High-p_T Particle Production in PHENIX

CIPANP 2006

Westin Rio Mar Beach

Puerto Rico

May 30 - June 3, 2006

David L. Winter

for the PHENIX Collaboration

COLUMBIA UNIVERSITY

IN THE CITY OF NEW YORK

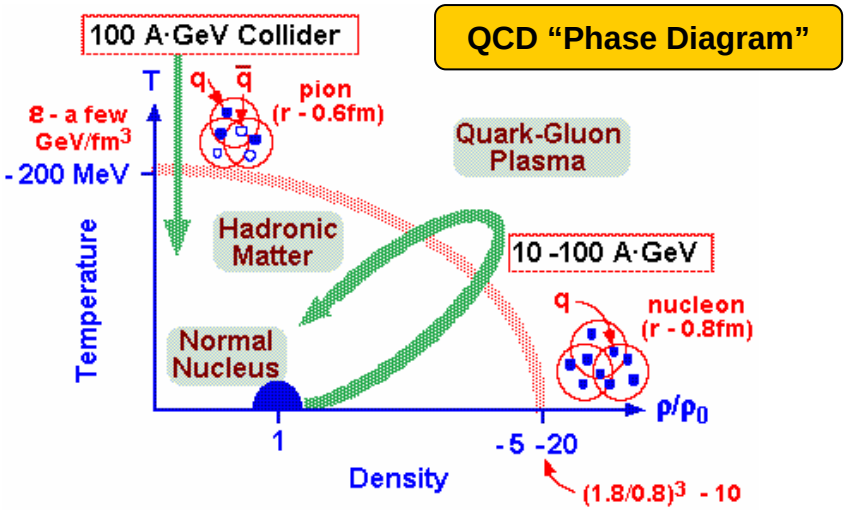
Thanks for swapping timeslots…

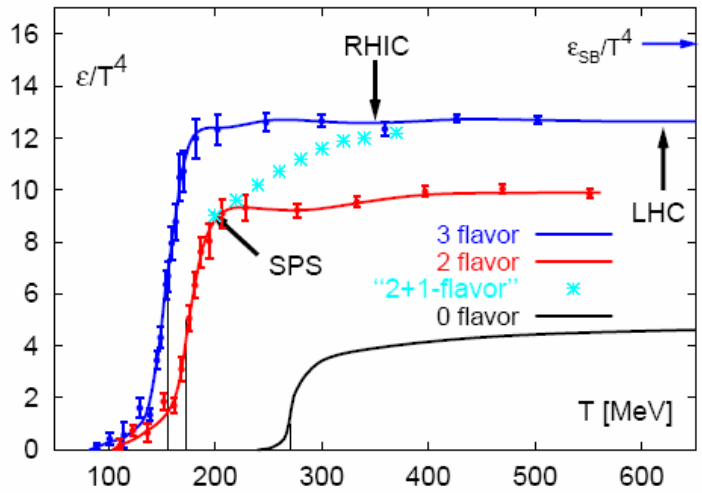
And now, for something completely different…

Outline

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

The Case for Relativistic Heavy-Ion Collisions

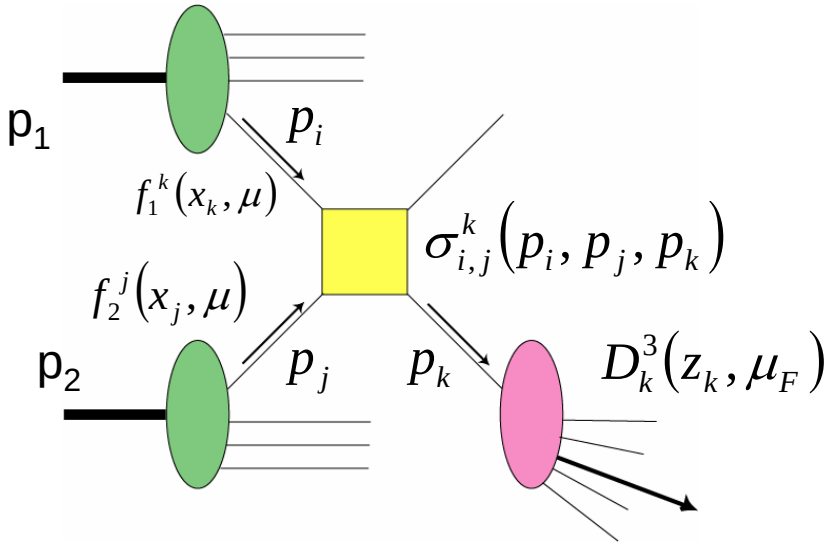




F. Karsch, Prog. Theor. Phys. Suppl. 153, 106 (2004)

- 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
  - $\varepsilon \sim 1.0$ 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?

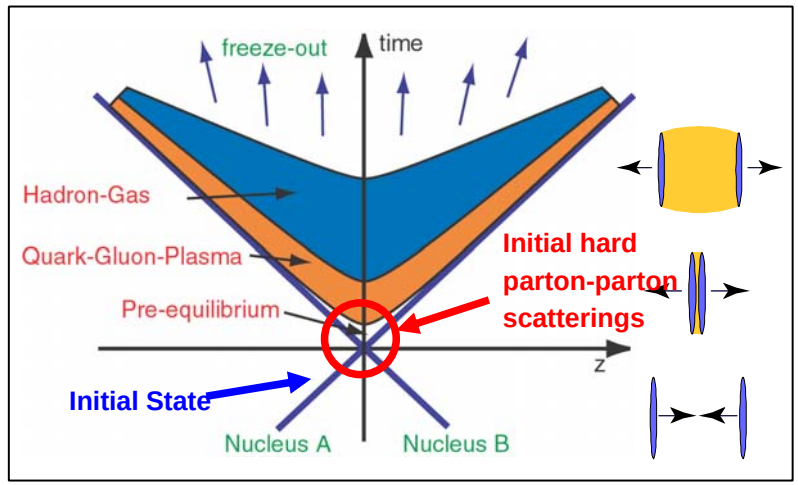


PDFs

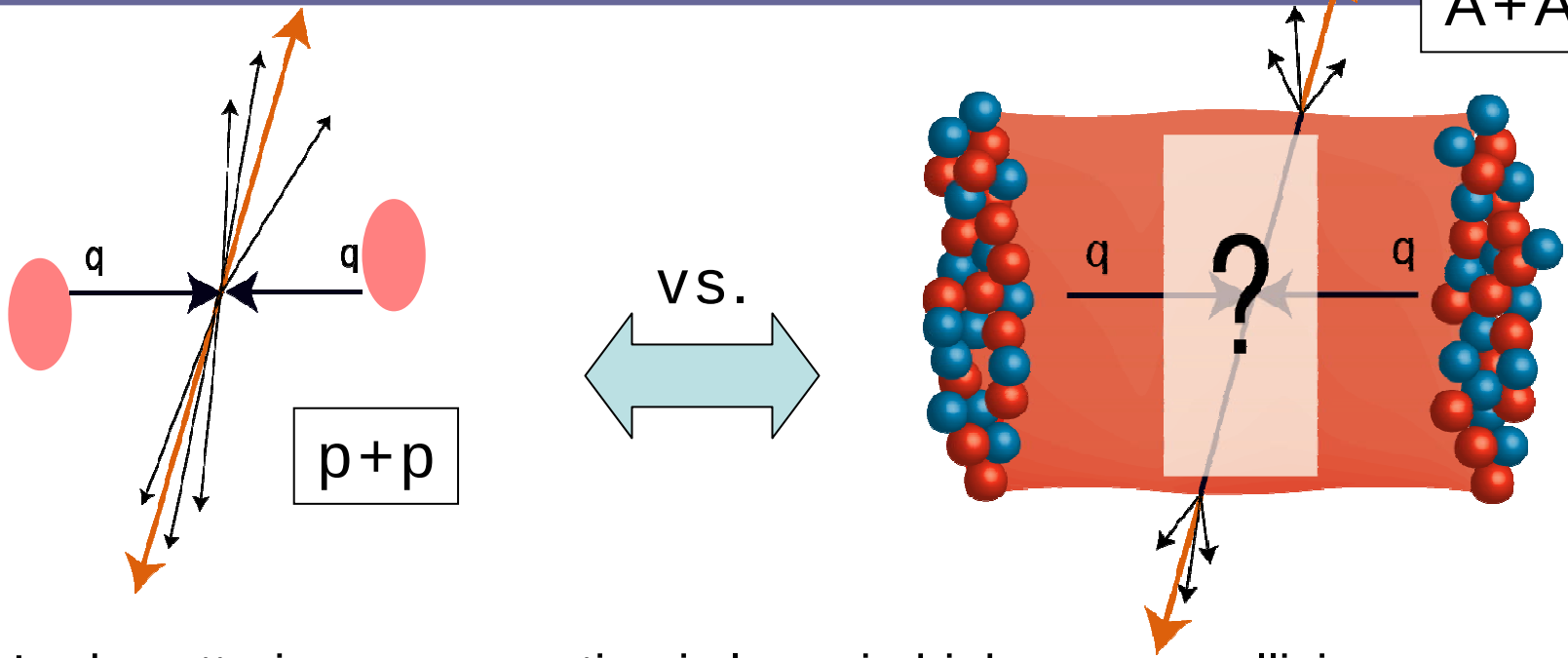
$$\sigma_{1+2}^3 = \sum_{i,j,k}\int dx_i dx_j dx_k \times f_1^k(x_k,\mu)\cdot f_2^j(x_j,\mu) \times \sigma_{i,j}^k\left(p_i,p_j,p_k,\alpha_s(\mu_R),Q^2/\mu_F,Q^2/\mu_F\right) \times D_k^3(z_k,\mu_F)$$

