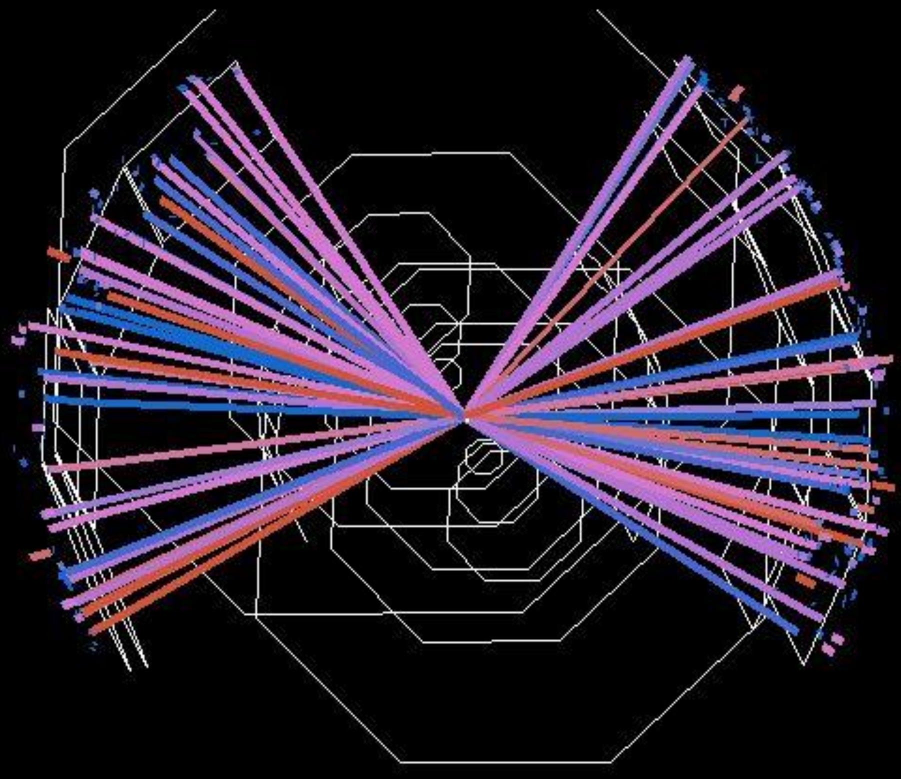
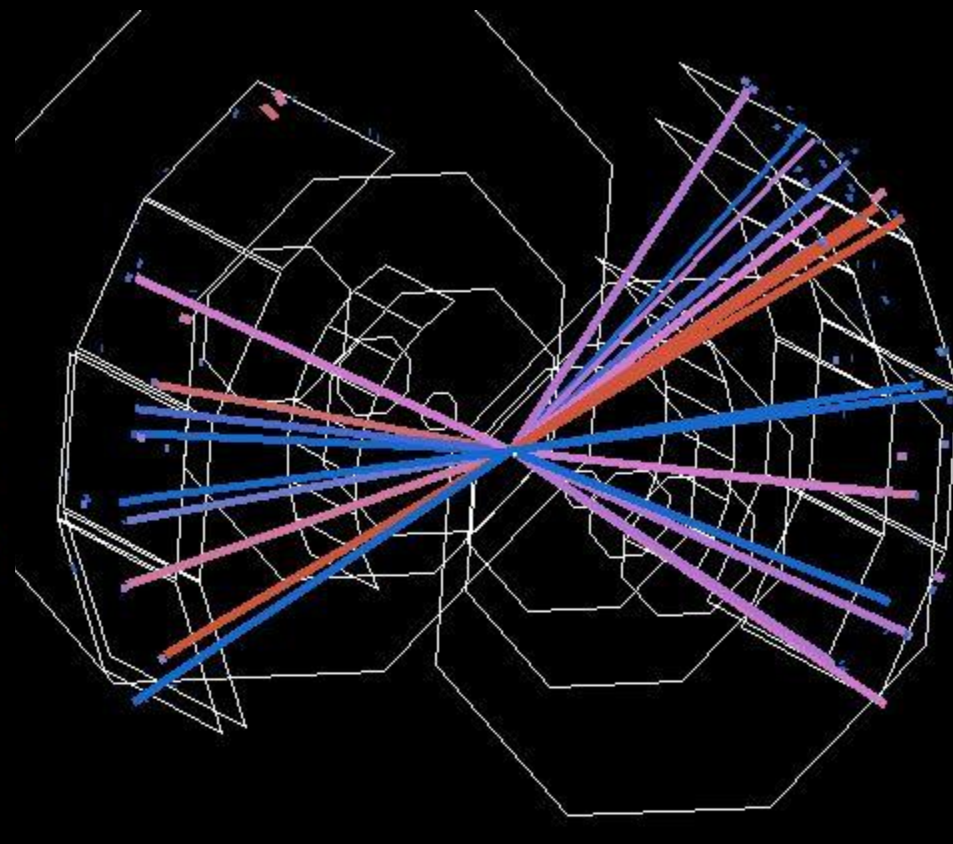
PHENIX Results from the RHIC Beam Energy Scan Program

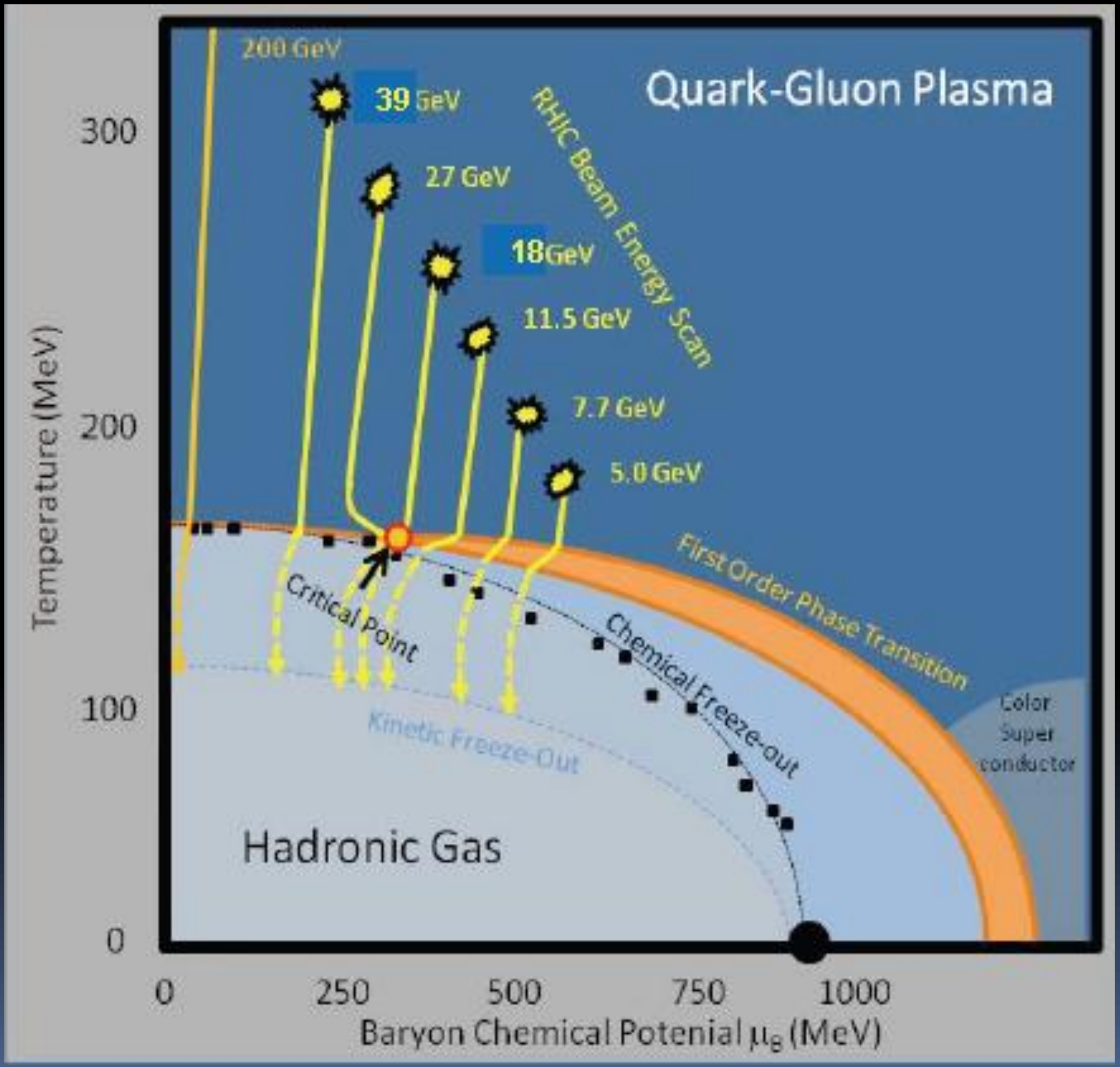
Jeffery T. Mitchell
Brookhaven National Laboratory





Search for the QCD Critical Point: Experimental Strategy

By systematically varying the RHIC beam energy, heavy ion collisions will be able to probe different regions of the QCD phase diagram.



The RHIC Beam Energy Scan Program: Overview

Species: Gold + Gold

Collision Energies [sqrt(s_{NN})]:
200 GeV (2010), 130 GeV, 62.4 GeV (2010),
39 GeV (2010), 27 GeV (2011 this week), 19.6 GeV (2011),
11 GeV (2010, STAR only)
9.2 GeV (2009, short test run), 7.7 GeV (2010)

Species: Copper + Copper

Collision Energies [sqrt(s_{NN})]:
200 GeV, 62.4 GeV, 22 GeV

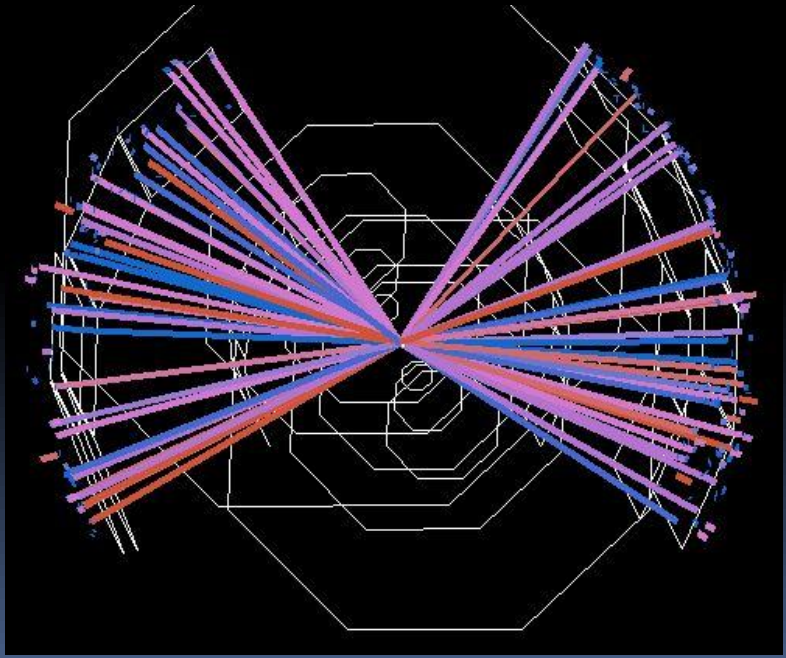
Species: Deuteron + Gold

Collision Energies [sqrt(s_{NN})]:
200 GeV

Species: Proton + Proton
Collision Energies [sqrt(s_{NN})]:
500 GeV, 200 GeV, 62.4 GeV

PHENIX RHIC Beam Scan Results

- Energy Loss: π^0 R_{AA}, ϕ R_{AA}
- J/Ψ : Yield, R_{CP}
- Flow: v_2, v_3, v_4, participant quark scaling
- Critical point signatures



Searching for the Onset of Deconfinement: Energy Loss Measurements

$$R_{AA}(p_T) = \frac{d^2N^{AA} / dp_T d\mathrm{h}}{\langle N_{binary} \rangle d^2N^{pp} / dp_T d\mathrm{h}}$$

PHENIX Energy Loss Measurements in the Beam Energy Scan: π^0

In Au+Au at 200 GeV:

• Strong suppression (x5) in central Au+Au collisions

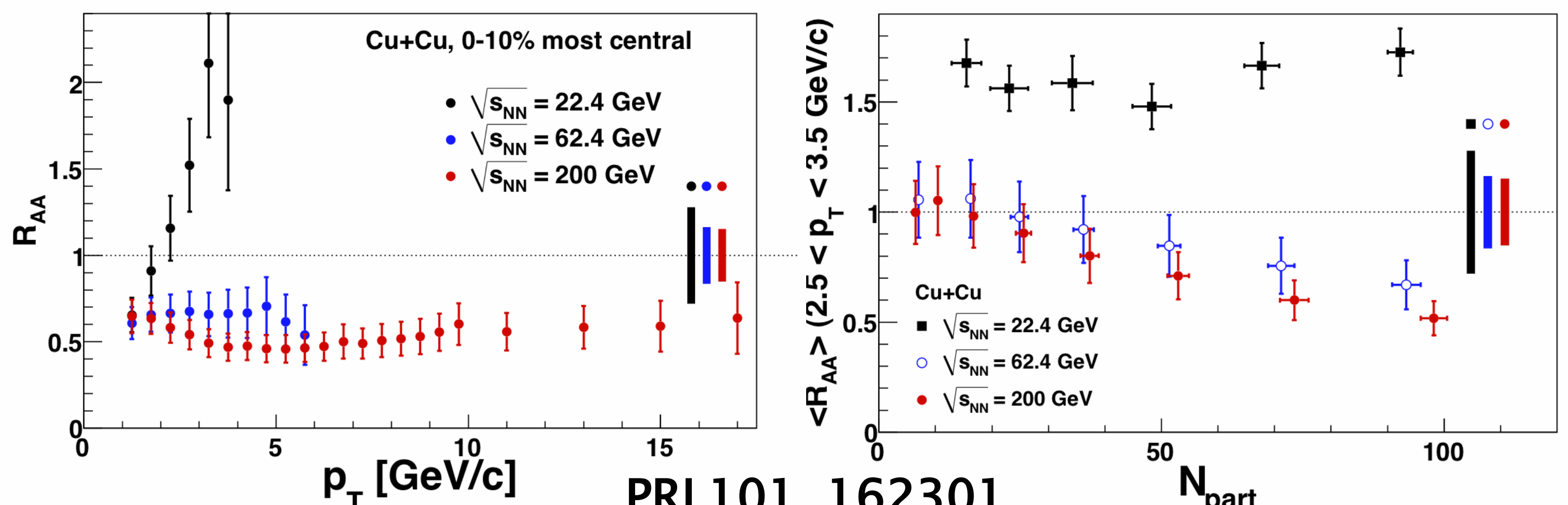
• No suppression in peripheral Au+Au collisions

• No suppression (Cronin enhancement) in control d+Au collisions

Convincing evidence for **final state partonic** interactions → emergence of **sQGP**

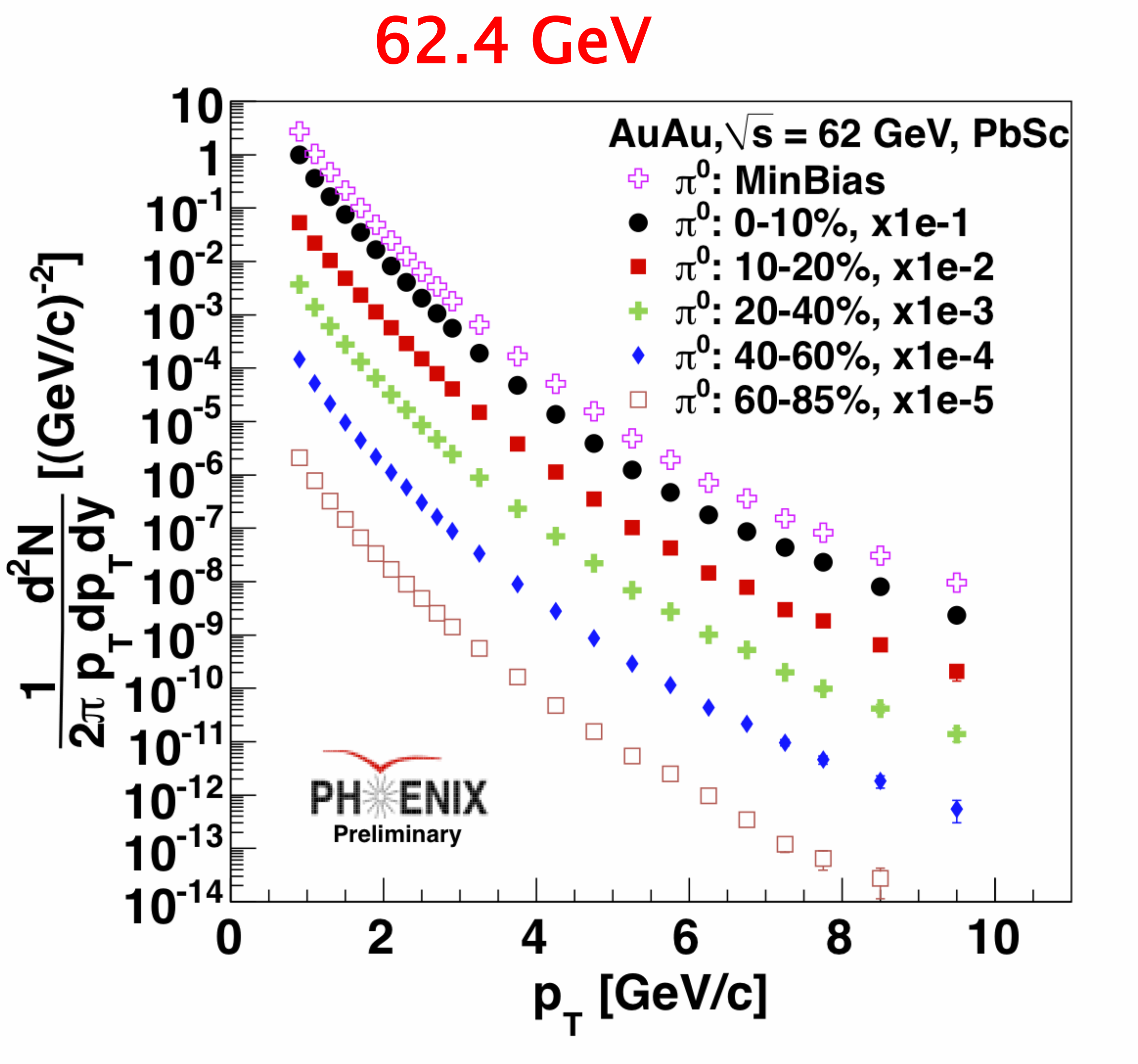
From the Cu+Cu energy scan:

- **Significant suppression** at $\sqrt{s_{NN}}$ = 200 and 62.4 GeV
- **Moderate enhancement** at $\sqrt{s_{NN}}$ = 22.4 GeV



PRL101, 162301

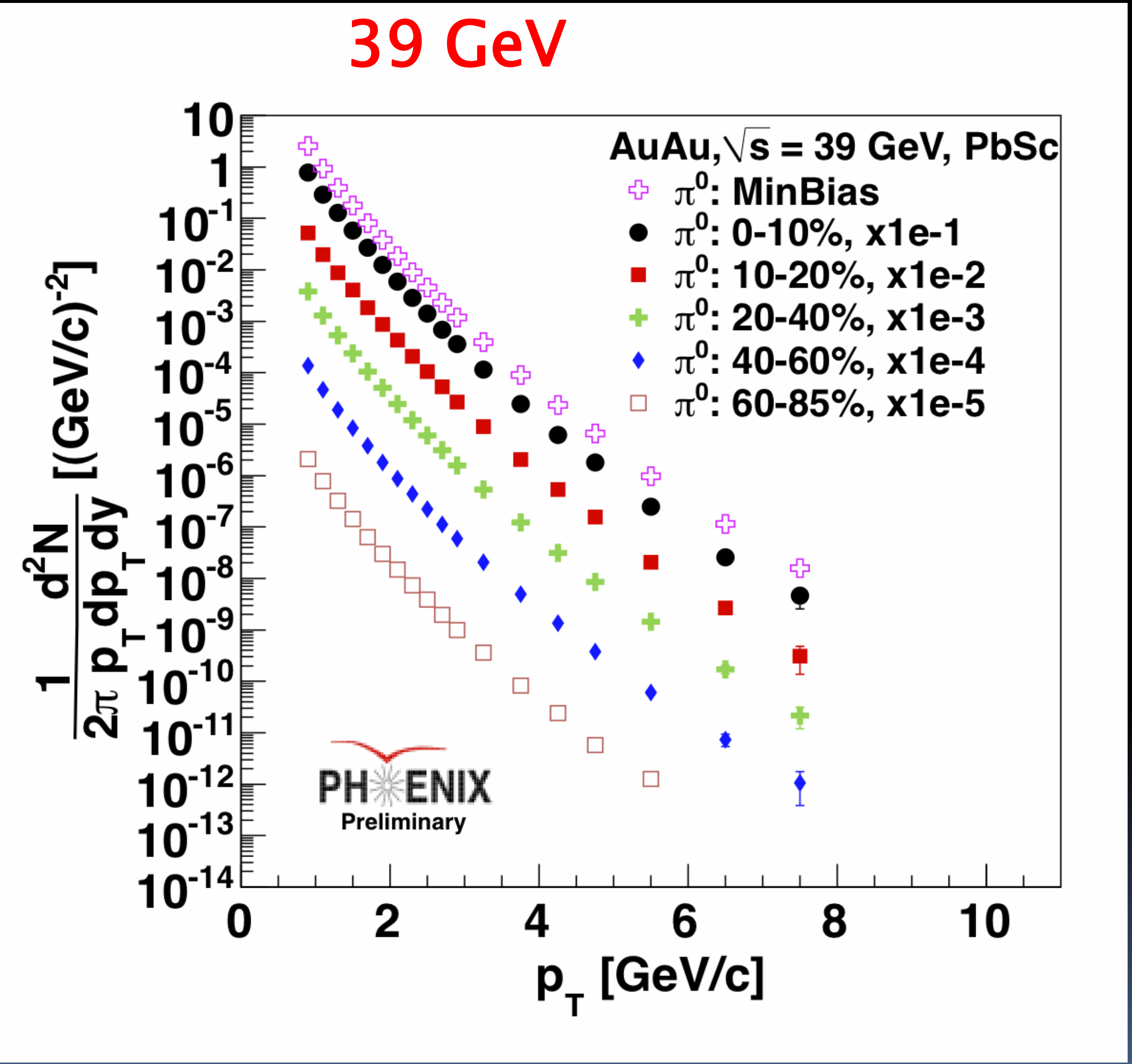
π^0 invariant yields: Au+Au Collisions at 62.4 GeV



At lower $\sqrt{s}$ the contribution from some processes are larger:

- Running a(Q^2)
- PDF evolution
- k_T smearing
- Higher-twist phenomena

π^0 invariant yields: Au+Au Collisions at 39 GeV



The minimum bias spectra are fit with a power-law shape function for $p_T > 4$ GeV/c :

$$\boxed{f(x) = \frac{A}{(p_T)^n},}$$

$n_{200GeV} = 8.1 \pm 0.03$

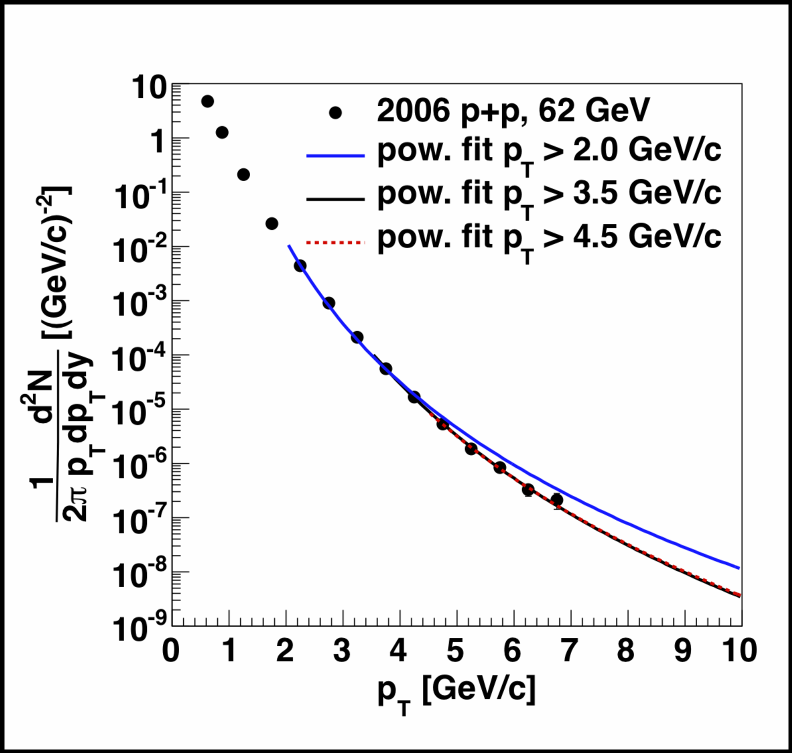
$n_{62GeV} = 10.9 \pm 0.03$

$n_{39GeV} = 12.1 \pm 0.1$

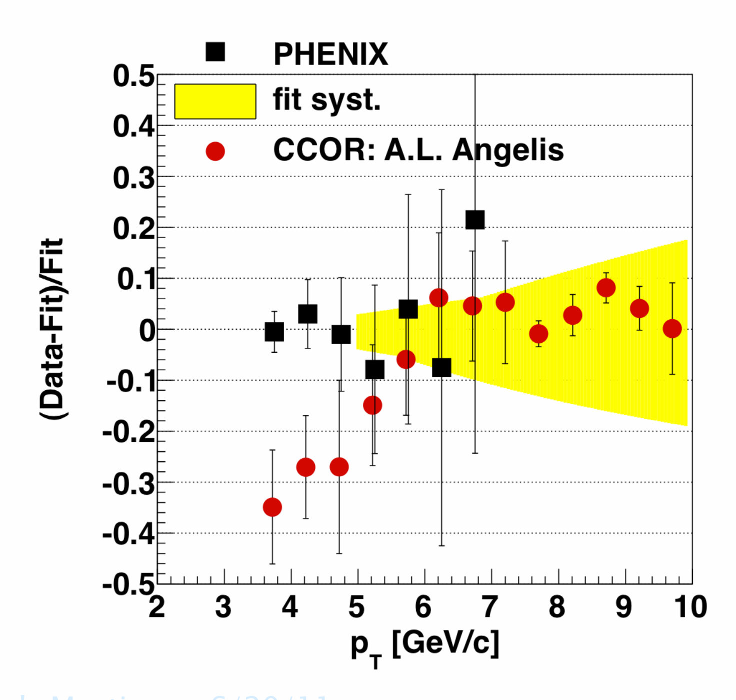
Nuclear Modification Factor

- For the R_{AA} measurement, obtaining a p+p reference from the same experiment is vital. External references increase systematic errors.
  - 62.4 GeV p+p data is available from PHENIX, however **only up to** $p_T < 7$ GeV/c (heavy-ion up to 10 GeV/c)
  - 39.0 GeV p+p data is **not yet available** from PHENIX, but it is on our to-do list
    - Because of that we used data from a fixed target p+p experiment at the Tevatron, E0706 ($\sqrt{s}$ = 39 GeV, PRD68: 052001, 2003).

62.4 GeV p+p reference extrapolation

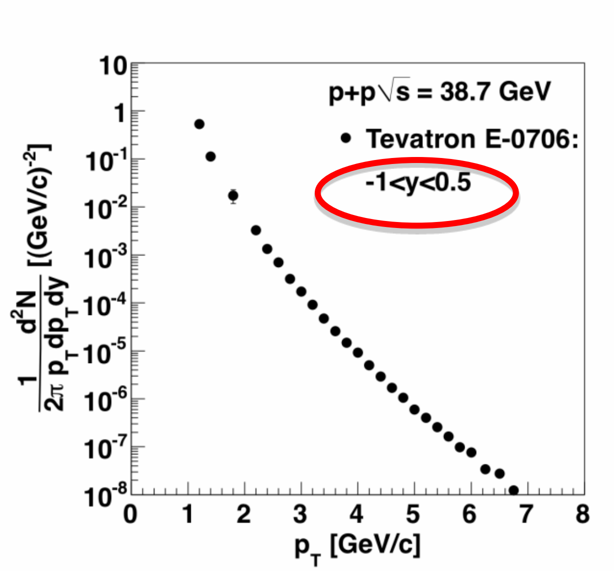


- Data from PHENIX for p+p collisions are available up to $p_T < 7$ GeV/c
- To extrapolate to higher p_T points, a power-law function was used:
  - The limit of the fits is vital, Contributing to the systematic errors.

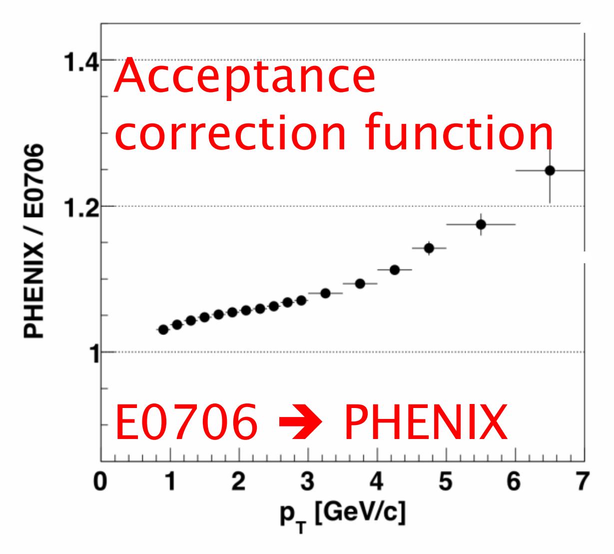


- The systematic uncertainty is calculated from the errors of the power-law fit
- It agrees well with the CCOR data (ISR) in p_T 7-10 GeV/c region

39 GeV p+p reference

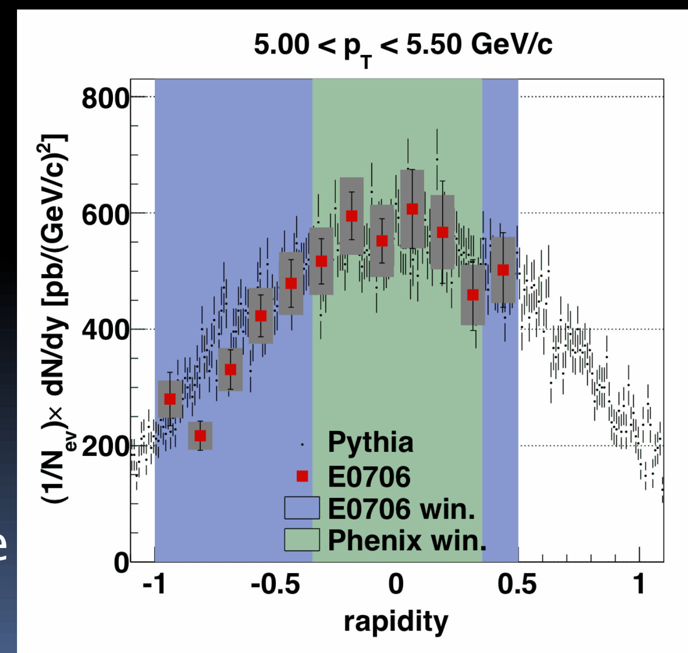


- p+p data are measured only in the fixed-target experiment E0706 at the Tevatron at a beam energy of 800 GeV. (**Phys.Rev.D68:052001,2003**)
- The E0706 has a different rapidity acceptance: −1.0 < y < 0.5 (PHENIX |y|<0.35).

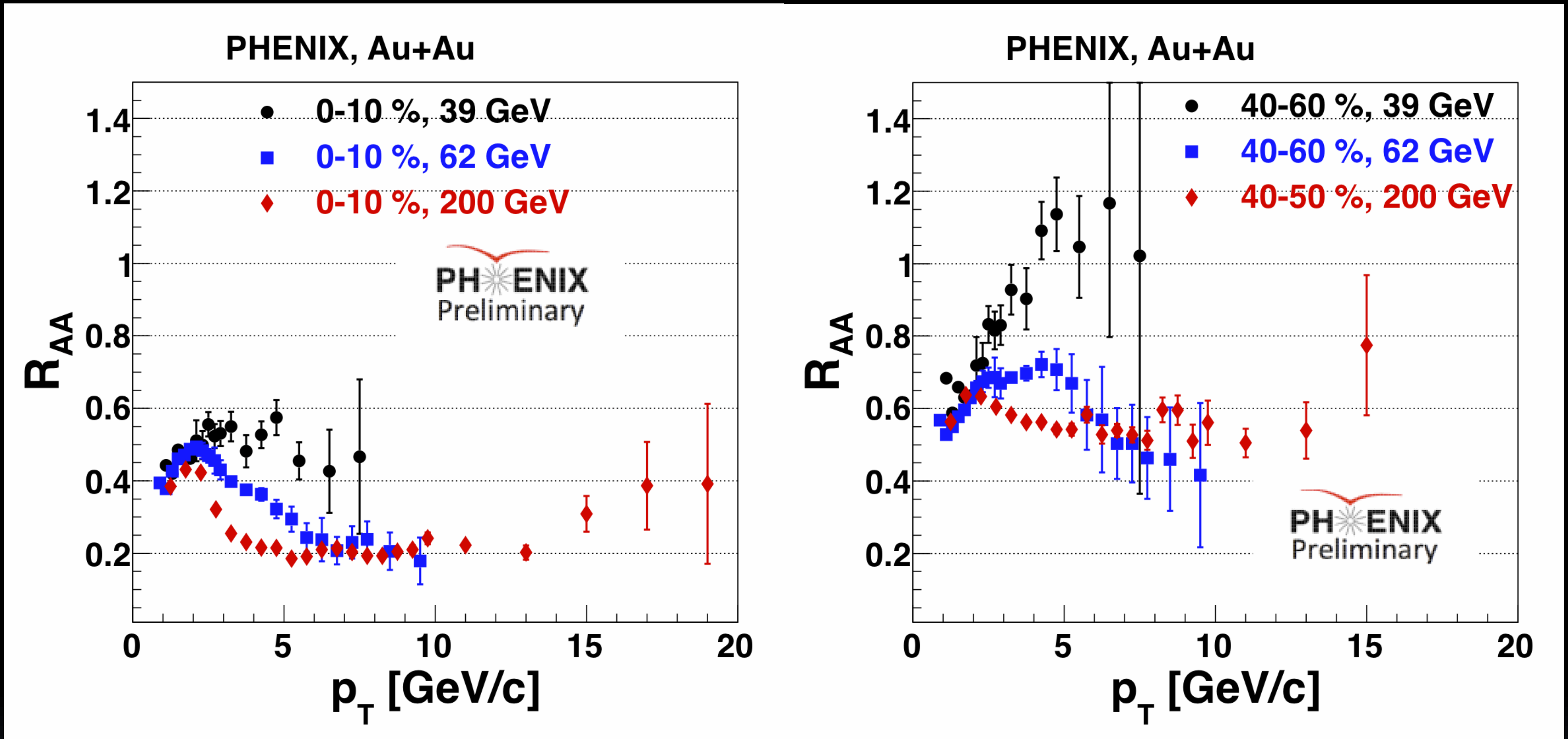


Acceptance correction based on a PYTHIA8 simulation.

The systematic uncertainty of the correction function is calculated based on the data to PYTHIA8 comparison.



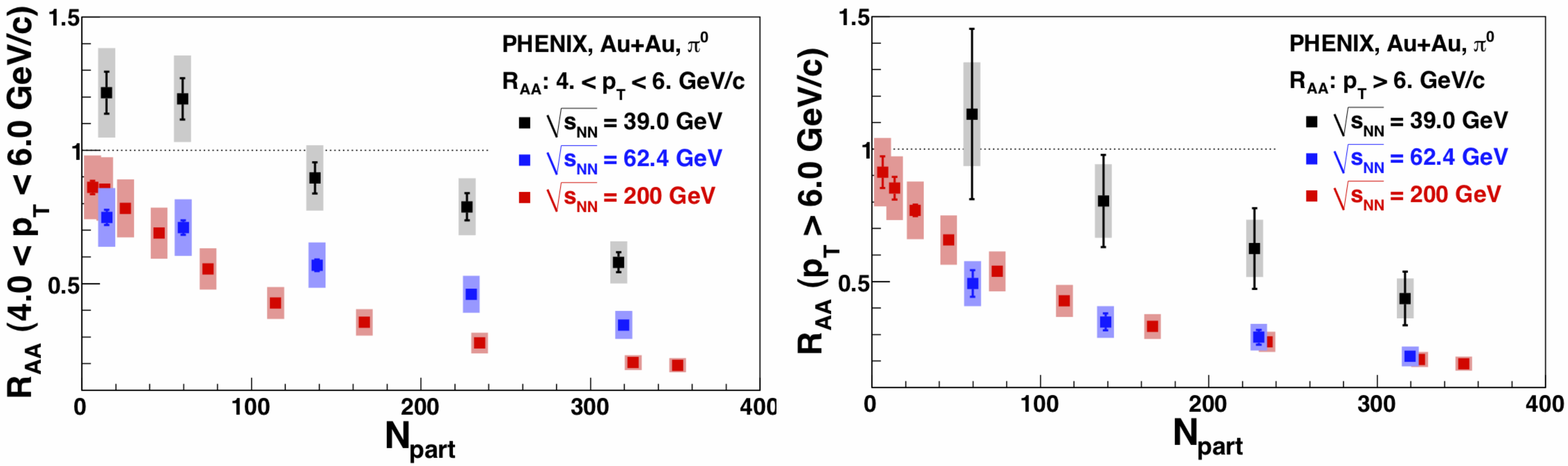
π^0 R_{AA} in Au+Au at 39 and 62 GeV



π^0 R_{AA} as a function of p_T in PHENIX at $\sqrt{s_{NN}}$ = 39, 62 and 200 GeV.

- Still observe a strong suppression (factor of 2) in the most central $\sqrt{s_{NN}}$ = 39 GeV collisions.
- R_{AA} from $\sqrt{s_{NN}}$ = 62 GeV data is comparable with the R_{AA} from $\sqrt{s_{NN}}$ = 200 GeV for p_T 6 >GeV/c.
- Peripheral $\sqrt{s_{NN}}$ = 62 and 200 GeV data show suppression, but the $\sqrt{s_{NN}}$ = 39 GeV does not.

R_{AA} : Centrality Dependence



At higher p_T ranges, the 62 GeV points are comparable to the 200 GeV points in all centralities.

R_{AA} evolution in Au+Au at $\sqrt{s_{NN}}$ = **39, 62 and 200** GeV:

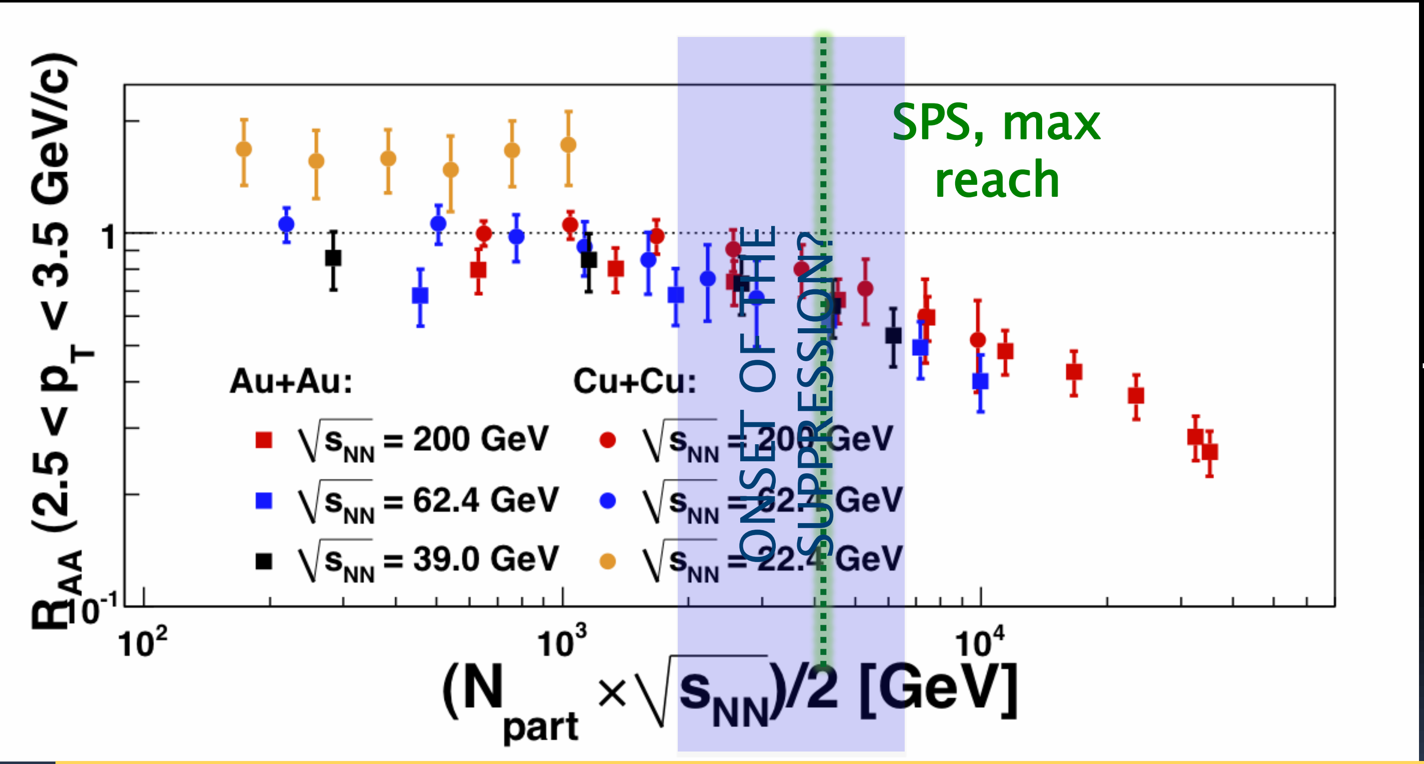
- 62-200 GeV shows a large **suppression**
- 39 GeV shows suppression only in **N_{part}**>100

Energy and System-Dependence of π^0 R_{AA}

Total energy available of the collision:

$$E_{AA} \propto \left(N_{part} \times \sqrt{s_{NN}}\right) / 2$$

System size:
- Circles: Cu+Cu
- Squares: Au+Au

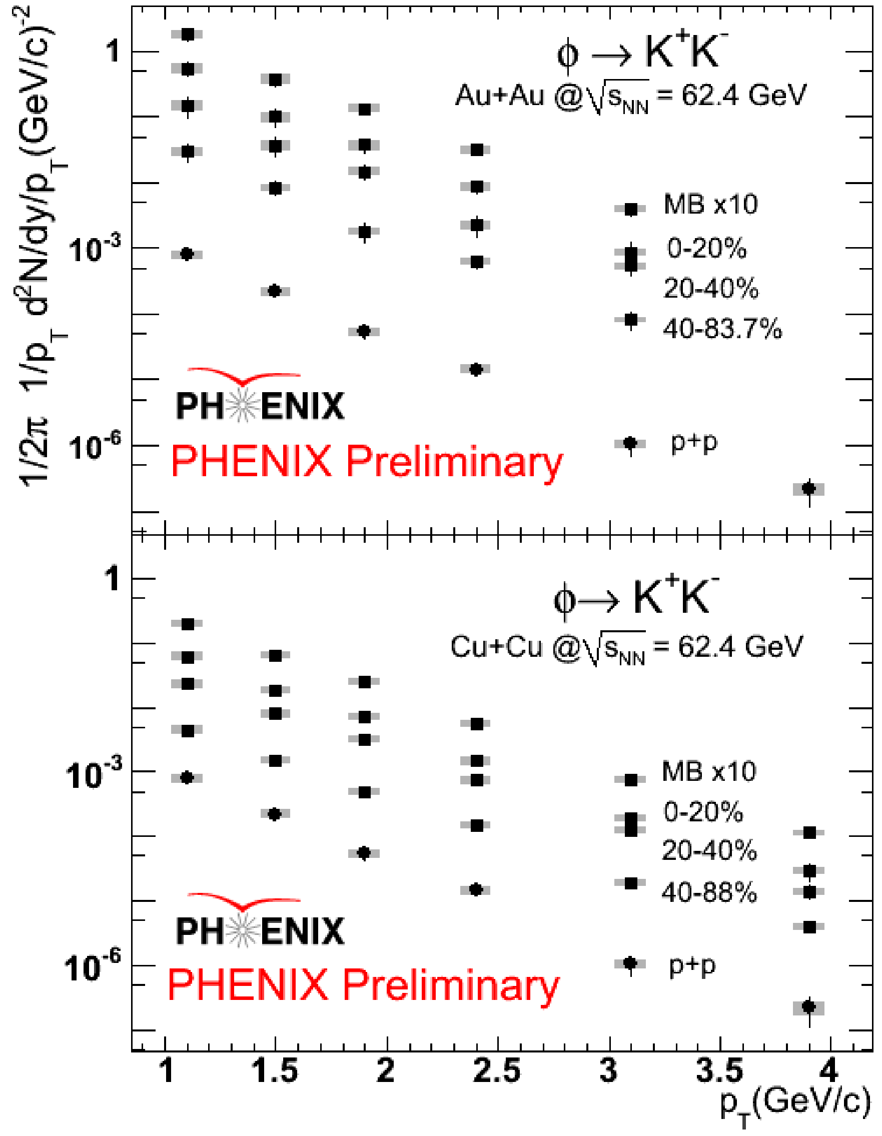


The R_{AA} values seem to have the same trend.

