J/ψ production at RHIC

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PHENIX Collaboration

Motivations

- **Theoretical point of view**
  - **Matsui and Satz** first proposed the study of quarkonia as a signature of Quark Gluon Plasma (QGP)
    - ✓ Phys. Lett. B 178 (1986) 416

« if high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then *color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region* …/… It is concluded that J/ψ suppression in nuclear collisions should provide an *unambigous signature* of quark-gluon plasma formation »

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J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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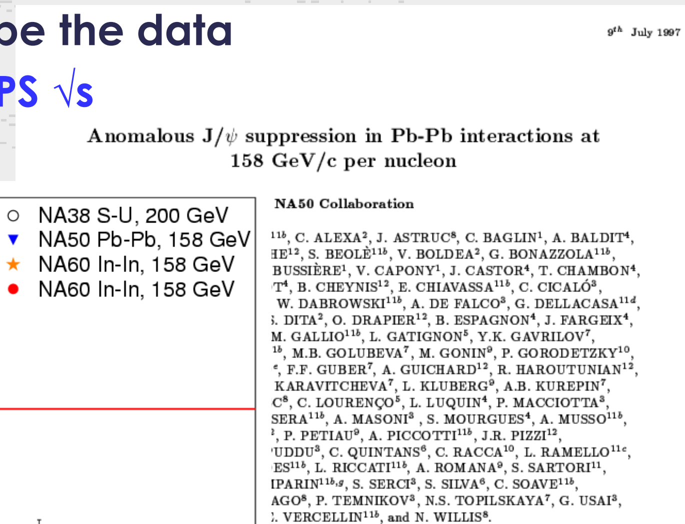
Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ 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 charmonium 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.

Since then, more models…

Motivations

- **Experimental point of view**
  - J/ψ production in p+A and A+A collisions studied at SPS starting 1986.
    - ✓ NA38, NA50, NA60
  - **Anomalous suppression** observed in **Pb+Pb** (NA50) and **In+In** (NA60) central collisions (high energy density, high temperature).
  - Different models (with or without QGP) describe the data
  - At RHIC, √s up to 200 GeV, 10 x bigger than SPS √s



9^{th} July 1997

Anomalous J/ψ suppression in Pb-Pb interactions at 158 GeV/c per nucleon

NA50 Collaboration

11b, C. ALEXA[2], J. ASTRUC[8], C. BAGLIN[1], A. BALDIT[4],
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BUSSIÈRE[1], V. CAPONY[1], J. CASTOR[4], T. CHAMBON[4],
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W. DABROWSKI[11b], A. DE FALCO[3], G. DELLACASA[11d],
. DITA[2], O. DRAPIER[12], B. ESPAGNON[4], J. FARGEIX[4],
M. GALLIO[11b], L. GATIGNON[5], Y.K. GAVRILOV[7],
1b, M.B. GOLUBEVA[7], M. GONIN[9], P. GORODETZKY[10],
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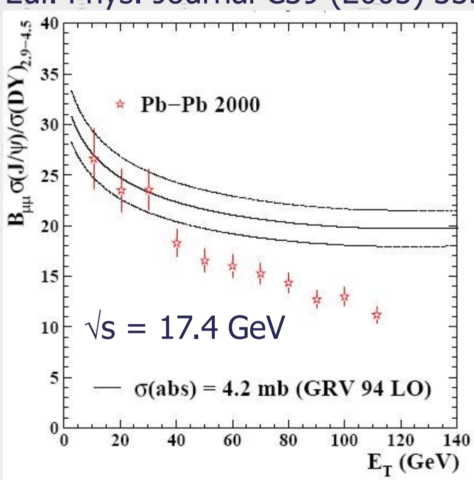
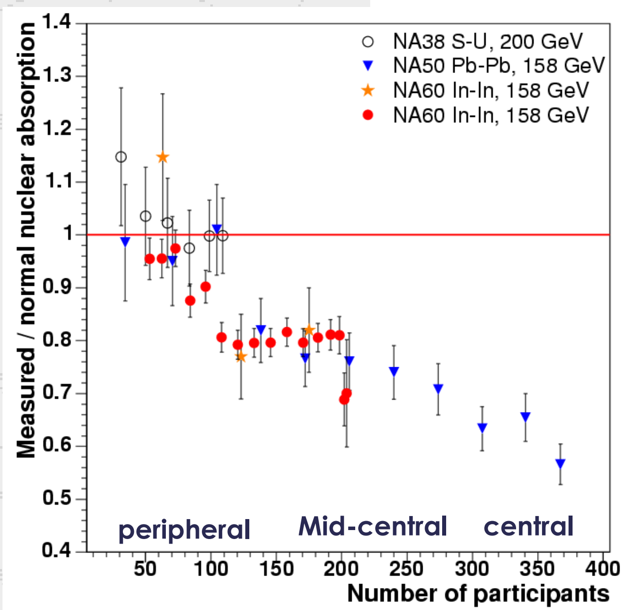
KARAVITCHEVA[7], L. KLUBERG[9], A.B. KUREPIN[7],
C[8], C. LOURENÇO[5], L. LUQUIN[4], P. MACCIOTTA[3],
SERA[11b], A. MASONI[3] , S. MOURGUES[4], A. MUSSO[11b],
2, P. PETIAU[9], A. PICCOTTI[11b], J.R. PIZZI[12],
UDDU[3], C. QUINTANS[6], C. RACCA[10], L. RAMELLO[11c],
ES[11b], L. RICCATI[11b], A. ROMANA[9], S. SARTORI[11],
IPARIN[11b,g], S. SERCI[3], S. SILVA[6], C. SOAVE[11b],
AGO[8], P. TEMNIKOV[3], N.S. TOPILSKAYA[7], G. USAI[3],
. VERCELLIN[11b], and N. WILLIS[8].

NA50, Eur. Phys. Journal C39 (2005) 335



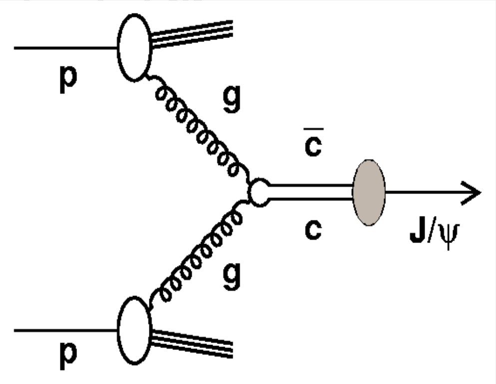


peripheral Mid-central central

collisions →

J/ψ at RHIC

- J/ψ production
  - Main production process : gluon fusion
  - Feed-down :
    - ✓ 60% from direct production
    - ✓ ~30% $\chi_c \rightarrow J/\psi + \gamma$
    - ✓ ~10% $\psi' \rightarrow J/\psi + X$
  - In nuclear matter :
    - ✓ Initial state effects
      - Nuclear shadowing *(Cold Nuclear Effect)*
      - pT broadening : Cronin effect *(Cold Nuclear Effect)*
    - ✓ Final state effects
      - Absorption in nuclear matter *(Cold Nuclear Effect)*
      - Anomalous suppression *(?)*



- Experimentally
  - At RHIC : $\sqrt{s}$ up to 200 GeV (<20 GeV at SPS)
  - J/ψ is mainly measured by the PHENIX experiment
  - Measure J/ψ in p+p : used as a reference
  - Measure J/ψ in d+Au : to study Cold Nuclear Effects
  - Measure J/ψ in Au+Au and Cu+Cu to study anomalous suppression.

The PHENIX experiment

Central arms:

hadrons, photons, electrons

$J/\psi \rightarrow e^+e^-$

$p > 0.2$ GeV/c

$|y| < 0.35$

$\Delta\phi = \pi$

Muon arms:

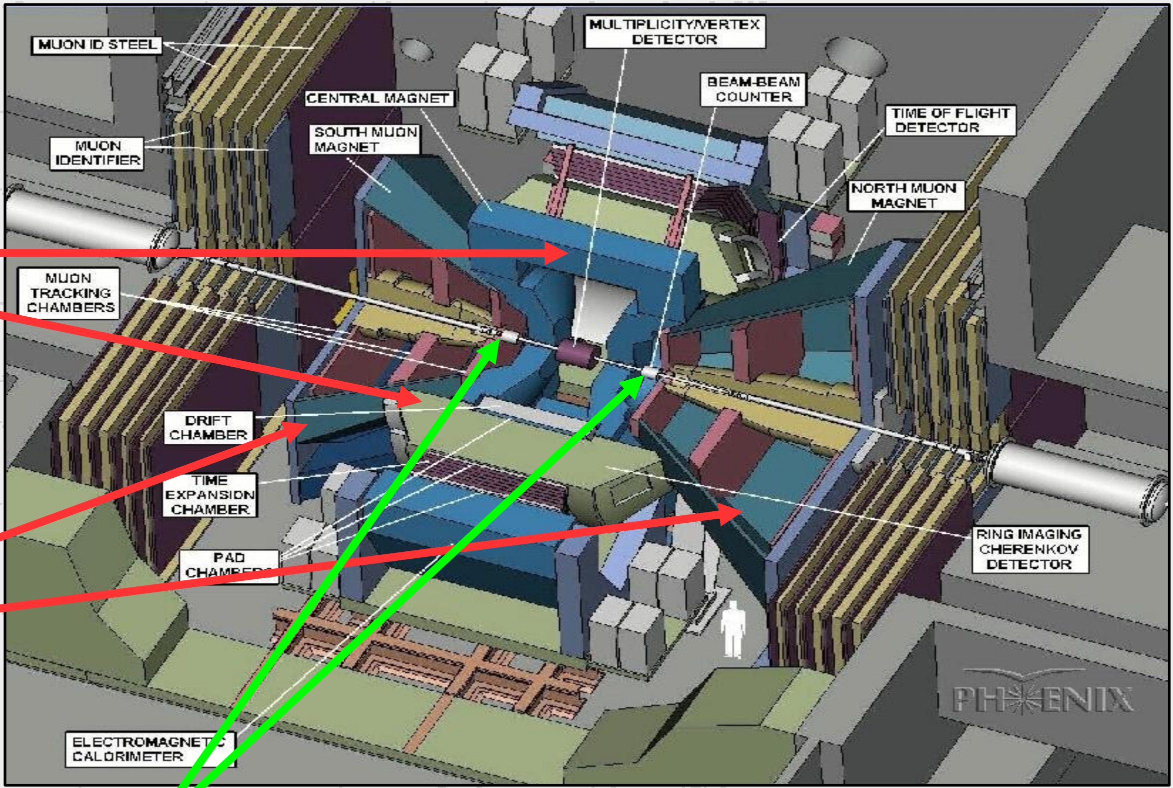
muons at forward rapidity

$J/\psi \rightarrow \mu^+\mu^-$

$p > 2$GeV/c

$1.2 < |y| < 2.4$

$\Delta\phi = 2\pi$



Centrality measurement:

beam beam counters (charged particle production)

zero degree calorimeters (spectator neutrons)

