Heavy quarkonium production in heavy ion collisions

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What is heavy quarkonia ?

- Bound states of heavy quark pairs: $c\bar{c}$ and $b\bar{b}$
- Typical masses:
  - > 2.9 GeV/c^2 for charmonium (m_c ~ 1.27 GeV/c^2)
  - > 9.3 GeV/c^2 for bottomonium (m_b ~ 4.6 GeV/c^2)
- Non-relativistic quark – antiquark system !

Spectroscopy (simple minded model)

- Lets assume a quark – antiquark pair
- Potential seen by the two quarks will have two components:
  - a Coulomb term: $V_{Coulomb}(\boldsymbol{r}) = \frac{q}{4\pi r}$
  - and a linear term: $V_{linear}(\boldsymbol{r}) = k\,r$

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- The potential energy of the pair is then $V_{total} = (-q)\frac{q}{4\pi r} + kr$
- The Hamiltonian can be written as $H = \frac{\boldsymbol{p}^2}{2\mu} - \frac{\alpha_{eff}}{r} + kr$

$\alpha_{eff} = q^2/4\pi$

$\mu = m_c/2$

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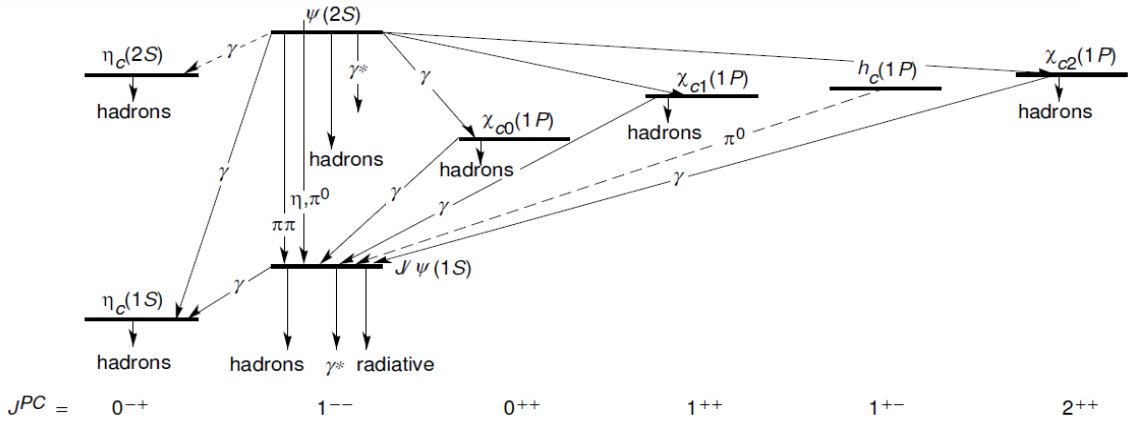
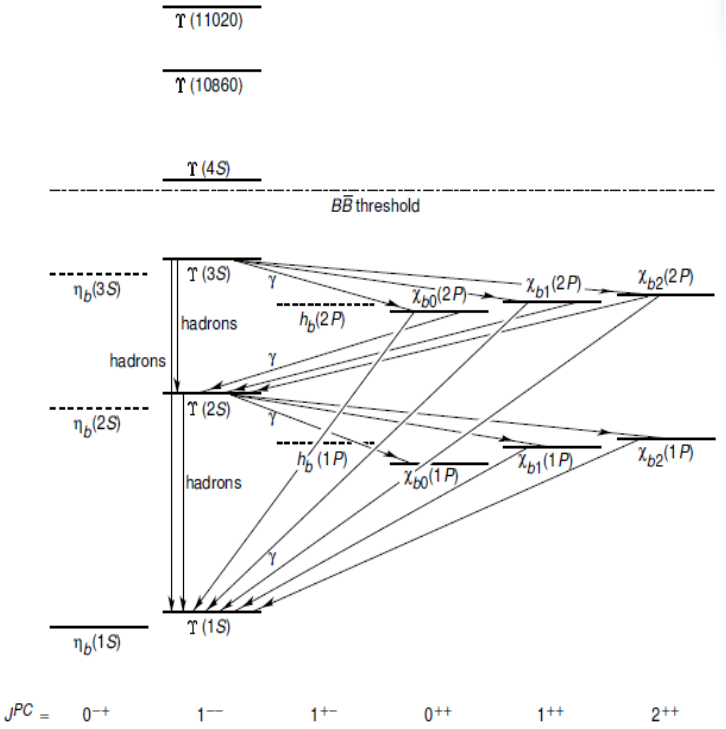
- The Hamiltonian can be written as $H = \frac{\boldsymbol{p}^2}{2\mu} - \frac{\alpha_{eff}}{r} + kr$ $\quad \alpha_{eff} = q^2/4\pi$ $\quad \mu = m_c/2$
- Surprisingly good quantitative description of the heavy quarkonia spectroscopy can be obtained with such a simple Hamiltonian

Spectroscopy

- Rich spectroscopy, many observed states …



Data from CLEO, BELLE, BABAR, CDF



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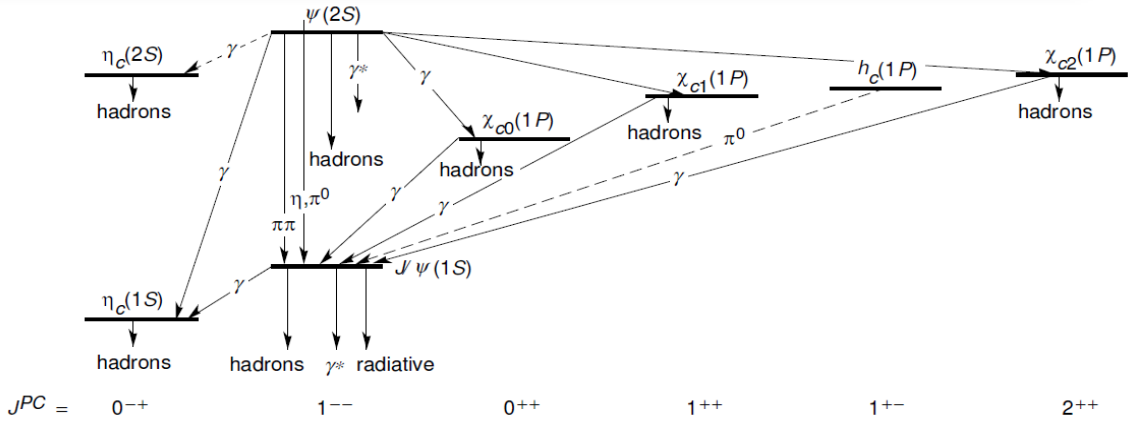
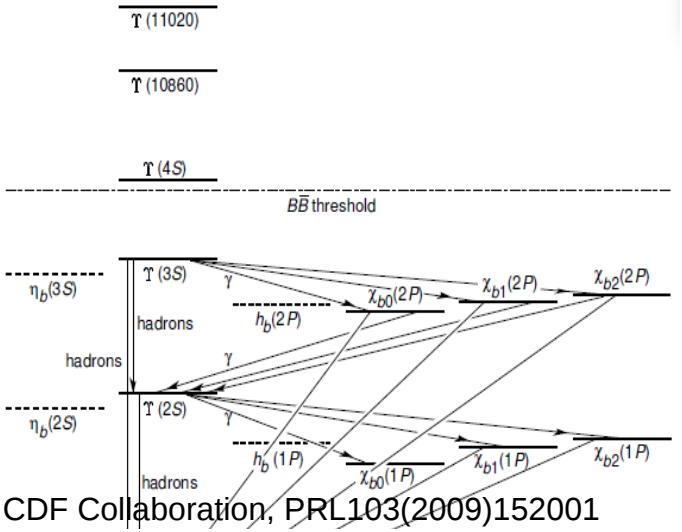
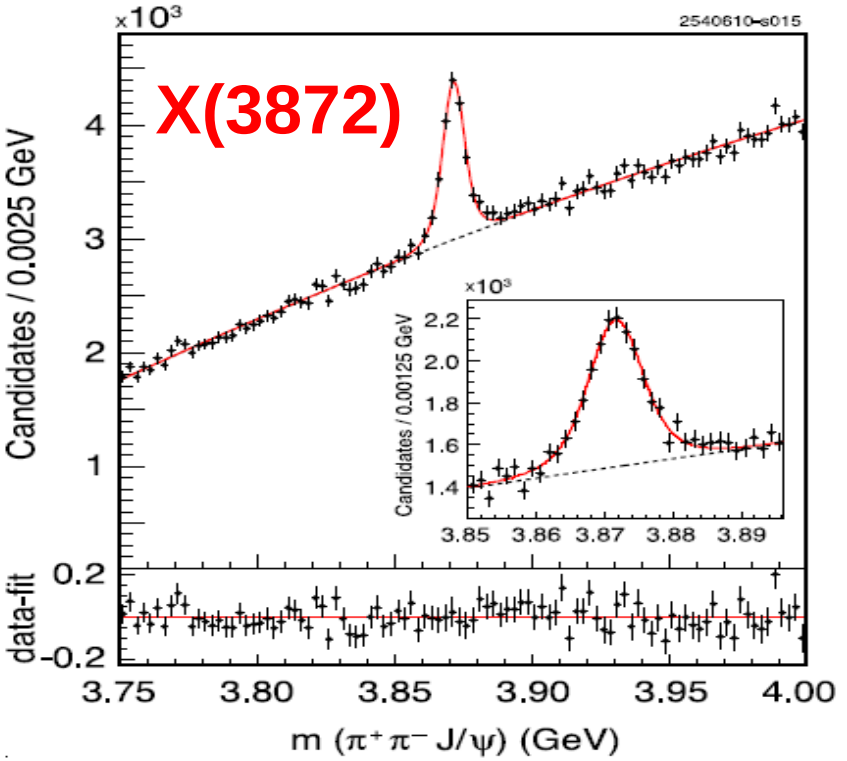




CDF Collaboration, PRL103(2009)152001

Data from CLEO, BELLE, BABAR, CDF

- … including some less conventiona



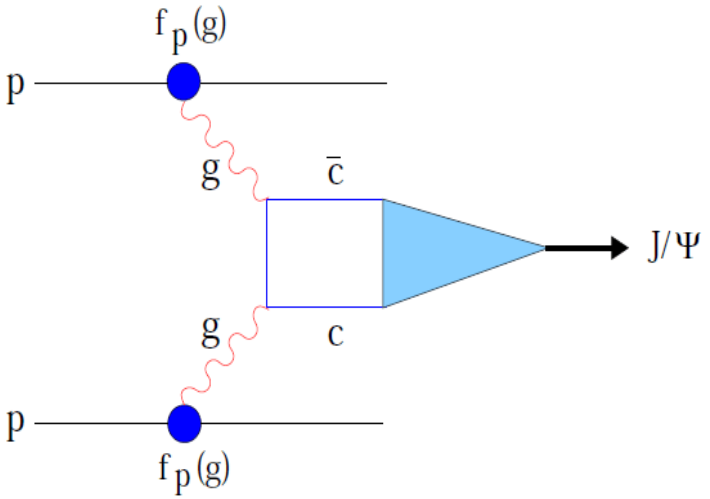
Quarkonium measurements in heavy-ion collisions

- Due to large backgrounds, quarkonium measurements in heavy ion collisions are limited mostly to the ψ ($c\bar{c}$) and Υ($b\bar{b}$) families
- Decay channels exploited:
  - e^+e^- and $\mu^+\mu^-$
- Experimental methods
  - Di-muon: spectrometers placed behind hadronic absorbers
  - Di-electron: tracking+PID, electro-magnetic calorimeters, transition radiation

Direct production and feed-down

- Inclusive quarkonium measurements normally contain both
  - Directly produced particles and…
  - Feed-down from higher mass quarkonium states
    - e.g. $\psi(2S) \rightarrow J/\psi + X$, $\chi c \rightarrow J/\psi + \gamma$, B->J/ψ+X
    - Feed-down contributions to J/ψ and Y(1S) can be as high as 50%

Quarkonia production (in vacuum)



- Unique test of QCD, very different scales:
  - Large momentum transfer for the $Q\overline{Q}$ pair creation (perturbative)
  - Small quark velocities in the $Q\overline{Q}$ rest frame (non-perturbative)

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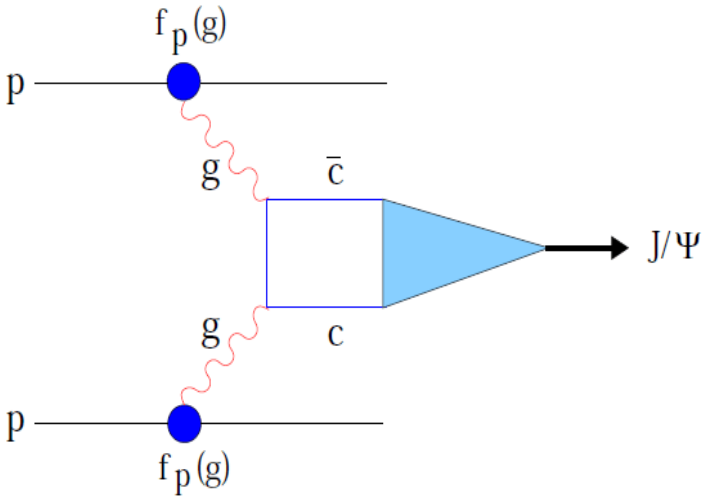

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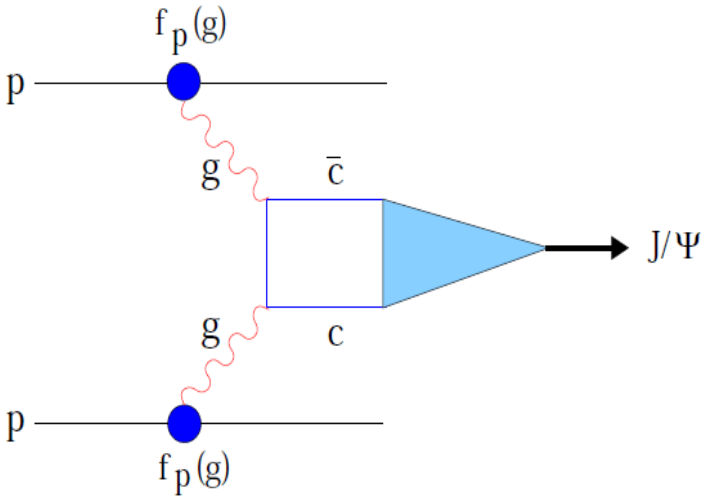

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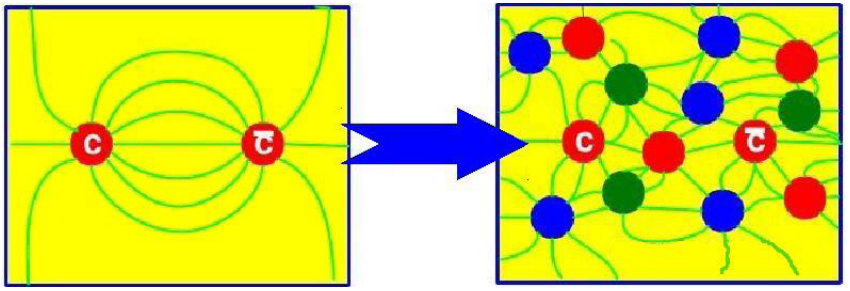
- Important reference for the nuclear modification factors
- Main theoretical models:
  - Color Singlet Model (CSM): S.D.Ellis, M.B.Einhorn, C.Quigg, PRL 36 (1976) 1263
    - $Q\overline{Q}$ pair created in physical color-singlet state
    - Bad description of Tevatron data
  - Non-Relativistic QCD G.Bodwin, E.Braaten, G.Lepage, PRD51 (1995) 1125
    - Rigorous effective field theory
    - Based on the factorization of the soft and hard scales

Heavy quarkonia in the QGP

- Vacuum potential: $V_{total} = (-q)\frac{q}{4\pi r} + kr$



- In a deconfined medium
  - string tension dissapears
  - Coulomb potential is screened (Debye)
- The quark-antiquark potential becomes a Yukawa-like short range potential

$$V_{medium}(\boldsymbol{r}) = \frac{q}{4\pi}\frac{e^{-r/\lambda_D}}{r}$$

$\lambda_D \simeq \frac{1}{T}$ - Debye screening length

- Quarkonium states will be melted if $\lambda_D > r$

Heavy quarkonia in the QGP

- Quarkonia becomes one of the most sensitive probes of the QGP

  Matsui and Satz, PLB178 (1986) 416

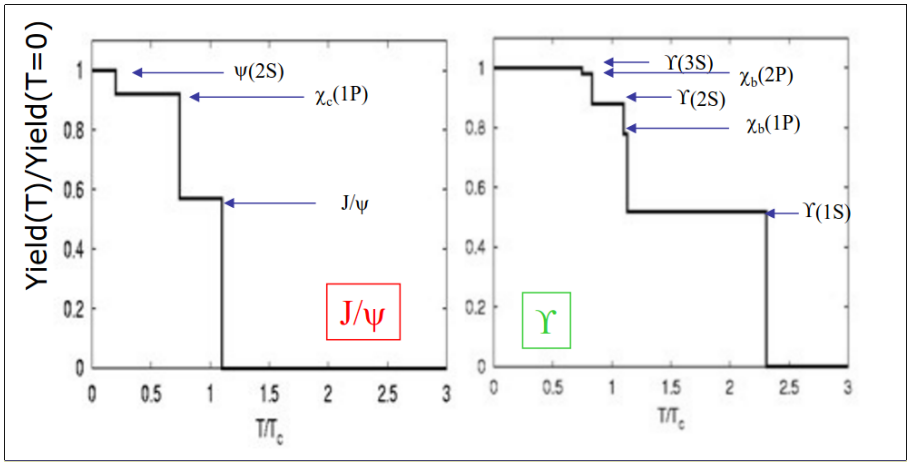
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

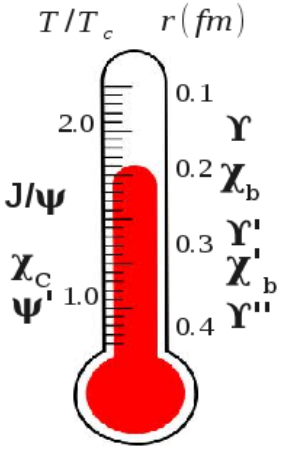
$(m_c = 1.25\ \text{GeV},\ m_b = 4.65\ \text{GeV},\ \sqrt{\sigma} = 0.445\ \text{GeV},\ \alpha = \pi/12)$

H.Satz, "Quarkonium Production – Probing QCD at the LHC, 2011 Vienna"

- Sequential melting of quarkonium states → thermometer of the QGP

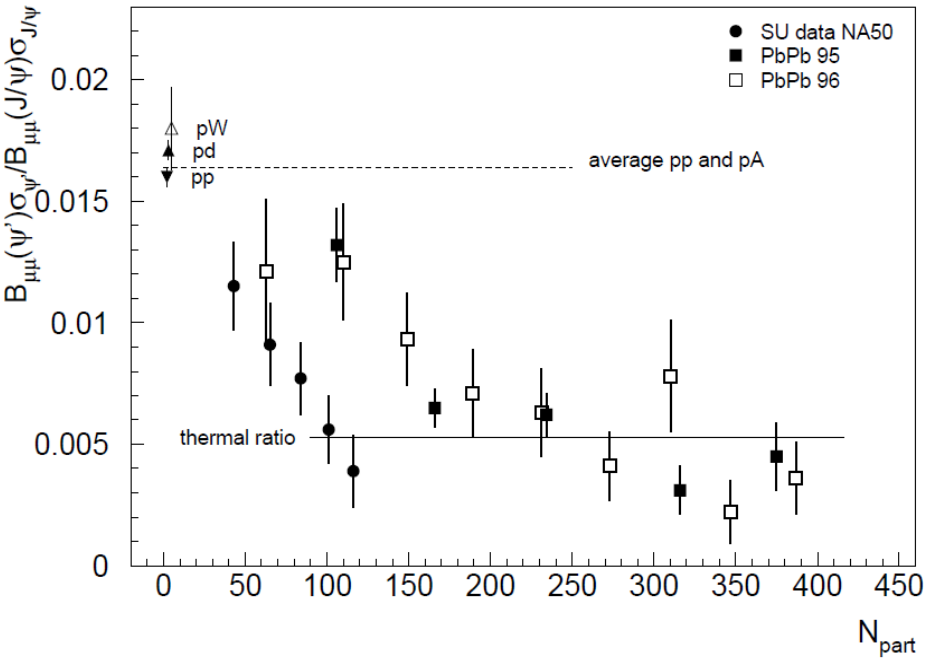
Digal et al., PRD64 (2001) 094015

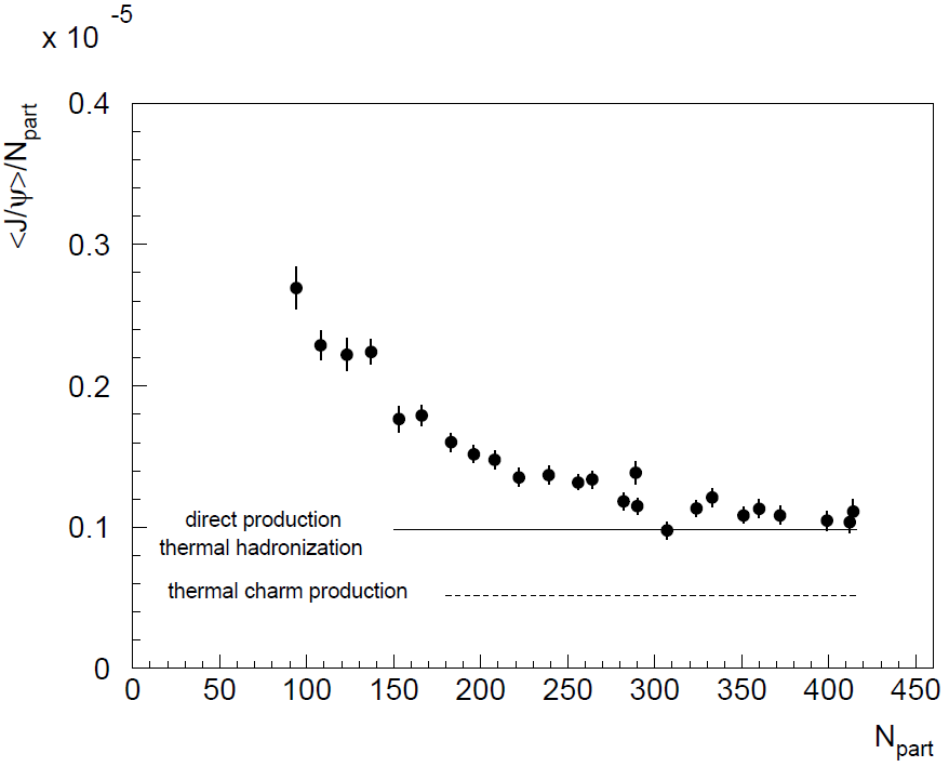




Statistical hadronization

P.Braun-Munzinger, J.Stachel (2000)

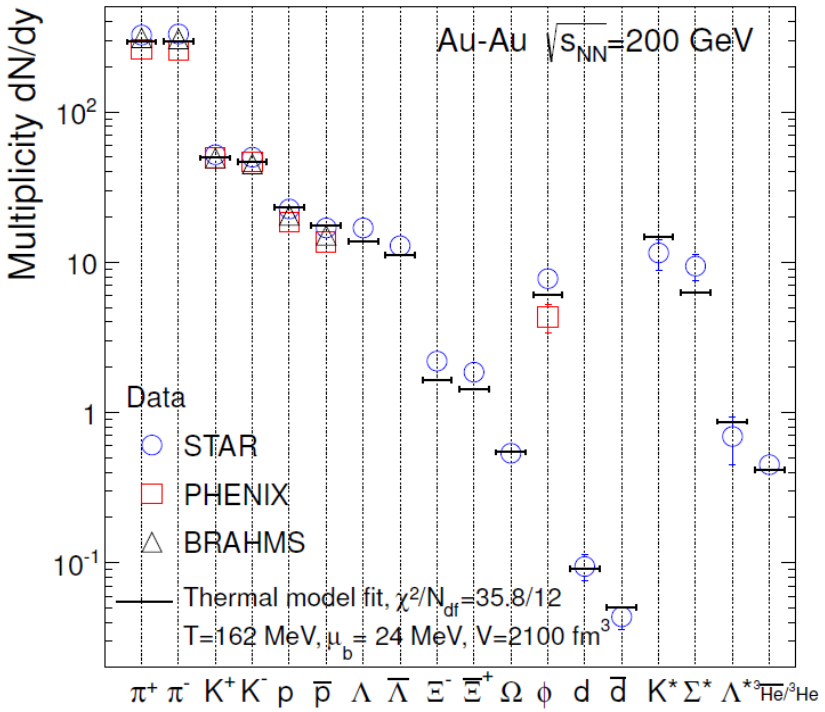


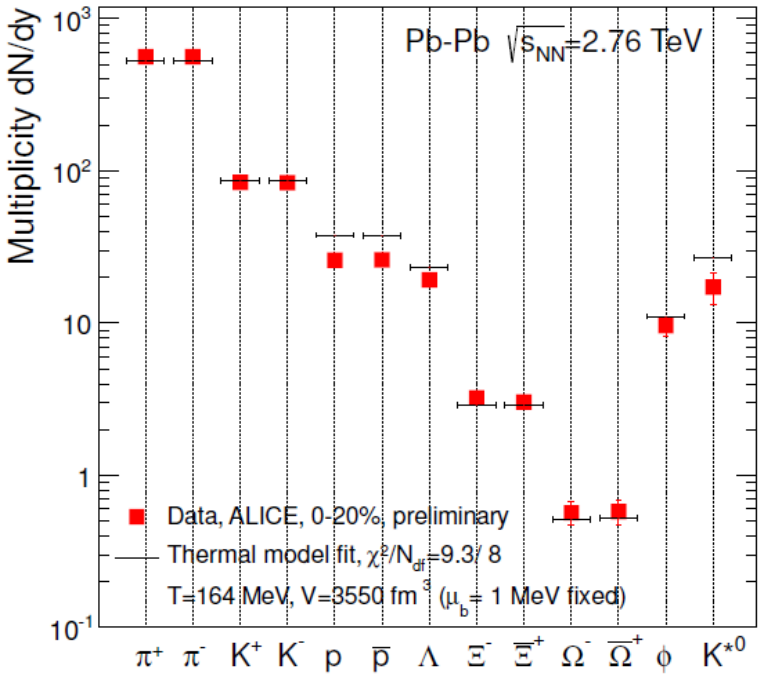


$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V \left(\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm} \right) + g_c^2 V \left(\sum_i n_{\psi_i}^{therm} \right) + \ldots.$$

- J/psi yields are not thermal, however the ψ'/J/ψ ratio reaches the thermal value in central collisions -> direct production of c-cbar pairs and statistical hadronization

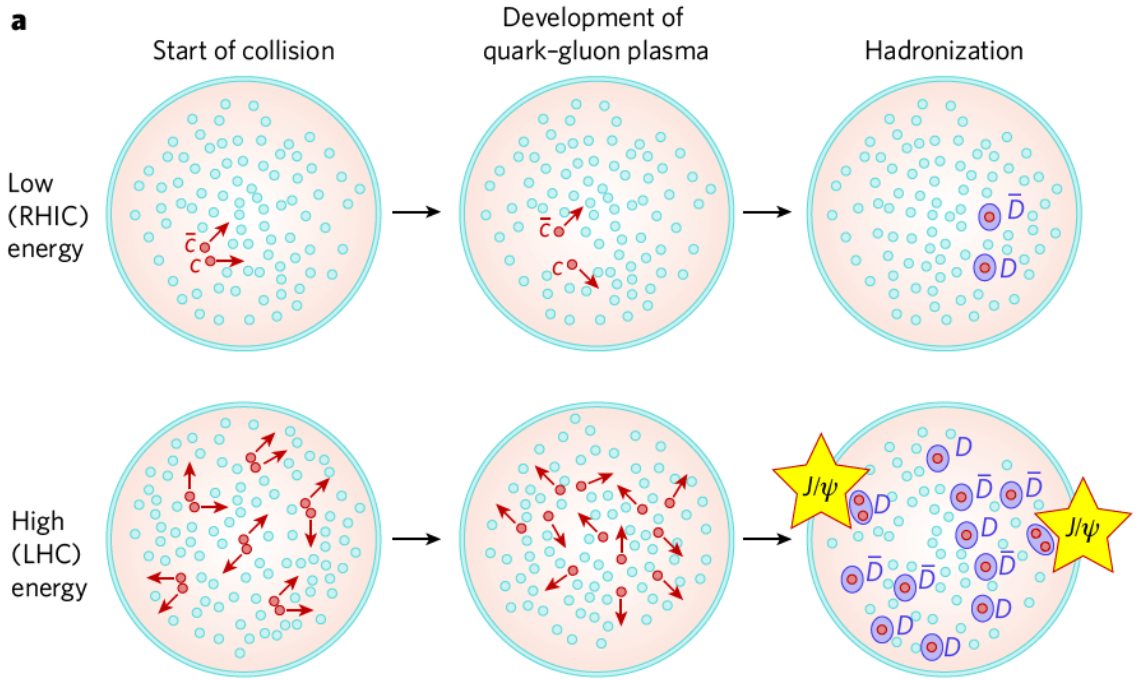
Statistical hadronization





- Light and strange flavoured particle yields well fitted at RHIC and LHC using 3 parameters (T,μ,V)
- Model is fully constrained if the total cc-bar density is specified

