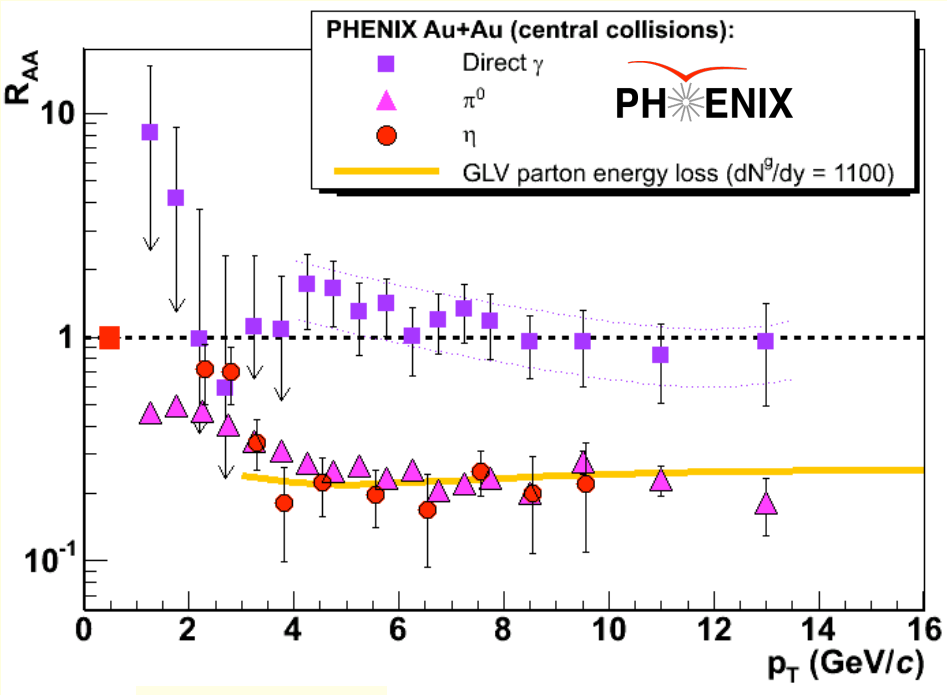
Characteristics of Parton Energy Loss Studied with High-p_T Particle Spectra from PHENIX

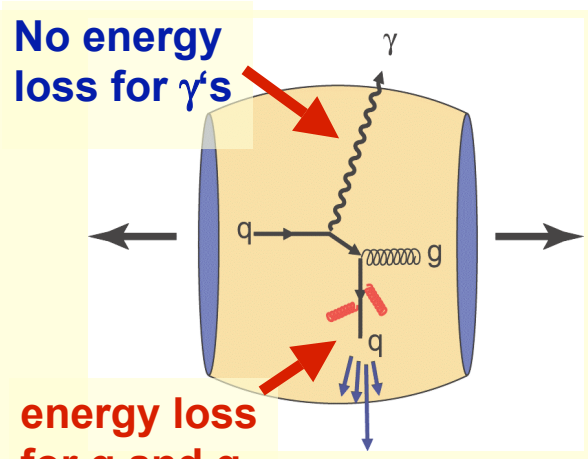
Quark Matter 2008, Jaipur, February 5, 2008

Klaus Reygers
University of Münster

for the PHENIX Collaboration

Starting Point: Conclusions After the First Three RHIC Runs





$$R_{AB} = \frac{\mathrm{d}N / \mathrm{d}p_T\big|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}} \rangle \times \mathrm{d}\sigma_{\mathrm{inv}} / \mathrm{d}p_{\mathrm{T}}\big|_{\mathrm{p+p}}},$$

$$\text{where } \langle T_{\mathrm{AB}} \rangle = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

- Hadrons are suppressed, direct photons are not
- No suppression in d+Au
- Evidence for parton energy loss
  - Static medium

$$\Delta E \propto \alpha_s \, C_{\mathrm{color}} \, \hat{q} \, L^2$$

  - 1D expansion, e.g., GLV model

$$\frac{\Delta E}{E} \propto \frac{1}{A_T} \frac{\mathrm{d}N_g}{\mathrm{d}y} L \frac{1}{E}$$

- R_{AA} constrains medium properties ($\hat{q}$, $\mathrm{d}N_g / \mathrm{d}y$)

Is Parton Energy Loss Really the Correct Explanation ?

Dependence on heavy ion species

Centrality and p_T Dependence of High-p_T Hadron Suppression ($\rightarrow$ extend p_T range)

T_{AB} scaling of hard scattering in A+A ($\rightarrow$ direct γ)

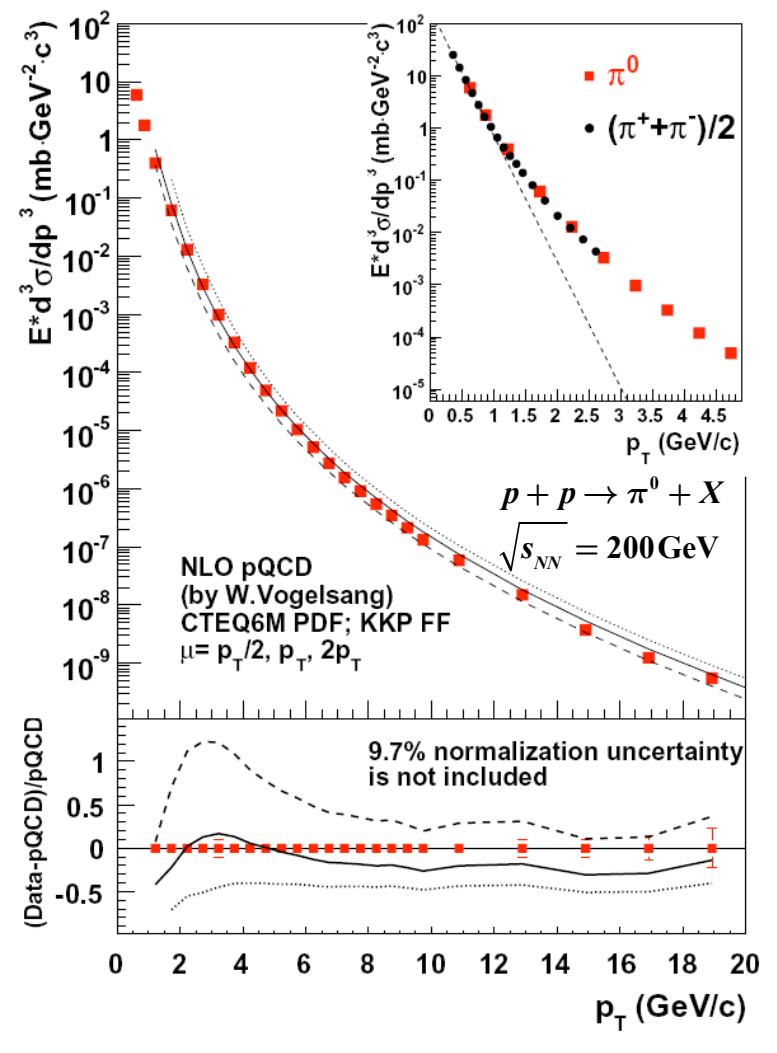
Determine more quantitative constraints on medium properties

