Centrality dependence of J/ψ production in Au+Au and Cu+Cu collisions by the PHENIX Experiment at RHIC

Taku Gunji
CNS, University of Tokyo
For the PHENIX Collaboration

PHENIX

Outline

- J/ψ and the medium
- J/ψ measurement at SPS
- Results of J/ψ R_{AA} vs. centrality in Au+Au and Cu+Cu collisions
- Comparison to SPS results
- Comparison to theoretical Models
- Summary

J/ψ and the medium

- J/ψ is created at the initial stage of collisions.
  - All J/ψ ~ 0.6J/ψ(Direct) + ~0.3 χ_c + ~0.1ψ'
- Initial state effects (Cold Nuclear Matter effects)
  - Nuclear Absorption, Gluon shadowing and/or CGC
- Final state effects in Hot and Dense medium
  - Dissociation of J/ψ in dense gluon field
    - T_{diss} (J/ψ) ~ $2T_c$, T_{diss}(ψ', χ_c) ~ 1.1 T_c from (quenched) L-QCD
    - *Direct J/ψ may survive at RHIC!?*
  - Recombination from uncorrelated charm pairs
    - can not be negligible at RHIC

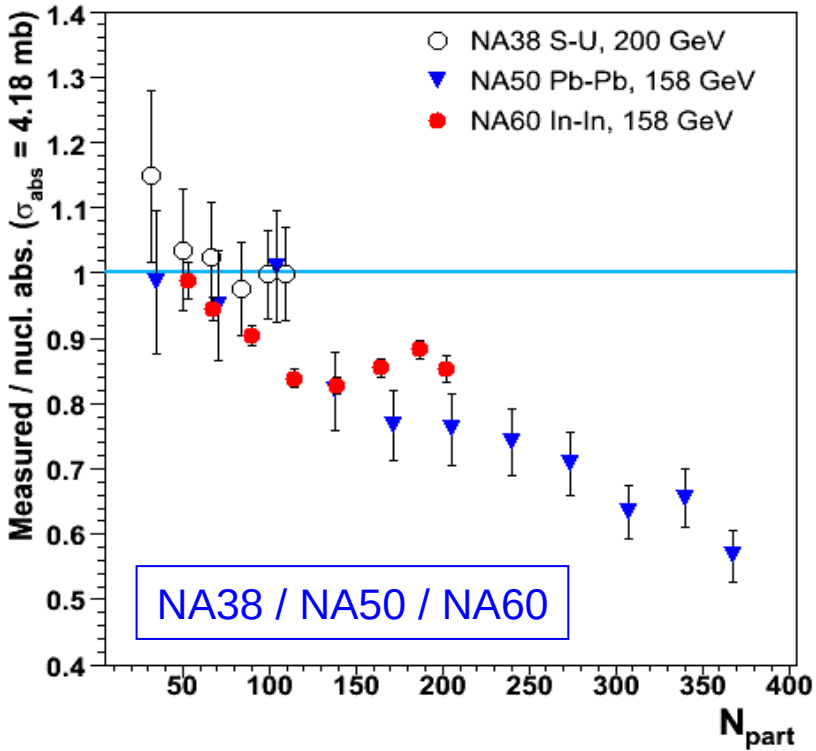
PHENIX can study these effects from the measurement of J/ψ as a function of Rapidity, centrality, collision species.

J/ψ measurement at SPS

- NA38(S+U), NA50(Pb+Pb), NA60(In+In) at $\sqrt{s_{NN}}$ = 17.3 GeV
- J/ψ yield is suppressed relative to nuclear absorption.

$B\sigma(J/\psi)/\sigma(DY)$

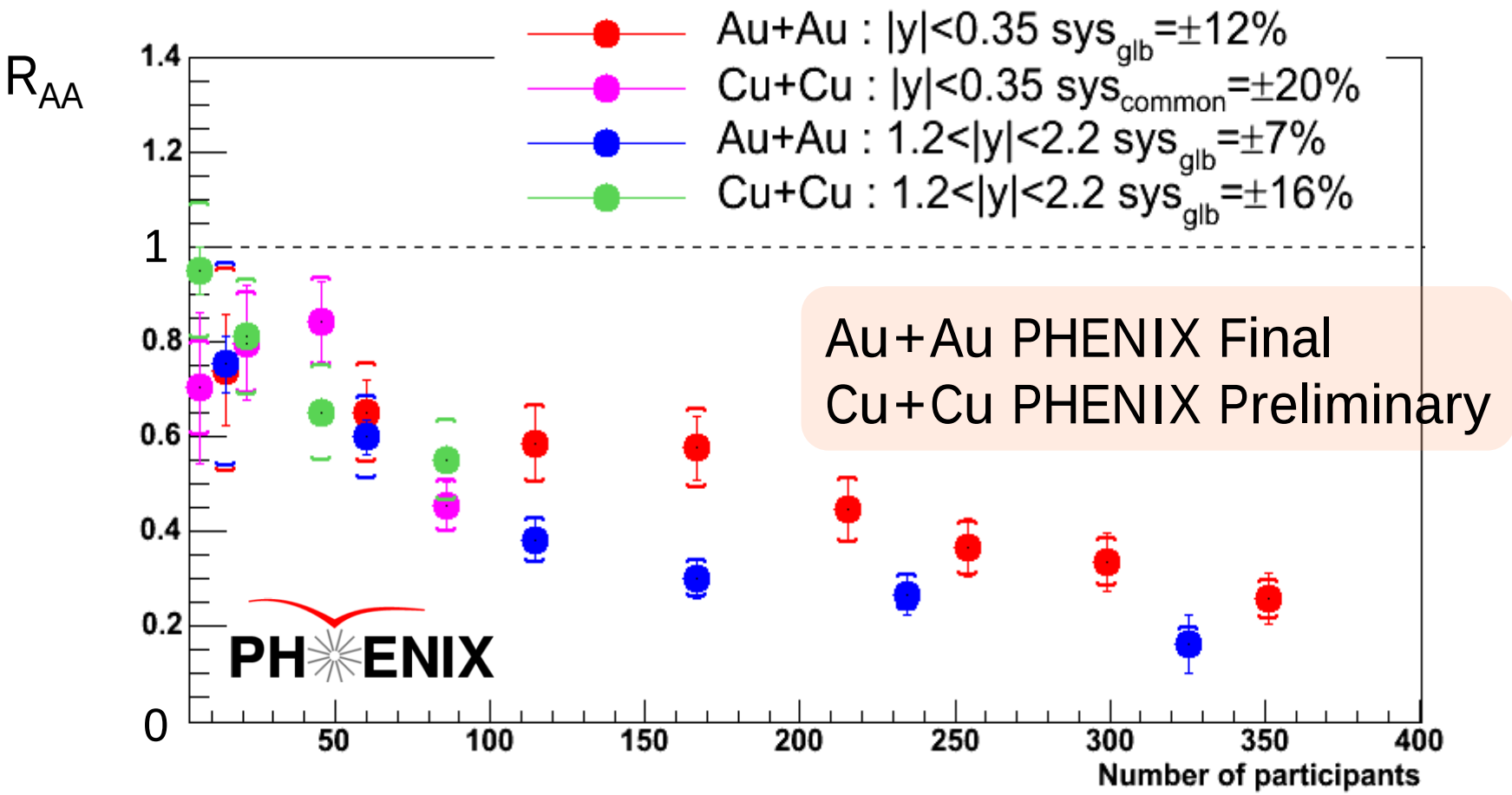
$(B\sigma(J/\psi)/\sigma(DY))$ expected from nuclear absorption



- It is very promising to study J/ψ production in A+A collisions at higher collision energy and higher partonic density.
  - 10x $\sqrt{s_{NN}}$ at RHIC
  - 2-3x gluon density at RHIC

Results of the centrality dependence of J/ψ production in Au+Au and Cu+Cu collisions

PHENIX Results of R_{AA} vs. N_{part}

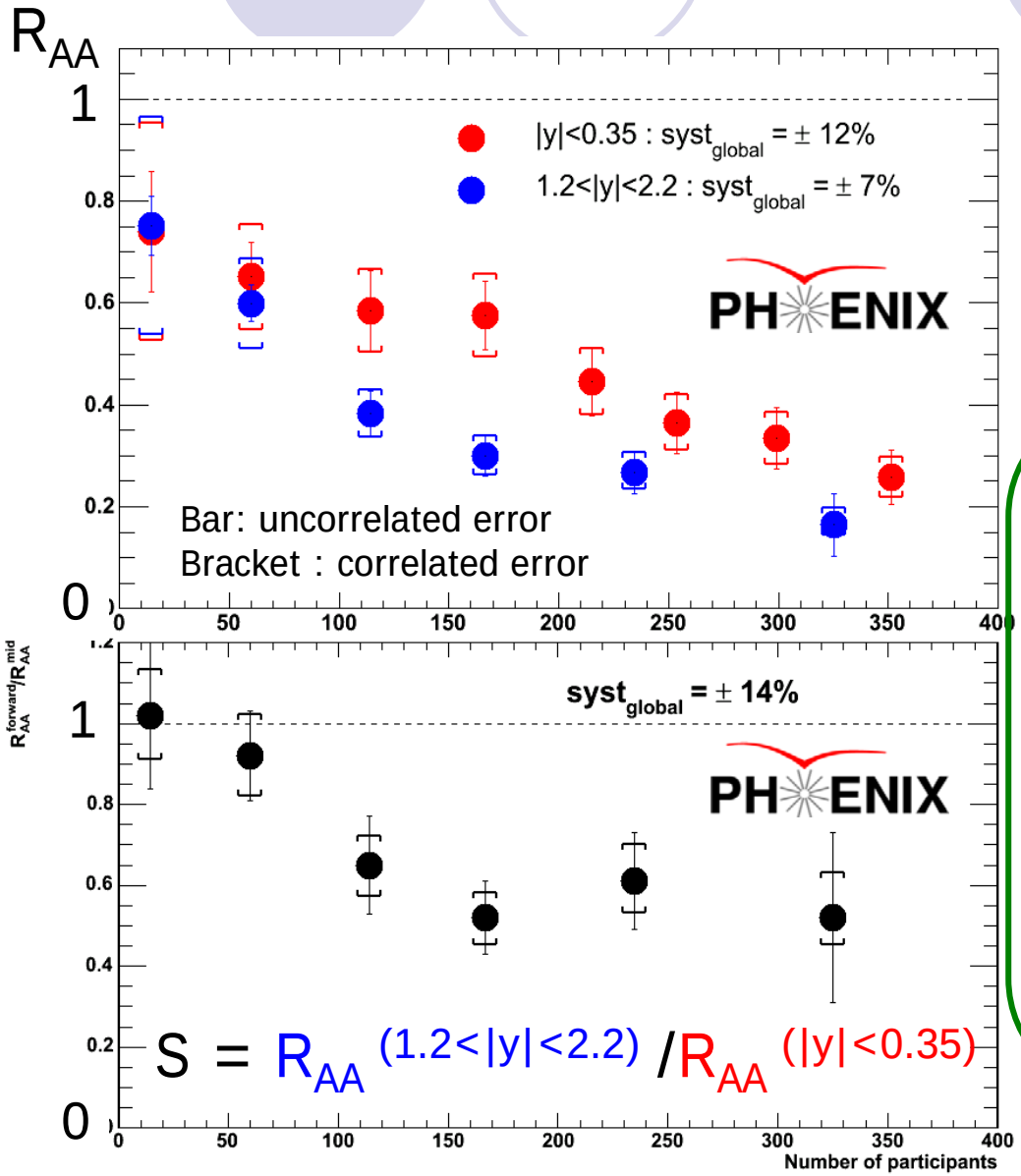


- Final results for Au+Au : **nucl-ex/0611020** (submitted to PRL)
- Analysis for Cu+Cu will be finalized soon!

Observation 1

Different suppression pattern between mid-rapidity and forward-rapidity

R_{AA} vs. N_{part} in Au+Au collisions

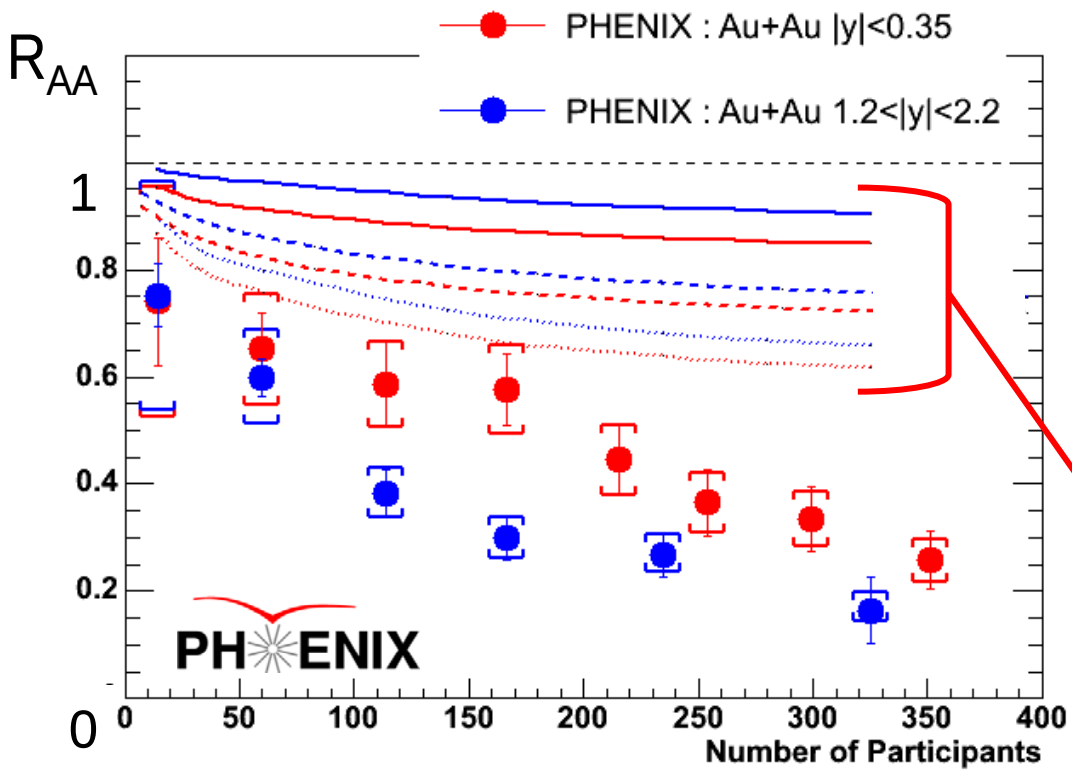


- R_{AA} vs. N_{part}.
  - |y|<0.35
  - 1.2<|y|<2.2

- Different behavior in R_{AA} between mid-rapidity and forward-rapidity.