Centrality is mapped to N_{part} (N_{coll}) using Glauber model

The PHENIX experiment

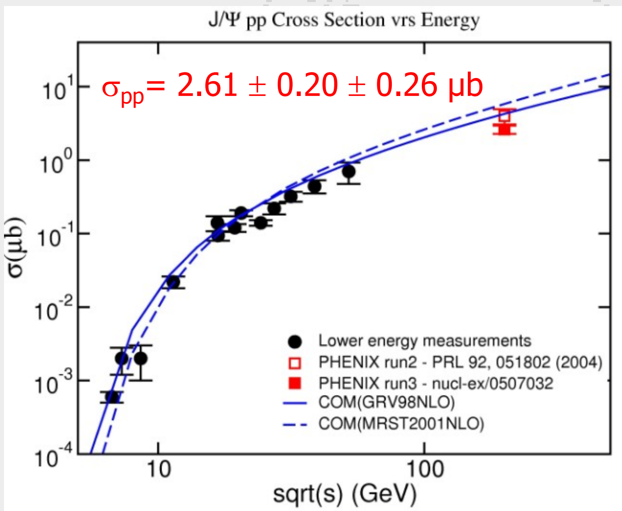
- Data collection

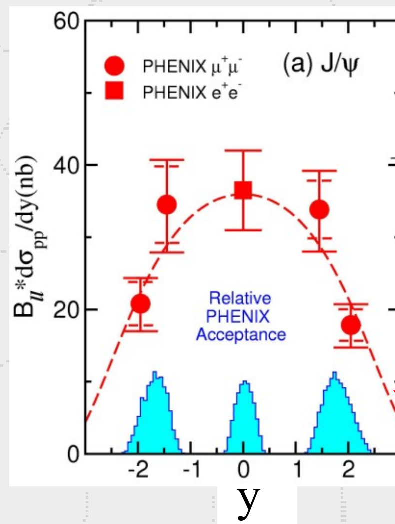
Year	Systems (ions)@√S	Integrated luminosity	# J/ψ (ee + μμ)
2002	Au+Au @ 200 GeV p+p @ 200GeV	24 μb^{-1} 0.15 pb^{-1}	13 + 0 46 + 66
2003	d+Au @ 200 GeV p+p @ 200 GeV	2.74 nb^{-1} 0.35 pb^{-1}	~300 + 1400 ~100 + 420
2004	Au+Au @ 200GeV	240 μb^{-1}	~600 + 5000
2005	Cu+Cu @ 200GeV Cu+Cu @ 62GeV p+p @ 200 GeV	3.06 nb^{-1} 0.19 nb^{-1} 3.8 pb^{-1}	~1200 + 10000 ~40 + 200

J/ψ production in p+p

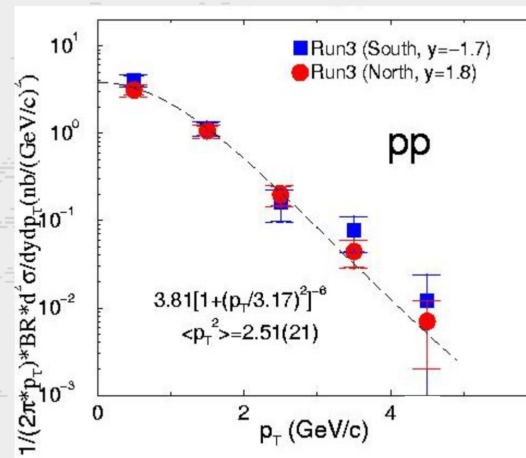
- σ_{pp} to be used as a **reference** for A+A
- Cross section in agreement with Color Octet Model
- Cross-section .vs. Rapidity agrees with PYTHIA shape

Phys. Rev. Lett. 96, 012304





PYTHIA shape



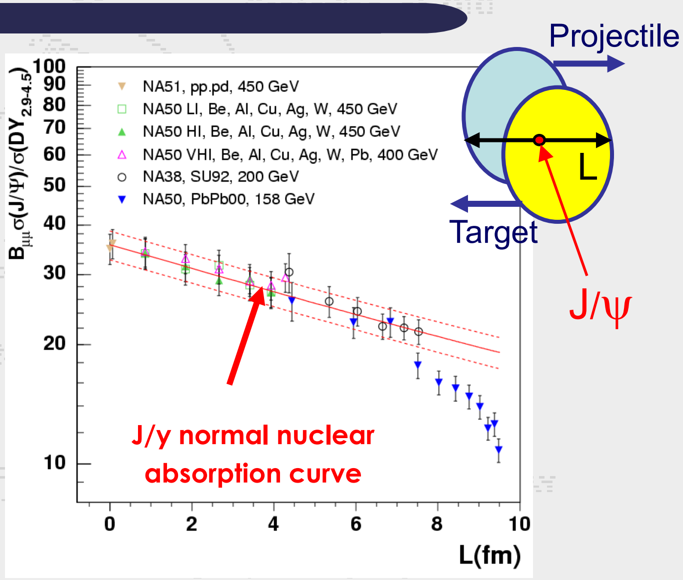
$\langle p_t^2 \rangle = 2.51\ (\mathrm{GeV}/c)^2$

J/ψ is a **rare process** ➔ expect in A+A collisions : $(\sigma_{J/\psi})_{AA} \propto \langle N_{coll} \rangle \times (\sigma_{J/\psi})_{pp}$

In the following, we'll use $$R_{AA} = \frac{dN_{AA}^{J/\psi}}{\langle N_{coll} \rangle \times dN_{pp}^{J/\psi}}$$ (if no nuclear effect R_{AA}=1)

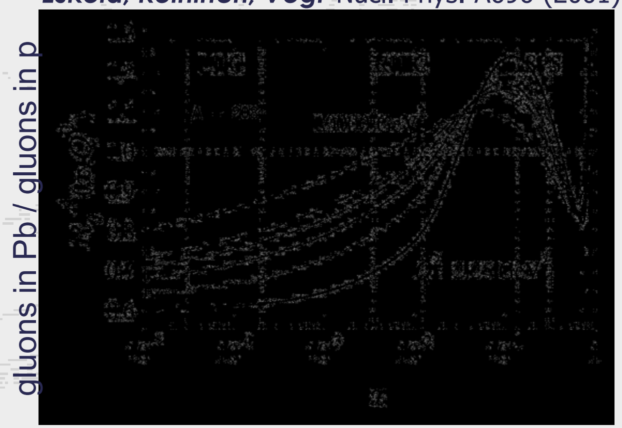
Cold nuclear effects

- **Absorption by nuclear matter**
  - After its production, charmonium can interact with nucleons from projectile and target
    - ✓ Introducing L, the « length » of nuclear matter seen by the J/ψ
    - ✓ J/ψ survival probability : $S(J/\psi) \propto e^{-\rho\sigma_{abs}L}$
  - At SPS : $\sigma_{abs}^{J/\psi} = 4.18 \pm 0.35\,\text{mb}$
  - Expect some absorption at RHIC



- **Shadowing**
  - Nuclear shadowing is an initial-state effect on the parton distributions.
  - Gluon distribution function can be different when comparing proton and nucleus.
  - Expect some (anti) shadowing at RHIC

Eskola, Kolhinen, Vogt Nucl. Phys. A696 (2001)

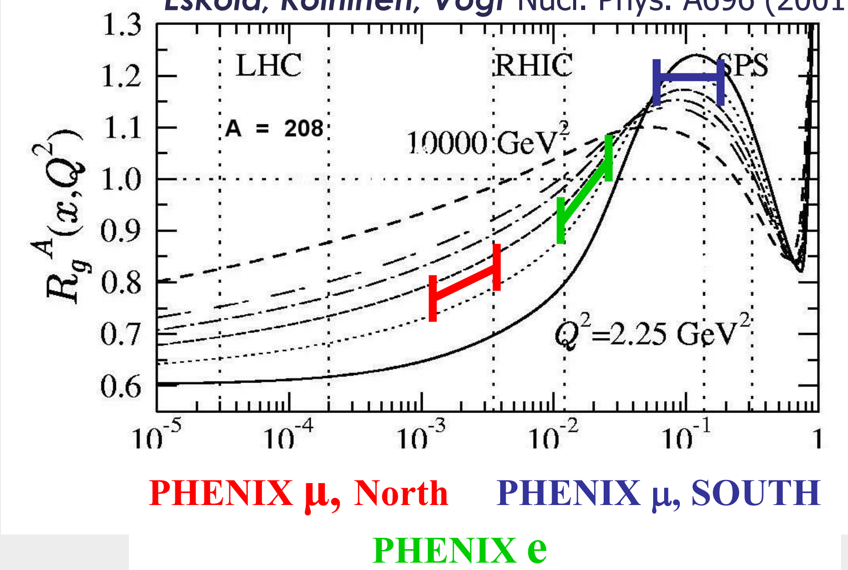


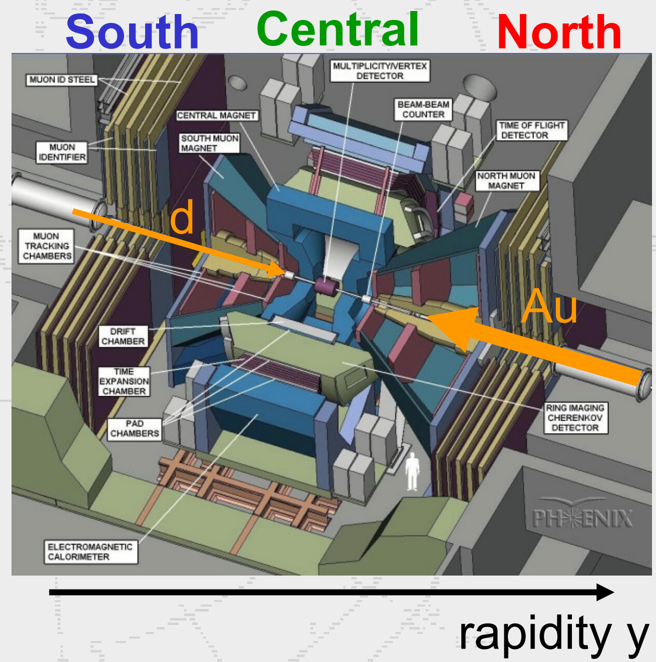
x is the momentum fraction of the nucleon that a parton (quark or gluon) carries.

