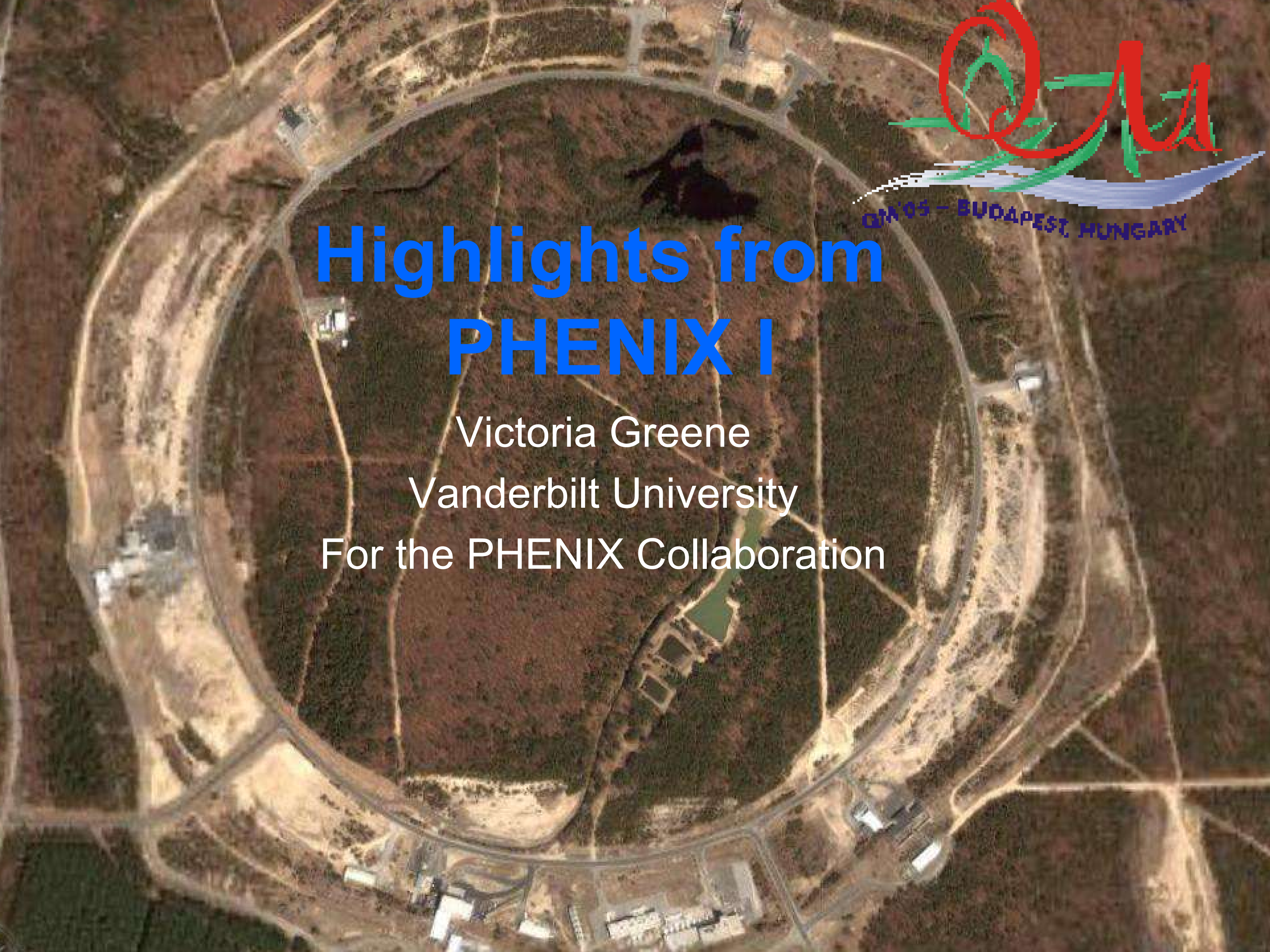


QM'05 – BUDAPEST, HUNGARY

Highlights from PHENIX I

Victoria Greene

Vanderbilt University

For the PHENIX Collaboration


PHOENIX

Quark Matter 2005
Highlights from PHENIX I and II

2. Introduction
3. The first epoch of RHIC*
4. Soft-hard transitions/baryon anomaly
5. Jet quenching
6. Chiral symmetry
7. Thermal Radiation
8. J/ψ suppression
9. Modification of jets

Vicki Greene

Henner Buesching

*Definition of the first RHIC epoch

Culminating in the publication of summary papers by the four RHIC experiments:

Nucl. Phys. A757, 2005 I&II

These are informally called the “white papers”

Some First Epoch Conclusions from PHENIX

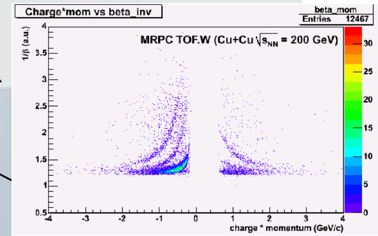
1. Jets are suppressed in central Au + Au collisions
   - Suppression is flat for $p_t < 10$ GeV/c
   - Absence of suppression in d+Au
2. Strong elliptic flow is seen
   - Scaling of v_2 with eccentricity shows that a high degree of collectivity builds up at a very early stage of collision – evidence for early thermalization
   - Data described by ideal hydrodynamic models   fluid description of matter applies.
3. Energy density allows for a non-hadronic state of matter
   - Energy density estimates from measurements of dN/dy are well in excess of the ~1 GeV/fm^3 lattice QCD prediction for the energy density needed to form a deconfined phase.

Some open questions after first epoch

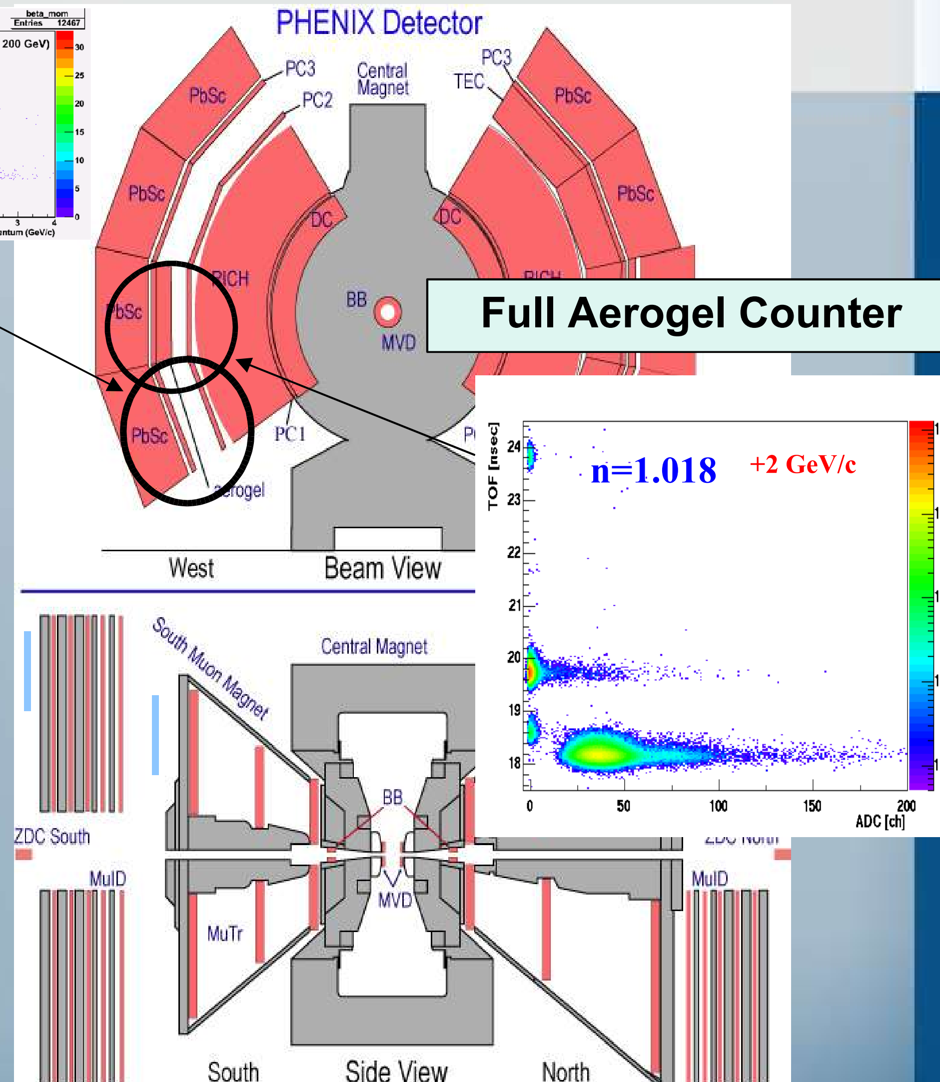
The key predictions that derive from the properties of the QGP should be established, and subsequent predictions should be tested using data from Run4 and beyond. For example:

- R_{AA} at very high p_T
- Charm energy loss
- Source of the baryon anomaly
- Chiral symmetry restoration
- Thermal radiation
- Fate of J/ψ
- Modification of jets

TOF-West RPC prototype installed and tested in CuCu running.



Full Aerogel Counter



***ALSO*:**
New LVL1 Triggers (MuID and ERT)
Improved DAQ (>5kHz)
Multi-Event Buffering (95% live)
OnCal calibrations
LVL2 Filtering rare events

Run-1 to Run-5 Capsule History

Run	Year	Species	$s^{1/2}$ [GeV]	∫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

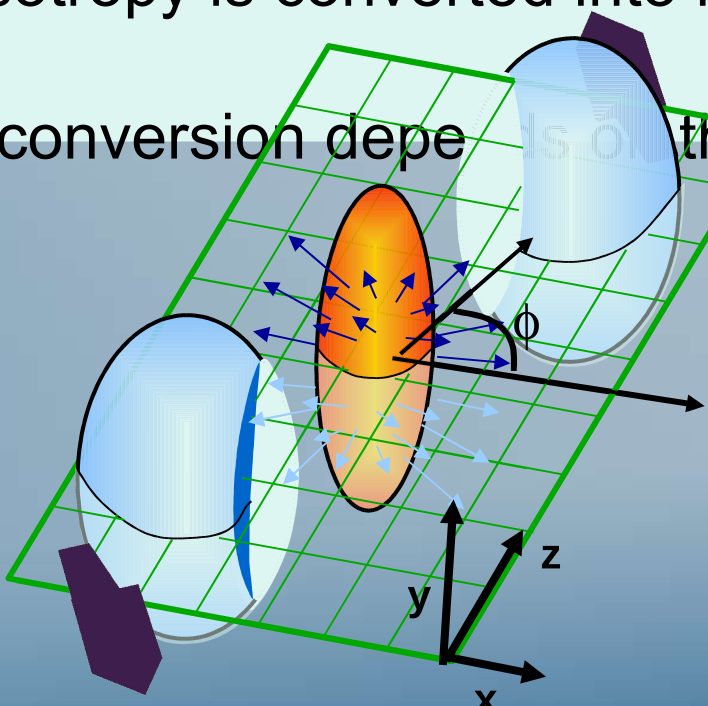
Thermalization

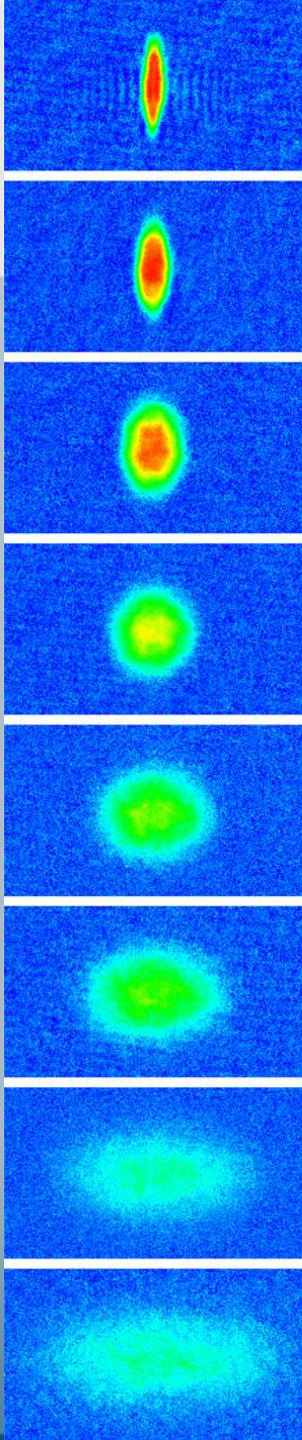
Flow: A collective effect

Elliptic flow = v_2 = 2nd Fourier coefficient of momentum anisotropy

$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi) + \ldots$$

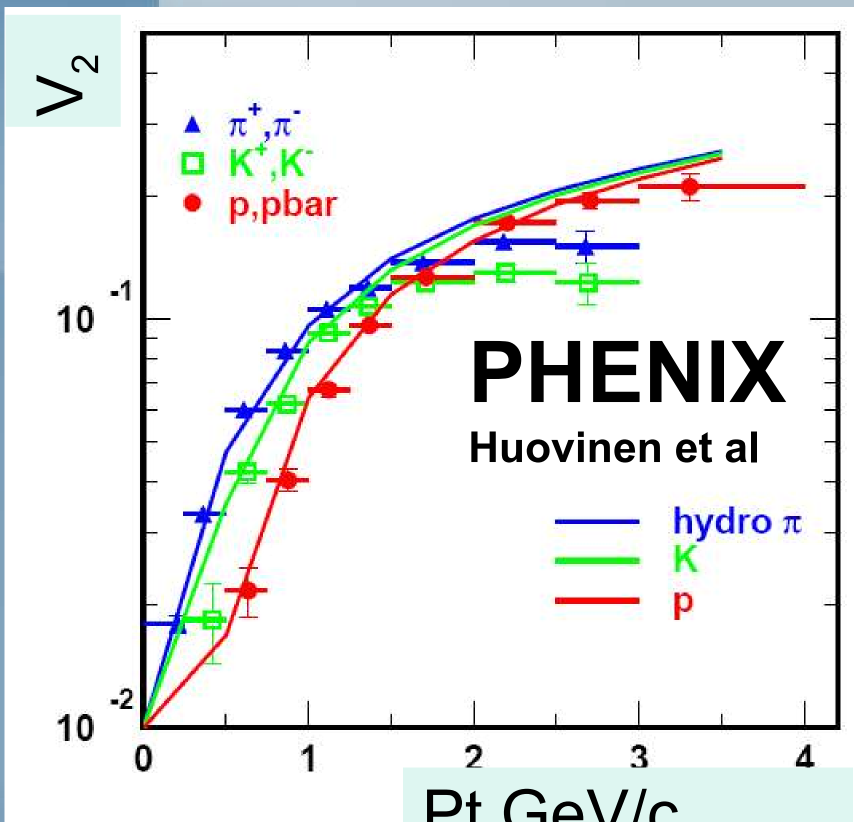
Initial spatial anisotropy is converted into momentum anisotropy.
Efficiency of the conversion depends on the properties of the medium

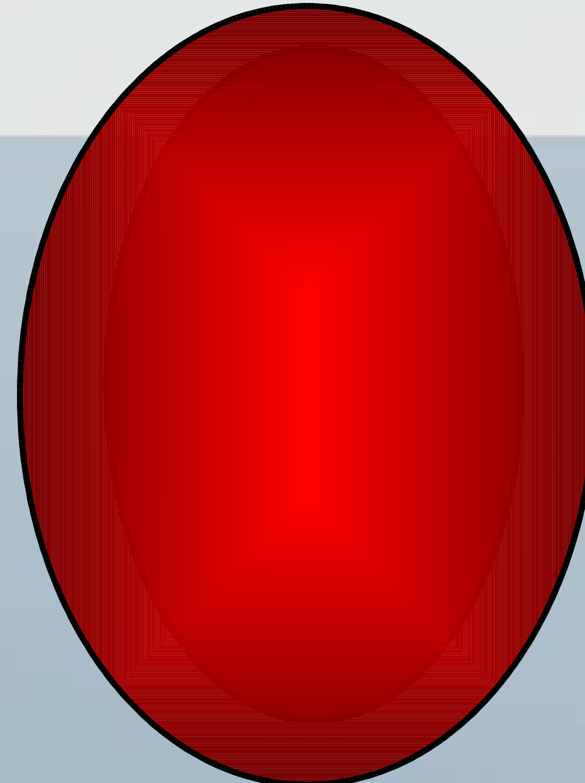




Why does large flow imply early thermalization?

