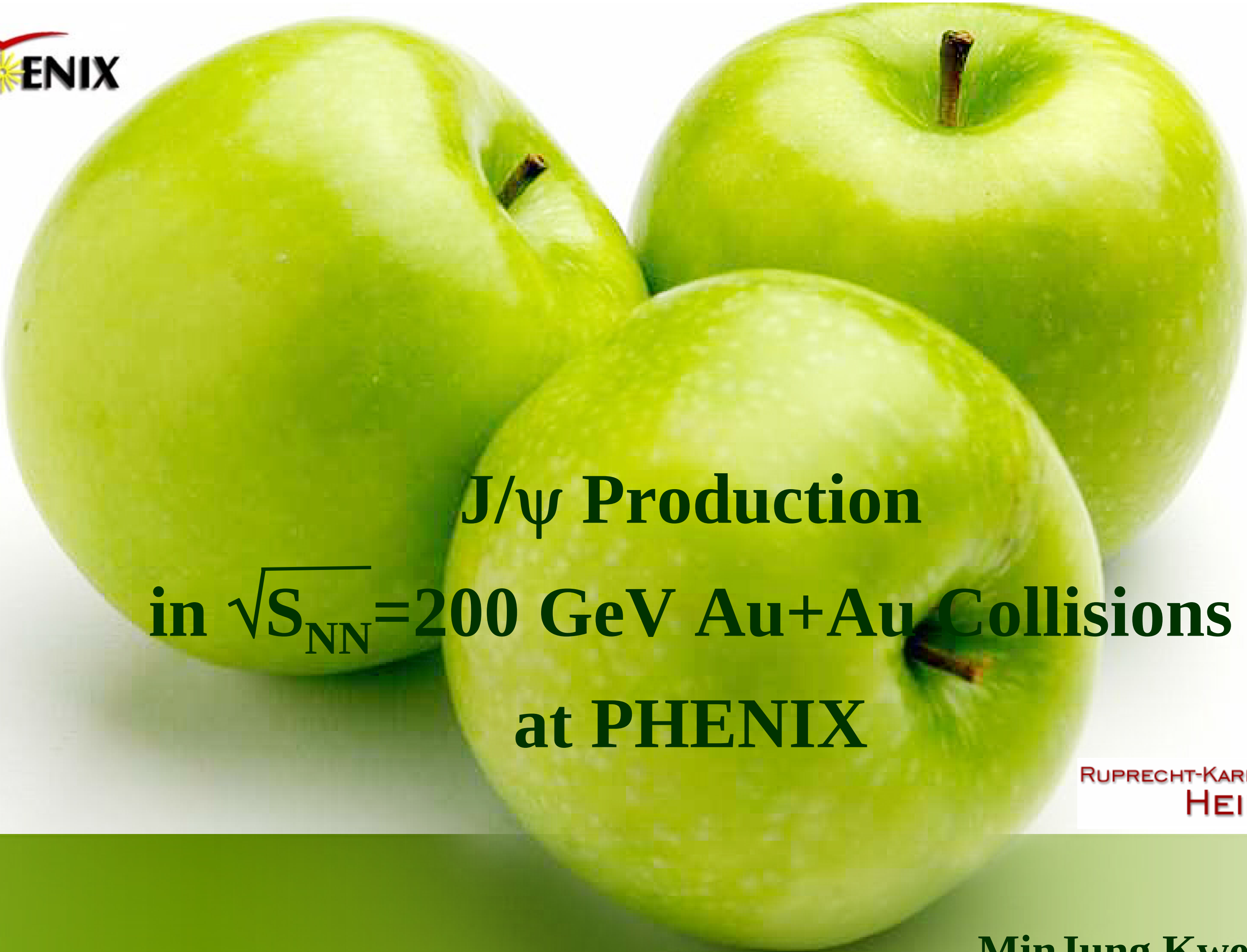


J/ψ Production in $\sqrt{S_{NN}}$=200 GeV Au+Au Collisions at PHENIX

Ruprecht-Karls-Universität Heidelberg

MinJung Kweon
Heidelberg University

PI Lunch Meeting, May. 16. 2006.

Outline

Physical Background

- Why Quarkonia?
- Quarkonia in QGP
- Charmonia Production Properties in Nuclear Collision

Experimental Setup

- PHENIX Detector
- Analysis Method

Result

- Previous experiment : SPS Result
- RHIC Result

Summary

Why Quarkonia?

- Quarkonia : bound states of a heavy quark and its antiquark

  $m_c \sim 1.2 - 1.5$ GeV
  $m_b \sim 4.5 - 4.8$ GeV } **heavy**

  can apply non-relativistic potential theory

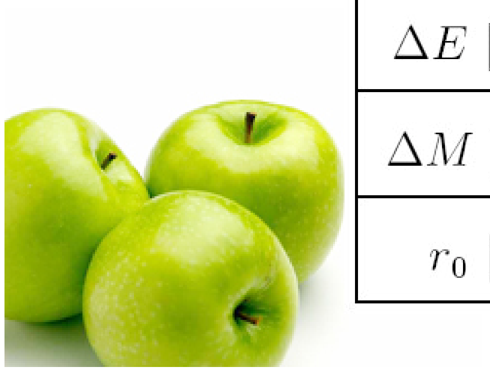
- Quarkonium spectroscopy from non-relativistic potential theory

Ref) H. Satz, hep-ph/0512217

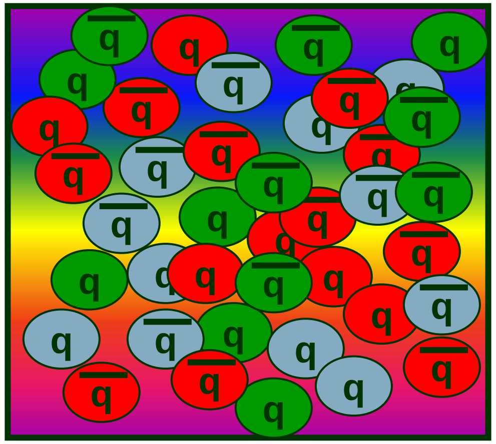
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

smaller

larger



Quarkonia in QGP

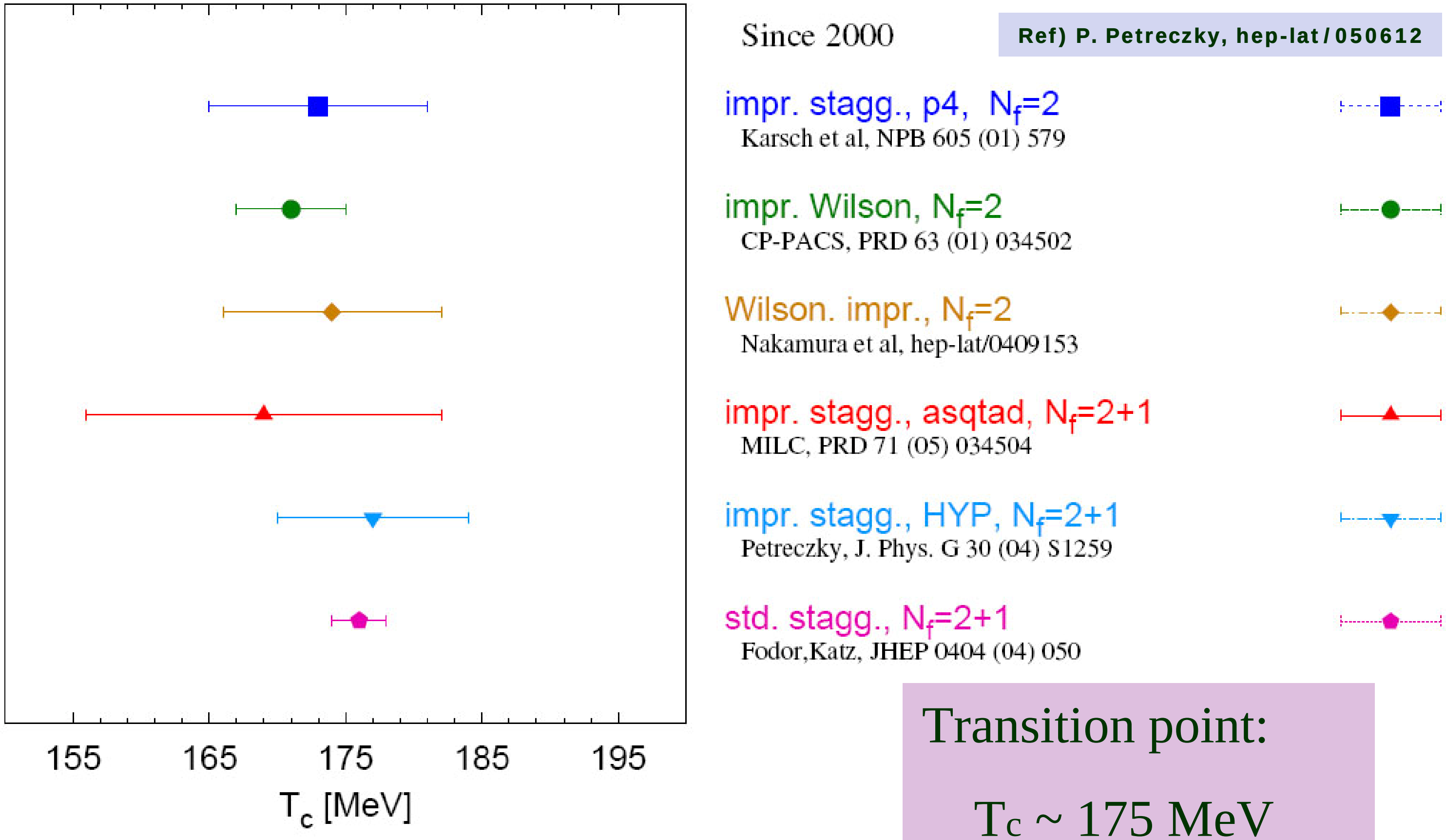


- What happens in QGP to the much smaller quarkonia?
- When do they become dissociated?

⇨ Disappearance of specific quarkonia signals the presence of a deconfined medium of a specific temperature.

Critical Temperature

- For two light as well as for two light plus one heavier quark flavor, most studies indicate Tc=175+-10 MeV



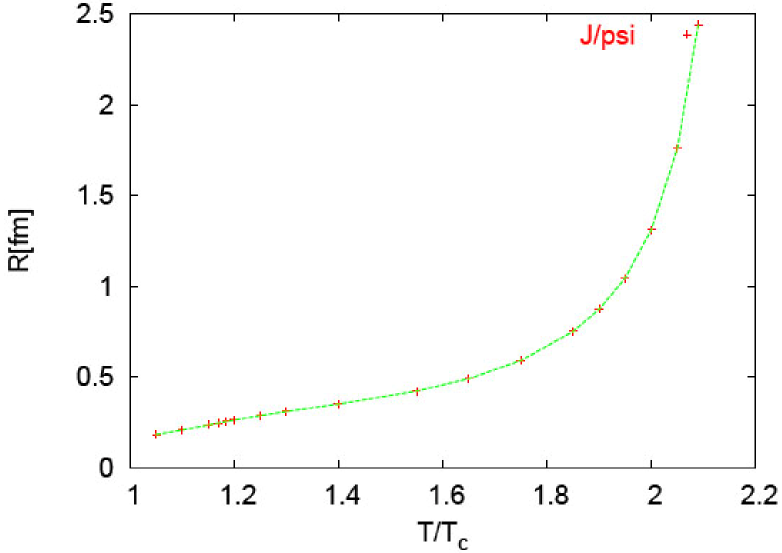
Transition point:

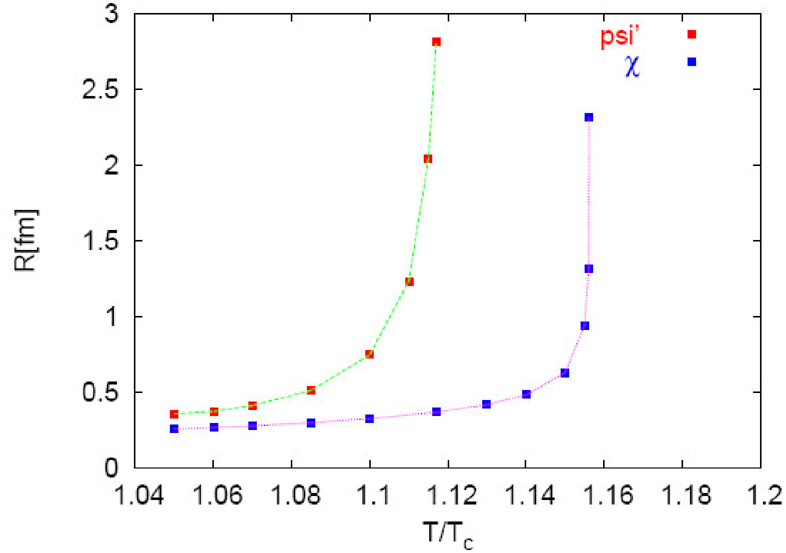
$T_c \sim 175$ MeV
$\varepsilon \sim$ 1.0 GeV/fm^3

T-dependence of Bound State Radii for J/ψ and for χ_c / ψ'

- Divergence of the radii defines quite well the different dissociation points

Ref) H. Satz, hep-ph/0512217



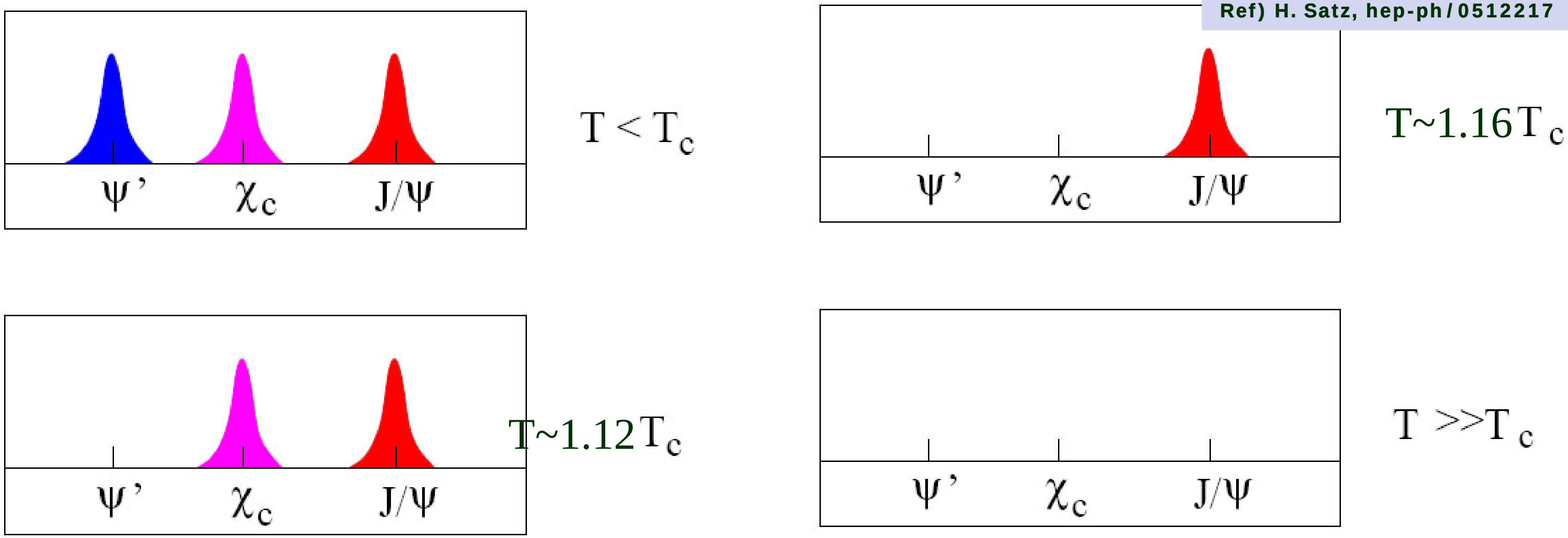


- Quarkonium dissociation temperatures

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Schematic View of Dissociation Sequence