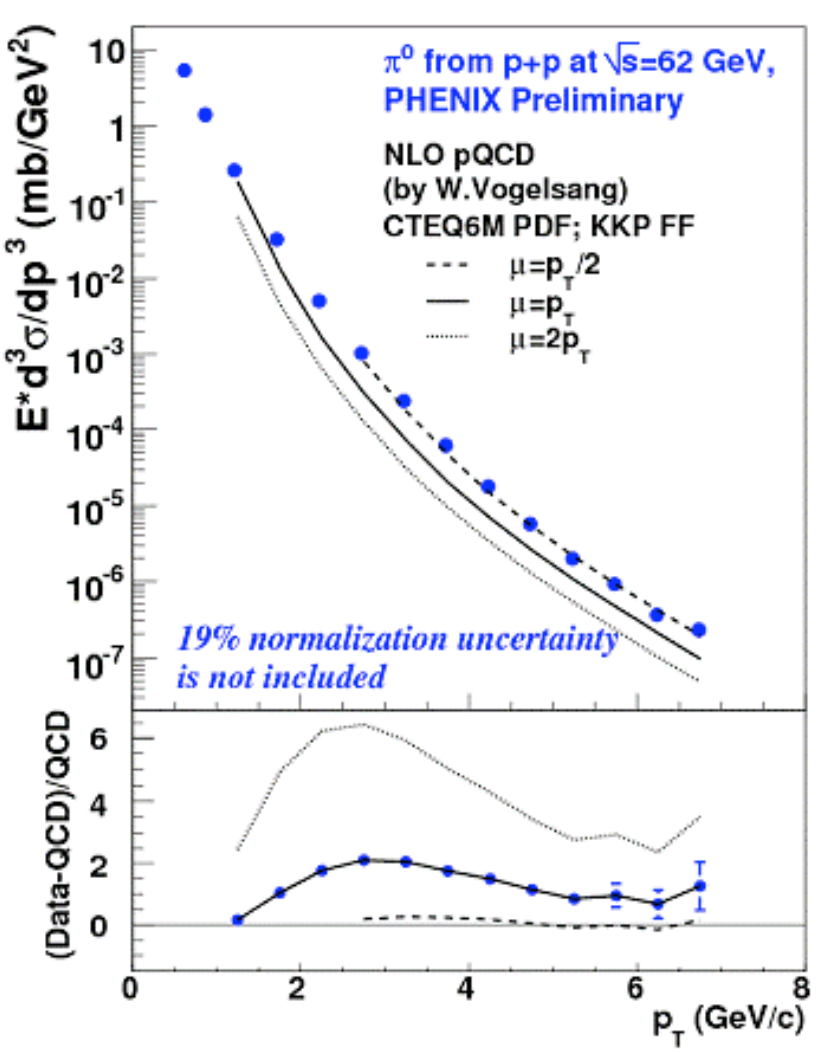
Dependence on hadron species

Dependence on $\sqrt{s_{NN}}$

Test as many assumptions/predictions of parton energy loss models as possible

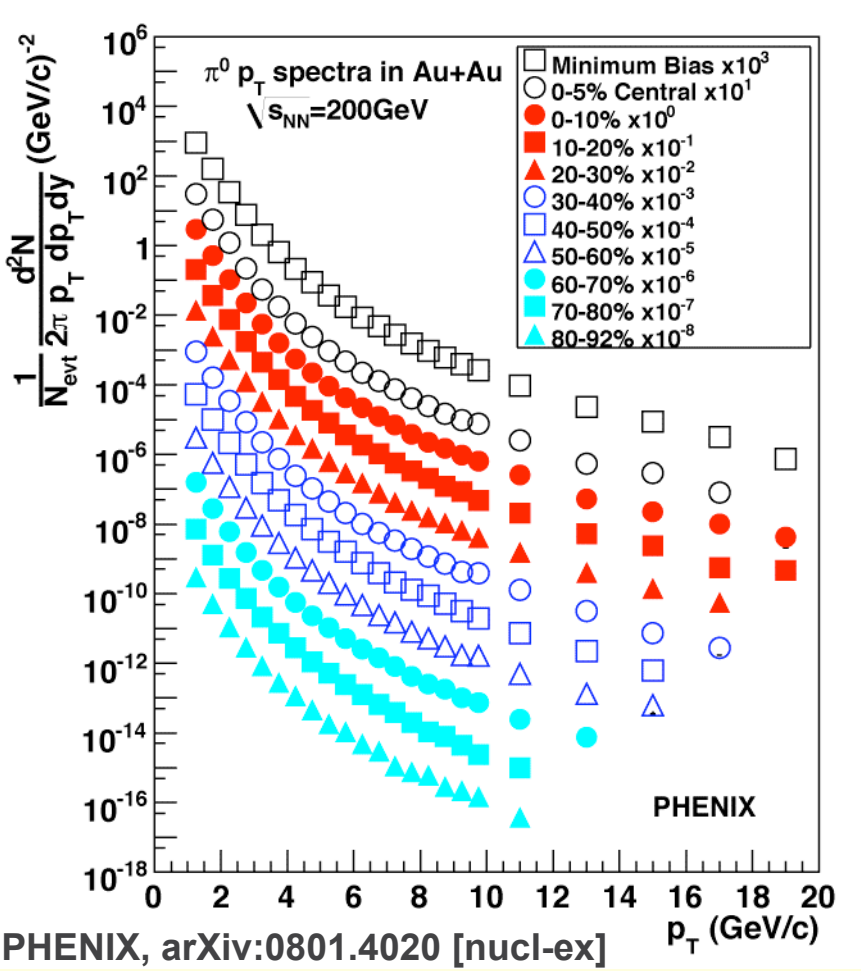
The Basis for Parton Energy-Loss Models: Measured π^0 Spectra in p+p Agree with pQCD



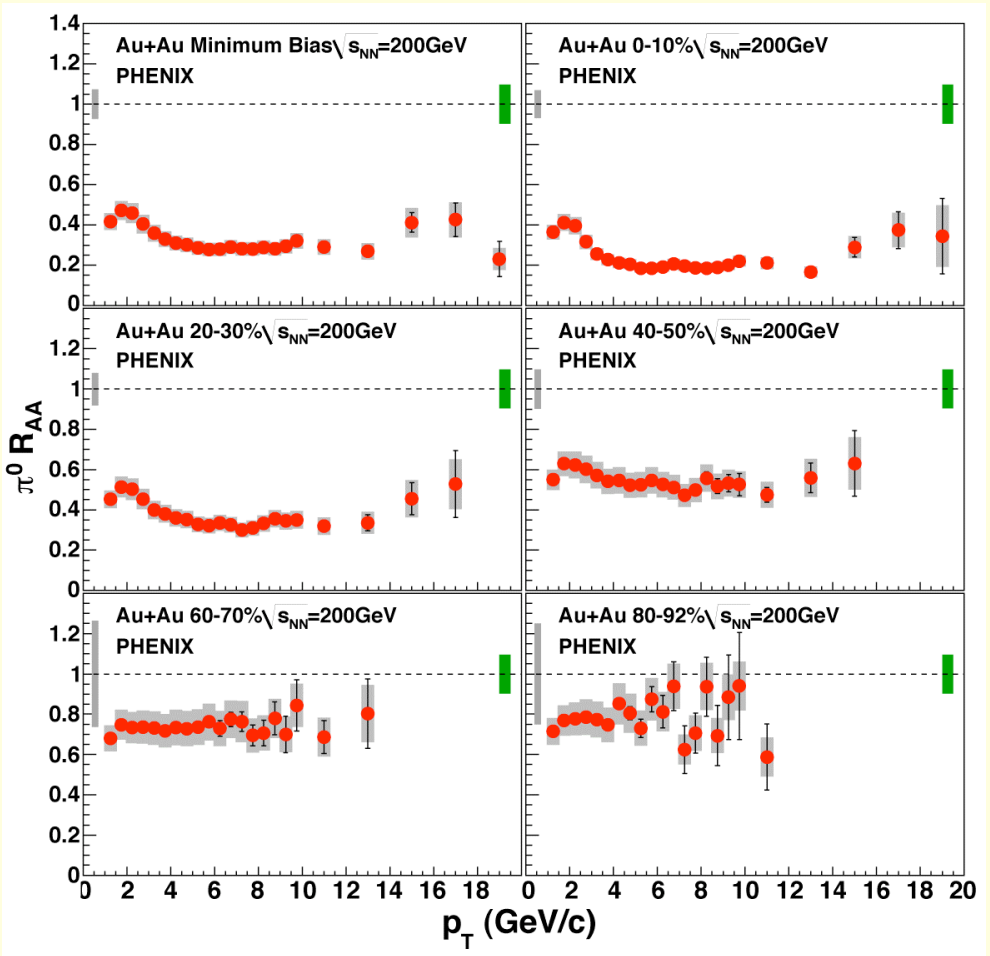


Agreement with pQCD is a prerequisite for jet quenching models

p_T- and Centrality Dependence (I): π^0 Spectra in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV (Run 4)



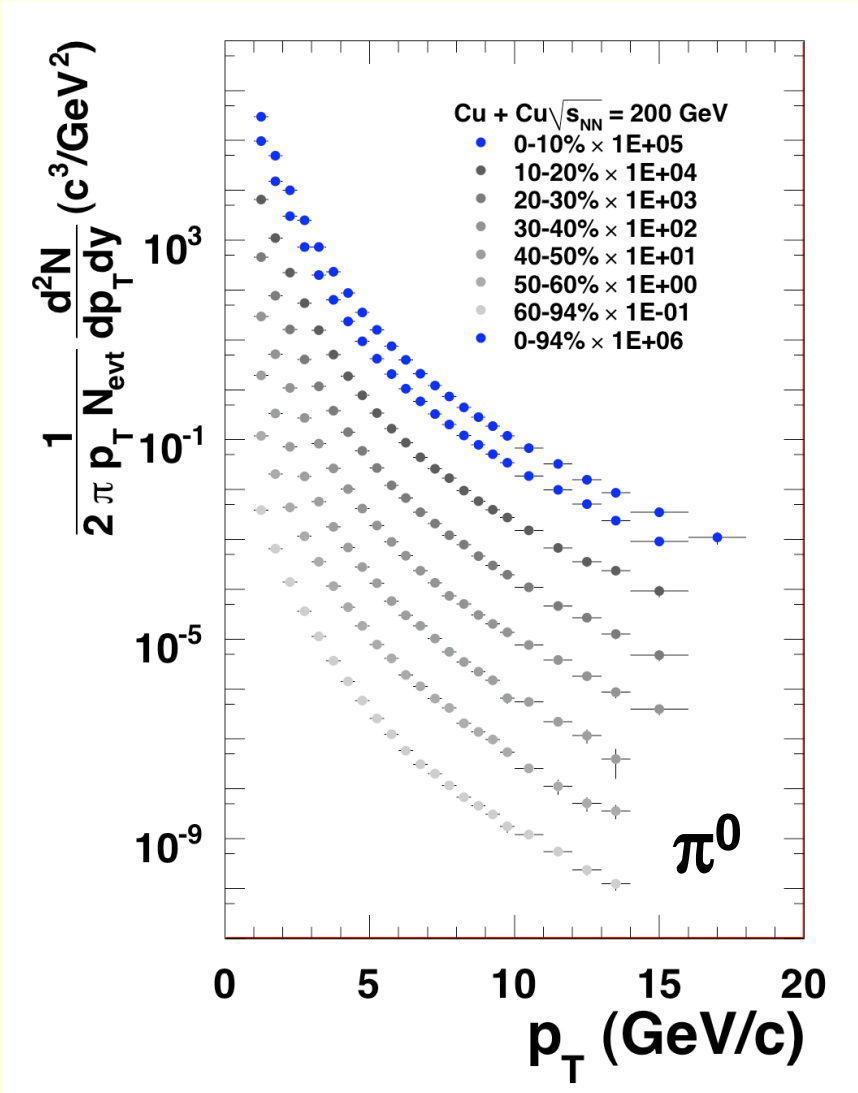
PHENIX, arXiv:0801.4020 [nucl-ex]

