Hard Scattering and (some) MPI Observables in A+A Collisions

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Klaus Reygers
Institut für Kernphysik
University of Münster
Germany

Outline

- Incoherent point-like scaling in A+A
- Discovery of jet quenching at RHIC
- MPI Observables in p+p in comparison with A+A Data

How to Study Hard Scattering in A+A?

- Measurement of particle yields at high p_T
- Measurement of two-particle angular correlations
- Jet reconstruction on single event basis
  - Difficult in central A+A collisions at RHIC due to large particle multiplicity from underlying event
  - Will possible in central Pb+Pb at the LHC for E_{jet} > ~50 GeV

Background energy in cone of radius R = 0.7:

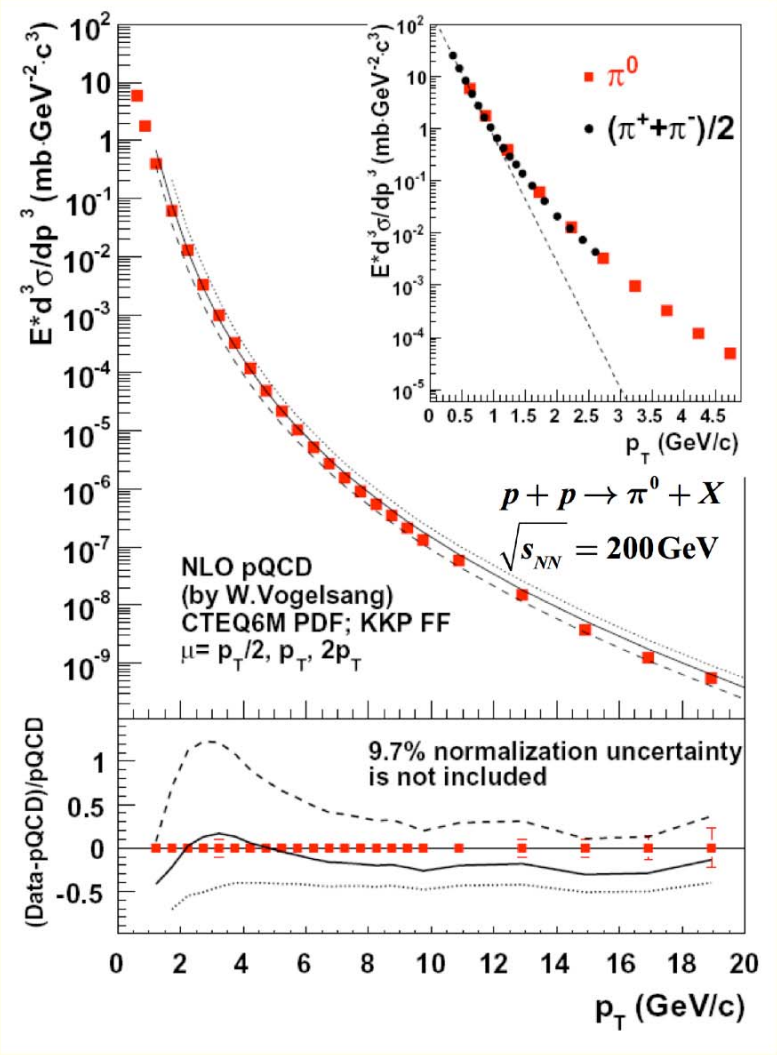
$$dE_T / d\eta \approx 500 \text{ GeV}$$

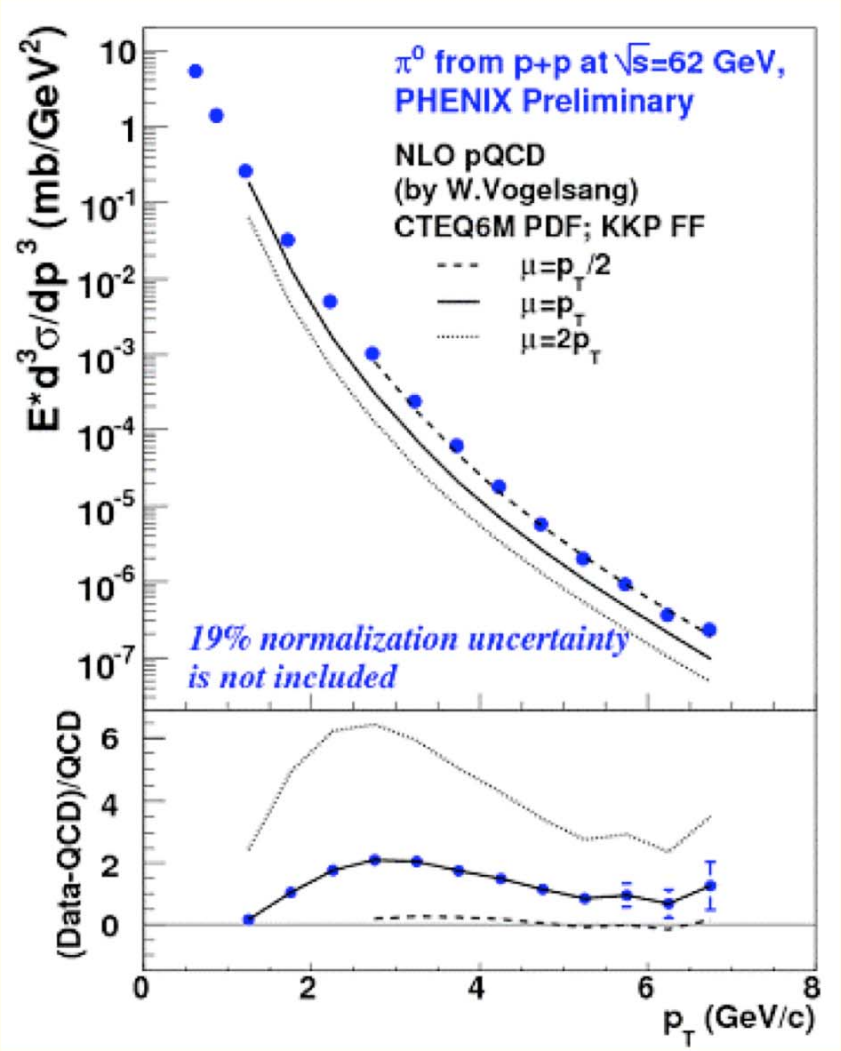
$$\text{(central Au+Au at } \sqrt{s_{NN}} = 130 \text{ GeV)}$$

$$\Rightarrow E_T^{\text{cone}} = \frac{d^2 E_T}{d\eta d\varphi} \cdot \pi R^2$$

$$= \frac{1}{2\pi} \frac{dE_T}{d\eta} \cdot \pi R^2 \approx 120 \text{ GeV}$$

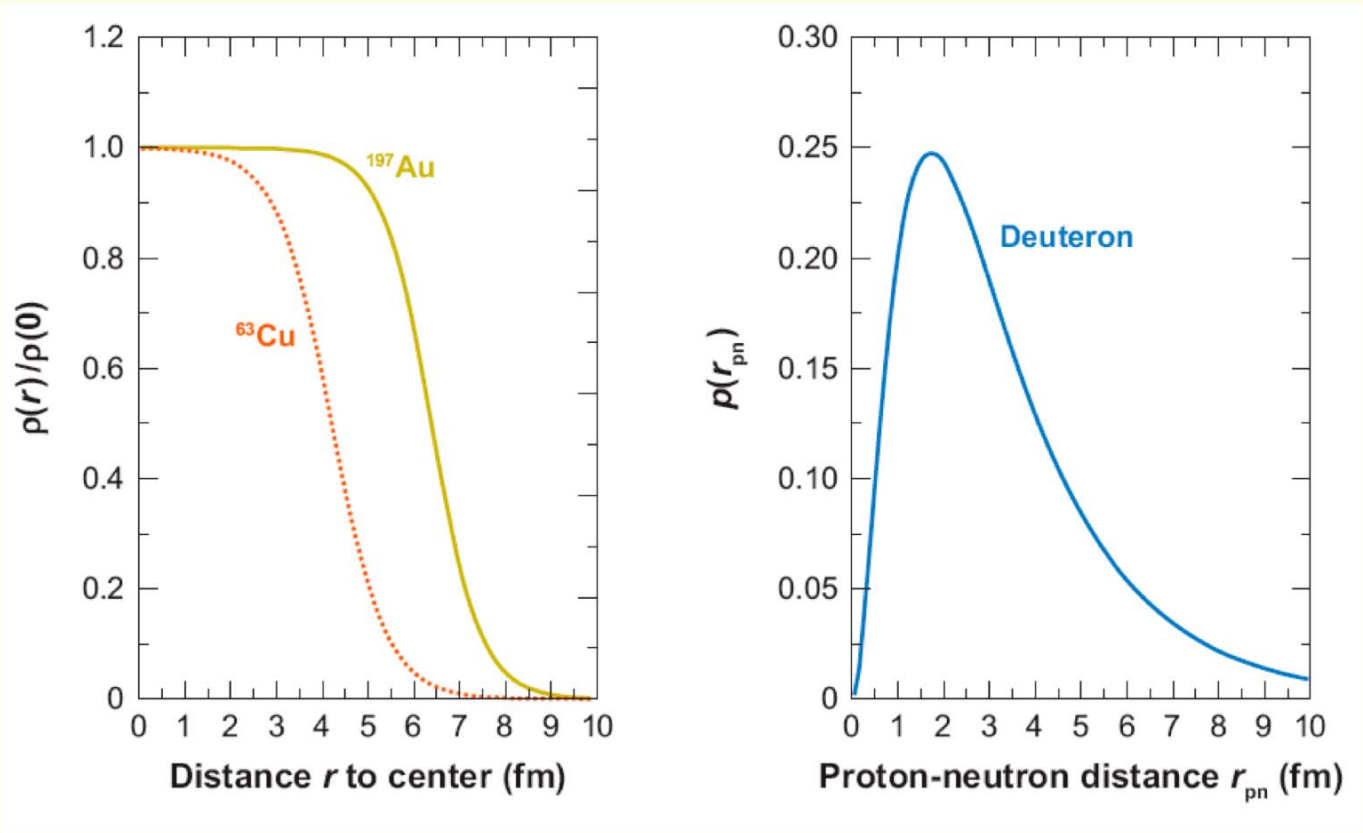
π^0 Spectra in p+p at RHIC: Agreement with NLO pQCD





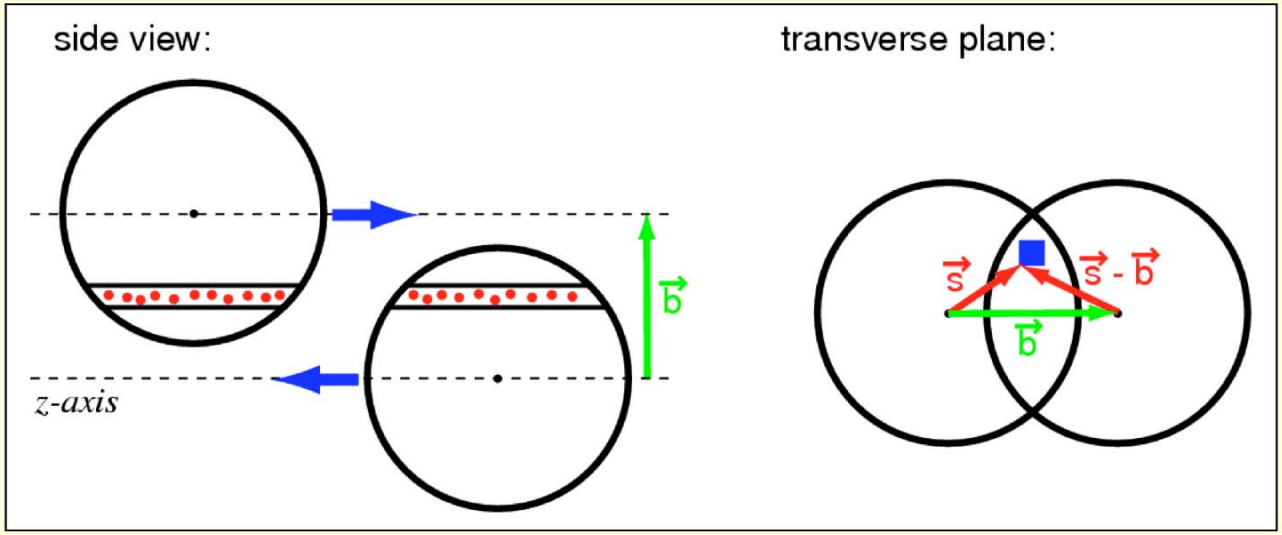
Agreement with pQCD is a prerequisite for jet quenching models

Point-like Scaling in A+A: Starting Point: Nuclear Density Profile



- **Nuclear density profile from e^-+nucleus scattering**
- **Deuteron: Hulthen wavefunction (or more recent form)**

Effective Nucleon Luminosity: The Nuclear Overlap Function



Nuclear thickness:

$$T_A(\vec{s}) := \int \rho_A(\vec{s}, z)\,\mathrm{d}z$$

Normalization:

$$\int T_A(\vec{s})\,\mathrm{d}^2 s = A$$

"nucleon luminosity" in area $\mathrm{d}^2 s$ at $\vec{s}$: $\mathrm{d}T_{AB}(\vec{s}) = T_A(\vec{s}) \cdot T_B(\vec{s} - \vec{b})\,\mathrm{d}^2 s$

"Total nucleon luminosity" for collisions at impact parameter *b* (*nuclear overlap function*): unit: 1/area

$$T_{AB}(b) = \int T_A(\vec{s}) \cdot T_B(\vec{s} - \vec{b})\,\mathrm{d}^2 s$$

Thus, the number of interactions for a process with cross section σ_{int} is:

$$\langle N_{int}(b) \rangle = T_{AB}(b) \cdot \sigma_{int}$$

In particular: $\langle N_{coll}(b) \rangle = T_{AB}(b) \cdot \sigma_{inel}^{p+p}$

Averaging $T_{AB}(b)$ over the Impact Parameter Distribution

Observable: Hard process *per inelastic A+A collisions*, i.e.

$$N_{\text{hard}}^{\text{A+B}}(b) = \frac{T_{AB}(b)}{p_{\text{inel}}^{\text{A+B}}(b)} \cdot \sigma_{\text{hard}} \qquad p_{\text{inel}}^{\text{A+B}}(b) = 1 - \exp(-T_{AB}(b) \cdot \sigma_{\text{inel}}^{\text{NN}})$$

probability for an inelastic A+B collision at impact parameter *b*

Typical example: p_T dependent pion yield per inelastic event:

$$\frac{1}{N_{\text{inel}}^{A+B}} \frac{\mathrm{d}N^{\pi}}{\mathrm{d}p_T}(b) = \frac{T_{AB}(b)}{p_{\text{inel}}^{\text{A+B}}(b)} \cdot \frac{\mathrm{d}\sigma^{p+p}}{\mathrm{d}p_T}$$

Averaging over an impact parameter range f (say $b_1 \le b \le b_2$):

weighting factor:

$p_{\text{inel}}^{\text{A+B}}(b)$

$$\frac{1}{N_{\text{inel}}^{A+B}} \frac{\mathrm{d}N^{\pi}}{\mathrm{d}p_T}\bigg|_f = \frac{\int_{b_1}^{b_2} 2\pi b \; T_{AB}(b)\,\mathrm{d}b}{\int_{b_1}^{b_2} 2\pi b \; p_{\text{inel}}^{\text{A+B}}(b)\,\mathrm{d}b} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}p_T} \equiv \langle T_{AB} \rangle_f \cdot \frac{\mathrm{d}\sigma^{p+p}}{\mathrm{d}p_T}$$

Nuclear Modification Factor

Consider special case $b_1 = 0$, $b_2 = \infty$:

$$\frac{1}{N_{\text{inel}}^{A+B}} \frac{\mathrm{d}N^{\pi}}{\mathrm{d}p_T}\bigg|_f = \frac{\int_0^\infty 2\pi b\, T_{AB}(b)\,\mathrm{d}b}{\int_0^\infty 2\pi b\, p_{\text{inel}}^{\text{A+B}}(b)\,\mathrm{d}b} \cdot \frac{d\sigma}{dp_T} = \frac{AB}{\sigma_{\text{inel}}^{\text{A+B}}} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}p_T} \quad \rightarrow \quad \frac{\mathrm{d}\sigma^{A+B}}{\mathrm{d}p_T} = AB \cdot \frac{\mathrm{d}\sigma^{p+p}}{\mathrm{d}p_T}$$

