Measurement of Large Transverse Momentum Hadrons and Constraints on Medium Opacity Parameters

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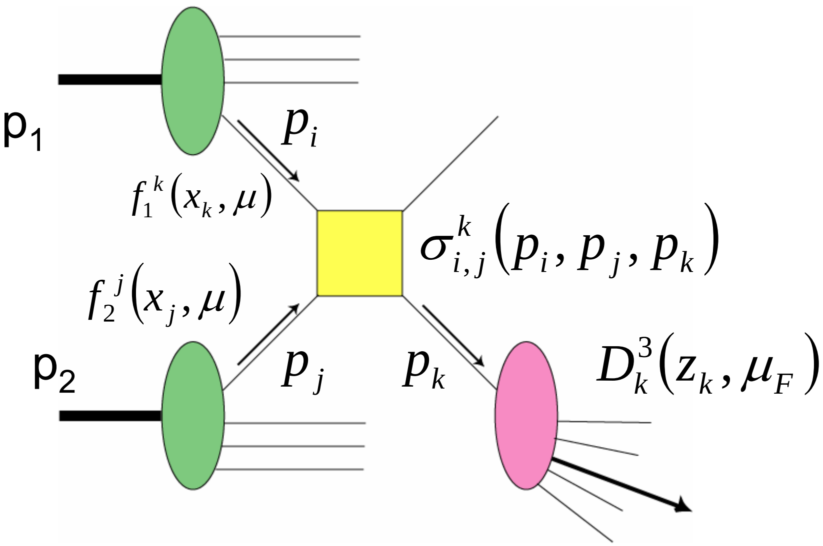
IN THE CITY OF NEW YORK

High-p_T Particle Production



PDFs

$$\sigma^3_{1+2} = \sum_{i,j,k}\int dx_i\,dx_j\,dx_k \times f_1^k(x_k,\mu)\cdot f_2^j(x_j,\mu)$$
$$\times\,\sigma^k_{i,j}\left(p_i,p_j,p_k,\alpha_s(\mu_R),Q^2/\mu_F,Q^2/\mu_F\right)$$
$$\times\,D^3_k(z_k,\mu_F)$$

Fragmentation Function

- Domain of hard scattering processes
  - Partonic collisions characterized by large Q^2 ($\sim p_T^2$)
  - Cross-sections are factorizable

High-p_T and Heavy Ion Collisions

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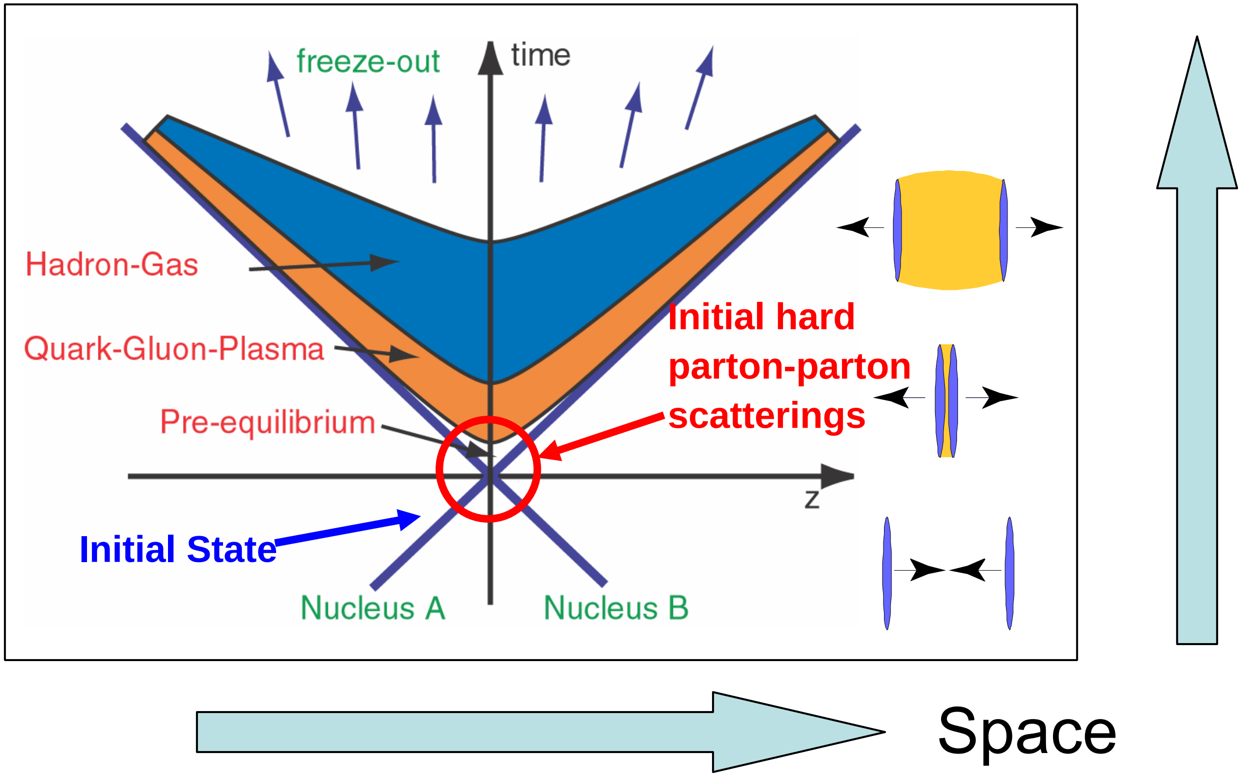
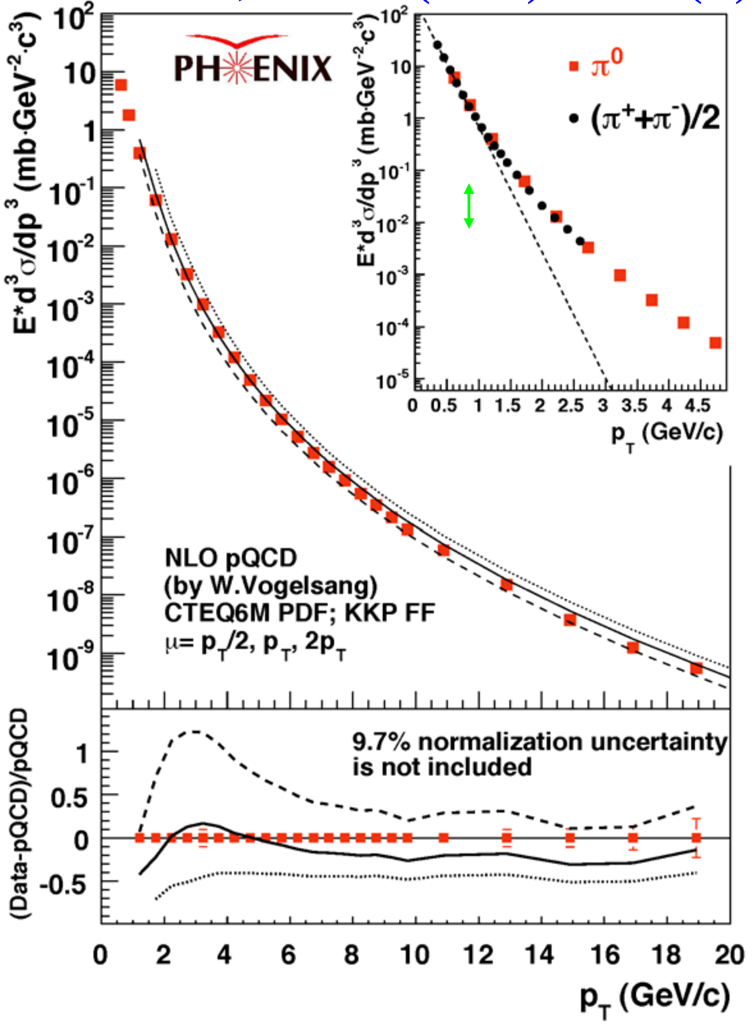
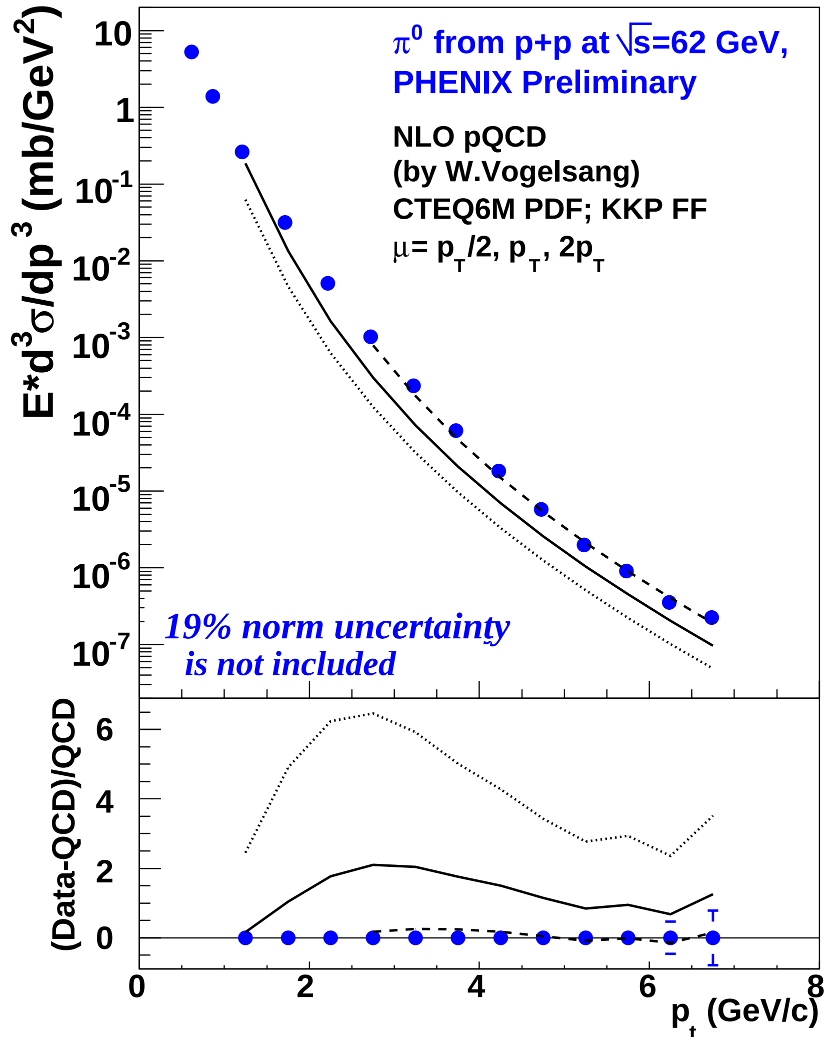


