2nd International Conference on the Initial Stages in High-Energy Nuclear Collisions
Napa Valley, December 3 – 7, 2014

Quarkonium at RHIC

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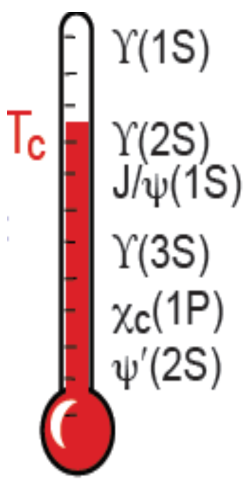
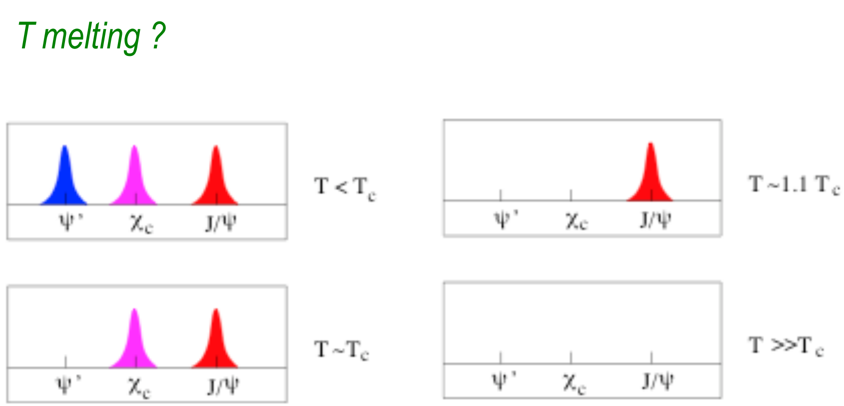
BERKELEY LAB

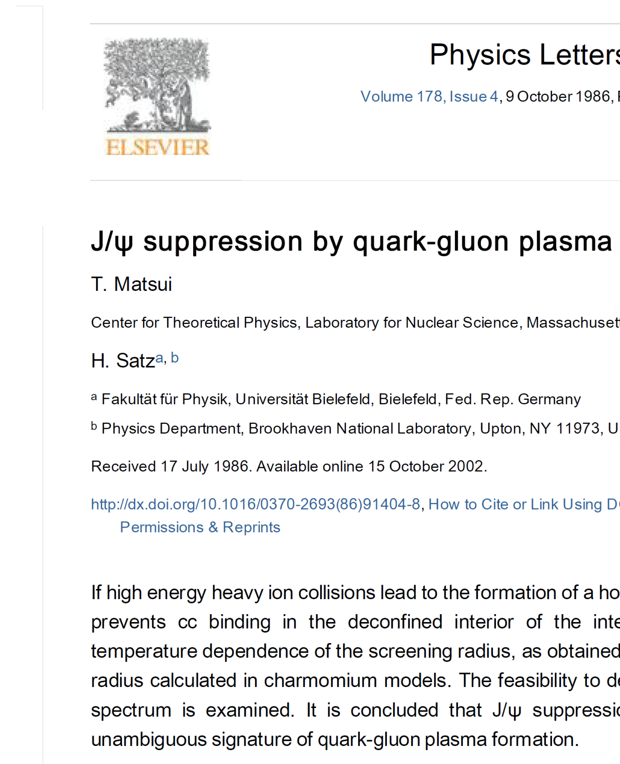
Theory: Quarkonia suppression

Charmonia ($c\bar{c}$): J/ψ, ψ', χ_c
Bottomonia ($b\bar{b}$): Υ (1S), Υ(2S), Υ(3S), χ

Key idea (1986): quarkonia melt in plasma (T.Matsui, H.Satz)
- color screening of static potential between heavy quarks
- suppression of states determined by Tc and binding energy
- sequential melting of quarkonia: a thermometer of QGP






Physics Letters
Volume 178, Issue 4, 9 October 1986,

J/ψ suppression by quark-gluon plasma

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Received 17 July 1986. Available online 15 October 2002.
http://dx.doi.org/10.1016/0370-2693(86)91404-8, How to Cite or Link Using D
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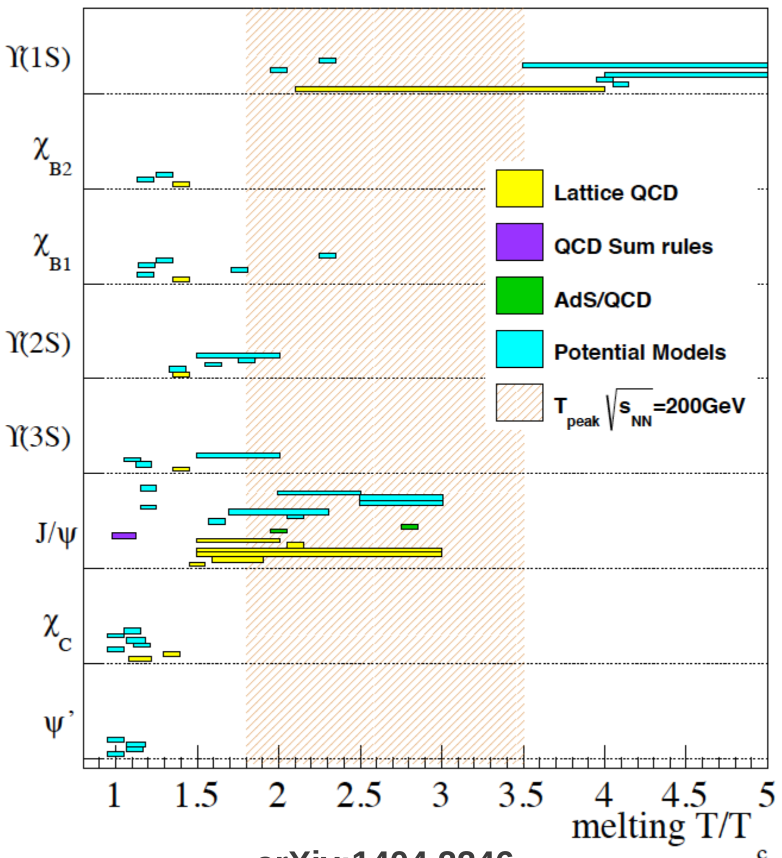
If high energy heavy ion collisions lead to the formation of a ho
prevents cc binding in the deconfined interior of the inte
temperature dependence of the screening radius, as obtained
radius calculated in charmonium models. The feasibility to d
spectrum is examined. It is concluded that J/ψ suppressi
unambiguous signature of quark-gluon plasma formation.

Melting temperature ?

(large effort from theoretical side to calibrate thermometer)



arXiv:1404.2246

Compilation of expectations

bottom line: the most loosely bound states disappears first, the ground state last i.e. J/ψ should survive ψ'

To do: Implant quarkonia into the QGP and observed their modification, suppression or enhancement, with and without plasma formation in <u>respect to reference</u>

… but quarkonia production is rather complex (many entangled effects):

Cold nuclear effects (CNM): pdf modification in nucleus (gluon saturation, Color Glass Condensate), initial state energy loss, nuclear absorption, Cronin effect, ….

Hot/dense medium effects: color screening, gluon dissociation, regeneration, feed-down, …

→ requires several measurements (systems, energies, centralities) to isolate different effects

at RHIC:

J/Ψ

p+p, √s = 62, 200, 500 GeV, and Ψ(2S)
d+Au, √s = 200 GeV
Au+Au, $\sqrt{s_{NN}}$ = 200, 62.4, 39 GeV
U+U, $\sqrt{s_{NN}}$ = 193 GeV

Upsilon

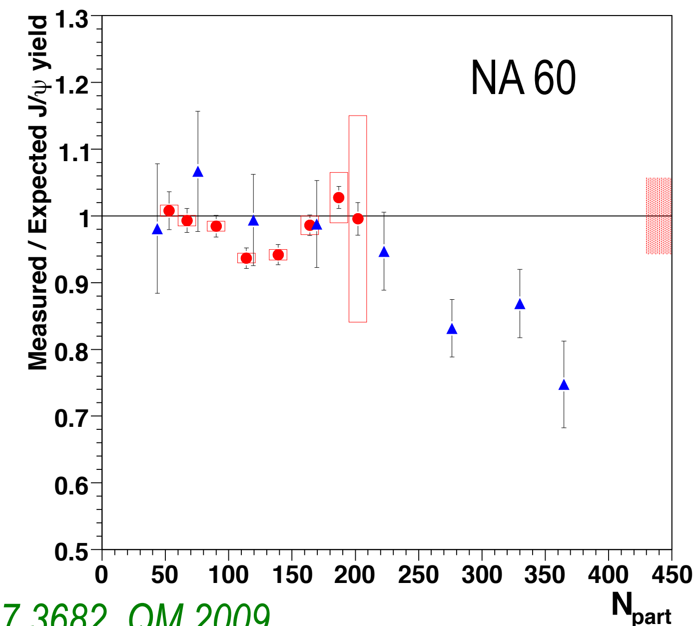
p+p, √s = 200 GeV
d+Au, $\sqrt{s_{NN}}$ = 200 GeV
Au+Au, $\sqrt{s_{NN}}$ = 200 GeV
U+U, $\sqrt{s_{NN}}$ = 193 GeV

U+U - higher energy density
- test sequential melting
- constrain models

Upsilon - a cleaner probe
- negligible regeneration at RHIC energy
- less CNM effects

Legacy from CERN SPS: S+U, In+In, Pb+Pb

Anomalous J/ψ suppression in In+In (circles) and Pb+Pb collisions (triangles) as a function of N_{part}



arXiv:0907.3682, QM 2009

Up to N_{part} ~ 200 : J/ψ (measured) is compatible with extrapolation from p+A
For N_{part} > 200 – anomalous suppression at the level of 20-30 % and only in central Pb+Pb

Expectations from lattice calculations, *e.g. M.Asakawa, T.Hatsuda Phys.Rev.Lett.92 (2004) 012001*. that J/ψ suppression does not occur until T~2T_c is compatible with this observation

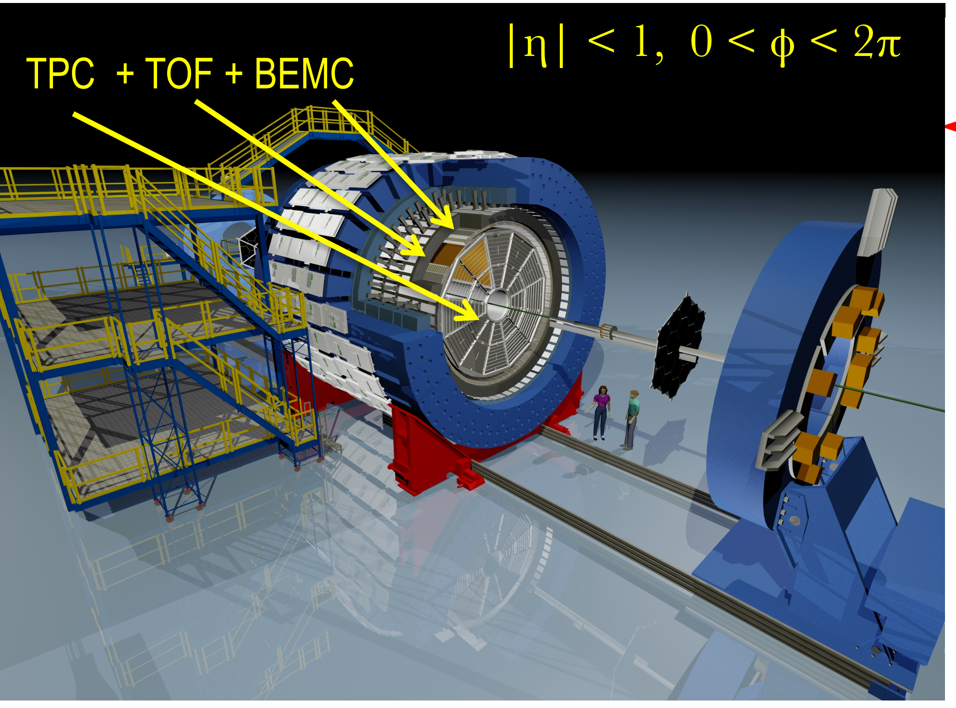
p+Pb data at 158 GeV was used to calculate the expected size of CNM effects on J/ψ production

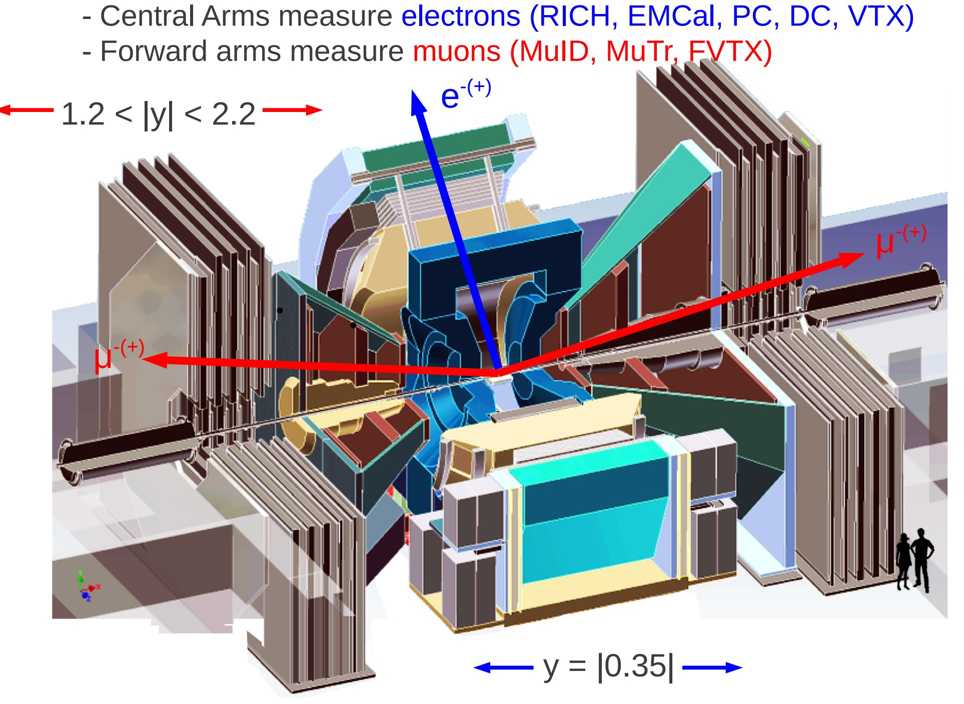
Quarkonia at RHIC: STAR and PHENIX experiments

