PHENIX-Measurement of High p_T Particles in Au+Au and d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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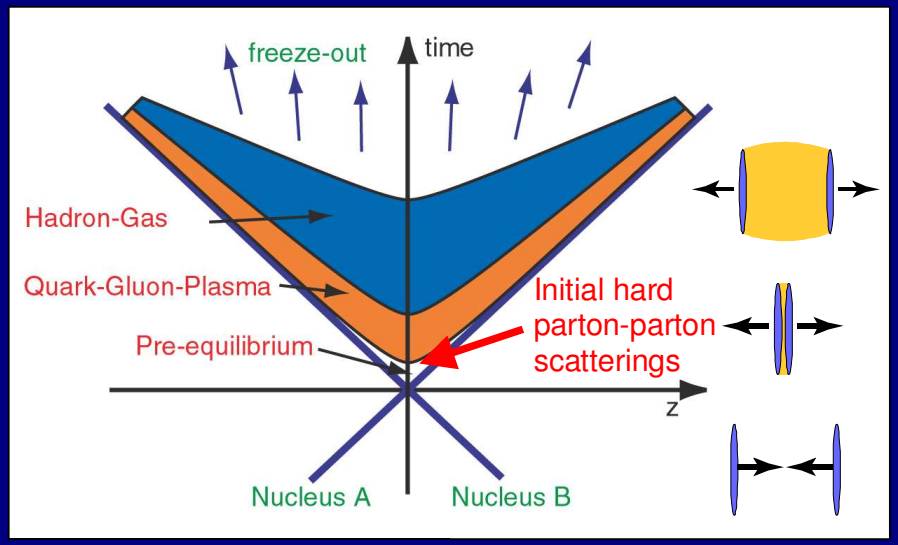
for the PHENIX Collaboration

Quark Matter 2004
Oakland, January 13th

Particle Production at High p_T

- **General**
  - ***Hard*** processes: Parton collisions with large Q^2 ("Jets")
  - Factorization:
    - PDF ⊗ pQCD ⊗ FF
- **p+p**
  - Fragmentation into QCD-vacuum
- **Au+Au**
  - Early reaction-phase
  - Probe for a later hot and dense phase

- **Medium influences:**
  - "Jet"-like correlations
  - Particle ratios
  - Particle yields



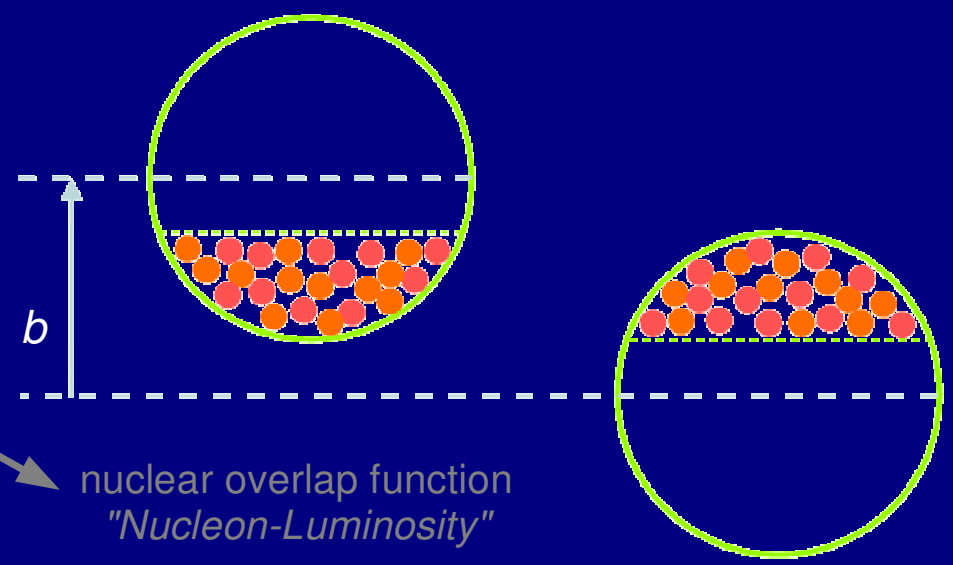
Nuclear Modifiction Factor

- **Glauber model:**
  - AA/dA incoherent superposition of NN

$$\sigma_{AB}^{hard} \approx \int d^2 b \, \sigma_{NN}^{hard} \, T_{AB}(b)$$

$$\langle N_{coll} \rangle \approx \sigma_{NN} T_{AB}$$

$$\sigma_{AB} \propto \langle N_{coll} \rangle$$



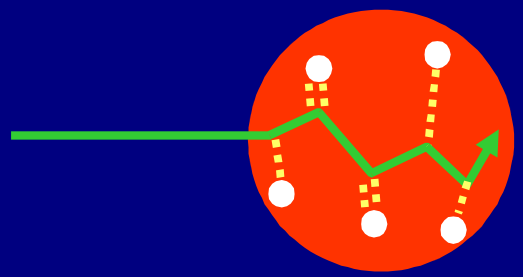
nuclear overlap function
"Nucleon-Luminosity"

- **Comparison with scaled NN**
  - $R_{AA} \approx 1$ (for $p_T > 2$ GeV) ?
  - Deviation ⇒ medium effects ?

$$R_{AA} = \frac{d^2 N_{AA'} dydp_T}{T_{AB} \, d^2 \sigma_{pp'} dydp_T}$$

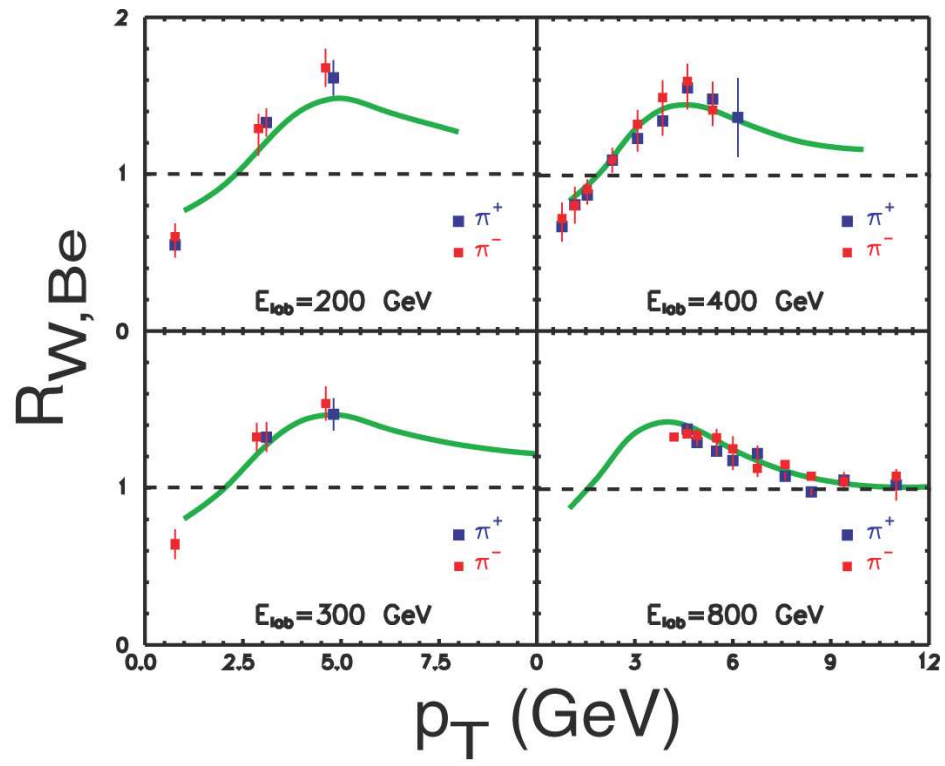
Known Effects N→A

- **Multiple soft scattering**

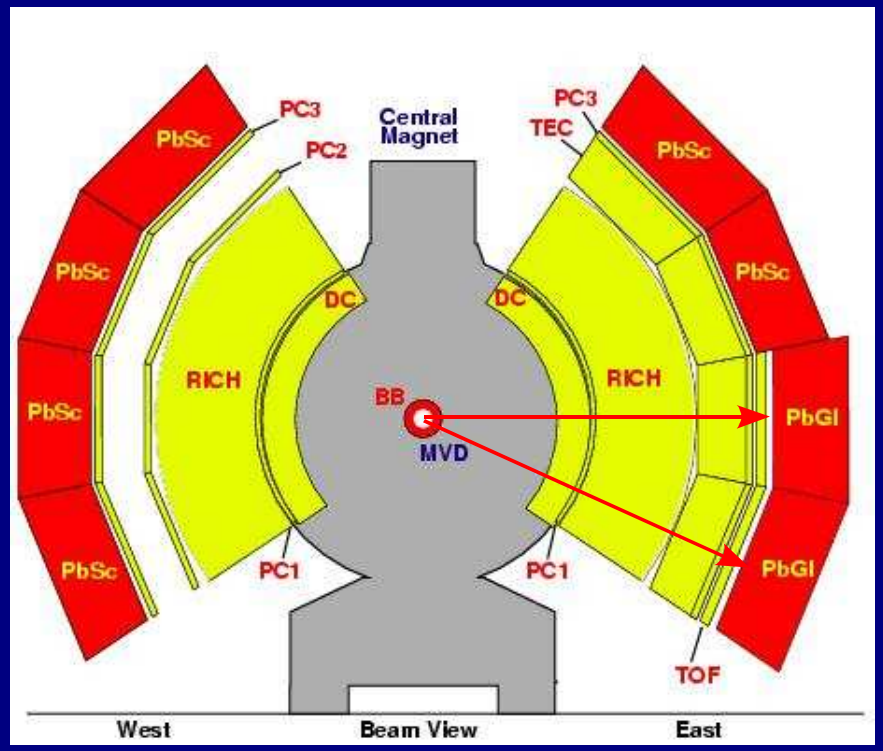


  - Broadens p_T spectrum
  - Cronin Effect
- **Change of the nuclear structure function / PDF**
  - Shadowing ($R_{AA} < 1$)
  - Anti-shadowing ($R_{AA} > 1$)

Cronin-Effect observed in p+A experiments:



π^0's @ PHENIX

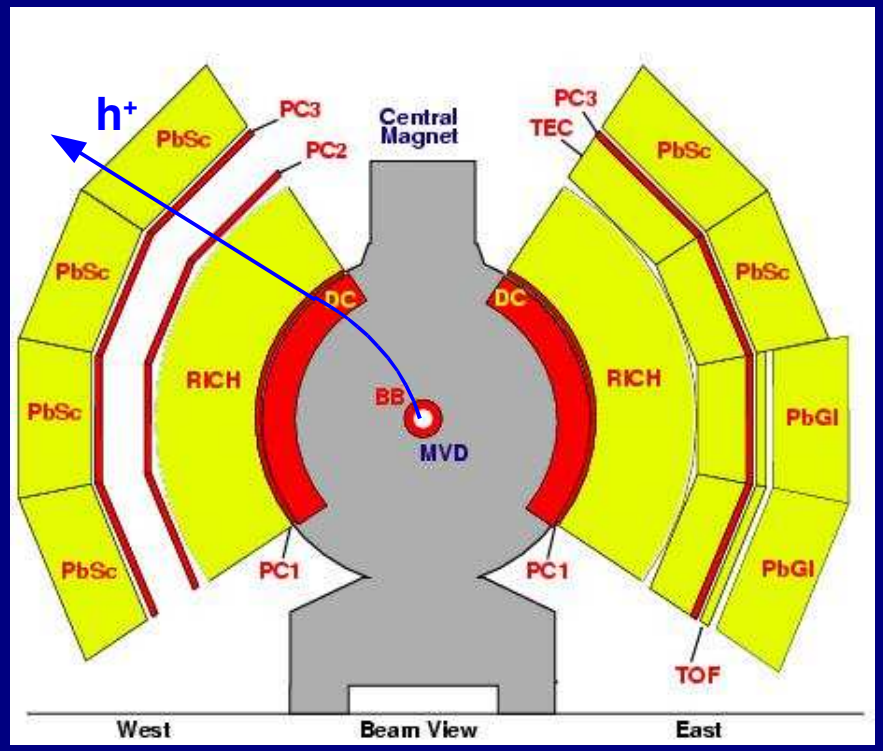


- **Reconstruction $\pi^0 \rightarrow 2\gamma$**
  - All pair combinations
  - Invariant mass