(holds for hard scattering in the absence of nuclear effects)

Definition of nuclear modification factor:

$$R_{AB}(p_T) = \frac{\mathrm{d}\sigma^{A+B} / \mathrm{d}p_T}{\left[\int_f d^2b\, T_{AB}(b)\right] \cdot \mathrm{d}\sigma^{p+p} / \mathrm{d}p_T} = \frac{\frac{1}{N_{\text{inel}}^{A+B}} \frac{\mathrm{d}N^{\pi}}{\mathrm{d}p_T}\bigg|_f}{\langle T_{AB} \rangle_f \cdot \mathrm{d}\sigma^{p+p} / \mathrm{d}p_T} = 1$$

(in the absence of nuclear effects)

In practice:

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

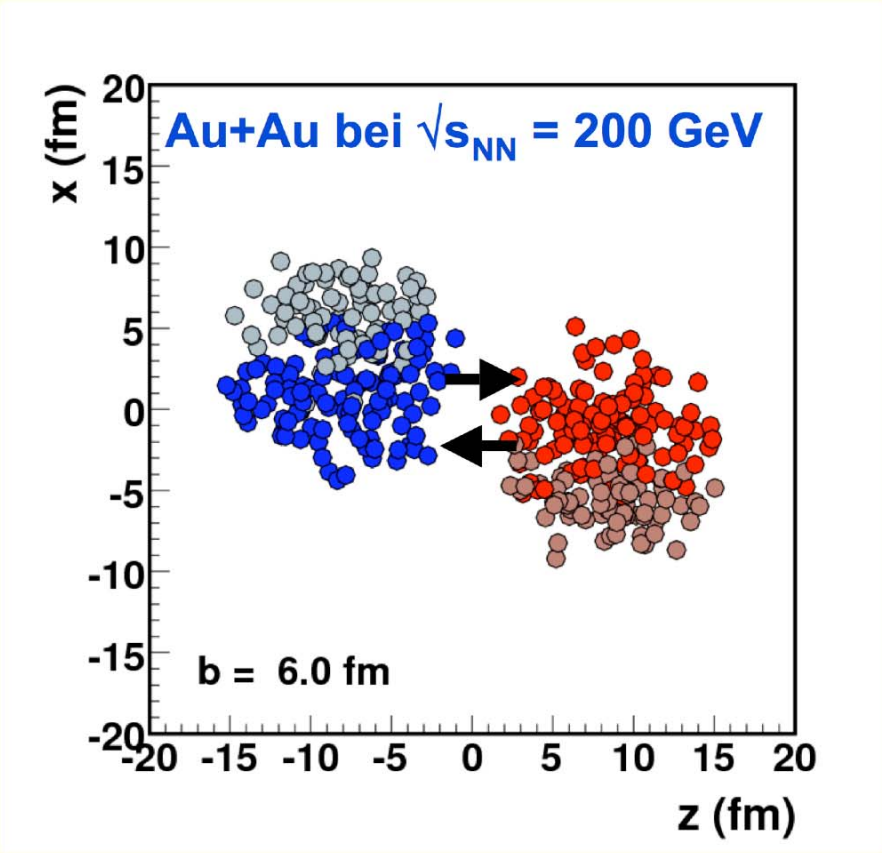
where $\langle N_{\text{coll}} \rangle_f$ is determined with a Glauber Monte Carlo code

Glauber Monte-Carlo Approach

- Distribute nucleons of both nuclei randomly according to Woods-Saxon distribution
- A collision between two nucleons takes place if their distance *d* in the transverse plane satisfies

$$d \leq \sqrt{\sigma_{\text{inel}}^{\text{NN}} / \pi}$$

- Simulate N_{ch}: $N_{ch} \sim N_{part}^{\alpha}$
- Determine $\langle N_{\text{part}} \rangle$ and $\langle N_{\text{coll}} \rangle$ for a given centrality class by applying the same cuts on the measured and simulated N_{ch}

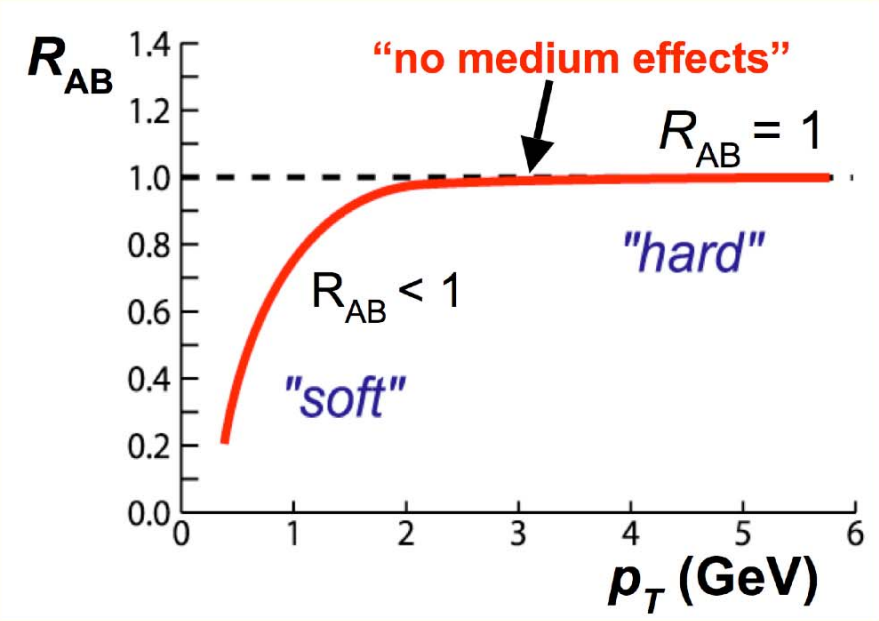


$$\sigma_{\text{inel}}^{\text{NN}} \approx 42 \text{ mb at } \sqrt{s_{NN}} = 200 \text{ GeV}$$

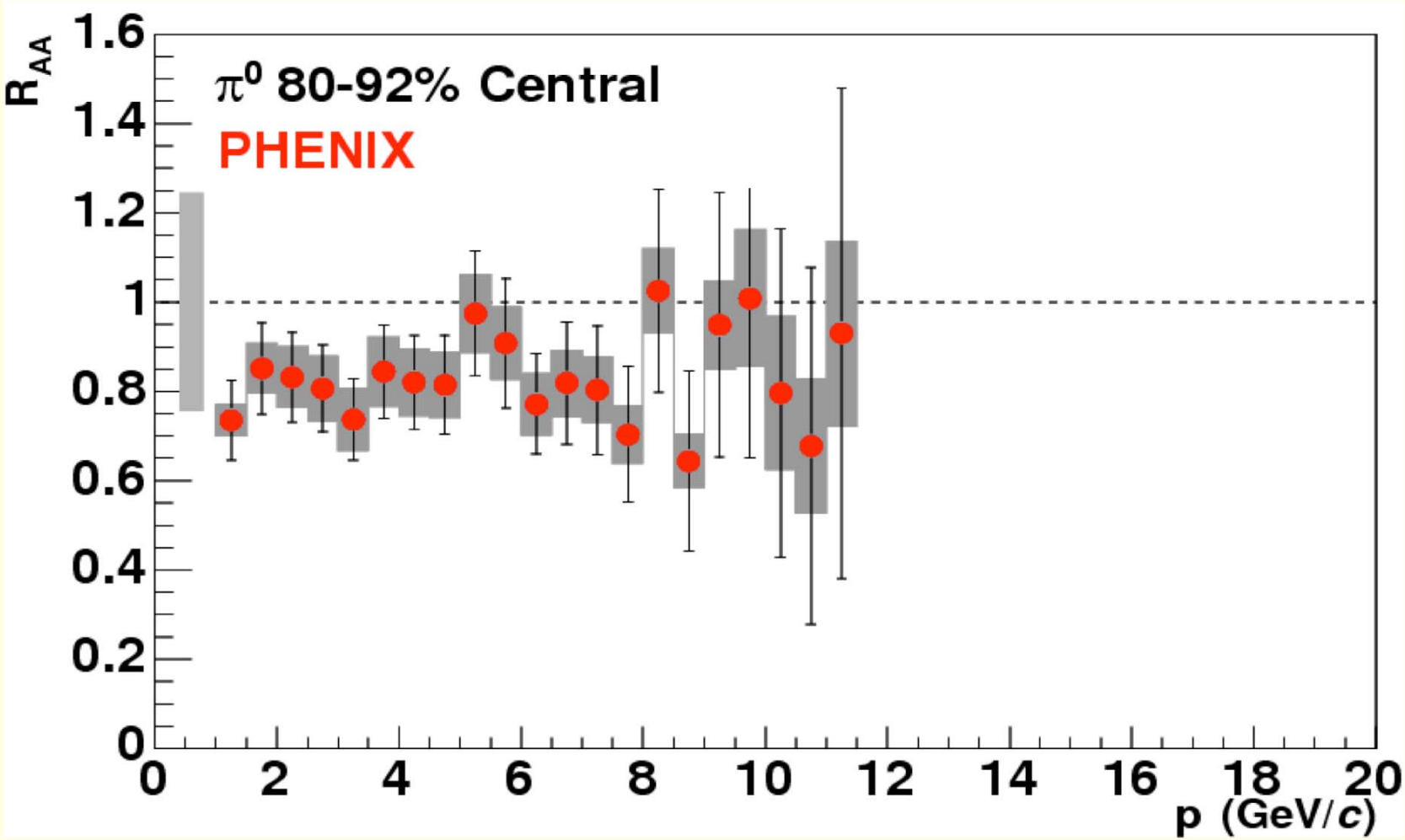
Summary on Point-Like Scaling in A+A

$$R_{AB}(p_T) = \frac{d^2N / dp_T dy \big|_{A+B}}{\langle T_{AB} \rangle_f \times d^2\sigma / dp_T dy \big|_{p+p}}$$

- $\langle T_{AB} \rangle_f = \langle N_{coll} \rangle_f / \sigma_{inel,NN}$
- $\langle N_{coll} \rangle$ from Glauber Monte-Carlo calculation
- In the absence of nuclear effects: $R_{AB} = 1$ at high p_T ($p_T > 2$ GeV/c)



Suppression of High-p_T Hadrons in Au+Au at $\sqrt{s}$ = 200 GeV



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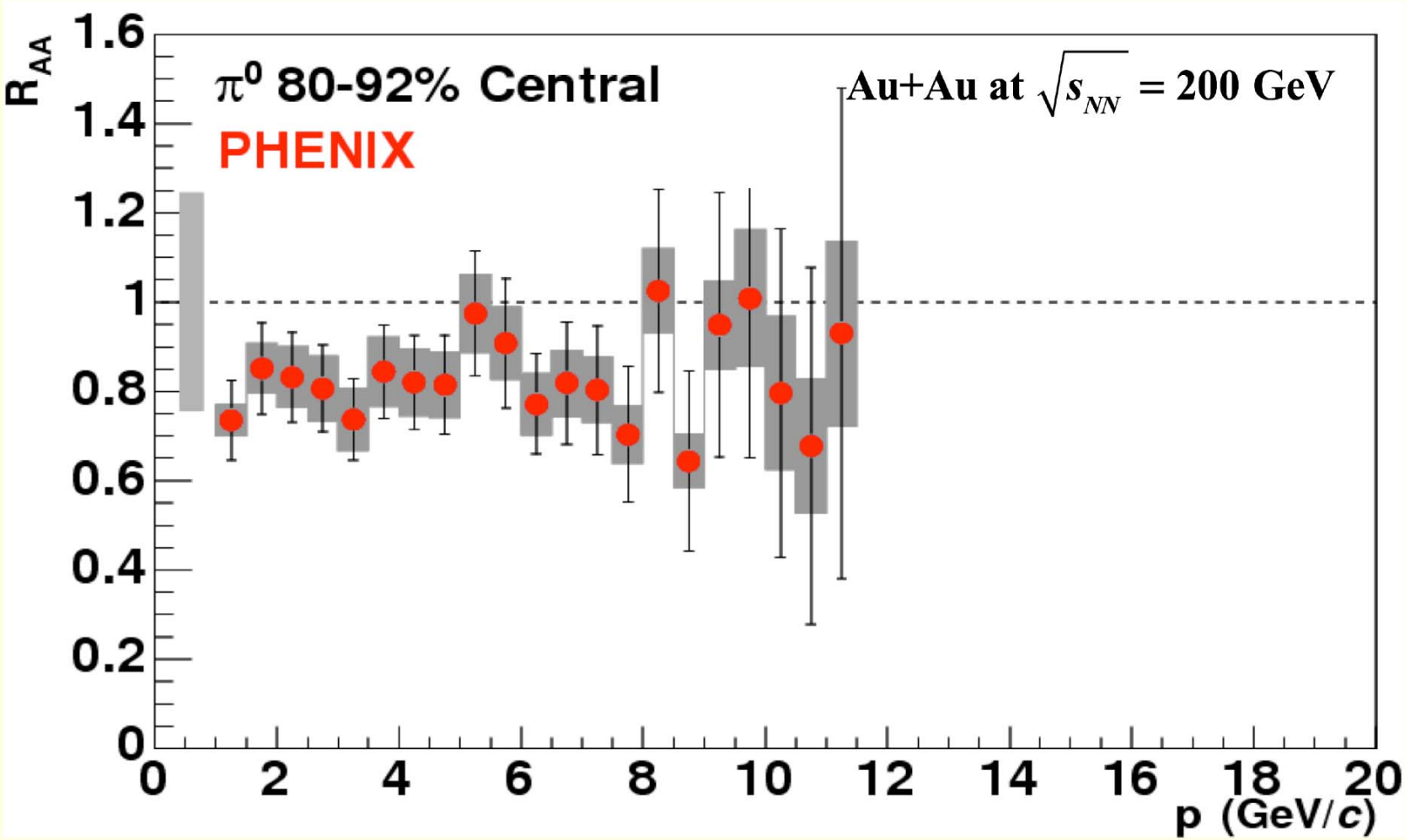

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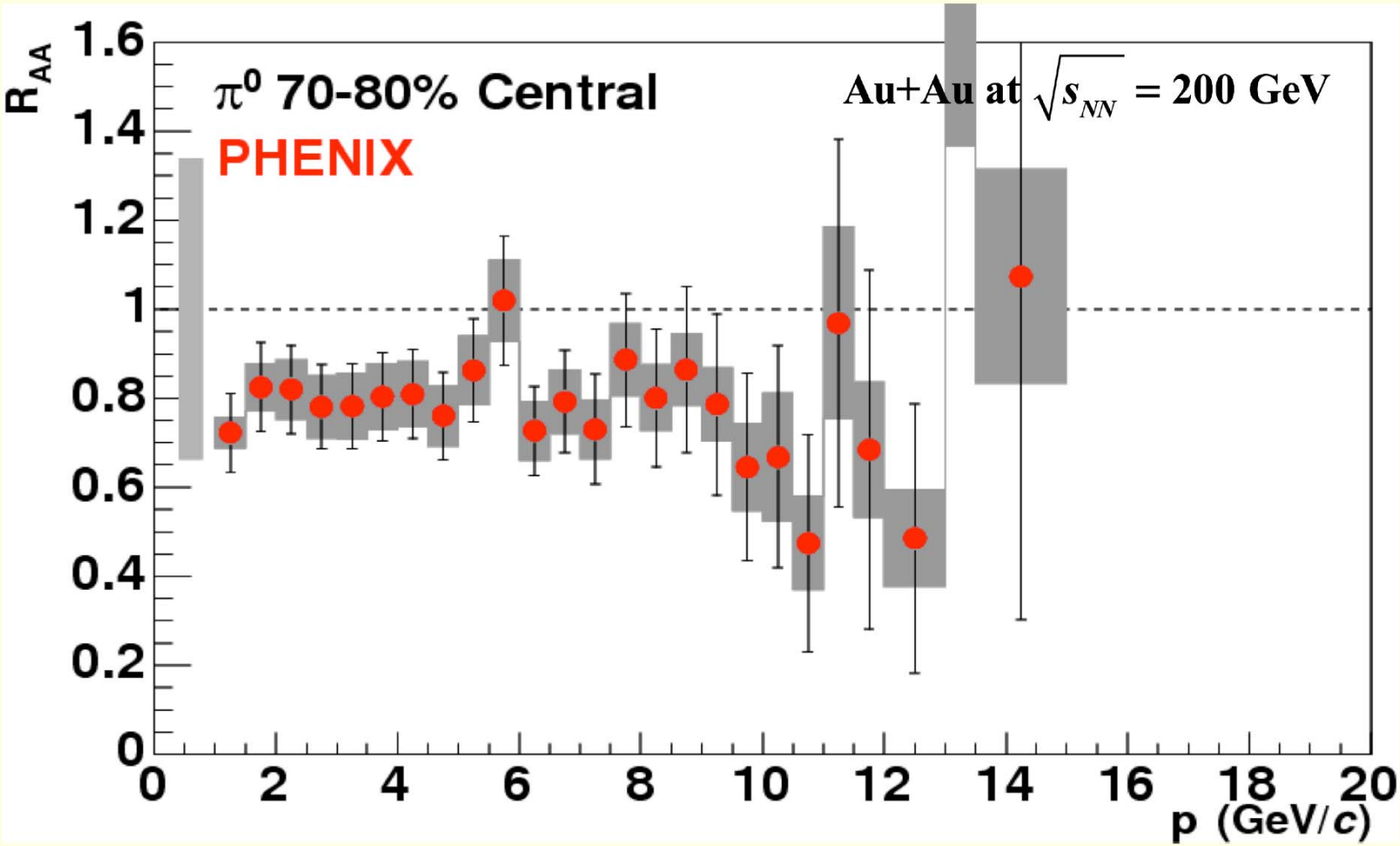