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



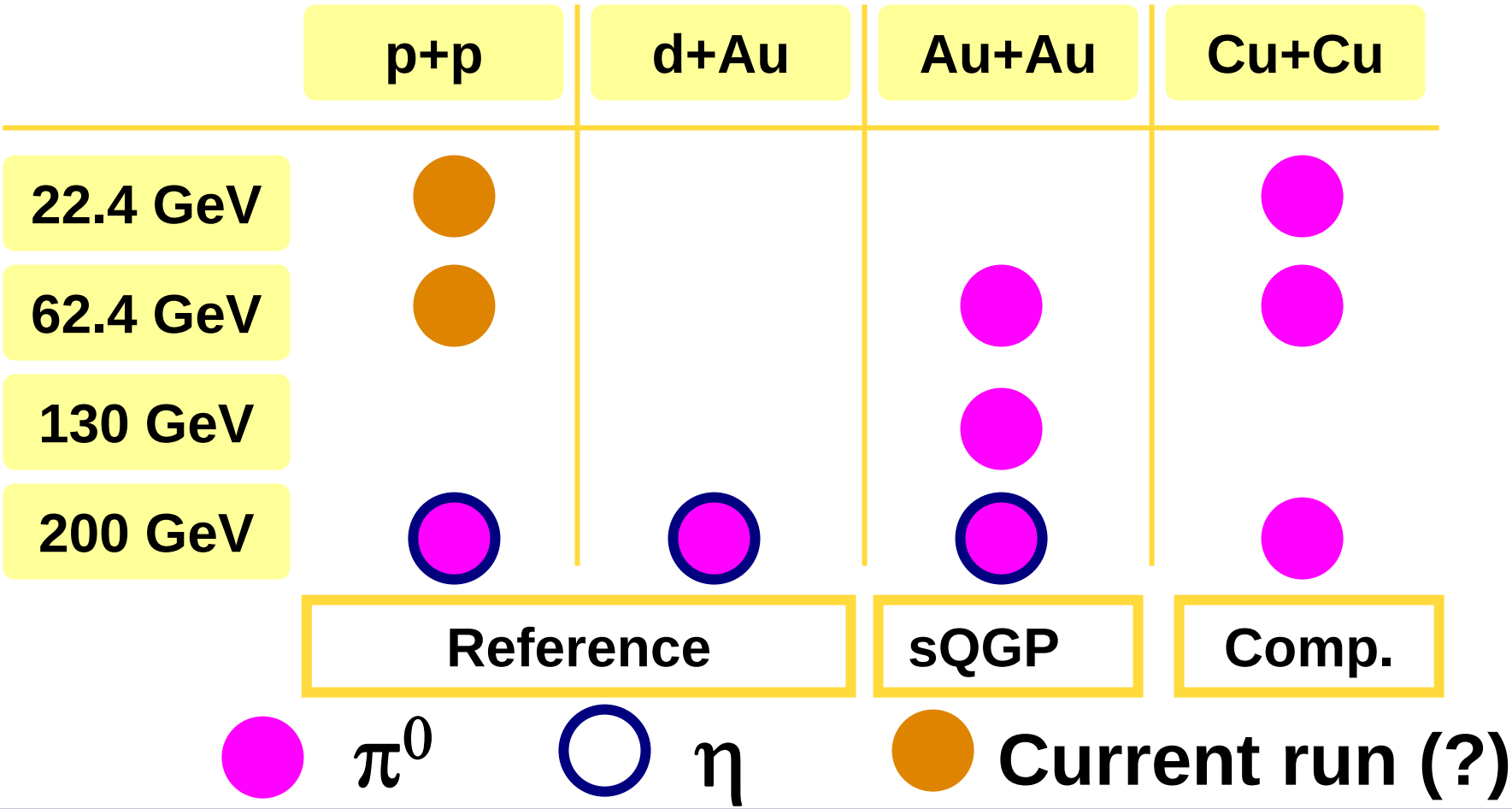
High-p_T as hard probe of the medium



- 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 source of information
  - 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

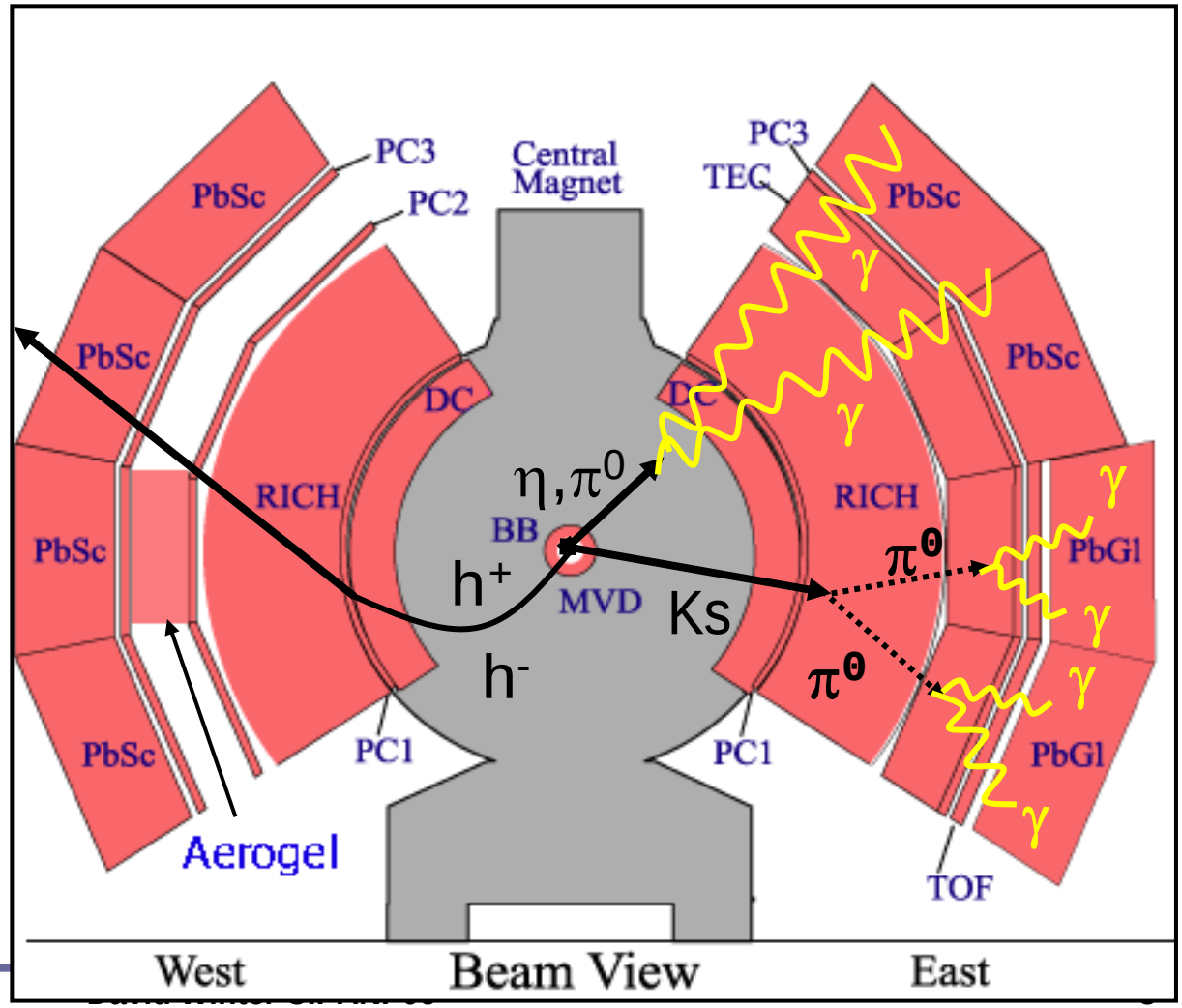
DC --- obtain momentum of charged particles

