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

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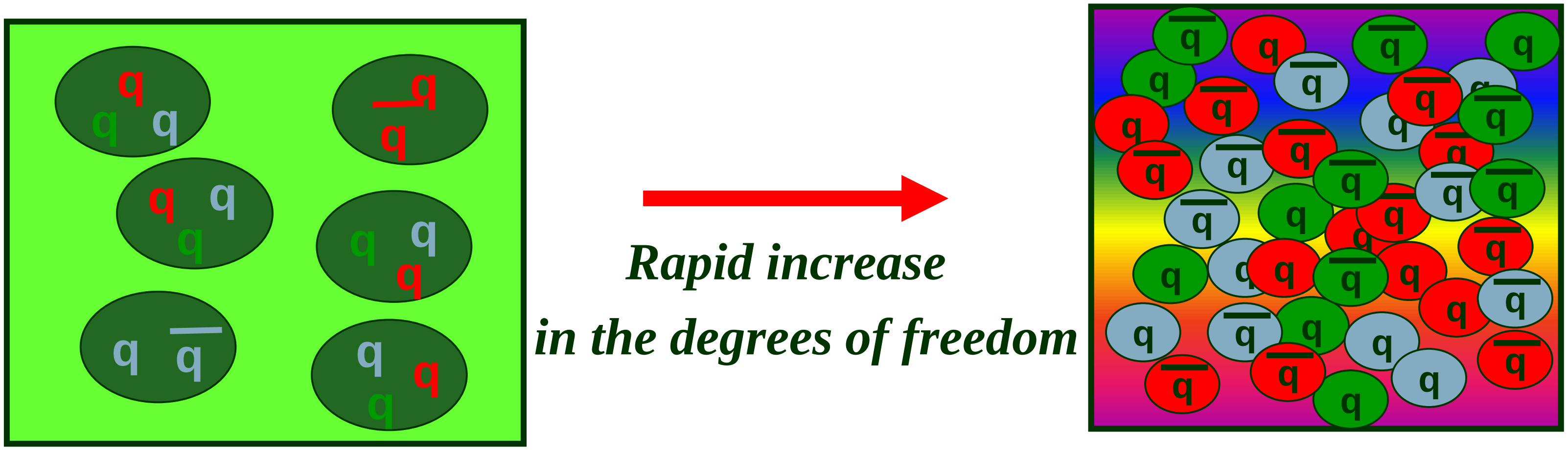
HIM Talk Feb/23-24/2006

Predicted New State of Matter

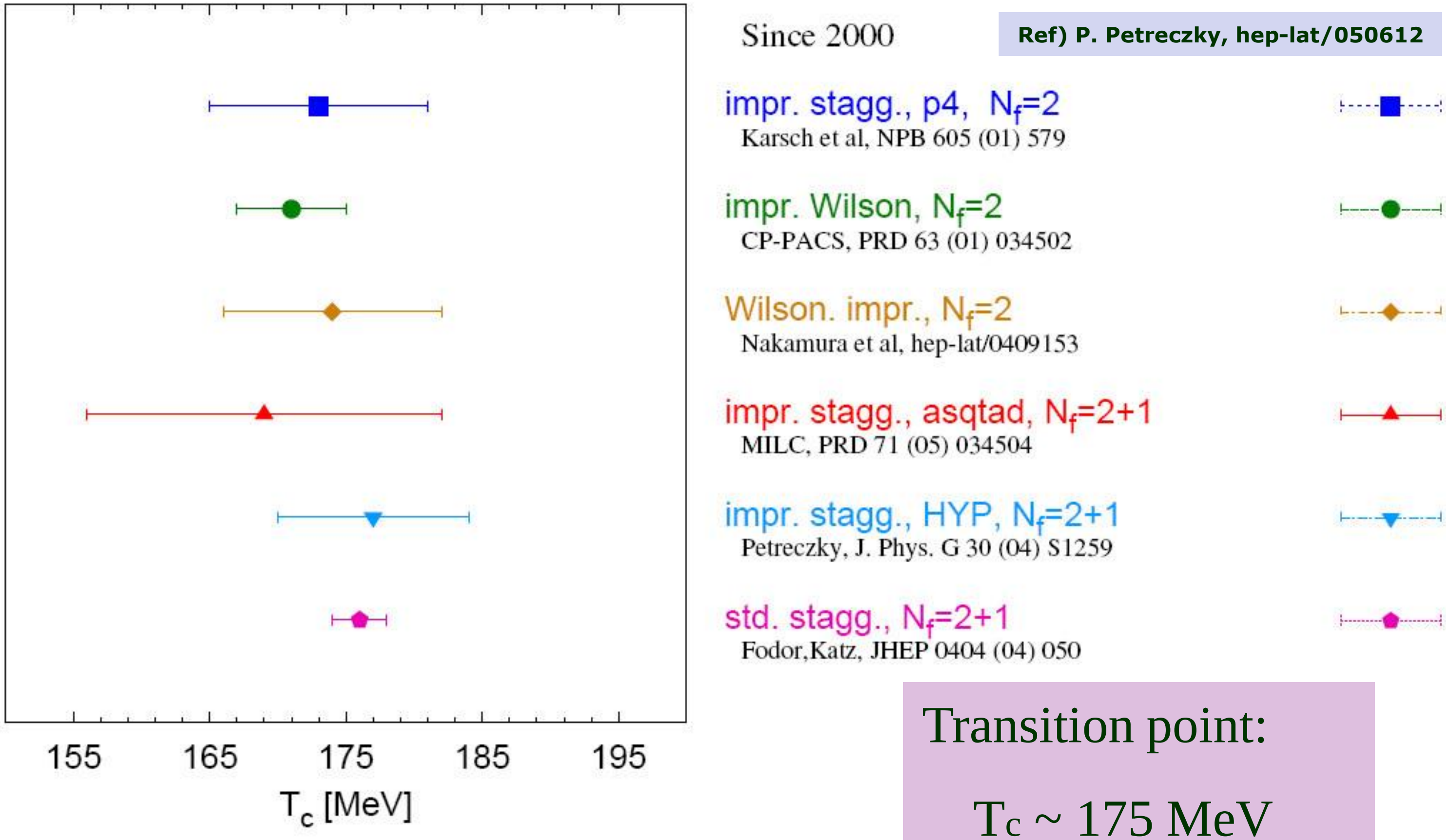
- QCD predicts that at high energy densities a new type of matter will be created – Quark-Gluon Plasma



Hot, dense state of matter in which partons have became deconfined from the normal hadronic state

Critical Temperature

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



Ref) P. Petreczky, hep-lat/050612

Transition point:

$T_c \sim 175$ MeV

$\varepsilon \sim$ 1.0 GeV/fm^3

Where and How?

- New state of strongly interacting matter

where and how to observe it?

- Very early universe (in the first 10 micro sec after the big bang)
- Core of neutron stars
- High energy nuclear collisions to form small and short-lived quark-gluon plasma in the laboratory.

how to probe?

=> through in-medium behavior of Quarkonia

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

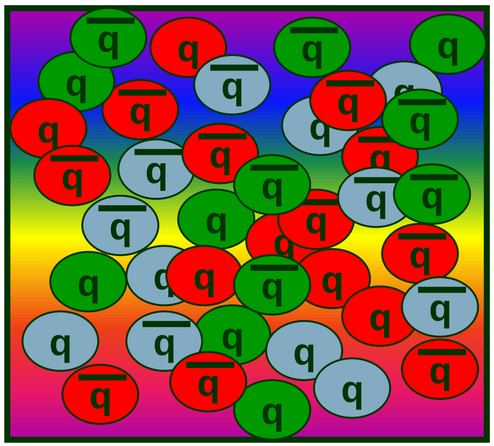
Ref) H. Satz, hep-ph/0512217

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 (ΔE: $J/\psi \rightarrow \psi'$)

larger (r_0: $J/\psi \rightarrow \psi'$)

Quarkonia in QGP



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

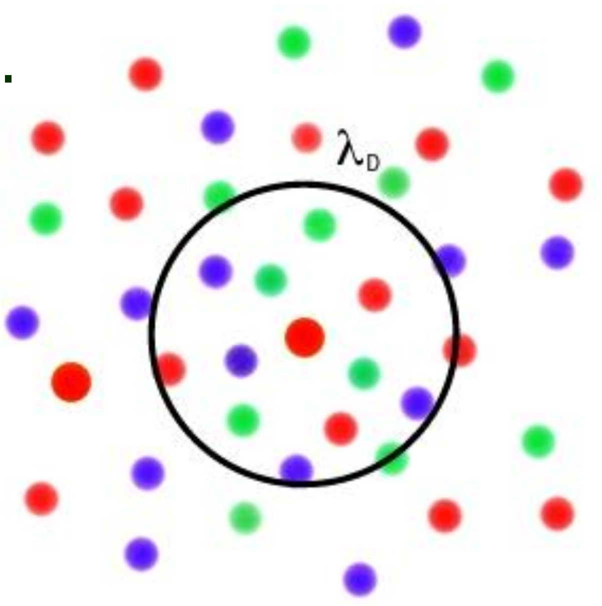
⇨ Disappearance of specific quarkonia signals the presence of a deconfined medium of a specific temperature.

Screening theory : Debye Screening

- Originally defined for electromagnetic plasma, later extended to plasma of color charges.

- The charge of one particle is screened by the surrounding charges.

- Debye Screening Radius (λ_D): The distance at which the effective charge is reduced by 1/e.



Charmonia Potential

- Properties of Charmonia ($c\bar{c}$) is represented well (at T ≈ 0) by the potential:

$$V(r) = \sigma\, r - \frac{\alpha}{r}$$

E. Eichten et al., Phys. Rev. D17 (1978) 3090; Phys. Rev. D 21(1980) 203.

But at T = $T_{c,}$, in medium

$$V(r) = -\frac{\alpha\; e^{-r/\lambda_D}}{r}$$

L. D. Landau and E. M. Lifshitz, Statistical Physics, Pergamon Press, 1958.

J/ψ in the QGP

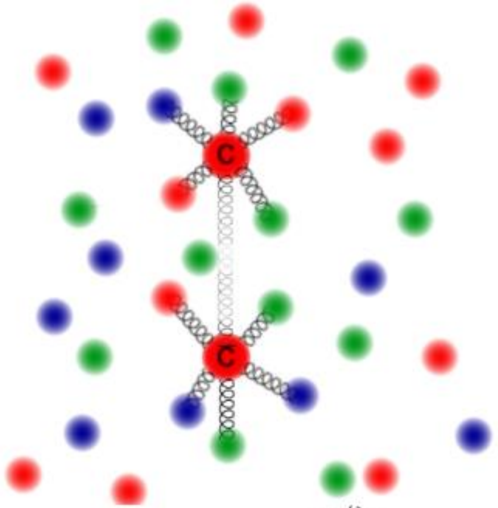
Matsui & Satz :

Ref) Phys. Lett. B178 (1986) 416.