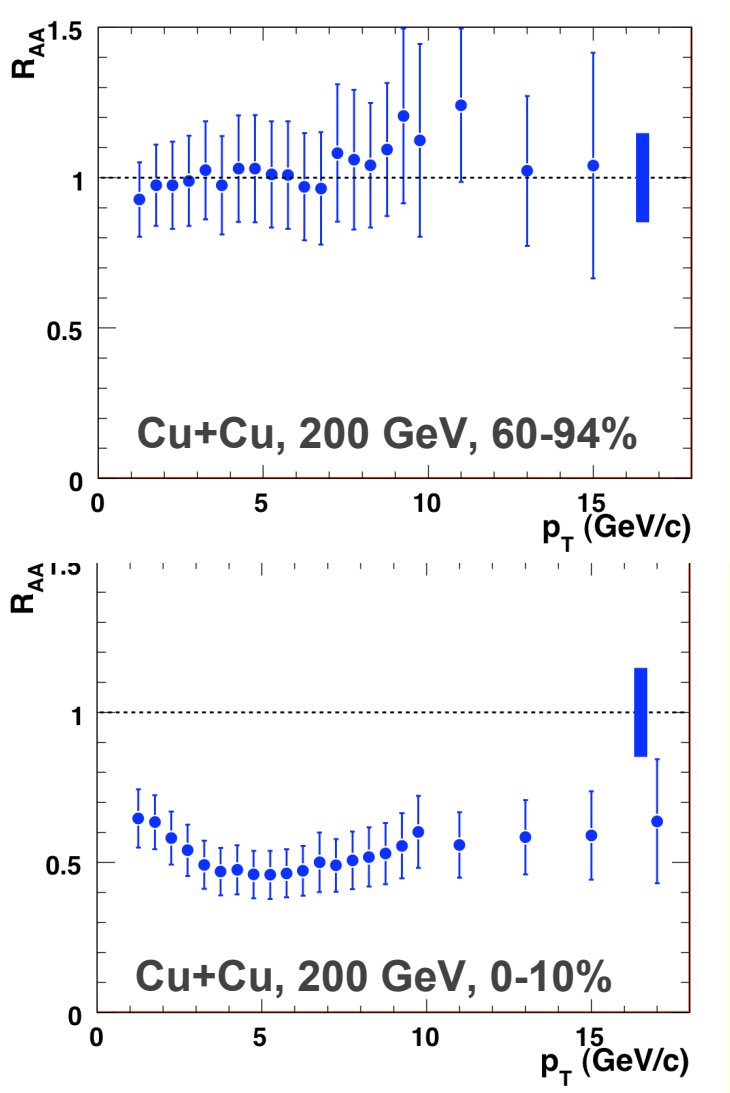


- π^0 R_{AA} now measured up to p_T = 20 GeV/c (central Au+Au)
- Constant $R_{AA} \approx 0.2$ in central Au+Au up to highest p_T ($5 < p_T < 20$ GeV/c)

p_T- and Centrality Dependence (II): π^0 Spectra in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV

PHENIX, arXiv:0801.4555 [nucl-ex]





π^0 $R_{AA} \approx 0.6 - 0.7$ in central Cu+Cu collisions at 200 GeV

p_T- and Centrality Dependence (III): N_{part} Dependence of π^0 R_{AA} in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

Parton energy loss models suggest:

$$\varepsilon_{\text{eff}} \equiv \frac{\Delta E_{\text{eff}}}{E} \propto \frac{1}{A_T}\frac{dN_g}{dy} L \frac{1}{E} \propto N_{\text{part}}^{2/3}$$

transverse area: $A_T \propto N_{\text{part}}^{2/3}$

initial gluon density: $dN_g / dy \propto N_{\text{part}}$

path length: $L \propto N_{\text{part}}^{1/3}$

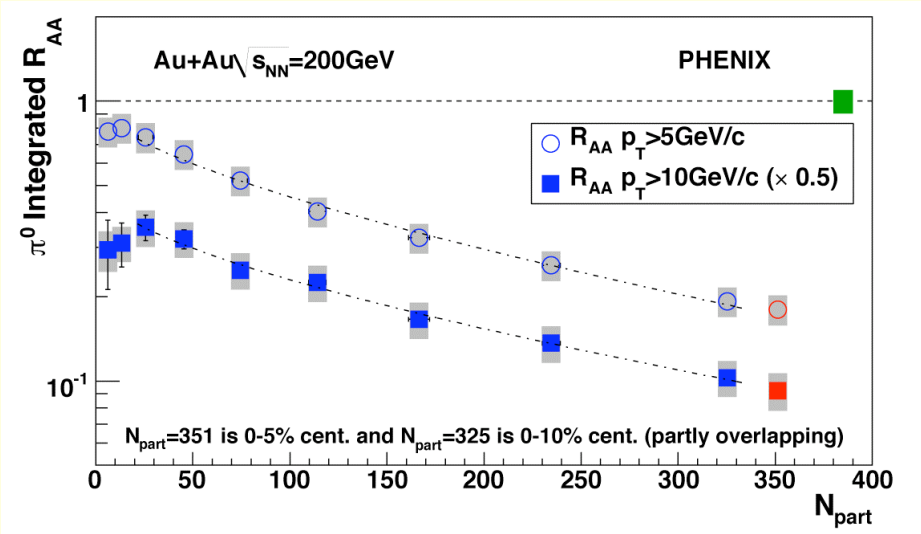
Relation to R_{AA}:

$$R_{AA} = \left(1-\varepsilon_{\text{eff}}\right)^{n-2} = \left(1-\kappa N_{\text{part}}^{2/3}\right)^{n-2}$$

Fit N_{part} dependence of R_{AA} with:

$$R_{AA} = \left(1-\kappa N_{\text{part}}^{\alpha}\right)^{n-2}$$

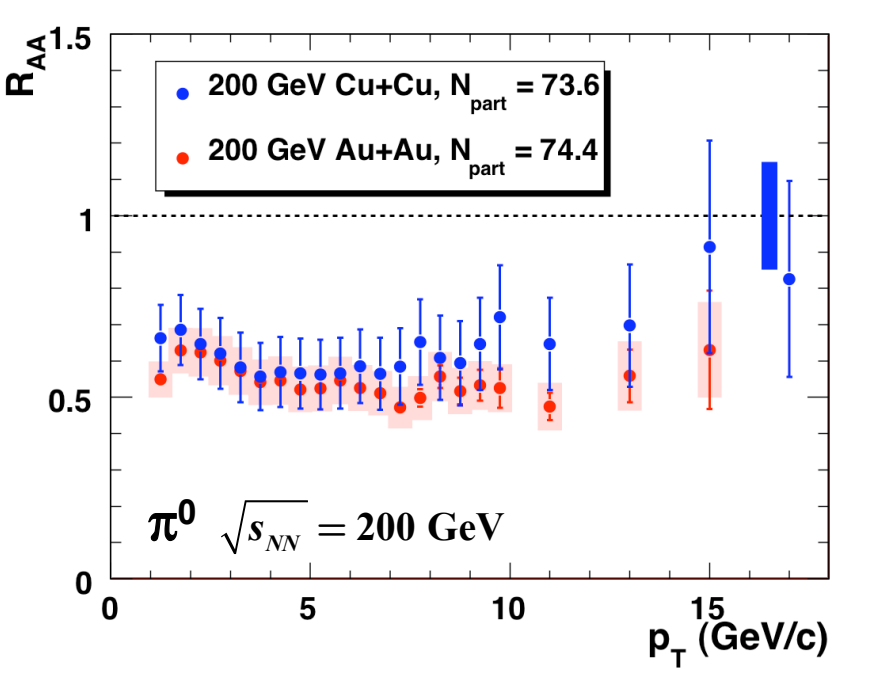
PHENIX, arXiv:0801.4020 [nucl-ex]

