Hard Probes 2004

Lisbon, Portugal

RHIC Experimental Program

-Background in preparation for meeting

Wit Busza

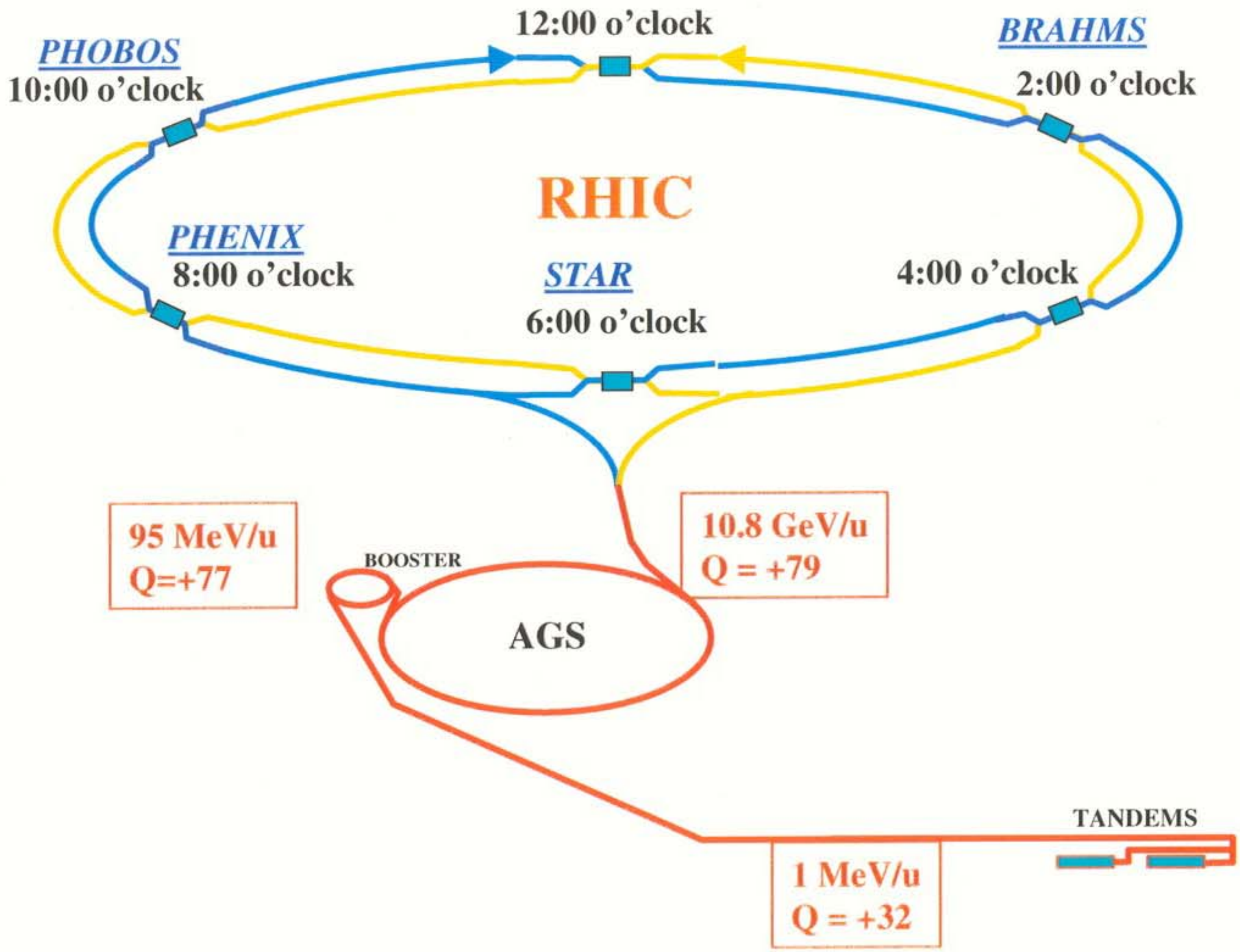
MIT

Many thanks to Michael Miller for help in preparation of this talk, to Conor Henderson for making some of the transparencies, and to the four RHIC collaborations for most of the material presented in the talk.

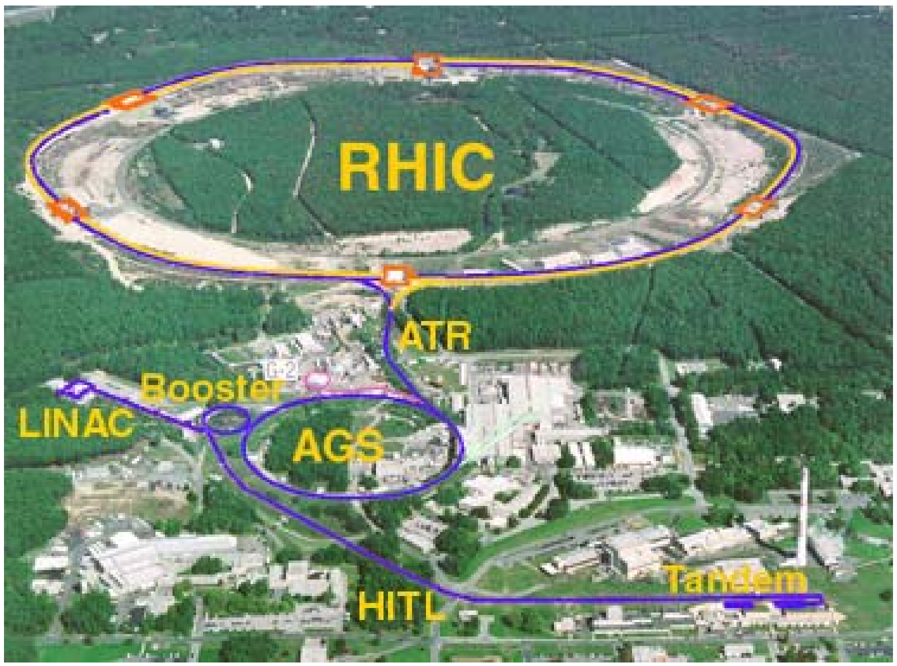
The Relativistic Heavy Ion Collider at BNL

Gold Ion Collisions in RHIC

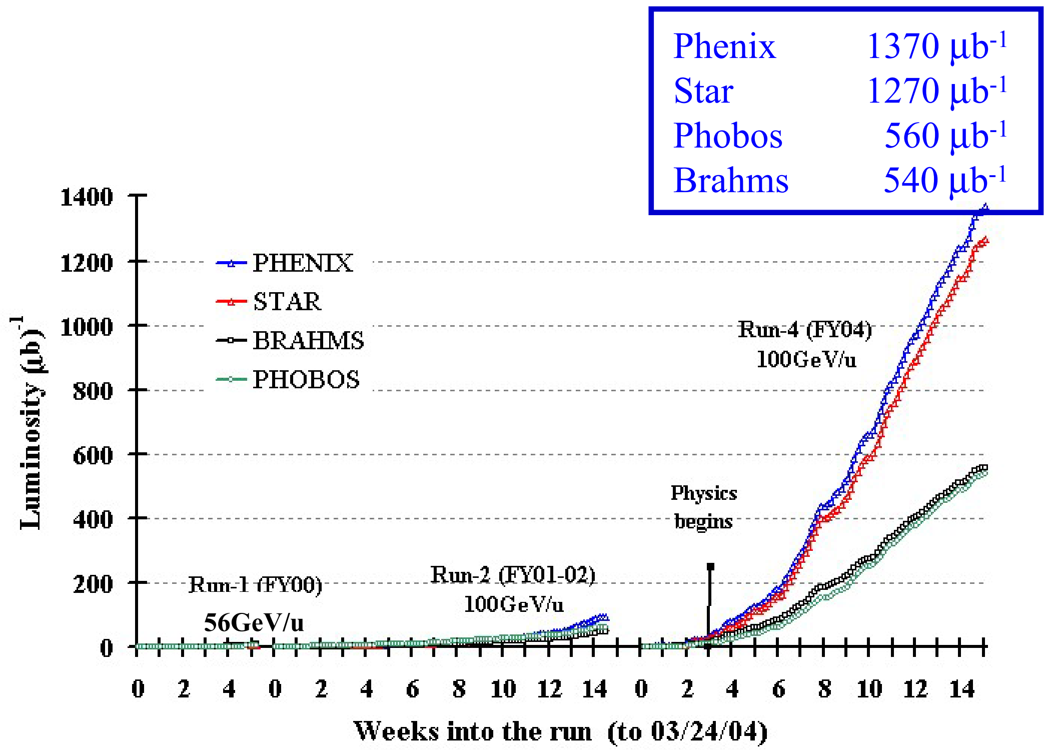
Beam Energy = 100 GeV/u	T_{store} = 10 hours
No. Bunches = 57	
No. Ions /Bunch = $1x10^9$	$L_{ave} = 2x10^{26}$ $cm^{-2}sec^{-1}$



RHIC First Commissioned, June 2000



2000-2004 RHIC PERFORMANCE



RHIC Run	Colliding System	$\sqrt{s_{NN}}$
1	Au+Au Au+Au	55.87GeV 130.4GeV
2	Au+Au Au+Au Au+Au p+p	130.4GeV 200.0GeV 19.59GeV 200.0GeV
3	d+Au p+p	200.7GeV 200.0GeV
4	Au+Au Au+Au p+p	200.0GeV 62.40GeV 200.0GeV

THE DETECTORS

The Two Large Detectors

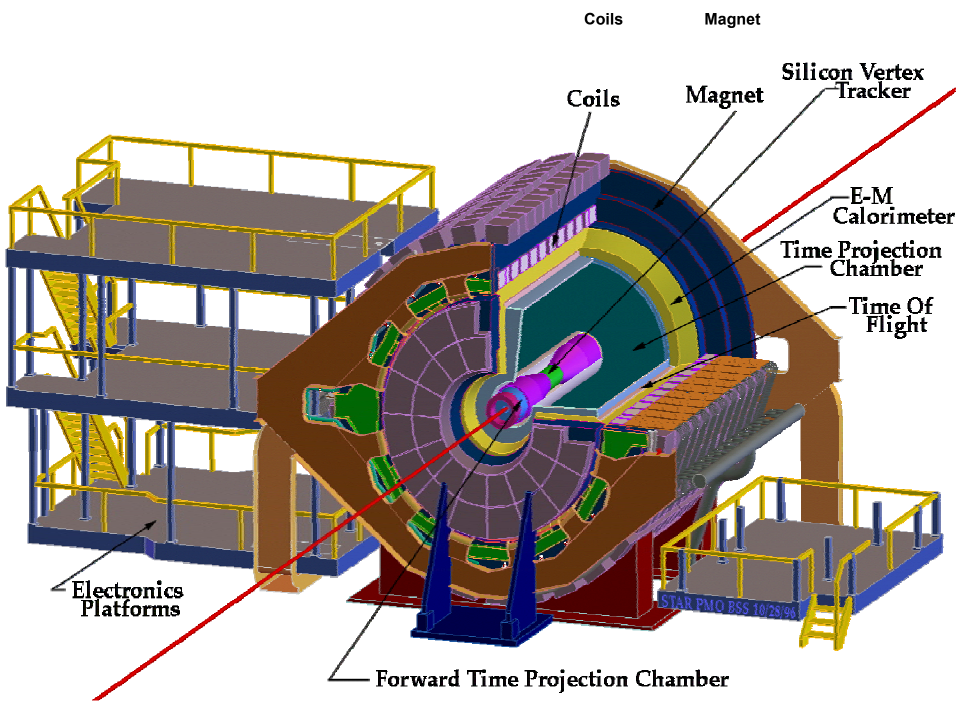
STAR

Solenoidal field, large-Ω tracking

TPC's, Si-vertex tracking

RICH, TOF, large EM Cal

~420 participants



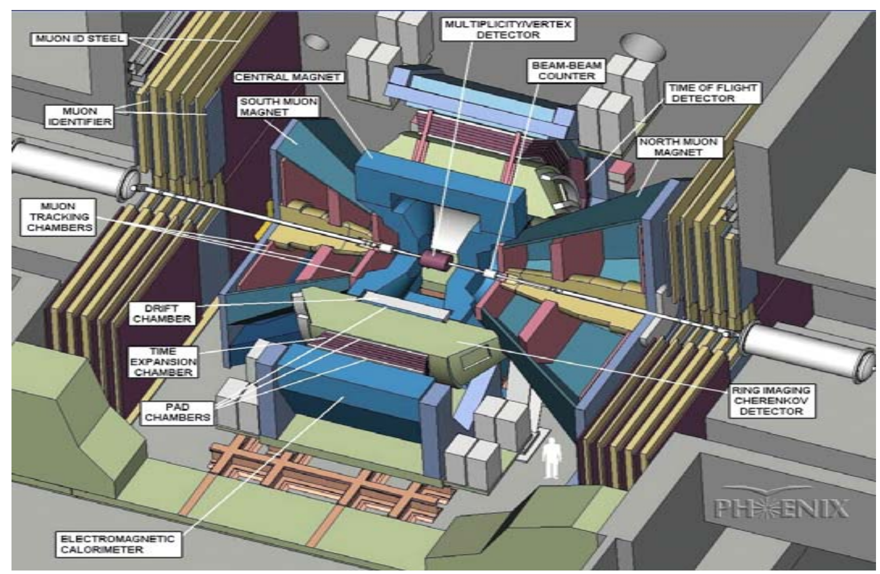
PHENIX

Axial field, high resolution & rates

2 central arms, 2 forward muon arms

TEC, RICH, EM Cal, Si, TOF, μ-ID

~450 participants



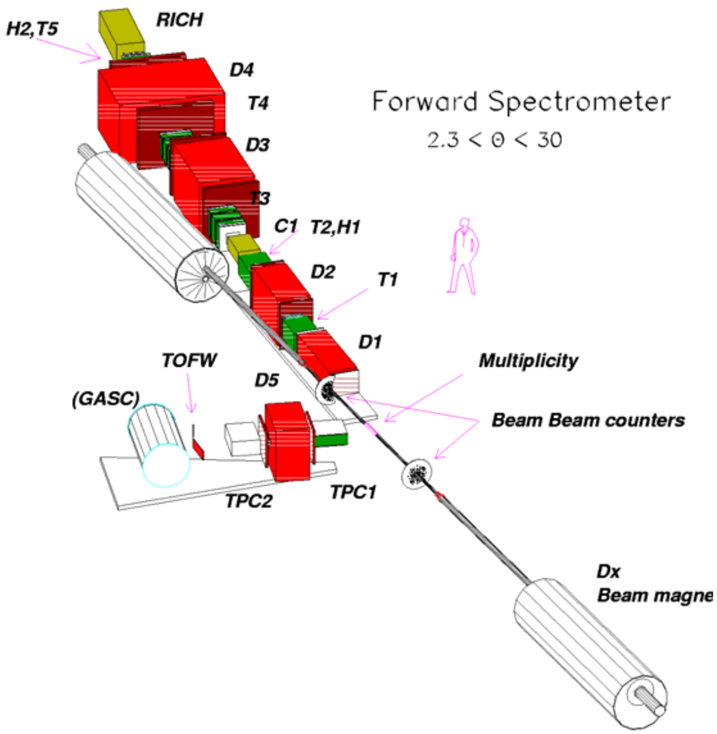
The Two Small Detectors

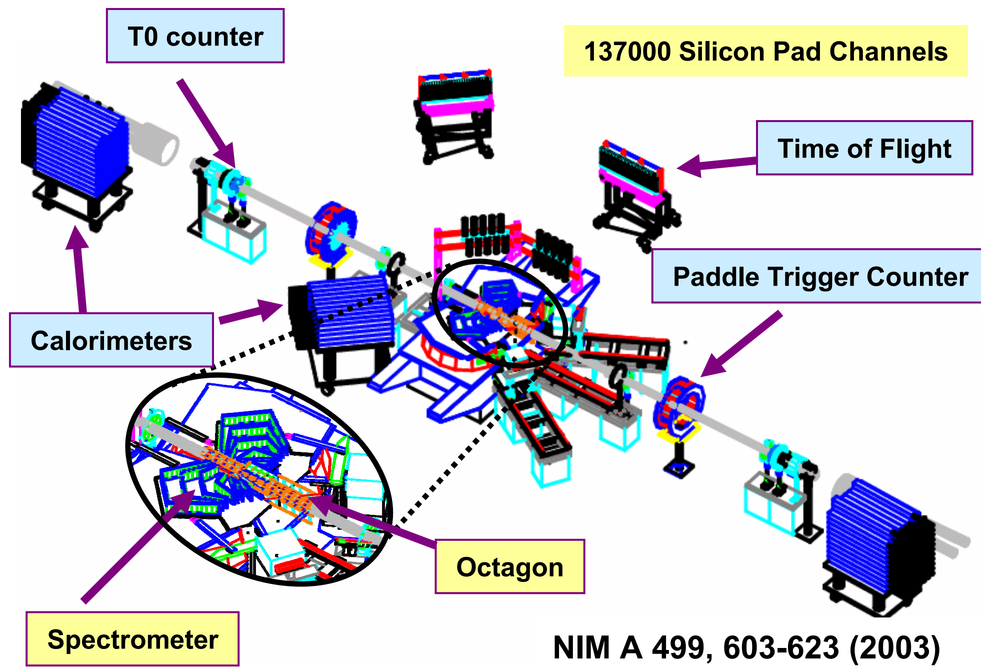
BRAHMS

2 "conventional" spectrometers
Multiplicity detector
with large phase space coverage
Magnets, TPCs, TOF, RICH
~40 participants

