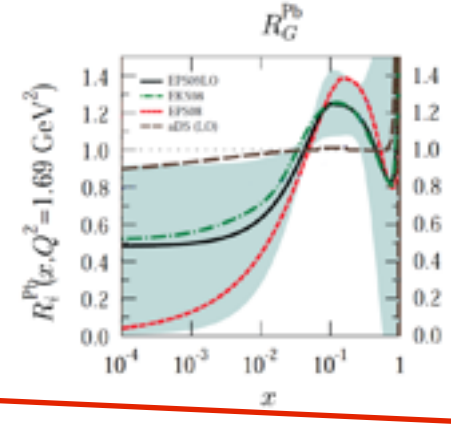


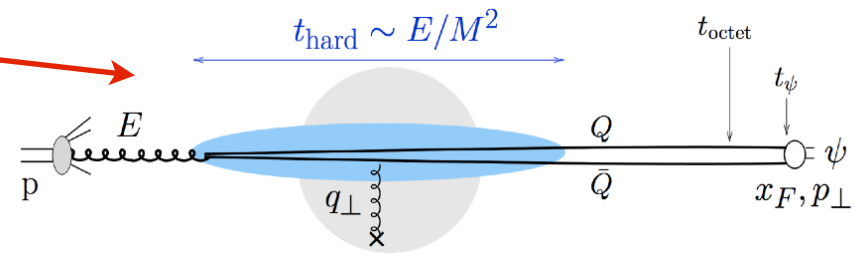
Cold nuclear matter effects

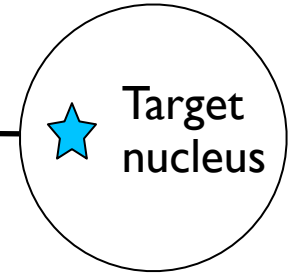
The lack of a pattern in the R_{AA} values is due to processes that modify the quarkonia yield in a nuclear target - cold nuclear matter (CNM) processes

CNM effects include

- Gluon shadowing – parton distributions modified in a nucleus
- Breakup of the precursor J/ψ by collisions with nucleons
- Initial state energy loss of partons in cold nuclear matter
- Cronin effect – multiple elastic scattering of partons







Notes:

- Gluon shadowing affects the underlying charm yield.
- Breakup reduces the **fraction** of charm forming bound charmonium.
- Initial state energy loss changes the rapidity distribution
- Cronin effect modifies only the p_T distribution.

A note on time scales in nuclear collisions

At 100 GeV/nucleon (200 GeV/nucleon center of mass) the colliding nuclei have $\gamma = 100$. Time scales are roughly (in the CM):

- Nuclear crossing time ~ 0.3 fm/c (0.001 fm/c at LHC). CNM effects
- J/ψ meson formation time ~ 0.3 fm/c
- QGP thermalization time ~ 0.3 to 0.6 fm/c
- QGP lifetime ~ 5-7 fm/c
- J/ψ lifetime (free space) ~ 2000 fm/c

The creation of the charm pair that evolves into the J/ψ and its modification in the hot medium occur on different time scales. They are often taken as being factorizable.

If so, we can study the cold nuclear matter (CNM) effects using p+A to help understand the initial J/ψ population in A+A.

Parameterizing CNM effects

Shadowing is observed in DIS data. Parameterizations of the nuclear modified parton distribution functions (nPDF's) are available, including:

- EPS09 [JHEP 04, 065 (2009)]
- nDSg [PRD 69, 074028(2004)]
- EKS98 [EPJ C9, 61 (1999)]

We are interested in the gluon nPDF's, since gluon fusion dominates in quarkonia production at high energy

Initial state energy loss is less easy to identify experimentally.

What is easy to do is to fit shadowing corrected data with an effective absorption cross section, σ_{abs}.

- In certain kinematic regimes, interpreting σ_{abs} as a breakup cross section makes sense
- In others it makes no sense, and we are likely seeing the effects of energy loss

Systematic studies of CNM effects (17.3-200 GeV)

Method: fit effective σ_{abs} to **shadowing corrected** (p_T integrated) data.

Effective σ_{abs} extracted for **17.3 - 200 GeV** collisions-examples:

- Lourenco et al., JHEP02, 014 (2009).
- Arnaldi et al. (NA60), Nucl. Phys. A 830, 345C (2009).
- McGlinchey et al., Phys.Rev. C87 (2013) 054910.

Caveats:

- All use **central** EKS98 or EPS09 shadowing parameterizations - ie. nPDF uncertainties ignored.
- Effective σ_{abs} and shadowing **only** are considered.

Provides **shadowing corrected** effective absorption cross sections. Now we can **correct** heavy ion data for CNM effects

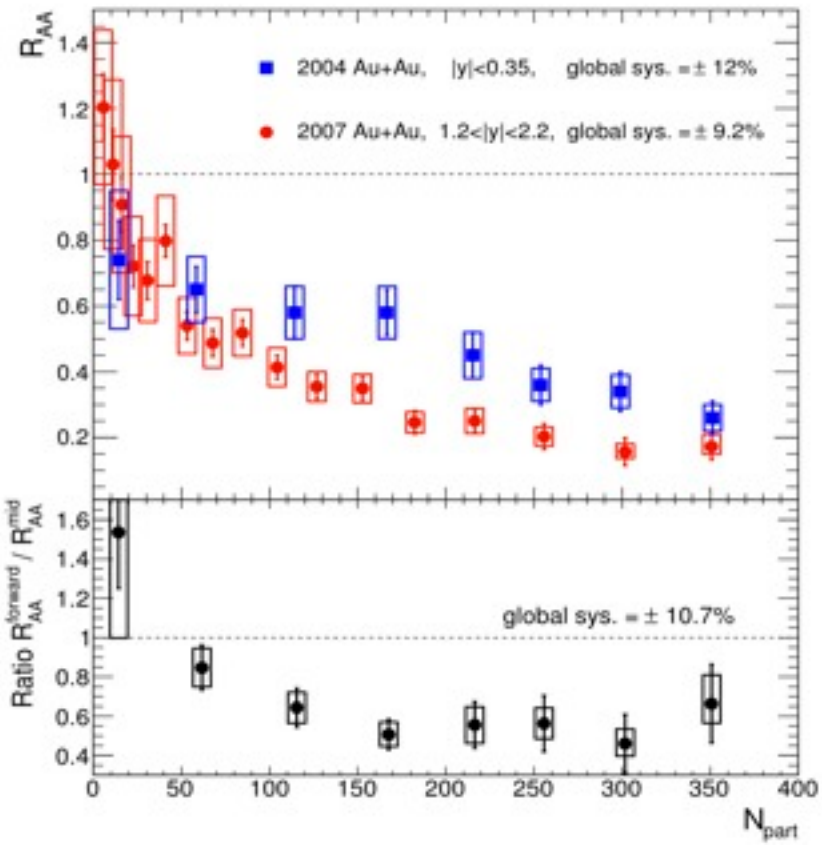
- This assumes CNM and hot matter effects are factorizable!

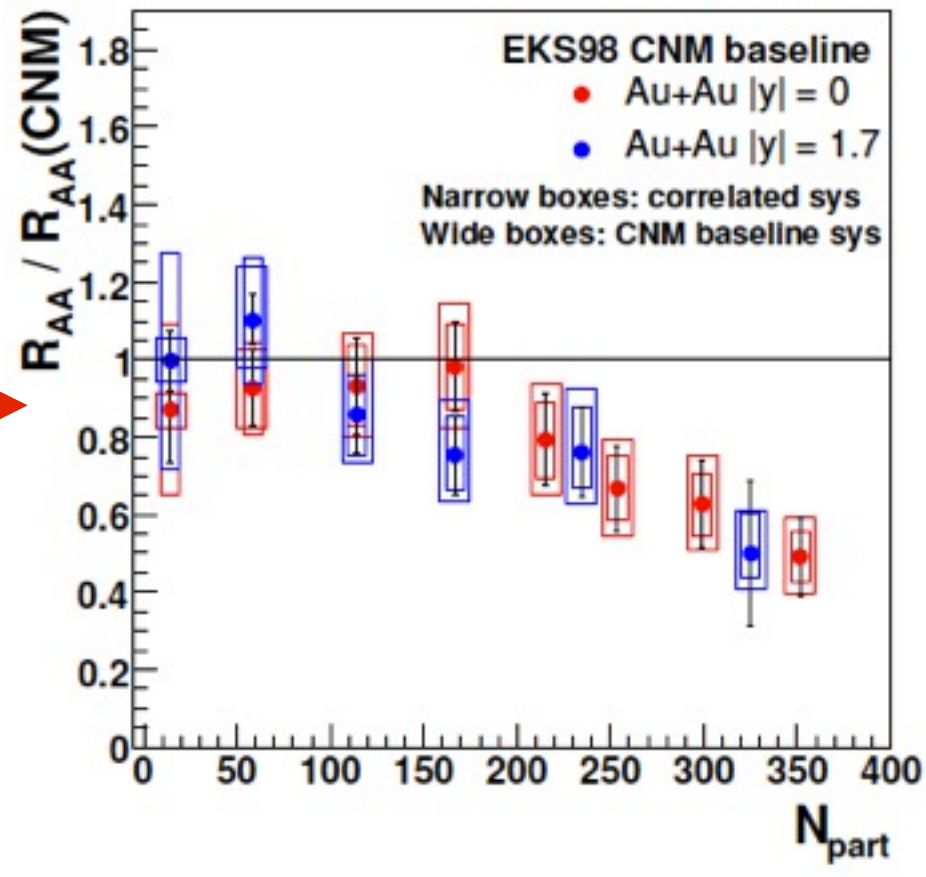
Au+Au J/ψ at 200 GeV - corrected for CNM

- Parameterize d+Au data: EKS98 nPDF's + absorption cross section
- Use parameterization in Glauber model to estimate R_{AA}(CNM)

Quarkonium Working Group report, Eur. Phys. J **C71** (2011) 1534
PHENIX PRC 84 054912 (2011)

Suggests stronger suppression at large rapidity is due to CNM effects





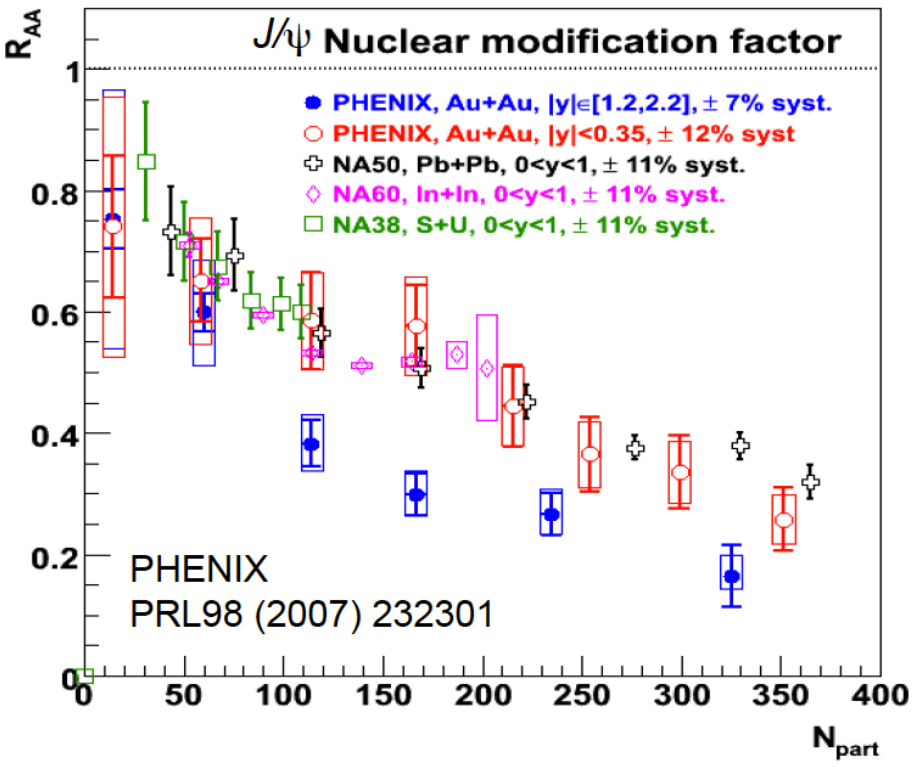
Au+Au J/ψ at 200 GeV - corrected for CNM

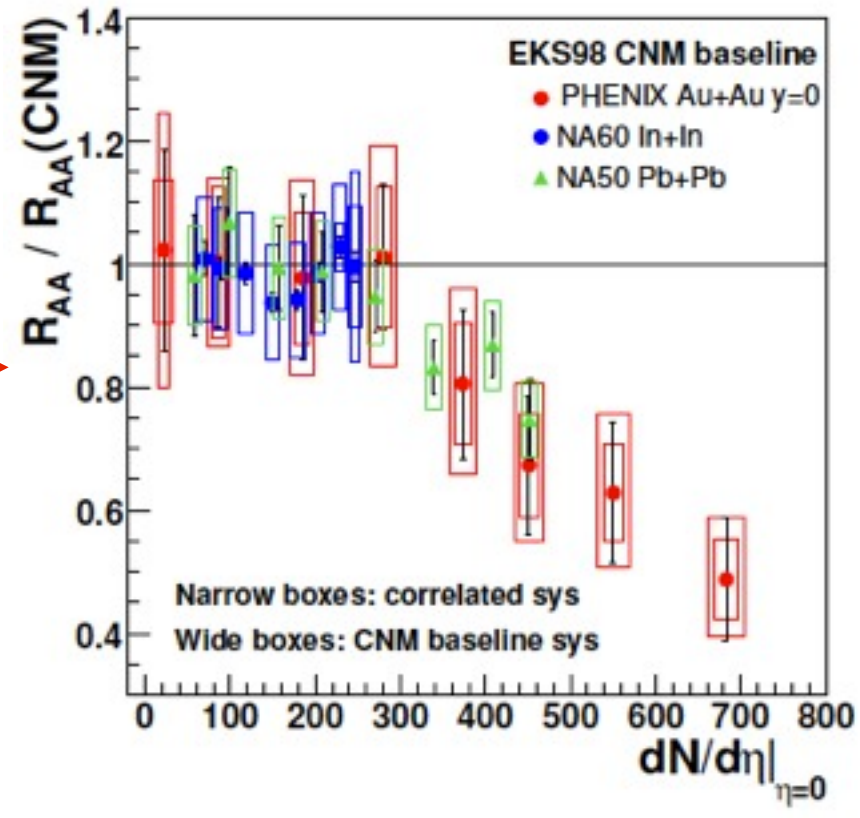
Compare with similar treatment of NA50/NA60 data from SPS at 17.3 GeV

- Plot CNM corrected data vs dN/dη (proxy for energy density)
- After correction for CNM effects, suppression pattern seems to make sense

Quarkonium Working Group report, Eur. Phys. J **C71** (2011) 1534
PHENIX PRC 84 054912 (2011)

Now the suppression increases with increasing energy density, as expected.





Coalescence

That makes a pretty good story - so why are we not done?

In addition to Debye screening, due to the high density in the hot medium, there is another effect that can occur due to QGP formation: coalescence

There are two coalescence scenarios:

- A quark and anti-quark that are produced in the same hard process - and are nearly bound - can become bound through interactions with the medium
- A quark and anti-quark that were produced in different hard processes can thermalize in the medium and combine statistically at (or before) hadronization

The first scenario occurs even if only one heavy quark pair is produced in the collision. It is often called **"regeneration"**.

The second scenario only becomes important if we have a large number of heavy quarks produced in a single collision.

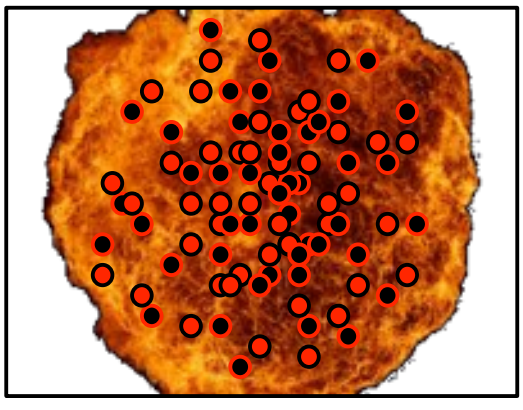
- At the LHC we expect ~ 100 charm pairs in a central collision!

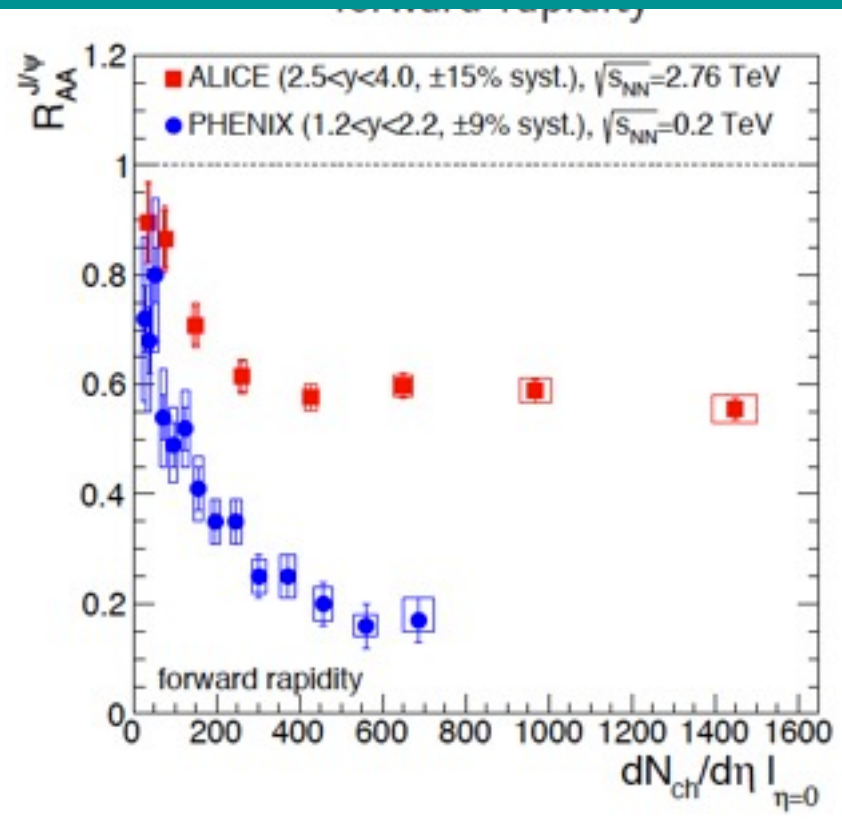
Move up to 2.76 TeV - ALICE data

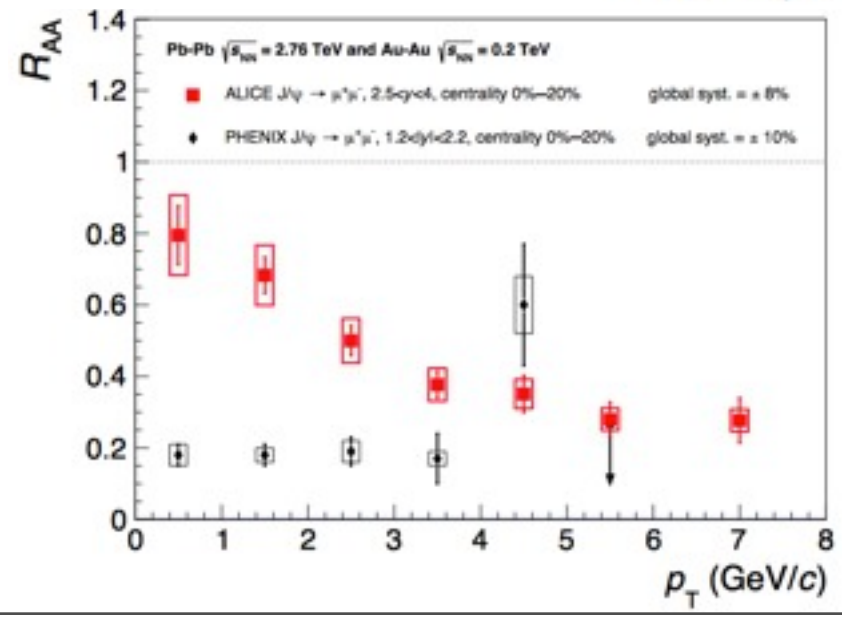
ALICE J/ψ results show that at 2.76 TeV J/ψ suppression is much reduced compared with PHENIX data at 200 GeV (**compare blue with red**).