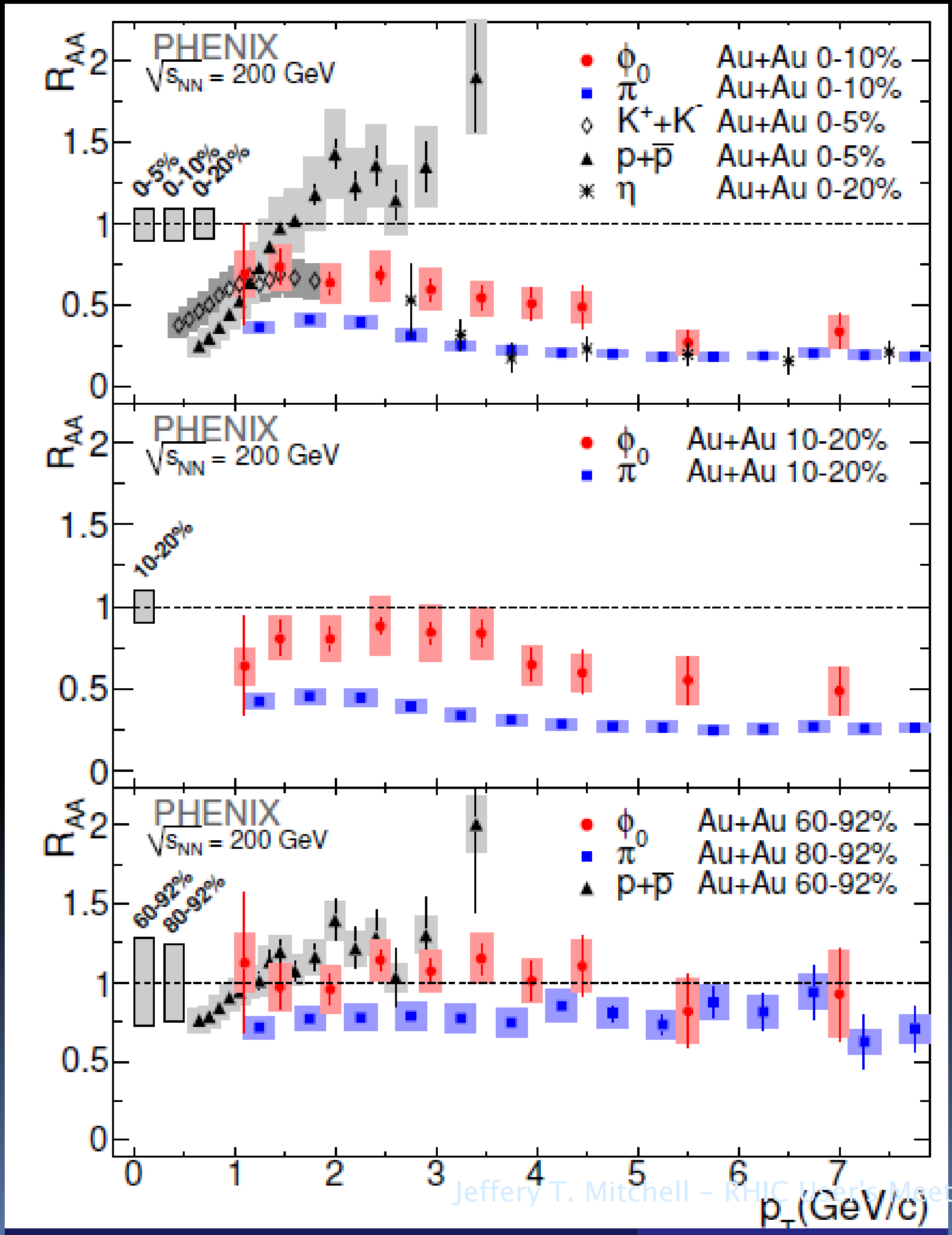
SPS, max reach: $2 \times 208(\text{Pb}) \times 17.3$ GeV $(\sqrt{s_{NN}})/2 = 3598.4$ GeV

$E_{AA} = 2 - 5$ TeV

$\phi \to K^+K^-$ Spectra in 62.4 GeV Au+Au Collisions



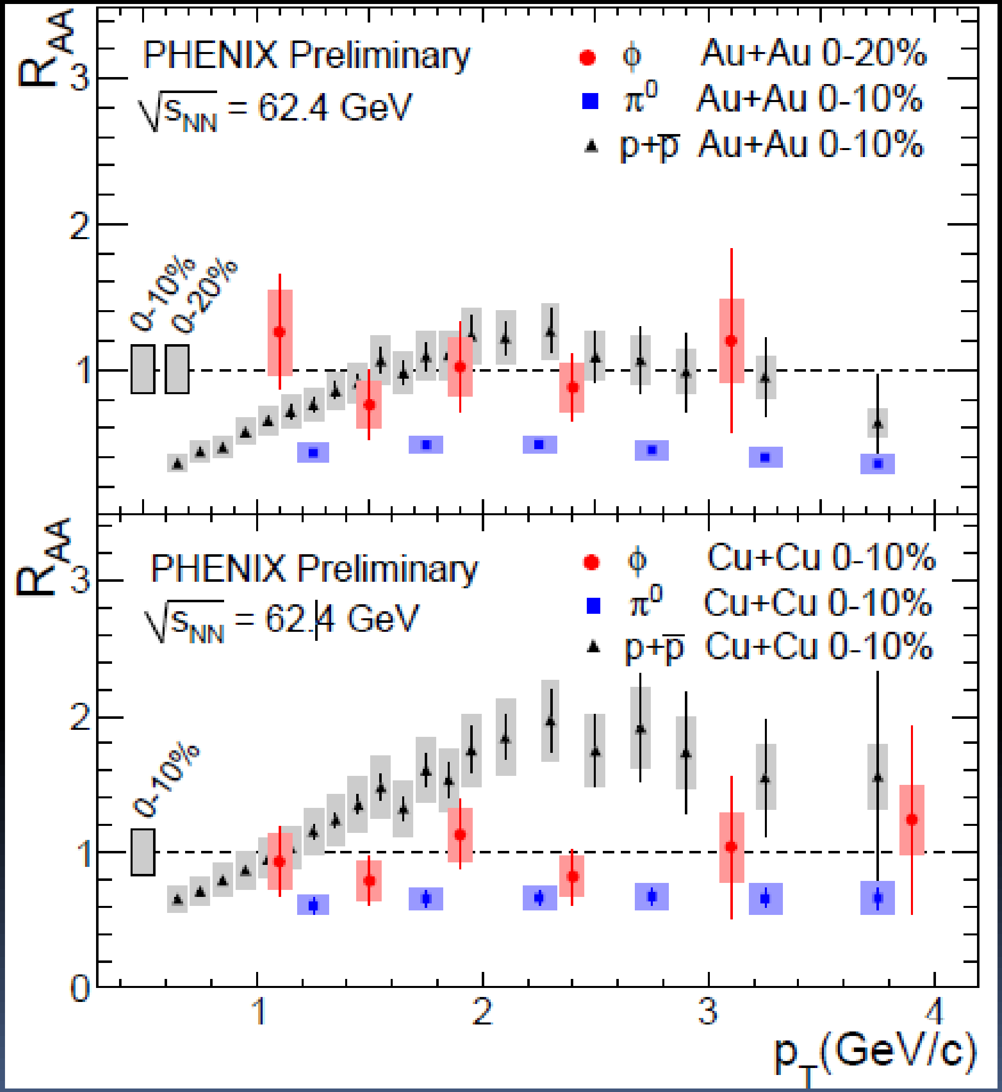
$\phi \rightarrow K^+K^-$ R_{AA} in 200 GeV Au+Au Collisions



The ϕ is suppressed in central 200 GeV Au+Au collisions.

The R_{AA} of the ϕ lies between that of the proton and the π^0.

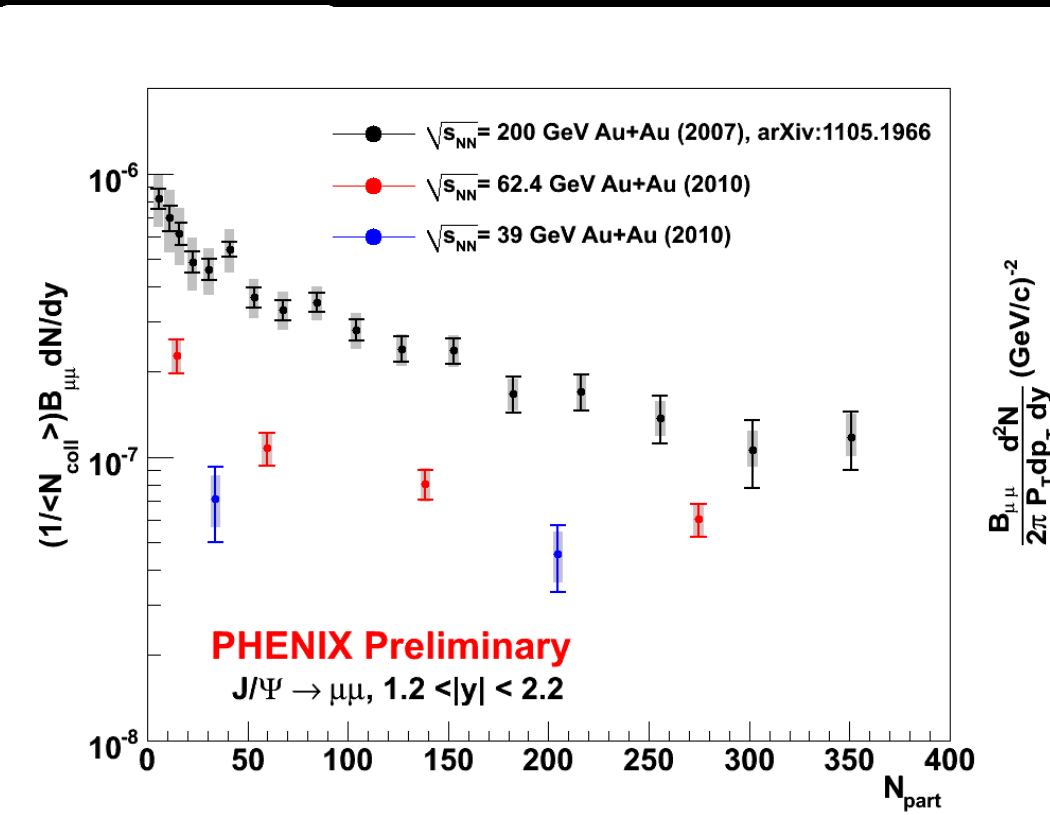
$\phi \rightarrow K^+K^-$ R_{AA} in 62.4 GeV Au+Au Collisions

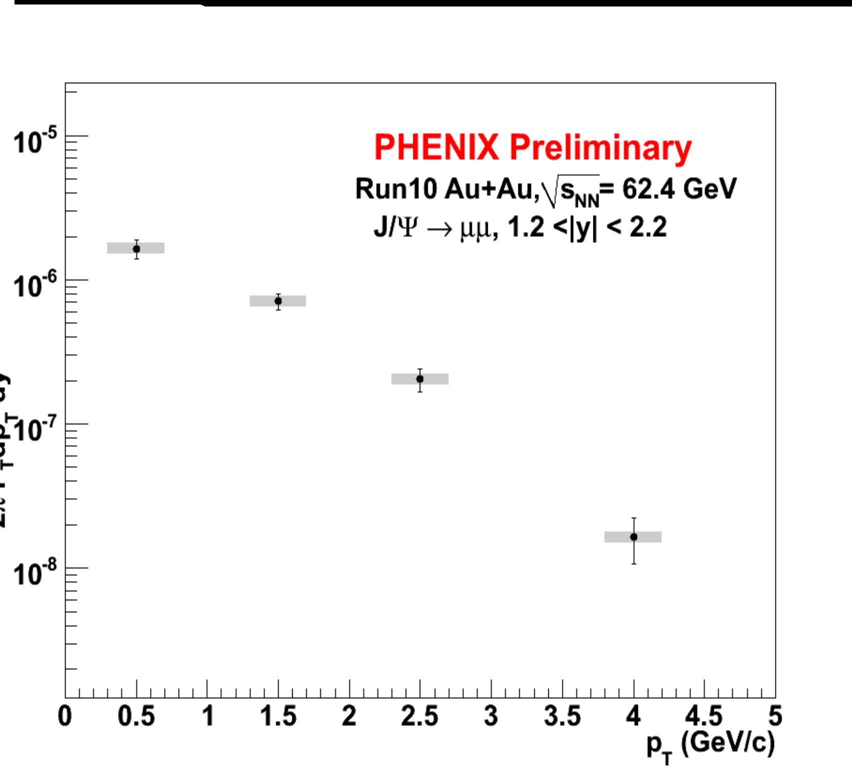


Within the current precision, no suppression at 62.4 GeV. Similar to the 200 GeV results, the R_{AA} of the ϕ lies between that of the proton and the π^0.

Searching for the Onset of Deconfinement: J/Ψ Measurements

J/ψ Yields from 62 and 39 GeV Au+Au Collisions

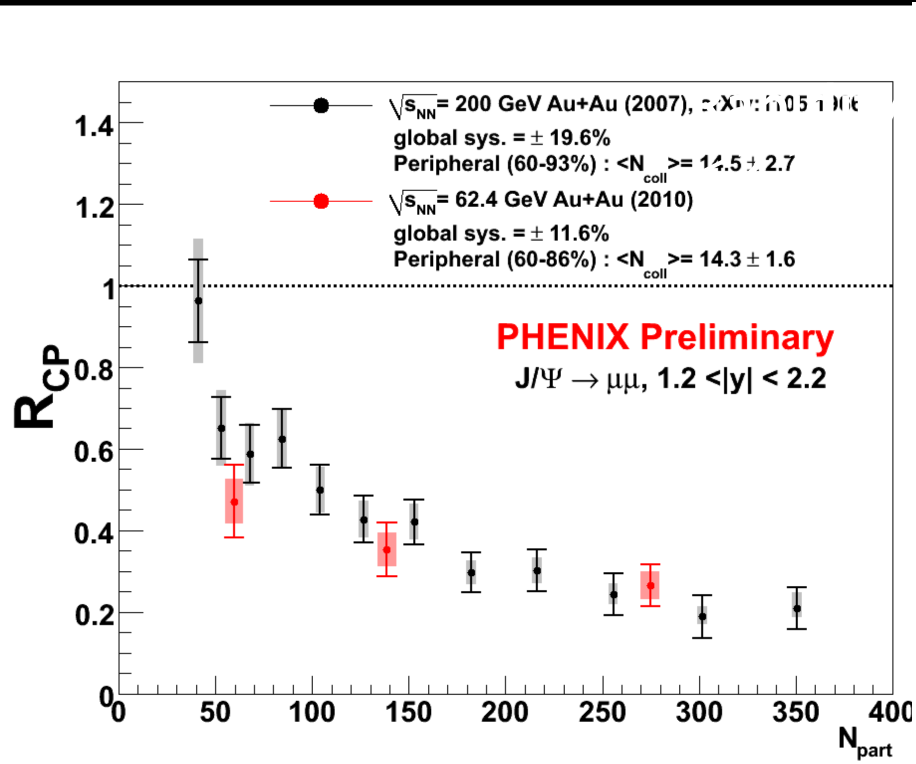


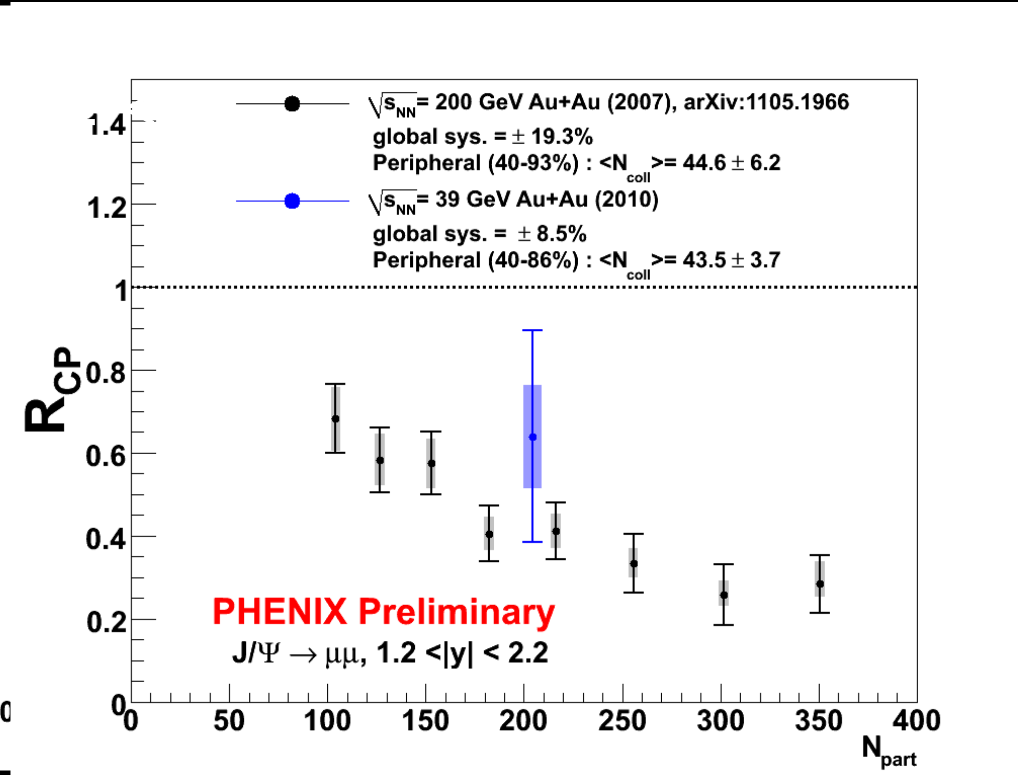


In 2010, PHENIX collected 700M (250M) MB events from 62.4 GeV (39 GeV) Au+Au collision.

Rapidity 1.2 <|y| <2.2

Energy dependence of J/ ψ R_{CP}

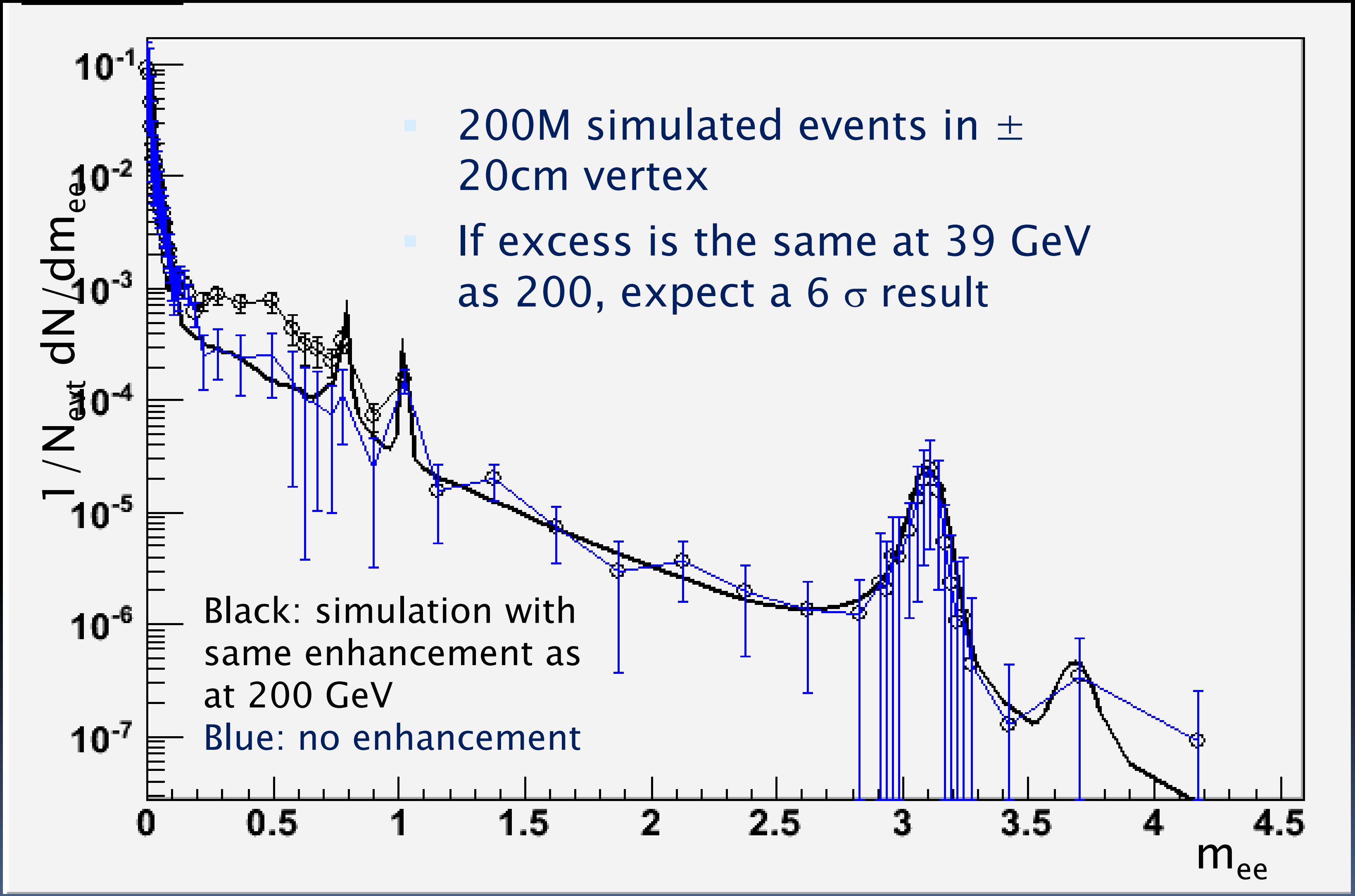


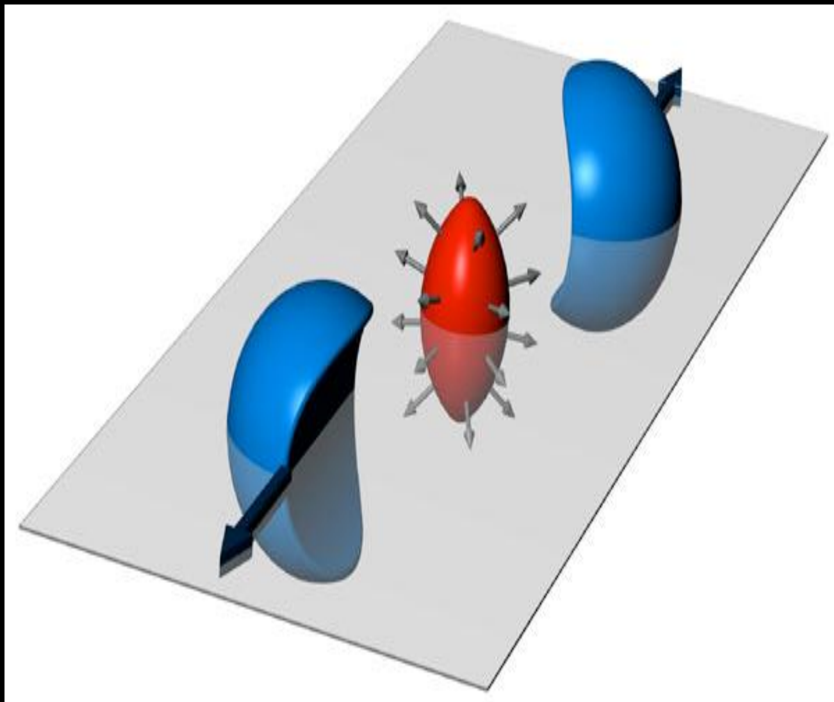


- ❑ PHENIX does not yet have a p+p reference at 62 and 39 GeV.
- ❑ Lacking a reference, R_{CP} can still give us insight about the suppression level.
- ❑ The suppression is at a similar level at all energies.