PHOBOS

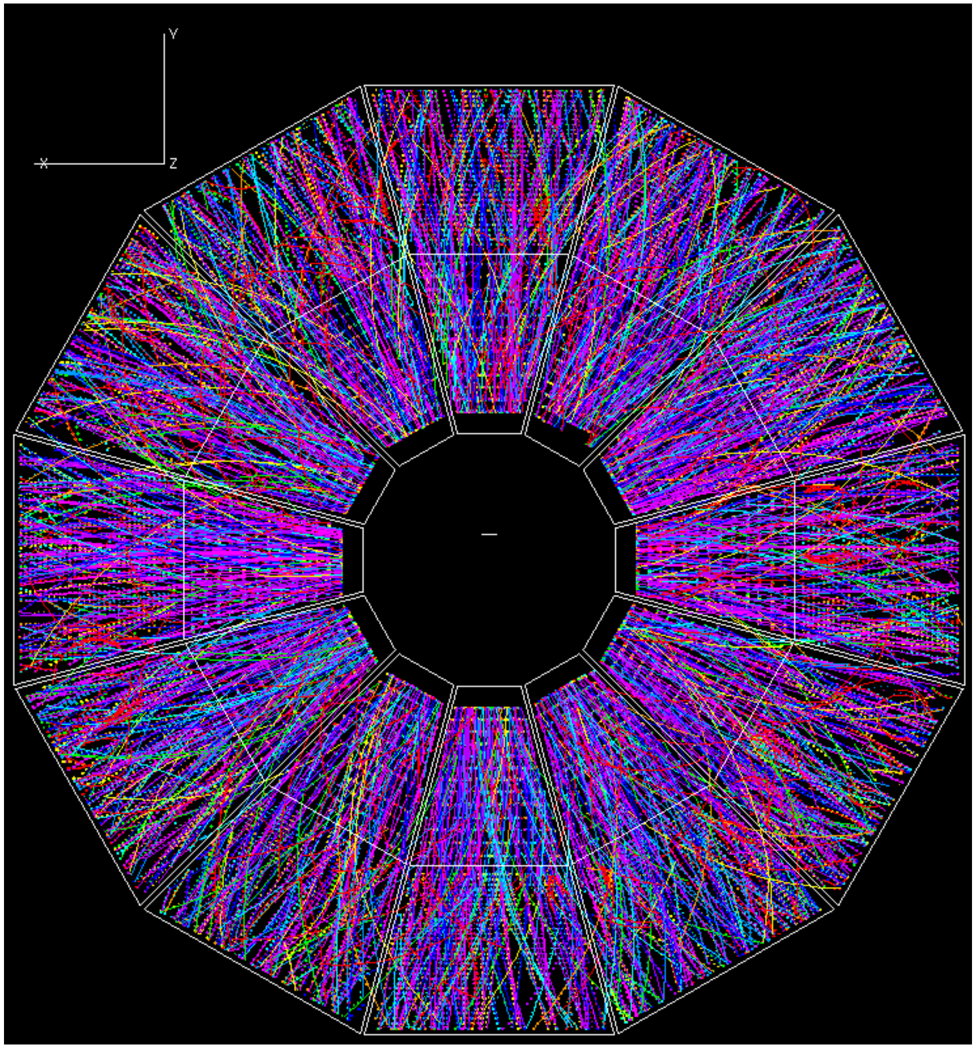
"Table-top" 2-arm spectrometer
full phase space multiplicity measurement
Magnet, Si pad detectors, TOF+dE/dx
~70 participants



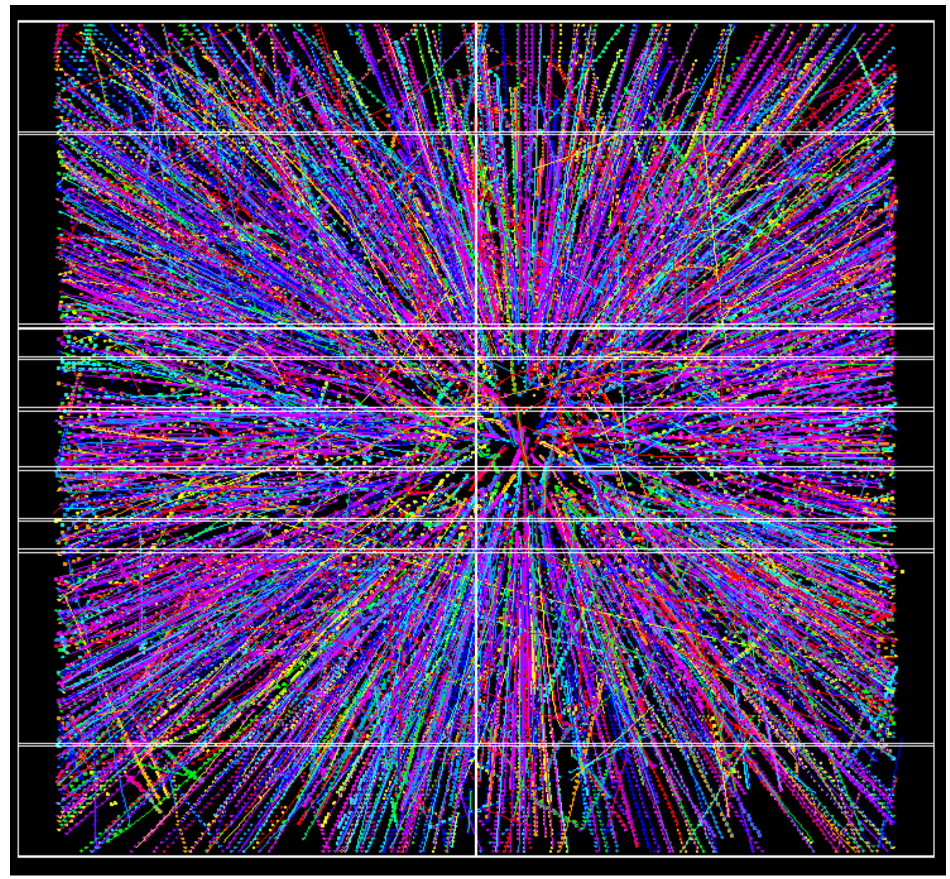


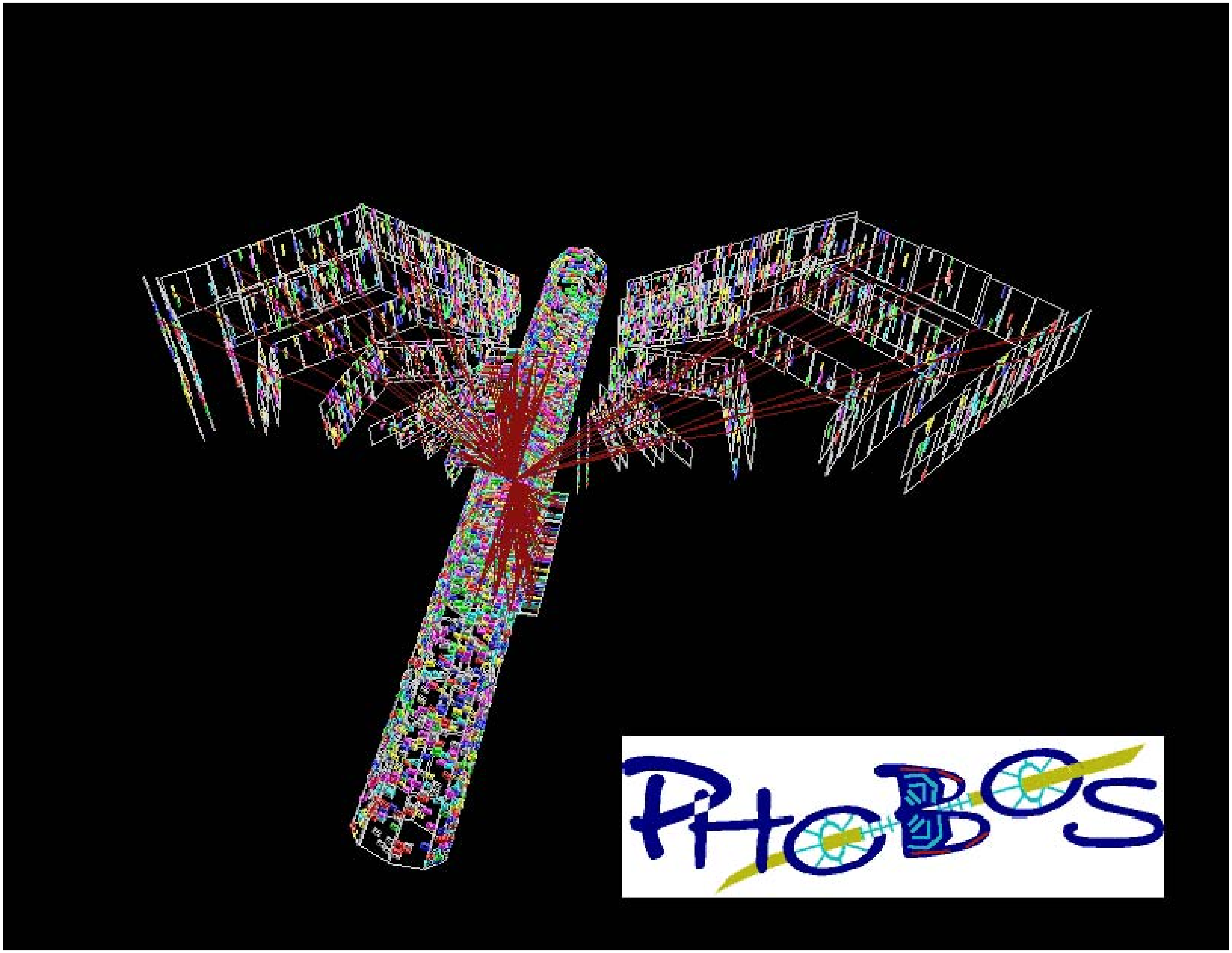
NIM A 499, 603-623 (2003)

High Multiplicity Au+Au Collision at $\sqrt{s_{NN}}$=130 GeV

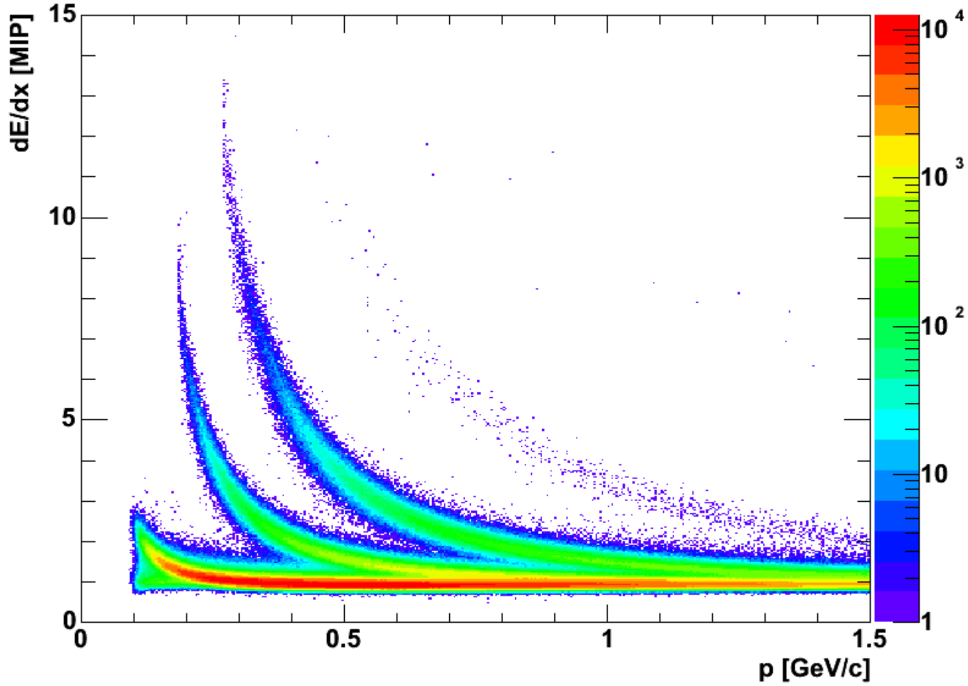


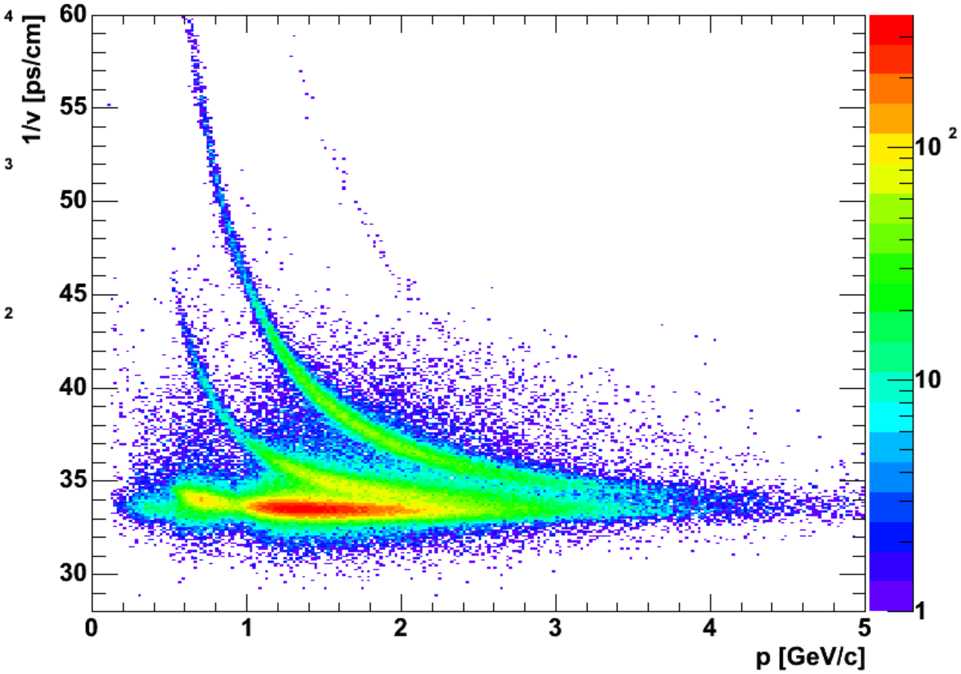
colors ~ momentum: low - - - high

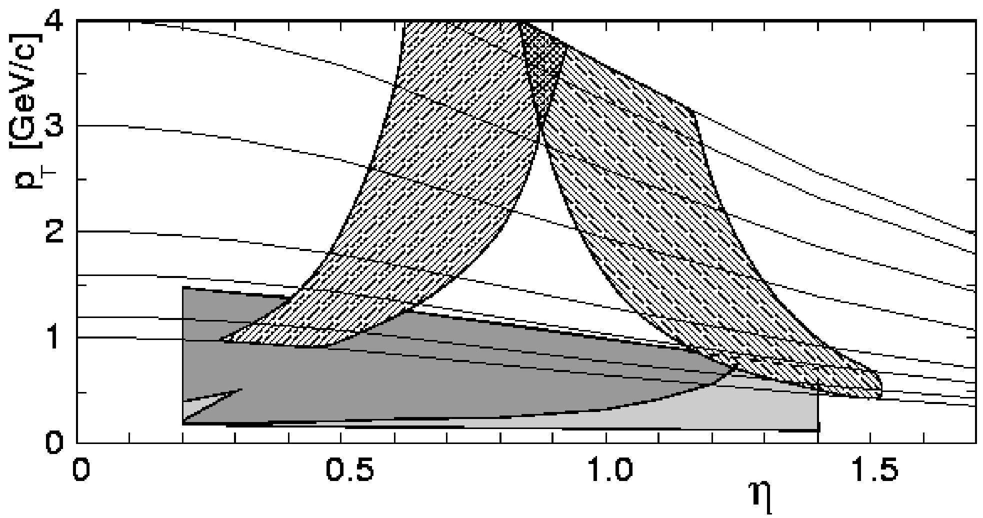



PHOBOS

PHOBOS PID & ACCEPTANCE







Measured Quantities

Single Particles

Tracking $\rightarrow \vec{p}$

time of flight, $\frac{dE}{dx} \rightarrow$ mass

$\Big\}$ P_μ

Event Characteristics

$$\frac{d^2 n_{ch}}{d\eta d\phi}$$

$$\frac{dE_T}{d\eta d\phi}$$

$\Big\}$ n_{ch}^{total}, E_T^{total}

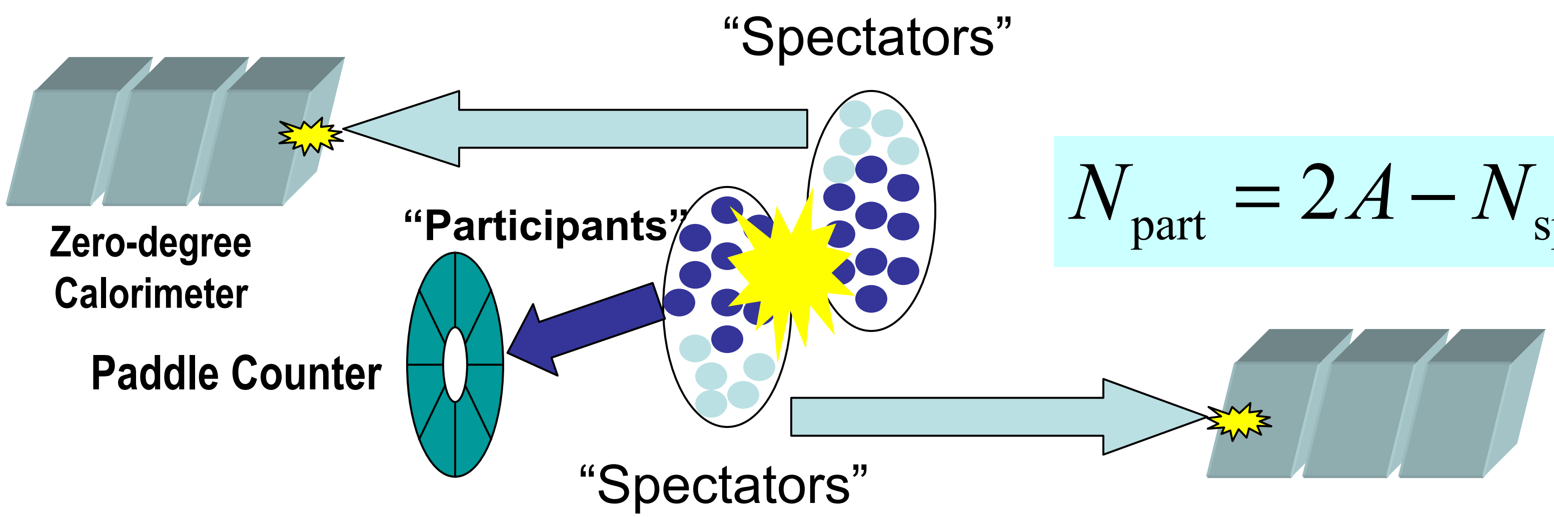
Forward Neutral Energy

"spectators"

