Systematic Study of Particle Production at High p_T with PHENIX

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La Jolla, San Diego
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IKP Münster

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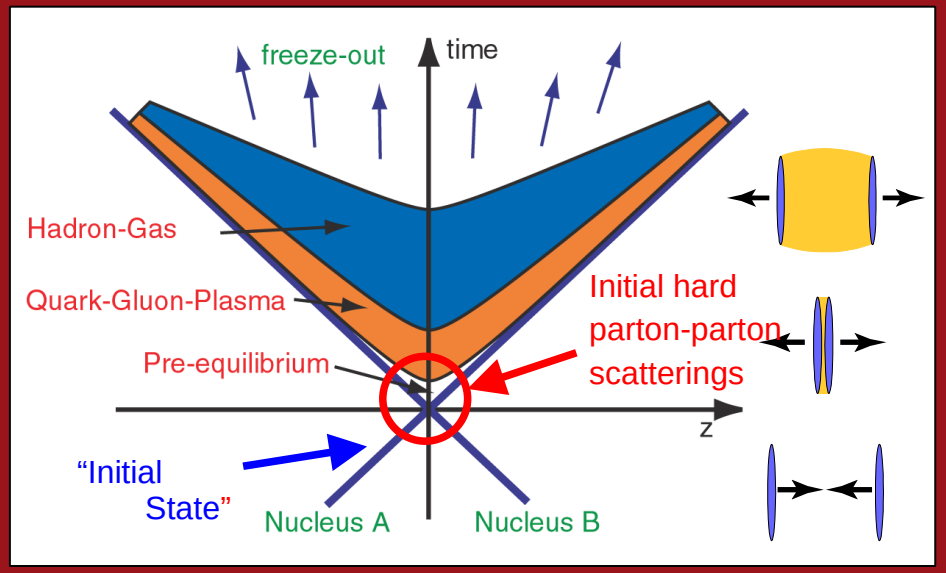
Why High p_T?

- **Studying *hard* processes**
  - Parton collisions with large Q^2 (~ p_T^2)
  - Factorization:

$$\frac{d^2\sigma_\pi}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \mathrm{FF}(q \to \pi^0)$$



- **p+p**
  - Fragmentation into QCD-vacuum
- **Au+Au**
  - Early reaction-phase
  - Probe for a later hot and dense phase

- **Quantifying the medium influence (Step 1)**
  - Single particle (incl.) spectra
  - Leading hadron carries large fraction of initial parton momentum

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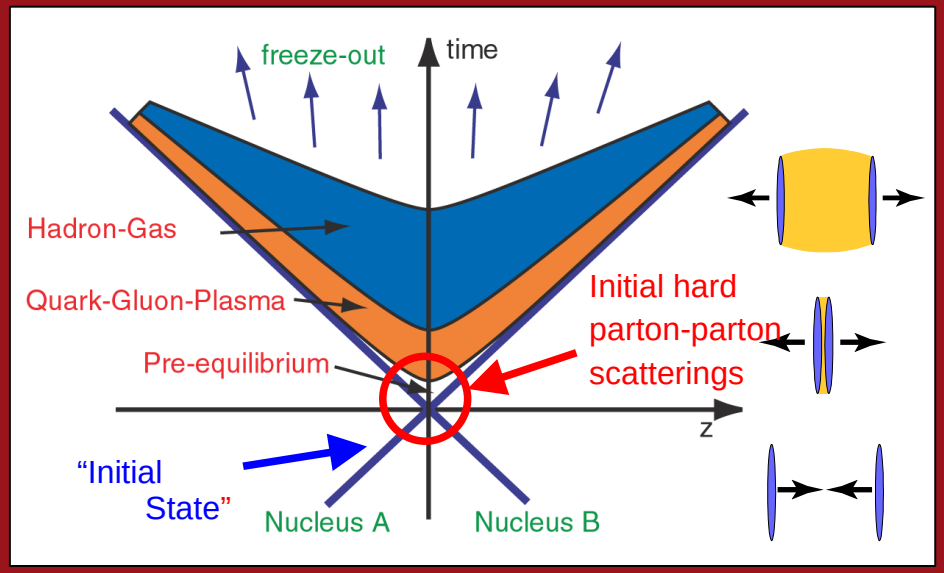

- **Quantifying the medium influence (Step 1)**

$$R_{AA} = \frac{dN_{AA}}{T_{AA}\,d\sigma_{pp}}$$

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How High is "High" p_T?

- **First year of RHIC (130 GeV Au+Au):**
  - p_T= 4 GeV/c was high "Suppression of Hadrons with **Large** Transverse Momentum in Central Au+Au Collisions at sqrt(s) = 130 GeV" (PRL 88,022301 (2002)
- **Where hard scattering is the dominant source of particle production (power law spectrum)**
- **Consider mainly p_T > 6 GeV/c**
- **Main source of information π^0, η, γ**
  - Identified particles
  - Test different aspects of the medium
    - Mesons from parton fragmentation
    - Direct photons also produced in hard scatterings
      - And thermal radiation, jet-plasma interaction etc. (talk by **Oliver Zaudtke**)

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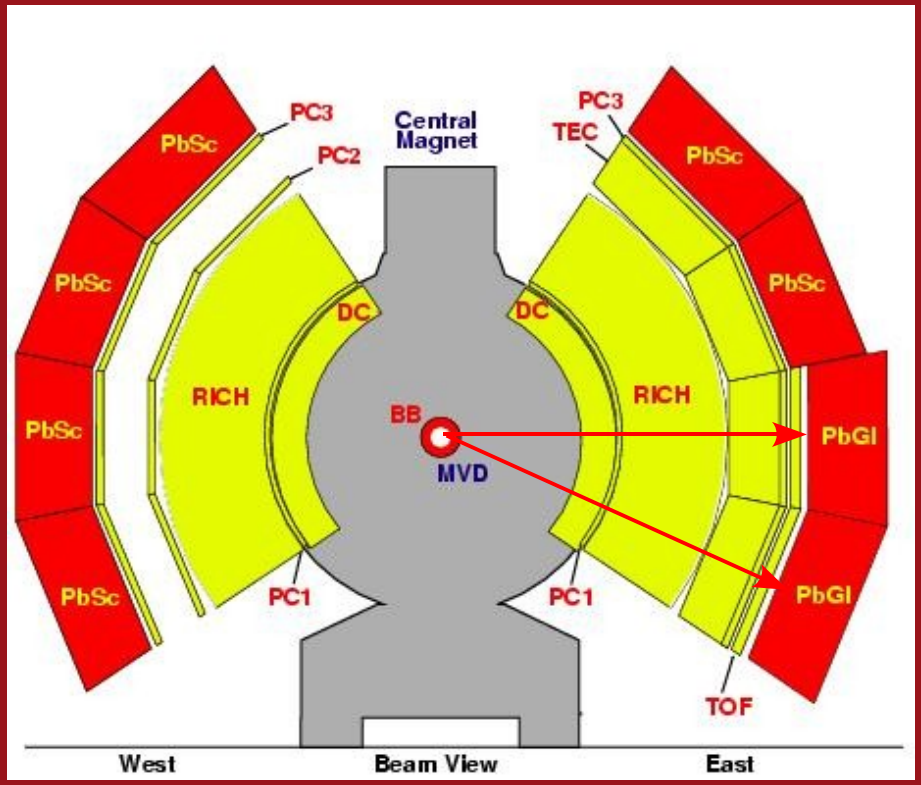
π^0, η and direct γ @ PHENIX

- **Measurement with the EMCal**
  - Two different detector types
- **Reconstruction**
  - $\pi^0\,(\eta) \rightarrow 2\gamma$
  - Invariant mass

$$m_{inv} = \sqrt{2E_1E_2(1-\cos\theta)} \approx 135\ (548)\ \text{MeV}$$

- **Combinatorial Background:**
  - Determination via “mixed event” technique
  - Photons from different events a priori uncorrelated



- **Direct γ more sophisticated**
  - Subtraction of all decay photons
  - Tagging etc.

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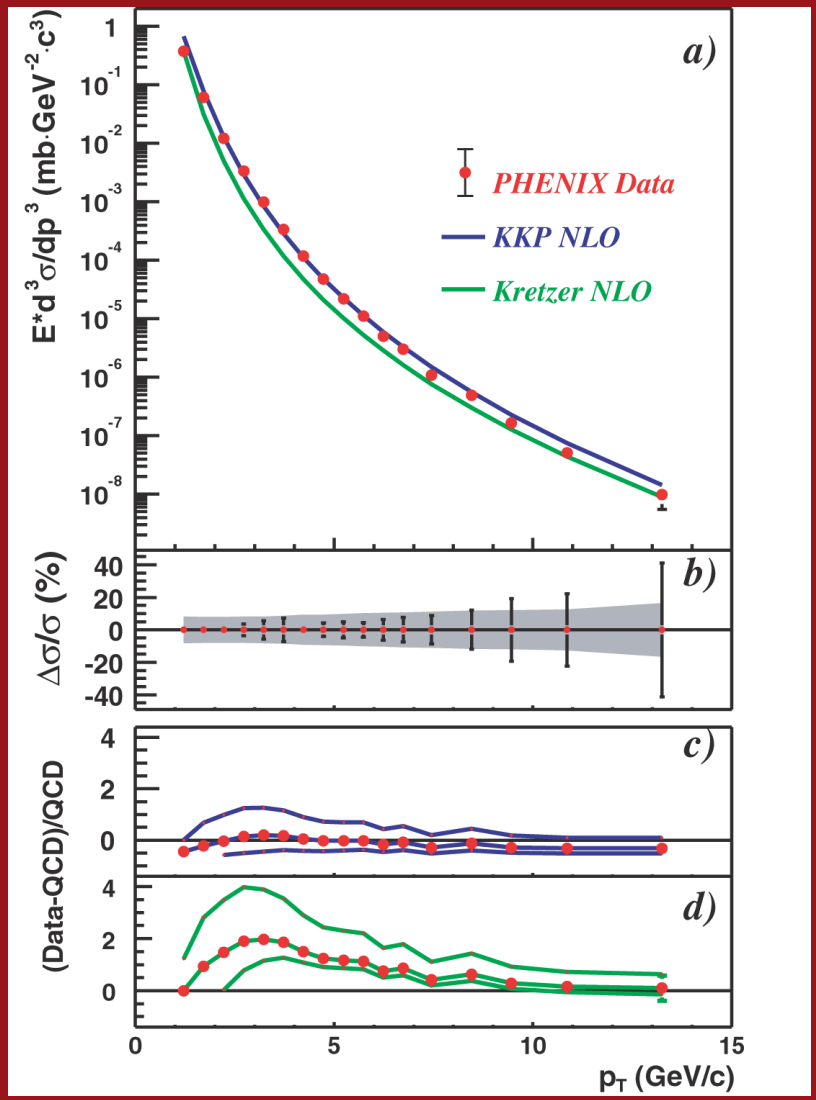
The Baseline @ 200 GeV

PRL **91**, 241803 (2003)



- **Remarkable agreement with NLO pQCD**

$$\frac{d^2\sigma_\pi}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \mathrm{FF}(q \to \pi^0)$$

  - Even sensitiv to choice of fragmentation function *FF(g→π)*
- **Measured by the same experiment!**

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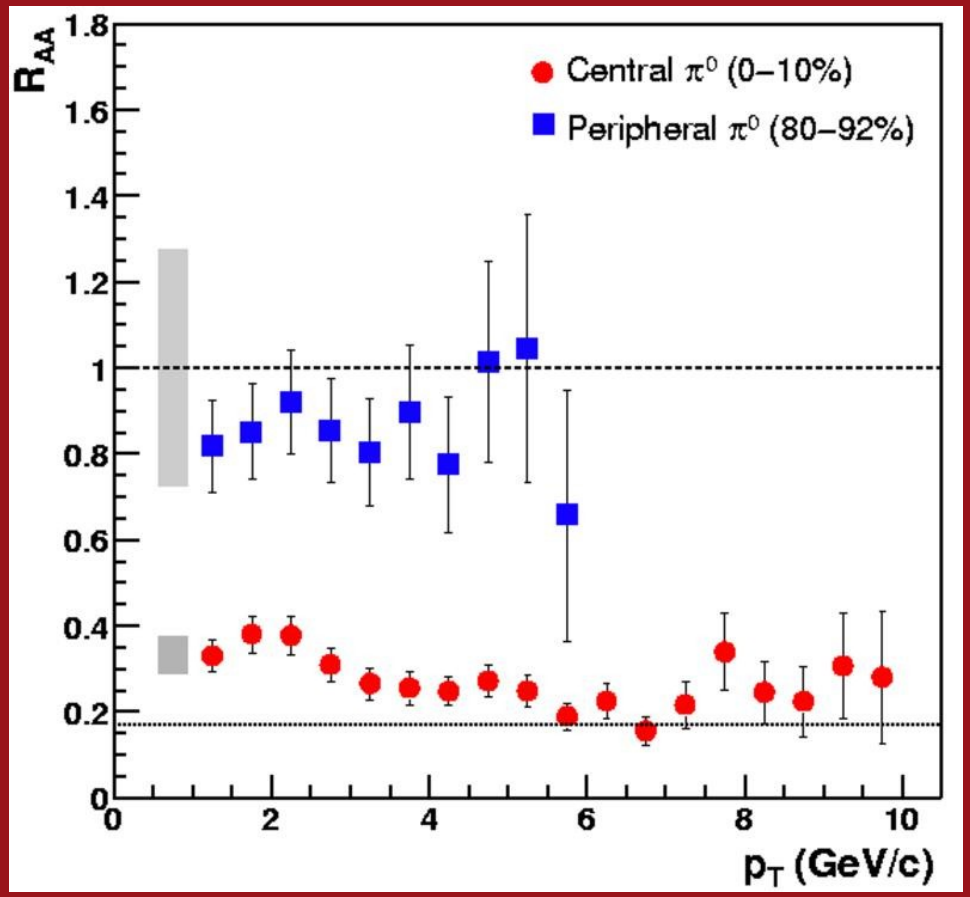
PHENIX High p_T Highlights

- Suppression of high p_T hadrons in central Au+Au relative to scaled p+p
- Also seen in charged hadrons
- Initial state or final state?

$$\frac{d^2\sigma_\pi}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \mathrm{FF}(q \to \pi^0)$$



PRL **91**, 072301 (2003)

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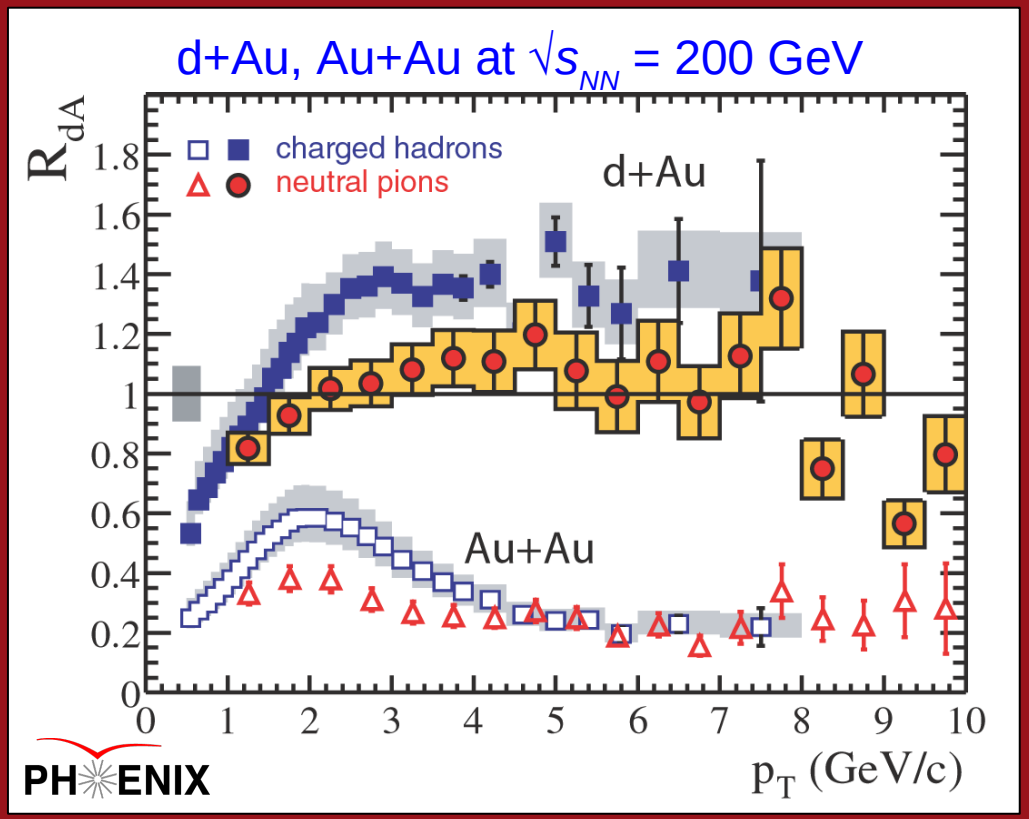
PHENIX High p_T Highlights

- **No suppression in d+Au collisions**
- **Initial state effects ruled out as explanation for observed suppression**
  - No effects of CGC at $y = 0$
- **Difference between charged hadrons and π^0 at intermediate p_T**
  - Coalesscence/recombination of quarks from thermal source?



PRL **91**, 072303 (2003)

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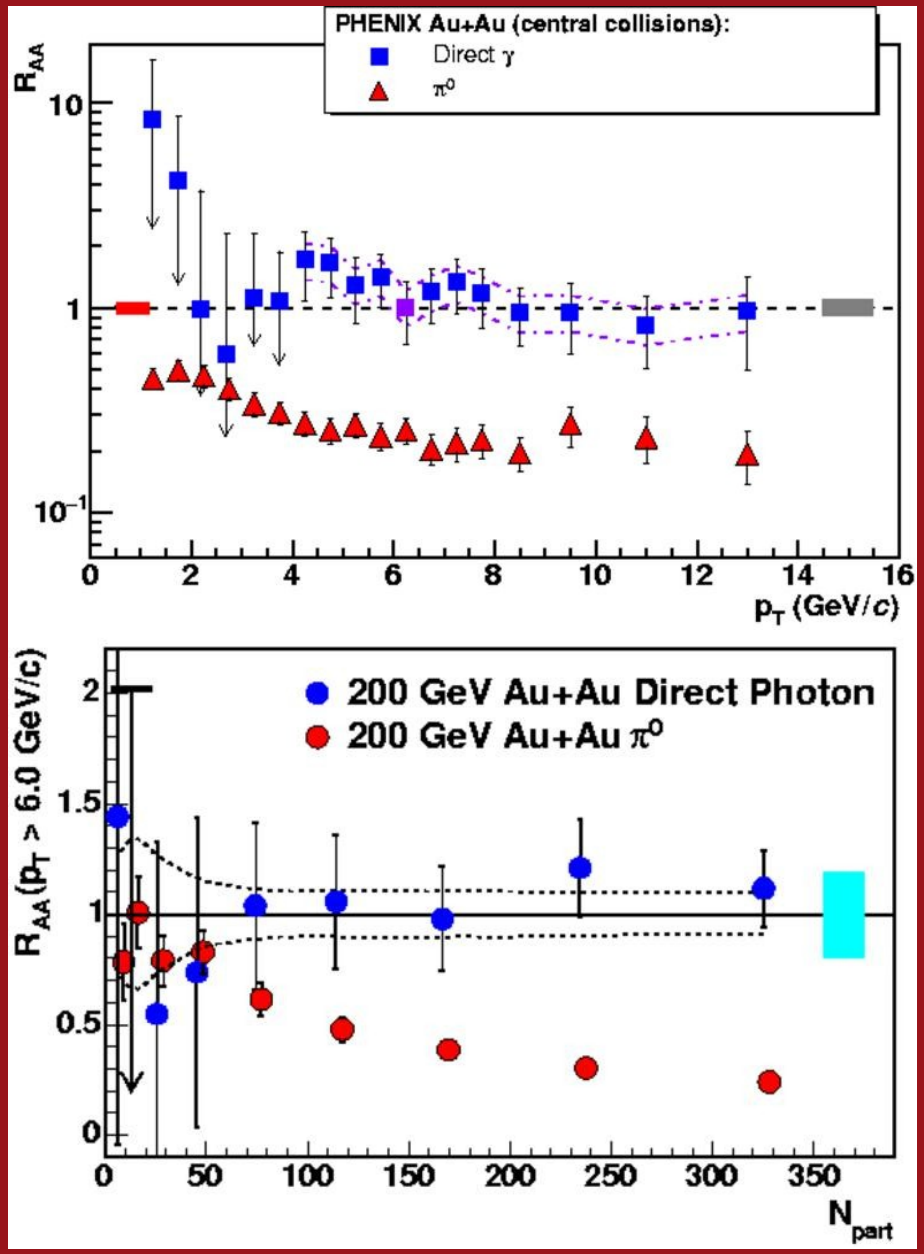
PHENIX High p_T Lights

- Direct Photons
- Ultimate test for hard scatterings

$$\frac{d^2\sigma_\gamma}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \delta$$



PRL **94**, 232301 (2005)

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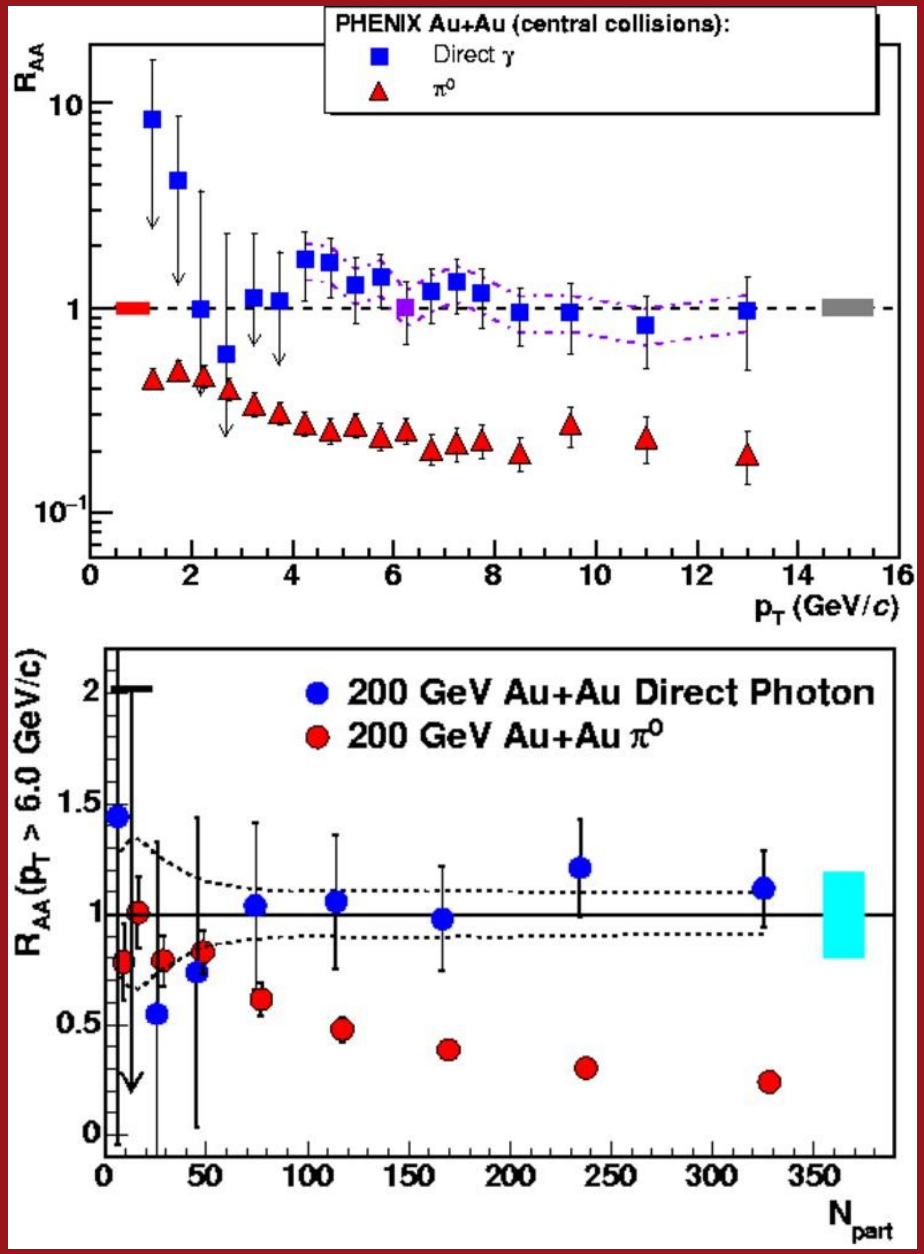
PHENIX High p_T Lights

