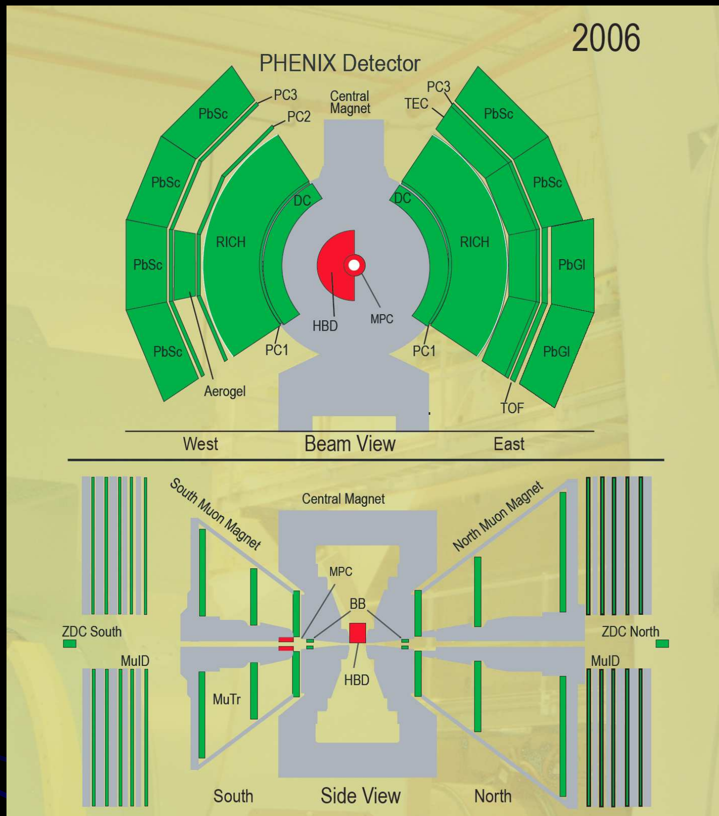
PHENIX Plans for Low Energy Running

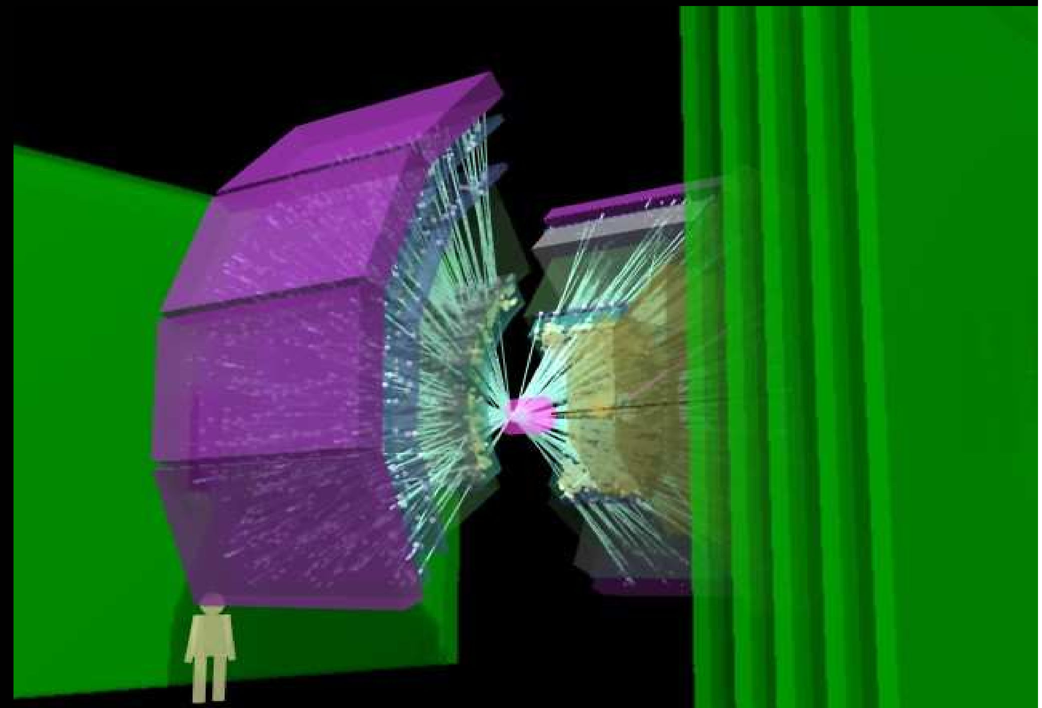
Future Prospects in QCD at High Energy – 7/21/06
Jeffery T. Mitchell for the PHENIX Collaboration
(Brookhaven National Laboratory)

<u>Outline</u>

- **PHENIX Detector and Performance**
- **Demonstration of Low Energy Capabilities and Plans with Current Measurements**
- **Contribution of Upgrades**