In the QGP the screening radius could become smaller than the J/ψ radius, effectively screening the quarks from each other

	T=0	T=200
α	0.52	0.20
$R_{Bohr}\,(J/\psi) = \frac{1}{\alpha\,\mu}$	0.41 fm	1.07 fm
$\lambda_D\,(pQCD) = \sqrt{\frac{2}{9\pi\alpha}}\frac{1}{T}$	∞	0.59 fm

Ref) Introduction to High-Energy Heavy-Ion Collisions, C.Y. Wong 1994



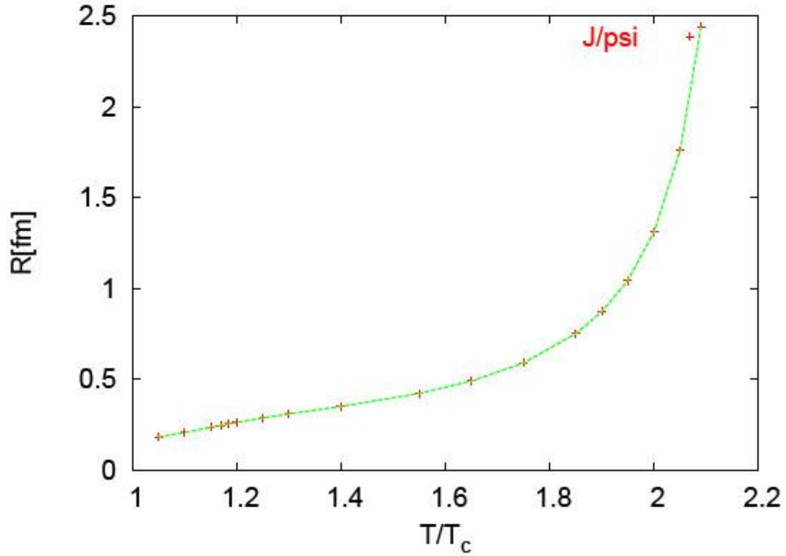
$$V(r) = -\frac{\alpha\, e^{-r/\lambda_D}}{r}$$

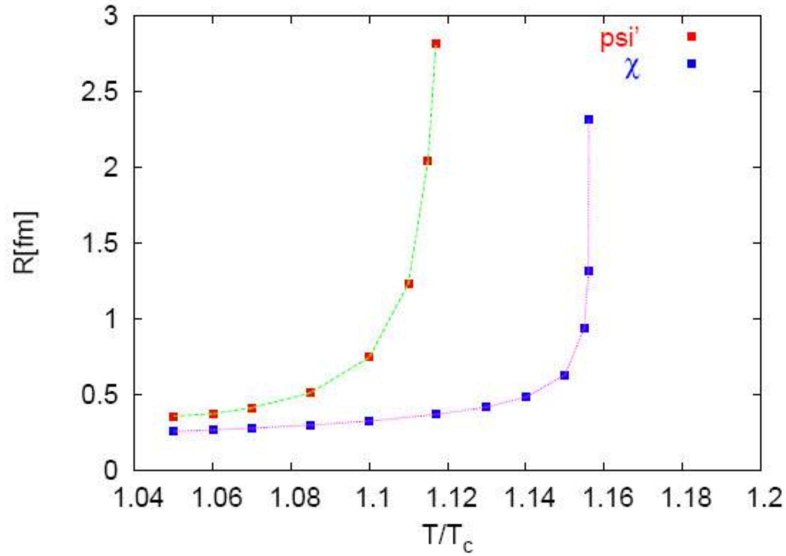
The charm and anti-charm become unbound, and may combine with light quarks to emerge as “open charm” mesons.

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



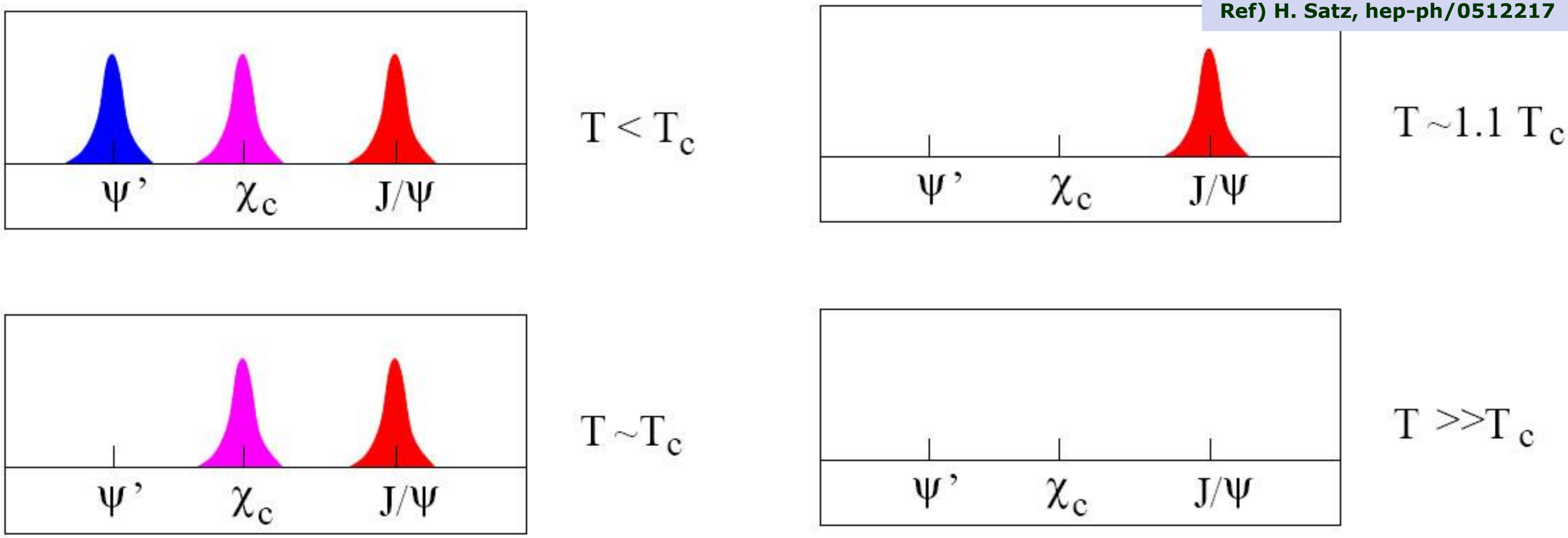


- Quarkonium dissociation temperatures

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



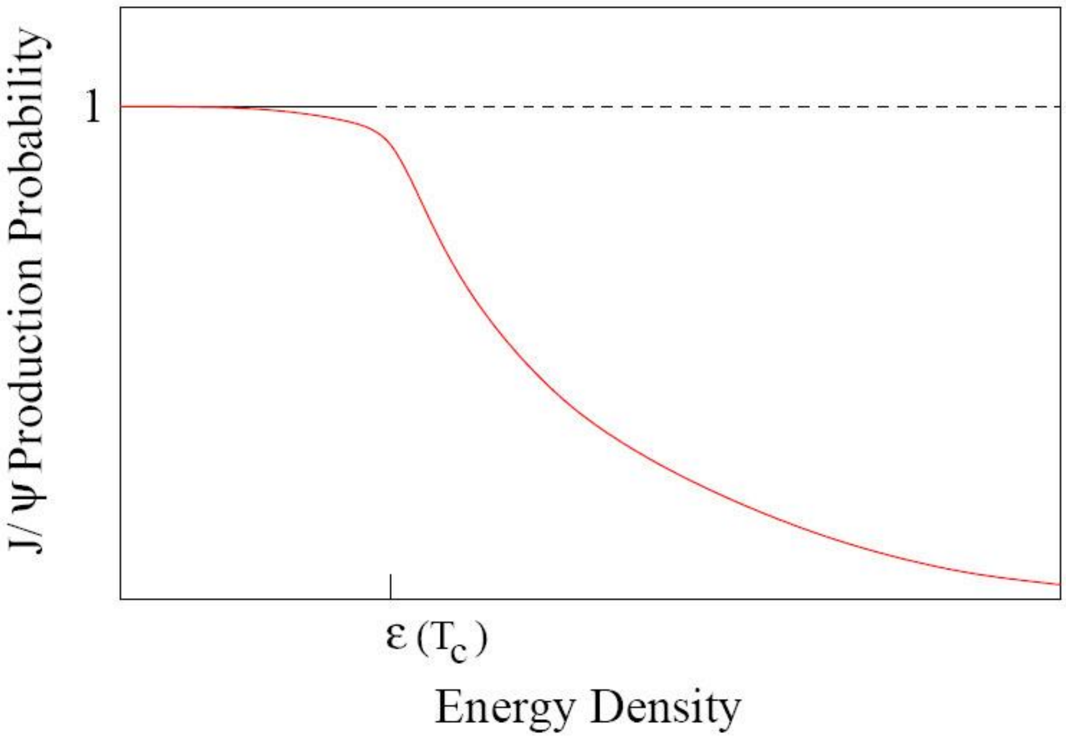
- With increasing temperature the different charmonium states "melt" sequentially as function of their binding strength;
- The most loosely bound state disappears first, the ground state last.
- The dissociation points of the different quarkonium states provide a way to measure the temperature of the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

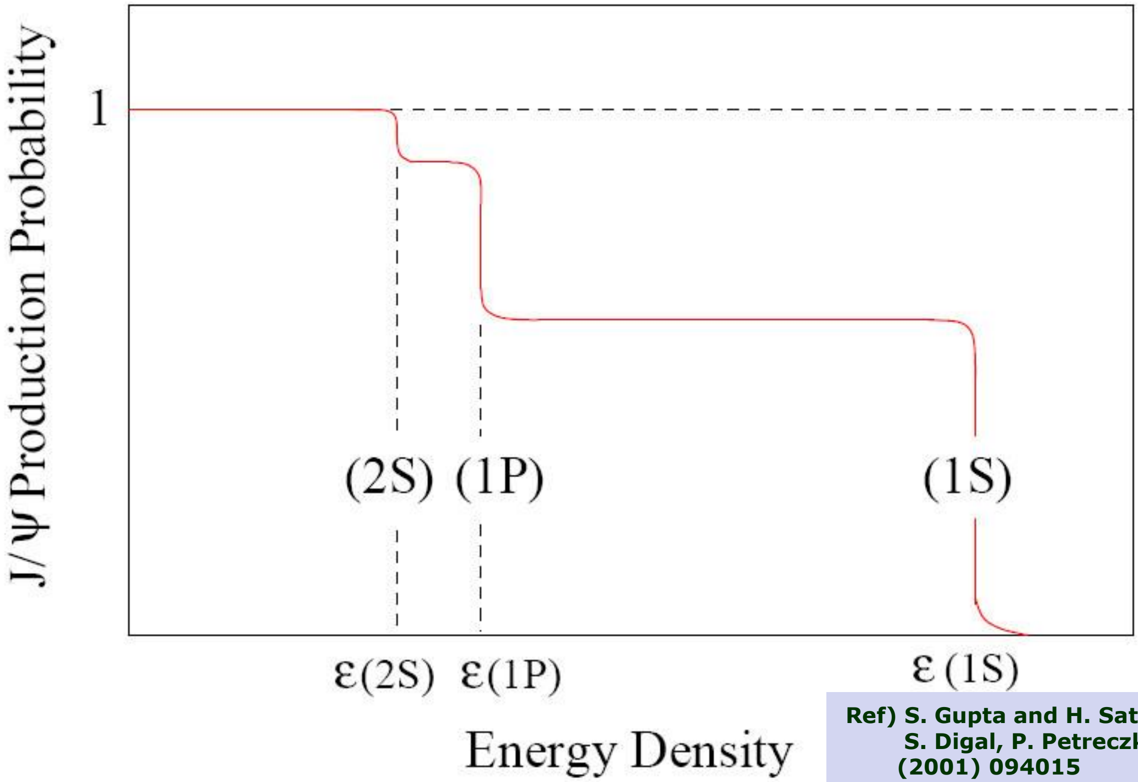
  : dissociation by interaction with hadronic comover

- 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

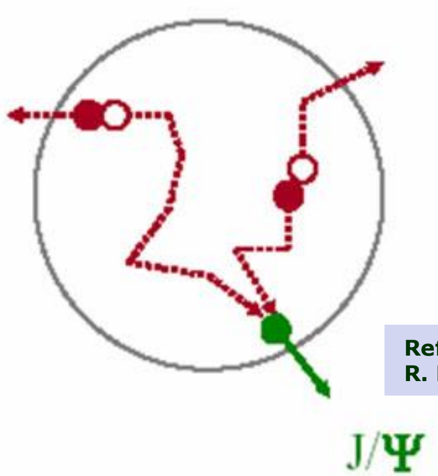


Ref) S. Gupta and H. Satz, Phys. Lett. B 283 (1992) 439; S. Digal, P. Petreczky and H. Satz, Phys. Rev. D 64 (2001) 094015

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.