- Direct Photons
- Ultimate test for hard scatterings

$$\frac{d^2\sigma_\gamma}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \delta$$

- No suppression of direct photons in central Au+Au
- Strong final state effect



PRL **94**, 232301 (2005)

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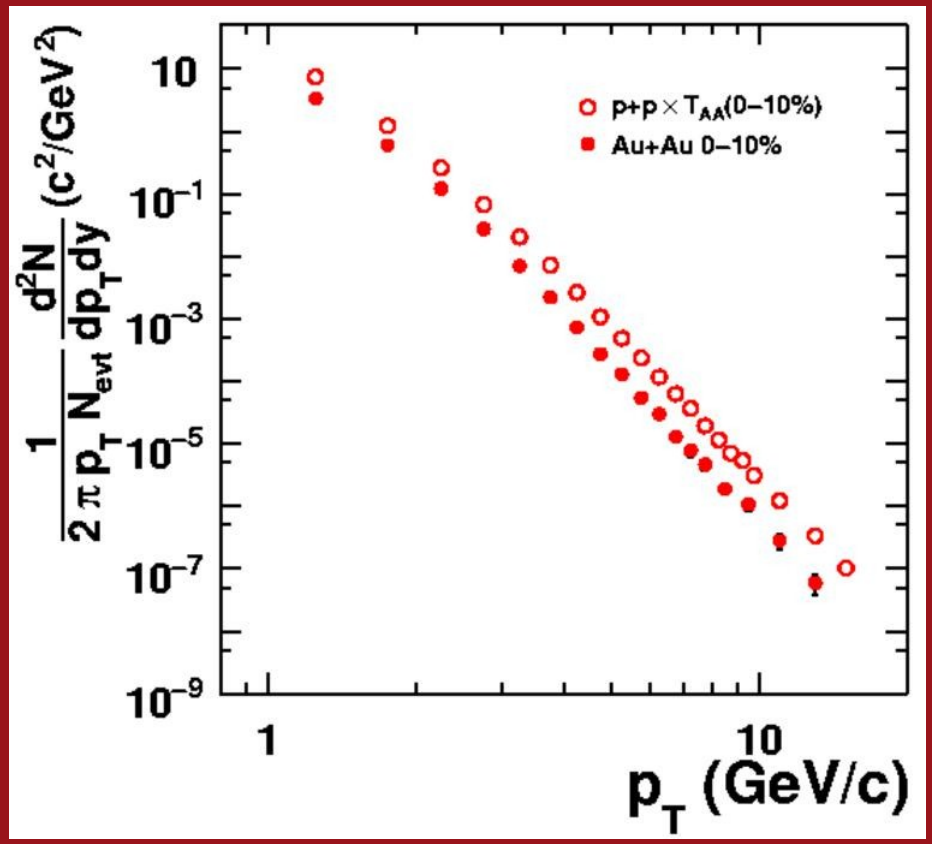
Common Explanation

- **Partons lose energy by (coherent) gluon Bremstrahlung in the medium:**

$$\frac{\langle \Delta E \rangle}{E} \sim \alpha_s^3 C_R \frac{1}{A_T} \frac{dN_g}{dy} L \frac{1}{E} \ln \frac{2E}{\mu^2 L}$$

  - Gluon density can be constrained via multiplicity



- **Average energy loss can be determined from spectrum shift (R_{AA})**

- **For power law:**

$$\frac{\langle \Delta p_T \rangle}{p_T} = S_{loss} = 1 - R_{AA}(p_T)^{1/n-2}$$

~ constant above 4 GeV/*c*

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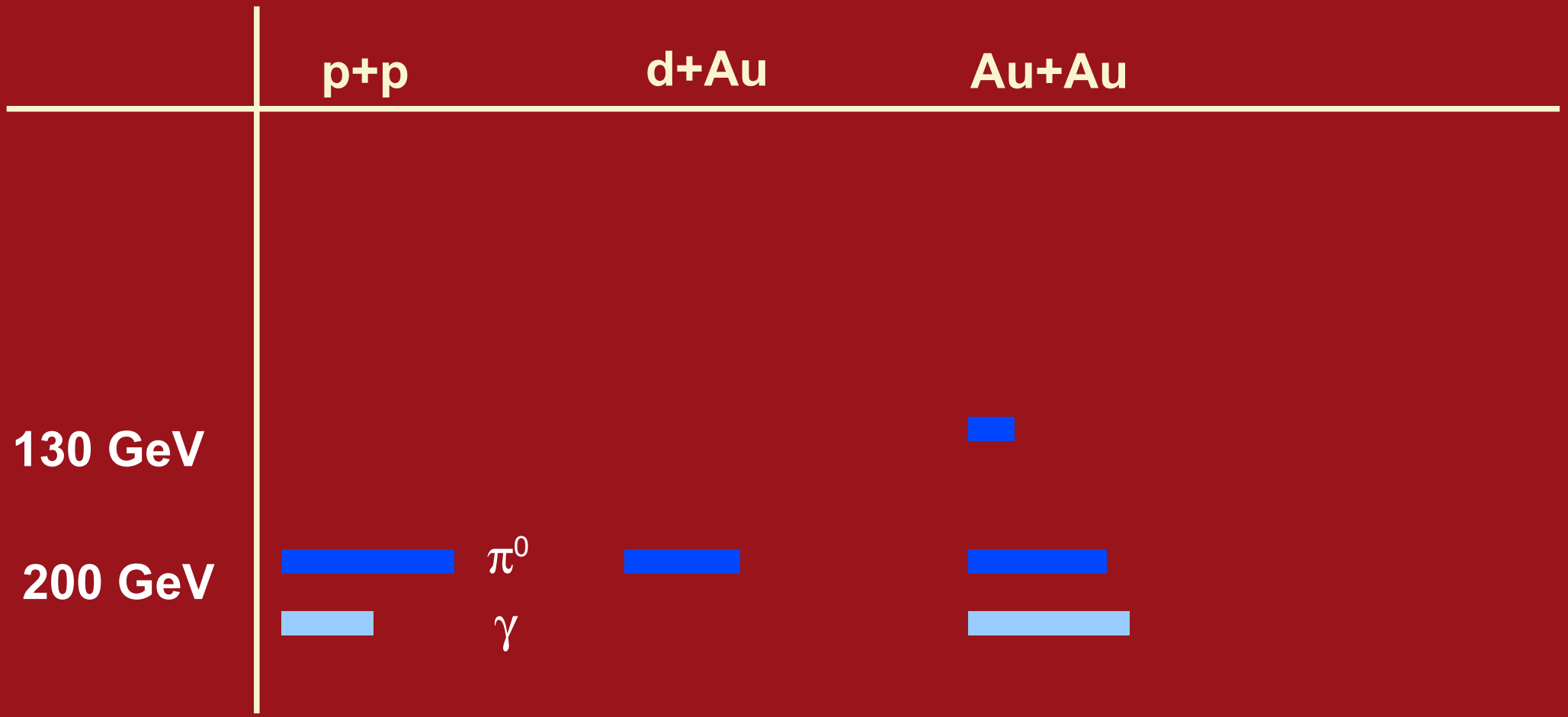
Single Particle Spectra @ High p_T
The First Three Years



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What else can be done at high p_T?

- **More differential studies of the (existing) data at high p_T**
  - Finer bins in centrality (use of high-p_T trigger)
  - Different particle types (e.g. η)
  - Quark-mass dependence, heavy flavor (talk by **Cesar Luis da Silva**)
  - Jet correlations (talk by **Nathan Grau**)
  - Reaction plane (L) dependence (talk by **Dave Winter**)
- **New Au+Au data**
  - Improve p_T-reach
- **Vary the collision energy**
- **Vary the system size**

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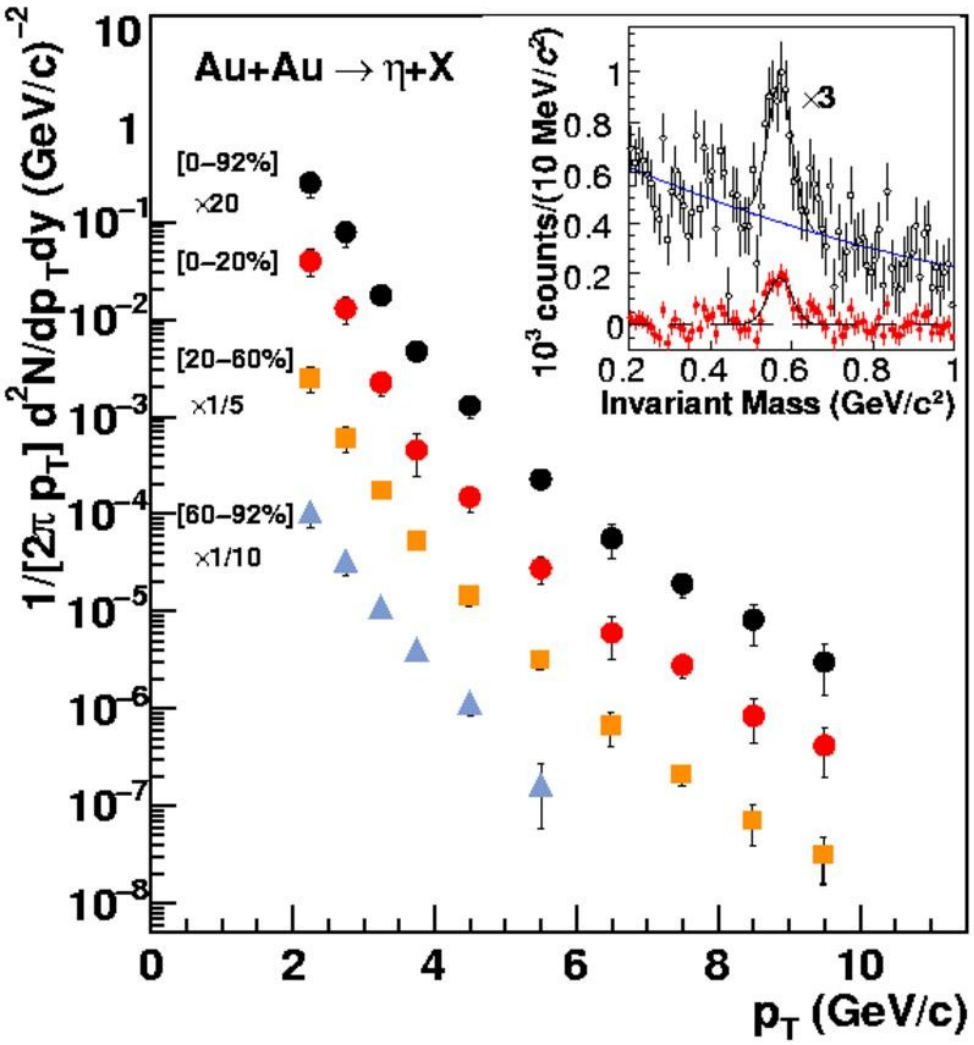
Mass dependence at high p_T

- η same quark content as π^0
- Factor 4 heavier



nucl-ex/0601037

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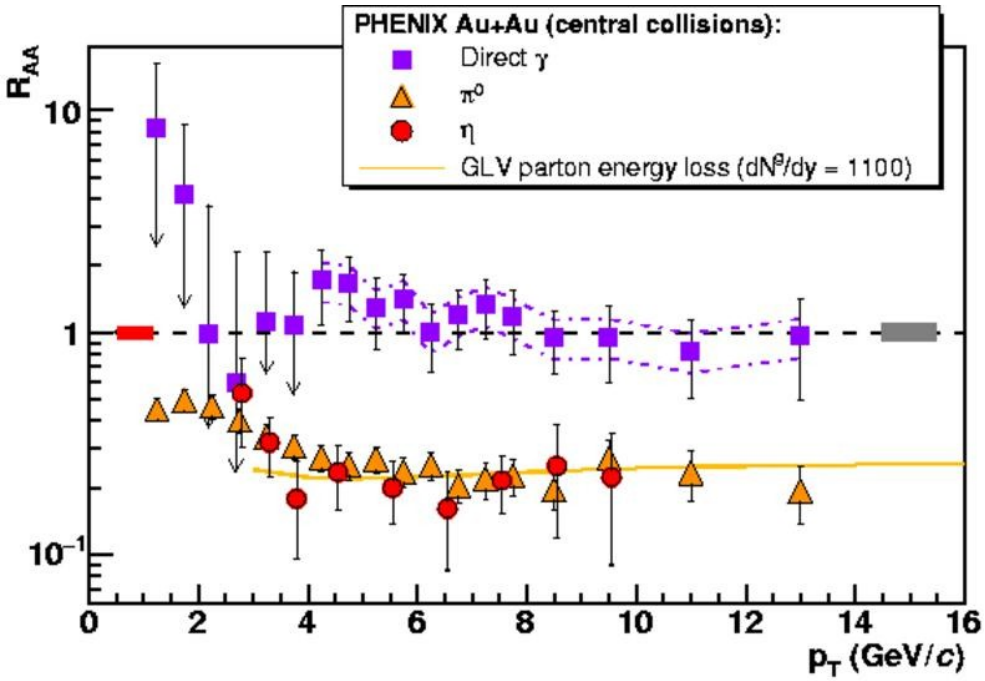
Mass dependence at high p_T

- η same quark content as π^0
- Factor 4 heavier
- Same R_{AA} as π^0
  - Suppression does not depend on hadron-mass



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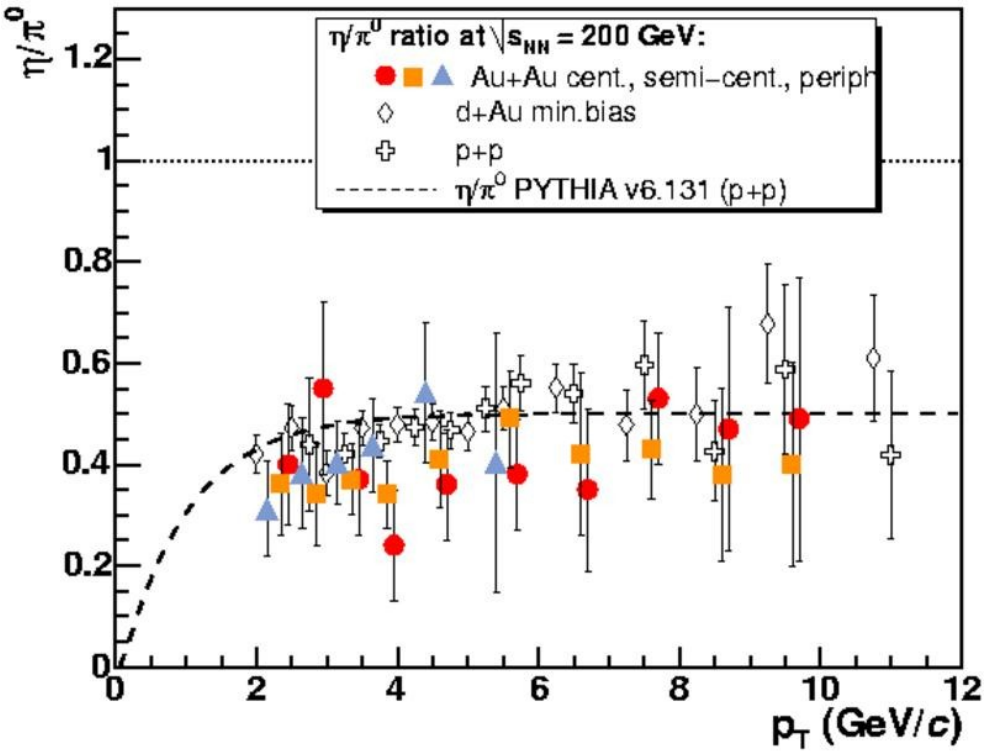
Mass dependence at high p_T

- η same quark content as π^0
- Factor 4 heavier
- Same R_{AA} as π^0
  - Suppression does not depend on hadron-mass
- η/π^0 similar for all colliding species and centralities
  - Suppression happening at the partonic level
  - Fragmentation function not strongly influenced by the medium



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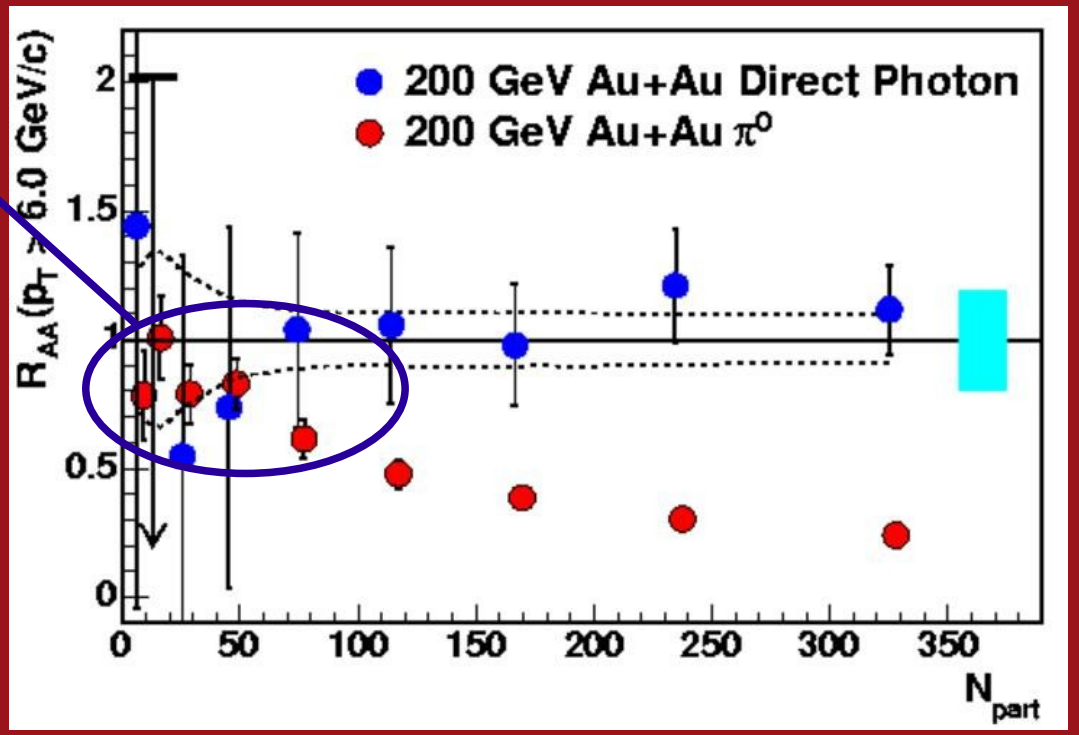
System Size Dependence...

System Size Dependence

- **Variation of centrality**
  - Onset of suppression: $N_{part} \approx 50$
  - No good discrimination in Au + Au



PRL **94**, 232301 (2005)

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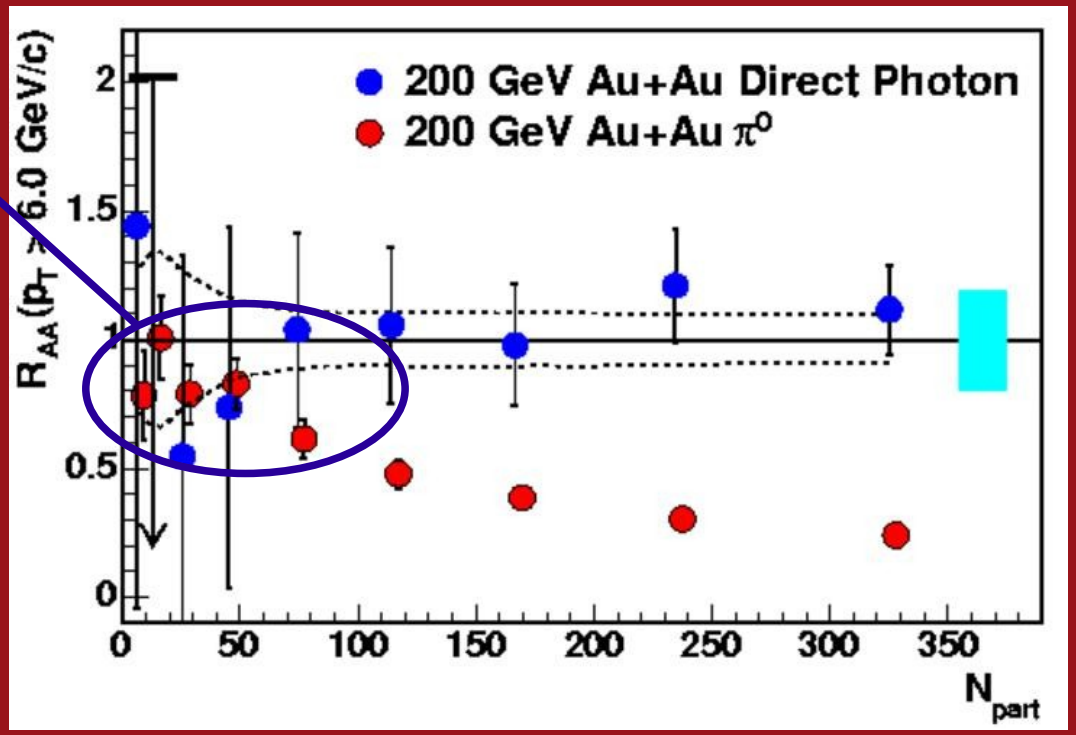
System Size Dependence

- **Variation of centrality**
  - Onset of suppression: $N_{part} \approx 50$
  - No good discrimination in Au + Au
- **Cu+Cu (*A* = 64)**
  - Finer N_{part} "resolution"
  - Different geometry
    - Surface/volume effects



PRL **94**, 232301 (2005)