PC --- measure hit position of charged particles

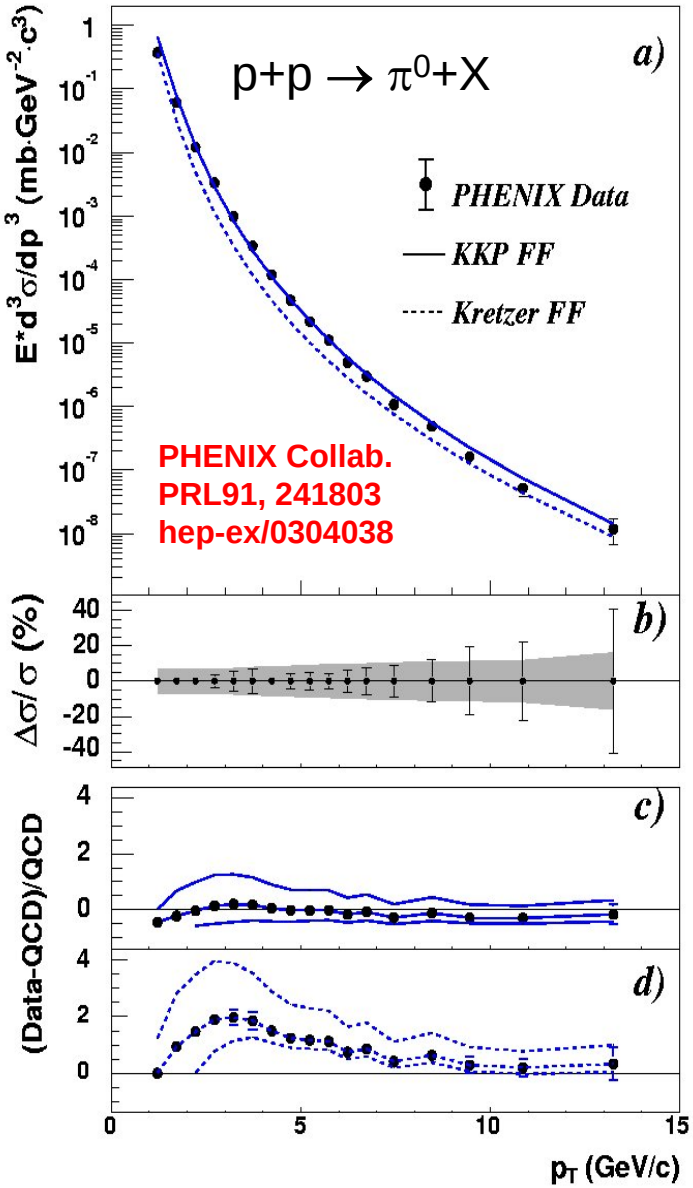
Tracking and Matching (DC, PC)
→charged hadrons

EMCAL (PbSc + PbGl)

→η,π^0,Ks

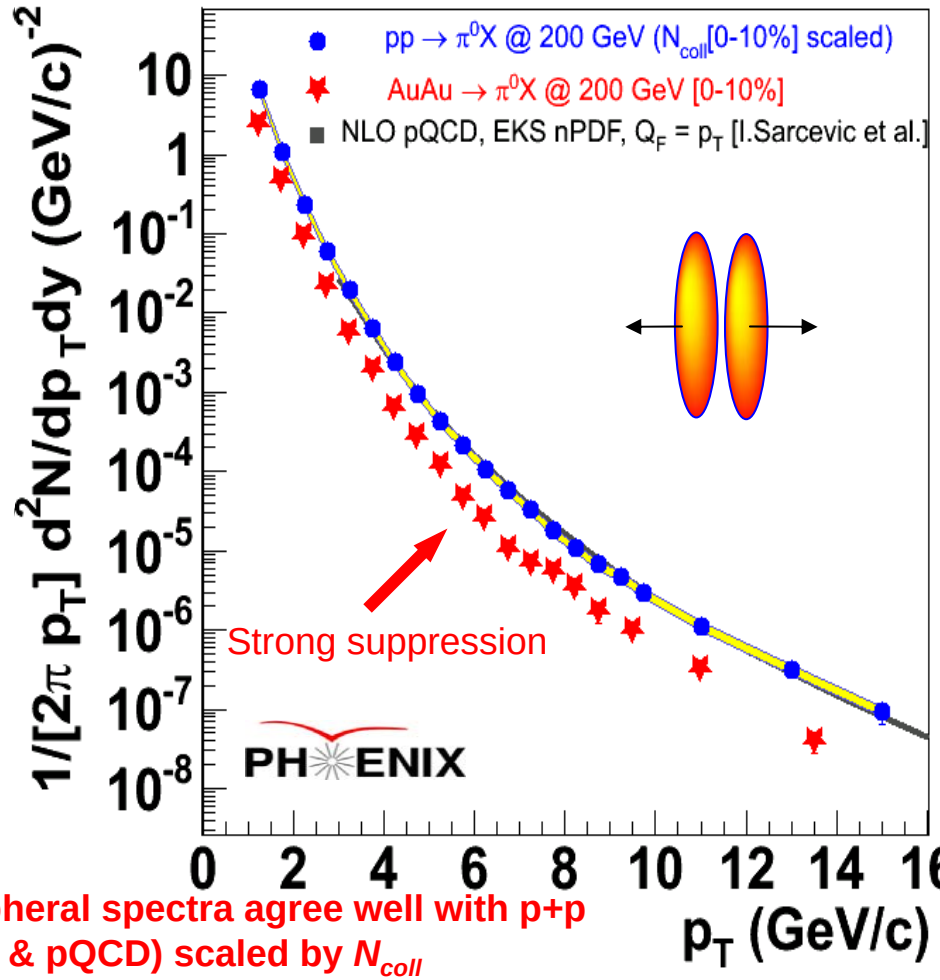


Do we observe hard-scattering?



- Single-particle spectrum and QCD predictions

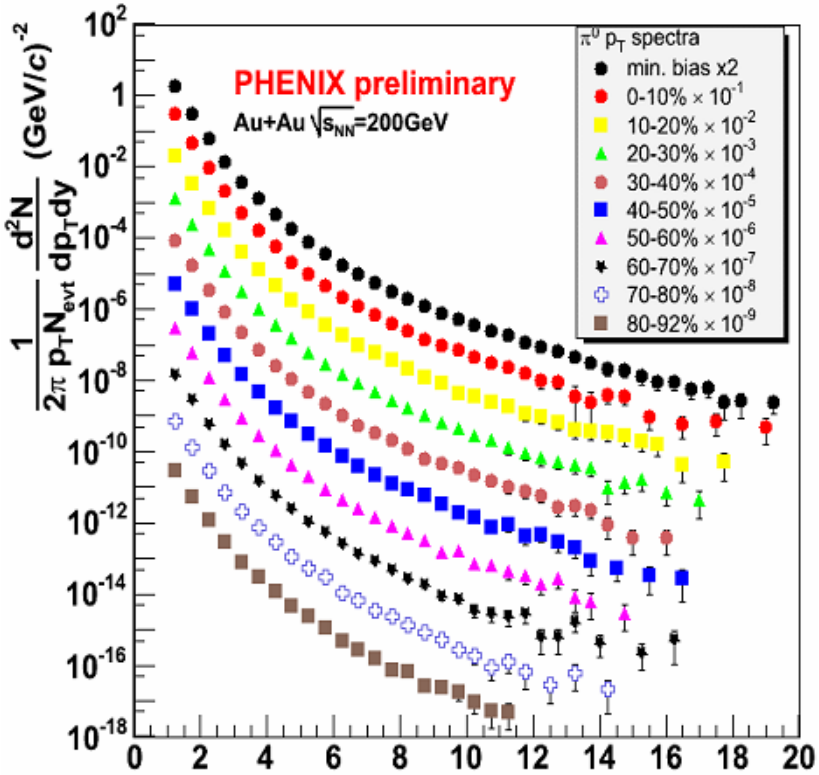
Au+Au → π^0 + *X* (central)

