J/Ψ's at RHIC

W.A. Zajc
Columbia University

With thanks to my PHENIX (and other RHIC) colleagues,
and special thanks to
V. Cianciolo, M. Leitch, Hugo Pereira Da Costa, V.N. Tram, W. Xie

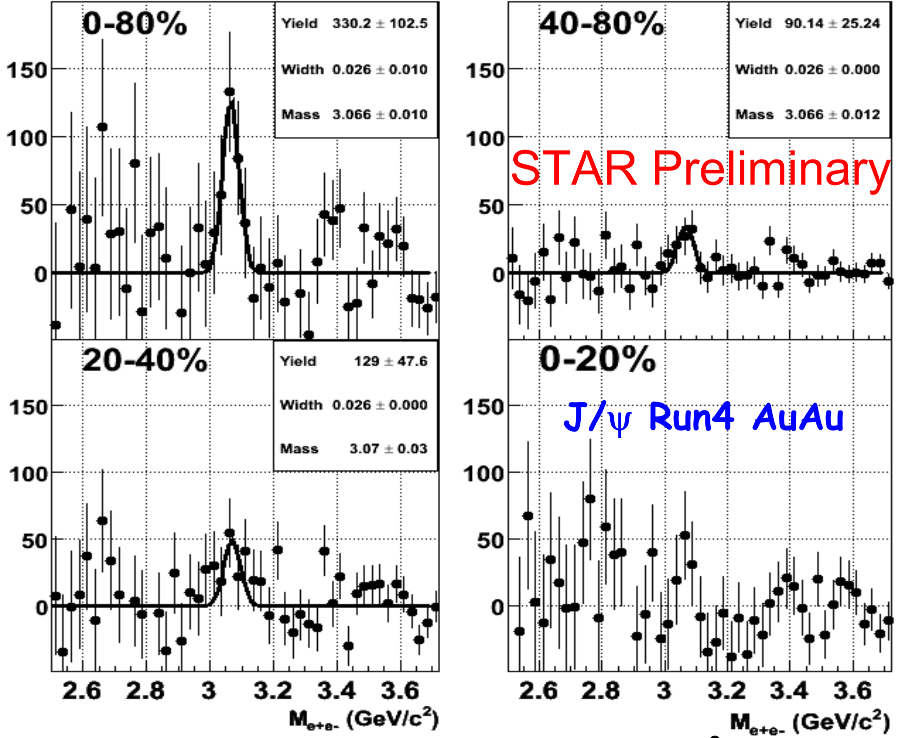
See especially *Quarkonia Production at RHIC*, M. Leitch, SQM 2006.

Outline

- *Experiments*
- *Yields*
- *Ratios*
- *Models*
- *Future*
- *Helmut*

Experiments

Charmonium and Beyond in STAR

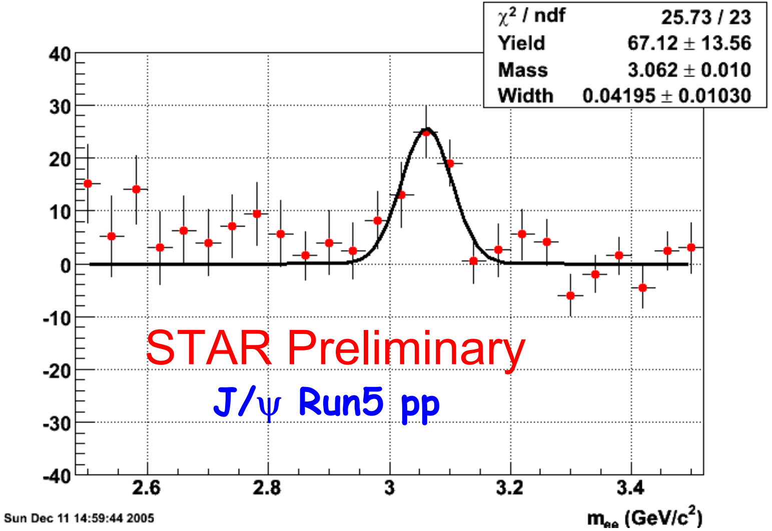


STAR Preliminary

J/ψ Run4 AuAu

Dielectron Invariant Mass (GeV/c^2)

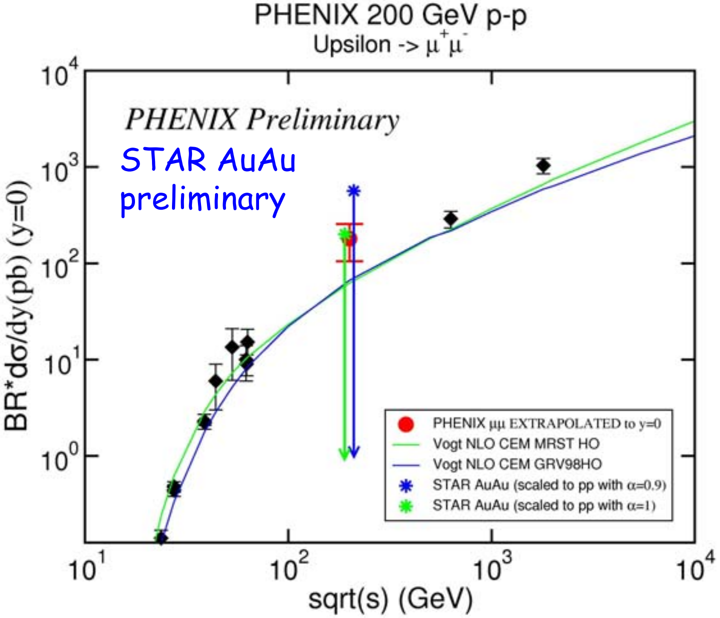
J. Gonzalez, SQM



STAR Preliminary

J/ψ Run5 pp

Dielectron Invariant Mass (GeV/c^2)



STAR AuAu preliminary

Signal	RHIC Exp. (Au+Au)	RHIC I (>2008)	RHIC II	LHC ALICE⁺
J/ψ →e⁺e⁻ J/ψ →μ⁺μ⁻	PHENIX	3,300 29,000	45,000 395,000	9,500 740,000
Υ→ e⁺e⁻ Υ→ μ⁺μ⁻	STAR PHENIX	830 80	11,200 1,040	2,600 8,400

(Compilation courtesy of M. Leitch, Strange Quark Matter, 2006)

The PHENIX detector

Central arms:

hadrons, photons, electrons

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

$p > 0.2$ GeV/c

$|y| < 0.35$

$\Delta\phi = \pi$

Muon arms:

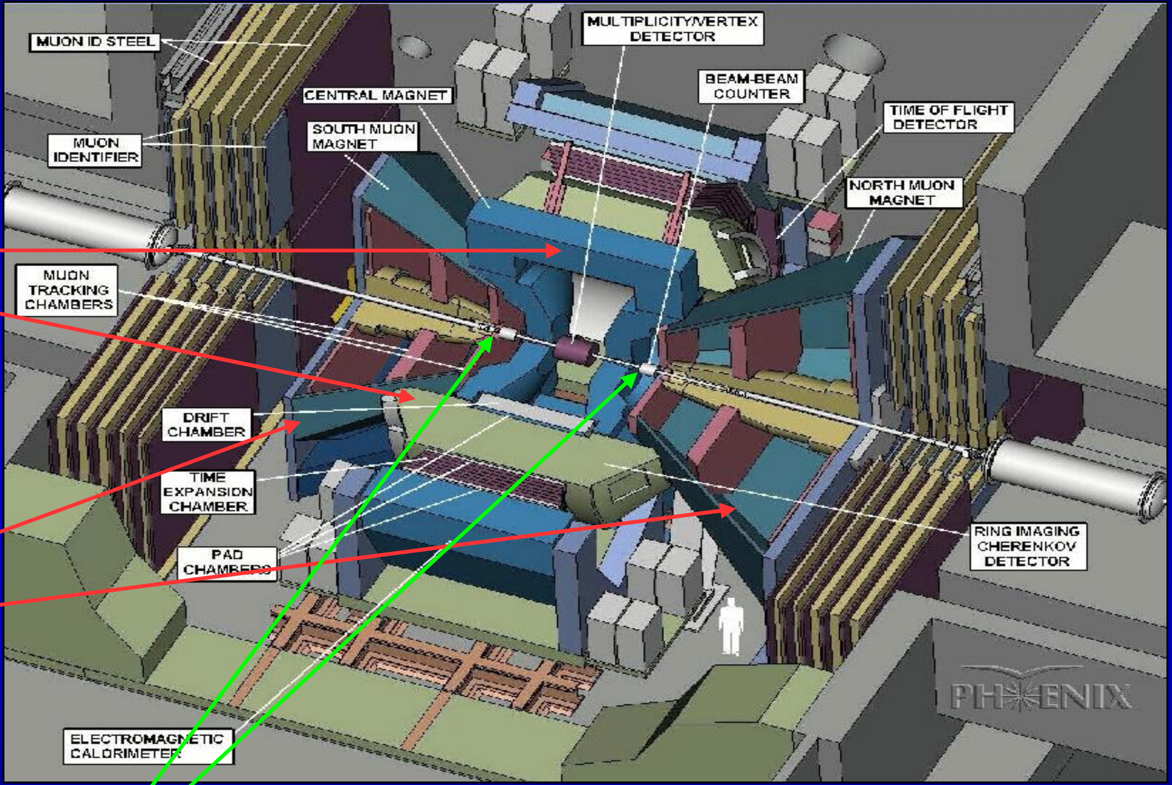
muons at forward rapidity

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

$p > 2$GeV/c

$1.2 < |y| < 2.4$

$\Delta\phi = 2\pi$

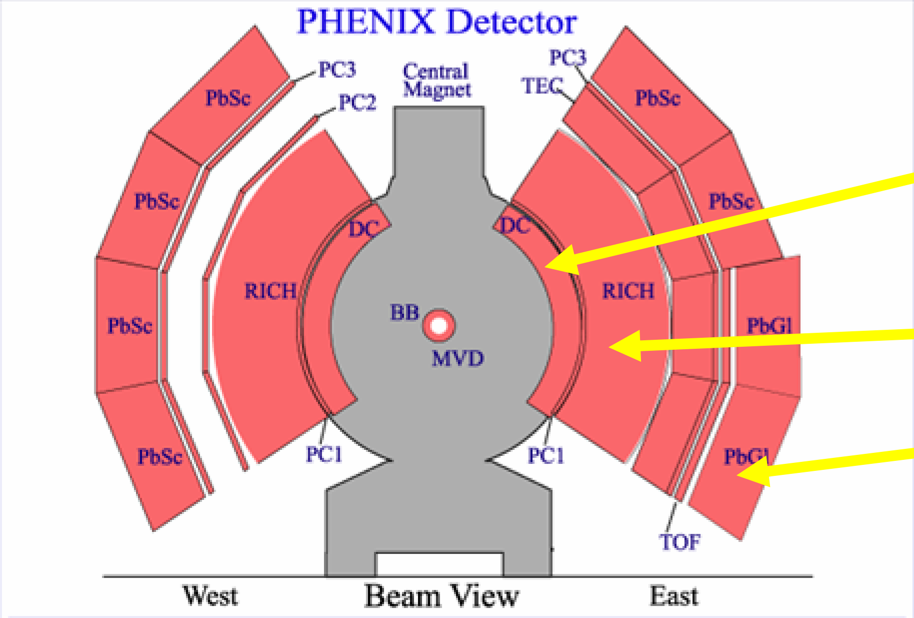


Centrality measurement:

We use beam beam counters together with zero degree calorimeters

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

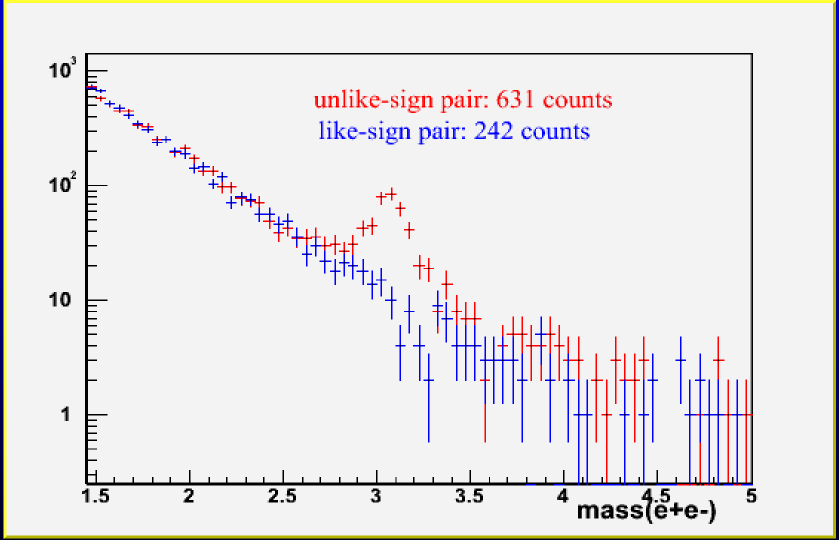
How PHENIX Measures J/ψ's

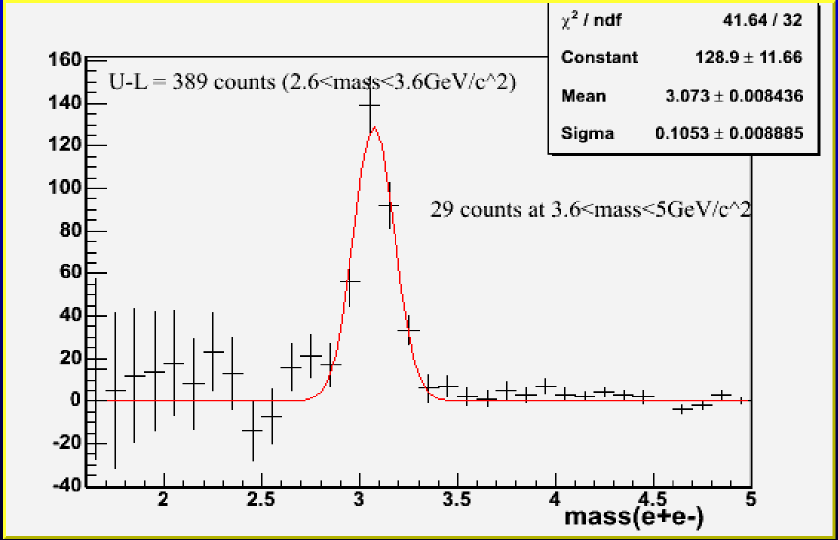


- High resolution tracking and momentum measurement from Drift chamber.

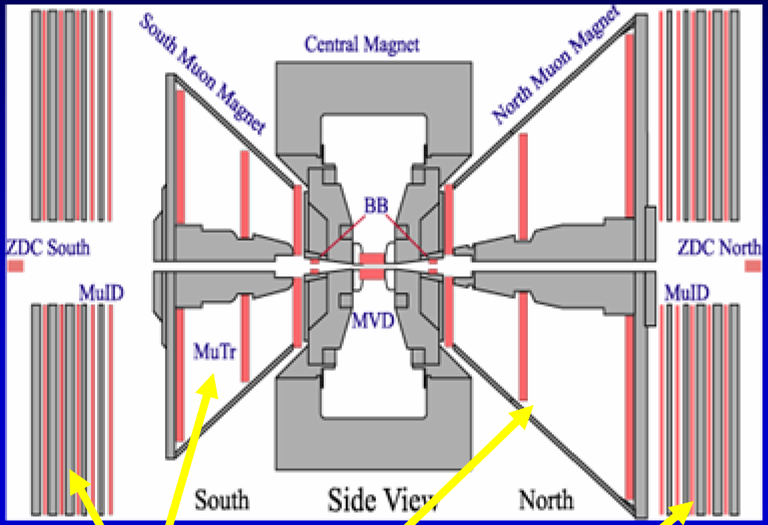
Good electron identification from Ring Imaging Cherenkov detector (RICH) and Electromagnetic Calorimeter (EMCal).

High rate capability: powerful level-1 electron trigger



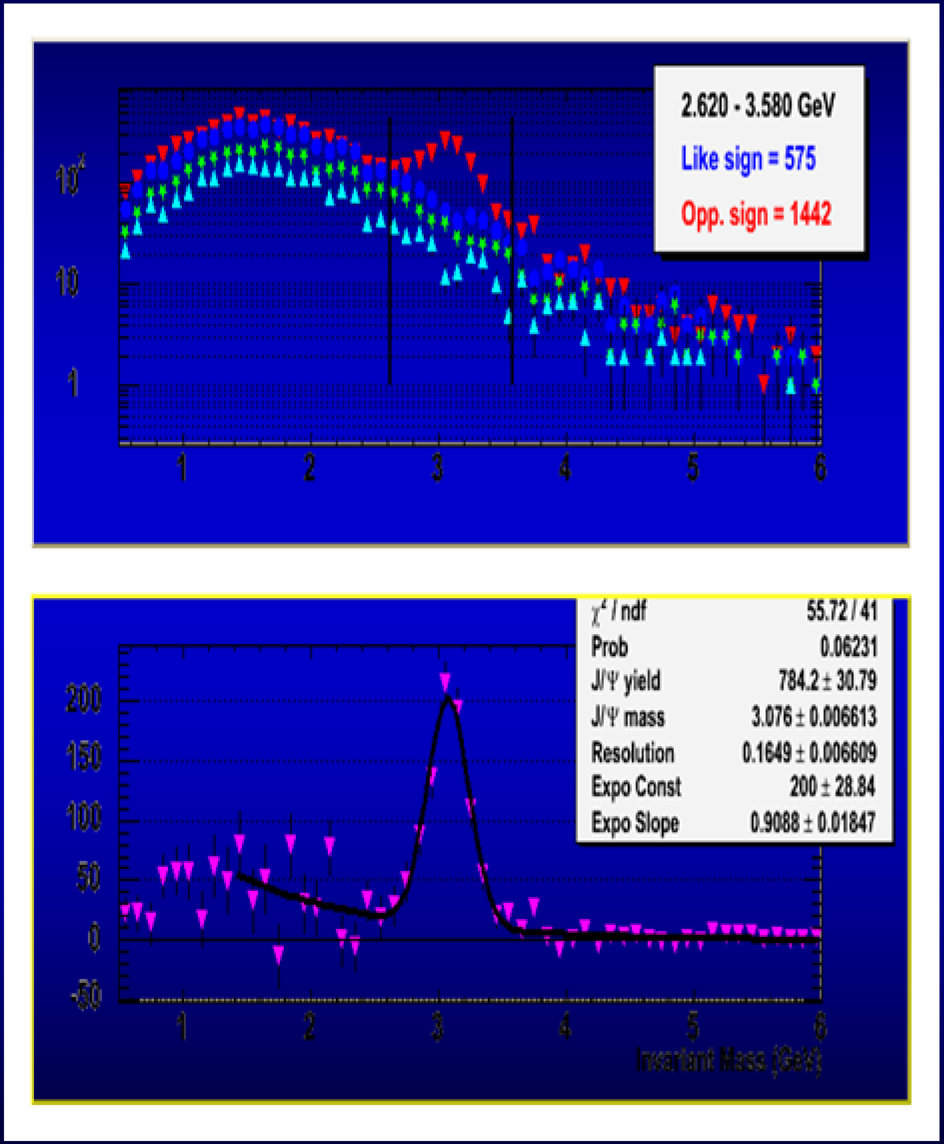


How PHENIX Measures J/ψ's



Good momentum resolution and muon identification from μTrk and μID.

