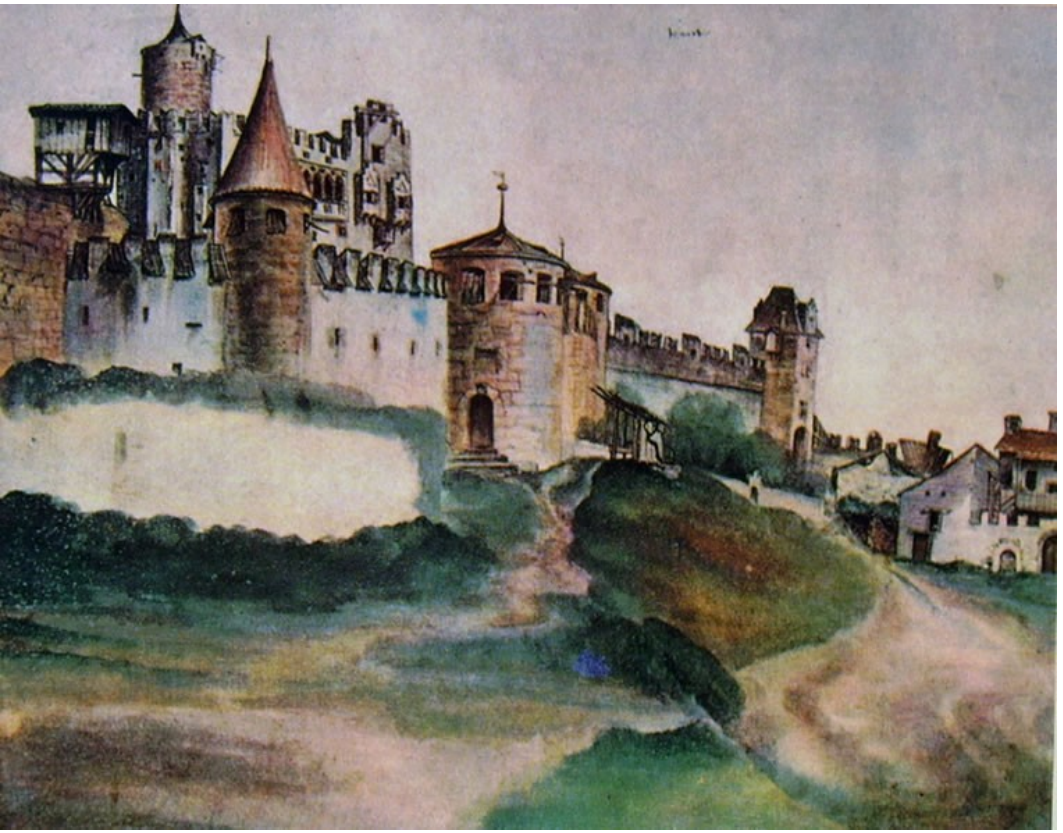
J/ψ production in nucleus-nucleus collisions from SPS to LHC



Ionut Arsene

University of Oslo

ECT* Workshop: New observables in Quarkonium Production, 1 march 2016

J/ψ measurements in AA collisions

- SPS-CERN: $\sqrt{s_{NN}}$=17 GeV
  - NA38, NA50, NA60 Collaborations
  - S-U, In-In, Pb-Pb
- RHIC-BNL: $\sqrt{s_{NN}}$=39,63,200 GeV
  - PHENIX and STAR Collaborations
  - Cu-Cu, Cu-Au, Au-Au, U-U
- LHC-CERN: $\sqrt{s_{NN}}$=2760, 5020 GeV
  - ALICE, ATLAS, CMS and LHCb Collaborations
  - Pb-Pb

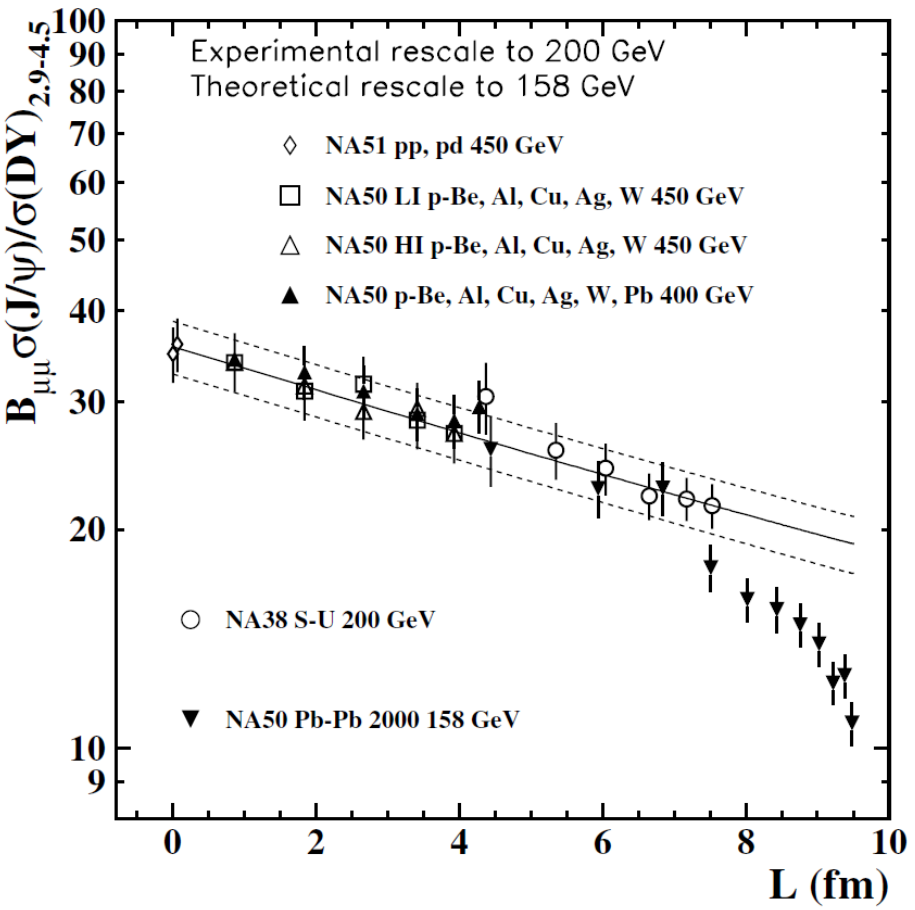
J/ψ sources

- Directly produced J/ψ
- Secondary J/ψ from
  - Prompt decays of higher mass charmonia (χ_C,ψ(2S)): ~40%
  - Non-prompt decays of beauty hadrons: ~10%
- J/ψ nuclear modification affected by feed-down if the nuclear modification of the feeding states is different wrt J/ψ
- Feed-down corrections typically NOT performed for experimental results

SPS (17 GeV)

J/ψ suppression at SPS

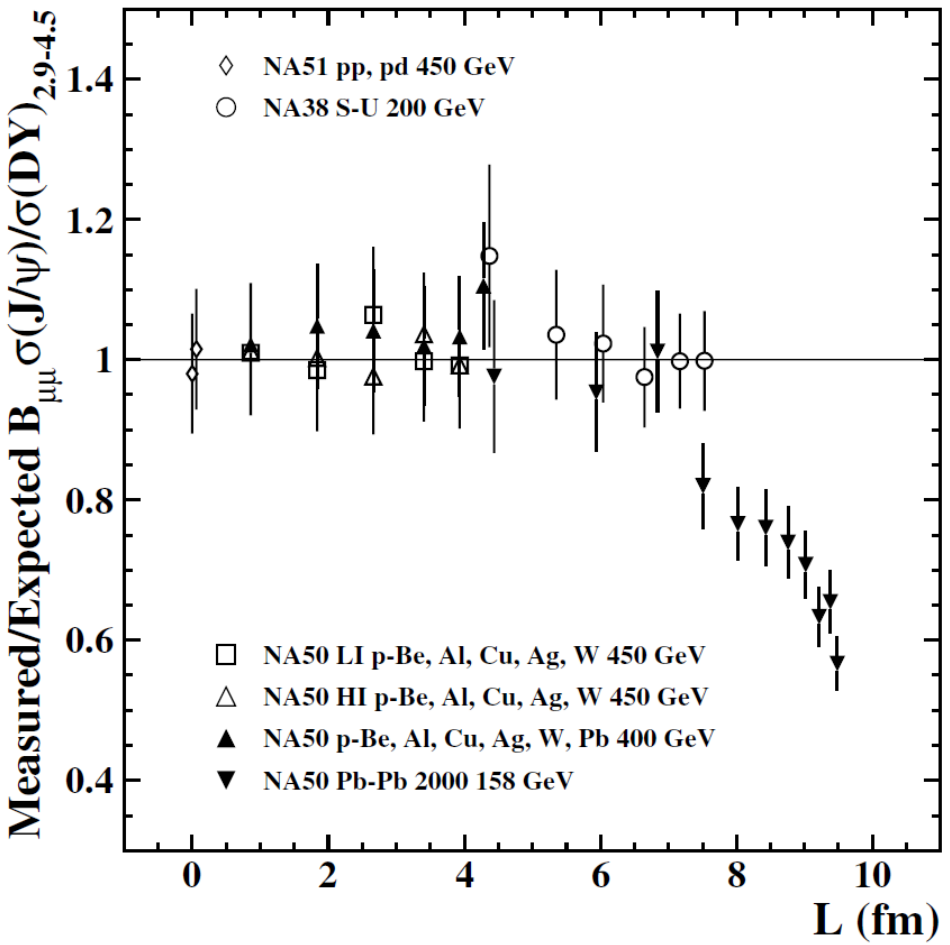
NA50 EPJC39 (2005) 335



- p-A collision results well reproduced using an effective absorption cross-section σ_{abs} in the (cold) nuclear matter
- Nuclear modifications in nucleus-nucleus collisions:
  - Expected suppression from σ_{abs}
  - Anomalous suppression

J/ψ suppression at SPS

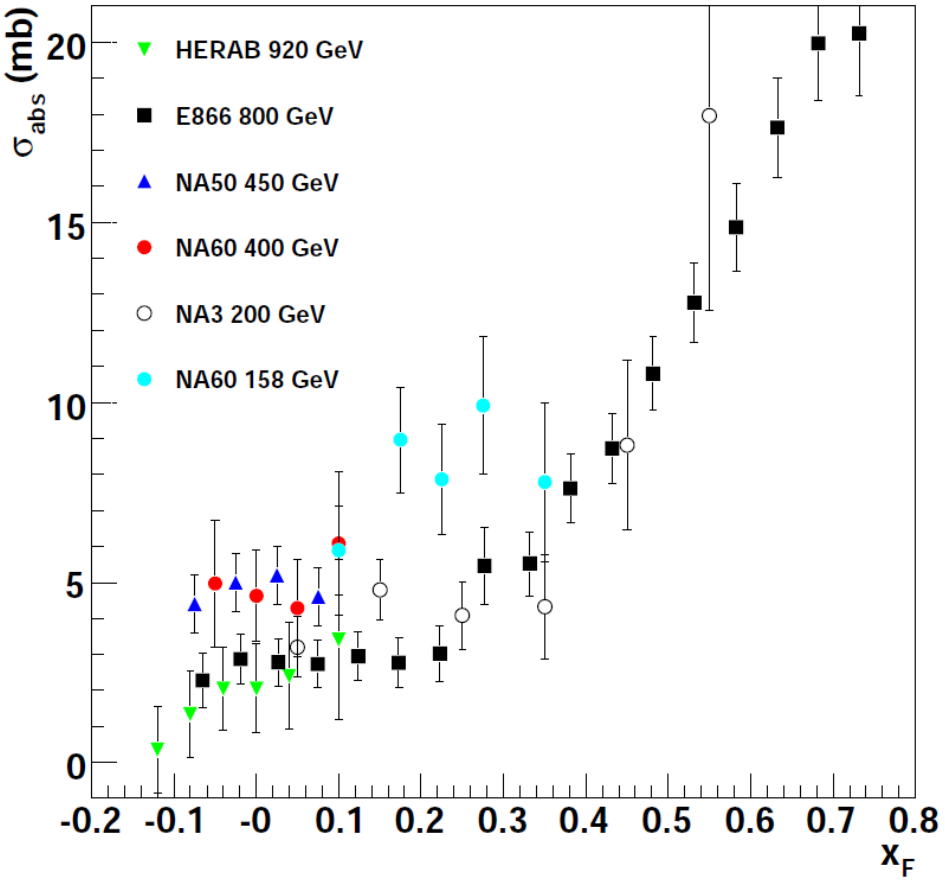
NA50 EPJC39 (2005) 335



- p-A collision results well reproduced using an effective absorption cross-section σ_{abs} in the (cold) nuclear matter
- Nuclear modifications in nucleus-nucleus collisions:
  - Expected suppression from σ_{abs}
  - Anomalous suppression
- First NA50 results indicated a sizable anomalous suppression for the J/ψ production in Pb-Pb at $\sqrt{s_{NN}}$=17GeV
- Caveat! Expected suppression was based on p-A collisions at a beam energy of 400/450 GeV

J/ψ suppression at SPS

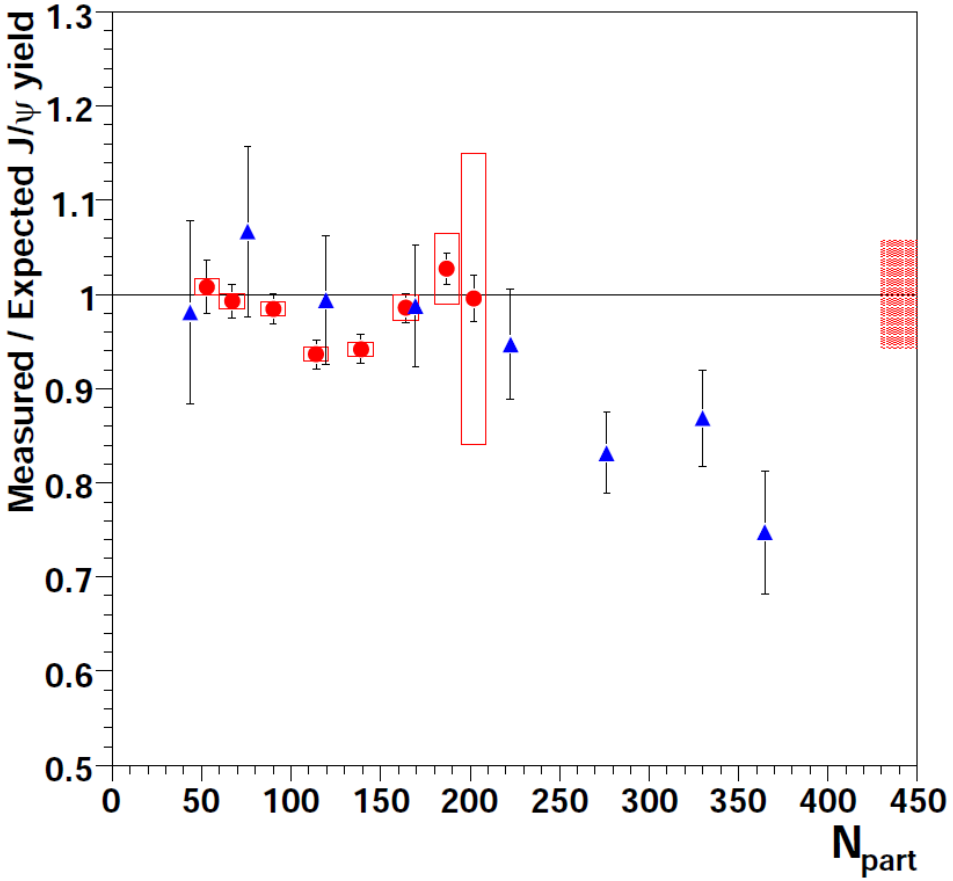
NA60 Nucl.Phys.A (2009) 345



- It was shown that σ_{abs} depends strongly on the p-A collision energy and it is significantly larger at a beam energy of 158 GeV compared to 400 GeV

J/ψ suppression at SPS

NA60 Nucl.Phys.A (2009) 345

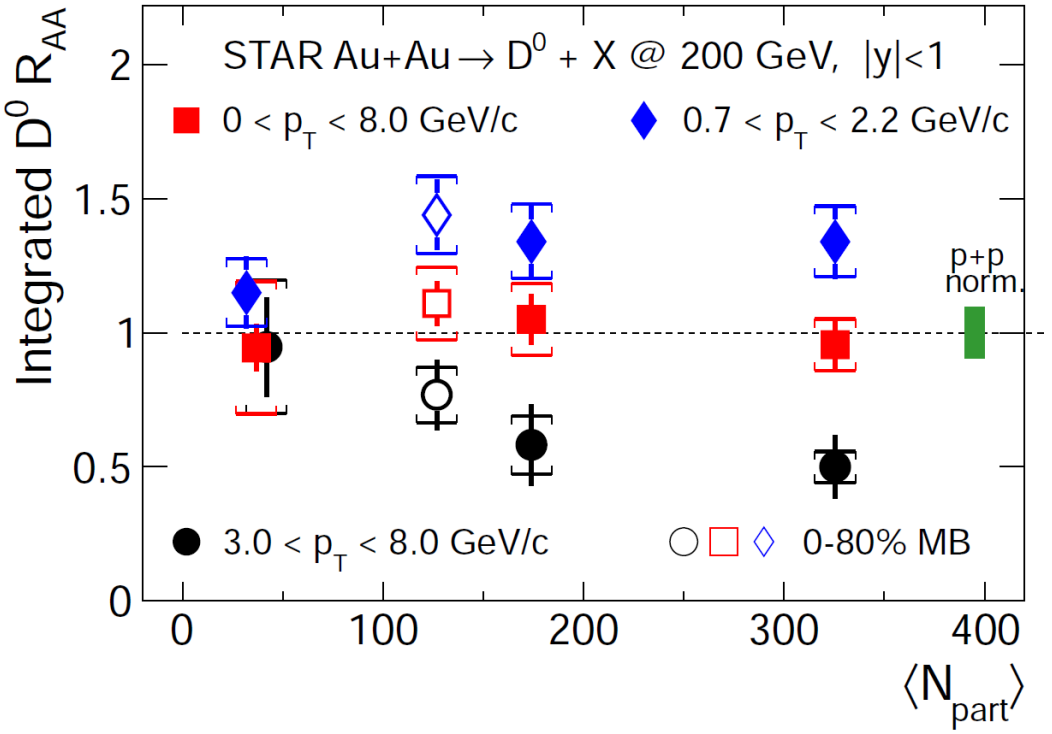


- It was shown that σ_{abs} depends strongly on the p-A collision energy and it is significantly larger at a beam energy of 158 GeV compared to 400 GeV
- Anomalous J/psi suppression still remaining in central Pb-Pb collisions even after the update of σ_{abs}

RHIC (200 GeV)

Open charm

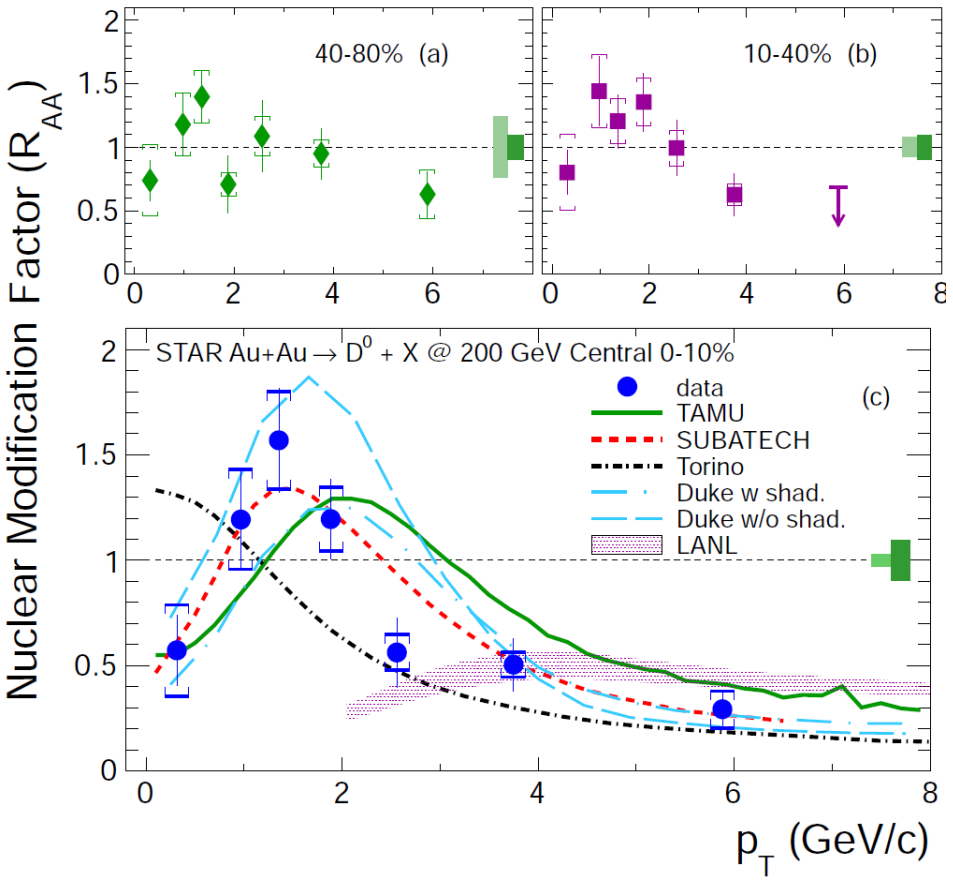
STAR arXiv:1404.6185



- Integrated D^0-meson production proportional to the number of binary collisions
  - Negligible shadowing effects?