Heavy quarkonium at the LHC



- At the LHC, there are many charm quark-pairs created in one single collision (~100)
- Possible to create charmonium states on a statistical basis → enhancement of charmonium states at LHC

Phenomenological models for nuclear collisions

Dissociation / regeneration model

R.Thews, M. Schroedter, J.Rafelski PRC62 (2000) 024905

- Dynamical evolution of the cc-bar pairs produced in central collisions
- Medium is an ideal gas of free gluons and light quarks
- J/psi dissociation via interactions with free thermal gluons

$$J/\psi + g \rightarrow c\bar{c}$$

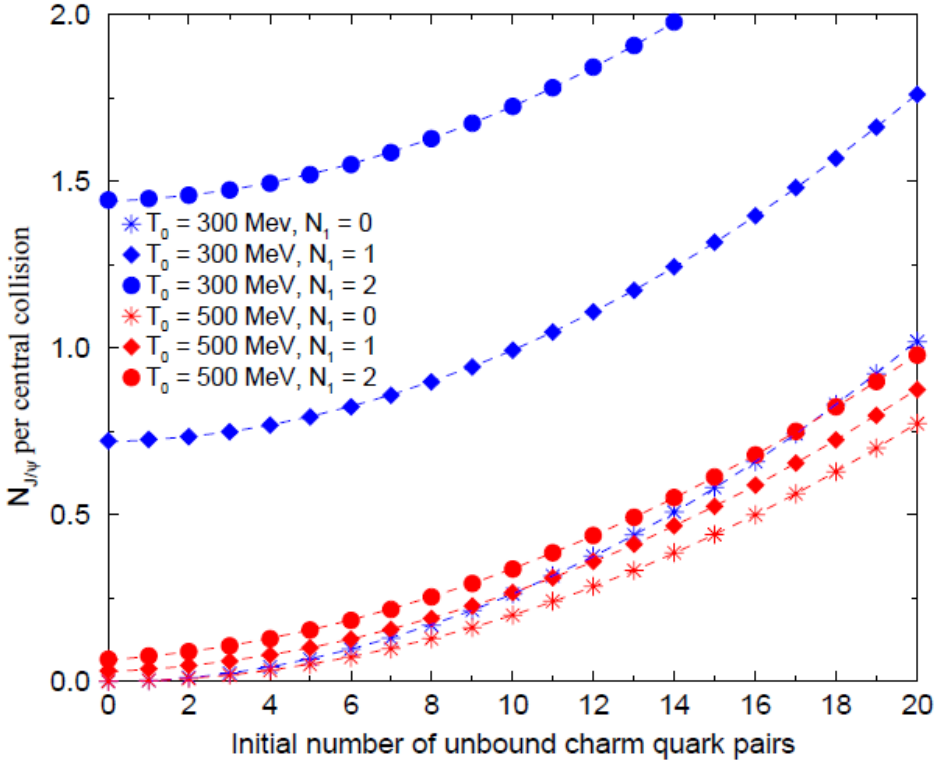
- Formation mechanism is the inverse of the dissociation reaction (detailed balance)

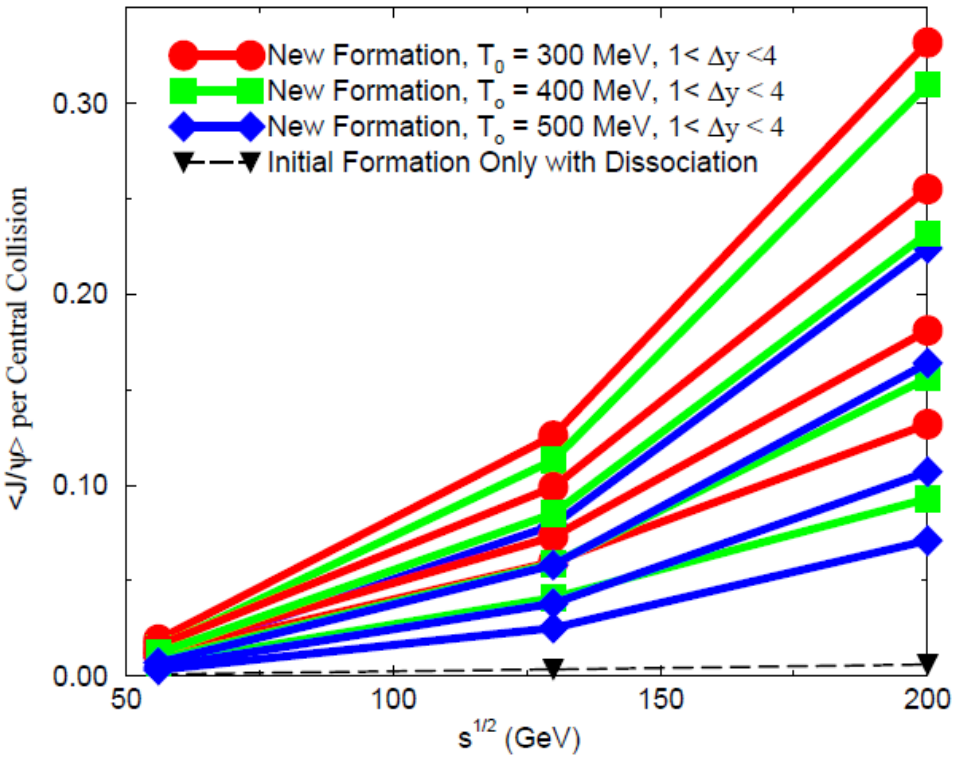
$$c\bar{c} \rightarrow J/\psi + g$$

- Kinetic rate equation

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_{\mathrm{F}} N_c \rho_{\bar{c}} - \lambda_{\mathrm{D}} N_{J/\psi} \rho_g$$

Dissociation / regeneration model





Central collisions at RHIC

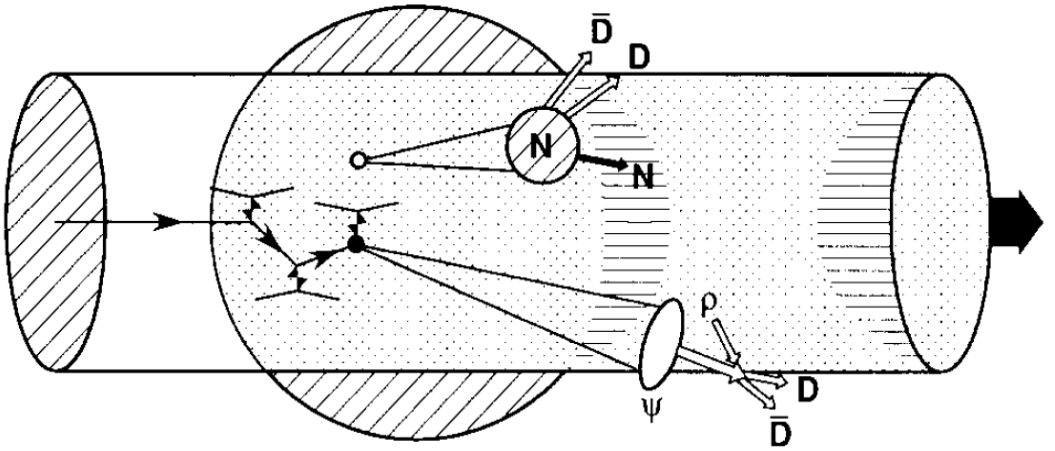
T_0-Initial temperature;

N_1-initial number of J/ψ

- Predicted J/psi yields are much larger than data

Comover models

S.Gavin, M.Gyulassy, A.Jackson 1988

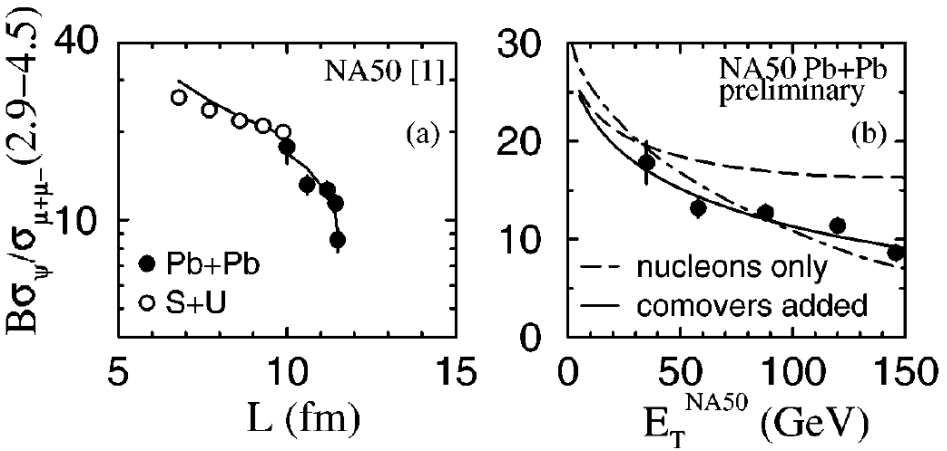


S.Gavin, R.Vogt, Nucl.Phys.B345 (1990) 104

Comovers: Produced soft particles which may interact with the Ψ states leading to

- Chemical reactions: e.g. $\Psi\pi \leftrightarrow \eta_c\pi\pi$
- Dissociation: e.g. Ψ+ρ(ω)->D+anti-D

Ψ suppression at SPS energies arising from scattering with nucleons and comovers



S.Gavin, R.Vogt, PRL 78 (1997) 6

Comover models

- A.Capella, E.G.Ferreiro EPJC 42 (2005) 419
- Initial state nuclear effects (shadowing and nuclear absorption) taken into account
- Ψ dissociation via interactions with the comoving matter (no thermal equilibrium is required)

$$\tau \frac{\mathrm{d}N_{J/\psi}}{\mathrm{d}\tau}(b, s, y) = -\sigma_{\mathrm{co}} N^{\mathrm{co}}(b, s, y) N_{J/\psi}(b, s, y),$$

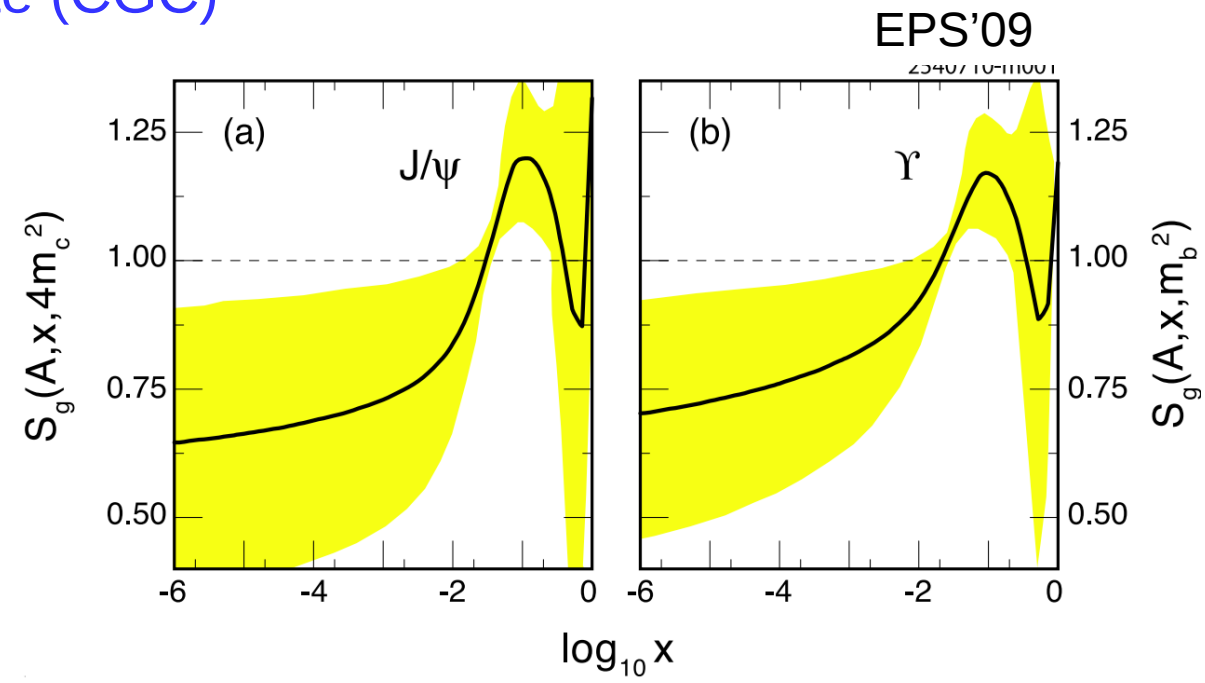
- Initial model contained no Ψ (re)generation mechanisms

Microscopic transport

- Main transport models
  - Texas model: X.Zhao, R.Rapp NPA859 (2011) 114
  - Tsingua model: Y.Liu, P.Zhuang et al. PLB678 (2009) 72
- Boltzmann equation accounting for both suppression and regeneration reactions
- Use spectral properties of charmonia from lattice QCD
- Modeling of the medium evolution
- Main source of model uncertainty is the total open-charm cross-section and its shadowing in Pb-Pb collisions

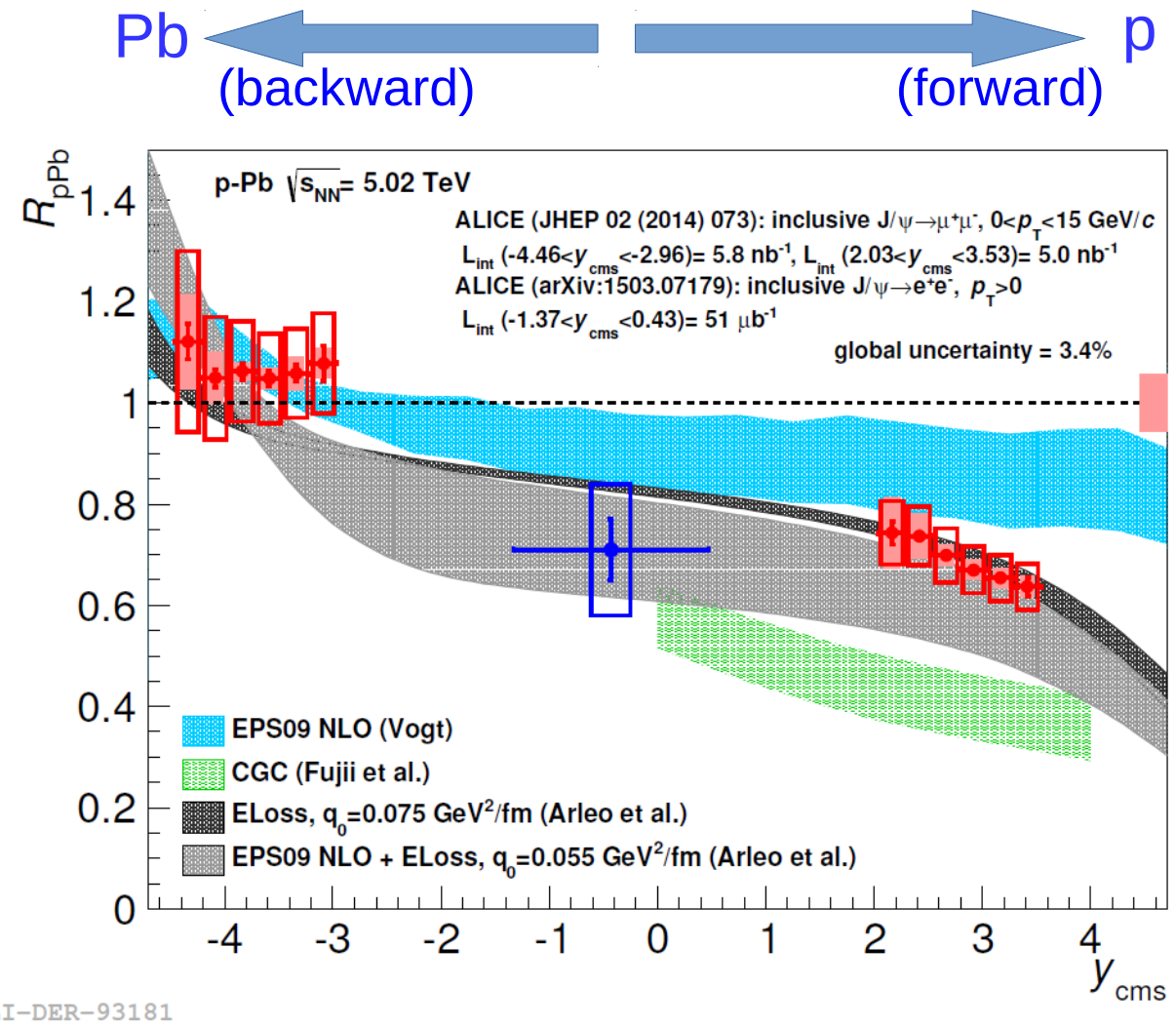
Cold nuclear matter (CNM) effects

- Initial state
  - Modification of the parton PDF in nuclear matter: shadowing and Color Glass Condensate (CGC)



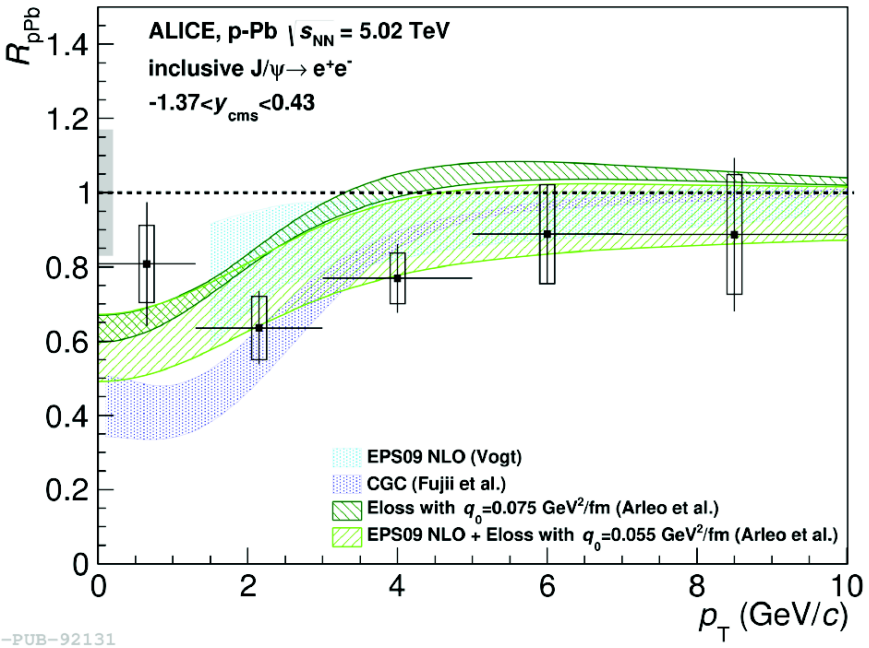
- Final state
  - Nuclear absorption, Cronin, comover interaction
- CNM effects studied using proton-nucleus collisions

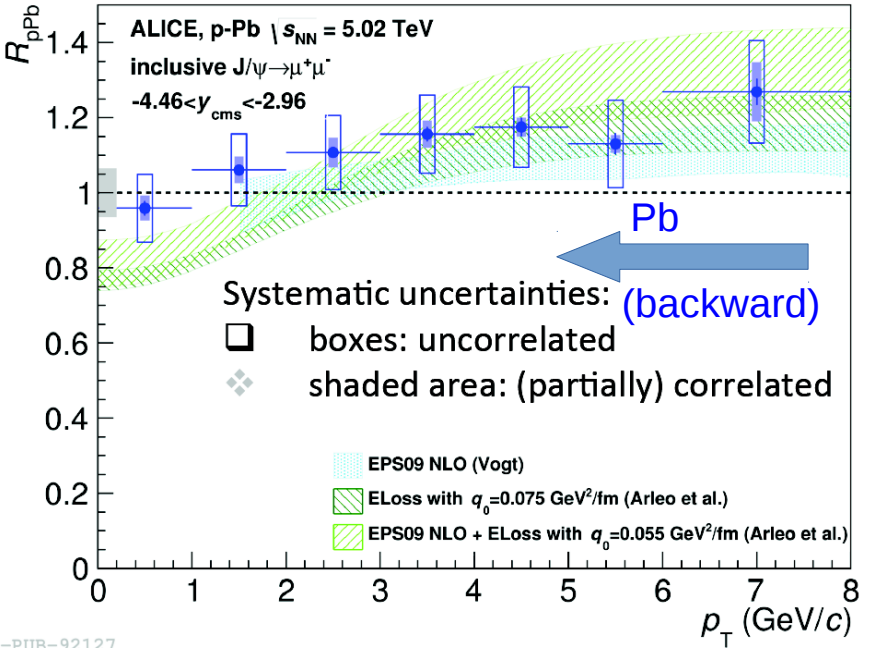
Inclusive J/ψ in p-Pb collisions

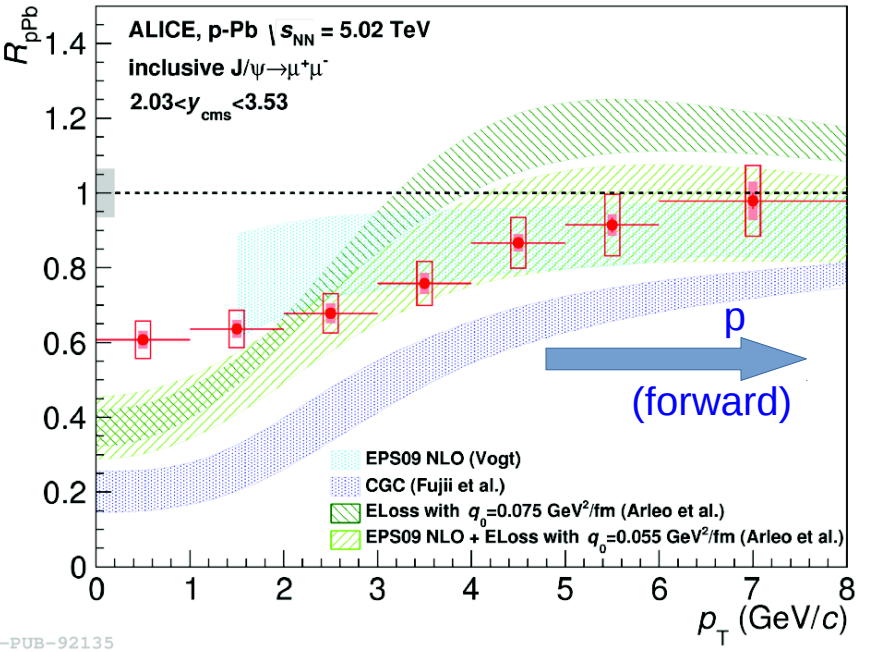


- J/ψ is suppressed at mid-rapidity and in the forward direction, compatible with energy loss (+shadowing) models
- No suppression observed in the backward direction

Inclusive J/ψ in p-Pb collisions

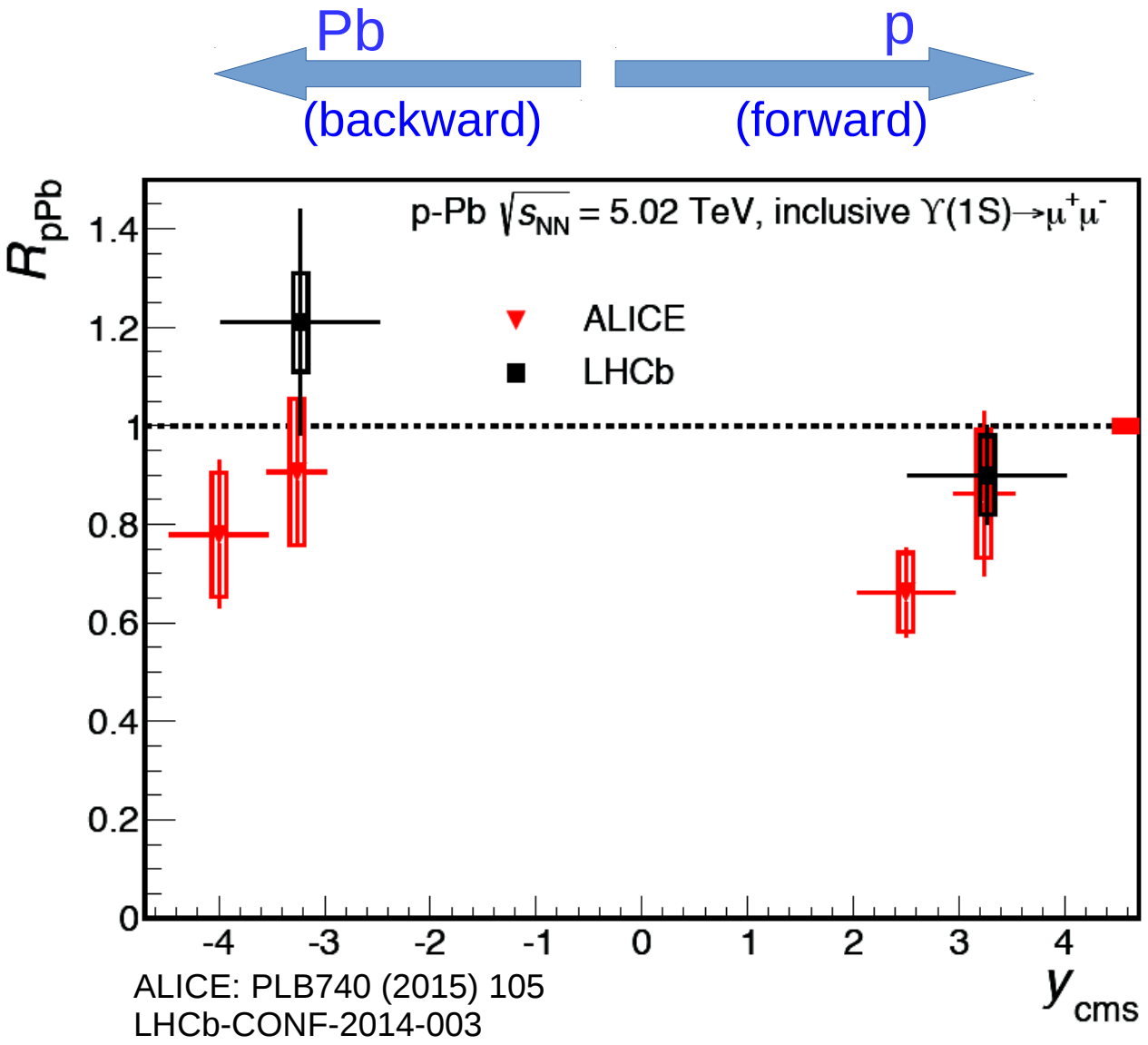






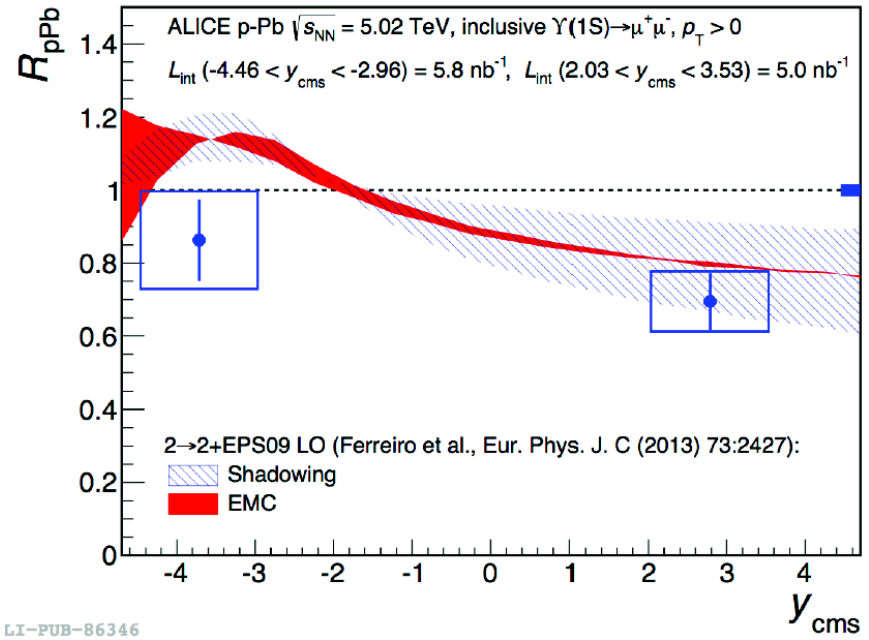
- J/ψ is suppressed at mid- and forward rapidity, except for the highest-p_T region
- R_{pPb} grows with p_T, consistent with expectations from shadowing and energy loss calculations
- Early CGC calculations overestimate the suppression at forward rapidity

Y(1S) in p-Pb collisions

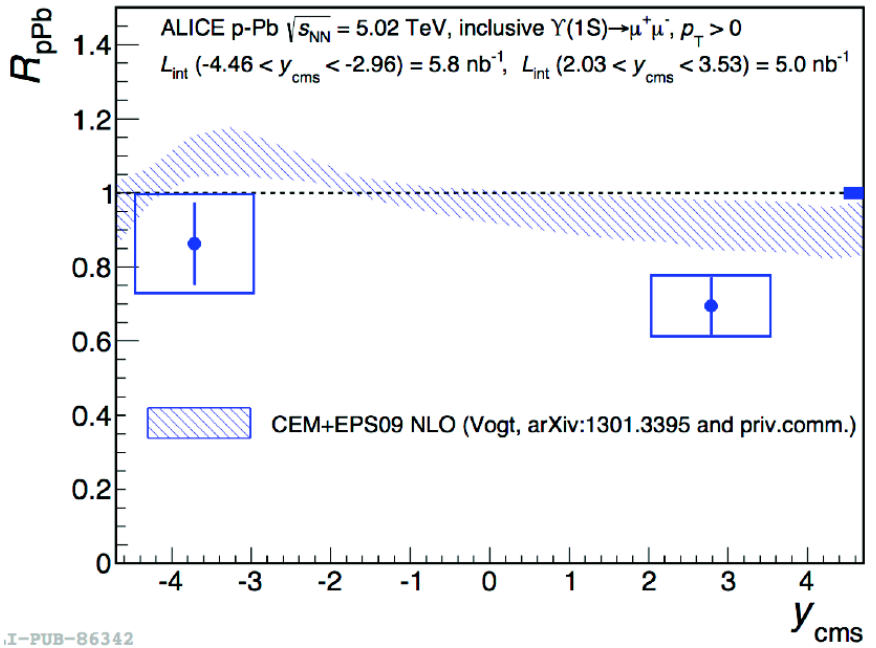


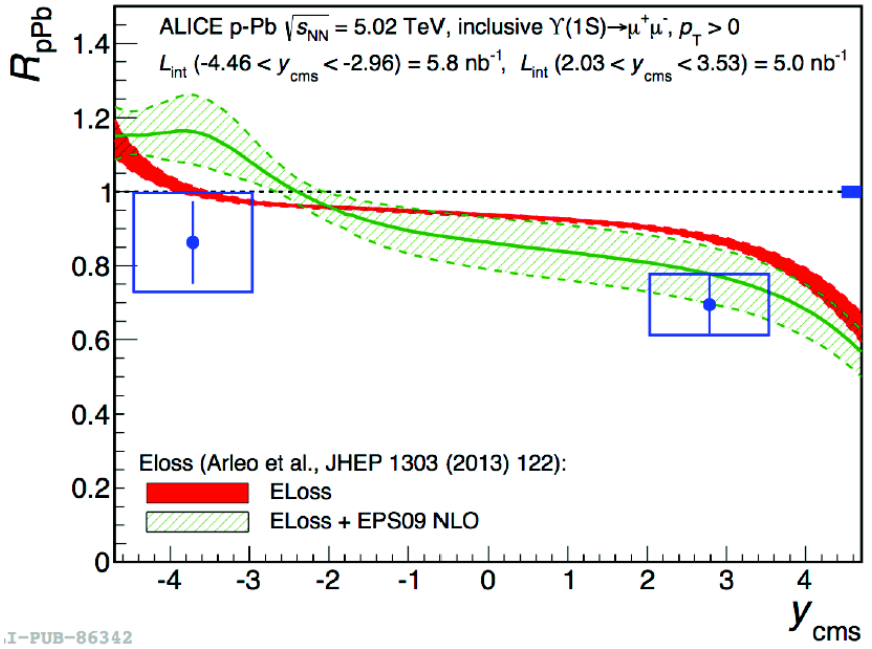
- Indication of a suppression at forward rapidity
- Consistent with no suppression at backward rapidity

Υ(1S) in p-Pb collisions



PLB740(2015)105





- Fair agreement with various calculations including:
  - 2->2 production model at LO (Ferreiro et al.)
  - CEM at NLO (Vogt)
  - Coherent parton energy loss (Arleo et al.)