$$m_{inv} = \sqrt{2E1E2\,(1-\cos\theta)} \approx 135 \text{ MeV}$$

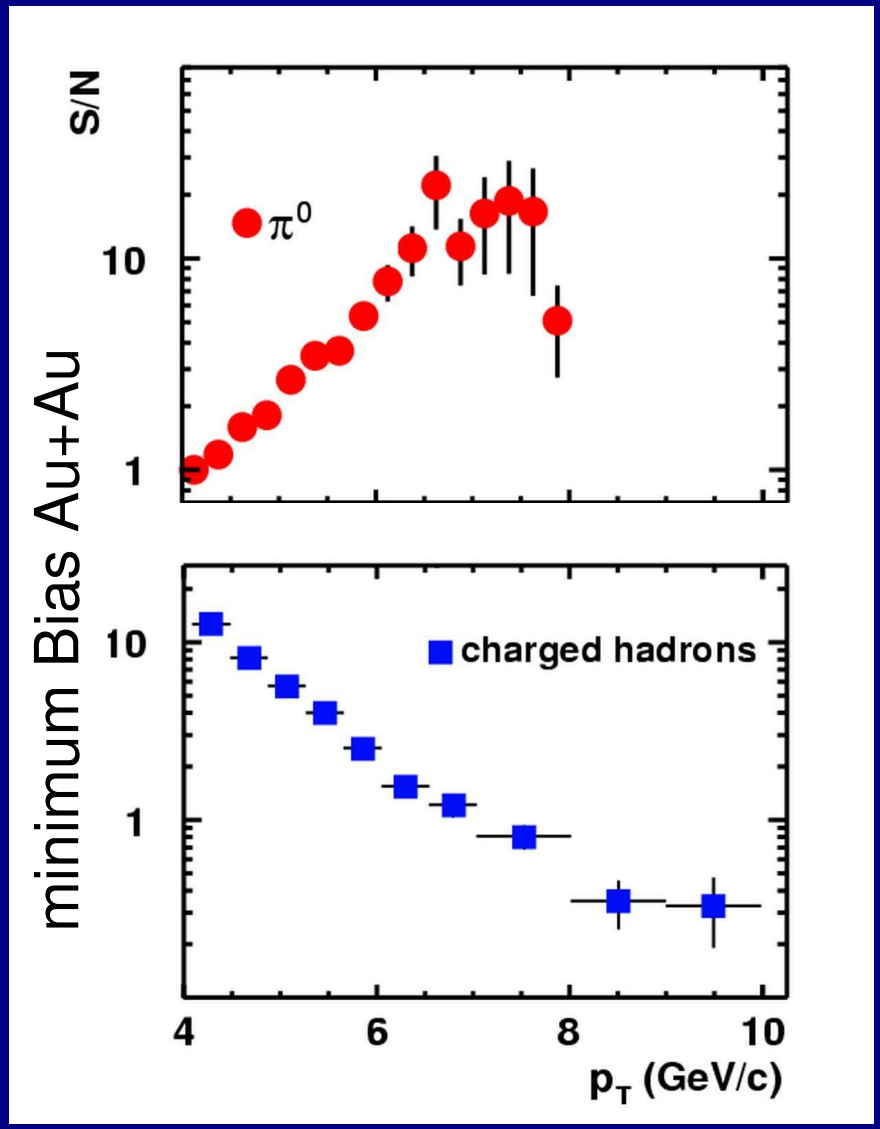
  - Combinatorial background:
    - "Mixed events"
    - γ_1 from current event γ_2 from old event
- **Corrections**
  - Acceptance
  - Efficiency

Charged Particles @ PHENIX



- **Tracking in west arm**
  - Momentum reconstruction with BBC,PC1 and DC
- **Background rejection**
  - Matching PC2 and PC3 hits
  - Remaining background:
    - Conversions and decays
    - Determined and subtracted statistically
- **Corrections**
  - Acceptance, decay in flight
  - Efficiency

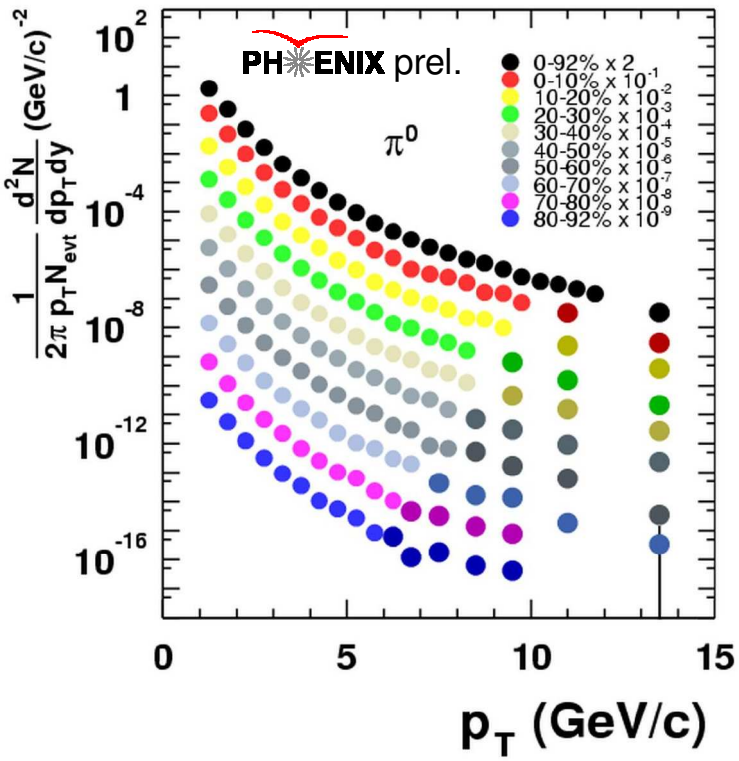
Signal/Background



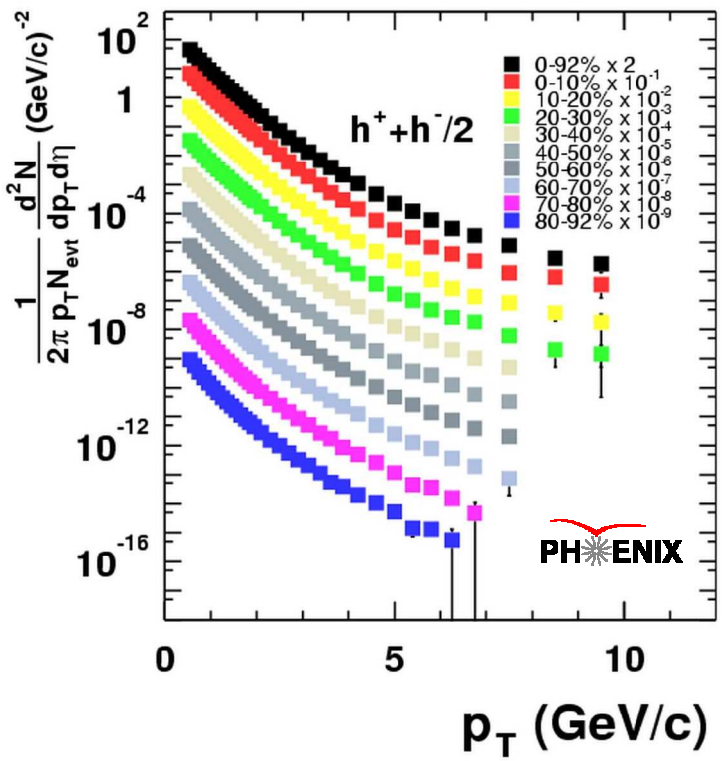
- **π^0 analysis limited by statistics**
  - Further improvement with high p_T photon triggers
- **Charged particle analysis limited by background:**
  - $\delta p/p = 0.7\% \oplus 1.1\% p$ (GeV/c)
  - Background from conversion electrons hardly seperable from charged π

