The PHENIX Potential in the Search for the QCD Critical Point

Workshop on the Critical Point and the Onset of Deconfinement – 7/4/06

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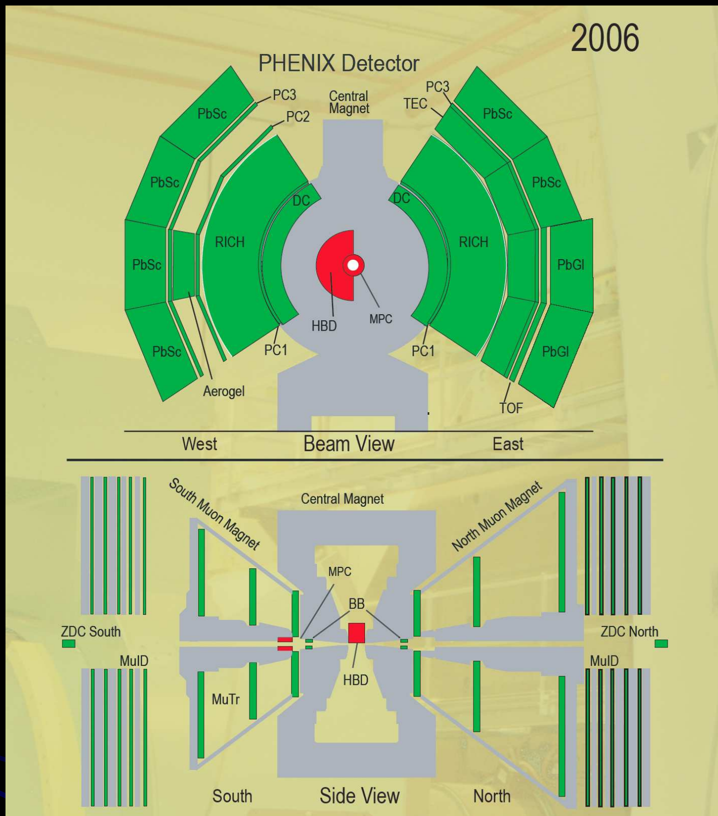
(Brookhaven National Laboratory)

<u>Outline</u>

- **PHENIX and the critical point**
- **PHENIX Performance**
- **Demonstrating Capabilities with Current Measurements**
- **Contribution of Upgrades**

The PHENIX Detector 2006



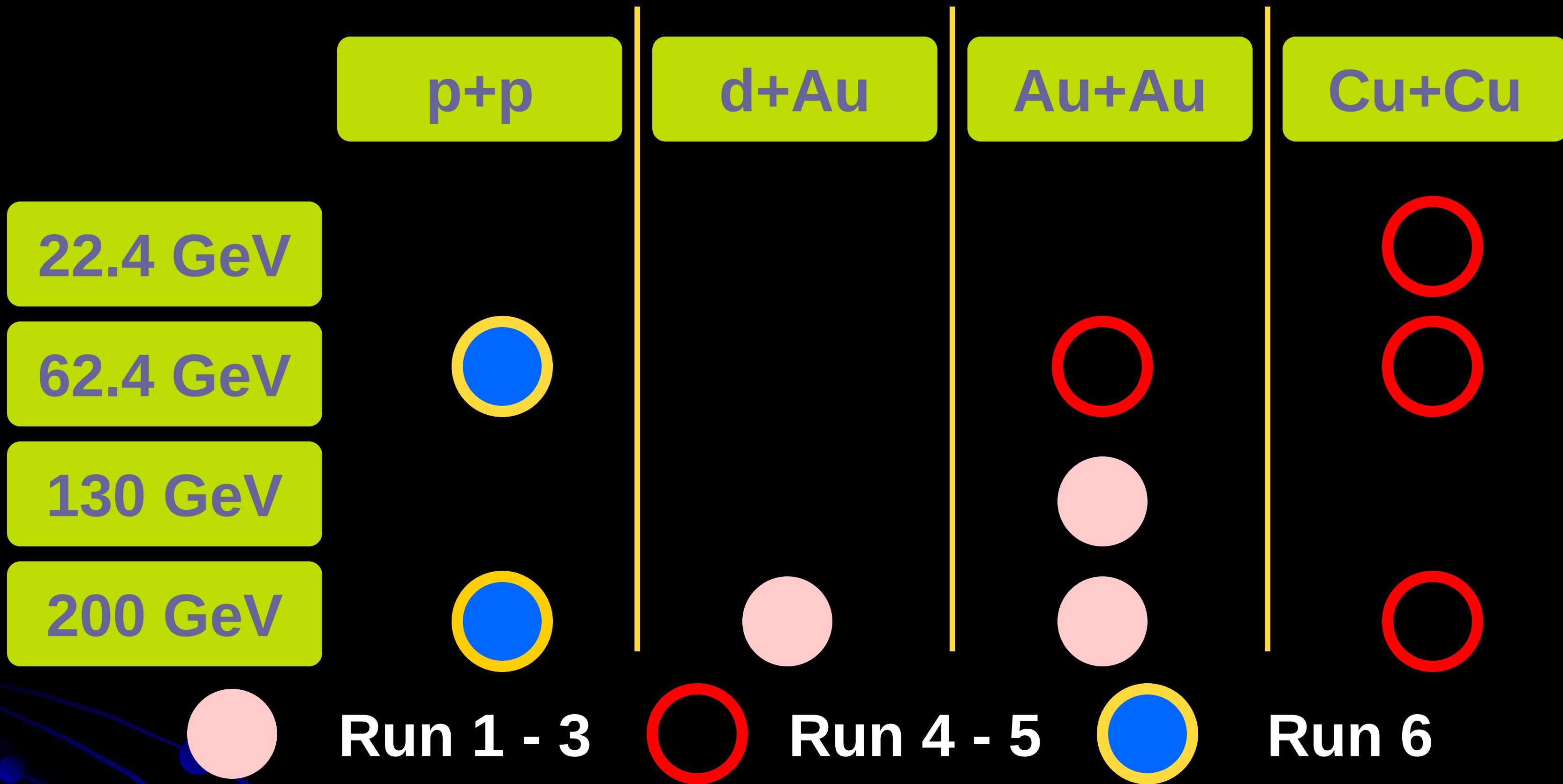
Charged Particle Tracking:
- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)

Particle ID:
- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)

Calorimetry
- Pb Scintillator
- Pb Glass

Event Characterization
- Beam-Beam Counter
- Zero Degree Calorimeter
- Shower Max Detector
- Forward Calorimeter

Current PHENIX Datasets



CuCu	200GeV	1.08 Billion Events	157TB on tape
CuCu	62.4GeV	630 Million Events	42TB on tape
CuCu	22GeV	48 Million Events	3TB on tape
p-p	200GeV	6.8 Billion Events	286TB on tape

Advances in data logging and the implementation of “multi-event buffering” increased or Event rate dramatically in Runs 4 and 5

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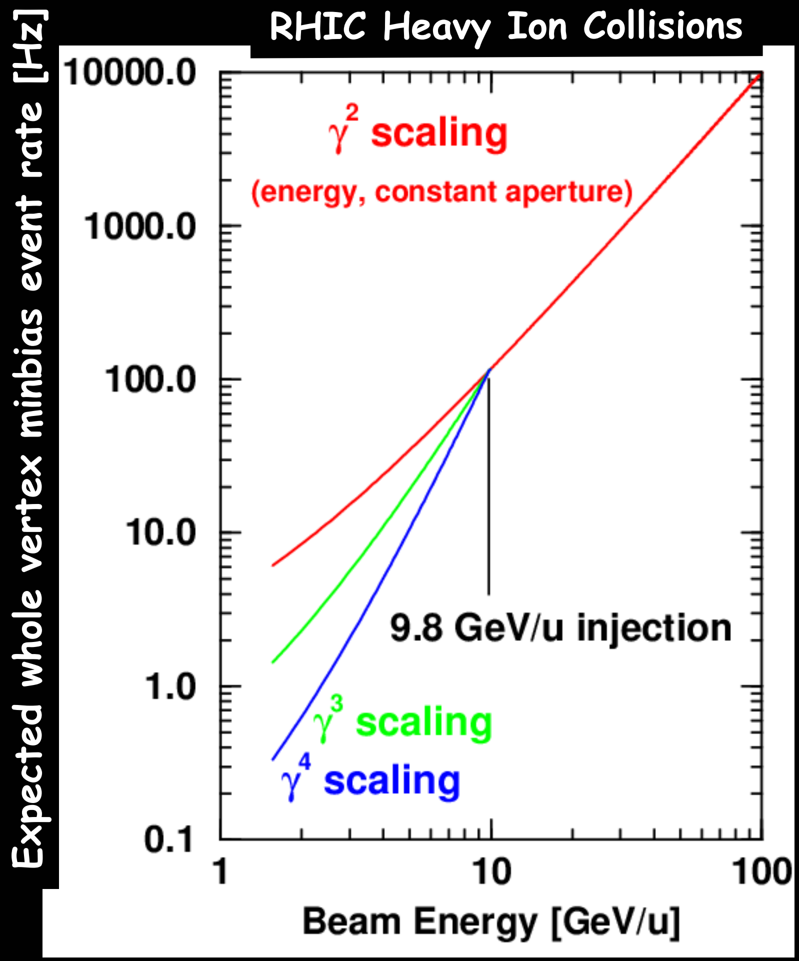
488 TB on tape for Run 5

RHIC low-E Feasibility

- No apparent show-stoppers for RHIC collisions at E_{cm} = 5-50 GeV/n
  - Only equal energies
  - Unequal species possible only if minimum rigidity > 200 T-m
  - Without cooling → long vertex distribution
- Small set of specific energies (and species?) should be a workshop deliverable for planning:
  - 2.5,3.2,3.8,4.4… GeV/n total beam energy
- Studies that should be done soon:
  - A ~1 day study period at low total beam energy to identify power supply, lifetime, tuning issues/limitations
  - Low-current superconducting magnet measurements
- Pre-cooling in AGS → 10x luminosity ?
- Electron beam cooling would make this a fantastic facility: ~100x luminosity, small vertex distribution, long stores.



T. Roser, T. Satogata

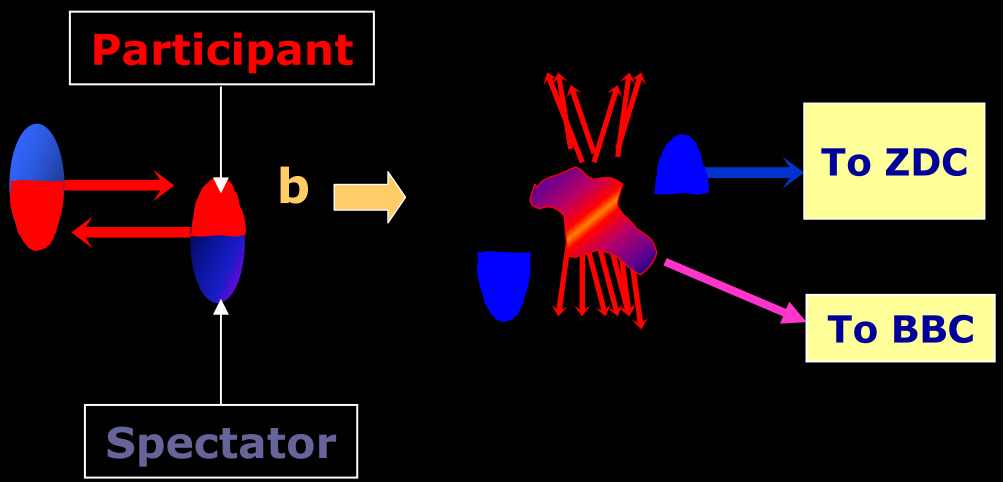
Initial Machine Projections

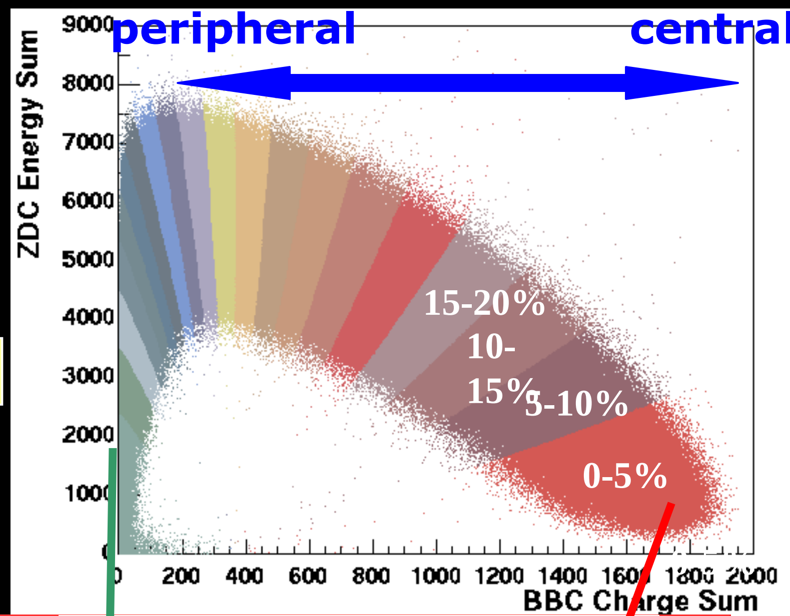
Mode	Beam Energy [GeV/u]	$N_{bunches}$	Ions/bunch $[10^9]$	β^* [m]	Emittance [μm]	L_{peak} $[cm^{-2}s^{-1}]$
Au-Au 2001-2	9.8	55	0.6	3	15	8.0×10^{24}
Au-Au 2003-4	31.2	45	1.0	3	15-30	1.2×10^{26}
Au-Au	9.8	55	1.2	10	15-40	1.0×10^{25}
Au-Au	2.5	55	1.0	10	15-30	1.1×10^{23}
Au-Au	25	55	1.2	3	15-40	2.0×10^{26}

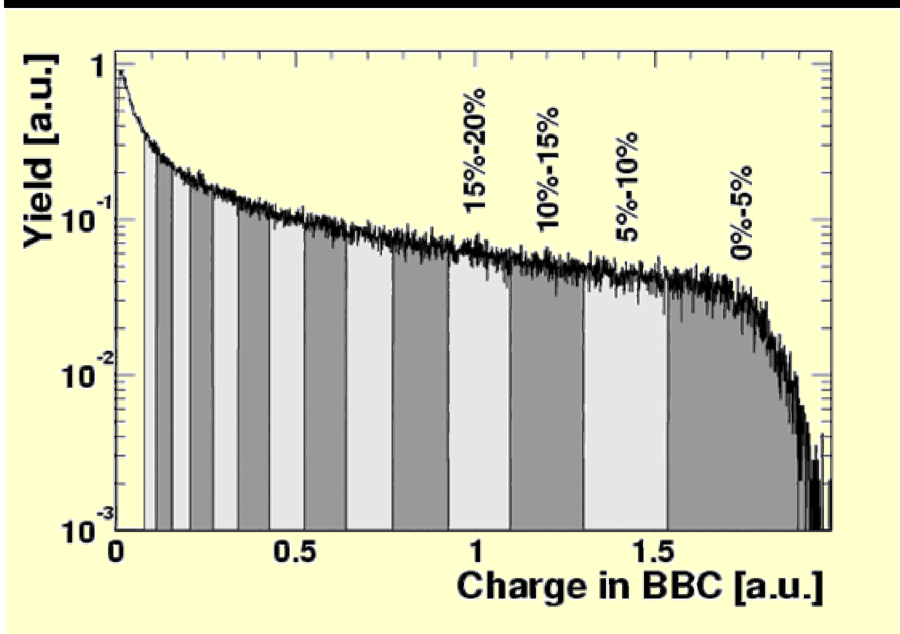
T. Roser, T. Satogata

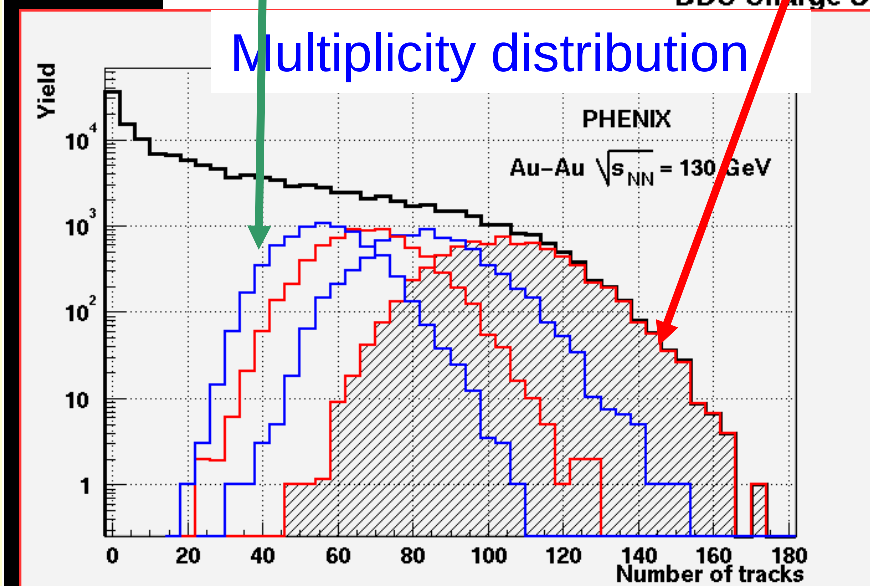
- Assumes expected luminosity scaling as γ^3 below 9.8 GeV/u
- β^*/aperture and integrated luminosity tradeoffs must be studied
- Projections do not include potential improvements
  - Electron and stochastic cooling (peak and integrated luminosity)
  - Lattice modifications to mitigate IBS (integrated luminosity)
  - Total bunch intensity from vacuum improvements (peak luminosity)