The PHENIX Detector 2006





Calorimetry

Pb Scintillator
Pb Glass

Event Characterization

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

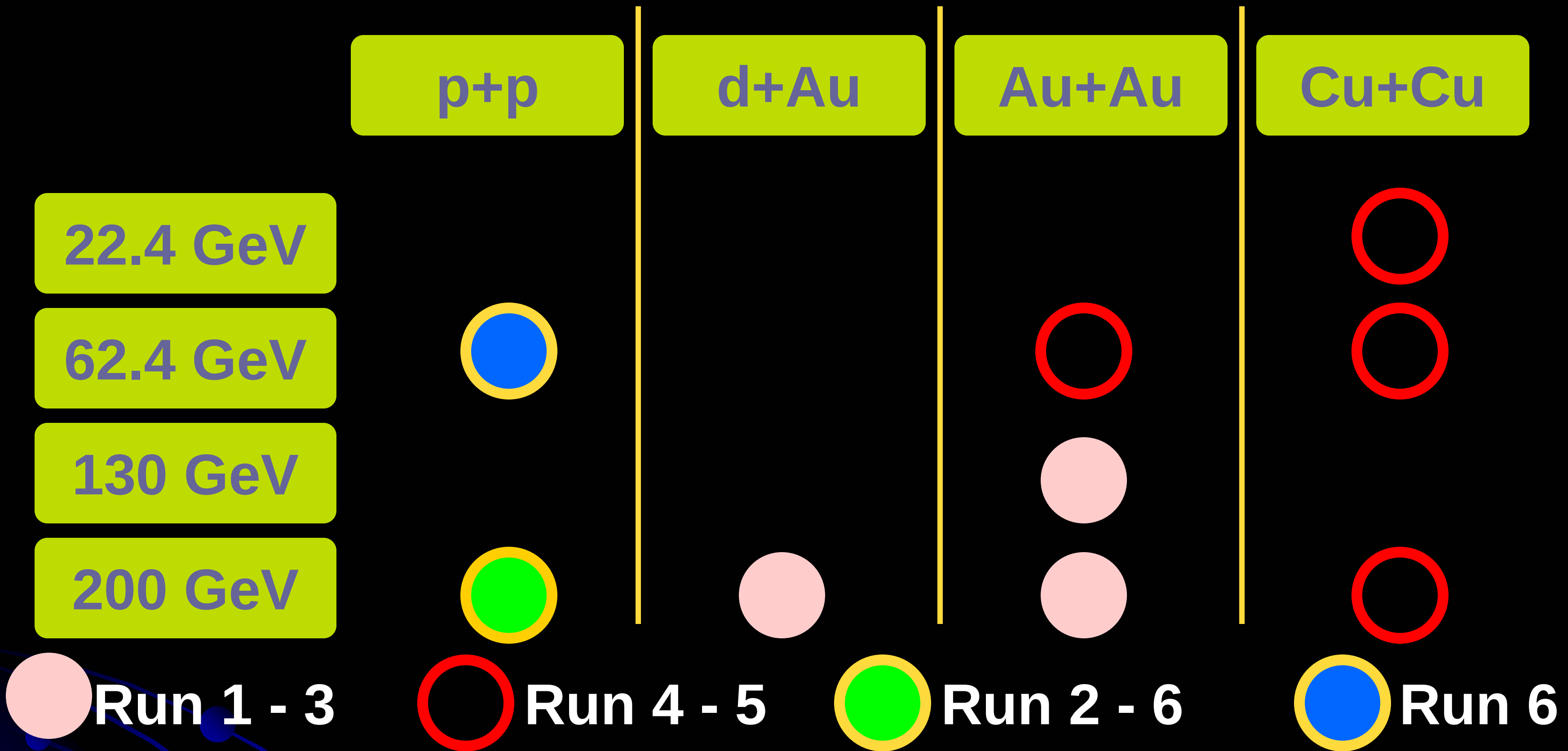
Charged Particle Tracking:

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)

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 our Event rate dramatically in Runs 4 and 5