Open charm

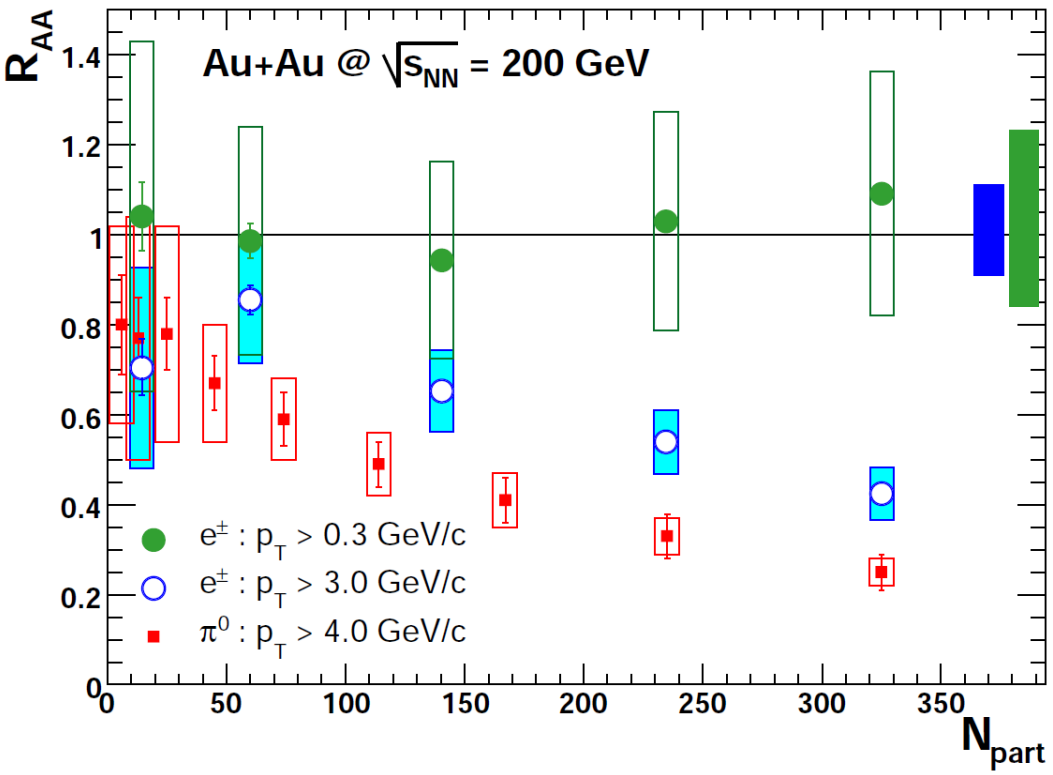
STAR arXiv:1404.6185



- Integrated D^0-meson production proportional to the number of binary collisions
  - Negligible shadowing effects?
- However, the D^0 p_T distribution is modified wrt pp collisions
  - Strong suppression at high pT (energy loss)
  - Enhancement at 1-2 GeV/c (charm conservation)

Heavy flavor electrons (HFE)

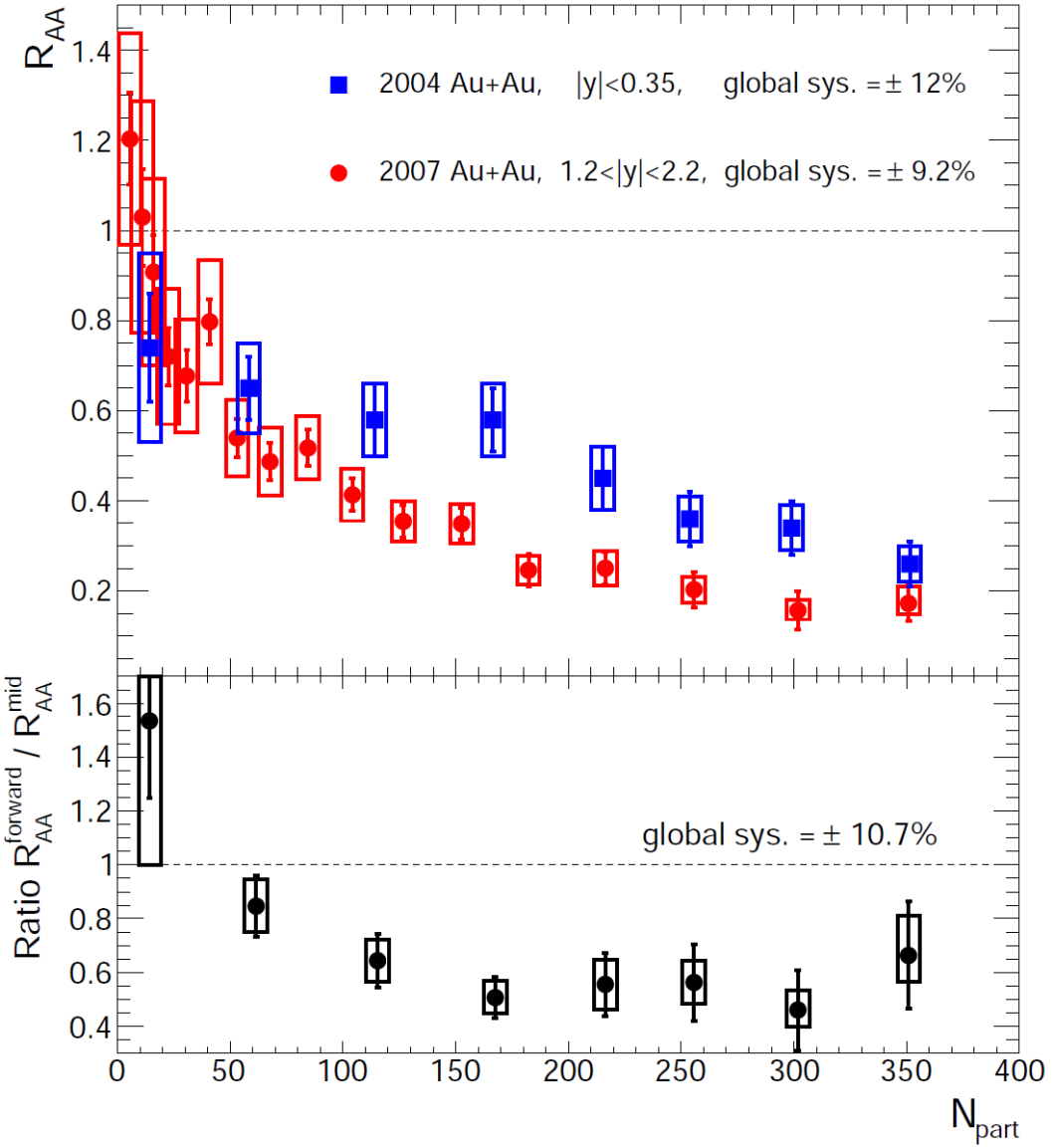
PHENIX arXiv:0611018



- Integrated D^0-meson production proportional to the number of binary collisions
  - Negligible shadowing effects?
- However, the D^0 p_T distribution is modified wrt pp collisions
  - Strong suppression at high pT (energy loss)
  - Enhancement at 1-2 GeV/c (charm conservation)
- Qualitatively similar observations for p_T integrated heavy flavor electrons

J/ψ suppression in Au-Au collisions

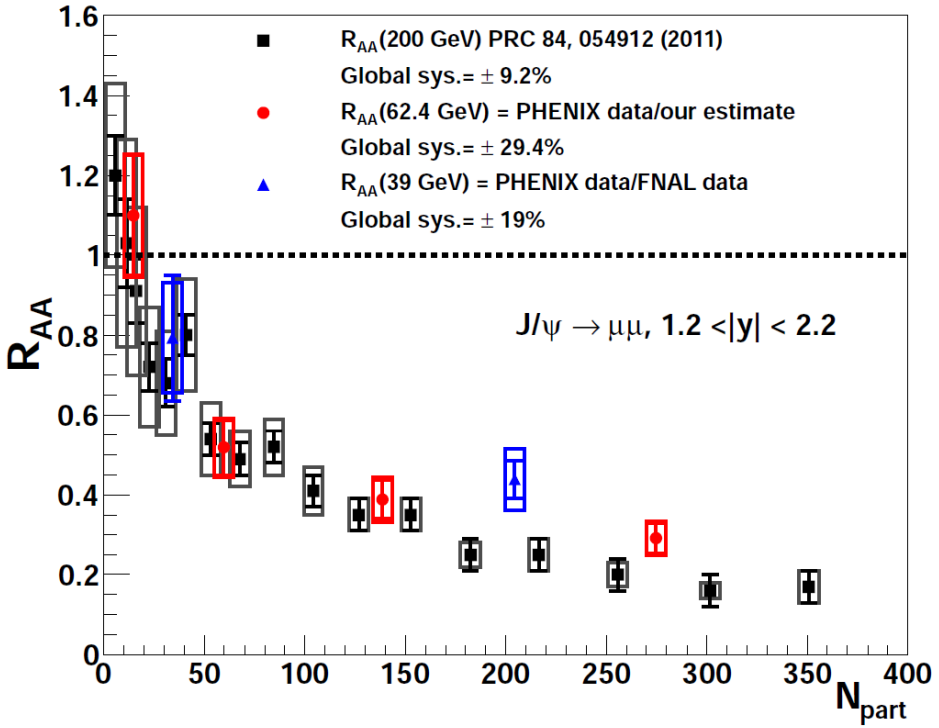
PHENIX arxiv:1103.6269



- Strong suppression both at mid- and forward-rapidity

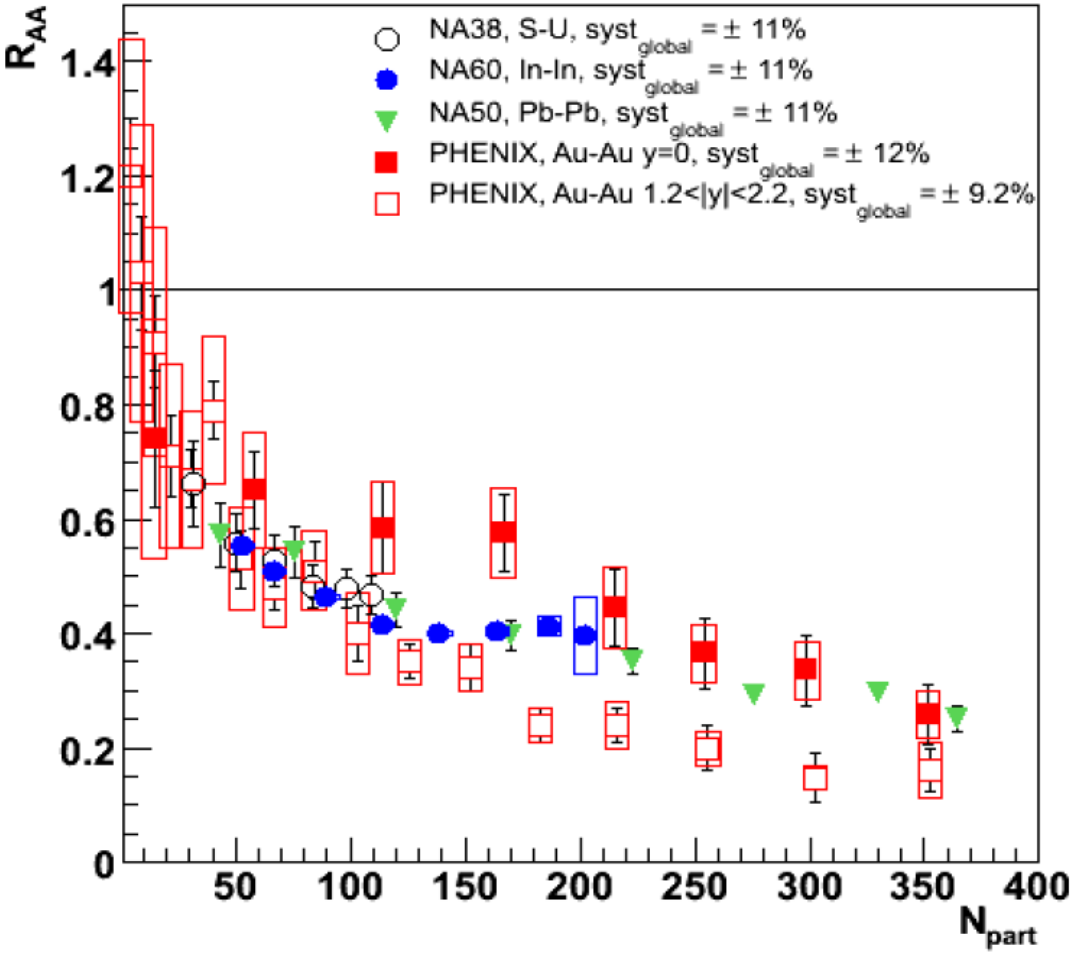
J/ψ suppression in Au-Au collisions

PHENIX arXiv:1208.2251



- Strong suppression both at mid- and forward-rapidity
- Very similar suppression patterns seen at lower RHIC energies

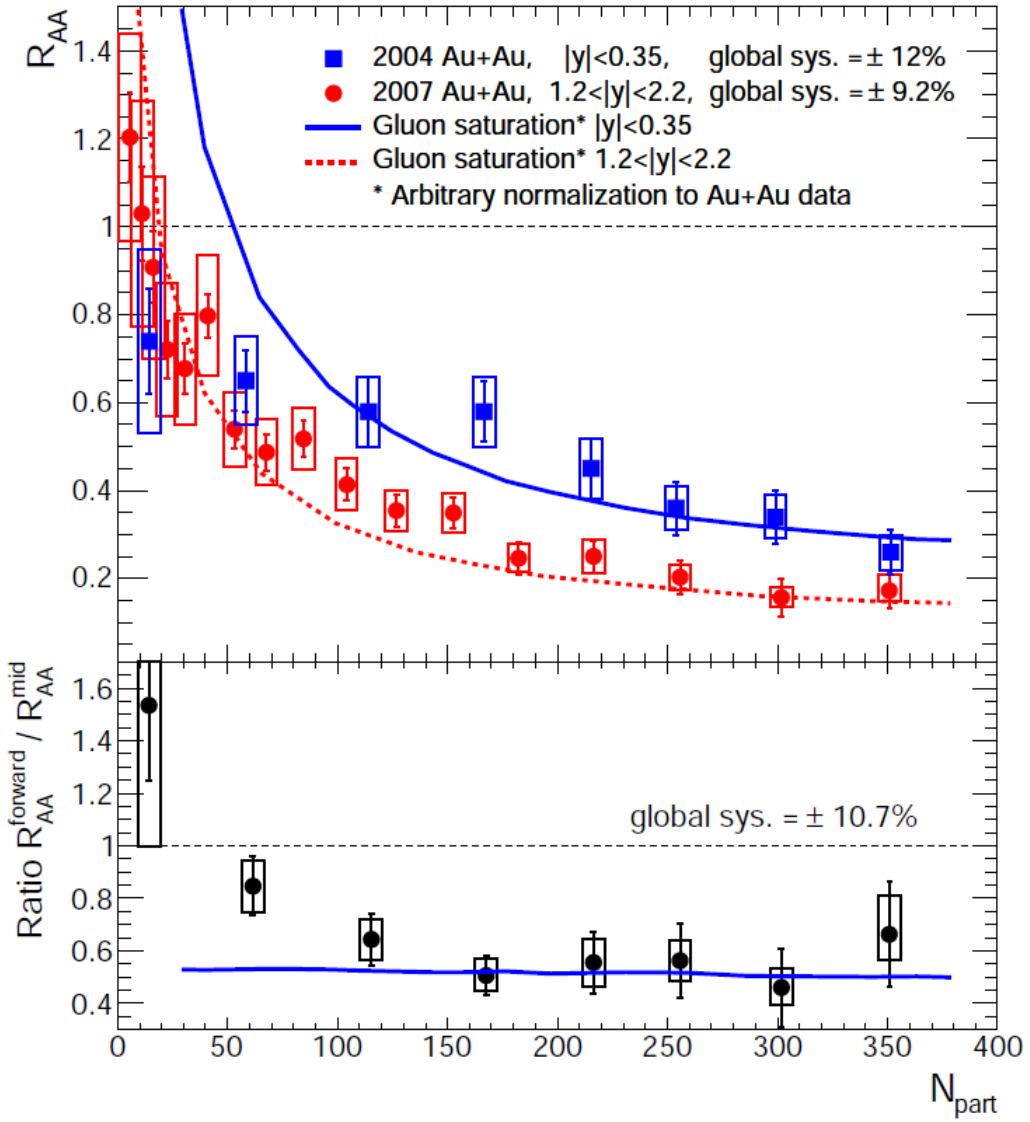
J/ψ suppression in Au-Au collisions



- Strong suppression both at mid- and forward-rapidity
- Very similar suppression patterns seen at lower RHIC energies
- And also at SPS !

J/ψ suppression in Au-Au collisions

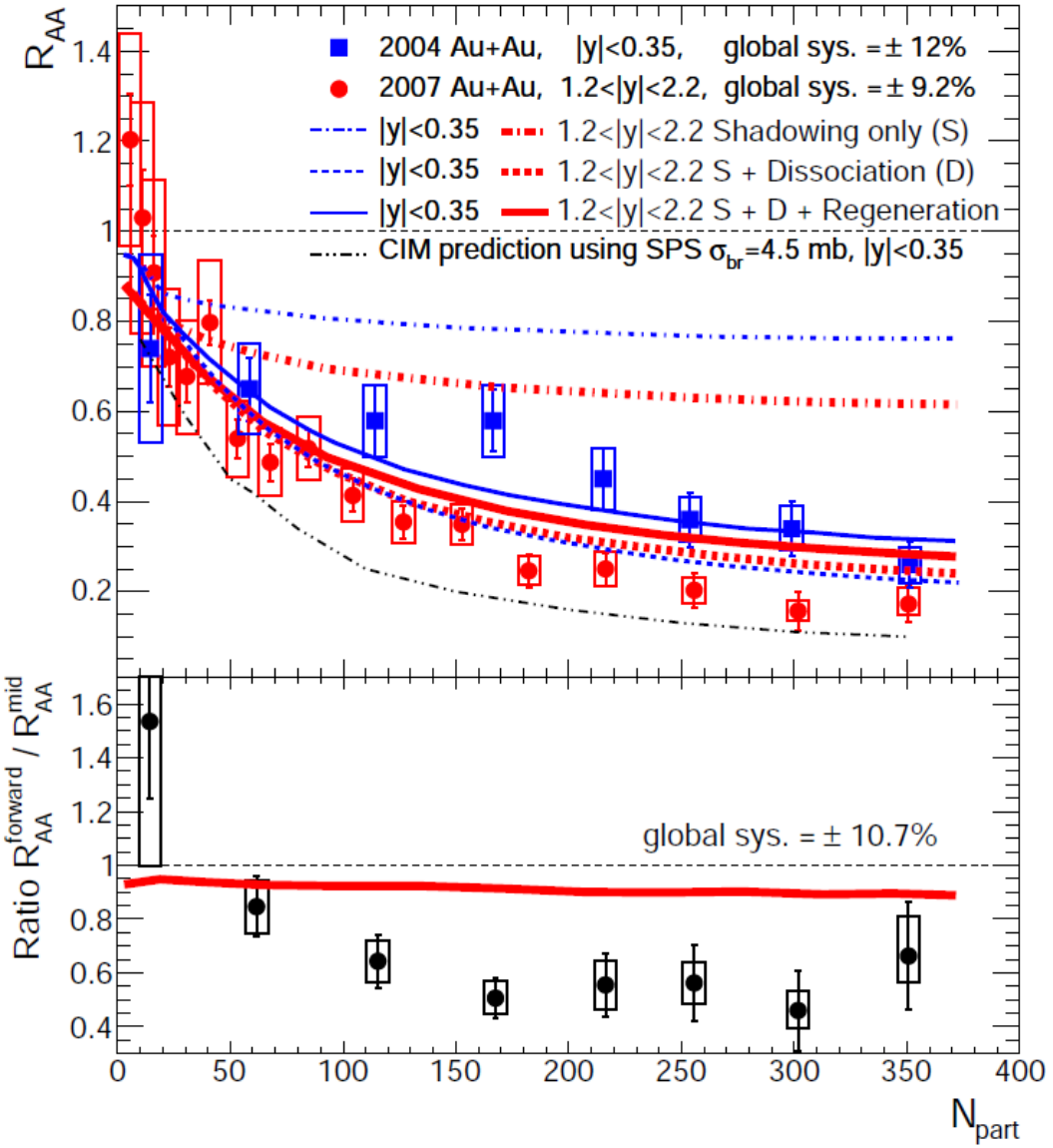
PHENIX arxiv:1103.6269



- Strong suppression both at mid- and forward-rapidity
- Significantly more suppression at forward rapidity wrt mid-rapidity
- Rapidity dependence could be explained by a CGC calculation (Kharzeev et al.), but not the overall level of suppression
  - Calculation scaled to match the mid-rapidity results

J/ψ suppression in Au-Au collisions

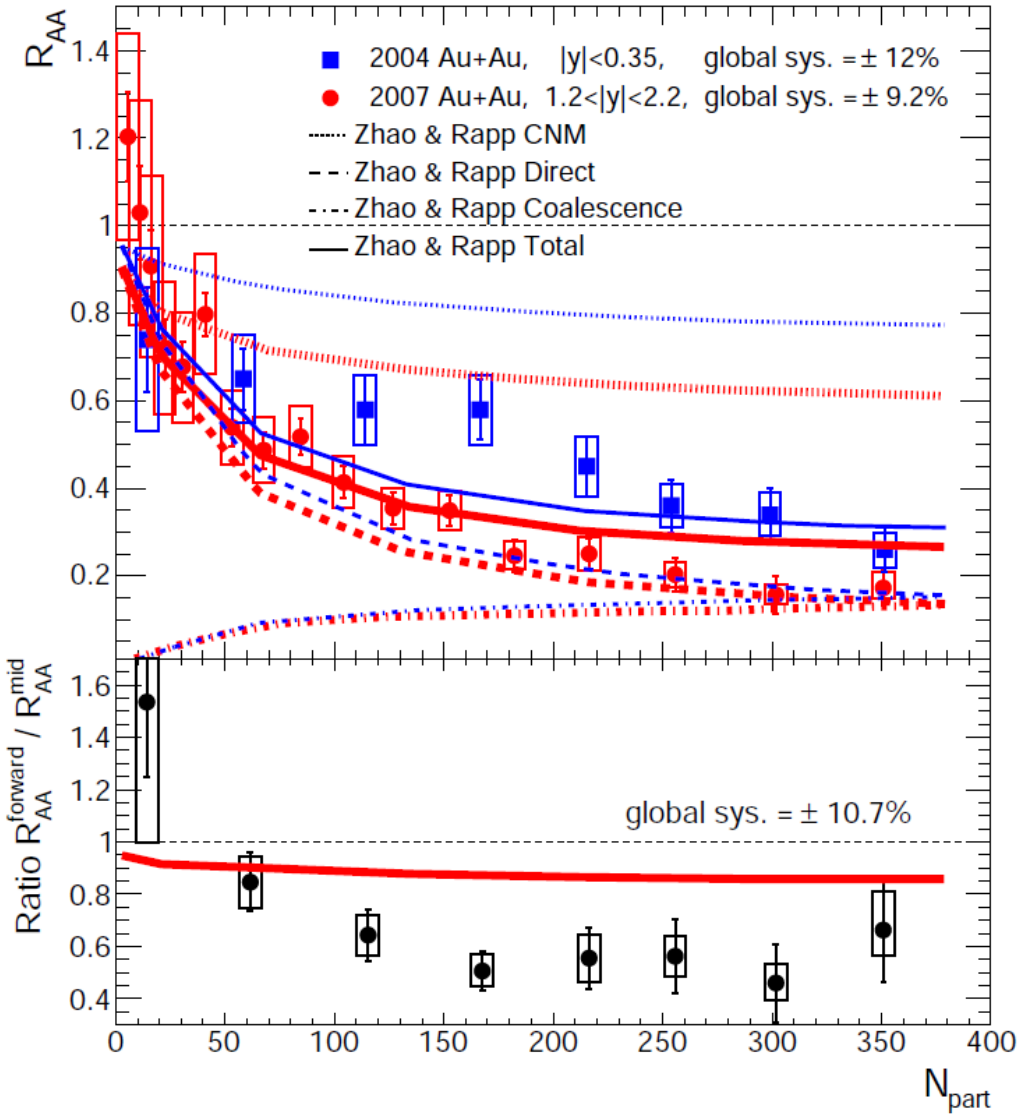
PHENIX arxiv:1103.6269



- Strong suppression both at mid- and forward-rapidity
- Significantly more suppression at forward rapidity wrt mid-rapidity
- Rapidity dependence could be explained by a CGC calculation (Kharzeev et al.), but not the overall level of suppression
- Comover interaction model (Ferreiro et al.) in good agreement with the overall level of suppression but the rapidity dependence is not well reproduced