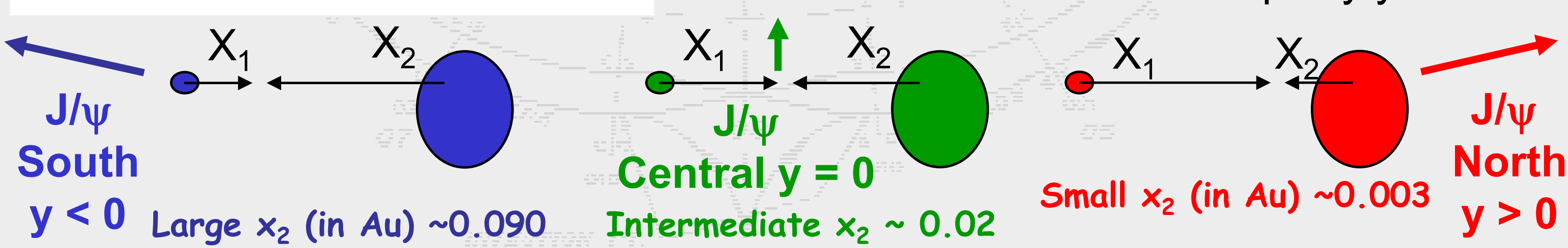
Shadowing at RHIC

- Using d-Au data
  - PHENIX measurements cover expected shadowing, anti-shadowing range

Eskola, Kolhinen, Vogt Nucl. Phys. A696 (2001)



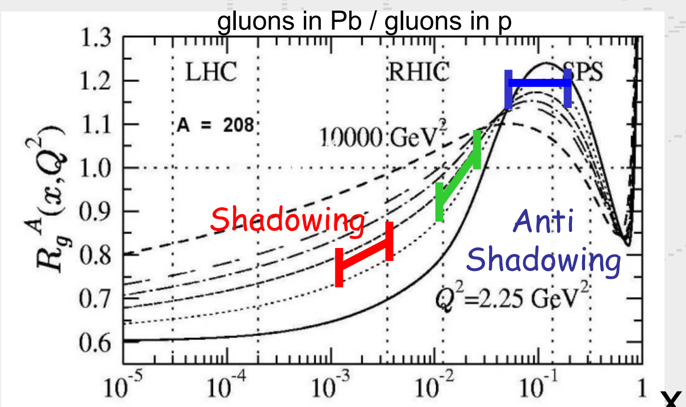




Cold nuclear effects – J/ψ in d+Au

- **Determine effects from cold nuclear matter**
  - **Absorption of J/ψ by nuclear matter**
  - **Modification of PDF due to possible gluon shadowing**

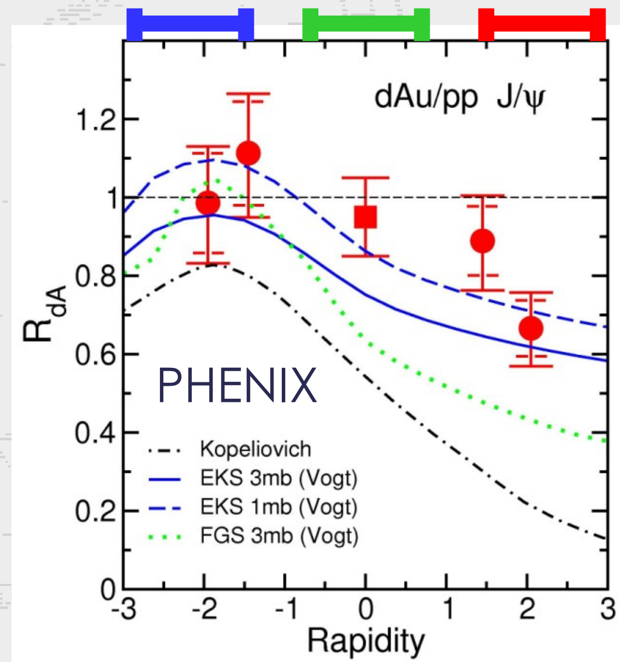
predictions



Nucl. Phys. A696 (2001) 729-746

PHENIX dAu data

PHENIX PRL 96, 012304 (2006)



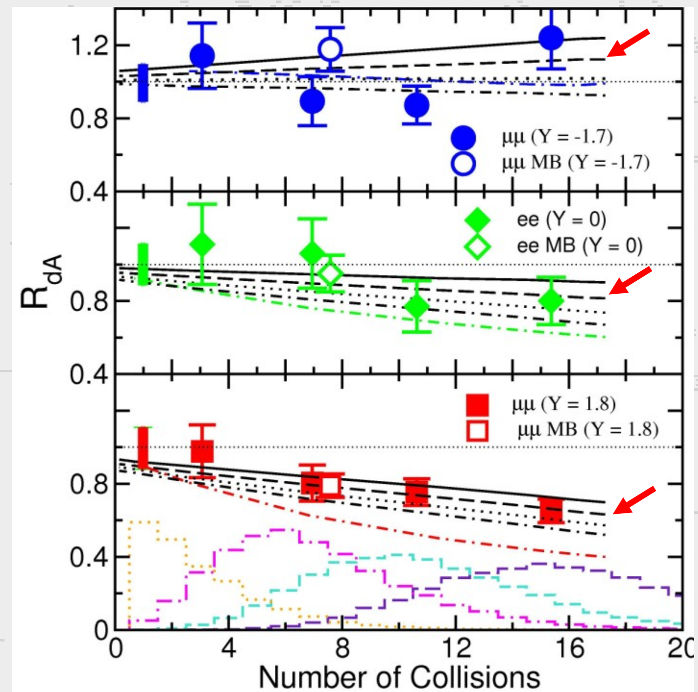
Vogt, Phys. Rev. C71:054902, 2005
Kopeliovich, NP A696:669,2001

PHENIX data compatible with :
- **weak gluon shadowing**
- **weak absorption : 1 to 3 mb**

Cold nuclear effects – J/ψ in d+Au

- Centrality dependance

PHENIX PRL 96, 012304 (2006)



Large
$x_2 \approx 0.09$

Intermediate
$x_2 \approx 0.02$

Small
$x_2 \approx 0.003$

Small centrality dependence

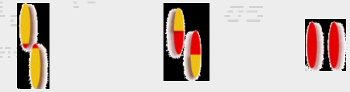
Black lines :
- shadowing EKS98
- σ^{abs} = 0 to 3 mb

Color lines : FGS

σ^{abs} = 1 mb good agreement
σ^{abs} = 3 mb is an upper limit

peripheral Mid-central central

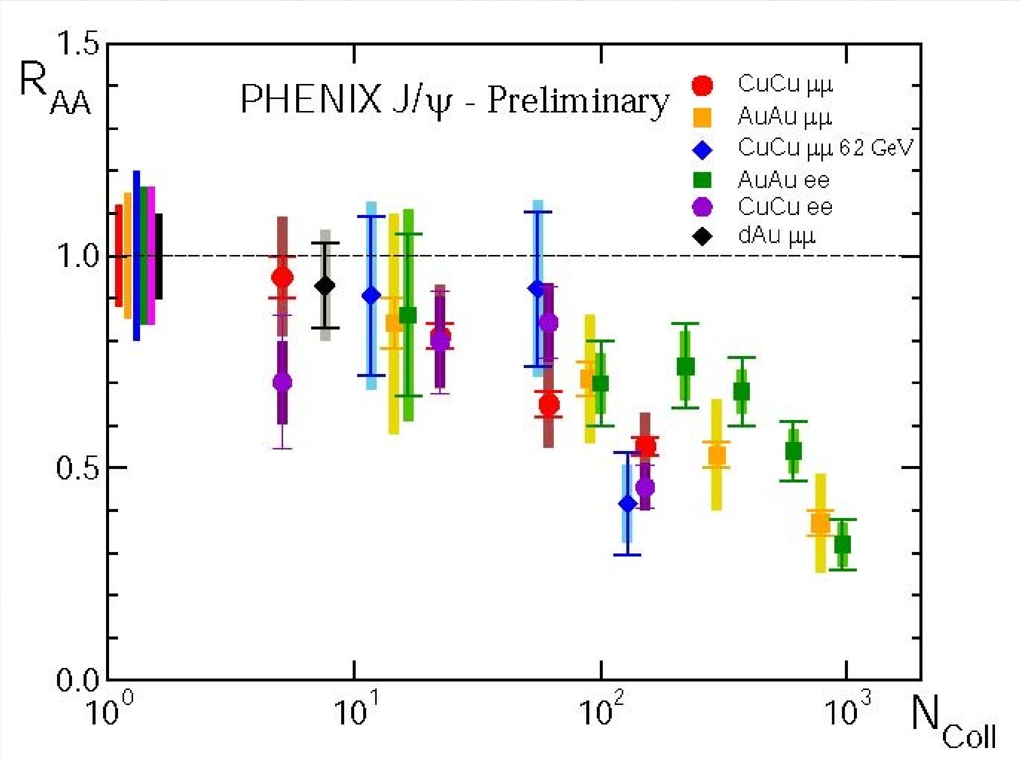
collisions →



Overall PHENIX results

Hugo Pereira da Costa, for PHENIX, QM05, nucl-ex/0510051

$$R_{AA} = \frac{dN_{AA}^{J/\psi}}{< N_{coll} > \times dN_{NN}^{J/\psi}}$$ = J/ψ yield per binary collision



J/ψ μμ
muon arm
1.2 < |y| < 2.2

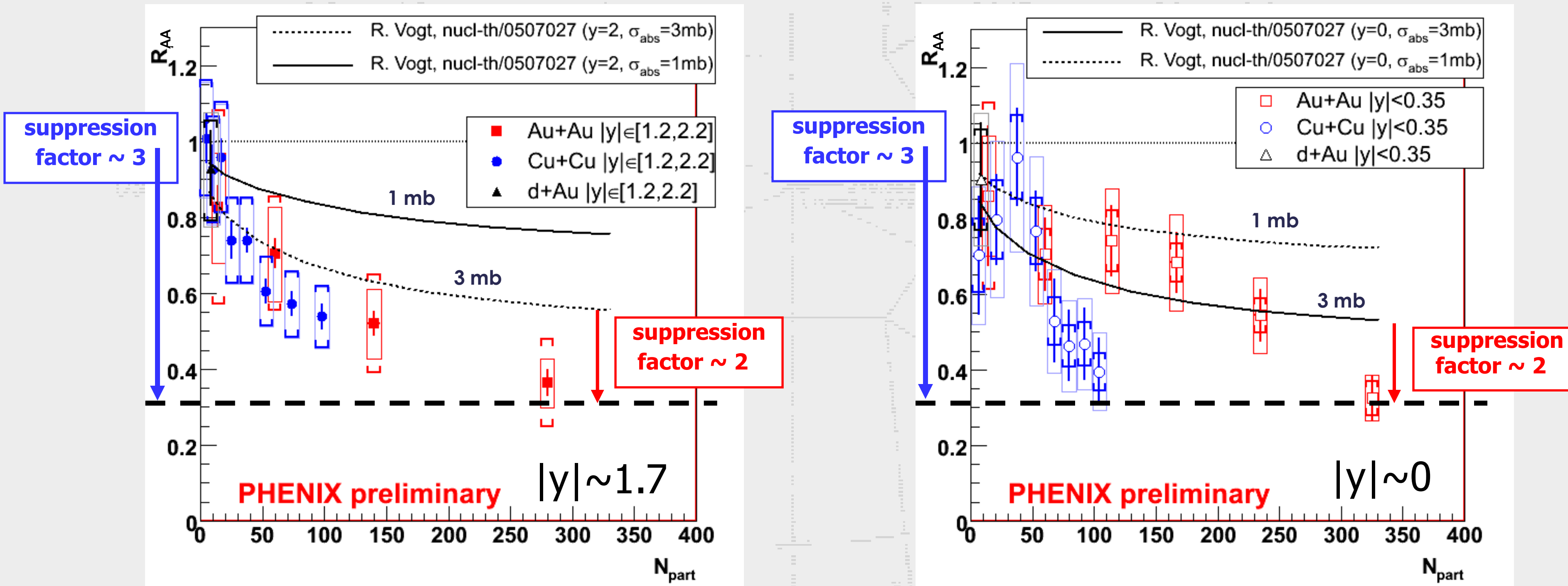
J/ψ ee
Central arm
-0.35 < y < 0.35

dAu	AuAu	CuCu	AuAu	CuCu	CuCu
μμ	μμ	μμ	ee	ee	μμ
200 GeV/c	200 GeV/c	200 GeV/c	200 GeV/c	200 GeV/c	62 GeV/c

Results in A+A

- R_{AA} and centrality

$$R_{AA} = \frac{dN^{J/\psi}_{AB}}{dN^{J/\psi}_{pp} \times \langle N_{coll} \rangle}$$



Observe an anomalous suppression (> factor 2) beyond cold nuclear effets.