$J/\psi \ / \ \Upsilon \rightarrow e^{+} e^{-} \ (\mu^{+} \mu^{-})$

STAR

PHENIX

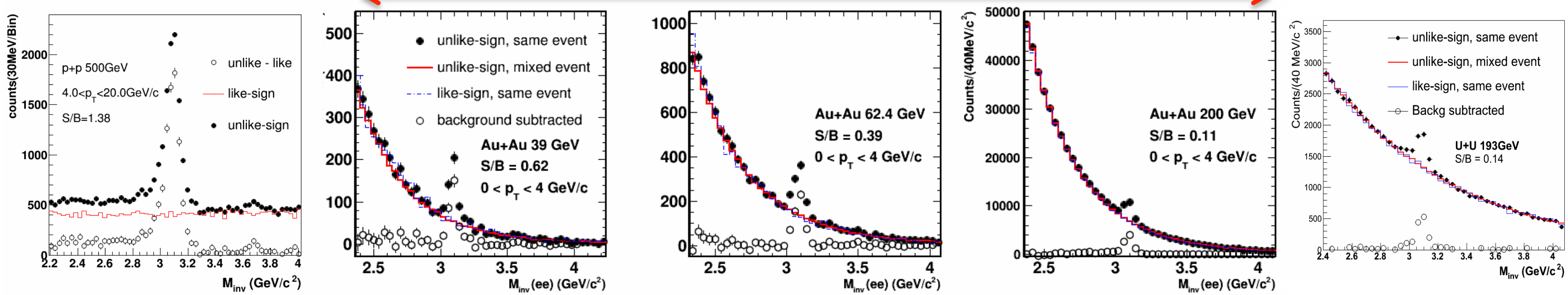




TPC: dE/dx PID, large acceptance, uniform in a wide energy range
TOF: PID using fight time (extends PID to low momenta)
BEMC: PID with E/p ratio, high p_t trigger

J/ψ

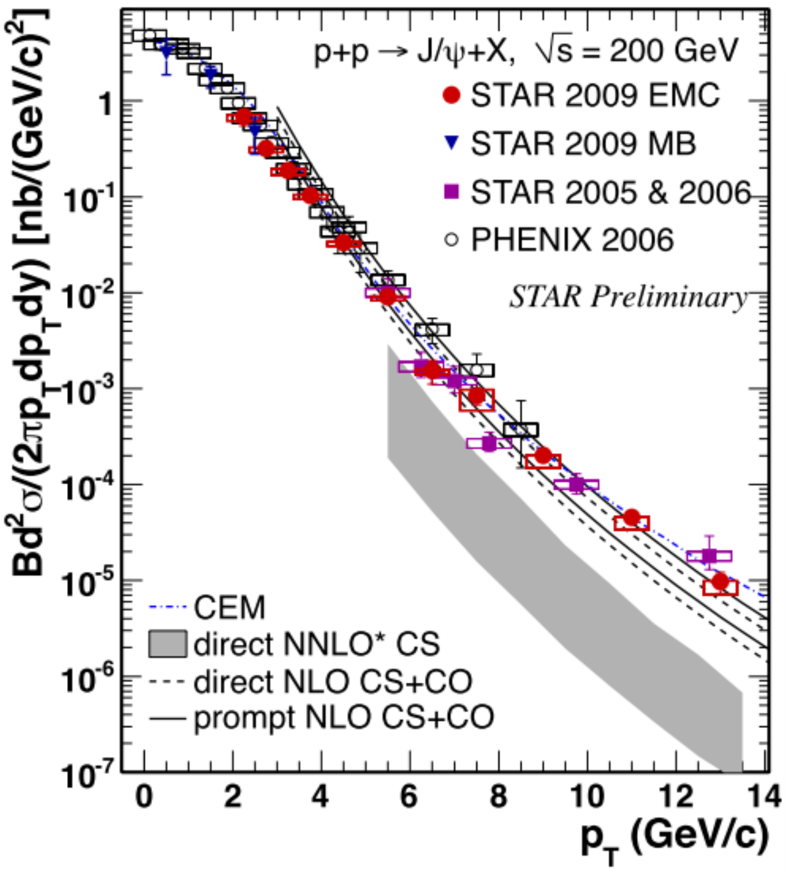
p+p   Au+Au   U+U



counts(30MeV/Bin)
p+p 500GeV
$4.0<p_T<20.0$GeV/c
S/B=1.38
unlike - like
like-sign
unlike-sign
M_{inv} (GeV/c^2)
unlike-sign, same event
unlike-sign, mixed event
like-sign, same event
background subtracted
Au+Au 39 GeV
S/B = 0.62
$0 < p_T < 4$ GeV/c
M_{inv}(ee) (GeV/c^2)
Au+Au 62.4 GeV
S/B = 0.39
$0 < p_T < 4$ GeV/c
M_{inv}(ee) (GeV/c^2)
Counts/(40MeV/c^2)
Au+Au 200 GeV
S/B = 0.11
$0 < p_T < 4$ GeV/c
M_{inv}(ee) (GeV/c^2)
Counts/(40 MeV/c^2)
unlike-sign, same event
unlike-sign, mixed event
like-sign, same event
Backg subtracted
U+U 193GeV
S/B = 0.14
M_{inv} (GeV/c^2)

J/ψ in p+p at 200 GeV

Inclusive J/ψ spectra:



STAR 2009 EMC : Phys. Lett. B 722 (2013) 55
STAR 2009 MB: Acta Phys. Polonica B Vol.5, No 2 (2012), 543
STAR 2005 & 2006: Phys. Rev. C80, 041902(R) (2009)
PHENIX 2006: Phys. Rev. D 85, 092004 (2012)

Data:

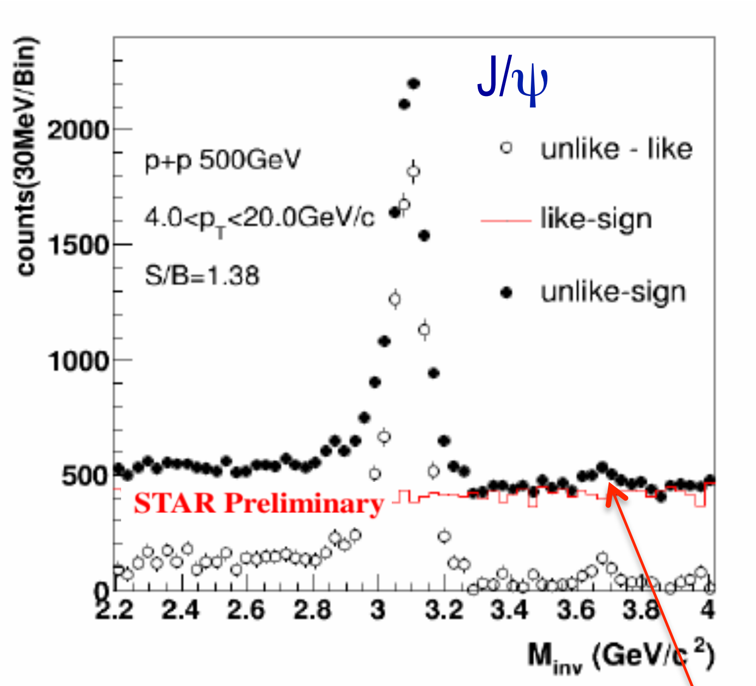
Reach: $0<p_t<14$ GeV
Agreement between STAR and PHENIX

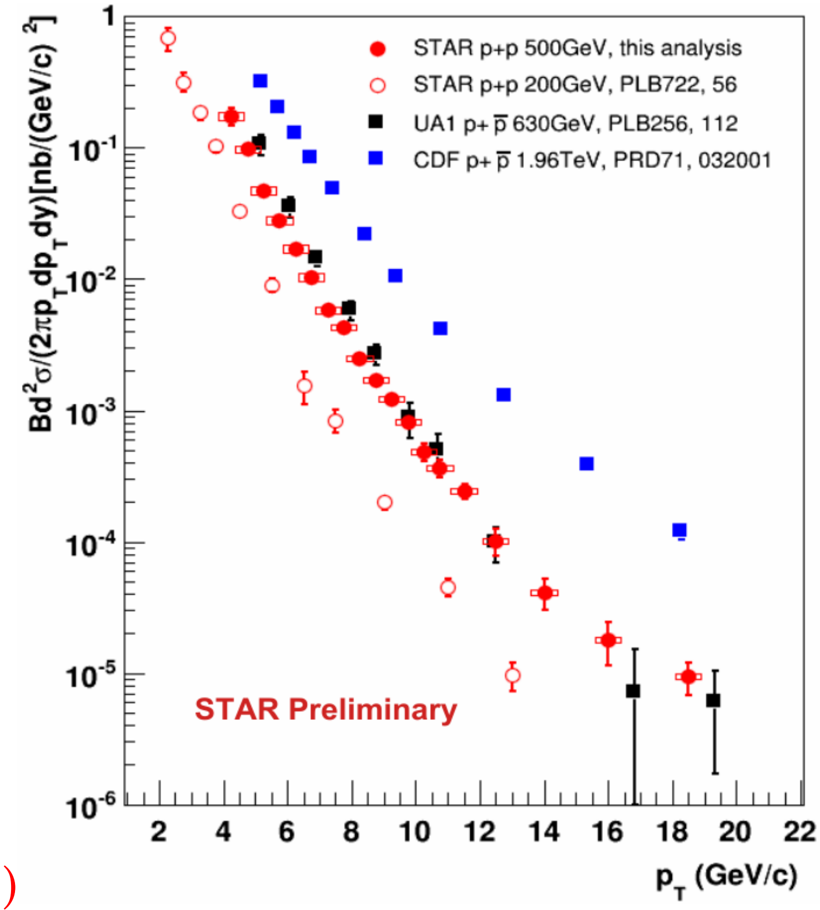
Models:

Prompt NLO CS+CO describes data for $p_t>4$ GeV/c
Prompt CEM describes data at high p_t
(over-predicts data at p_t ~ 3 GeV/c)
Direct NNLO*CS under-predicts high p_t part

direct NNLO CS: P.Artoisenet et al., Phys. Rev. Lett. 101, 152001 (2008) and J.P.Lansberg private communication
NLO CS+CO: Y.-Q.Ma, K.Wang, and K.T.Chao, Phys. Rev. D 84, 51 114001 (2011) and priv. comm.
CEM: A.D. Frawley, T Ullrich, R. Vogt, Pys. Rept. 462 (2008) 125, and R.Vogt priv. comm.

J/ψ in p+p 500 GeV





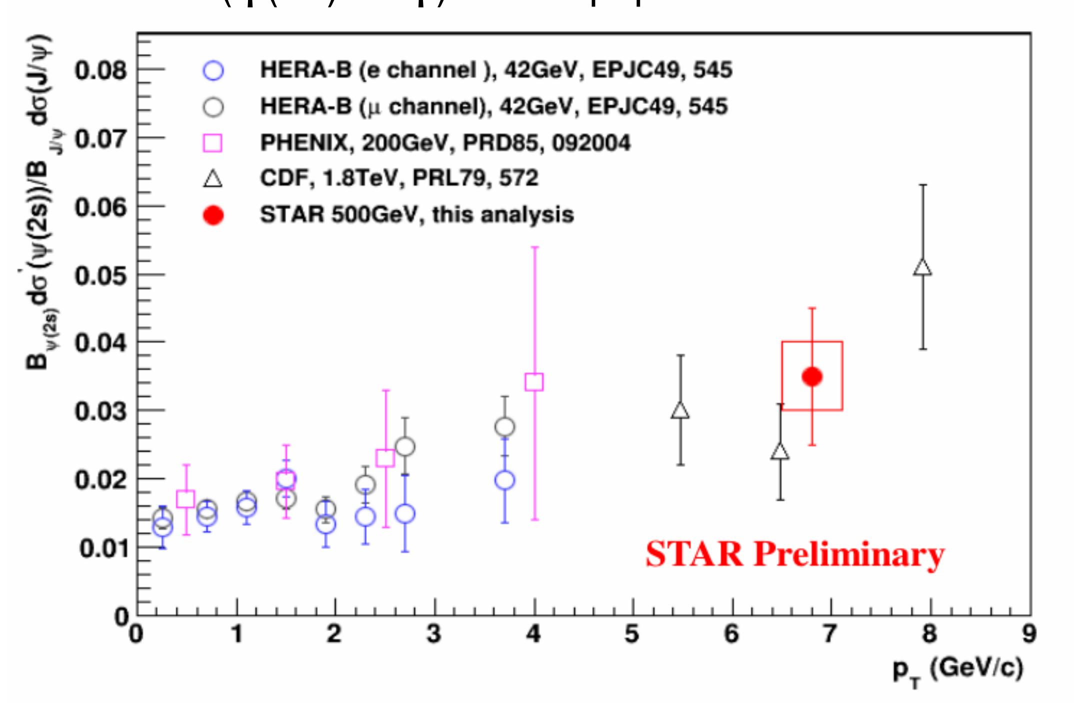
ψ'
or ψ(2S)