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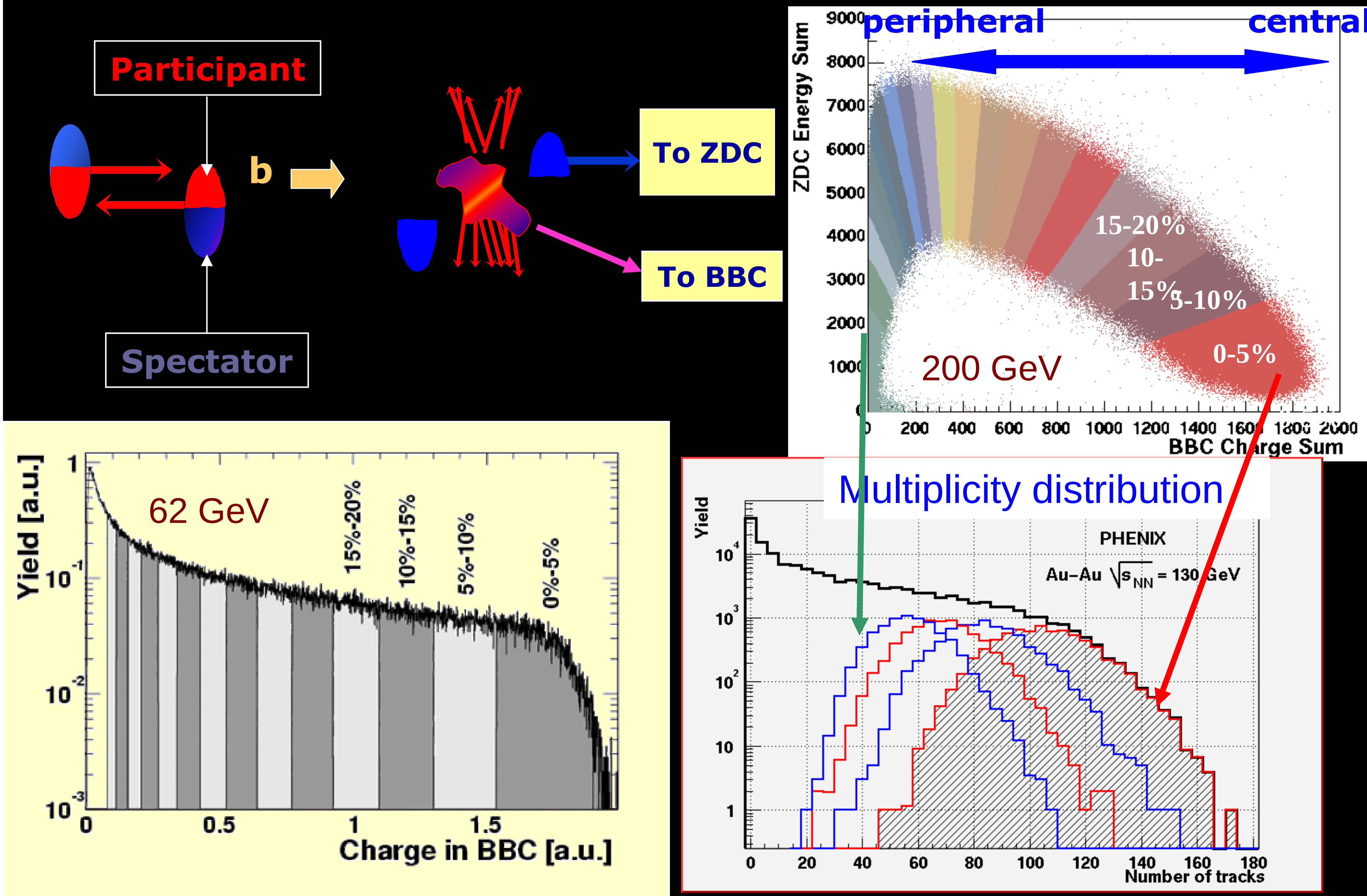
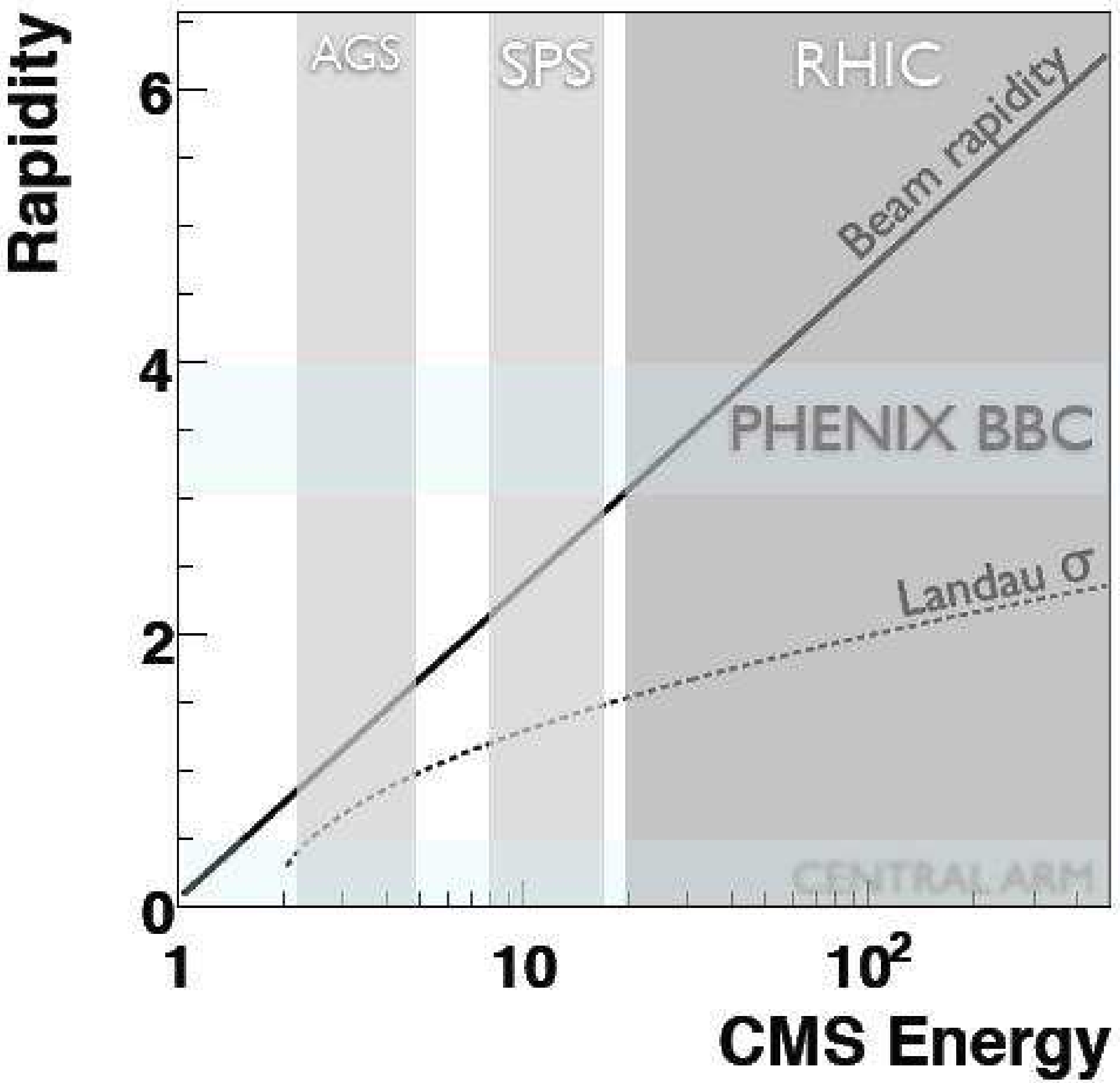
488 TB on tape for Run 5

