Probing Hot Nuclear Matter with Quarkonium

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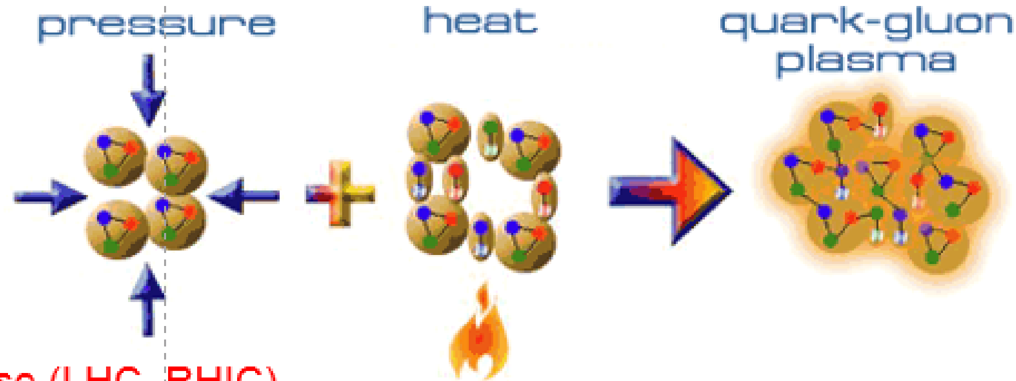
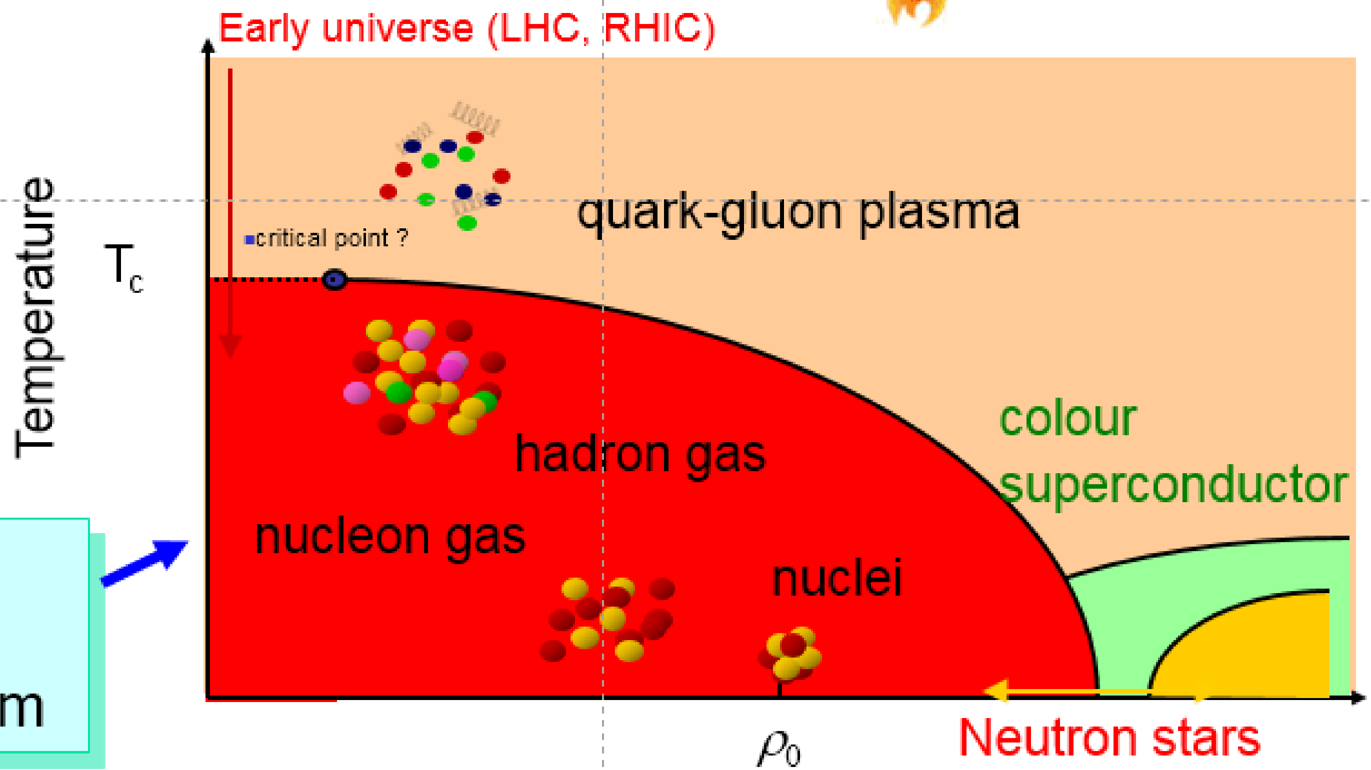
Slide borrowed from Pengfei Zhuang, Seminar at ICTS@USTC

温度密度效应
—> 波函数重叠
—> 最深层次物质形态
夸克胶子等离子体，QGP





QCD Phase Diagram

Probing hot matter with quarkonium

Physics Letters B

Volume 178, Issue 4, 9 October 1986, Pages 416–422

J/ψ suppression by quark-gluon plasma formation

1986

T. Matsui

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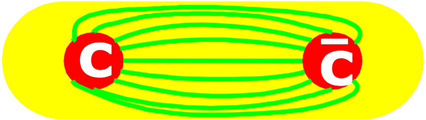
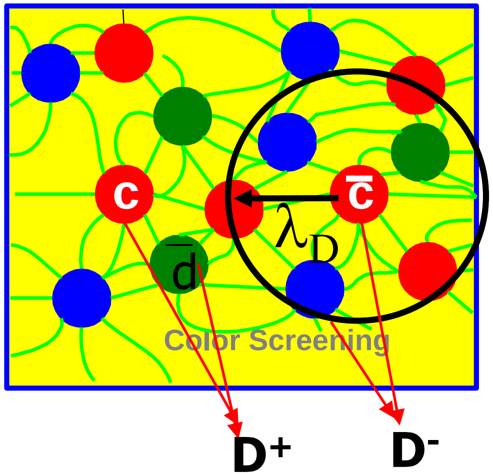
http://dx.doi.org/10.1016/0370-2693(86)91404-8, How to Cite or Link Using DOI

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents cc binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmomium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.



$$V(r) = -\frac{\alpha}{r} + kr$$



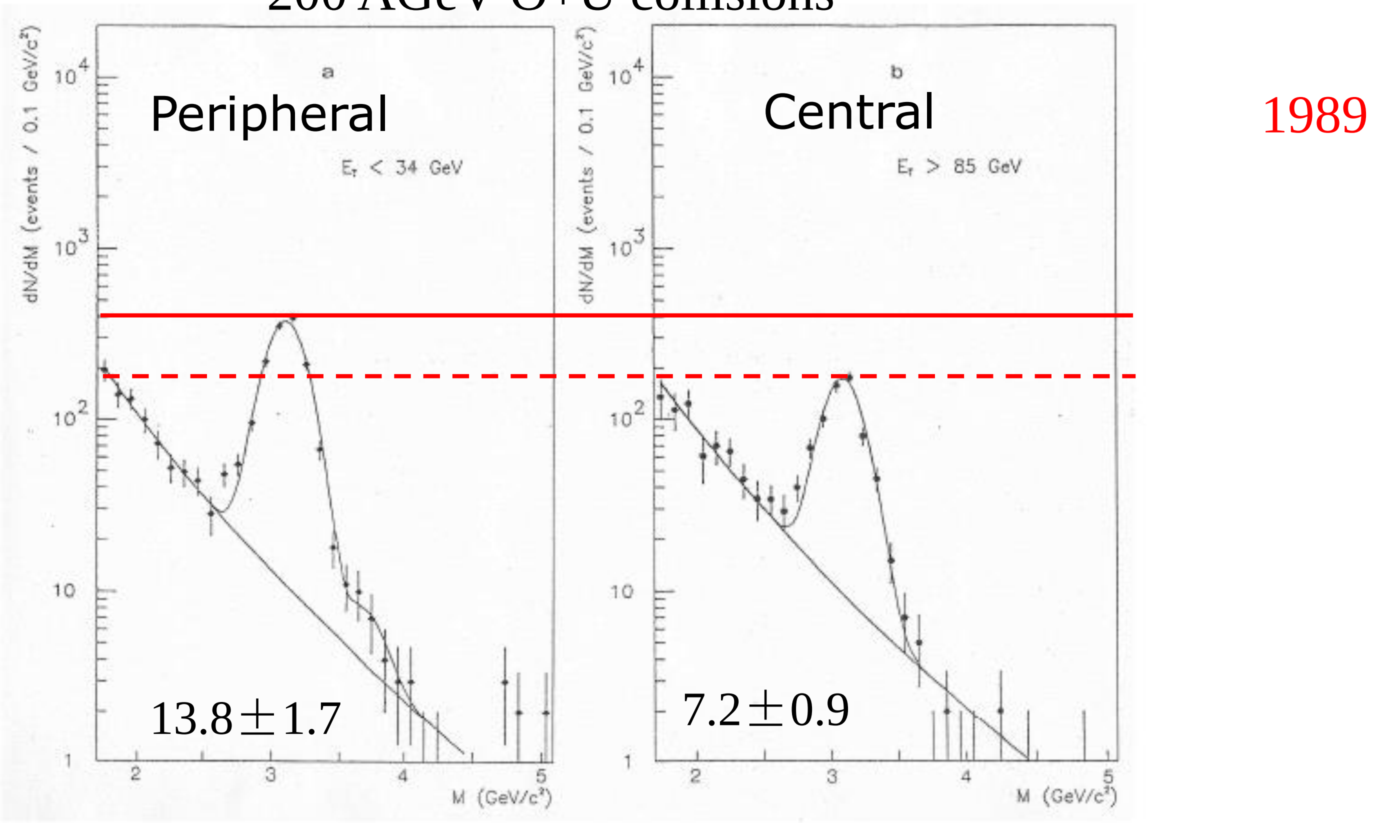
$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

$$\lambda_D \propto 1/T$$

It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation

J/ψ suppression observed in HIC

200 AGeV O+U collisions



NA38, PLB220, 471 (1989)

Figure 1: First observation of the J/ψ suppression effect in O(200 AGeV)-U collisions in the NA38 experiment at CERN-SPS. When comparing the invariant-mass spectrum of muon pairs produced in peripheral collisions (characterized by a small transverse energy $E_T < 34$ GeV; left panel) with that in central collisions (at high transverse energy, $E_T > 85$ GeV; right panel), a reduction of the J/ψ signal over the Drell-Yan continuum is apparent (from [8]).

