PHENIX High-p_T Results

Hard Probes of Nuclear Collisions at RHIC

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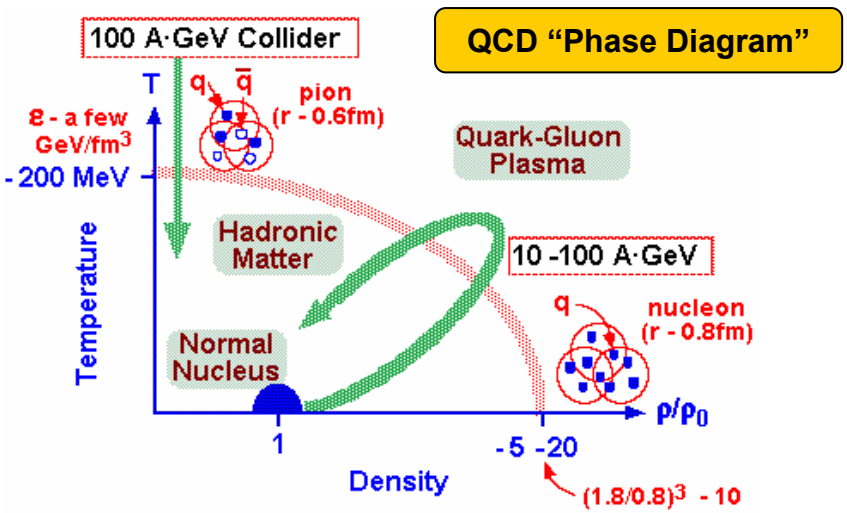
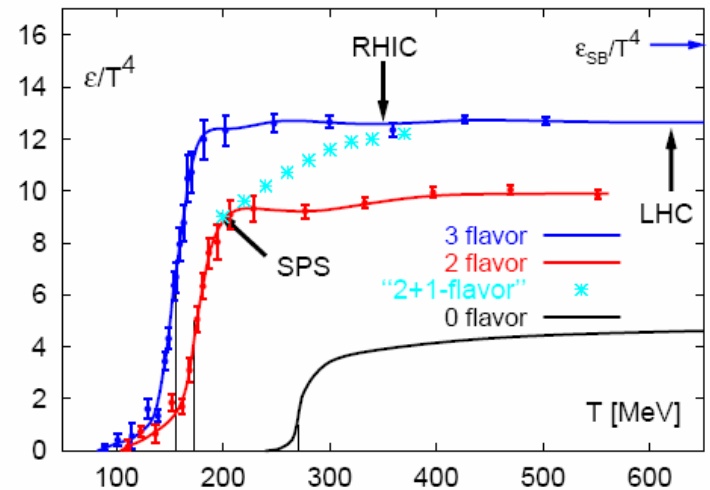
Outline

- Physics Motivation
  - Why High-p_T is important to Heavy-Ion Collisions
- Measuring High-p_T production
  - The PHENIX detector
  - Calibrated measurements
- Results
  - Single-particle spectra
    - Inclusive R_{AA} for Au+Au and Cu+Cu
  - Differential measurements
    - R_{AA} with respect to the Reaction Plane
    - Jets/di-hadron correlations
- Summary

The Case for Relativistic Heavy-Ion Collisions

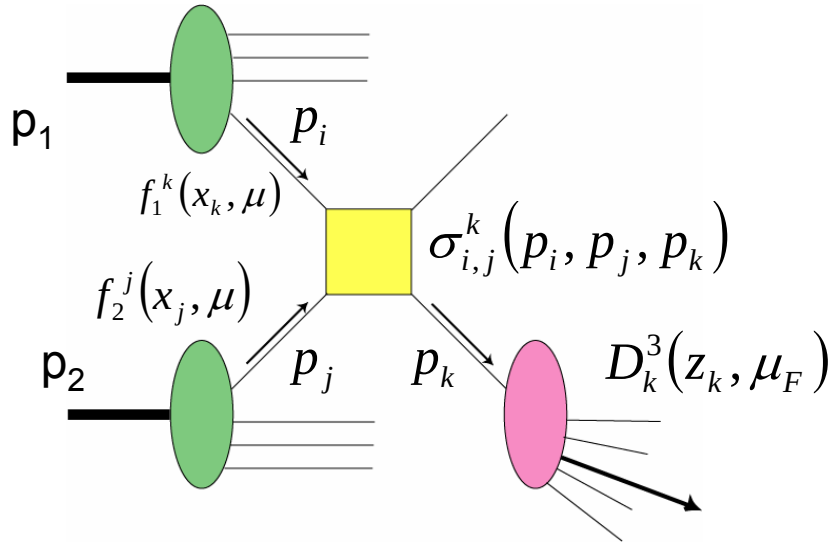




F. Karsch, Prog. Theor. Phys. Suppl. 153, 106 (2004)

- Seeking the Quark Gluon Plasma (QGP)
  - Existed early in the universe
  - Expected to be created in RHIC collisions
- Lattice QCD predicts a transition to the QGP
  - T ~ 170 MeV
  - ε ~ 1.0 GeV/fm^3
- For QGP, strong interaction plays critical role
  - Deconfinement of quarks and gluons
  - Need to study properties and dynamics of this strongly interacting system

Why high-p_T?

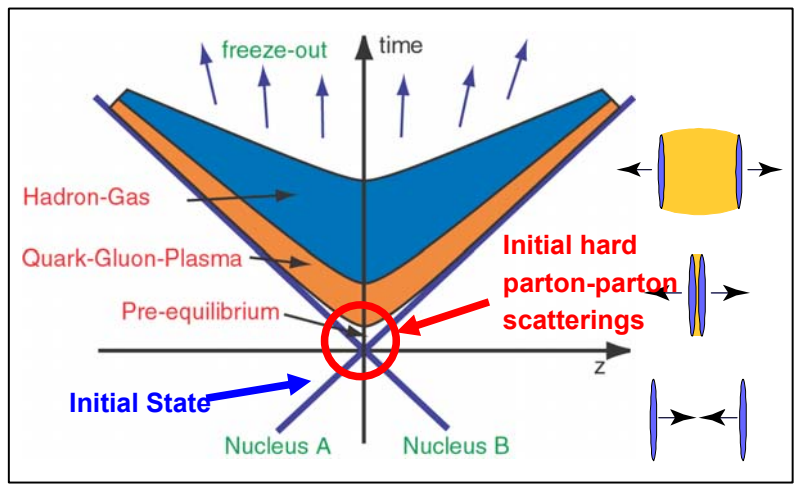


PDFs

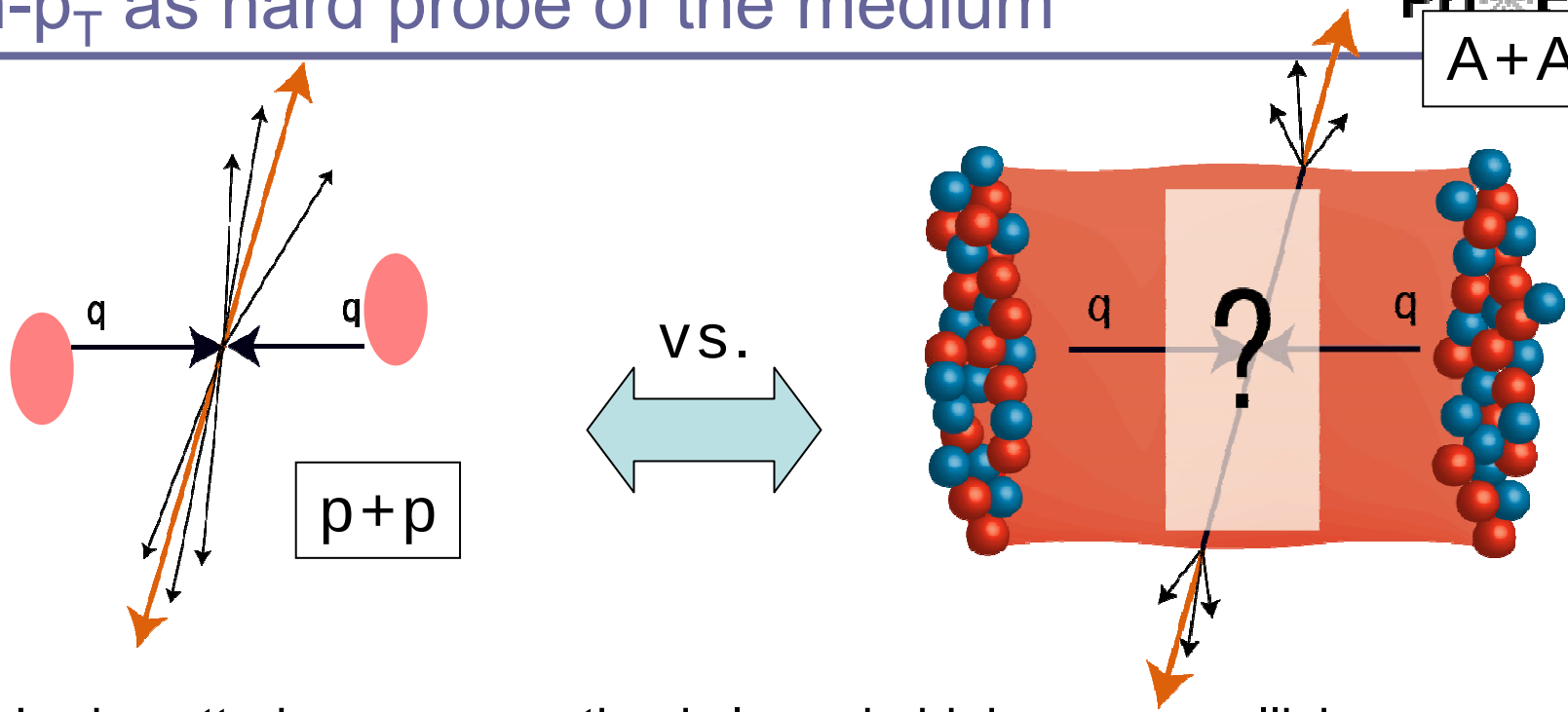
$$\sigma_{1+2}^3 = \sum_{i,j,k}\int dx_i dx_j dx_k \times f_1^k(x_k,\mu)\cdot f_2^j(x_j,\mu) \times \sigma_{i,j}^k\left(p_i,p_j,p_k,\alpha_s(\mu_R),Q^2/\mu_F,Q^2/\mu_F\right) \times D_k^3(z_k,\mu_F)$$

Fragmentation Function

- Domain of hard scattering processes
  - Partonic collisions are characterized by large Q^2 (~p_T^2)
  - Cross-sections are factorizable
- p+p
  - Fragmentation into QCD-vacuum
- A+A
  - Occurs early in reaction phase
  - Probe for evolution of later hot and dense phase



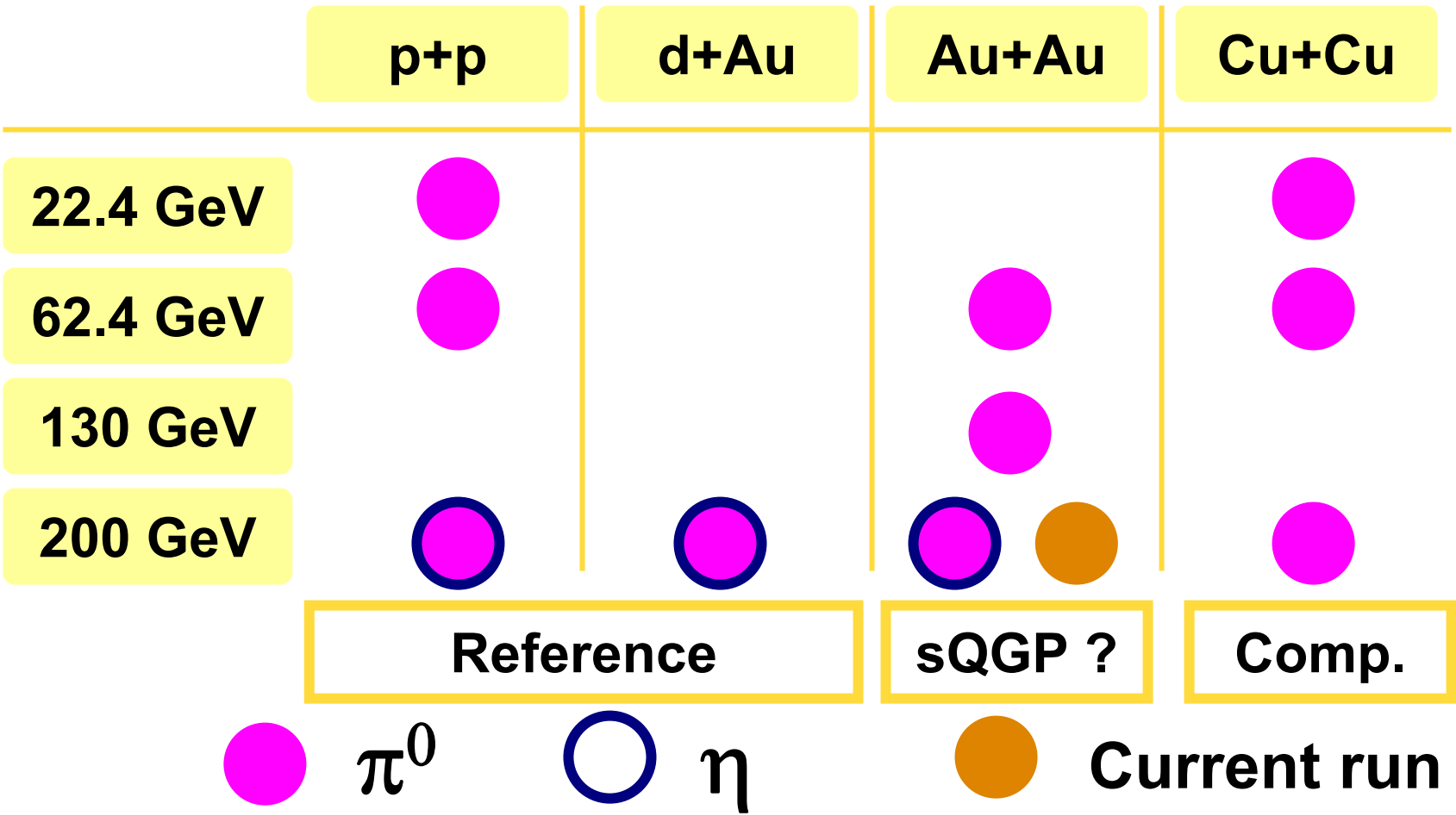
High-p_T as hard probe of the medium



- Hard-scattering cross-section is large in high energy collisions
- Initial yields and p_T distributions can be predicted from p+p measurements + pQCD + collision geometry + cold (initial) nuclear effects
  - Critical to perform measurements in reference p+p and p(d)+A systems
- Observed deviations from reference measurements can be attributed to the medium
- Need observables that can shed insight even with large BG (dN/dy ~ 700)