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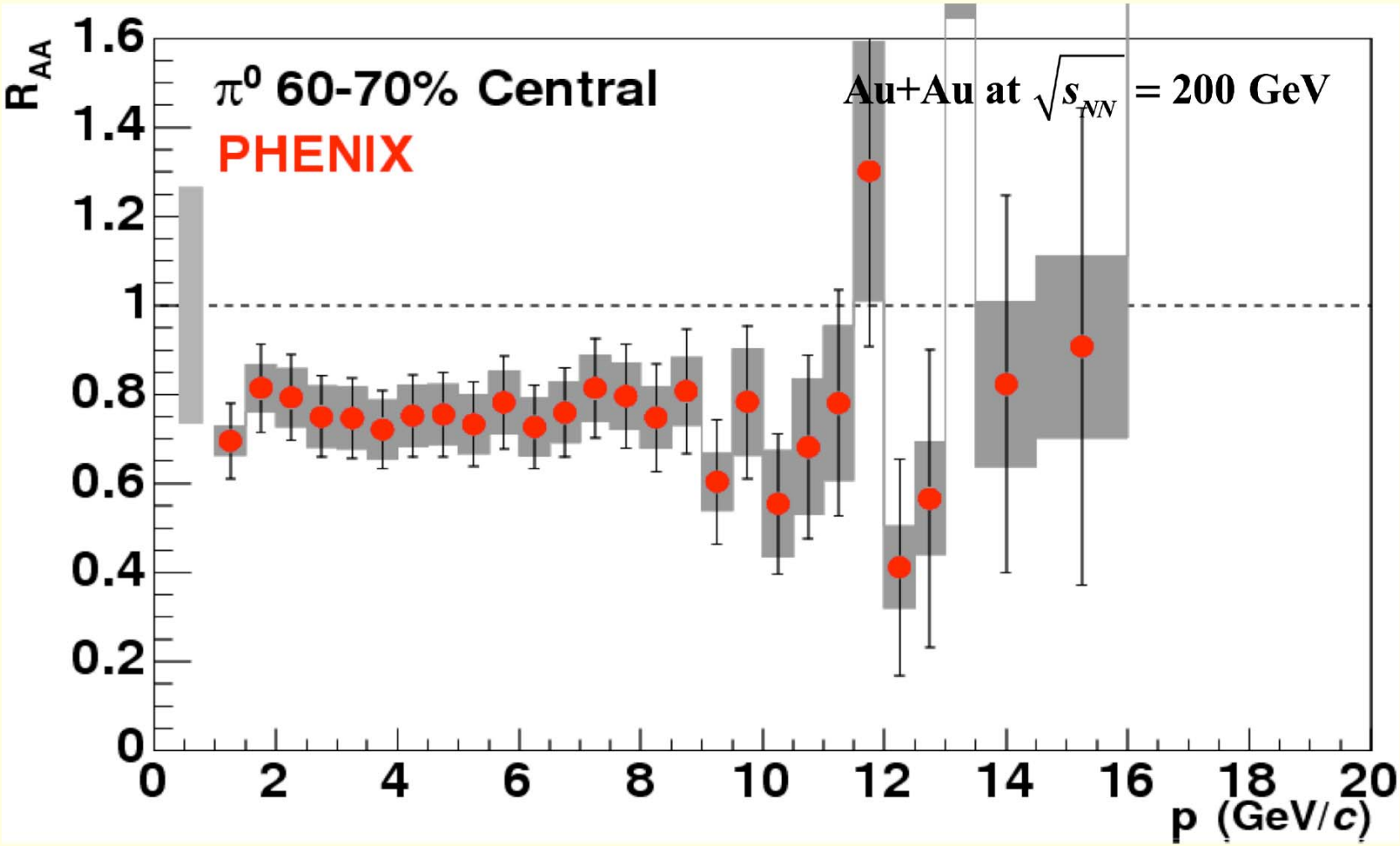

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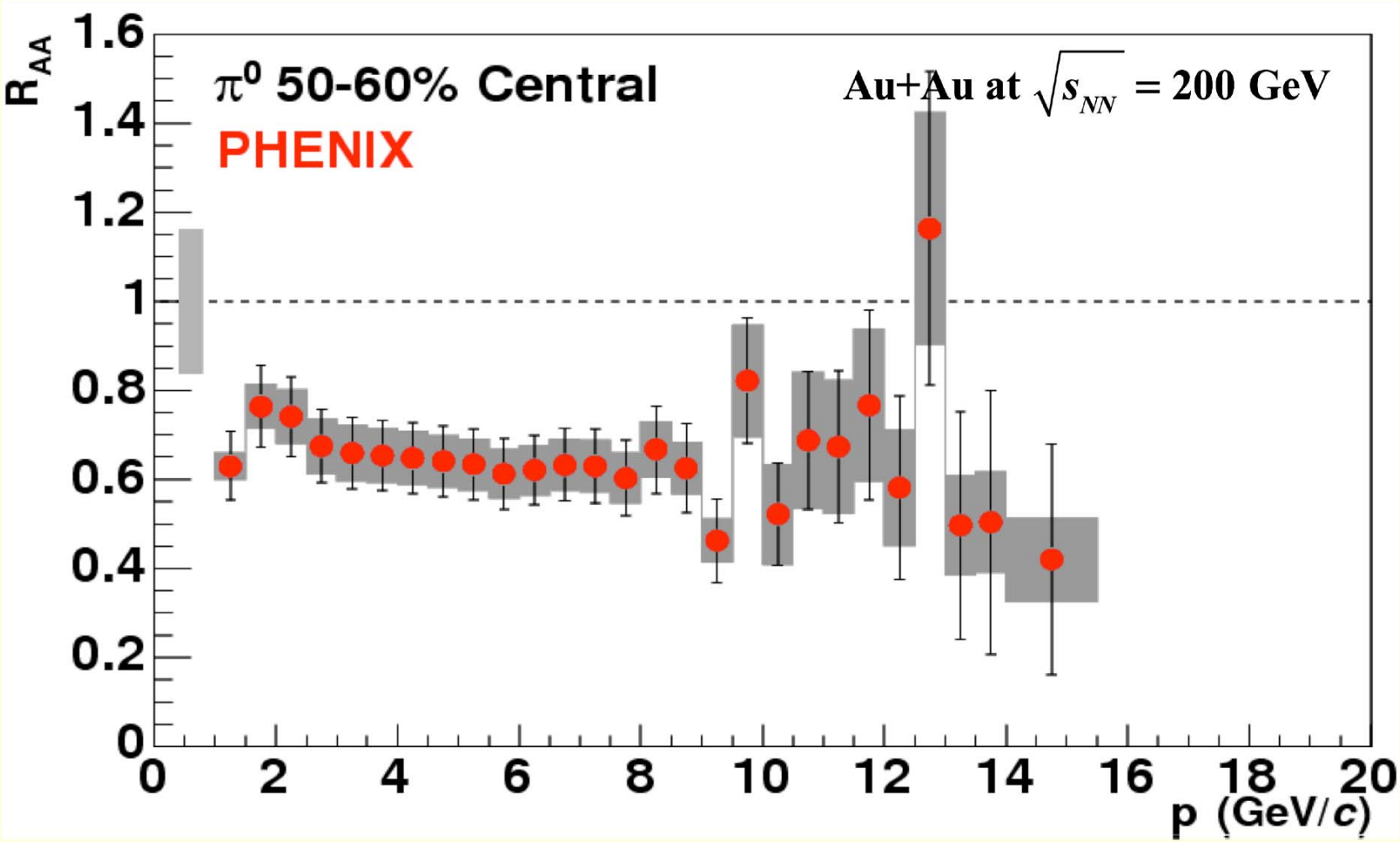
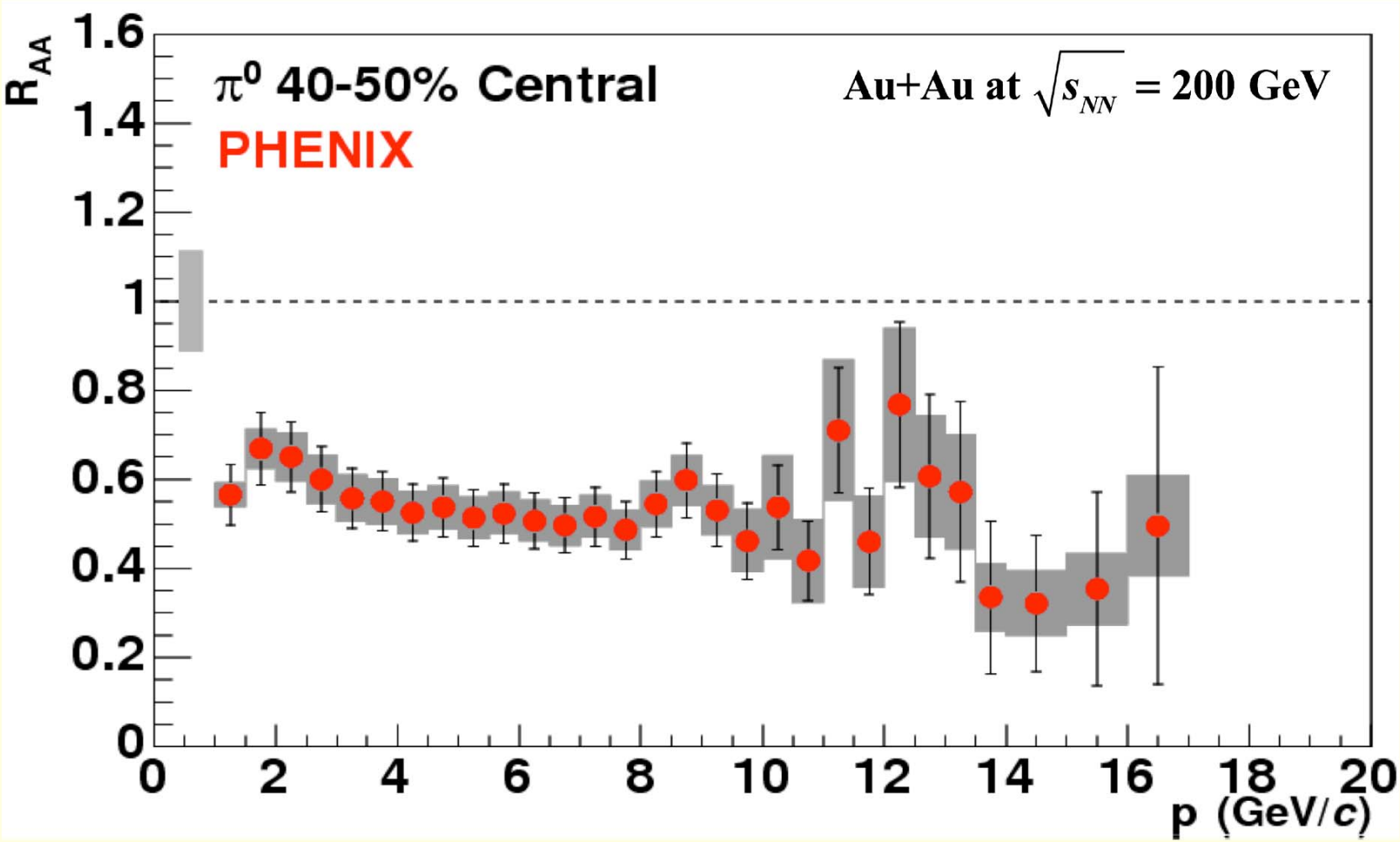
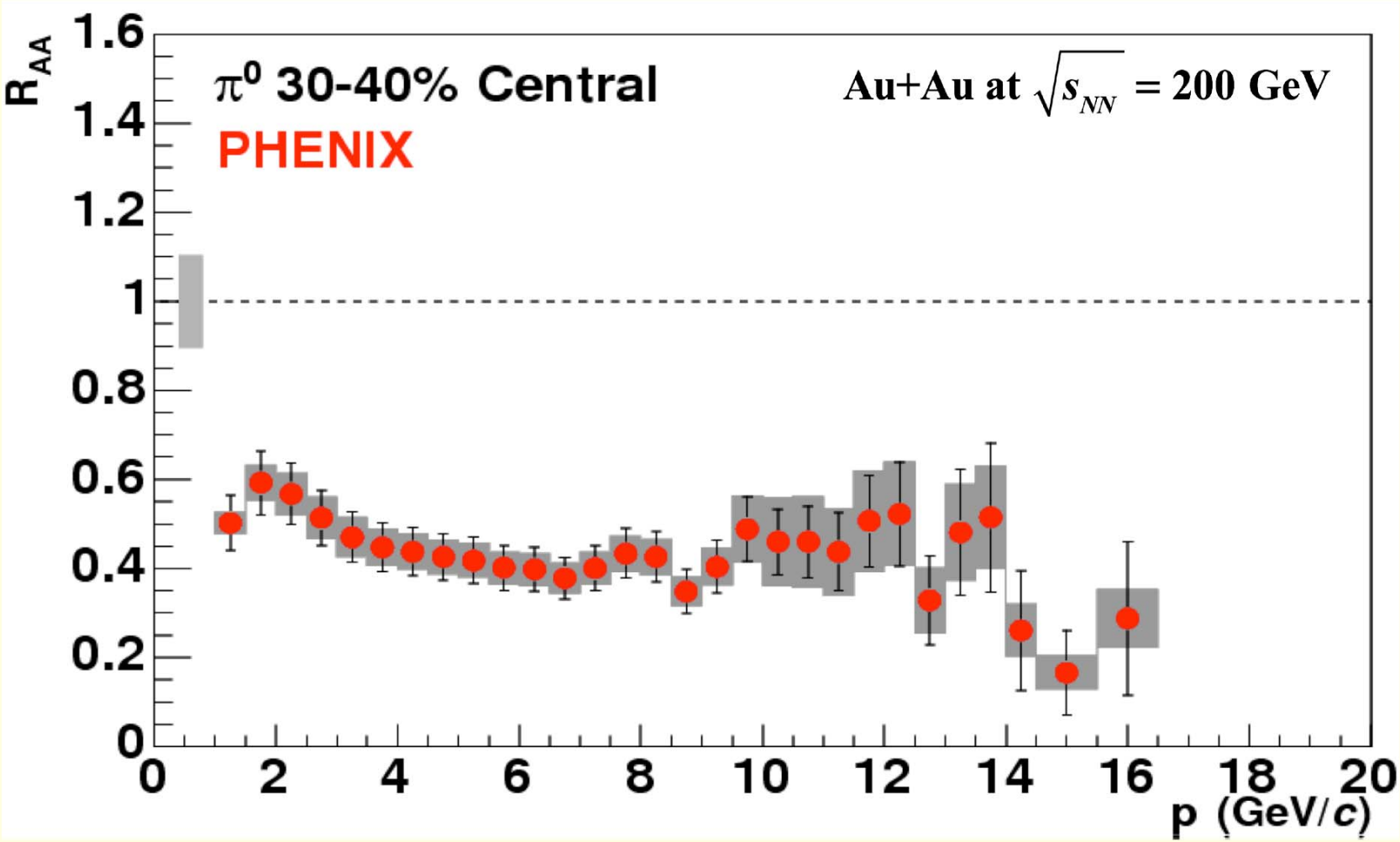