Quarkonium measurements in AA collisions

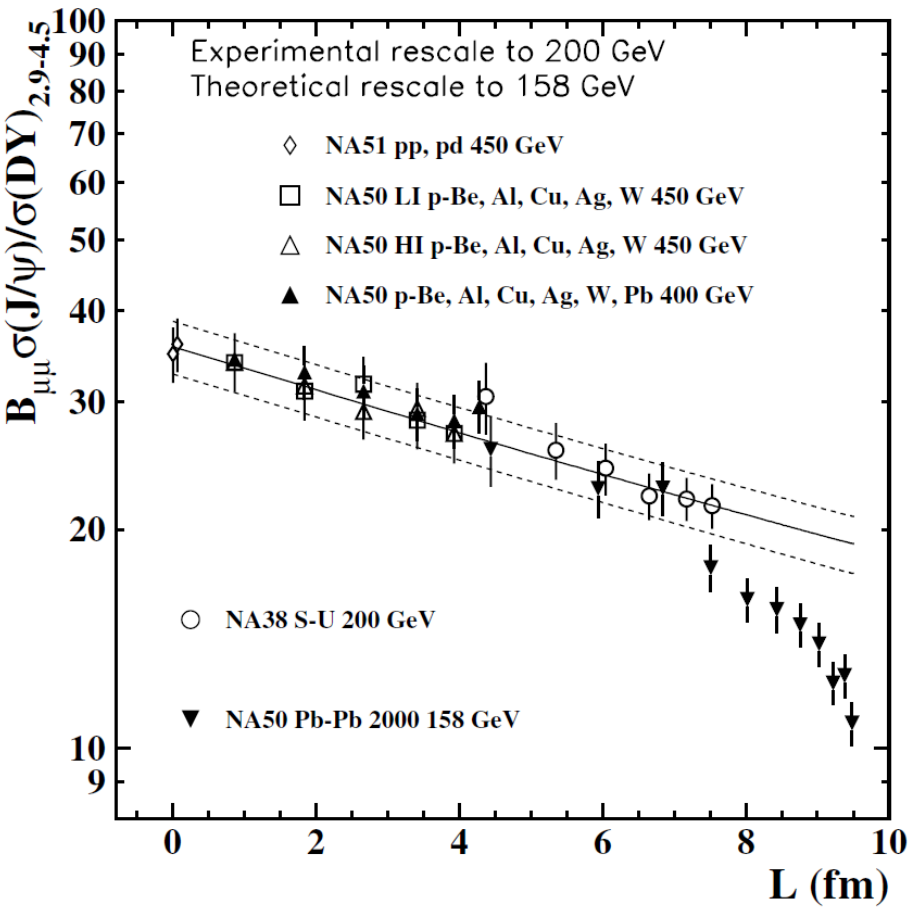
- SPS-CERN: $\sqrt{s_{NN}}$=17 GeV
  - NA38, NA50, NA60 Collaborations
  - S-U, In-In, Pb-Pb
- RHIC-BNL: $\sqrt{s_{NN}}$=39,63,200 GeV
  - PHENIX and STAR Collaborations
  - Cu-Cu, Cu-Au, Au-Au, U-U
- LHC-CERN: $\sqrt{s_{NN}}$=2760, 5020 GeV
  - ALICE, ATLAS, CMS and LHCb Collaborations
  - Pb-Pb

Charmonium measurements

SPS (17 GeV)

J/ψ suppression at SPS

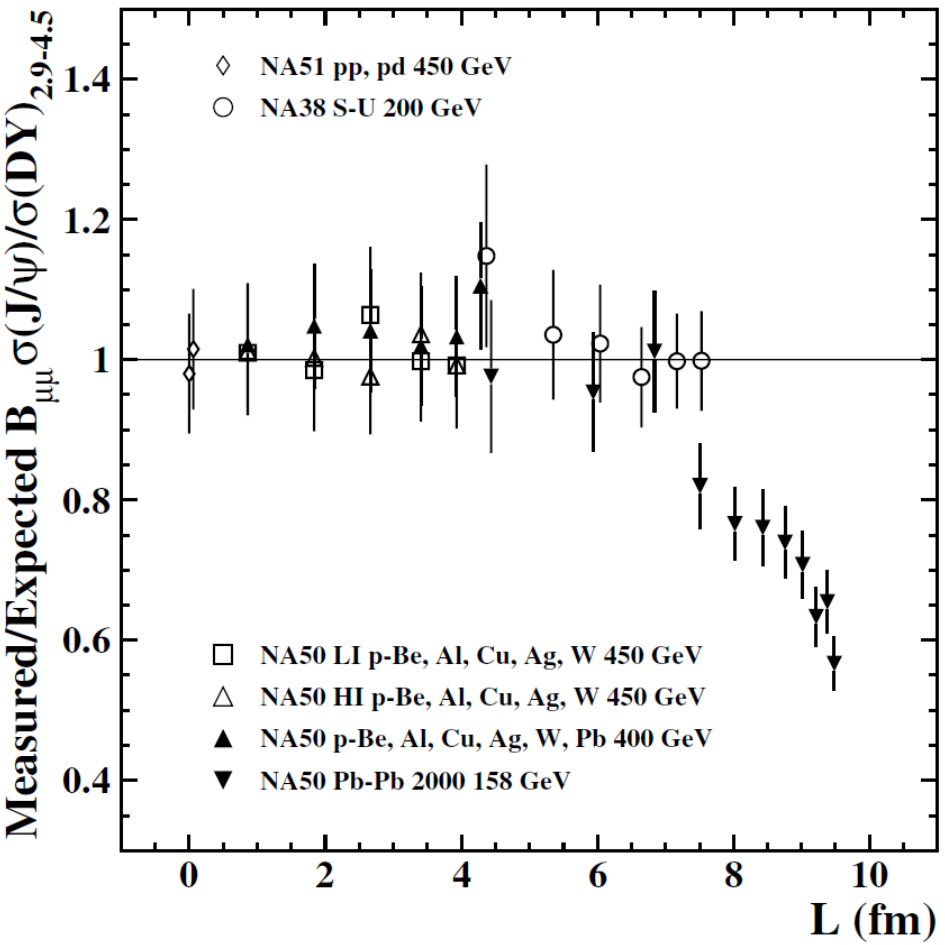
NA50 EPJC39 (2005) 335



- 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}

J/ψ suppression at SPS

NA50 EPJC39 (2005) 335

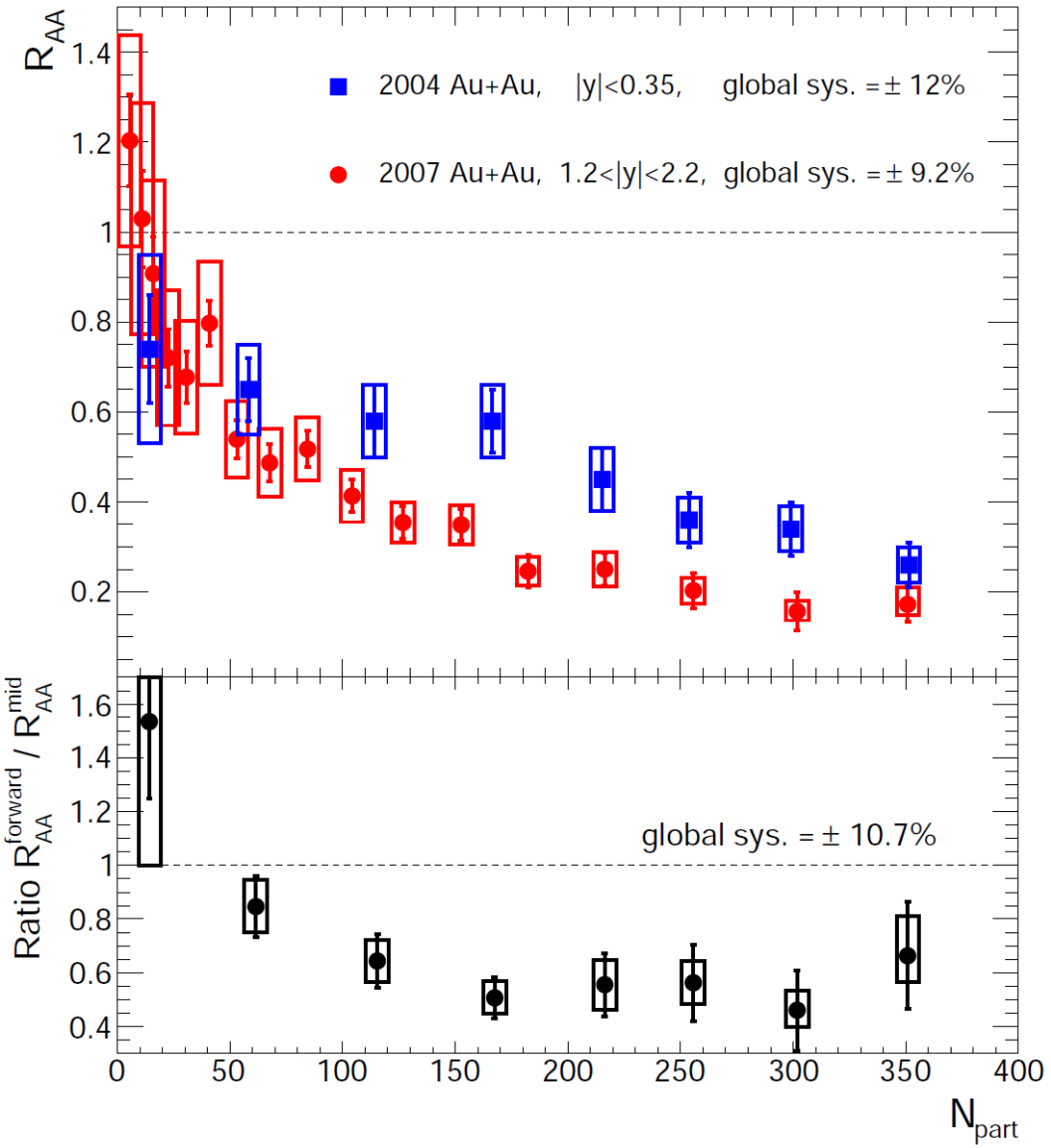


- p-A collision results well reproduced using an effective absorption cross-section σ_{abs} in the (cold) nuclear matter
- Nuclear modifications in nucleus-nucleus collisions:
  - Expected suppression from σ_{abs}
- First NA50 results indicated a sizable anomalous suppression for the J/ψ production in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

RHIC (200 GeV)

J/ψ suppression in Au-Au collisions

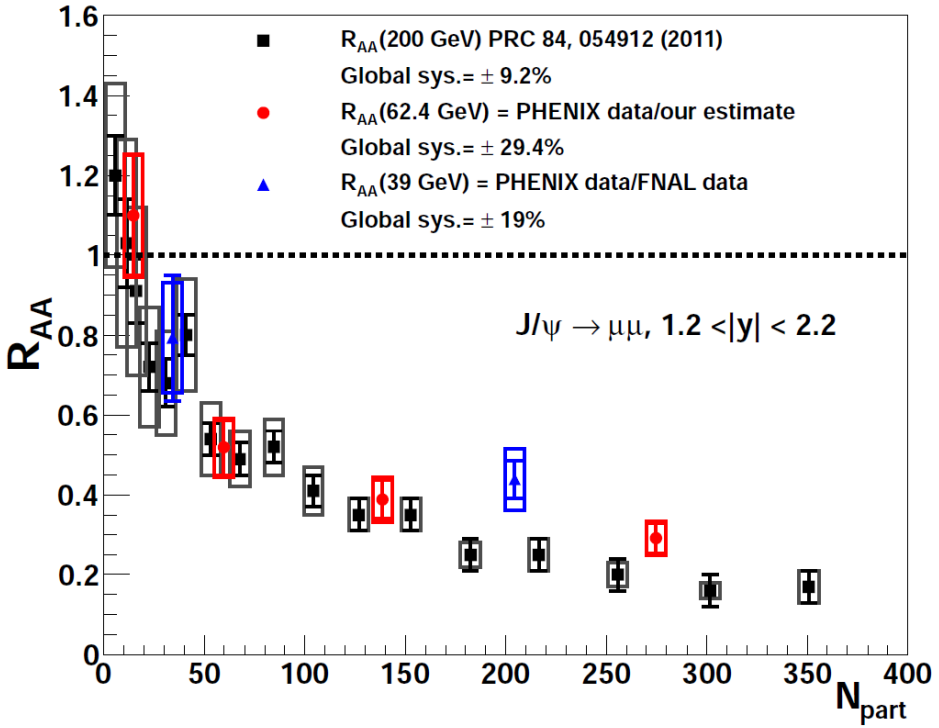
PHENIX arxiv:1103.6269



- Strong suppression both at mid- and forward-rapidity

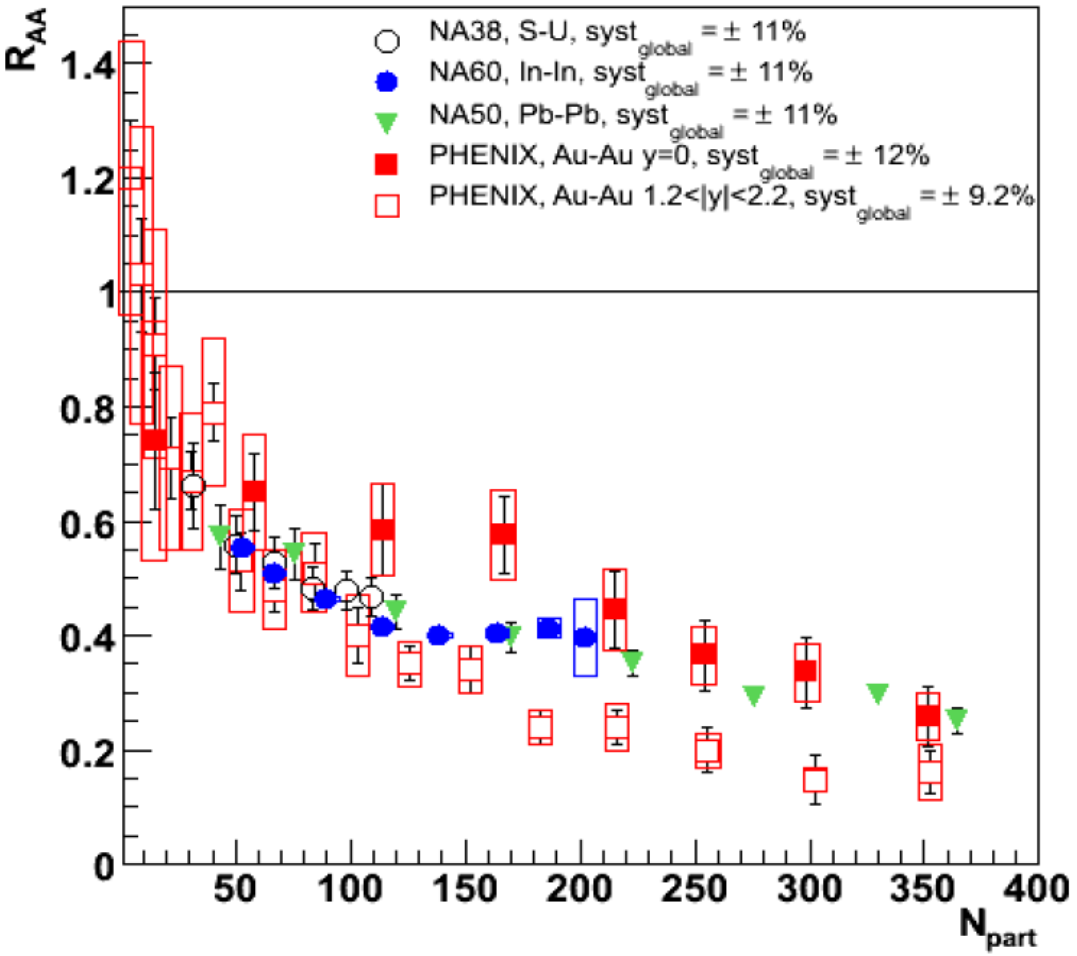
J/ψ suppression in Au-Au collisions

PHENIX arXiv:1208.2251



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

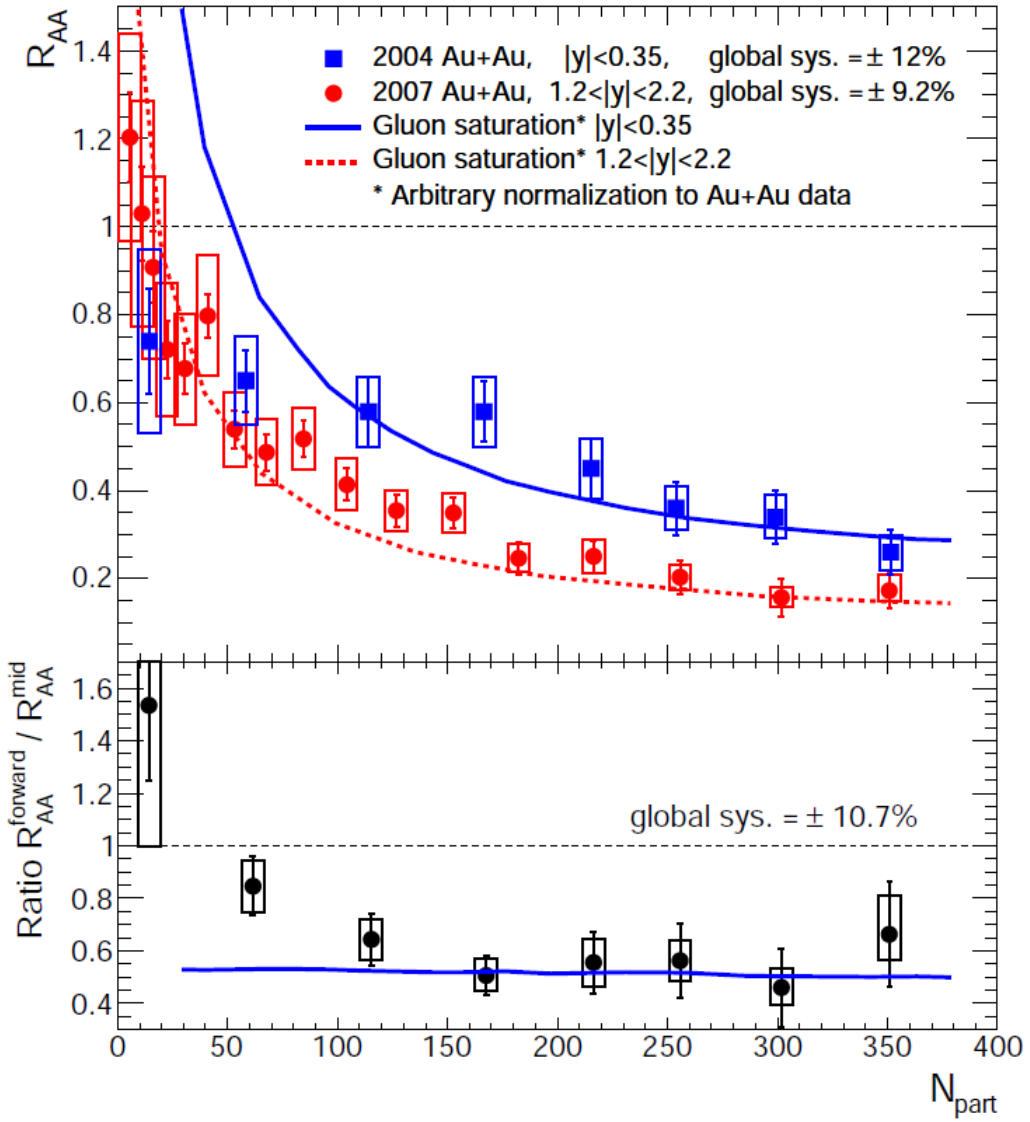
J/ψ suppression in Au-Au collisions



- 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

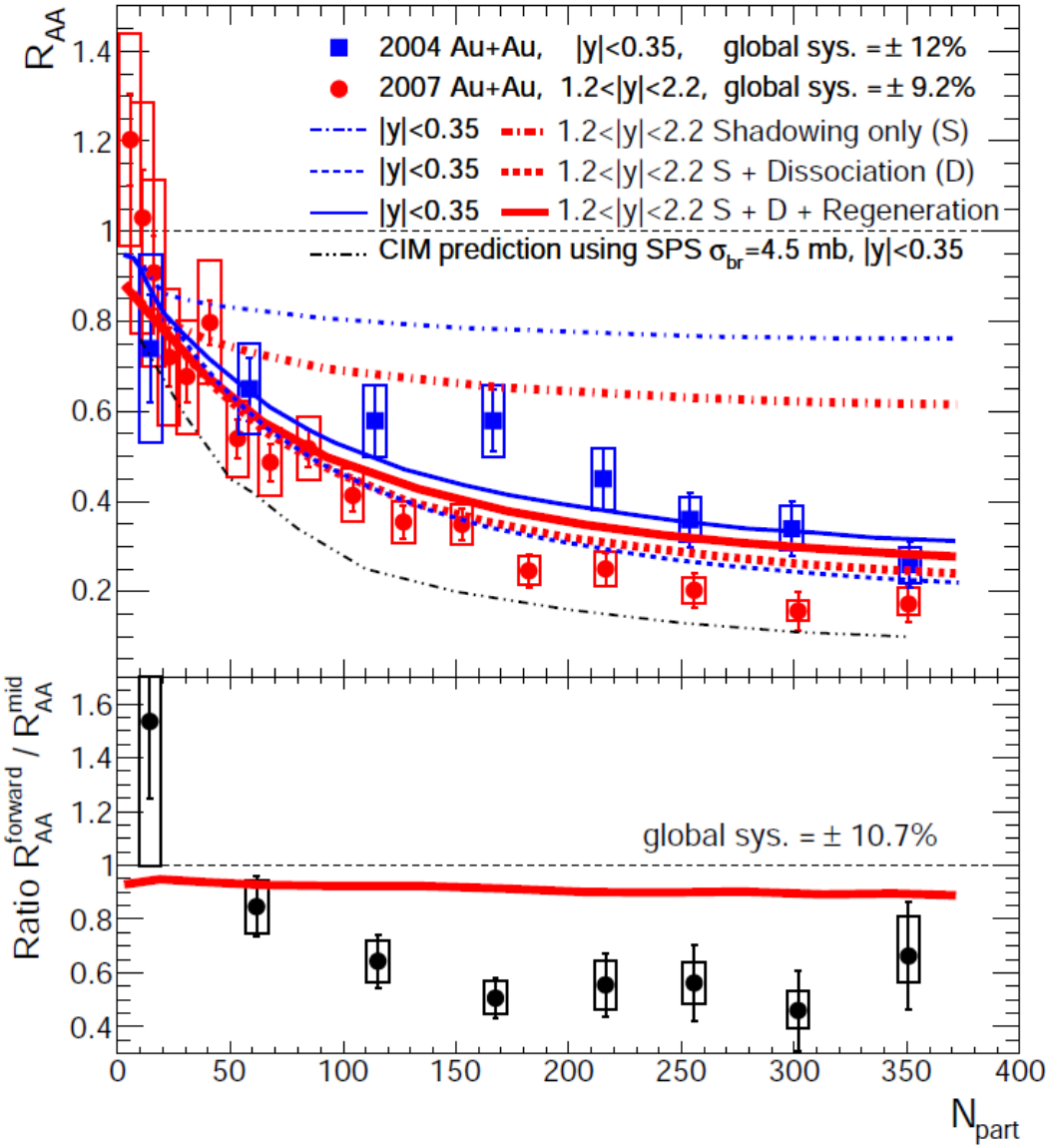
PHENIX arxiv:1103.6269



- 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

J/ψ suppression in Au-Au collisions

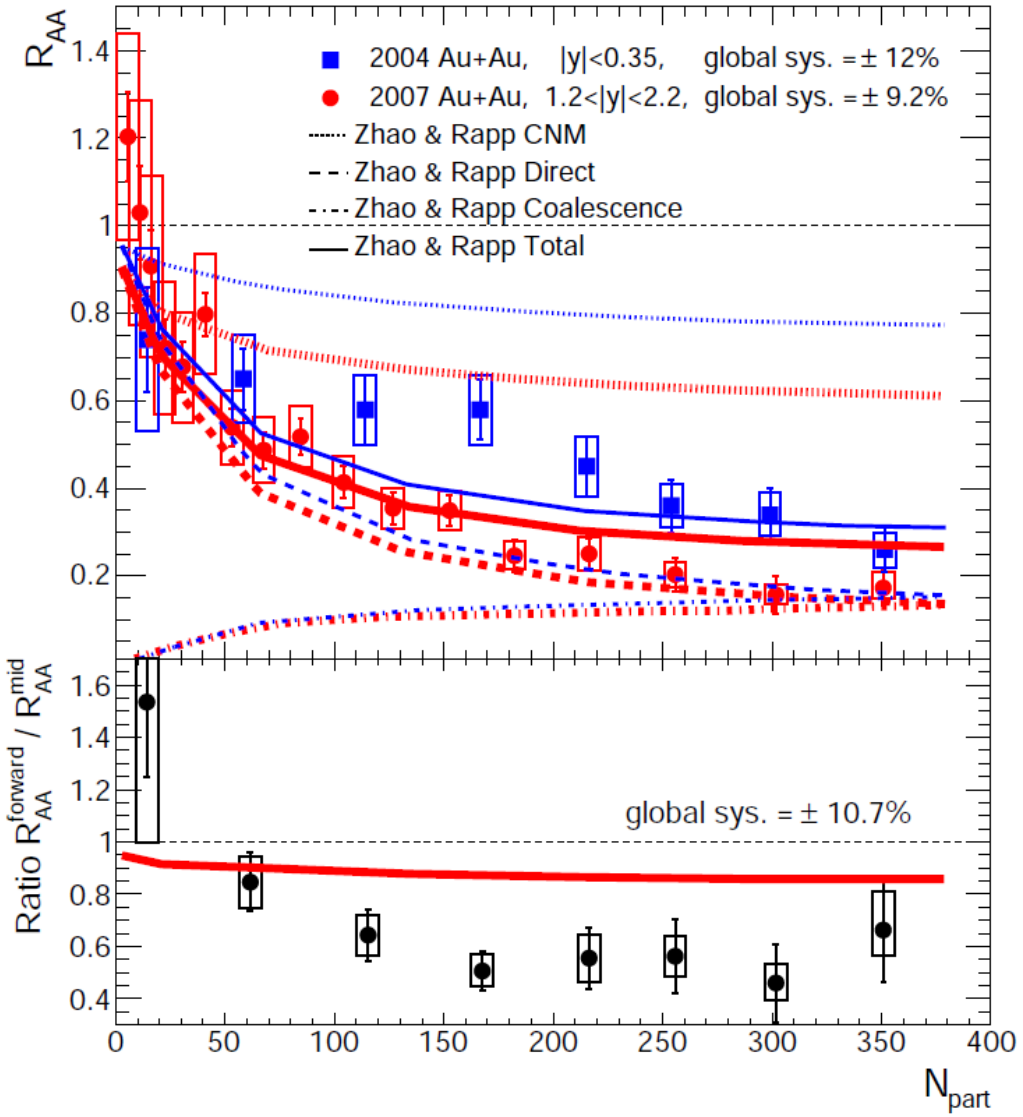
PHENIX arxiv:1103.6269



- 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

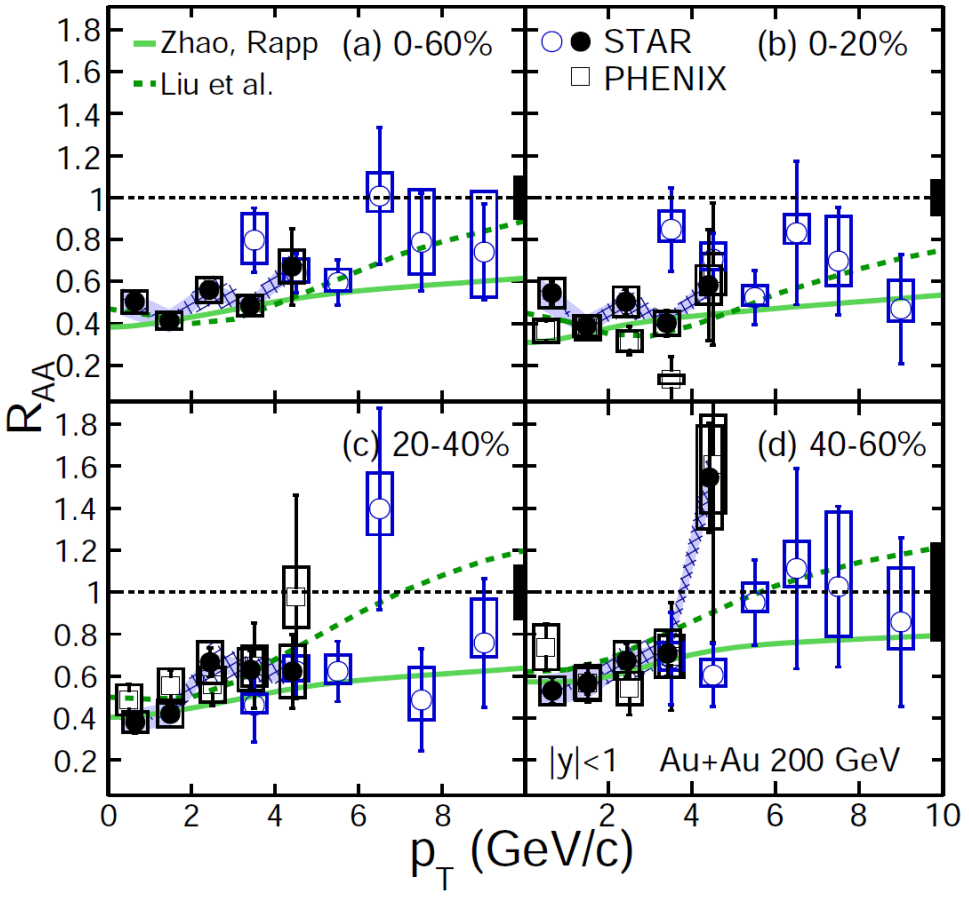
PHENIX arxiv:1103.6269



- 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
- The Texas transport model 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