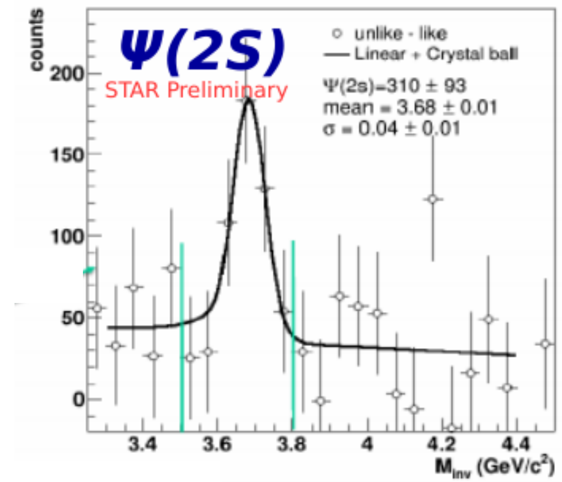
High precision measurement at new beam energy, up to p_T = 20 GeV/c

Constrain model parameters

ψ(2S) in p+p 500 GeV

(ψ(2S) / J/ψ) ratio in p+p at 500 GeV





First measurement at p+p at 500 GeV

No collision energy dependence observed

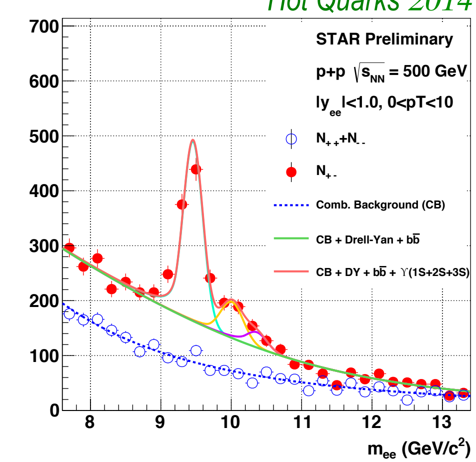
Consistent with previous measurements from other experiments

Constrain feed-down contribution to J/ψ production

Additional test for production mechanisms of charmonium

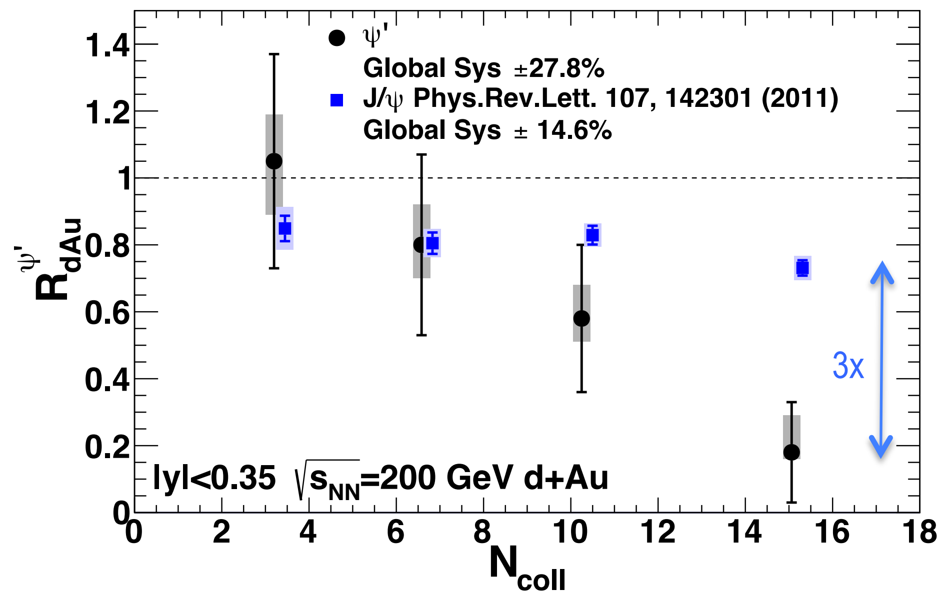
Also ϒ !

Hot Quarks 2014

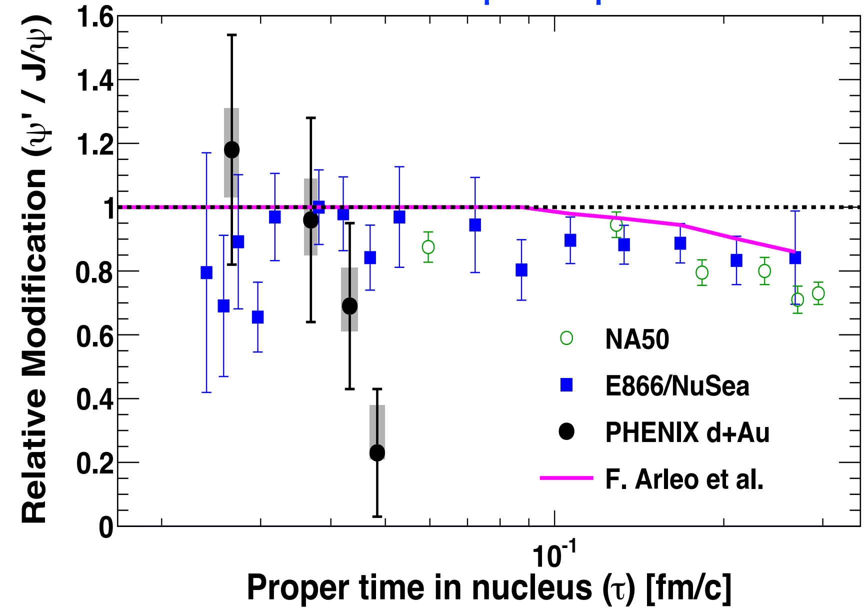


J/ψ and ψ' suppression in d +Au

PHENIX: PRL 111, 202301 (2013)



relative modification of ψ' to J/ψ as function of τ

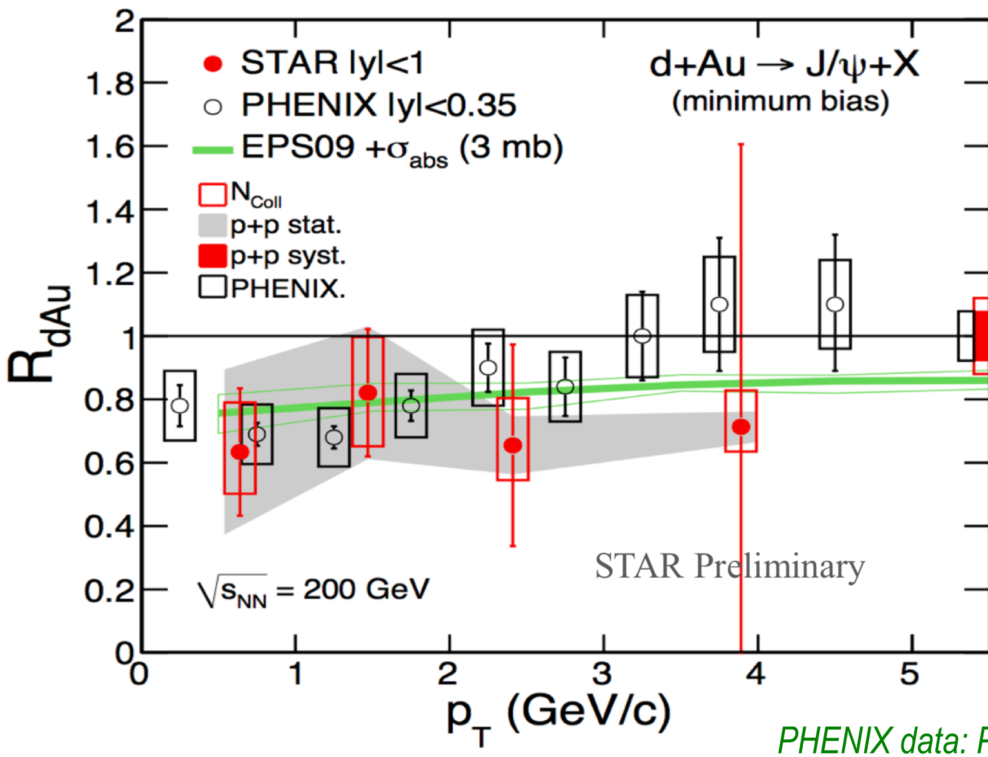


Suppression increases with increasing N_{coll}
ψ' production is heavily suppressed in central d+Au collisions relative to J/ψ →
ψ' is more sensitive to the final state effects
(ψ' binding energy is 12x smaller than J/ψ)

Nuclear crossing time at RHIC ~ 0.05 fm at mid-y while $c\bar{c}$ formation time ~ 0.15 fm →
bound $c\bar{c}$ may cross nucleus as a pre-resonant state
→ J/ψ and ψ' should have the same level of suppression → data shows something else !
(similar result seen at LHC)

Other process occurring on the time scale of $c\bar{c}$ formation that differently suppresses J/ψ and ψ' ?

$R_{dAu}^{J/\psi}$ vs p_t



PHENIX data: Phys.Rev. C 87 , 034904 (2013)
Model: E.Eskola et al., Nucl.Phys. A830, 599 (2009)

R_{dAu} ~ 1 at high p_t – CNM effects are small at high p_t

High p_t J/ψ carry cleaner signal with less CNM influence

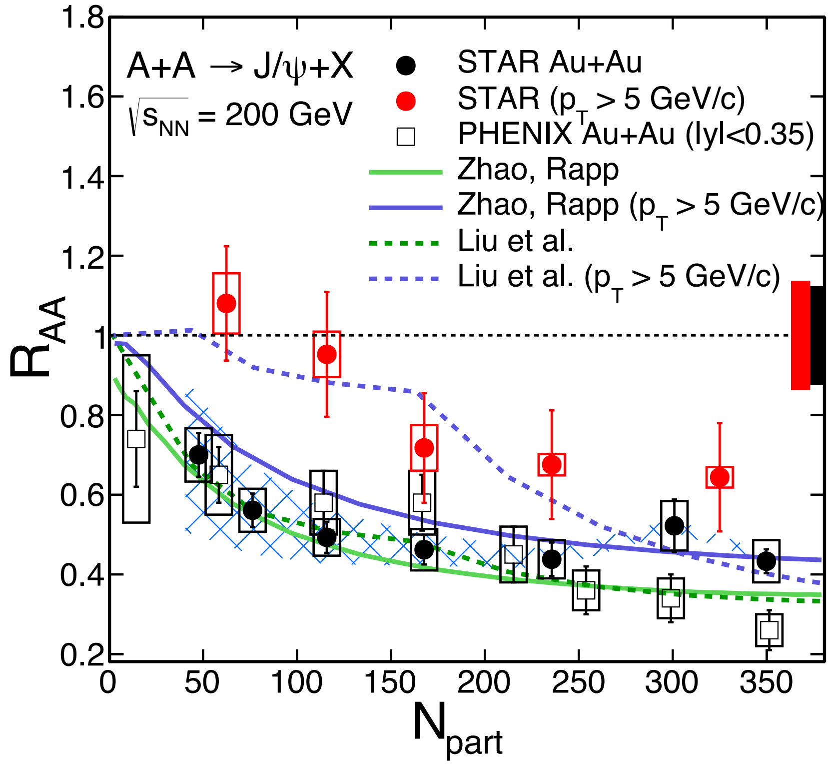
R_{dAu} consistent with model calculations

shadowing from EPS09 nPDF, nuclear absorption $\sigma_{abs}^{J/\psi}$ ~ 3mb

$R_{AA}^{J/\psi}$ in Au+Au 200 GeV (high p_t J/ψ)

- i.e. almost NOT effected by recombination and CNM effects

X .Zhao, R.Rapp, Phys. Rev. C82, 064905 (2010)



STAR low-p_T : arXiv:1310.3563
STAR high-p_T : PLB722, 55 (2013)
Liu et al., PLB 678, 72 (2009)
Zhao and Rapp, PRC 82, 064905(2010), PLB 664, 253 (2008)
PHENIX Phys. Rev. Lett. 98, 232301 (2007)

High-p_T J/ψ suppression in central collision

Suppression increases with collision centrality

$R_{AA}^{J/\psi}$ for high p_t is systematically higher than for low p_t →

may indicate color screening

presence of QGP

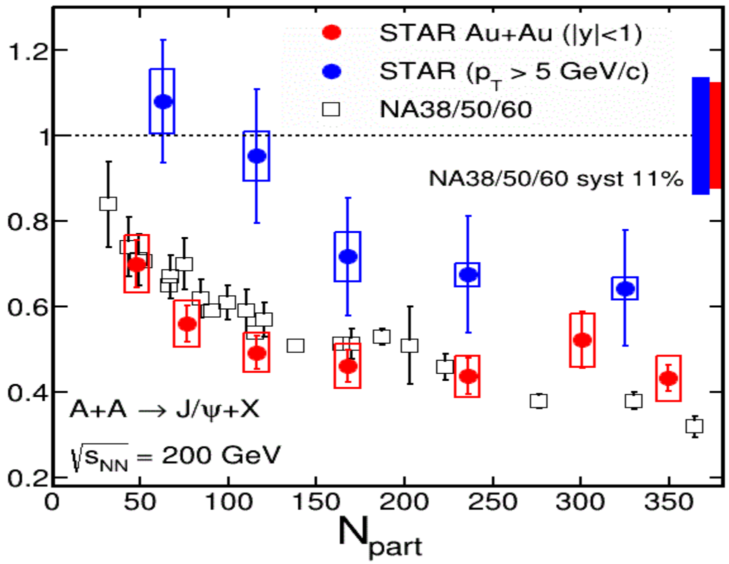
low p_t - both models agree with data (green lines)

high p_t - good agreement with Liu et al.,

Zhao and Rapp model underpredicts measured R_{AA} (blue lines)