Au+Au @ $\sqrt{s_{NN}}$= 200 GeV at Midrapidity

PRL **91**,072301 (2003) + high p_T triggered data



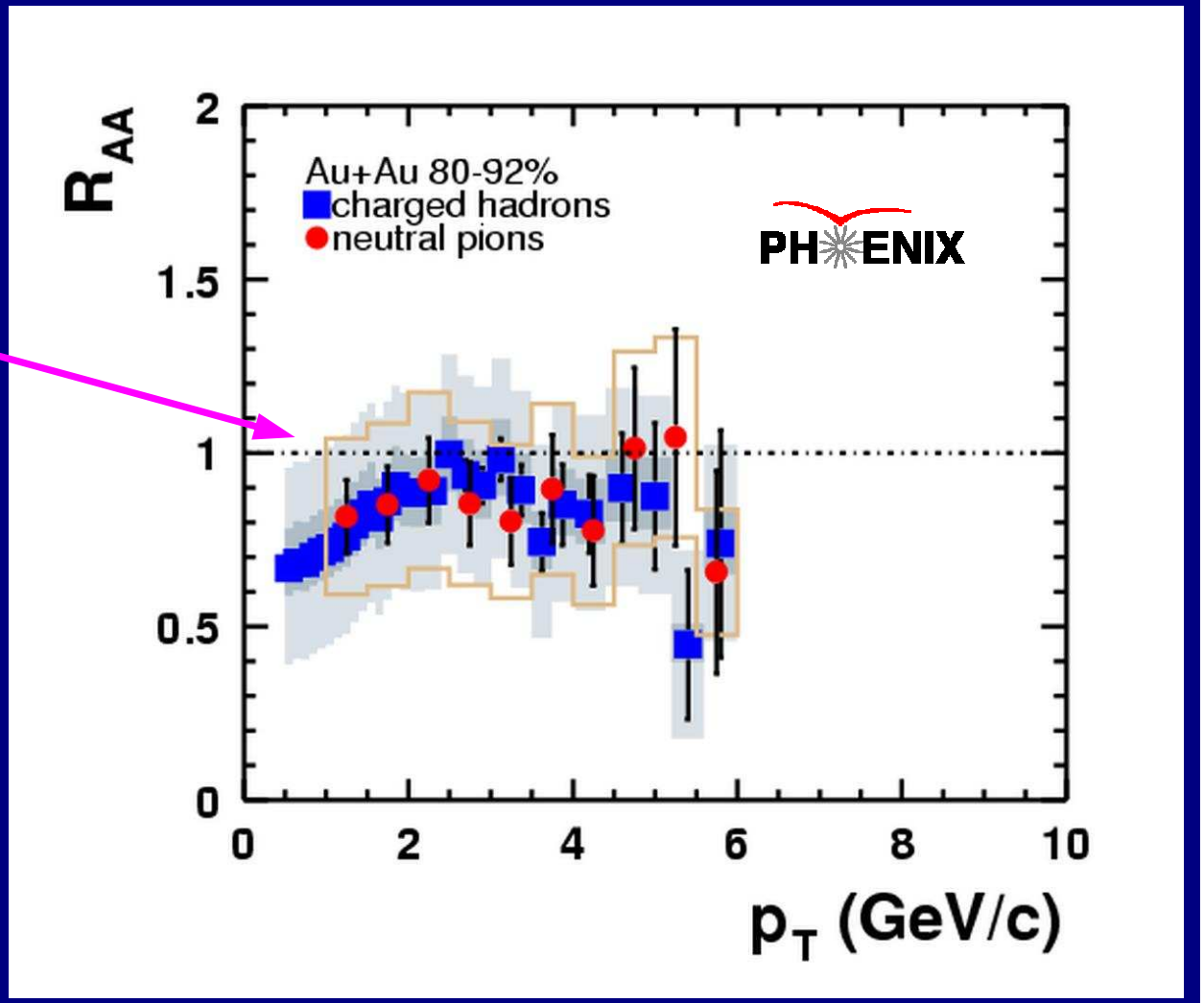
nucl-ex/0310005



Poster V. Pantuev P33

Peripheral Au+Au Compared to Scaled p+p

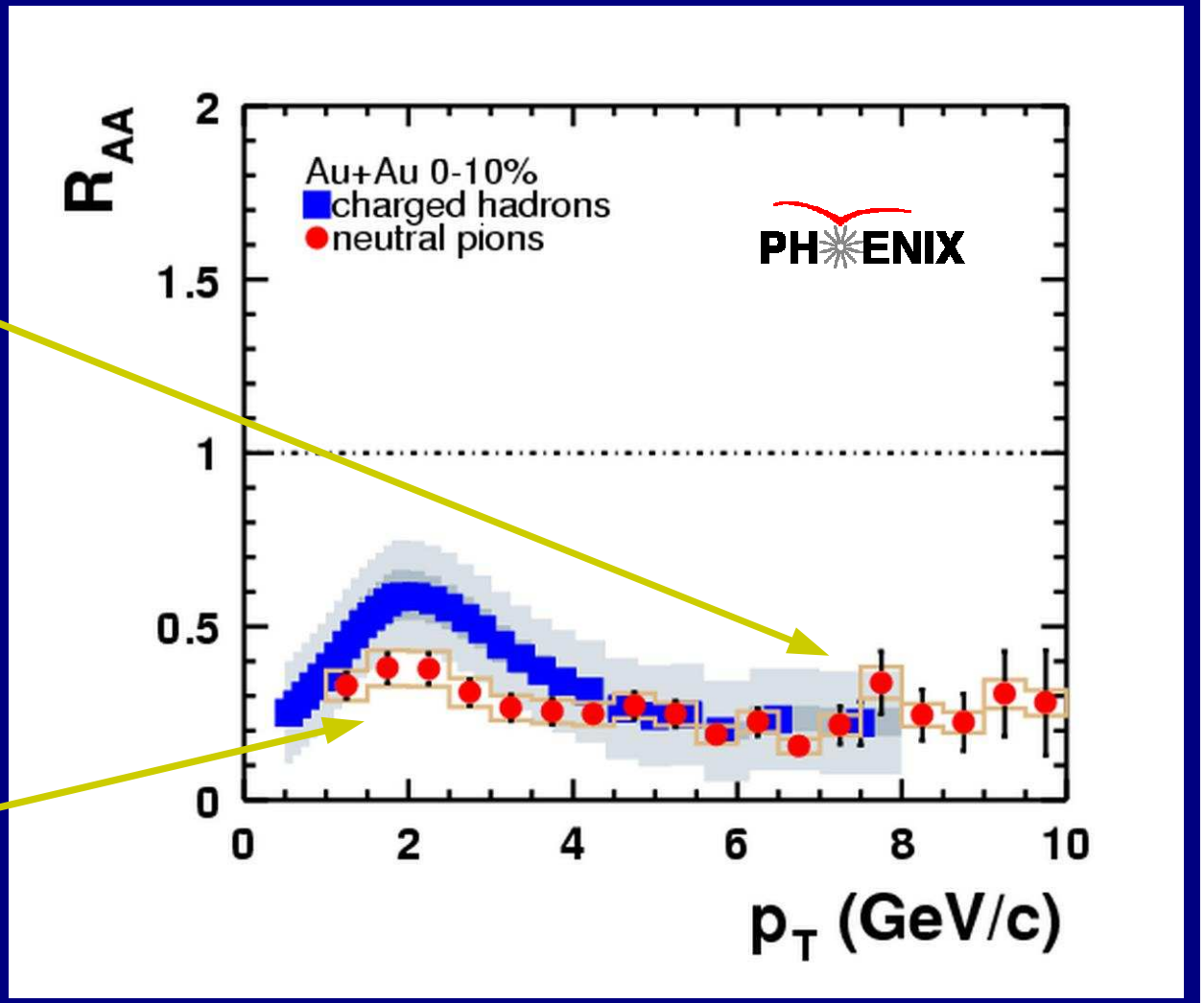
consistent with N_{coll} scaling



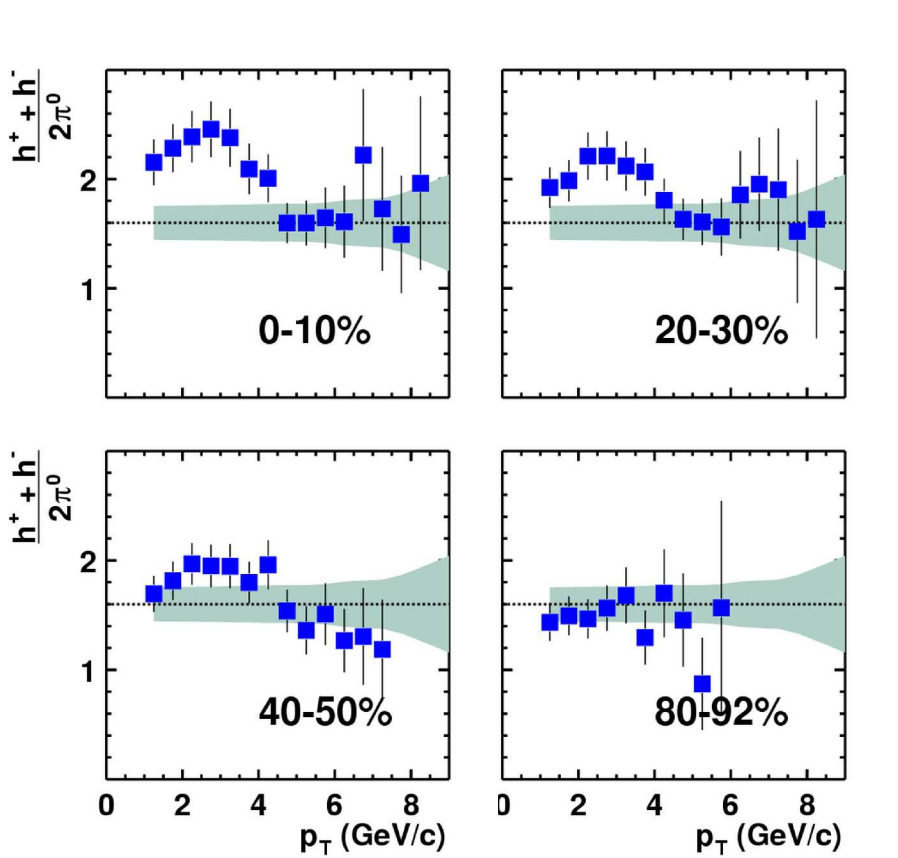
Central Au+Au Compared to Scaled p+p

factor 5 suppression

factor 2 difference



h/π Ratios



Au+Au @ 200AGeV

PHENIX nucl-ex/0310005

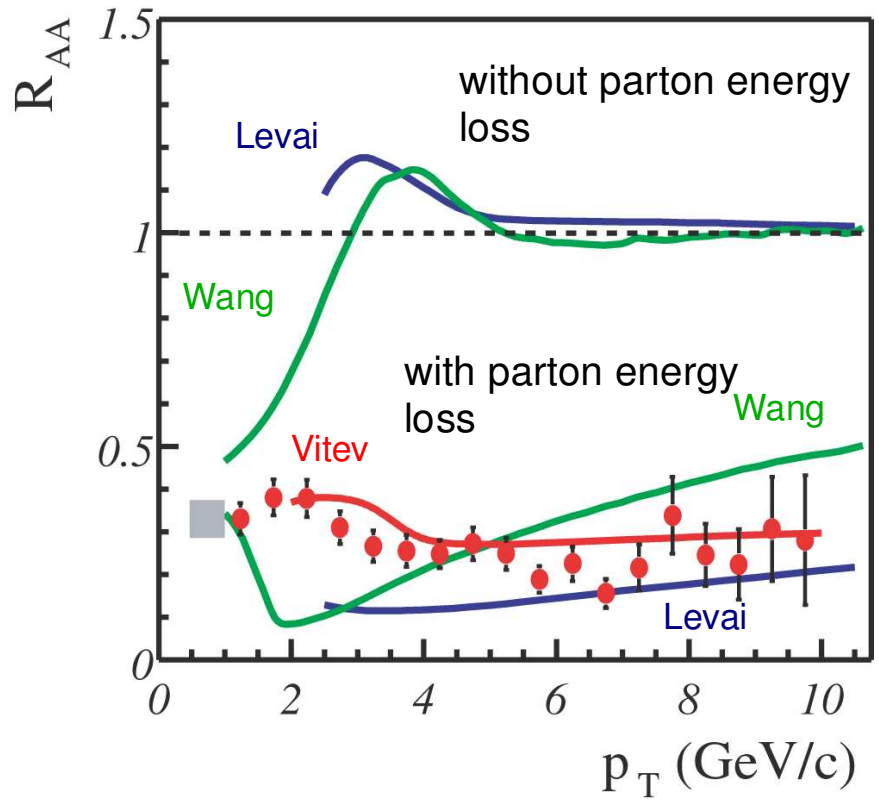
- **Expectation (pp, e^+e^-):**
  - $h/\pi \approx 1.6$
- **Only the case in peripheral collisions and above 5GeV**
- **Identified Hadrons**
  - Anomalous p/π
  - Data suggests baryon vs. meson effect (from λ,p vs ϕ,π)
  - Talks: F. Matathias
- **Approaches**
  - E.g. recombination of quarks in a thermal phase

Possible Explanations

- **Jet quenching**
  - Hard scattered partons lose energy via gluon-bremsstrahlung
  - Depends on color charge density
  - Depends on traversed distance in medium (→correlations)
- **Theoretical models**
  - Good quantitativ description within energy loss scenario

Comparison to model calculations with and without parton energy loss:

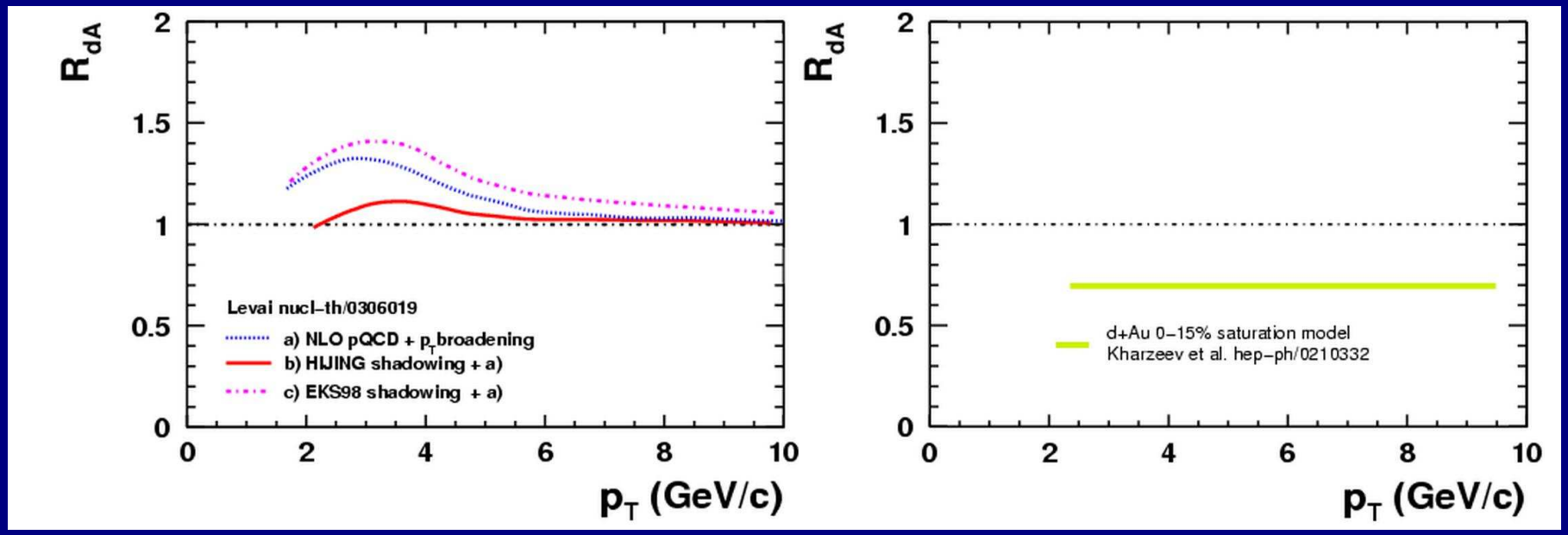
Au+Au at $\sqrt{s_{NN}}$ = 200 GeV



But .....