Due to a much smaller R_{AA} at low p_T at 200 GeV.

Seems to be a clear signature of coalescence - 100 charm quark pairs in central collisions!





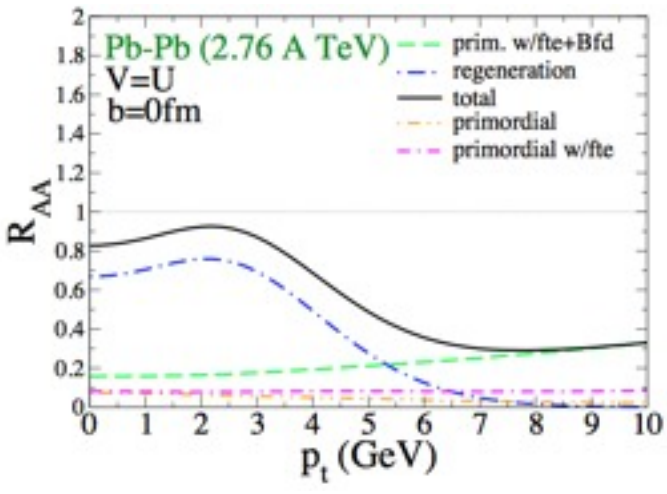


Introduce 2.76 TeV ALICE data

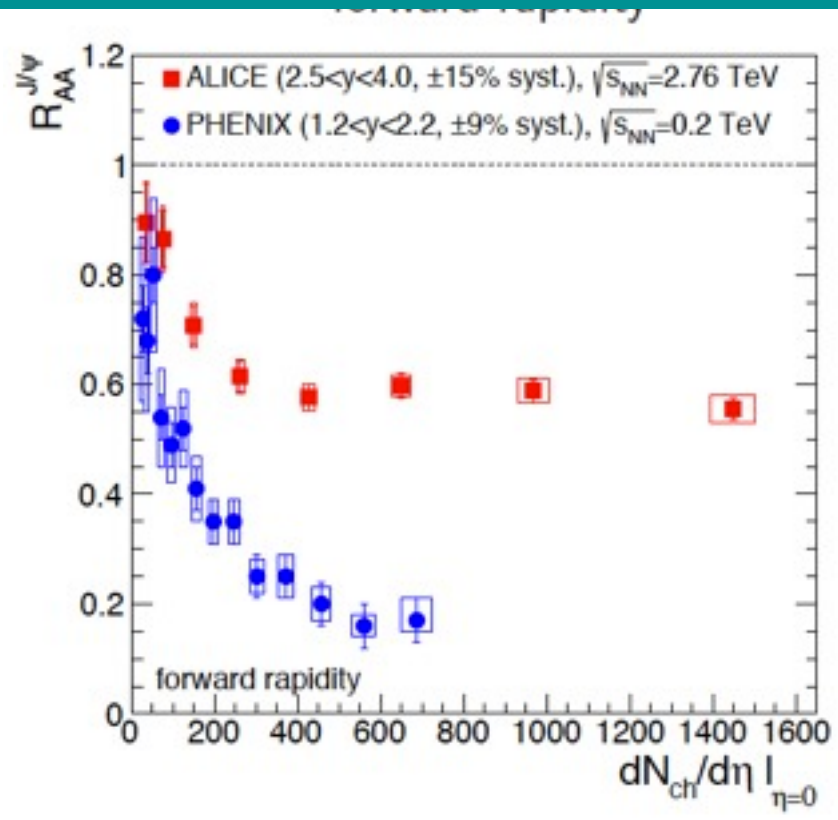
The ALICE J/ψ results show that at 2.76 TeV J/ψ suppression is much reduced compared with PHENIX data at 200 GeV (**compare blue with red**).

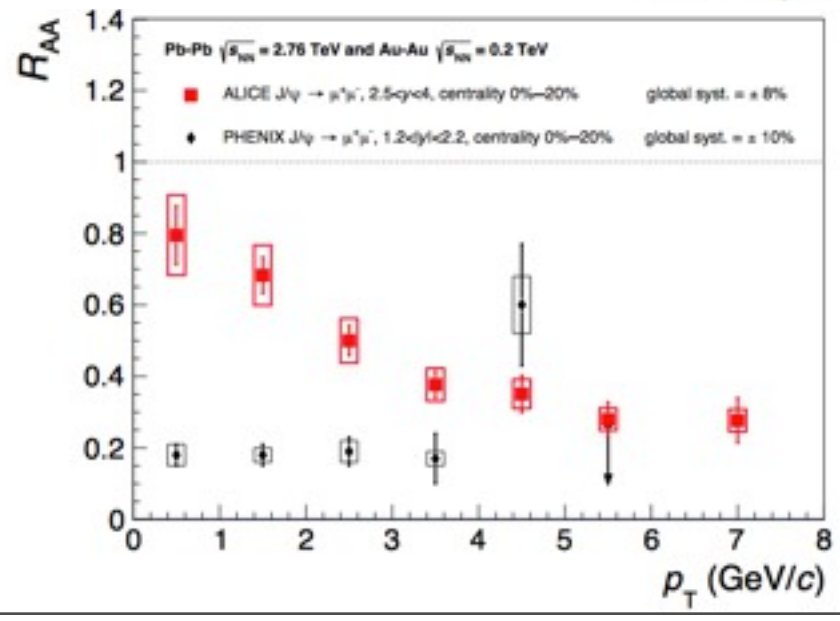
Due to a much smaller R_{AA} at low p_T at 200 GeV.

In good agreement with a prediction from Rapp et. al.



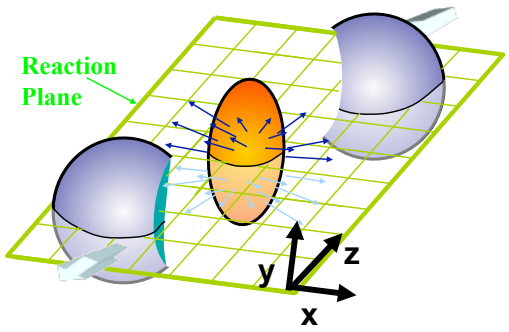
How important is coalescence at RHIC?

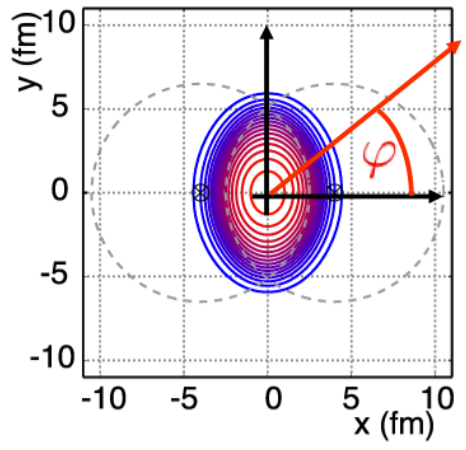


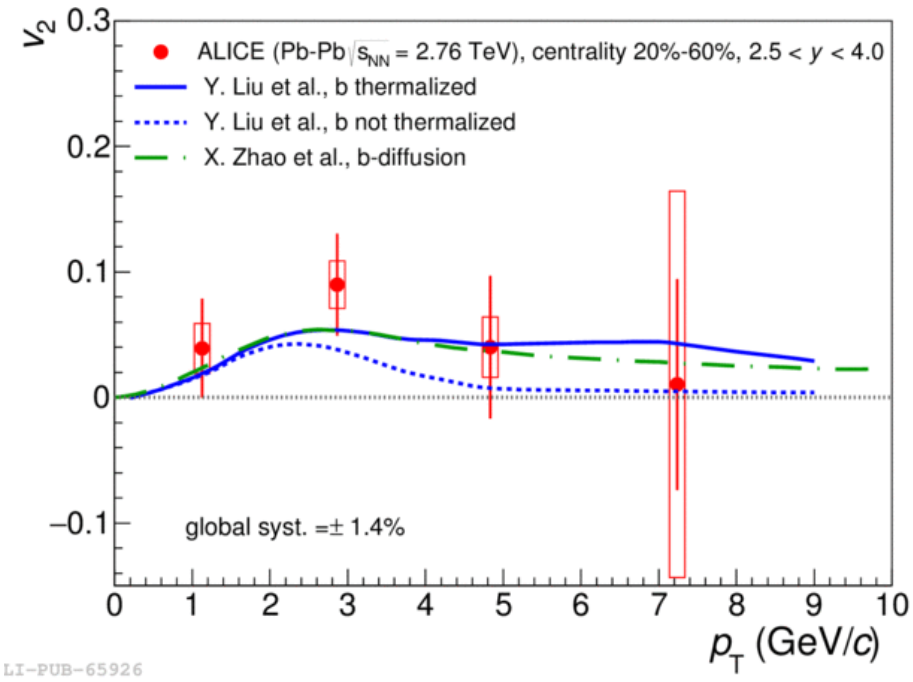


J/ψ elliptic flow data from ALICE and STAR

"Flow" means collective motion due to pressure gradients in the hot medium formed in the collision.

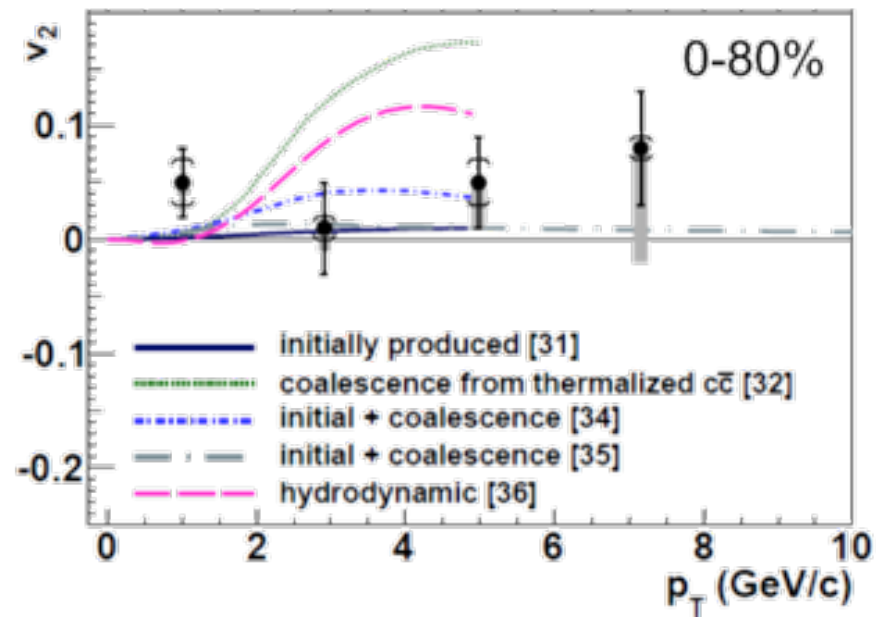






Elliptic flow - asymmetry in particle distributions due to the almond shaped overlap region. Measured relative to the reaction plane event-by-event

Non zero elliptic flow implies the J/ψ are formed from (at least partly) thermalized quarks.

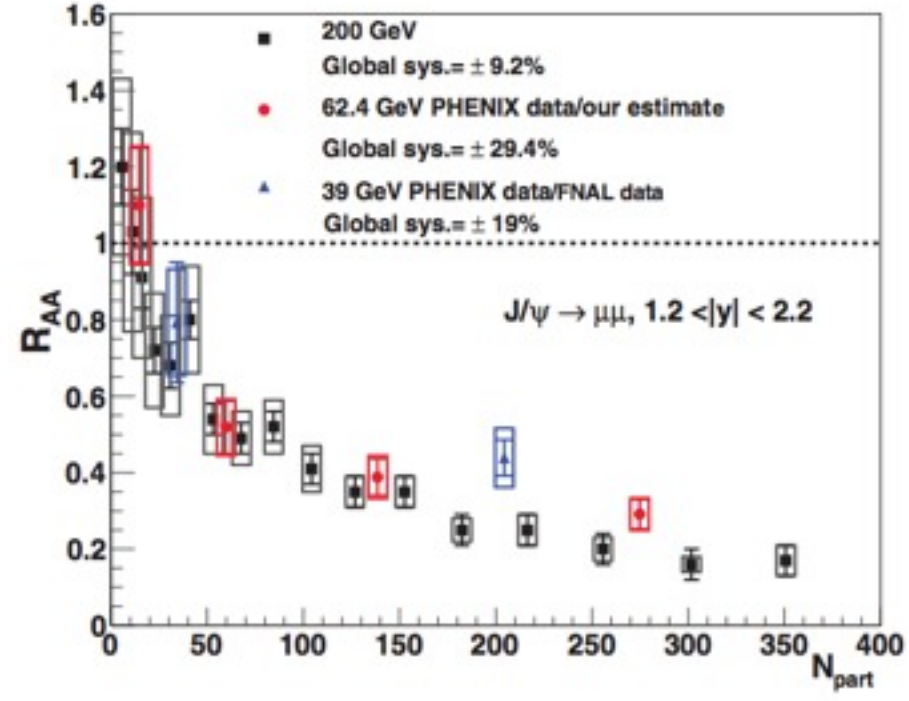


Au+Au J/ψ vs energy

PHENIX data at 39, 64 and 200 GeV.

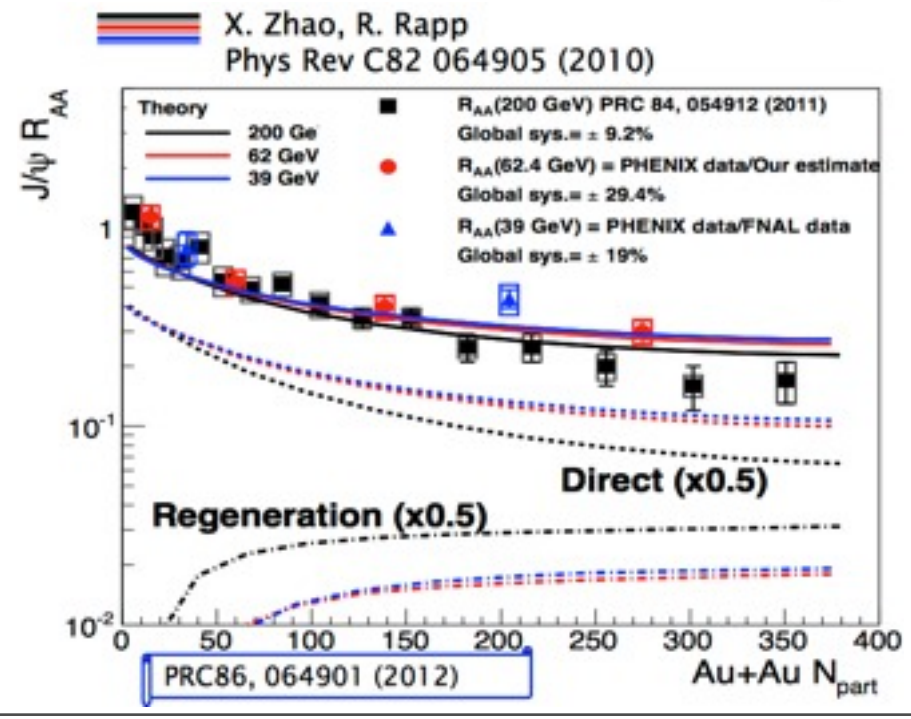
The suppression seems to be:

- Strongest at 200 GeV
- Weaker at 64 GeV
- Weaker again at 39 GeV



Model (Zhao & Rapp): the suppression is similar at the three energies:

- As the energy increases, suppression increases
- **But** increased suppression is compensated by increased regeneration.