J/ψ in Au+Au at 200 GeV: two surprises

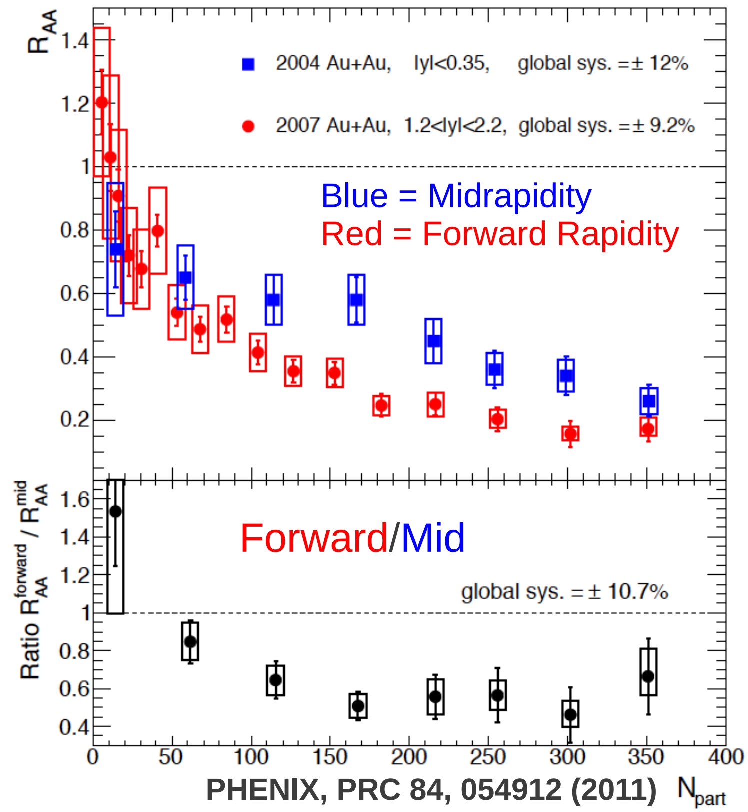
1: R^{RHIC}_{AuAu} (mid-y) ≈ R^{SPS}_{PbPb}



At mid-y R_{AA} looks similar, while there are obvious differences:

- at a given N_{part}, at RHIC much higher energy densities…
- cold nuclear matter effects should be drastically different ($x_{Bjorken}$, σ_{abs}…)
- …

2: R_{AuAu} (forward) < R_{AuAu} (mid-y)



Expectation from color screening:

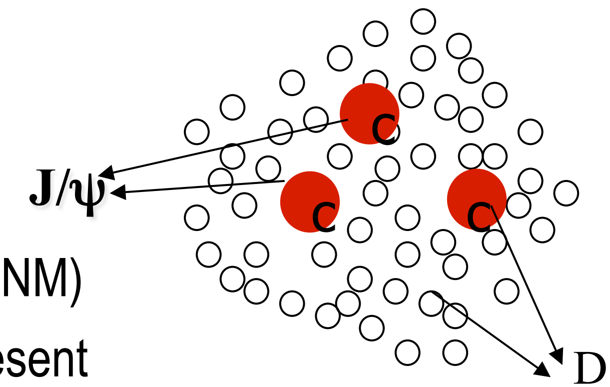
R_{AA}(mid-y) < R_{AA}(forward y)

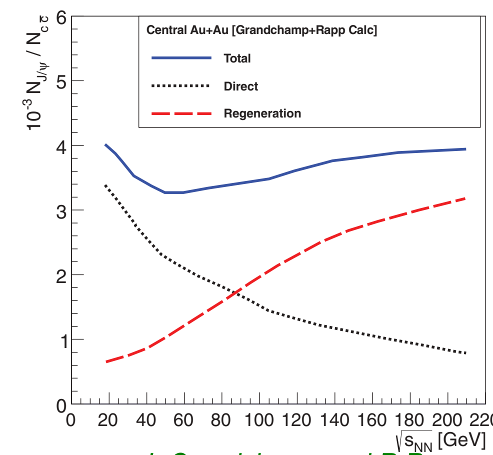
clearly data shows something else !

R_{AA}(mid-y) > R_{AA}(forward y)

Possible explanations …

- Regeneration models
  - give enhancement that compensate screening, initially uncorrelated c and $\bar{c}$ can recombine ($N_{c\bar{c}}$ ~ 12 in most central collisions)
  - qualitative explanation: less suppression in y-mid because there is more c and $\bar{c}$ to recombine





L.Grandchamp and R.Rapp, Nucl. Phys. A 709, 415 (2002)

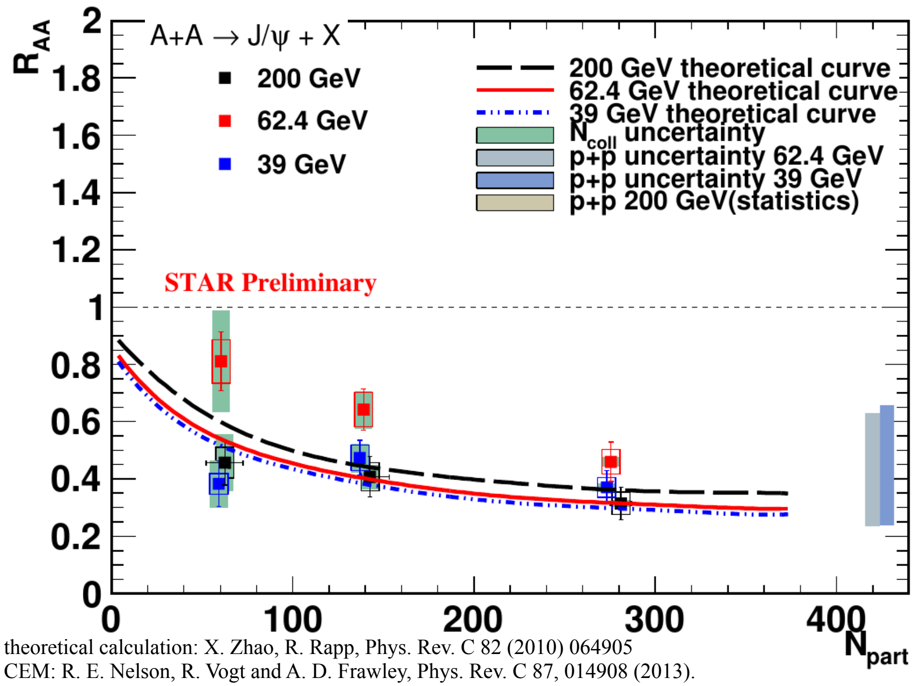
- Cold nuclear matter effects (CNM)
  - in any case are always present

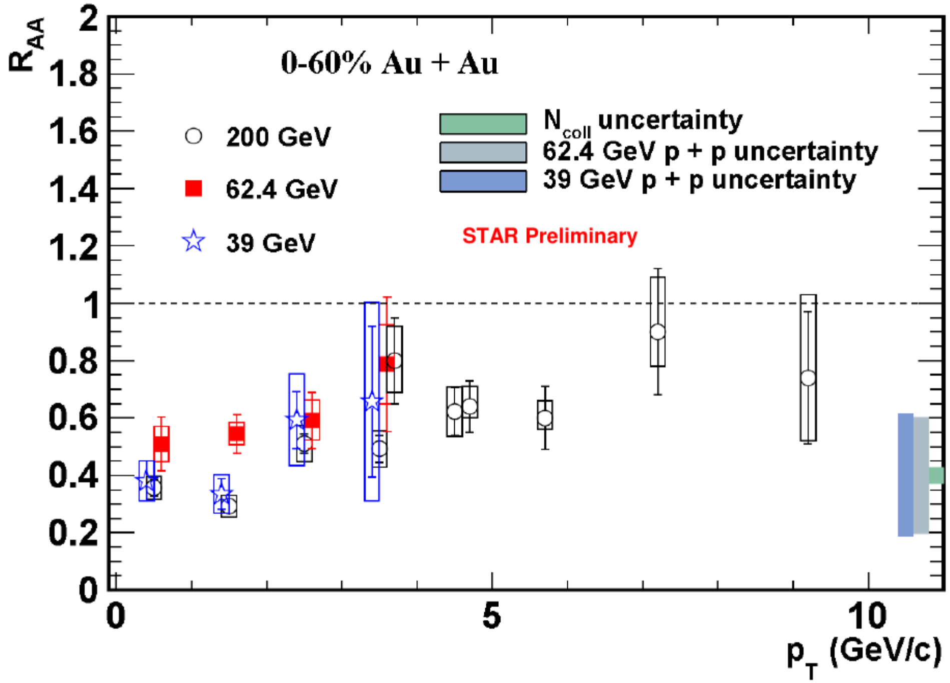
- Sequential suppression
  - QGP screening only of χ_c and ψ' removing their feed-down contributions to J/ψ

Presently one can not exclude/favor one or other of the above scenarios !

J/ψ R_{AA} energy dependence

RHIC BES – a unique tool to study the interplay of J/ψ direct production, recombination and CNM effects





theoretical calculation: X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905
CEM: R. E. Nelson, R. Vogt and A. D. Frawley, Phys. Rev. C 87, 014908 (2013).

p+p reference for 62.4 and 39 GeV data from Color Evaporation Model (CEM) - large theoretical uncertainties

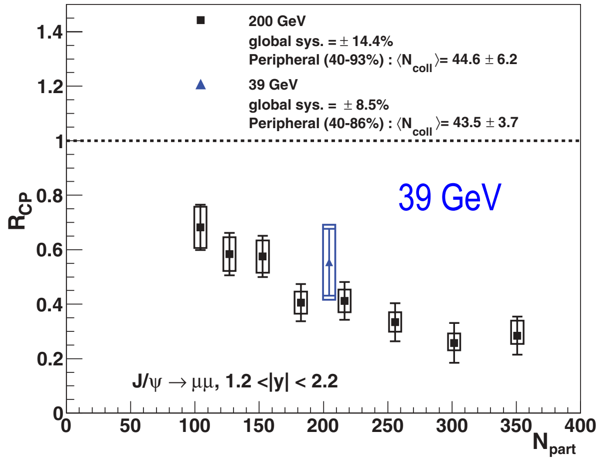
Significant suppression of J/ψ production observed for all energies (200, 62.4 and 39 GeV) in respect to N_{coll} scalled with p+p yields. Consistent with suppression of directly produced J/ψ.

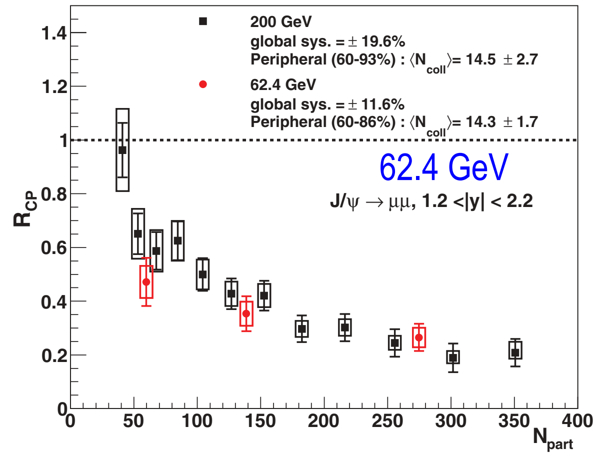
No significant energy dependence for R_{AA}
Two-component model (color screening, direct suppression + statistical regeneration) calculations consistent with data

R_{AA} increases from low p_t to high p_t, similar trend in 39, 62.4 and 200 GeV data the “same” in the forward direction:

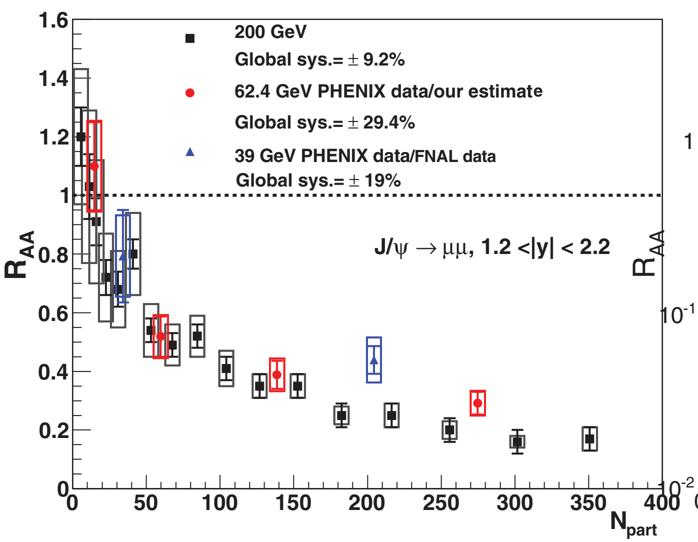
R_{CP}, R_{AA} $J/\psi \rightarrow \mu\mu$, $1.2<|y|<2.2$

