The Search for the Quark-Gluon Plasma with the PHENIX EMCal

EP Seminar
CERN
April 23rd 2007

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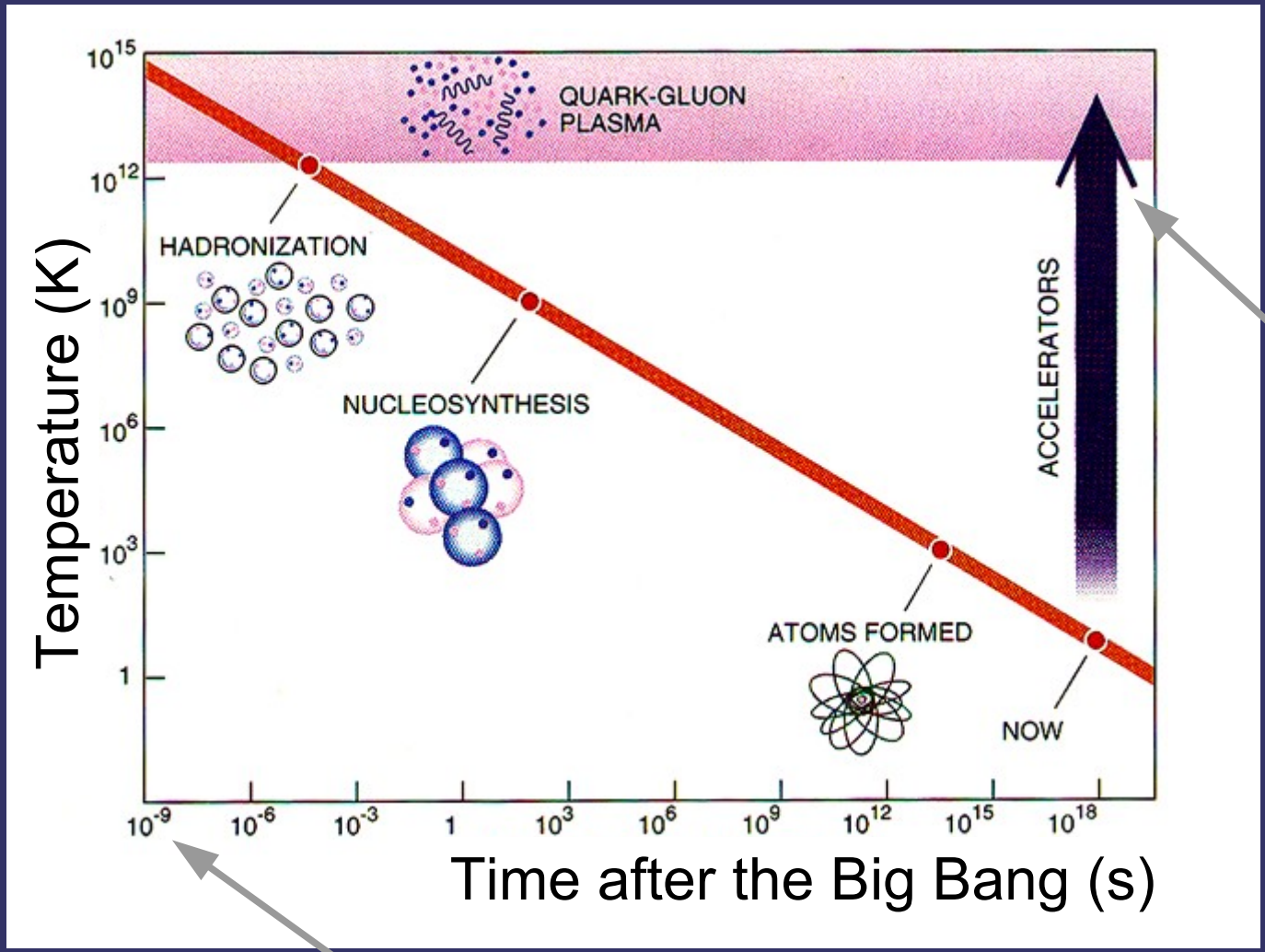
CERN PH-AIP

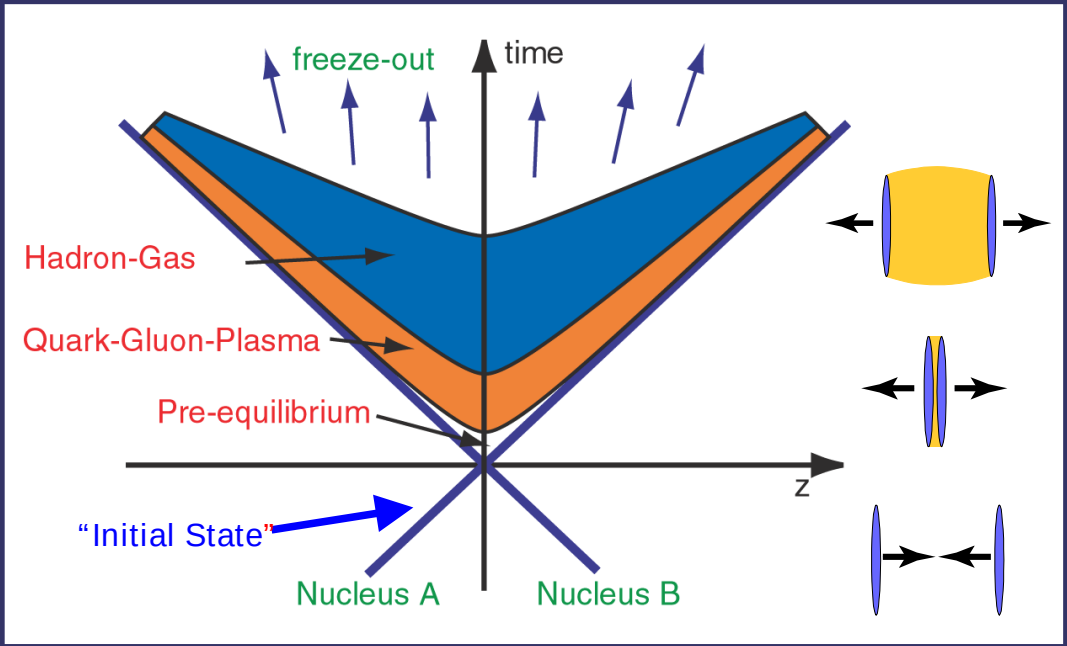
How it all Began...



Little Bangs

13.7 billion years ago

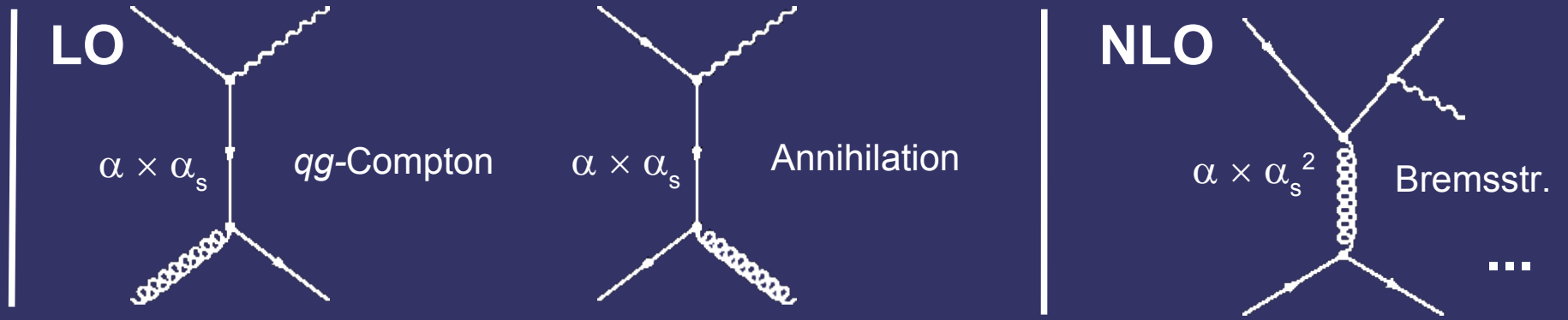
The Search for the QGP



- **Global/collective parameters**
  - T, p, ε
  - Hydrodynamic flow (EOS)
- **Medium modification of well "calibrated" probes**
  - Melting J/ψ
  - Absorbtion of jets
  - ...
- **Thermal radiation**

EMCal Measures Photons...

- **Decay photons**
  - $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$ ...
  - Background to direct photons but signal in itself!
- **Direct photons (i.e. non decay photons)**
  - 30 year history of measurements in p+p
    - Hard processes with large Q^2



  - First measurement in Pb+Pb at CERN
    - WA98 PRL **85** 3595 (2000)

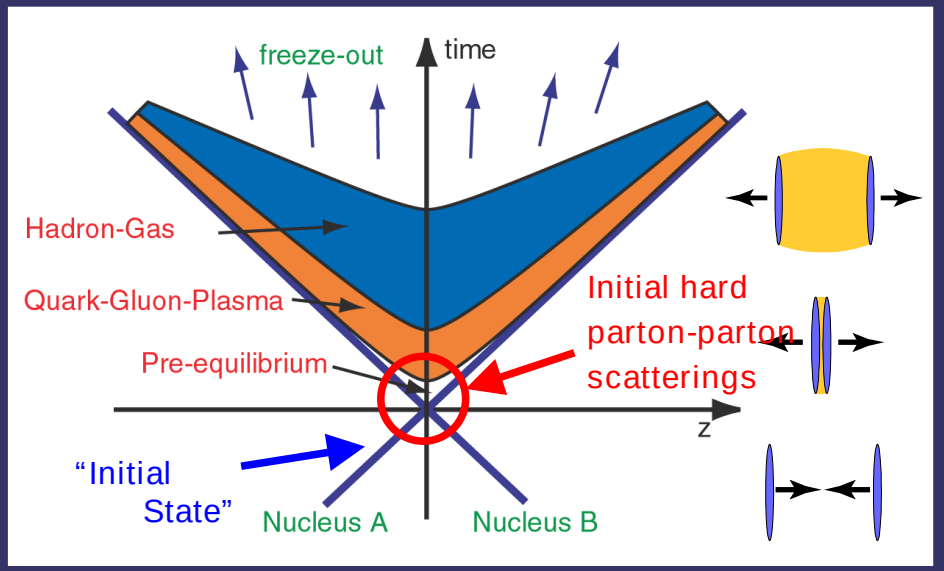
What to learn from $\pi^0 \to \gamma\gamma$...

... at High p_T?

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

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

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



- **Quantifying the medium influence**
  - Single particle (incl.) spectra
  - Assumption: A+A independent superposition of N_{coll} p+p collisions

... at High p_T?

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  - Parton collisions with large Q^2 (~ p_T^2), jets
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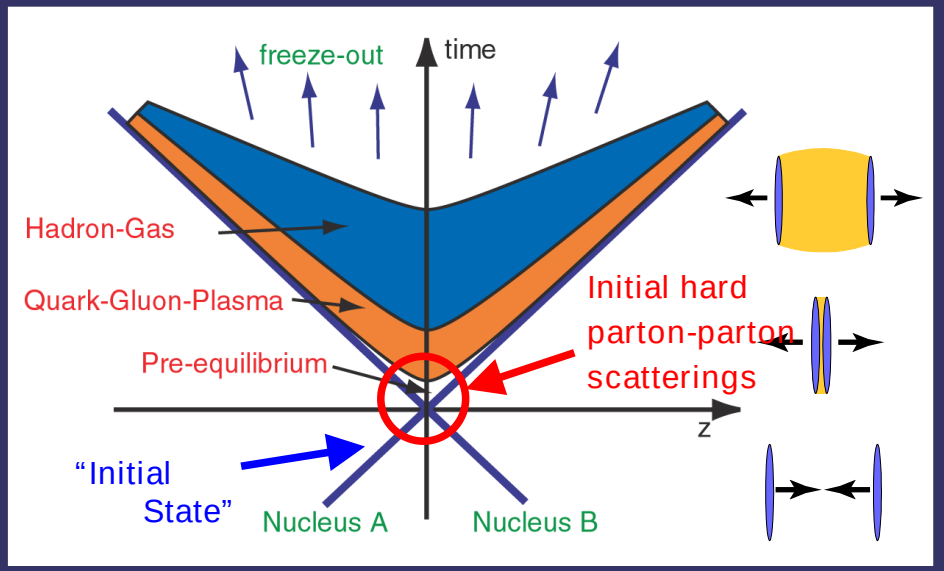

- **Quantifying the medium influence**

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

$N_{coll} \approx T_{AA}\,\sigma_{pp}$

... at High p_T

- **Studying *hard* processes**
  - Parton collisions with large Q^2 ($\sim p_T^2$), jets
  - Factorization:

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

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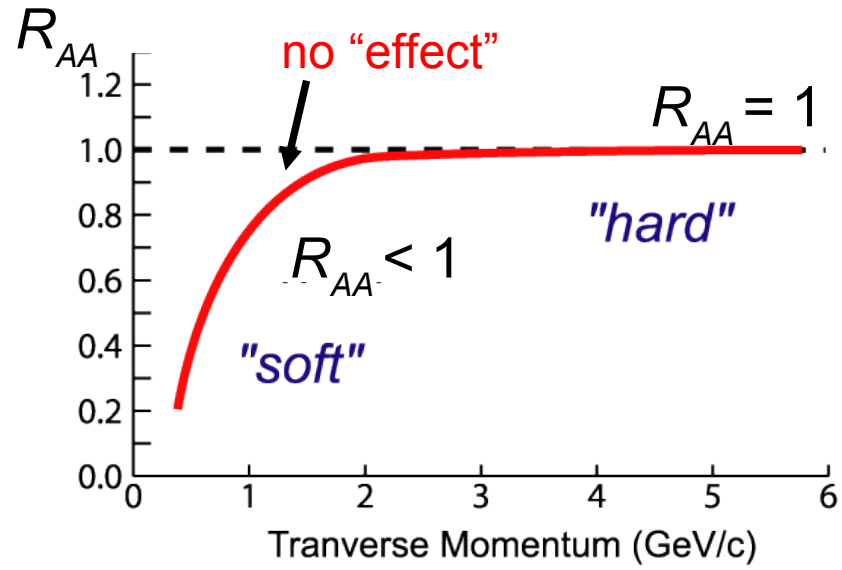
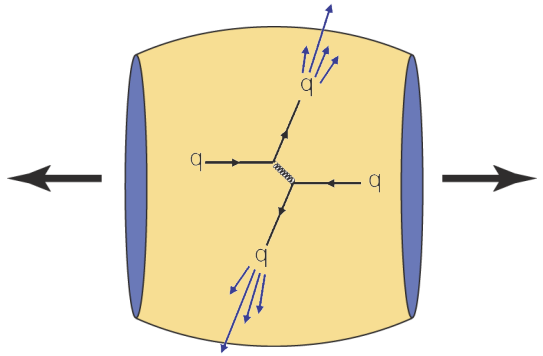


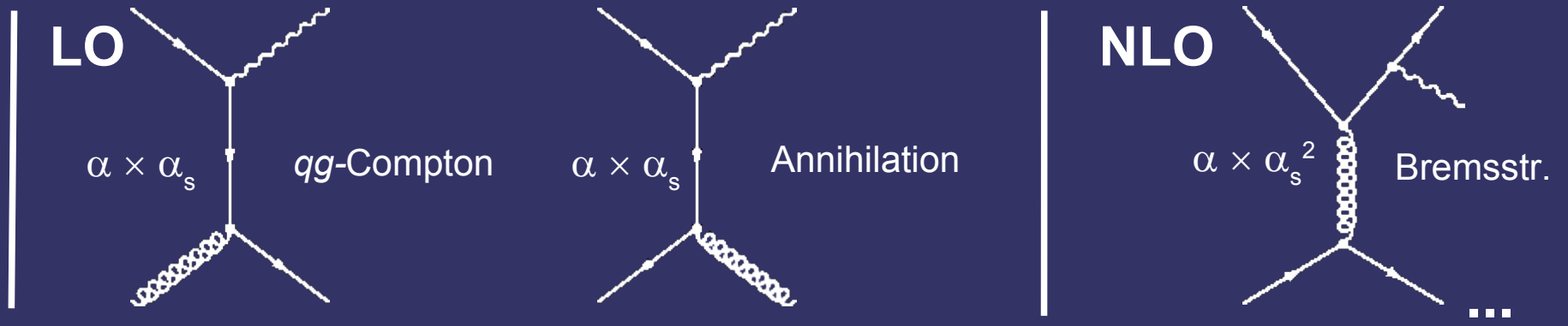
Jet-Tomographie



What to learn from direct γ...

... at High p_T?

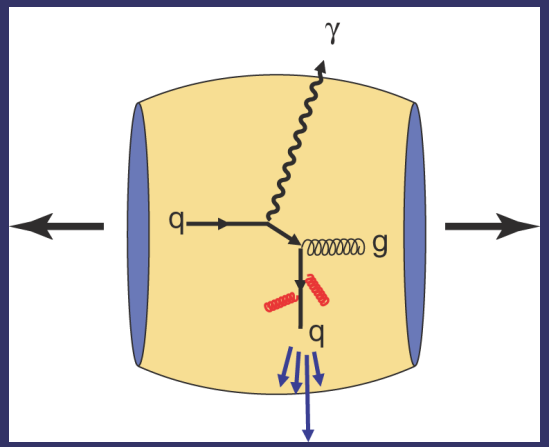
- **In A+A**
  - Hard processes but no strong medium interaction



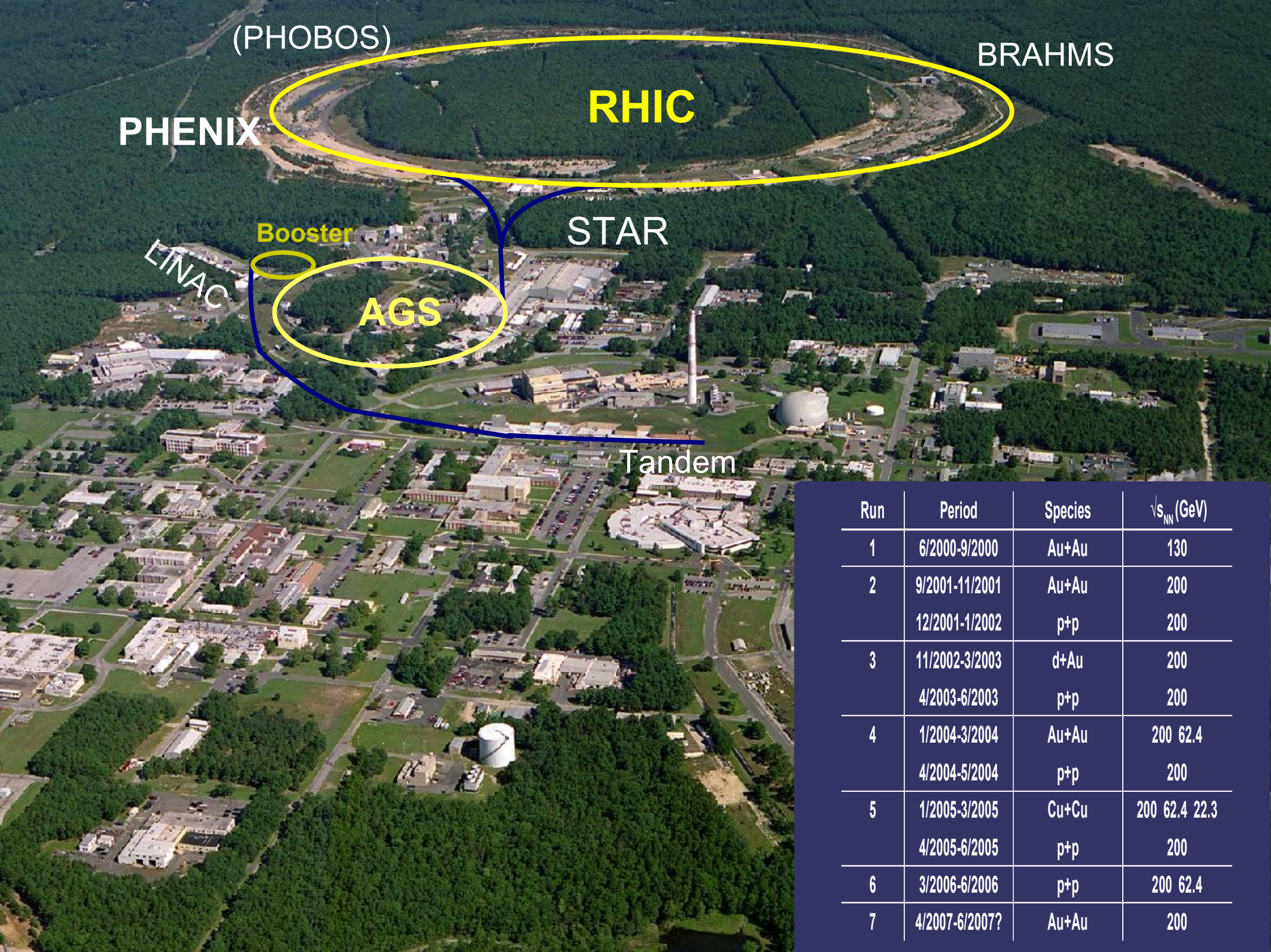
- **In situ control of hard scattering**
  - At LO

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

  - Many other sources of photons at lower p_T
    - **Thermal** radiation from QGP and hadron gas
    - Jet plasma interactions...

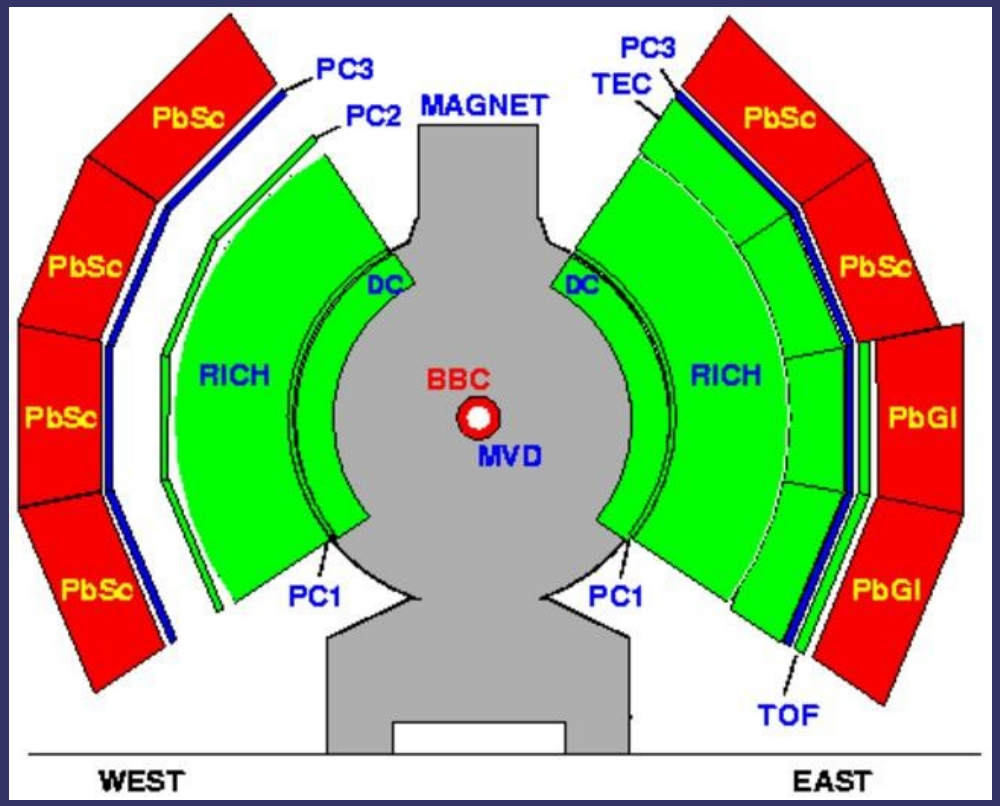


The Devices



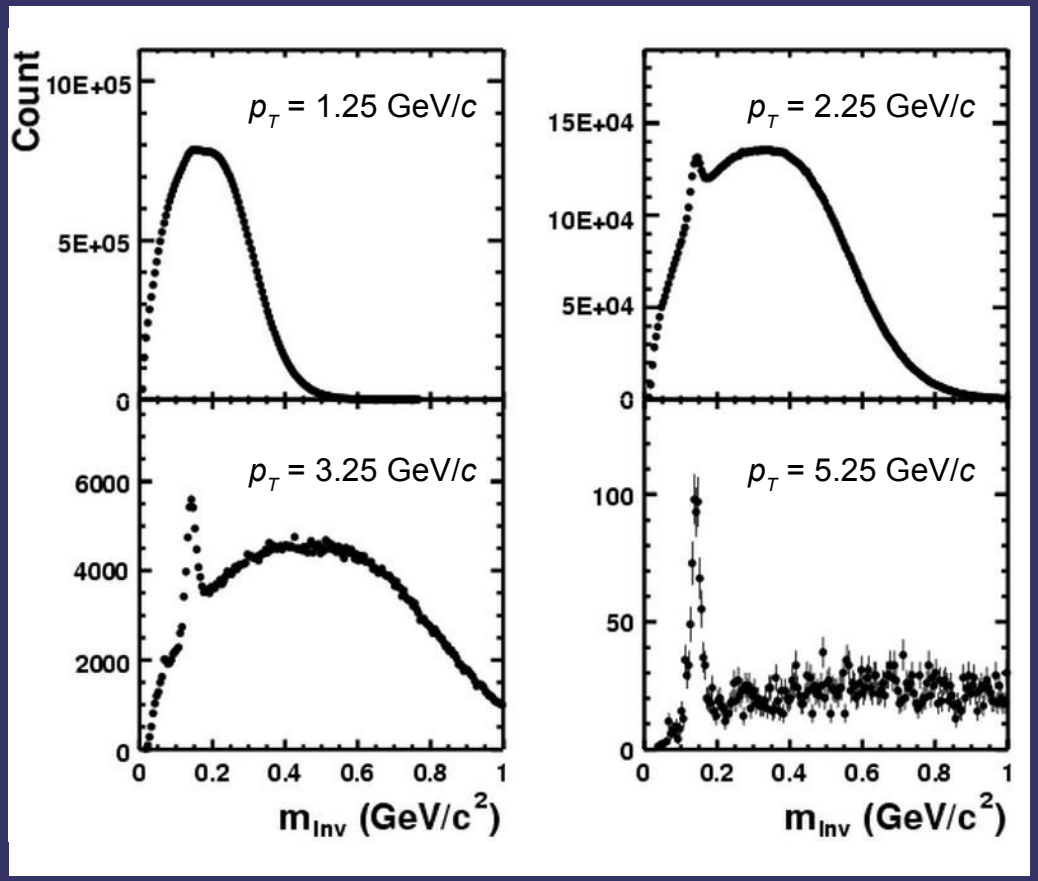
Run	Period	Species	$\sqrt{s_{NN}}$ (GeV)
1	6/2000-9/2000	Au+Au	130
2	9/2001-11/2001	Au+Au	200
	12/2001-1/2002	p+p	200
3	11/2002-3/2003	d+Au	200
	4/2003-6/2003	p+p	200
4	1/2004-3/2004	Au+Au	200 62.4
	4/2004-5/2004	p+p	200
5	1/2005-3/2005	Cu+Cu	200 62.4 22.3
	4/2005-6/2005	p+p	200
6	3/2006-6/2006	p+p	200 62.4
7	4/2007-6/2007?	Au+Au	200

PHENIX EMCal



- **Central arm coverage**
  - $\Delta\phi$: $2 \times \pi/2$
  - $-0.35 < \eta < 0.35$
- **Two detector types**
  - 6 sectors PbSc sandwich
  - 2 sectors PbGl Cherenkov
- **Highly segmented**
  - 5×5 cm^2 (PbSc)
  - 4×4 cm^2 (PbGl)
  - $\Delta\phi \times \Delta\eta < 0.01 \times 0.01$
- **Photons/electrons**
  - High p_T trigger
  - Shower shape
  - (Charged particle veto with PC3)

π^0 Measurement



28 M Au+Au minimum-bias events (PbGl)

- **Reconstruction**
  - $\pi^0\,(\eta) \rightarrow \gamma\gamma$
  - Invariant mass

  $m_{inv} = \sqrt{2E_1E_2(1-\cos\theta)} \approx$ **135 (548) MeV**
- **Combinatorial background via "Mixed Events":**
  - Combine photons from different events
  - A priori uncorrelated
- ***S/N* improves with p_T**
  - Opposite to track reconstruction
  - Access to identified particles at highest p_T