- p+p
  - Fragmentation into QCD-vacuum
- A+A
  - Occurs early in reaction phase
  - Probe for evolution of later hot and dense phase

Do we observe hard-scattering?

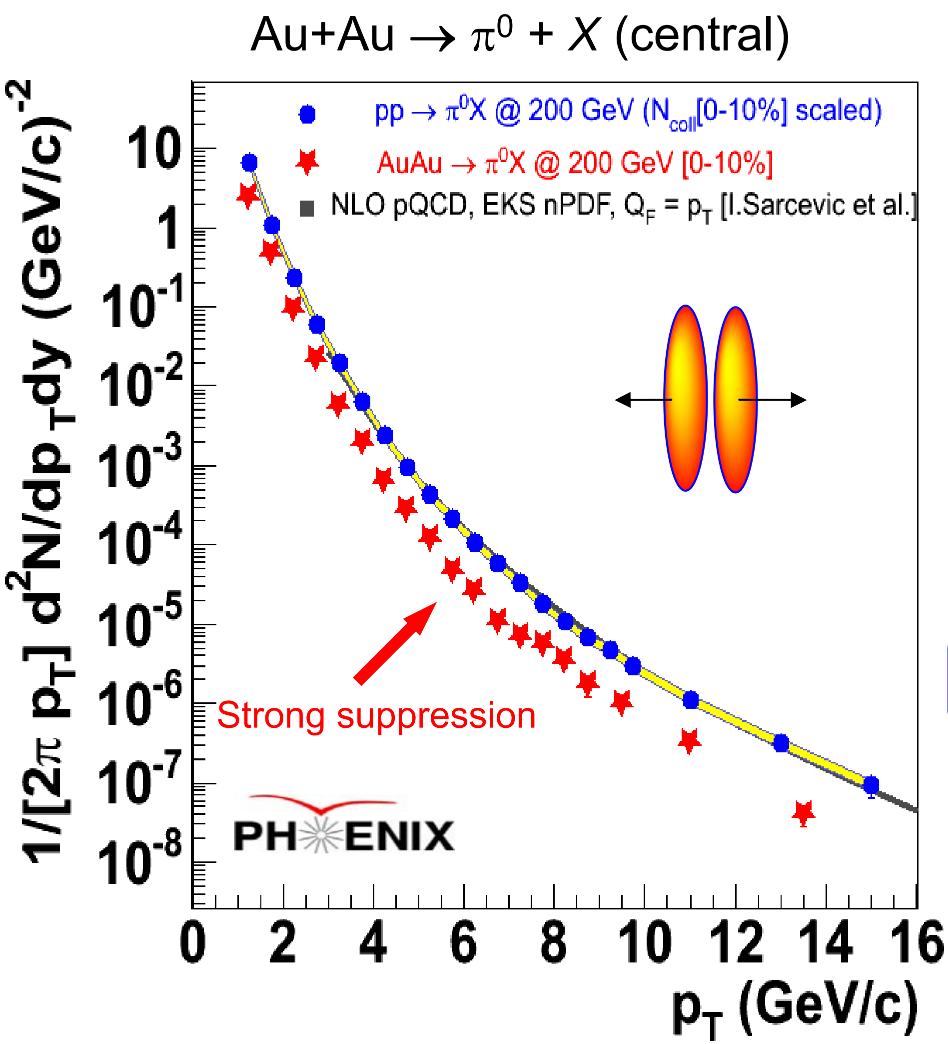
PHENIX, PRD**76**(2007)051006(R)





NLO-pQCD precision agreement!