Centrality Determination: 62, 200 GeV



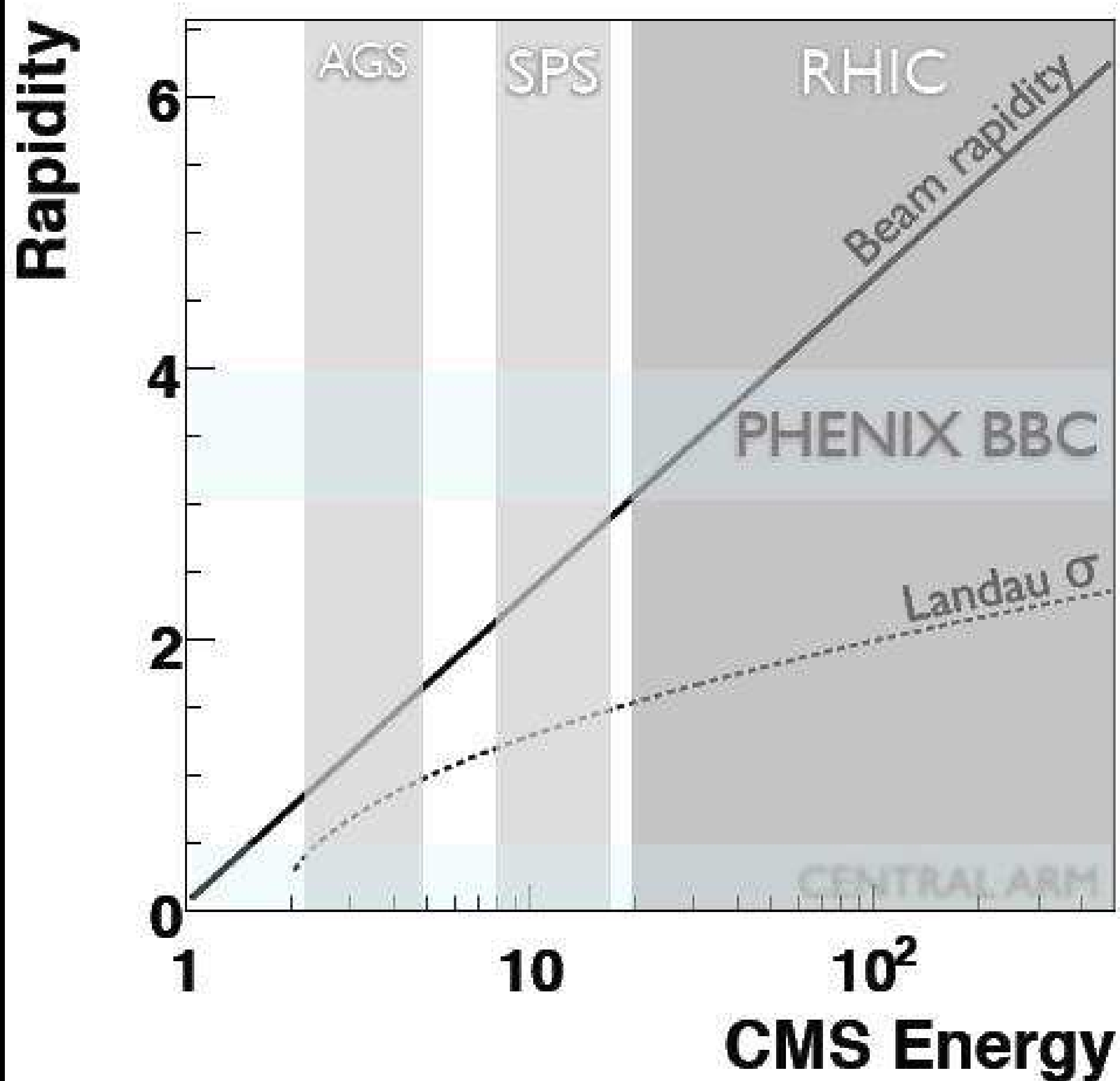




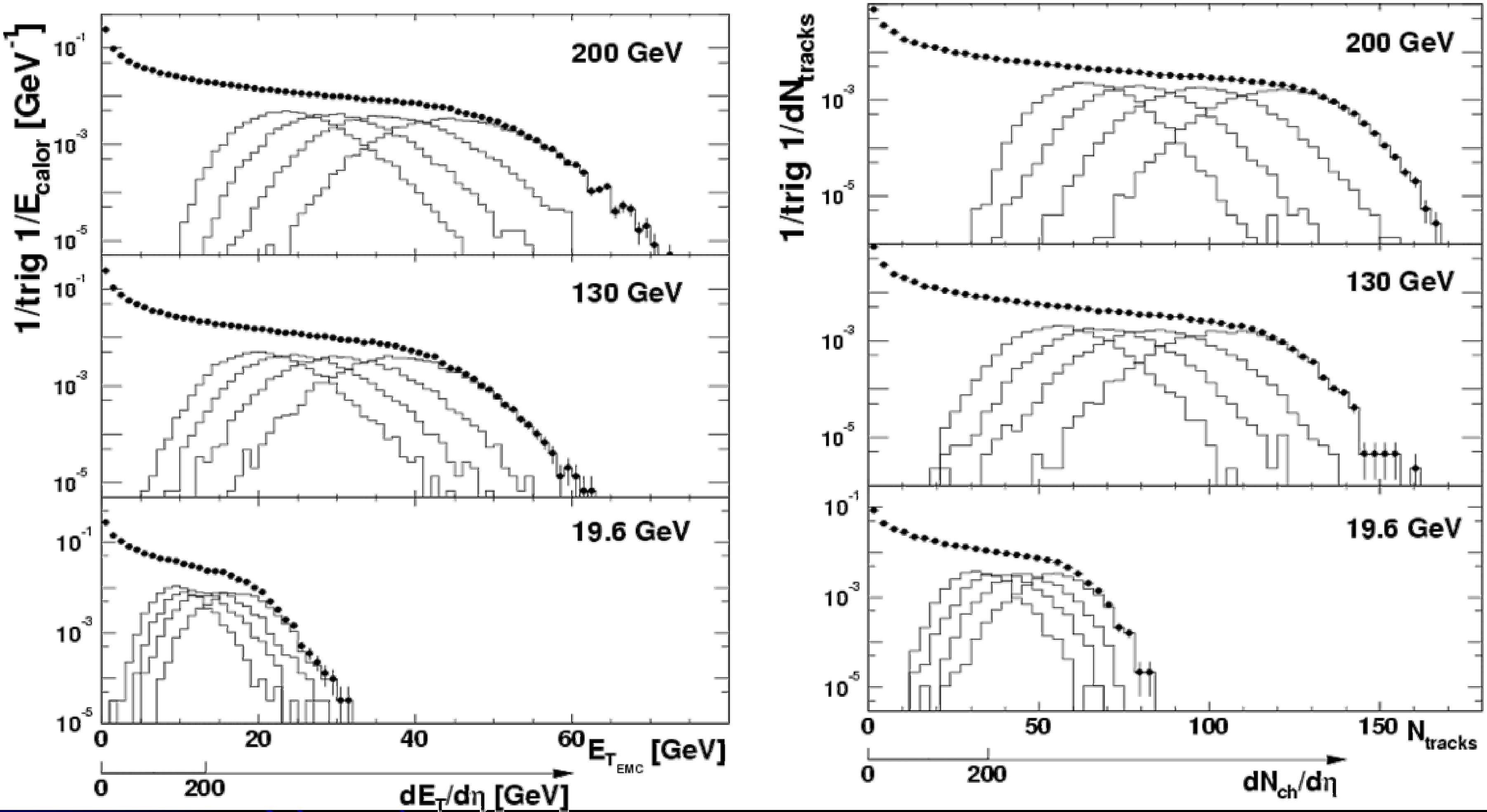


Centrality Determination: <25 GeV

- At low beam energy, the BBC acceptance can cover spectator nucleons, affecting the linearity of the response.
- For 22.5 GeV Cu+Cu, pad chamber 1 is used for the centrality determination.
- Only 4 centrality bins (0-10%, 10-30%, 30-60%, and 60-88% are defined.
- Using PC1 can introduce autocorrelations into some measurements.
- A new centrality detector would be very useful for PHENIX at low energies.

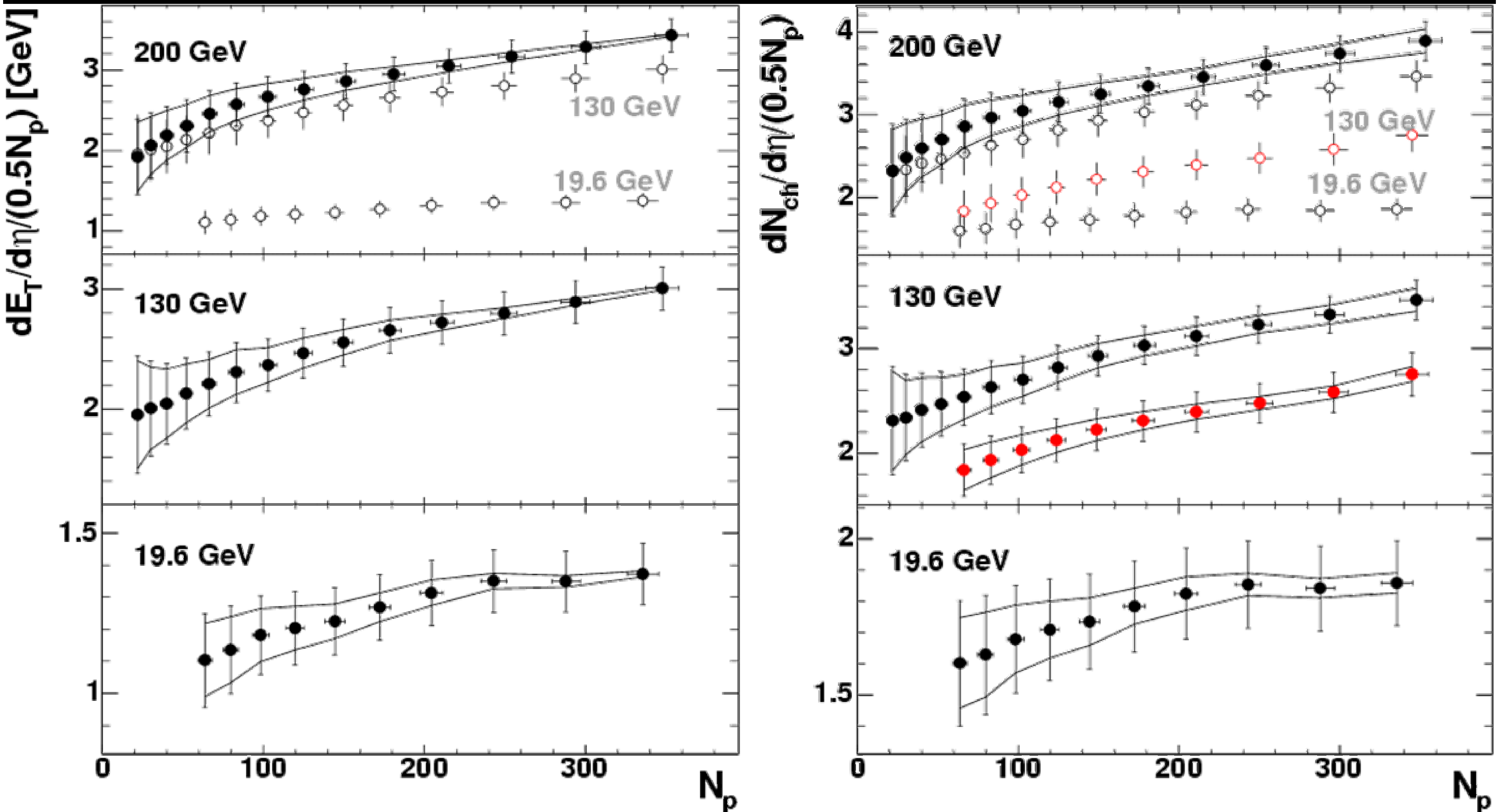


Measurement: Multiplicity



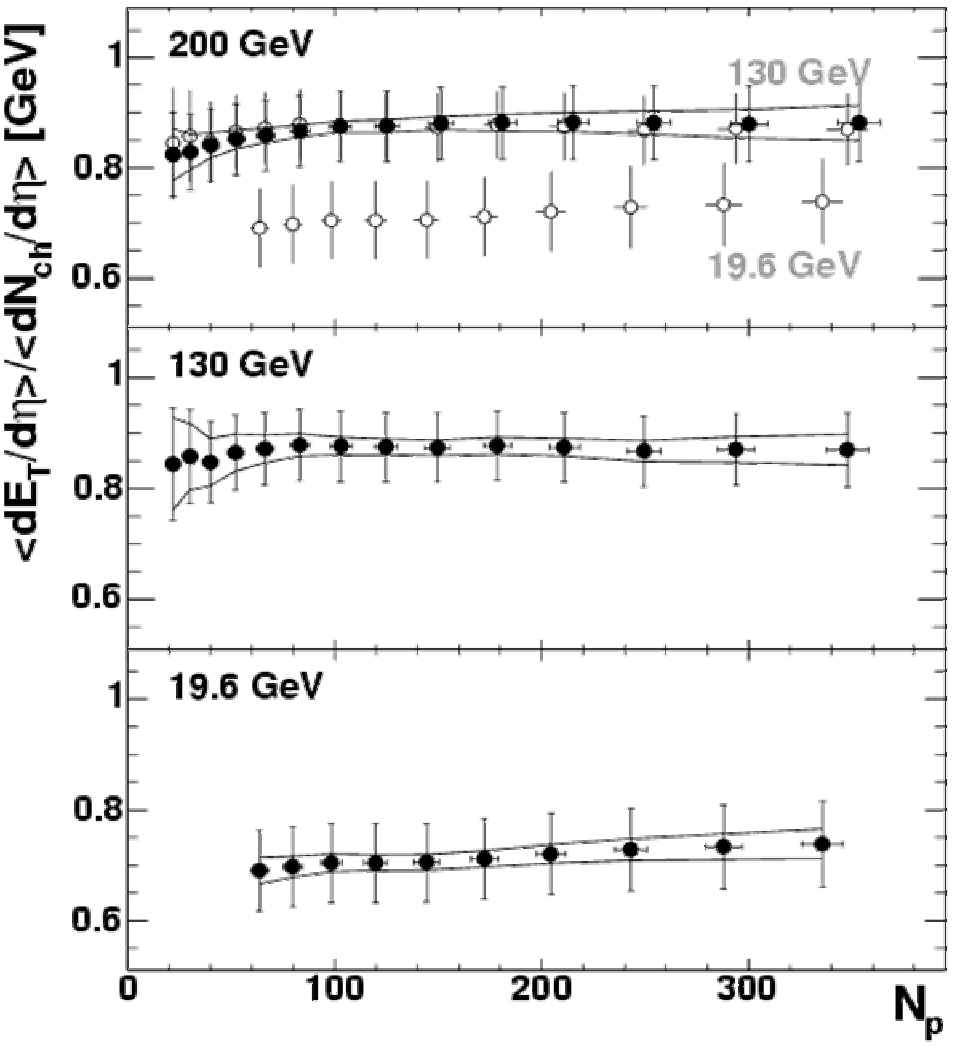
- "Classical" Shape: Peak, Valley, Edge.
- Centrality classes shown.
- Edge might be modified due to acceptance limitation

Measurement: Transverse Energy



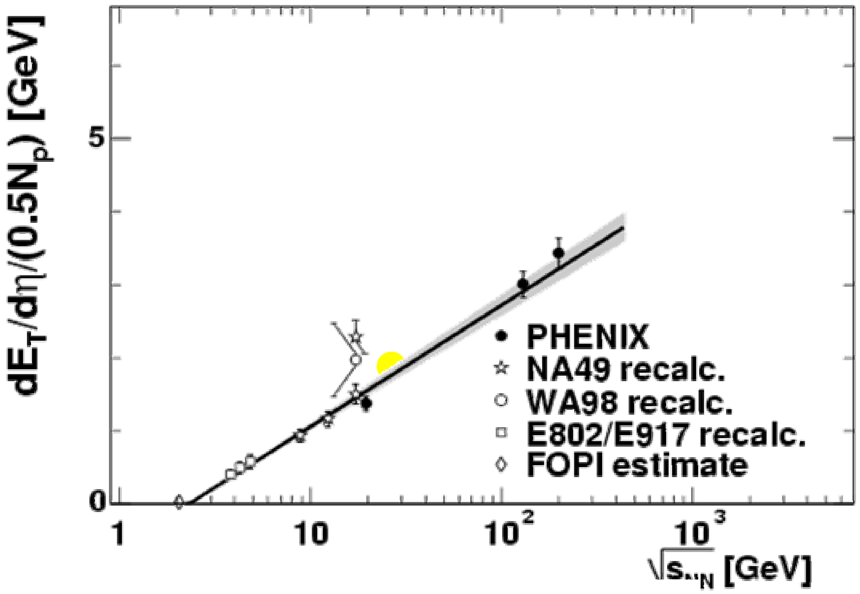
- Consistent behavior for E_T and N_{ch}
- Both increase with energy
- Both show steady rise from peripheral to central

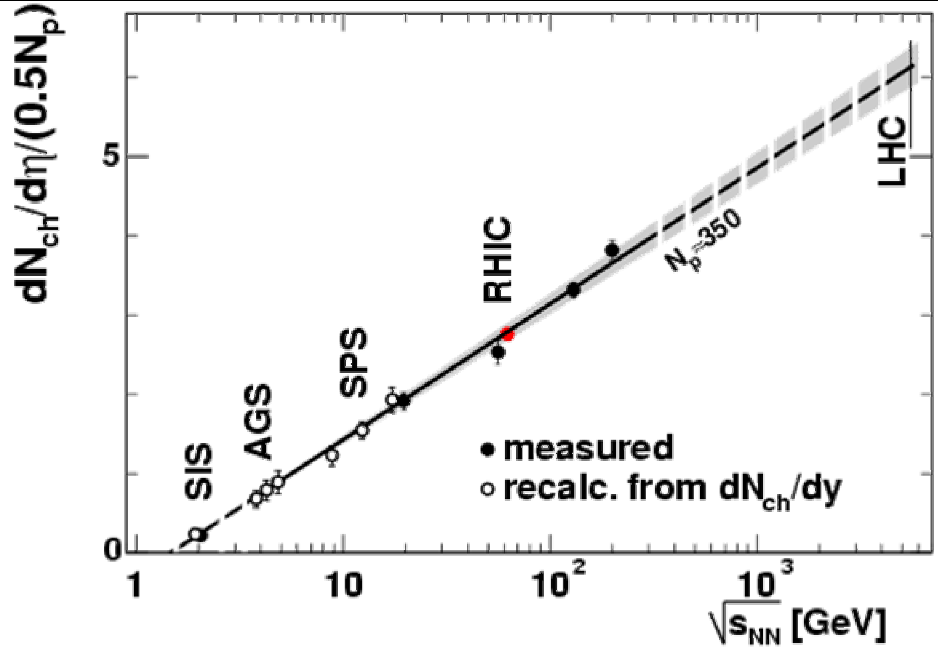
Measurement: $\langle E_T \rangle / \langle N_{ch} \rangle$

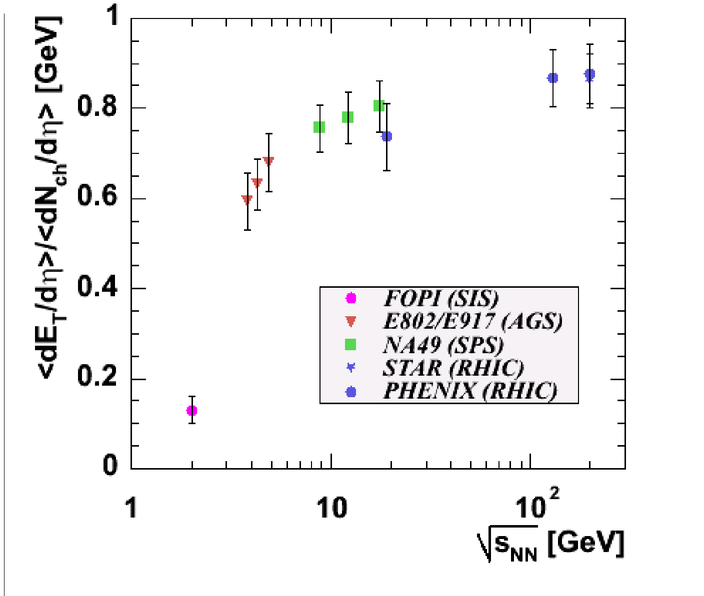


- Ratio $\langle E_T \rangle / \langle N_{ch} \rangle$ increases by ~20% from 19.6 GeV to 200 GeV and stays the same between 200 GeV and 130 GeV
  - Consistent with the average particle momentum increase between those two energies.
- Ratio $\langle E_T \rangle / \langle N_{ch} \rangle$ is independent of centrality
  - Still a puzzle.
  - Same freeze-out conditions?
  - Since trigger and centrality related uncertainties cancel out, the flatness of the curves is quite precise statement.

$\sqrt{s_{NN}}$ dependence



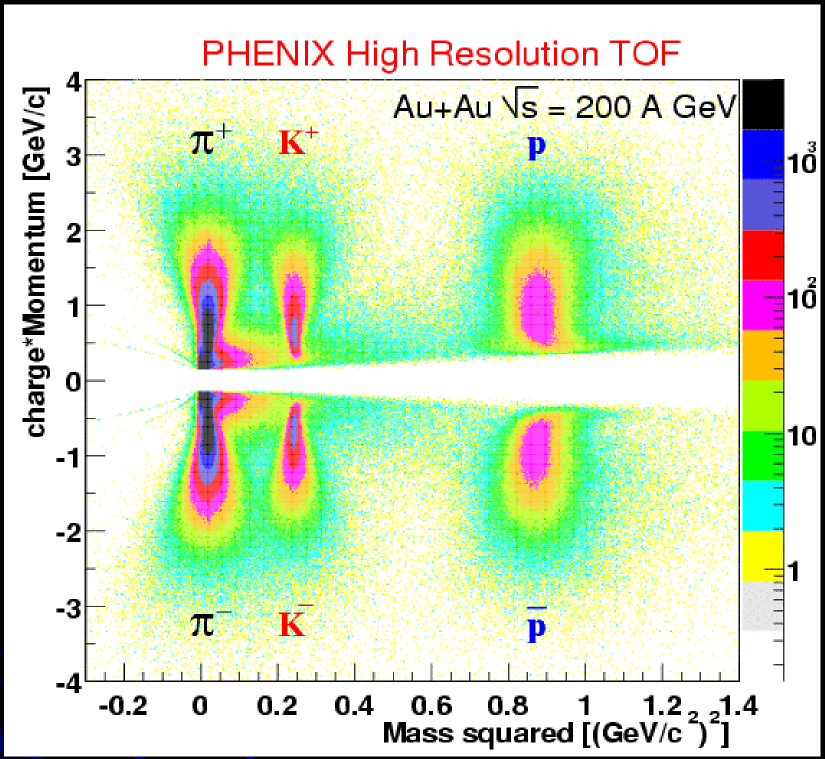


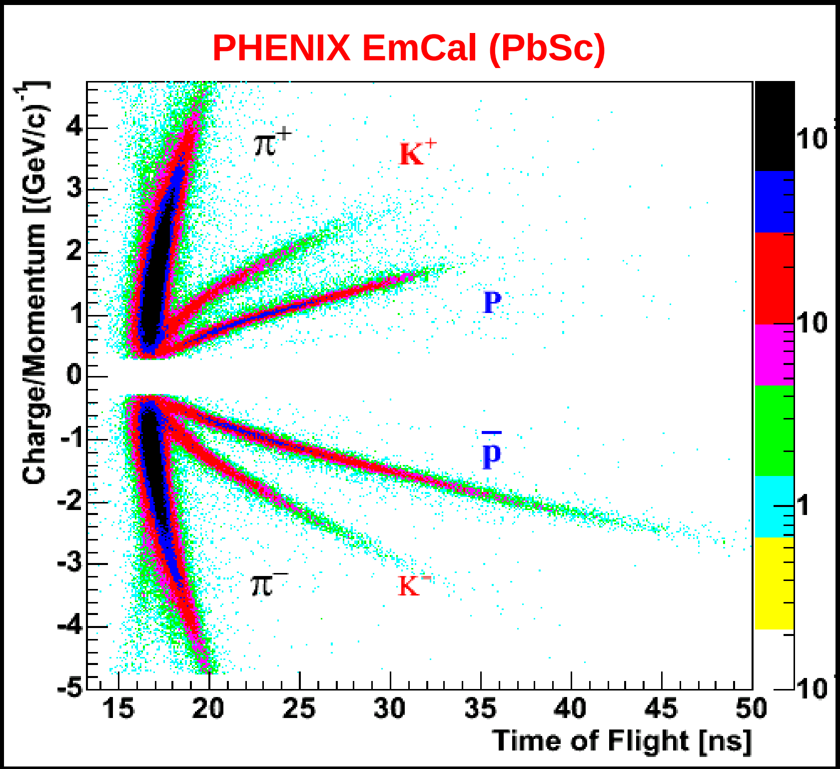


- PHENIX suggested $\ln(s_{NN})$ at QM01 and it works well with better and larger data-set.
- Both in E_T and in N_{ch} show log-scaling.
- Works even better on N_{ch} for N_p = 350.