- J/ψ suppression is larger at forward-rapidity than at mid-rapidity
  - S ~ 0.6 for N_{part}>100

R_{AA} and Cold Nuclear Matter (CNM) effects



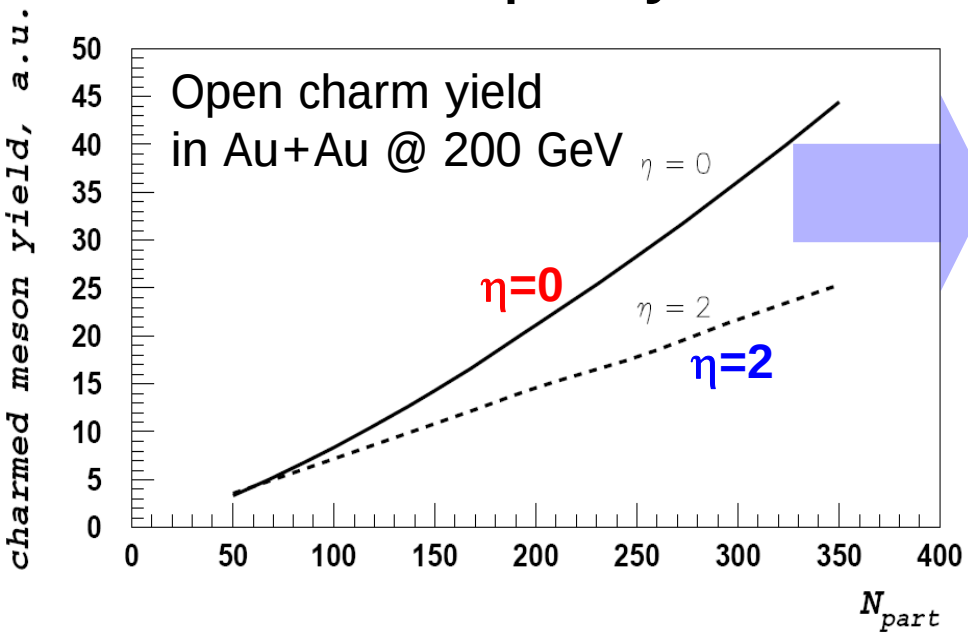
- CNM effects
  - Gluon shadowing + nuclear absorption
  - J/ψ measurement in d+Au collisions.
  - **σ_{abs} ~ 1mb**
  - PRL, 96, 012304 (2006)

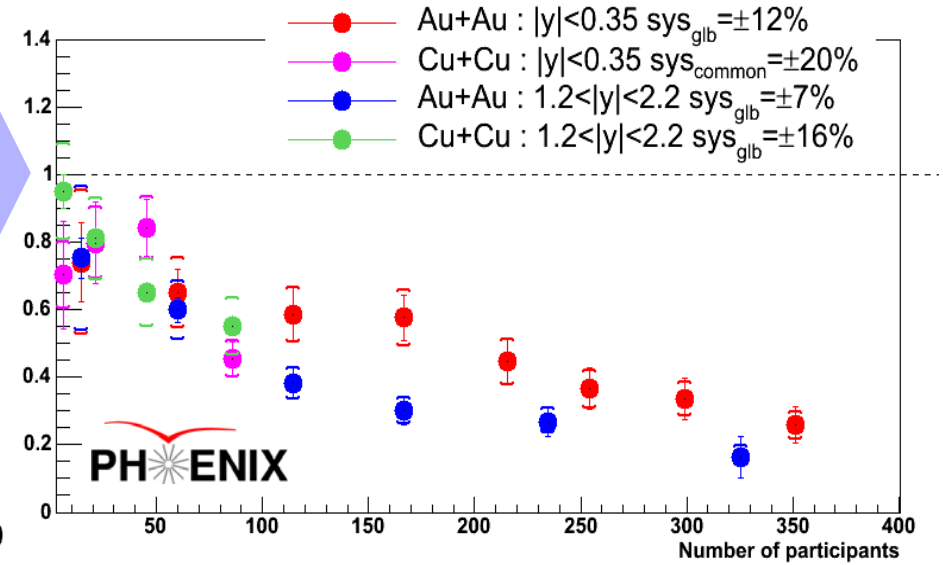
RHIC CNM effects
(σ_{abs} = 0, 1, 2mb at y=0, y=2)
R. Vogt *et al.*, nucl-th/0507027

- Significant suppression relative to CNM effects.
- CNM effects predict larger suppression at mid-rapidity, while data shows larger suppression at forward-rapidity.

Larger suppression by CGC?

- Heavy quark production is expected to be suppressed due to "Color Glass Condensate" at forward-rapidity. K. L. Tuchin hep-ph/0402298



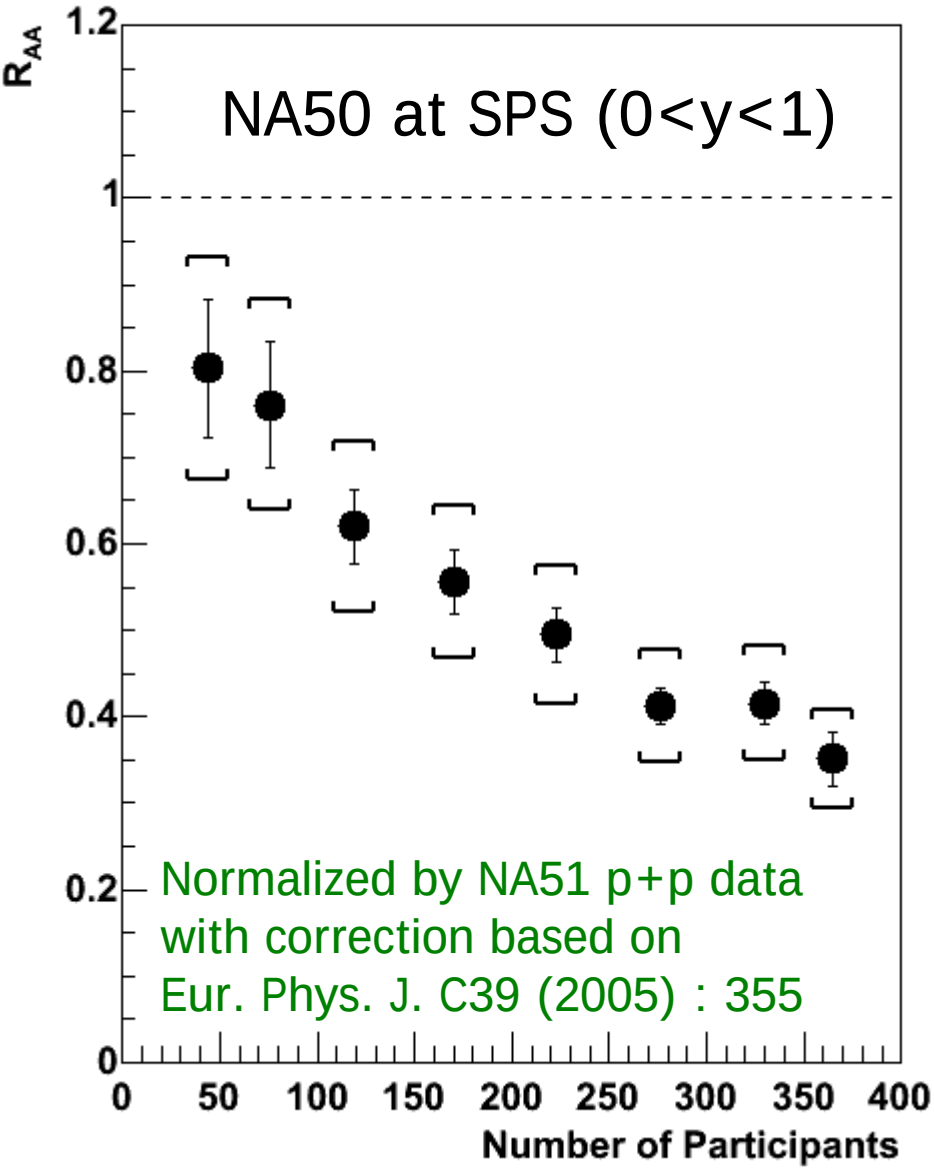


- Larger suppression of J/ψ at forward-rapidity (N_{part}>100) could be ascribed to Color Glass Condensate?

Observation 2

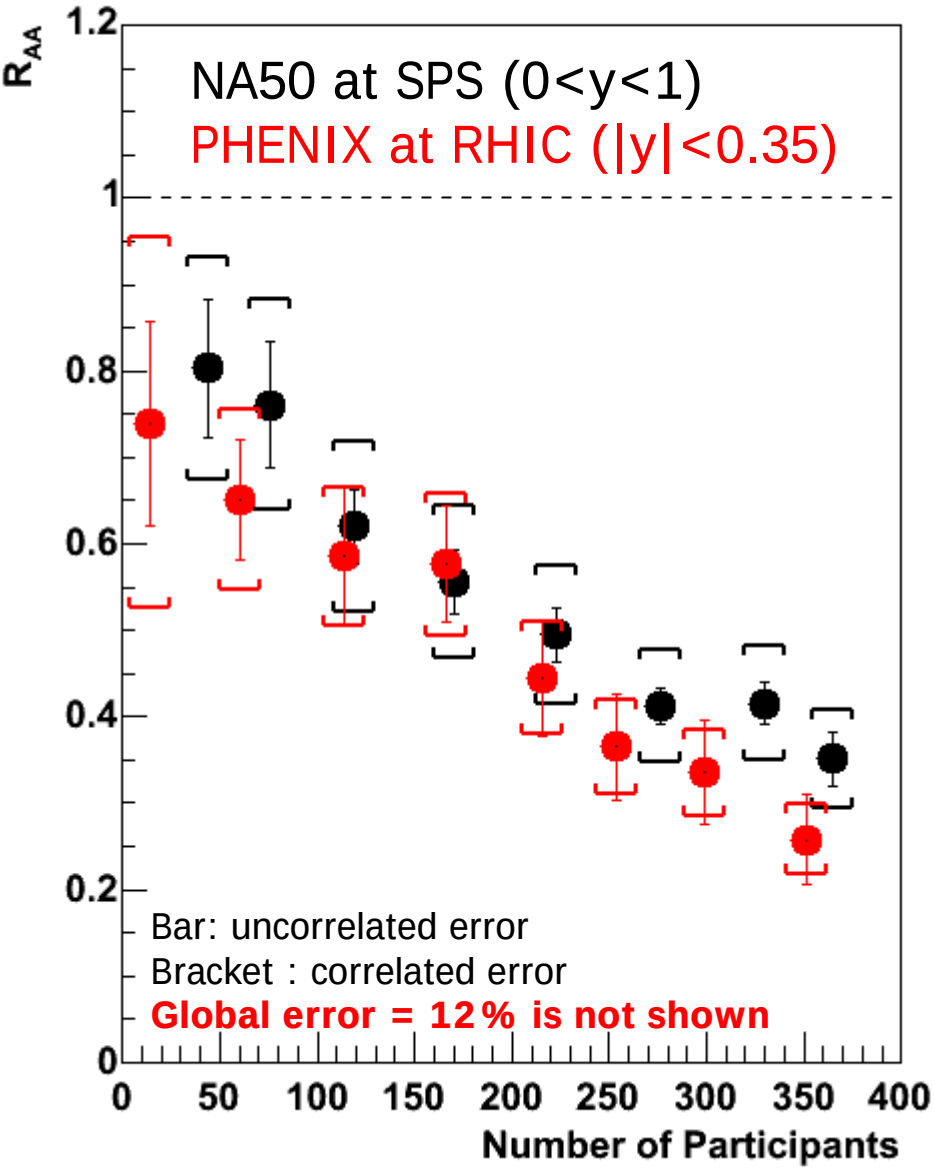
J/ψ suppression at mid-rapidity at RHIC is similar compared to SPS

Comparison to NA50



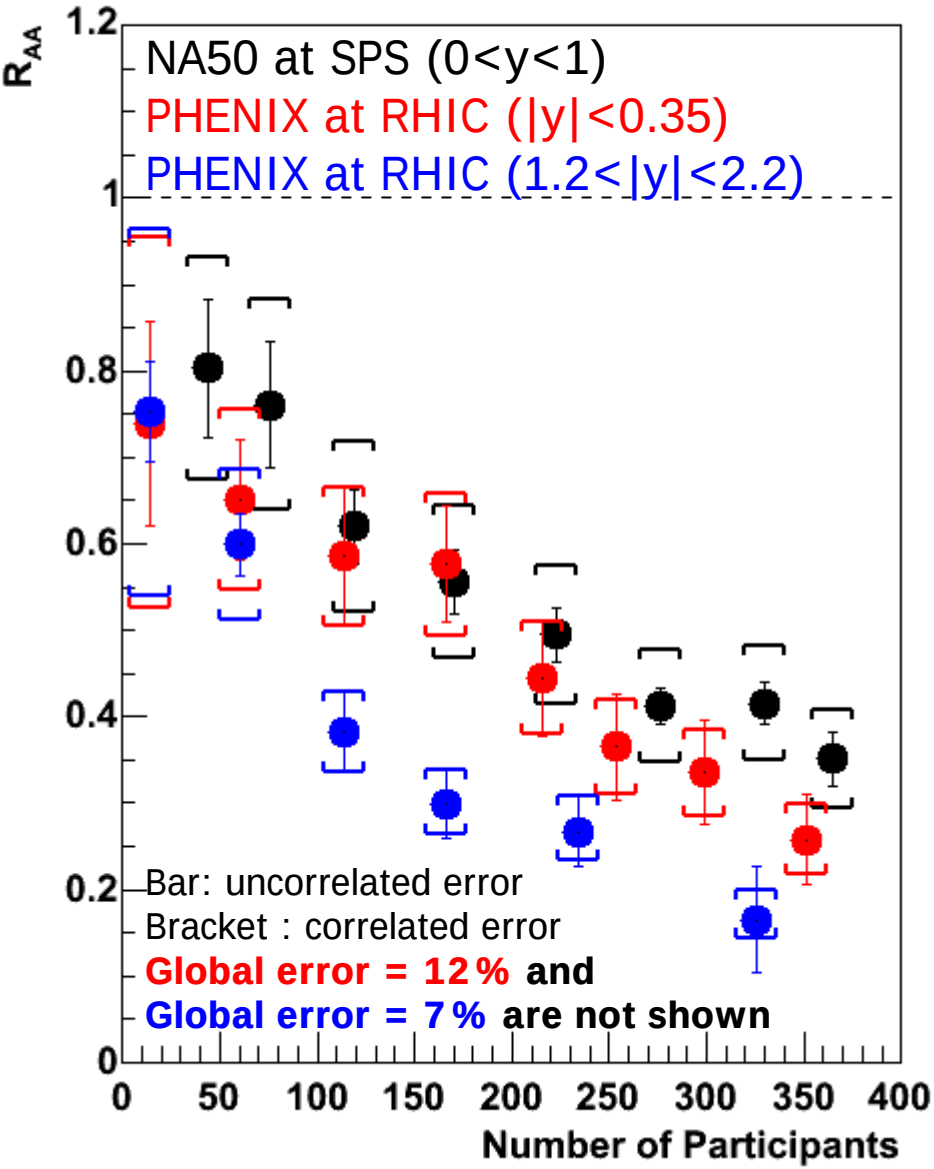
- R_{AA} vs. N_{part}
  - NA50 at SPS
    - 0<y<1
  - Bracket : Systematic error (16%) in R_{AA} due to:
    - Stat. error of $B\sigma(J/\psi)/\sigma(DY)$ in NA51 p+p collisions. (3%)
    - Uncertainty from rescaling of $B\sigma(J/\psi)/\sigma(DY)$ from 450 GeV to 158 GeV. (15%)
      - Eur. Phys. J. C39 (2005) : 355
      - Phys. Lett. B 553, 167 (2003)

Comparison to NA50



- R_{AA} vs. N_{part}
  - NA50 at SPS
    - 0<y<1
  - PHENIX at RHIC
    - |y|<0.35

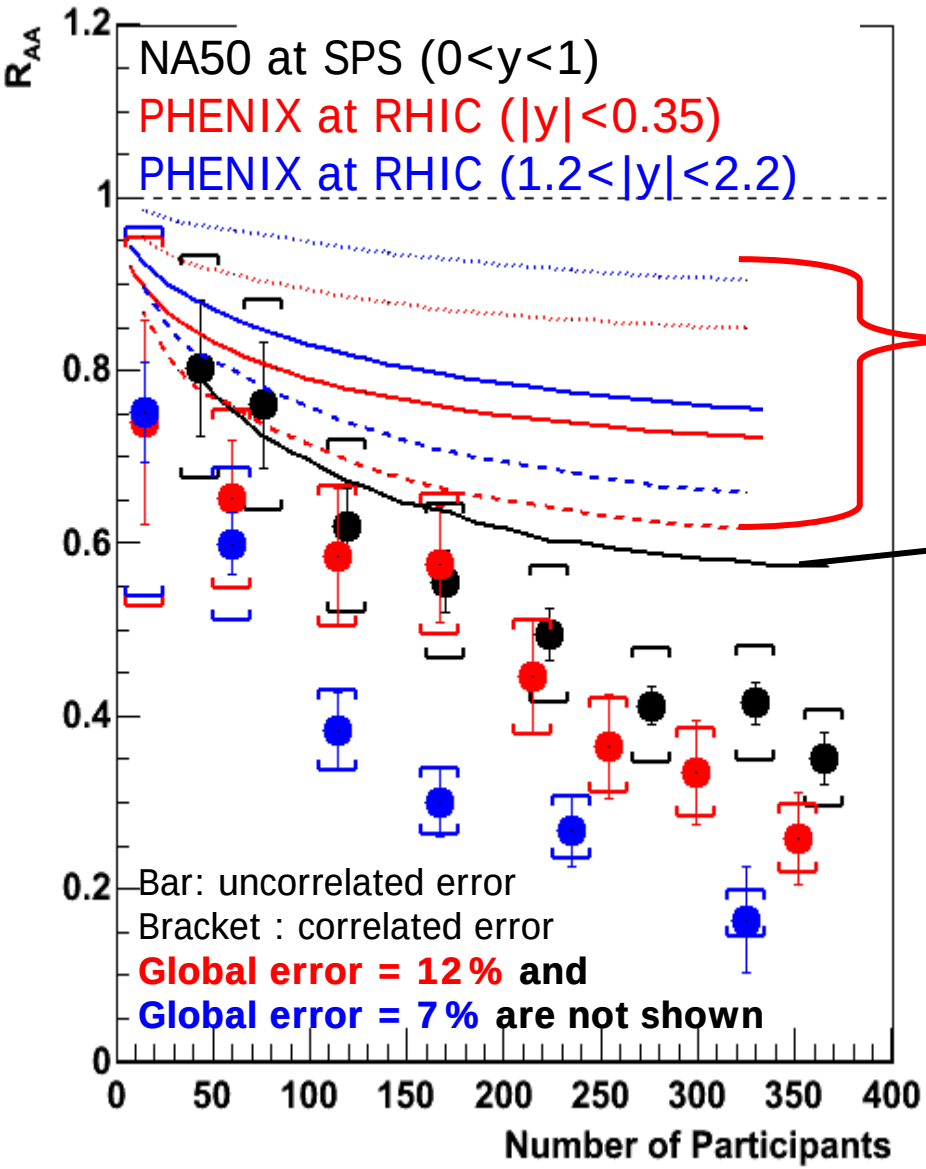
Comparison to NA50



- R_{AA} vs. N_{part}
  - NA50 at SPS
    - 0<y<1
  - PHENIX at RHIC
    - |y|<0.35
    - 1.2<|y|<2.2

• J/ψ Suppression (CNM effects included) is similar at RHIC (y=0) compared to at SPS (0<y<1).