Hard-scattered partons in Au+Au



p+p data scaled by assuming independent N+N collisions, N_{coll}, agrees well with peripheral Au+Au

Central data exhibit suppression!

Models of the Medium

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- Suppression currently attributed to:
  - Energy loss due to coherent medium-dependent gluon bremsstrahlung
  - Collisional energy loss
- Existing models:
  - Describe geometry and evolution of medium differently
  - Properties of the medium represented by a (single) parameter
- Examples:

Model	Parameter
Parton Quenching Model (PQM)	$\langle \hat{q} \rangle$ – Average 4-momentum transferred per mean free path
Wicks-Horowitz-Djordjevic-Gyulassy (WHDG)	dN^g/dy – Initial gluon density
Gyulassy-Levai-Vitev (GLV)	dN^g/dy – Initial gluon density
Zhang-Owens-Wang-Wang (ZOWW)	ε_0 – Initial energy density

High-p_T measurement with PHENIX

EMCAL --- measure energy deposit of electrons and gammas

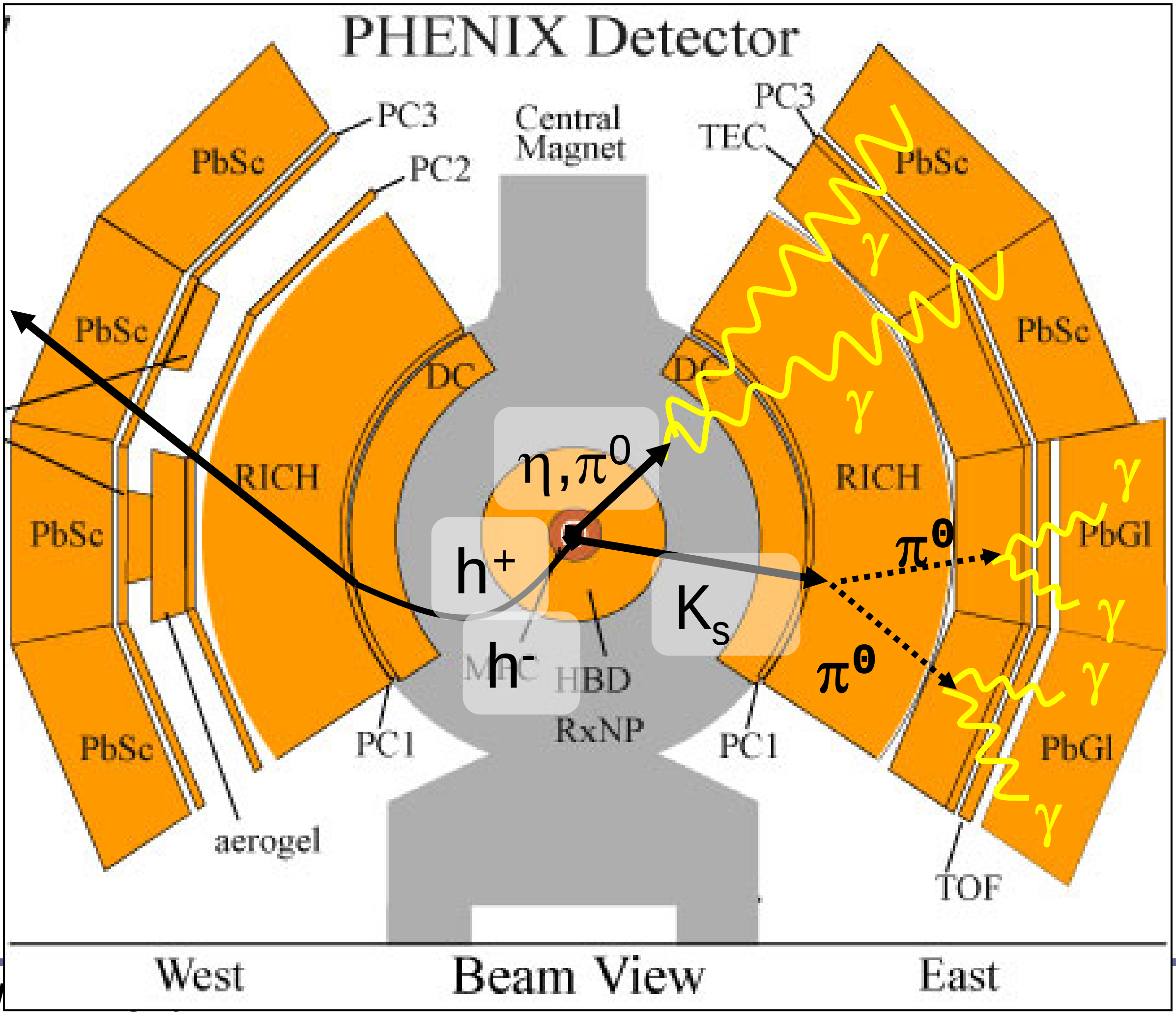
DC --- obtain momentum of charged particles