  Band on the right is 2σ error!
- Extrapolation to LHC $dN_{ch}/d\eta$ = (6.1±0.13)×(0.5Np).
- Extrapolation to lowest energy gives:
  - for E_T: $\sqrt{s^0_{NN}}$ = 2.35 ± 0.2 GeV
  - for N_{ch}: $\sqrt{s^0_{NN}}$ = 1.48 ± 0.02 GeV

Charged hadron identification in PHENIX

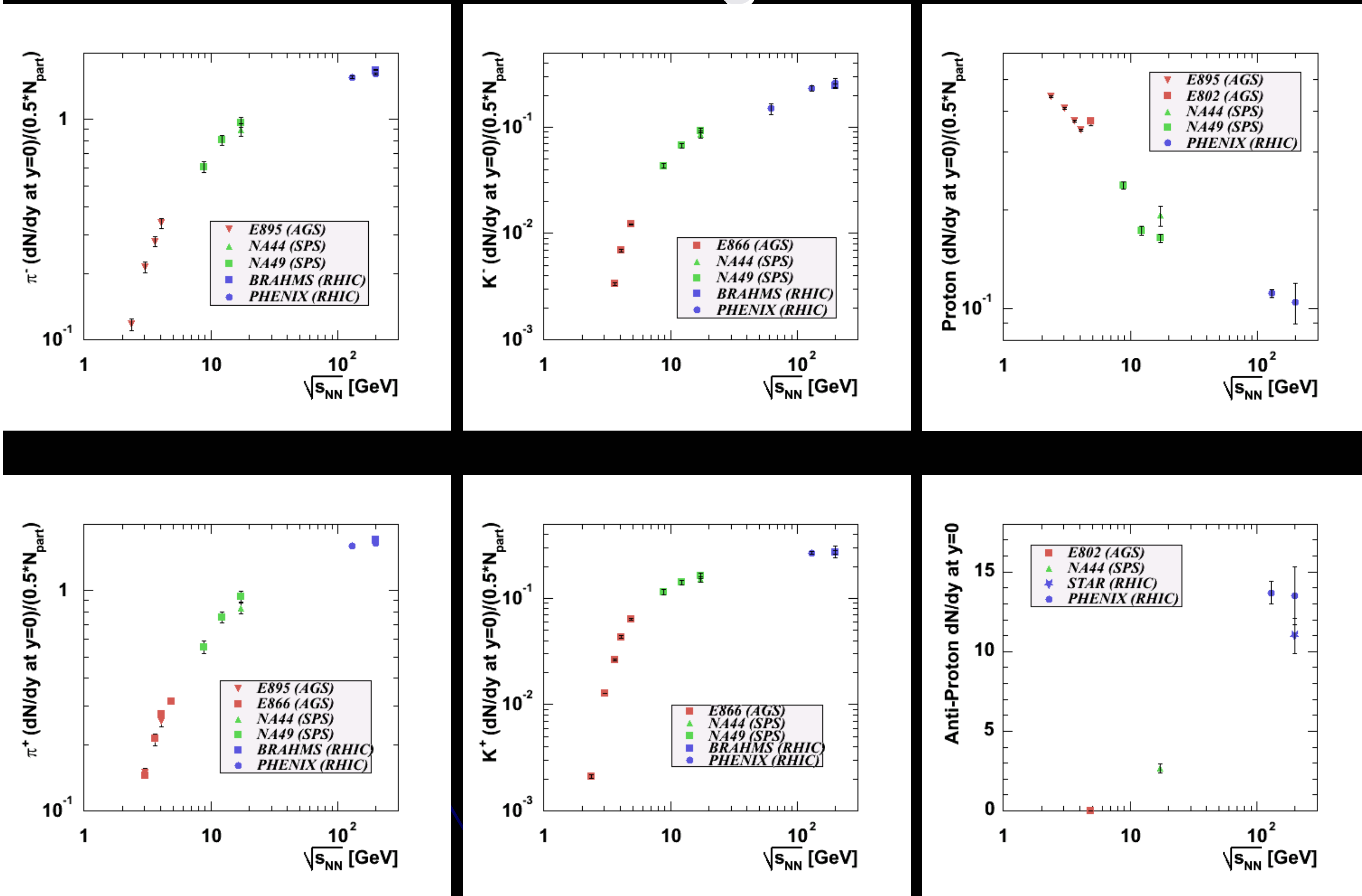




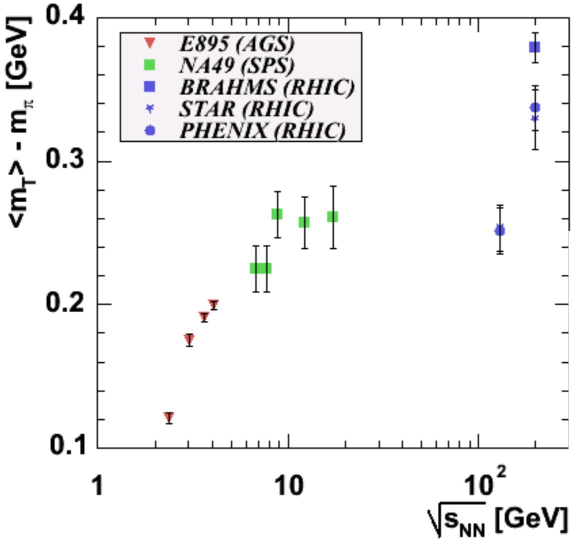
Time of Flight
- π/K separation ~ 3 GeV/c
- K/p separation ~ 5 GeV/c

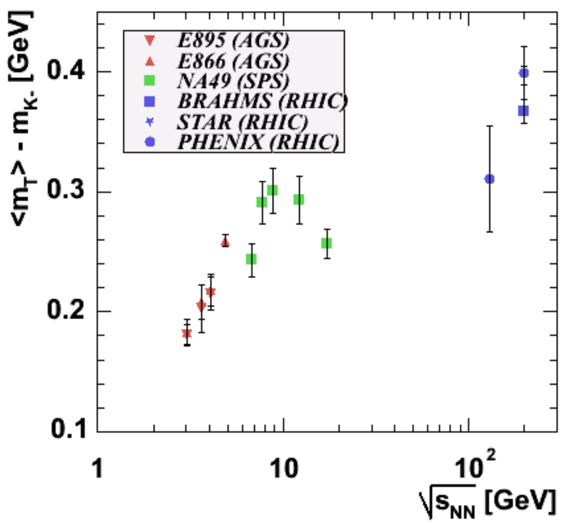
Electromagnetic Calorimeter
- π/K separation ~ 1 GeV/c
- K/p separation ~ 2 GeV/c

