Systematic Study of High p_T Hadron and Photon Production with PHENIX

Strange Quark Mater 2007
Levoča
June 26th 2007

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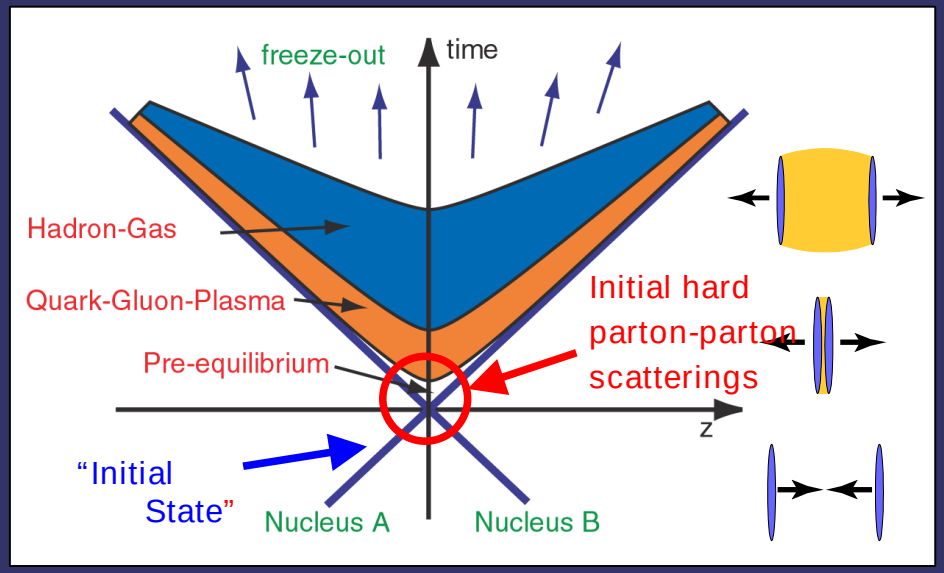
Why High p_T Hadrons?

- **Studying *hard* processes**
  - Parton collisions with large $Q^2 (\sim p_T^2) \Rightarrow$ Jets
  - 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
  - QCD probe for a later hot and dense phase



- **Quantifying the medium influence**
  - First step: single particle (incl.) spectra
  - Leading hadron carries large fraction of initial parton momentum

Why High p_T Hadrons?

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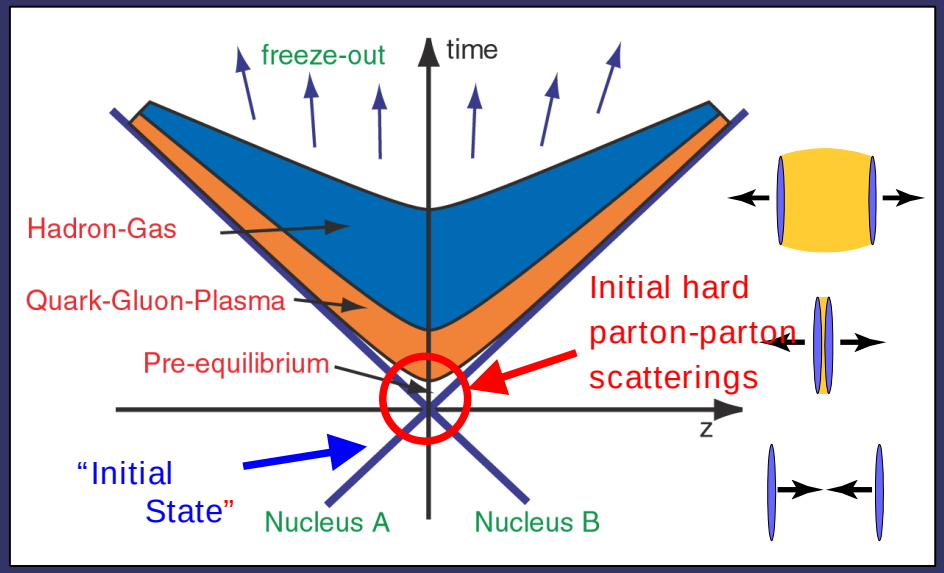
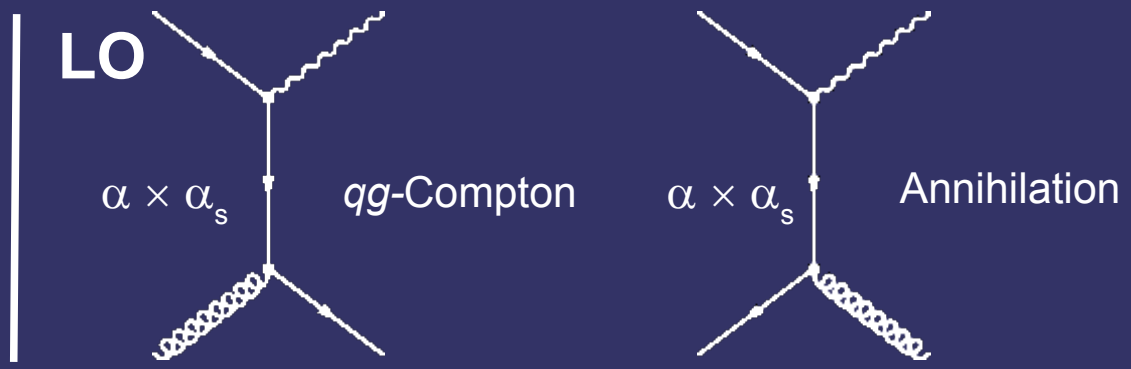


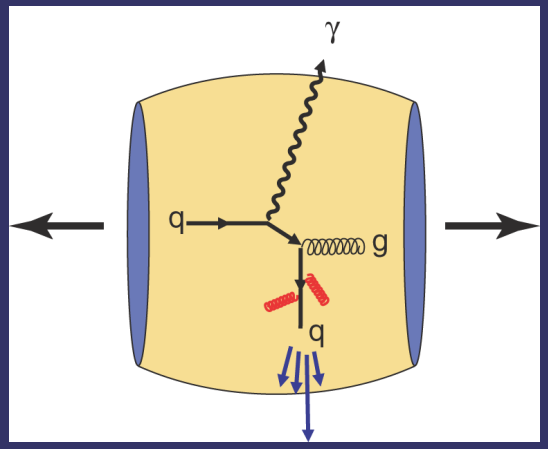
- **Quantifying the medium influence**

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

High p_T Direct Photons

- **Direct: Non-decay photons (e.g. $\pi^0 \rightarrow \gamma\gamma$)**
- **Also produced in early hard scatterings**
  - No strong interaction: QED probe





- **In situ control in A+A**
  - In LO not influenced by fragmentation

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

  - But also photons from fragmentation and jet-plasma interaction

How High is "High" p_T?

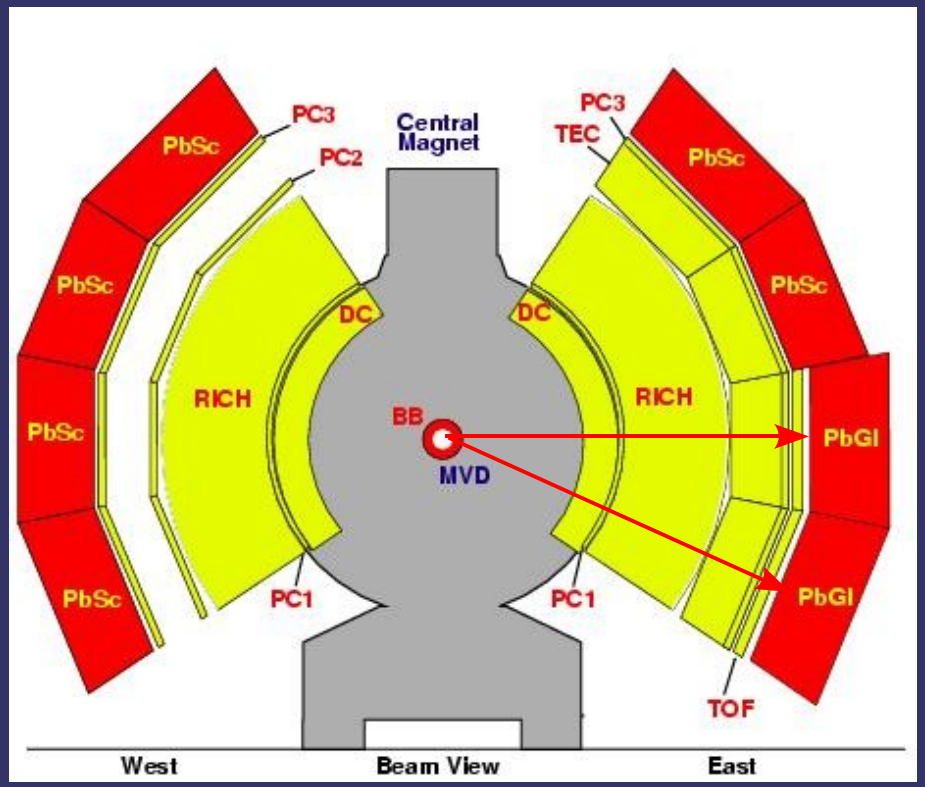
- **First year of RHIC (130 GeV Au+Au):**
  - p_T= 4 GeV/c was high "Suppression of Hadrons with **Large** Transverse Momentum in Central Au+Au Collisions at sqrt(s) = 130 GeV" (PRL 88,022301 (2002)
- **Where hard scattering is the dominant source of particle production (power law spectrum)**
- **Consider 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 produced in hard scatterings
  - Heavy Quarks (talk by DongJo Kim)
  - Correlations (talk by Hua Pei)

π^0, η and direct γ @ PHENIX

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

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

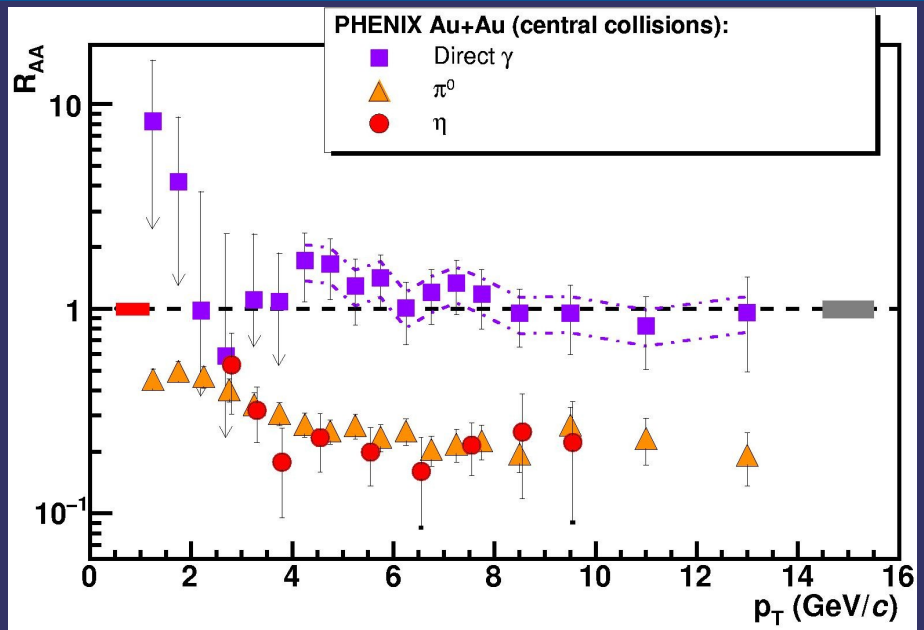
PHENIX High p_T Highlights

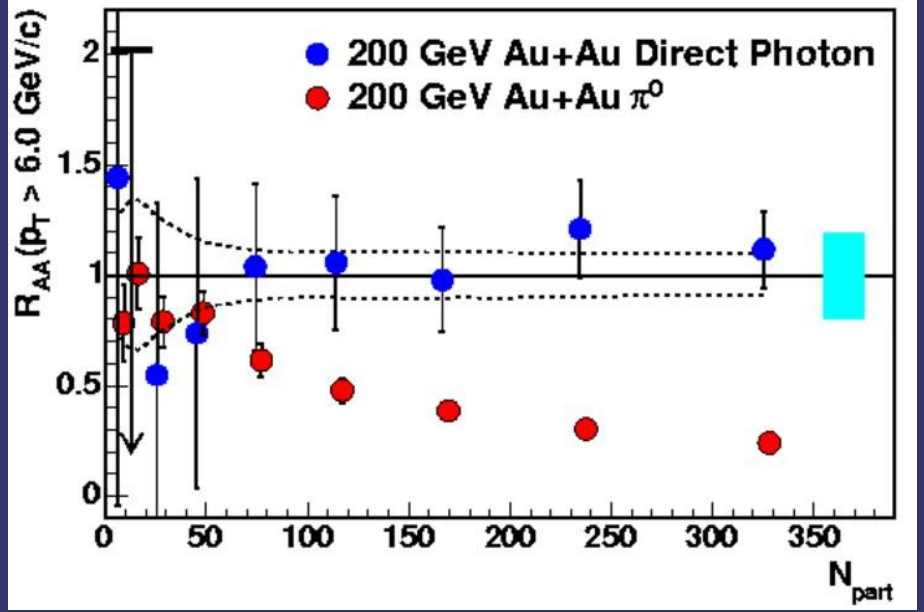
- **Strong suppression of hadrons (QCD probe)**
  - Similar for π^0 and η
  - No suppression in d+Au
    - PRL **91**, 072303 (2003)
- **Direct photons (QED probe)**
  - R_{AA} with pQCD reference
  - Ultimate test for hard scatterings

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

  - No suppression of direct photons

Strong final state effect





PRL **94**, 232301 (2005)

Common Explanation: In-medium Energy Loss

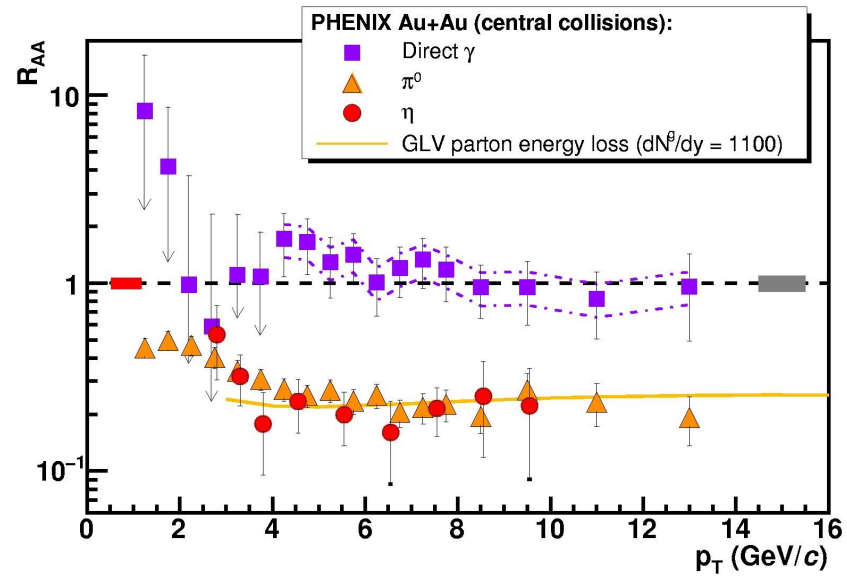
- **Partons lose energy by coherent gluon bremstrahlung:**
  - E.g .Gyulassy et. al nucl-th/0302077

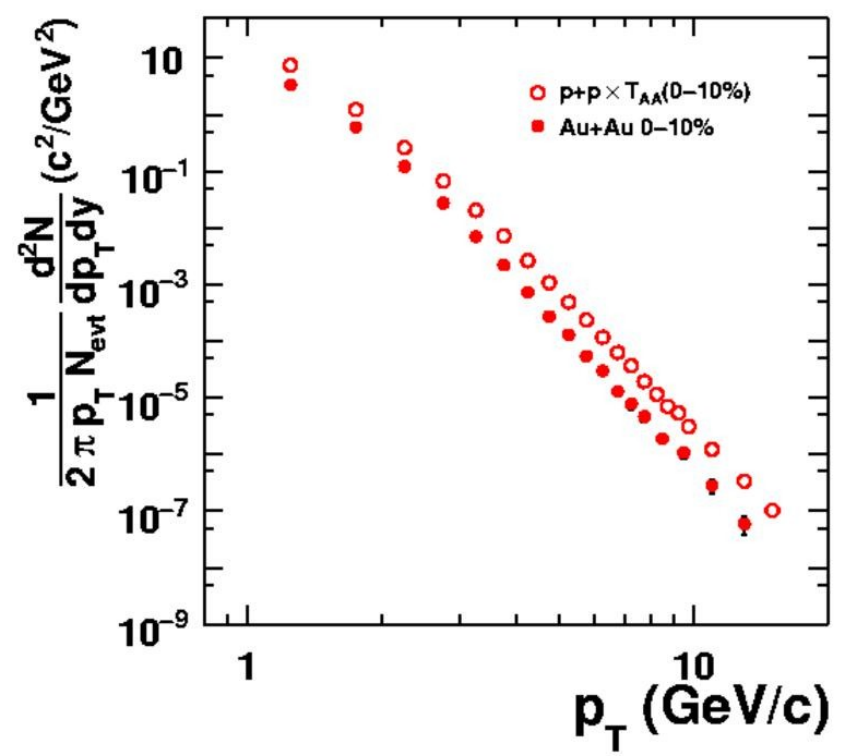
$$\frac{\langle \Delta E \rangle}{E} \sim \alpha_s^3 C_R \frac{1}{A_T} \frac{dN_g}{dy} L \frac{1}{E} \ln \frac{2E}{\mu^2 L}$$

  - Main parameter gluon density
  - Other models: e.g. transport coefficient
- **Average loss related to spectrum shift (R_{AA})**
  - Power law

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

  - ~ 20% above p_T = 4 GeV/c





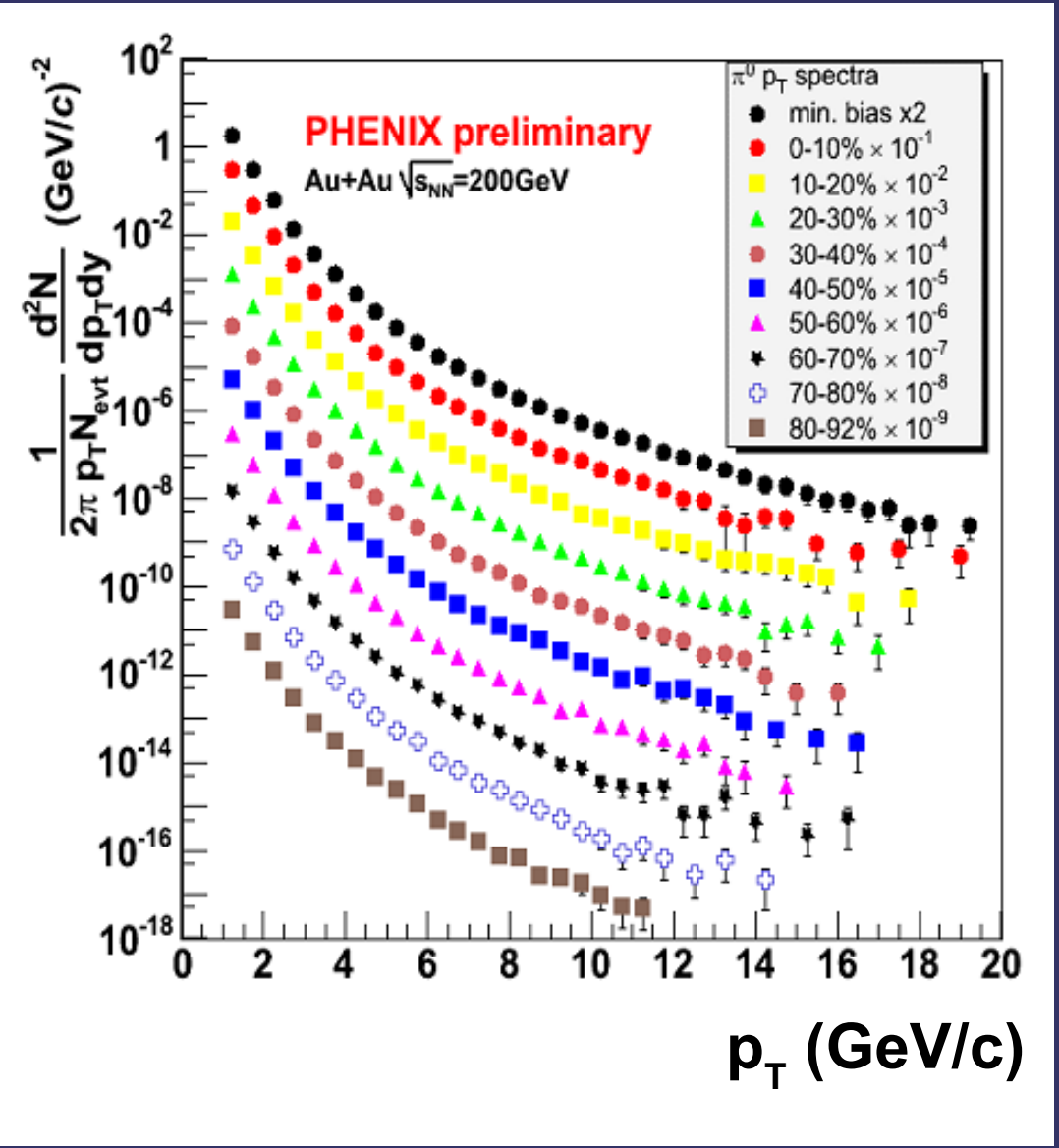
PHENIX

What else can be done at high p_T?