PC --- measure hit position of charged particles

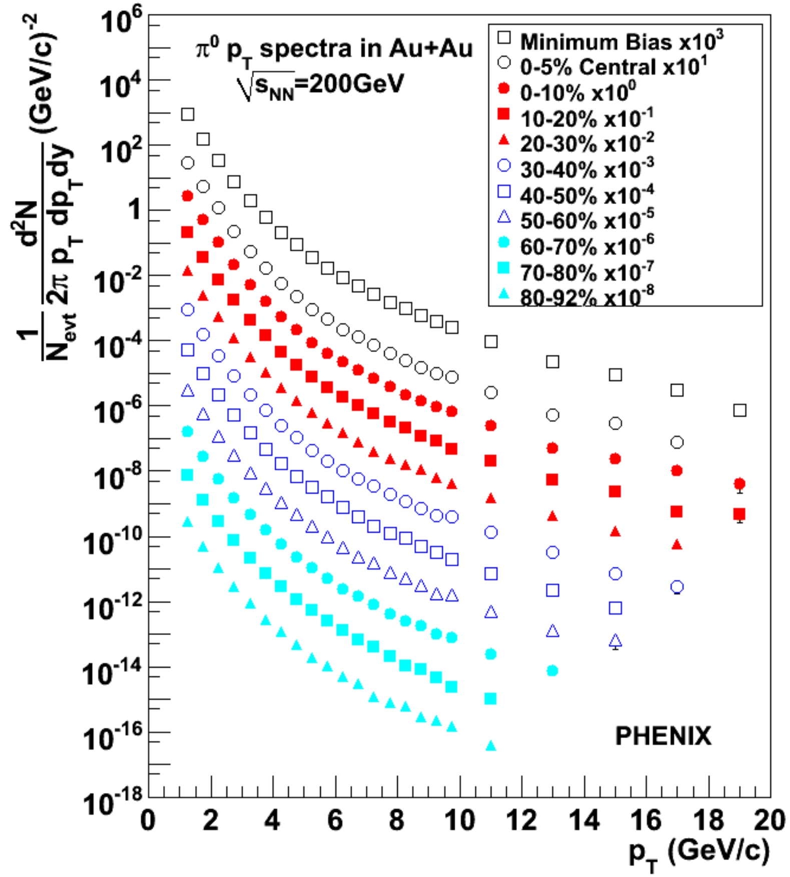
Tracking and Matching (DC, PC)
→charged hadrons

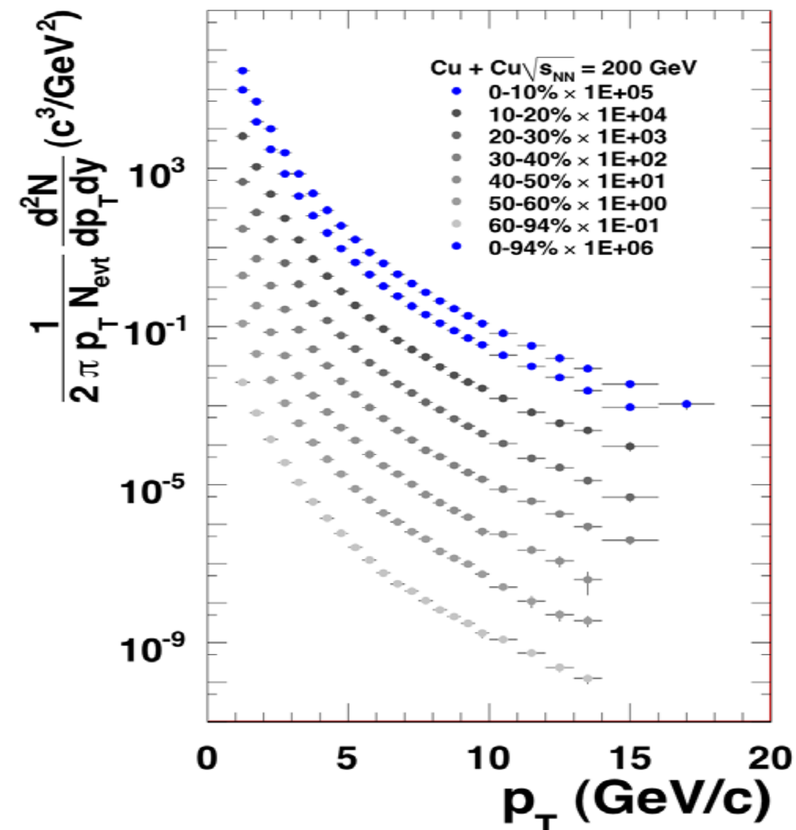
EMCAL (PbSc + PbGl)

→ η, π^0, K_s



π^0 measurement in Au+Au and Cu+Cu





RHIC Run4 Au+Au data

- Sampled 241 μb^{-1}
- 197^2 x 241 μb^{-1} ~ 1 pb^{-1} p+p equivalent
- 1.5 B events recorded