PHENIX Dilepton Expectations at 39 GeV

How does the dilepton excess and ρ modification at SPS evolve into the large low-mass excess at RHIC?





Searching for the onset of deconfinement: Flow Measurements

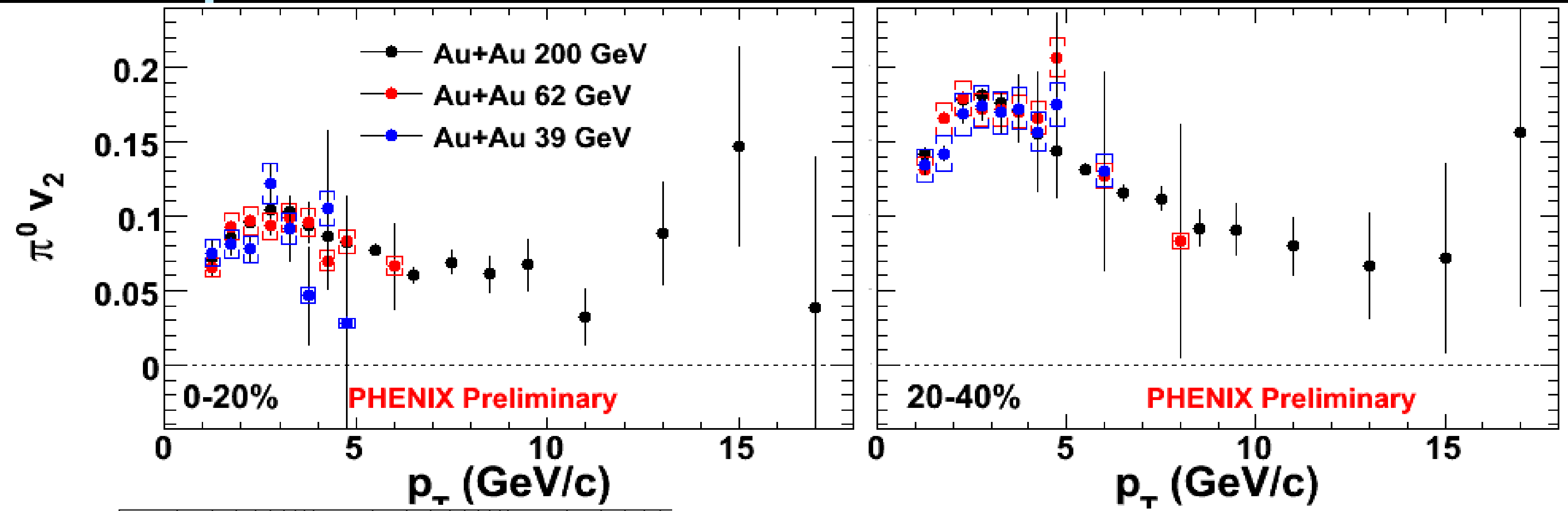
$$E\frac{d^3N}{d^3p}=\frac{1}{\pi}\frac{d^2N}{dp_T^2dy}\left[1+2v_1\cos(\varphi-\Psi_R)+2v_2(2[\varphi-\Psi_R])+\ldots\right] \rightarrow \boxed{v_2=\left\langle\cos(2[\varphi-\Psi_R])\right\rangle}$$

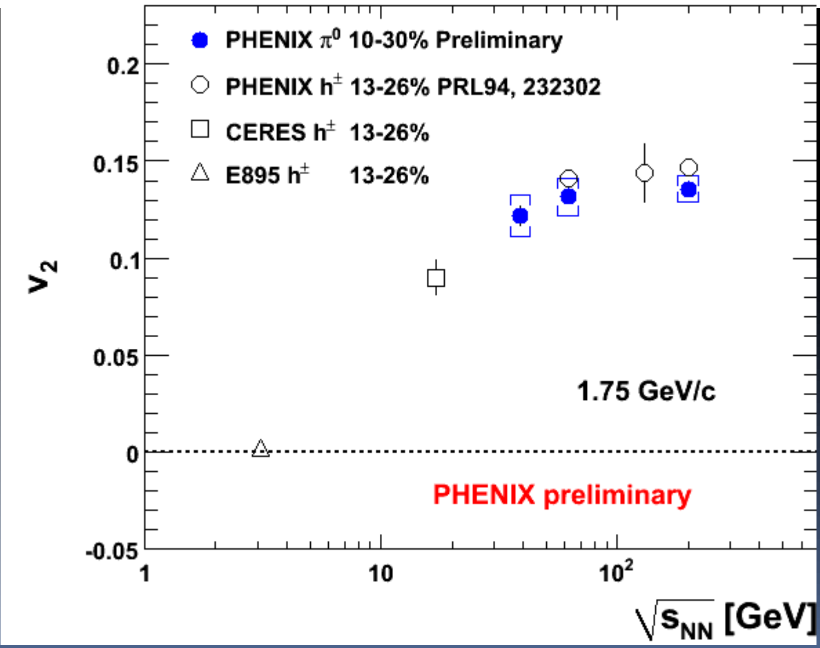
$$v_1 = <\frac{p_x}{p_T}> \quad \text{- directed flow}$$

$$v_2 = <\frac{p_x^2-p_y^2}{p_x^2+p_y^2}> \quad \text{- elliptic flow}$$

$v_2>0$: in-plane emission of particles
$v_2<0$: squeeze-out perpendicular to reaction plane.

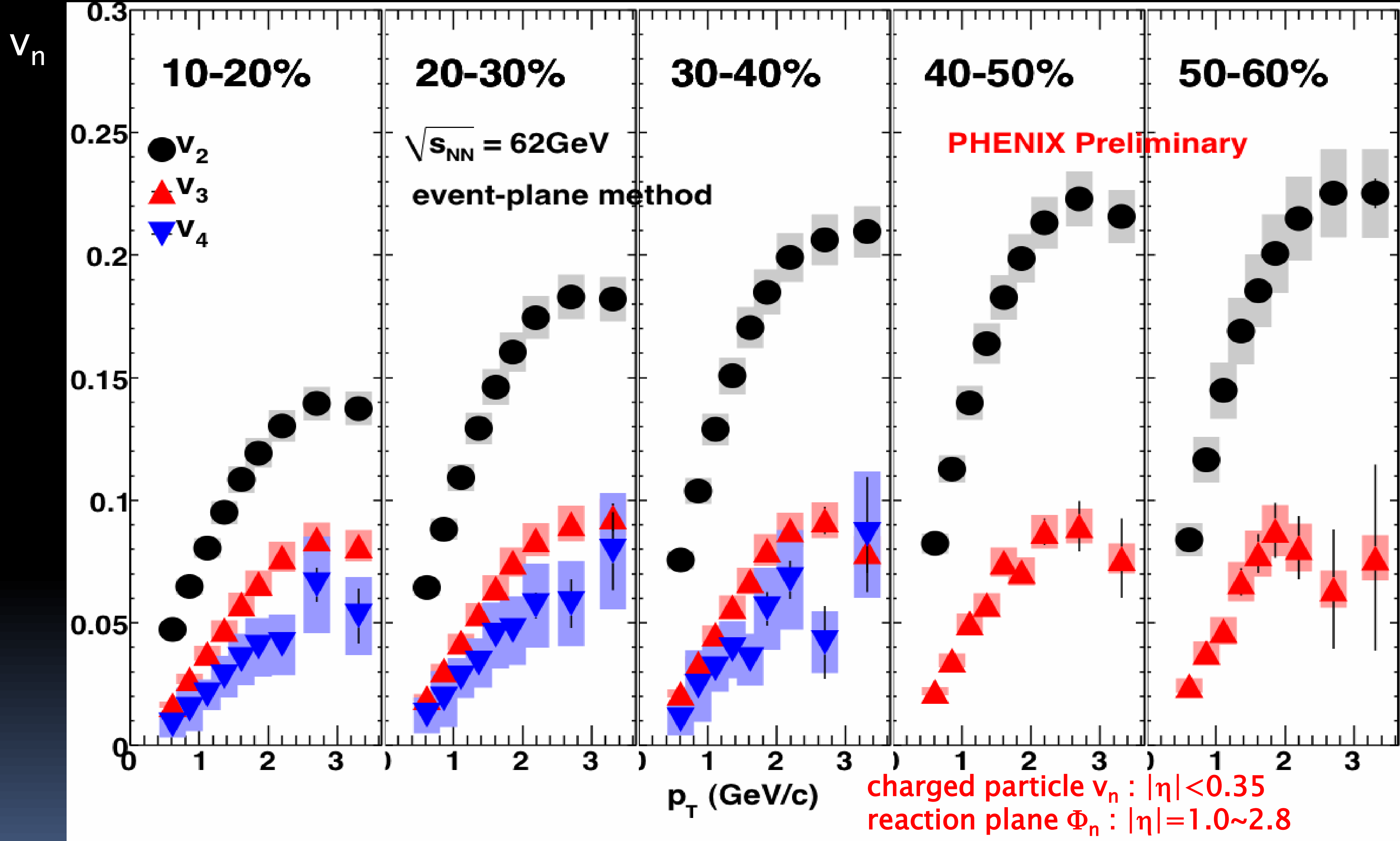
Elliptic Flow at 62 and 39 GeV: π^0



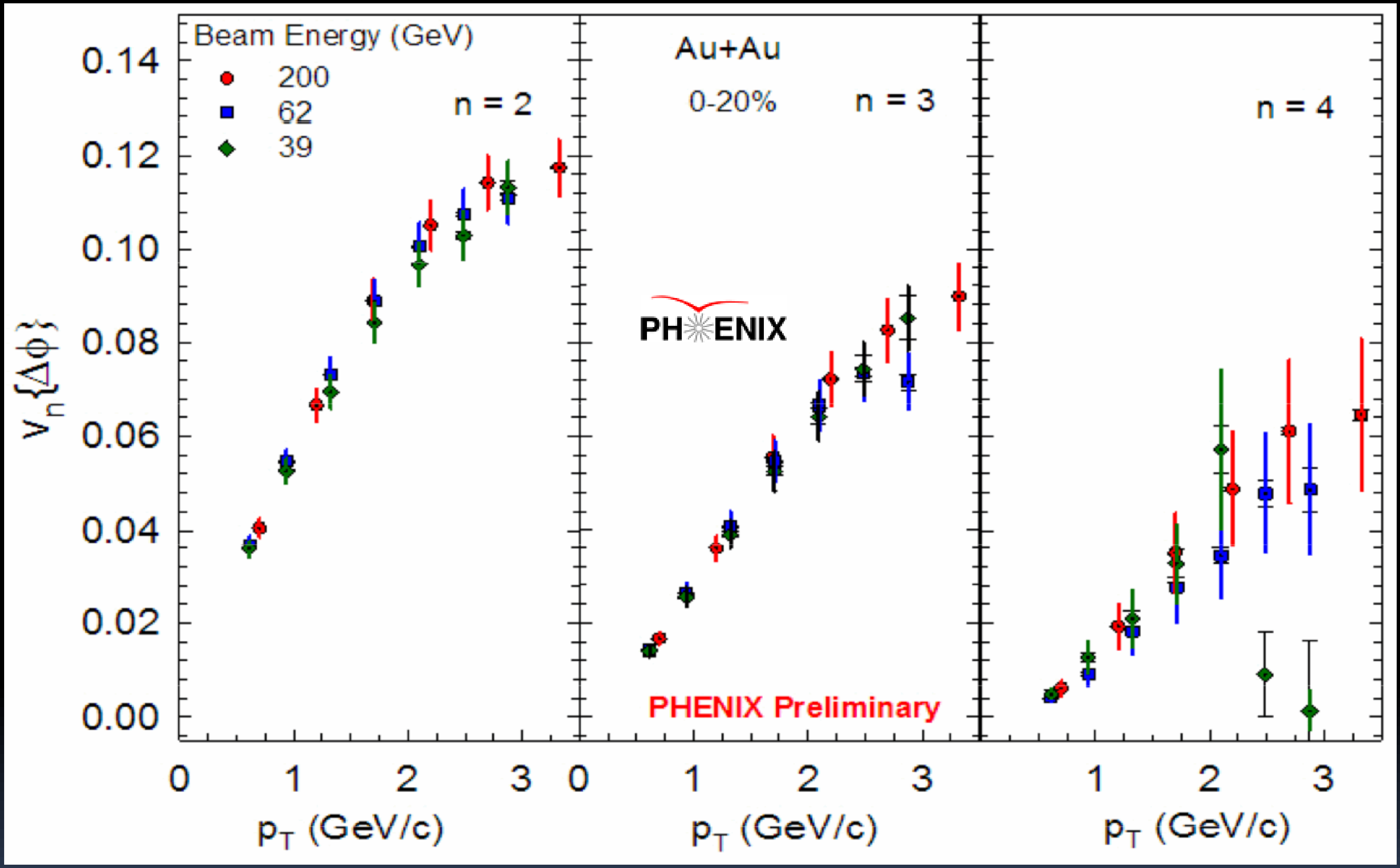


There is little change in the magnitude of v_2 from 39 GeV to 200 GeV.

$v_2\{\Phi_2\}$, $v_3\{\Phi_3\}$, $v_4\{\Phi_4\}$ at 62 GeV Au+Au

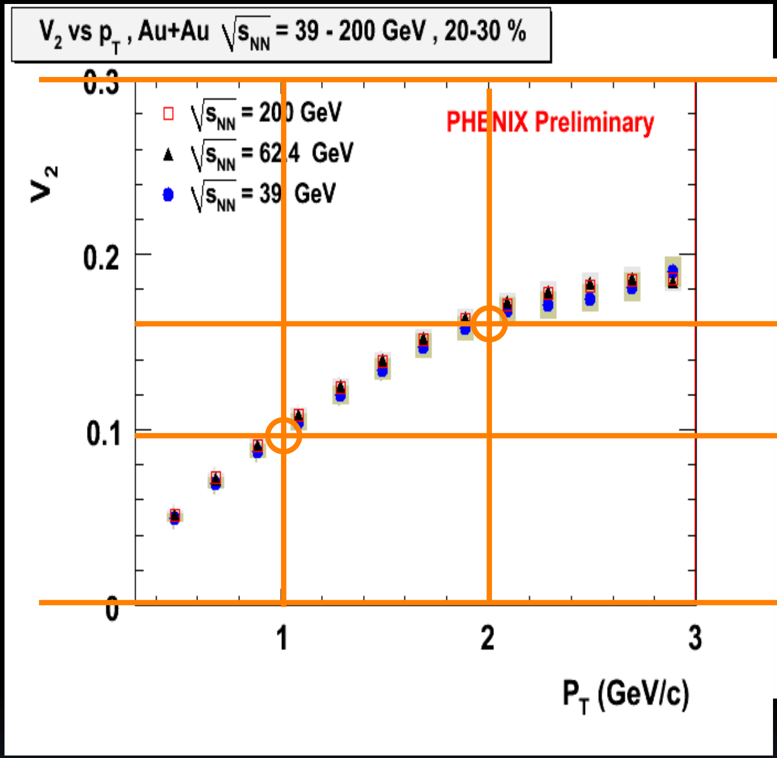


v_2, v_3, v_4 as a function of $\sqrt{s_{NN}}$

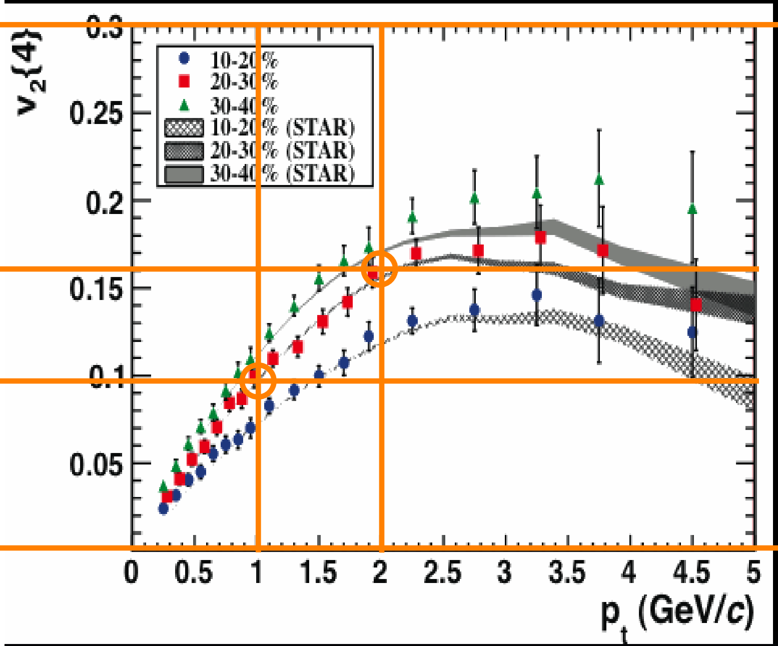


v_2, v_3, v_4 are independent of $\sqrt{s_{NN}}$ for 39, 62.4, 200 GeV

v_2 vs p_T from 39 GeV to 2.76 TeV

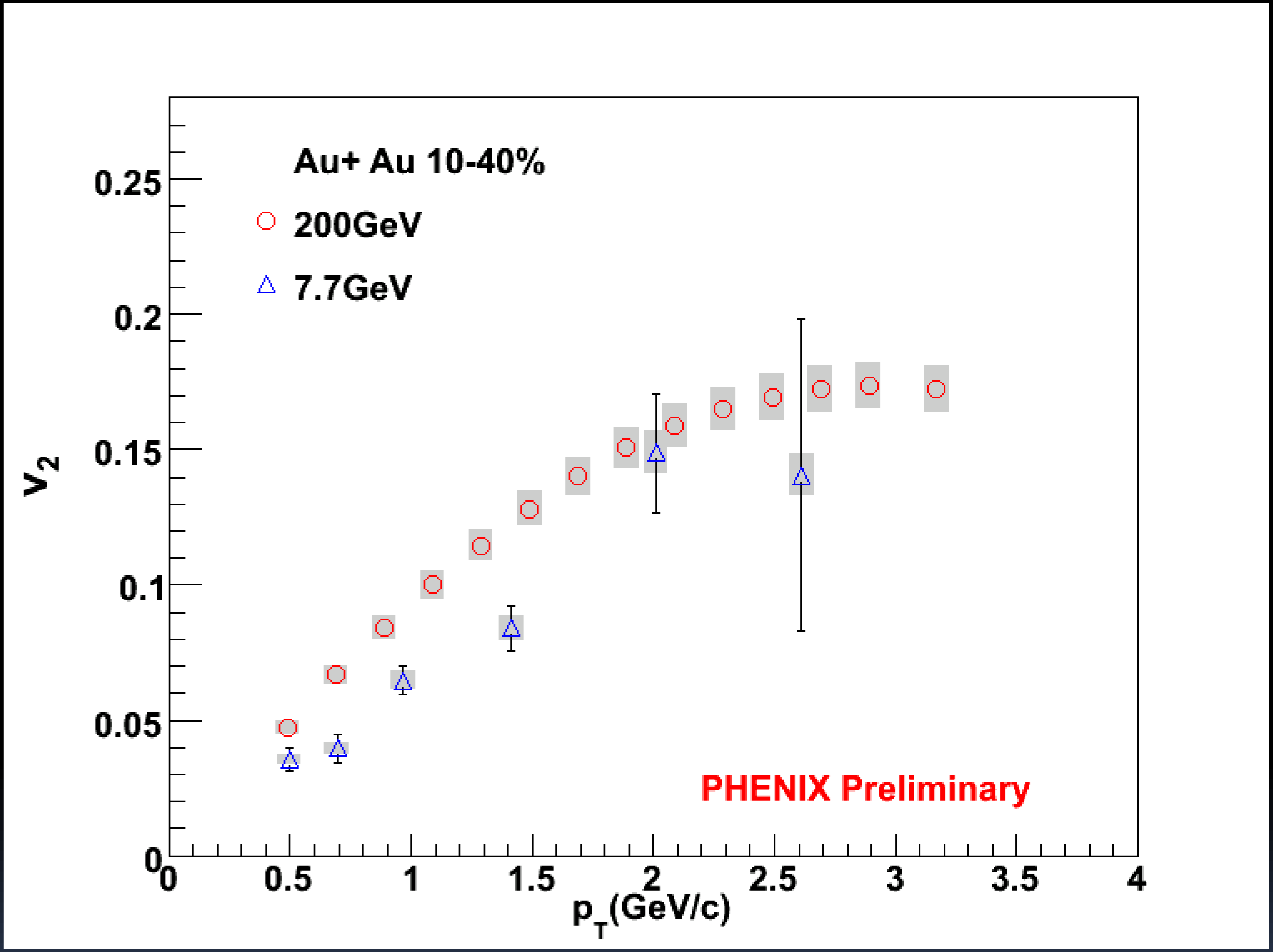


ALICE Experiment, PRL105,252302 (2010)



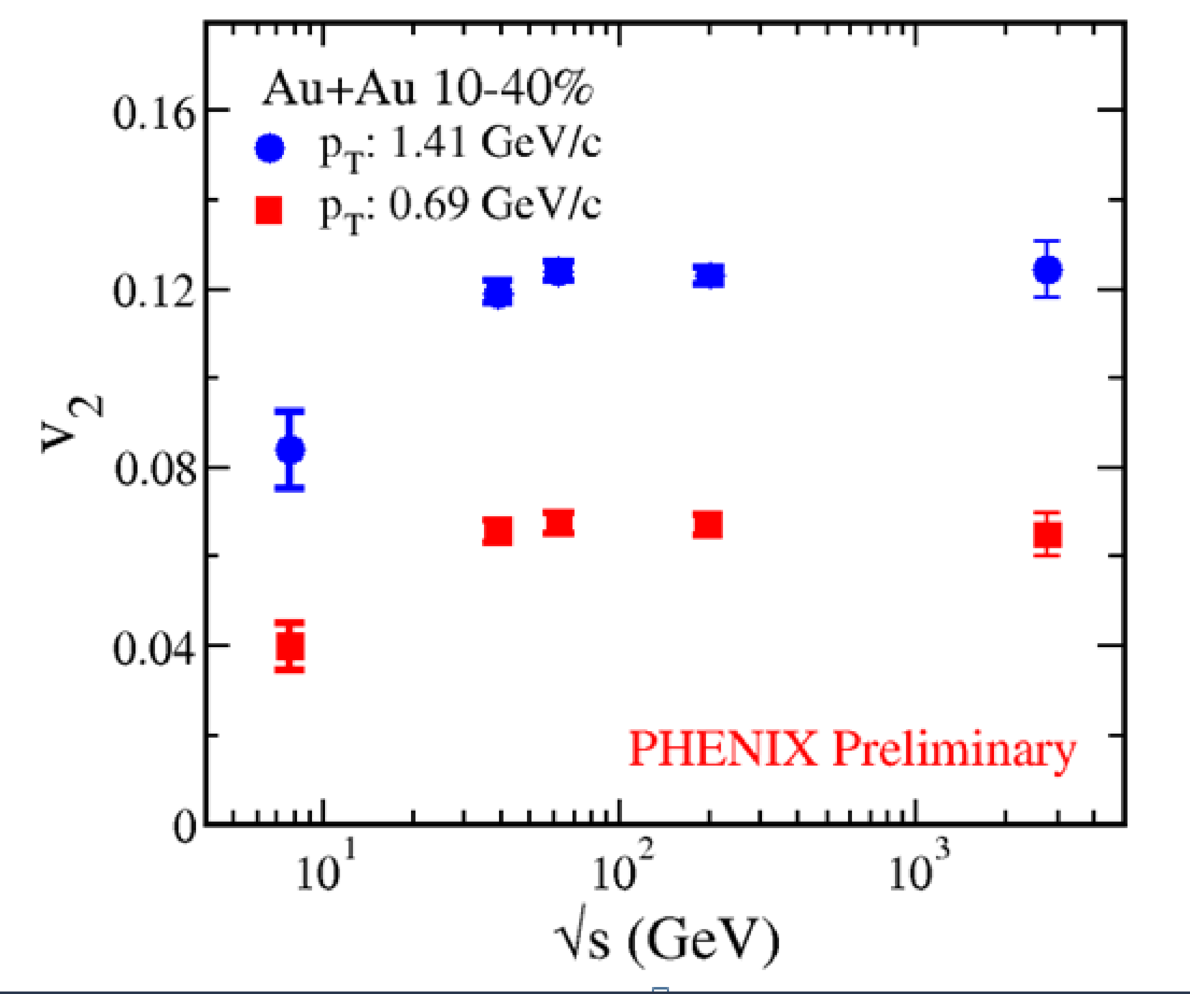
This implies that the system demonstrates similar hydrodynamic properties from 39 GeV to 2.76 TeV

v_2 in 7.7 GeV Au+Au Collisions



The magnitude of v_2 at 7.7 GeV is significantly lower than the magnitudes at 39, 62 and 200 GeV