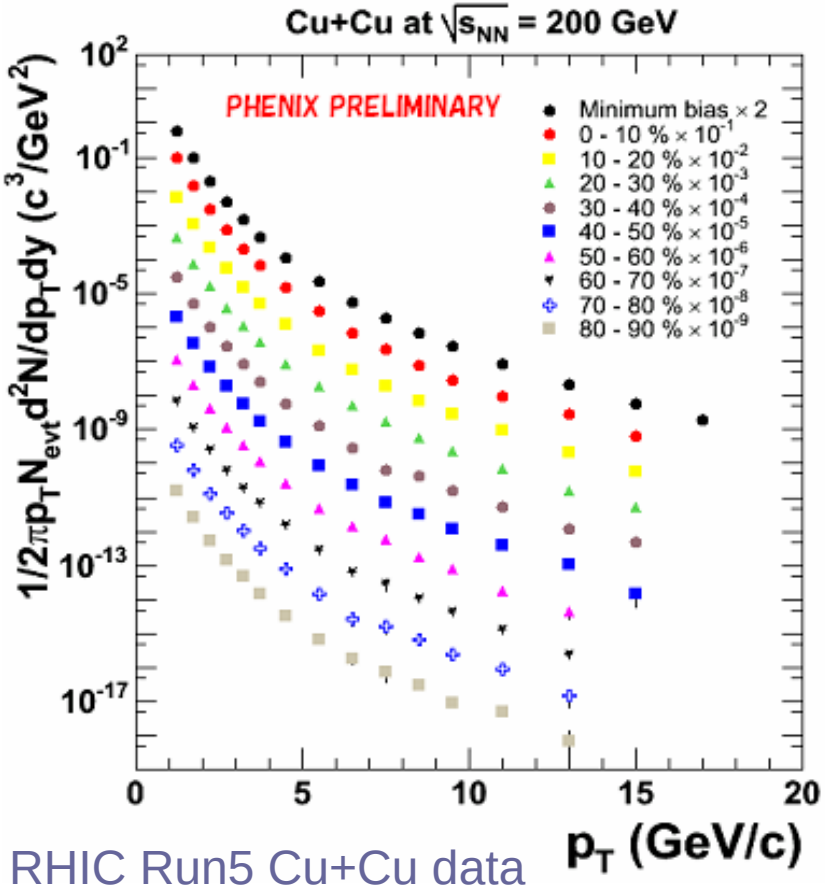


Peripheral spectra agree well with p+p (data & pQCD) scaled by N_{coll}

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

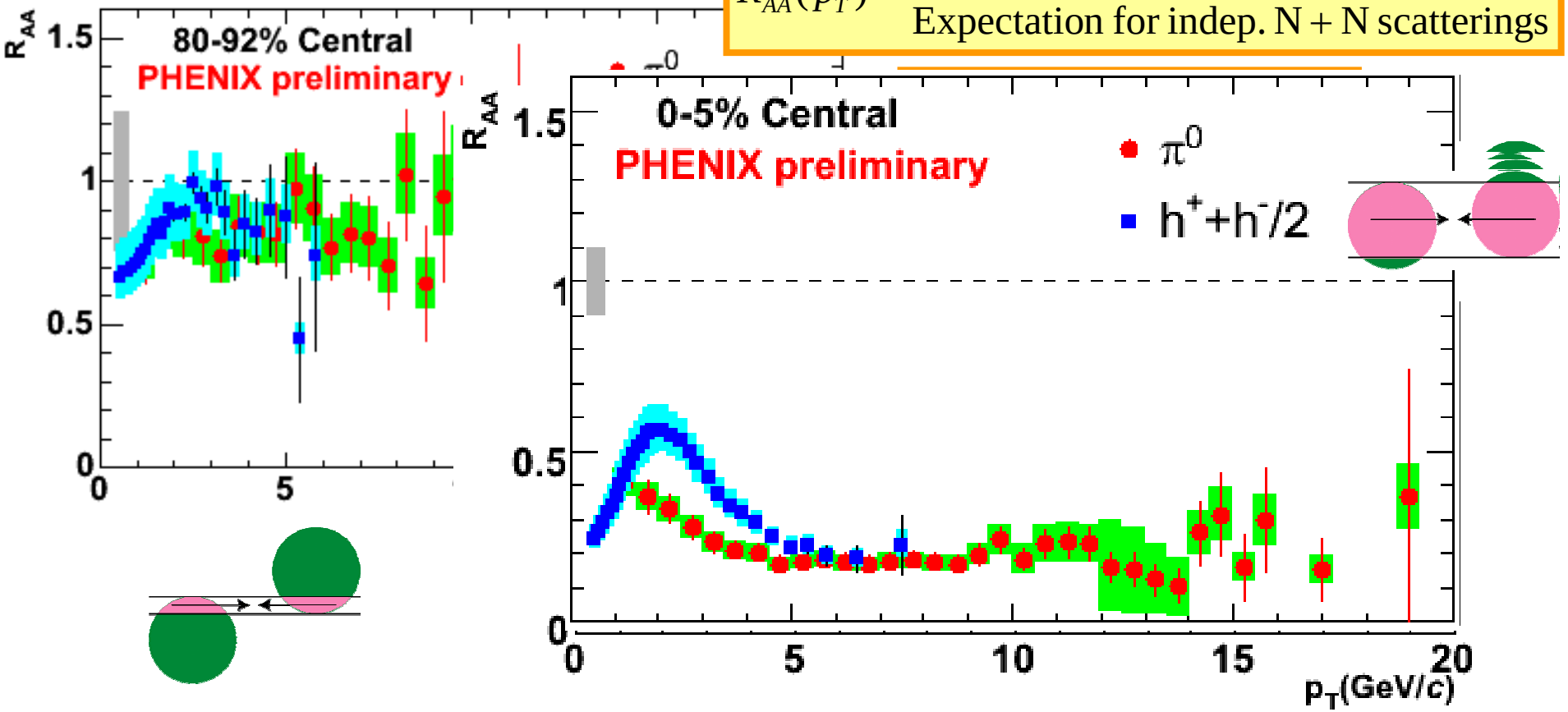
RHIC Run5 Cu+Cu data

- 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

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

Nuclear Modification Factor

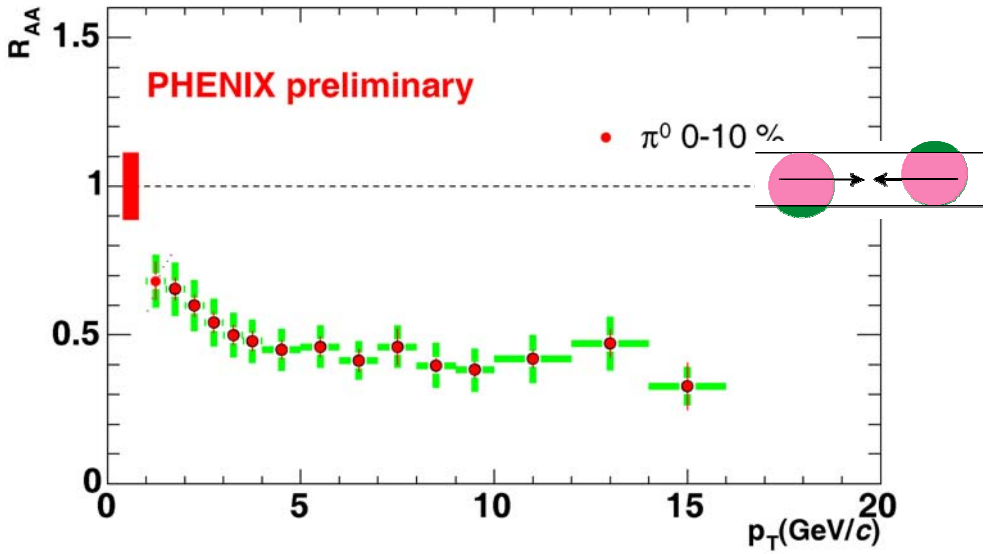
$$R_{AA}(p_T) = \frac{\text{Measured yield in A + A}}{\text{Expectation for indep. N + N scatterings}}$$