Au+Au and Cu+Cu results

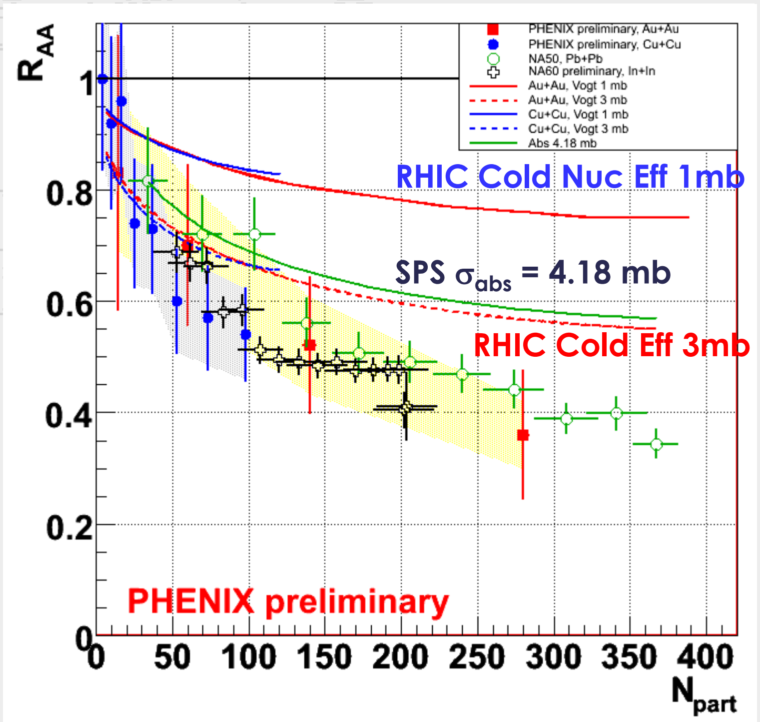
- Comparison with SPS results

On the experimental point of view :
Suppression at RHIC = suppression at SPS
Altough √s@RHIC=200 GeV and √s@SPS<20 GeV

But cold nuclear effects should be :

- different (different suppression pattern)
- or not (same suppression pattern)

Need more precise measurement
of cold nuclear effect at RHIC
→ need more dAu (dCu ?) data



SPS normalized to NA51 p+p value (NA60 preliminary points from Arnaldi, QM05).

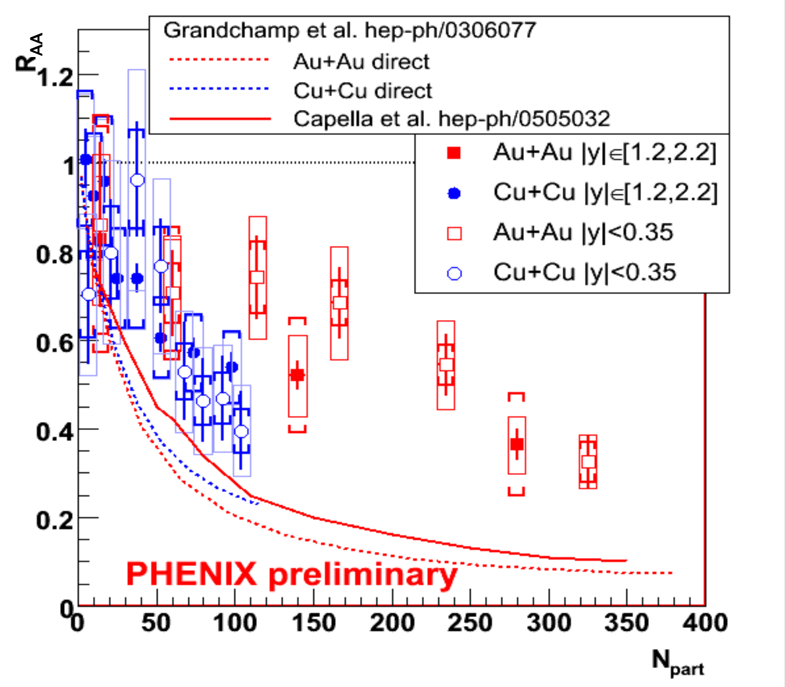
Suppression Models

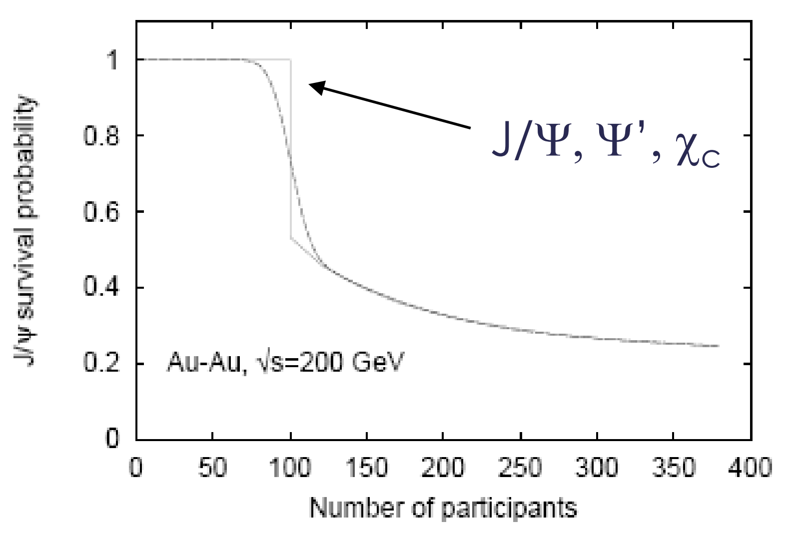
(Hadronic?) co-mover scattering — Capella, Ferreiro, EPJC42 (2005) 419

Cu+Cu ········ Au+Au ······· Direct suppression in a hot medium — Grandchamp et al, PRL92 (2004) 212301

Direct suppression and comovers models which reproduce NA50 data…

… Overestimate the suppression at PHENIX





… So does percolation (simultaneous J/ψ, χ_c, ψ')

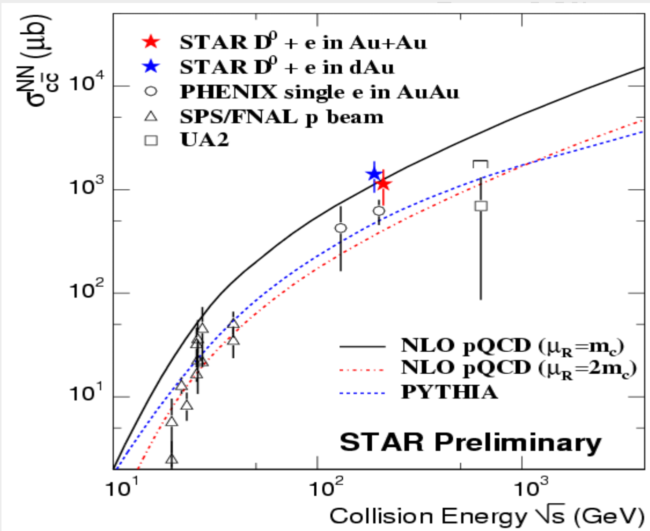
Digal, Fortuno, Satz, EPJC32 (2004) 547

Suppression models

- Models used to reproduce SPS data fail to reproduce RHIC data
  - Direct suppression
  - Comovers
  - Percolation

- Need new ingredients
  - Regeneration
  - Sequential charmonium dissociation
  - QGP hydro + J/ψ transport

Regeneration models



- **At RHIC energies** a fair amount of $c\bar{c}$ pairs is produced → $N_{c\bar{c}}$>10 in central AuAu (~10 x more than at SPS)
- Recombinaison: $c\bar{c}$ → J/ψ + g
- $N_{J/\psi} \propto N_{c\bar{c}}^2$
- (huge amount expected at LHC, $N_{c\bar{c}}$~100)

Grandchamp et al. hep-ph/0306077

PHENIX data :

Adding regeneration compensates direct suppression

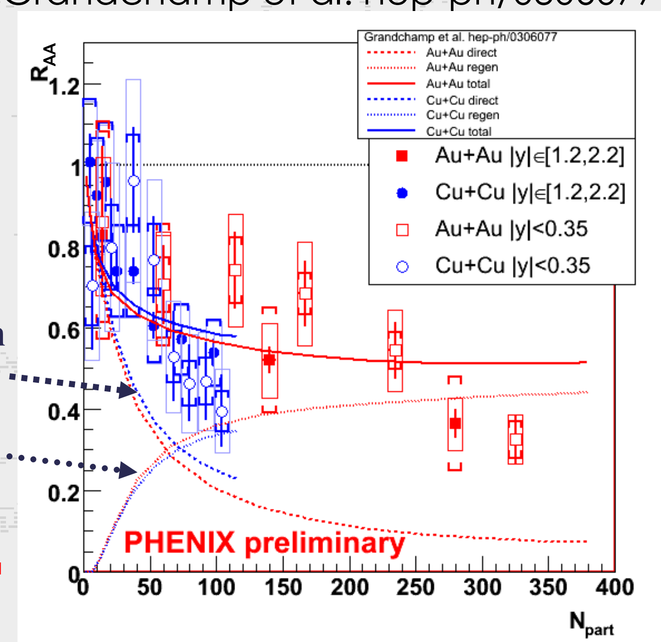
→ better agreement between models and data

