PHENIX Results from the RHIC Beam Energy Scan Program

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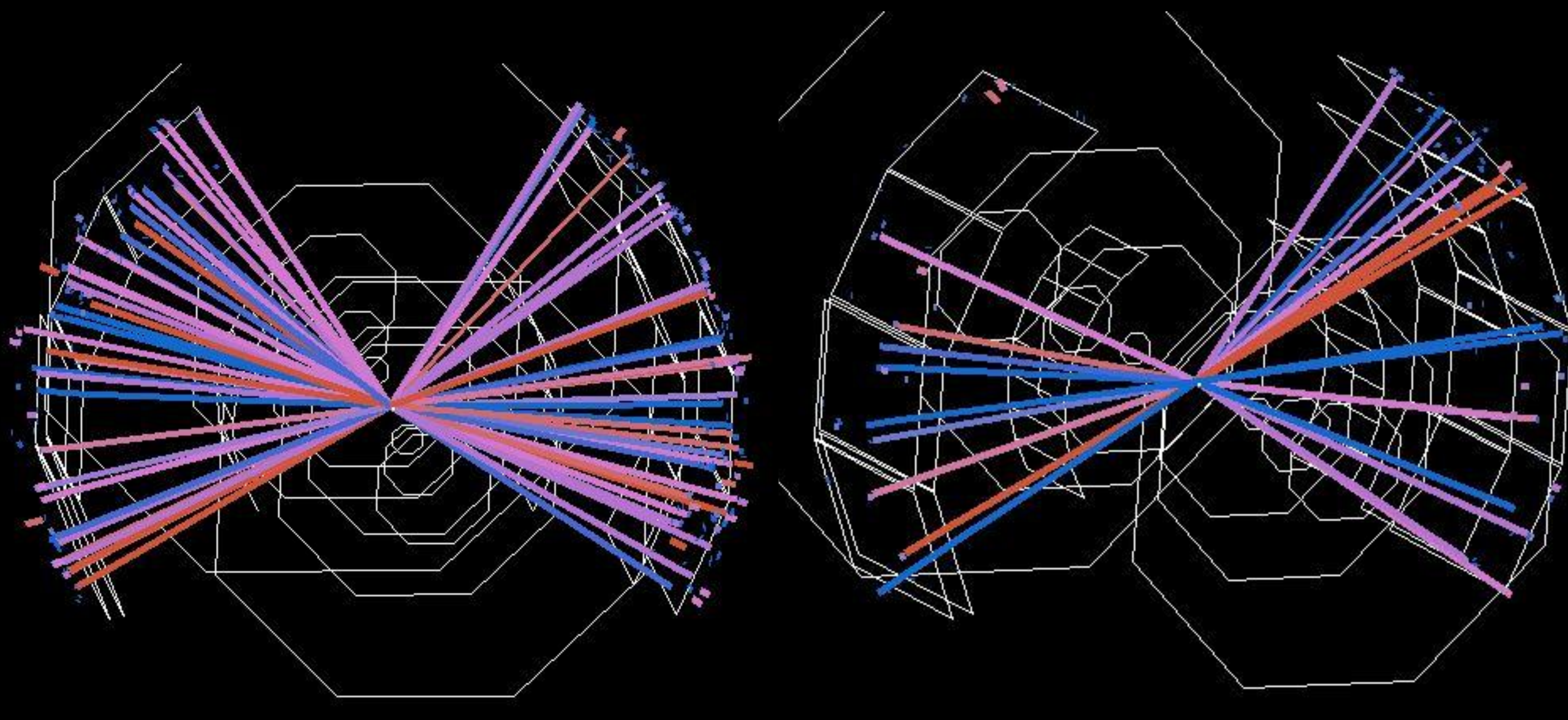
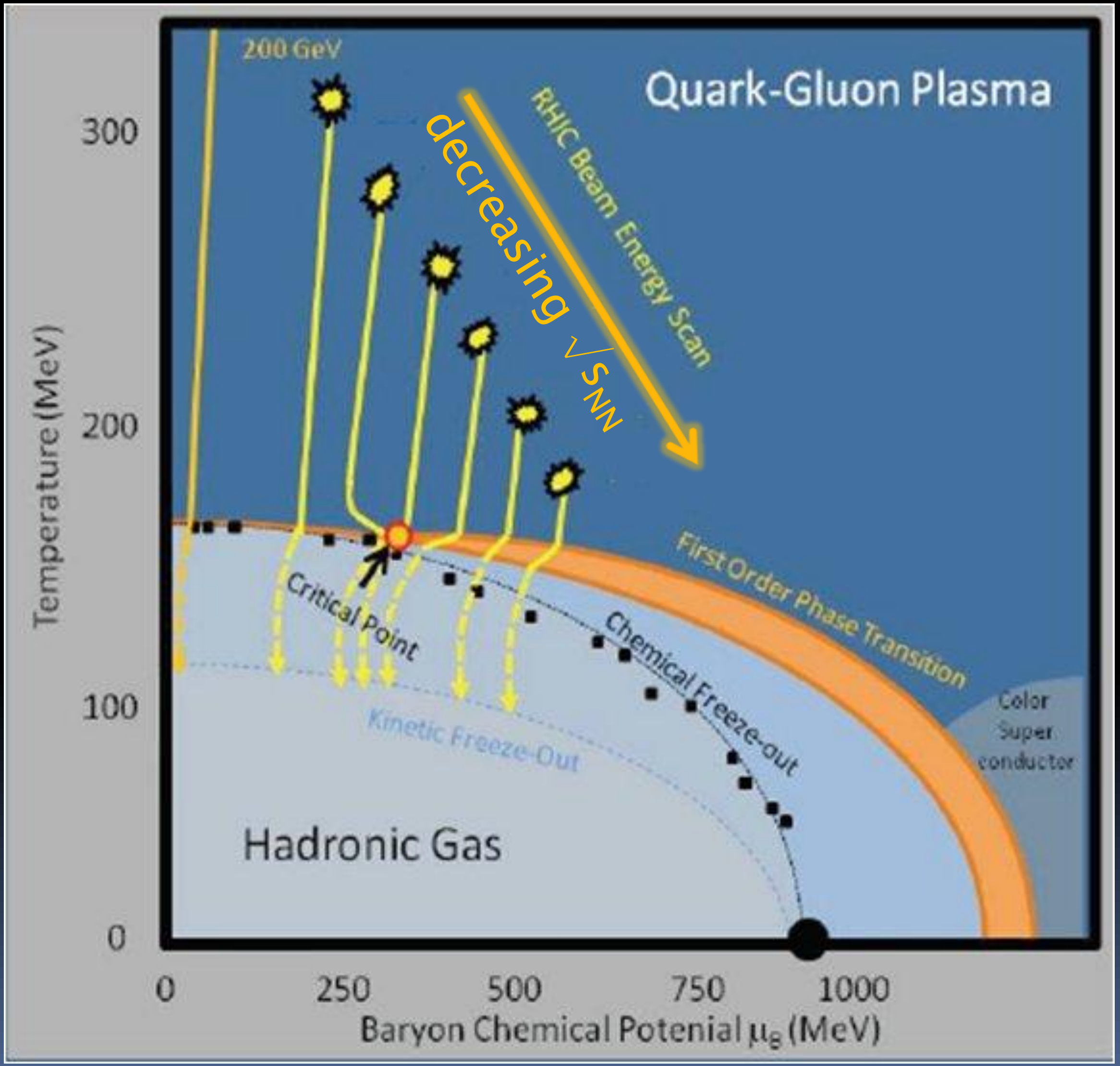


The RHIC Beam Energy Scan Program: Probing the Nuclear Matter Phase Diagram

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

Searching for signatures of the onset of deconfinement.

Searching for signatures of the critical point.



The RHIC Beam Energy Scan Program: Overview

Species: Gold + Gold

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

200 GeV (2010), 130 GeV (2001), 62.4 GeV (2010),
39 GeV (2010, 250M events), 27 GeV (2011),
19.6 GeV (2002 for 1 day, 2011 13M events),
11 GeV (2010, STAR only)
9.2 GeV (2009, short test run), 7.7 GeV (2010, 1.5M events)

Species: Copper + Copper

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

200 GeV (2005), 62.4 GeV (2005), 22 GeV (2005)

Species: Deuteron + Gold

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

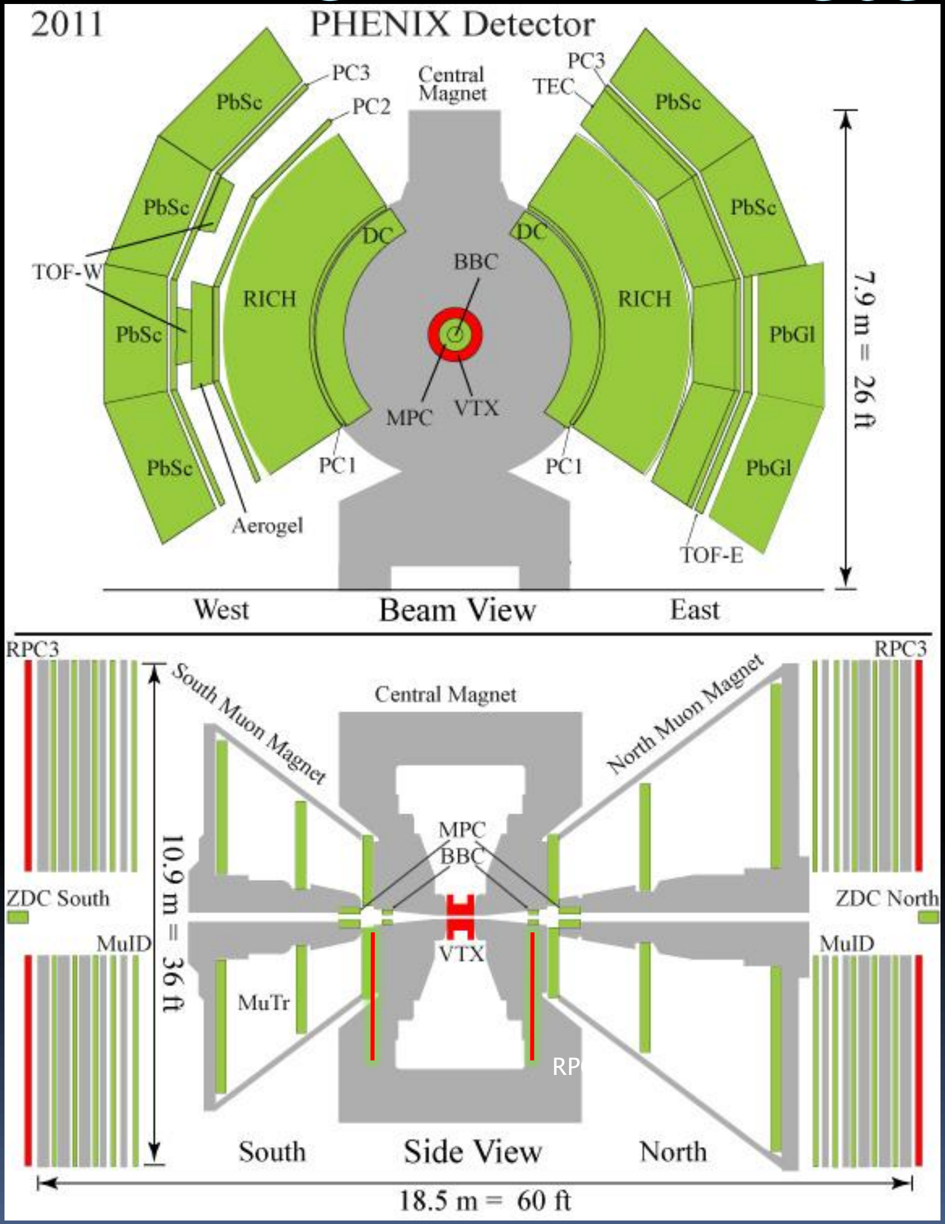
200 GeV

Species: Proton + Proton

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

500 GeV, 200 GeV, 62.4 GeV

The PHENIX Detector at RHIC



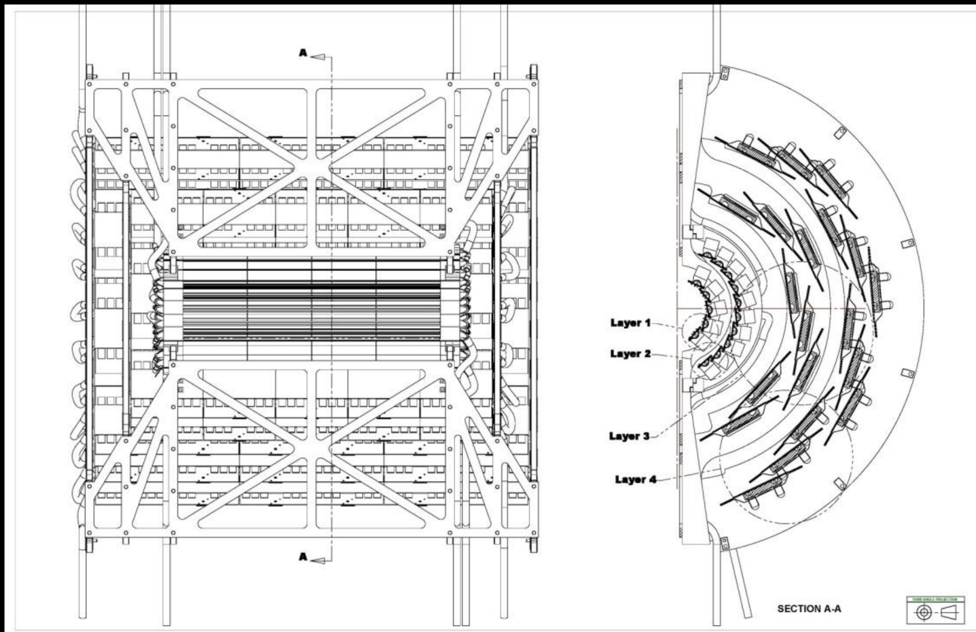
Central arms: Hadrons, photons, electrons

- $J/\psi \rightarrow e^+e^-$; $\psi' \rightarrow e^+e^-$; $\chi_c \rightarrow e^+e^-\Upsilon$;
- $|\eta|<0.35$
- $p_e > 0.2$ GeV/c
- $\Delta\phi = \pi$ (2 arms x $\pi/2$)

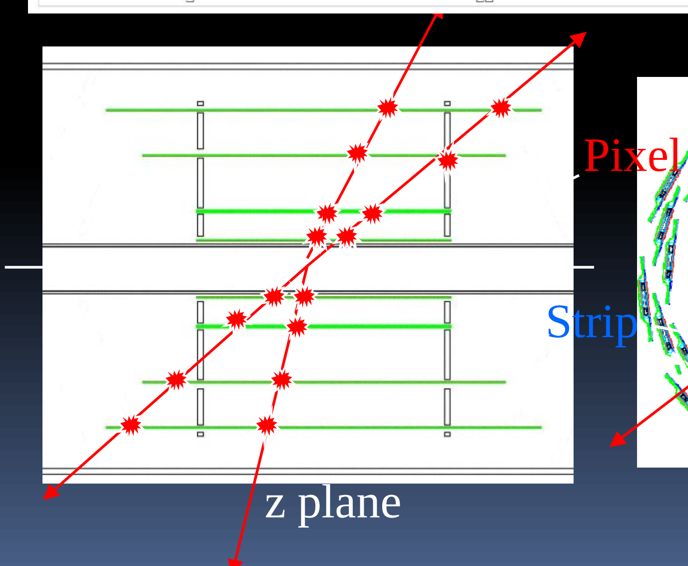
Forward rapidity arms: Muons

- $J/\psi \rightarrow \mu^+\mu^-$; $\Upsilon \rightarrow \mu^+\mu^-$
- $1.2<|\eta|<2.2$
- $p_\mu > 1$ GeV/c
- $\Delta\varphi = 2\pi$

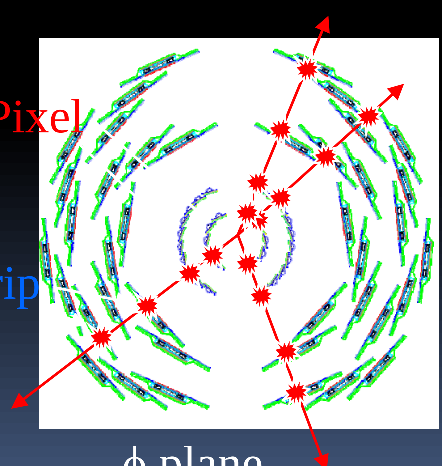
New in 2011: The VTX Detector



- ✓Fine granularity, low occupancy
  - 50μm × 425μm pixels for L1 and L2
  - R1=2.5cm and R2=5cm
- ✓ Stripixel detector for L3 and L4
  - 80μm × 1000μm pixel pitch
  - R3=10cm and R4=14cm
- ✓Large acceptance
  - $|\eta|<1.2$, almost 2π in ϕ plane
- ✓Stand-alone tracking capability



z plane



ϕ plane

Will help with background rejection at low energies

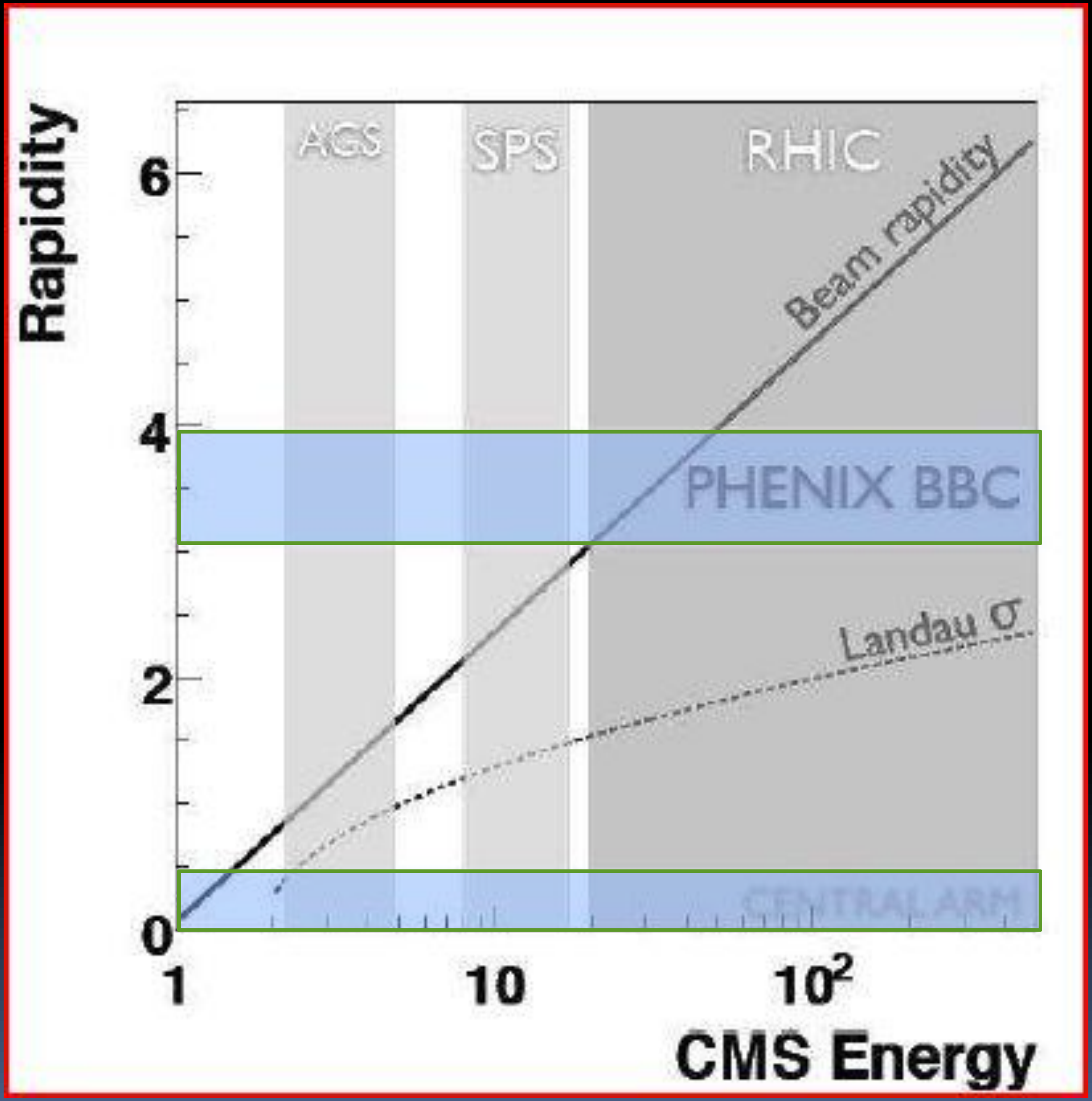
The VTX was installed in PHENIX in Nov-Dec 2010.

Triggering at Low Energy

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.

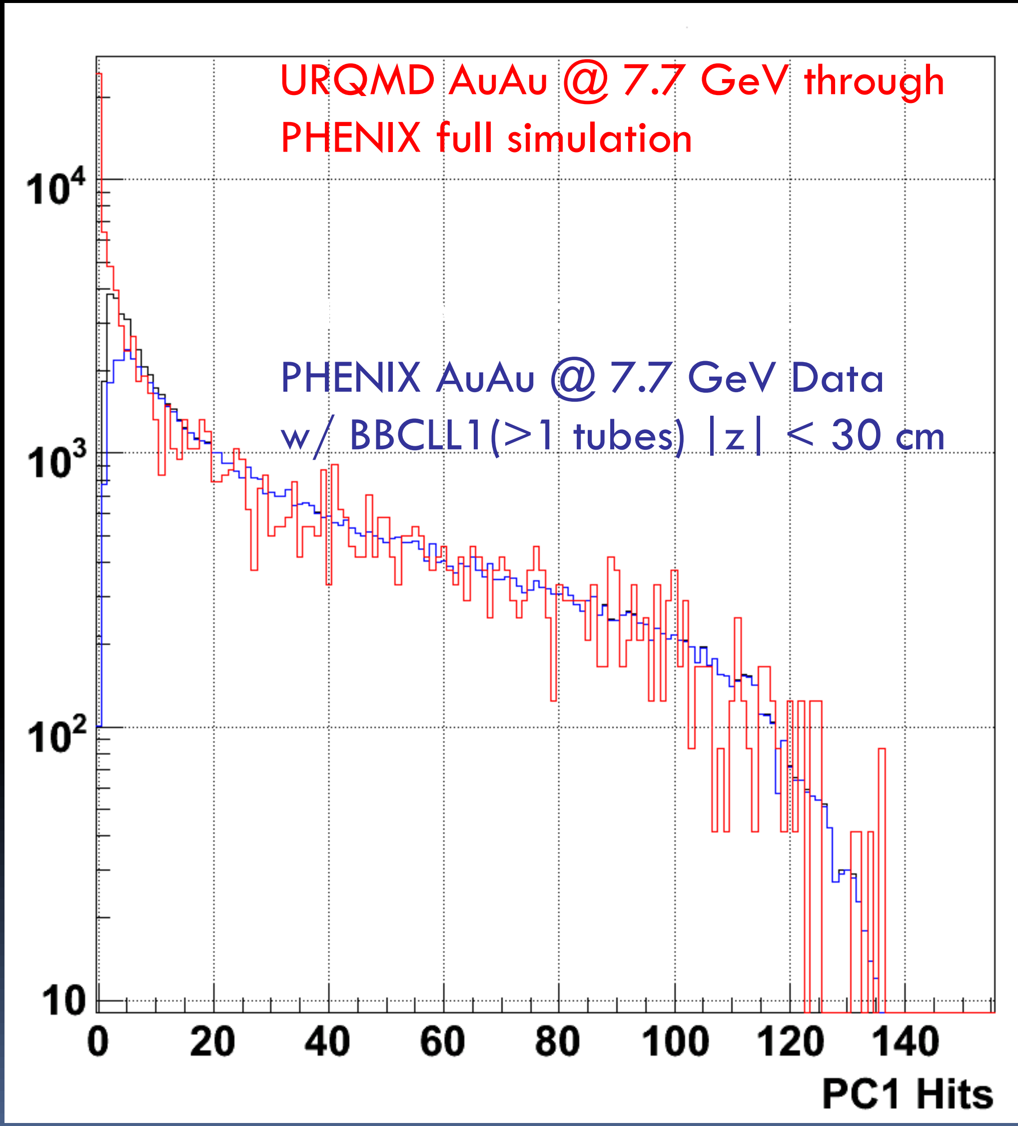
Fermi motion comes to the rescue!

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.

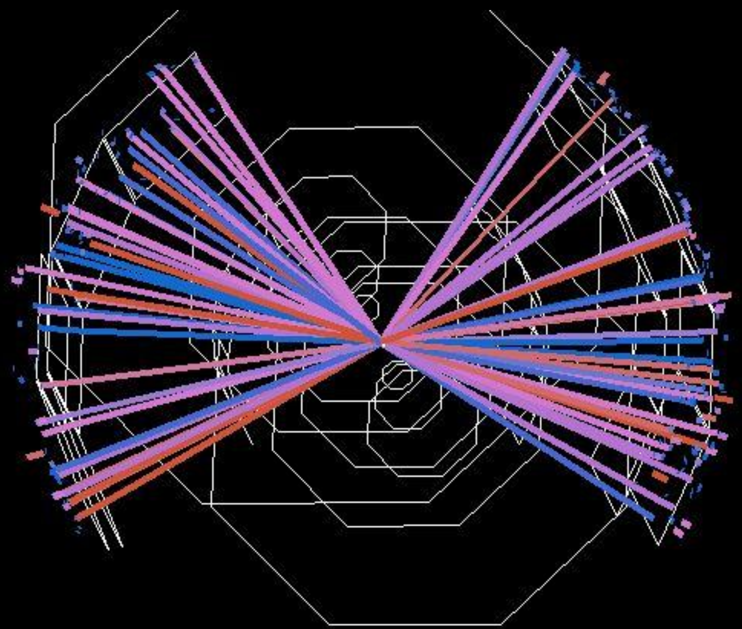
URQMD not matched to z distribution in real data.