Summary of high-p_T data in PHENIX

- π^0, η (and γ) important sources of information
  - They are identified particles
  - Test different aspects of the medium
  - Highest p_T reach of all measured particles



High-p_T measurement with the PHENIX Detector

EMCAL --- measure energy deposit of electrons and gammas

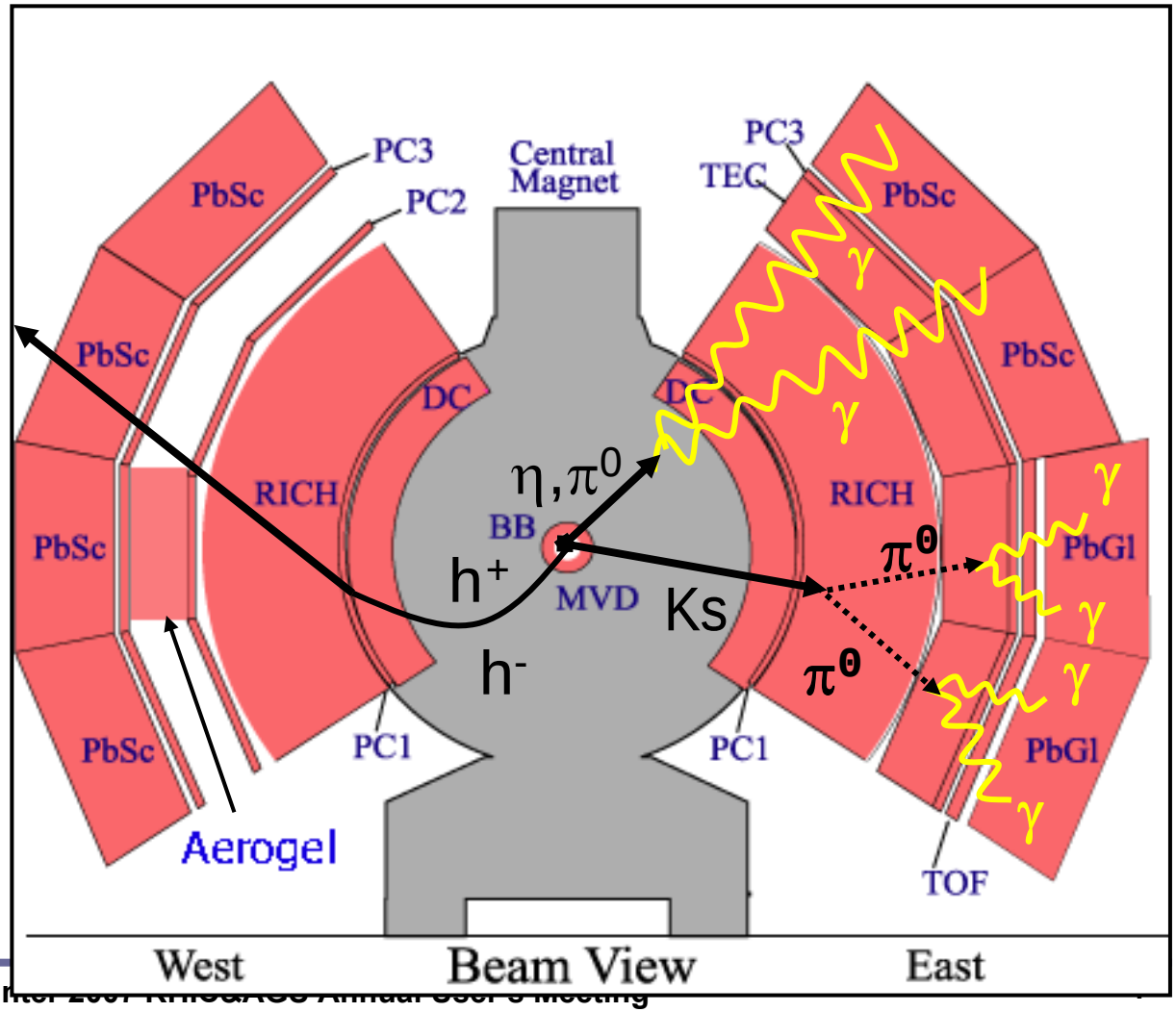
DC --- obtain momentum of charged particles

PC --- measure hit position of charged particles

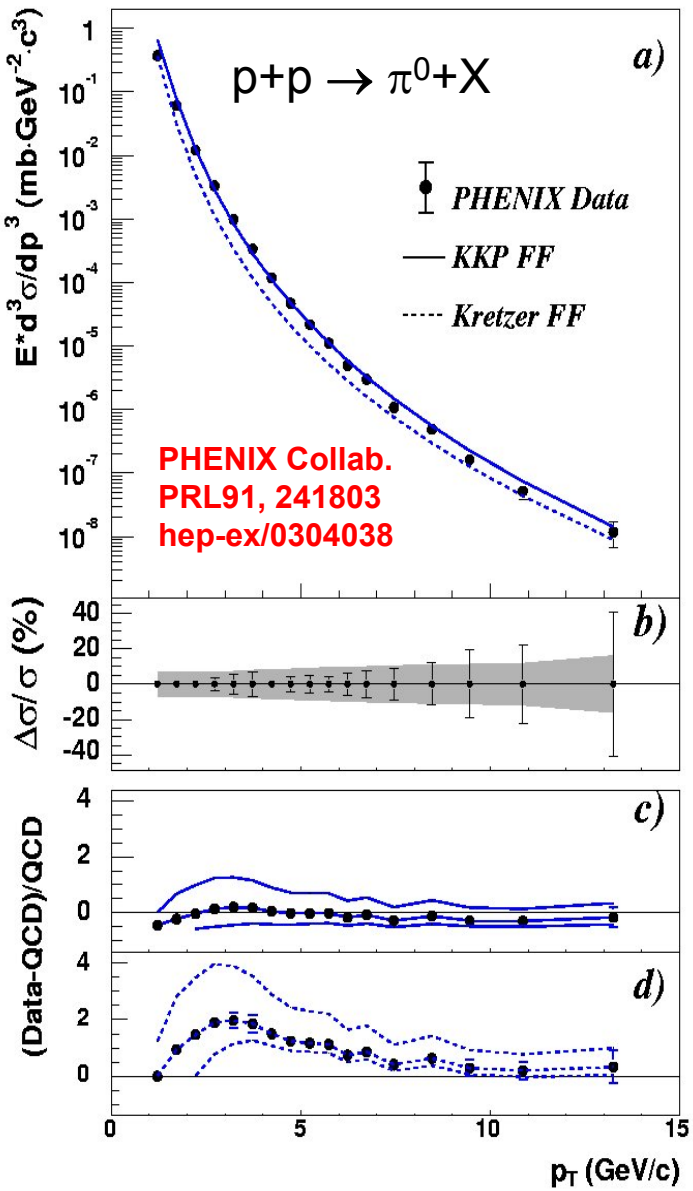
Tracking and Matching (DC, PC)
→charged hadrons

EMCAL (PbSc + PbGl)

→η,π^0,Ks

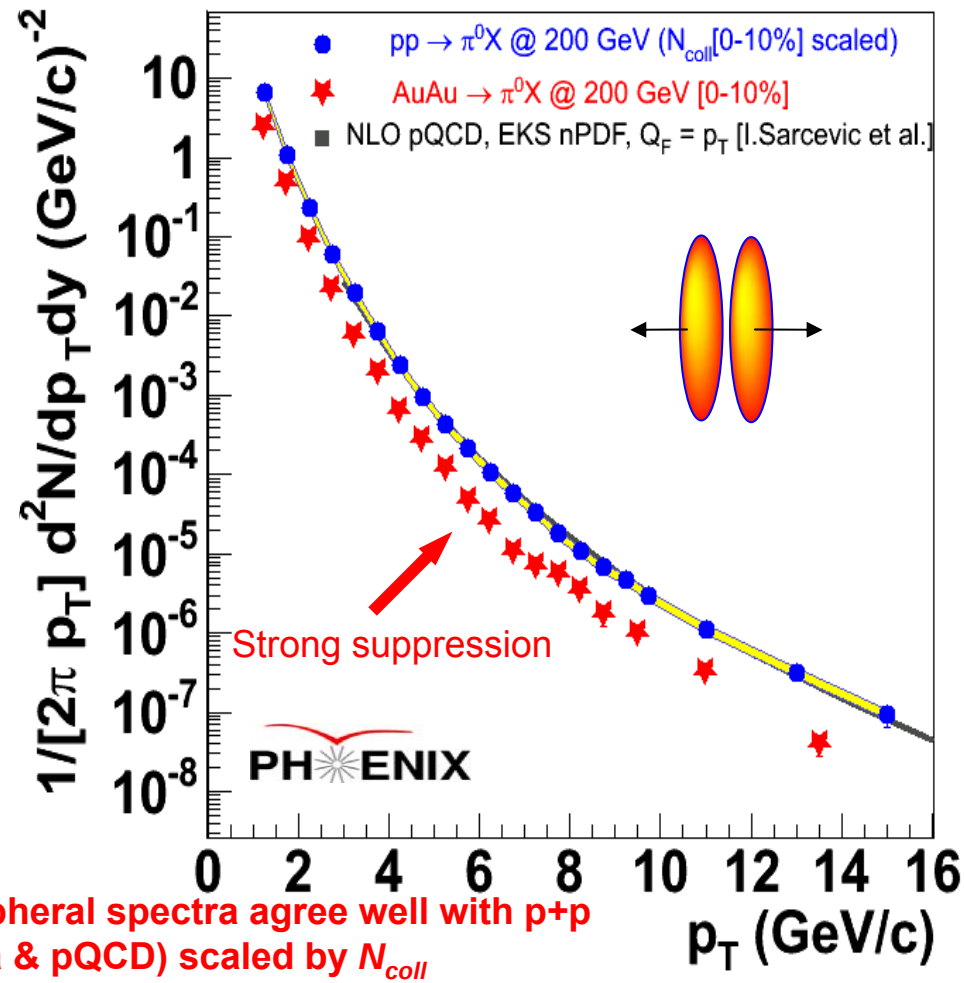


Do we observe hard-scattering?



- Single-particle spectrum and QCD predictions

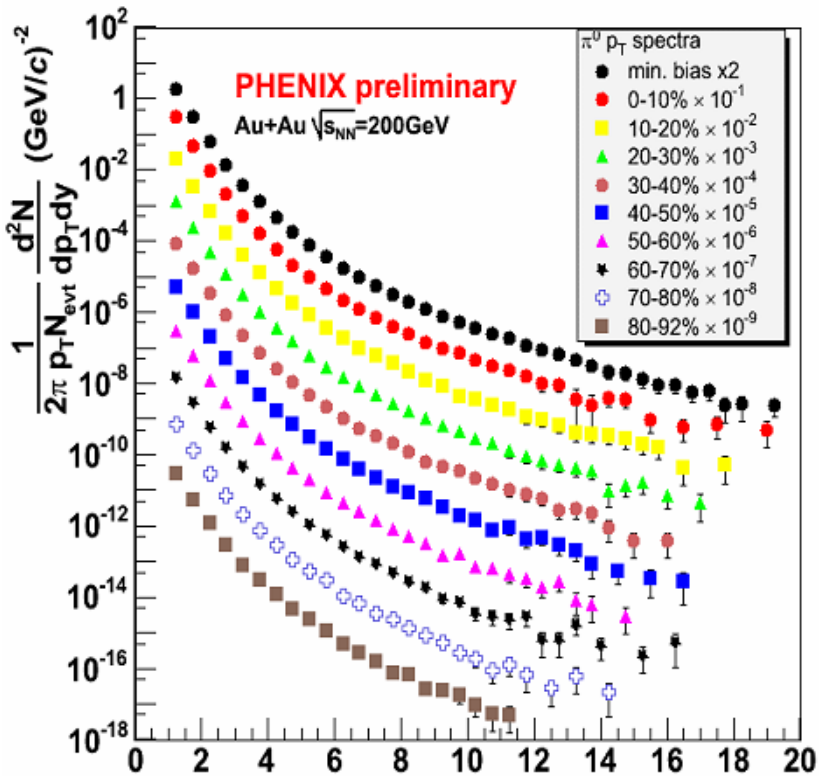
Au+Au → π^0 + *X* (central)