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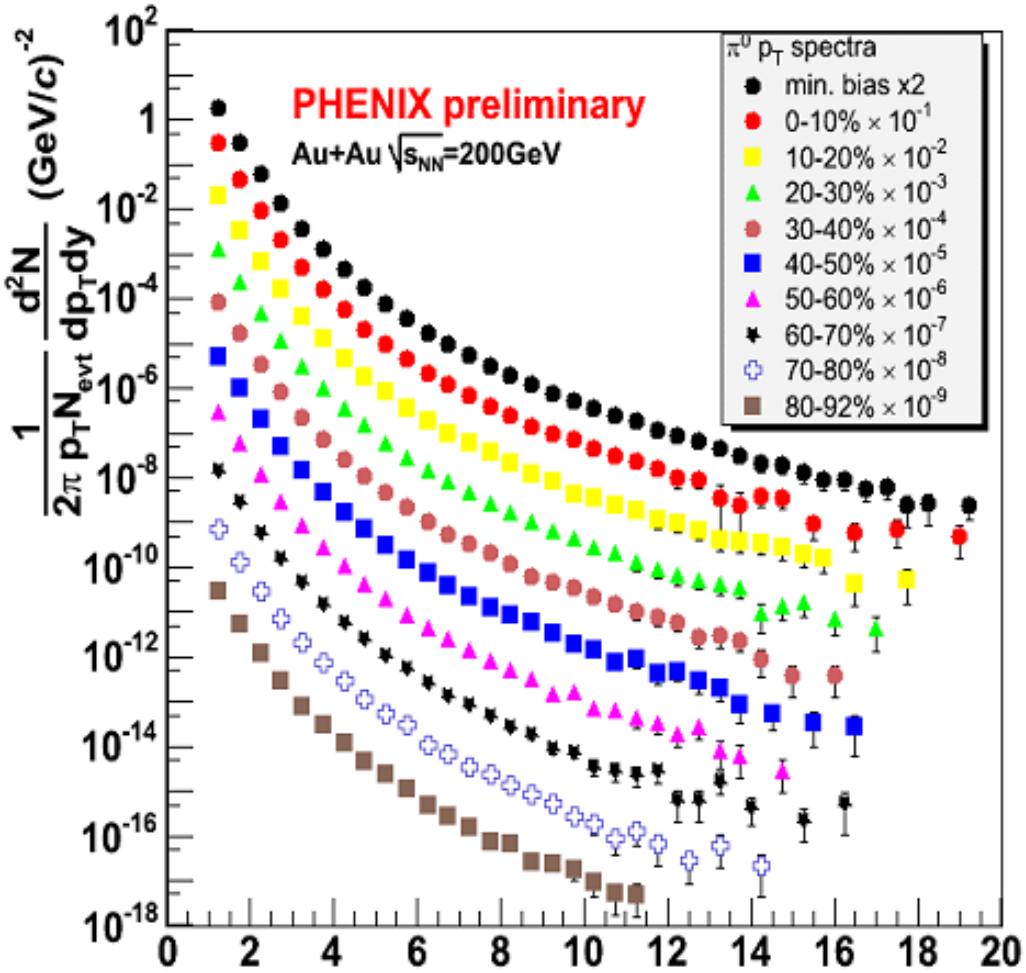
The Measurement in Au+Au

- **New RHIC Run4 Au+Au data**
- **Sampled 241 μb^{-1}**
  - 1.5 B events
- **Spectra up to 20 GeV/c**



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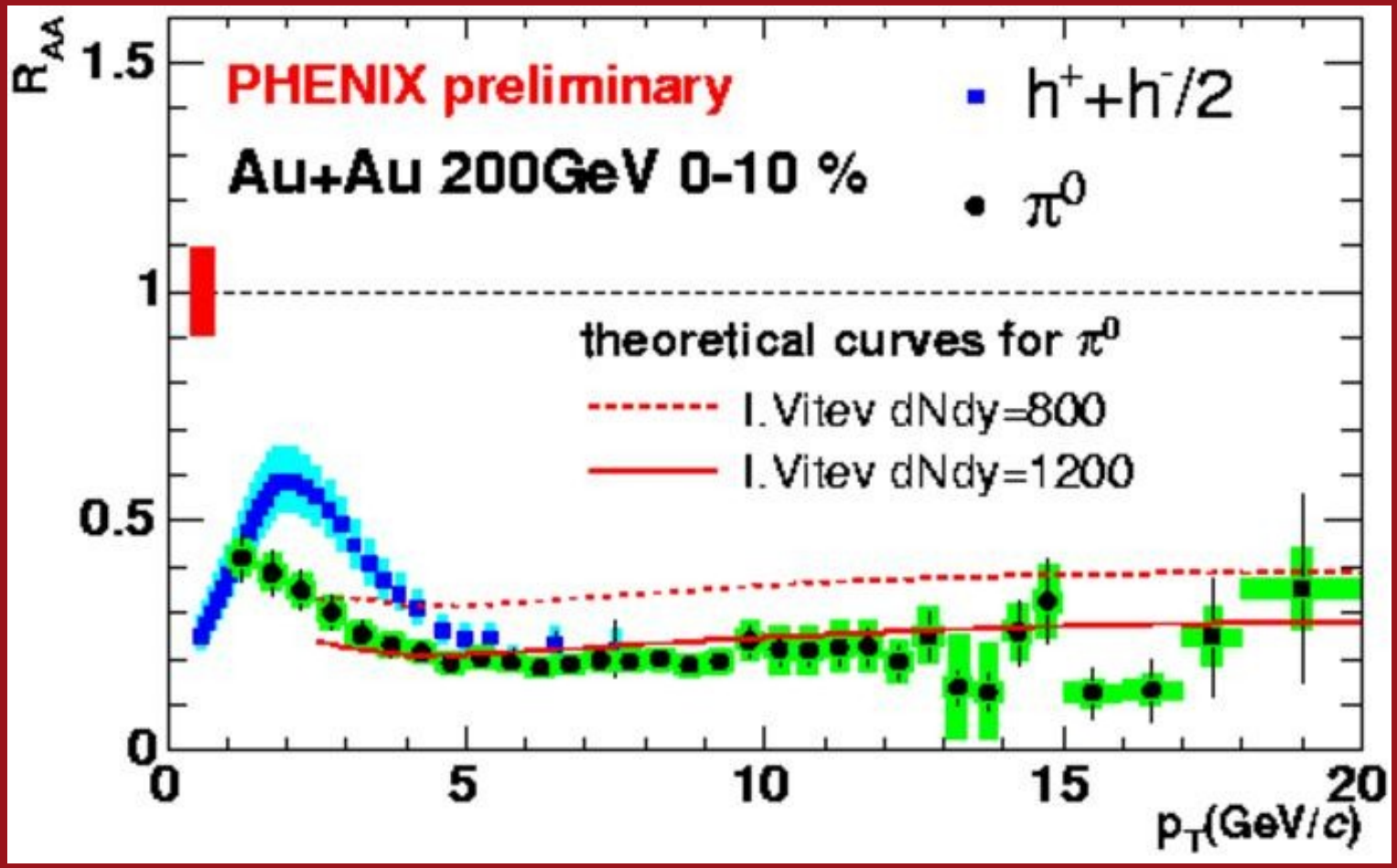
The Measurement in Au+Au



Suppression stays nearly constant up to 20 GeV
Consistent with $dN_g/dy \sim 1200$ calculation

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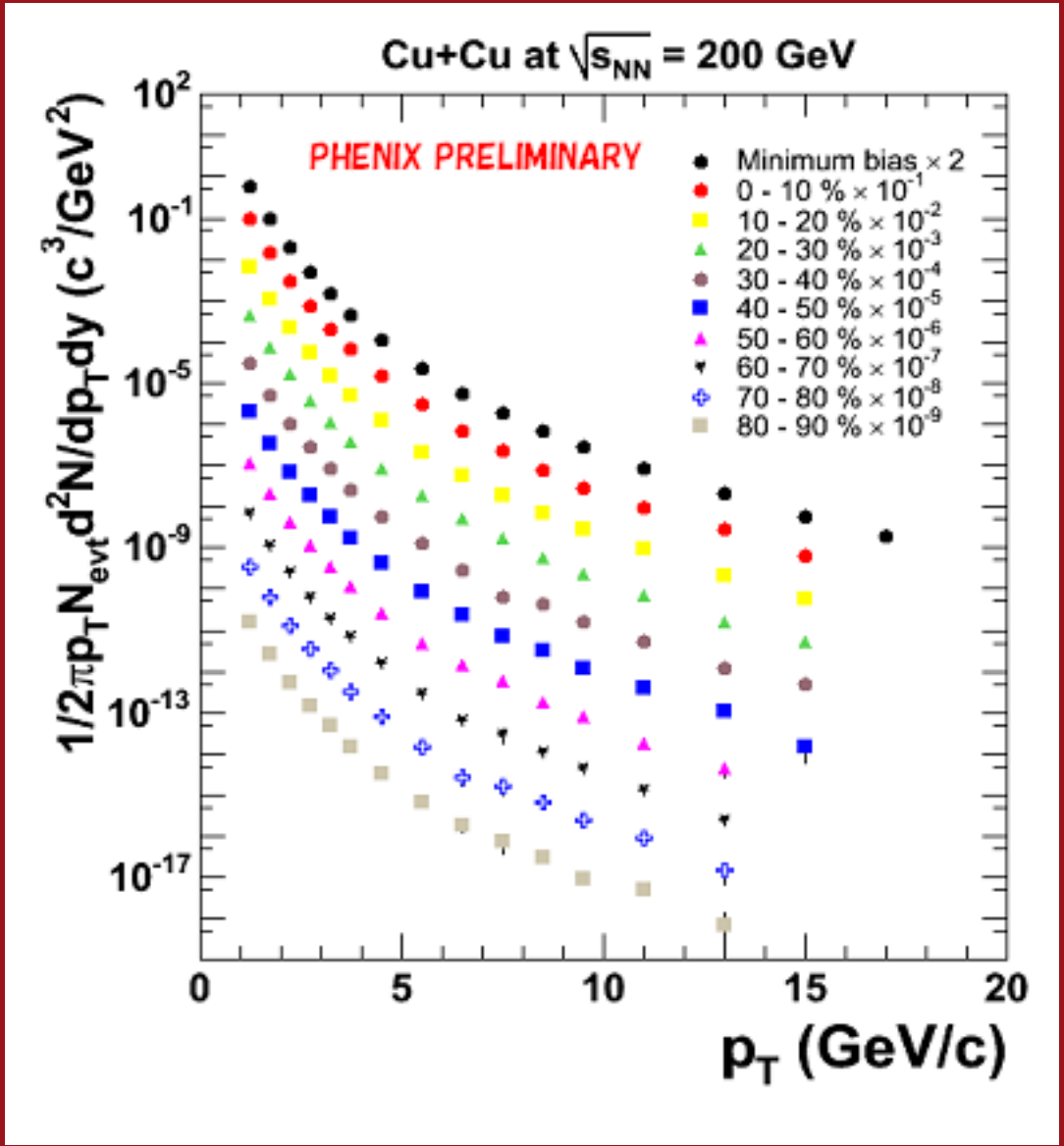
The Measurement in Cu+Cu

- **RHIC Run5 (2005)**
- **59 M minimum bias events**
- **1.9 M high-p_T triggered**
  - 2.2 B events sampled
- **Spectra up to 18 GeV/c**



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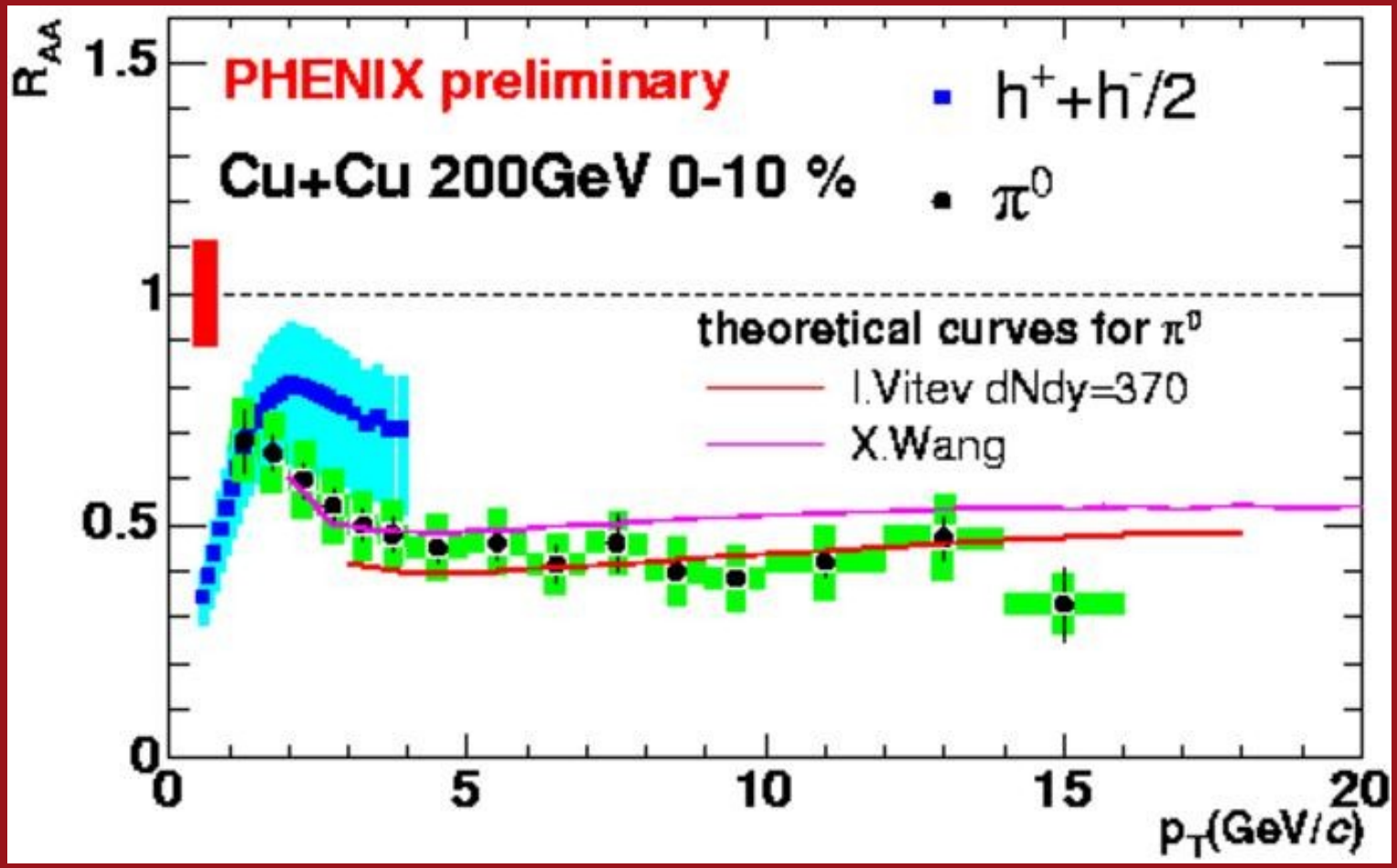
The Measurement in Cu+Cu



Central Cu+Cu also suppressed
Consistent with energy-loss calculation $dN_g/dy = 370$

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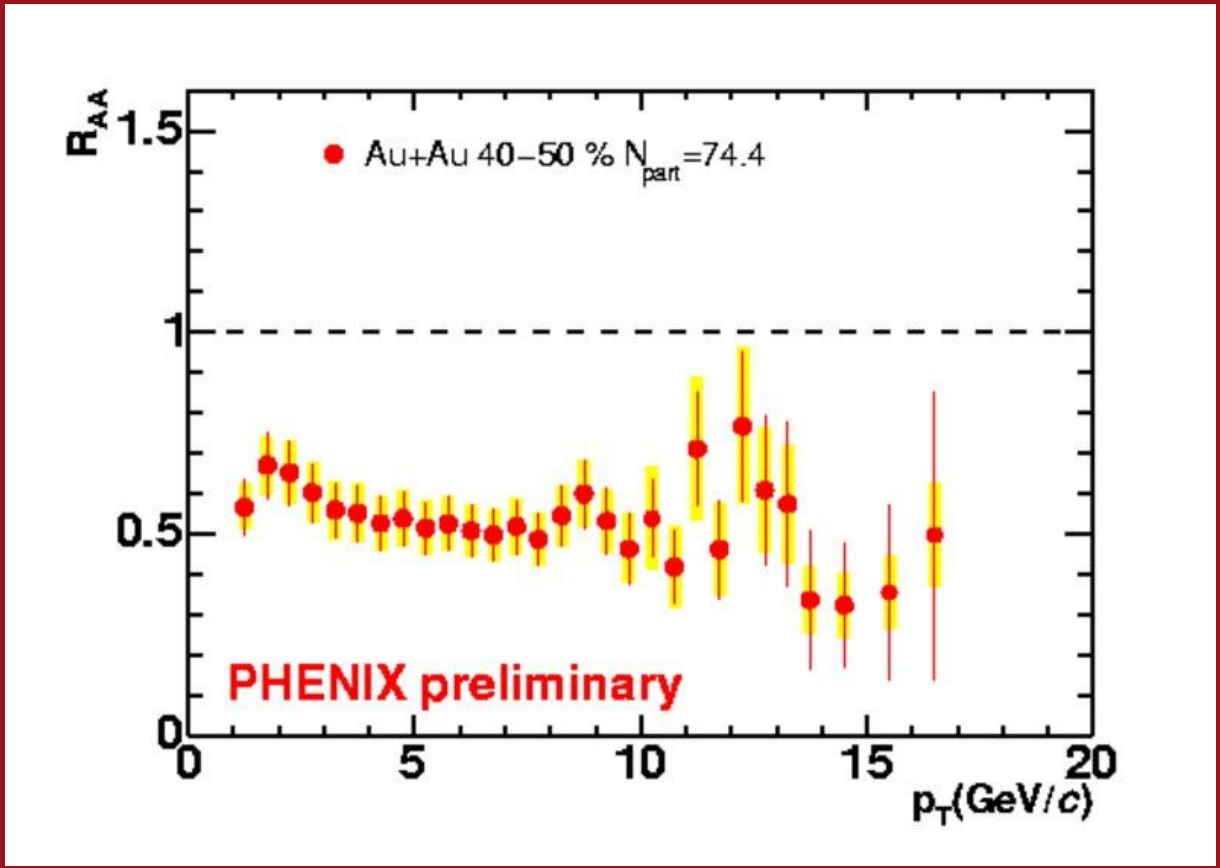
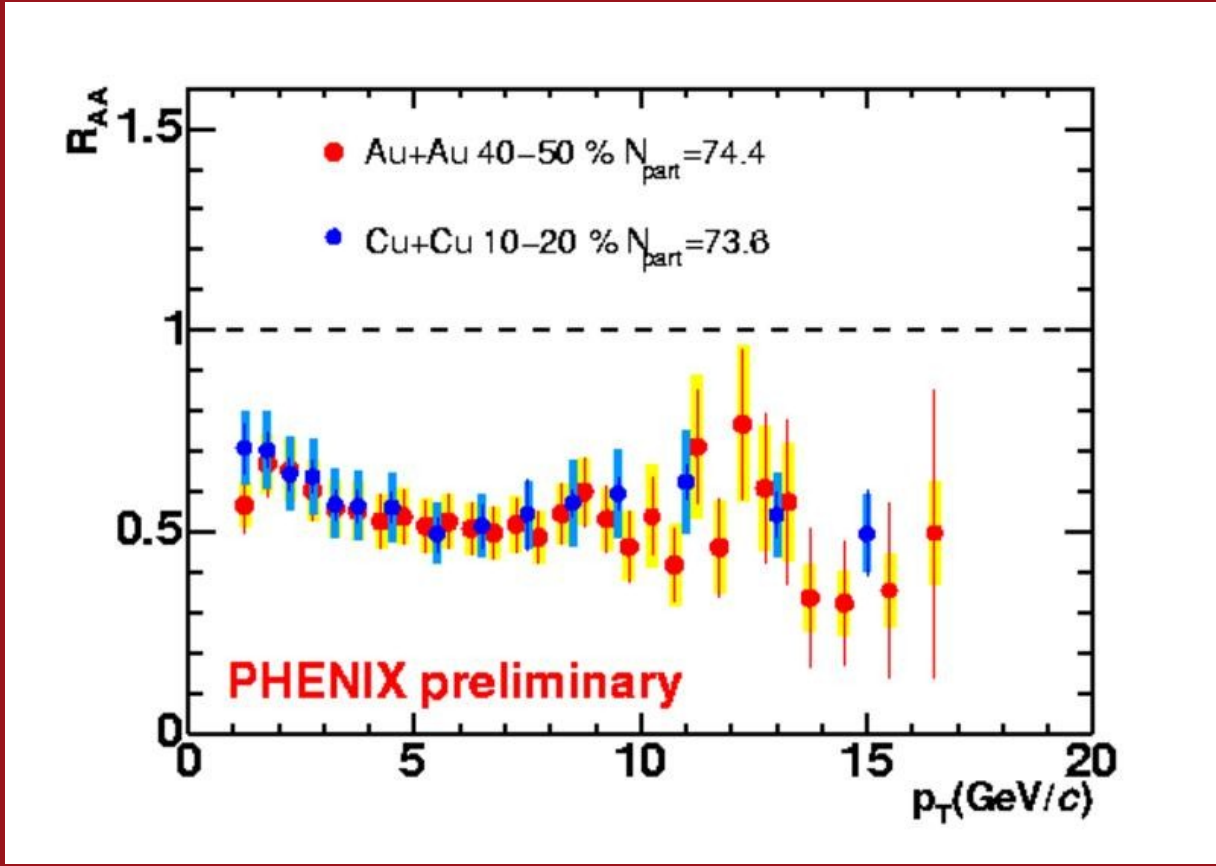
Au+Au vs. Cu+Cu



Au+Au vs. Cu+Cu



Suppression pattern identical at same N_{part}

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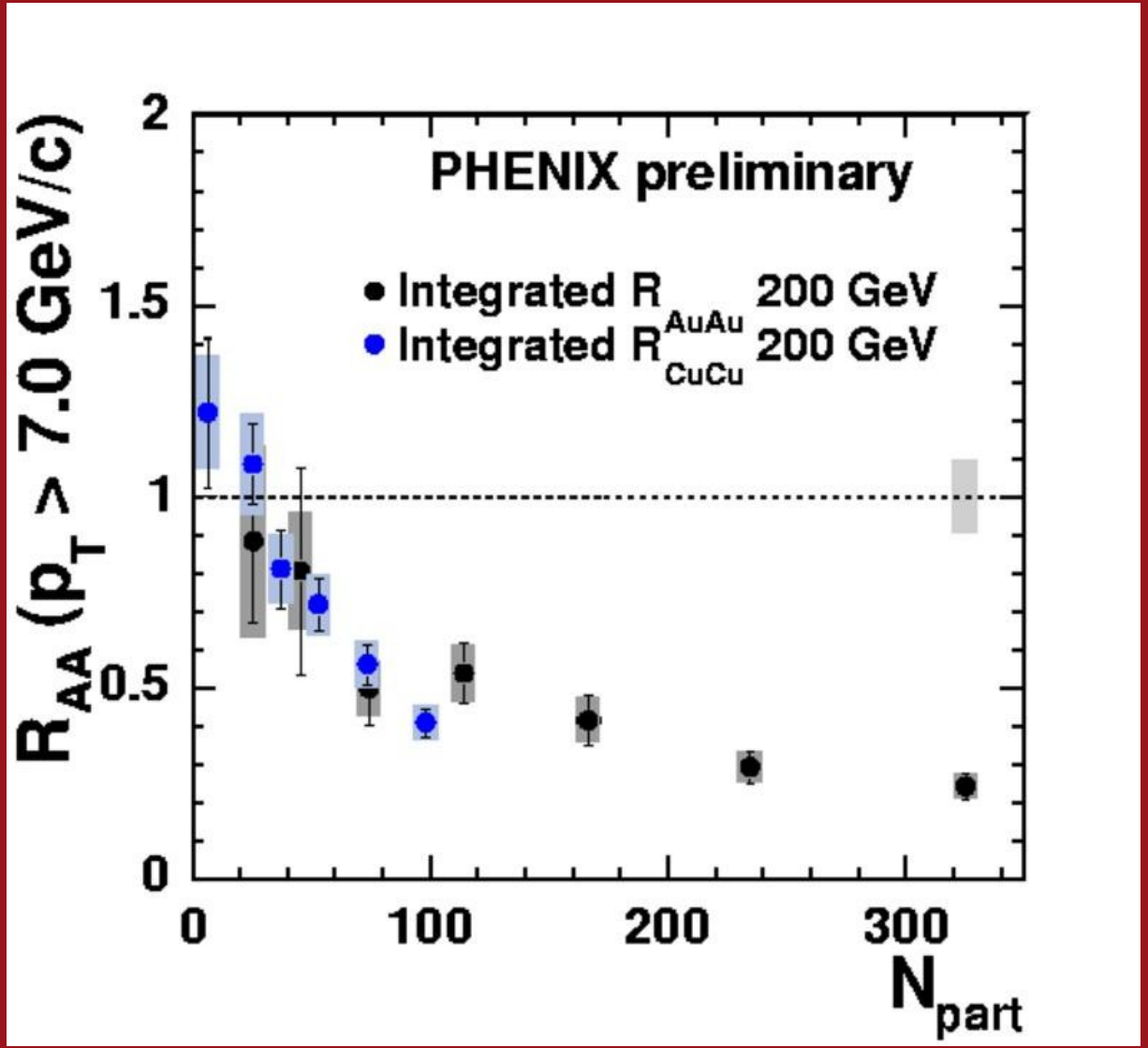
Centrality Dependence Integrated R_{AA}

- Similar N_{part} dependence
- Hints for different slope
  - Surface effects?