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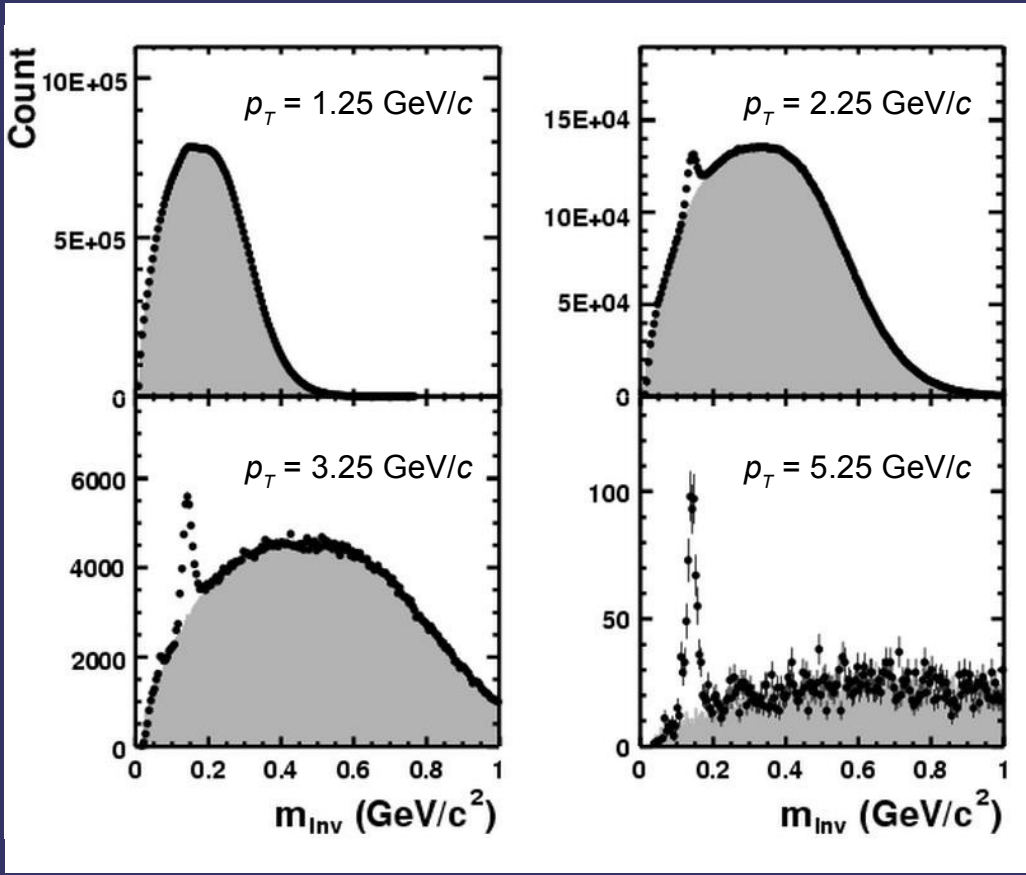

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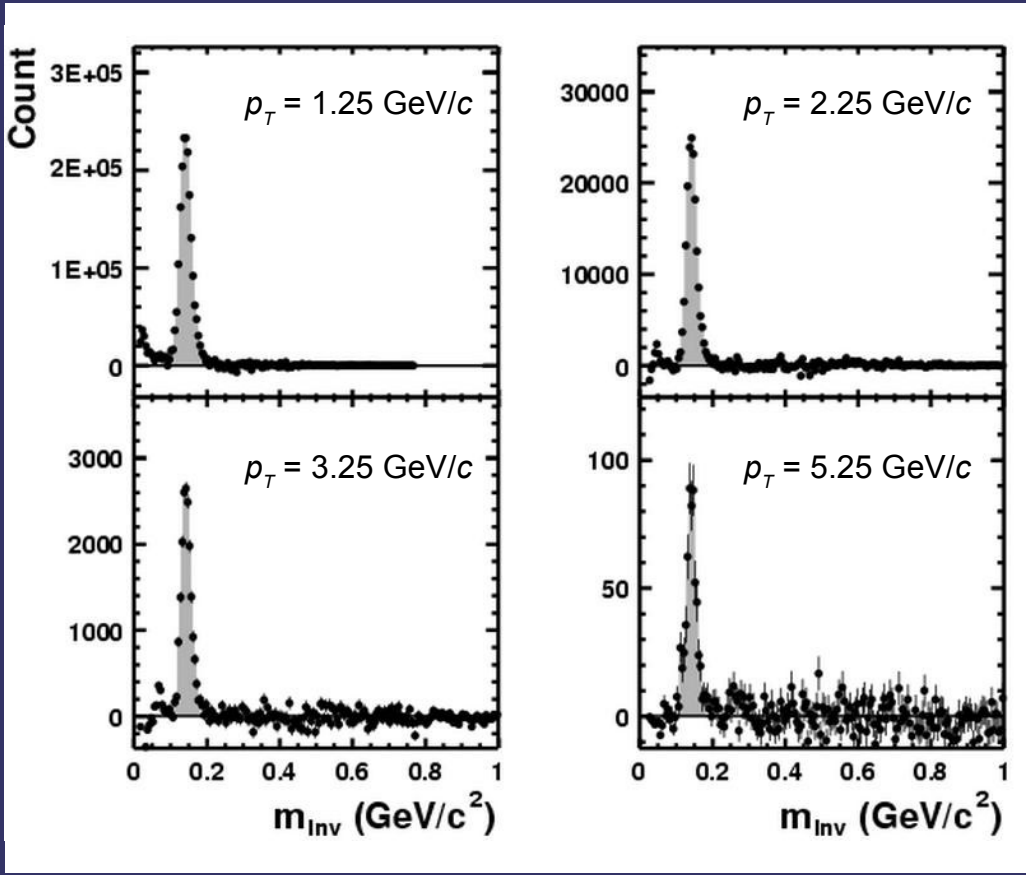

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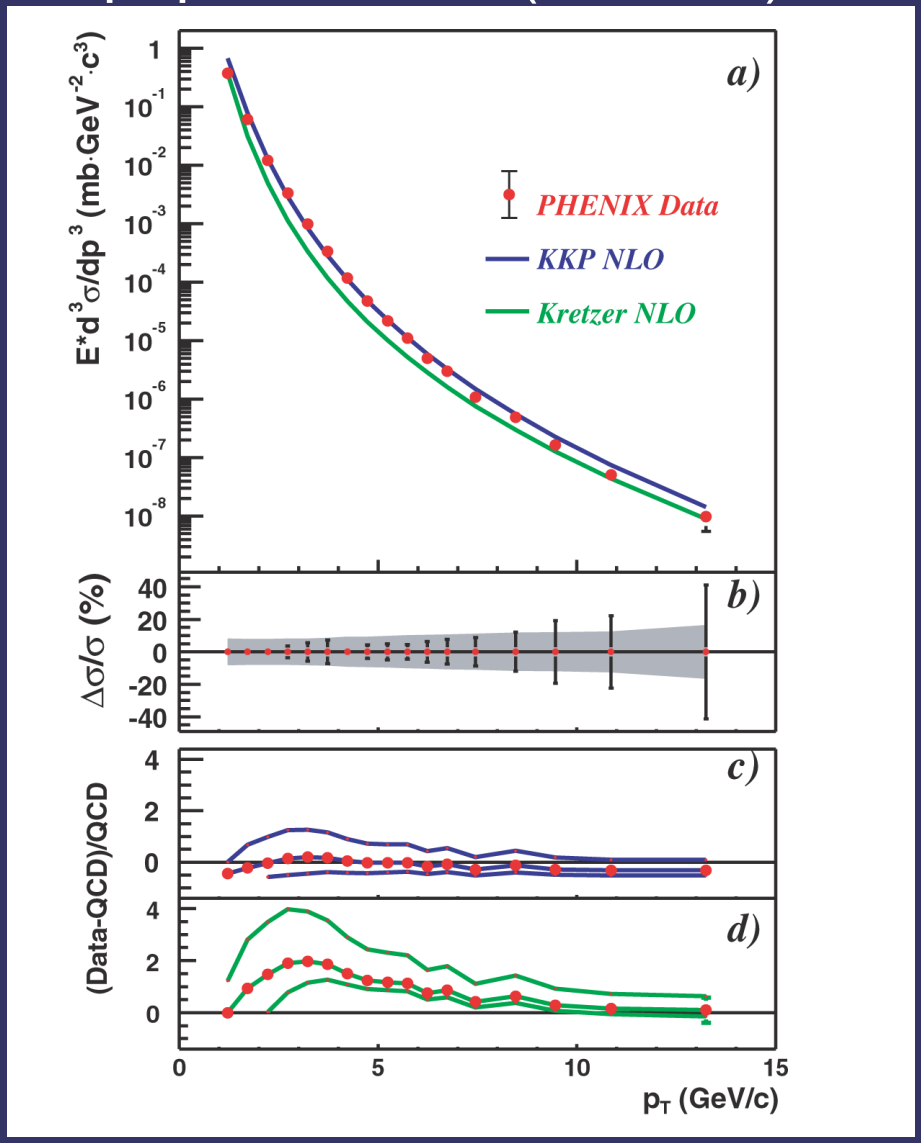
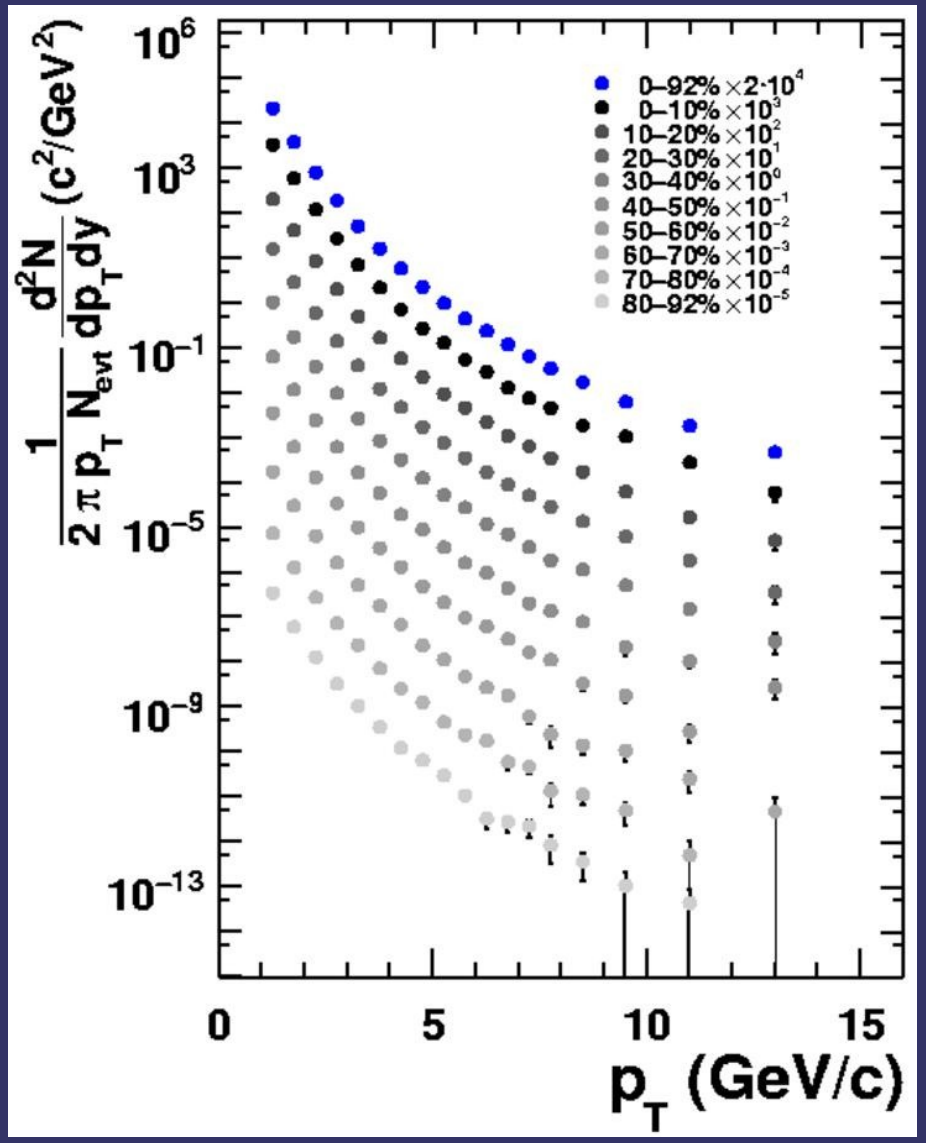
The Spectra @ 200 GeV

p+p reference (vacuum)



PRL **91**, 241803 (2003)

Au+Au

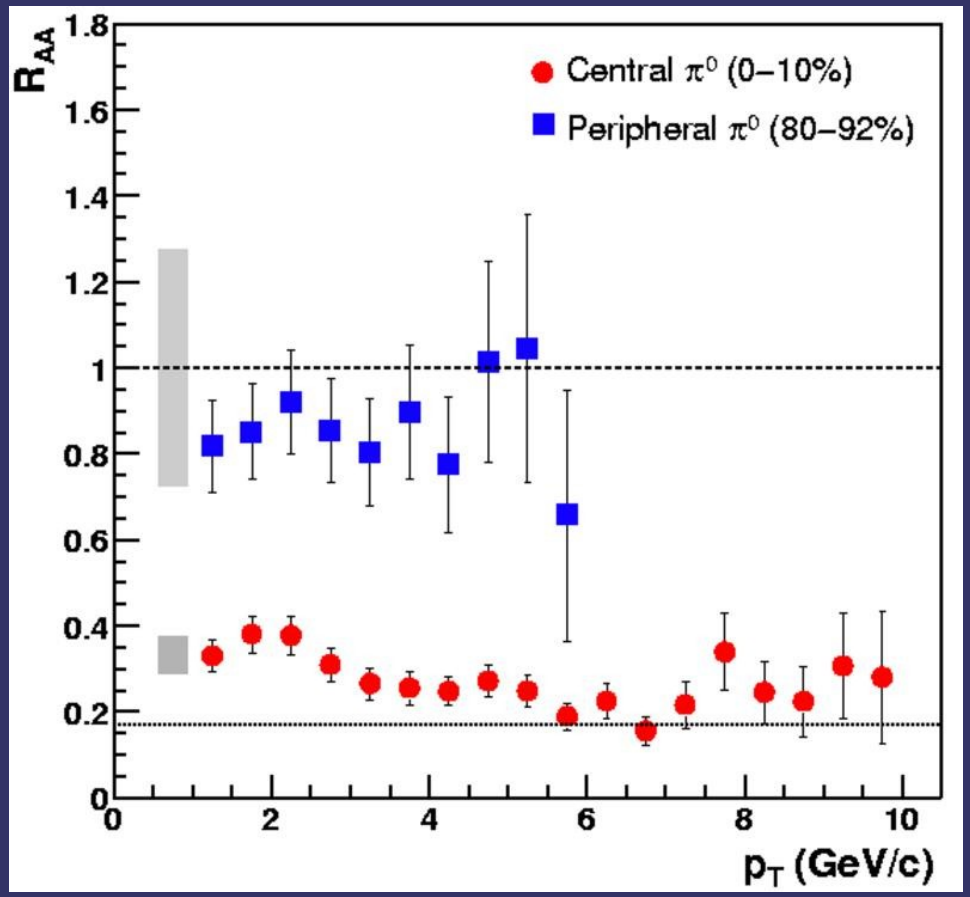


PRL **91**, 072301 (2003)
nucl-ex/0611007

Phenix High p_T Highlight

- **Suppression of high p_T hadrons in central Au+Au relative to scaled p+p**
  - "Jet quenching"

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



PRL **91**, 072301 (2003)

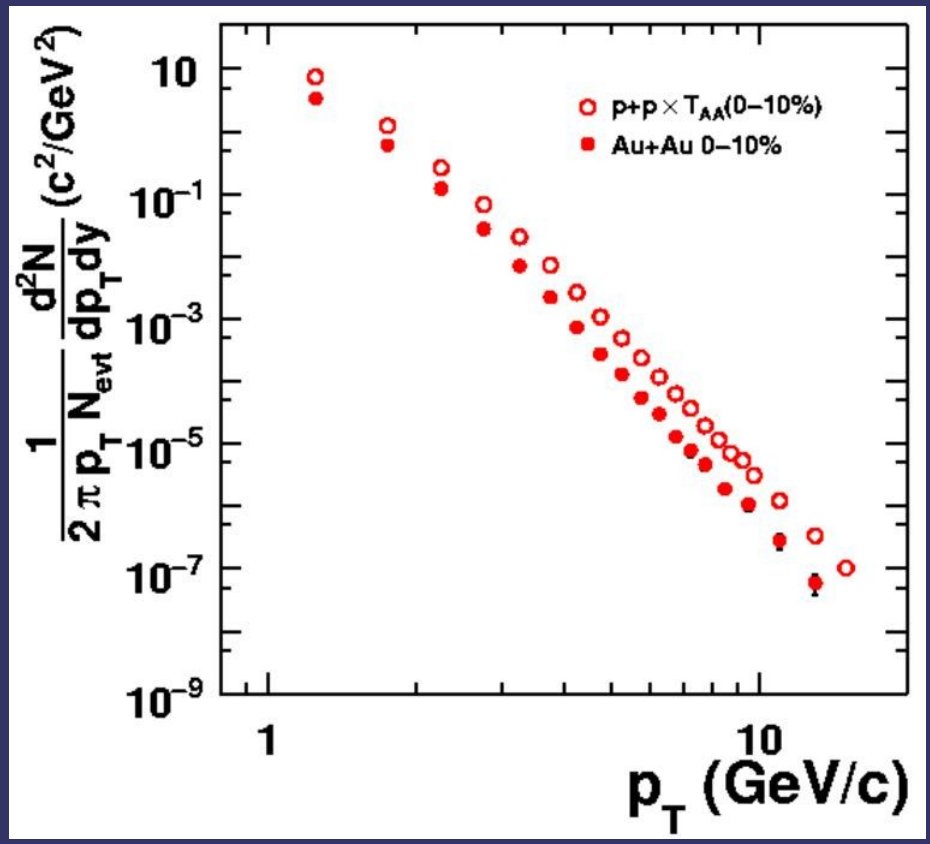
Common Explanation

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

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

  - Main parameter gluon density
  - Other models: e.g. transport coefficient

- **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
→ ~20%

What about direct photons?

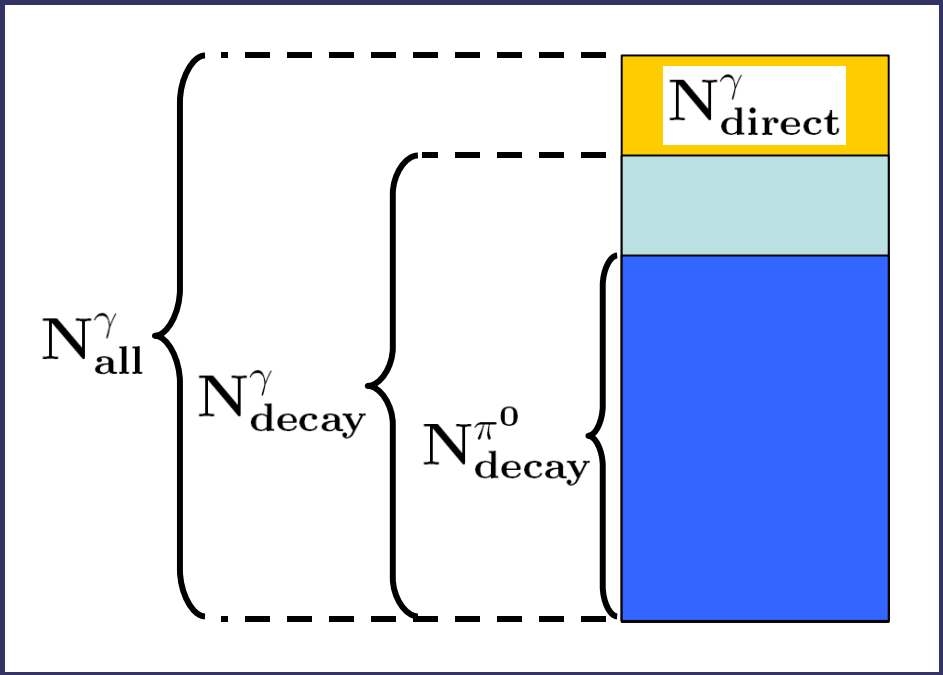
Measuring Direct Photons

- **Inclusive photons**

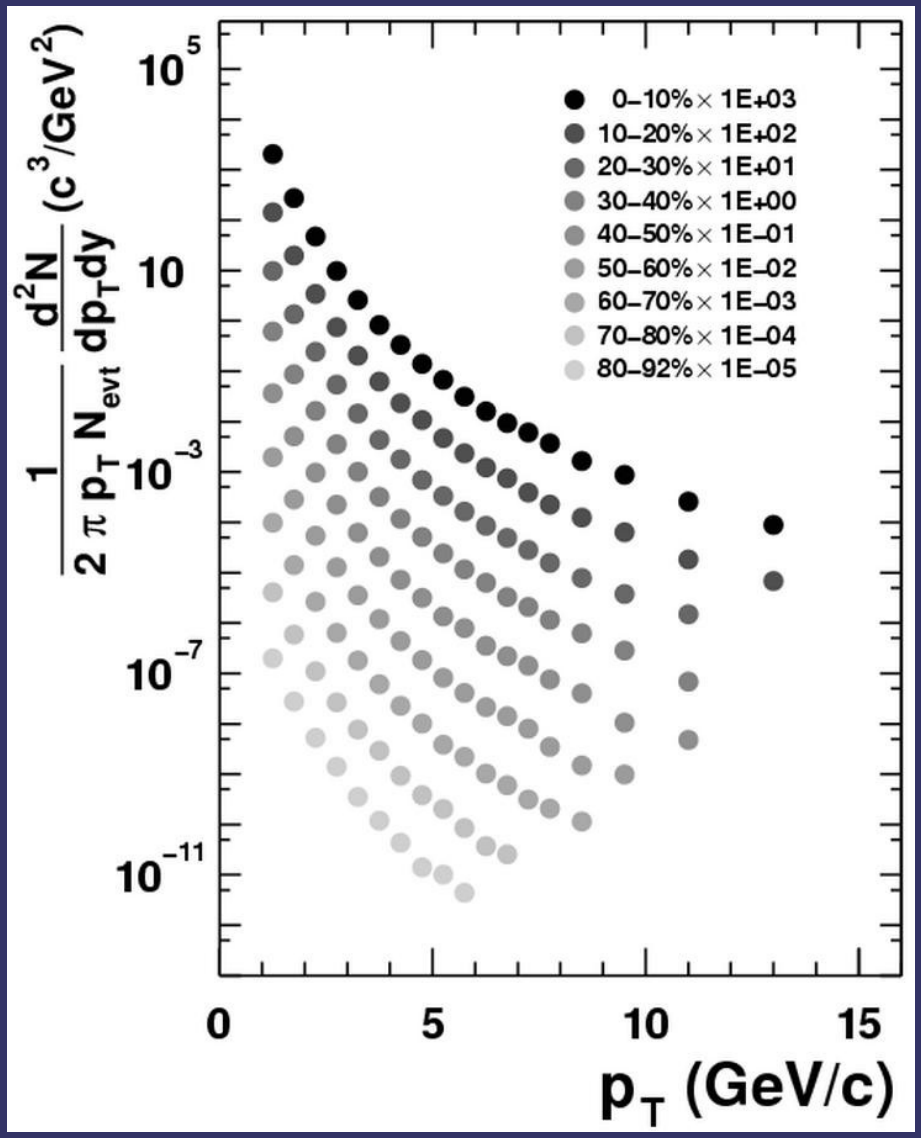
$$N^{\gamma}_{all} = N^{\gamma}_{direct} + N^{\gamma}_{decay}$$

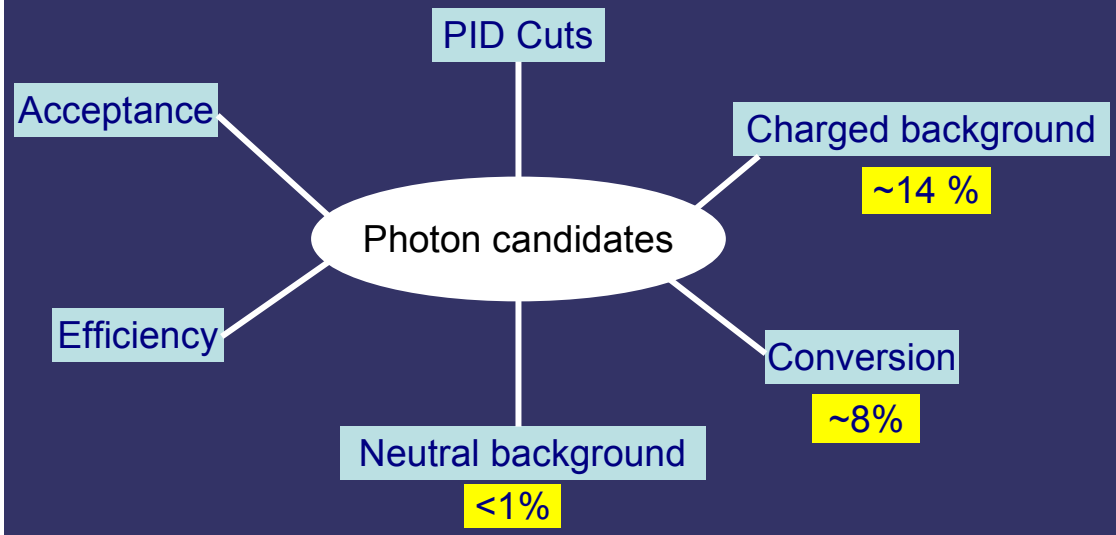
- **Challenge to separate signal from decay background**
  - Mainly $\pi^0 \rightarrow \gamma\gamma$
- **Direct separation**
  - Event-by-event isolation cuts
- **Statistical separation**
  - Compare measured inclusive γ to expected decay γ

$$N^{\gamma}_{direct} = N^{\gamma}_{all} - N^{\gamma}_{decay}$$



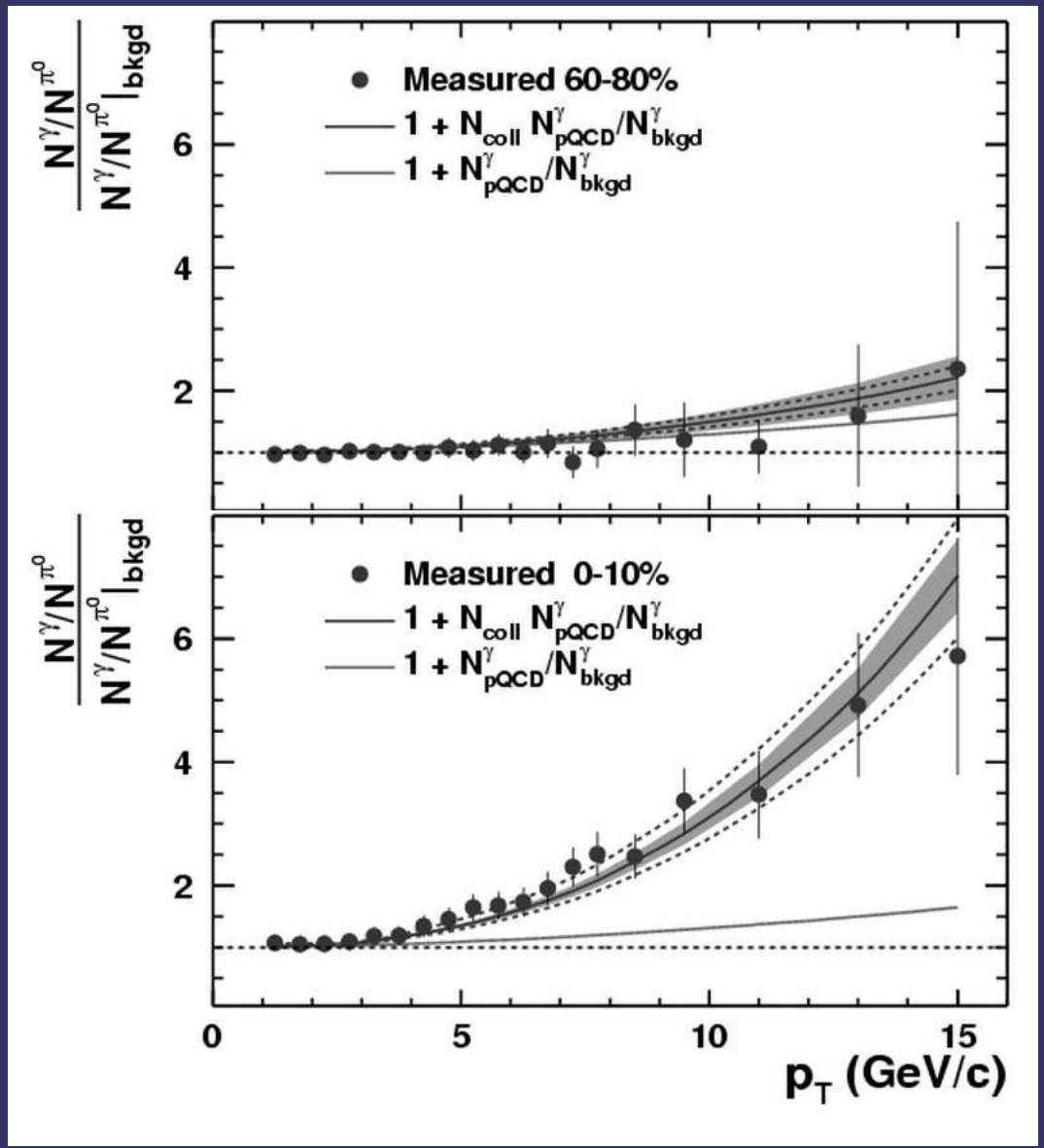
Inclusive Photons





- **Suffers from calorimeter resolution and background at low p_T**
  - Alternative approach e.g. via tracking of photon conversions ($\gamma \rightarrow e^+e^-$)