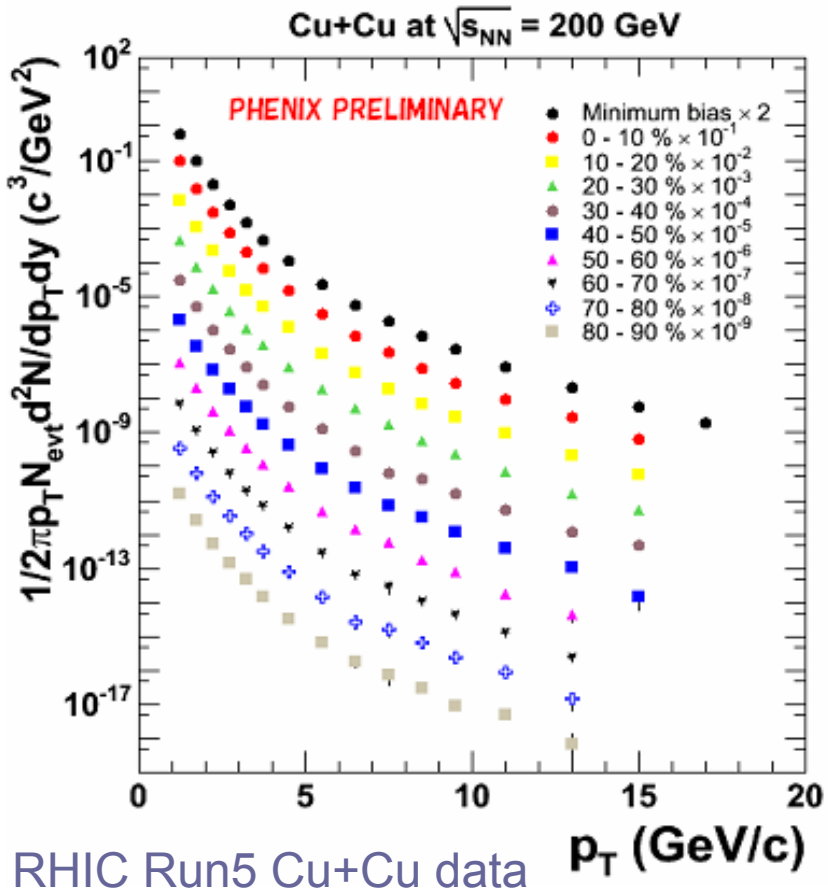


Peripheral spectra agree well with p+p (data & pQCD) scaled by N_{coll}

Central data exhibits suppression!

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

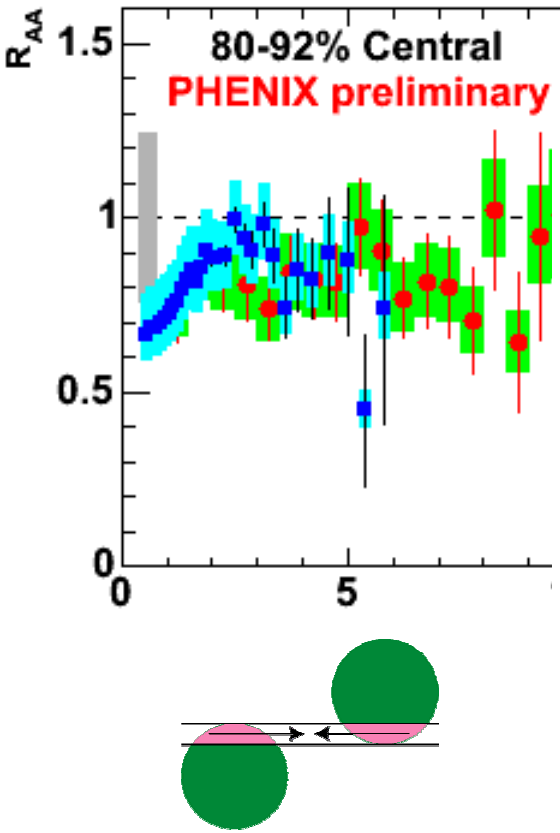
RHIC Run5 Cu+Cu data

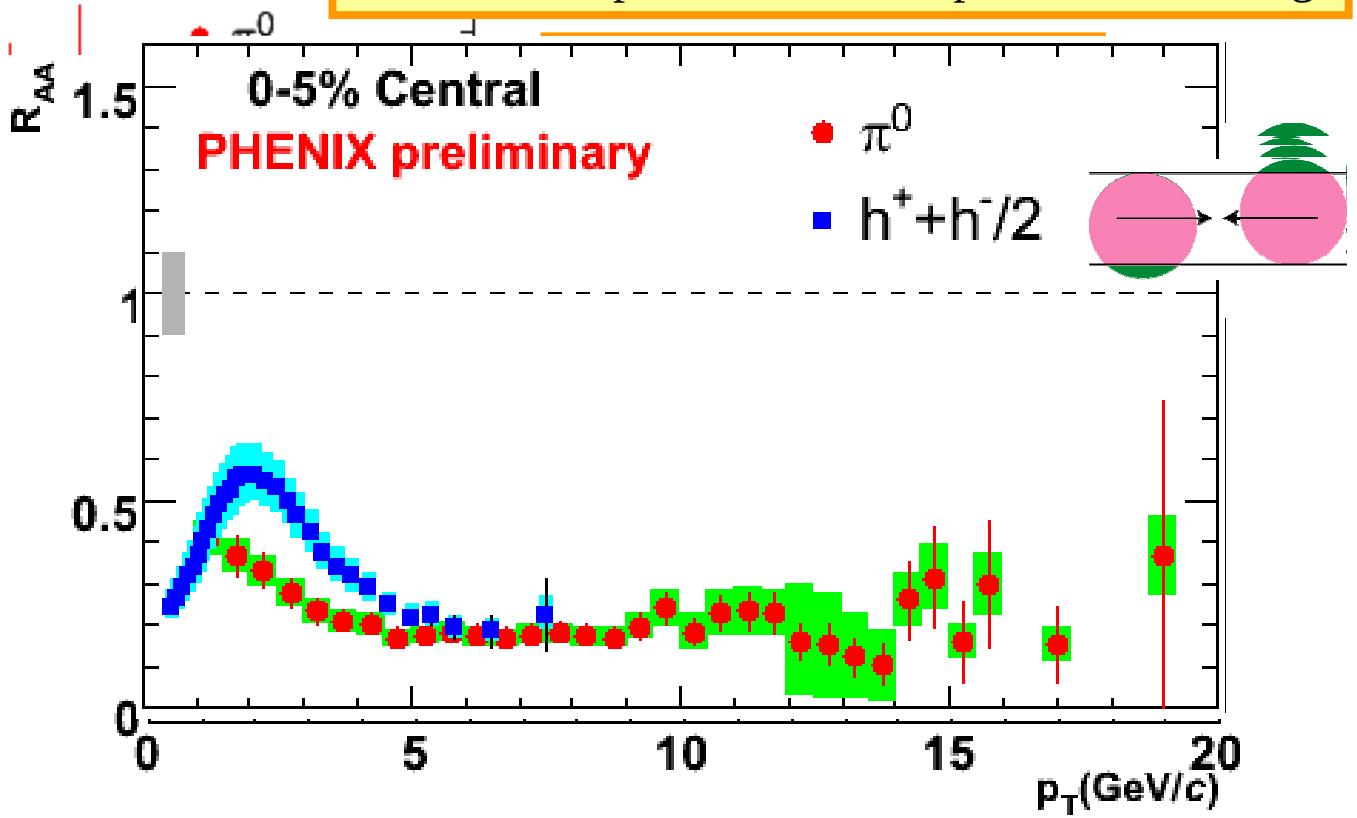
- Sampled 3 nb^{-1}
- 63^2 x 3 nb^{-1} ~ 1 pb^{-1} p+p equivalent
- 2.2 B events sampled
  - 59 M minimum bias events
  - 1.9 M high-p_T triggered

π^0 R_{AA} in $\sqrt{s_{NN}}$ = 200 GeV Au+Au

Nuclear Modification Factor

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

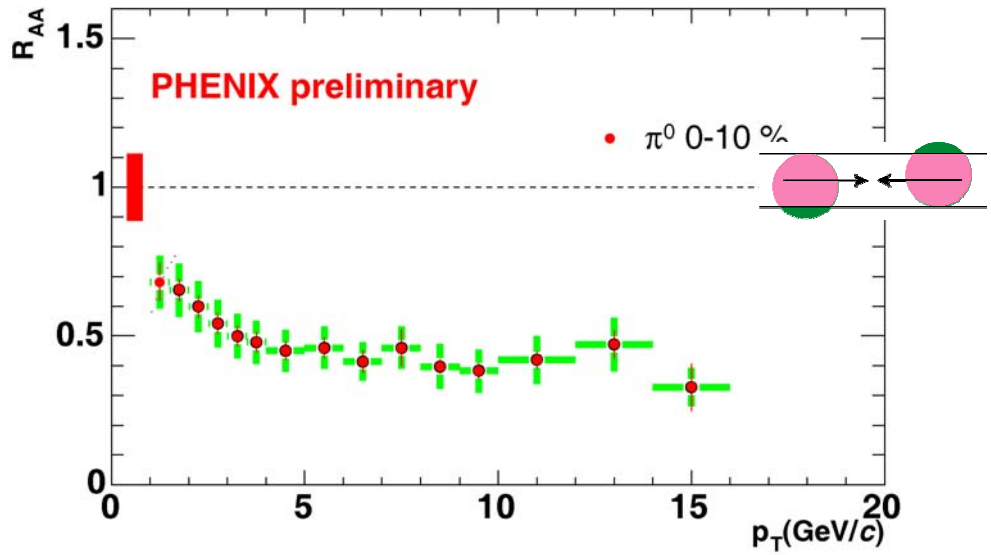




- Strong suppression (R_{AA} ~ 0.2) is seen even at high p_T
- Constant for p_T>4GeV/*c* for all centralities

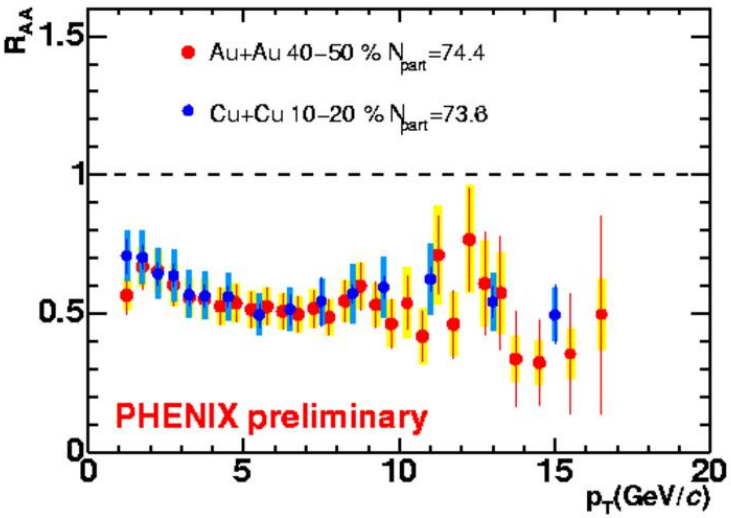
π^0 R_{AA} in $\sqrt{s_{NN}}$ = 200 GeV Cu+Cu

Cu+Cu



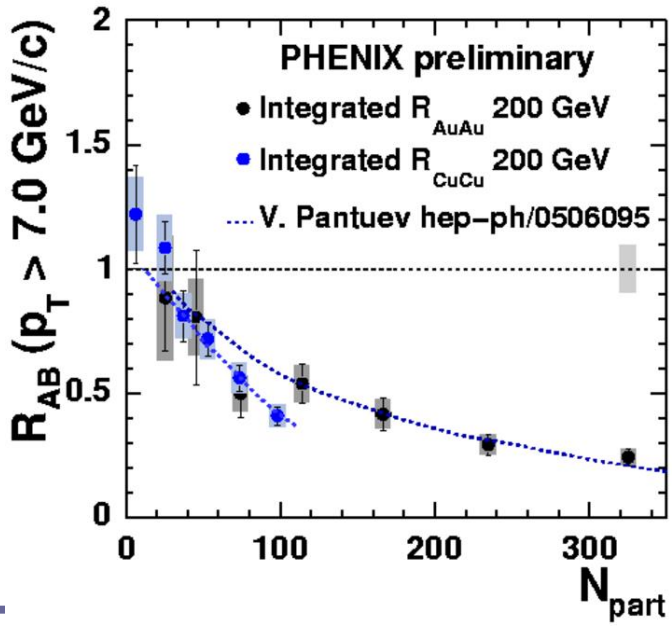
- R_{AA} ~ 0.4 for central collisions
- Similar suppression pattern as Au+Au
  - Constant for p_T>4 GeV/c
  - Strength of suppression increases with centrality

Au+Au vs. Cu+Cu



System size dependence

- Centrality (in % bins) dependence differs between AuAu and CuCu
- For cent bins with ~ same number of participants, suppression pattern is identical!