Ref) H. Satz, hep-ph/0512217



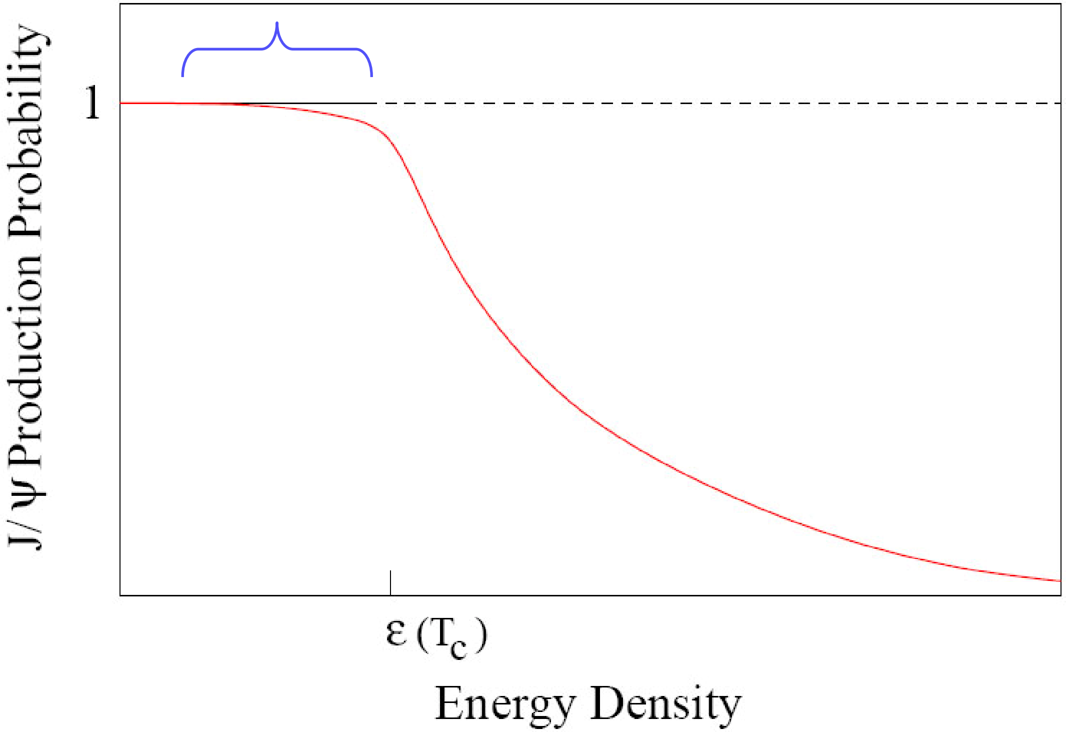
- With increasing temperature the different charmonium states “melt” sequentially as function of their binding strength;
- The most loosely bound state disappears first, the ground state last.
- The dissociation points of the different quarkonium states provide a way to measure the temperature of the medium.

Charmonium Production in Nuclear Collisions

- Possible/different effects impacting on quarkonium production due to the produced medium
  - Suppression by comover collisions
  - Suppression by color screening
  - Enhancement by recombination
  - Initial state suppression

! Normal nuclear absorption : effect due to the interaction with the surrounding nuclear matter initially produced - need accounted by p-A collision

Suppression by comover collisions

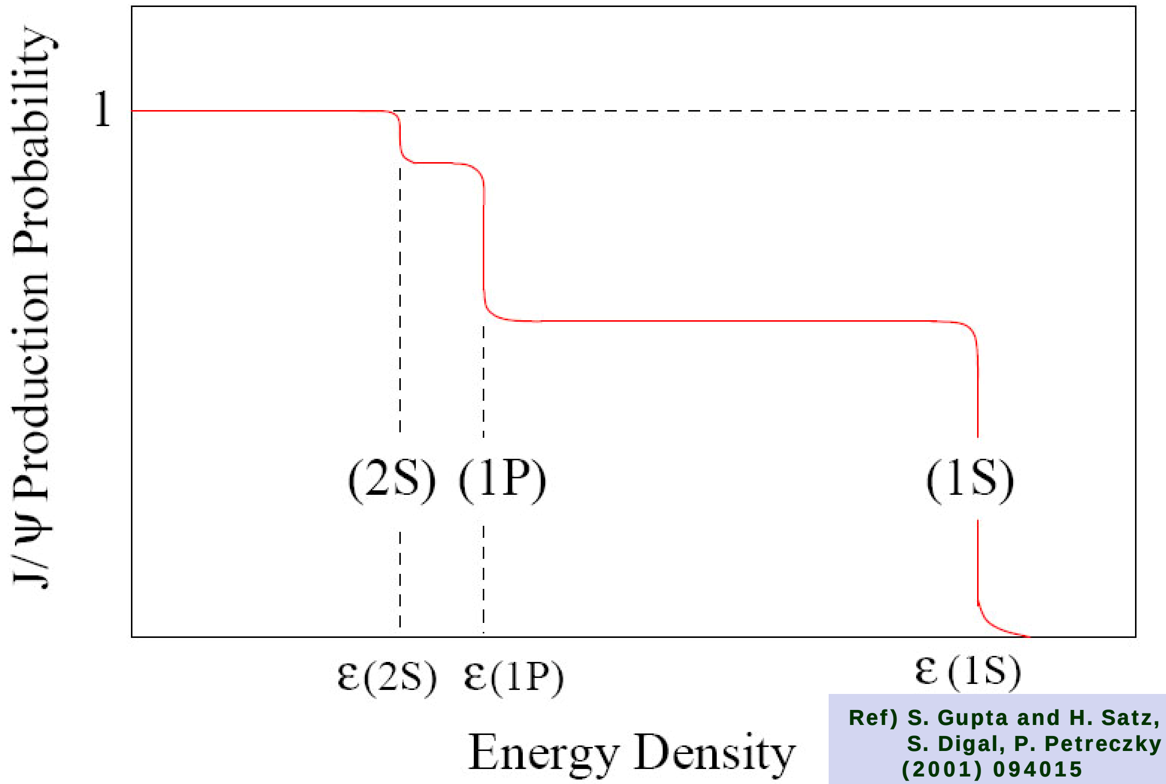


- J/ψ suppression by comover collision
  : dissociation by interaction with hadronic comover
- Little or no prior suppression in the hadronic regime.

Ref) S. J. Brodsky and A. H. Mueller, Phys. Lett. 206 B (1998) 685;
N. Armesto and A. Capella, Phys. Lett. B 430 (1998) 23.

Suppression by Color Screening

- Produced medium affects the intermediate excited states,
- Stepwise onset of suppression
- Sequential J/ψ suppression by color screening

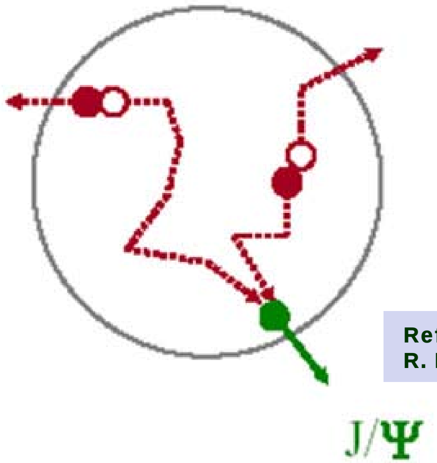


Ref) S. Gupta and H. Satz, Phys. Lett. B 283 (1992) 439;
S. Digal, P. Petreczky and H. Satz, Phys. Rev. D 64 (2001) 094015

Enhancement through Recombination

- c from one NN collision can also bind with a $\bar{c}$ from another NN collision ⇨ enhancement J/ψ production.

- Combination of random c and $\bar{c}$ quarks from different primary nucleon-nucleon interactions becomes more and more likely with increasing energy.



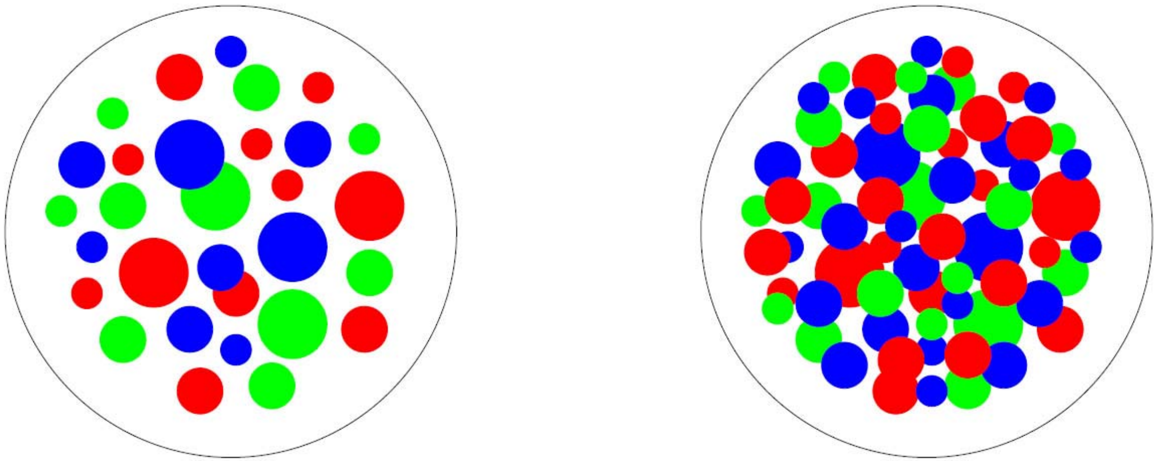
Ref) P. Braun-Munzinger and J. Stachel, Nucl. Phys. A690 (2001) 119; R. L. Thews et al., Phys. Rev. C 63 (2001) 054905

Initial State Suppression

- At large enough A and energy, the density of partons in the transverse plane becomes so large

  ⇨ partons percolate, producing an internal connected network

  ⇨ sufficient to resolve charmonia



- This scenario is similar to suppression by color screening.
- It is possible to calculate the percolation point, but its effect on the different charmonium states is not evident.

Experimental Setup

Energy Scale of Heavy-Ion Collisions

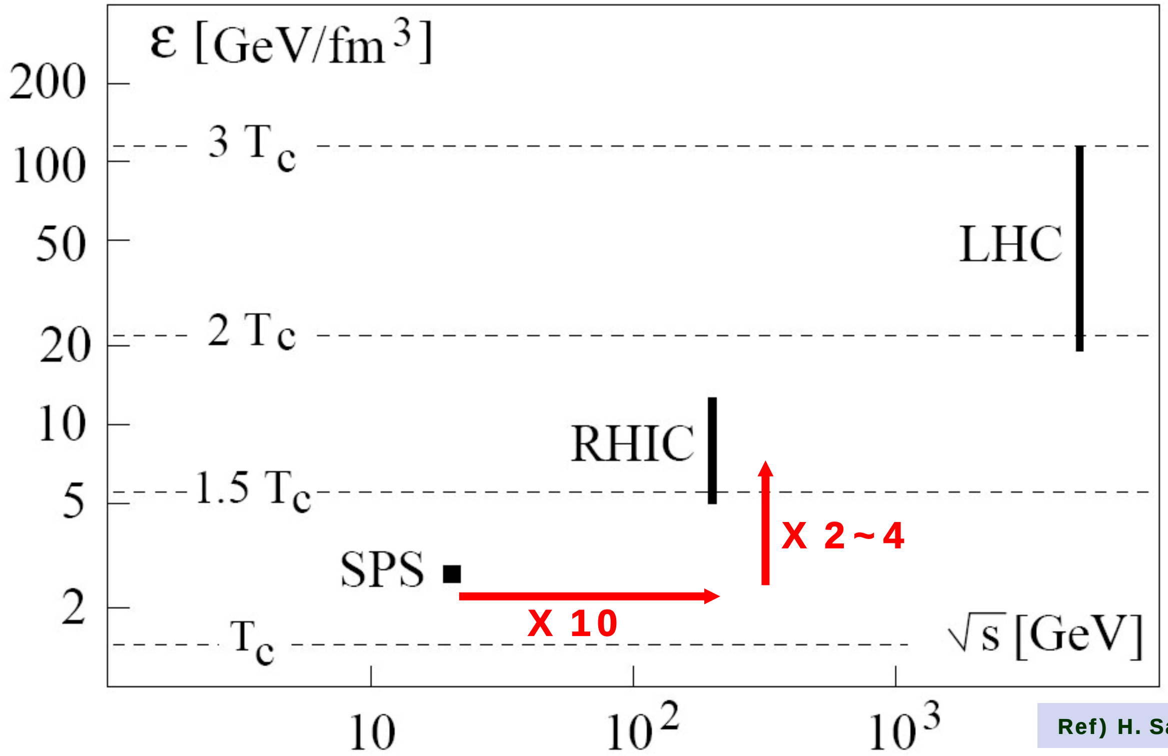
- In a high energy heavy-ion collision, a large amount of energy is deposited in a very small volume

- Au+Au collision at RHIC
  - Total energy for the nucleus :
    - 100 GeV * 197 nucleons = 19.7 TeV
    - For collider, lab frame = center of mass frame ; $\sqrt{s_{NN}}$ = 200 GeV
    - Total of 39.4 TeV is for a short time in a very small volume

- Pb+Pb collision at LHC in CERN (upcoming)
  - Total energy for the nucleus :
    - 2.76 TeV * 207 nucleons = 571 TeV
    - Total 1143 TeV

Energy density vs. maximum collision energies

- Energy density estimates vs. maximum collision energies, for different accelerators, compared to corresponding temperature