Centrality Determination: 62, 200 GeV

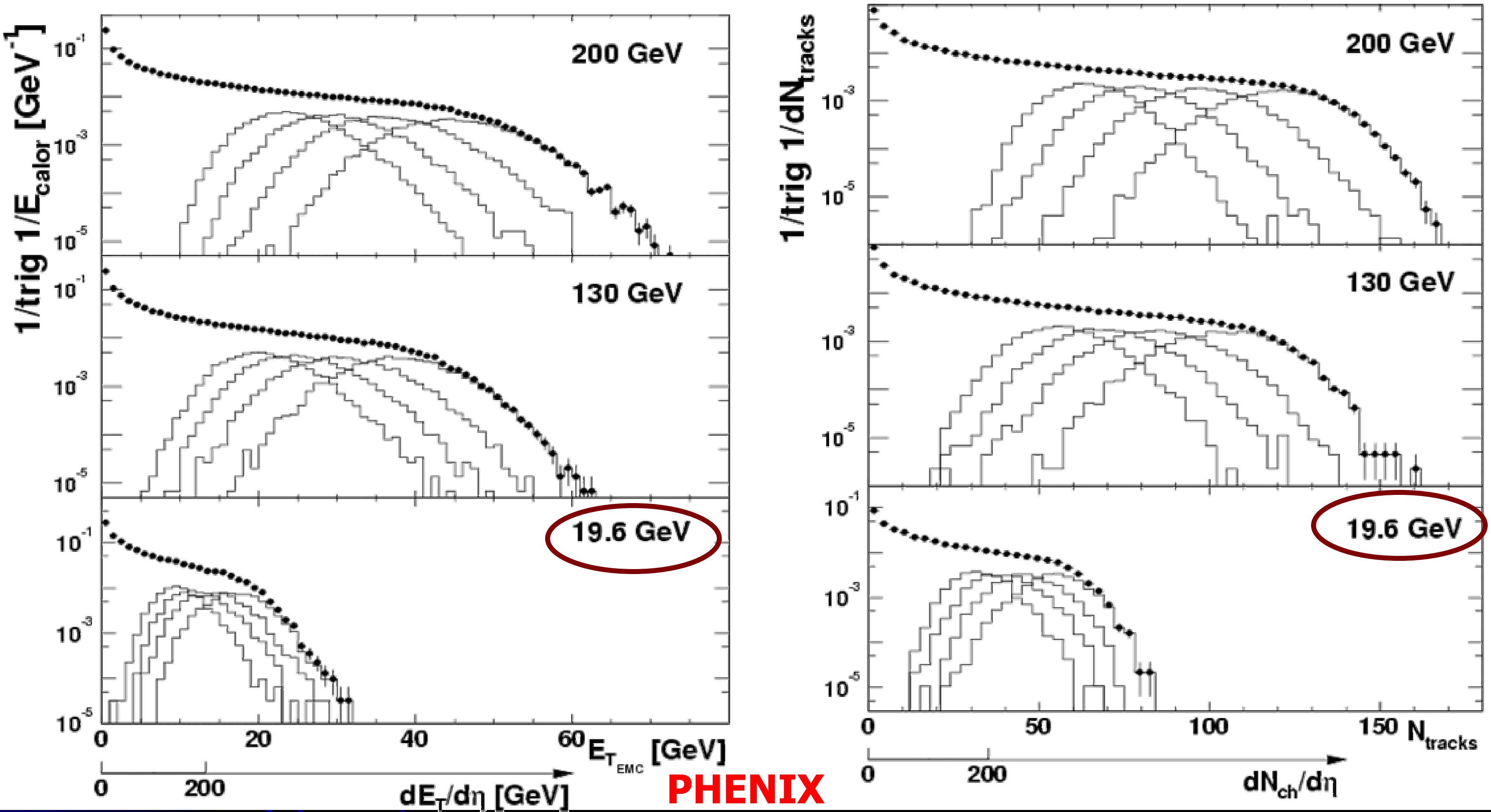


Centrality Determination: <25 GeV

- 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: E_T, Multiplicity

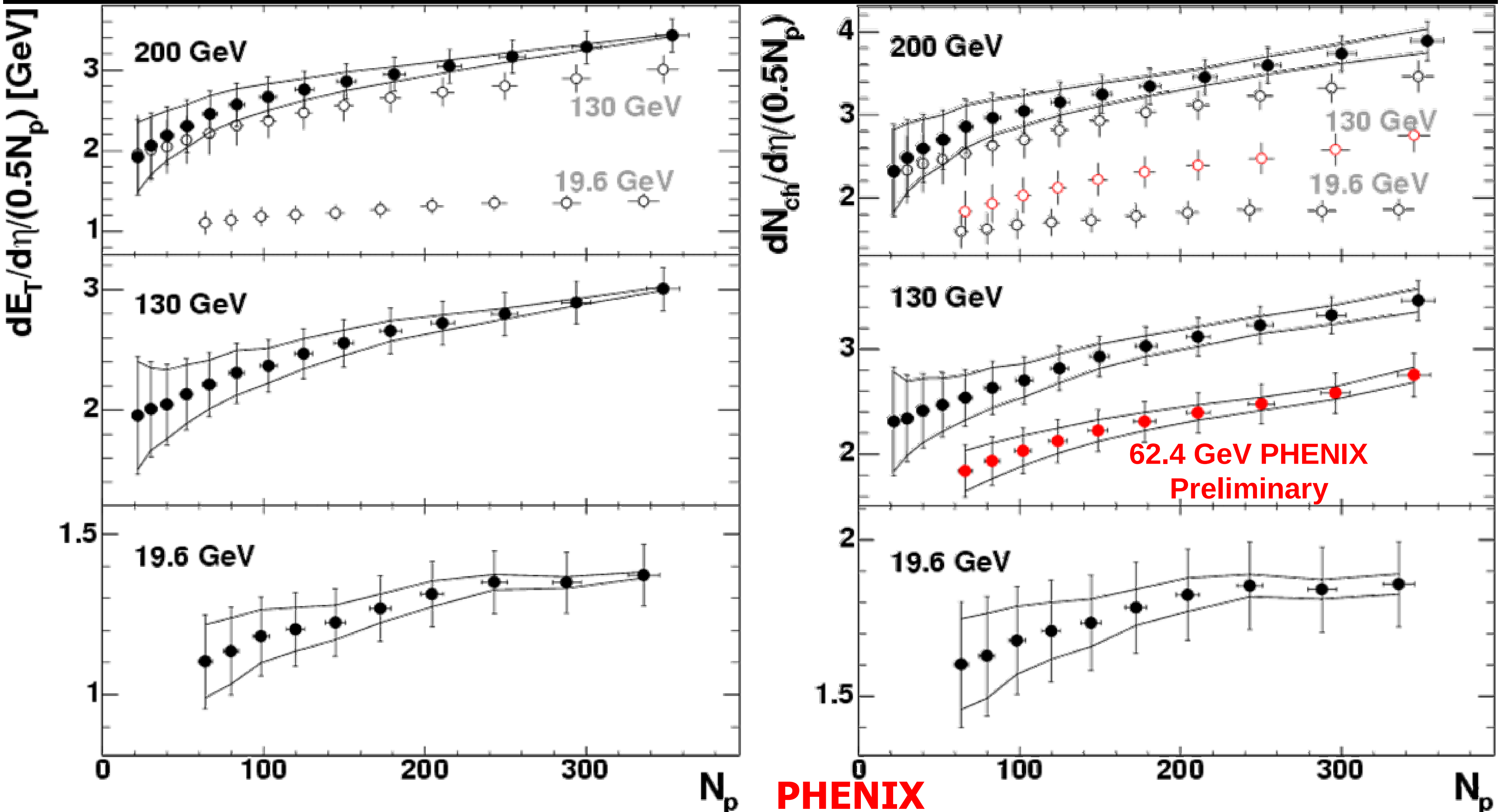


Phys. Rev. C 71, 034908 (2005)

BEHOLD THE LOW ENERGY PHENIX DATA…

- **"Classical" Shape: Peak, Valley, Edge.**