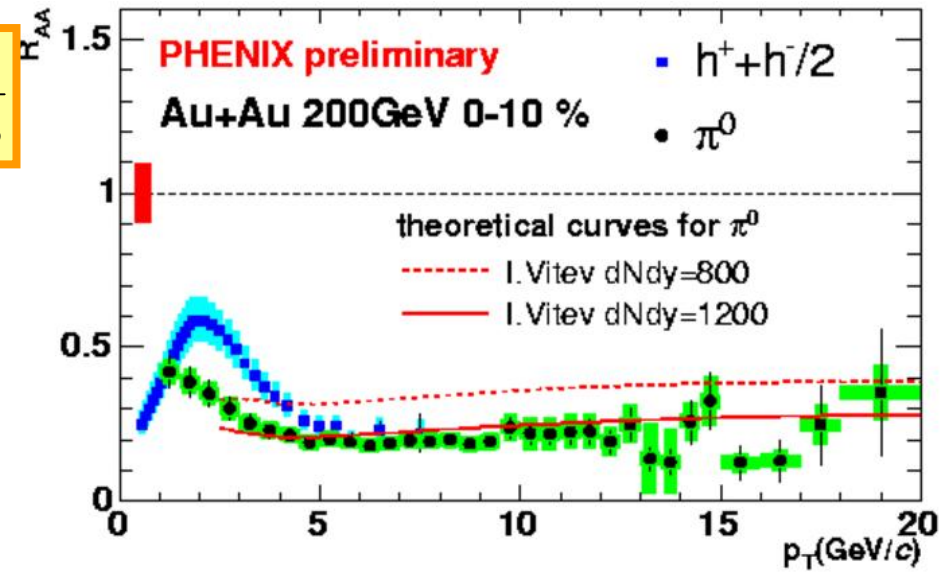
Integrated R_{AA}

- Similar qualitative N_{part} dependence
- Vitev: Fair agreement with AuAu, but misses trend in CuCu
  - Fixed to AuAu, no surface effects
- Pantuev: geometrical model including "corona"
  - Surface jet bias, ellipticity included

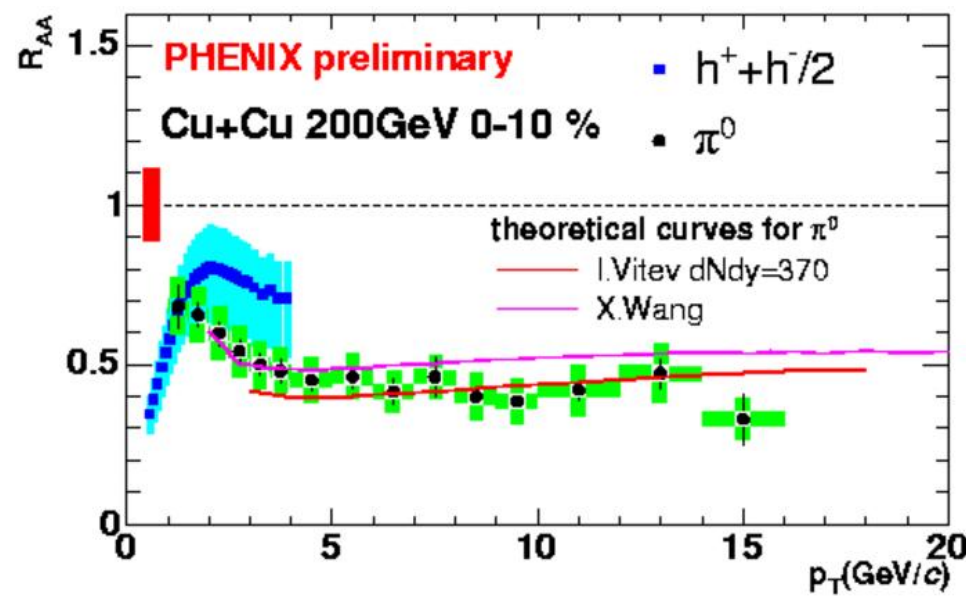
Modeling $R_{AA}(p_T)$ of Au+Au and Cu+Cu

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

- R_{AA} for central Au+Au
  - Suppression strong and nearly constant up to 20 GeV/c
  - Consistent with dN_g/dy ~ 1200

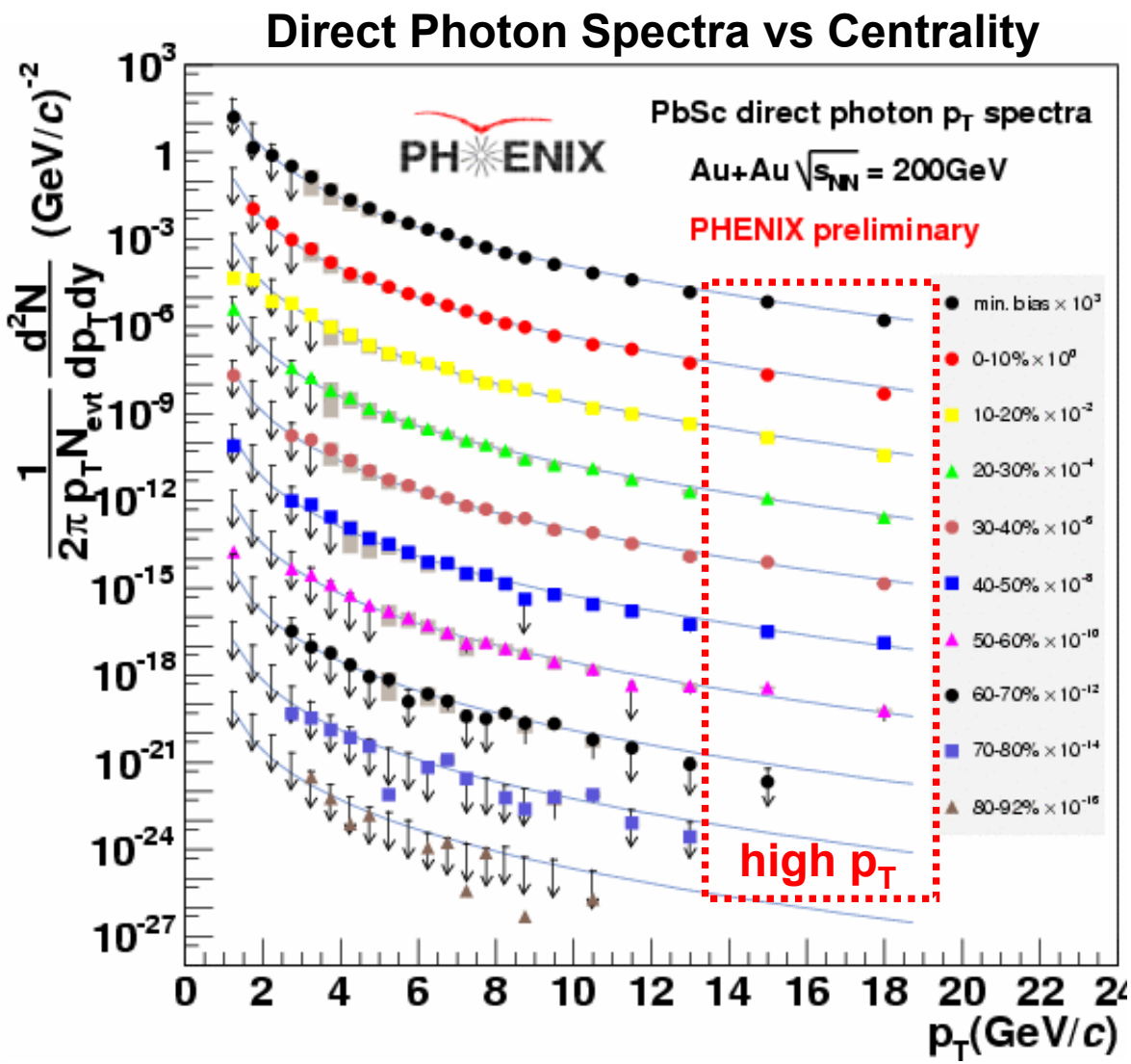


- R_{AA} for central Cu+Cu
  - Also suppressed to high-p_T
  - Consistent with dN_g/dy ~ 370

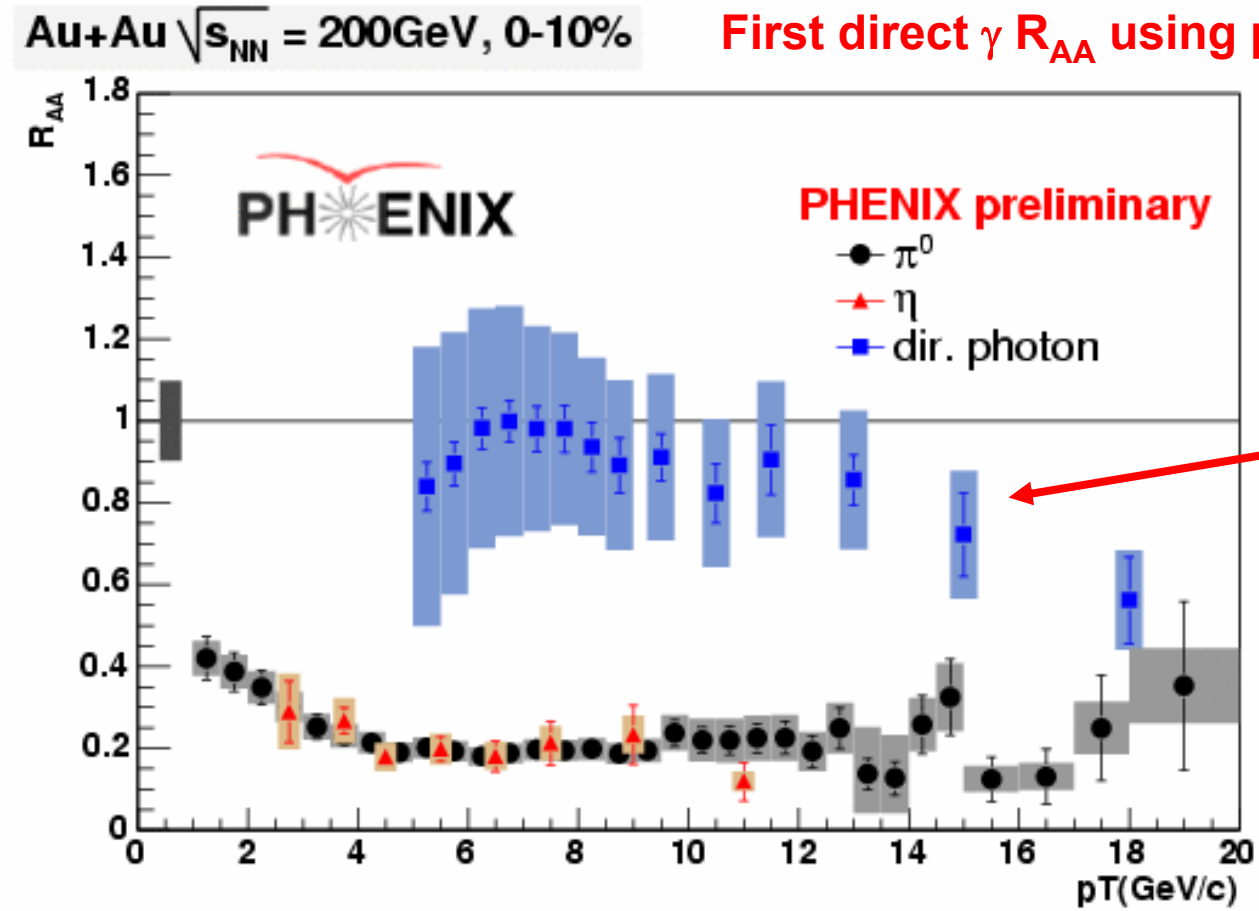


Direct Photons

- Prompt photons don't interact strongly – ideal hard scattering probe
- Run 4 ∫Ldt extends measurement to 20 GeV/c
- And R_{AA}… ?



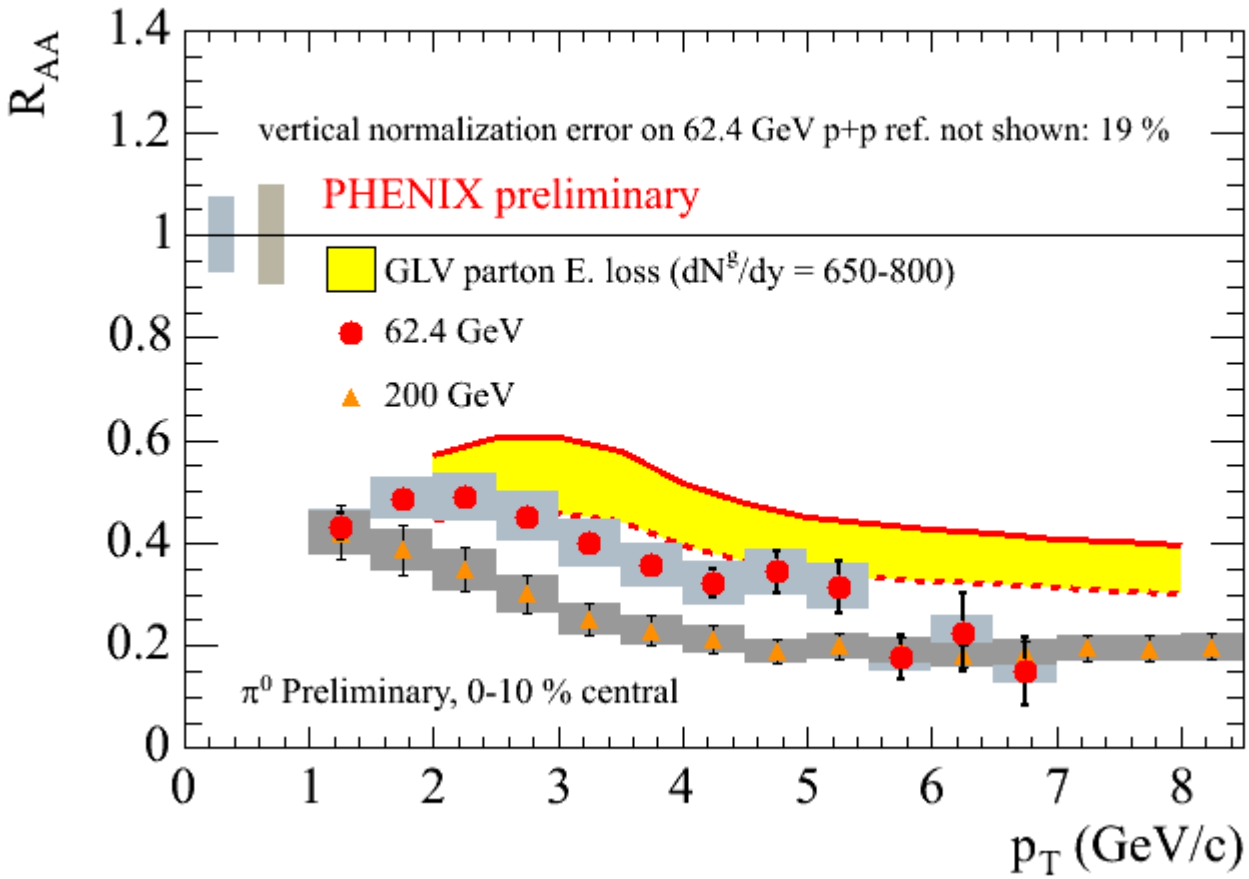
Photons shine, hadrons don't



Drop possibly due to isospin difference between p+p and A+A, other investigations underway