Direct suppression in a hot medium

Regeneration

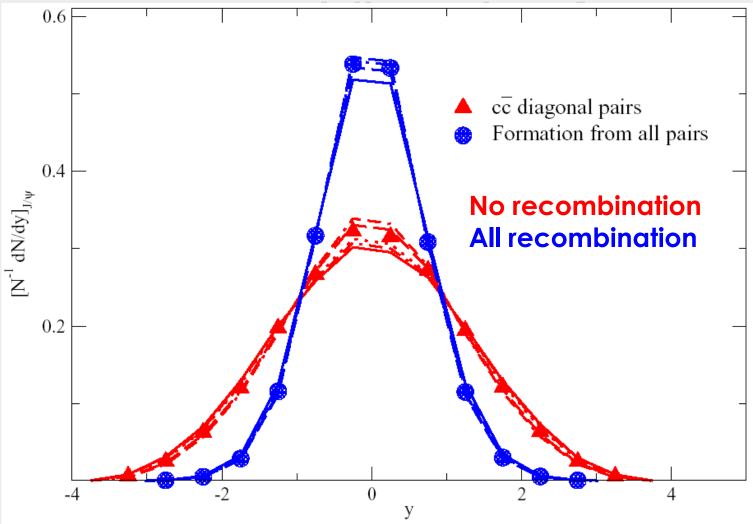
Total :

Cu+Cu Au+Au



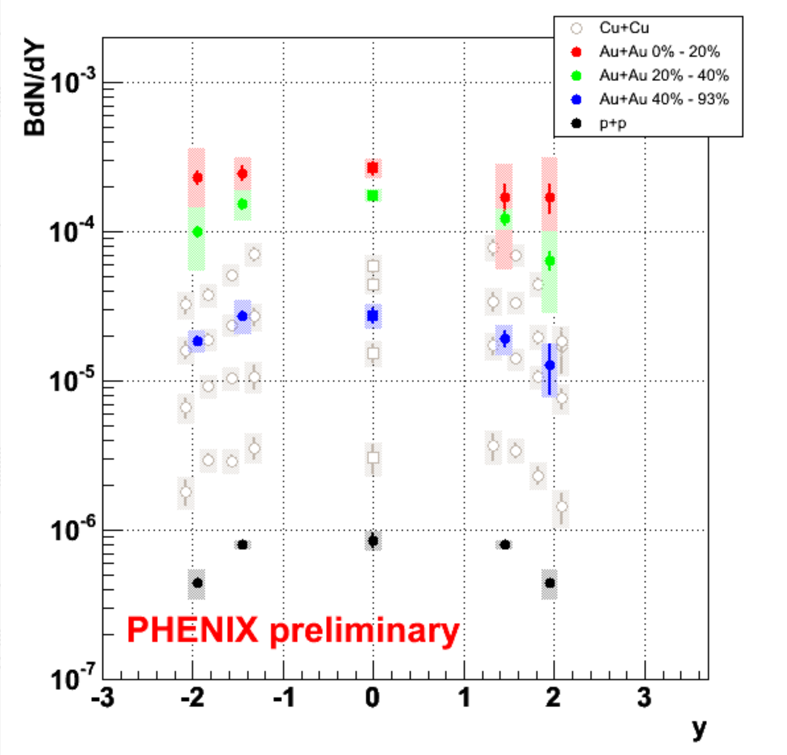
Regeneration

- Rapidity spectrum



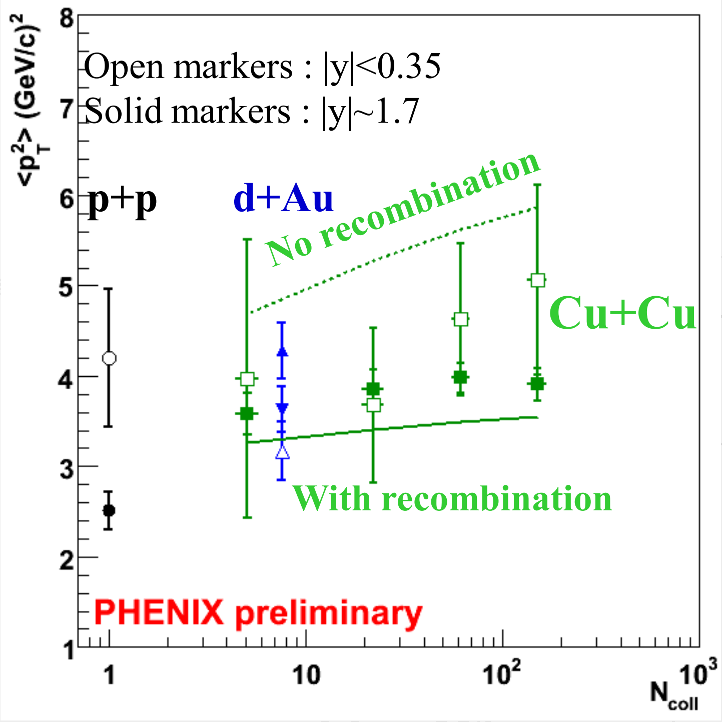
Recombination (Thews et al., nucl-th/0505055) predicts a narrower rapidity distribution.

Experimentally: from p+p to the most central Au+Au, no significant change seen in the shape of the rapidity distribution.



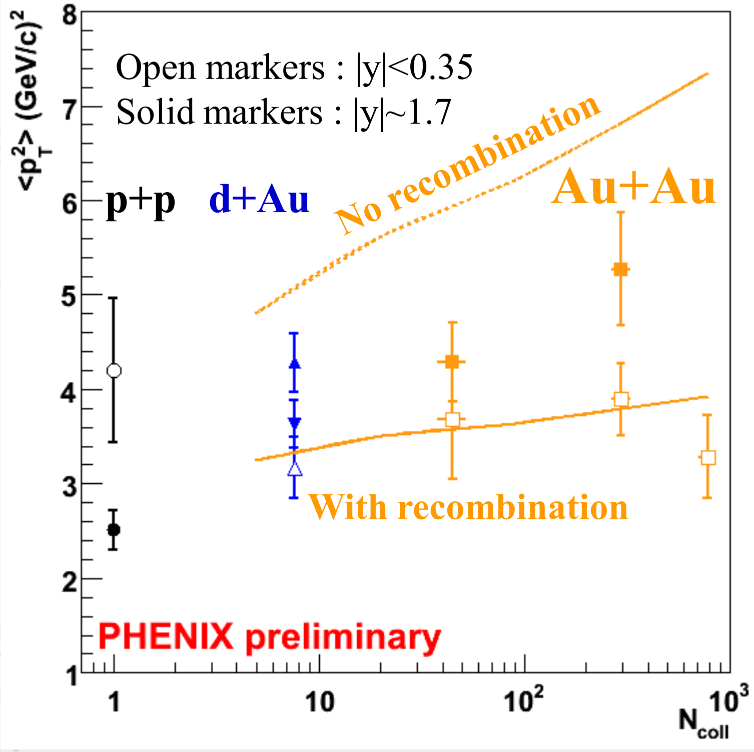
Regeneration

- **p_T spectrum**



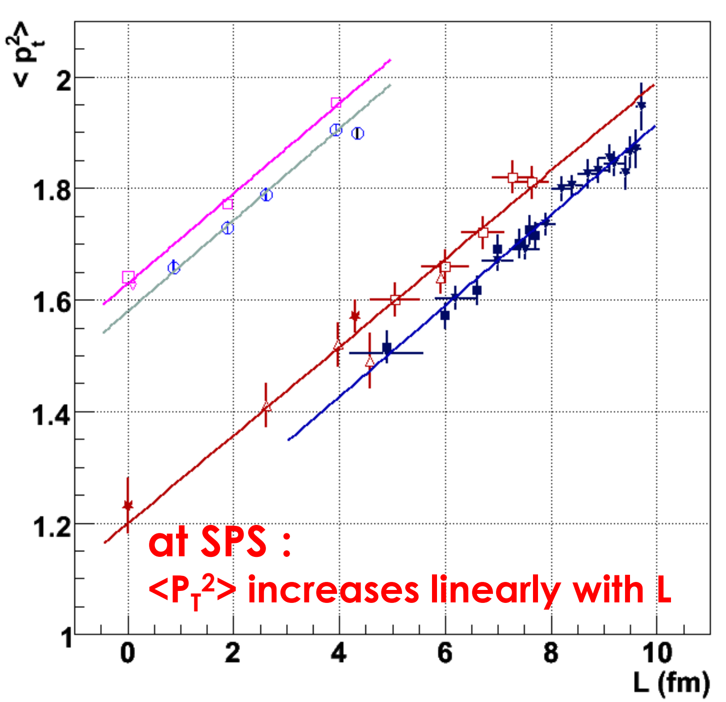
Experimentally : data fall between the two hypothesis
⇒ partial recombination ?

Recombination (Thews et al., nucl-th/0505055) predicts a narrower p_T distribution, leading to a lower $\langle p_T^2 \rangle$



p_T spectrum

- **Cronin effect :** $\langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + \Delta_{\langle p_T^2 \rangle} \rho\sigma L_{AA}$



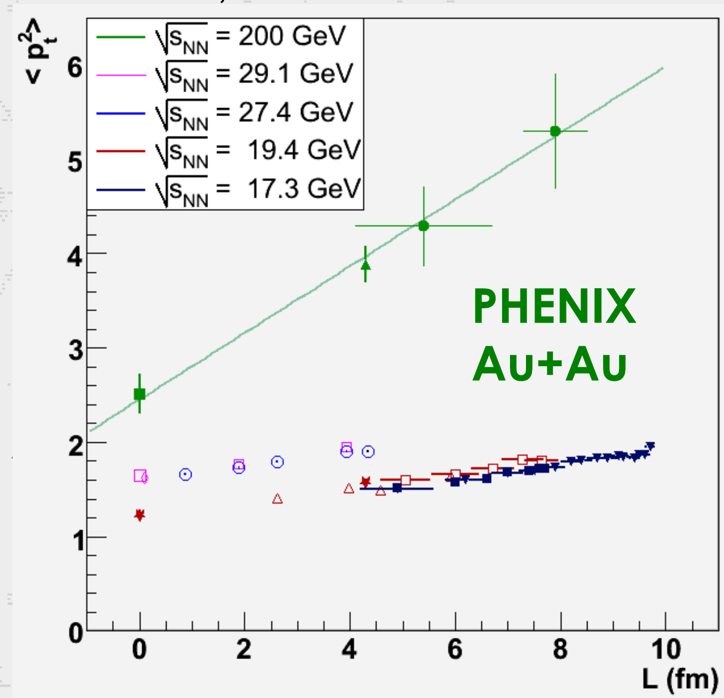
√s =17,3 GeV : NA50/60 Pb+Pb, In+In

√s = 19,4 GeV : NA3 p+p, NA38 p+Cu, p+U,O+U, S+U

√s = 27,4 GeV : NA50 p+Be, p+Al, p+Cu, p+W

√s = 29,1 GeV :NA51 p+p, p+d, NA50 p+Al, p+W

V-N Tram, Moriond 2006 & PhD thesis



At RHIC :