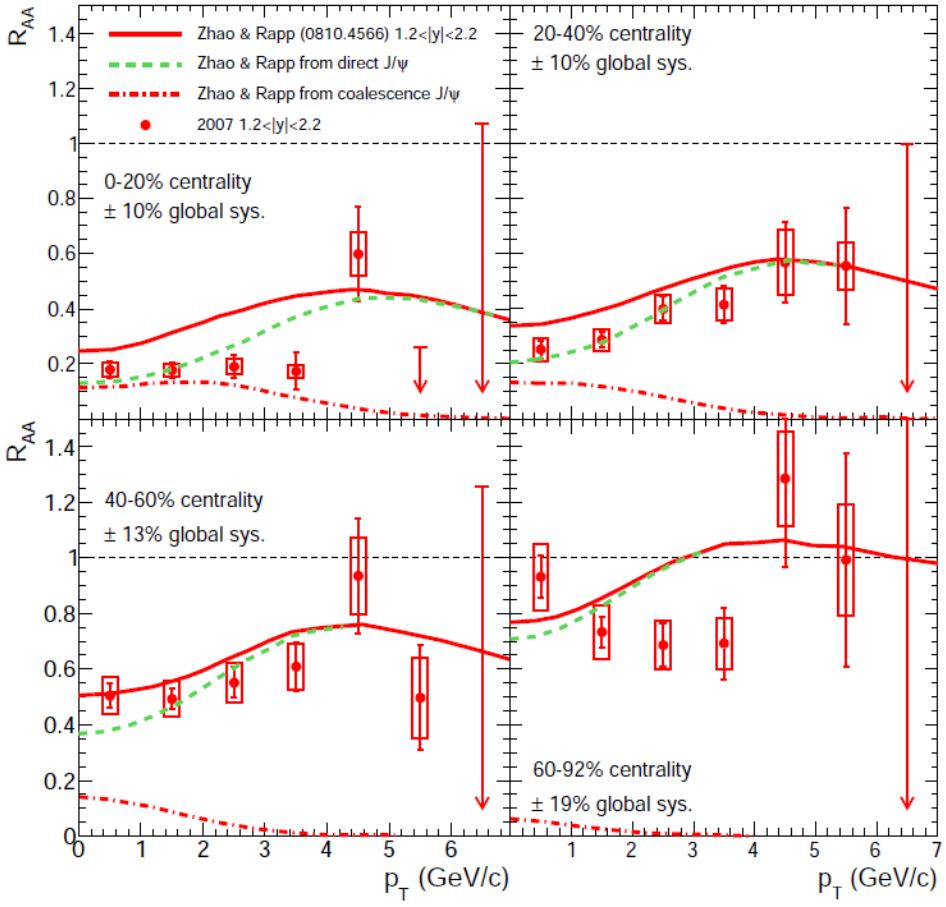
STAR arxiv 1310.3563



- 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

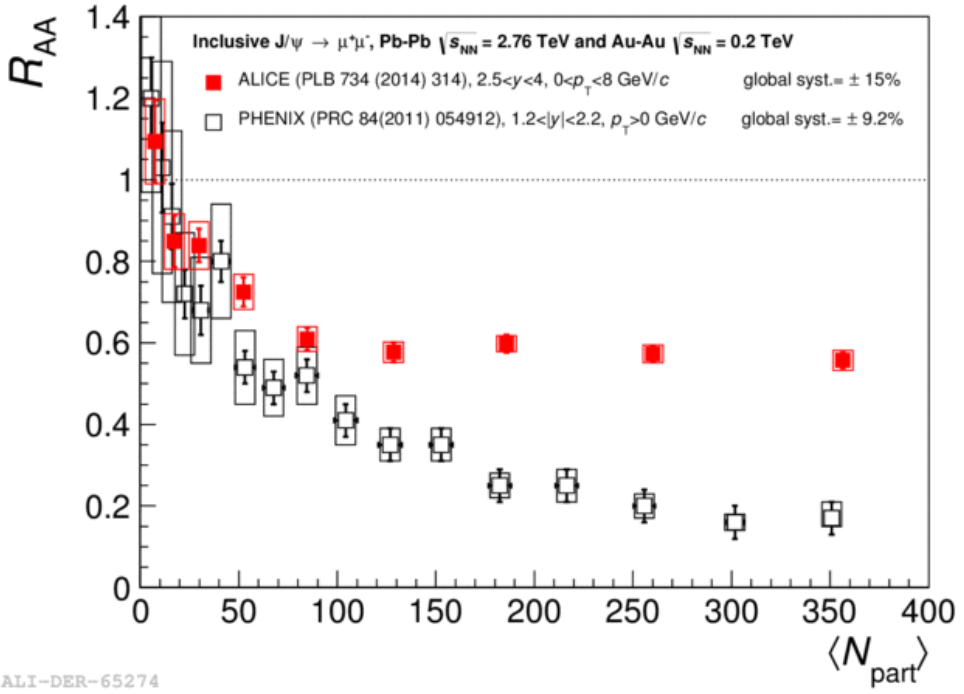
PHENIX arxiv:1103.6269

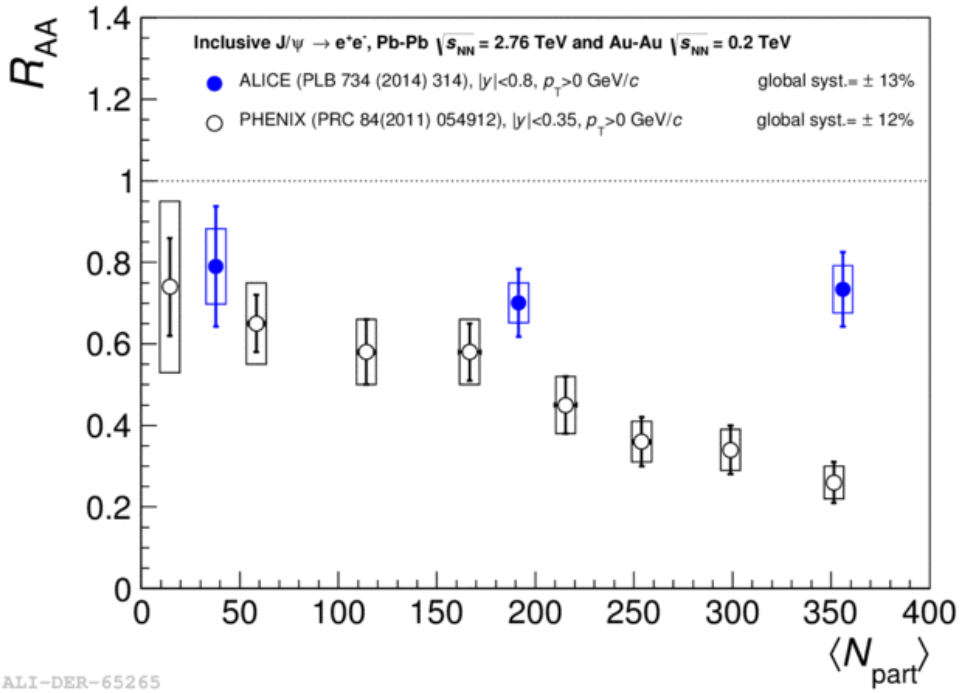


- Suppression is strongest at low p_T and decreases at high p_T
- Transport model calculations in good agreement with data
- Regeneration component contributes mainly at low p_T, as naively expected
- No clear evidence of charmonium regeneration at RHIC

LHC

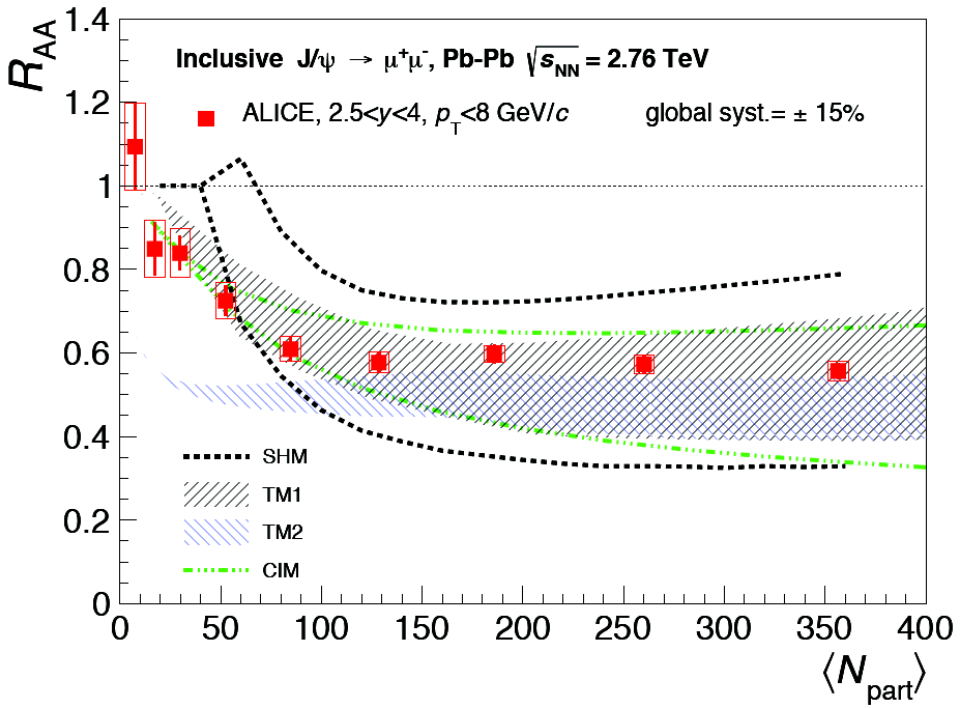
J/ψ suppression vs centrality (2.76 TeV)

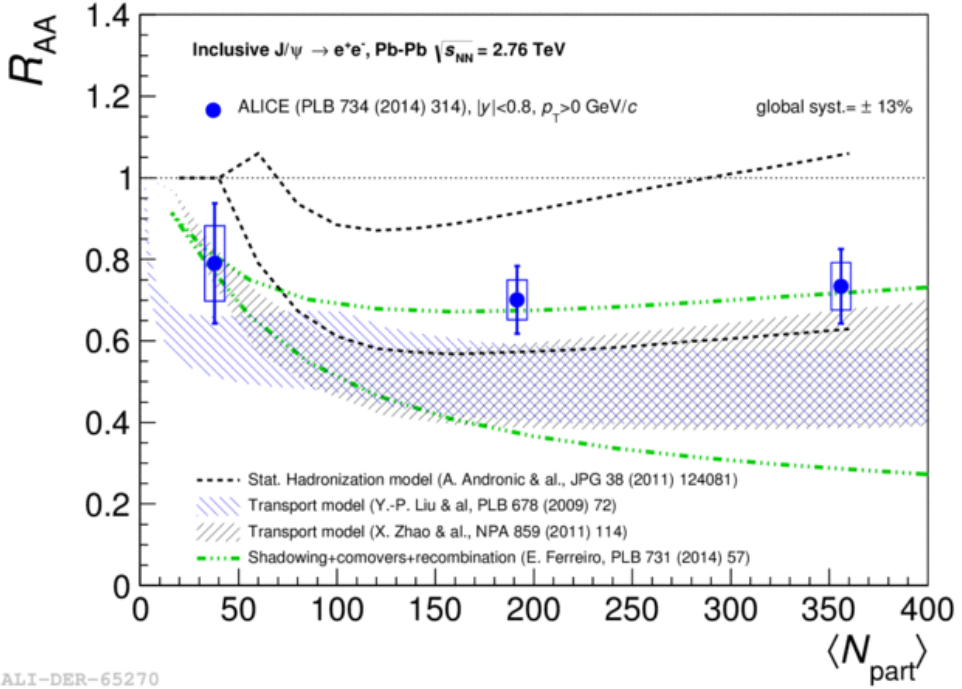




- Much less suppression in central and semi-central collisions wrt to the lower energy measurements
- Indication of a lower suppression at mid-rapidity compared to forward rapidity

J/ψ suppression vs centrality





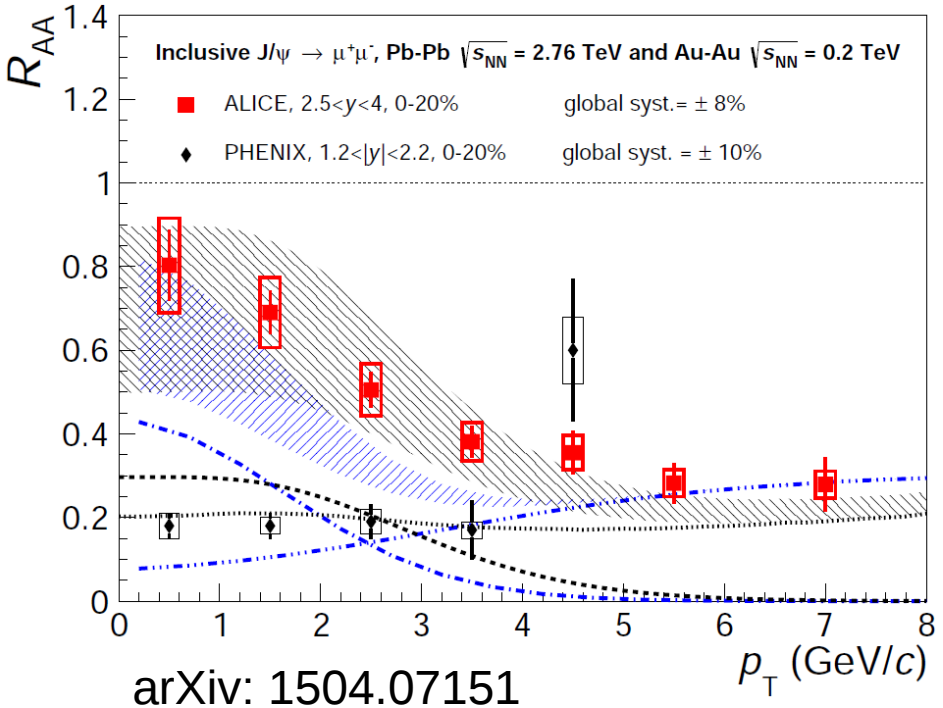
- Models which implement a regeneration component are in agreement with data
- Model uncertainties are dominated by the poor knowledge of the total $c\bar{c}$ cross-section / CNM effects

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

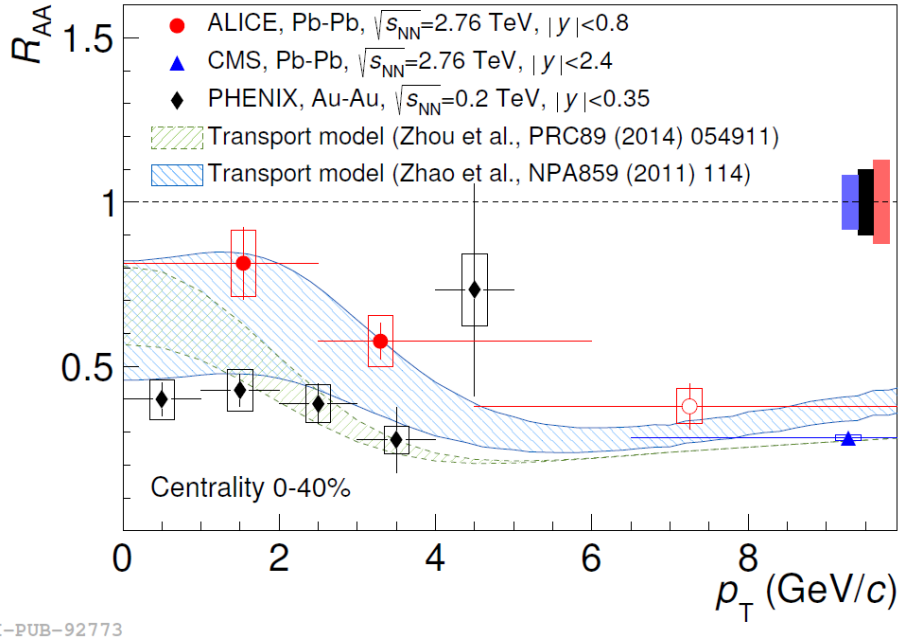
ALI-DER-65270

J/ψ suppression vs p_T

arXiv: 1506.08804



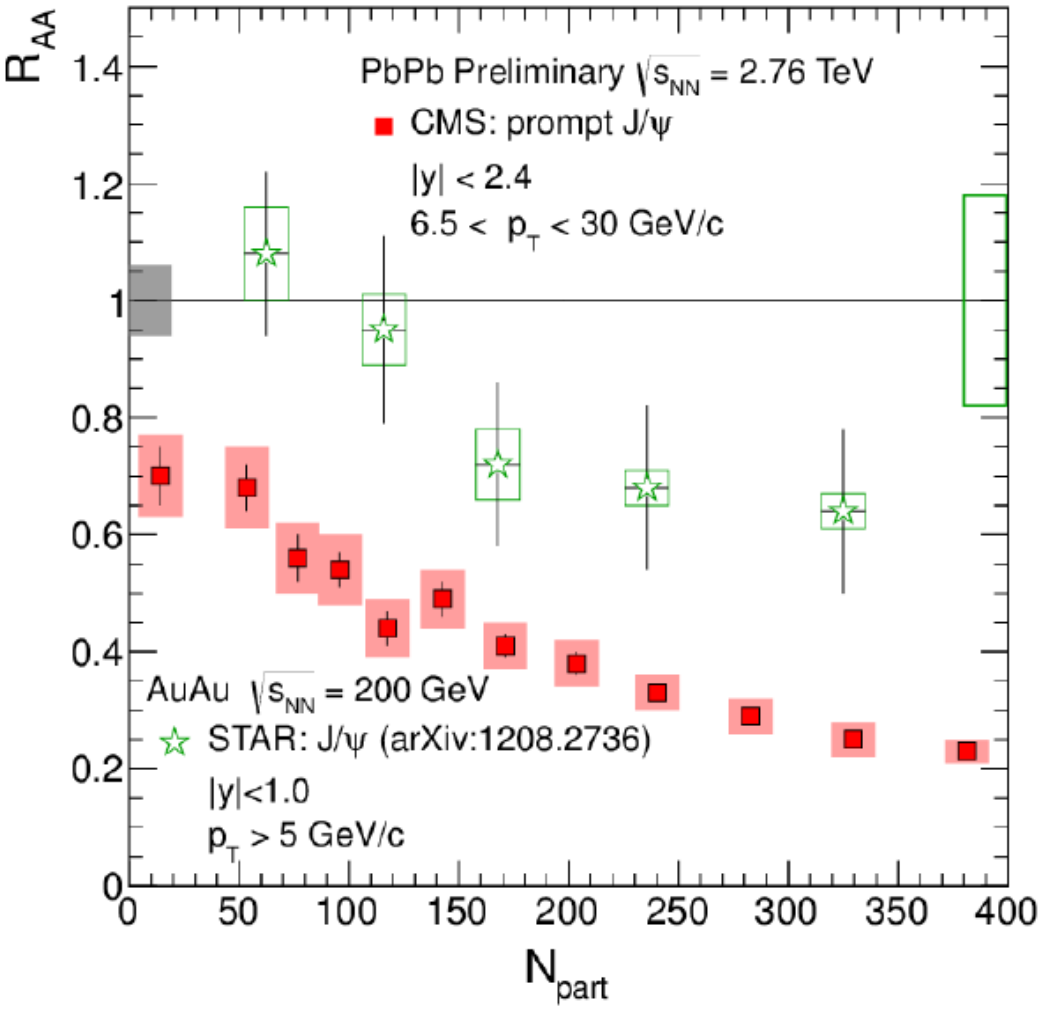
arXiv: 1504.07151



- Low p_T : striking difference between LHC and RHIC
- Clear evidence for (re)generation ?
- Transport model calculations using regeneration describe qualitatively the data

ALI-PUB-92773

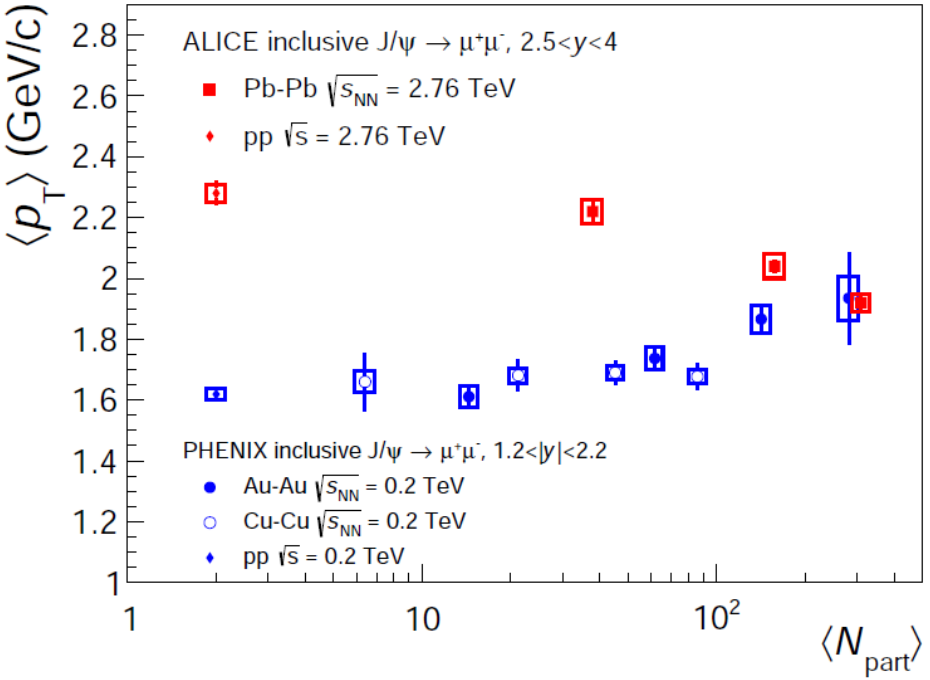
J/ψ suppression vs p_T

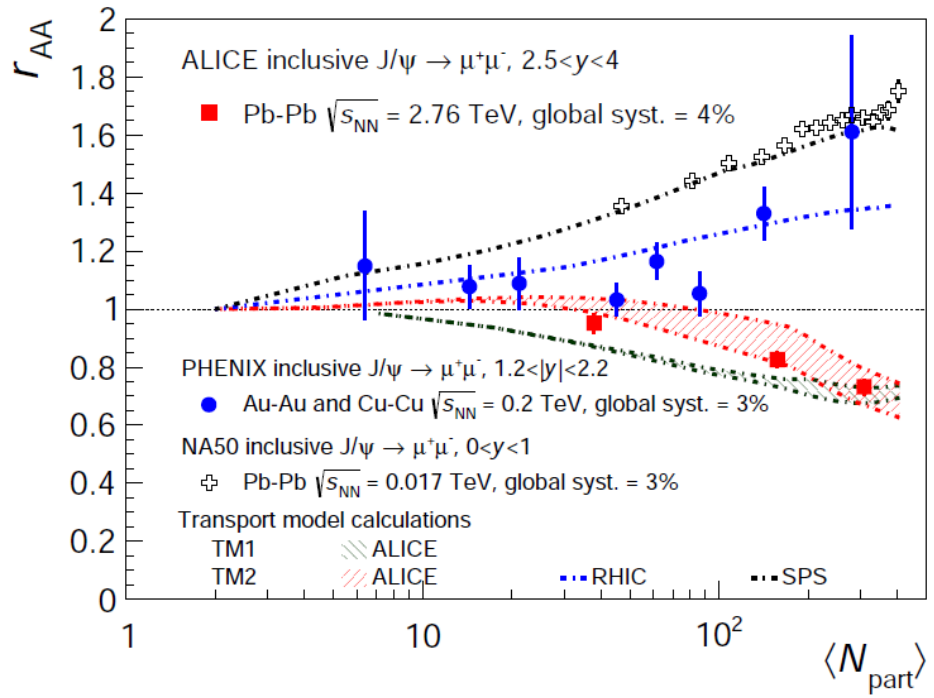


- High p_T : the suppression is stronger at LHC wrt RHIC, as expected

Modification of the J/ψ p_T distribution

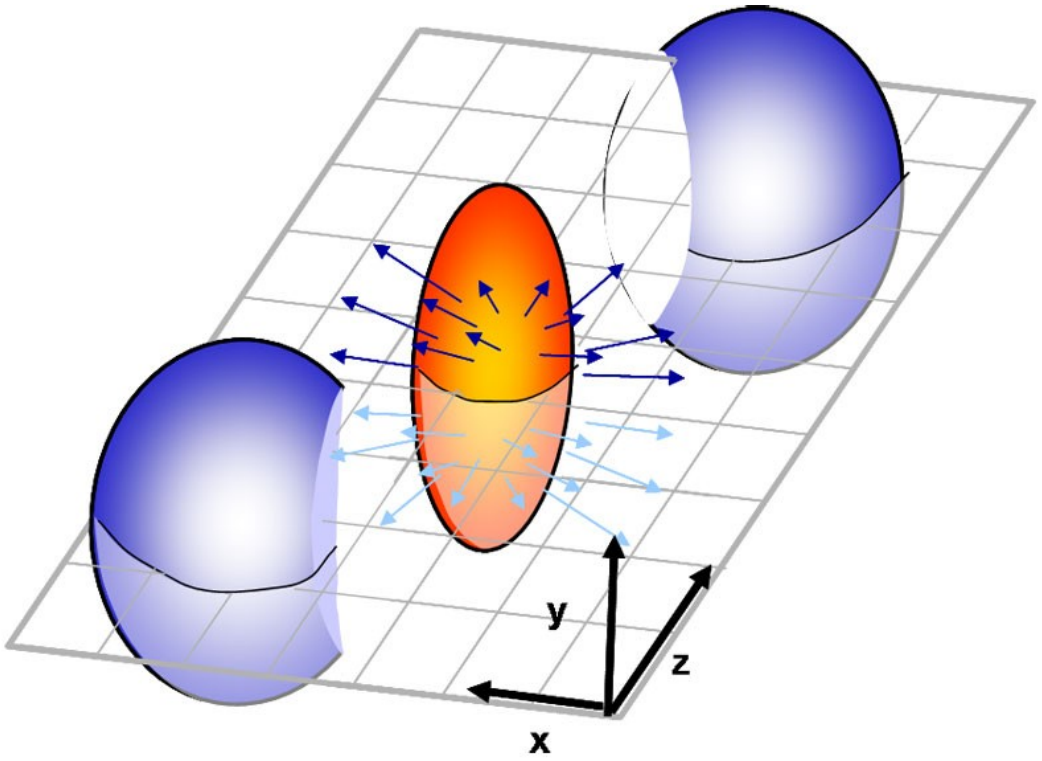
arXiv: 1506.08804

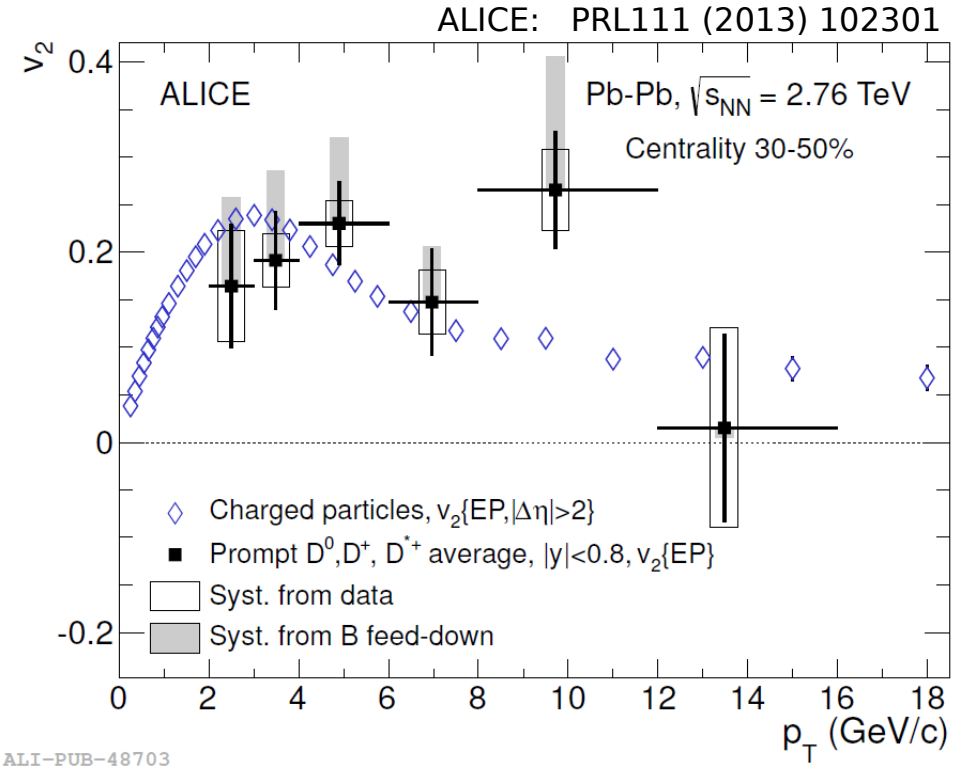




- <pT> drops with increasing collision centrality at LHC while it grows at RHIC
- $r_{AA} = \langle p_T^2 \rangle_{AA} / \langle p_T^2 \rangle_{pp}$
- r_{AA} (p_T distribution broadeness) decreases with increasing centrality at LHC while it strongly grows at SPS