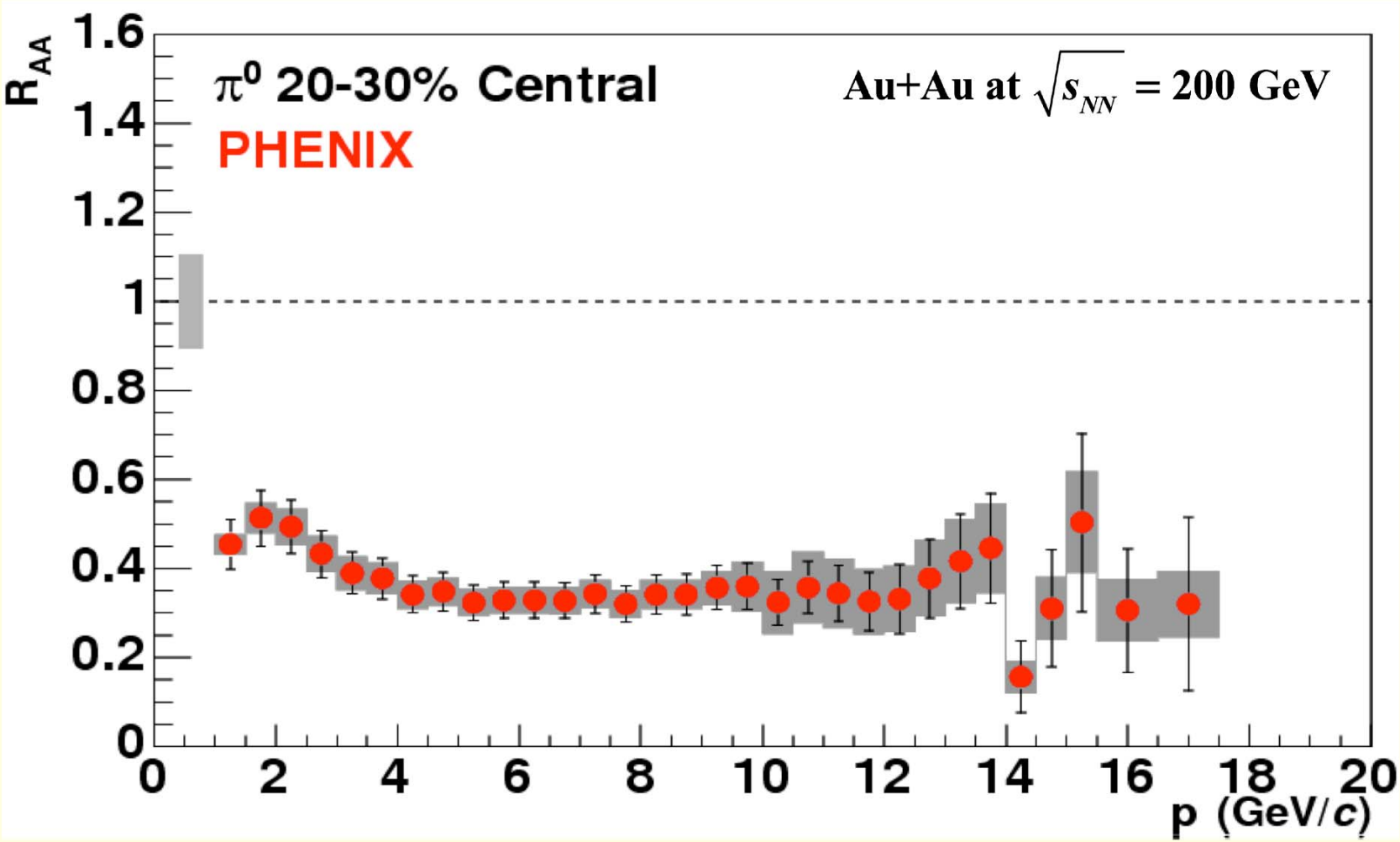
Suppression of High-p_T Hadrons in Au+Au at $\sqrt{s}$ = 200 GeV



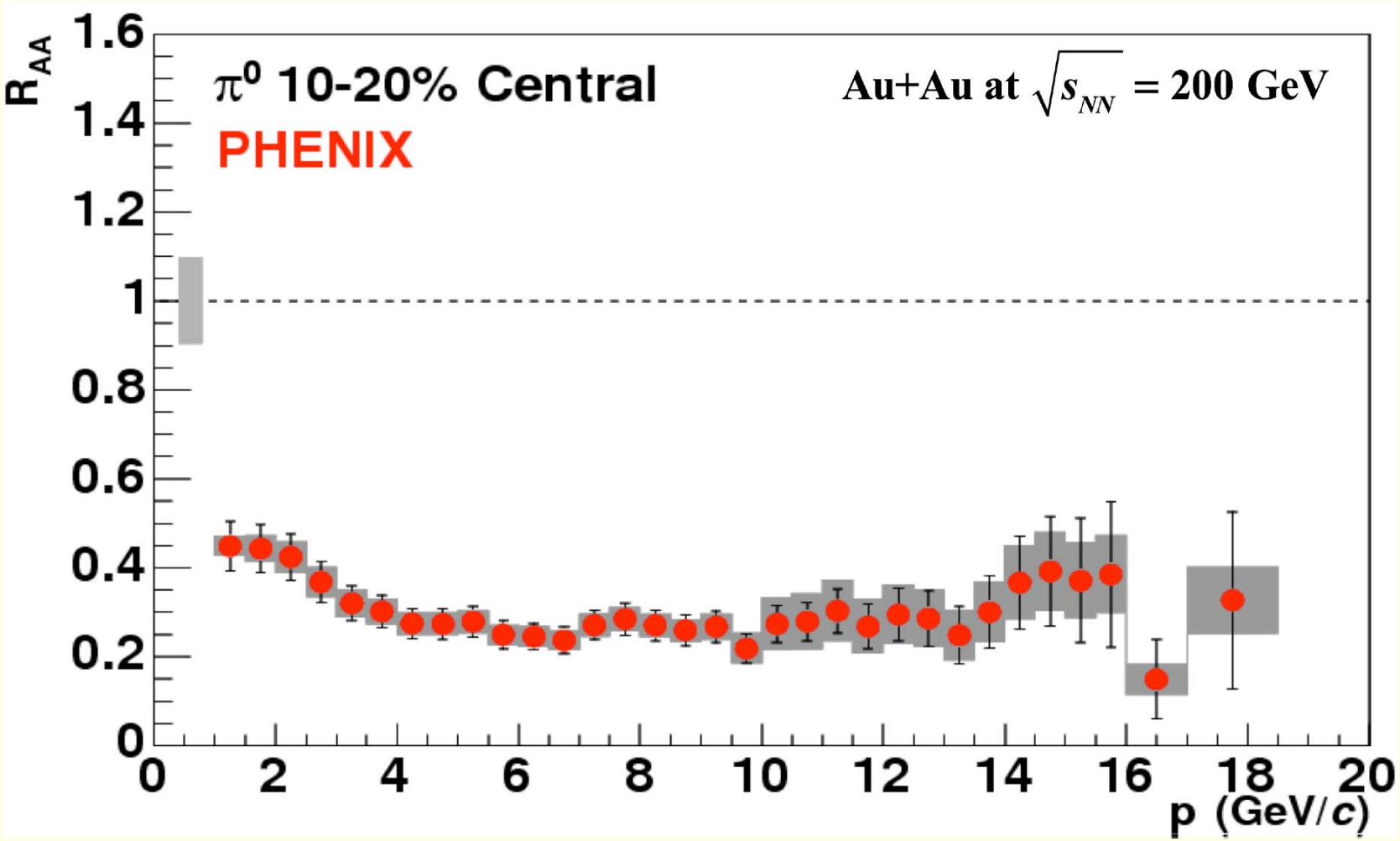
Suppression of High-p_T Hadrons in Au+Au at $\sqrt{s}$ = 200 GeV



Suppression of High-p_T Hadrons in Au+Au at $\sqrt{s}$ = 200 GeV



Suppression of High-p_T Hadrons in Au+Au at $\sqrt{s}$ = 200 GeV



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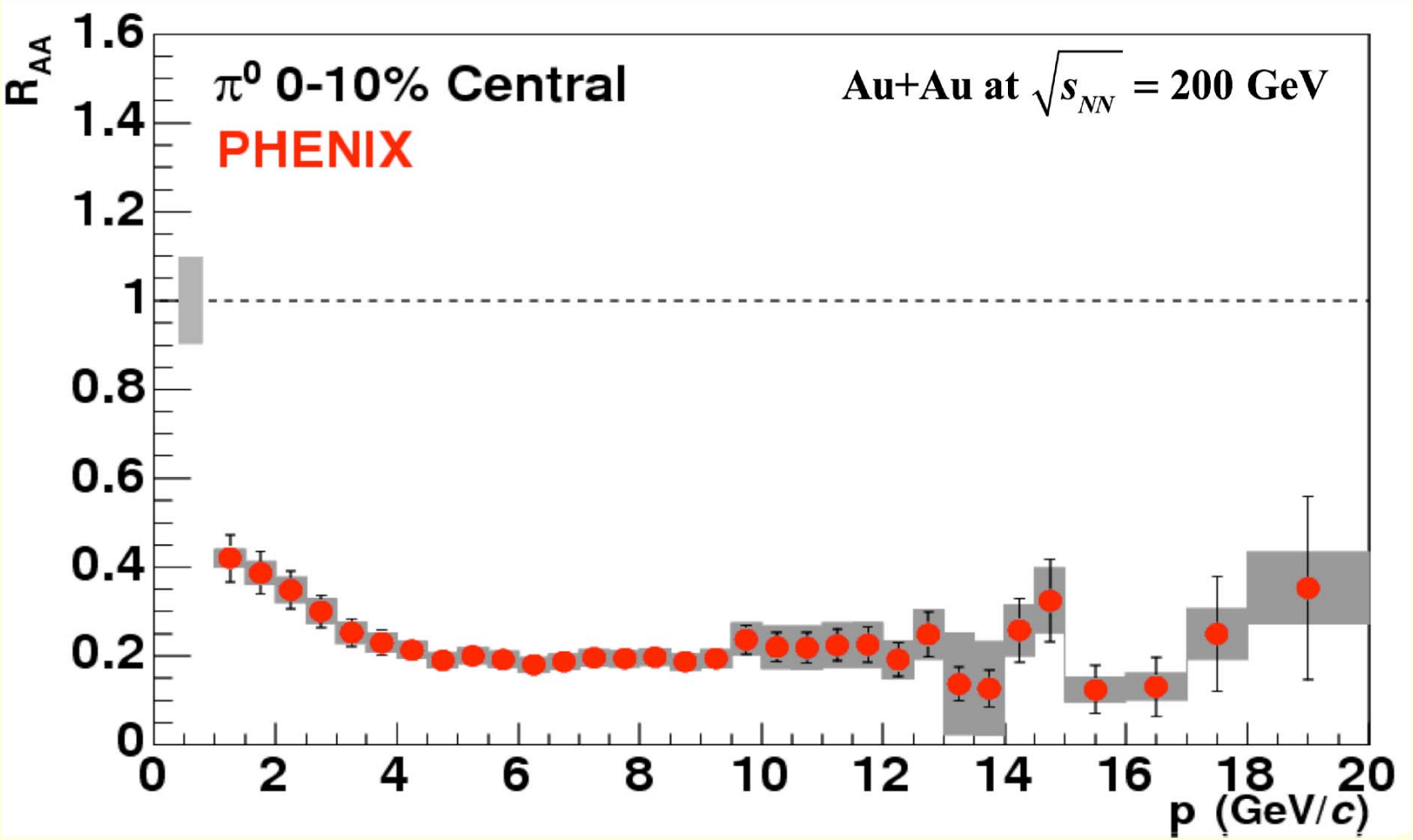

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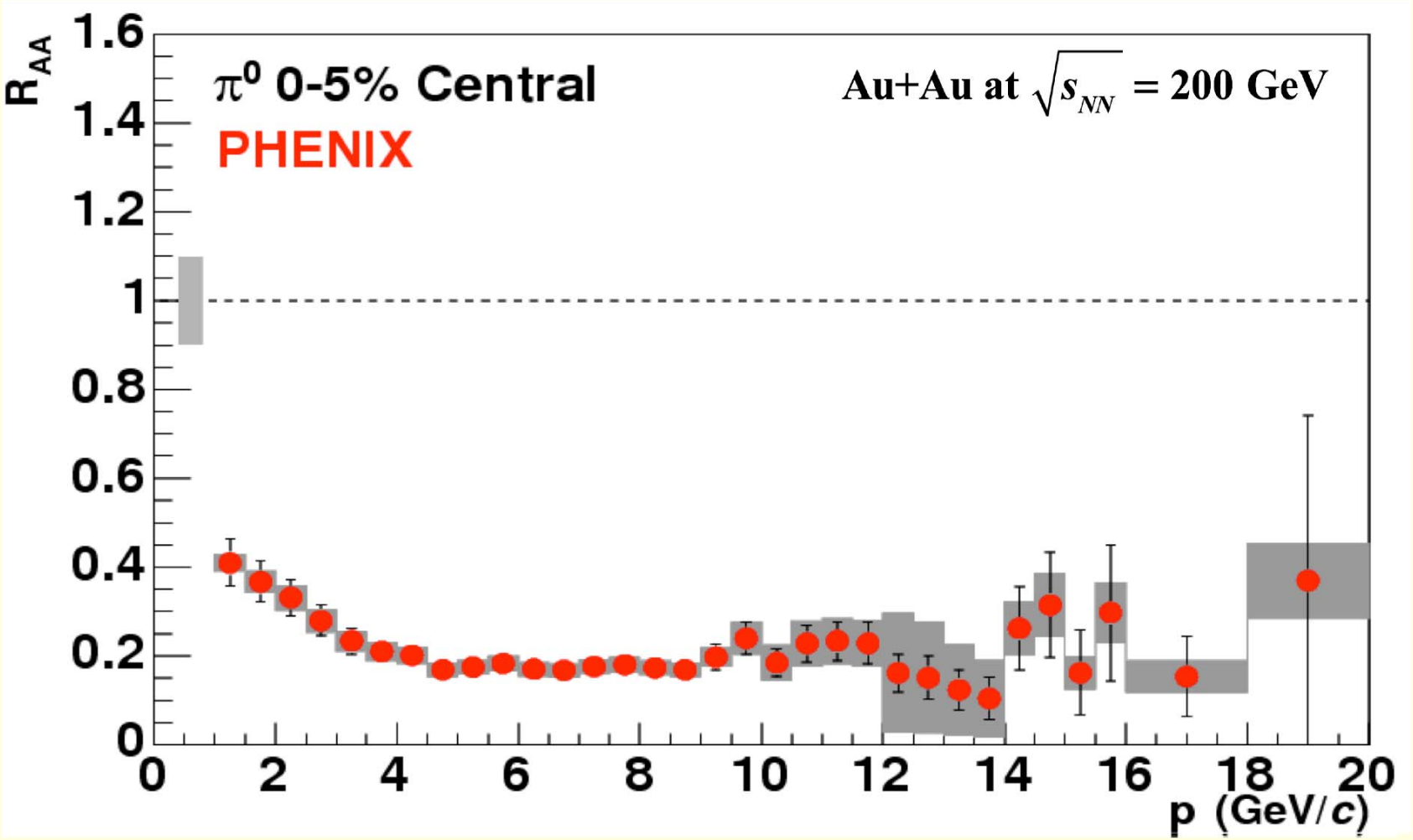