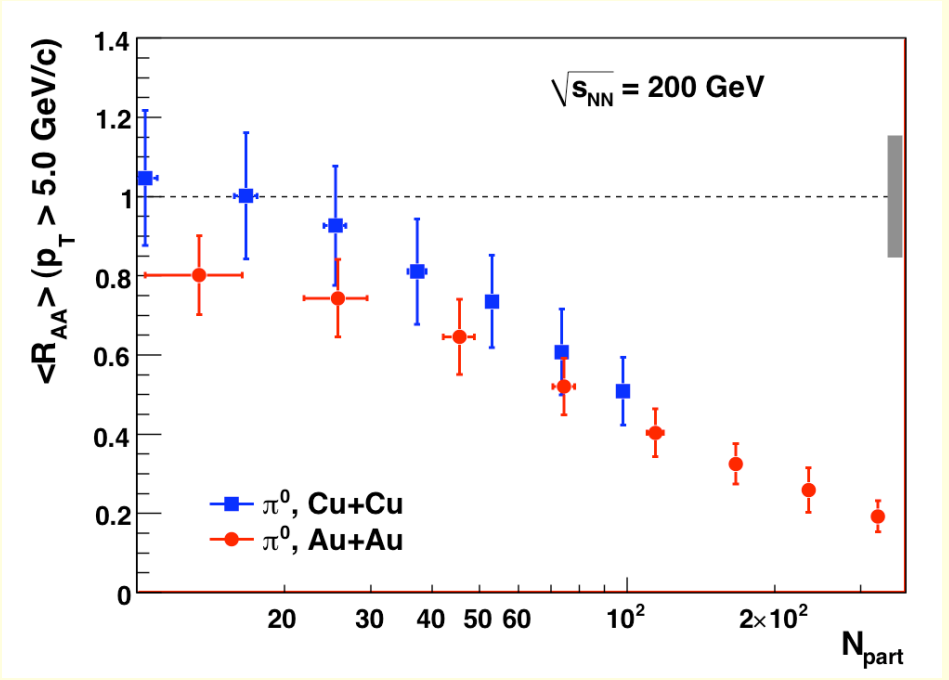


fit range	α
p_T > 5 GeV	0.58 ± 0.07
p_T > 10 GeV	0.56 ± 0.10

Centrality Dependence of R_{AA} consistent with parton energy loss

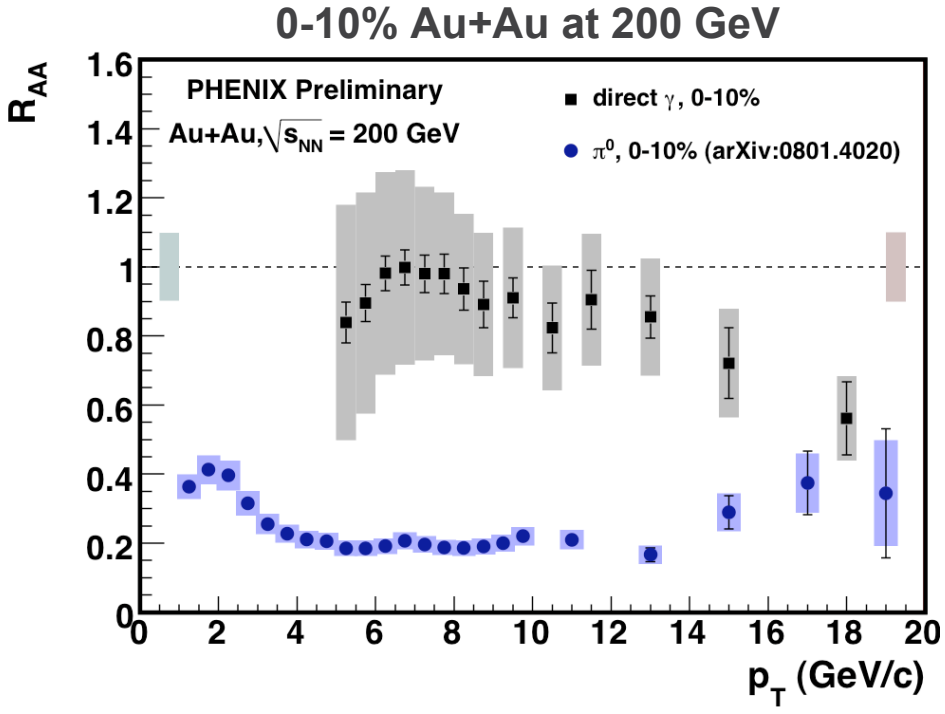
p_T- and Centrality Dependence (IV): N_{part} Dependence of π^0 R_{AA} in Au+Au and Cu+Cu

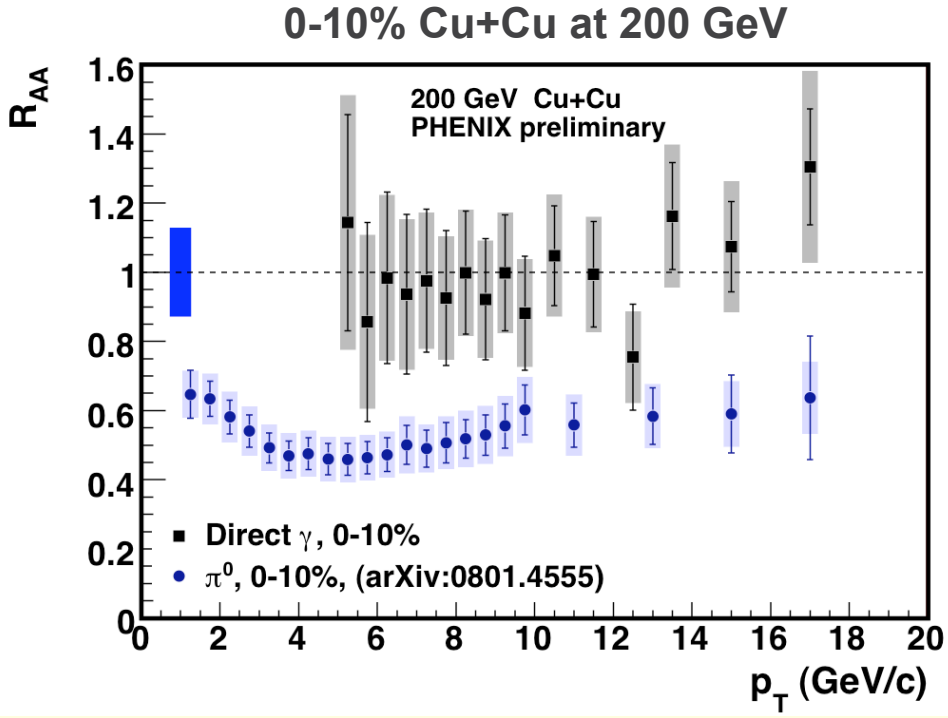




- N_{part} scaling of R_{AA} expected at the same $\sqrt{s_{NN}}$
- Indeed observed: R_{AA} in Au+Au and Cu+Cu similar at same N_{part}

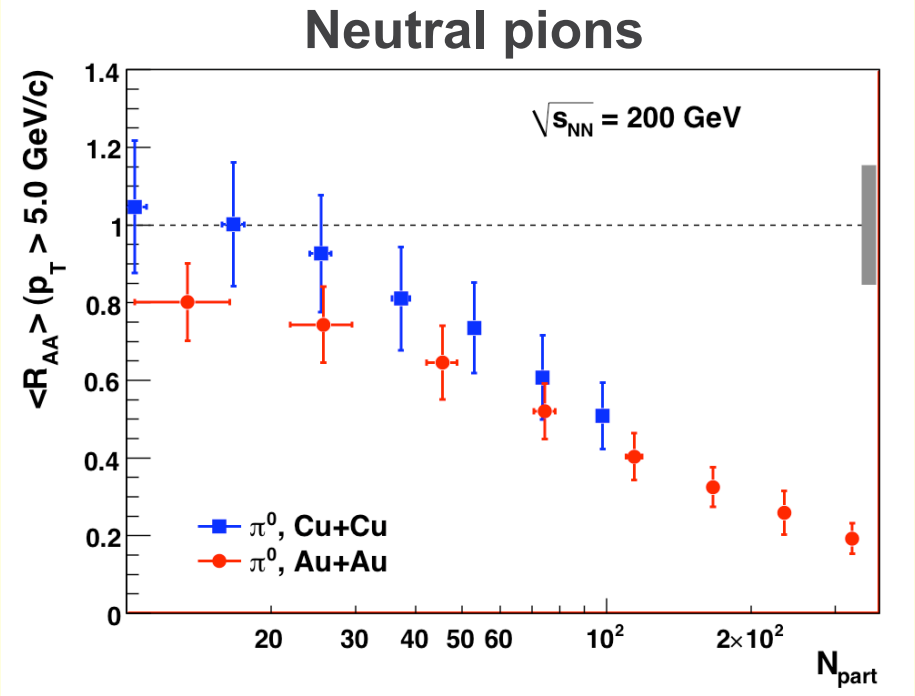
Test of T_{AB} Scaling in A+A (I): Direct Photons at High p_T

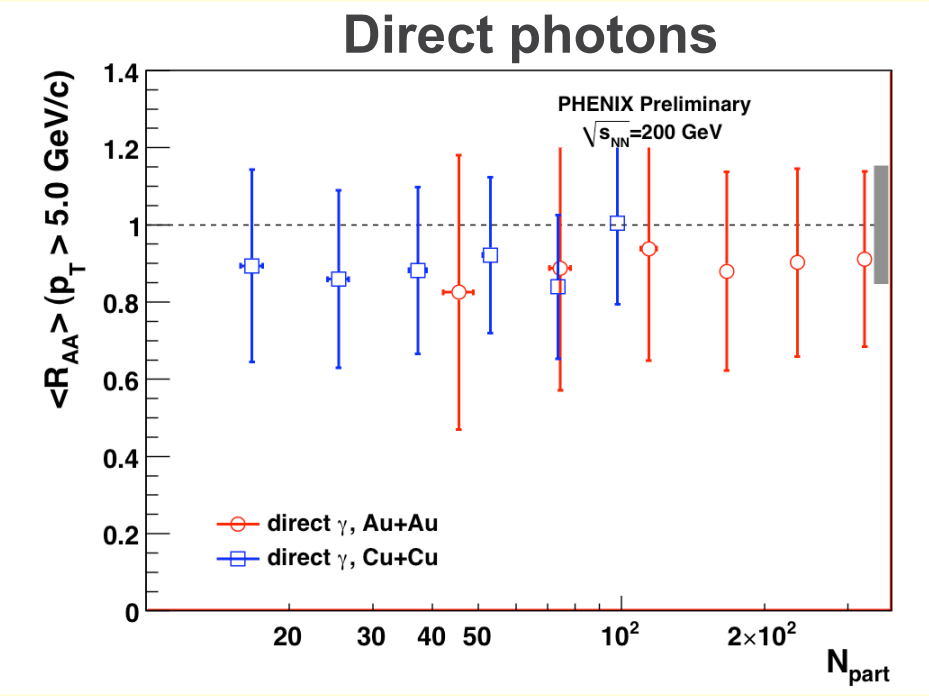




- Au+Au: Direct γ R_{AA} < 1 at $p_T \approx 18$ GeV/c ?
  - Isospin effect? EMC effect? Suppression of fragmentation photons? Check other system: Cu+Cu!
- Cu+Cu: Direct γ R_{AA} flat up to $p_T \approx 17$ GeV/c
- Direct photon R_{AA} in Cu+Cu supports simple T_{AB} scaling of hard scattering up to highest p_T