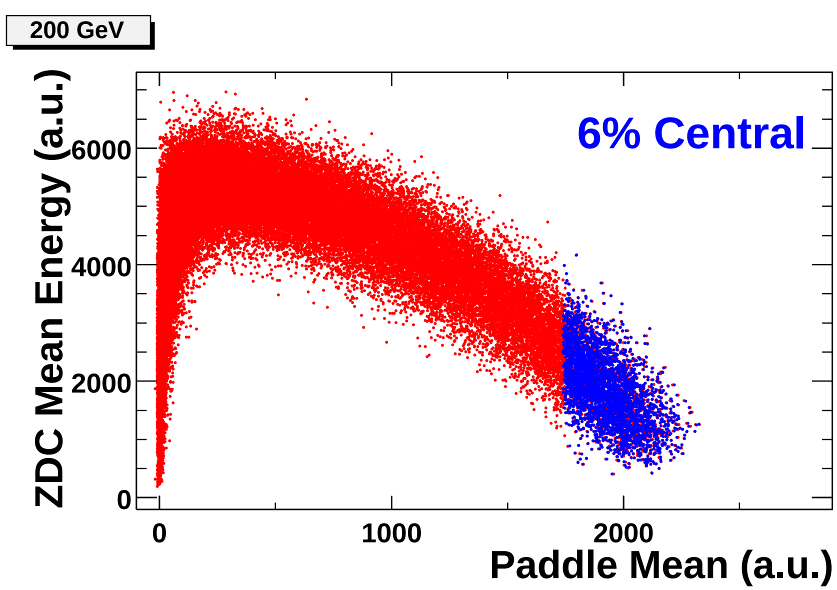
$\Big\}$ Centrality or impact parameter, b

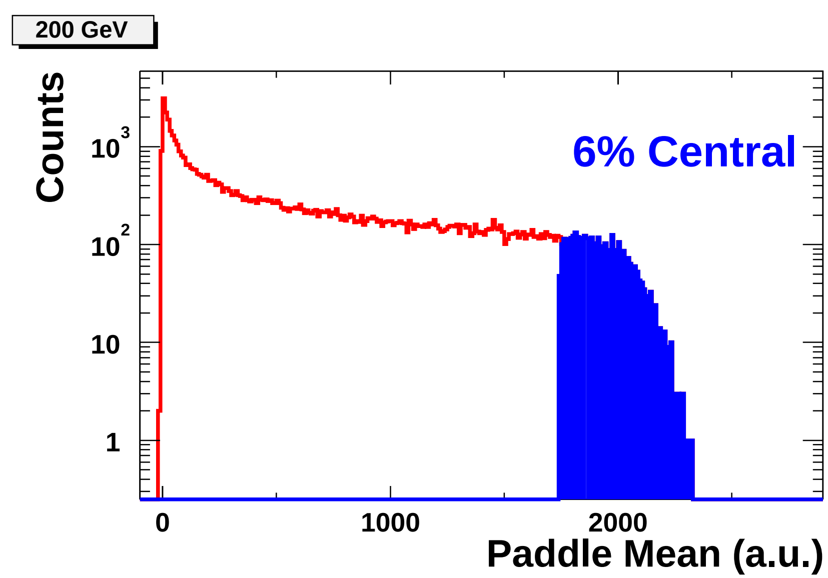
["N_{part}", "N_{coll}"]

Experimental Control of Centrality or Impact Parameter

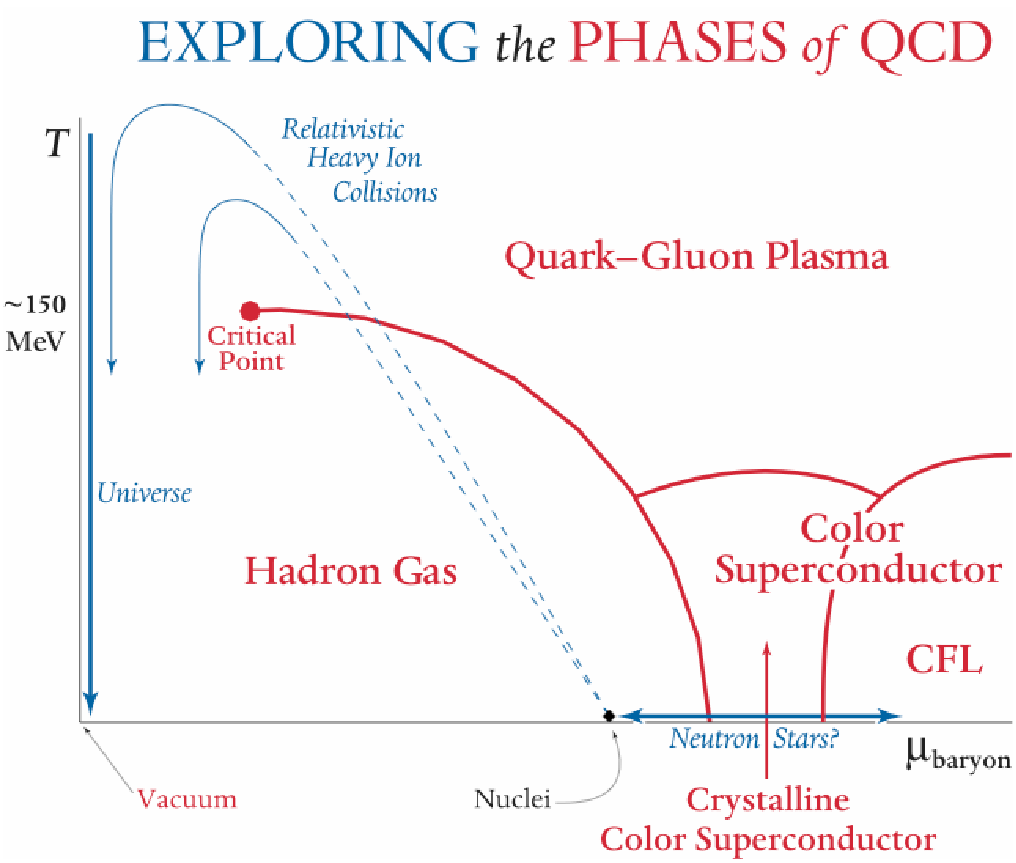


$$N_{\text{part}} = 2A - N_{\text{spec}}$$





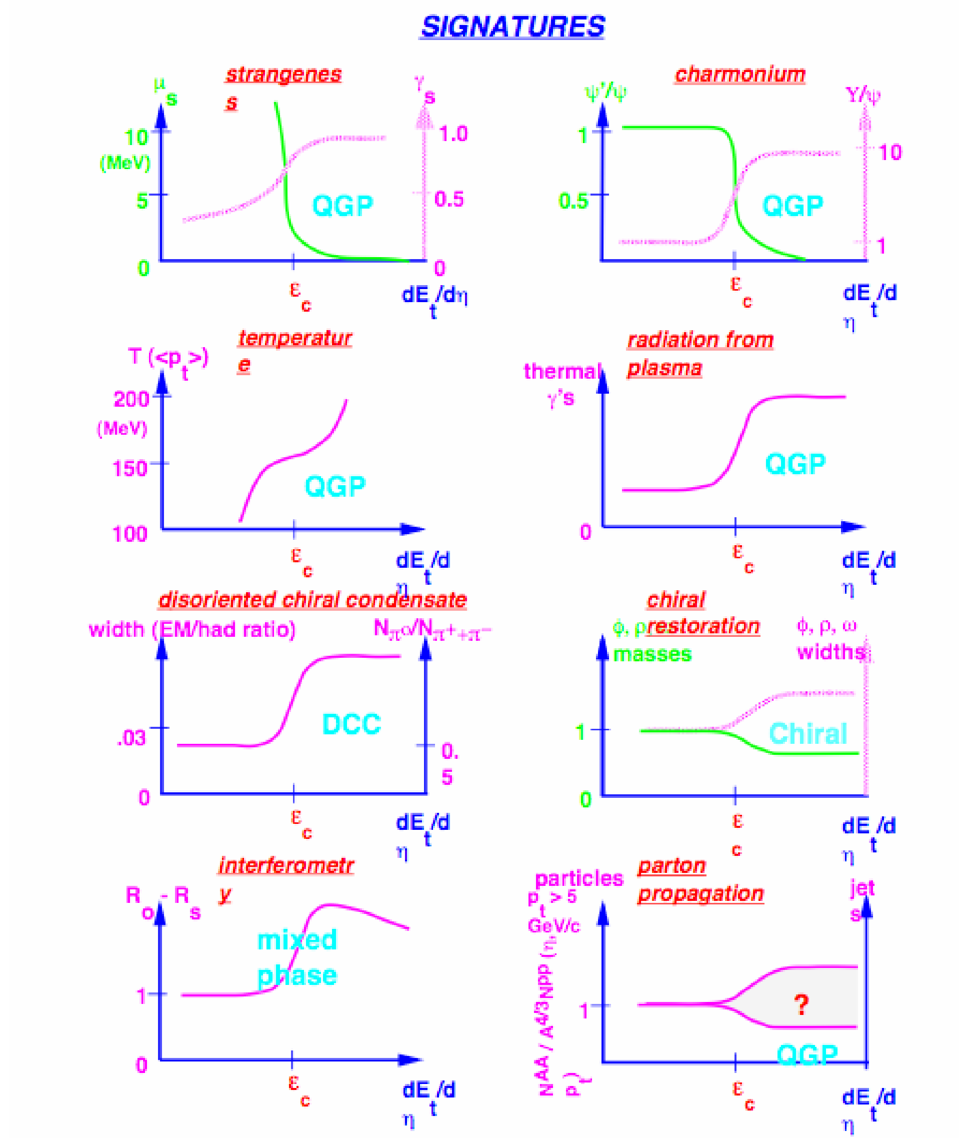
Aim of Research:



Bi-product: Study of Mechanism of Particle Production

See, for example, W. Busza arXiv: nucl-ex/0410035

Too good to be true!



From Harris and Mueller
Ann. Rev. Nucl. Sci. 1996

But RHIC program is an incredible success

BRAHMS, Phenix, Phobos & STAR "White Papers":

"Perspectives on Discoveries at RHIC"

To be submitted to NPA November, 2004

BRAHMS arXiv: nucl-ex/0410020

Phenix arXiv: nucl-ex/0410003

Phobos arXiv: nucl-ex/0410022

RIKEN BNL Workshop May 14-15, 2004

Submitted to NPA 2004

New Discoveries at RHIC
A RIKEN BNL Research Center Workshop, May 14-15, 2004
Proceedings, Volume 62, BNL-72391-2004

Where Are We Now?

In Au + Au Collisions at RHIC

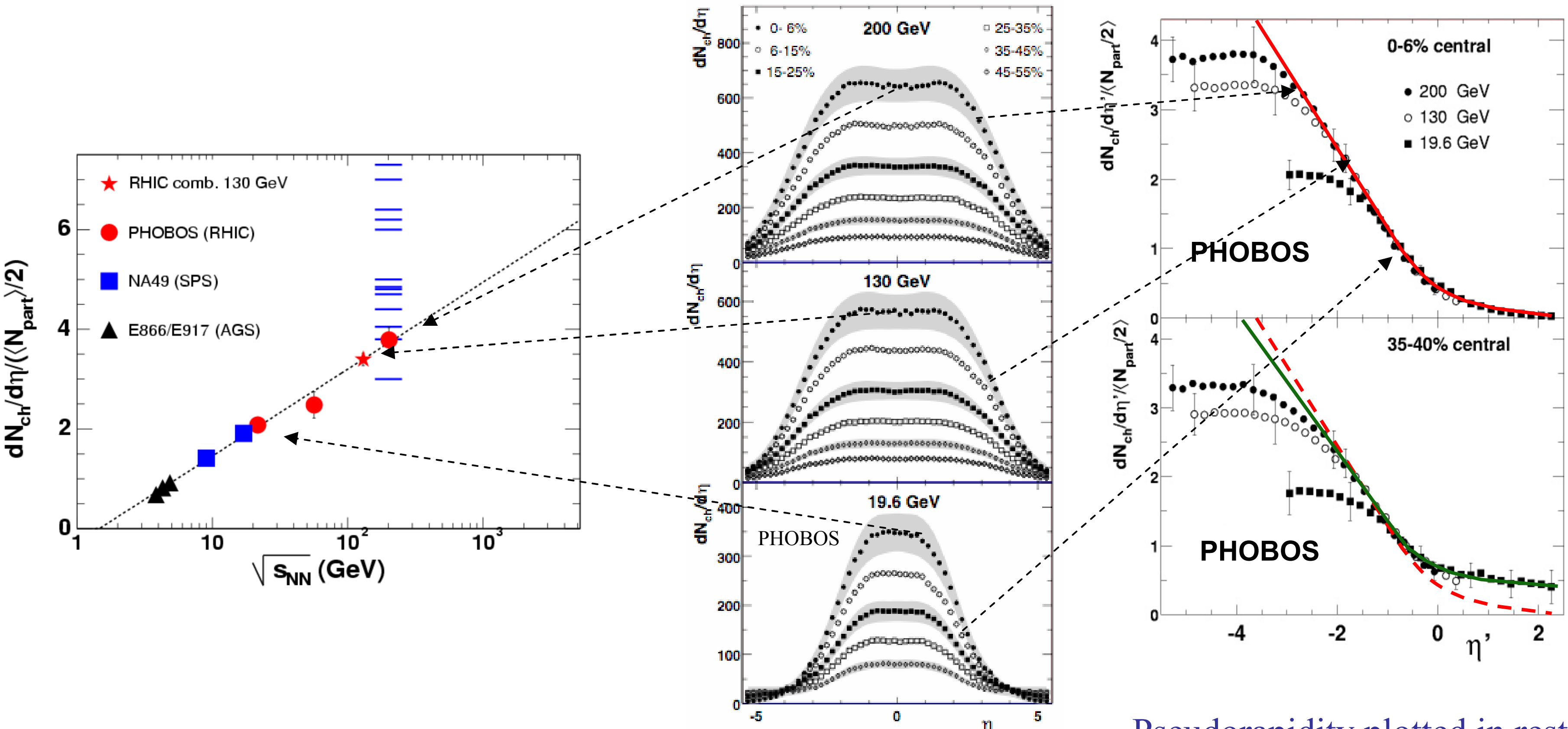
1. In $\leq$ 1 fm/c energy density$\geq$3GeV/fm^3
2. Description of the created system in terms of simple hadronic degrees of freedom is inappropriate
3. Constituents of this novel system are found to interact very strongly

In addition large body of high quality data has been collected on a broad range of topics. Much of it is not well understood.

Phenomenology is often simpler than the interpretations.