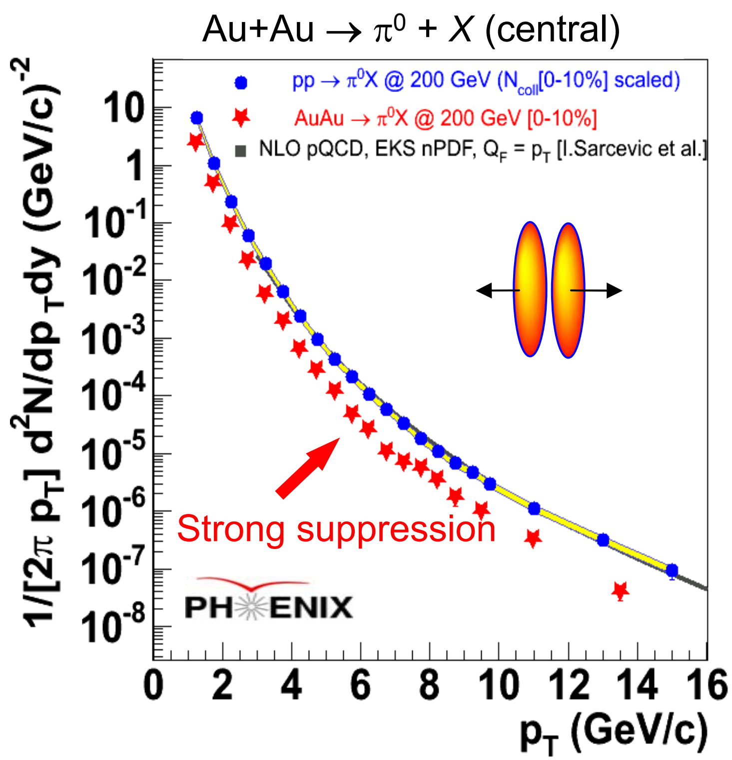
RHIC Run5 Cu+Cu data

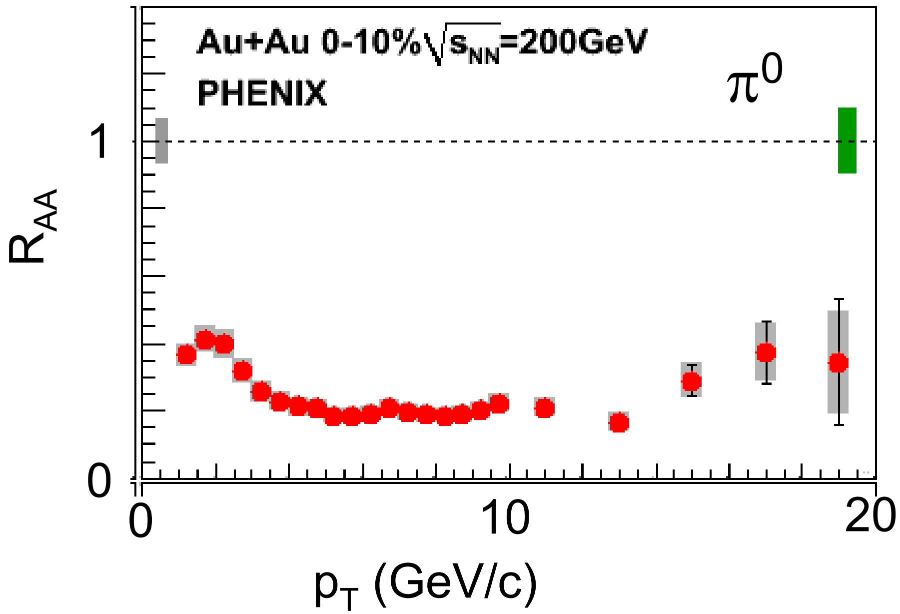
- Sampled 3 nb^{-1}
- 63^2 x 3 nb^{-1} ~ 1 pb^{-1} p+p equivalent
- 2.2 B events sampled
  - 59 M minimum bias events
  - 1.9 M high-p_T triggered

R_{AA} – Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{1/N_{evts}\, d^2N/dydp_T}{\langle T_{AB}\rangle d^2\sigma_{pp}/dydp_T}$$

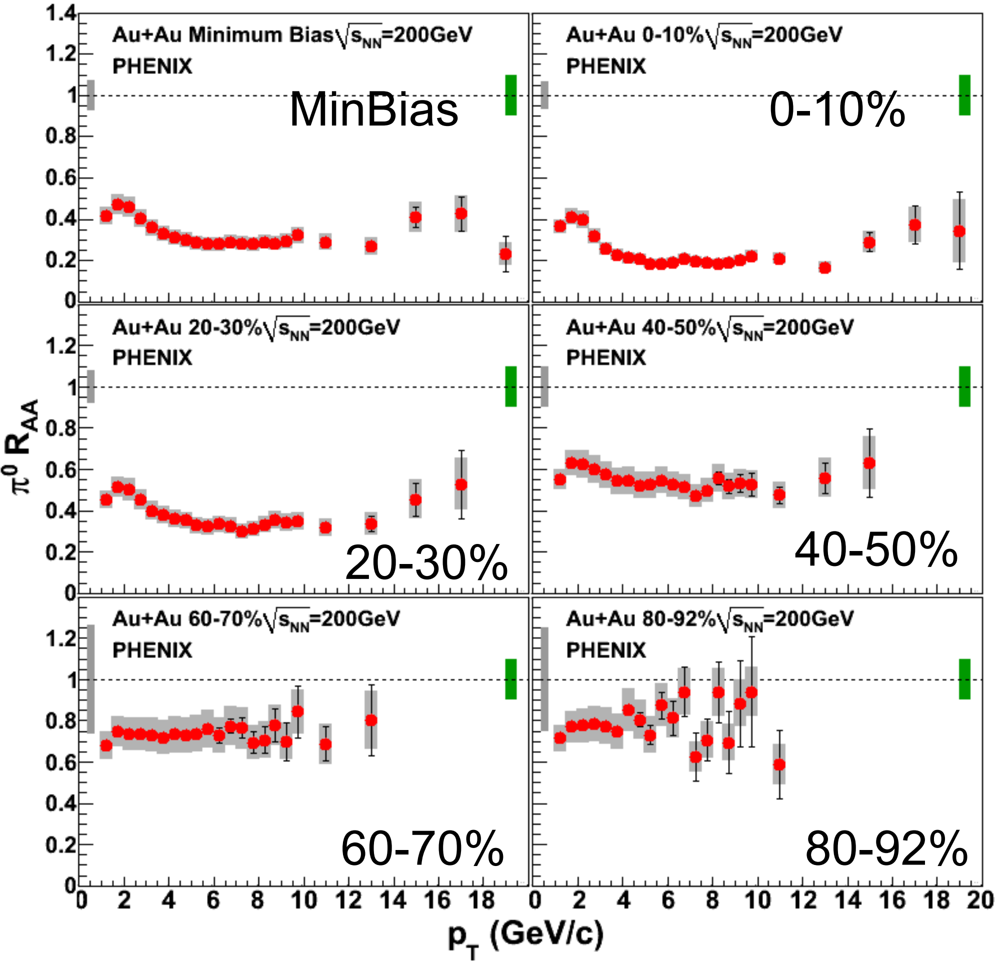
$$R_{AA}(p_T) = \frac{\text{Measured yield in A + A}}{\text{Expectation for indep. N + N scatterings}}$$

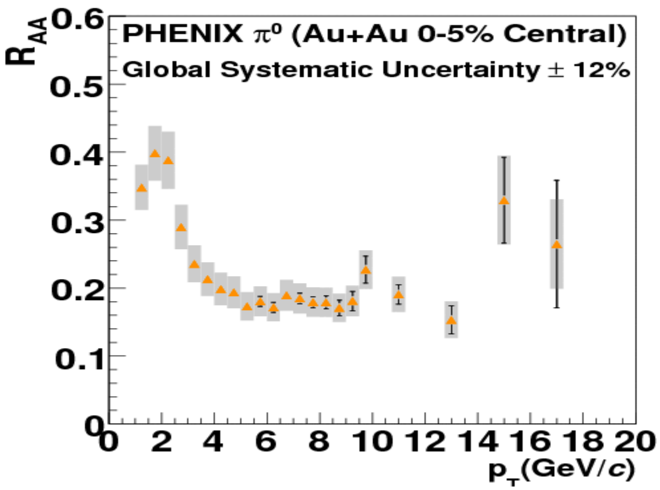




- R_{AA} ~ 0.2 for p_T > 5.0 GeV/c

R_{AA} measurement in PHENIX





0-5%

- Little if any p_T dependence
  - Consistent with most energy loss models, except where semi-opaque medium assumed
- Suppression pattern similar across centralities
  - Sensitive only to N_{part} (not geometry)?