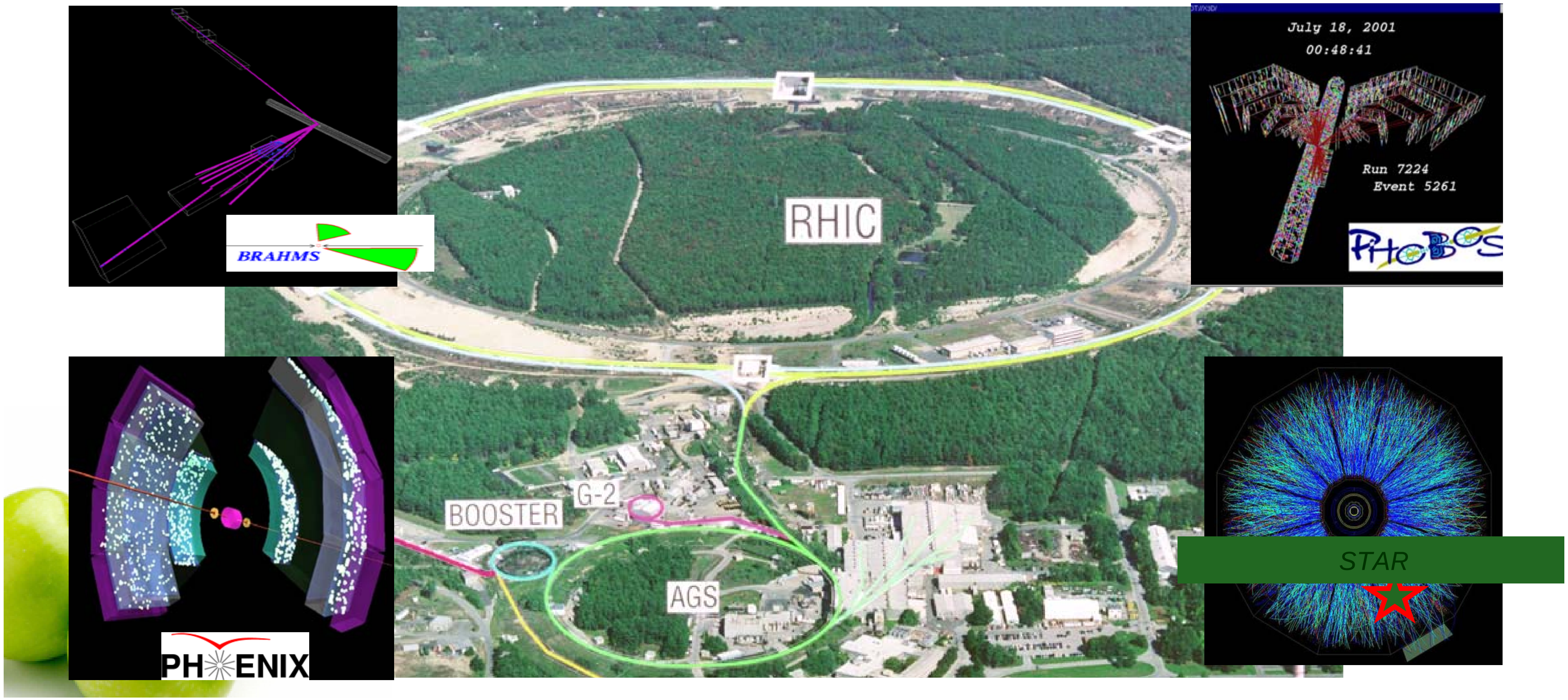


Ref) H. Satz, hep-ph/0512217

- In all cases the energy densities exceed the deconfinement value $\varepsilon(T_c) \sim 0.5\text{-}1.0$ GeV/fm³

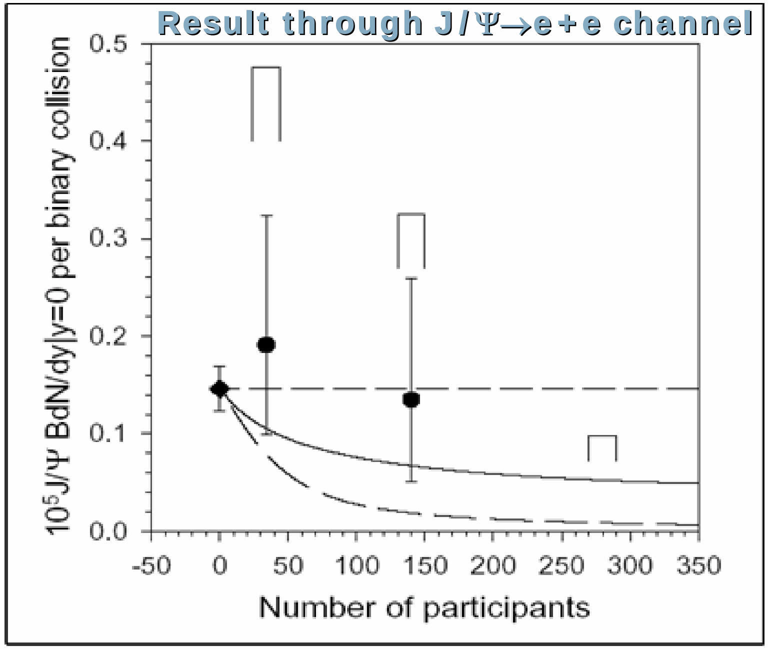
RHIC Facility

- Relativistic Heavy Ion Collider online since 2000.
- Design Gold Gold energy and luminosity achieved.
- All experiments successfully taking data



PHENIX Measurement capability

PHENIX, Phys. Rev. C 69, 014901 (2004)



RUN 2

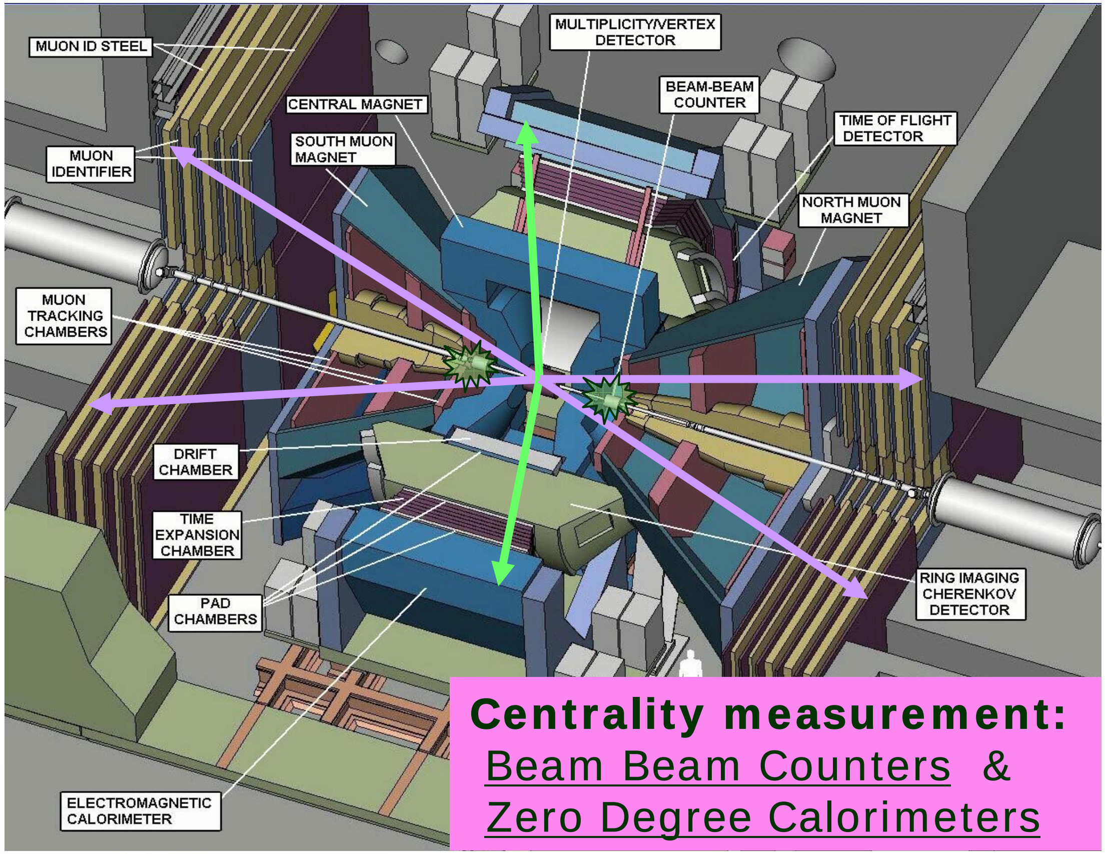
- Low statistics result on J/Psi production

RUN 4

- Archived very high statistics on Au+Au collision at 200GeV

Year	Ions	Luminosity	#Events
2003	p+p @200GeV D+Au @200GeV	350 nb^{-1} 2.74 nb^{-1}	
2004	Au+Au @200GeV	241 μb^{-1}	1.5 x 10^9

PHENIX Experiment



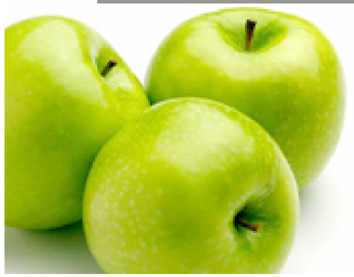
Centrality measurement:
Beam Beam Counters &
Zero Degree Calorimeters

Central Arms:
Hadrons, photons, electrons

- $J/\psi \rightarrow e+e-$
- $|\eta|<0.35$
- $P_e > 0.2$ GeV/c
- $\Delta\phi = \pi$ (2 arms x $\pi/2$)

Muon Arms:
Muons at forward rapidity

- $J/\psi \rightarrow \mu+\mu-$
- $1.2< |\eta| < 2.4$
- $P\mu > 2$ GeV/c
- $\Delta\phi = 2\pi$



J/ψ measurement from Run4

Reconstructed ~ 600 $J/\psi \rightarrow e+e-$ and ~ 5000 $J/\psi \rightarrow$ m+m-

Invariant J/ψ Yield

Invariant yield :

$$B_{\mu\mu}\frac{dN}{dy}(AA \rightarrow J/\psi \rightarrow \mu^+\mu^-) = \frac{N_{J/\psi}}{\Delta y \ A\varepsilon_{J/\psi}\varepsilon_{BBC}^{J/\psi}} / \frac{N_{MB}}{\varepsilon_{BBC}^{MB}}$$

$N_{J/\psi}$: number of J/ψ 's reconstructed

$A\varepsilon^{J/\psi}$: probability for a J/ψ thrown and embeded into real data to be found (considering reconstruction and trigger efficiency)

N_{MB} : total number of events

$\varepsilon_{BBC}^{J/\psi}$: BBC trigger efficiency for events with a J/ψ

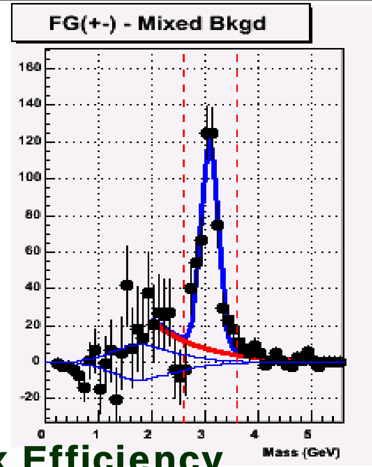
ε_{BBC}^{MB} : BBC trigger efficiency for minimum bias events

For Au+Au collision : $\varepsilon_{BBC}^{MB} \sim \varepsilon_{BBC}^{J/\psi}$

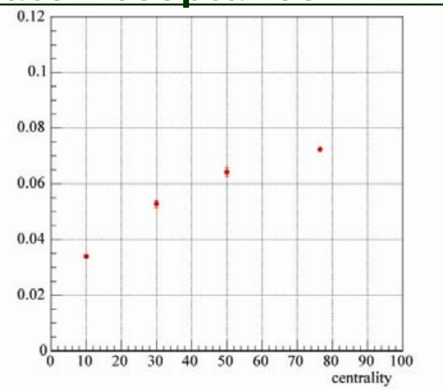
Analysis Procedure

1. **Get momentum of tracks**
   - Muon tracker
2. **Identify muons**
   - Depth in Muon Identifier (MUID)
3. **Extract J/ψ signal**
   - Event mixing technique
4. **Correct for acceptance and efficiencies**
   - Realistic detector simulation
5. **Calculate corresponding luminosity**
   - run4AuAu Level-2 filtered at *CCF* (78%) - 170 mb^{-1}
6. **Estimate systematic errors**

→ **Cross section**

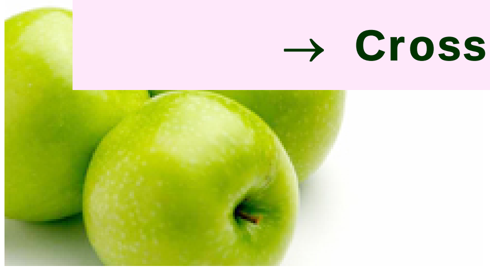


Calculate Acceptance x Efficiency



Systematic error estimation

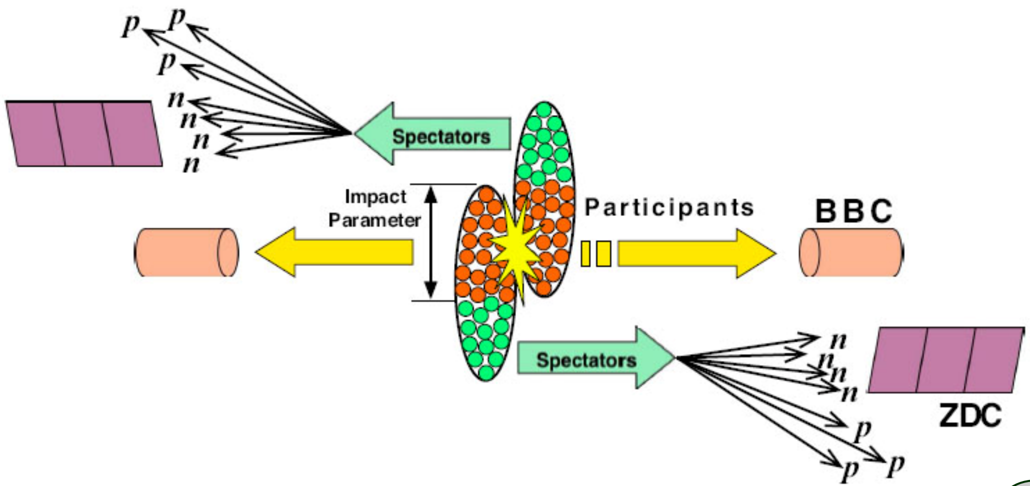
Acceptance × efficiency (considered various factors)	12 %
Luminosity	2 %
Signal extraction	Different (bin by bin)



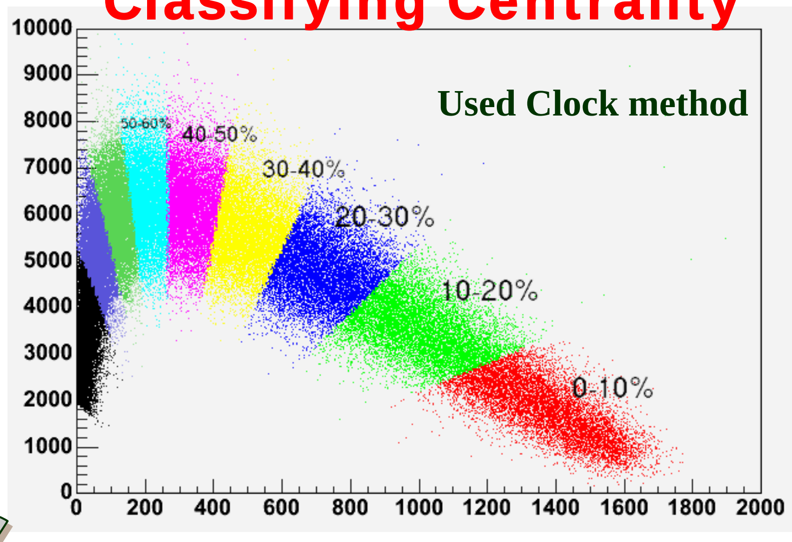
More Detail of Analysis

- Data sets and production
- Centrality determination
- Cut Variables
- Efficiency x Acceptance
- Signal extraction
- Systematic