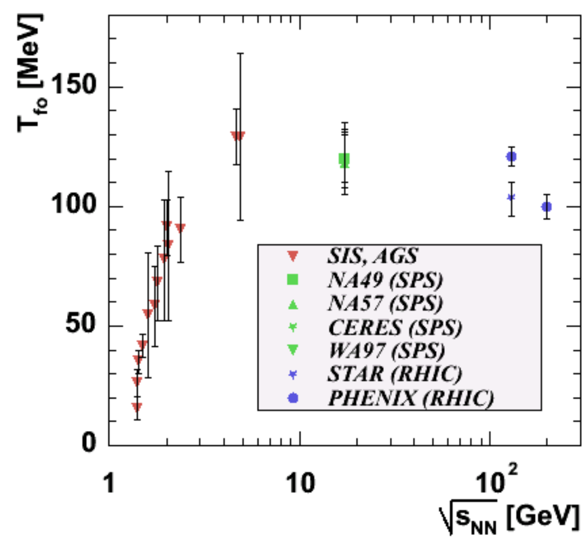
Measurement: Charged Hadron Yields

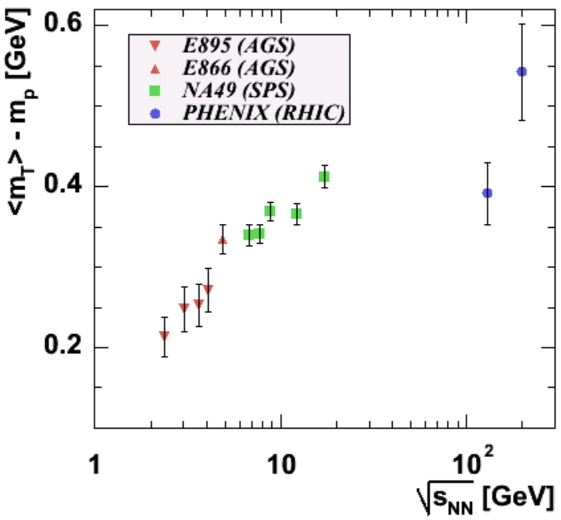


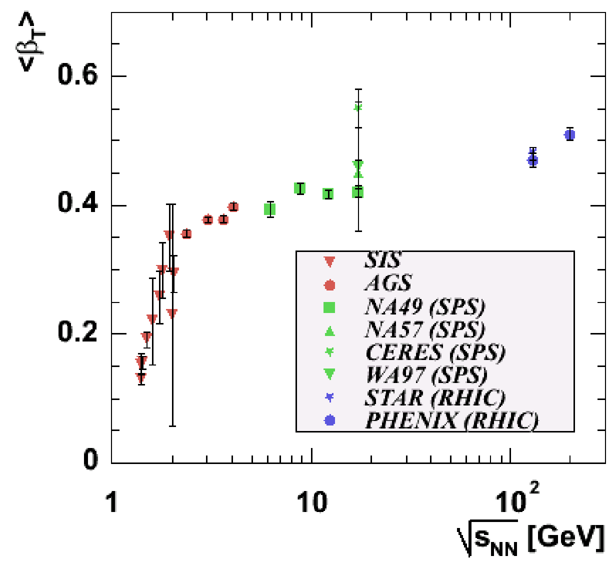
Measurement: Charged Hadron Spectra



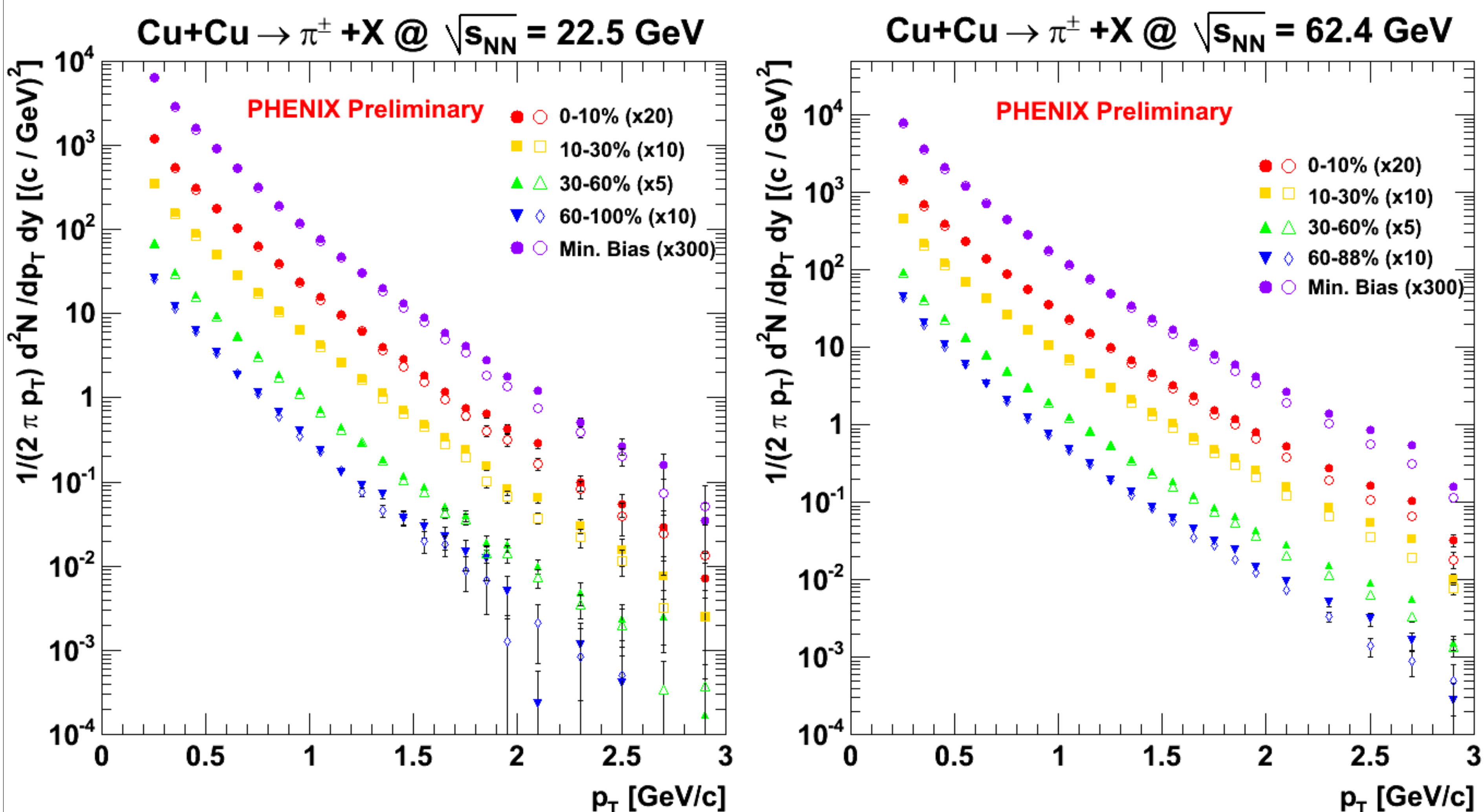






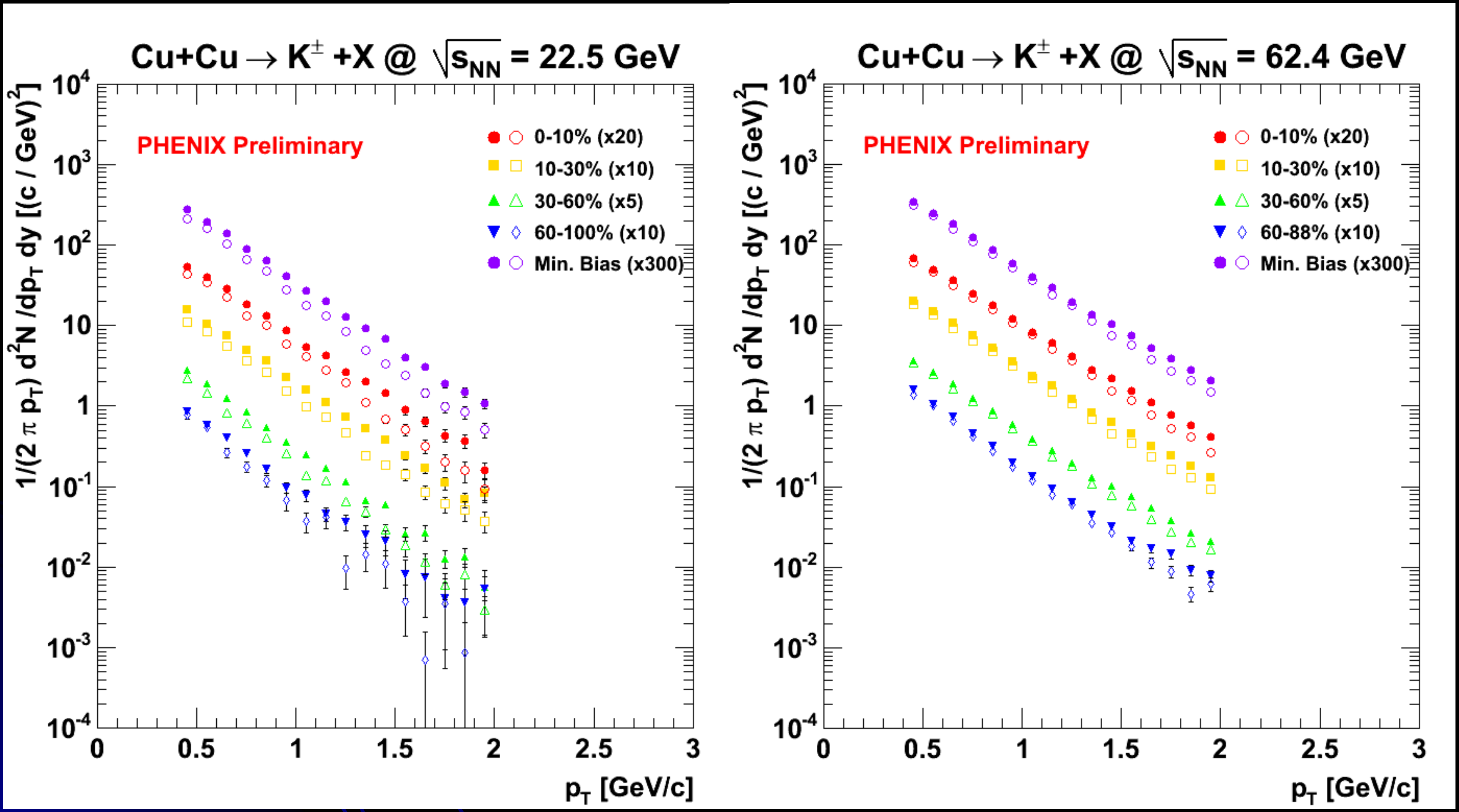


Measurement: p_T spectra for pions



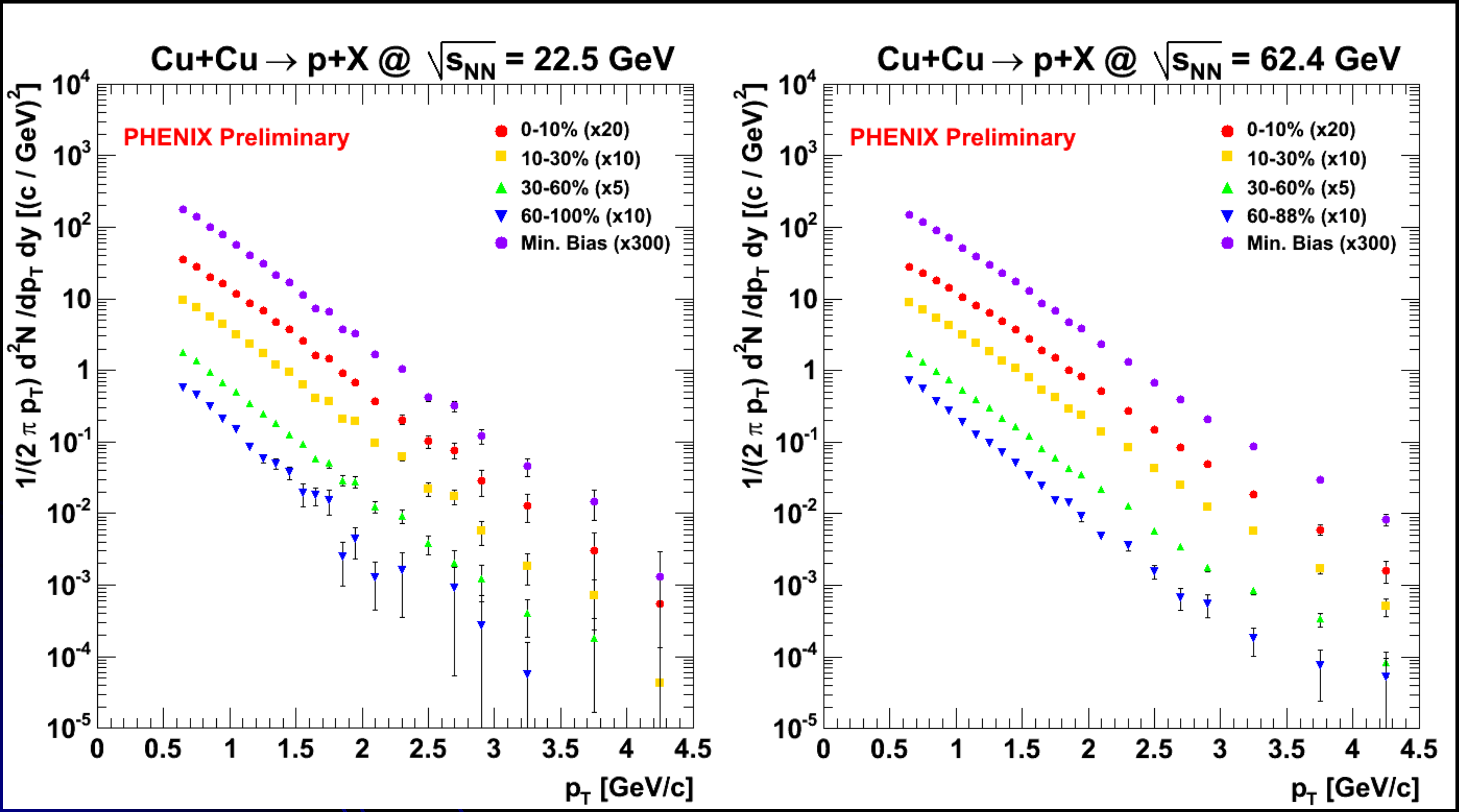
Filled symbols : π^+
Open symbols : π^-

Measurement: p_T spectra for kaons



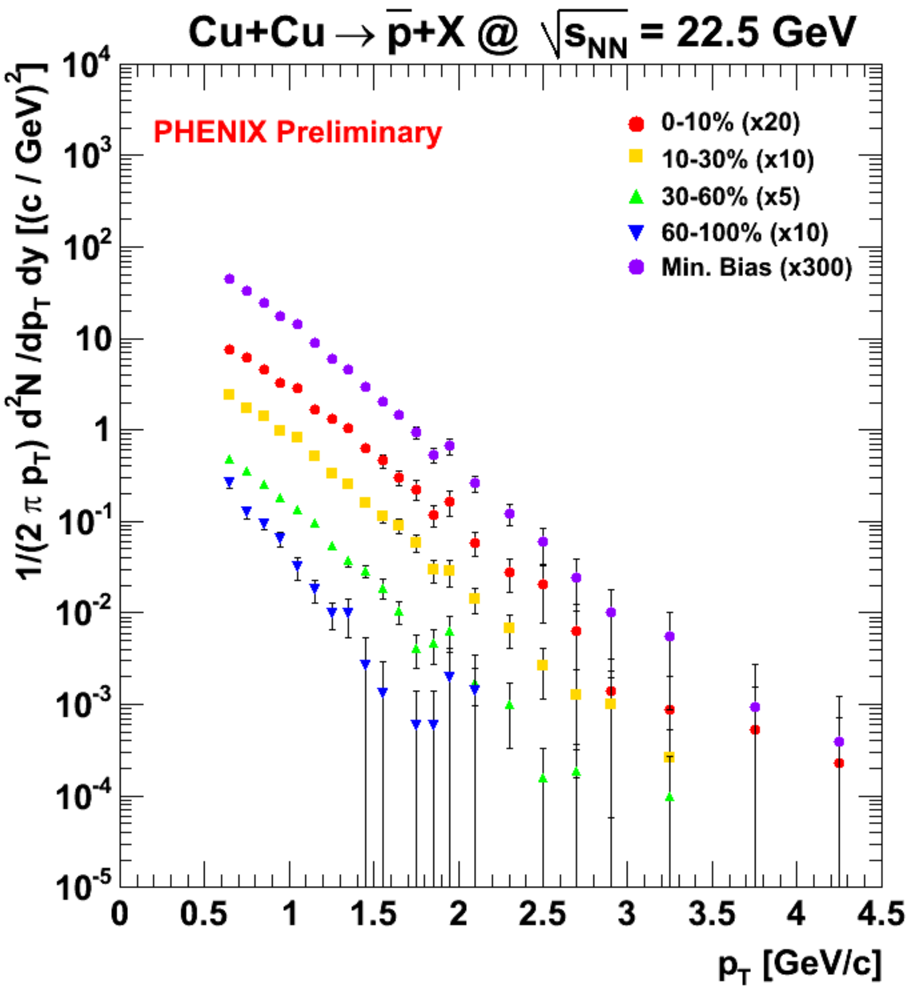
Filled symbols : K^+
Open symbols : K^-

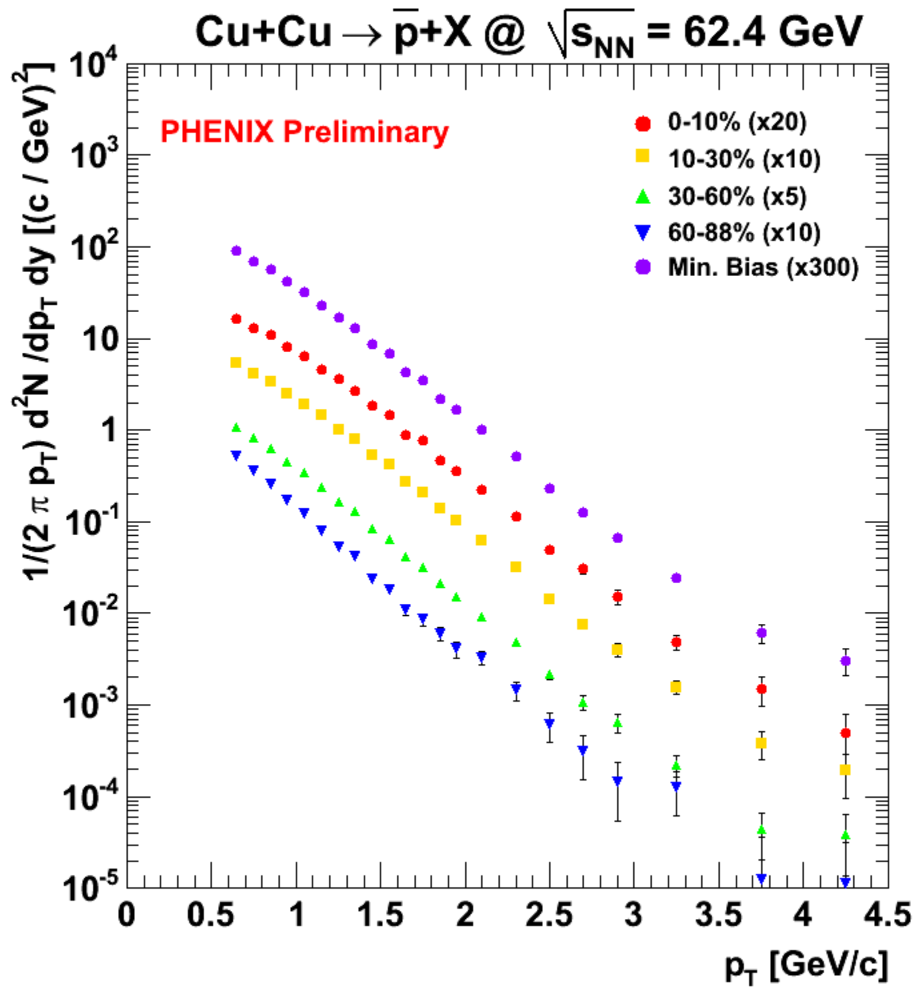
Measurement: p_T spectra for protons



*** No weak decay feed-down correction applied**

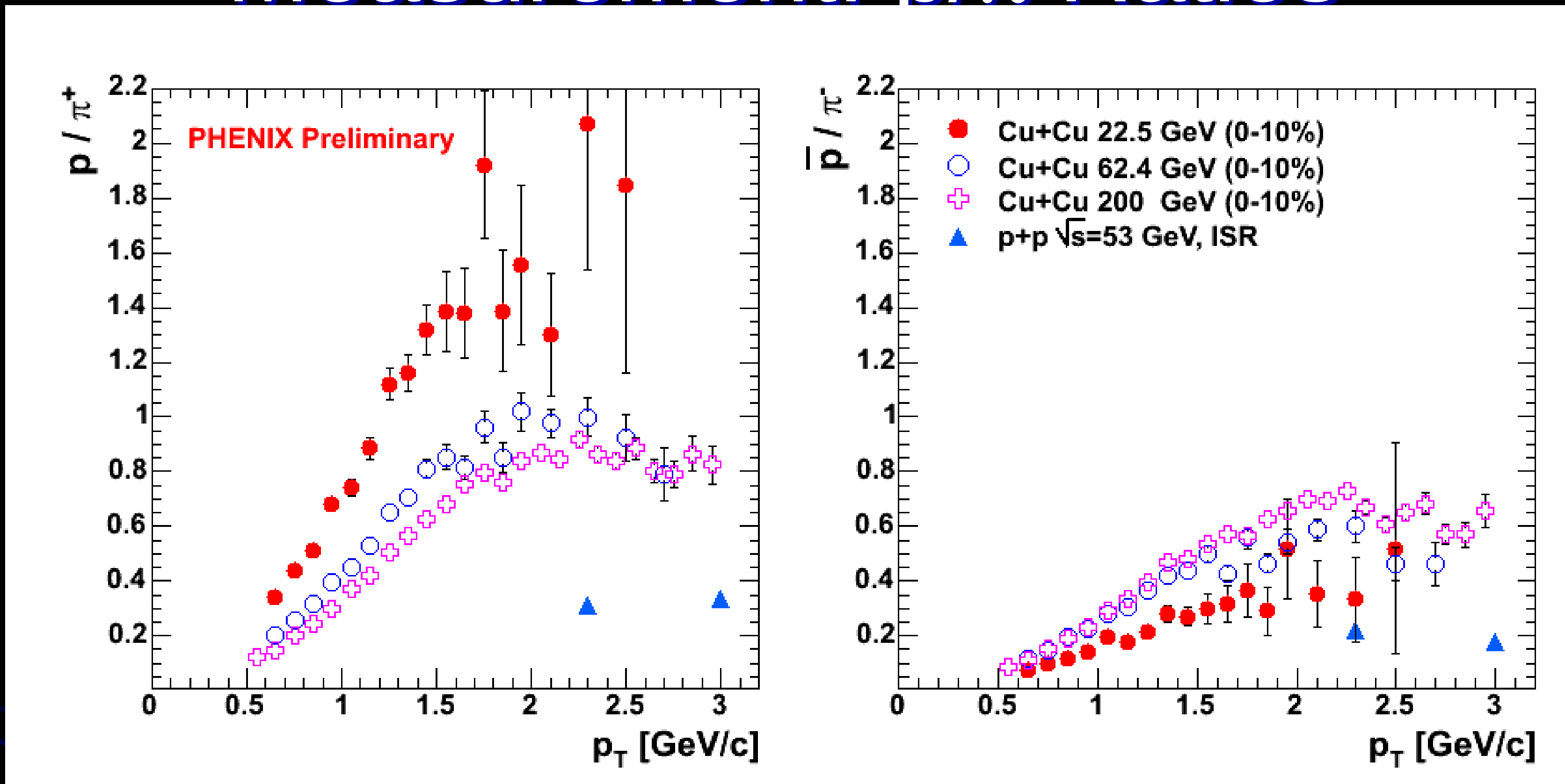
Measurement: p_T spectra for antiprotons



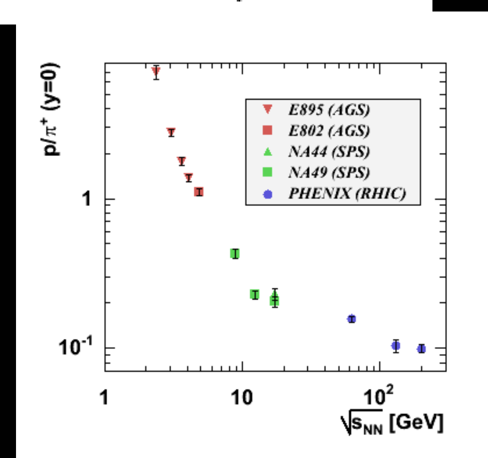


* No weak decay feed-down correction applied

Measurement: p/π Ratios

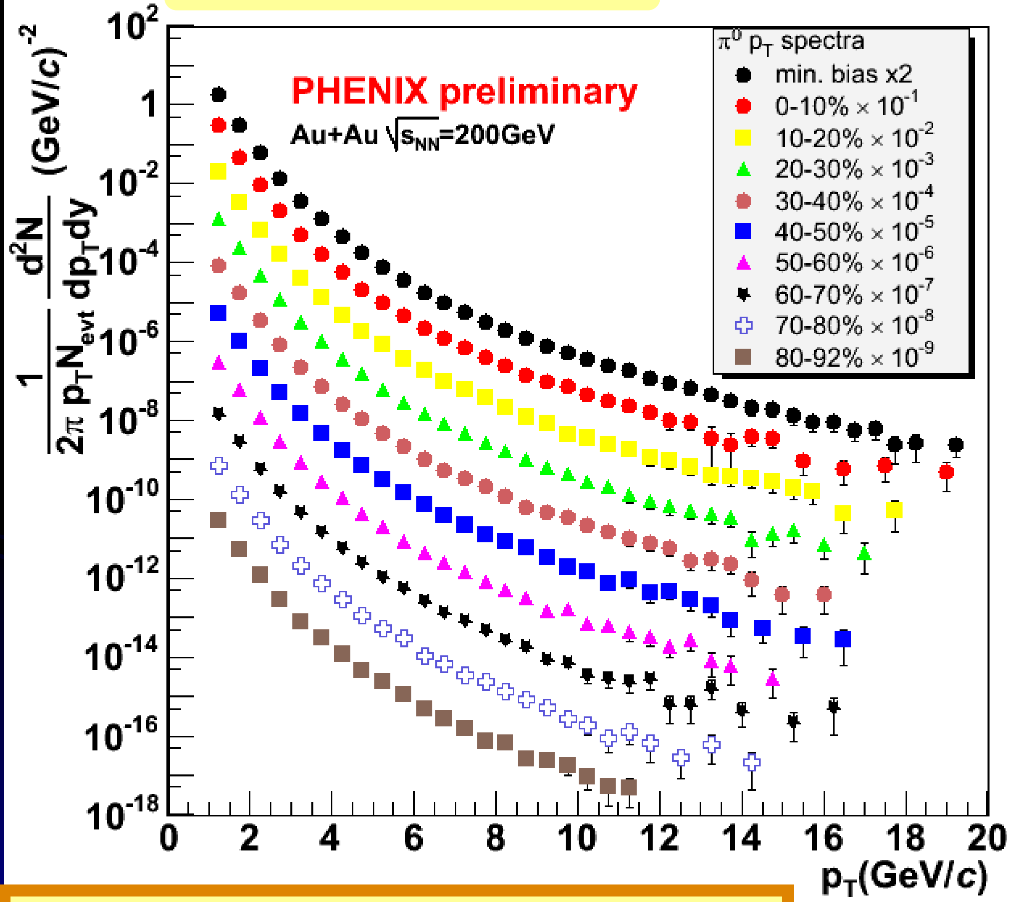


- **p/π^+ ratio** : decreasing as a function of $\sqrt{s_{NN}}$.
- **$\bar{p}/\pi^-$ ratio** : increasing as a function $\sqrt{s_{NN}}$.
  - Cu+Cu 22.5 GeV central data reaches the p+p values.
  - Cu+Cu 62.4 GeV central data is higher than that in 22.5 GeV.



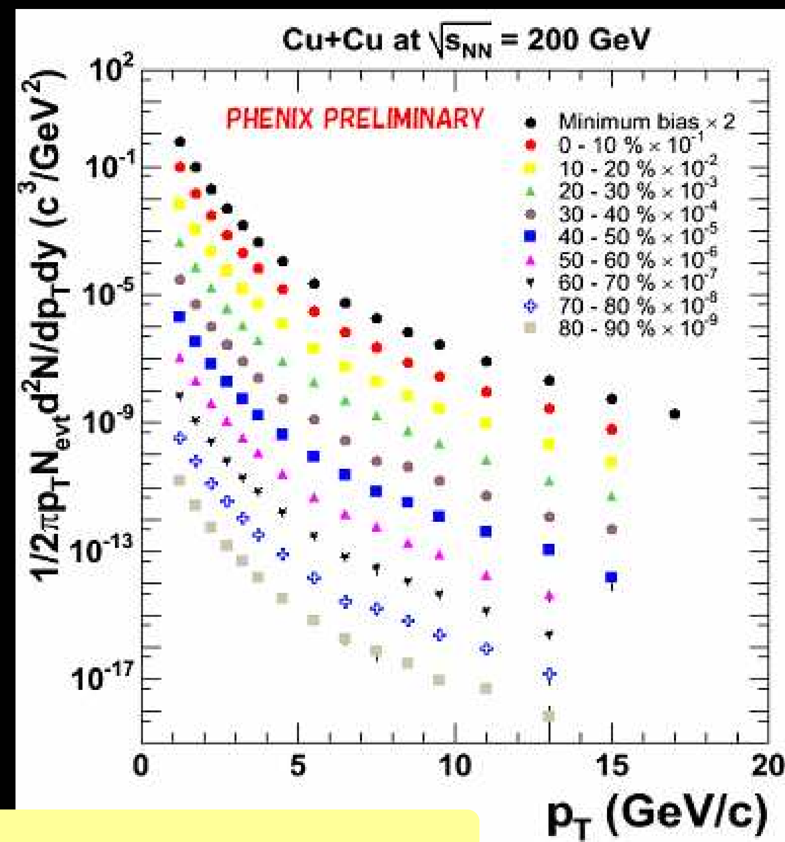
Measurement: π^0 p_T Spectra

New Run4 Data



<u>Au+Au 200 GeV</u>
Luminosity 241μb-1 (sampled)
1.5B events

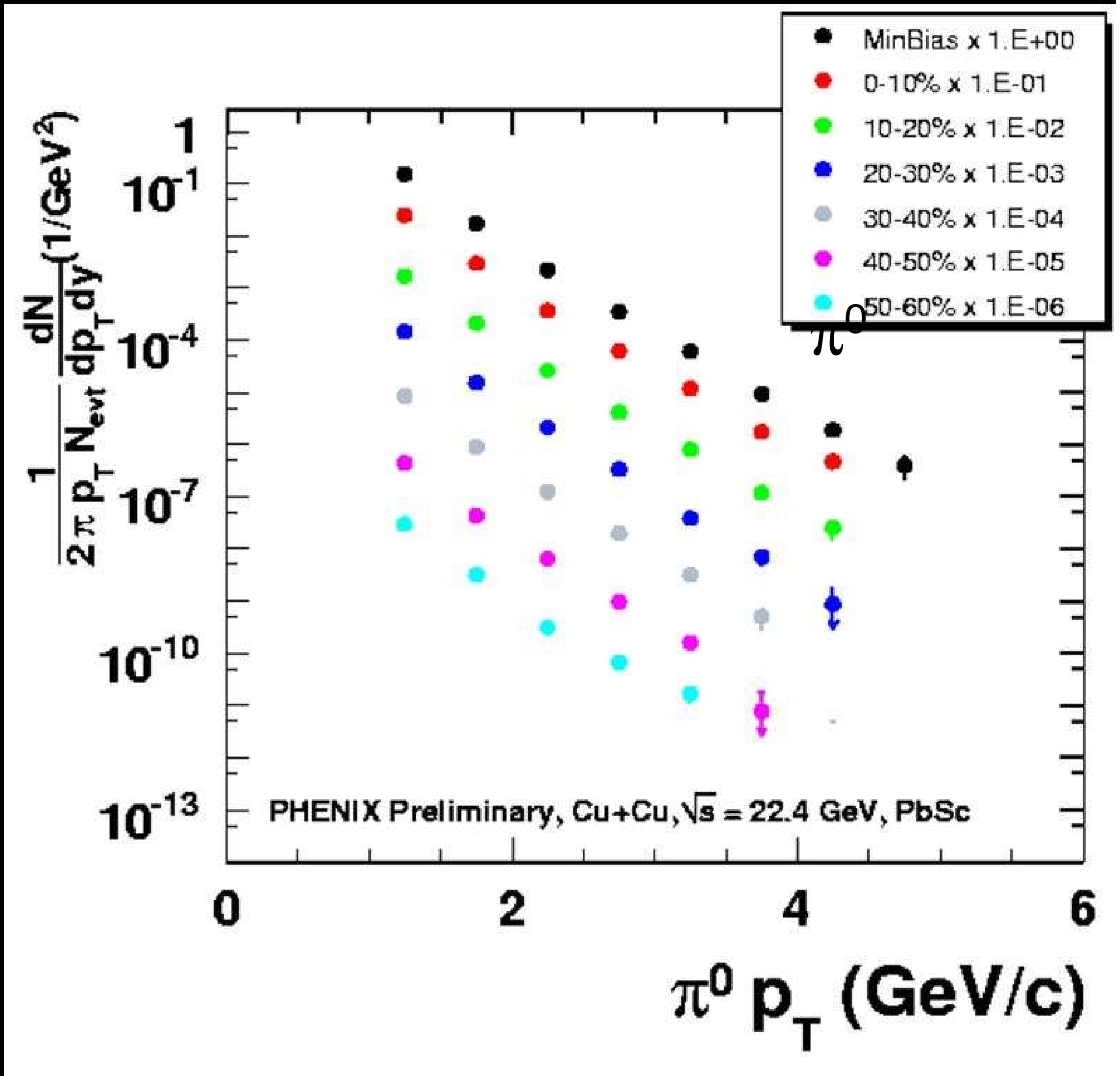
<u>Cu+Cu 200 GeV</u>
2.2 B sampled



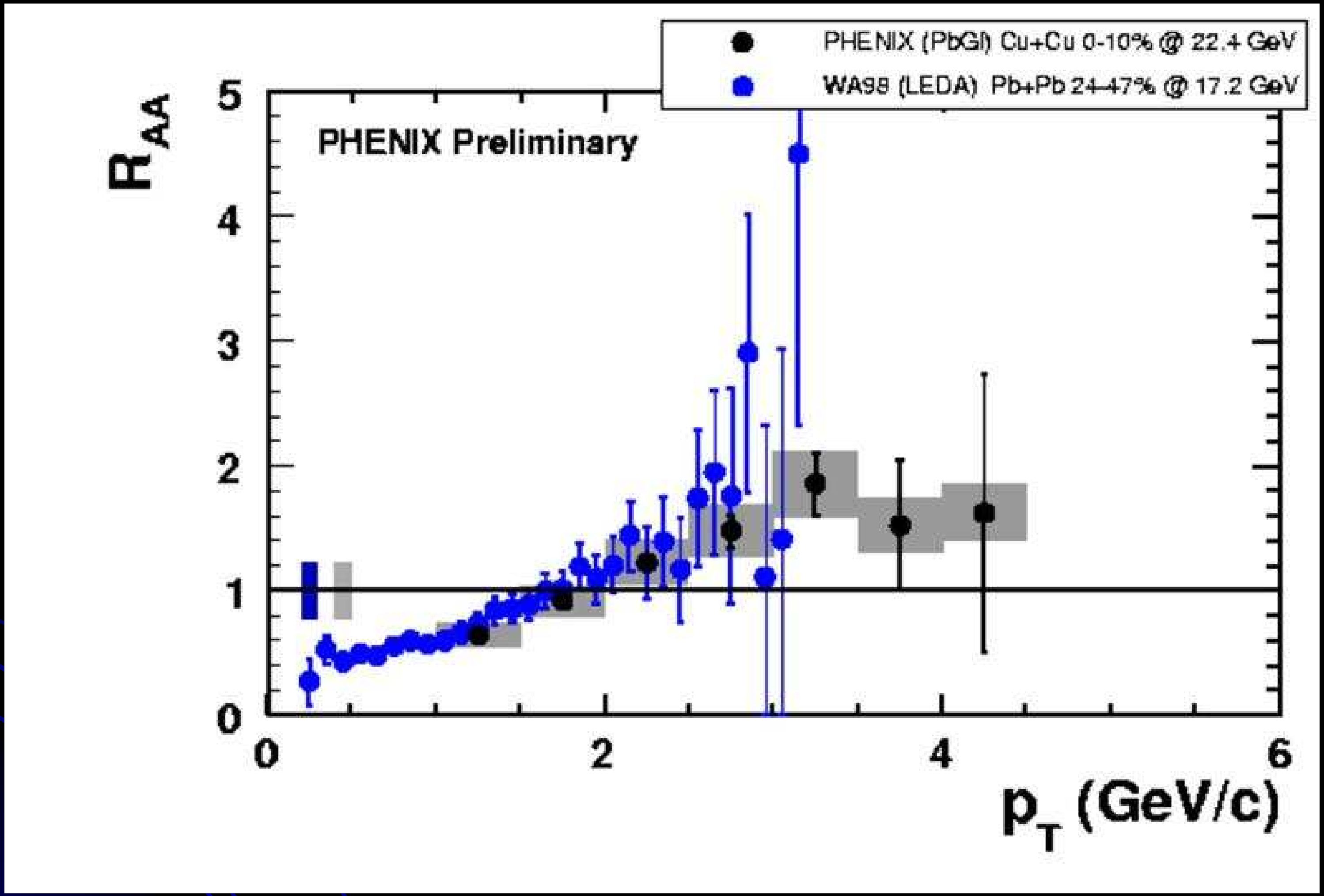
New Run5 Data

Measurement: π^0 p_T Spectra

- Go near SPS Energies
  - p+p data at 21.7 – 23 GeV
  - Use of parameterization as reference
- 3 days of RHIC Run5
  - 6.8M Events after quality cuts
  - Centrality via PC1 multiplicity