Look at the converse: for a free-streaming system, spatial anisotropy and thus v_2 do not develop





From detailed hydrodynamics:

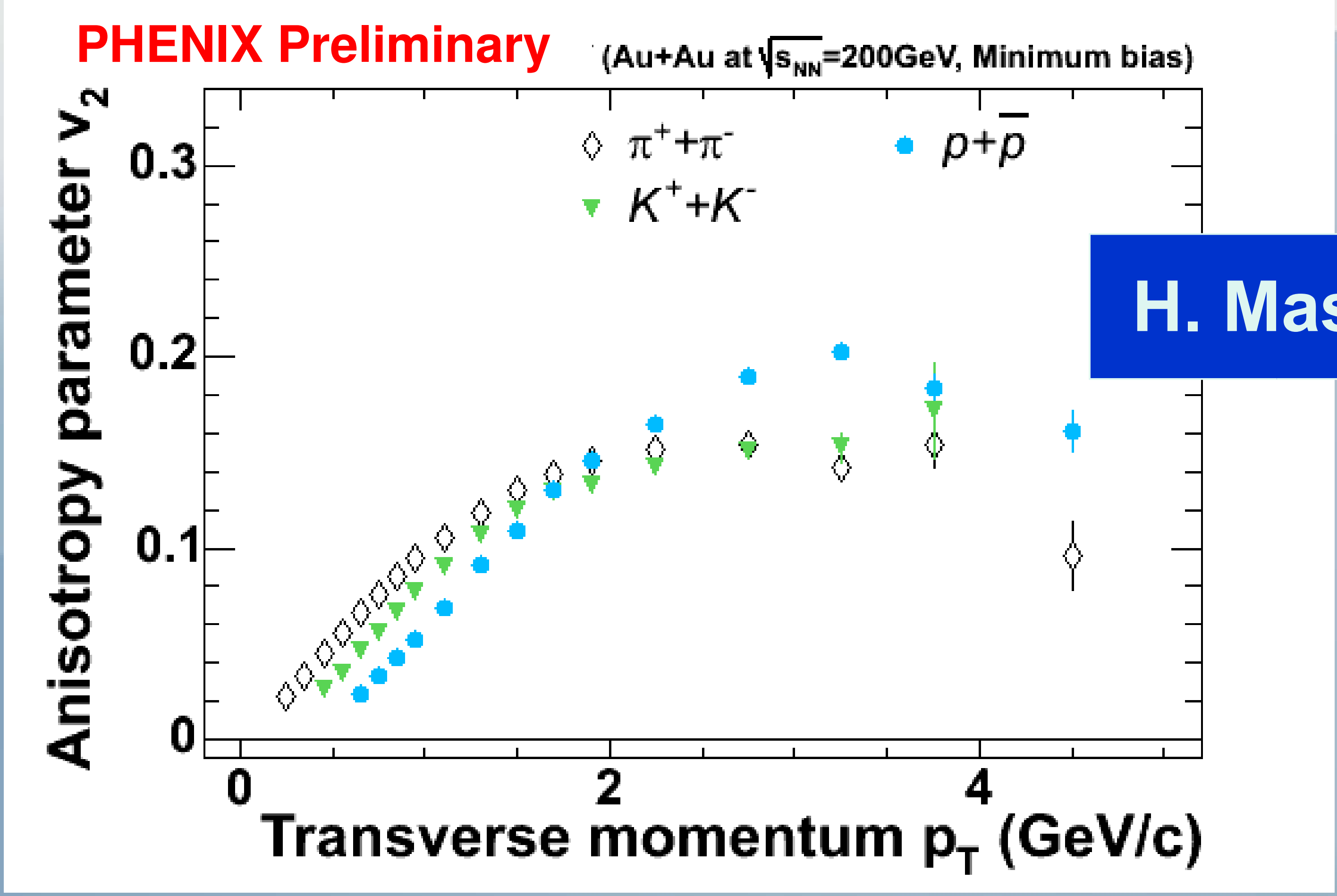
τ_{therm} ~ 0.6 -1.0 fm/c

ε~15-25 GeV/fm^3

cold matter 0.16 GeV/fm^3

Teany et al, Huovinen et al

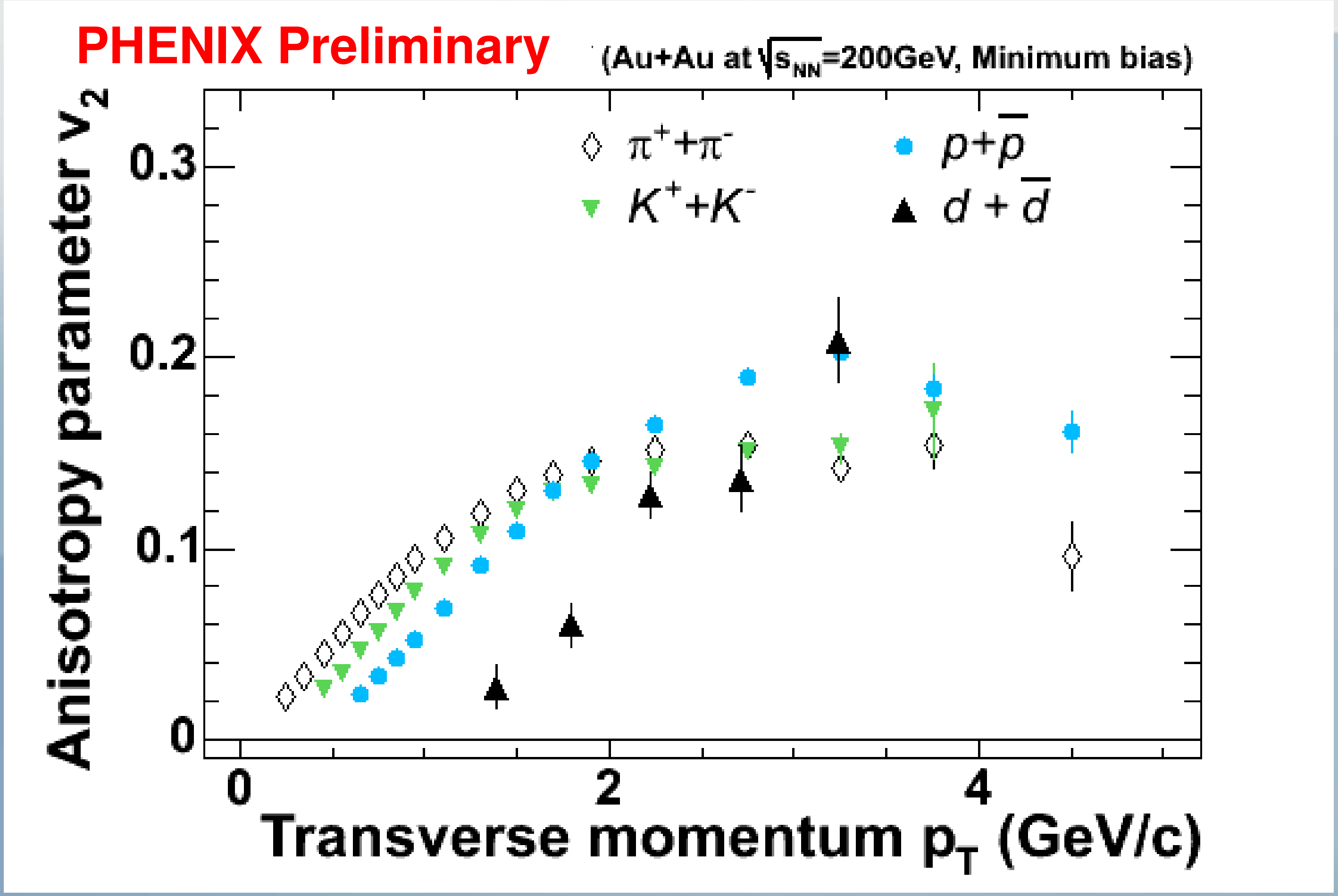
Flow of π, K, and p



H. Masui

Amount of v_2 (azimuthal asymmetry) indicates early thermalization

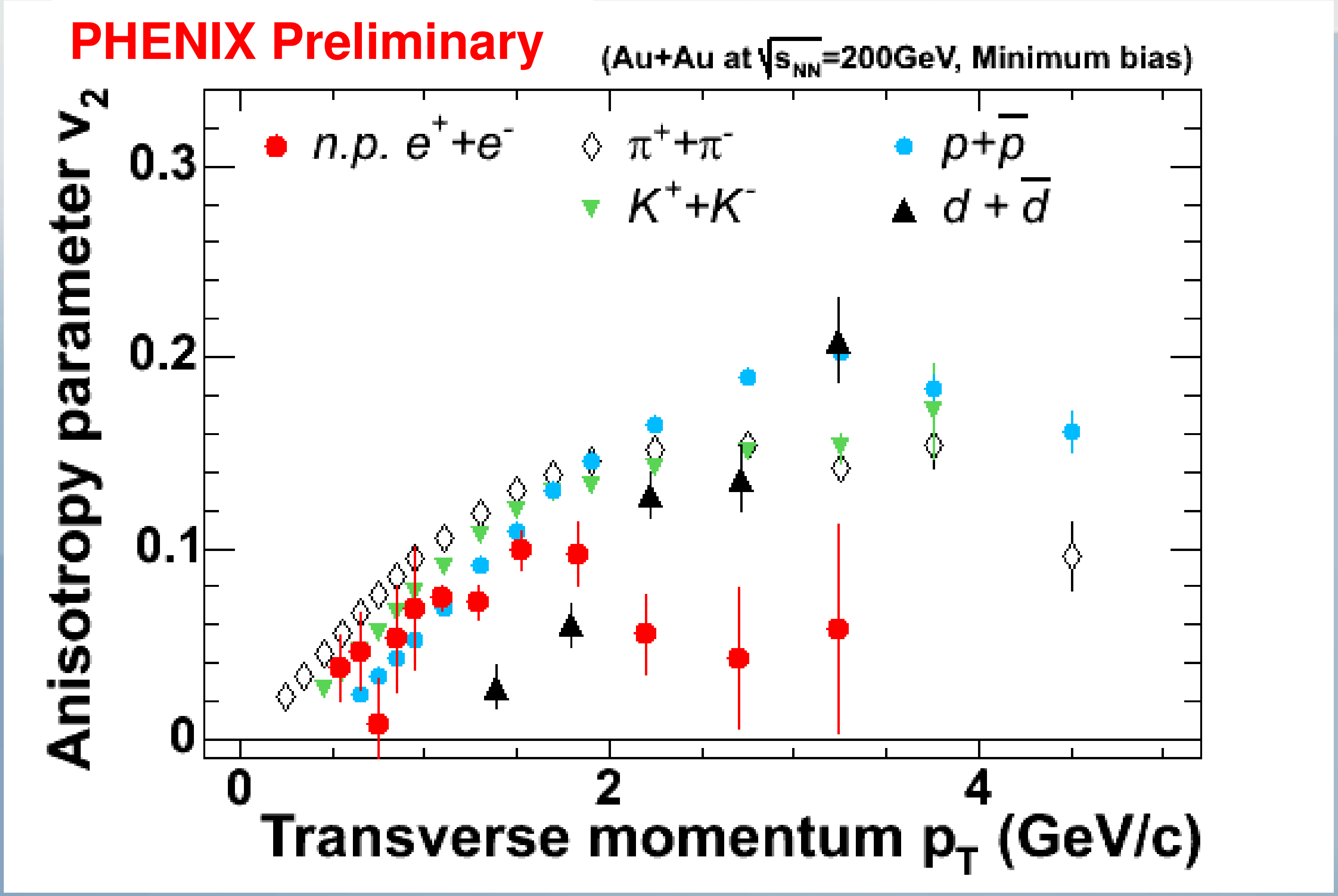
Flow of heavier particles…



Substantial v_2 now also seen for deuterons

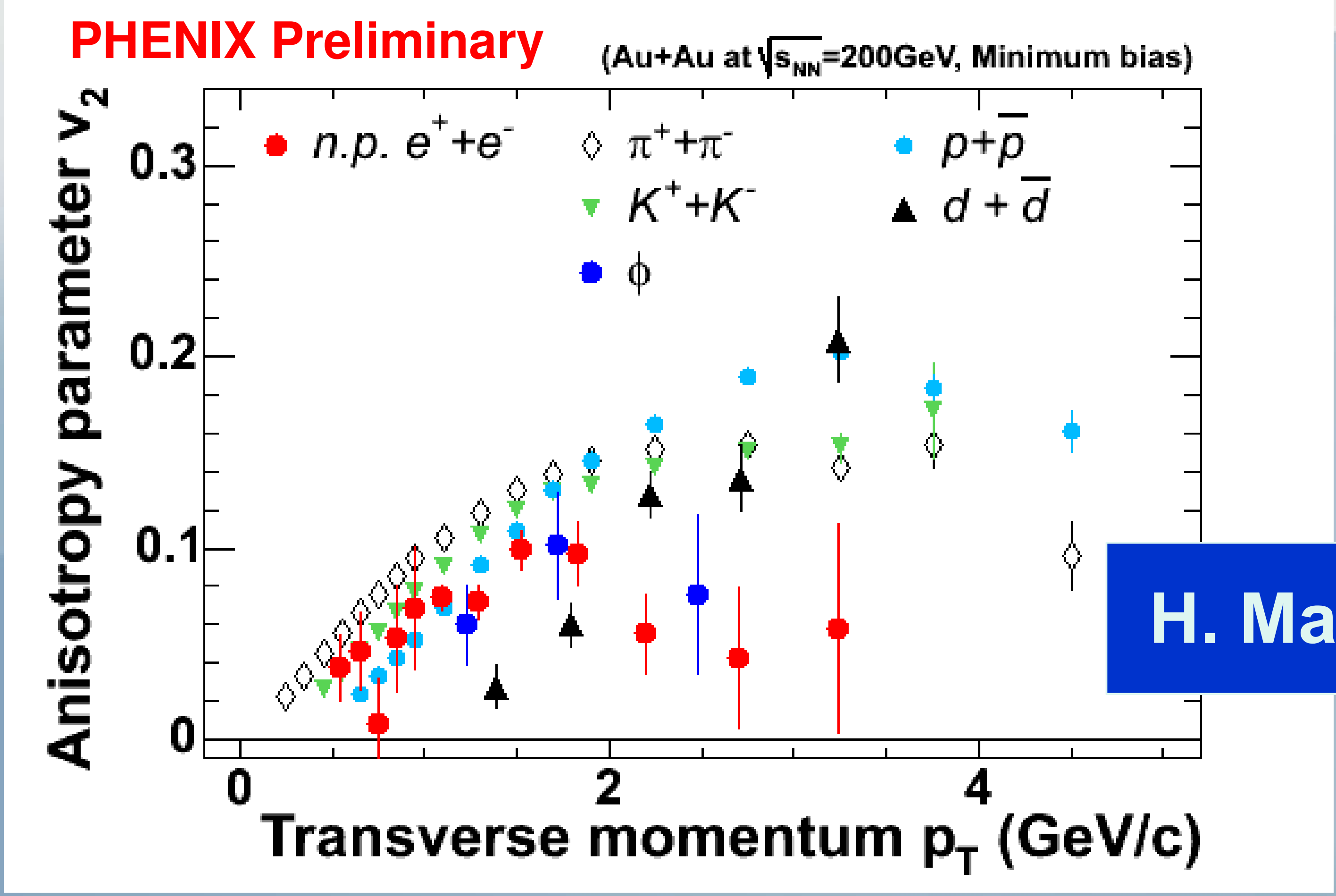
Flow of heavier particles…

Why e? Remember semileptonic open charm decays such as $D^0 = cu_{bar}$ $K^- + e + \nu$



For heavy flavor (open charm)