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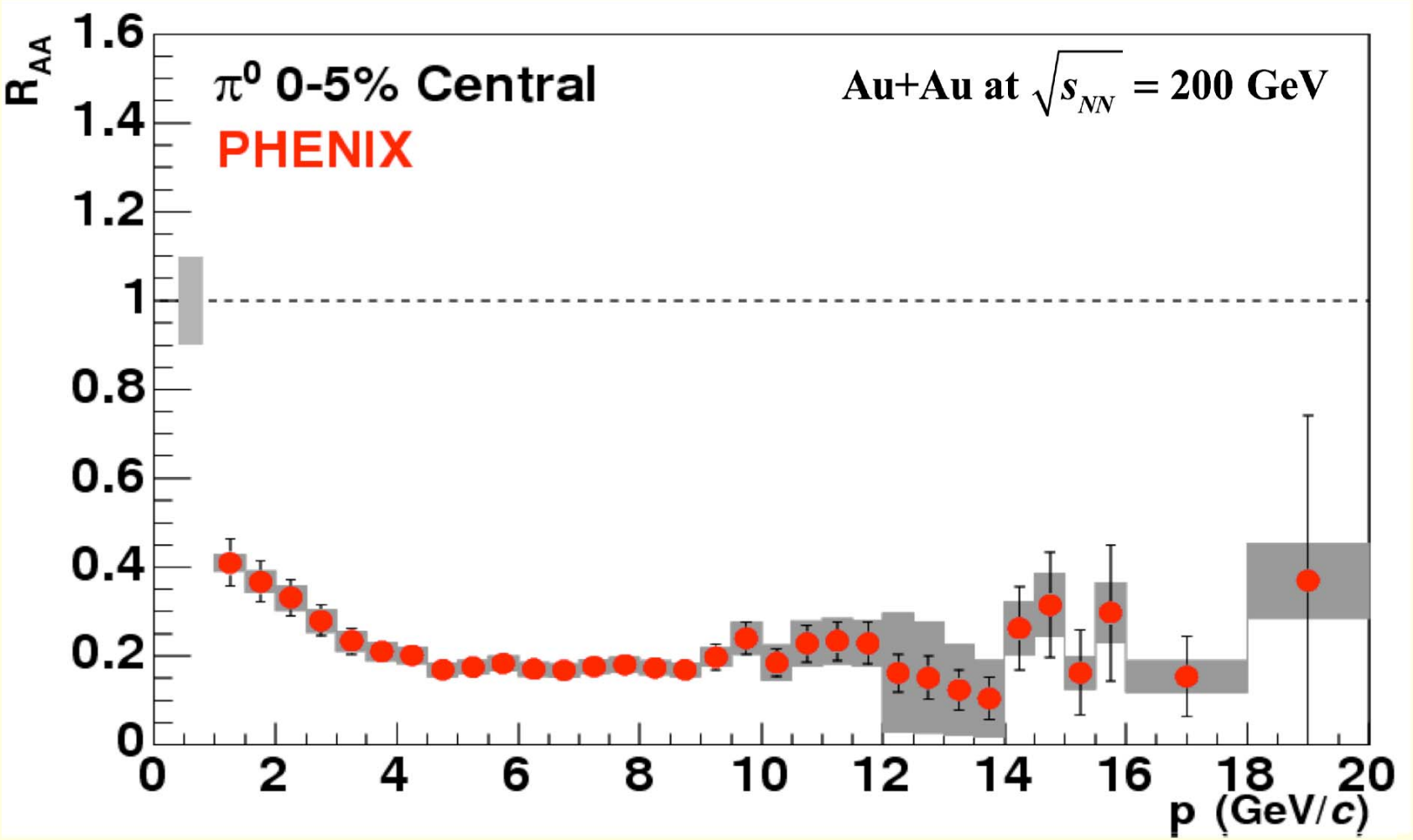
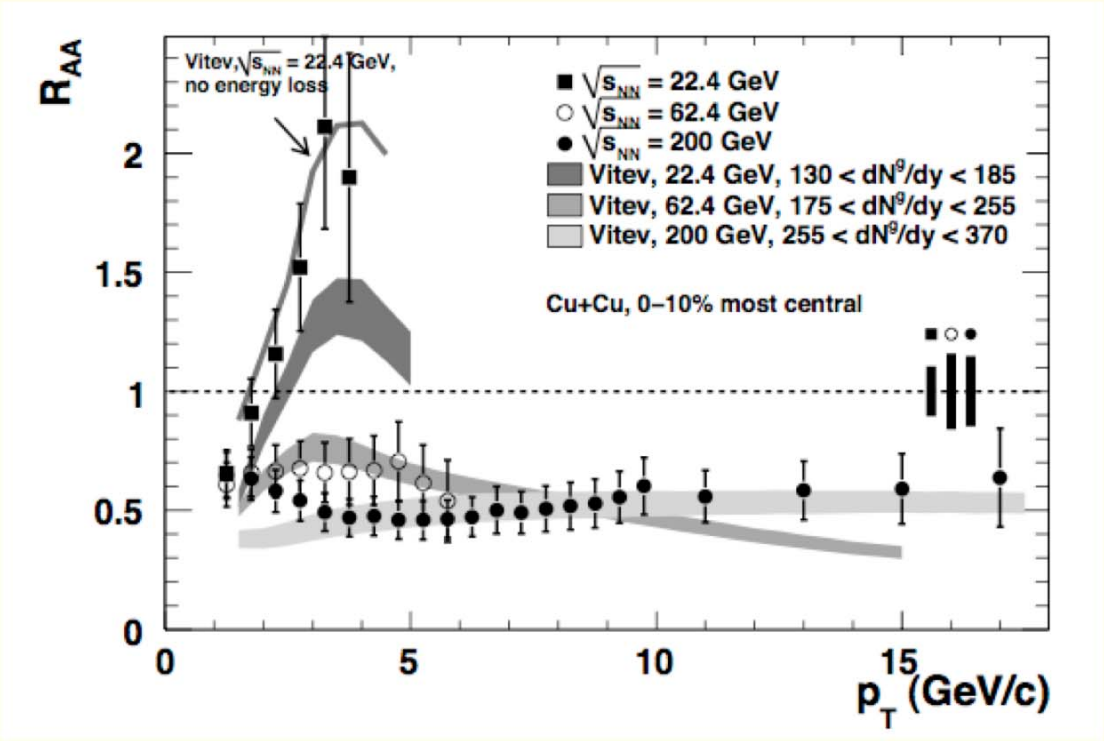


Factor ~ 5 suppression in central Au+Au at 200 GeV

$\sqrt{s_{NN}}$ Dependence of Jet Quenching: π^0's in Cu+Cu at 22.4, 62.4, and 200 GeV



PHENIX, Phys. Rev. Lett. 101,162301(2008)

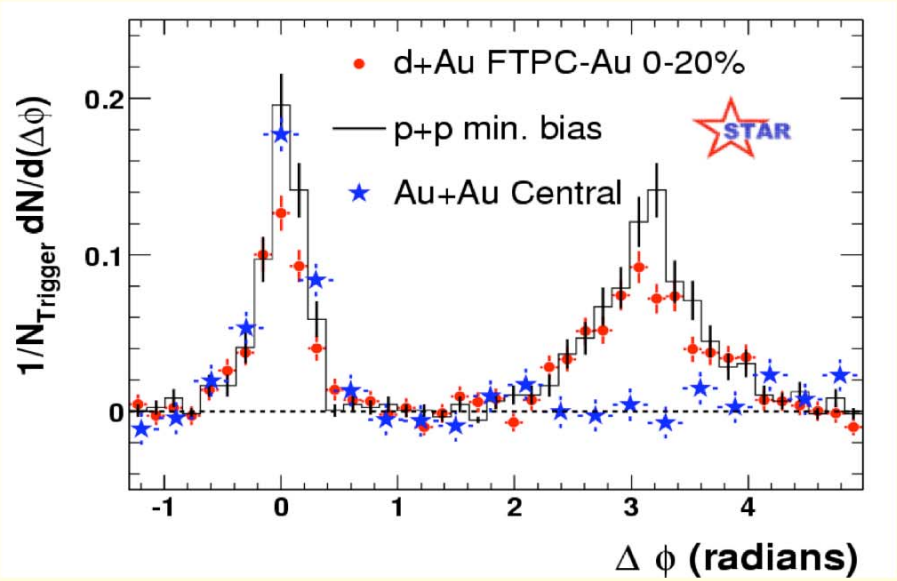
- **62.4, 200 GeV:**
  - **Suppression consistent with parton energy loss for p_T > 3 GeV/c**
- **22.4 GeV:**
  - **No suppression**
  - **Enhancement consistent with calculation that describes nuclear k_T enhancement in p+A ("Cronin effect")**
- **Parton energy loss starts to prevail over Cronin enhancement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

$dN_{ch}/d\eta$ in semi-central Cu+Cu@62.4 GeV also reached in p+p at the LHC
→ Could jet quenching be important in "central" p+p coll. at the LHC?

Two-Particle Angular Correlations at RHIC: Intermediate and Low p_T

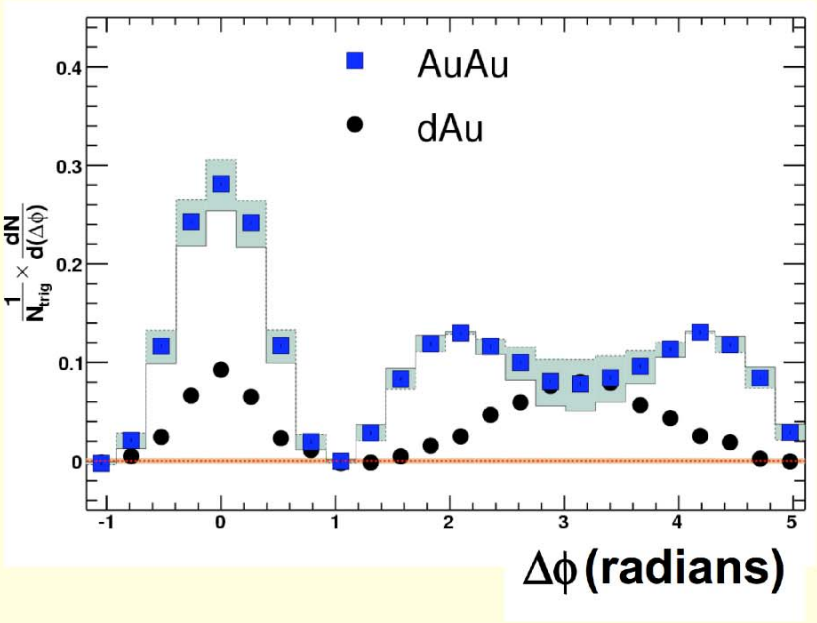
Away side yield modification - Jet Quenching

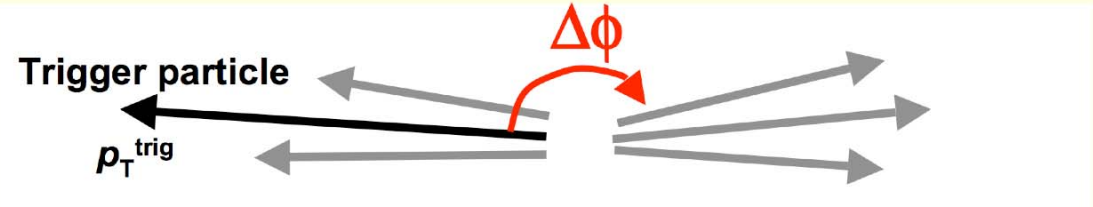
$4 < p_T^{trig} < 6$ GeV/c, $p_T^{assoc} > p_T^{trig} - 2$ GeV/c



Away side shape modification - Medium response

$2.5 < p_T^{trig} < 4$ GeV/c, $1 < p_T^{assoc} < 2.5$ GeV/c

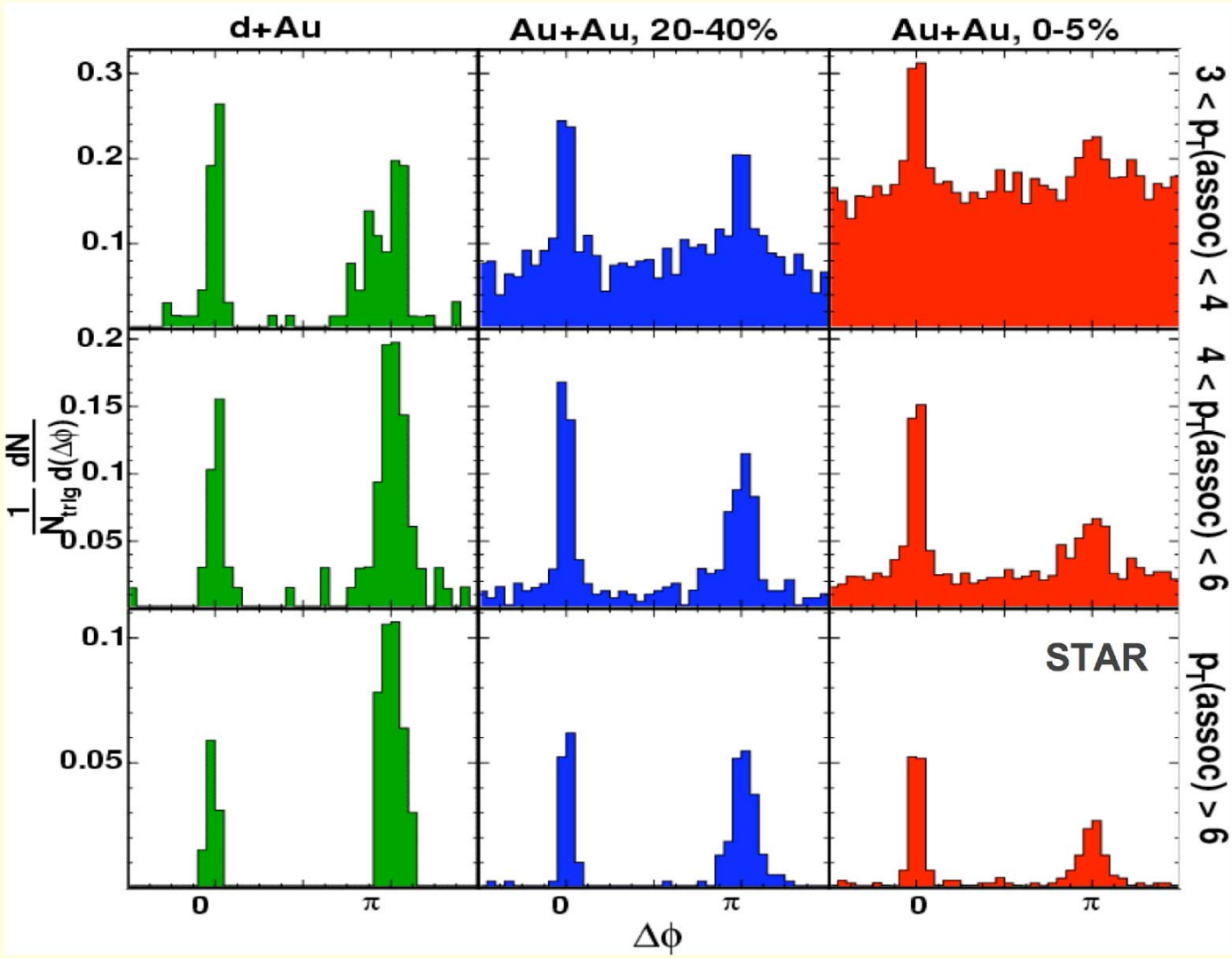




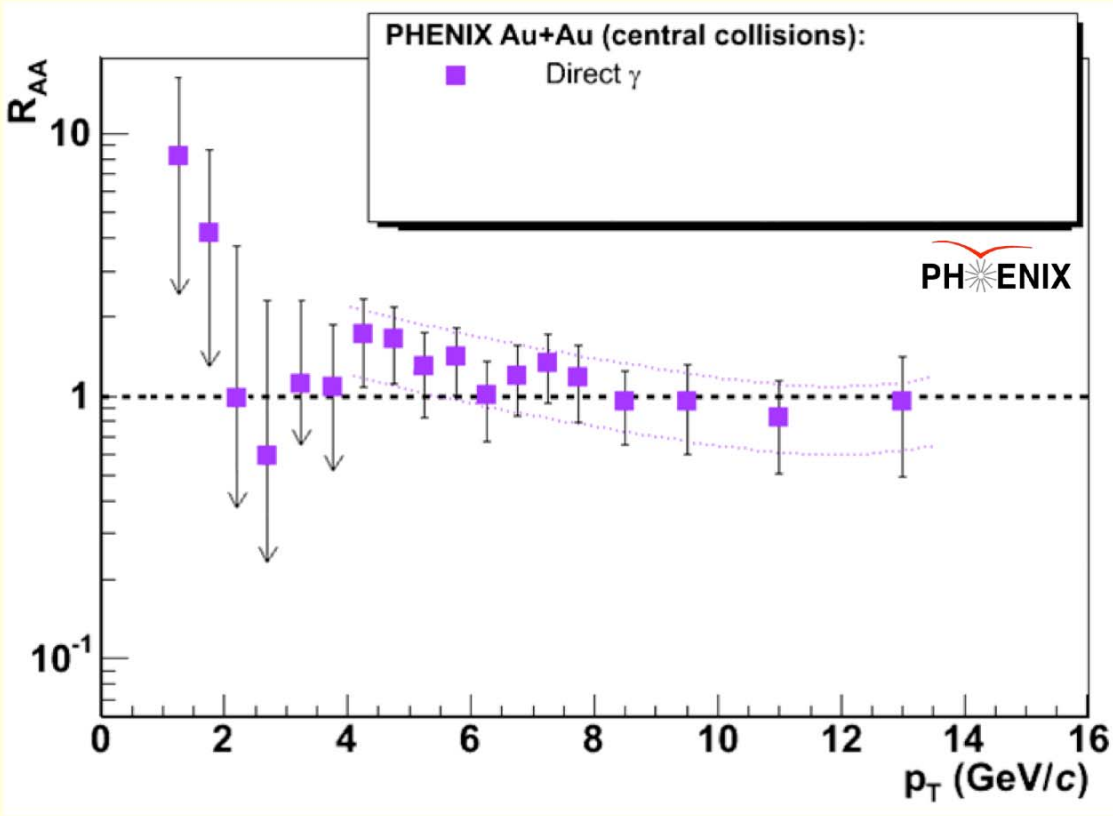
Two-Particle Angular Correlations at RHIC: High p_T