Elliptic flow



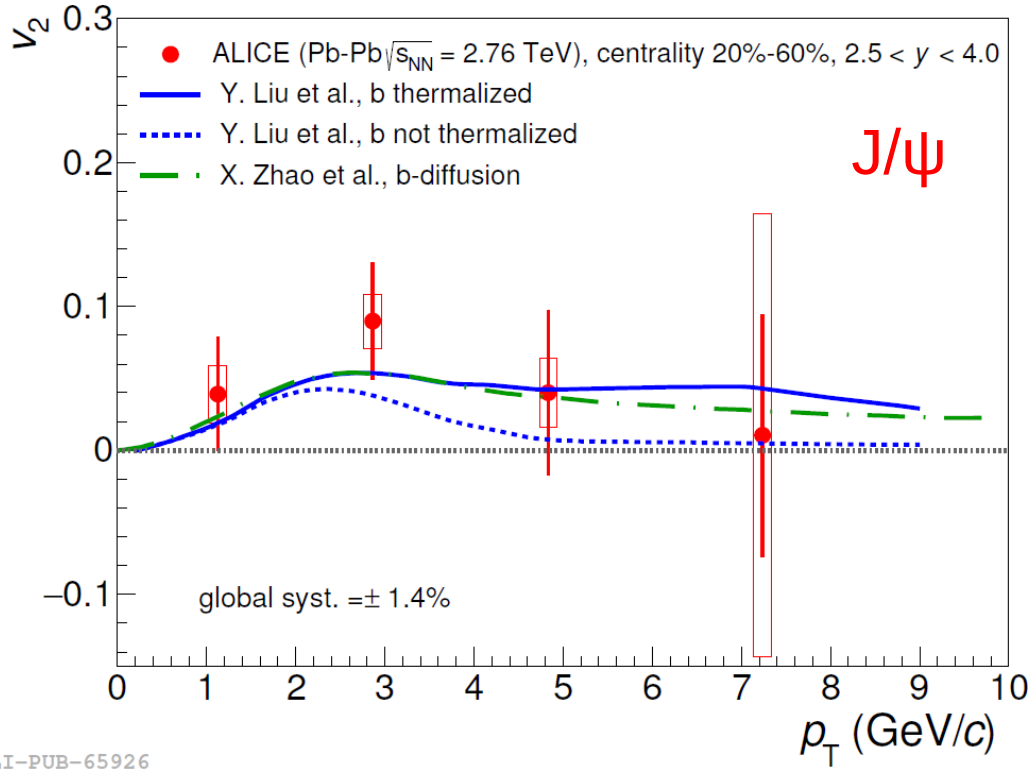


$$\frac{dN}{d\phi} \simeq 1+2v_1\cos(\phi-\Psi_r)+2v_2\cos(2(\phi-\Psi_r))+\ldots$$

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

Elliptic flow

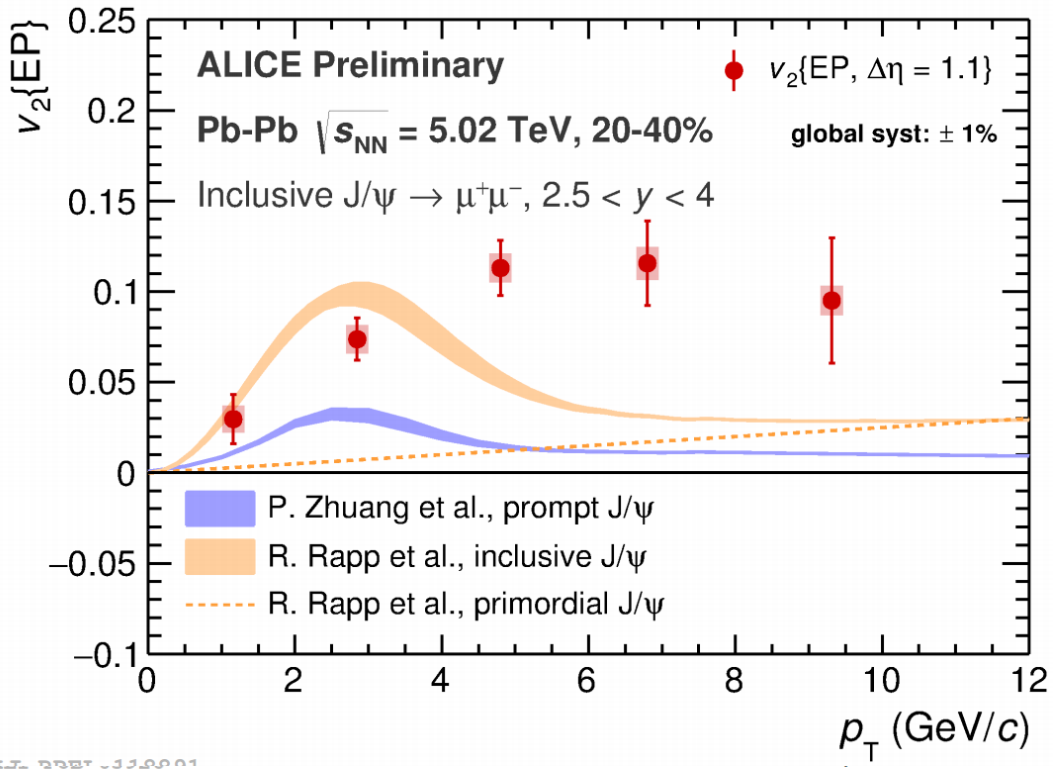
PRL111 (2013) 162301



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

Elliptic flow

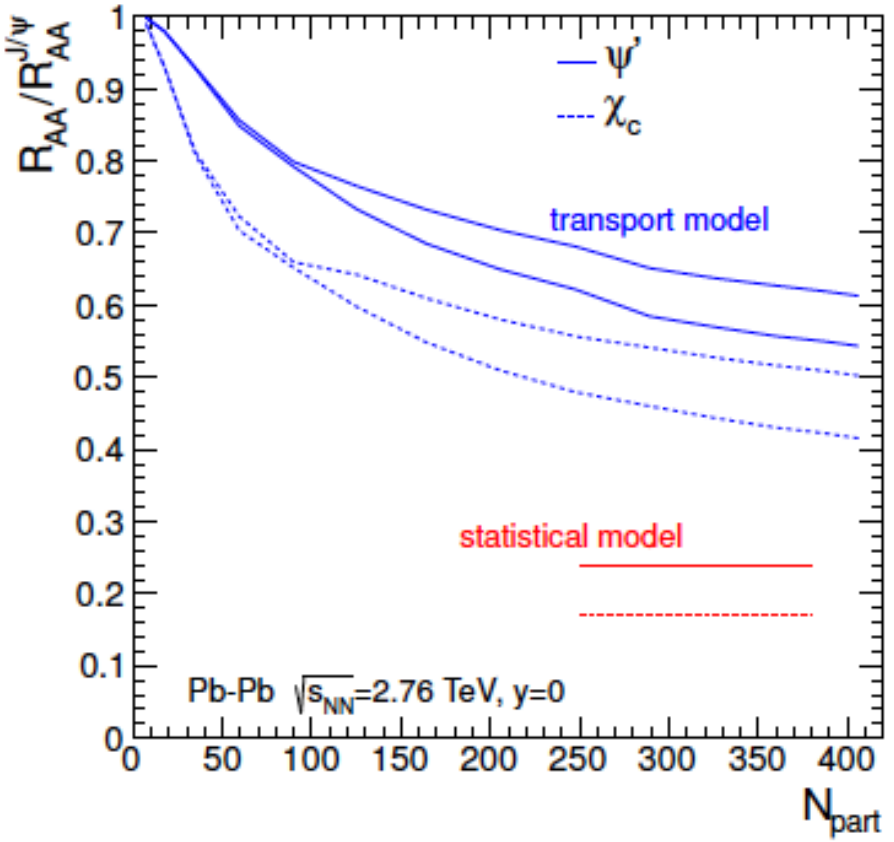
PRL111 (2013) 162301



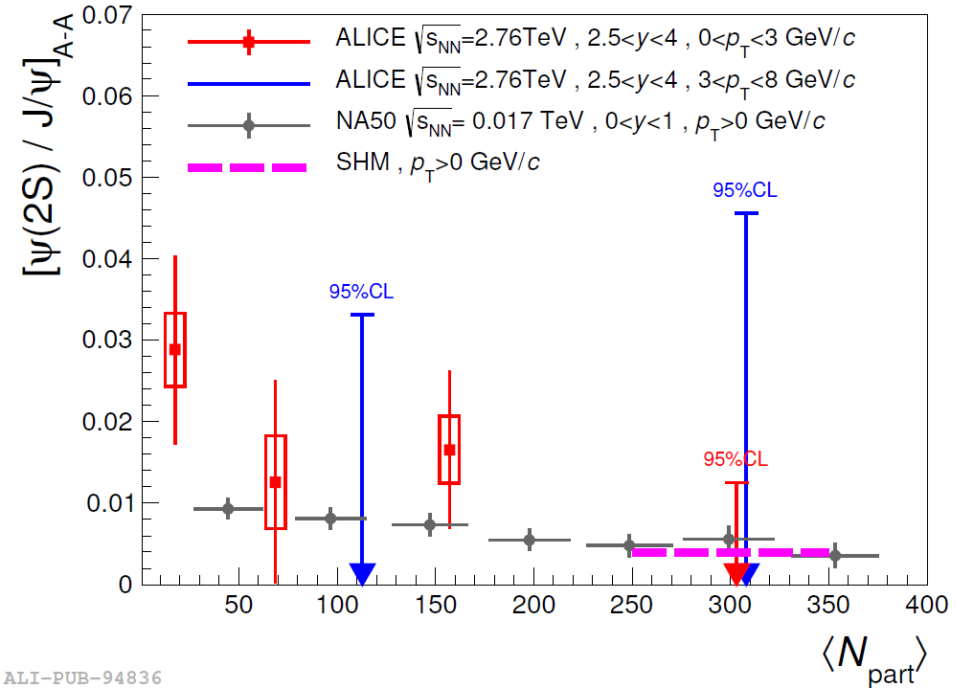
- Strong elliptic flow observed for light particles and D mesons
- Hint of non-zero elliptic flow ?
- Run-2 data reveals a strong J/psi elliptic flow
  - Hint of charm quark thermalization ?

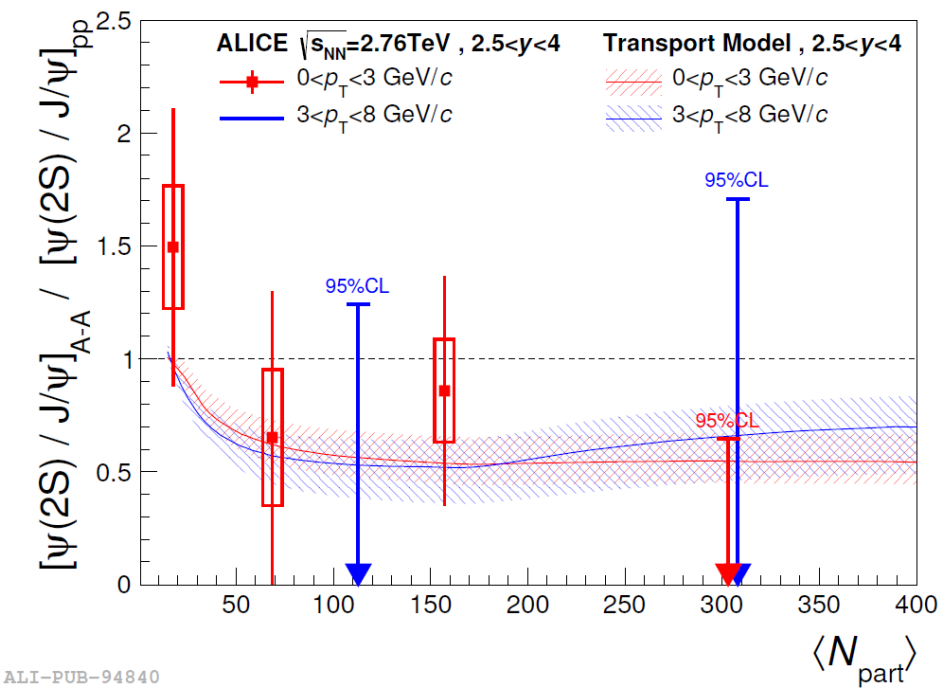
ψ(2S)

- Important test for regeneration models (transport vs statistical hadronization)
- ψ(2S) much less bound than J/ψ
- Ratio of RAA less dependent on the charm cross-section



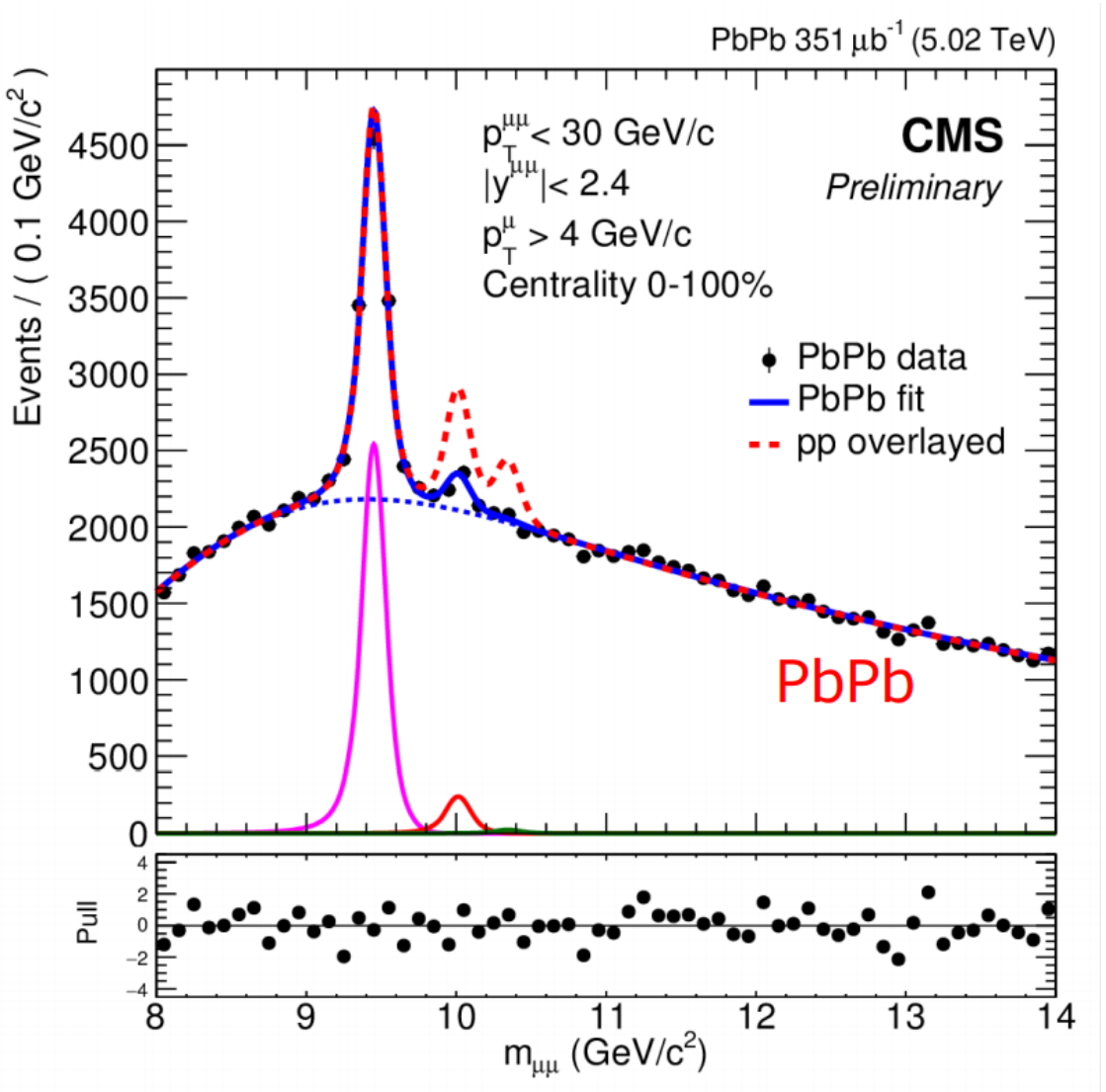
ψ(2S)





- No strong conclusion can be drawn with the present data
- Both SHM and transport models are consistent with the present results
- Key measurement for the ALICE upgrade

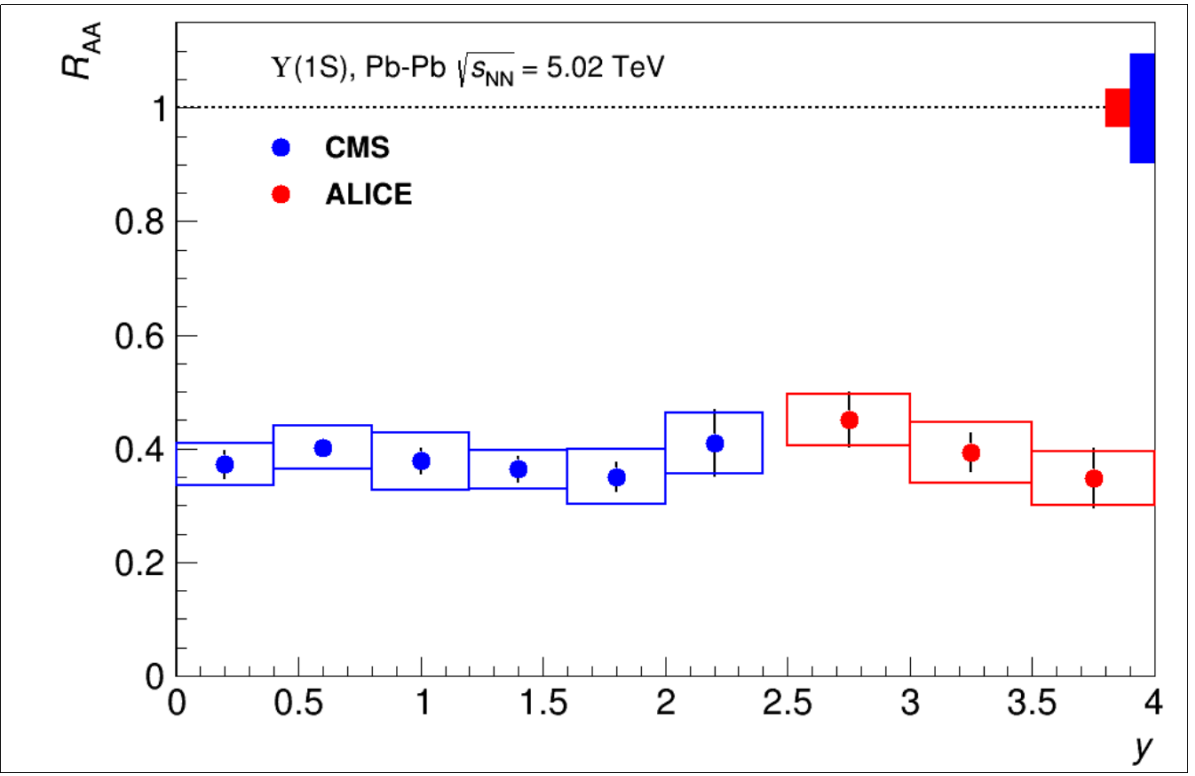
Bottomonium ($b\bar{b}$)

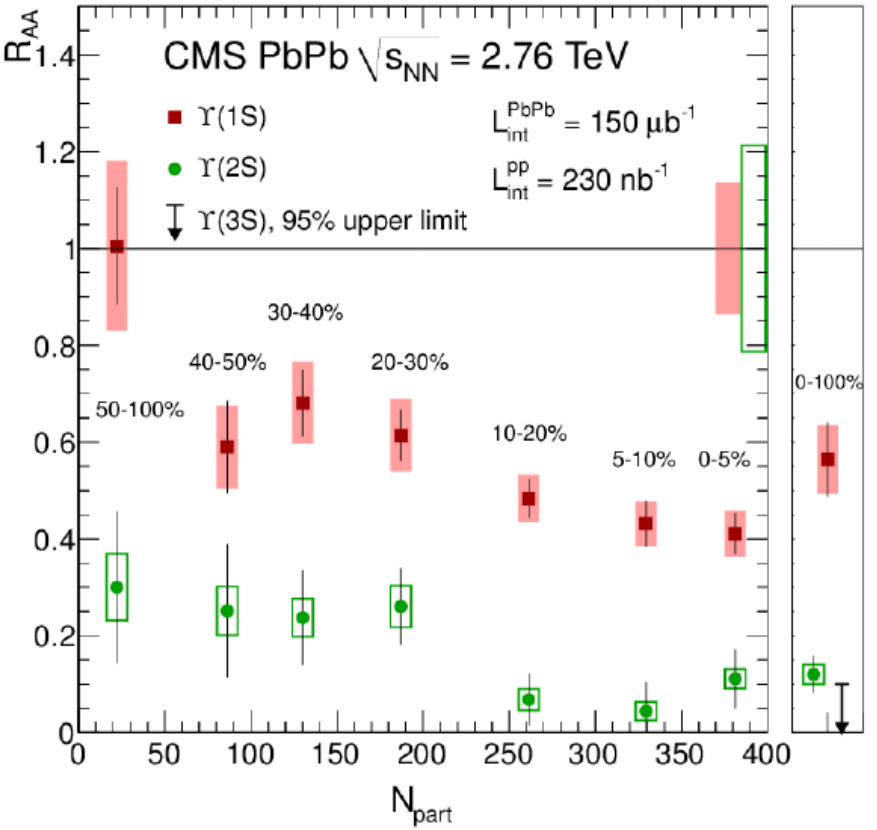


- CMS and ALICE measured the suppression of the Upsilon meson family
- A clear suppression of the Upsilon(2S) and Upsilon(3S) relative to the ground state is observed in Pb-Pb

Inclusive Y production vs rapidity and centrality

PRL109 (2012) 222301

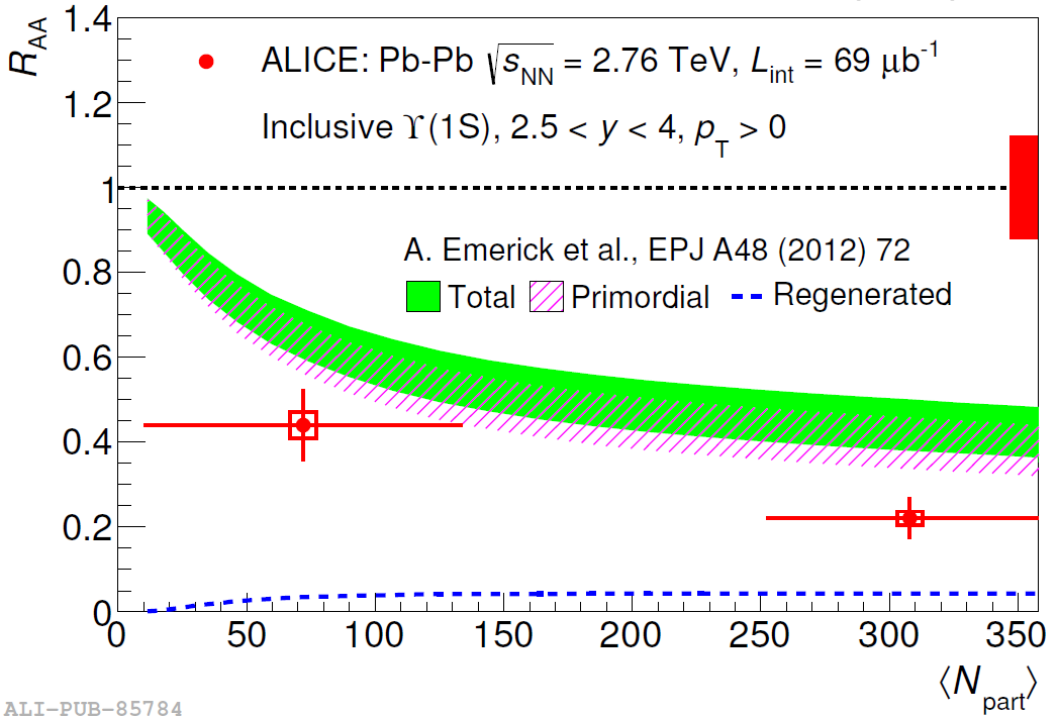


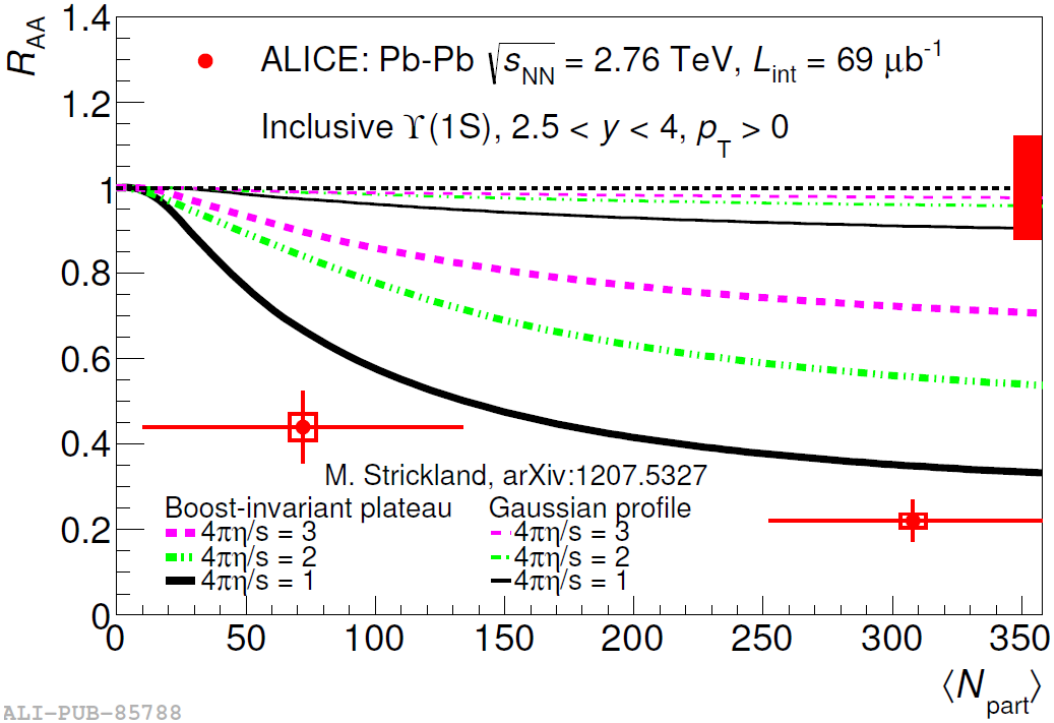


- CMS and ALICE measured the suppression of the Upsilon meson family
- A clear suppression of the Upsilon(2S) and Upsilon(3S) relative to the ground state is observed in Pb-Pb
- Evidence for sequential melting: $R_{AA}\{Y(1S)\} > R_{AA}\{Y(2S)\} > R_{AA}\{Y(3S)\}$