- **Top centrality classes are shown individually.**

Measurement: E_T, Multiplicity



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

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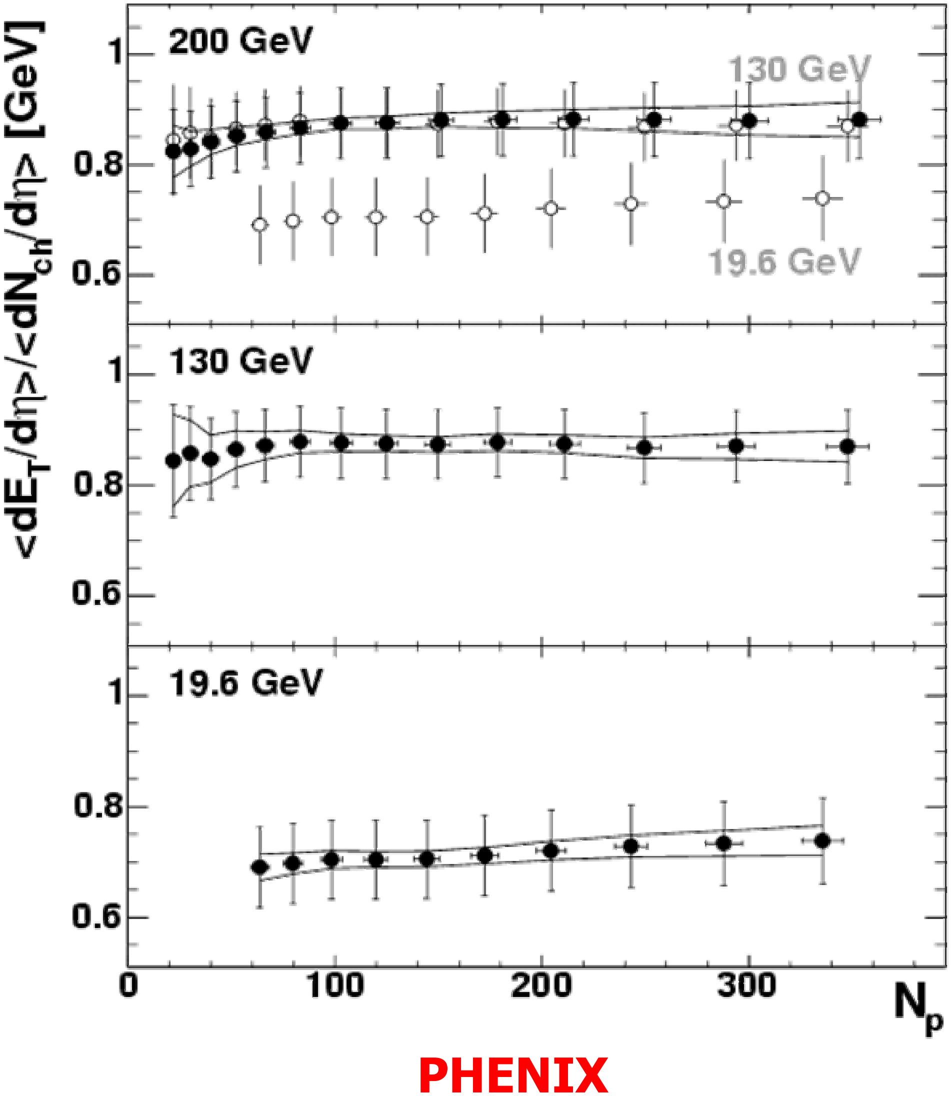
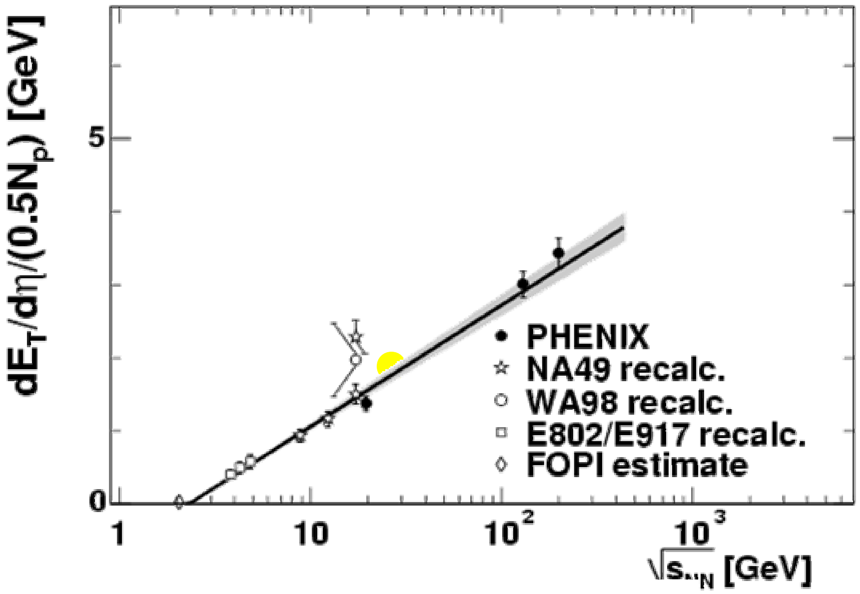
Measurement: $\langle E_T \rangle / \langle N_{ch} \rangle$