Effects of cold nuclear matter ("initial state") at $\sqrt{s_{NN}}$ = 200 GeV unknown

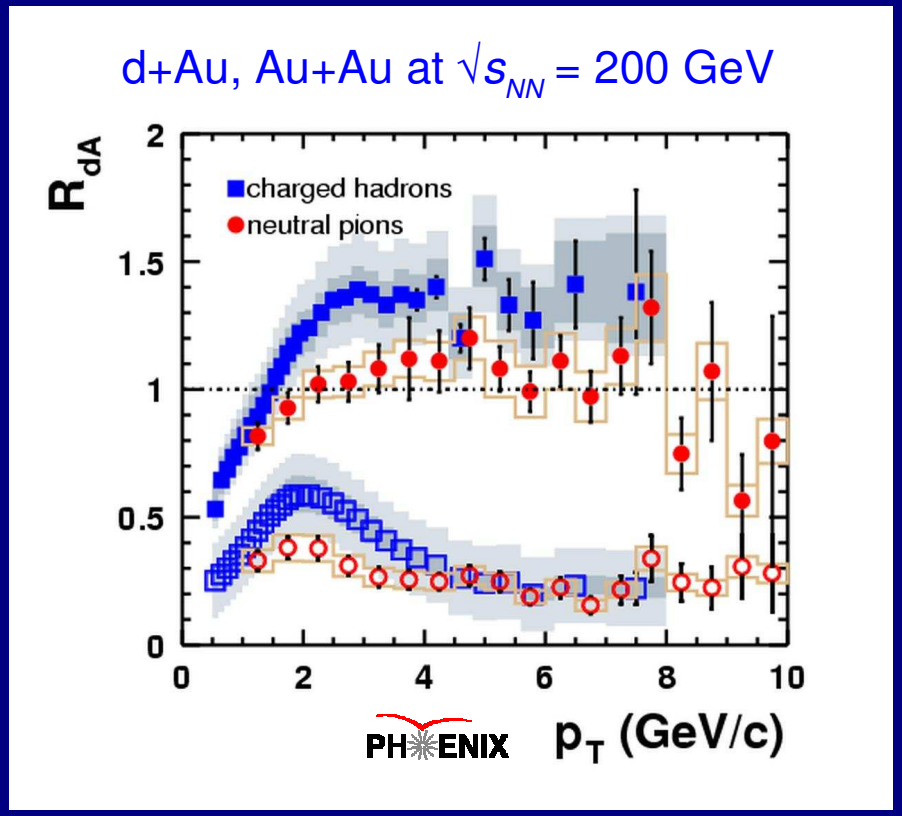
- Shadowing
- Gluon Saturation



d+Au needed as reference case:
No produced medium...

PHENIX

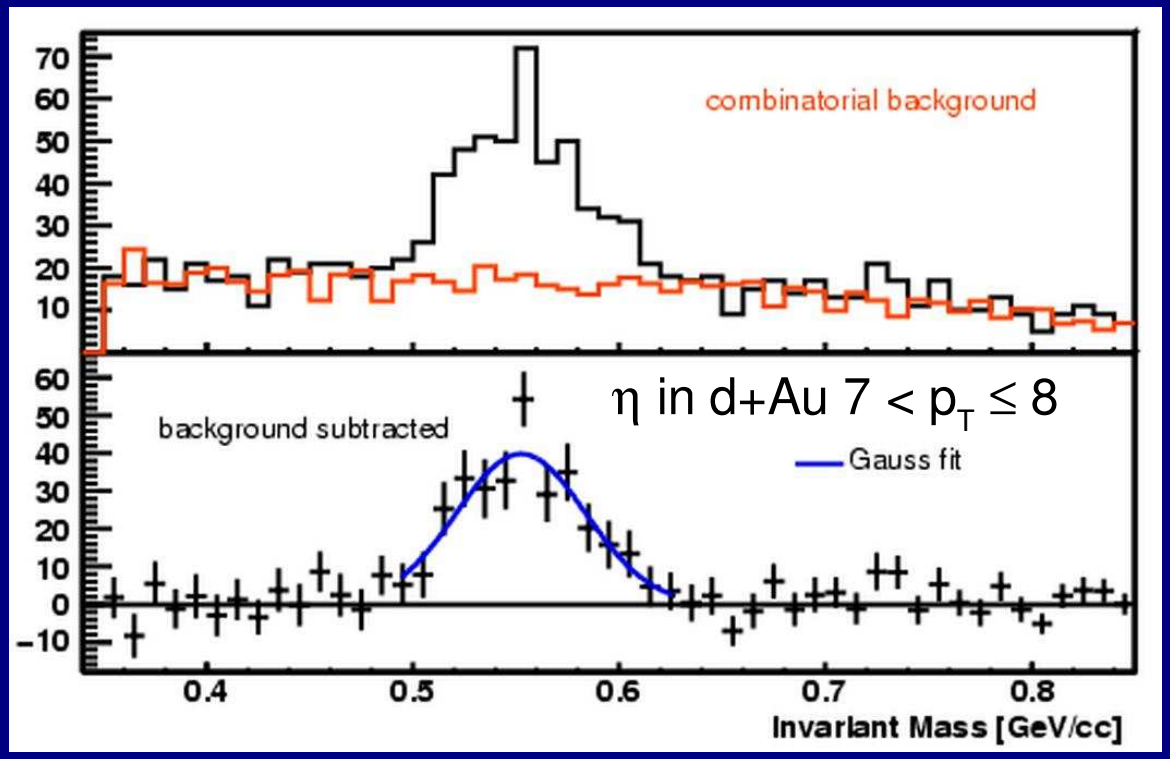
d+Au @ PHENIX



- **No suppression in d+Au collisions @ $\sqrt{s_{NN}}$ = 200 GeV**
  - PRL 91, 0723903 (2003)
- **Similar results from STAR, PHOBOS, BRAHMS**

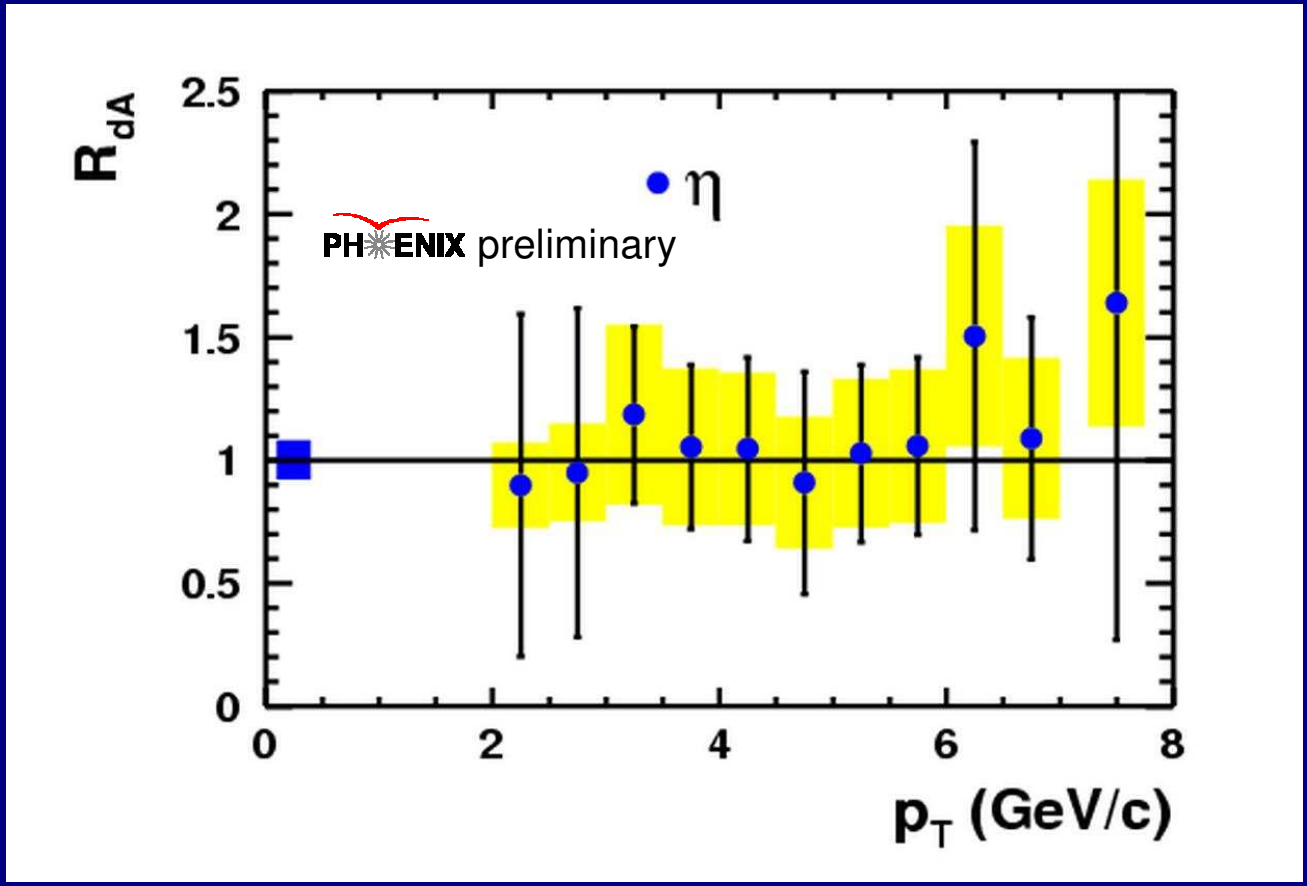
⇒ Initial state effects excluded

R_{dA} for η's



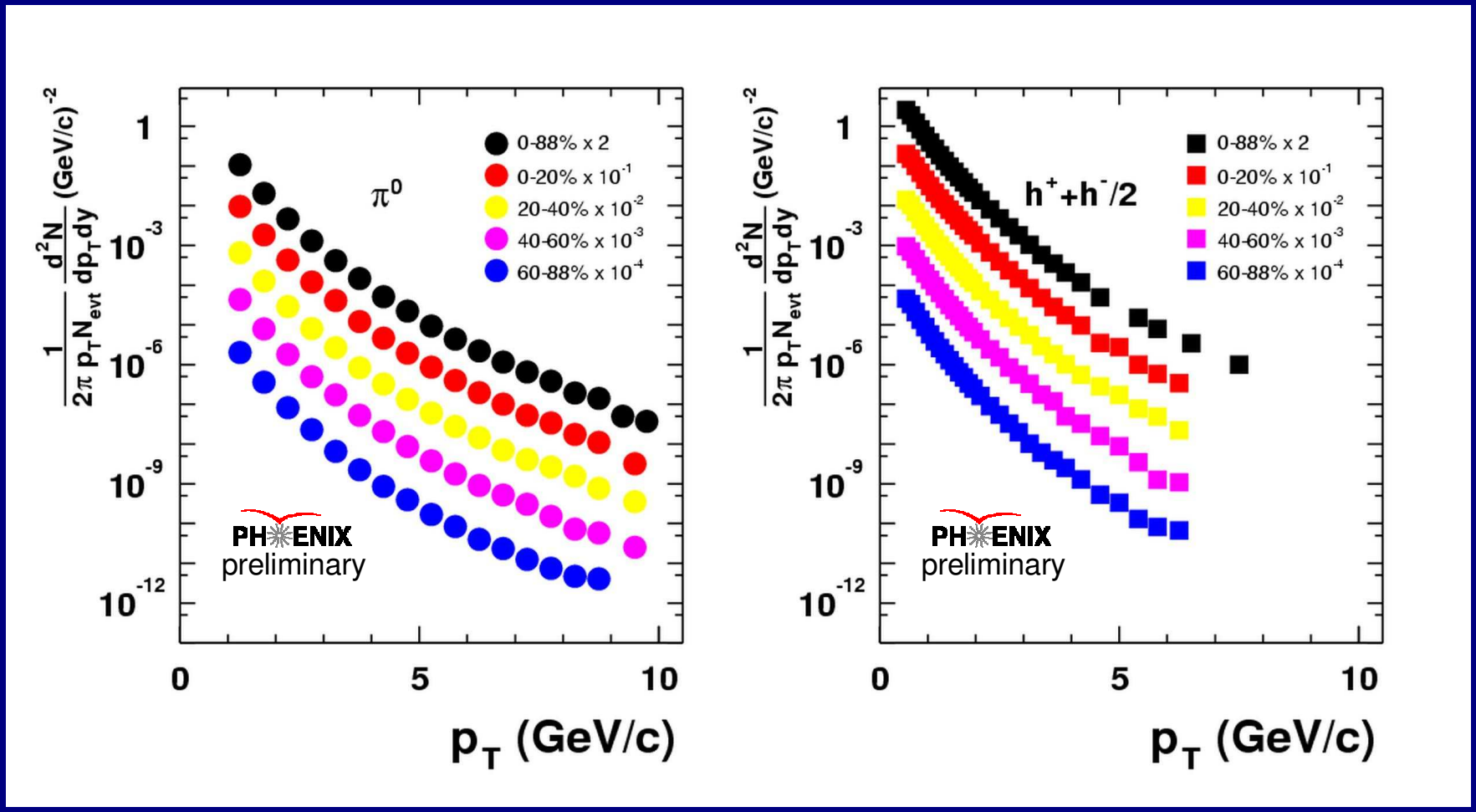
Poster
p+p: V. Hiejima D6
Au+Au: S. Mioduszewski P8