Saturation of v_2 with beam energy

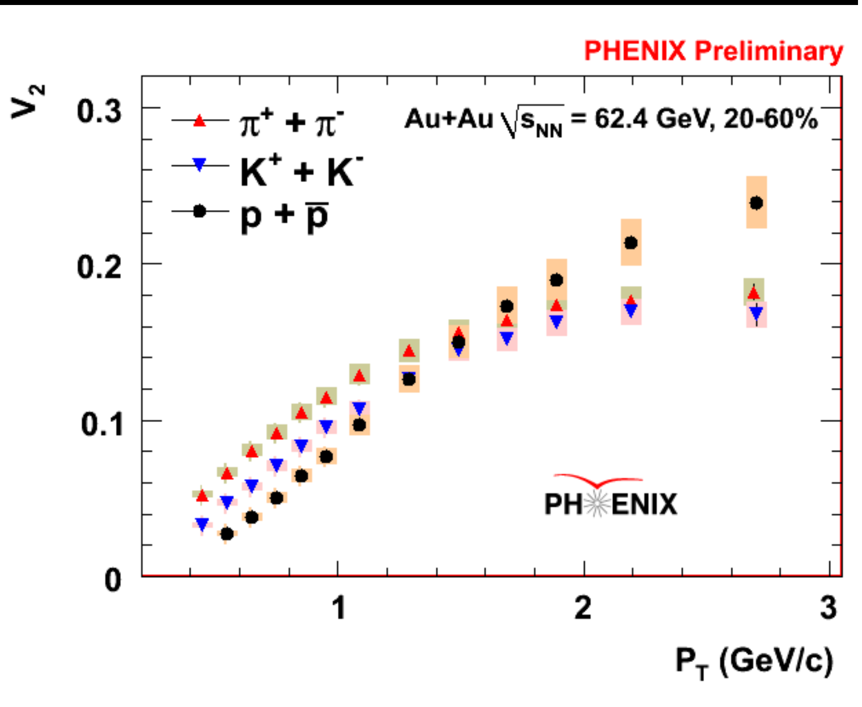


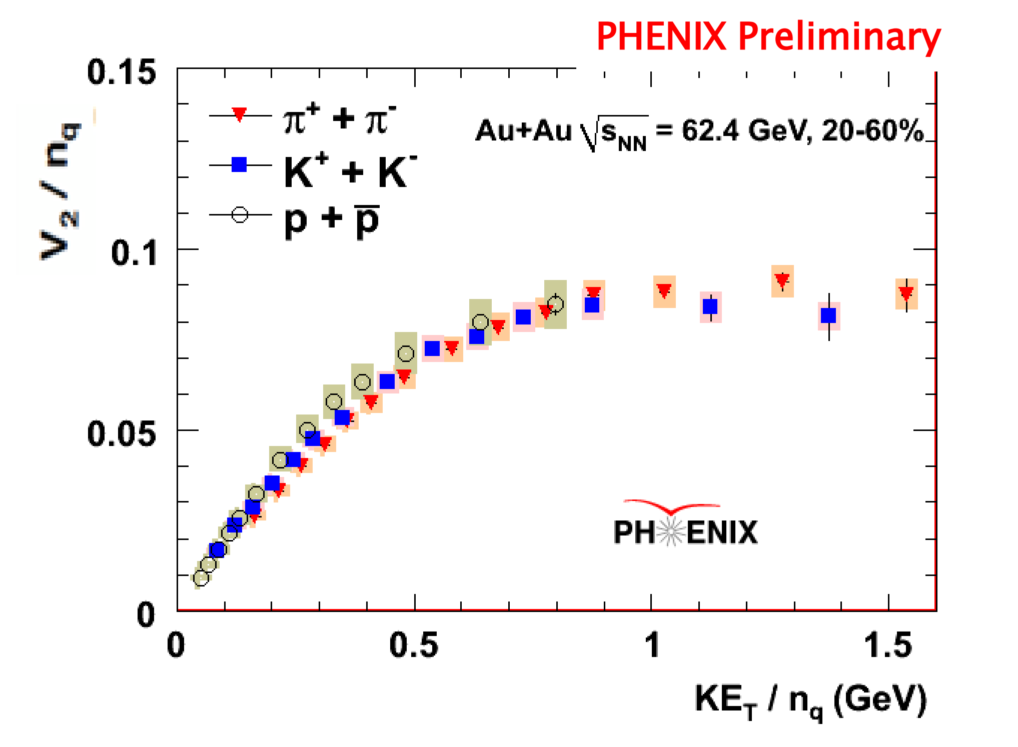
v_2 saturates for a given p_T around or below 39 GeV

$\langle v_2 \rangle$ still increases mainly because of the $\langle p_T \rangle$ rise.

Almost perfect fluidity from 39 GeV to 2.76 TeV

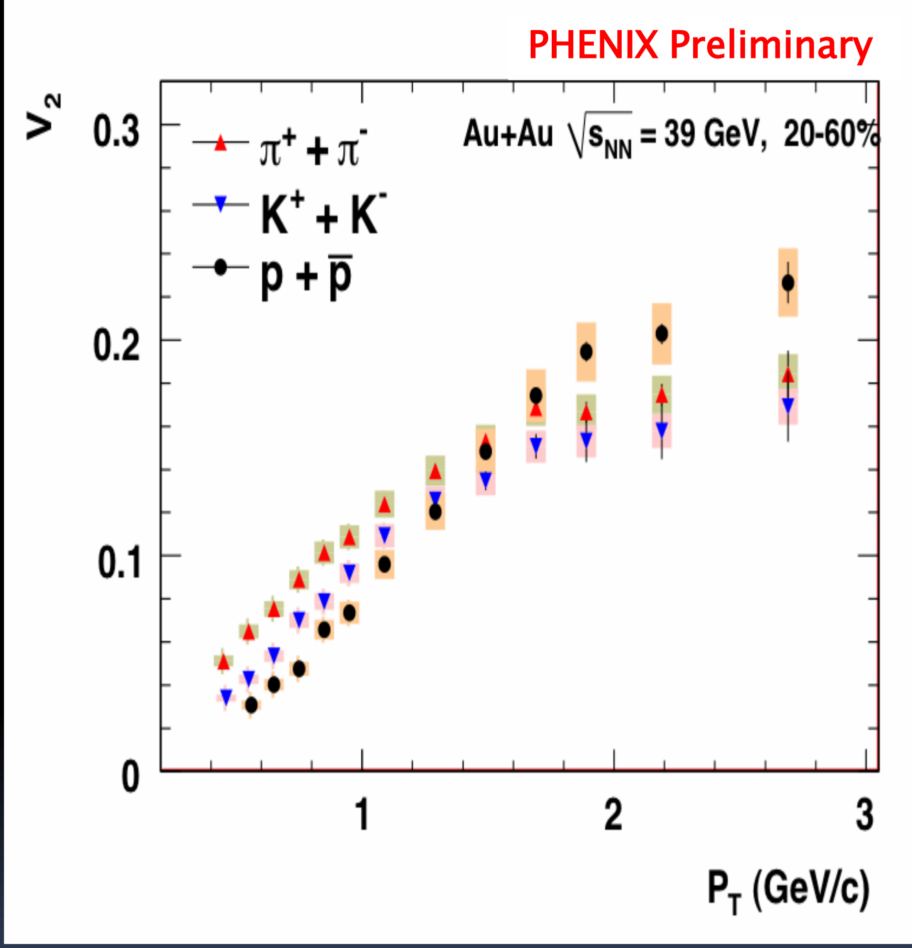
Identified hadron v_2 in 62.4 GeV Au+Au Collisions

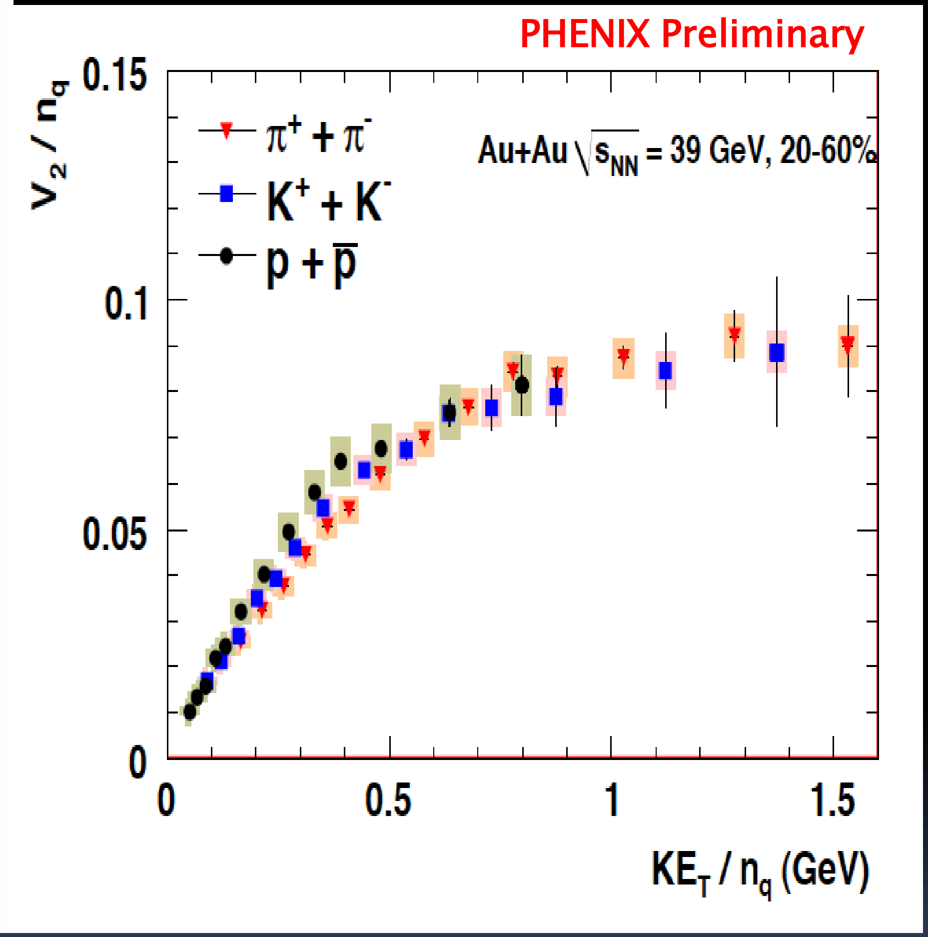




Partonic collective flow is observed down to 62 GeV and …

Identified hadron v_2 in 39 GeV Au+Au Collisions



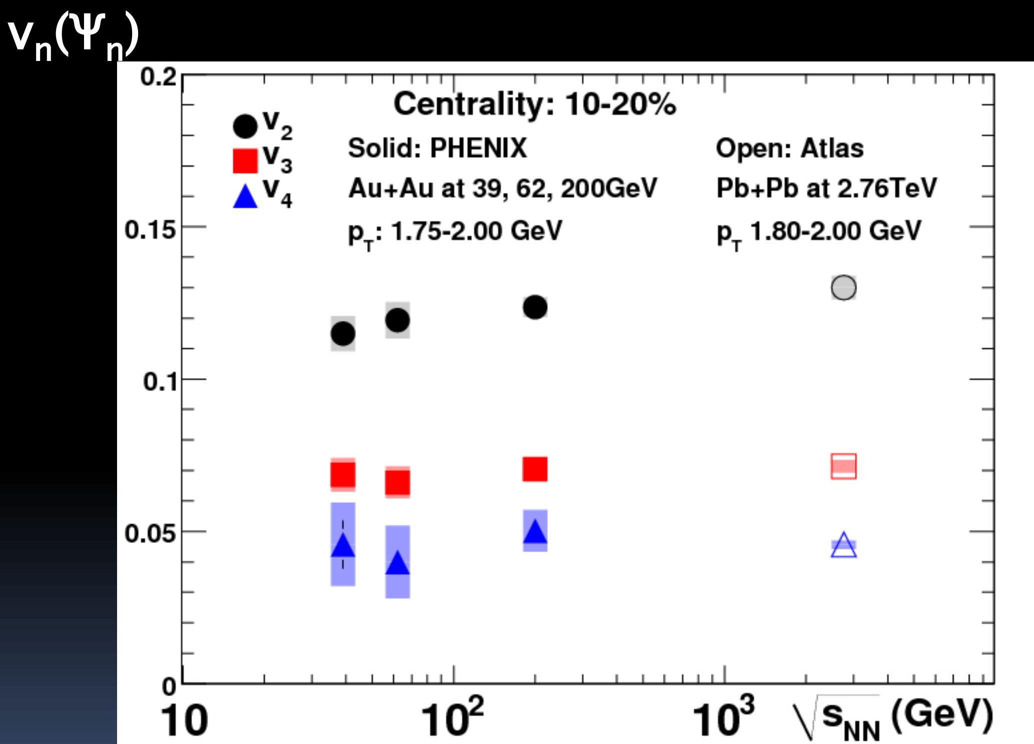


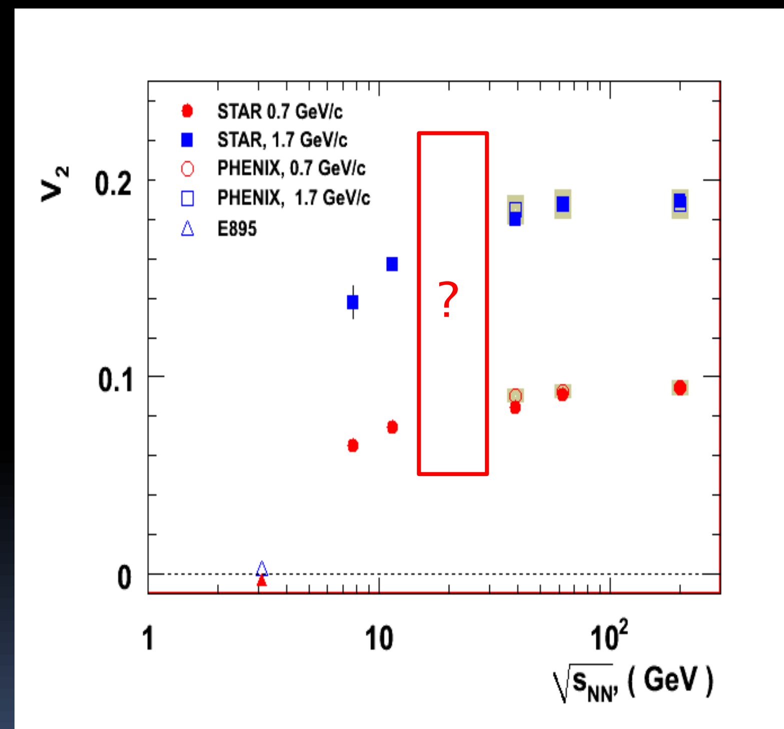
Partonic collective flow is observed down to 39 GeV

Flow Summary

- v_2, v_3 and v_4 are measured in 39, 62 and 200 GeV. The magnitudes are similar.
- v_2 of pion, kaon, and (anti)proton show quark number scaling down to 39 GeV.
- v_2 saturates in intermediate p_T.

These observations suggest similar initial geometry fluctuations and dynamic evolution of nuclear matter above 39 GeV.





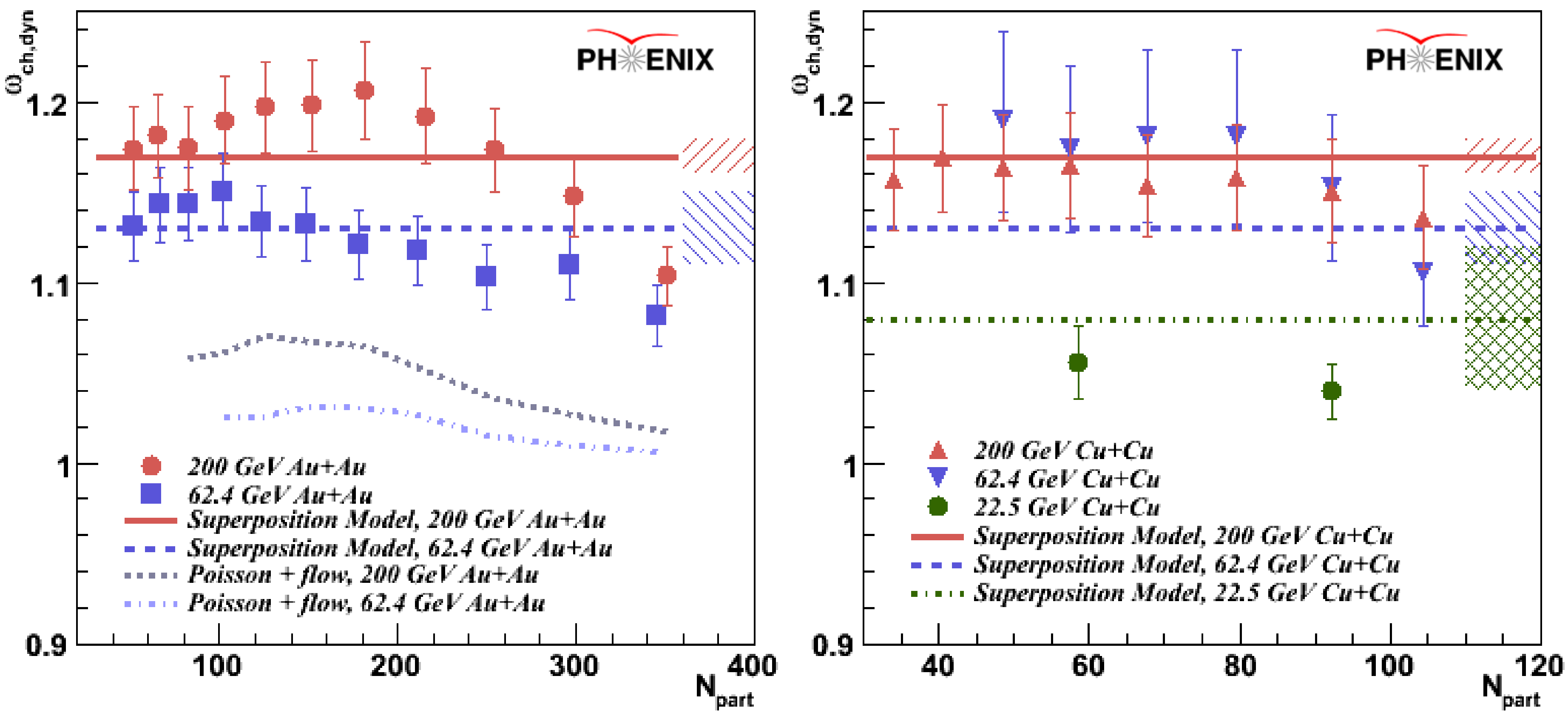
Data taken at 19.6 and 27 GeV this year will help us fill in the “gap” in the excitation function.

Searching for Signatures of the Critical Point: Fluctuations, Correlations

Multiplicity Fluctuations

Near the critical point, the multiplicity fluctuations should exceed the superposition model expectation → **No significant evidence for critical behavior is observed.** Low energy results are being prepared.

$\omega_{ch,dyn}$ = variance/mean, corrected for impact parameter fluctuations.



Searching for the Critical Point with HBT Q_{inv} Correlations

T. Csorgo, S. Hegyi, T. Novák, W.A. Zajc,

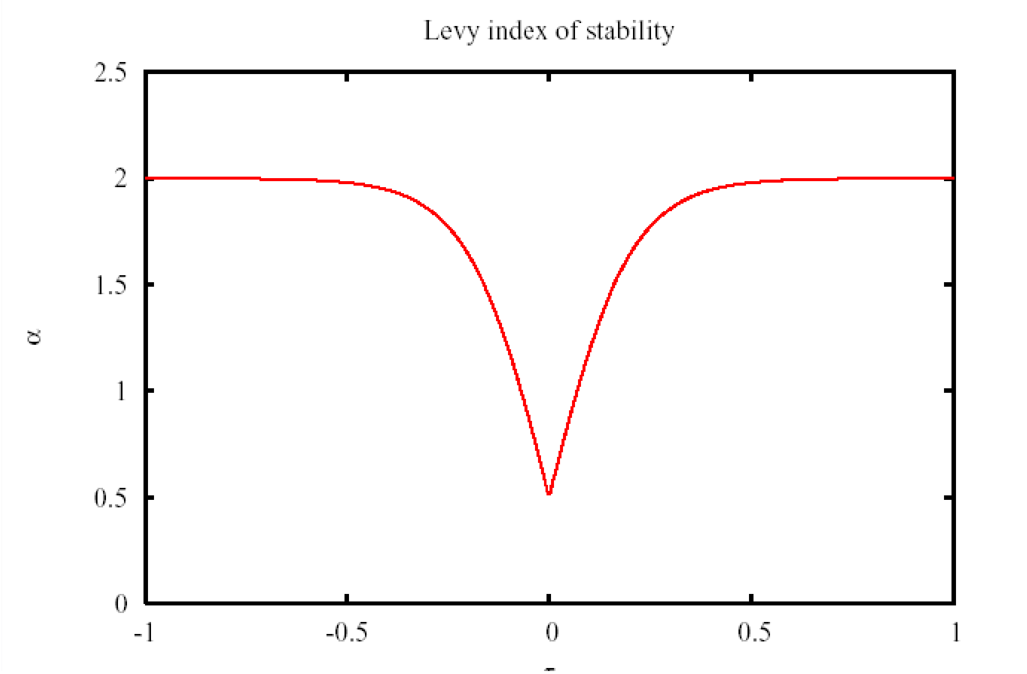
Acta Phys. Pol. B36 (2005) 329-337

- This technique proposes to search for variations in the exponent η.
- The exponent η can be extracted by fitting HBT Q_{inv} correlations with a Levy function:

$$C(Q_{inv}) = \lambda \exp(-|Rq/hc|^{-\alpha})$$

α = Levy index of stability = η
α = 2 for Gaussian sources
α = 1 for Lorentzian sources

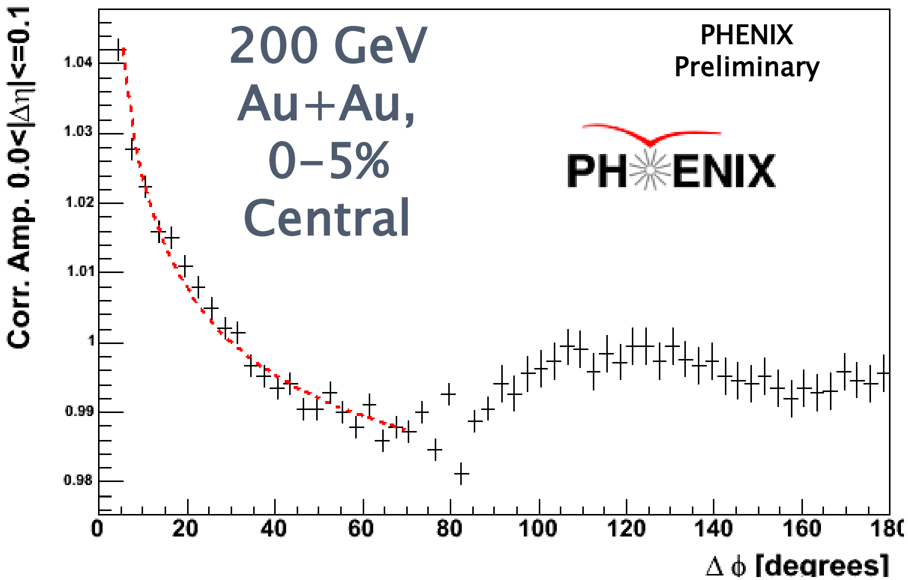
- Measure a as a function of collision energy and look for a change from Gaussian-like sources to a source corresponding to the expectation from the universality class of QCD.