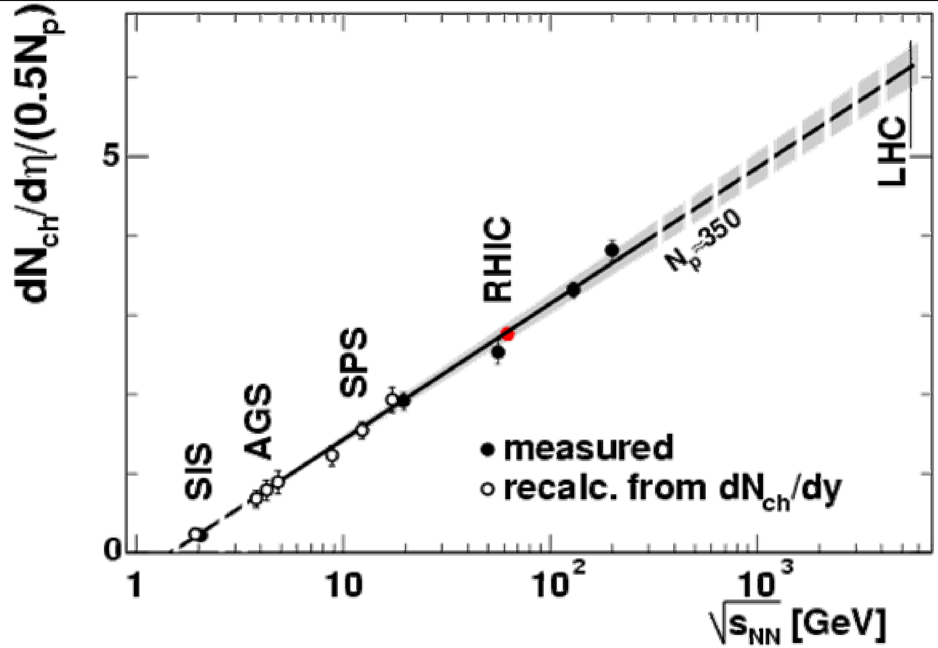


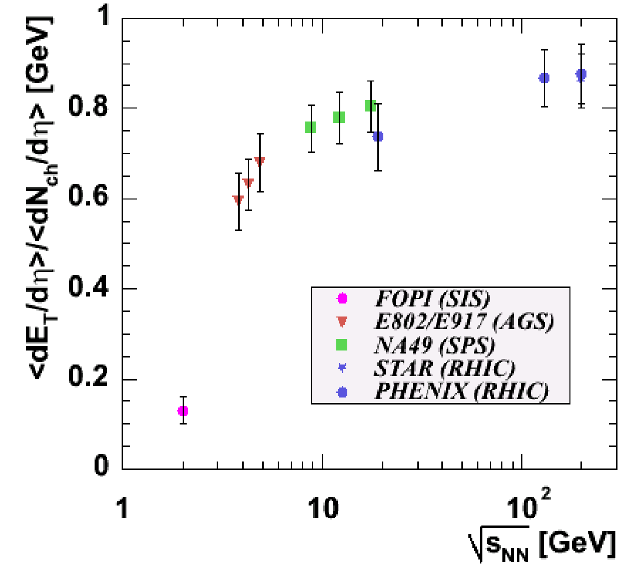
- The ratio $\langle E_T \rangle / \langle N_{ch} \rangle$ increases by ~20% from 19.6 GeV to 200 GeV and stays the same between 200 GeV and 130 GeV
  - Consistent with the average particle momentum increase between those two energies.
- The ratio $\langle E_T \rangle / \langle N_{ch} \rangle$ is independent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

Phys. Rev. C 71, 034908 (2005)

$\sqrt{s_{NN}}$ dependence







- Both E_T and N_{ch} show log-scaling.
- Works even better on N_{ch} for N_p = 350.

  [The band on the right is a 2σ error]
- Extrapolation to LHC $dN_{ch}/d\eta$ = (6.1±0.13)×(0.5Np).