Direct Photon Signal in Au+Au



- **Double ratio gives significance of the signal**

$$\frac{\left(\gamma/\pi^0\right)_{meas}}{\left(\gamma/\pi^0\right)_{decay}} = \frac{\gamma_{meas}}{\gamma_{decay}}$$

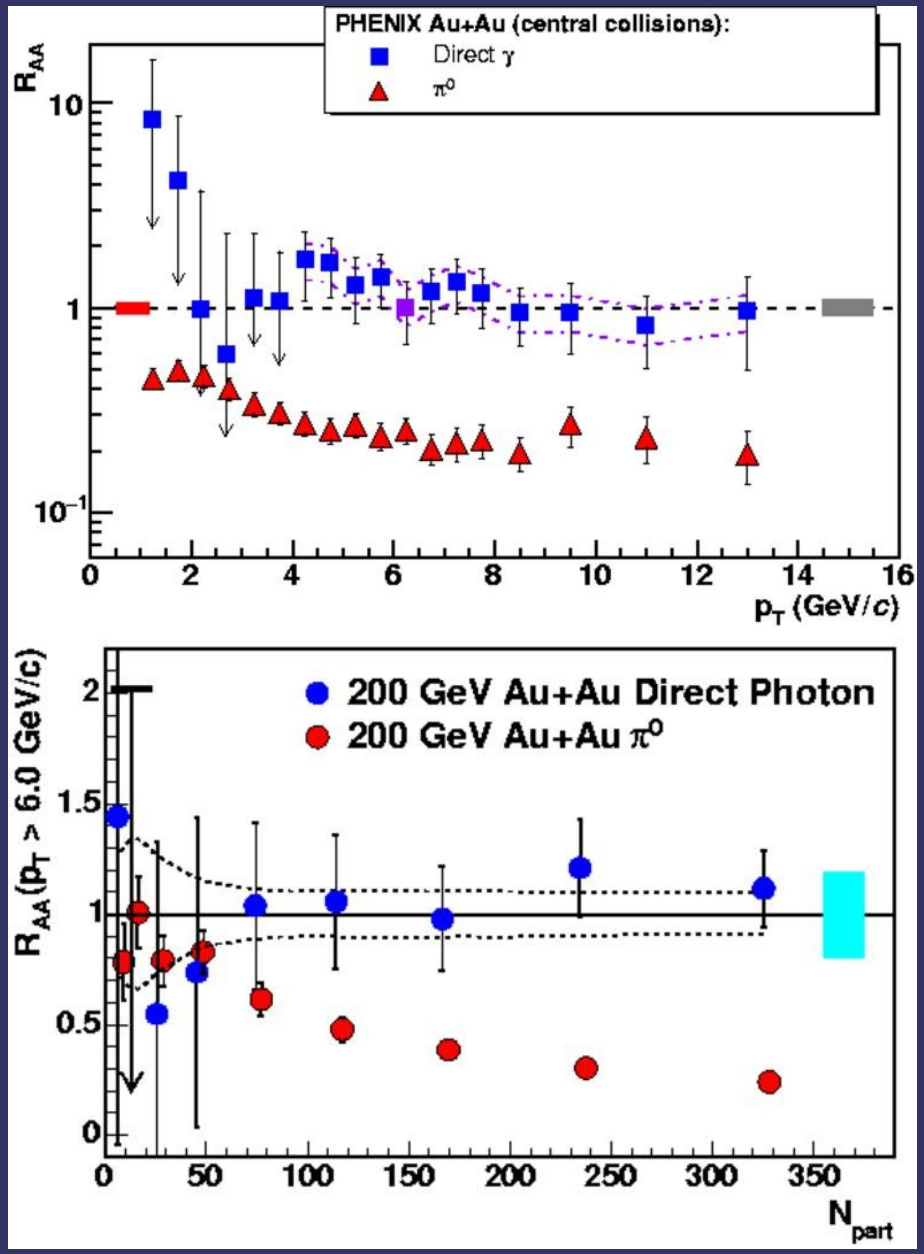
  - Decay photons simulated based on measured π^0s and η
  - Many systematics cancel
    - Energy scale
    - Photon efficiency and acceptance
    - Photon conversion

π^0 suppression in central Au+Au improves *S/N*

PHENIX High p_T Lights

- **Direct photons**
  - R_{AA} with pQCD reference
- **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)

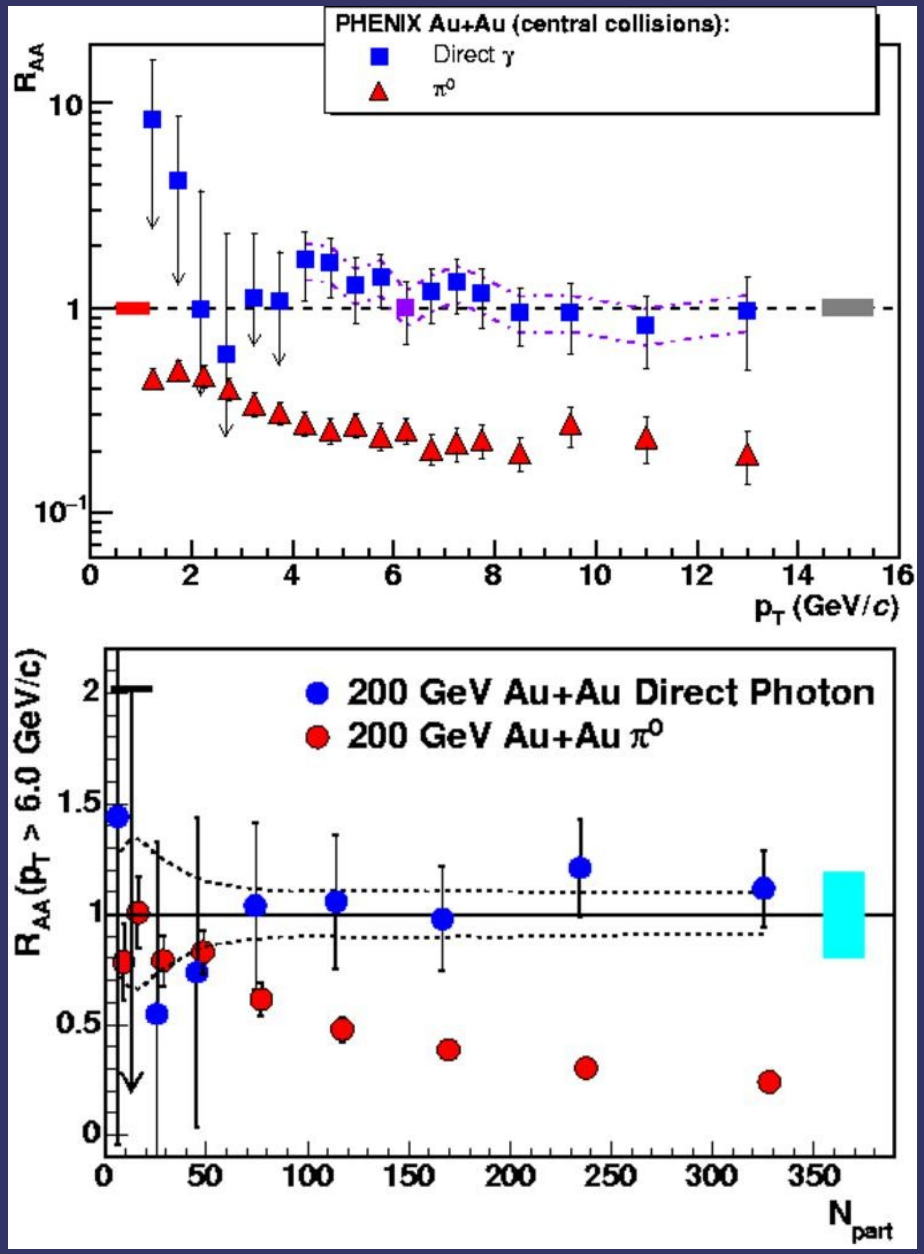
PHENIX High p_T Lights

- **Direct photons**
  - R_{AA} with pQCD reference
- **Ultimate test for hard scatterings**

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

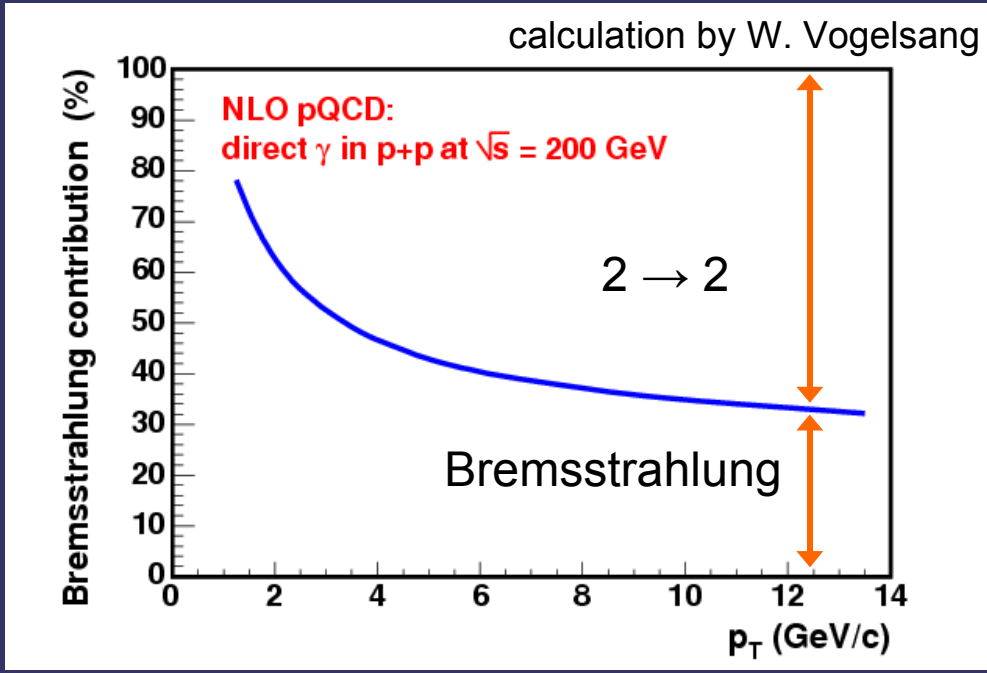
- **No suppression of direct photons in central Au+Au**
- **Also no suppression in d+Au**
  - PRL **91**, 072303 (2003)

Strong final state effect

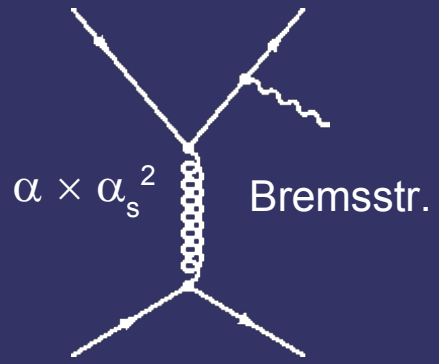


PRL **94**, 232301 (2005)

But...

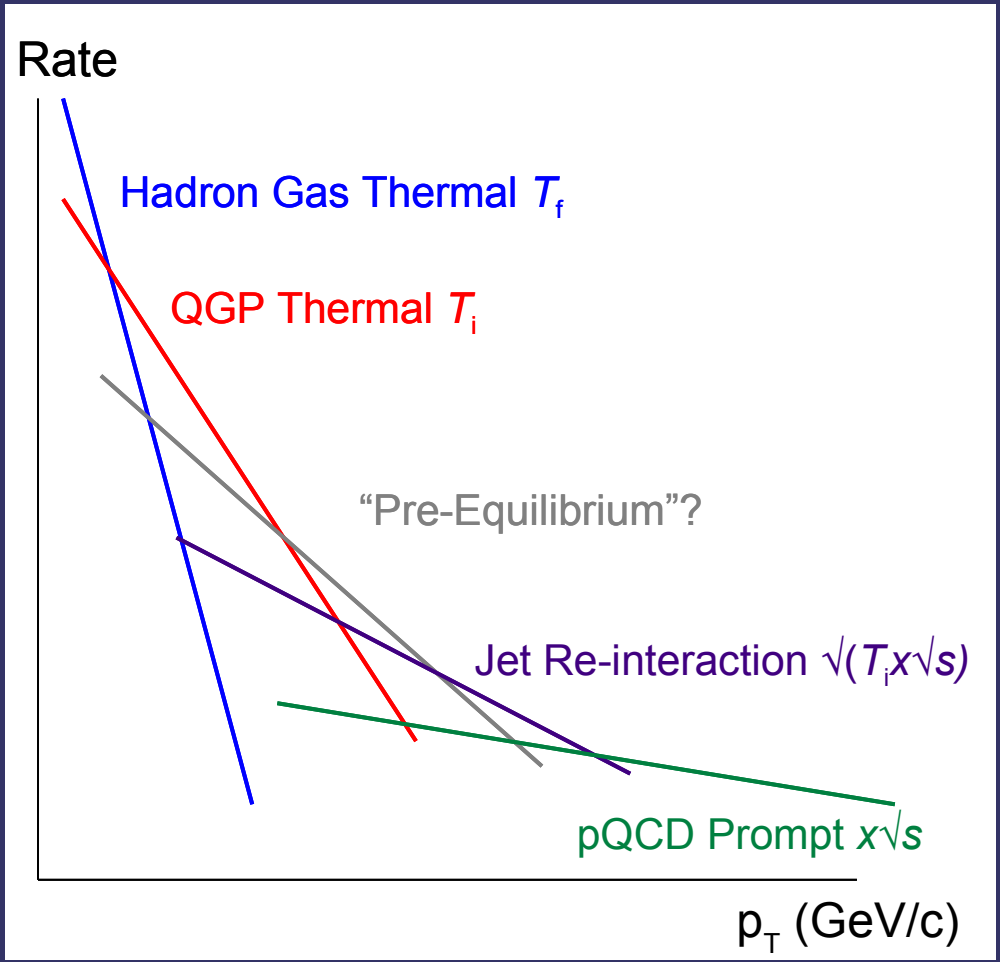


- **... shouldn't we see some suppression:**



- **Consider also multiple scattering and formation times**
- **Jet-plasma interaction**
  - $q_{hard}+g_{thermal} \rightarrow q+\gamma$ ...
- **Thermal**

Various other Sources

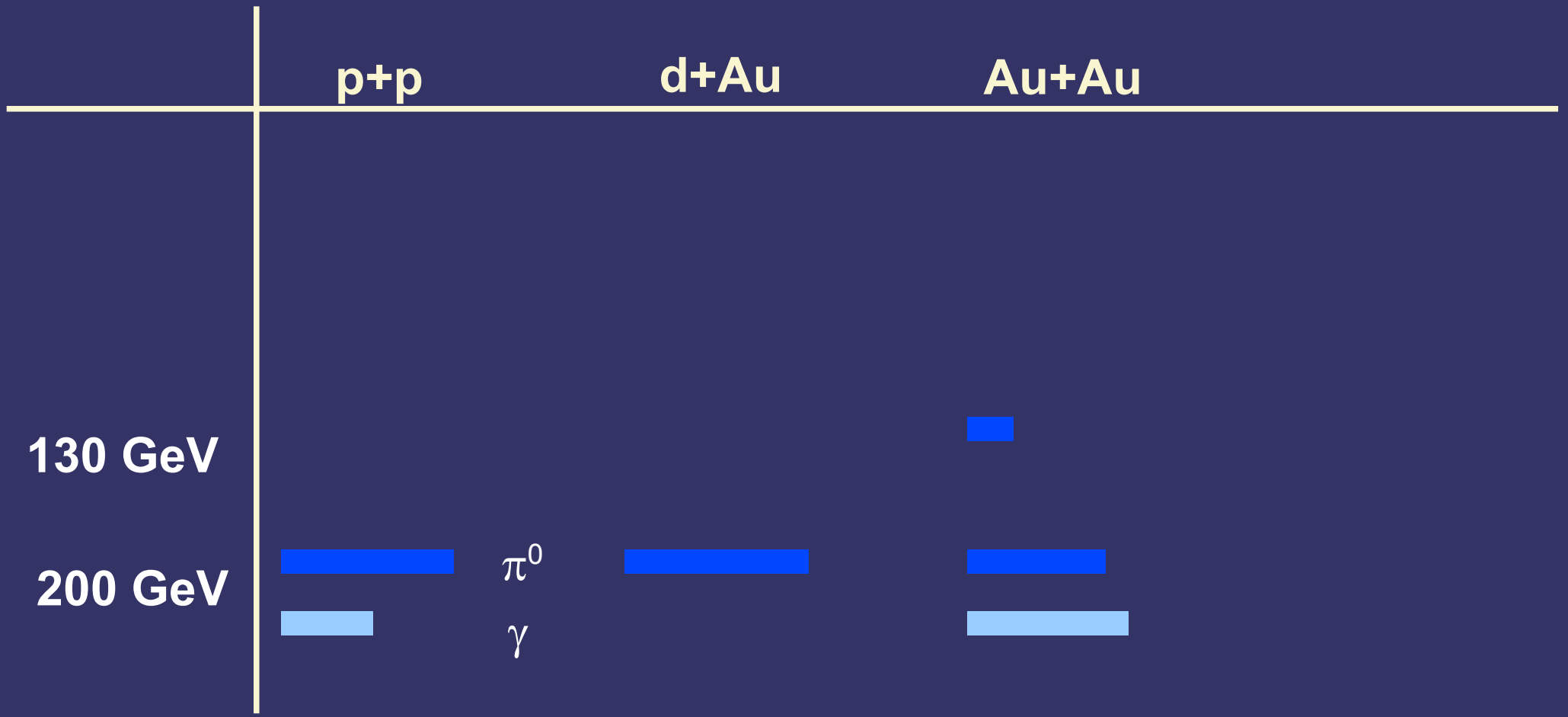


The promise and the peril:
Photon signal is very ambiguous!

- **Thermal photons**
  - Long dealt as THE signature of a QGP
- **Pre-equilibrium**
  - Nearly nothing known
  - Cascade models
- **Jet re-interaction**
  - Photon bremsstrahlung of quark-jets in the QGP
  - *qg*(Jet) scatters on *qg*(QGP)
- **pQCD photons**
  - Influence on fragmentation?

Need more data. Improve references and methods!

Single Particle Spectra @ High p_T
The First Three Years



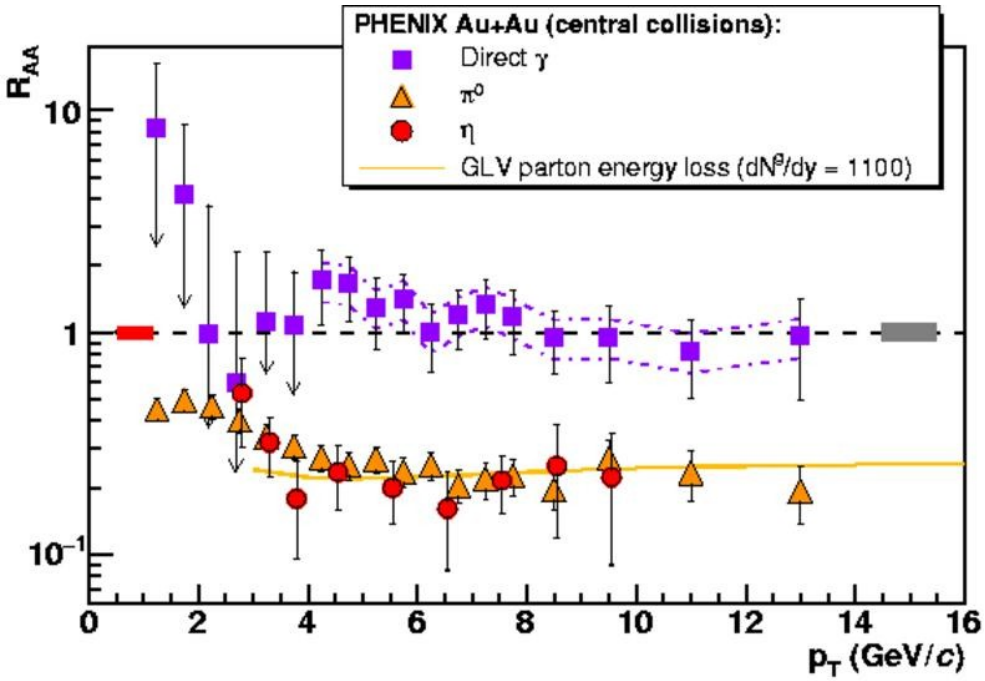
Christian Klein-Bösing

What else can be done at high p_T?

- **More differential studies of (existing) data at high p_T**
  - Different particle types (e.g. η)
  - Jet correlations
  - Reaction plane (L) dependence
- **New Au+Au data**
  - Improve p_T-reach
- **New p+p data**
  - Improve reference
- **Vary the collision energy**
- **Vary the system size**

Mass Dependence at High p_T

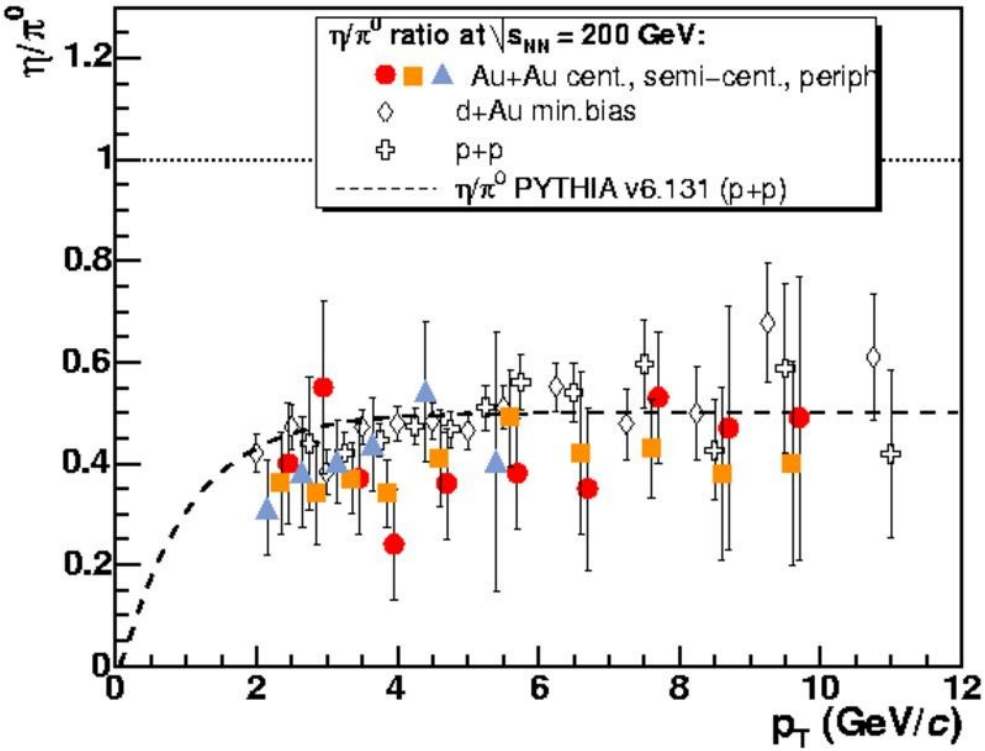
- η same quark content as π^0
- Factor 4 heavier
- Same R_{AA} as π^0
  - Suppression does not depend on hadron mass



PRL **96** 202301 (2006)

Mass Dependence at High p_T

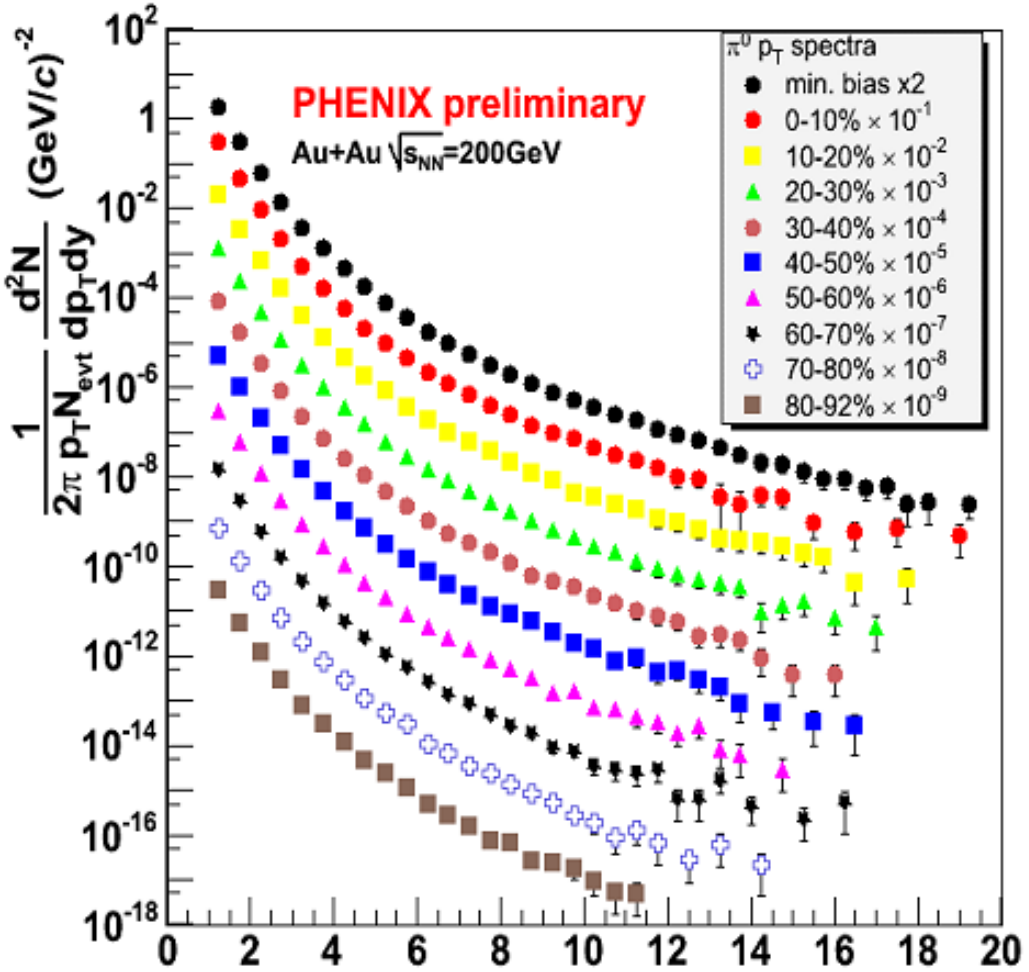
- η same quark content as π^0
- Factor 4 heavier
- Same R_{AA} as π^0
  - Suppression does not depend on hadron mass
- η/π^0 similar for all colliding species and centralities
  - Suppression happening at the partonic level
  - Fragmentation function not strongly influenced by the medium