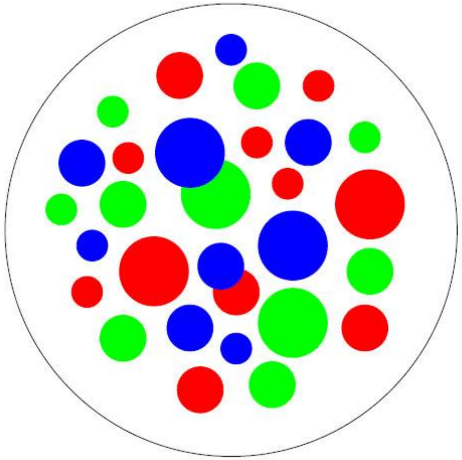
Ref) P. Braun-Munzinger and J. Stachel, Nucl. Phys. A690 (2001) 119;
R. L. Thews et al., Phys. Rev. C 63 (2001) 054905

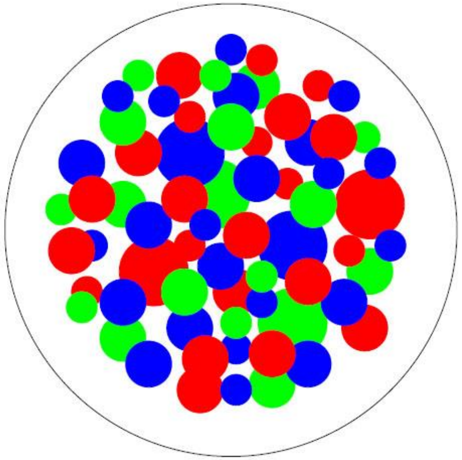
Initial State Suppression

- 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





Experimental Setup

Energy Scale of Heavy-Ion Collisions

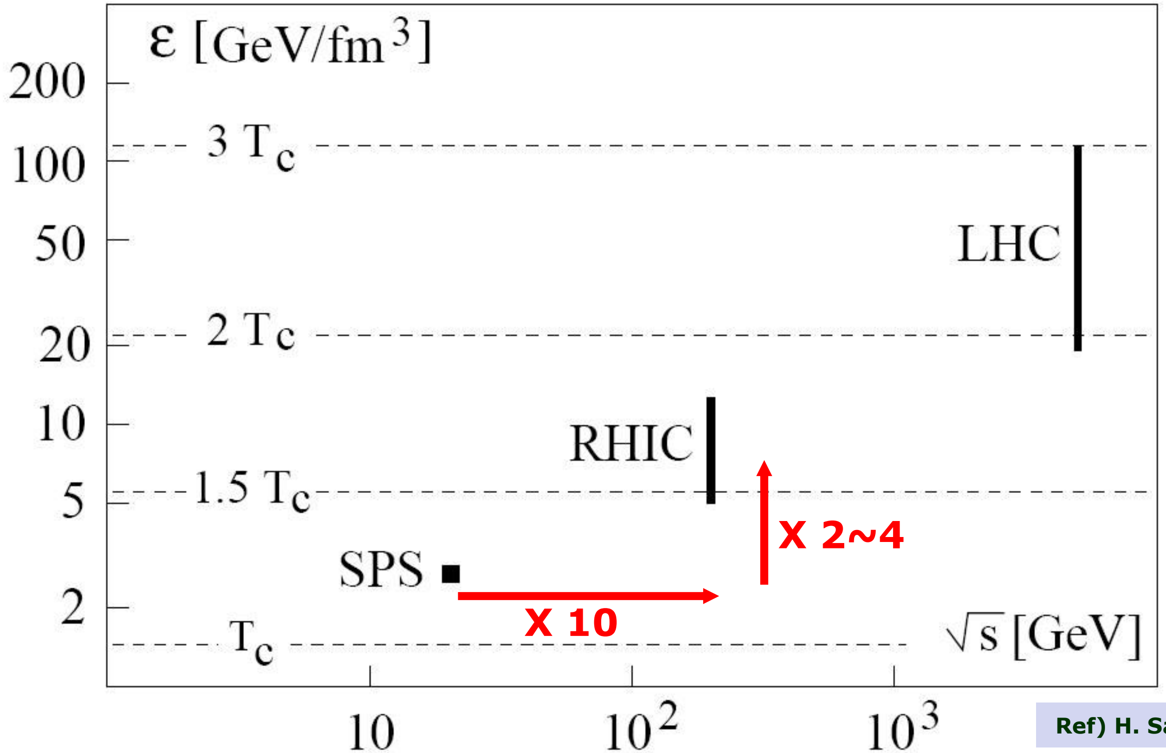
- In a high energy heavy-ion collision, a large amount of energy is deposited in a very small volume

- 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 $\varepsilon(T_c)$~0.5-1.0 GeV/fm^3

RHIC Facility

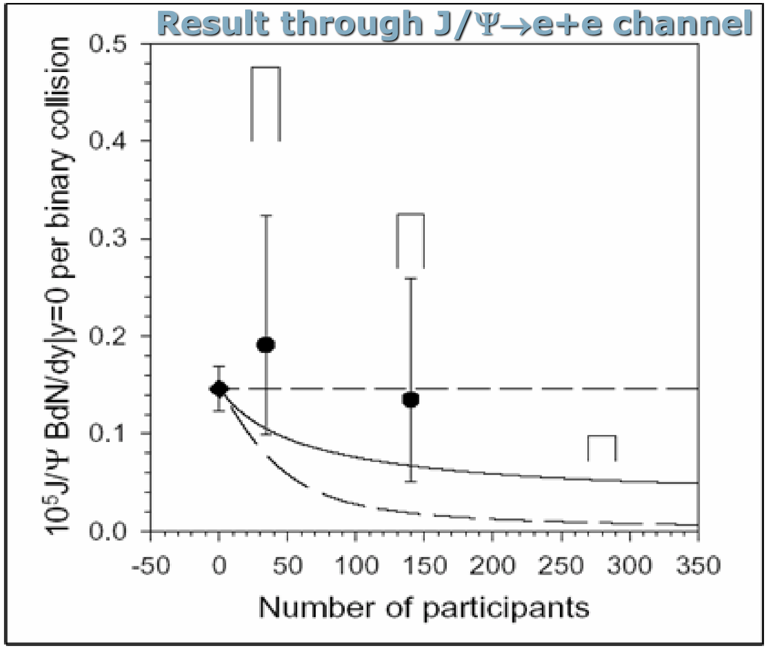
- Relativistic Heavy Ion Collider online since 2000.
- Design Gold Gold energy and luminosity achieved.
- All experiments successfully taking data

What PHENIX Measure?

RUN 2

- Low statistics result on J/Psi production (24 μb^{-1})

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

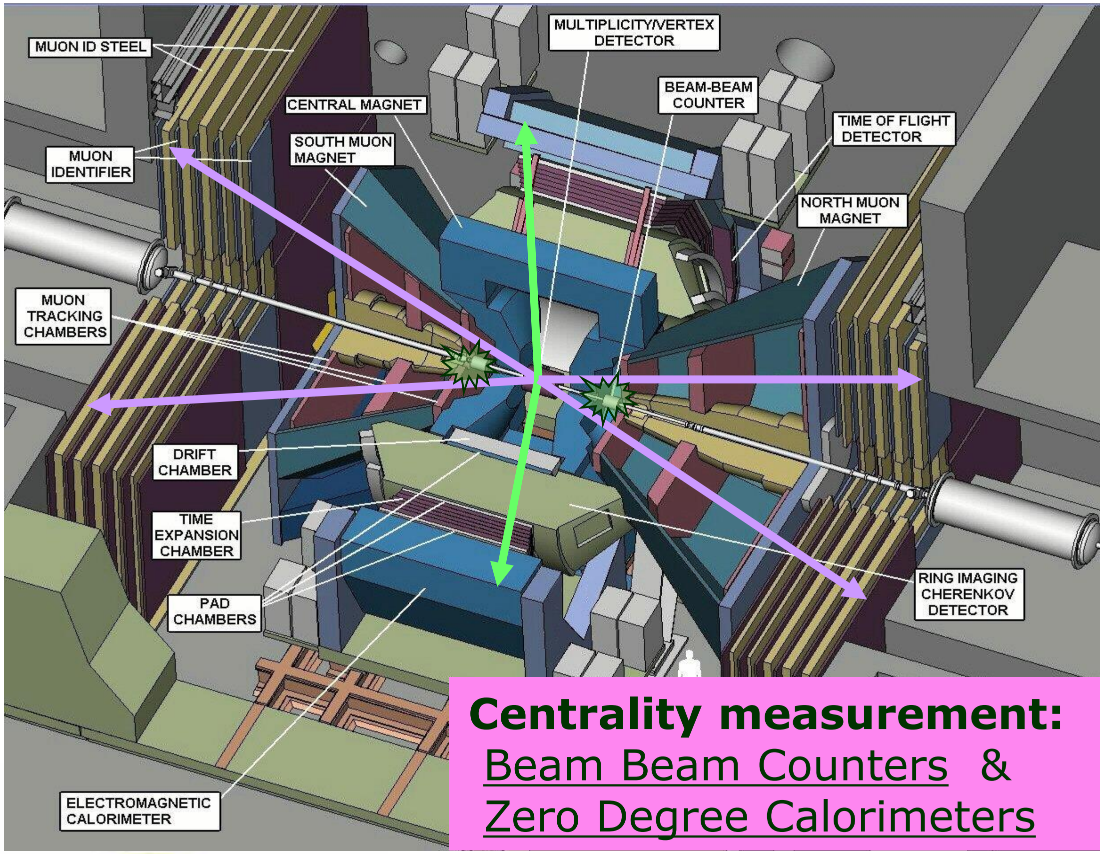


RUN 4

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

Year	Ions	Luminosity	#Events
2003	p+p @200GeV	350 nb^{-1}	
	D+Au @200GeV	2.74 nb^{-1}	
2004	Au+Au @200GeV	241 mb^{-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