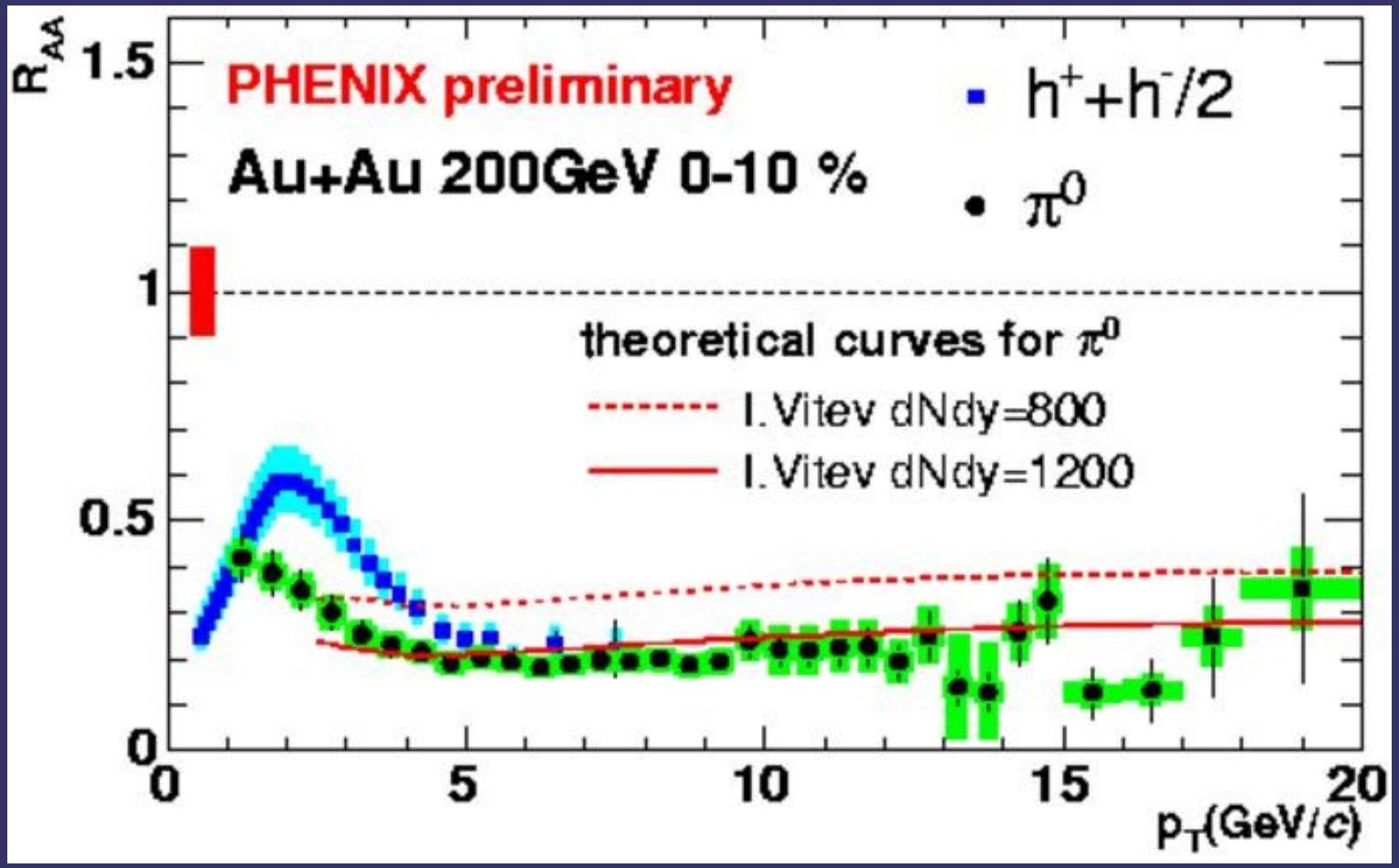
- **More differential studies of (existing) data at high p_T**
  - Quark-mass dependence, heavy flavor
  - Jet correlations
  - Reaction plane (L) dependence
- **New (larger) data-sets**
  - Improve p_T-reach in Au+Au and p+p refererence
- **Vary the system size**
- **Vary the collision energy**

Run04 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**



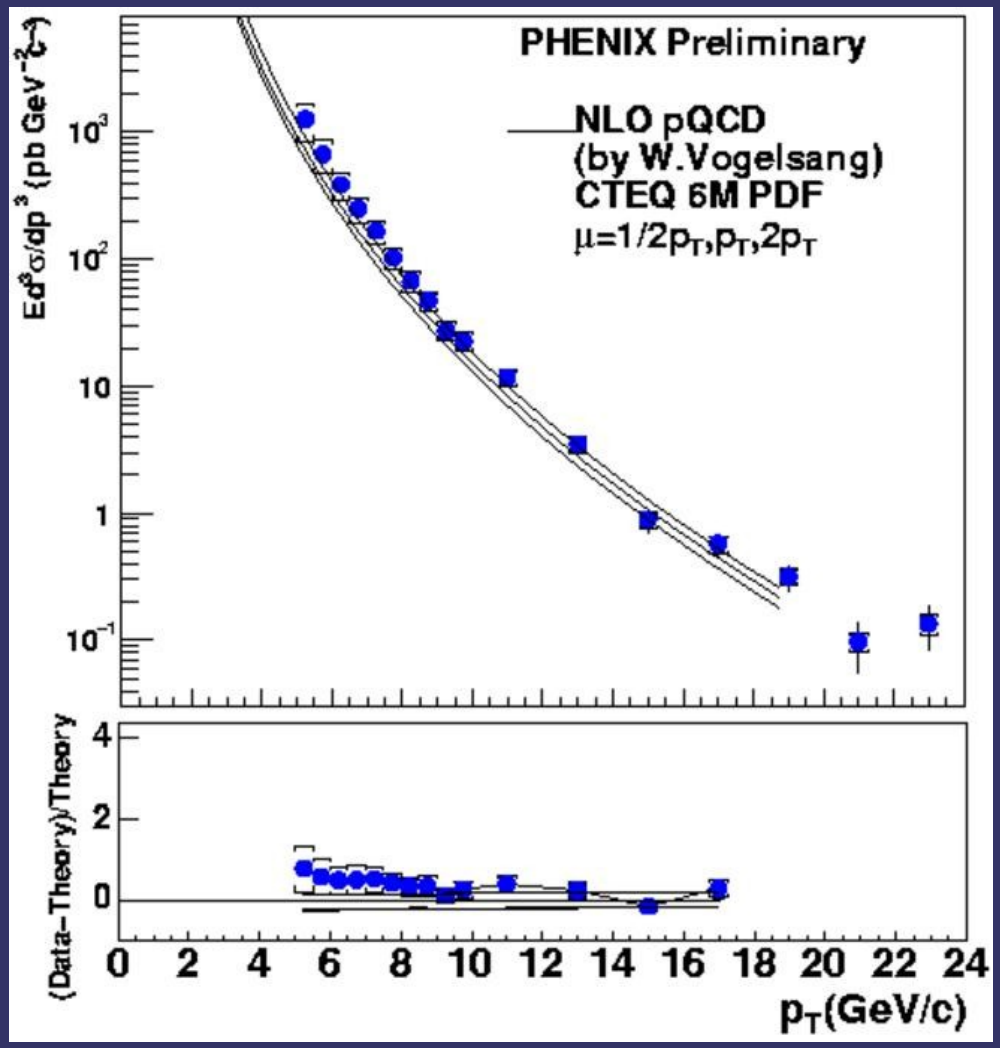
Run04 R_{AA} in Au+Au



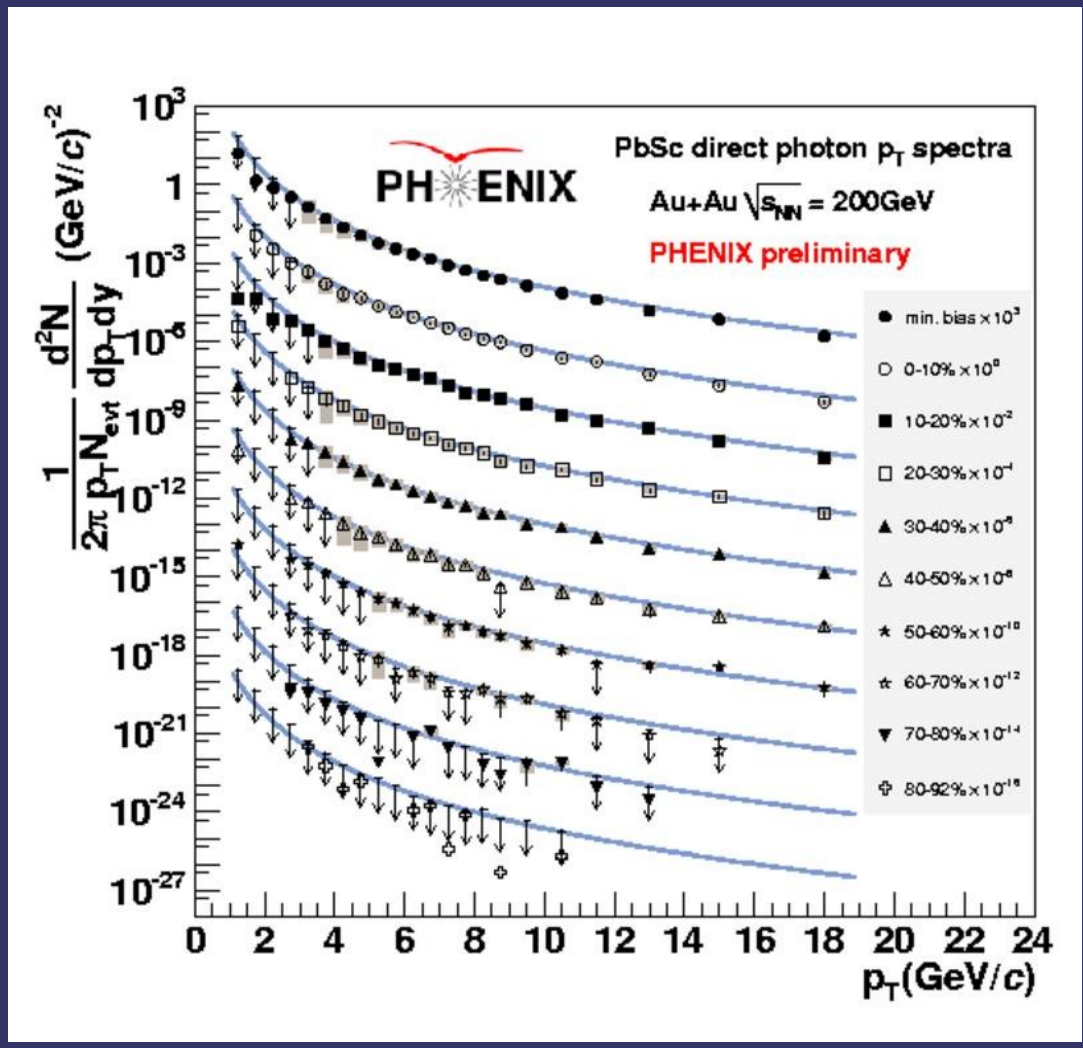
Suppression stays nearly constant up to 20 GeV
Consistent with dN_g/dy ~ 1200 calculation

New Direct Photon Data

New p+p reference Run05



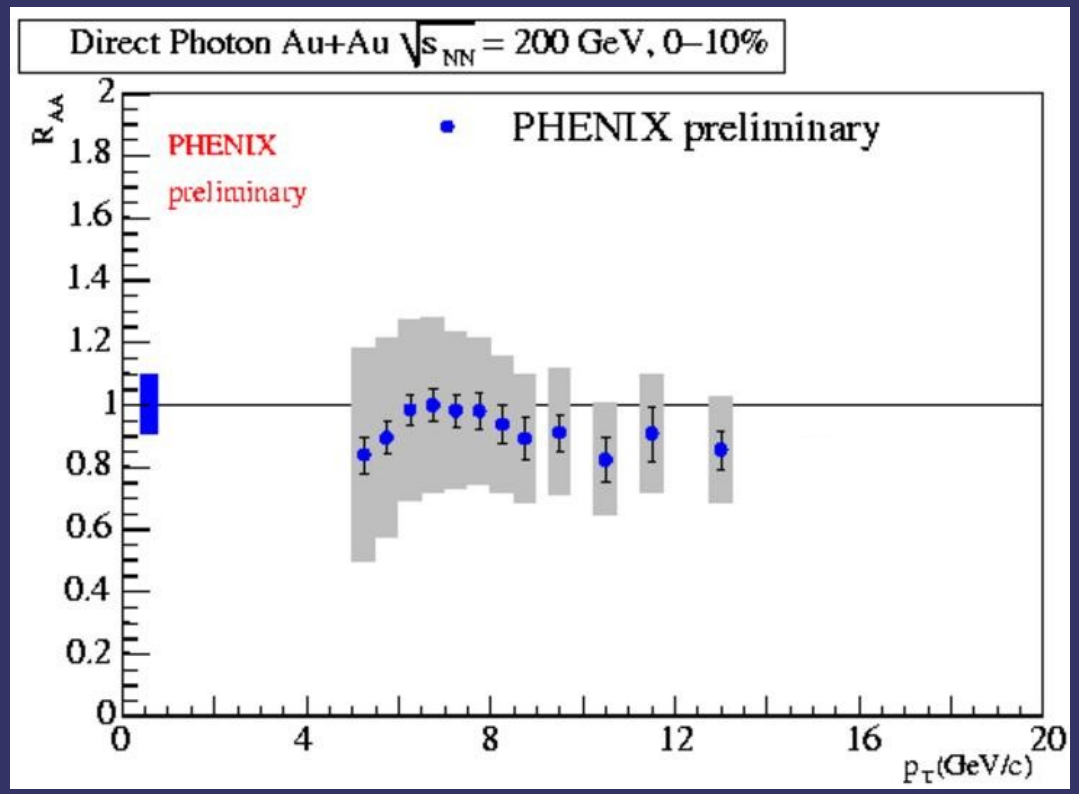
Au+Au Run04



New Direct Photon R_{AA}

- **Run02 result confirmed**
  - R_{AA} = 1 up to p_T = 14 GeV/c
  - Now measured reference

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



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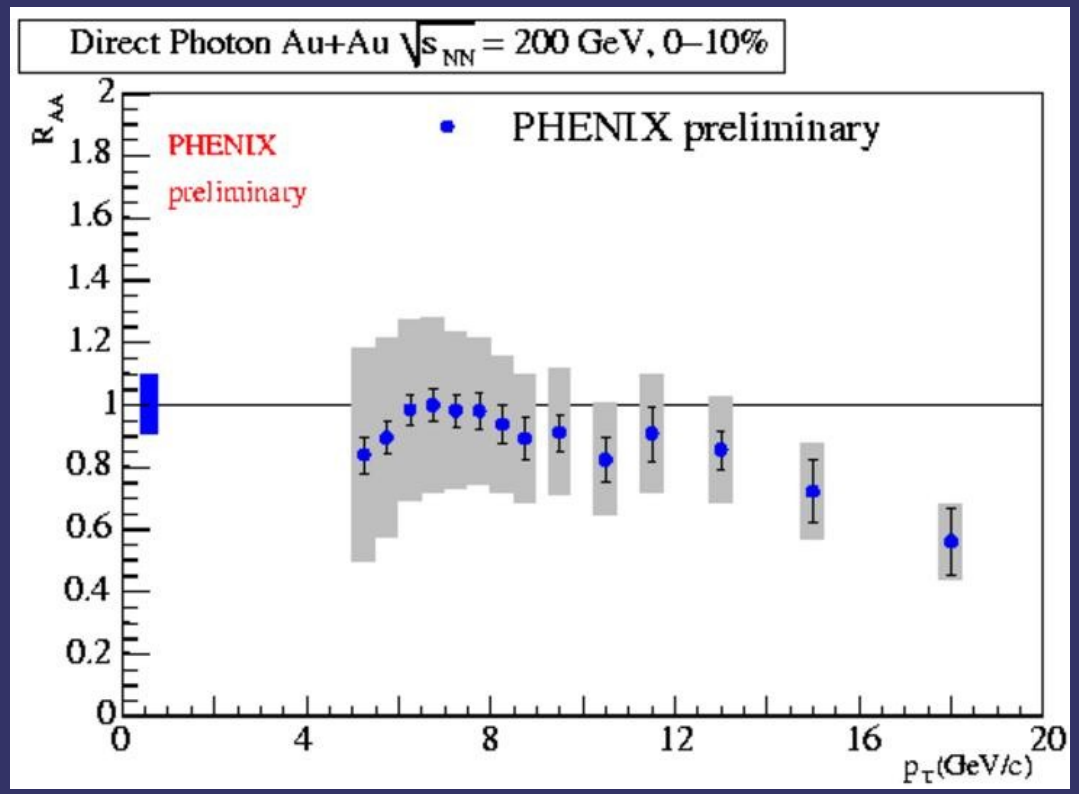
$$R_{AA} = \frac{dN_{AA}}{T_{AA}\, d\sigma_{pp}}$$

- **Highest p_T**
  - Decreasing trend
  - Trivial isospin effect?

