Out of the Quark-Gluon Quagmire
Emerge Hard Signals

John Harris
Yale University

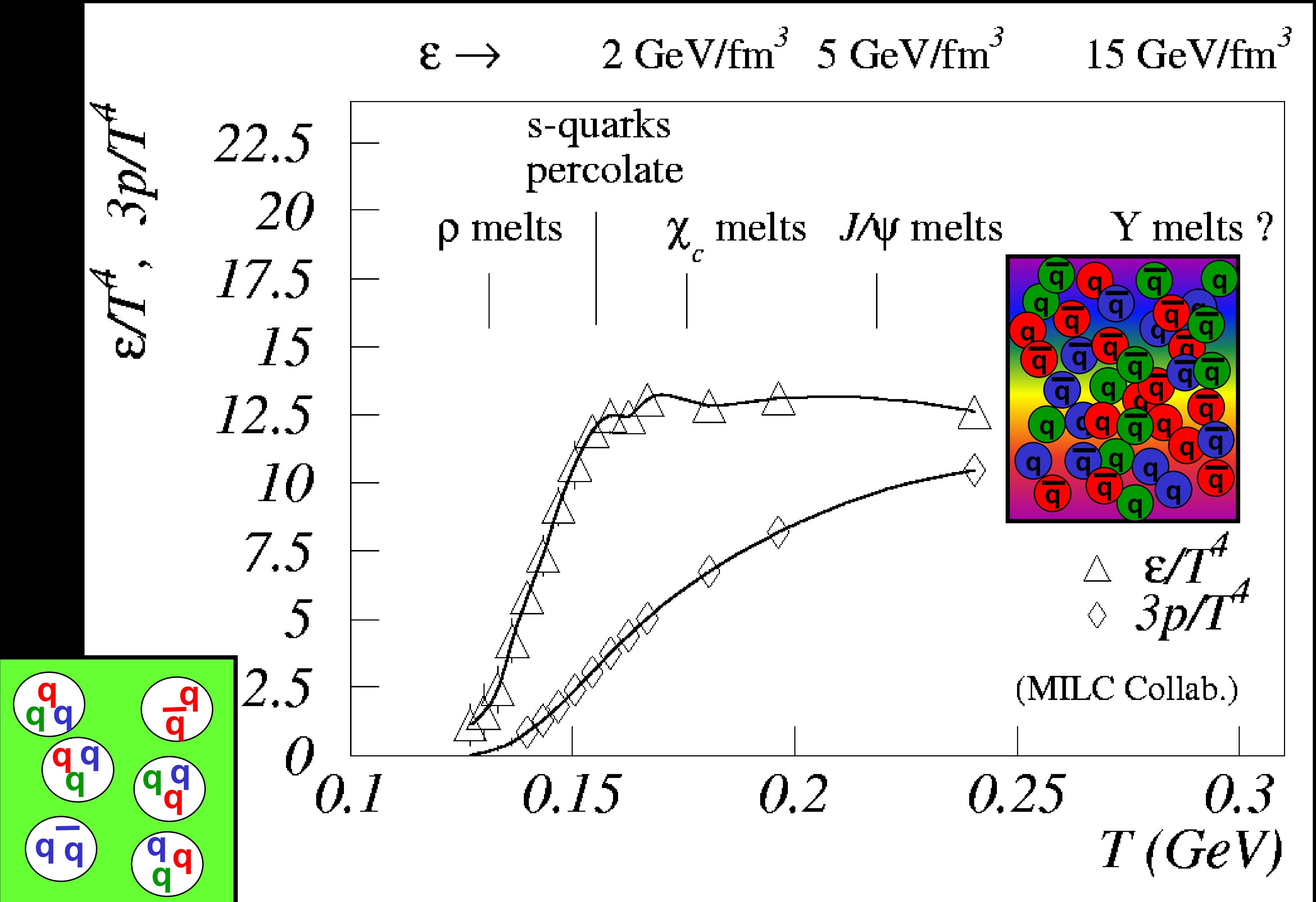
- **Introduction**
  - **Relativistic Heavy Ion Physics**
  - **Relativistic Heavy Ion Collider (RHIC)**
    - **+ RHIC Experiments**
- **General Characteristics of RHIC Collisions**
- ***Soft Physics - "Brief Overview"***
- **High P_T Physics – *"Hard Results"***
- **Summary and Outlook**

“In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.”

“In order to study the question of ‘vacuum’, we must turn to a different direction; we should investigate some ‘bulk’ phenomena by distributing high energy over a relatively large volume.”

T.D. Lee
Rev. Mod. Phys. 47 (1975) 267.

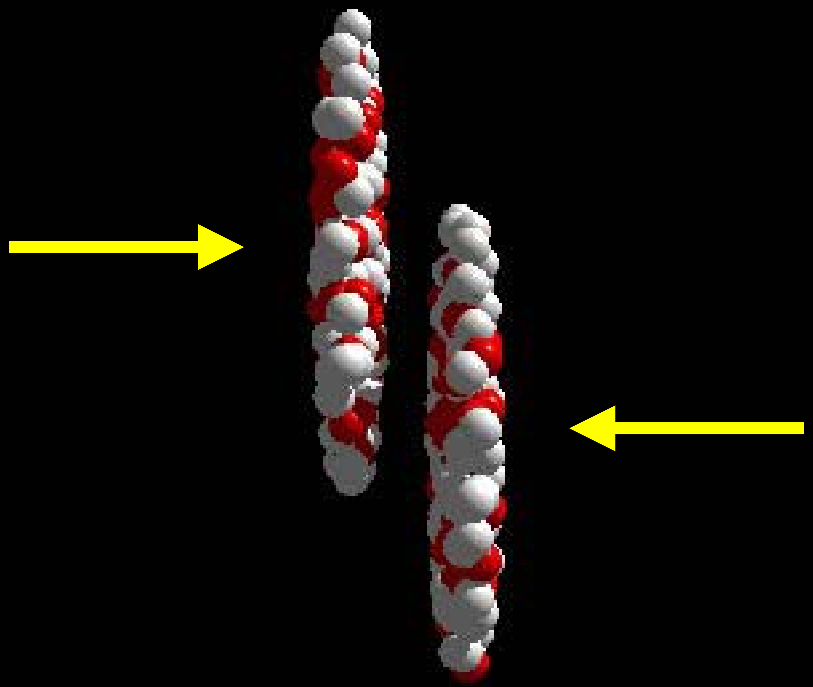
Lattice QCD Calculations



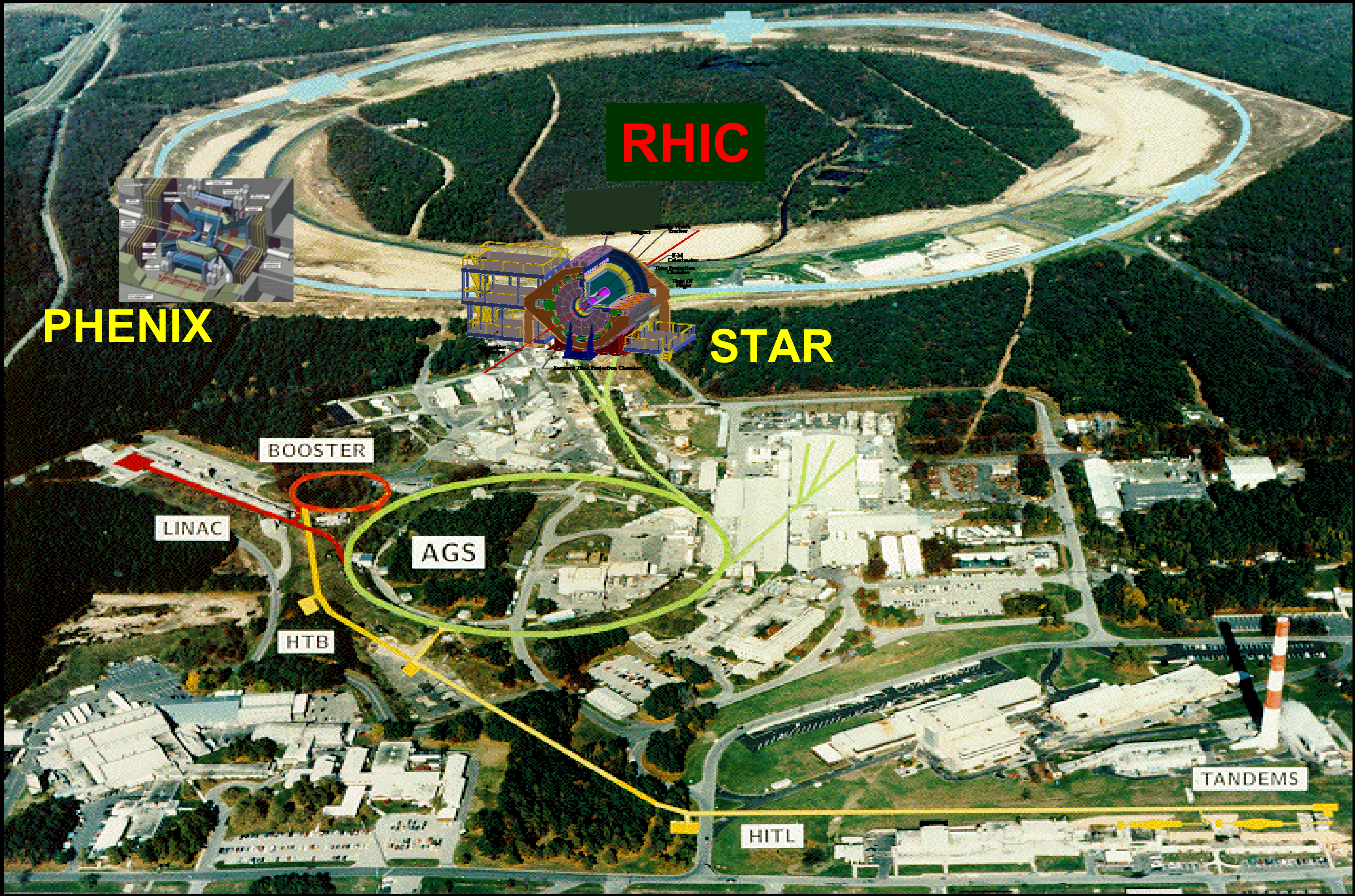
Purpose of Relativistic Heavy Ion Physics

- Investigate High Density QCD Matter in Laboratory
  - Determine its properties
- Phase Transitions?
  - Deconfinement to Quark-Gluon Plasma
  - Chiral symmetry restoration
- "Applications"?
  - Quark-hadron phase transition in early Universe
  - Cores of dense stars
  - High density QCD

Collisions at RHIC



Relativistic Heavy Ion Collider



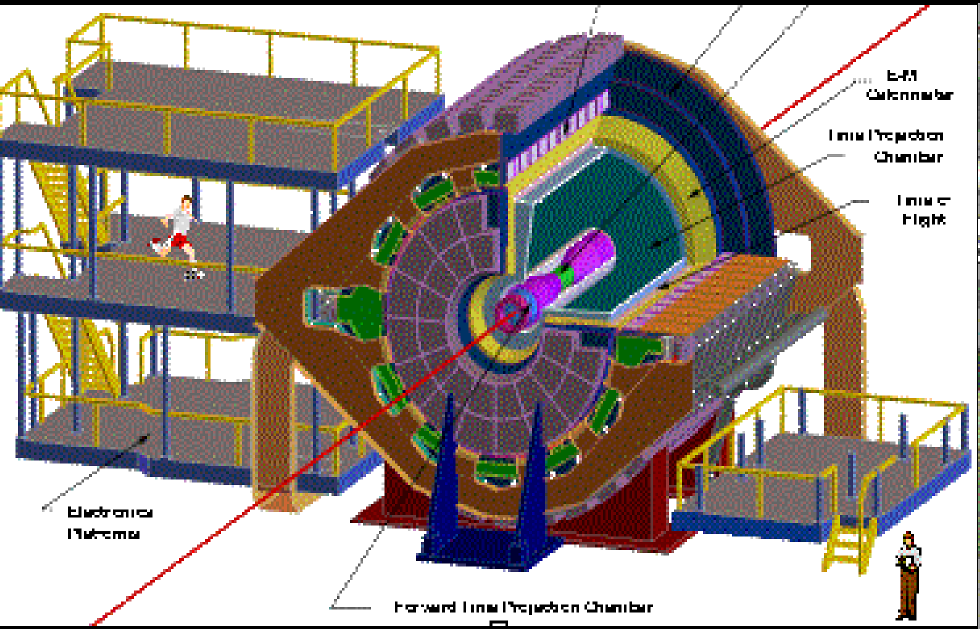
The Two "Large" Experiments at RHIC

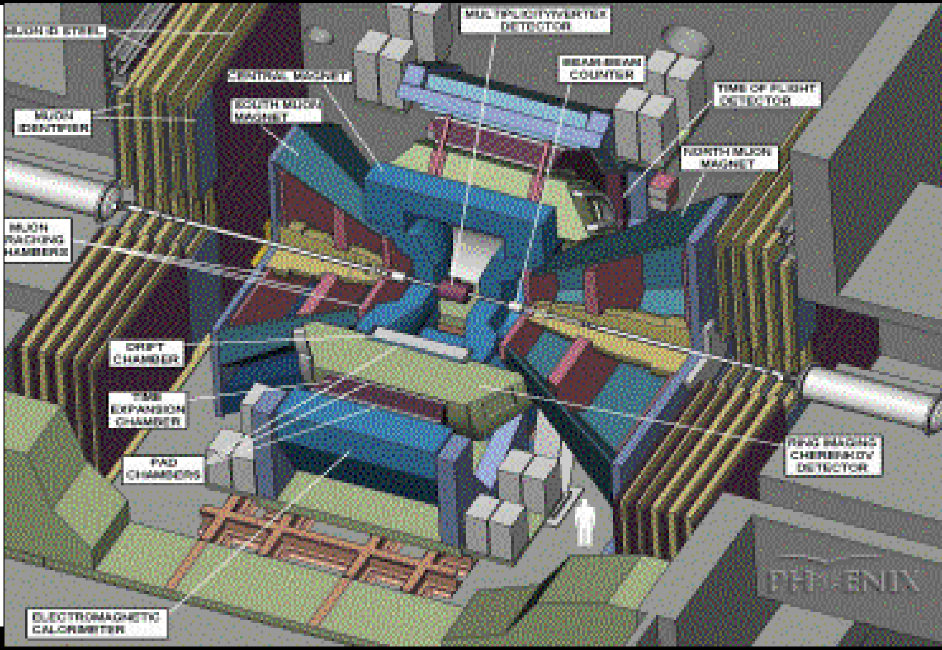
STAR

Solenoidal field
Large-Ω Tracking
TPC's, Si-Vertex Tracking
RICH, EM Cal, TOF

PHENIX

Axial Field
High Resolution & Rates
2 Central Arms, 2 Forward Arms
TEC, RICH, EM Cal, Si, TOF, μ-ID

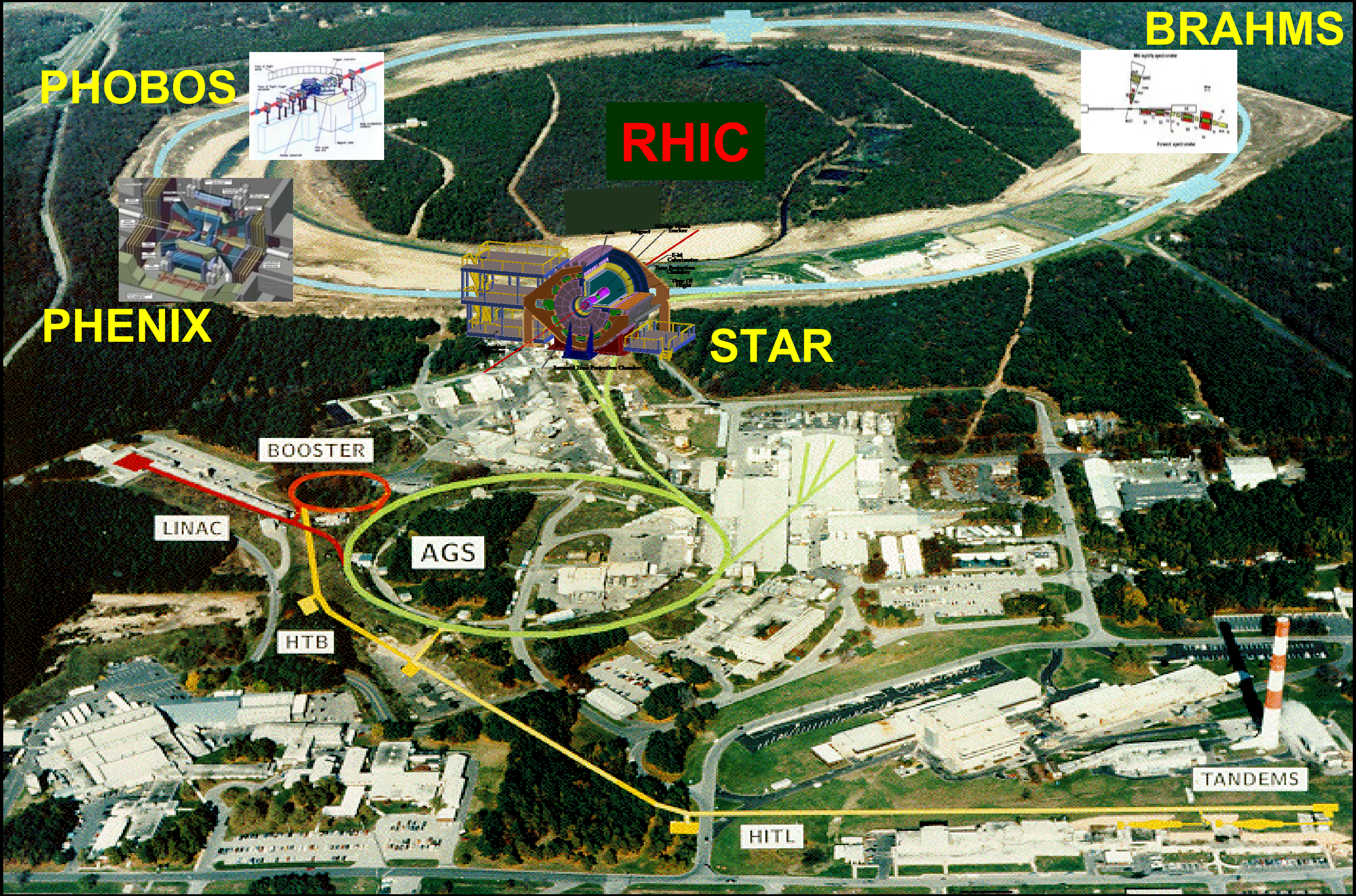




- Hadronic Observables
- Large Acceptance, Jets
- Event-by-Event Analyses

- Leptons, Photons, & Hadrons
- Simultaneous Detection of Various Transition Phenomena