arXiv:0801.4020

R_{AA} and Energy Loss

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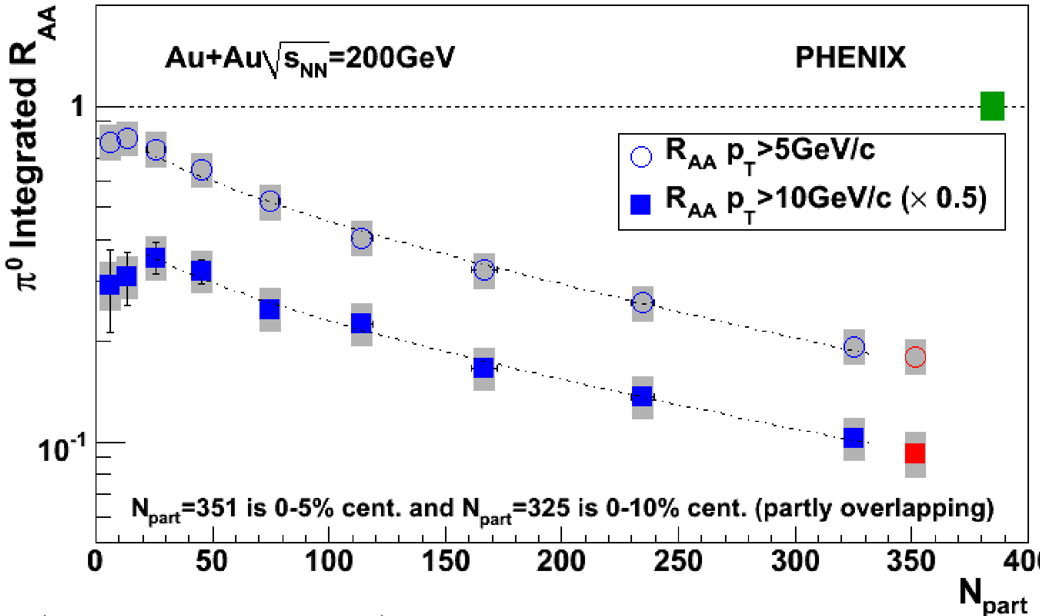
p+p and Au+Au both power law p_T>5
Reinterpret suppression as a effective fractional energy loss S_{loss}:

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

$$\propto N_{part}^{a}$$



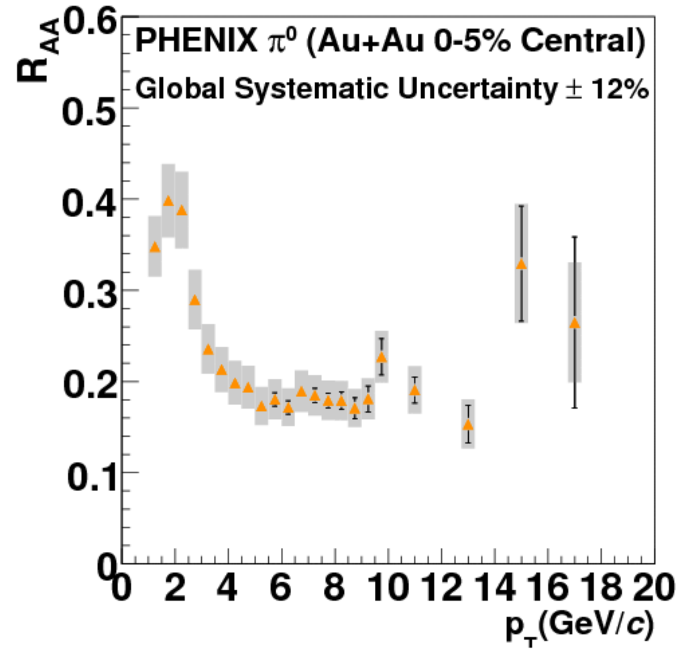
Fit N_{part} dependence: $$R_{AA} = \left(1 - S_0 N_{part}^{a}\right)^{n-2}$$

- p_T>5 : a = 0.58±0.07, S_0 = (8.3±3.3)x10^{-3}
- p_T>10 : a = 0.56±0.10, S_0 = (9.2±4.9)x10^{-3}
- GLV & PQM predict a ≈ 2/3
- R_{AA} vs. centrality does not saturate

Energy loss increases with p_T

Quantitative Analysis

- Fit the data by varying the model parameters, and determine the most likely range of values (at 1σ and 2σ levels)
- Careful categorization of uncertainties
  - "Type A": point-to-point uncorrelated [err bars]
  - "Type B": point-to-point correlated [boxes]
  - "Type C": globally correlated (normalization factors)



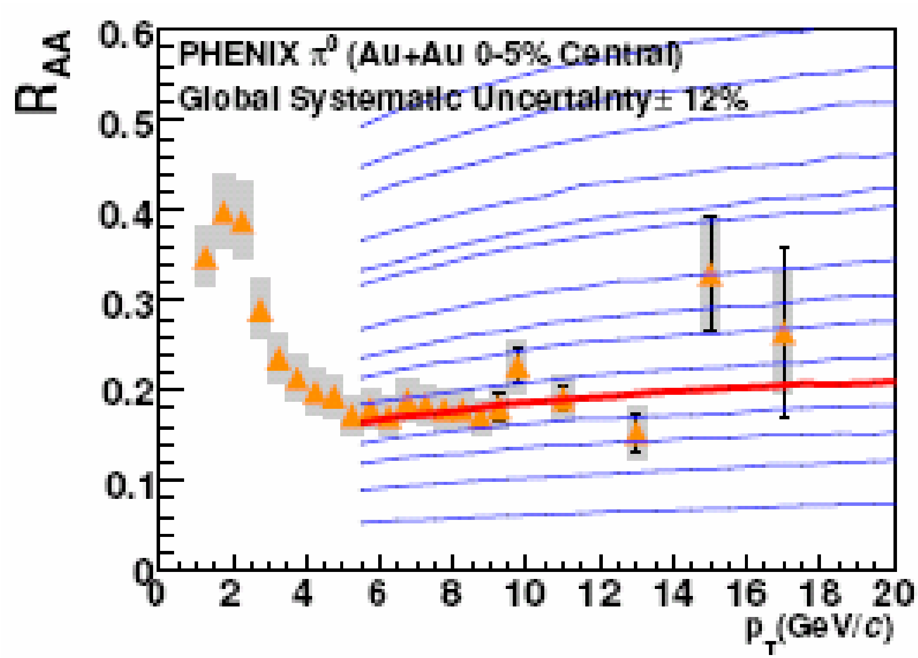
$$\tilde{\chi}^2(\epsilon_b, \epsilon_c, p) = \left[\sum_{i=1}^{n} \frac{(y_i + \epsilon_b \sigma_{b_i} + \epsilon_c y_i \sigma_c - \mu_i(p))^2}{\tilde{\sigma}_i^2} + \epsilon_b^2 + \epsilon_c^2 \right]$$