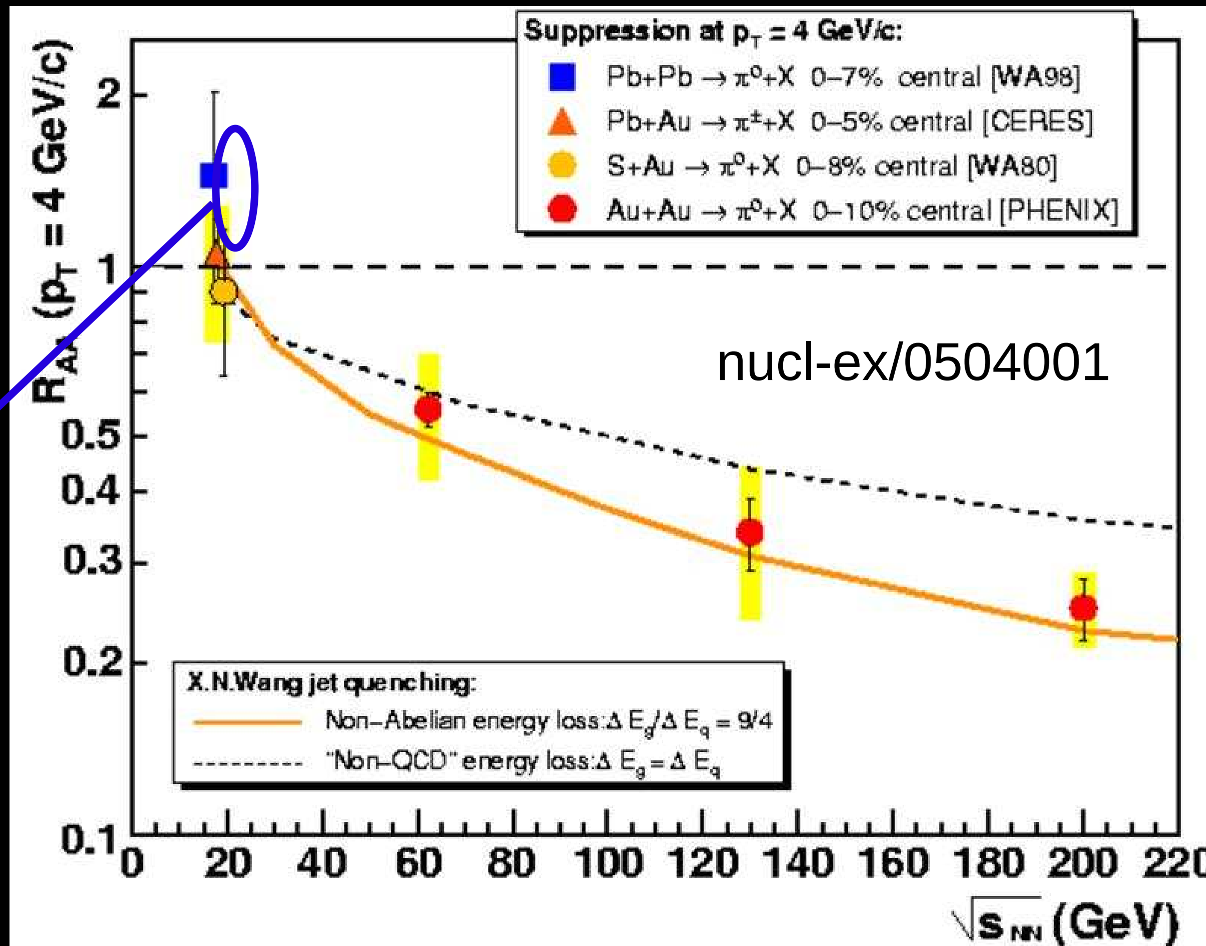
Measurement: π^0 R_{AA}



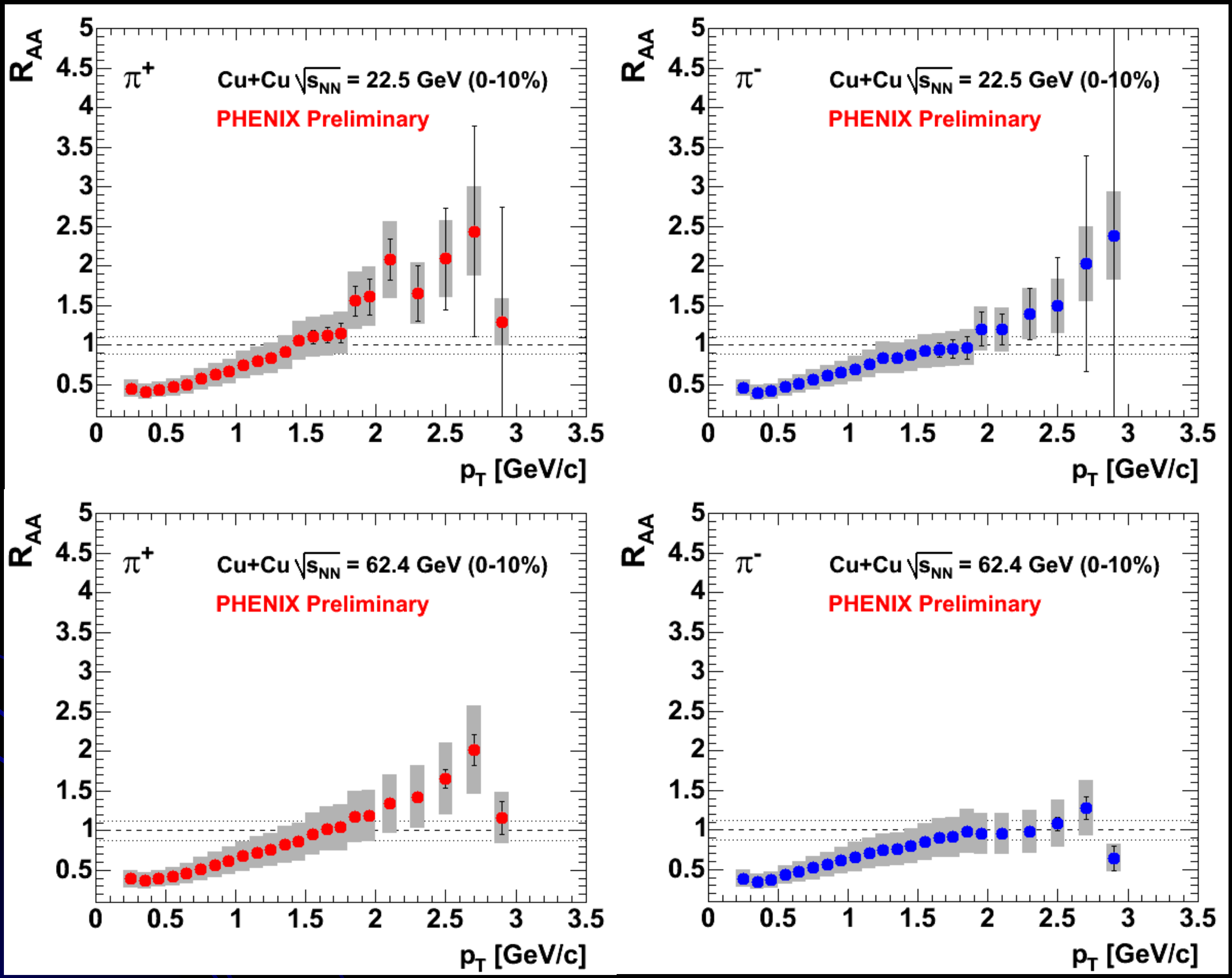
Similar N_{part} (WA98 : 132, PHENIX: 140)
same behaviour

Measurement: π^0 R_{AA}

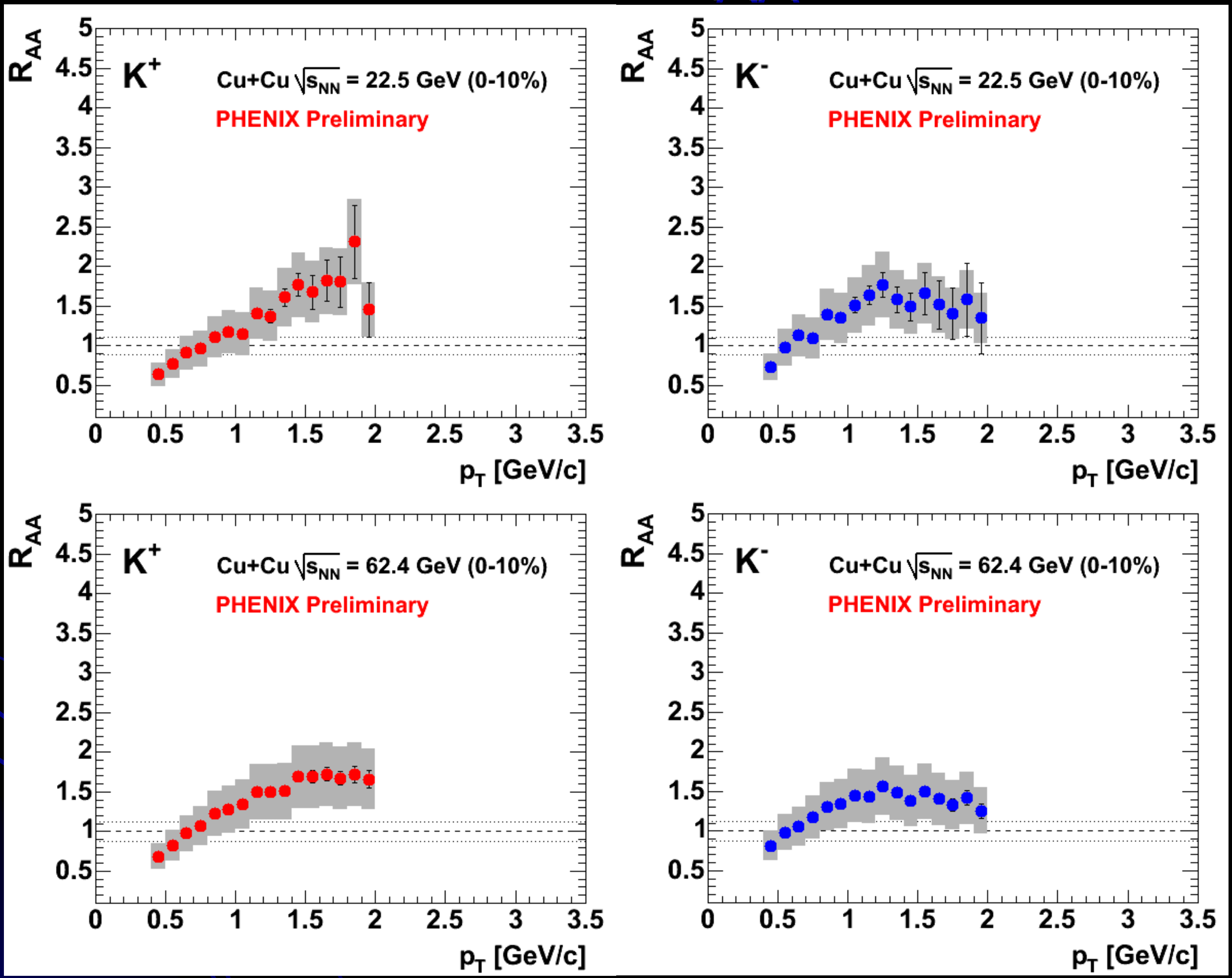
Cu+Cu @ 22.4 GeV
consistent with SPS
(NB: different system size)