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

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

Cu+Cu

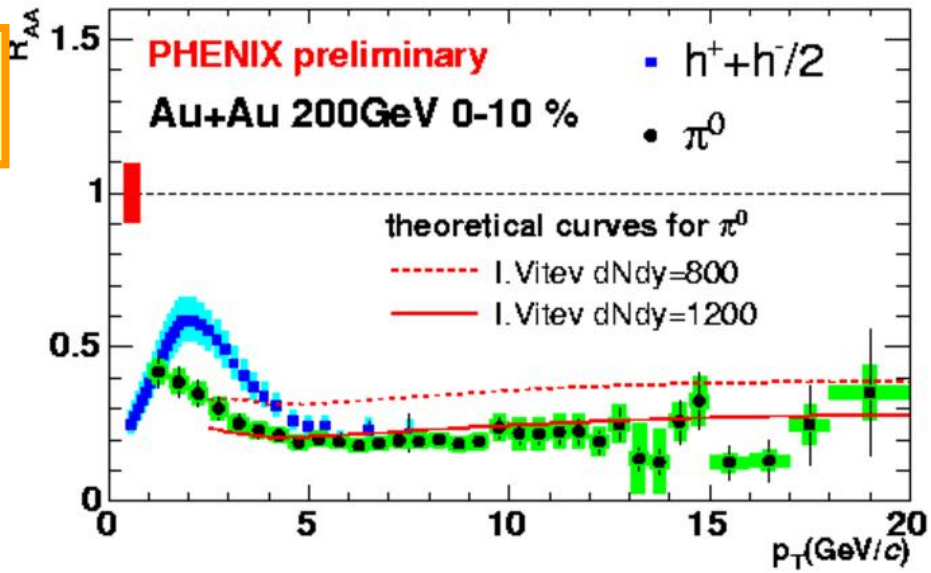


- R_{AA} ~ 0.4 for central collisions
- Similar suppression pattern as Au+Au
  - Constant for p_T>4 GeV/c
  - Strength of suppression increases with centrality

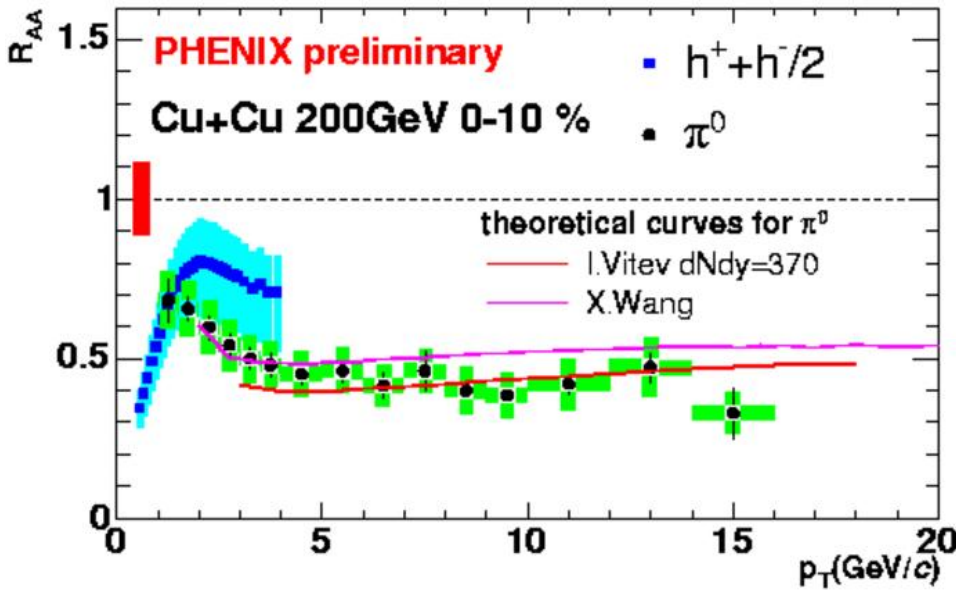
Modeling $R_{AA}(p_T)$ of Au+Au and Cu+Cu

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

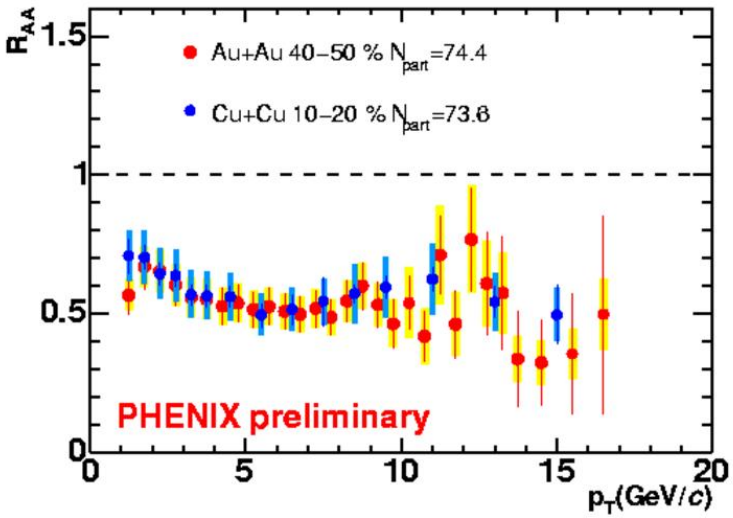
- R_{AA} for central Au+Au
  - Suppression strong and nearly constant up to 20 GeV/c
  - Consistent with dN_g/dy ~ 1200