- Mesons suppressed ≈ 5 → energy-lost in QGP
  - Same suppression pattern for both π^0, η
- γ scale with parton flux

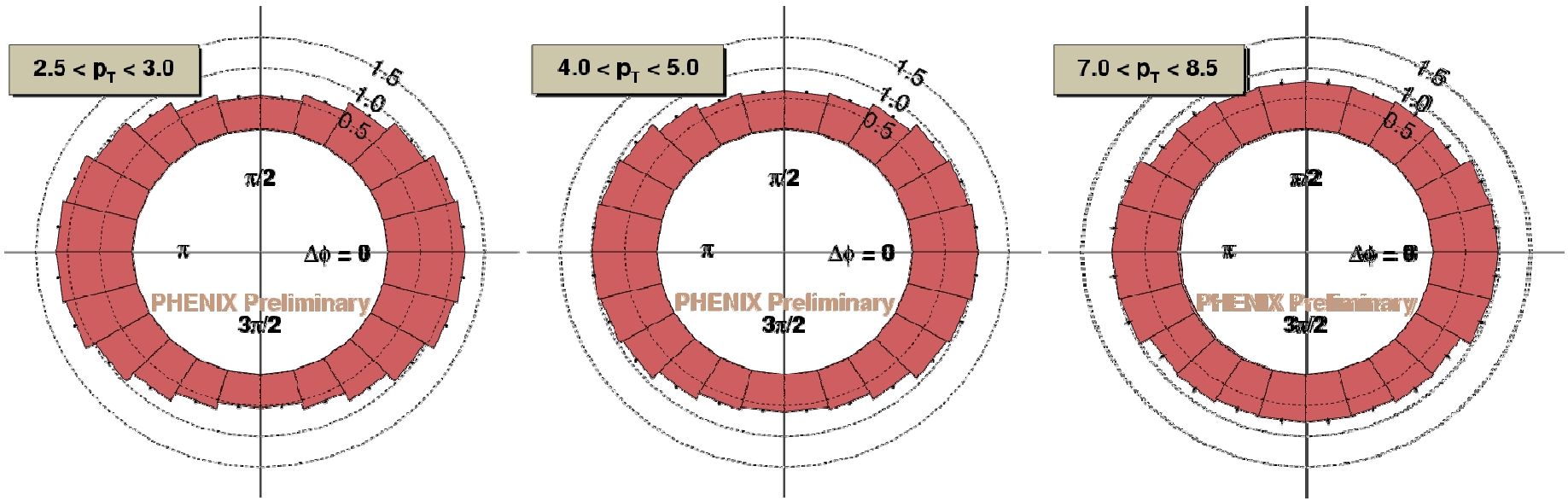
π^0 R_{AA} 62.4 GeV : NEW!!

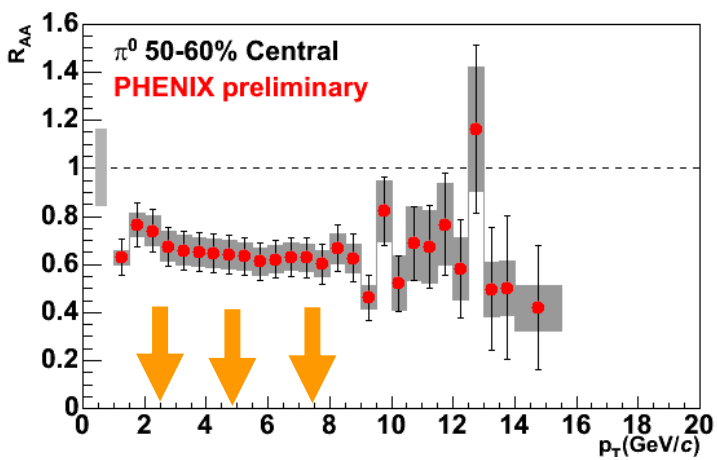


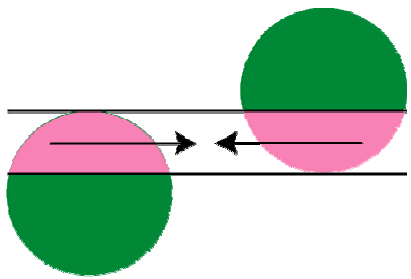
- "Old": p+p reference from fit to ISR data
- "New": p+p reference measured at RHIC!
- Suppression in 62.4 GeV is now more similar to that for 200 GeV

Measuring R_{AA} as fcn of angle wrt React Plane

π^0 $R_{AA}(\Delta\phi, p_T)$ plotted in polar coords (folded to 2π)

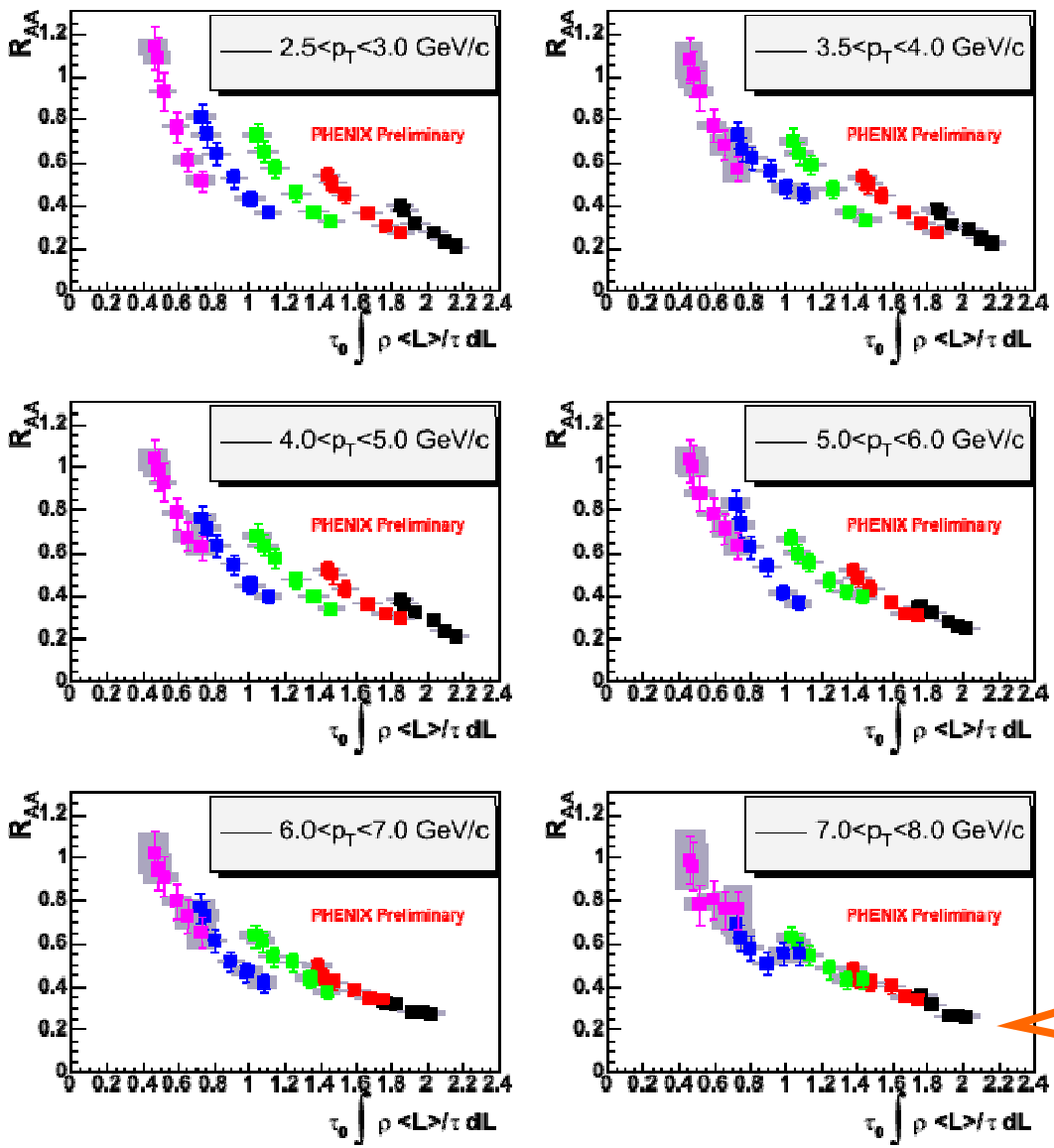


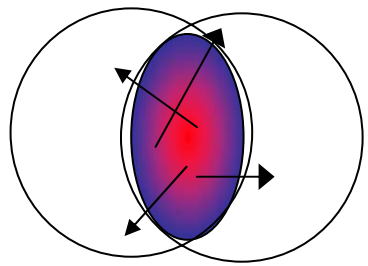




Au+Au $\sqrt{s_{NN}}$ = 200 GeV
50-60 % Centrality

π^0 R_{AA} vs. "ρ L dL"





$$\Delta E \propto L^2$$

$$R_{AA} \sim \int d\vec{l}\ \rho_{\text{color}}^{\text{init}}(\vec{L}) \frac{L\,\tau_0}{L+\tau_0}$$???

10-20 % Centrality

20-30 % Centrality

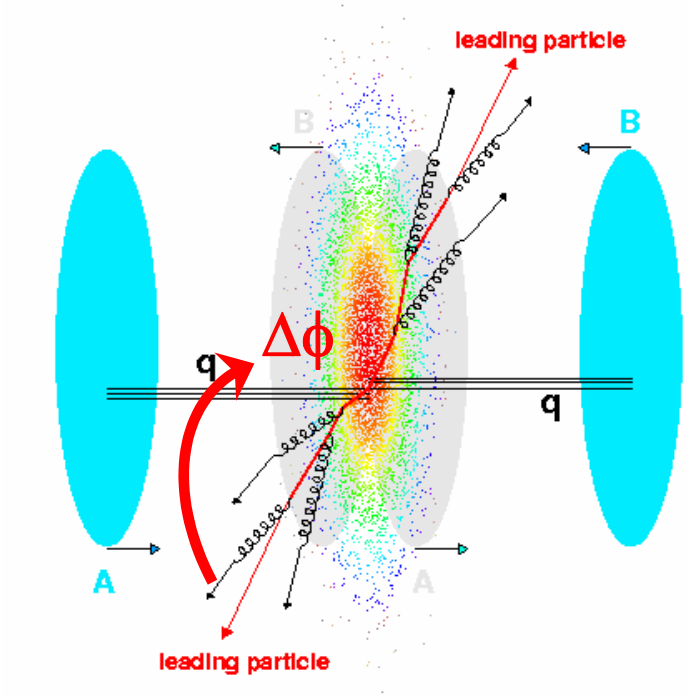
30-40 % Centrality

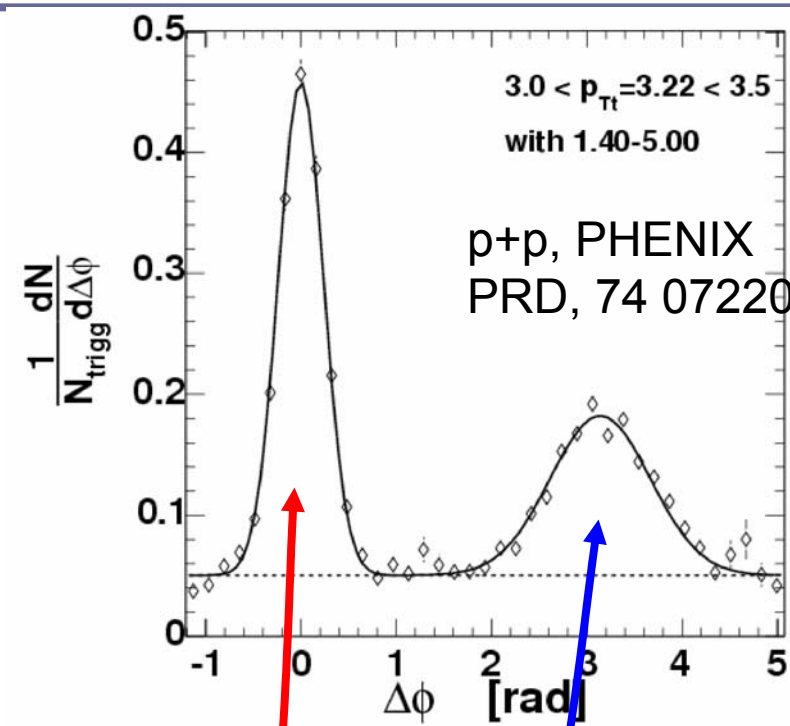
40-50 % Centrality

50-60 % Centrality

Angular and centrality dependence described by single curve!! Implies energy loss is dominant at high-p_T