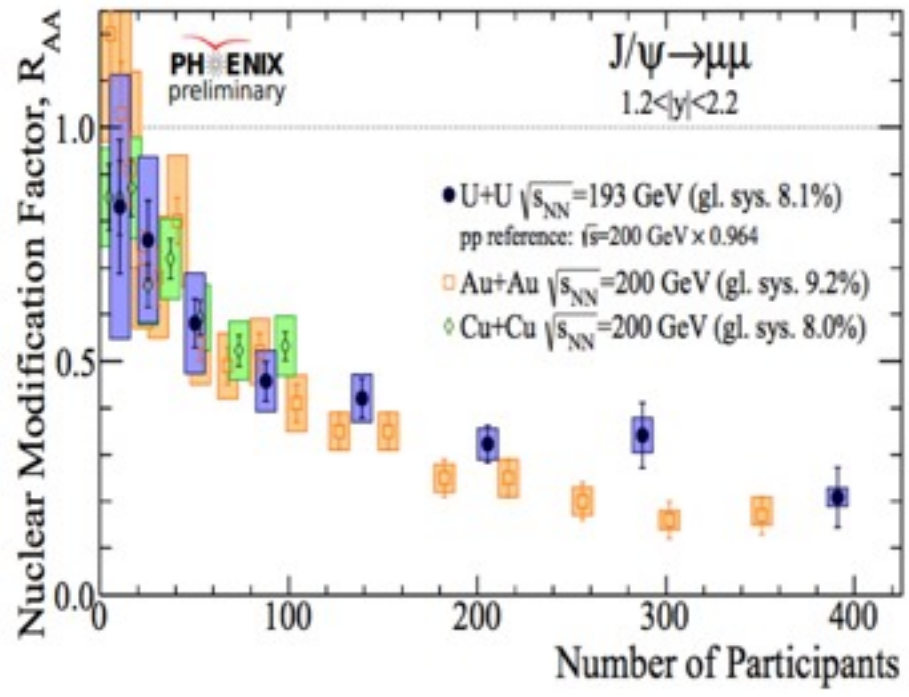


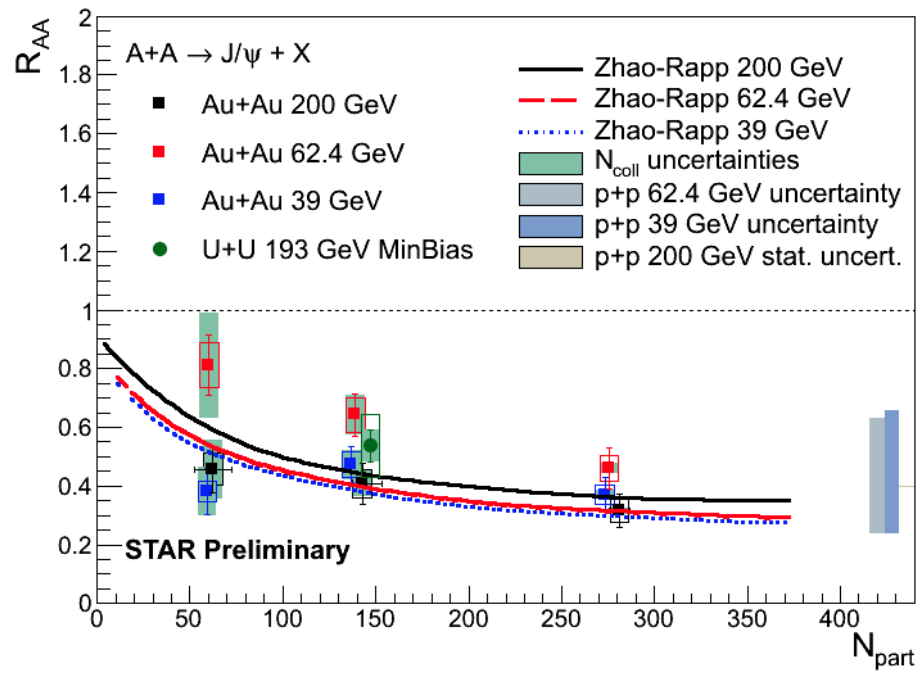
J/ψ R_{AA} - increase system size at 200 GeV - U+U

PHENIX and STAR preliminary data indicate that U+U is less suppressed than Au+Au.

- Expect about 20% higher energy density (Kikola, Odyniec, Vogt, PRC 84, 054907 (2011))
- CNM effects are expected to be very similar
- Charm production is higher - N_{coll} increases
- Higher energy density does not translate to stronger suppression

Increased regeneration overcomes increased screening?





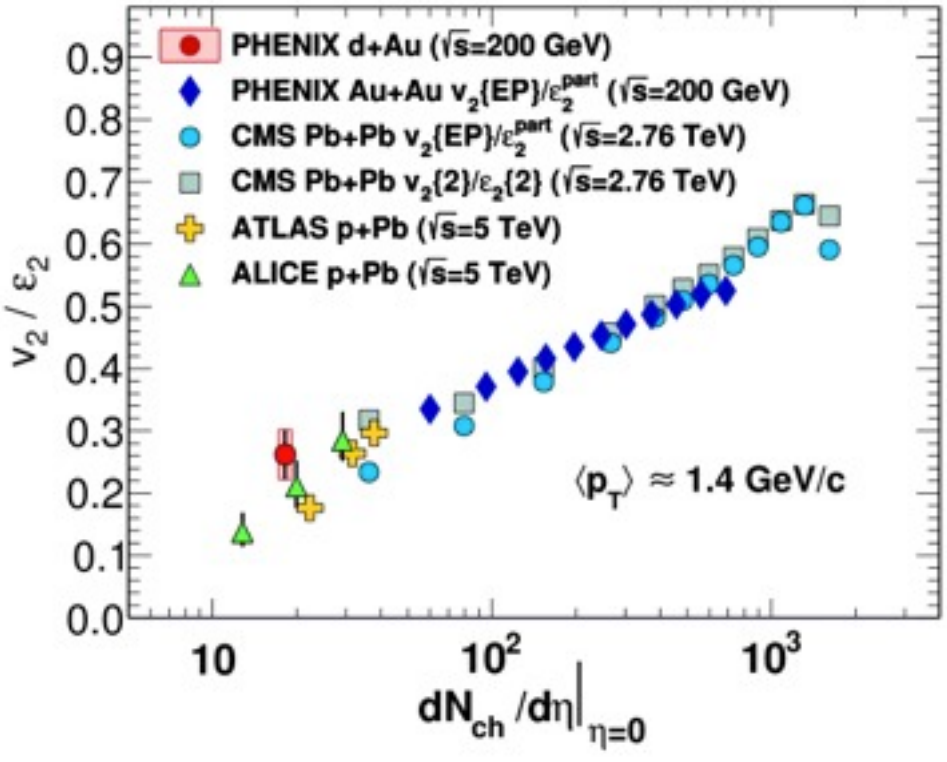
p(d)+A charmonium results

Initially, interest in p(d)+A collisions by the heavy ion community was focused on establishing a CNM baseline for quarkonium production in A +A collisions.

However a recent observation has suggested that a (small) fireball is produced in p(d)+A collisions - the evidence is the presence of elliptic flow that scales with particle production in a similar way to A+A

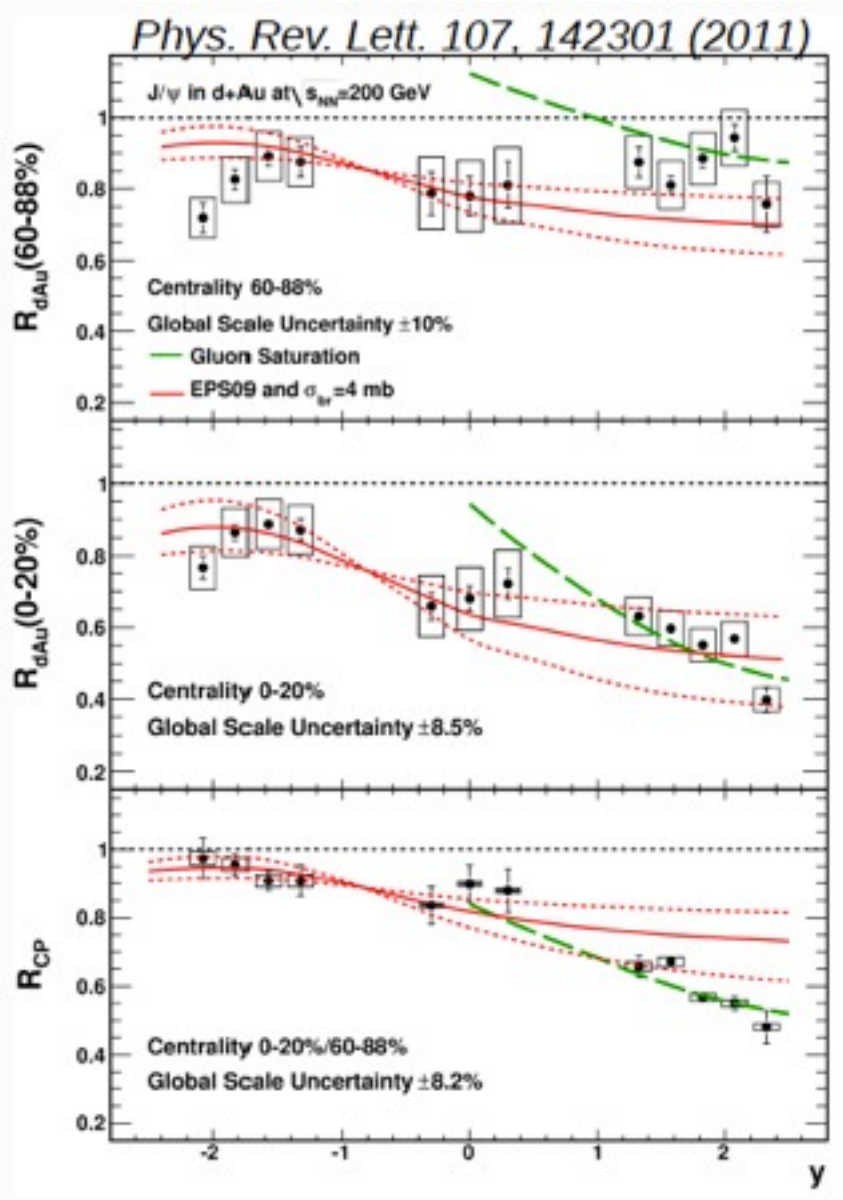
However there is no evidence so far that the "hot spot" formed in p+A collisions suppresses the signal from hard probes

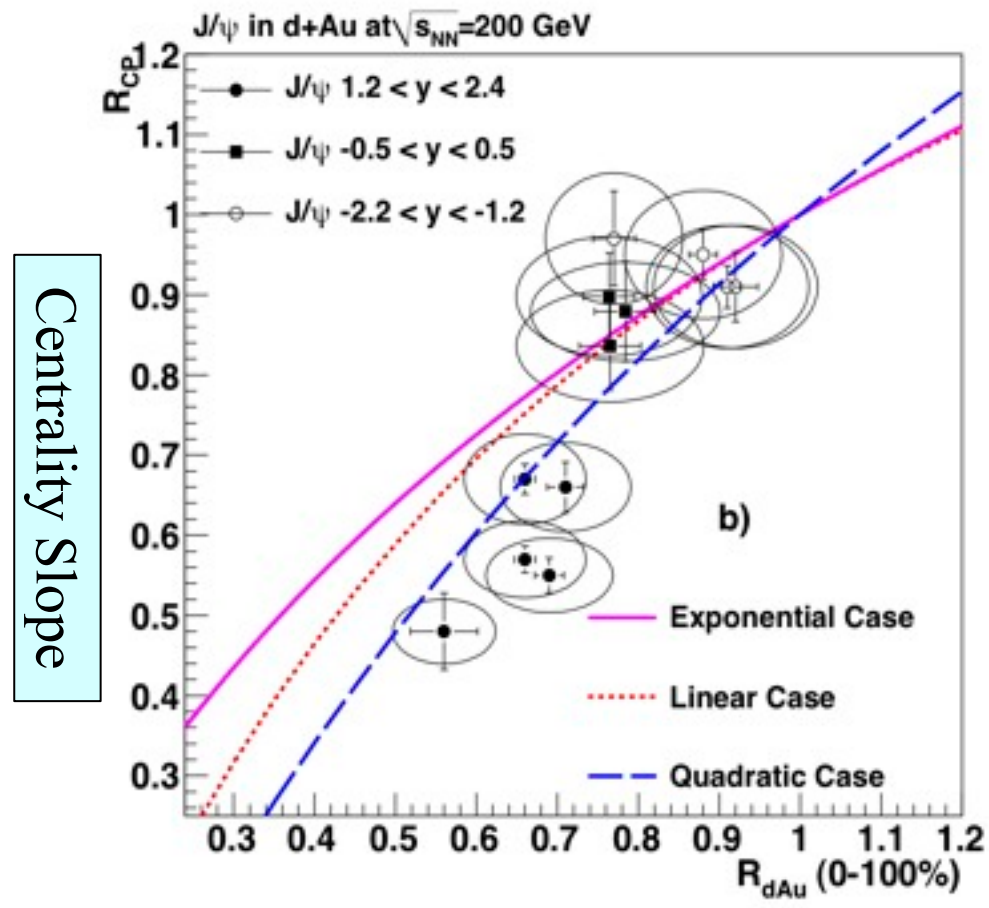
- Except, possibly, for the ψ' and excited Upsilon states



d+Au J/ψ results from PHENIX

Left: twelve rapidities, centrality 0-20%, 20-40%, 40-60%, 60-88%
Right: Plot RdAu vs RCP to see **overall modification** vs **centrality slope**





Centrality Slope

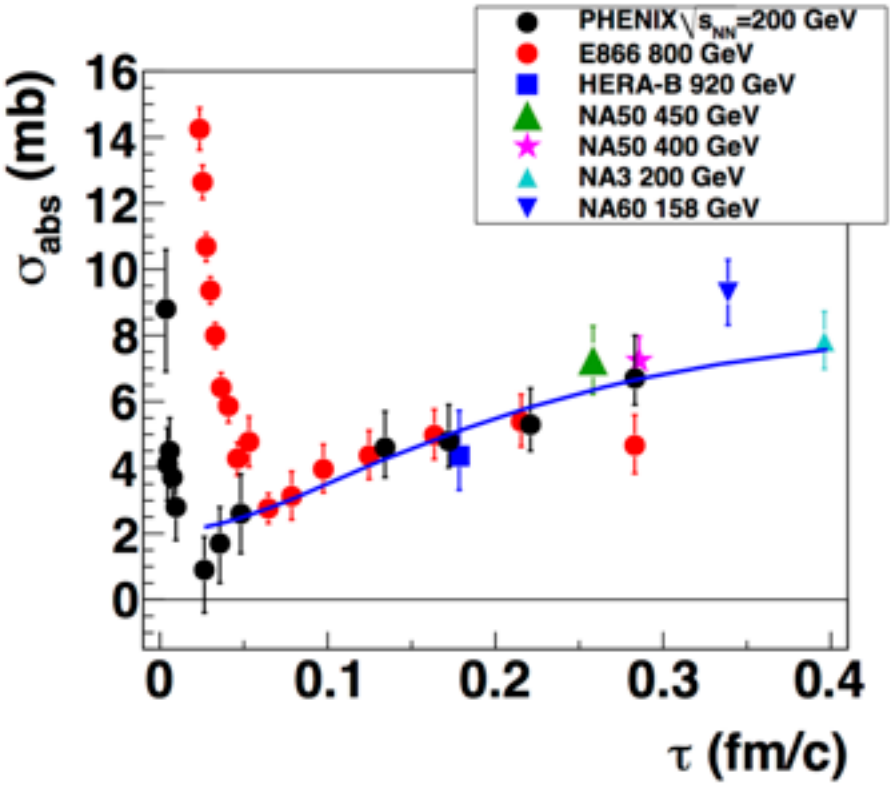
Overall modification

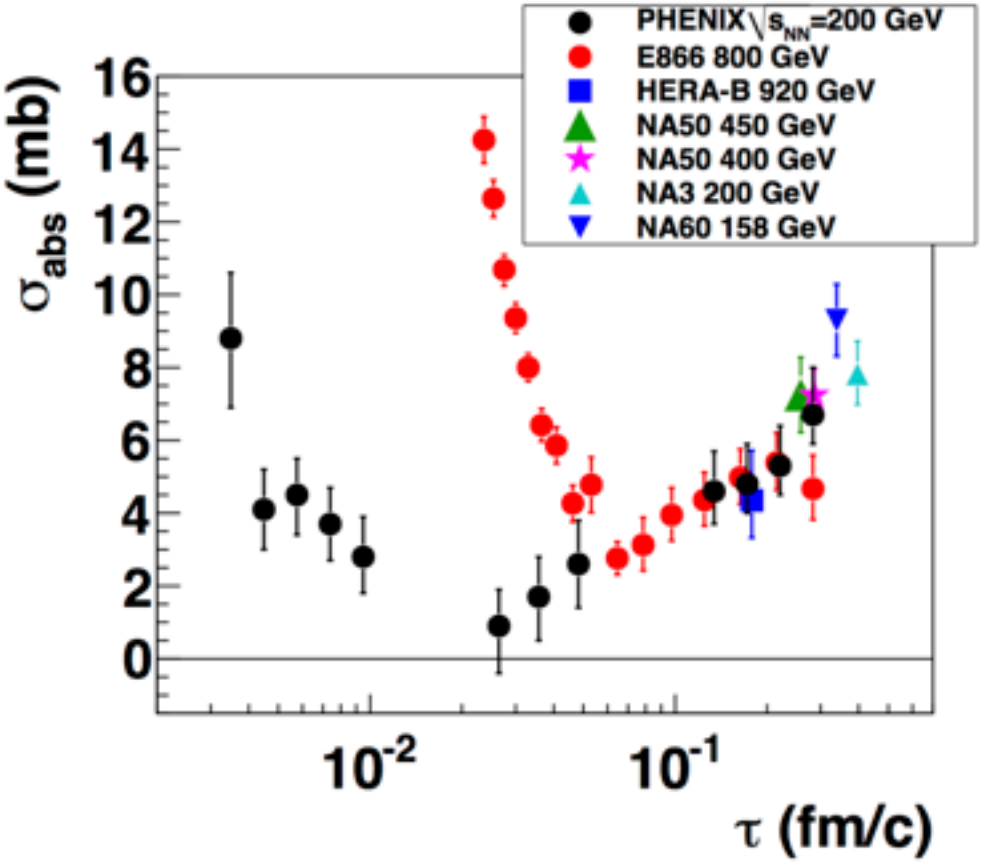
The suppression at forward rapidity has a very strong impact parameter dependence

dA/pA: dependence of σ_{abs} on nuclear crossing time

Effective absorption parameter vs nuclear crossing time (τ) for pA or dA at 17.3 - 200 GeV collision energy (PHENIX data plus 6 other experiments)

Phys.Rev. C87 (2013) 5, 054910





Fit region above τ ~ 0.05 fm/c with model of **expanding color neutral meson**.