$\langle p_T^2 \rangle$ increases linearly with L

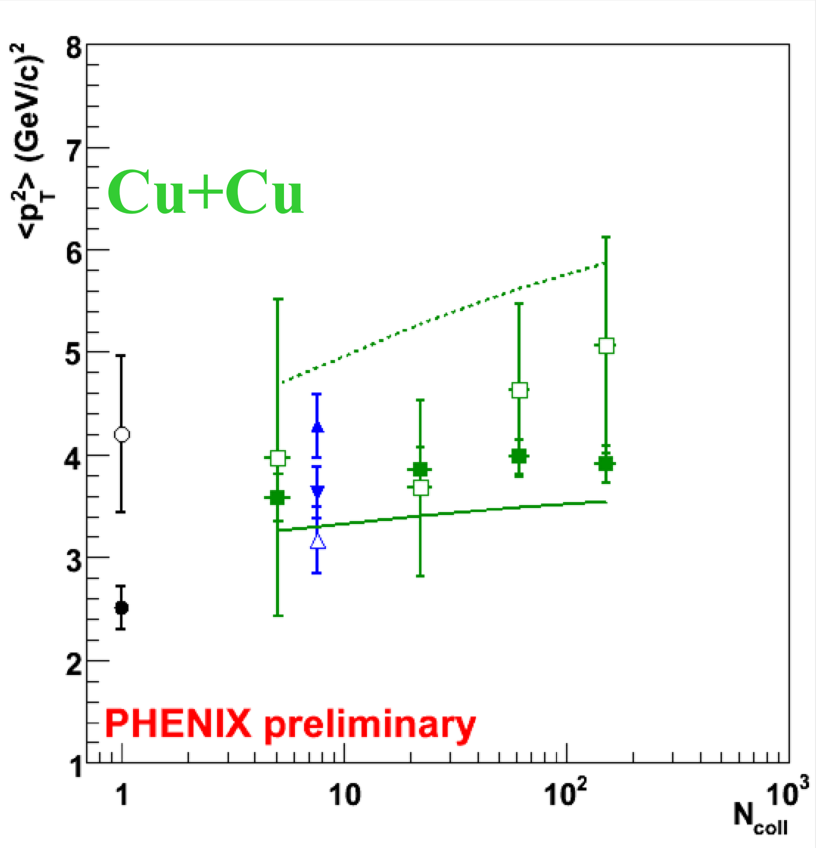
Cronin effect .vs. regeneration

- p_T spectrum

At forward rapidity, $<P_T^2>$ pattern compatible with Cronin effect.

At mid rapidity, observe a weak Cronin effect.

Need more precise measurements.



V-N Tram, Moriond 2006 & PhD thesis

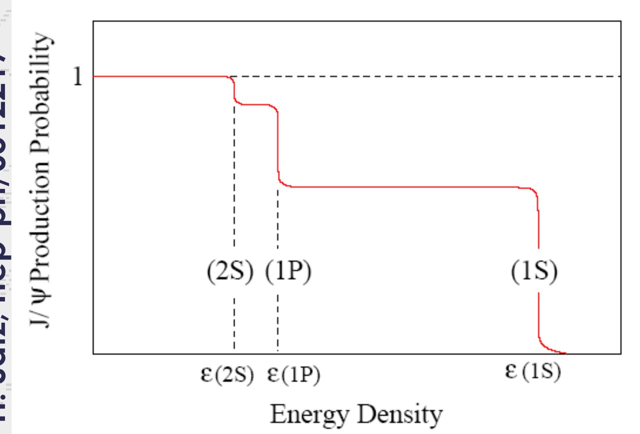
Sequential charmonium dissociation

→ Based on recent lattice QCD calculations, J/ψ melting temperature could be higher than initially expected ➔ suppression of direct J/ψ could be out of the range of RHIC

→ On the other hand χ_c and ψ' should melt at a temperature close to T_C (~1.1 – 1.2 T_C)

➔ **Anomalous suppression comes from χ_c and ψ' feed-down.**

H. Satz, Hep-ph/0512217



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

Quarkonium dissociation temperatures – Digal, Karsch, Satz

Karsch, Kharzeev and Satz, hep-ph/0512239

Overall J/ψ survival probability = measured/expected

direct J/ψ survival probability assume to be 1 at SPS energy

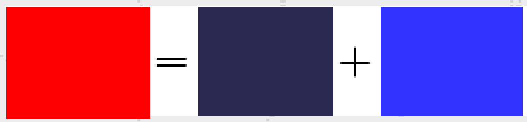
Feed-down J/ψ survival probablity

$$0.4\,S_x = 0.3\,S_{\chi_c} + 0.1\,S_{\psi'}$$

J/ψ feed-down :
- ~60% from direct production
- ~30% χ_c → J/ψ + γ
- ~10% ψ' → J/ψ + X

Sequential charmonium dissociation

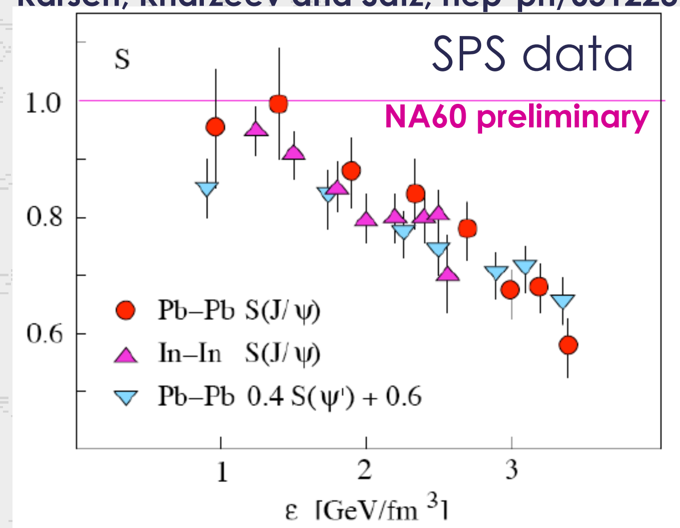
At SPS, NA50 measured :
- J/ψ suppression
- ψ' suppression
- but not χ_c



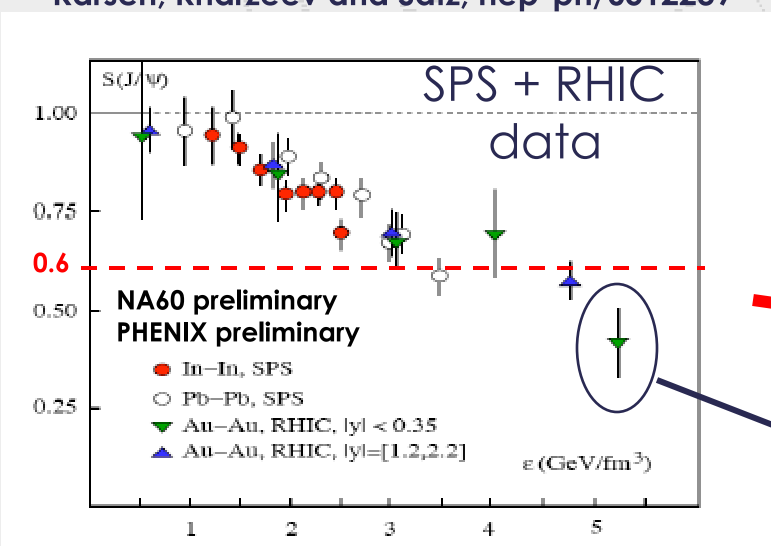
$$\approx 0.6 + 0.4\, S_{\psi'}$$

(Lattice QCD ➔ $S\psi' \sim S\chi_c$)

Karsch, Kharzeev and Satz, hep-ph/0512239



Karsch, Kharzeev and Satz, hep-ph/0512239



At RHIC, PHENIX measured :
- J/ψ suppression

data look consistent with sequential charmonium dissociation at both RHIC and SPS

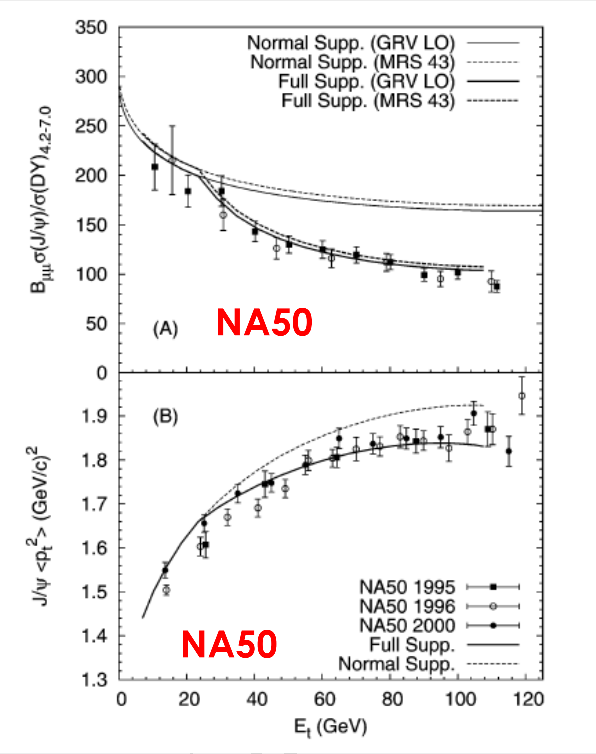
More data needed

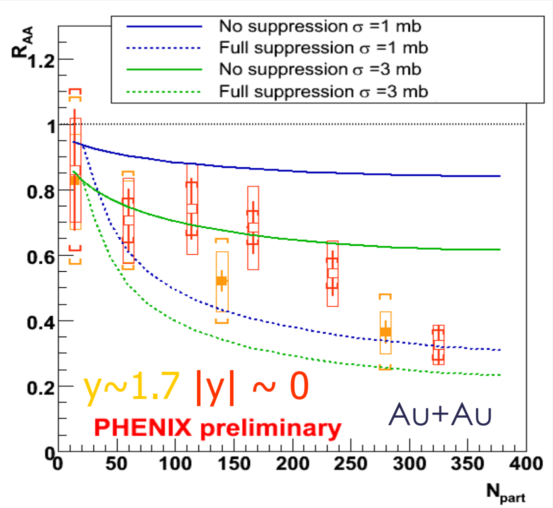
J/ψ transport model

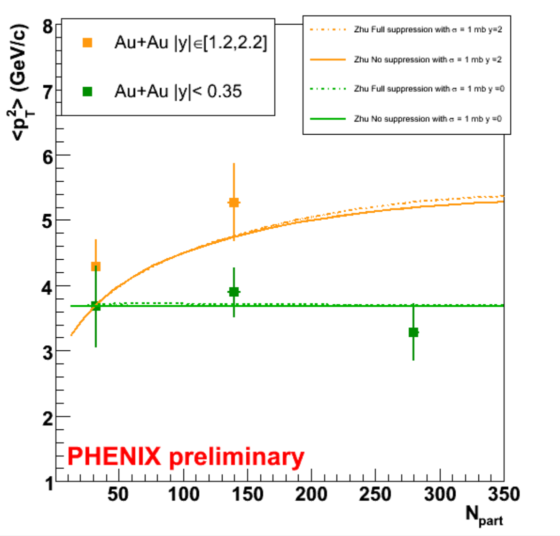
Model includes :