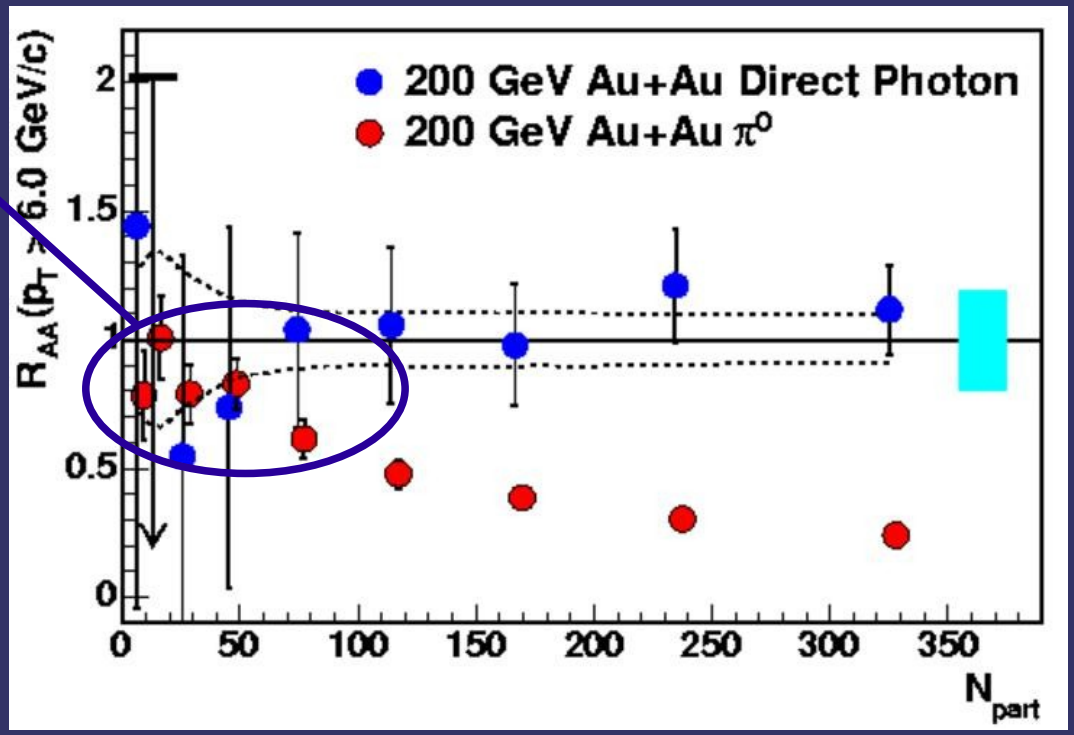


$$x \approx x_T = \frac{2\,p_T}{\sqrt{s_{NN}}} = \frac{p_T}{100}$$

System Size Dependence...
RHIC Run05 Cu+Cu

System Size Dependence

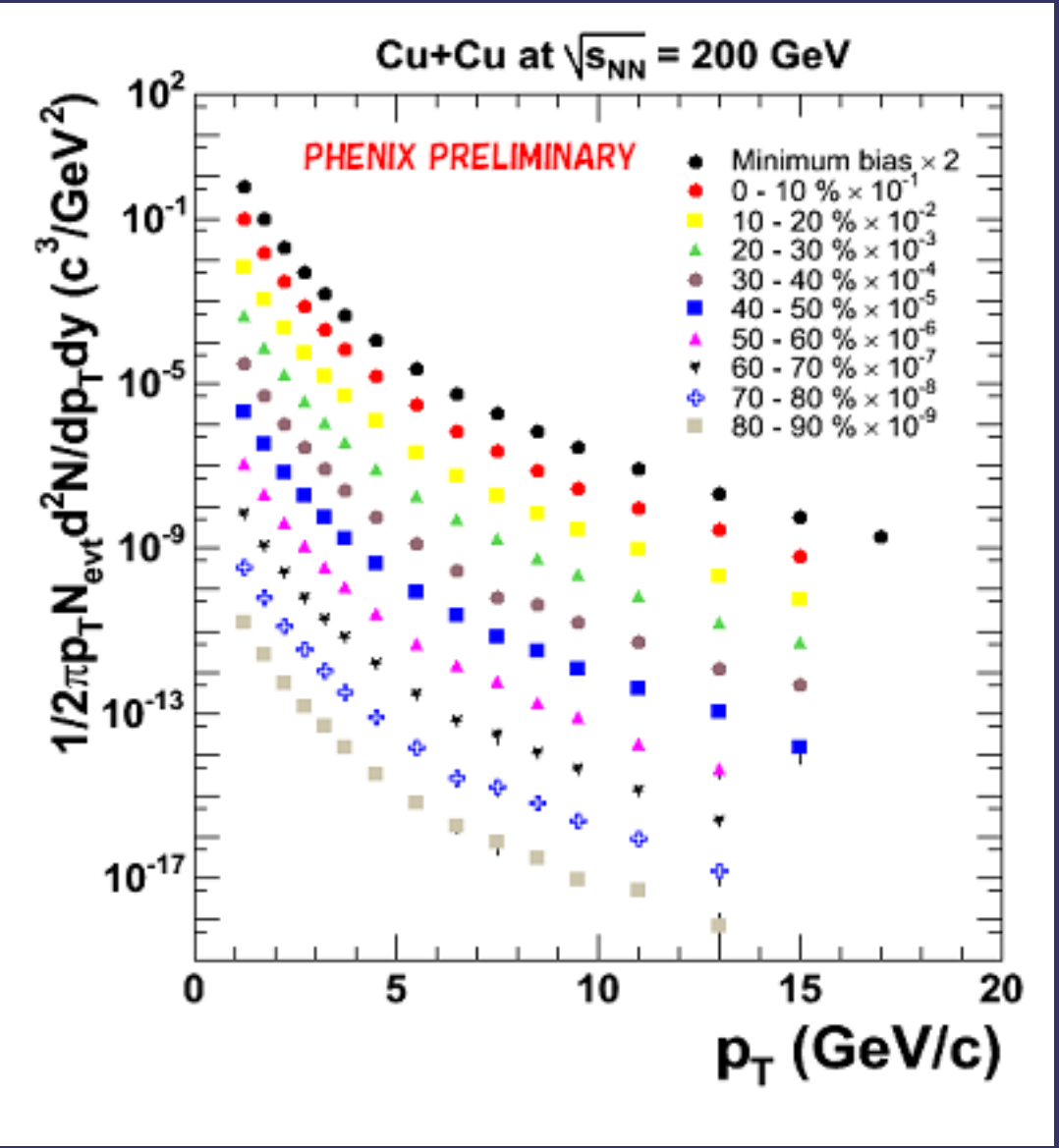
- **Variation of centrality**
  - Onset of suppression: $N_{part} \approx 50$
  - No good discrimination in Au+Au
- **Cu+Cu (A = 64)**
  - Better N_{part} "resolution"
  - Different geometry
    - Surface/volume effects



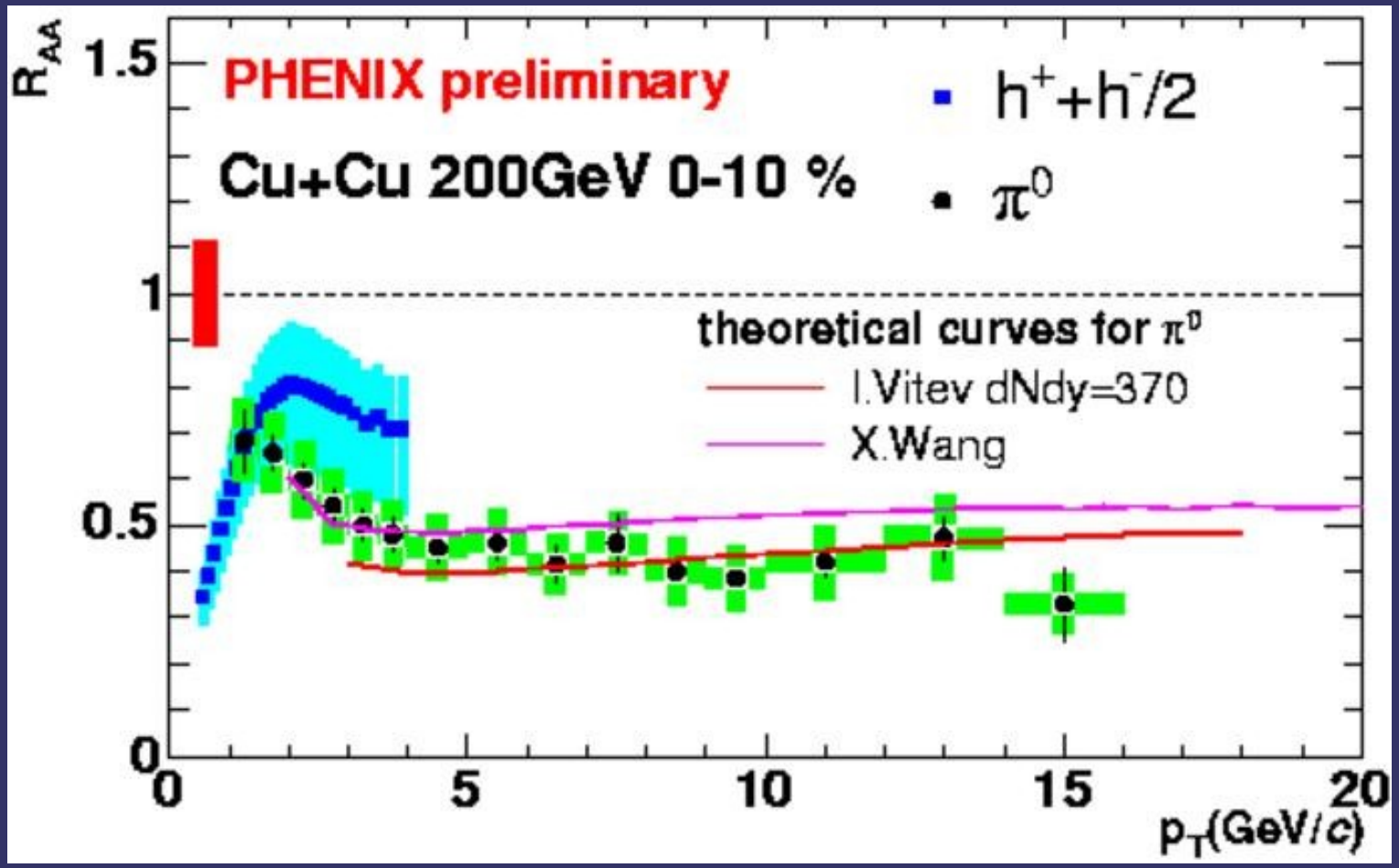
PRL **94**, 232301 (2005)

The Measurement in Cu+Cu

- **RHIC Run5 (2005)**
  - Sampled 0.52 nb^{-1}
- **59 M minimum bias events**
- **1.9 M high-p_T triggered**
  - Correspond to 2.2 B events
- **Spectra up to 18 GeV/c**

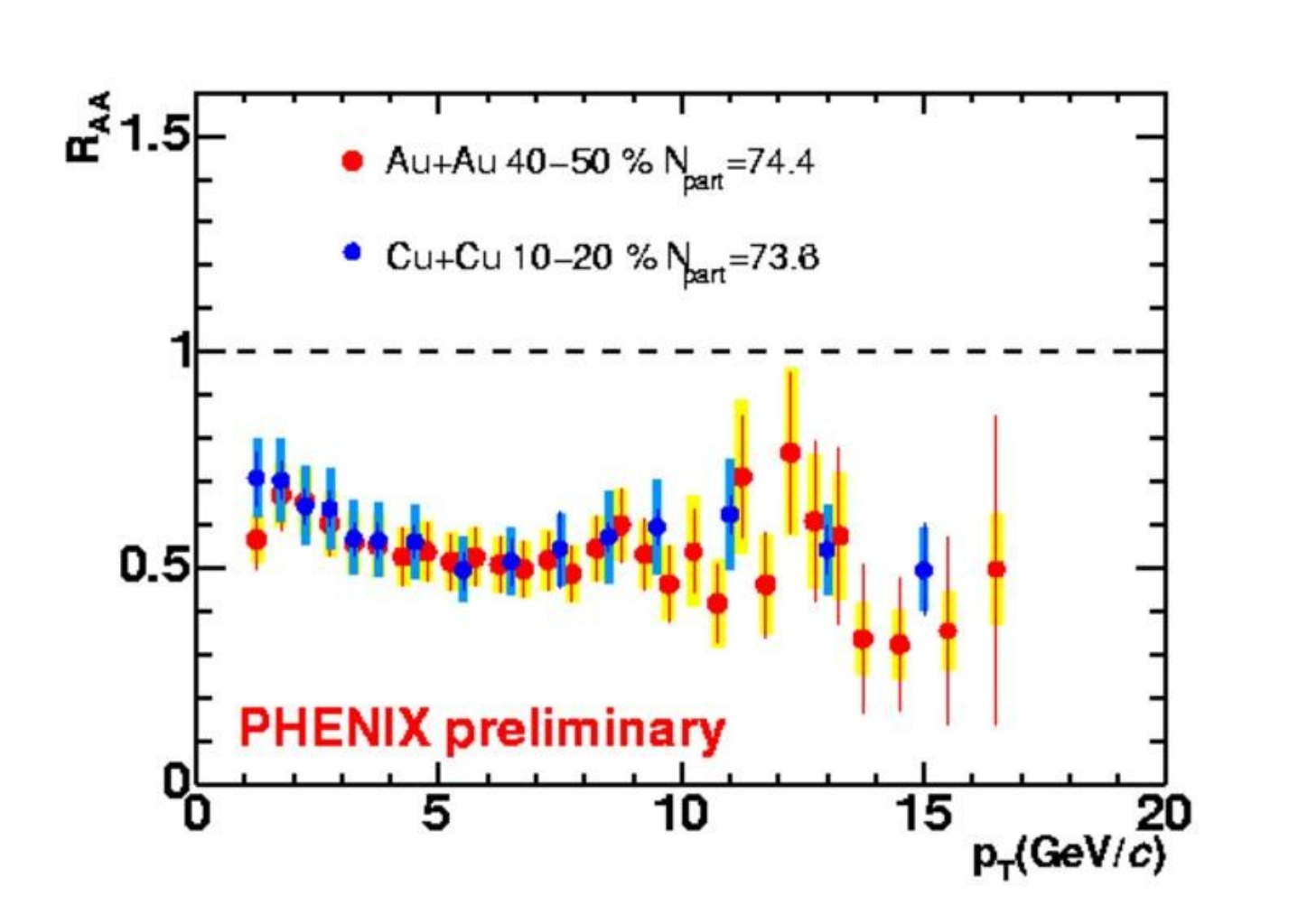


R_{AA} in Cu+Cu



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

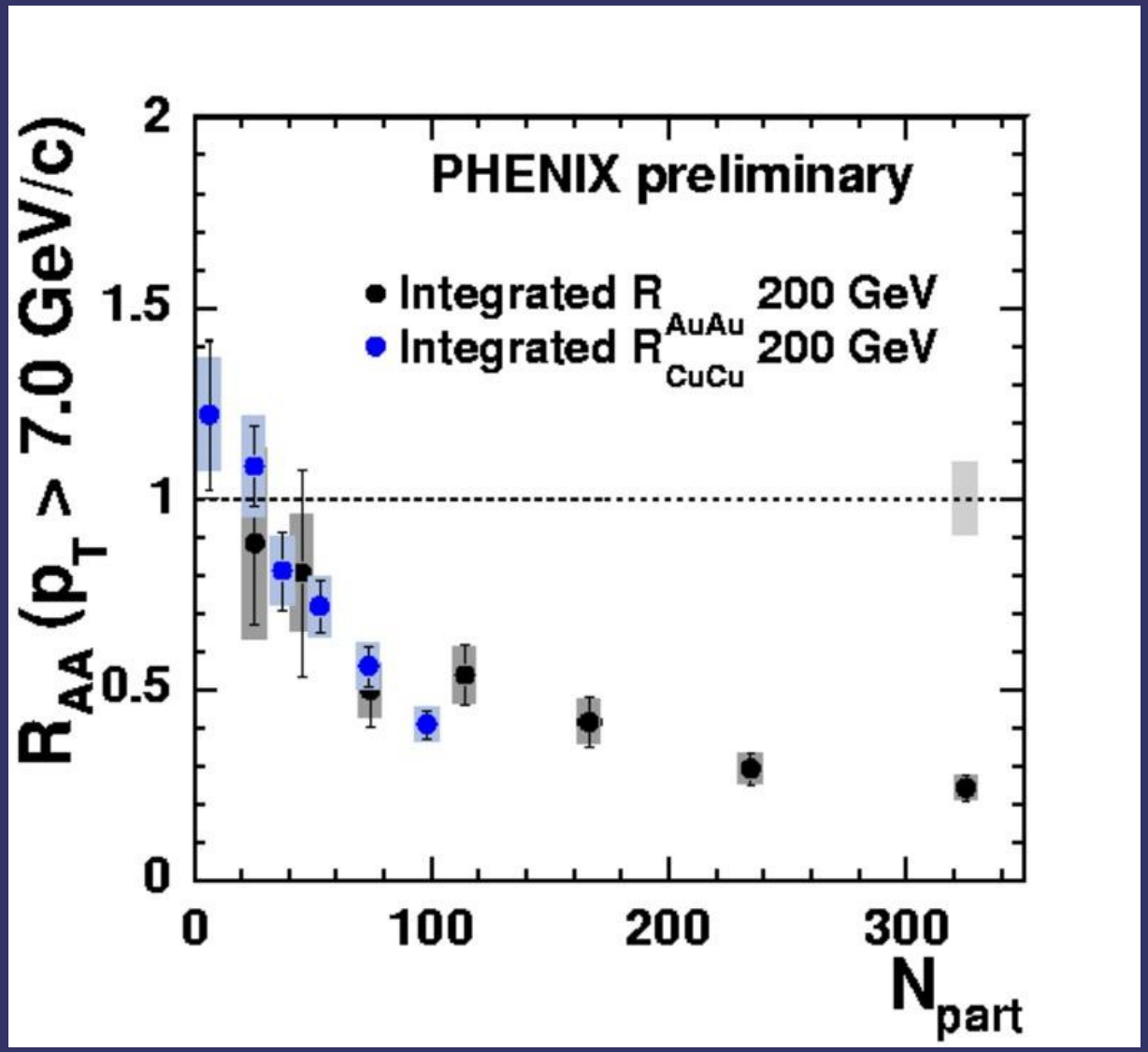
Au+Au vs. Cu+Cu



Suppression pattern identical at same N_{part}

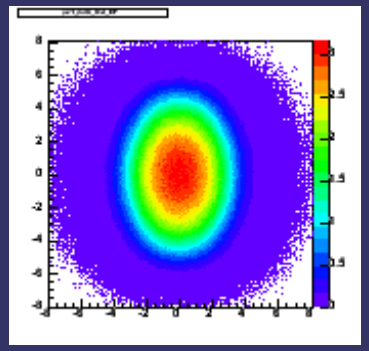
Centrality Dependence: Integrated R_{AA}