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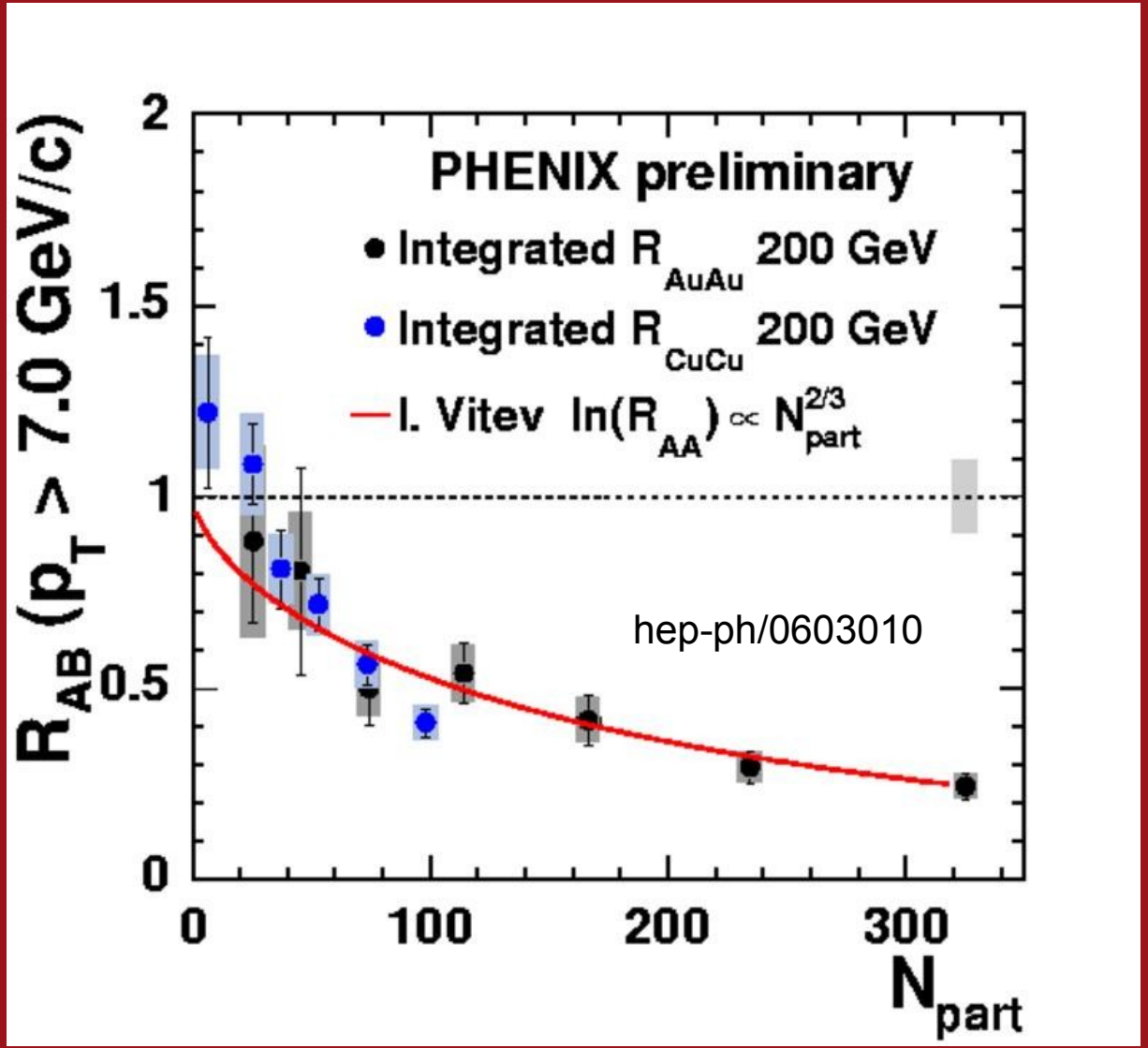
Centrality Dependence Integrated R_{AA}

- **Path length and density dependent**
  - Fixed to central Au+Au
  - No surface effects
- **Fair agreement but trend in Cu+Cu missed**



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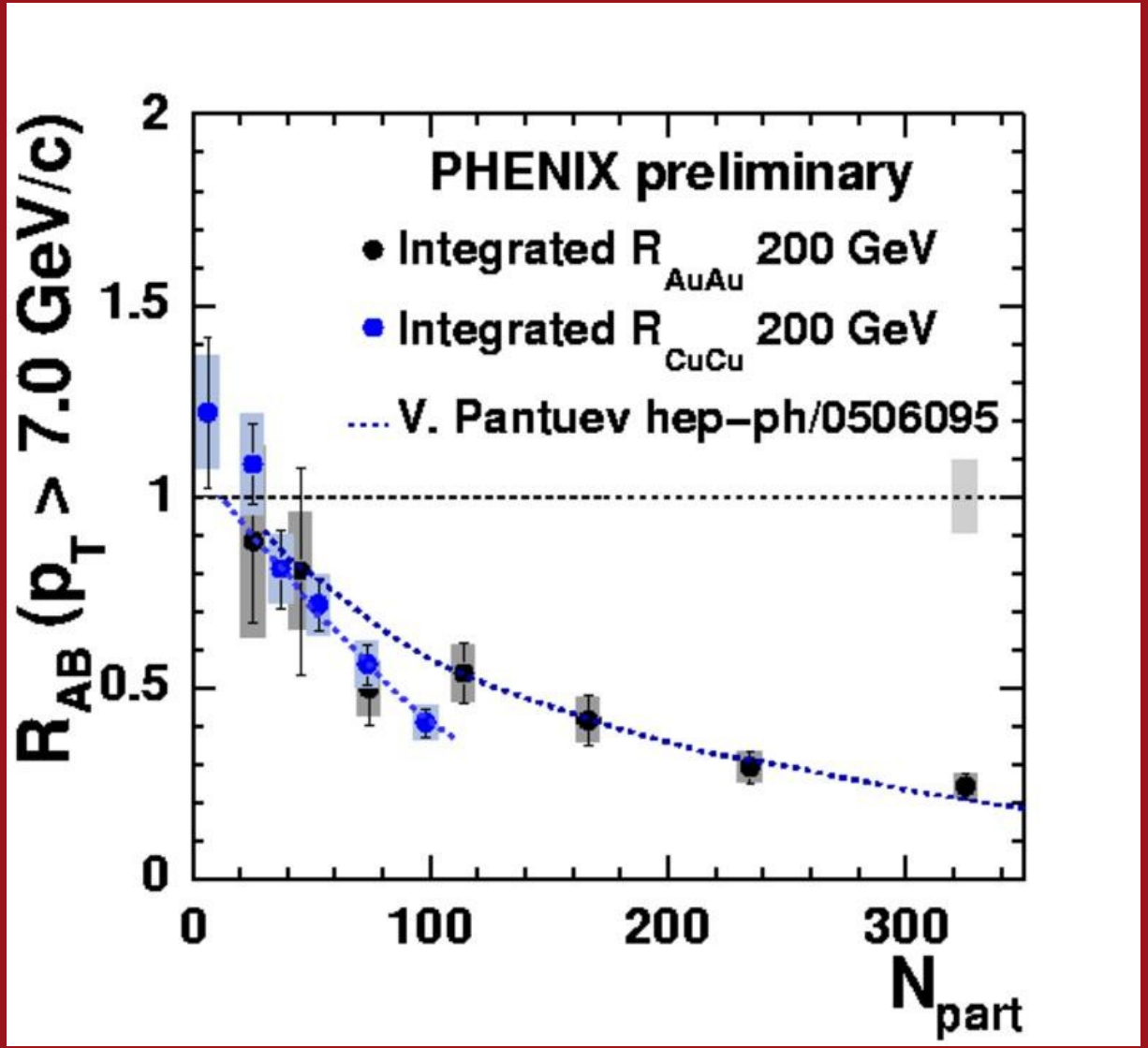
Centrality Dependence Integrated R_{AA}

- **Geometrical model with "corona" effect**
  - More jets from surface
  - Correlated with ellepticity
    - Minimal for sphere



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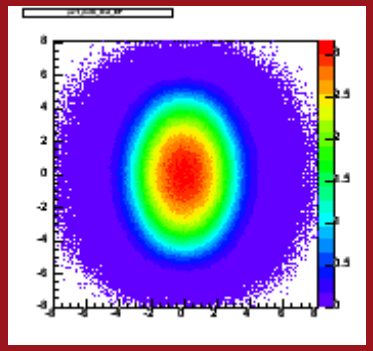
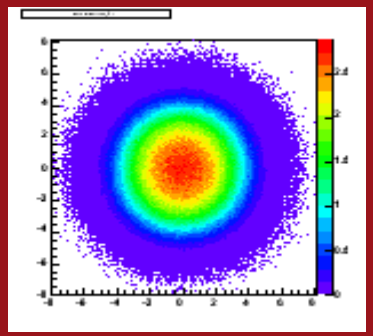
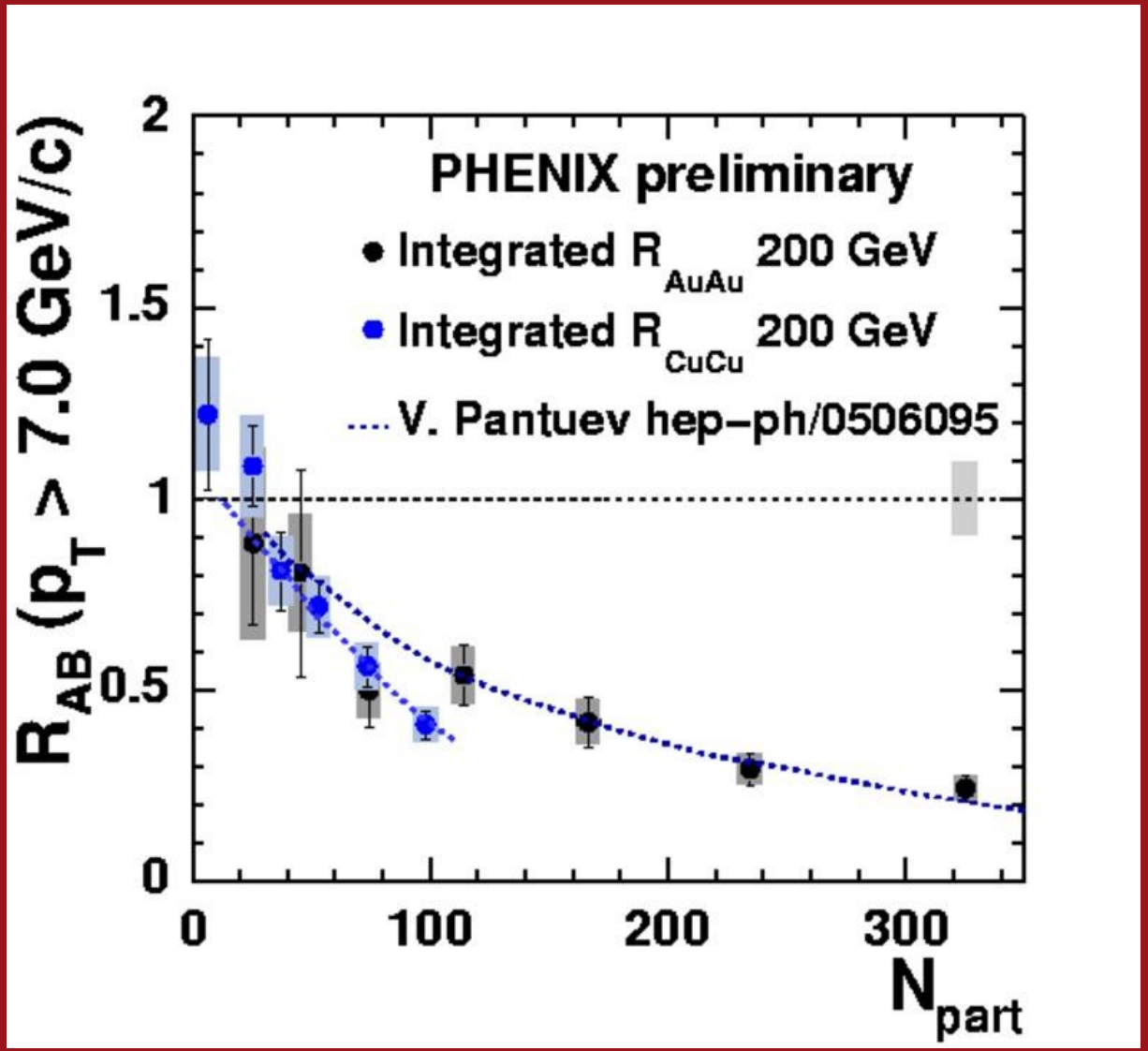


Au+Au
30-40%
N_{part} = 114



Cu+Cu
0-10%
N_{part} = 98.2



Energy Dependence...
Going down!

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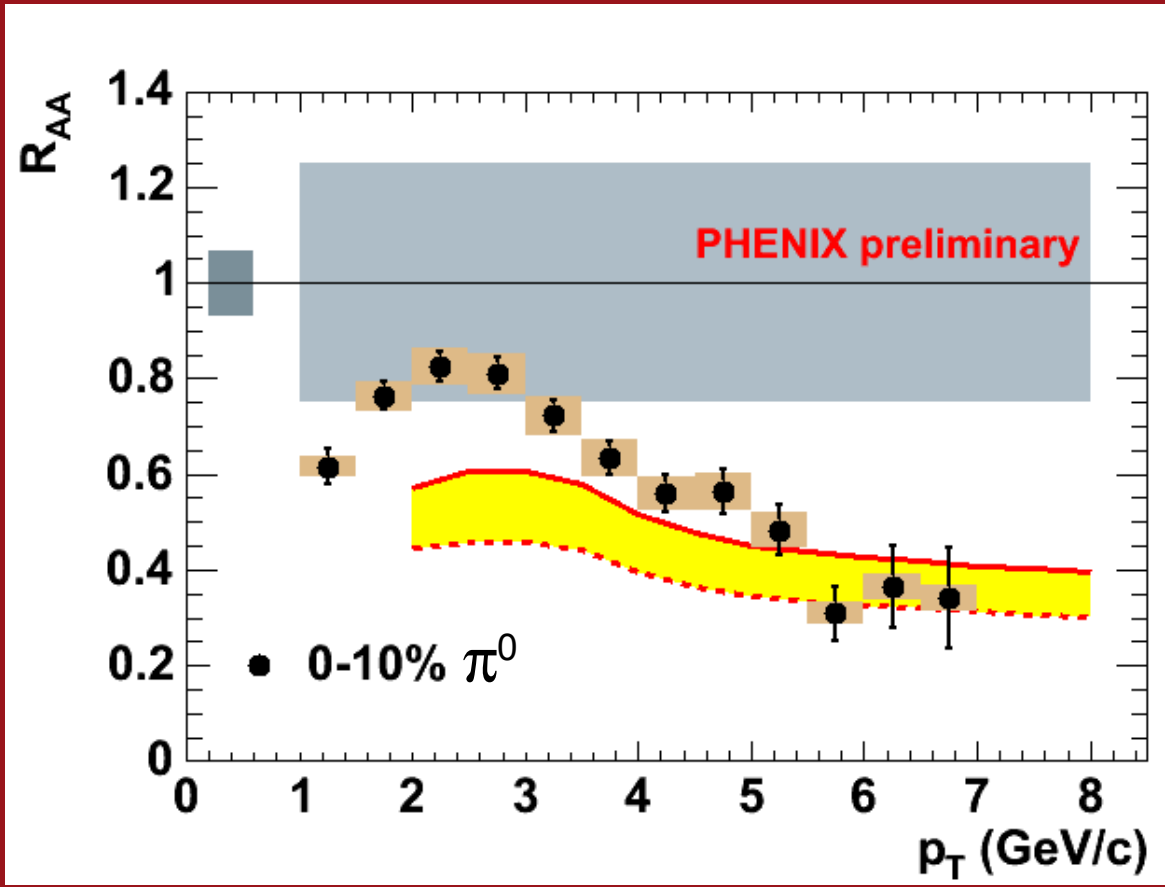
Au+Au @ 62.4 GeV

- **RHIC Run4**
  - 40M Events
- **π^0 production also suppressed**
  - Reasonable agreement with theory ($dN_g/dy \sim 650$-800)
    - Vitev: Phys. Lett. B **606** (2005) 303
  - N.B.: p+p reference not measured at RHIC, large uncertainties (shape)



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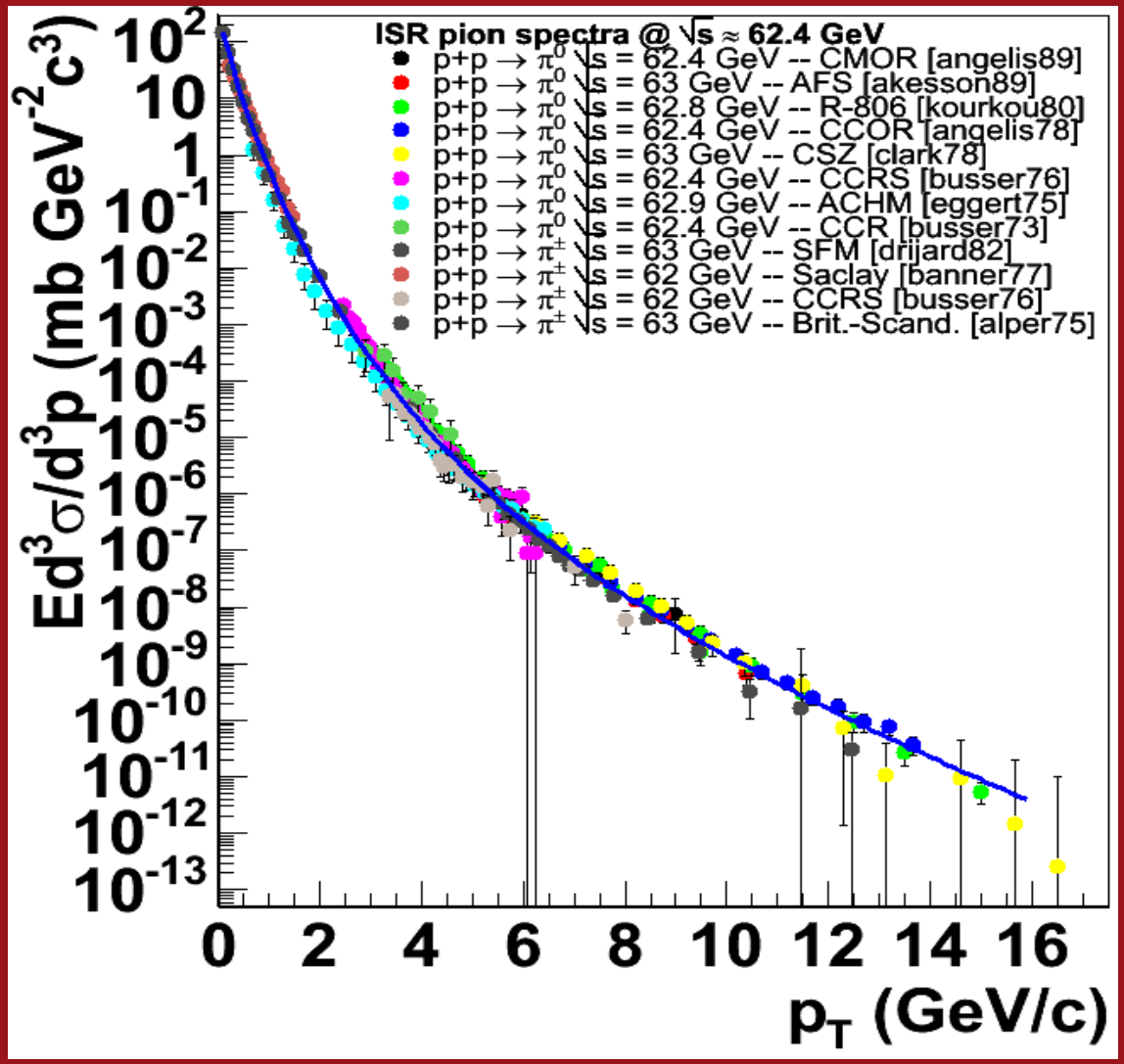
p+p Reference @ 62 GeV