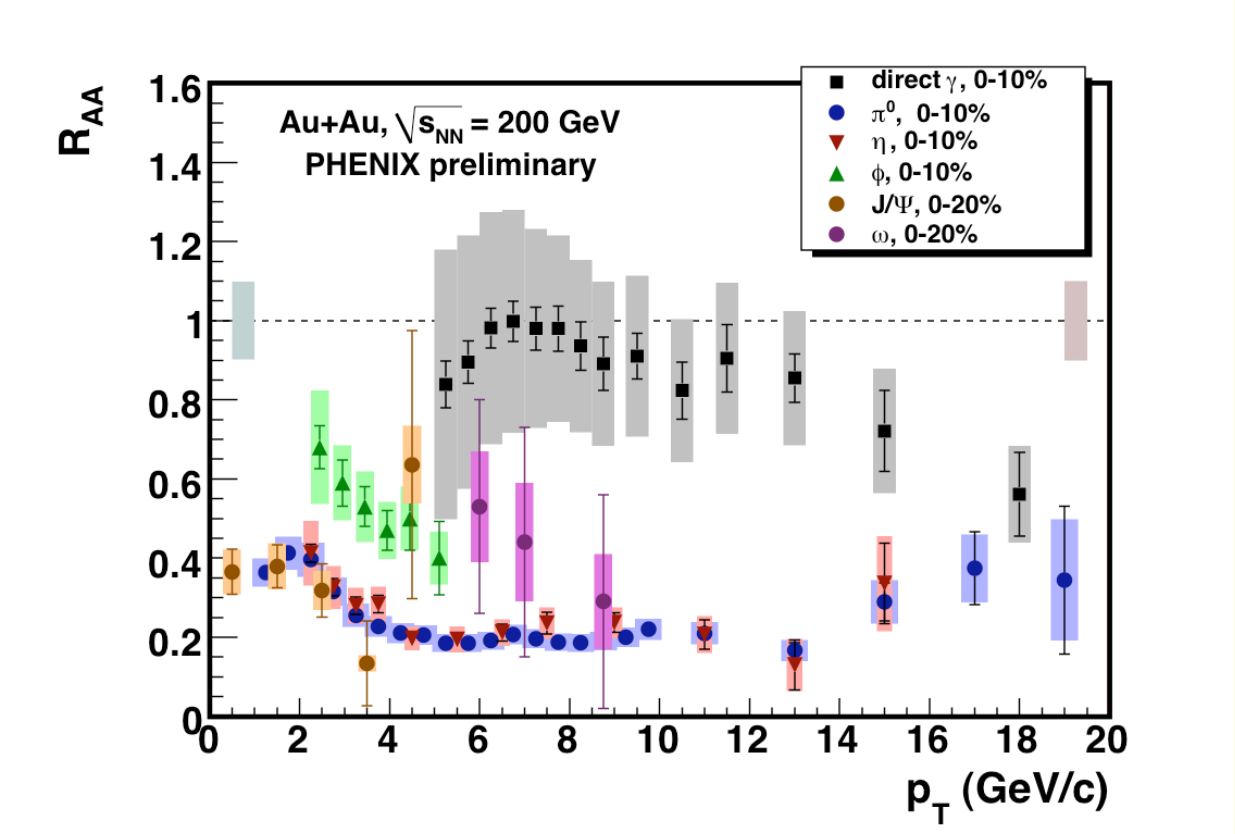
Test of T_{AB} Scaling in A+A (II): Centrality Dependence of π^0's and Direct γ's





T_{AB} scaling of high-p_T direct photons (p_T > 5 GeV/c) holds for all centralities

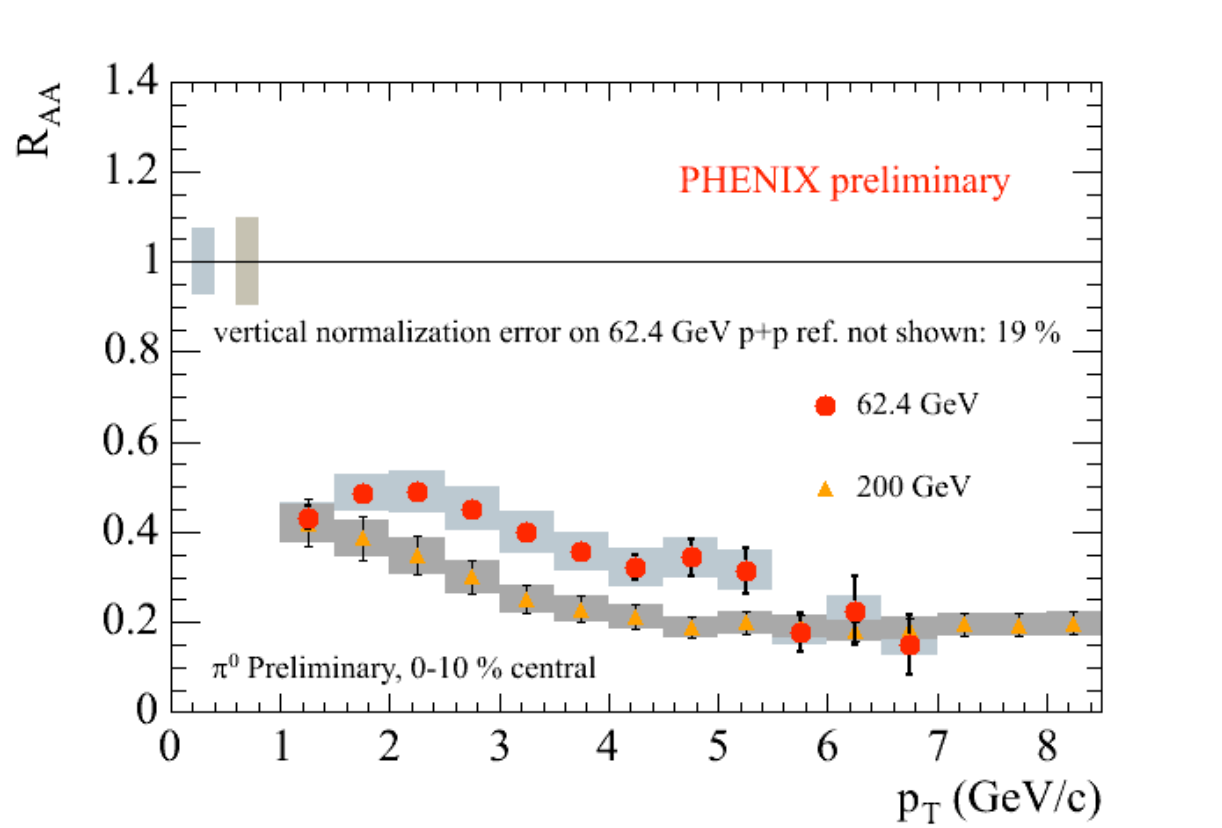
Dependence on Particle Species: π^0, η, ϕ, J/ψ, ω Mesons and Direct γ in Au+Au at 200 GeV



See talk by Y. Nakamiya on vector mesons

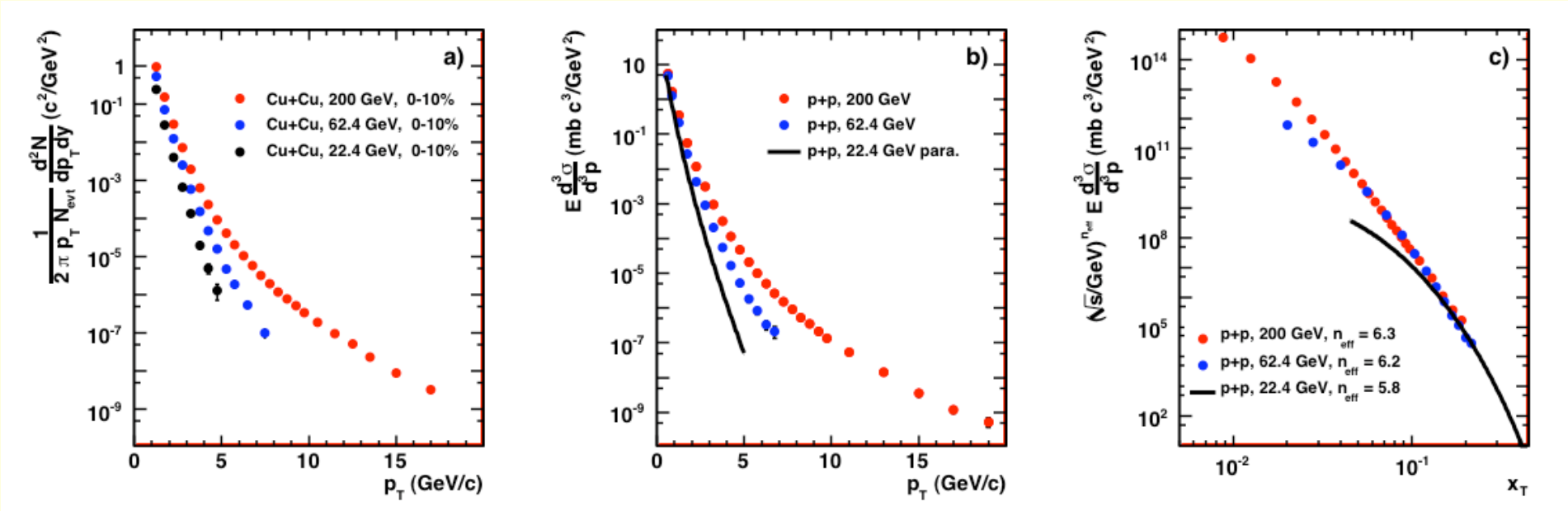
- Same suppression pattern for π^0 and η: Consistent with parton energy loss and fragmentation in the vacuum
- R_{AA} for ϕ's larger than π^0 R_{AA} for $2 < p_T < 5$ GeV/c