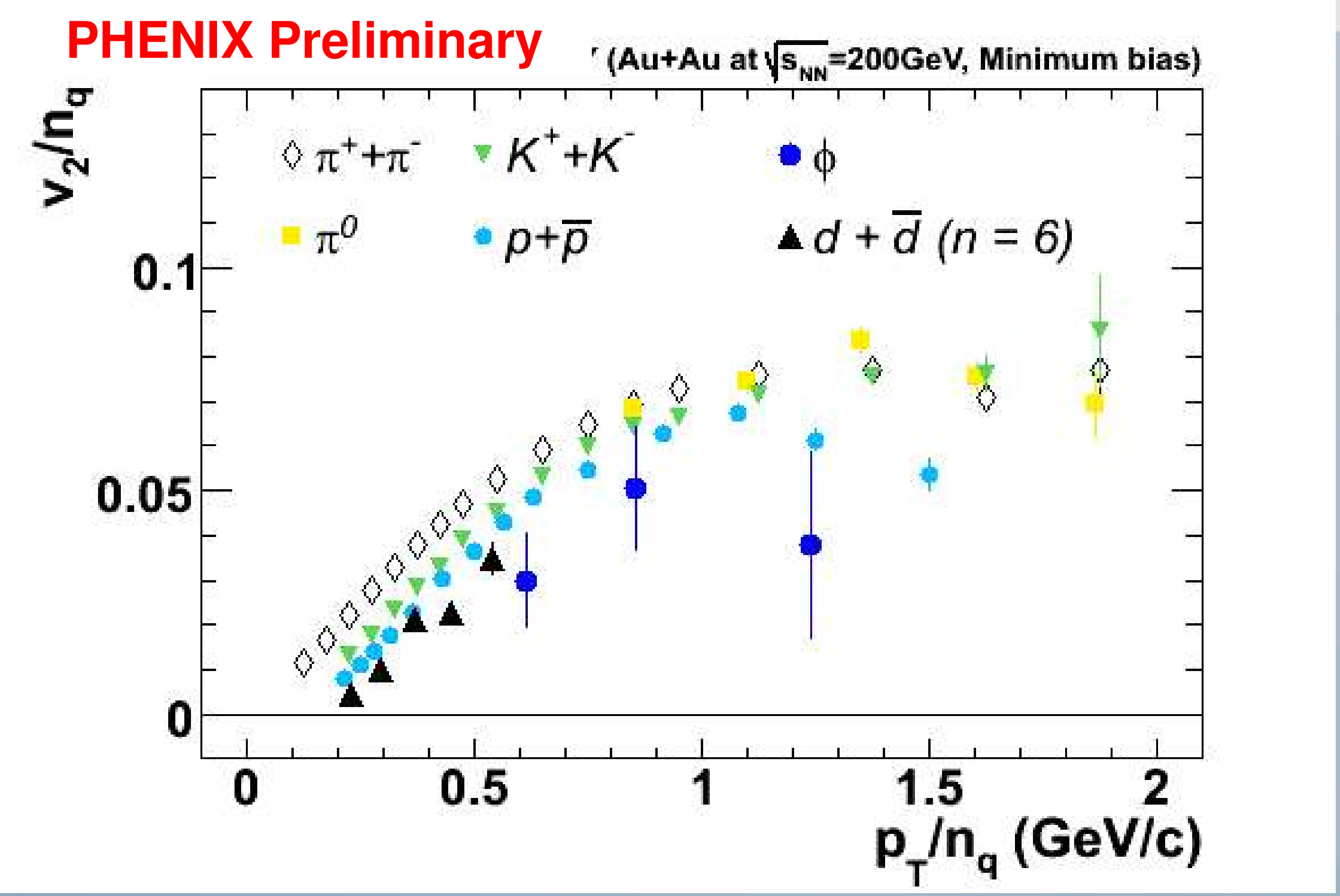
And even heavier particles



H. Masui

Even the φ flows, consistent with fast thermalization

V_2 per number of quarks



Flow happens at the partonic level

A digression
How PHENIX measures heavy flavor:
(adapted from Sergey Butsyk's parallel talk)

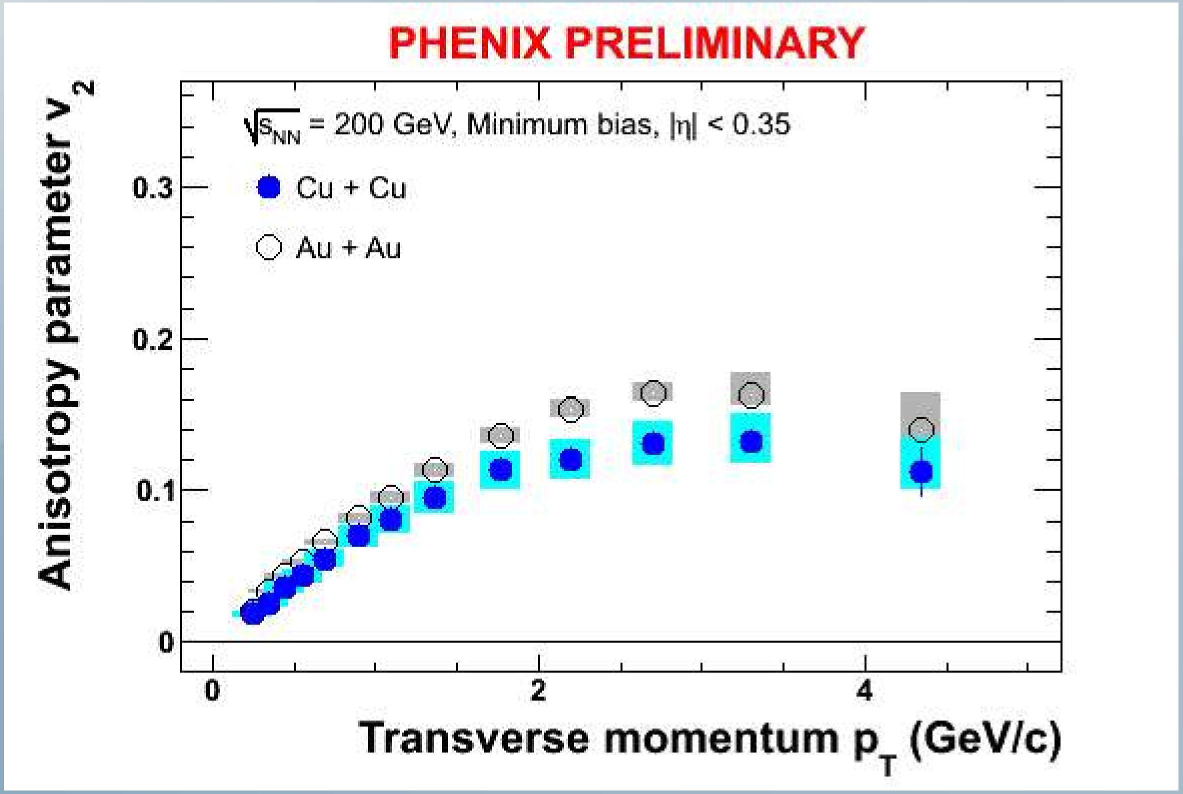
Two distinct techniques are used:

- "Cocktail subtraction" – simulation of "photon–related" electron background from conventional sources (light meson Dalitz decays, photon conversions, Ke3 decays)

- "Converter subtraction" method – extraction of "photonic" electron signal by enhancing photon conversion rate over a period of run by adding a material in the detector aperture (!)

Both analysis clearly show the excess electron signal originates from heavy flavor particle's semi-leptonic decays

Charged hadron v_2 vs p_t for minimum bias Cu+Cu and Au+Au collisions



Hadronization

Hadronization/Baryon puzzle

We just saw considerable evidence that elliptic flow at RHIC obeys simple valence quark scaling. This suggests that the scaling arises from recombination of the quarks.

In this context, look at some initial questions:

Why is there a large proton to pion ratio at high pt?

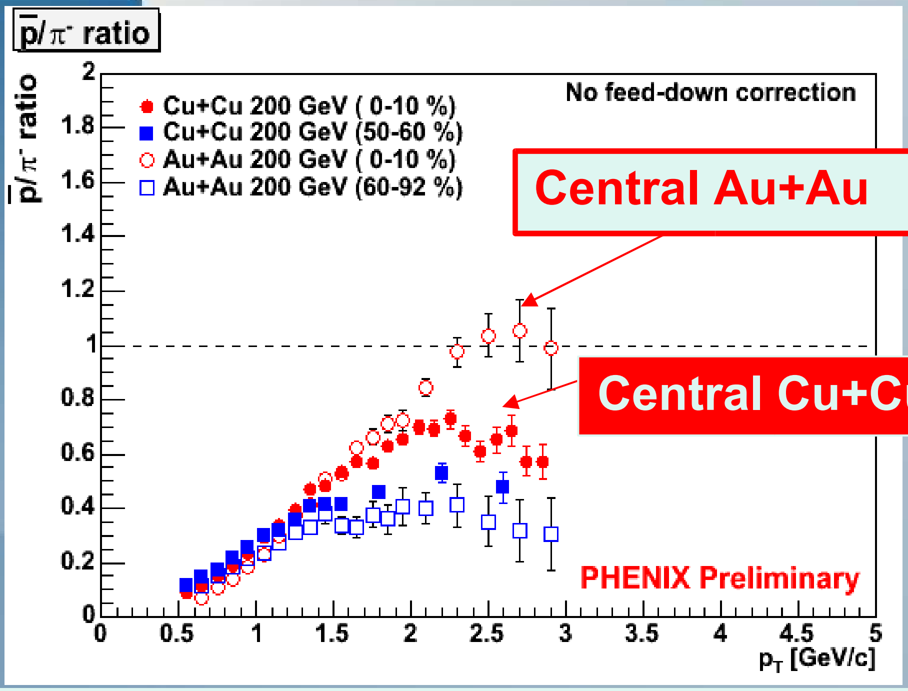
Why are protons less suppressed than pions?

- Possible contributions are flow, recombination, and energy loss

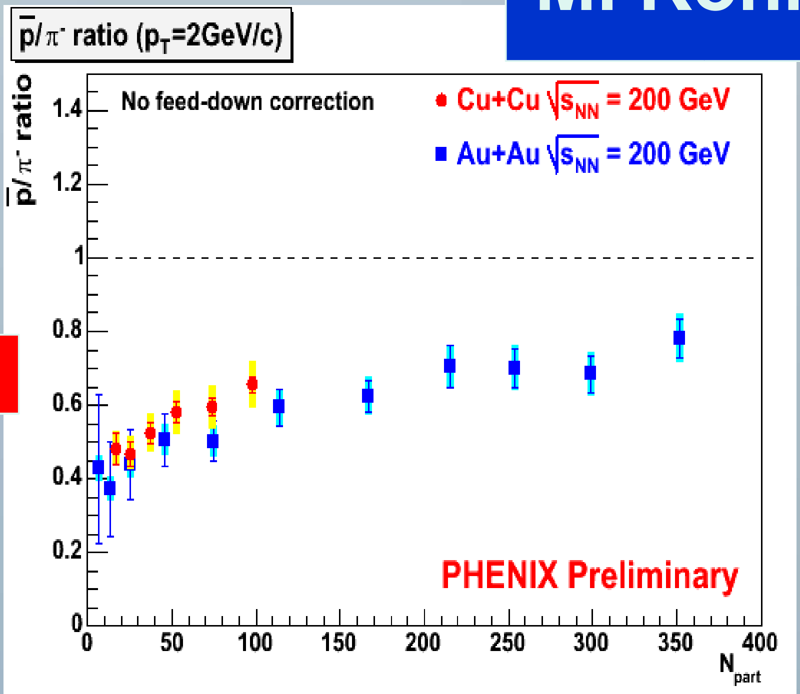
- Recombination or coalescence: at low p_t, the quark and antiquark spectra are thermal and they recombine into hadrons locally in space and time
  - The spectrum is shifted to higher p_t for hadrons which can account for the large p/π ratio
- Fragmentation starts with a single fast parton and energy loss affects pions and protons similarly.
  - Fragmentation yields $Np/N\pi \ll 1$

Baryon "anomaly"

M. Konno



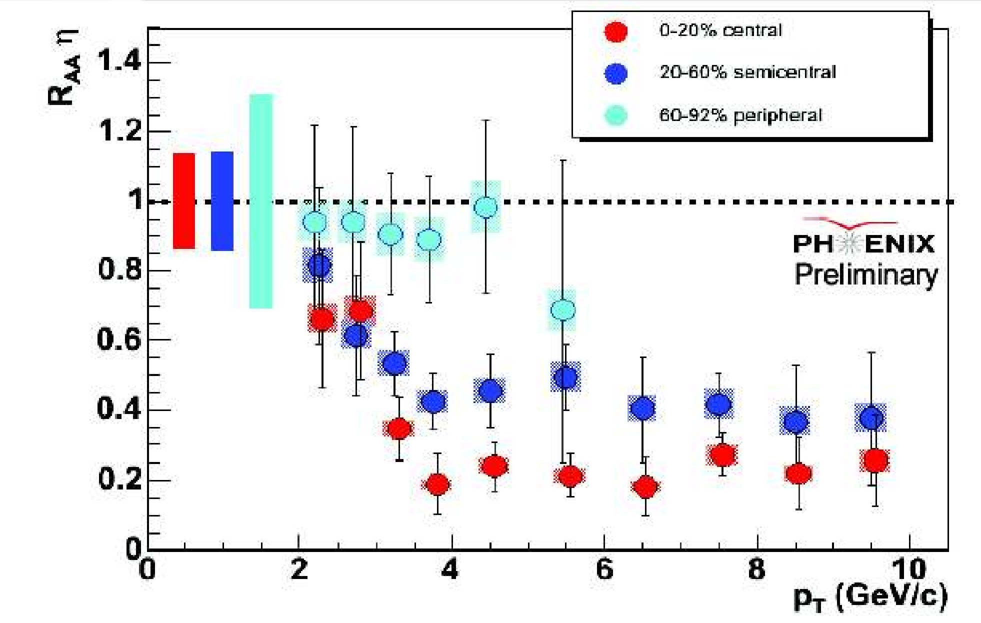
$\bar{p}/\pi$ ratio in Cu+Cu/Au+Au collisions

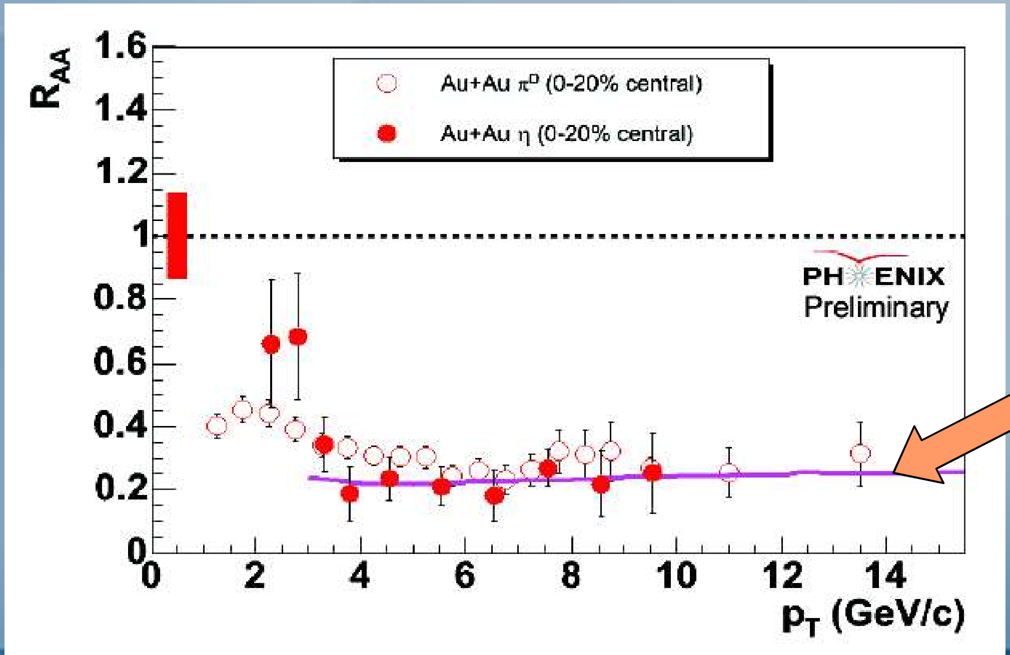


Baryon/meson ratio at 2 GeV in Cu+Cu collisions scales as N_{part}.

Scaling is not specific to Au+Au but rather is smooth with number of participants.