J/ψ suppression in Au-Au collisions

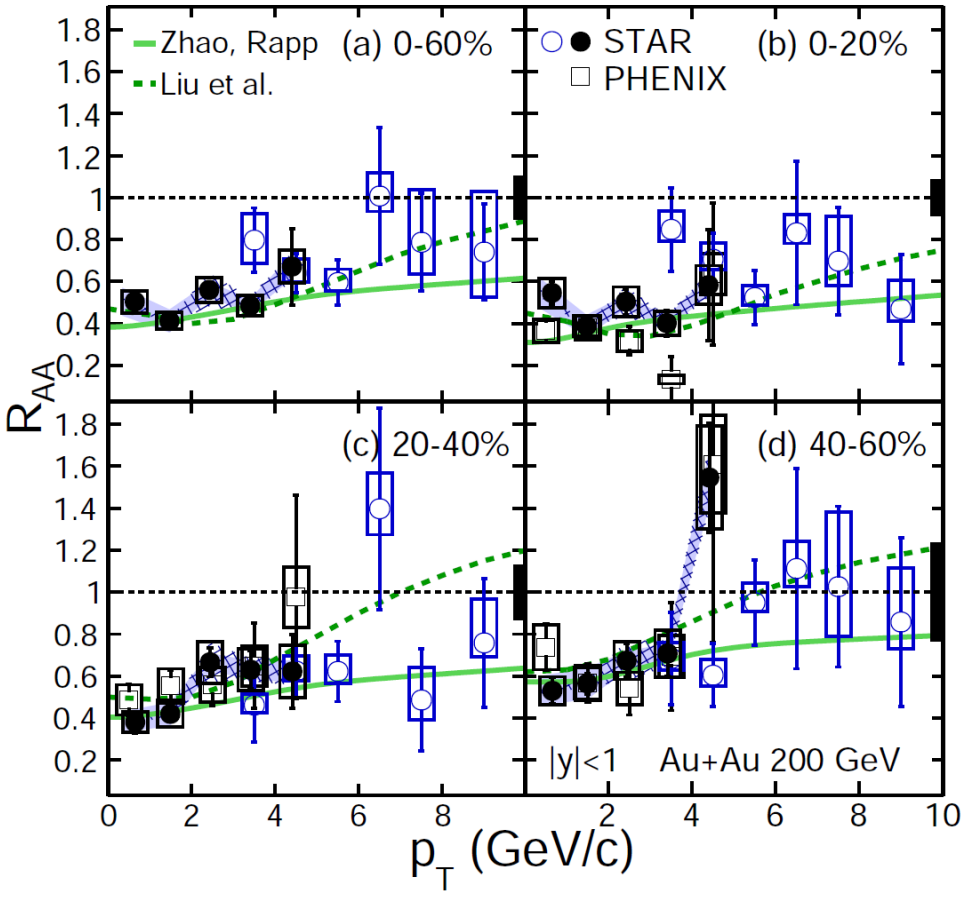
PHENIX arxiv:1103.6269



- Strong suppression both at mid- and forward-rapidity
- Significantly more suppression at forward rapidity wrt mid-rapidity
- Rapidity dependence could be explained by a CGC calculation (Kharzeev et al.), but not the overall level of suppression
- Comover interaction model (CIM) (Ferreiro et al.) in good agreement with the overall level of suppression but the rapidity dependence is not well reproduced
- A transport model approach (Zhao & Rapp) provides similar qualitative description of data as CIM
- Both CIM and transport approaches assume a small contribution from regeneration

p_T dependent J/ψ suppression

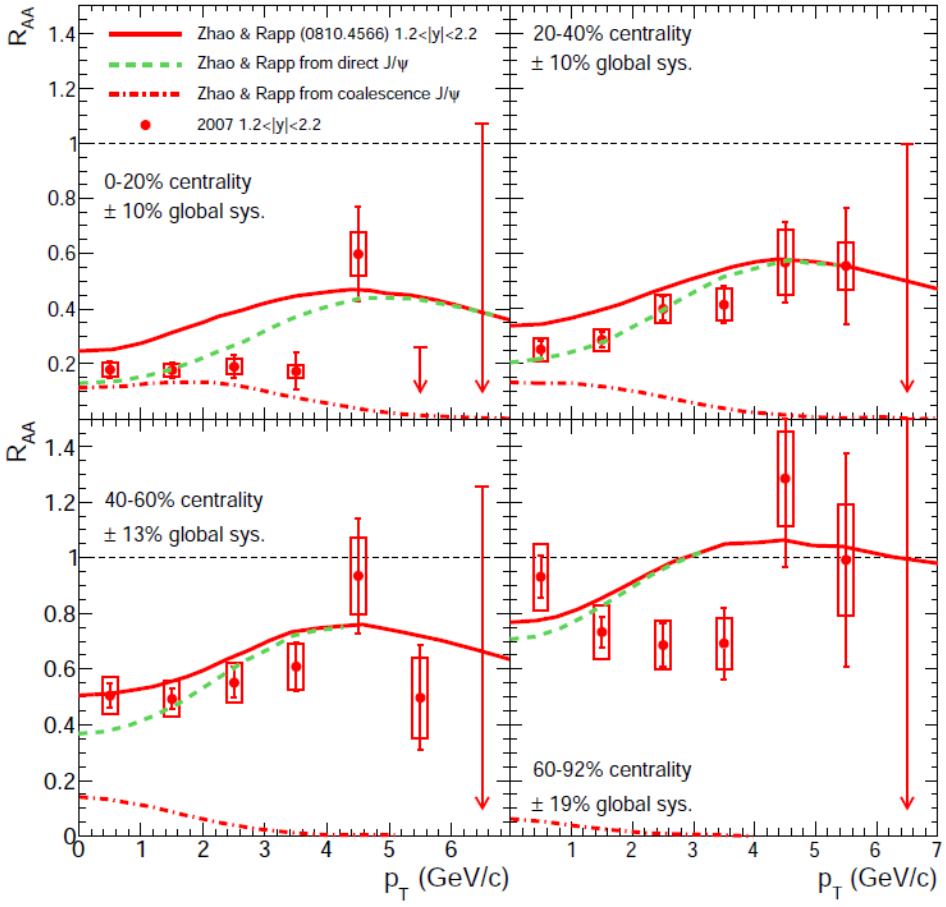
STAR arxiv 1310.3563



- Suppression is strongest at low p_T and decreases at high p_T
- Transport model calculations in good agreement with data

p_T dependent J/ψ suppression

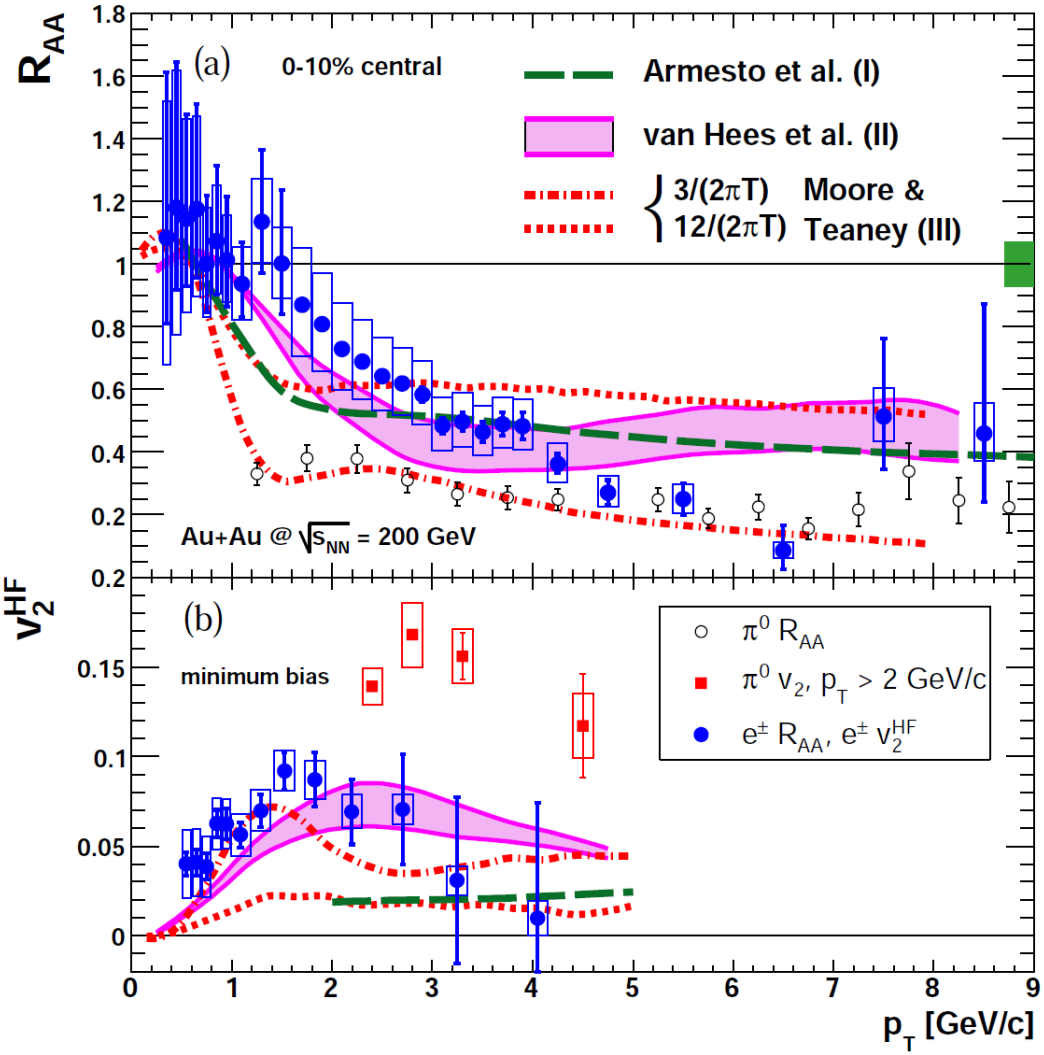
PHENIX arxiv:1103.6269



- Suppression is strongest at low p_T and decreases at high p_T
- Transport model calculations in good agreement with data
- Regeneration component contributes mainly at low p_T, as naively expected

Elliptic flow

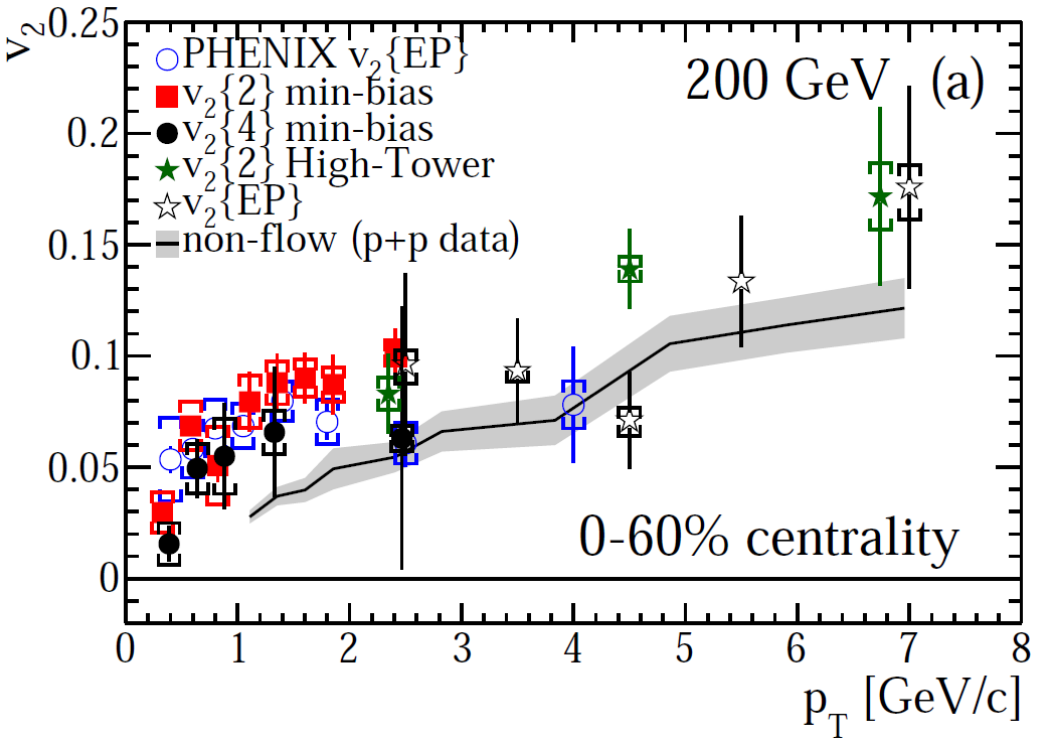
PHENIX arXiv:0611018



- Significant HFE v_2 observed at 200 GeV by PHENIX

Elliptic flow

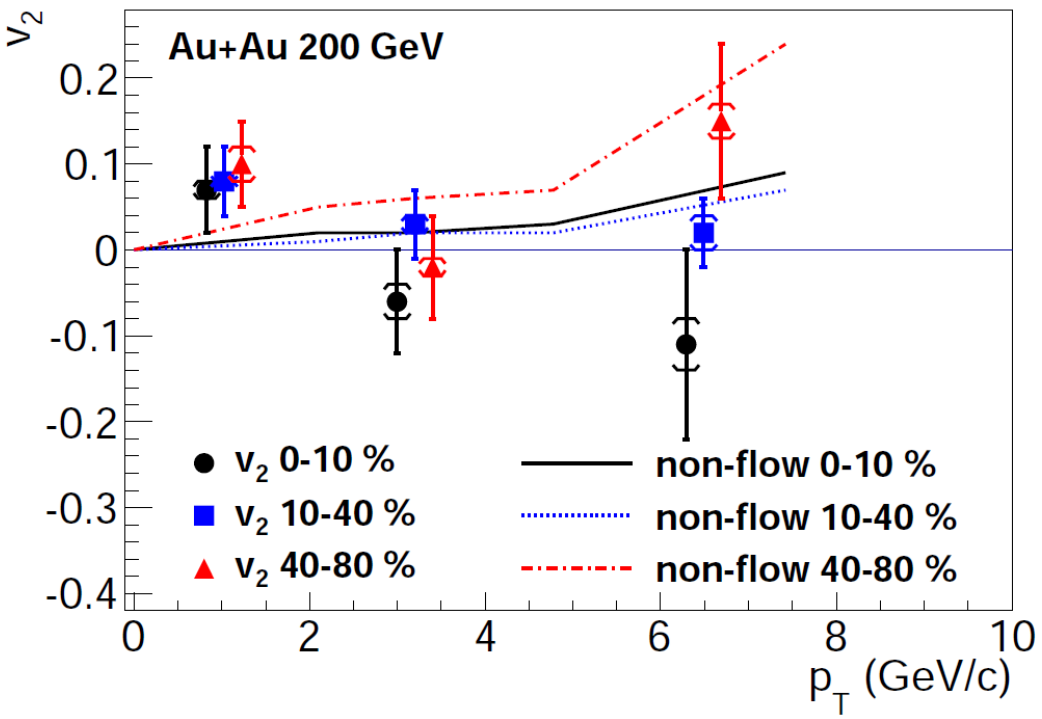
STAR arXiv:1405.6348



- Significant HFE v_2 observed at 200 GeV by PHENIX
- Similar observation done by STAR
  - Strong non-flow corrections affect the flow measurements but a remaining non-zero “true” flow is suggested by the data
- Hint of heavy quark thermalization?
- Does the J/ψ inherit any of this flow?

Elliptic flow

STAR arXiv: 1212.3304

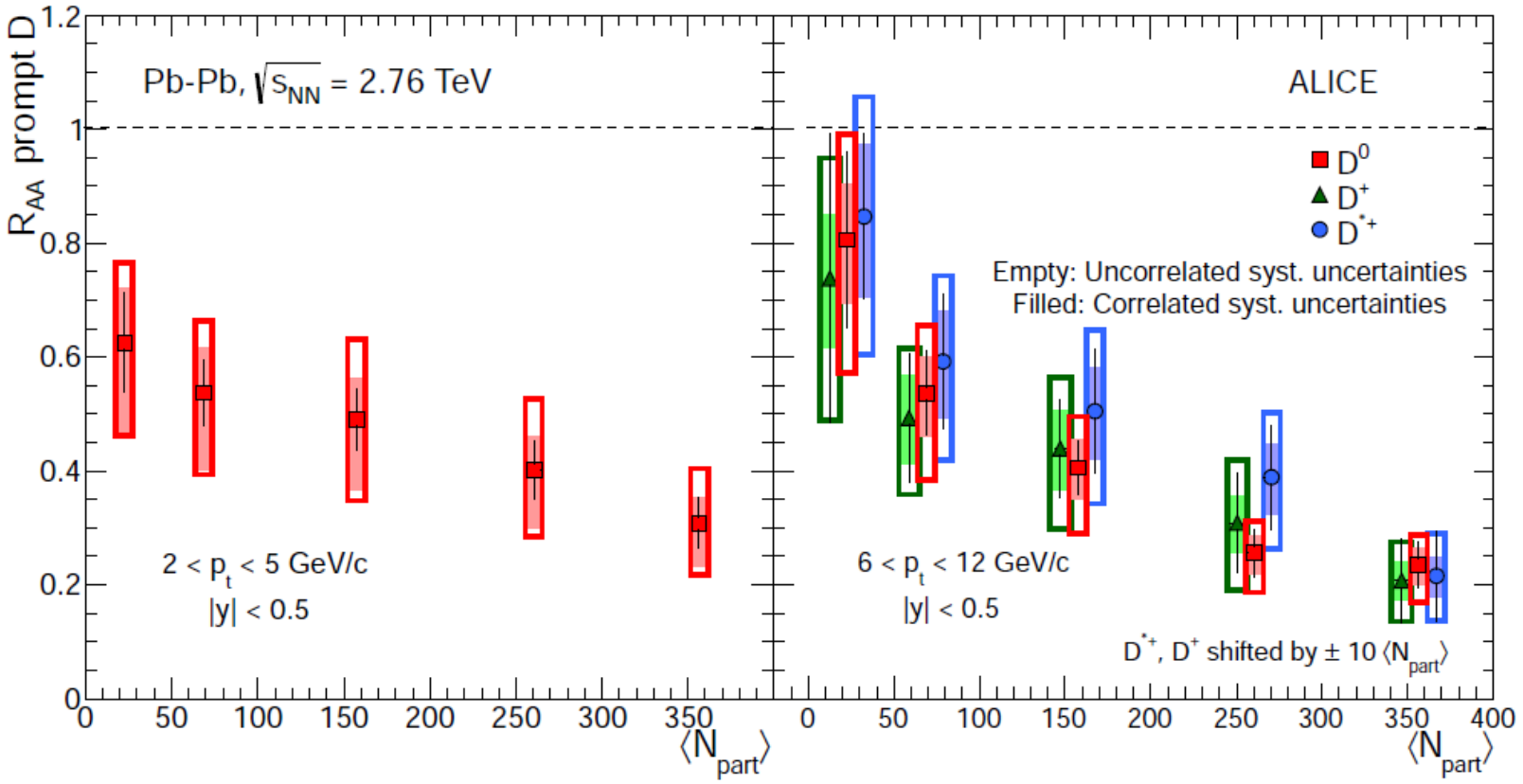


- Significant HFE v_2 observed at 200 GeV by PHENIX
- Similar observation done by STAR
  - Strong non-flow corrections affect the flow measurements but a remaining non-zero “true” flow is suggested by the data
- J/ψ v_2 results are compatible with no elliptic flow but with large uncertainties

LHC (2.76 TeV)