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

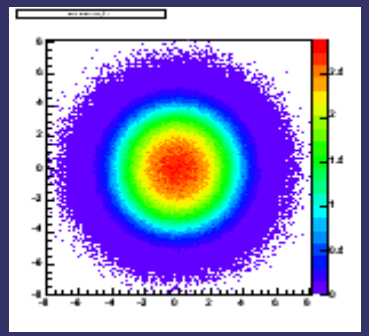


Centrality Dependence: Integrated R_{AA}

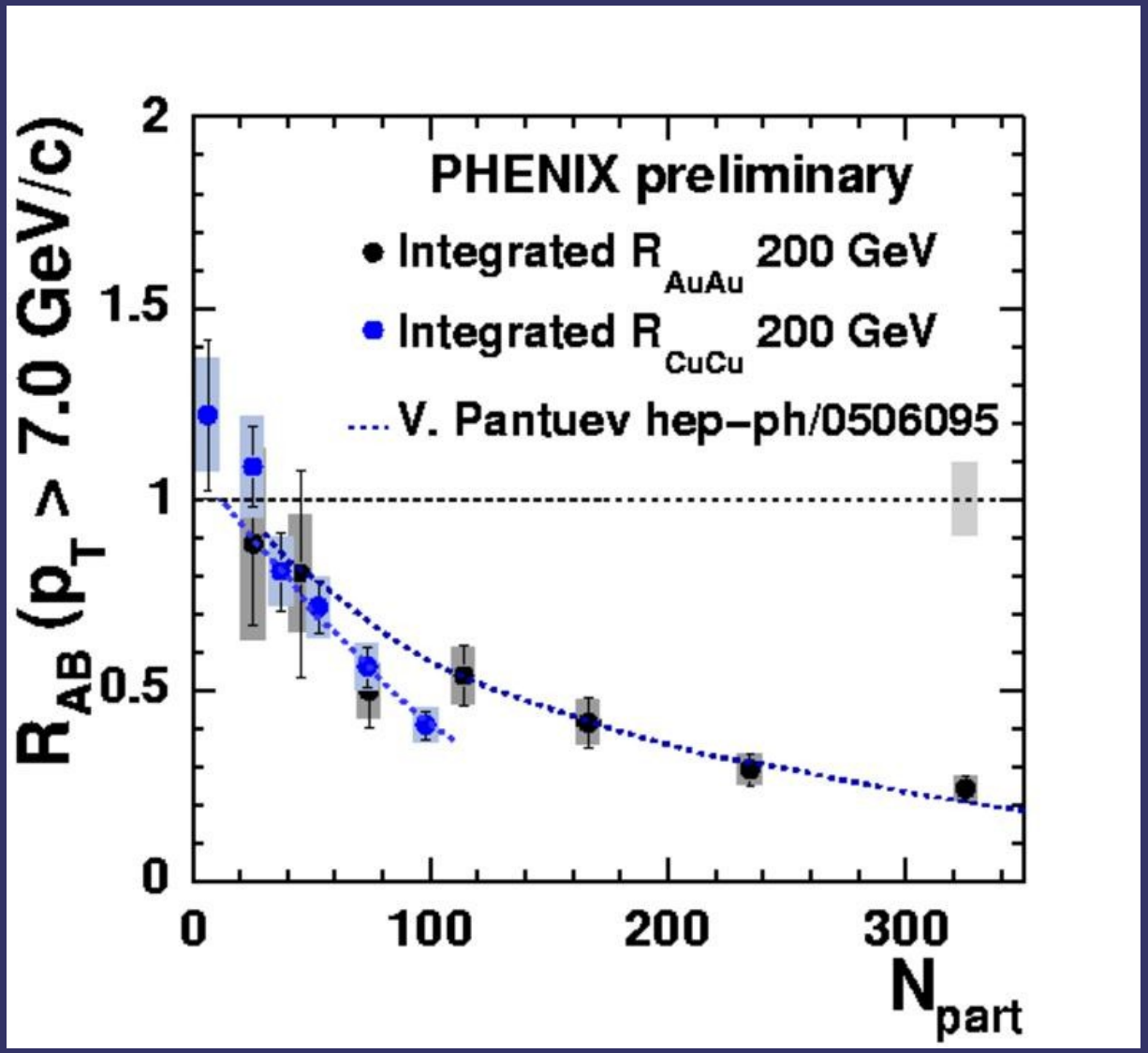
- **Geometrical model with "corona" effect**
  - More jets from surface
  - Correlated with ellepticity
    - Minimal for sphere



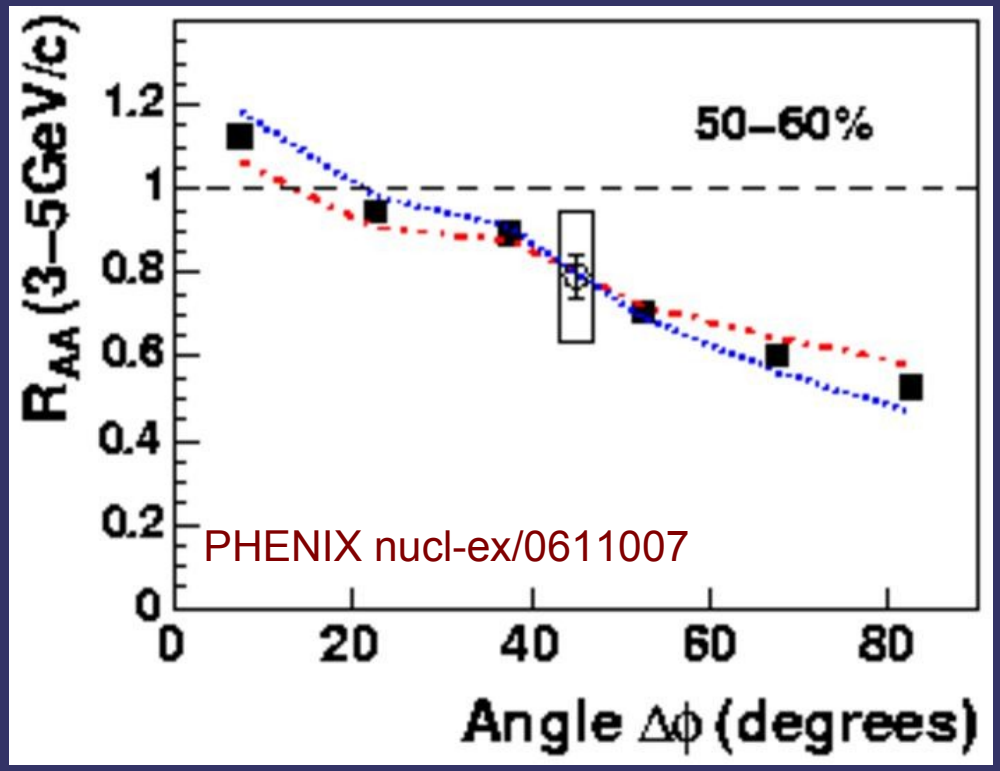
Au+Au
30-40%
***N_{part}* = 114**

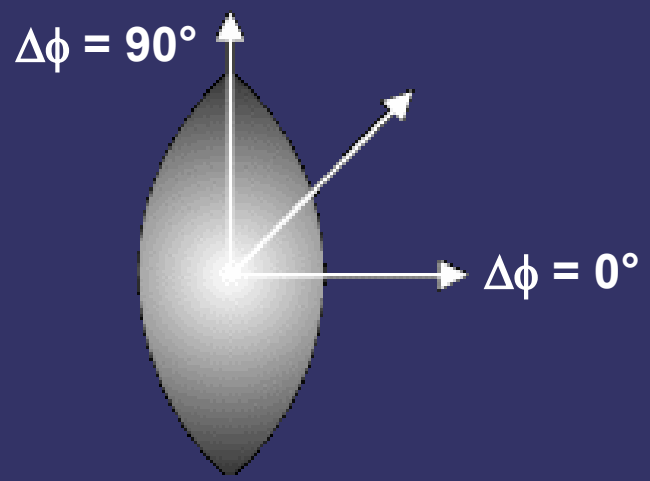


Cu+Cu
0-10%
***N_{part}* = 98.2**



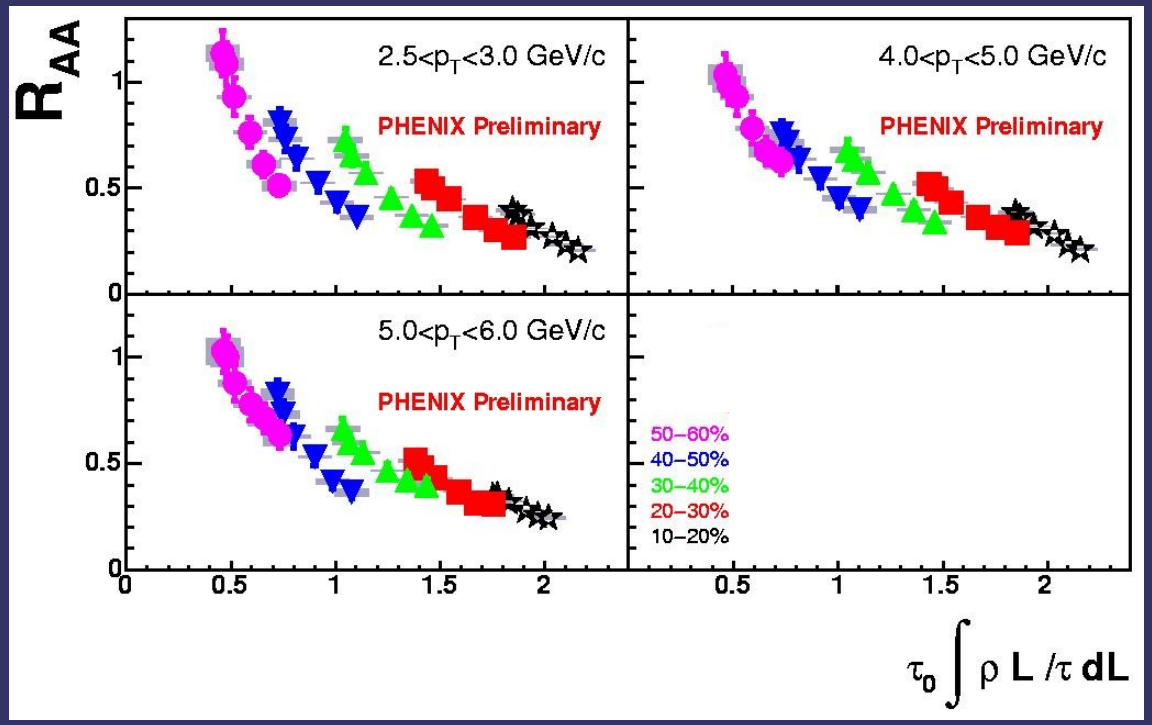
Δϕ-Tomographie in Au+Au



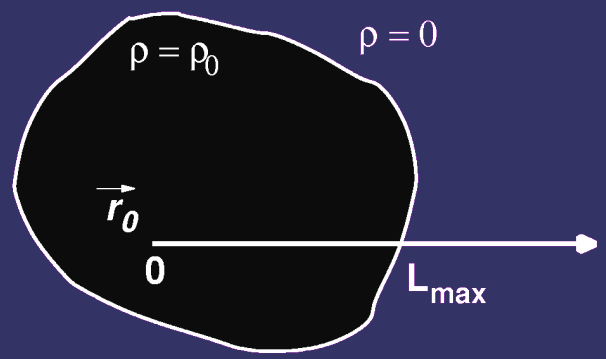


- **Collision asymmetry**
  - Studying angular dependence
    - Same energy density
    - Different paths
      - *L*-dependence
      - Surface emission
- **Strong angular dependence**
  - $R_{AA}(0°) = 0.5 \times R_{AA}(90°)$
  - Less medium, less suppression?

A more detailed look

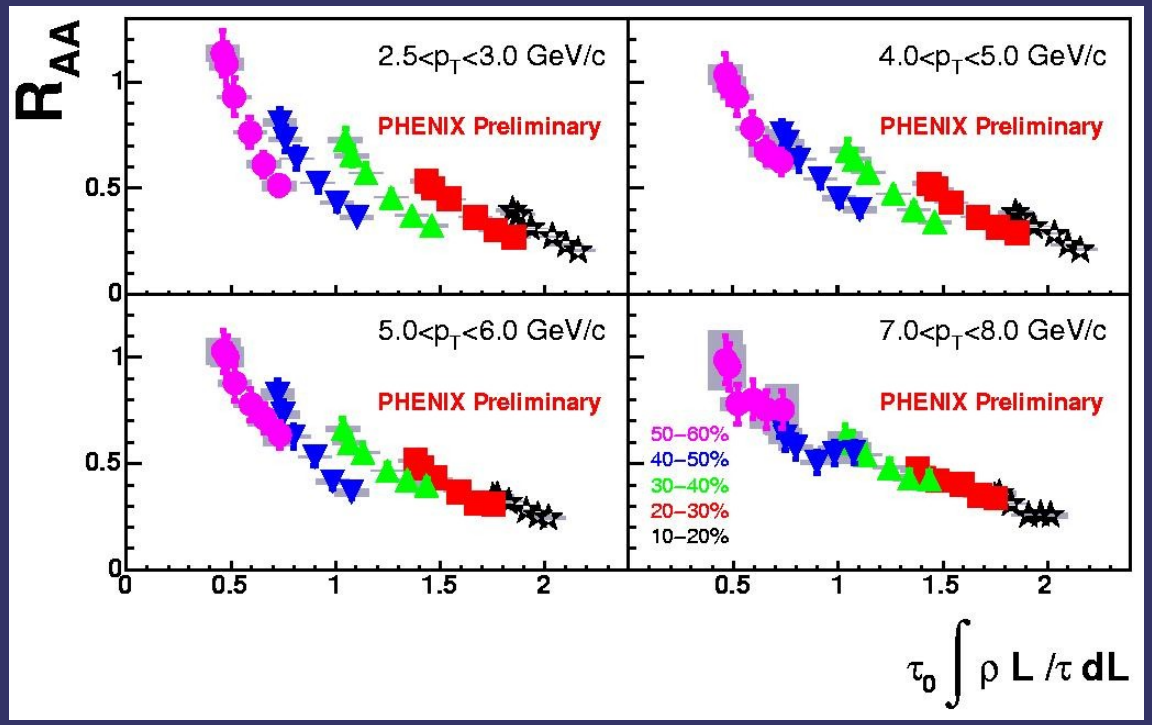


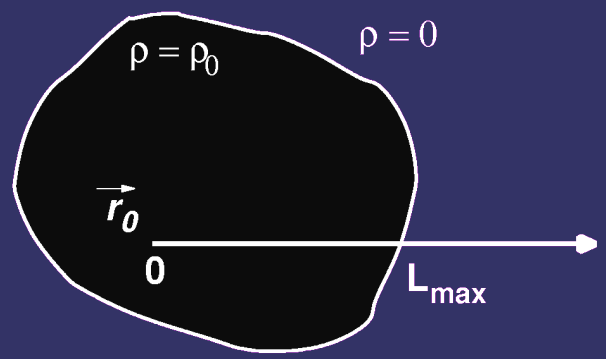
- GLV
  - $\Delta E \propto \rho_0 L_{max}^2$
- Consider expansion $\rho(\tau)$
  - $R_{AA} \propto \int dL\, \rho_0 \frac{L \tau_0}{L + \tau_0}$?
  - L_{max} from Glauber MC



changes with angle and centrality

A more detailed look





changes with angle and centrality

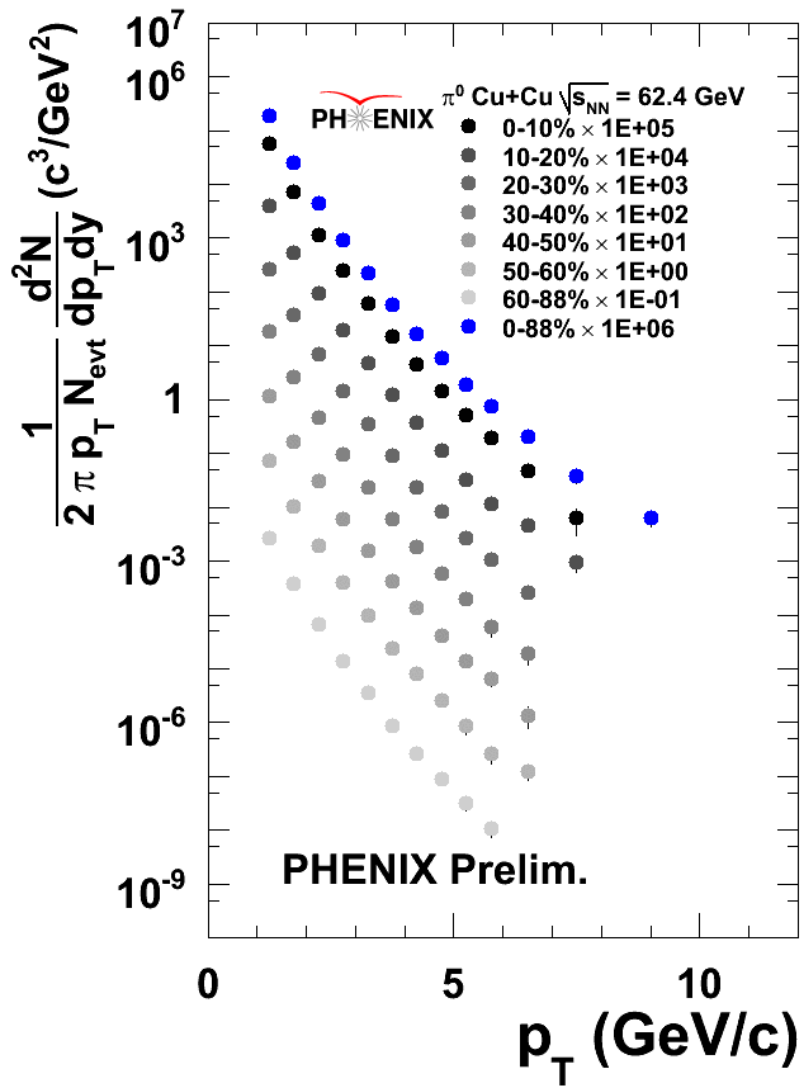
- **GLV**
  - $\Delta E \propto \rho_0 L_{max}^2$
- **Consider expansion $\rho(\tau)$**
  - $R_{AA} \propto \int dL\, \rho_0 \frac{L\tau_0}{L+\tau_0}$?
  - L_{max} from Glauber MC
- **Universal curve above 7 GeV/c**
  - Simple geometry dependence
  - Parton energy loss dominates R_{AA}