High rate capability: powerful level-1 dimuon trigger

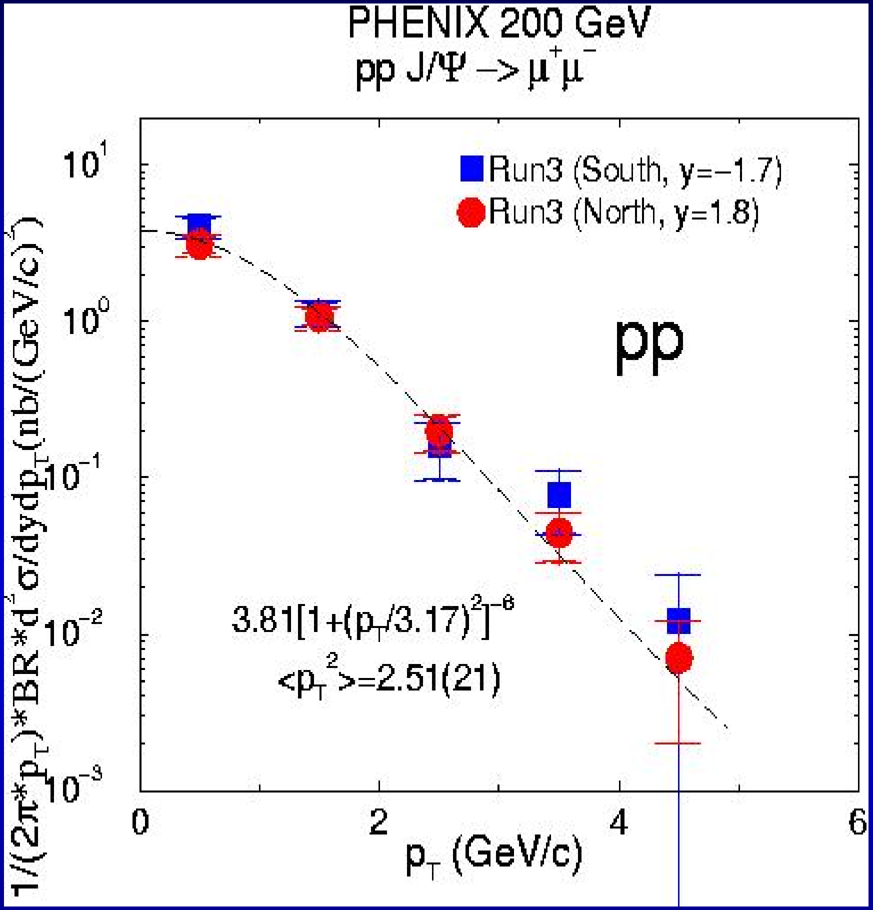


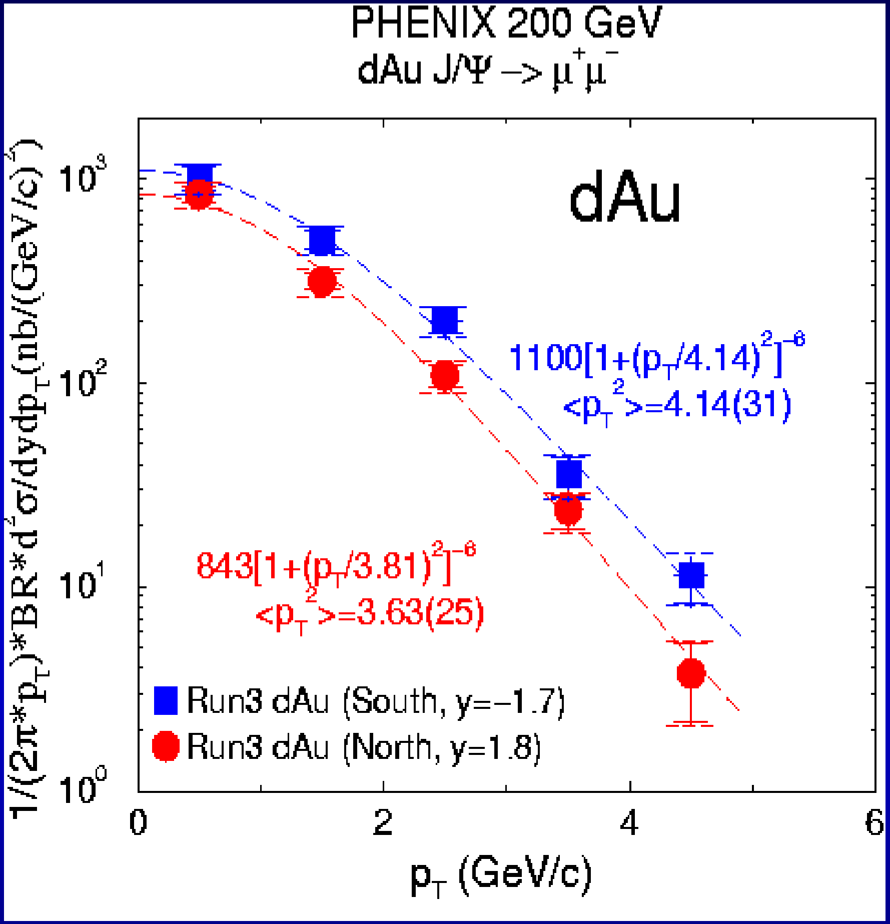
PHENIX Data Sets

Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{Tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB
05	2004/2005	Cu+Cu	200	3 nb^{-1}	8.6G	11.9 pb^{-1}	173 TB
		Cu+Cu	62	0.19 nb^{-1}	0.4G	0.8 pb^{-1}	48 TB
		Cu+Cu	22.5	2.7 μb^{-1}	9M	0.01 pb^{-1}	1 TB
		p+p	200	3.8 pb^{-1}	85B	3.8 pb^{-1}	262 TB

Yields

Cross sections vs p_T (p+p, d+Au)

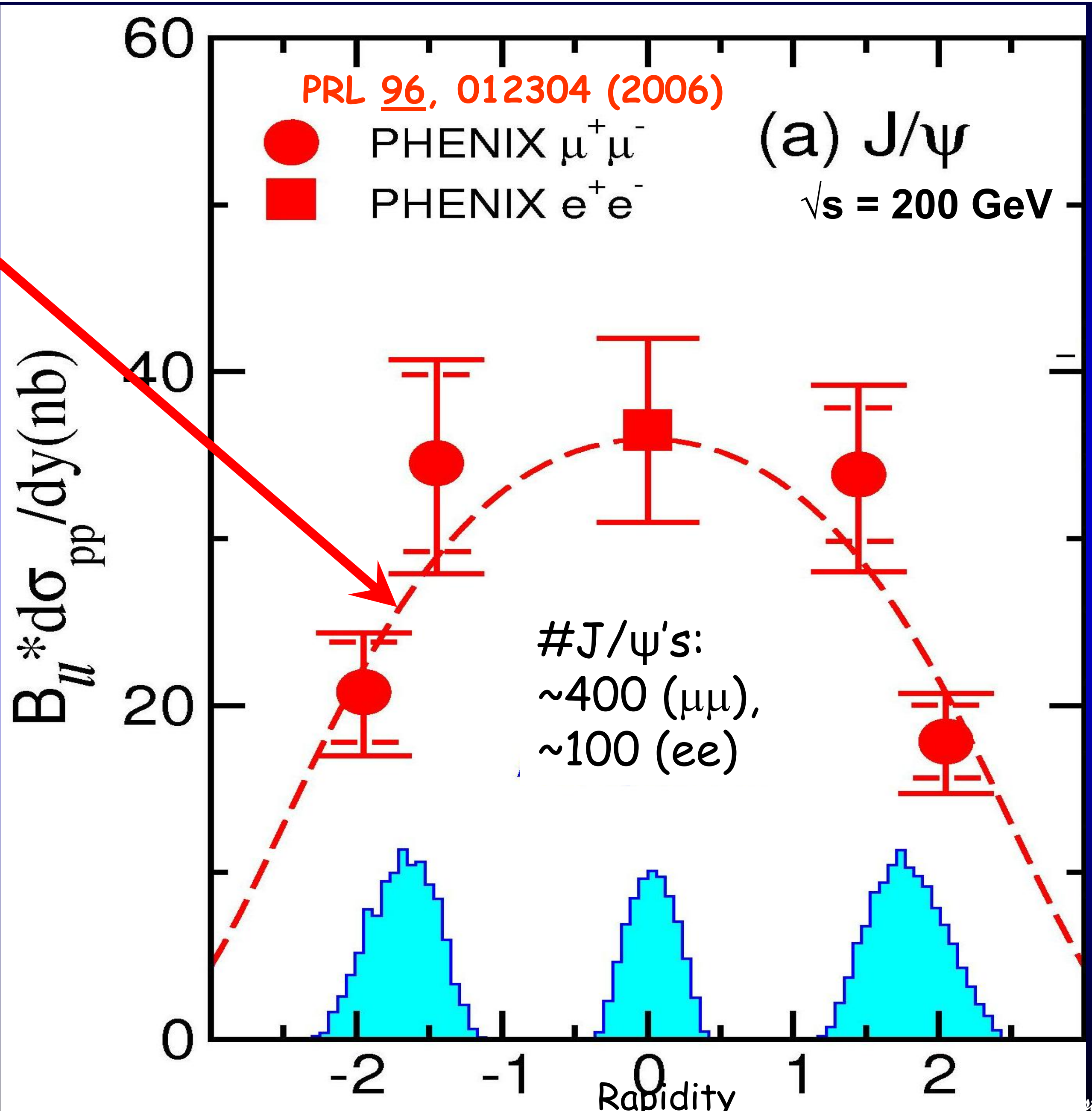




Fits to $\frac{dn}{p_T dp_T} \sim A[1+(p_T/B)^2]^{-6}$ used to extract $<p_T>^2$

Cross section vs Rapidity (p+p)

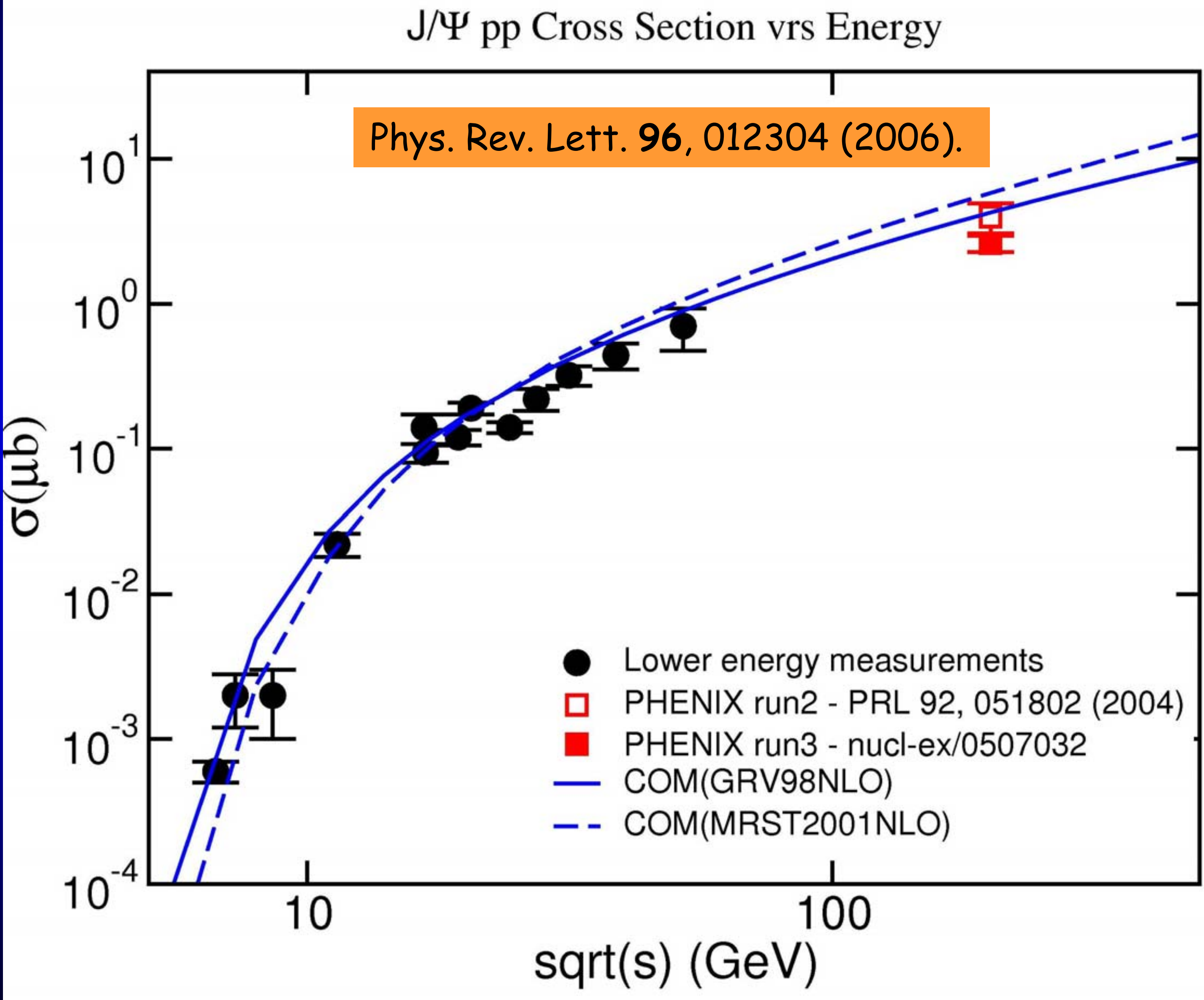
- Good agreement with PYTHIA shape
- These are Run-3 data
- Run-5: ~ x 10
- Run-6:
  ~ Run-5 today, expected to double


PRL 96, 012304 (2006)

#J/ψ's:
~400 (μμ),
~100 (ee)

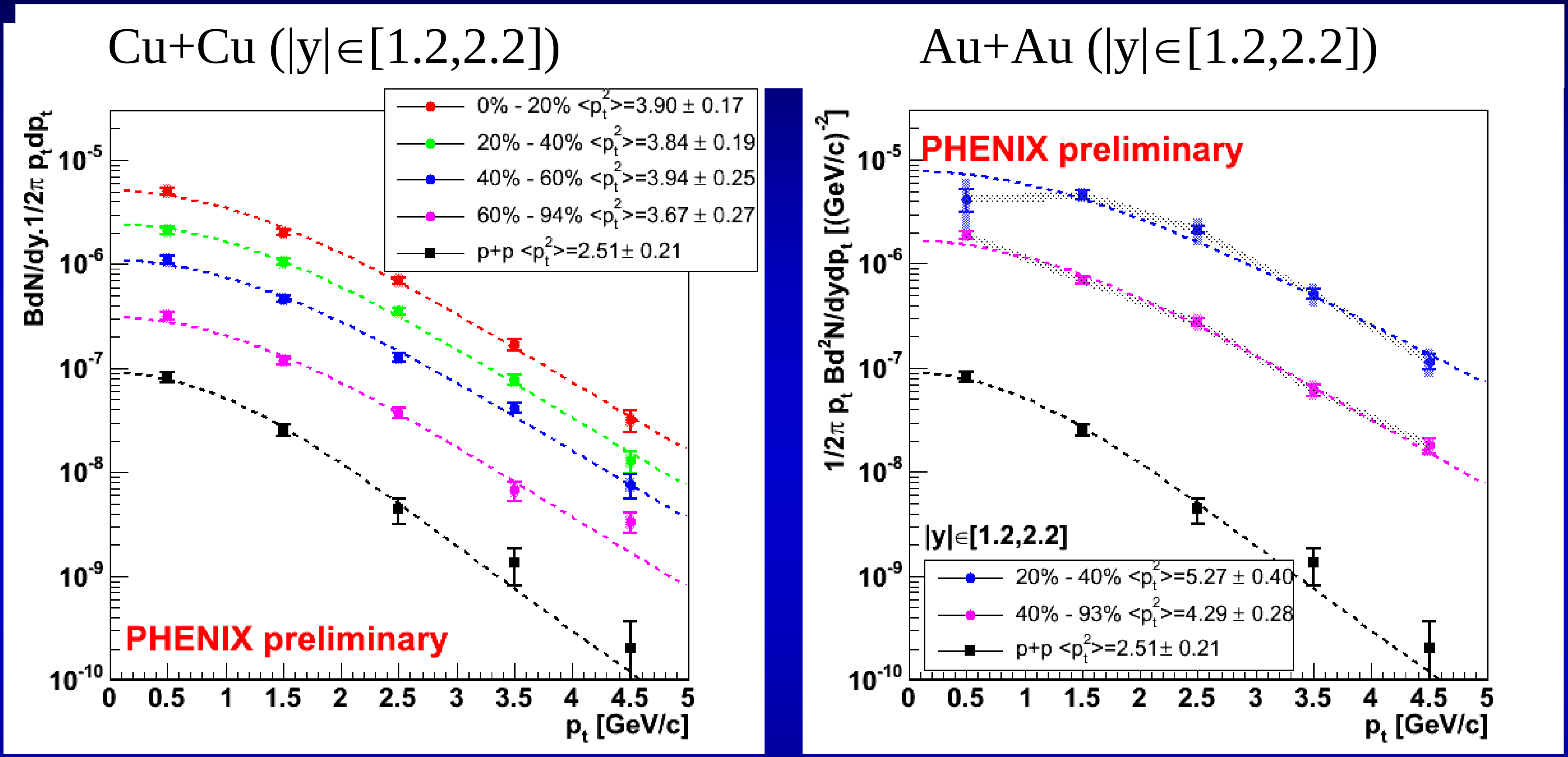
p+p Reference

- Consistent with trend of world’s data
- ~Consistent with at least one COM (Color Octet Model) calculation



Phys. Rev. Lett. **96**, 012304 (2006).