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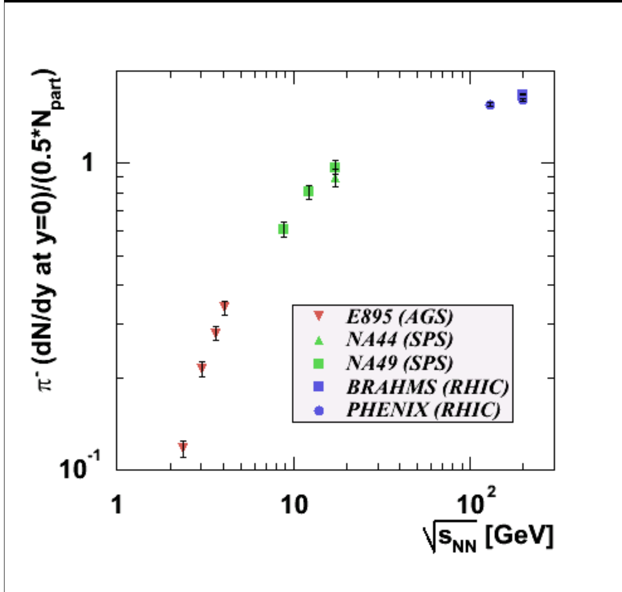
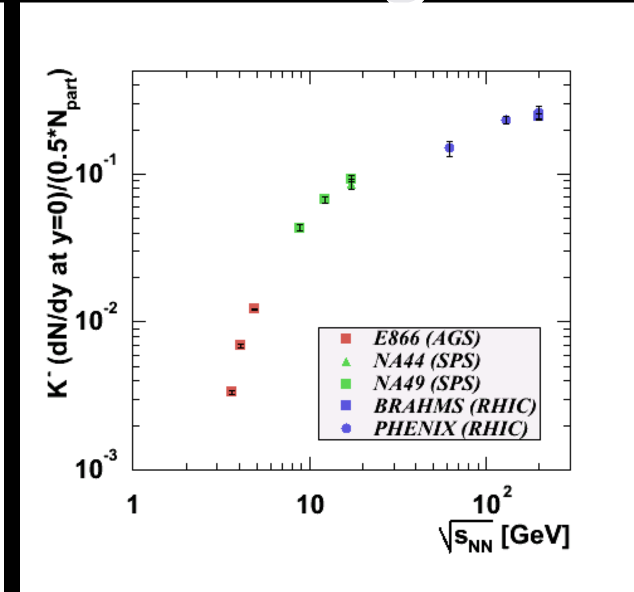
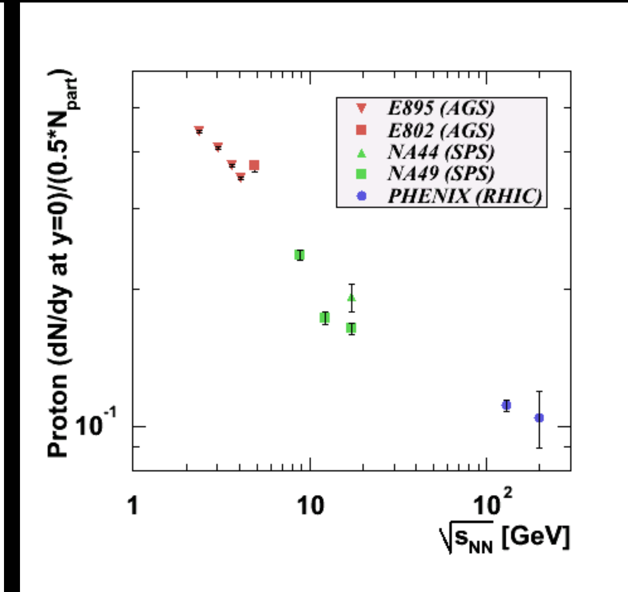
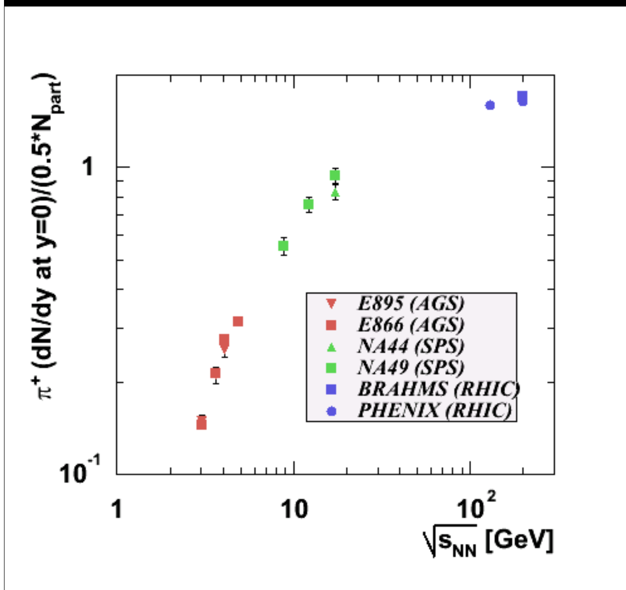
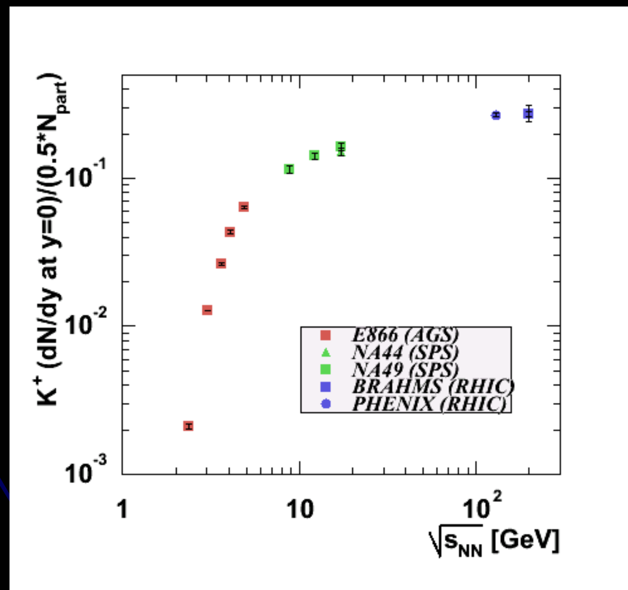
Measurement: Charged Hadron Yields