Important constraint to theories

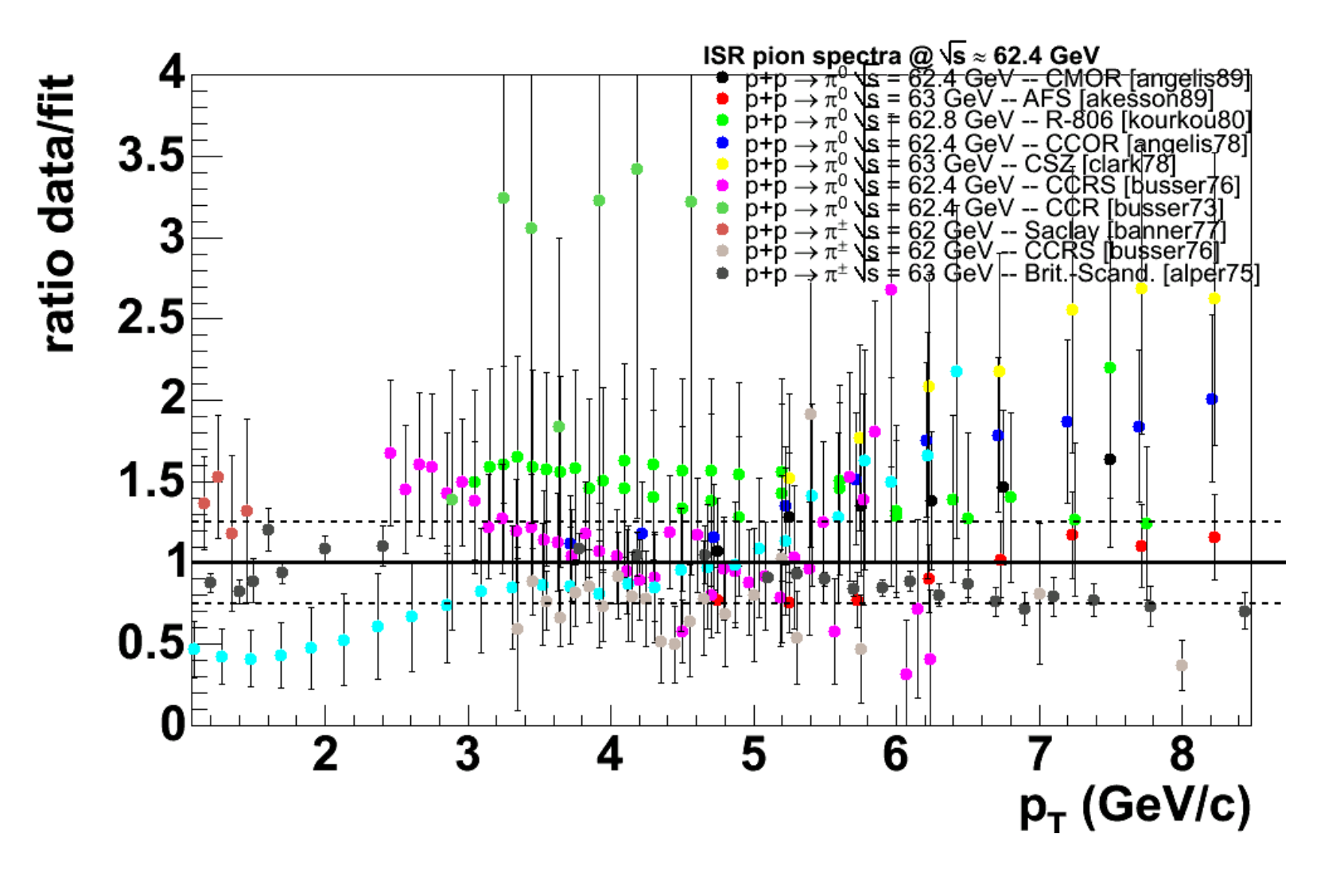
Energy Dependence...
Going down!

Au+Au and Cu+Cu @ 62.4 GeV

- **Cu+Cu 14 days RHIC Run05**
  - 197 M minimum bias events
- **Au+Au 9 days RHIC Run04**
  - 40 M minimum bias events
- **Problem up to date**
  - Poor p+p references
    - ISR Data



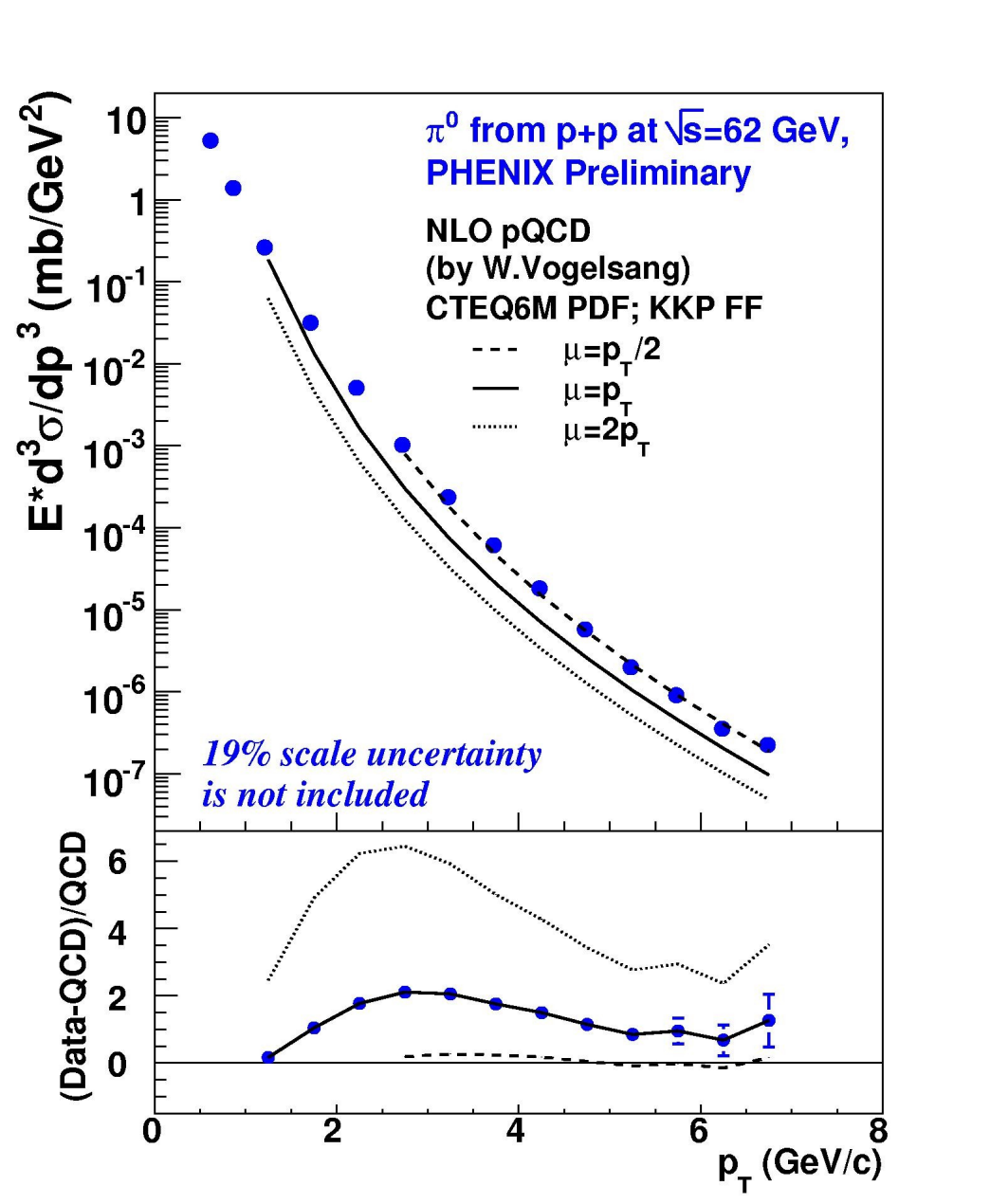
ISR p+p Reference @ 62.4 GeV



J.Phys.G31:S491 (2005)

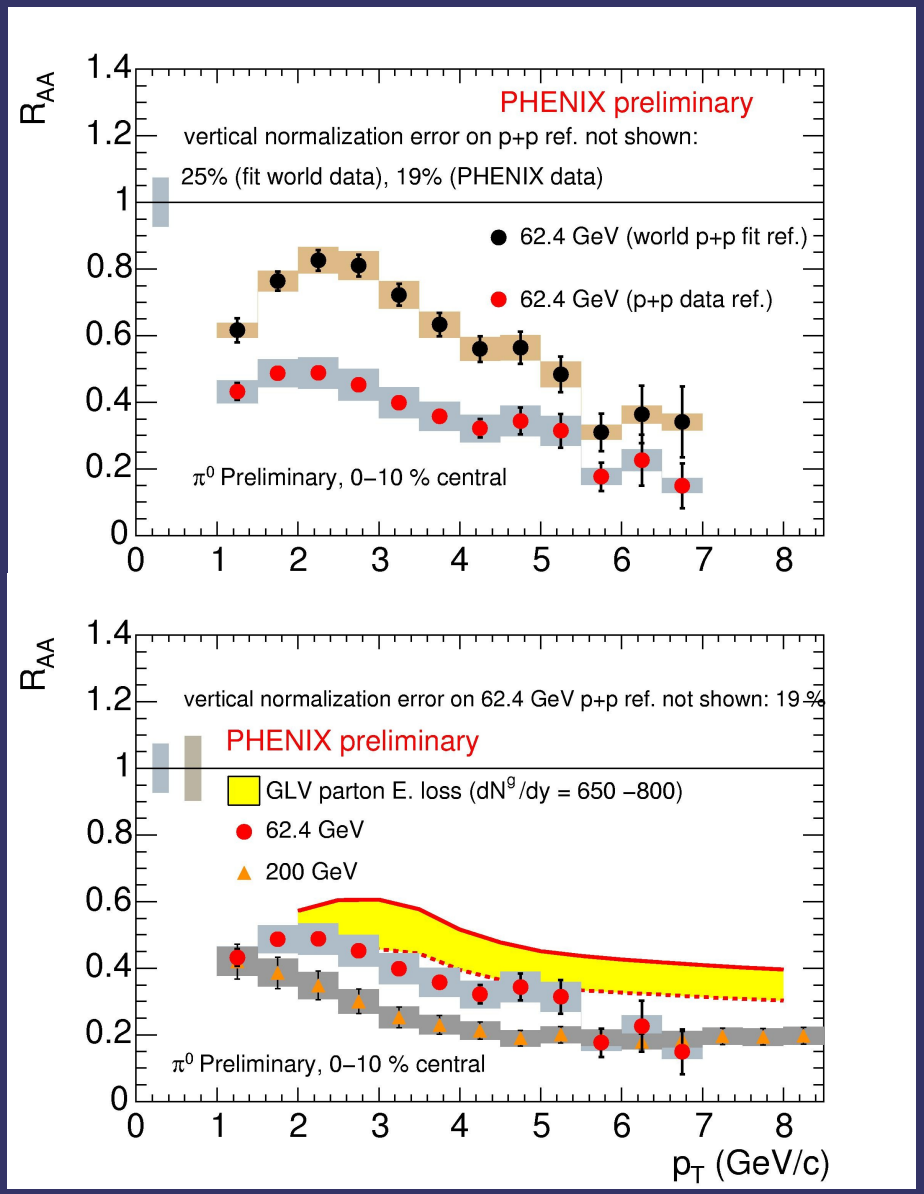
PHENIX Reference p+p @ 62.4 GeV

- **12 days of RHIC Run06**
  - 400 nb^{-1} sampled
  - 210 M min. bias + 22 M high-p_T triggered
  - Crucial for interpretation of Energy loss (R_{AA})

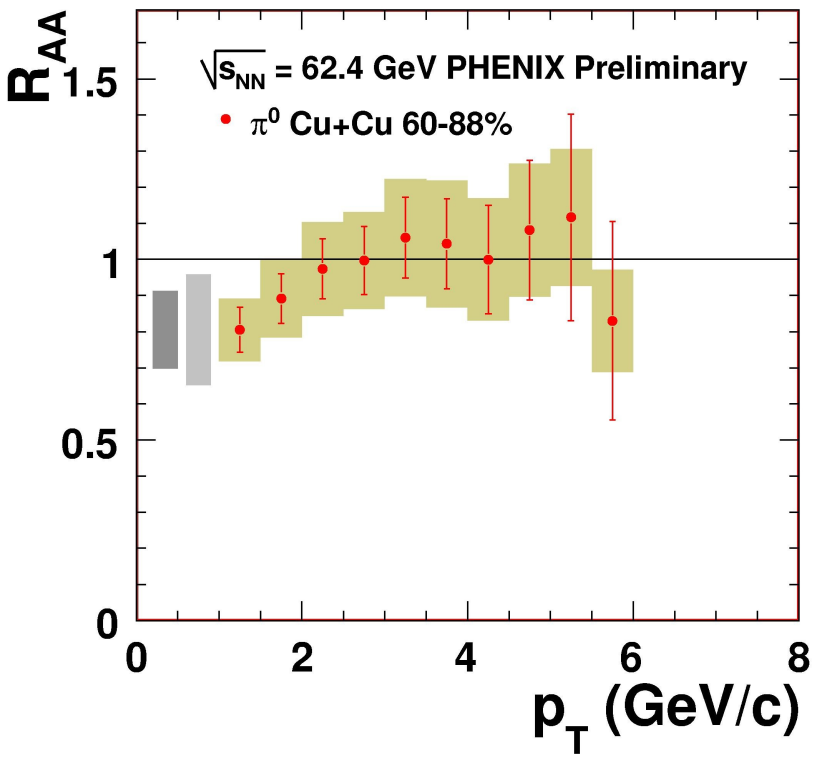


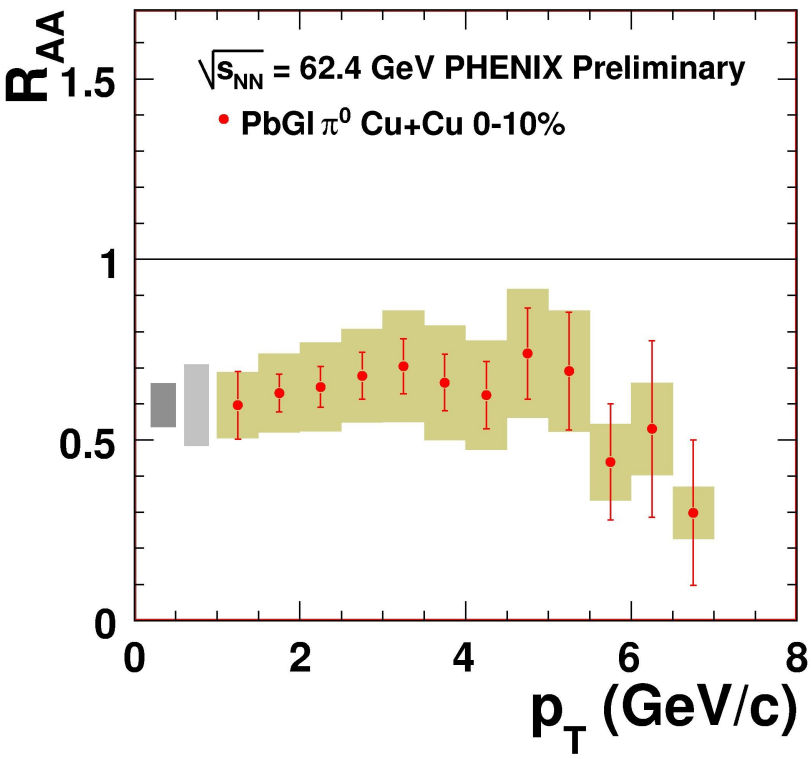
New R_{AA} in Au+Au @ 62.4 GeV

- **Large suppression**
  - Already at low p_T
  - Apparent with PHENIX reference
    - 50% difference to R_{AA} with ISR reference
- **Gluon density GLV**
  - $dN_g/dy \sim 650\text{-}800$
  - Vitev: Phys. Lett. B 606 (2005)



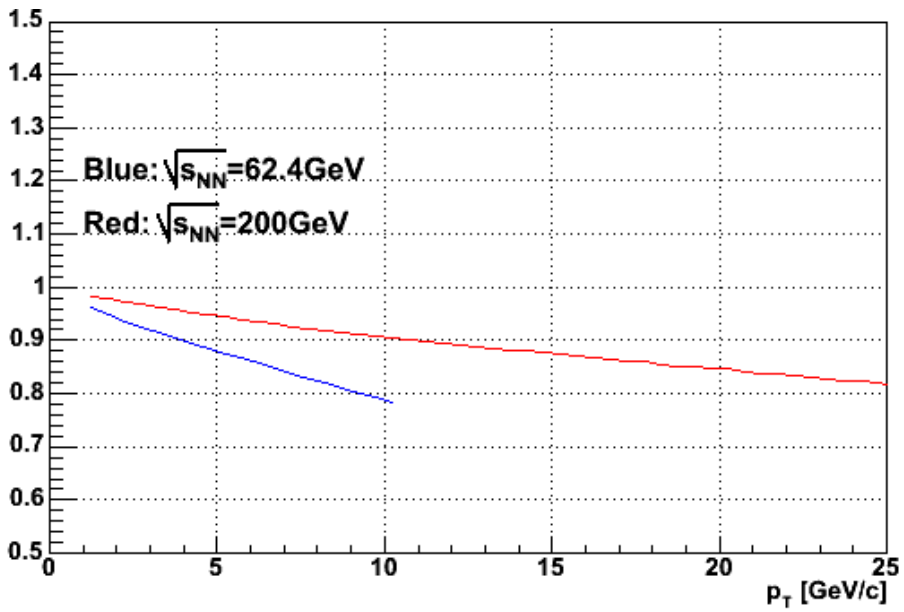
New Cu+Cu R_{AA} @ 62.4 GeV





Clear effect when going from peripheral to central
Also clear suppression in Cu+Cu

Direct Photons?