Nuclear absorption

Inelastic J/ψ scattering (dissociation) on primordial target and projectile nucleons

→ Suppression of J/ψ before the formation of QGP

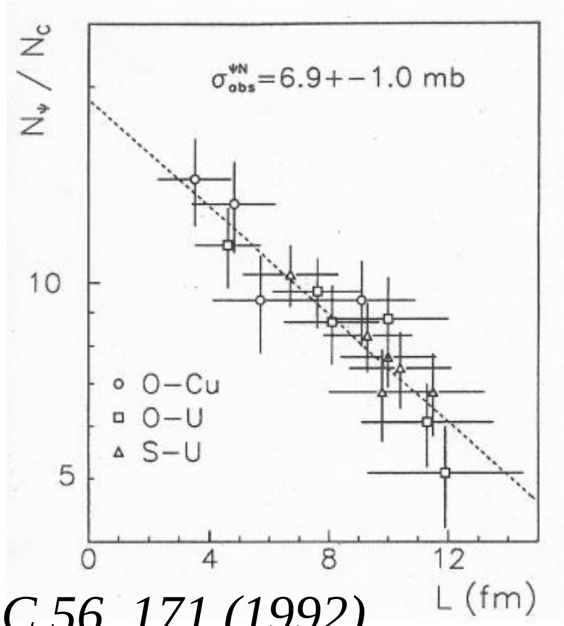
→ Nothing to do with QGP

→ Cold nuclear matter (CNM) effect

C. Gerschel and J. Hufner, PLB 207, 253 (1988)

$$S_{AB}^{abs} = \exp[-\rho_0 \sigma_{abs} L(A,B)],$$

$$\frac{\sigma_{J/\psi}^{AB}}{\sigma_{J/\psi}^{NN}} = AB \times S_{AB}^{abs},$$



Observed J/ψ suppression well described by nuclear absorption only

C. Gerschel and J. Hufner, ZPC 56, 171 (1992)

Anomalous J/ψ suppression

Anomalous J/Psi suppression in Pb-Pb interactions at 158 GeV/c per nucleon
Physics Letters B410 (1997) 337 PS file

J/Psi and Drell-Yan cross-sections in Pb-Pb interactions at 158 GeV/c per nucleon
Physics Letters B410 (1997) 327 PS file

The NA50 segmented target and vertex recognition system
Nuclear Instruments and Methods in Physics Research A398 (1997) 180 PS file

The NA50 proposal
CERN/SPSLC 91-55, SPSLC/P 265-Rev, November 1991 PS file-without figures

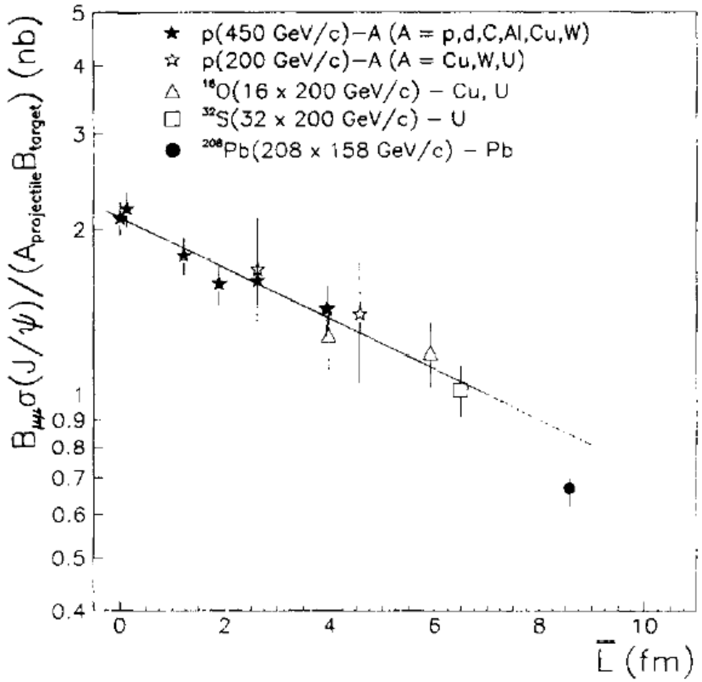


Fig. 3. The J/ψ "cross-sections per nucleon-nucleon collision" as a function of $\bar{L}$. The results obtained at 450 GeV/c and the Pb-Pb cross-section are rescaled as explained in the text.

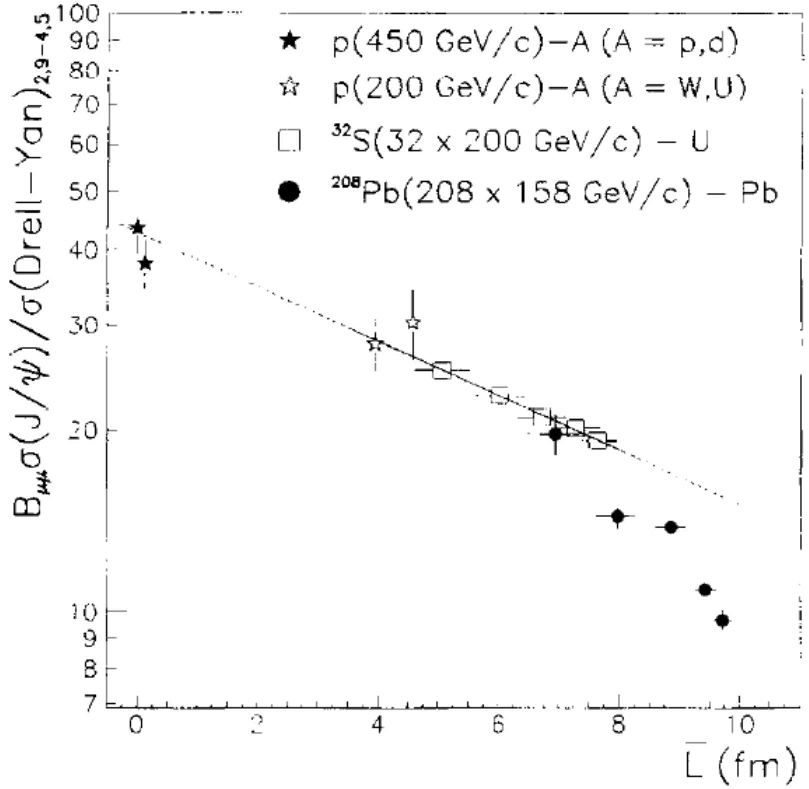
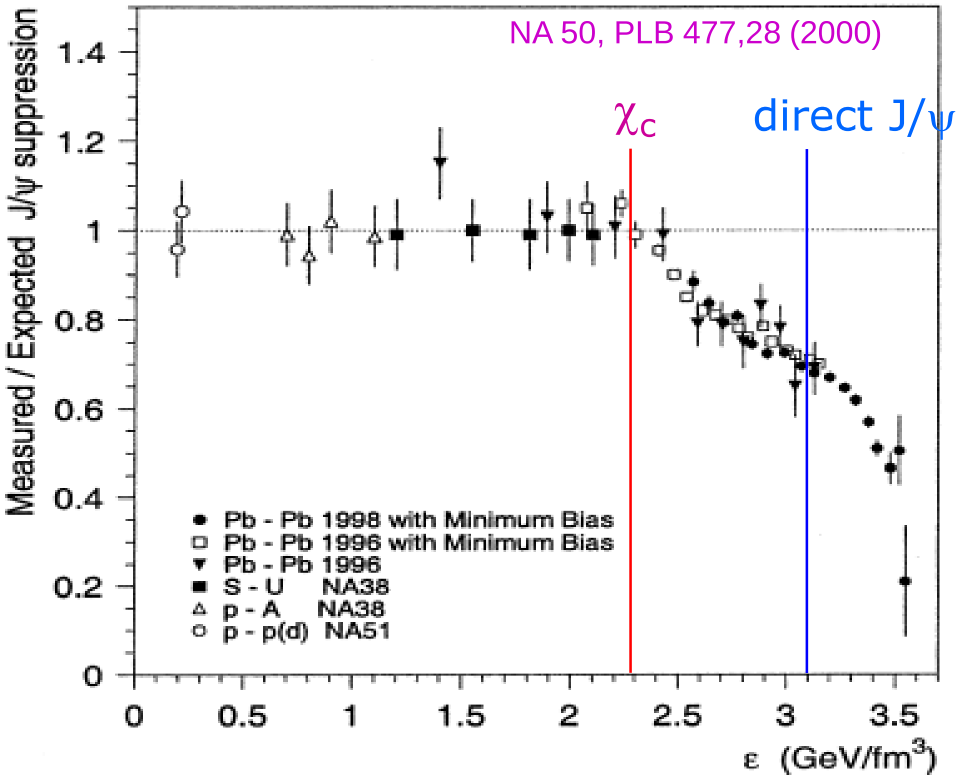


Fig. 5. The ratio of J/ψ to Drell-Yan cross-sections as a function of $\bar{L}$.

Evidence of deconfinement?

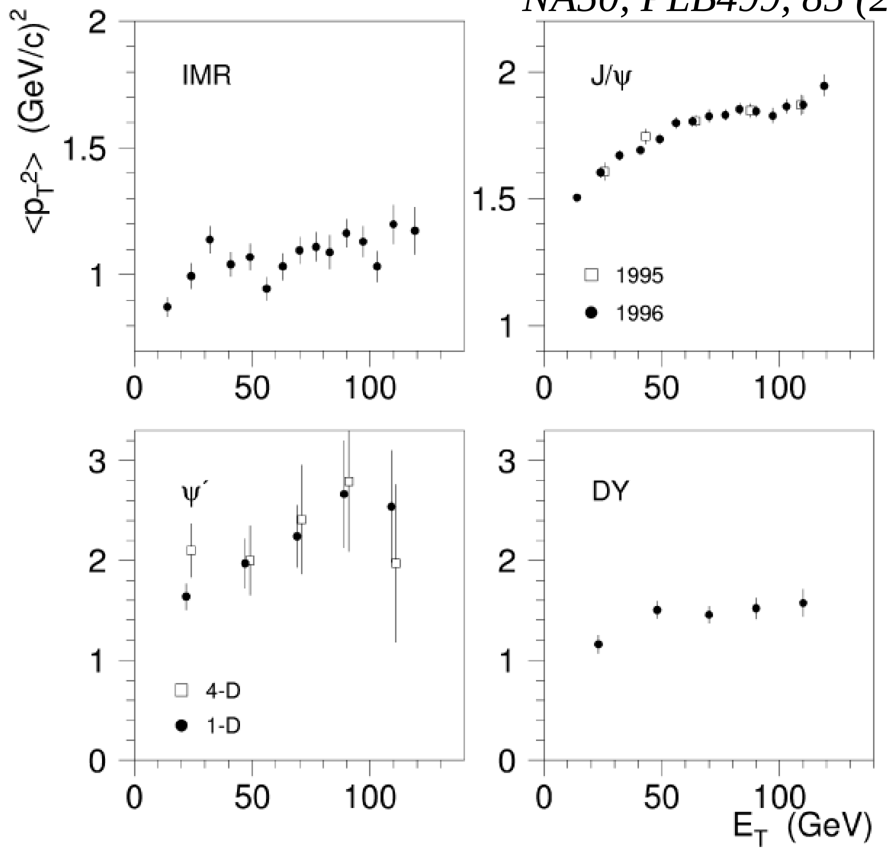


On the contrary, the behaviour seen in our data follows the stepwise pattern expected in case the matter produced in the Pb-Pb collisions undergoes a phase transition into a deconfined state of quarks and gluons. Therefore, we must conclude that the J/ψ suppression pattern observed in our data provides significant evidence for deconfinement of quarks and gluons in the Pb-Pb collisions probed by NA50.