- Suggests we really have breakup at backward rapidity, **something else** at forward rapidity

p+Pb J/ψ data from ALICE - rapidity

Consider ALICE centrality integrated data first

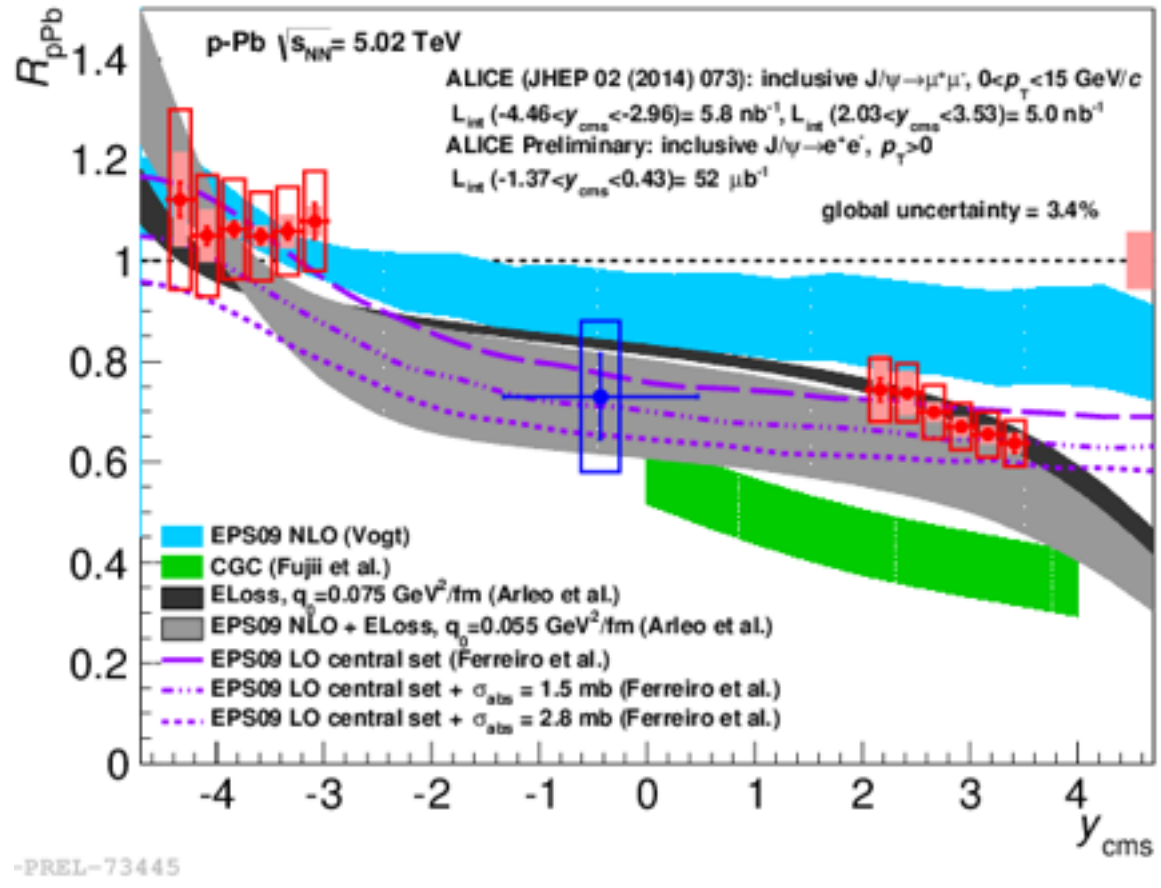
We do **not** expect breakup by collisions with nucleons at LHC energies (except maybe at the very most backward rapidities)

- For y= -4.5 to +3.5 expect τ ~ 0.1 to 3.5 x 10^{-5} fm/c

Expect both shadowing and energy loss to be important

EPS09 shadowing insufficient at forward rapidity

Pretty good description of the rapidity dependence of the data by EPS09 shadowing + energy loss calculation

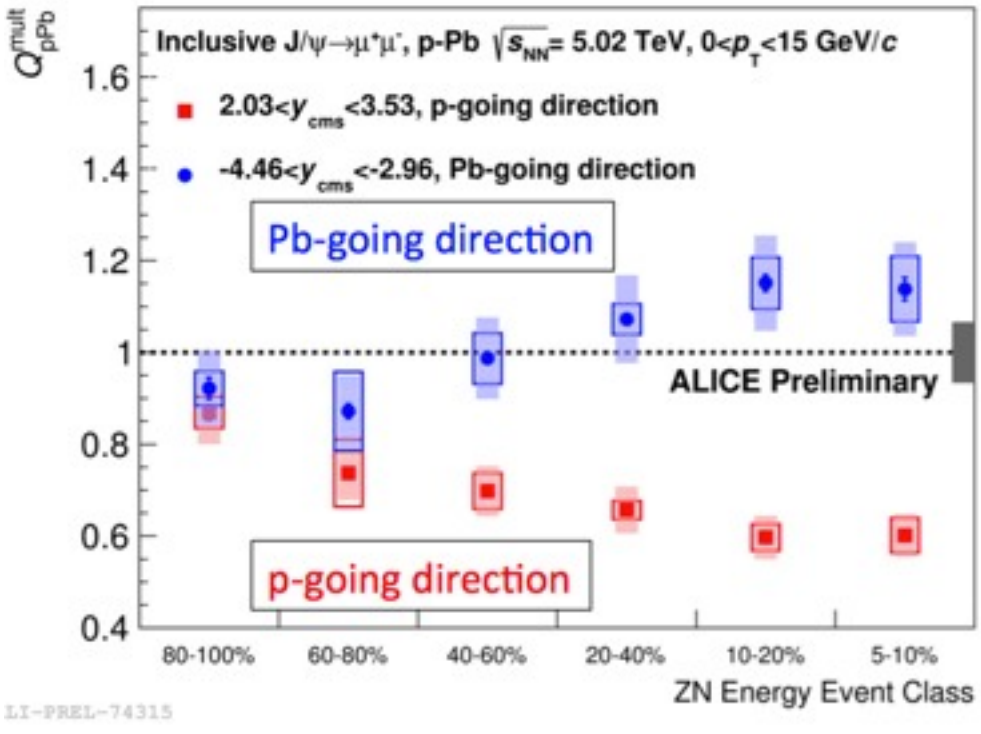


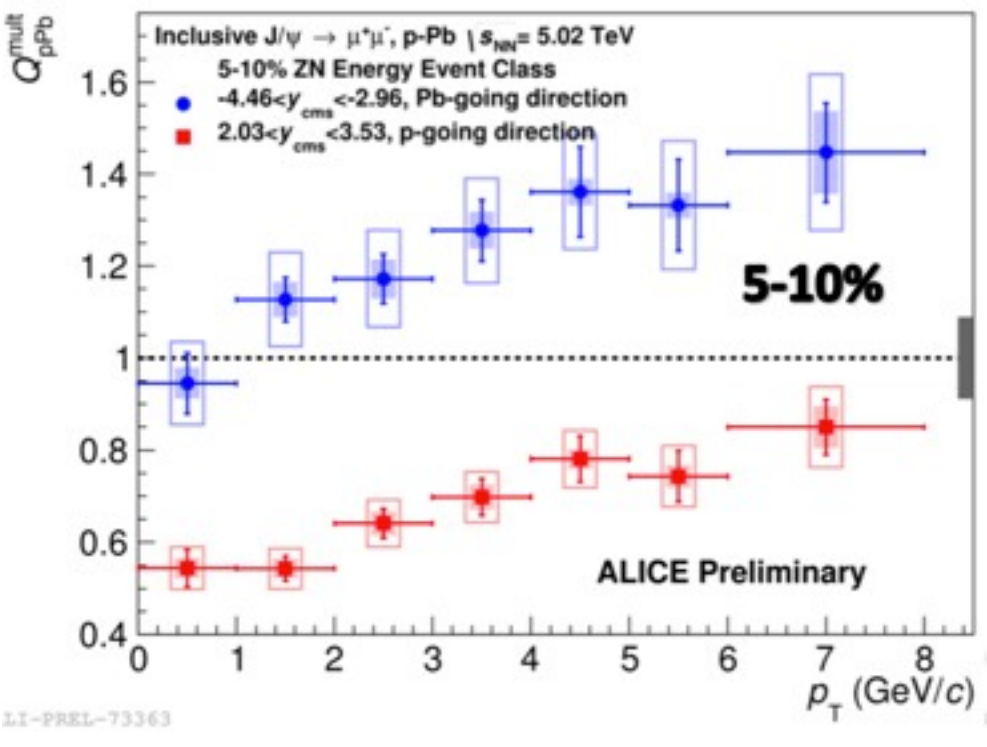
p+Pb J/ψ data from ALICE - centrality

Nice forward/backward rapidity preliminary dimuon data available from ALICE with centrality dependence

Again: we do not expect breakup by collisions with nucleons at LHC energies except maybe at the most backward rapidities

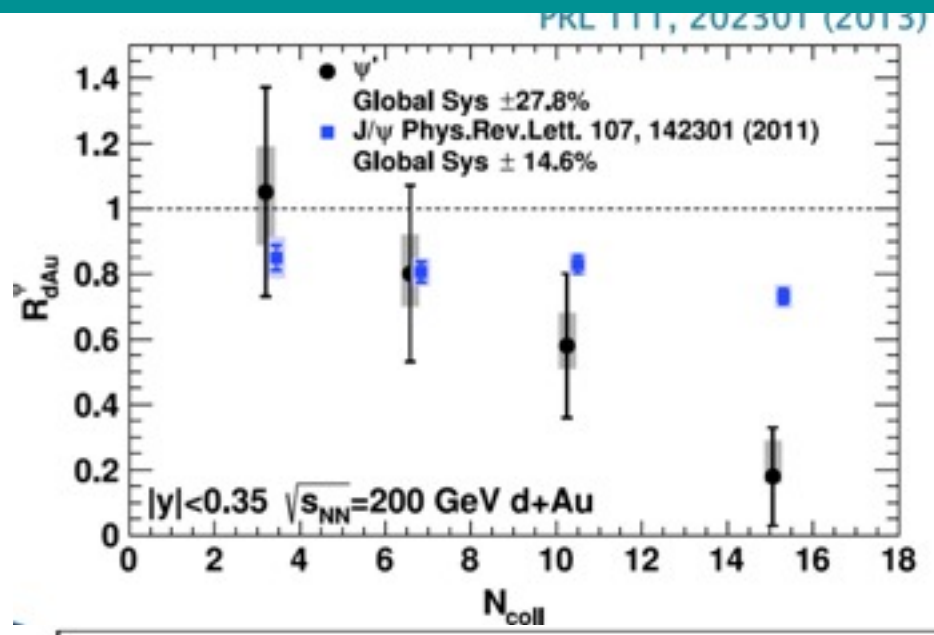
Expect **shadowing** and **energy loss** to be important - calculations still coming





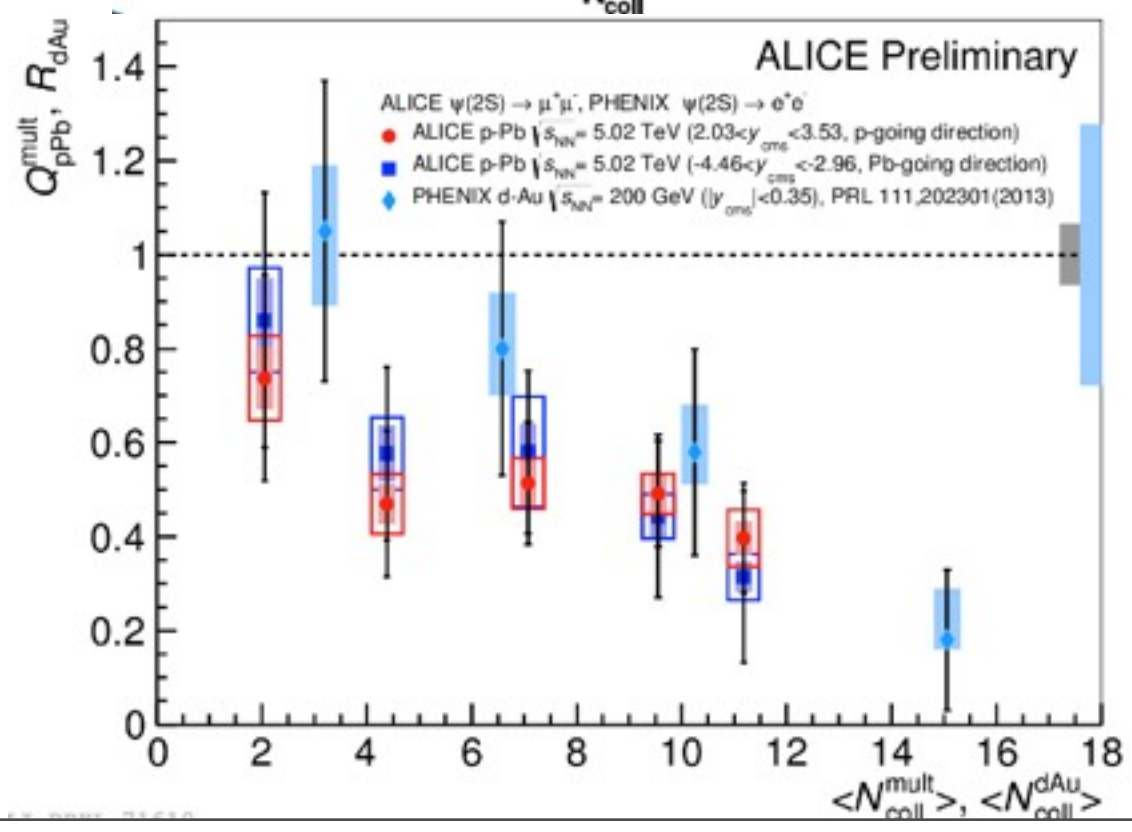
p(d)+A ψ' measurement

Observation of unexpectedly strong suppression of the ψ' in d+Au collisions. Difference from J/ψ can not be explained by (any known) CNM effects.



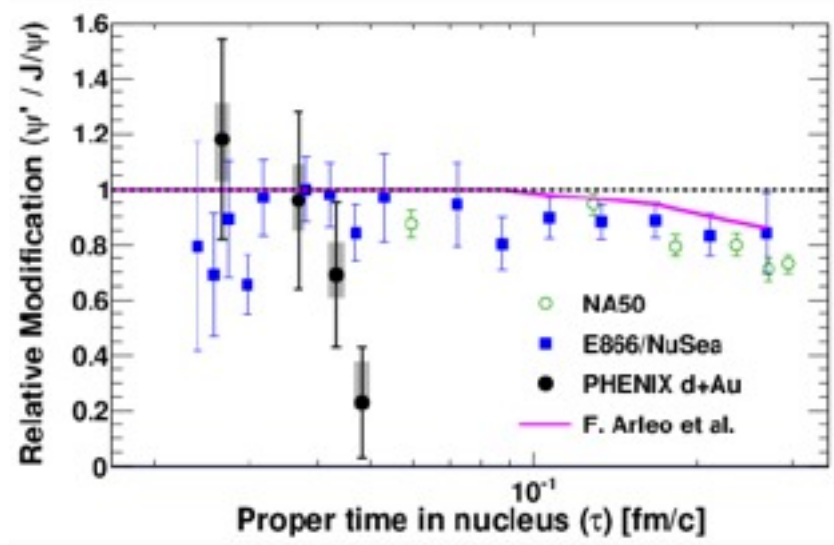
Comparison with ALICE preliminary data at 2.76 TeV: Remarkably, the ψ' suppression at RHIC and LHC energies is very similar.

In all cases the ψ' is much more strongly suppressed than the J/ψ.



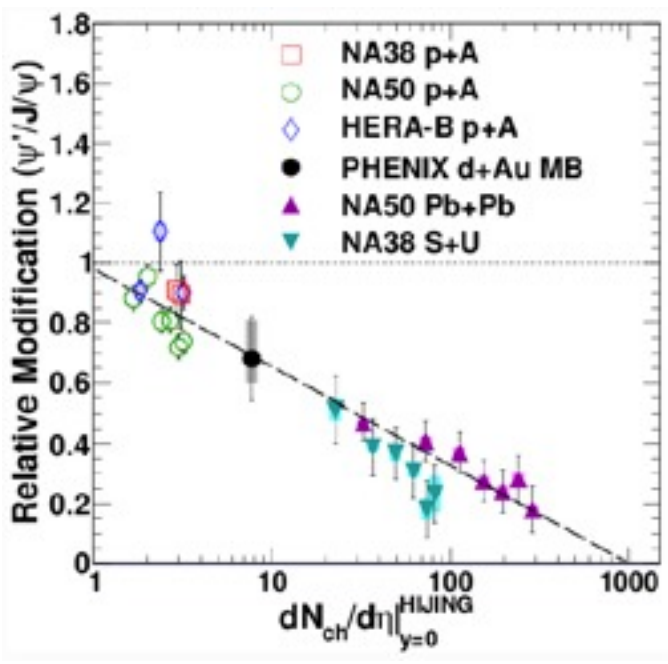
ψ' suppression

The nuclear crossing time scale at midrapidity at RHIC is < 0.05 fm/c - too short to explain ψ' suppression as breakup of a forming meson by nucleons.



The systematic behavior of ψ' to J/ψ **relative** modification with multiplicity seems to be a clue.

- Co-mover or hot matter effects on very fragile ψ' ?



This plot contains data from pA and AA collisions, so it is a varying mix of "cold" and hot matter effects

Maybe not so "cold" for the ψ' ?

Upsilons

Comparison of the J/ψ modification at RHIC and LHC energies has revealed some very interesting physics.

But it did **not** give us the opportunity to compare Debye screening effects at LHC and RHIC energies, since the dominant mechanism for modifying J/ψ production at the LHC is different - coalescence.

For a direct comparison of screening effects at RHIC and LHC, the Upsilon states seem to be more appropriate:

The Y(1S), Y(2S) and Y(3S):

- Span a broad range of sizes
- Are accessible in the same experiment via e^+e^- or $\mu^+\mu^-$
- Have similar nPDF's
- Will not have a large coalescence contribution at RHIC **or** LHC
    - Bottom pairs in central events at LHC similar to charm pairs at RHIC

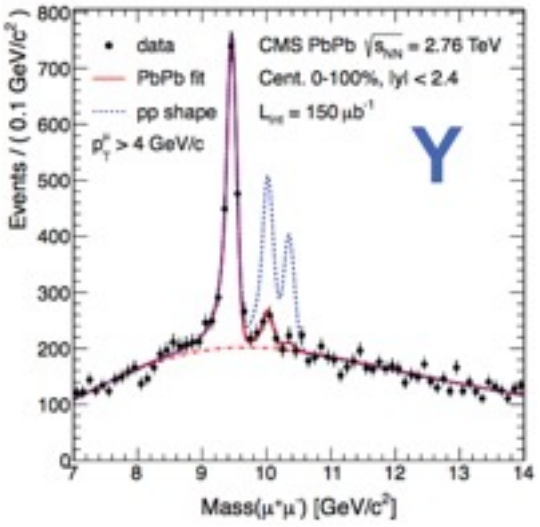
But their cross sections and mass differences are small. Studying them requires large acceptance, and excellent momentum resolution!