Centrality Determination



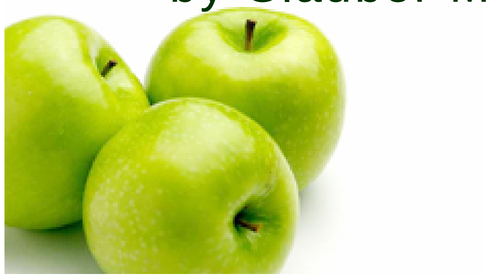
Classifying Centrality



Calculate N_{coll} and N_{part}

- N_{coll} and N_{part} for each centrality class determined by Glauber Model

Centrality	N_{part}	N_{coll}
0-20	279.9±4.1	779±76
20-40	140.4±4.9	297±31
40-93	32.3±3.1	45.4±7.4
40-60	60.0±3.6	90.7±11.9
60-93	13.9±2.7	15.3±4.4

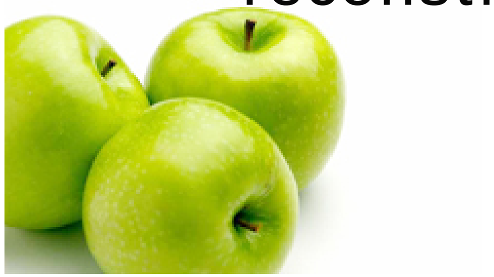


Efficiency Determination

- Generate J/ψ using PYTHIA, selecting only those within acceptance

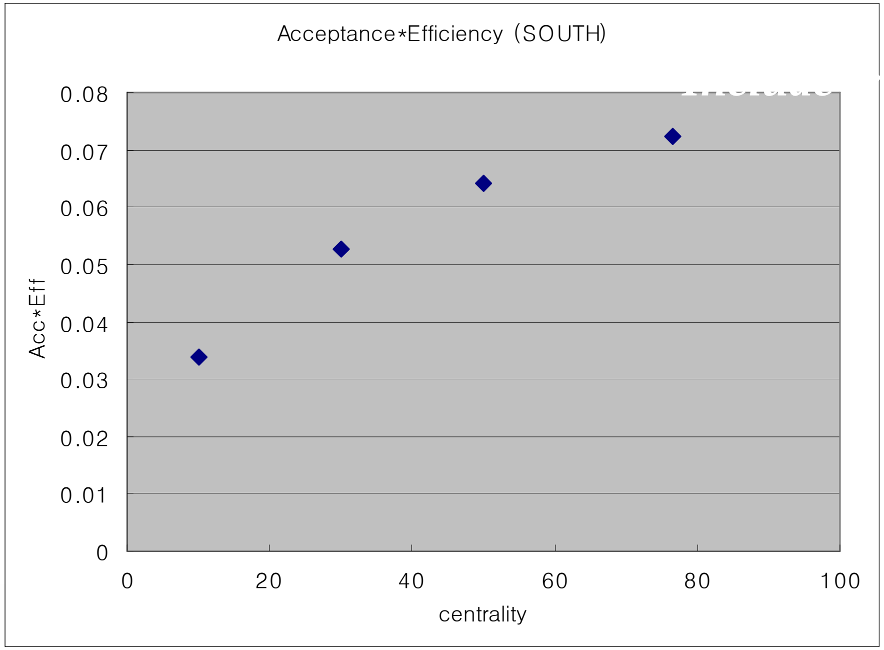
- Embed them in real minimum bias data
  - Match simulated J/Ψ vertex to real data vertex
  - Realistic response for simulation
    - Consider high voltage and electronics condition of MuTR
    - Consider intrinsic efficiency of MuID

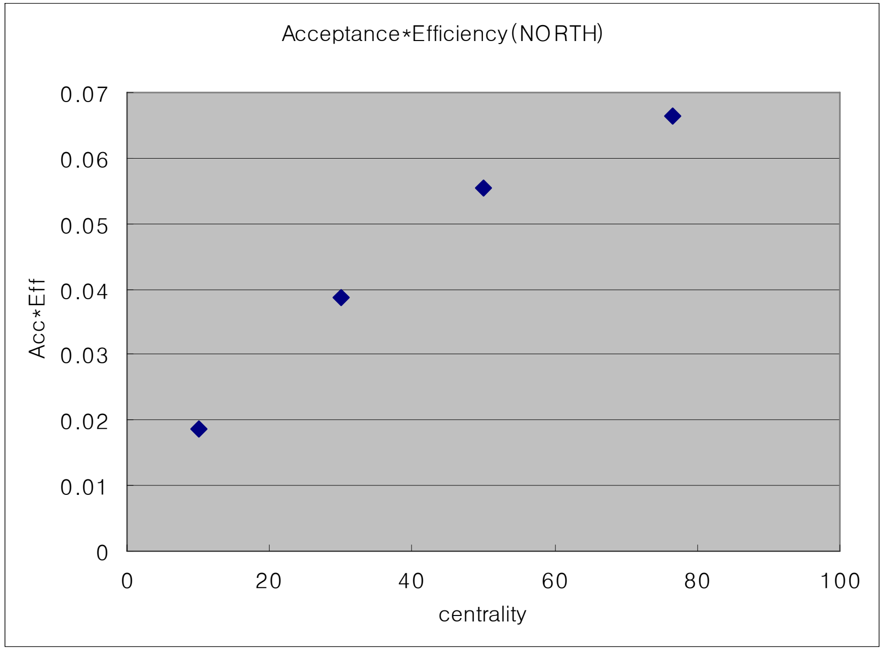
- Measure combined trigger(Level2) and reconstruction efficiencies



Dimuon Reconstruction Efficiency

SOUTH **NORTH**





Central → Peripheral

Estimating Combinatorial Background and Signal counting (Event Mixing Used) – Periph.

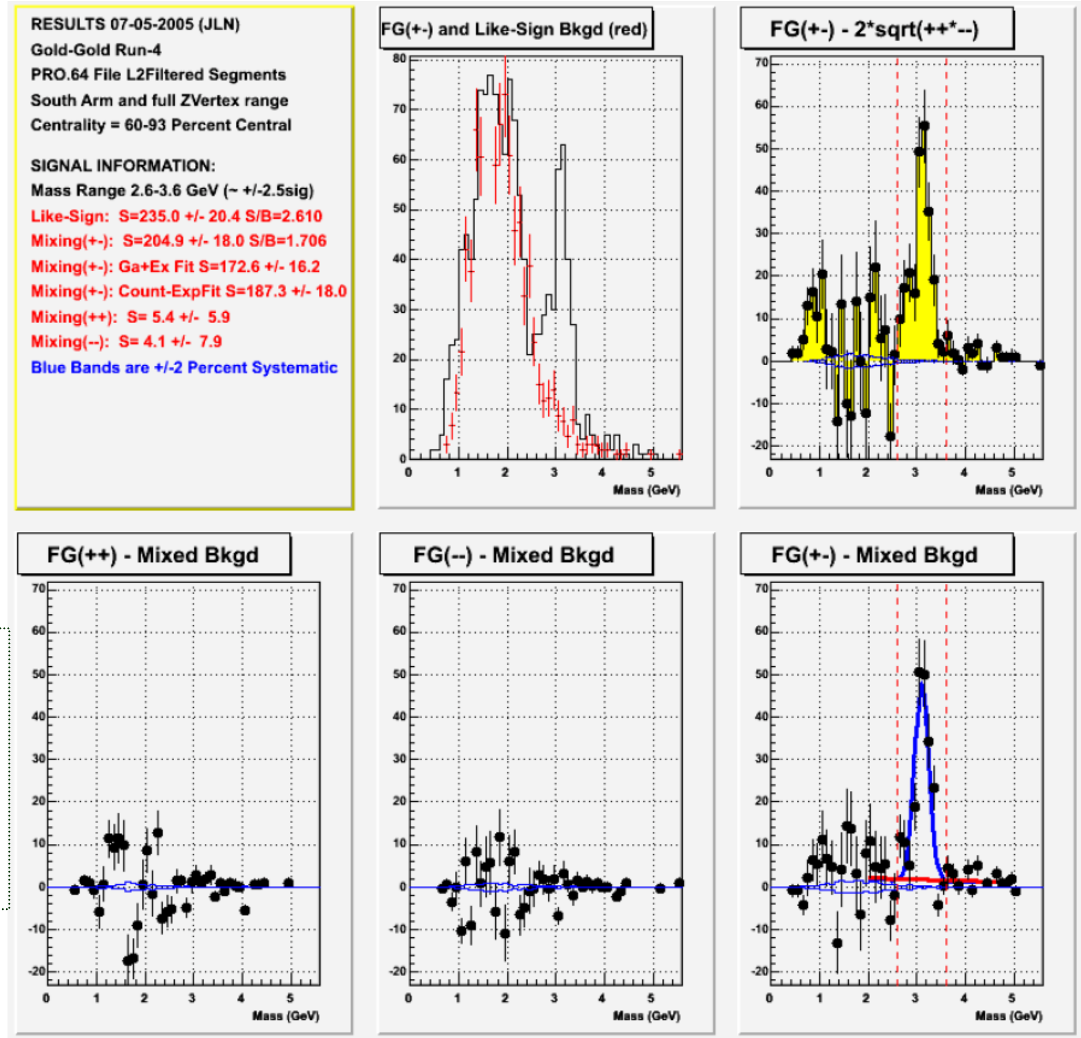
- Artificial events constructed from data by mixing particles (tracks) from different events to eliminate possible correlations.

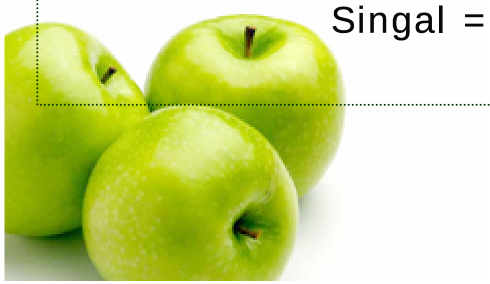
- For the signal extraction, we used event mixing method with the lvl2 filtered set.

Example plots)

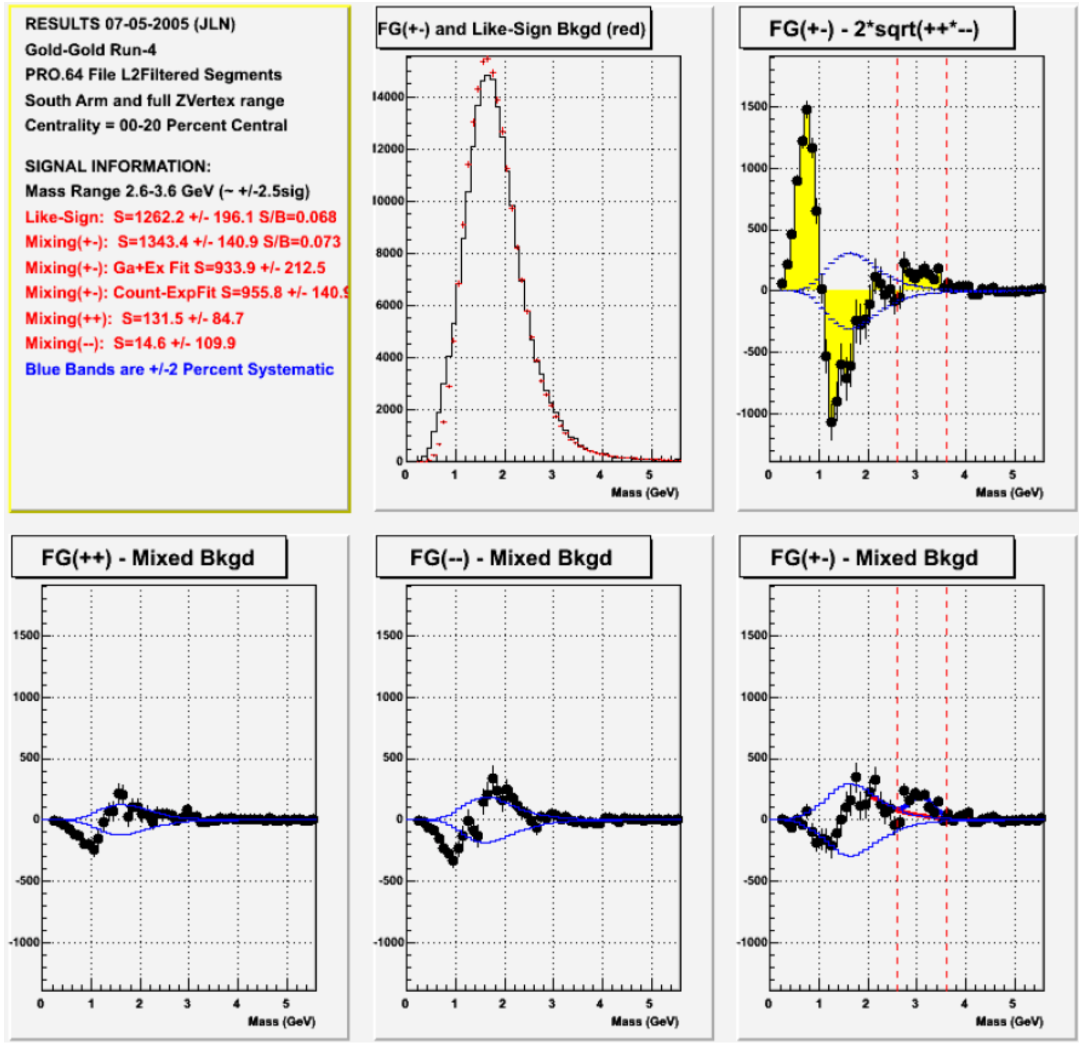
South Arm : Centrality 60-93%, All Pt , All Rapidity

Singal = 204 +/- 18(stat) +/- 19(sys)

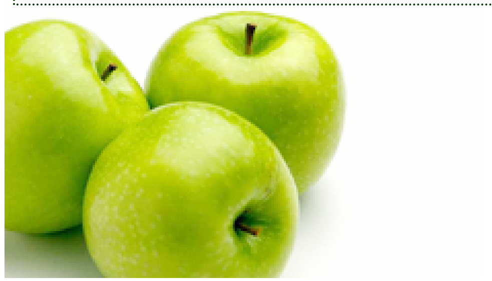




Estimating Combinatorial Background and Signal counting (Event Mixing Used) – Central.