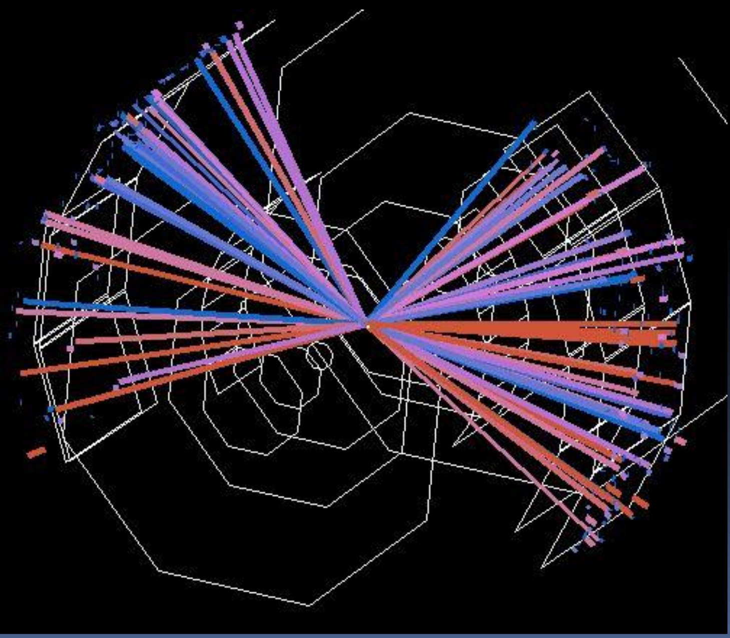
The trigger fires on 75% of the cross section.

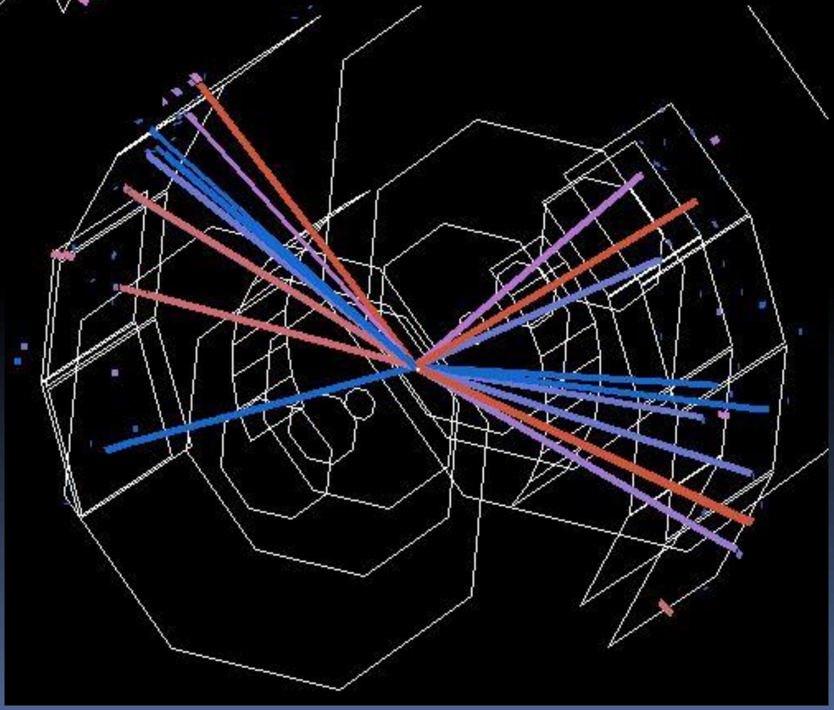
No indication of deviation of low multiplicity events from background.

Centrality determination uses the outer ring of the Reaction Plane detector: $1.5<|\eta|<2.8$

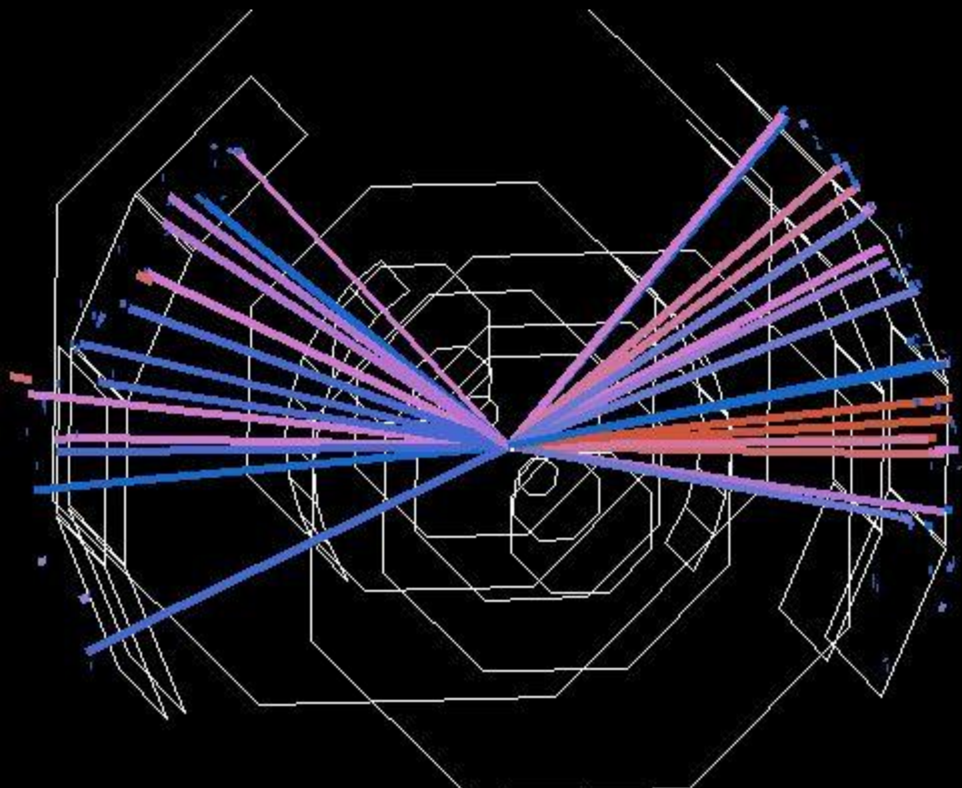
PHENIX 39 GeV Au+Au Event Displays

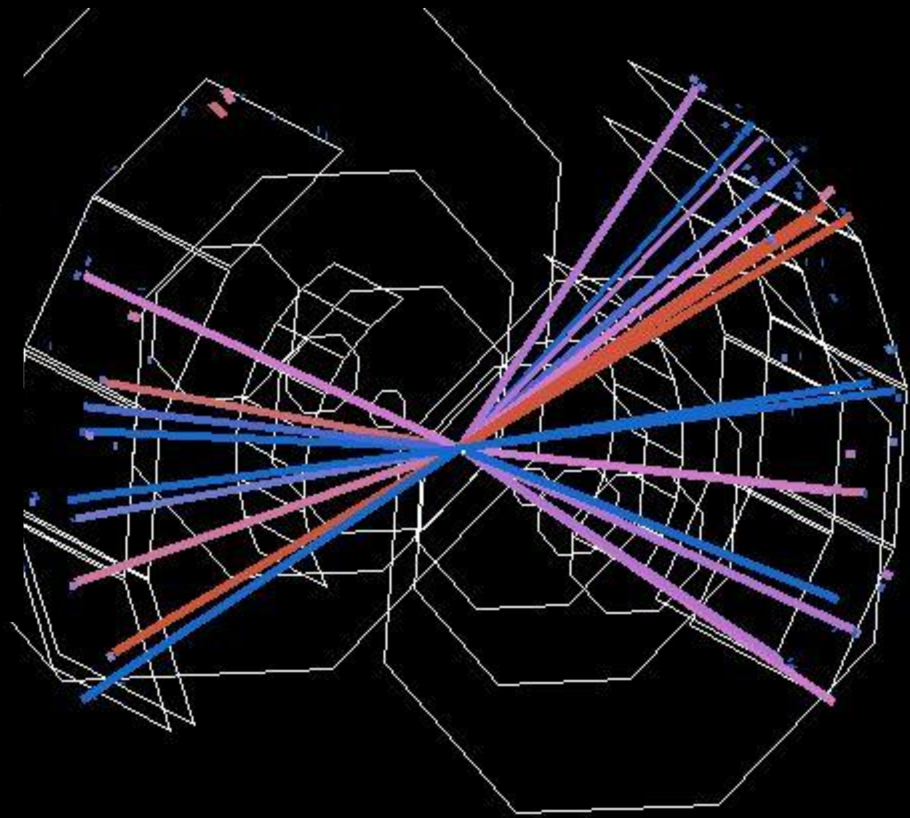




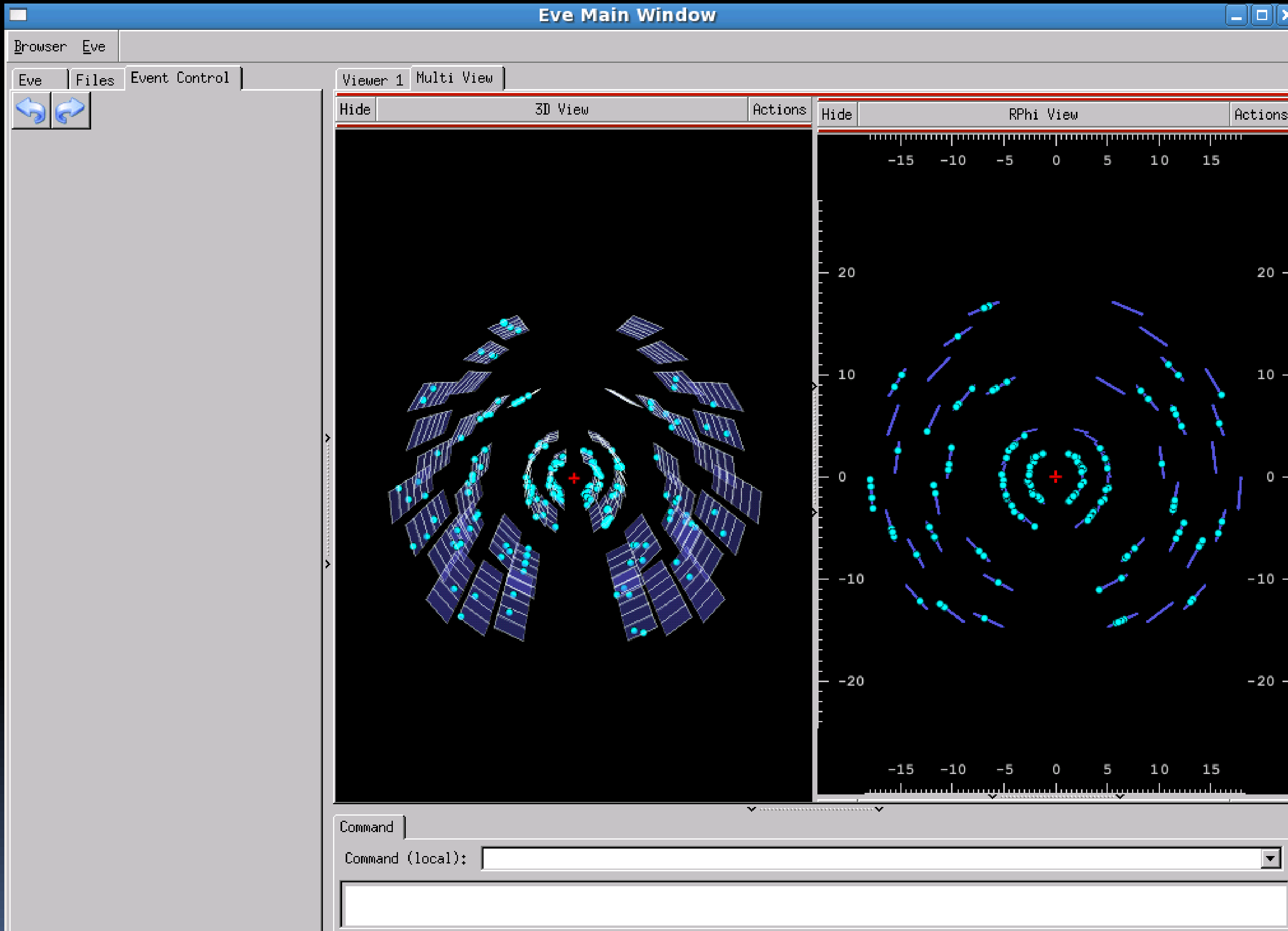


PHENIX 7.7 GeV Au+Au Event Displays



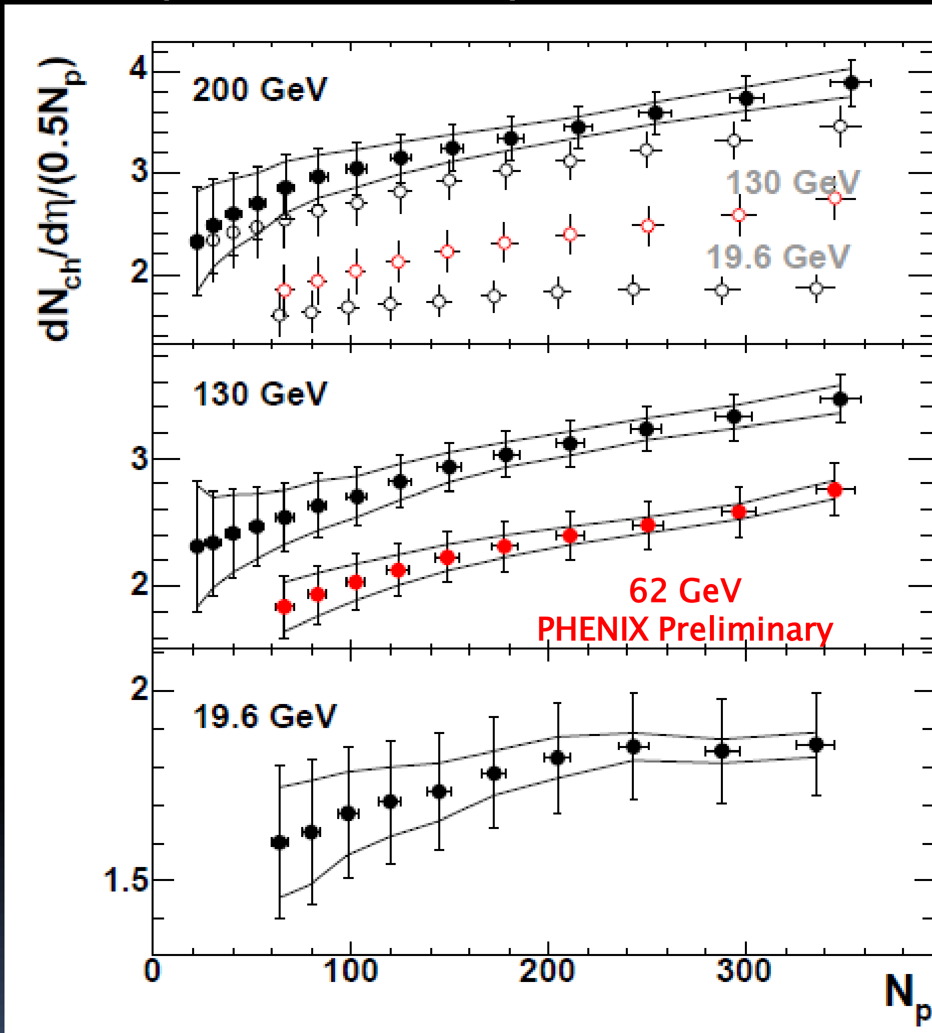


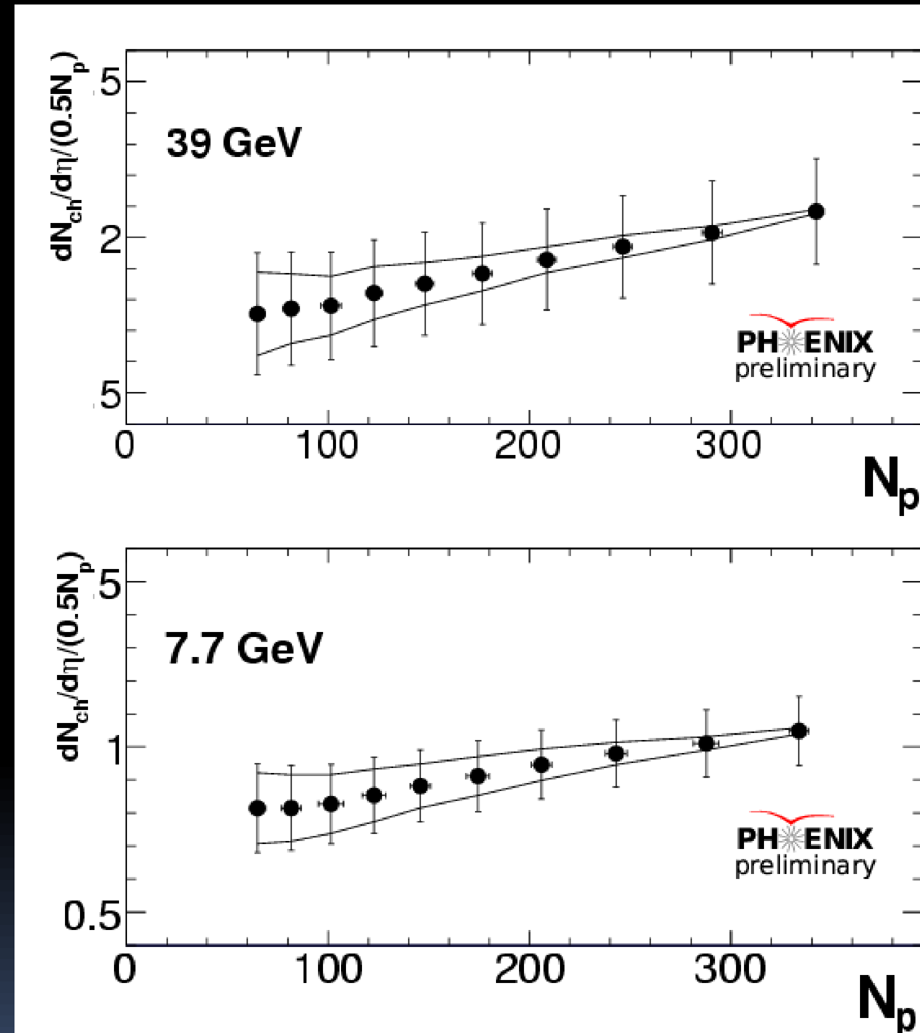
VTX Event Display – 19.6 GeV Au+Au



Au+Au Charged Particle Multiplicity

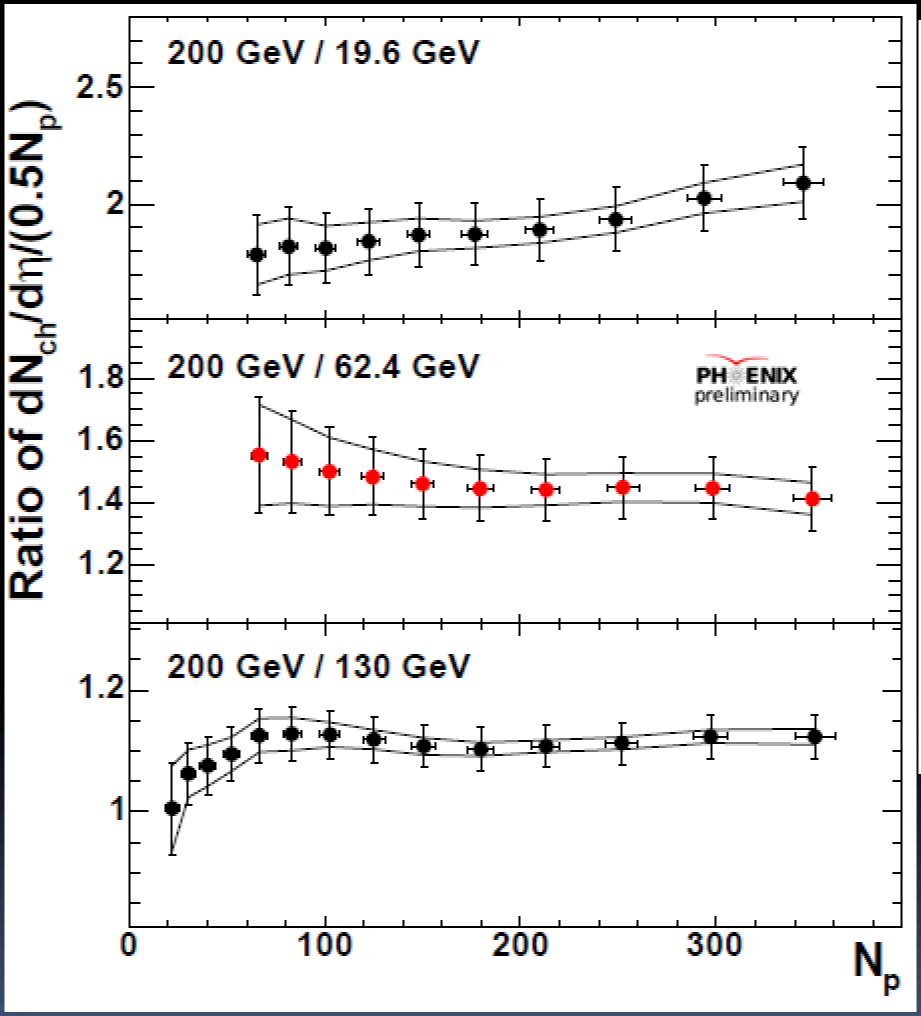
Black points from Phys. Rev. C71 (2005) 034908

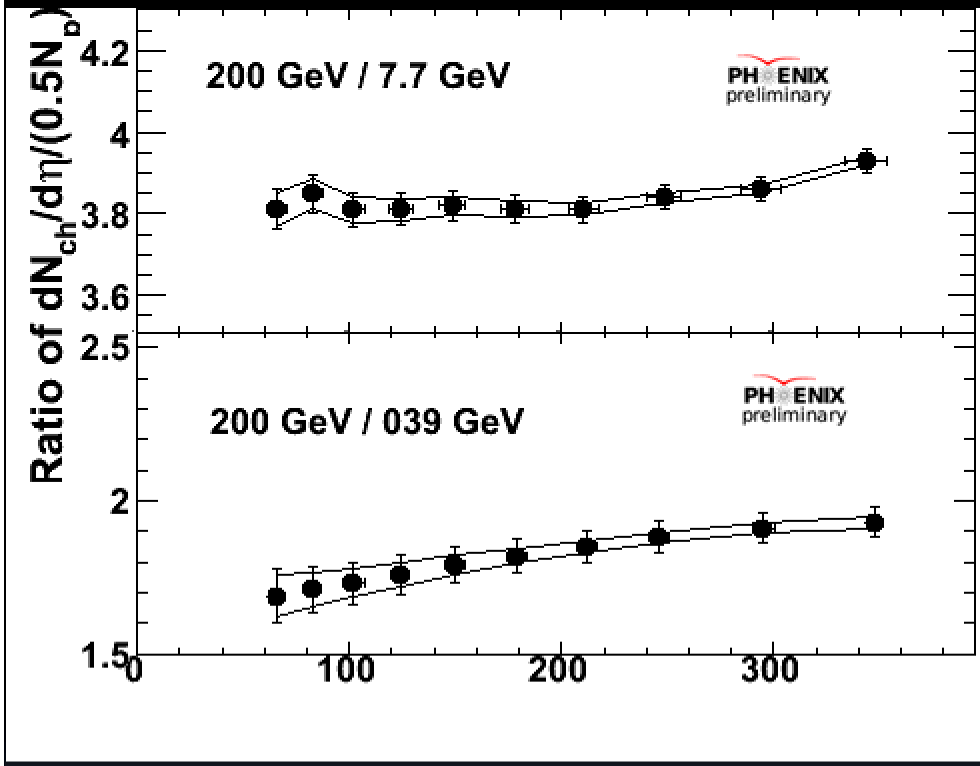




Error bars represent the systematic errors. The lines represent the “tilt” error due to the uncertainty in the trigger cross section.