η Production



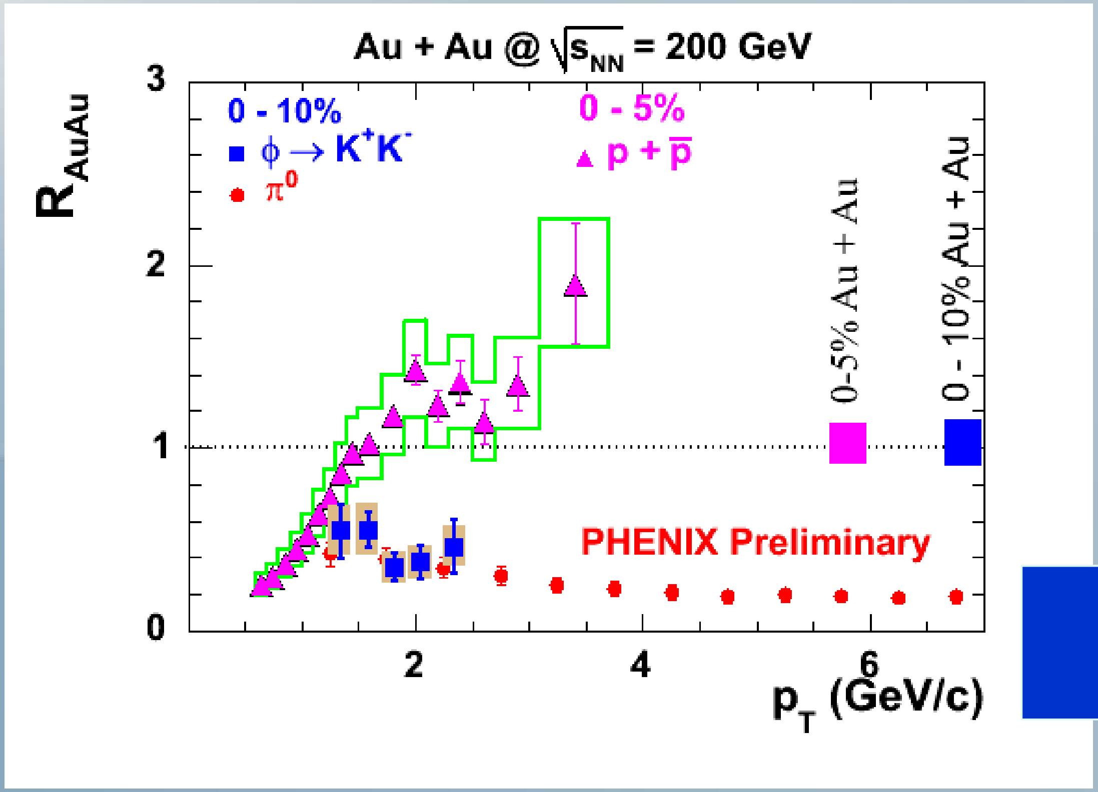


π^0 and η suppression consistent in magnitude and p_T dependence

- Suppression factor of 5 in central collisions
- Agreement with parton energy loss predictions up to highest pT measured so far

GLV R_{AA}
$dN^g/dy = 1100$

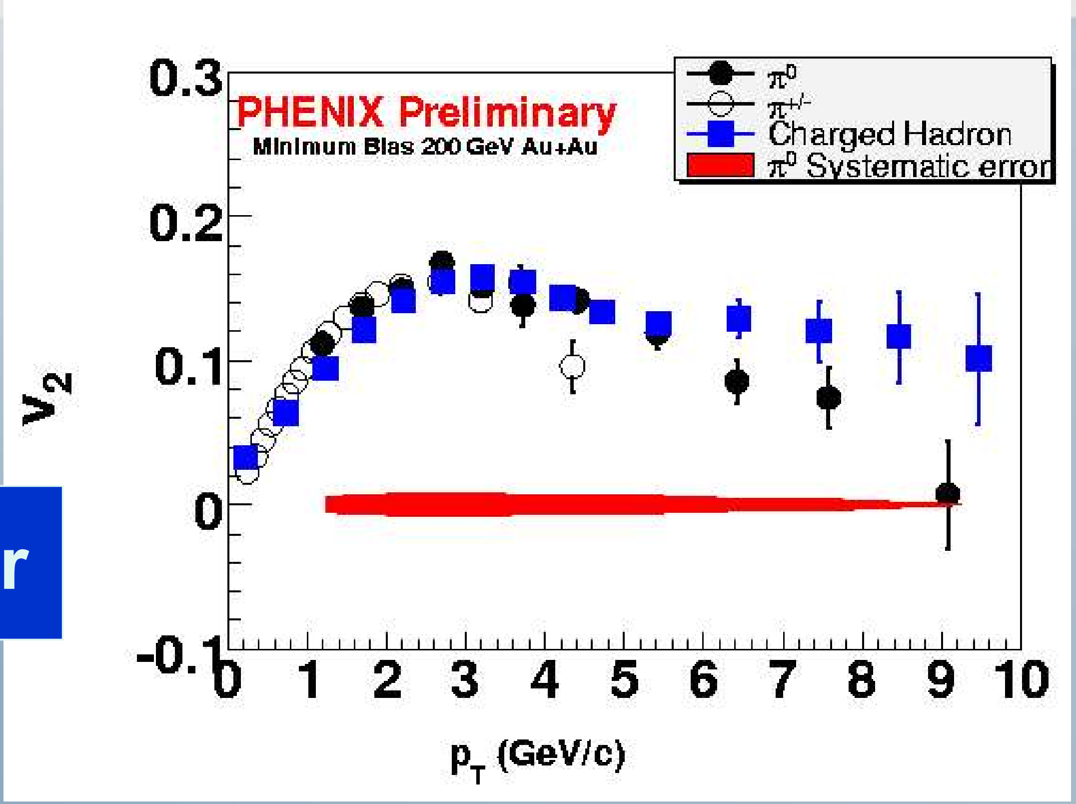
$\Phi \rightarrow K^+K^-$ R_{AA} for Au-Au 200 GeV/c



D. Pal

Φ R_{AA} looks like the π rather than the proton, consistent with recombination models

v_2 at high p_t



D. Winter

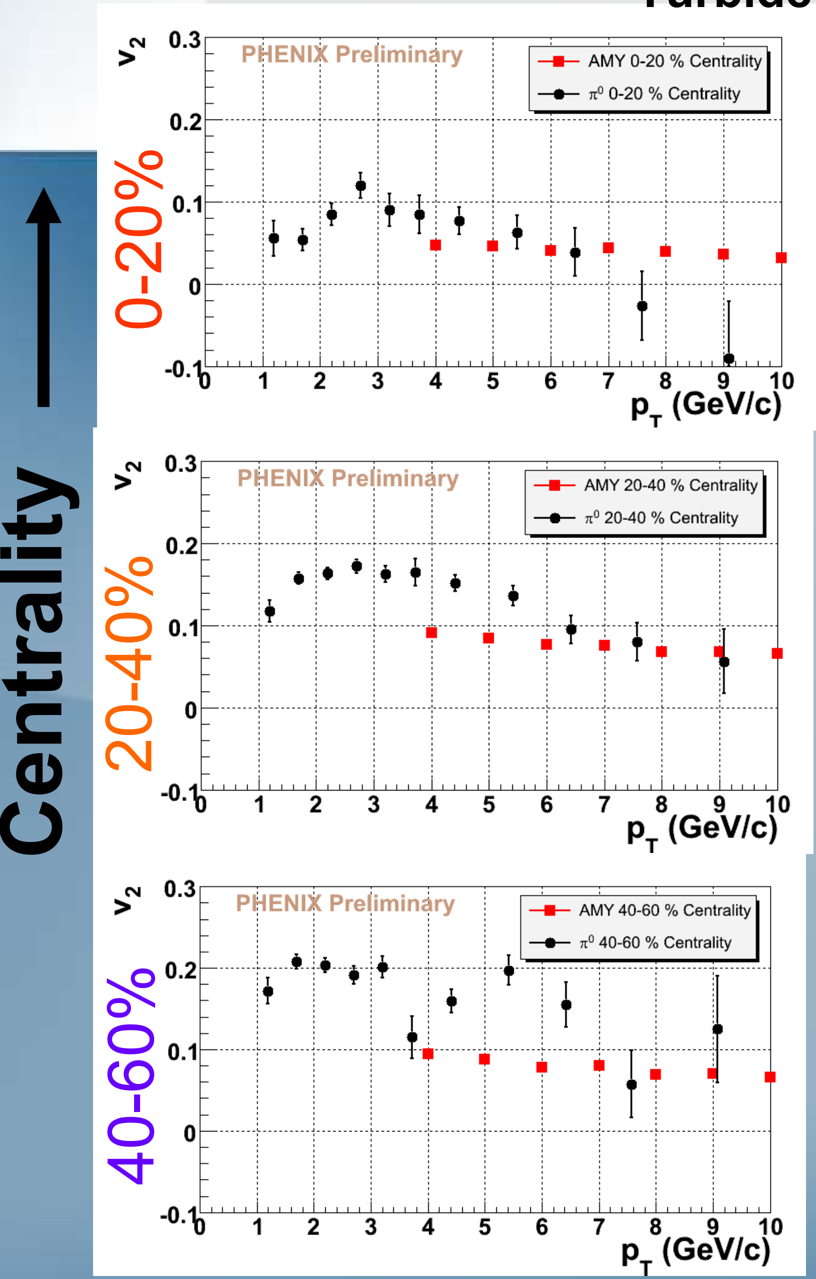
v_2 starts to fall at 6-7 GeV/c – expected from energy loss

What is the source of v2 at intermediate pt (3-7 GeV/c)?

π^0 v_2 Theory Comparison:

Turbide et al. private communication

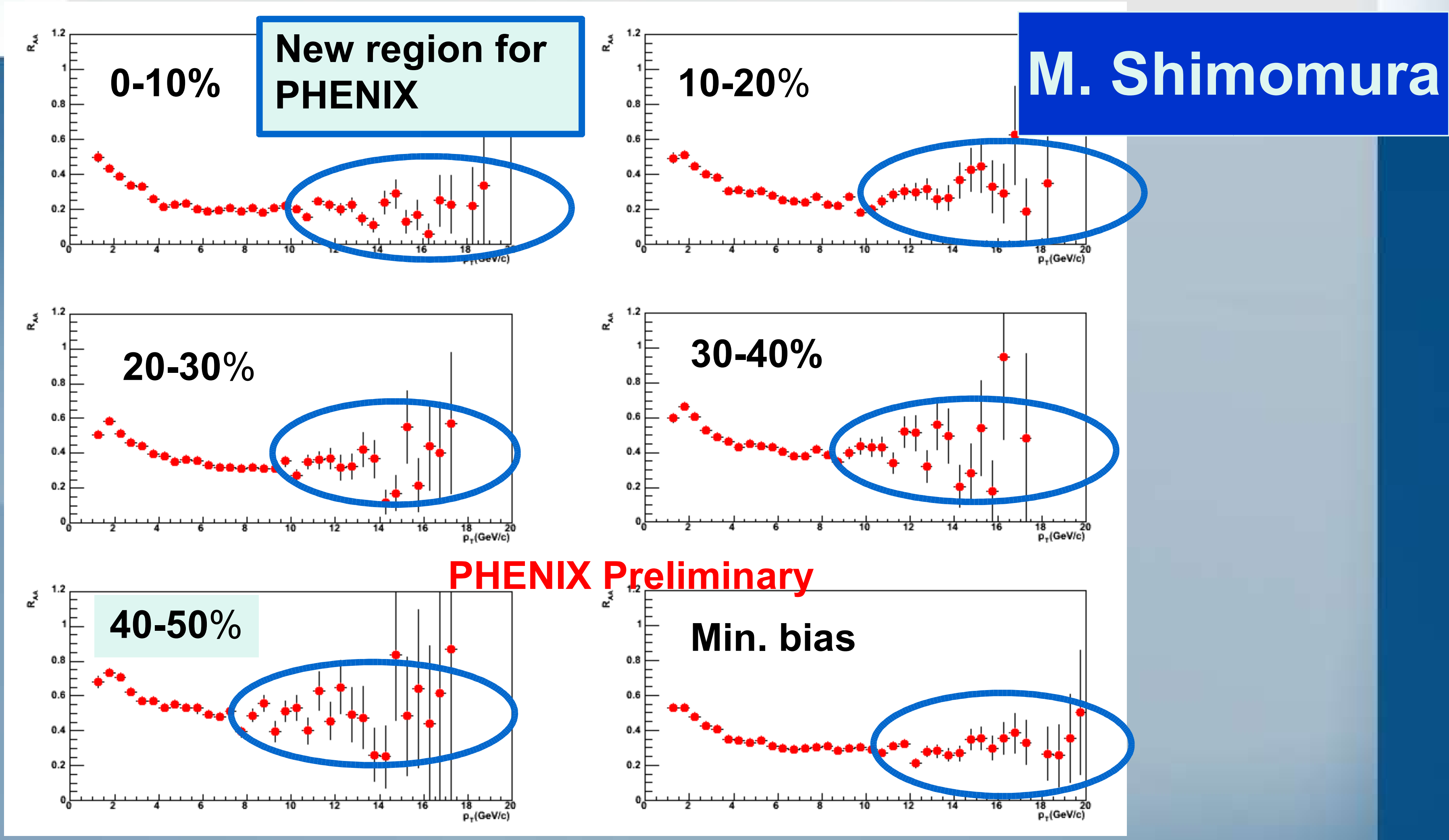
● data ● theory



- AMY formalism
  - Arnold, Moore, Yaffe, JHEP 0305:51 2003
- Energy loss only (no "soft" effects)
- High-p_T
  - v_2 appears to decrease to energy loss calculation at 6 or 7 GeV/c
- Conclusion: additional physics at intermediate-p_T (< 7 GeV/c) even in pions

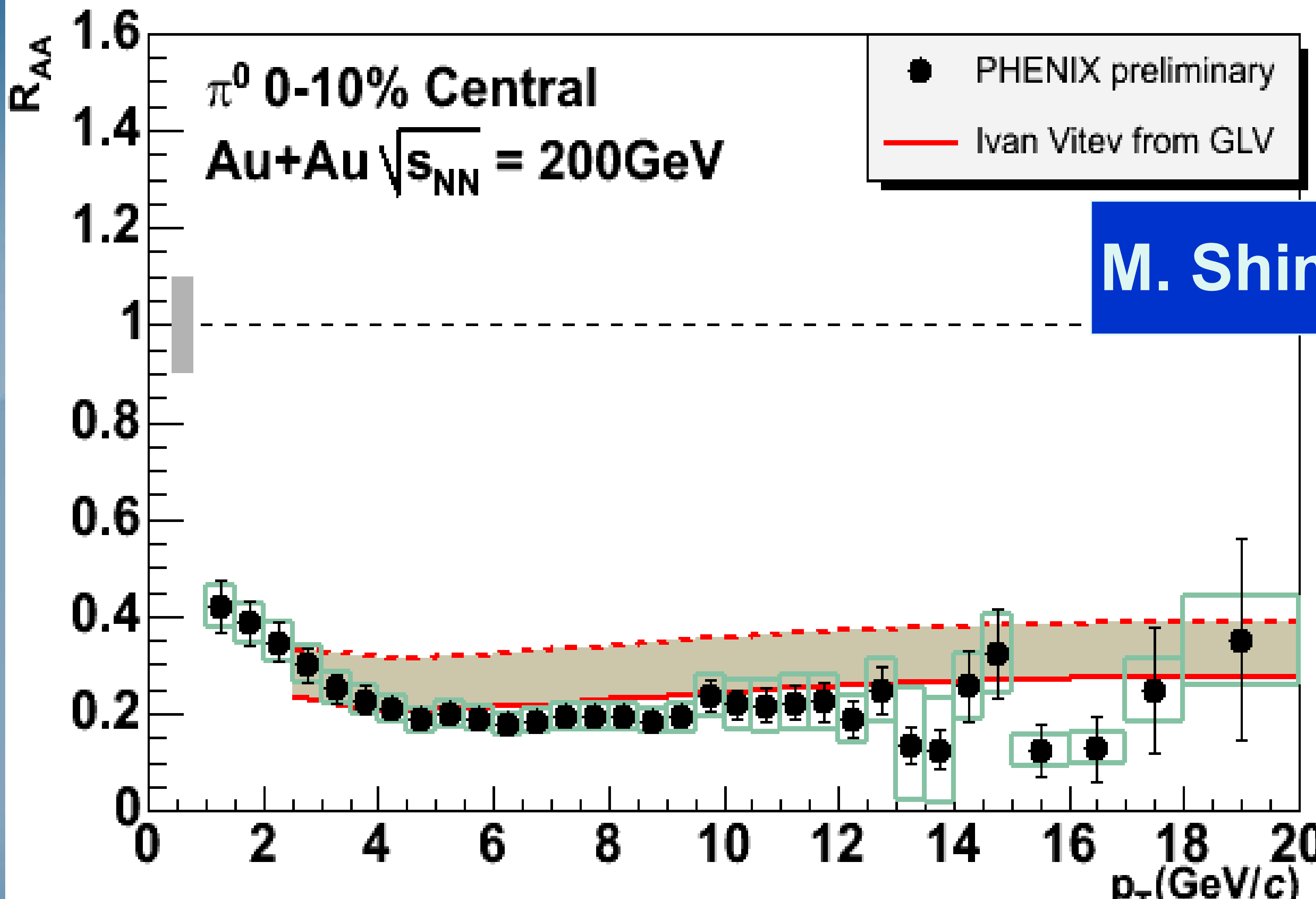
R_{AA} at high p_t

π^0 R_{AA} for 200 GeV Au Au Collisions



R_{AA} appears flat all the way to p_T~20 GeV/c

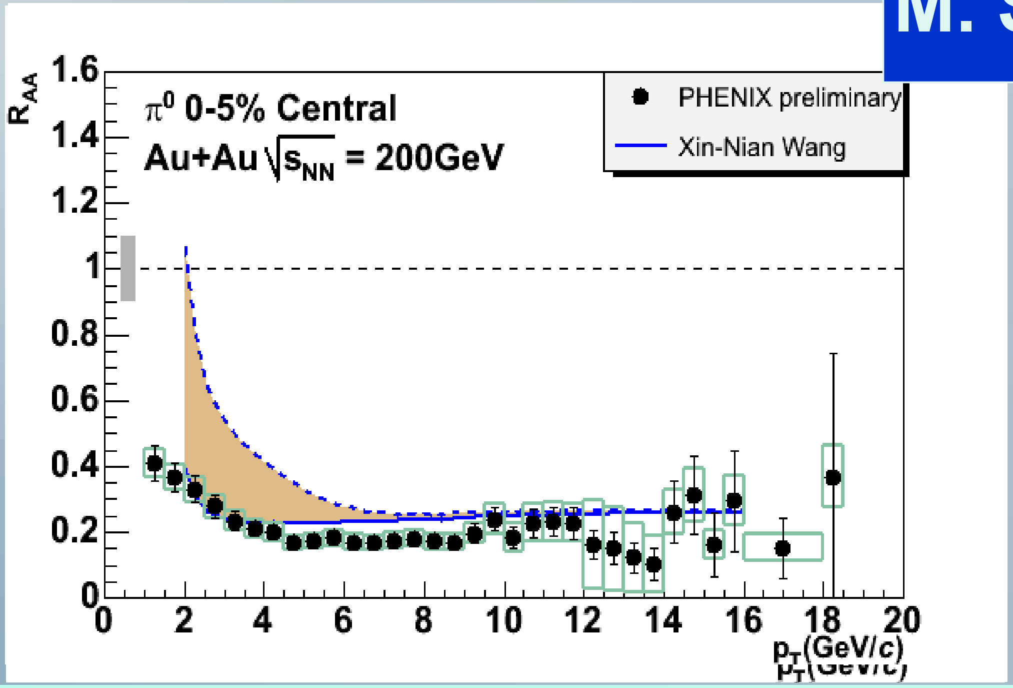
Ivan Vitev comparison to high-p_t π^0 from GLV (0-10%)