Mock-up R_{AA}

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

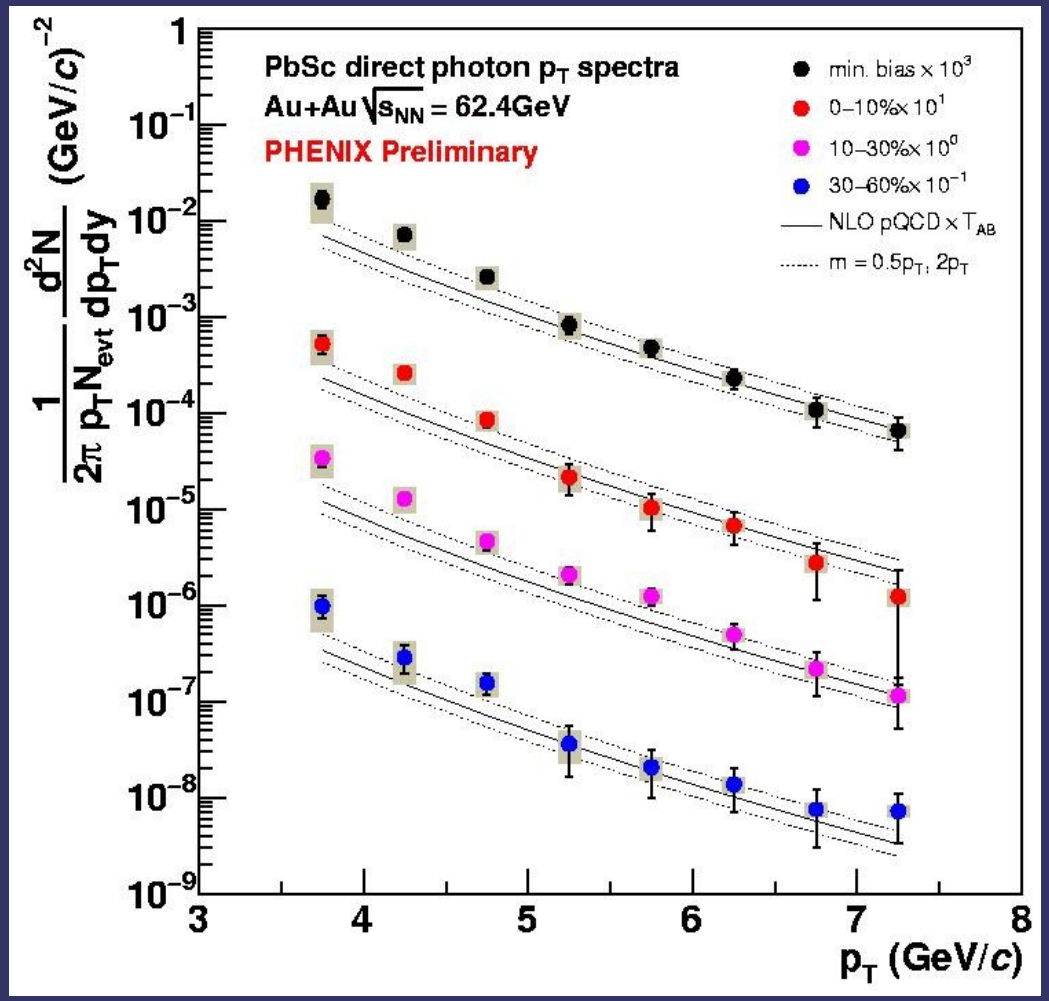
- **At high *x* quark distributions become dominant**
  - Difference for em-processes in n+p, p+p and n+n scattering at high p_T

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

- **At lower energies**
  - Study SAME effect at lower p_T
  - Systematic uncertainties smaller in this domain
    - Better separation of decay photons

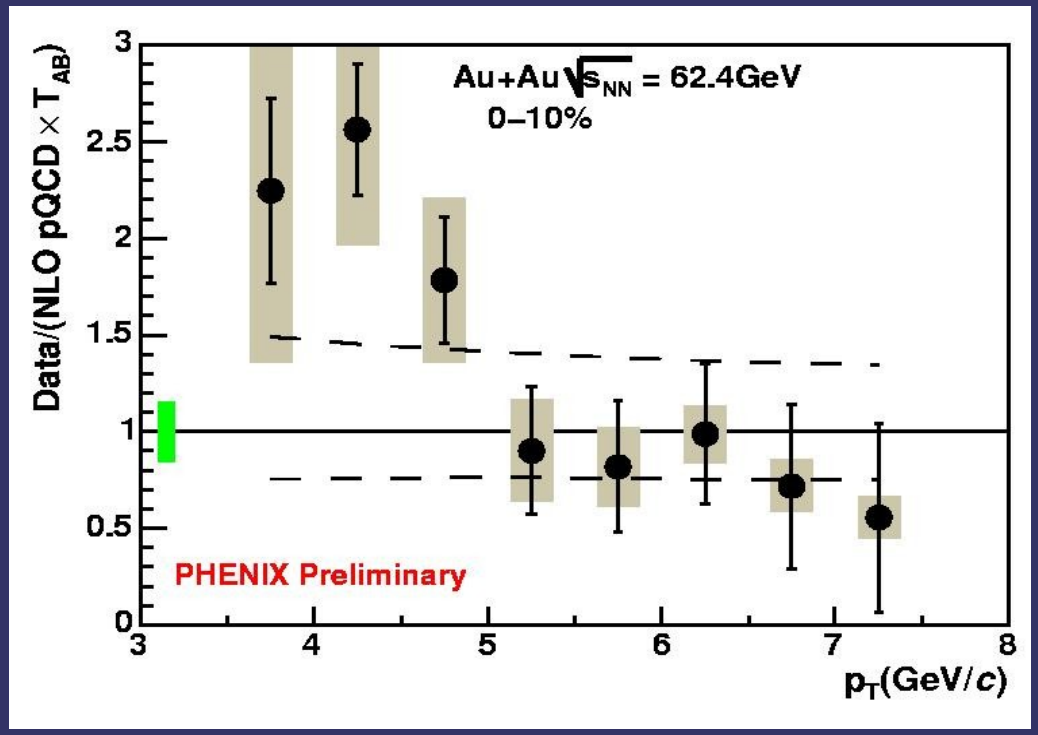
Data @ 62.4 GeV essential to separate isospin effect

Direct Photons @ 62.4 GeV



- **Au+Au Run04**
  - Same run as 200 GeV data
- **Comparison to pQCD calculation (W. Vogelsang)**

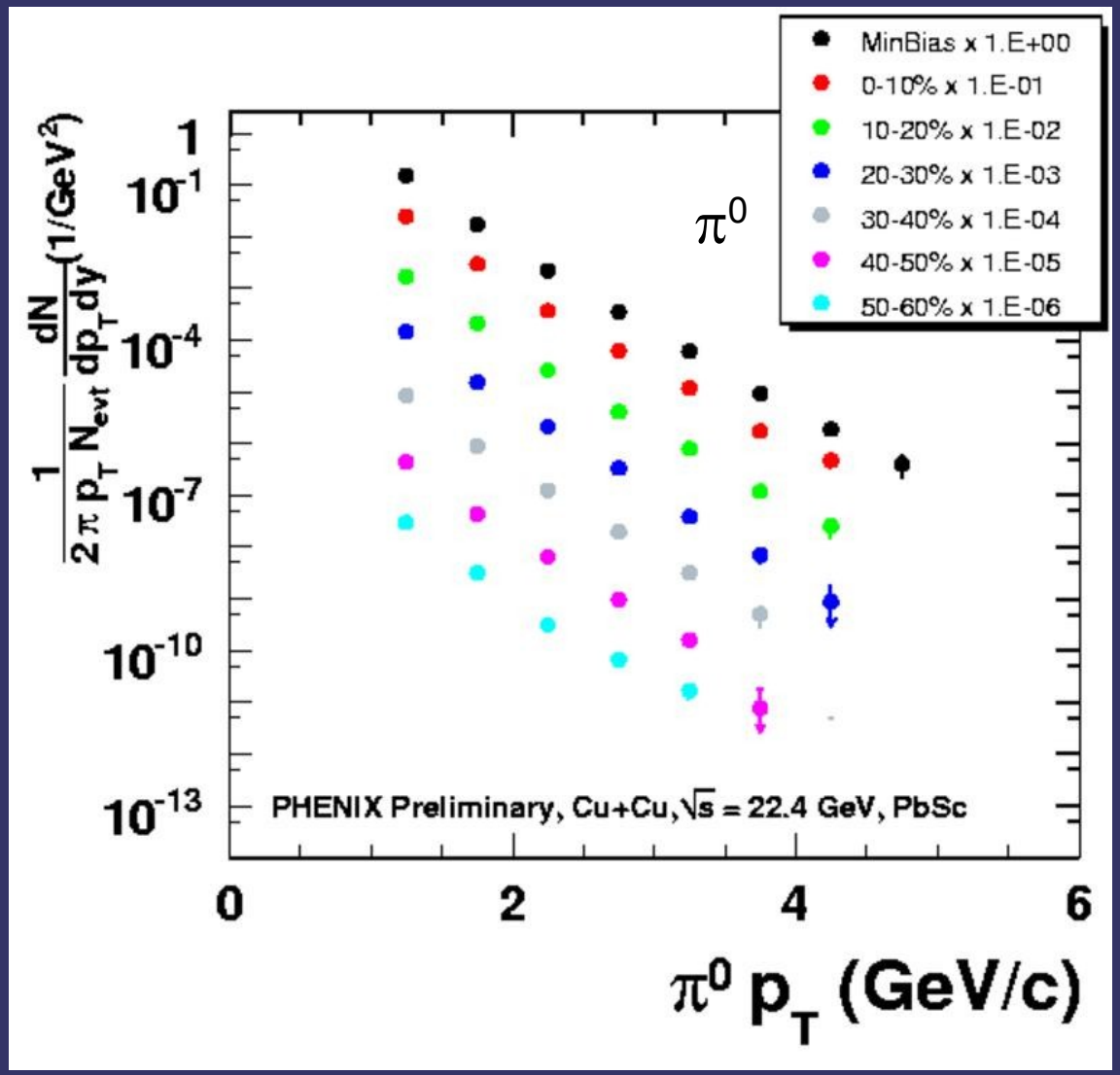
Direct Photons @ 62.4 GeV



- **Au+Au Run04**
  - Same run as 200 GeV data
- **Comparison to pQCD calculation (W. Vogelsang)**
- **R_{AA} with pQCD**
  - Need p+p reference
  - Now we are limited by statistics
  - Also look in Cu+Cu