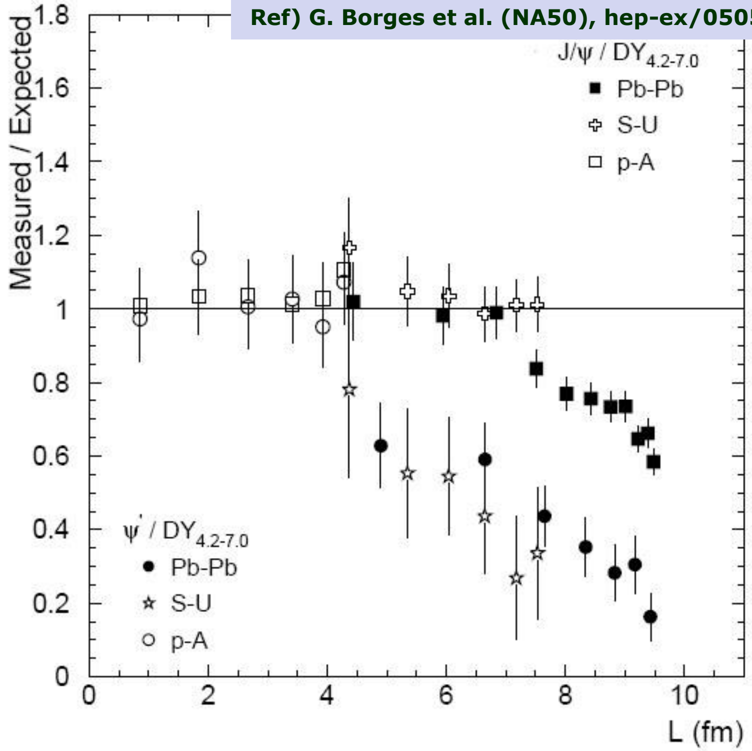
- $J/\psi \rightarrow \mu+\mu-$
- $1.2< |\eta| < 2.4$
- $P\mu > 2$ GeV/c
- $\Delta\phi = 2\pi$

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

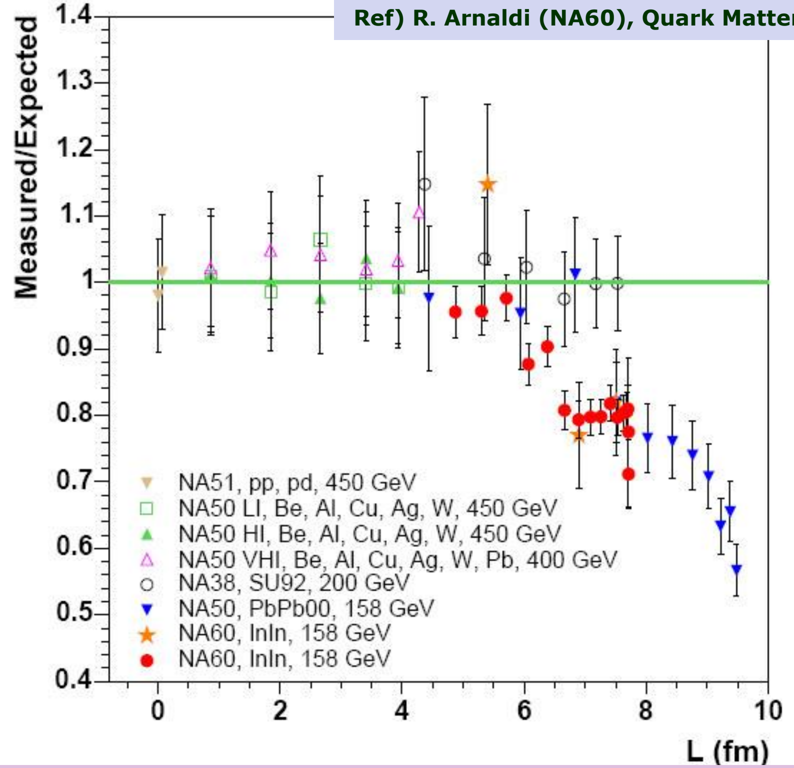
Result

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 $\left\{ \begin{array}{l} \sigma^{abs}_{J/\psi} = 4.18 \pm 0.35 \text{ mb} \\ \sigma^{abs}_{\psi'} = 7.3 \pm 1.6 \text{ mb} \end{array} \right.$

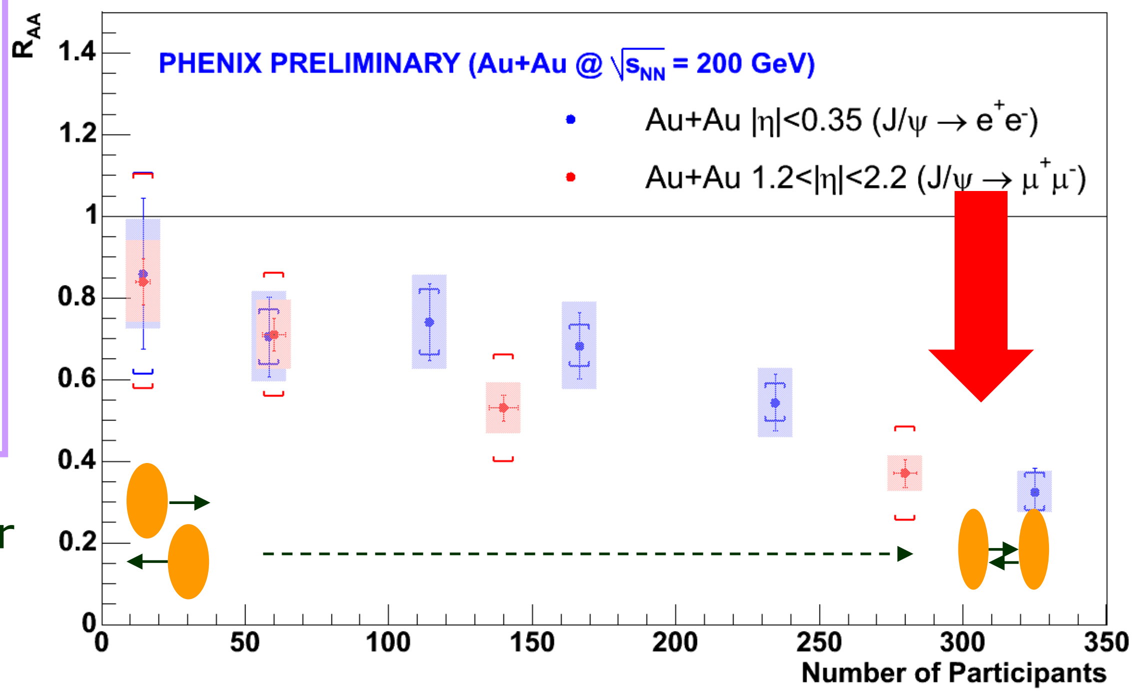
Nuclear Modification Factor

- Nuclear Modification Factor :

$$R_A = \frac{dN_{J/\psi}^{AuAu}/dy}{dN_{J/\psi}^{pp}/dy \; \langle N_{coll} \rangle}$$

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

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

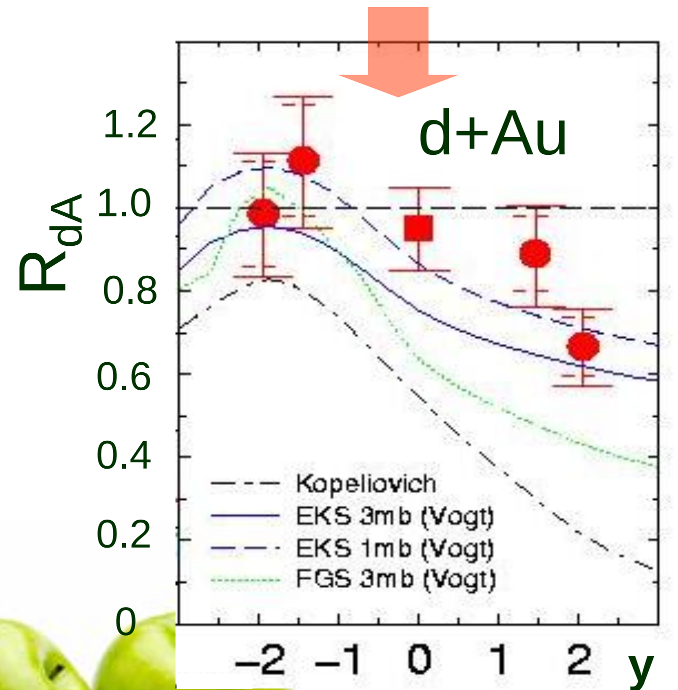


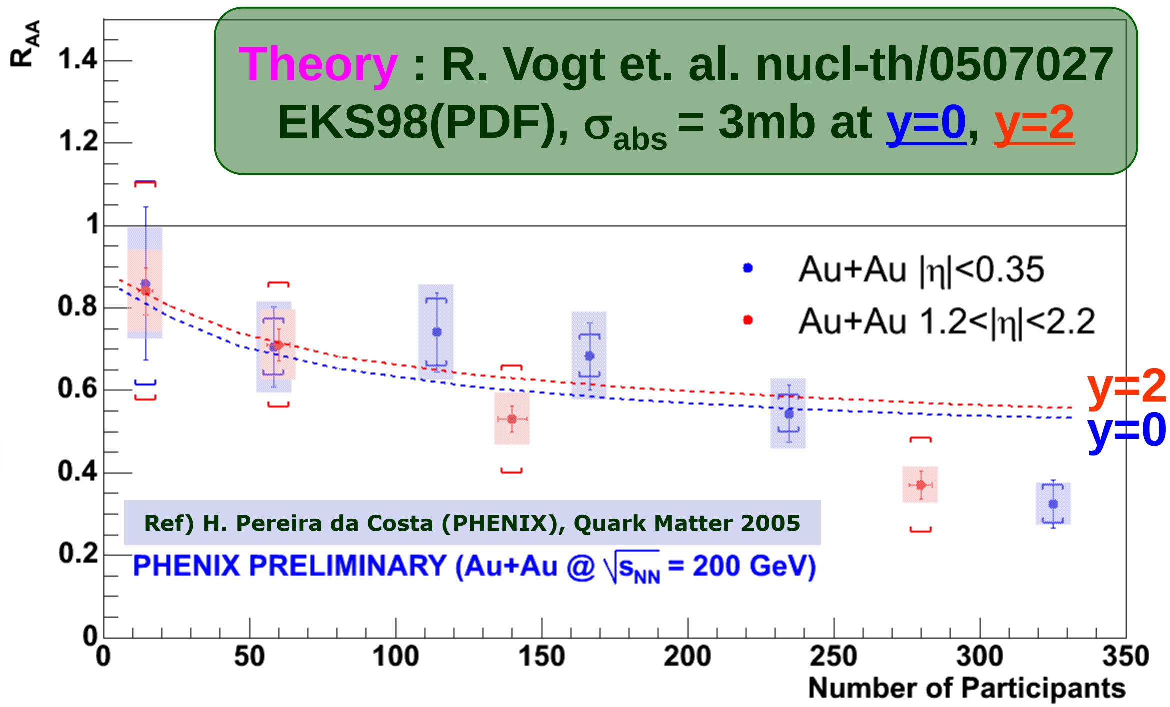
J/y yield is suppressed compared to that in p+p collisions.