$\sqrt{s_{NN}}$ Dependence (I): π^0 R_{AA} in Au+Au at 62 GeV



- **Central Au+Au:**
  Similar R_{AA} at 62.4 and 200 GeV (for p_T > 6 GeV/c)
- **Possible reason: Smaller parton dE/dx in conjunction with steeper parton p_T spectrum at 62 GeV**

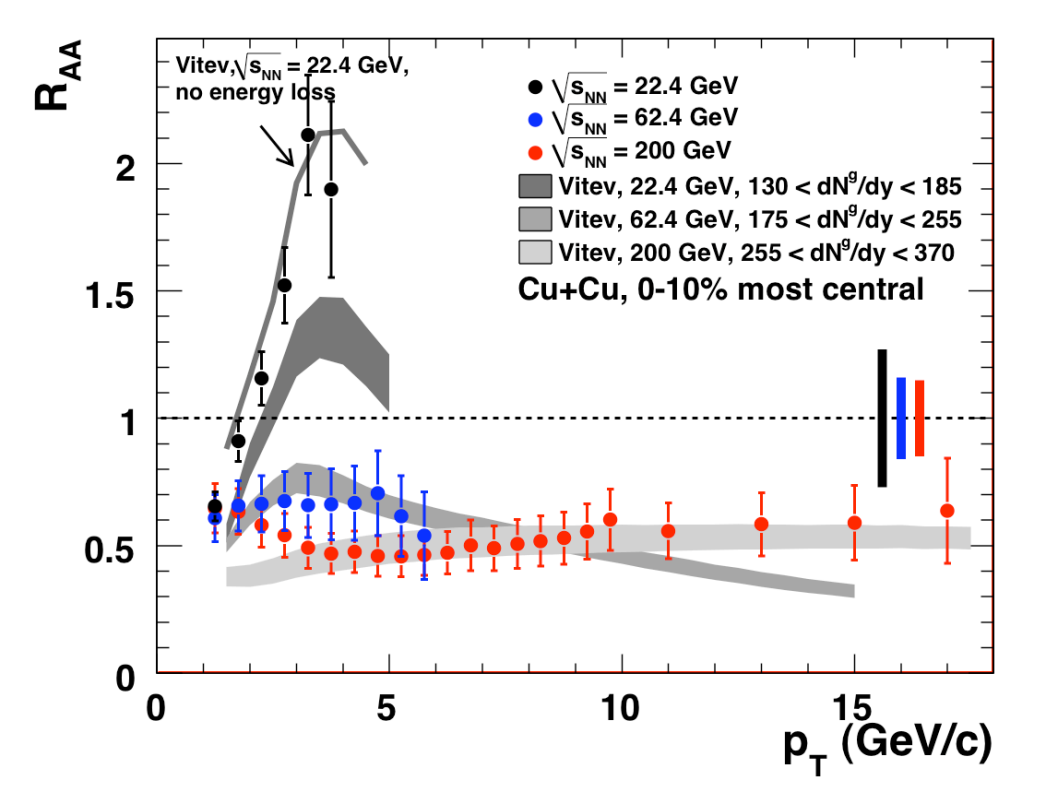
$\sqrt{s_{NN}}$ Dependence (II): π^0 Spectra in Cu+Cu at 22.4, 62.4, and 200 GeV



PHENIX, arXiv:0801.4555 [nucl-ex]

- p+p reference measured at 62.4 GeV and 200 GeV by PHENIX
- p+p reference at 22.4 GeV
  - World data for $21.7 < \sqrt{s_{NN}} < 23.8$ GeV rescaled to 22.4 GeV
  - Fit describes data within 25%
- Scaling in $x_T = 2\,p_T/\sqrt{s}$: Pion production dominated by hard scattering for $p_T > 2$ GeV/c at all three energies

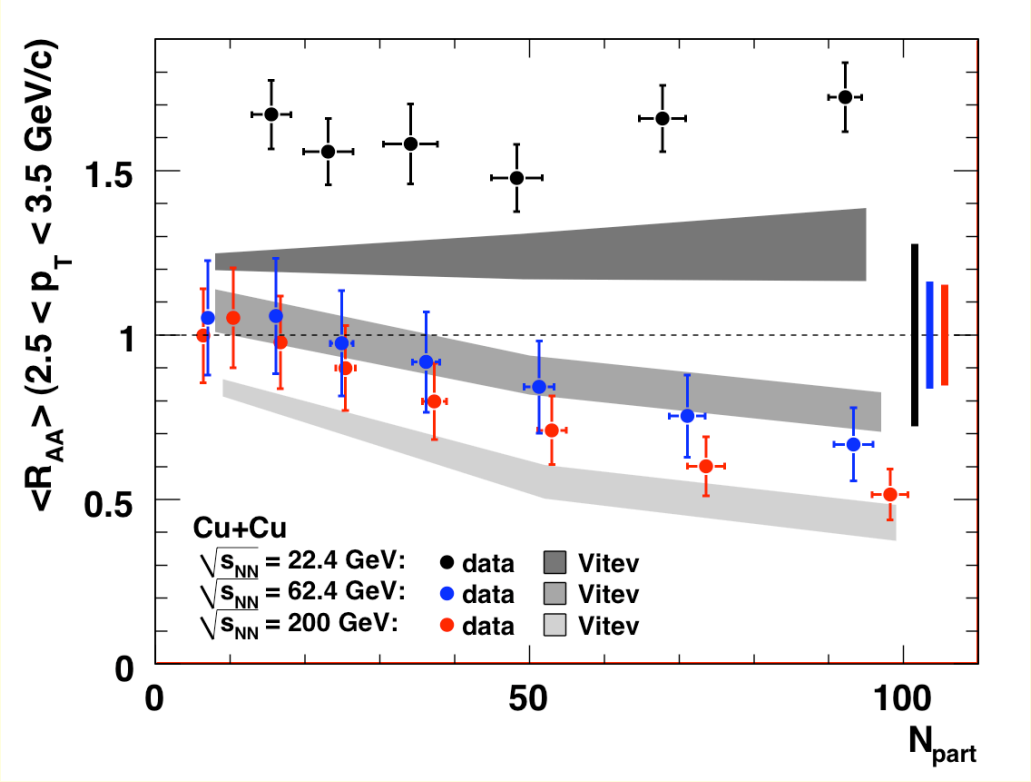
$\sqrt{s_{NN}}$ Dependence (III): p_T Dependence of π^0 R_{AA} in Cu+Cu



PHENIX, arXiv:0801.4555 [nucl-ex]

- 62.4, 200 GeV:
  - Suppression consistent with parton energy loss for $p_T > 3$ GeV/c
- 22.4 GeV:
  - No suppression
  - Enhancement consistent with calculation that describes Cronin enhancement in p+A
- Parton energy loss starts to prevail over Cronin enhancement between 22.4 and 62.4 GeV

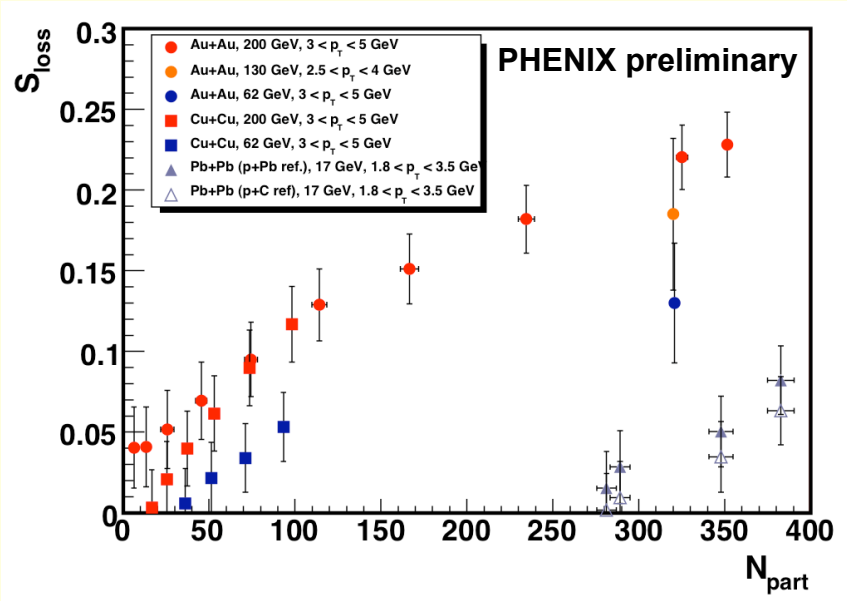
$\sqrt{s_{NN}}$ Dependence (IV): Centrality Dependence of π^0 $\langle R_{AA} \rangle$ in Cu+Cu