Another Example plots)
South Arm: Centrality 0-20%, All Pt
, All Rapidity
Singal = 1343 +/- 140(stat)
+/- 387(sys)



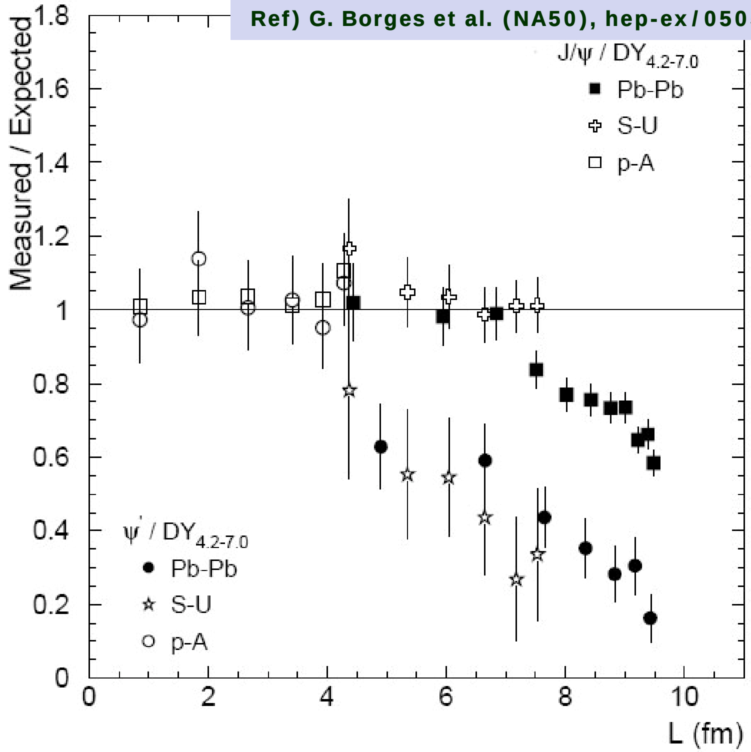
Systematic Errors

- Error on Acceptance*Efficiency calculation
- Error on counting total number of events
- Error on subtracting background and extracting signal

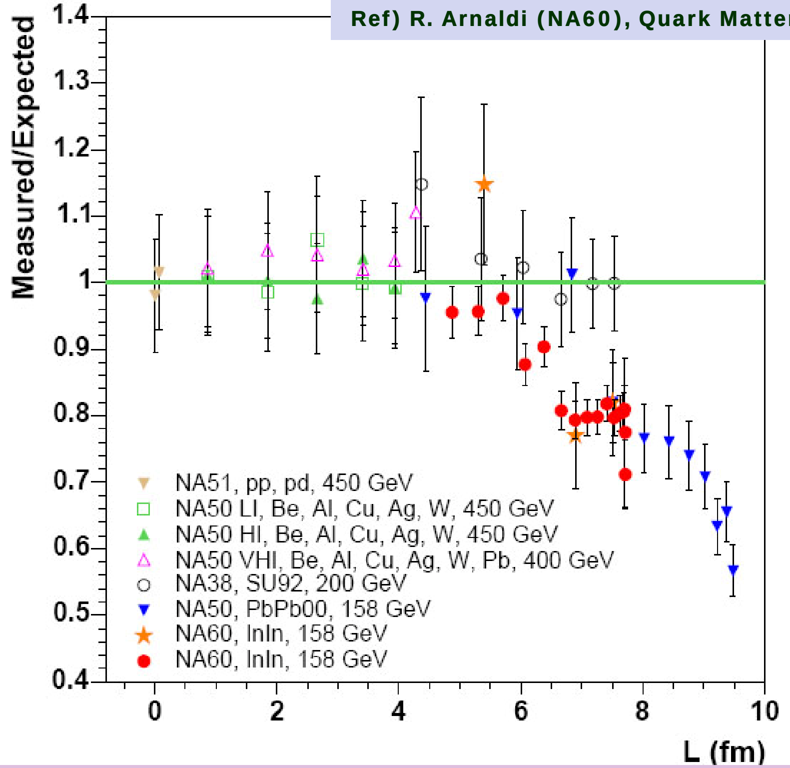
Result

SPS Result

Ref) G. Borges et al. (NA50), hep-ex/0505065



Ref) R. Arnaldi (NA60), Quark Matter 2005



S-U collisions (NA38) at c.m. energy = 19.4 GeV
Pb-Pb Collisions (NA50) at c.m. energy = 17.3 GeV , In-In Collisions (NA60) at c.m. energy = 17.3 GeV

Ref) B. Alessandro et al. (NA50), Eur. Phys. J. C 33 (2004) 31.

- Charmonium production rates are measured relative to Drell-Yan pair production
- Normal nuclear absorption is considered

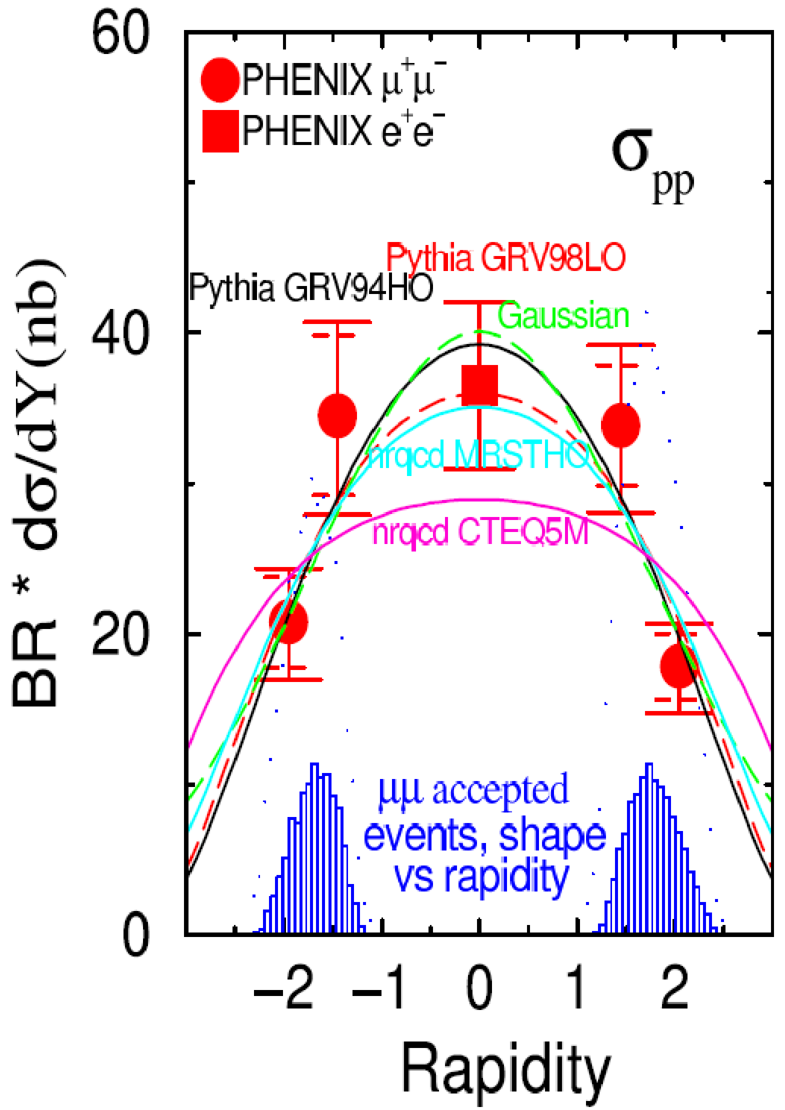
$$\begin{cases} \sigma^{abs}_{J/\psi} = 4.18 \pm 0.35 \text{ mb} \\ \sigma^{abs}_{\psi'} = 7.3 \pm 1.6 \text{ mb} \end{cases}$$

J/ψ production in $\sqrt{S_{NN}}$=200 GeV p+p collisions

- Total cross section Ref) nucl-ex/0510020

  = 2.61+-0.20(fit)+-0.26(abs)μb

  - J/ψ dilepton decay branching ratio of 5.9%
  - PYTHIA predicted rapidity shape using GRV94HO parton distribution function
  - Uncertainty from different PDFs is less than 3%



J/ψ production in $\sqrt{S_{NN}}$=200 GeV d+Au collisions

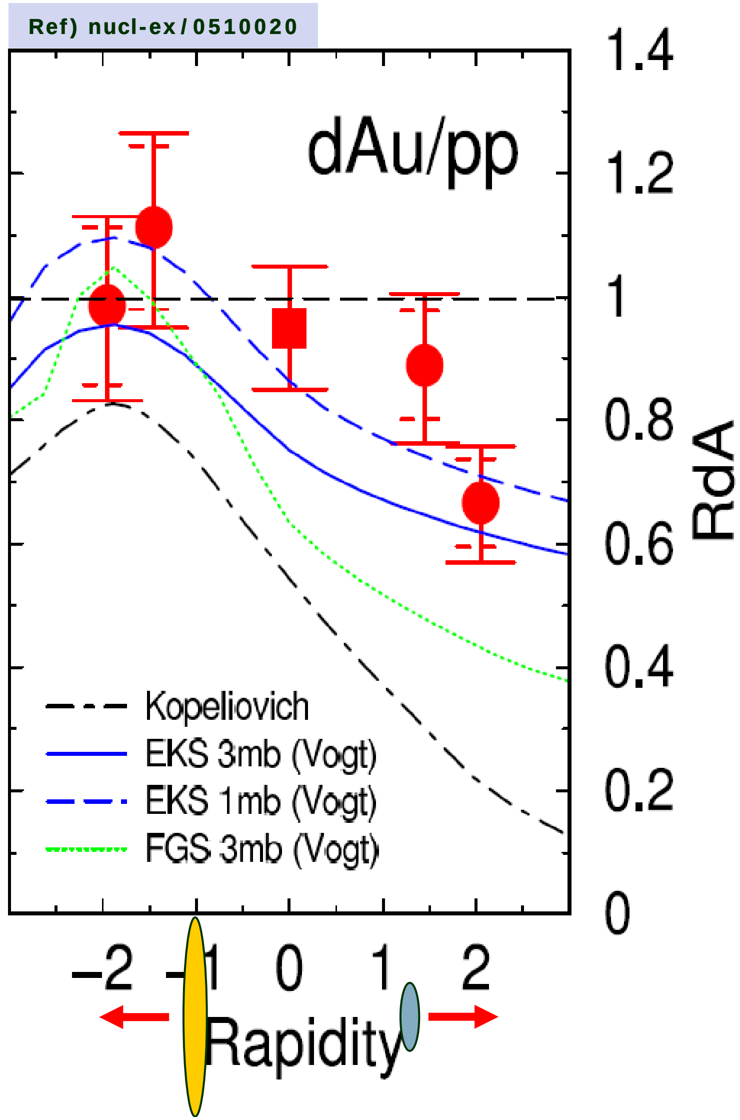
- Nuclear modification factor

  $R_{dAu}=\sigma_{dAu}/(2\text{x}197\text{x}\sigma_{pp})$ vs. rapidity

- Bjorken variable *x*
  - Forward rapidity : *x* ~ 0.003

    shadowing region
  - Backward rapidity : *x* ~ 0.09

    anti-shadowing region
- nuclear absorption cross section is marginal at order 1-3mb



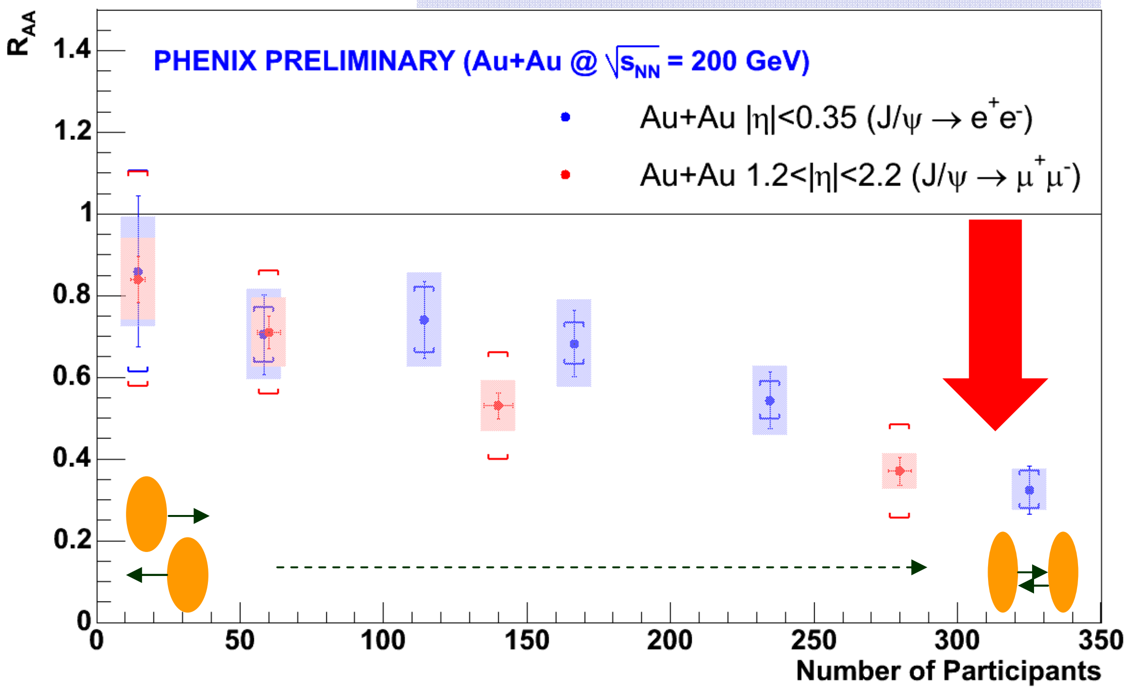
Nuclear Modification of J/ψ production in $\sqrt{S_{NN}}$=200 GeV Au+Au collisions

- Nuclear Modification Factor

$$R_{AA} = \frac{dN_{J/\psi}^{AuAu}/dy}{dN_{J/\psi}^{pp}/dy \ \langle N_{coll} \rangle} \quad \text{vs. } N_{part}$$

bar : stat. error
bracket : point-by-point sys. error
box : common sys. error

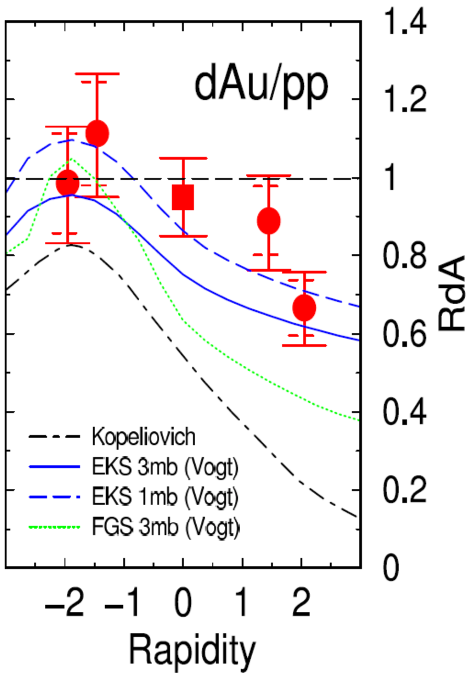
- N_{coll} = Number of binary N-N collisions.
- R_{AA} =1
  - Yield is scaled by N_{coll}. (same as p+p)
  - No medium effects.
- R_{AA} < 1
  - Suppression