- Suppression is larger for more central collisions.
- Factor of 3 suppression at most central collisions.

Cold Nuclear Matter Effects

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

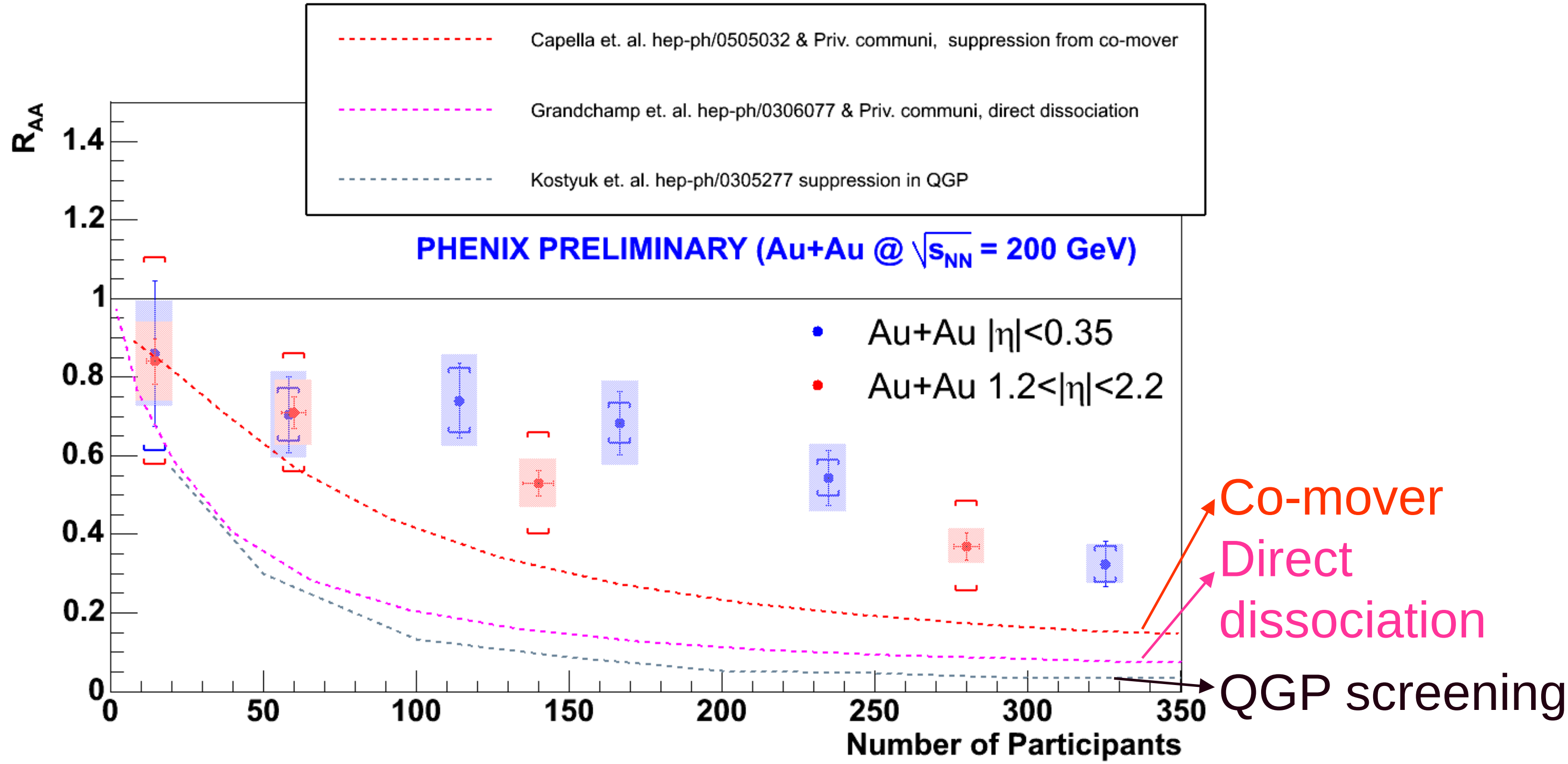




Beyond the suppression from cold nuclear matter effects for most central collisions even if σ_{abs} ~ 3 mb.

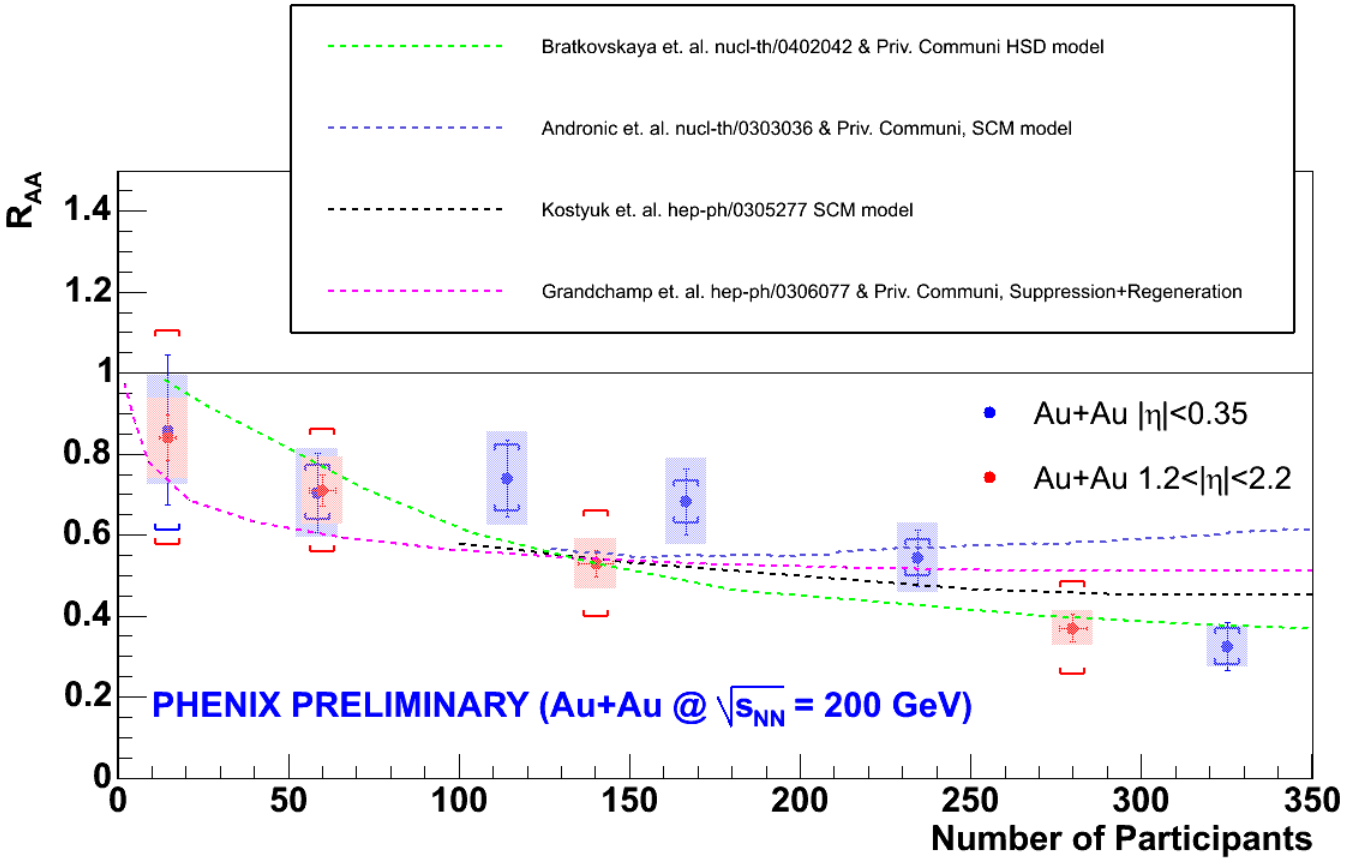
Suppression Models

- Color screening, direct dissociation, co-mover scattering



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

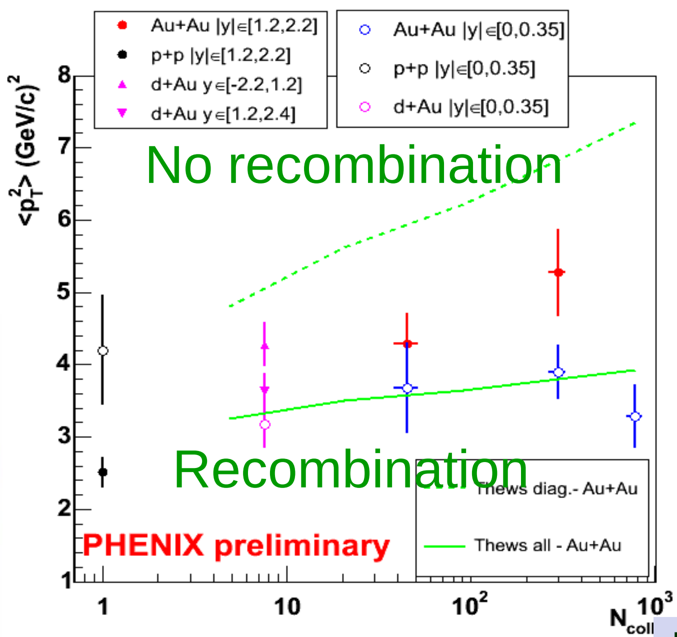
Suppression + Recombination Models

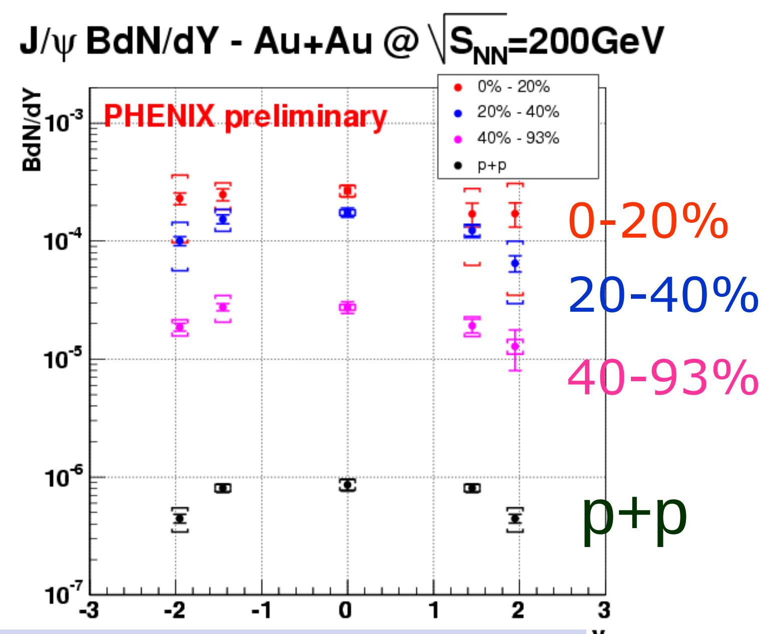


Better matching with results compared to suppression models. At RHIC (energy): Recombination compensates stronger suppression?

$<p_T^2>$ 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.