Y(1S) production vs centrality

PLB 738 (2014) 361





- Strong suppression observed for Y(1S) in central collisions
- Very small contribution from recombination effects expected for bottomonia (Emerick et al. - Texas model)
- Thermal suppression in a hydrodynamical model with shear viscosity (Strickland et al.) requires the lowest η/s to fit the data

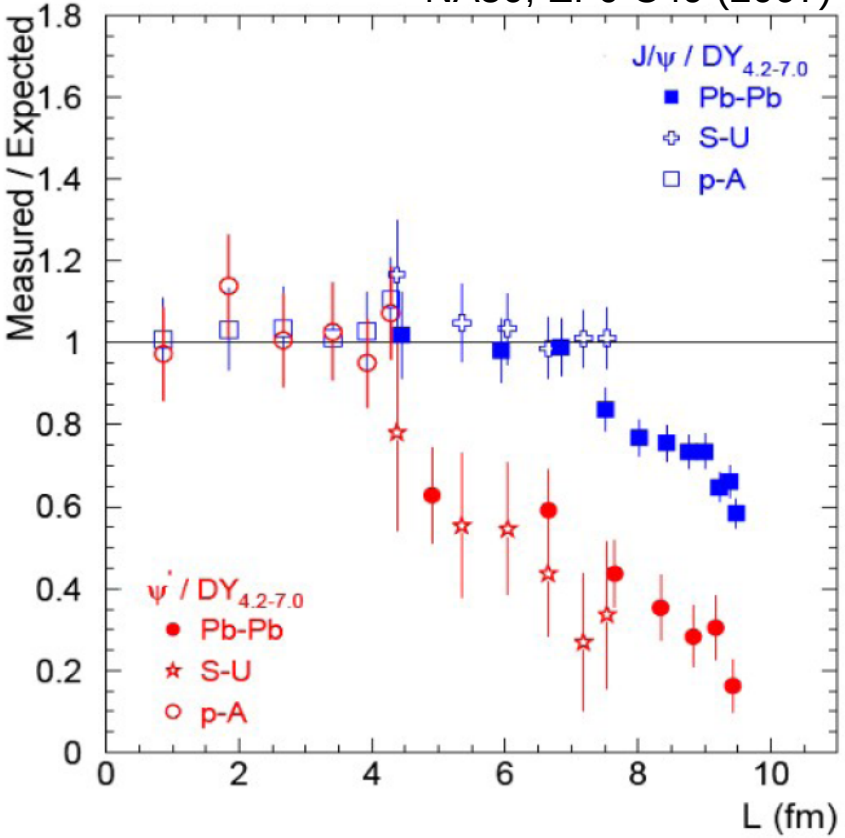
Summary

- Quarkonium measurements in heavy ion collisions exhibit a rich phenomenology
- Charmonia:
  - Long time predicted charmonium suppression observed at RHIC
  - At the LHC a strong regeneration component was observed
    - Charmonia cannot be used as a “plasma thermometer” at LHC
    - Good probe of deconfinement
  - Indication that psi(2S) is suppressed more than J/psi, however experimental uncertainties are still very large
- Bottomonia
  - Strong suppression of Y(1S) in central collisions, possibly more than what can be explained by the melting of Y(2S) and chi_b
  - Strong indication of sequential melting of the Y family states

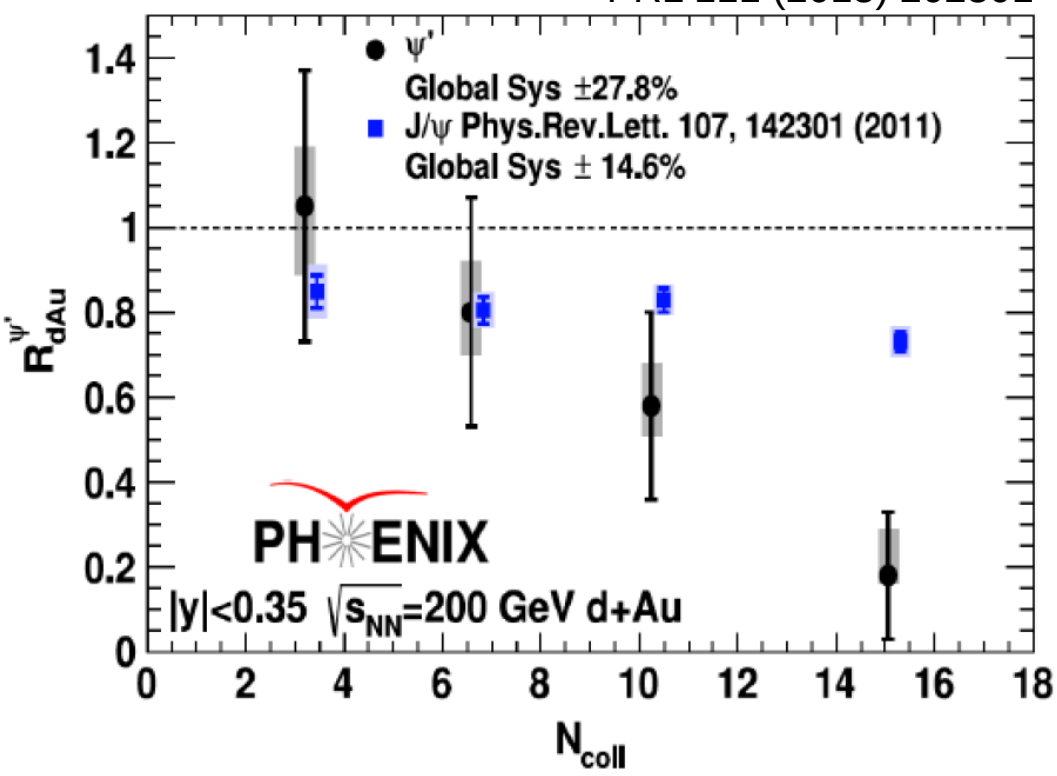
Backup

ψ(2S) at SPS and RHIC

NA50, EPJ C49 (2007)



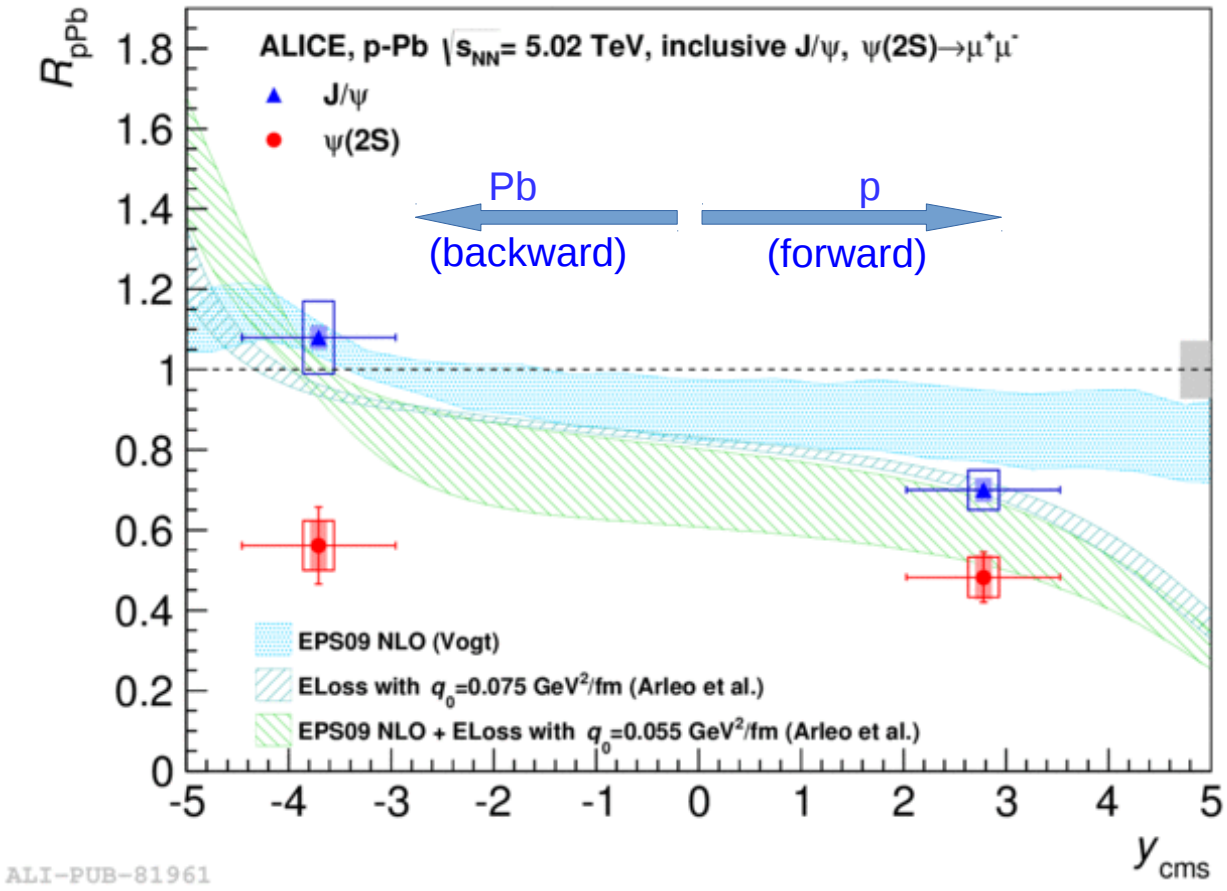
PRL 111 (2013) 202301



- At SPS, no ψ' suppression w.r.t. CNM expectations in p-A collisions
  - Final state interactions of the formed resonance in the cold nuclear medium
- Puzzle? ψ' suppressed more than J/ψ in d-Au at RHIC
  - No significant differences between J/ψ and ψ' expected at RHIC and LHC from shadowing or formation time effects

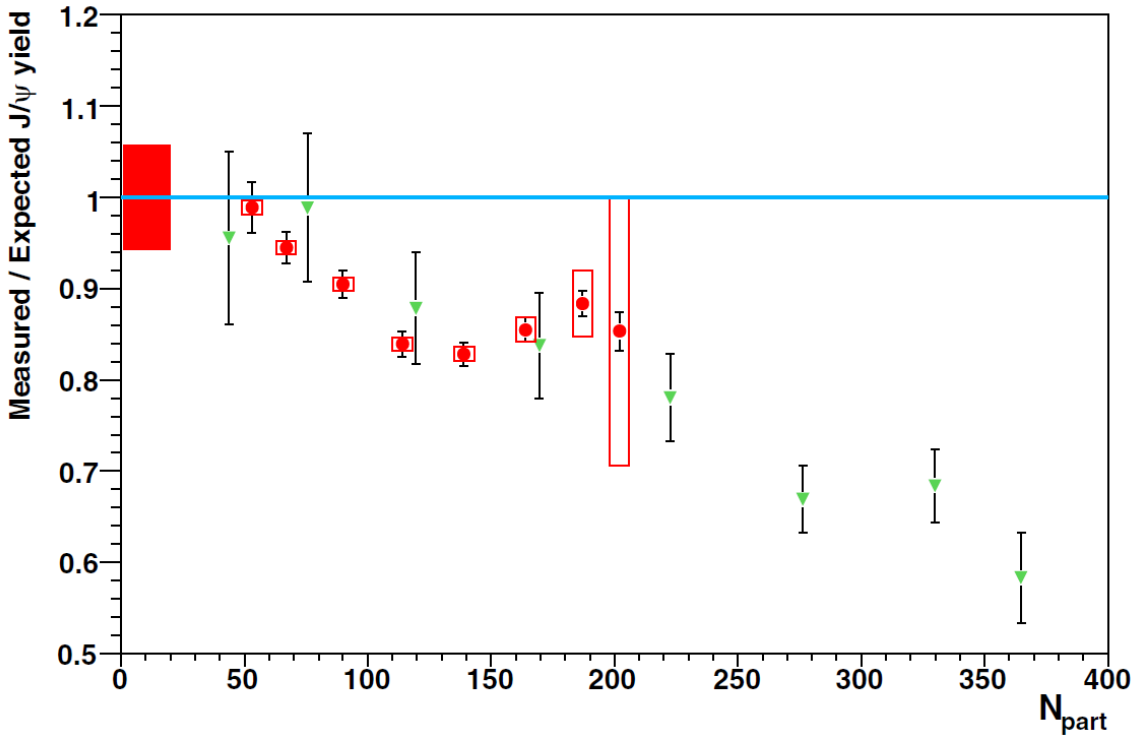
ψ(2S) vs rapidity at the LHC

arXiv:1405.3796



- Strong ψ' suppression observed in p-Pb at both forward and backward rapidities
- Not expected from either shadowing or energy loss models

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

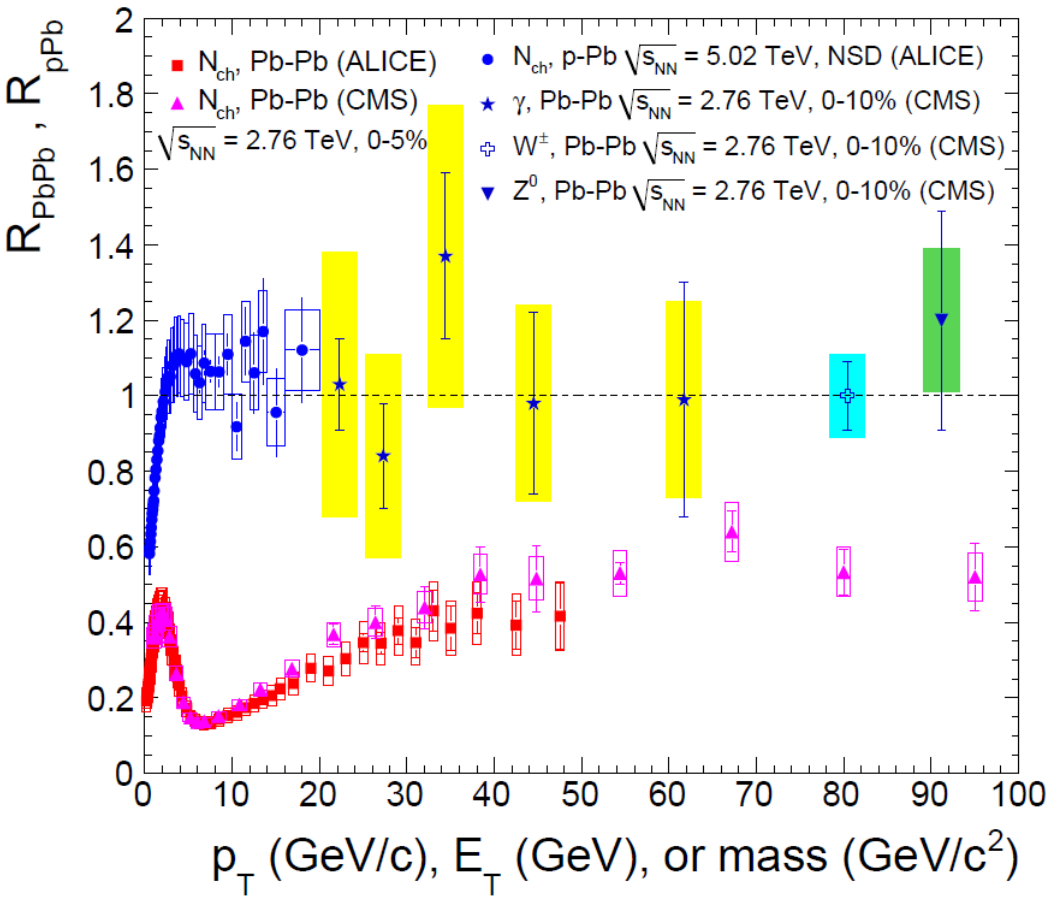


Results based on extrapolation of sigma_abs from p-A collisions at 400/450 GeV

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

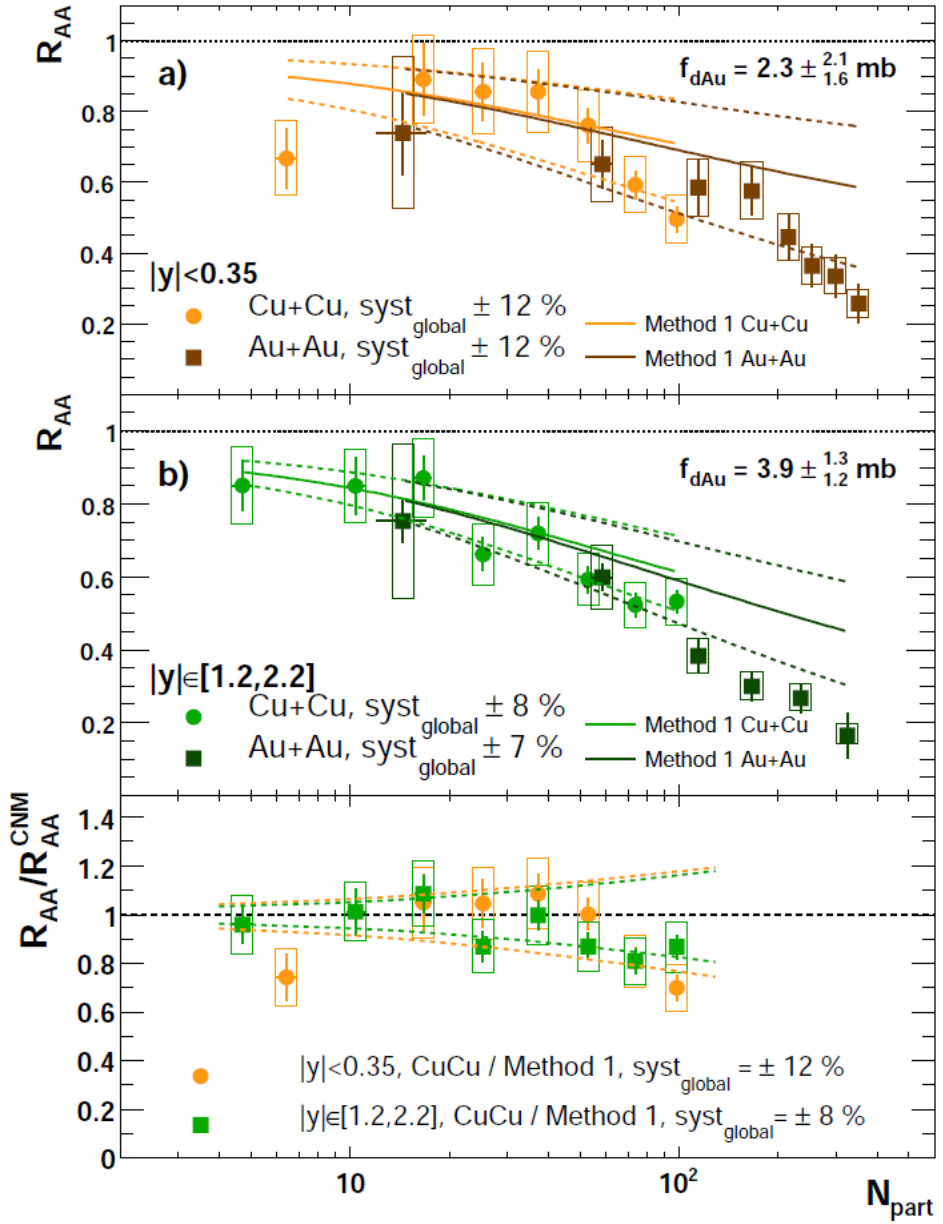


$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

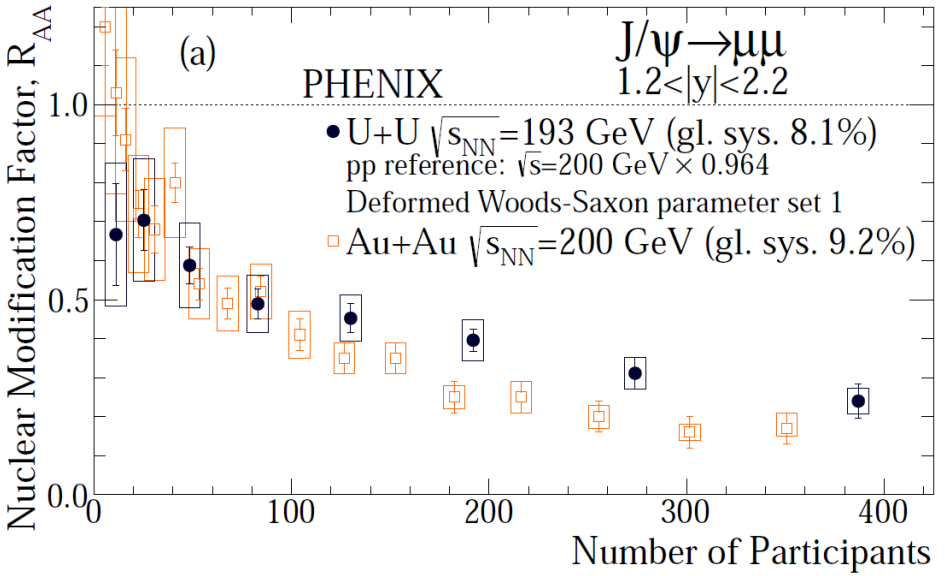
- N_{coll}: the number of binary nucleon-nucleon collisions
- Superposition of NN collisions → $R_{AA}=1$
  Suppression → $R_{AA}<1$
  Enhancement → $R_{AA}>1$
- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 bosons R_{AA} are compatible with 1

Collision system dependence

PHENIX arxiv:0801.0220



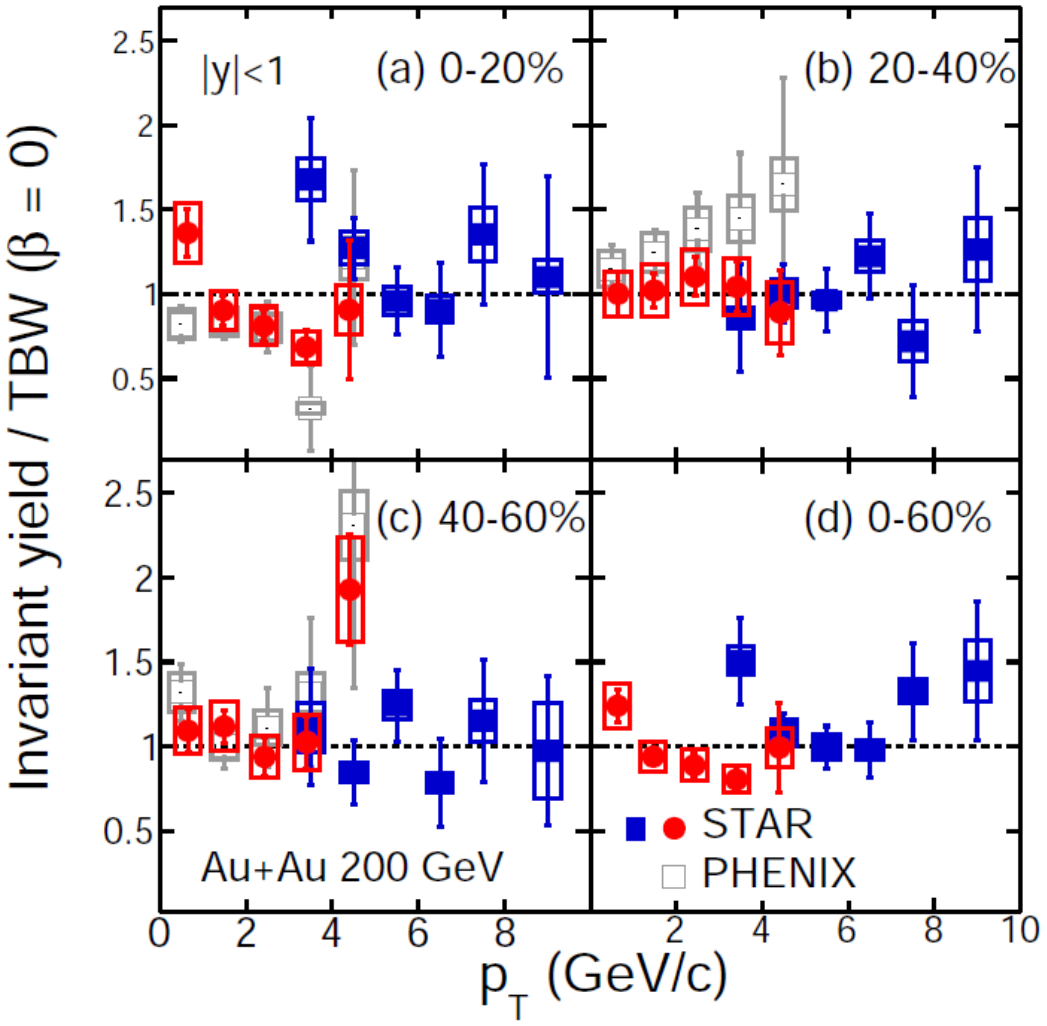
PHENIX arxiv:1509.0538

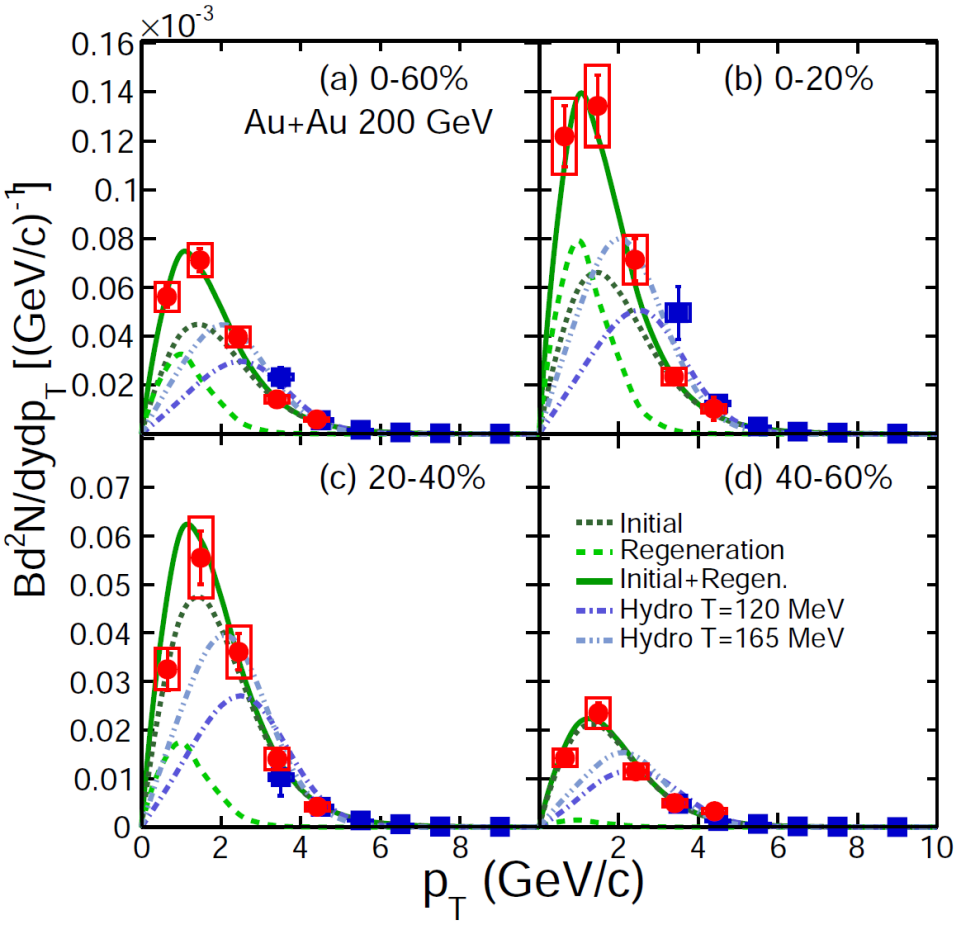


- J/ψ production studied also in Cu-Cu and U-U systems
- Similar J/ψ R_{AA} observed at similar N_{part} and N_{coll}