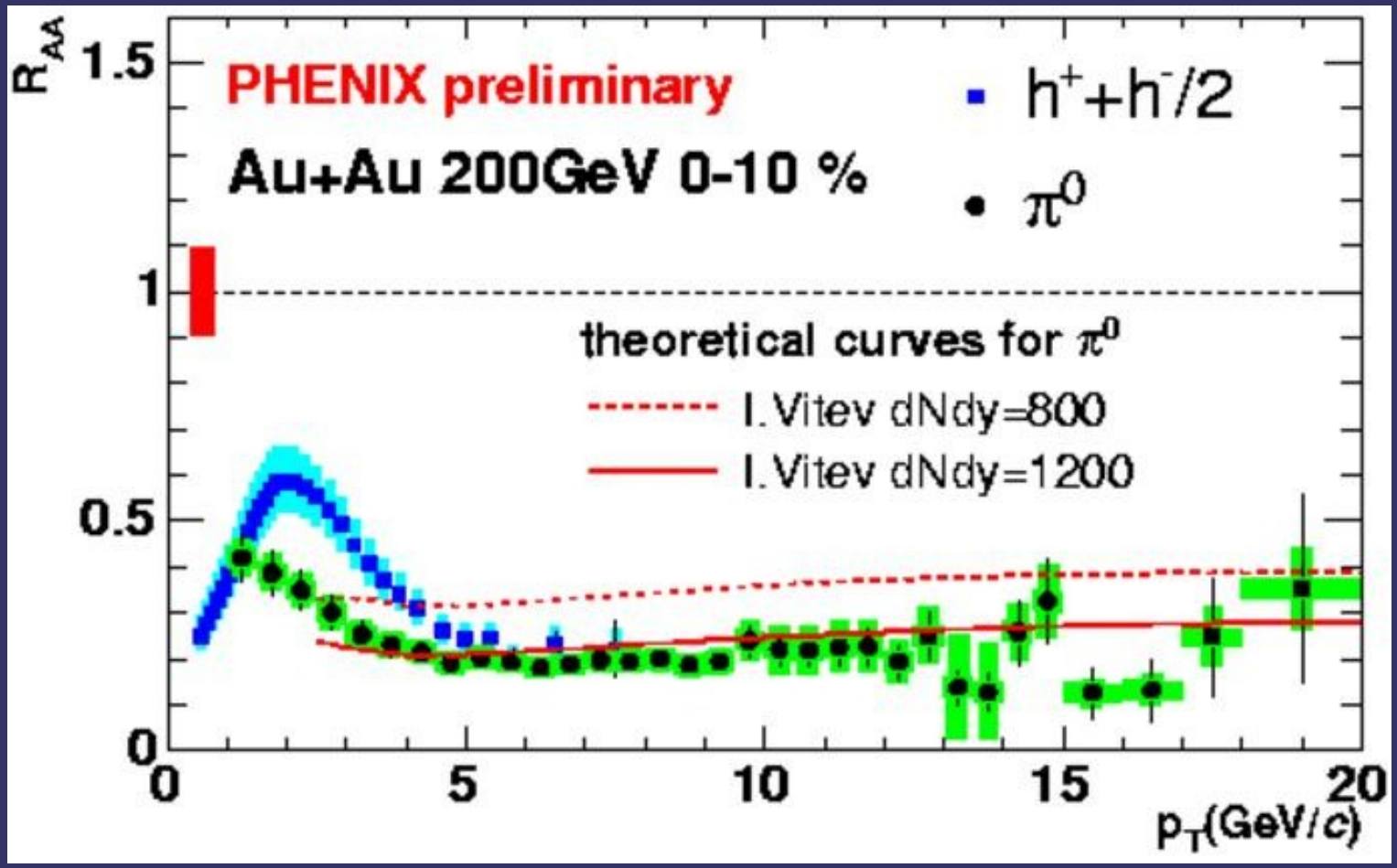
PRL **96** 202301 (2006)

New Au+Au π^0 Data

- **RHIC Run04 Au+Au data**
- **Sampled 1370 μb^{-1}**
  - 1.5 B events (15 × Run02)
- **Spectra up to 20 GeV/c**
- **p+p reference also improved**



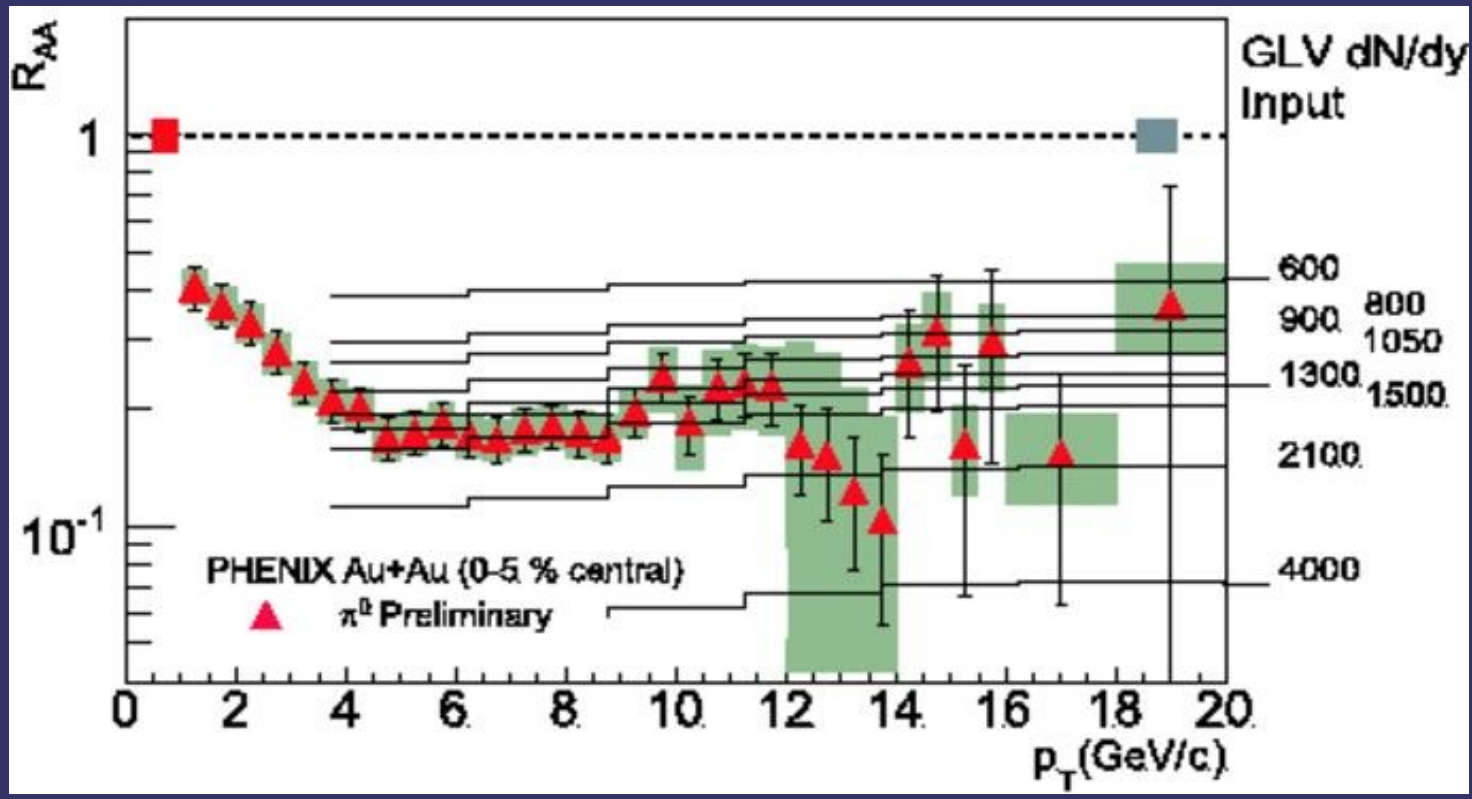
New R_{AA} in Au+Au



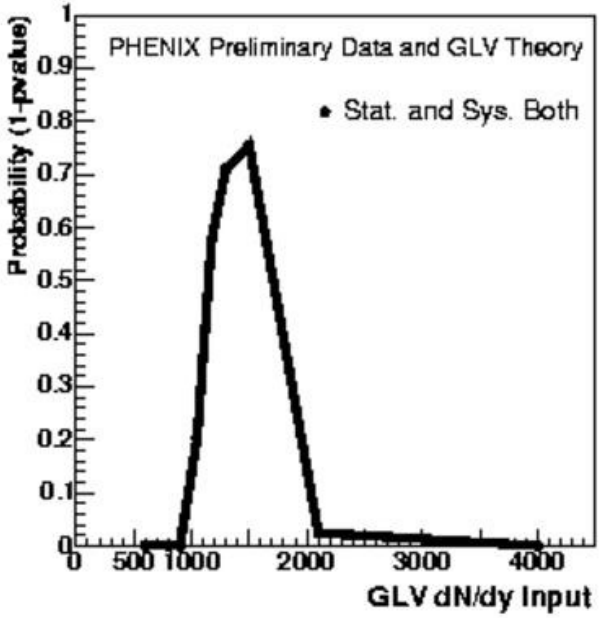
Suppression stays nearly constant up to 20 GeV
Consistent with $dN_g/dy \sim 1200$ calculation

Testing Theory with Data

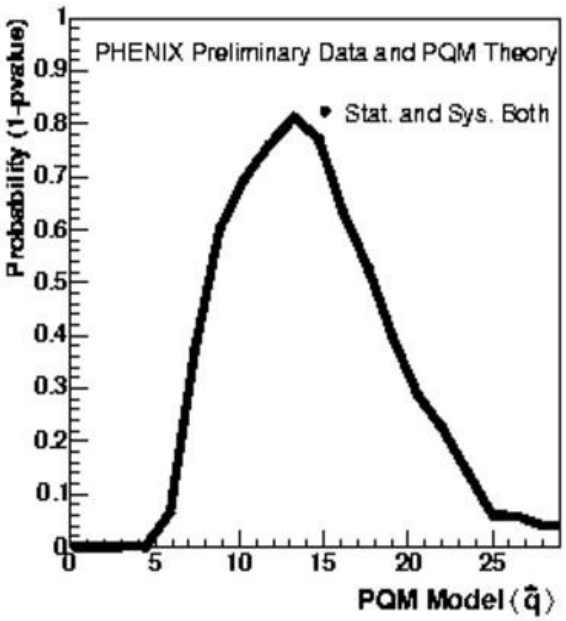
- **Precision data helps to constrain energy loss parameters**
  - E.g. χ^2 test of different gluon densities
  - Theory taken as truth, let data fluctuate according to their errors



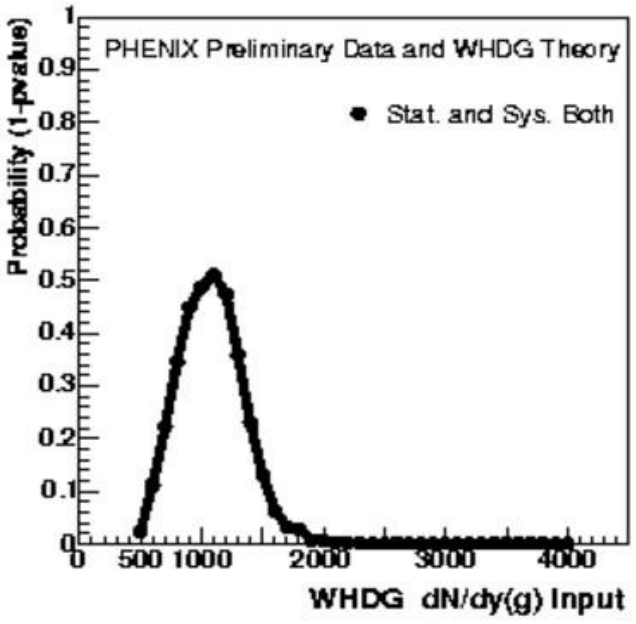
Probability Distributions



Gluon Density
Gyulassy PRL 89 252301 (2002)



Transport Coefficient (GeV^2/fm)
Loizides EPJ 49:339 (2007)

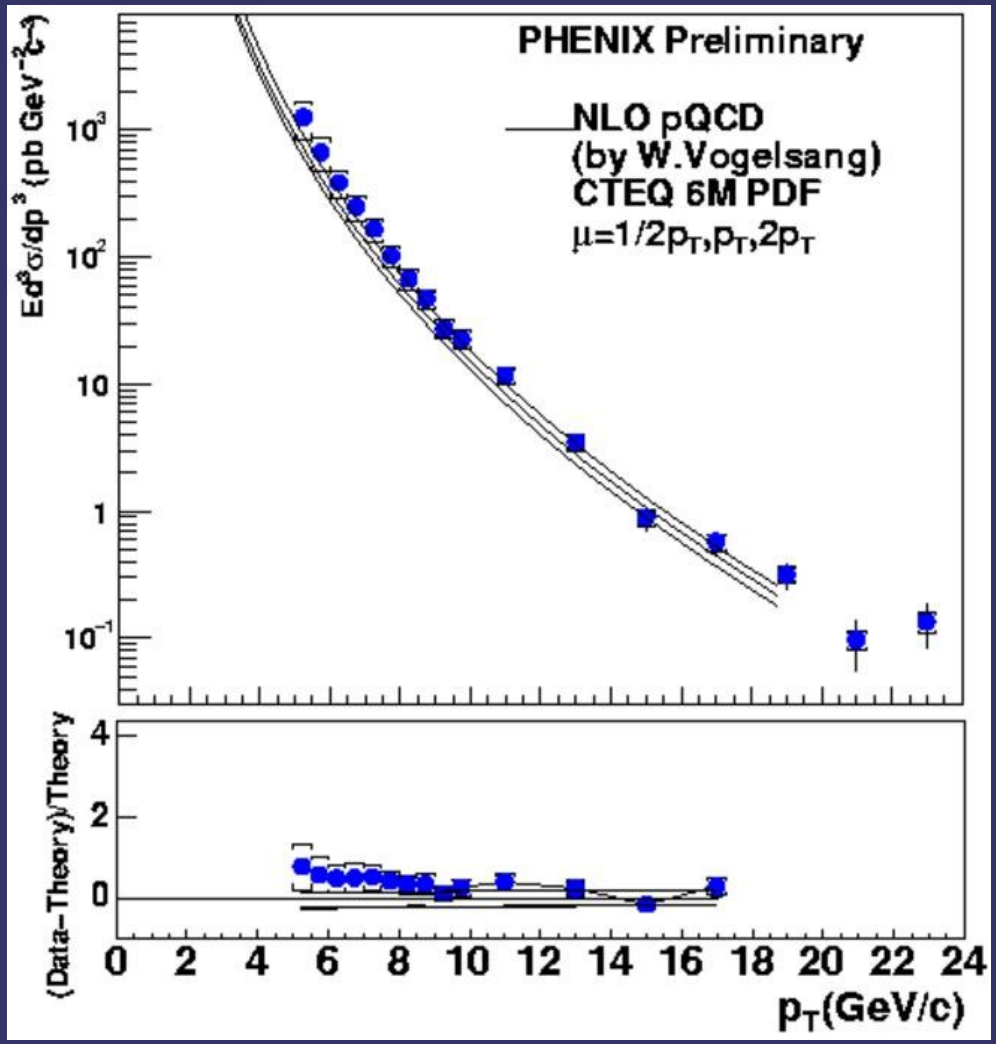


Gluon Density
Horowitz nucl-th/0512076

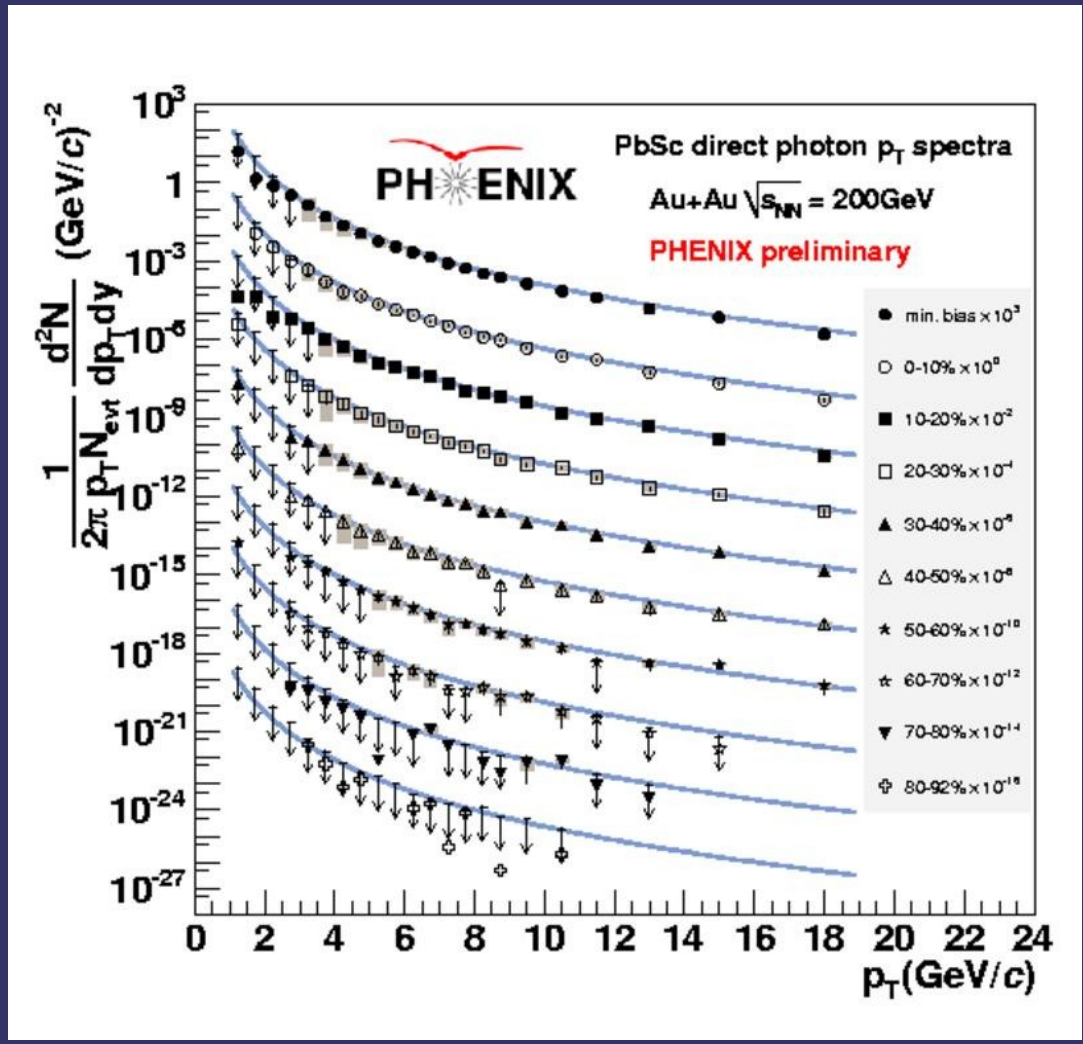
Single particle spectra provide quantitative theory constraints

New Direct Photon Data

p+p reference Run05



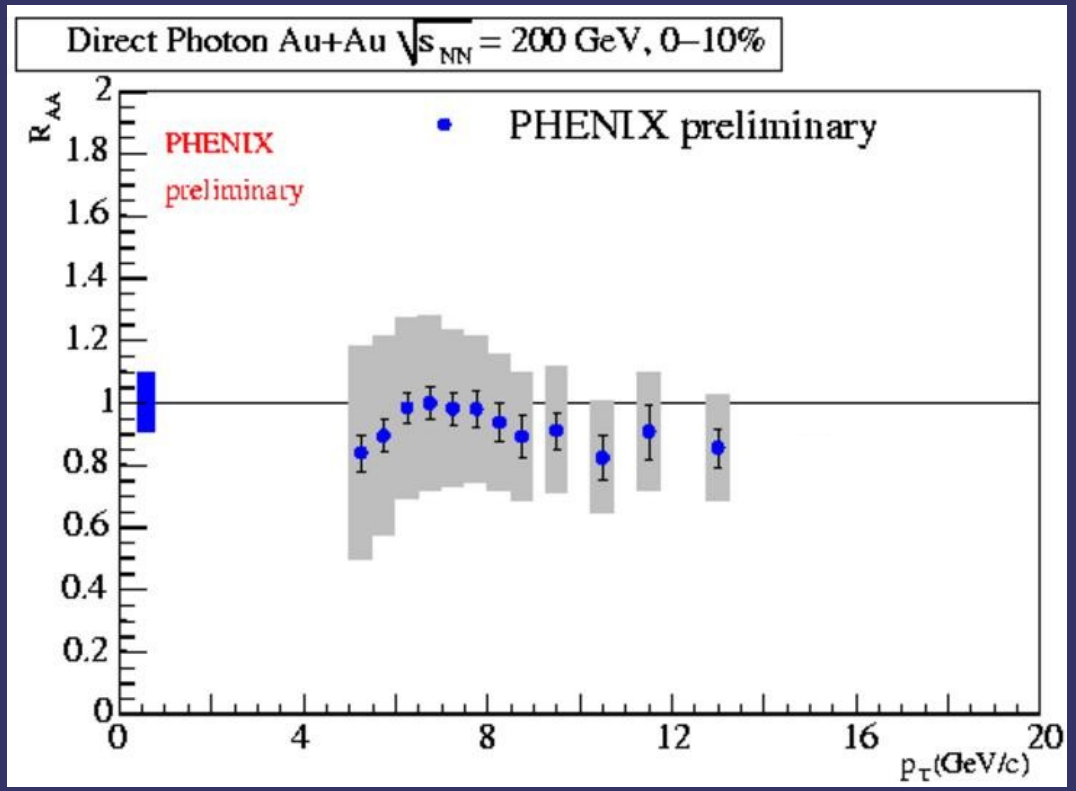
Au+Au Run04



New Direct Photon R_{AA}

- **Run02 result confirmed**
  - $R_{AA} = 1$ up to $p_T = 14$ GeV/c
  - Now measured reference
- **Highest p_T**
  - Decreasing trend
  - Trivial isospin effect?

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



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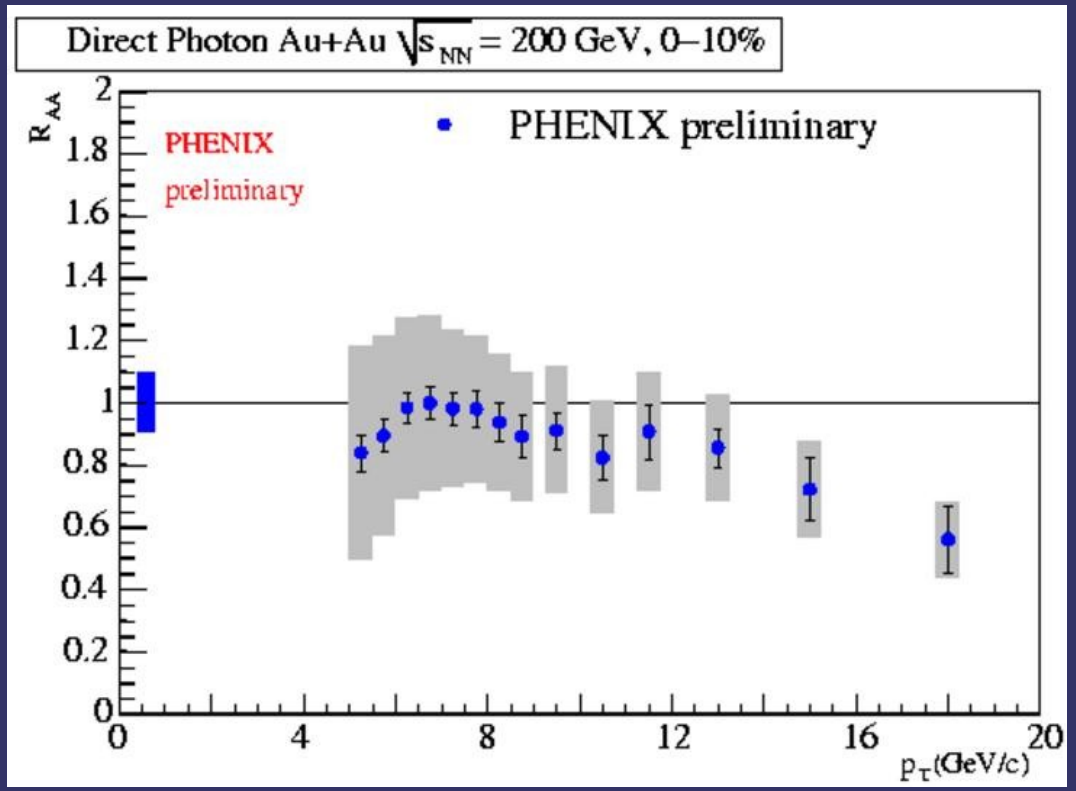
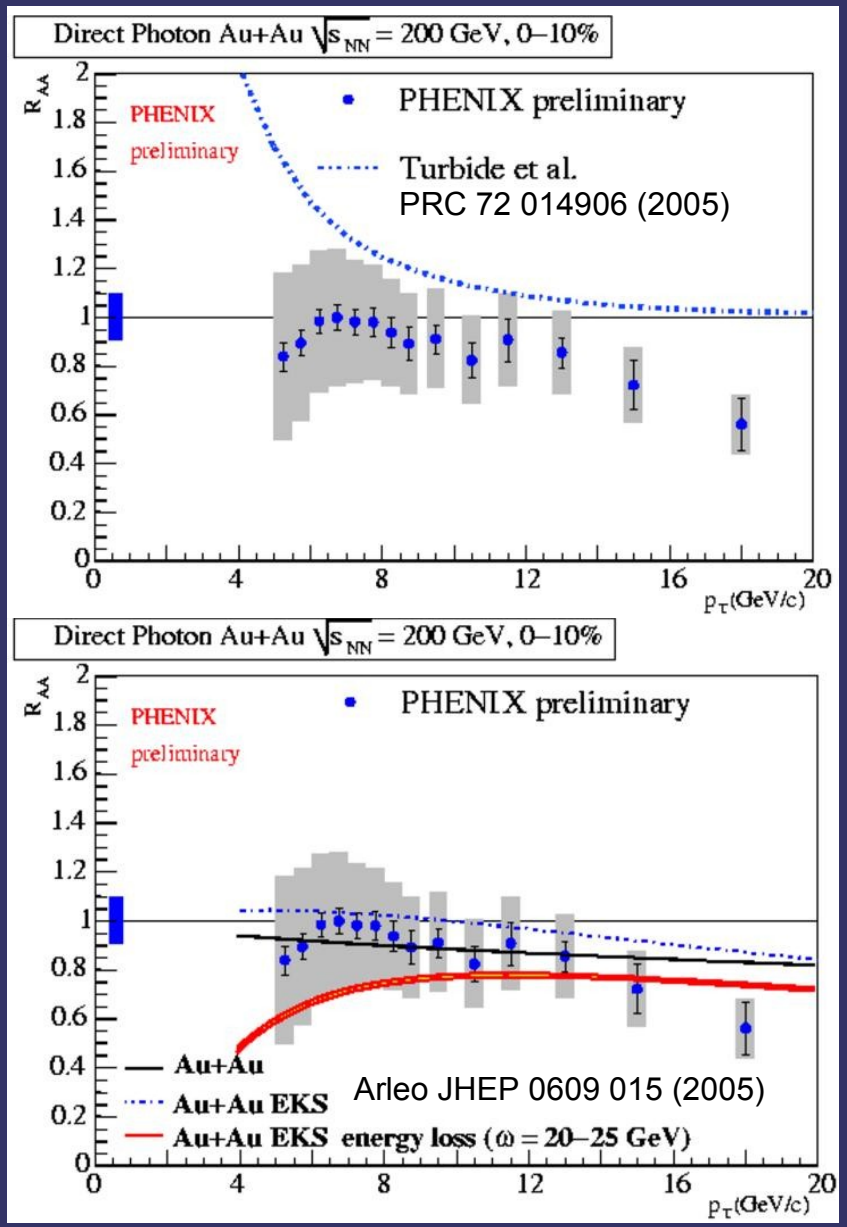


$$x \approx x_T = \frac{2\,p_T}{\sqrt{s_{NN}}} = \frac{p_T}{100}$$

Theory Comparison

- **Turbide et. al**
  - Shadowing
  - Fragmentation, energy loss
  - Thermal photons and medium induced photons
  - No isospin effects
- **Arleo**
  - Shadowing, energy loss
  - Isospin considered
  - No medium induced photon bremsstrahlung