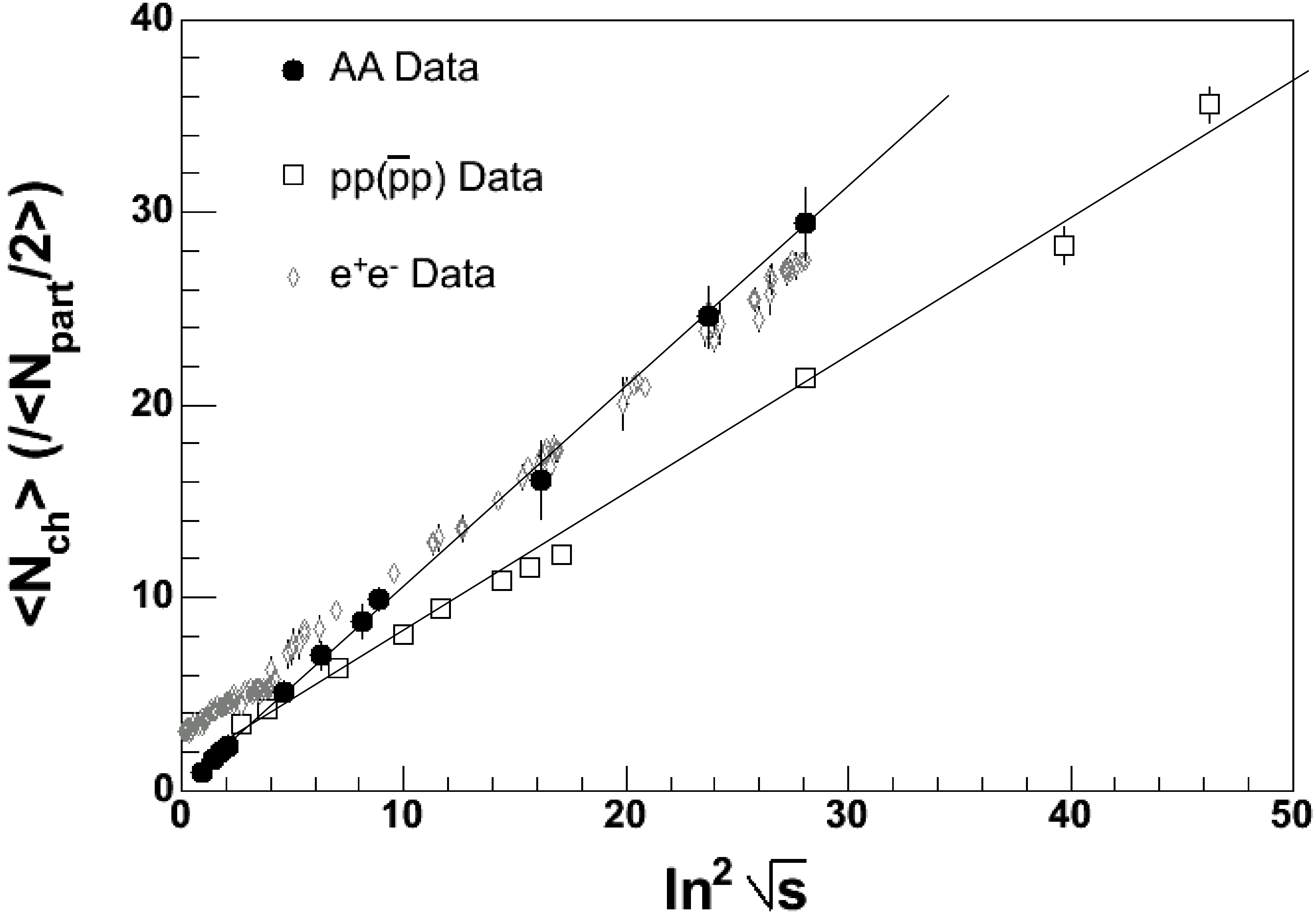
Global Properties

Data smooth as a function of energy

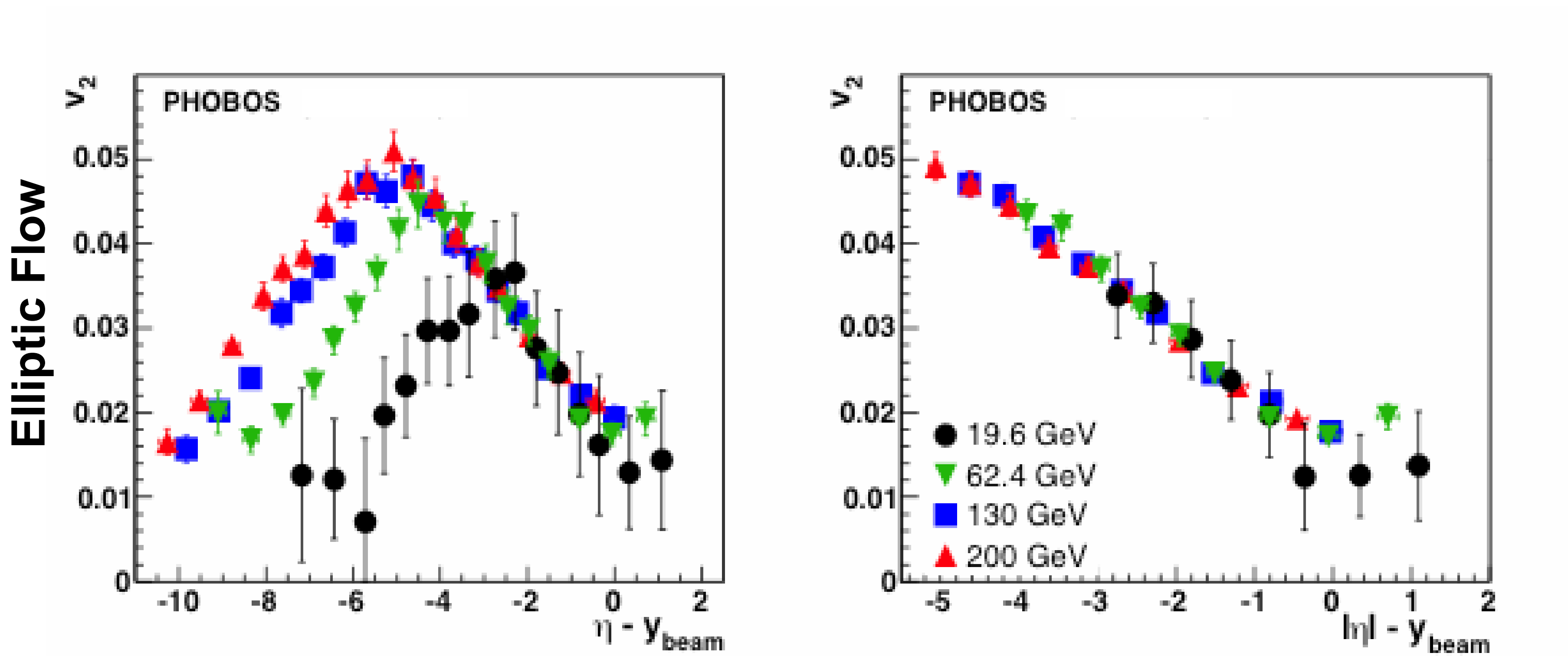


Pseudorapidity plotted in rest frame of one of the nuclei

TOTAL CHARGED MULTIPLICITY



Elliptic Flow

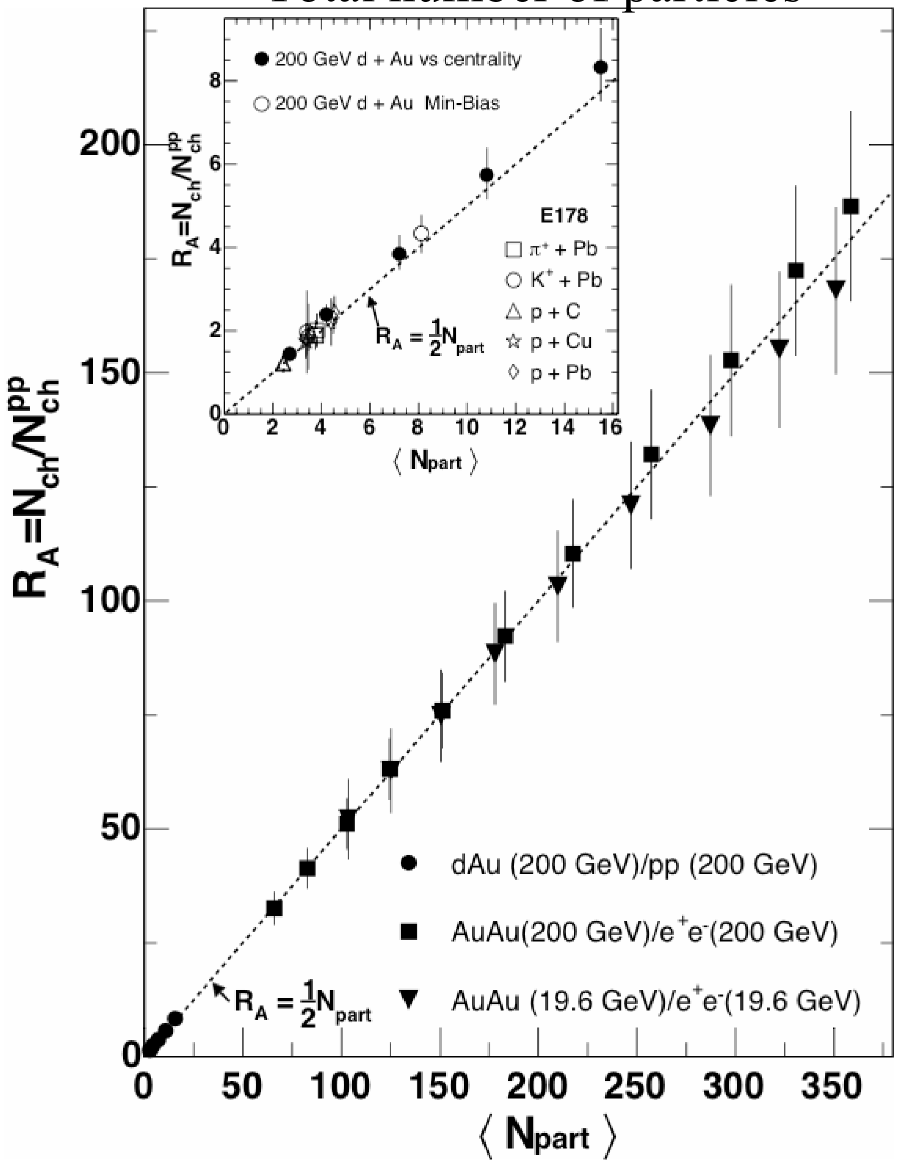


Pseudorapidity plotted in rest frame of one of the nuclei

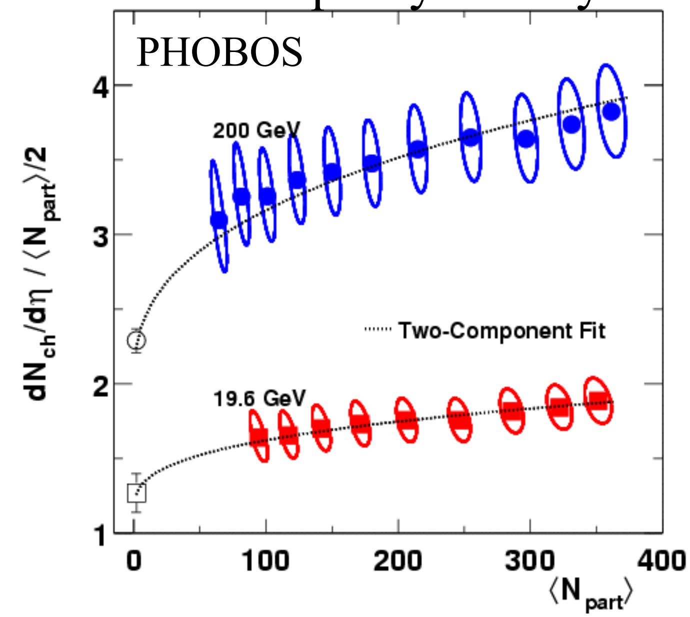
PHOBOS nucl-ex/0406021 Au+Au 0-40%

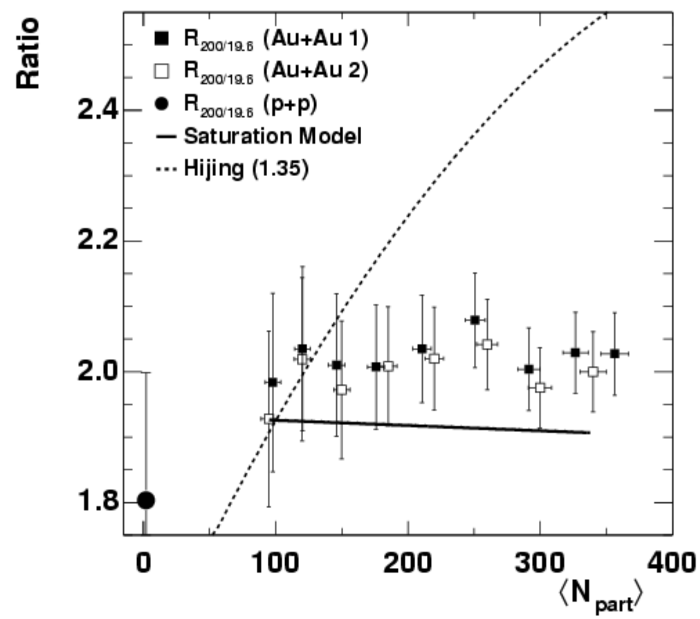
Data smooth as a function of centrality or impact parameter

Total number of particles

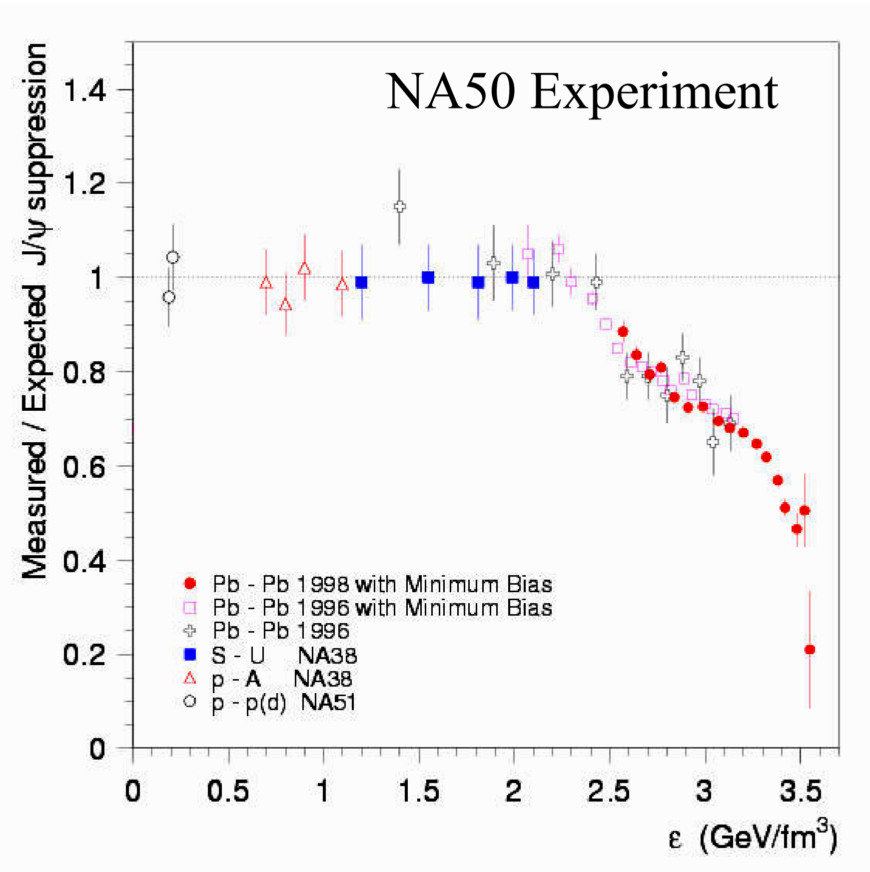


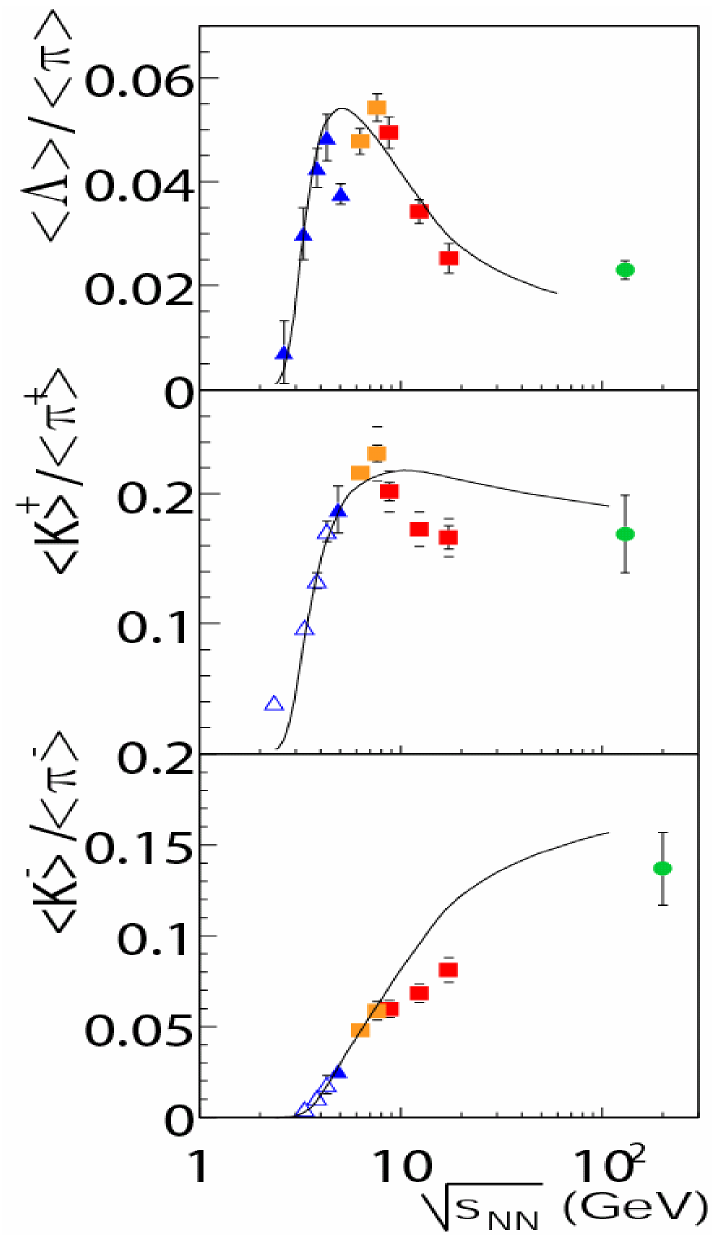
Mid rapidity density





SOME EXCEPTIONS:





NA49 (from Agnes Richard)

Although in the RHIC Energy Range (20-200 GeV) there are no obvious discontinuities, with very reasonable assumptions we can conclude

Time of equilibration is short $\leq 1\, fm/c$

Energy Density is very high, $\geq 3\, GeV/fm^3$

Note: Cold Nuclear Matter Density $\sim$ $150\, MeV/fm^3$

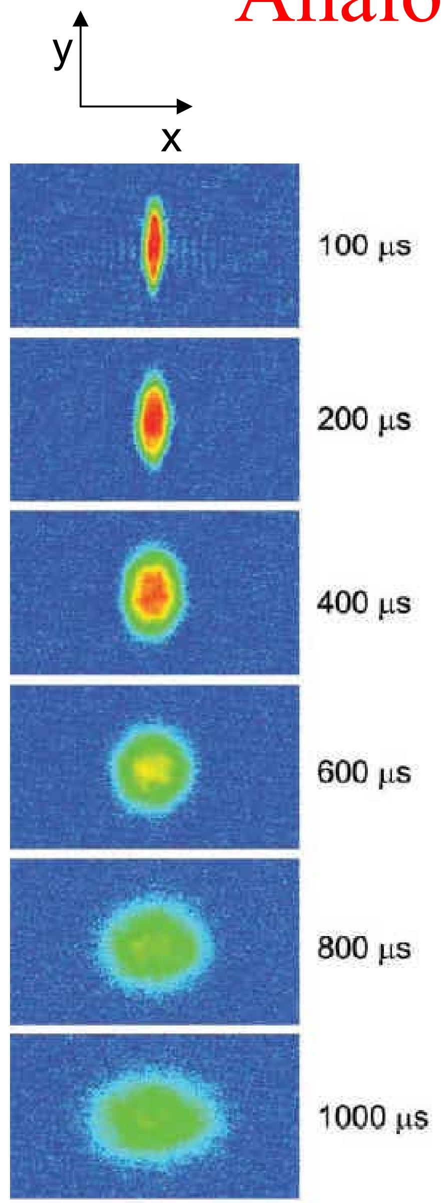
Energy Density Inside Hadrons $\sim$ $500\, MeV/fm^3$

Not only is the energy density very high, the matter is strongly interacting at early times