PRC 86, 064901 (2012)

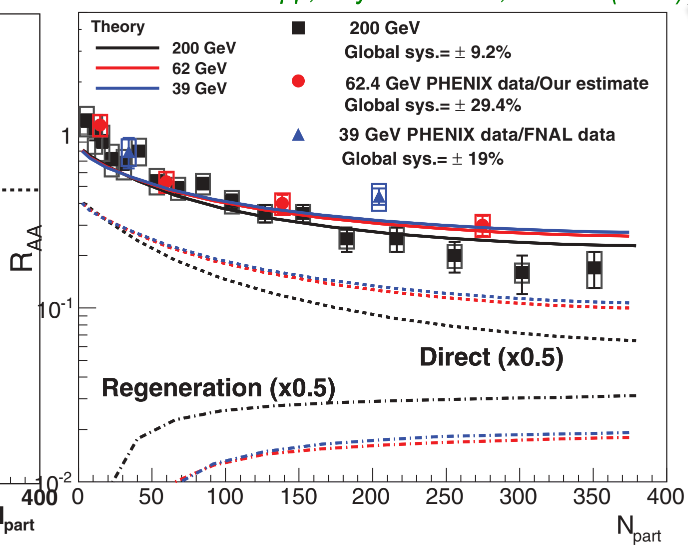




Similarity of J/ψ nuclear modifications R_{CP} and R_{AA} from 39 to 200 GeV is a challenge for models



X.Zhao and R.Rapp, Phys.ReV. C82, 064905 (2010)



Model includes CNM effects, regeneration and QGP suppression for J/ψ forward rapidity is consistent with data

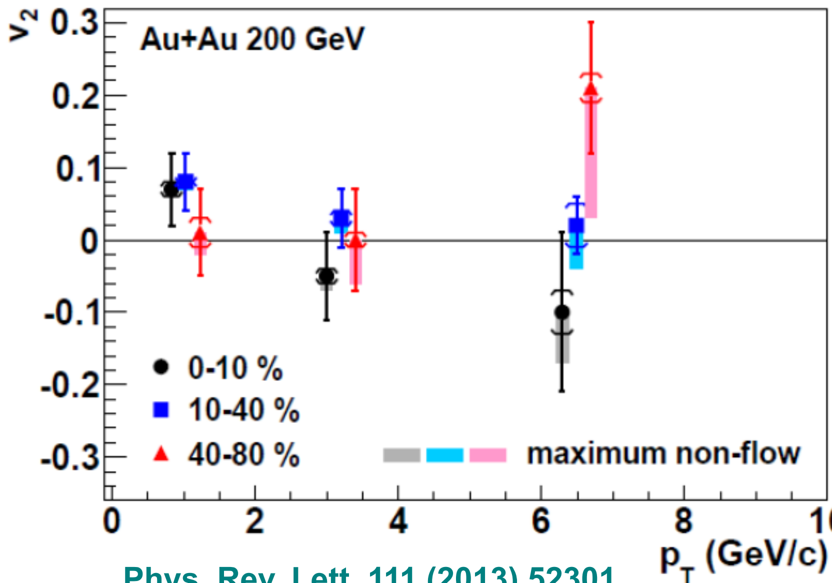
Does coalescence compensate for melting ?

Needs reference p+p data !

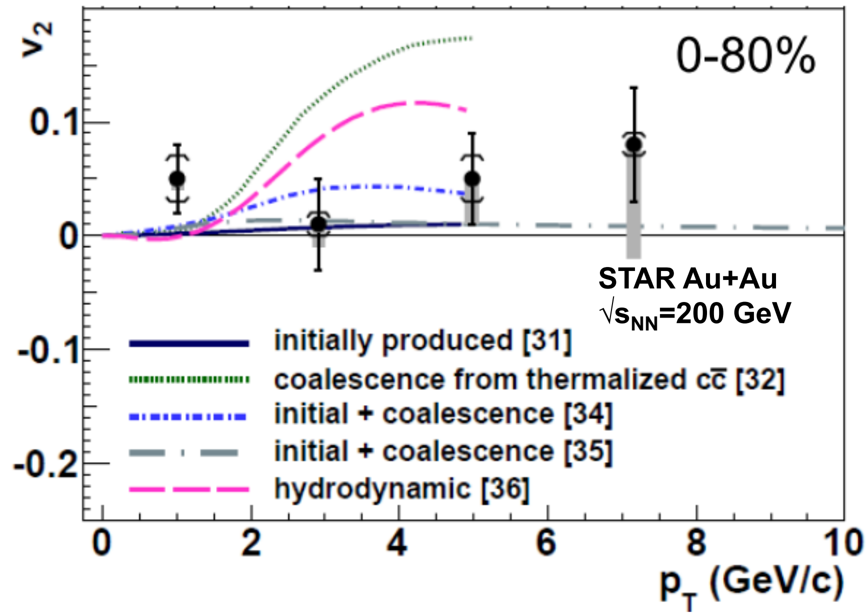
p+p reference data determine taken from ISR, Fermilab and CEM

J/ψ does not flow

[31] Yan, Zhuang,Xu, PRL97 (2006) 232301
[32] Greco, Ko, Rapp, PLB595 (2004) 202
[34] Zhao, Rapp, PLB 655 (2007) 126
[35] Liu,Xu,Zhuang, NPA834 (2010) 317c
[36] Heinz, Chen (2012)

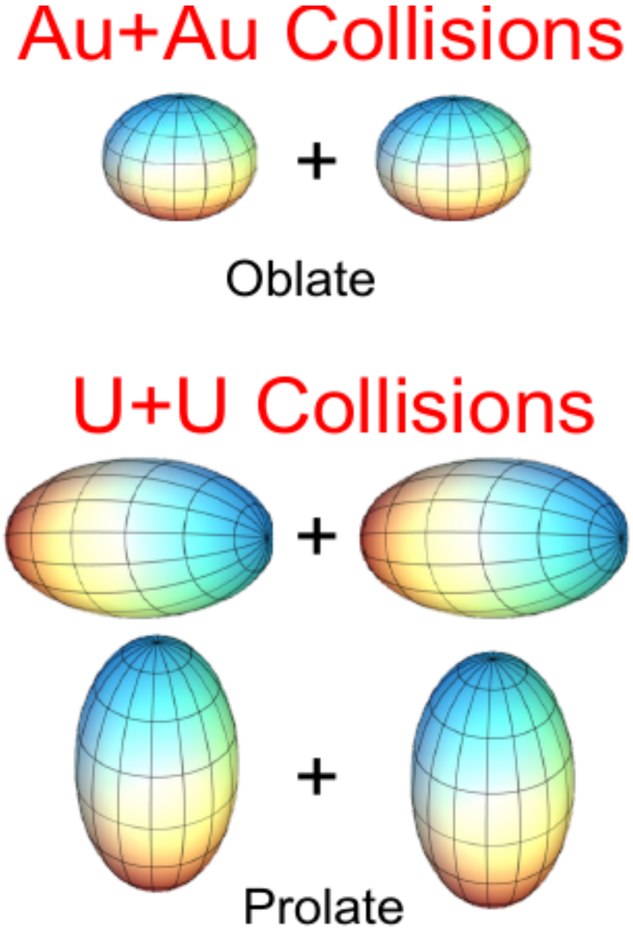


Phys. Rev. Lett. 111 (2013) 52301

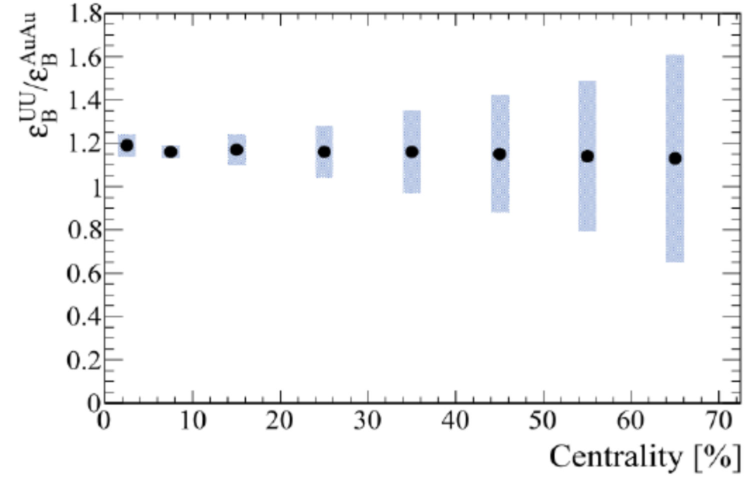


J/ψ v_2 consistent with 0 in p_t range of 2 to 8 GeV/c for all centralities
Disfavors J/ψ coalescence from thermalized charm quarks at RHIC
J/ψ is the ONLY hadron so far that does not flow !

Why J/ψ in U+U 193 GeV so interesting ?

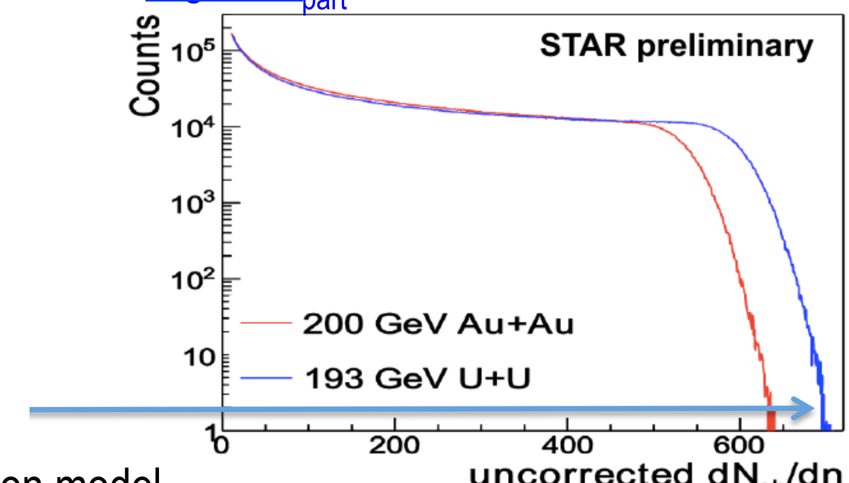


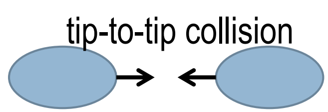
1. Higher energy density in U+U collisions (~ 20 %)