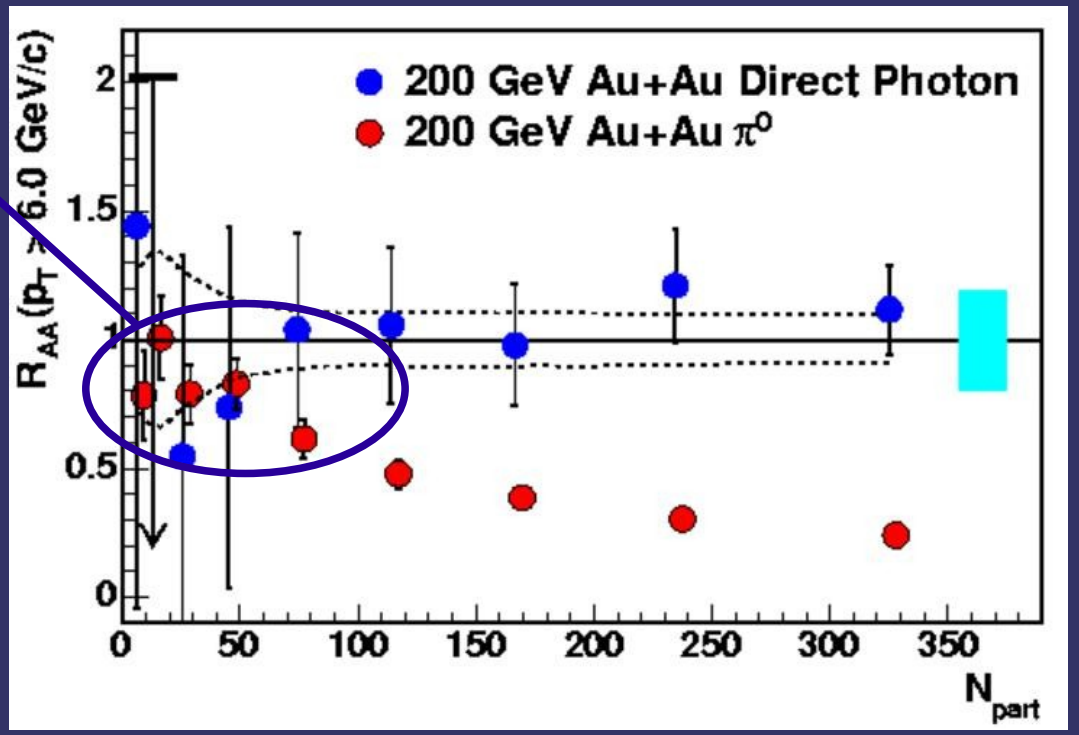
Isospin likely explanation
Experimental confirmation needed



System Size Dependence...
RHIC Run05 Cu+Cu

System Size Dependence

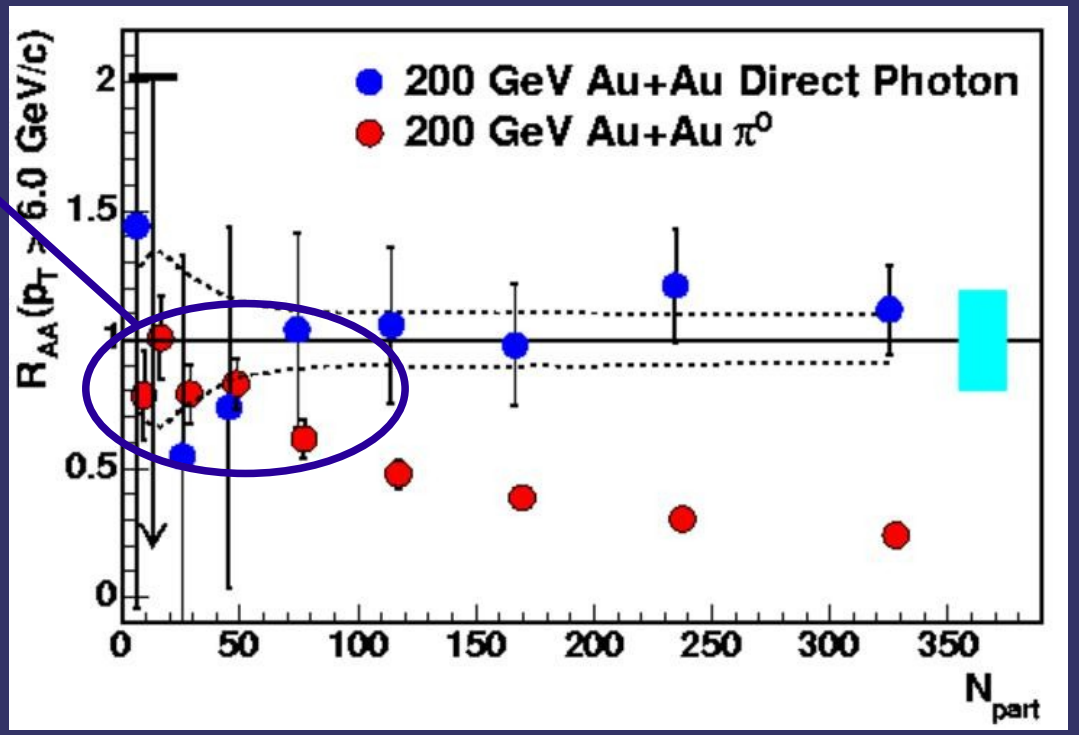
- **Variation of centrality**
  - Onset of suppression: $N_{part} \approx 50$
  - No good discrimination in Au+Au



PRL **94**, 232301 (2005)

System Size Dependence

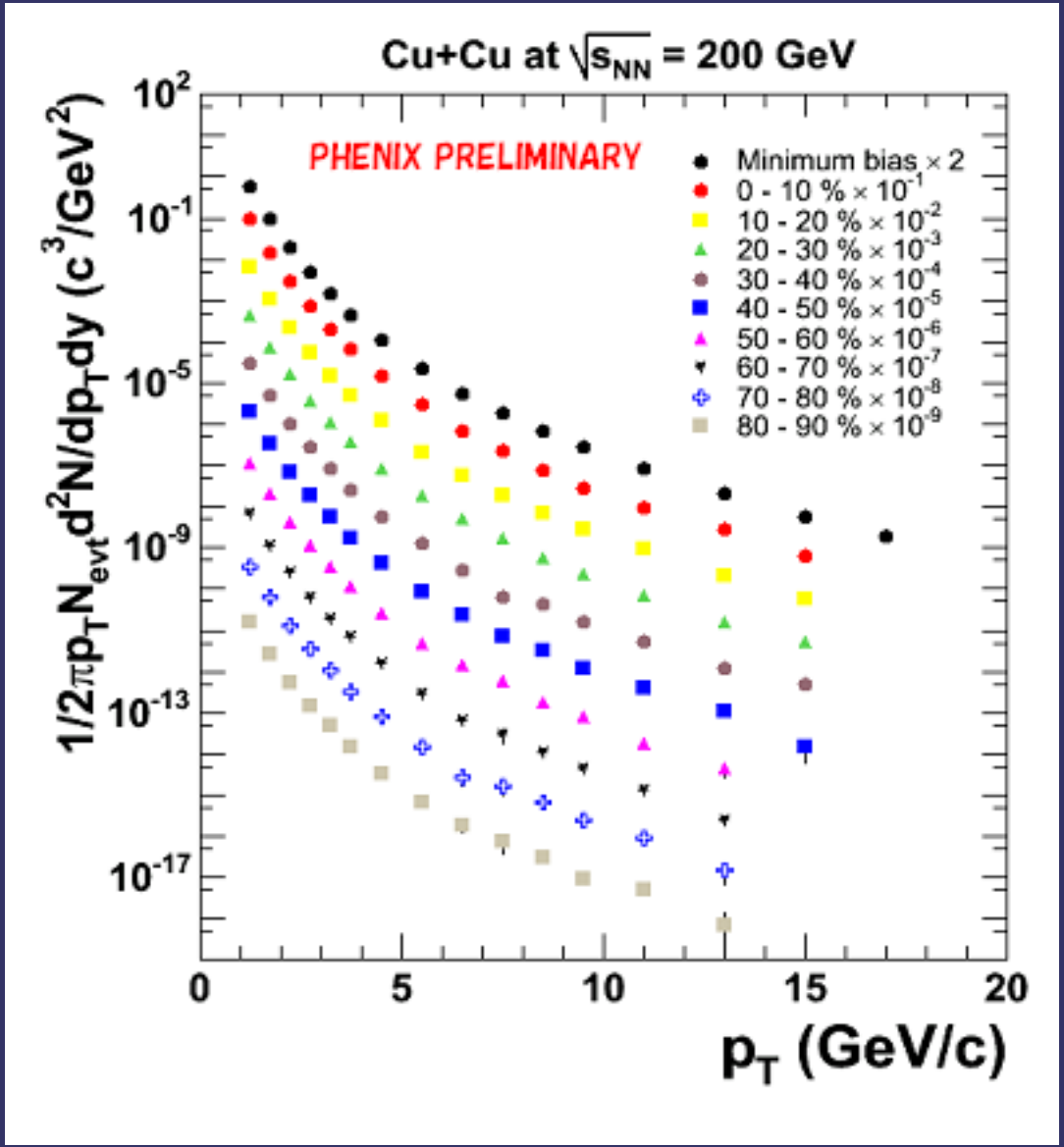
- **Variation of centrality**
  - Onset of suppression: $N_{part} \approx 50$
  - No good discrimination in Au+Au
- **Cu+Cu ($A = 64$)**
  - Better N_{part} "resolution"
  - Different geometry
    - Surface/volume effects



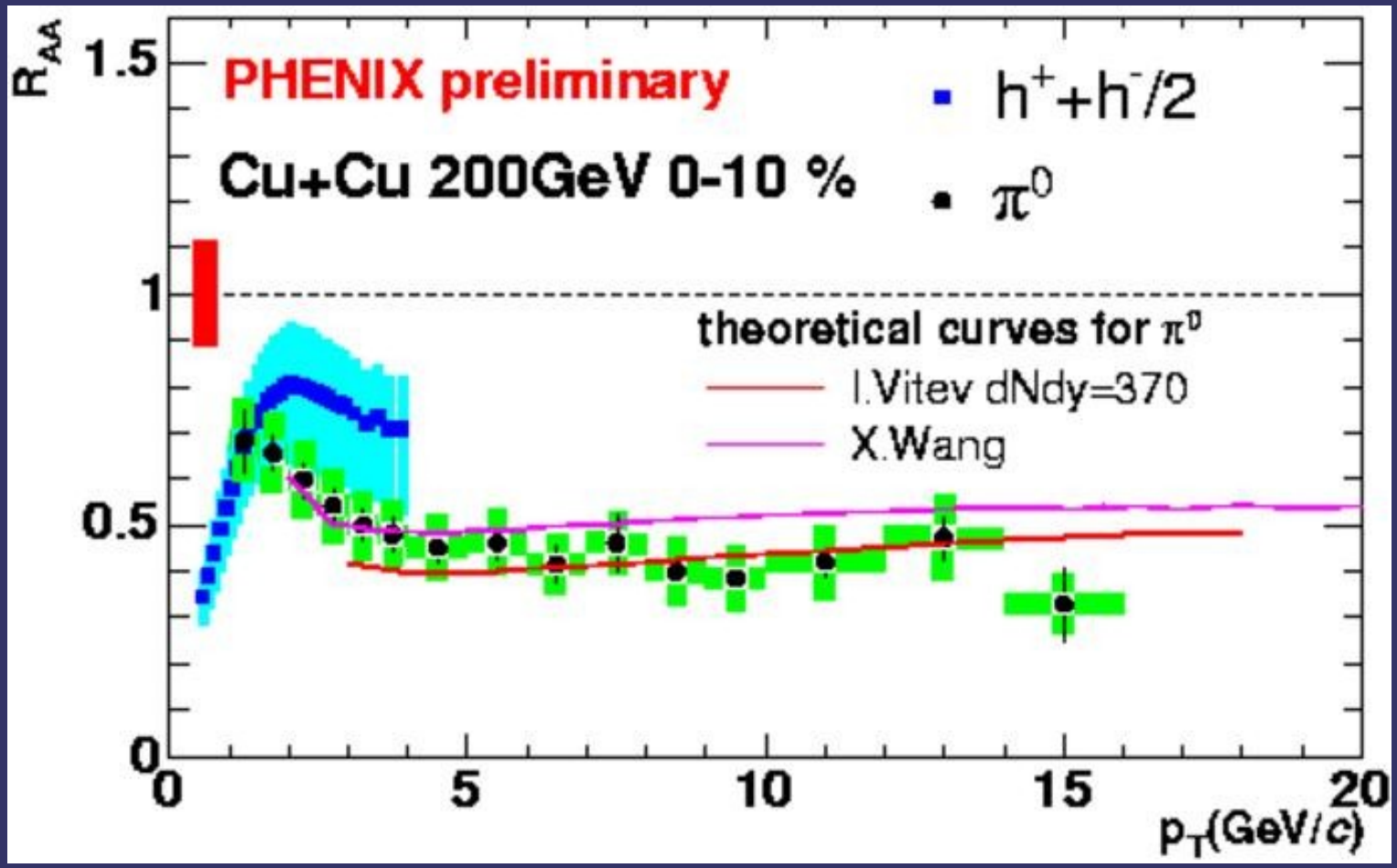
PRL **94**, 232301 (2005)

π^0 Measurement in Cu+Cu

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

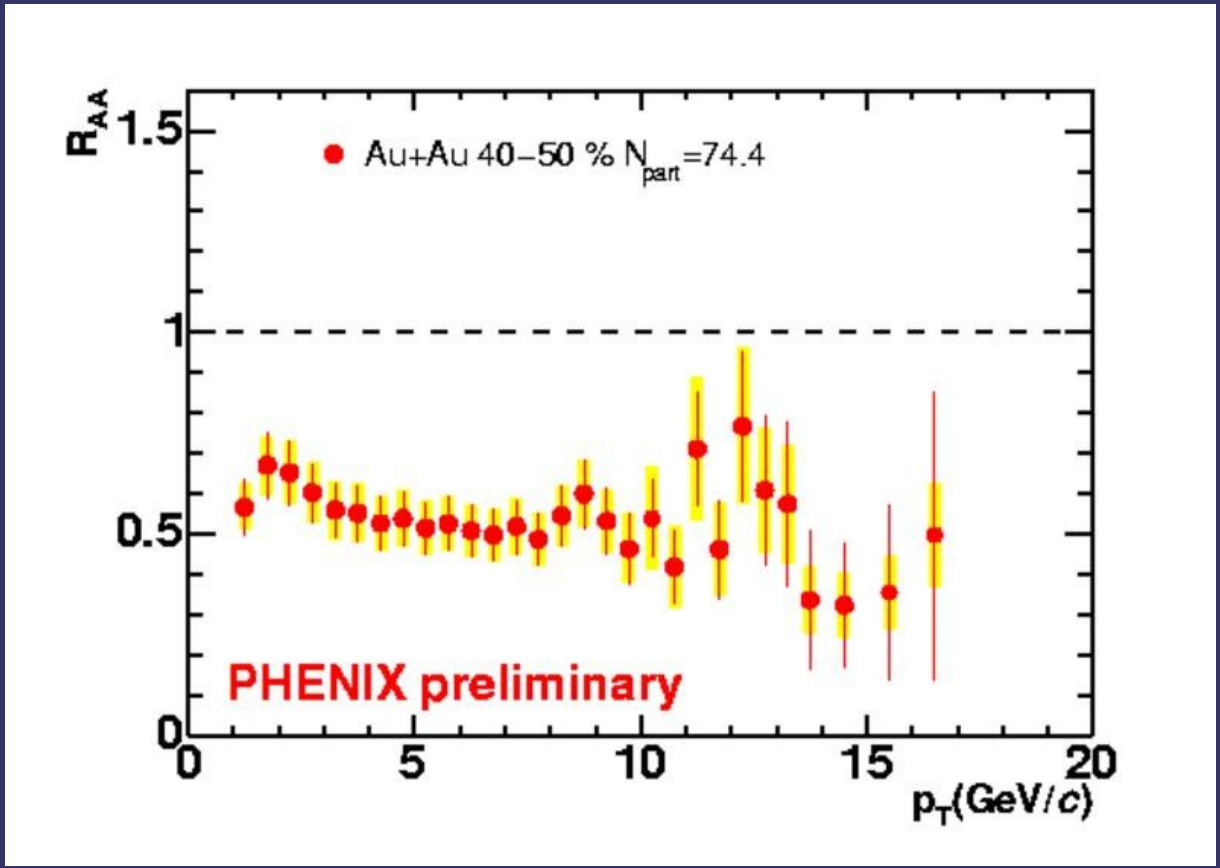


R_{AA} in Cu+Cu

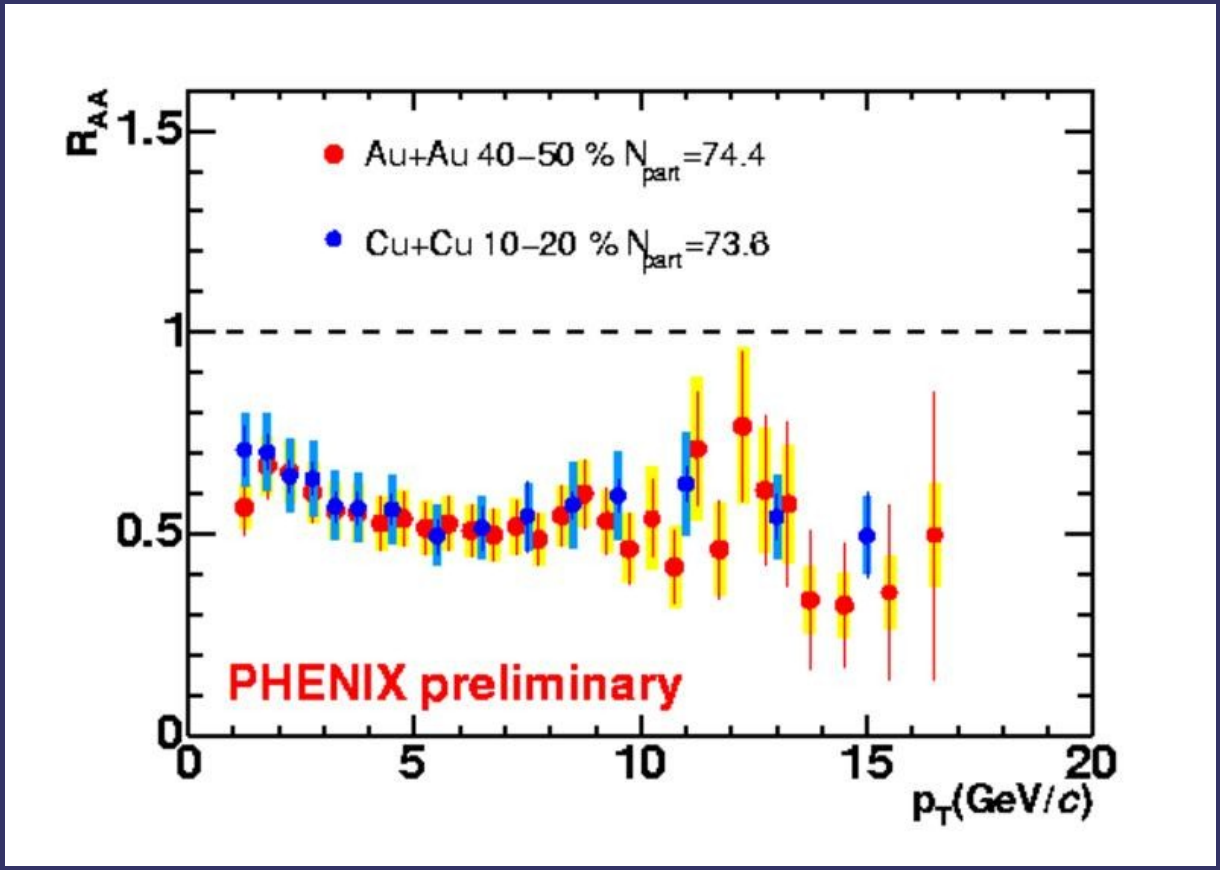


Central Cu+Cu also suppressed
Consistent with energy-loss calculation $dN_g/dy = 370$

Au+Au vs. Cu+Cu


R_{AA}
1.5
1
0.5
0
Au+Au 40–50 % N_{part}=74.4
PHENIX preliminary
0
5
10
15
20
p_T(GeV/c)

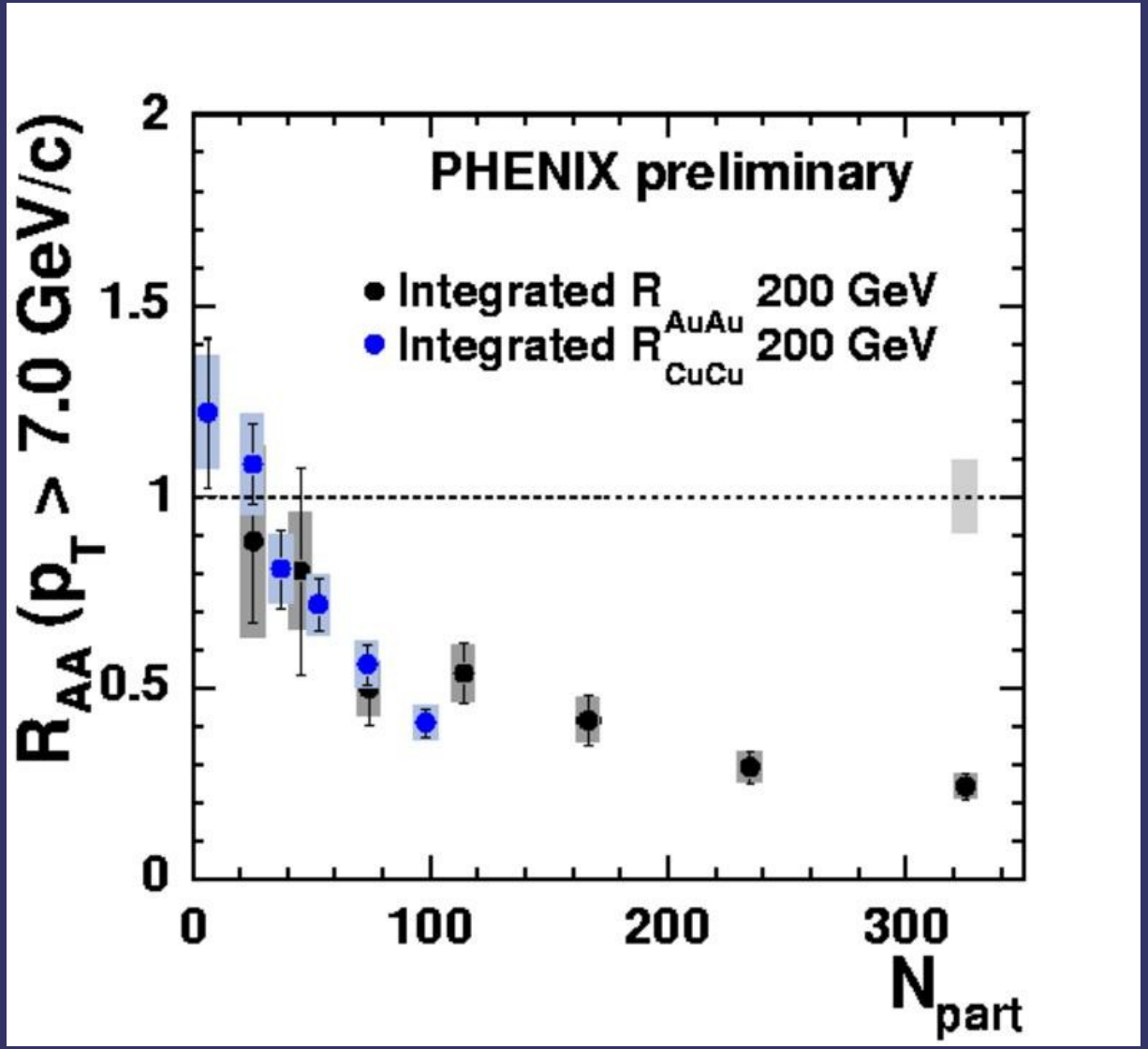
Au+Au vs. Cu+Cu



Suppression pattern identical at same N_{part}

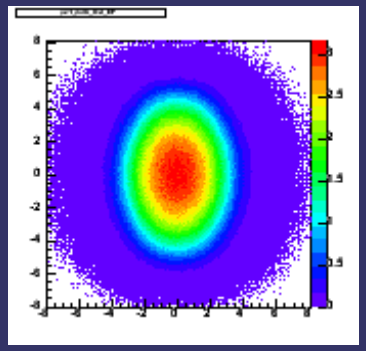
Centrality Dependence Integrated R_{AA}

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

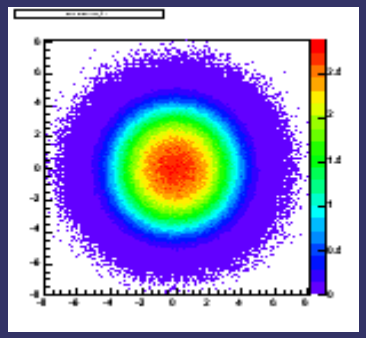


Centrality Dependence Integrated R_{AA}

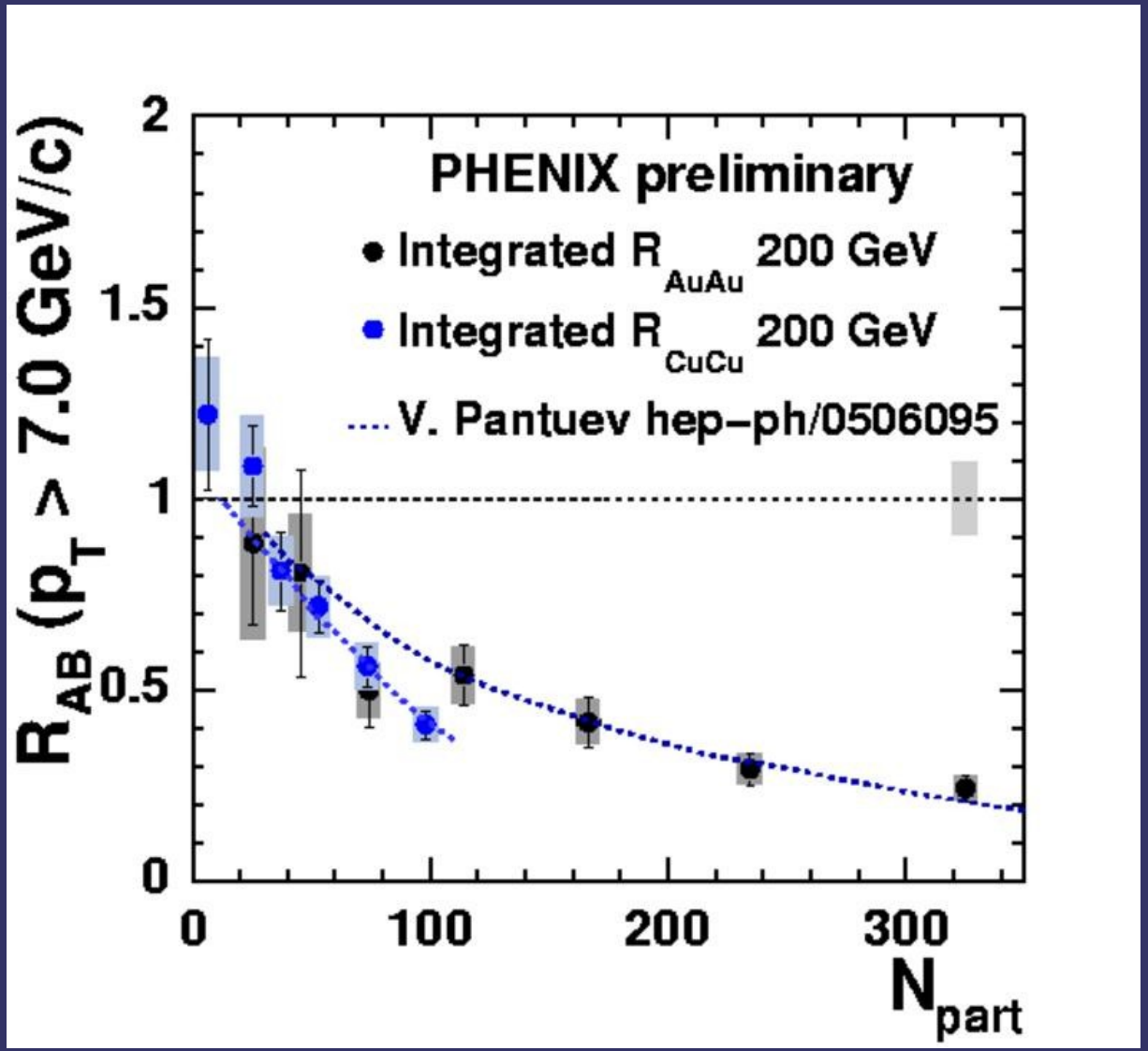
- **Geometrical model with "corona" effect**
  - More jets from surface
  - Correlated with ellepticity
    - Minimal for sphere



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



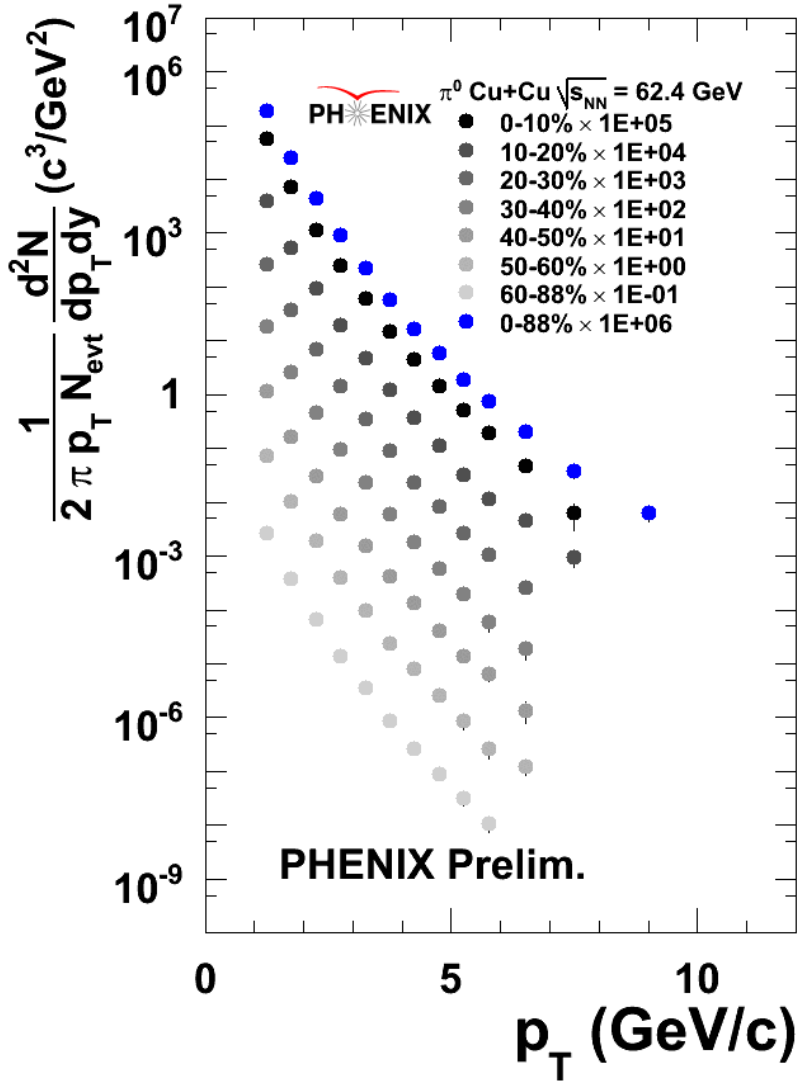
Cu+Cu
0-10%
N_{part} = 98.2



Energy Dependence...
Going down!