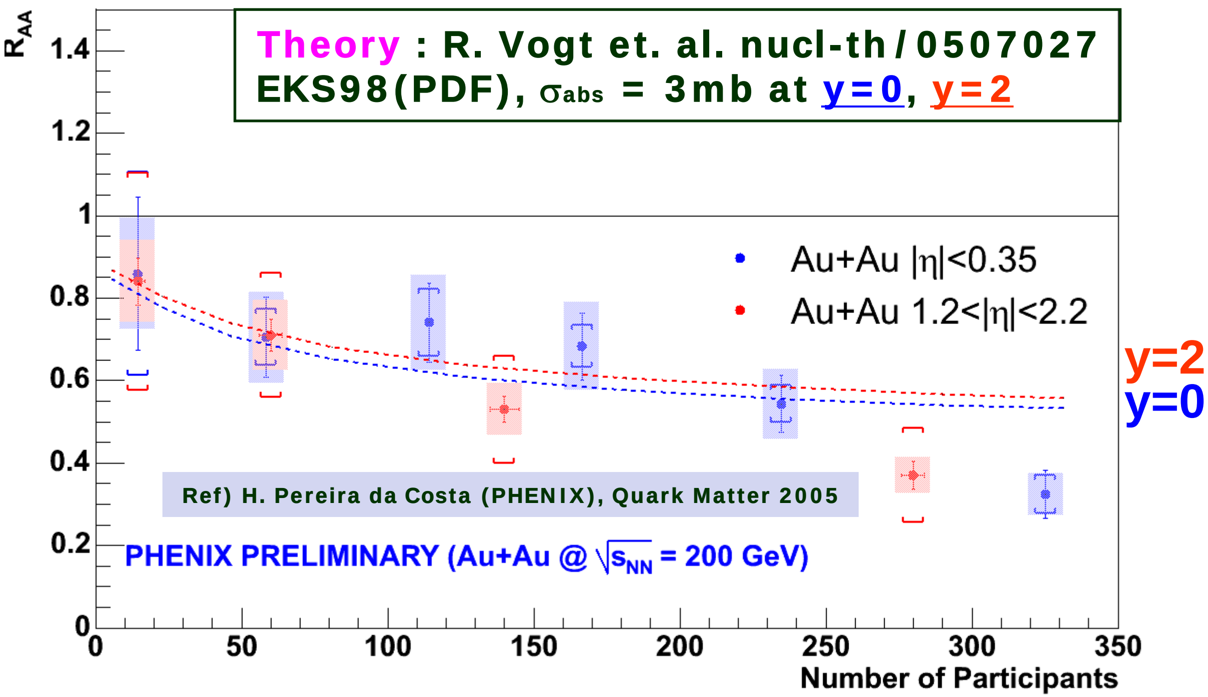


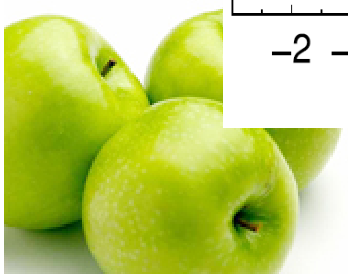
- J/ψ yield is suppressed compared to that in p+p collisions
  - Suppression is larger for more central collision
  - Factor of 3 suppression at most central collisions

Cold Nuclear Matter Effects

- Compared to R. Vogt prediction Ref) nucl-ex/0507032
  - assuming 3mb Nuclear Absorption and EKS98 Gluon Shadowing
- Evaluated from PHENIX d+Au results
  - σ_{abs} < 3mb and σ_{abs} of 1 mb is the best fit result.



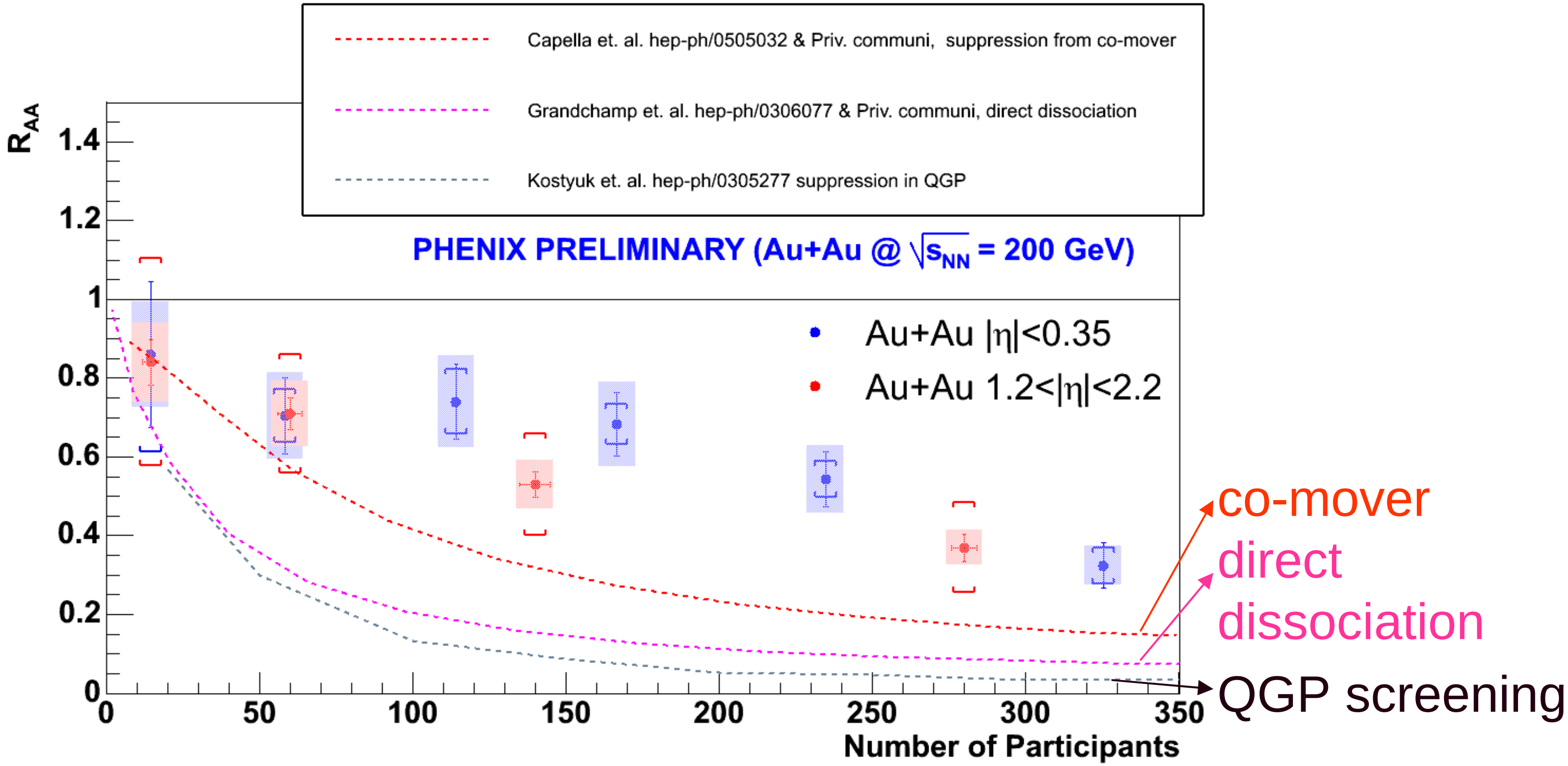


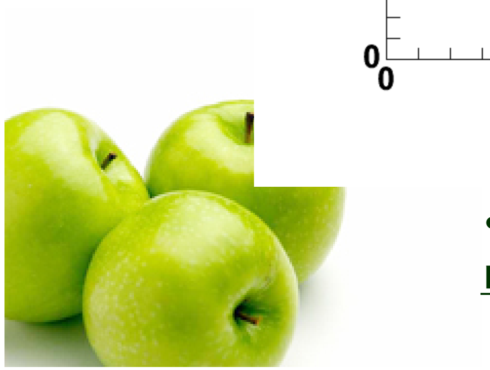


- 3mb is an upper bound for the nuclear absorption
- more suppression on the most central points beyond cold nuclear matter effect

Suppression Models

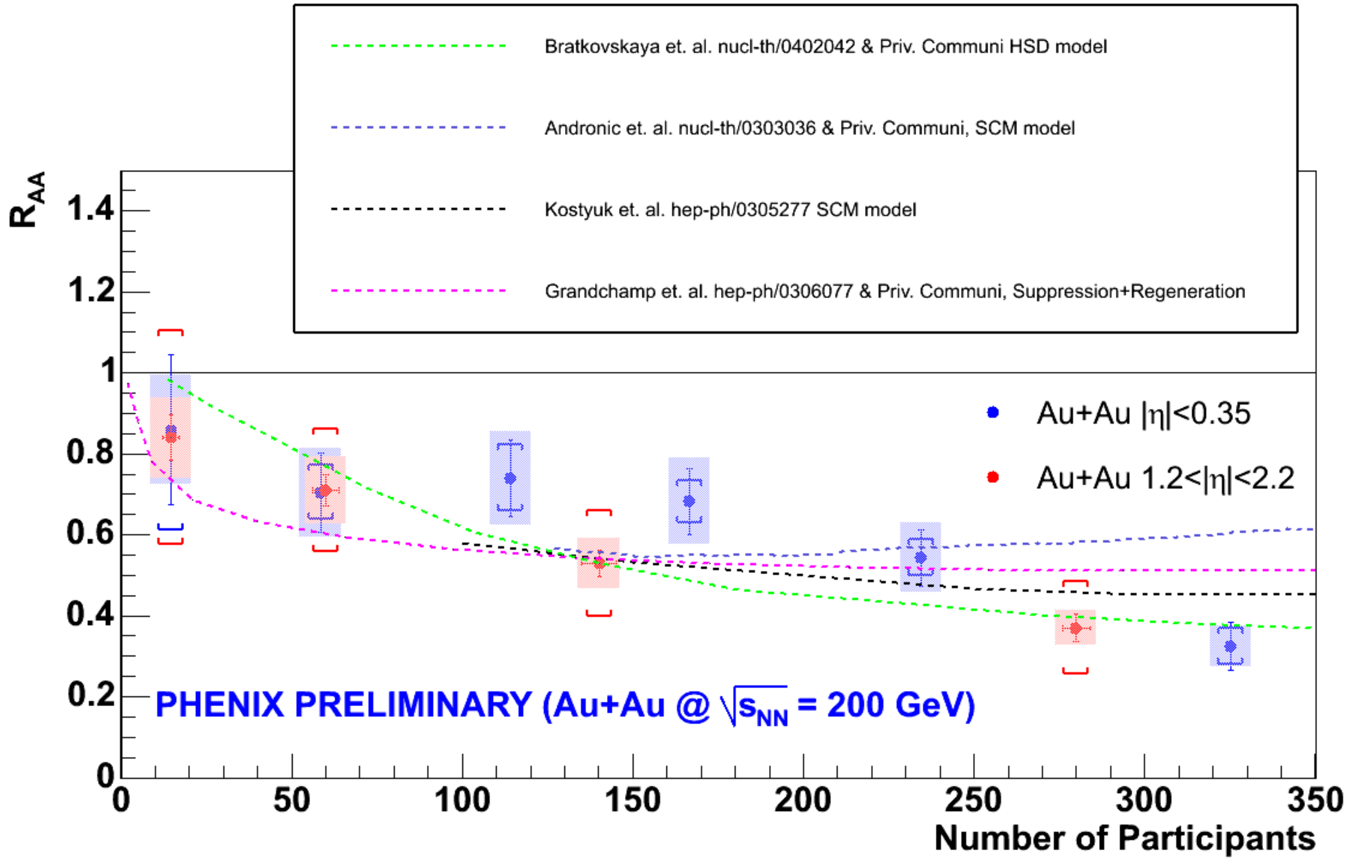
- Color screening, direct dissociation, co-mover scattering

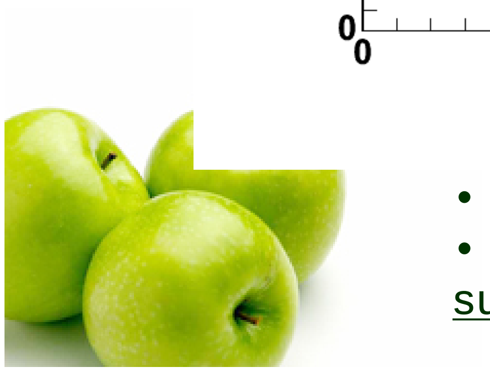




- J/ψ suppression at RHIC is over-predicted by the suppression models that described SPS data successfully

Suppression + Recombination Models

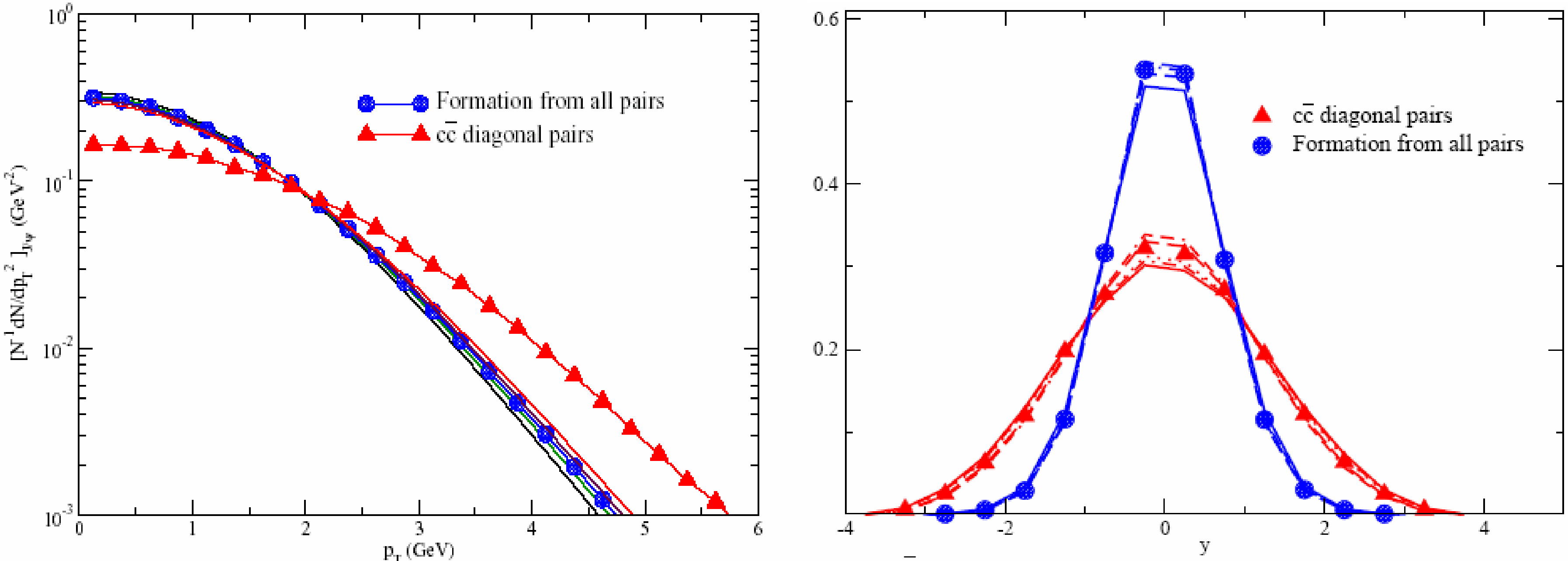




- Better matching with results compared to suppression models.
- At RHIC energy, recombination compensates stronger suppression?