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

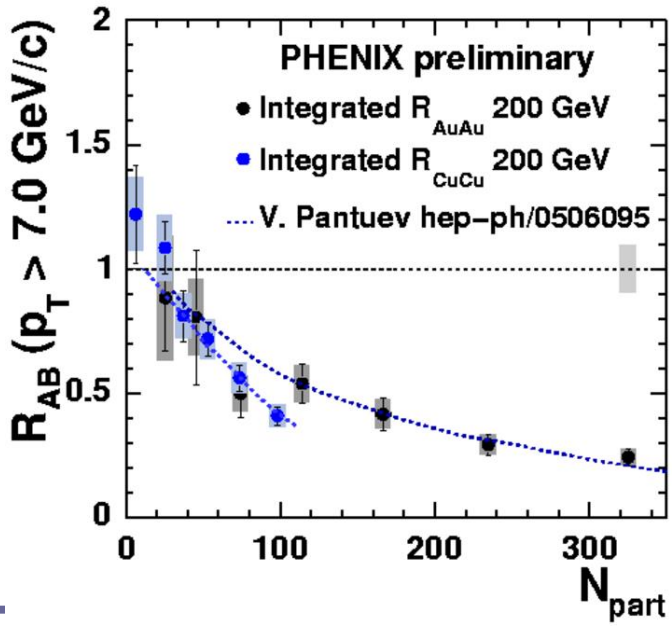


Au+Au vs. Cu+Cu



System size dependence

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

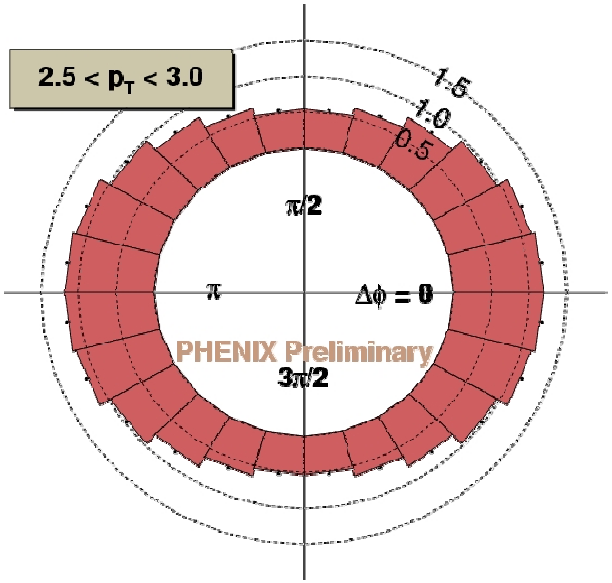


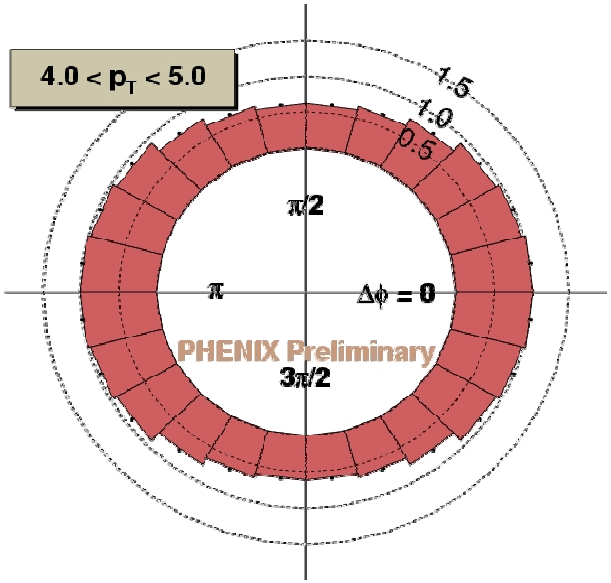
Integrated R_{AA}

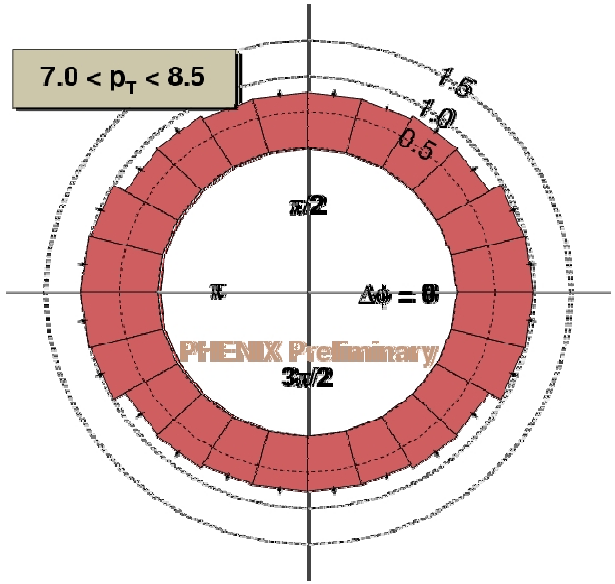
- Similar qualitative N_{part} dependence
- Vitev: Fair agreement with AuAu, but misses trend in CuCu
  - Fixed to AuAu, no surface effects
- Pantuev: geometrical model including "corona"
  - Surface jet bias, ellipticity included

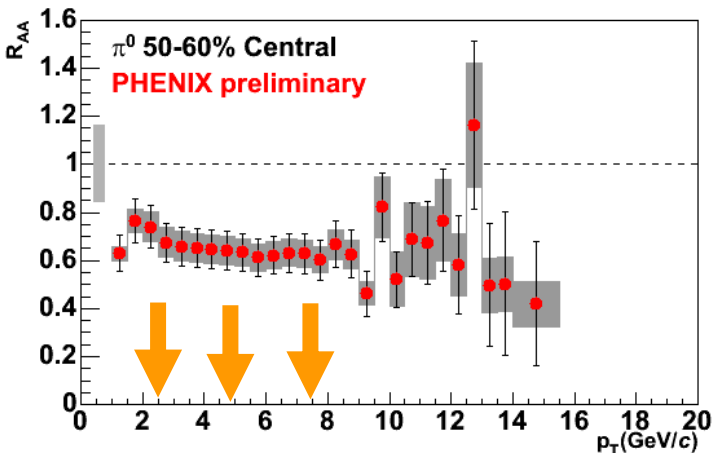
Measuring R_{AA} as fcn of angle wrt React Plane

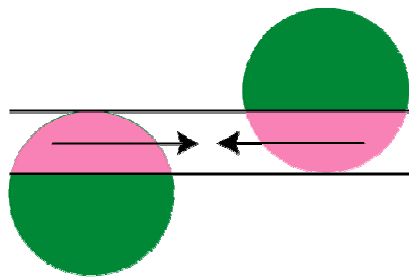
$R_{AA}(\Delta\phi, p_T)$ plotted in polar coords (folded to 2π)





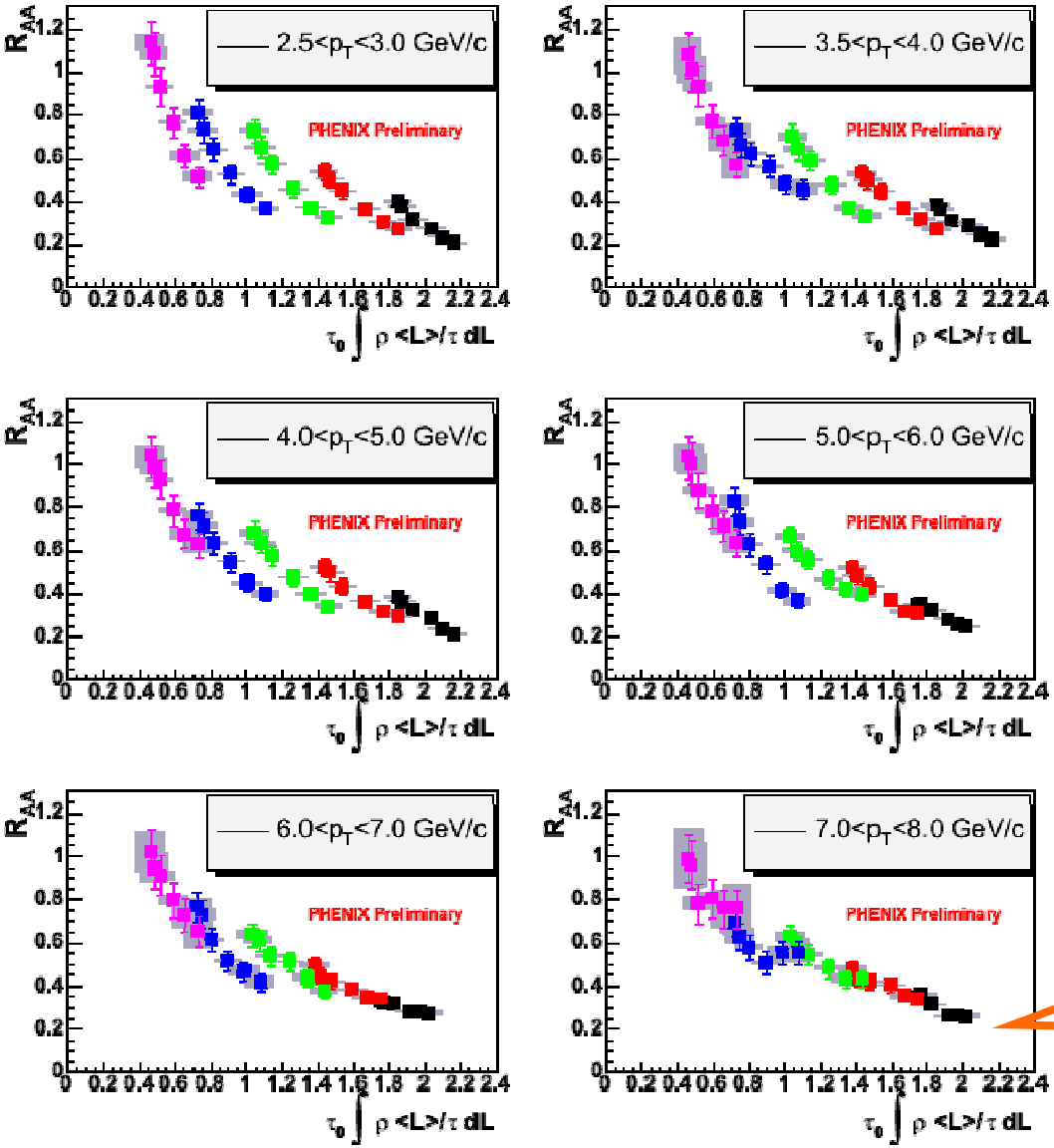


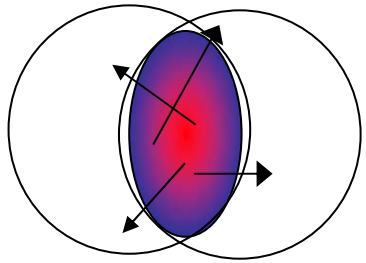




Au+Au $\sqrt{s_{NN}}$ = 200 GeV
50-60 % Centrality

R_{AA} vs. "ρ L dL"