Invariant yields vs p_T (A+A)


Cu+Cu (|y|∈[1.2,2.2])

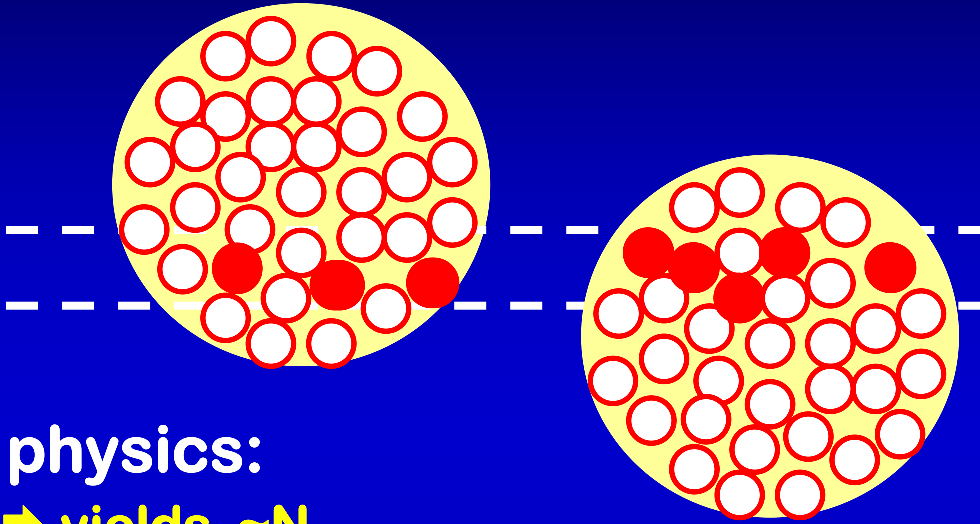
Au+Au (|y|∈[1.2,2.2])

Fits to $\frac{dn}{p_T dp_T} \sim A[1+(p_T/B)^2]^{-6}$ used to extract $\langle p_T\rangle^2$

Ratios

Basis for Comparison

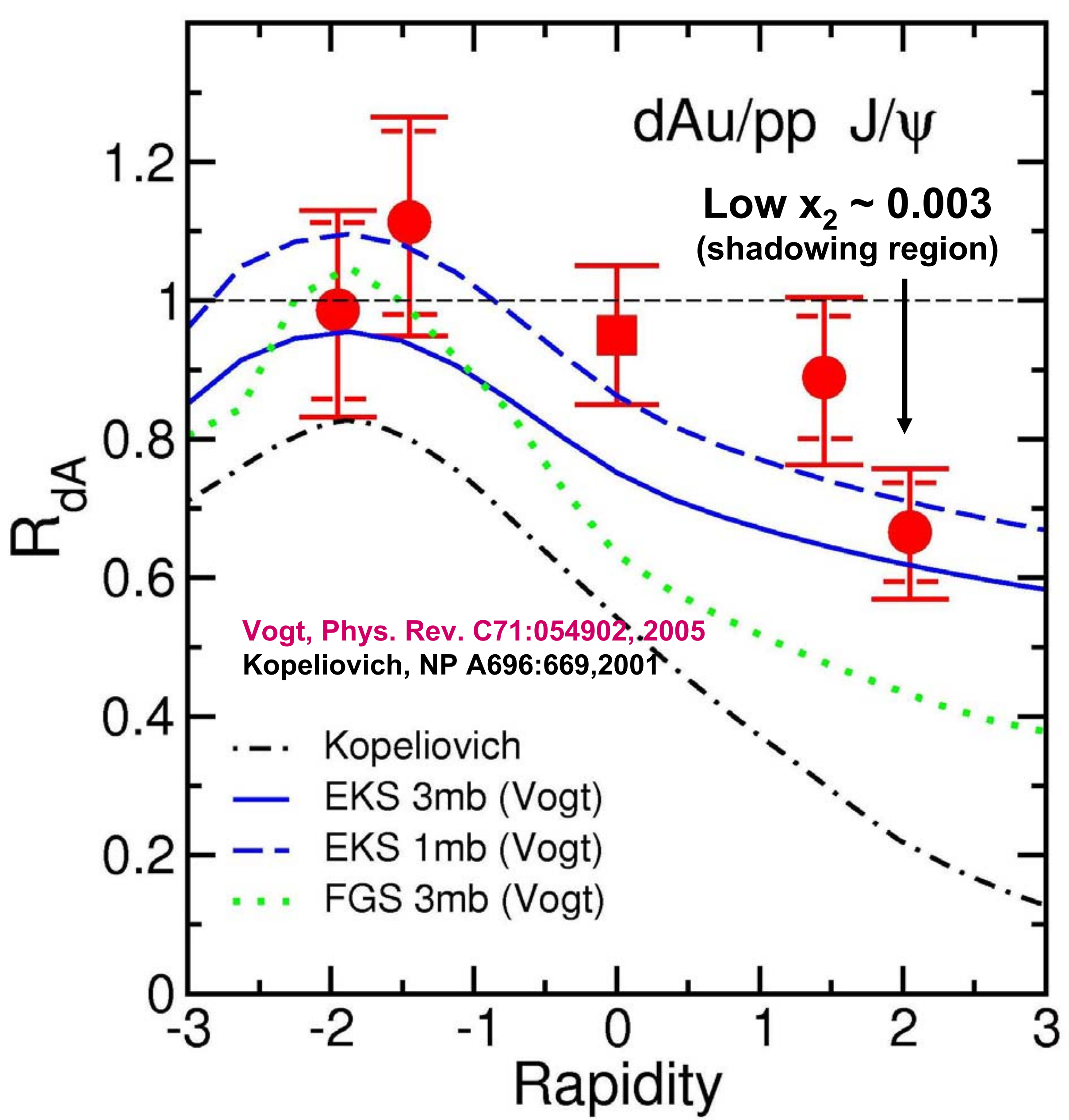
- Focus on some slice of collision:
  - Assume 3 nucleons struck in A, and 5 in B
  - Could weight contribution as
    - $N_{part} \equiv 3 + 5$
    - $N_{coll} \equiv 3 \times 5$



- Choice driven by underlying physics:
  - Low p_T ➡ large cross sections ➡ yields $\sim N_{part}$
    - Soft, non-perturbative, “wounded nucleons”, ...
  - High p_T ➡ small cross sections ➡ yields $\sim N_{coll}$
    - Hard, perturbative, “binary scaling”, point-like, A*B, ...
- J/Ψ’s are complicated ...
  - (This a general theme of what follows)
  - Will use N_{coll} to *form* ratios R_{dA} and R_{AA}
  - Will *present* same as functions of both N_{part} and N_{coll}

Cold Nuclear Matter (CNM)

- Modest nuclear effects as a function of rapidity
  - Suppression for low x_2 ~0.003 (x_{Au})
  - No suppression for higher x_2 ~0.02-0.09
- Modest agreement with models incorporating shadowing and absorption



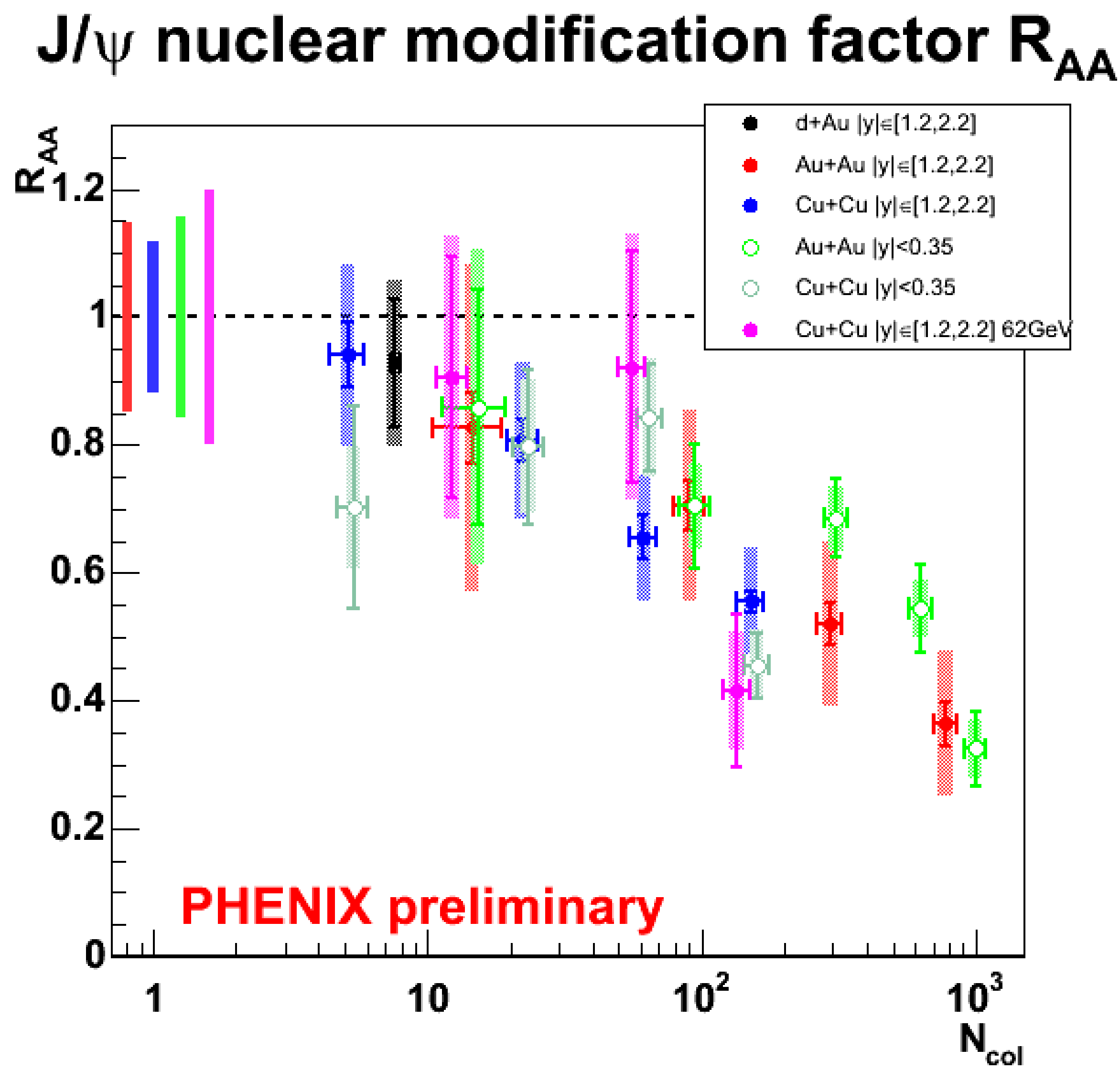
Vogt, Phys. Rev. C71:054902, 2005
Kopeliovich, NP A696:669,2001

Hot Nuclear Matter

- Good agreement between
  - Au+Au (muons, red)
  - Cu+Cu (muons, blue)

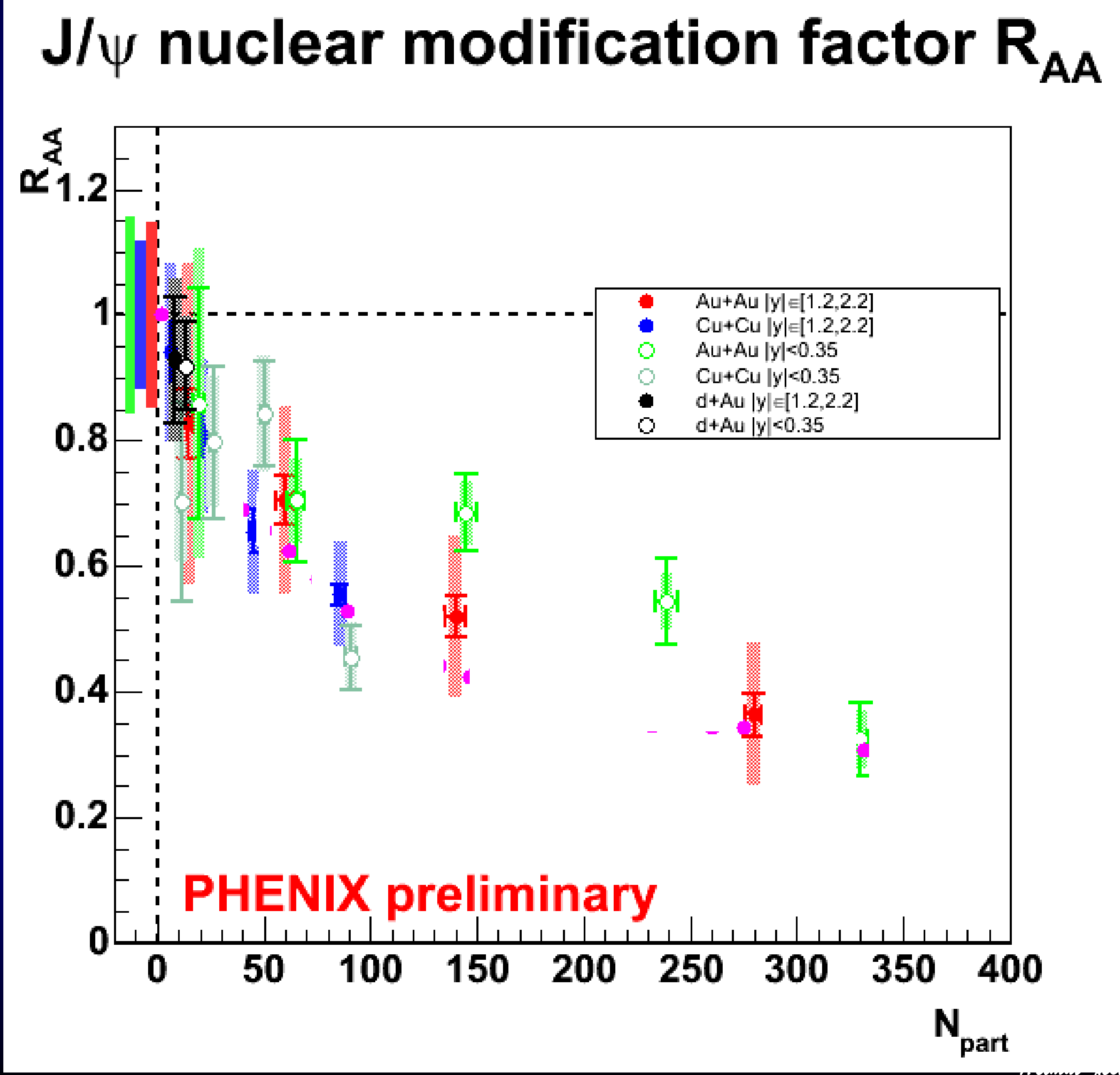
    in overlap region
- Central arm data
  - Au+Au (green)

    slightly higher(?) than muon arms
  - Note different rapidity intervals
    - Central |y| < 0.35
    - Muons |y| ∈ [1.2,2.2]
- “Large” suppression effects in A+A



Large Compared to What?