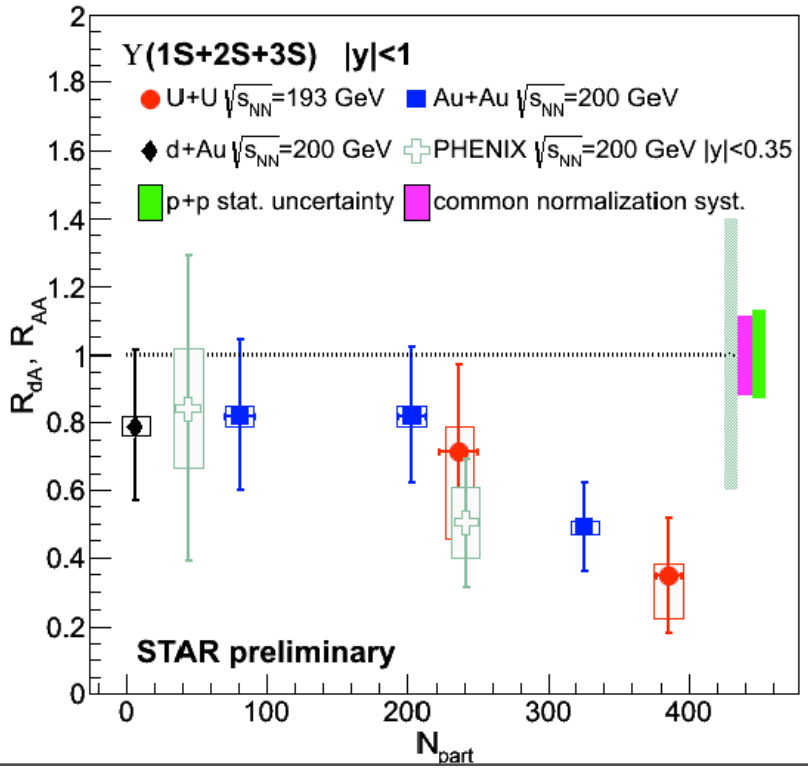
Upsilons at RHIC and LHC

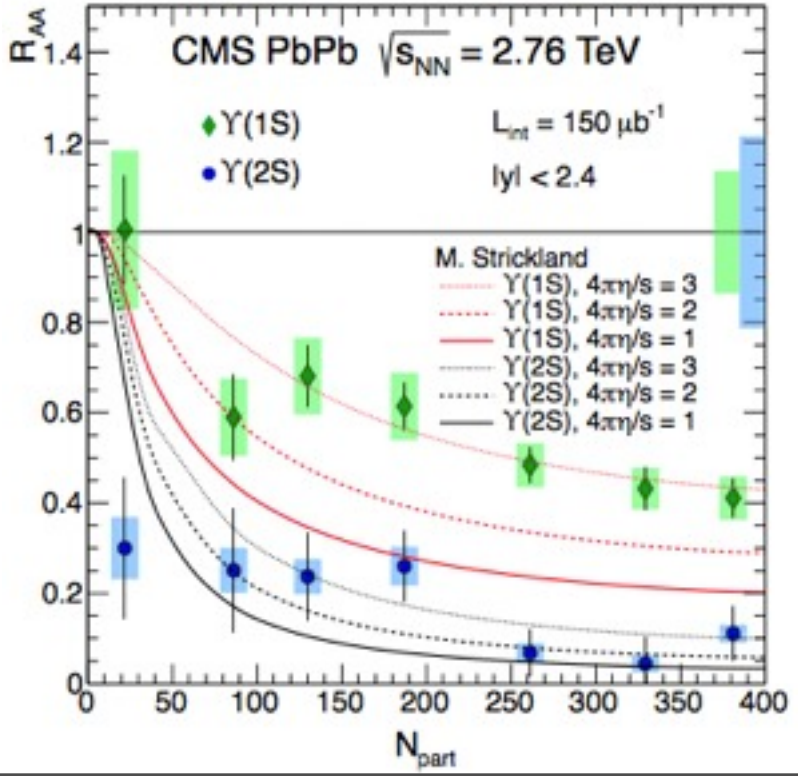
The CMS experiment has excellent capabilities for measuring Upsilon yields for the three states.

Data from Run 1 at 2.76 GeV already show clearly the difference in suppression between the 1S and 2S states in PbPb collisions.

Current data from STAR and PHENIX do not place very strong constraints on models.







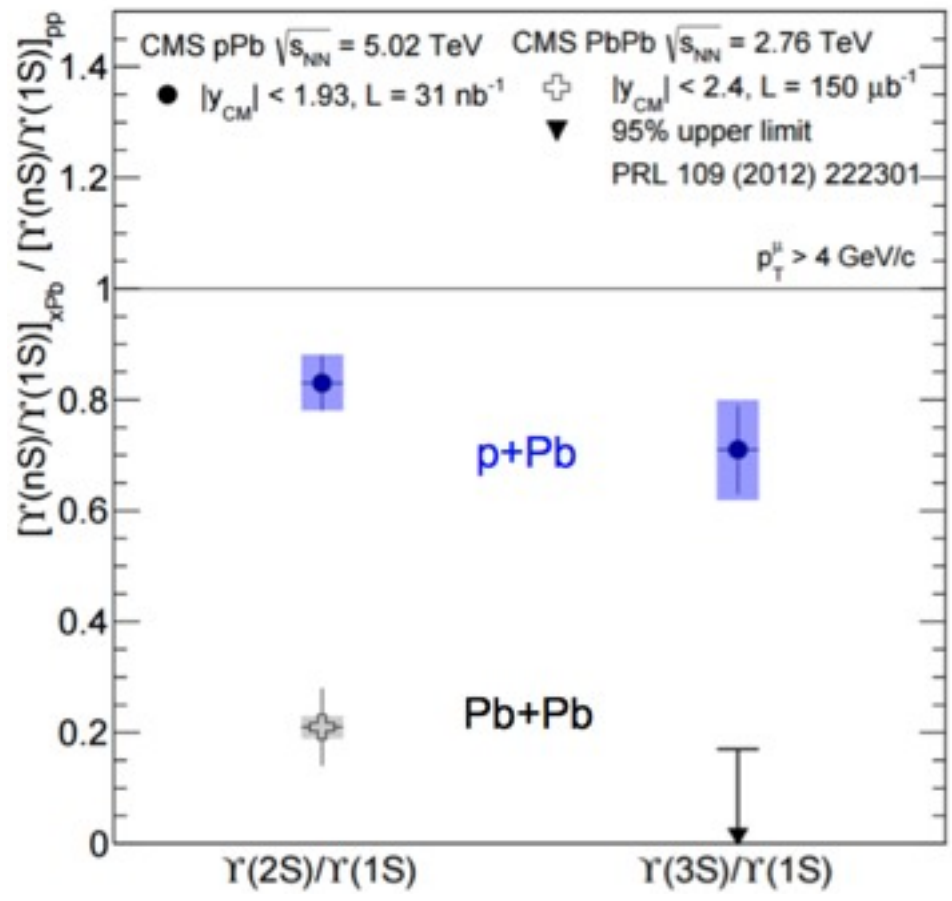
Upsilons in p+Pb at LHC

There are pPb ϒ data available from the LHC now, but not much yet in the form of **R_{AA} values** precise enough to tightly constrain models. Such data should be available soon from LHC run 1.

But CMS has measured the ratio of the ϒ(2S) and ϒ(3S) to the ϒ(1S) in pp & pPb collisions.

The plot shows the ratio for pPb from centrality integrated data **divided** by the one for pp

The 2S and 3S states are differentially suppressed in pPb - but not as strongly as in PbPb.

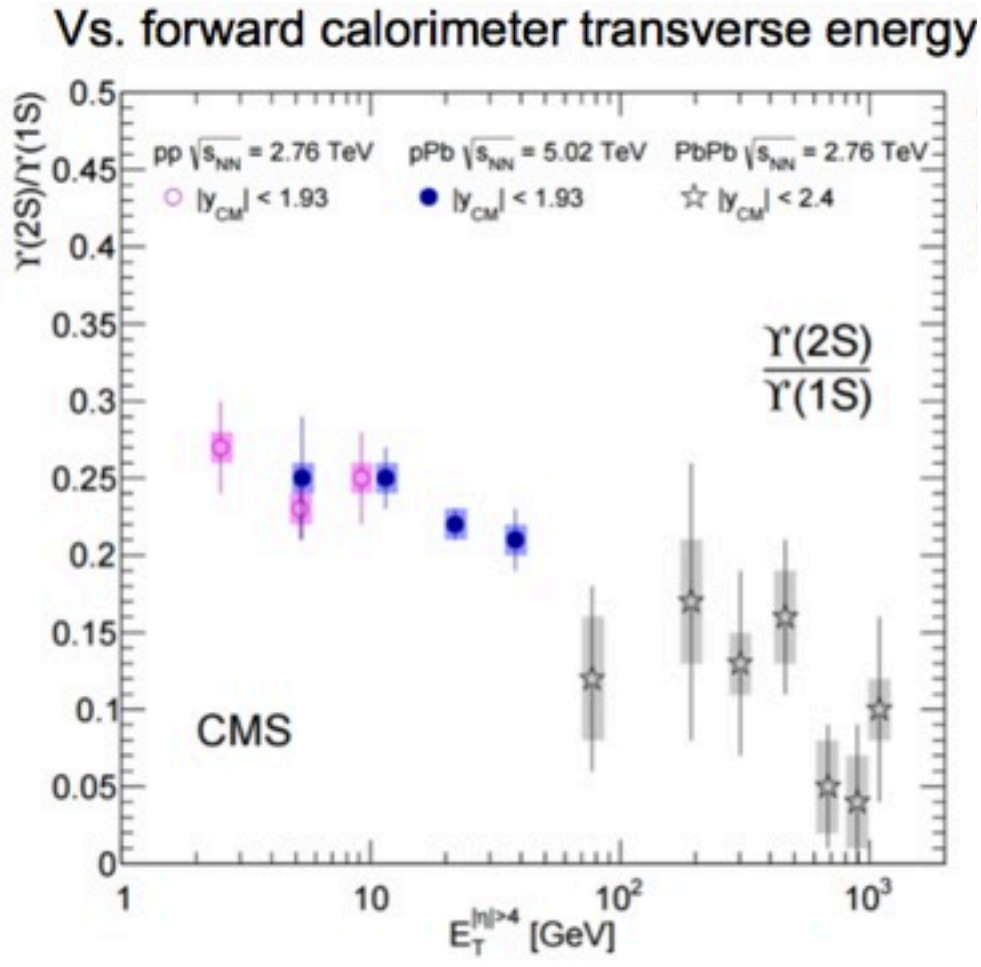


Upsilons in p+Pb at LHC

CMS has compared the ratios of the Υ(2S) to the Υ(1S) as a function of multiplicity in the event for pp, pPb and PbPb collisions.

It is still an open question whether for pp and pPb:

- The Upsilons affect the event size
- The event size affects the Upsilons



Mix of pp, p+Pb, Pb+Pb data.

Reminiscent of the systematic dependence of the ψ'/J/ψ ratio on multiplicity.

Future Upsilon measurements at RHIC and LHC

Upsilon measurements at RHIC will improve.

The **STAR MTD** upgrade was installed prior to the 2014 RHIC AuAu run. It will provide dimuon measurements of Upsilon yields with a resolution sufficient to separate the 1S from the (2S+3S). The data are being analyzed now.

Longer term, the proposed **sPHENIX** upgrade - planned to start in 2021 - will provide large acceptance combined with mass resolution good enough to separate all three states.

Summary

Excellent charmonium data available from SPS to LHC energies.

In A+A collisions:

- Up to 200 GeV - dominated by CNM and screening effects
- At ~ 200 GeV R_{AA} is a minimum - coalescence balances screening?
- At 2.76 TeV - dominated by coalescence

In p+A collisions:

- Understanding of kinematic regime where breakup occurs (large τ)
- Parton energy loss models describe suppression beyond shadowing in small τ region - but no clear signature of the mechanism
- Strong *b* dependence of suppression seen in d+Au not yet understood
- Strong ψ' suppression at small τ at RHIC and LHC is not understood yet

Measurements of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ in Pb+Pb and p+Pb coming in now from LHC experiments (and to come from the RHIC experiments).

- $\Upsilon(2S)$ strongly suppressed, $\Upsilon(3S)$ ~ gone in Pb+Pb collisions at 2.76 TeV
- Differential suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$ in p+Pb collisions at 5.02 TeV
  - Same mechanism as ψ' differential suppression?

Backups

d+Au J/ψ and open HF results vs rapidity

Comparison of p_T dependence of J/ψ modification with that for **open HF** leptons provides a sanity check.

Caveat: Different kinematics!

The J/ψ suppression at **backward & mid rapidity** is much stronger than for HF.

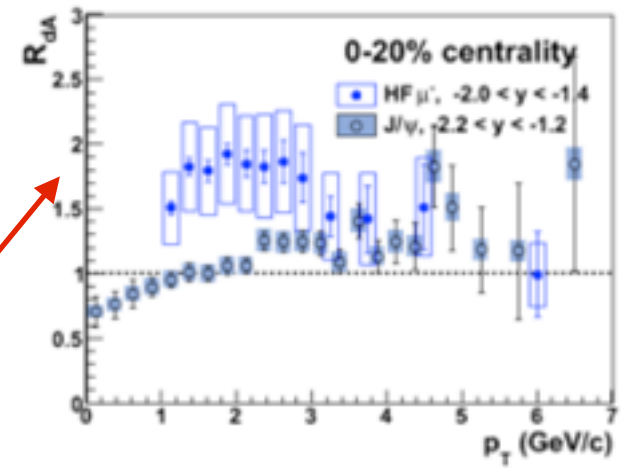
- Implies J/ψ is suppressed **beyond** the underlying HF production.

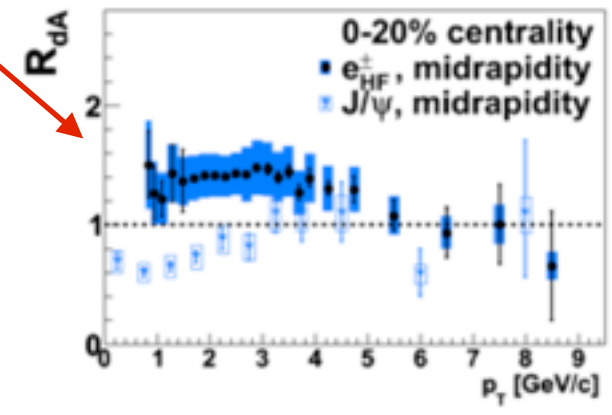
At **forward rapidity** they are similar.

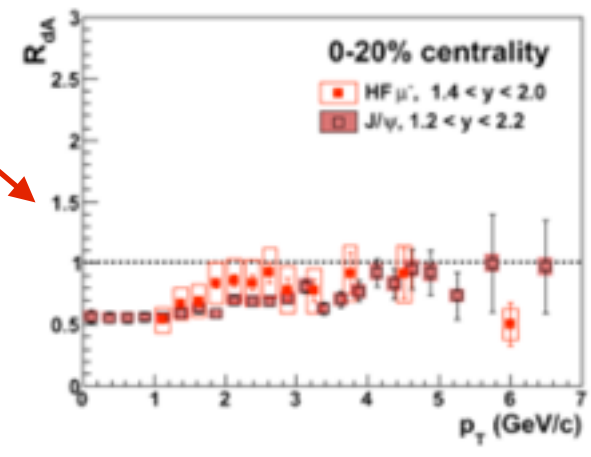
- Implies J/ψ suppressed at forward rapidity **because** the underlying HF is suppressed.

Consistent with

- Breakup at backward rapidity
- A process like energy loss of a colored dipole in CNM at forward rapidity.