Kikola, Odyniec, Vogt, Phys. Rev. C 84, 054907

2. Higher N_{part}

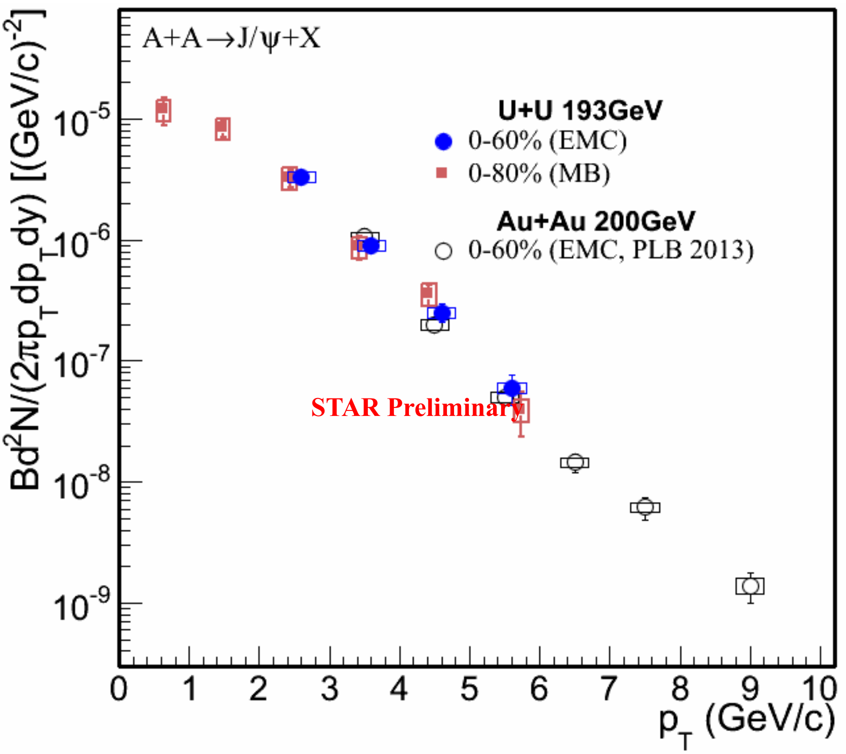


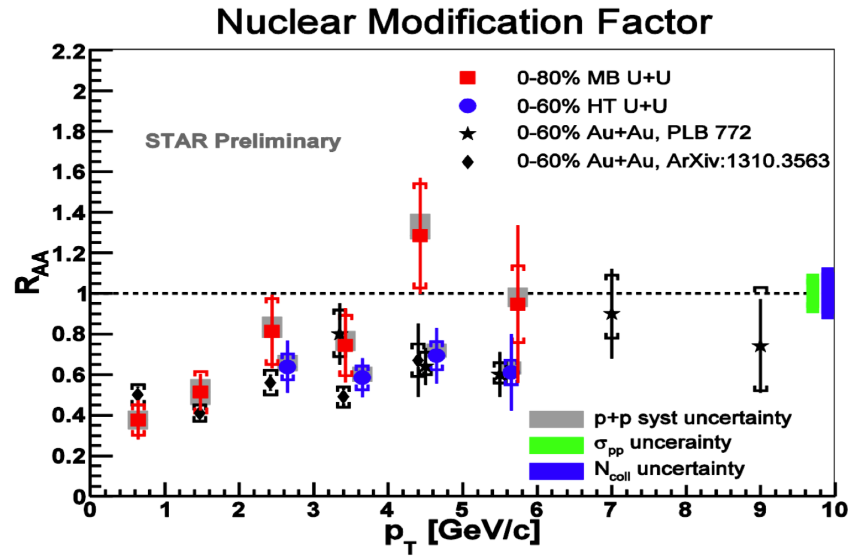


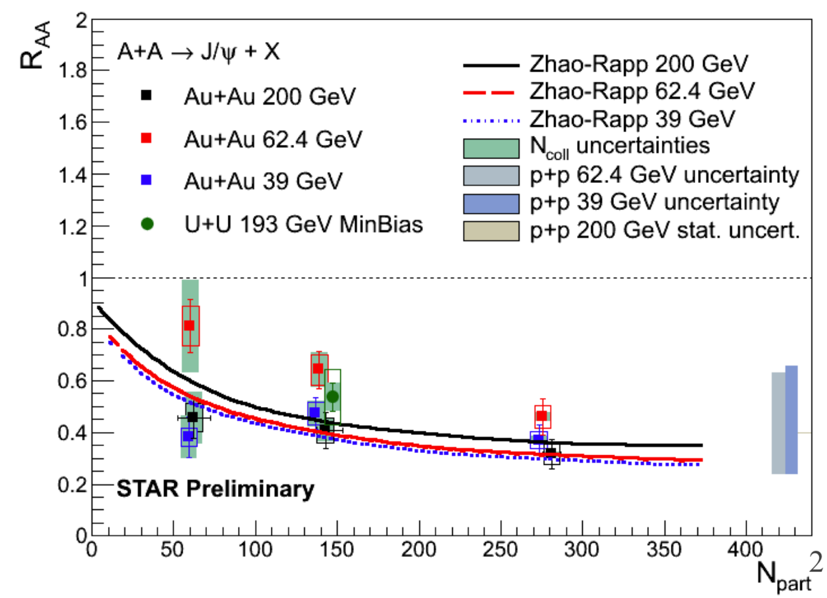
It should be a good test for sequential suppression model …

- greater suppression due to color screening
- N_{coll} increases ⟶ N_{charm} increases ⟶ greater probability for regeneration

J/ψ in U+U 193 GeV



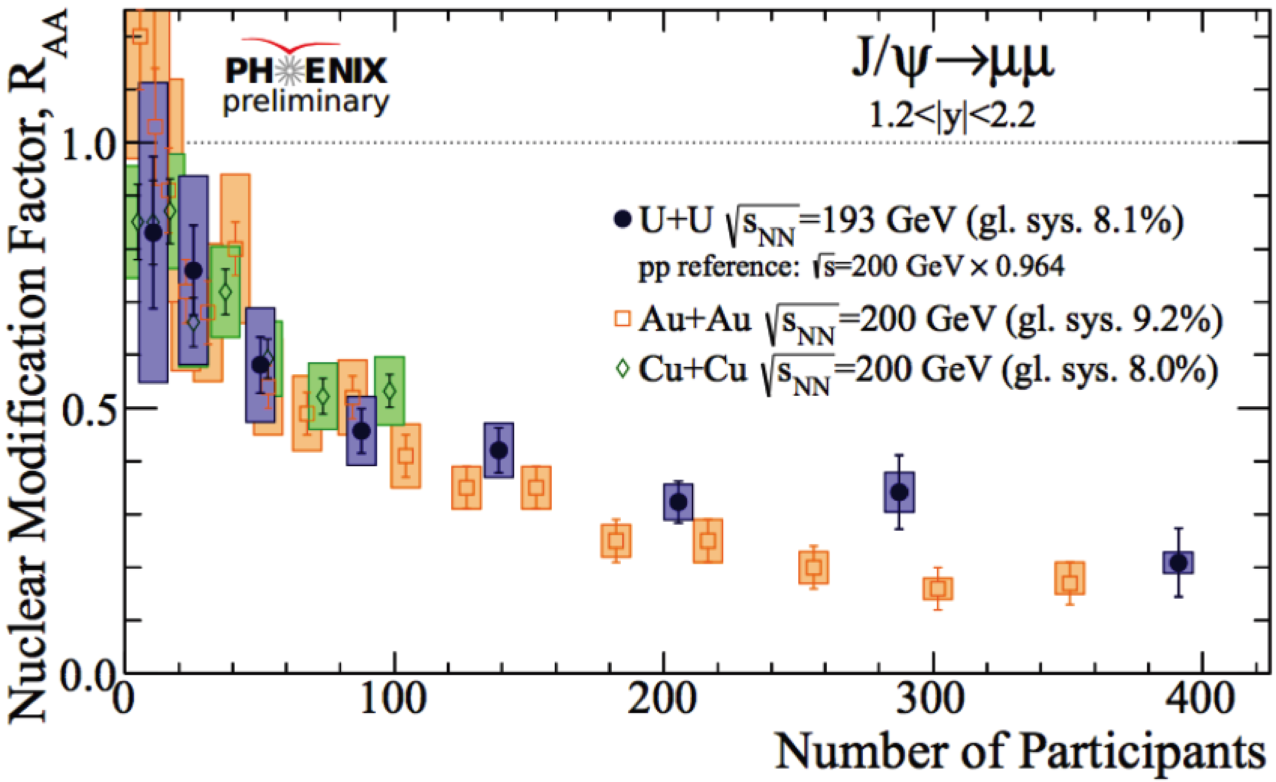




Similar suppression pattern in U+U as that in Au+Au 200 GeV

Baseline: J/ψ measurements in p+p 200 GeV

System size ?



Not much net effect from system size increase

Upsilon

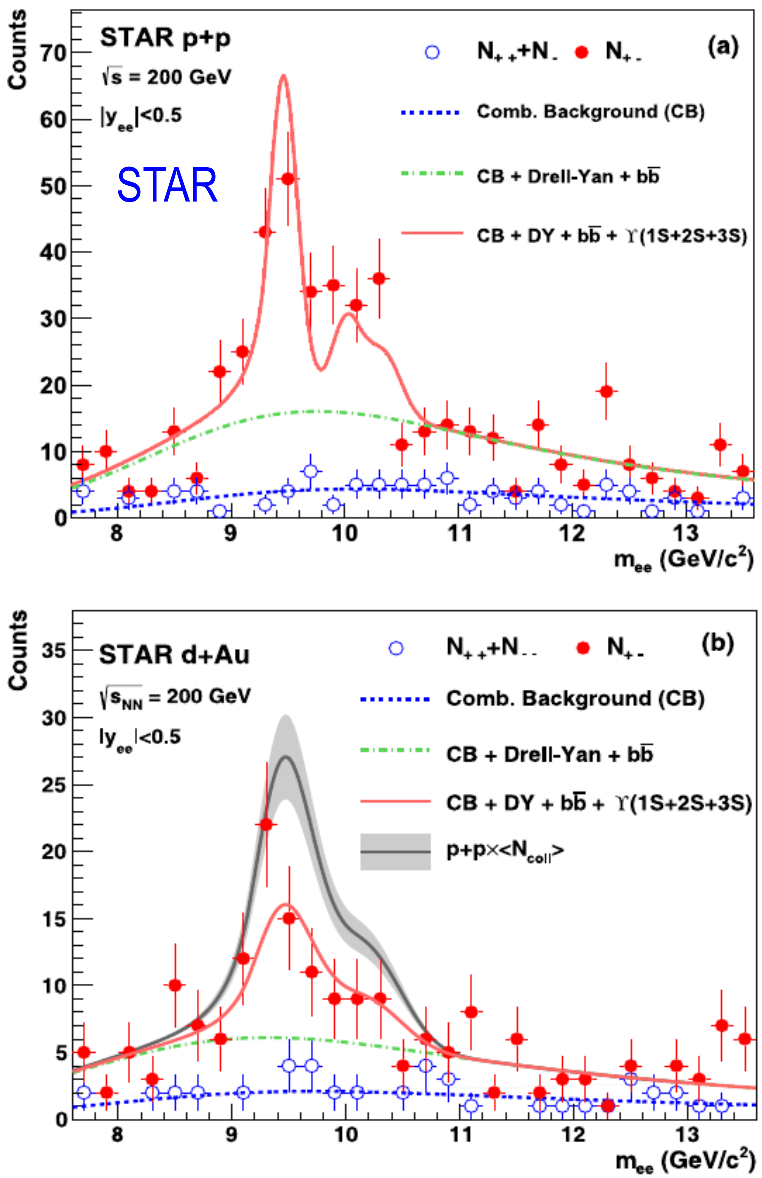
a cleaner (compare to J/ψ) probe:

- co-mover absorption negligible
- recombination negligible

~ 12 $c\bar{c}$ and ~ 0.07 $b\bar{b}$ pairs per central Au+Au collision at 200 GeV

but, rare probe, low rate …

Upsilon in p+p and d+Au 200 GeV



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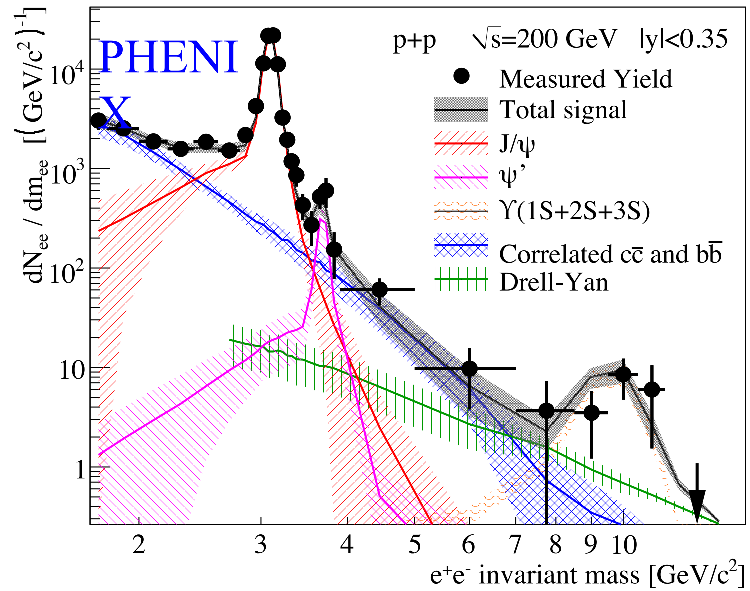
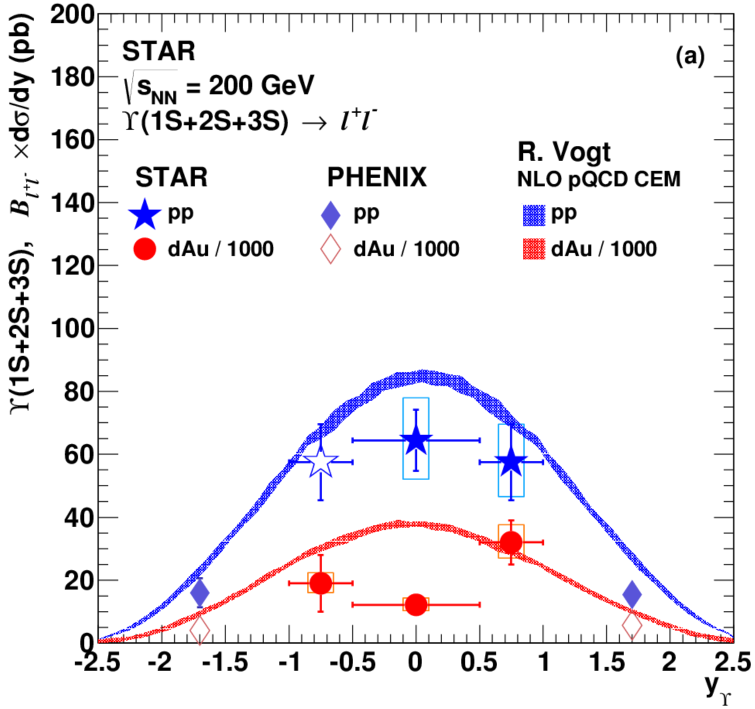
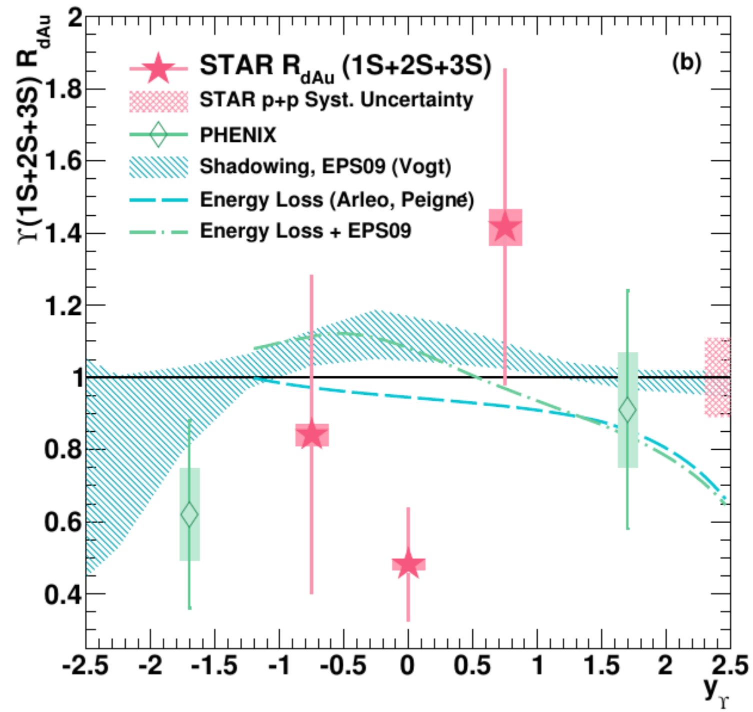


Upsilon suppression in d+Au !