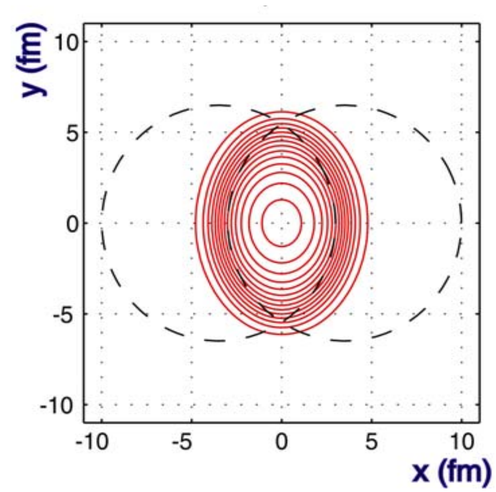
Evidence:

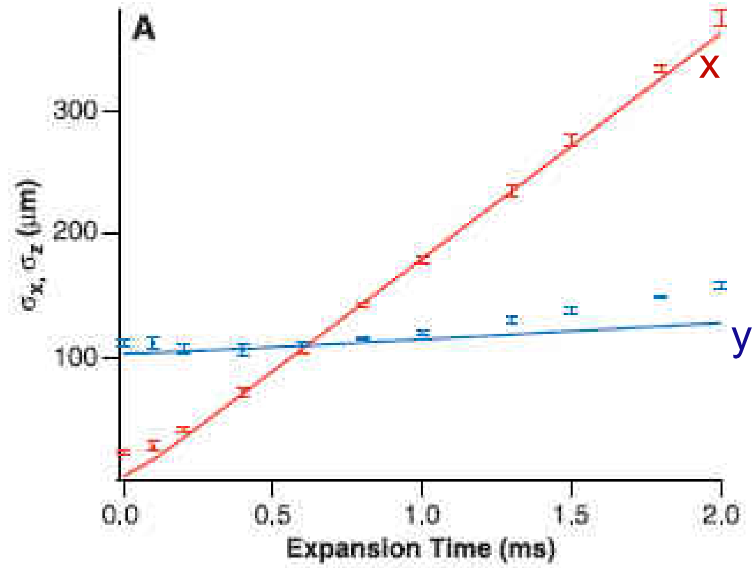
Strong Flow Signal

Analogy: Elliptic Flow of Ultracold Li_6 Atoms



T~ 50 10^{-9} K

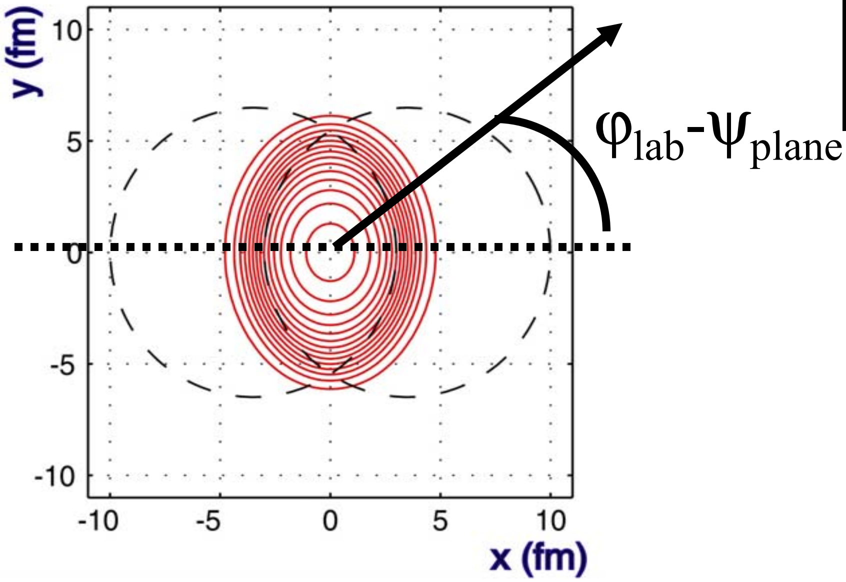




Elliptic Flow a very real phenomenon!

K.M.O'Hara *et al*, Science, 298 (2179) 2002

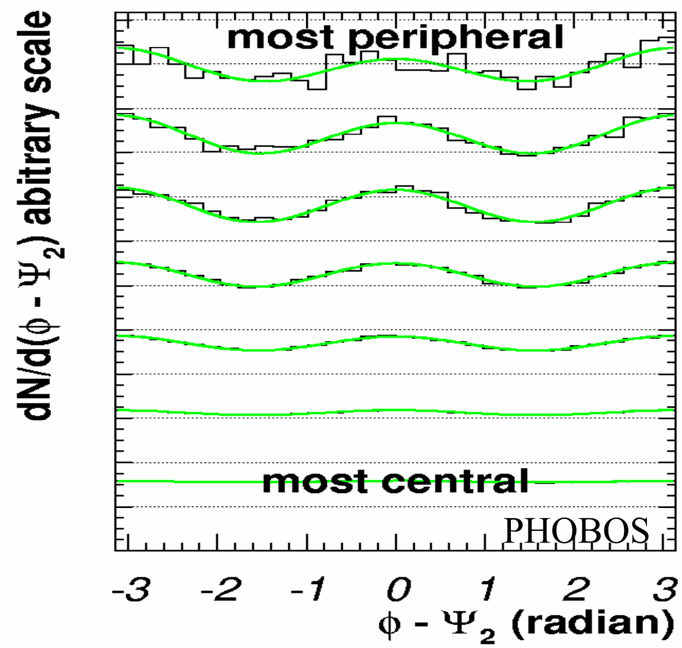
Elliptic Flow at RHIC



Geometry: asymmetric initial state

Asymmetry + interactions creates final state azimuthal correlations:

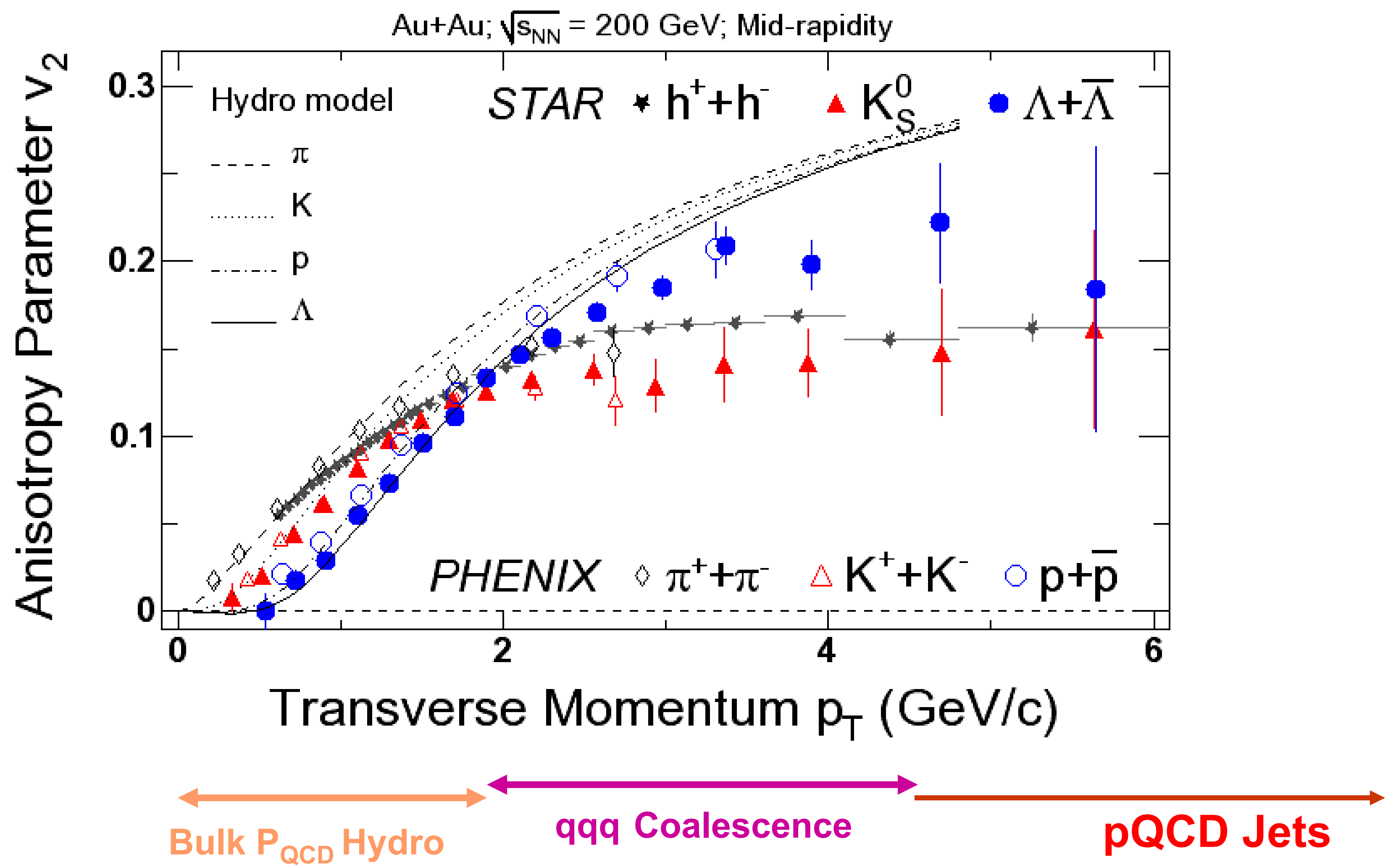
elliptic flow



Fourier analysis ⇒

$1+2\boldsymbol{v_2}\cos 2(\varphi_{lab}-\Psi_{plane})$

Large v_2 - strongly interacting matter at early time

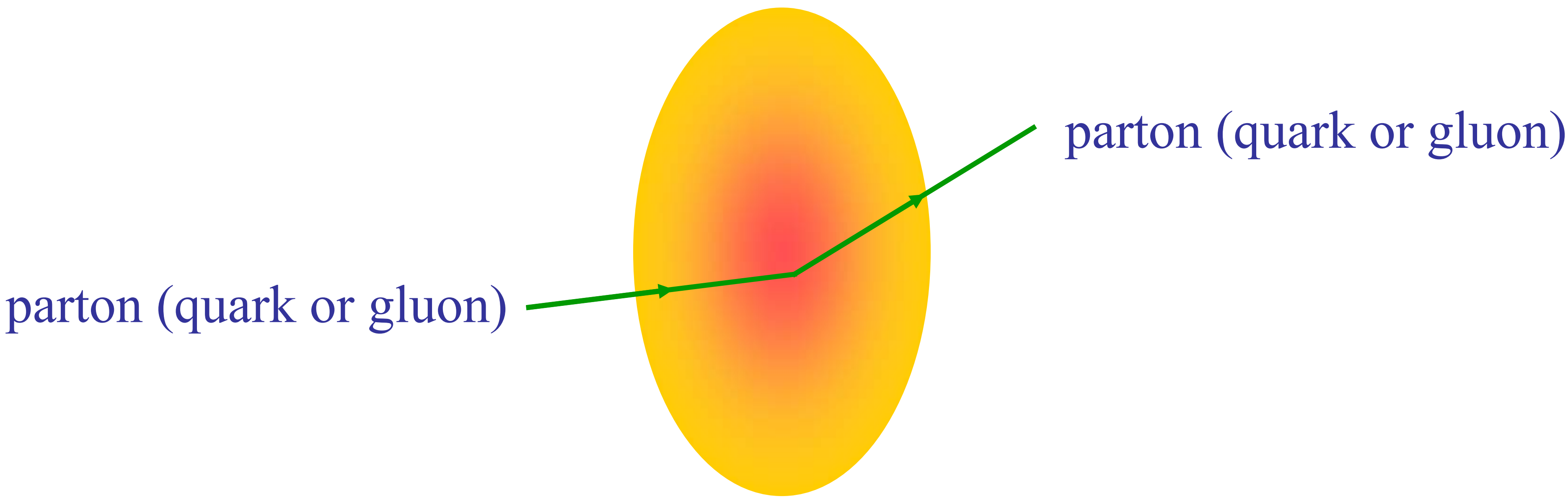


From Gyulassy DNP 2004

What is the novel medium?
What is the origin of its strong interactions?

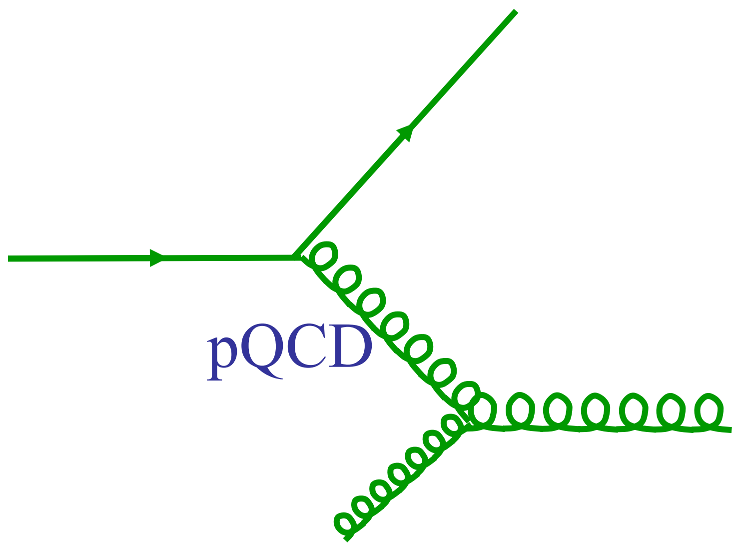
To answer these questions one needs localized penetrating probes

Such probes do exist → main topic of this meeting



HARD PROBES

$q+g \rightarrow q+g$



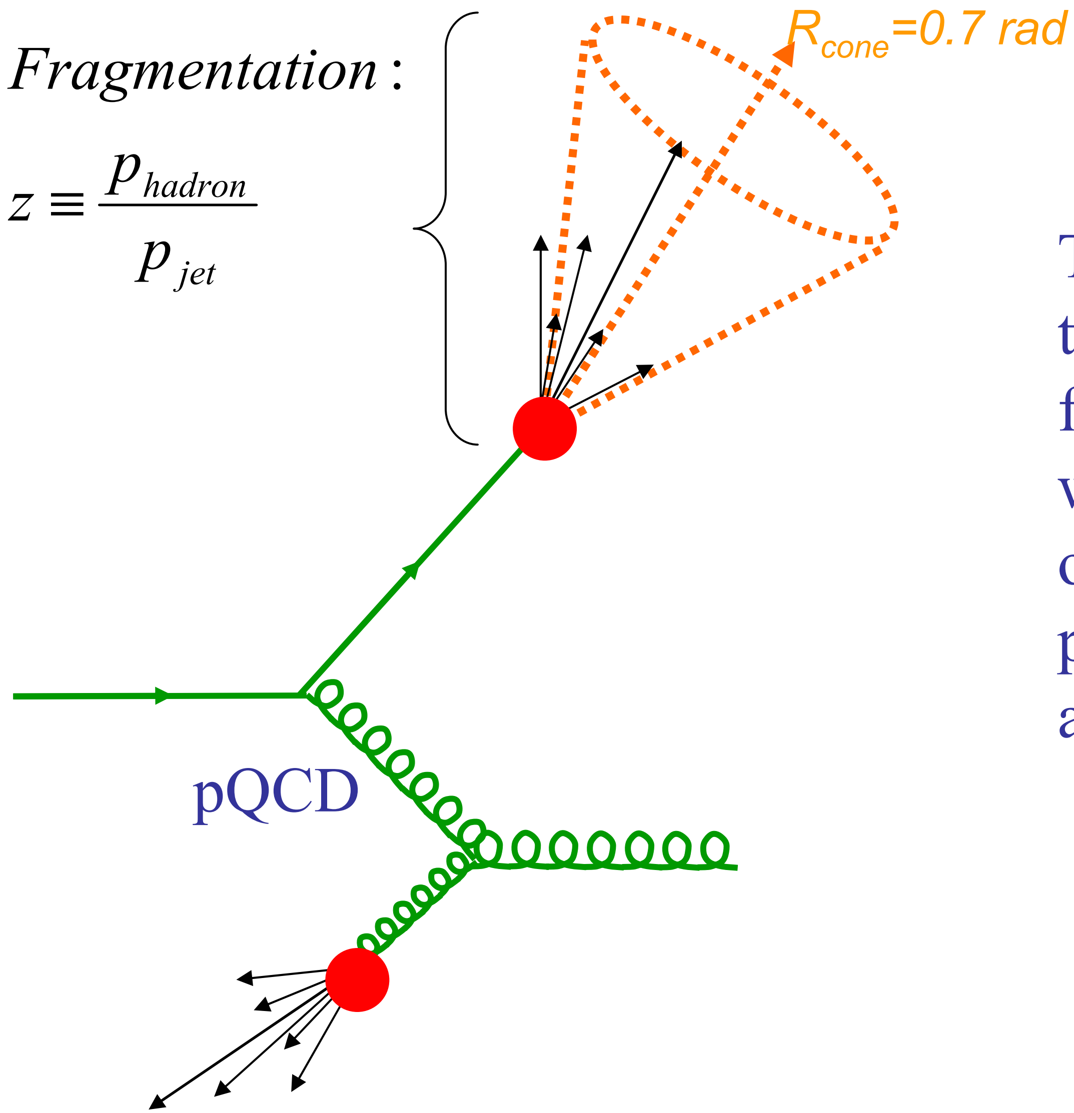
For parton-parton scattering with high Pt

The basic interaction is understood → pQCD

(Nobel Prize 2004)

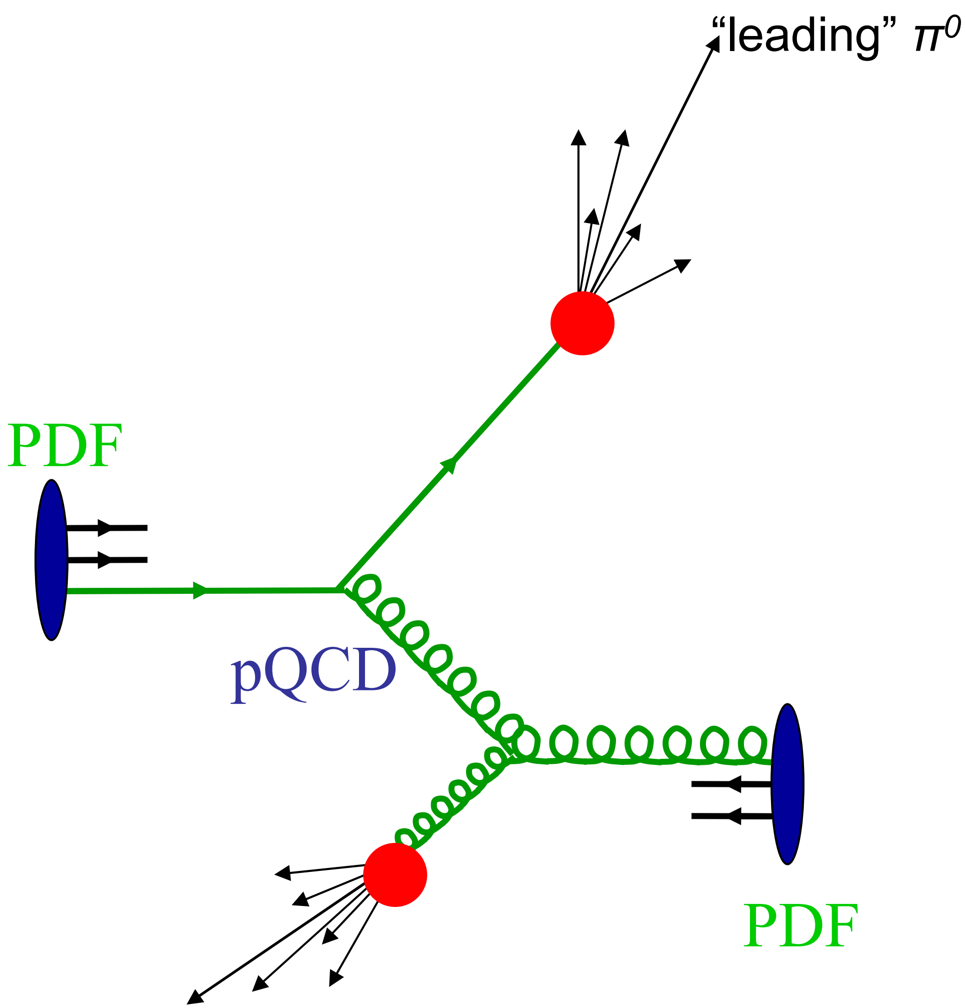
If parton beams of known momentum where available and scattered partons could be directly detected, life would be beautiful!