R_{dA} for η's



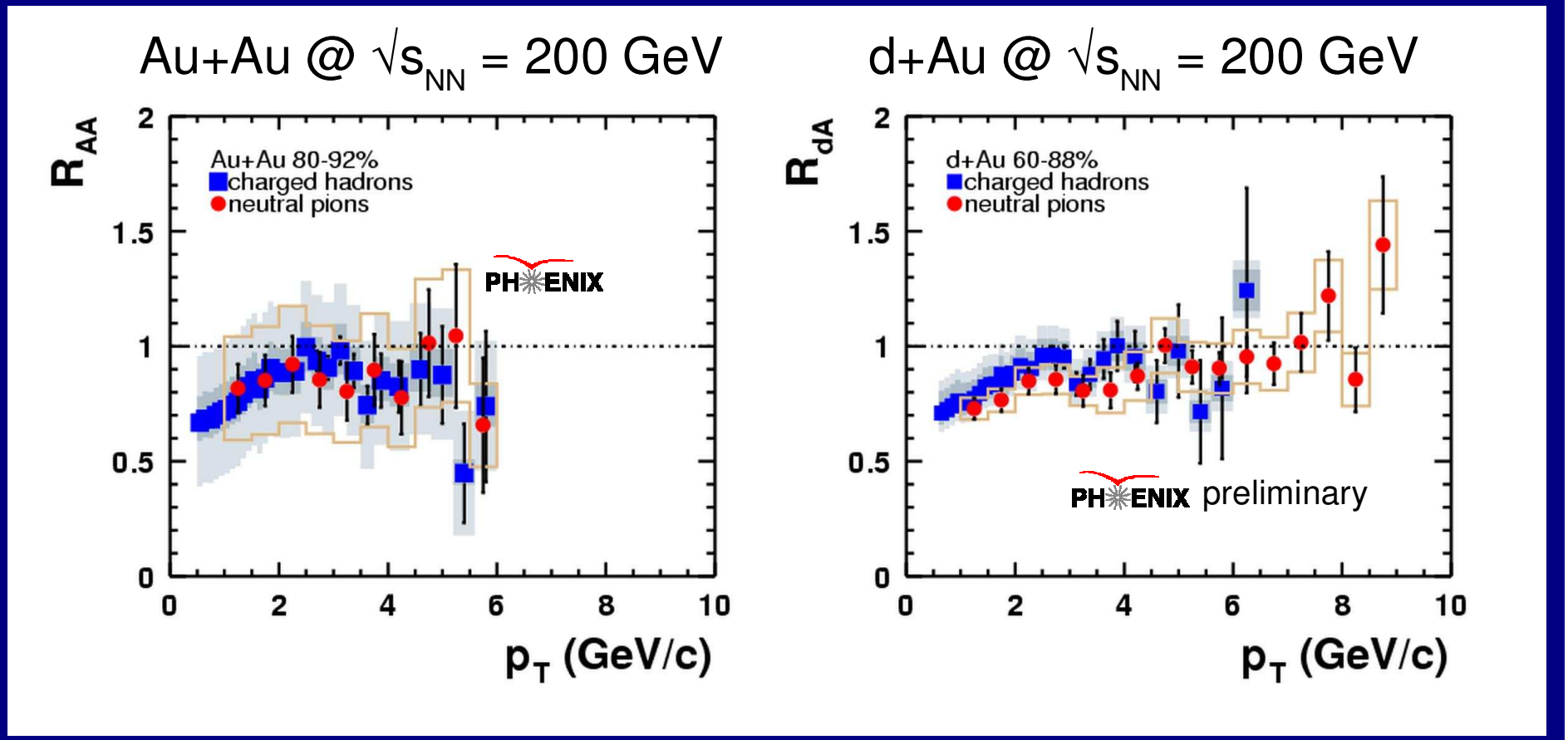
- Similar to π^0
- No obvious mass dependence for mesons