J.Phys.G31:S491-S512,2005

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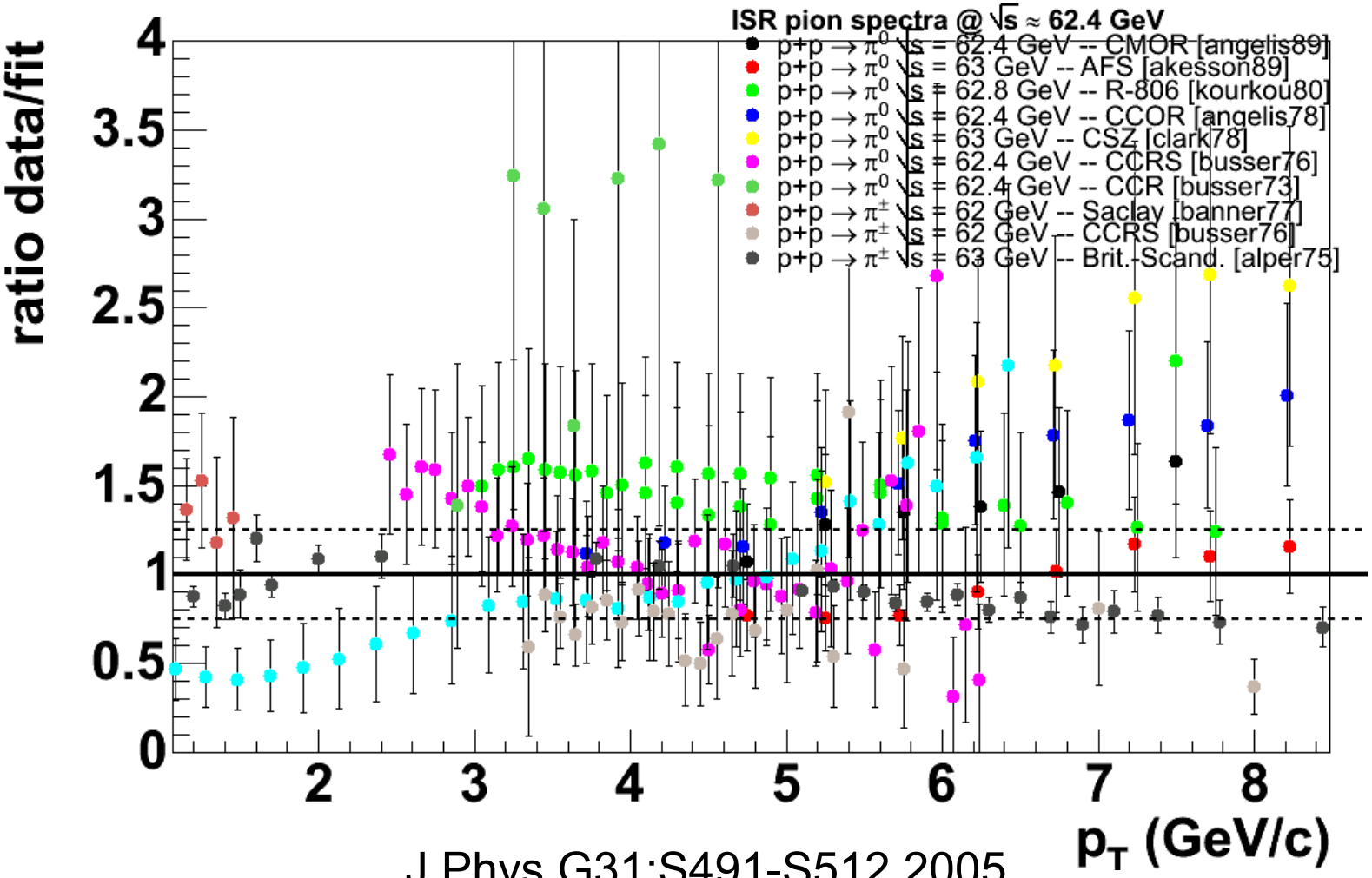
p+p Reference @ 62 GeV



J.Phys.G31:S491-S512,2005

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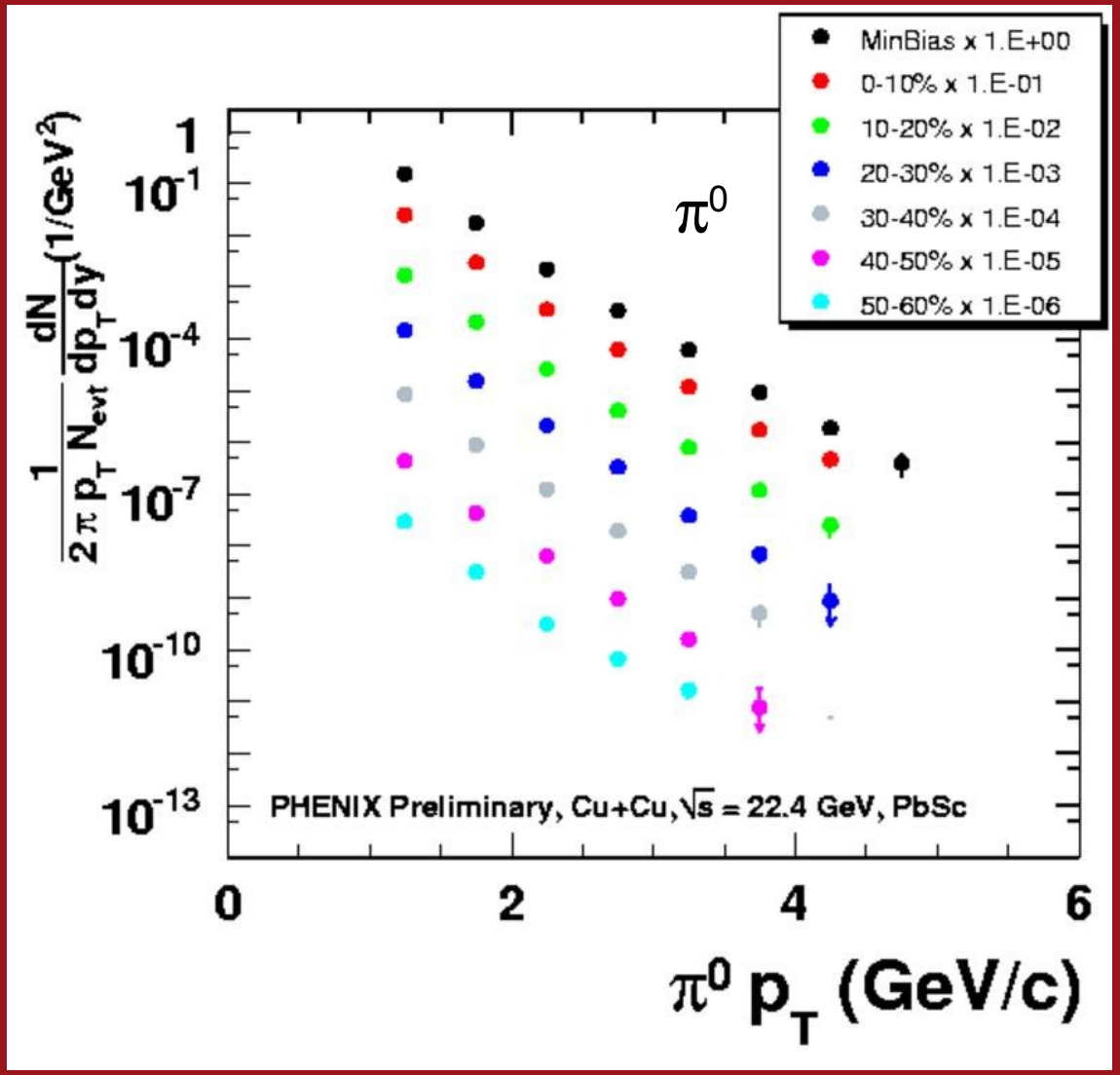
Cu+Cu @ 22.4 GeV (Premiere)

- **Go near SPS Energies**
  - p+p data at 21.7 – 23 GeV
  - Use of parameterization as reference
- **3 days of RHIC Run5**
  - 6.8M Events after quality cuts
  - Centrality via PC1 multiplicity



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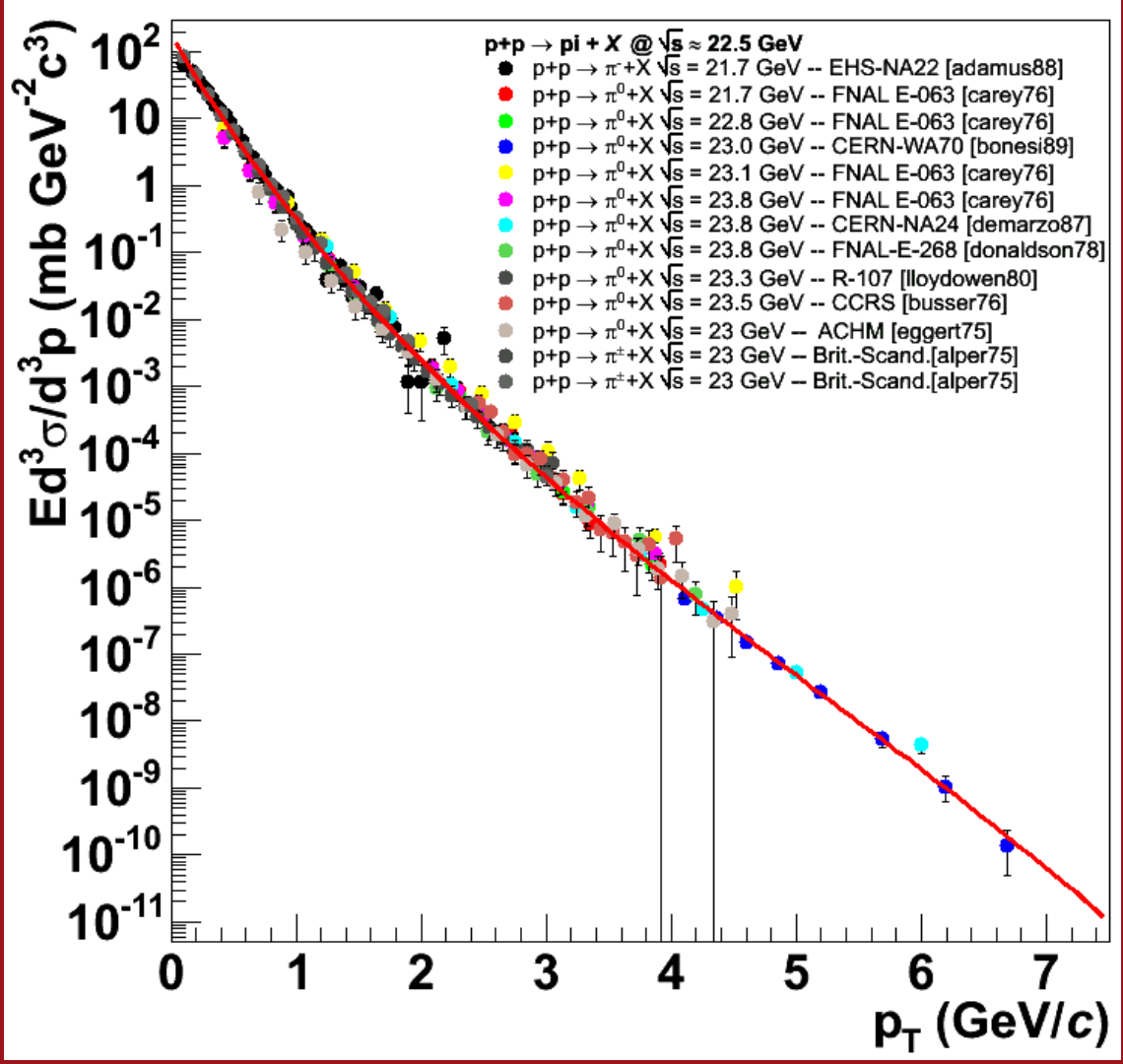
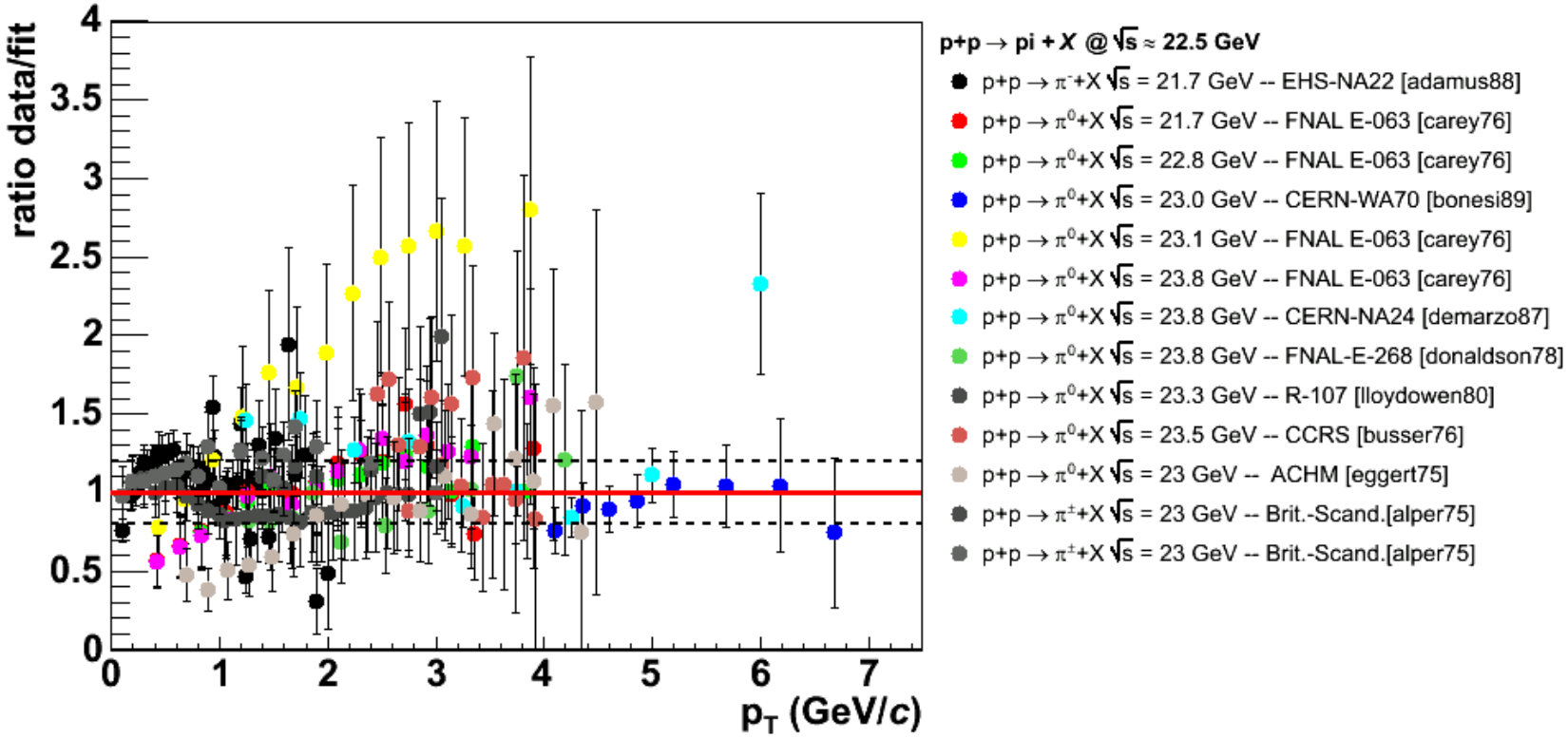
p+p Reference @ 22 GeV



p+p Reference @ 22 GeV



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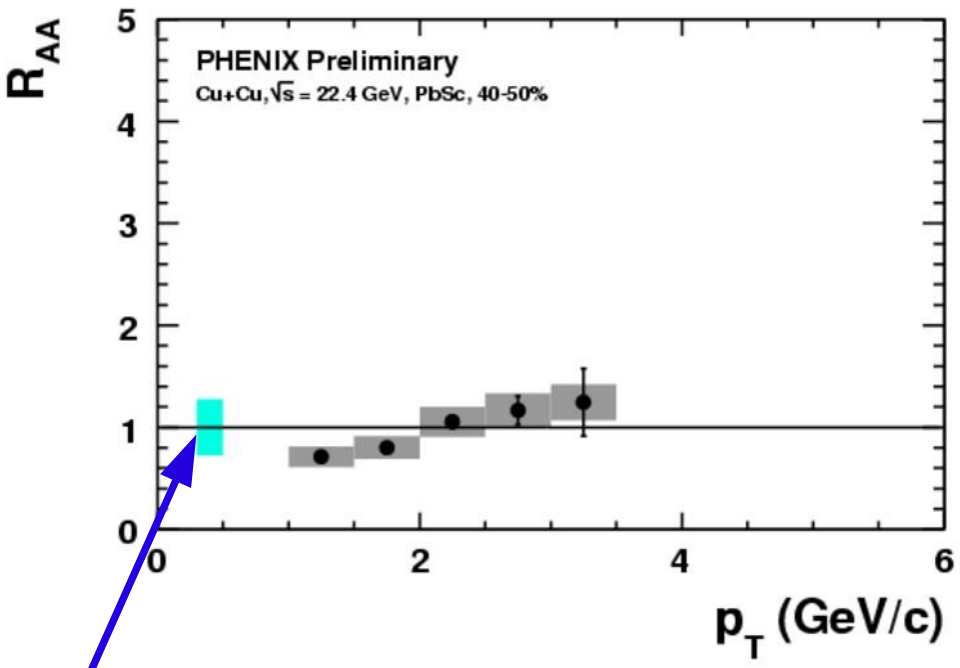
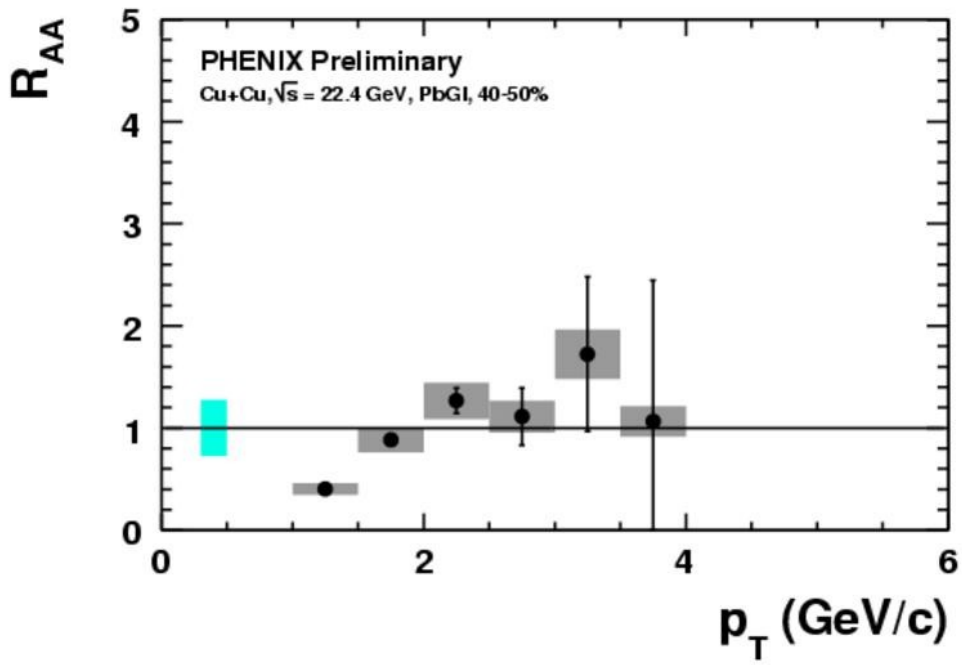
π^0 R_{AA} 40-50%

PbSc



PbGl



$N_{coll} = 22.9 \pm 4.4$ $N_{part} = 23.1 \pm 3.3$

Uncertainty in N_{coll} and p+p param. (20%)

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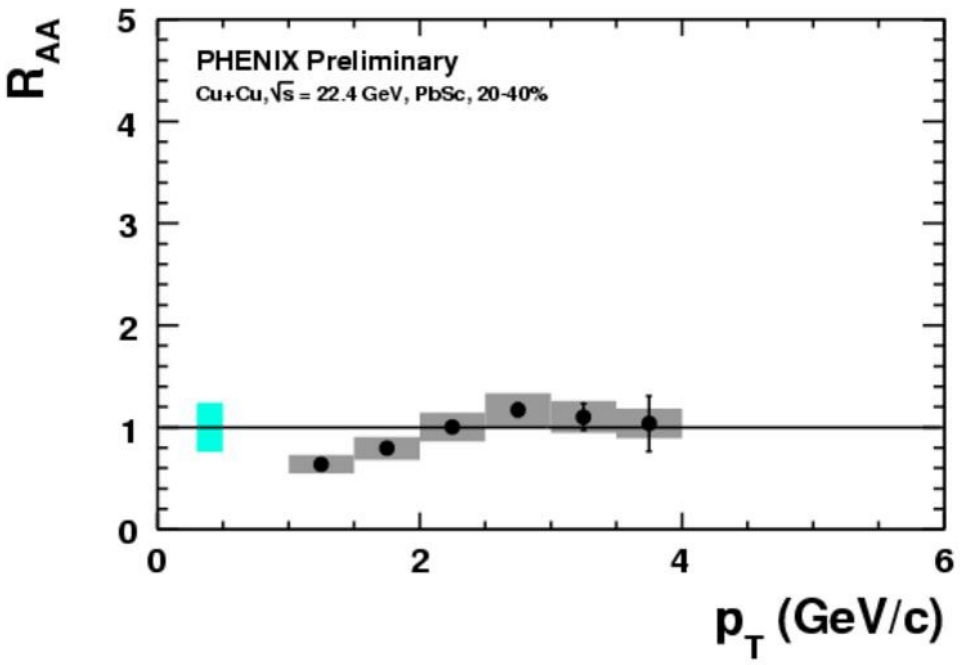
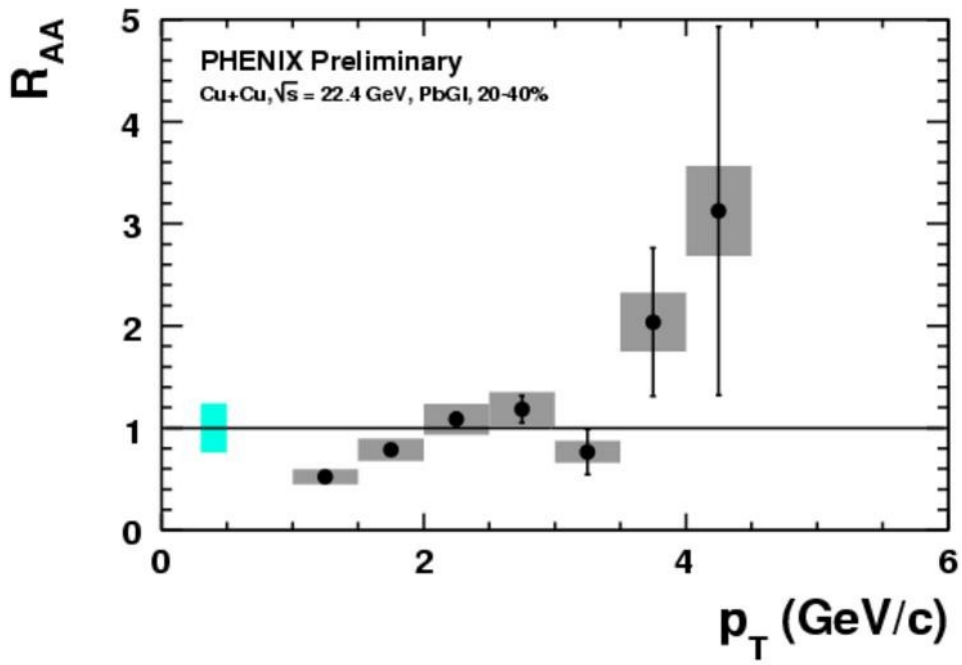
π^0 R_{AA} 20-40%