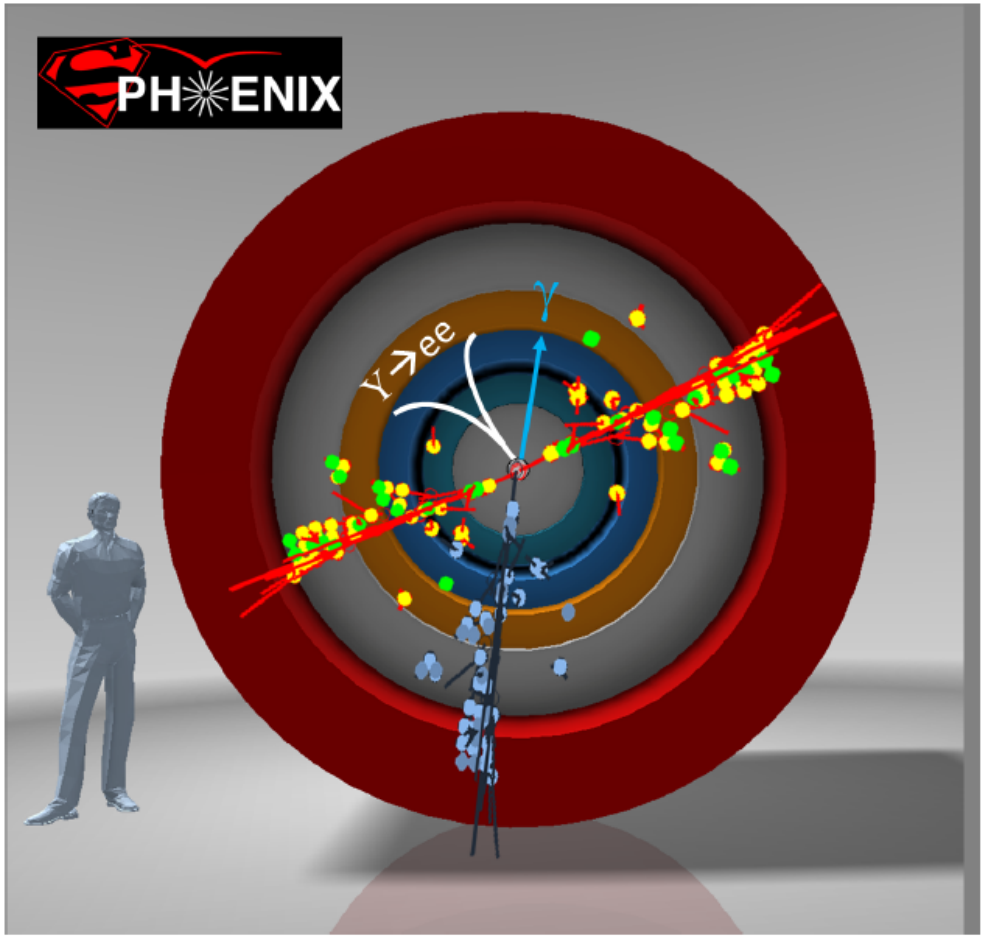
Longer term: sPHENIX

PHENIX, arXiv:1501.06197

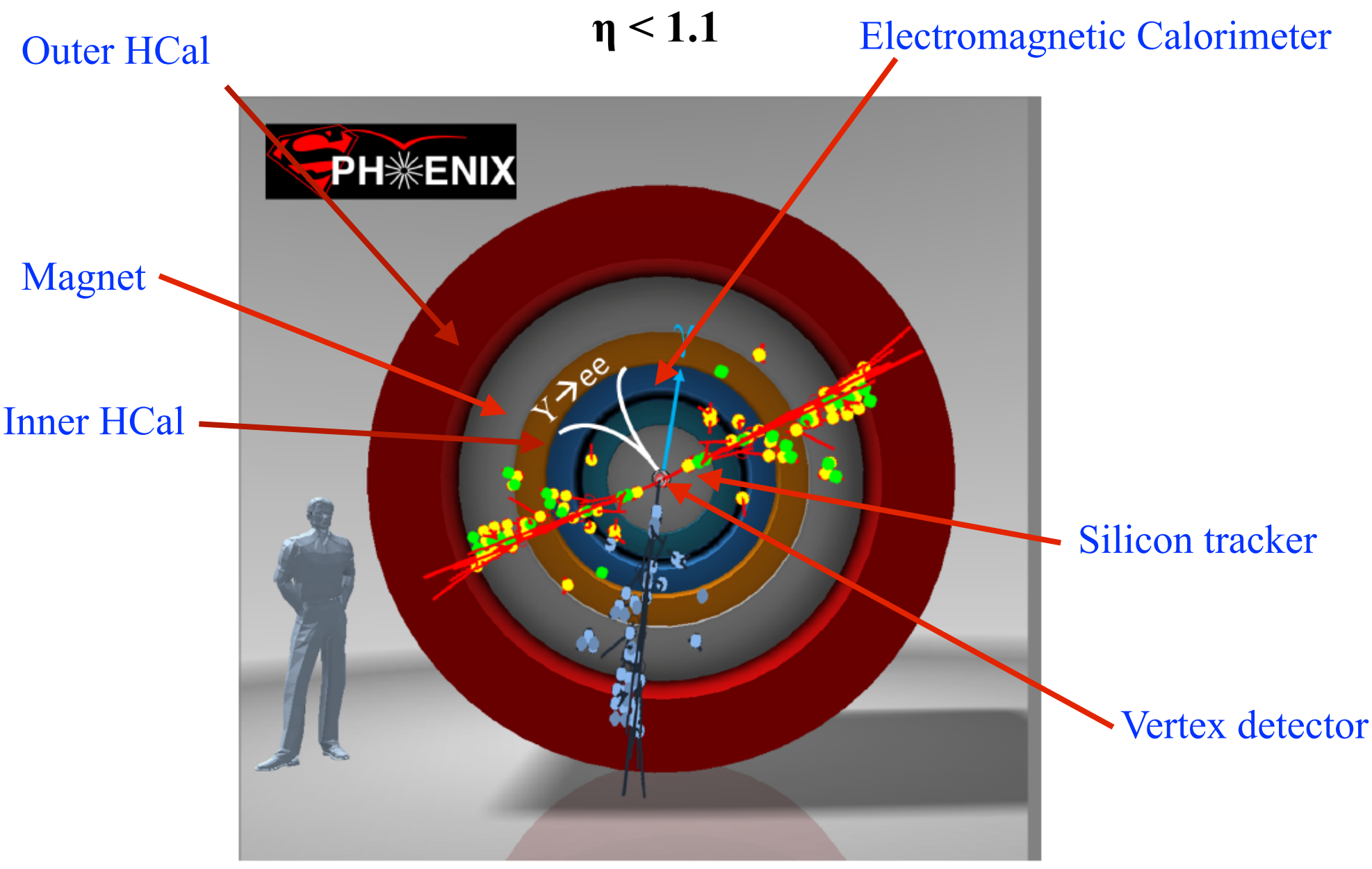
After the 2016 run, the BNL plan has PHENIX being removed.

In 2021 it will have been replaced by sPHENIX, a compact solenoidal detector that is optimized for **jet** and **Upsilon** measurements.

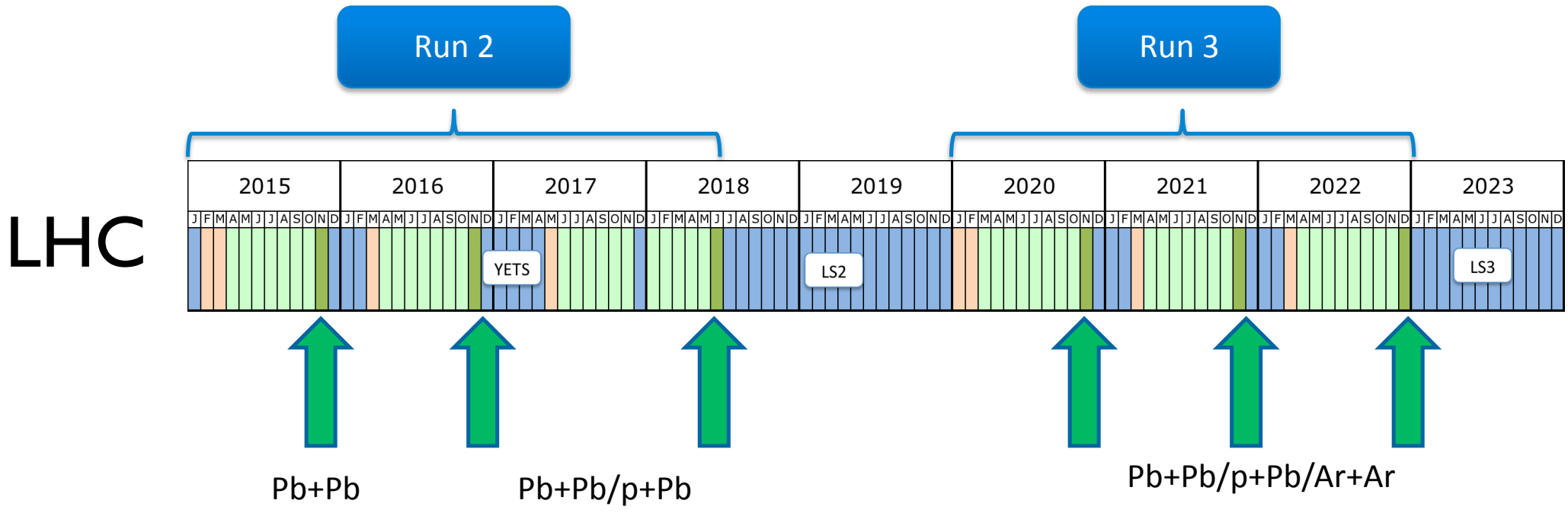
sPHENIX will provide (unbiased) jet and Upsilon data that will complement the very precise data available from LHC by the end of Run 3 (~2023).

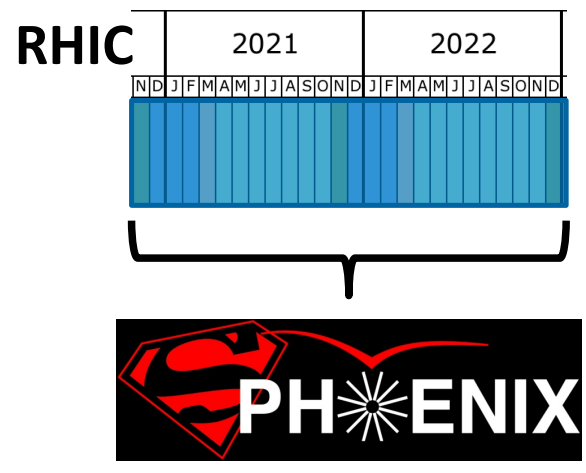


sPHENIX - compact solenoidal detector



RHIC: BNL proposed schedule





Proposed sPHENIX run plan

p+p	**10 weeks**
Au+Au	**22 weeks**
p+Au	**10 weeks**

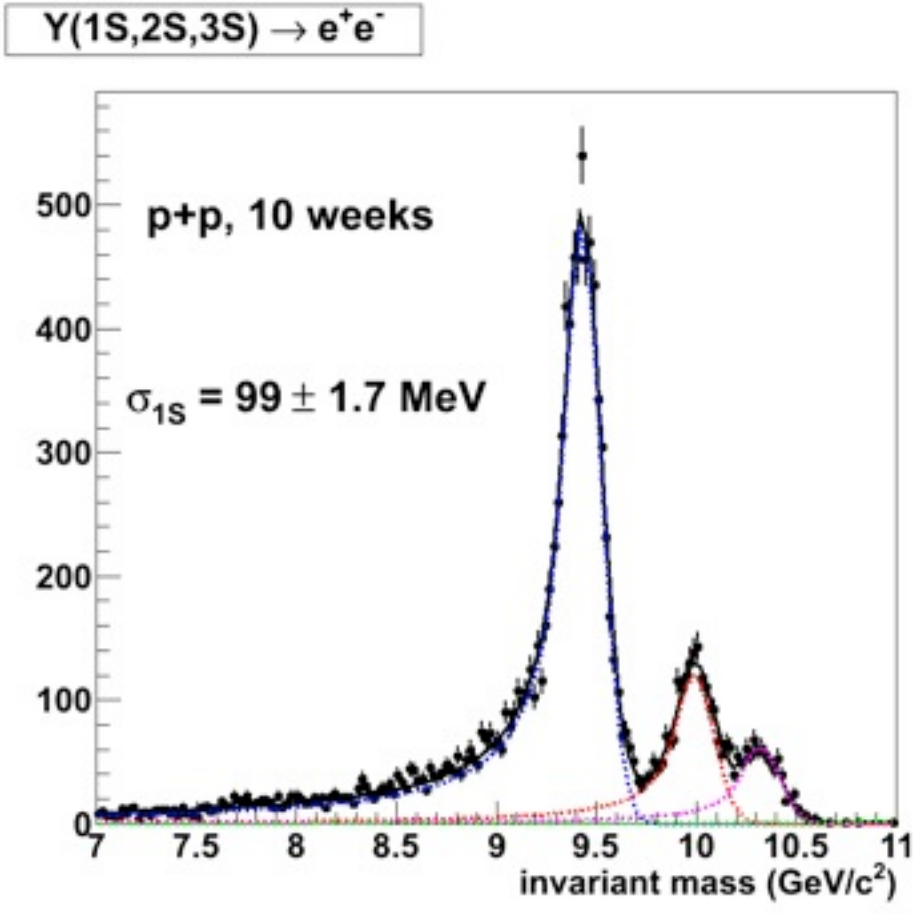
sPHENIX upsilons

For **quarkonia**, our major goal has always been the **characterization of the Debye screening as a function of temperature**. The SPS, RHIC and LHC J/ψ results have already shown the value of high quality **data covering a broad range of initial temperatures**.

The proposed large acceptance **sPHENIX** detector, will have a mass resolution of ~ 100 MeV for Upsilons.

We will use the **dielectron** decay channel - but the radiative tails are manageable.

This spectrum is from a Geant 4 simulation for **10 weeks of pp running**.



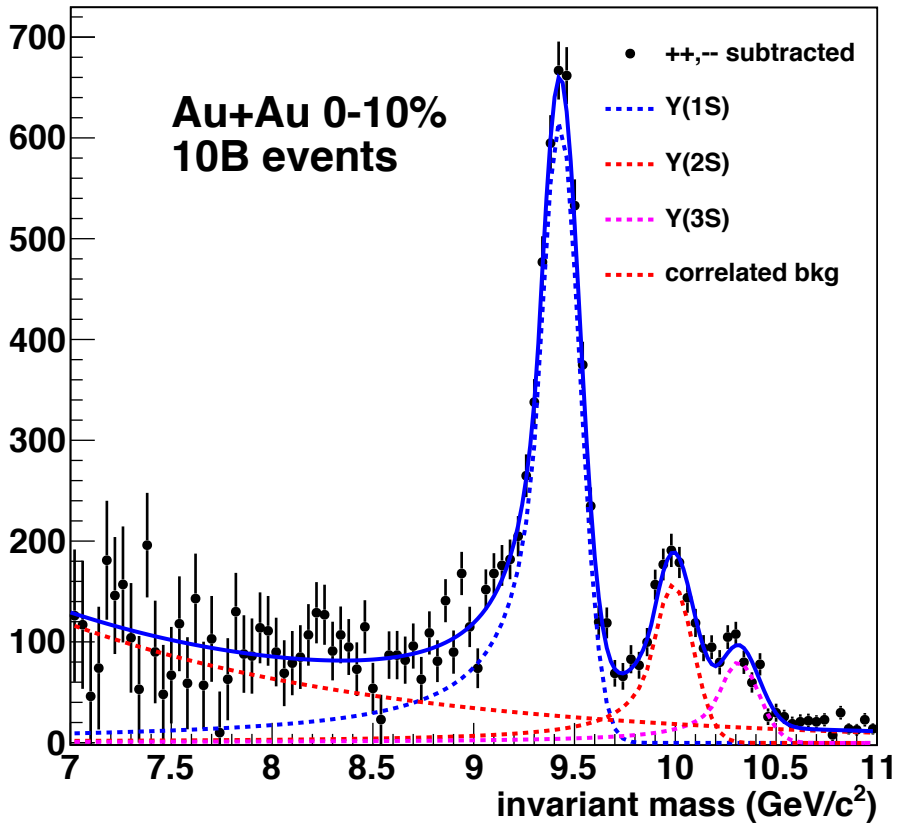
sPHENIX upsilons - AuAu

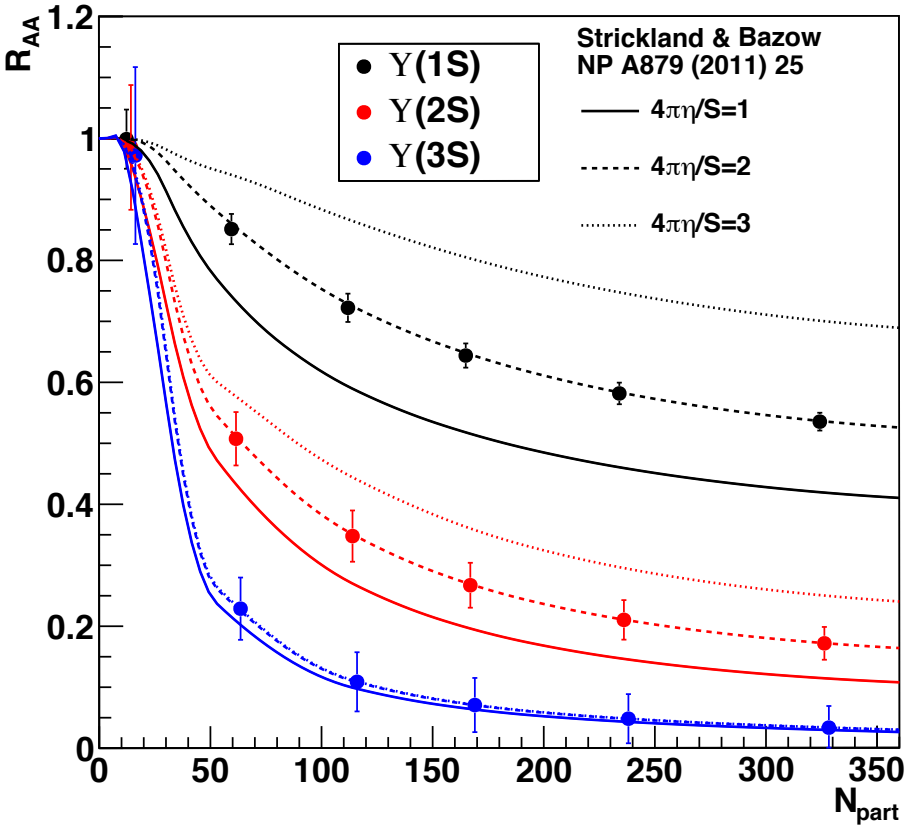
Electron ID (hadron rejection) from EM calorimeter, hadronic calorimeter.

central AuAu collisions
combinatorial background subtracted

AuAu collisions, expected statistical precision from 10 week run

Υ(1S,2S,3S)

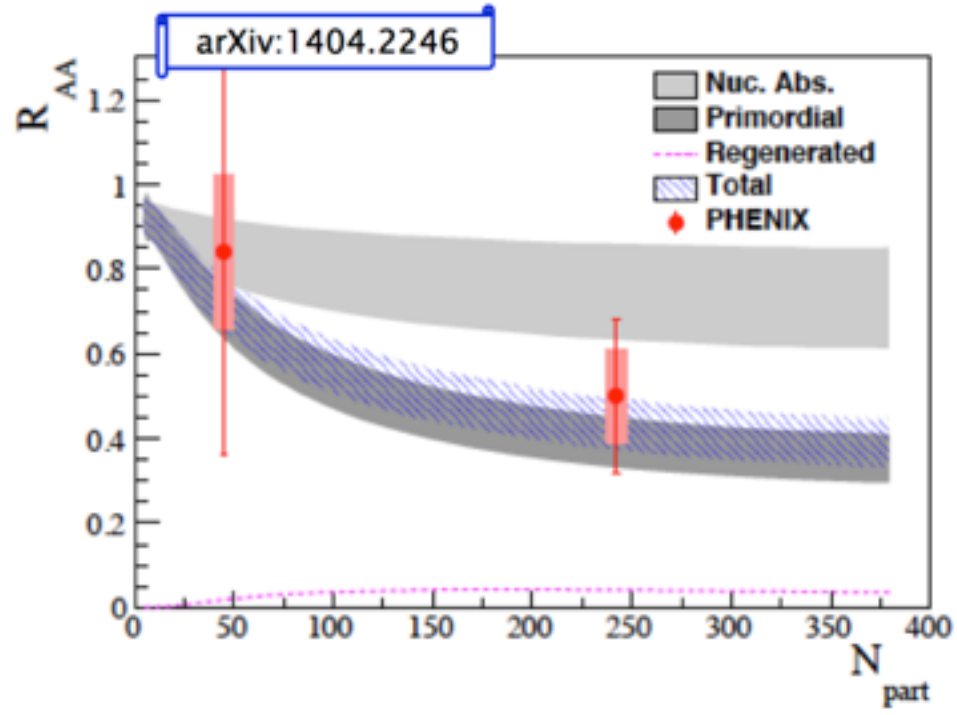




Υ(1S+2S+3S) theory comparisons

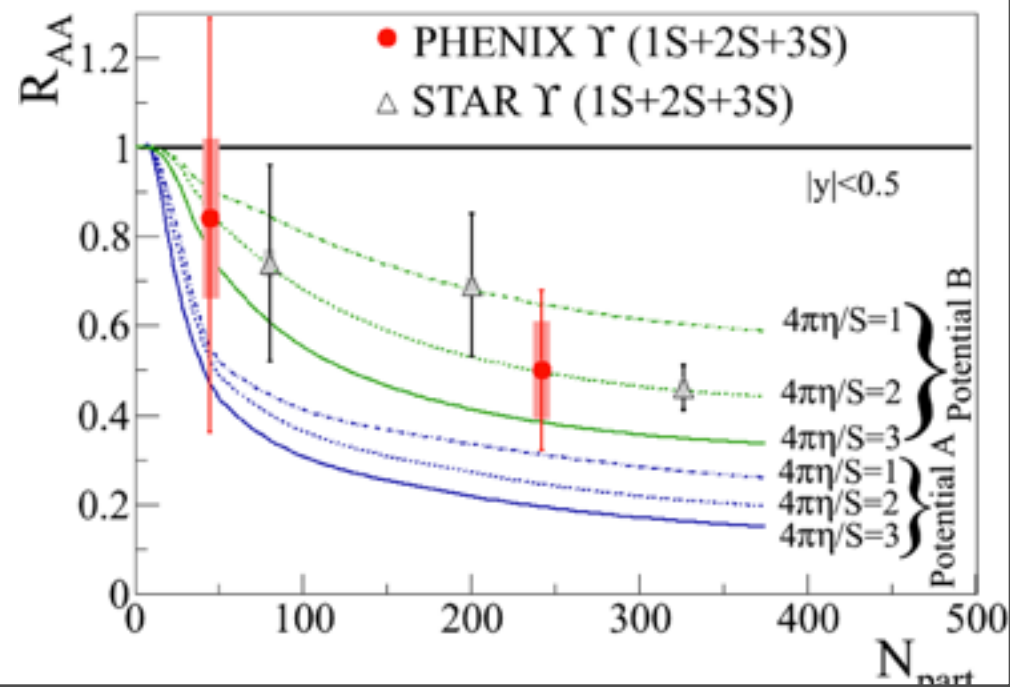
Potential model with rate equation - Emerick, Zhao and Rapp, Eur. Phys. J A48, 72 (2012).