Comparison to NA50

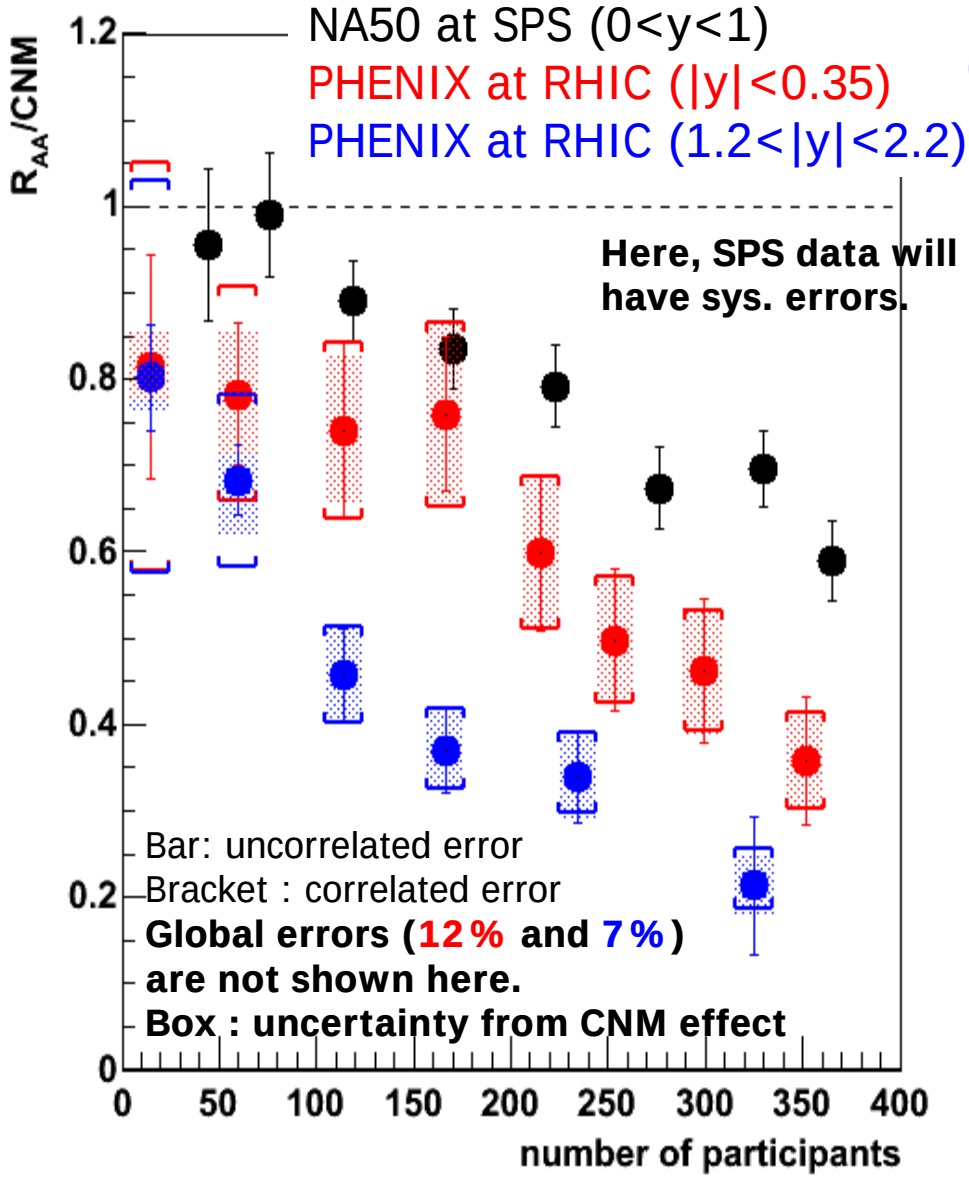


- R_{AA} at RHIC and SPS

RHIC CNM effects
(σ_{abs} = 0, 1, 2mb at y=0, y=2)
R. Vogt *et al.*, nucl-th/0507027

SPS CNM effects (σ_{abs} = 4.18 mb)
NA50, Eur. Phys. J. C39 (2005):355

R_{AA}/CNM vs. N_{part}



- R_{AA}/CNM at RHIC and SPS. CNM:
  - σ_{abs} = 4.18 mb for SPS
  - σ_{abs} = 1 mb for RHIC
    - Additional sys. error due to the uncertainty of CNM (0-2mb) is shown as box.

- J/ψ suppression relative to CNM effects is larger at RHIC for the similar N_{part}. However, error is large.
  - Need more precise CNM measurements.

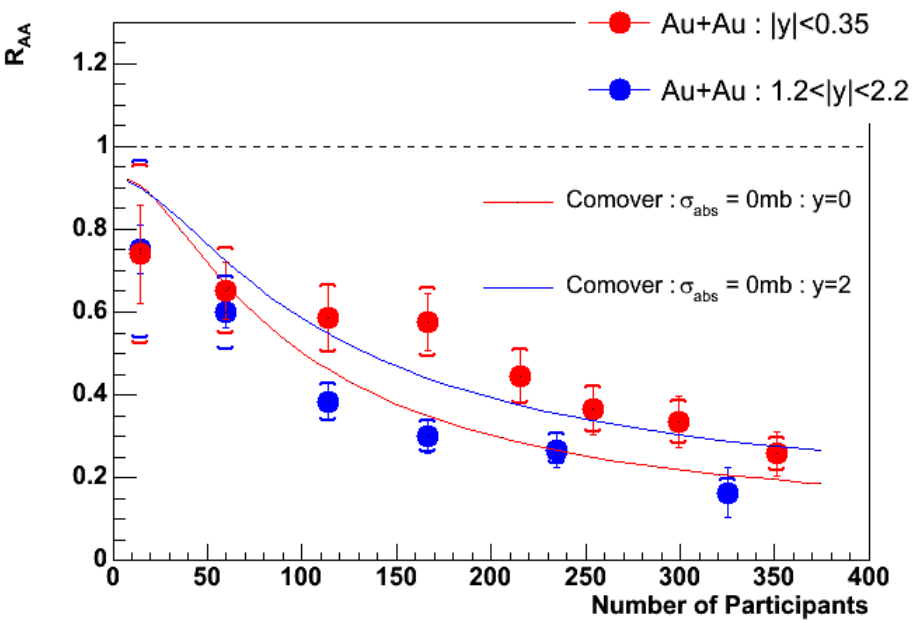
Exercise :
Comparison to theoretical models

Extrapolation of J/ψ suppression from SPS

Dissociation by comoving partons and hadrons

Capella *et al.*, hep-ph/0610313

Calculation for y=0 and y=1.8

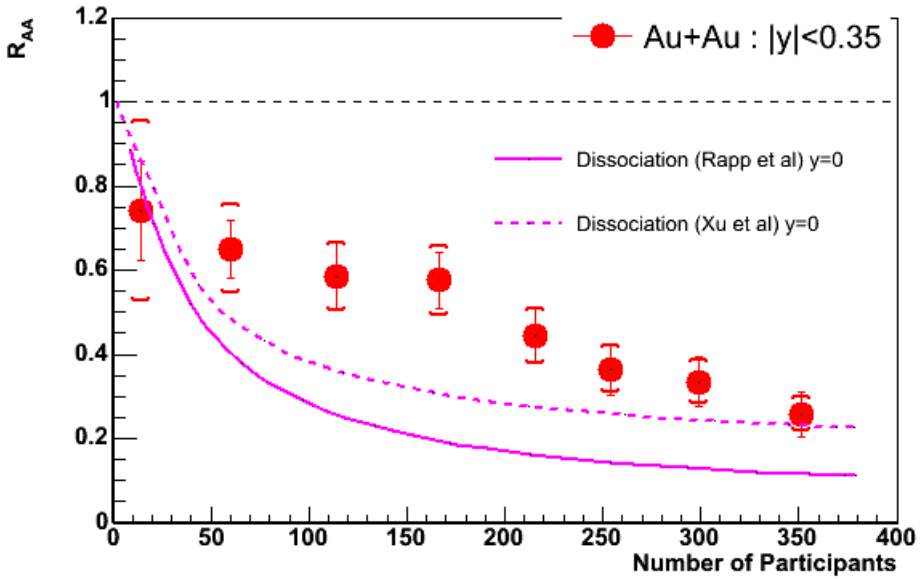


Dissociation by thermal gluons

R. Rapp *et al.*, nucl-th/0608033

Nu Xu *et al.*, nucl-th/0608010

Calculation for only y=0

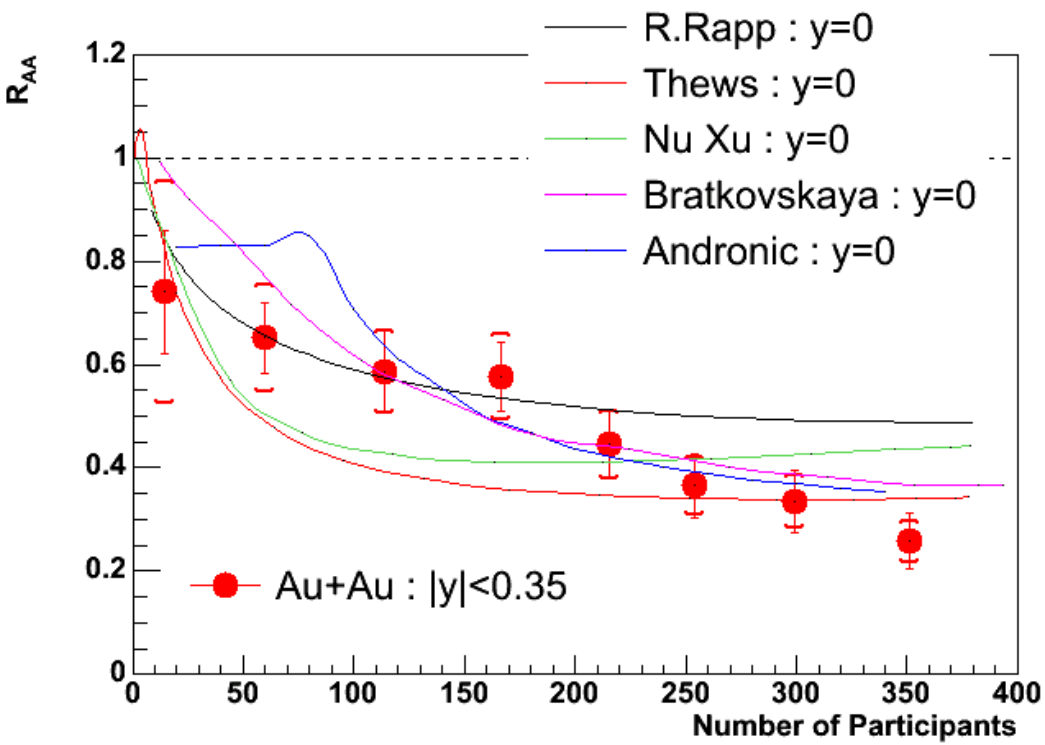


- Data shows opposite trend.

- At mid-rapidity, suppression is weaker compared to the dissociation scenario in QGP.

Recombination models

- Various Suppression+ Recombination models

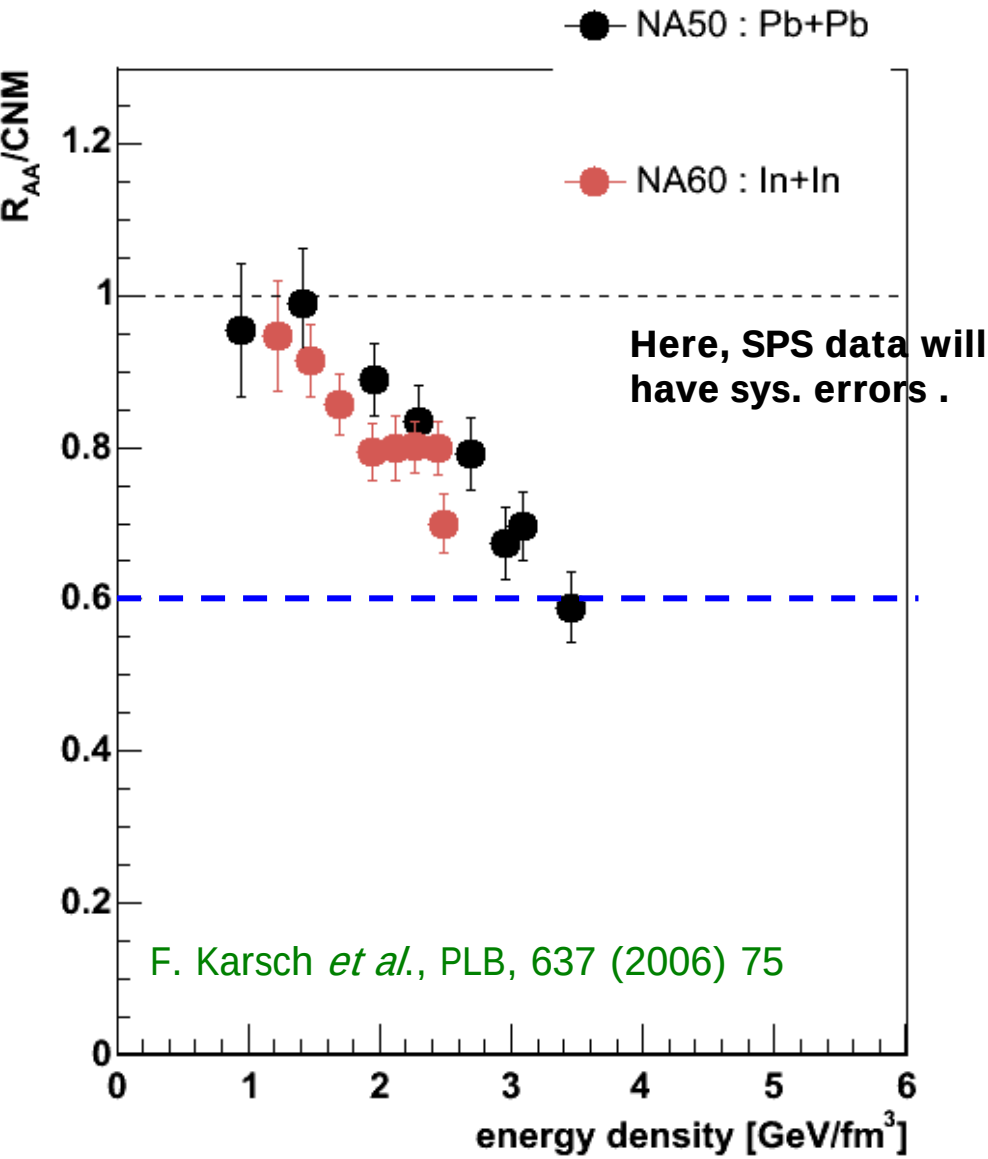


Calculation for mid-rapidity.