p_T dependence

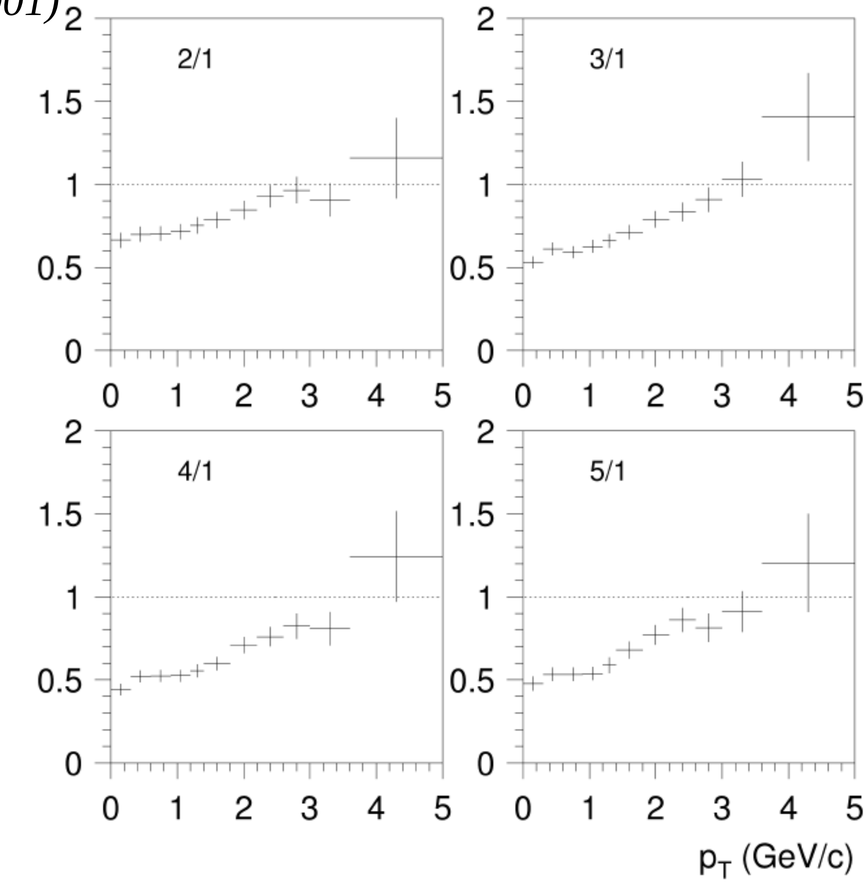
$<p_T^2>$ vs. centrality

NA50, PLB499, 85 (2001)



Increase and then fatter

J/ψ suppression vs. p_T



Less suppression at higher p_T

Theoretical calculations

Transverse momentum dependence of anomalous J/ψ suppression in Pb–Pb collisions 2001

Jörg Hüfner [a], Pengfei Zhuang [b]

PHYSICS LETTERS B

Time structure of anomalous J/ψ and ψ' suppression in nuclear collisions 2003

www.elsevier.com/locate/npe

Jörg Hüfner [a], Pengfei Zhuang [b]

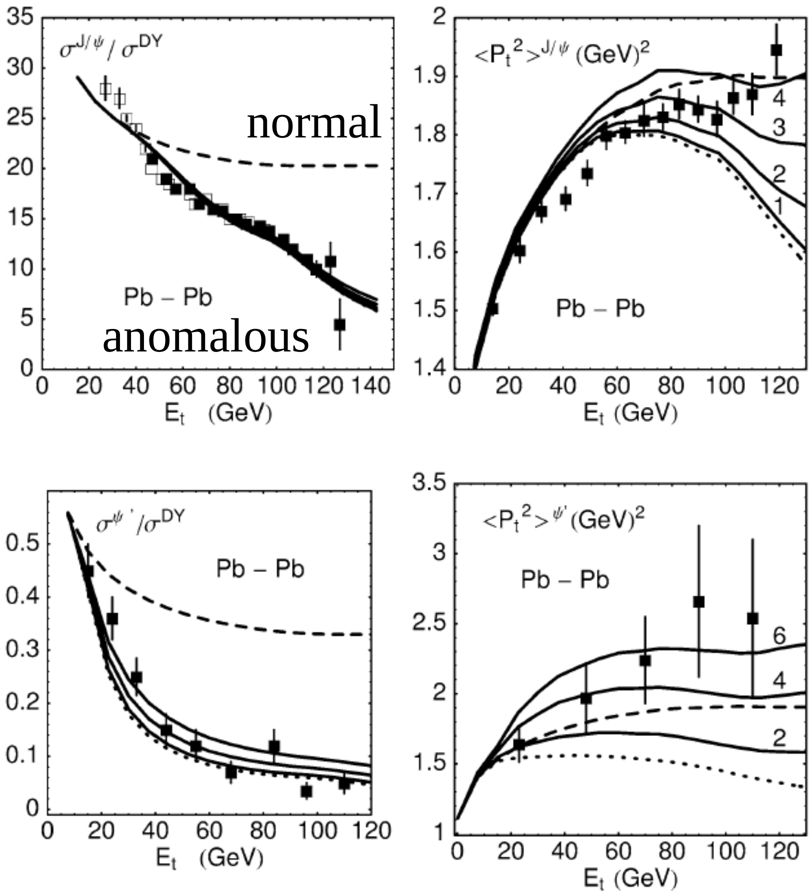
PHYSICAL REVIEW C 67, 067901 (2003)

Leakage effect on J/ψ p_t distributions in different centrality bins for Pb-Pb collisions at $E/A = 160$ GeV 2003

Pengfei Zhuang and Xianglei Zhu
Physics Department, Tsinghua University, Beijing 100084, China
(Received 13 March 2003; published 3 June 2003)