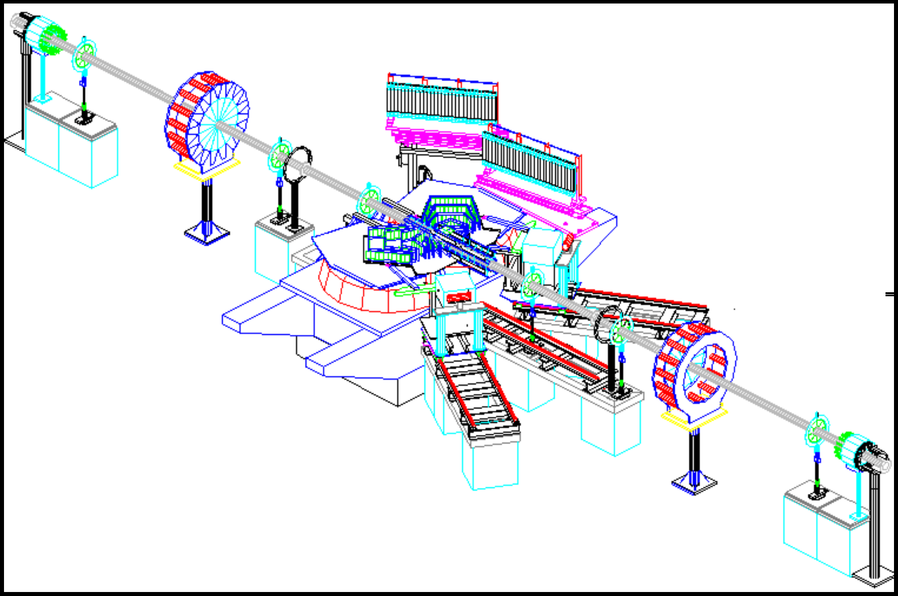
Relativistic Heavy Ion Collider



The Two "Smaller" Experiments at RHIC

PHOBOS

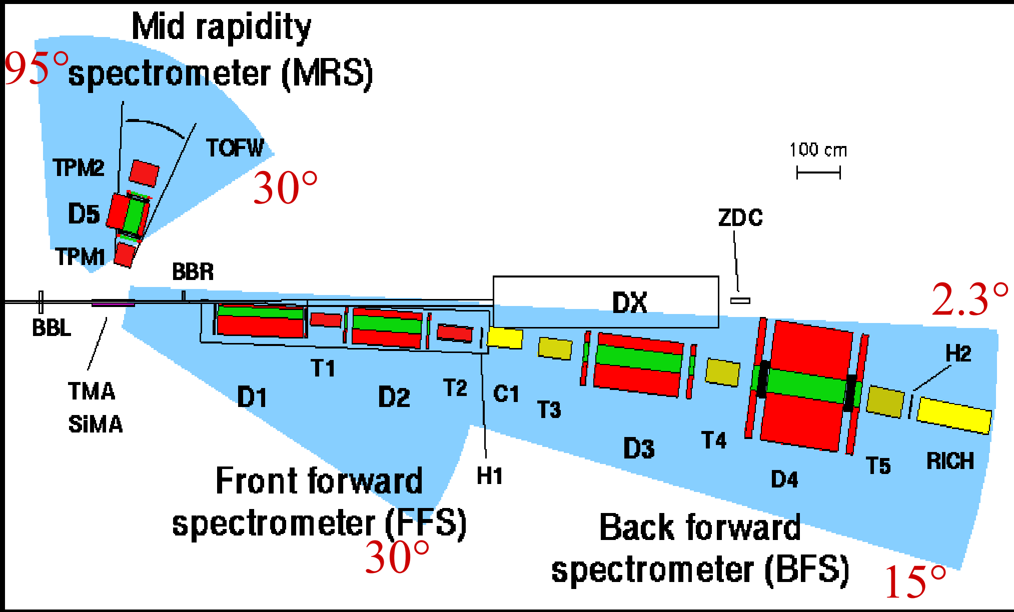
"Table-top" Spectrometer



- Charged Hadrons
- Particle Correlations

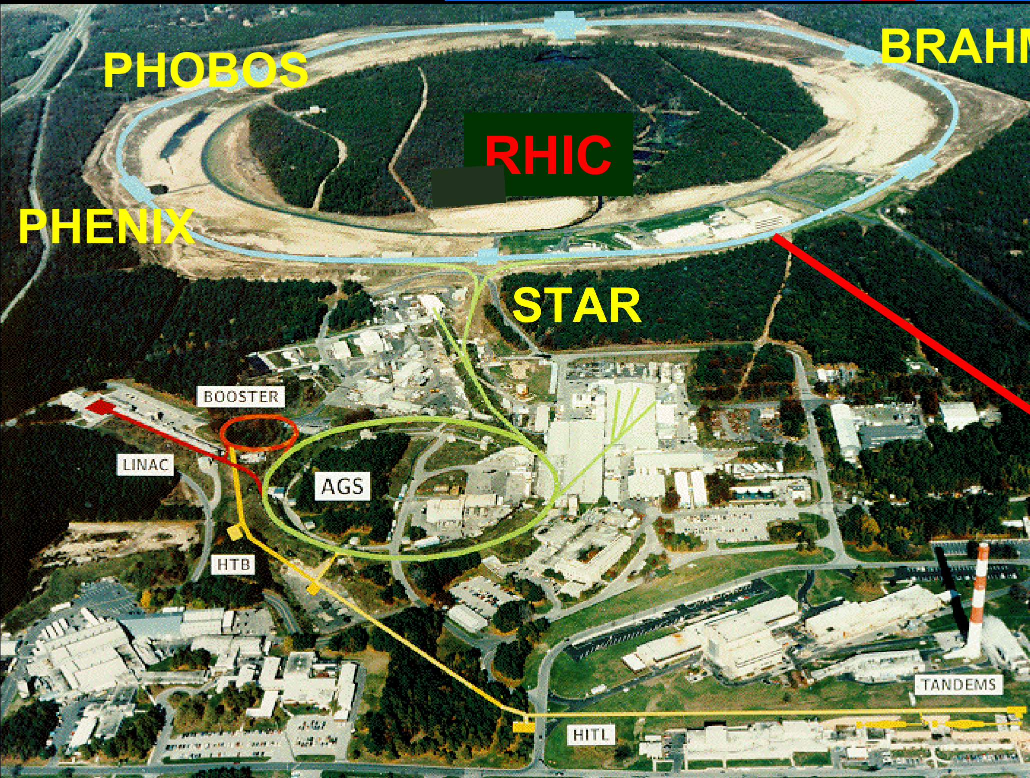
BRAHMS

2 Spectrometers



- Inclusive Particle Production
- Large Rapidity Range

Relativistic Heavy Ion Collider

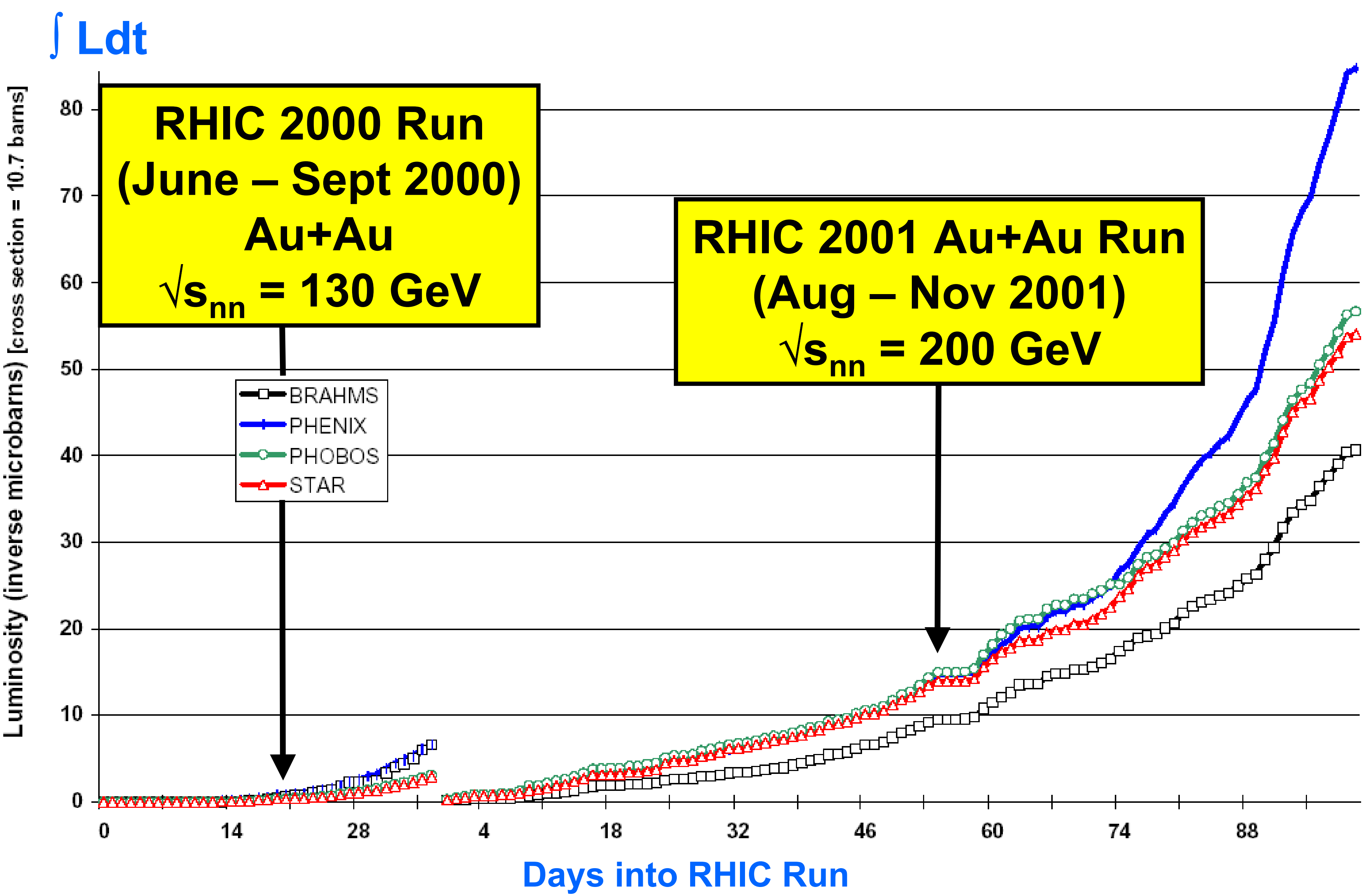


Two Concentric Superconducting Rings

Ions: A = 1 ~ 200, $\vec{p}\vec{p}$, pA, AA, AB

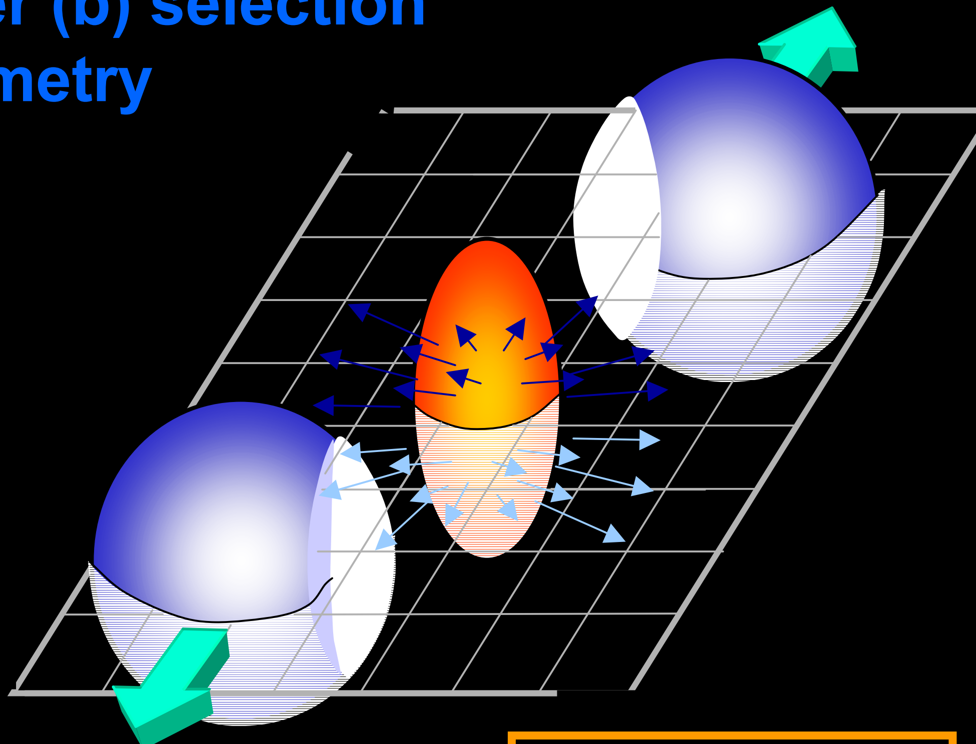
Design Performance	Au + Au	p + p
Max $\sqrt{s_{nn}}$	200 GeV	500 GeV
L [cm^{-2} s^{-1}]	2×10^{26}	1.4×10^{31}
Interaction rates	1.4×10^{3} s^{-1}	3×10^{5} s^{-1}

RHIC Running



Collisions at RHIC

Centrality $\rightarrow$ impact parameter (b) selection
on collision geometry

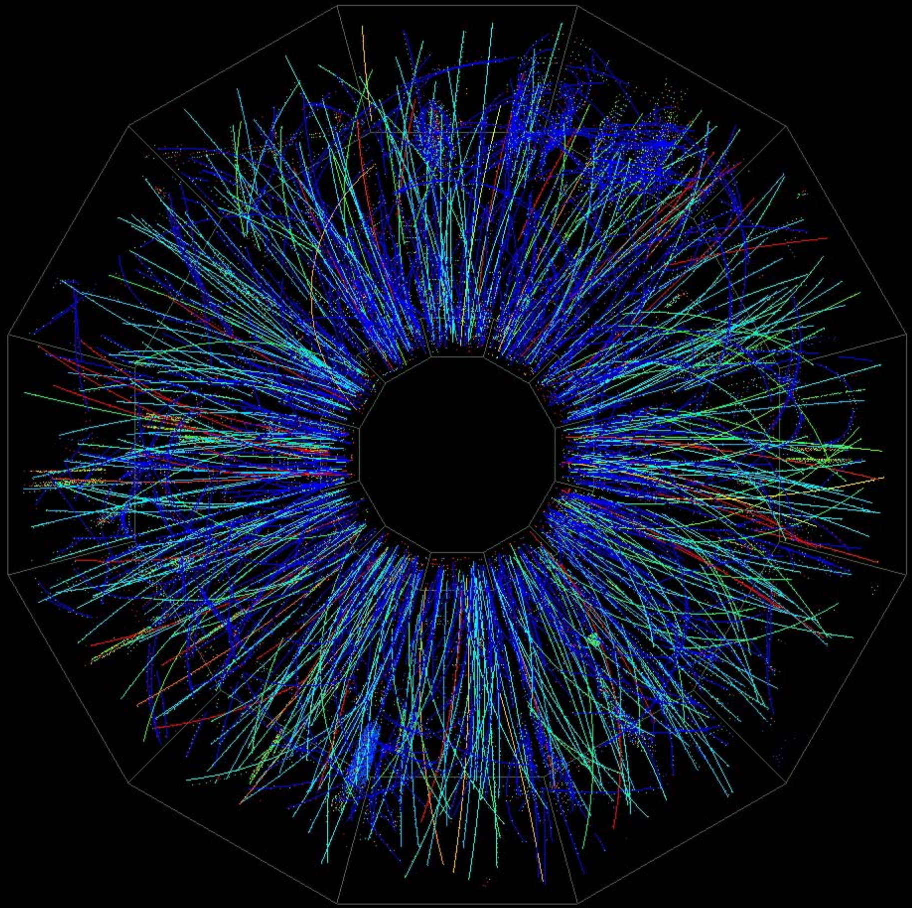


participants:
nucleons in
nuclear overlap

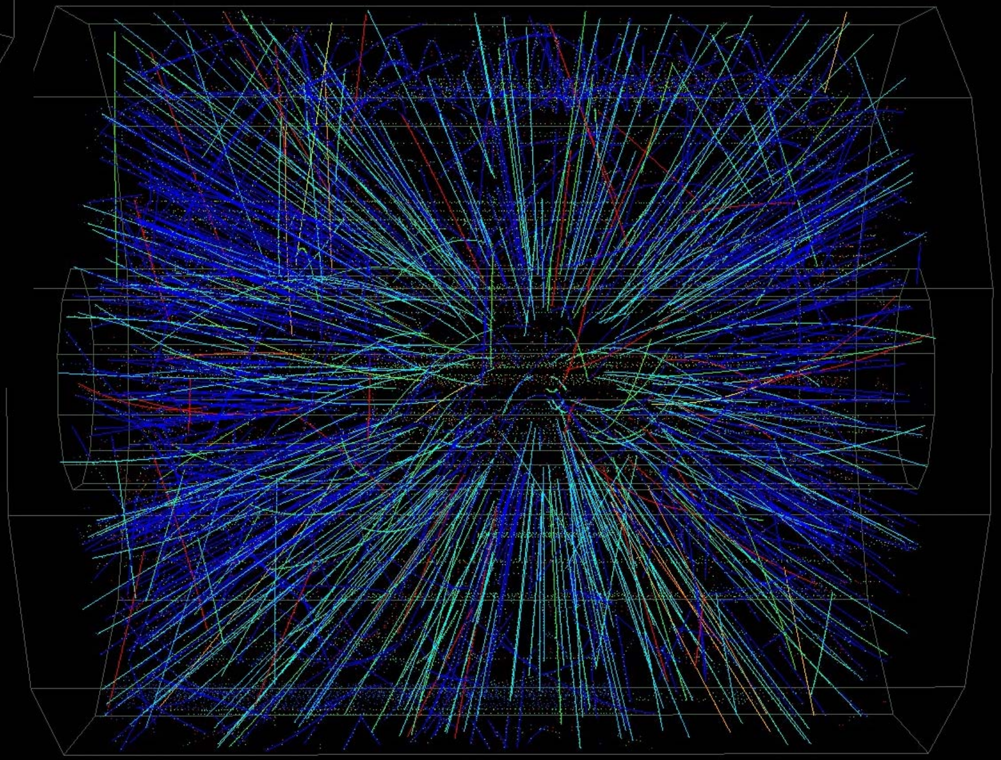
"peripheral" = collision ($b \sim b_{max}$)

"central" = head-on collision ($b \sim 0$)