Predicted Feature : p_T and Rapidity Narrowing

Predicted p_T and rapidity spectra of J/Ψ in Au+Au interaction at 200GeV from pQCD. [Thews : (nucl-th/0505055)]

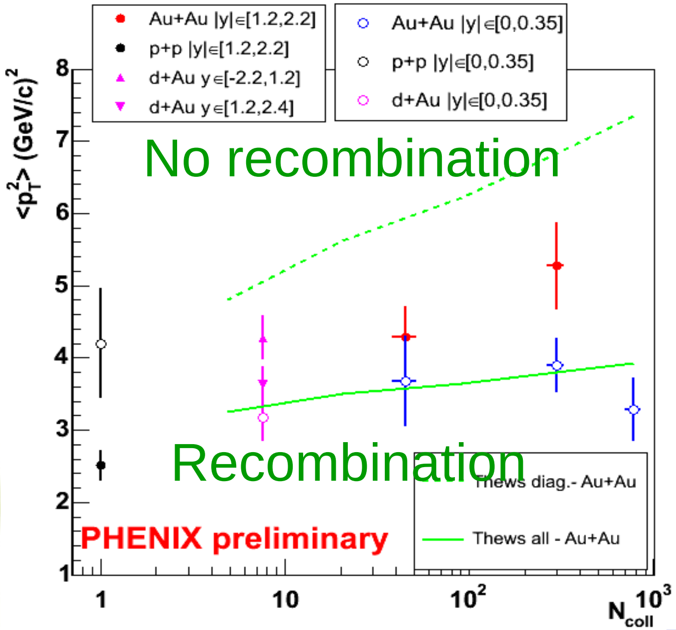


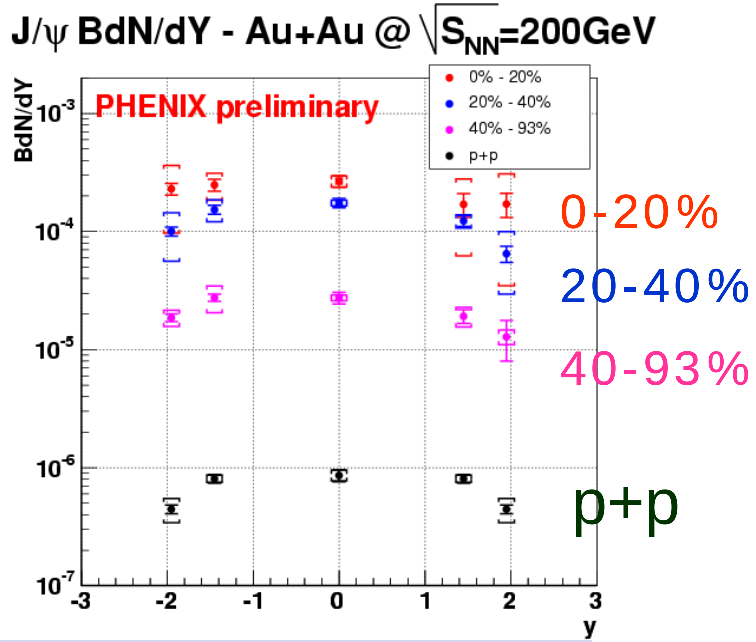
- Triangles are for initial production via diagonal $c\bar{c}$ pairs.
- Circles are for in-medium formation via all pairs.
- Sensitivity of the formation spectra to variation of $\langle k_T^2 \rangle$ is indicated by the spread in the solid lines.

- <u>Recombination model assuming all $c\bar{c}$ pairs' recombination predict narrower p_T and rapidity distribution</u>

$<p_T^2>$ vs. Ncol, BdN/dy vs. Rapidity

- Recombination predicts narrower p_T and rapidity distribution.
  - $<p_T^2>$ vs. Ncol
    - **Predictions of recombination model matches better.**
  - BdN/dy vs. Rapidity
    - **No significant change in rapidity shape compared to p+p result.**
- But charm p_T and rapidity distributions at RHIC is open question.





Ref) H. Pereira da Costa (PHENIX), Quark Matter 2005

Summary

- Theoretical background of the in-medium behavior of quarkonia are shown.
- PHENIX has measured J/ψ production as a function of several independent variables and compared with various theory.
  - Observed a factor 3 suppression for the most central events
  - Recombination/regeneration is needed in order not to overestimate the suppression when extrapolating from CERN experiments
  - No large modification of rapidity and transverse momentum distributions in comparing proton-proton but large error bar
- PHENIX hope to have more power on discerning various theories by reducing of our current systematic error and performing future measurement
- It is very challenging to construct models incorporating as many of the observed features as possible

BACKUP SLIDES

Quarkonium Spectroscopy

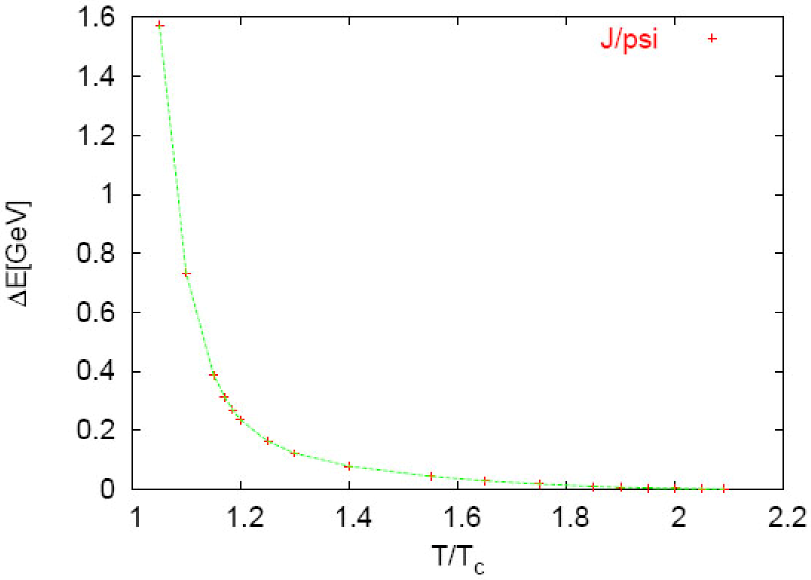
- Quarkonium spectroscopy from non-relativistic potential theory $V(r) = \sigma\, r - \frac{\alpha}{r}$

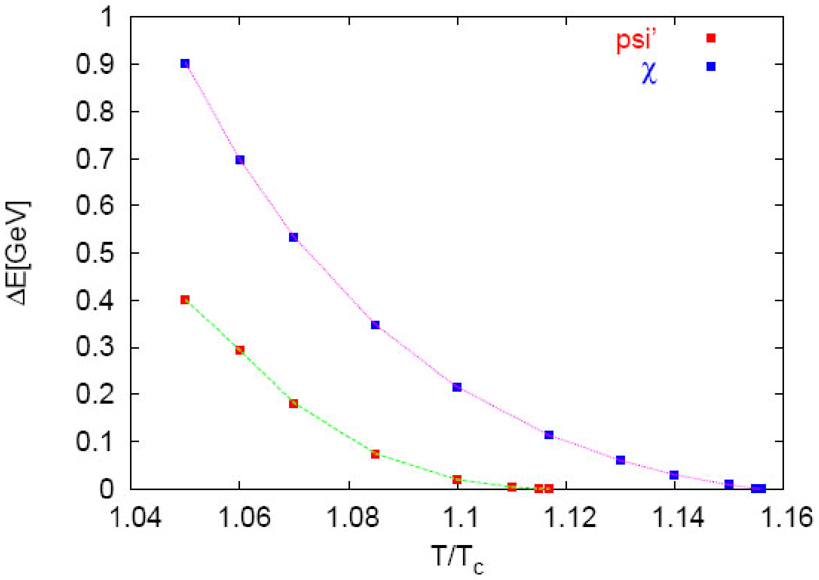
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

•Delta E : differences between the quarkonium masses and the open charm or beauty threshold
•Delta M : differences between the experimental and the calculated values, less than 1%
•R0 : QQbar separation for the states
•Input parameters : $m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$

T-dependence of binding energy for J/ψ and for χ_c / ψ'

Ref) H. Satz, hep-ph/0512217

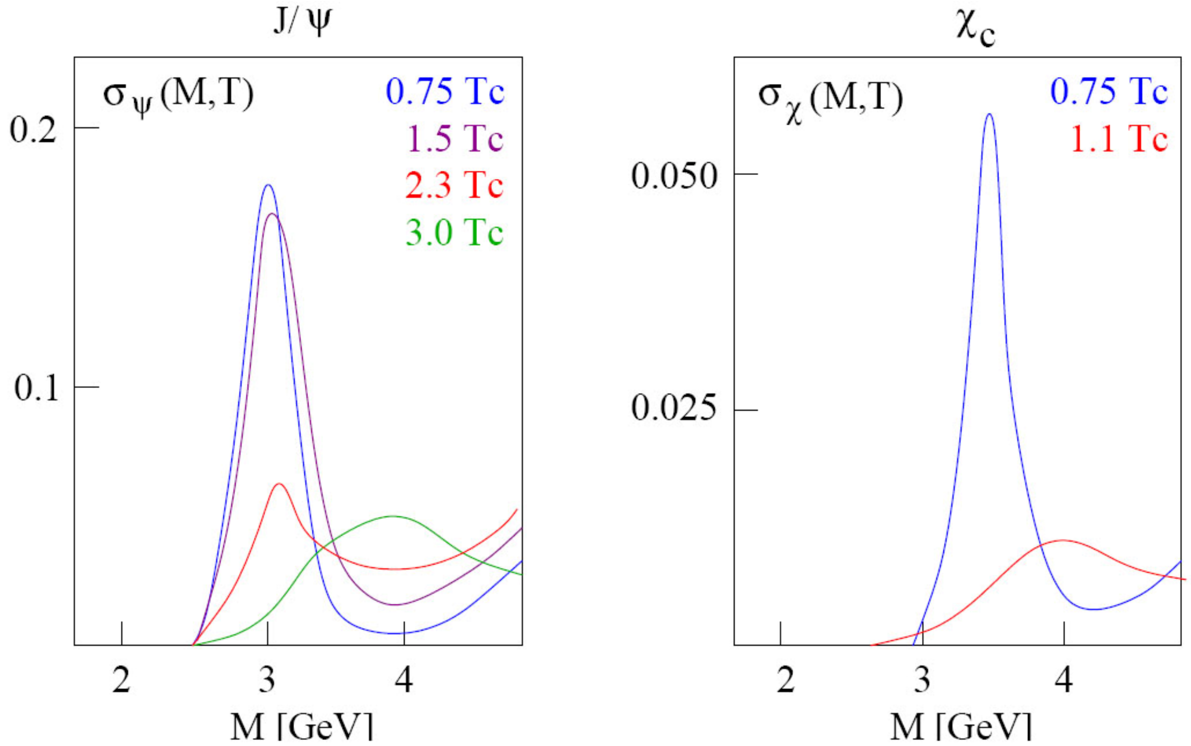




J/ψ and χ_c spectral functions at different temperature (direct from lattice QCD calculation)

- Spectrum for the ground state J/ψ remains essentially unchanged even at $1.5T_c$.

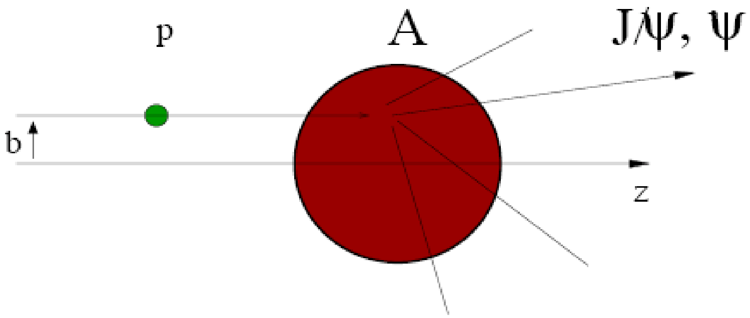
  At $3T_c$, it has disappeared.
- In contrast, χ_c is already absent at $1.1T_c$



Recent Lattice QCD results indicate J/ψ spectral function may persist up to 3 T_c.

Temperature Bound < 3 T_c (?)

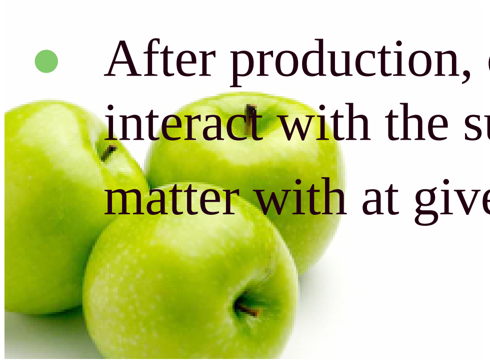
Normal Nuclear Absorption : Calculate Using Glauber Model



- Charmonia production follows the hard process cross-section

$$\sigma_{\mathrm{p-A}} = A\,\sigma_{\mathrm{NN}}$$

- After production, charmonia states can interact with the surrounding nuclear matter with at given cross-section (σ_{abs})



- Taking into account both processes
  - Production of the charmonia state,
  - Possible absorption on it's way through nuclear matter, we get

$$\frac{\sigma_{\mathrm{p-A}}}{A} = \sigma_0 \frac{1}{(A-1)\sigma_{abs}} \times \int d^2b\; e^{-(A-1)T_A(\vec{b})\,\sigma_{abs}}$$

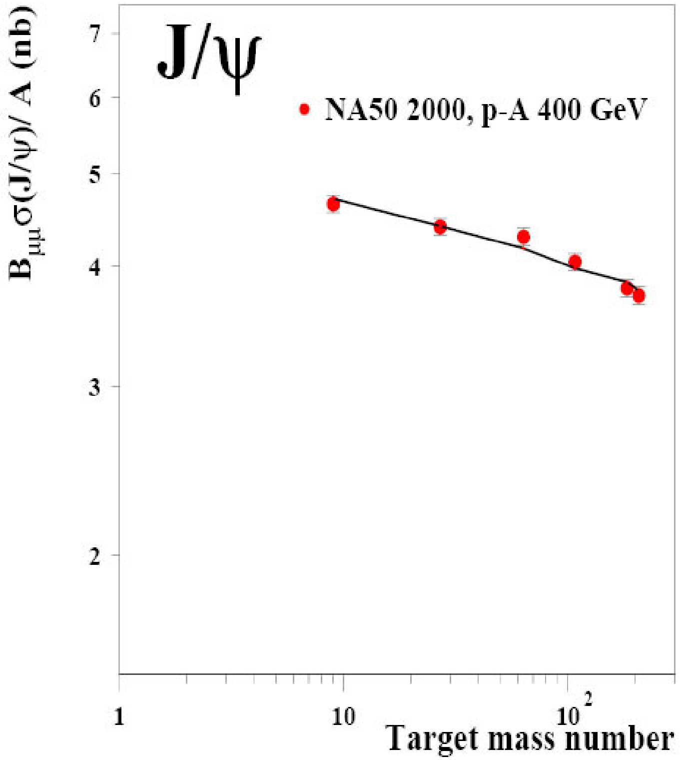
$T_A(\vec{b})$: **Nuclear thickness function**