PbSc



PbGl



$N_{coll} = 48.4 \pm 6.5$ $N_{part} = 41 \pm 3.6$

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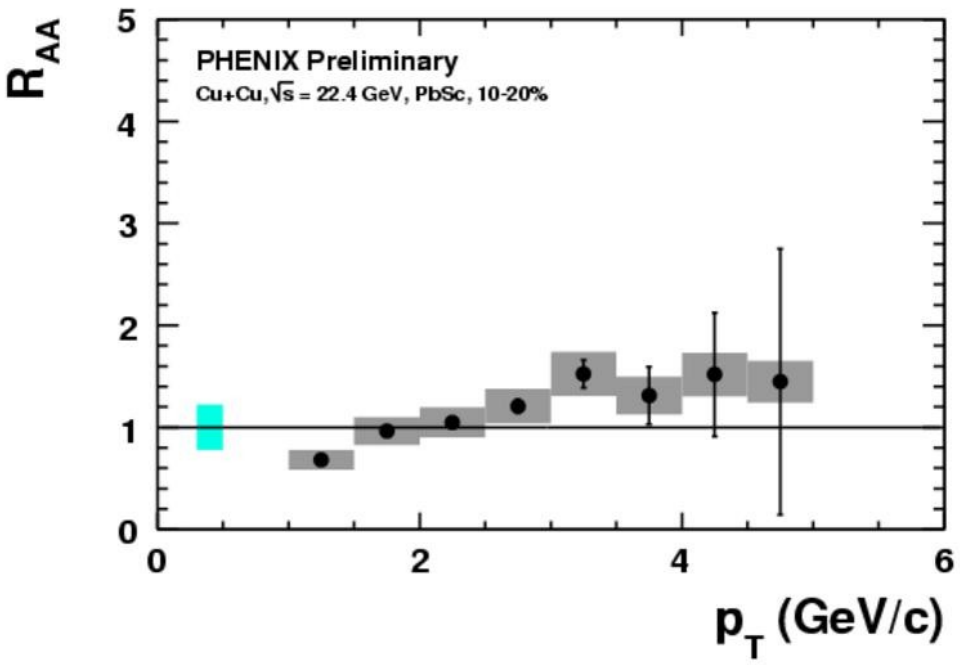
π^0 R_{AA} 10-20%

PbSc



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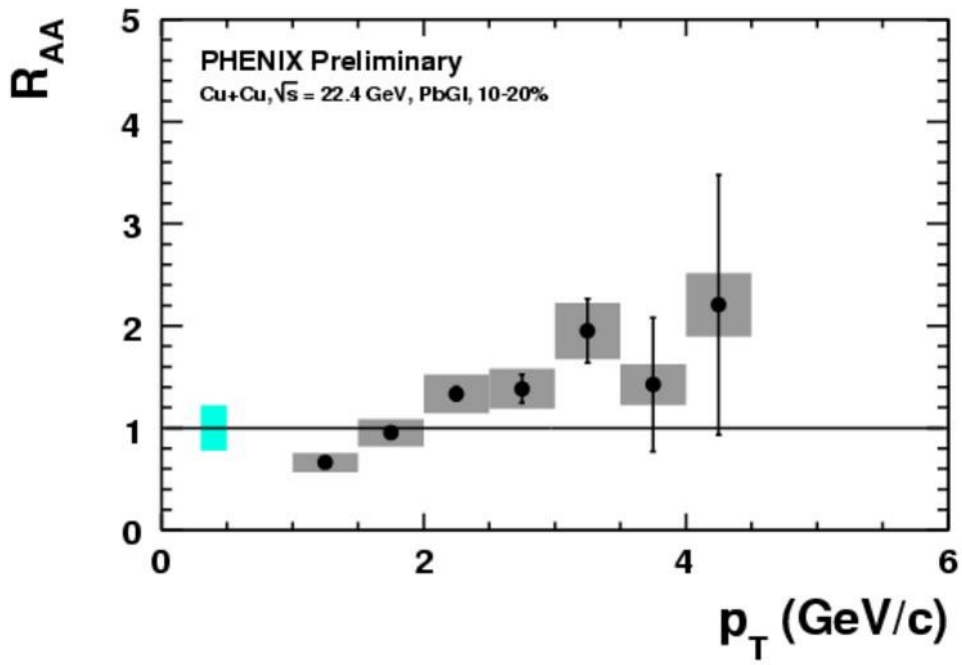

$N_{coll} = 93.6 \pm 9.4$ $N_{part} = 67.8 \pm 3.1$

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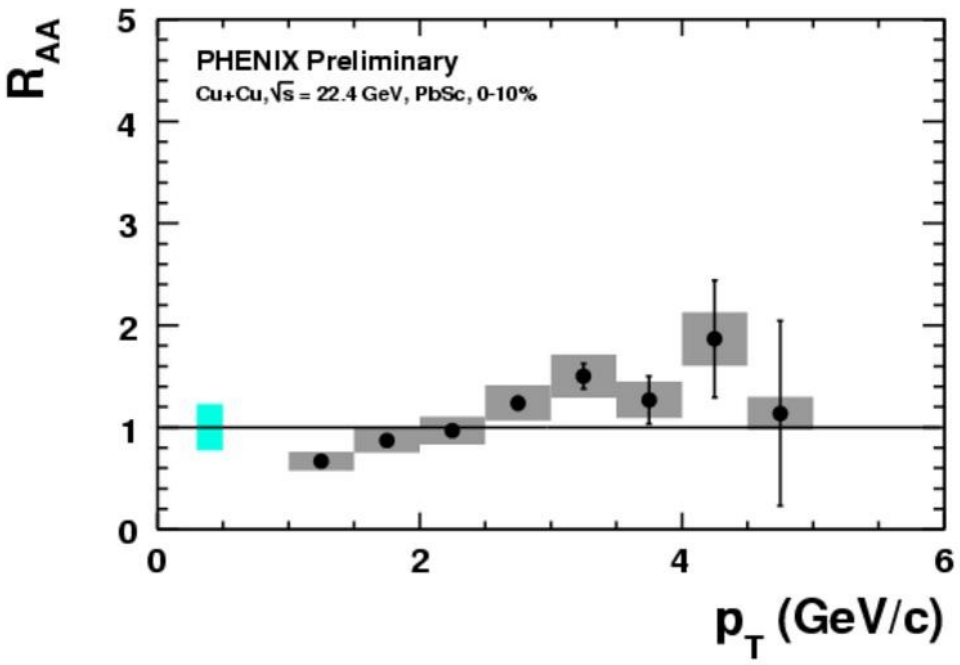
π^0 R_{AA} 0-10%

PbSc



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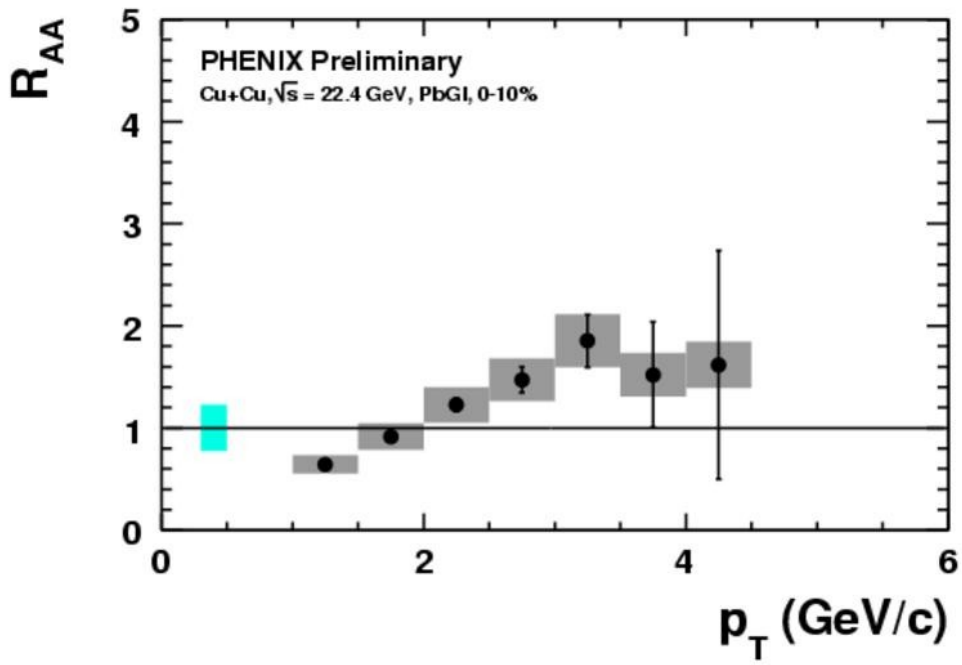

$N_{coll} = 140.7 \pm 14.8$ $N_{part} = 92.2 \pm 2.2$

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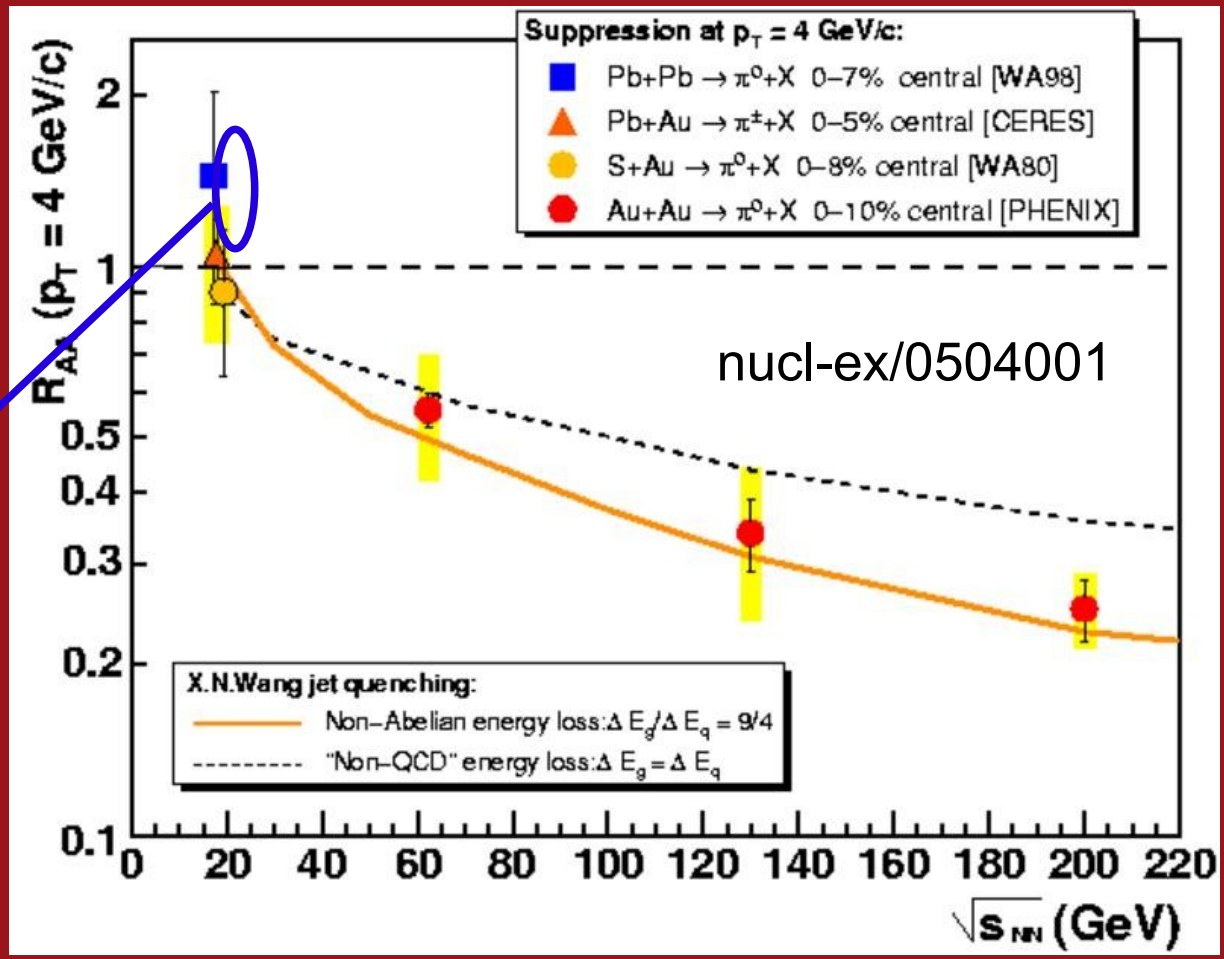
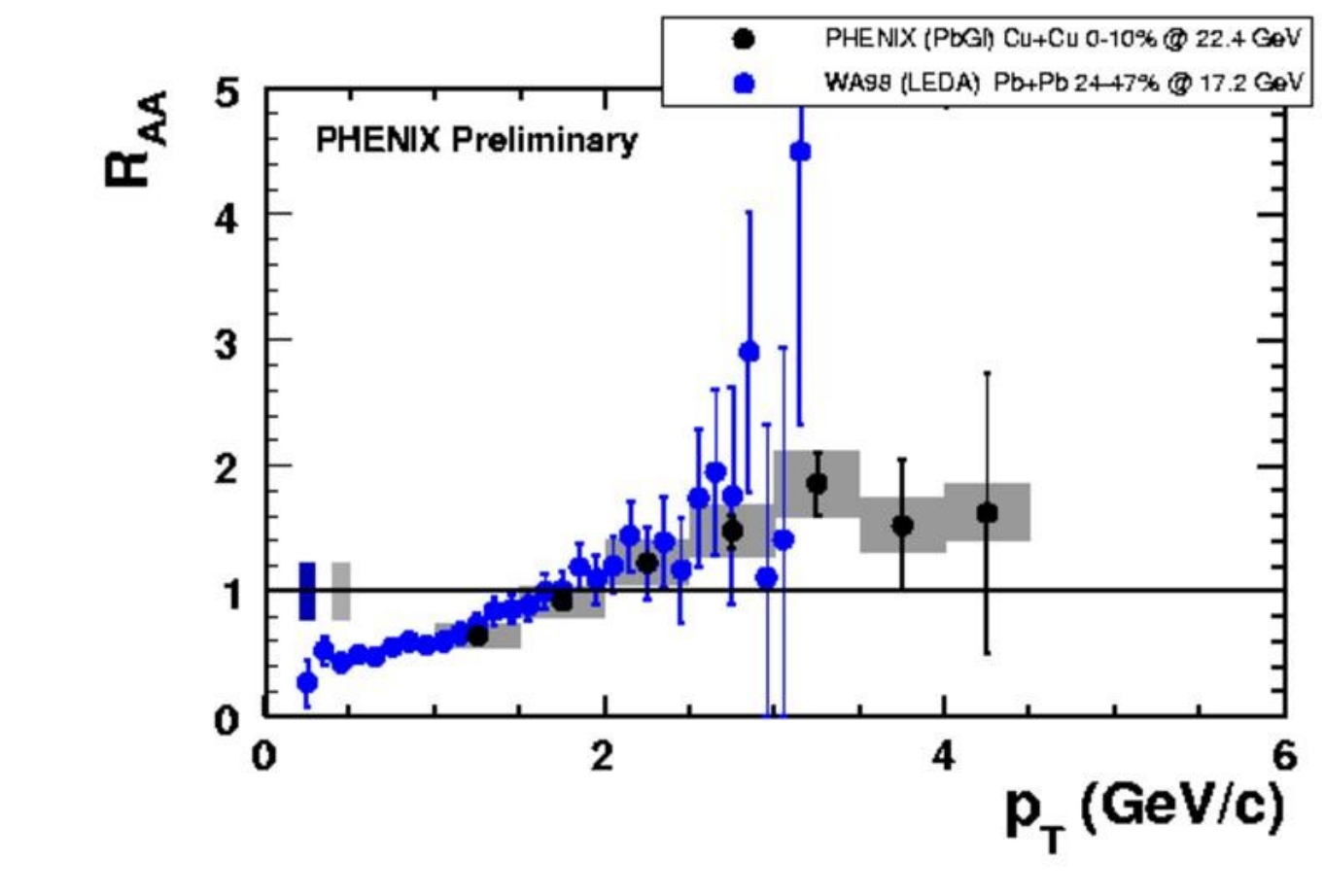
Excitation Function

Cu+Cu @ 22.4 GeV
consistent with SPS
(NB: different system size)



PHENIX/RHIC does SPS Physics

WA98 vs. PHENIX



Similar N_{part} (WA98 : 132, PHENIX: 140)
same behaviour

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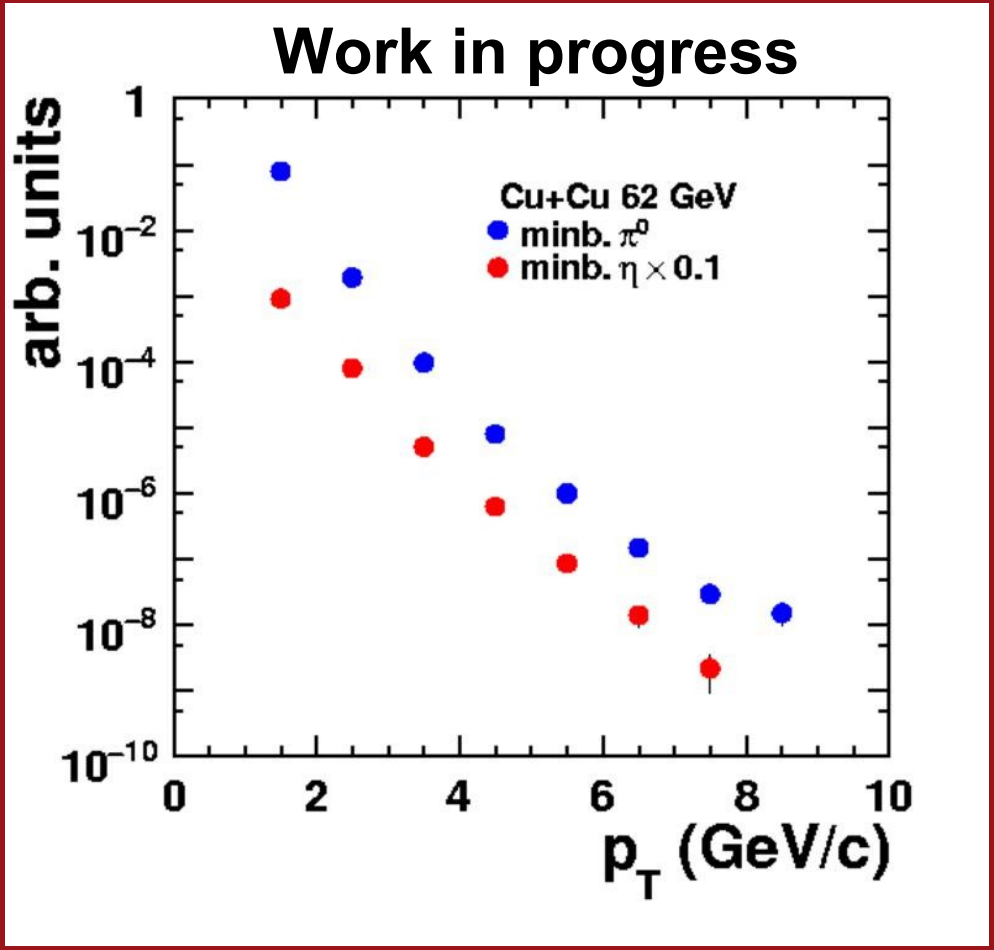
What's next?

- **Cu+Cu @ 200 GeV**
  - η
- **Cu+Cu @ 62.4 GeV**
  - η and π^0
- **p+p @ 62.4 GeV**
  - Current RHIC run
  - Essential baseline
- **p+p @ 22.4 GeV**
  - Hopefully this RHIC Run?



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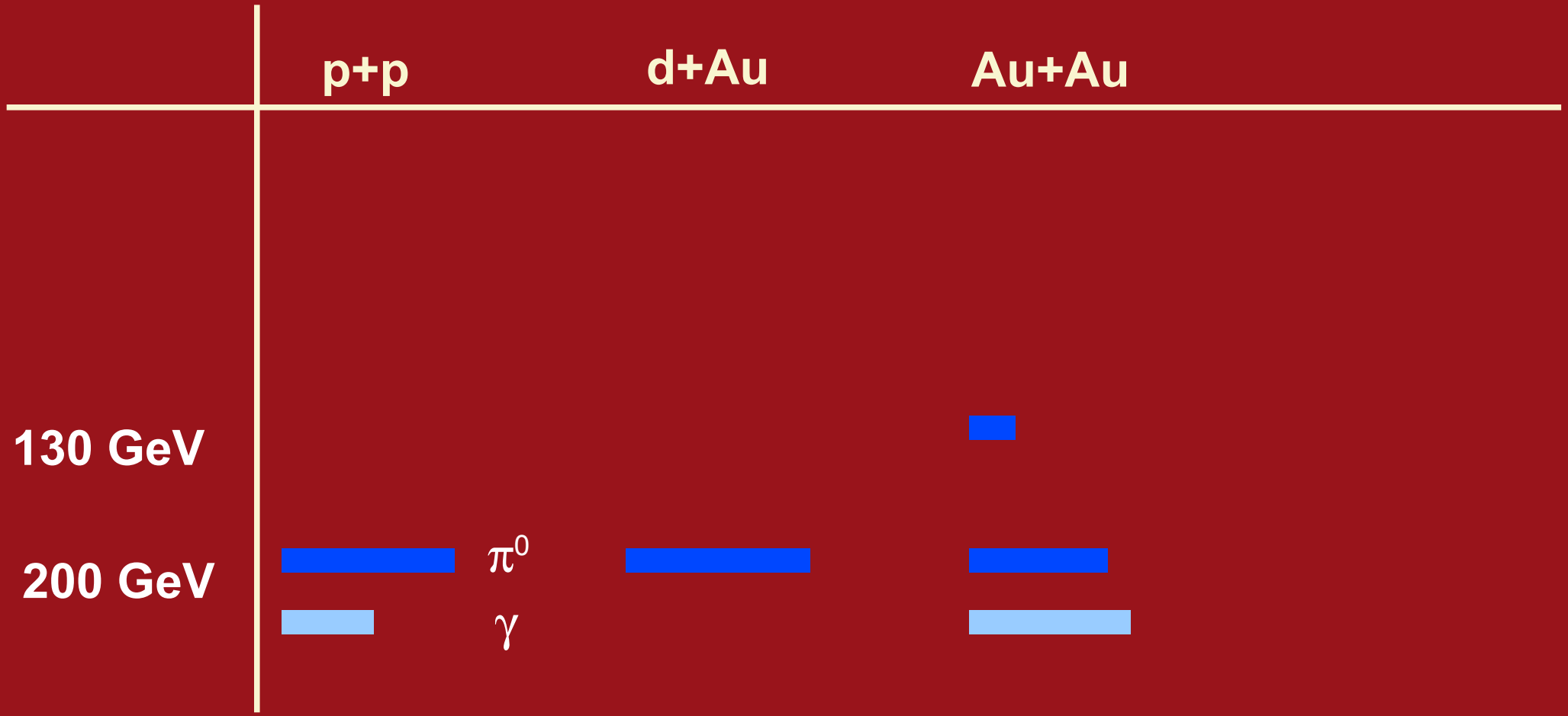
Single Particle Spectra @ High p_T
The First Three Years