- R. Rapp *et al.* (for y=0)
  - PRL 92, 212301 (2004)
- Thews (for y=0)
  - Eur. Phys. J C43, 97 (2005)
- Nu Xu *et al.* (for y=0)
  - nucl-th/0608010
- Bratkovskaya *et al.* (for y=0)
  - PRC 69, 054903 (2004)
- A. Andronic *et al.* (for y=0)
  - nucl-th/0611023

- Data matches better. However, charm production in A+A is unclear.
- J/ψ v2 measurement will provide direct & useful information.
  - 4 x stat. in 2007 Au+Au collisions + 2.5 x RP resolution by PHENIX

Sequential Melting (SPS+RHIC)



F. Karsch *et al.*, PLB, 637 (2006) 75

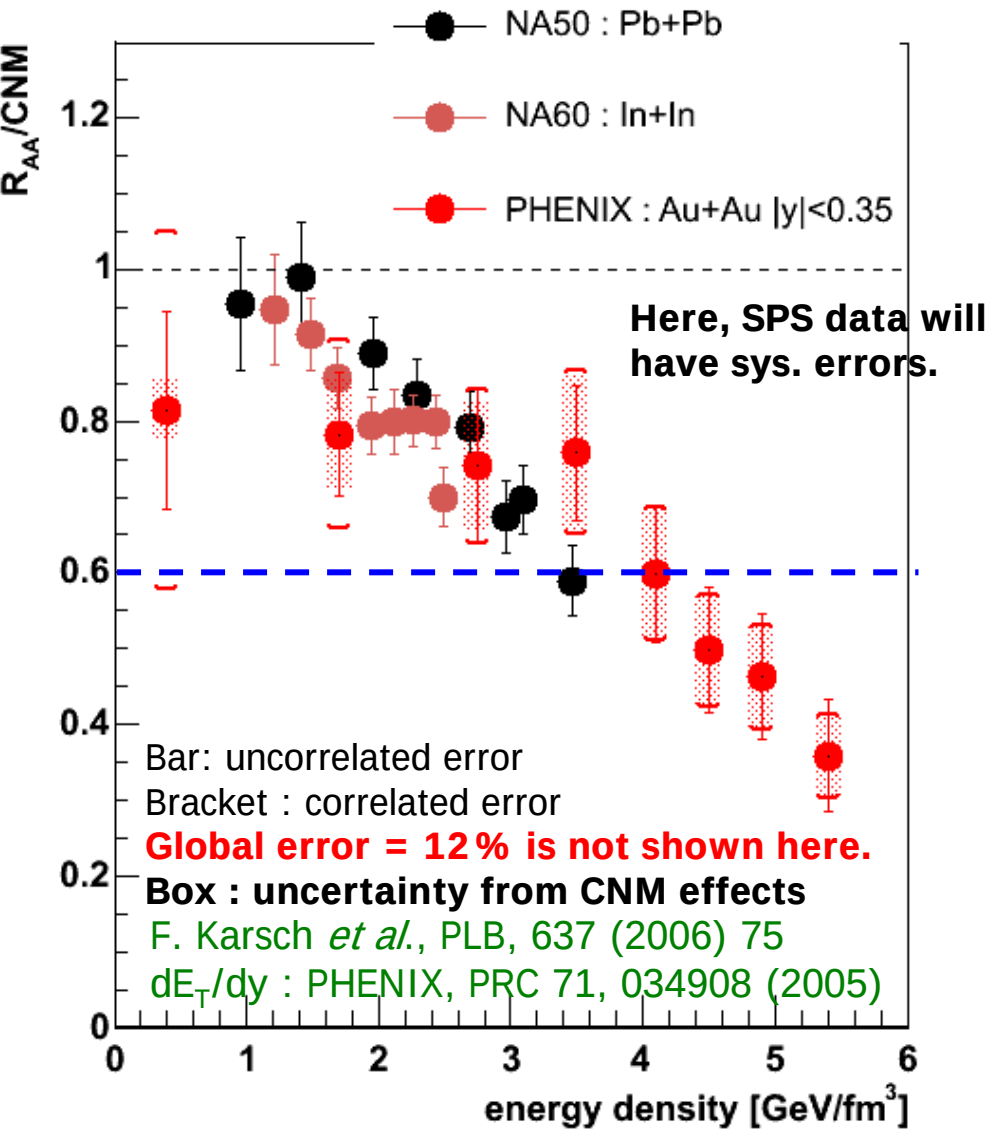
- R_{AA}/CNM vs. Bjorken energy density

$$\varepsilon_{Bj} = \frac{1}{\tau_0 A_\perp} \frac{dE_T}{dy}\bigg|_{y=0}$$

  - τ_0 = 1 fm/c. Be careful!
    - Not clear τ_0 at SPS
    - Crossing time ~ 1.6 fm/c

• J/ψ suppression at SPS can be understood from the melting of ψ' and χ_c.

Sequential Melting (SPS+RHIC)

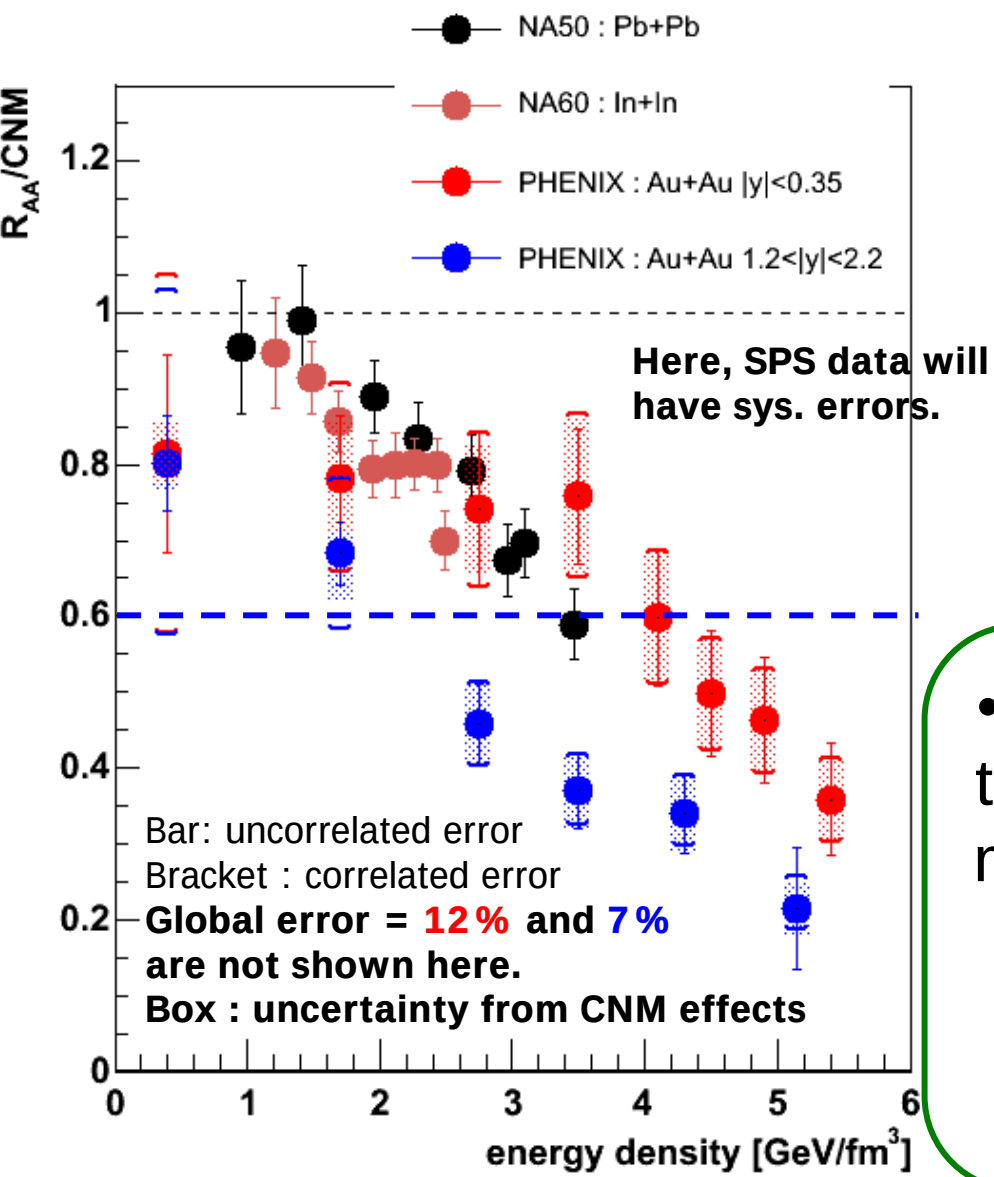


- R_{AA}/CNM vs. Bjorken energy density

$$\varepsilon_{Bj} = \frac{1}{\tau_0 A_\perp} \frac{dE_T}{dy}\bigg|_{y=0}$$

  - τ_0 = 1 fm/c. Be careful!
    - Not clear τ_0 at SPS and RHIC.
    - τ_0 < 1 fm/c at RHIC
    - Nucl. Phys. A757, 2005

Sequential Melting (SPS+RHIC)



- R_{AA}/CNM vs. Bjorken energy density

$$\varepsilon_{Bj} = \frac{1}{\tau_0 A_\perp} \frac{dE_T}{dy}\bigg|_{y=0}$$

  - τ_0 = 1 fm/c Be careful!
    - τ_0 < 1 fm/c at RHIC

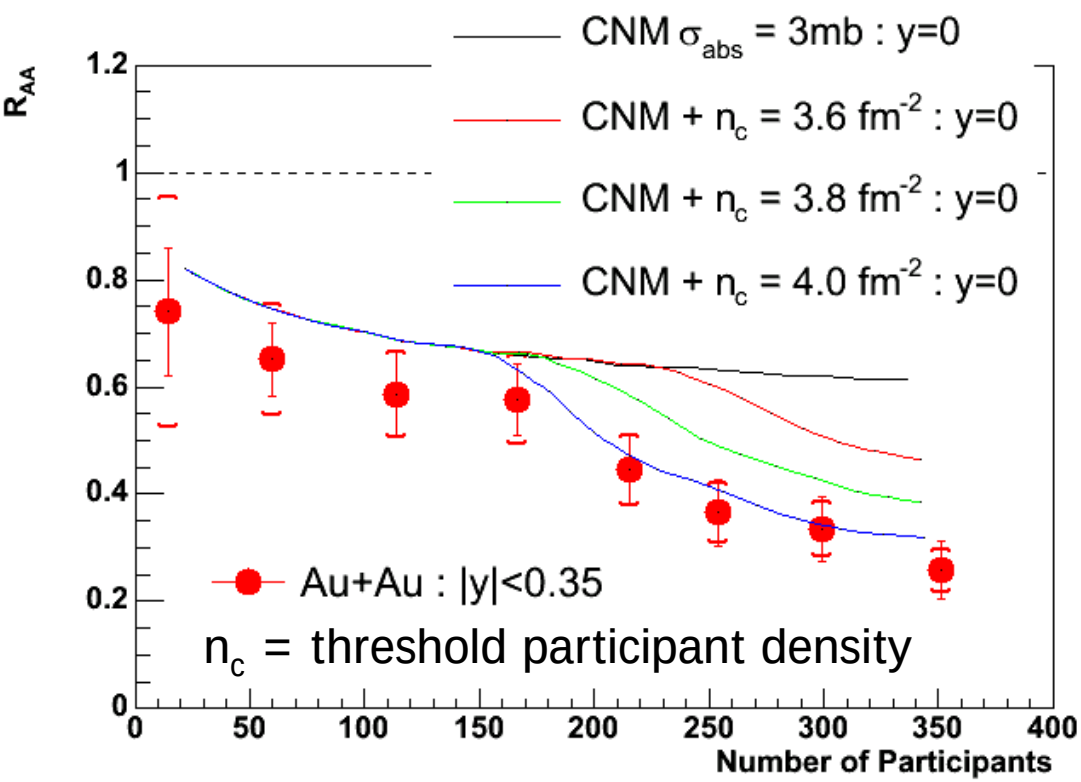
•Data seem not consistent with the picture from sequential melting (melt only χ_c and ψ').

- Error is large and need better CNM measurements at RHIC.
- Need to measure feed-down contribution at RHIC energy.

Threshold Model

- All J/ψ is suppressed above a threshold density.

A. K. Chaudhuri, nucl-th/0610031
Calculation for only y=0.



- Fate of J/ψ depends on the local energy density (∝ participants density, n)
- Similar model to the sequential melting and associated to "onset of J/ψ suppression".
- n_c = 4.0 fm^{-2} matches to our mid-rapidity data. (cf. n~4.32 fm^{-2} in most central Au+Au collisions)

- Describes well mid-rapidity data.
- How about forward-rapidity?

Summary

- PHENIX measured J/ψ in Au+Au and Cu+Cu collisions at mid-rapidity and forward-rapidity.
- Suppression is larger at forward-rapidity than at mid-rapidity for N_{part}>100.
  - Suggesting initial state effect such as Color Glass Condensate?
- R_{AA}/CNM seems to be lower at RHIC compared to at SPS
  - However, suppression at mid-rapidity isn't so strong as expected by the models (destruction by comovers, thermal gluons) extrapolated from SPS to RHIC.
  - Suppression + Recombination models match better. J/ψ v2 will be the key measurement to discuss the recombination.
  - Not consistent with the picture of only ψ' and χ_c melting at RHIC
    - Direct J/ψ suppression? Error is still large. To clarify this,
    - Need to measure CNM effects precisely.
    - Need to measure feed-down contribution at RHIC energy.

PHENIX

- University of São Paulo, São Paulo, Brazil
- Academia Sinica, Taipei 11529, China
- China Institute of Atomic Energy (CIAE), Beijing, P. R. China
- Peking University, Beijing, P. R. China
- Charles University, Faculty of Mathematics and Physics, Ke Karlovu 3, 12116 Prague, Czech Republic
- Czech Technical University, Faculty of Nuclear Sciences and Physical Engineering, Brehova 7, 11519 Prague, Czech Republic
- Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague, Czech Republic
- Laboratoire de Physique Corpusculaire (LPC), Universite de Clermont-Ferrand, 63 170 Aubiere, Clermont-Ferrand, France
- Dapnia, CEA Saclay, Bat. 703, F-91191 Gif-sur-Yvette, France
- IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406 Orsay, Fra
- Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Rou Saclay, F-91128 Palaiseau, France
- SUBATECH, Ecòle des Mines at Nantes, F-44307 Nantes France
- University of Muenster, Muenster, Germany
- KFKI Research Institute for Particle and Nuclear Physics at the Hungai Academy of Sciences (MTA KFKI RMKI), Budapest, Hungary
- Debrecen University, Debrecen, Hungary
- Eövös Loránd University (ELTE), Budapest, Hungary
- Banaras Hindu University, Banaras, India
- Bhabha Atomic Research Centre (BARC), Bombay, India
- Weizmann Institute, Rehovot, 76100, Israel
- Center for Nuclear Study (CNS-Tokyo), University of Tokyo, Tanashi, Tokyo 188, Japan
- Hiroshima University, Higashi-Hiroshima 739, Japan
- KEK - High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
- Kyoto University, Kyoto, Japan
- Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki, Japan
- RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan
- RIKEN – BNL Research Center, Japan, located at BNL
- Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
- Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
- University of Tsukuba, 1-1-1 Tennodai, Tsukuba-shi Ibaraki-ken 305-8577, Japan
- Waseda University, Tokyo, Japan
- Cyclotron Application Laboratory, KAERI, Seoul, South Korea
- Kangnung National University, Kangnung 210-702, South Korea
- Korea University, Seoul, 136-701, Korea
- Myong Ji University, Yongin City 449-728, Korea
- System Electronics Laboratory, Seoul National University, Seoul, South Korea
- Yonsei University, Seoul 120-749, Korea
- IHEP (Protvino), State Research Center of Russian Federation "Institute for High Energy Physics", Protvino 142281, Russia
- Joint Institute for Nuclear Research (JINR-Dubna), Dubna, Russia
- Kurchatov Institute, Moscow, Russia
- PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
- Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Vorob'evy Gory, Moscow 119992, Russia
- Saint-Petersburg State Polytechnical Univiversity, Politechnicheskayastr, 29, St. Petersburg, 195251, Russia

13 Countries; 62 Institutions; 550 Participants*

- Lund University, Lund, Sweden
- Abilene Christian University, Abilene, Texas, USA
- Brookhaven National Laboratory (BNL), Upton, NY 11973, USA
- University of California - Riverside (UCR), Riverside, CA 92521, USA
- University of Colorado, Boulder, CO, USA
- Columbia University, Nevis Laboratories, Irvington, NY 10533, USA
- Florida Institute of Technology, Melbourne, FL 32901, USA
- Florida State University (FSU), Tallahassee, FL 32306, USA
- Georgia State University (GSU), Atlanta, GA, 30303, USA
- University of Illinois Urbana-Champaign, Urbana-Champaign, IL, USA
- Iowa State University (ISU) and Ames Laboratory, Ames, IA 50011, USA
- Los Alamos National Laboratory (LANL), Los Alamos, NM 87545, USA
- Lawrence Livermore National Laboratory (LLNL), Livermore, CA 94550, USA
- University of New Mexico, Albuquerque, New Mexico, USA
- New Mexico State University, Las Cruces, New Mexico, USA
- Department of Chemistry, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA
- Department of Physics and Astronomy, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA
- Oak Ridge National Laboratory (ORNL), Oak Ridge, TN 37831, USA
- University of Tennessee (UT), Knoxville, TN 37996, USA
- Vanderbilt University, Nashville, TN 37235, USA

Related talks and posters

- Parallel 2.1 “Heavy Quark Production”
  - A. Glenn for the PHENIX Collaboration
    - “PHENIX results for J/y transverse momentum and rapidity dependence in Au+Au and Cu+Cu collisions”
  - A. Bickley for the PHENIX Collaboration
    - “Heavy Quarkonia production in p+p collisions from the PHENIX Experiment”
- Posters
  - 63. S. X. Oda
  - 154. E. T. Atomssa

Backup slides

AdS/CFT gives answer?