Cu+Cu @ 62.4 GeV

- **14 days in RHIC Run05**
  - 197 M Minimum bias events
- **Problem:**
  - Poor p+p references
    - ISR data
    - 25% uncertainty
    - Shape
  - p+p @ 62.4 GeV measured in Run06 is on the way



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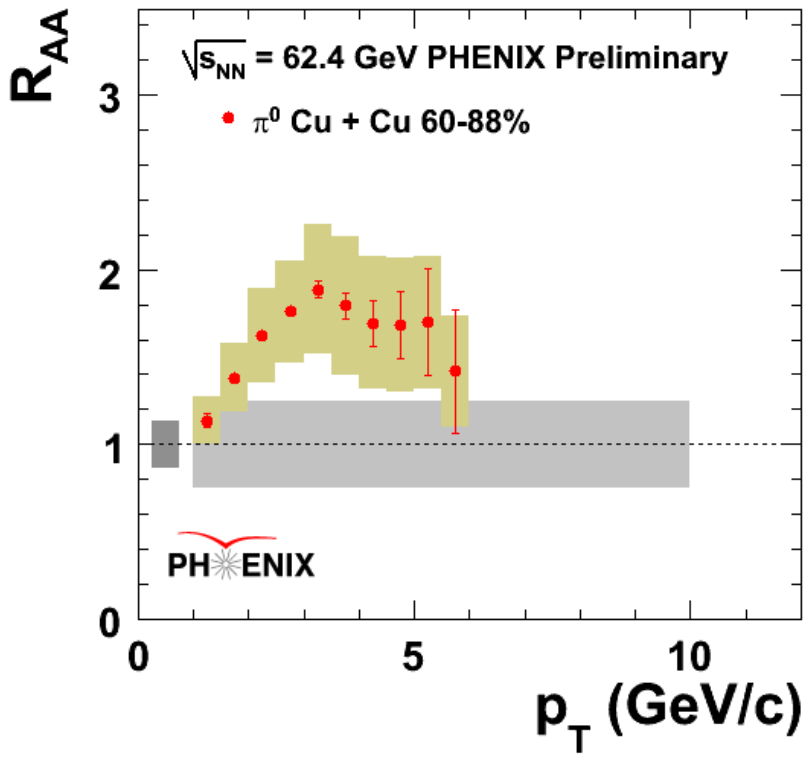

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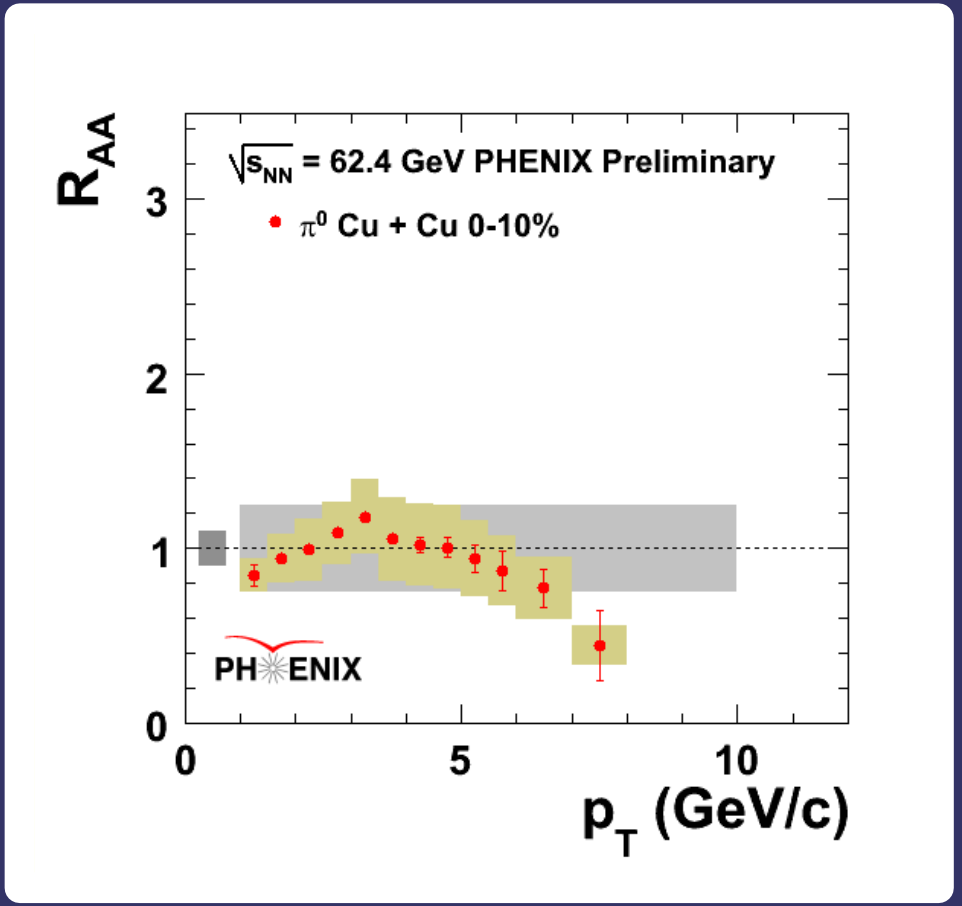
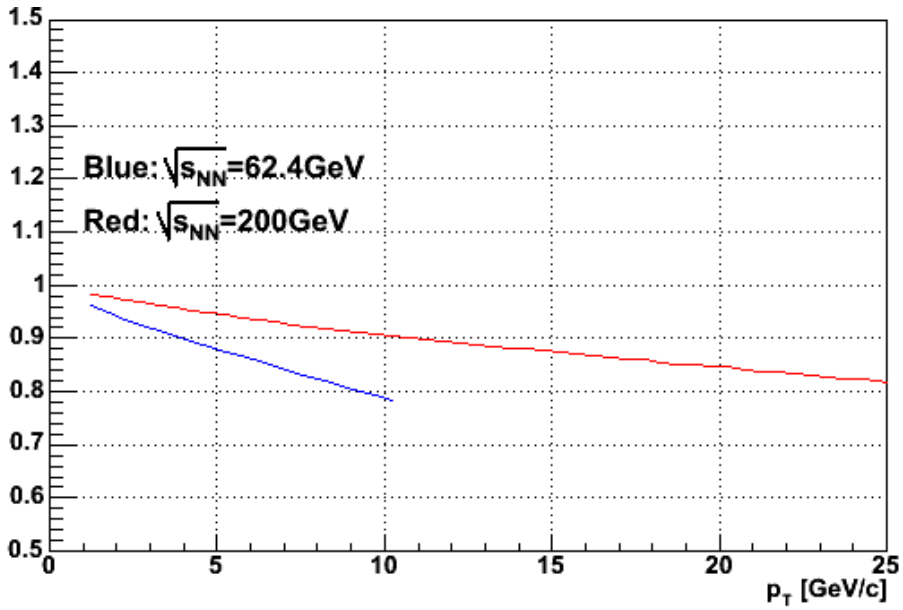


Clear effect when going from peripheral to central

Direct Photons?



Mock-up R_{AA}

A+A: Superposition of pQCD (p+p. p+n, n+n)
pQCD (p+p)

- **At high *x* quark distributions become dominant**
  - Difference for em-processes in n+p, p+p and n+n scattering at high p_T

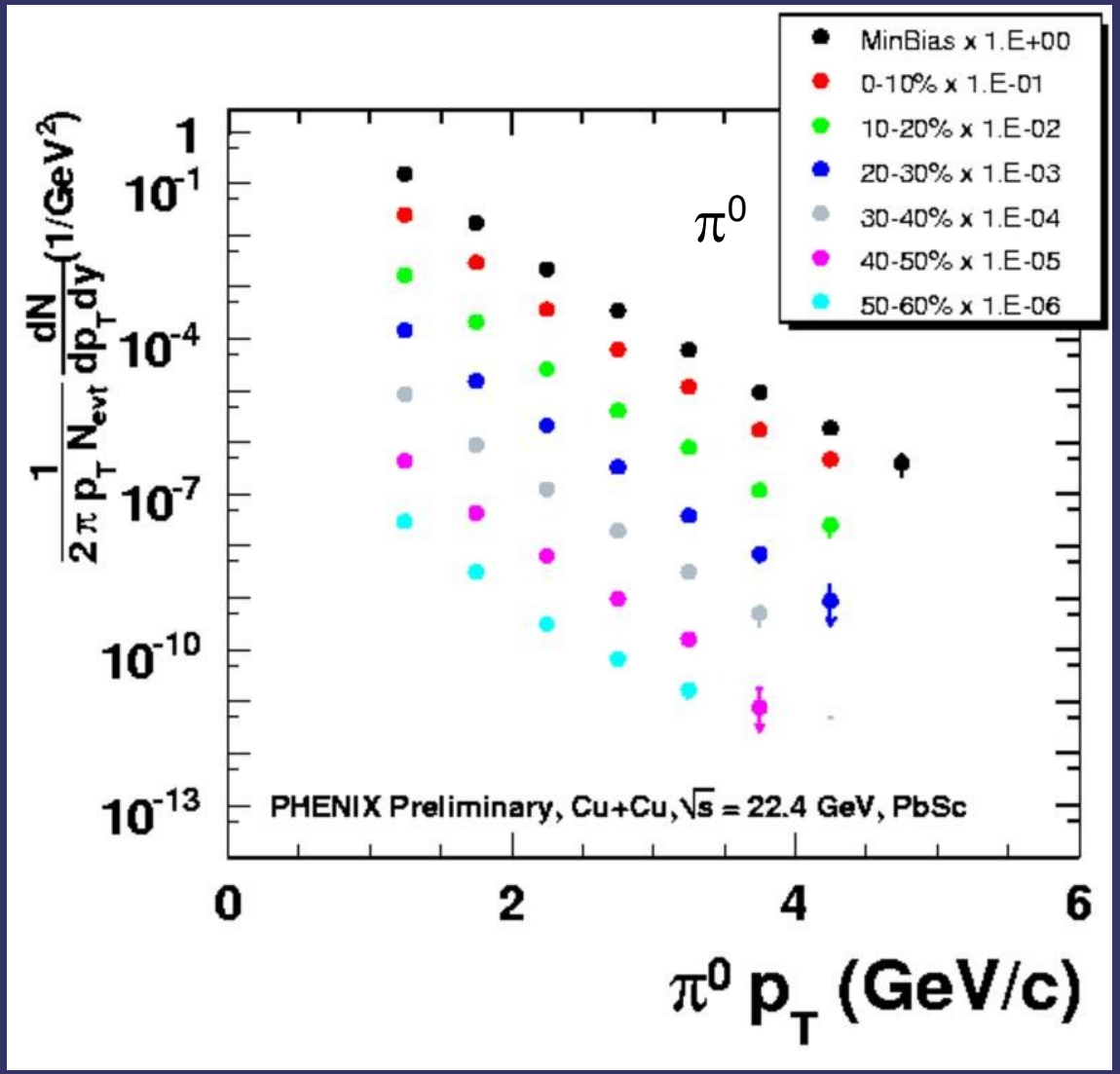
$$x \approx x_T = \frac{2\,p_T}{\sqrt{s_{NN}}}$$

- **Go to lower energies**
  - Study SAME effect at lower p_T
  - Systematic uncertainties smaller in this domain

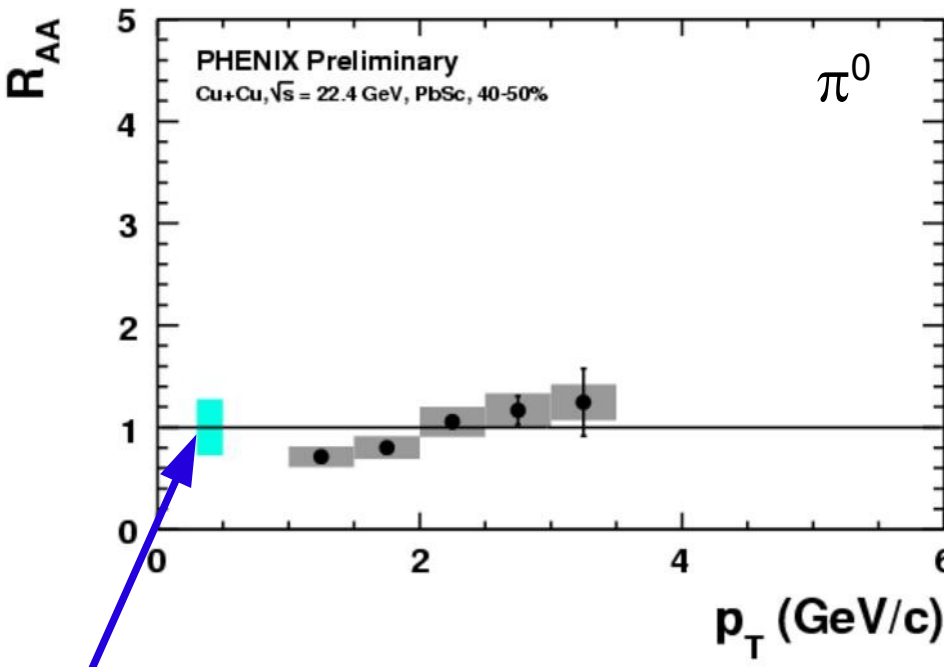
Data @ 62.4 GeV will be essential to separate isospin effect

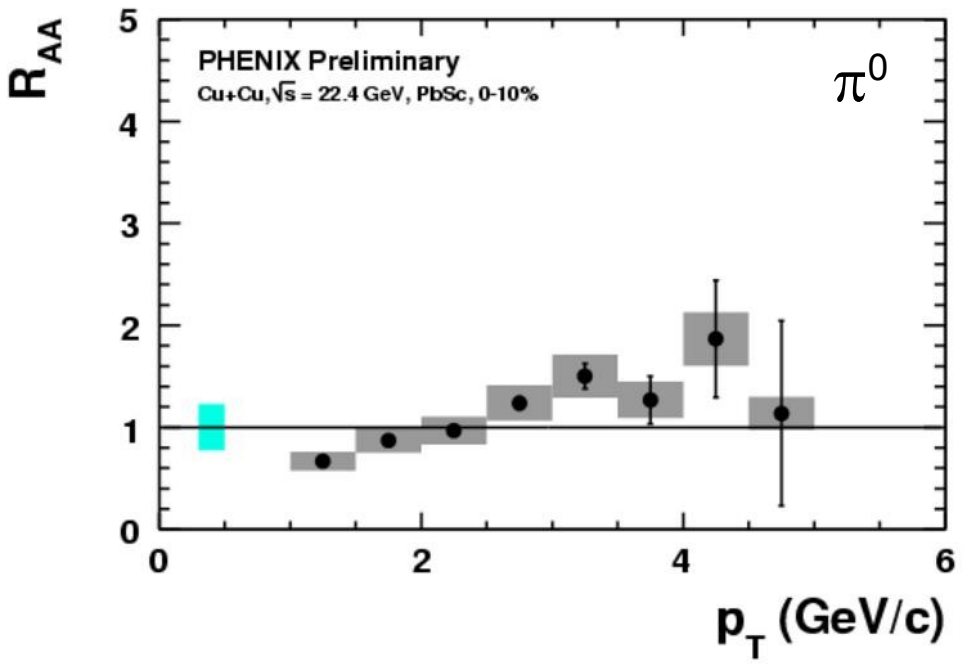
Cu+Cu @ 22.4 GeV

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



Cu+Cu @ 22.4 GeV





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

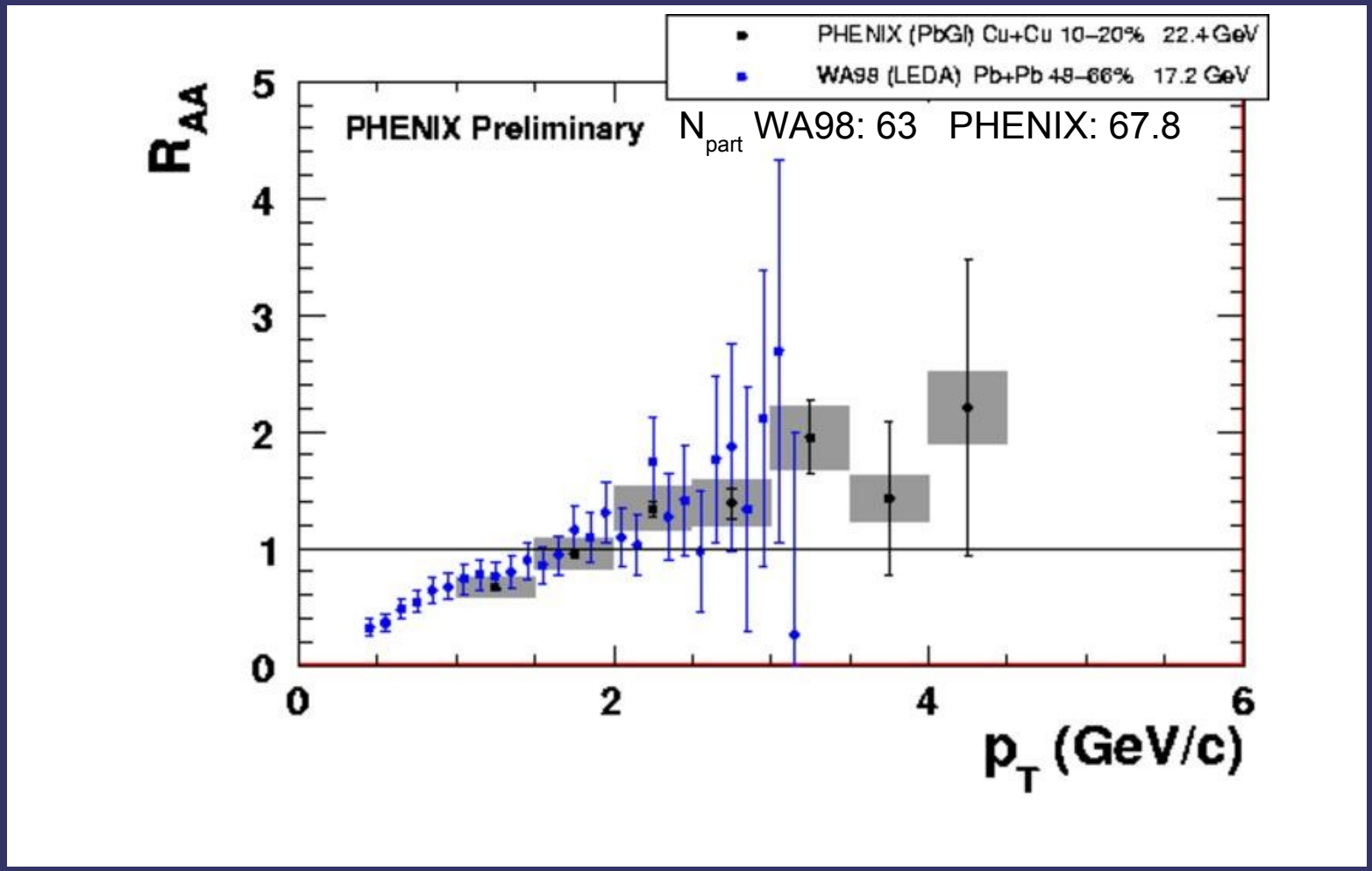
$N_{coll} = 140.7 \pm 14.8$ $N_{part} = 92.2 \pm 2.2$