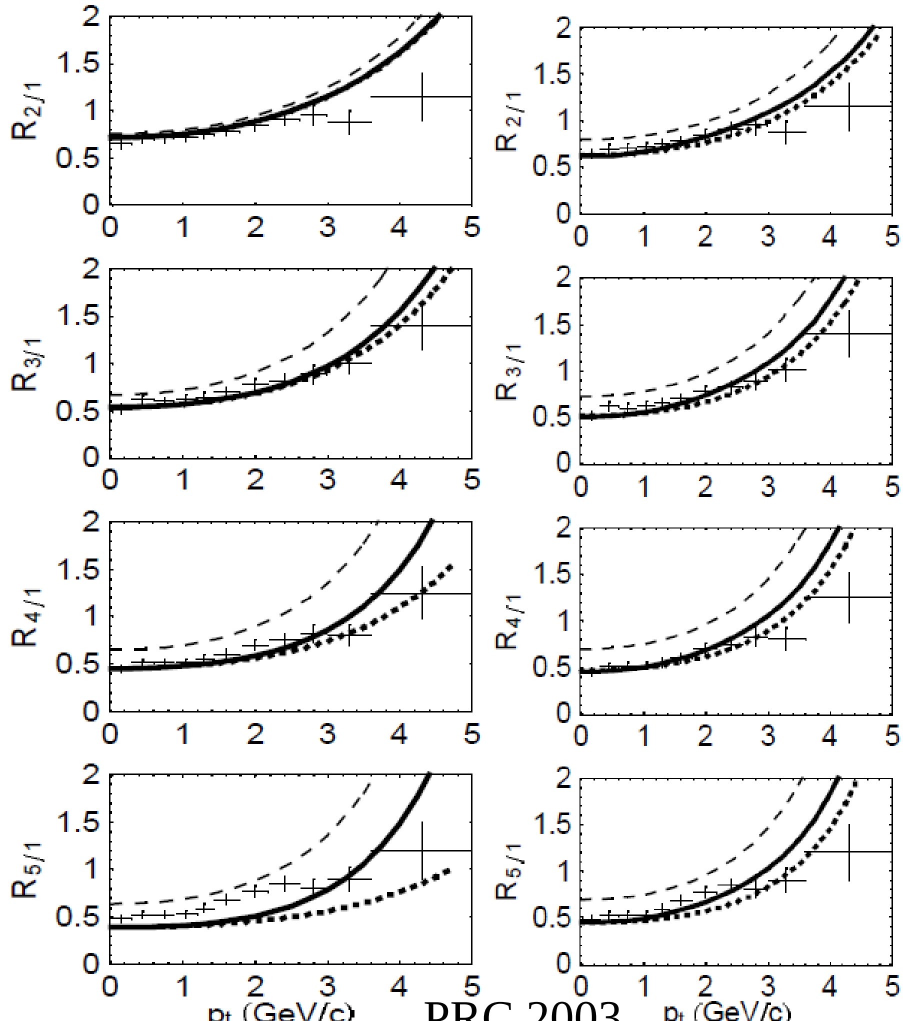
Describes data well

Threshold model with time structure



PLB 2003

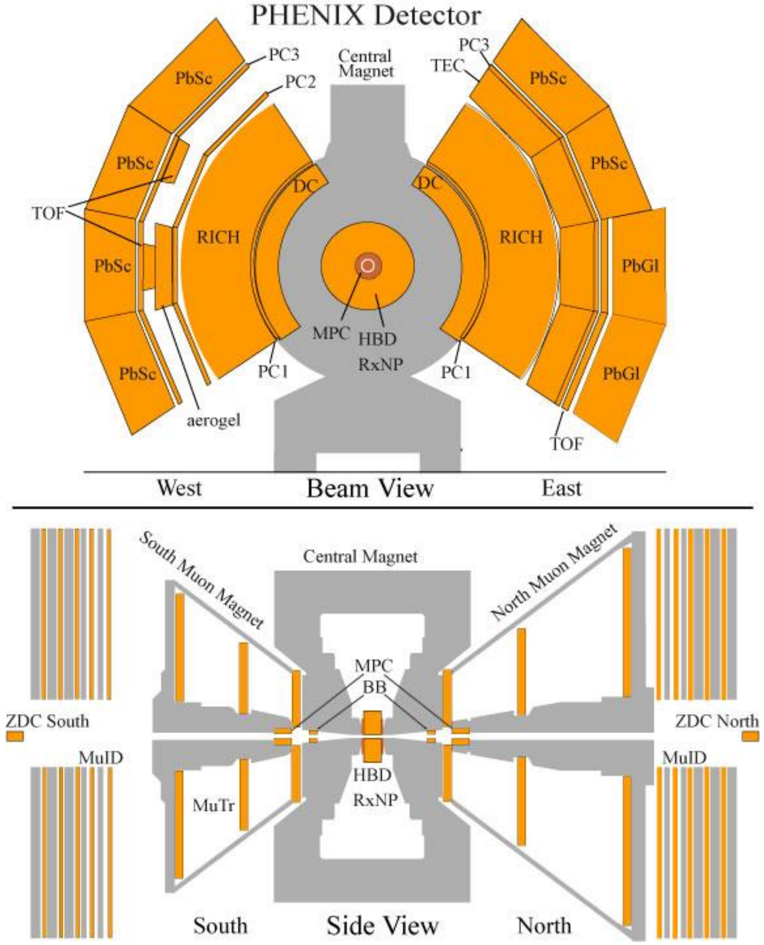
Threshold model Comover model



PRC 2003

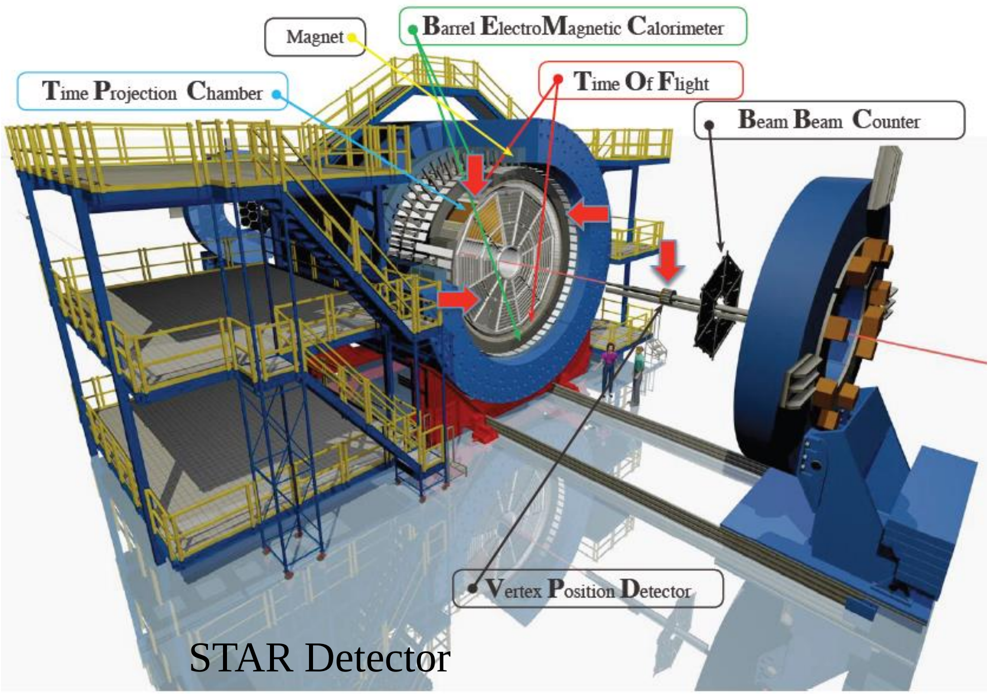
RHIC Experiments

Mid-rapidity: e^+e^-, $|\eta|<0.35$, $\Delta\phi=2 \times \pi/2$



Forward rapidity: $\mu^+\mu^-$, $1.2<|\eta|<2.2$, $\Delta\phi=2\pi$

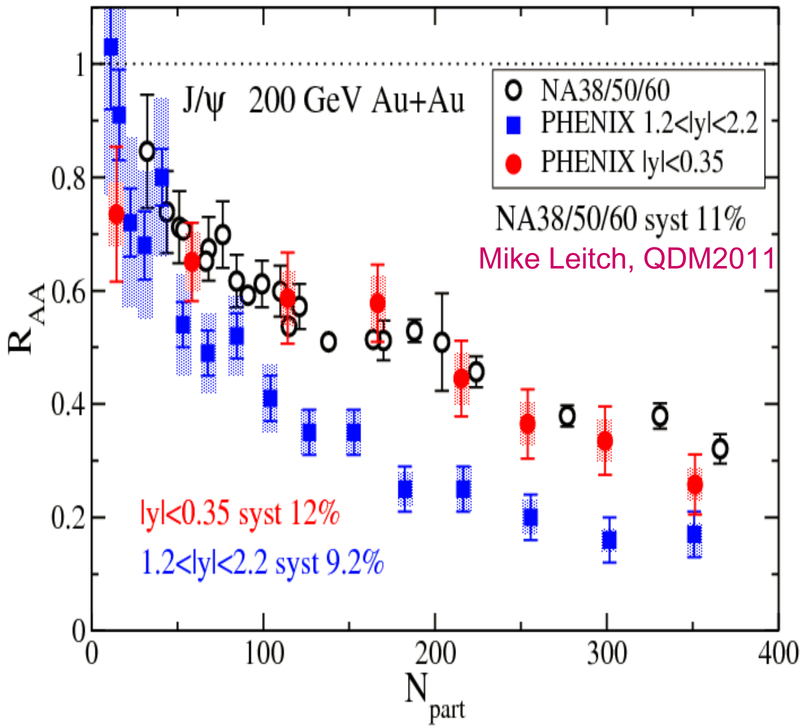
Mid-rapidity: e^+e^-, $|\eta|<1$, $\Delta\phi=2\pi$ full coverage

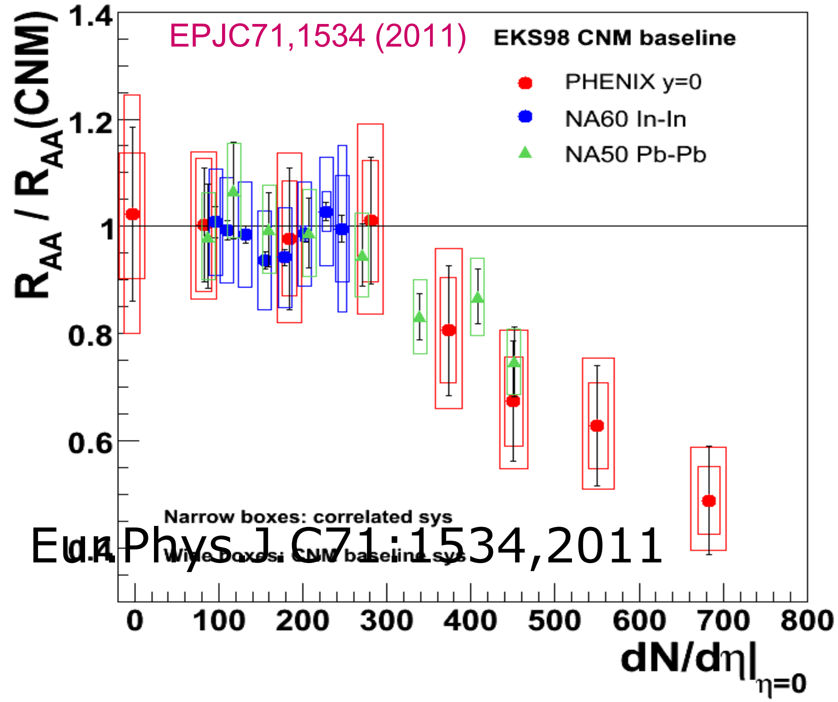


Time-Of-Flight (TOF):
China-US detector (MRPC)
Fully installed since 2009-2010

Muon Telescope Detector (MTD):
China-US detector (LMRPC)
Fully installed since 2013-2014

J/ψ suppression at RHIC





Similar anomalous suppression

Mid-rapidity:

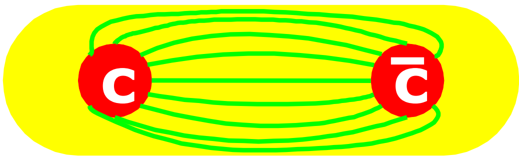
Similar suppression as SPS

Forward rapidity:

More suppression than in mid-rapidity

Two Puzzles!!

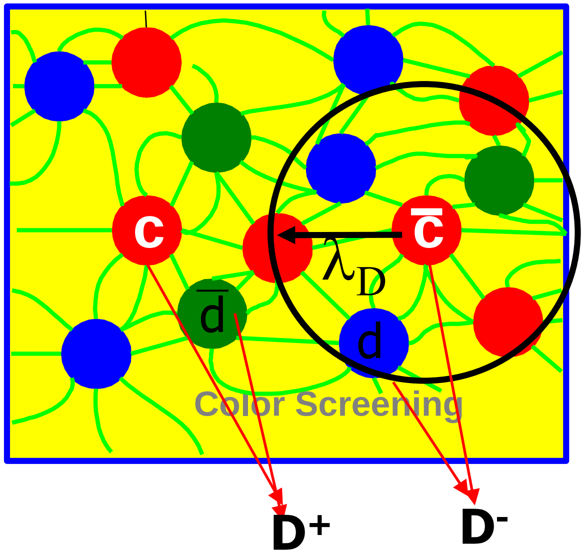
Color screening vs. (Re)generation



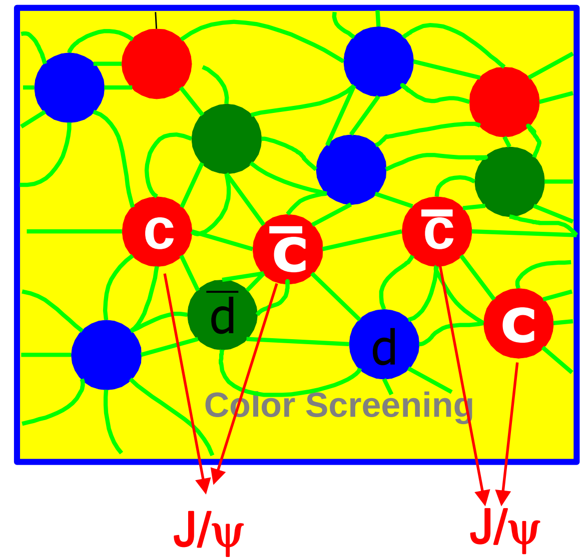
$$V(r) = -\frac{\alpha}{r} + kr$$

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

$\lambda_D \propto 1/T$



Quarkonium melting in QGP



Quarkonium (re)generation in QGP

Braun-Munzinger & Stachel, Thews et al., Rapp et al, Zhuang et al., …

Transport approach

Xianglei Zhu, Li Yan, Yungpeng Liu, Zhen Qu, Kai Zhou, Baoyi Chen, Zhengyu Chen, Nu Xu and ***Pengfei Zhuang***

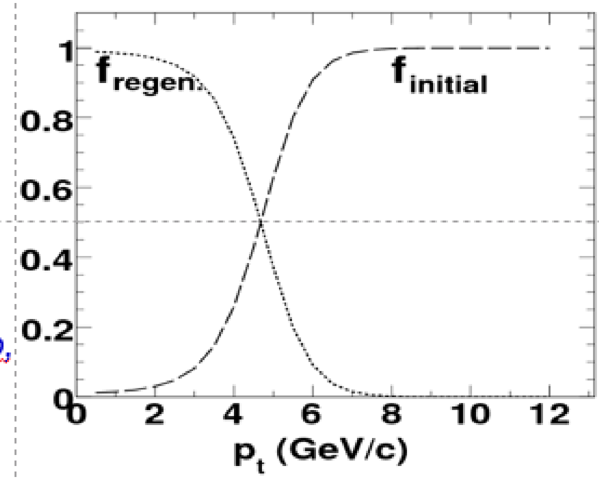
Review talk
given by Prof. Zhuang
on Quark Matter 2015

$$f(p) = f_{ini}(p) + f_{reg}(p)$$

initially production:
1)Cronin effect in the initial stage,
2)strong low p_t suppression and high p_t leakage effect
⇒ initial p_t broadening

regeneration:
1) coalescence mechanism
2) energy loss induced thermalization
⇒ low p_t regeneration

5.5TeV central Pb+Pb,
Liu et al., 2009



while $f(p)$ is nPDF dependent, the averaged transverse momentum

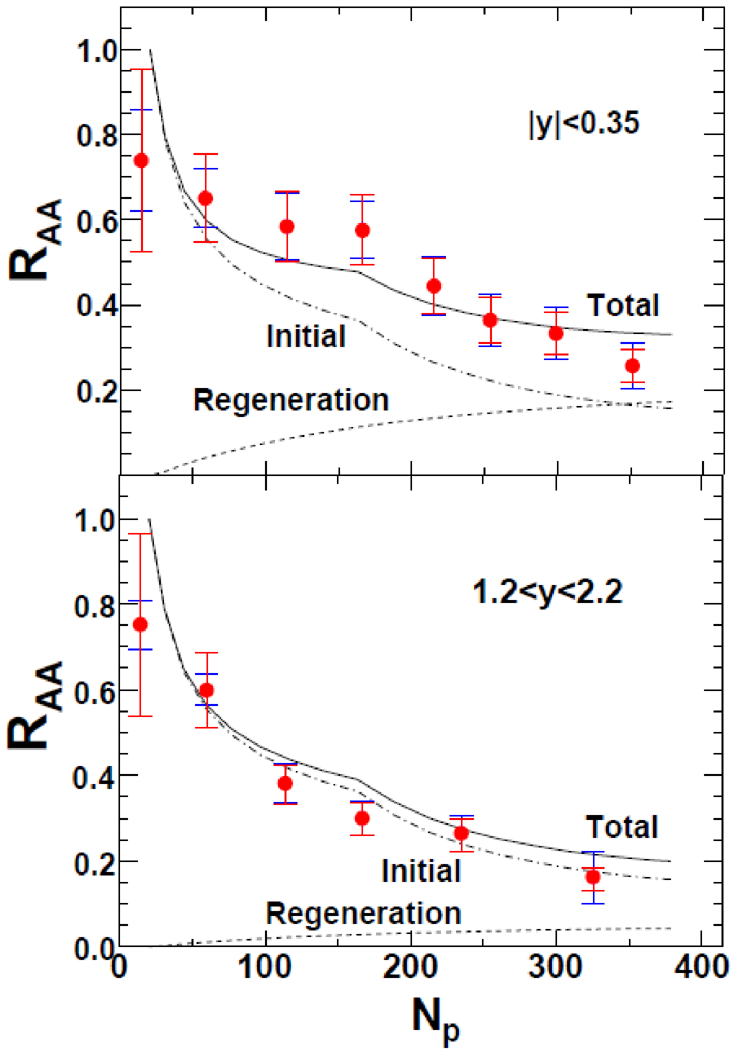
$$\langle p_t^2 \rangle = \frac{\int p_t^2 f(p_t) dp_t}{\int f(p_t) dp_t}$$