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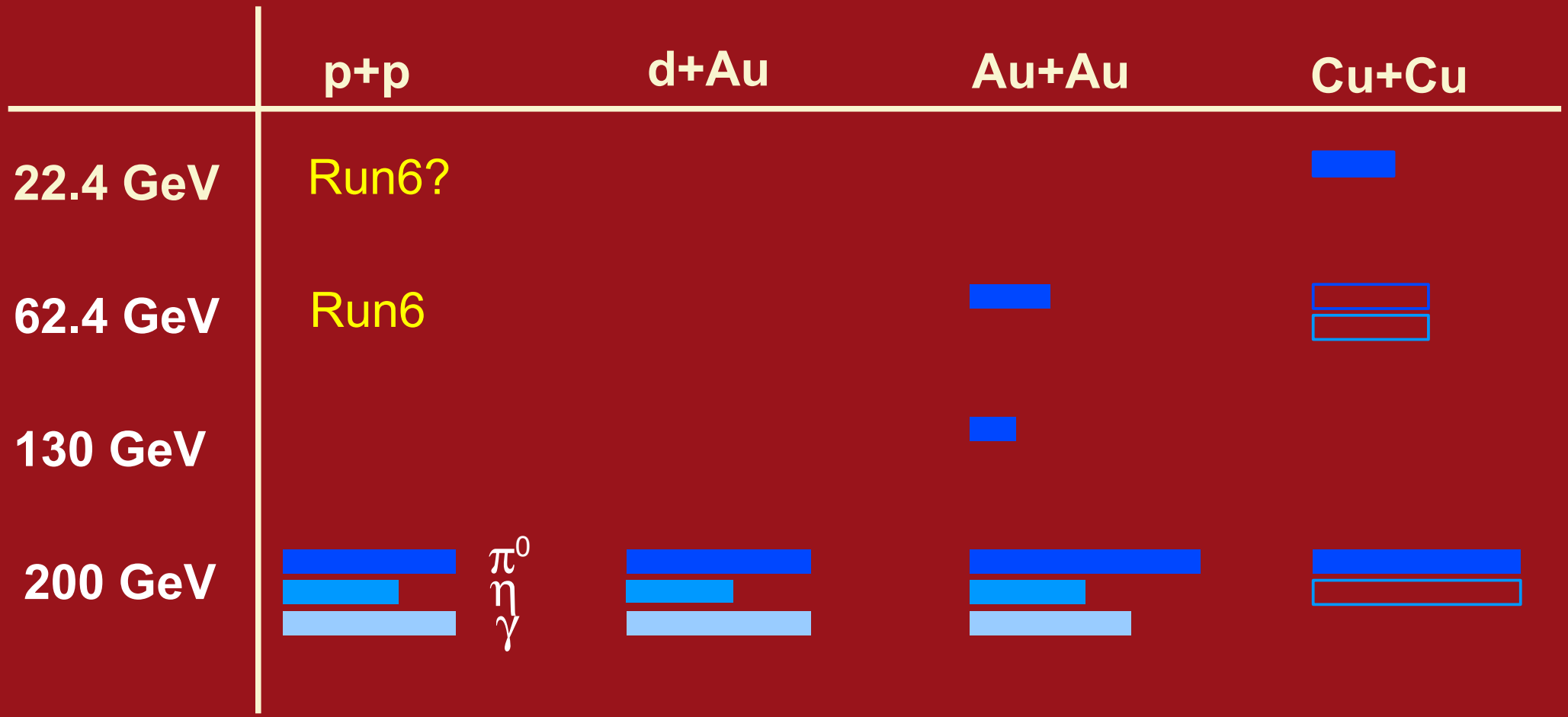
Single Particle Spectra @ High p_T Today



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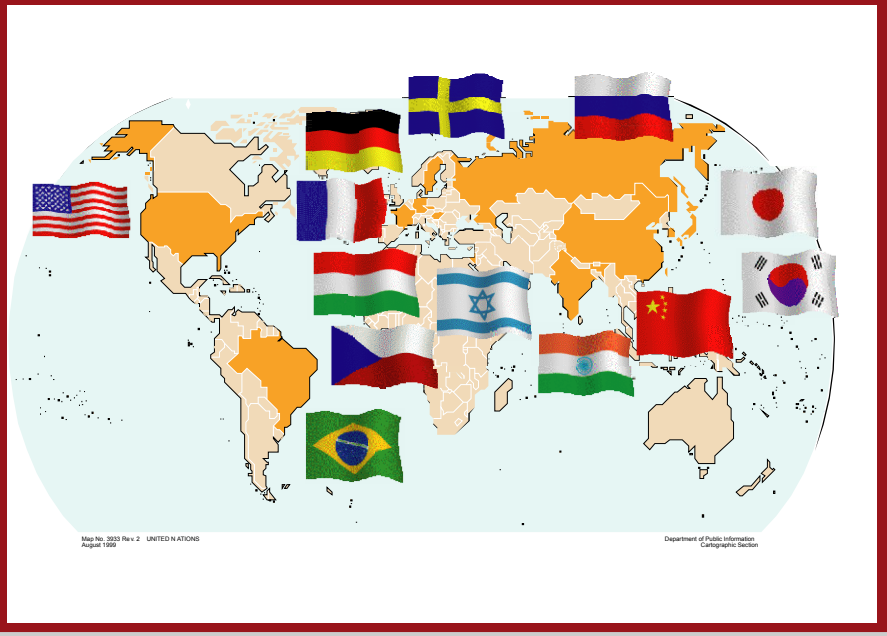
Summary

- **Particle suppression in Au+Au**
  - π^0 R_{AA} flat up to p_T = 20 GeV/c
  - η and π^0 show same suppression pattern
- **System Size Dependence**
  - Similar R_{AA} for Cu+Cu and Au+Au for similar N_{part}
  - Hints for surface/corona effects
- **$\sqrt{s_{NN}}$ dependence**
  - Follows expectation from energy-loss models
  - RHIC/PHENIX able to do SPS Physics
  - First systematic study of jet quenching from $\sqrt{s_{NN}}$ ~ 20 – 200 GeV within the same experiment

PHENIX



Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
Czech	Charles University, Prague
Republic	Czech Technical University, Prague
	Institute of Physics, Academy of Sciences of the Czech, Prague
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

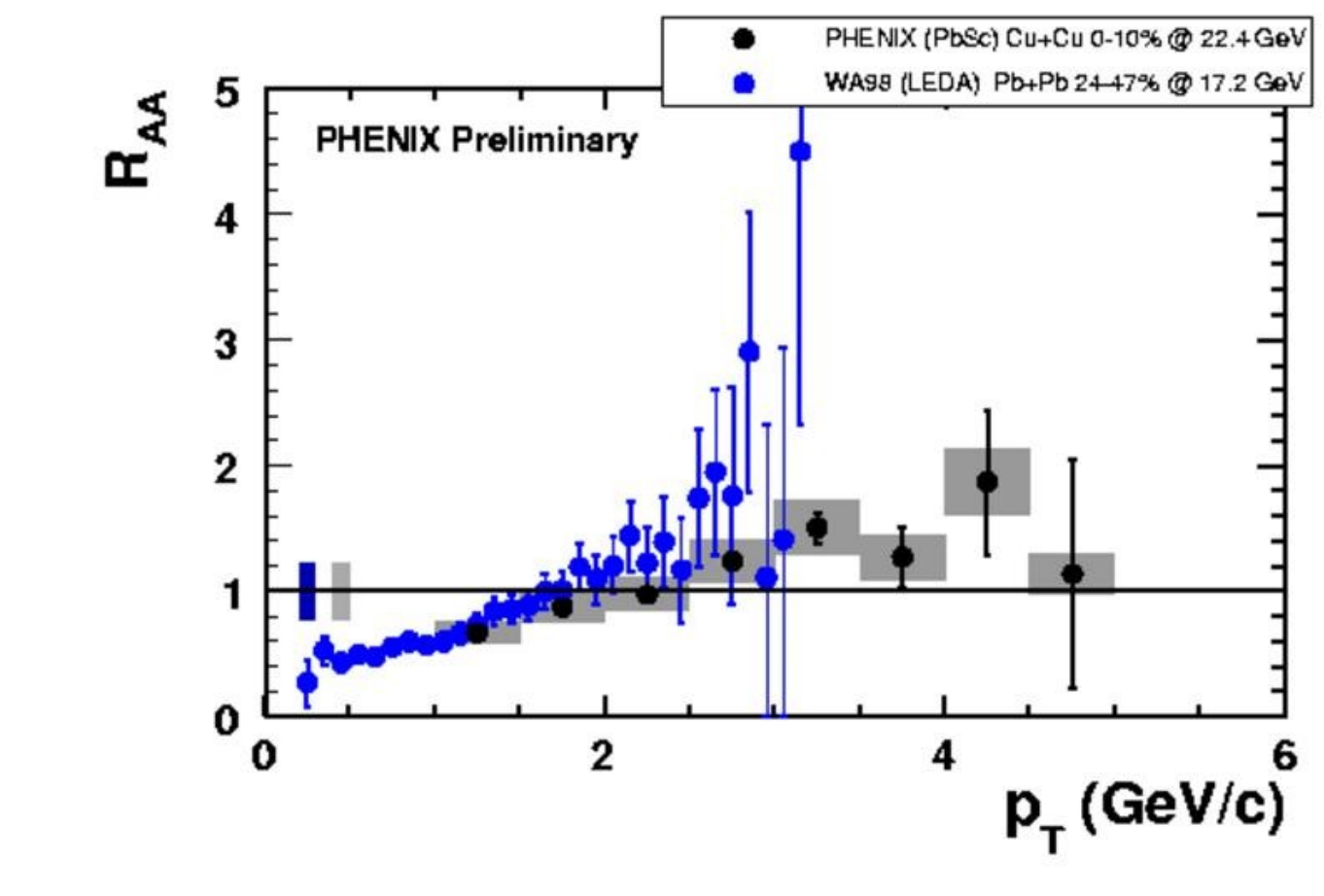
13 Countries; 62 Institutions; 550 Participants*

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

*as of March 2005

Backup Slides

WA98 vs. PHENIX



Similar N_{part} (WA98: 132, PHENIX: 140)
same behaviour!!

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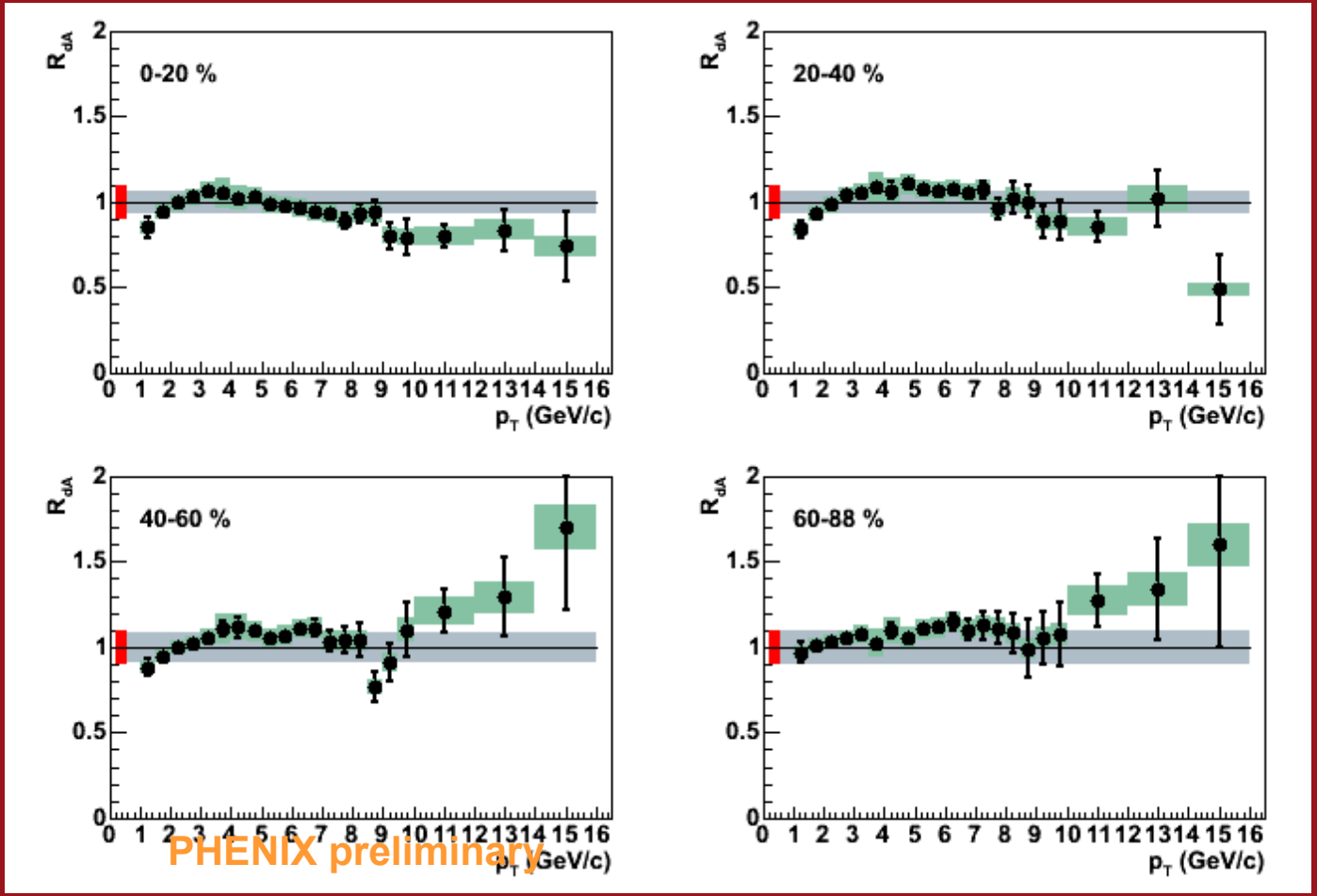
π^0s in d+Au



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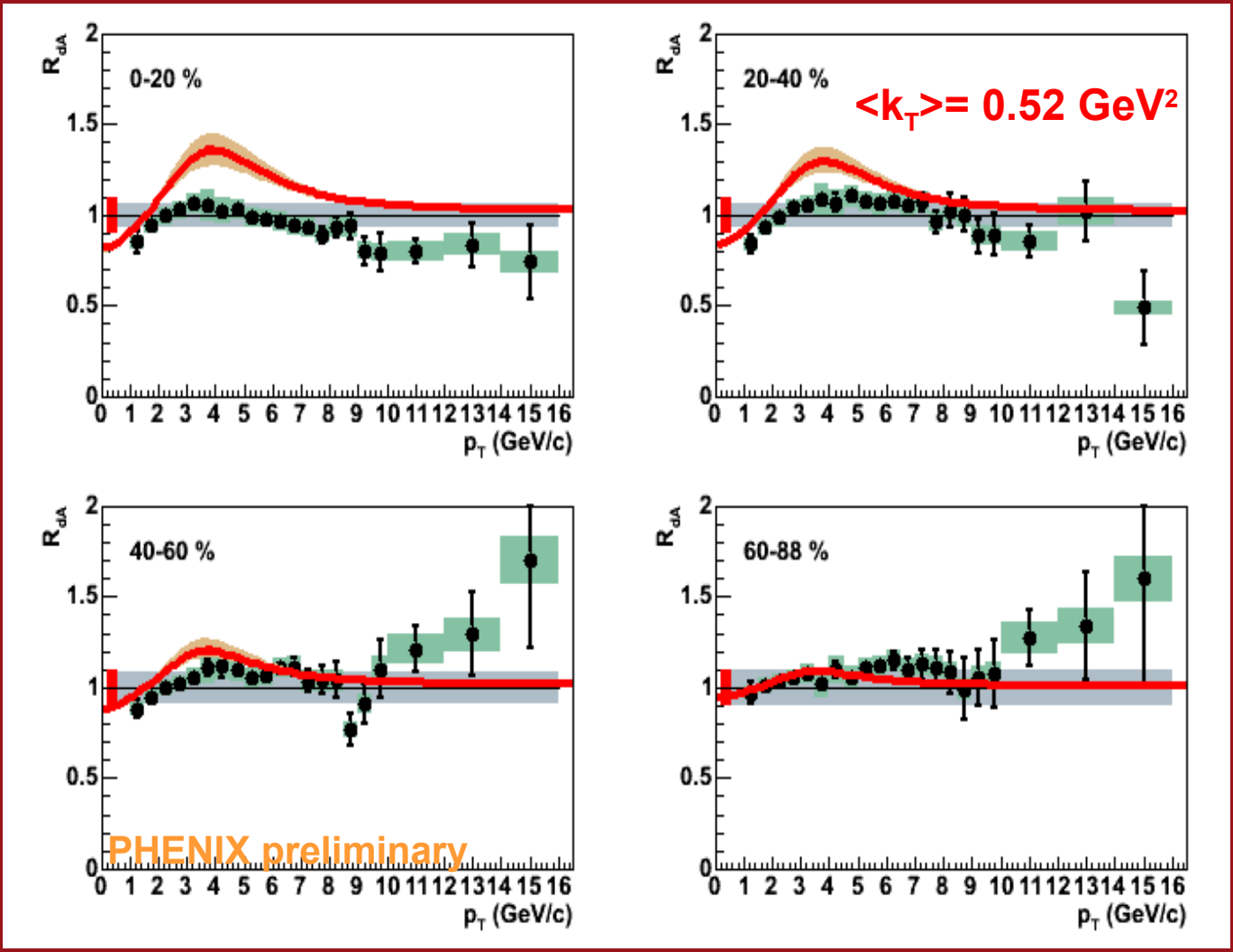
π^0s in d+Au



Accardi, Gyulassy. Partonic Glauber-Eikonal approach: sequential multiple partonic collisions. Phys. Lett. B **586** (2004) 244. Centrality dependence not very well reproduced

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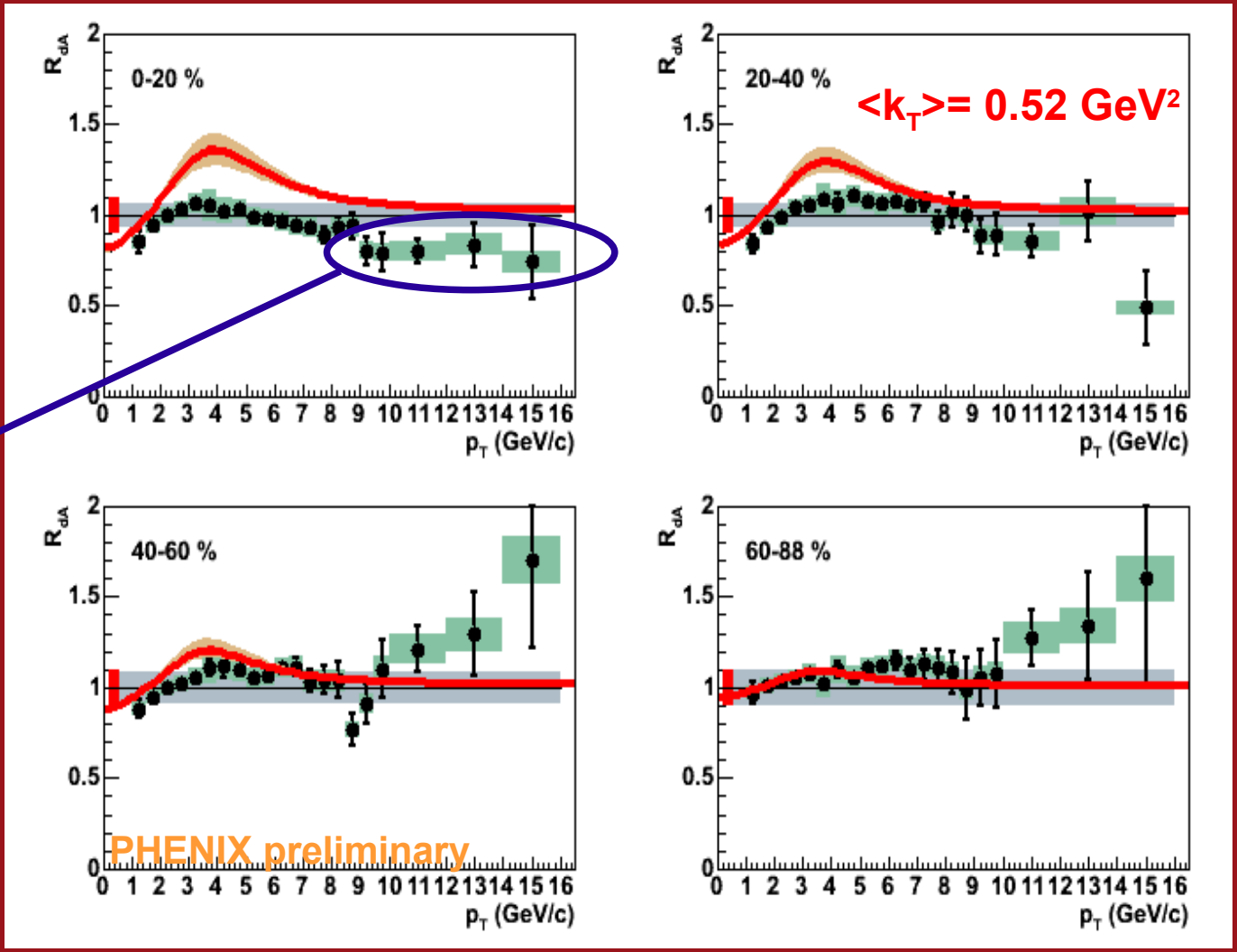
π^0s in d+Au



$R_{dA} \approx 0.7$!?

Kharzeev, Kovchegov, Tuchin, Phys. Rev. D **68,** 094013 (2003):
Saturation scale can influence particle Production even for $Q_s < k_T$ ...