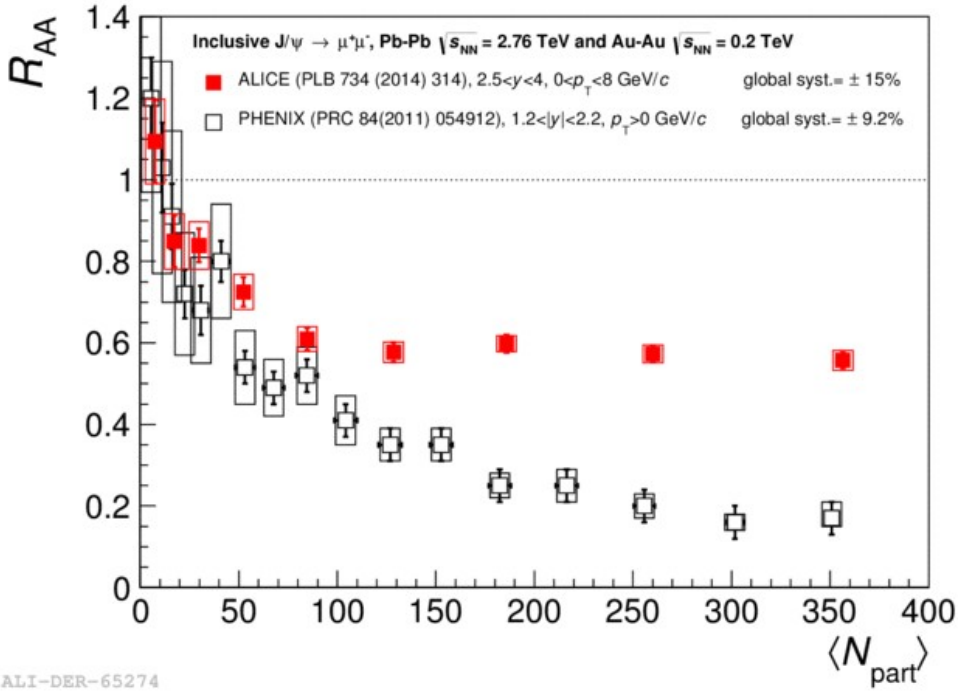
Open charm suppression vs centrality

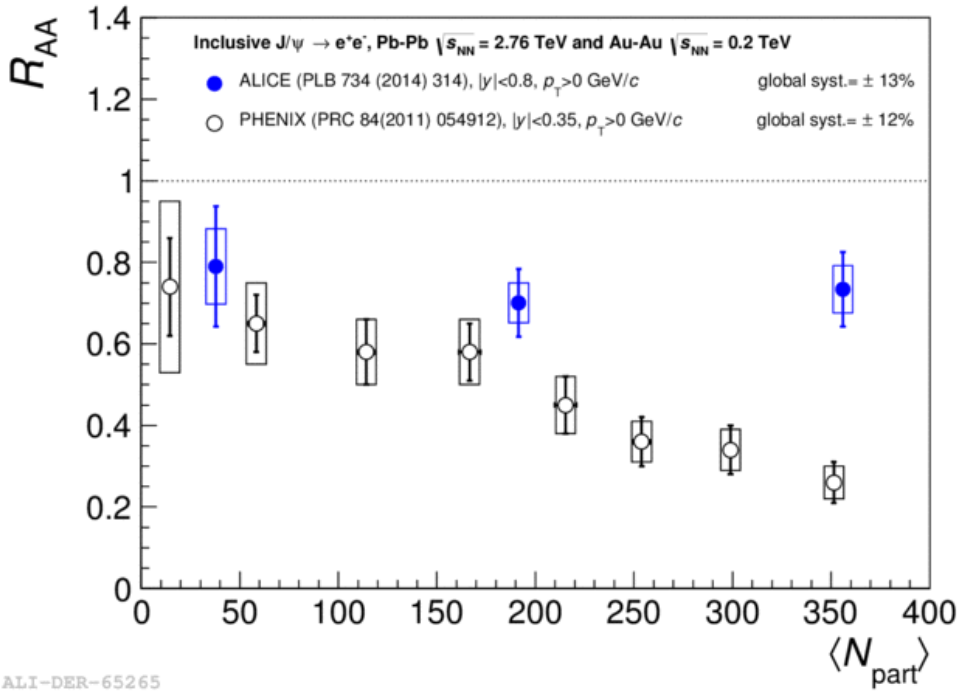
ALICE JHEP1209 (2012) 112



- Fully p_T integrated open charm results not available yet
- Strong suppression of D mesons for p_T>2 GeV/c observed

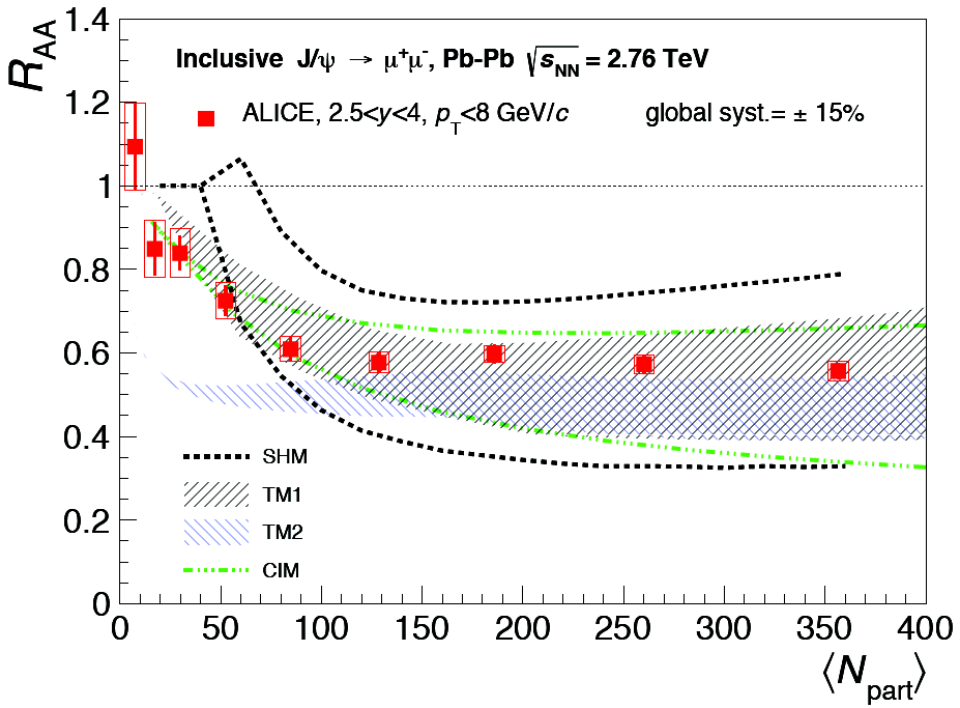
J/ψ suppression vs centrality

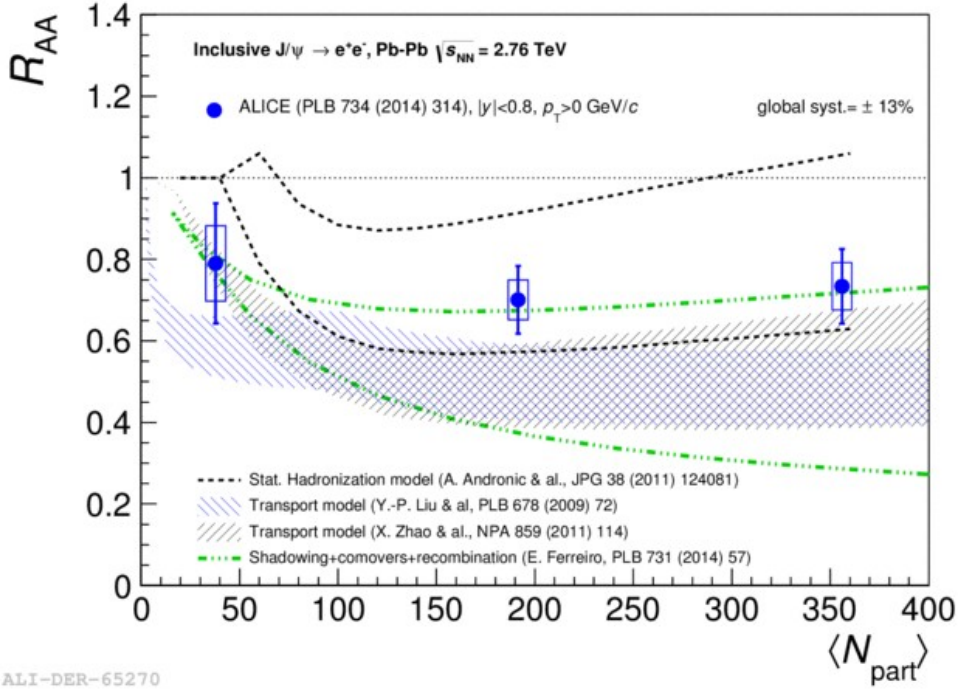




- Much less suppression in central and semi-central collisions wrt to the lower energy measurements
- Indication of a lower suppression at mid-rapidity compared to forward rapidity

J/ψ suppression vs centrality



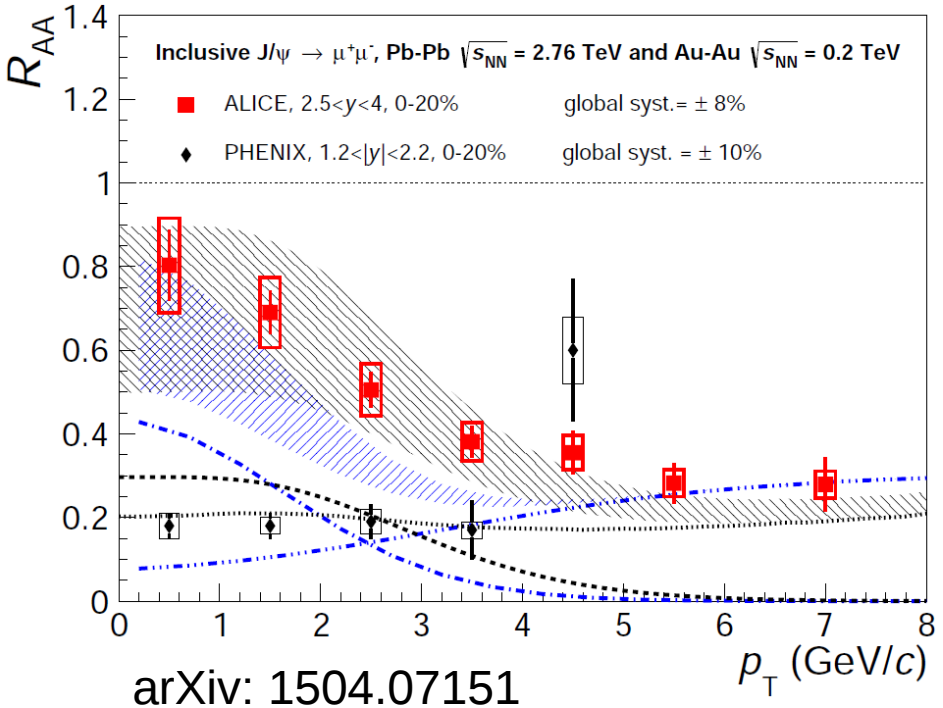


- Much less suppression in central and semi-central collisions wrt to the lower energy measurements
- Indication of a lower suppression at mid-rapidity compared to forward rapidity
- Models which implement a regeneration component are in agreement with data
- Model uncertainties are dominated by the poor knowledge of the total $c\bar{c}$ cross-section / CNM effects

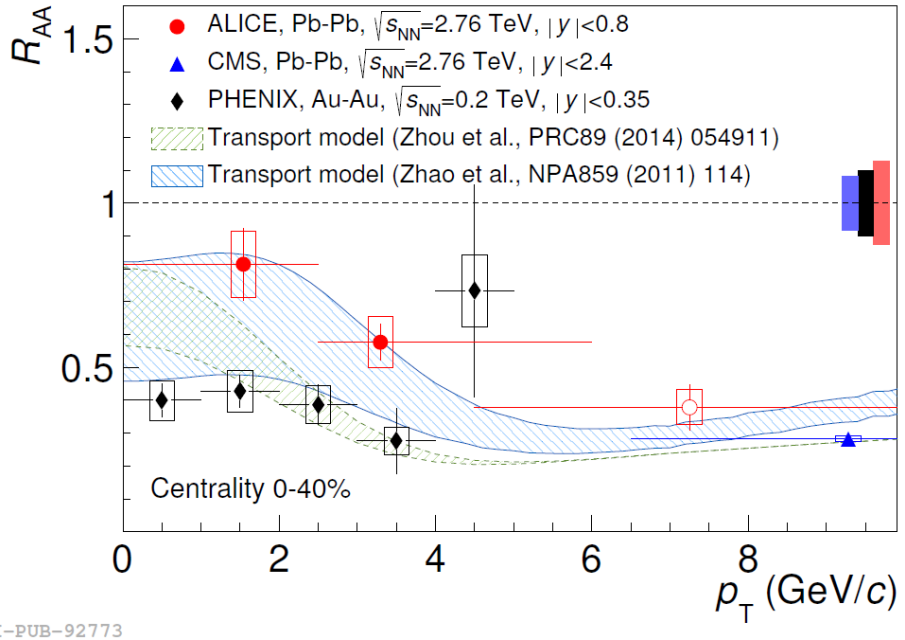
SHM: A.Andronic et al., JPG38 (2011)12408
TM1: X.Zhao et al.,NPA859 (2011) 114
TM2: Y.-P.Liu et al., PLB578 (2009) 72
CIM: E.Ferreiro, PLB731 (2014) 57

J/ψ suppression vs p_T

arXiv: 1506.08804

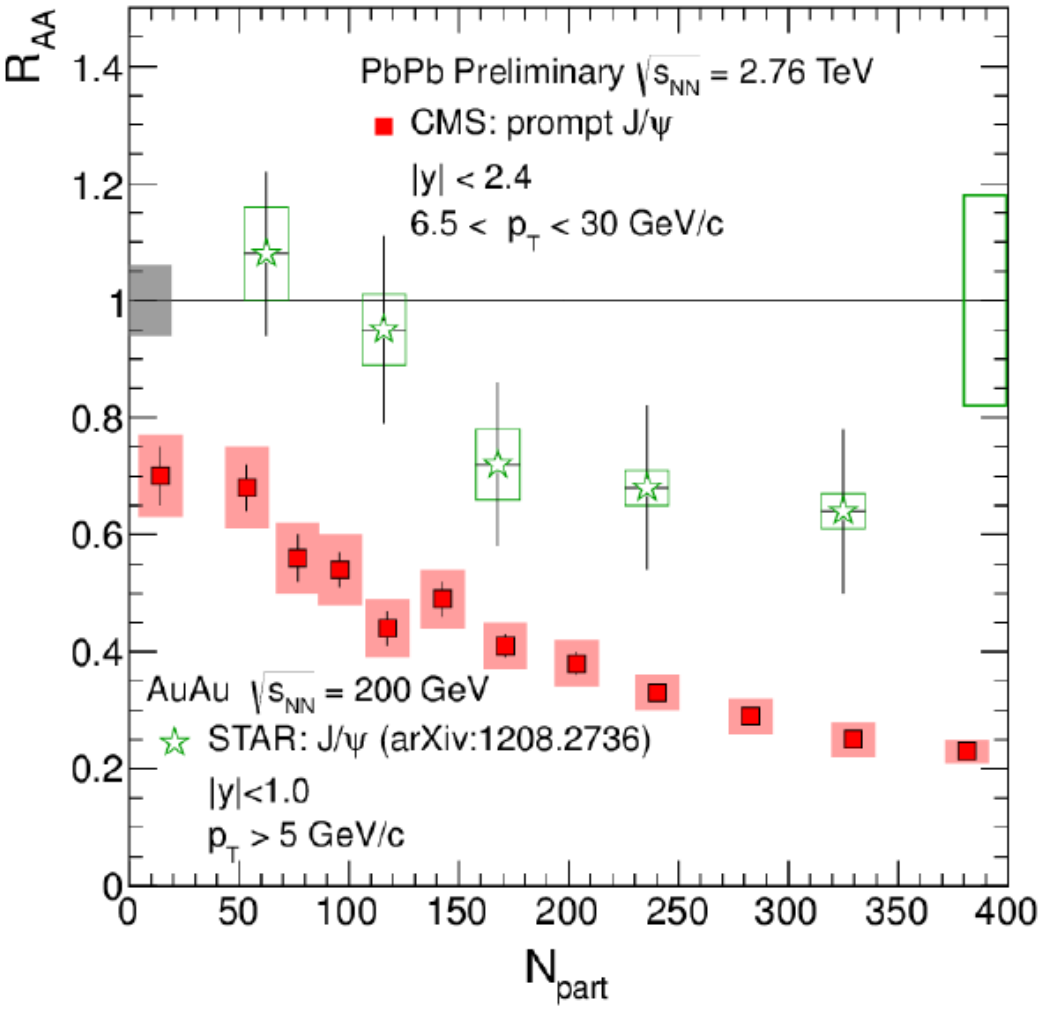


arXiv: 1504.07151



- Striking difference between LHC and RHIC data at low p_T
- Clear evidence for (re)generation ?
- Transport model calculations describe qualitatively the data

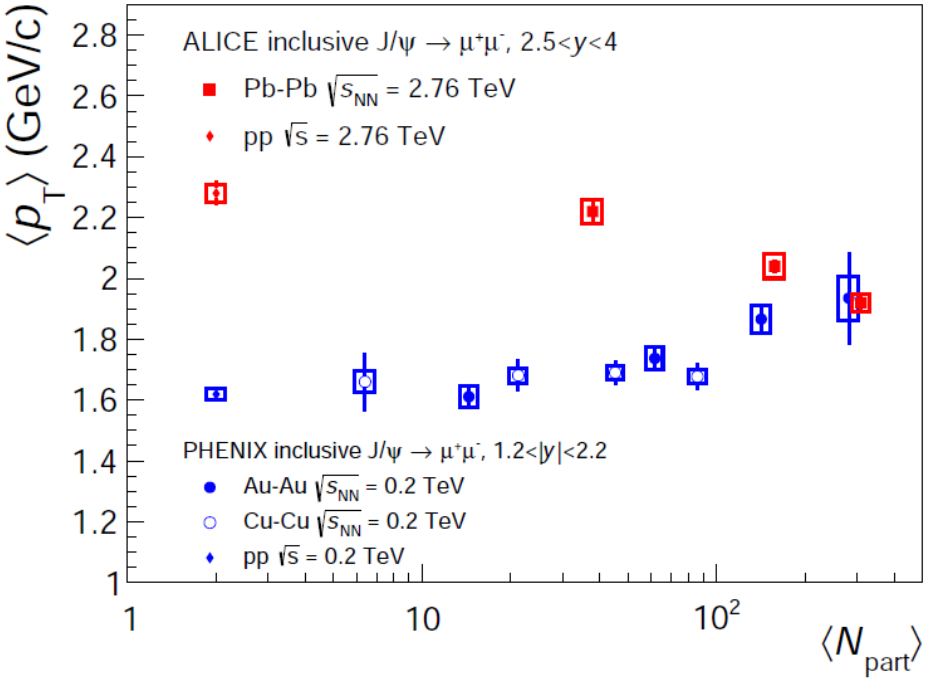
J/ψ suppression vs p_T

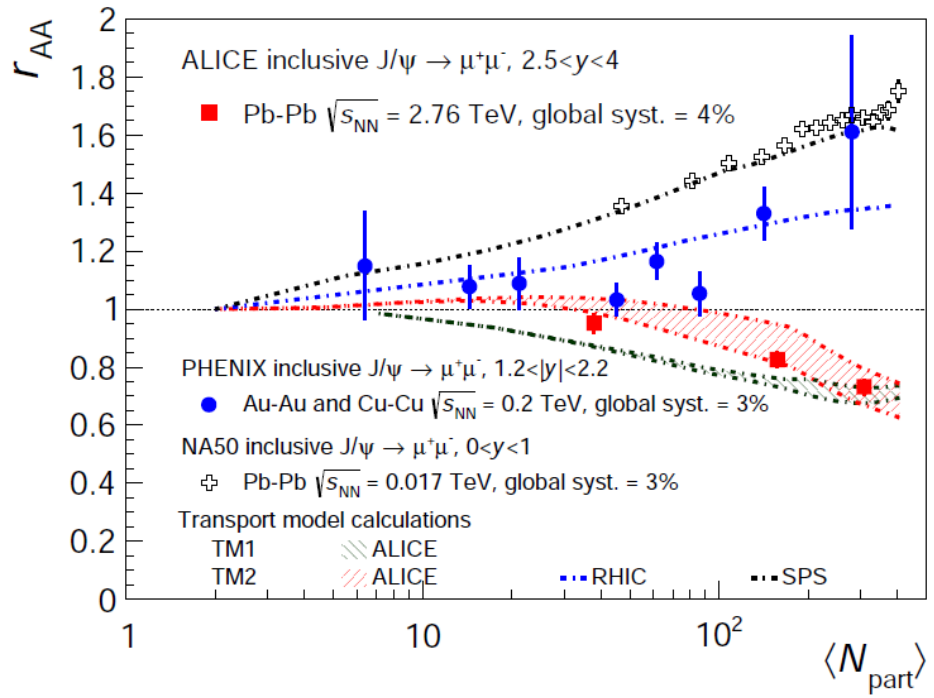


- Striking difference between LHC and RHIC data at low p_T
- Clear evidence for (re)generation ?
- Transport model calculations describe qualitatively the data
- At high p_T the suppression is stronger at LHC wrt RHIC

Modification of the J/ψ p_T distribution

arXiv: 1506.08804

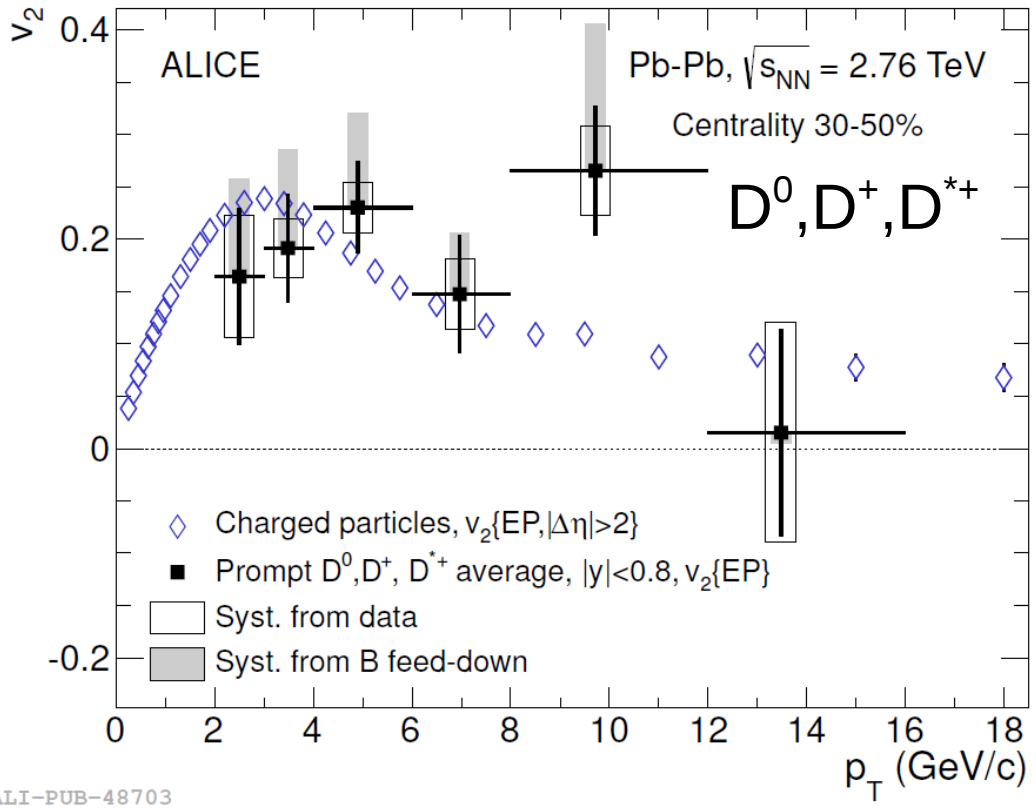




- <pT> drops with increasing collision centrality at LHC while it grows at RHIC
- $r_{AA} = \langle p_T^2 \rangle_{AA} / \langle p_T^2 \rangle_{pp}$
- r_{AA} (p_T distribution broadeness) decreases with increasing centrality at LHC while it strongly grows at SPS