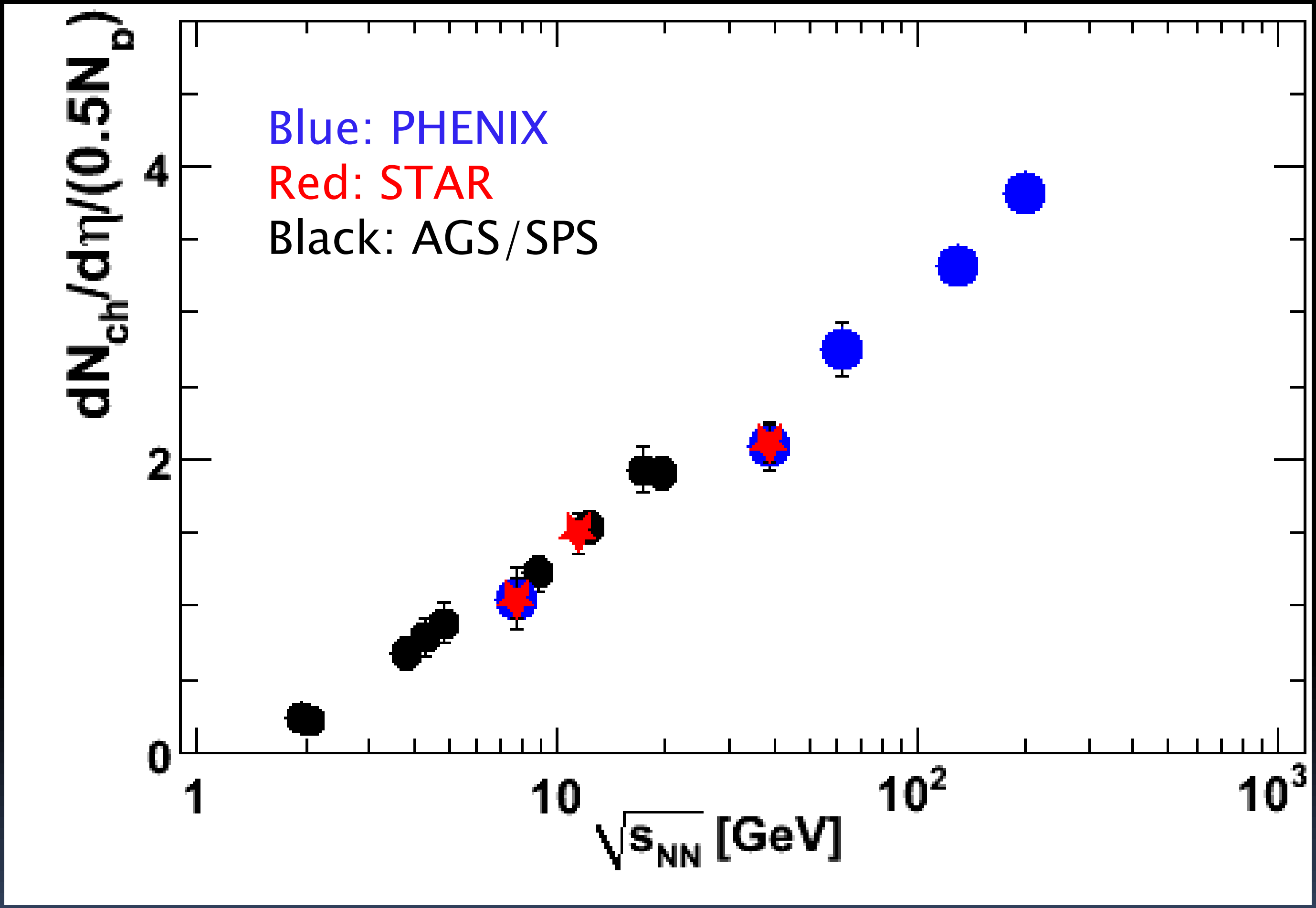
Au+Au Charged Particle Multiplicity Ratios





There is relatively little variation in the centrality-dependent shape of the multiplicity from 200 to 7.7 GeV.

Charged Particle Multiplicity: Excitation Function



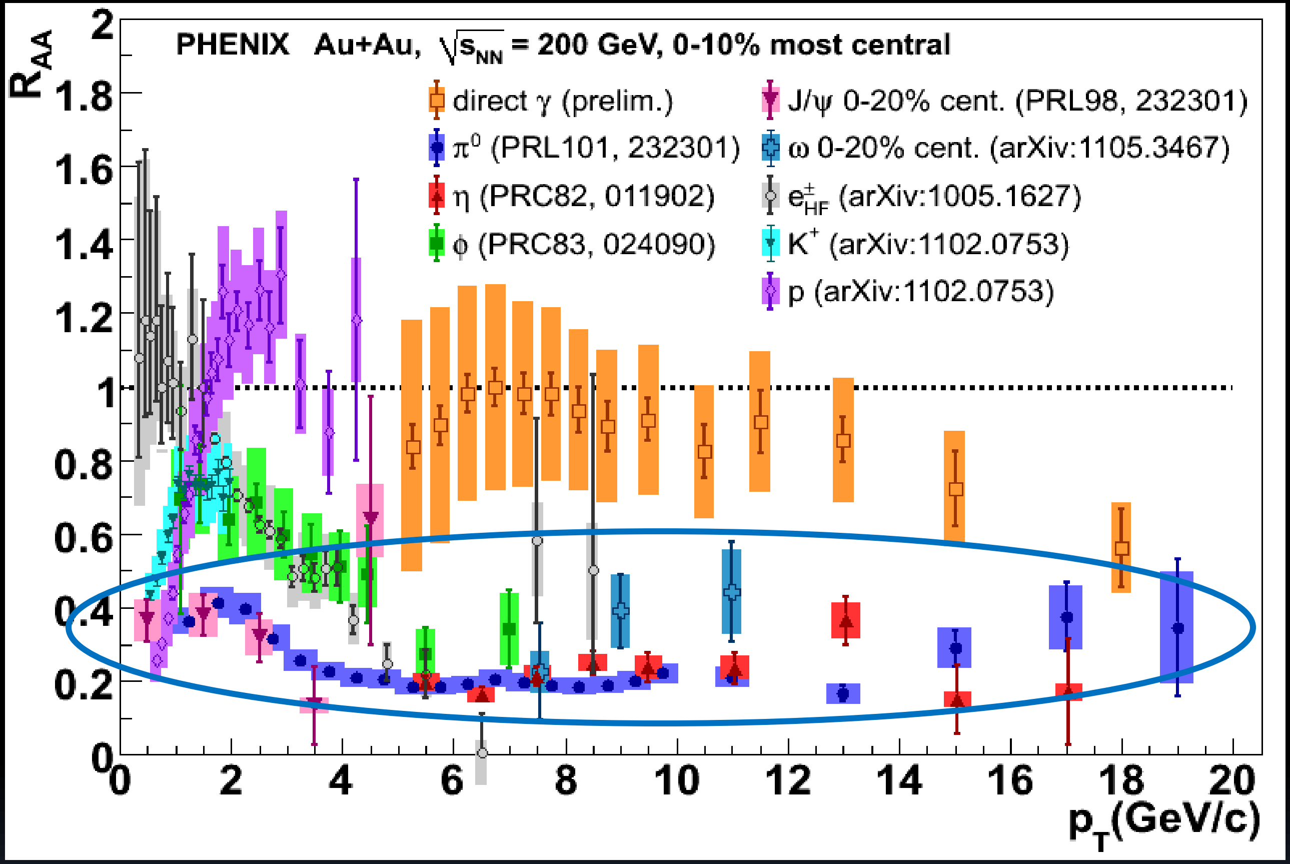
The multiplicity per participant pair increases linear with log(sqrt(s_{NN})).

PHENIX and STAR results from the Run-10 RHIC beam energy scan are in agreement.

Searching for the Onset of Deconfinement: Energy Loss Measurements

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

PHENIX R_{AA} Measurements in 200 GeV Au+Au Collisions



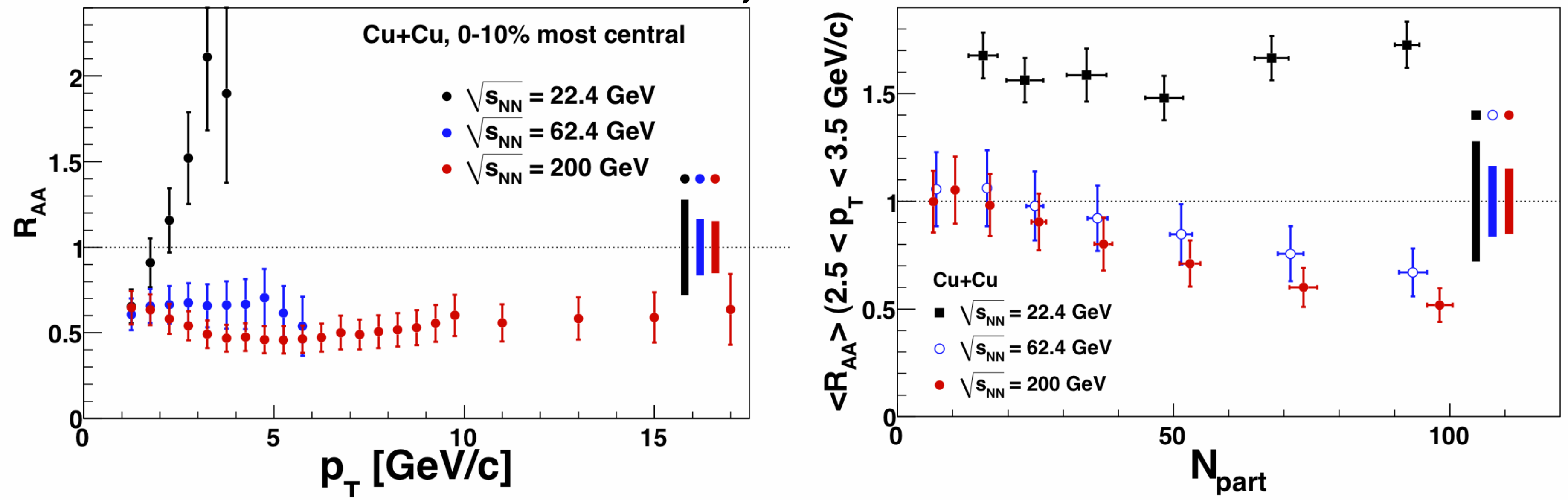
From the 200 GeV Au+Au π^0 measurement:

- 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

PHENIX π^0 Energy Loss Measurements in Cu+Cu Collisions

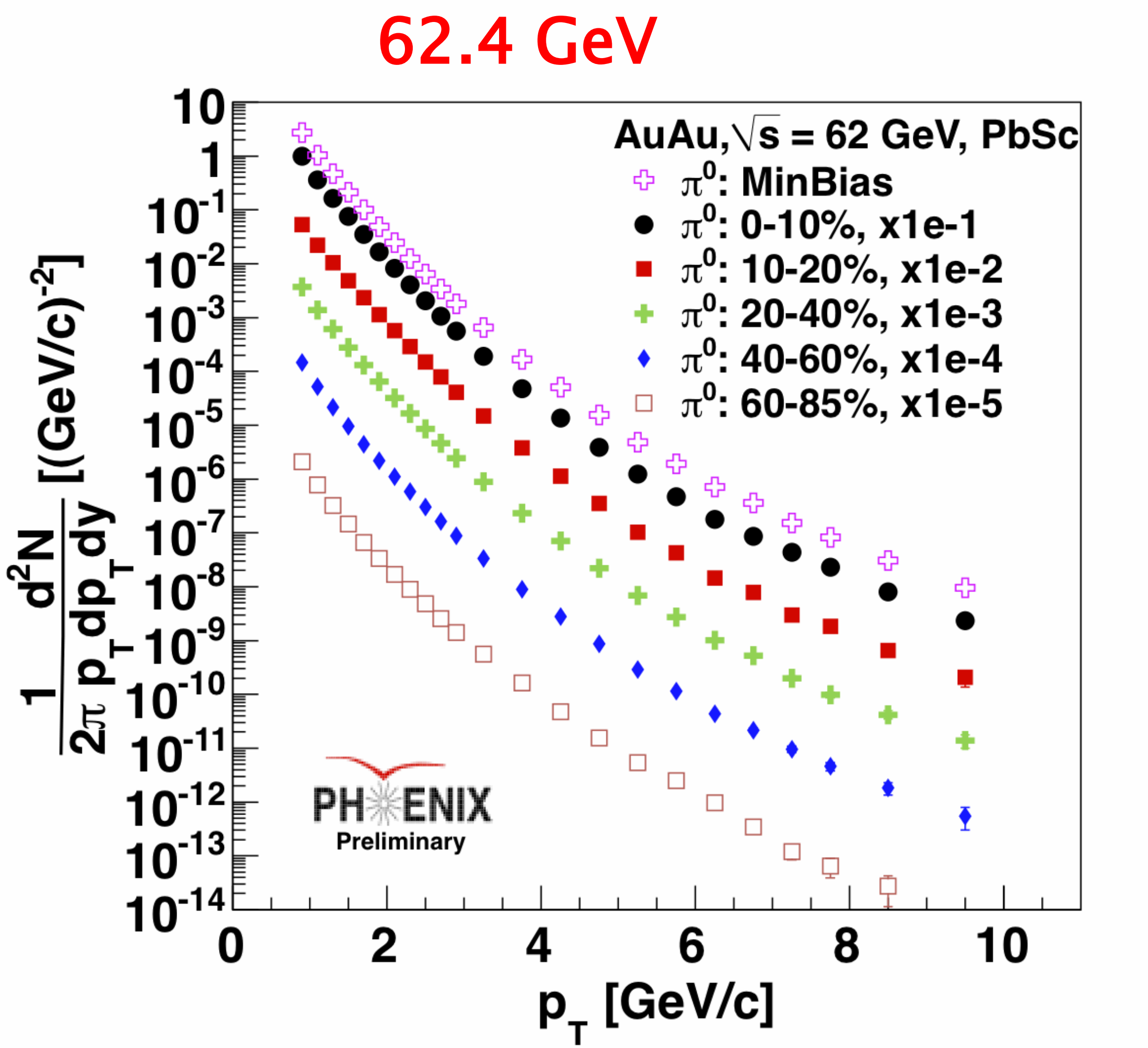
PRL101, 162301



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

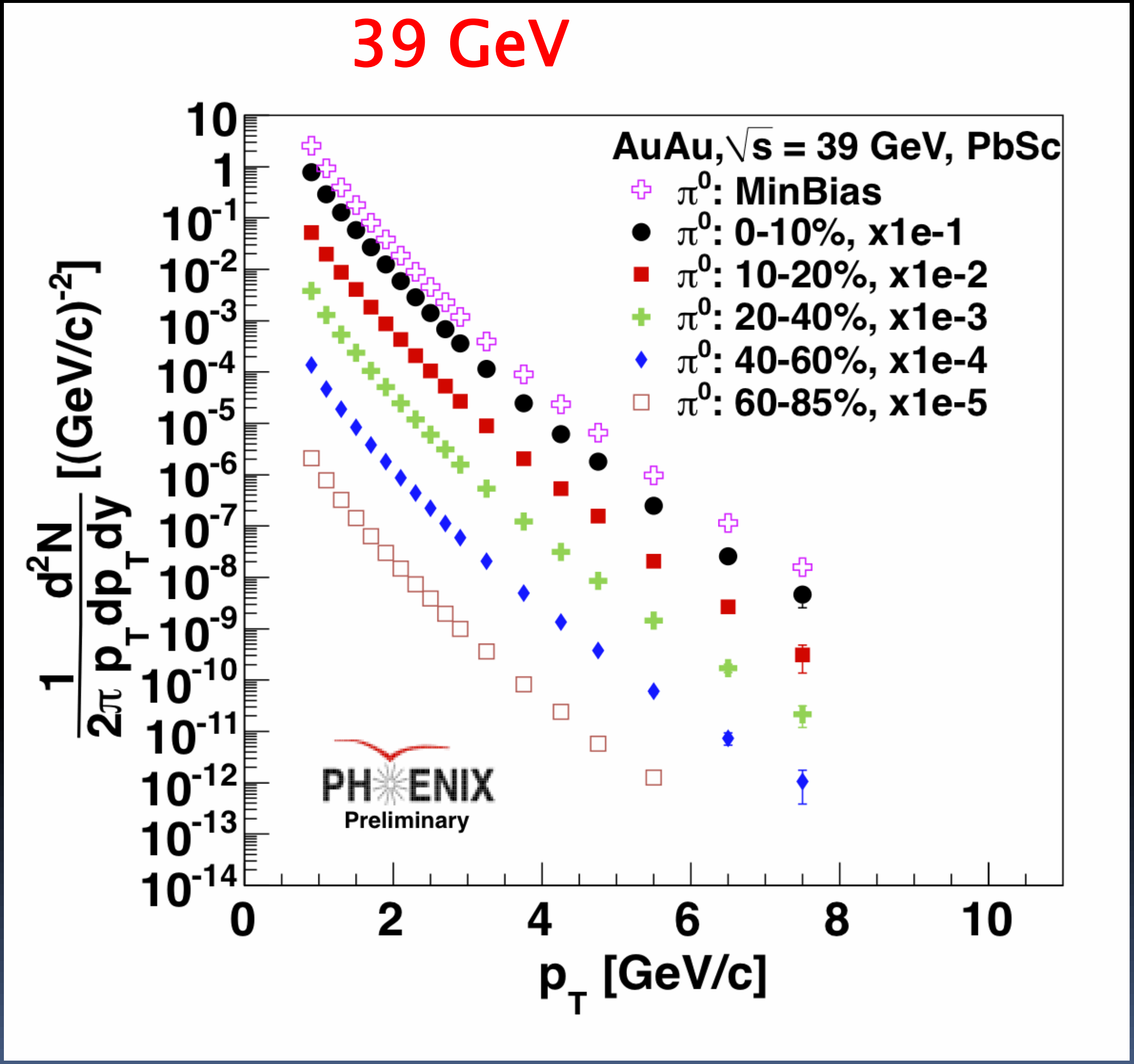
π^0 invariant yields: Au+Au Collisions at 62.4 GeV



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

- Running $\alpha(Q^2)$
- 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 :

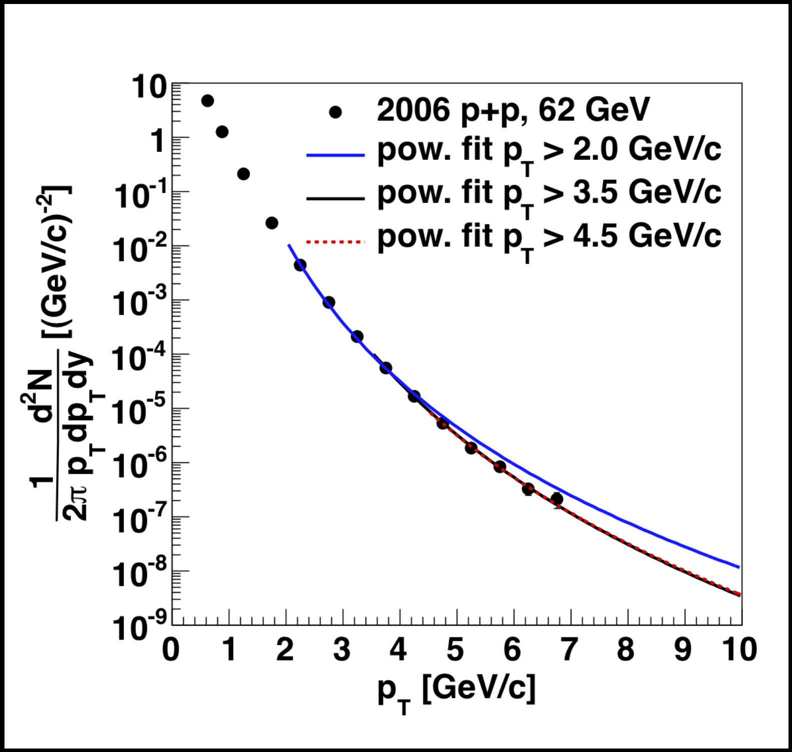
$$f(x) = \frac{A}{(p_T)^n},$$

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

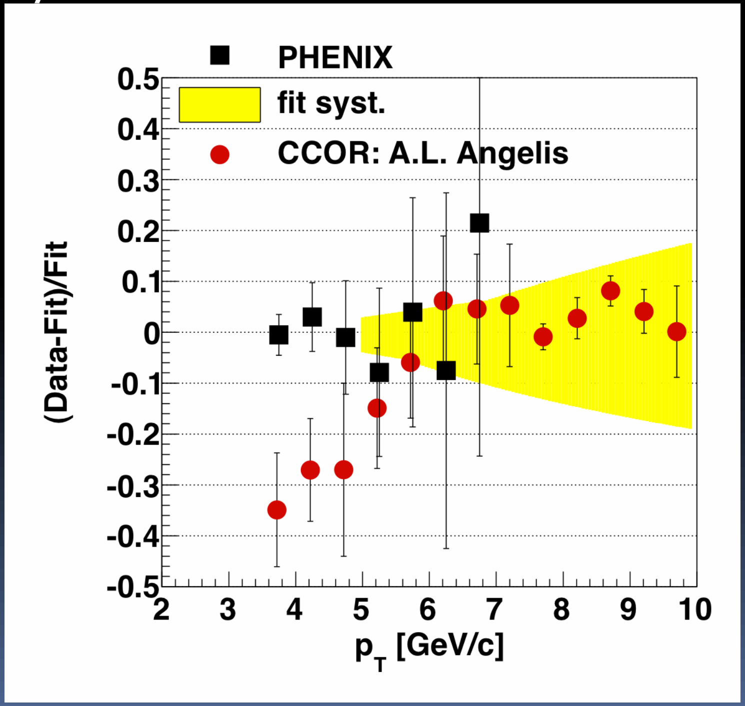
$n_{62GeV} = 10.9 \pm 0.03$

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

62.4 GeV p+p reference extrapolation

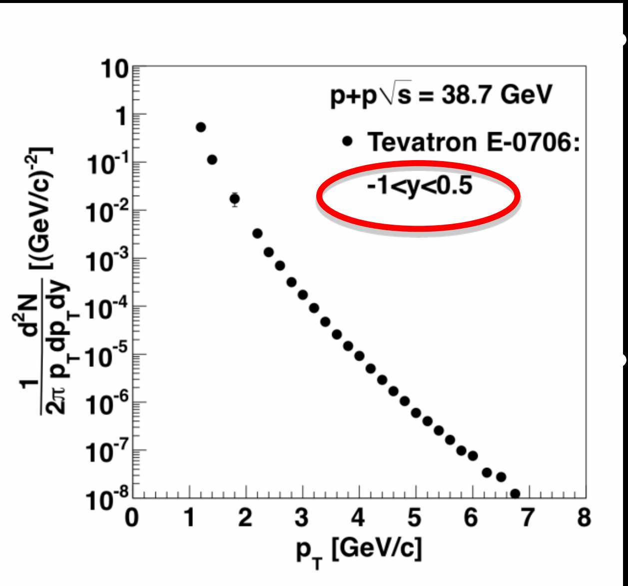


- Data from PHENIX for p+p collisions are available up to $p_T < 7$ GeV/c
- To extrapolate to higher p_T points, a power-law function was used:
  - The limit of the fits is important and contributes to the systematic errors.

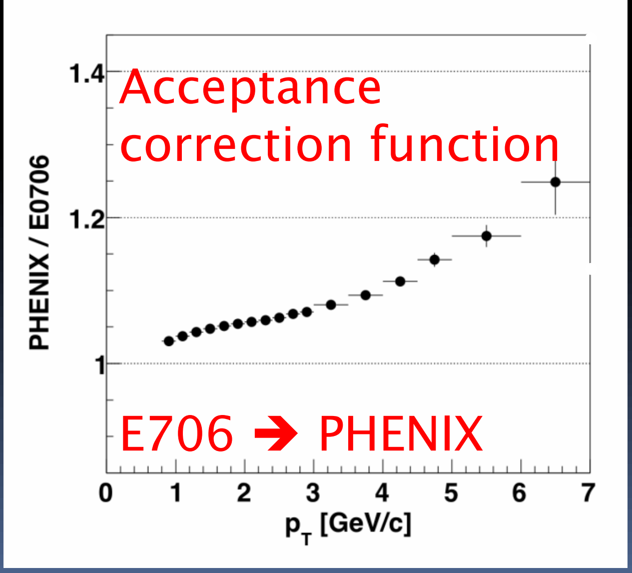


- The systematic uncertainty is calculated from the errors of the power-law fit
- It agrees well with the CCOR data (ISR) in p_T 7-10 GeV/c region

39 GeV p+p reference

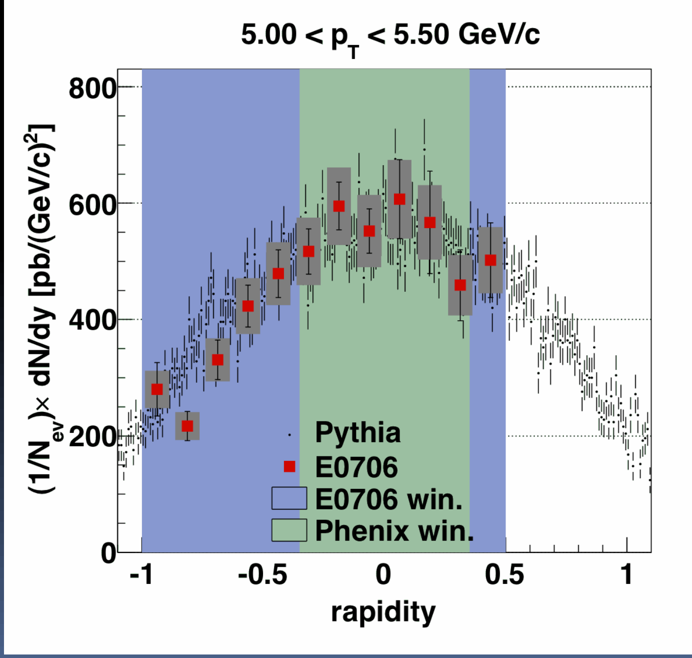


- p+p data are measured only in the fixed-target experiment E706 at the Tevatron at a beam energy of 800 GeV. (**Phys.Rev.D68:052001,2003**)
- The E706 has a different rapidity acceptance:
  $-1.0 < y < 0.5$ (PHENIX $|y|<0.35$).