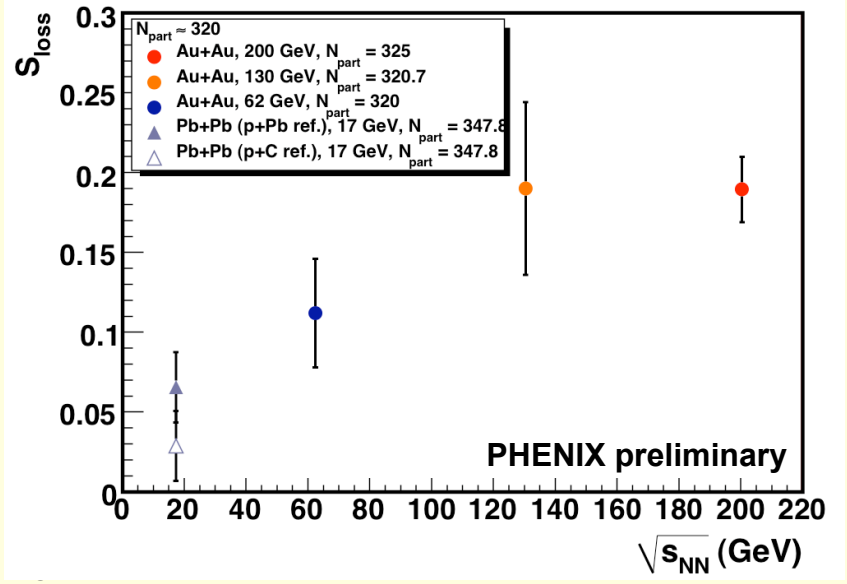


PHENIX, arXiv:0801.4555 [nucl-ex]

- 62.4, 200 GeV:
  - N_{part} Dependence of R_{AA} consistent with parton energy loss
- 22.4 GeV
  - Enhancement independent of centrality
  - Possible explanations
    - Weak centrality dependence of Cronin enhancement
    - Cronin enhancement offset by parton energy loss

S_{loss}: A Rough Measure of the Fractional Parton Loss $\Delta E/E$





- R_{AA} depends on energy loss *and* steepness of parton spectrum
- Thus, define "fractional energy loss":

$$S_{loss} := \Delta p_T / p_T$$

- Relation to R_{AA} for a pion spectrum described by power law with power n

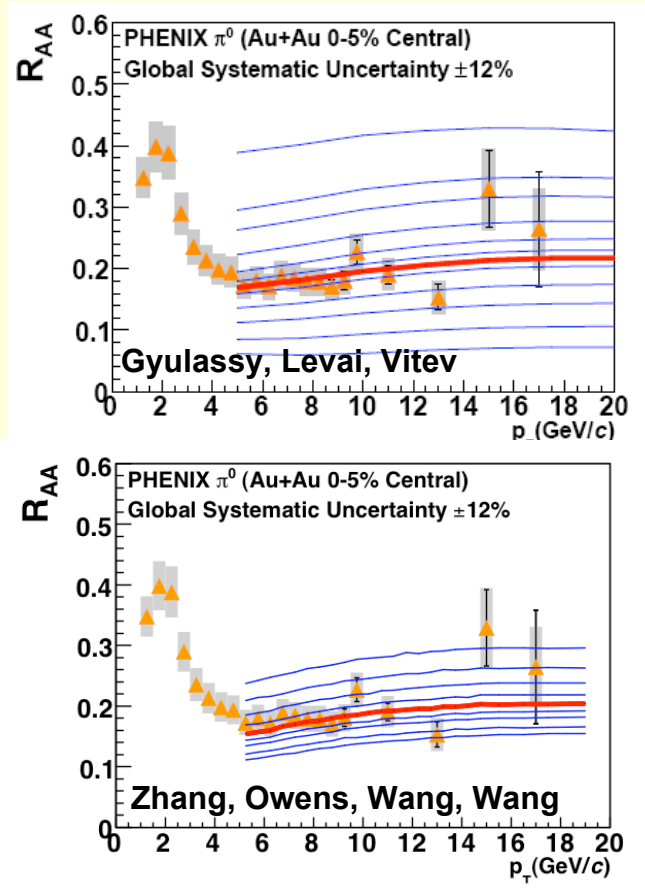
$$S_{loss} = 1 - R_{AA}^{1/(n-2)}$$

- $R_{AA} \approx 0.5 - 0.6$ in Pb+Pb at 17.3 GeV (0-1%, p+C reference, WA98)
- However, S_{loss} at 17.3 GeV is much smaller than at RHIC
  - Au+Au, 200 GeV: $S_{loss} = 0.2$
  - Pb+Pb, 17.3 GeV: $S_{loss} = 0.05$

Quantitative Constraints on Medium Parameters

see Poster by James Nagle

PHENIX, arXiv:0801.1655 [nucl-ex]



- Fit of model parameters to data requires correct treatment of exp. uncertainties
  - Type A: point-by-point uncorrelated
  - Type B: Correlated (in p_T)
  - Type C: Normalization (constant factor for all points)
- Least square fit for this case

$$\tilde{\chi}^2 = \sum_{i=1}^{n} \frac{\left(y_i + \varepsilon_b \sigma_{b_i} + \varepsilon_c y_i \sigma_c - \mu_i\right)^2}{\tilde{\sigma}_i^2} + \varepsilon_b^2 + \varepsilon_c^2$$

Takes type B and C uncertainties correctly into account

Results (1σ range): **Caveat: theoretical uncertainties not included**

PQM	GLV	WHDG	ZOWW
$\hat{q} = 13.2^{+2.1}_{-3.2}\ \mathrm{GeV}^2/\mathrm{fm}$	$dN^g/dy = 1400^{+270}_{-150}$	$dN^g/dy = 1400^{+200}_{-540}$	$\varepsilon_0 = 1.9^{+0.2}_{-0.5}\ \mathrm{GeV/fm}^3$

Conclusions

Centrality and p_T Dependence of High-p_T Hadron Suppression

→ Consistent with parton energy loss

Dependence on heavy ion species

→ R_{AA} depends only on N_{part} for same $\sqrt{s_{NN}}$

T_{AB} scaling of hard scattering in A+A ($\rightarrow$ direct γ)

→ Confirmed

Constraints on medium properties

→ $\hat{q}$, dN_g/dy constrained within ± 20-25% at the 1σ level

Dependence on hadron species

→ Consistent with parton energy loss

Dependence on $\sqrt{s_{NN}}$

→ Parton energy loss starts to prevail over Cronin enhancement between 22.4 and 62.4 GeV (Cu+Cu)

PHENIX

13 Countries; 62 Institutions; 550 Participants*

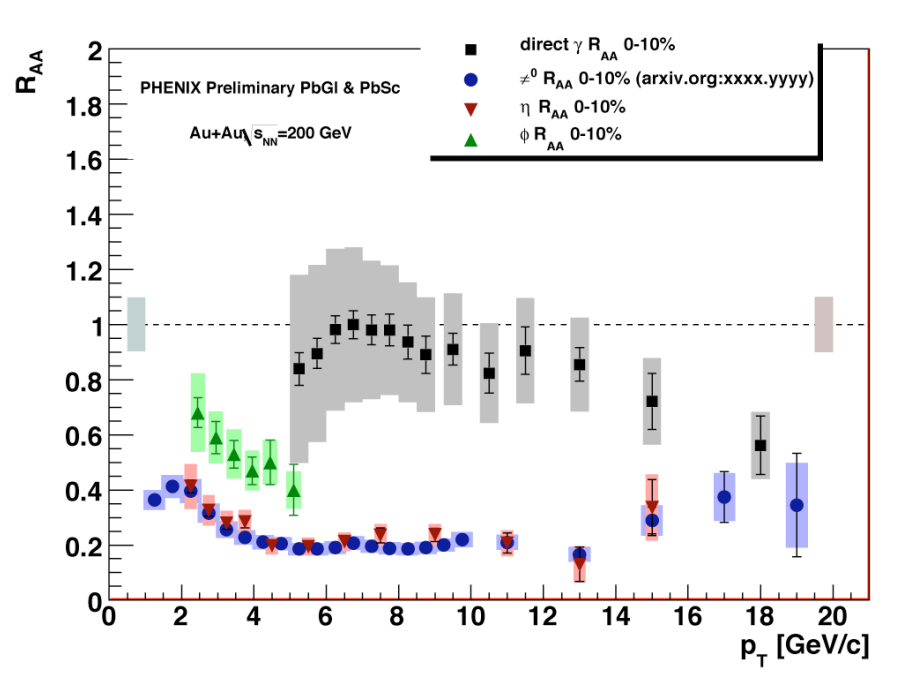
- University of São Paulo, São Paulo, Brazil
- Academia Sinica, Taipei 11529, China
- China Institute of Atomic Energy (CIAE), Beijing, P. R. China
- Peking University, Beijing, P. R. China
- Charles University, Faculty of Mathematics and Physics, Ke Karlovu 3, 12116 Prague, Czech Republic
- Czech Technical University, Faculty of Nuclear Sciences and Physical Engineering, Brehova 7, 11519 Prague, Czech Republic
- Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague, Czech Republic
- Laboratoire de Physique Corpusculaire (LPC), Universite de Clermont-Ferrand, 63 170 Aubiere, Clermont-Ferrand, France
- Dapnia, CEA Saclay, Bat. 703, F-91191 Gif-sur-Yvette, France
- IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406 Orsay, Fra
- Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Rout Saclay, F-91128 Palaiseau, France
- SUBATECH, Ecòle des Mines at Nantes, F-44307 Nantes France
- University of Muenster, Muenster, Germany
- KFKI Research Institute for Particle and Nuclear Physics at the Hungari Academy of Sciences (MTA KFKI RMKI), Budapest, Hungary
- Debrecen University, Debrecen, Hungary
- Eövös Loránd University (ELTE), Budapest, Hungary
- Banaras Hindu University, Banaras, India
- Bhabha Atomic Research Centre (BARC), Bombay, India
- Weizmann Institute, Rehovot, 76100, Israel
- Center for Nuclear Study (CNS-Tokyo), University of Tokyo, Tanashi, Tokyo 188, Japan
- Hiroshima University, Higashi-Hiroshima 739, Japan
- KEK - High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
- Kyoto University, Kyoto, Japan
- Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki, Japan
- RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan
- RIKEN – BNL Research Center, Japan, located at BNL
- Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
- Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
- University of Tsukuba, 1-1-1 Tennodai, Tsukuba-shi Ibaraki-ken 305-8577, Japan
- Waseda University, Tokyo, Japan
- Cyclotron Application Laboratory, KAERI, Seoul, South Korea
- Kangnung National University, Kangnung 210-702, South Korea
- Korea University, Seoul, 136-701, Korea
- Myong Ji University, Yongin City 449-728, Korea
- System Electronics Laboratory, Seoul National University, Seoul, South Korea
- Yonsei University, Seoul 120-749, Korea
- IHEP (Protvino), State Research Center of Russian Federation "Institute for High Energy Physics", Protvino 142281, Russia
- Joint Institute for Nuclear Research (JINR-Dubna), Dubna, Russia
- Kurchatov Institute, Moscow, Russia
- PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
- Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Vorob'evy Gory, Moscow 119992, Russia
- Saint-Petersburg State Polytechnical Univiversity, Politechnicheskayastr, 29, St. Petersburg, 195251, Russia