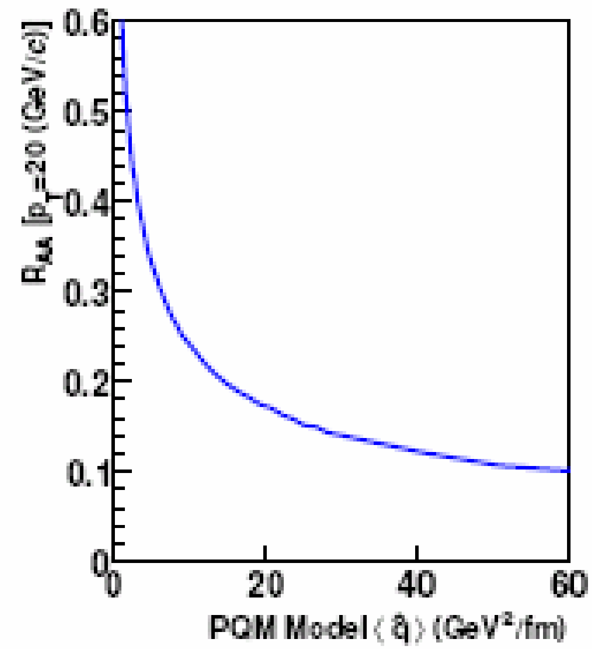
$$\tilde{\sigma}_i = \sigma_i (y_i + \epsilon_b \sigma_{b_i} + \epsilon_c y_i \sigma_c) / y_i$$

NB: Includes only experimental uncertainties!

Example: PQM and transport coeff

PRC77 064907 (2008)





- Monte Carlo using quenching weights from BDMPS
  - Realistic geometry and static medium
  - No initial-state mult. scattering or modified PDFs
- q-hat = color charge density × parton-medium cross-section
- <q-hat>: measure of average squared p_T transferred from parton to medium

PQM: constraints at 1 and 2 σ

(Fairly) Clear min in the modified χ^2:

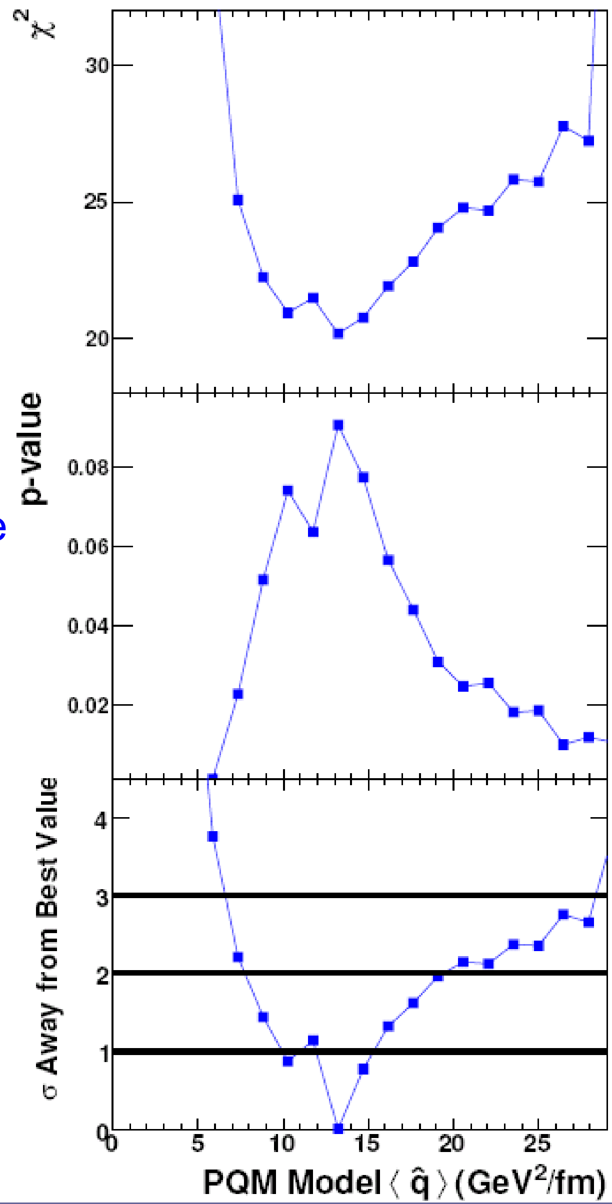
$$\tilde{\chi}^2(\epsilon_b, \epsilon_c, p) = \left[\sum_{i=1}^{n} \frac{(y_i + \epsilon_b \sigma_{b_i} + \epsilon_c y_i \sigma_c - \mu_i(p))^2}{\tilde{\sigma}_i^2} + \epsilon_b^2 + \epsilon_c^2 \right]$$

$$\text{p-value} = \int_{\tilde{\chi}^2}^{\infty} \chi^2_{(n_d)}(z)\,dz$$

Given infinite identical experiments, fraction of experiments having a worse χ^2 than real experiment

$$\langle \hat{q} \rangle = 13.2 \begin{matrix} +2.1 \\ -3.2 \end{matrix} \quad \begin{matrix} +6.3 \\ -5.2 \end{matrix} \ \text{GeV}^2/\text{fm}$$

(1 and 2 standard deviations)