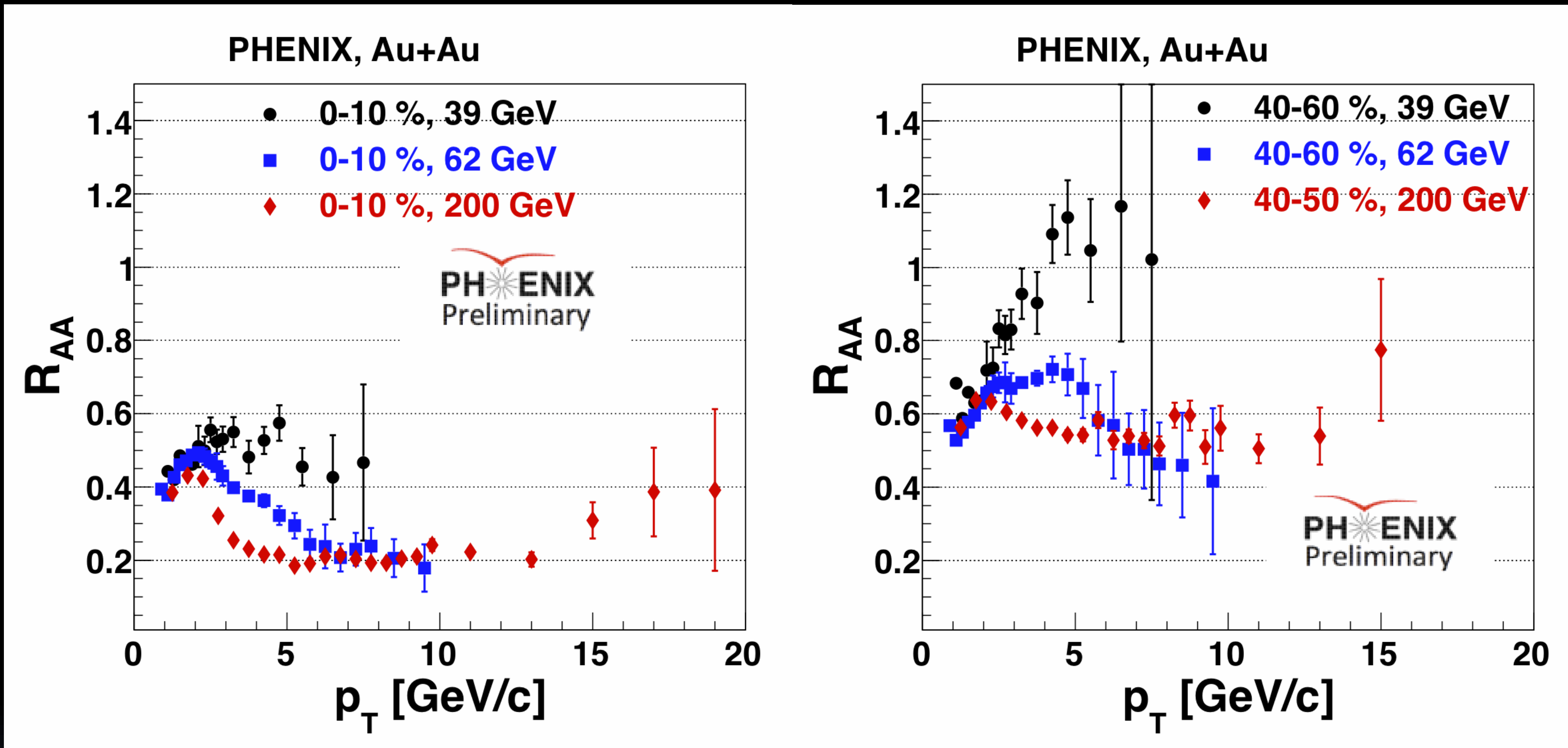


Acceptance correction based on a PYTHIA8 simulation.

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



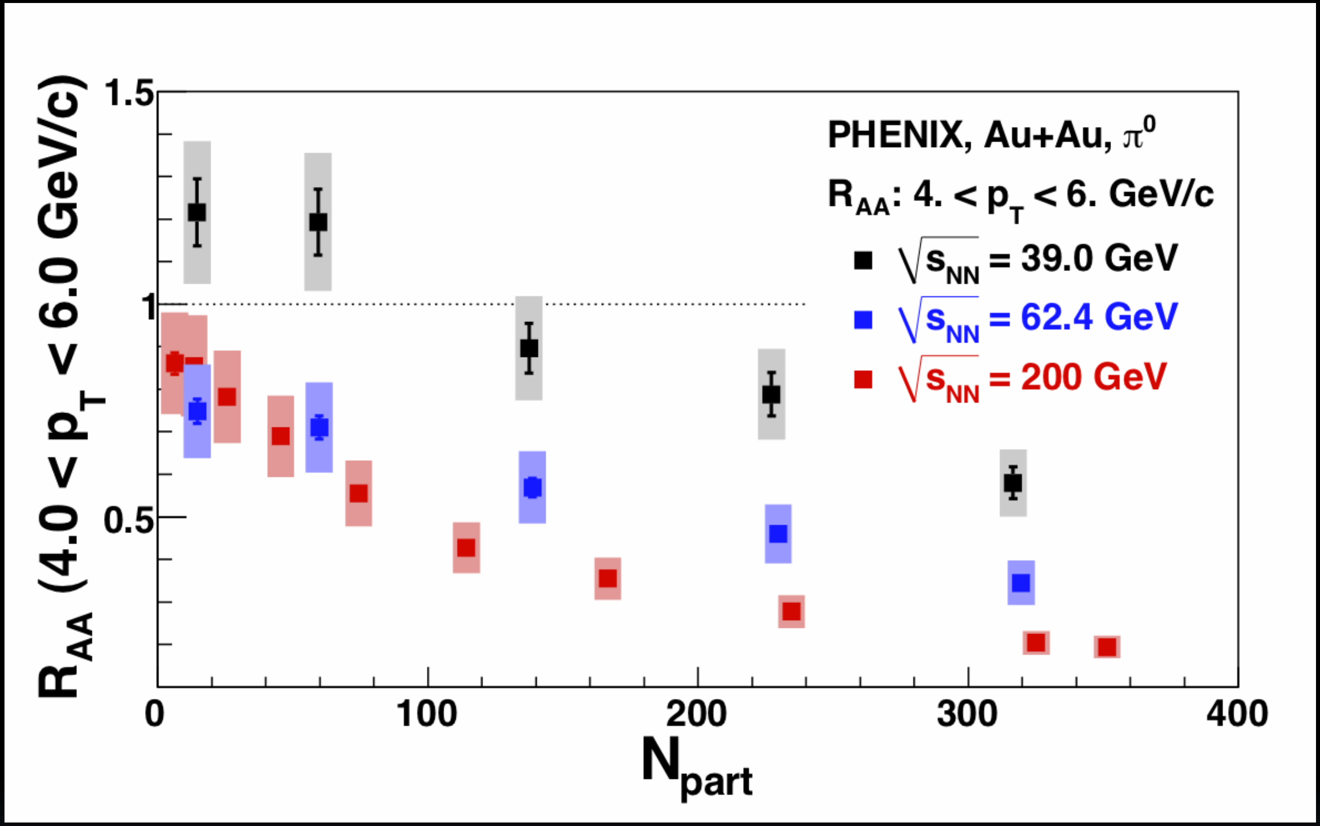
π^0 R_{AA} in Au+Au at 39 and 62 GeV



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.

π^0 R_{AA} : Centrality Dependence



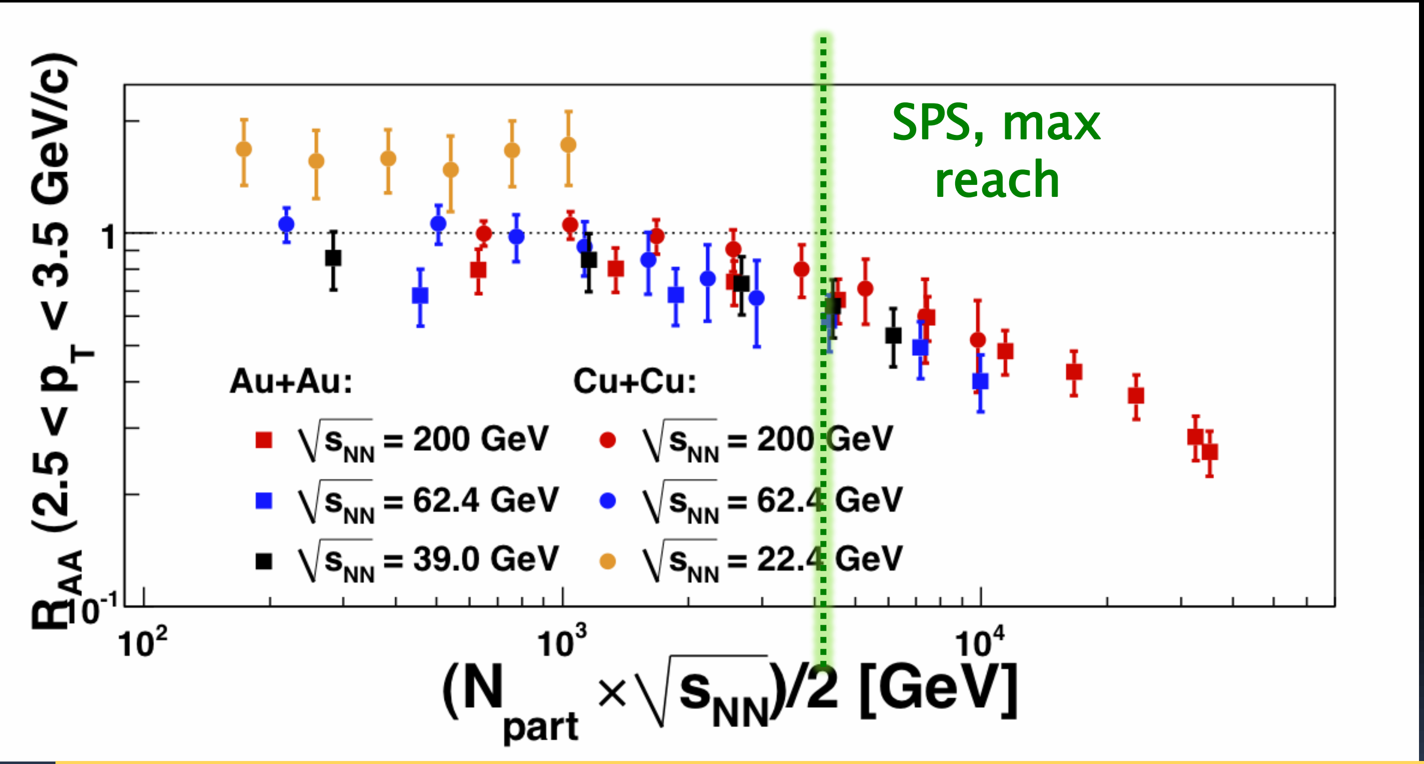
- Large suppression is observed at 200 and 62 GeV.
- 39 GeV Au+Au shows suppression only for N_{part}>100

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

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

System size:

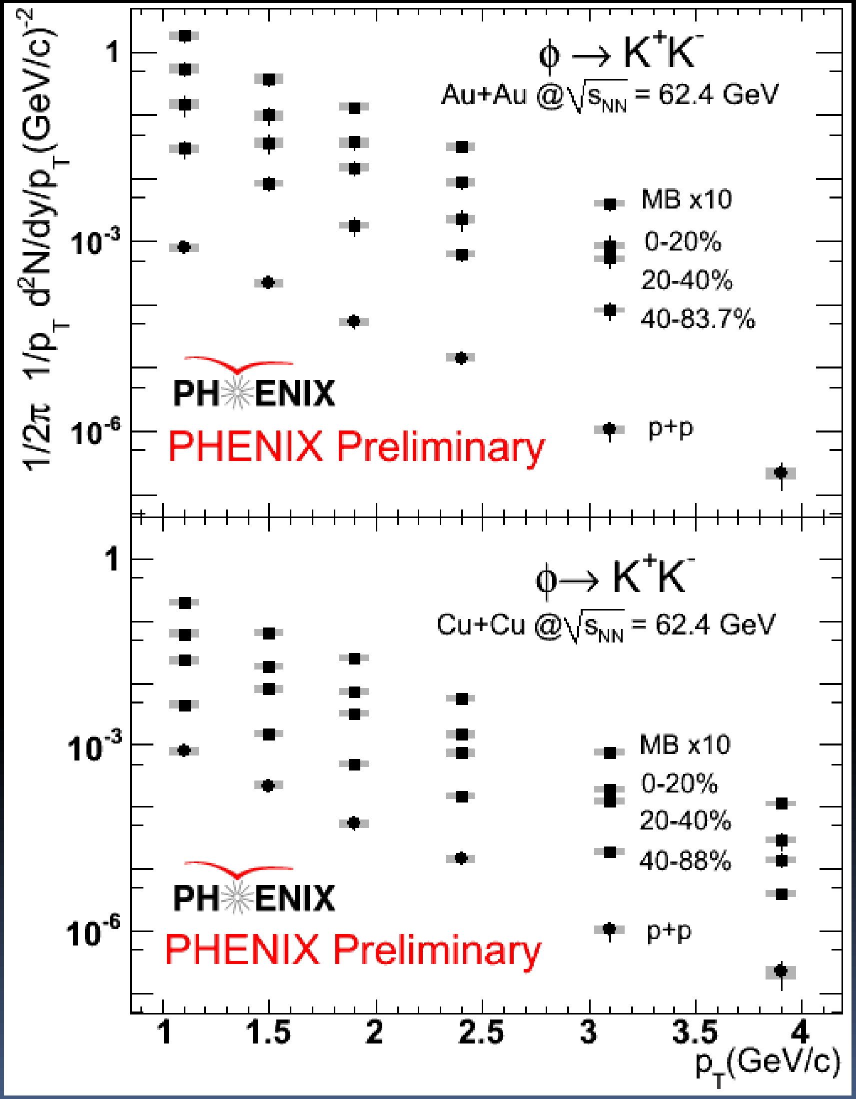
- Circles: Cu+Cu
- Squares: Au+Au



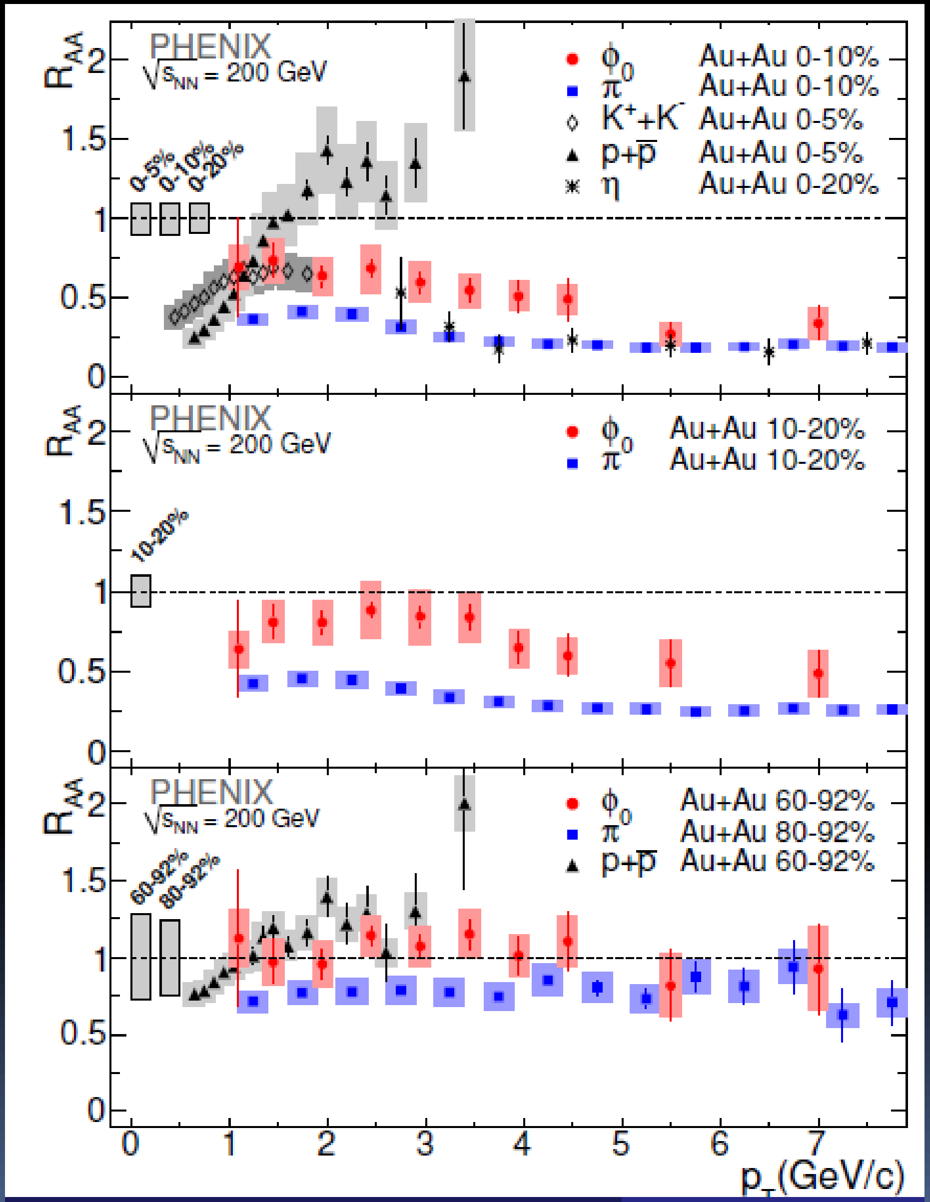
The R_{AA} values seem to have the same trend. But, the scaling does not work for all p_T ranges.

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

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



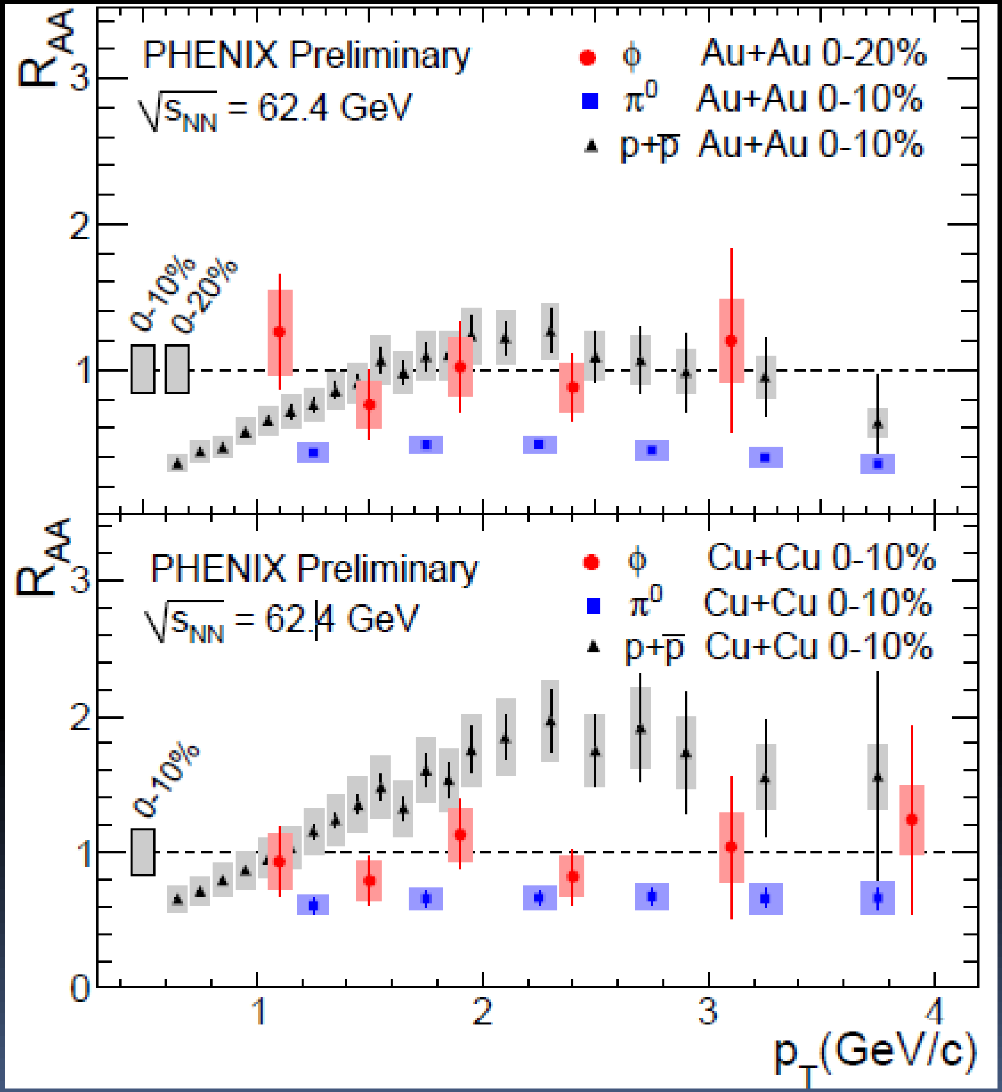
$\phi \rightarrow K^+K^-$ R_{AA} in 200 GeV Au+Au Collisions



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

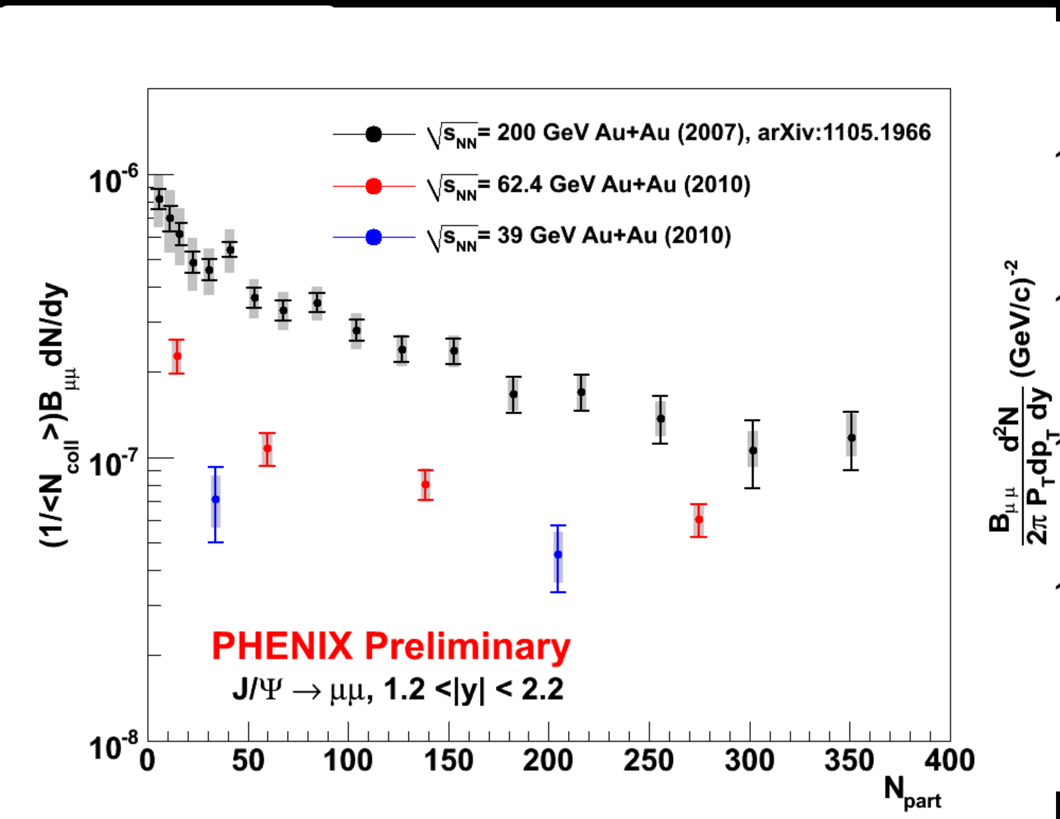
The R_{AA} of the ϕ lies between that of the proton and the π^0.

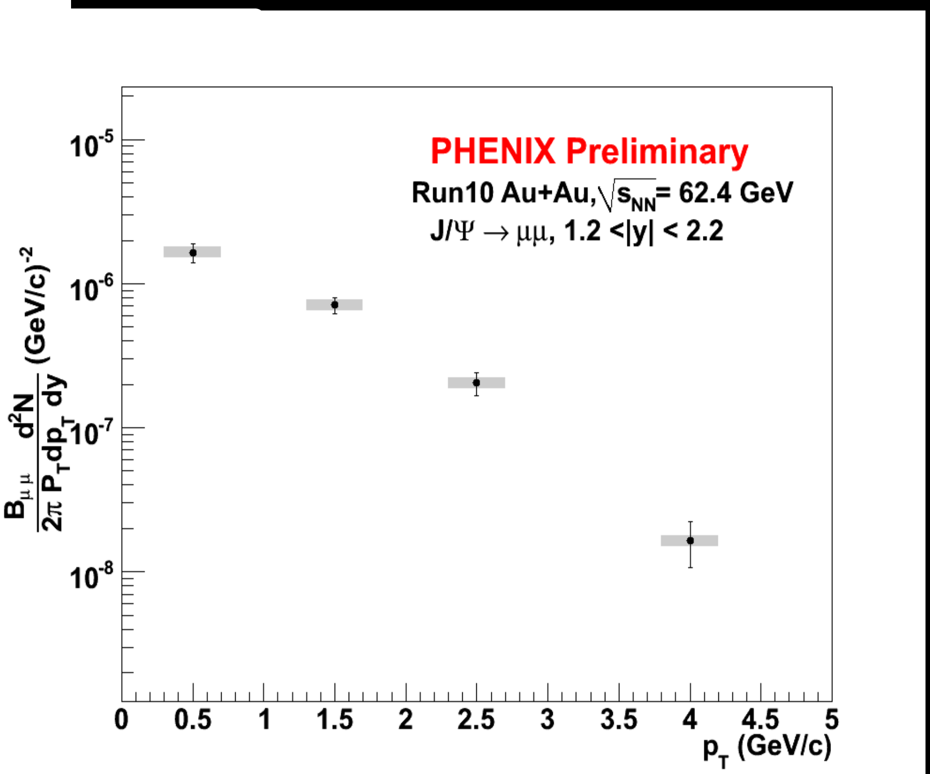
$\phi \rightarrow K^+K^-$ R_{AA} in 62.4 GeV Au+Au Collisions



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.