- Screening length depends on T and velocity with respect to the hot fluid in the collisions.
  - H. Liu *et al.*, hep-ph/0607062

$$Ls \propto 1/T\sqrt{\gamma}$$

- From AdS/CFT,
  - Significant suppression for high pT J/ψ.
  - For low pT J/ψ and no longitudinal expansion,

  $\gamma \sim E/m \sim mT/m\cosh(y) \sim \cosh(y)$

  → larger suppression at forward-rapidity!?

  → How large the longitudinal flow?

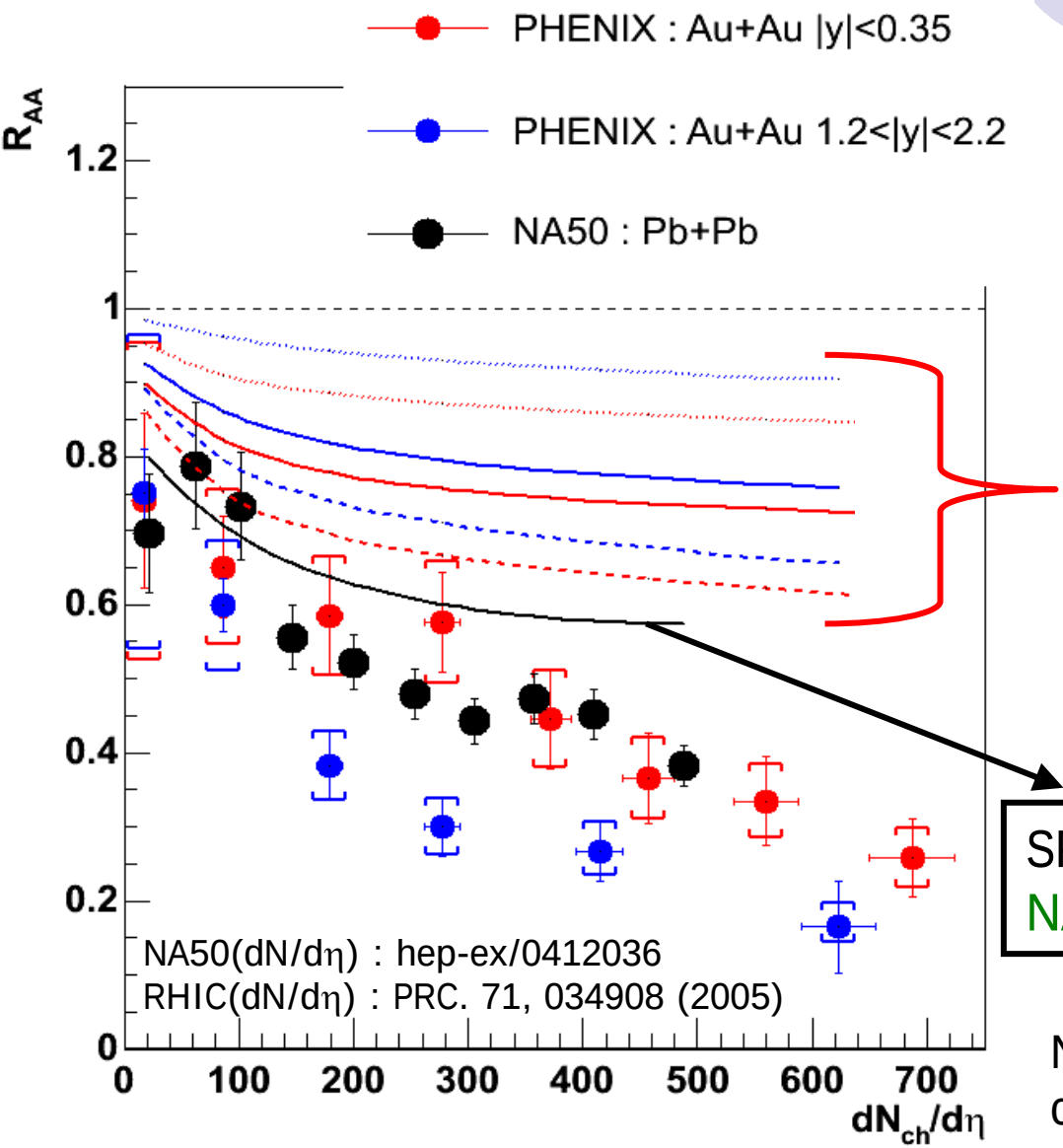
Lists of errors

- Lists of sys. errors

source	$\lvert y\rvert < 0.35$	$\lvert y\rvert \in [1.2, 2.2]$	type
signal extraction	6.5 to 9 %	4 to 24 %	A
acceptance	6 %	10 %	B
efficiency	4.5 to 8 %	4 to 16 %	B
run by run variation	4 %	5 %	B
input y, p_T distributions	2 %	4 %	B

- N_{col} : 10-28% (central-peripheral)
- $\delta s/s$ (stat. error) = 20-10% (central-peripehal)
- CNM : ~ 15%

Comparison to NA50



- Cold Nuclear Matter effect (CNM)
  - SPS : σ_{abs} ~ 4.18 mb
  - RHIC : σ_{abs} = 0-2 mb

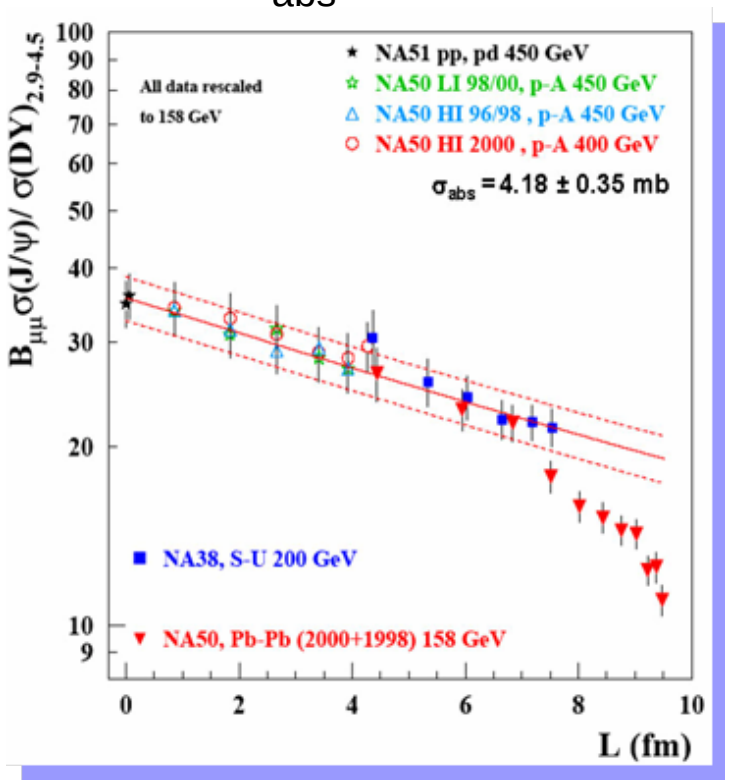
RHIC CNM effect
(σ_{abs} = 0, 1, 2mb at y=0, y=2)
R. Vogt *et al.*, nucl-th/0507027

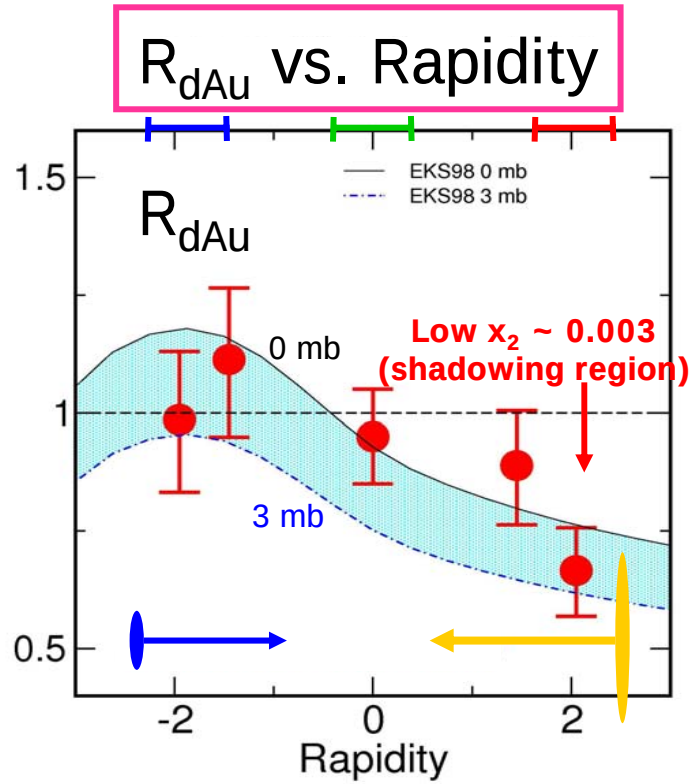
SPS CNM effect (σ_{abs} = 4.18 mb)
NA50, Eur. Phys. J. C39 (2005):355

Normalized by NA51 p+p data with correction based on hep-ex/0412036

Cold Nuclear Matter Effects at SPS and RHIC

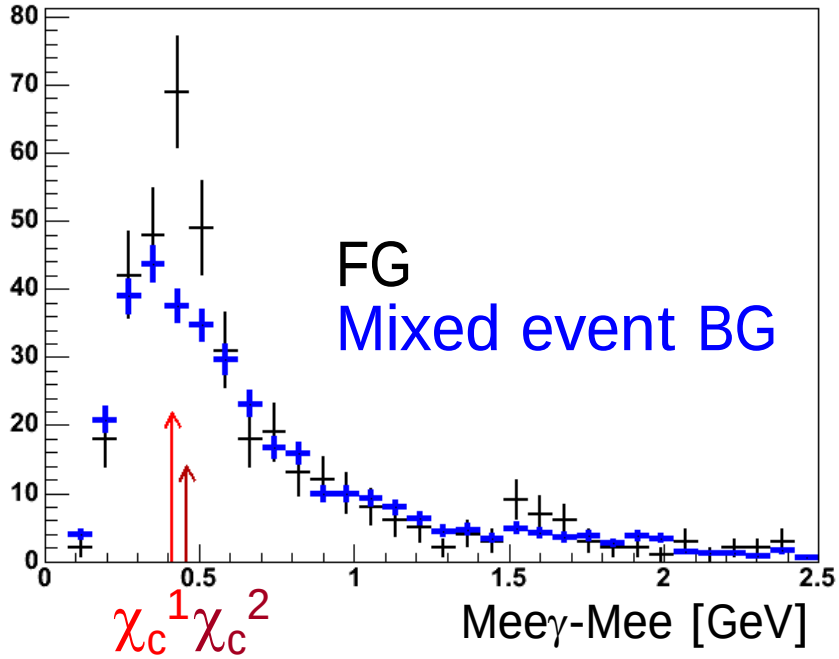
- Cold Nuclear Matter (CNM) effect
  - Shadowing + Nuclear Absorption
    - σ_{abs} = 4.18 mb at SPS, 0-3 mb at RHIC

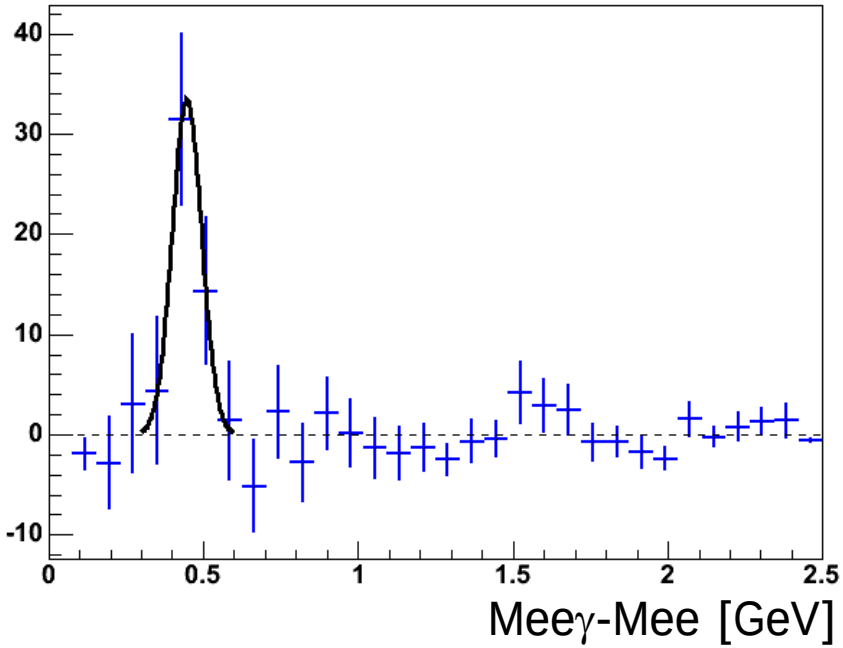




First χ_c observation

- From run5 p+p central arms
- Further analysis is on going.





Recorded data

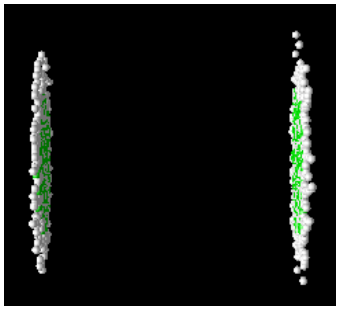
[1] PRL92 (2004) 051802
[2] PRC69 (2004) 014901
[3] PRL96 (2006) 012304
[4] QM05, nucl-ex/0510051
[5] nucl-ex/0611020
[6] hep-ex/06110202

- History of J/ψ measurement by PHENIX

Year	Ions	$\sqrt{s_{NN}}$	Luminosity	Status	J/ψ (ee + μμ)
2001	Au-Au	200 GeV	24 μb^{-1}	Central	13 + 0 [1]
2002	p-p	200 GeV	0.15 pb^{-1}	+ 1 muon arm	46 + 66 [2]
2002	d-Au	200 GeV	2.74 nb^{-1}	Central	360 + 1660 [3]
2003	p-p	200 GeV	0.35 pb^{-1}	+ 2 muon arms	130 + 450 [3]
	Au-Au	200 GeV	240 μb^{-1}	Final [5]	~ 1000 + 5000 [4]
2004	Au-Au	63 GeV	9.1 μb^{-1}	Analysis	~ 13
	p-p	200 GeV	324 nb^{-1}		
	Cu-Cu	200 GeV	4.8 nb^{-1}	Preliminary	~ 1000 + 10000 [4]
2005	Cu-Cu	63 GeV	190 mb^{-1}	Preliminary	~ 60 + 200
	p-p	200 GeV	3.8 pb^{-1}	Final [6]	~ 1500 + 10000

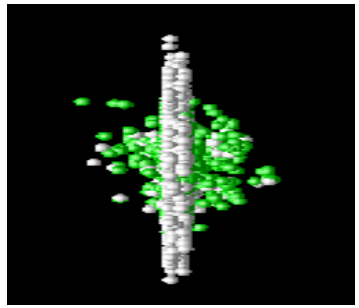
Charmonium in the Medium

- J/ψ production and evolution of the medium
  - All stage of collisions modify the J/ψ yield.