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

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

10-20 % Centrality

20-30 % Centrality

30-40 % Centrality

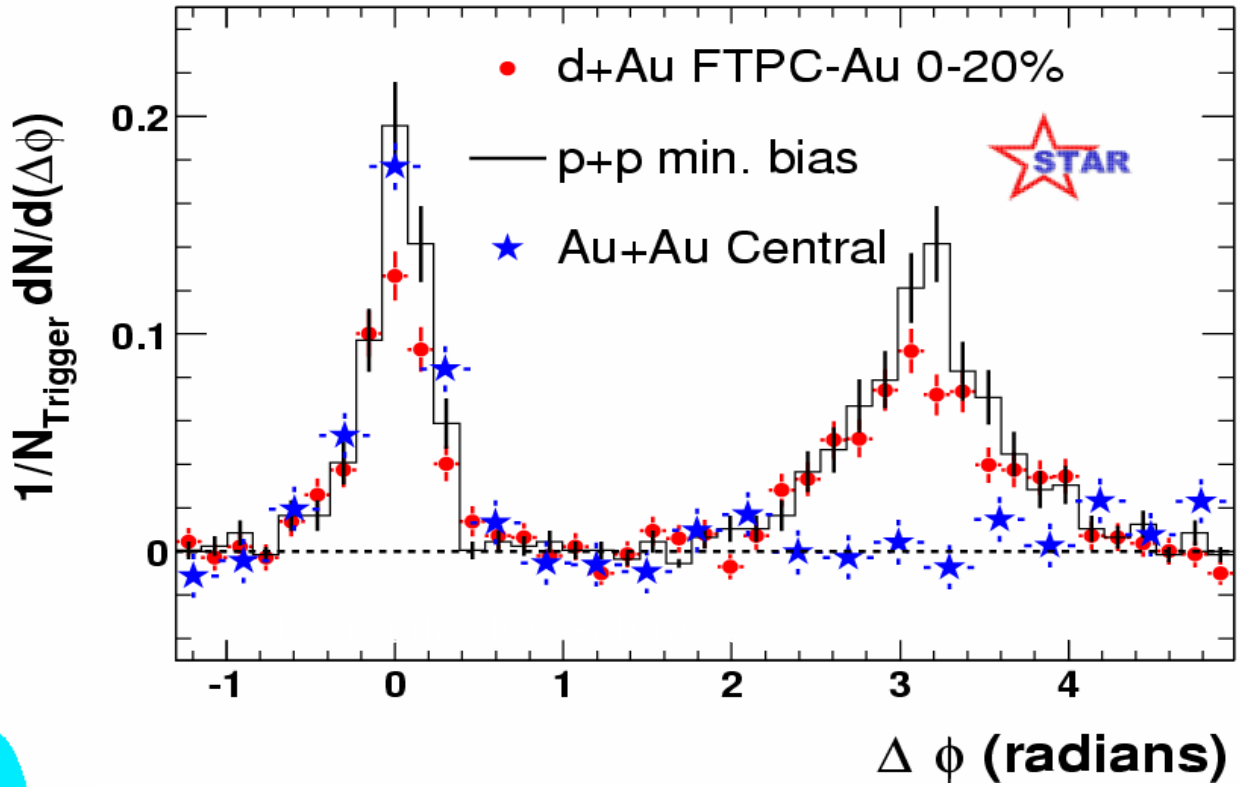
40-50 % Centrality

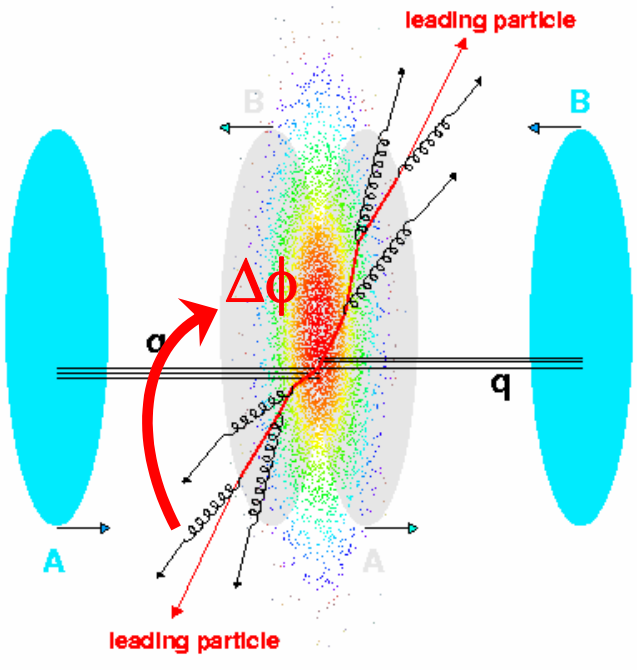
50-60 % Centrality

Angular and centrality dependence described by single curve!!

Azimuthal Correlations and Jet Suppression

- Azimuthal correlation functions show ~ complete absence of "away-side" jet





- ➡ Further evidence for surface emission only (?)
- That is, "partner" in hard scatter is absorbed in the dense medium

See parallel talk by Paul Stankus, QM & HIC III

Summary & Outlook

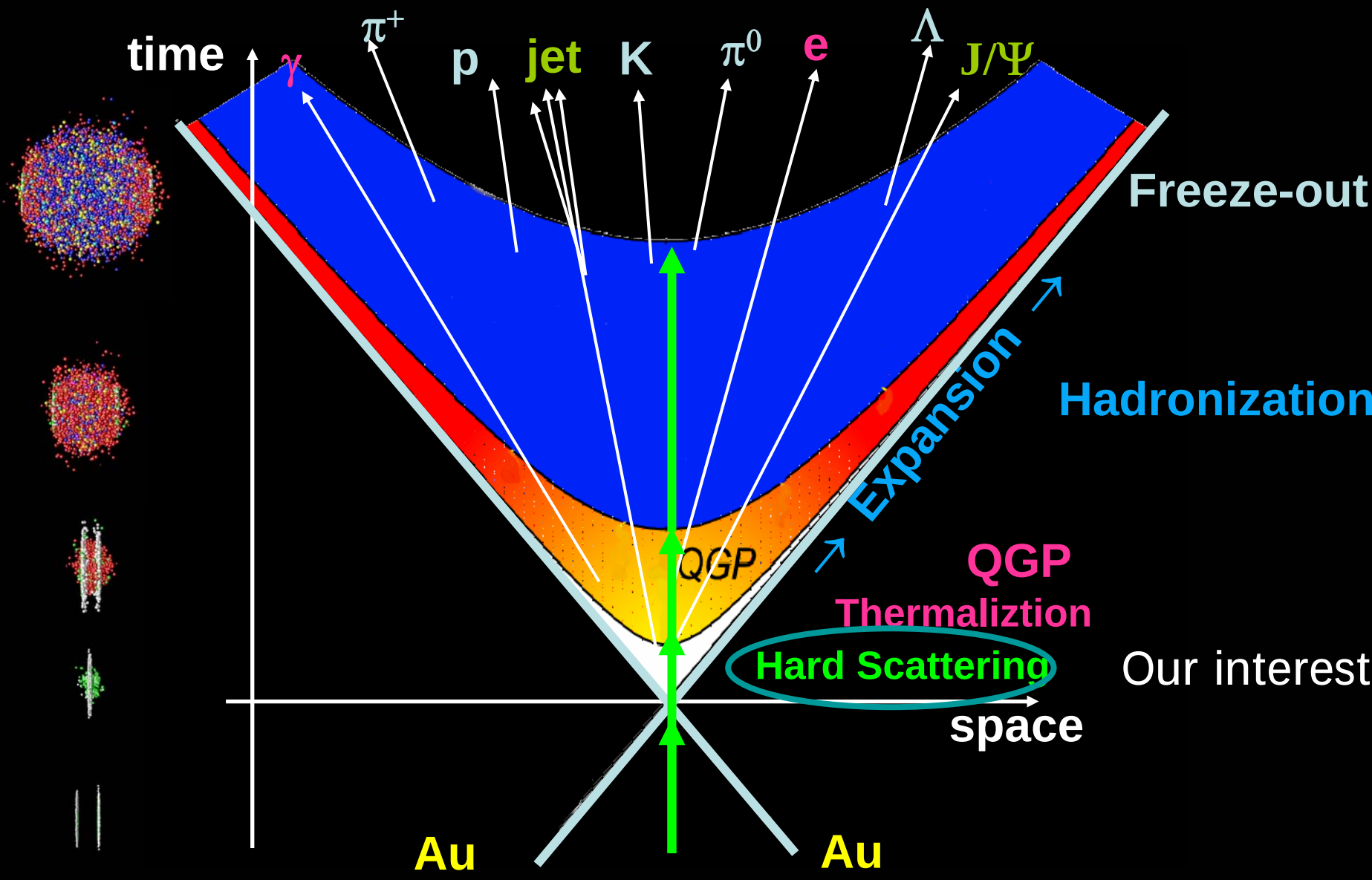
- High-p_T particle production gives access to hard-scattering processes
- Hard-scattering is a critical tool for probing the medium at early stages
- Important observables
  - Spectra with high-p_T reach
  - Suppression seen in $R_{AA}(p_T)$ at high-p_T
    - Similar patterns in AuAu vs. CuCu for same N_{part}
    - Hints for corona/surface effects
    - Evidence for energy loss as dominant effect
- Results shown here only scratch the surface of the methods for studying the medium in PHENIX, see talks:
  - High-p_T/Hard processes:
    - P. Stankus – Jets and the Medium
    - K. Reygers – Direct photons in AuAu
    - H. Torii – Direct photons in pp, dAu
  - Bulk properties, heavy flavor:
    - P. Chung, M. Issah, X. Wei, H. Masui, X. Wang