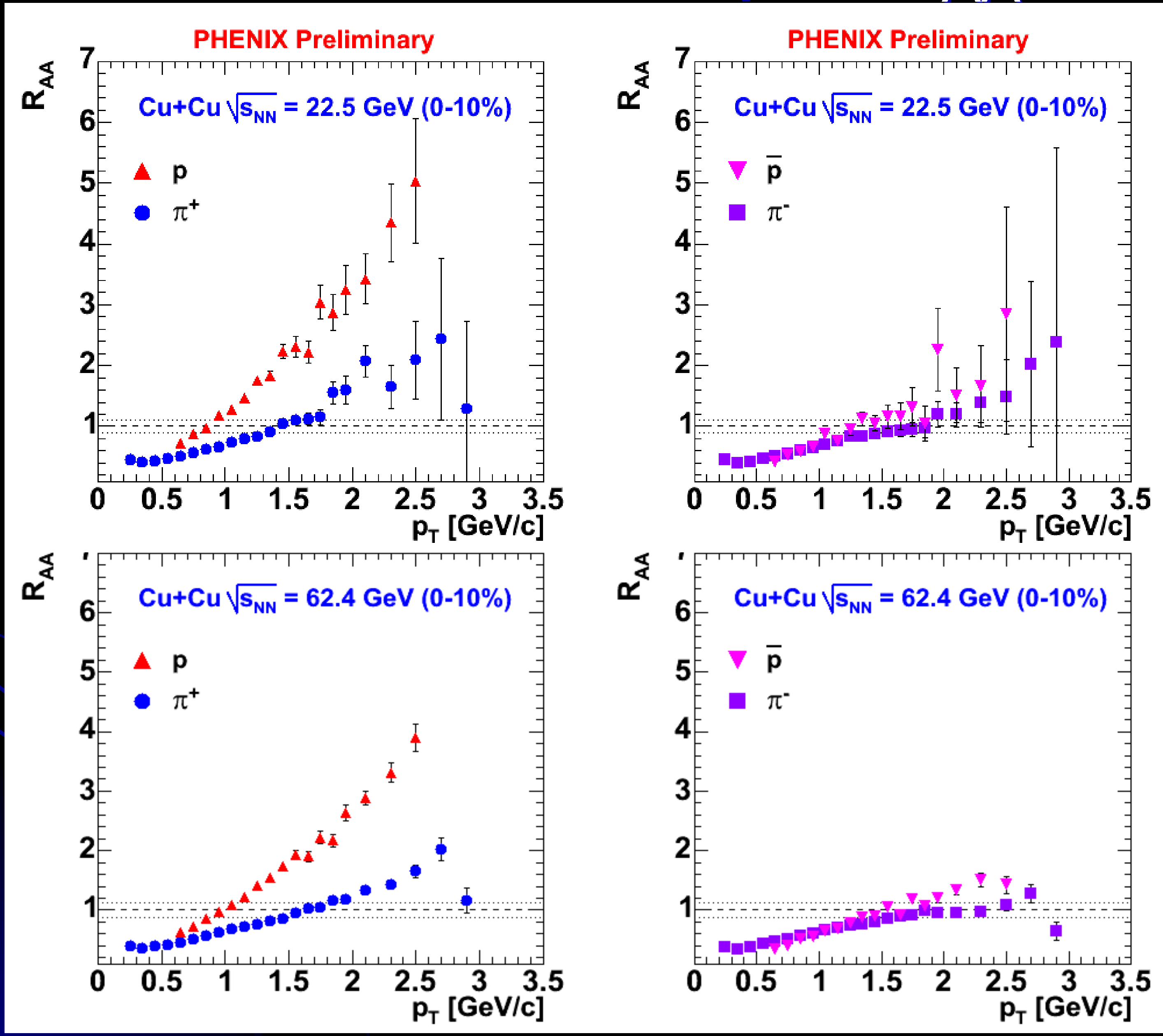
Measurement: R_{AA} for pions



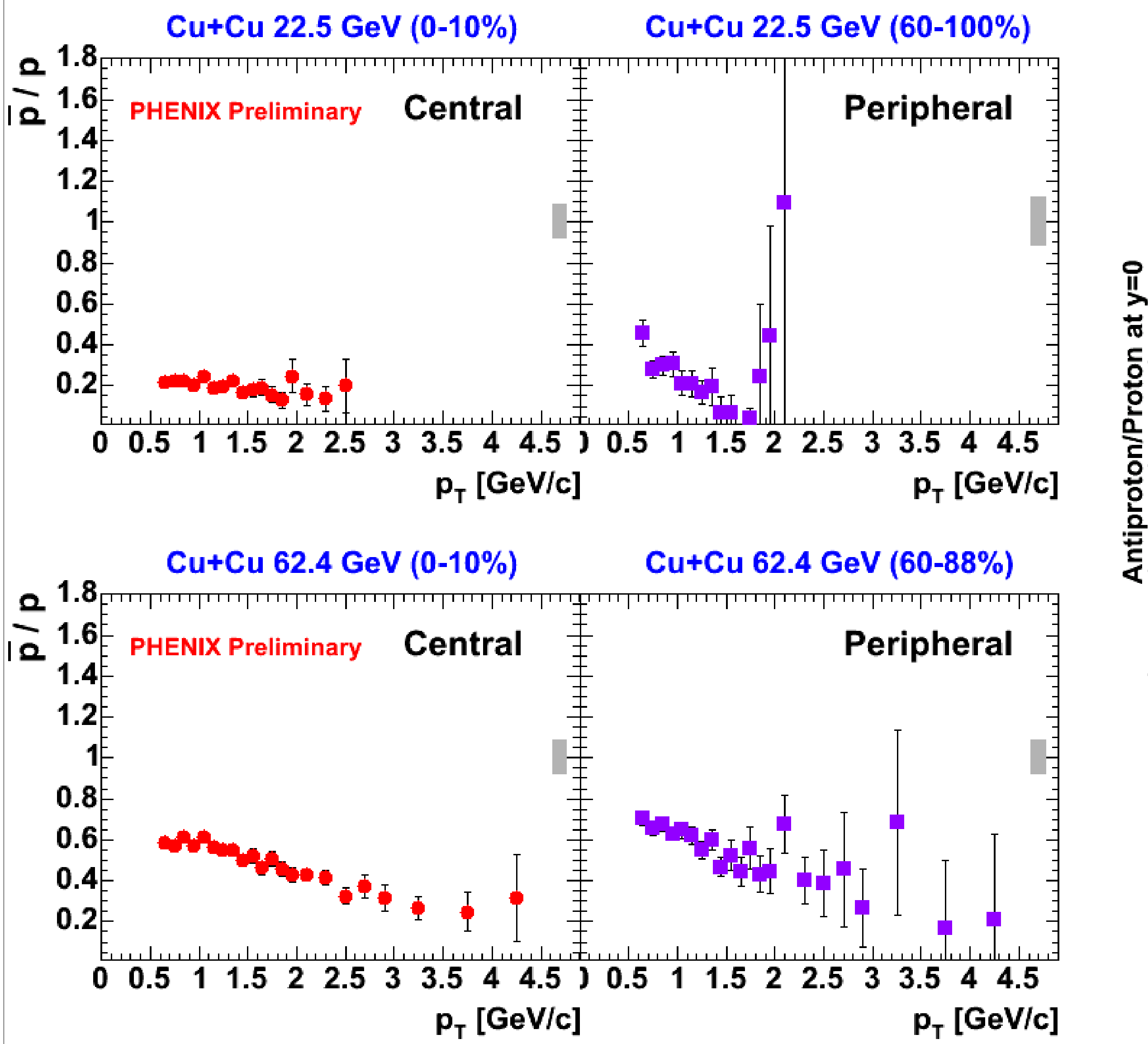
Measurement: R_{AA} for kaons

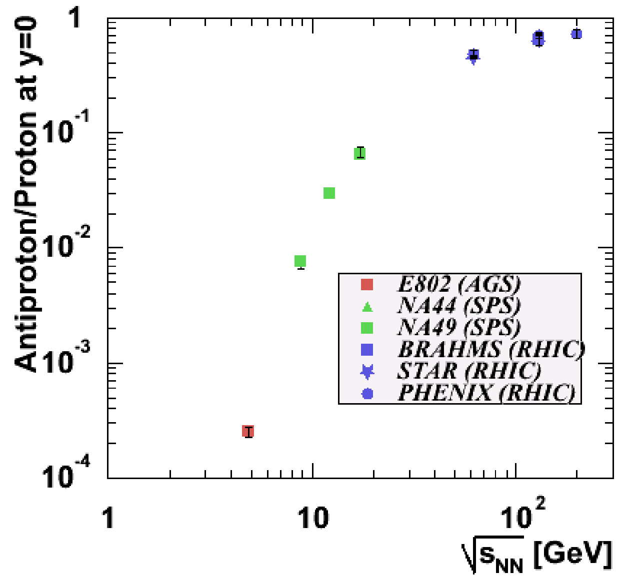


Measurement: p,π R_{AA}

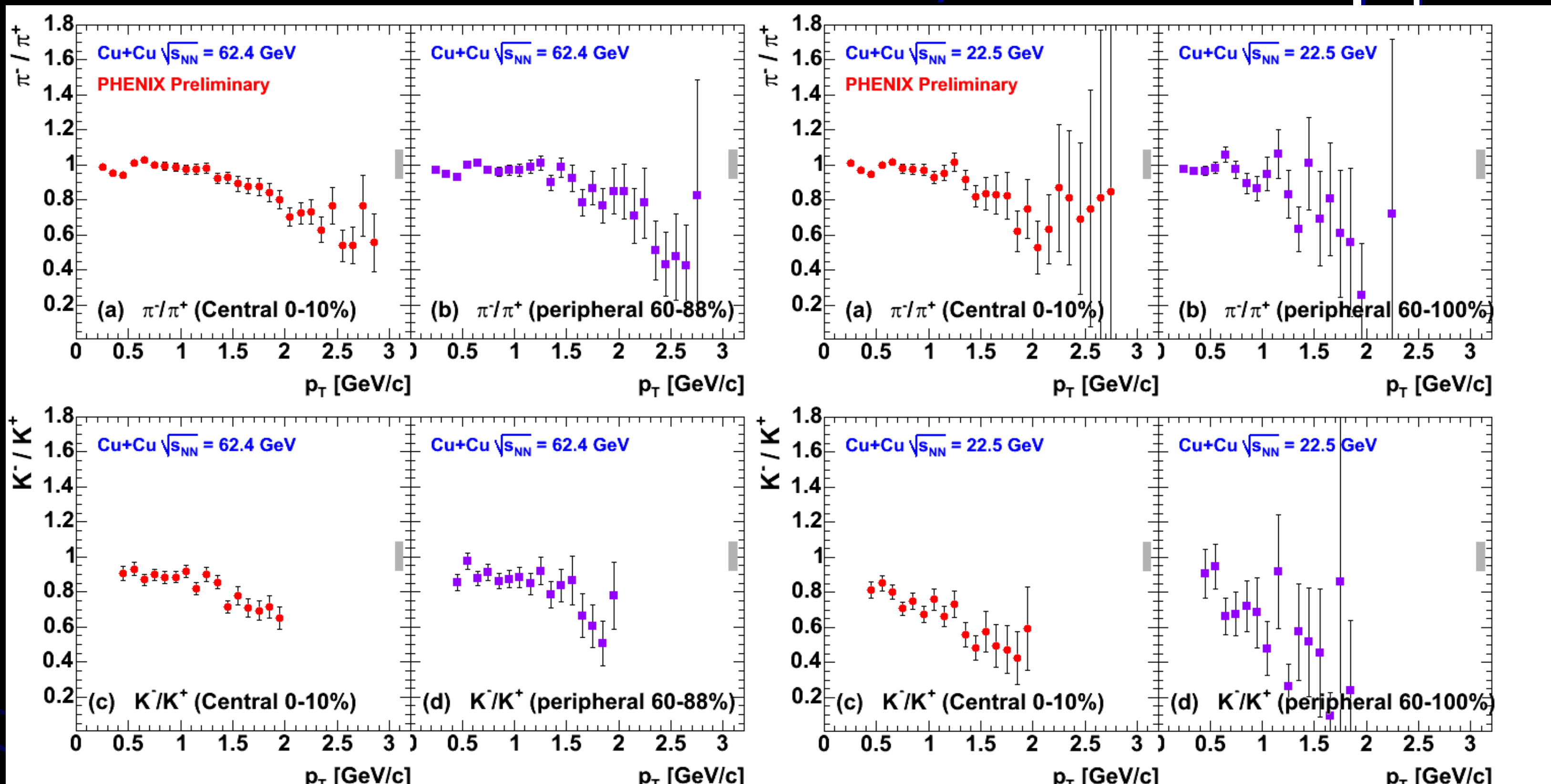


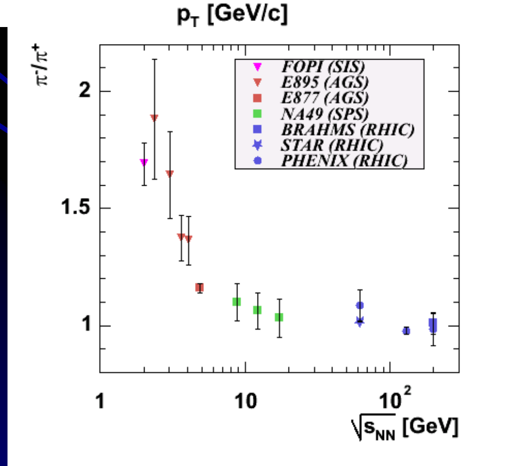
Measurement: pbar/p ratio vs. p_T

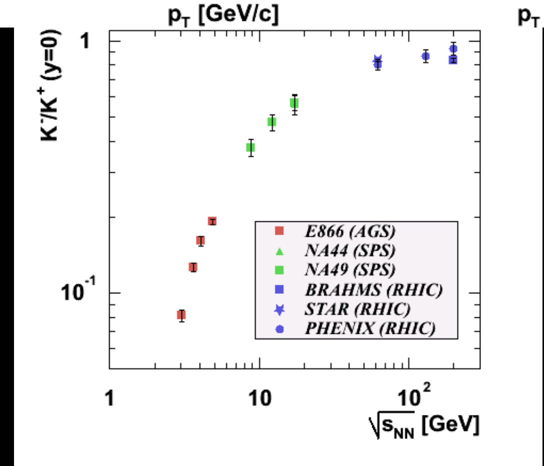




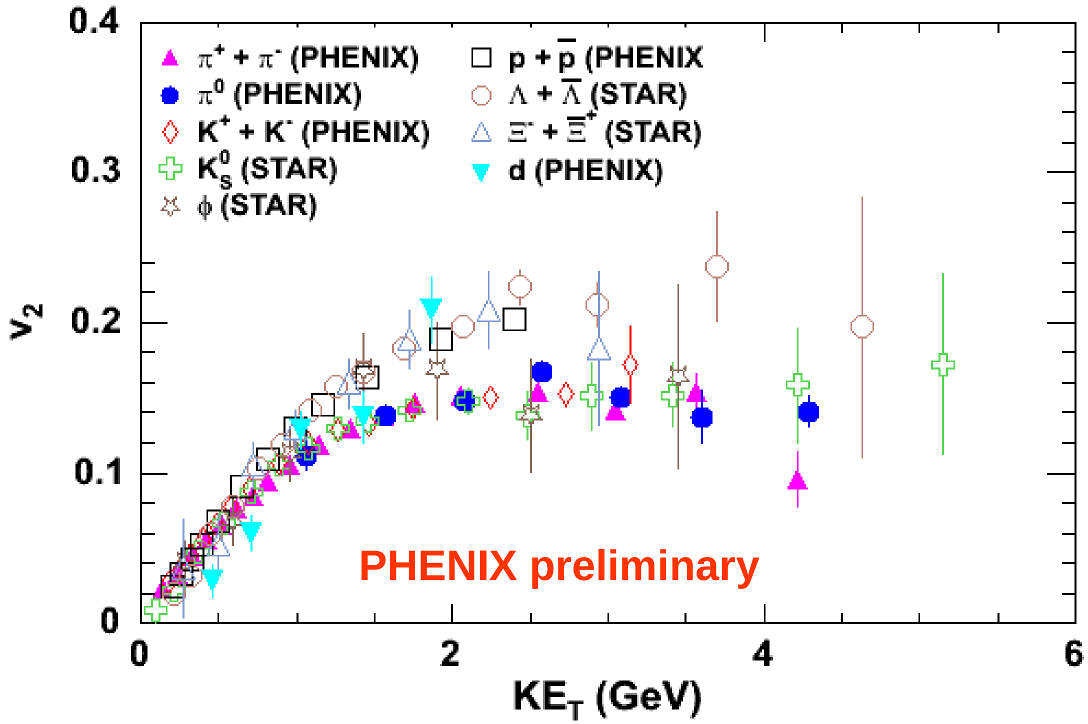
Measurement: π^-/π^+, K^-/K^+ vs. p_T

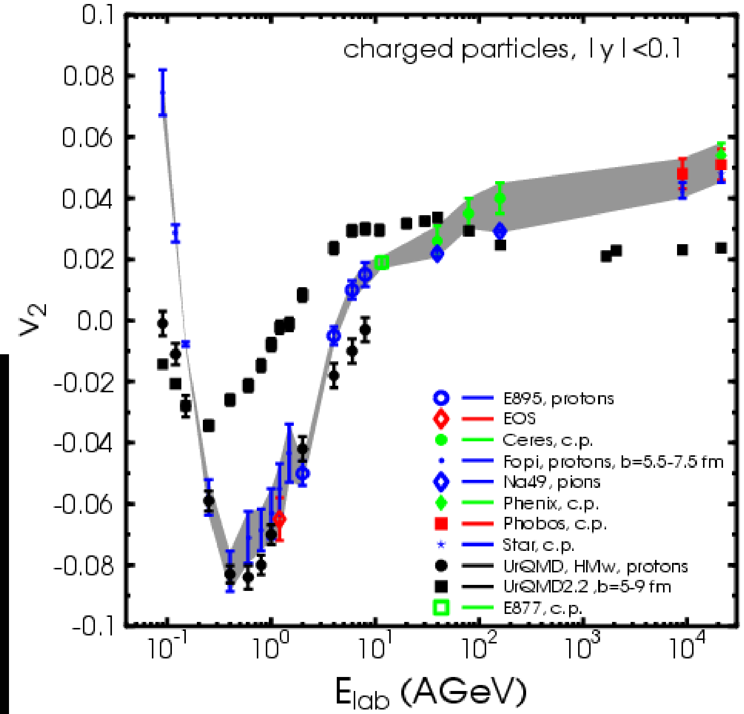






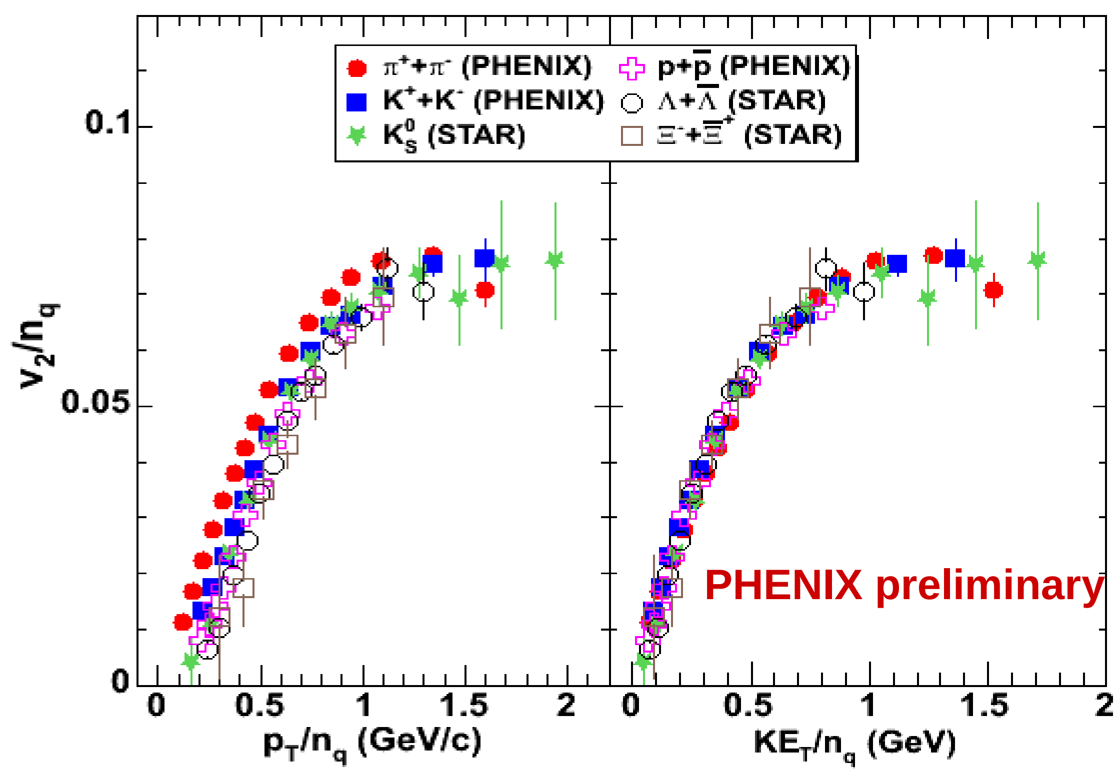
Measurement: v_2





- Transverse kinetic energy scaling works for a large selection of particles
- Supports the idea that all particles originate from a common flow field

Measurement: v_2



- Scaling holds over the whole range of KE_T

$$v_2^{\,h}\left(KE_T\right) = n v_2^{\,p}\left(KE_T / n\right)$$

- KE_T/n gives kinetic energy per quark, assuming that each quark carries equal fraction of kinetic energy of hadron

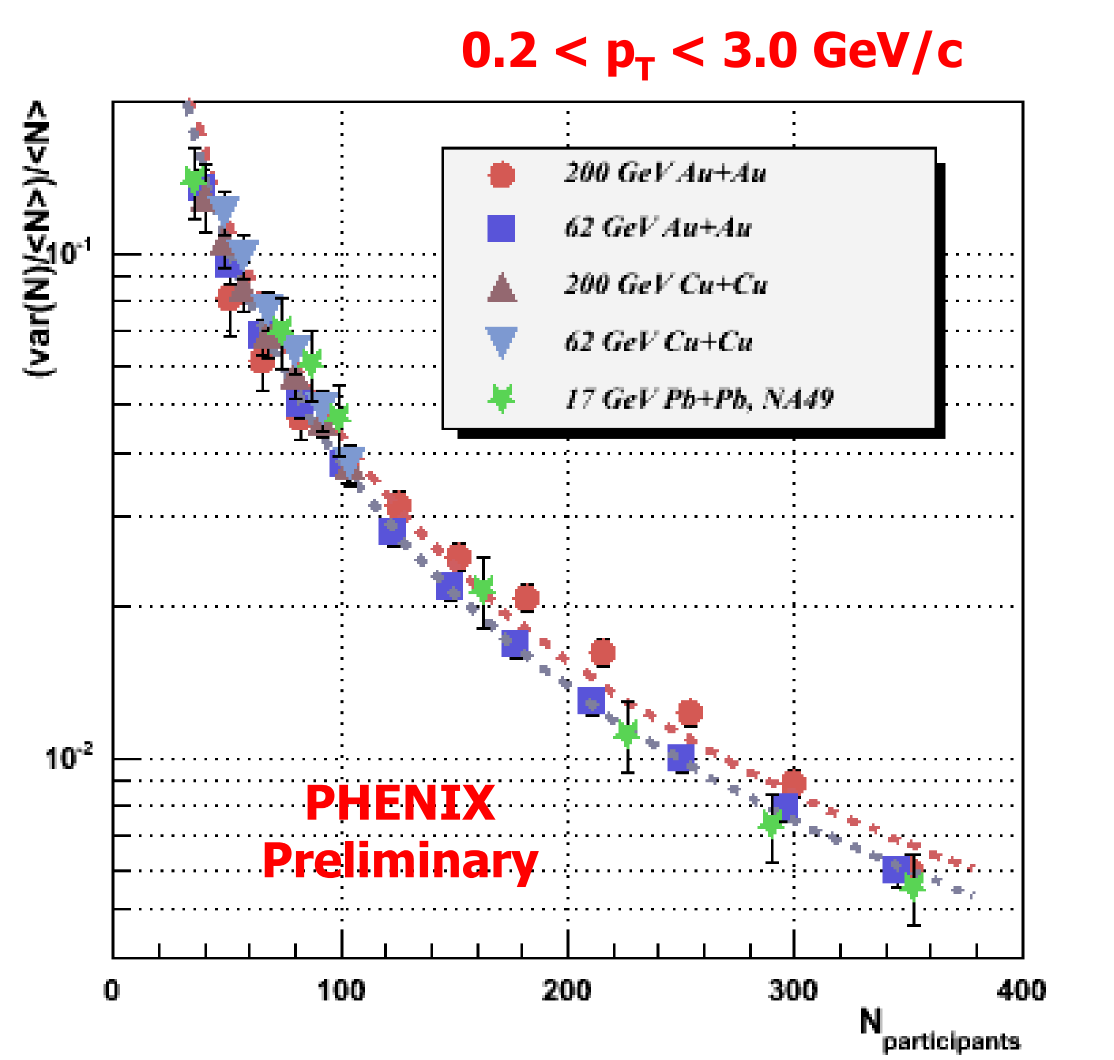
Observation of scaling of v_2 with quark kinetic energy could be used as input for recombination models

Measurement: Multiplicity Fluctuations → Critical Exponents?

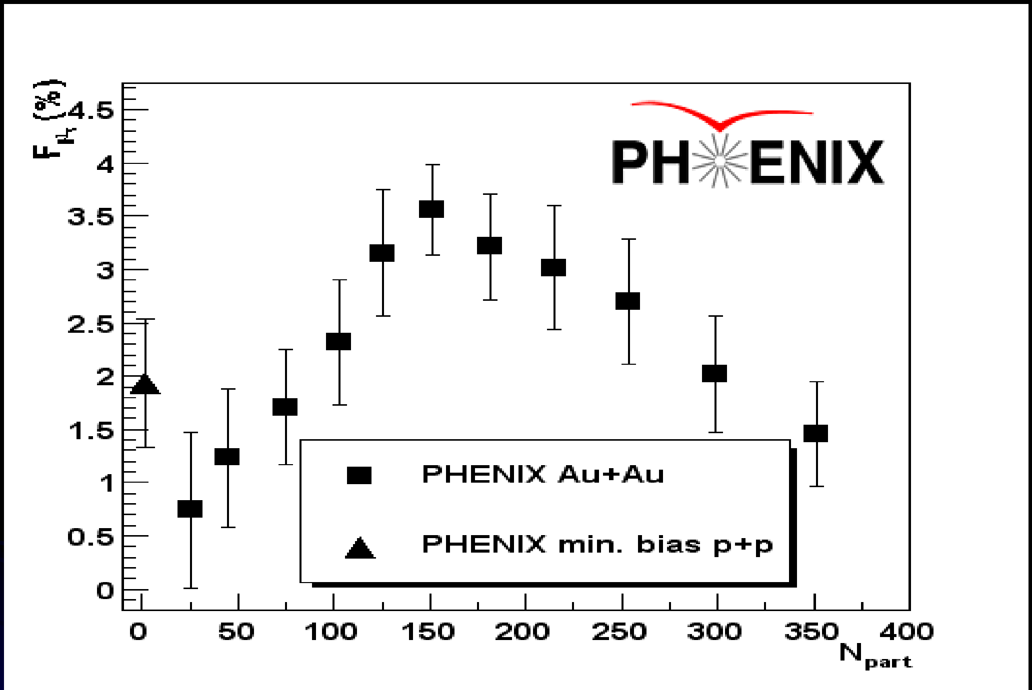
$$\frac{\left(\sigma^2/\mu\right)}{\mu} = \frac{k_B T}{V} k_T$$

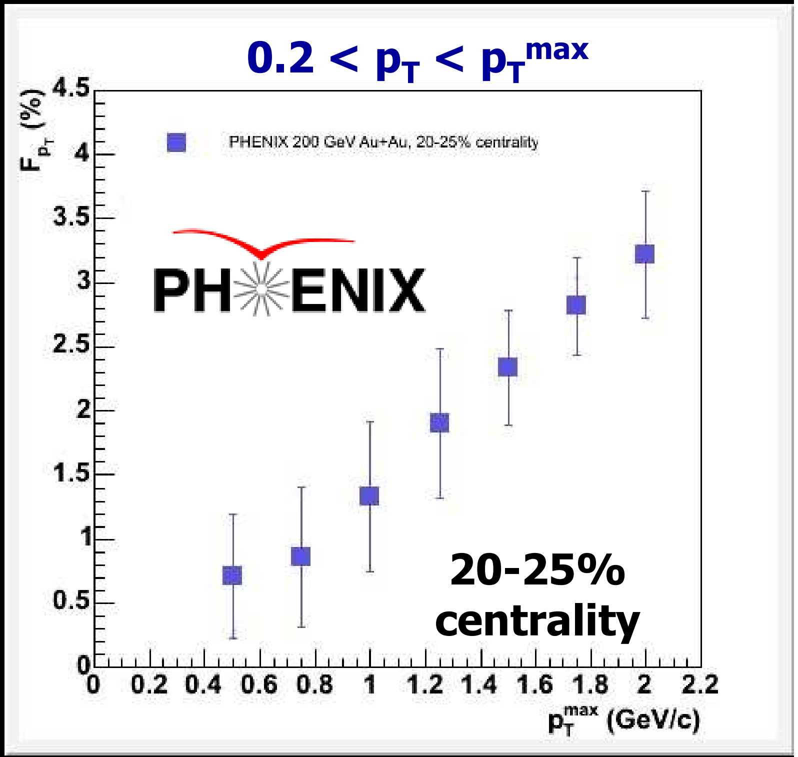
$$T \propto N_{part}^{1/3}$$

Comparison to NA49 measurements at SPS energies. The NA49 scaled variance data have been corrected for impact parameter fluctuations from their 10% wide centrality bins and scaled up by 20% to lie on the 200 GeV Au+Au curve. The fits use γ=-1.24. The NA49 data amazingly exhibit the same universal behavior!



Measurement: $<p_T>$ Fluctuations

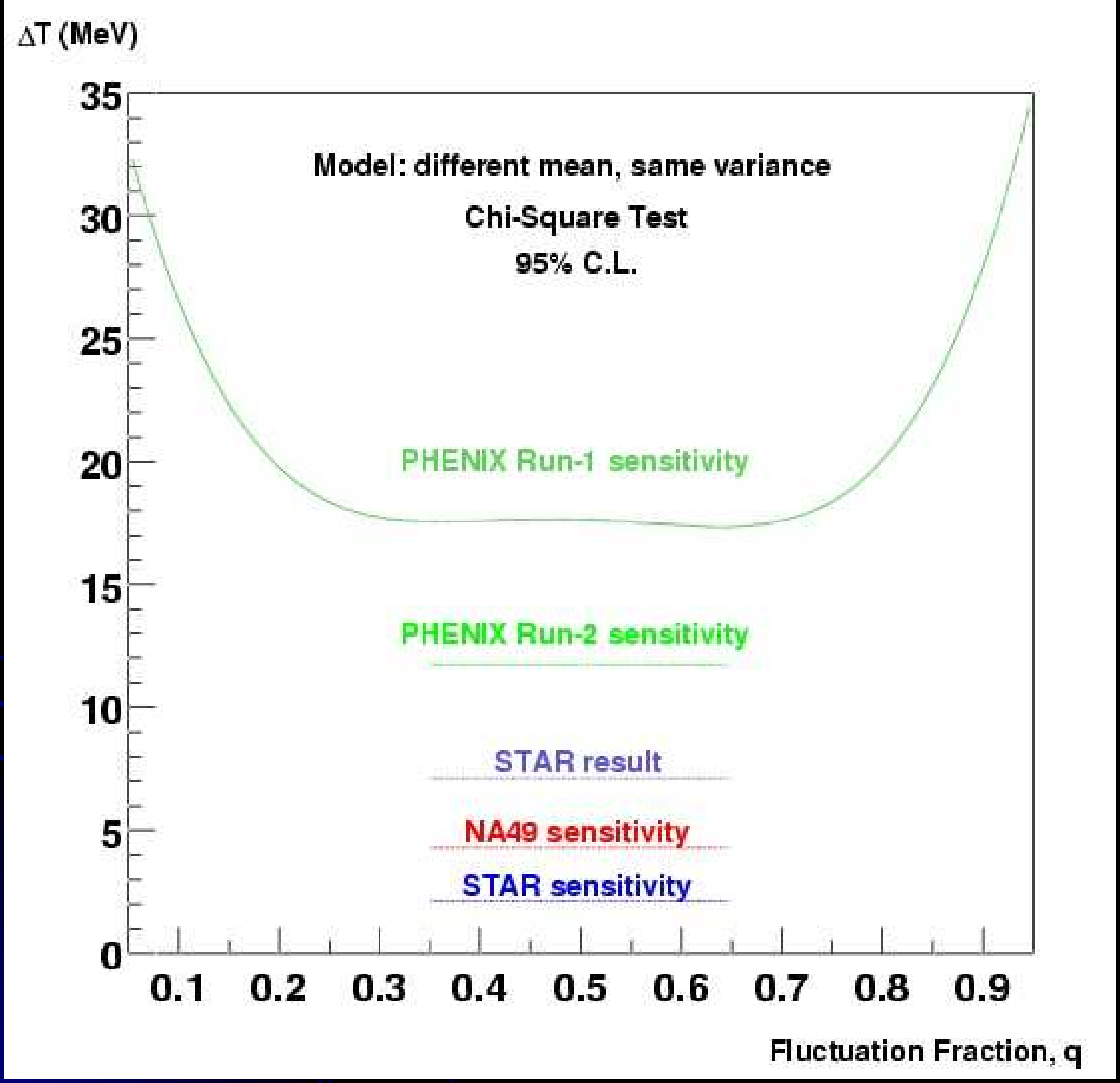




Highlights: Non-random fluctuations are observed. Non-monotonic centrality-dependence. Strong p_T-dependence. p_T fluctuations appear to be driven by high p_T particles. The shape can be explained using a PYTHIA-based simulation by the contribution of correlations due to jets.