Elliptic flow

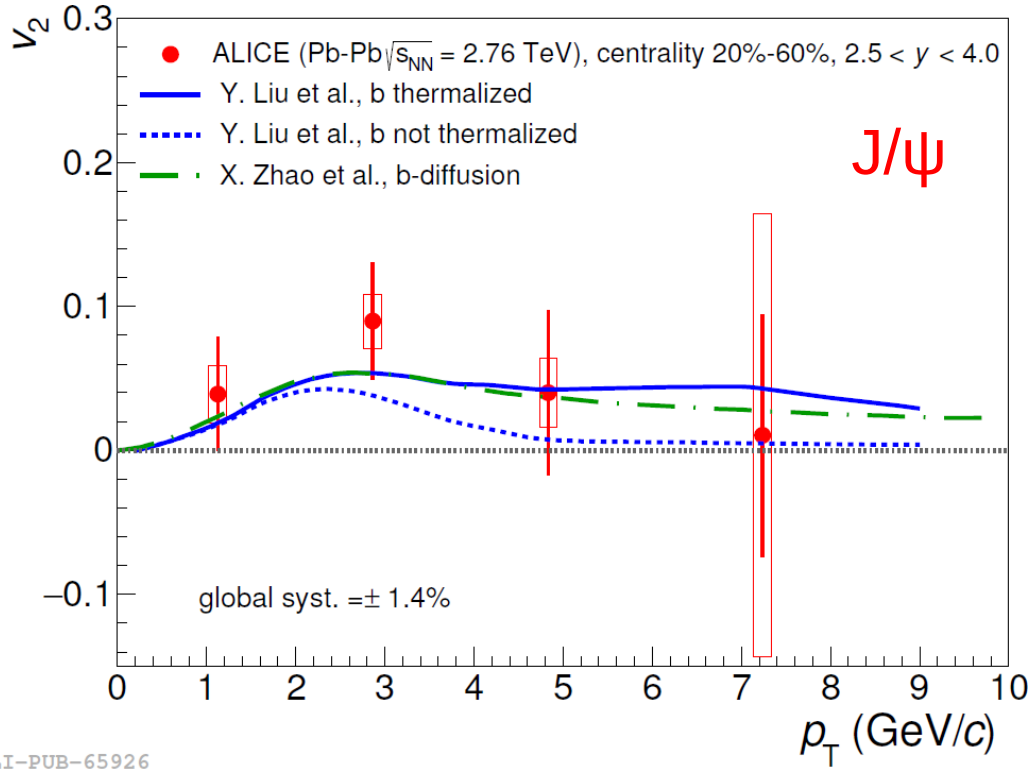
PRL111 (2013) 102301



- Strong elliptic flow observed for light particles and D mesons

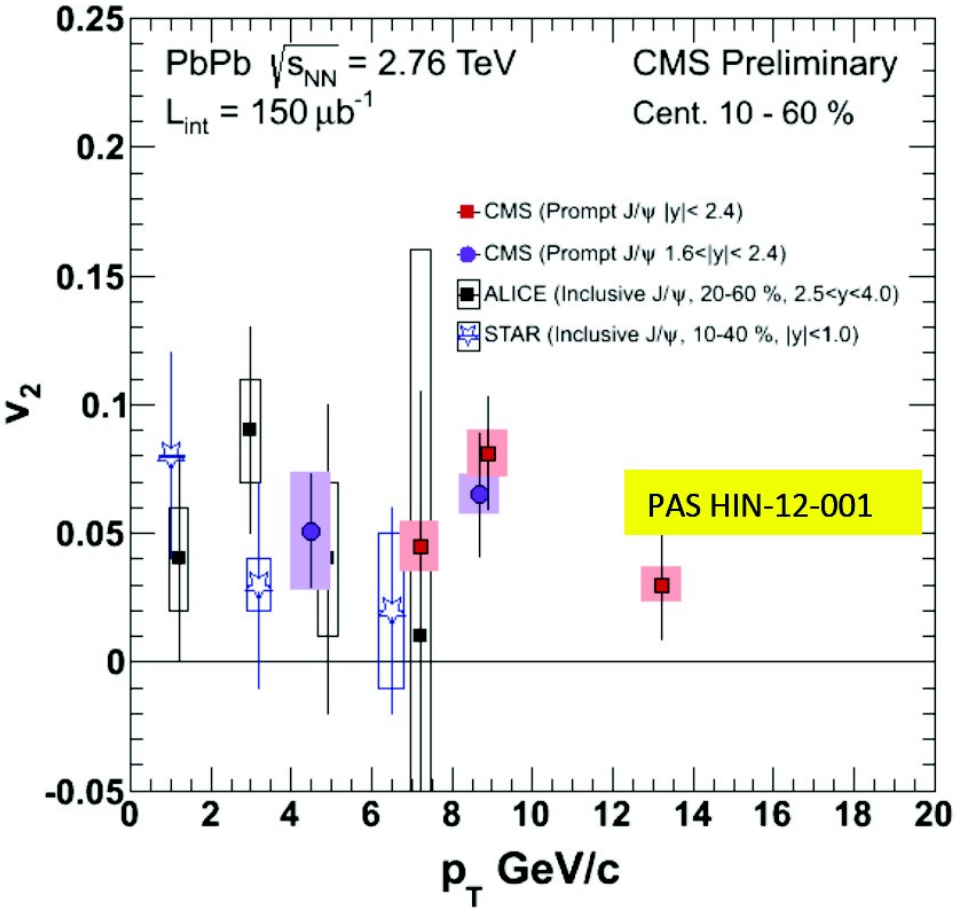
Elliptic flow

PRL111 (2013) 162301



- Strong elliptic flow observed for light particles and D mesons
- Hint of non-zero elliptic flow ?

Elliptic flow



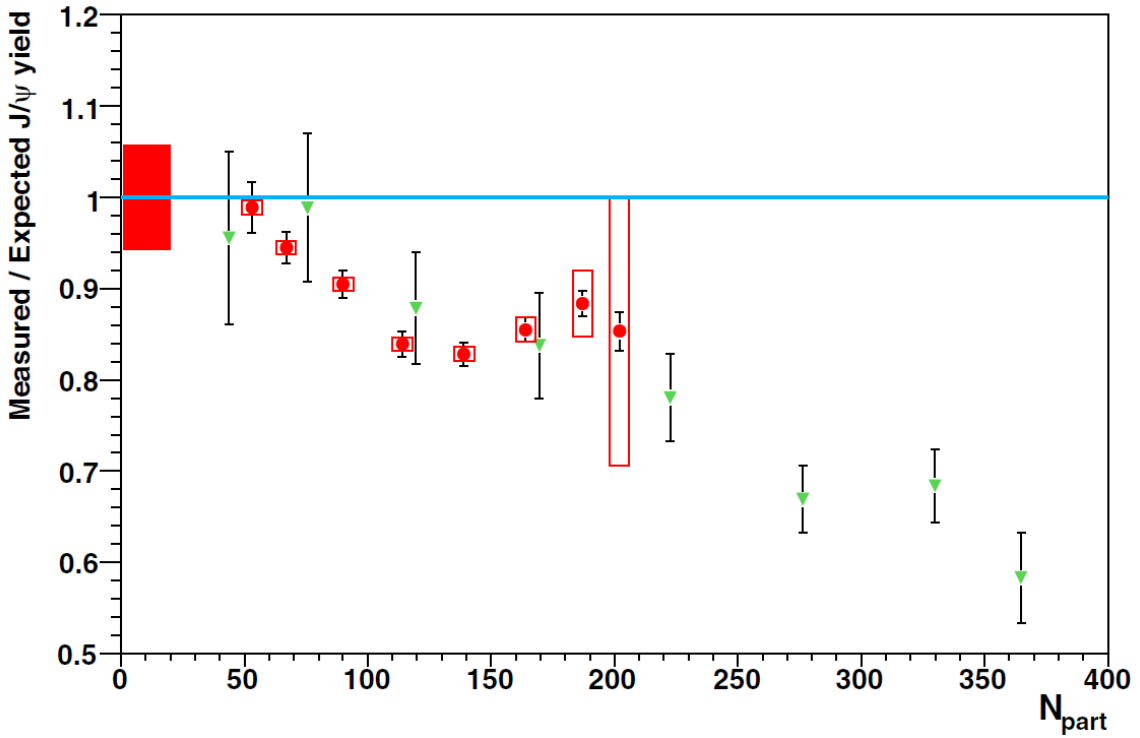
- Strong elliptic flow observed for light particles and D mesons
- Hint of non-zero elliptic flow ?
  - Not clear yet, but stay tuned for LHC Run-2 data

Summary

- SPS (17 GeV)
  - CNM effects dominated by nuclear absorption
  - Anomalous J/ψ suppression in central collisions
  - Suppression of excited states due to comover-like interactions ?
  - Onset of color screening ?
- RHIC (200 GeV)
  - CNM effects: nuclear absorption (and shadowing effects ?)
  - Suppression of J/ψ beyond the expectations from CNM effects
  - Flow of open heavy flavor
  - Onset of charm thermalization and recombination ?
- LHC (2760 GeV)
  - CNM effects: PDF modifications (shadowing, gluon saturation), initial state energy loss...
  - Much less suppression compared to RHIC at low p_T and large suppression at high p_T
    - Strong color screening and regeneration effects cancelling each other
  - Large D-meson elliptic flow
    - Charm quark thermalization
    - How does this translates to charmonium flow?

Backup

In-In(NA60) vs Pb-Pb(NA50) PRL99 (2007) 132302

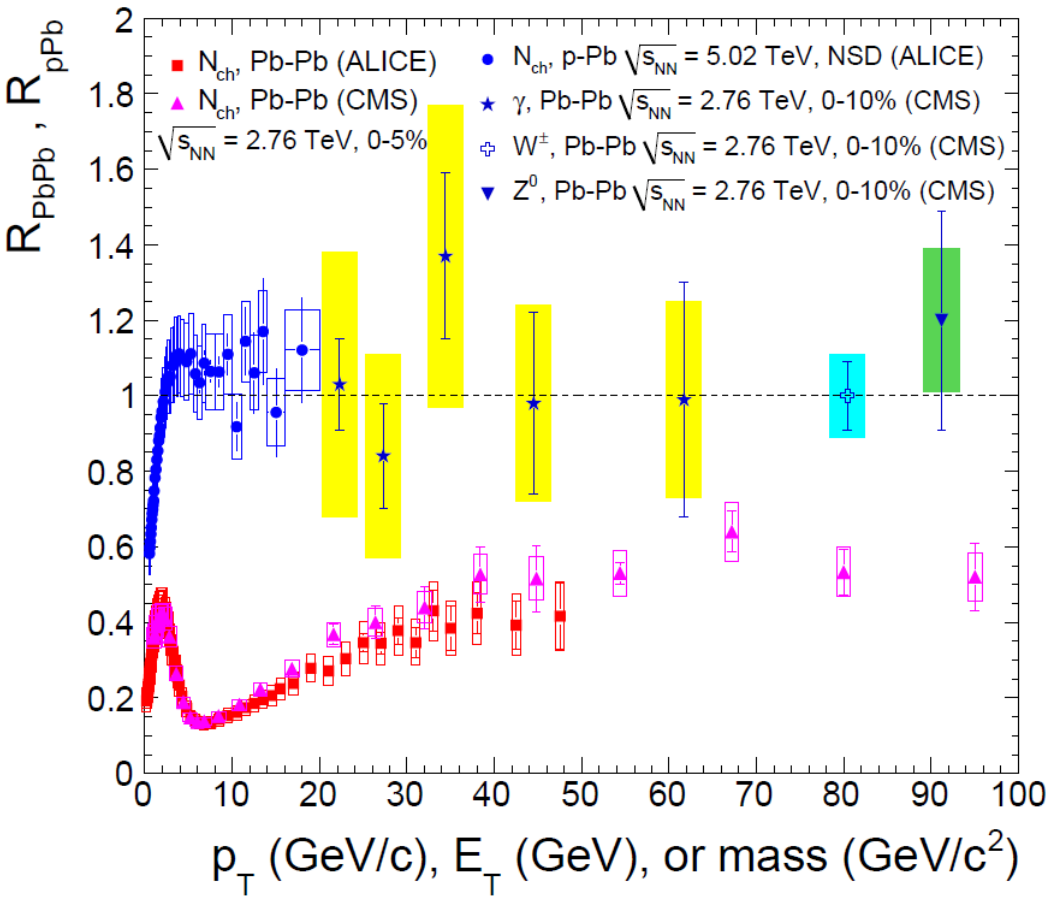


Results based on extrapolation of sigma_abs from p-A collisions at 400/450 GeV

Nuclear modification at RHIC and LHC

p-Pb, ALICE PRL110(2013)082302
Pb-Pb, ALICE, Phys.Lett.B720 (2013)52
Pb-Pb, CMS, EPJC (2012) 72

γ, CMS, PLB 710 (2012) 256
$W^{\pm}$, CMS, PLB715 (2012) 66
Z^0, CMS, PRL106 (2011) 212301

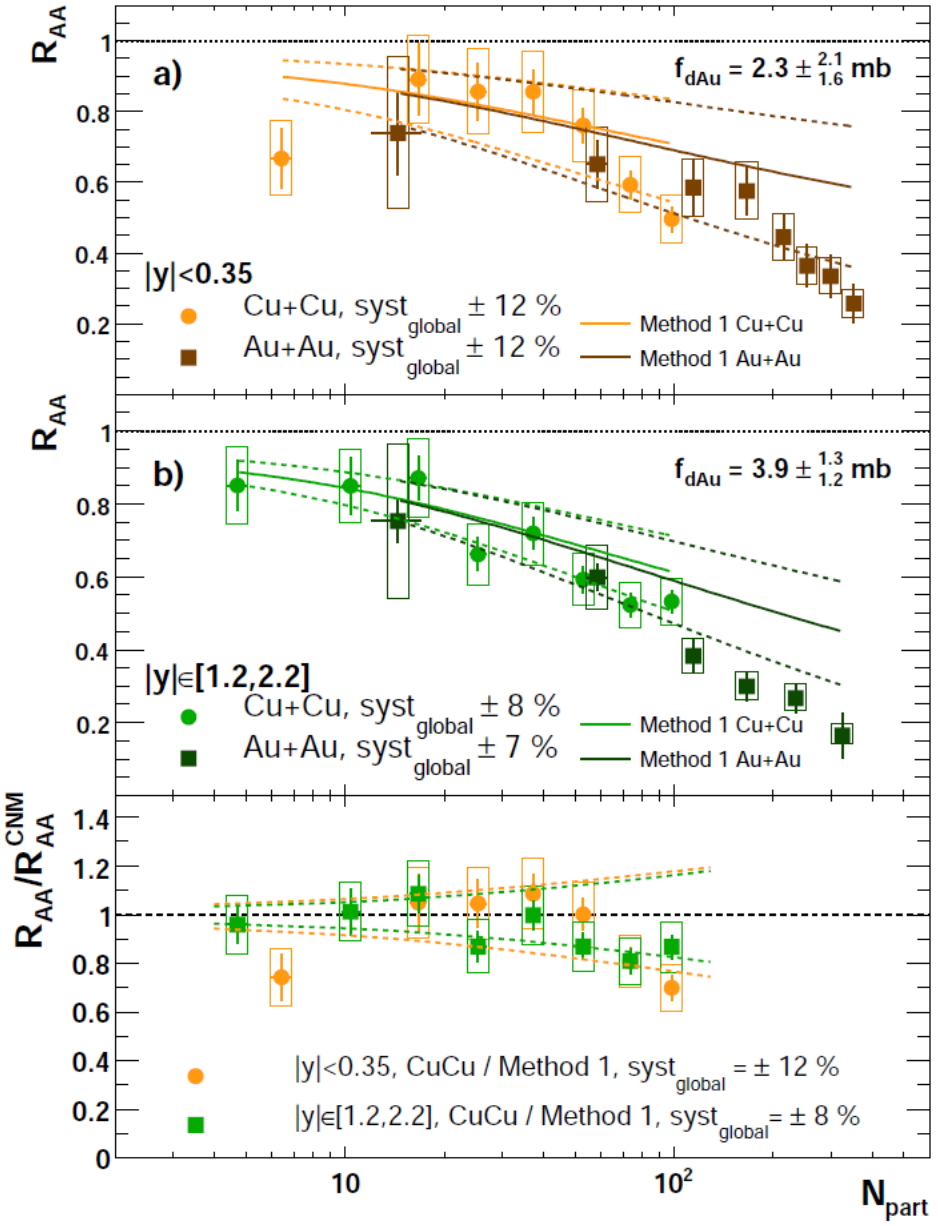


$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

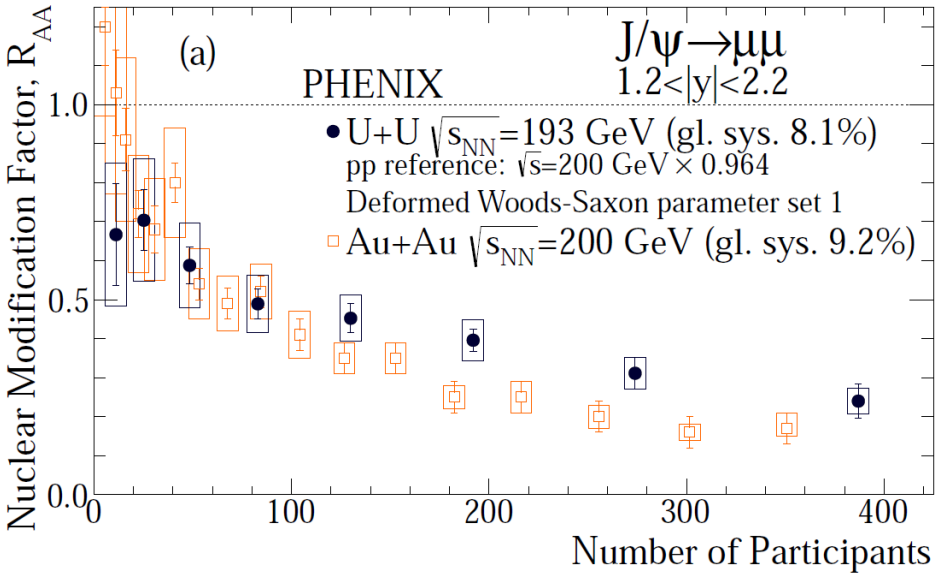
- N_{coll}: the number of binary nucleon-nucleon collisions
- Superposition of NN collisions → $R_{AA}=1$
  Suppression → $R_{AA}<1$
  Enhancement → $R_{AA}>1$
- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 bosons R_{AA} are compatible with 1