Azimuthal Correlations (Concept)

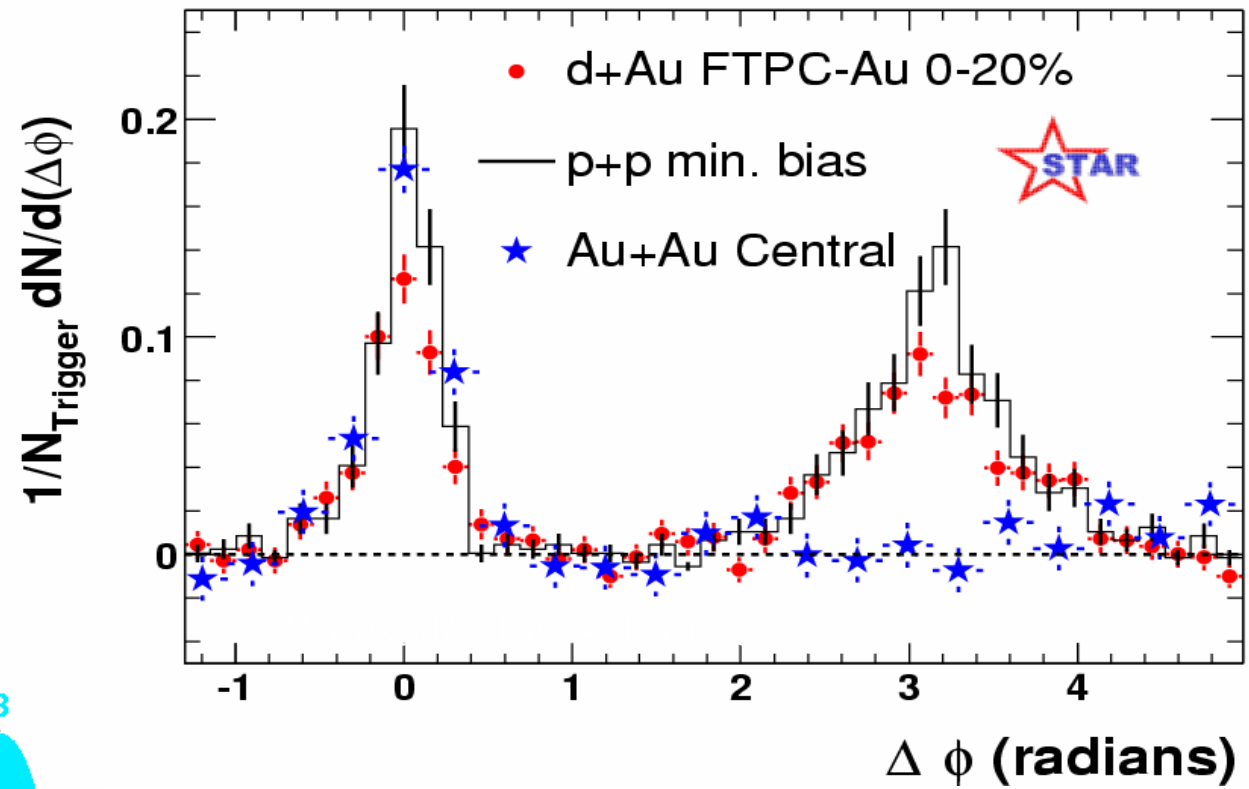


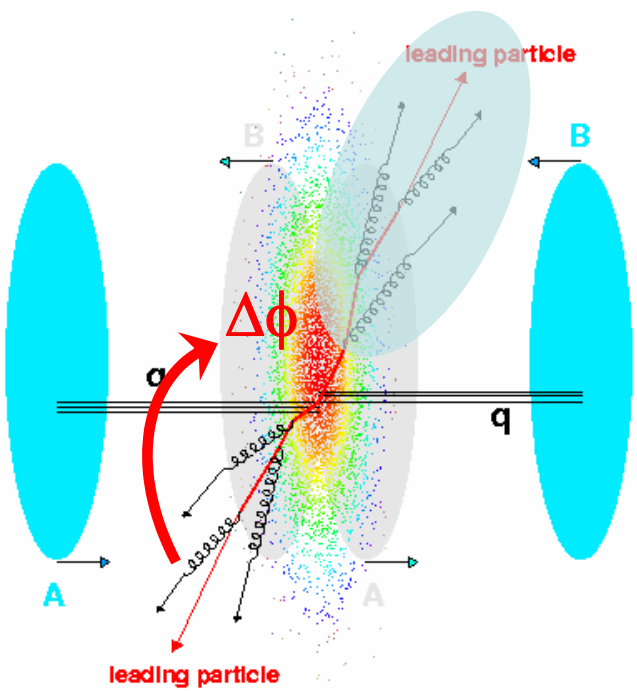


- Tag (high-p_T) particle: "trigger" particle
- Calculate $\Delta\phi = \phi_1 - \phi_2$ for "associated" particles in event
- Expect to observe correlations at
  - $\Delta\phi = 0$: "near side"
  - $\Delta\phi = \pi$: "away side"

Azimuthal Correlations and Jet Suppression

- Azimuthal correlation functions show ~ complete absence of "away-side" jet
  - $p_{T,trig}$: 4-6 or 3-4
  - $p_{T,assoc}$: 2 - $p_{T,trig}$

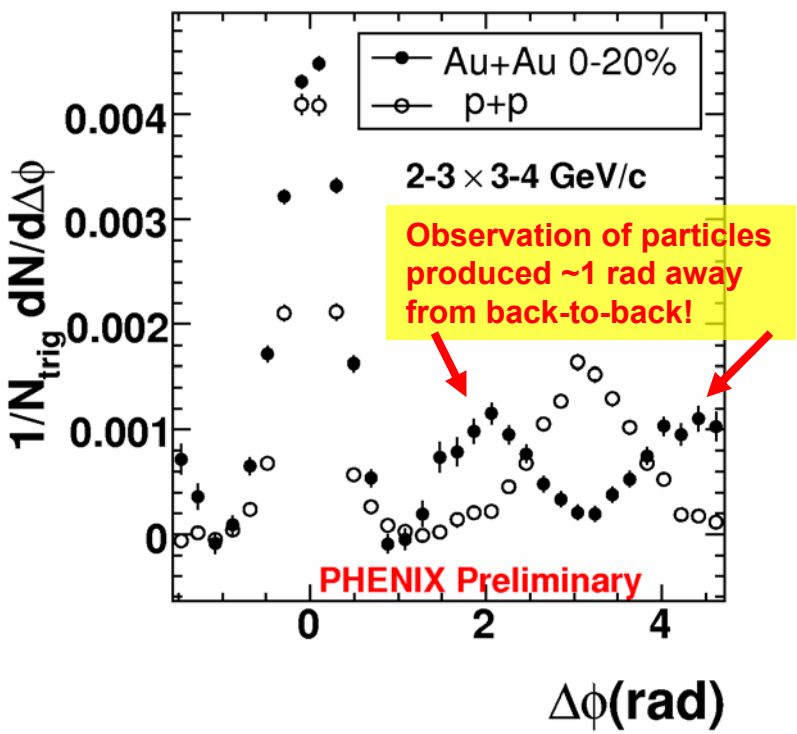




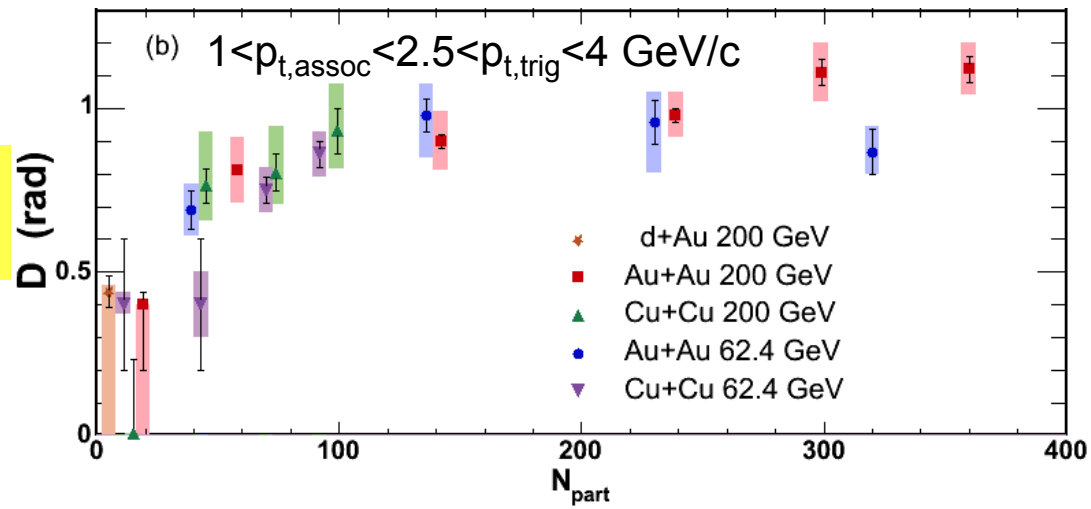
➡ Further evidence for surface emission only (?)

- That is, "partner" in hard scatter is absorbed in the dense medium
- Question: where has the energy gone?
  - (Partial) Answer: need to widen "search" in p_T

Studying the far-side production of particles



PHENIX, nucl-ex/0611019



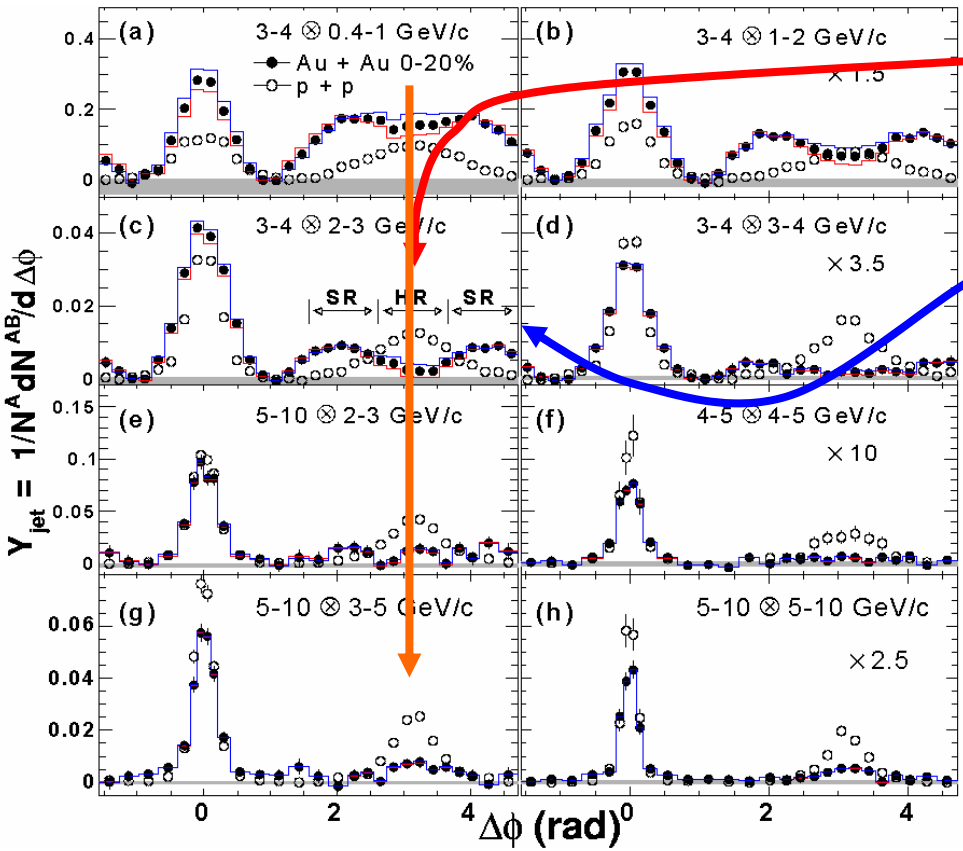
Fit away-side peak with double Gaussian, each centered at

$\Delta\phi = \pi \pm D$

- *D* scales with collision energy and system size!
- Emission consistent with strong medium response to energy deposited by the traversing medium

p_T Evolution of the Jet Shape

Au+Au & p+p $\sqrt{s}$ = 200 GeV



Per-trigger yield vs. $\Delta\phi$ for various trigger and partner p_T ($p^A_T \otimes p^B_T$), arranged by increasing pair momentum ($p^A_T + p^B_T$)

arXiv:0705.3238 [nucl-ex]