d+Au Spectra at Midrapidity



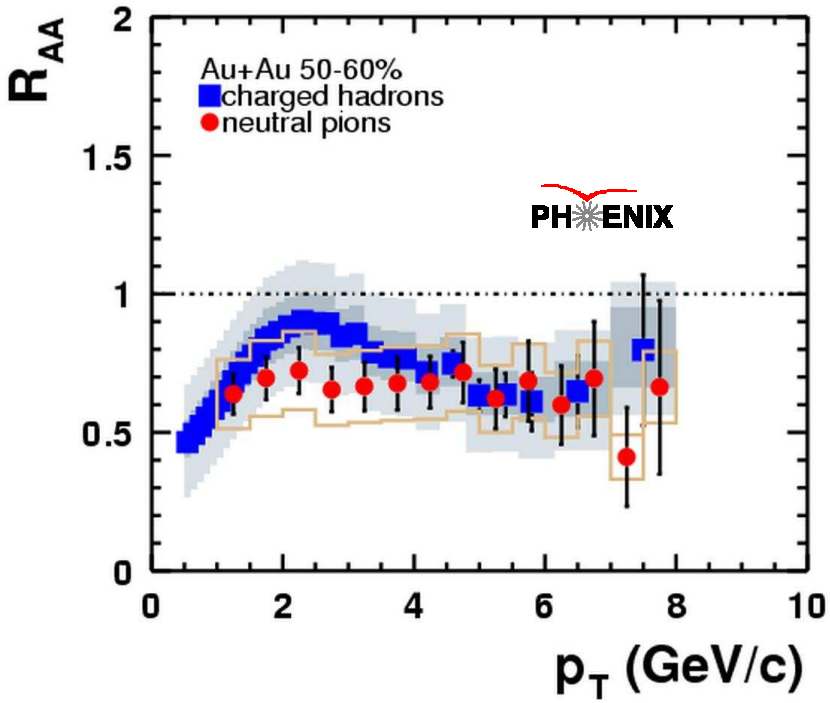
Poster H. Büsching P4

Centrality Dependence at Midrapidity

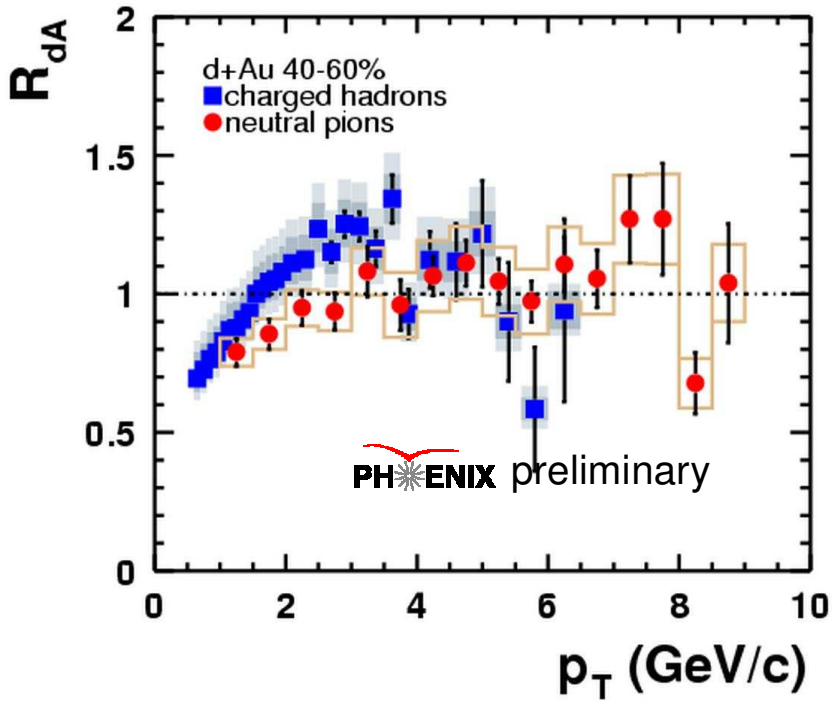


Centrality Dependence at Midrapidity

Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV

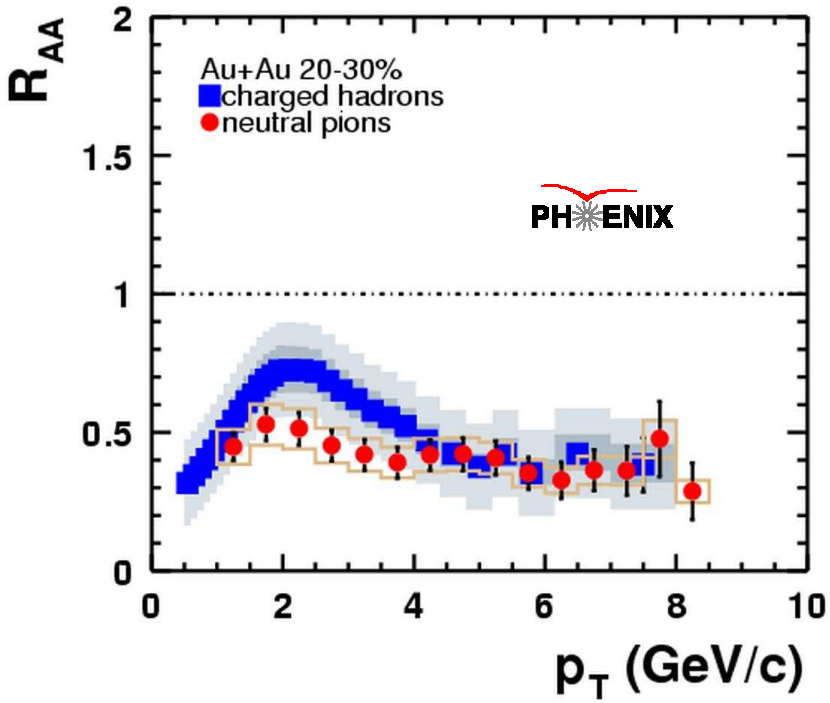


d+Au @ $\sqrt{s_{NN}}$ = 200 GeV

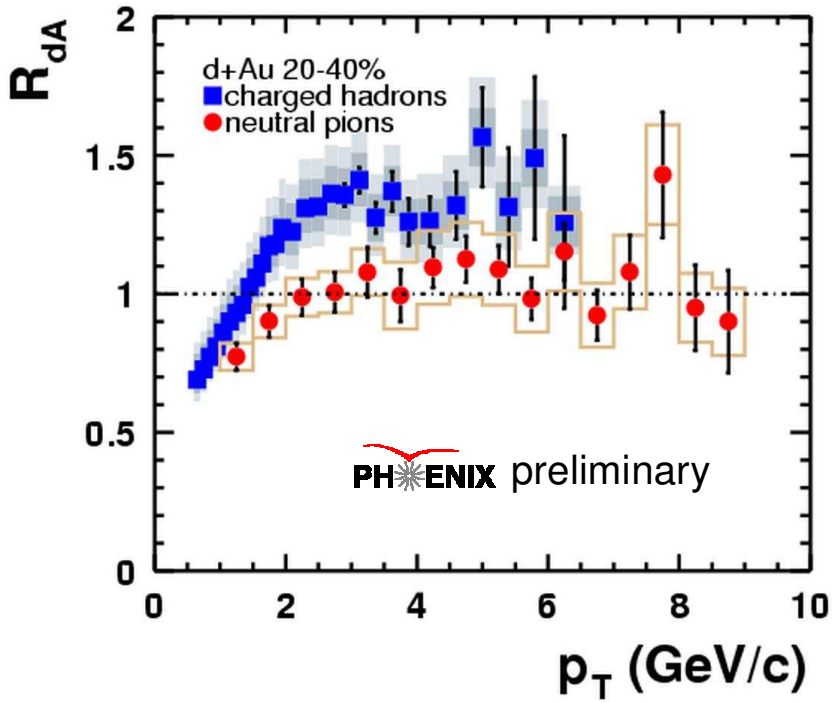


Centrality Dependence at Midrapidity

Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV



d+Au @ $\sqrt{s_{NN}}$ = 200 GeV



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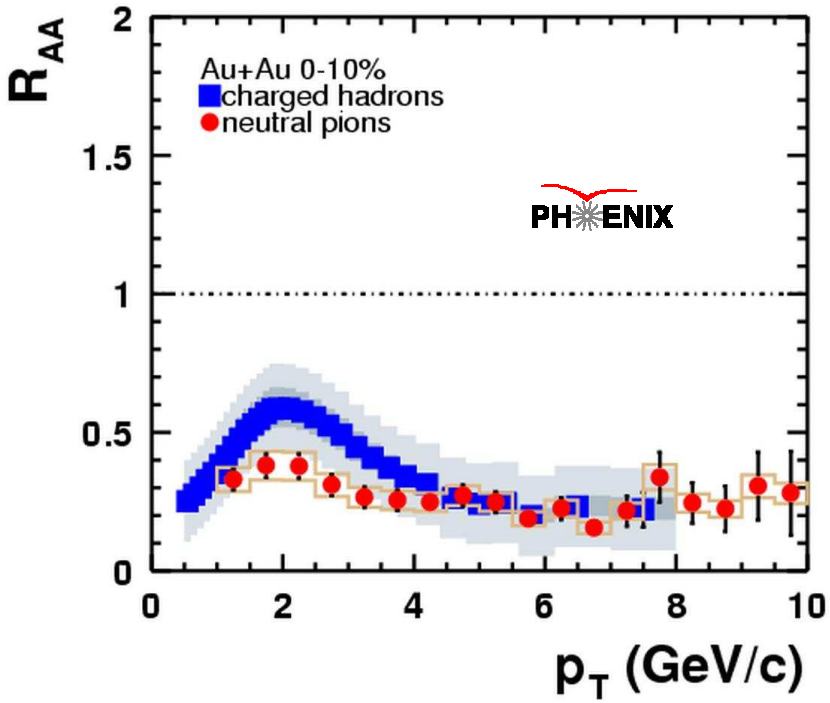
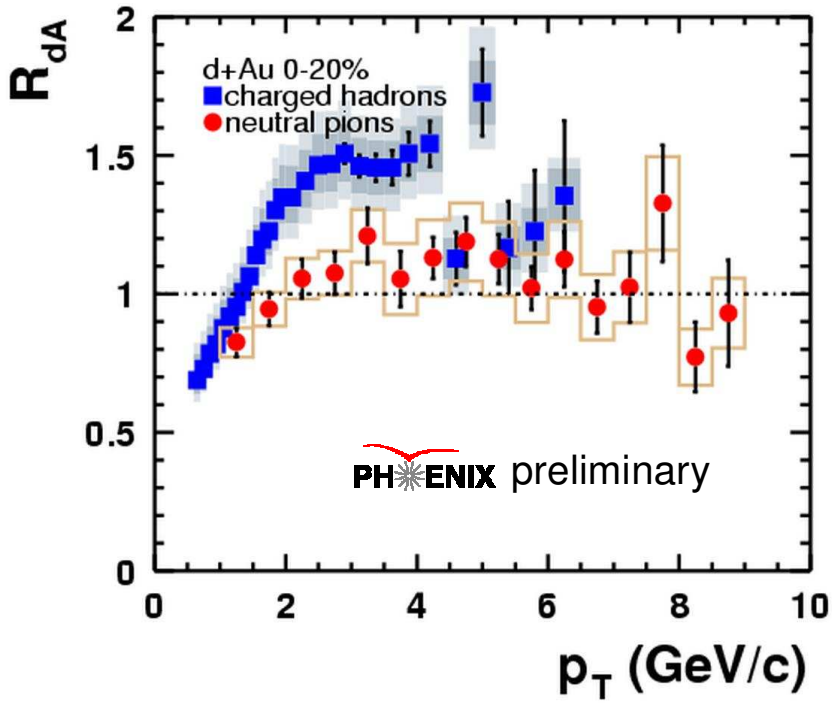
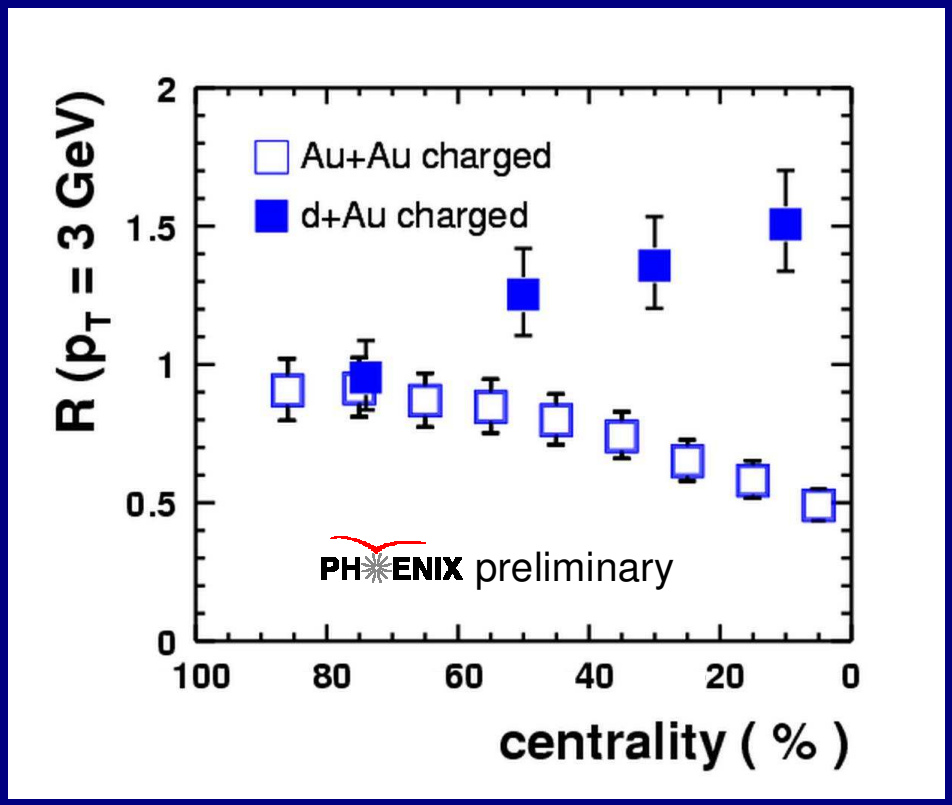


d+Au @ $\sqrt{s_{NN}}$ = 200 GeV



Centrality Dependence

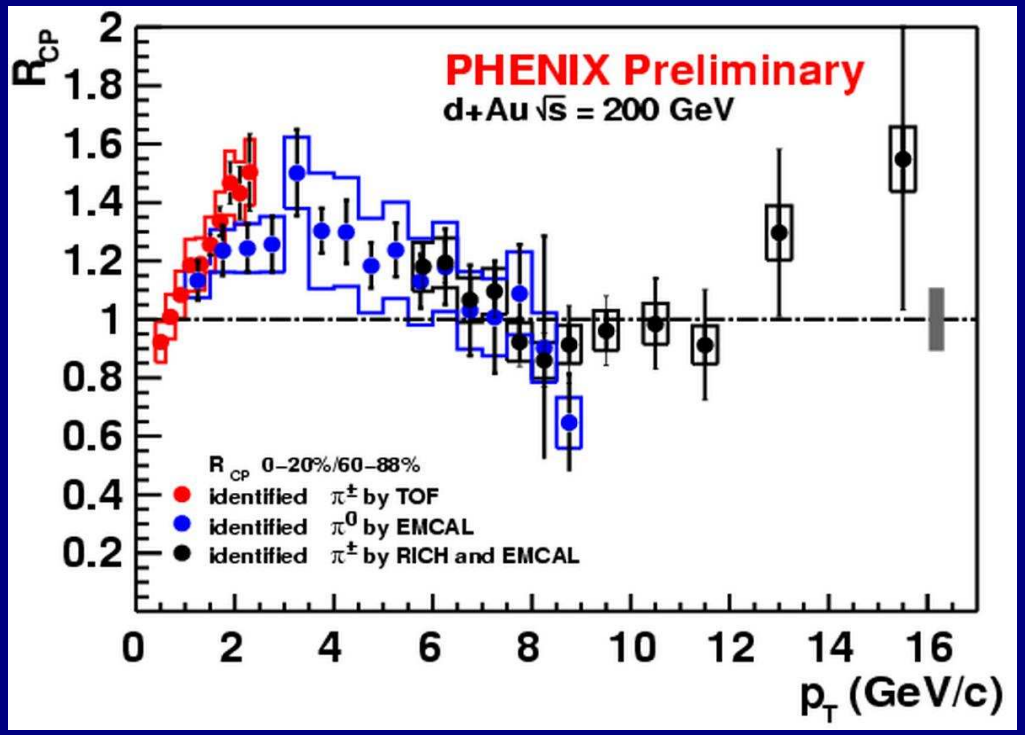


peripheral → central

- **Examine nuclear modification at fixed p_T**
  - Enhancement in central d+Au
  - Suppression in central Au+Au
  - Deviation from scaled pp vanishes in peripheral collisions

⇒ Strong medium effects in central Au+Au overcome initial Cronin enhancement

Does the Enhancement Vanish at High p_T ??