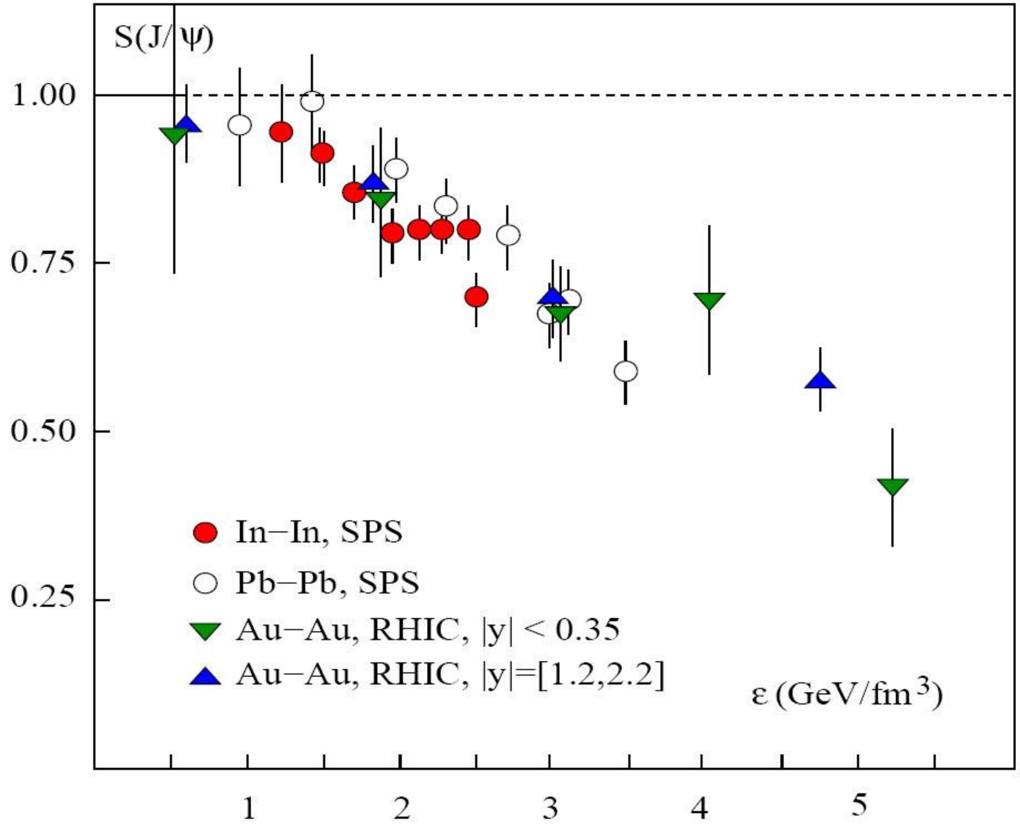




Ref) H. Pereira da Costa (PHENIX), Quark Matter 2005

J/ψ Suppression vs Energy Density

- From theory, J/ψ survive up to $\varepsilon \sim 10$ GeV/fm^3
- Suppression of the 40% coming from χ_c 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

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

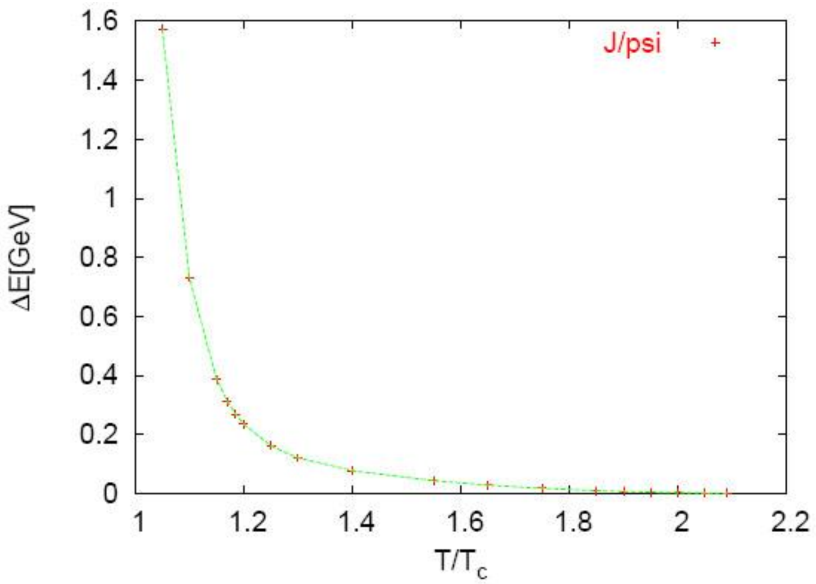
- Quarkonium spectroscopy from non-relativistic potential theory $V(r) = \sigma\, r - \frac{\alpha}{r}$

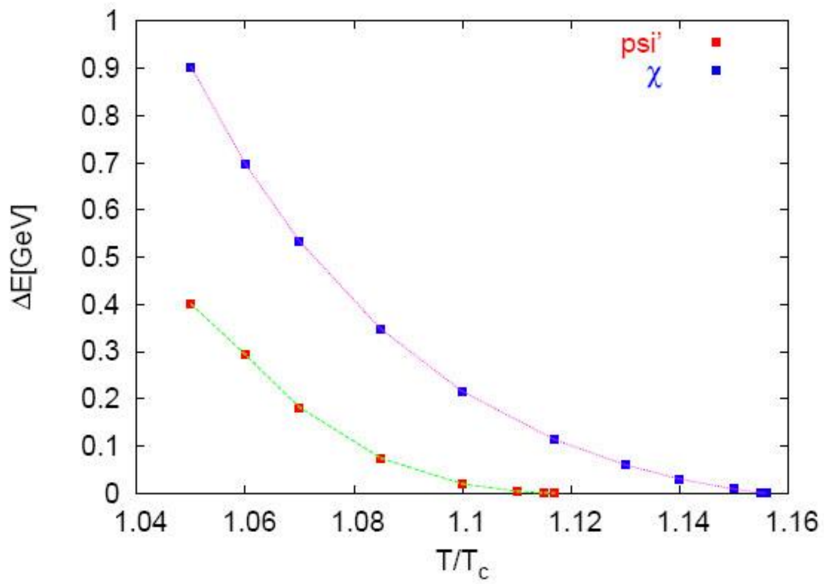
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

•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

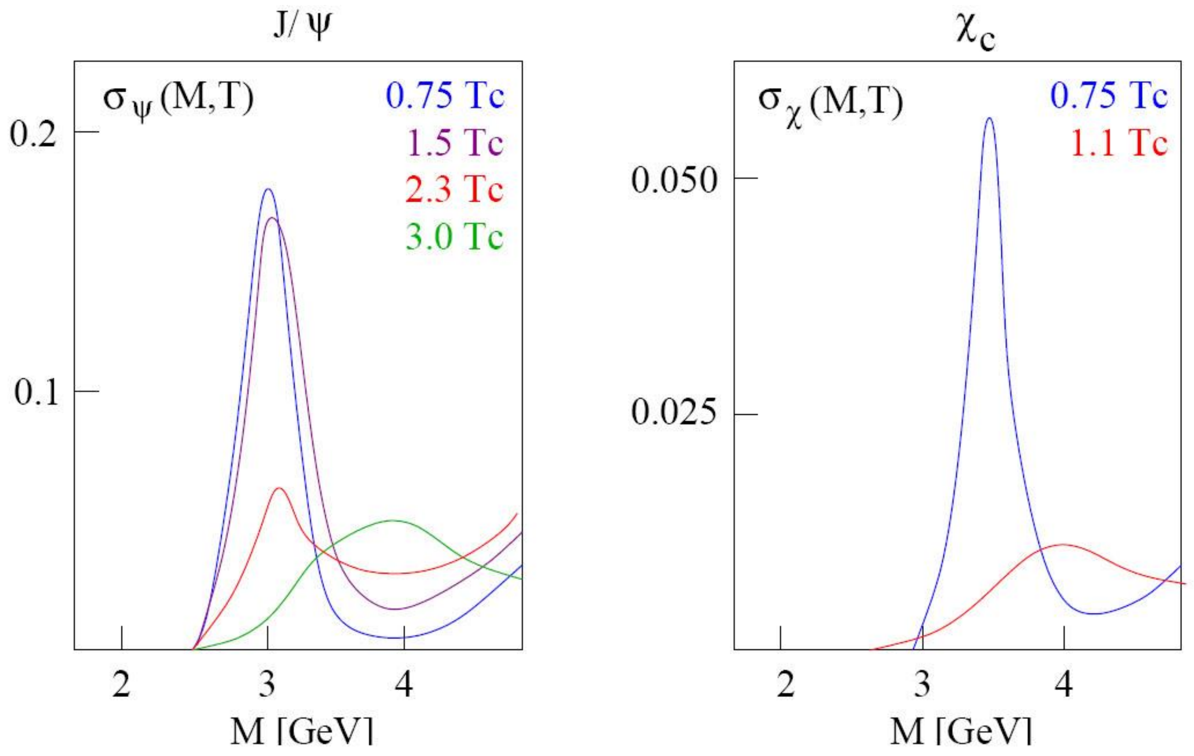




J/ψ and χ_c spectral functions at different temperature (direct from lattice QCD calculation)

- 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



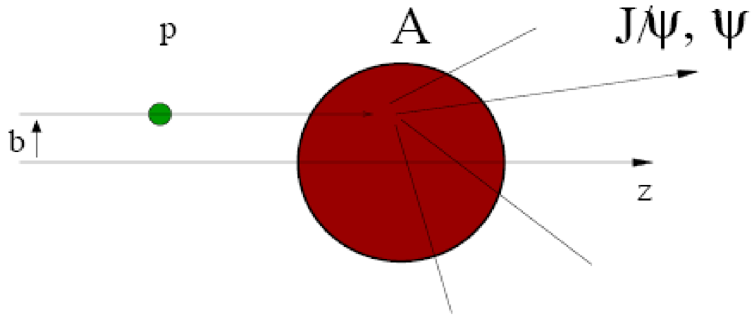
Recent Lattice QCD results indicate J/ψ spectral function may persist up to 3 T_c.

Temperature Bound < 3 T_c (?)