Au on Au Event at CM Energy ~ 130 A-GeV

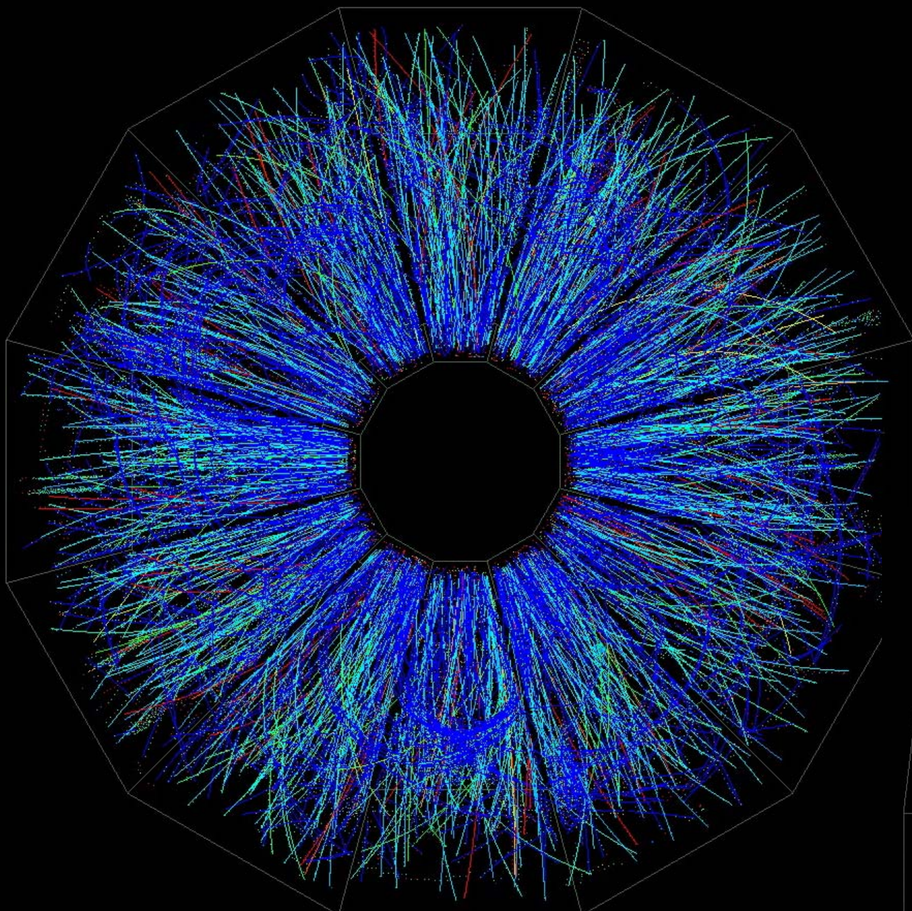


Peripheral Event

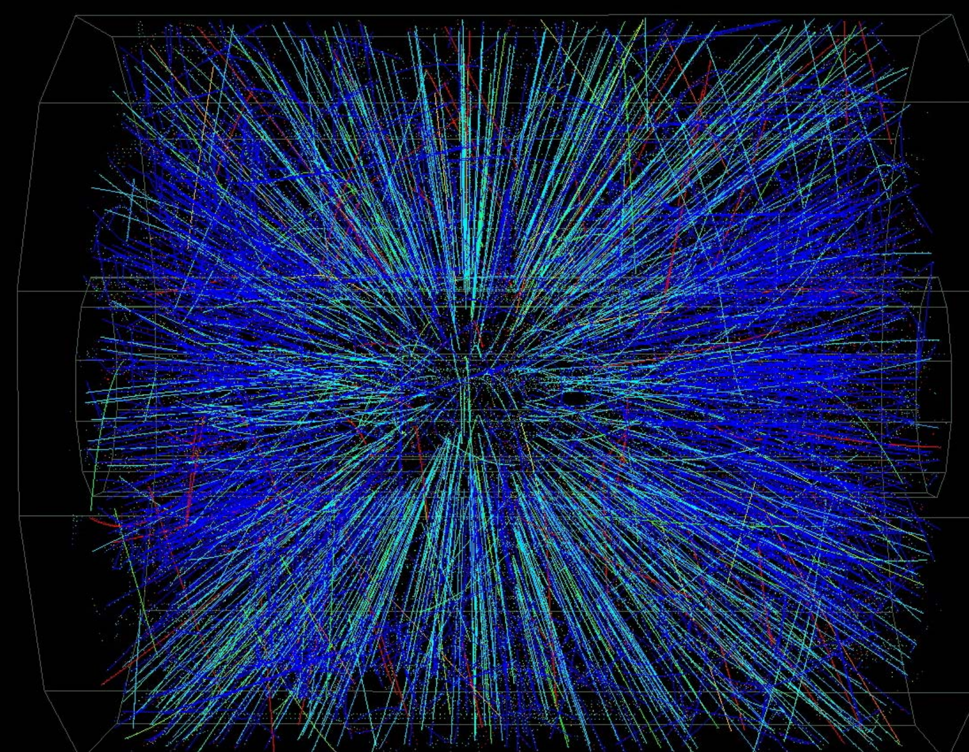


color code ⇒ energy loss

Au on Au Event at CM Energy ~ 130 A-GeV

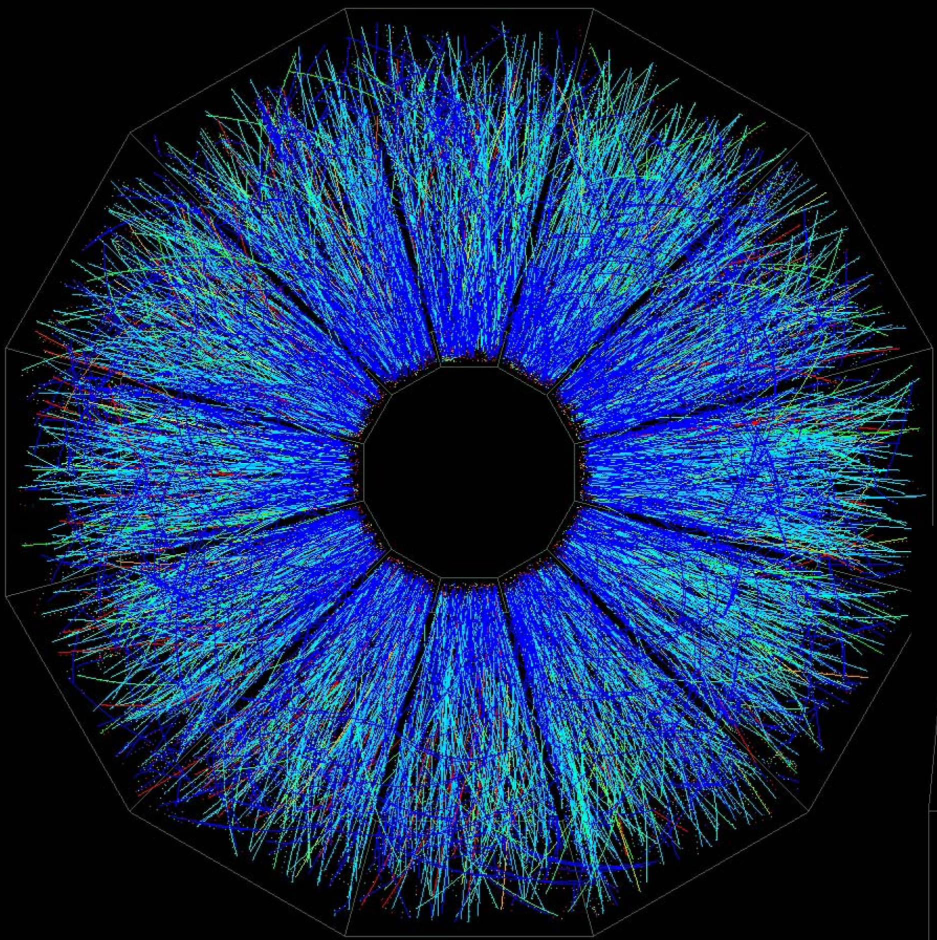


Mid-central Event

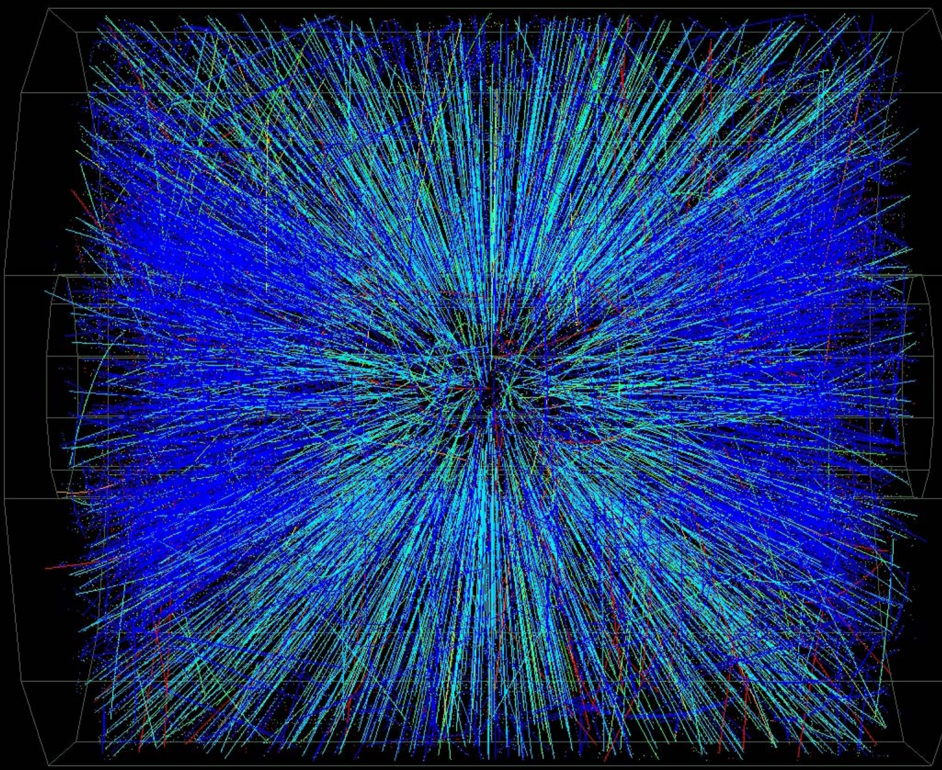


color code ⇒ energy loss

Au on Au Event at CM Energy ~ 130 A-GeV

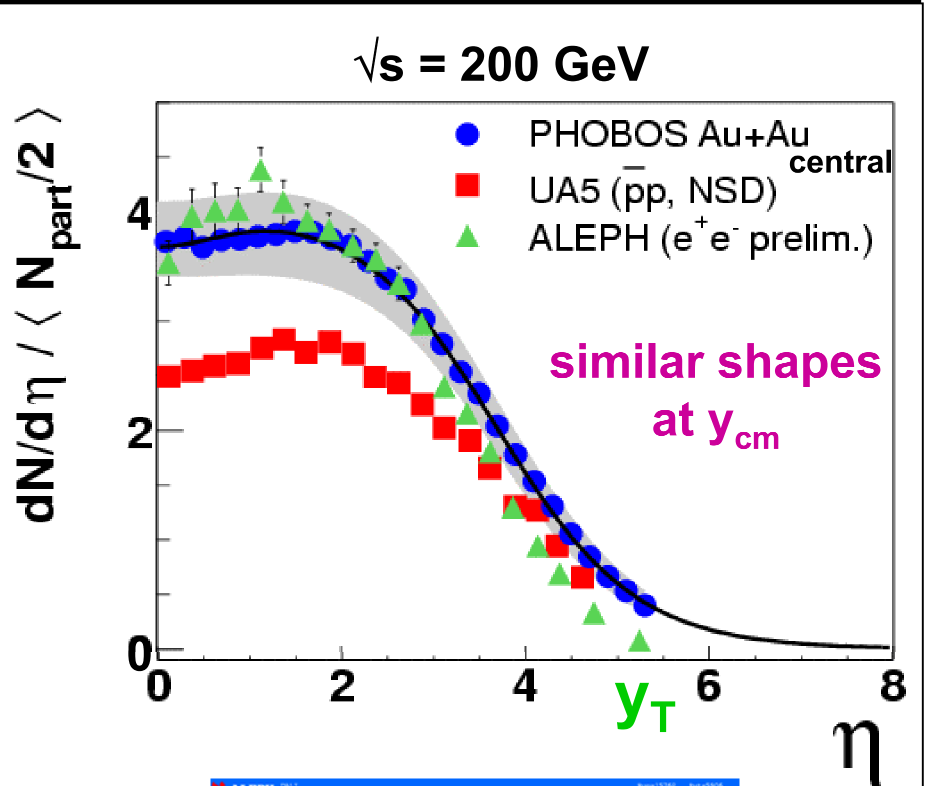


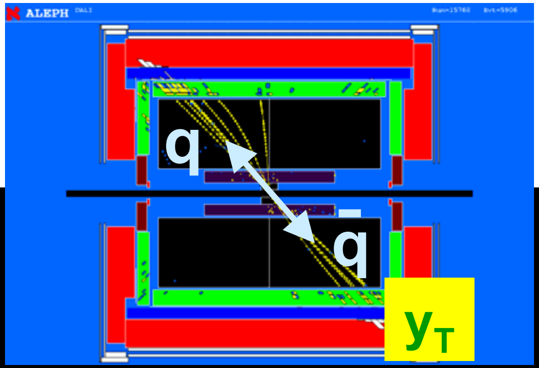
Central Event

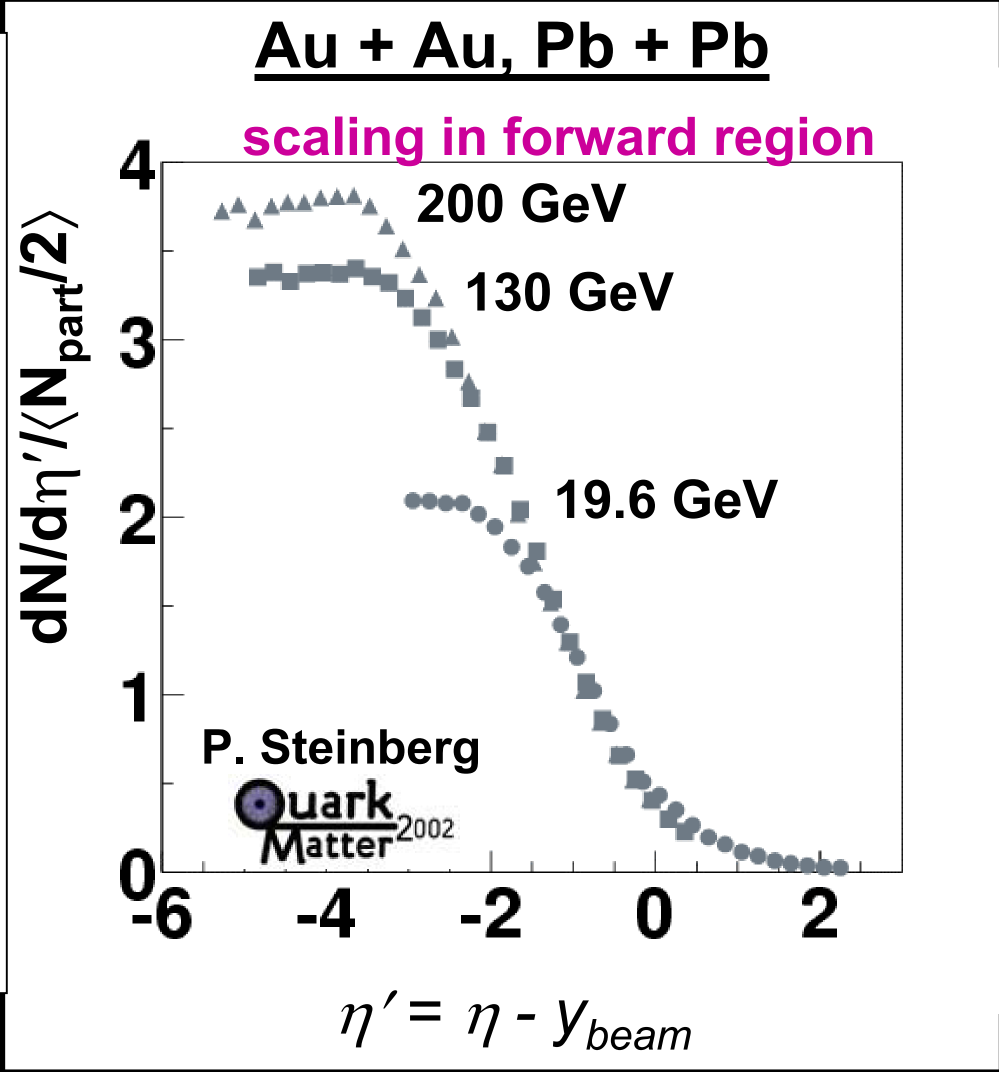


color code ⇒ energy loss

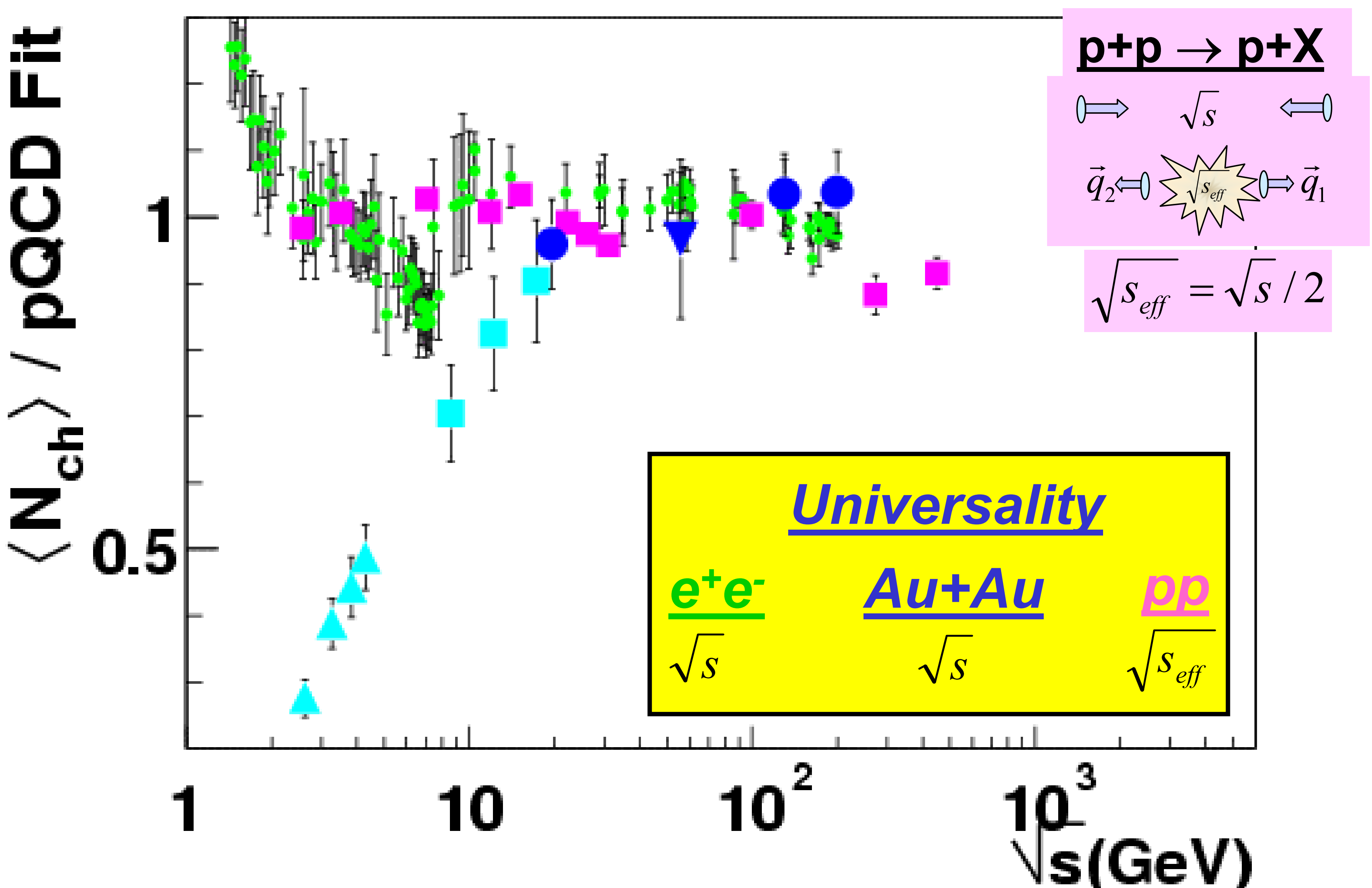
General Characteristics of RHIC Collisions







General Characteristics of RHIC Collisions



Soft Physics – Brief Overview

from the > (28 + 11) refereed journal publications from RHIC experiments:

Large Particle Multiplicities $\rightarrow$ $dn_{ch}/d\eta\,|_{y=0} = 670$, $N_{total} \sim 6000$

Large energy densities ($dE_T/d\eta$) $\rightarrow$ $\varepsilon \geq 5$ GeV/fm^3 / τ ($\tau \sim 0.1 - 1$)

Low net baryon density ($\bar{B}/B$ ratios) $\rightarrow$ $\mu_B \sim 40$ MeV

Chemical Freezeout T (particle ratios) $\rightarrow$ T ~ 170 MeV

Hadronization ($dn_{ch}/d\eta\,|_{y=0}$, particle ratios) $\rightarrow$ AA ~ e^+e^-

saturation, statistical hadronization, fragmentation (universality)?