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

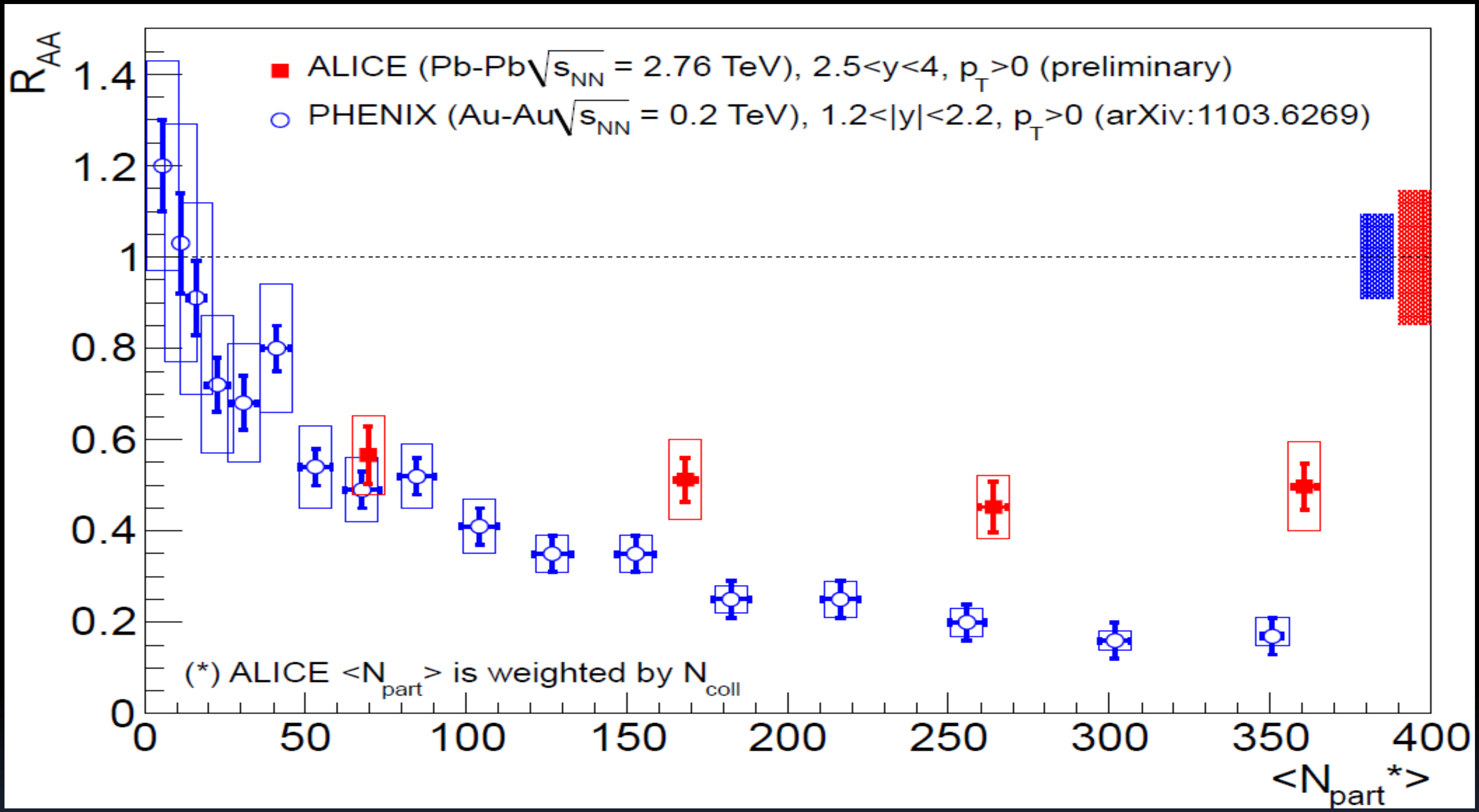




In 2010, PHENIX collected 700M (250M) MB events from 62.4 GeV (39 GeV) Au+Au collision.

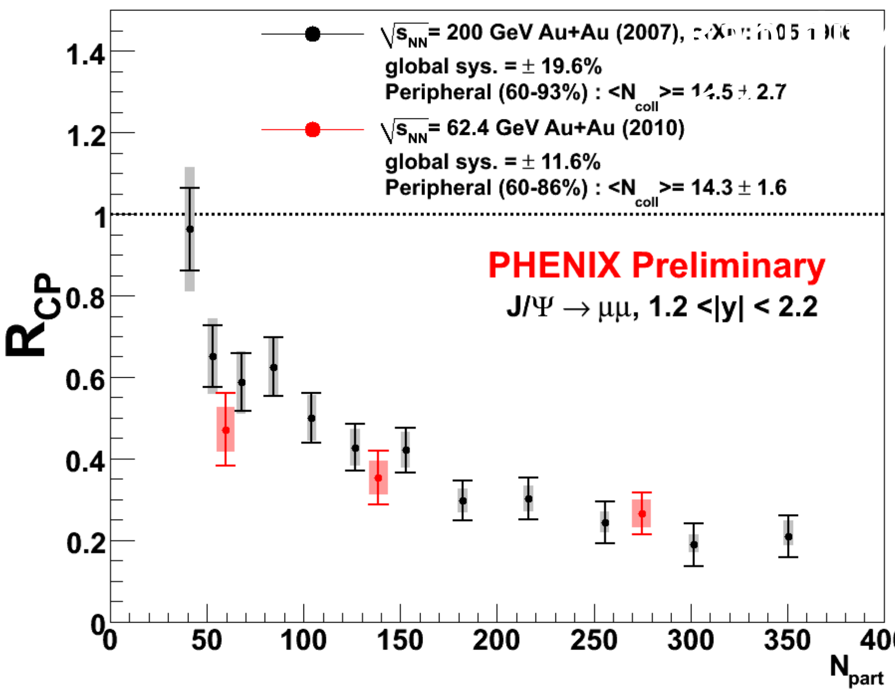
Rapidity 1.2 <|y| <2.2

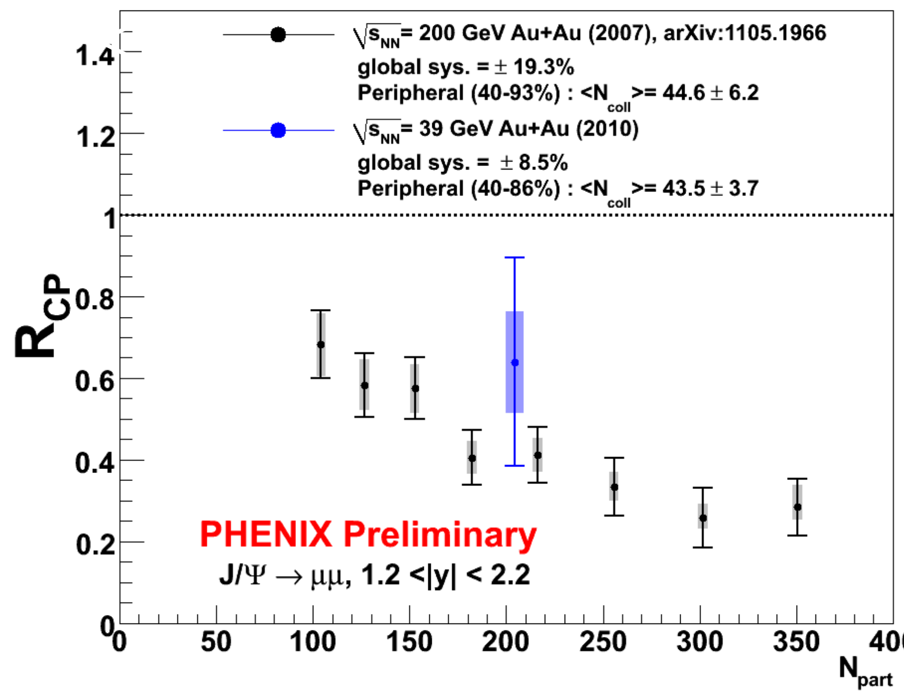
Energy Dependence of J/ψ Suppression



Less suppression is observed in central collisions at LHC energies.

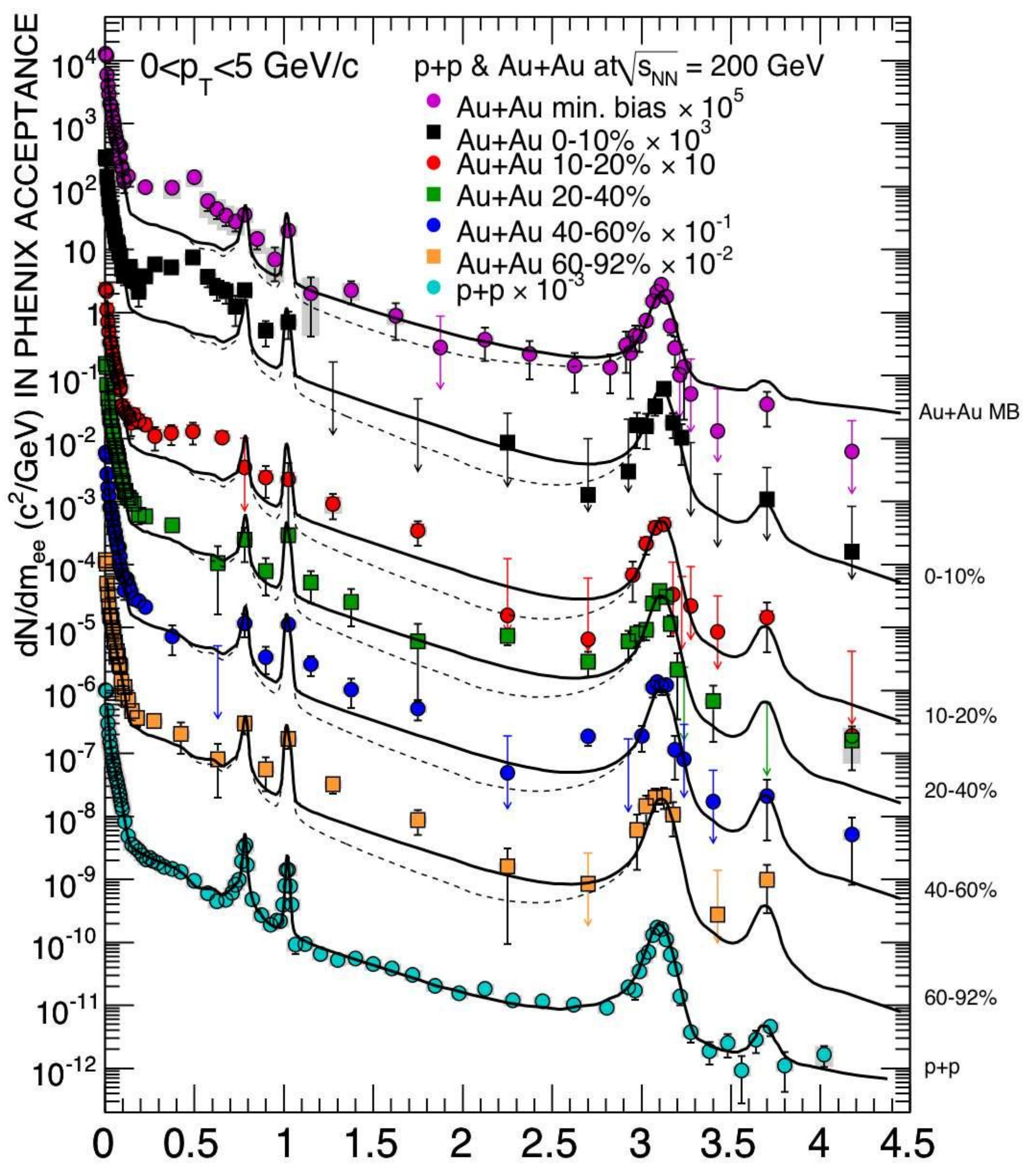
Energy dependence of J/ ψ R_{CP}





- 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



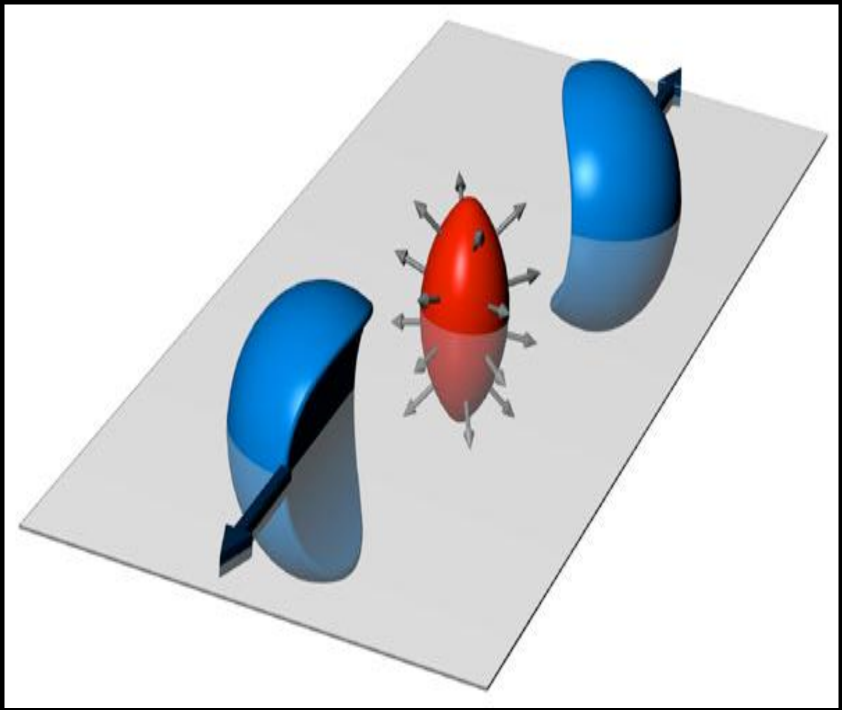
PRC81, 034911 (2010)

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

If the excess is the same at 39 GeV as at 200 GeV, we expect a 6σ result.

Addition of Hadron Blind Detector will significantly reduce background.

Searching for the onset of deconfinement: Flow Measurements



$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos[n(\varphi - \psi_n)]\right)$$

$$v_n\{\psi_n\} = \left\langle \cos\left[n\left(\varphi - \psi_n\right)\right]\right\rangle, \quad n = 1, 2, 3..,$$

$$E\frac{d^3N}{d^3p} = \frac{1}{\pi}d^2\frac{N}{dp_T^2dy}[1 + 2v_1\cos(\varphi - \Psi_R) + 2v_2(2[\varphi - \Psi_R]) + ...]$$

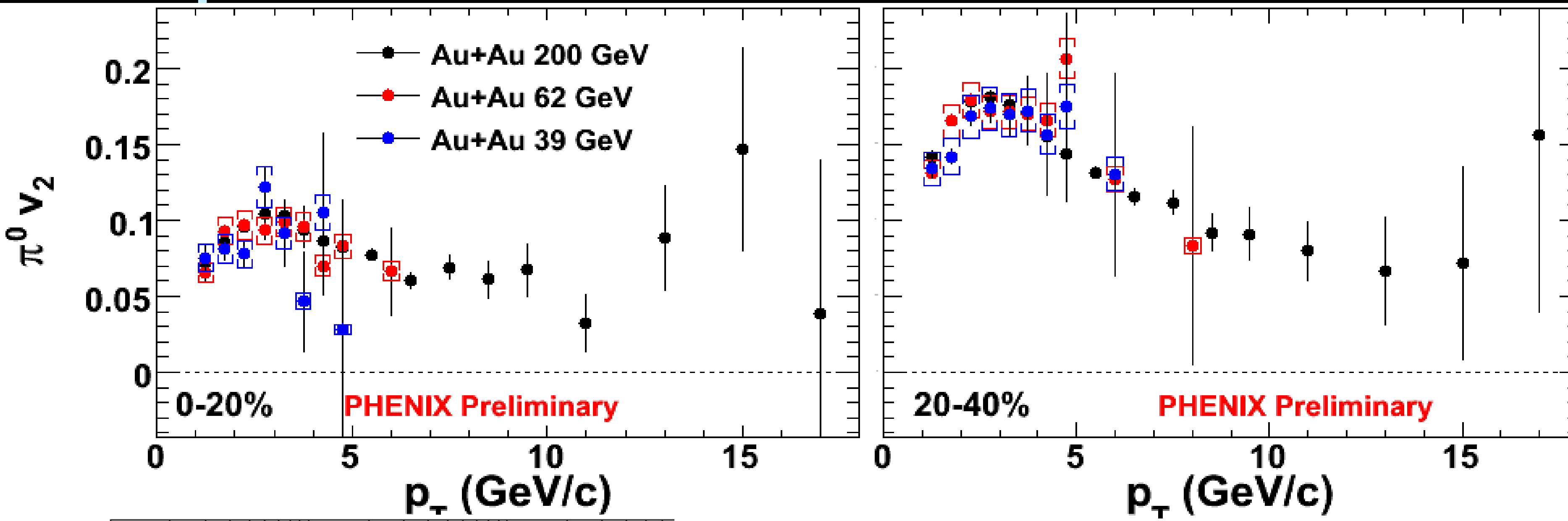
$$v_2 = \langle \cos(2[\varphi - \Psi_R])\rangle$$

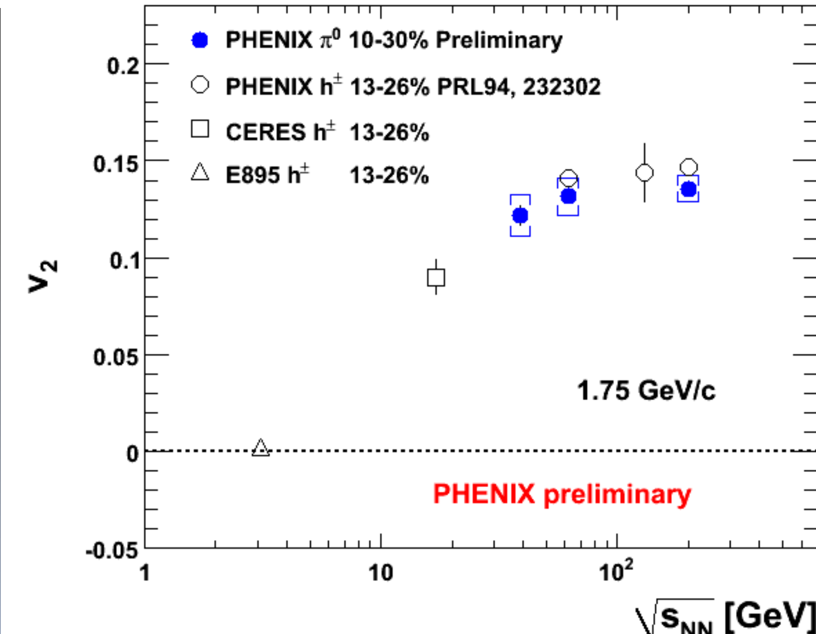
$$v_1 = < \frac{p_x}{p_T} >$$ – **directed flow**

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

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

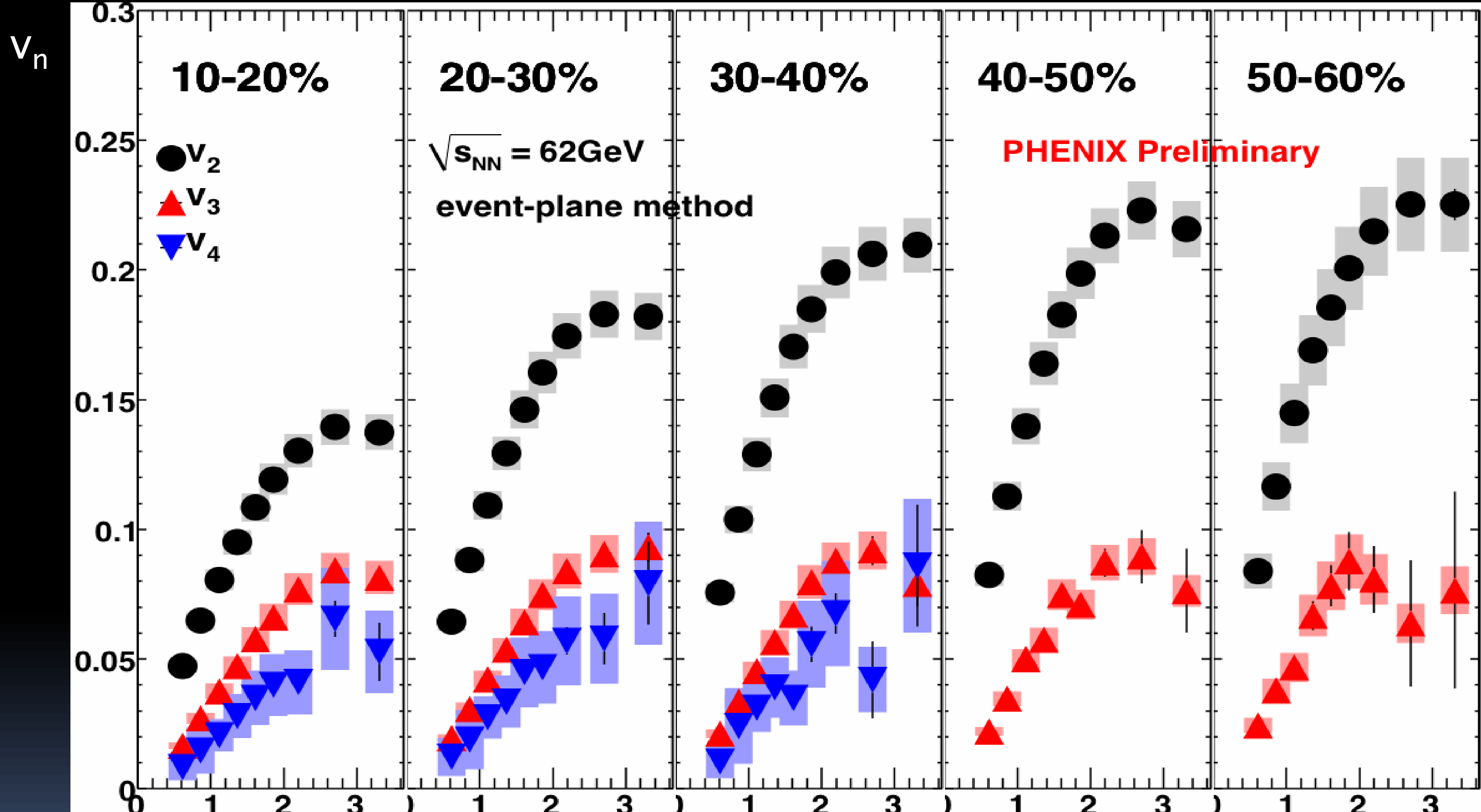
Elliptic Flow at 62 and 39 GeV: π^0





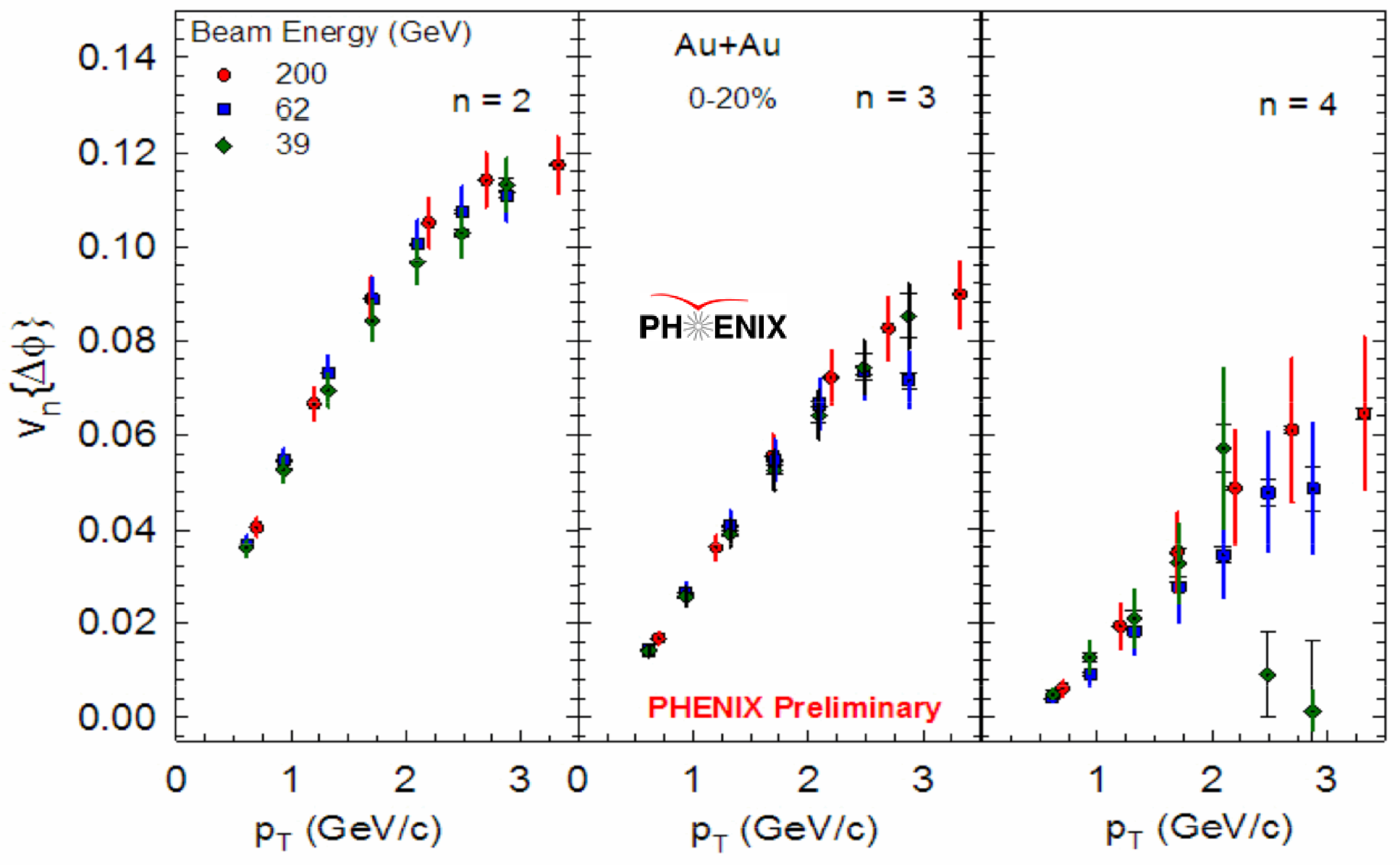
There is little change in the magnitude of v_2 from 39 GeV to 200 GeV.