Baseline Measurements

- p+p : study of direct production mechanism
  - Color evaporation model, color singlet model, color octet model
  - Differential and total cross sections and its transverse momentum, rapidity and sqrt(1/2) dependence
  - Baseline for p+A, d+Au and A+A
- p+A / d+Au : study of normal nucleus effect

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

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

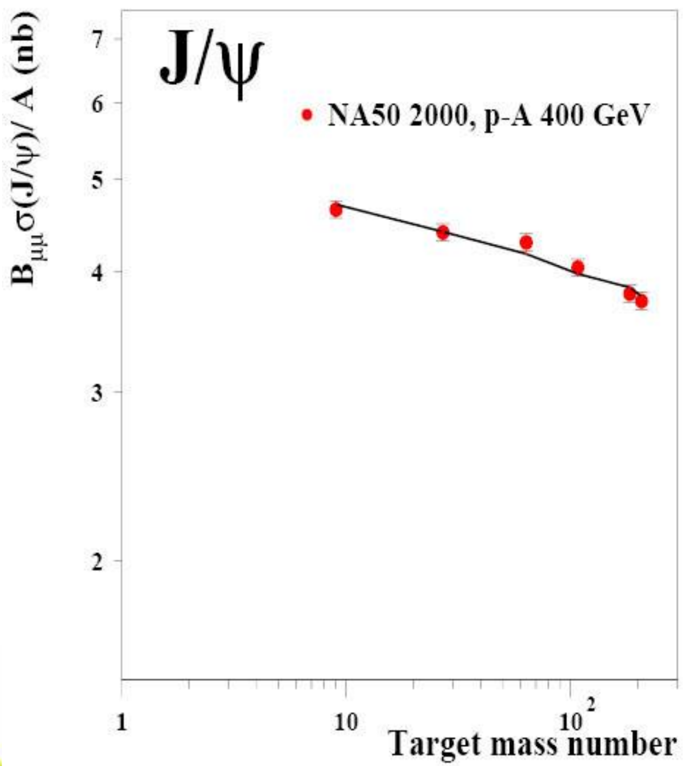
$T_A(\vec{b})$: **Nuclear thickness function**

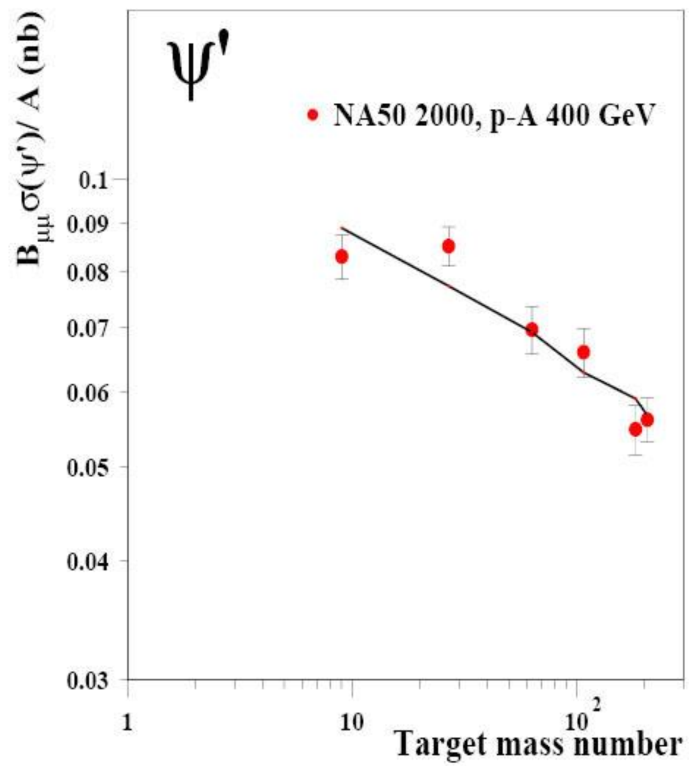
- Charmonia experimental cross-sections can be fitted using this Glauber model with 2 free parameters : $\sigma_0,\ \sigma_{\mathrm{abs}}$

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.





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

How do we get J/ψ Yield?

Invariant yield :

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

$N_{J/\psi}$: 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

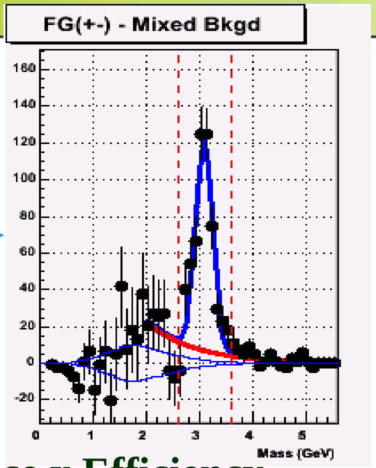
$\varepsilon_{BBC}^{J/\psi}$: BBC trigger efficiency for events with a J/ψ

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

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

Analysis Procedure

Extract signal with event mixing method

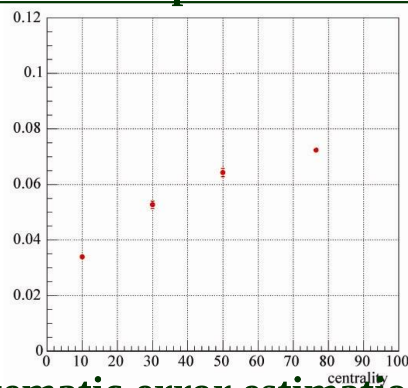


1. **Get momentum of tracks**
   - ➢ Muon tracker
2. **Identify muons**
   - ➢ Depth in Muon Identifier (MUID)

   } Track reconstruction
3. **Get di-muon invariant mass spectra**
4. **Extract J/ψ signal**
   - ➢ Event mixing technique
5. **Correct for acceptance and efficiencies**
   - ➢ Realistic detector simulation
6. **Calculate corresponding luminosity**
   - ➢ run4AuAu Level-2 filtered at *CCF* (78%) - 170 mb^{-1}
7. **Estimate systematic errors**

→ **Cross section**

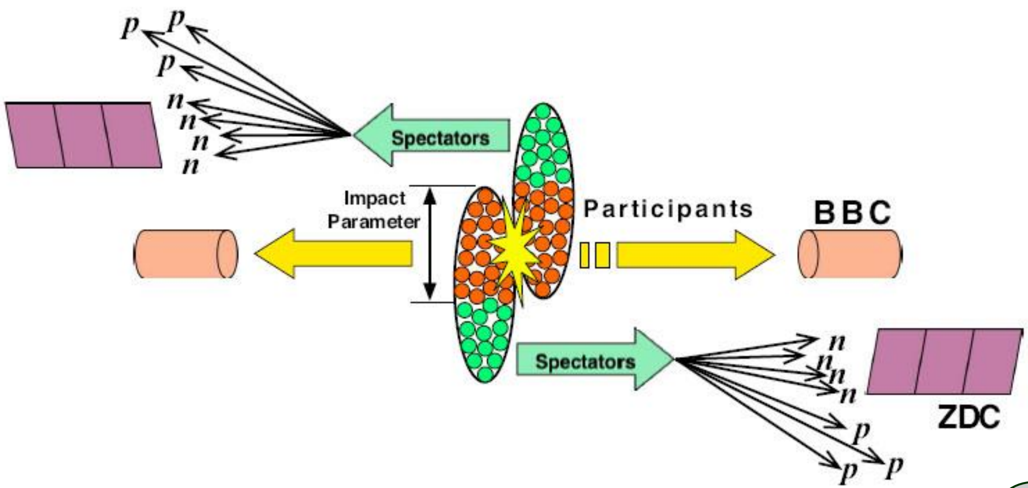
Calculate Acceptance x Efficiency



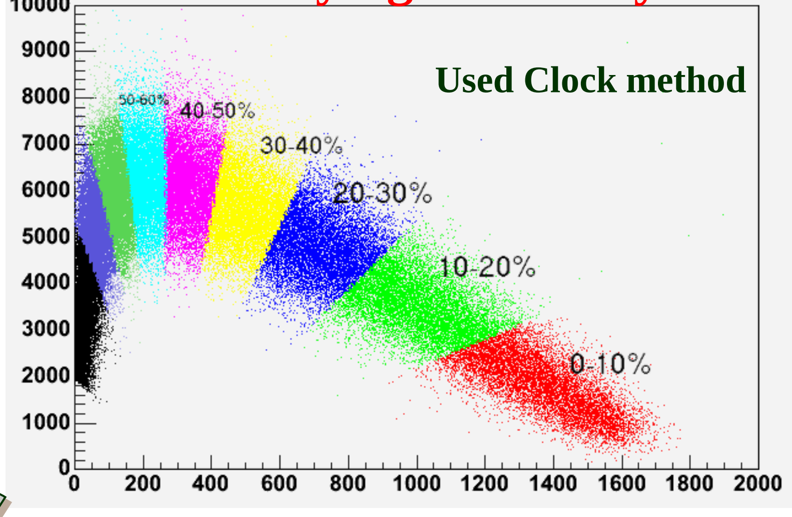
Systematic error estimation

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

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

Estimating Combinatorial Background and Signal counting :

Event Mixing Method – used for AuAu analysis

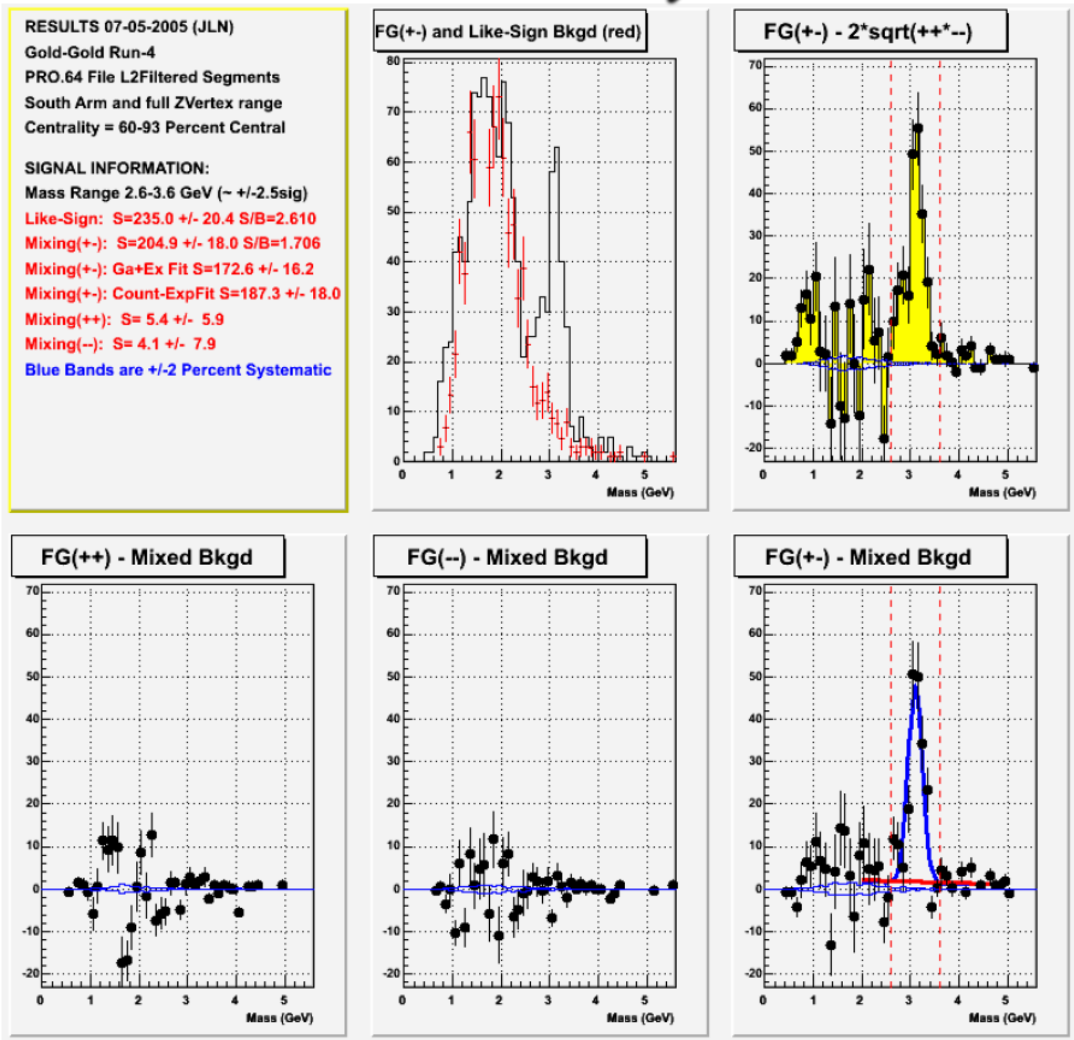
- Artificial events constructed from data by mixing particles (tracks) from different events to eliminate possible correlations.