- "Large", of course, with respect to the d+A reference data
- Comparable to the "large" suppression observed by NA50
- (Note change of horizontal axis to N_{part})

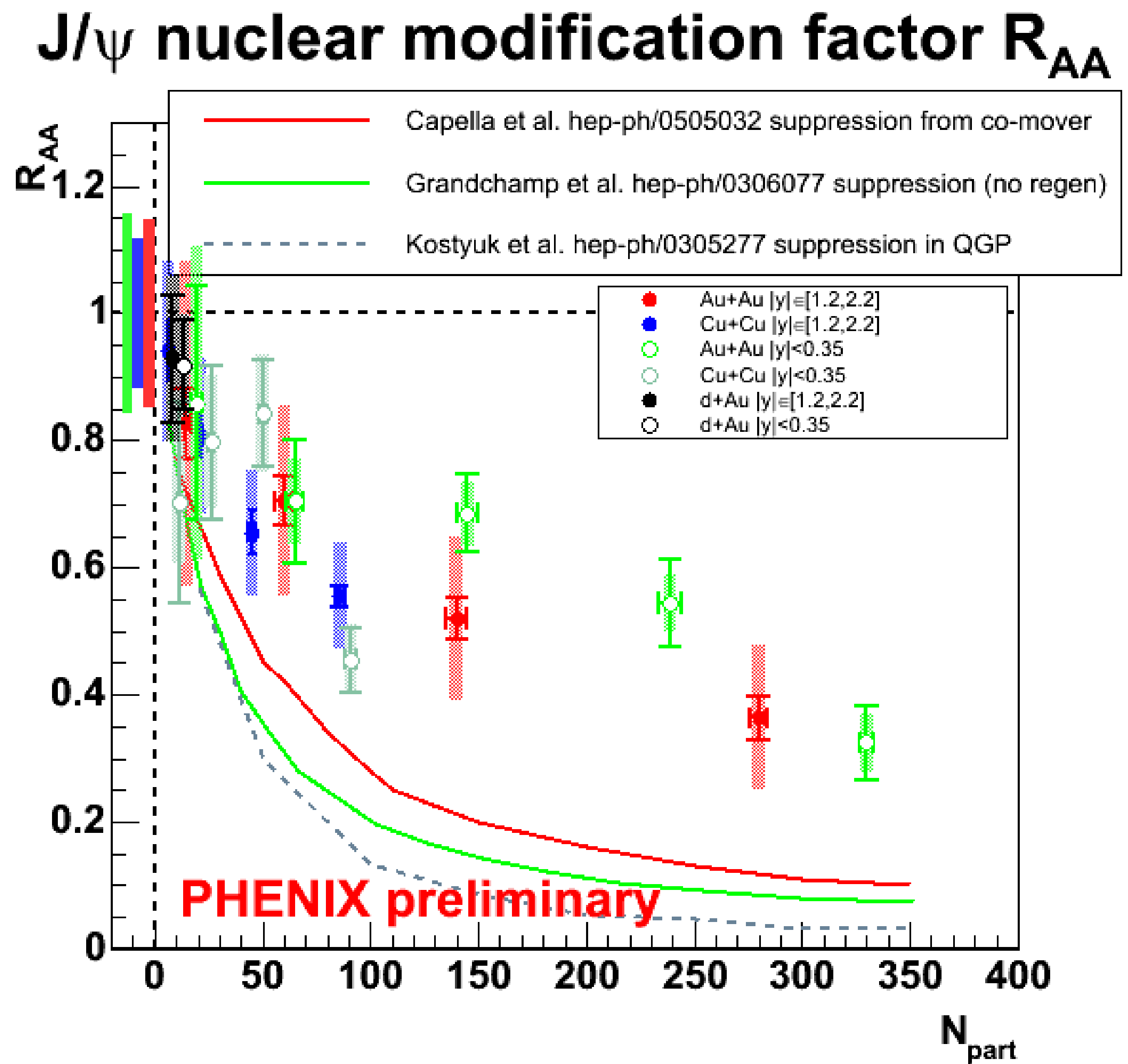


But Not Truly "Large"

- That is:

  Much smaller suppression effects than expected based on scaling from SPS to RHIC energies

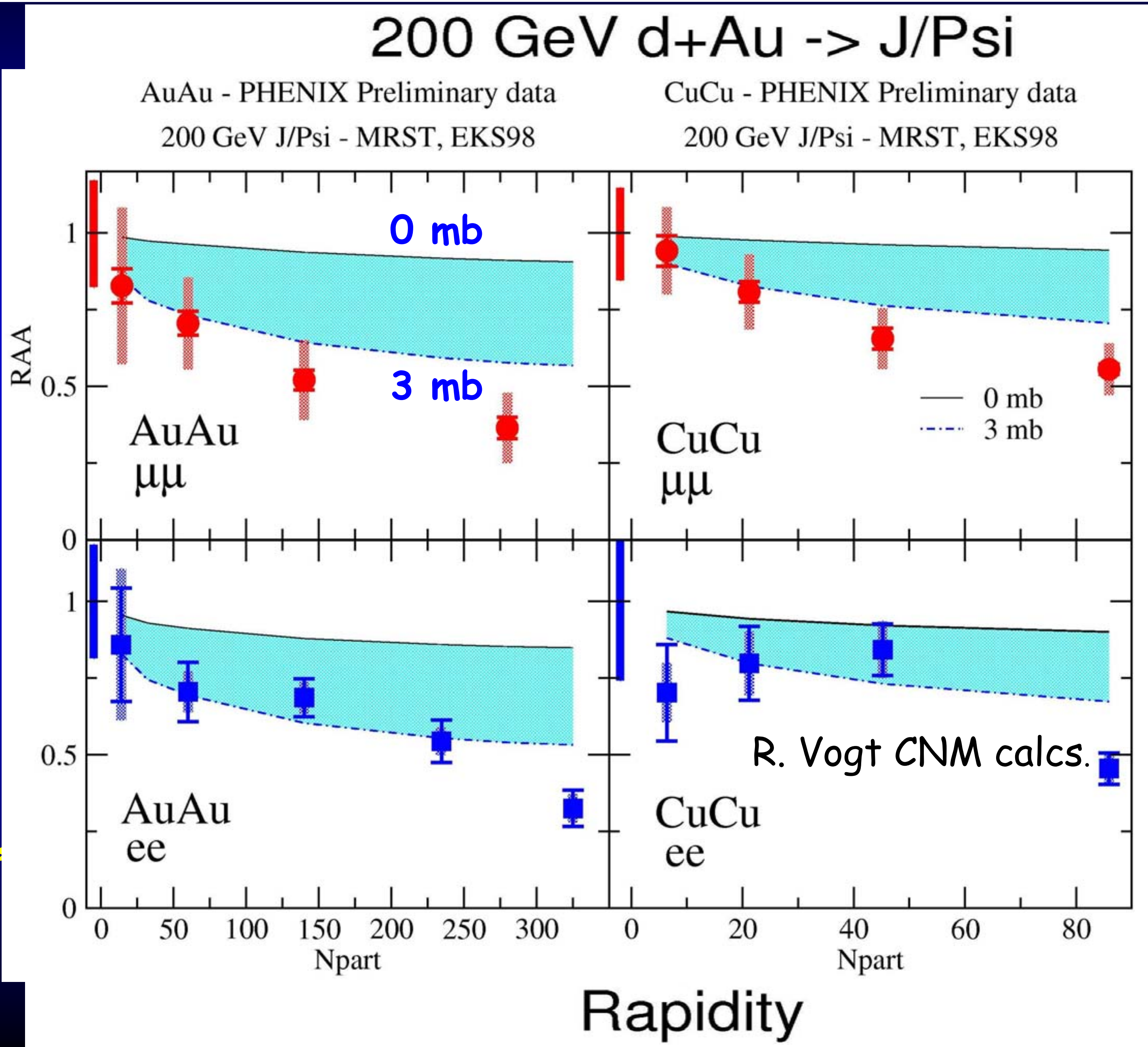
- Without "new" mechanisms



Models

Modeling "normal" suppression

- **Input:**
  - ☐ "EKS" shadowing
  - ☐ Absorption cross-section σ_{abs}
- **Output:**
  - ☐ Only modest constraints on value of σ_{abs}
  - ☐ Improvement needed as "background" other mechanisms


200 GeV d+Au -> J/Psi

0 mb

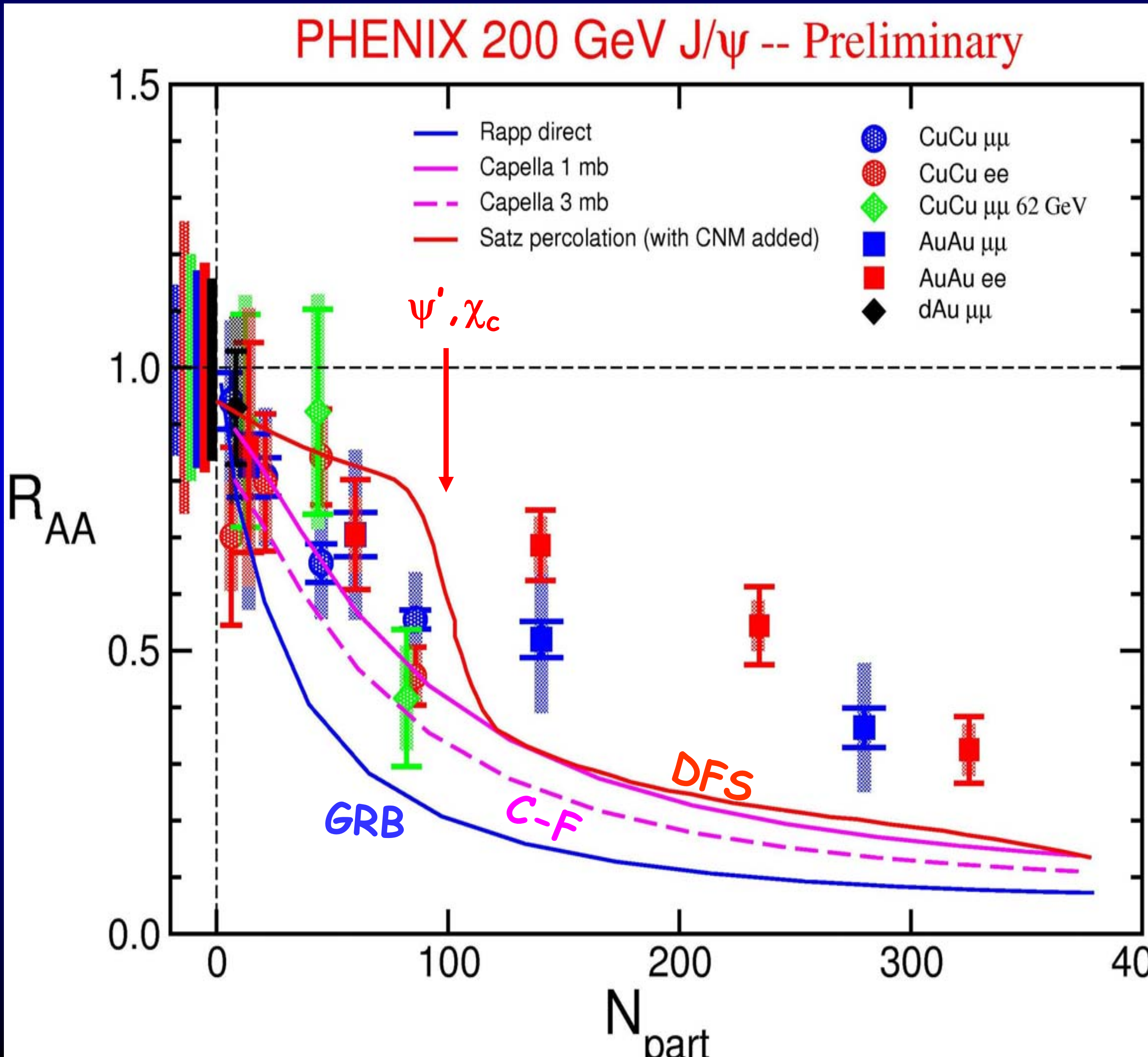
3 mb

R. Vogt CNM calcs.

Rapidity

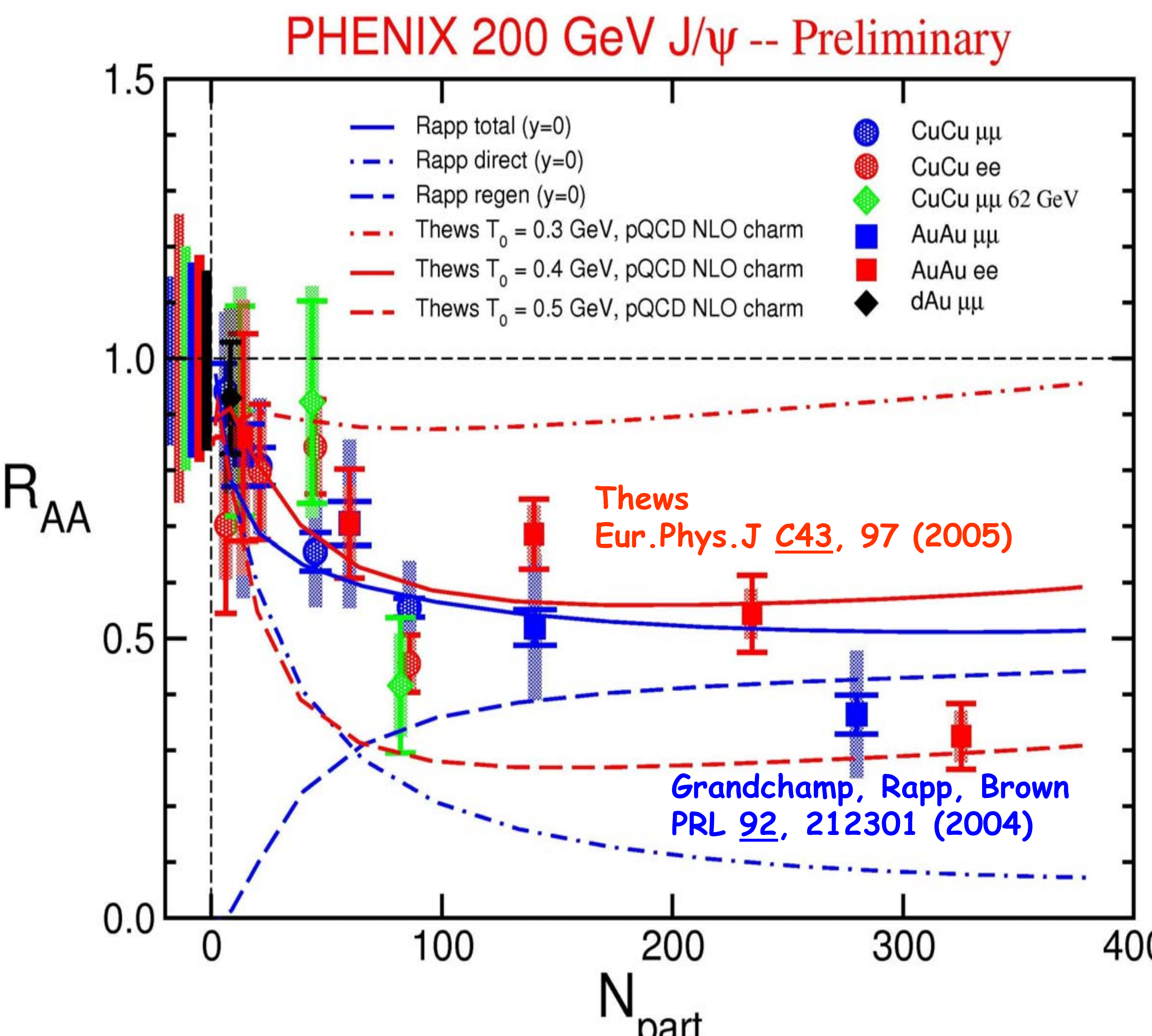
"Normal" Anomalous Suppression

- Grandchamp, Rapp, Brown; PRL 92, 212301 (2003)
  - In-media dissolution
- Cappella, Ferreiro; Eur. Phys. J C42, 419 (2005)
  - Absorption, shadowing, comovers
- Digal, Furtunato, Satz; Eur. Phys. J C32, 547 (2004)
  - Absorption, shadowing, percolation, color screening



“Anomalous” Anomalous Suppression

- That is, regeneration.
- One example: Grandchamp, Rapp, Brown; PRL 92, 212301 (2003)
  - ❑ In-media dissolution
  - ☞ Plus regeneration from “off-diagonal” c-cbar pairs

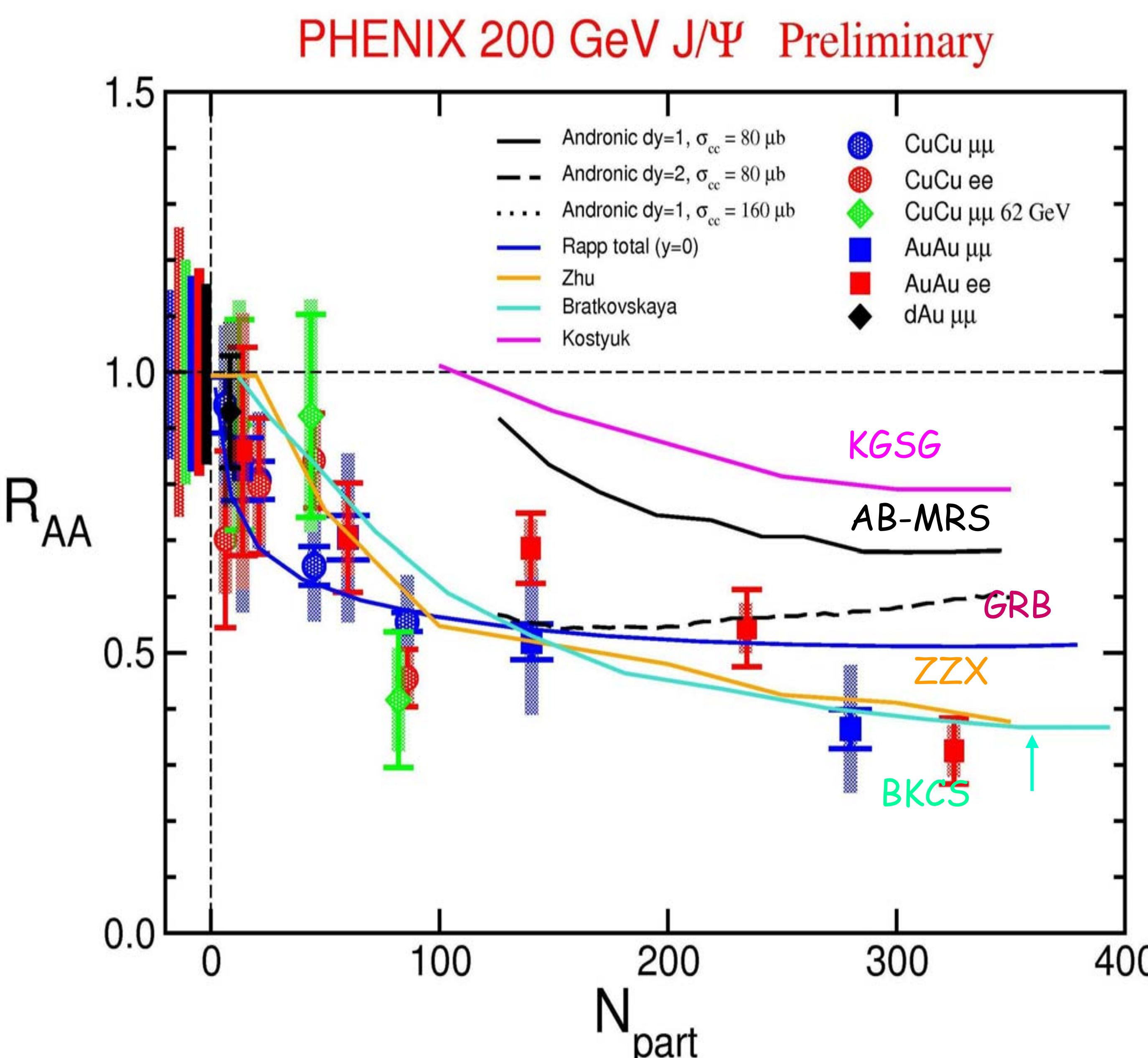


Thews
Eur.Phys.J C43, 97 (2005)