STAR AuAu

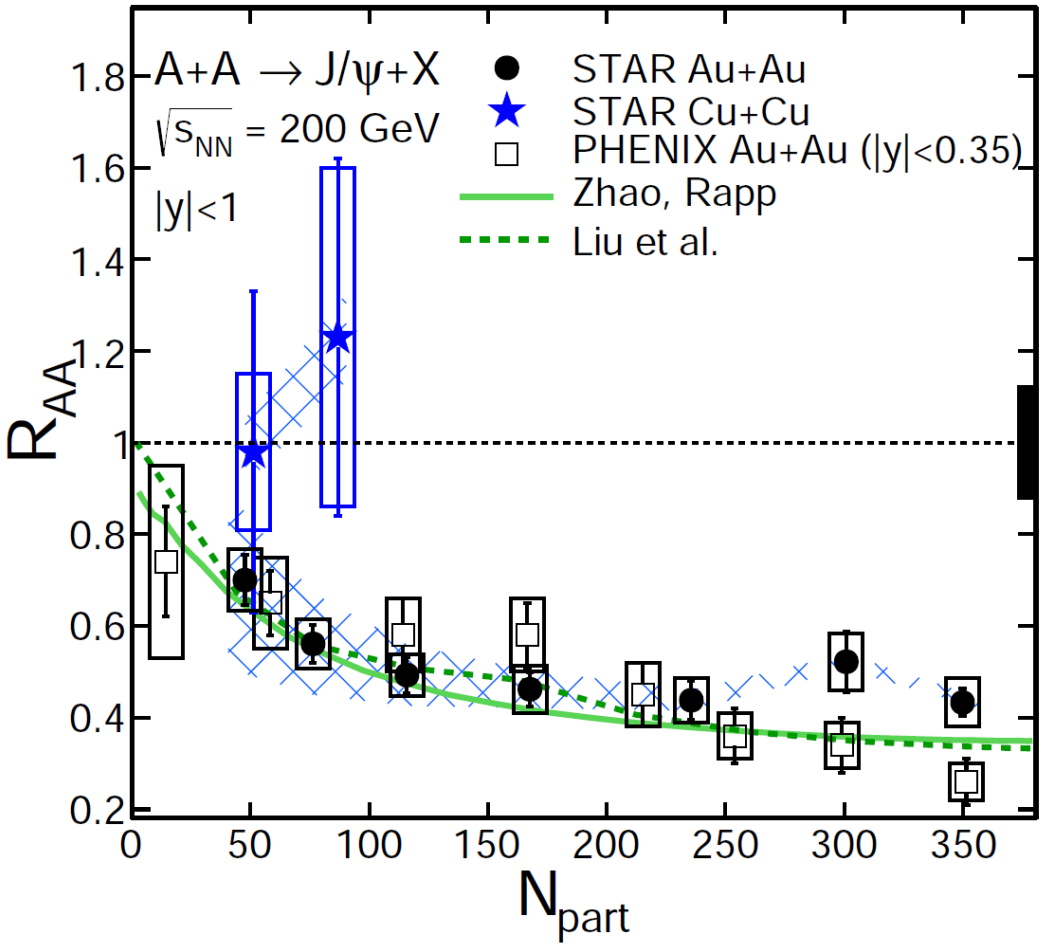
STAR arxiv 1310.3563



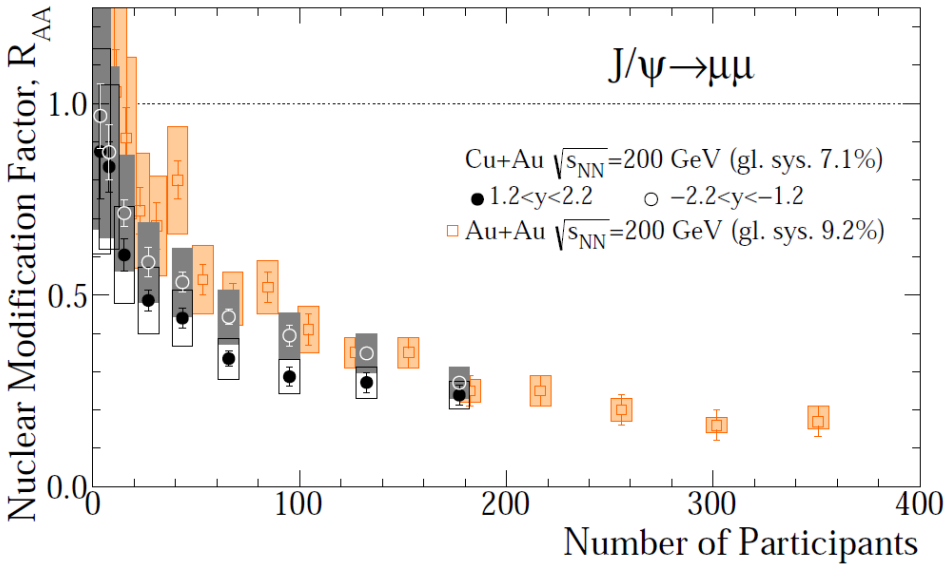


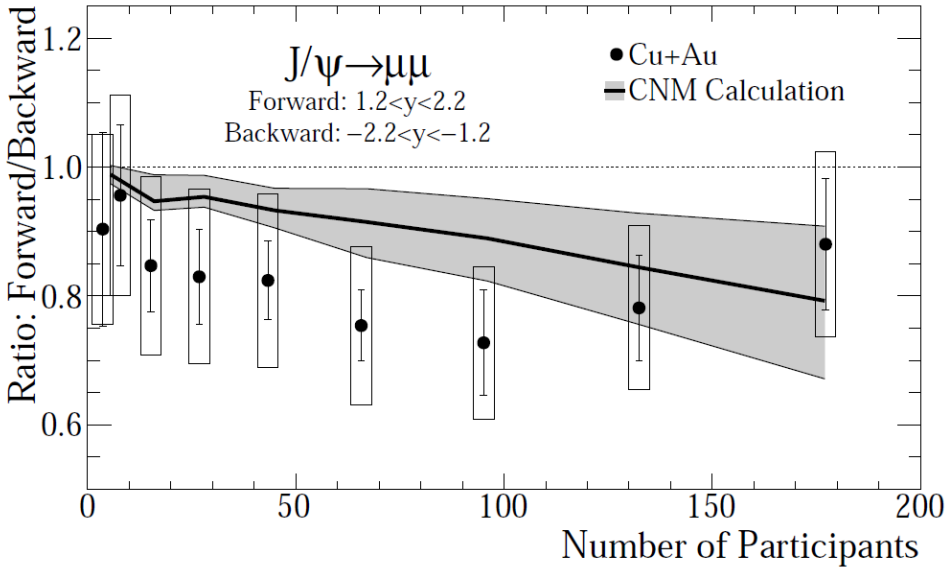
J/psi

STAR arxiv 1310.3563



PHENIX cuau200
arxiv:1404.1873





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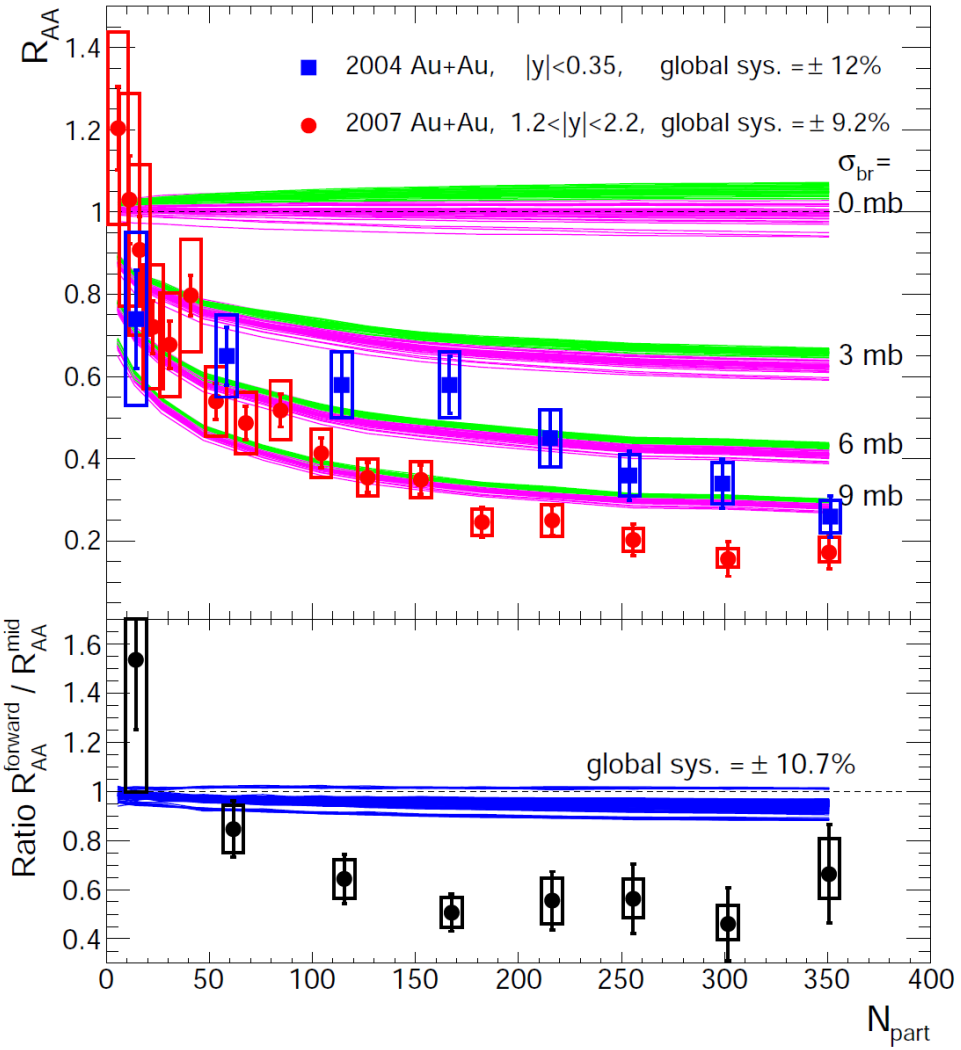
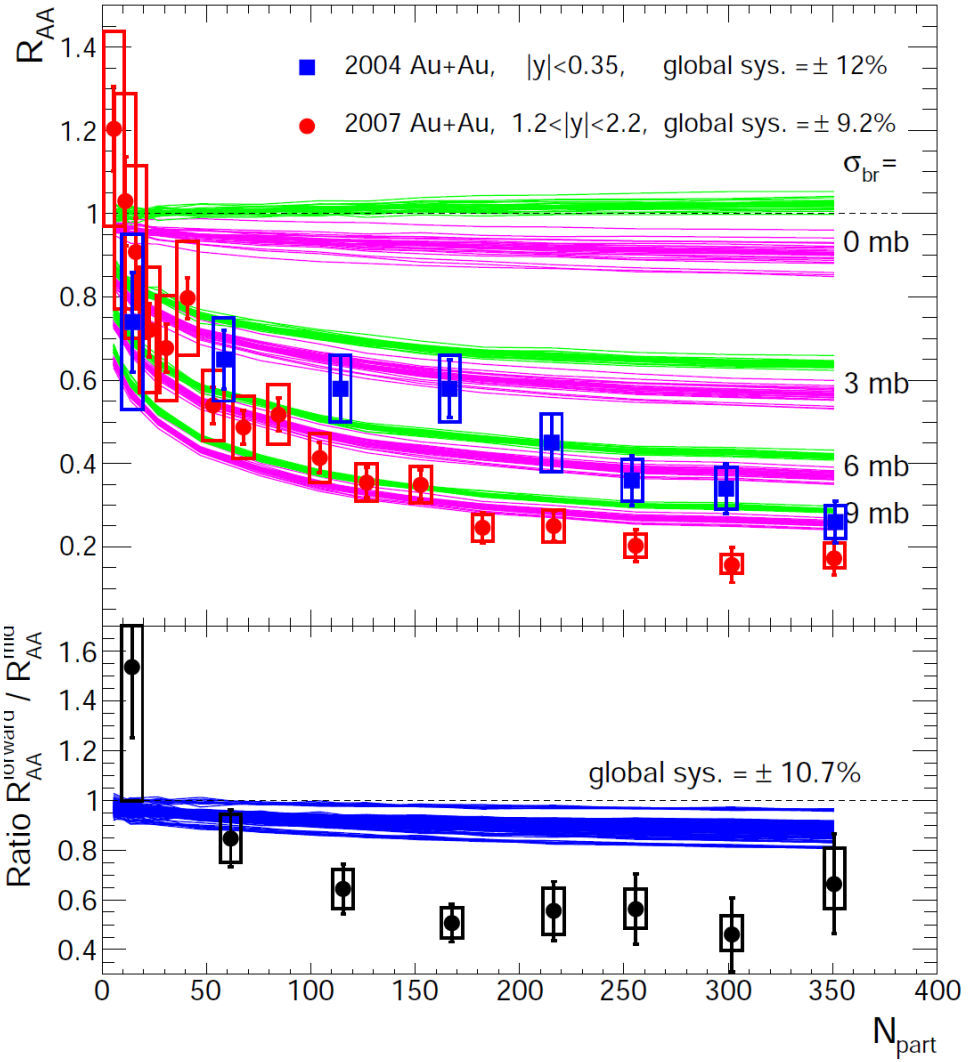
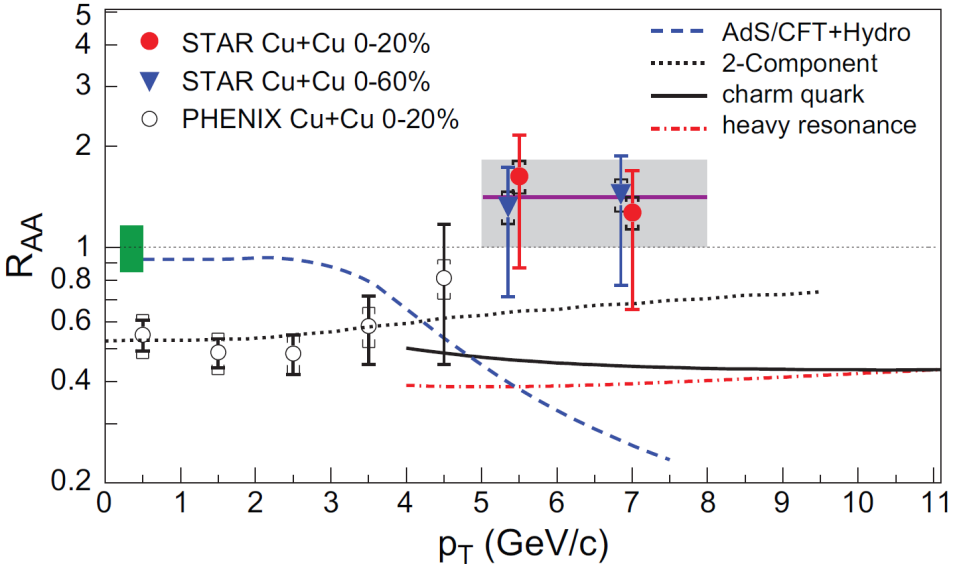

R_AA
2004 Au+Au, |y|<0.35, global sys. = ± 12%
2007 Au+Au, 1.2<|y|<2.2, global sys. = ± 9.2%
σ_br =
0 mb
3 mb
6 mb
9 mb
Ratio R_AA^forward / R_AA^mid
global sys. = ± 10.7%
N_part


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



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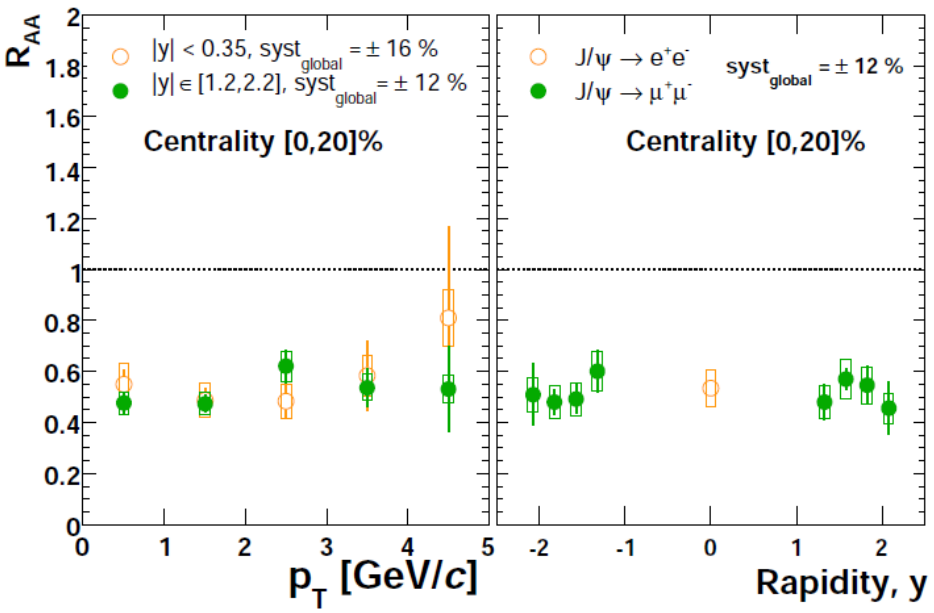

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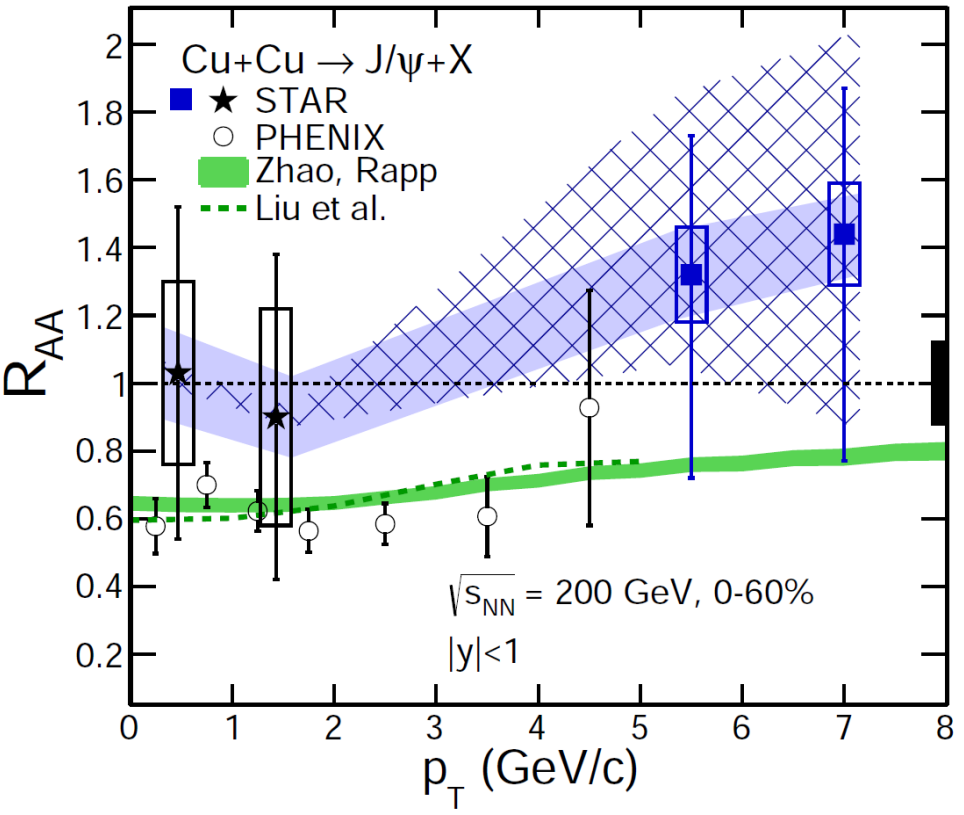

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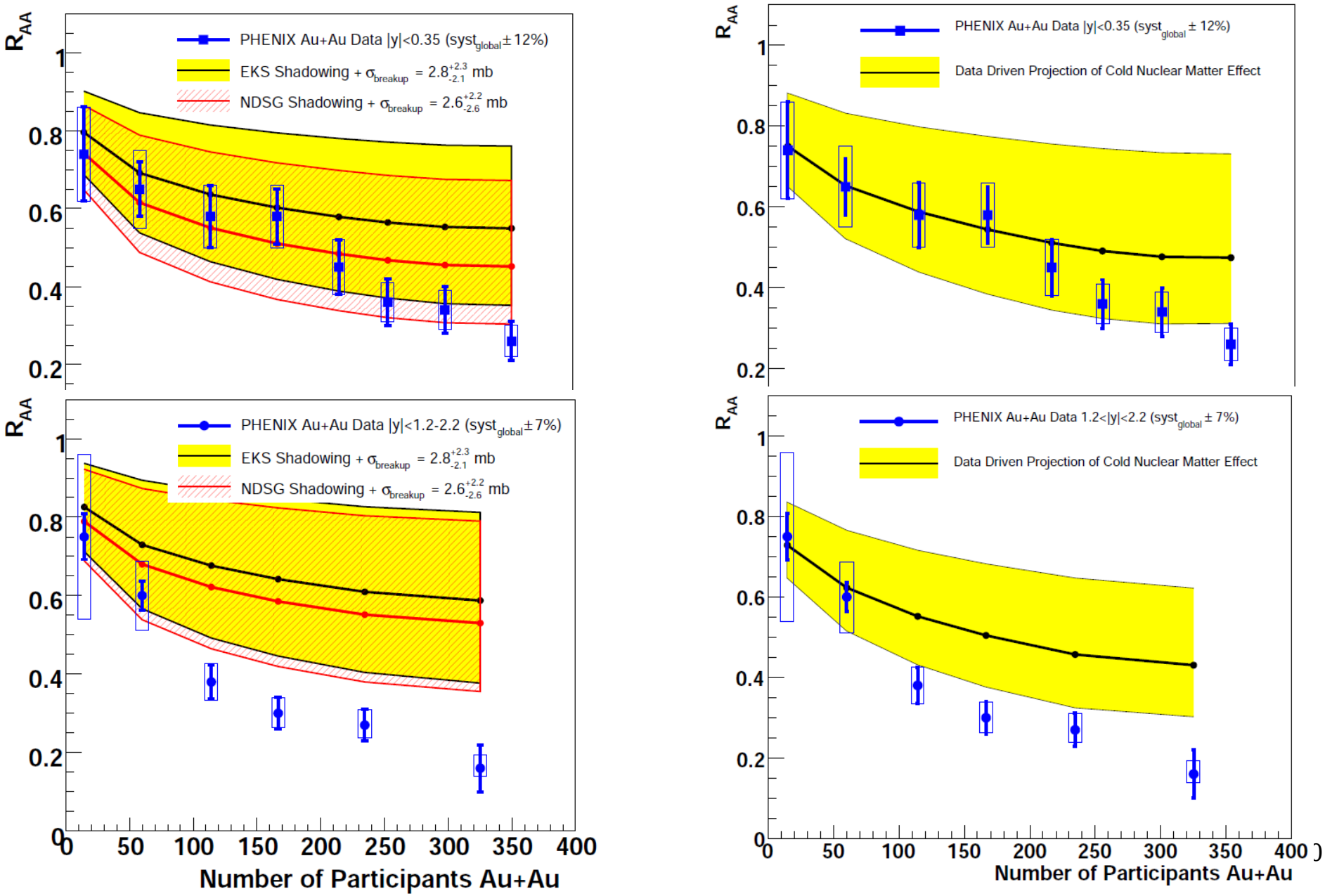

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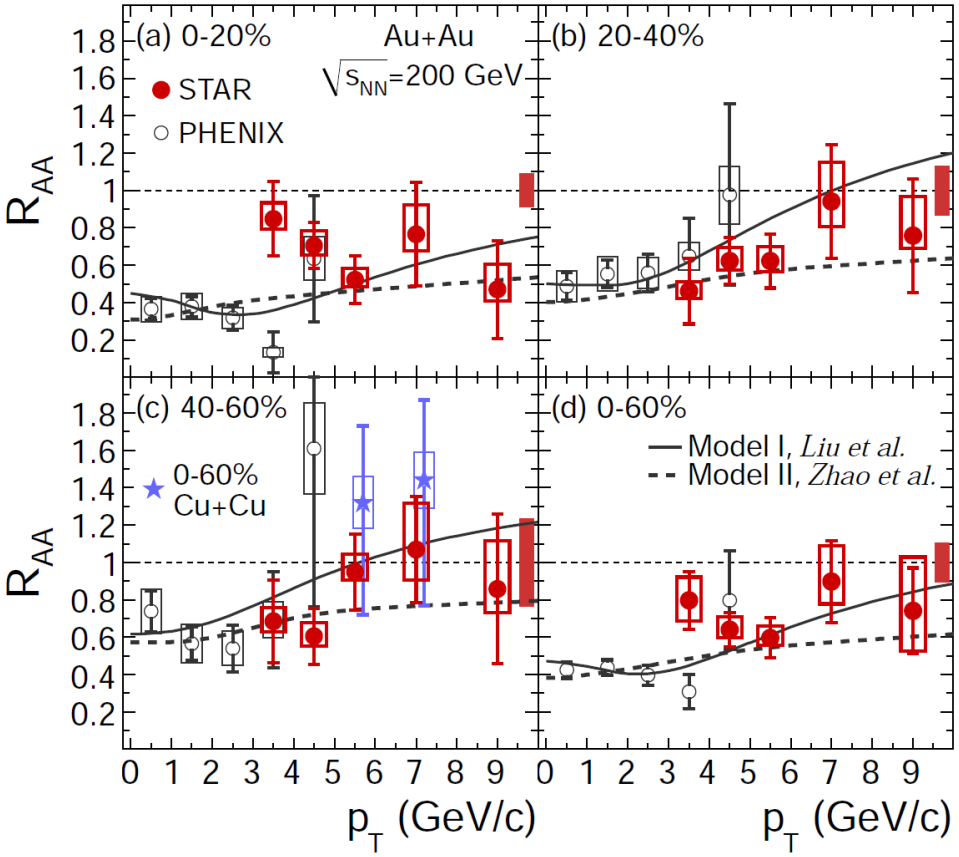

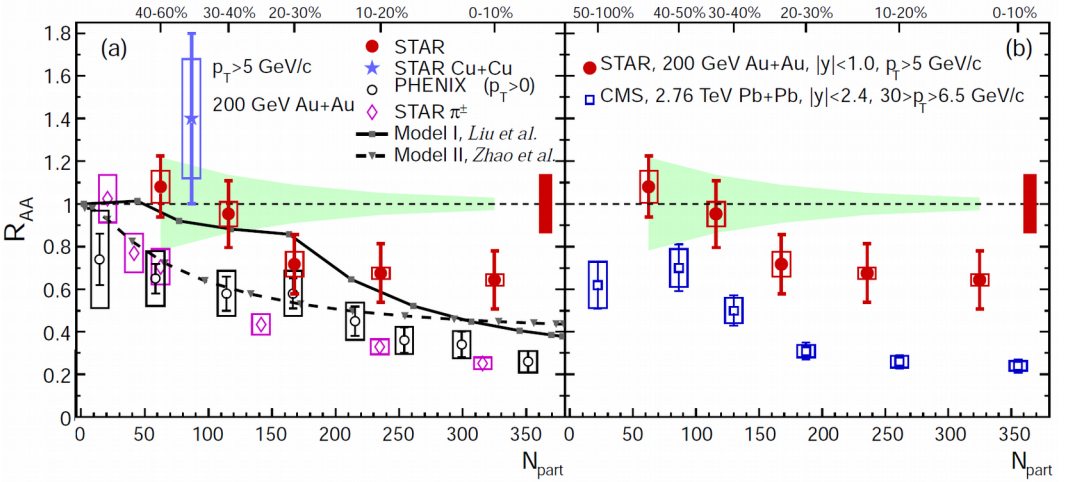

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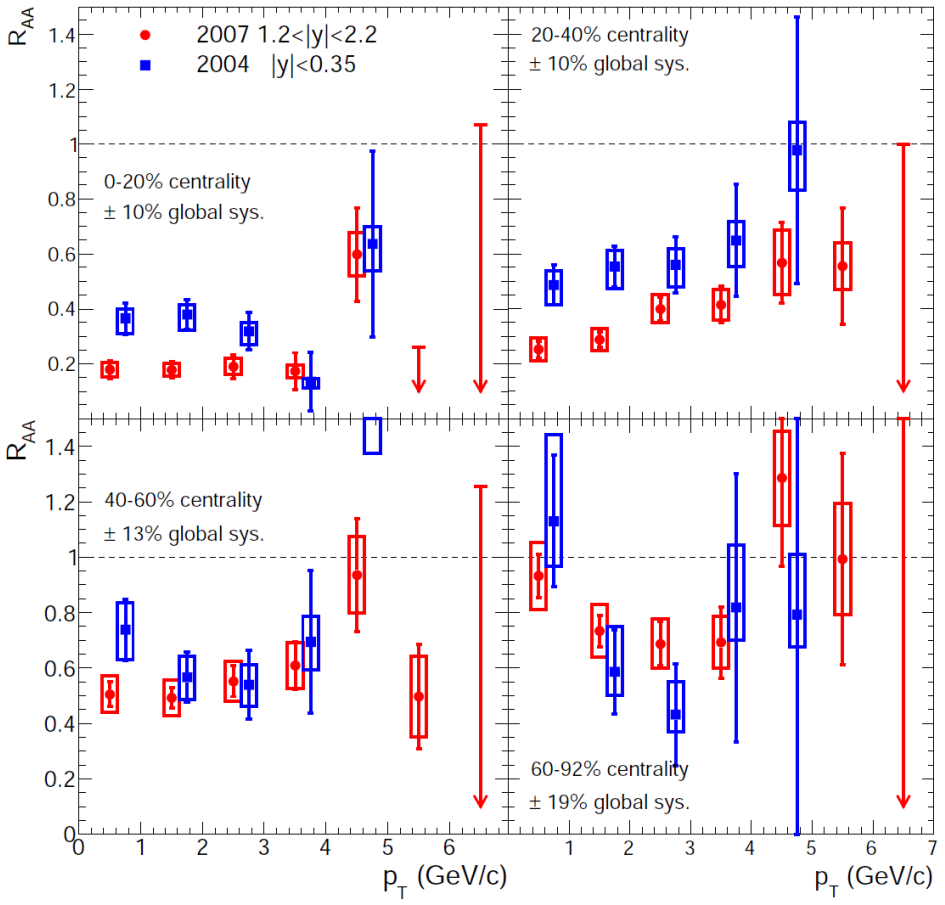