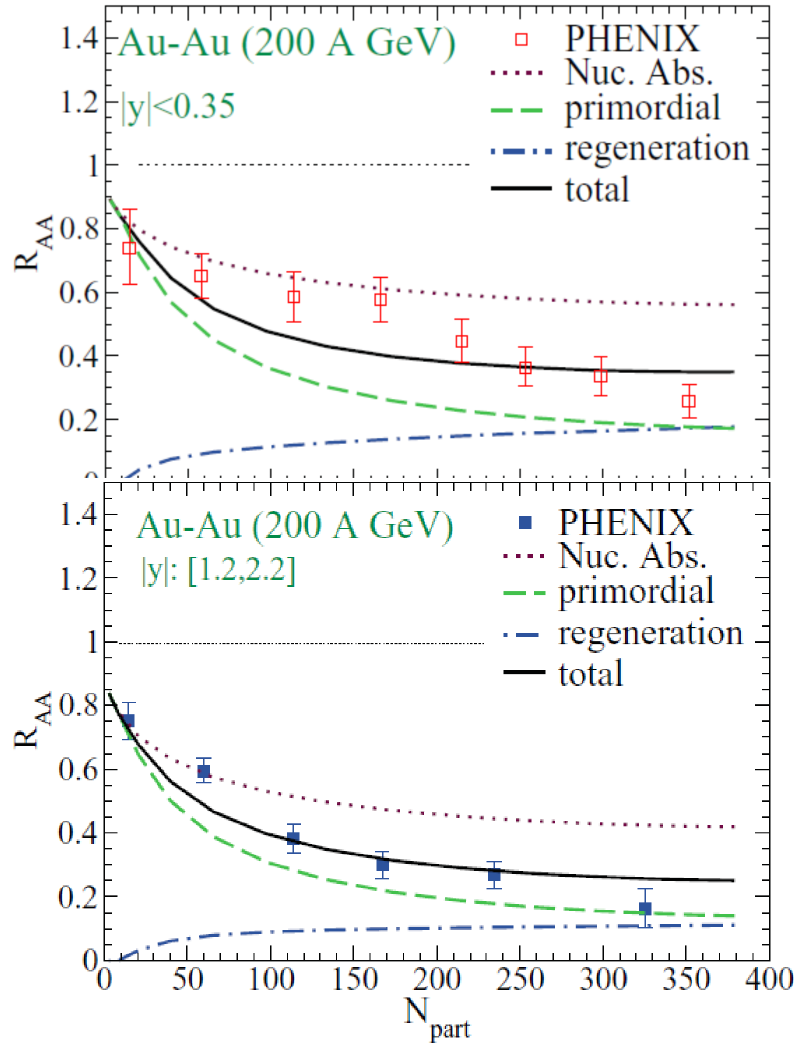
Is not sensitive to the nPDF and controlled by the hot effects.

Pengfei Zhuang (Tsinghua) 13 *QM2015 Kobe, October 2*

Comparison with data

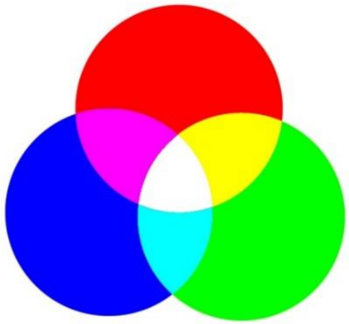
Z. Qu, Y. Liu, N. Xu, P. Zhuang, NPA830, 335c (2009)   X. Zhao, R. Rapp, PRC82, 064905 (2010)



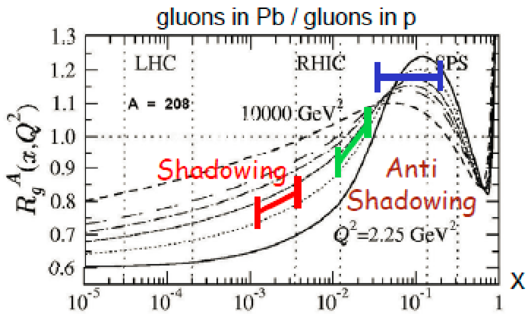


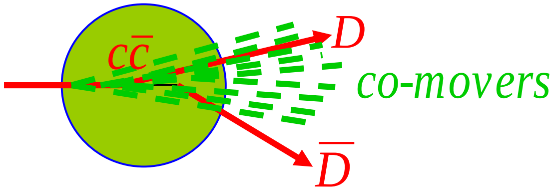
Quarkonium in heavy-ion collisions

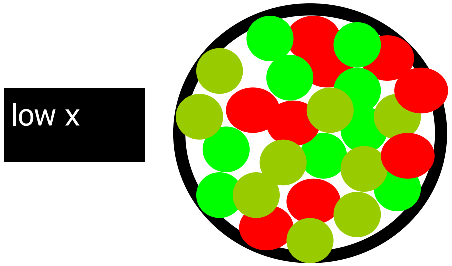
- Hot nuclear matter effects (QGP effects)
  - Suppression due to color-screening
  - Enhancement due to (re)generation

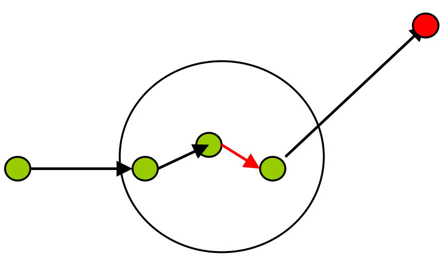


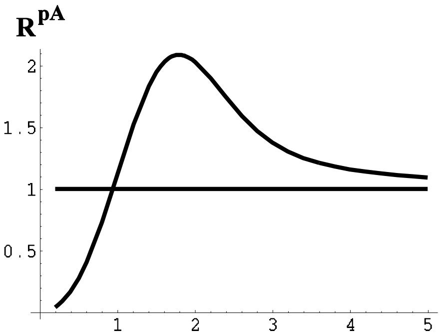
- Cold nuclear matter effects (CNM effects)
  - Gluon (anti-)shadowing
  - Absorption
  - Gluon saturation
  - Cronin effect
  - …



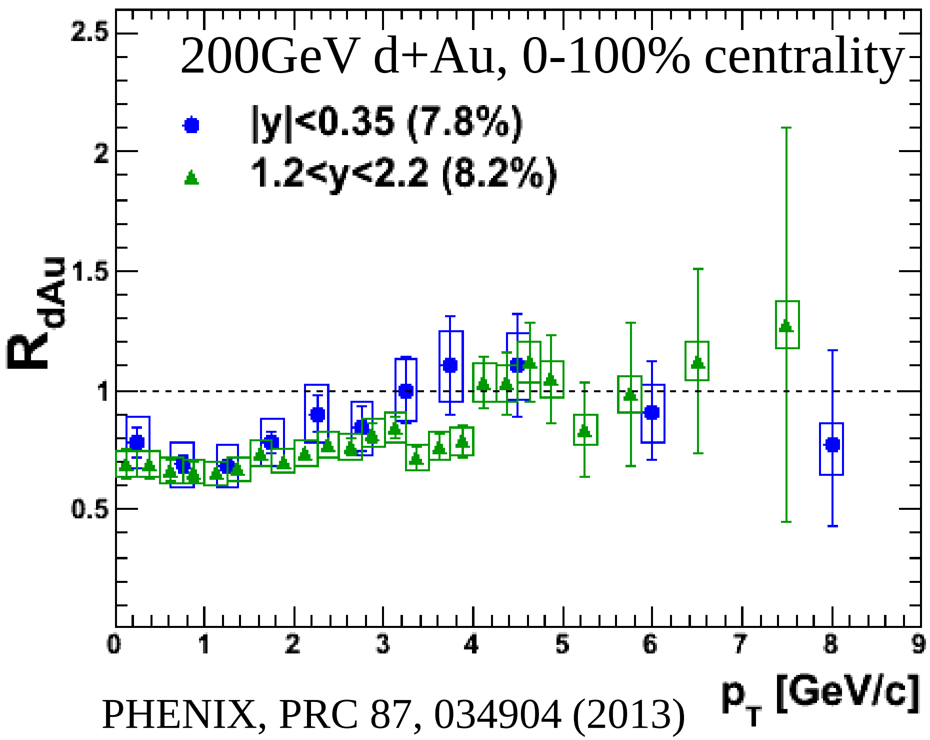








Go to high-p_T

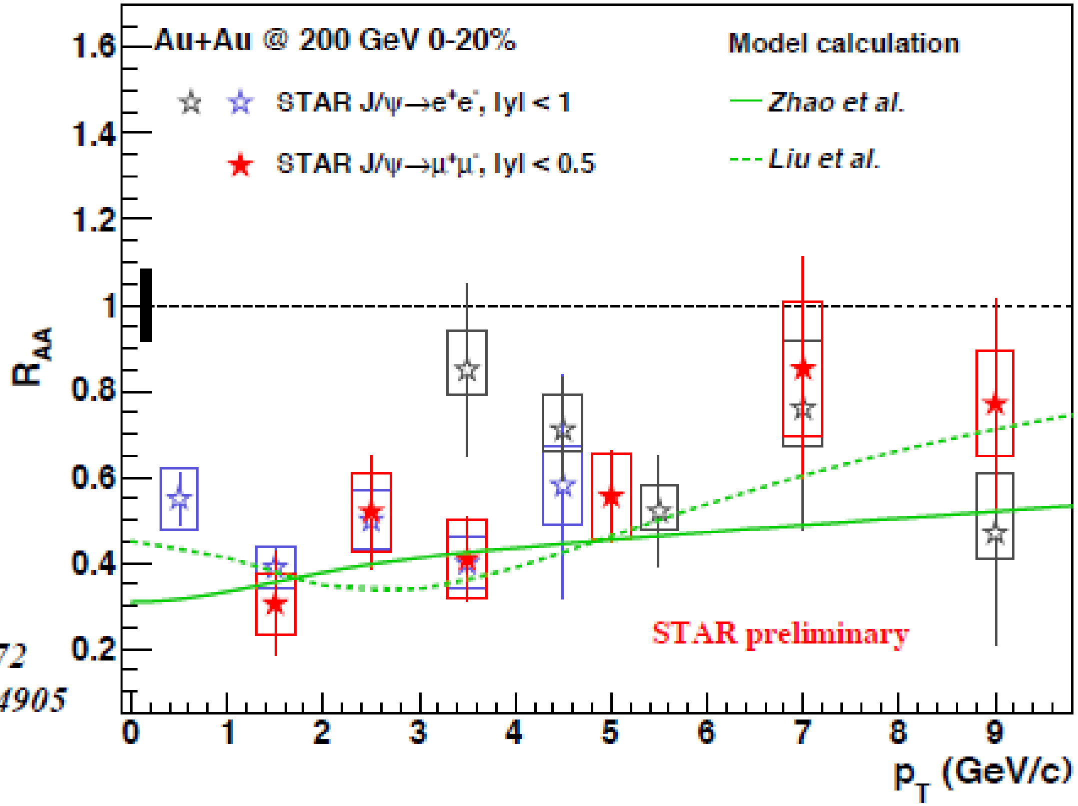


PHENIX, PRC 87, 034904 (2013)