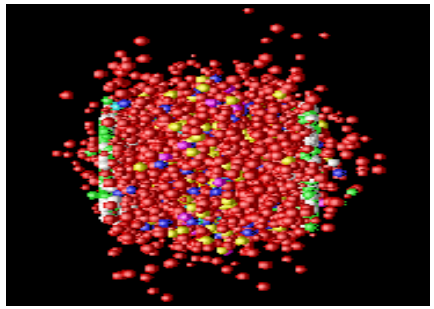
Initial stage

- Gluon Shadowing
- CGC



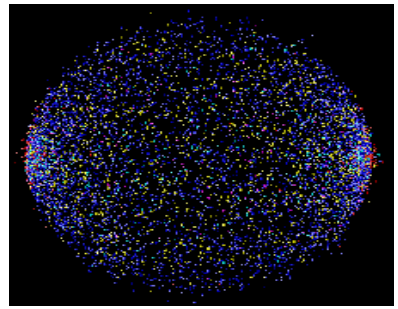
Nuclear medium

- Nuclear Absorption
- Cronin effect



Hot and dense medium

- Color screening
- Dissociation by gluons



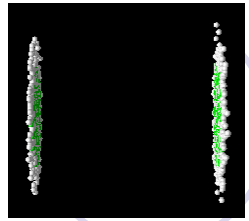
Mixed Phase Freeze out

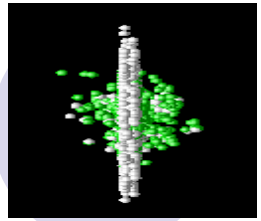
- $c\bar{c}$ coalescence
- Dissociation by secondary mesons

Cold Matter Effect

QGP Effect

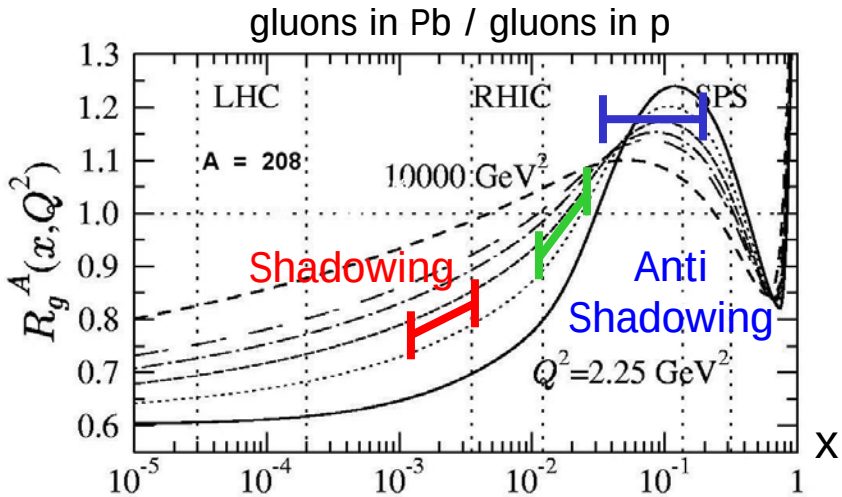
Cold Matter Effects





- Initial state effect:
  - Gluon Shadowing (or CGC gluon saturation)
    - Depletion of Gluon PDF in nuclei at small x.
- Final state effects:
  - Nuclear Absorption
    - Break up interaction of J/ψ or pre-resonance c-cbar state by spectators
  - Cronin effect
    - Initial state multiple scattering of partons
- d+Au collisions give the hints of these effects

Eskola et al. NPA696 (2001) 729

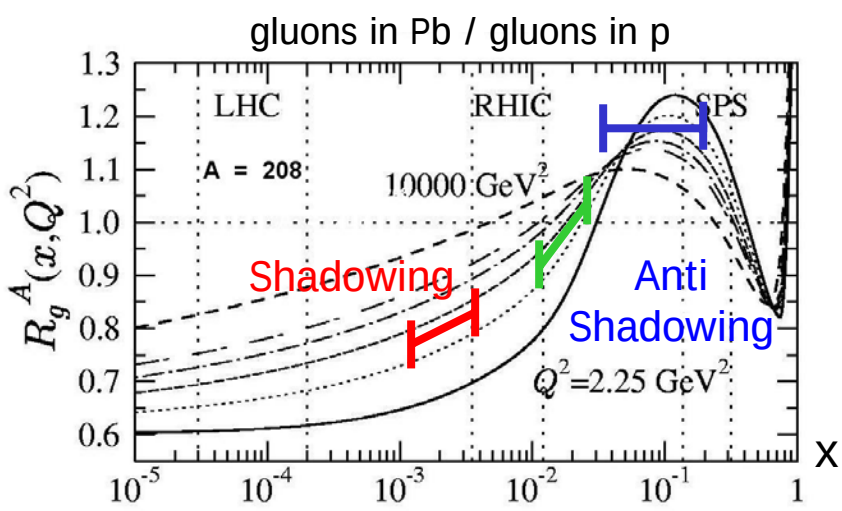


Converage of X in Au
By PHENIX
in d+Au experiments

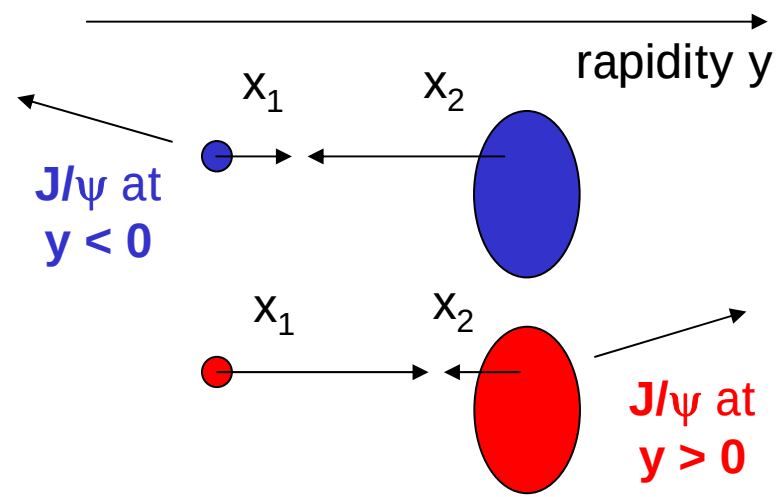
X_{Au} and Shadowing

- Three rapidity ranges probe different x of Au partons
  - South ($y < -1.2$) : large x_2 (in gold) ~ 0.090 (Anti-shadowing)
  - Central ($y \sim 0$) : intermediate x_2 ~ 0.020
  - North ($y > 1.2$) : small x_2 (in gold) ~ 0.003 (Shadowing)

An example of gluon shadowing prediction

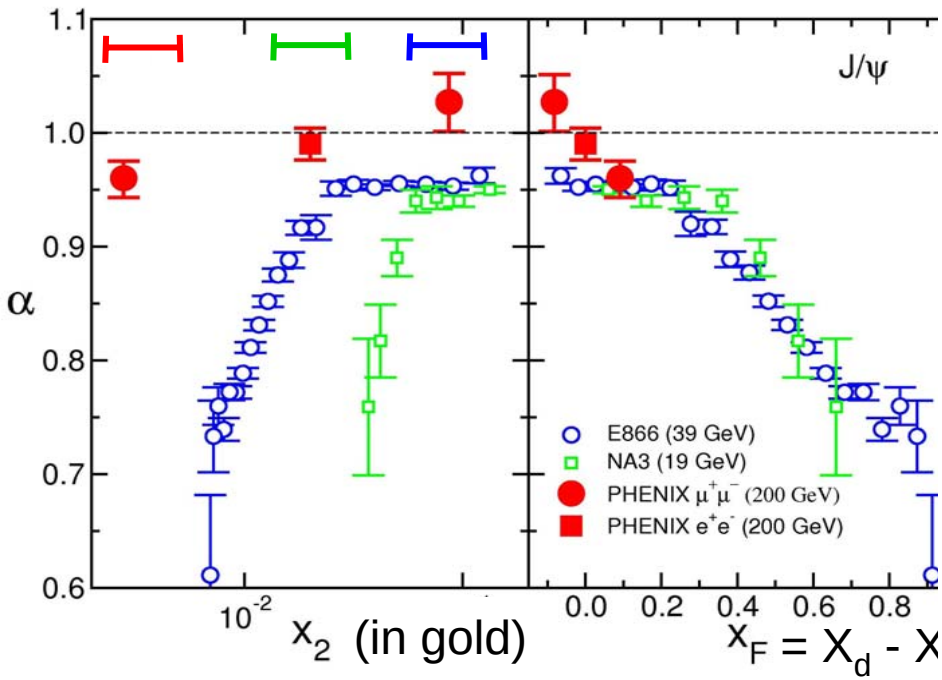


Eskola et al. NPA696 (2001) 729

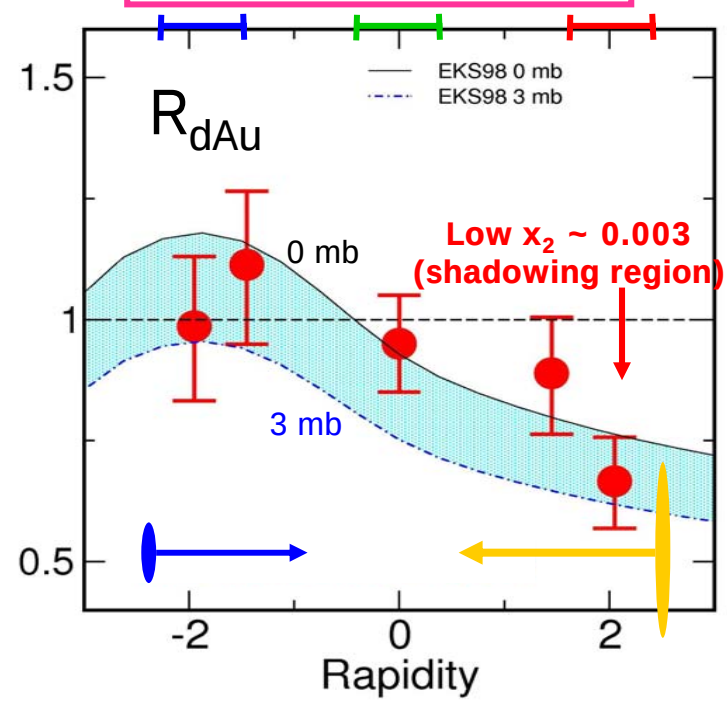


Results from d+Au Collisions

$\sigma_{dAu} = \sigma_{pp}\,(2x197)^{\alpha}$



R_{dAu} vs. Rapidity



Small effect from gluon shadowing

- α>0.92, scale with X_F not X_{Au}

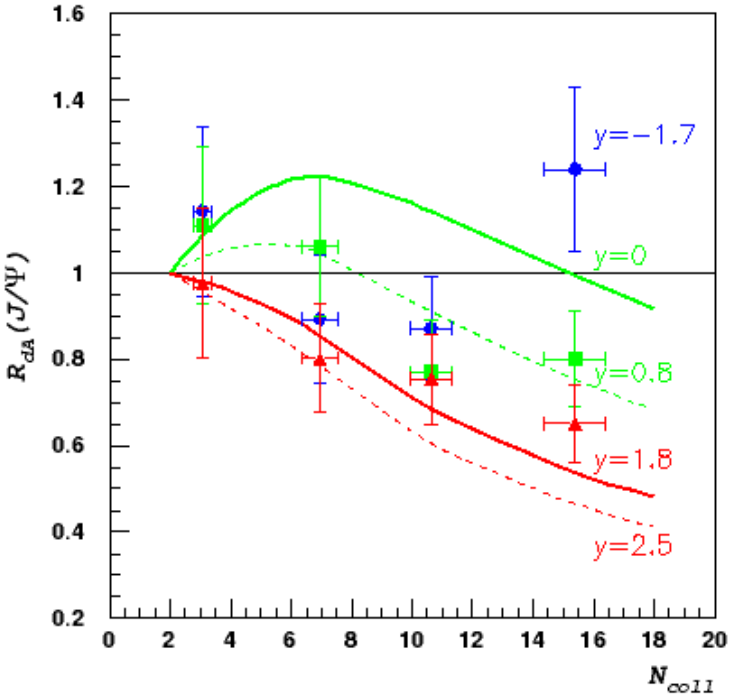
Small effect from nuclear absorption

- σ_{abs} = 0-3 mb, σ_{abs} = 4.2mb at SPS

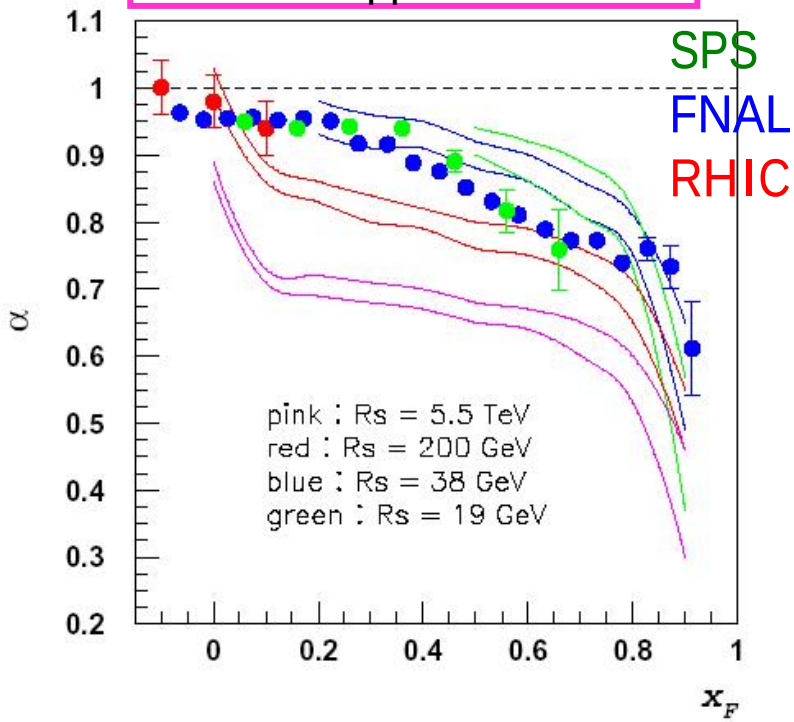
Need more data to quantify these effects.

Color Glass Condensate

- At RHIC, coherent charm production in nuclear color field at y>0 ($Q_s > m_c$) and dominant at y>2. → Description by Color-Glass-Condensate



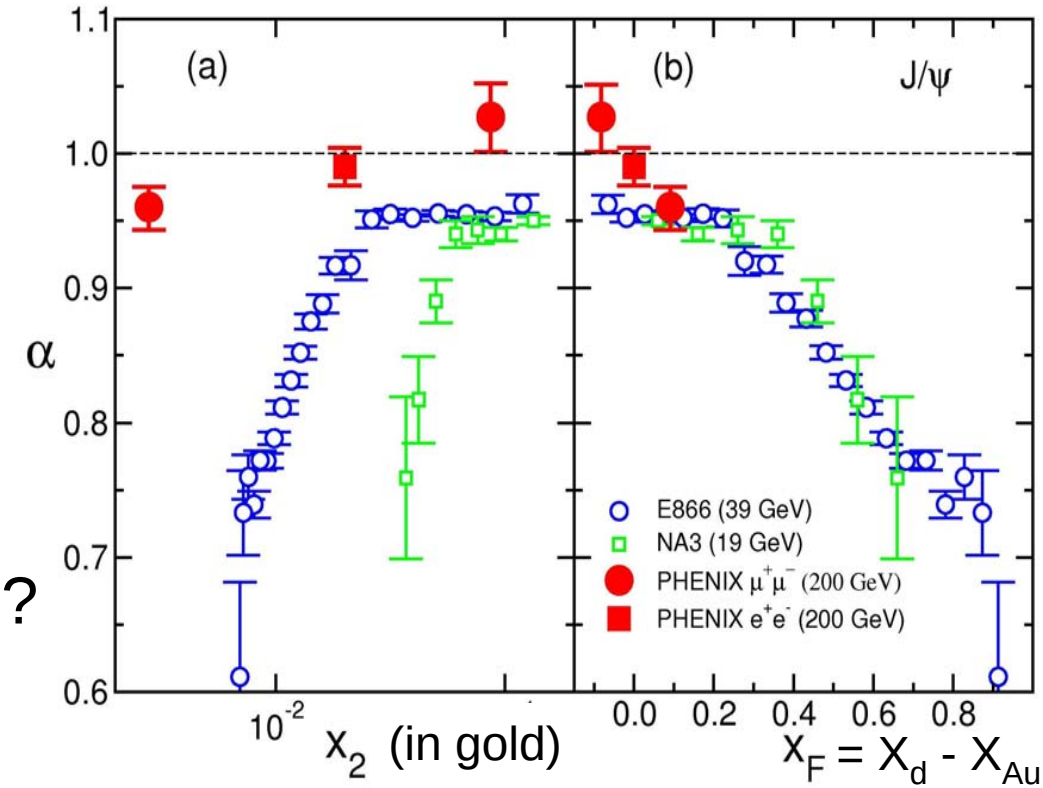
$\sigma_{dAu} = \sigma_{pp}\,(2x197)^{\alpha}$



X_{Au}, X_F dependence of α

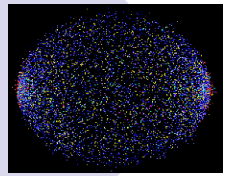
- Shadowing is weak.
- Not scaling with X_2 but scaling with X_F.
  - Coincidence?
    - Shadowing
    - Gluon energy loss
    - Nuclear Absorption
  - Sudakov Suppression?
    - Energy conservation
    - hep-ph/0501260
  - Gluon Saturation?
    - hep-ph/0510358

$\sigma_{dAu} = \sigma_{pp} (2x197)^{\alpha}$



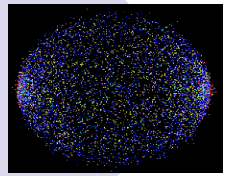
E866, PRL 84, (2000) 3256
NA3, ZP C20, (1983) 101
PHENIX, PRL96 (2006) 012304

Models of J/ψ production



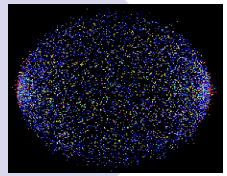
- J/ψ transport (Zhu et al, PLB 607 (2005) 107)
  - start with primordial charmonium from cold nuclear matter effect. Embedded in a relativistic hydrodynamics fireball
  - Charmonoium suppressed by thermal gluon dissociation in the QGP.
- Statistical hadronization (Andronic et al, PLB 571 (2003) 306)
  - Charm from primary collisions only. All charmonium destroyed in the QGP. Open and closed charm hadrons form statistically at the chemical freeze-out.