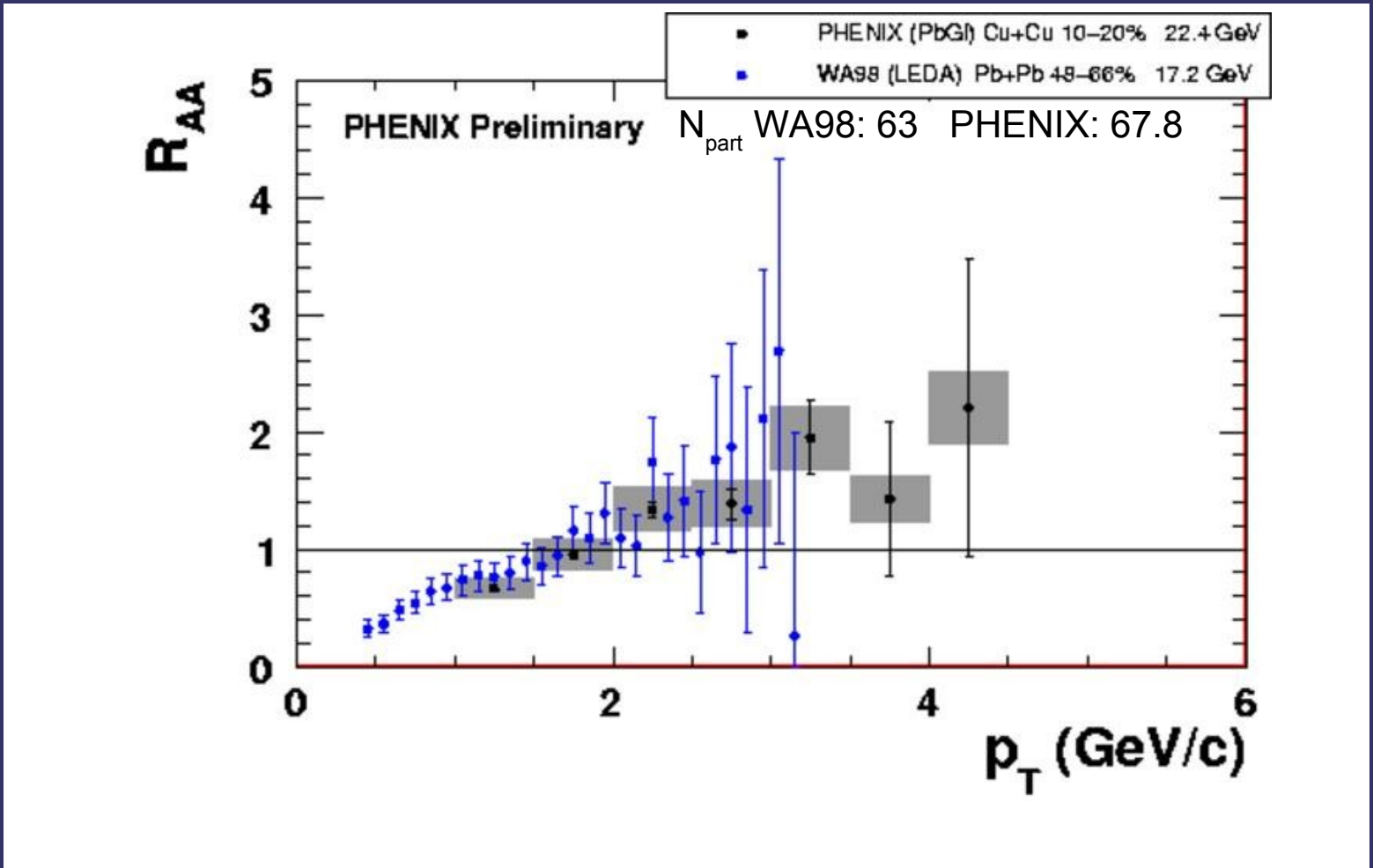
Cu+Cu @ 22.4 GeV

- **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



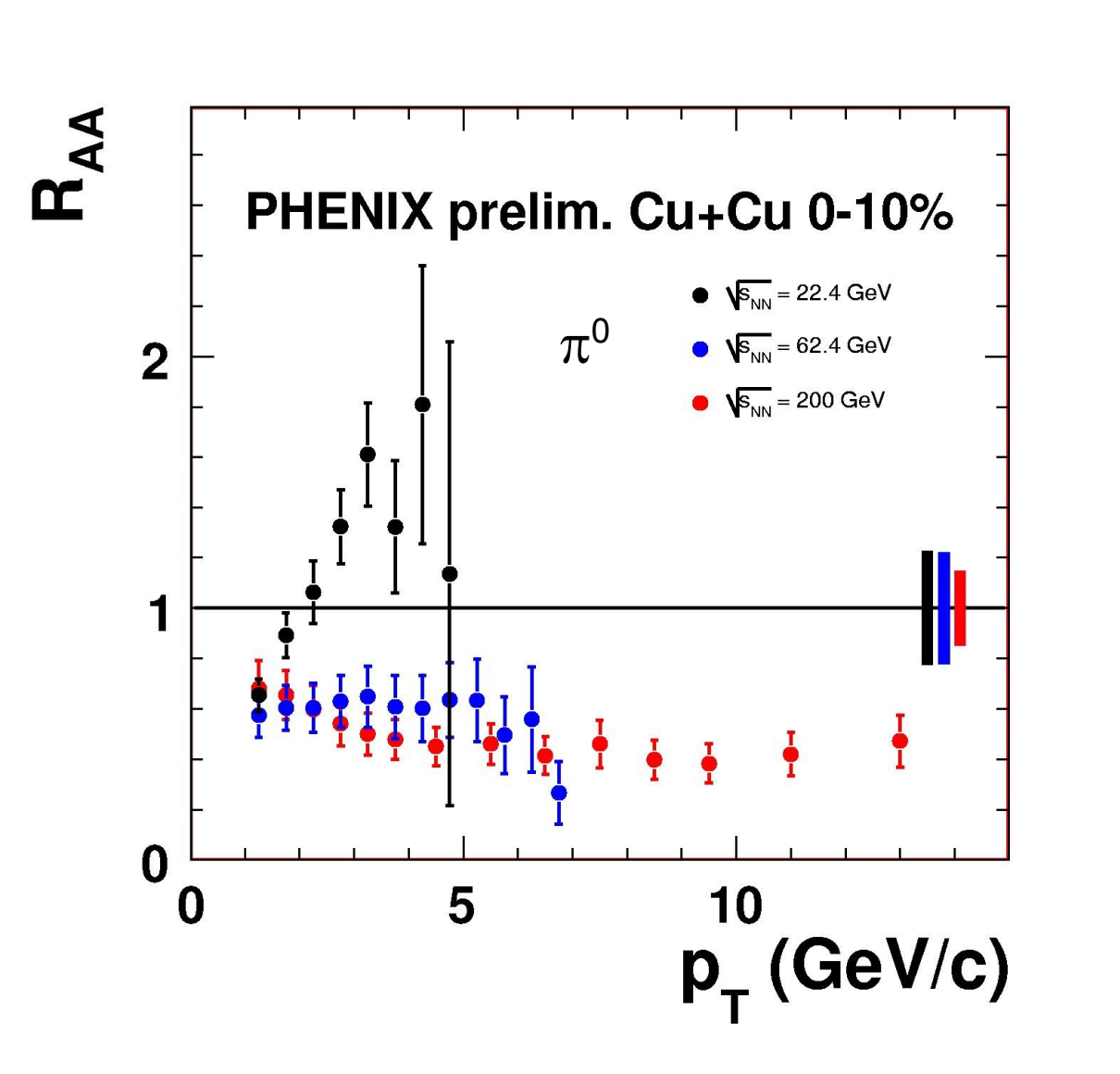
π^0 R_{AA} WA98 vs. PHENIX

We can do SPS Physics



Similar N_{part}: same behaviour

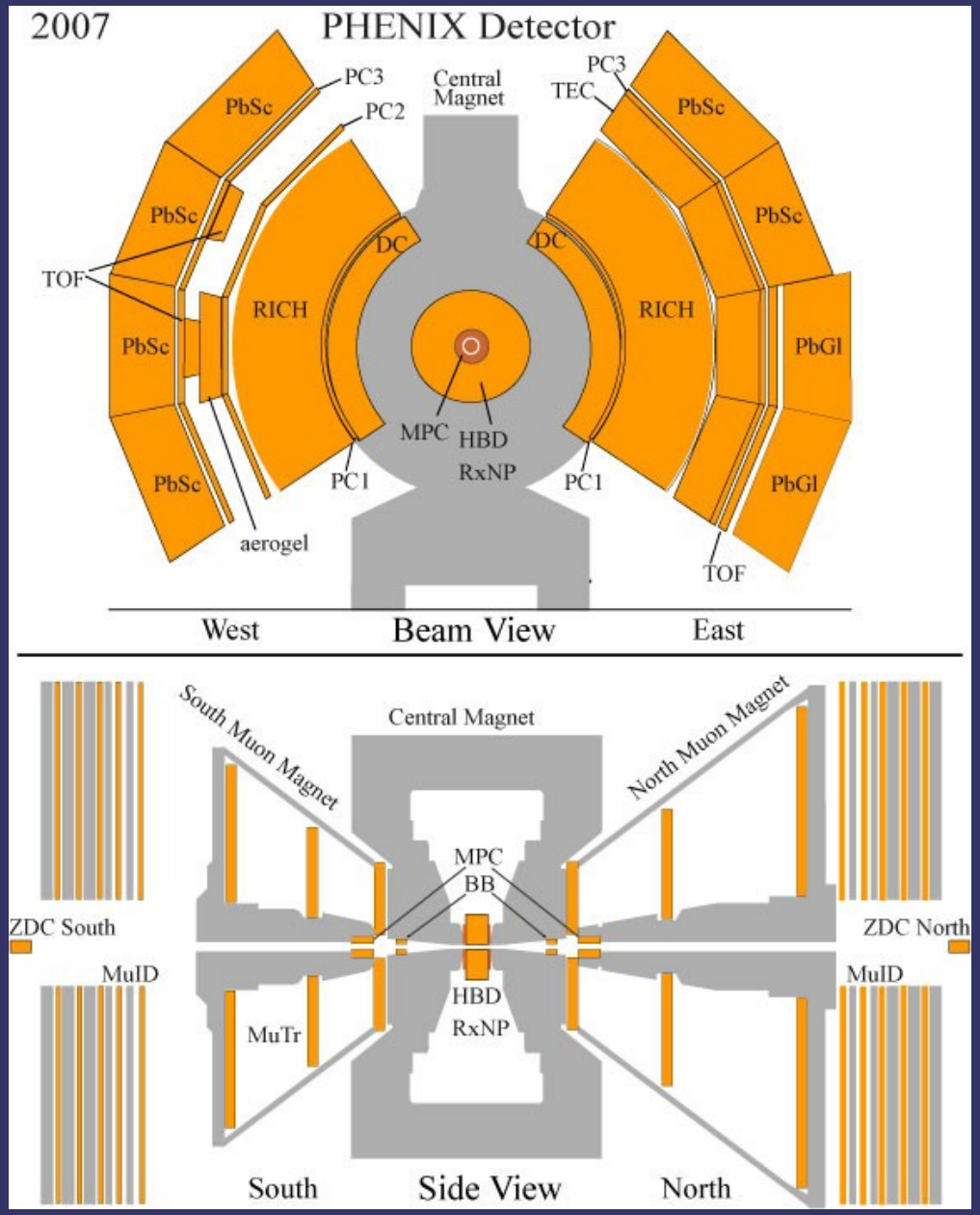
R_{AA} from 22.4 to 200 GeV



Summary

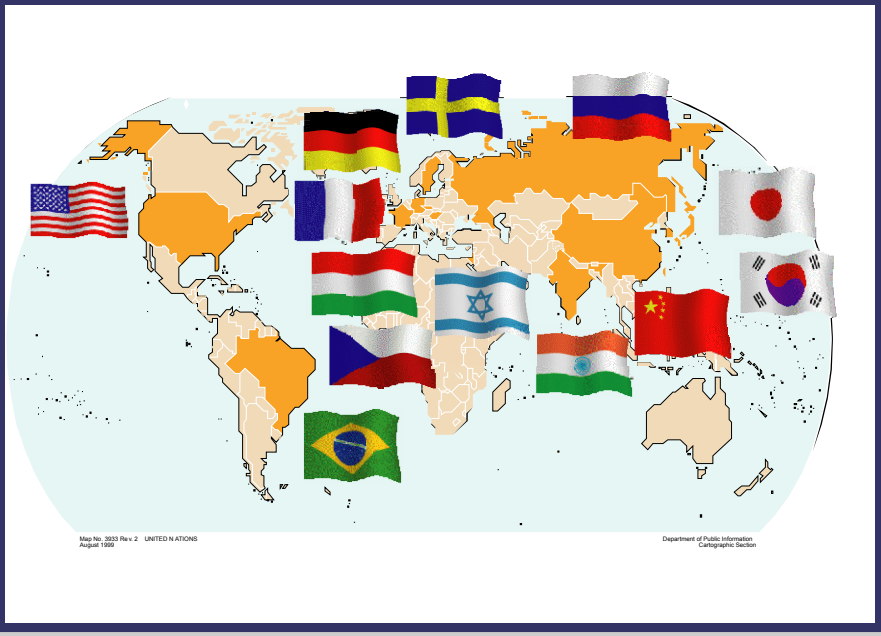
- **Systematic study of jet quenching**
  - p_T dependence
    - π^0 R_{AA} flat up to p_T = 20 GeV/c
  - System size dependence
    - Similar R_{AA} for Cu+Cu and Au+Au for similar N_{part}
    - Hints for surface effects
  - $\Delta\phi$ tomographie
    - Universal behavior above 7 GeV/c
  - $\sqrt{s_{NN}}$ dependence
    - First systematic study of jet quenching from $\sqrt{s_{NN}}$ ~ 20 – 200 GeV within the same experiment
    - RHIC/PHENIX able to do SPS Physics
- **Direct photons**
  - No suppression over a wide p_T range
  - Deficit at high p_T
    - Possibly due to isospin effect
  - First measurement in Au+Au at $\sqrt{s_{NN}}$ = 62.4 GeV

Outlook



- **Many things not covered**
  - New methods for low p_T photons
    - Internal and external conversions
    - γ-h correlations
  - Direct photon flow
- **Many more things to expect from PHENIX**
  - Major detector upgrades
    - Hadron Blind Detector
    - Reaction Plane Detector
  - Run07 Au+Au ends tomorrow (more than 2 $\times$ Run04)

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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	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
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	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund

13 Countries; 62 Institutions; 550 Participants*

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	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
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	Los Alamos National Laboratory, Los Alamos, NM
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	University of New Mexico, Albuquerque, NM
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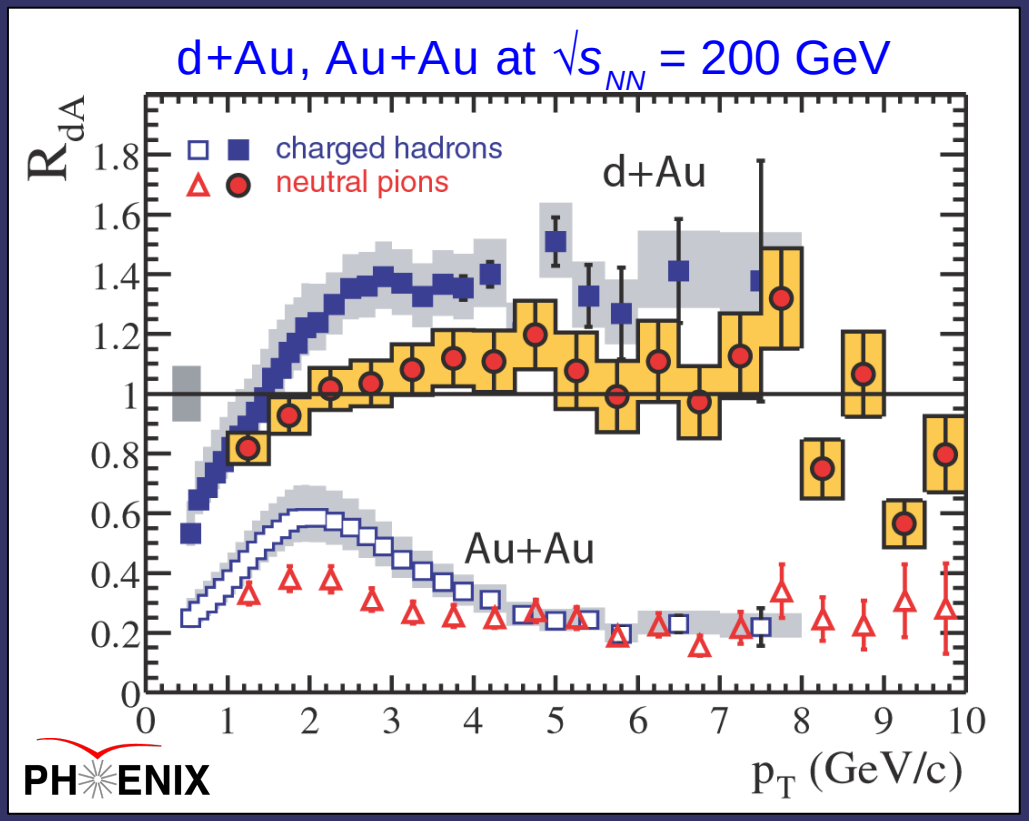
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

*as of March 2005

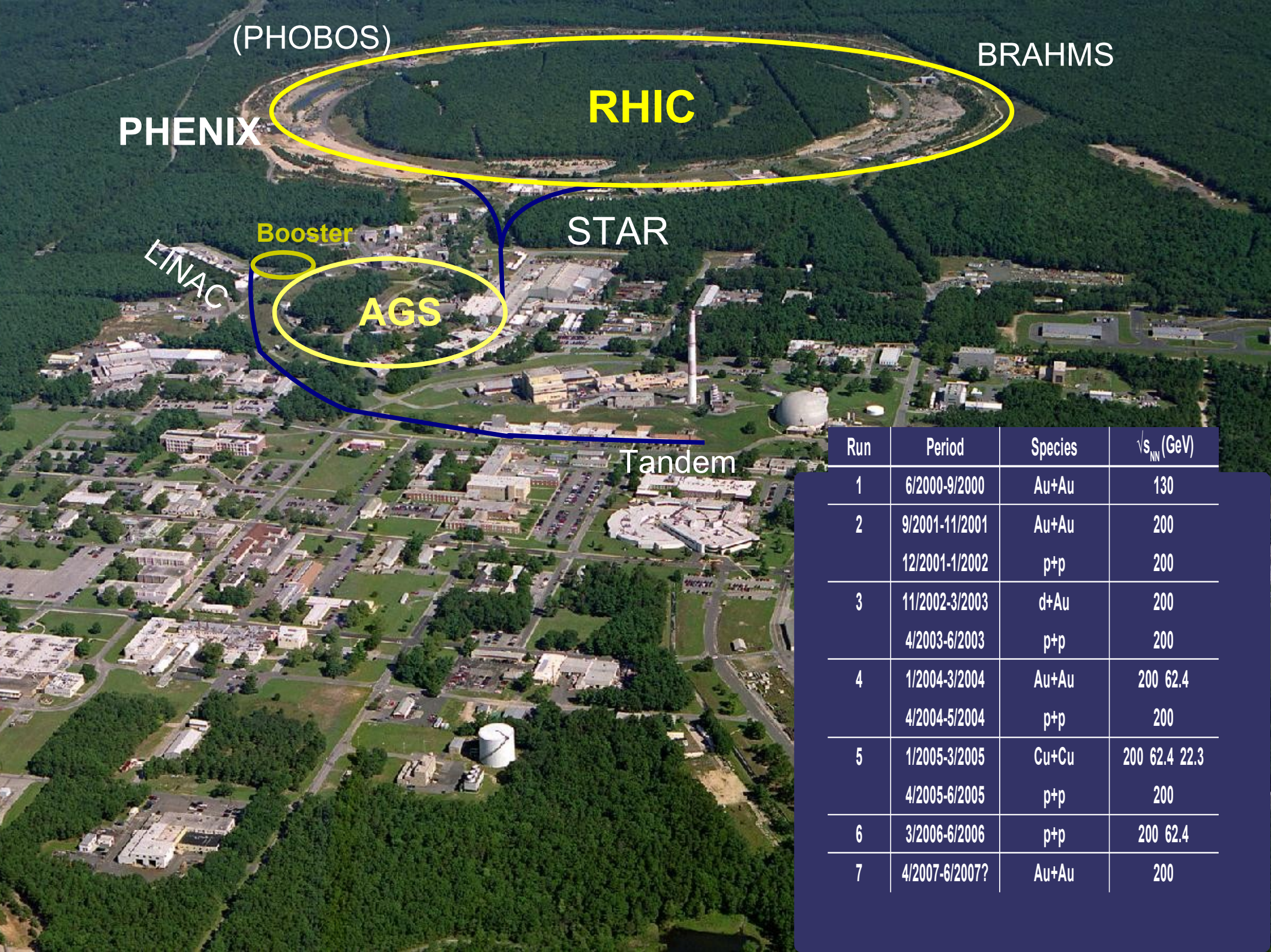
Backup Slides

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)



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

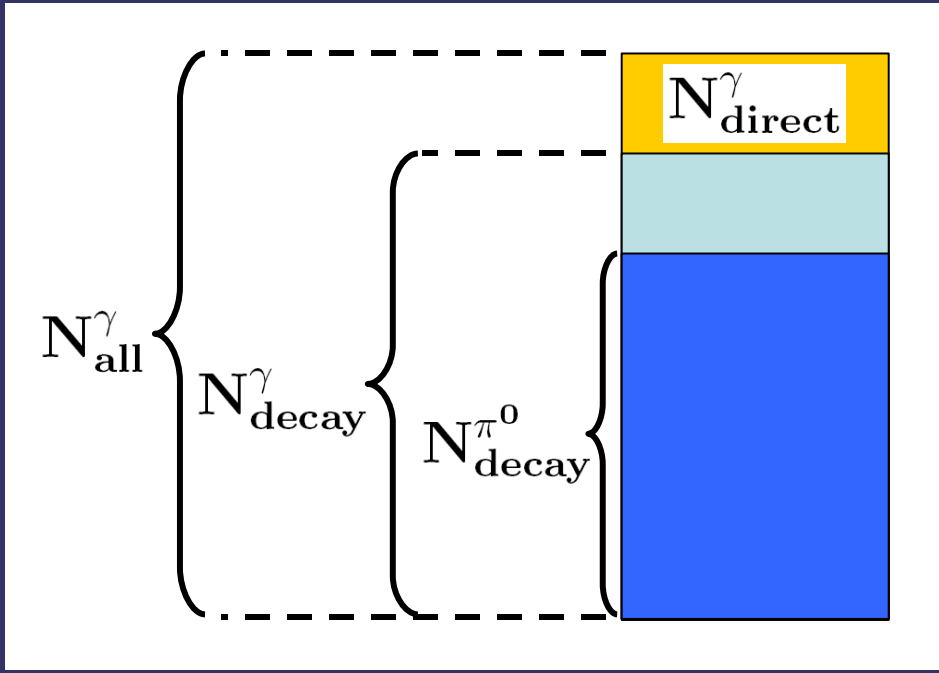
Measuring Direct Photons

- **Inclusive photons**

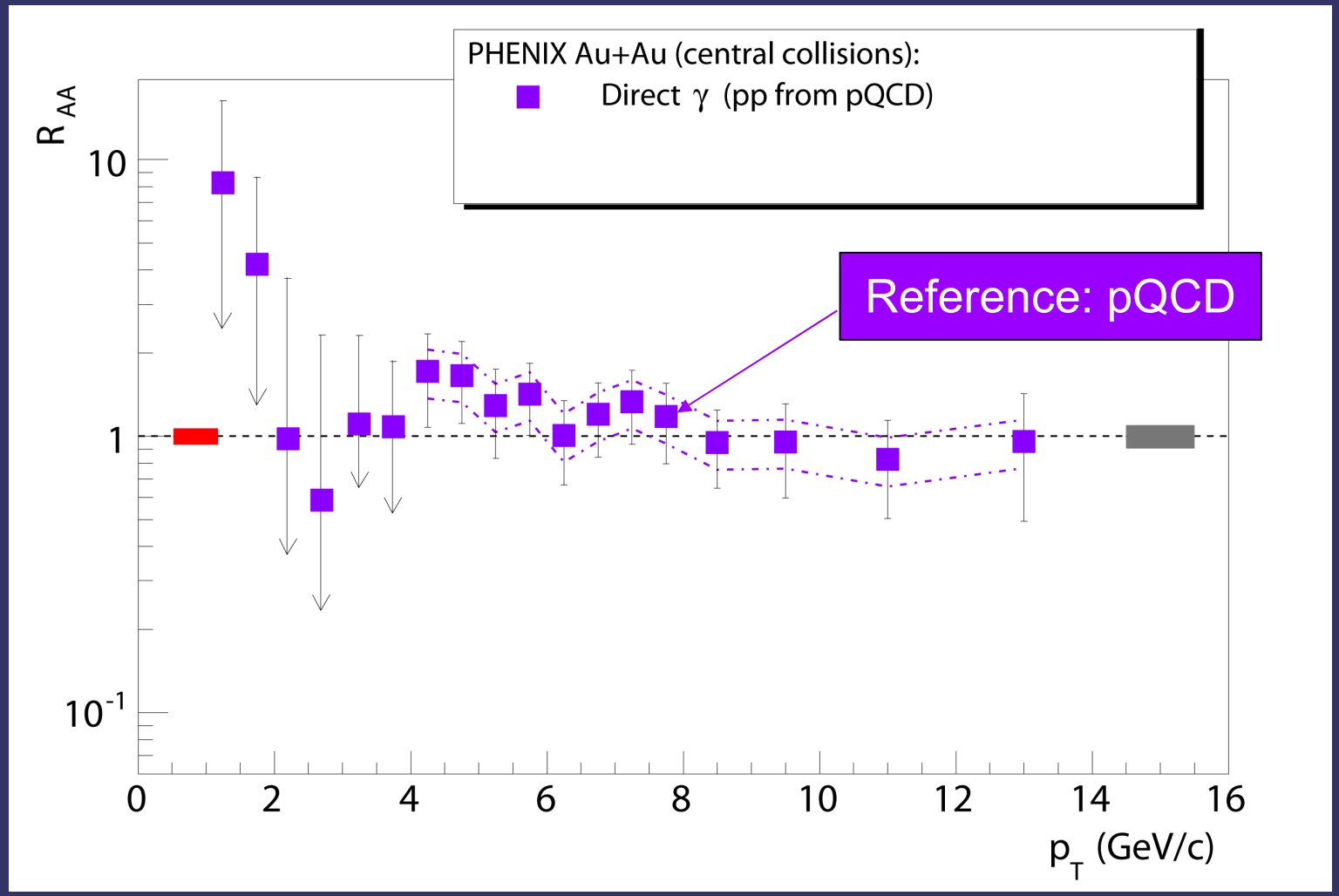
$$N^{\gamma}_{all} = N^{\gamma}_{direct} + N^{\gamma}_{decay}$$

- **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

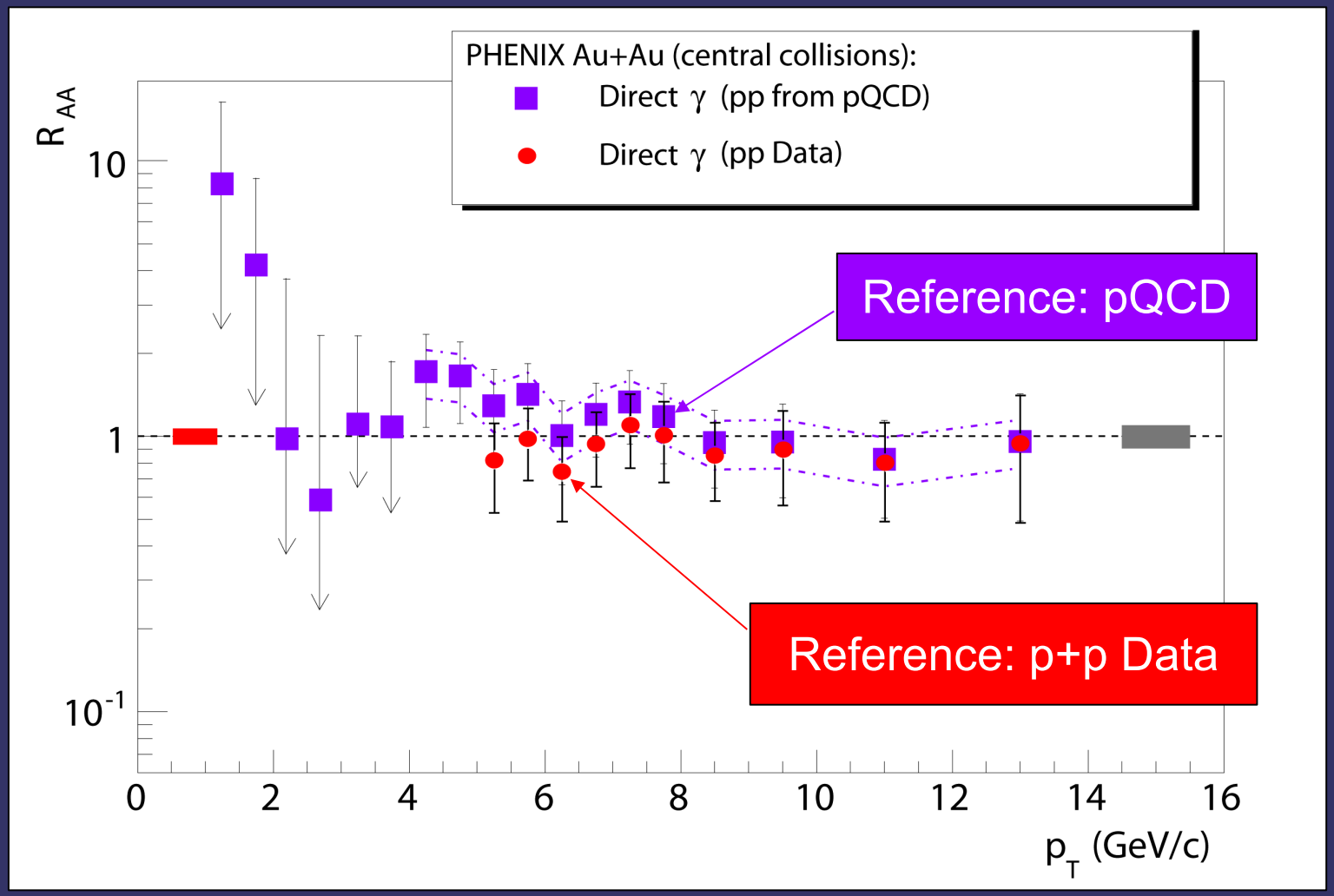
$$N^{\gamma}_{direct} = N^{\gamma}_{all} - N^{\gamma}_{decay}$$