Strong suppression at low-p_T

No suppression at p_T>4 GeV/c

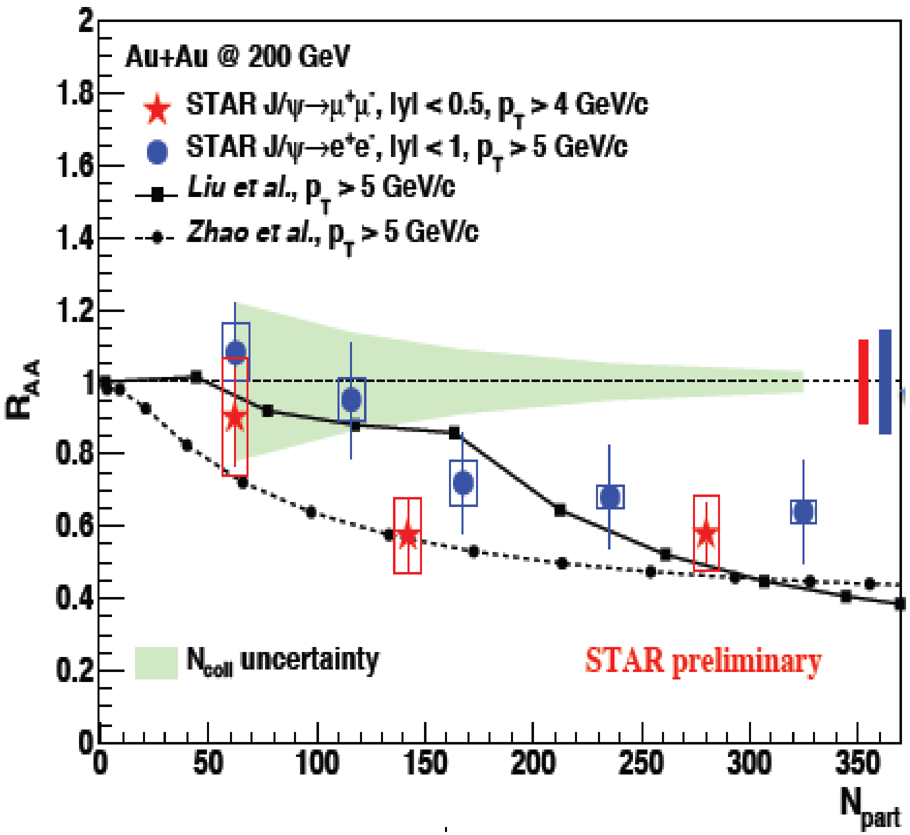
High-p_T J/ψ in 200 GeV Au+Au



STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)
Y.-p. Liu, et al. PLB 678 (2009) 72
X. Zhao et al. PRC 82 (2010) 064905

- Suppression seen at high-p_T in central Au+Au collisions
- Increase trend from low to high p_T can be described by theoretical calculations

Centrality dependence



STAR: PLB 722, 55 (2013), PRC 90, 024906 (2014)

Yunpeng Liu, Zhen Qu, Nu Xu and Pengfei Zhuang, PLB 678:72 (2009)

Xingbo Zhao and Ralf Rapp, PRC 82,064905(2010)

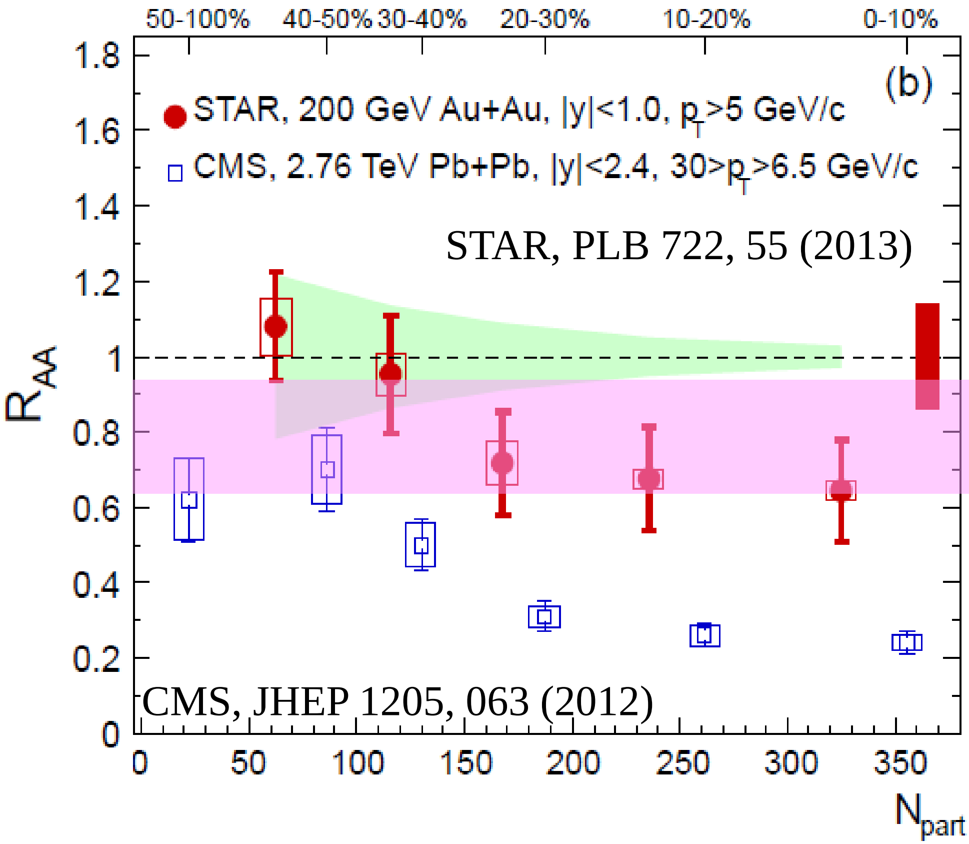
Consistent with unity in peripheral

Significant suppression in central

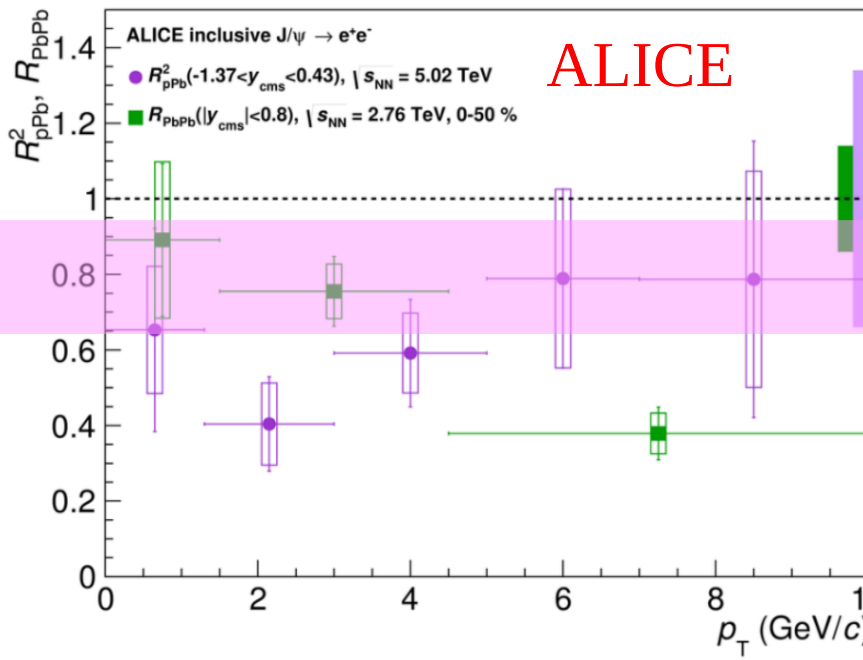
→ May indicate QGP melting

Models including color-screening and (re)generation describe data

High-p_T J/ψ at LHC



R_{pPb} x R_{pPb} at LHC

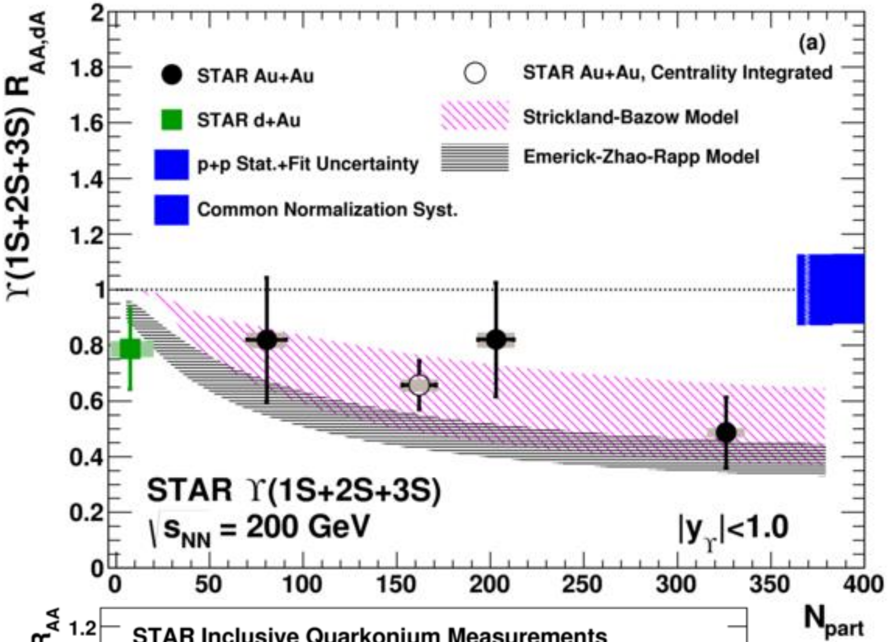


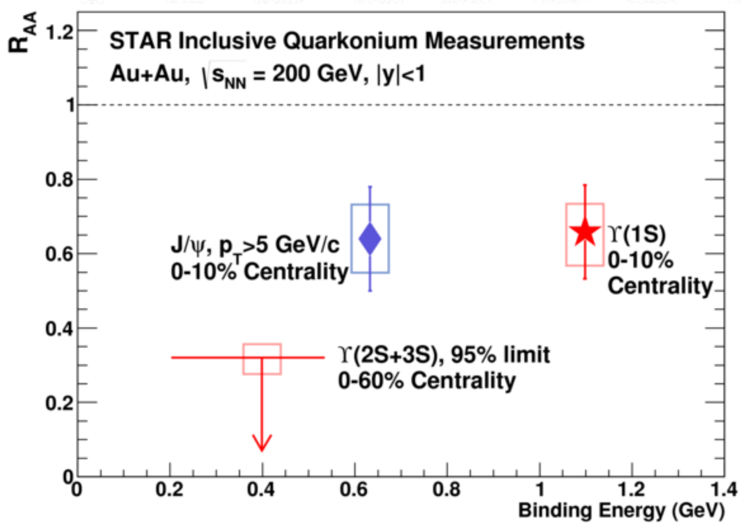
Significant suppression in central collisions at RHIC and LHC