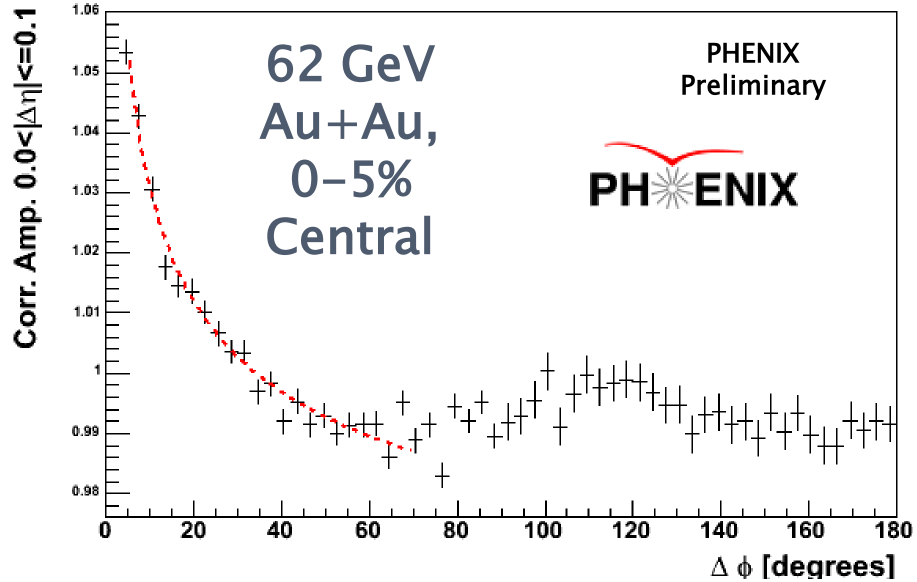


$$\alpha(\text{Lévy}) = \eta(\text{3d Ising}) = 0.50 \pm 0.05$$

Like-Sign Pair Azimuthal Correlations

$0.2 < p_{T,1} < 0.4$ GeV/c, $0.2 < p_{T,2} < 0.4$ GeV/c, $|\Delta$ pseudorapidity$|<0.1$





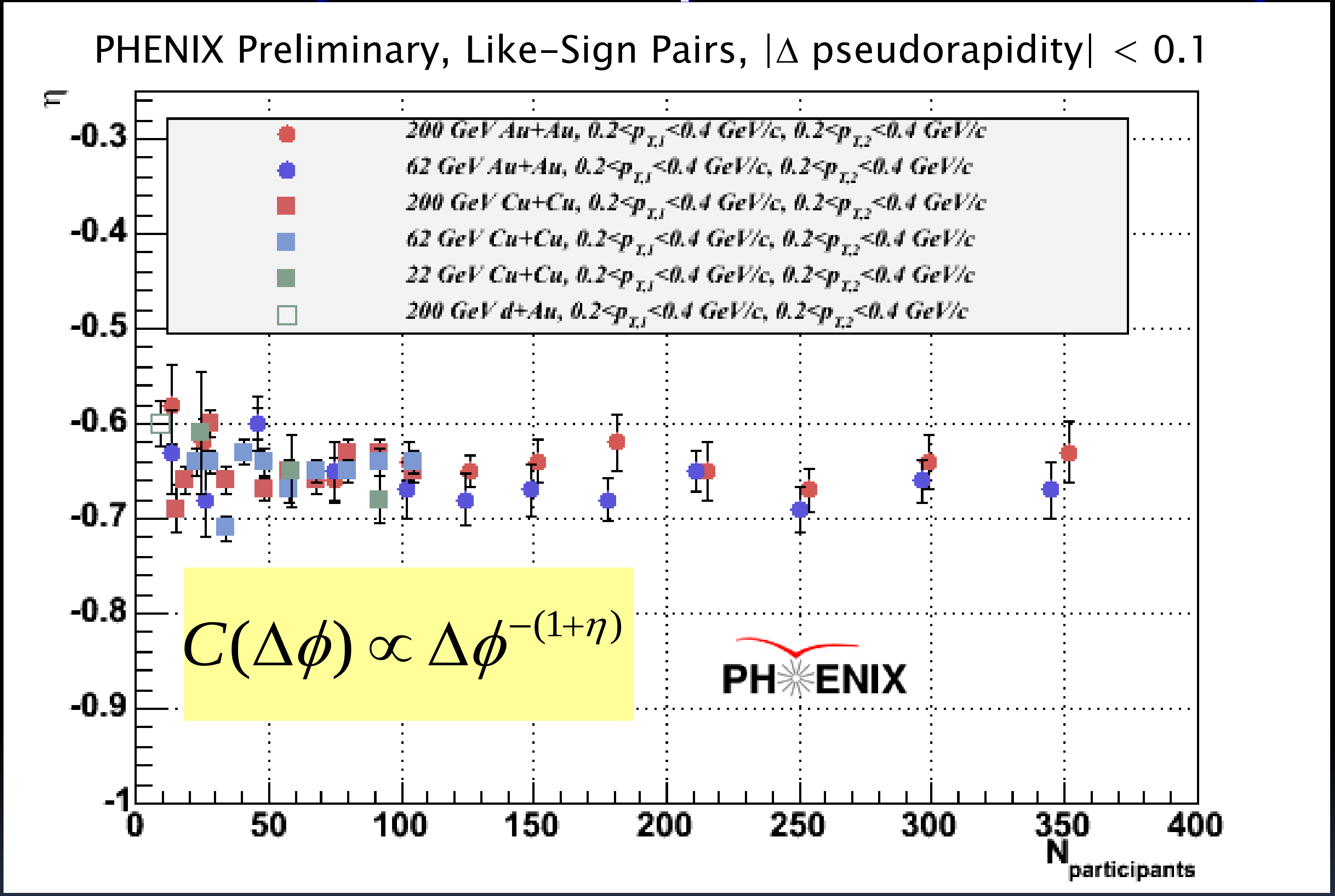
$$C(\Delta\phi) = (dN/d\phi_{data}/dN/d\phi_{mixed})*(N_{events,mixed}/N_{events,data})$$

$$C(\Delta\phi) \propto \Delta\phi^{-(1+\eta)}$$

Assuming that QCD belongs in the same universality class as the (d=3) 3-D Ising model, the expected value of η is 0.5 (Reiger, Phys. Rev. B52 (1995) 6659 .

- The power law function fits the data well for all species and centralities.

C(Δπ) Exponent η vs. Centrality



The exponent η is independent of species, centrality, and collision energy.

The value of η is inconsistent with the d=3 expectation at the critical point.

Summary and Outlook

- R_{AA}:
  - R_{AA} for $p_T>6$ GeV is comparable between 200 and 62 GeV.
  - R_{AA} at 39 GeV still shows a large suppression.
  - No significant suppression is observed for the ϕ at 62 GeV.
  - Initial measurements show suppression of J/Ψ at 39 and 62 GeV.

- Flow:
  - v_2 saturates at intermediate p_T at 39 and 62 GeV.
  - Quark number scaling holds at 39 and 62 GeV.
  - v_2 at 7.7 GeV is significantly lower than v_2 at 39 and 62 GeV.

- Outlook:
  - Many measurements are being analyzed, including:
    - multiplicity, net charge, and transverse momentum fluctuations
    - local parity violation
    - identified particle spectra
    - 2-particle correlations
    - dilepton spectra

  - Stay tuned for much more!

Auxiliary Slides

PHENIX Detector

Central Arm Tracking
- Drift Chamber
- Pad Chambers
- Time Expansion Chamb.