Expansion and Thermal Freezeout

quark coalescence ($\bar{B}/B$ ratios)

no long-lived mixed phase (Bose-Einstein correlations)

rather - freezeout at critical point or rapid hadronization

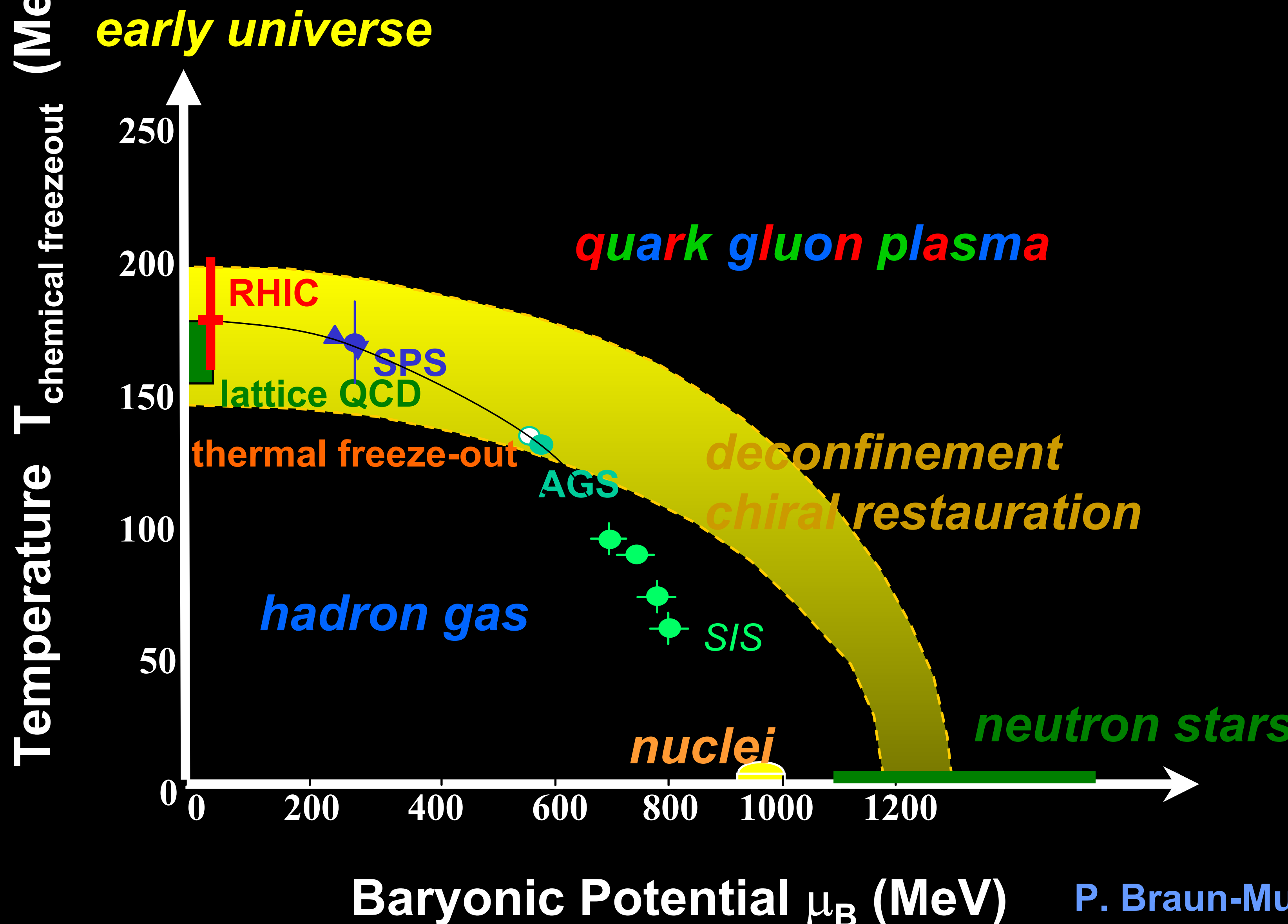
short chemical-to-thermal freeze-out interval

(particle spectra, resonances and particle yields,

multi-strange baryons spectra, HBT correlations)

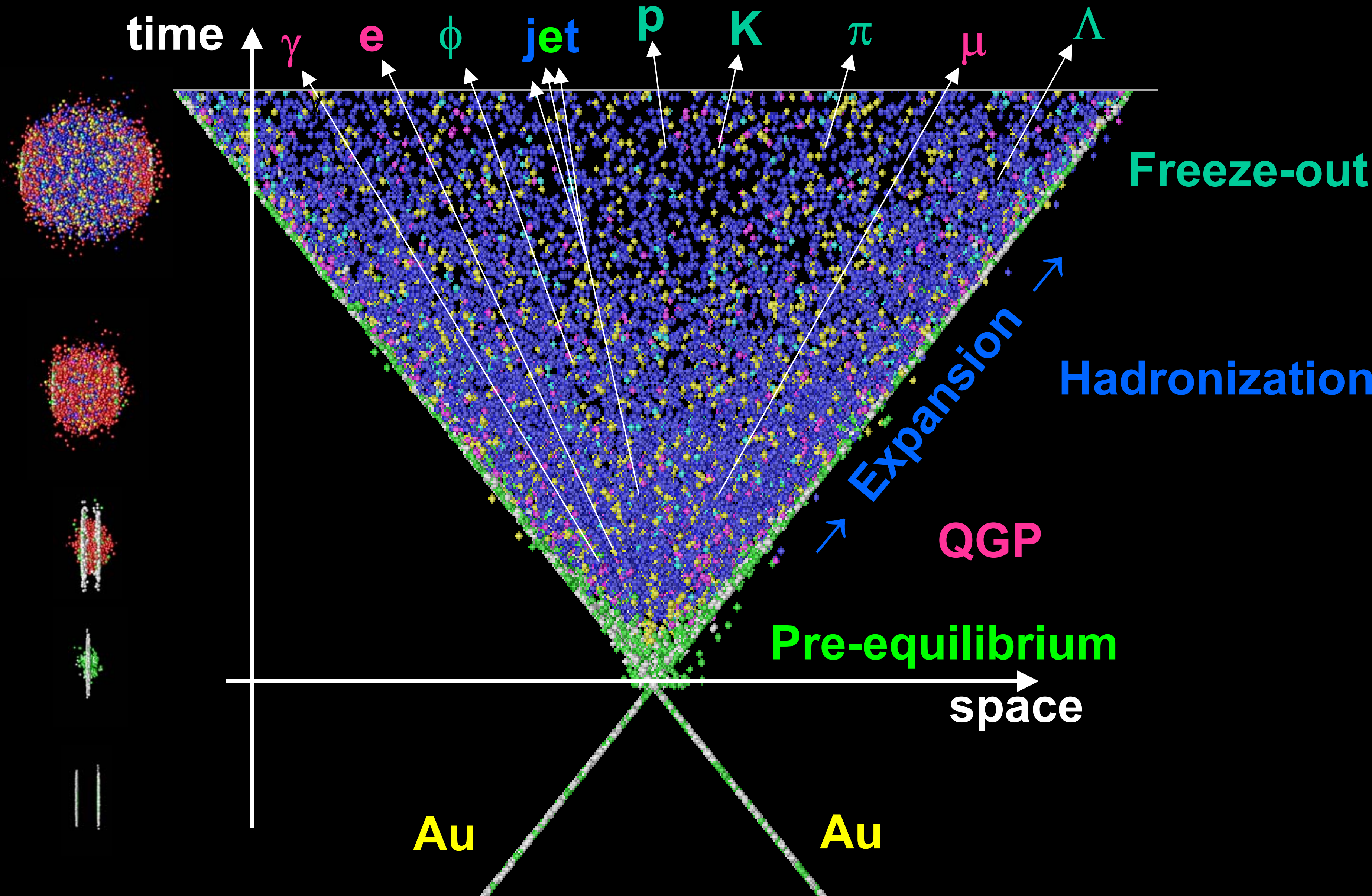
Space-time evolution of interaction still being determined

Nuclear Phase Diagram



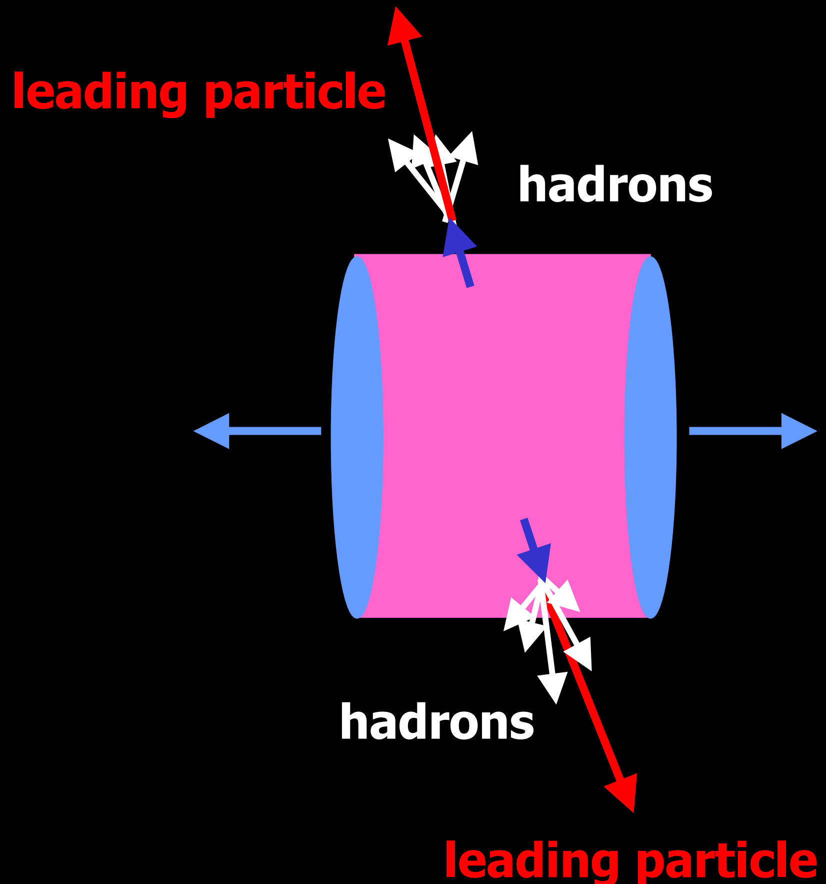
P. Braun-Munzinger
nucl-ex/0007021

Space-time Evolution of Collisions



Out of the Quark-Gluon Quagmire

Hard Scattering at RHIC



Hard Scattering as a Probe at RHIC

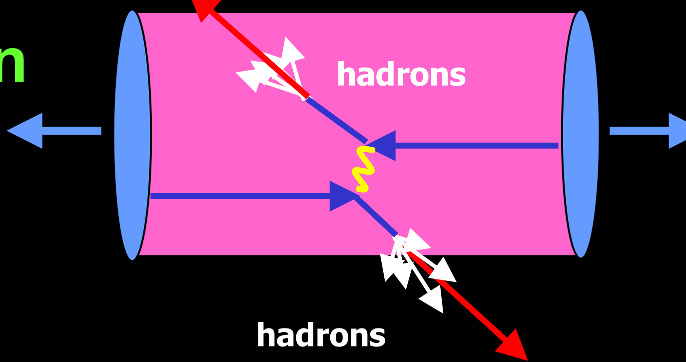
- New for heavy ion physics → ***Hard Parton Scattering***
  - $\sqrt{s_{NN}}$ = 200 GeV at RHIC (vs 17 GeV at SPS)

- Jets and mini-jets

  → 30 - 50 % of particle production

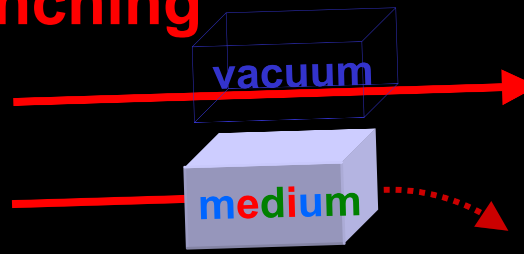
  → high p_t leading particles (jets?)

  → azimuthal correlations



- Scattered partons propagate through matter radiate energy (~ few GeV/fm) in colored medium
  - suppression of high p_t particles

    called "parton energy loss" or "jet quenching"
  - alter di-jets and azimuthal correlations

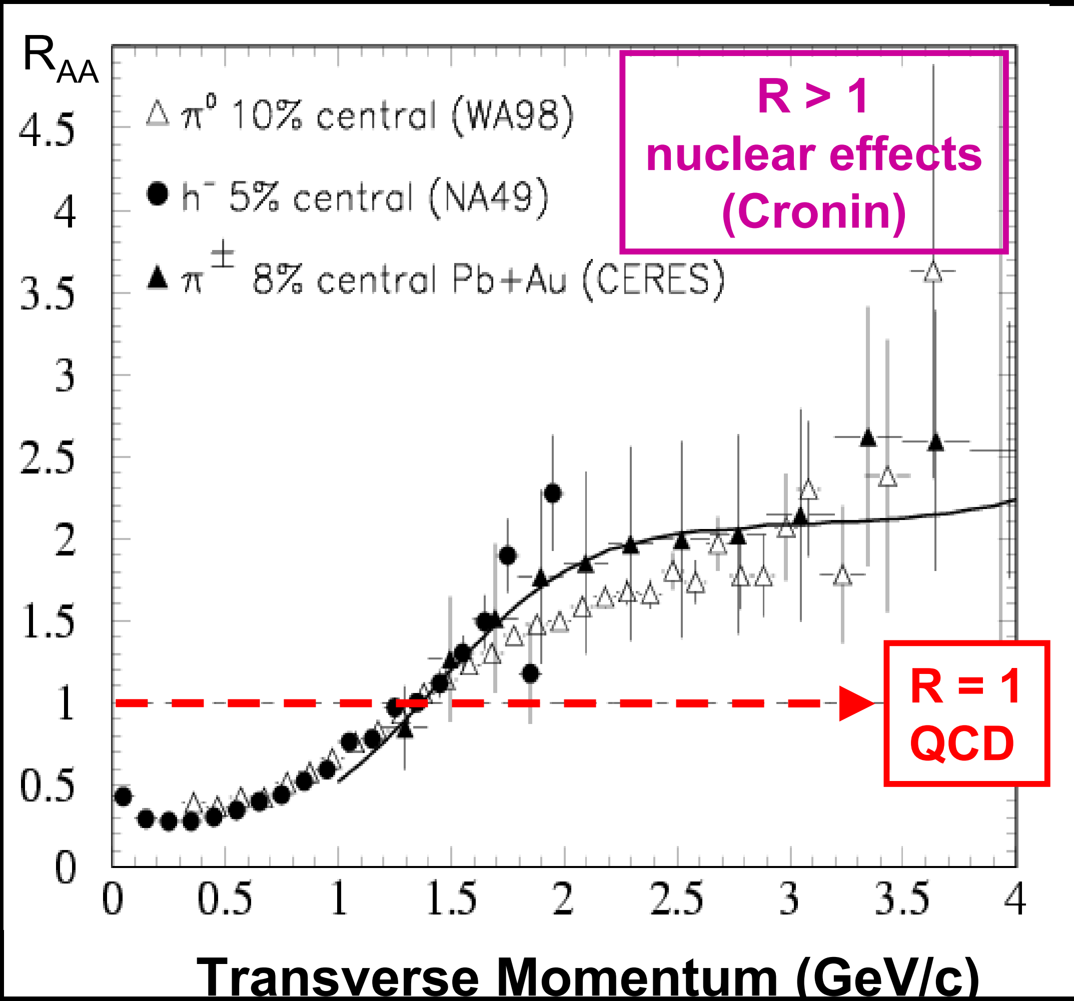


Comparison of Pb+Pb to p+p at $\sqrt{s}$ = 17.2 GeV

Nuclear Modification Factor R_{AA}

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

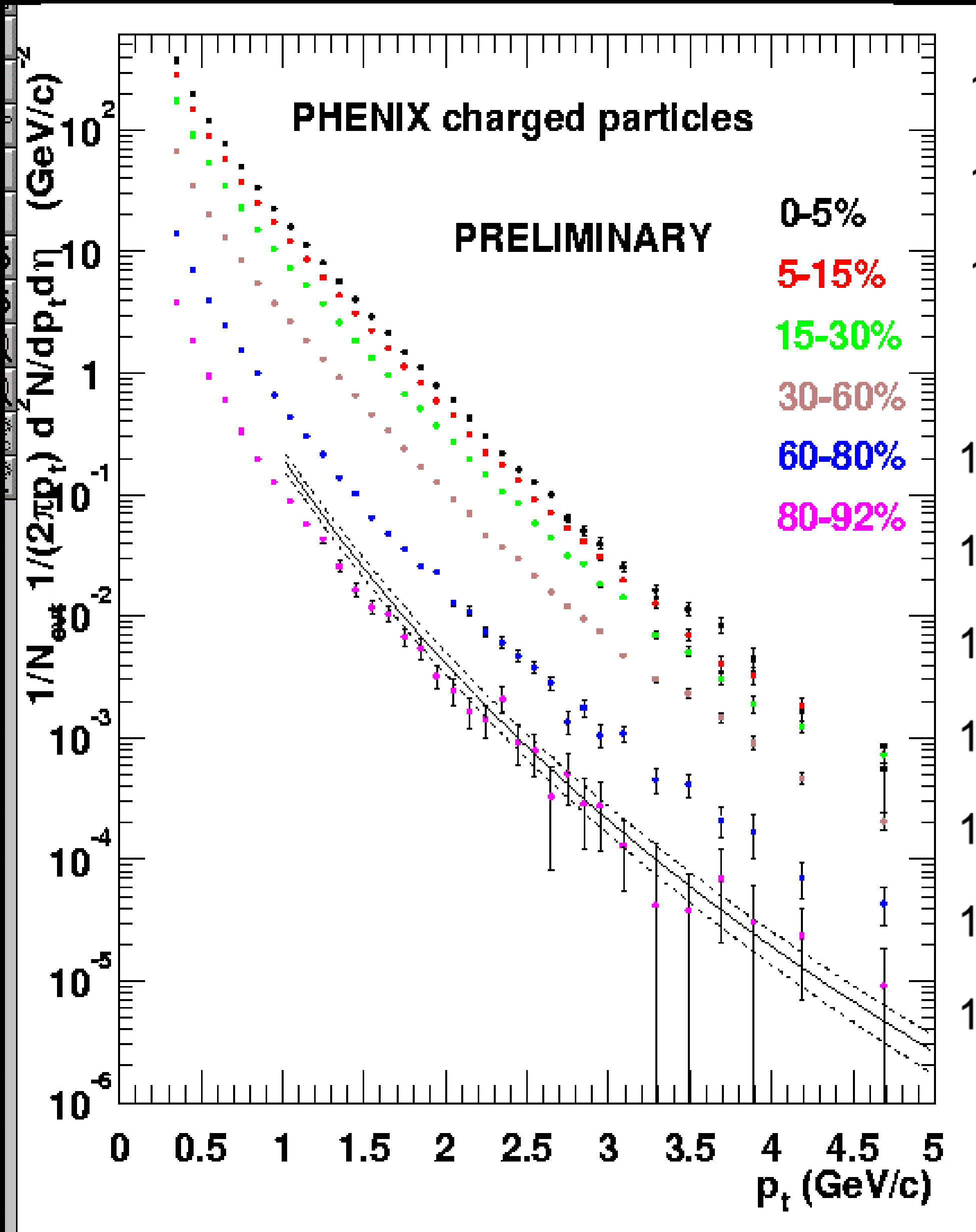
TAA: nuclear overlap integral (from Glauber model)

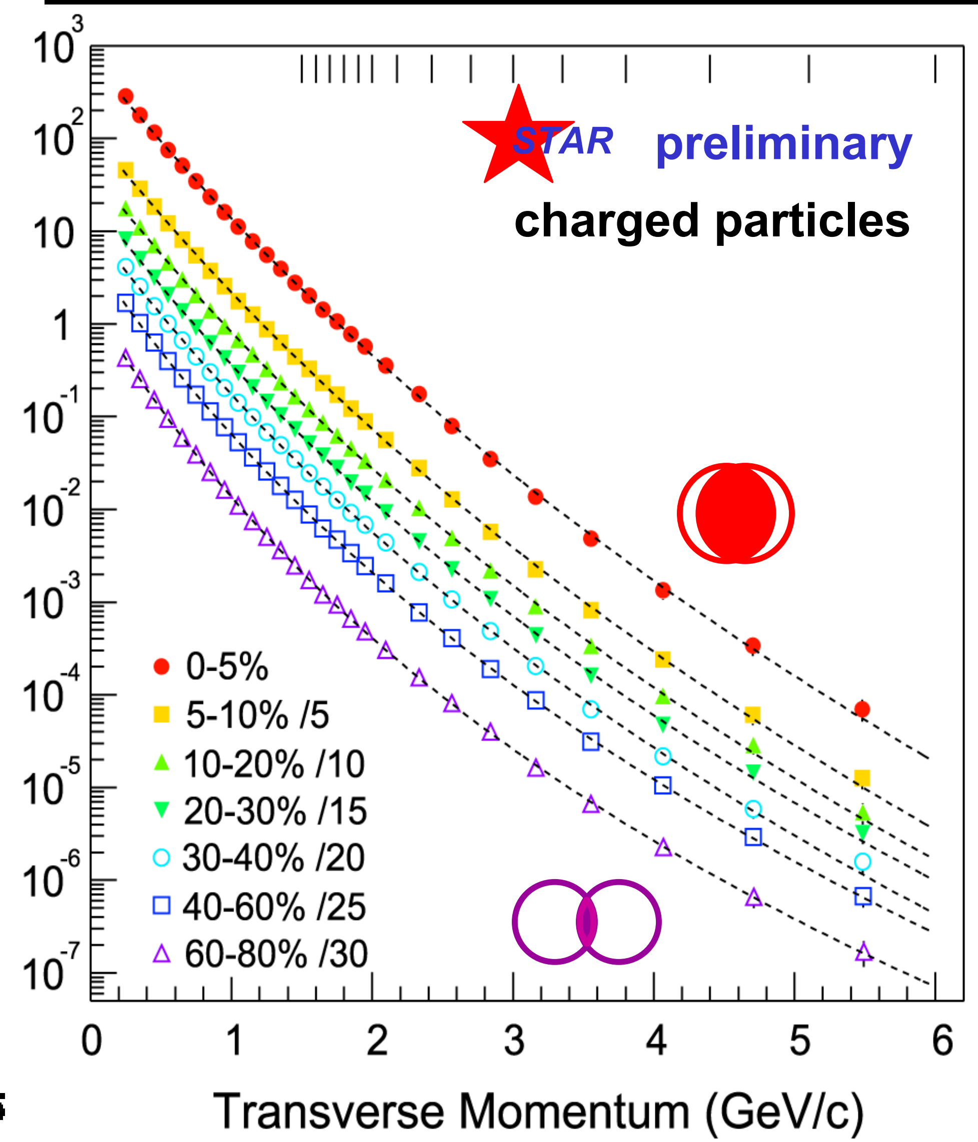


→ If any parton energy loss, it is overwhelmed by initial state soft multiple scattering (Cronin effect)