Grandchamp, Rapp, Brown
PRL 92, 212301 (2004)

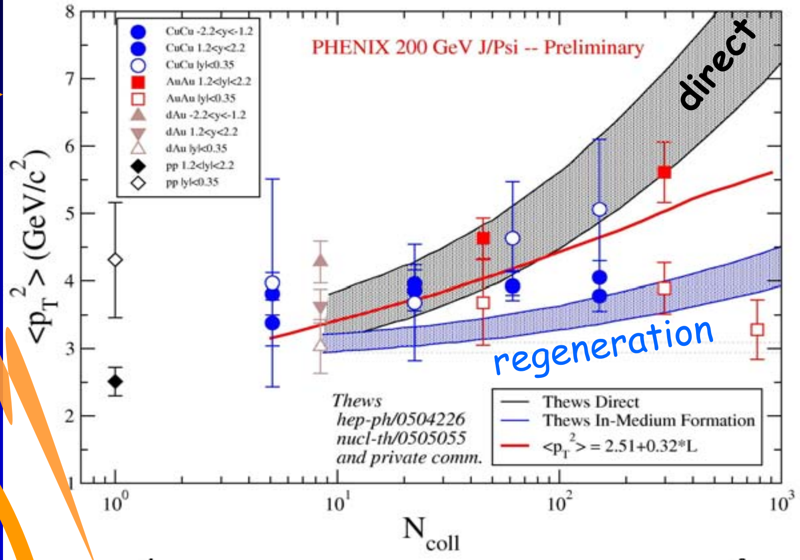
No Suppression of Models…

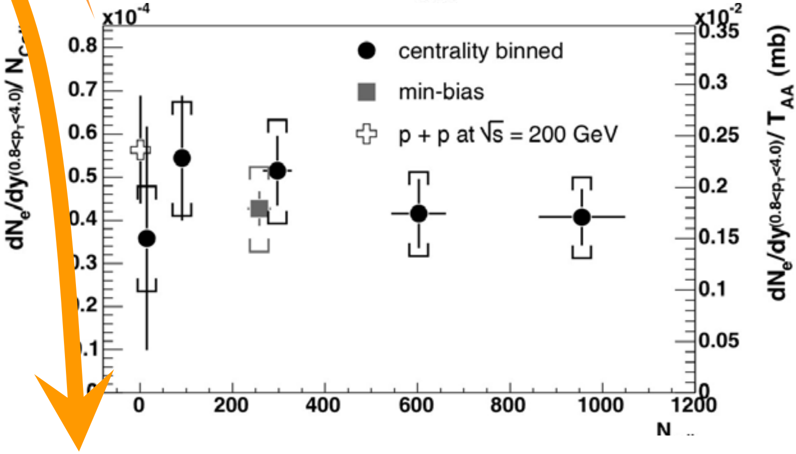
- GRB – see previous slide
- Thews- previous slide, next talk
- Andronic, Braun-Munzinger, Redlich, Stachel; Phys. Lett. B571, 36 (2003)
    - Color screening, recombination
- Bratkovskaya, Kostyuk, Cassing Stoecker; Phys. Rev. C69, 054903 (2004)
    - Hadron-string dynamics
- Kostyuk, Gorenstein, Stoecker, Greiner; Phys. Rev. C68, 041902 (2003)
    - Color screening, recombination
- Zhu, Zhuang, Xu; Phys. Lett. B607, 107 (2005)
    - Co-movers, gluon break-up, no regeneration

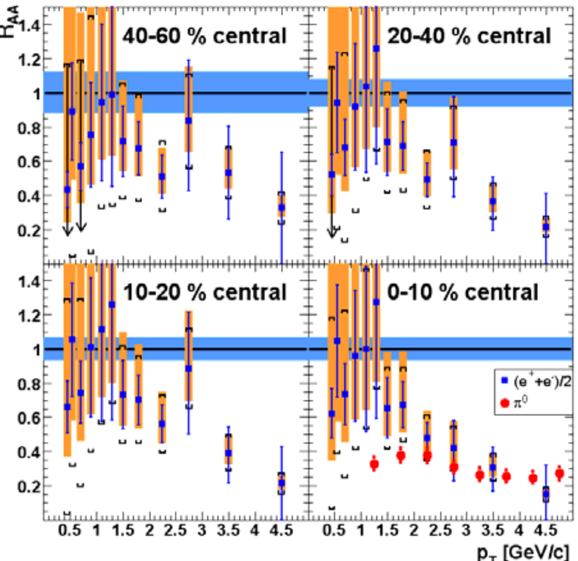


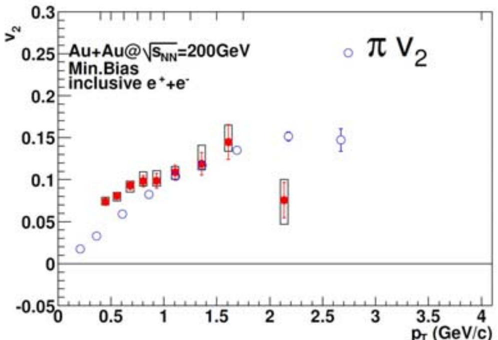
There Is So Much More To The Story

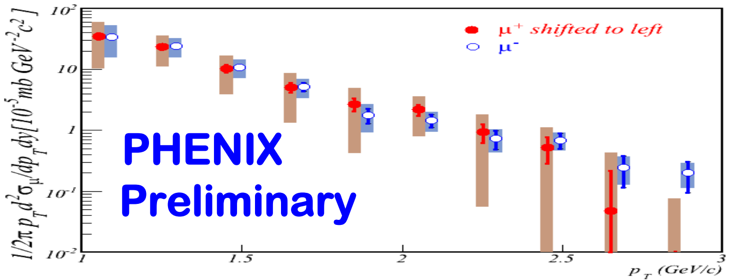
- (A Sampling)
  - ☐ $< p_T^{\,2} >$ behavior
  - ☐ Open charm yields
    Phys. Rev. Lett. 94, 082301 (2005).
  - ☐ Open charm distributions
  - ☐ Charm energy loss
    Phys. Rev. Lett. 96, 032301 (2006).
  - ☐ Charm flow
    Phys. Rev. C72, 024901 (2005)





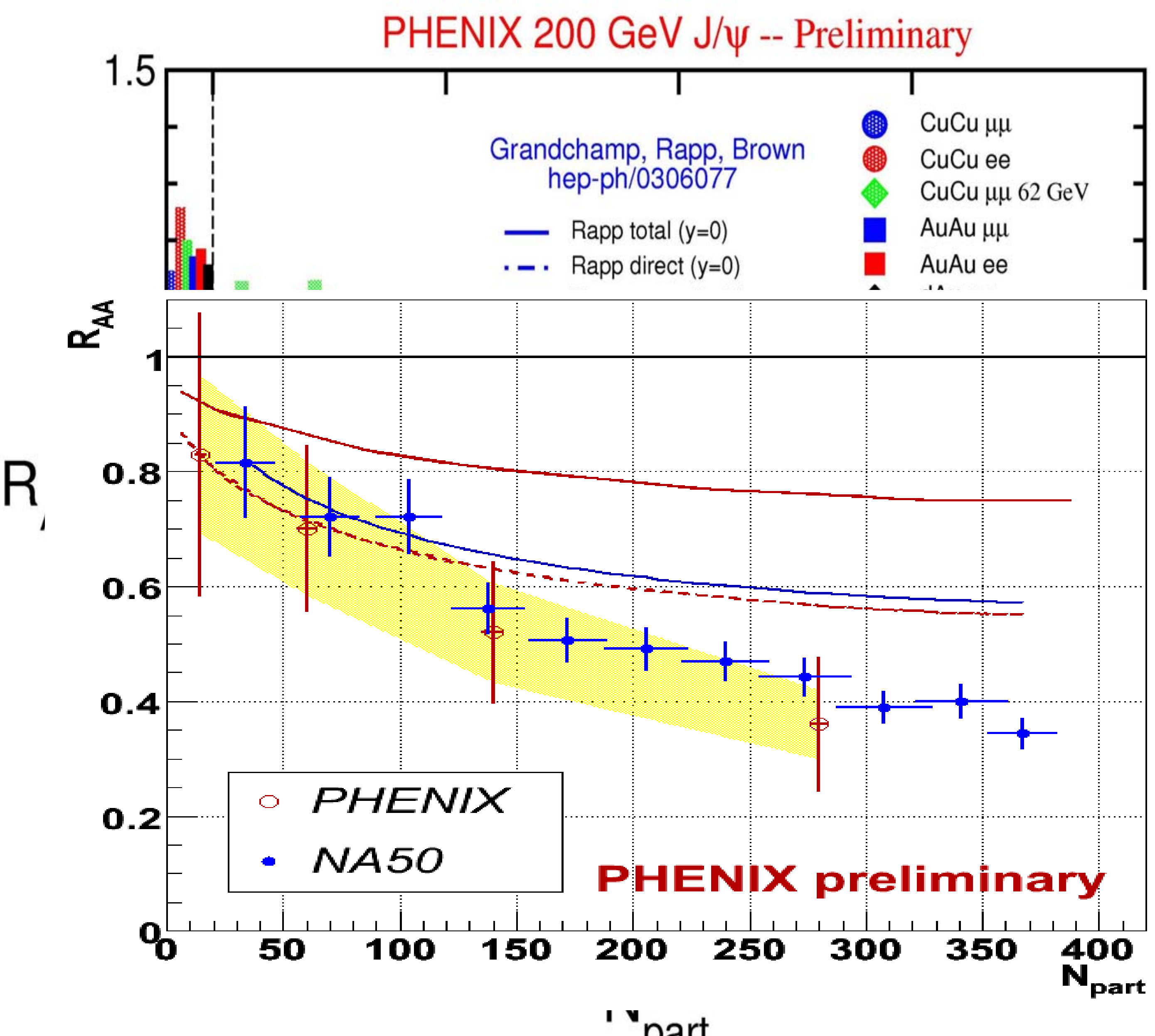






Not Suppressing the J/ψ (!)

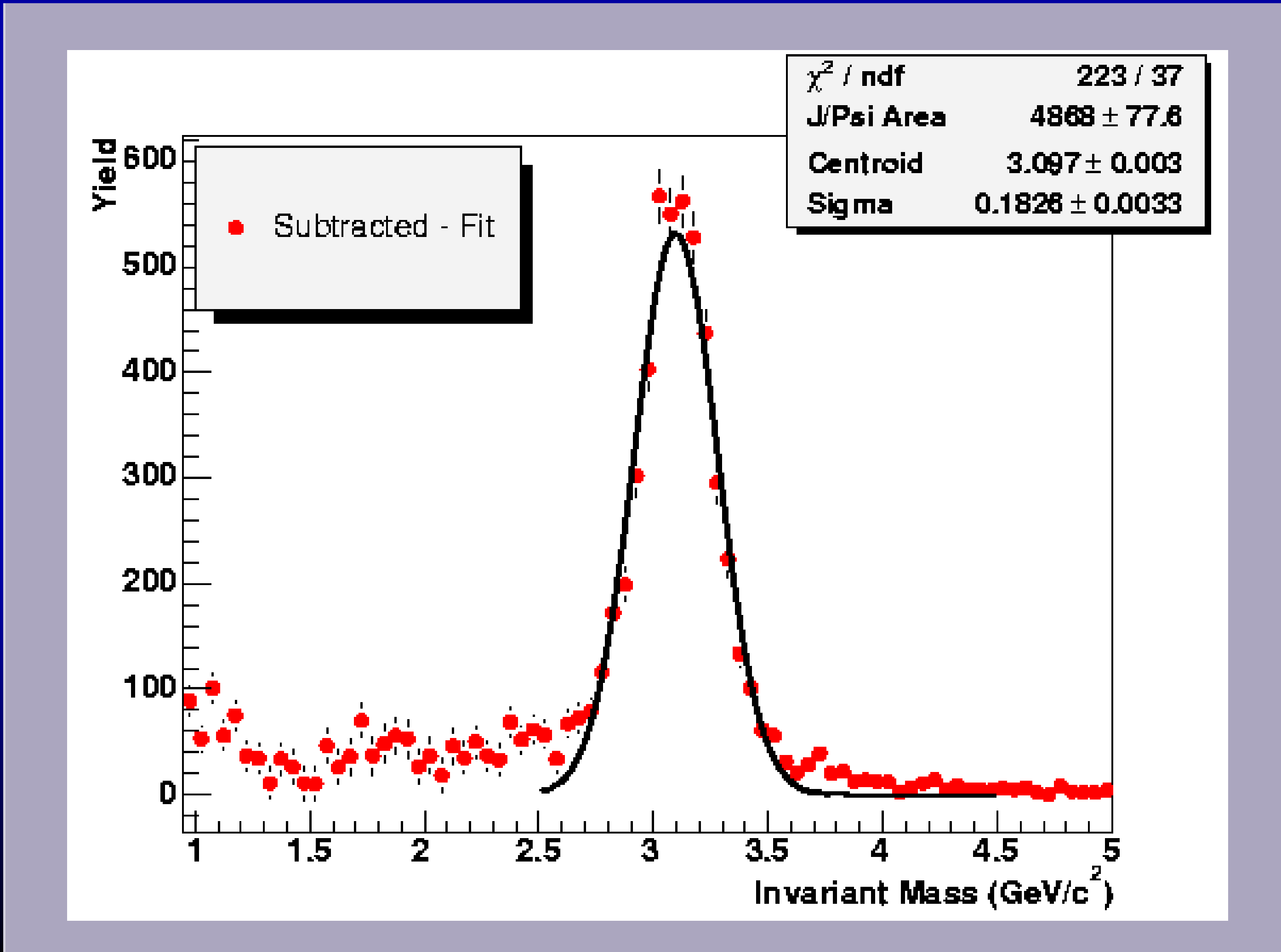
- Karsch, Kharzeev, Satz; hep-ph/0512239
  - ❑ Based on LQCD results suggesting $T_{J/\psi} \sim 2\,T_C$
  - ❑ Suppression (only) of Ψ’ and χ_C
  - ❑ See talk(s) to follow



Future

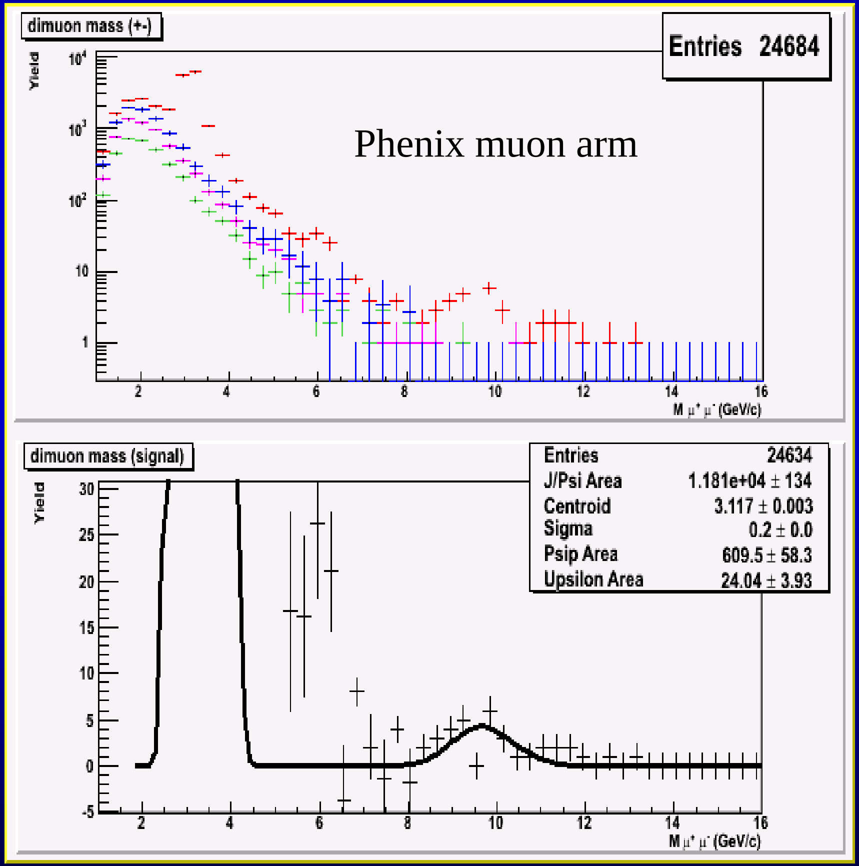
Run-6 (as of today)

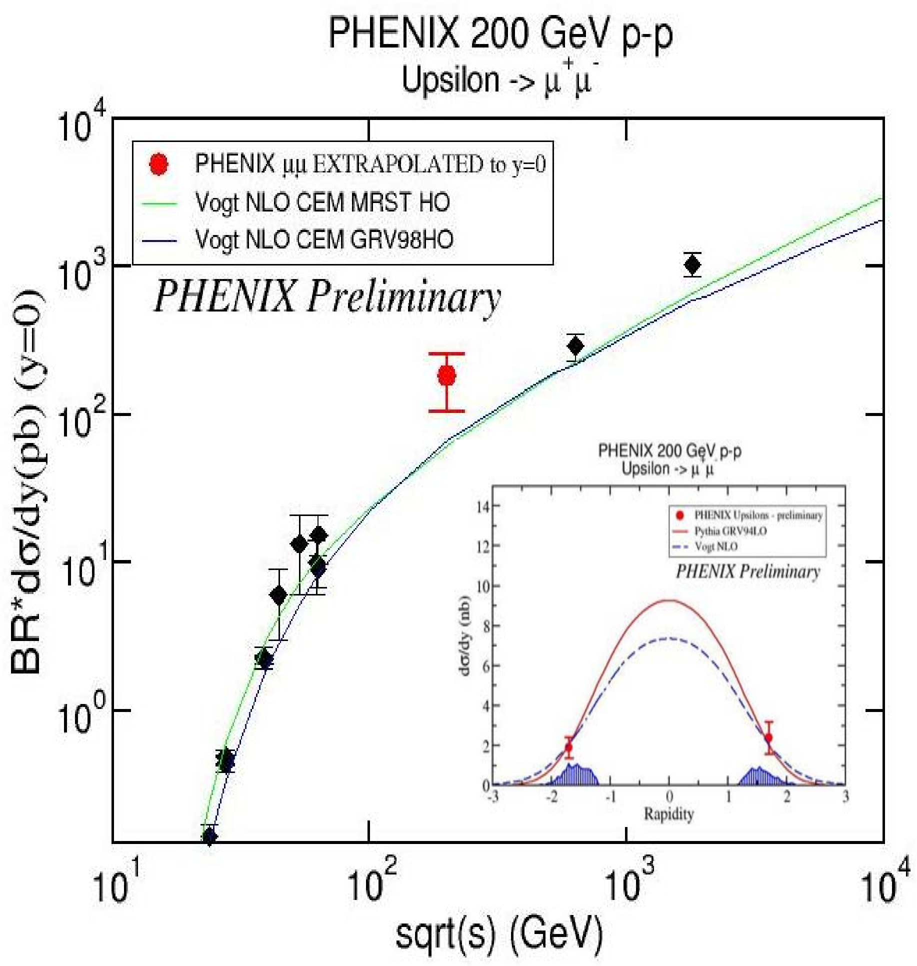
- 200 GeV polarized p+p collisions
- Results from ~ real-time production of Level-2 triggers
- Already equals or exceeds all of Run-5
- Expect ~ 3x this by end of proton running (~ 10 pb^{-1})