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

No obvious centrality dependence

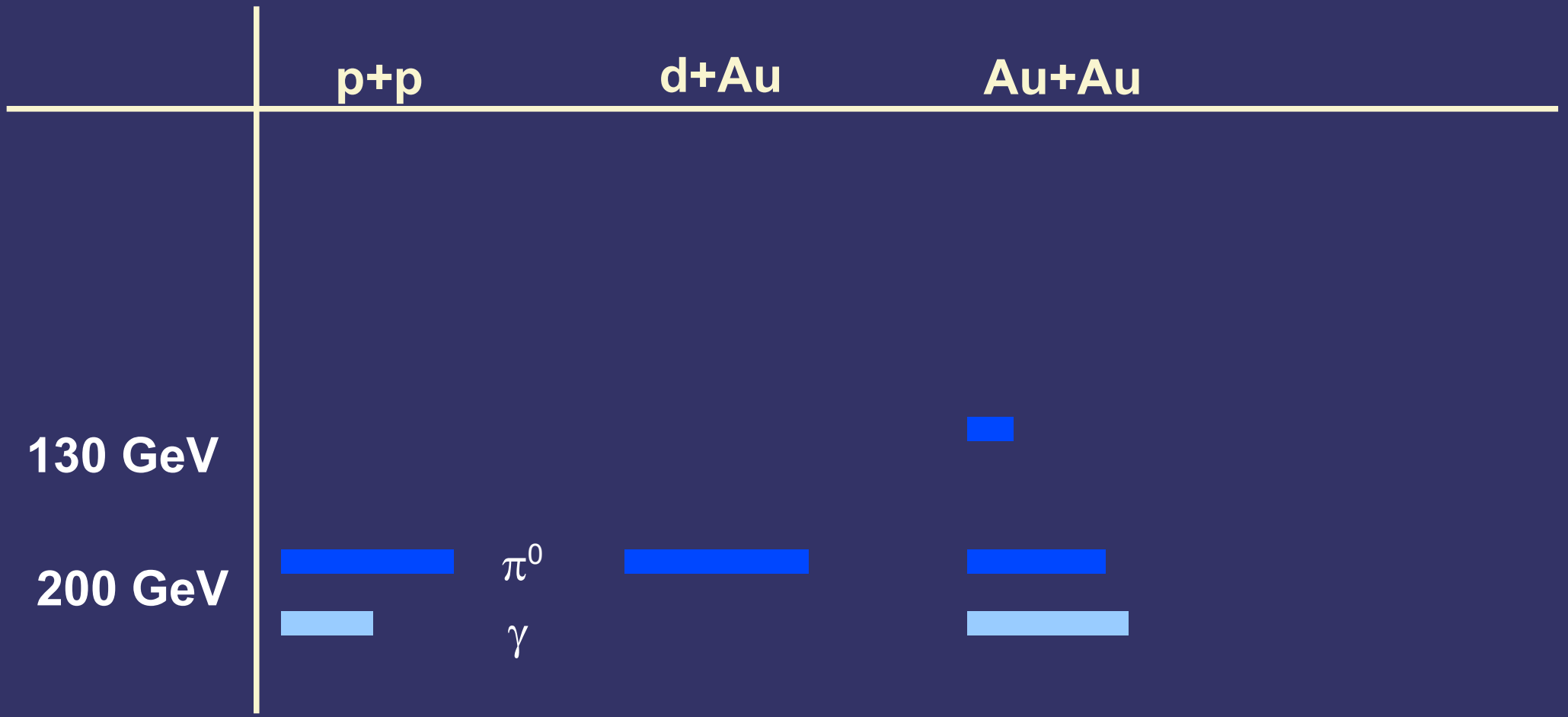
π^0 R_{AA} WA98 vs. PHENIX

We can do SPS Physics



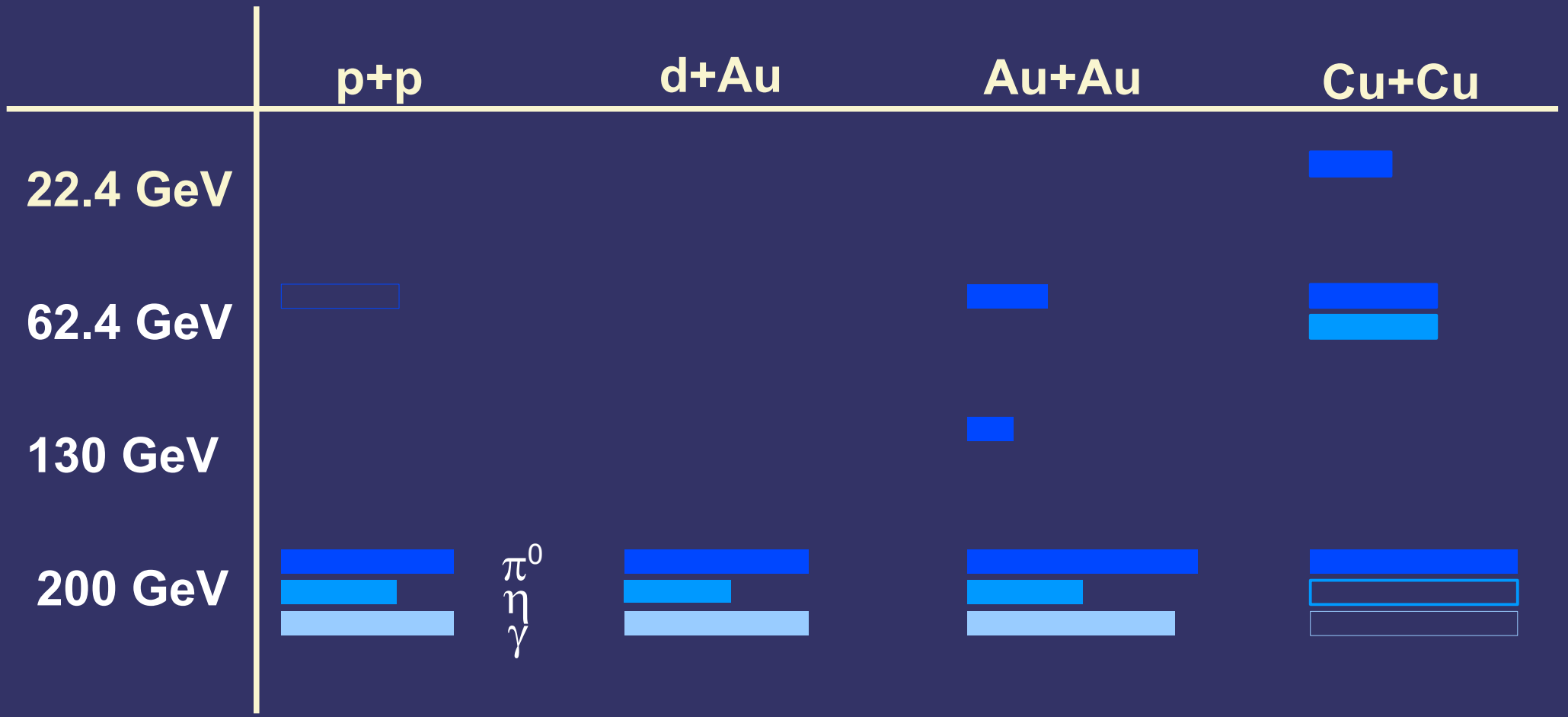
Similar N_{part}: same behaviour

Single Particle Spectra @ High p_T
The First Three Years



Christian Klein-Bösing

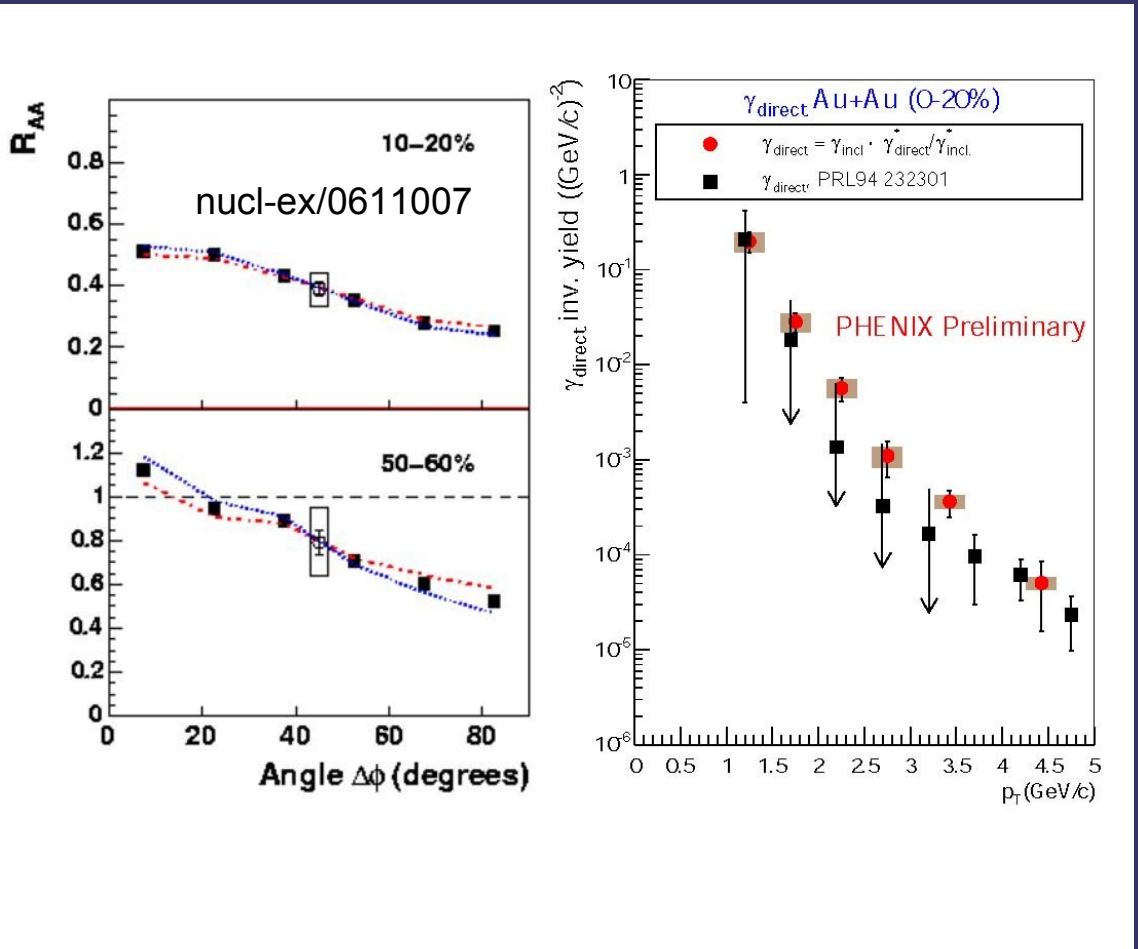
Single Particle Spectra @ High p_T Today



Summary

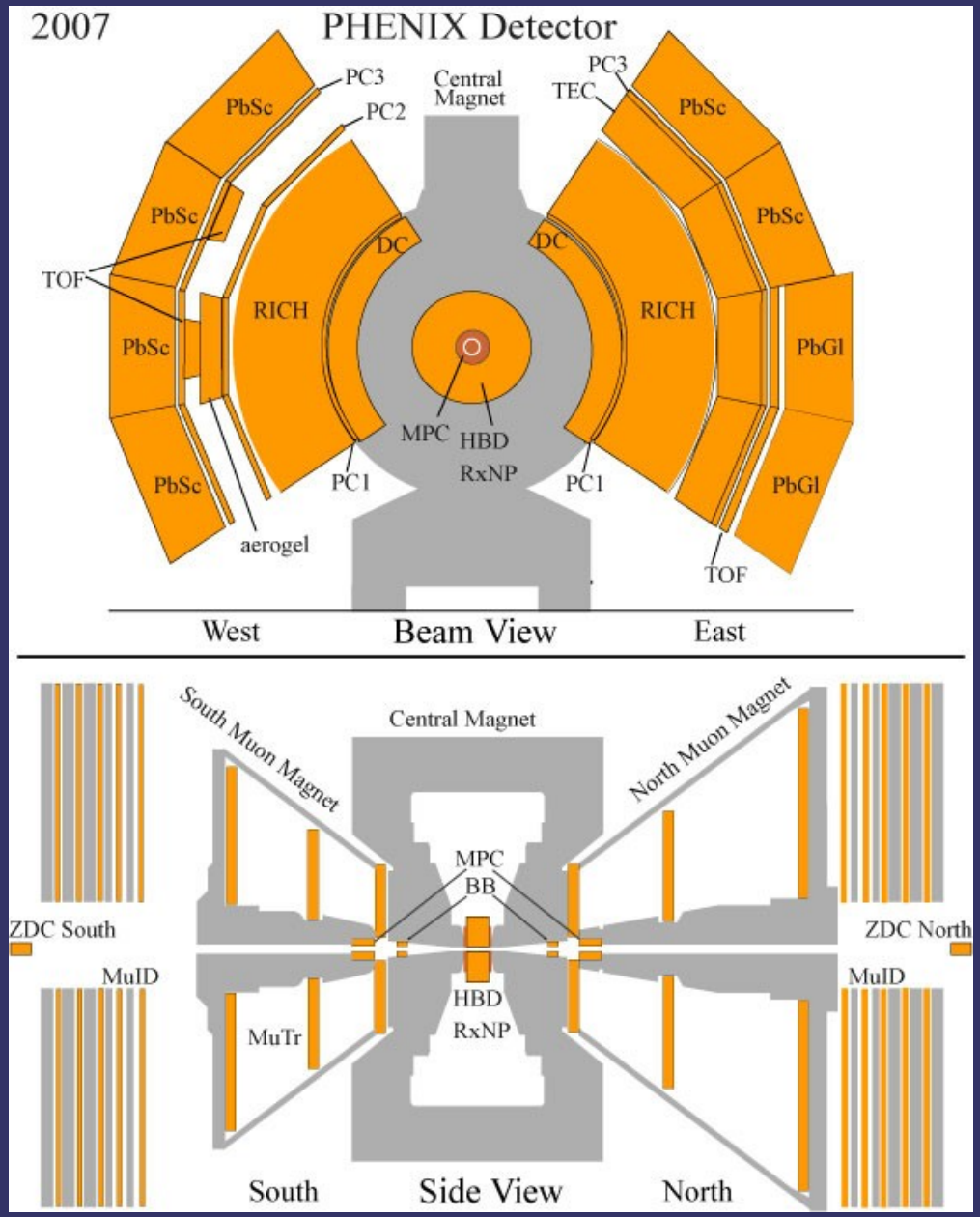
- **Jet Quenching**
  - p_T dependence
    - π^0 R_{AA} flat up to $p_T = 20$ GeV/c
    - η and π^0 show same suppression pattern
  - System size dependence
    - Similar R_{AA} for Cu+Cu and Au+Au for similar N_{part}
    - Hints for surface/corona effects
  - $\sqrt{s_{NN}}$ dependence
    - Follows expectation from energy-loss models
    - RHIC/PHENIX able to do SPS Physics
    - First systematic study of jet quenching from $\sqrt{s_{NN}} \sim 20 - 200$ GeV within the same experiment
- **Direct Photons**
  - No suppression over a wide p_T range
  - Deficit at high p_T
    - Suppression of fragmentation photons?
    - Isospin effect?

Side Glance / Outlook



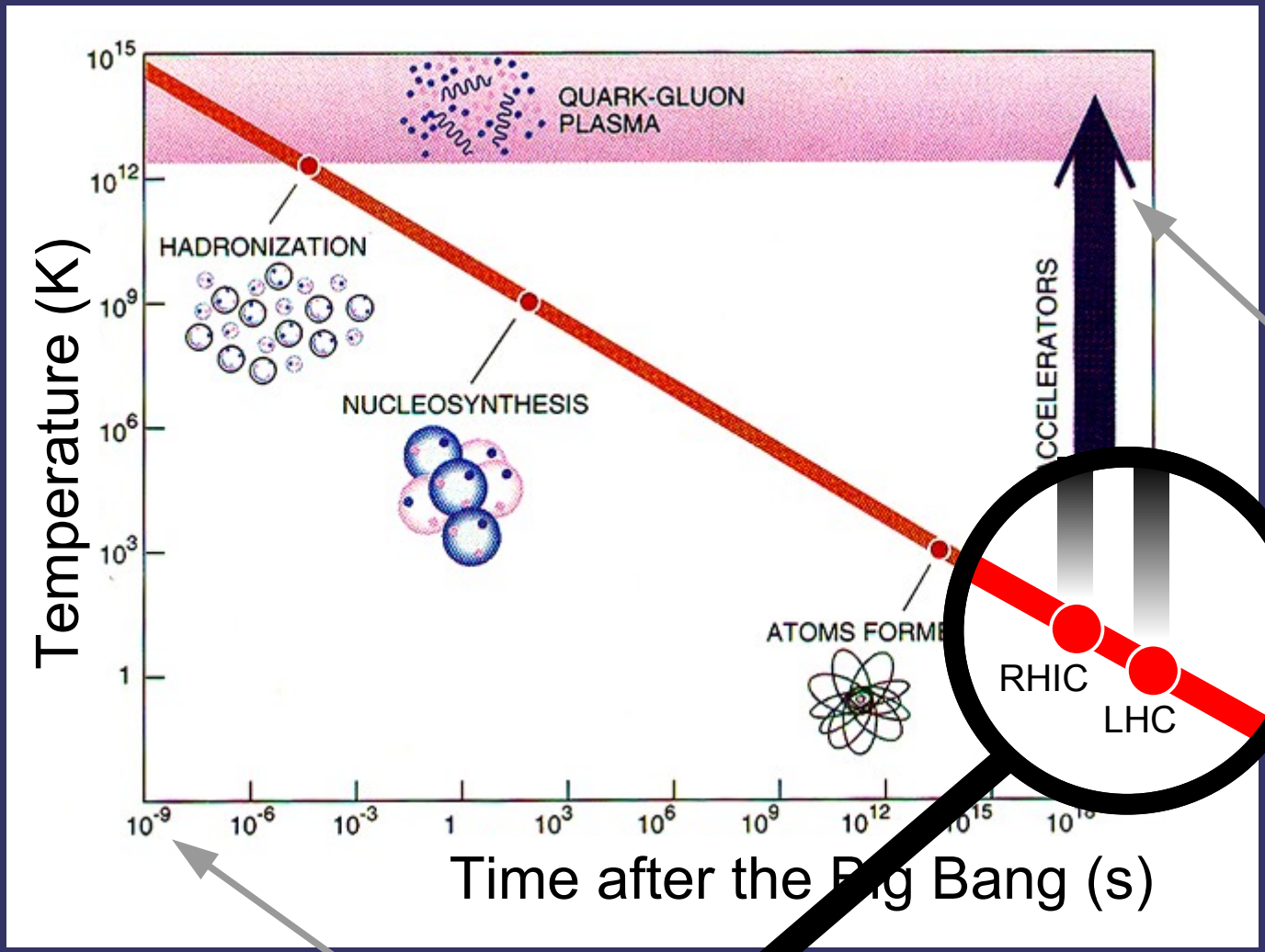
- **Many things not covered**
  - Reaction plane (*L*) dependence of R_{AA}
  - New methods for low p_T photons
    - Internal and external conversions
    - $\gamma\gamma$ correlations
  - Direct photon flow

Side Glance / Outlook

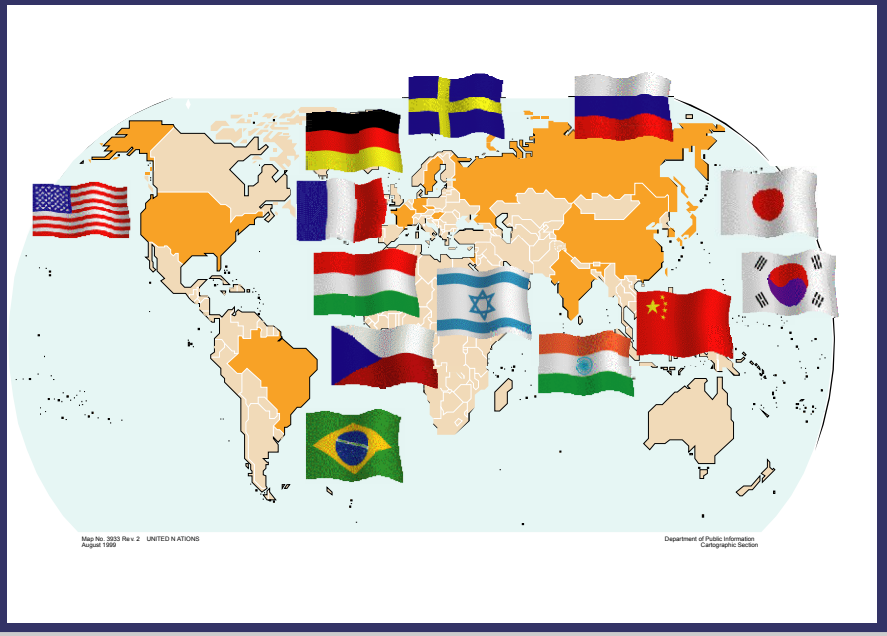


- **Many things not covered**
  - Reaction plane (L) dependence of R_{AA}
  - New methods for low p_T photons
    - Internal and external conversions
    - $\gamma\gamma$ correlations
  - Direct photon flow
- **Many more things to expect from PHENIX**
  - Major detector upgrades
    - Hadron Blind Detector
    - Reaction Plane Detector....
  - Run07 Au+Au is happening NOW

... to be continued



PHENIX



Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
Czech Republic	Charles University, Prague
	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
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	Rikkyo University, Tokyo, Japan
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	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
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	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
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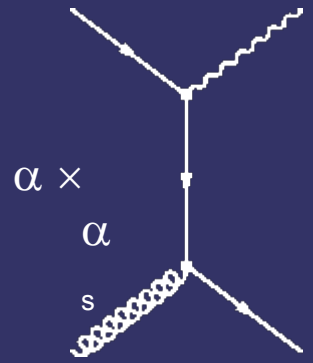
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

*as of March 2005

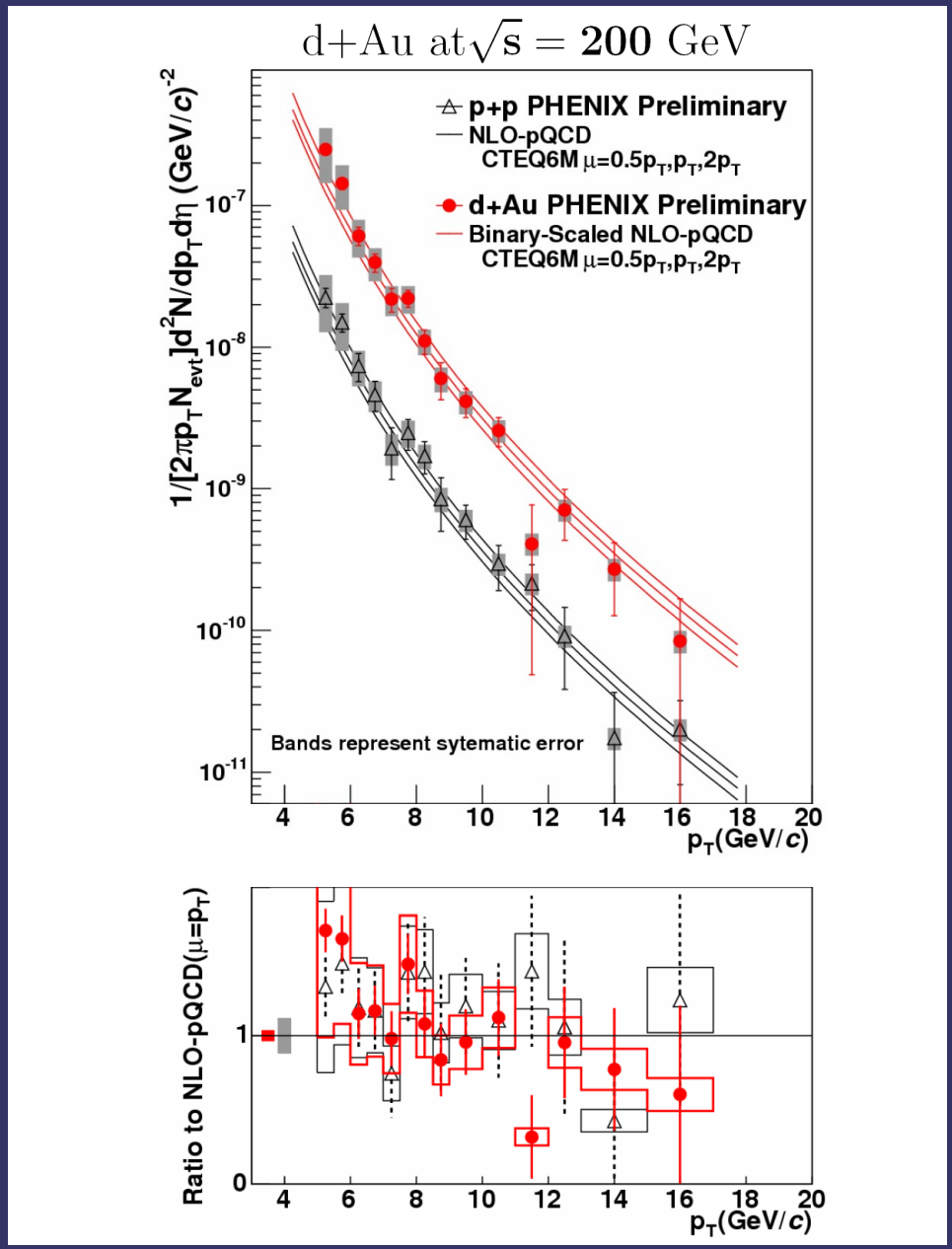
Backup Slides

Direct Photons in d+Au

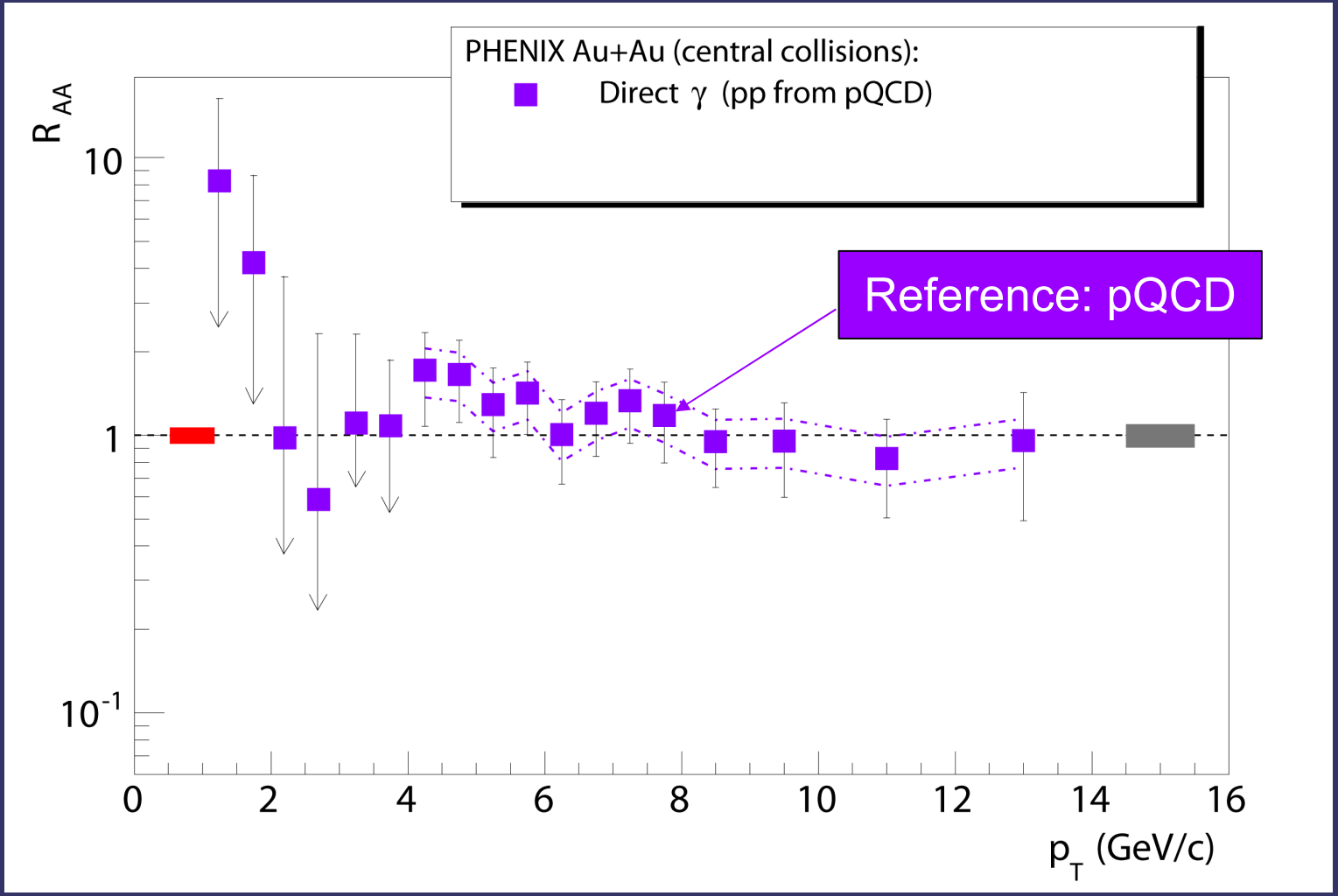
- **Directly sensitive to gluon distribution**



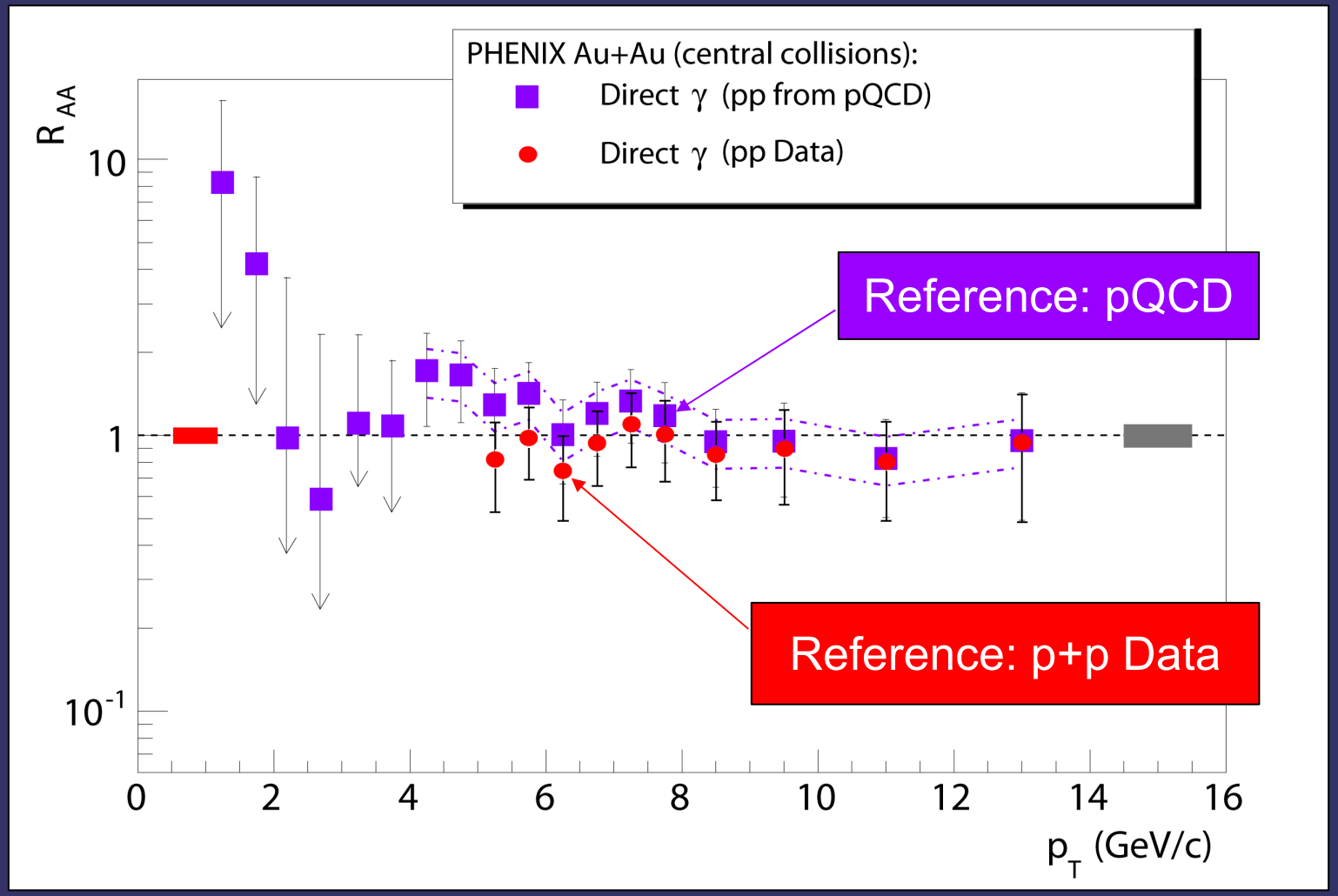
- **No effect at high p_T**
  - Large uncertainties