Includes CNM estimates and regeneration effects (small at RHIC).



Potential model with finite momentum space anisotropy - Strickland and Bazow, NP A 879, 23(2012). Does not include CNM effects or regeneration.

We obviously need a much better measurement at RHIC. These will come from the **STAR MTD** in the near term, **sPHENIX** in the longer term.



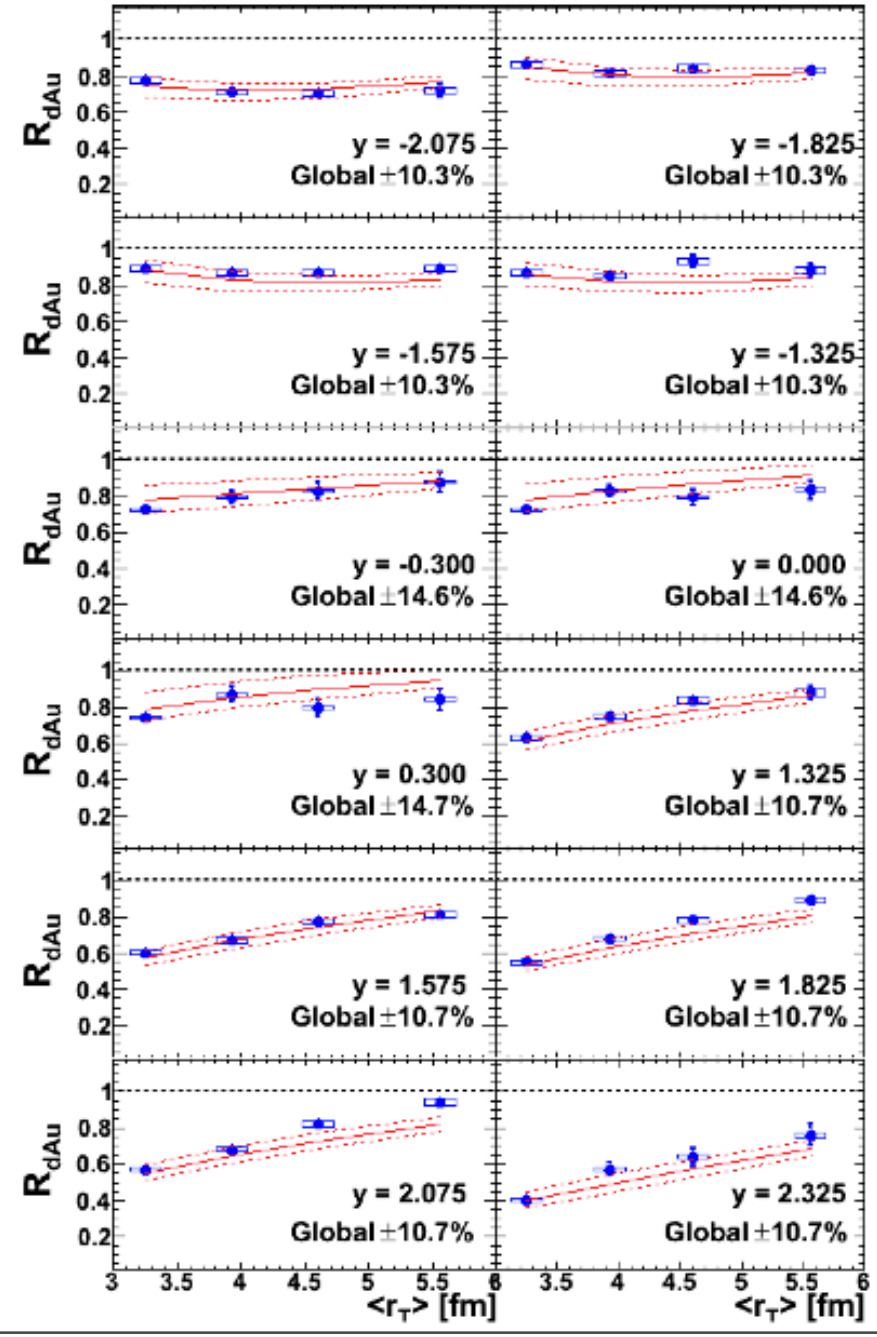
d+Au J/ψ results - one interpretation

McGlinchey, Frawley, Vogt, Phys.Rev. C87 (2013) 5, 054910

Fit the PHENIX d+Au J/ψ data separately at each rapidity with "absorption" σ_{abs} + EPS09 shadowing **with** a step-function impact parameter dependence.

The fitted **shadowing** parameterization is well defined (because the r_T dependence is very different from exponential) and extremely nonlinear

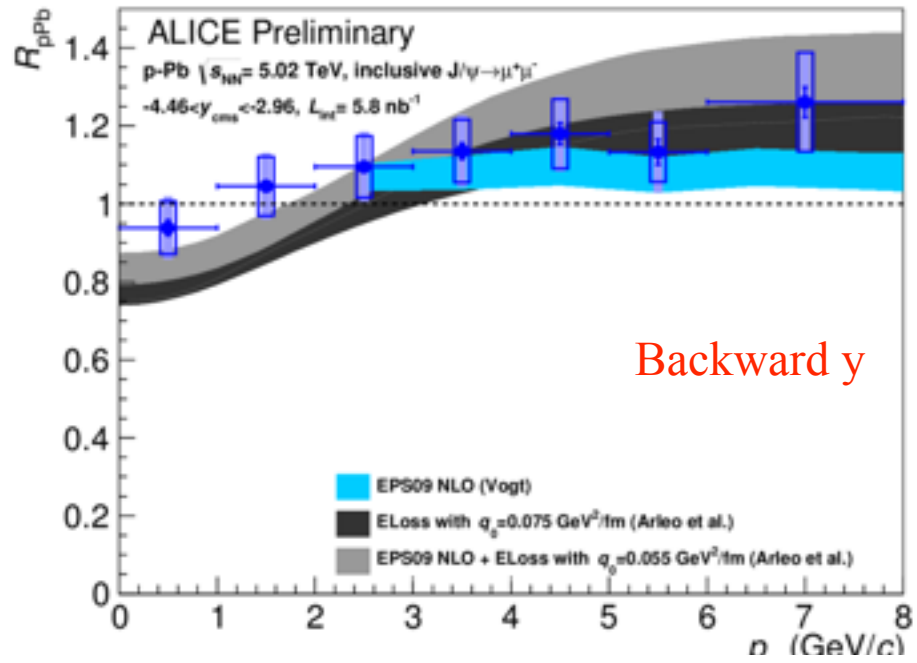
- it is heavily concentrated at small impact parameter!

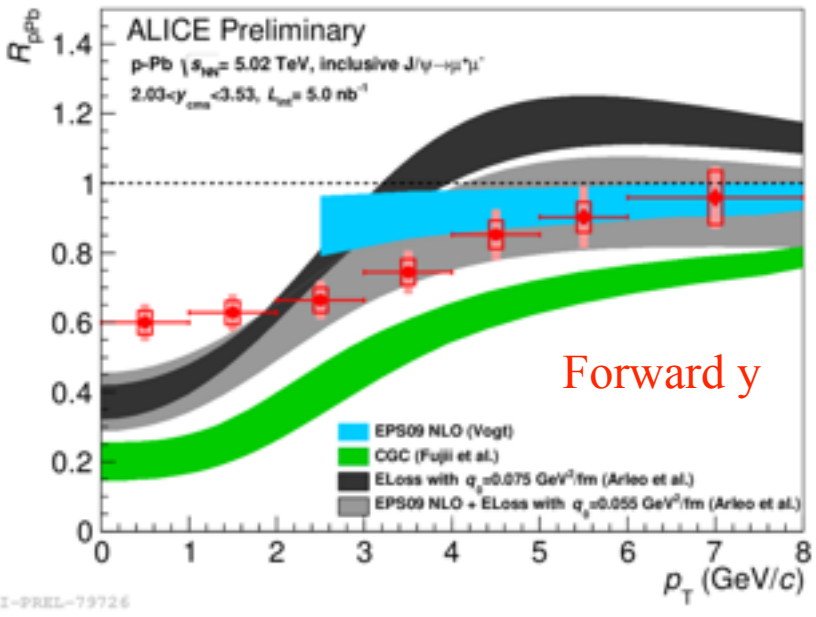


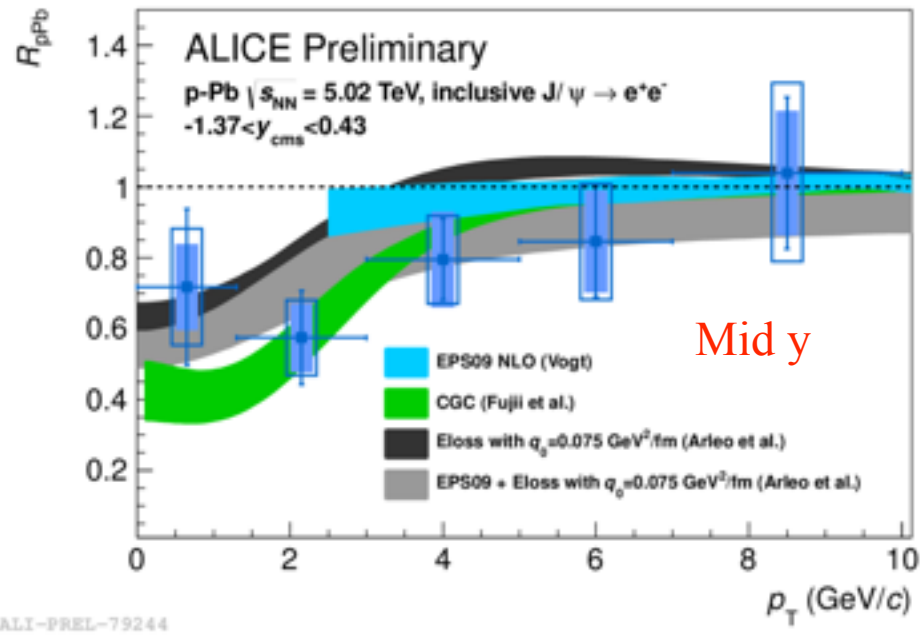
pPb J/ψ data from ALICE - p_T

ALICE centrality integrated data

Reasonable description of the p_T dependence of the data by EPS09 shadowing + energy loss calculation





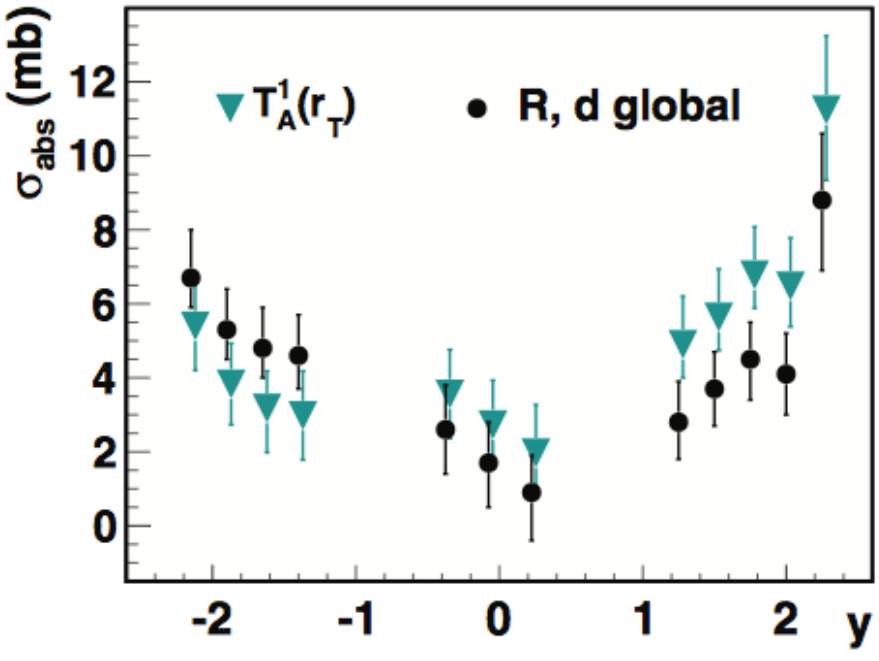


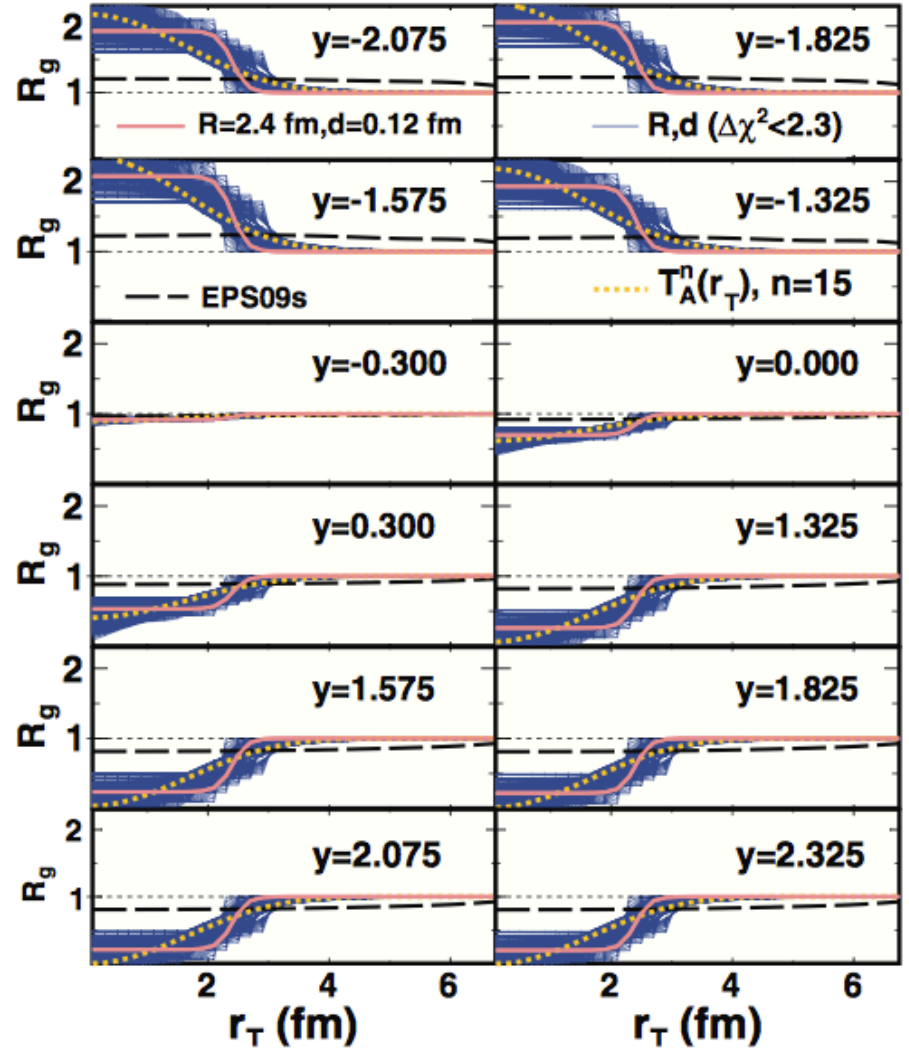
d+Au J/ψ results - one interpretation

Fit the PHENIX d+Au J/ψ data separately at each rapidity with "absorption" σ_{abs} + EPS09 shadowing with a step-function impact parameter dependence.

The shadowing parameterization is **extremely** nonlinear - only significant inside 3 fm!

Note: This strongly disagrees with EPS09s - which is determined from A dependence of pA data. We don't know why!