- R_{CP}
  - Compares Yields in central and peripheral scaled by N_{coll}
  - Many systematics cancel
- **Different parts of PHENIX measure different p_T ranges of π**
- **Enhancement in central vanishes at high p_T**

Poster J. Jia P3

Conclusion

- **Observation: Suppression of high p_T charged hadrons and π^0's in central Au+Au**
  - Suggests medium induced energy loss
- **Enhancement/absence of suppression at midrapidity in d+Au**
  - As expected from cronin effect
  - Rules out initial state effects for observed suppression in Au+Au
- **Established baseline for the effects of cold nuclear medium at $\sqrt{s_{NN}}$ = 200 GeV**

PHENIX

Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	Rikkyo University, Tokyo, Japan
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund

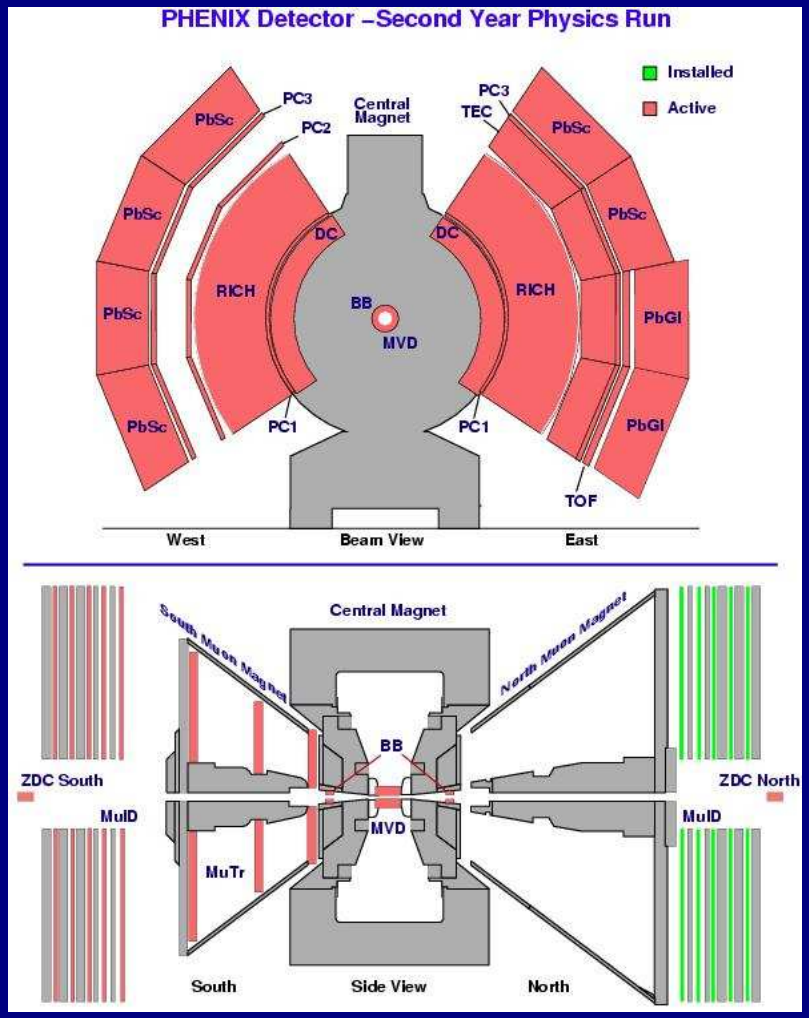
*as of January 2004

*12 Countries; 58 Institutions; 480 Participants**

USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Florida Technical University, Melbourne, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, Urbana-Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

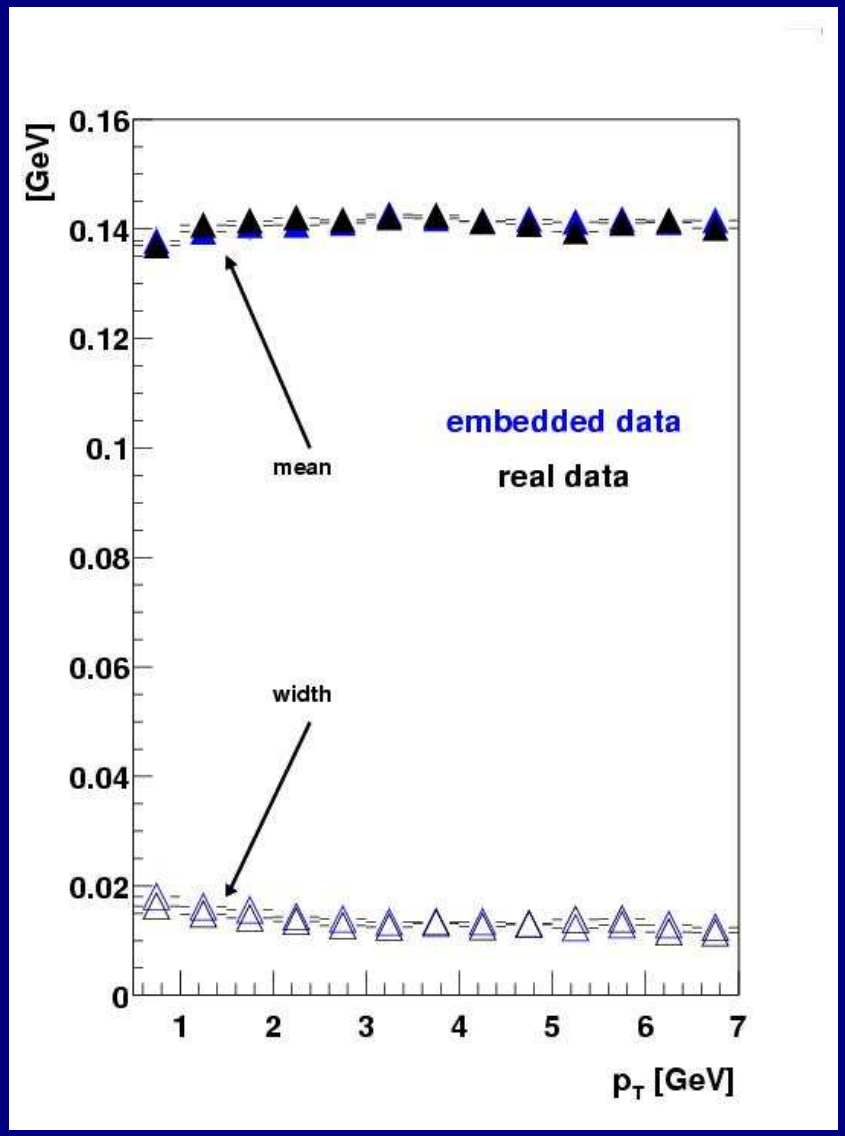
Backup Slides

Phenix @ RHIC



- **Central Arms**
  - $|\eta| < 0.35$
  - Calorimetrie (PbSc PbGl)
  - Tracking (PC, DC)
  - PID (RICH,TOF)
- **North and South Arms**
  - Muon PID and Tracking
- **Global**
  - Trigger (BBC)
  - Centrality (BBC, ZDC)

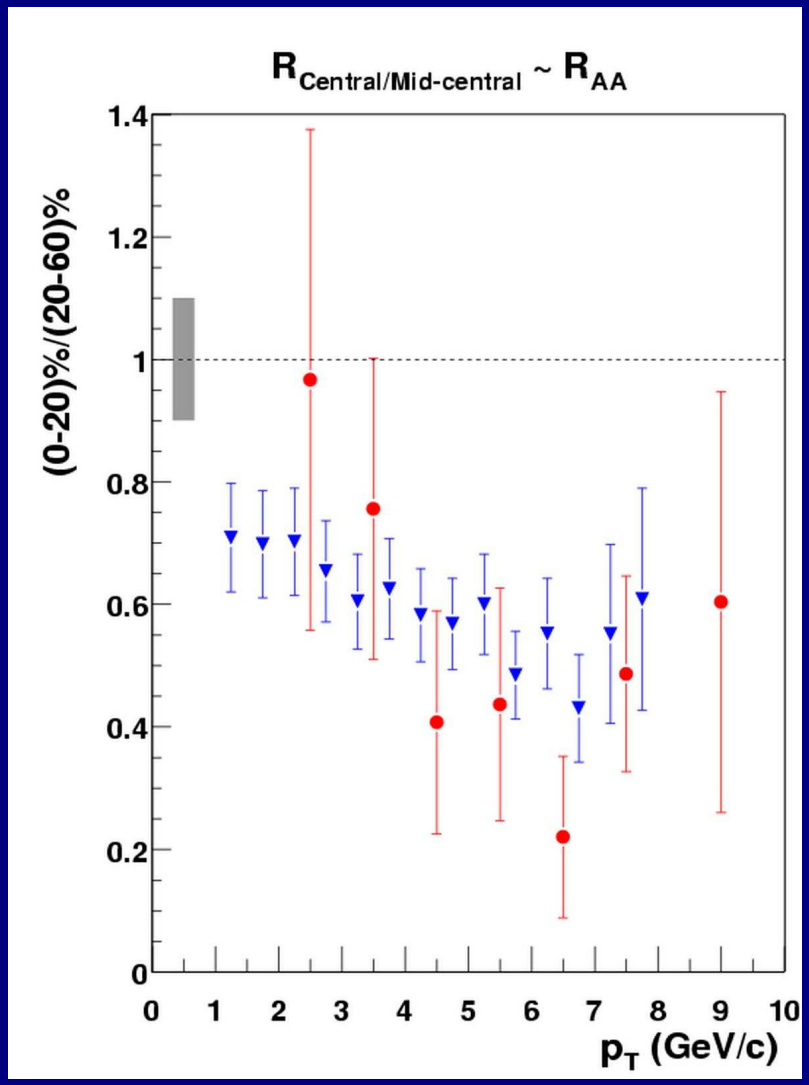
Corrections



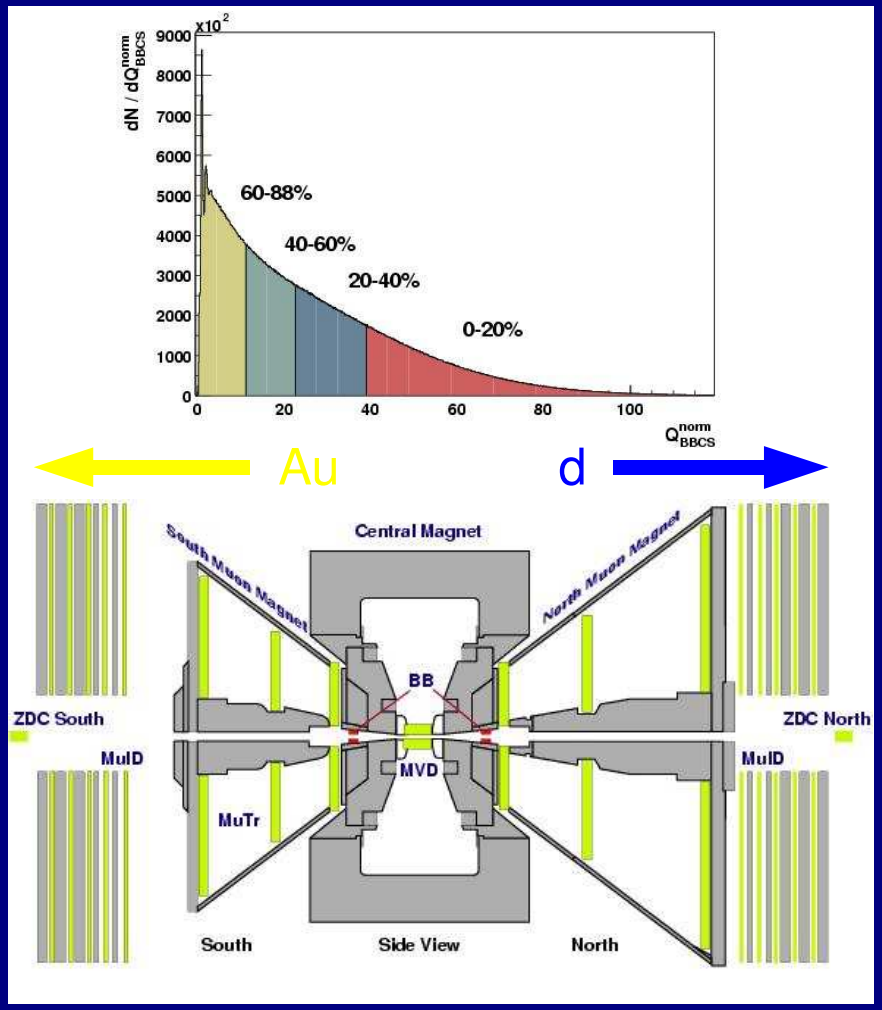
- **Geometrical acceptance**
- **Detector effects**
  - Multiplicity
  - Energy- / position resolution
- **Analysis cuts**
  - Asymmetrie
  - PID
  - Bad modules

Efficiency:
From embedding of simulated π^0 into real events

η in Au+Au


$R_{Central/Mid\text{-}central} \sim R_{AA}$
(0-20)%/(20-60)%
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10
p_T (GeV/c)