Reappearance of di-jets

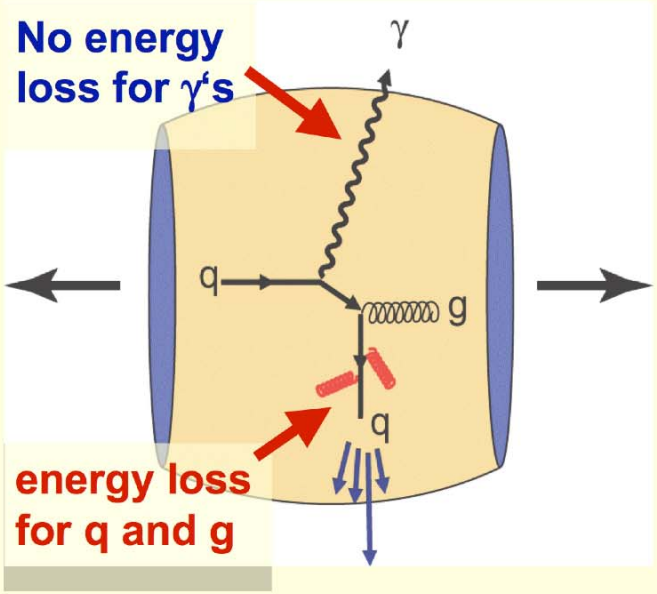
$8 < p_T^{trig} < 15$ GeV/c



Nuclear Modification Factor for Direct Photons (RHIC Run-2)



$$R_{AA} = \frac{dN/dp_T\big|_{A+A}}{\langle N_{coll}\rangle \times dN/dp_T\big|_{p+p}}$$



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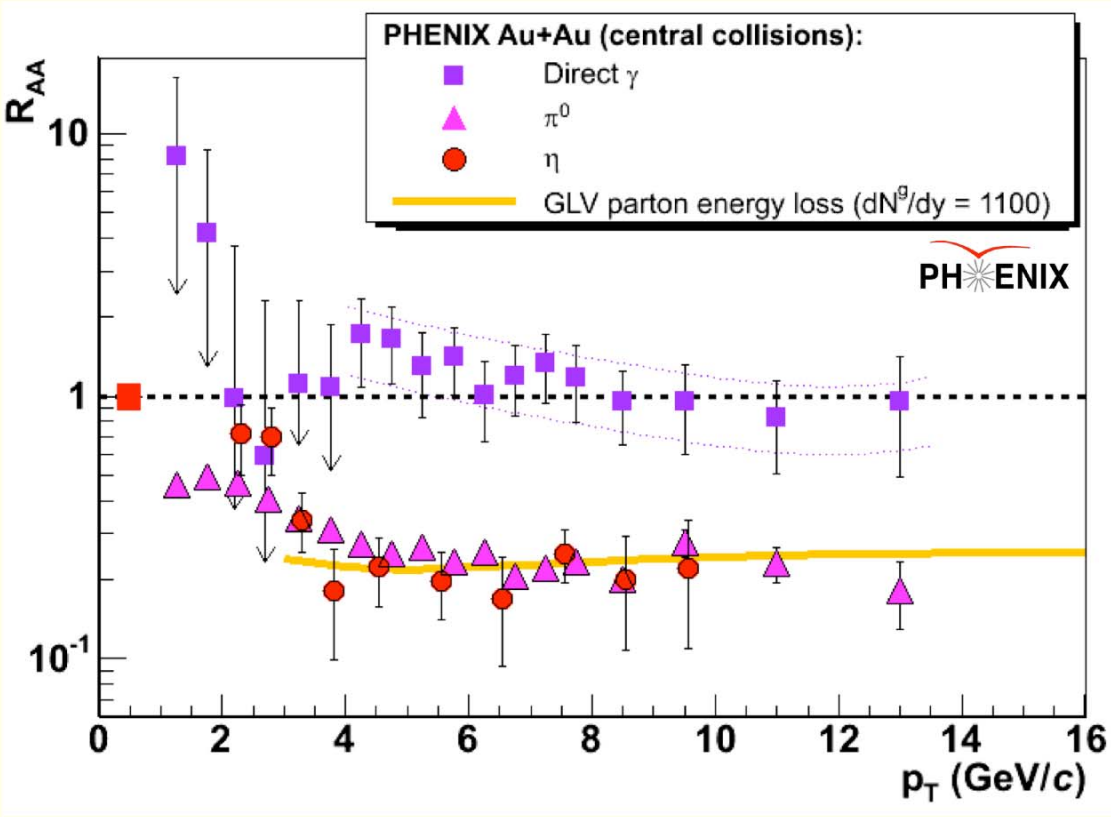

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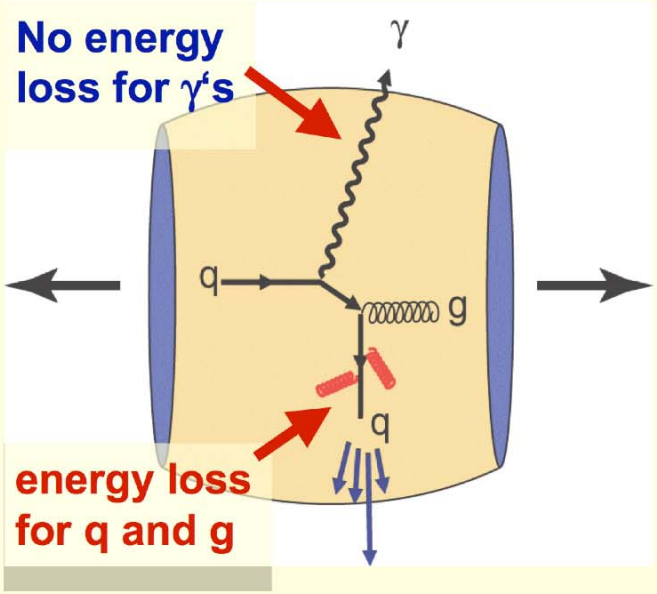
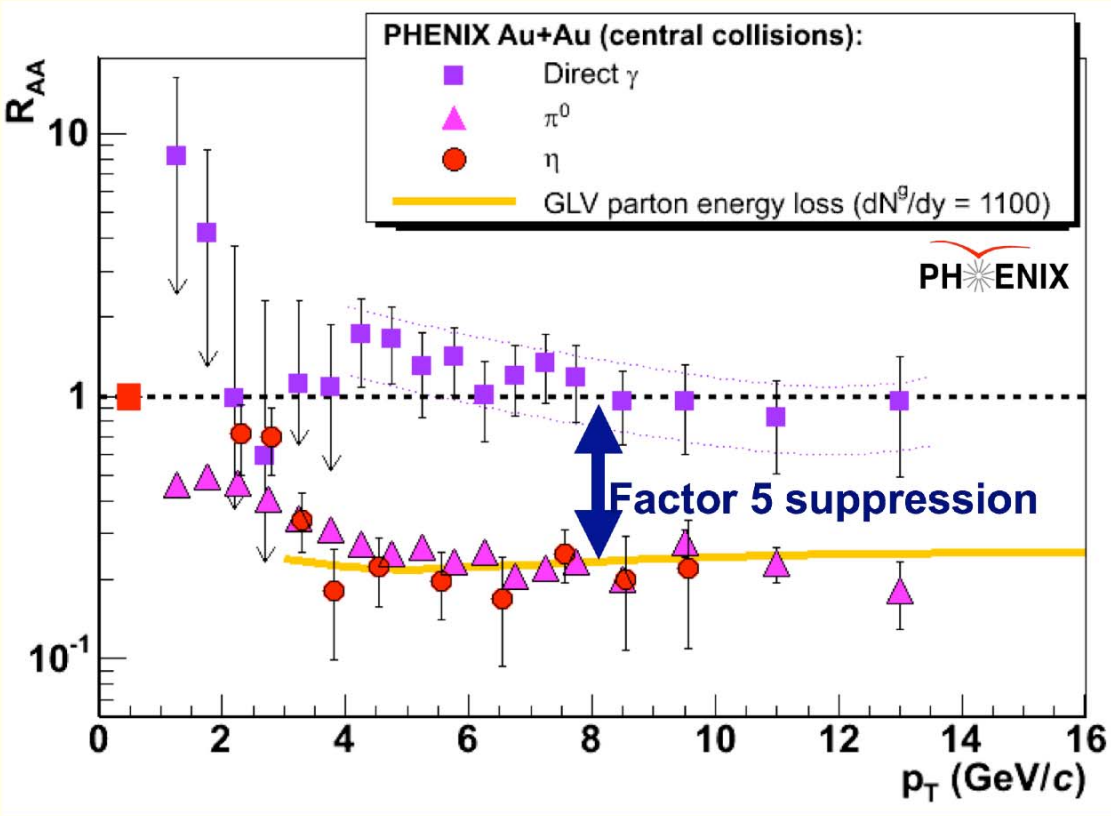


Nuclear Modification Factor for Direct Photons (RHIC Run-2)



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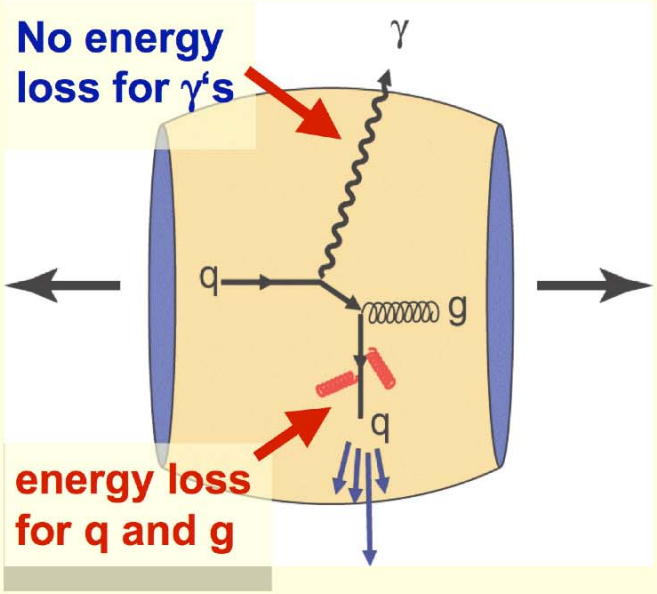
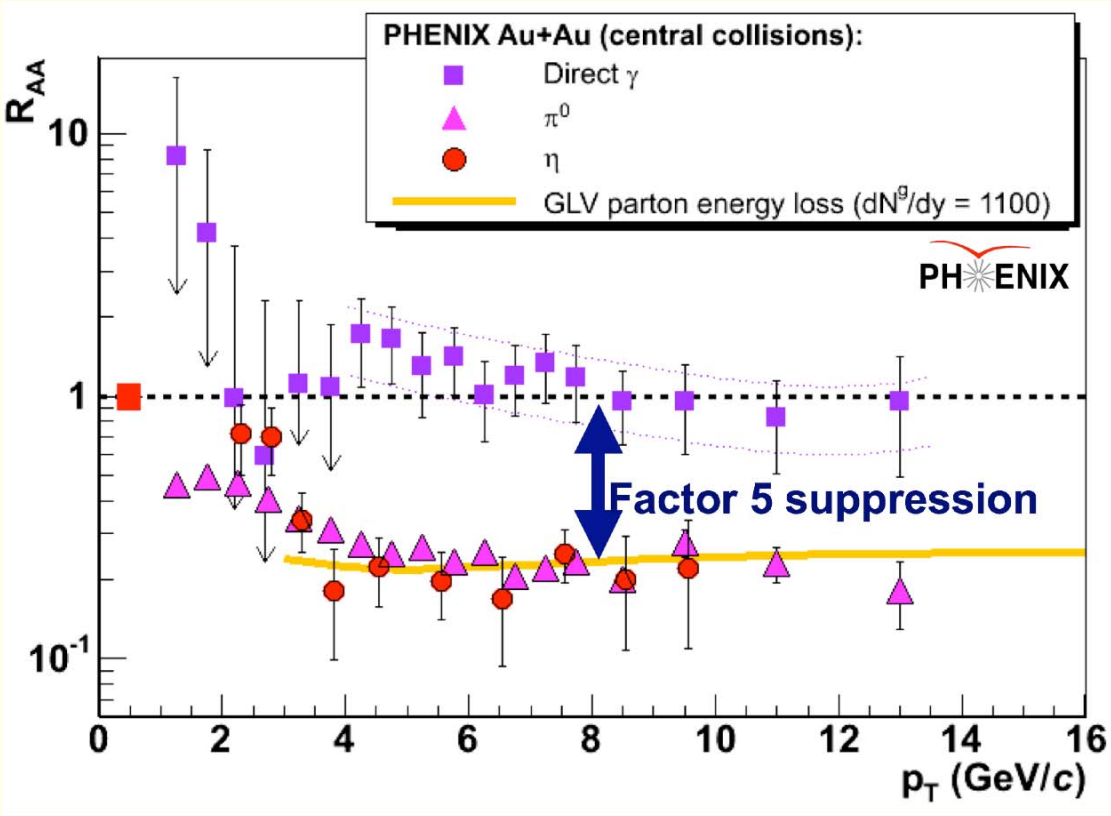


Nuclear Modification Factor for Direct Photons (RHIC Run-2)