Models of J/ψ production



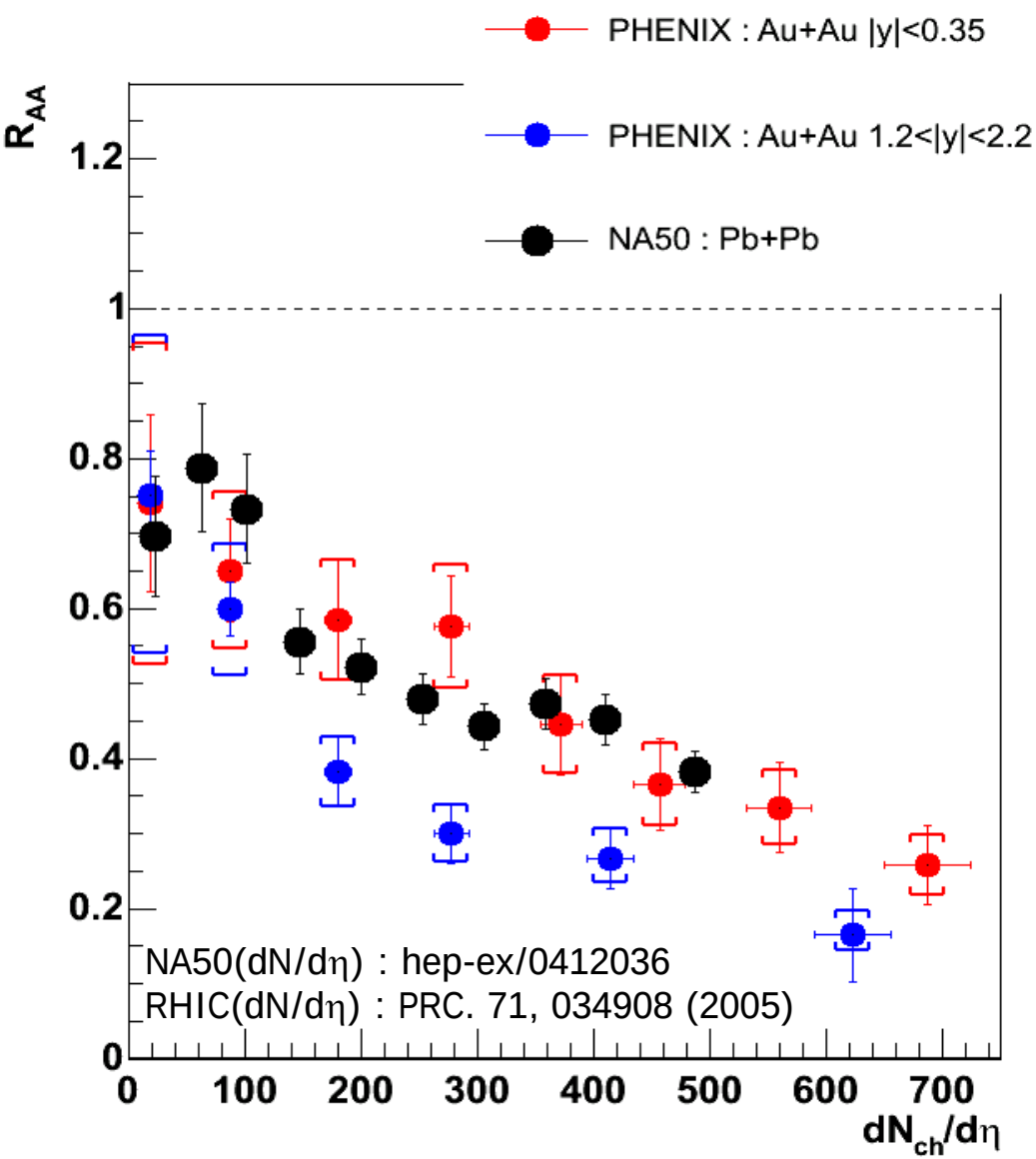
- 2 component model (Grandchamp et al, NPA 709 (2002) 415)
  - Uses in-medium binding energies of charm states inferred from lattice. Primordinal charmonium suppressed by partonic dissociation in QGP. Charm quark thermal relaxation time fitted to data. Additional charmonium from statistical hadronization of QGP. Suppression of all charmonium by hadron collisions in HG phase. (continuous formation in QGP and HG)
- Kenetic formation (Thews, hep-ph/0605322)
  - Start with primordial charm distributions from cold nuclear matter effects. Allow continuous formation/destruction of J/ψ in QGP. Calculation done for no charm thermalization, full charm thermalization. Explored consequences of in-medium formation of pT, y distribution.

Models of J/ψ production



- Kinetic theory (Grandchamp et al, PRL 92 (2004) 212301)
  - (Evolved from 2 component model)
  - Uses in-medium binding energies of charm states inferred from lattice. Primordial charmonium suppressed by partonic dissociation in QGP. Charm quark thermal relaxzation time fitted to data. Charmonium created/destroyed in QGP(HG) by $\psi + X1 \leftarrow\rightarrow X2 + c + c$
- Sequential melting (Karsch et al, PLB 637 (2006) 75)
  - Start with primordial charm distributions from cold nuclear matter effects. J/ψ bound at RHIC. ψ' and cc do not form in QGP. No destruction or formation of J/y after primordial formation. No interaction of J/ψ with the medium at all.

Comparison to NA50



- Suppression is similar at mid-rapidity.
- Larger suppression compared to SPS at forward-rapidity.
- But cold matter effect is different at RHIC and SPS energy.

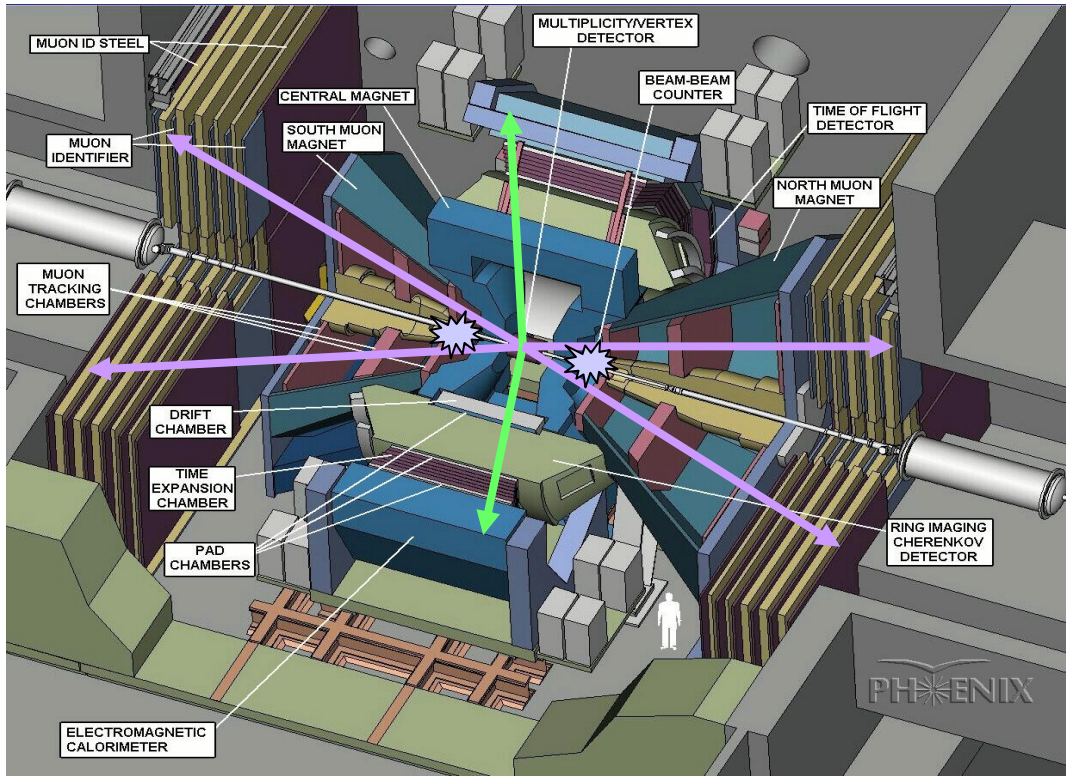
Normalized by NA51 p+p data with correction based on hep-ex/0412036

PHENIX Experiment

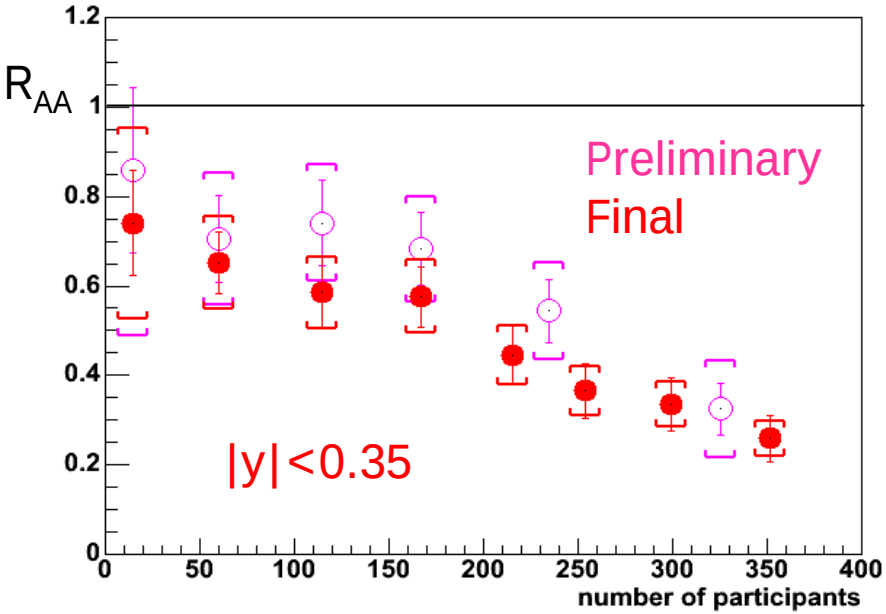
- PHENIX can measure J/ψ in wide rapidity coverage.

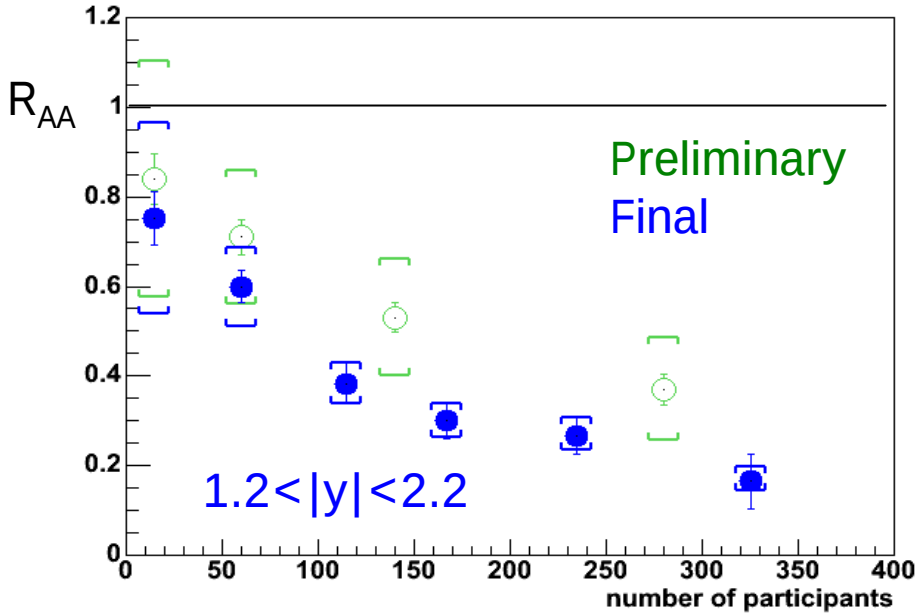
Central Arms:
Hadrons, photons, electrons
- J/ψ → e+e-
- $|\eta|<0.35$
- $P_e > 0.2$ GeV/c
- $\Delta\phi = \pi$ (2 arms x $\pi/2$)

Muon Arms:
Muons at forward rapidity
- J/ψ → $\mu+\mu-$
- $1.2< |\eta| < 2.4$
- $P\mu > 2$ GeV/c
- $\Delta\phi = 2\pi$