Stronger suppression at LHC than RHIC

May explained by stronger shadowing effect at LHC

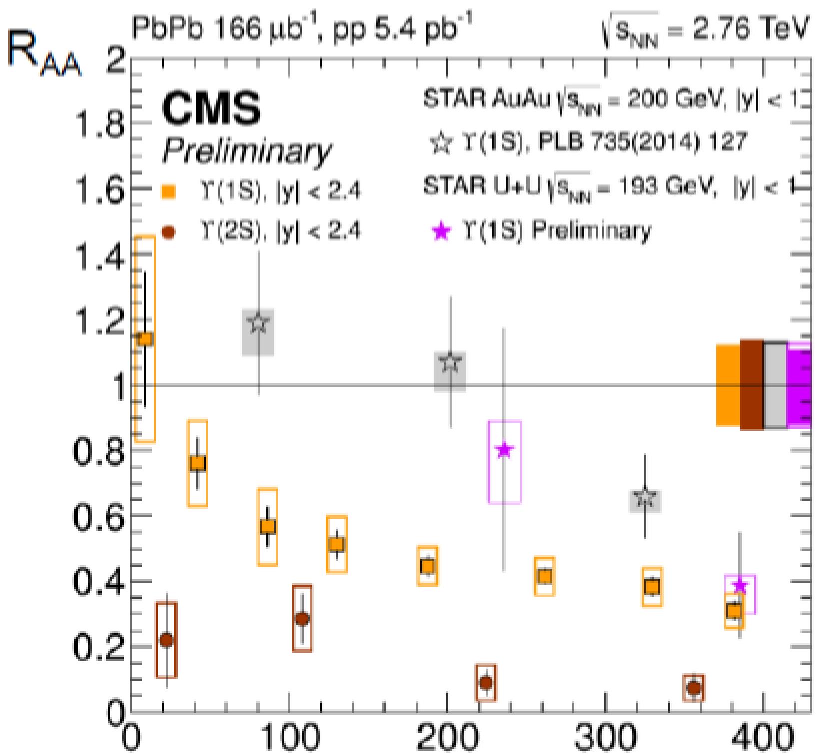
Upsilon at RHIC



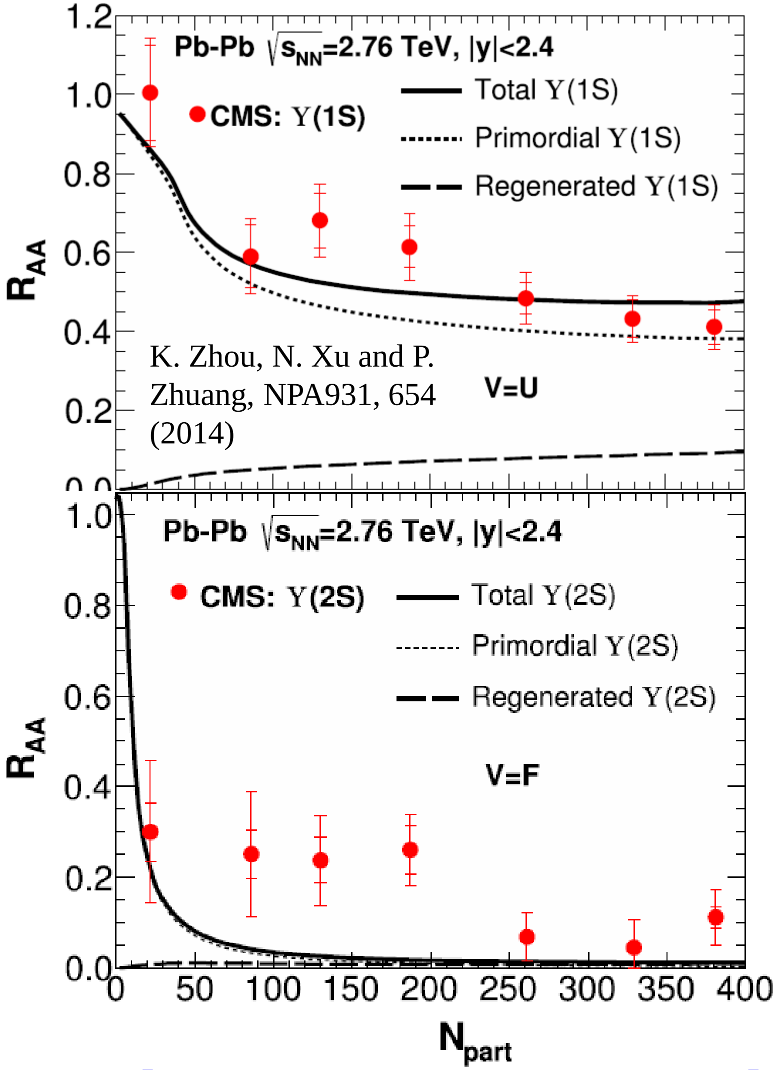


- (Re)generation negligible for Upsilon
- Similar suppression from d+Au to mid-central Au+Au
- Stronger suppression in central collisions
- Agree with model based on lattice QCD calculation of melting in hot medium

Upsilon at LHC



CMS, PRL109 (2012) 222301 and HIN-15-001
STAR, PLB735 (2014) 127 and preliminary U+U

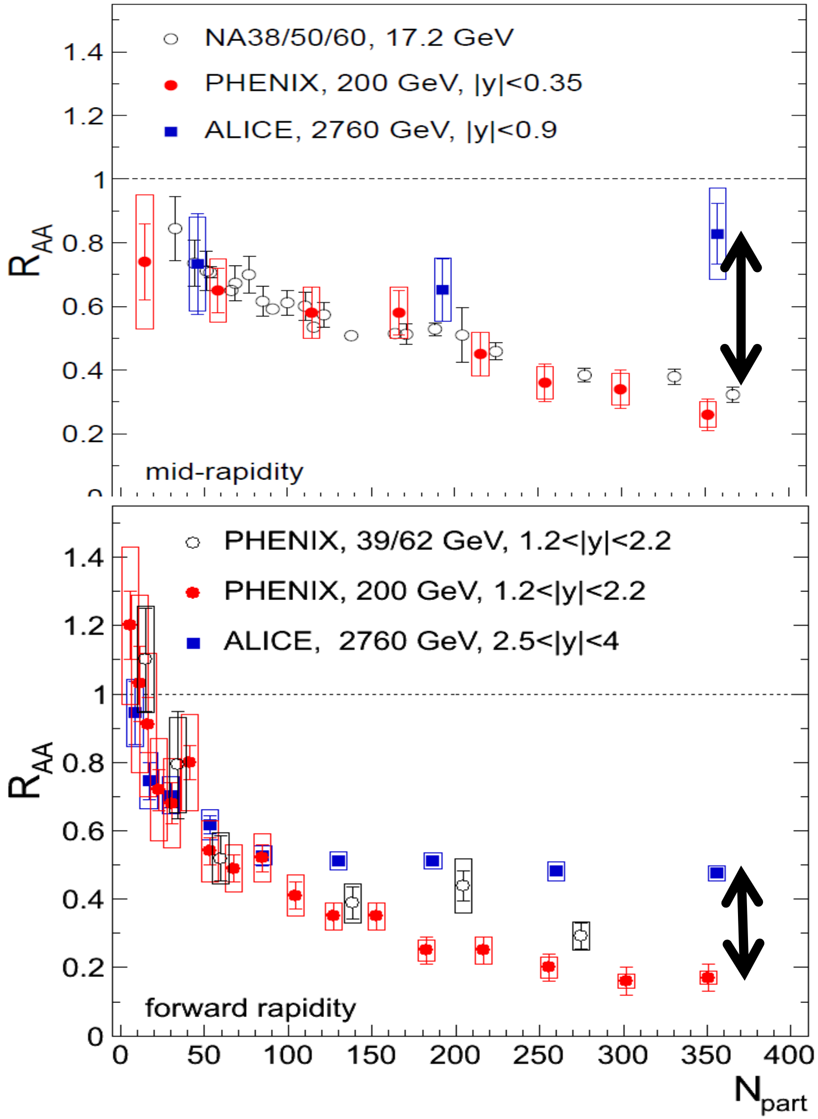


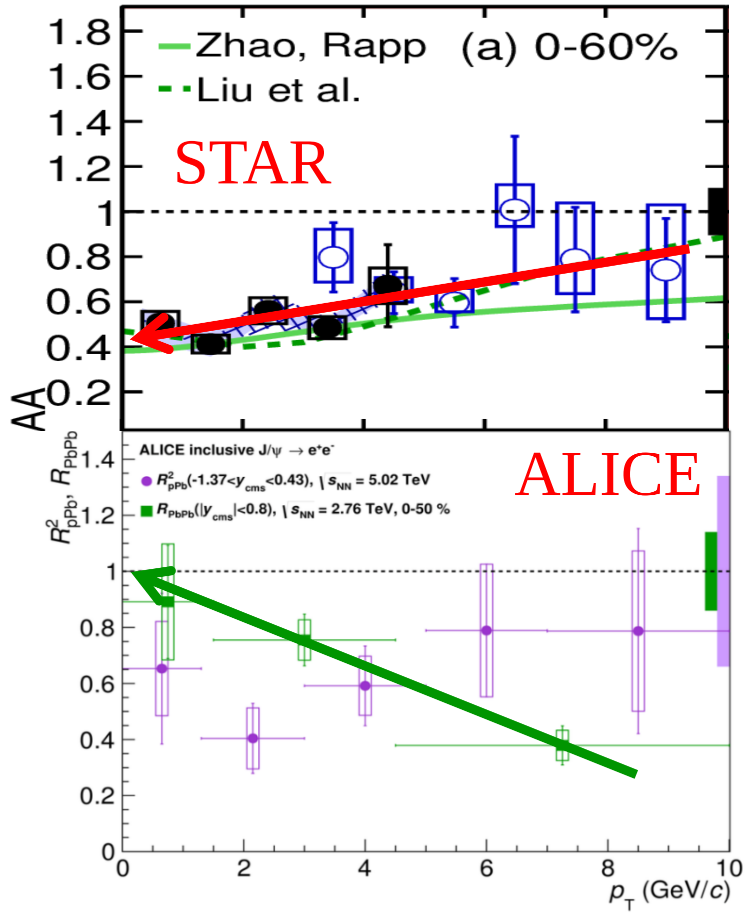
Significant Upsilon suppression
Feeddown is not enough to explain