Muon Arm Tracking
- Muon Tracker

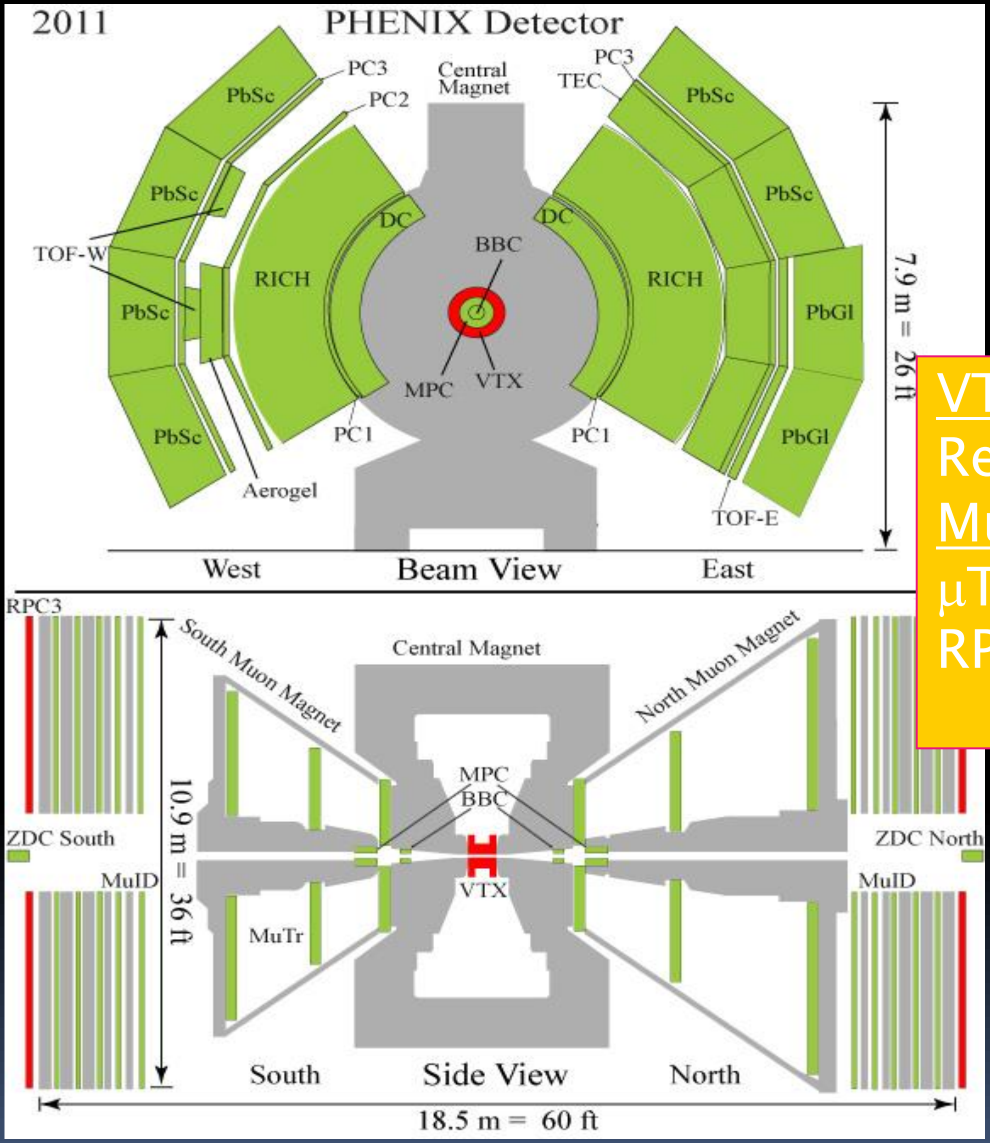
Calorimetry
- PbGl
- PbSc
- MPC

Particle Id
- Muon Identifier
- RICH, HBD
- TOF E & W
- Aerogel
- TEC

Global Detectors
- BBC
- ZDC/SMD Local Polarim.
- Forward Hadron Calo.
- RXNP

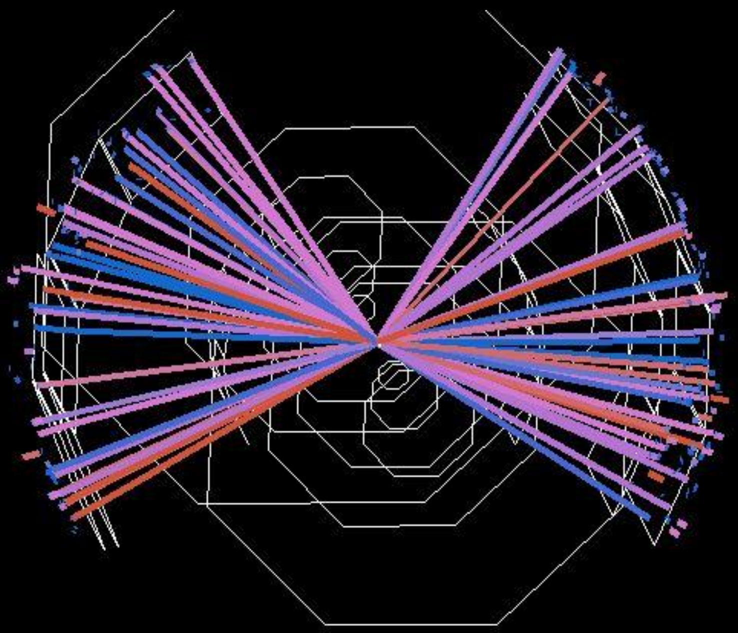
DAQ and Trigger System

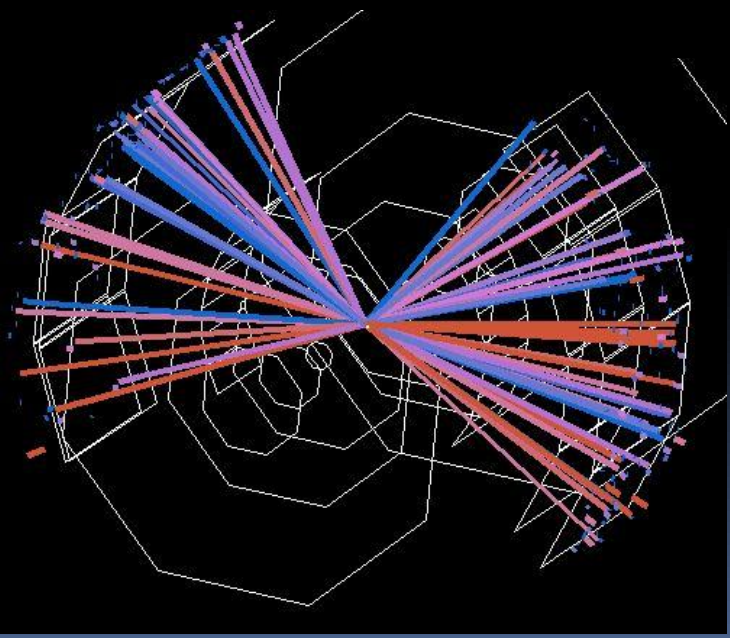
Online Calib. & Production

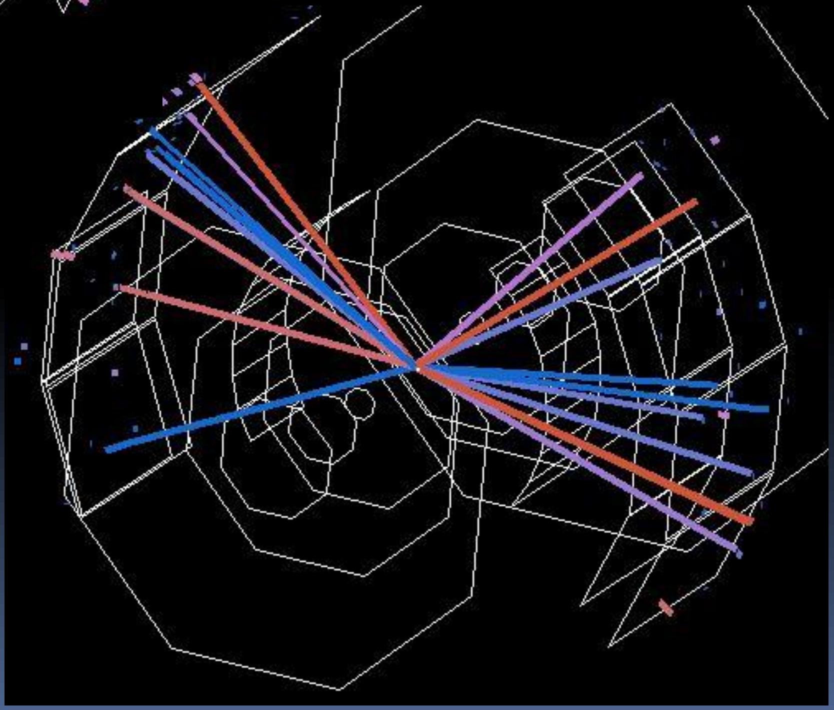


VTX
Replaces HBD
Muon Trigger:
μTr FEE
RPC station 3

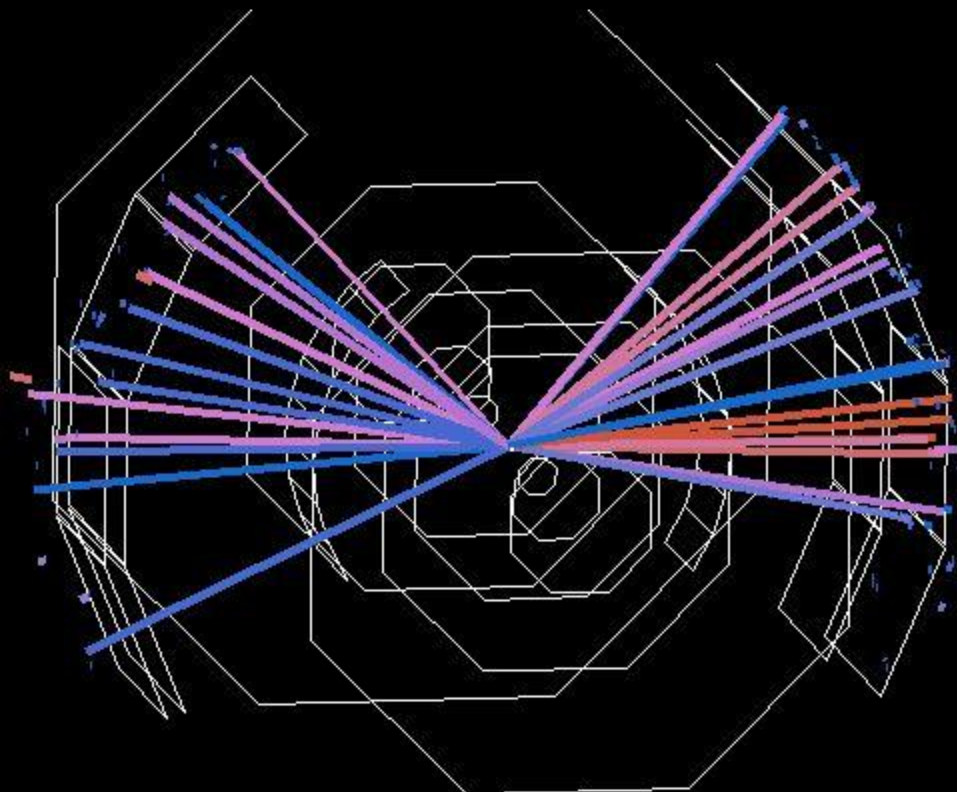
PHENIX 39 GeV Au+Au Event Displays

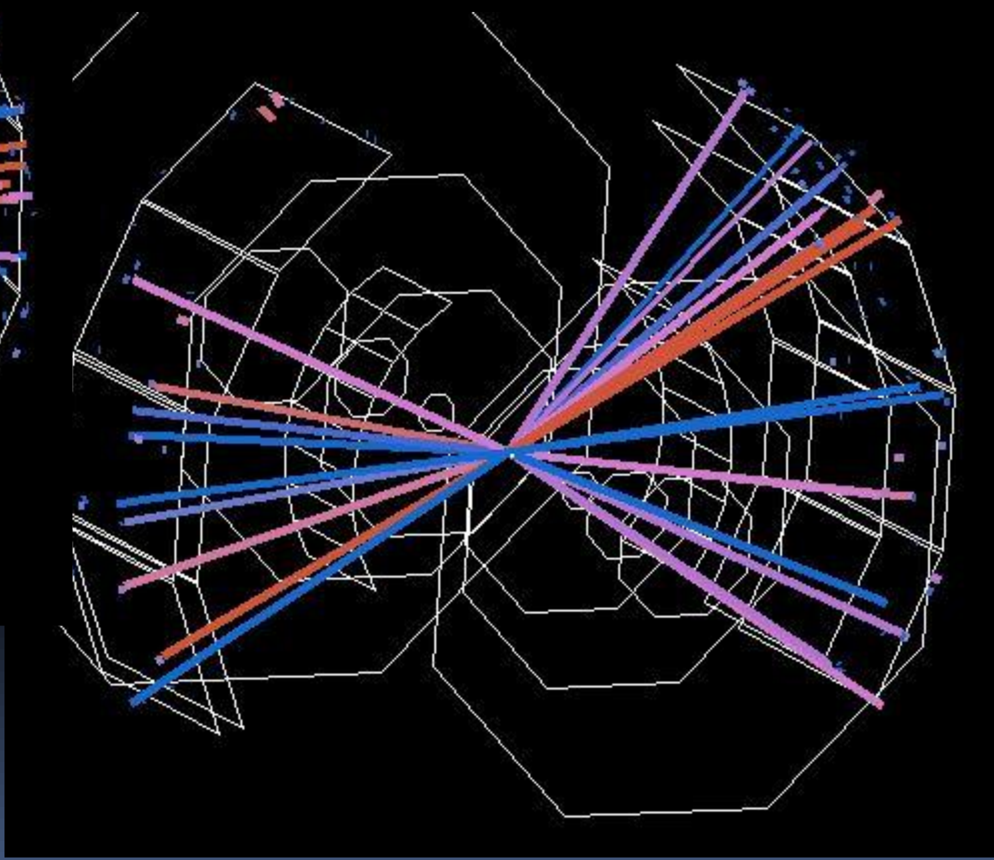






PHENIX 7.7 GeV Au+Au Event Displays





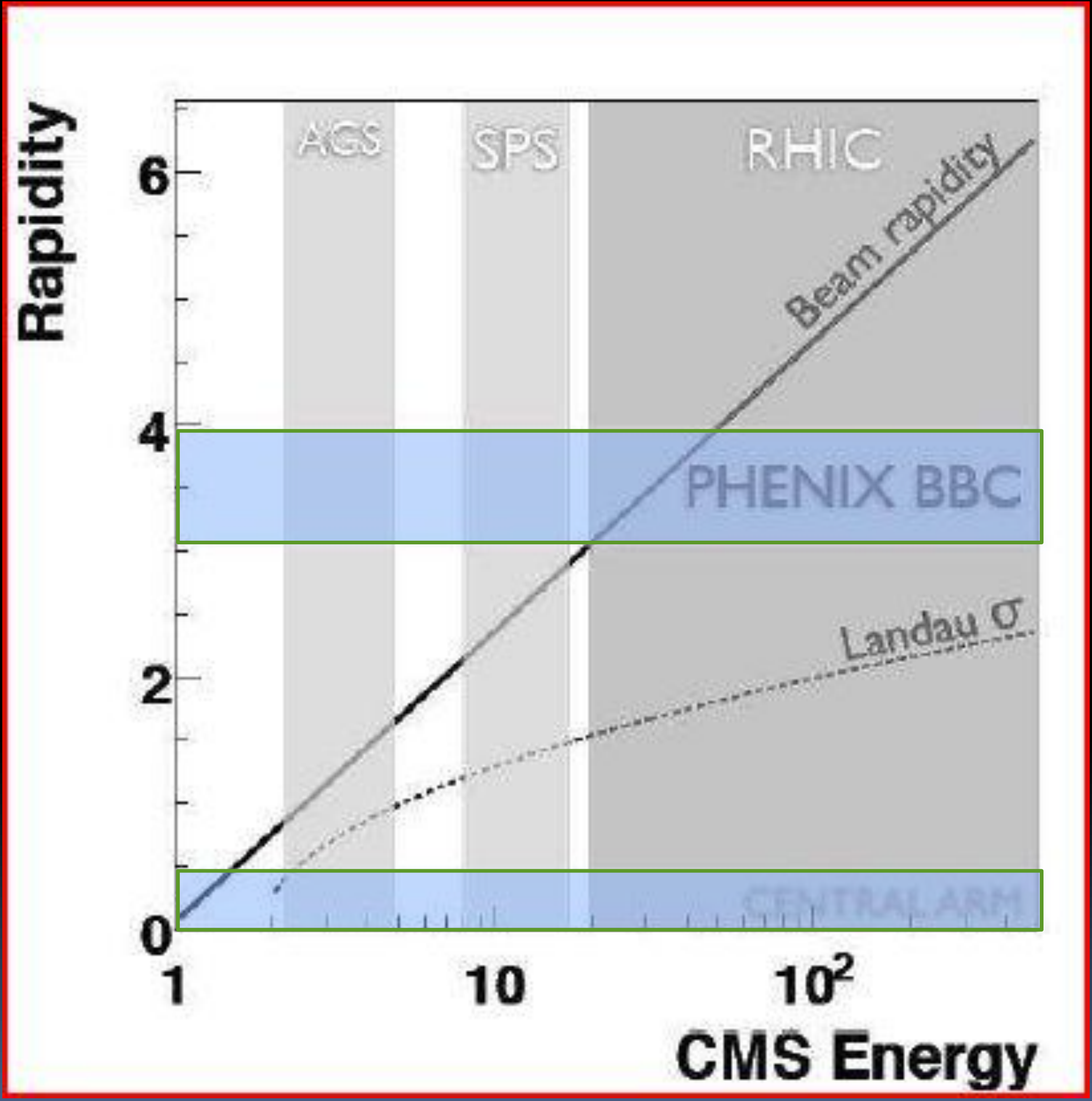
Triggering at Low Energy

The problem:

The placement of the trigger detectors (BBCs) are not optimized for low energy running.
They have a reduced acceptance, especially below RHIC energies of ~ 20 GeV.

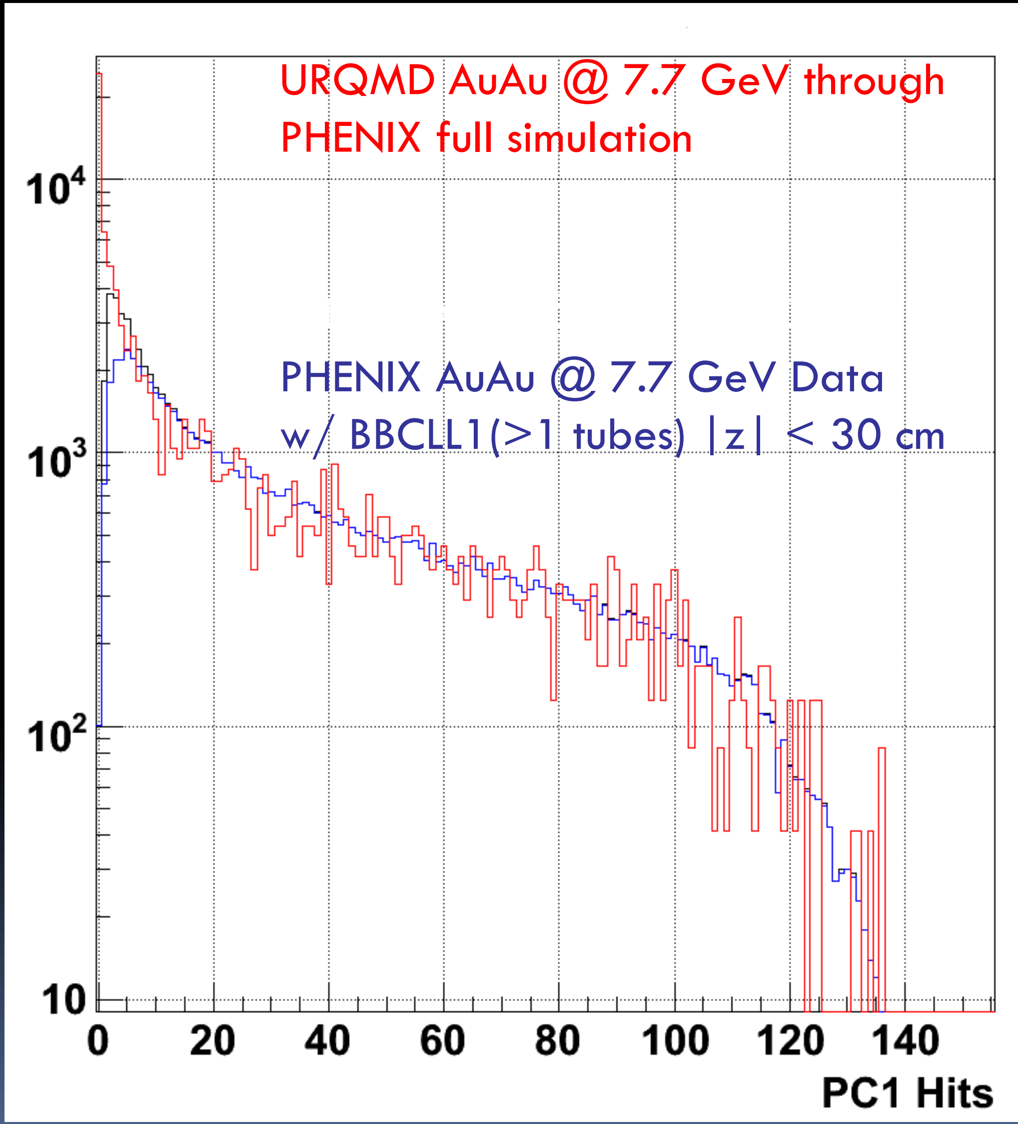
Fermi motion to the rescue!

At low energies, Fermi motion is enough to bring nucleons back into the BBC acceptance.



PHENIX Trigger Performance at 7.7 GeV

Tight timing cut on BBC North vs. South



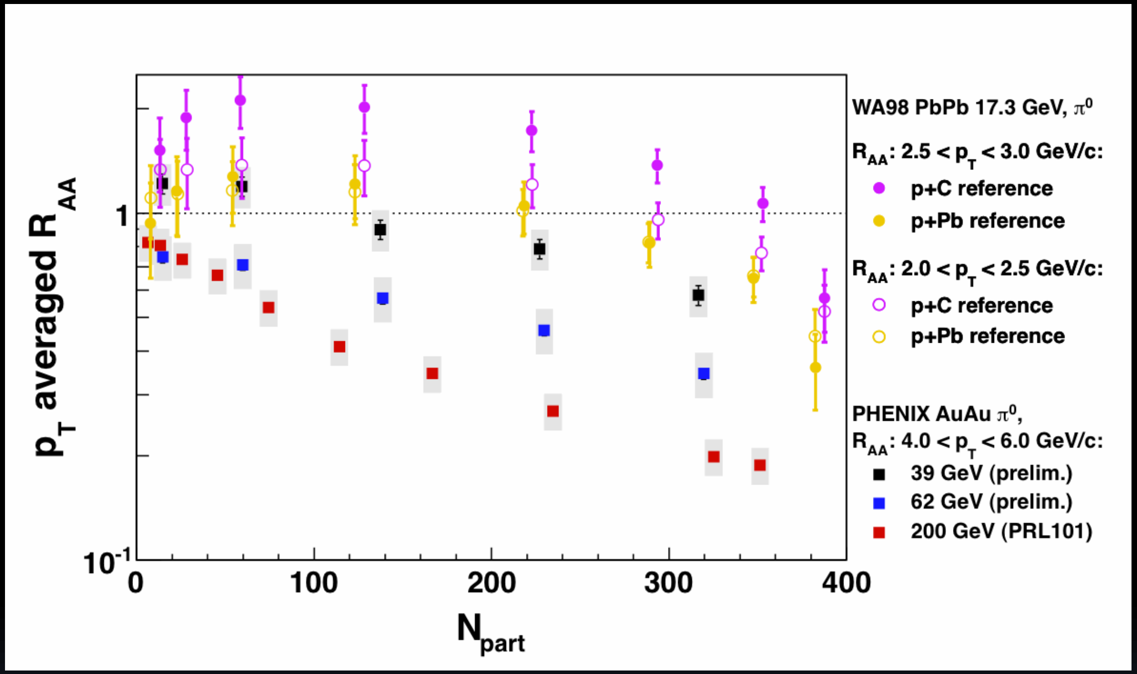
URQMD normalized to match real data integral for PC1 hits > 40.

URQMD not matched to z distribution in real data.

Estimate that the trigger fires on 77% of the cross section.

No indication of deviation of low multiplicity events from background.

Comparison with recent SPS R_{AA}



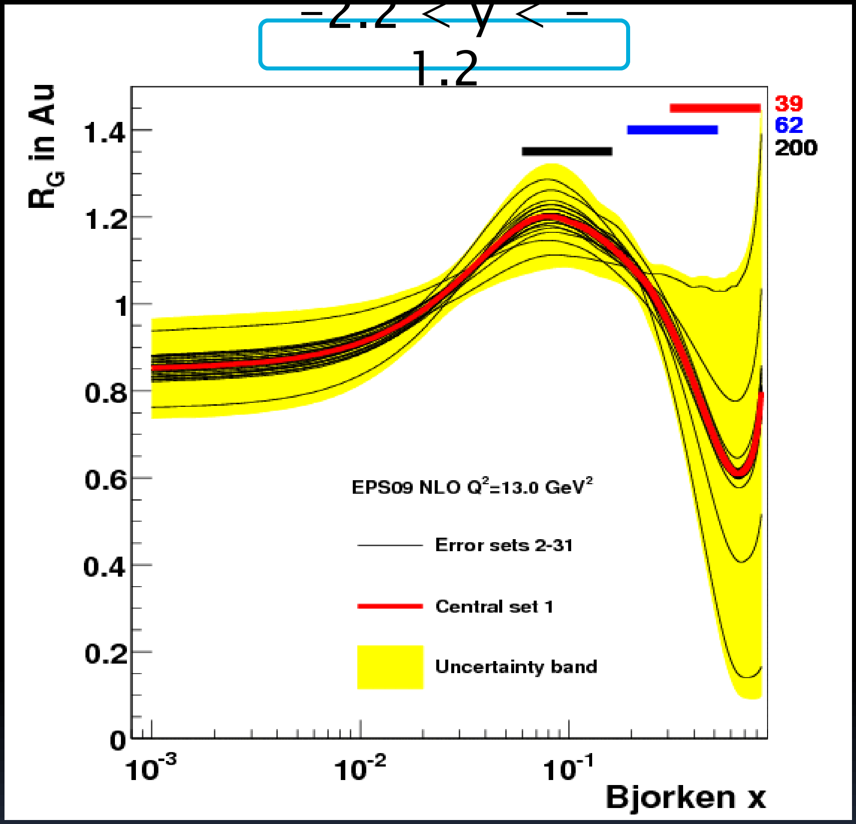
- In previous experiment at WA98 we see only (PRL 100 (2008), 242301) suppression at "ultra"-central (0-1%) collisions of Pb+Pb.
- The x_T is overlapping between the SPS and RHIC intervals.
- The "onset" of the energy loss is dependent on system size and collision energy.
- The energy loss is

The magenta closed circles are the most comparable with the PHENIX results, as they have

The "onset" of the suppression depends on collision energy and centrality or system size (and p_T)

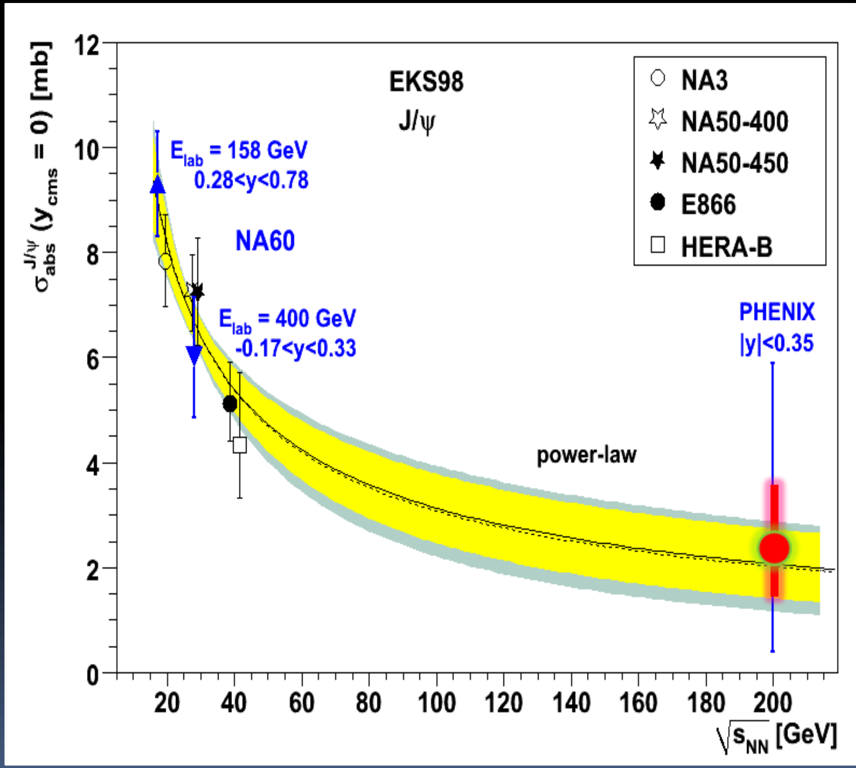
Energy dependence of CNMs

R_G for J/ψ production at RHIC



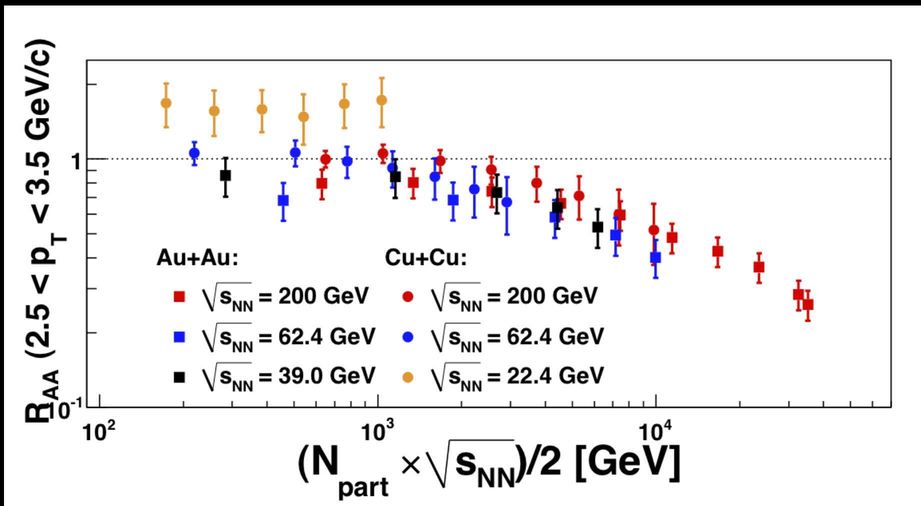
A systematic analysis at y~0 using EKS98 + $\sigma_{breakup}$ showed a clear **collision energy dependence** of $\sigma_{breakup}$.

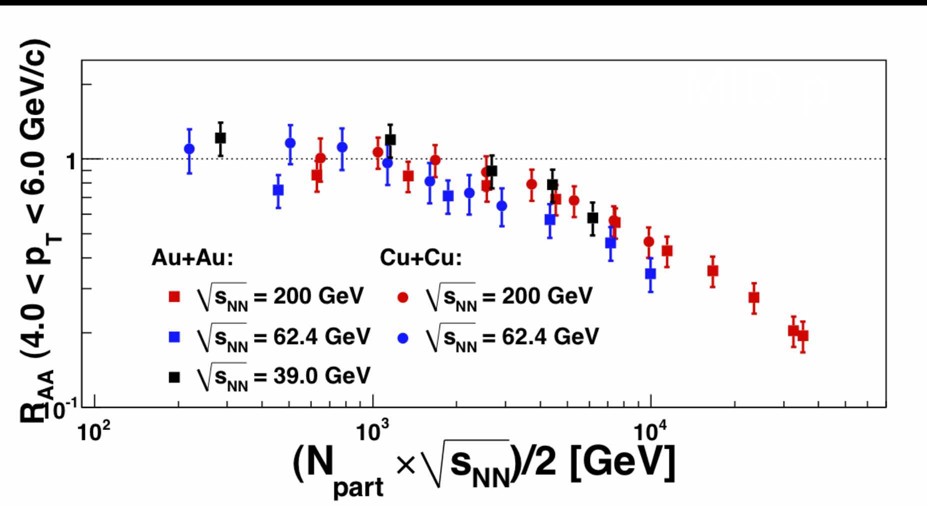
JHEP 0902:014 (2009)

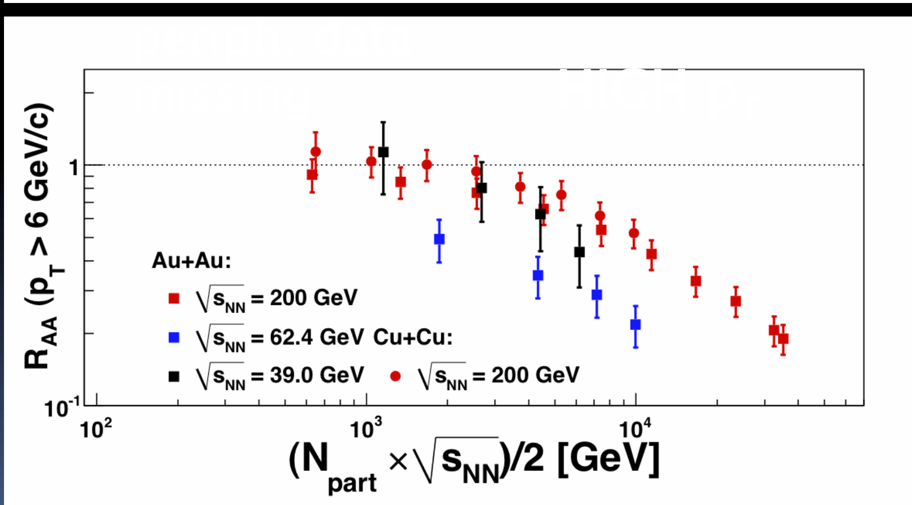


- ○ Proper geometry dependence need to be included.
- ○ Reduce uncertainties by measuring d+Au at the same energy.