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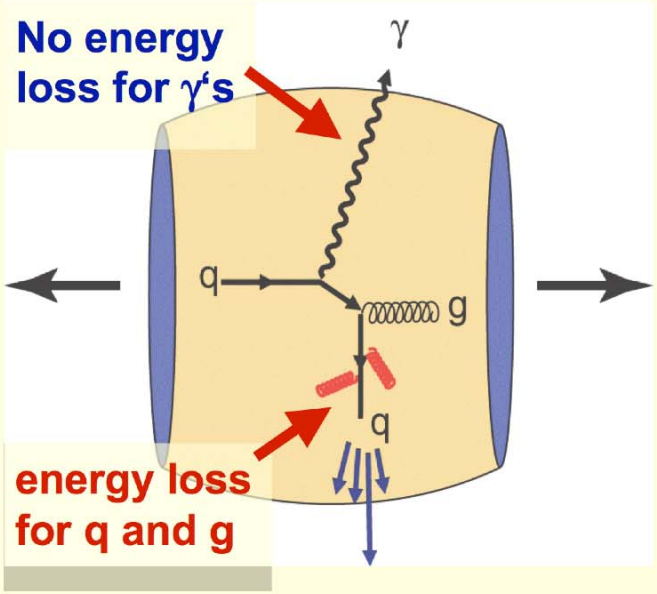
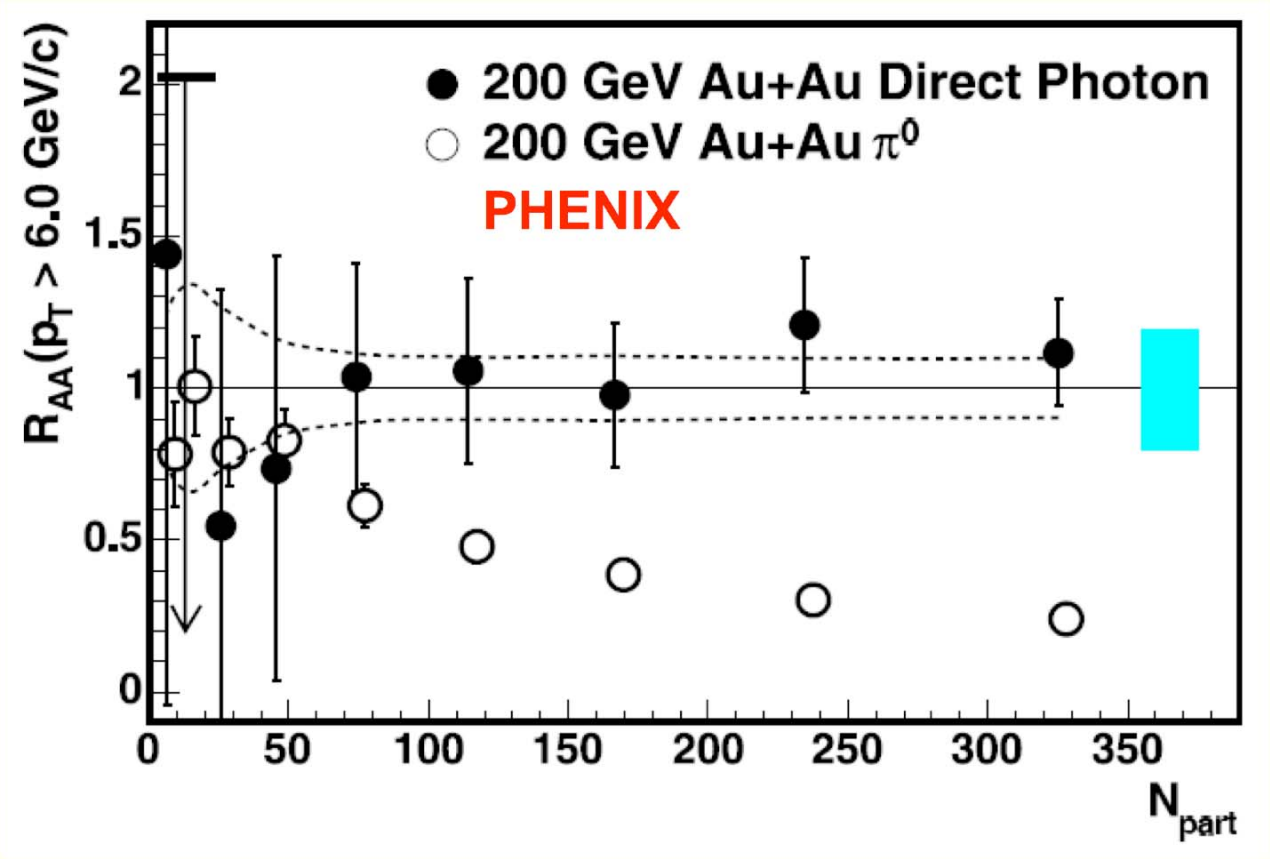


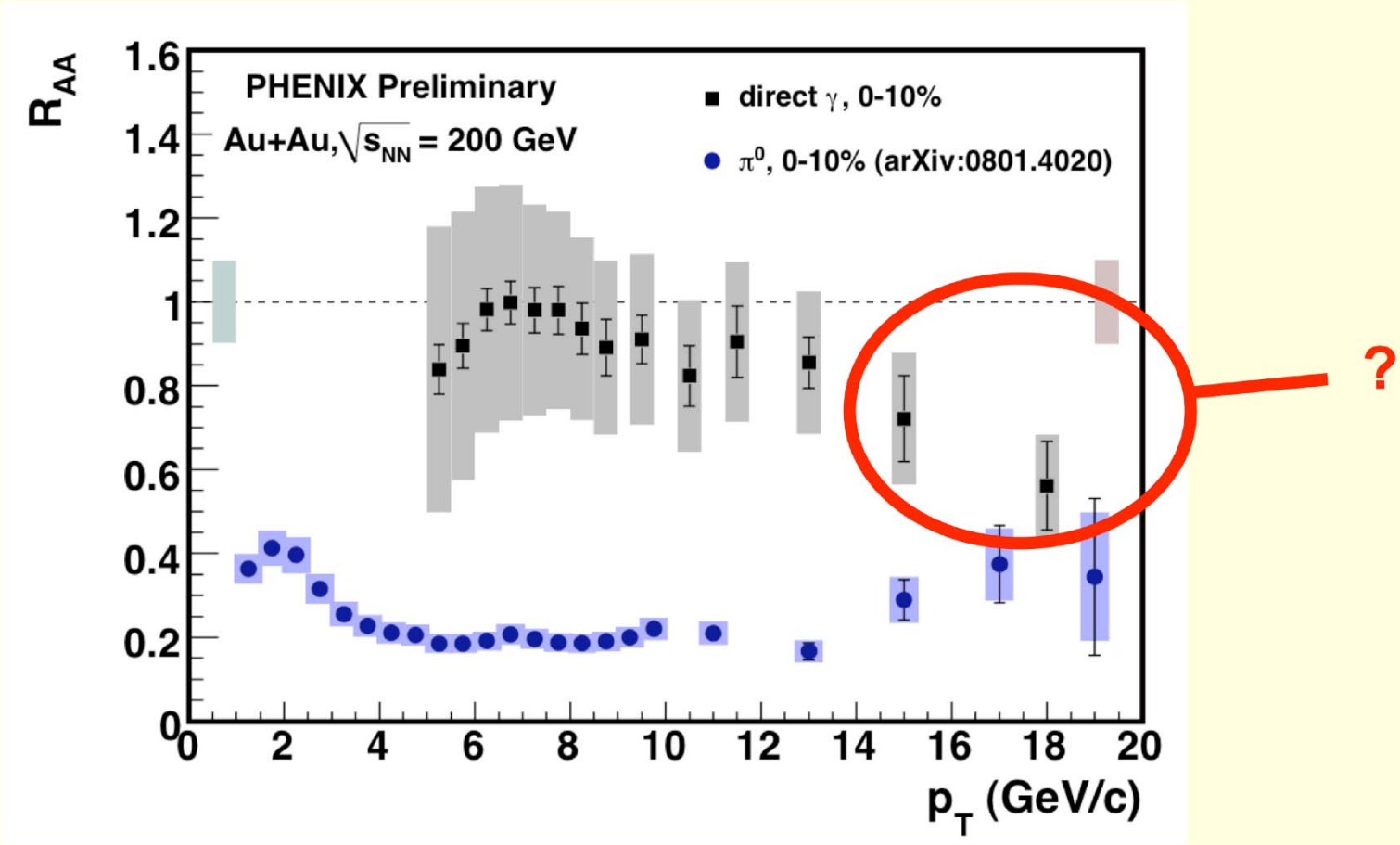
Hadrons are suppressed whereas direct photons are not: Evidence for parton energy loss (as expected in the QGP)

Centrality Dependence of π^0 and Direct γ



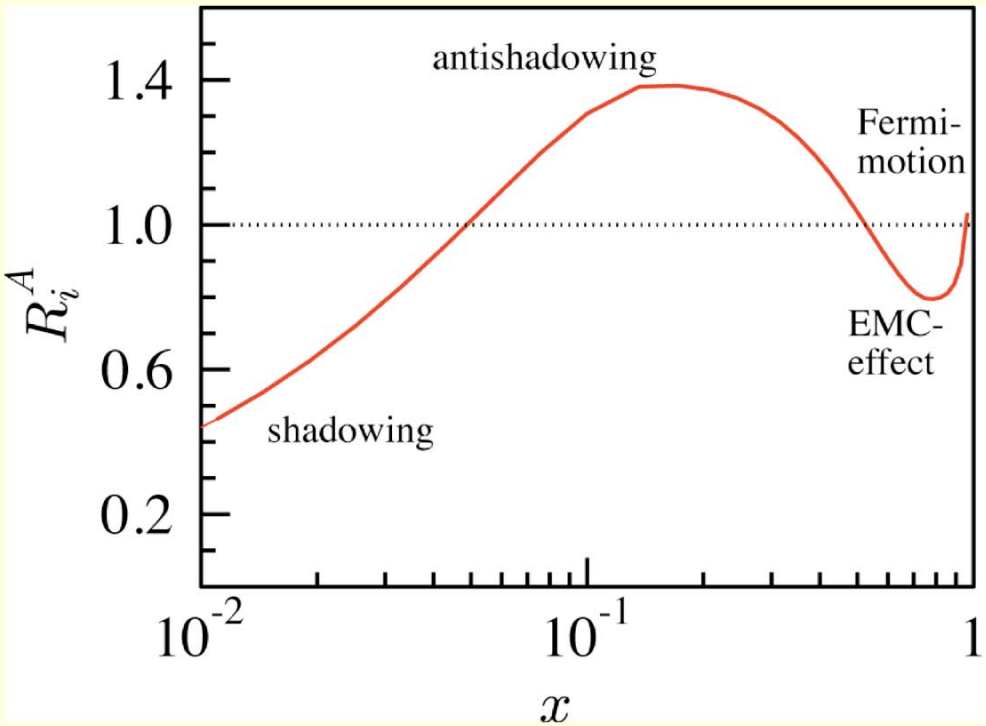
Point-like scaling for direct photons (as expected)

Direct Photons (RHIC Run 4): Suppression at High p_T?



- Au+Au: Direct γ R_{AA} < 1 at $p_T \approx$ 18 GeV/*c* ?
- Isospin effect + nuclear PDF's + Suppression of fragmentation photons?

Nuclear Modification of PDF's



$$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$

proton in nucleus

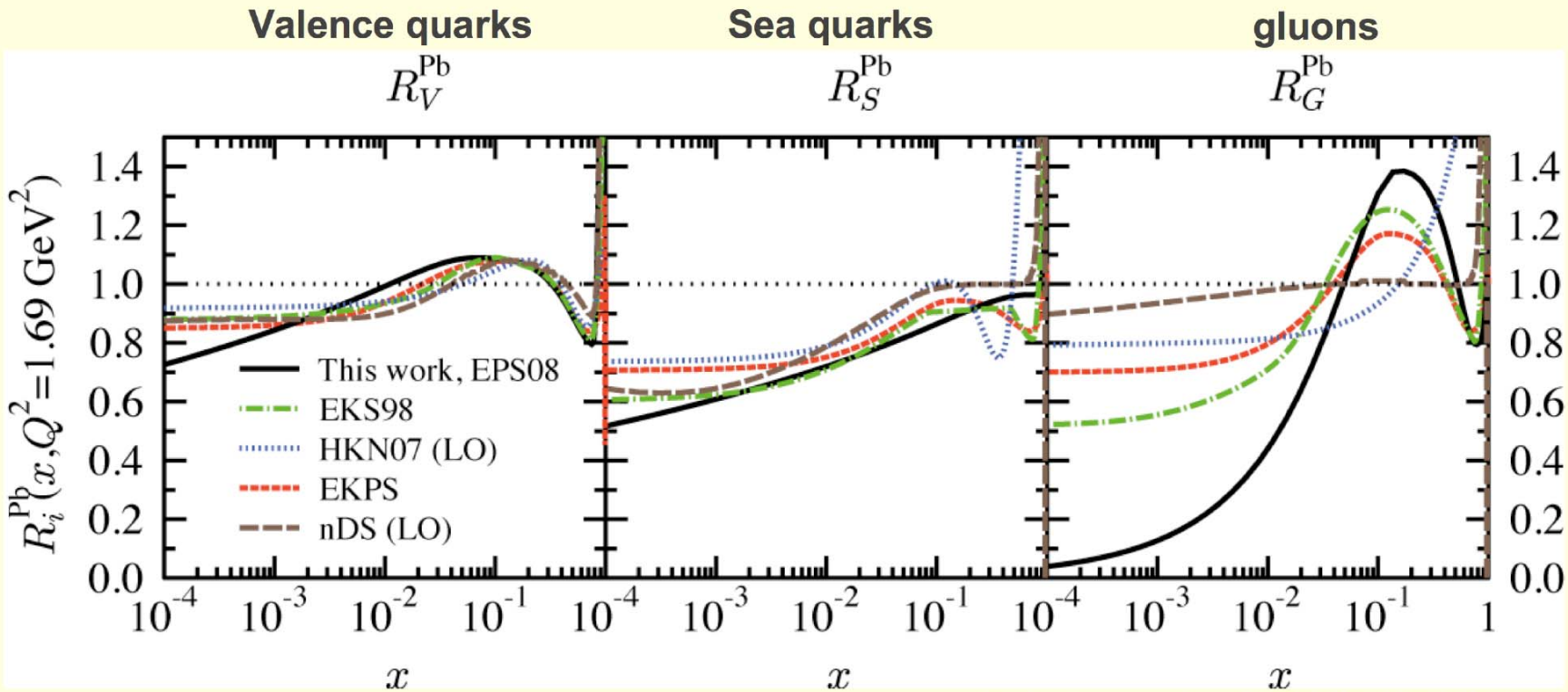
parton flavor

free proton

- **Nuclear PDF's**
  - Eskola et al. (e.g. EKS-98)
  - Hirai at al.
  - De Florian and Sassot
- **Approach**
  - Nuclear effects parameterized at fixed scale Q_0^2
  - PDFs at higher scale $Q^2 > Q_0^2$ from DGLAP evolution
- **Problem**
  - Lack of data for $x < 0.01$ and $Q^2 > 1$ GeV^2
  - Consequence: nPDF's not well constrained in this range (in particular gluon PDF's)

Comparison of Different PDF's for Lead (A = 208)

$$Q^2 = 1.69\ \mathrm{GeV}^2$$



Eskola et al., JHEP07 (2008) 102

Discrepancies for gluon PDF's critical for *x* range probed at the LHC

Multiple Mini-Jet Production and the Centrality Dependence of $dN_{ch}/d\eta$

- **Multiple mini-jet production in p+p explains**
  - Increase of $dN_{ch}/d\eta$ with $\sqrt{s}$
  - Increase of $\langle p_T \rangle$ with $\sqrt{s}$
  - Increase of $\langle p_T \rangle$ with N_{ch}
  - Violation of KNO scaling
- **Simple extrapolation to A+A: Two-Component Model**
  - Soft component: Coherent scattering → Scaling with N_{part}
  - Hard component: Incoherent scattering → Scaling with N_{coll}

$$\frac{dN_{ch}}{d\eta} = \frac{1}{2}\langle N_{part}\rangle\langle n_{soft}\rangle + \langle n_{hard}\rangle\langle N_{coll}\rangle\frac{\sigma_{hard}^{N+N}(\sqrt{s})}{\sigma_{inel}}$$

Mini-jet cross section per nucleon-nucleon collisions

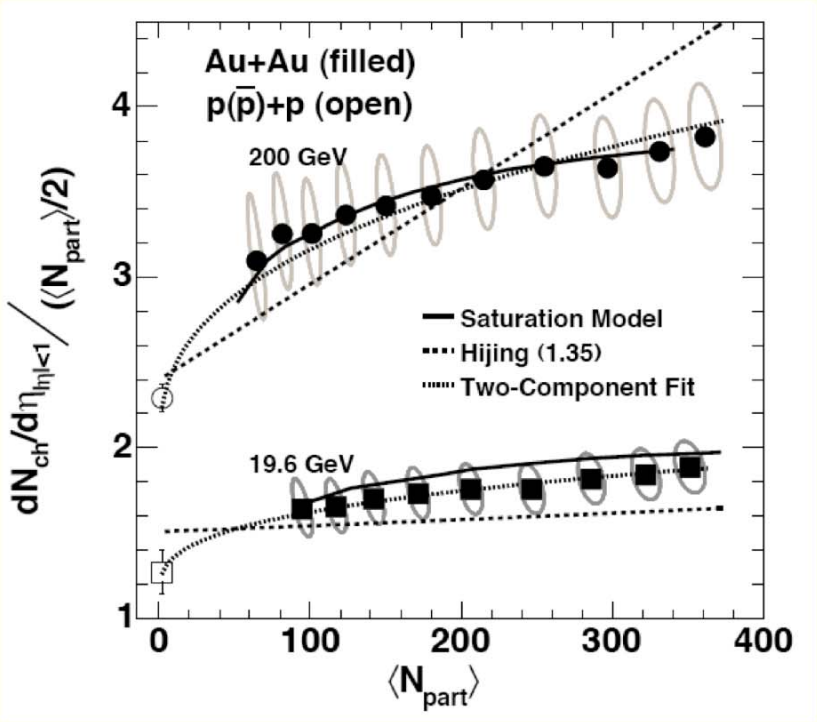
Fixed in p+p

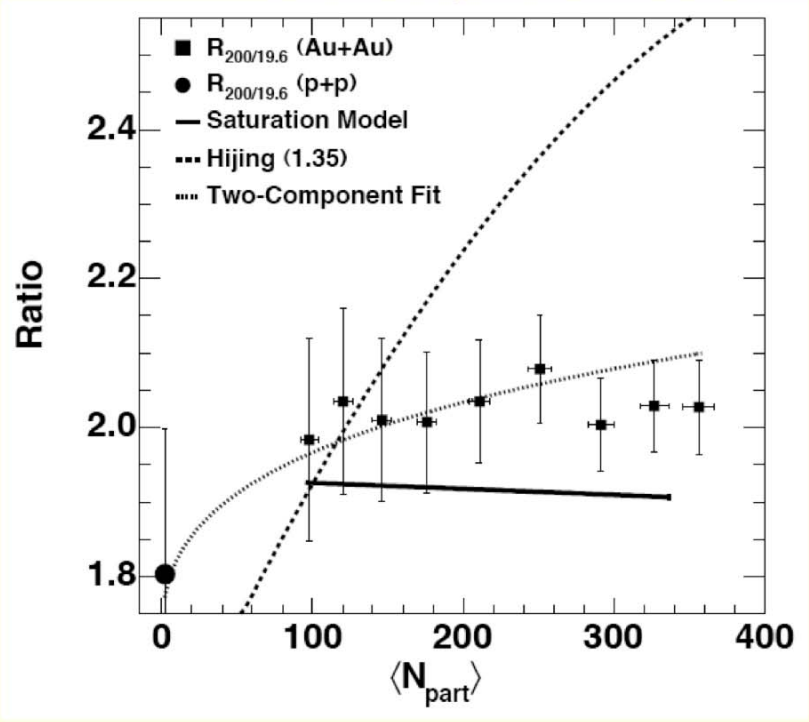
$\sigma_{hard}^{N+N}(\sqrt{s})$: Depends on lower p_T cut-off p_0. $\sqrt{s}$ independent value of p_0 = 2 GeV/c chosen in HIJING