S. Adler et al., Phys. Rev. Lett. 93 (2004) 092301.

Sensitivity: $<p_T>$ Fluctuations



From a simple model where 2 event classes are present with temperatures separated by ΔT. Here, is the fraction of the event sample at the lower temperature. The model generated N tracks per event reflecting the acceptance of each experiment and performs a chi-square test on the deviation of the $<p_T>$ distribution from the random expectation.

The Upgraded PHENIX Detector
Run-3 Design Configuration:

Charged Particle Tracking:

- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)
- Forward Muon Trigger Detector
- Si Vertex Tracking Detector- Barrel (Pixel + Strips)
- Si Vertex Endcap (mini-strips)

High rate trigger

Precision vertex tracking

Particle ID:

- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Gap Resistive Plate Chamber ToF
- Hadron Blind Detector

PID (k,π,p) to 10 GeV

Rejection of Dalitz/Conv.

Calorimetry:

- Pb Scintillator
- Pb Glass
- Nose Cone Calorimeter
- Muon Piston Calorimeter

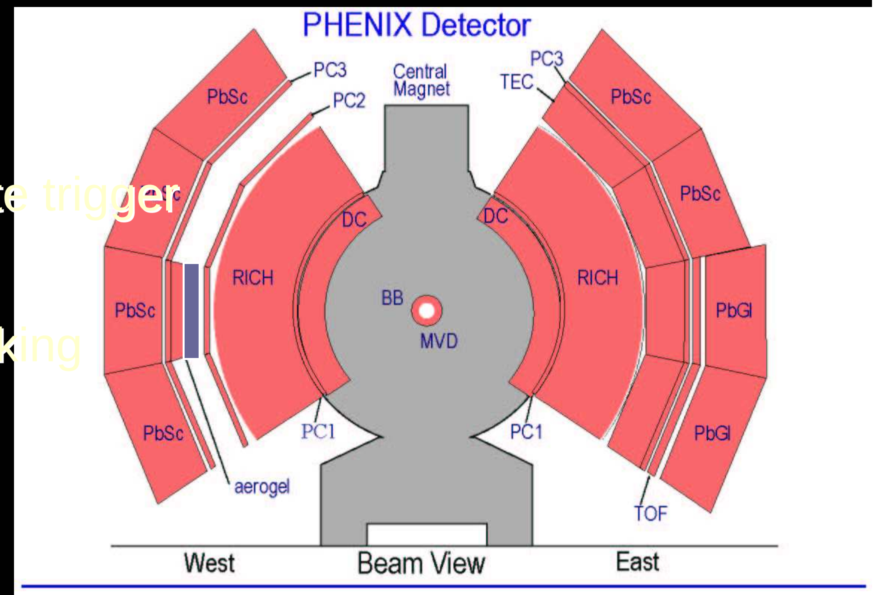
γ/π° coverage to very fwd

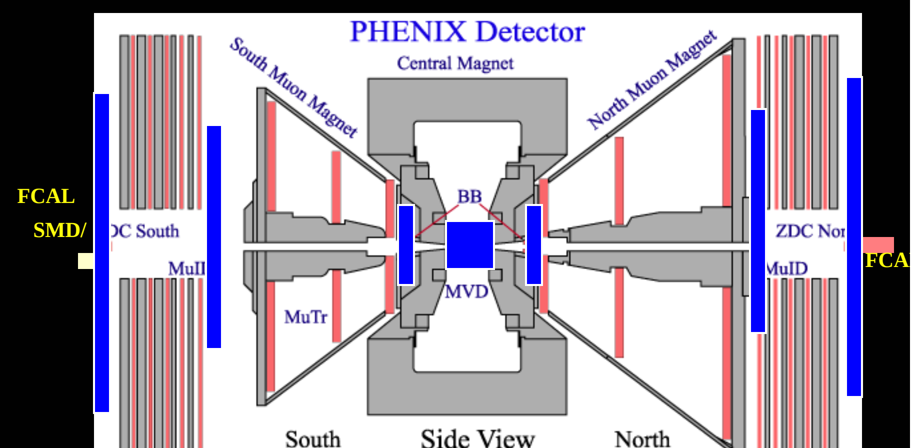
Event Characterization:

- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter
- Reaction Plane Detector

Data Acquisition:

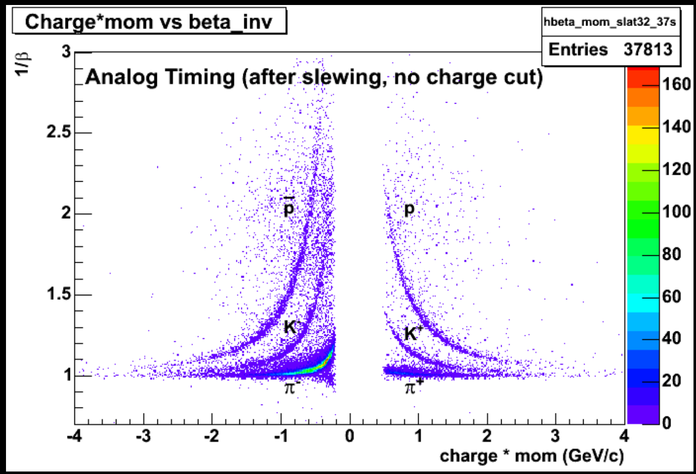
- DAQ Upgrade

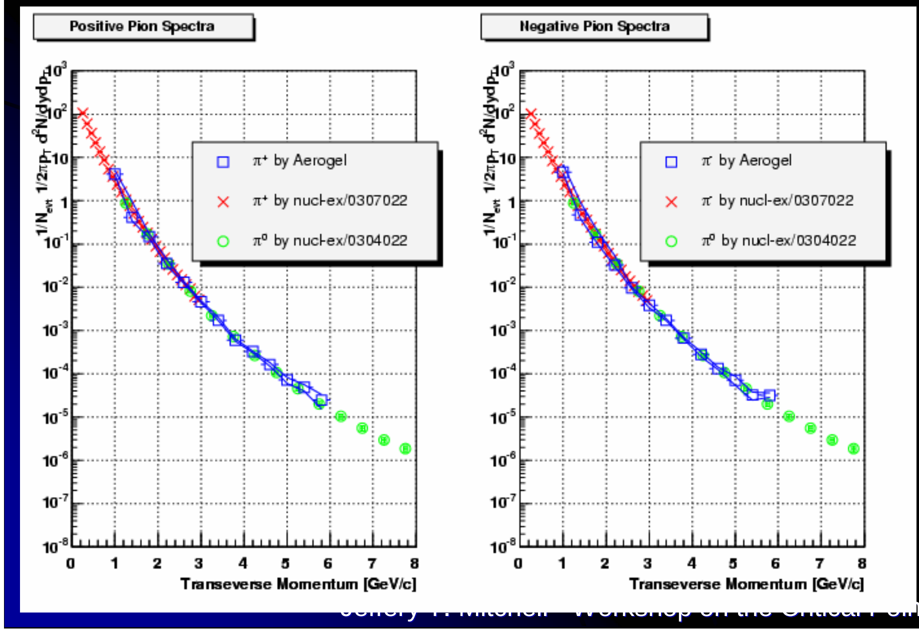


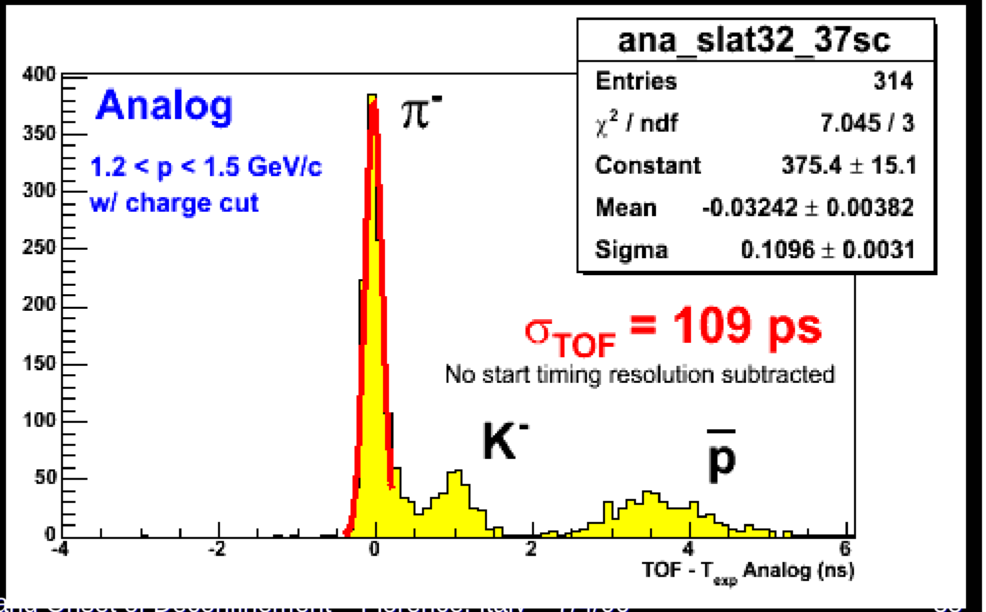


Extended PID: AGEL + TOF-W

- "An aerogel and time-of-flight system to provide complete π/K/p separation for momenta up to ~10 GeV/c."
- Project well underway
  - Aerogel completely installed (first physics results now available)
  - TOF-W ('Time-Of-Flight-West')
    - Partial funding: J. Velkovska (Vanderbilt) OJI
    - Prototypes tested in Run-5
    - System to be installed in next shutdown

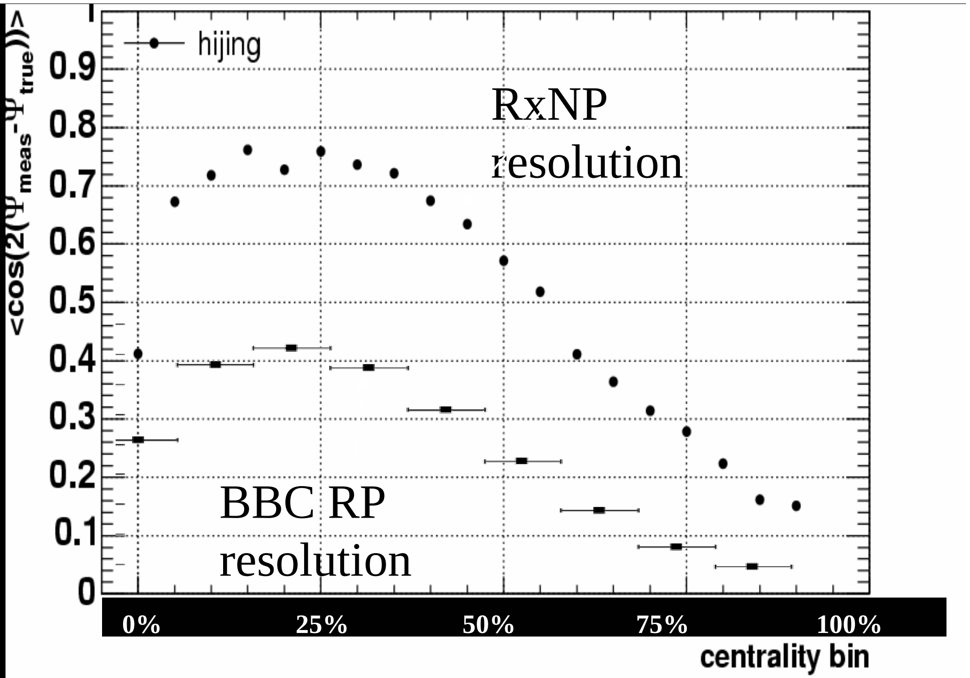


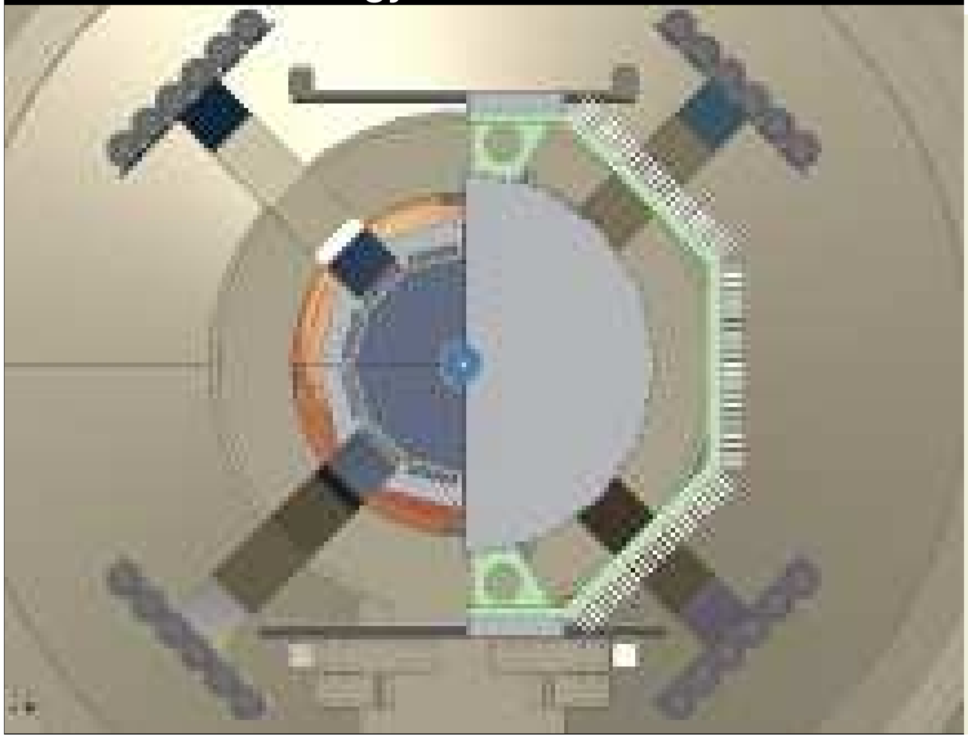


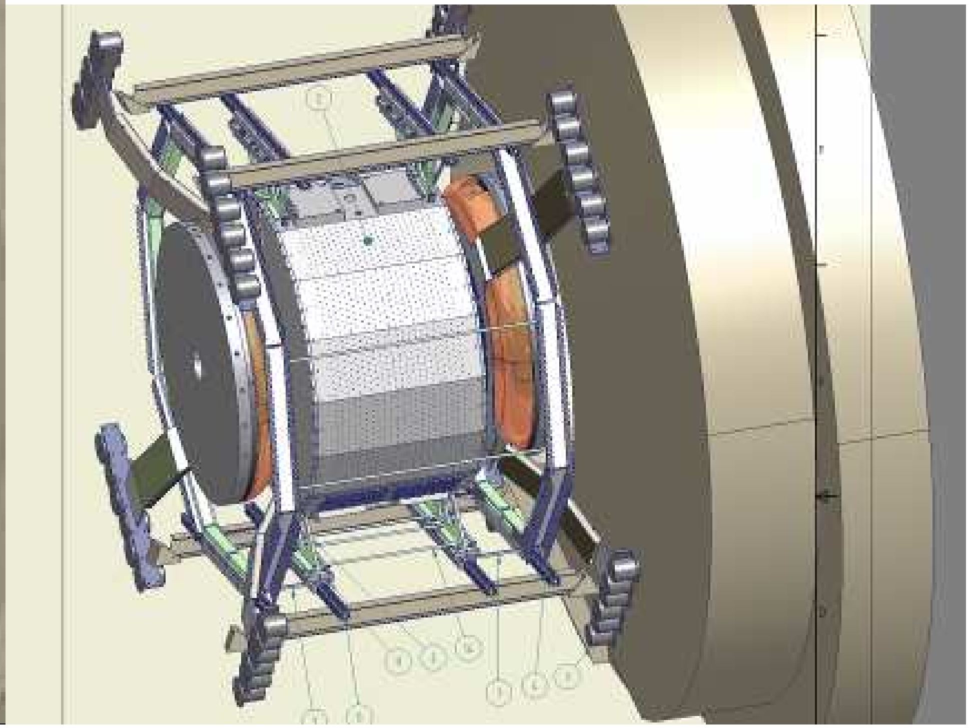


Reaction Plane Det (RxNP)

- •Scintillator paddles with lead converter at 1<|η|<3
    - •Measure reaction plane
        - •resolution better by factor 2
    - •Trigger counter for low energy running, where η is reduced from beam energy

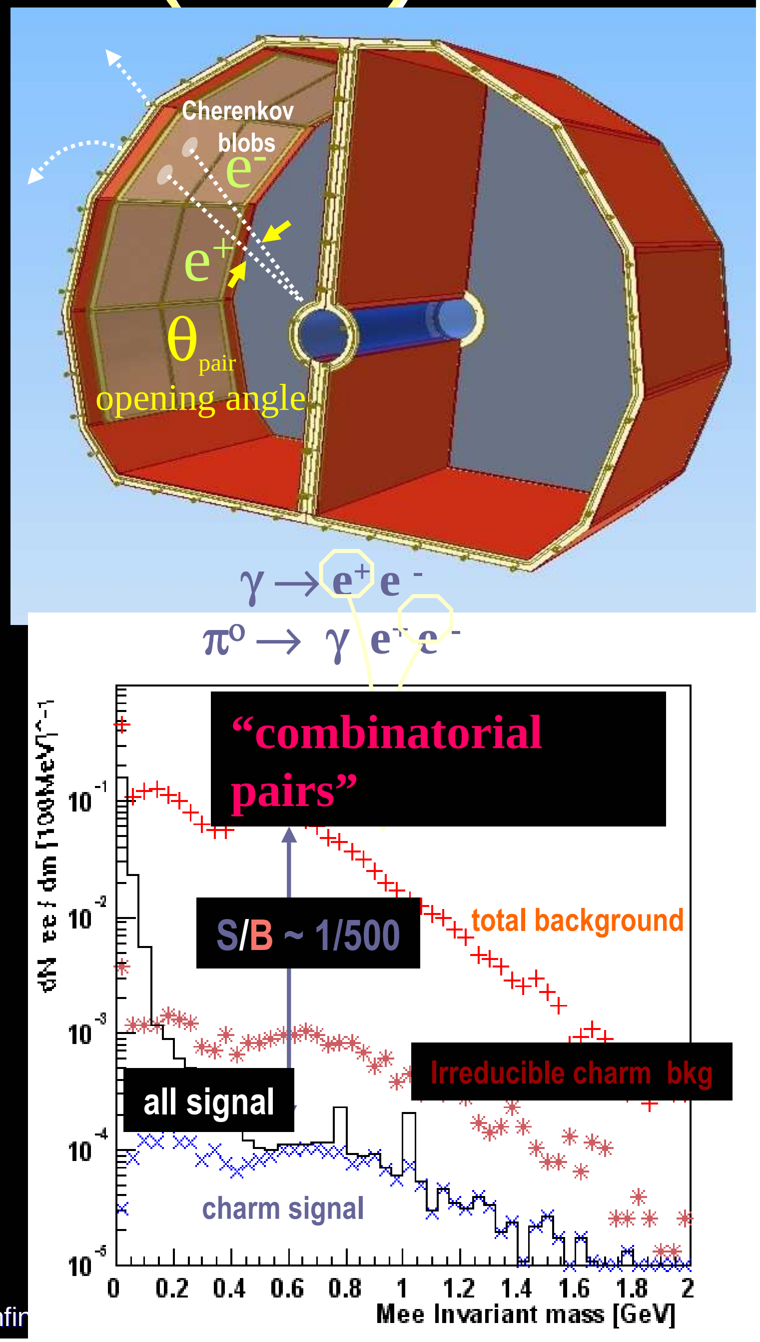






Hadron-Blind Detector (HBD)

- “A hadron-blind detector to detect electrons from near the vertex.”
- Dalitz rejection via opening angle
  - Identify electrons in field free region
  - Veto electrons with partner
- HBD: a novel detector concept:
  - windowless CF4 Cherenkov detector
  - 50 cm radiator length
  - CsI reflective photocathode
  - Triple GEM with pad readout
  - reverse bias → hadron blind
  - 2x135° in ϕ and $|\eta| < 0.45$
- Construction 2005-2006, Installation in 2007
  - Funding provided by DOE, NSF, Weizmann, Stony Brook
  - R&D completed