M. Shimomura

Xin-Nian Wang comparison to high-p_t π^0

M. Shimomura

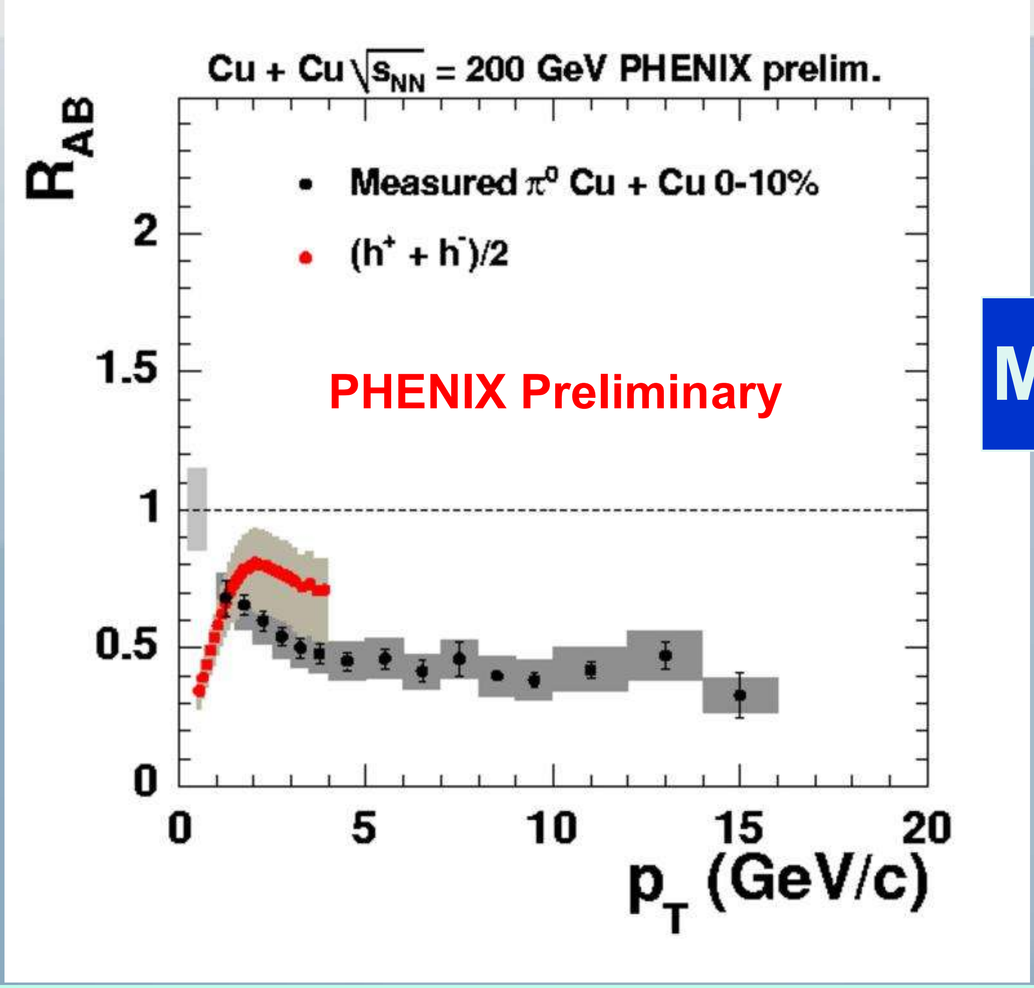


Energy loss models can reproduce nearly flat R_{AA} from p_T ~ 3-20 GeV/c

We concluded more physics for p_T<7 GeV/c

What does agreement with theory mean?

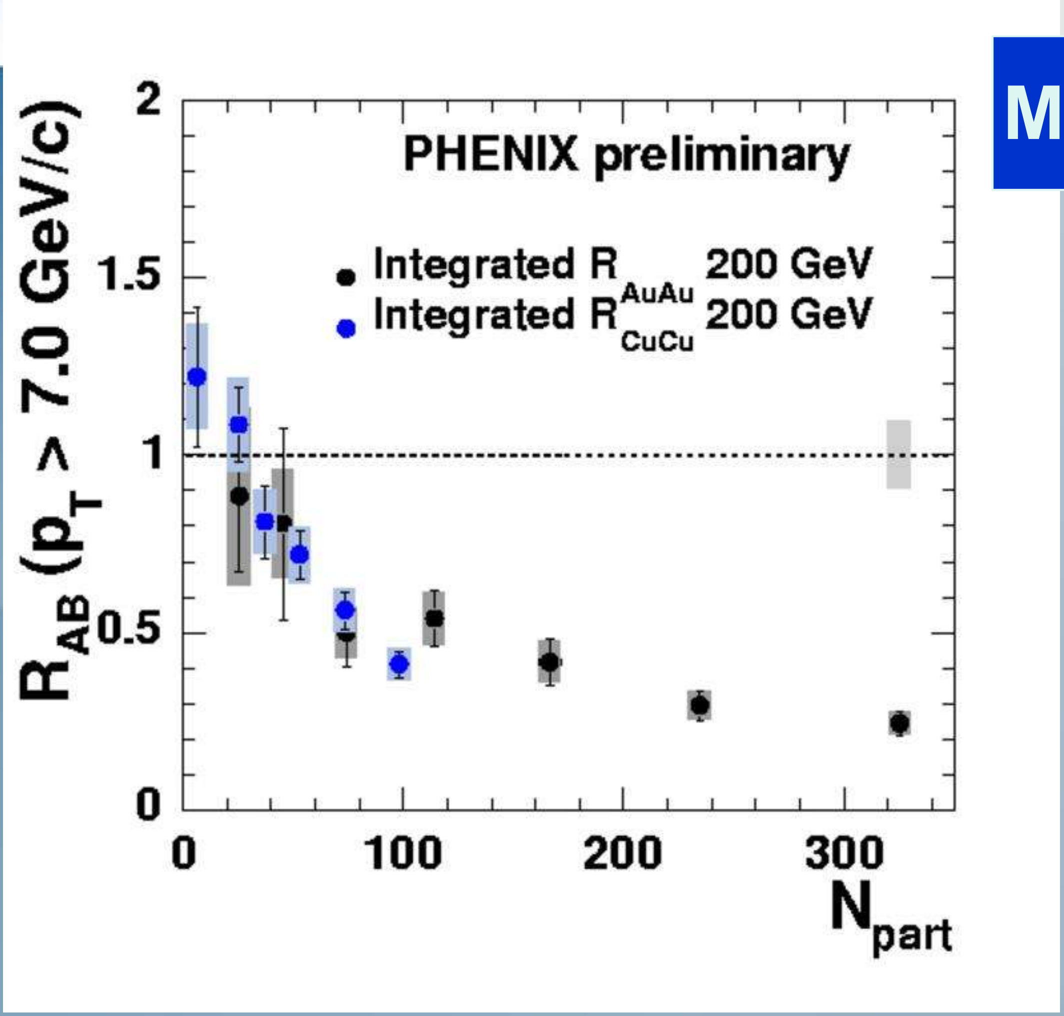
R_{AA} measured for Cu+Cu collisions



M. Shimomura

PHENIX has analyzed high-p_T data for Run-5 Cu+Cu collisions only months after end of run

R_{AA} vs. N_{part}



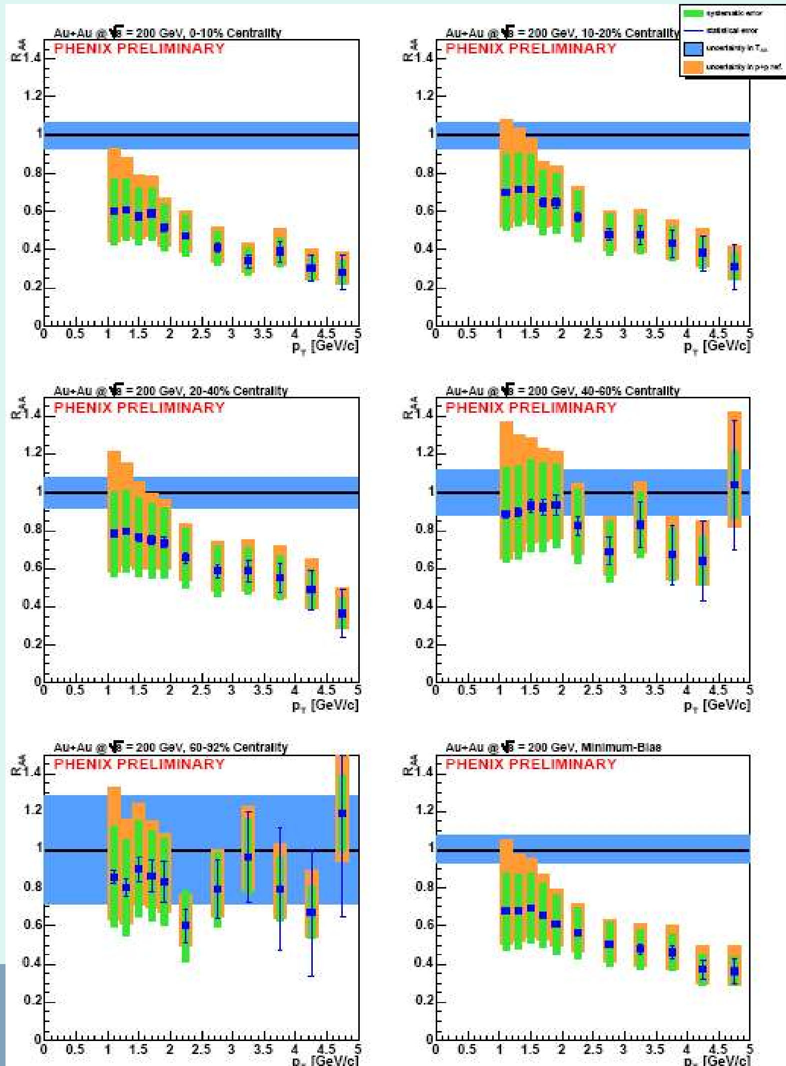
M. Shimomura

p_T>7 GeV/c (in "hard" region)

Centrality dependence of suppression in Au+Au scales as $N_{part}^{2/3}$

Cu+Cu consistency with this scaling barely within 90% CL (χ^2/Ndof=10.6/6)

Heavy Quark Energy Loss: Nuclear Modification Factor R_{AA}



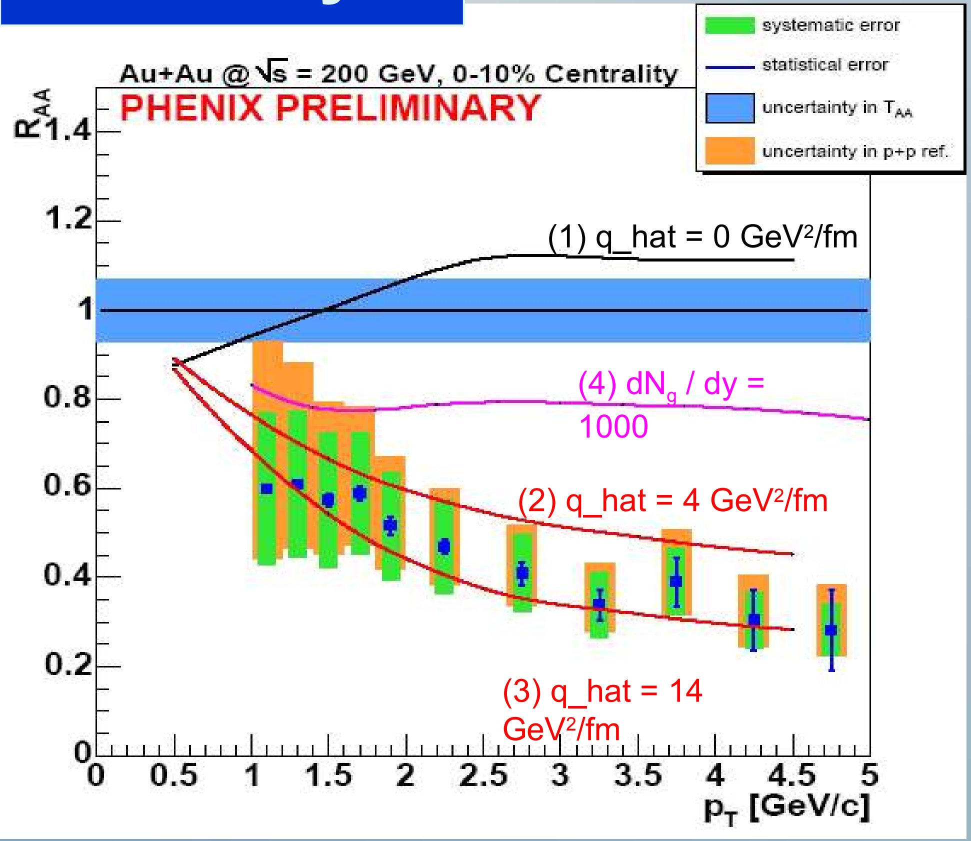
$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{T_{AA} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

- Strong suppression for central Au+Au collisions is observed at $p_T > 1$ GeV/c

S. Butsyk

Heavy quark energy loss: Comparison to Theory

S. Butsyk



- Observed suppression is in good agreement with one of theoretical calculations for the final state energy loss of heavy flavor
- The contribution from bottom electrons to the charm electrons need to be derived in order to understand the interplay between charm and bottom component of R_{AA}

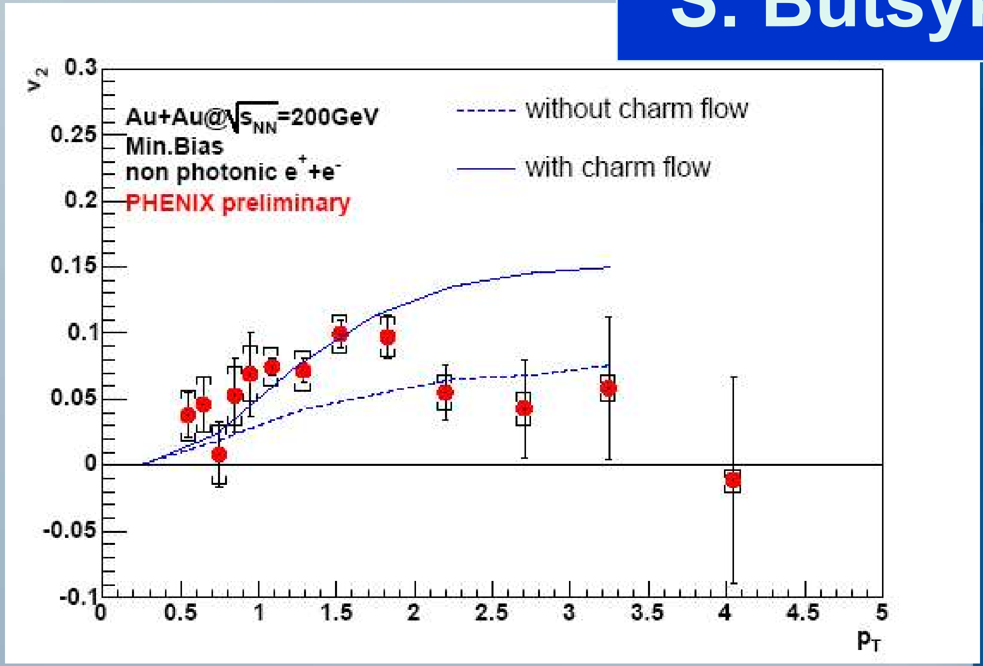
Theory curves (1-3) from N. Armesto, *et al.*, hep-ph/0501225
(4) from M. Djordjevic, M. Gyulassy, S.Wicks, Phys. Rev. Lett. 94, 112301