$q+g \rightarrow jet + X$

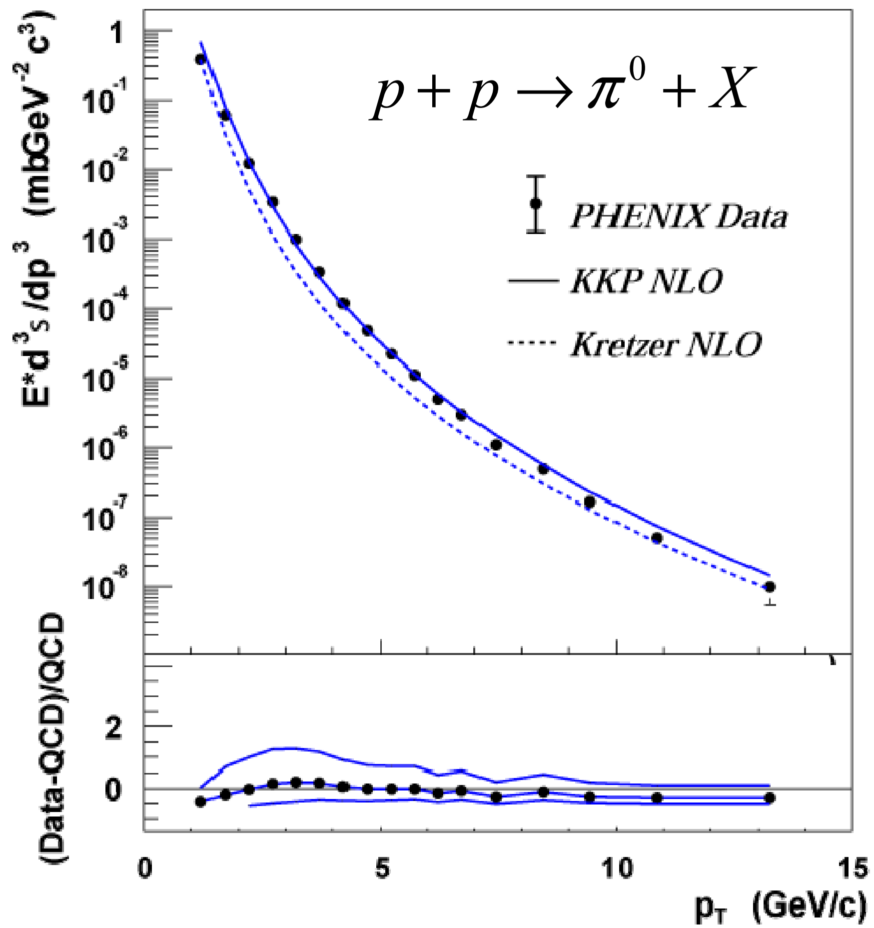


The best we can hope to do is to look at jets or jet fragments. This is reasonably well understood (combination of calculation and phenomenology, eg e+e- annihilation)

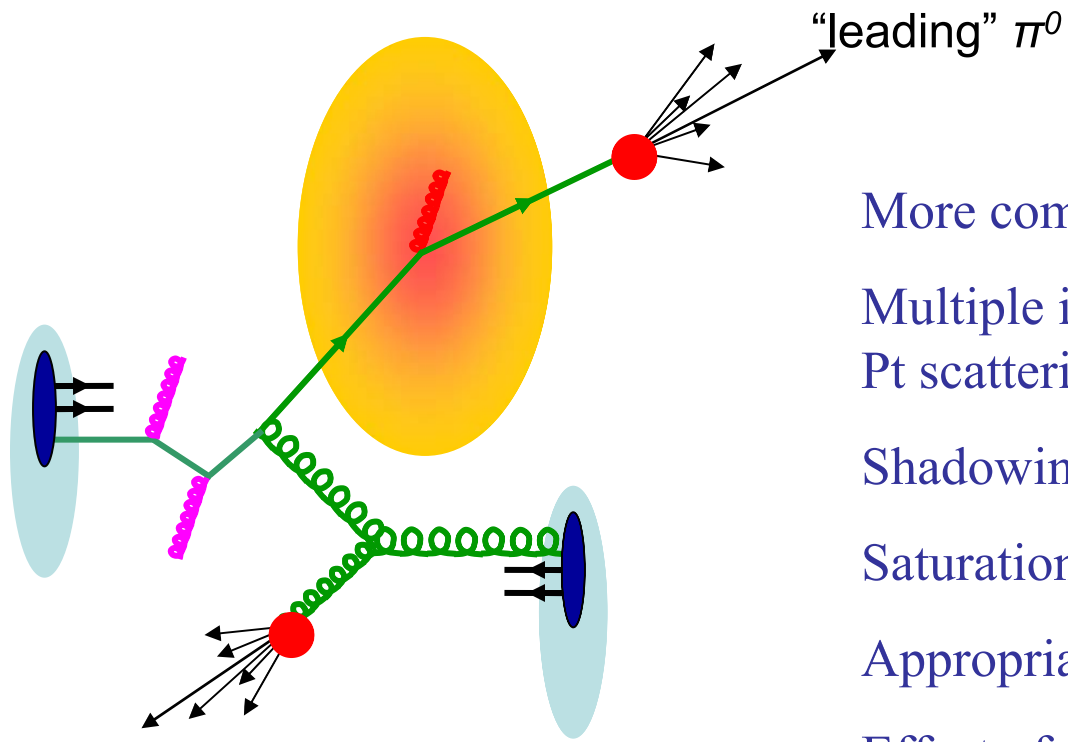
$p+p \rightarrow \pi^0 + X$



More phenomenology needed but under control:



$Au+Au \rightarrow \pi^0 + X$



More complications:

Multiple interactions and radiation before high Pt scattering (e.g.Cronin effect),

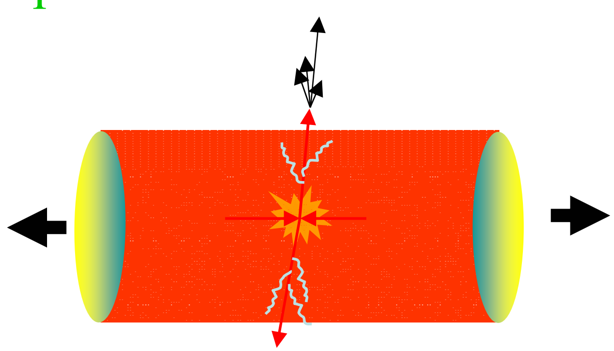
Shadowing

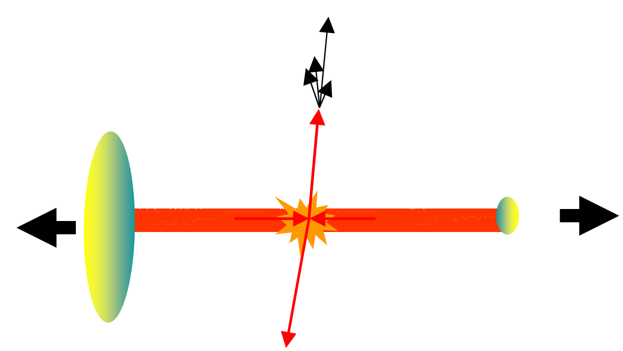
Saturation (e.g. Color Glass Condensate)

Appropriate normalization?

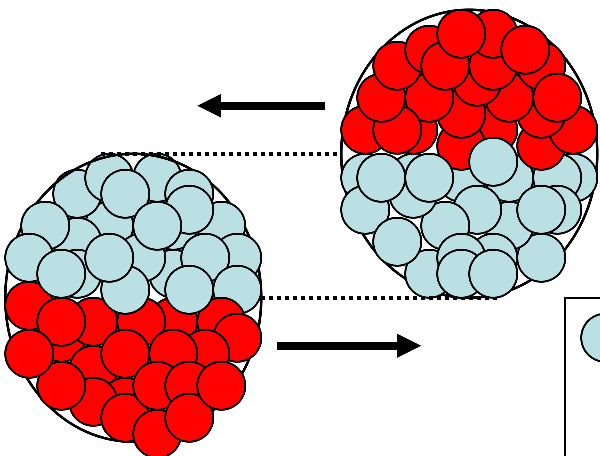
Effect of medium on fragmentation?

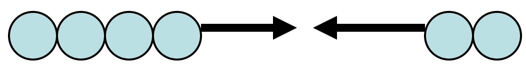
pA &dA helps to sort out initial state and final state effects



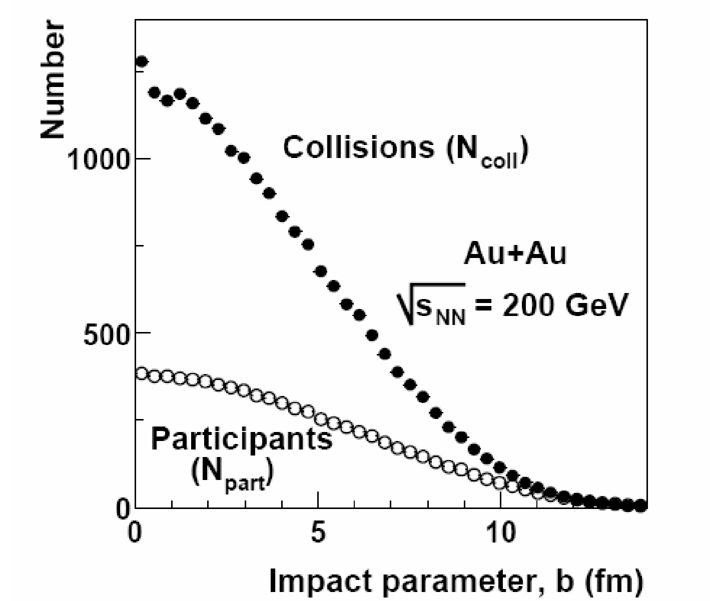


Correct Normalization, i.e. What is the Number of Relevant Collisions for Colliding Nuclei?





$$N_{part} = 4 + 2 = 6$$
$$N_{coll} = 4 \times 2 = 8$$



Numbers obtained from Glauber model:

Straight trajectories

Constant cross-section

Nuclear density profile

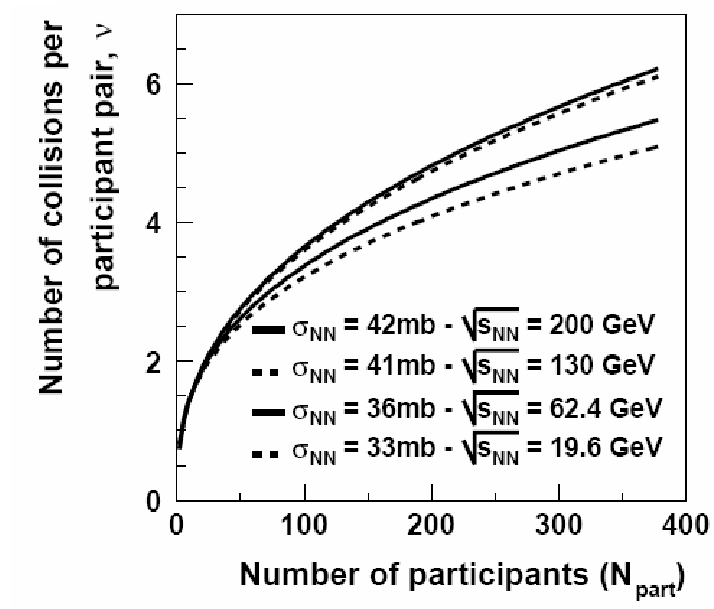
Issues:

Appropriate cross-section

Shadowing

Saturation

All of above are Pt dependent



Some vocabulary:

Nuclear Modification Factors

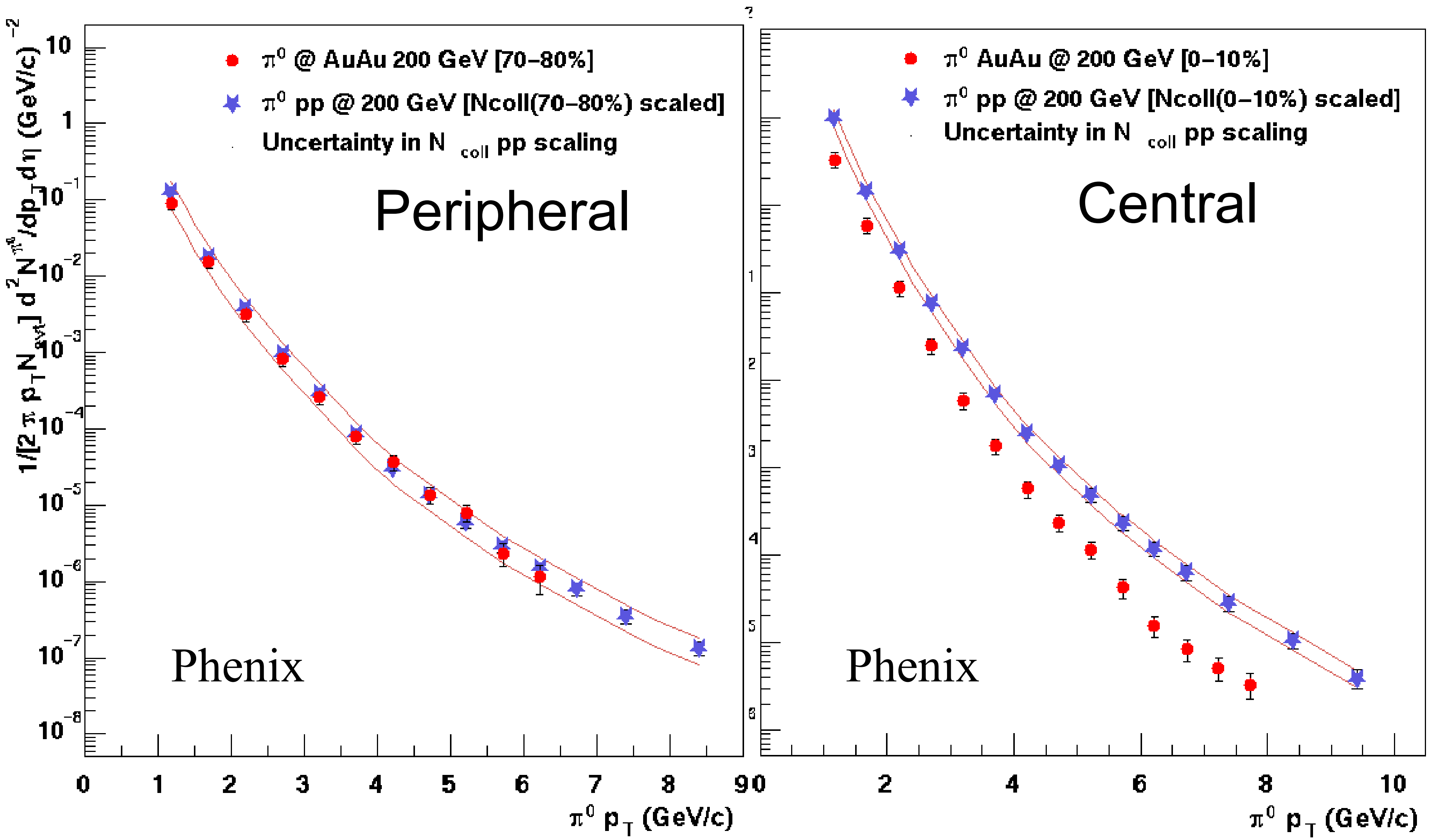
$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

$$R_{AA}^{N_{part}} = \frac{\sigma_{pp}^{inel}}{\langle N_{part}/2 \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