Extras

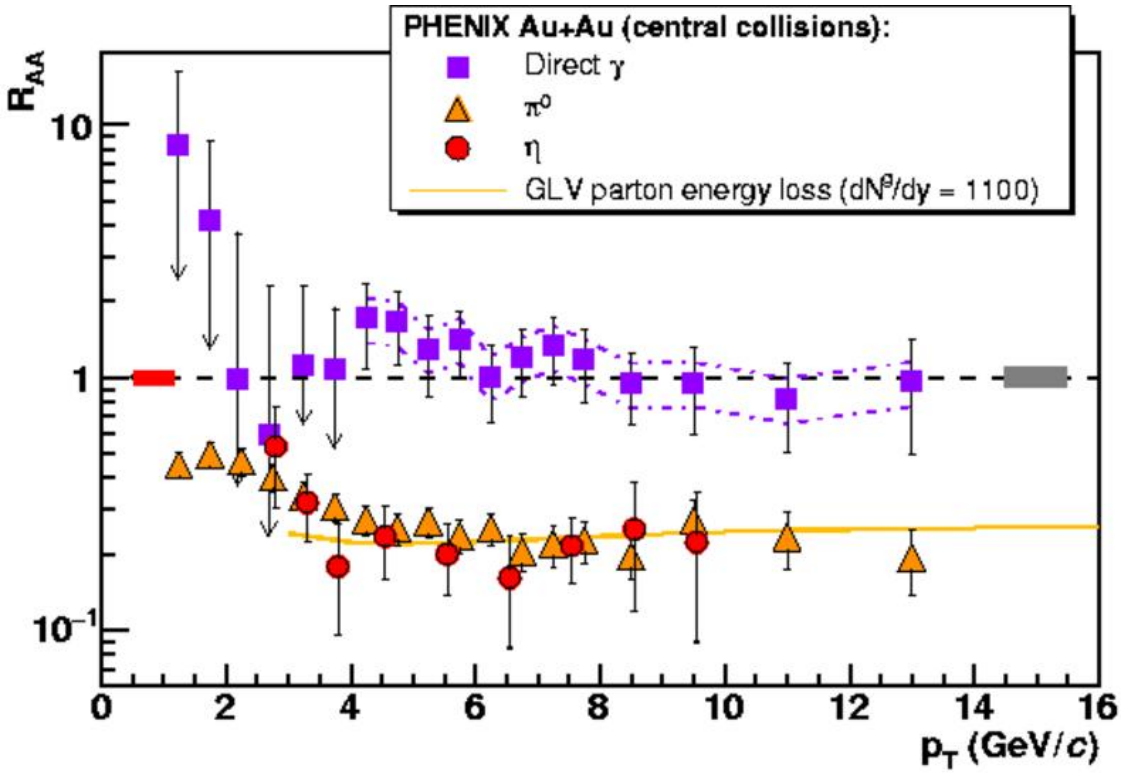
PHENIX Run-1 to Run-5 History

Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{Tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB
05	2004/2005	Cu+Cu	200	3 nb^{-1}	8.6G	11.9 pb^{-1}	173 TB
		Cu+Cu	62	0.19 nb^{-1}	0.4G	0.8 pb^{-1}	48 TB
		Cu+Cu	22.5	2.7 μb^{-1}	9M	0.01 pb^{-1}	1 TB
		p+p	200	3.8 pb^{-1}	85B	3.8 pb^{-1}	262 TB

Space-time Evolution of Collisions



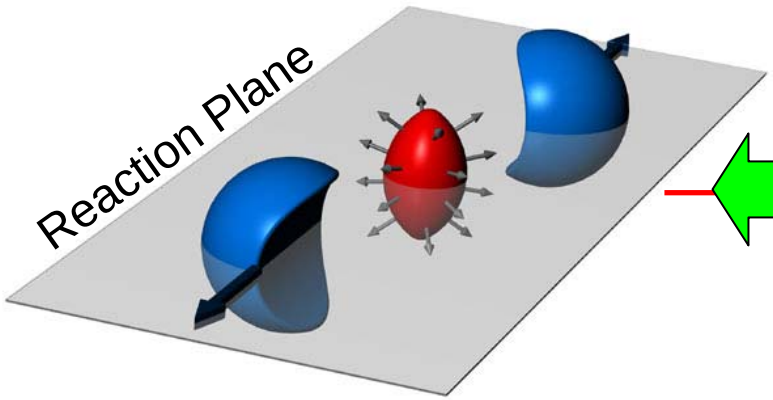
Mass dependence at high p_T

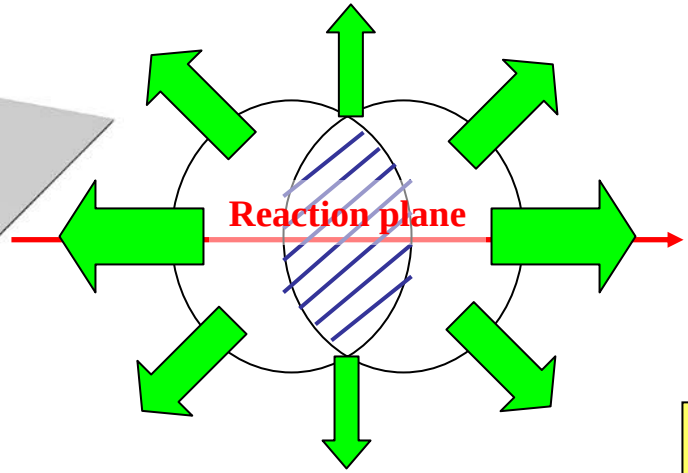


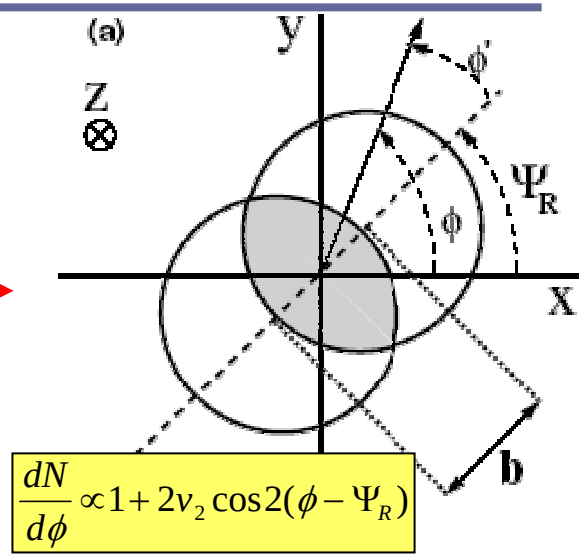
- η same quark content as π^0
- Factor 4 heavier
- Same R_{AA} as π^0
  - Suppression does not depend on hadron-mass

nucl-ex/0601037

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<|η|<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 Δφ
  - Measure π^0 dN/dp_T in 6 $\Delta\phi$ bins over [0,π/2]. (corrected for resolution)
  - Multiply the ratio

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

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