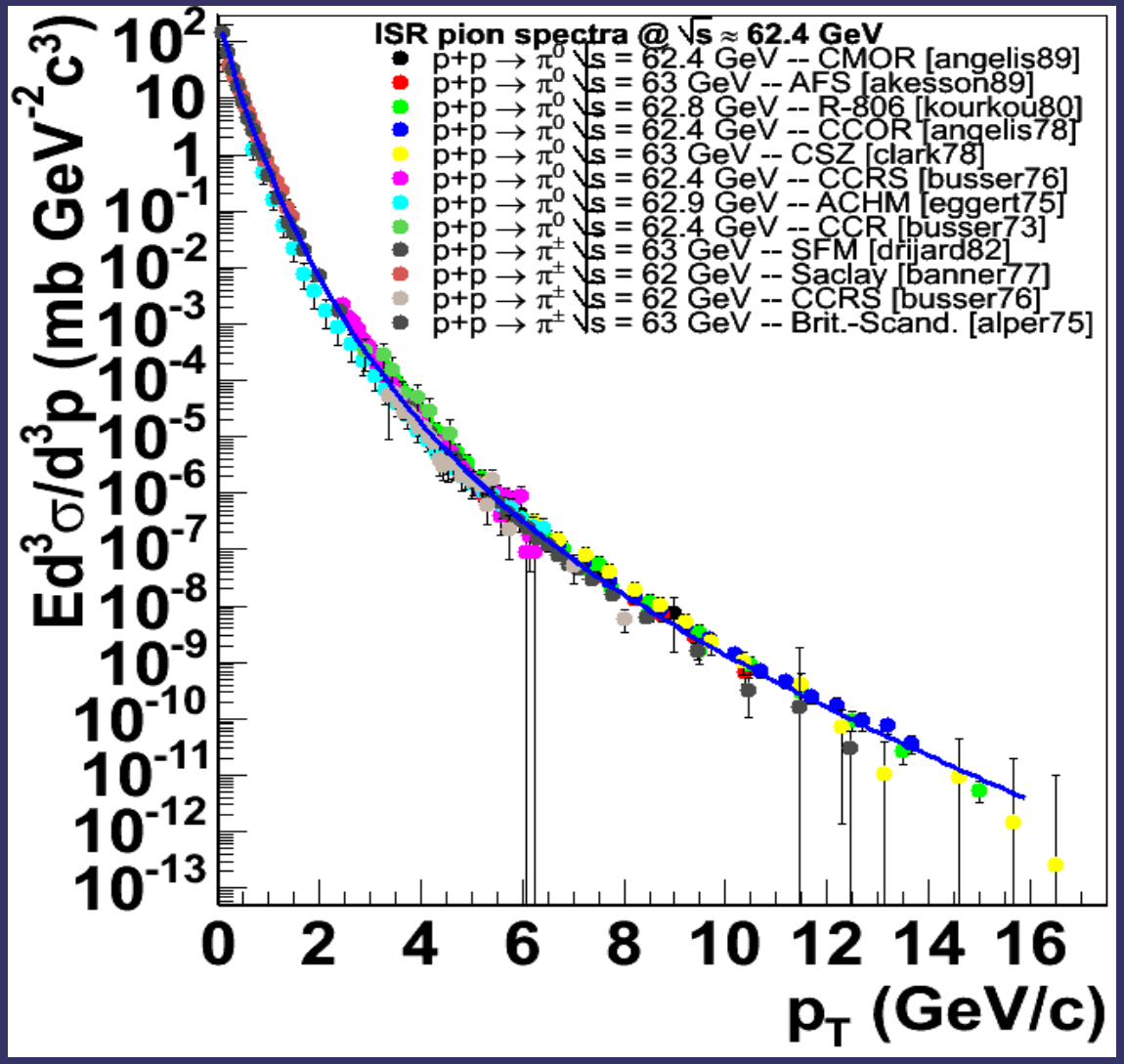
Direct Photon R_{AA}



Direct Photon R_{AA}

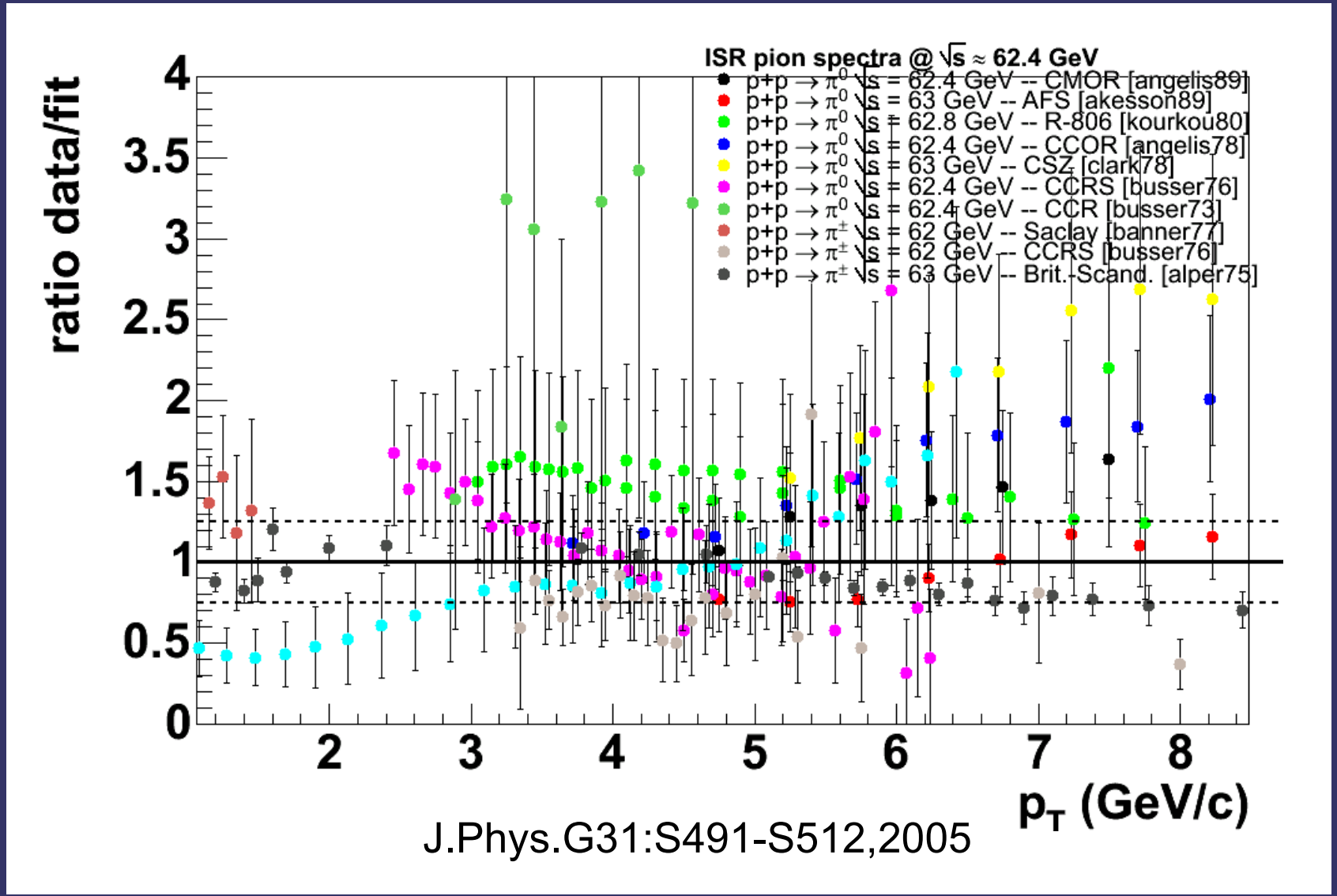


p+p Reference @ 62.4 GeV



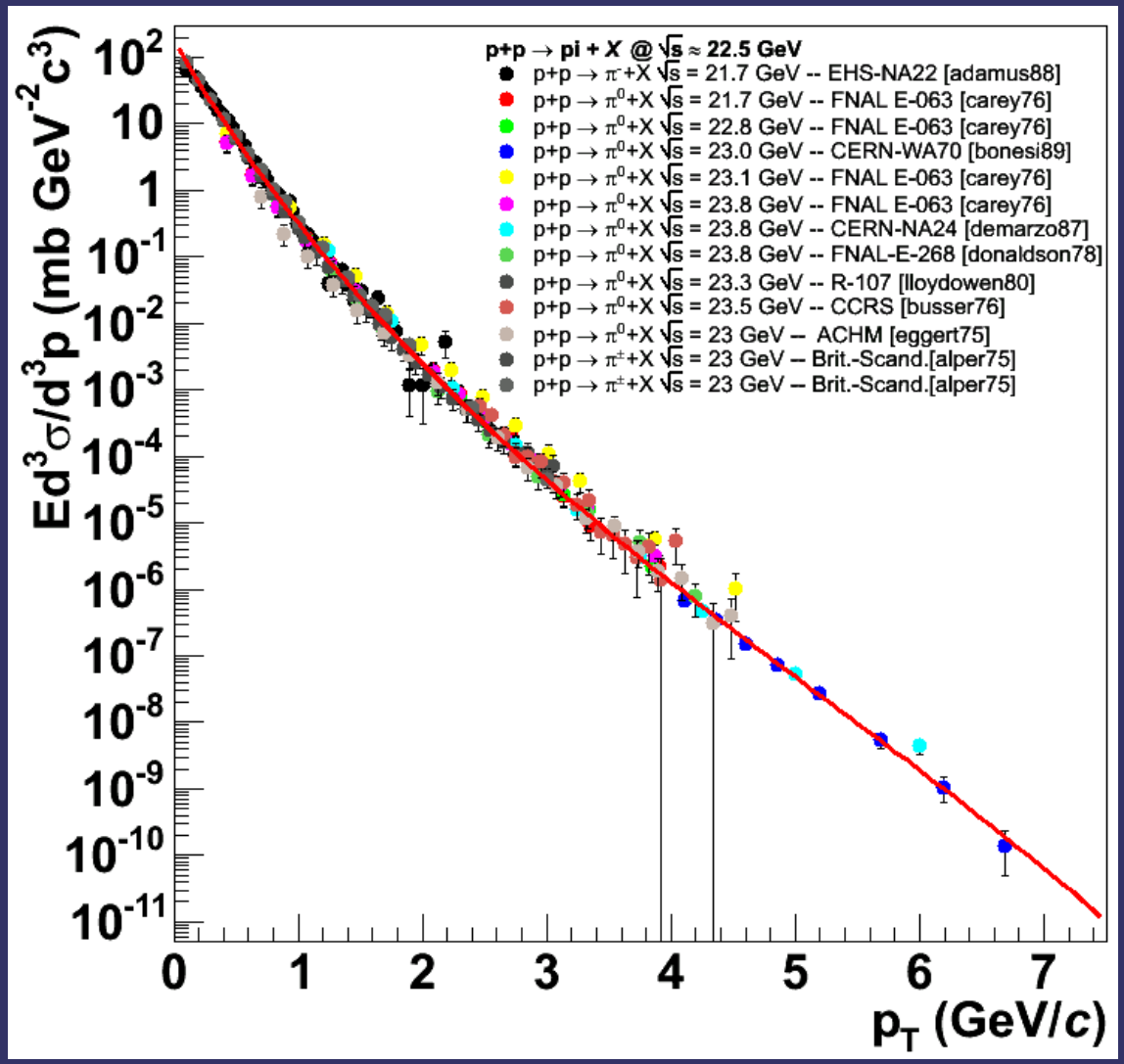
J.Phys.G31:S491-S512,2005

p+p Reference @ 62.4 GeV

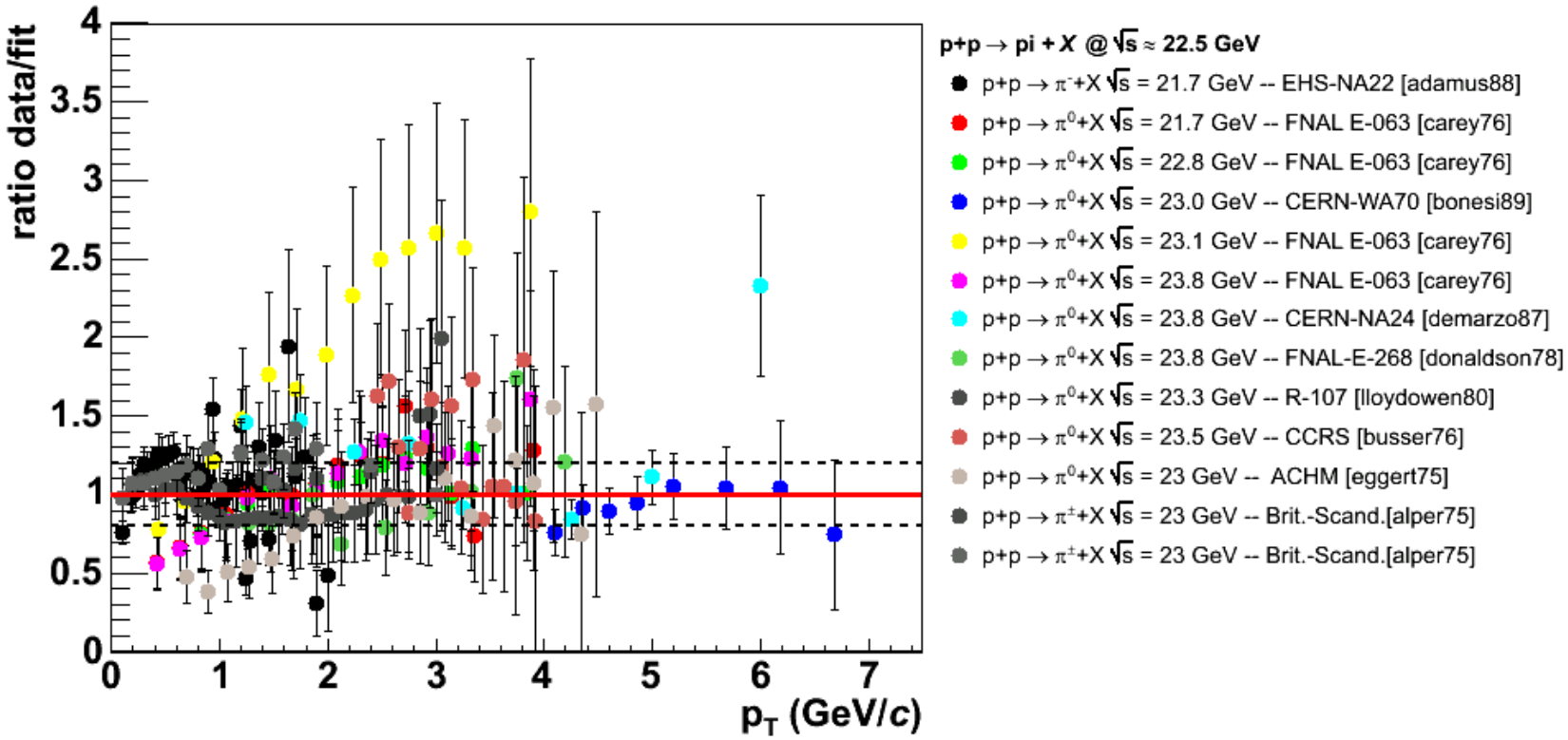


J.Phys.G31:S491-S512,2005

p+p Reference @ 22 GeV

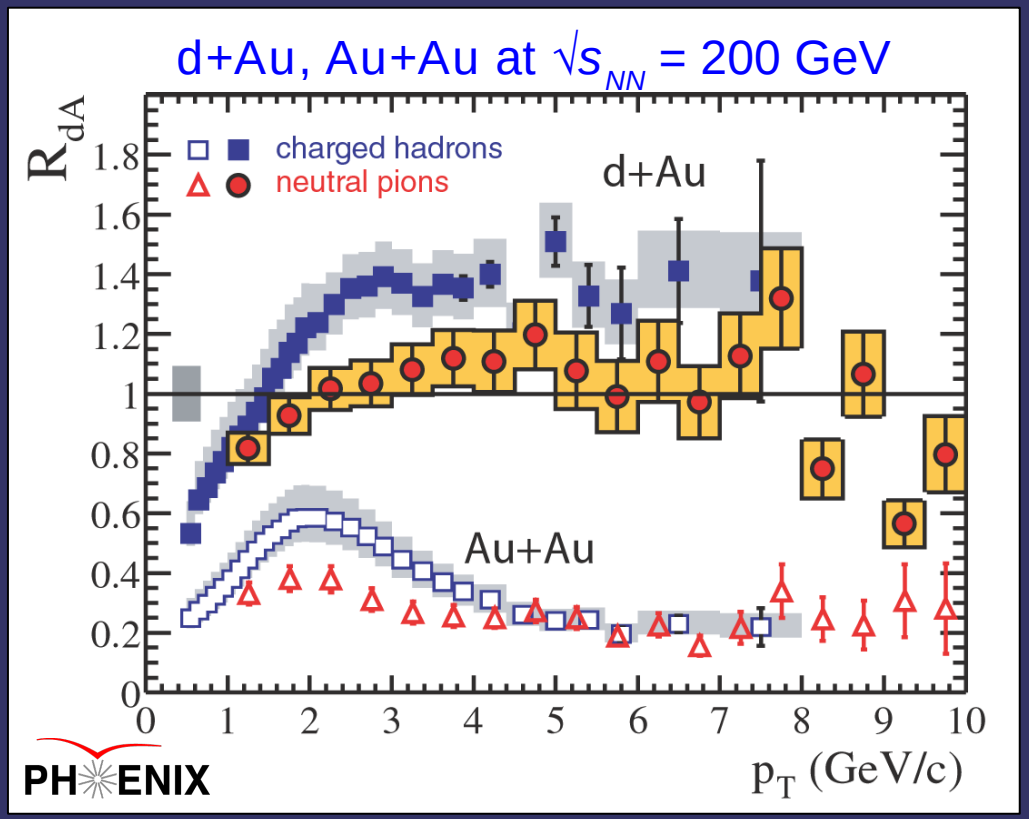


p+p Reference @ 22.4 GeV



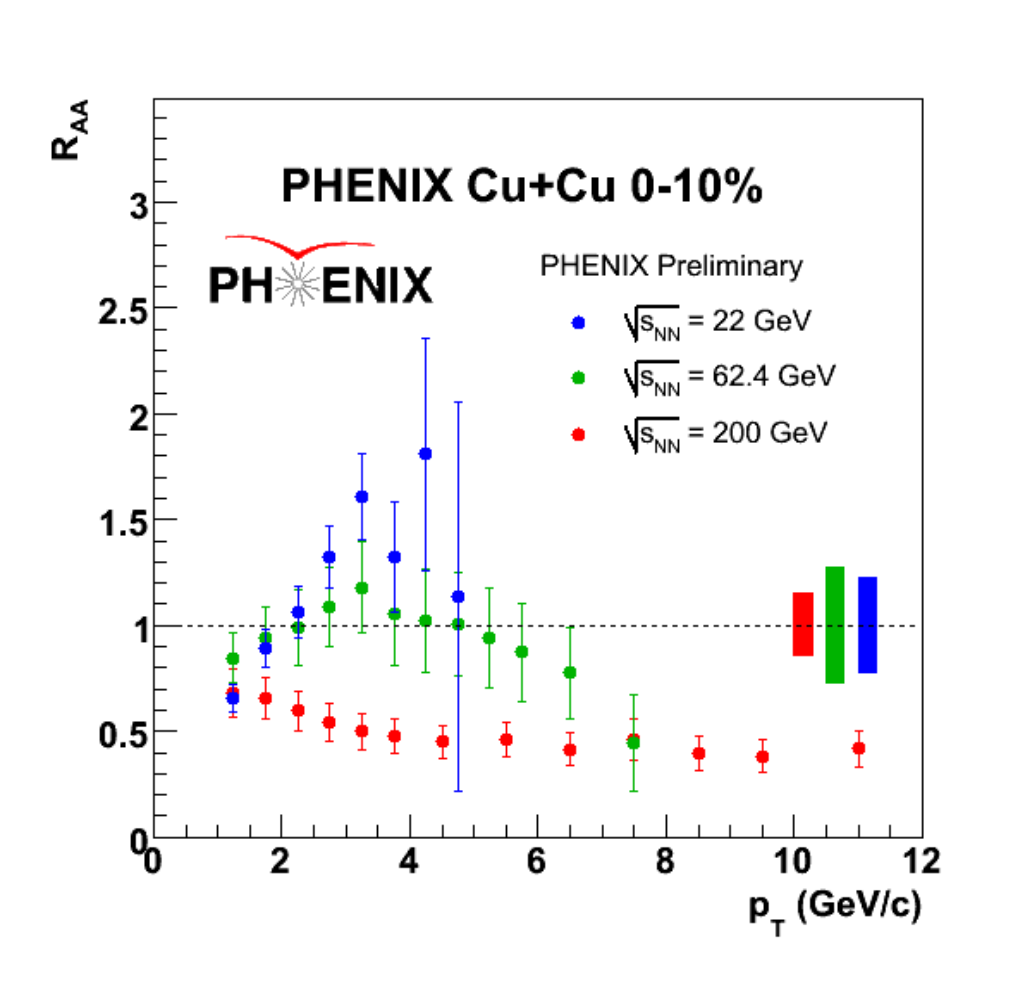
PHENIX High p_T Highlights

- **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?



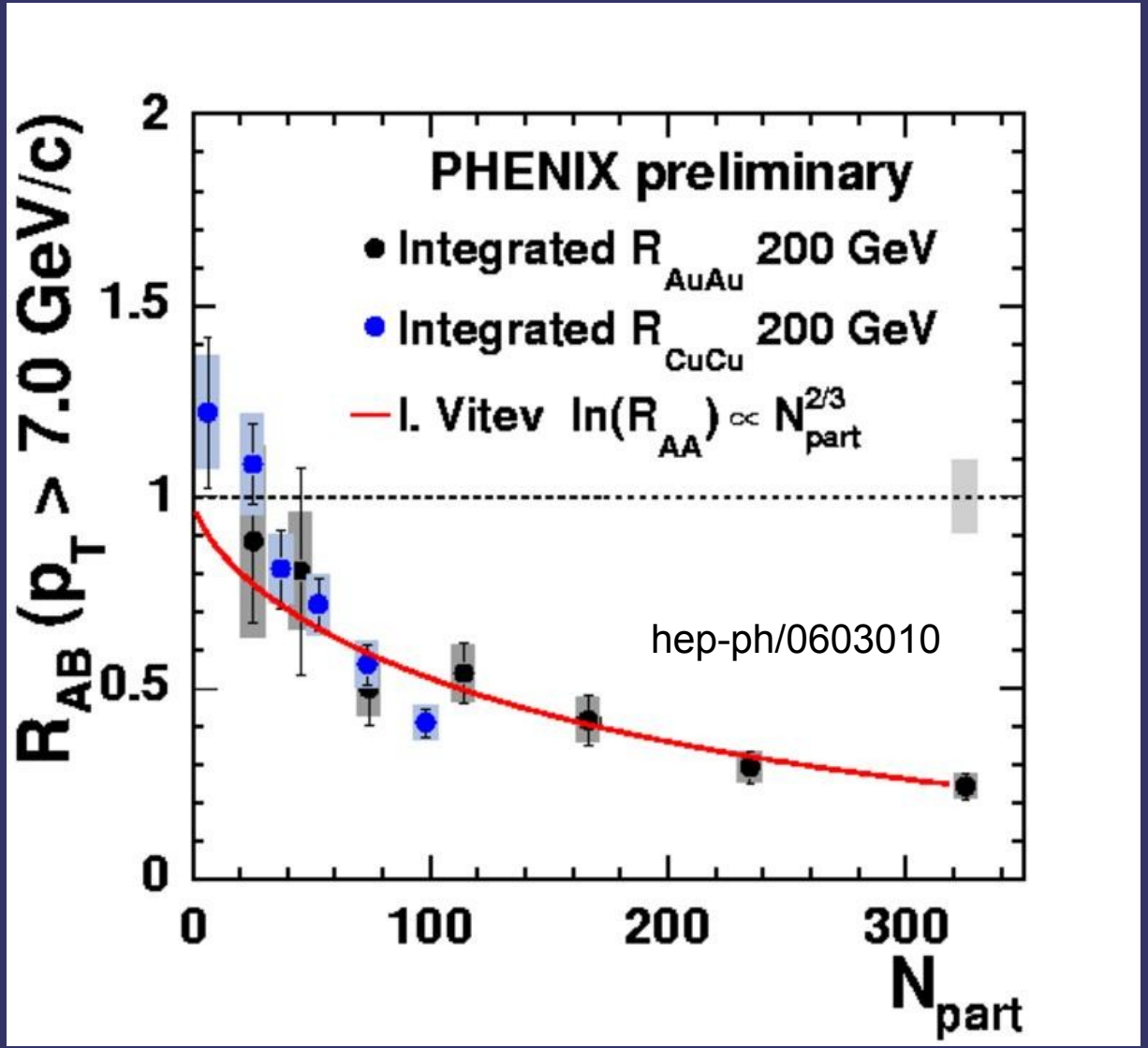
PRL **91**, 072303 (2003)

R_{AA} in Central Cu+Cu



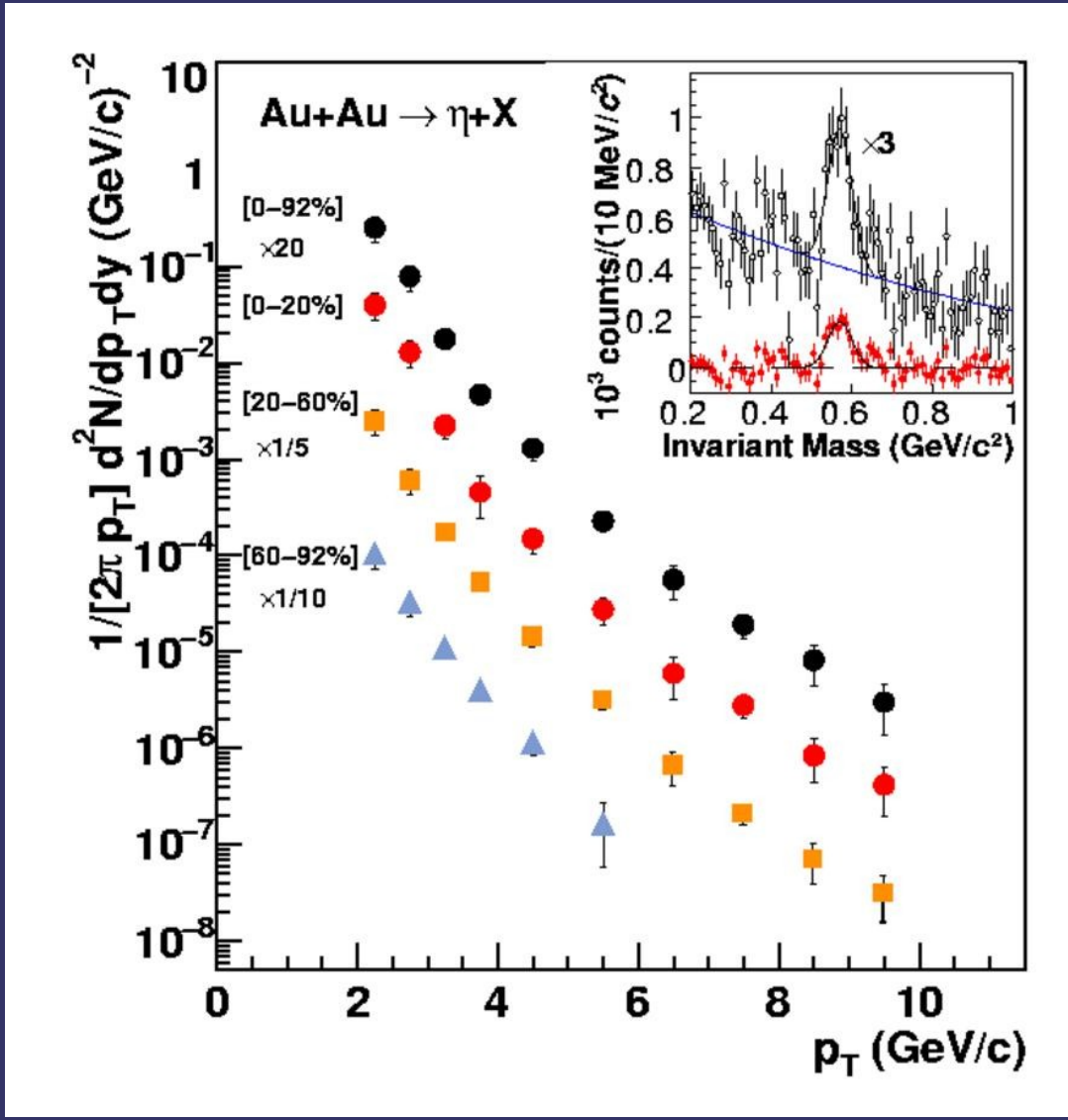
Centrality Dependence Integrated R_{AA}

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



Mass dependence at high p_T

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



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