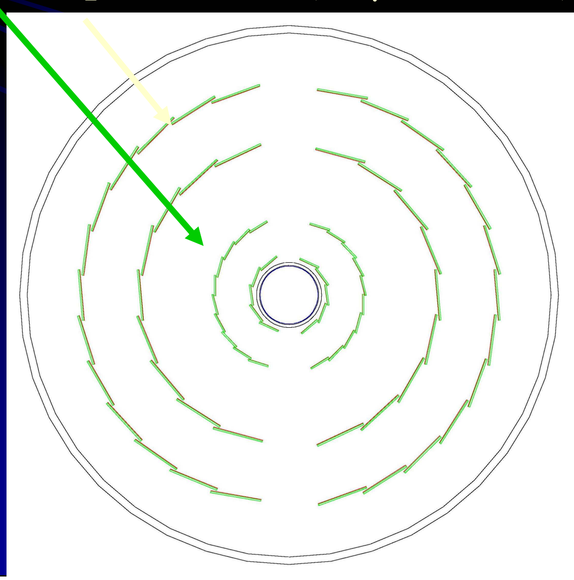


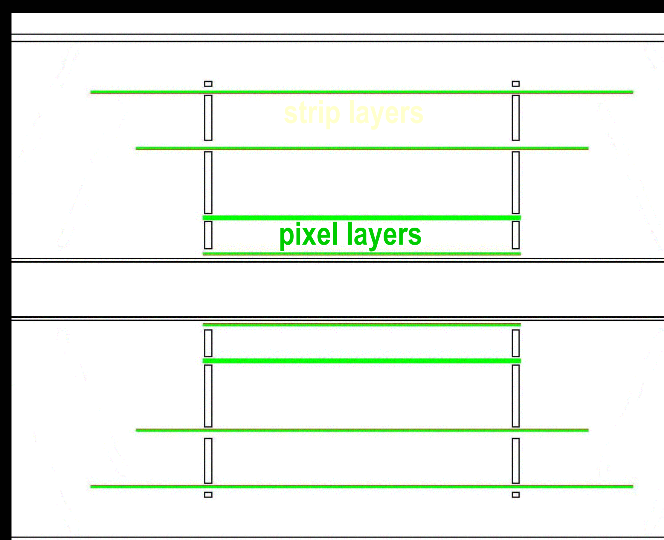
Silicon Tracker

- "A vertex detector to detect displaced vertices from the decay of mesons containing charm or bottom quarks."
  - ~$3M committed by RIKEN
  - MIE proposal submitted to DOE Aug-04:
    - DOE Cost & Schedule review May, 2006
    - Total Project Cost = $4.6M
    - In President's Budget for FY07
    - Very active ongoing R&D program

Hybrid Pixel Detectors (50 μm x 425 μm) at R ~ 2.5 & 5 cm

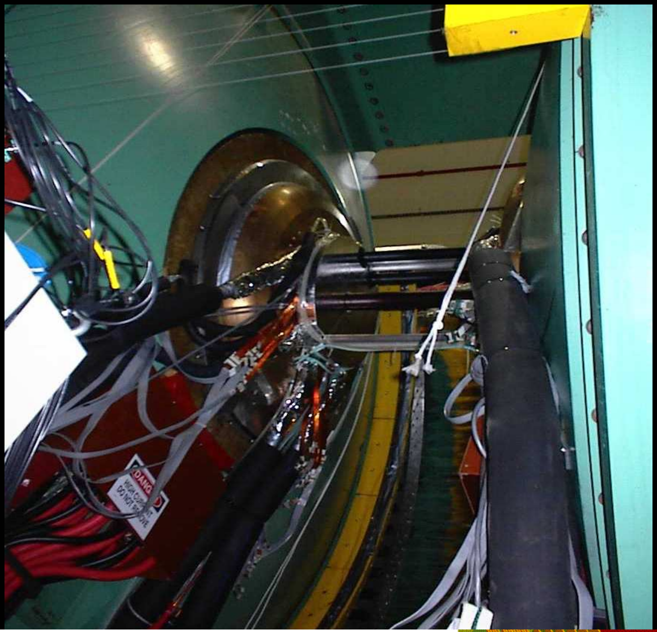
Strip Detectors (80 μm x 3 cm) at R ~ 10 & 14 cm





$|\eta|<1.2$
$\phi \sim 2\pi$
$z \sim \pm\ 10$ cm

Nosecone Calorimeter (NCC)

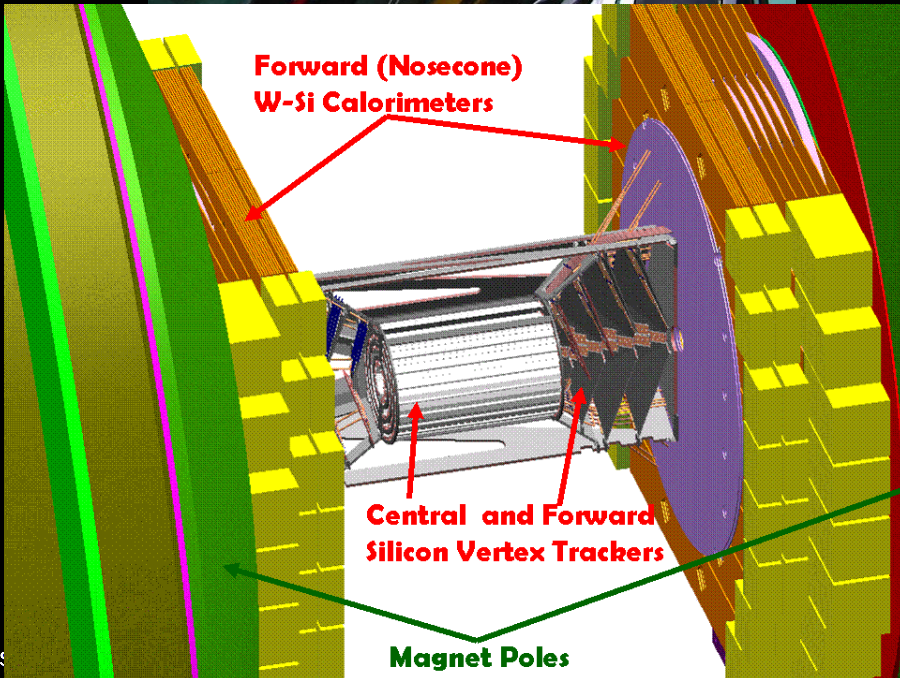


- "A forward calorimeter to provide photon+jet studies over a wide kinematic range."
- Forward physics with PHENIX
  - Large acceptance calorimeter
  - EM calorimeter ~42 X/X_o
  - hadronic section (1.6 λ/λ_0)
  - Tungsten with Silicon readout

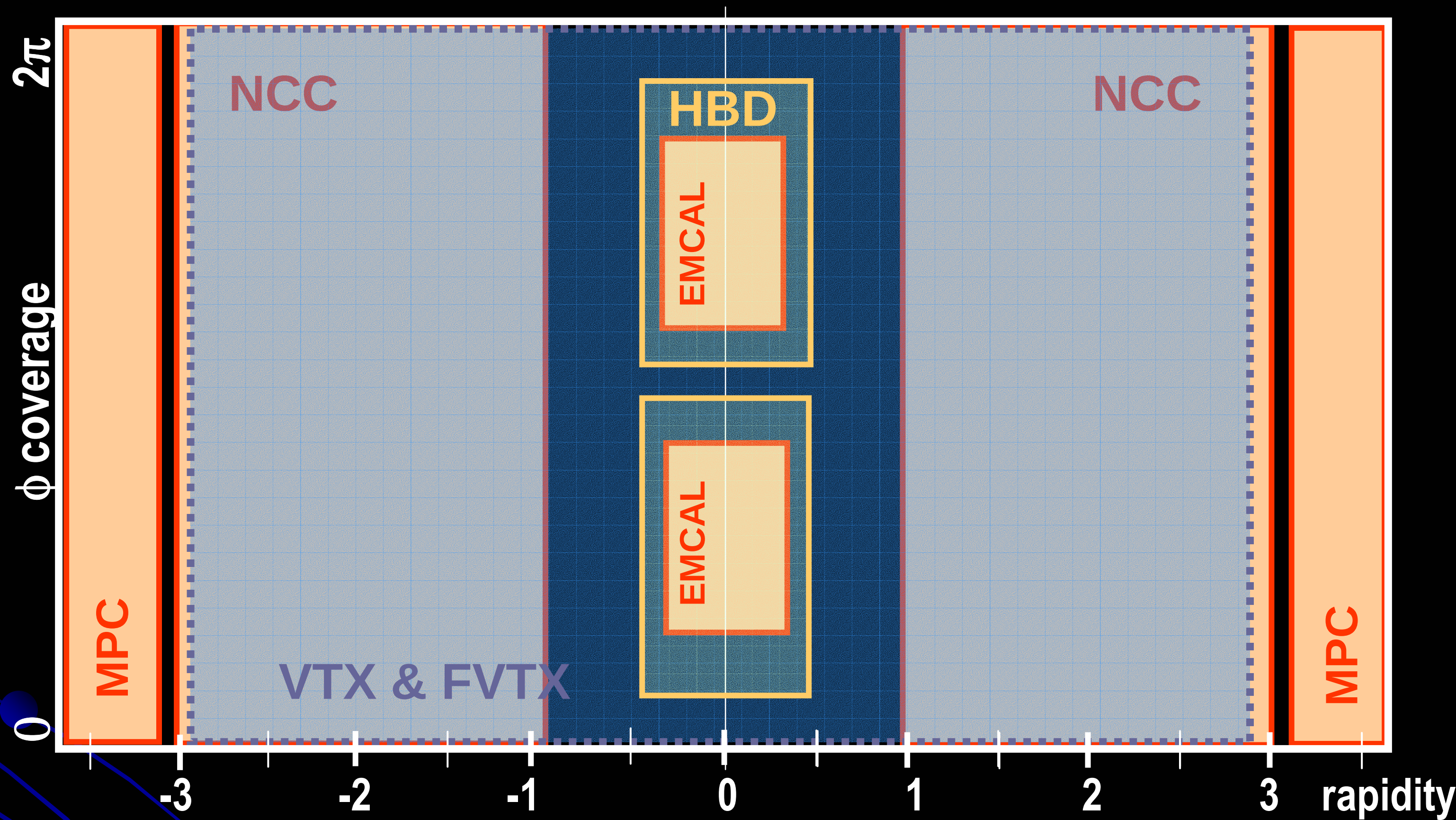
$0.9 < \eta < 3.0$

10 X Acceptance of Central Arms

- Extended physics reach with NCC
  - Extended A-A program
    - high p_T phenomena: π^0 and γ-jet
    - $\chi_c \rightarrow J/\psi + \gamma$ (deconfinement)
  - Small *x*-physics in p(d)-A
  - Polarized proton physics
    - $\Delta G(x)$ via γ-jet
- Status
  - Submitted to DOE for FY08 funding start
  - New expert groups join R&D
    (Moscow State, Czech groups)
  - Construction FY08 – FY10



Future PHENIX Acceptance for Hard Probes



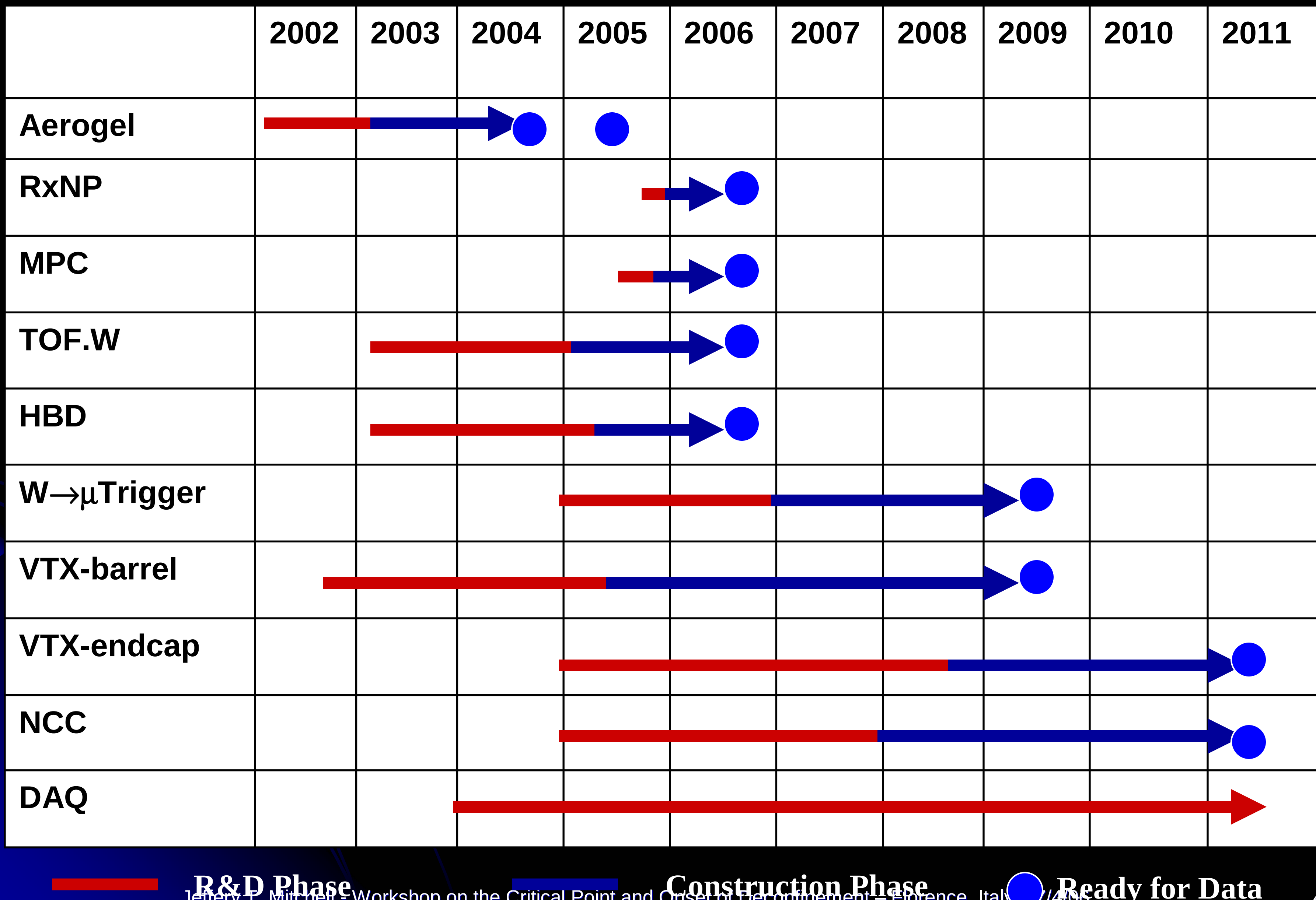
(i) π^0 and direct γ with combination of all electromagnetic calorimeters

(ii) heavy flavor with precision vertex tracking with silicon detectors

combine (i)&(ii) for jet tomography with γ-jet

(iii) low mass dilepton measurements with HBD + PHENIX central arms

Upgrade Schedule Scenario



PHENIX Upgrades Physics Capabilities

X upgrade critical for success
O upgrade significantly enhancements program

PHENIX Upgrades	High T QCD				Spin		Low x
	e+e-	heavy flavor	jet tomography	quarkonia	W	$\Delta G/G$	
hadron blind detector (HBD)	X						
vertex tracker (VTX)	X	X	O	O		X	O
μ trigger				O	X		
forward calorimeter (MPC)							X
forward Vertex tracker (FVTX)		X	O	O	O	O	O
forward calorimeter (NCC)			O	O	O	O	X
RHIC luminosity	O	O	X	X	O	O	O

PHENIX upgrades designed for optimum physics output with RHIC II luminosity

Conclusions

- RHIC is capable of performing a low energy scan.
- PHENIX is capable of producing high quality measurements now and in the future on the wide variety of observables that could be needed to isolate the QCD critical point.
- PHENIX would benefit from a centrality detector designed specifically for low energy running.
- However, to do the program right, it would be nice to complete the program with:
  - Enough energy steps with sufficient statistics to map out the inflections about the critical point.
  - More than one species in order to investigate universal behavior and critical exponents near the critical point.
  - Companion p+p and d+Au data at each energy in order to reduce any systematic errors in measuring baseline distributions – important for R_{AA} measurements.

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- Henner Buesching
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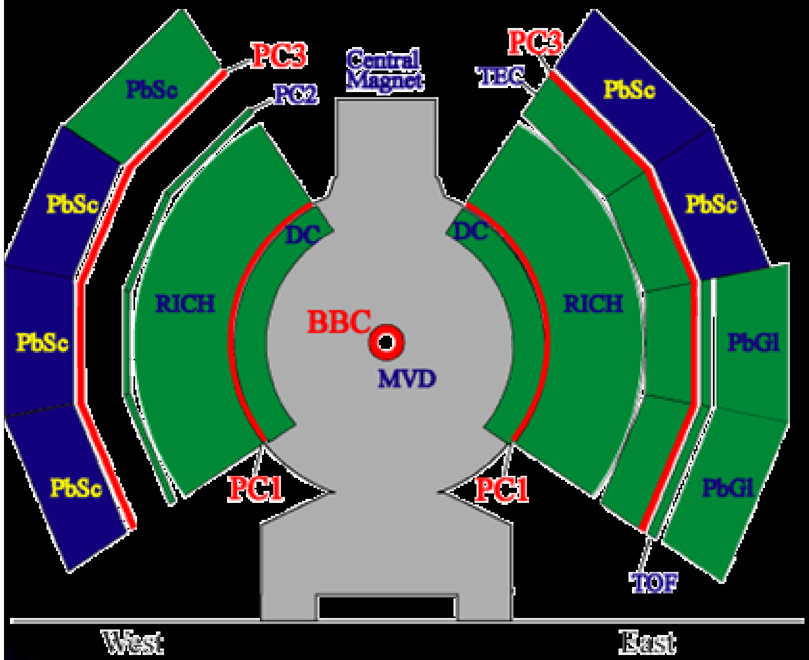
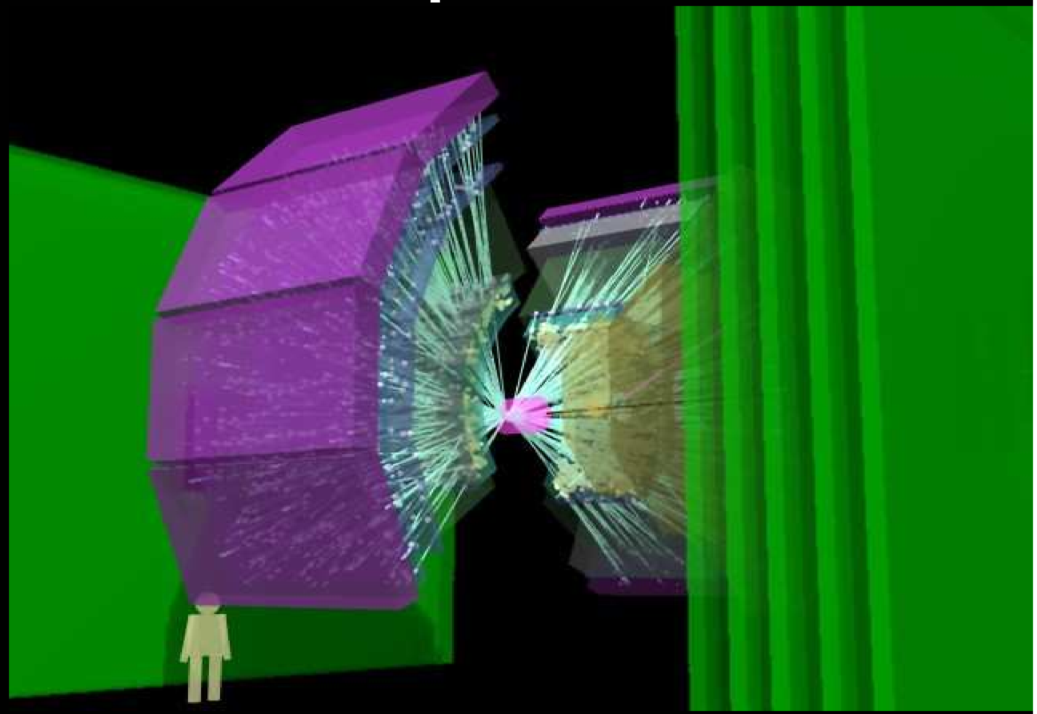
- Michael Issah
- Todd Satogata
- Mickey Chiu
- … and many more

Auxiliary Slides

PHENIX Static Backup Slide





- **Beam-Beam Counters:**
  - **64 Cherenkov Counters**
  - **$3.1<|\eta|<3.9$ $\Delta\varphi = 360^0$**
  - **σ_{vertex}= ~5mm (central)**
  - **σ_t= ~100 ps**

- **Pad Chamber Detectors:**
  - **MWPC with binary pad readout**
  - **2.5m and 5.0m from the IP**
  - **$|\eta|< 0.35$ $\Delta\varphi = 90^0$**
  - **σ_φ= 1.4mrad (3.5mm PC1)**
  - **σ_η= 0.7×10^{-3} (1.7mm PC1)**
  - **Double Hit Resolution ~4cm**

- **Electromagnetic Calorimeter:**
  - **Lead+Scintillator 18 X_0**
  - **5.1m from the IP**
  - **$|\eta|< 0.38$ $\Delta\varphi = 90^0$**
  - **σ_E= $8.1\%/\sqrt{E[GeV]} \times 2.1\%$**

PHENIX Sensitivity: Modelling a fluctuation

Goal: Produce a fluctuation that does not change the mean or variance of the final inclusive distribution.

- The final inclusive distribution (fixed by observation) can be expressed as:

$$\frac{dN}{dp_t} = \Gamma(p_t, p, b)$$

where T = 1/b is the *inverse slope parameter* of the distribution.

- Consider an event sample with two classes of events.

Define $q = N_{\text{events, class 1}} / N_{\text{events, total}}$

- The distribution for the two component fluctuating sample can be taken as:

$$f(p_t) = q \times \Gamma(p_t, b1, p1) + (q-1) \times \Gamma(p_t, b2, p2)$$