E_{AA} dependence on p_T



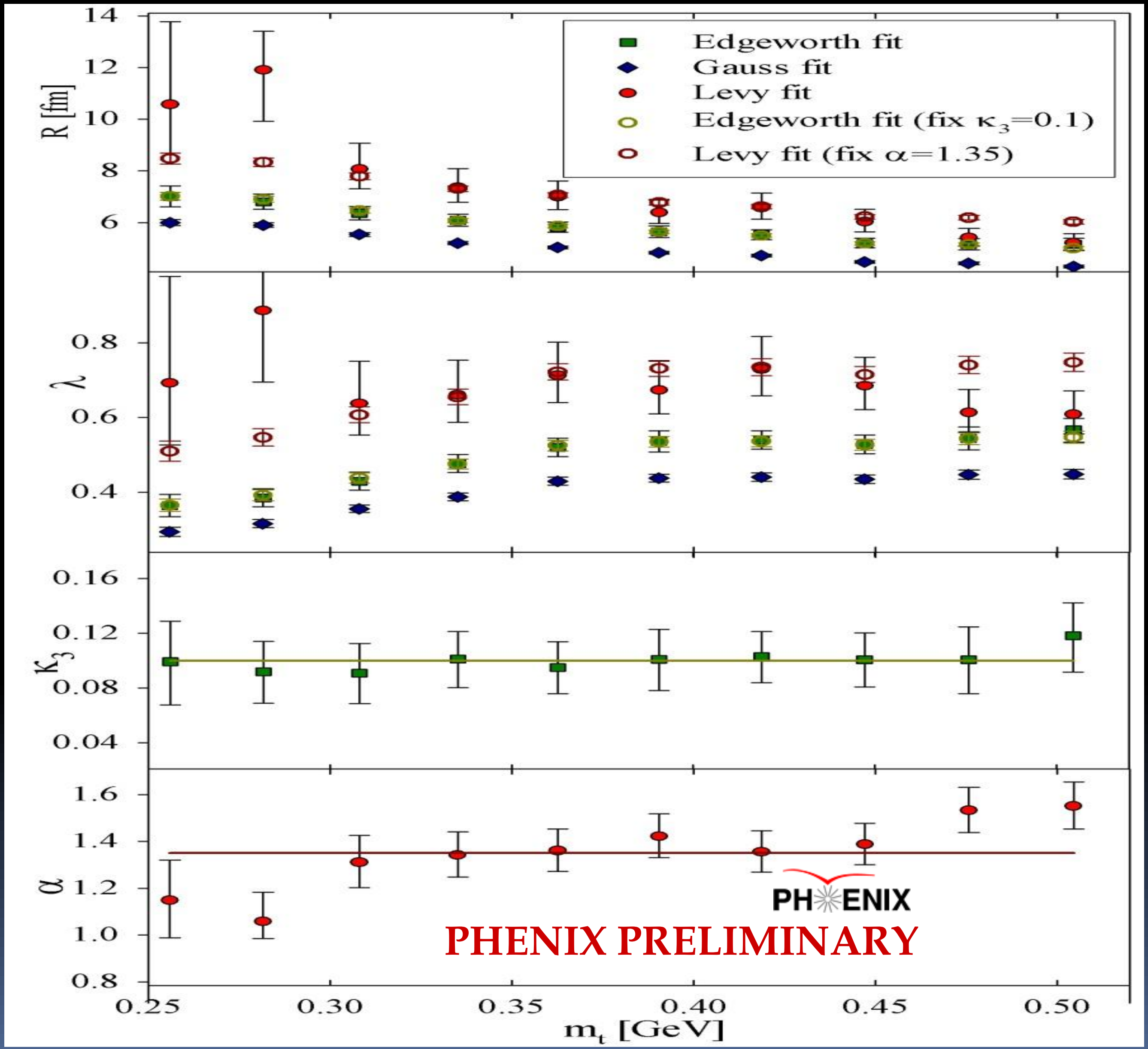




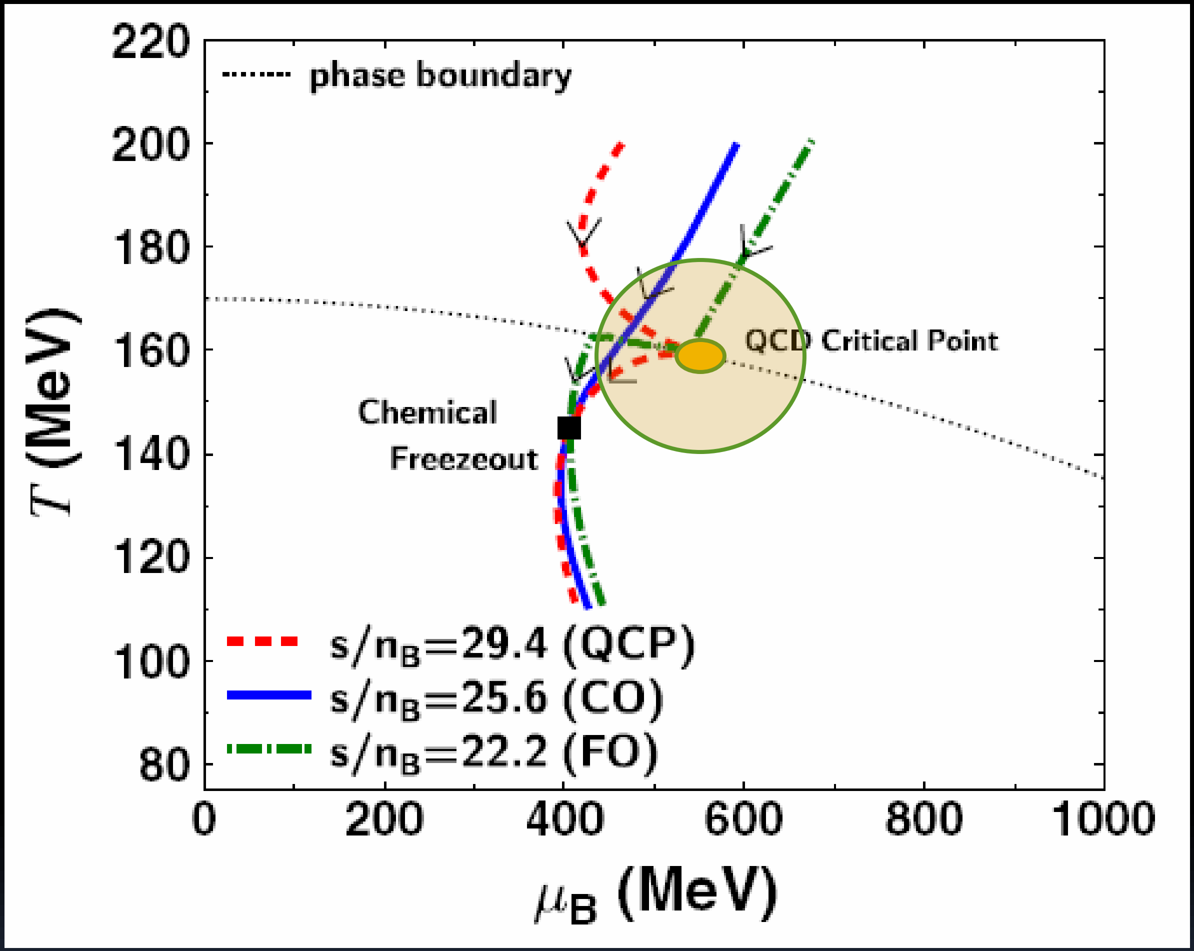
In higher p_T the scaling does not work.

shadowing? Bjorken energy density?

Lévy fits to q_{inv} in Central 200 GeV Au+Au



How big is the target?



M.Asakawa et al.,PRL 101,122302(2008)

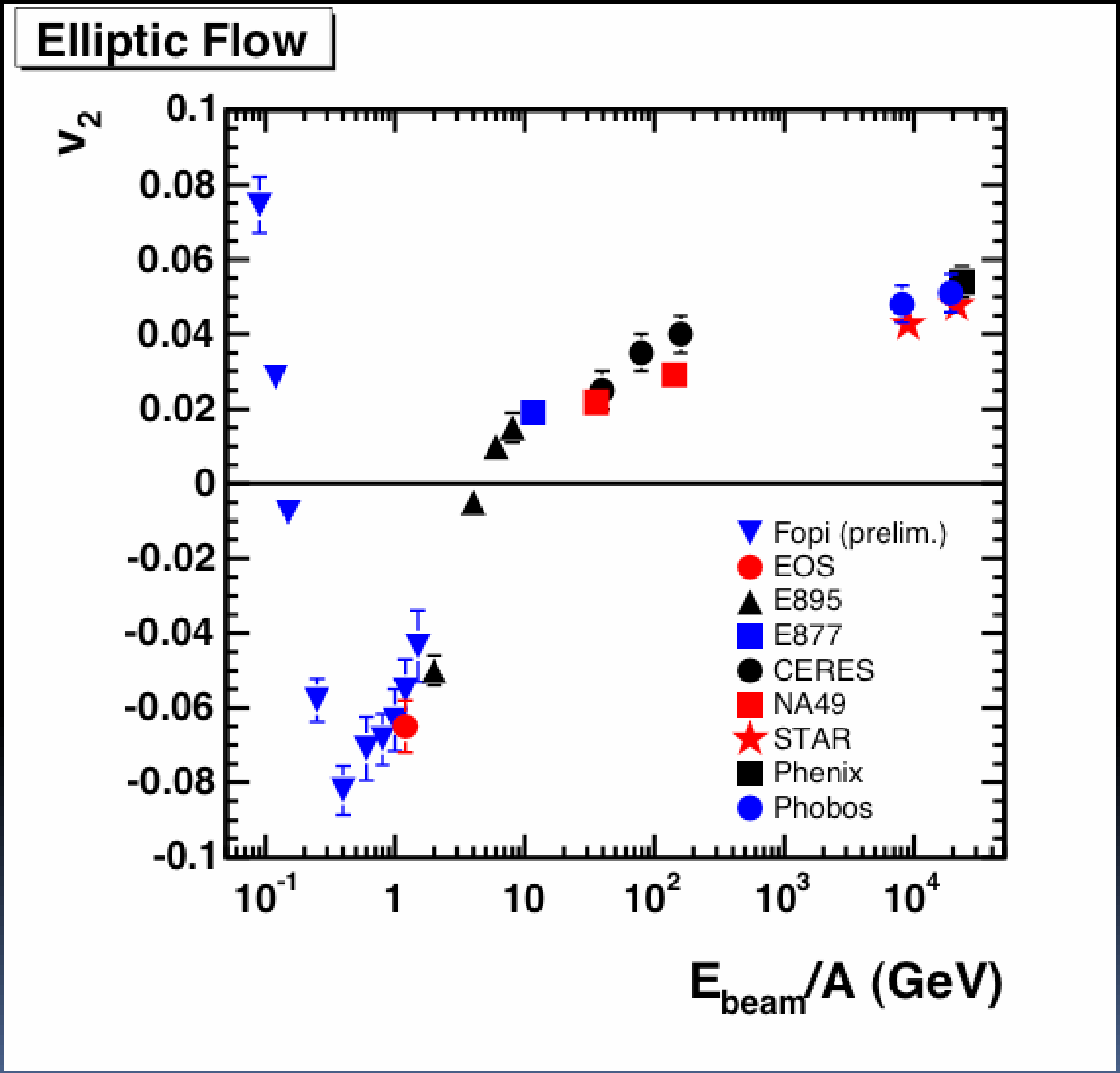
From a hydrodynamics calculation.

For a given chemical freeze-out point, 3 isentropic trajectories (s/n_B=constant) are shown.

The presence of the critical point can deform the trajectories describing the evolution of the expanding fireball in the (T,μ_B) phase diagram.

A large region can be affected, so we do not need to hit the critical point precisely.

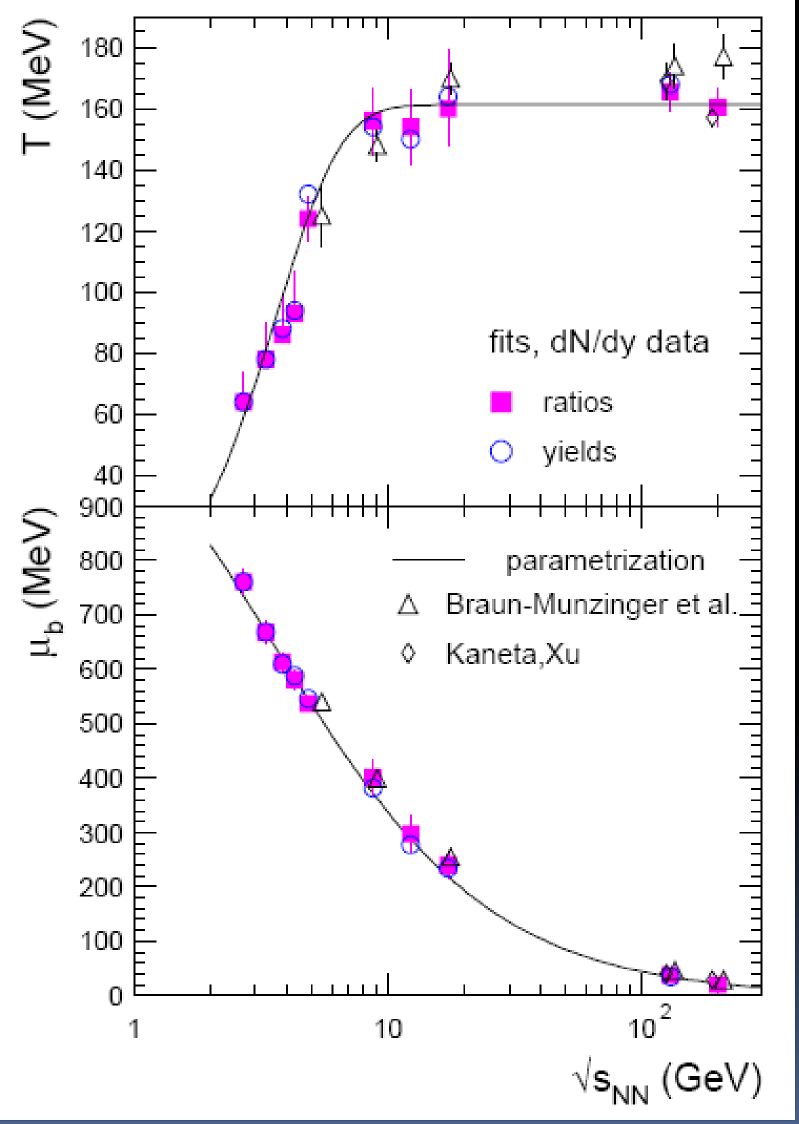
Elliptic Flow: Excitation Function

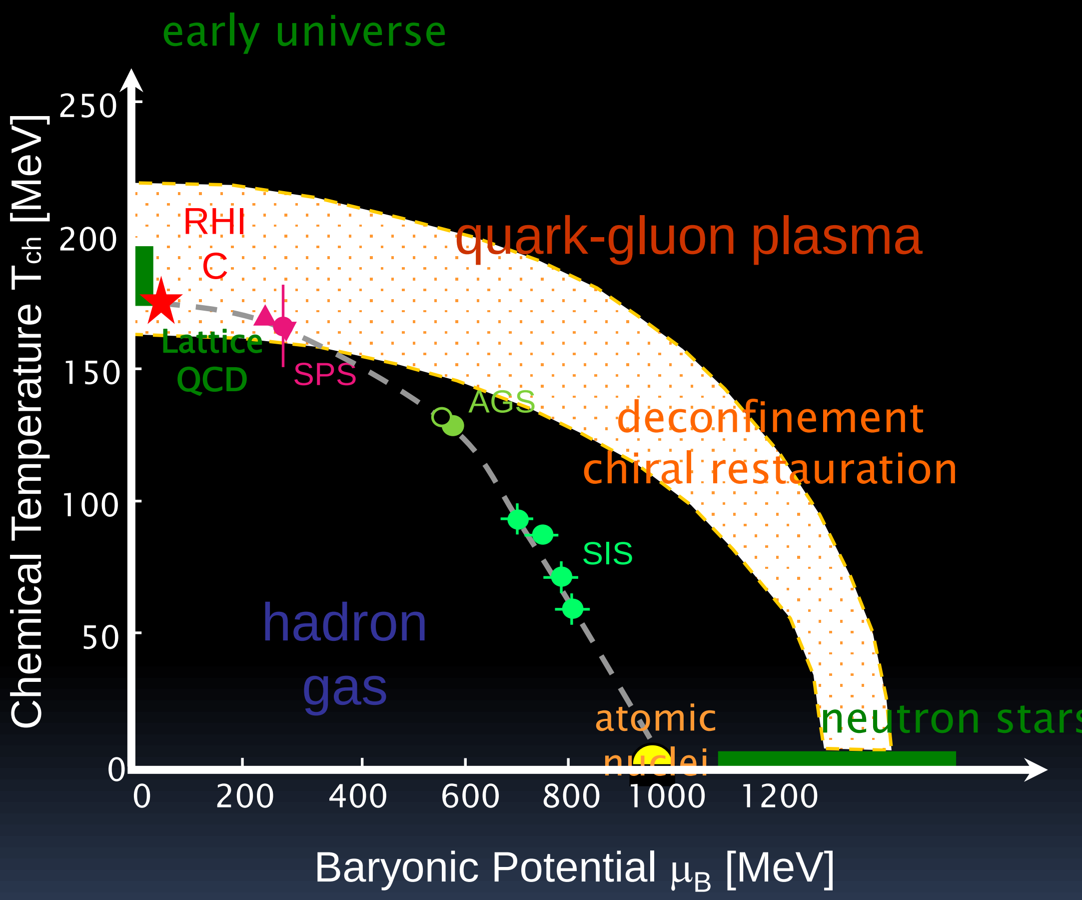


There is a transition from squeeze-out flow to in-plane flow between AGS and SPS energies

Statistical Model Fits

Extracted T & μ_B values





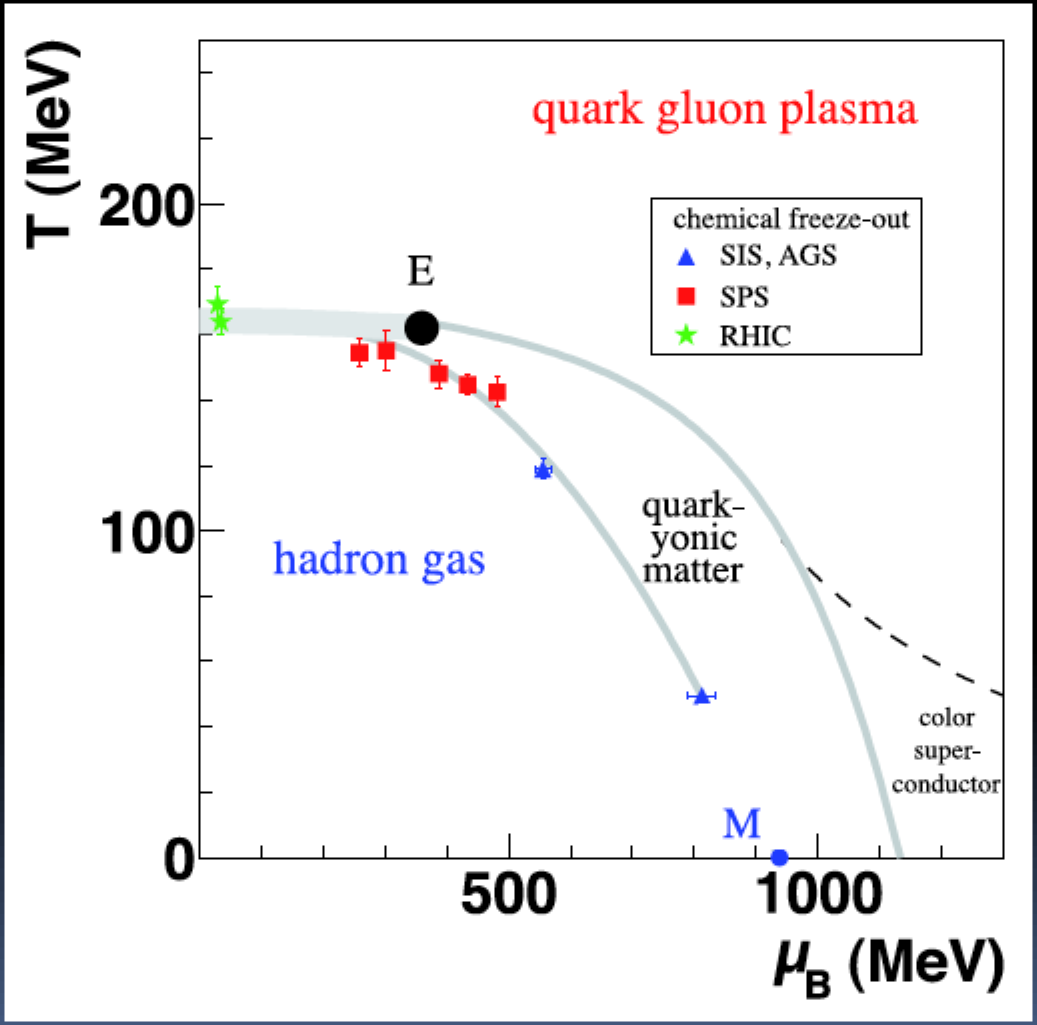
For $\sqrt{s}$ >≈ 10 GeV , chemical freeze-out very close to phase boundary

Statistical Model Results

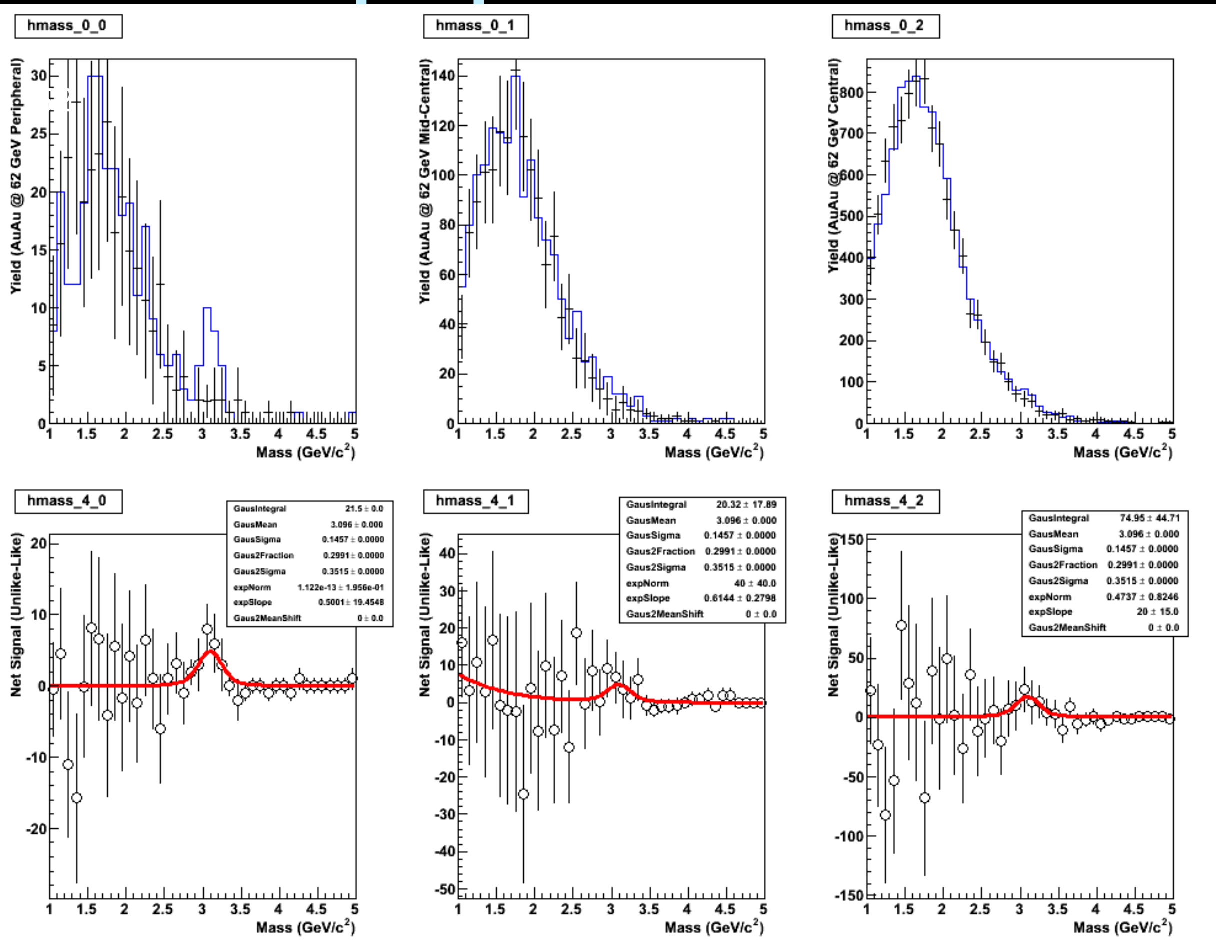
Results from different beam energies

Analysis of particle yields with statistical models

Freeze-out points reach QG phase boundary at top SPS energies



J/ψ: analyzed 25% of 62 GeV



- Recombination
  - (e.g. Rapp et al.)
    - J/ψ yield at 200 GeV is dominantly from recombination
- Predict suppression greater at 62 GeV
  - J/ψ yield down by 1/3
  - Recombination down 1/10

600 M min. bias events → 500 J/ψ ∴ measure J/ψ suppression

Key test of recombination!