Hitting Bottom

- From Run-5 p+p: ~ 3 pb^{-1}
- Current Run-6 : ~4 pb^{-1}

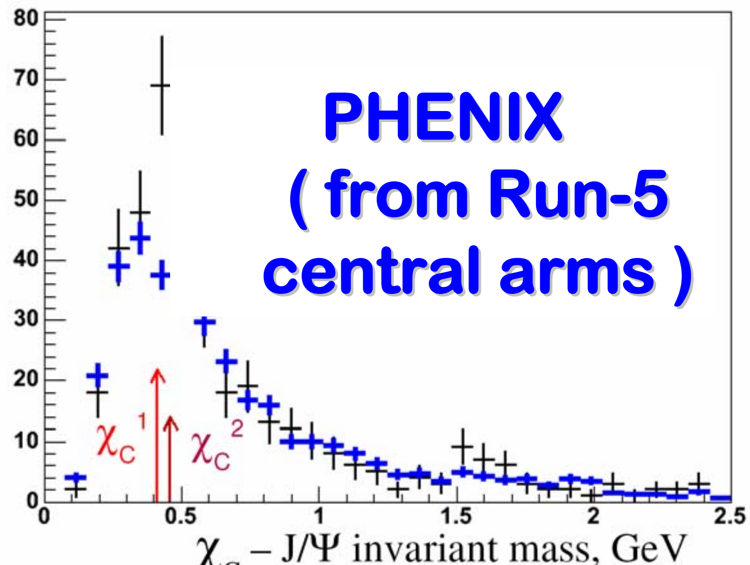




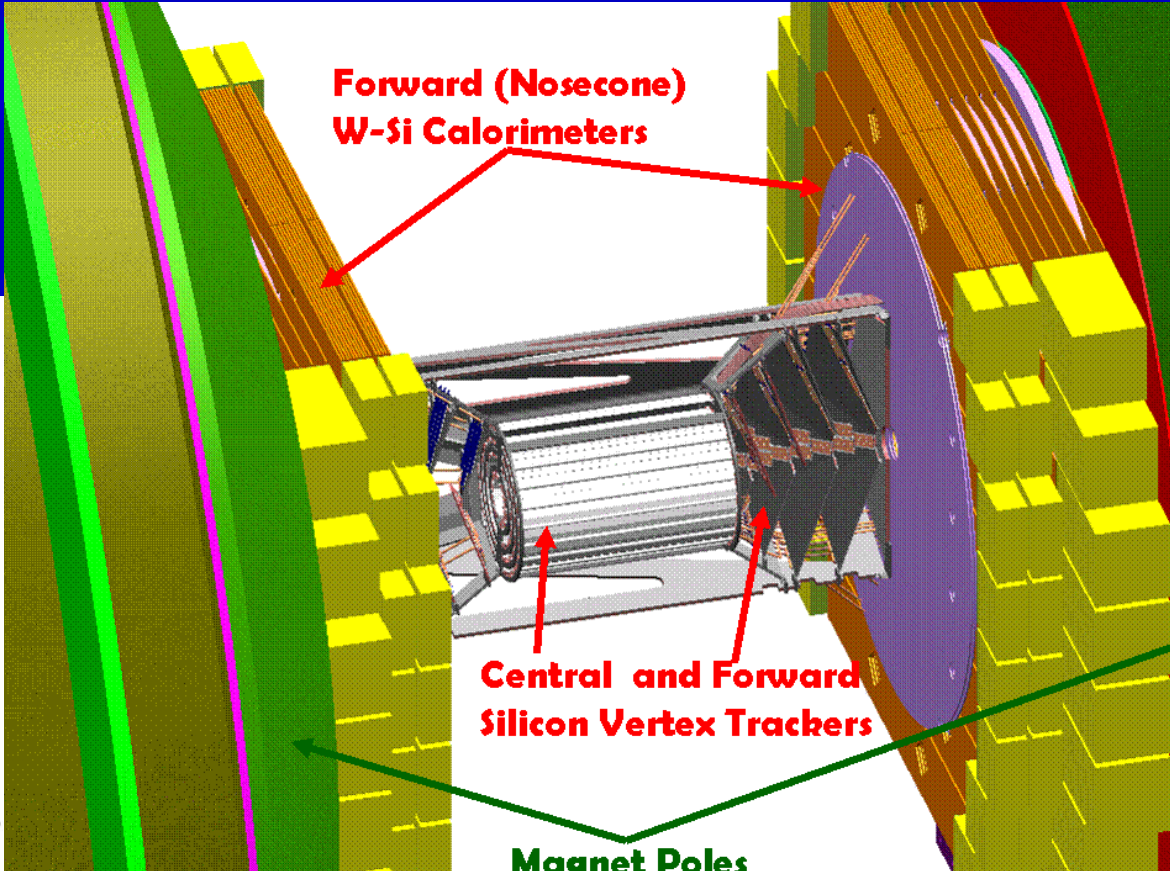
First Upsilons at RHIC

Future: Nose Cone Calorimeter

- Replace central arm magnet nosecones (Cu) w/ tungsten-silicon calorimeters
- Coverage at forward/backward rapidity: $0.9 < |\eta| < 3.5$
  - ☐ γ/π^0 separation for $p_T < 30$ GeV/c
  - ☐ Jet identification
- γ identification gives good acceptance for $\chi_c \rightarrow J/\Psi + \gamma$



PHENIX (from Run-5 central arms)



Forward (Nosecone) W-Si Calorimeters

Central and Forward Silicon Vertex Trackers

Magnet Poles

RHIC-II - Heavy Flavor Yields

All numbers are first rough estimates
(including trigger and reconstruction efficiencies)
for 12 weeks Au+Au run ($\int L_{eff}\,dt \sim 18\ nb^{-1}$)

Signal	RHIC Exp.	Obtained	RHIC I (>2008)	RHIC II	LHC/ALICE+
$J/\psi \to e^+e^-$ $J/\psi \to \mu^+\mu^-$	PHENIX	~800 ~7000	3,300 29,000	45,000 395,000	9,500 740,000
$\Upsilon \to e^+e^-$ $\Upsilon \to \mu^+\mu^-$	STAR PHENIX	- -	830 80	11,200 1,040	2,600 8,400
$B \to J/\psi \to e^+e^-$ $B \to J/\psi \to \mu^+\mu^-$	PHENIX	- -	40 420	570 5,700	N/A N/A
$\chi_c \to e^+e^-\gamma$ $\chi_c \to \mu^+\mu^-\gamma$	PHENIX	- -	220 8,600	2,900* 117,000*	N/A N/A
$D \to K\pi$	STAR	$\sim 0.4\times10^6$ (S/B~1/600)	30,000**	30,000**	8000

* Large backgrounds, quality uncertain as yet
** Running at 100 Hz min bias
+ 1 month (= year), P. Crochet, EPJdirect A1, a (2005) and private comm.

T. Frawley, PANIC'05,
RHIC-II Satellite Meeting

Helmut

Before Matsui-Satz

PHYSICAL REVIEW D VOLUME 17, NUMBER 7 1 APRIL 1978

Lepton pair production in hadron collisions

K. Kinoshita,* H. Satz, and D. Schildk
Department of Theoretical Physics, University of Bielefeld,
(Received 12 October 1977)

We construct a model for lepton pair production in the low-mass region production characteristics of inclusive hadron production at small p_T. Thi pair data up to 3.1 GeV. We then apply our model at higher masses an pointlike-parton annihilation.

I. INTRODUCTION

The aim of this work is to examine a hadronlike model for lepton pair production in hadron-hadron collisions. By "hadronlike" we mean that the functional behavior of the transverse- and longitudinal-momentum spectra, their dependence on the incident energy, and all relevant parameters of these distributions, are taken from low-p_T hadron physics.

also show th

$f(E_T)=e^{-}$

with λ = 6 Ge
quite well.

For the p_T
like producti
tion $f(E_T)$ fr

$(d\sigma/dp_T^2)$

- First "m_T scaling" plot ? →

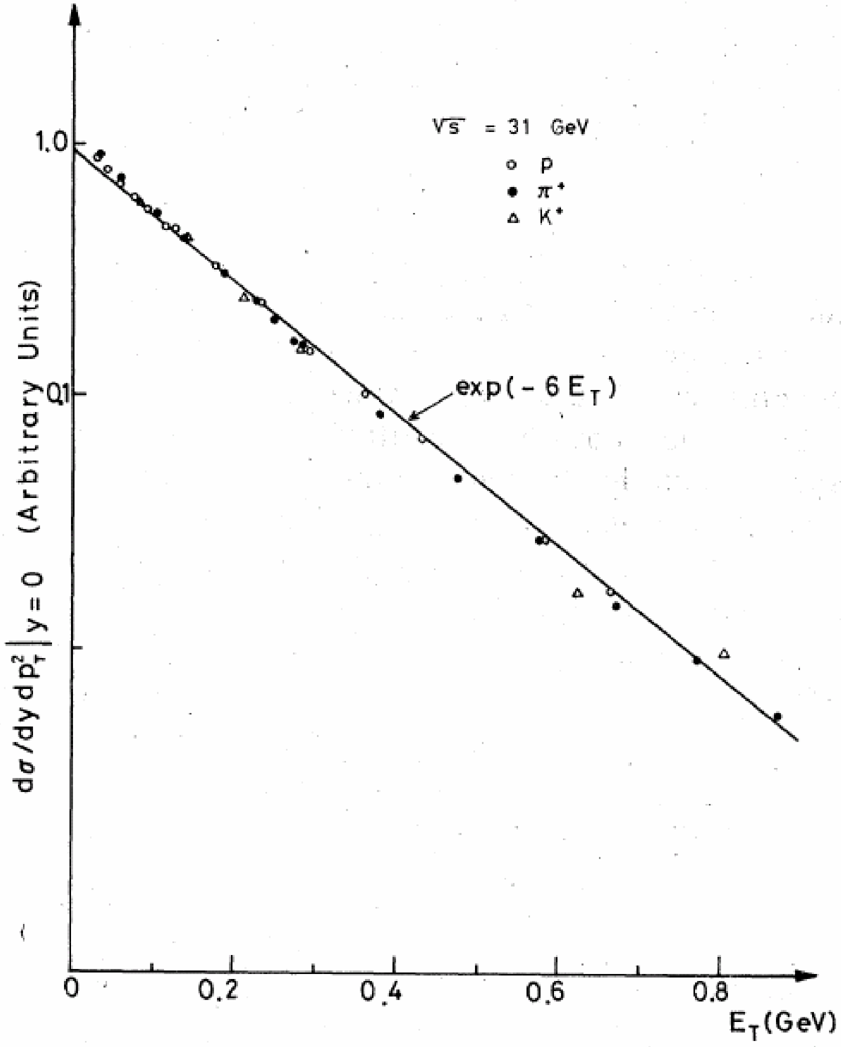
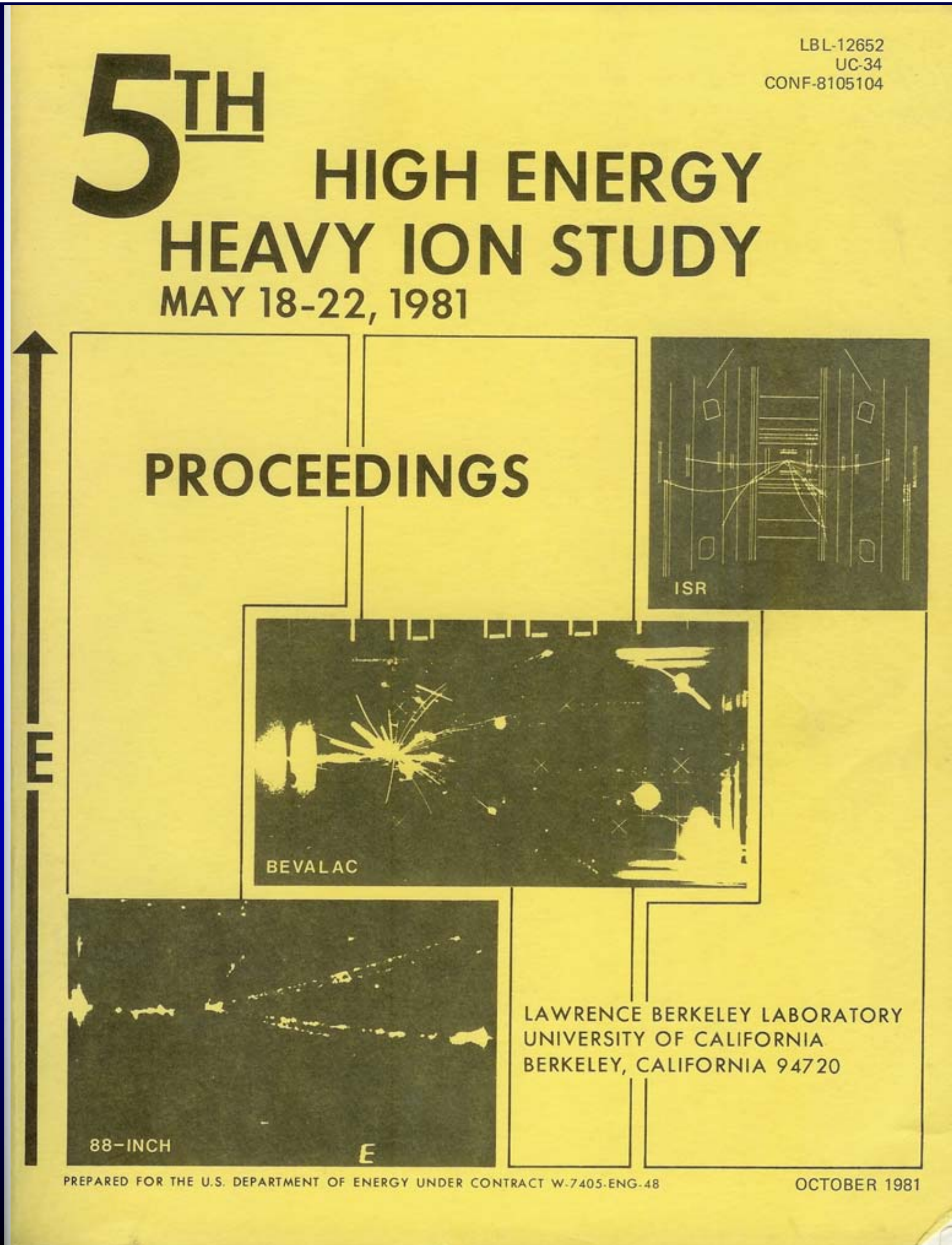


FIG. 1. Data (Ref. 3) on $pp \to (p, \pi^+, K^+) + X$ at 90° compared with $\exp(-6E_T)$.

My First Helmut Sighting

- *Deconfinement in Dense Matter*, by H. Satz

- Abstract:
  - ❑ We survey recent developments in the study of strongly interacting matter by means of quantum chromodynamics on the lattice. The Monte Carlo evaluation of SU(2) Yang-Mills systems is shown to provide a unified thermodynamic description from the hadronic region through the deconfinement transition to a non-interacting gluon gas. We … discuss possible signals for the formation of a quark-gluon plasma in relativistic heavy ion collisions.