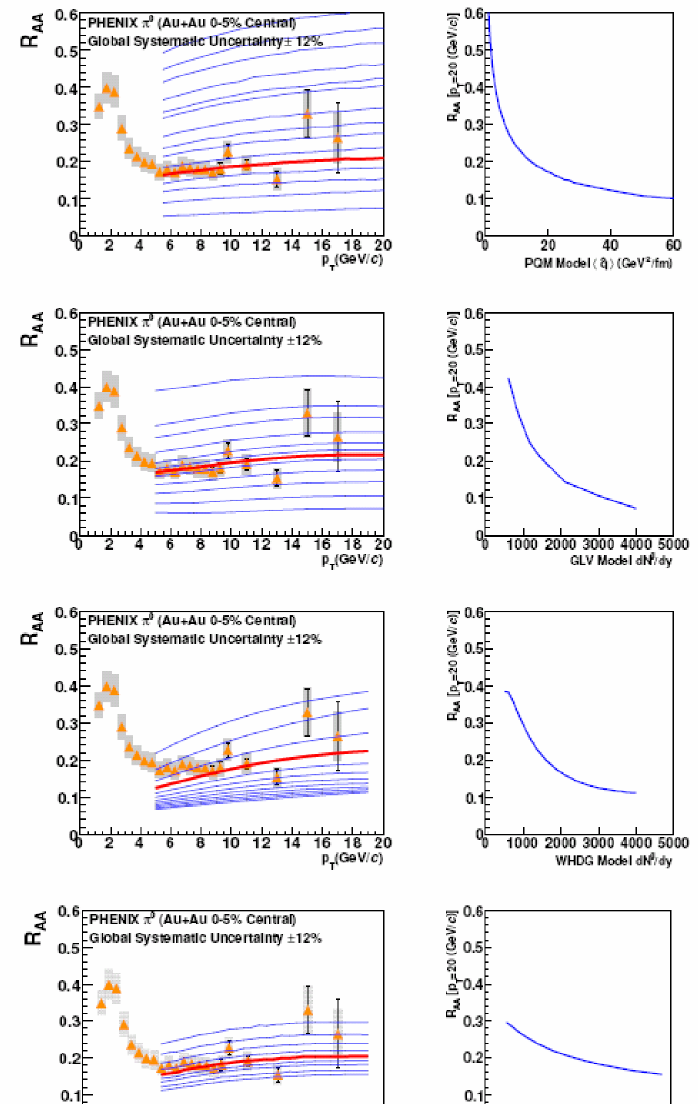
Summary of Constraints

PQM $\langle\hat{q}\rangle = 13.2 \,^{+2.1}_{-3.2}$ GeV^2/fm

GLV $dN^g/dy = 1400 \,^{+270}_{-150}$

WHDG $dN^g/dy = 1400 \,^{+200}_{-375}$

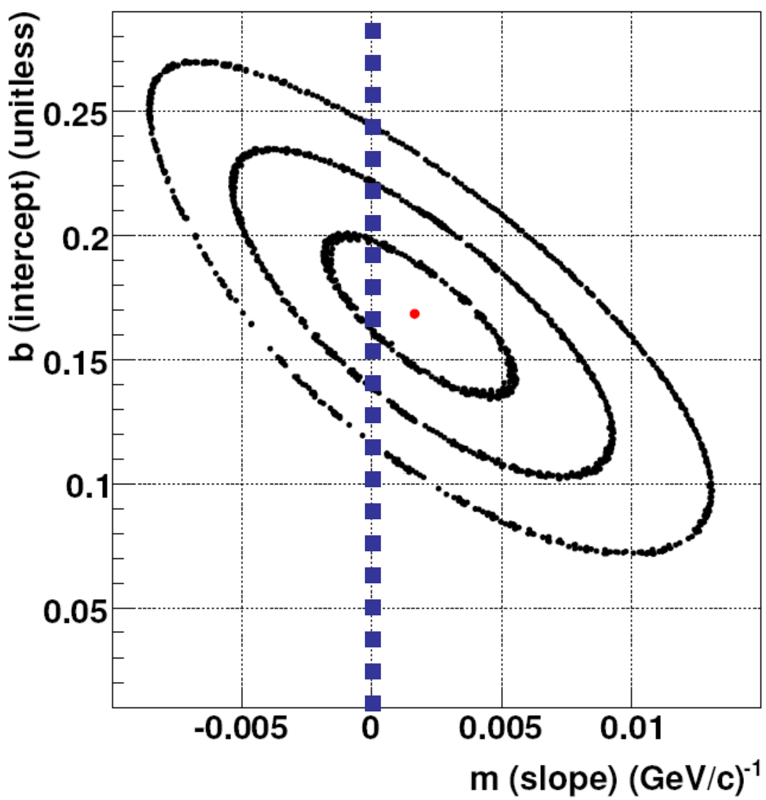
ZOWW $\varepsilon_0 = 1.9 \,^{+0.2}_{-0.5}$ GeV/fm

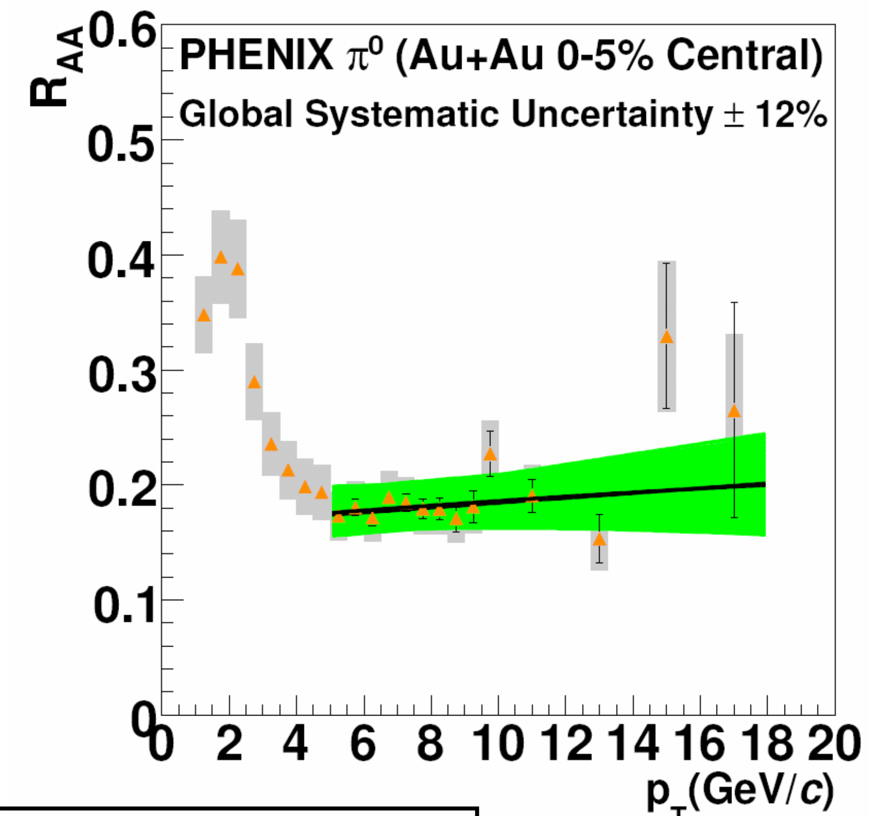


- Assumes perfect model with a single

All parameters are constrained to 10-20% at 1 std dev!

What about a simpler approach?





$$\boxed{\text{Slope } m = 0.0017 \begin{matrix} +0.0035 & +0.0070 \\ -0.0039 & -0.0076 \end{matrix}}$$

- Basically consistent with flat R_{AA} within one std dev contour
- Indicates energy loss proportional to p_T

Summary

- PHENIX has measured high-p_T hadrons in Au+Au 200 GeV collisions with unprecedented statistics and precision
  - π^0s over $1 < p_T < 20$ GeV/c
  - Most central $R_{AA} \sim 0.2$ (above $p_T = 5$ GeV/c) and constant to highest p_T
- R_{AA} suggests energy loss is proportional to p_T
  - Essentially constant in p_T (for p_T>5 GeV/c)
  - Integrated R_{AA} does not saturate with N_{part}
  - Data is consistent with predicted $S_{loss} \propto N^a_{part}$
  - High-p_T spectra follows same power law from p+p to Au+Au ($n \approx 8.1$)
- Unprecedented ability to constrain models
  - Quantitative analysis using complete set of experimental uncertainties
    - Eg. <q-hat> = 13.2 +2.1 -3.2 (PQM)
    - Eg. dN^g/dy = 1400 +270 -150 (GLV)

10 – 20 % level!