Open Charm Flow

S. Butsyk

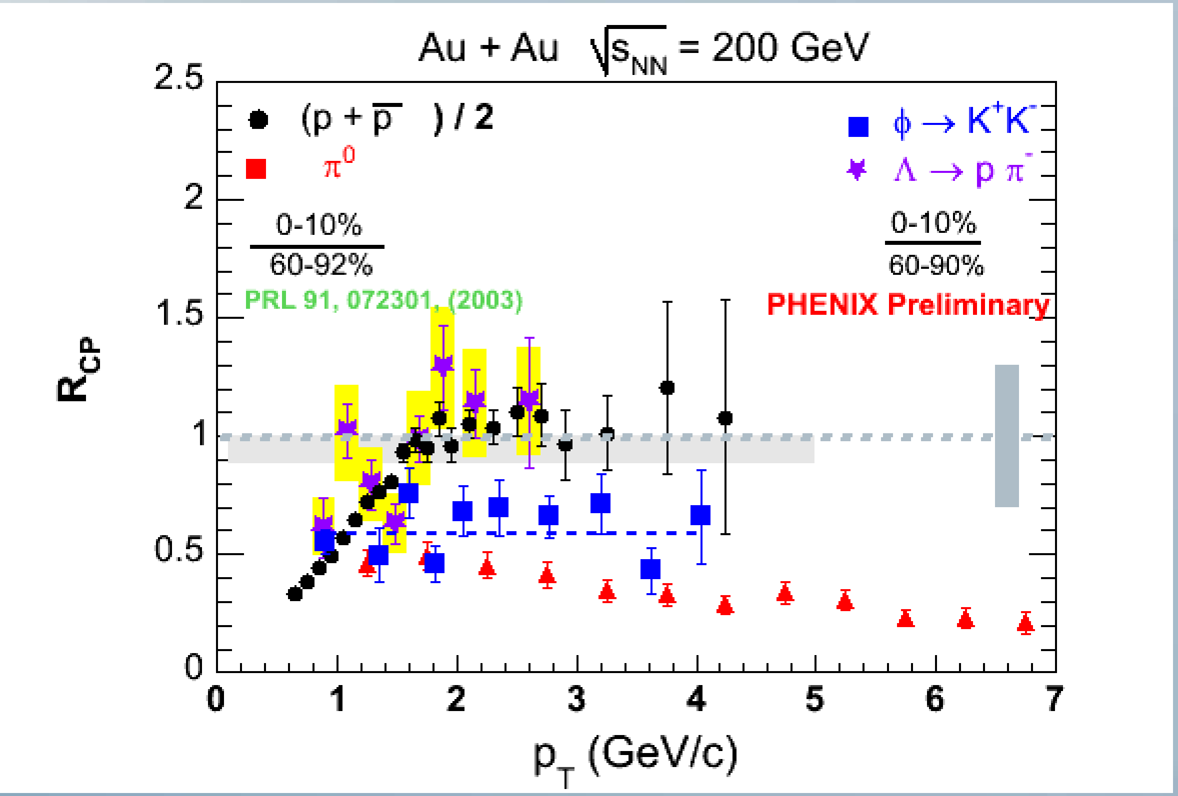
R_{AA} and v_2 should be described within same theoretical framework provides a more stringent test for theory

- New v_2 results from Run04
- Preliminary results indicate reduction of v_2 strength at $p_T > 2$ GeV/c
- Bottom v_2 contribution??



Theory curves from:
Greco, Ko, Rapp: Phys. Lett. B595 (2004) 202

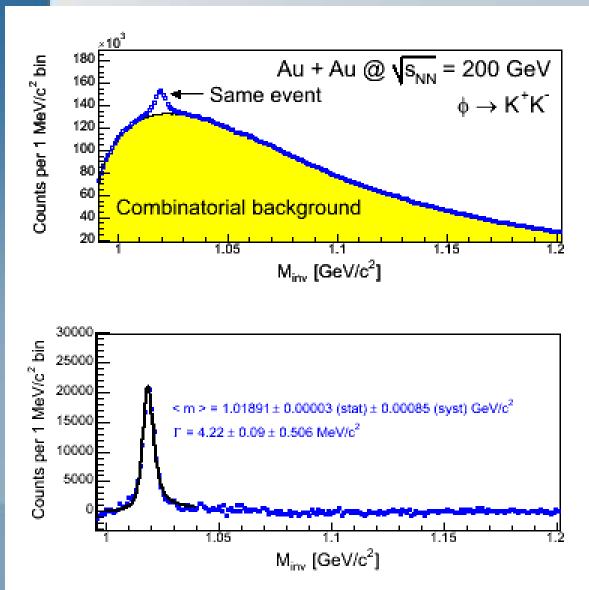
R_{CP} vs p_t for Au+Au Collisions at 200 GeV
λ teaser

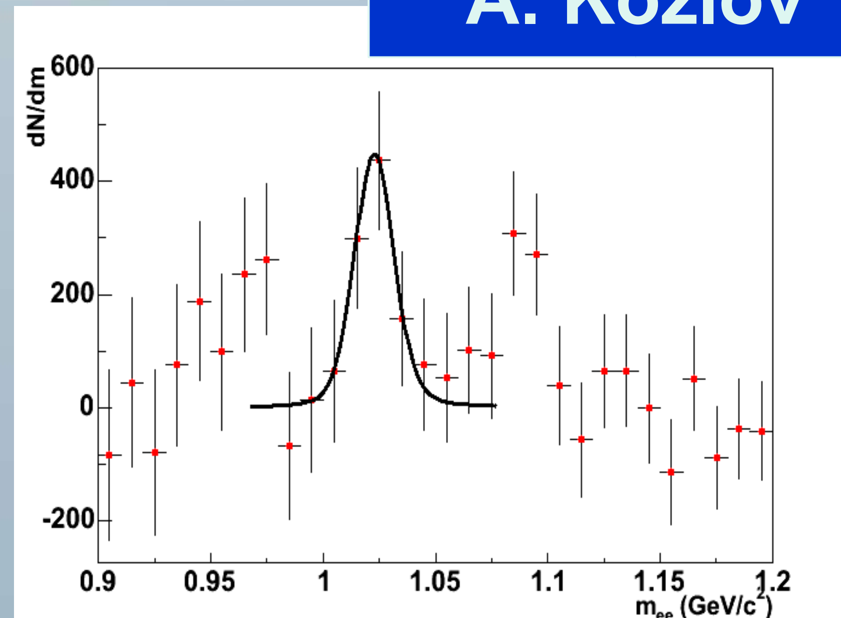


Chiral Symmetry Restoration

Φ ee vs. Φ KK mass line-shapes

A. Kozlov



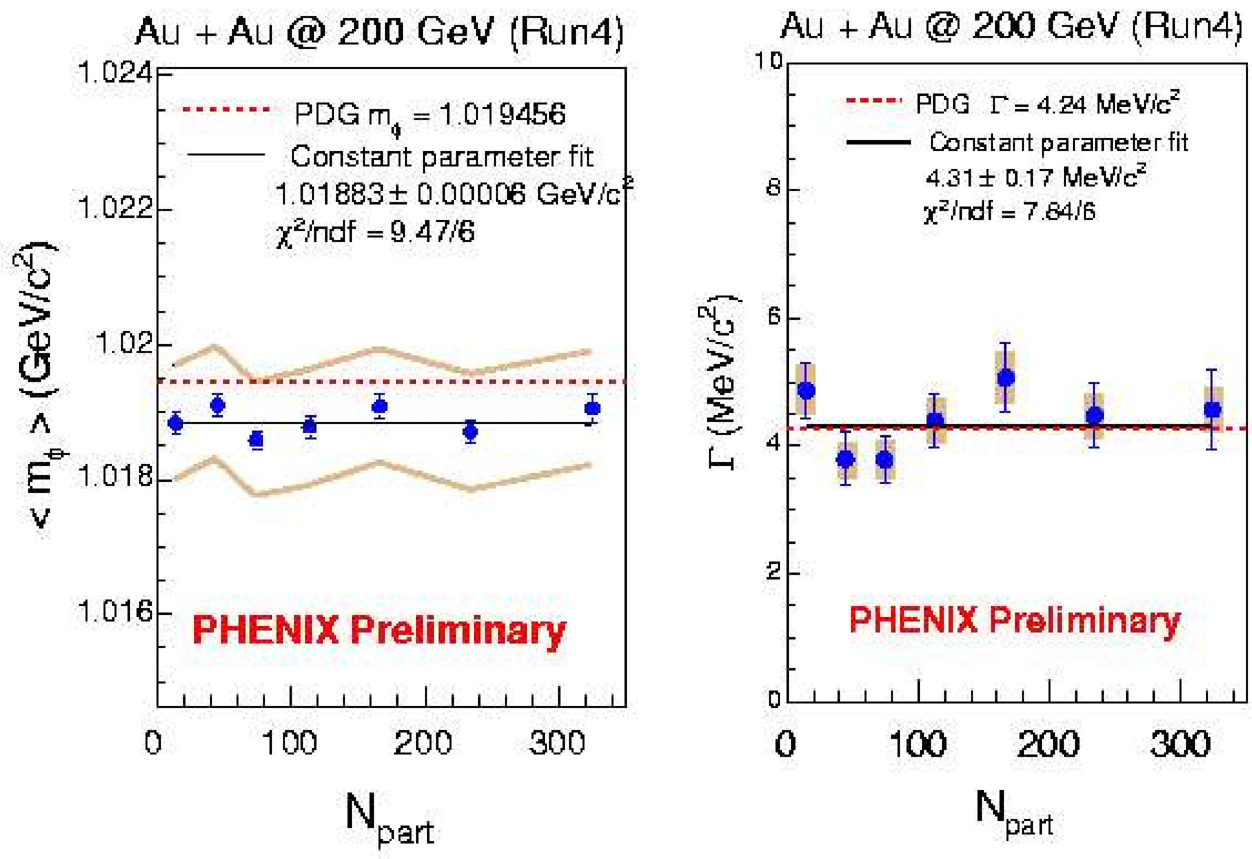


m(Φ KK) = 1.02891 ± 0.00003(stat) ± 0.00085 (syst) GeV/c²,

Γ(Φ KK) = 4.22 ± 0.09 ± 0.506 MeV/c²

Γ(Φ ee) = 8.9 ± 12.3 MeV/c²

Φ KK mass vs. N_{part}

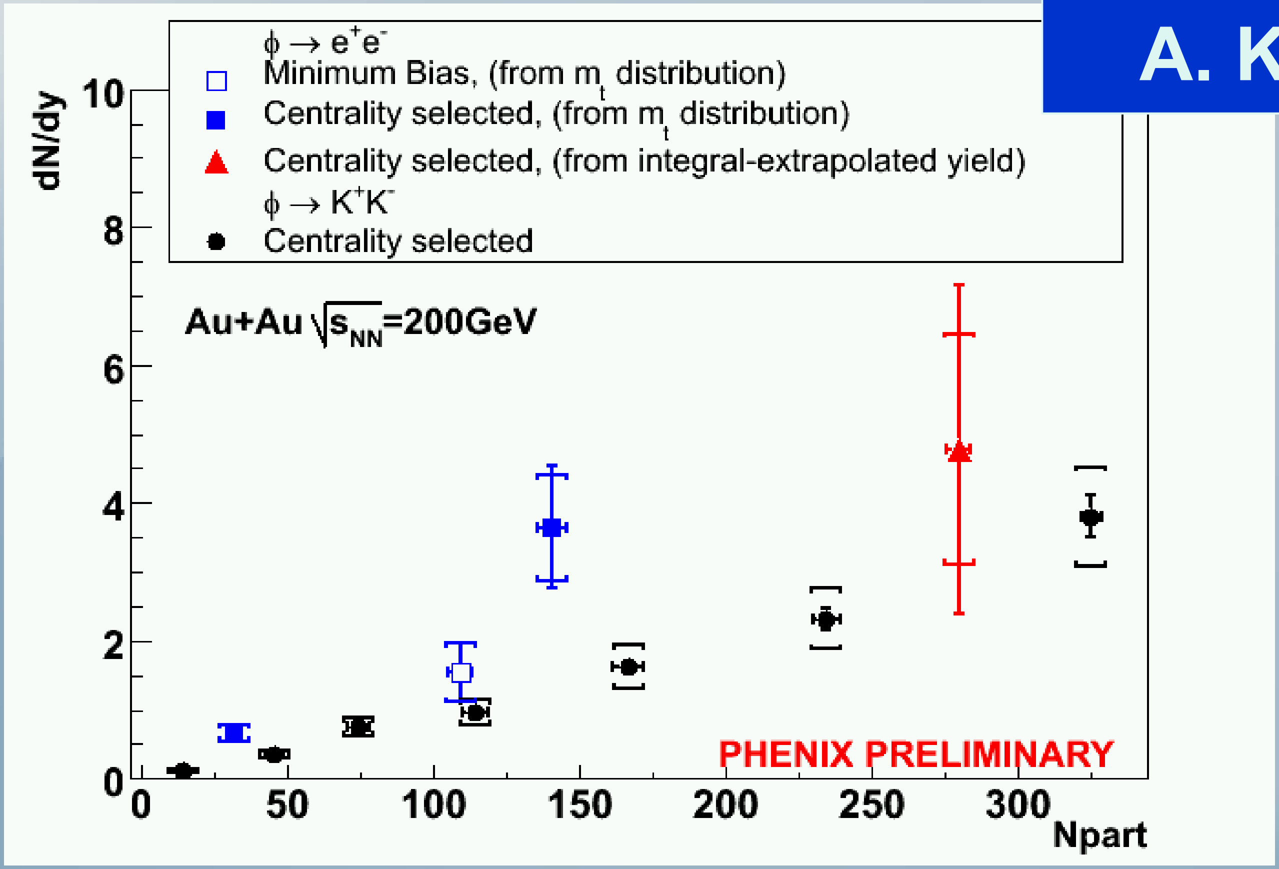


A. Kozlov

- Φ KK line shape and mass are flat (and consistent with PDG values) within errors as functions of N_{part}