LBL-12652
UC-34
CONF-8105104

5TH
HIGH ENERGY
HEAVY ION STUDY
MAY 18-22, 1981

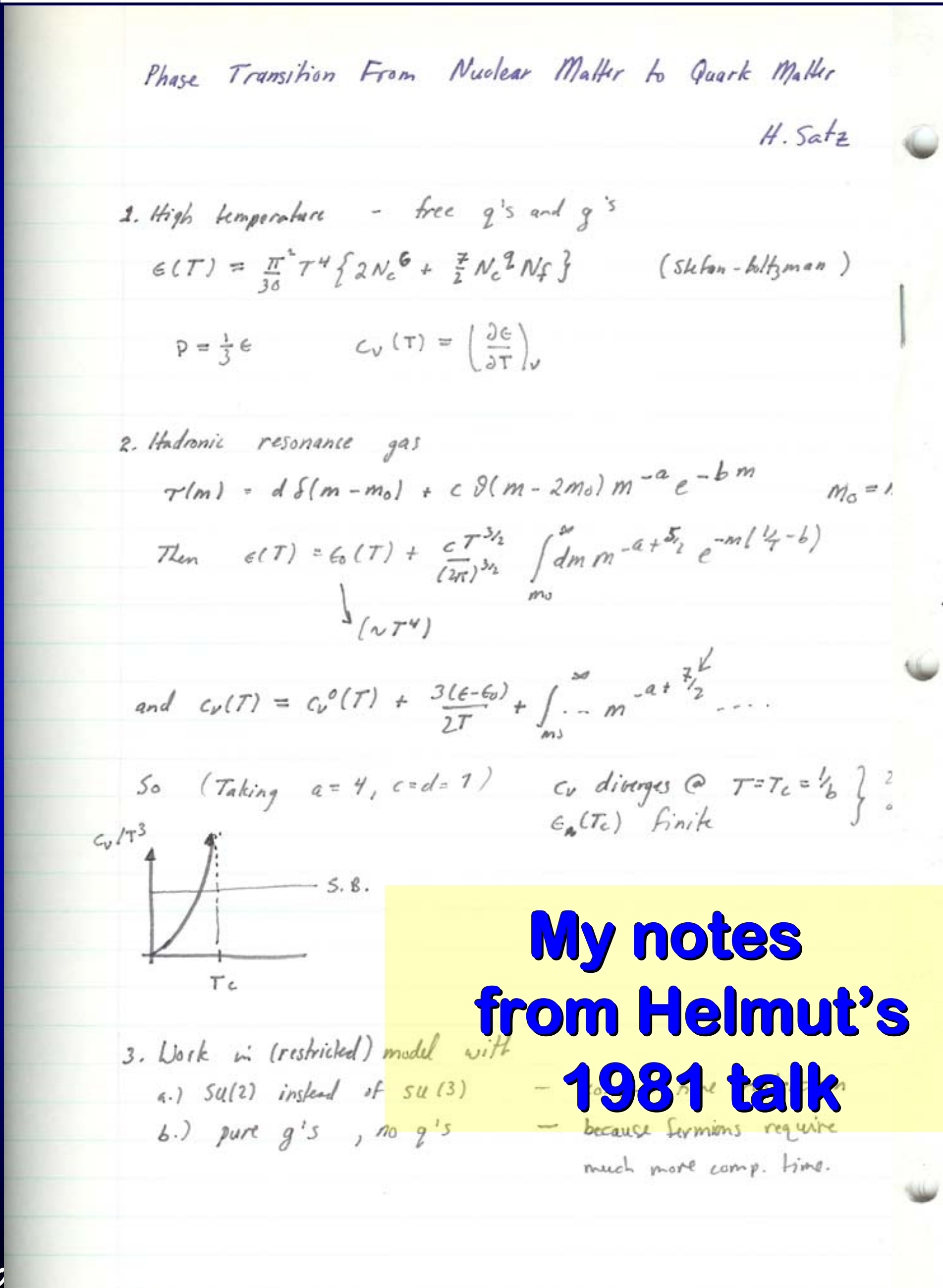
PROCEEDINGS

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT W-7405-ENG-48

OCTOBER 1981

A Furtive Note-Taker...



Phase Transition From Nuclear Matter to Quark Matter

H. Satz

1. High temperature - free q's and g's

$\epsilon(T) = \frac{\pi^2}{30} T^4 \{ 2 N_c^G + \frac{7}{2} N_c^q N_f \}$ (Stefan-Boltzman)

$p = \frac{1}{3}\epsilon$ $c_v(T) = \left(\frac{\partial \epsilon}{\partial T}\right)_v$

2. Hadronic resonance gas

$\tau(m) = d\,\delta(m - m_0) + c\,\vartheta(m - 2m_0)\, m^{-a} e^{-bm}$ $m_0 =$

Then $\epsilon(T) = \epsilon_0(T) + \frac{c T^{3/2}}{(2\pi)^{3/2}} \int_{m_0}^{\infty} dm\, m^{-a+5/2} e^{-m(1/T - b)}$

$\searrow (\sim T^4)$

and $c_v(T) = c_v^0(T) + \frac{3(\epsilon - \epsilon_0)}{2T} + \int_{m_0}^{\infty} \cdots m^{-a+7/2} \cdots$

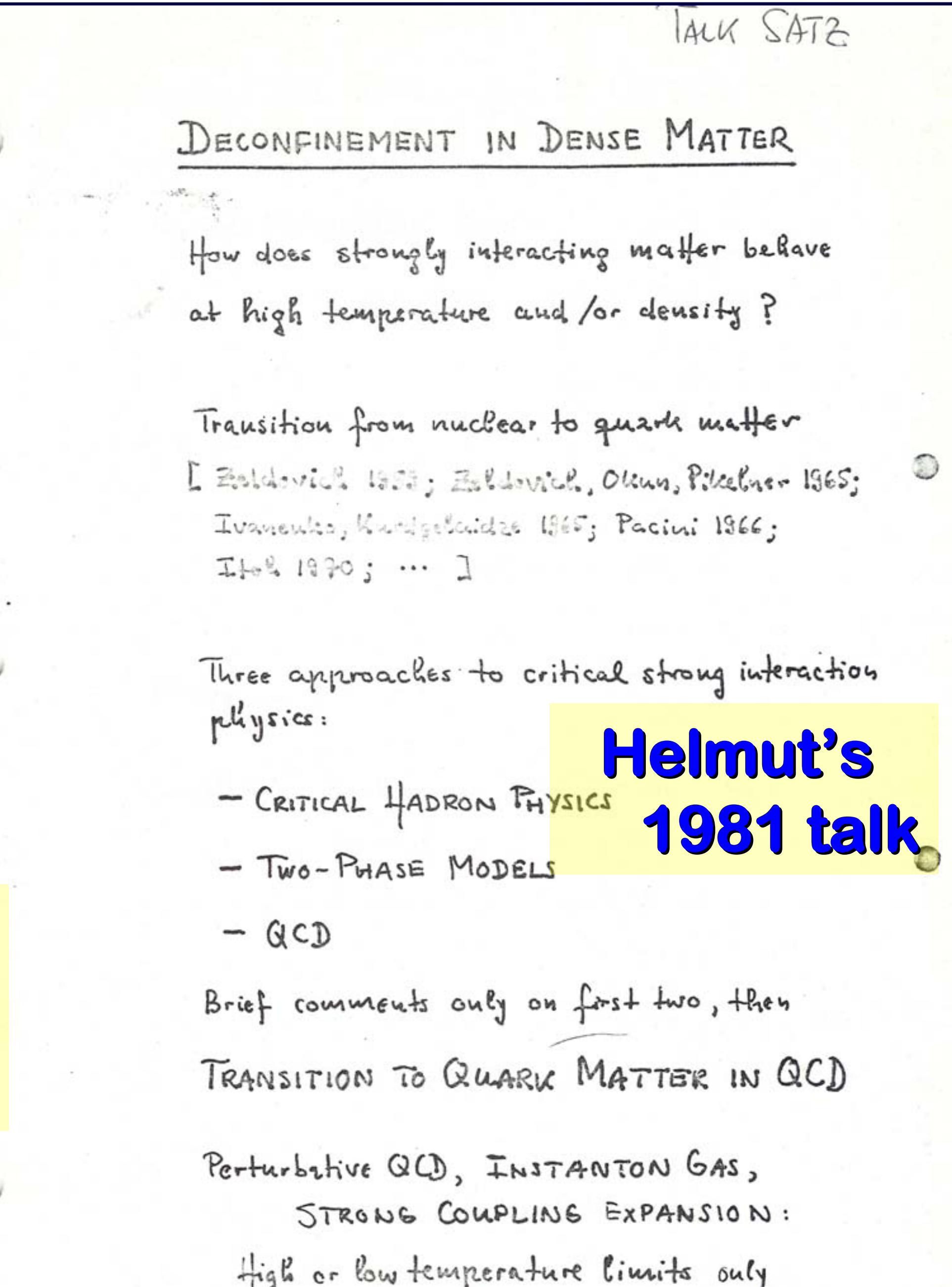
So (Taking $a = 4$, $c = d = 1$) c_v diverges @ $T = T_c = 1/b$; $\epsilon_h(T_c)$ finite

3. Work in (restricted) model with

a.) SU(2) instead of SU(3) — [illegible]

b.) pure g's, no q's — because fermions require much more comp. time.

My notes from Helmut's 1981 talk



TALK SATZ

DECONFINEMENT IN DENSE MATTER

How does strongly interacting matter behave at high temperature and/or density?

Transition from nuclear to quark matter

[Zeldovich [illegible]; Zeldovich, Okun, Pikelner 1965; Ivanenko, Kurdgelaidze 1965; Pacini 1966; Itoh 1970; ...]

Three approaches to critical strong interaction physics:

- CRITICAL HADRON PHYSICS
- TWO-PHASE MODELS
- QCD

Brief comments only on first two, then

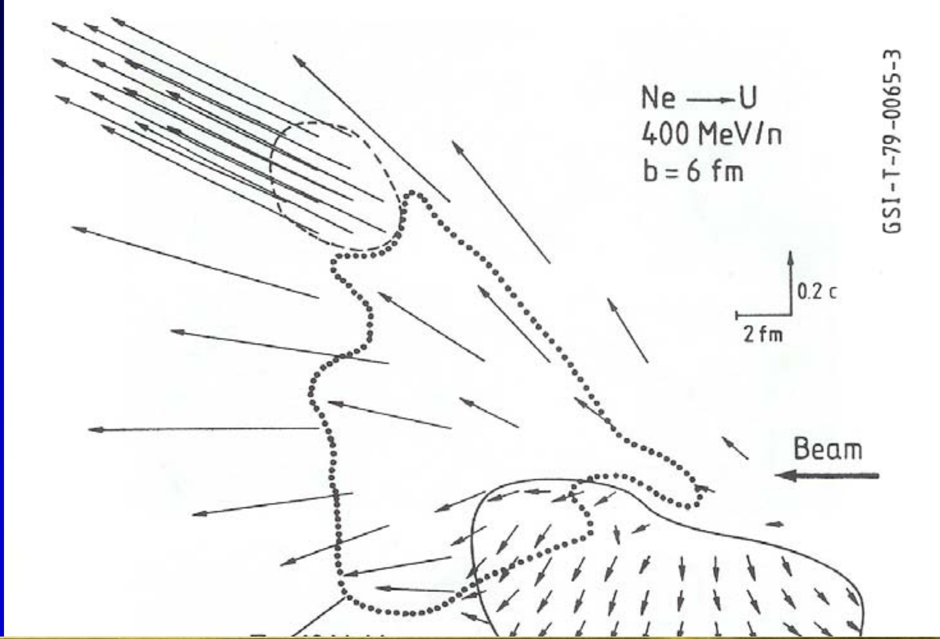
TRANSITION TO QUARK MATTER IN QCD

Perturbative QCD, INSTANTON GAS, STRONG COUPLING EXPANSION: High or low temperature limits only

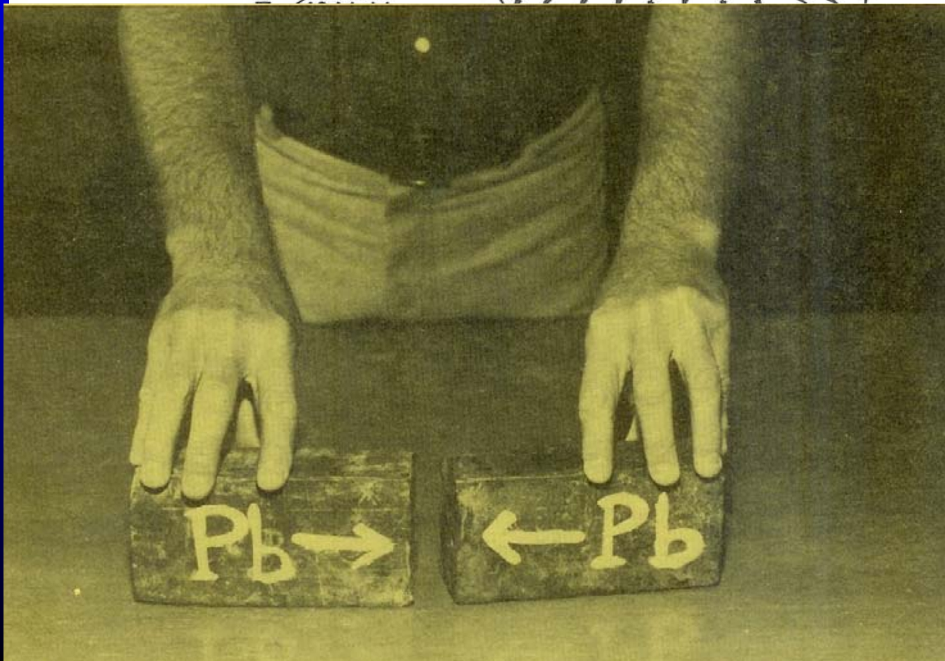
Helmut's 1981 talk

1981 In Context

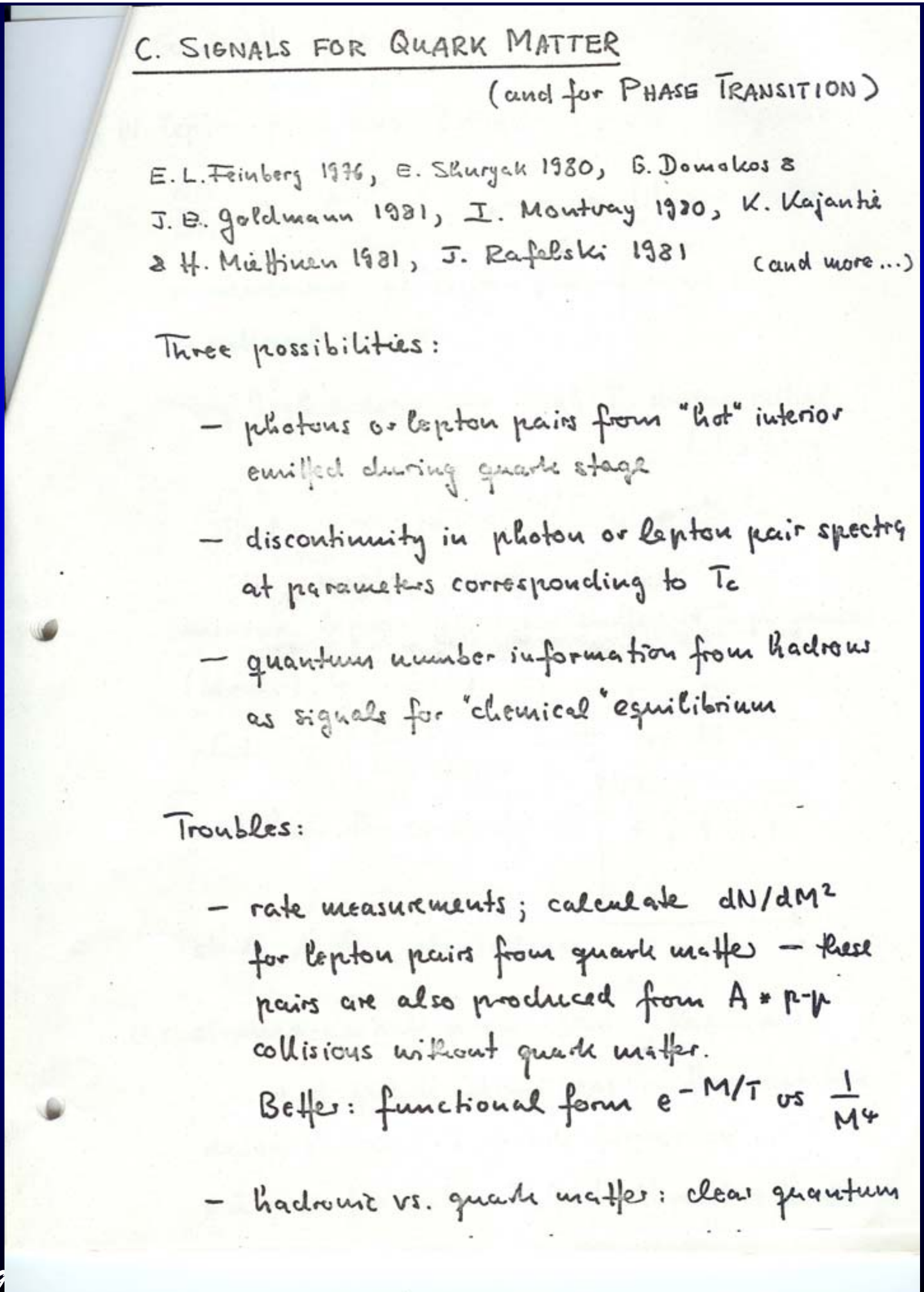
- State of the art in graphics:



- State of the art in simulations:



The End is the Beginning



C. SIGNALS FOR QUARK MATTER

(and for PHASE TRANSITION)

E. L. Feinberg 1976, E. Shuryak 1980, G. Domokos & J. B. Goldmann 1981, I. Montvay 1980, K. Kajantie & H. Miettinen 1981, J. Rafelski 1981 (and more ...)