Inclusive Hadron p_t-distributions

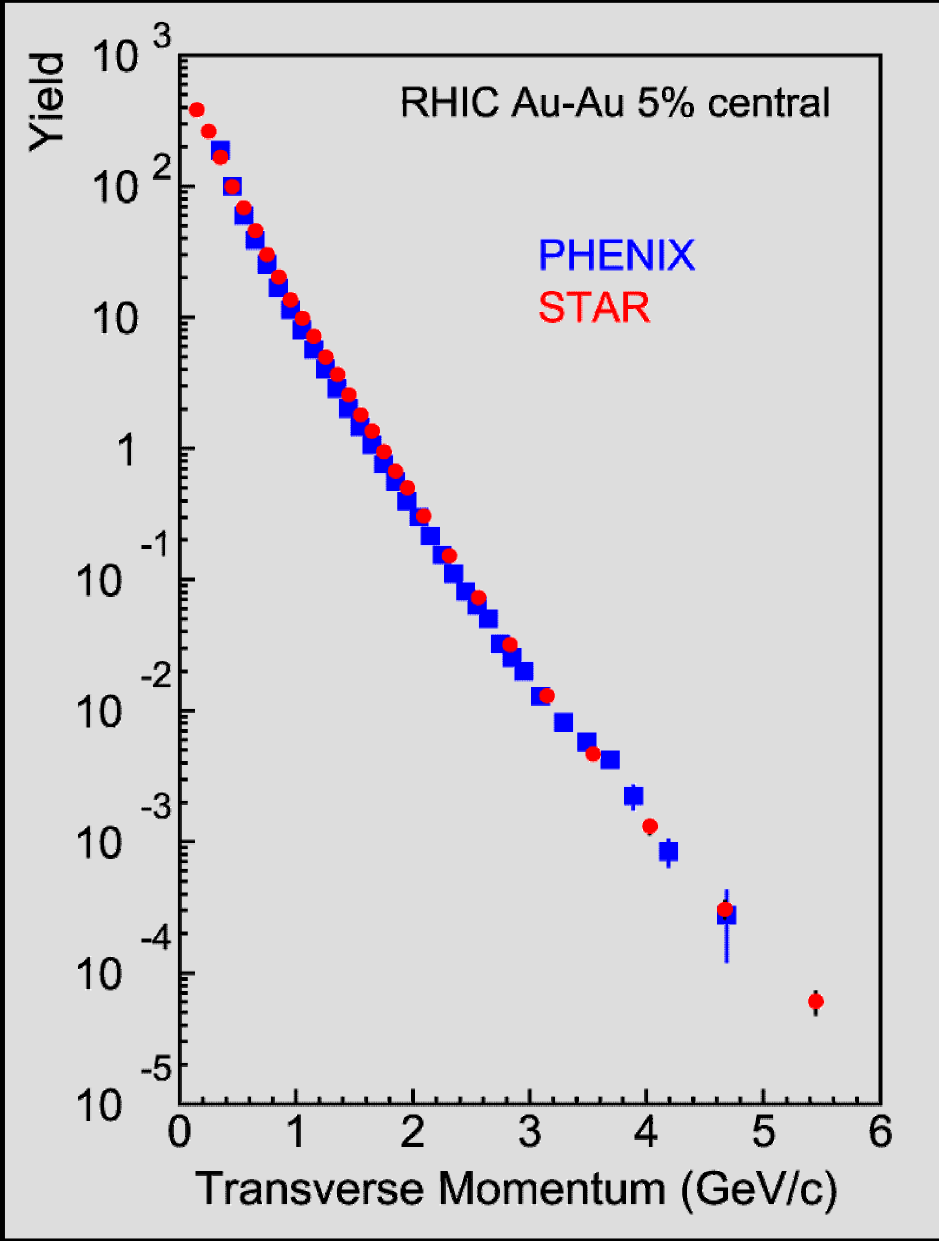
$\sqrt{s}$ = 130 GeV Au + Au





High-p_T Spectra in 130 GeV Au+Au Collisions

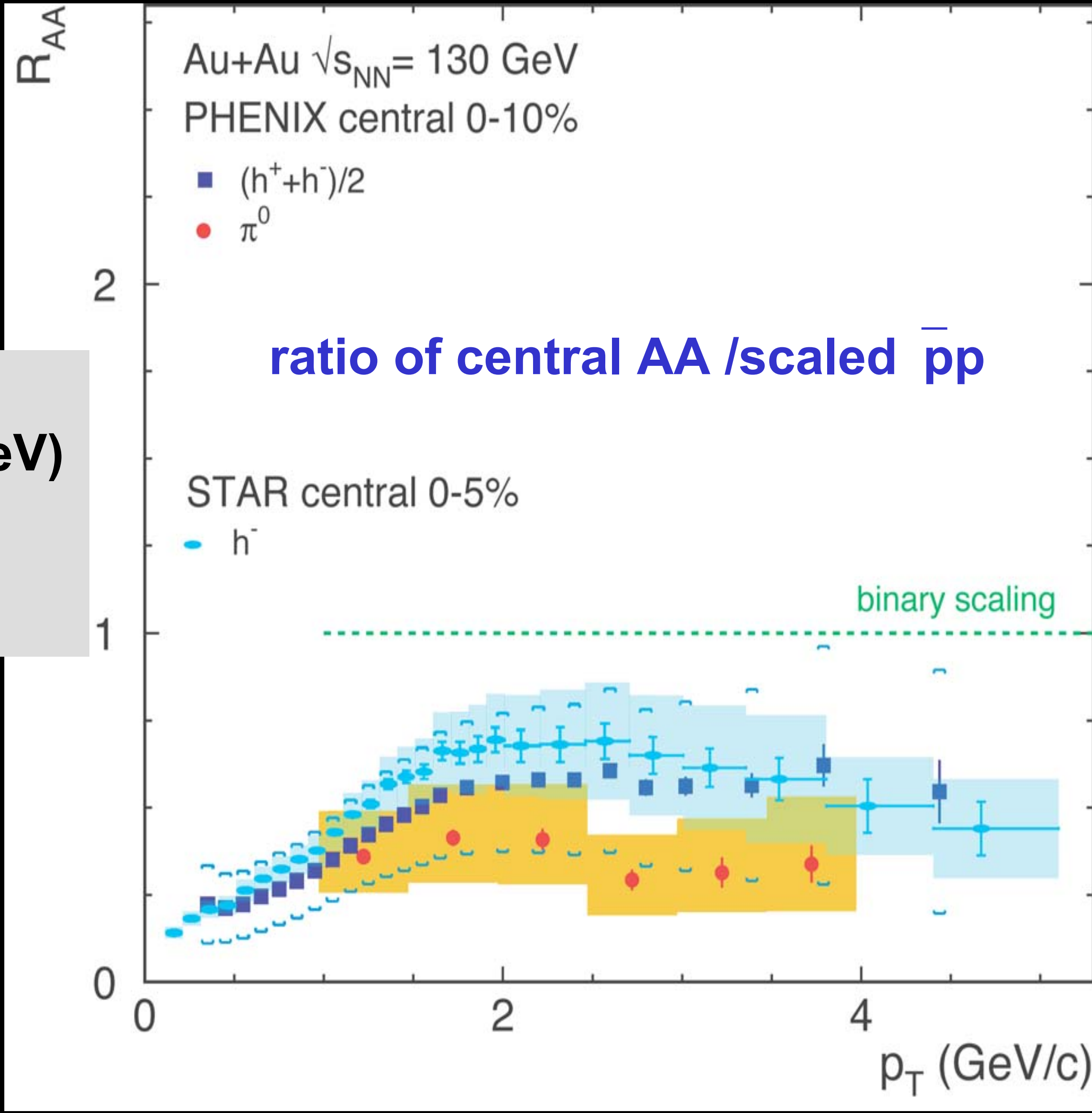
spectra from PHENIX + STAR agree over 6 orders of magnitude



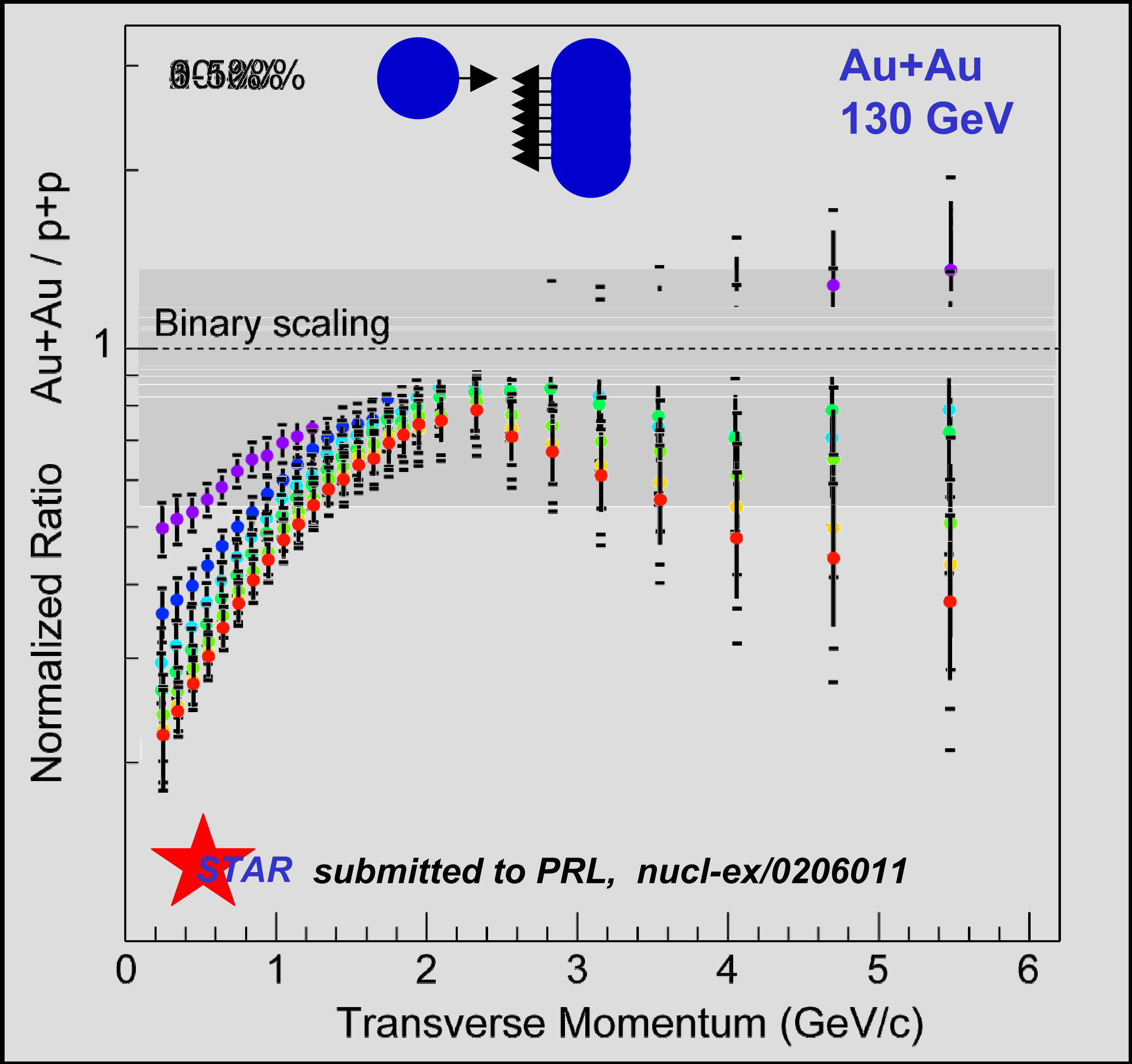
Suppression of Hadron Production

$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_T}{d^2N^{pp}/dydp_T \cdot \langle N_{coll}^{AA} \rangle}$$

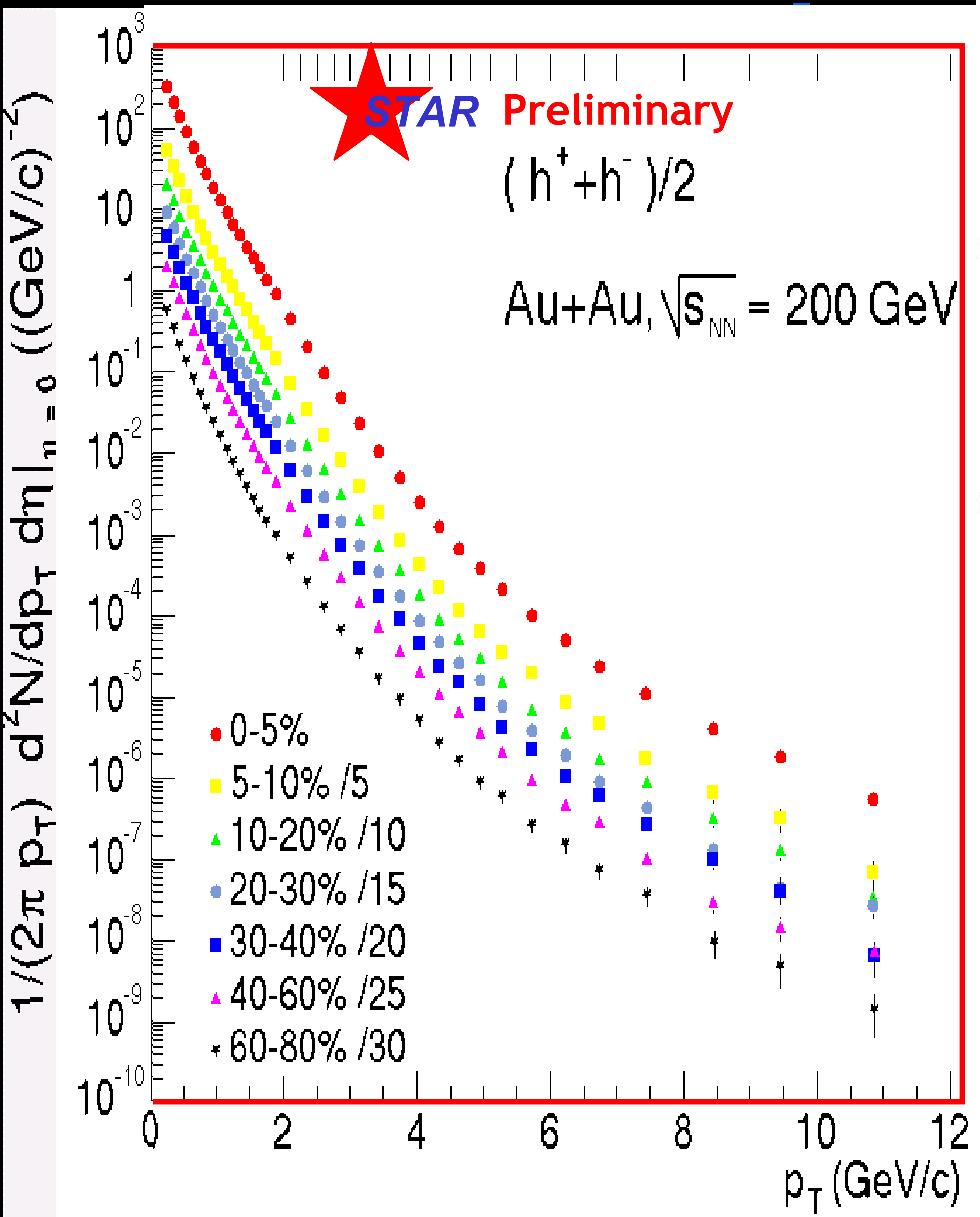
- **$R_{AA} < 1$ for central Au+Au reactions at RHIC (130 AGeV)**
  - **observed in (PHENIX and STAR)**