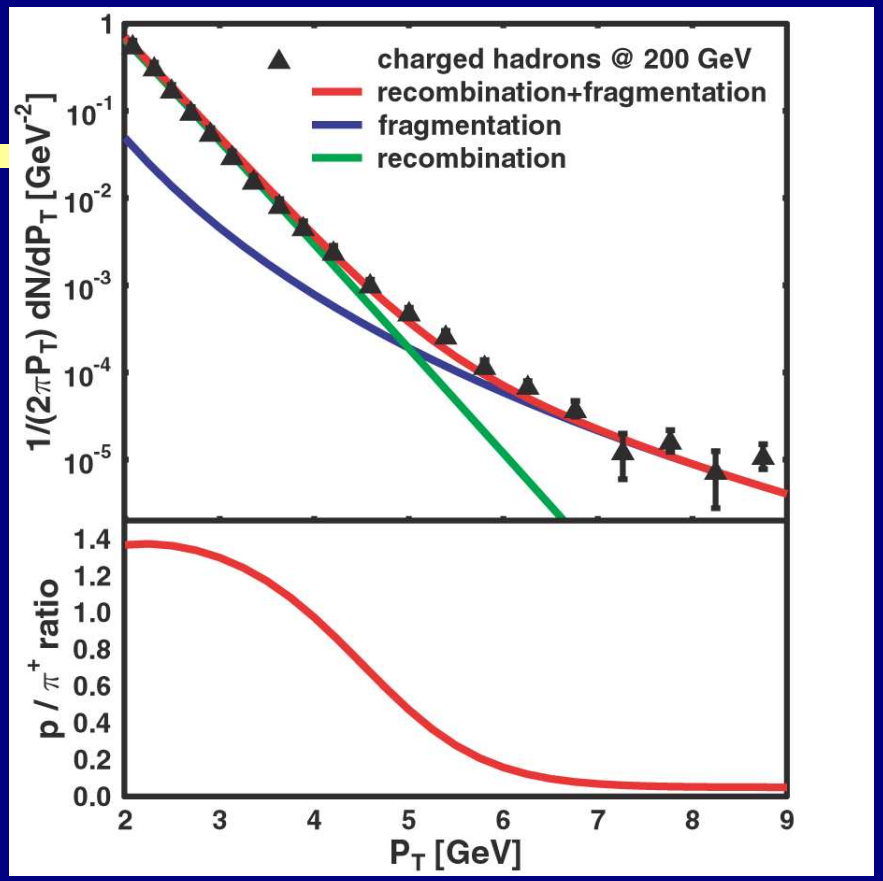
d+Au Centrality Dependence



- **Centrality Selection with BBC-South**
  - Au going side
  - $3 < |\eta| < 3.9$
  - Charge sum $\Rightarrow$ multiplicity
- **N_{coll} from Glauber model**

centrality	N_{coll}
0-20%	15.0 ± 1.0
20-40%	10.4 ± 0.7
40-60%	6.9 ± 0.6
60-88%	3.2 ± 0.3

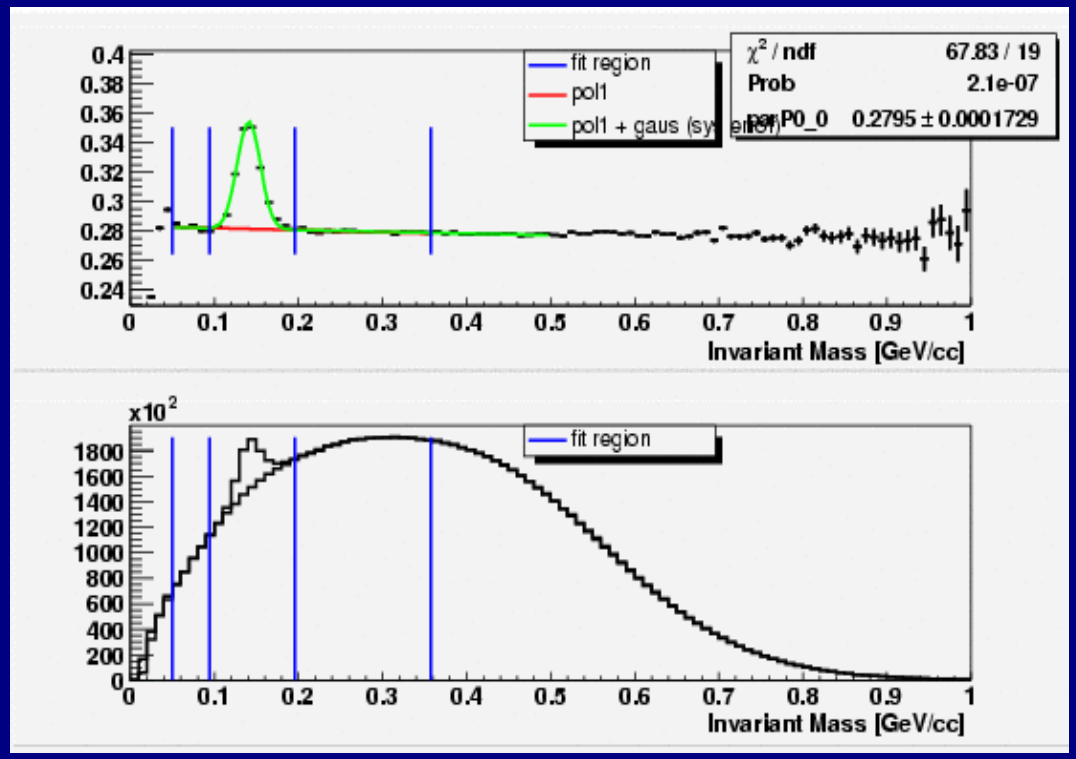
Recombination



Fries, et al, nucl-th/0301087
also, Greco, Ko, Levai, nucl-th/0301093

- **Two competing processes for hadron production**
  - Jet fragmentation
  - Recombination of 3 quarks or a quark/anti-quark pair in a densely populated phase space
- **Fries et al.:**
  - In case of thermalized partons fragmentation wins over recombination only above 5 GeV/c
  - Explains p/π ratio
  - "Such a phase may be appropriately called a QGP"

π^0 Peaks

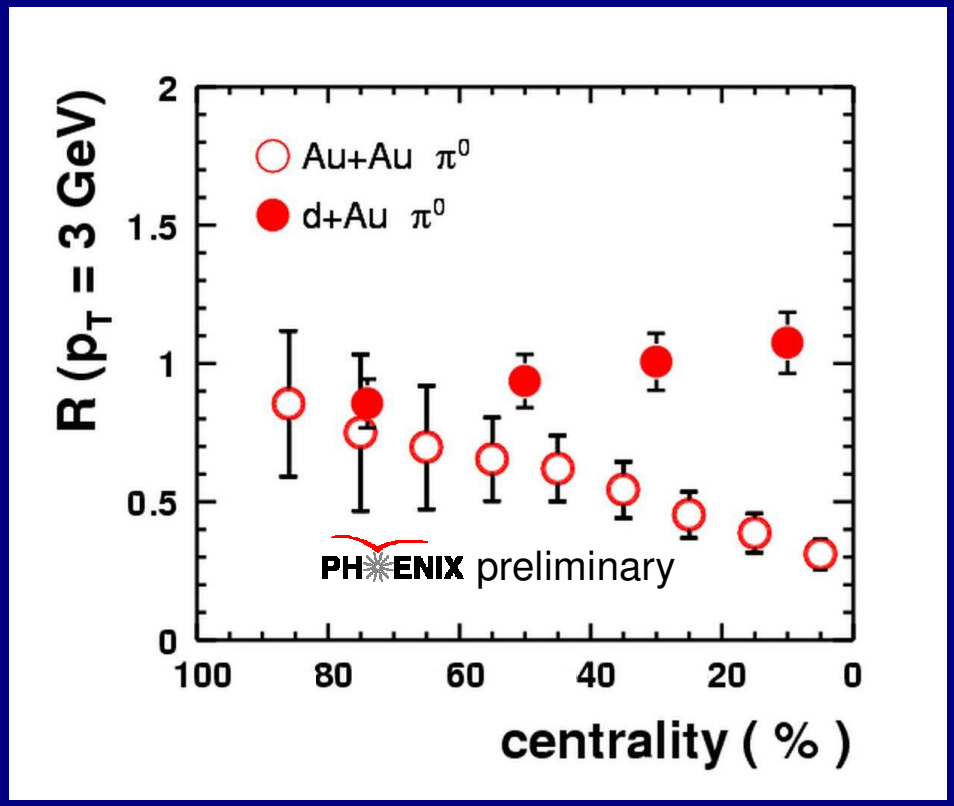


$2\ \text{GeV} \leq p_T < 2.5\ \text{GeV}$

$134\,939 \pm 3184\ \pi^0$ from

26 M minimum bias events (PbGl)

Centrality Dependence π^0

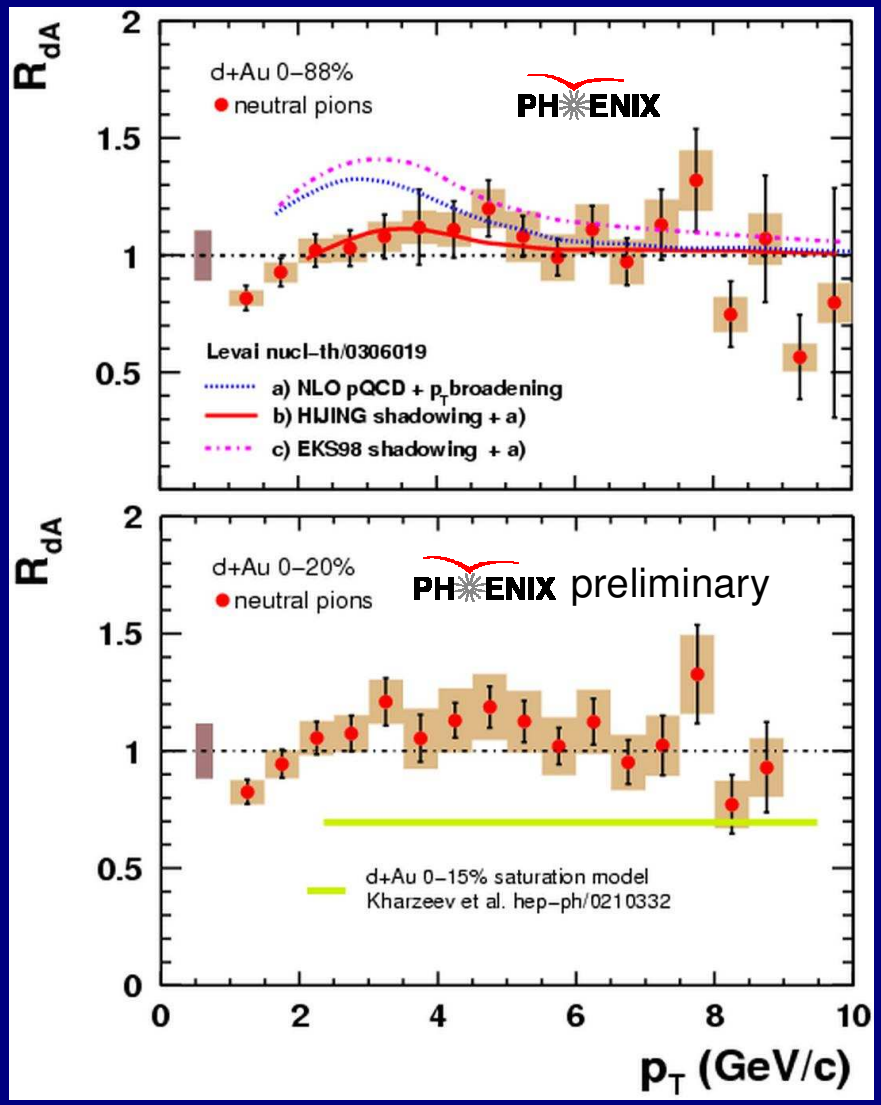


peripheral → central

- **Examine nuclear modification at fixed p_T**
  - Enhancement in central d+Au
  - Suppression in central Au+Au
  - Deviation from scaled pp vanishes in peripheral collisions

⇒ Strong medium effects in central Au+Au overcome initial state Cronin enhancement

Theory Comparison



- **Prediction from pQCD**
  - Tuned to pp ($\langle k_T^2 \rangle$...)
  - Good qualitativ agreement with expactation from Cronin enhancement
  - Further improvement with inclusion of shadowing
- **Prediction from saturation models**
  - Fails, no suppression in central d+Au at midrapidity
  - Different rapidity region
  - PHENIX