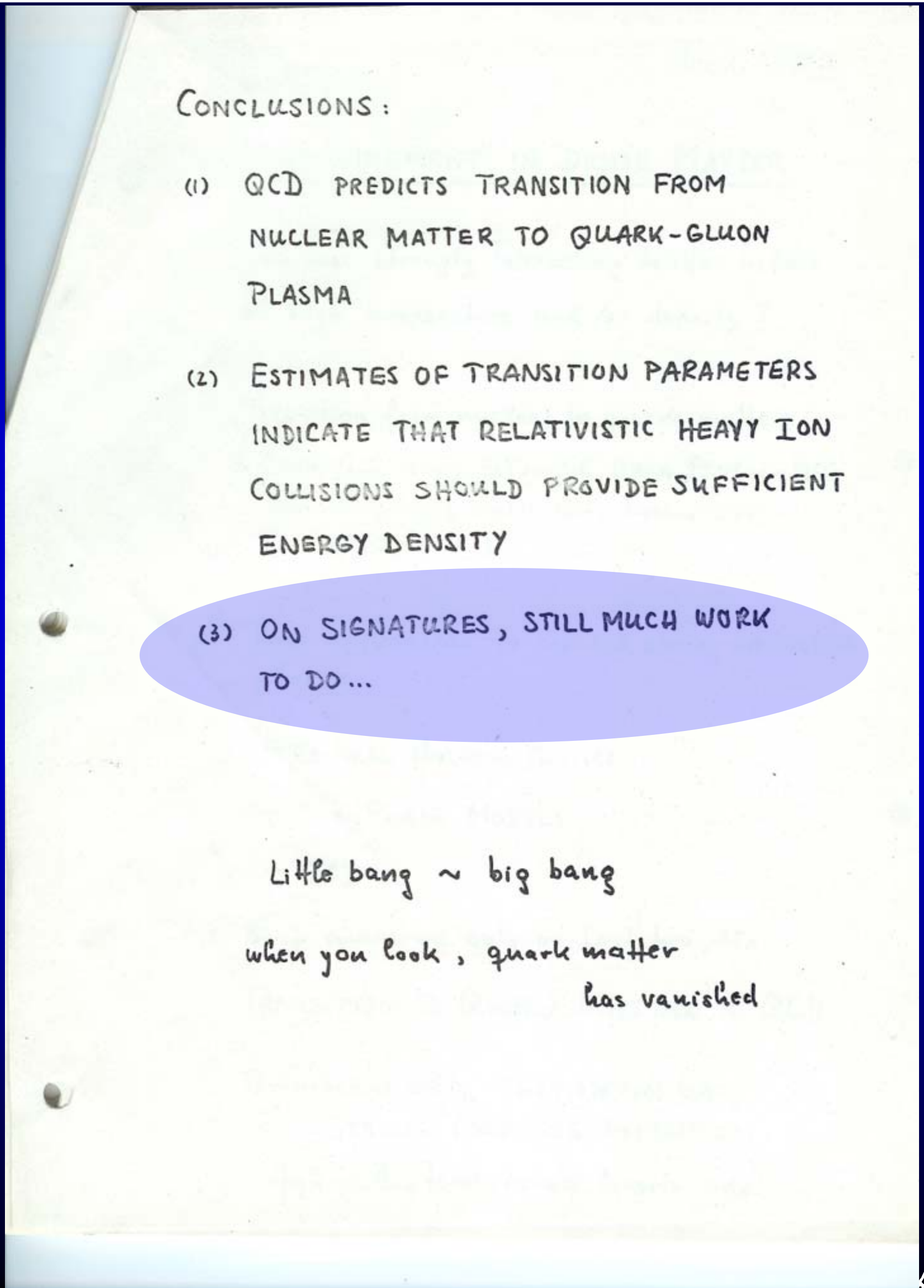
Three possibilities:

- photons or lepton pairs from "hot" interior emitted during quark stage
- discontinuity in photon or lepton pair spectra at parameters corresponding to T_c
- quantum number information from hadrons as signals for 'chemical' equilibrium

Troubles:

- rate measurements; calculate dN/dM^2 for lepton pairs from quark matter — these pairs are also produced from A * p-p collisions without quark matter.

  Better: functional form $e^{-M/T}$ vs $\frac{1}{M^4}$
- hadronic vs. quark matter: clear quantum



CONCLUSIONS:

(1) QCD PREDICTS TRANSITION FROM NUCLEAR MATTER TO QUARK-GLUON PLASMA

(2) ESTIMATES OF TRANSITION PARAMETERS INDICATE THAT RELATIVISTIC HEAVY ION COLLISIONS SHOULD PROVIDE SUFFICIENT ENERGY DENSITY

(3) ON SIGNATURES, STILL MUCH WORK TO DO...

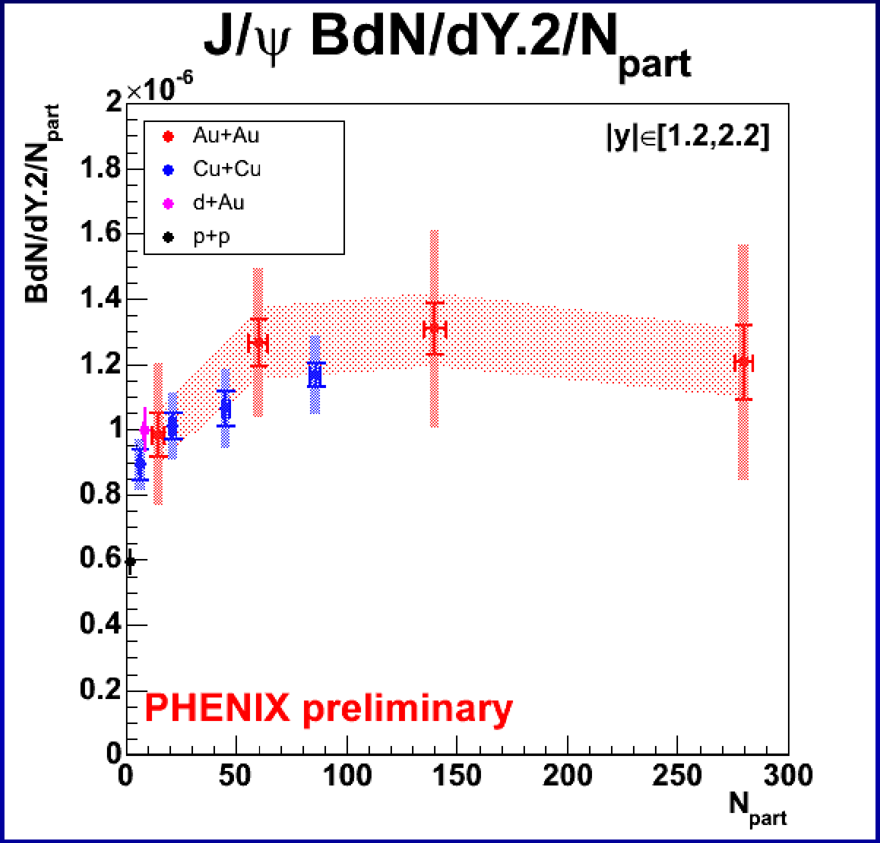
Little bang ~ big bang

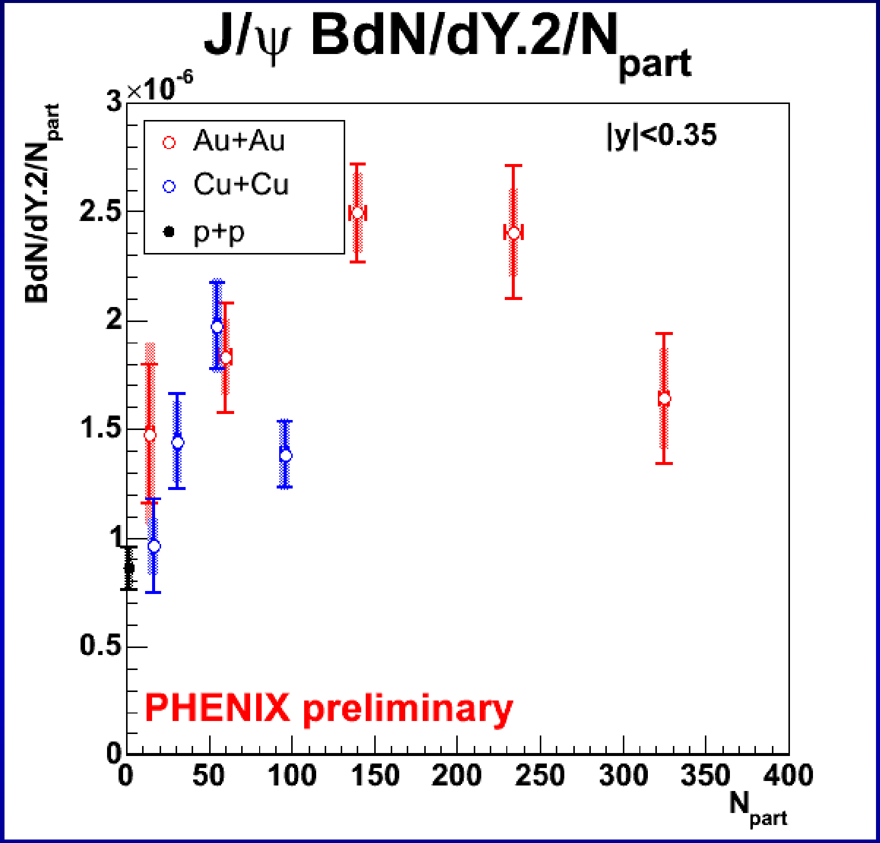
when you look, quark matter has vanished

Thanks Helmut, for the continuing intellectual journey !

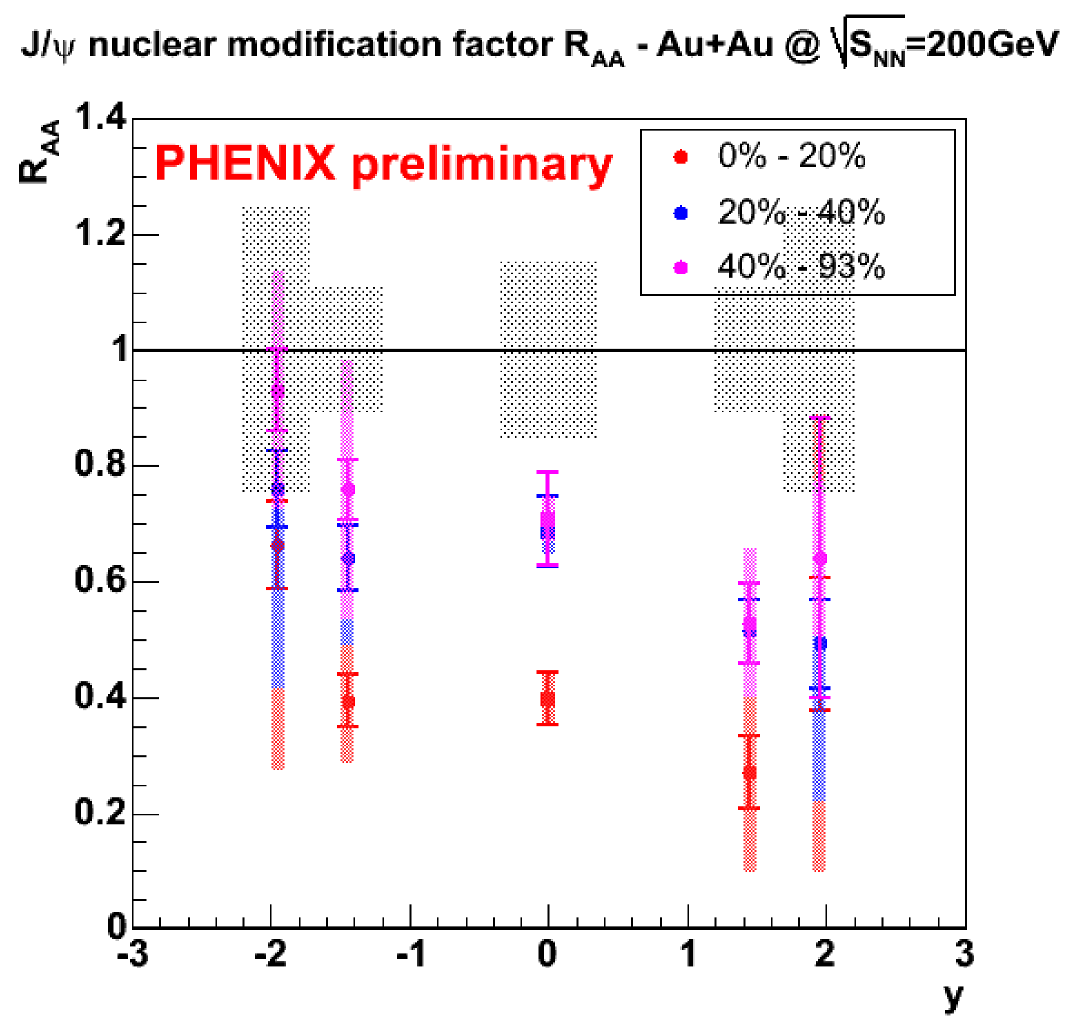
Backup

Test of N_{part} scaling

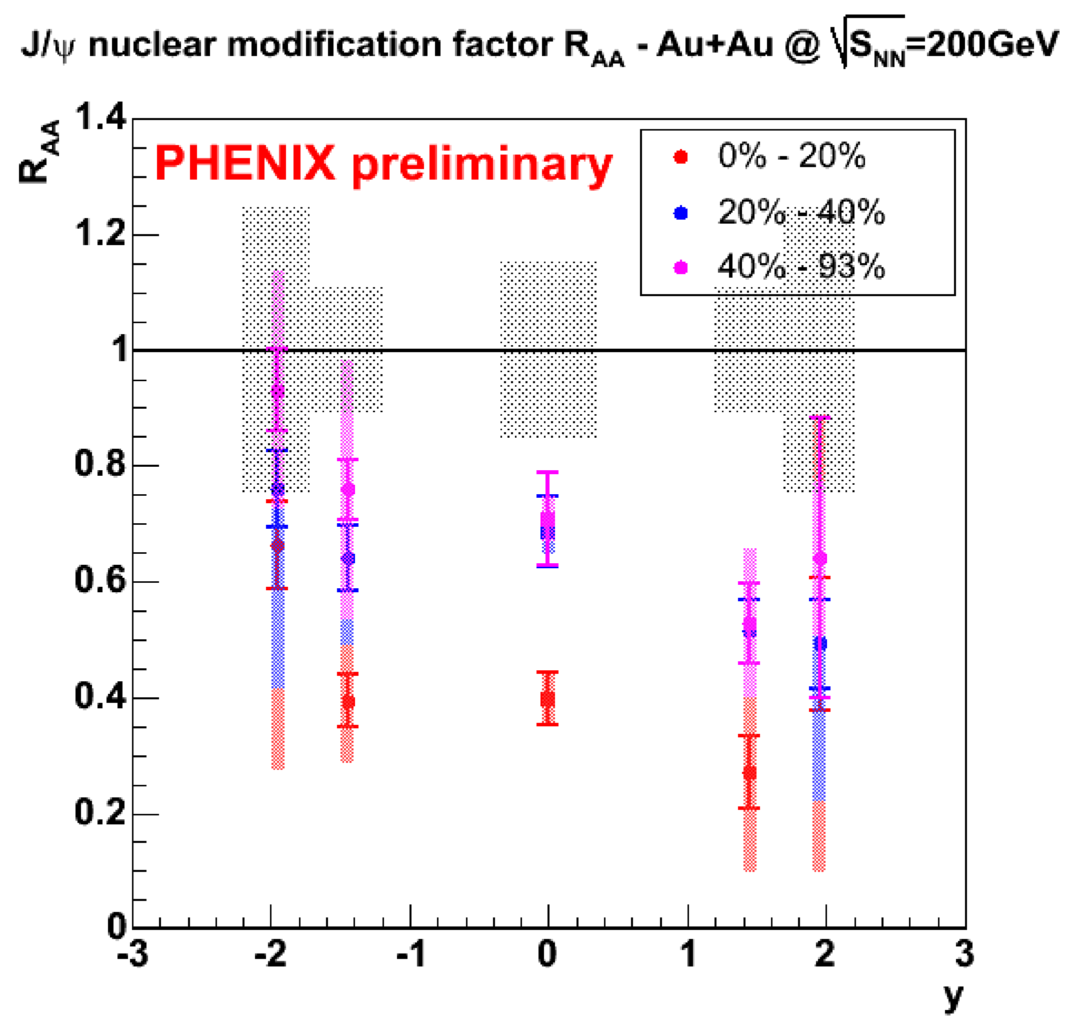




R_{AA} vs rapidity



R_{AA} vs rapidity



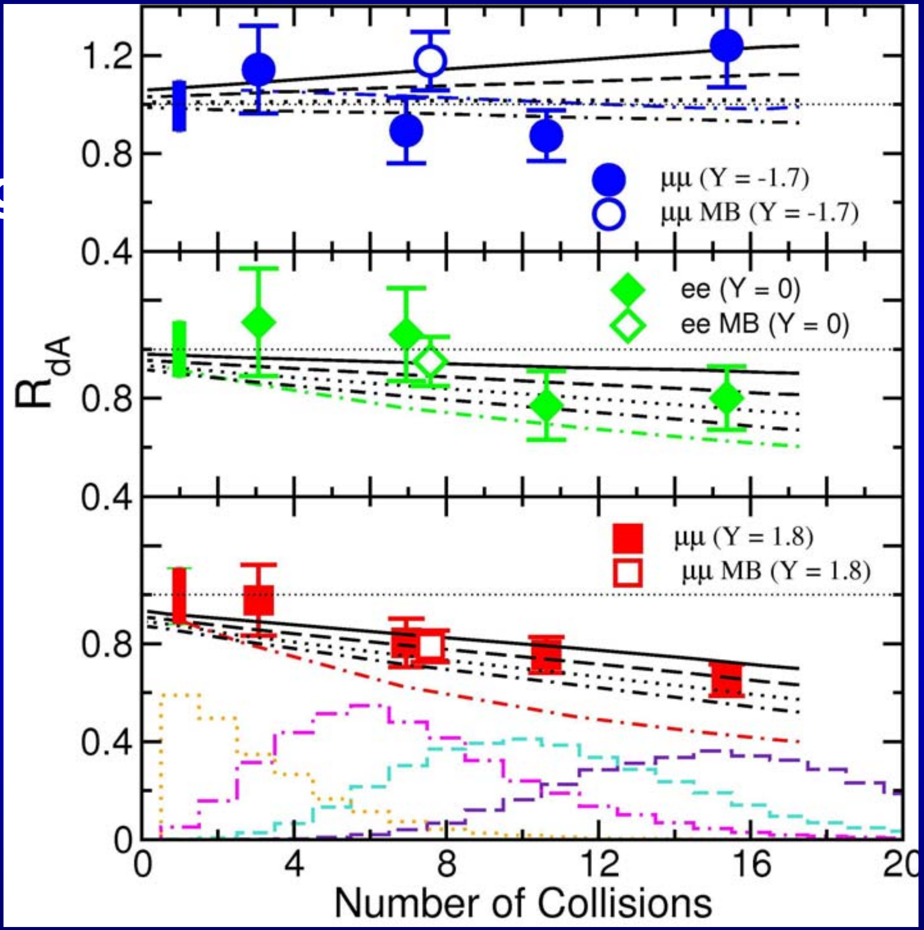
J/Ψ production in d+Au vs centrality

Small centrality dependence

Models with absorption + shadowing

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

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



Weak shadowing and weak nuclear absorption observed