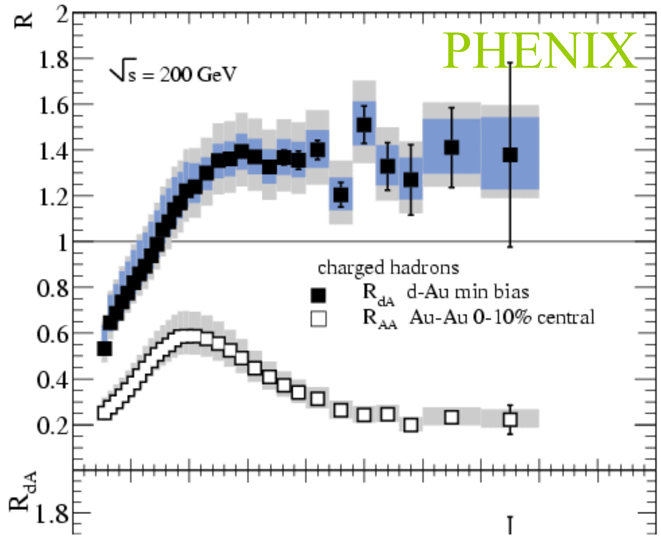
$$R_{PC}^{N_{part}} = \frac{\langle N_{part}^{0-6\%} \rangle}{\langle N_{part} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 N_{AA}^{0-6\%}/dp_T d\eta}$$

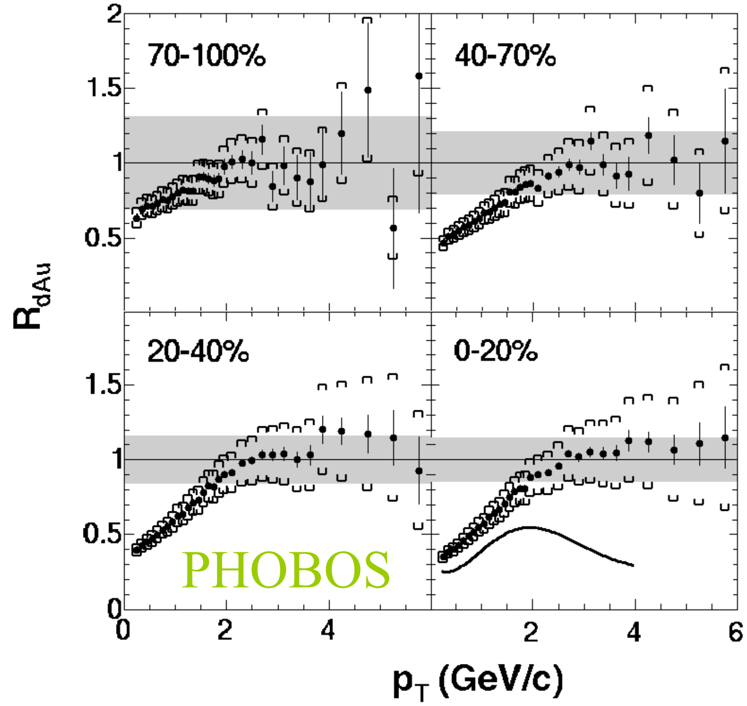
EXAMPLES OF DATA

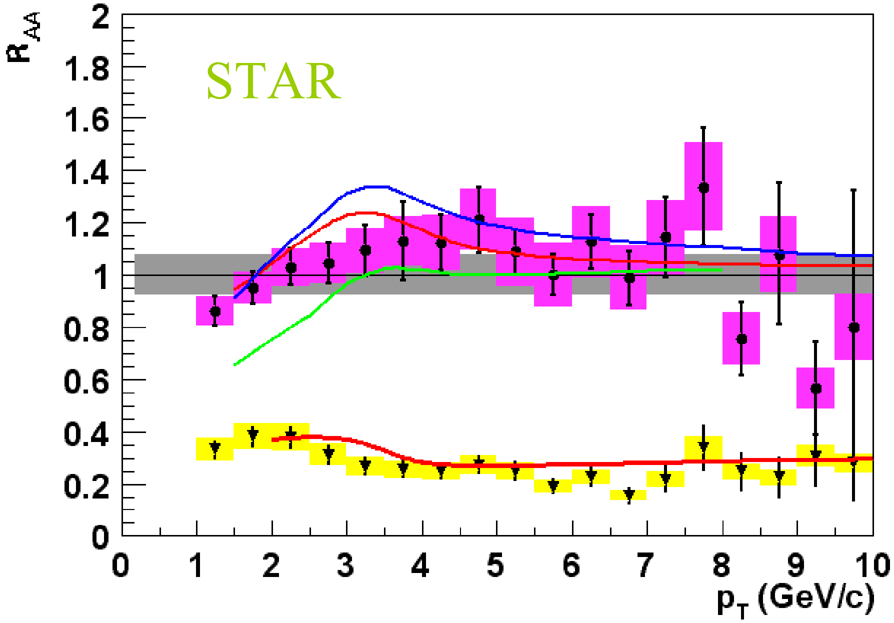
“Jet quenching” or Suppression of High P_T Particles

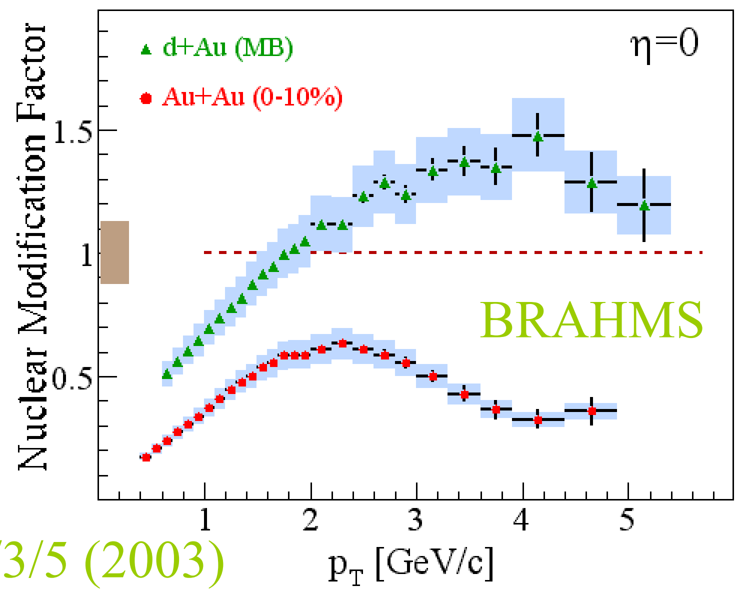


AuAu and dAu comparison (N_{coll} normalization):



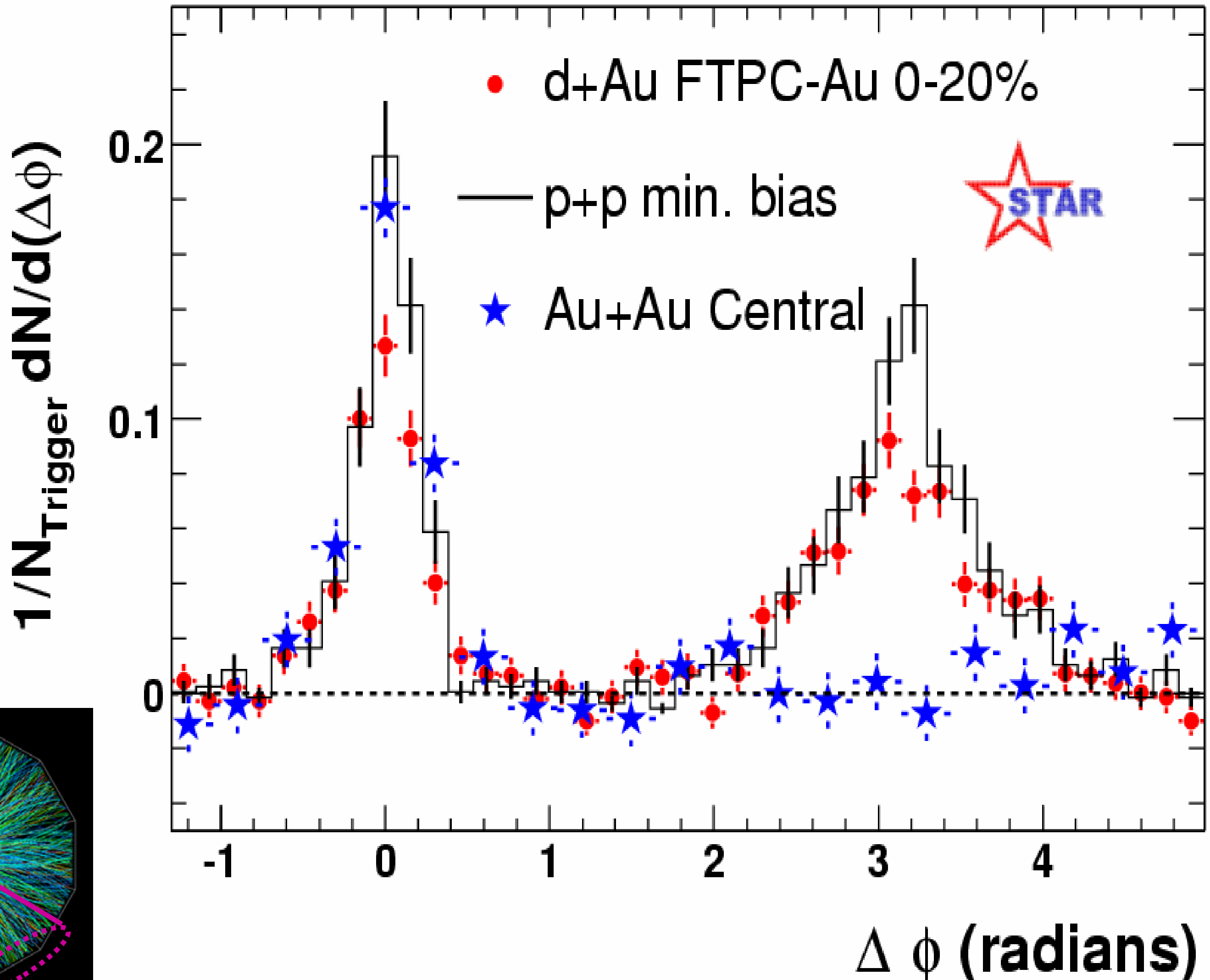


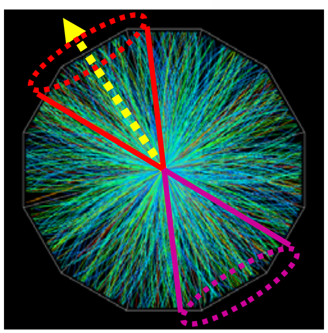




Phys Rev Lett 91, 072302/3/5 (2003)

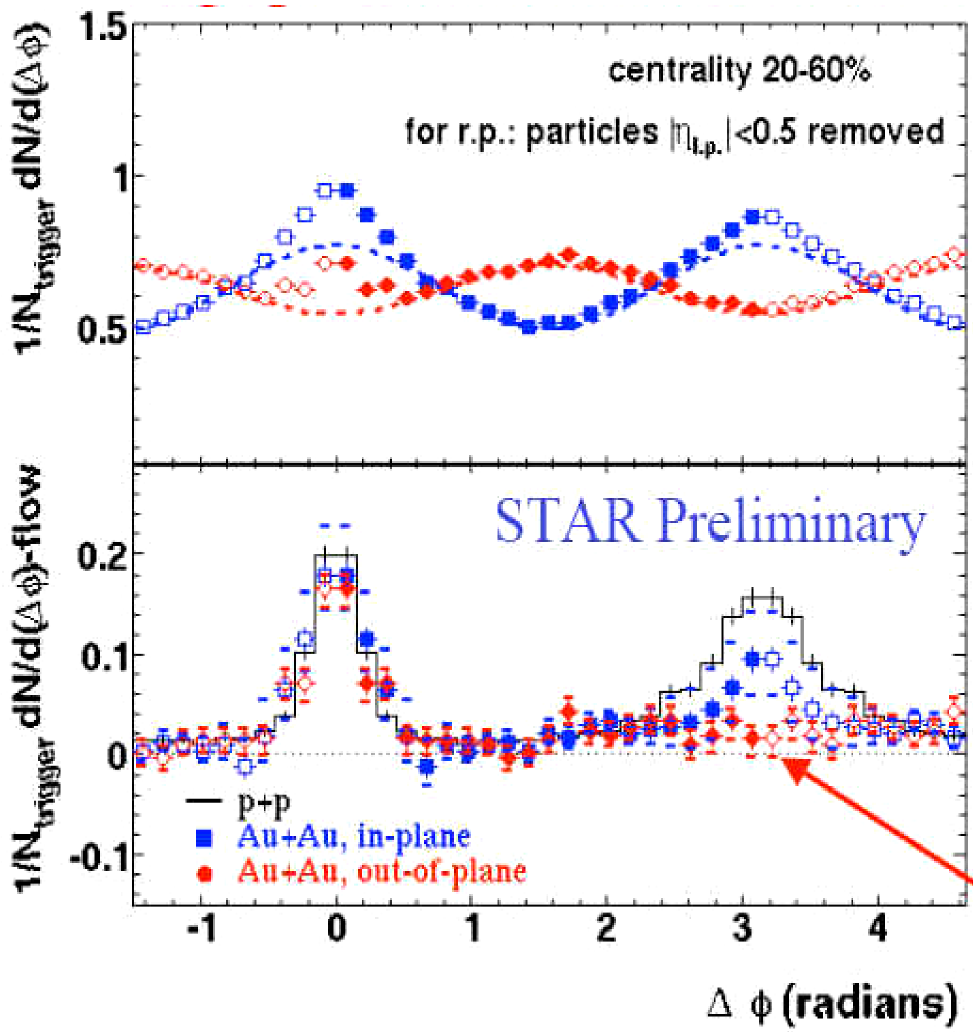
Back-to-back jets:

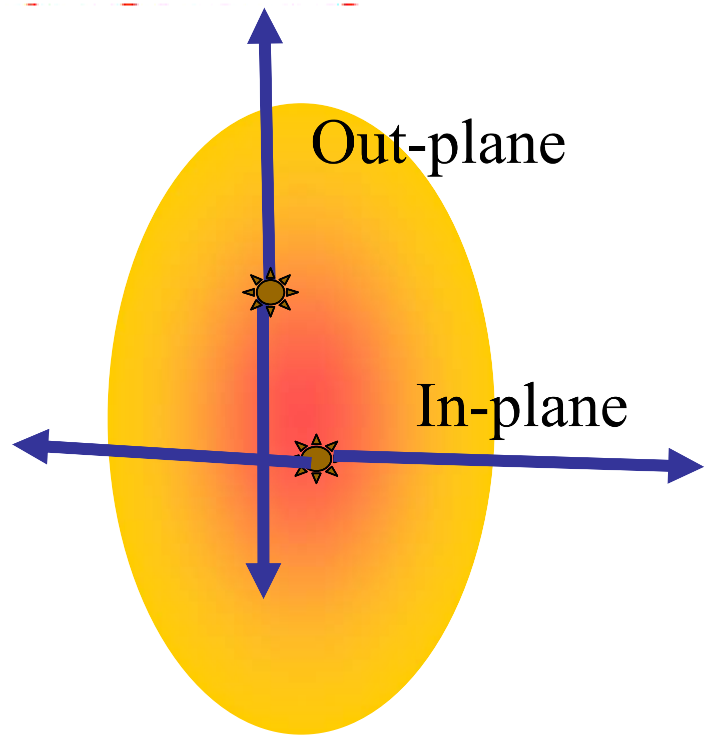




STAR: Phys.Rev.Lett.91:072304, 2003

Correlation of suppression with reaction plane:





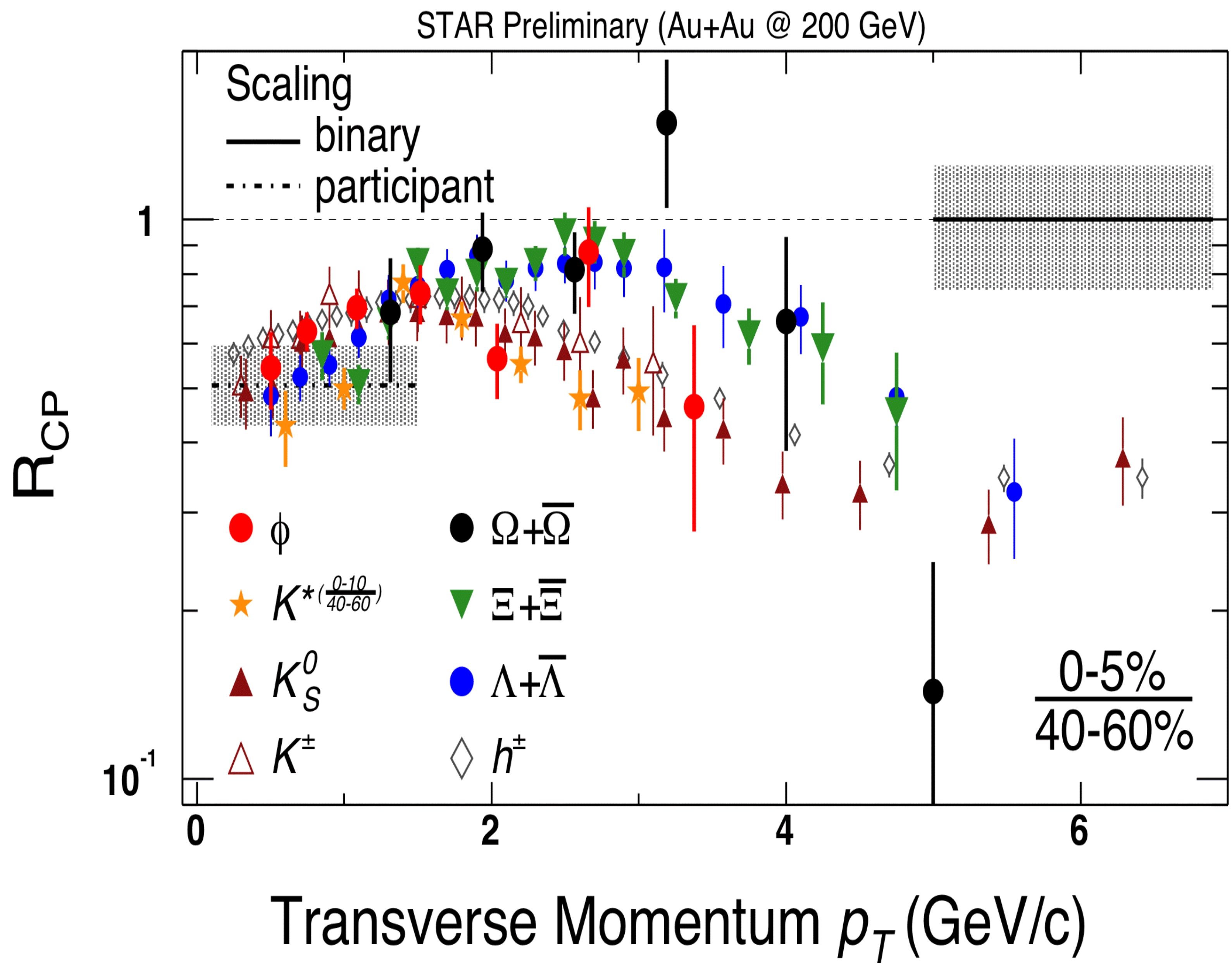
Back-to-back suppression is larger in the out-of-plane direction

K. Filimonov: DNP 10.31.03; nucl-ex/0410009

THERE ARE ISSUES ONE SHOULD BE AWARE OF WHILE LISTENING TO THE TALKS

- **Different particles may behave differently. Looking at the behavior of all charged particles together may be misleading.**
- Theorists may be pushing their luck using a high Pt approximation to a regime where it is clearly not applicable.
- Most data are for single particles and yet one speaks of them as if they are scattered partons or jets
- Inappropriate or unknown normalization can enhance or suppress an effect
- Important to ask if a "high Pt effect" is not there at low Pt
- Is there evidence that jet quenching goes approximately like density times the square of path length?