→ May indicate QGP melting

Help to constraint potential

Low-p_T at LHC – (Re)generation





Less suppression at LHC at low-p_T

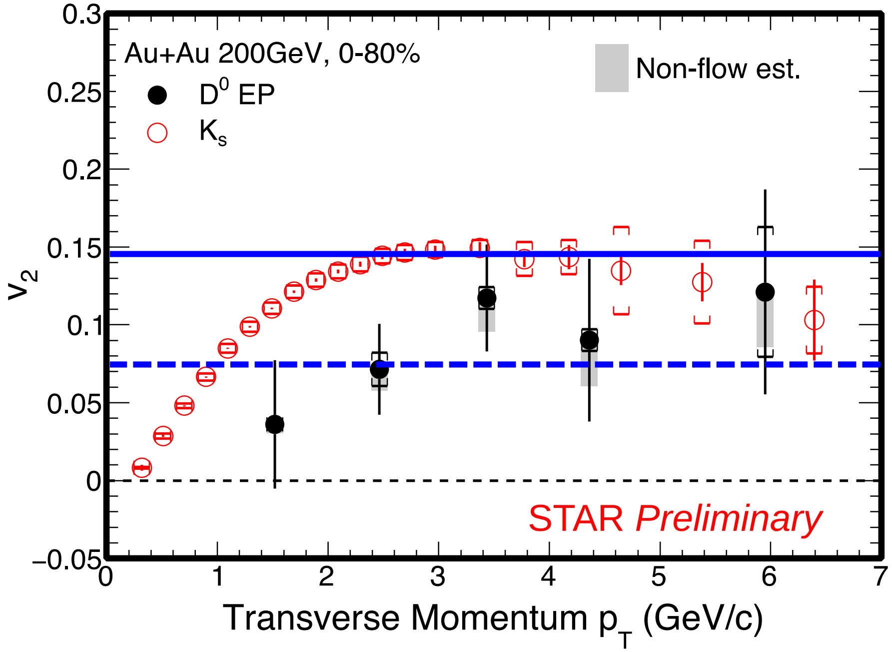
Different p_T dependence

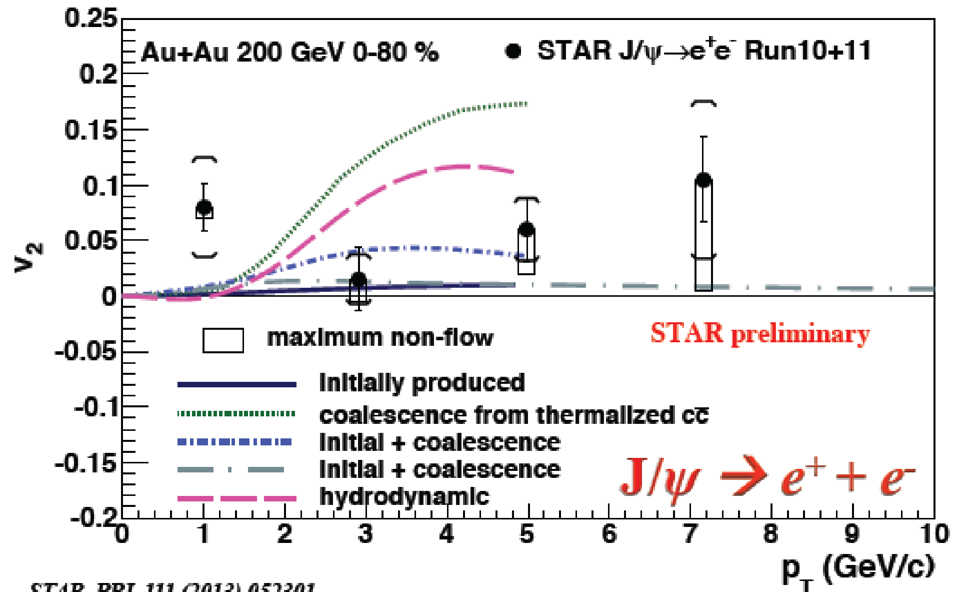
Strong indication of (Re)generation

J/ψ flow

Primordial: little or zero v_2

Regenerated: inherit v_2 from charm quarks





STAR, PRL 111 (2013) 052301
L. Yan, P. Zhuang, and N. Xu, PRL 97 (2006) 232301
V. Greco, C.M. Ko, and R. Rapp, PLB 595 (2004) 202
X. Zhao and R. Rapp, arXiv: 0806.1239
Y. Liu, N. Xu and P. Zhuang, NPA 834 (2010) 317
U.W. Heinz and C. Shen, (private communication)

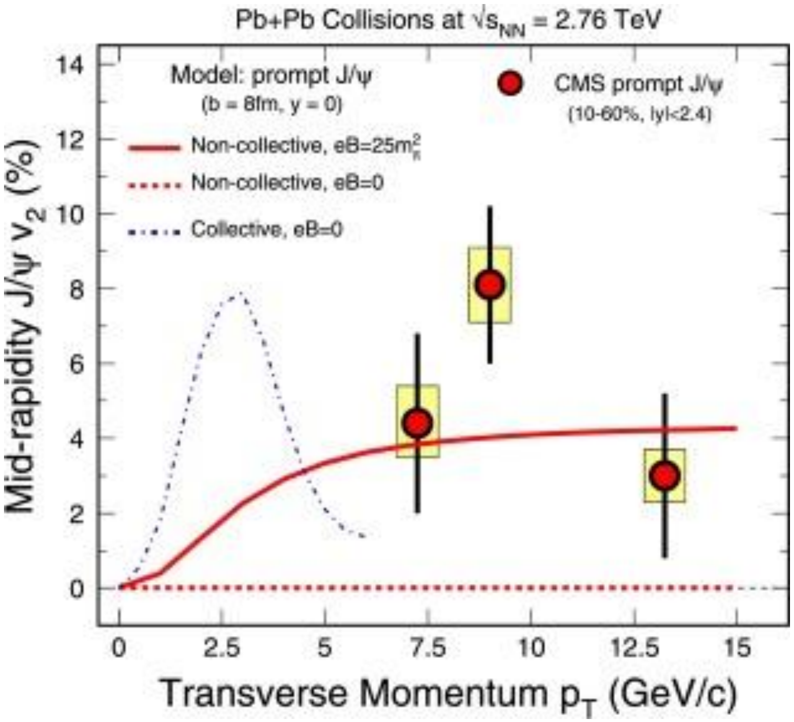
Significant D-meson flow

Consistent with no flow at p_T>2 GeV/c

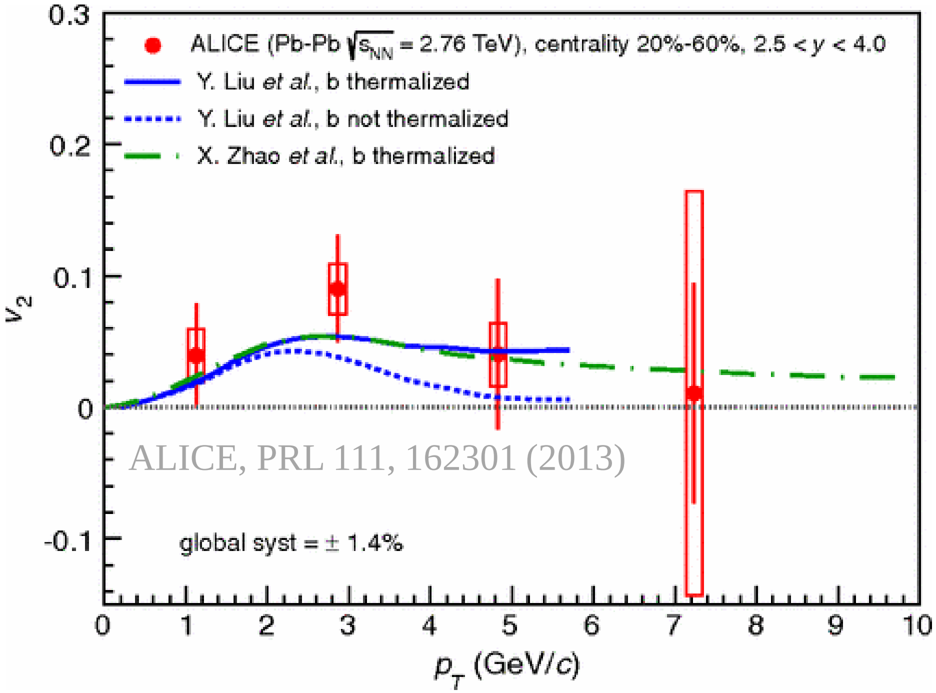
Disfavor dominantly produced by thermalized charm quark coalescence

J/ψ flow at LHC

CMS mid-rapidity



ALICE forward rapidity

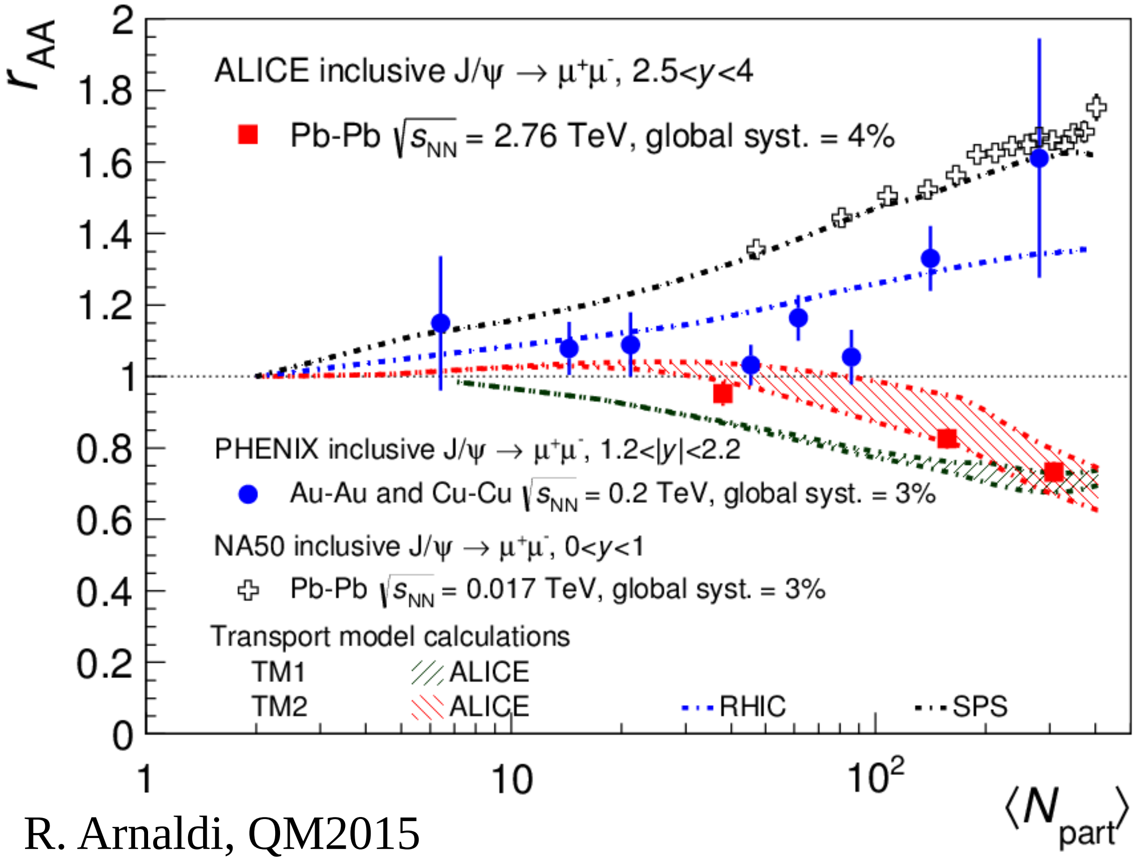


Low-p_T data still missing

Favors calculation with (Re)generation and even B thermalized

High-p_T requires different mechanism

p_T nuclear modification factor r_{AA}



R. Arnaldi, QM2015

$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

New observable proposed by Pengfei Zhuang

Sensitive to medium properties

Significant energy dependence of the trend

Decreasing trend at LHC reproduced by transport models

Summary

Quakronium production in heavy-ion collisions may involves the combination of CNM effects, QGP melting and (re)generation

High-p_T J/ψ and Upsilon:
Significant suppression in central heavy-ion collisions
→ QGP melting

Low-p_T J/ψ: Significantly less suppression at LHC than at RHIC
J/ψ elliptic flow: no flow at RHIC, significant flow at LHC
→ (Re)generation at LHC

p_T nuclear modification factor r_{AA}:
Sensitive to nuclear modification mechanisms
SPS: CNM effects dominant
RHIC: Competing between (re)generation and suppresion
LHC: (Re)generation dominant

Thank Prof. Pengfei Zhuang!