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



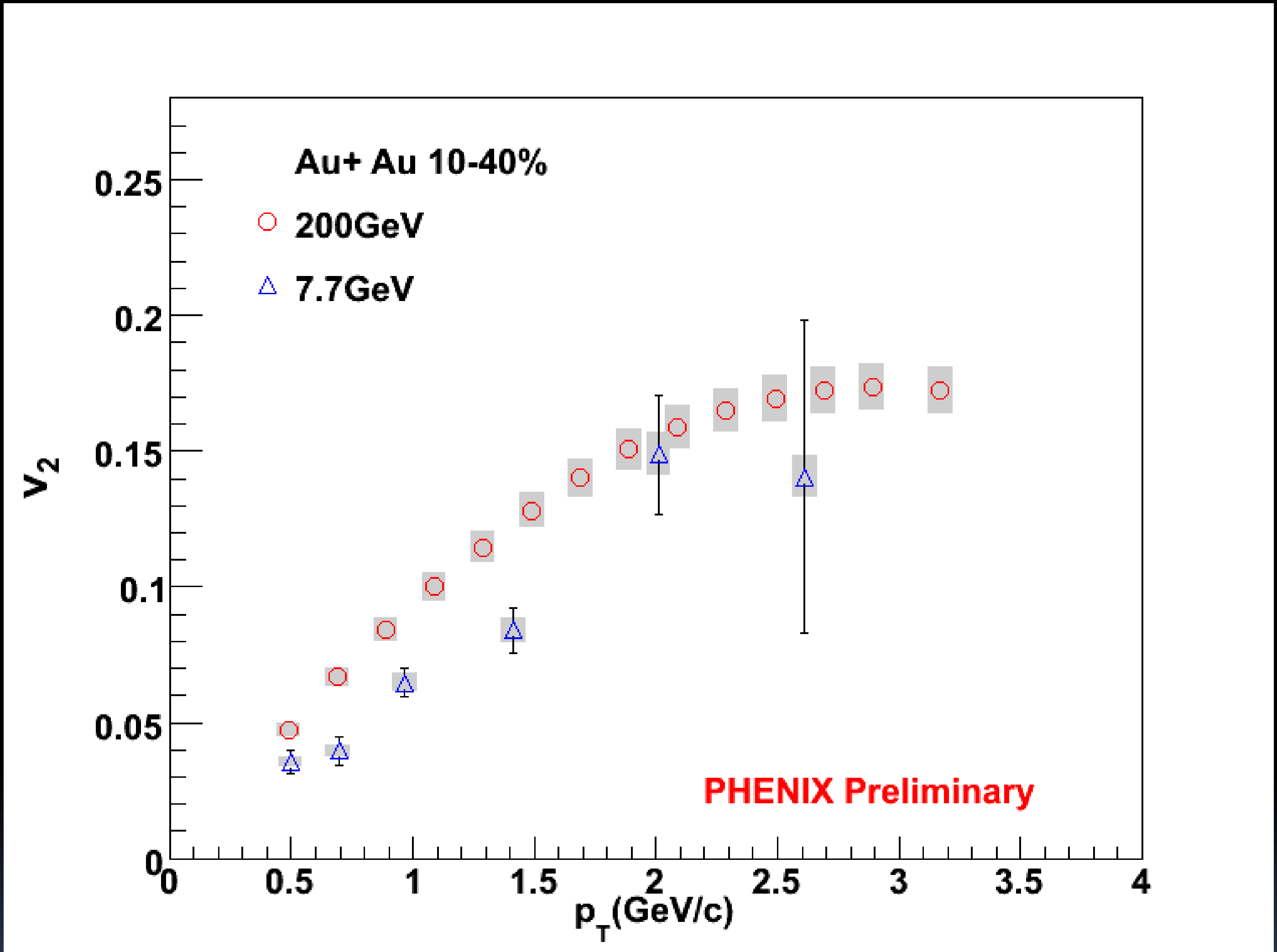
charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

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



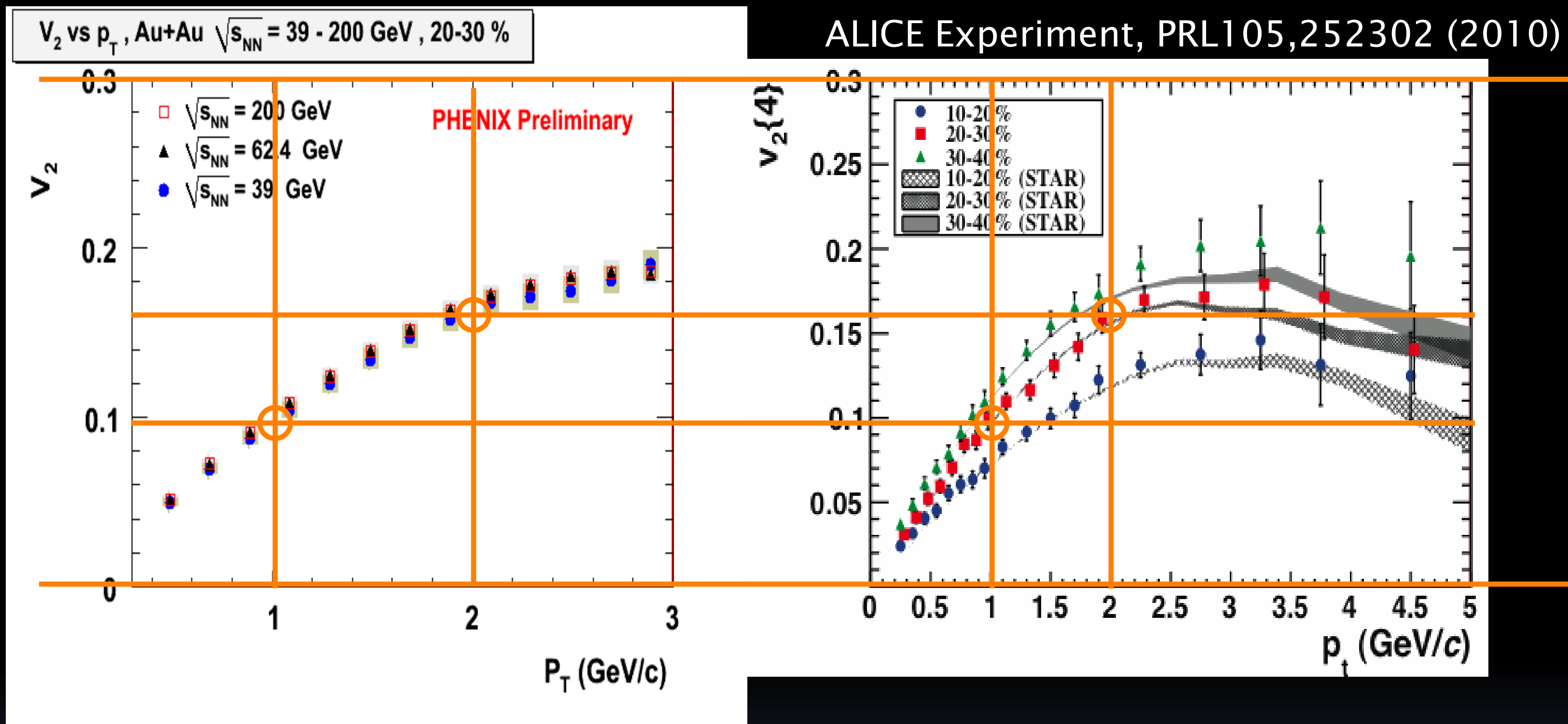
v_2, v_3, v_4 are independent of $\sqrt{s_{NN}}$ for 39, 62.4, 200 GeV

v_2 in 7.7 GeV Au+Au Collisions



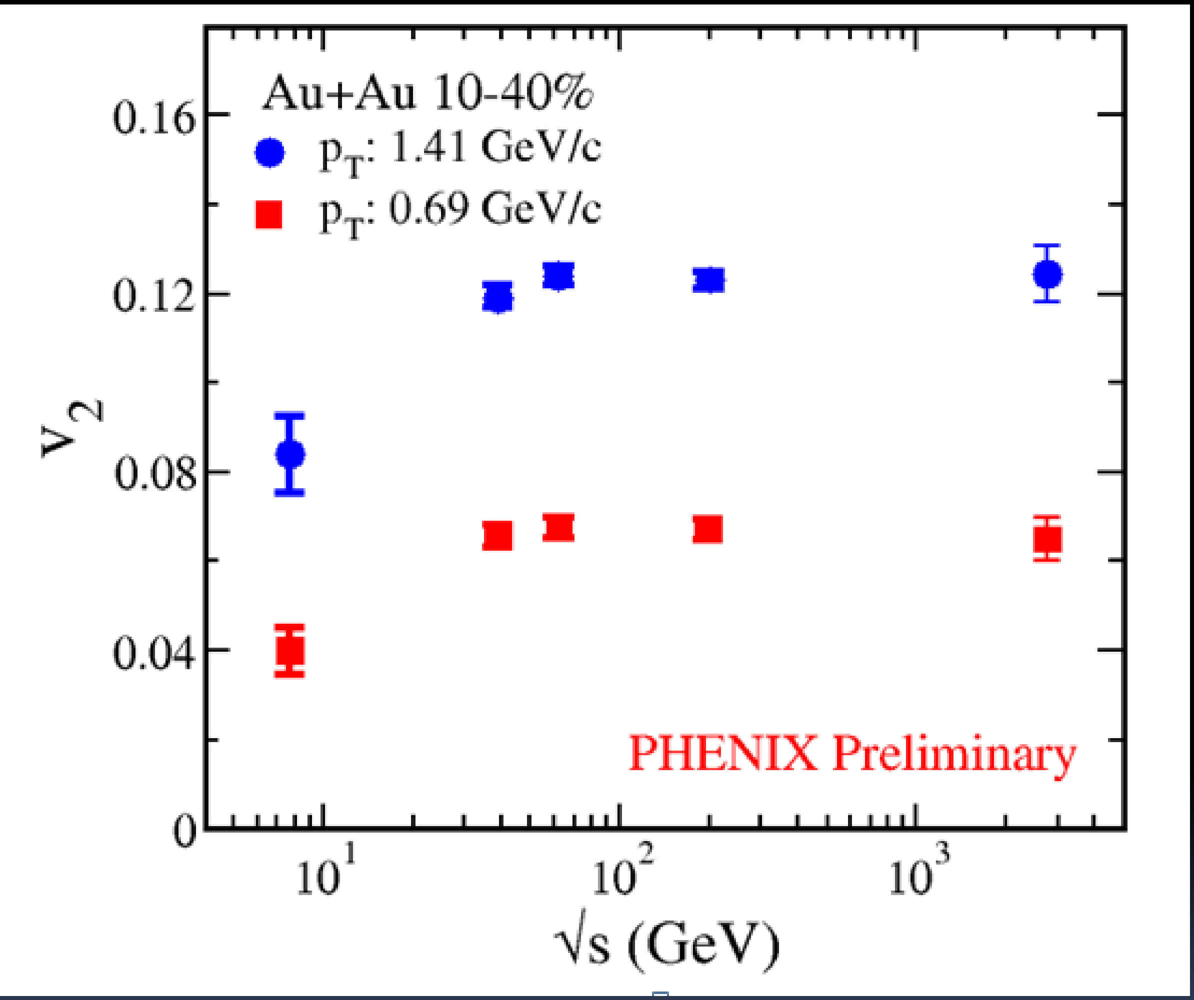
The magnitude of v_2 at 7.7 GeV is significantly lower than the magnitudes at 39, 62 and 200 GeV

v_2 vs p_T from 39 GeV to 2.76 TeV

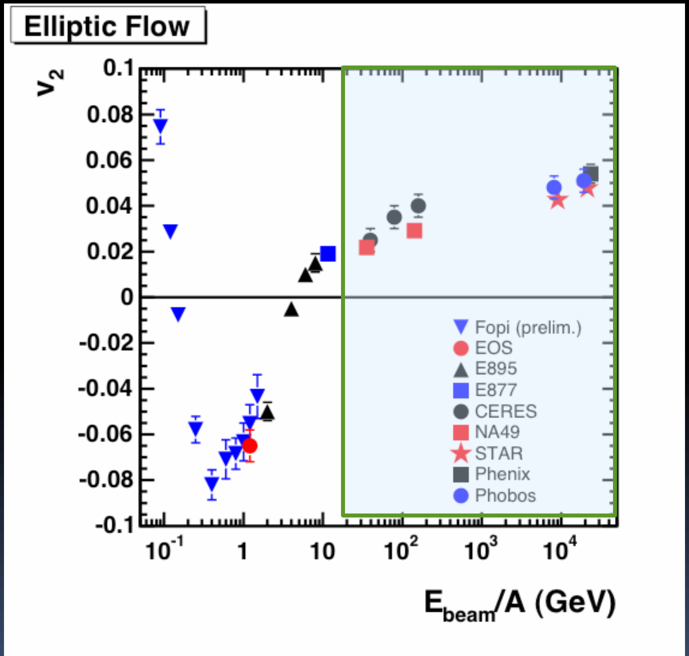


It appears that the system demonstrates similar hydrodynamic properties from 39 GeV to 2.76 TeV

Saturation of v_2 with beam energy



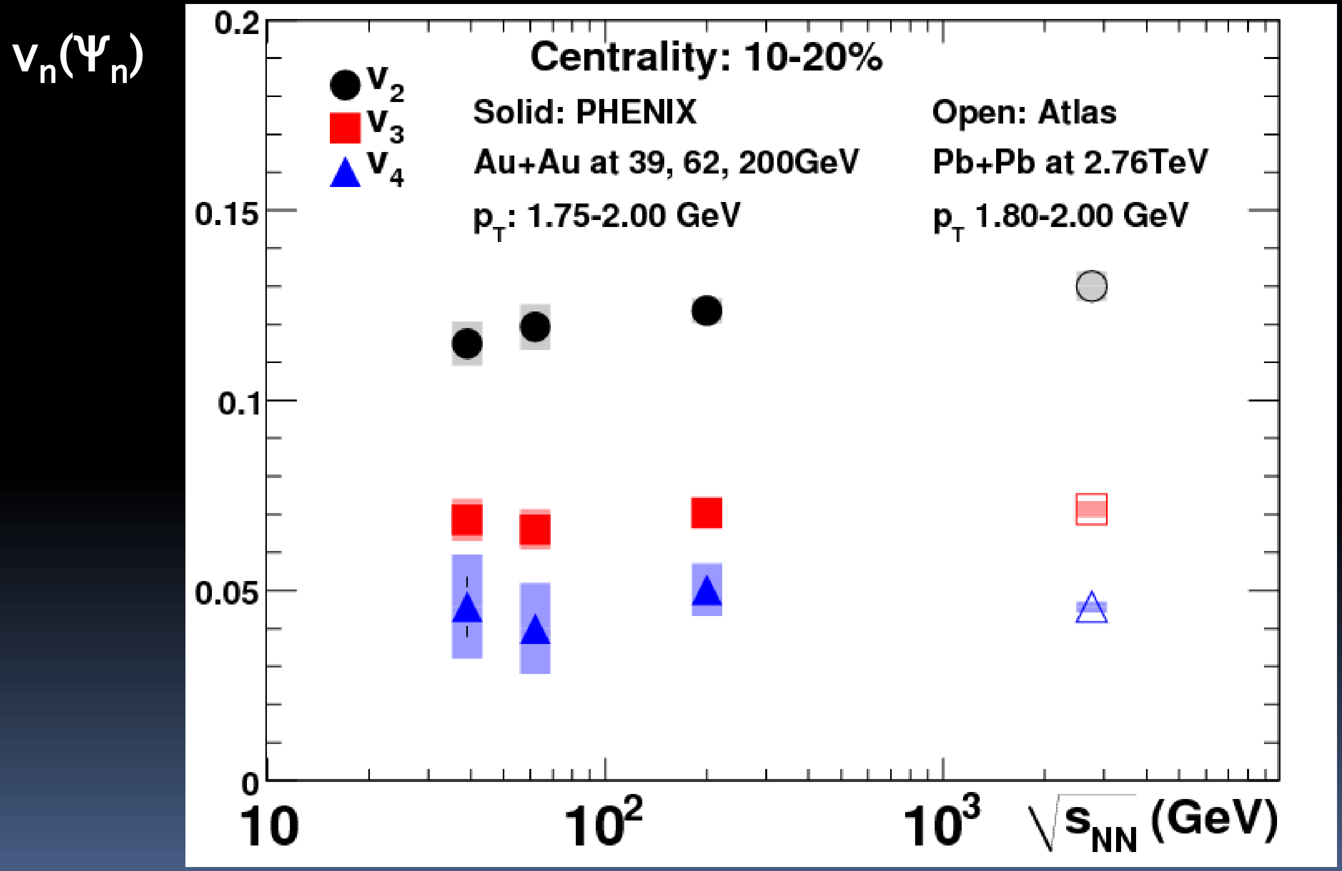
v_2 saturates for a given p_T around or below 39 GeV



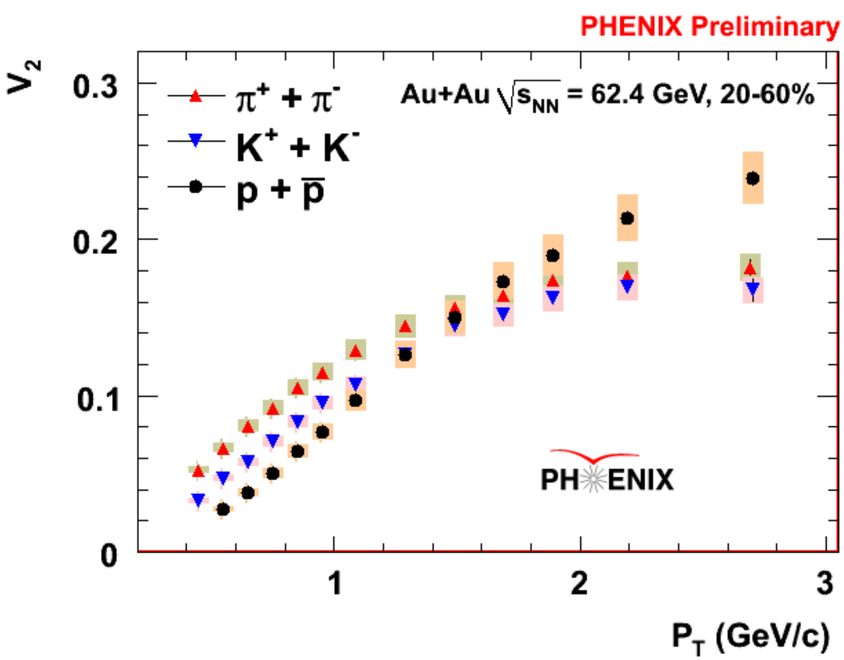
Almost perfect fluidity from 39 GeV to 2.76 TeV

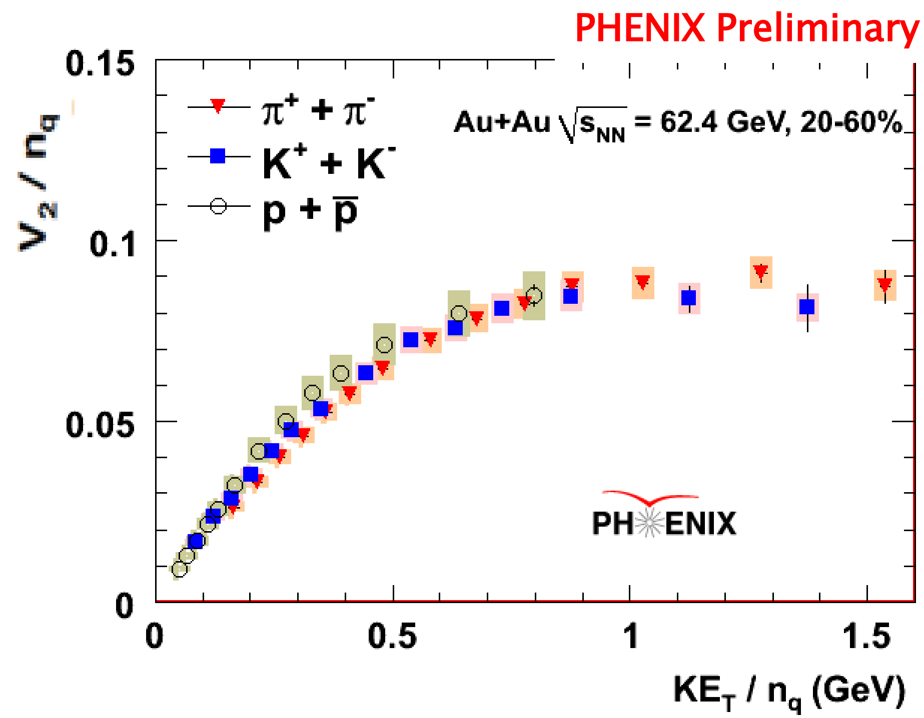
Saturation of v_3, v_4 with beam energy

- v_2, v_3 and v_4 are measured in 39, 62 and 200 GeV. The magnitudes are similar.
- The observations suggest similar initial geometry fluctuations and dynamical evolution of nuclear matter above 39 GeV.