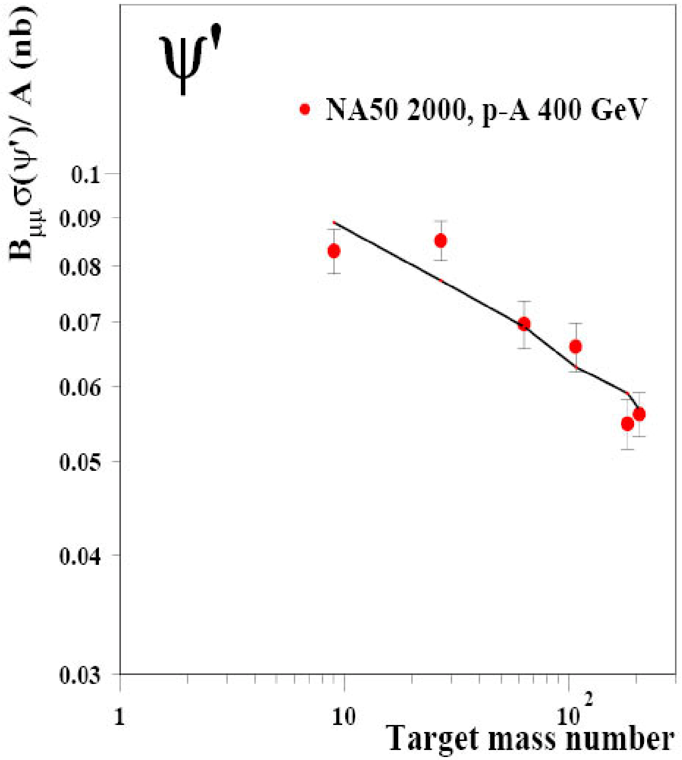
- Charmonia experimental cross-sections can be fitted using this Glauber model with 2 free parameters : $\sigma_0,\ \sigma_{\mathrm{abs}}$

NA50 σ_{abs} Result with Glauber Model

- J/ψ and ψ' results

Ref) B. Alessandro et al. (NA50), Eur. Phys. J. C 33 (2004) 31.





$$\sigma_{J/\psi} = 4.18 \pm 0.35 \text{ mb} \qquad \sigma_{\psi'} = 7.3 \pm 1.6 \text{ mb}$$

Good Run Selection/Data Production

Data samples

- Take total ~1500 Million Minimum Bias events during the Run-4 Au+Au collision

Run selection

- Take into account :
  - MuTr/MuID HV conditions
  - Large number of MuTr clusters/event
  - Low MuTr cluster peak ADC value
  - A number of hot planes/packets or dead planes/packets in MuTr
  - Runs with low hit rate in MuTr or MuID
- Categorize simulation sets and real data sets based on this

Data production

- At CCF, processed ~78% of the entire Run-4 data sample using a Level-2 trigger filtered data sample

Cut Variables

Variables we have to cut on

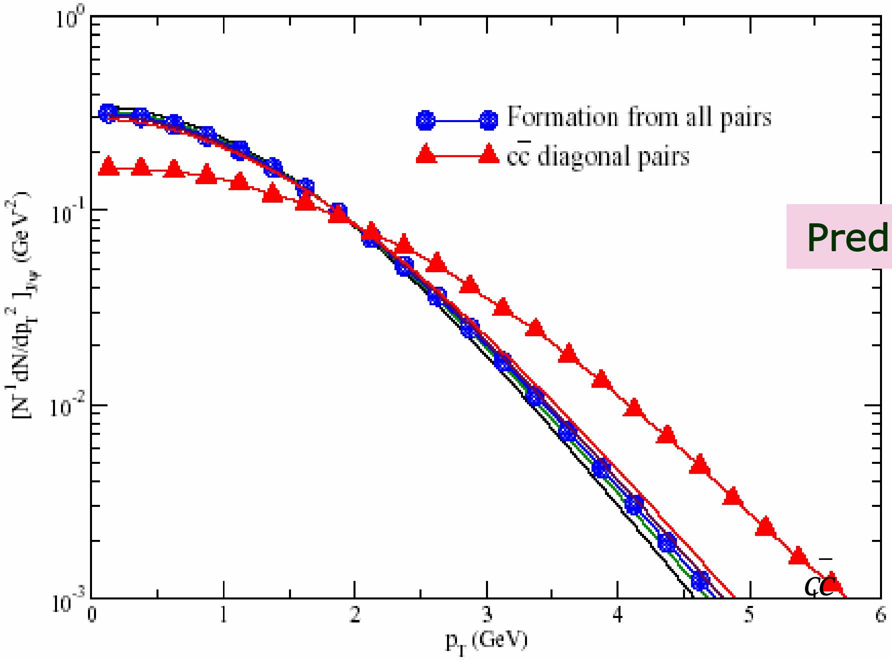
- Rapidity
- Road depth (deep-deep) due to Level2
- Track z directional momentum (to match road depth)
- Level2 decision for corresponding arm
- Levle2 cuts on associated Level2 primitives
- BBC z-vertex

Additional quality variables

- Road to track association (DG0, DDG0)
- Track chisquare
- Vertex chisquare

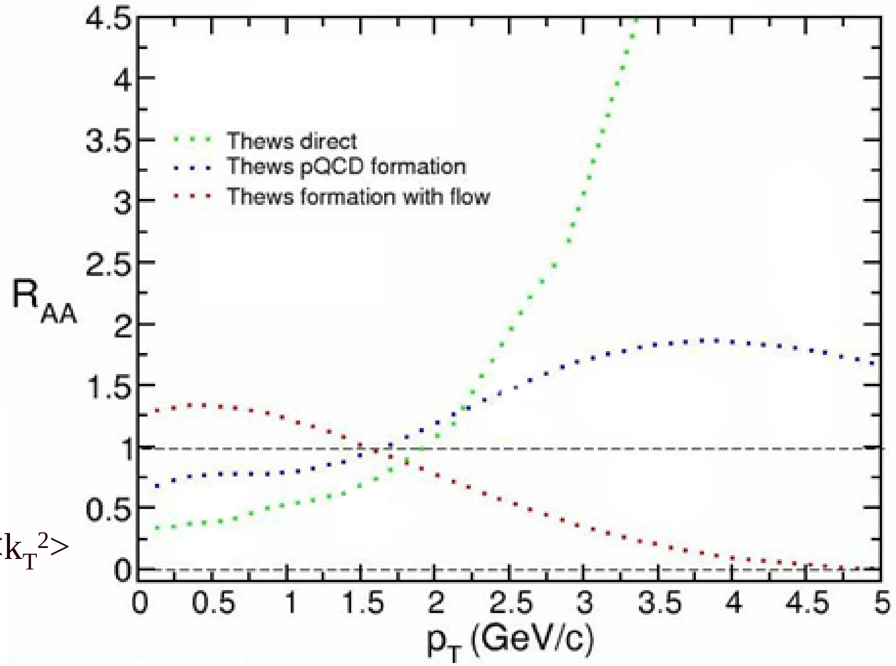
Model Prediction for Transverse Momentum

Thews : (nucl-th/0505055)
Predicted p_T spectra of J/Ψ in Au-Au interaction at 200GeV from pQCD.

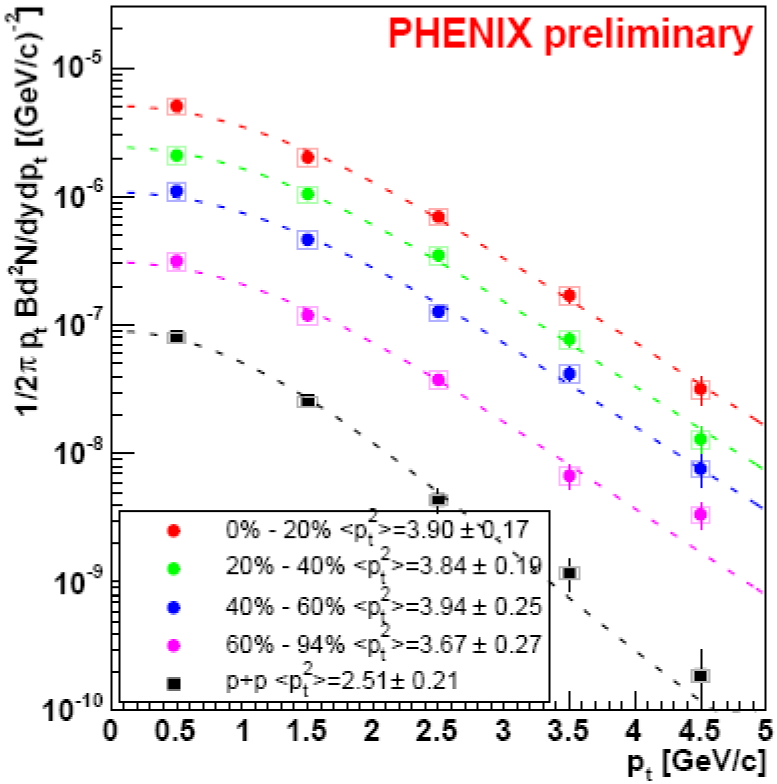


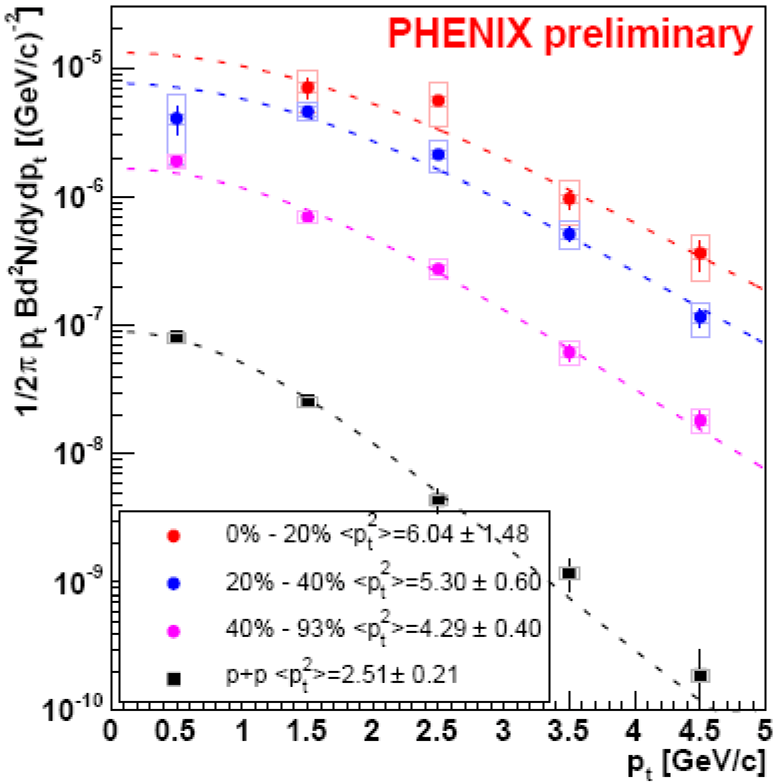
- Triangles are for initial production via diagonal pairs.
- Circles are for in-medium formation via all pairs.
- Sensitivity of the formation spectra to variation of <k_T^2> is indicated by the spread in the solid lines.

Predicted R_{AA} of J/Ψ vs p_T in Au-Au interaction at 200GeV



p_T Distribution

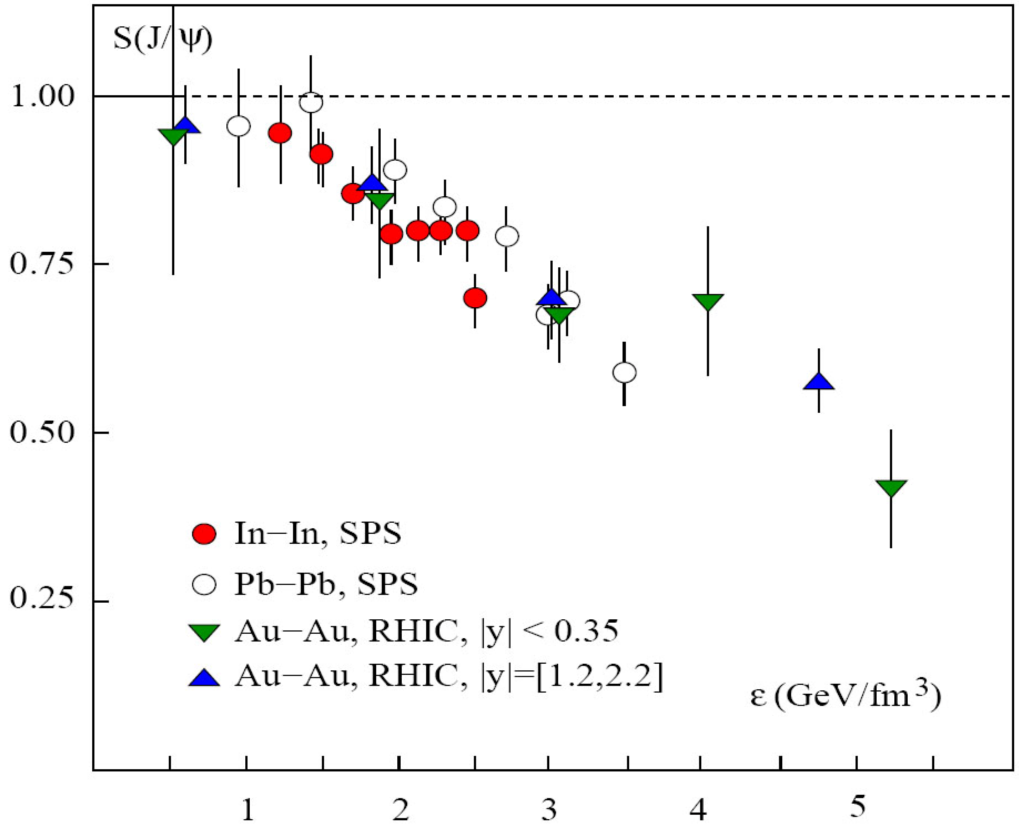




- Cu+Cu, Au+Au : mu+mu- channel
- Fit function : $A\left[1+(p_t/B)^2\right]^{-6}$

J/ψ Suppression vs Energy Density

- From theory, J/ψ survive up to ε~10 GeV/fm^3
- Suppression of the 40% coming from χc and ψ'
- 60% directly produced J/ψ remain unaffected until much higher ε
- Onset of suppression occurs at the expected energy density
- J/ψ survival probability converges towards 50-60%



Ref) H. Satz, hep-ph/0512217