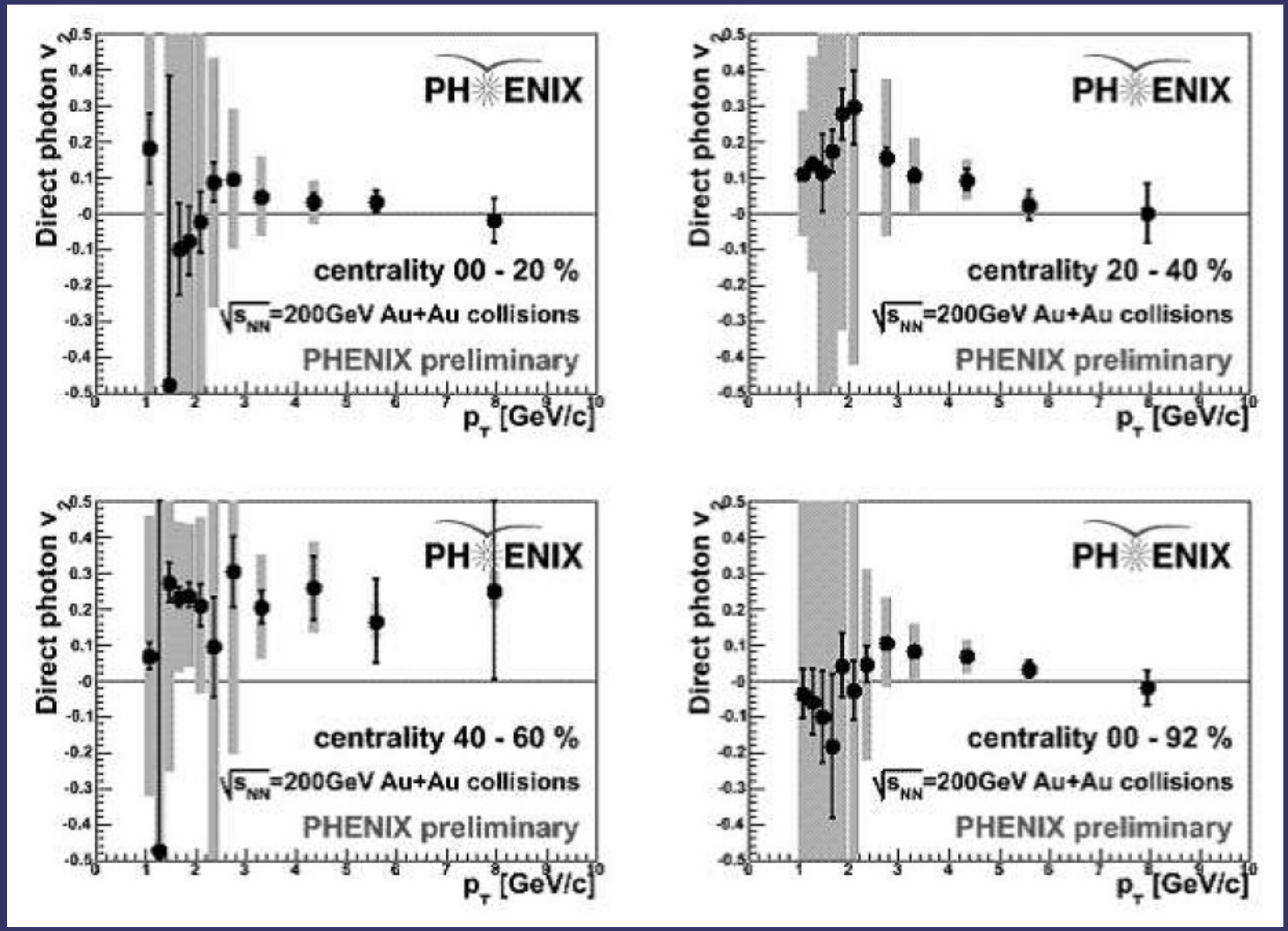
Direct Photon R_{AA}



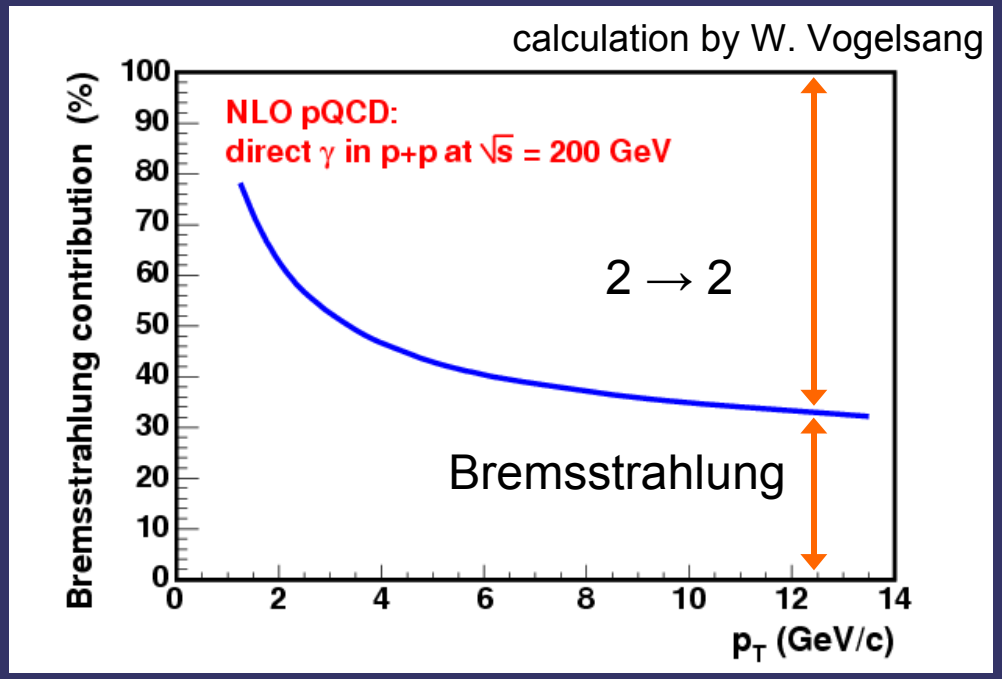
Direct Photon R_{AA}



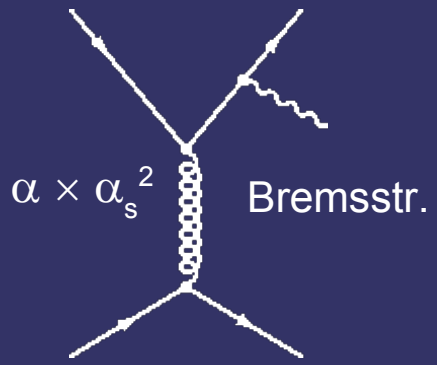
Direct Photon v_2



But...



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

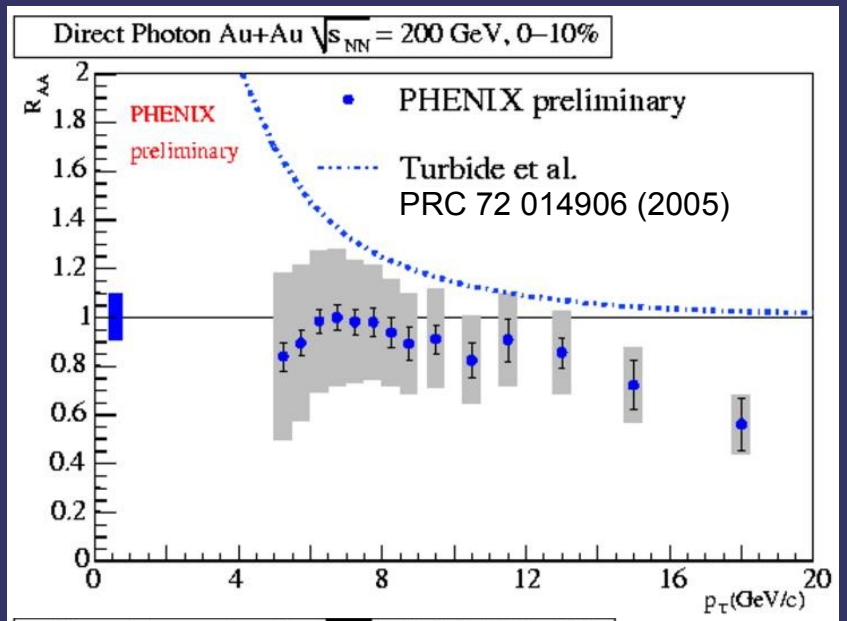


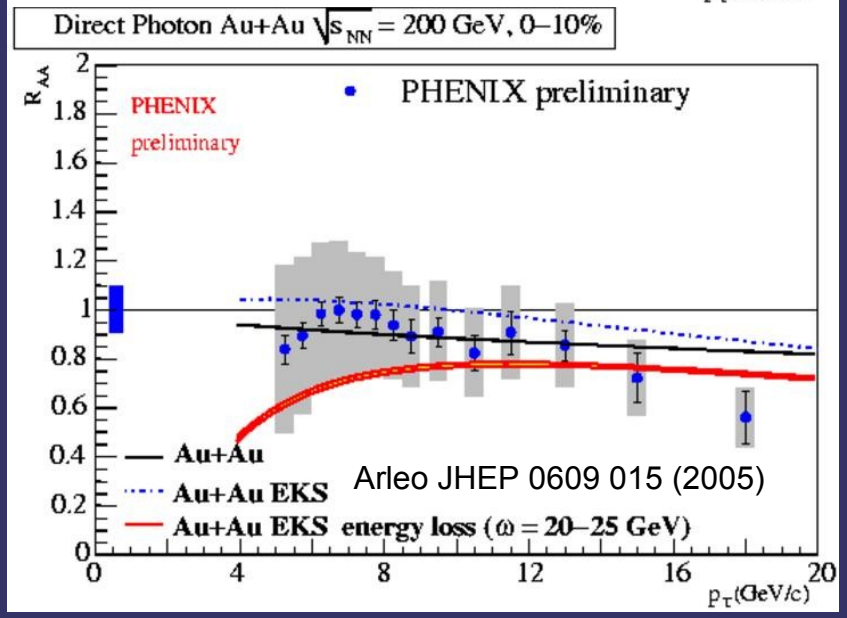
- **Consider also multiple scattering and formation times**
- **Jet-plasma interaction**
  - $q_{hard}+g_{thermal} \rightarrow q+\gamma \ldots$
- **Thermal**

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

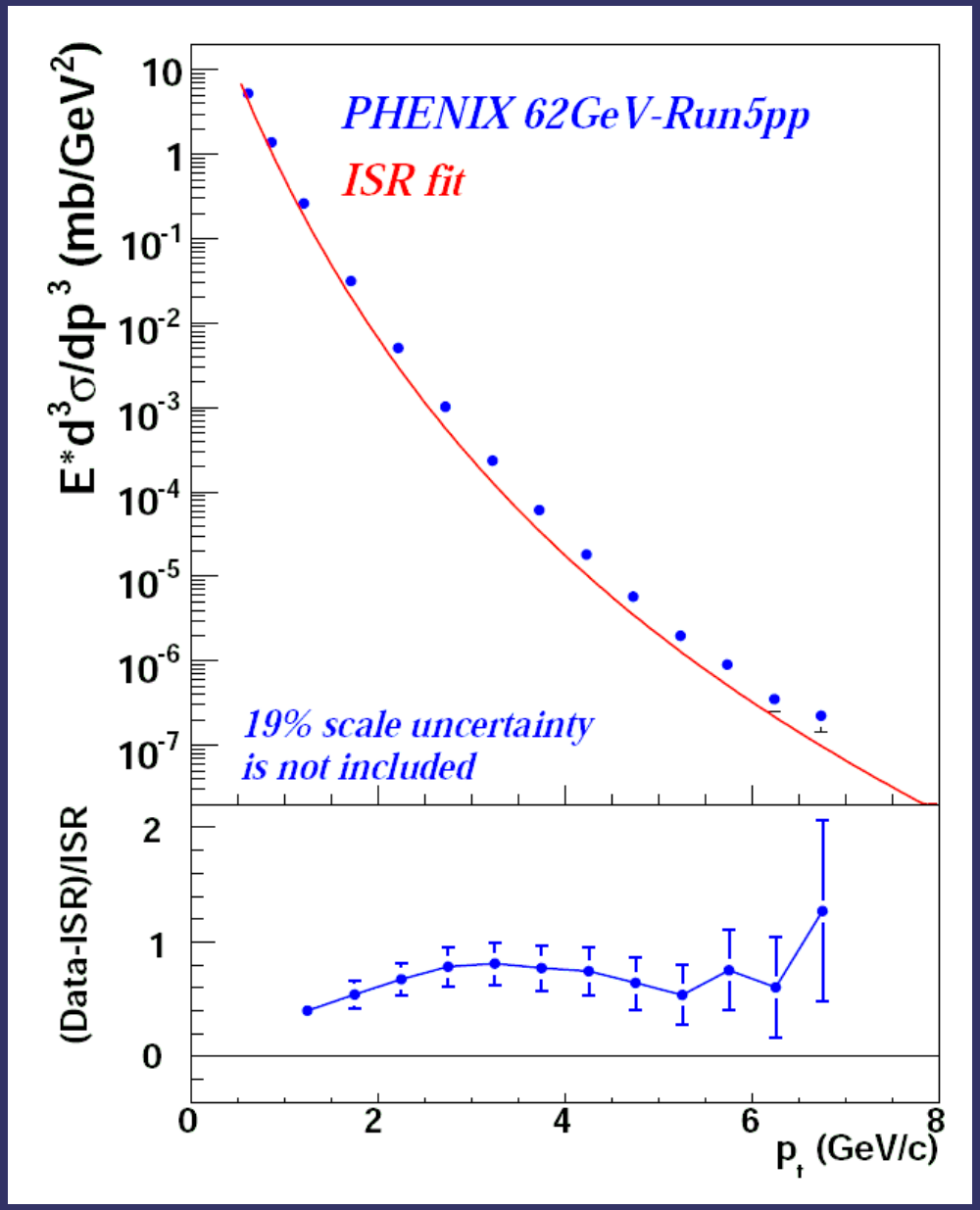
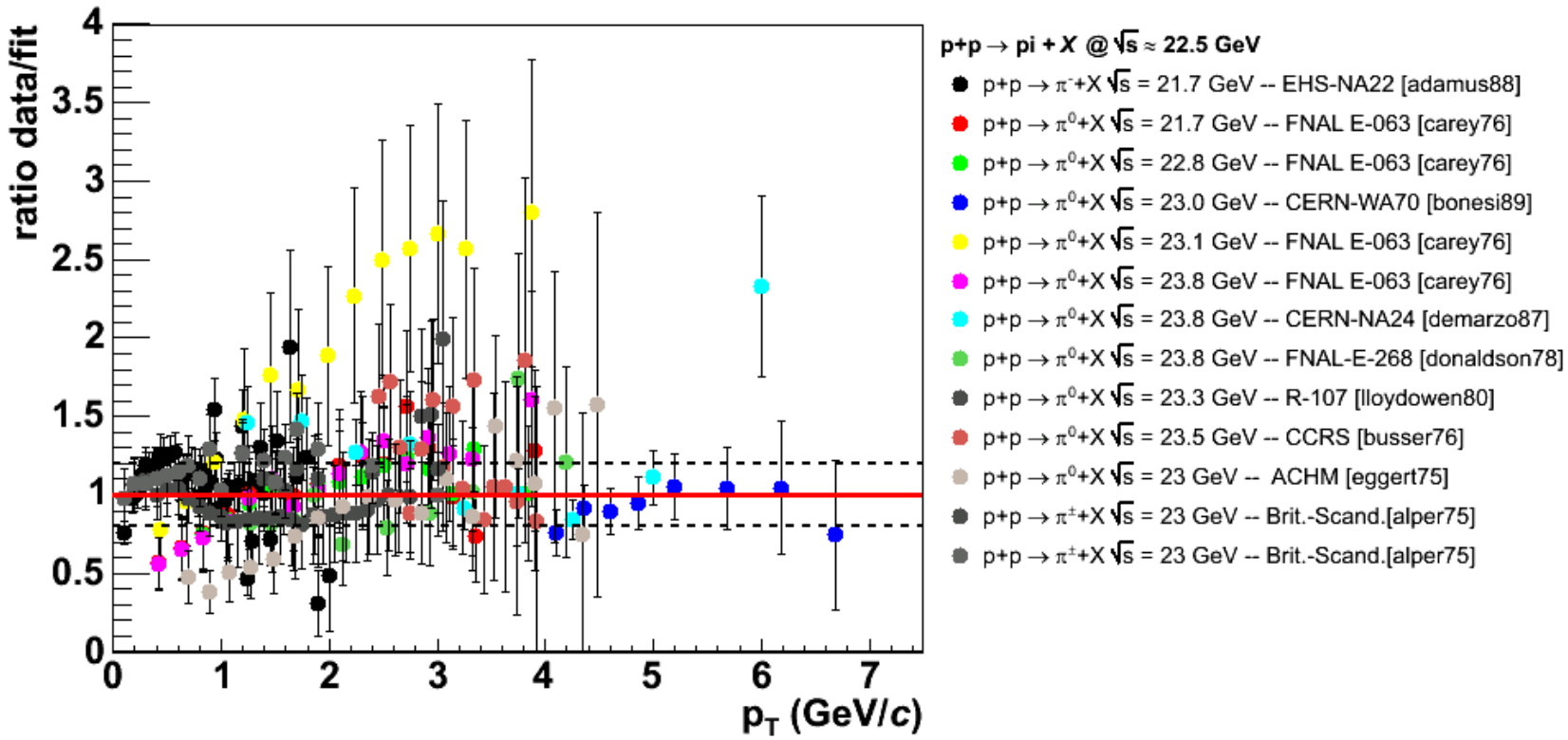
Isospin likely explanation
Experimental confirmation needed





PHENIX Reference p+p @ 62.4 GeV

- **12 days of RHIC Run06**
  - 400 nb^{-1} sampled
  - 210 M min. bias + 22 M high-p_T triggered
- **Considerable difference to ISR fit**
  - 50% difference
  - Crucial for interpretation of Energy loss (R_{AA})



p+p Reference @ 22.4 GeV