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

Example plots)

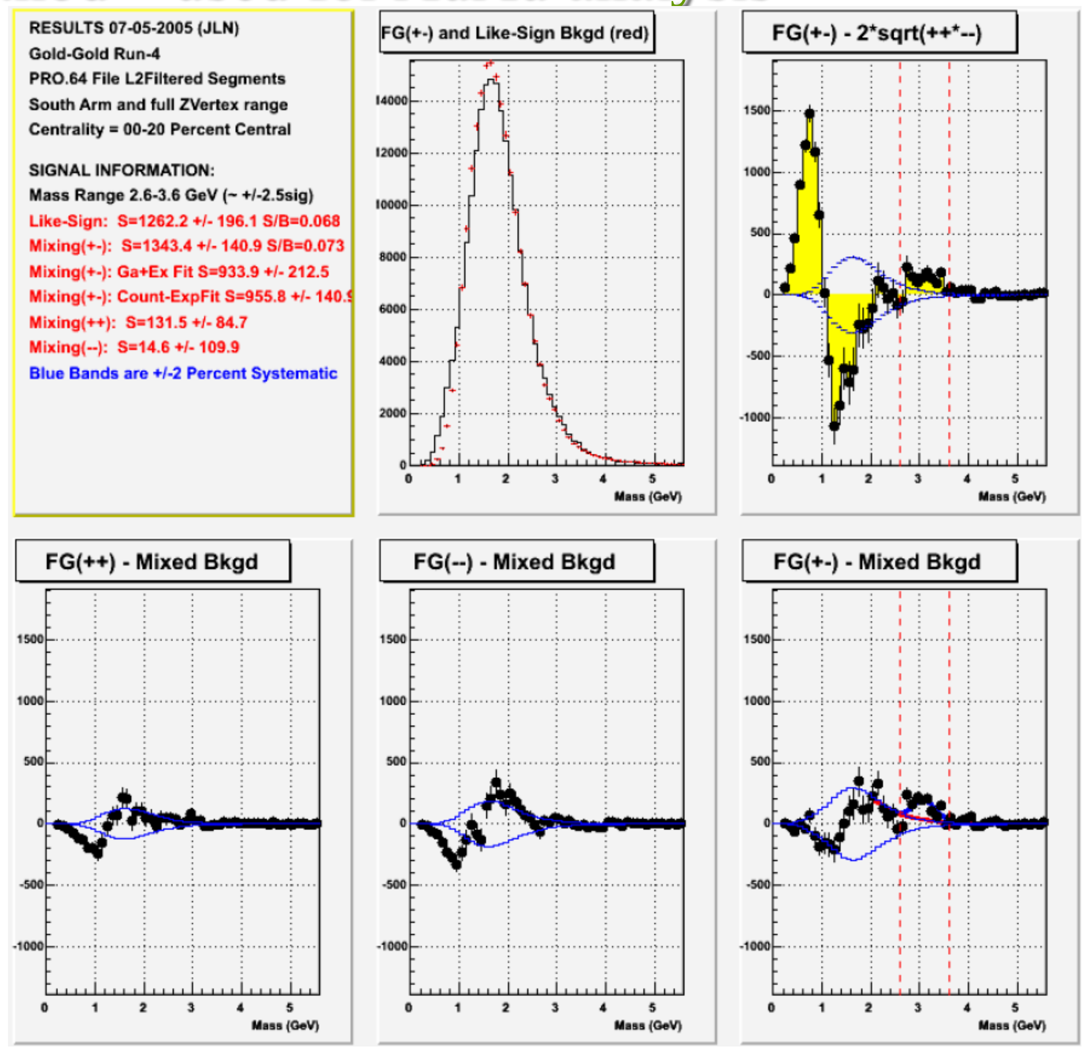
South Arm : Centrality 60-93%, All Pt , All Rapidity

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



Estimating Combinatorial Background and Signal counting :

Event Mixing Method – used for AuAu analysis

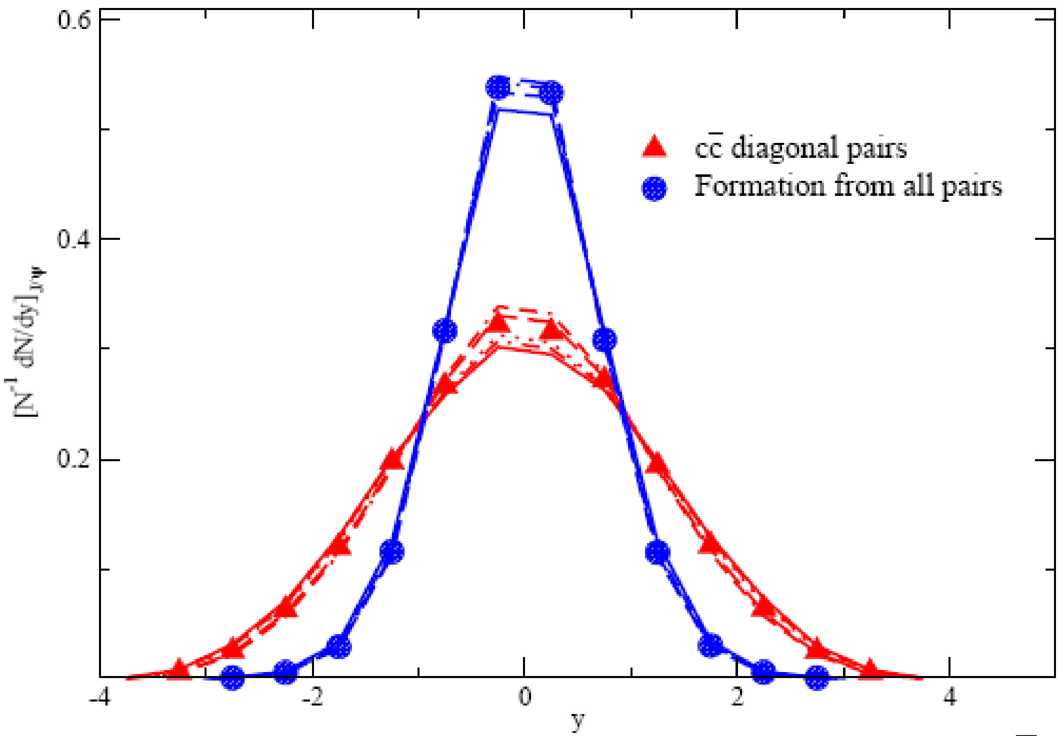


Another Example plots)

South Arm : Centrality 0-20%, All Pt , All Rapidity

Singal = 1343 +/- 140(stat) +/- 387(sys)

Common Feature : Rapidity Narrowing



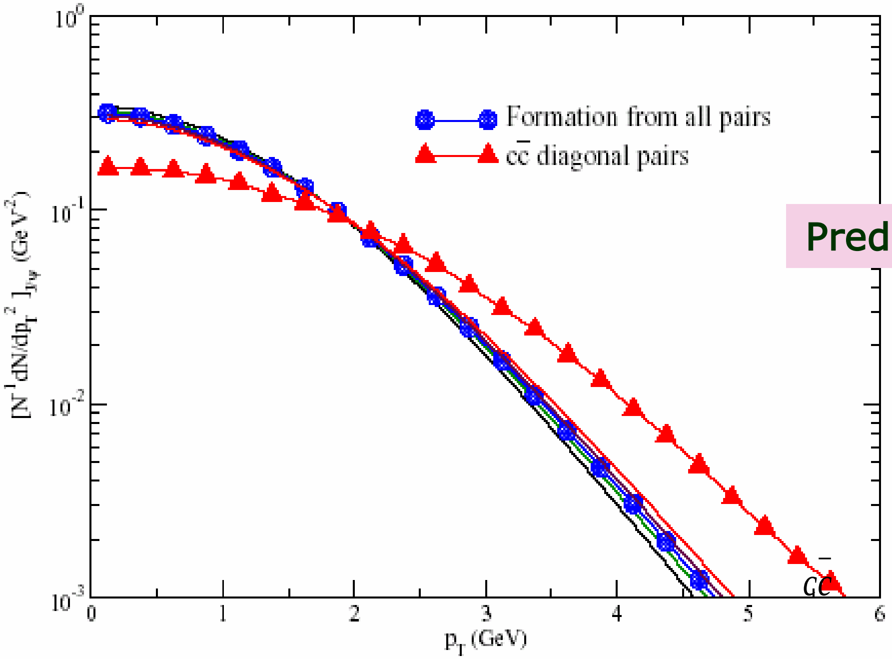
- Triangles are for initial production via diagonal $c\bar{c}$ pairs.
- Circles are for in-medium formation via all pairs.

- Recombination model assuming all $c\bar{c}$ pairs' recombination predict narrower rapidity distribution with the centrality

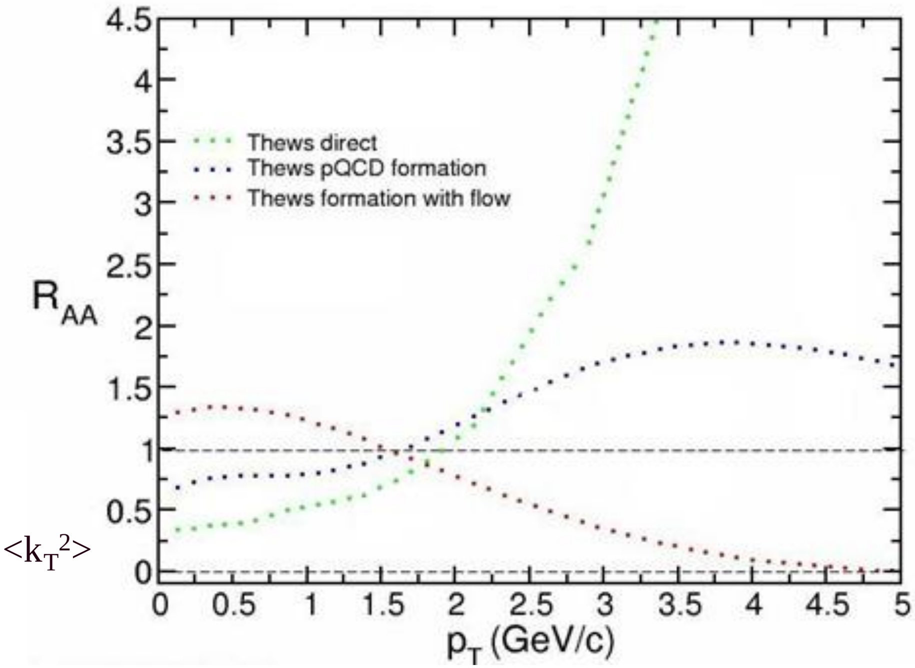
Model Prediction for Transverse Momentum

Thews : (nucl-th/0505055)

Predicted p_T spectra of J/Ψ in Au-Au interaction at 200GeV from pQCD.



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



- 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.