Suppression depends on produced particle type:



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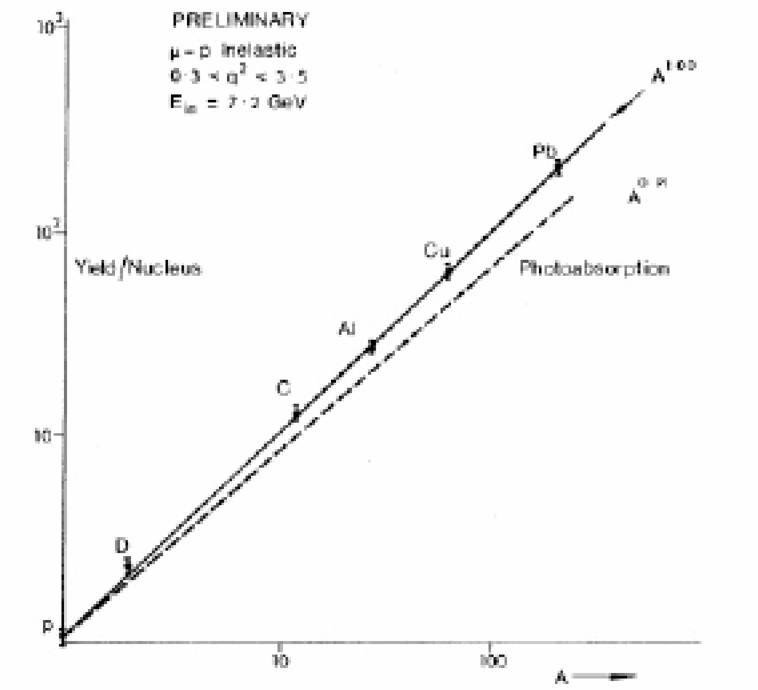
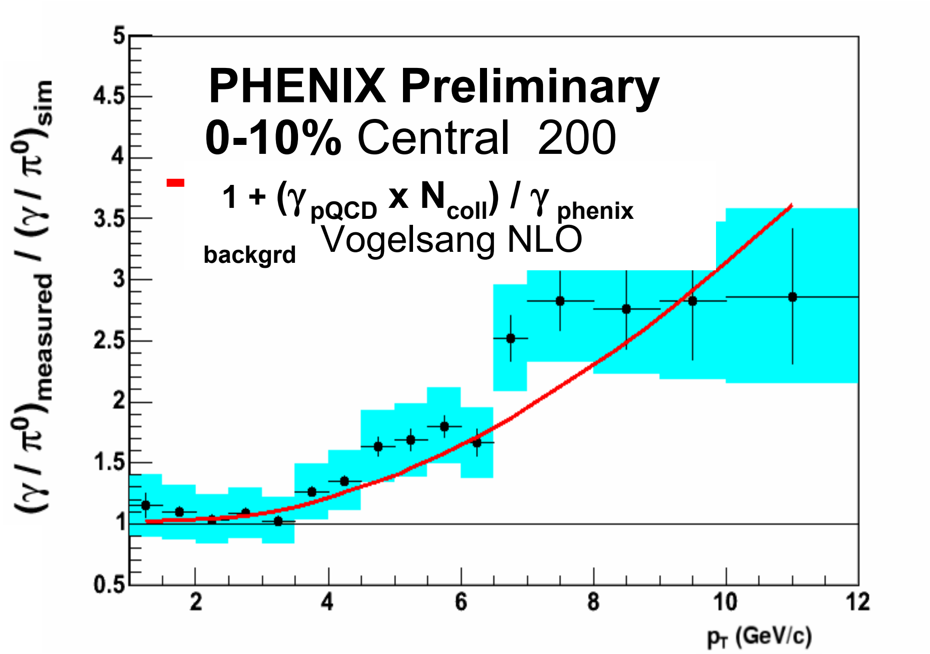
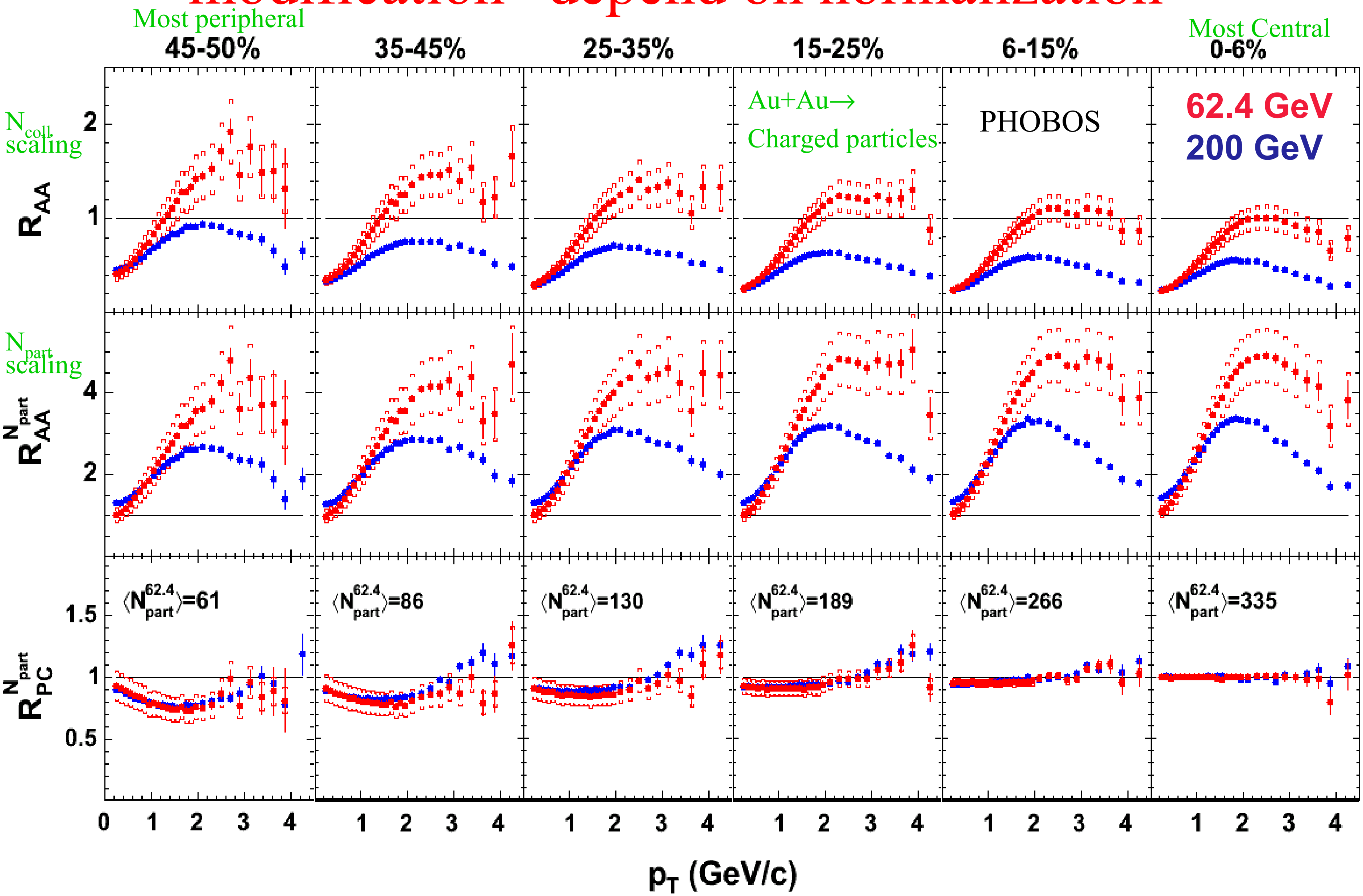
μA inelastic cross-section consistent with N_{coll} scaling



AuAu→Direct photons consistent with N_{coll} scaling

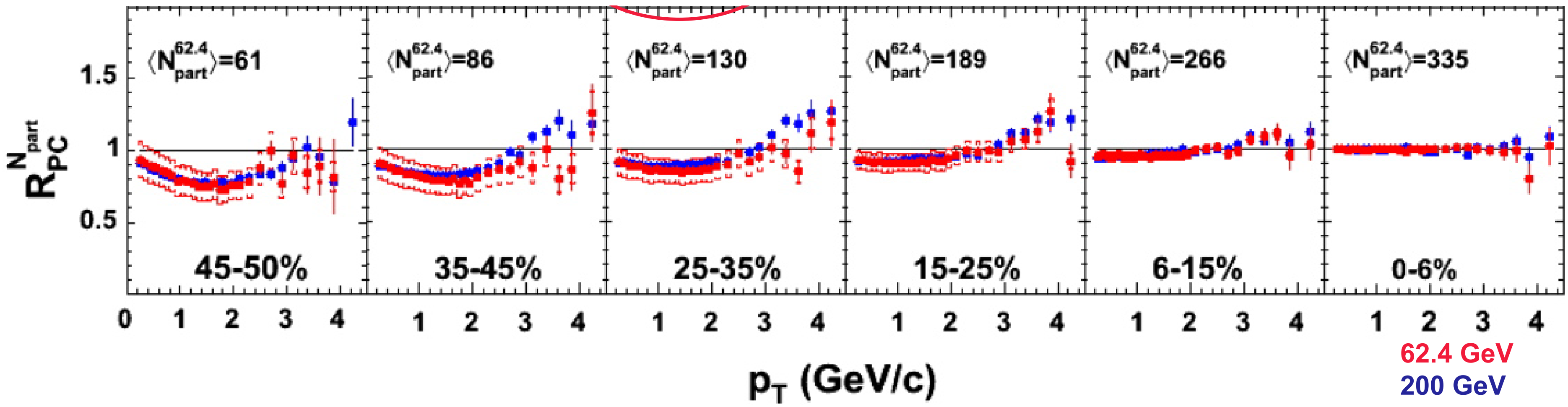


Trends seen in "suppression" or "nuclear modification" depend on normalization

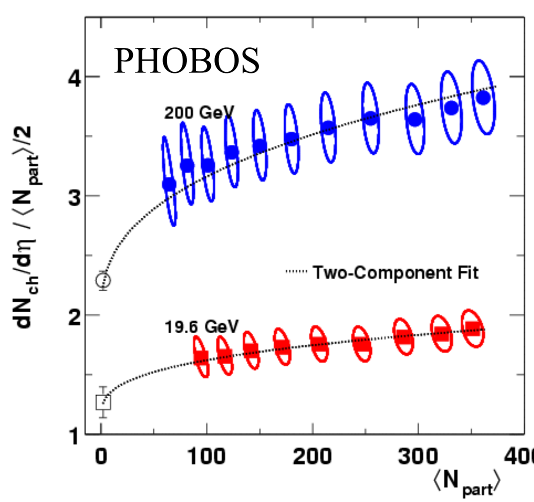


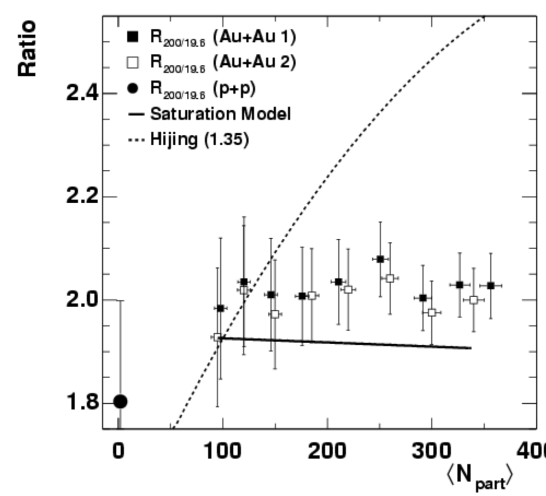
Factorization of Energy/Centrality Dependence

$$R_{PC}^{N_{part}} = \frac{\langle N_{part}^{0-6\%} \rangle}{\langle N_{part} \rangle} \frac{d^2 N_{AA} / dp_T d\eta}{d^2 N_{AA}^{0-6\%} / dp_T d\eta}$$



Mid rapidity density





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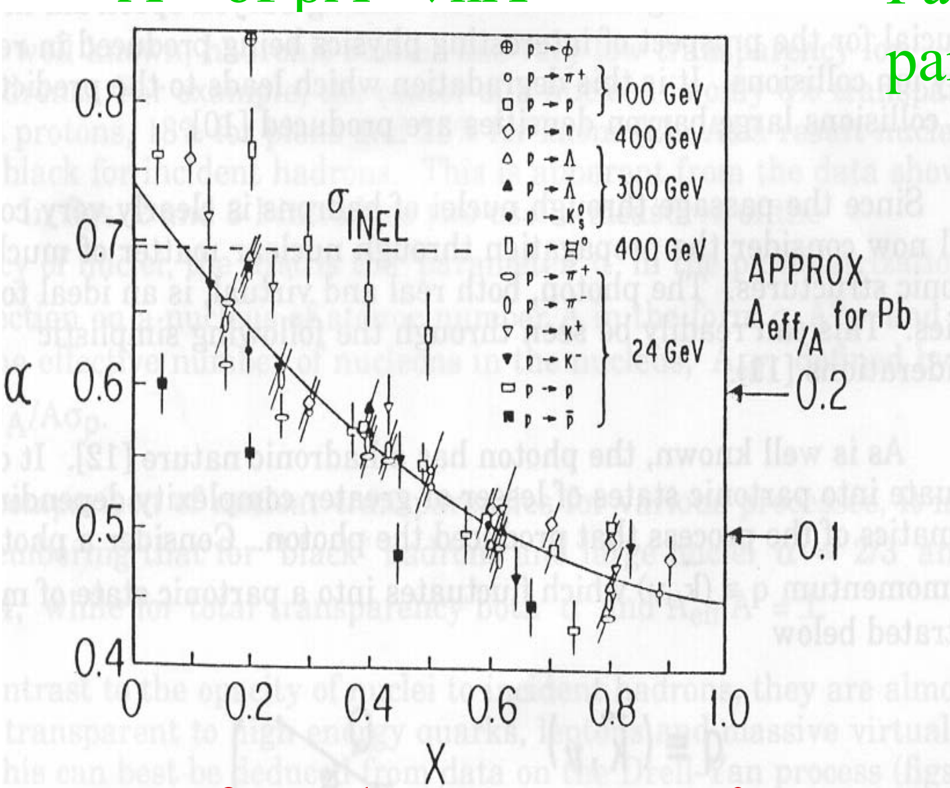
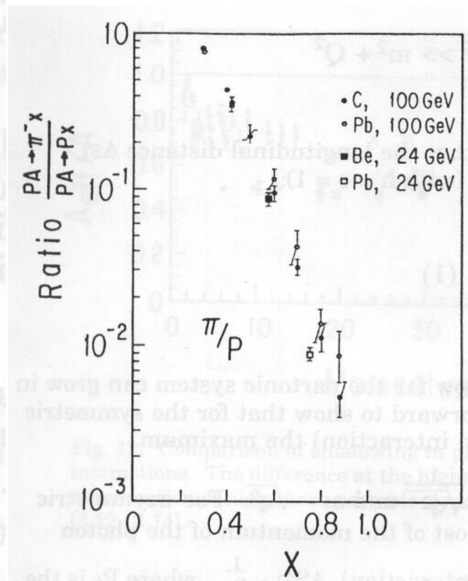
“Quenching” is seen in production of all particles in the very forward region of rapidity (≤ 2 units)

A^{α} of $pA \rightarrow hX$

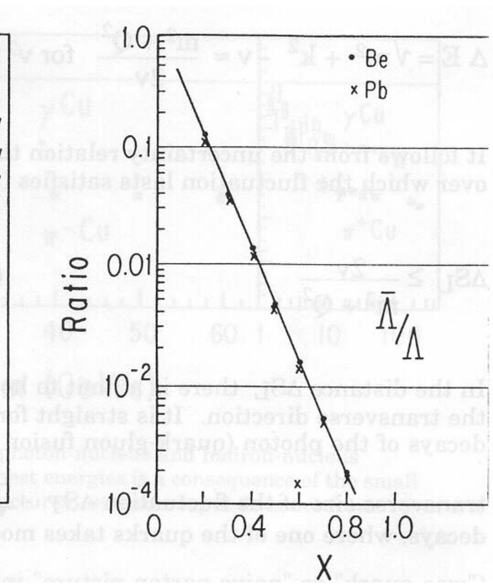


From E451:Barton et al Phys Rev 27 (1983) 2580

Particle ratios in forward production of particles are independent of A



Barton et al



Skupic et al

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Last Words

LISTEN WITH SOME SKEPTICISM

ENJOY THE MEETING

IT IS AN EXCITING ERA FOR THE FIELD