Inclusive J/ψ as a function of p_T

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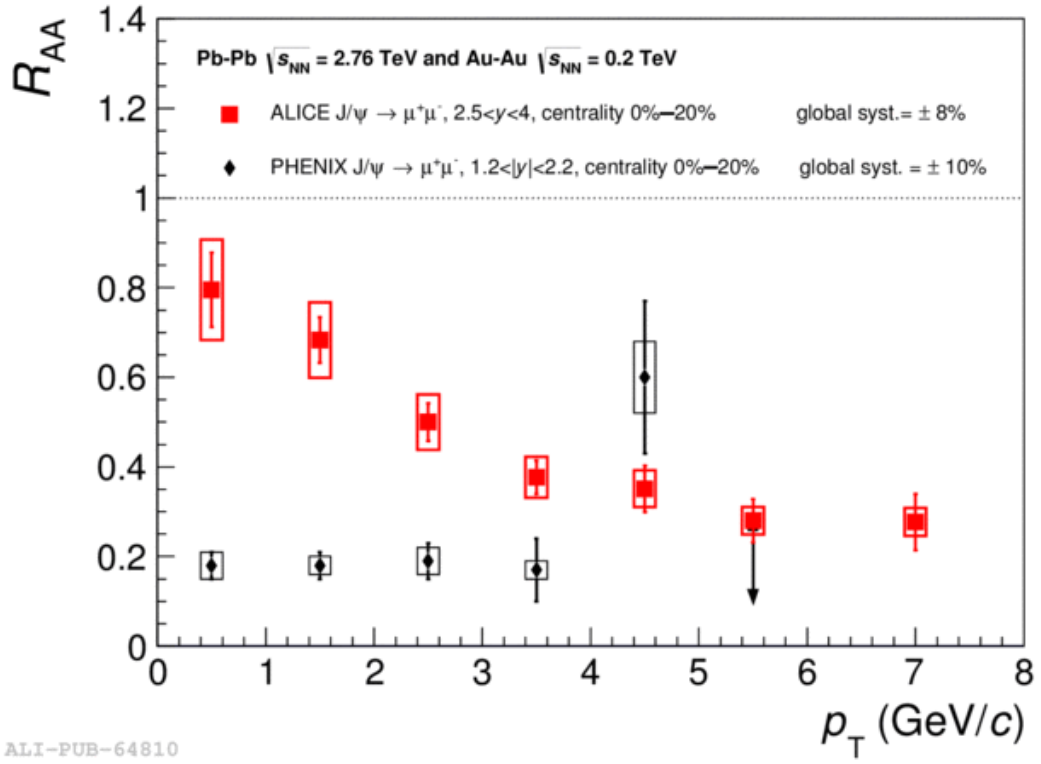
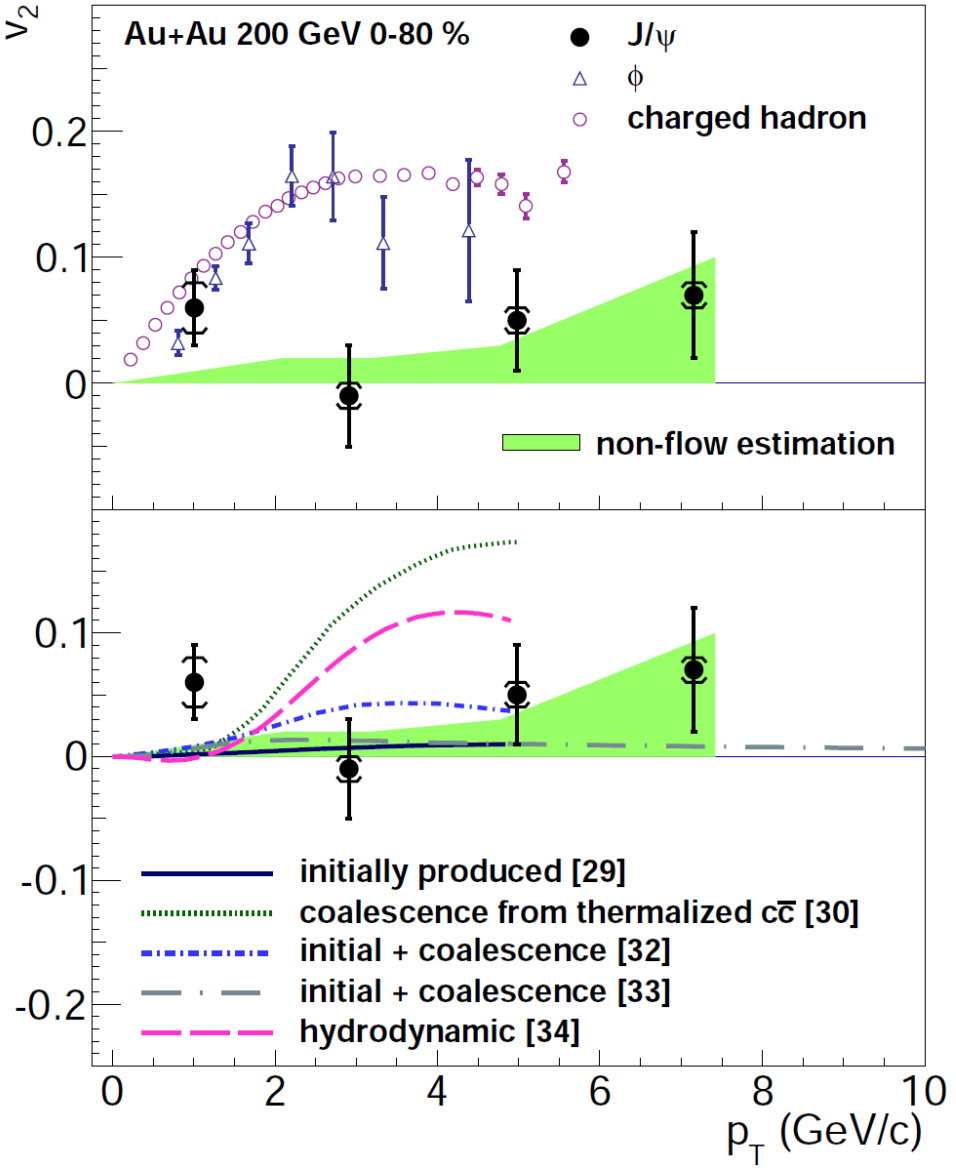
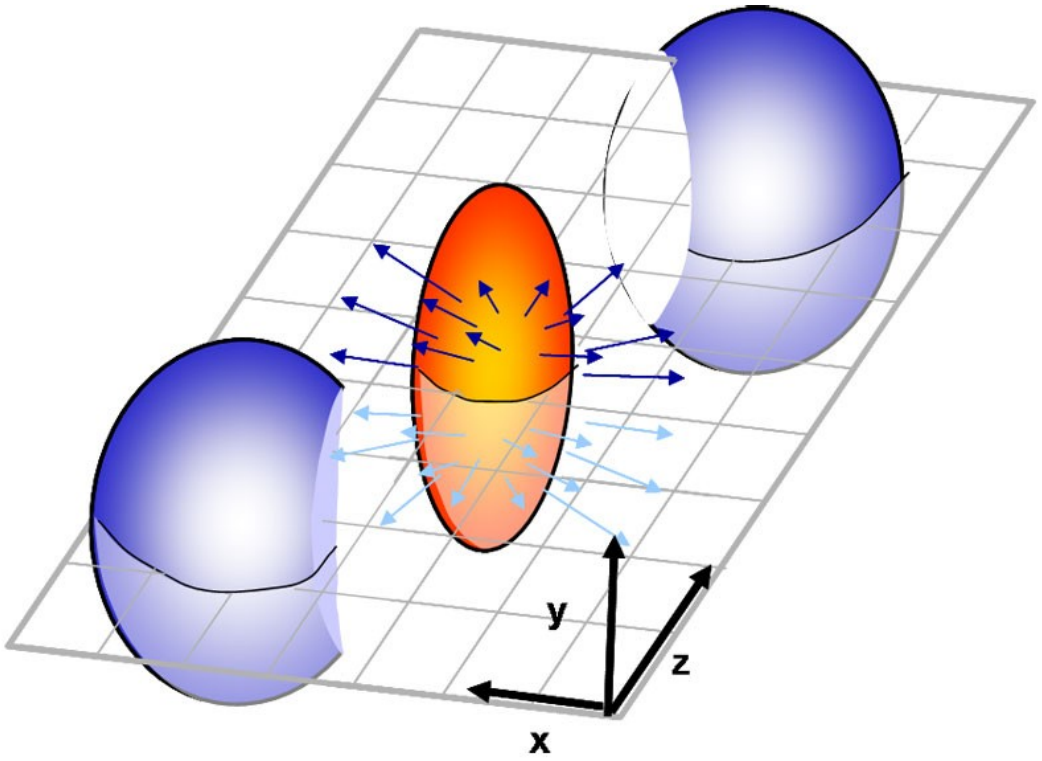
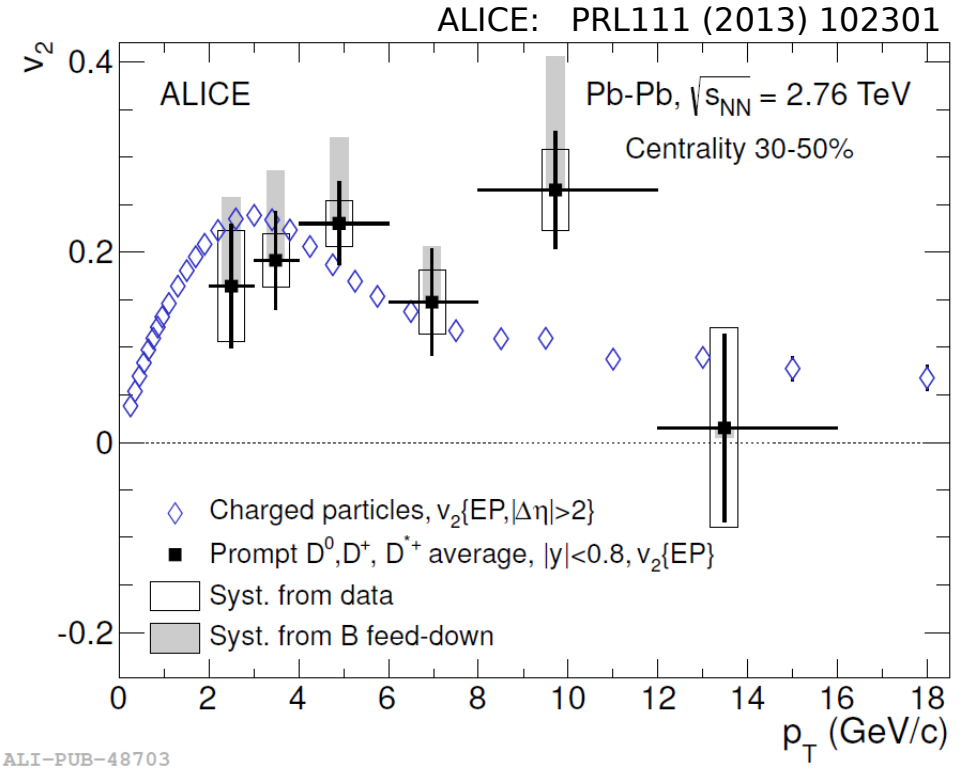


J/psi elliptic flow



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 ?

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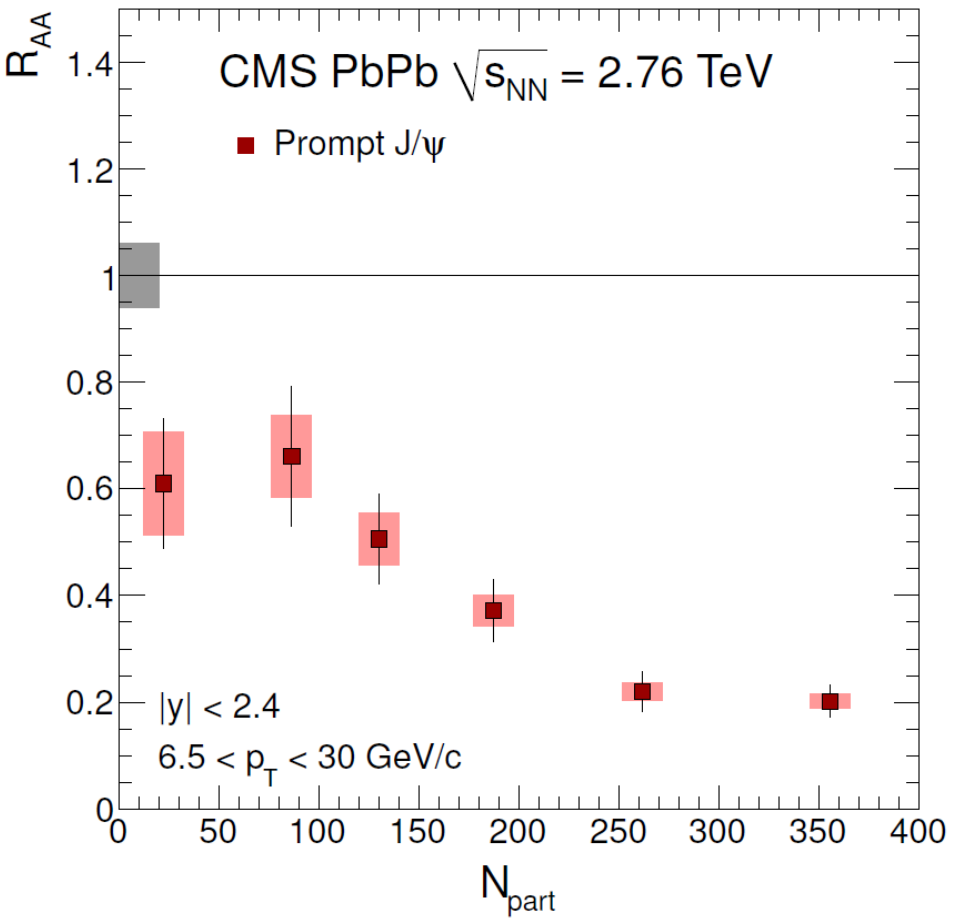
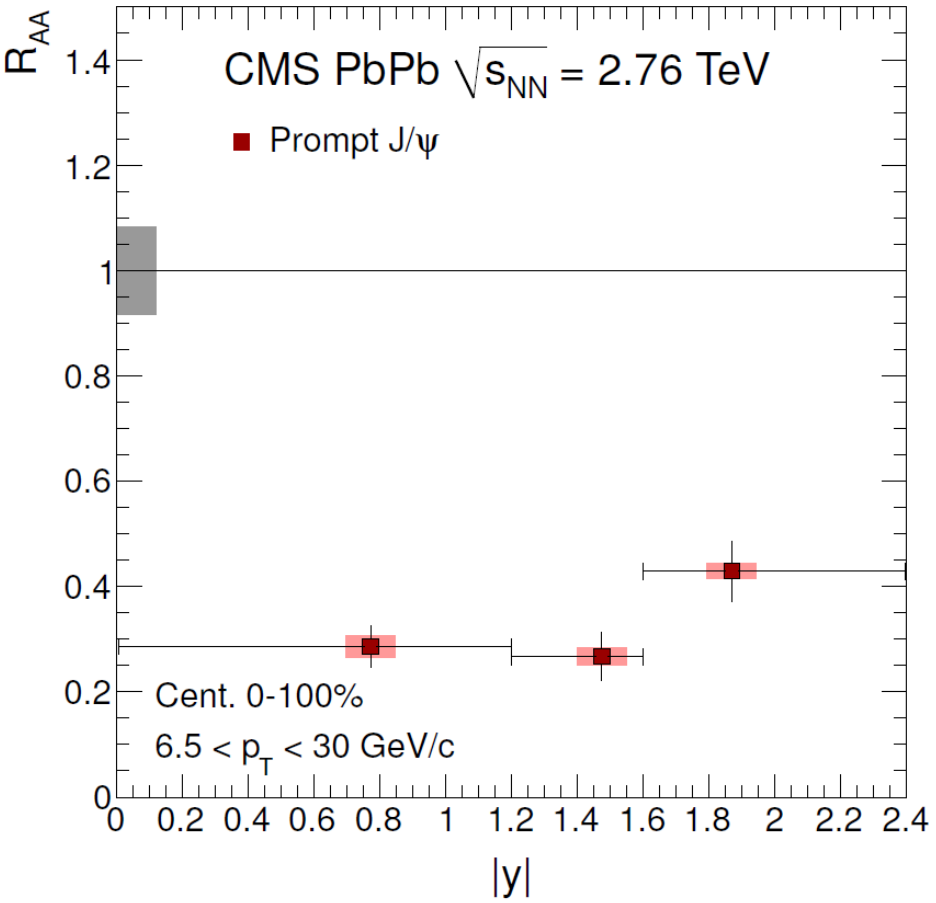
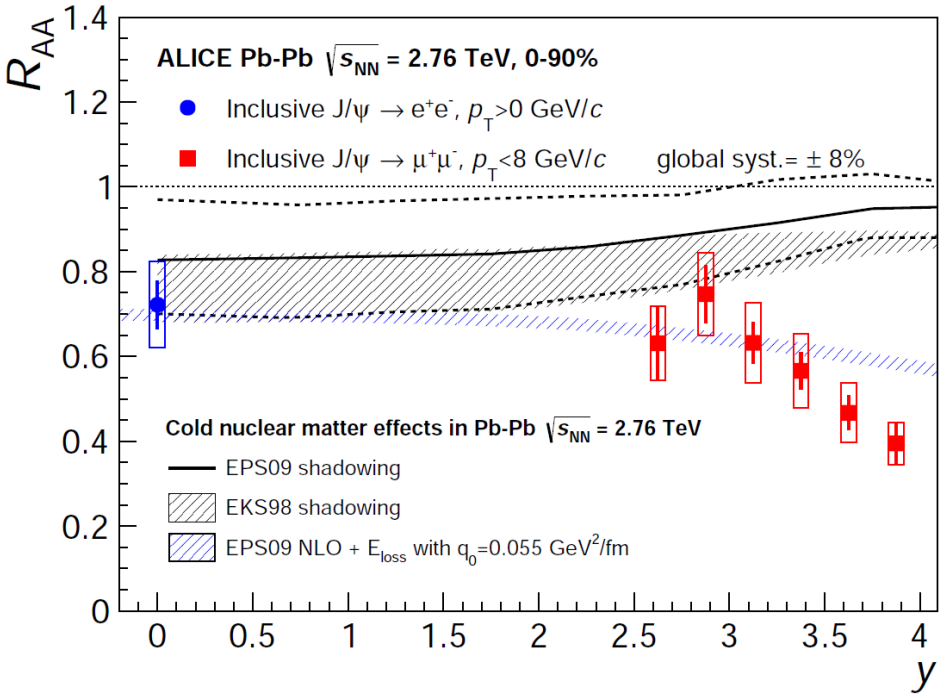




J/psi Raa vs rapidity



Open charm suppression vs centrality

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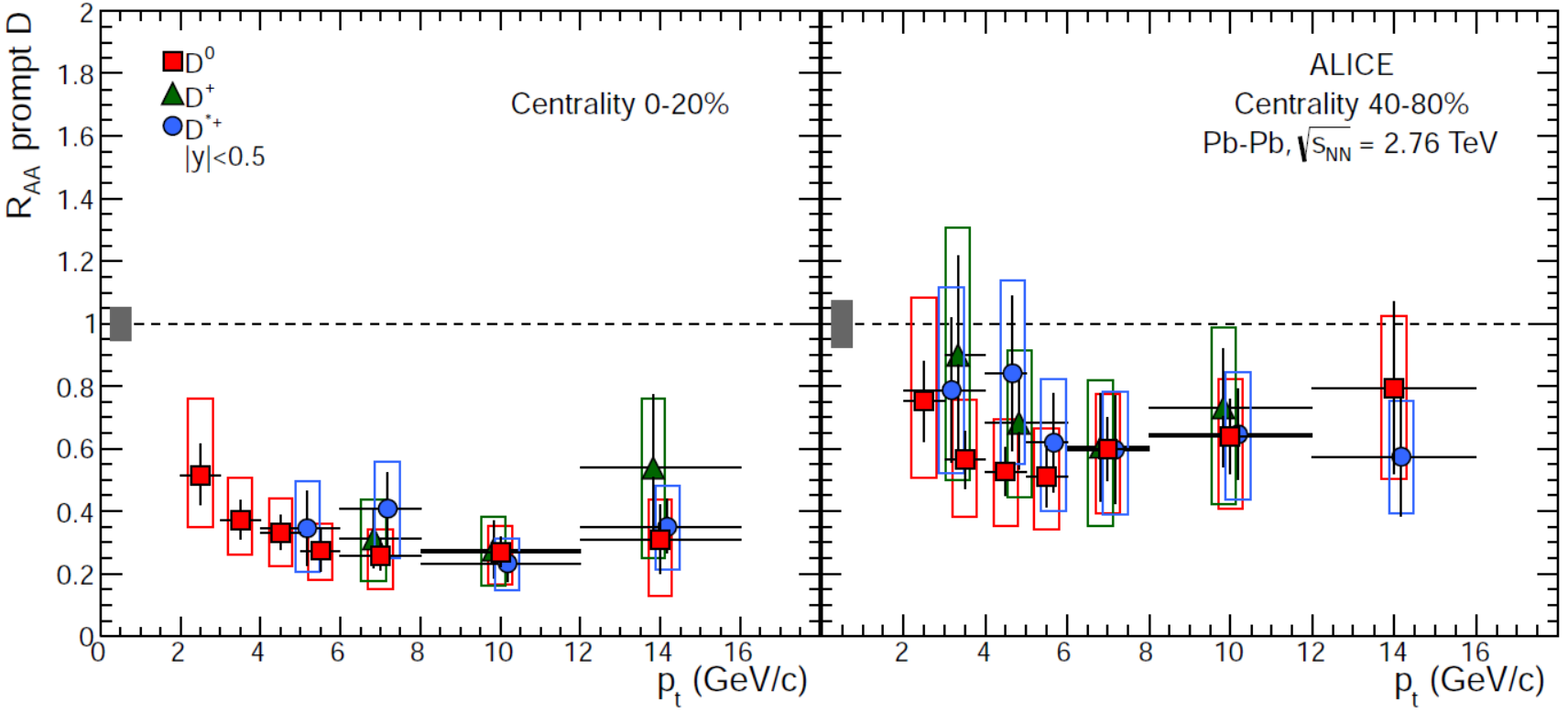
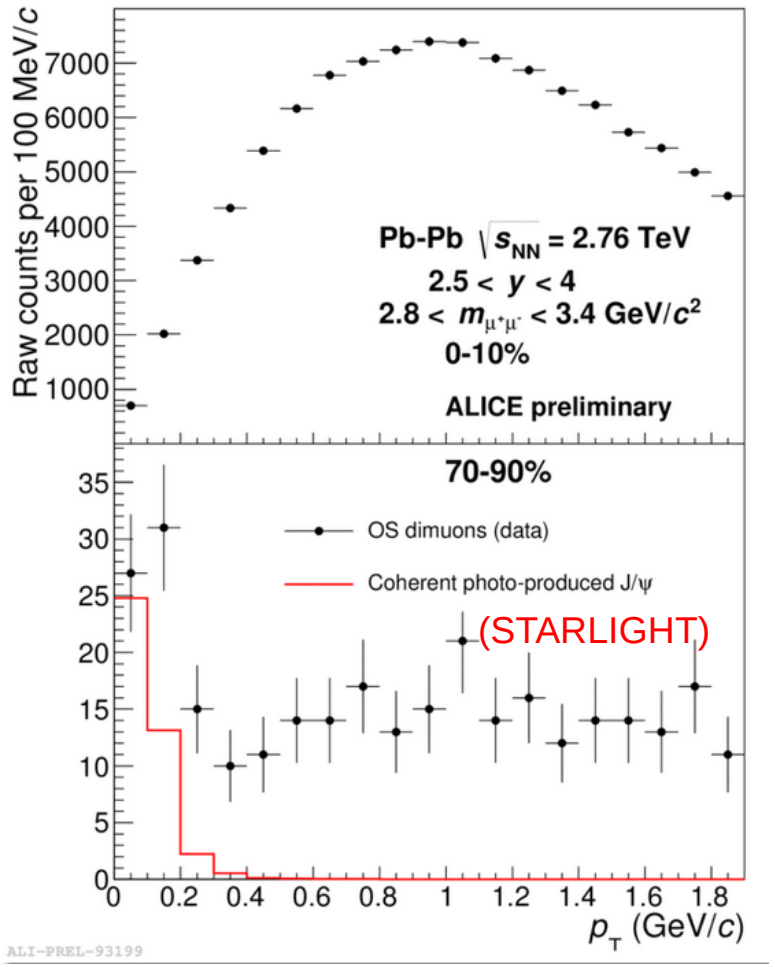
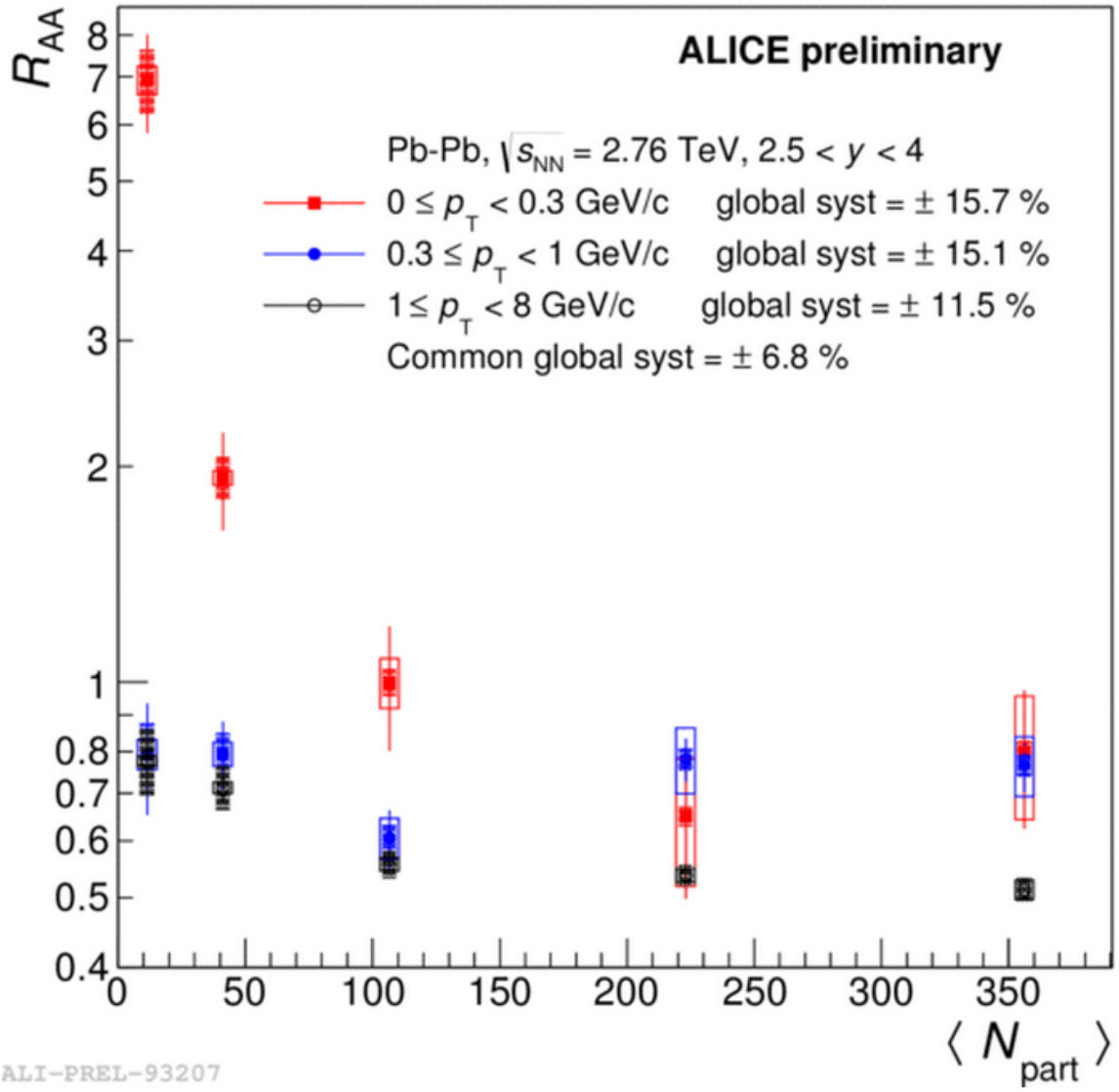


- Fully pT integrated open charm results not available yet
- Strong suppression of D mesons for pT>2 GeV/c observed

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 !!!