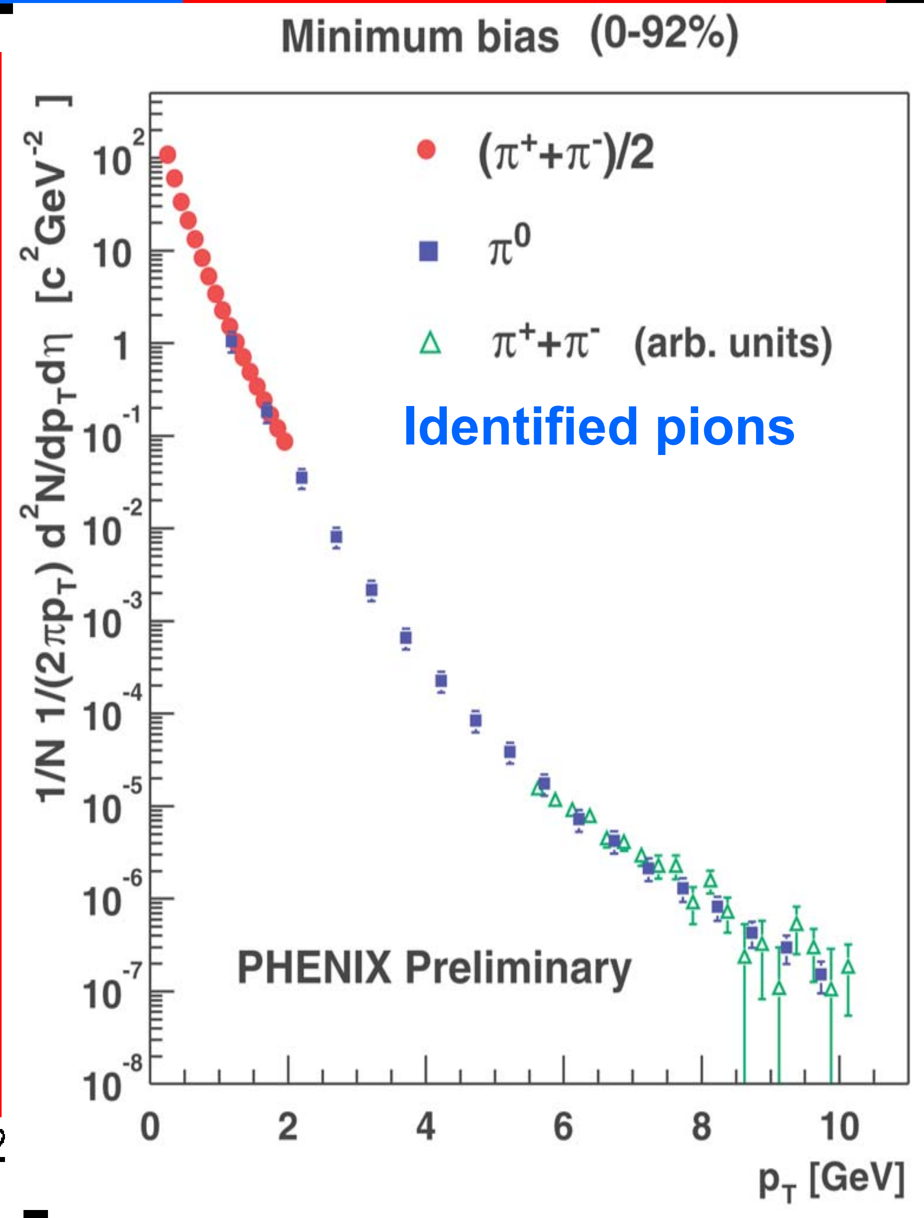


Centrality Dependence of Suppression

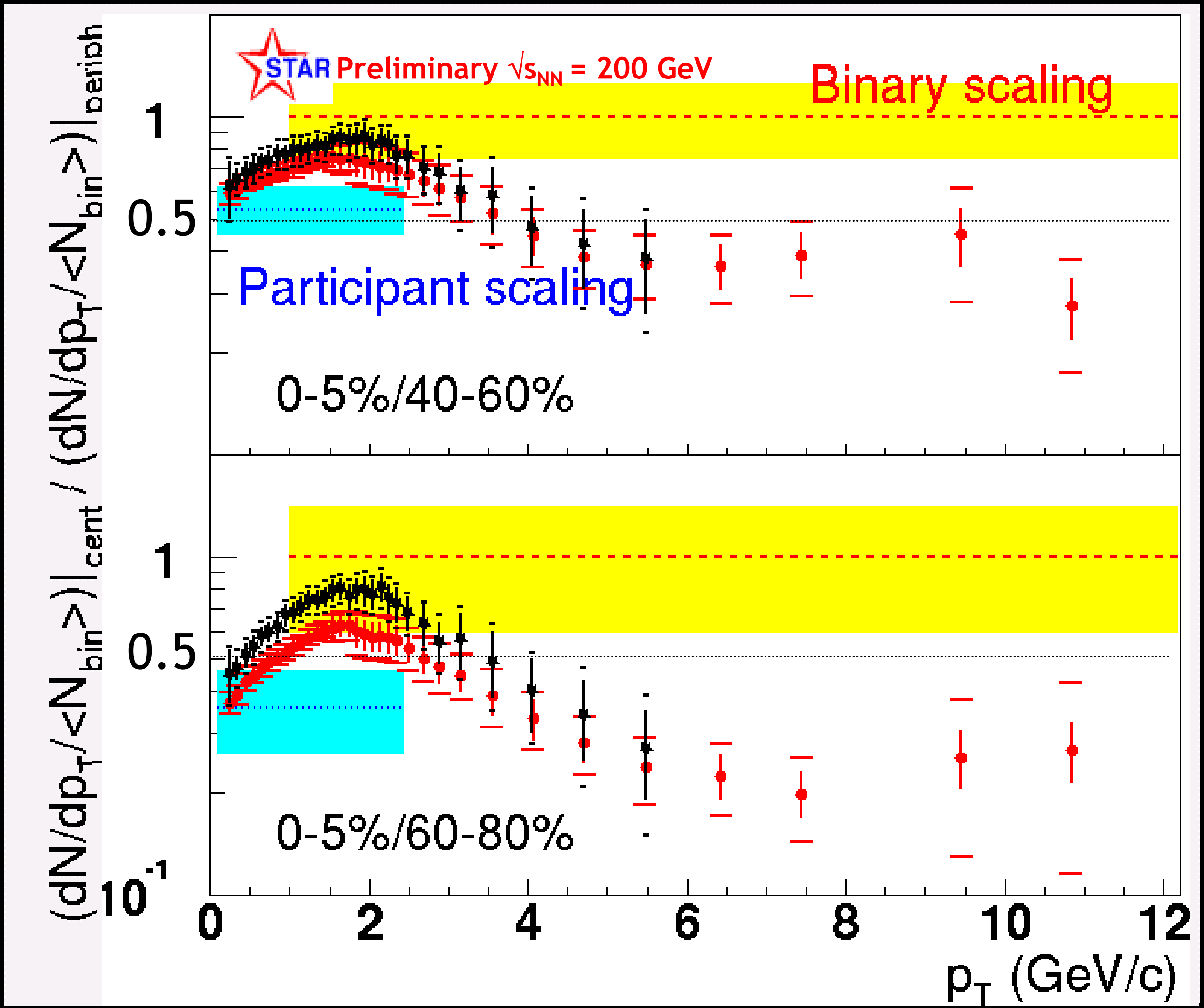


Inclusive Hadron p_t-spectra: $\sqrt{s}$ = 200 GeV AuAu





Central/Peripheral Comparisons



suppression increases up to p_T = 6 GeV/c

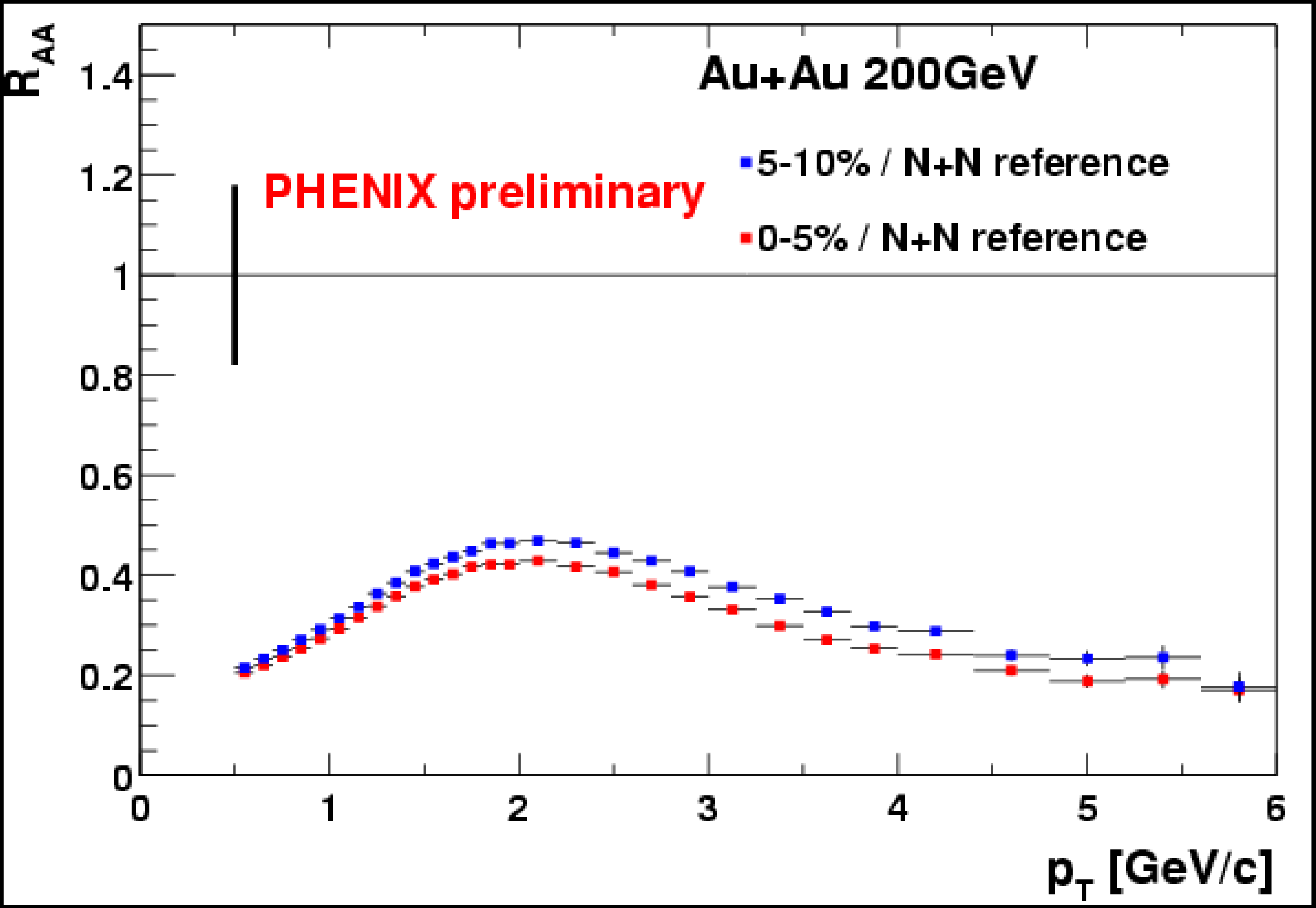
suppression saturates beyond p_T ~6 GeV/c

★	130 GeV
●	200 GeV

Comparison with N+N Reference Data

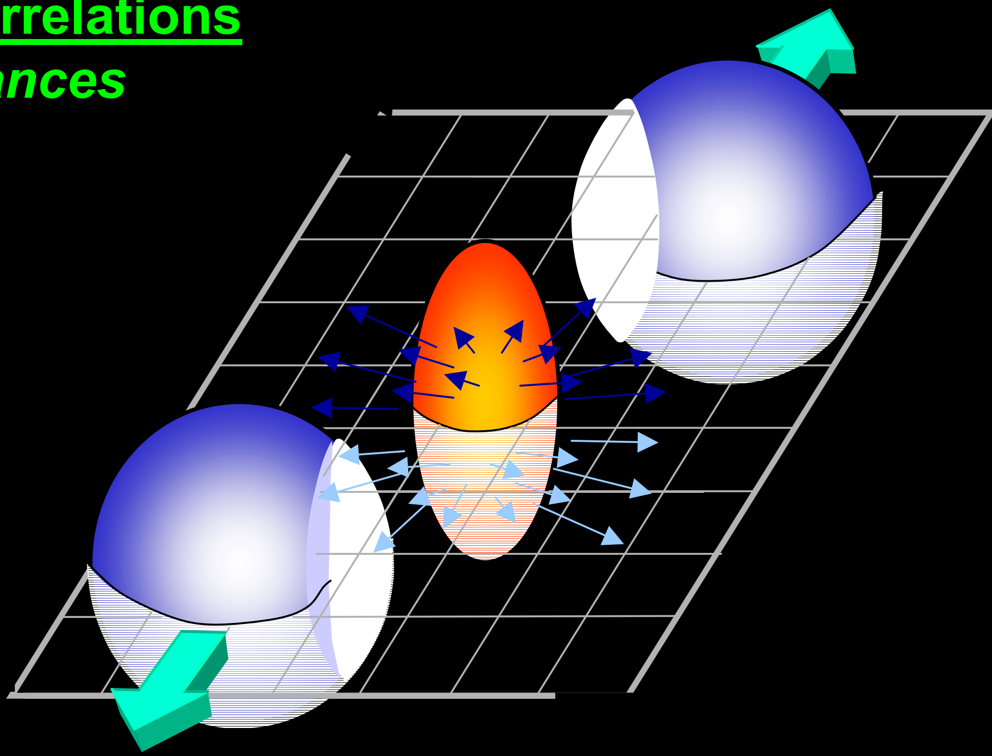
Suppression increases with centrality

more pronounced at higher p_T



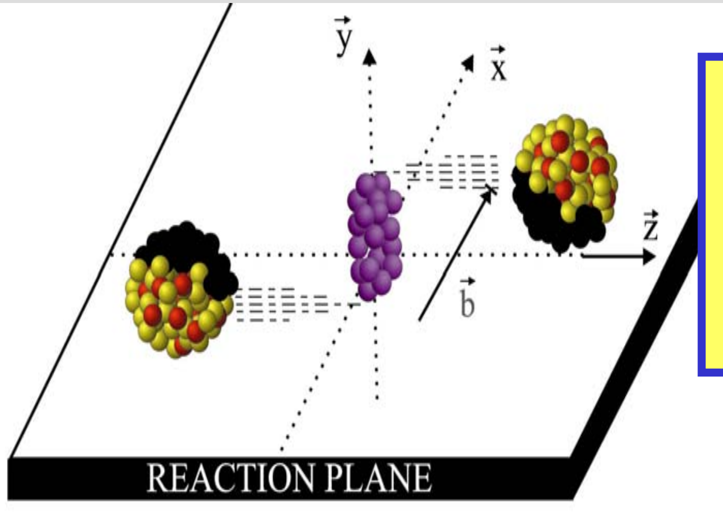
Azimuthal Correlations in AA Collisions

Short-range correlations
jets, resonances

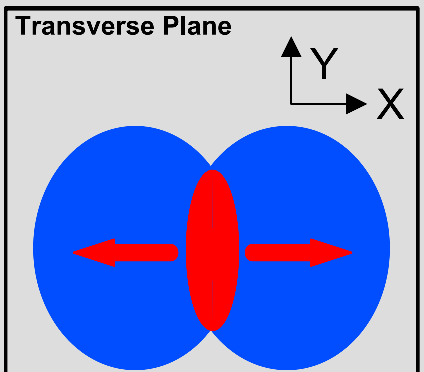


Long-range correlations
momentum conservation,
az. anisotropy of event (soft)

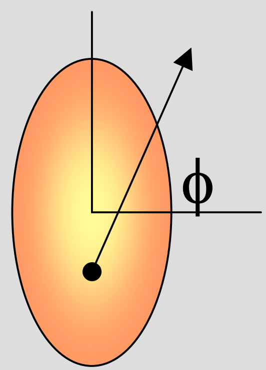
A Probe of Early Dynamics

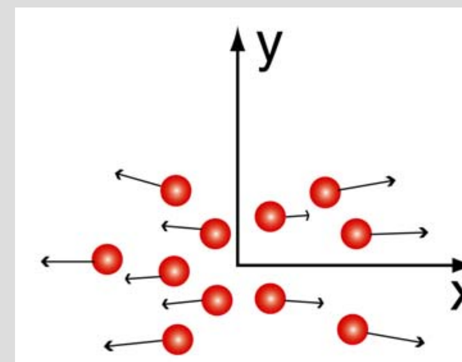


Azimuthal anisotropy → elliptic flow measures
→ response of the system to early pressure
→ the system's ability to convert original spatial anisotropy into momentum anisotropy
- sensitive to early dynamics of initial system



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$





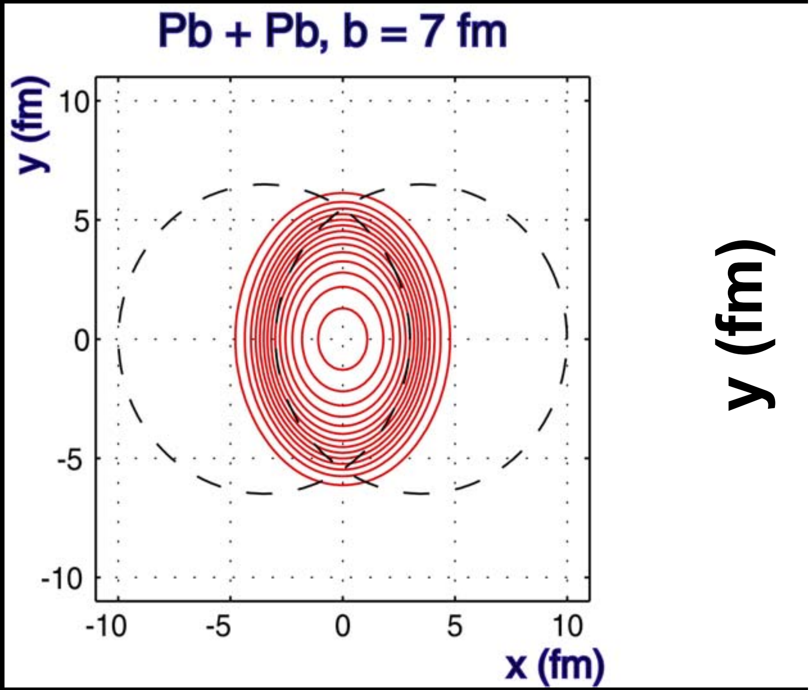
$$\phi = \operatorname{atan} \frac{p_y}{p_x} \qquad v_2 = \langle \cos 2\phi \rangle$$

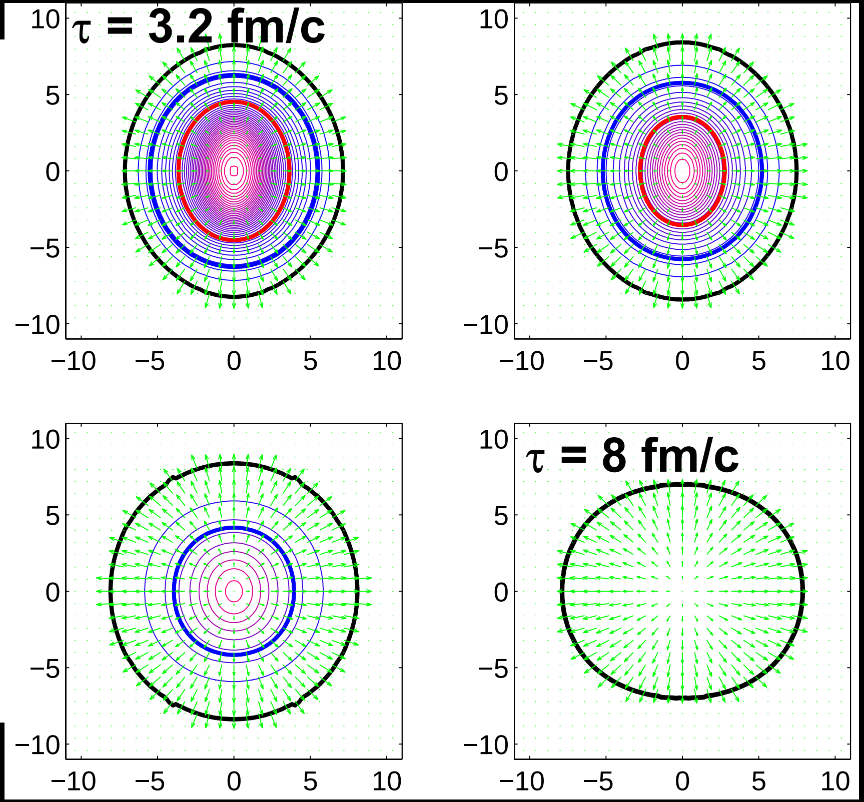
XZ-plane - the reaction plane

v_2: 2nd Fourier harmonic coefficient of azimuthal distribution of particles with respect to the reaction plane → measures elliptic flow

Hydrodynamic Calculation of Elliptic Flow

P. Kolb, J. Sollfrank, and U. Heinz

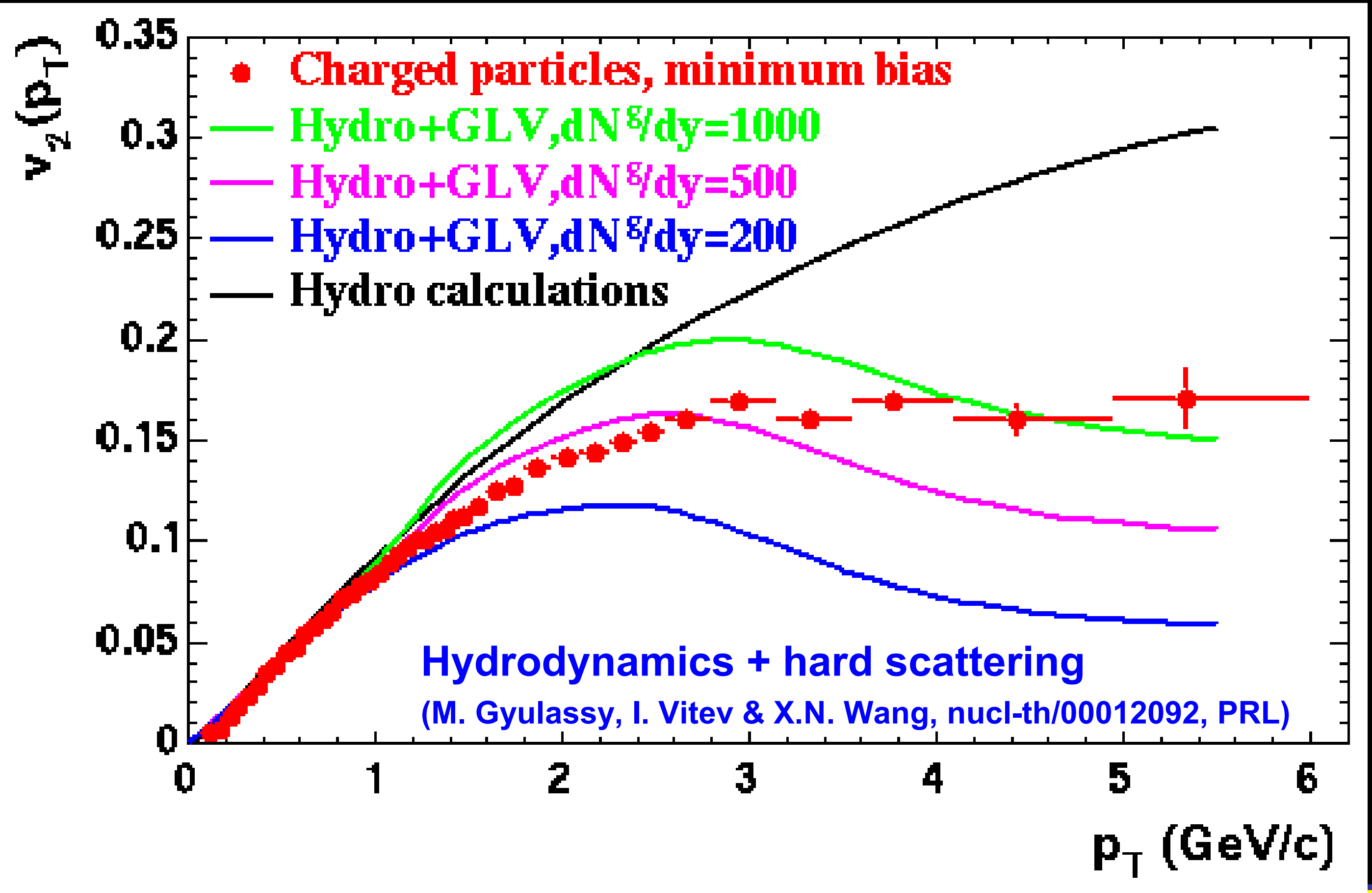




Equal energy density lines

Charged Particle Elliptic Flow (v_2)