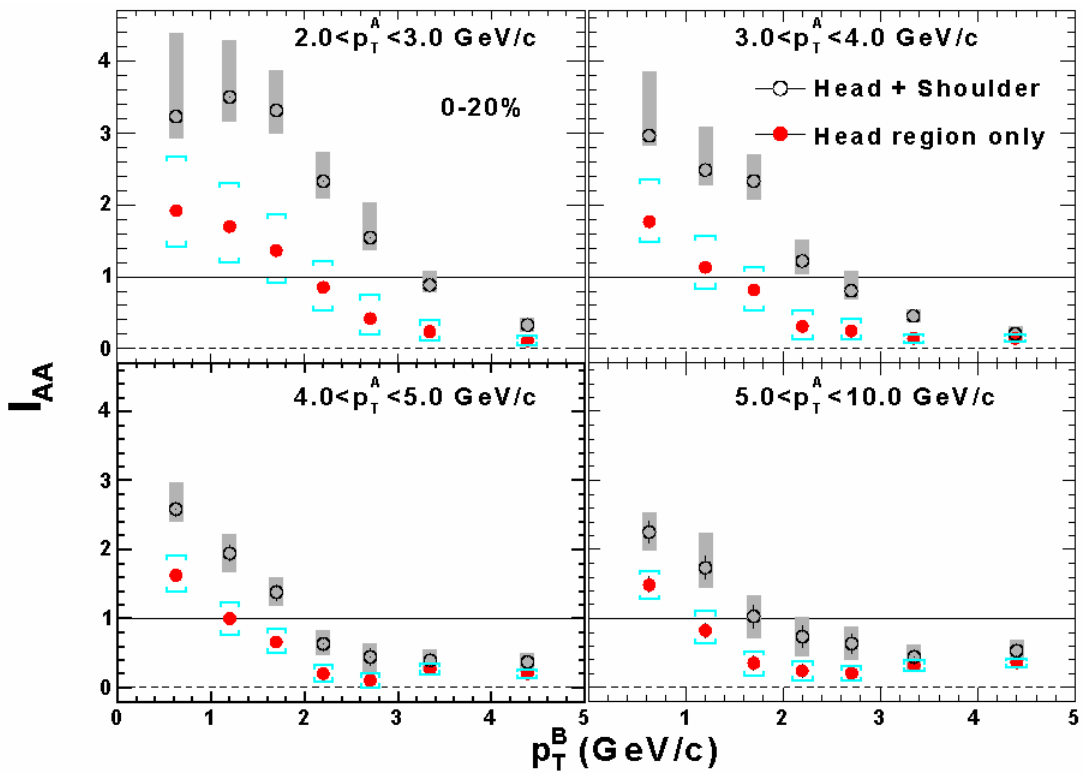
- Establish the punch-through jet component ("Head Region")
- and the medium-induced component ("Shoulder Region")

- Evolves from flat → concave → convex
- Suppression in HR, Enhancement in SR
- Reappearance of peak is not due to merging of side peaks. High p_T is consistent with jet fragmentation.

Yield modification (I_{AA})

$$I_{AA}^{W} = \int_{\Delta\phi \in W} d\Delta\phi Y_{\text{jet}}^{\text{Au-Au}} \Big/ \int_{\Delta\phi \in W} d\Delta\phi Y_{\text{jet}}^{p-p}$$

Analogous to R_{AA}, but describes jet yield



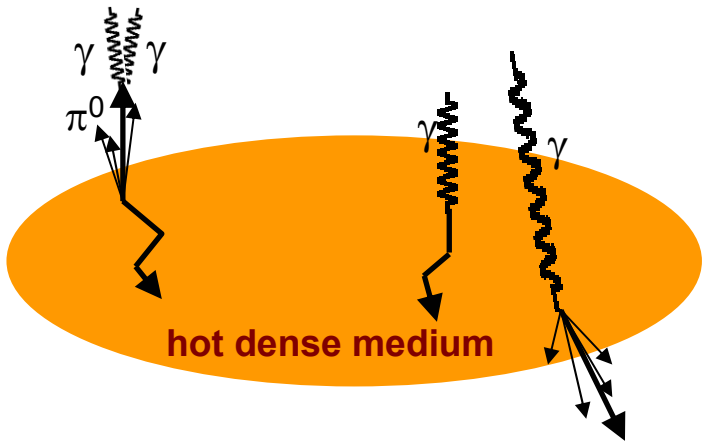
- HR exhibits early onset of suppression, relative to p+p
- H+S (entire away side) exhibits overall enhancement

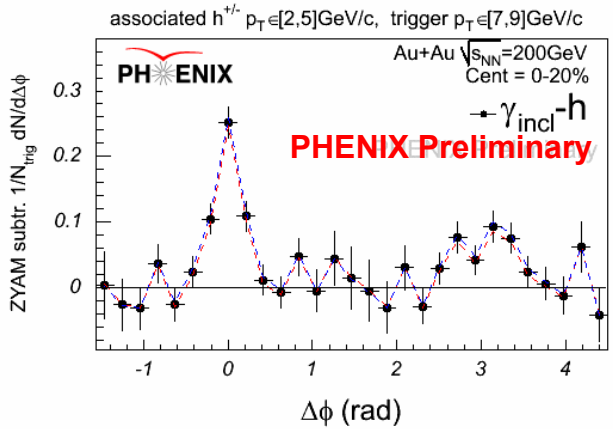
HR is suppressed due to jet quenching, SR is enhanced, reflecting the response of medium to deposited energy.

Future directions: γ-h correlations

- Normal dijet (π^o-h):
  - Trigger bias: $E_\pi < E_{jet}$,
  - Possible surface bias
- Direct γ tagged jet:
  - No fragmentation: $E_\gamma \sim E_{jet}$
  - No strong interaction, sensitive to the whole medium
- Inclusive γ-h Yield
  - Trigger photon is a mixture of direct and hadron-decay photon
  - Need to subtract decay part

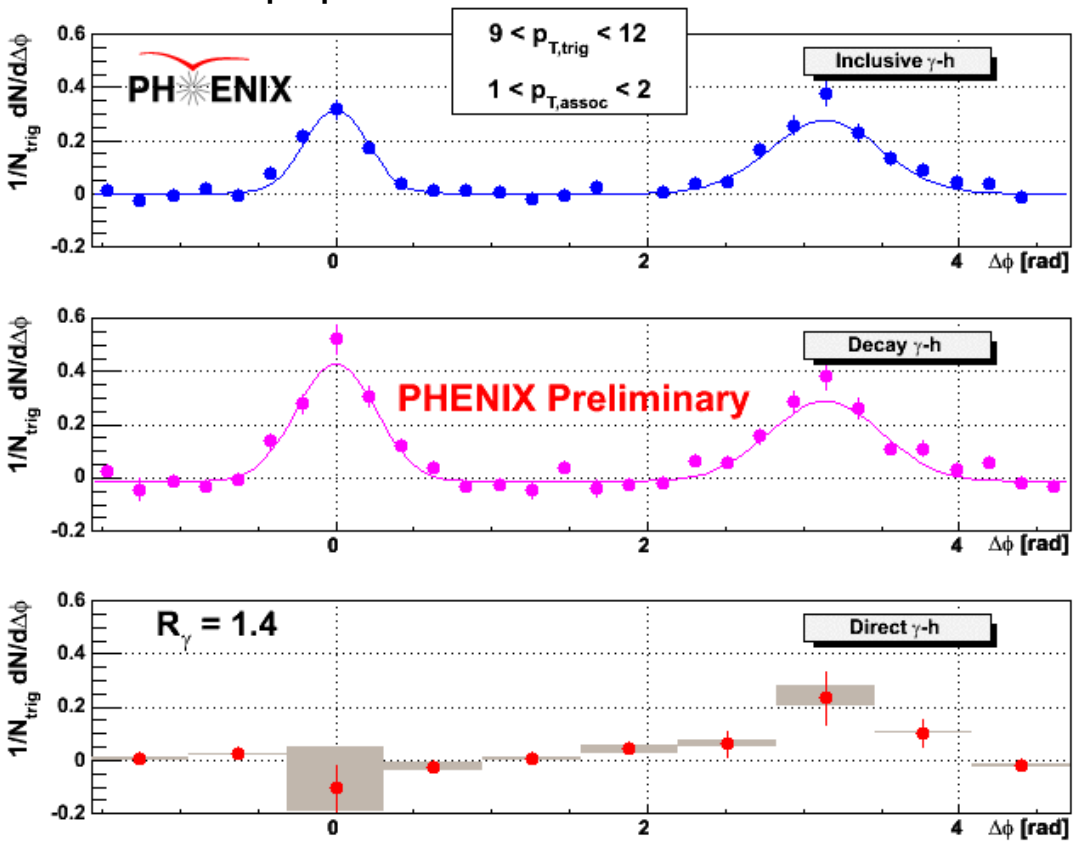
Proposed in hep-ph/9605213 ~10 years ago





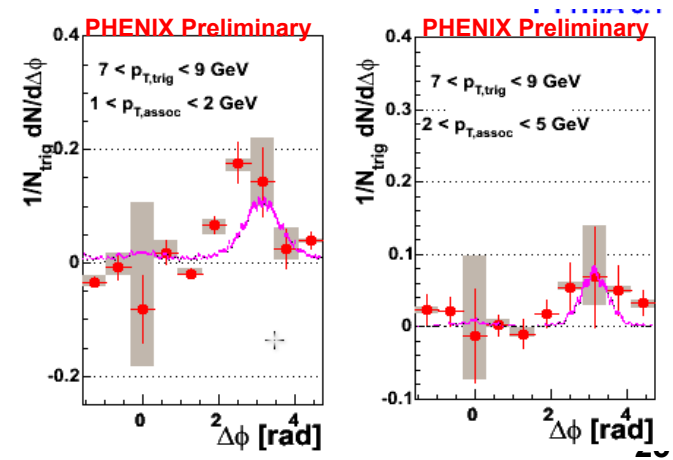
γ-h: the method

p+p collisions at 200 GeV



PHENIX Preliminary

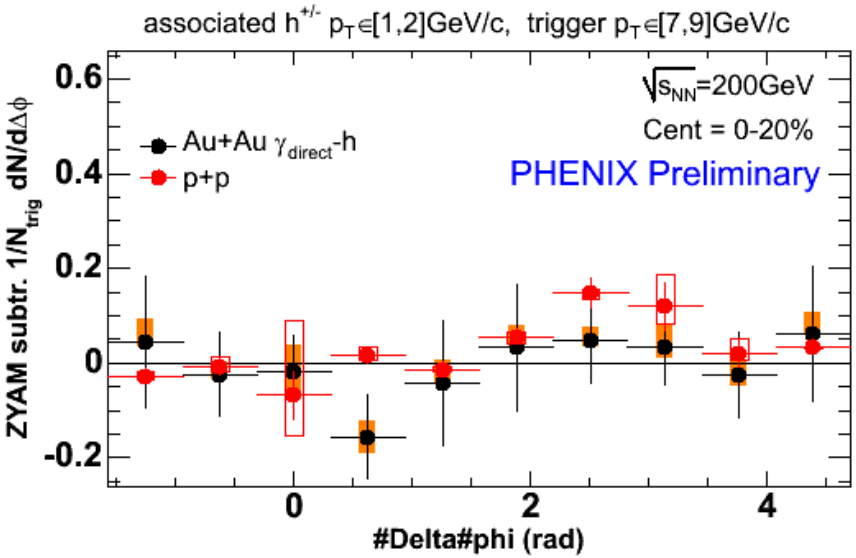
1. Inclusive γ-h
2. Decay γ-h contribution (via π^0-hadron)
3. Direct γ-h !