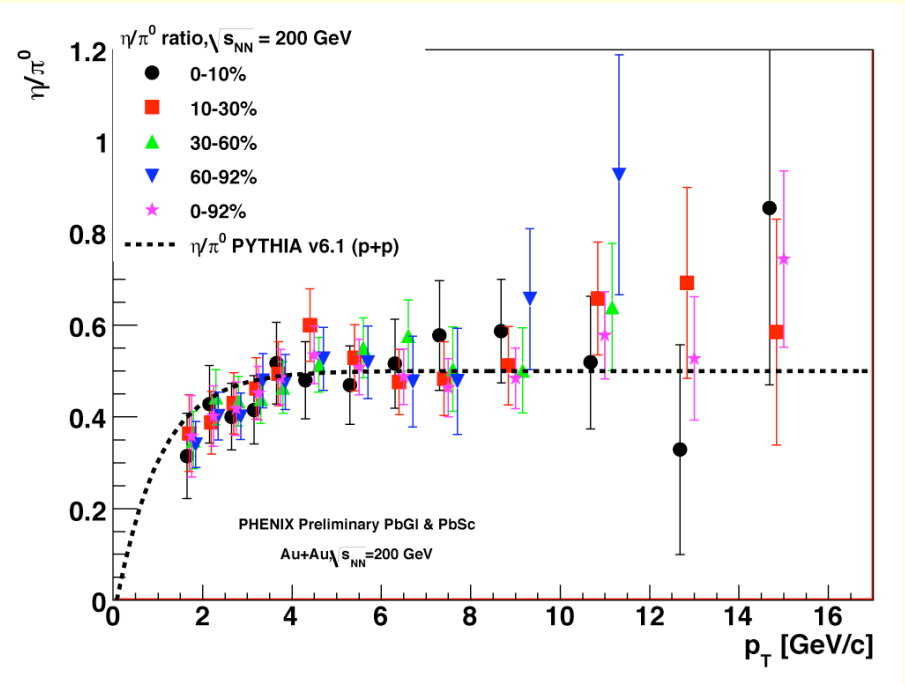
- Lund University, Lund, Sweden
- Abilene Christian University, Abilene, Texas, USA
- Brookhaven National Laboratory (BNL), Upton, NY 11973, USA
- University of California - Riverside (UCR), Riverside, CA 92521, USA
- University of Colorado, Boulder, CO, USA
- Columbia University, Nevis Laboratories, Irvington, NY 10533, USA
- Florida Institute of Technology, Melbourne, FL 32901, USA
- Florida State University (FSU), Tallahassee, FL 32306, USA
- Georgia State University (GSU), Atlanta, GA, 30303, USA
- University of Illinois Urbana-Champaign, Urbana-Champaign, IL, USA
- Iowa State University (ISU) and Ames Laboratory, Ames, IA 50011, USA
- Los Alamos National Laboratory (LANL), Los Alamos, NM 87545, USA
- Lawrence Livermore National Laboratory (LLNL), Livermore, CA 94550, USA
- University of New Mexico, Albuquerque, New Mexico, USA
- New Mexico State University, Las Cruces, New Mexico, USA
- Department of Chemistry, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA
- Department of Physics and Astronomy, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA
- Oak Ridge National Laboratory (ORNL), Oak Ridge, TN 37831, USA
- University of Tennessee (UT), Knoxville, TN 37996, USA
- Vanderbilt University, Nashville, TN 37235, USA

*as of March 2005

Extra Slides

Dependence on Particle Species: π^0, η, ϕ Mesons and Direct γ in Au+Au at 200 GeV

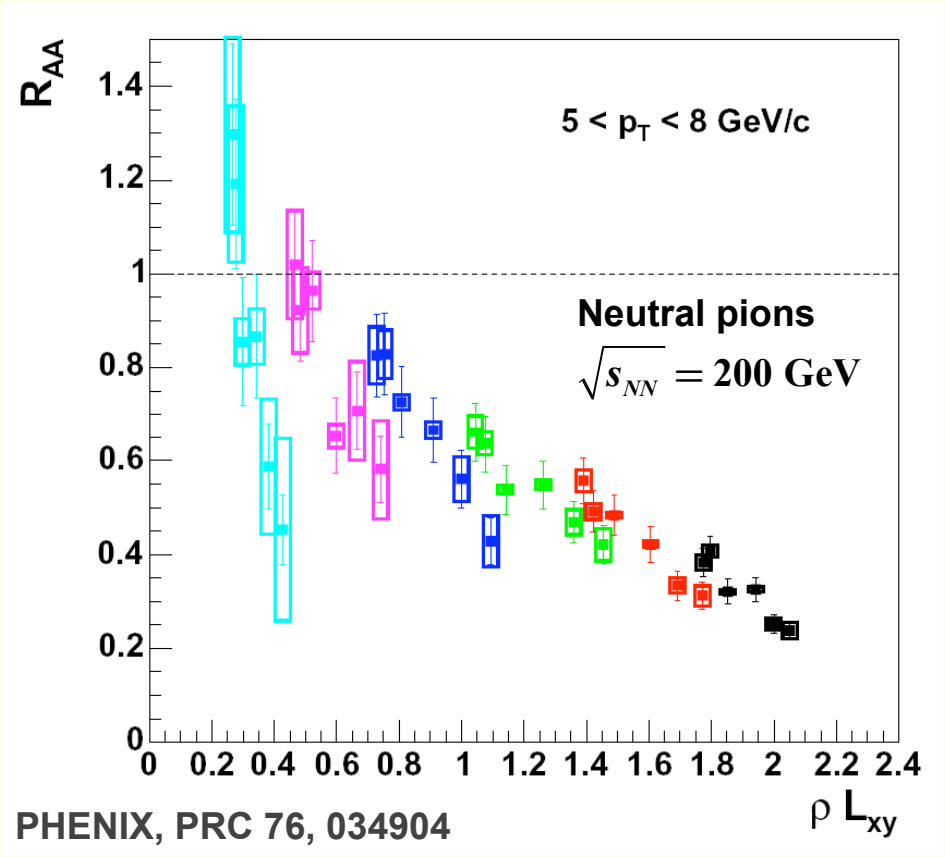




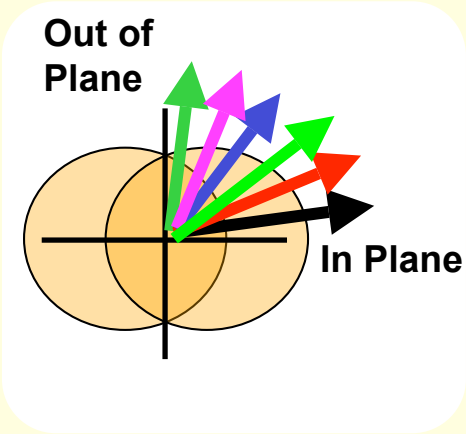
Poster
Baldo Sahlmüller

- η/π^0 ratio independent of centrality
- Same suppression pattern for π^0 and η: Consistent with parton energy loss and fragmentation in the vacuum

Path Length Dependence: R_{AA} as Function of Angle w.r.t. the Reaction Plane



PHENIX, PRC 76, 034904



- Approximate scaling in $\langle \rho \cdot L_{xy} \rangle$ expected for parton energy loss
- Experimental evidence weak
- Path length dependence of parton energy loss remains an open question

$$\rho L_{xy} = \int_0^\infty dl \; \rho_{\mathrm{part}}(x_0 + l\cos\Delta\phi, y_0 + l\sin\Delta\phi)$$

Density time path length averaged over jet productions points in transverse (x,y) plane