Upsilon rapidity dependence in p+p and d+Au 200 GeV

Phys.Lett. B 735 (2014) 127





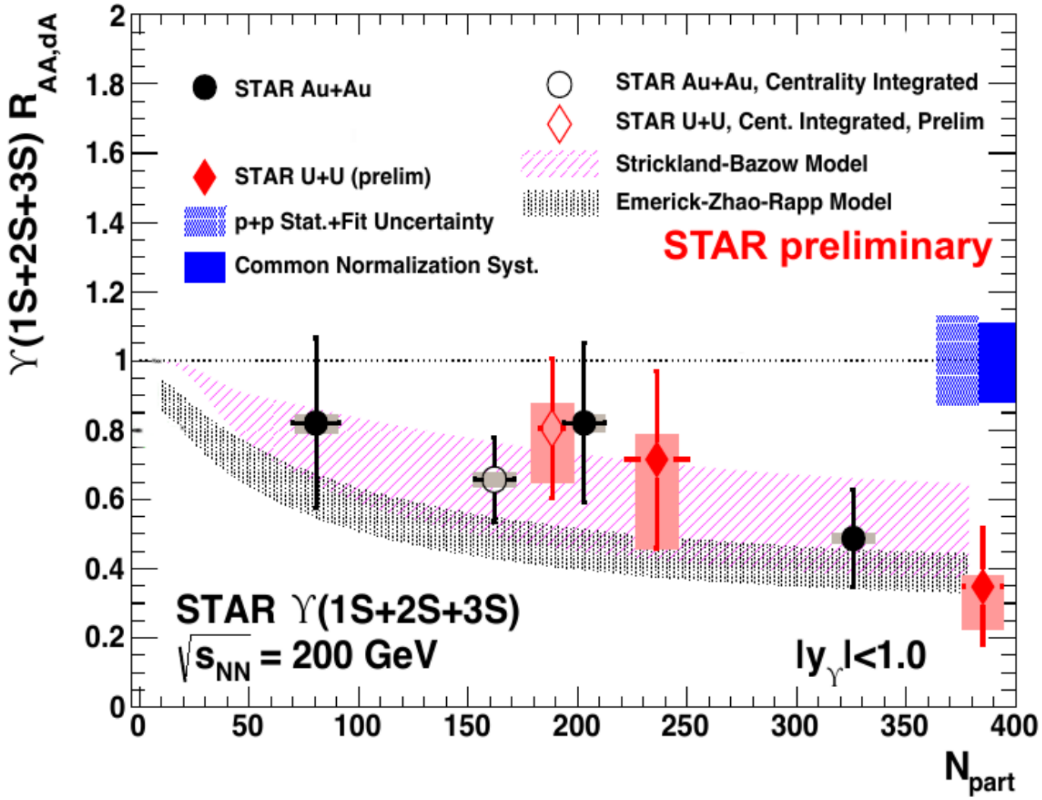
Υ cross section in p+p vs rapidity consistent with NLO pQCD CEM predictions across all y, in d+Au also, except y~0

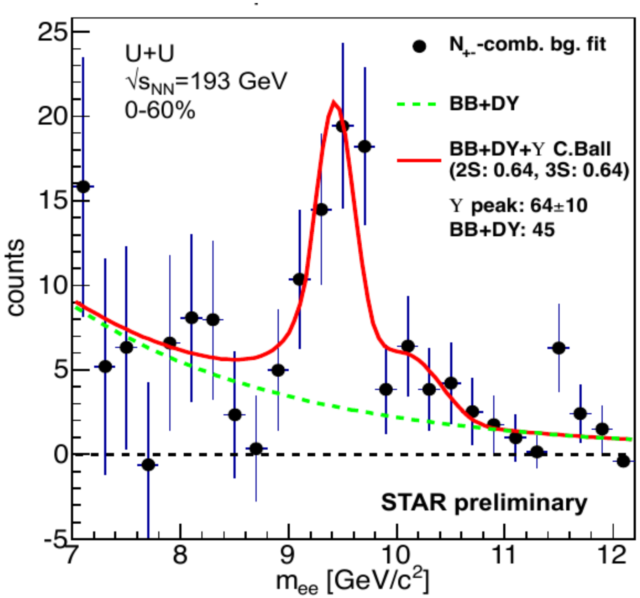
R. Vogt, Phys. Rep. 462125, 2008

R_{dAu} consistent with predictions except mid-rapidity -> indication of additional suppression at y ~ 0 beyond that of current models (i.e. in addition to shadowing and initial state parton energy loss)

- requires further studies → p+A run

Upsilon in U+U 193 GeV





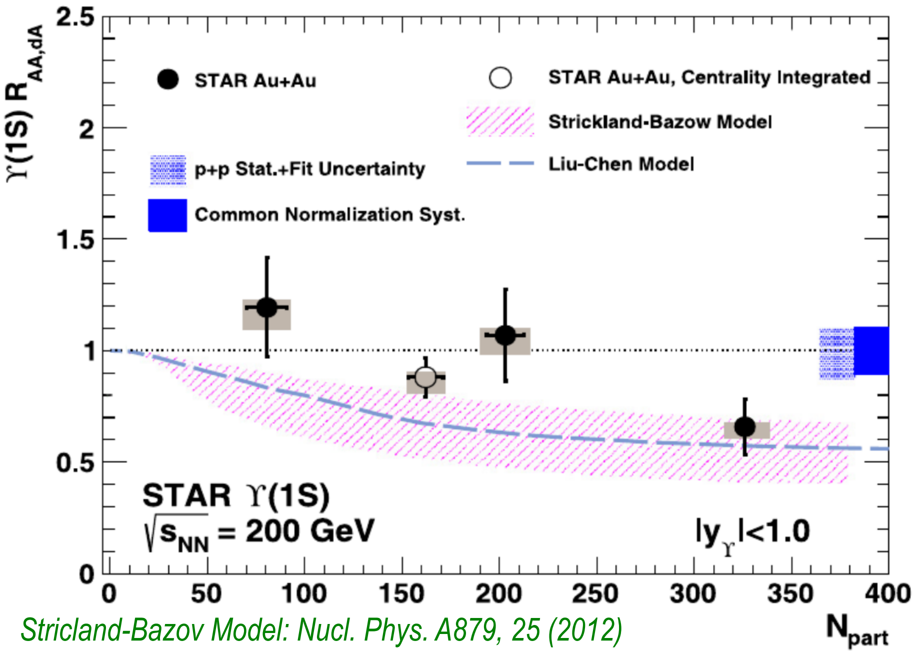
Consistent increase of suppression with centrality in both Au+Au and U+U

Strong suppression in central collisions. Trend in U+U follows and extends trend in Au+Au

Agreement with models that include presence of QGP. Strickland model predicts temperature range :

428 MeV < T < 442 MeV

ϒ(1S) state suppression in Au+Au

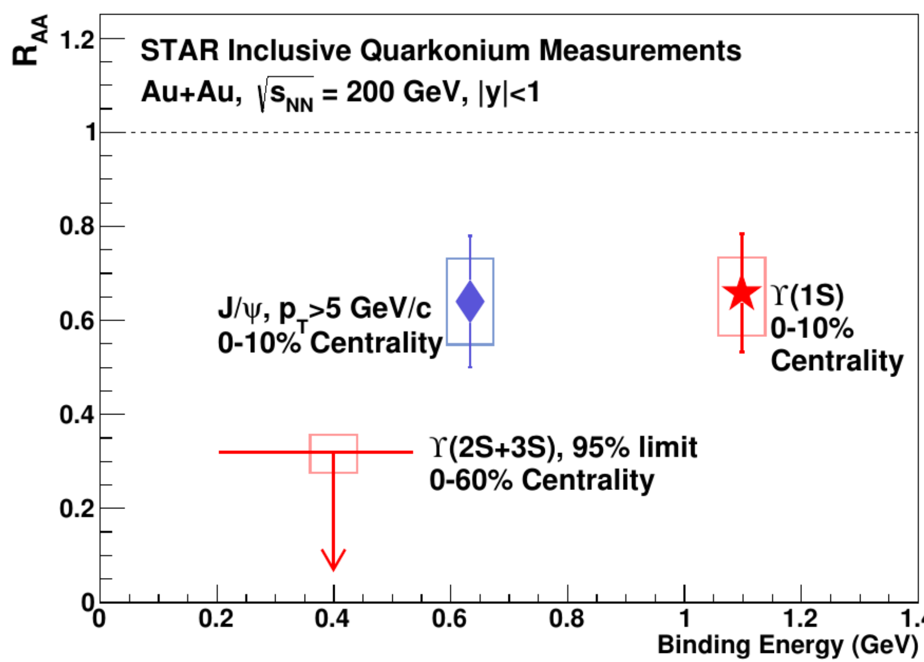


Stricland-Bazov Model: Nucl. Phys. A879, 25 (2012)
Liu-Chen Model: Phys. Lett. B697 (2011) 32

Suppression of ϒ(1S) in central collisions consistent with model calculations

- *Liu et al. Model* – suppression mostly due to dissociation of the excited states (CNM effects not included)
- *Strickland-Bazow Model* – hot and cold nuclear effects

No suppression: $R_{AA}^{\Upsilon(1S)} \sim 1$ in dAu, in peripheral and mid-central AuAu collisions



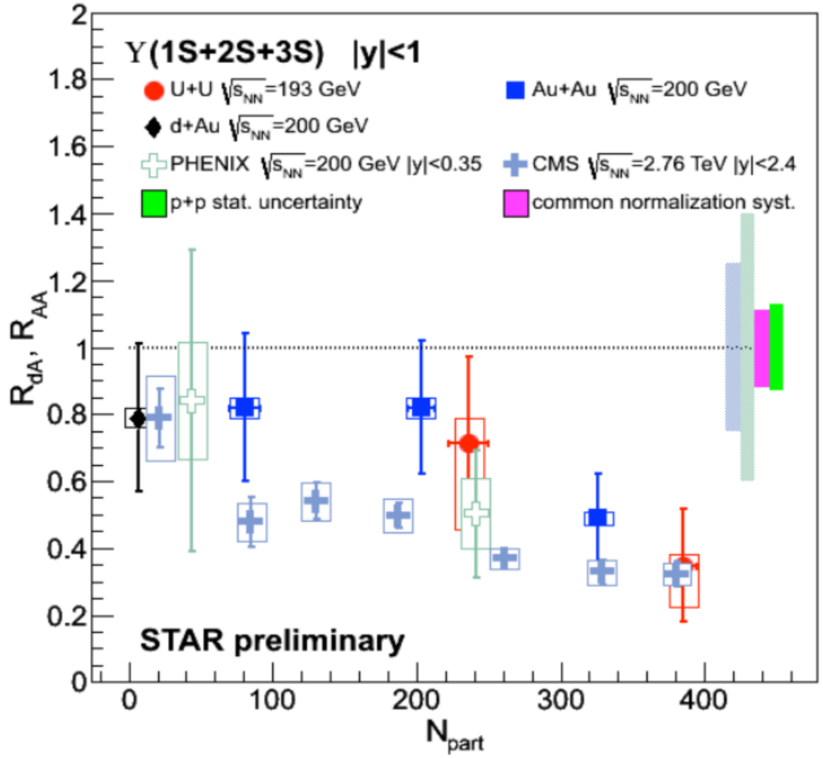
Indication of complete melting of ϒ(2S) and ϒ(3S) suppression in central collisions, consistent with predictions for central Au+Au

Suppression of ϒ(1S) similar to high-p_T J/ψ

ϒ suppression pattern supports sequential melting

Υ R_{AA} at RHIC and LHC

Phys. Lett. B735 (2014) 127, arXiv: 1404.2246, PRL 109 (2012) 222301



STAR vs PHENIX
RHIC vs LHC

Agreement between RHIC experiments
Larger suppression at CERN LHC energies, however at most central collisions comparable
Υ suppression indicates color deconfonement
however, uncertainties are substantial

Where we are :

- Significant suppression of J/ψ production in central Au+Au from 39 to 200 GeV with respect to N_{coll} scalled p+p yields

- This J/ψ suppression similar in Au+Au at 200, 62.4 and 39 GeV

Does recombination compensate fully for melting ?

- Indications of no system size dependence of J/ψ suppression (similar in Au+Au and U+U)

- No collective behavior of J/ψ observed – thermalizes $c\bar{c}$ coalescence unlikely

- d+Au – hint of “additional” suppression (beyond model calculations)

Some final state effects (even in such a small system) ?

- Υ(2S) and Υ(3S) suppression stronger then Υ(1S) in central collisions

Signal of deconfined medium ?