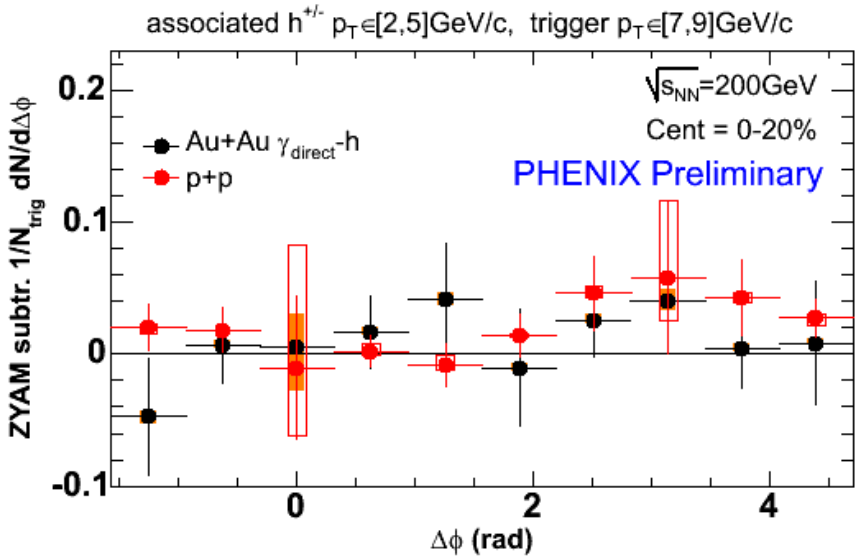


- *Reasonable agreement between data and Pythia*
  - Pythia 6.1, k_T = 2.5 GeV

Direct γ-h Yield in p+p and Au+Au

Black: Au+Au Red: p+p





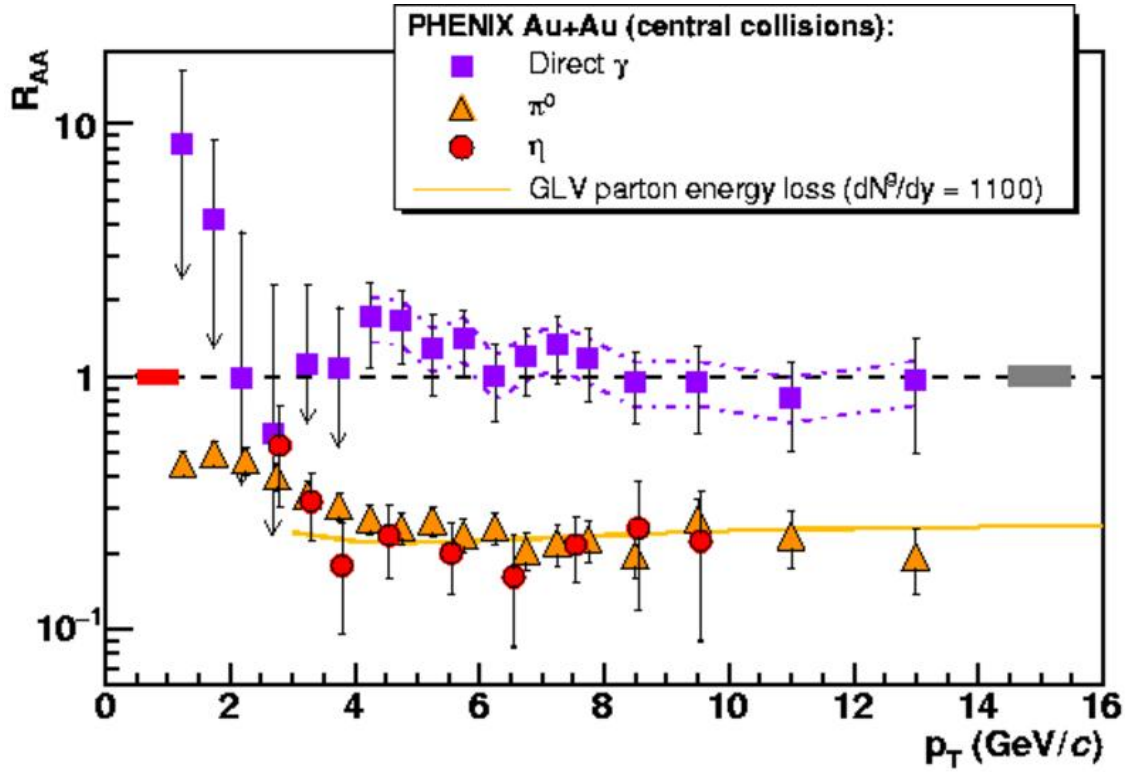
- First yield measurement in Au+Au!
- *Hint* of away side modification in Au+Au
  - Au+Au data systematically lower than p+p
  - We have the tools, now we need the statistics …

Summary

- High-p_T particle production gives access to hard-scattering processes
- Important observables:
  - Spectra with high-p_T reach
  - Suppression seen in $R_{AA}(p_T)$ at high-p_T
    - Similar patterns in AuAu vs. CuCu for same N_{part}
    - Hints for corona/surface effects
    - Evidence for energy loss as dominant effect
  - Azimuthal Correlations provide path to jet studies of medium
- PHENIX physics program has steady progressed beyond "discovery" stage, have begun addressing next level of questions:
  - How are jets affected by passage through the medium created in RHIC collisions?
  - How does the medium respond to the impact of a high-pT probe?
  - Future directions involve mapping out properties of the plasma
- Results shown here only scratch the surface of the methods for studying the medium in PHENIX!

Extras

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

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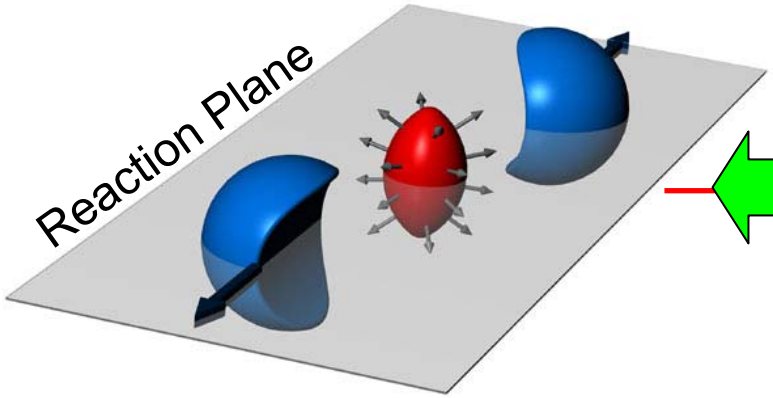
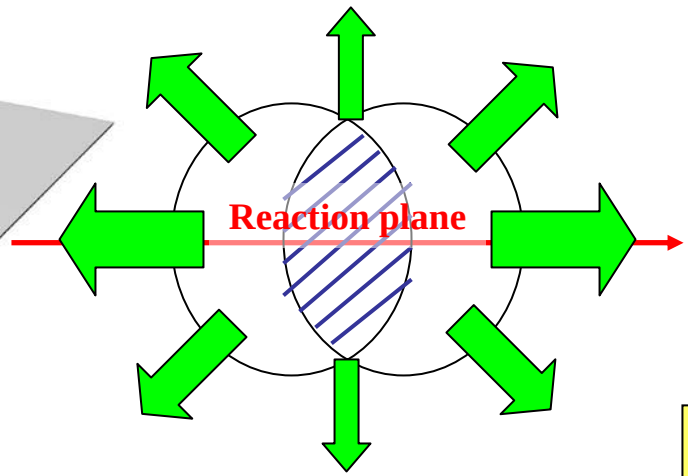
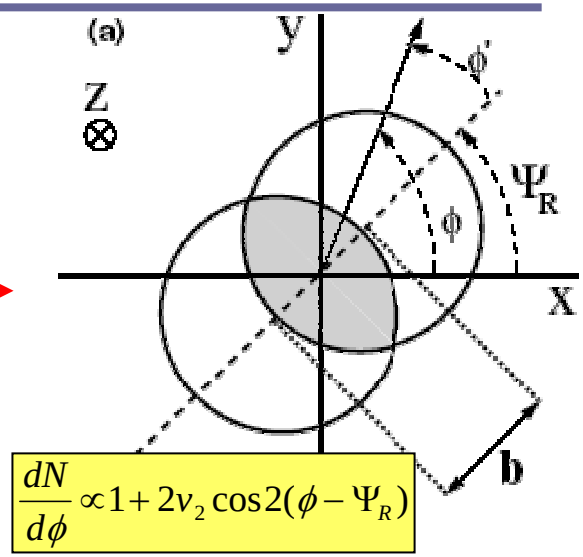
Measurements wrt the R.P. in PHENIX







$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_R)$$

- Reaction Plane determination
  - Use the Beam-Beam Counters @ $3<|\eta|<4$, azimuthally symmetric
  - Measure charged particle multiplicity as function of φ
  - Event-by-event determination
  - 2 independent measurements from N and S counters – estimate of resolution
- Relative Yields as a function of $\Delta\phi$
  - Measure π^0 dN/dp_T in 6 $\Delta\phi$ bins over $[0,\pi/2]$. (corrected for resolution)
  - Multiply the ratio

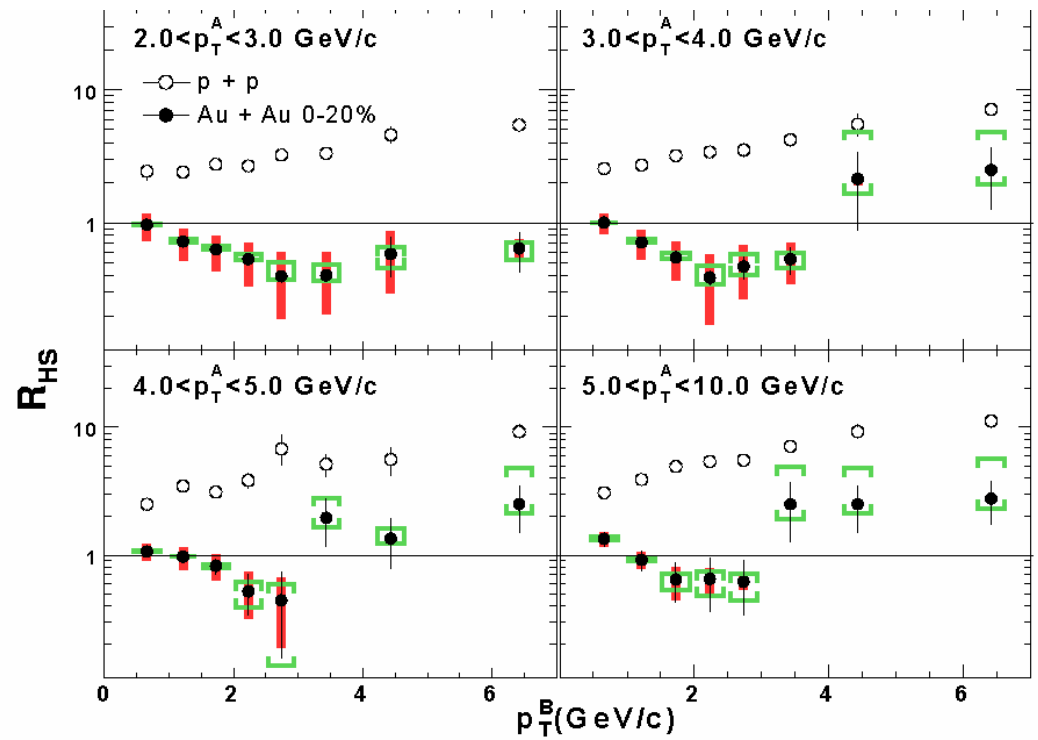
$$r_{\Delta\phi} = \mathrm{Yield}(\Delta\phi)/\mathrm{Yield} \equiv R_{AA}(\Delta\phi)/R_{AA}$$

  - With previously measured $R_{AA} \Rightarrow R_{AA}(\Delta\phi)$

Quantifying Evolution: Ratio of Head/Shoulder

$$R_{HS} = \int_{Head} d\Delta\phi Y_{jet}(\Delta\phi) \Big/ \int_{Shoulder} d\Delta\phi Y_{jet}(\Delta\phi)$$

R_{HS} characterizes the evolution of the two regions. It qualitatively shows the transition between Shoulder-dominated (concave) region and Head-dominated (convex) region in p^A_T and p^B_T.

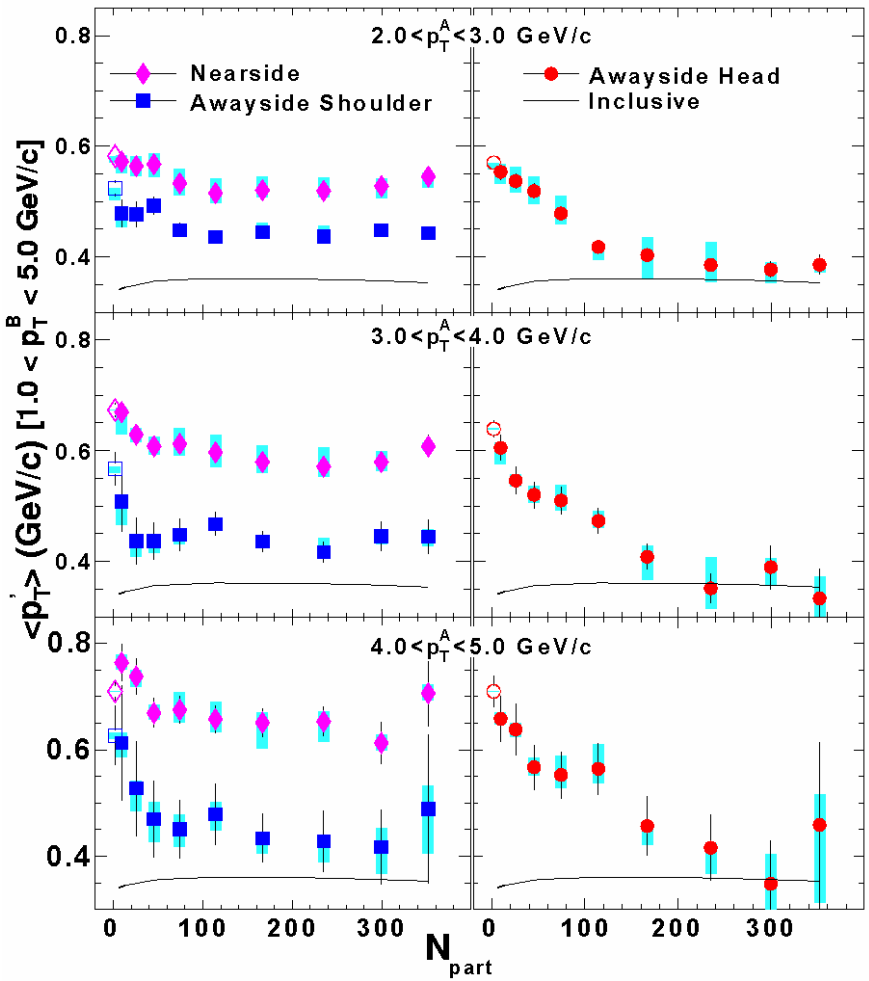


- R_{HS} is symmetric wrt p^A_T, p^B_T.
- Non-monotonic evolution with trigger and partner p_T
  1) R_{HS}~1 for $p_T^{A,B} < 1$
  2) R_{HS}<1 for $1<p_T^{A,B} < 4$
  3) R_{HS}>1 for $p_T^{A,B} >5$

Truncated mean-pT for $1<p_T^B<5$, vs. N_{part}

Intermediate p_T: shows a very different centrality and p_T^A dependence of the <pT> between HR and SR.

- HR behavior consistent with jet quenching
- SR however, shows an universal partner spectra shape, reflecting the property of response of medium to lost energy.



- Nearside: flat with N_{part} (>100), increase with p_T^A.
- **S** region: flat with N_{part} (>100) and p_T^A.
- **H** region: smooth decrease with N^{part} up to 200.