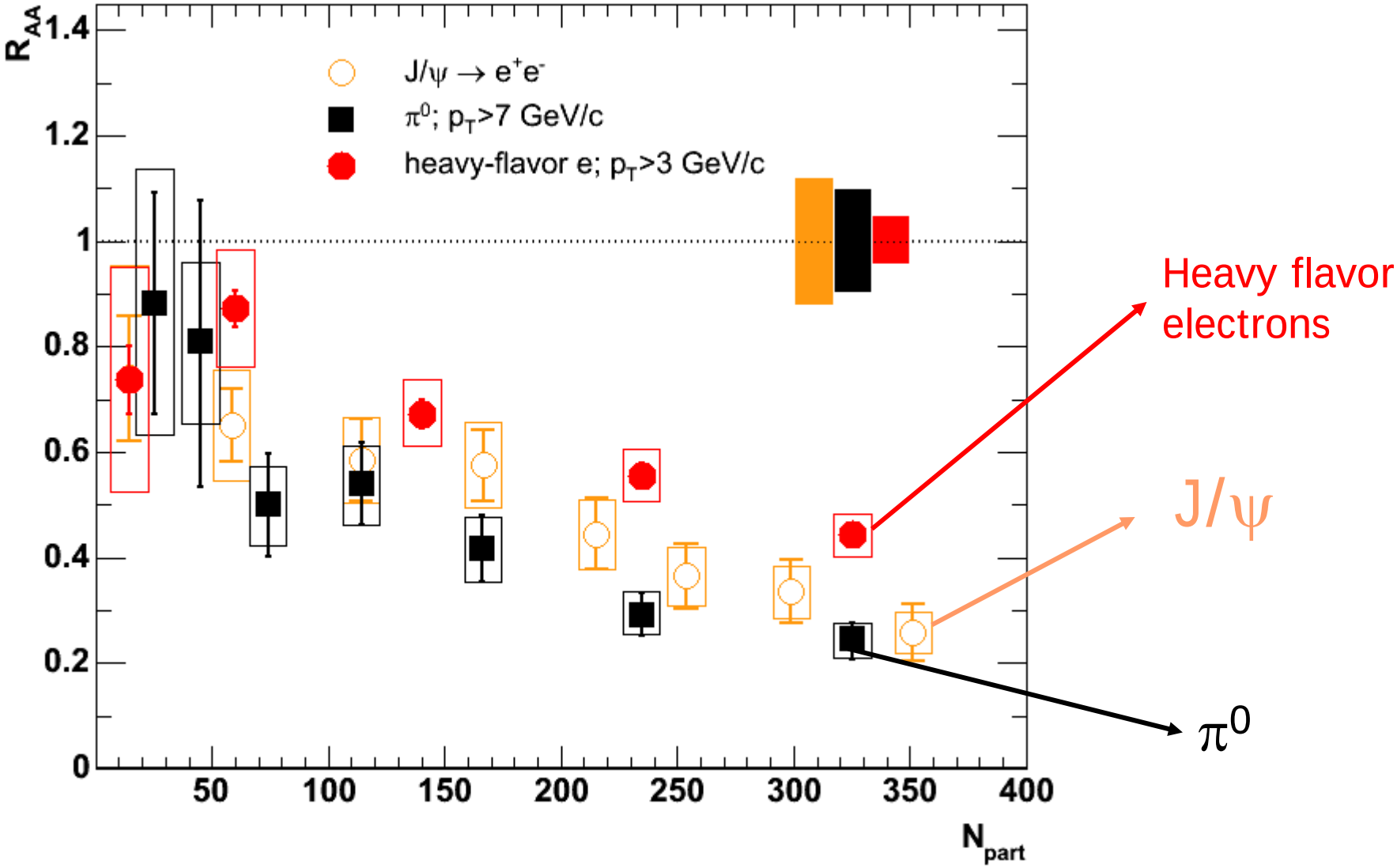


Preliminary vs. Final results





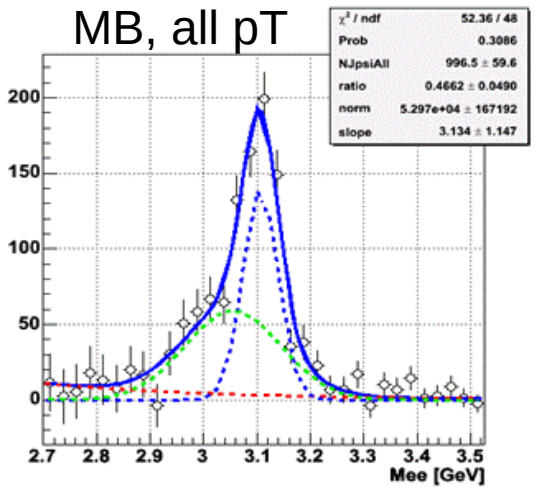
J/ψ suppression vs. light hadrons



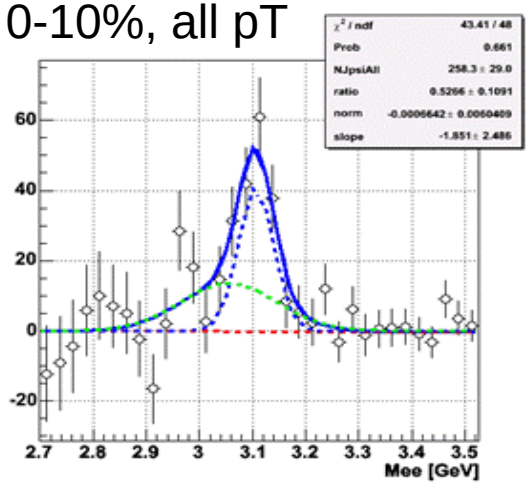
Mass spectrum

- dielectrons

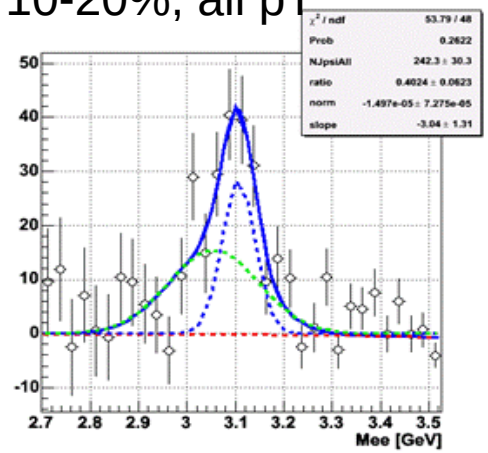
MB, all pT



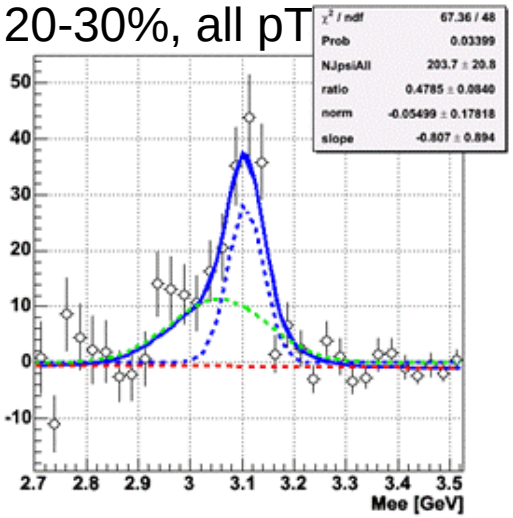
0-10%, all pT



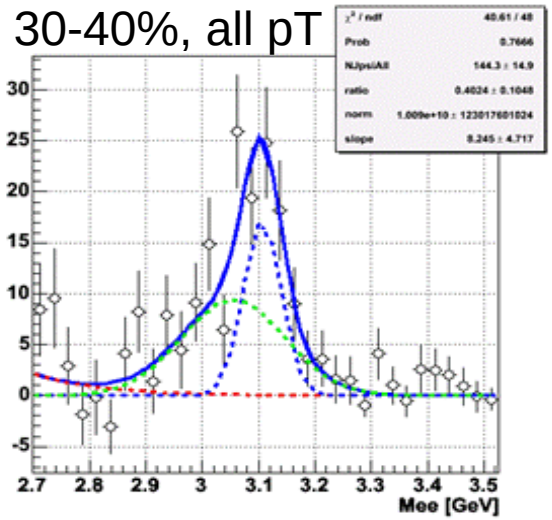
10-20%, all pT



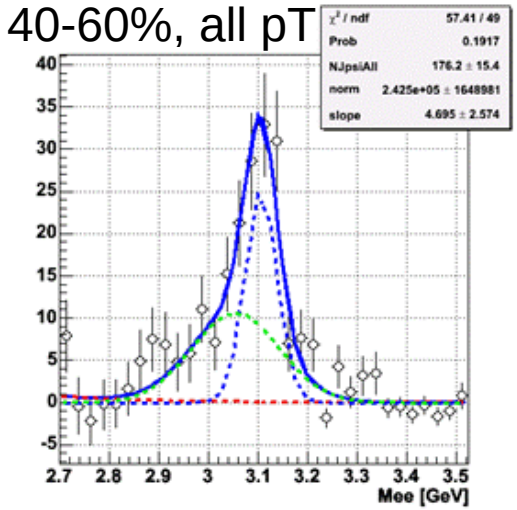
20-30%, all pT



30-40%, all pT

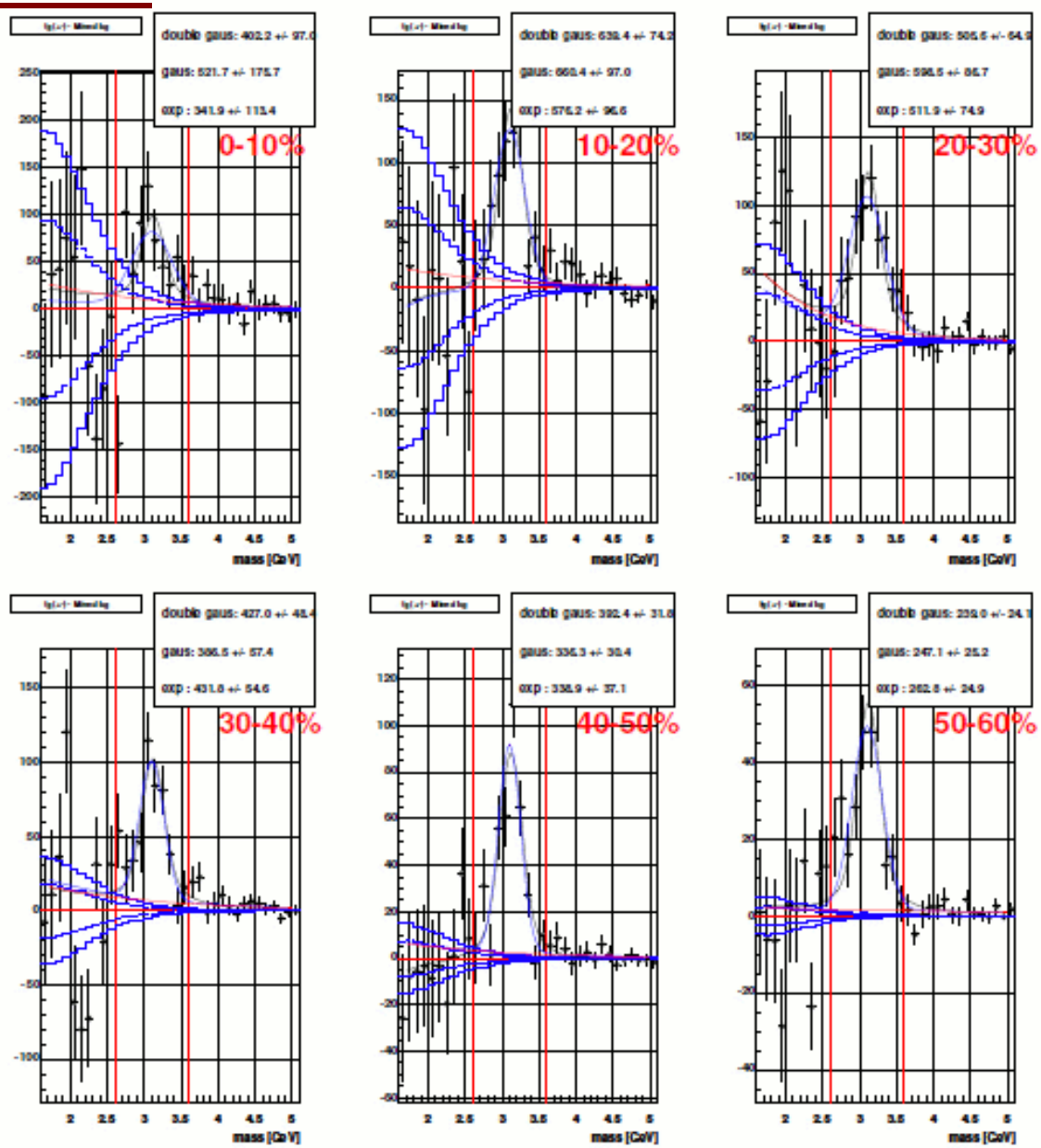


40-60%, all pT



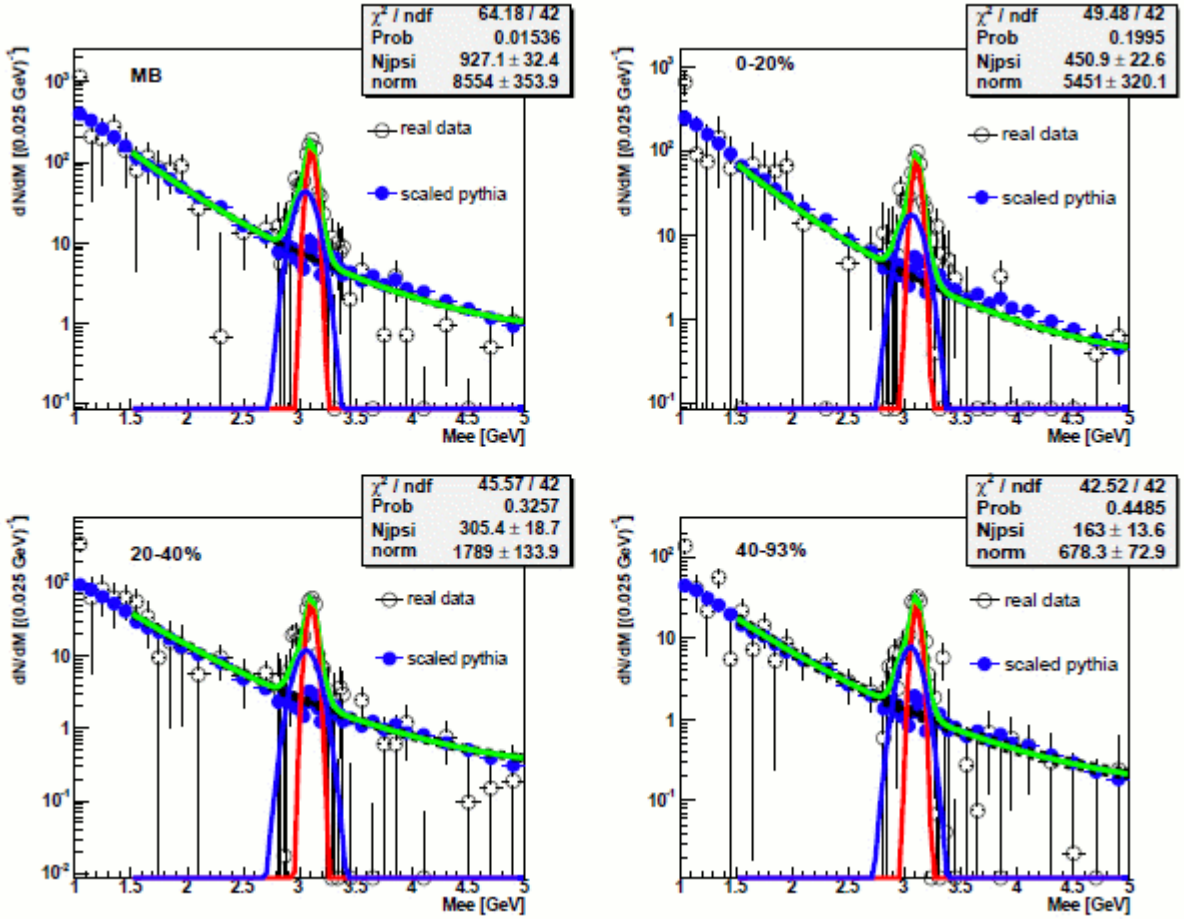
Mass spectrum

- dimuons



Continuum contribution

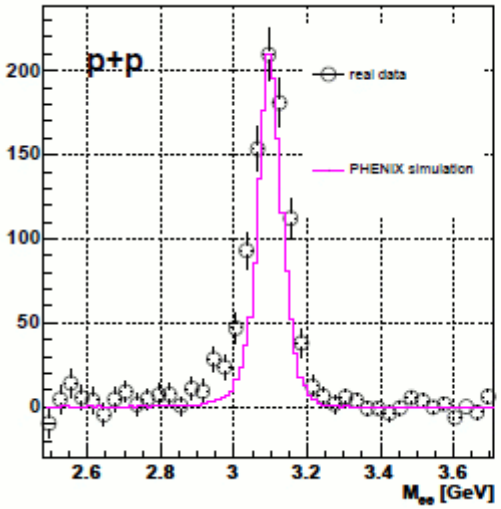
- Continuum contribution (charm and bottom pairs)

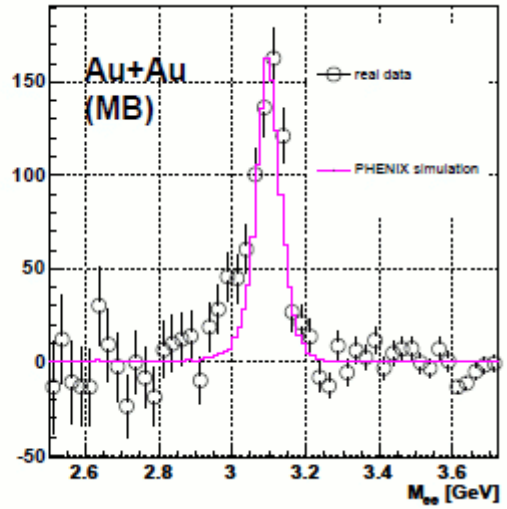


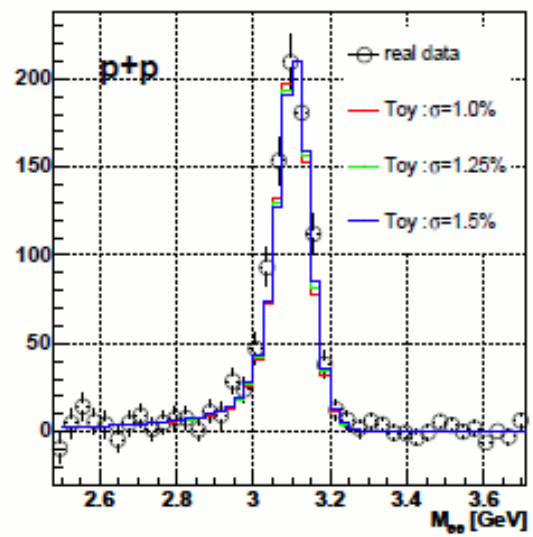
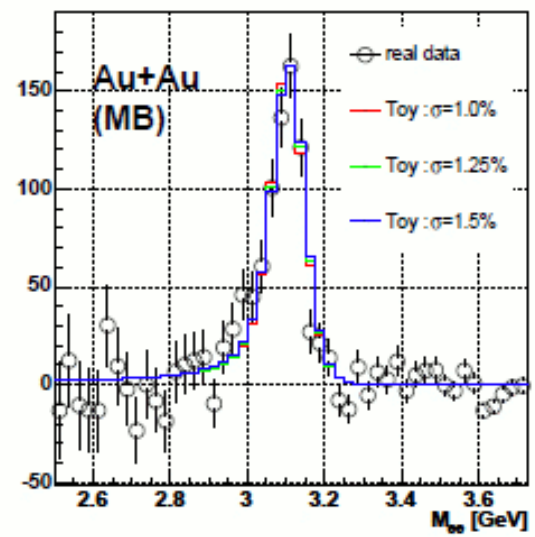
Contribution under J/psi mass (2.9<Mee<3.3) = 10% +- 5%

Line shape of J/ψ

- Checked with external and internal radiation.





Only the external radiation is took into account.

External and internal radiation are took into account.
Smearing was done according to mass resolution.
hep-ex/0510076