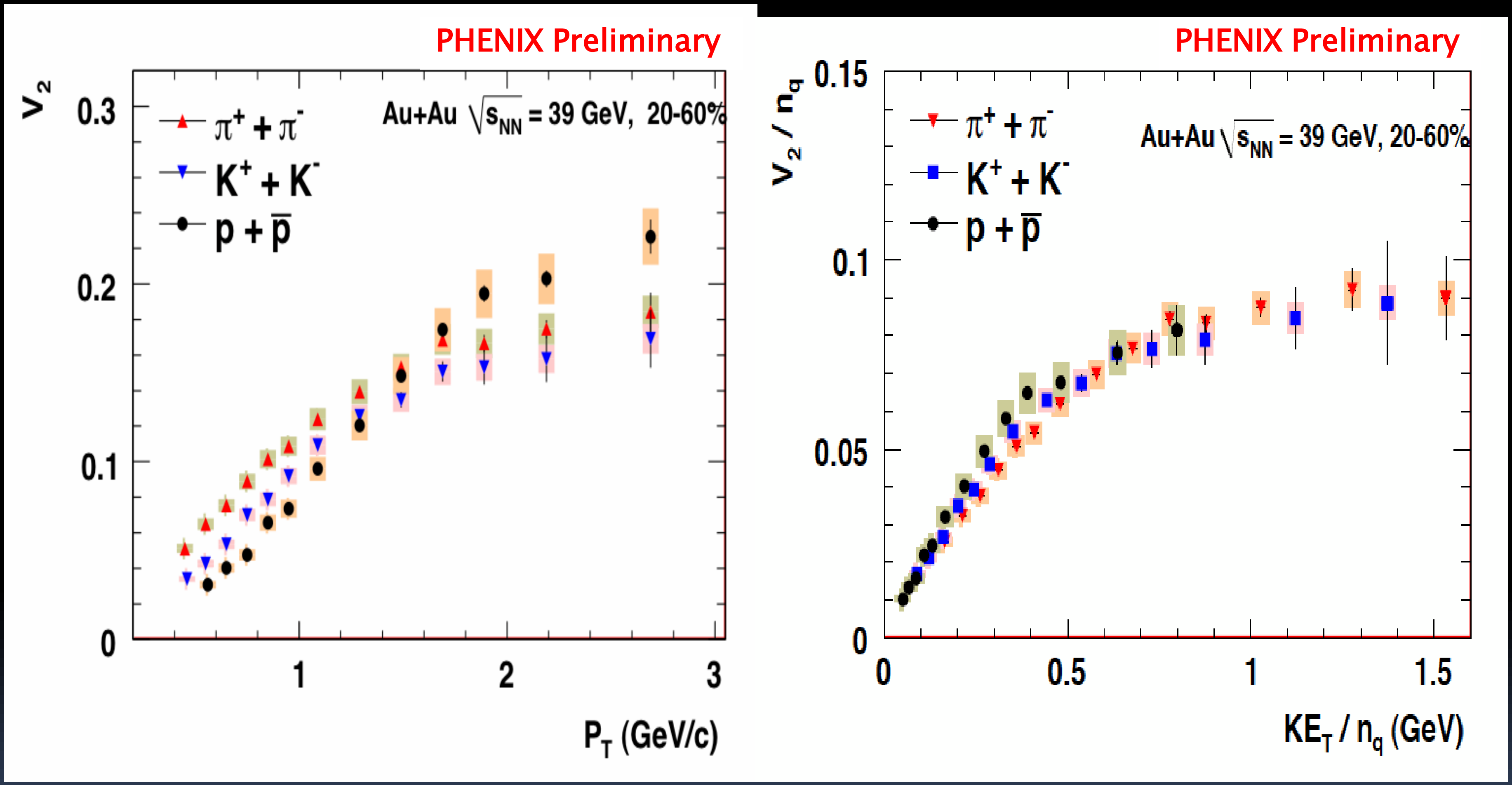
Identified hadron v_2 in 62.4 GeV Au+Au Collisions





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

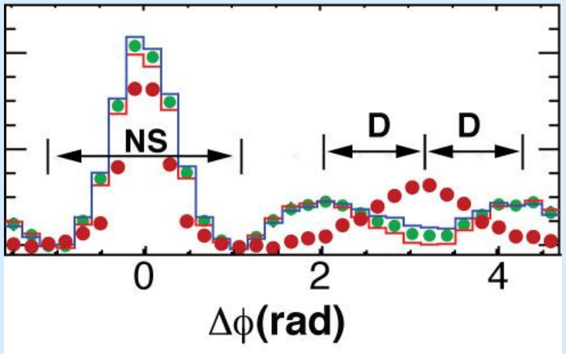
Searching for Signatures of the Critical Point: Fluctuations and Correlations

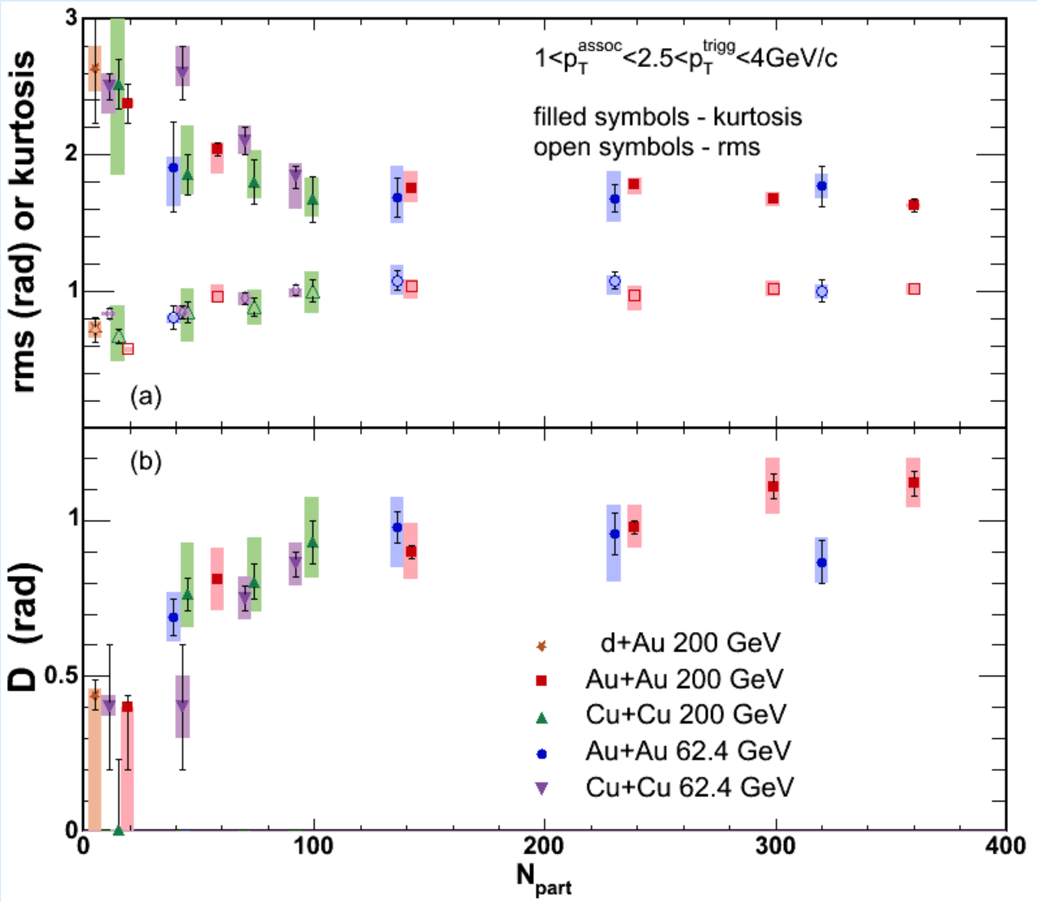
Two-Particle Correlations: 200 and 62 GeV

$$J(\Delta\phi) = G(\Delta\phi) + G(\Delta\phi - \pi - D) + G(\Delta\phi - \pi + D)$$

$$\mu_n \equiv (\Delta\phi - \pi)^n, n = 2,4\ldots \quad rms \equiv \sqrt{\mu_2} \quad kurtosis \equiv \mu_4 / \mu_2^2$$

Phys.Rev. C 77, 011901 (2008)





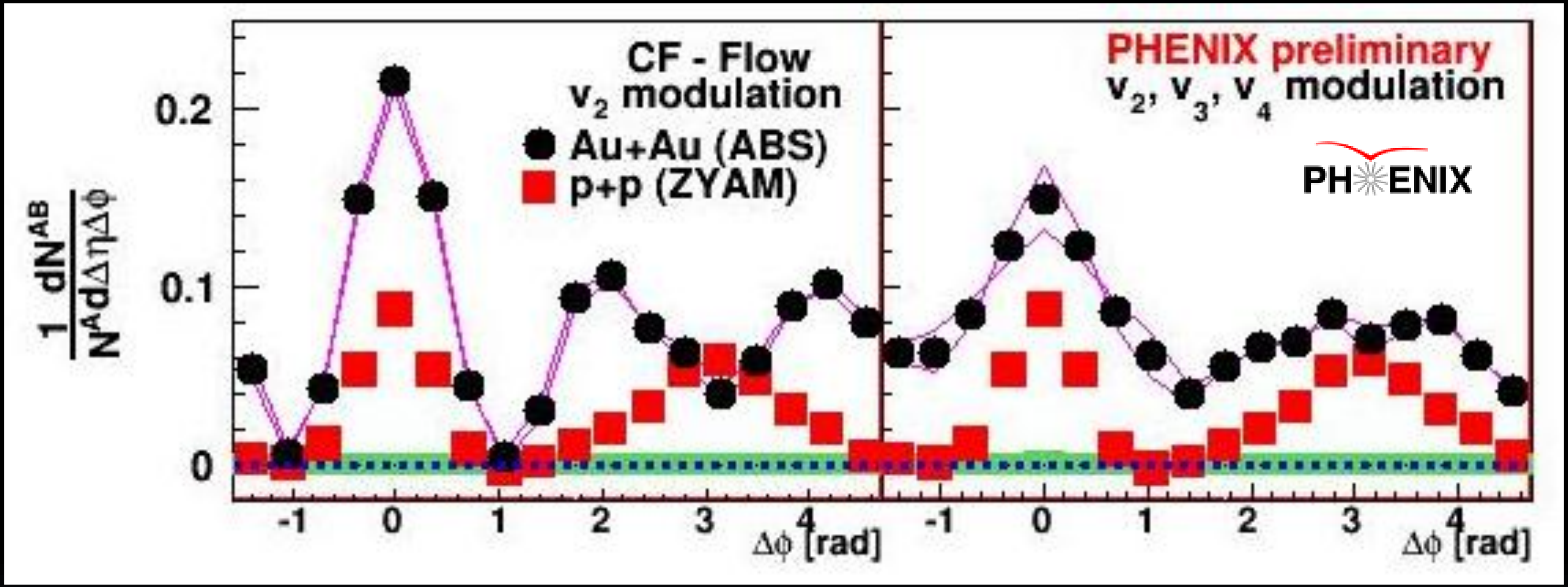
PRL 98, 232302 (2007)

h – h correlations

$1 < p_{Ta} < 2.5 < p_{Tt} < 4$GeV/c

With increasing N_{part} the away side jets broaden and move away from each other but remain flat over most of N_{part}

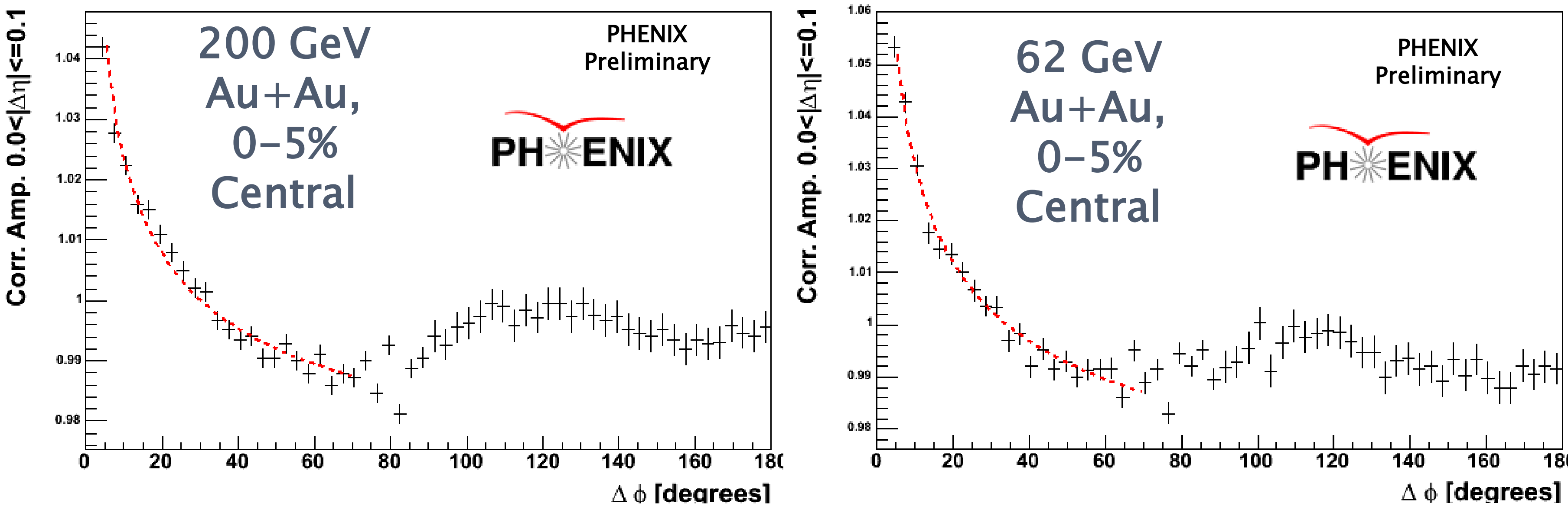
Two-Particle Correlations: v_3 and the Double Hump Structure



- v_2 correction only
  - double-hump
- v_2, v_3, v_4 correction
  - double-hump disappears
  - Peak still broadened

Like-Sign Pair Azimuthal Correlations

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



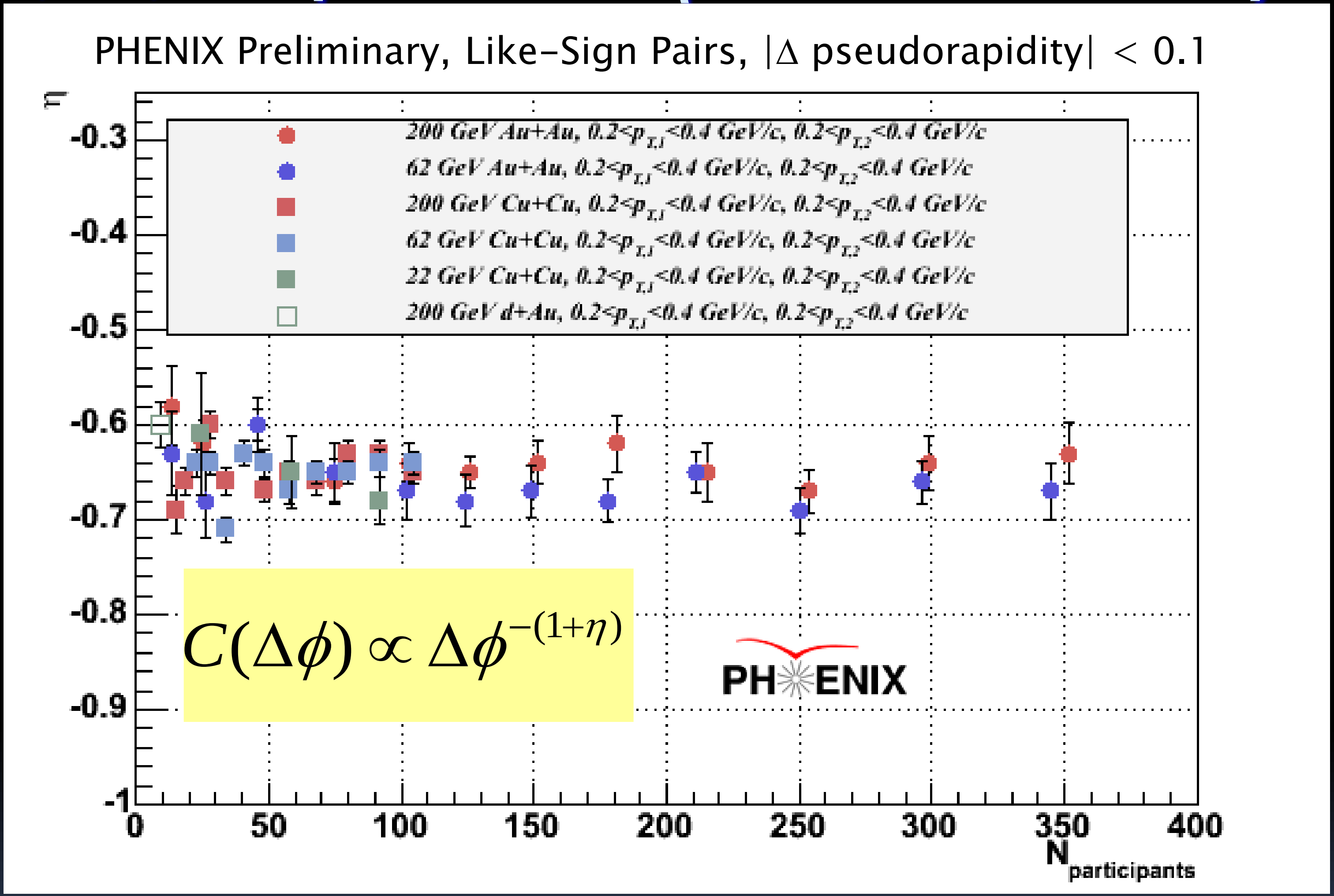
$$C(\Delta\phi) = (dN/d\phi_{data}/dN/d\phi_{mixed})*(N_{events,mixed}/N_{events,data})$$

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

Assuming that QCD belongs in the same universality class as the (d=3) 3-D Ising model, the expected value of η is 0.025 (Reiger, Phys. Rev. B52 (1995) 6659 .

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

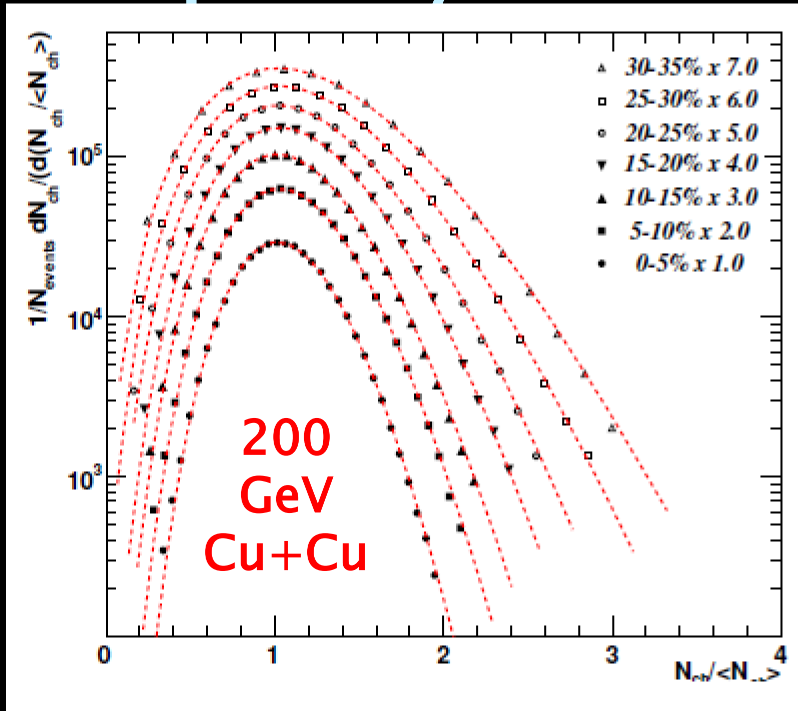
C(Δπ) Exponent η vs. Centrality

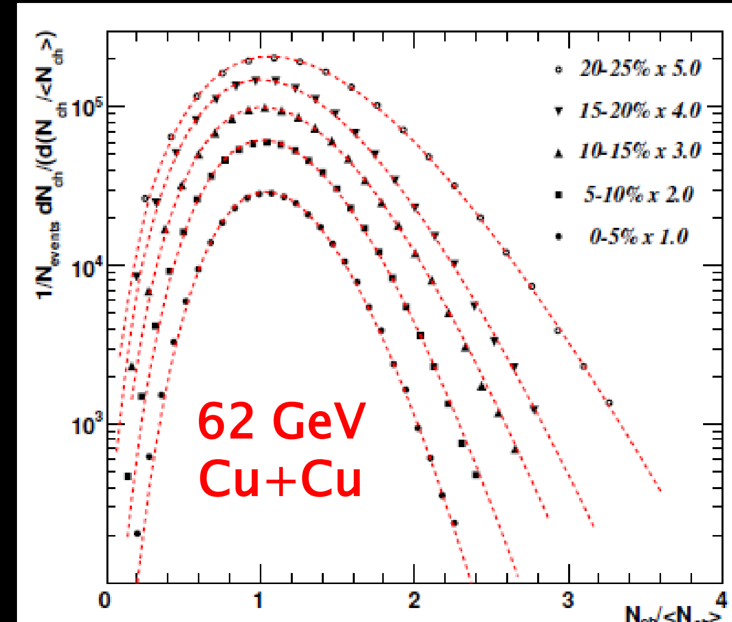


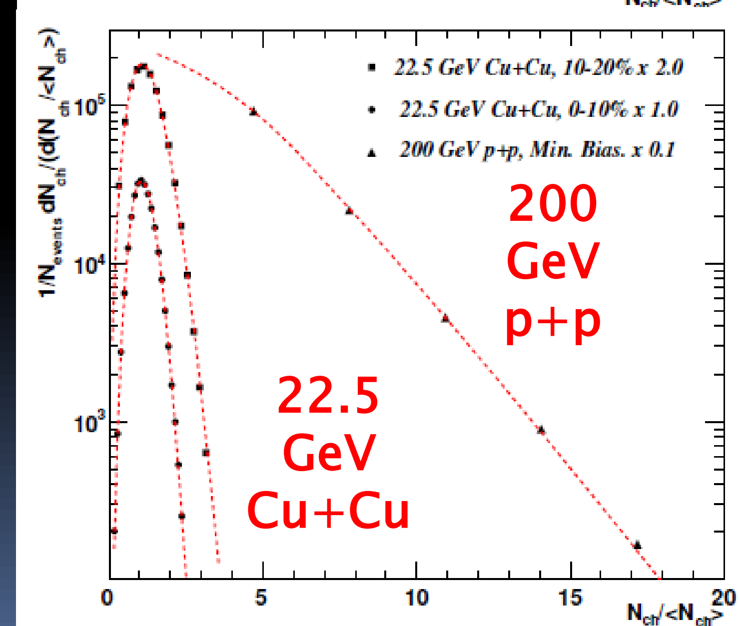
The exponent η is independent of species, centrality, and collision energy.

The value of η is inconsistent with the d=3 expectation at the critical point (0.025 for 3-D Ising).

Multiplicity Fluctuations







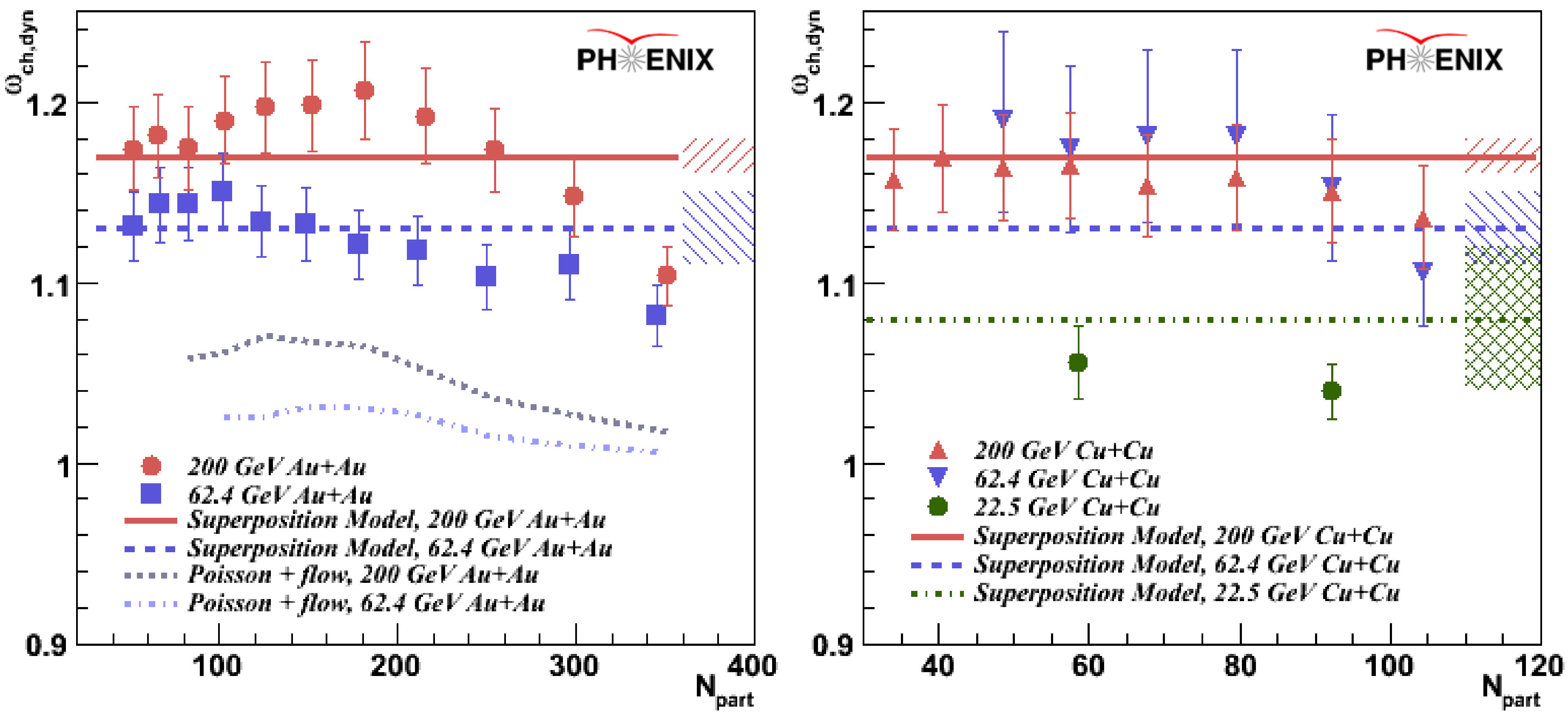
The black points are the data. The dashed red lines are Negative Binomial Distribution fits to the data.

Multiplicity fluctuations are quantified as the scaled variance: $\omega_{ch,dyn}$ = variance/mean, corrected for impact parameter fluctuations

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.



Summary and Outlook

- Multiplicity: Linear scaling with log(sqrt(s_{NN})).

- R_{AA}:
  - π^0 R_{AA} at 39 GeV still shows a large suppression.
  - Initial measurements show suppression of J/Ψ at 39 and 62 GeV.
  - No significant suppression is observed for the ϕ at 62 GeV.