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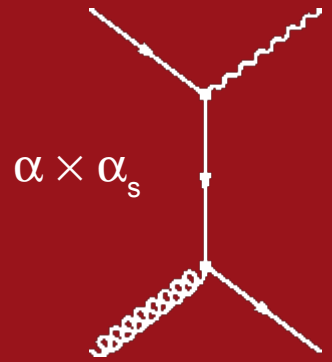
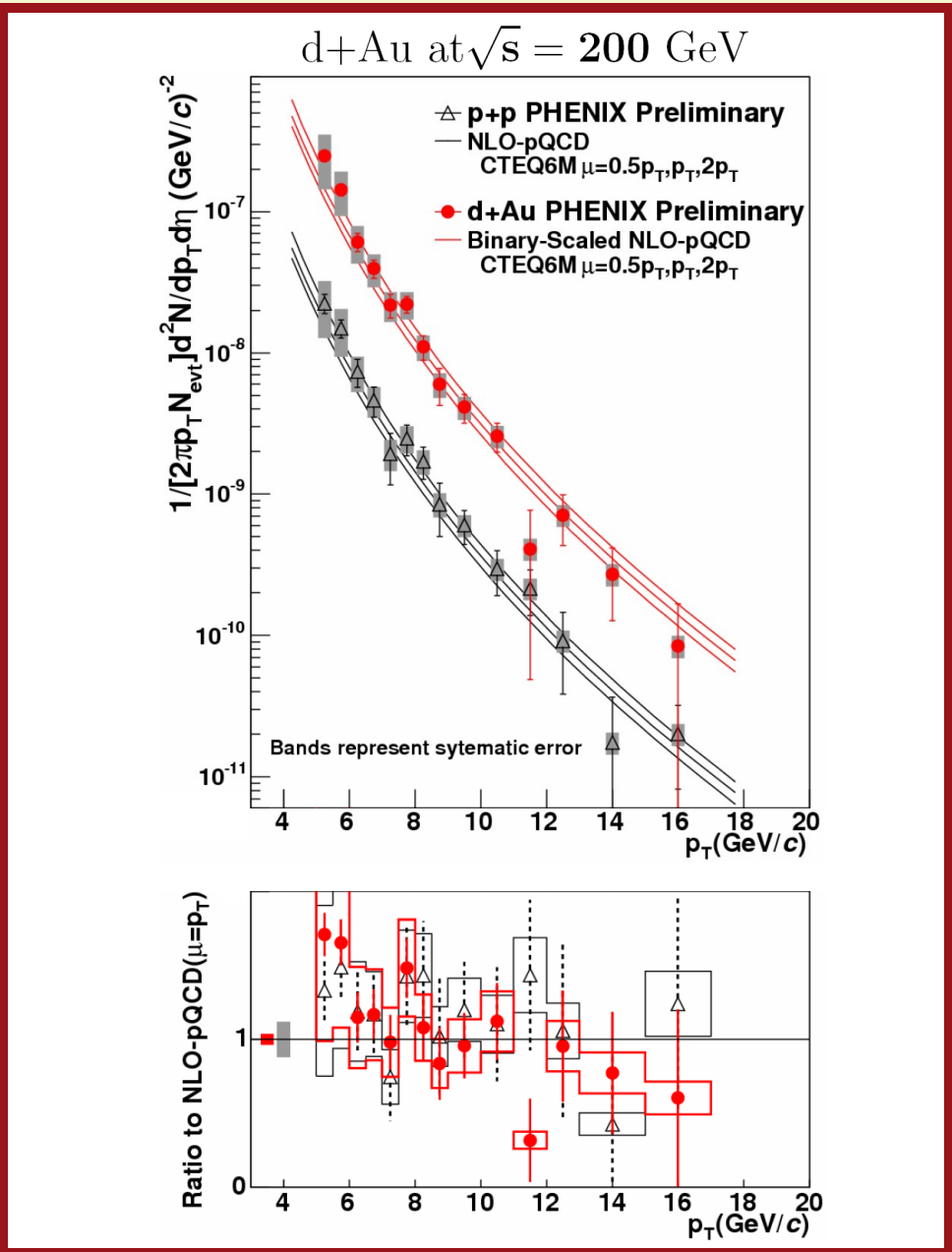
Direct Photons in d+Au

- **Directly sensitive to gluon distribution**



- **No effect at high p_T**
  - Large uncertainties



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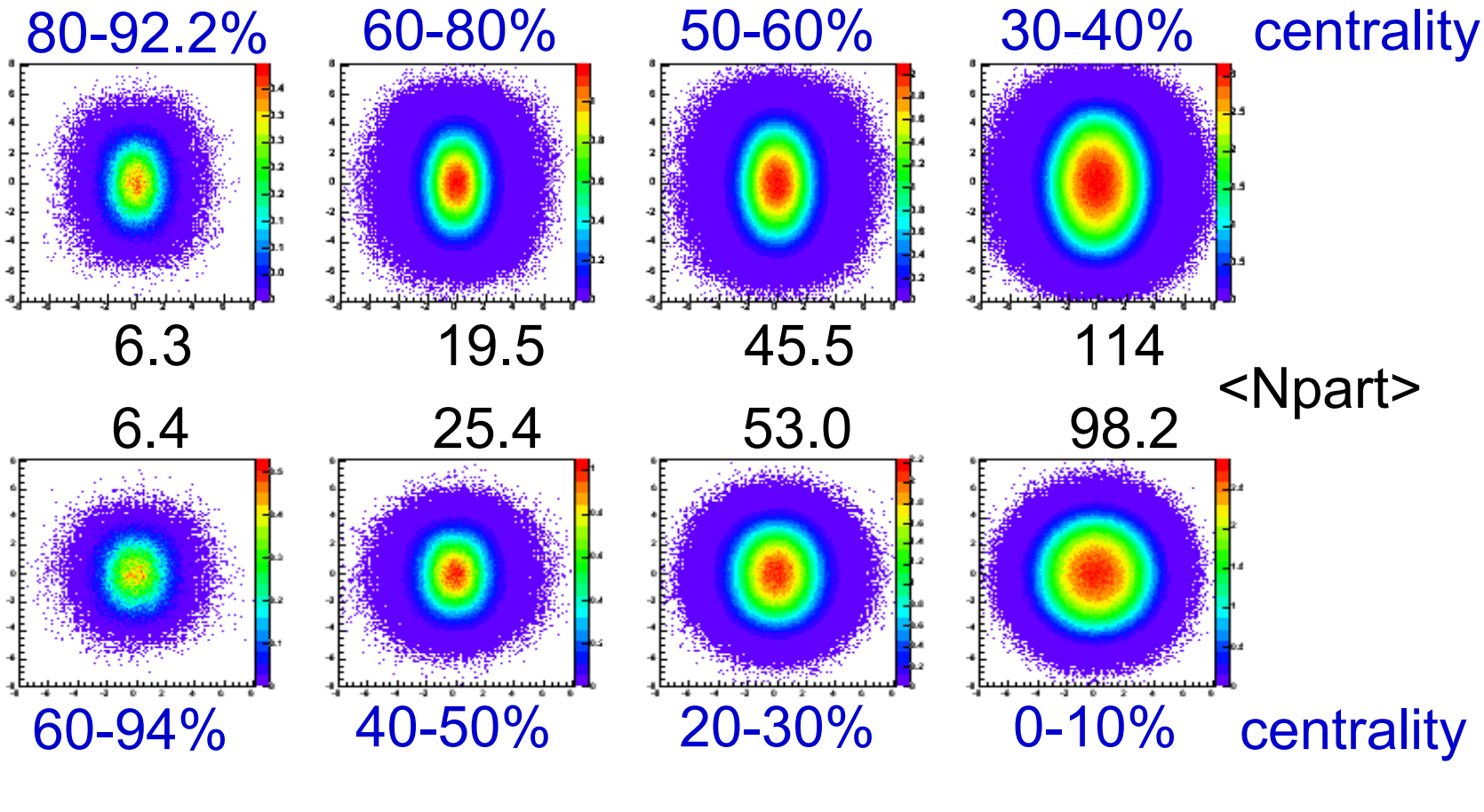
$N_{part}(x,y)$

Transverse N_{part} density for similar $\langle N_{part} \rangle$ in Au+Au and Cu+Cu



ellipticity different

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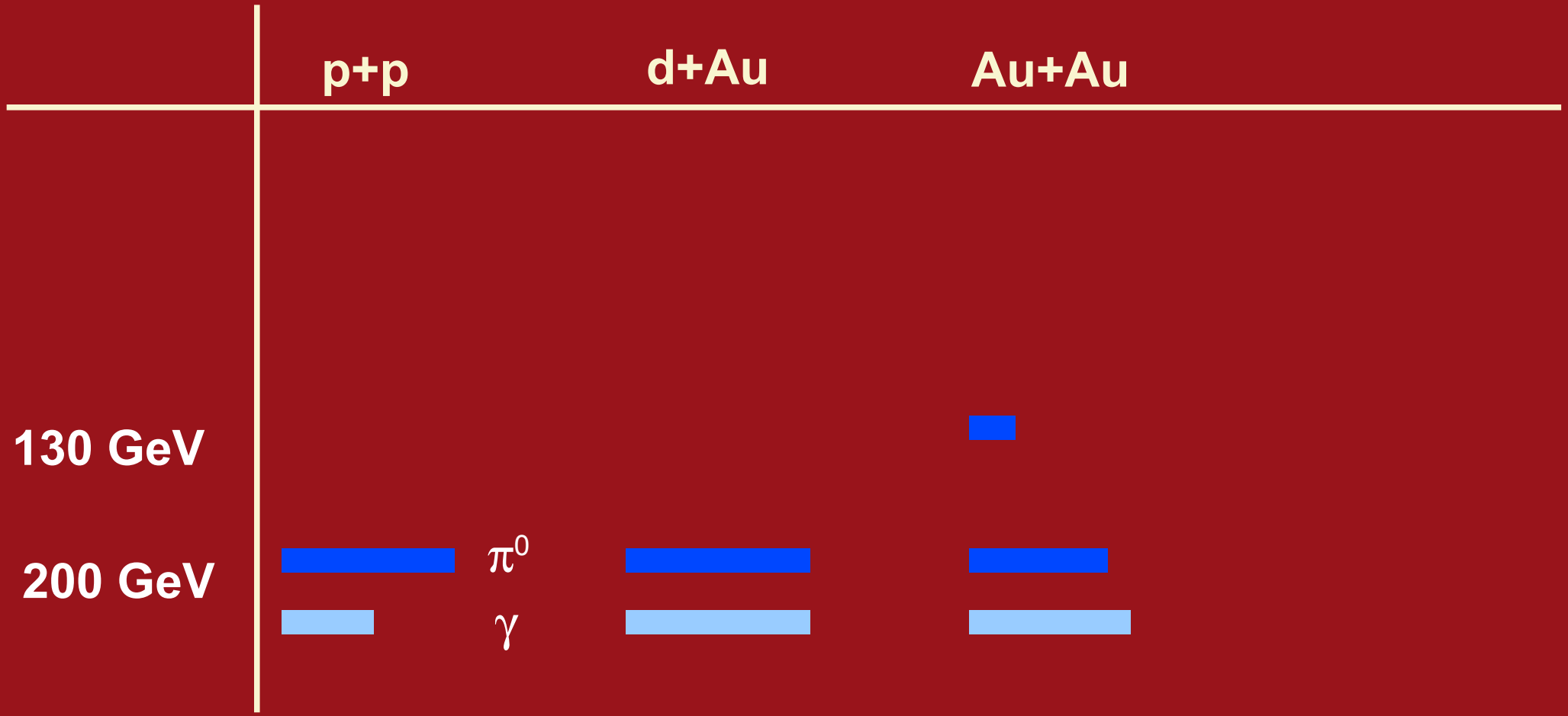
Single Particle Inclusive Spectra
What's New?



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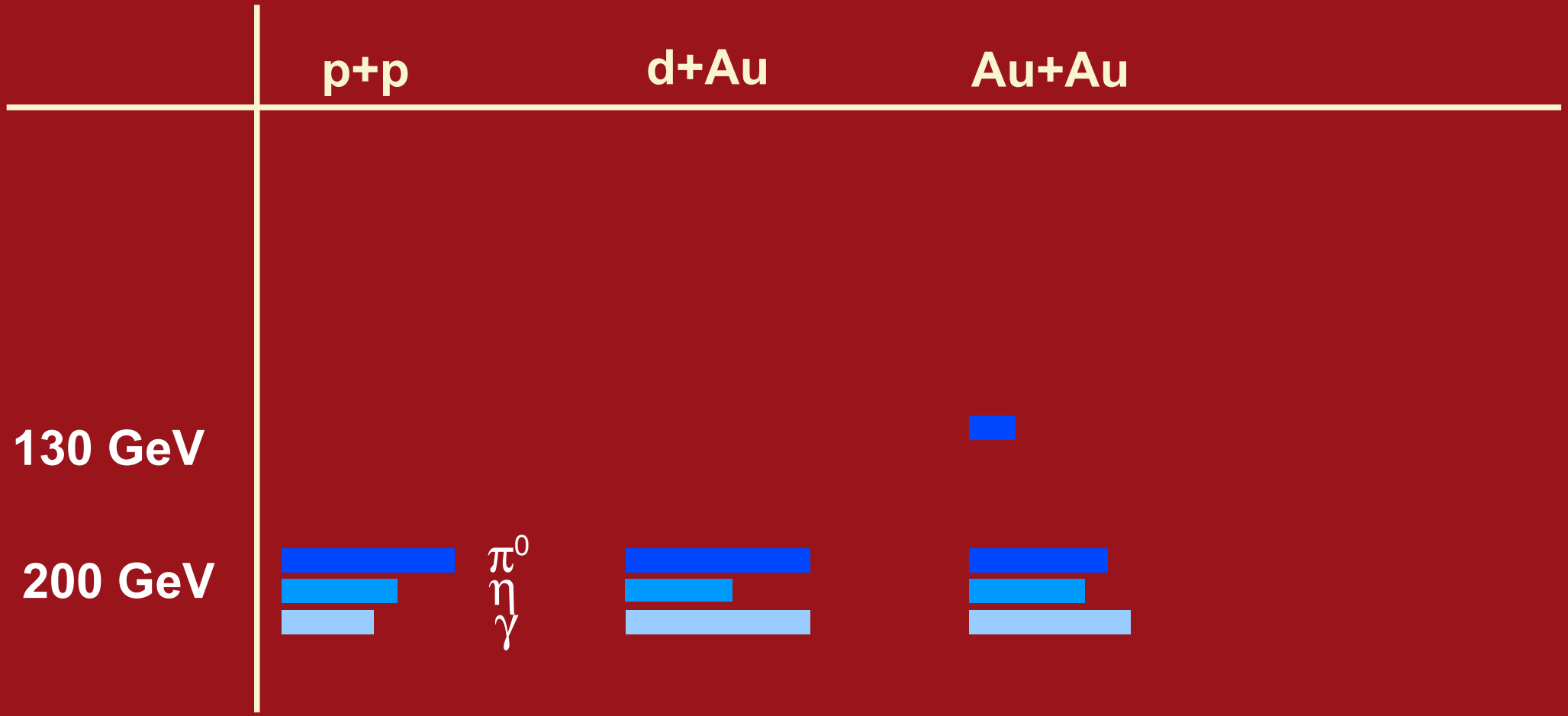
Single Particle Inclusive Spectra
What's New?



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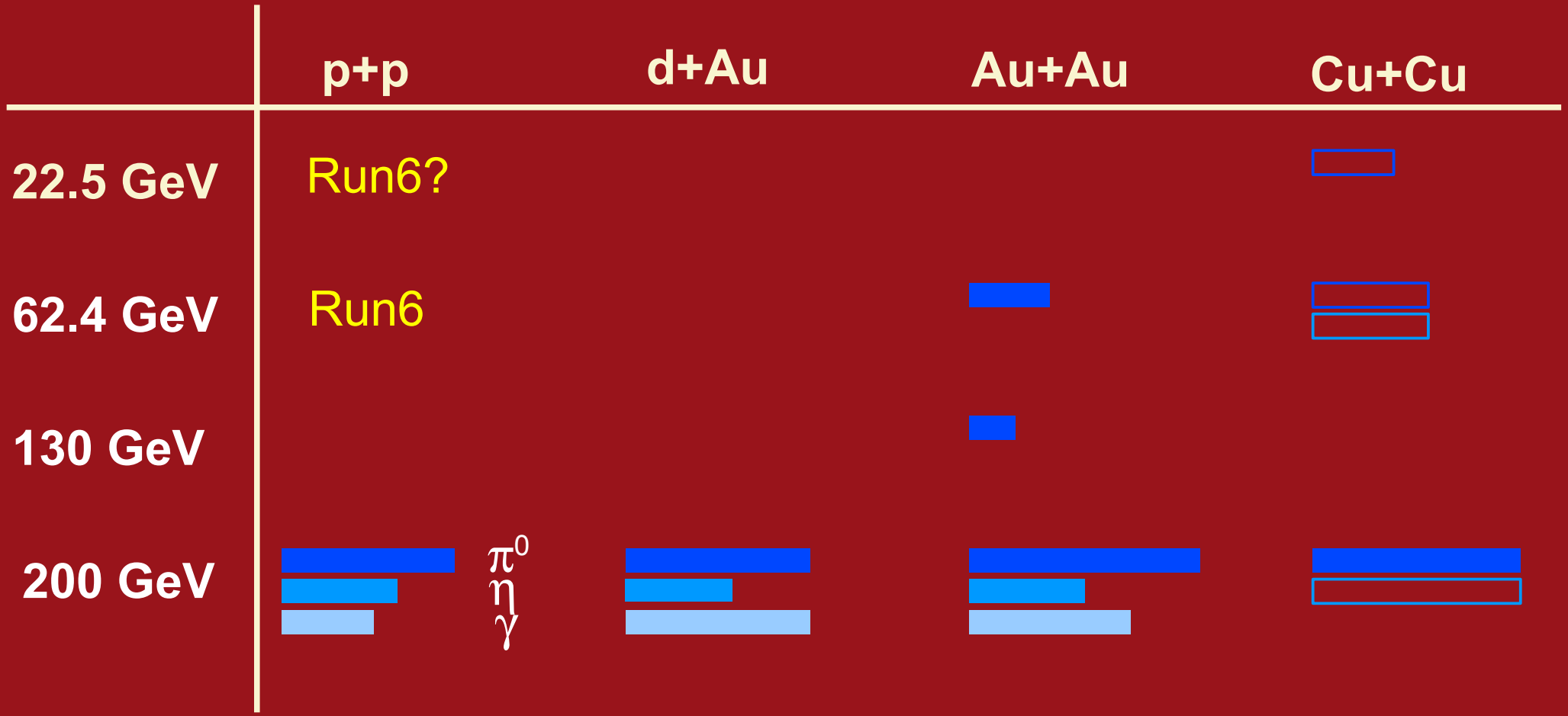
Single Particle Inclusive Spectra



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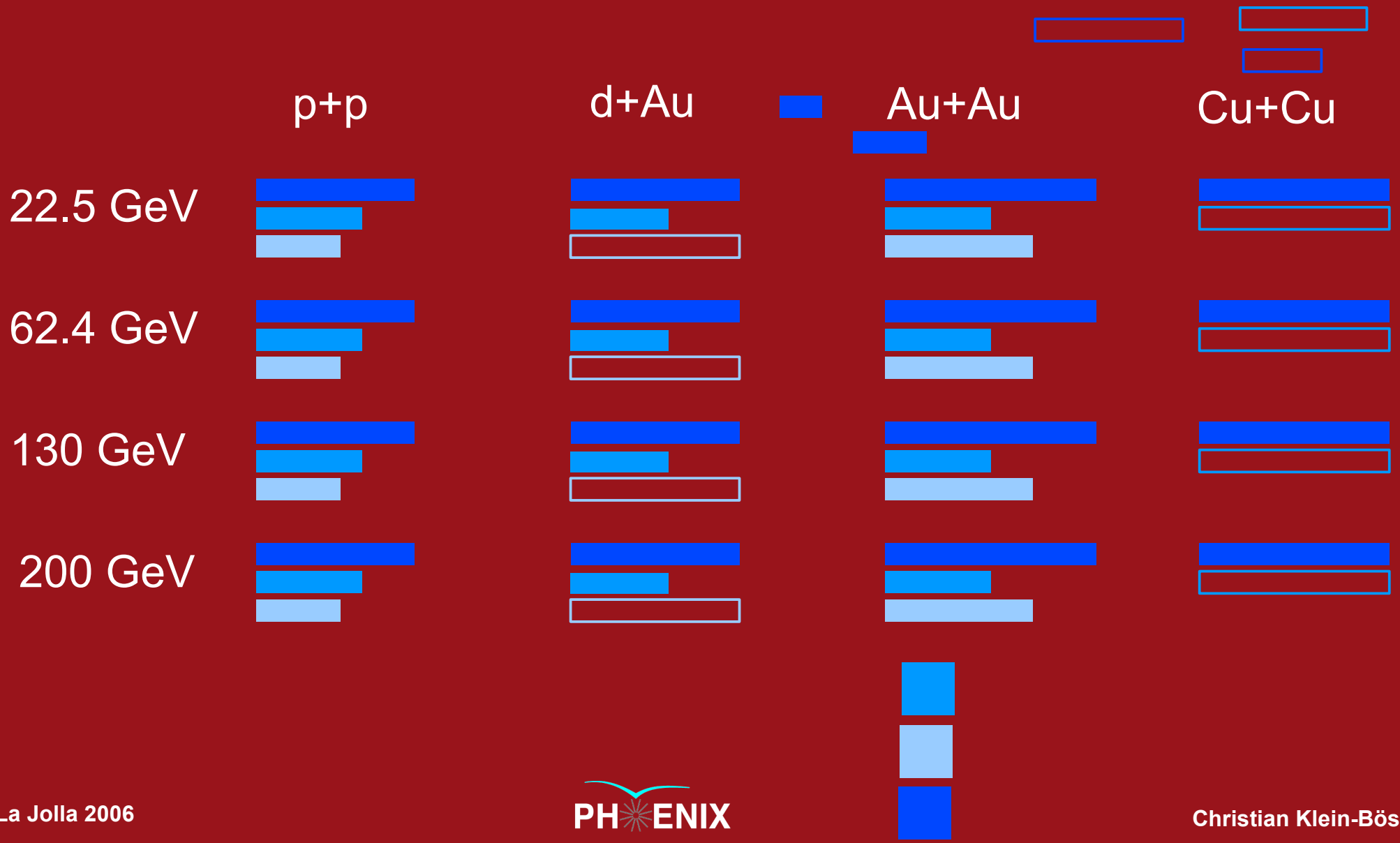
Single Particle Inclusive Spectra



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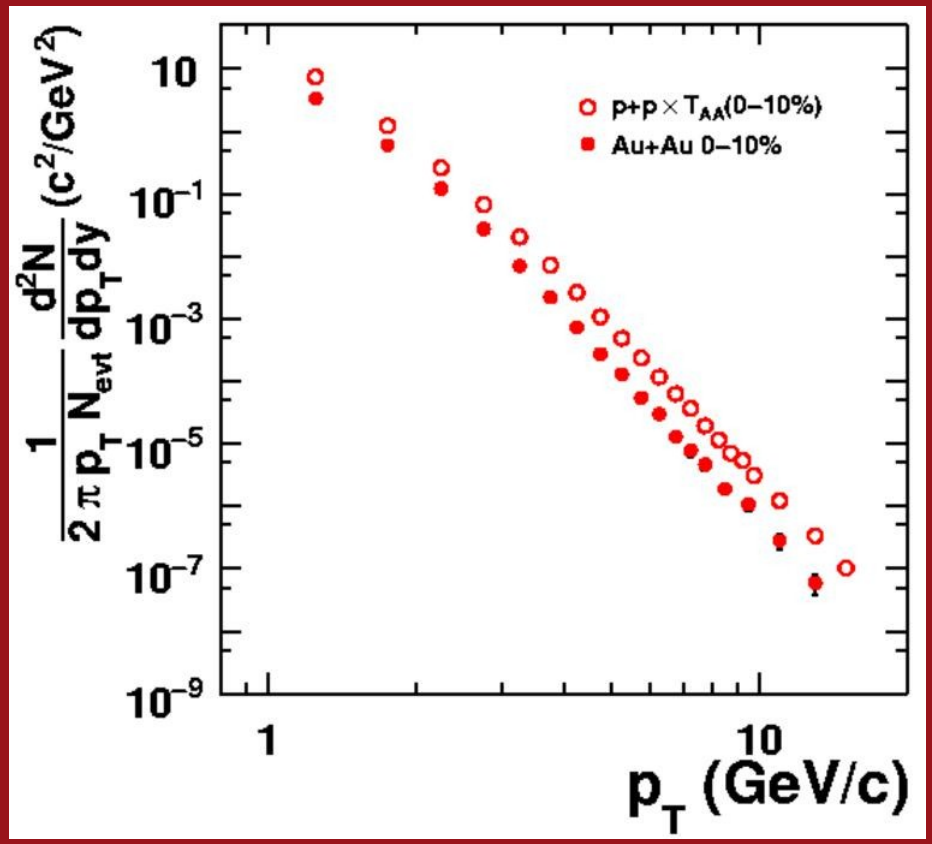
Common Explanation

- **Partons lose energy by (coherent) gluon Bremstrahlung in the medium:**

$$\frac{\langle \Delta E \rangle}{E} \sim \alpha_s^3 C_R \frac{1}{A_T} \frac{dN_g}{dy} L \frac{1}{E} \ln \frac{2E}{\mu^2 L}$$

  - Gluon density can be constrained via multiplicity



- **Average energy loss can be determined from spectrum shift (R_{AA})**

- **For power law:**

$$\frac{\langle \Delta p_T \rangle}{p_T} = S_{loss} = 1 - R_{AA}(p_T)^{1/n-2}$$

~ constant above 4 GeV/*c*