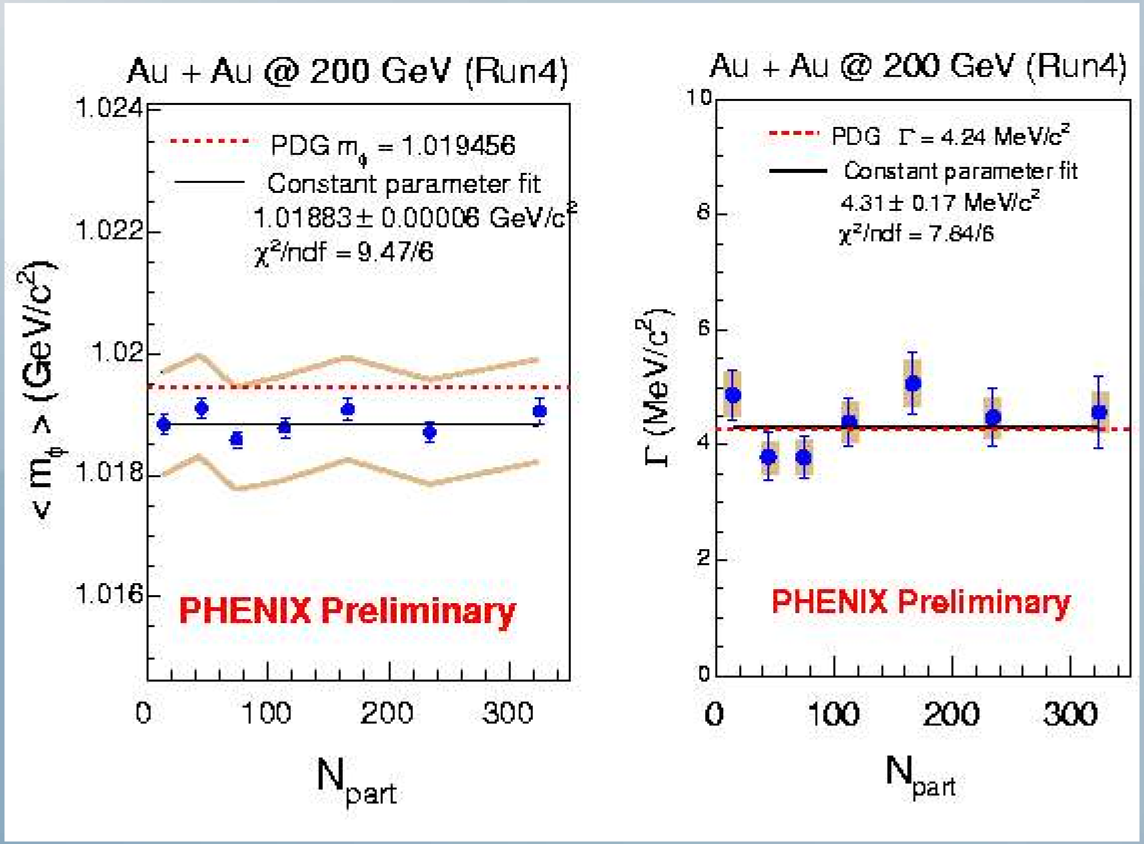
Φ ee vs. Φ KK dn/dy

A. Kozlov



dn/dy for Φ ee tends to be larger than for Φ KK

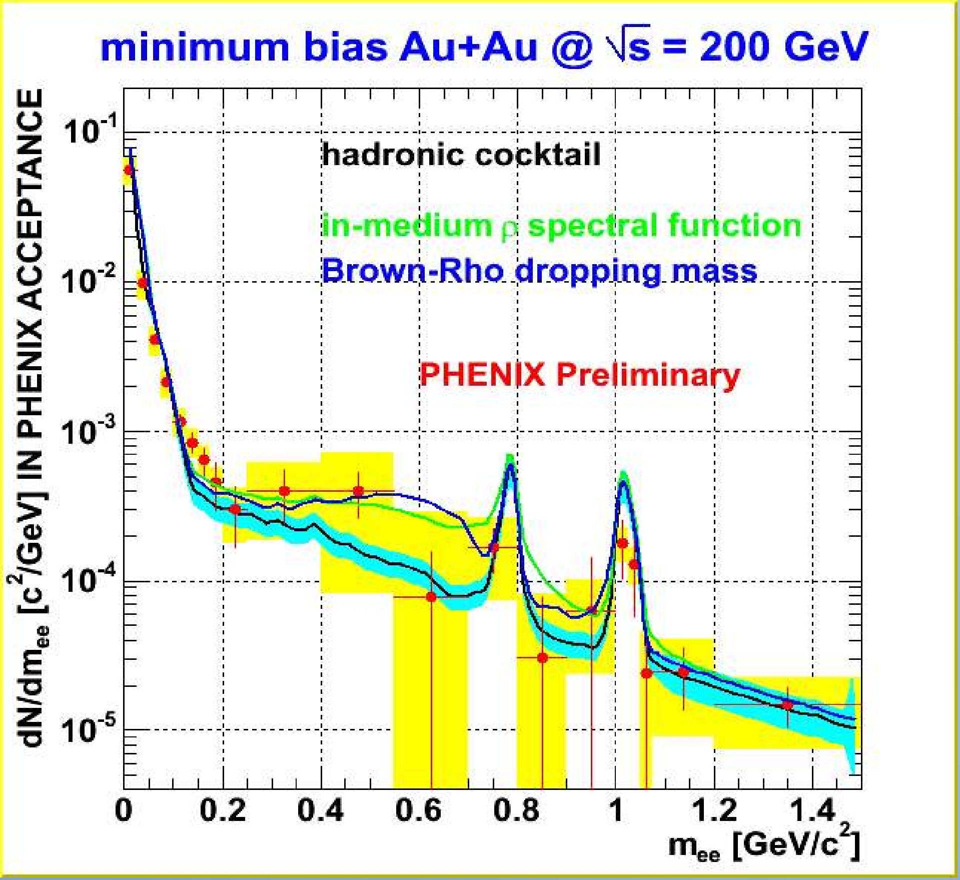
$\Phi \rightarrow K^+K^-$



$\varphi \rightarrow K^+K^-$ line shape and mass are consistent within errors as functions of $N_{participants}$

Dilepton Continuum

A. Toia



- No significant enhancement above cocktail
- Consistent with theoretical calculations, including chiral symmetry restoration
- Large systematic errors.
- Hadron Blind Ddetector upgrade for PHENIX should produce a conclusive result

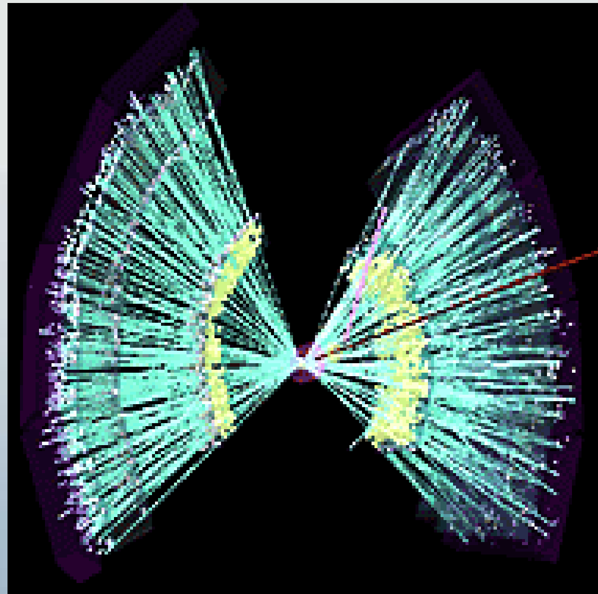
More on thermal radiation in next talk….

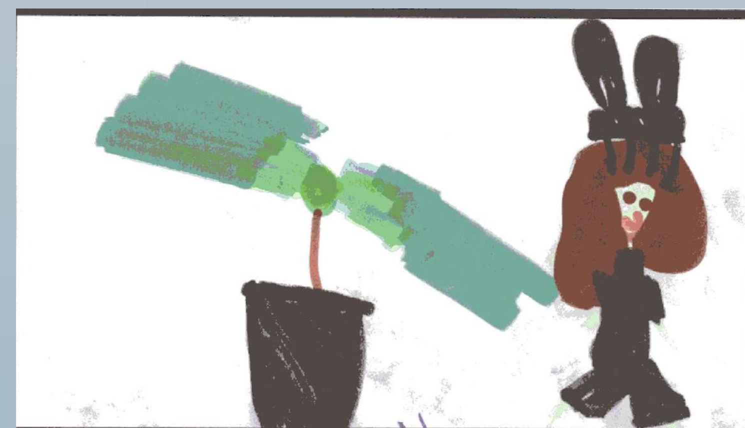
Conclusions I

- Thermalization: Significant v_2 measured even for φ
- Soft-Hard transition:
  - Smooth Npart dependence of baryon-meson ratio in Cu+Cu and Au+Au
  - High p_t v_2 indicates pQCD plus energy loss dominates above 7 GeV/c; additional physics below
- R_{AA} at high p_t:
  - Apparently flat for p_T up to 20 GeV/c
  - Suppression in Cu+Cu mid-central collisions is similar to peripheral Au+Au collisions

Conclusions II

- Charm R_{AA} and charm v_2:
  - PHENIX measures strong suppression for heavy flavor in central Au+Au collisions
  - Heavy flavor v_2 increases up to 10% ~ 2 GeV/c and tends to decrease above 2 GeV/c
- Chiral Symmetry restoration:
  - Φ K^+K^- and Φ e^+e^- show no difference in line shape within errors (errors are large in Φ e^+e^-)
  - dn/dy possibly larger in Φ ee than Φ KK
  - First measurement of dilepton continuum (albeit with large errors)

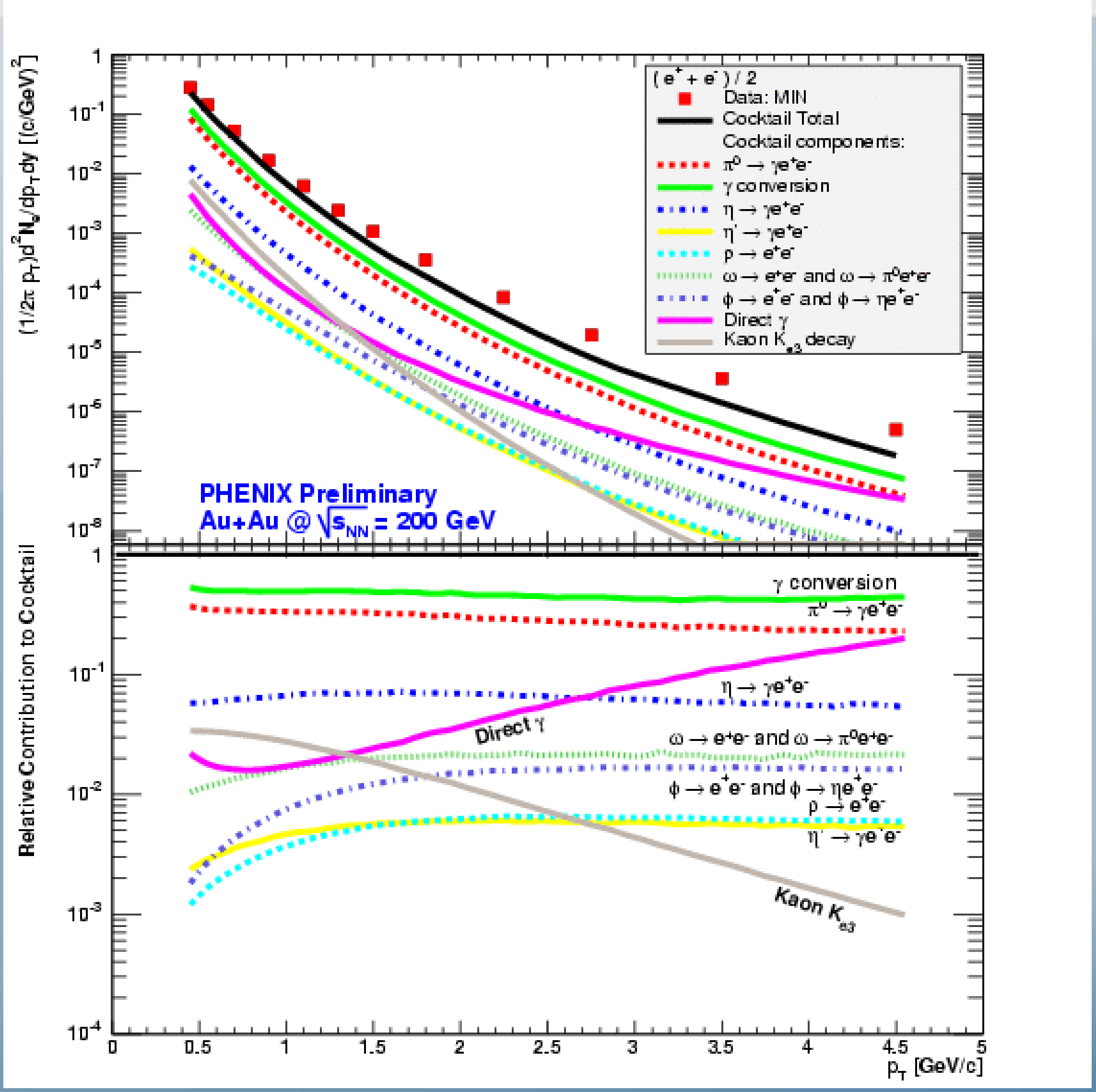




My thanks

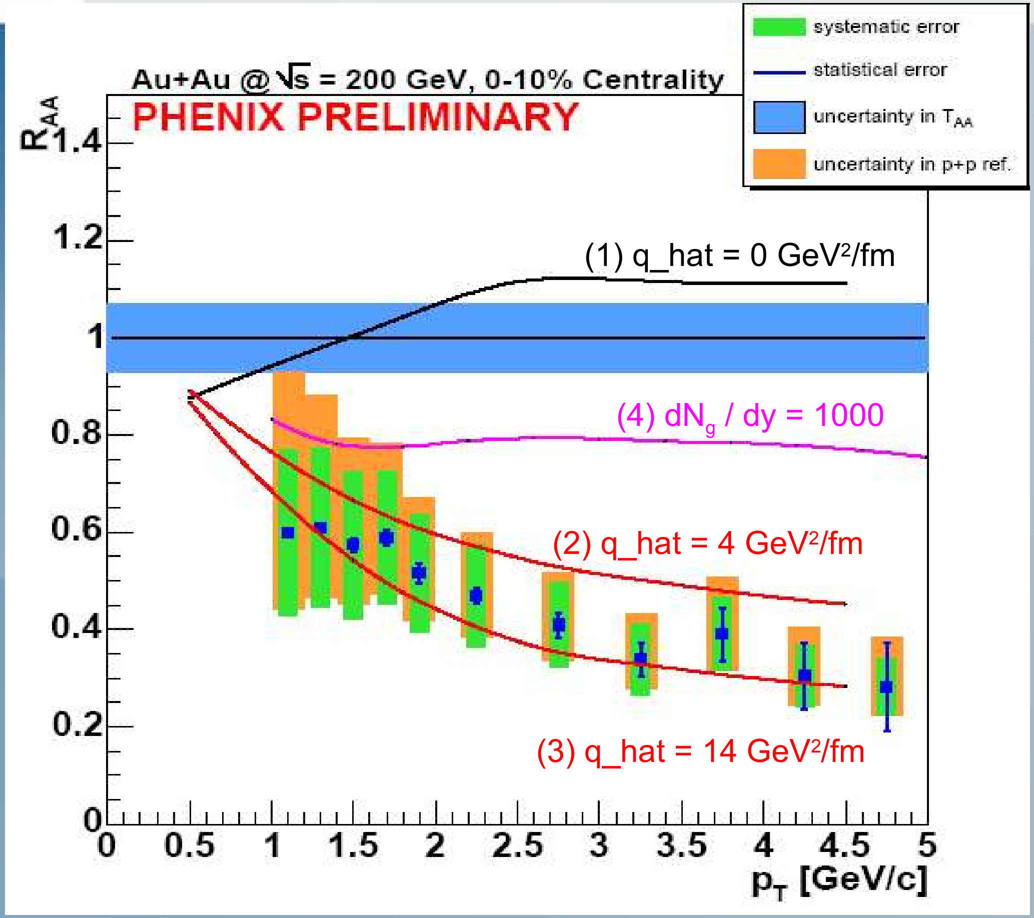
to the organizers of Quark Matter ’05 for the opportunity to present these results; to my PHENIX colleagues, whose hard work has discovered such incredible physics and who entrusted me to represent them; to the United States Department of Energy for its continued support of the RHIC program; and finally, to Barbara Jacak and Saskia Mioduszewski for all their help.