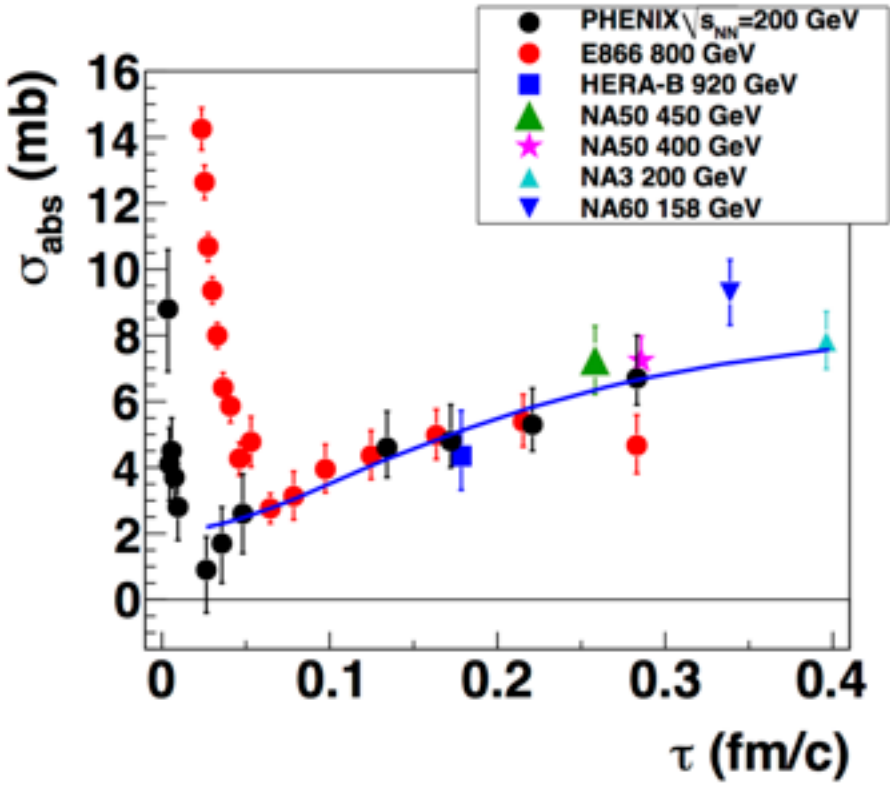


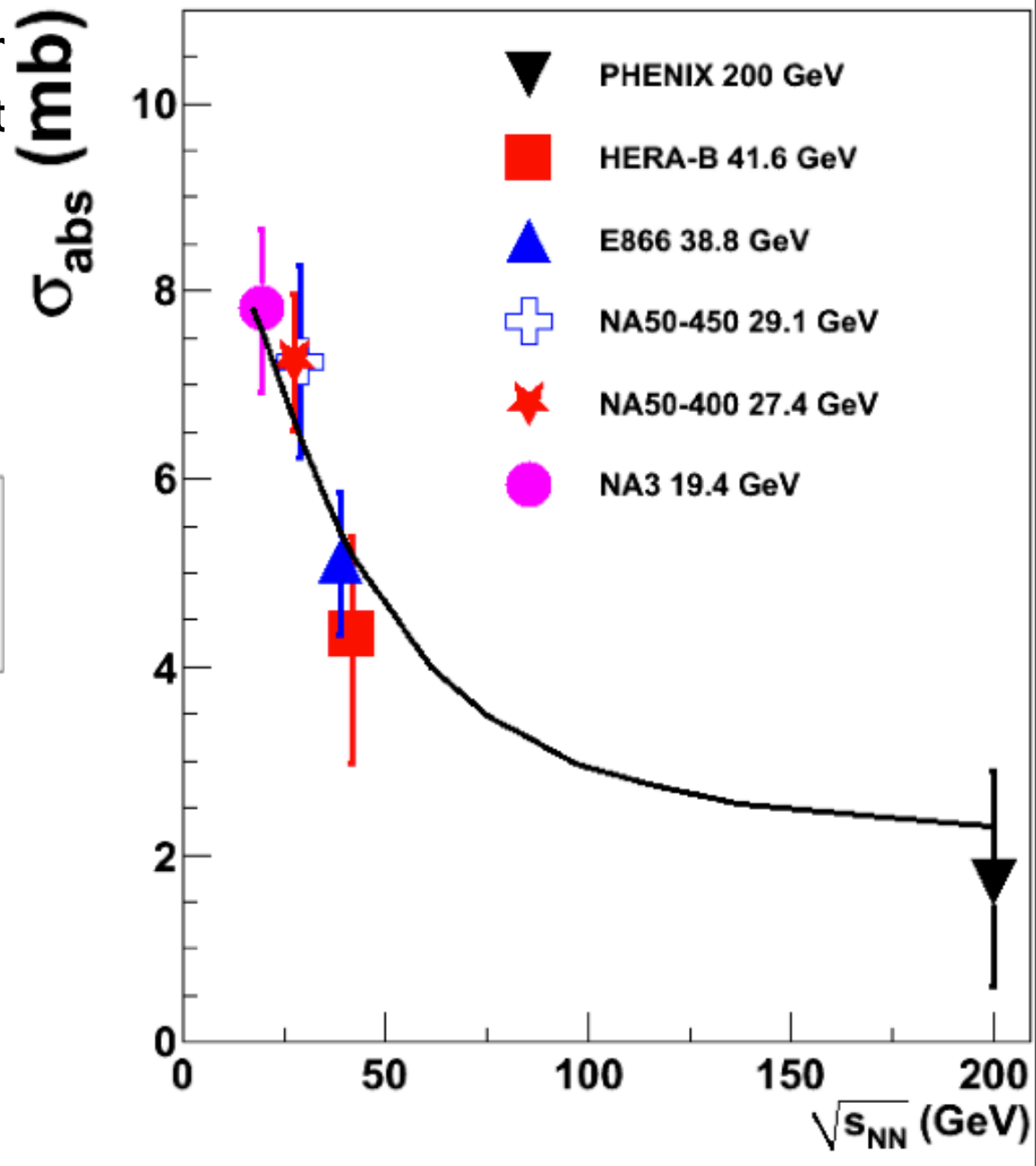
But what physics does the "absorption" parameter represent?

dA/pA: dependence of σ_{abs} on nuclear crossing time

Absorption parameter vs nuclear crossing time (τ) for pA or dA at 17.3 - 200 GeV collision energy (from PHENIX data plus 6 other experiments)

Phys.Rev. C87 (2013) 5, 054910





Asymmetric collisions - Cu+Au

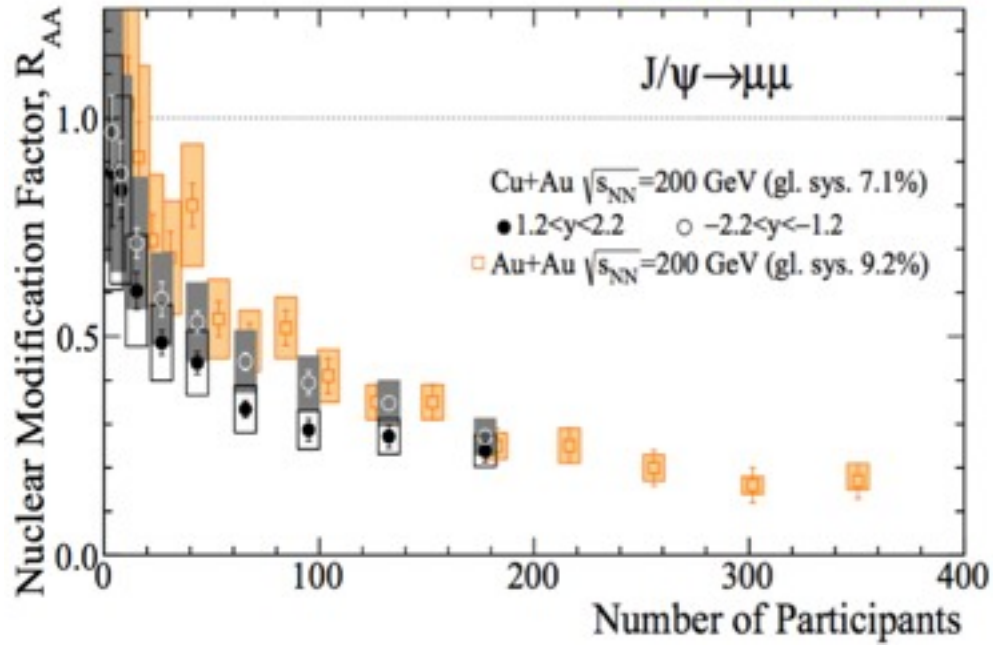
Au-going direction similar to Au+Au. Cu-going direction is more strongly suppressed.

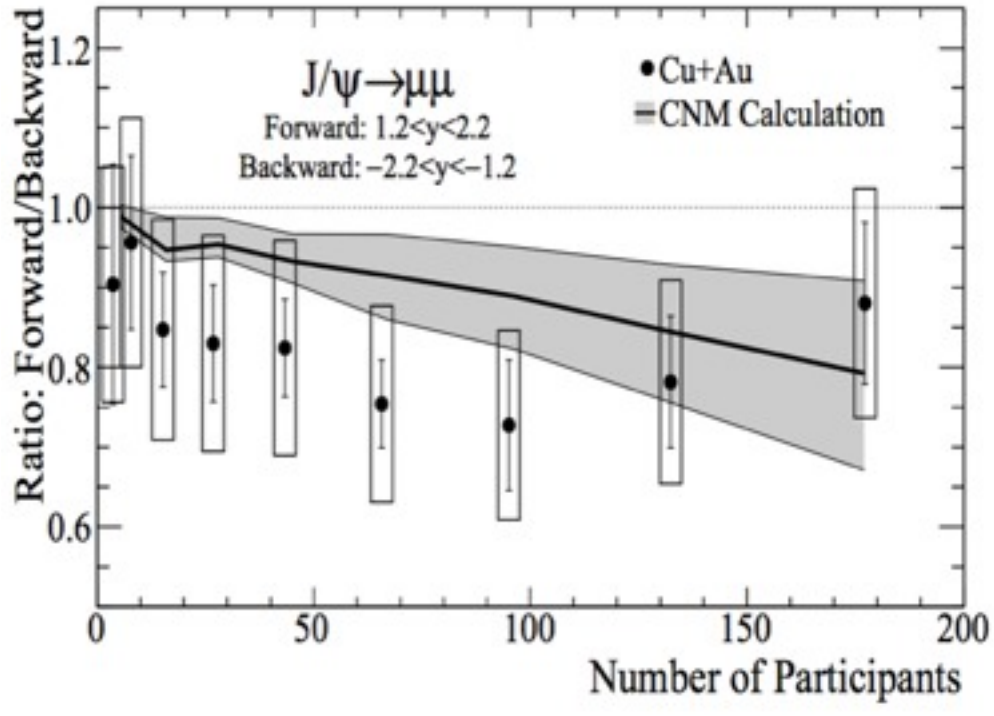
- **Qualitatively** what we would expect from shadowing

Taking the ratio cancels some systematics.

The calculation is **very** simple - just σ_{abs} = 4 mb + EPS09 shadowing

- Calculation effectively shows the **ratio of shadowing effects** at forward/backward rapidity

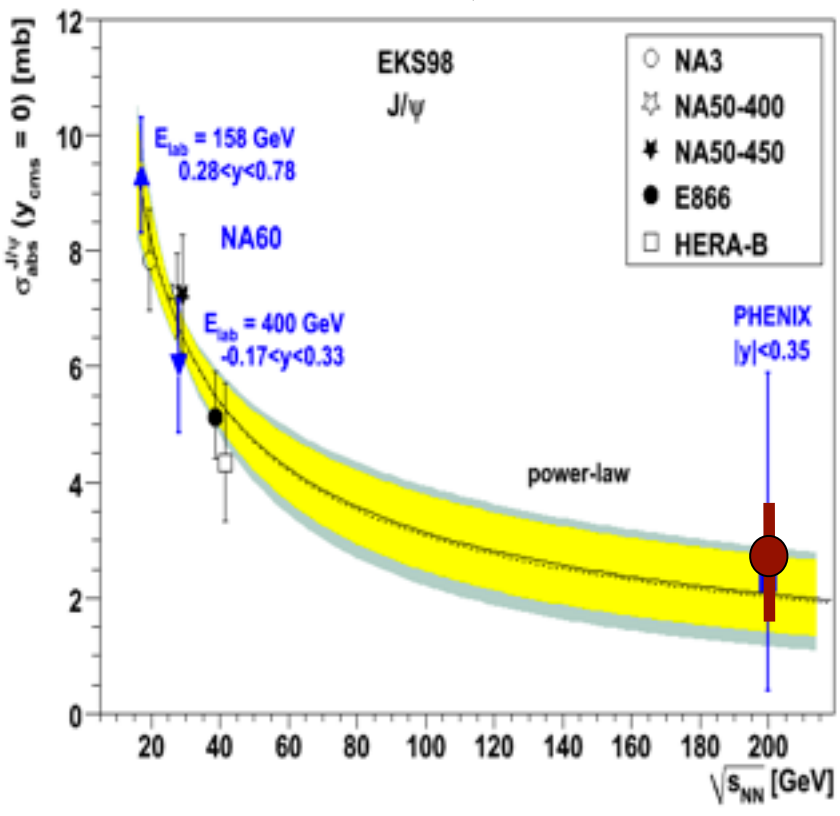




But different collision energy leads to different CNM effects!

Direct comparison of R_{AA} data at different energies and for different systems is inconclusive - CNM effects are known to vary strongly.

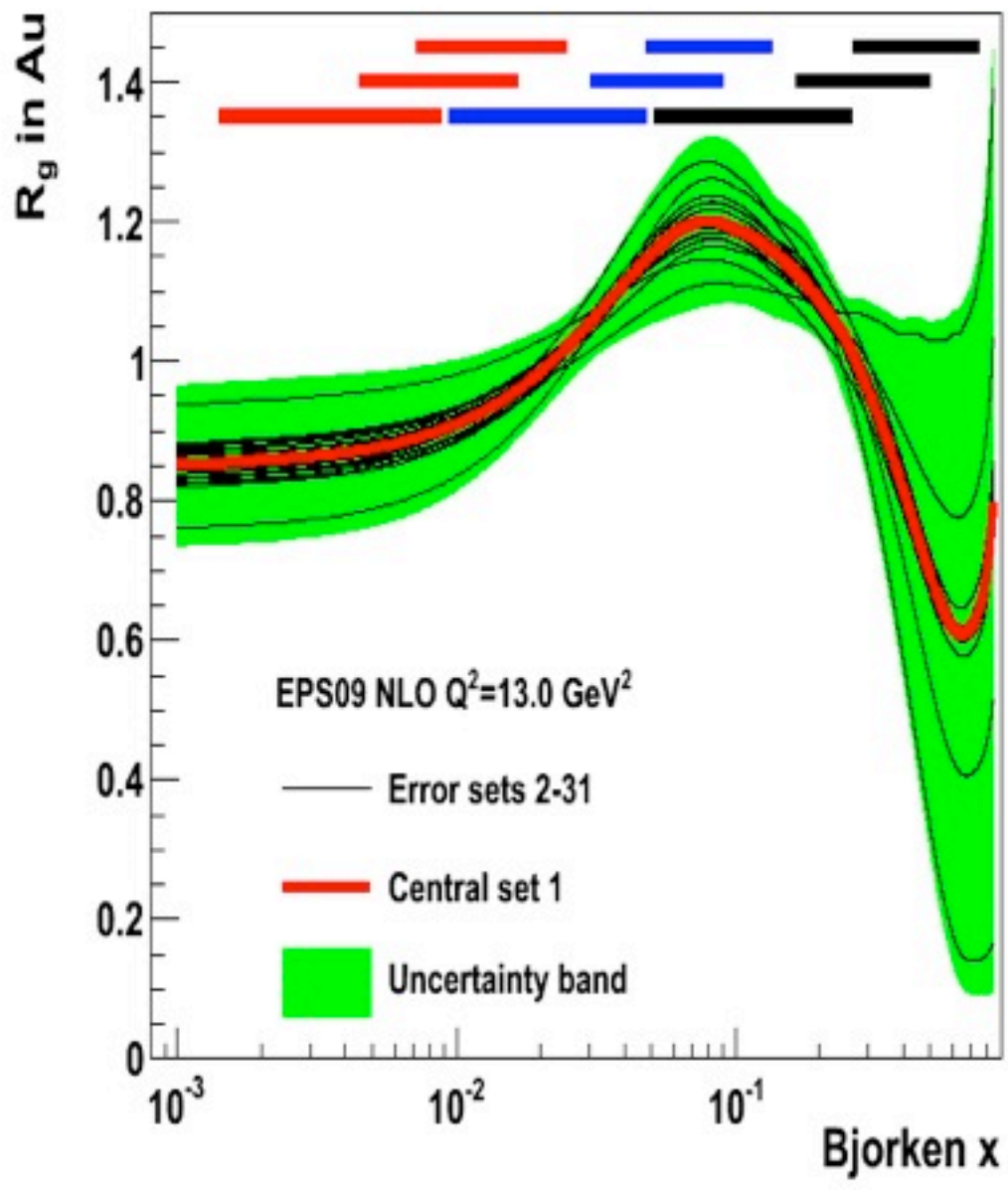
JHEP 0902:014 (2009)



Approximate PHENIX *x* coverage

2.2>y>1.2 0.5>y>-0.5 -1.2>y>-2.2

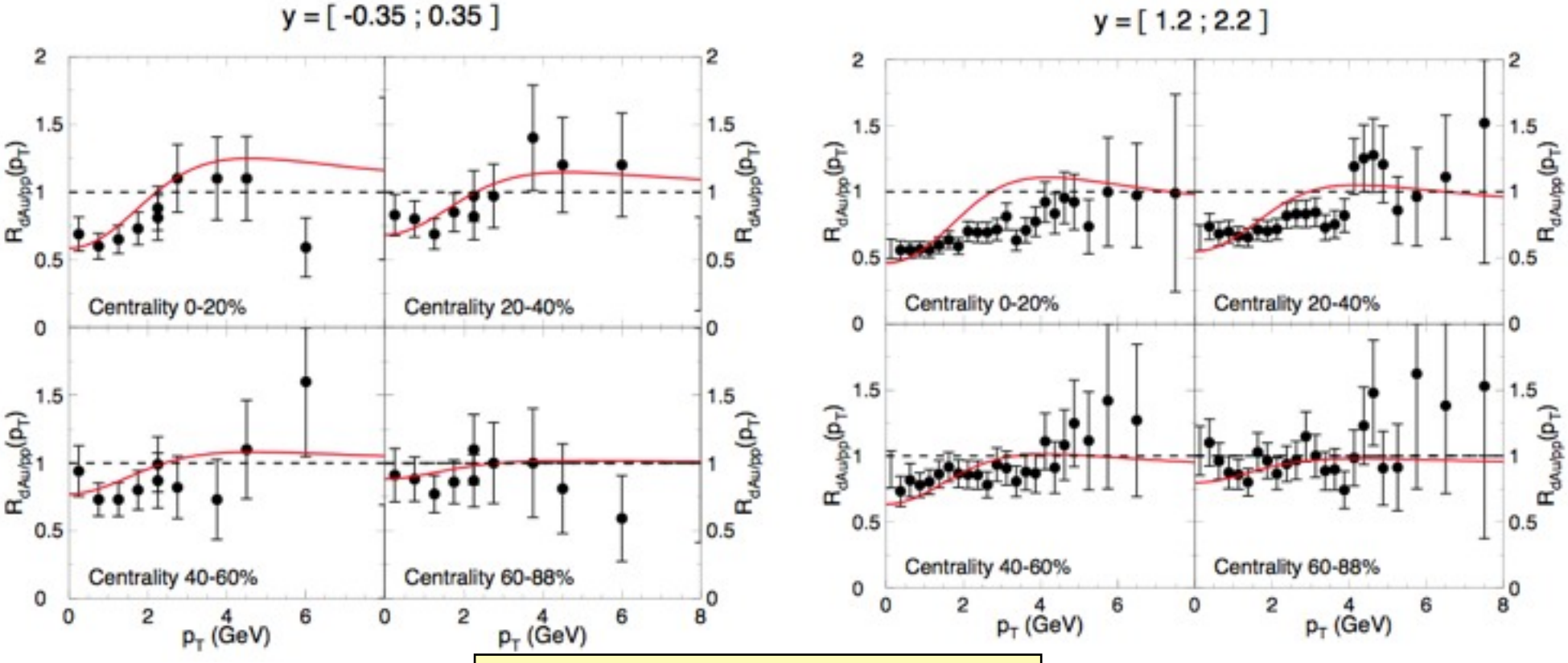
39
62
200



J/ψ modification at forward rapidity in d+Au

Models of parton radiative energy loss (Arleo et al., JHEP 1305 (2013) 155; Sharma and Vitev, Phys.Rev. C87 (2013) 044905) and absorption (Kopeliovich et al., Nucl.Phys. A864 (2011) 203; Ferriero et al., Few Body Syst. 53 (2012) 27).

These seem to describe J/ψ data over a **broad CM energy range**.



Arleo et al. JHEP 1305 (2013) 155