Collision system dependence

PHENIX arxiv:0801.0220



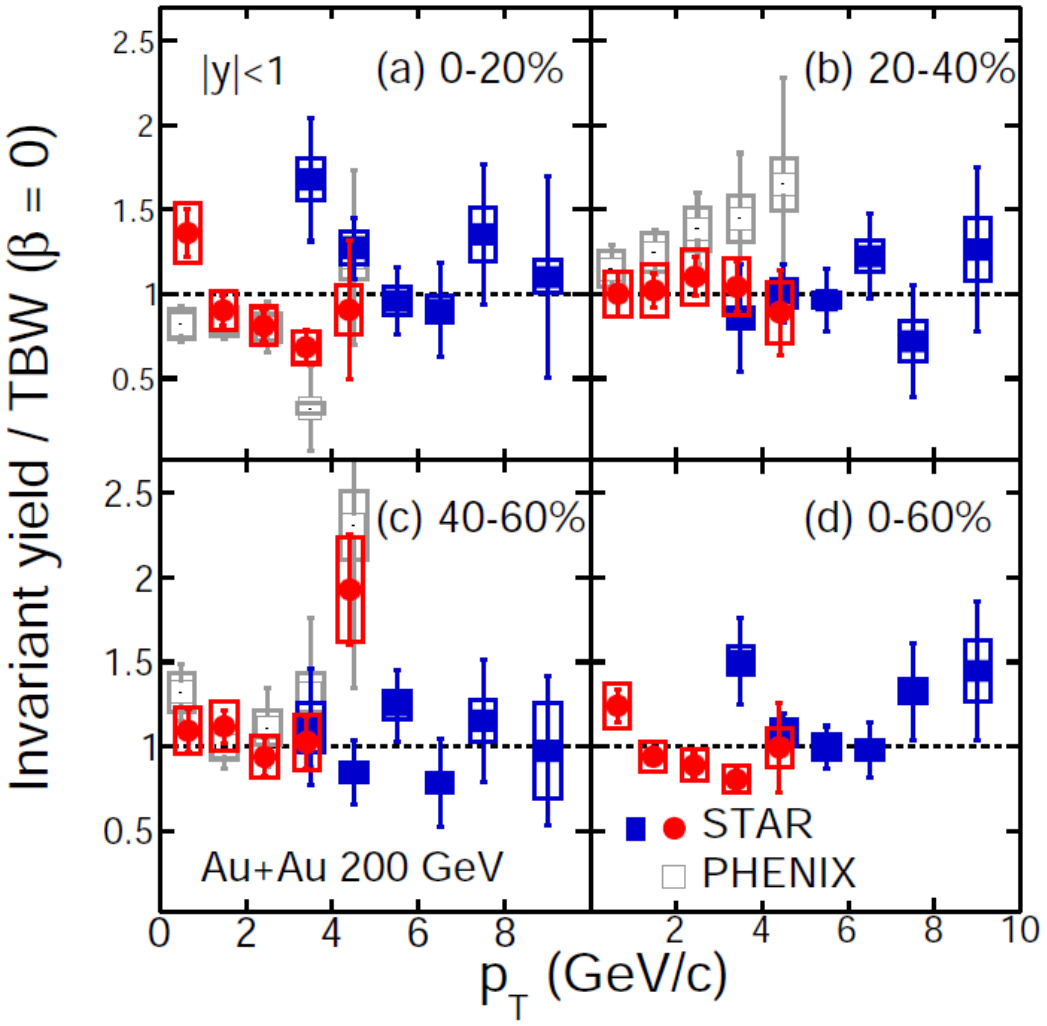
PHENIX arxiv:1509.0538

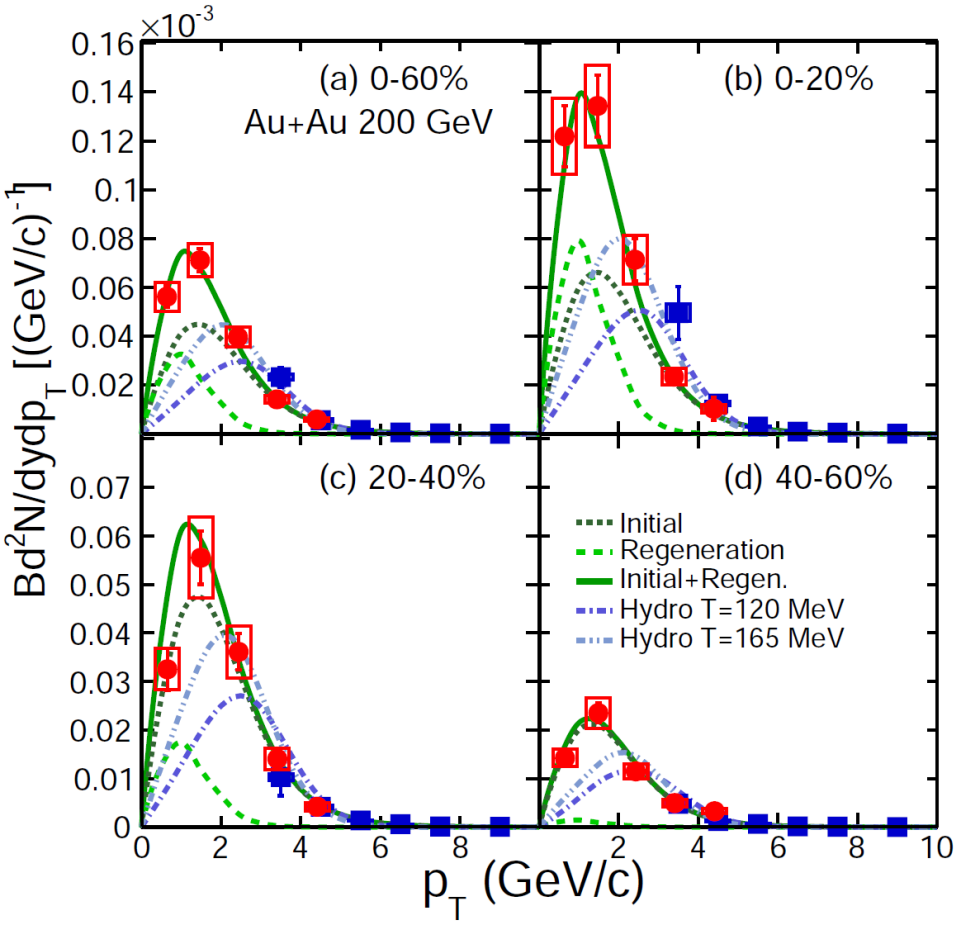


- J/ψ production studied also in Cu-Cu and U-U systems
- Similar J/ψ R_{AA} observed at similar N_{part} and N_{coll}

STAR AuAu

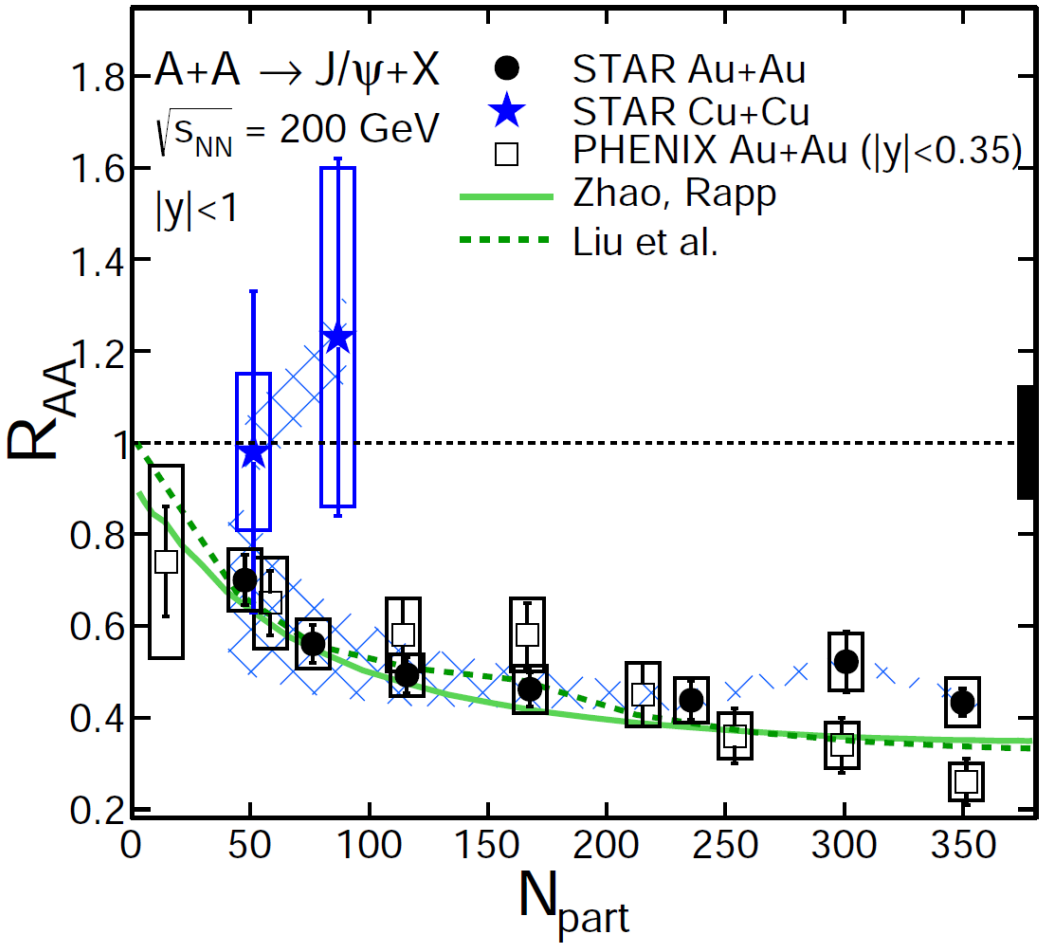
STAR arxiv 1310.3563



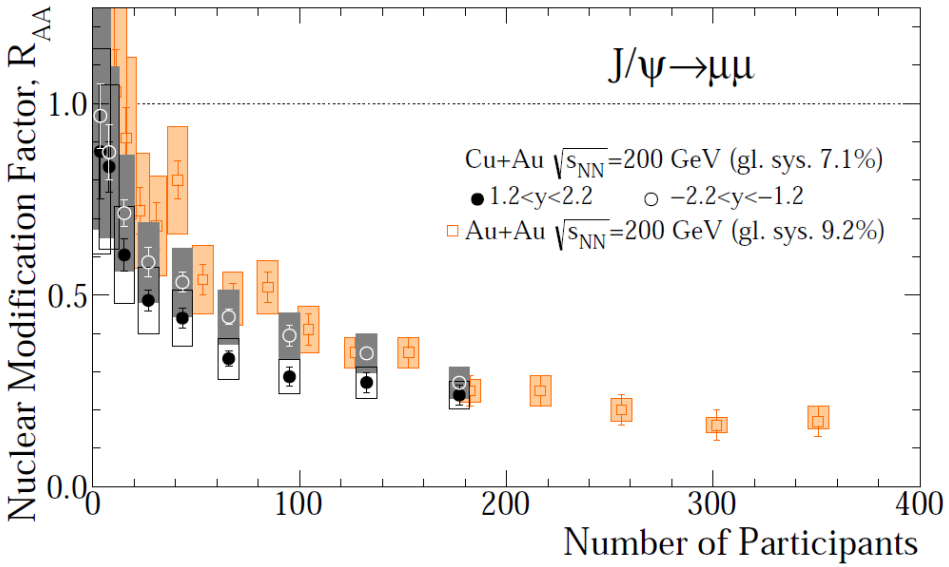


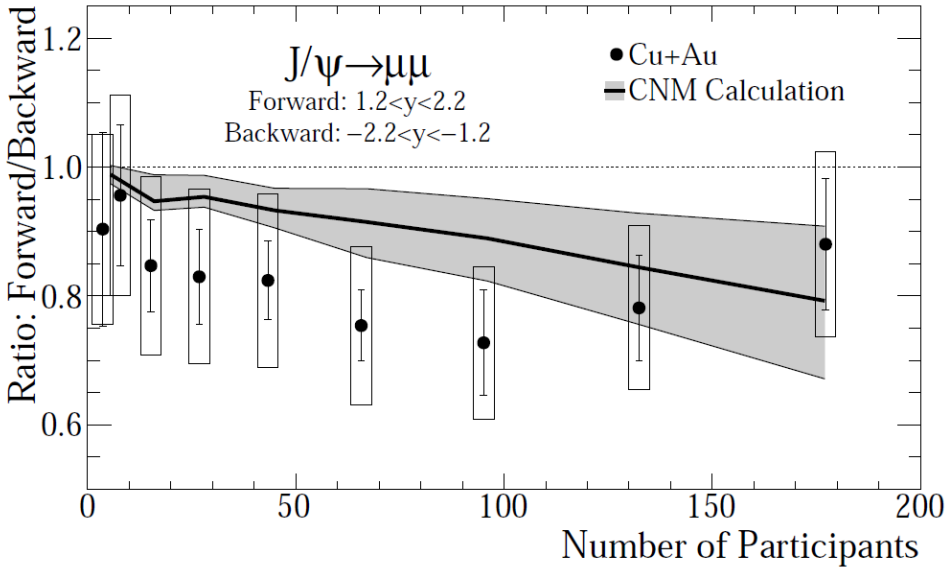
J/psi

STAR arxiv 1310.3563

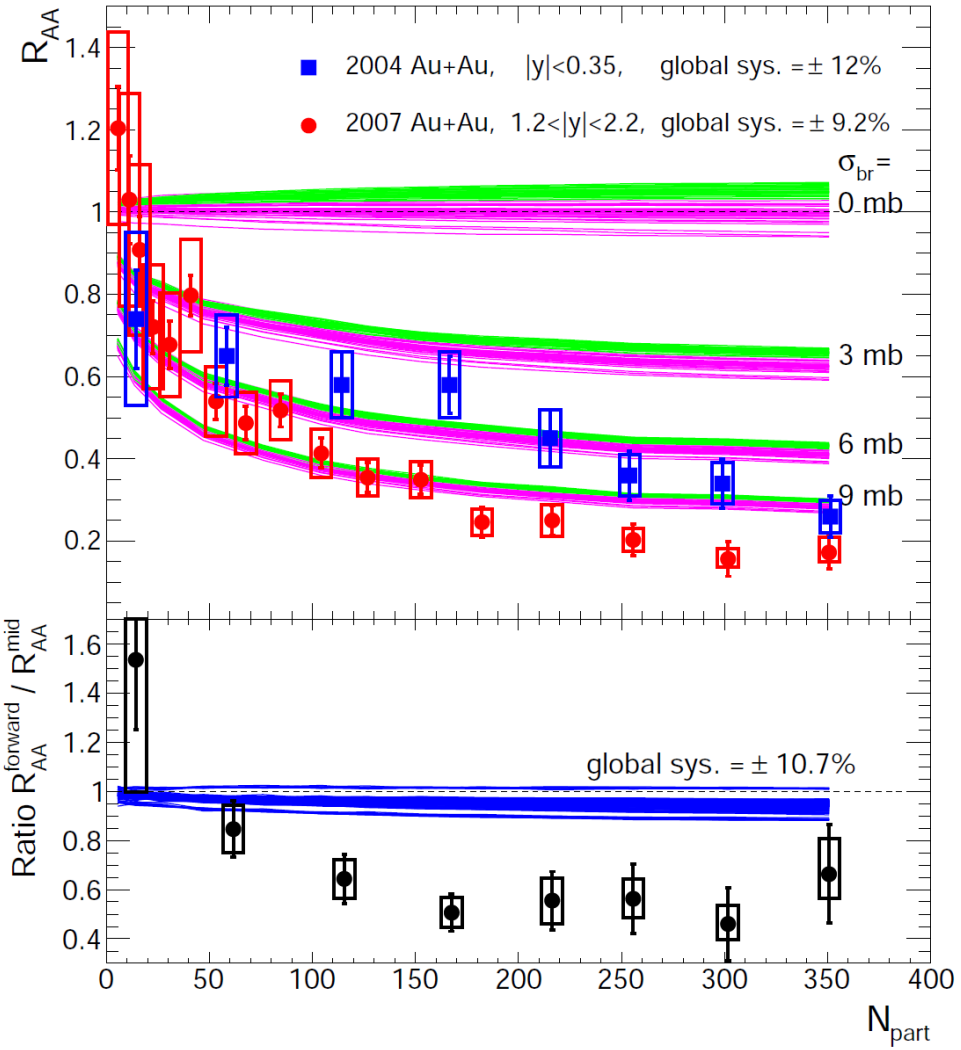


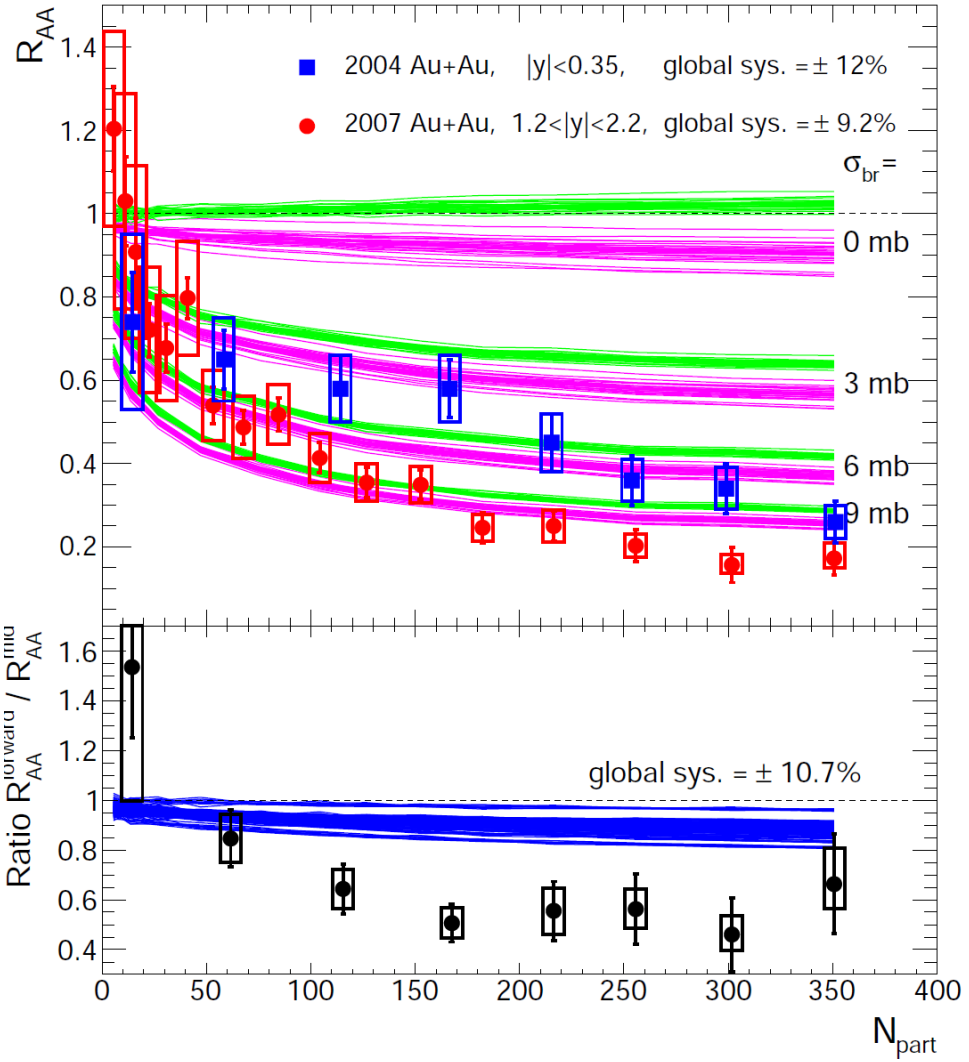
PHENIX cuau200
arxiv:1404.1873





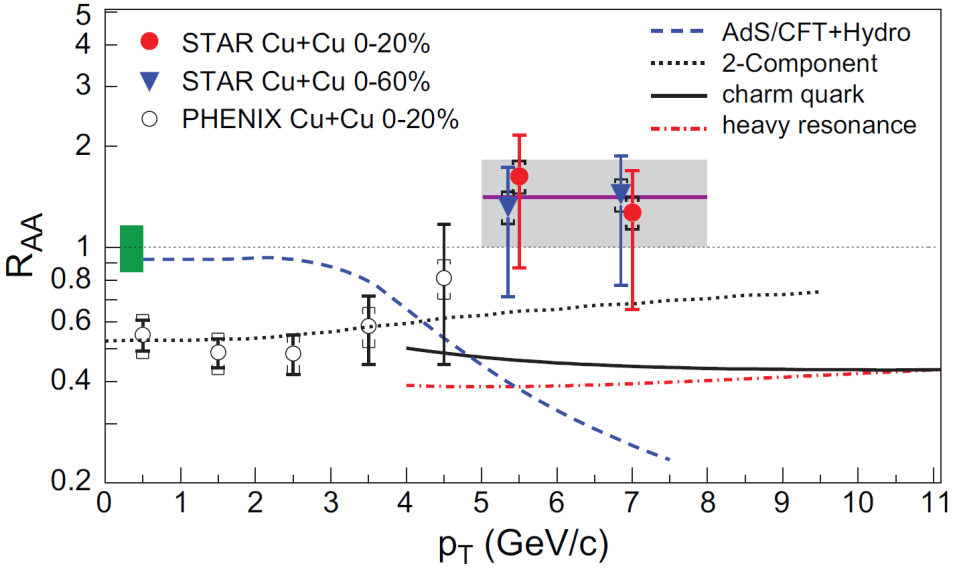
PHENIX


R_AA
2004 Au+Au, |y|<0.35, global sys. = ± 12%
2007 Au+Au, 1.2<|y|<2.2, global sys. = ± 9.2%
σ_br =
0 mb
3 mb
6 mb
9 mb
Ratio R_AA^forward / R_AA^mid
global sys. = ± 10.7%
N_part

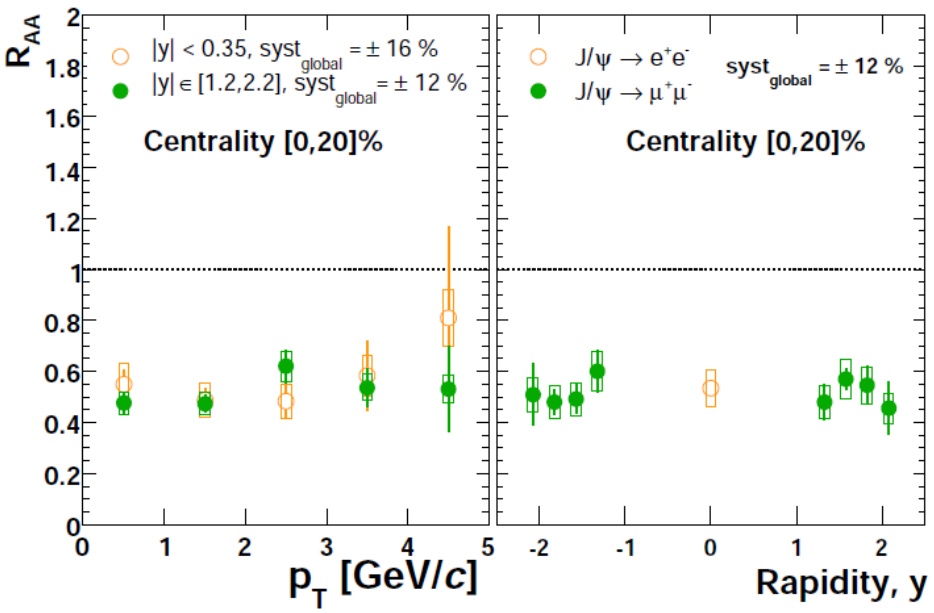

R_AA
2004 Au+Au, |y|<0.35, global sys. = ± 12%
2007 Au+Au, 1.2<|y|<2.2, global sys. = ± 9.2%
σ_br =
0 mb
3 mb
6 mb
9 mb
Ratio R_AA^forward / R_AA^mid
global sys. = ± 10.7%
N_part