STAR

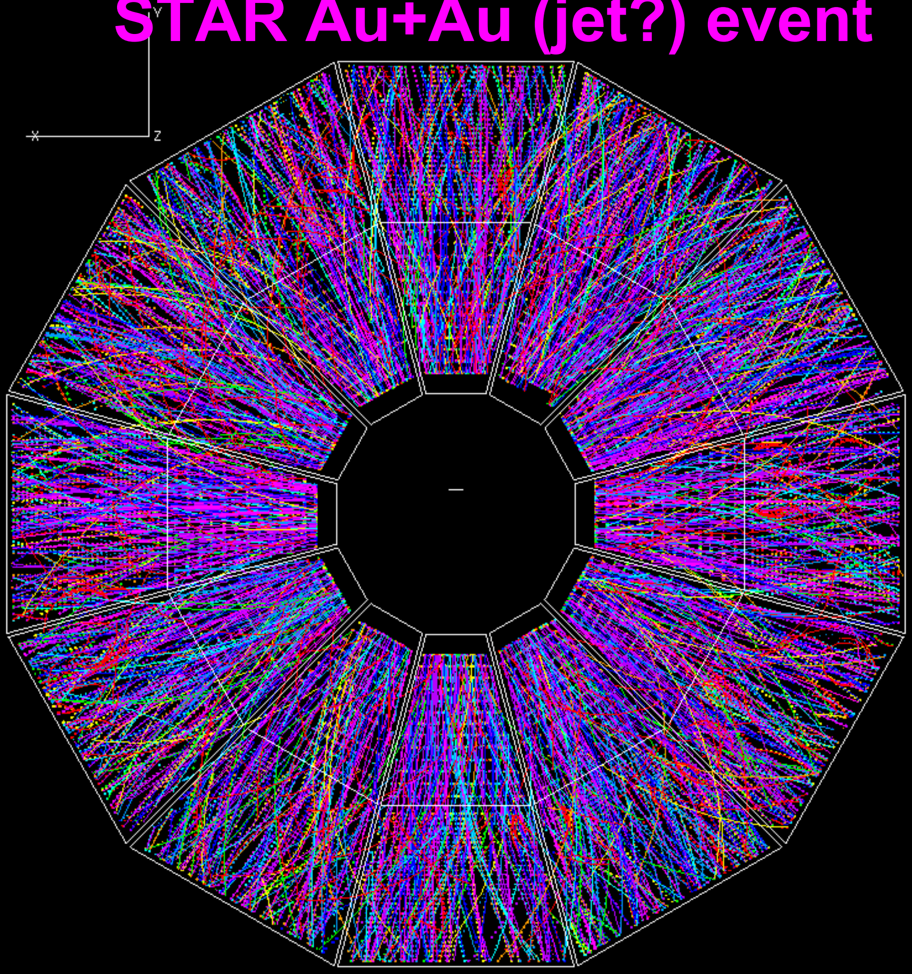


Hydro + hard scattering model and data:

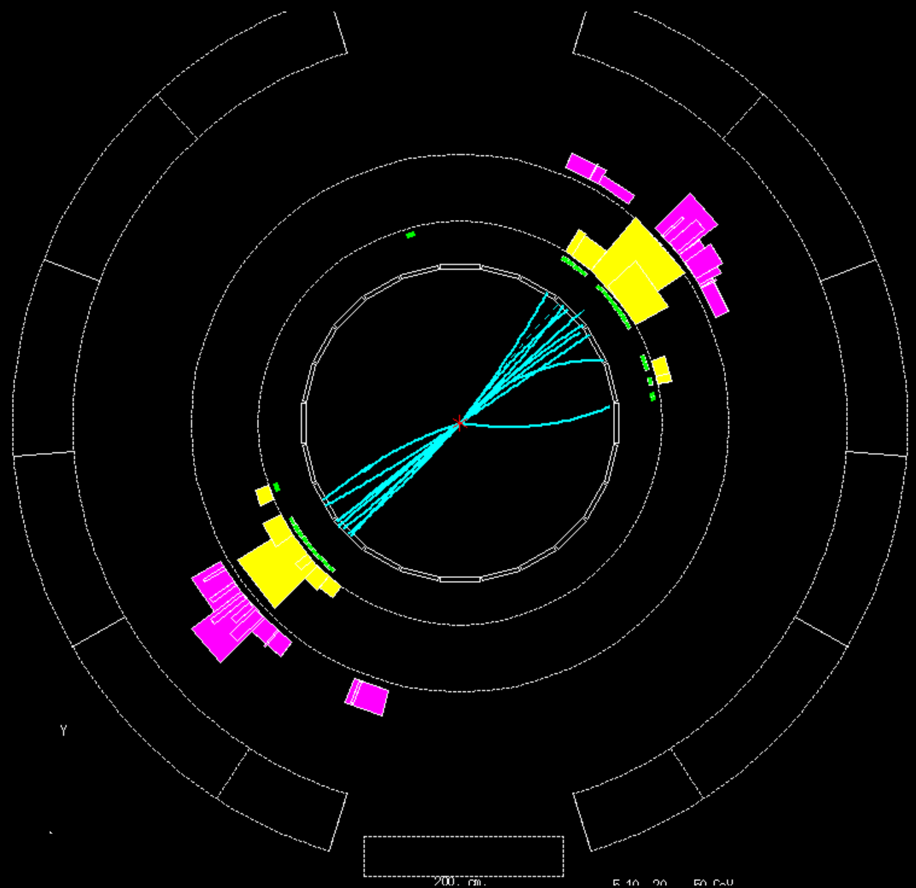
- hydrodynamic behavior up to ~1.5 GeV/c
- v_2 saturates at high p_t
  - reflects gluon density
- data → compatible with scenario of large parton energy loss in medium

Hard Scattering (Jets) as a Probe at RHIC

STAR Au+Au (jet?) event



Jet event in e^+e^- collision



Can we see jets in high energy Au+Au?

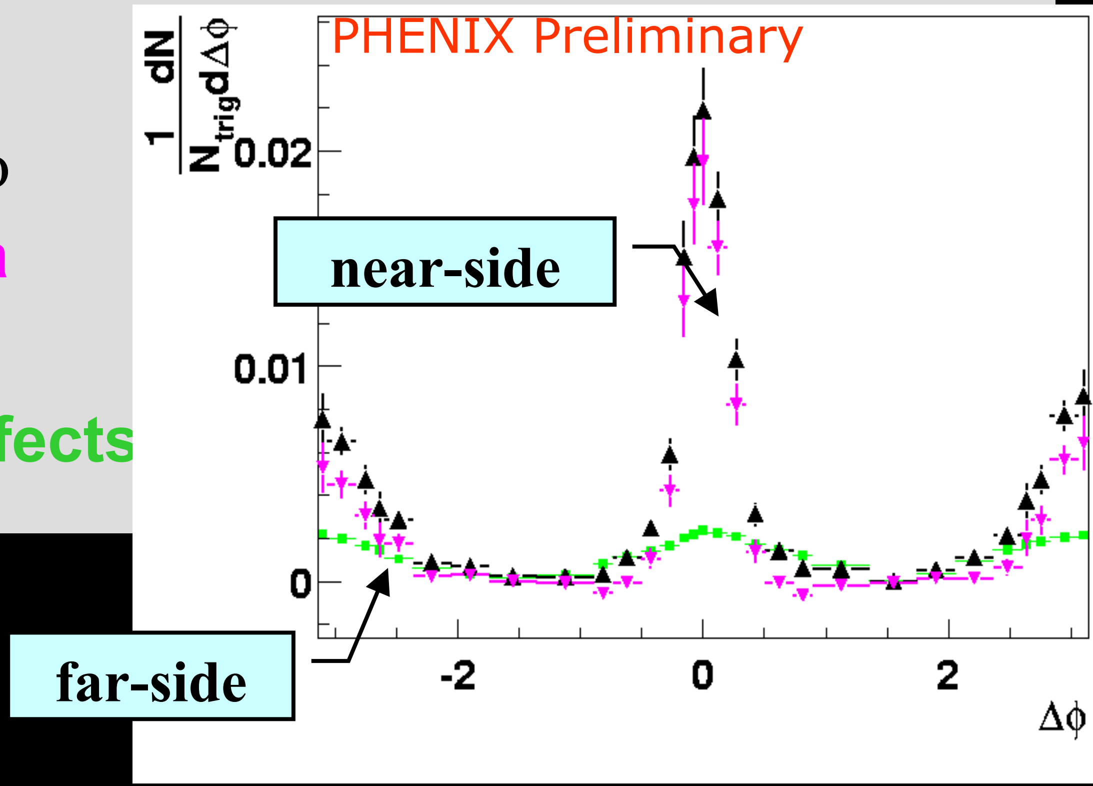
Hard Scattering via Angular Correlations

Charged tracks (1 - 2 GeV/c) associated with a high energy leading photon (>2.5 GeV/c)

Remove soft background by subtraction of mixed event distribution.

Fit remainder:

- **particle correlation in $\Delta\phi$**
- **shape taken from Pythia**
- **add v_2 component to account for flow effects**



Two-Particle Azimuthal Correlations

Technique:

$$C_2(\Delta\Phi) = \frac{1}{N_{trigger}} \frac{1}{efficiency} \int d(\Delta\eta) N(\Delta\Phi, \Delta\eta)$$

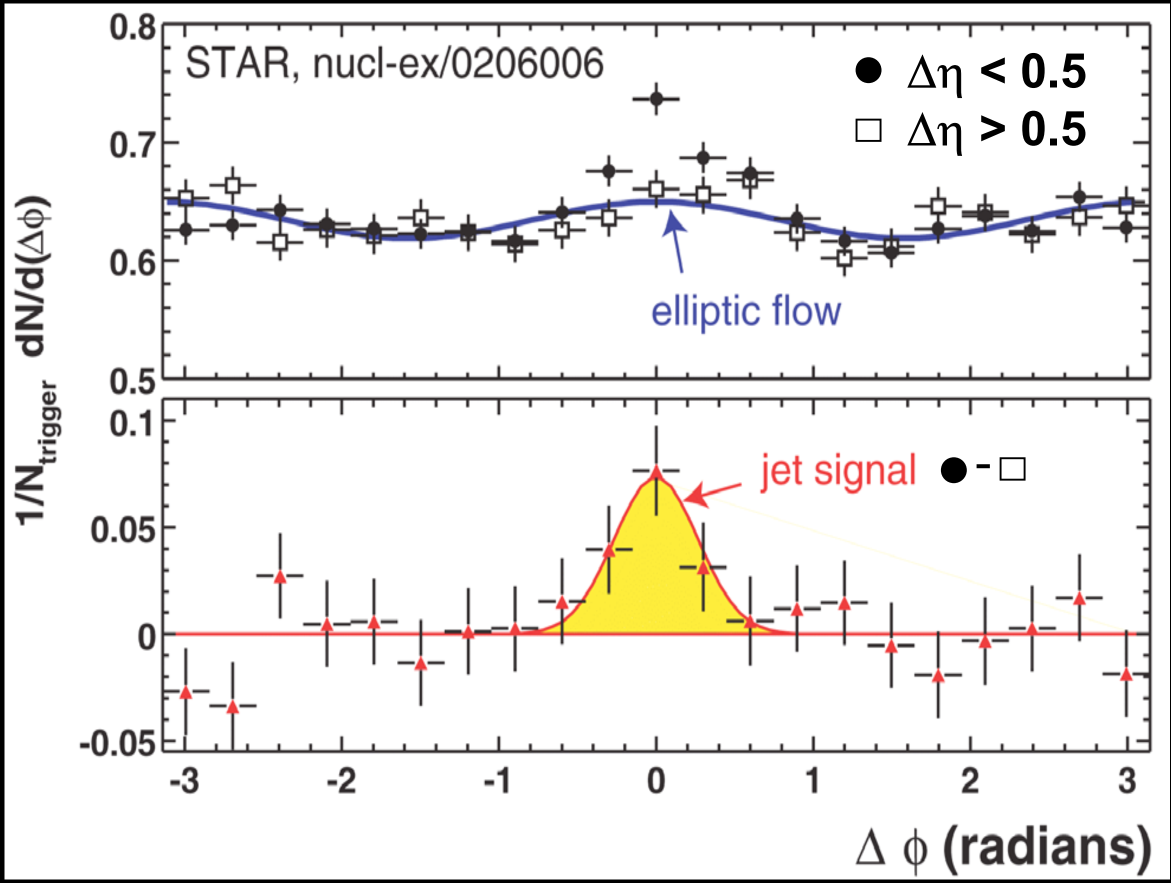
Azimuthal correlation function

Trigger particle

$p_T > 4$ GeV/c

Associate tracks

$2 < p_T < p_T(\text{trigger})$



short range η correlation:

jets + elliptic flow

long range η correlation:

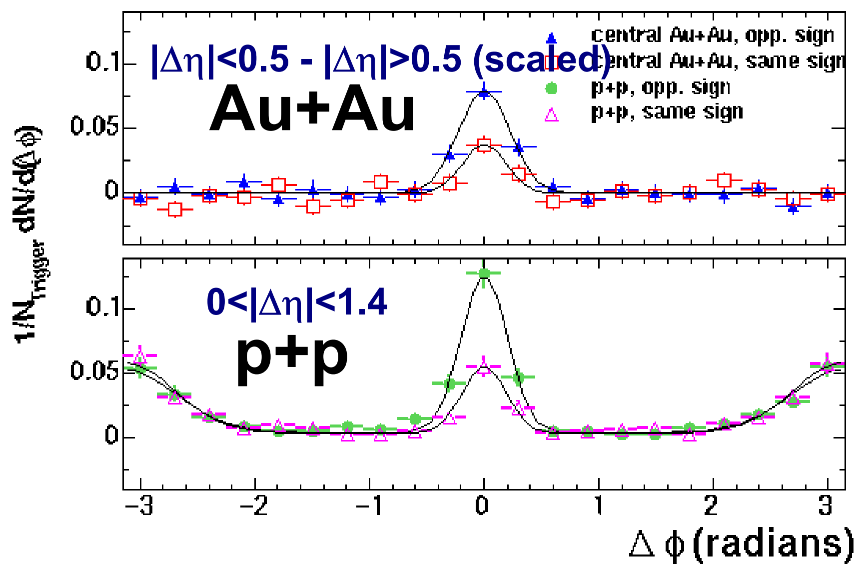
elliptic flow

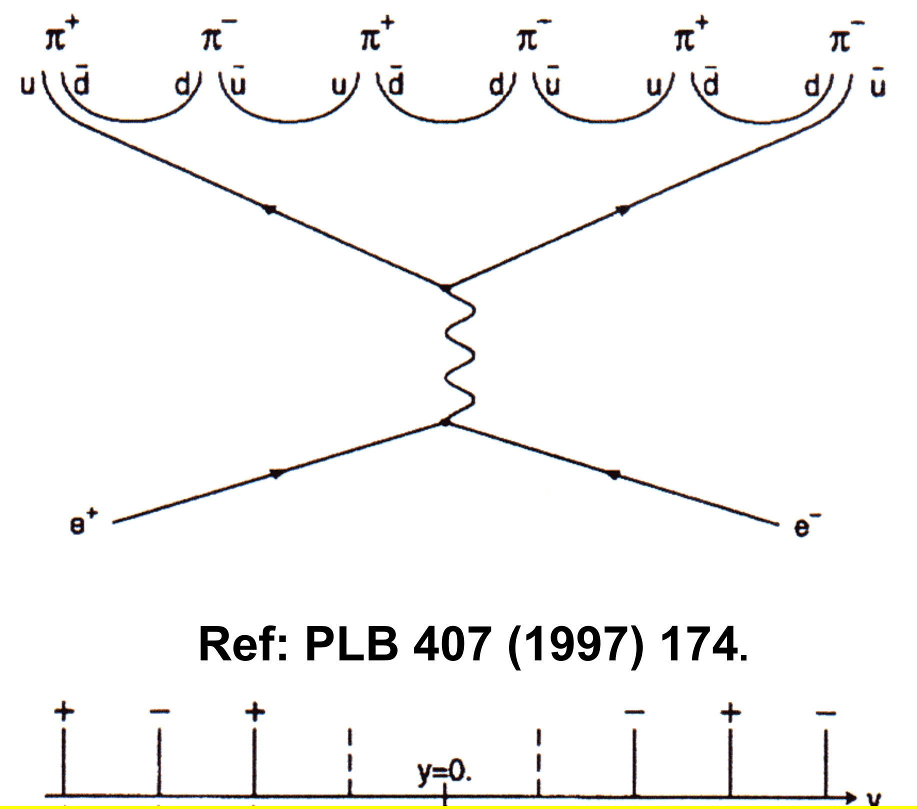
Relative Charge Dependence

Compare ++ and - - correlations to +-

System	(+-)/(++ & --)
p+p	2.7+-0.6
0-10% Au+Au	2.4+-0.6
Jetset	2.6+-0.7

Strong dynamical charge correlations in jet fragmentation → "charge ordering"





Ref: PLB 407 (1997) 174.

p_T > 4 GeV/c particle production mechanism same in central Au+Au & pp

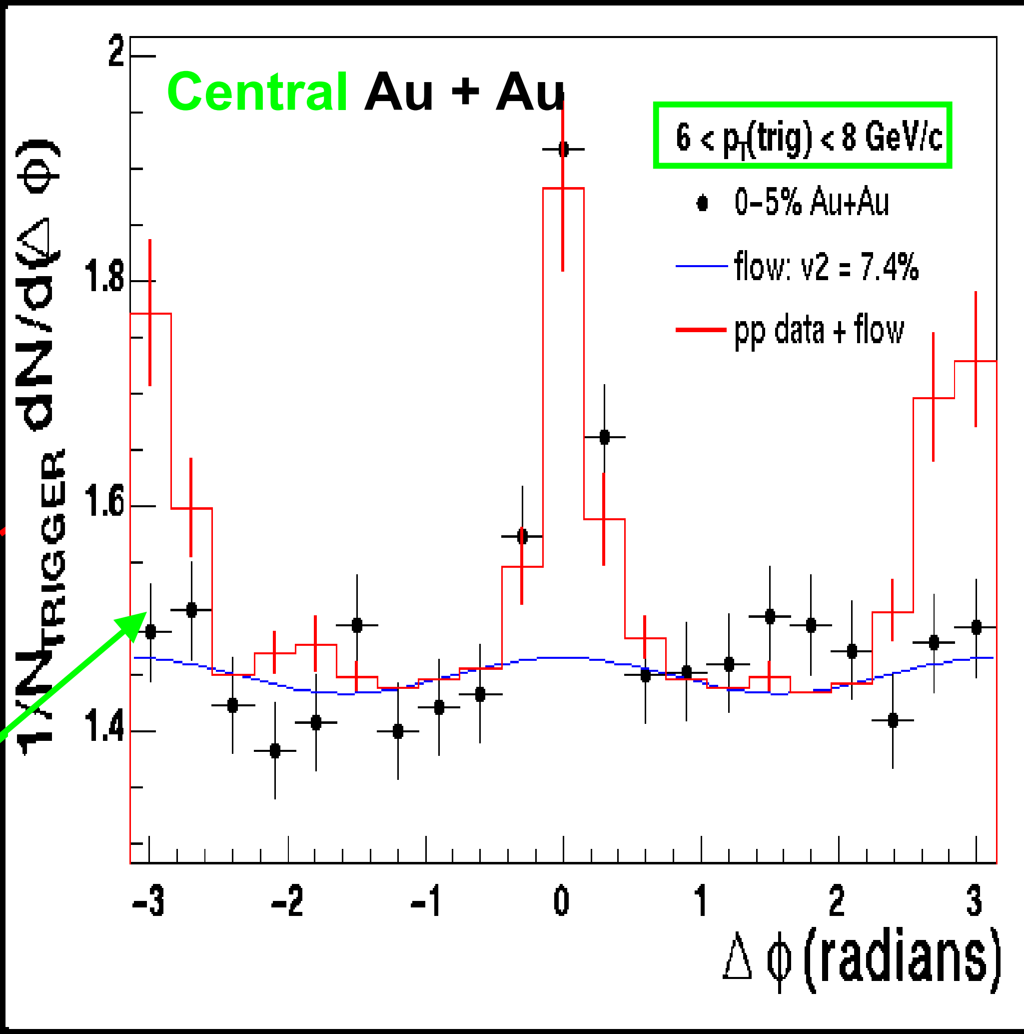
Using p+p to Study Au+Au Jet Correlations

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

Assume:

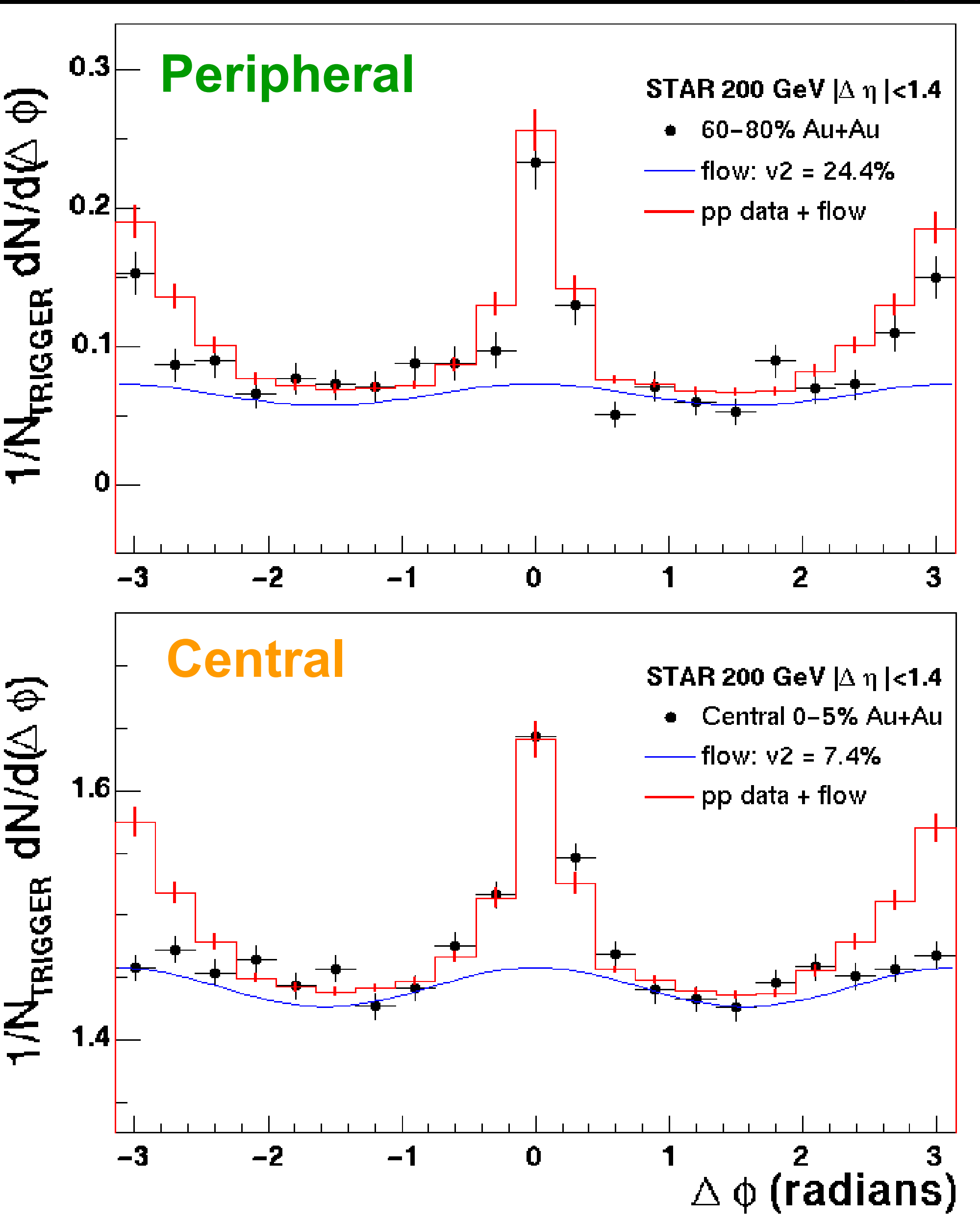
high p_T triggered Au+Au event
is a superposition:
high p_T triggered p+p event +
elliptic flow of AuAu event

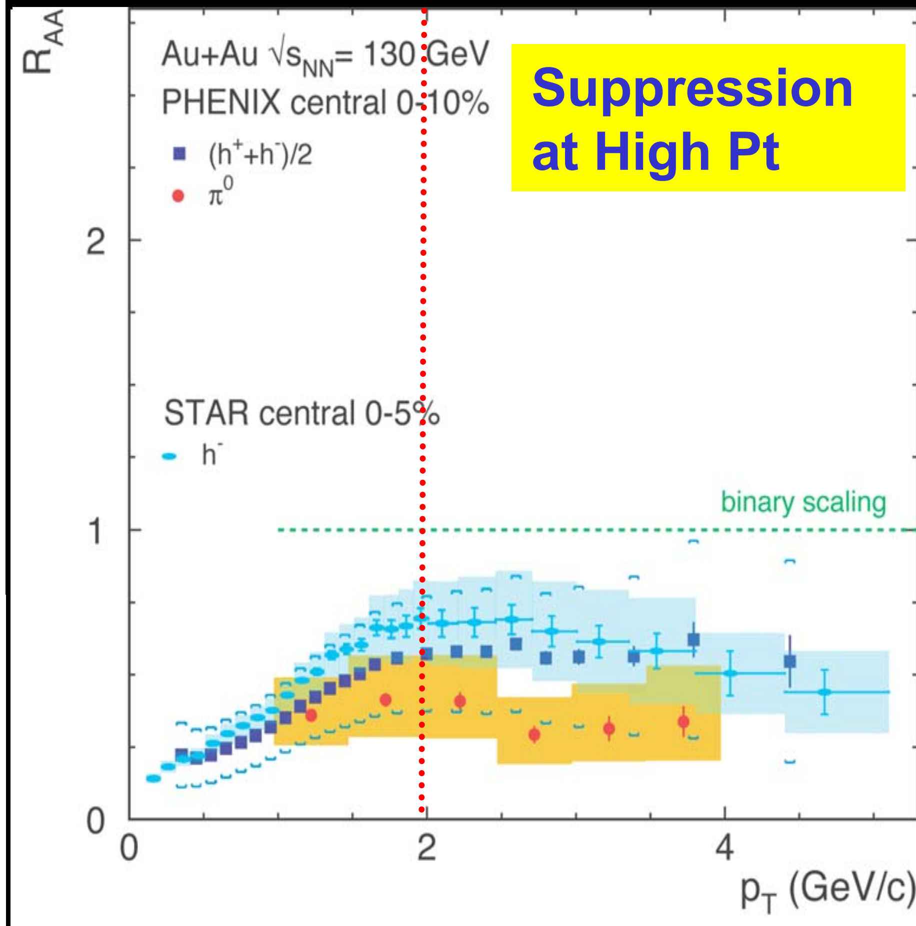
- v_2 from reaction plane analysis
- A from fit in non-jet region ($0.75 < |\Delta\phi| < 2.24$)



disappears

Summary – “High” Pt





Suppression at High Pt

- **See jet characteristics**
- **Away-side jet quenched in central AuAu**

Summary – “High” Pt

After first 2 RHIC Runs –

Picture emerging:

- rapid formation of dense medium
- high Pt hadrons suppressed
- jets quenched
- emission from surface?

Need theory input on:

- space-time evolution (dynamic models)
- energy loss
  - estimate: dE/dx ~ 10-15 times cold matter
- quarks on lattice
- medium effects
- fragmentation function (baryons and mesons at high z)

Outlook – "High" Pt

Still ahead:

Charmonium ($c\bar{c}$ suppression/enhancement)

Higher Pt triggers, EMC, jets?

pA, dA for nuclear effects

(hard scattering, gluon structure function)

Open Charm (charm production rates)

Polarized pp measurements up to $\sqrt{s}$ = 500 GeV

(gluon and sea-quark contribution to proton spin)

Understand gluon saturation (link between RHIC & HERA!)

Direct Photon Radiation?

Answers to questions on "new phenomena"…….

Thanks

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RHIC Operations Group

for contributions and/or discussions:
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And all others I forgot to mention

Using p+p to Study Au+Au Jet Correlations

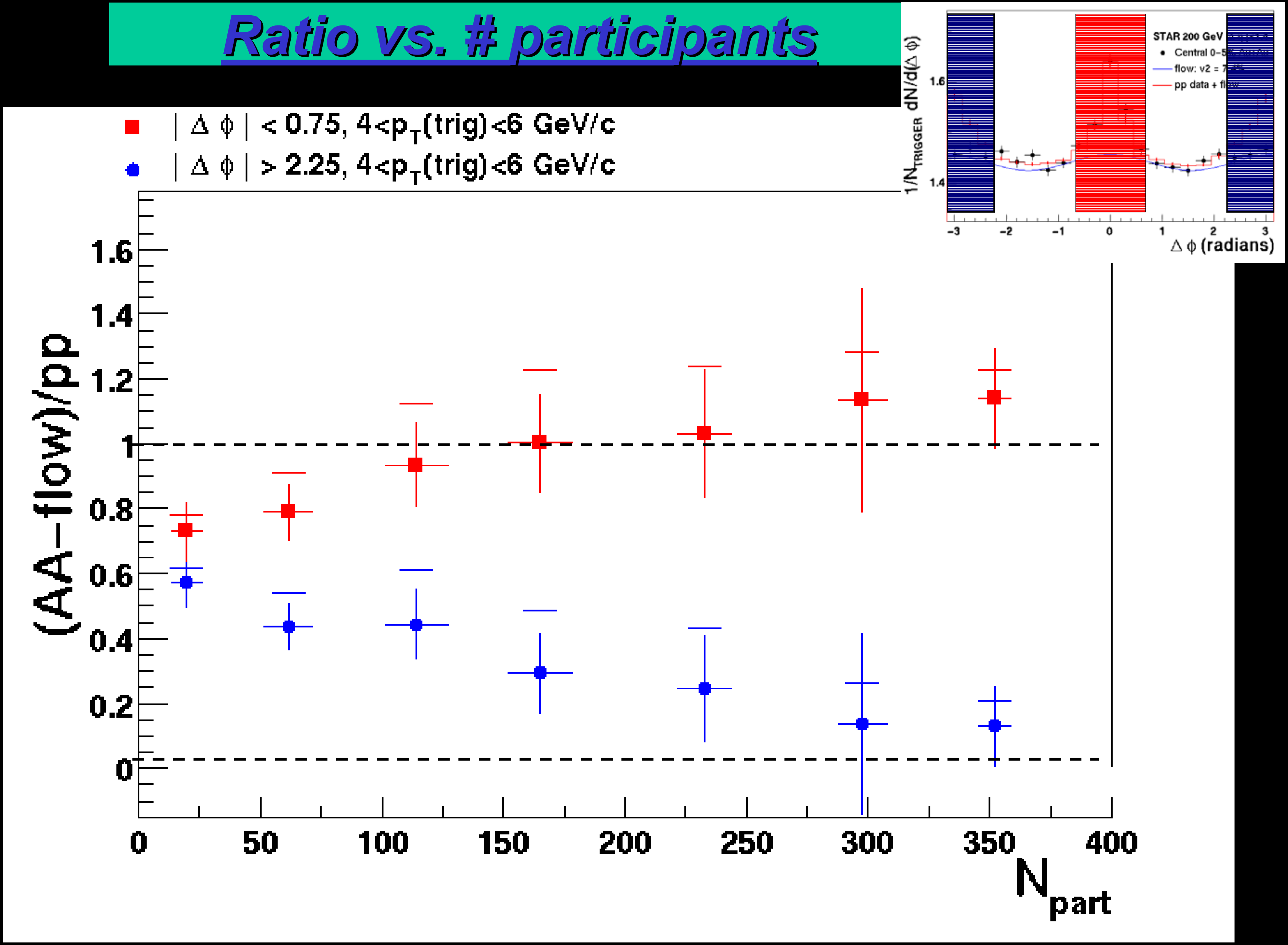
- high p_T triggered Au+Au event
  - superposition of high p_T triggered p+p event + elliptic flow of AuAu event

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

  - v_2 from reaction plane analysis
  - A from fit in non-jet region (0.75 < |Δφ| < 2.24)
- Quantify deviations for jet cone region (|Δφ|<0.75) and back-to-back region (2.24<|Δφ|<3.14):

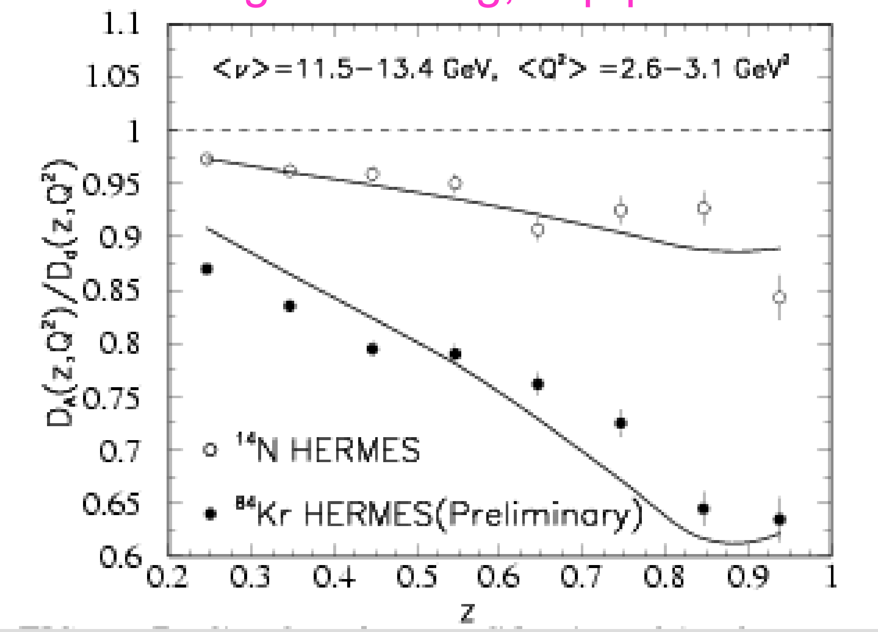
$$ratio = \frac{\int d(\Delta\phi)[C_2(Au+Au) - A*(1+2v_2^2\cos(2\Delta\phi))]}{\int d(\Delta\phi)[C_2(p+p)]}$$

Ratio vs. # participants



Energy loss in cold matter

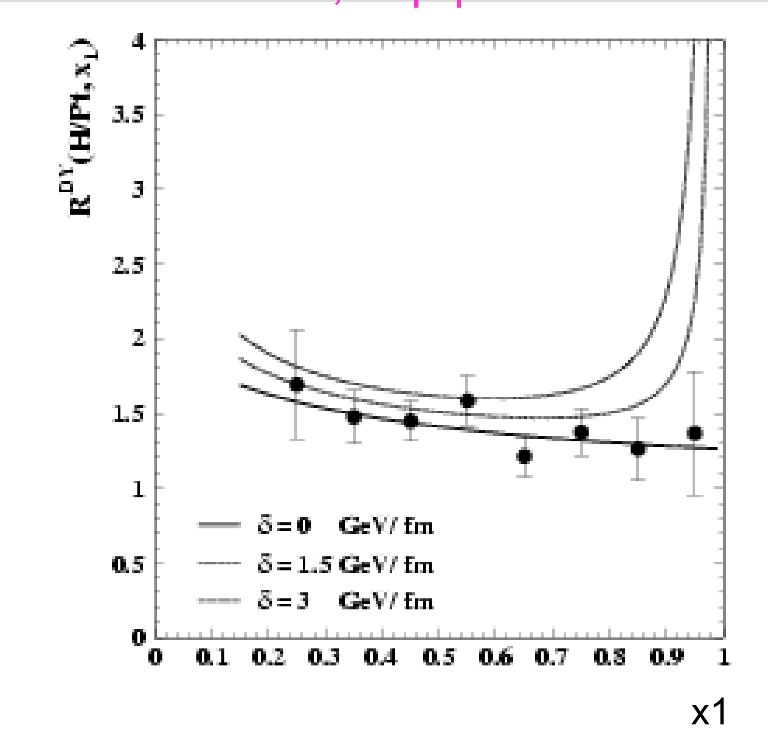
Wang and Wang, hep-ph/0202105



Modification of fragmentation fn in eA:

dE/dx ~ 0.5 GeV/fm for 10 GeV quark

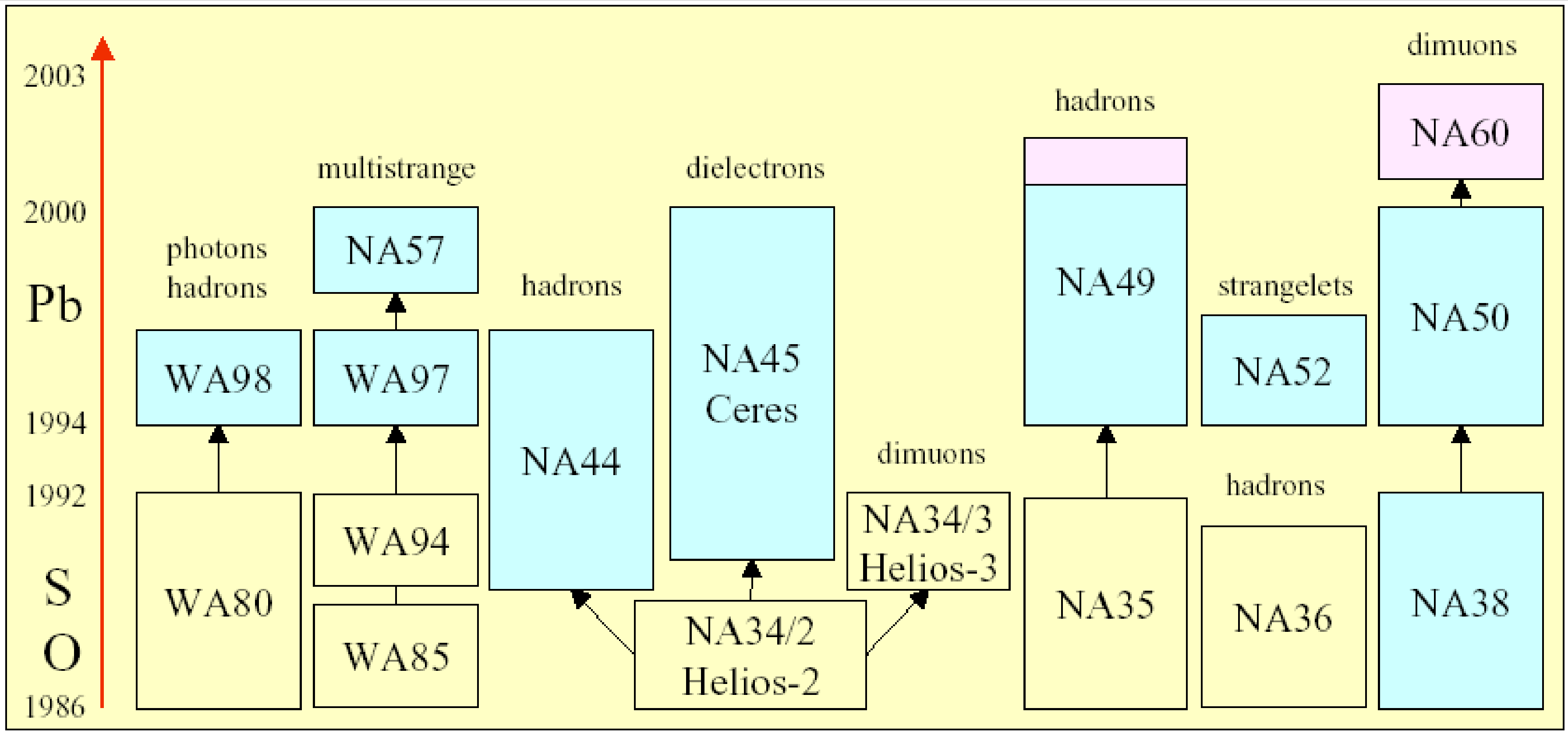
F. Arleo, hep-ph/0201066



Drell-Yan production in π-A:

dE/dx <0.2 GeV/fm for 50 GeV quark

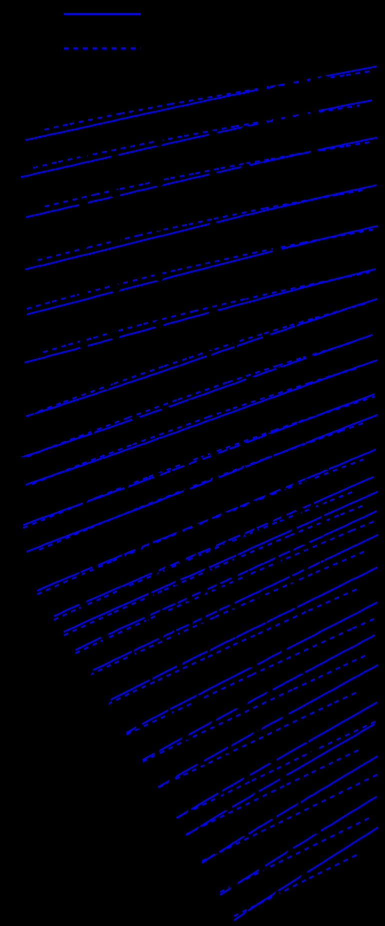
Relativistic Heavy Ion Physics at the SPS



- 1986 - 1987 : Oxygen @ 60 & 200 GeV/nucleon
- 1987 - 1992 : Sulphur @ 200 GeV/nucleon
- 1994 - 2000 : Lead @ 40, 80 & 158 GeV/nucleon
- 2002 - 2003 : Indium and Lead @ 158 GeV/nucleon
  + proton beams for reference studies

Gluon Saturation – the RHIC & HERA Connection

- Gluon densities at RHIC
  - at low x and their Q^2 evolution *same* as in saturation models for HERA:
    - A.M. Stasto, K. Golec-Biernat, J. Kwiecinski, Phys. Rev. Lett. 86, 596 (2001)
    - J. Bartels, K. Golec-Biernat, H. Kowalski hep-ph/0203258



- Much activity to determine
  - the precise connection
  - implications for other RHIC observables