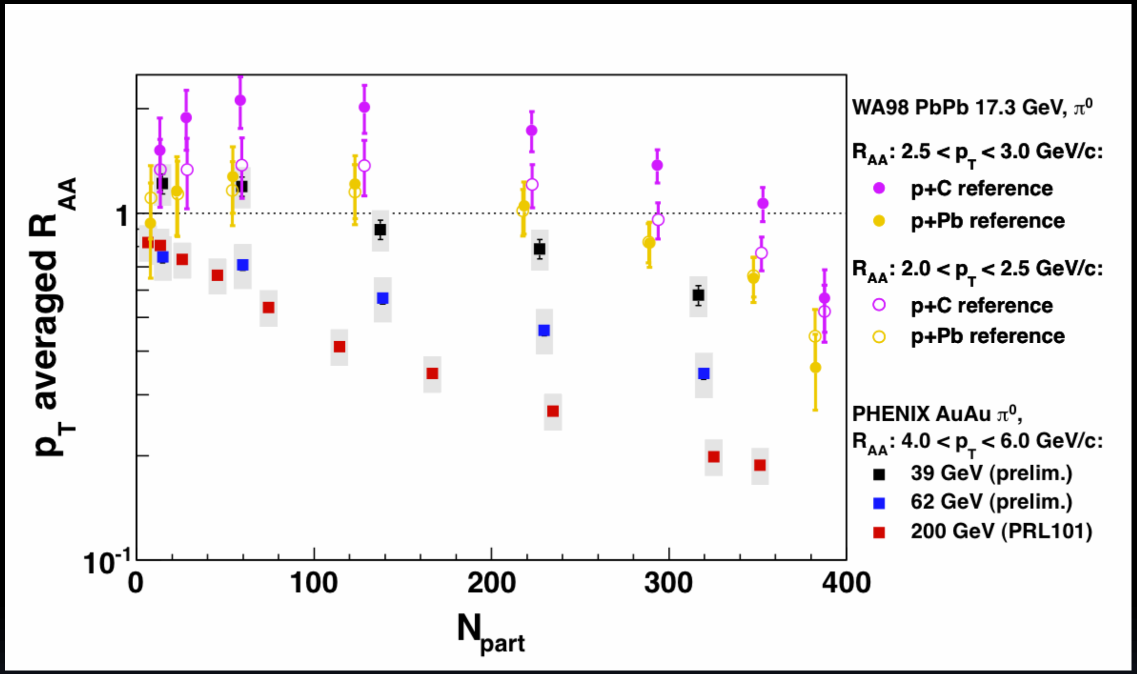
- Flow:
  - v_2 ,v_3, v_4 saturates at intermediate p_T at 39 and 62 GeV.
  - Quark number scaling holds at 39 and 62 GeV.
  - v_2 at 7.7 GeV is significantly lower than v_2 at 39 and 62 GeV.

- Outlook:
  - Many measurements are being analyzed from the new datasets at 7.7, 19.6, 27.0, and 39.0 GeV, 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

Comparison with recent SPS R_{AA}

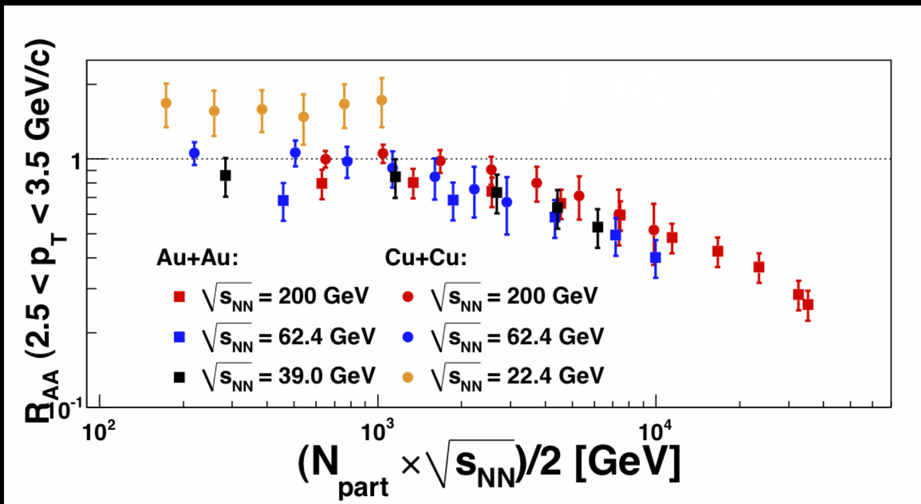


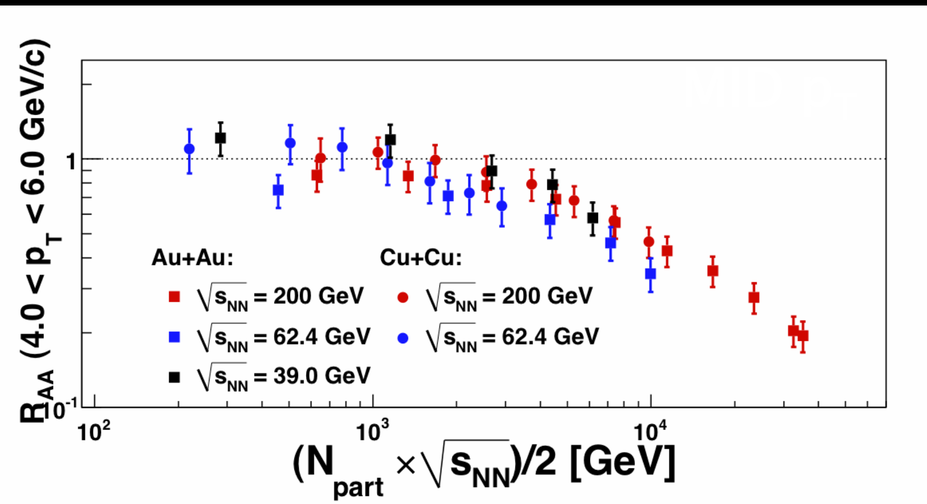
The magenta closed circles are the most comparable with the PHENIX results, as they have the smaller system (p+C) for reference.

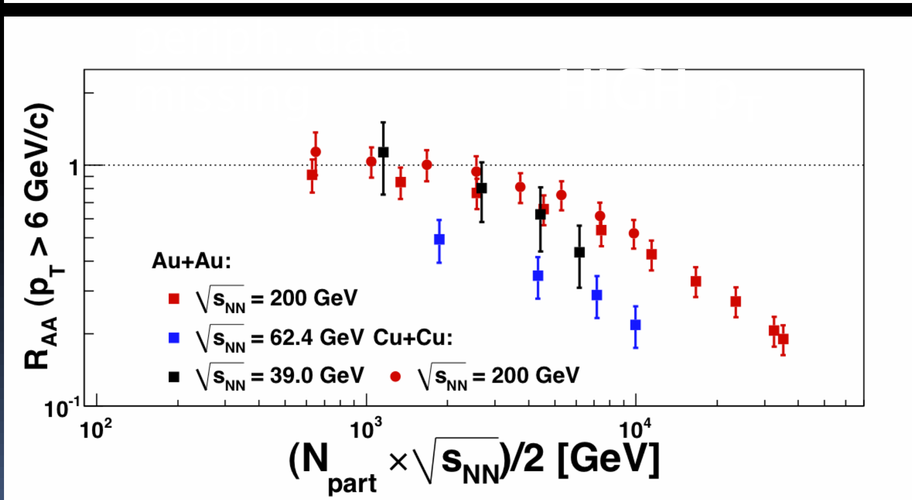
- In previous experiment at WA98 we see only (PRL 100 (2008), 242301) suppression at "ultra"-central (0-1%) collisions of Pb+Pb.
- The x_T is overlapping between the SPS and RHIC intervals.
- The "onset" of the energy loss is dependent on system size and collision energy.
- The energy loss is present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

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

E_{AA} dependence on p_T

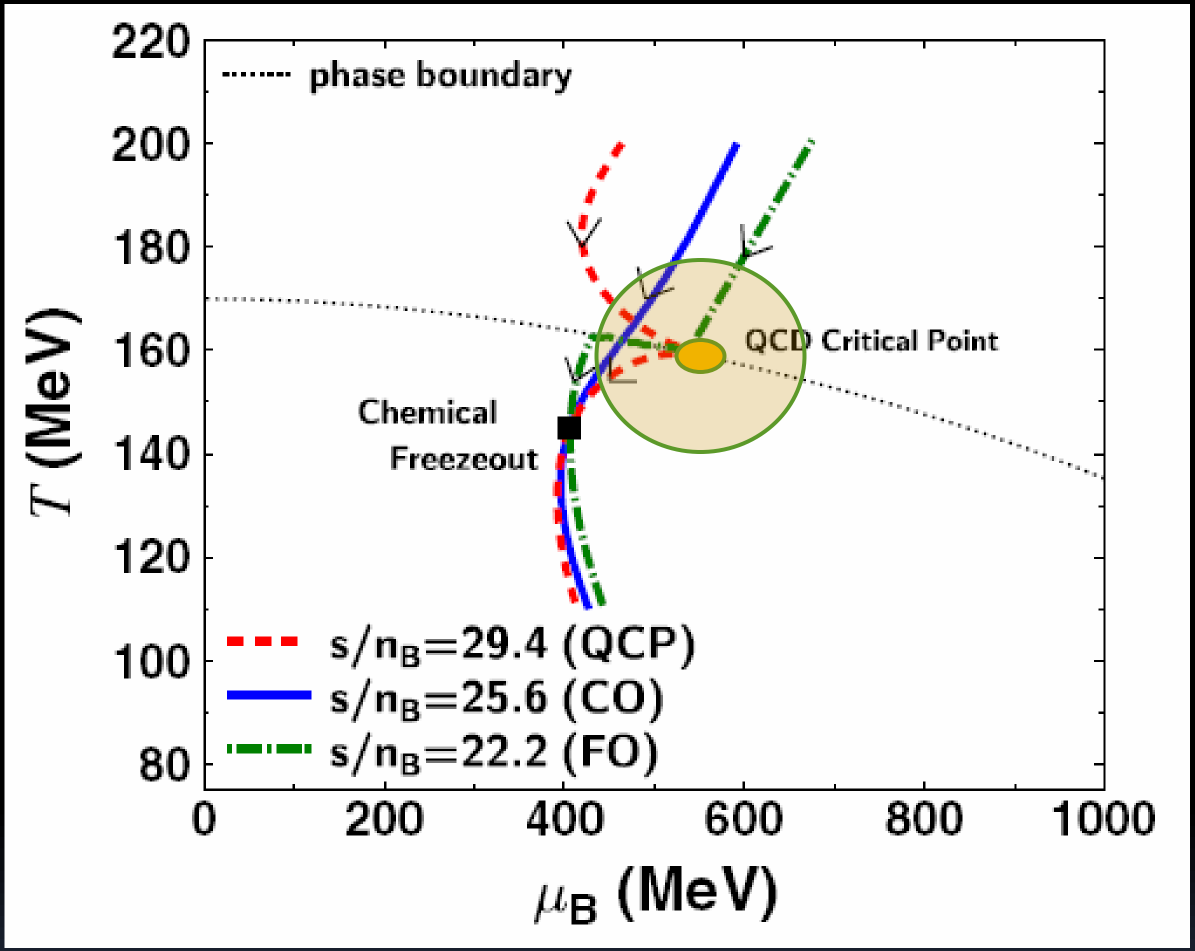






In higher p_T the scaling does not work.

How big is the target?



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

From a hydrodynamics calculation.

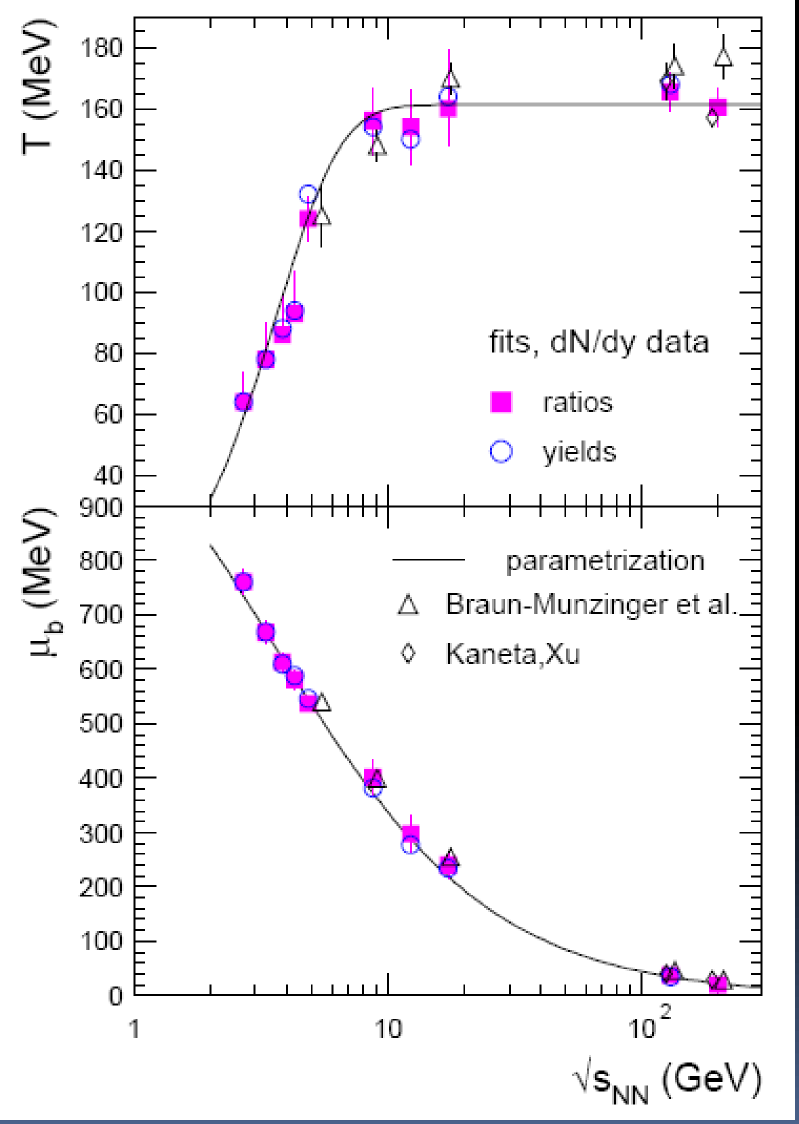
For a given chemical freeze-out point, 3 isentropic trajectories (s/n_B=constant) are shown.

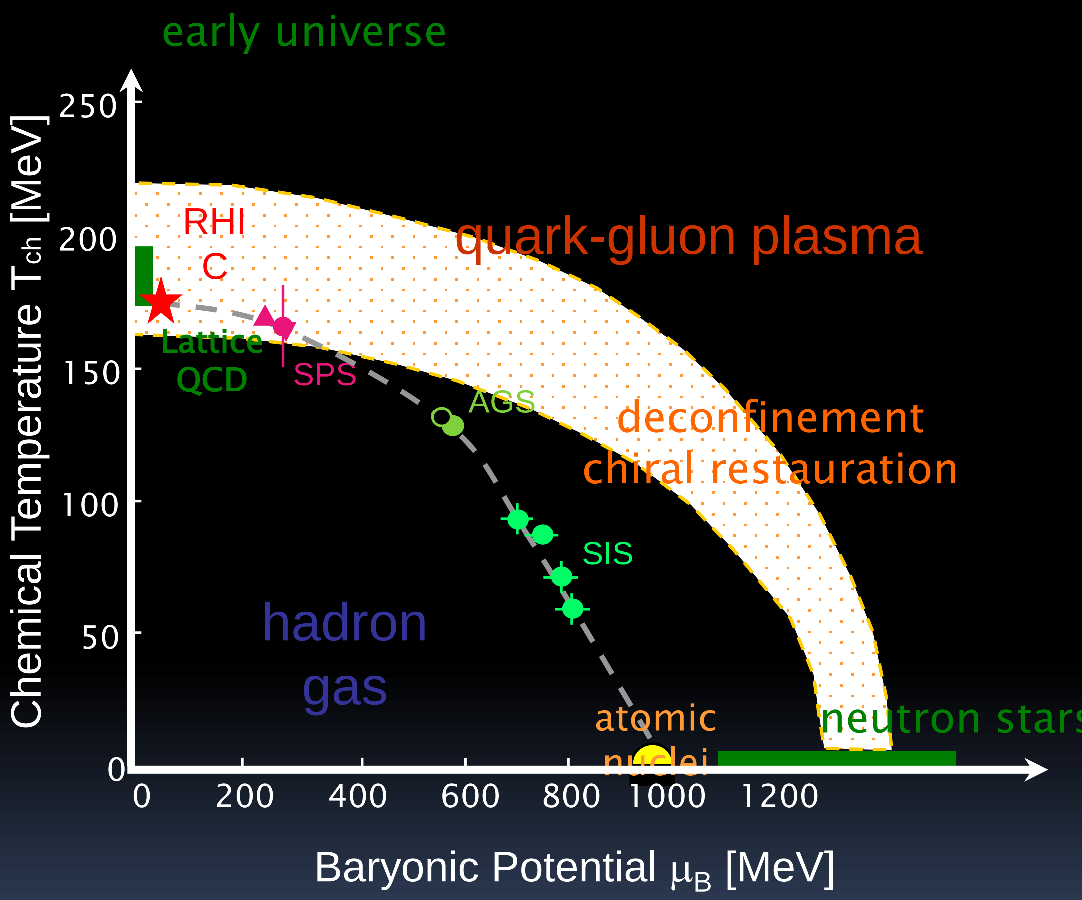
The presence of the critical point can deform the trajectories describing the evolution of the expanding fireball in the (T,μ_B) phase diagram.

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

Statistical Model Fits

Extracted T & μ_B values





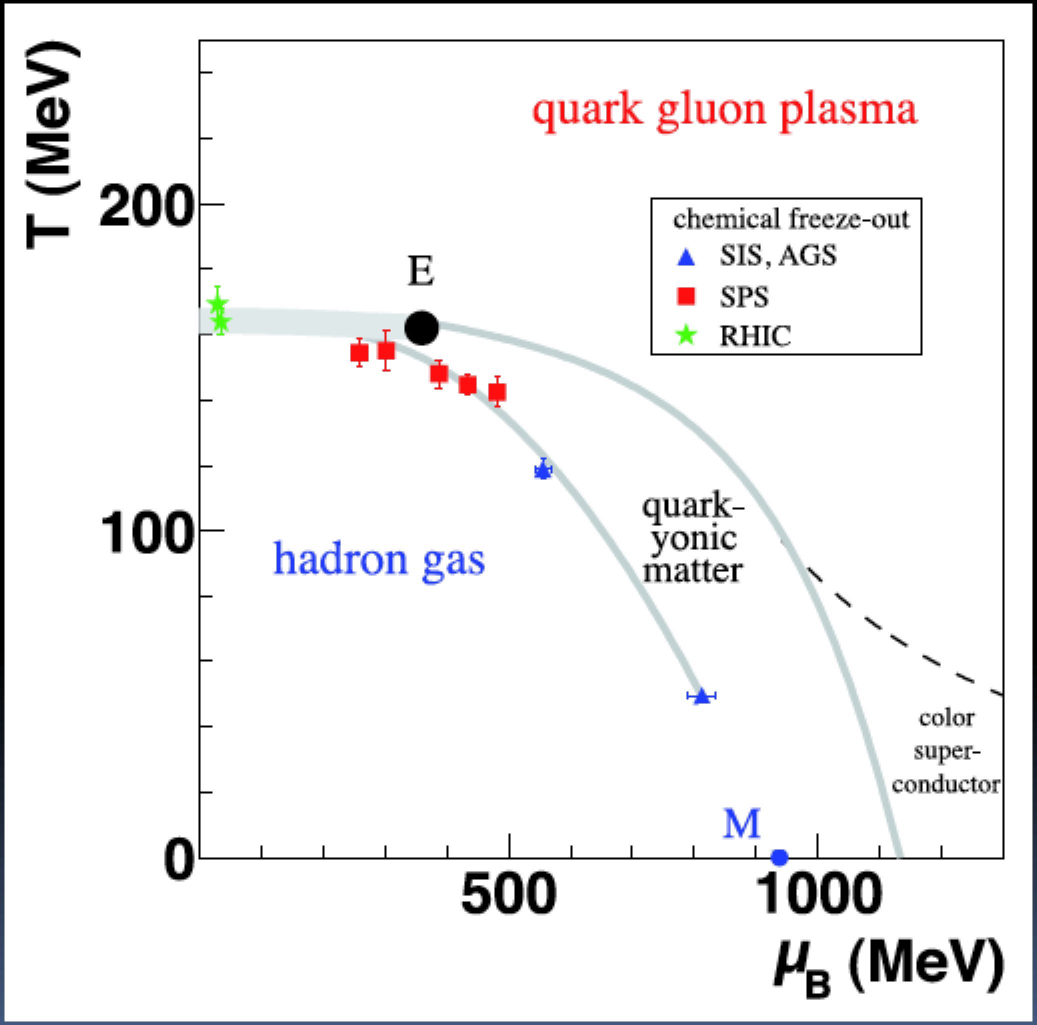
For $\sqrt{s}$ >≈ 10 GeV , chemical freeze-out very close to phase boundary

Statistical Model Results

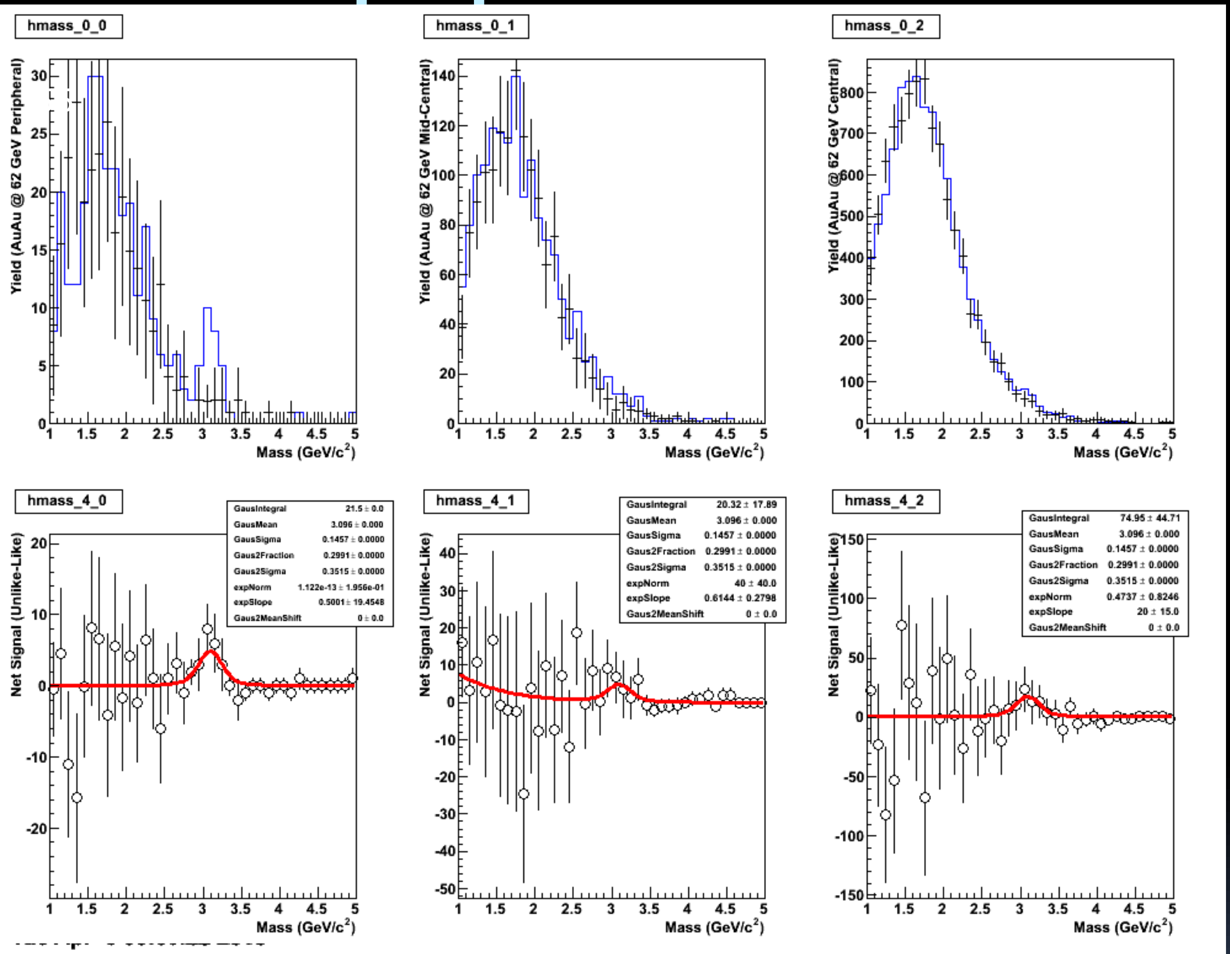
Results from different beam energies

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!

Comparisons to the Wounded Nucleon Model

- In the Wounded Nucleon Model, multiplicity fluctuations are given by:

  $$\omega_N = \omega_n + \langle N \rangle \omega_{Np}$$

  $\omega = \sigma^2/\mu$. ω_N = total fluctuation, ω_n = fluctuation of each source (e.g. hadron-hadron collision), ω_{Np} = fluctuation in number of sources (participants).
- After correcting for fluctuations due to impact parameter, $\omega_N = \omega_n$ independent of centrality.
- Multiplicity fluctuations are also dependent on acceptance:

  $$\omega_n = 1 - f + f\omega_\nu$$

  $f = N_{accepted}/N_{total}$. ω_n = fluctuations from each source in 4π