Cocktail



(e⁺ + e⁻) / 2
Data: MIN
Cocktail Total
Cocktail components:
π⁰ → γe⁺e⁻
γ conversion
η → γe⁺e⁻
η' → γe⁺e⁻
ρ → e⁺e⁻
ω → e⁺e⁻ and ω → π⁰e⁺e⁻
φ → e⁺e⁻ and φ → ηe⁺e⁻
Direct γ
Kaon K_e3 decay
PHENIX Preliminary
Au+Au @ √s_NN = 200 GeV
(1/2π p_T)d²N_e/dp_Tdy [(c/GeV)²]
Relative Contribution to Cocktail
γ conversion
π⁰ → γe⁺e⁻
η → γe⁺e⁻
Direct γ
ω → e⁺e⁻ and ω → π⁰e⁺e⁻
φ → e⁺e⁻ and φ → ηe⁺e⁻
ρ → e⁺e⁻
η' → γe⁺e⁻
Kaon K_e3
p_T [GeV/c]

Comparison with Theory



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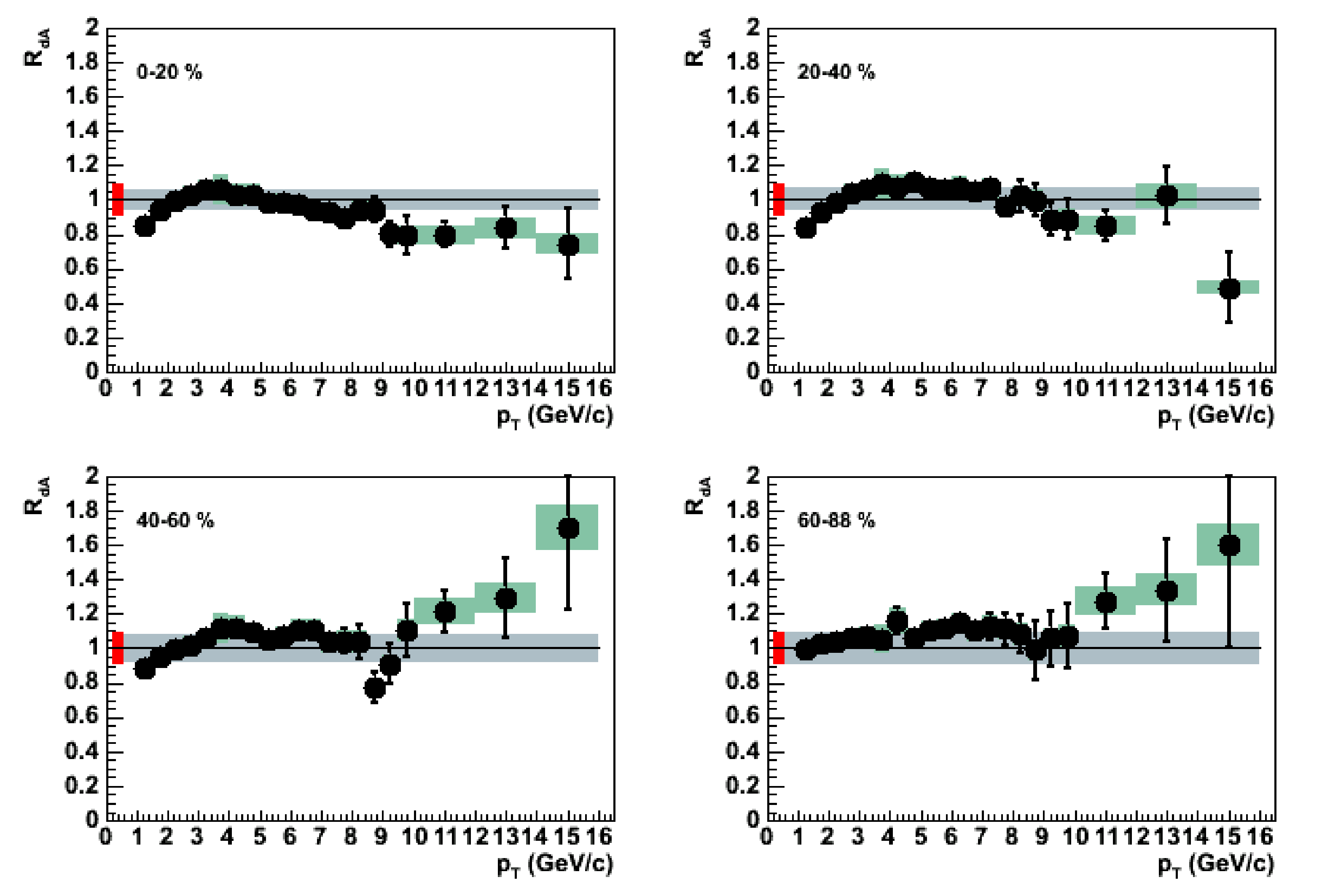
(4) from M. Djordjevic, M. Gyullasy, S.Wicks, Phys. Rev. Lett. 94, 112301

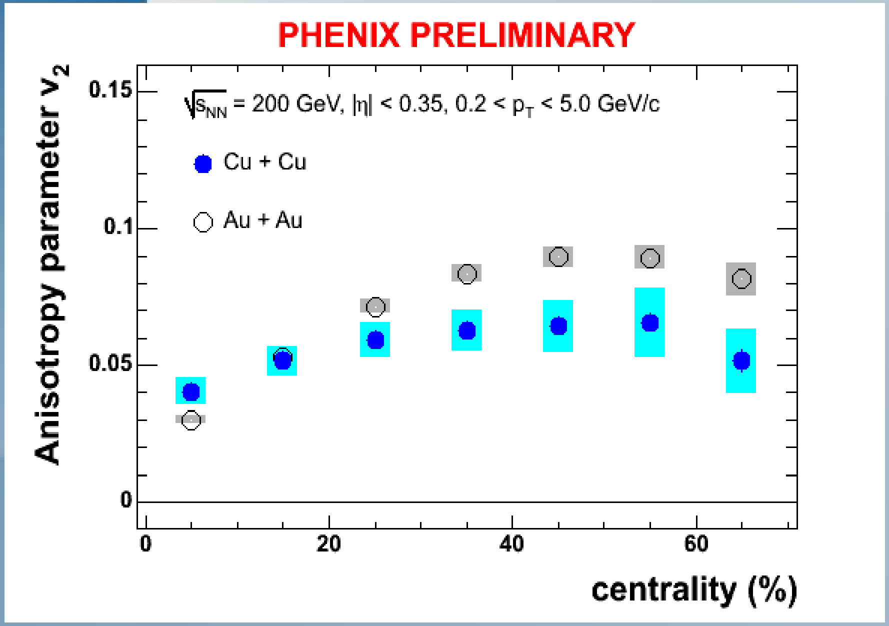
backups

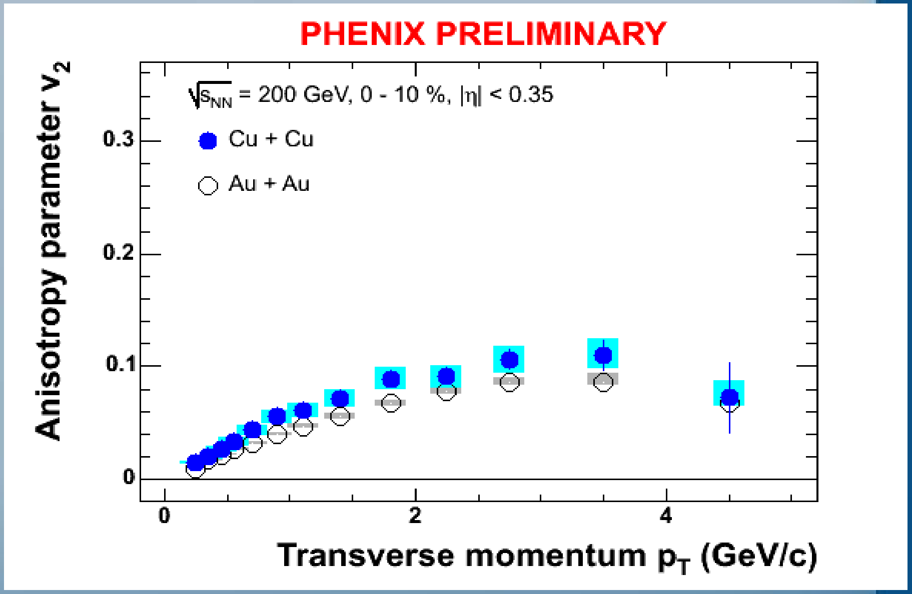
Results from ppg044 π^0 R_{dA} as a function of centrality

Henner Buesching

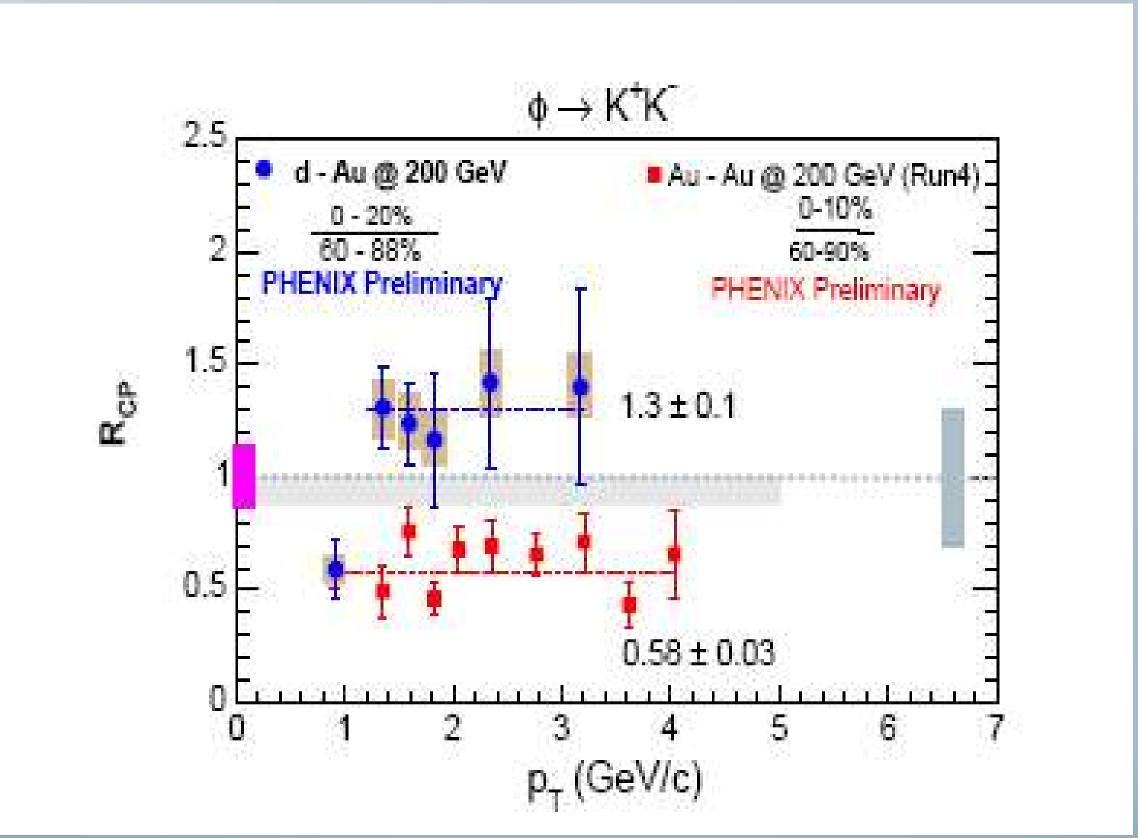


v_2 vs p_T in top 10 %, Au+Au vs Cu+Cu



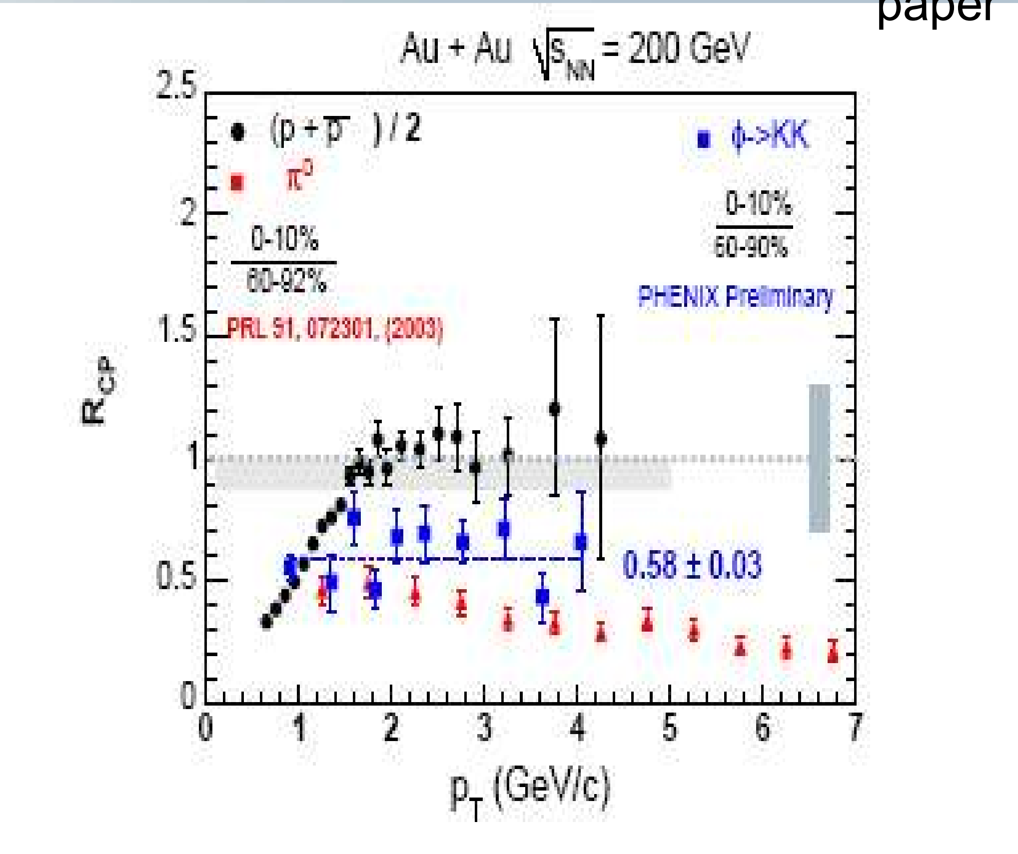


d-Au compared to Au Au

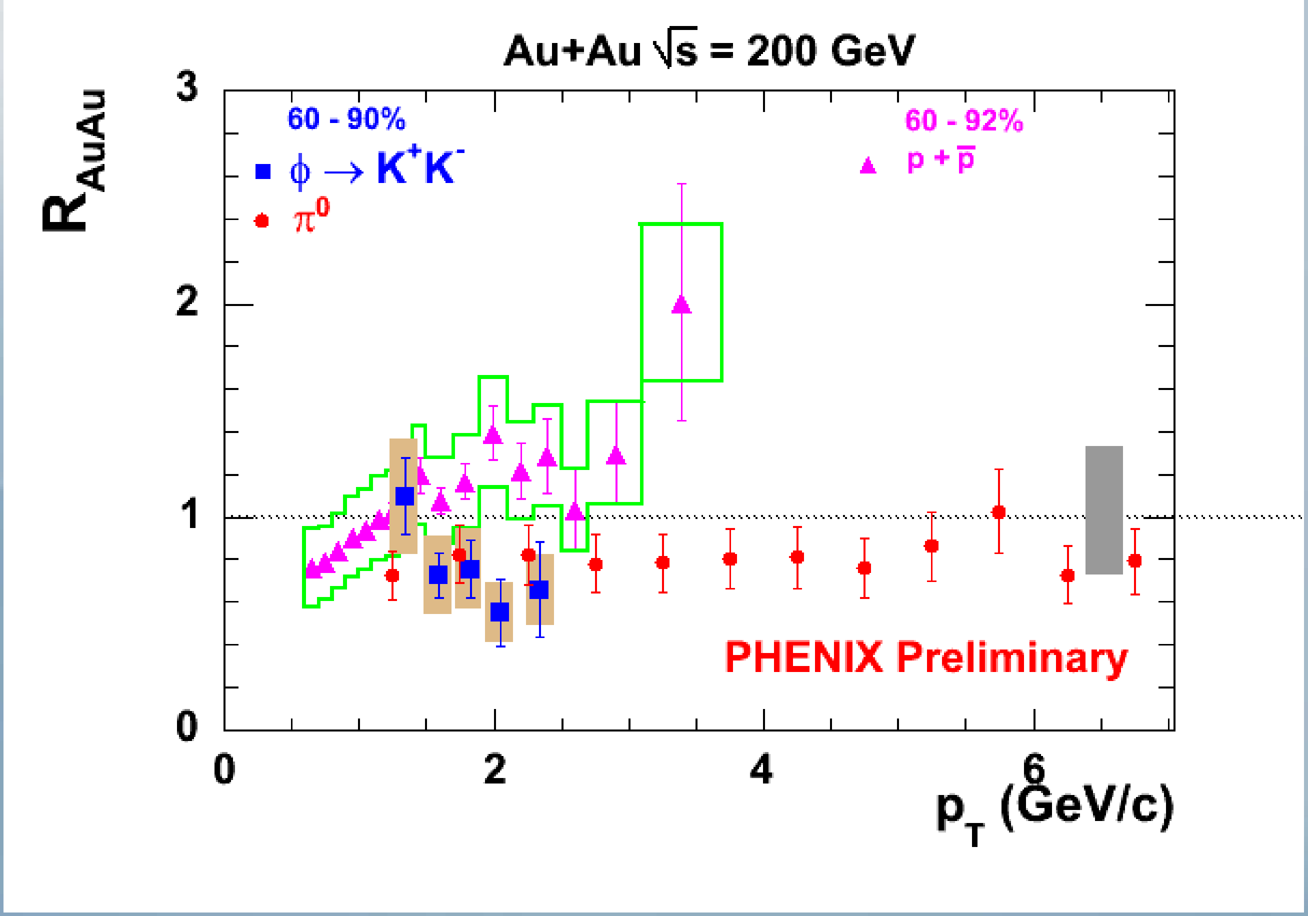


R_{cp} for φ compared to p and π

Better statistics than white paper



R_{AA} vs pt for AU+AU Collisions



Clean electron sample

- Clean sample of electrons is selected by
  - Requiring well defined RICH ring (at least 2 PMT hit within 5 cm area around track projection)
  - Good spatial matching of the track to EMC cluster
  - Total Energy to Momentum match