Gyulassy, Wang, Phys. Rev. Lett. 86, 3496 (2001)

Mini-jet Model fails to Describe Centrality Dependence of $dN_{ch}/d\eta$

PHOBOS, nucl-ex/0410022

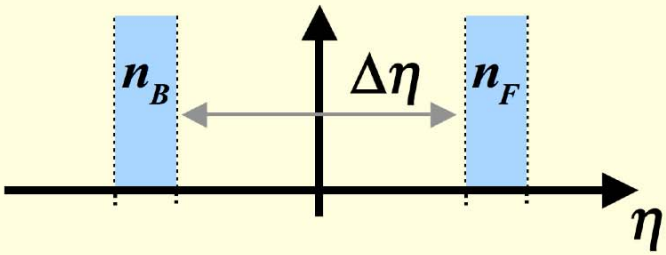


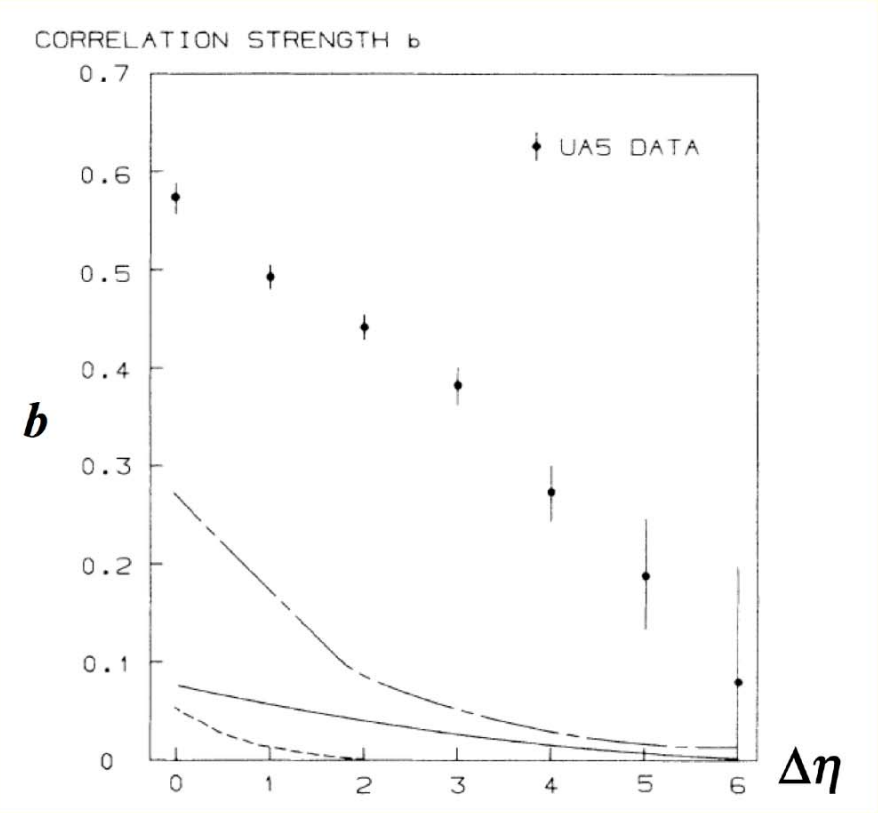


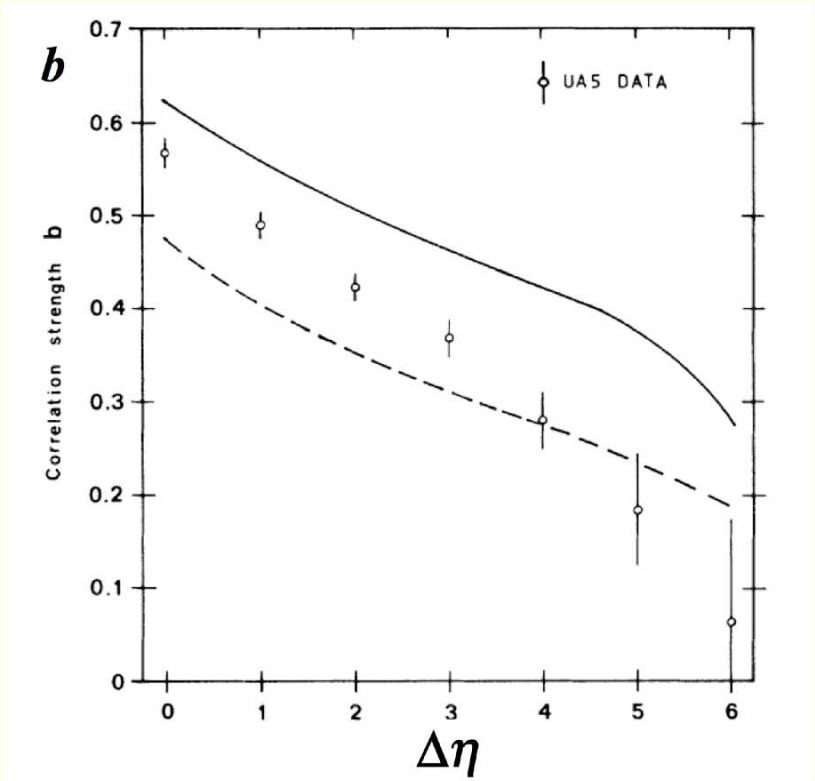
- **Mini-jet model predicts stronger rise with N_{part} at higher $\sqrt{s}$**
- **Data show: Relative increase of $dN_{ch}/d\eta$ for N_{part} > 100 identical for Au+Au at $\sqrt{s_{NN}}$ = 19.6 GeV and $\sqrt{s_{NN}}$ = 200 GeV**

Forward-Backward Correlations in p+p(bar): Explained by MPI

$$n_B = a + b \cdot n_F, \qquad b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle \langle n_B \rangle}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$





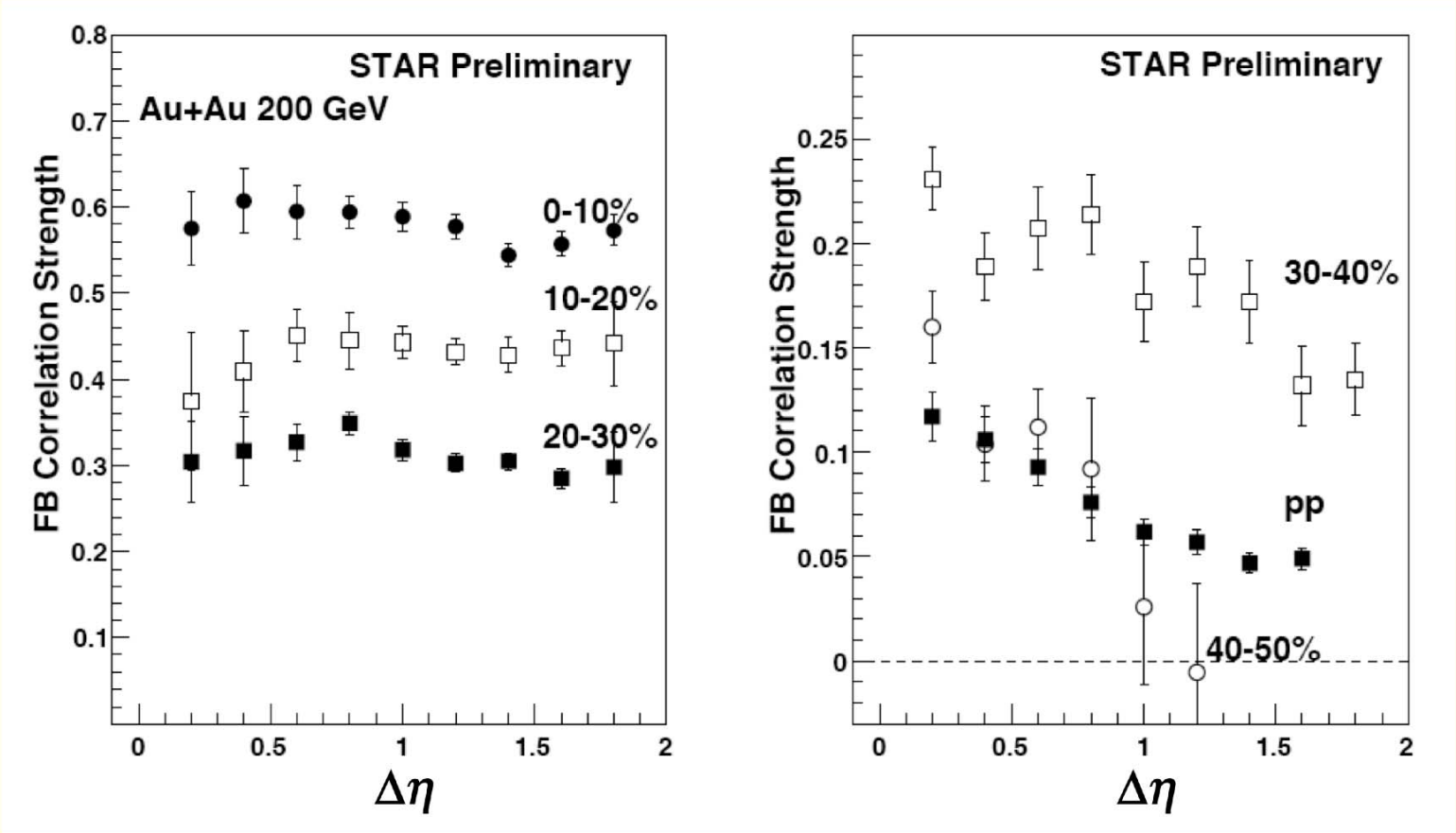


Sjöstrand, van Zijl, PRD 36, 2019 (1987)

Forward-Backward Correlations in A+A: Long Range Correlations

Westfälische Wilhelms-Universität Münster

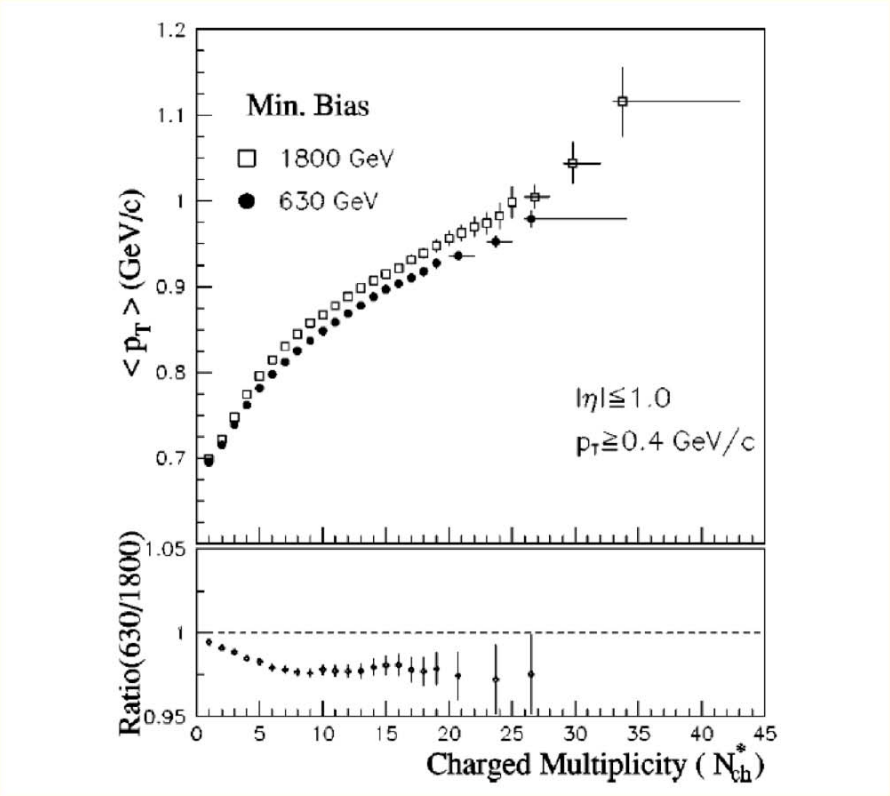
Forward-backward correlation strength *b* vs. $\Delta\eta$: **STAR, arXiv:0804.4661**



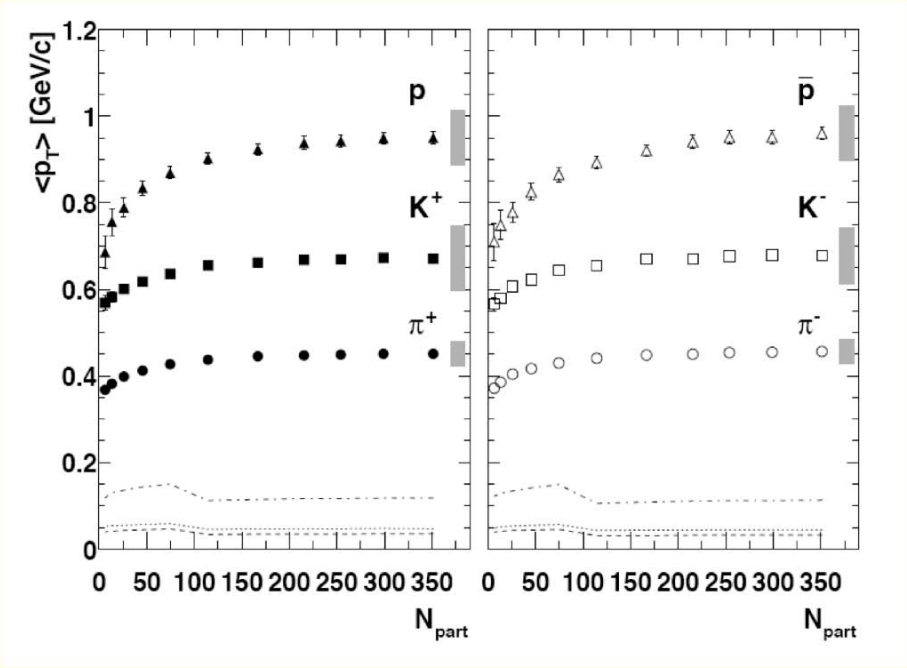
- **Correlation strength *b* flat as function of $\Delta\eta$ in central A+A**
- **Simply due to impact parameter correlation?**

$\langle p_T \rangle$ vs. "Centrality" in p+p and A+A: Similar Trend, Different Explanations (!?)

p+pbar at Tevatron



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



→ **Explained by multiple mini-jet production**

→ **Typically explained by collective radial flow**

Summary

- **High-p_T hadron suppression discovered at RHIC in central Au+Au collisions**
  - **High-p_T particle yields**
  - **Angular two-particle correlations**
- **Direct photons are not suppressed: Hadron suppression is a final state effect**
- **Interpretation: Energy loss of partons in a medium of high color-charge density ("jet quenching")**
- **It will be interesting to see whether jet-quenching even plays a role in "central" p+p collisions at the LHC**