Jpsi CuCu

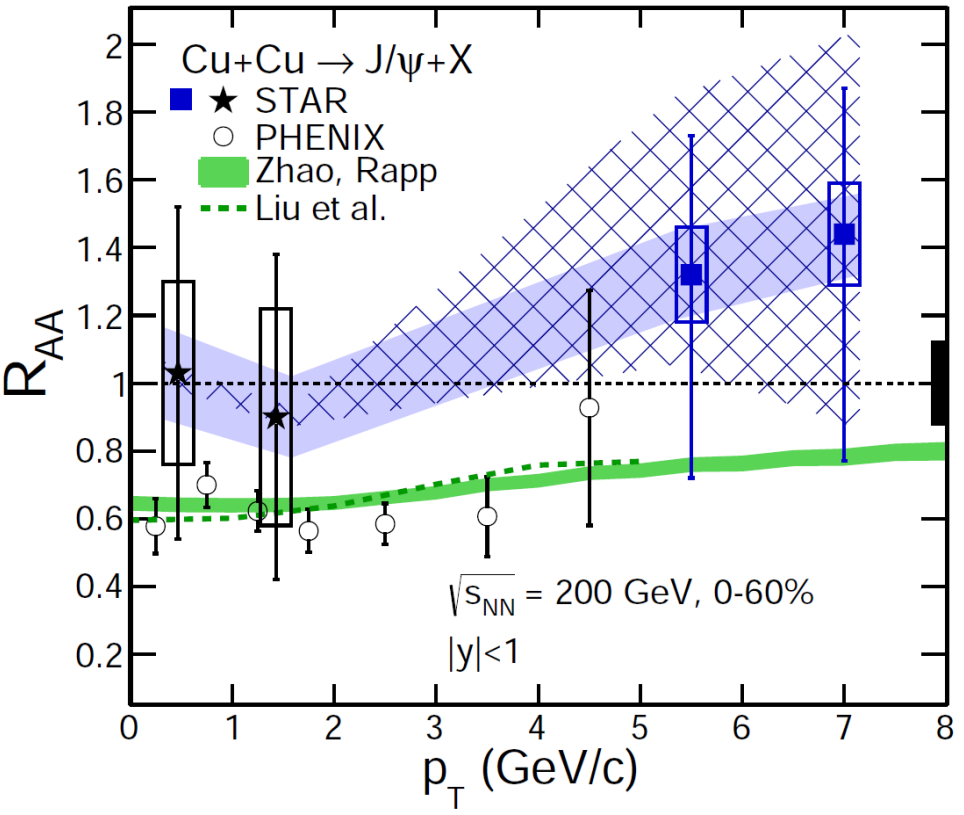
STAR arxiv:0904.0439



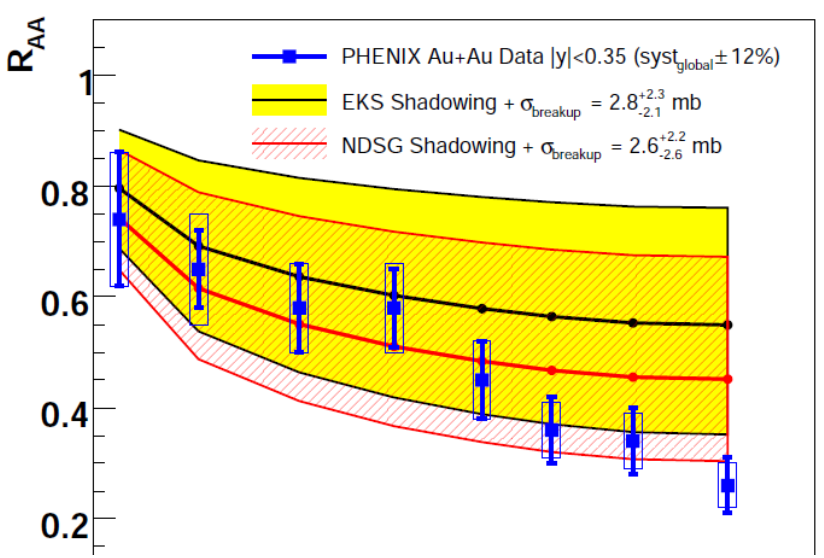
PHENIX arxiv:0801.0220

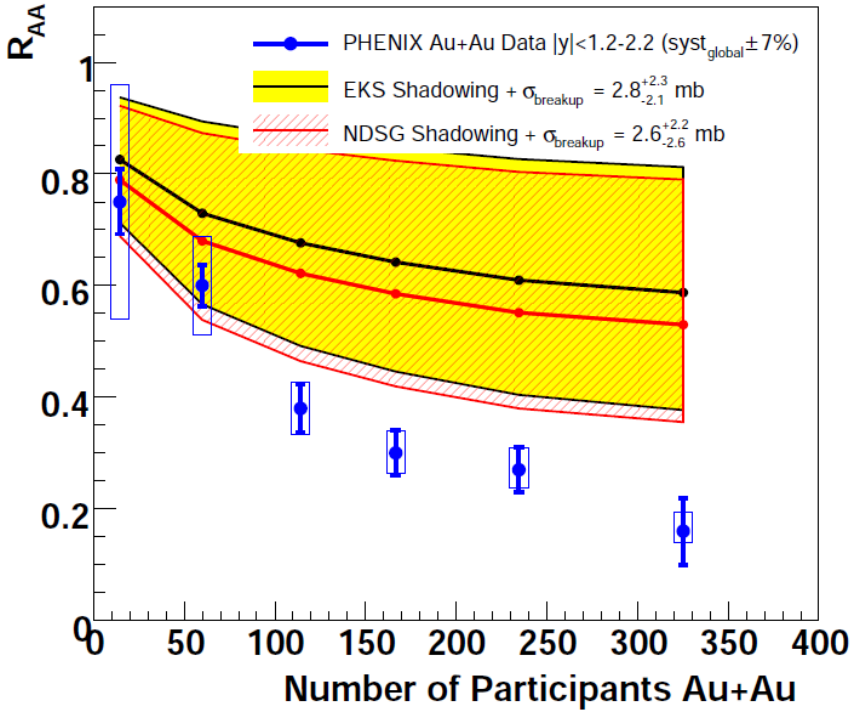


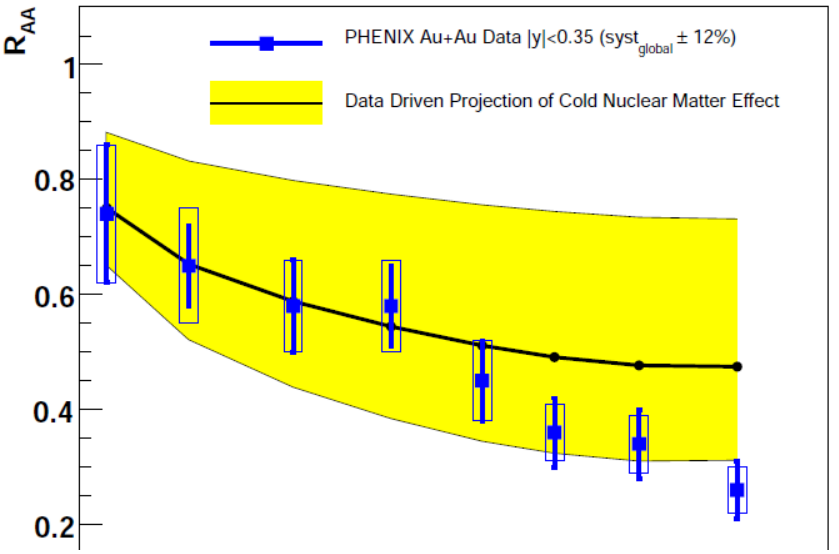
STAR arxiv 1310.3563

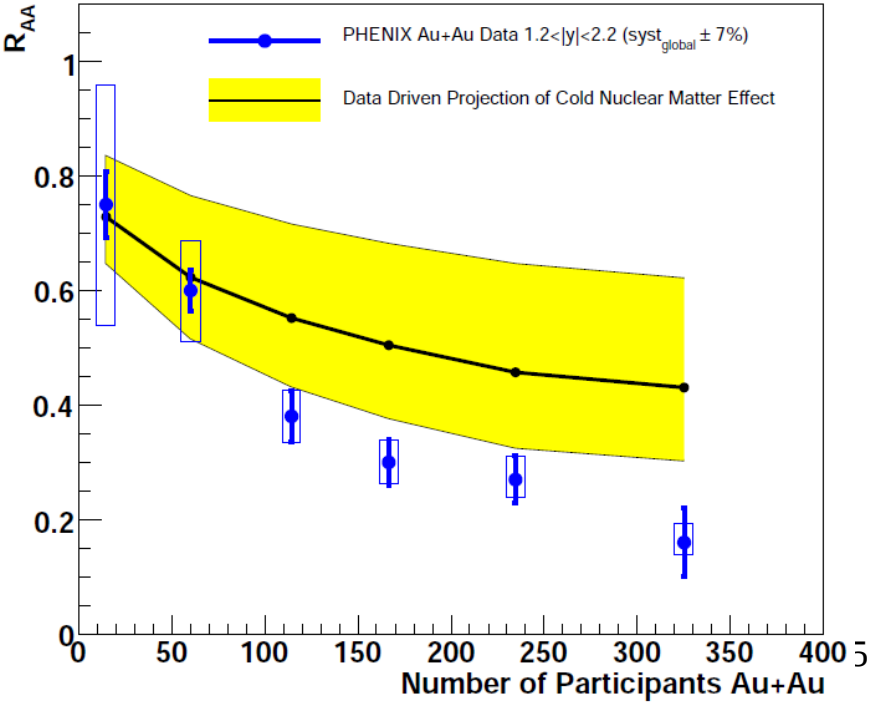


PHENIX upsilon data200
arxiv:0711.3917

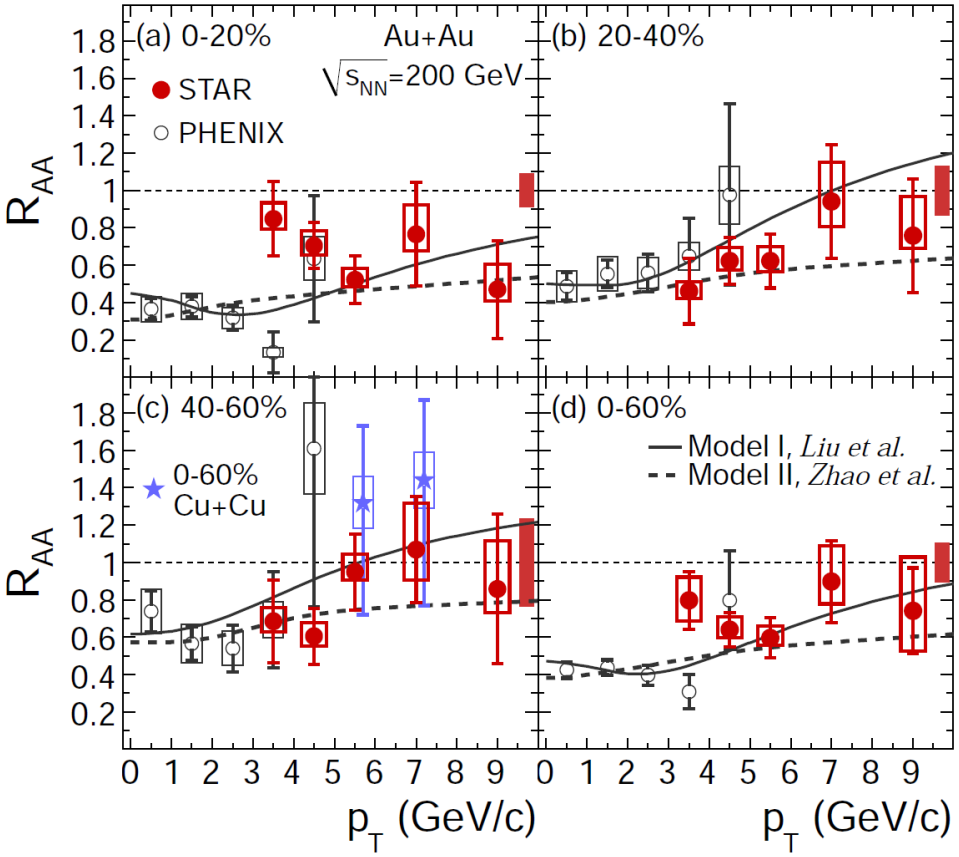


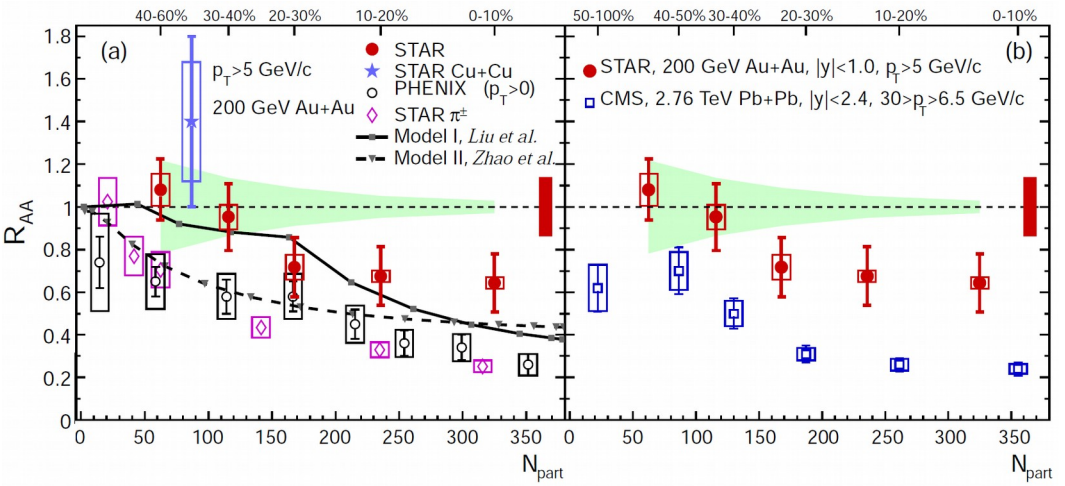




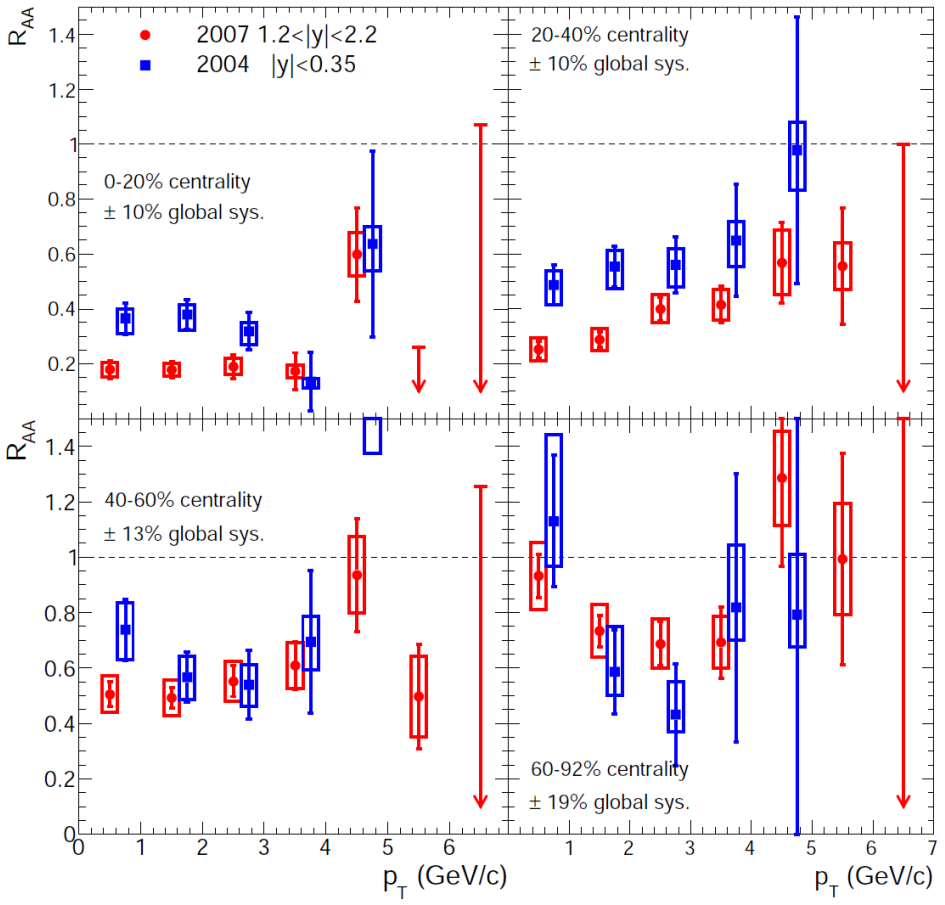


STAR AuAu
arxiv: 1208.2736





PHENIX Jpsi auau200 arxiv:1103.6269



Inclusive J/ψ as a function of p_T

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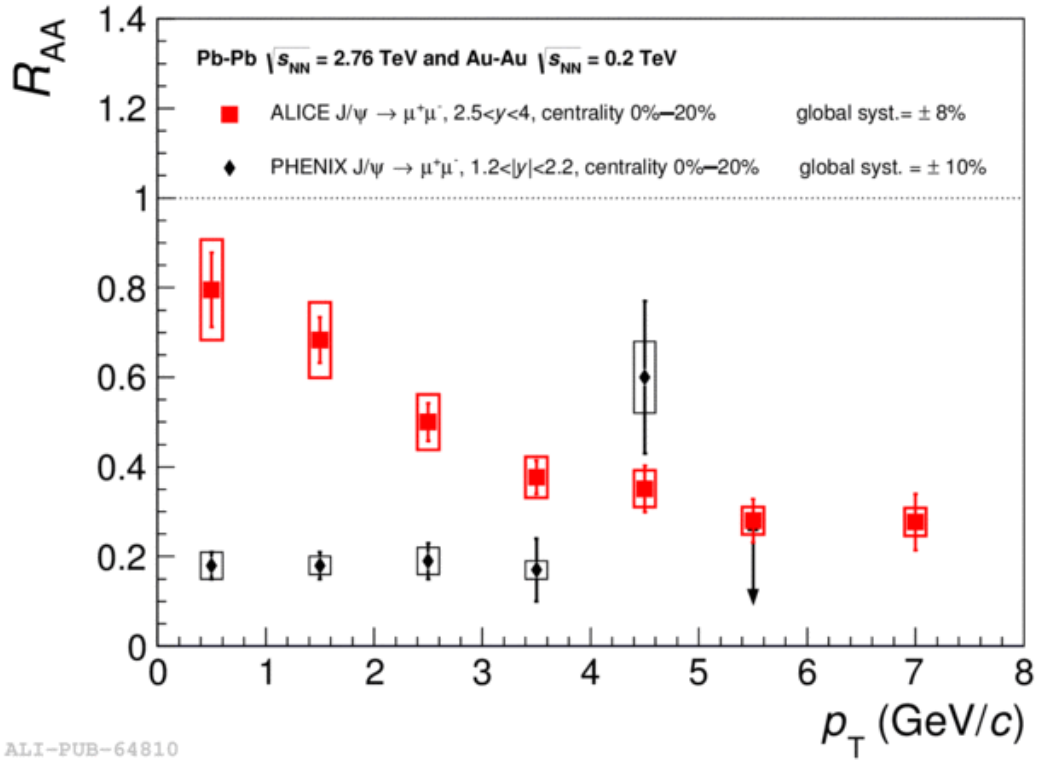
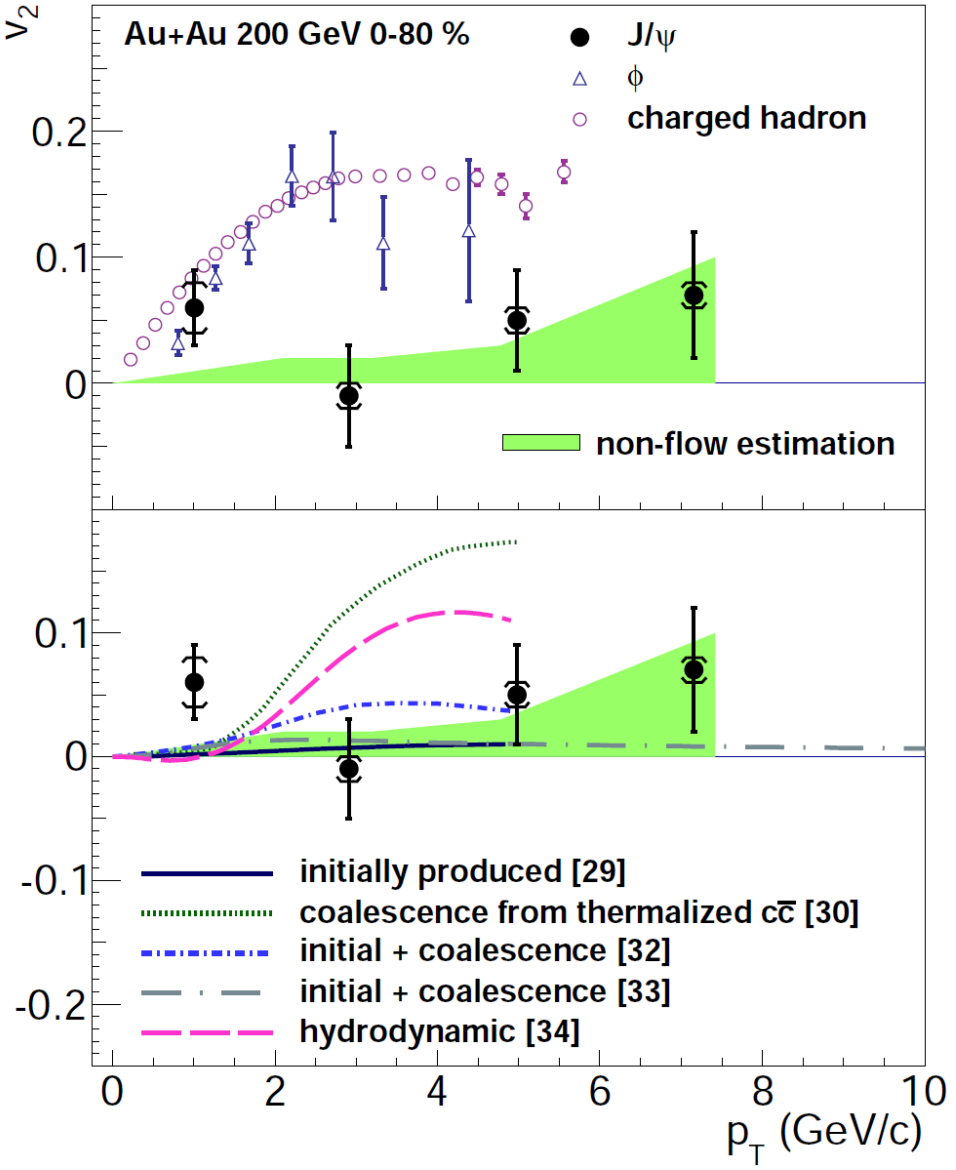
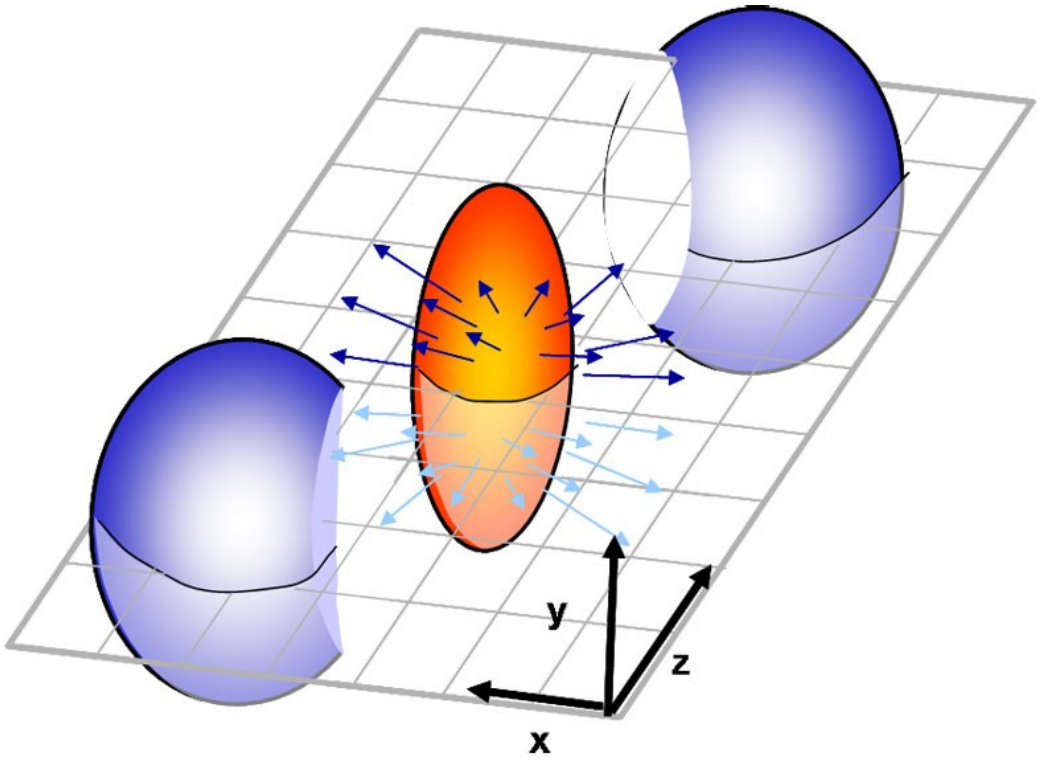
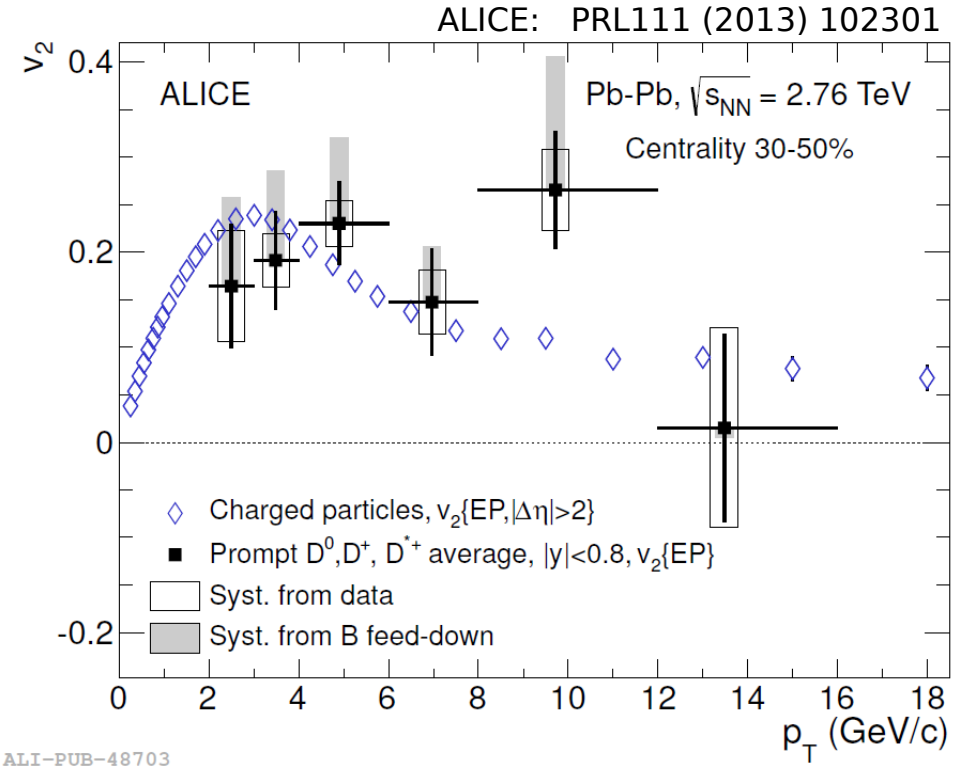