- first ψ’ measurements

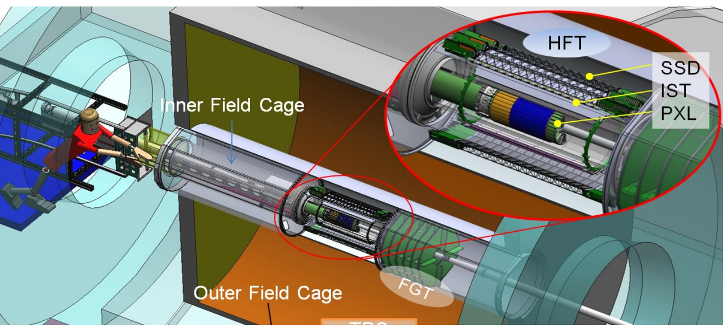
Near future

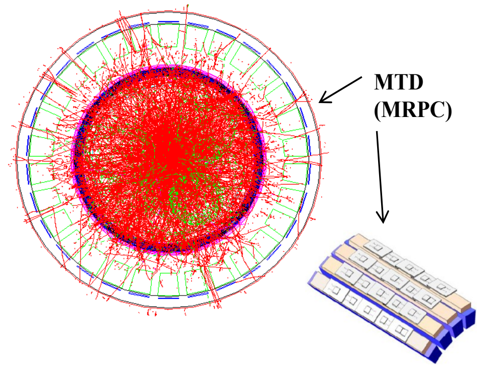
Very soon – detailed quarkonium measurements

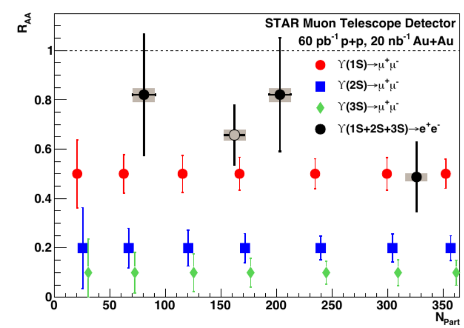
In STAR (fully installed and taking data in 2014):

HFT – separation of prompt and non-prompt J/ψ

MTD - J/ψ, ϒ → μ+μ− (compliment to e+e-)





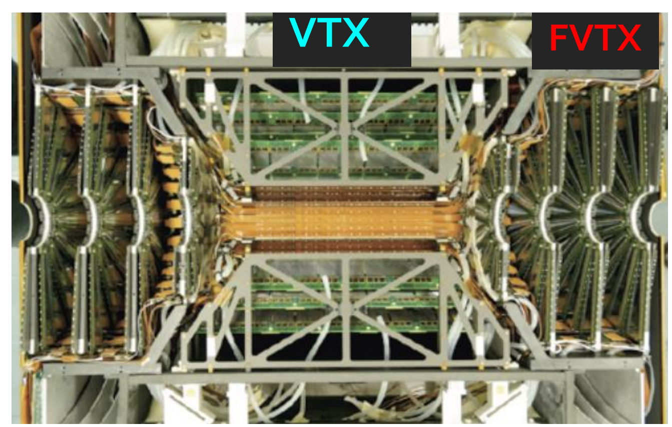


Statistical projection of ϒ R_{AA} for different ϒ states with MTD

In PHENIX:

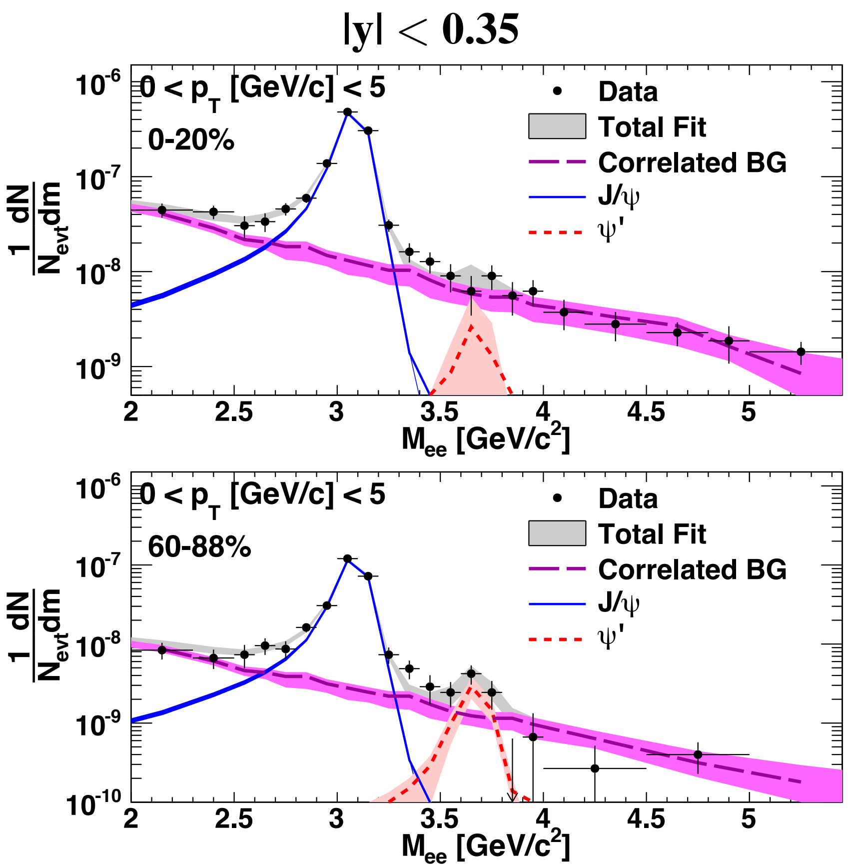
VTX, FVTX –

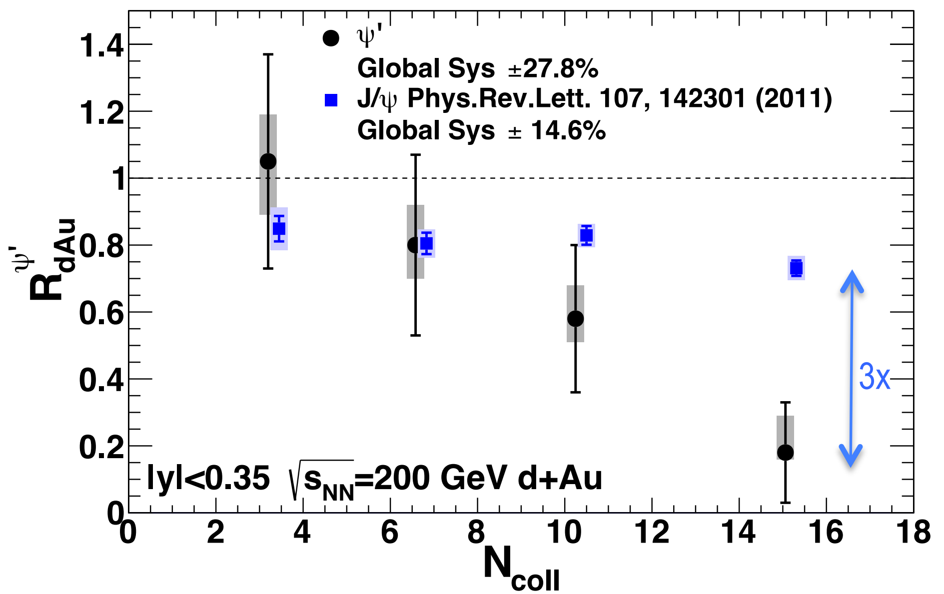
nuclear modification and collective flow of charm and bottom separately using DCA



Thank you !

ψ' in d +Au



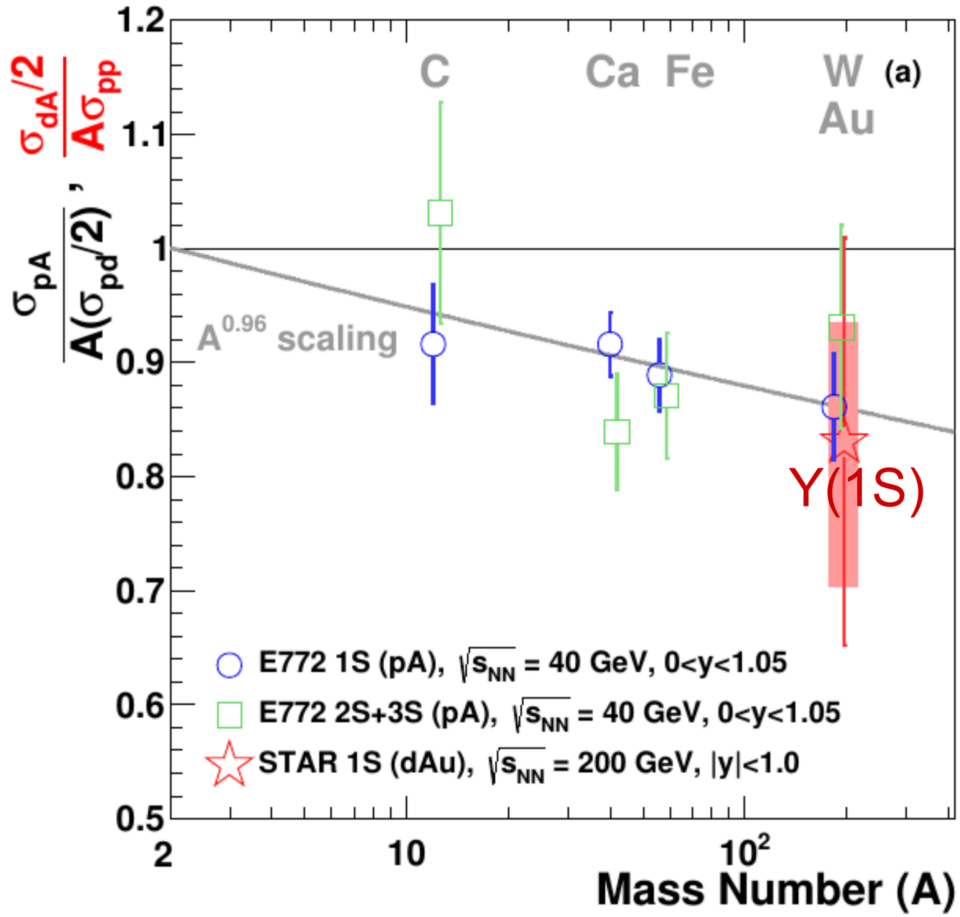


Suppression increases with increasing N_{coll}

ψ' production is heavily suppressed in central d+Au collisions relative to J/ψ ⟶

ψ' is more sensitive to the final state effects (ψ' binding energy is 12x smaller than J/ψ)

CNM effects, Υ in d+Au 200 GeV,

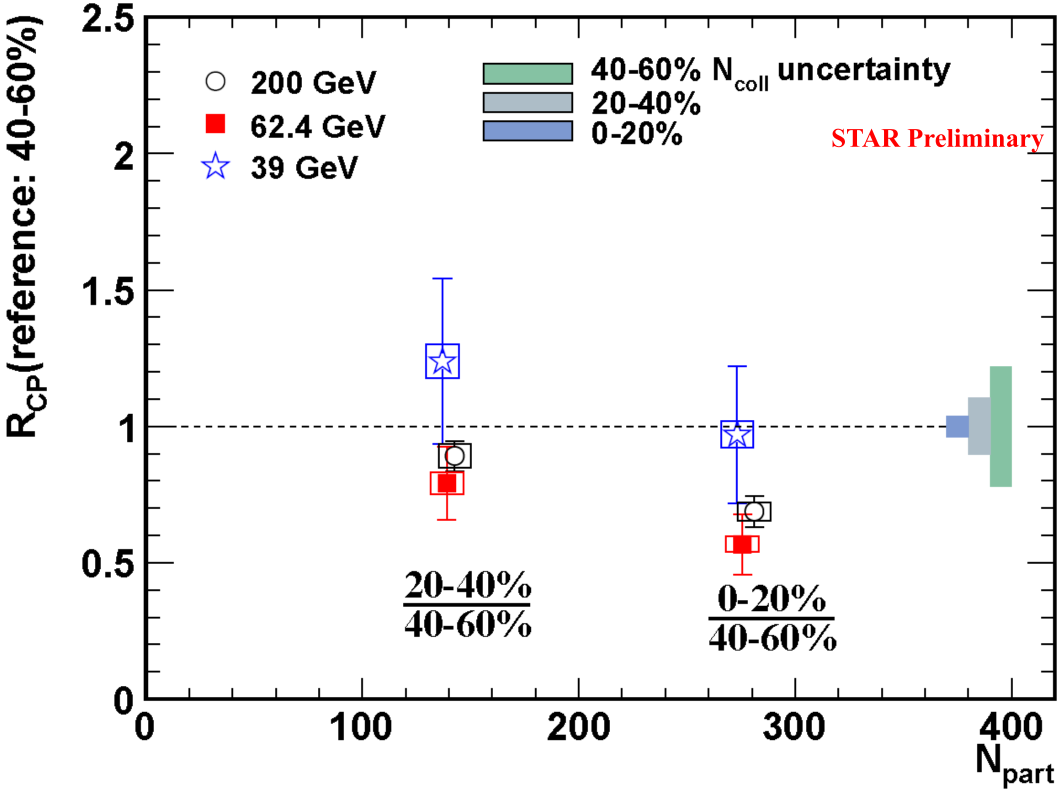


Similar suppression seen at E772

Suppression increases with the size of the system

Energy dependence of J/ψ R_{cp}

RHIC BES program – a unique tool to study the interplay of J/ψ direct production (with color screening), CNM effects and recombination with changing energy



$$R_{CP} = \frac{\dfrac{dN/dy}{\langle N_{coll} \rangle}(\text{central})}{\dfrac{dN/dy}{\langle N_{coll} \rangle}(\text{peripheral})}$$

No p+p reference data at 62.4 and 39 GeV – using R_{CP} ratio of centrals to peripherals

Nuclear modification factor R_{CP} shows significant suppression in central Au + Au collisions at 62.4 GeV, similar as at 200 GeV

Note, at 39 GeV large error bars