- **Detailed QGP hydro**
- **J/ψ transport**
- **normal nuclear absorption**

Zhu, Zhuang, Xu, PLB607 (2005) 107







QGP hydro + J/ψ transport

→Reasonnable agreement with observed suppression

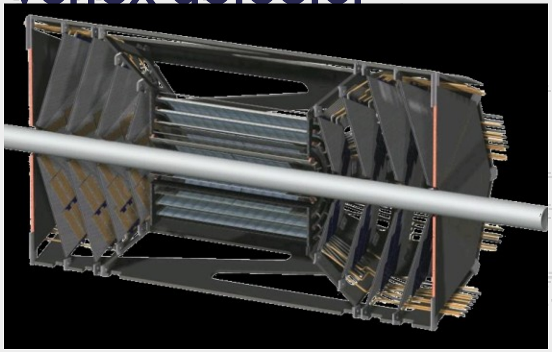
→Reproduce p_T

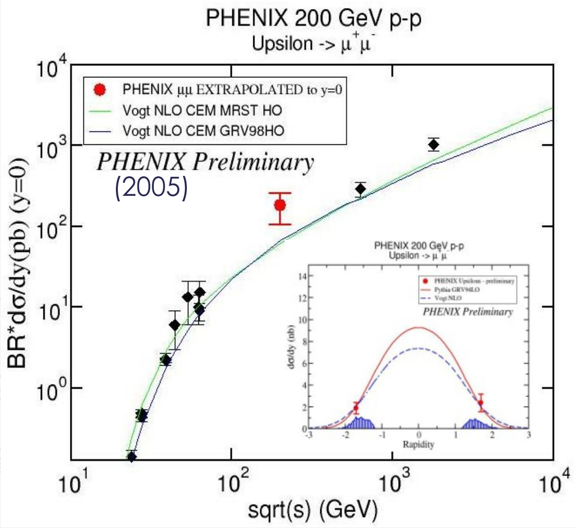
Summary…

- Since 1986, J/ψ, as a probe for QGP, has been extensively studied both theoritically and experimentally
  - At SPS, NA50 observed an anomalous suppression in Pb+Pb data (also observed by NA60 in In+In)
  - At RHIC, PHENIX observed a similar anomalous suppression in Au+Au and Cu+Cu (but cold nuclear effets could be different).
- Model(s)
  - assuming a direct suppression of J/ψ as well as hadronic suppression fail to reproduce RHIC data.
  - Involving J/ψ regeneration → reasonnable agreement with suppression but still open questions : pT and rapidity distributions ? J/ψ flow ?
  - Involving QGP hydro + J/ψ transport → reasonnable agreement with suppression; reproduce p_T ; predictions for J/ψ flow
  - Assuming Sequential suppression seems consistant with the data

...and outlook

- More things to come
  - Final A+A results
  - p+p 2005 (x10 compare to 2003) and p+p 2006 (x3 compare to 2005) data
- Need
  - More d+A to understand cold nuclear effects
  - More A+A data
    - ✓ More centrality bins, J/ψ flow
    - ✓ Investigate ψ', χ_c, and Υ
- PHENIX upgrade
  - New Si vertex detector





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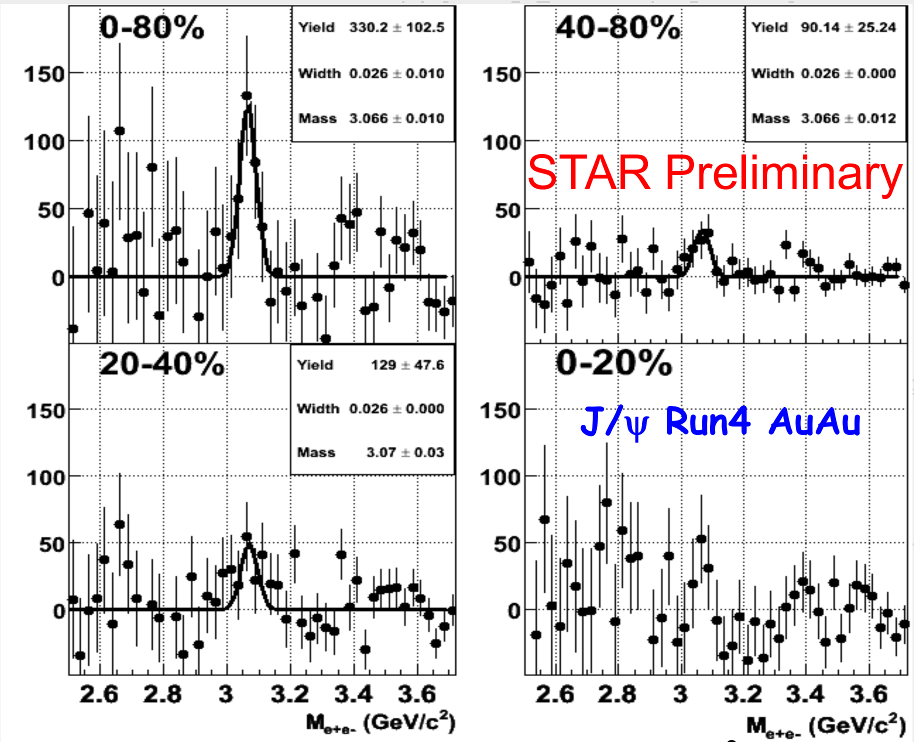
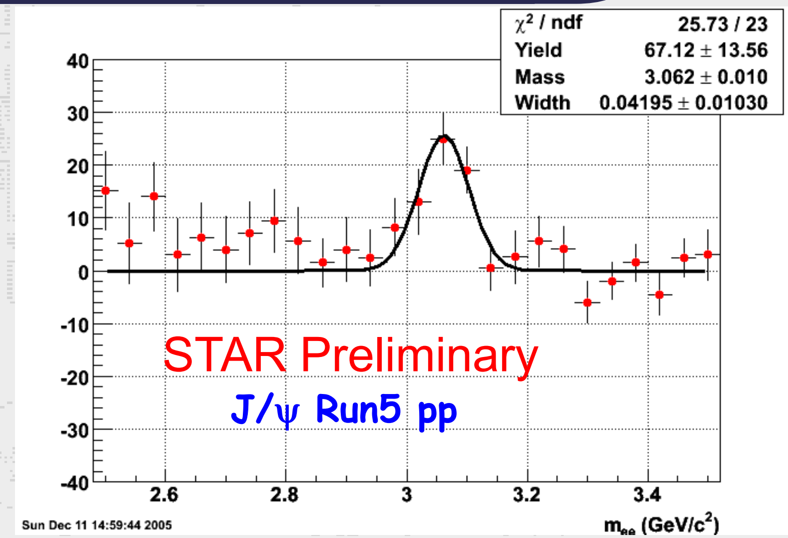
*as of March 2005

Backup slides

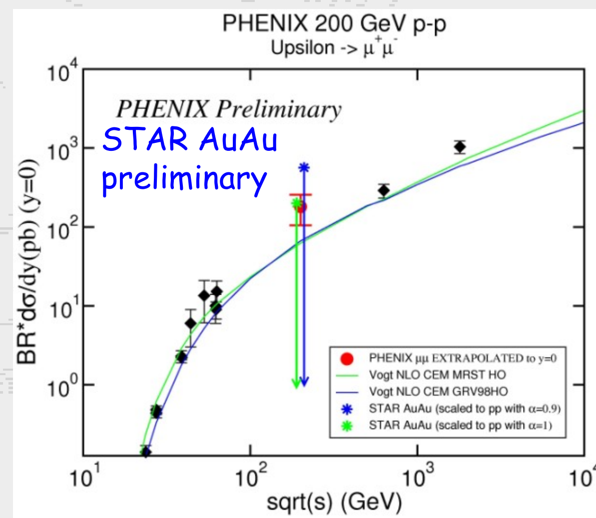
J/ψ in STAR



Dielectron Invariant Mass (GeV/c²)



Dielectron Invariant Mass (GeV/c²)



(J. Gonzalez, SQM, 2006)

J/ψ flow

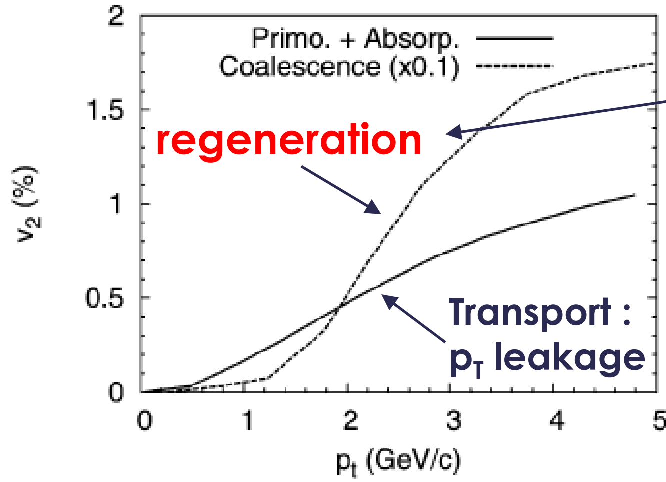


Fig. 4. The elliptical flow of J/ψ as a function of p_t at RHIC energy. The solid line is the maximal v_2 with impact parameter $b = 7.8$ fm calculated in the frame of J/ψ transport, and the dashed line is the minimum-bias v_2 (scaled by a factor of 0.1) of the coalescence model with the assumption of complete charm quark thermalization.