J/psi elliptic flow



Elliptic flow

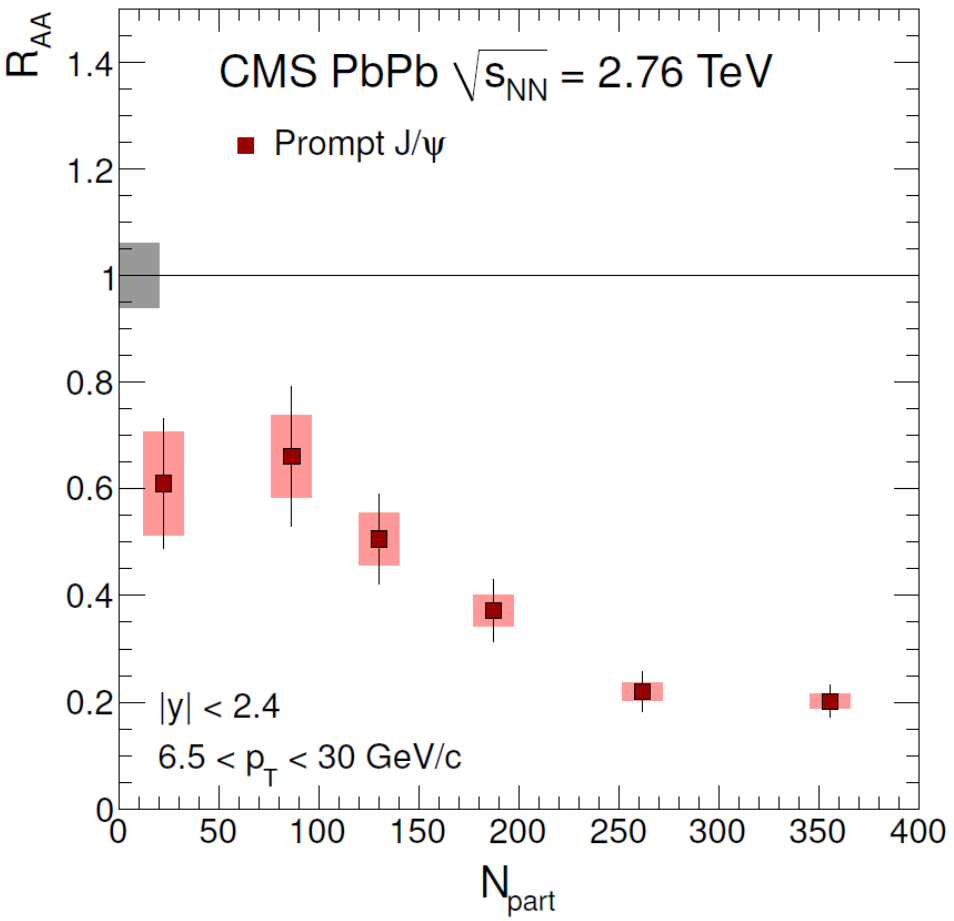


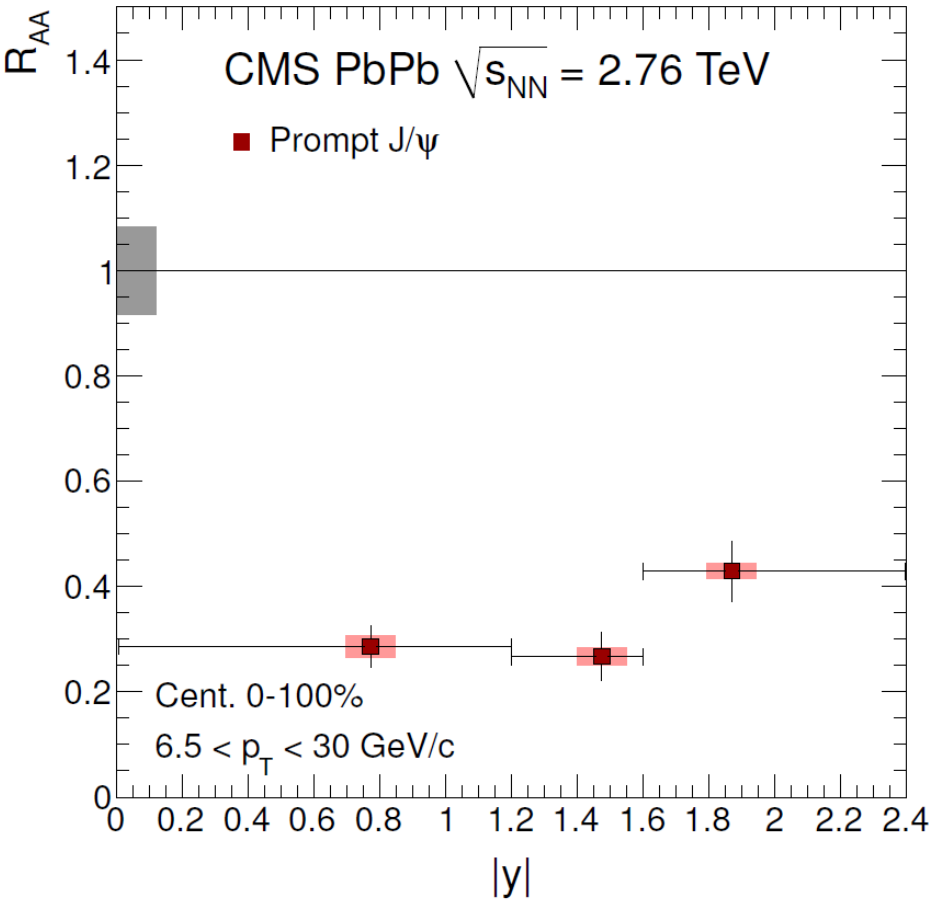


$$\frac{dN}{d\phi} \simeq 1+2v_1\cos(\phi-\Psi_r)+2v_2\cos(2(\phi-\Psi_r))+\ldots$$

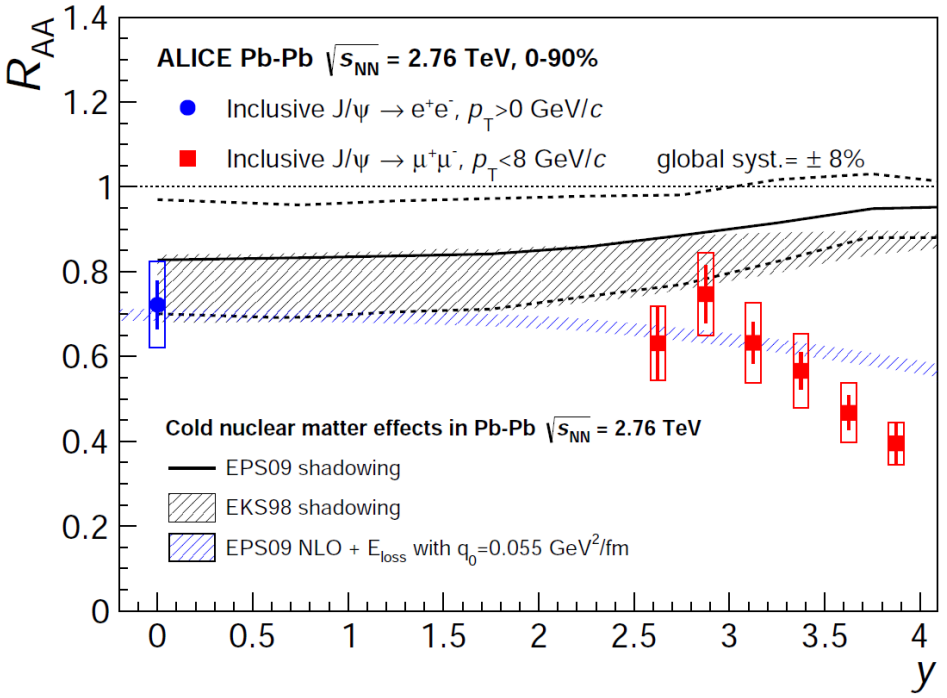
- Strong elliptic flow observed for light particles and D mesons
- Is J/ψ inheriting any of the fireball collective flow ?

CMS
jhep05 (2012) 063



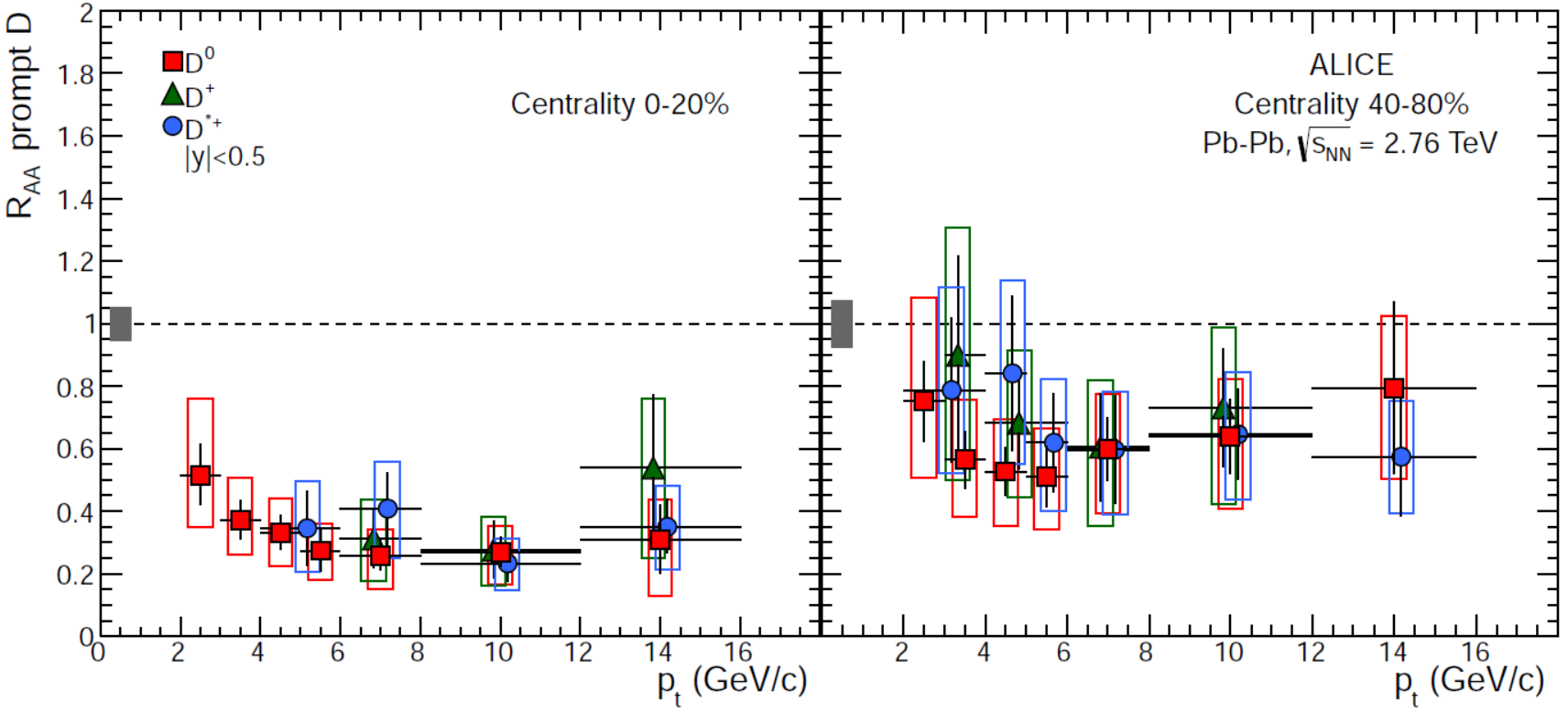


J/psi Raa vs rapidity



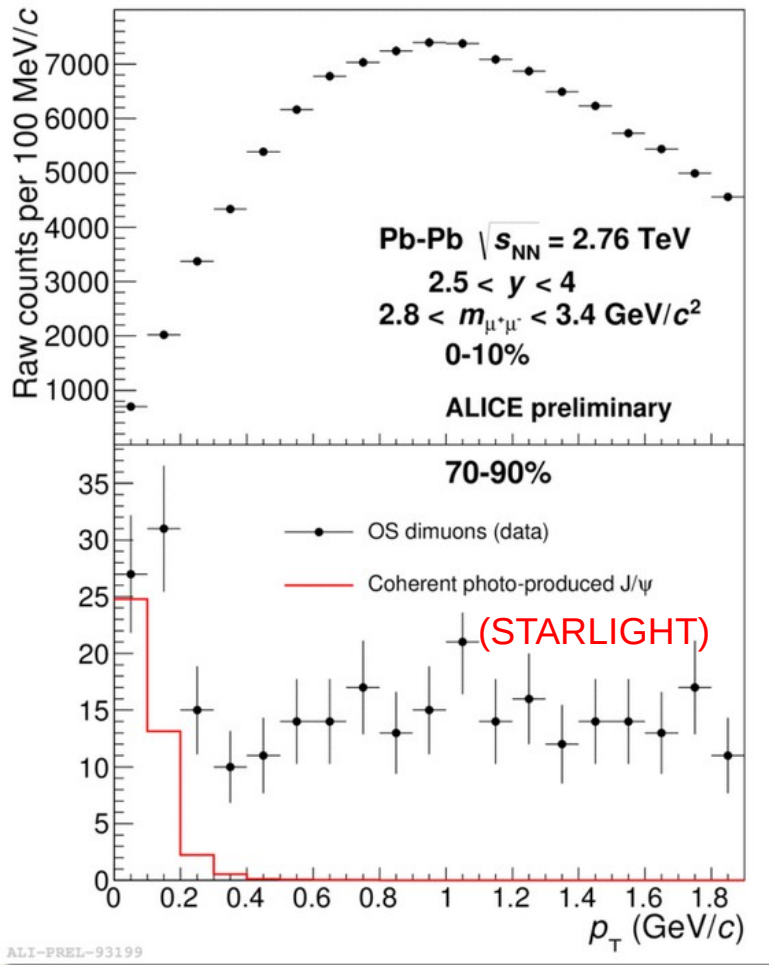
Open charm suppression vs centrality

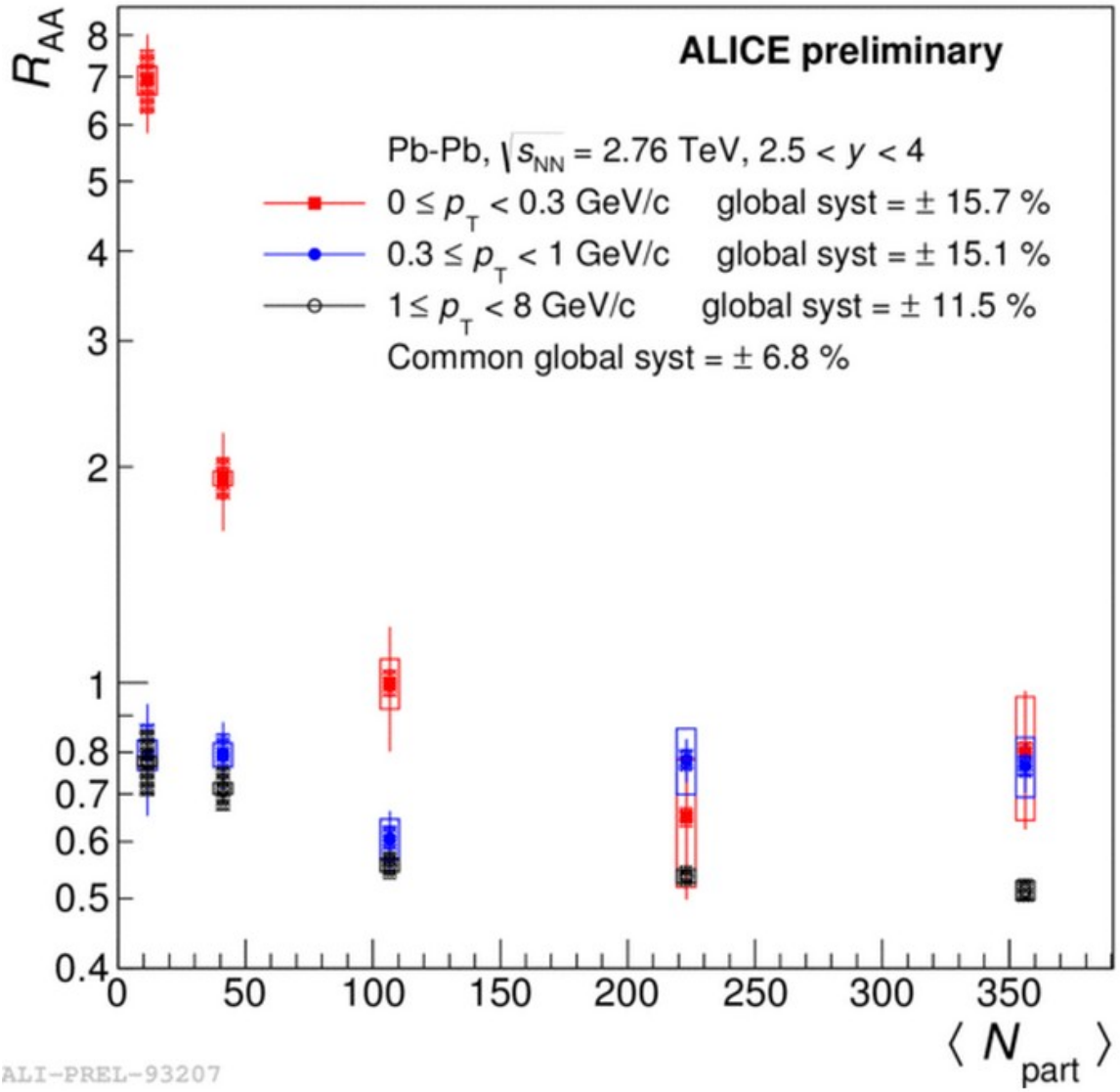
ALICE JHEP1209 (2012) 112



- Fully pT integrated open charm results not available yet
- Strong suppression of D mesons for pT>2 GeV/c observed

Digression: "very" low-p_T J/ψ R_{AA}





- J/ψ p_T spectrum at low p_T similar to the one from photo-production in $b>2R$ collisions
- J/ψ R_{AA} for p_T<300 MeV/c ~ 7 for the most peripheral collisions !!!