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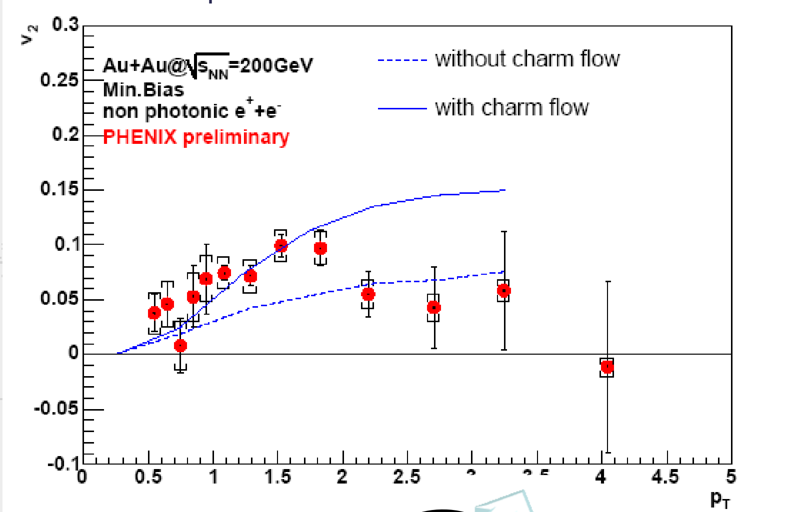
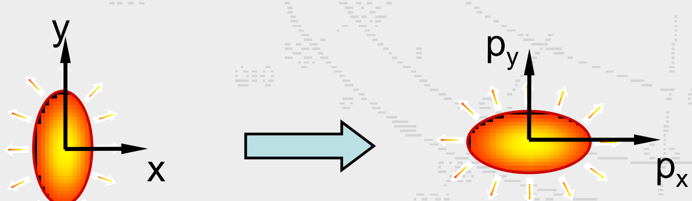
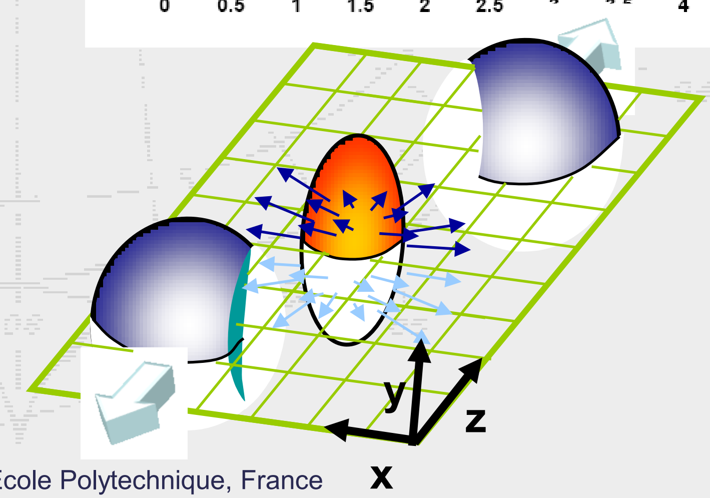
c quarks flow







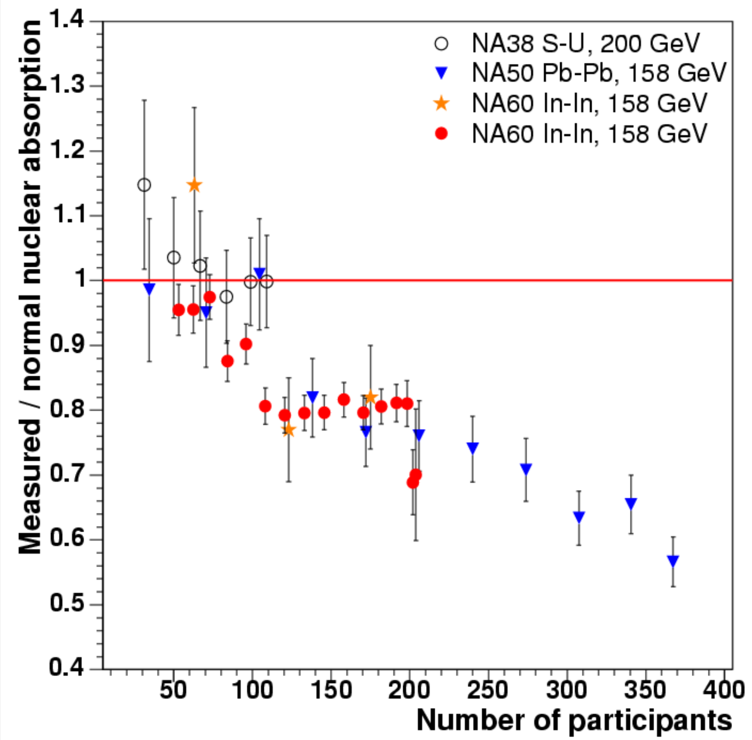
$$\frac{dN}{d\varphi dp_T} = 1 + v_2(p_T)\cos(2\varphi)$$

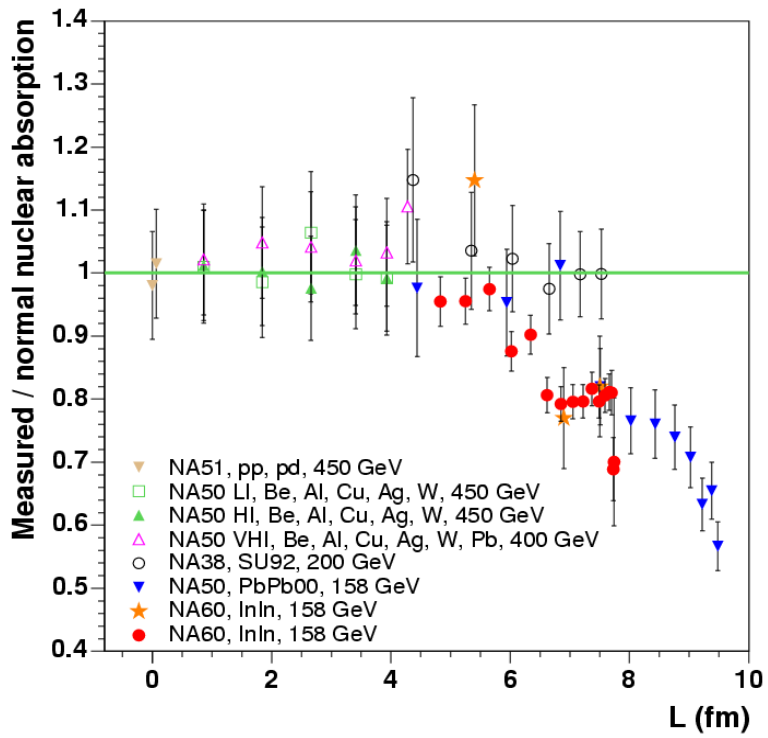
$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

J/ψ in PHENIX

	Year	Ions	√s [GeV]	∫Ldt	Number of J/Ψ	Data Size
Run 1	2000	Au+Au	130	1 μb^{-1}	0	3 TB
Run 2	2001	Au+Au	200	24 μb^{-1}	13 + 0	10 TB
	2002	p+p	200	0.15 pb^{-1}	46 + 66	20 TB
Run 3	2002	d+Au	200	2.74 nb^{-1}	300 + 1400	46 TB
	2003	p+p	200	0.35 pb^{-1}	100 + 420	35 TB
Run 4	2004	Au+Au	200	241 μb^{-1}	~600 + 5000	270 TB
			62.4	9.1 μb^{-1}	50 expected	10 TB
		p+p	200	324 nb^{-1}		
Run 5	2005	Cu+Cu	200	3 nb^{-1}	~1200+10000	173 TB
			62.4	0.19 nb^{-1}	~40+200	48 TB
			22.5	9.1 μb^{-1}		1 TB
		p+p	200	3.8 pb^{-1}	> 6500 expected	262 TB

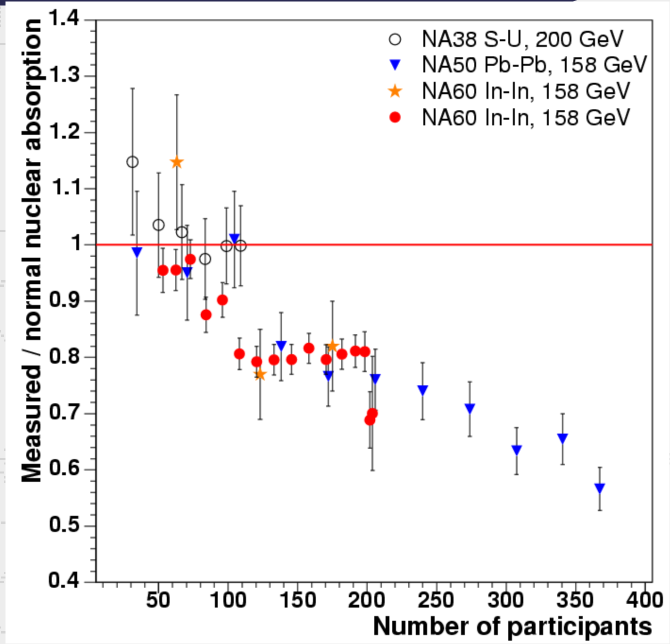
NA50 versus NA60 (QM05)

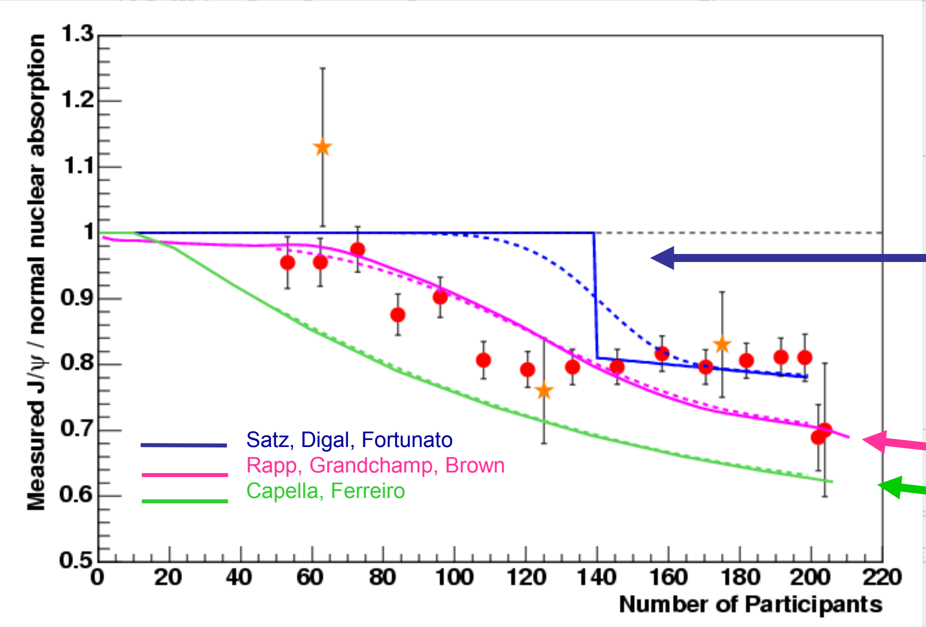


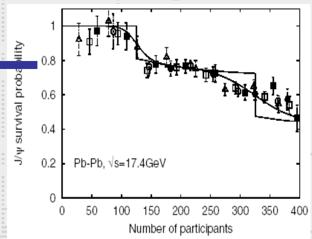


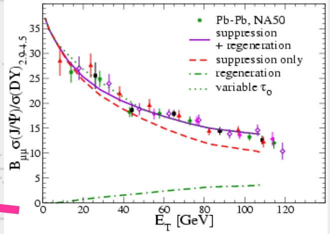
J/ψ at SPS (QM05)

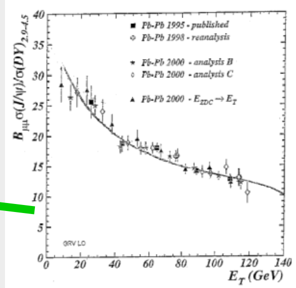
- J/ψ in NA60 poorly reproduced by models which fit NA50 data











Computing the J/Ψ yield

Invariant yield :

i : i-th bin (centrality for e.g.)

$N^i_{J/\psi}$: number of J/ψ s reconstructed

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

N^i_{MB} : total number of events

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

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

For Au+Au or Cu+Cu collision : $\varepsilon^{MB}_{BBC} \sim \varepsilon^{J/\psi}_{BBC}$