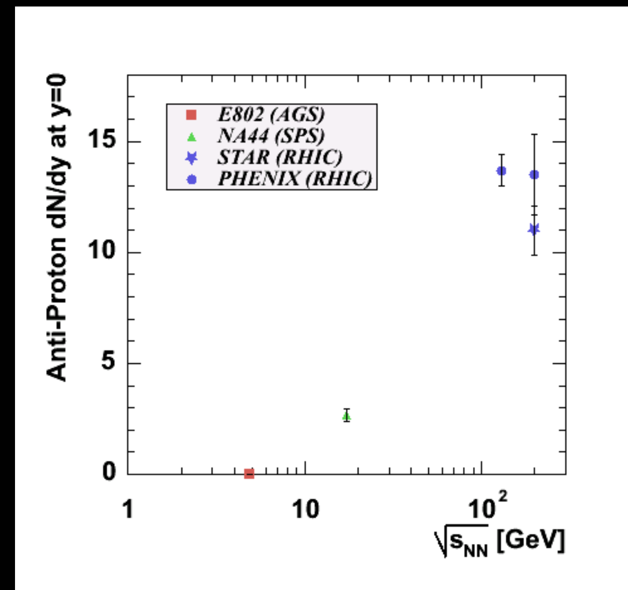




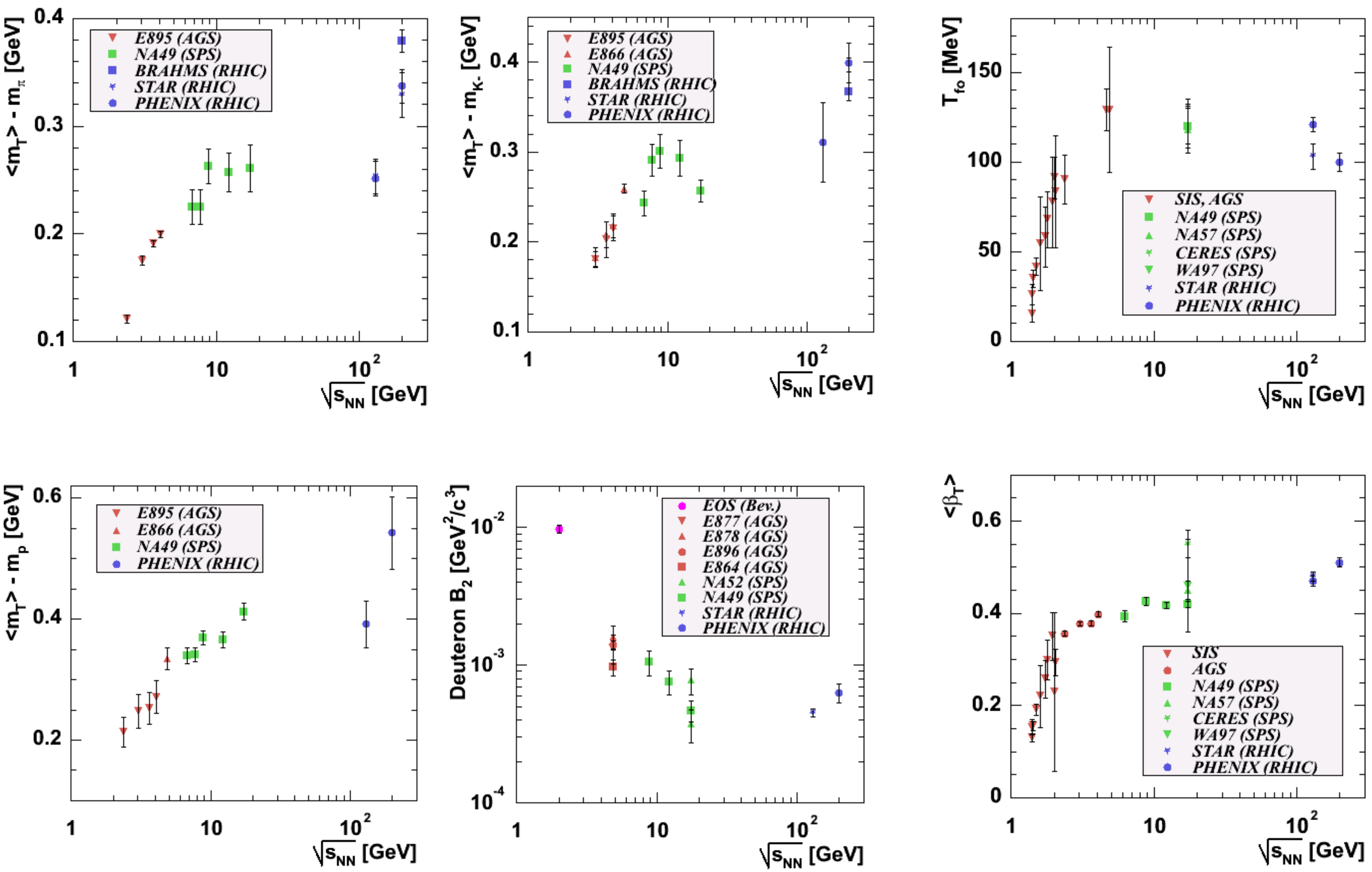




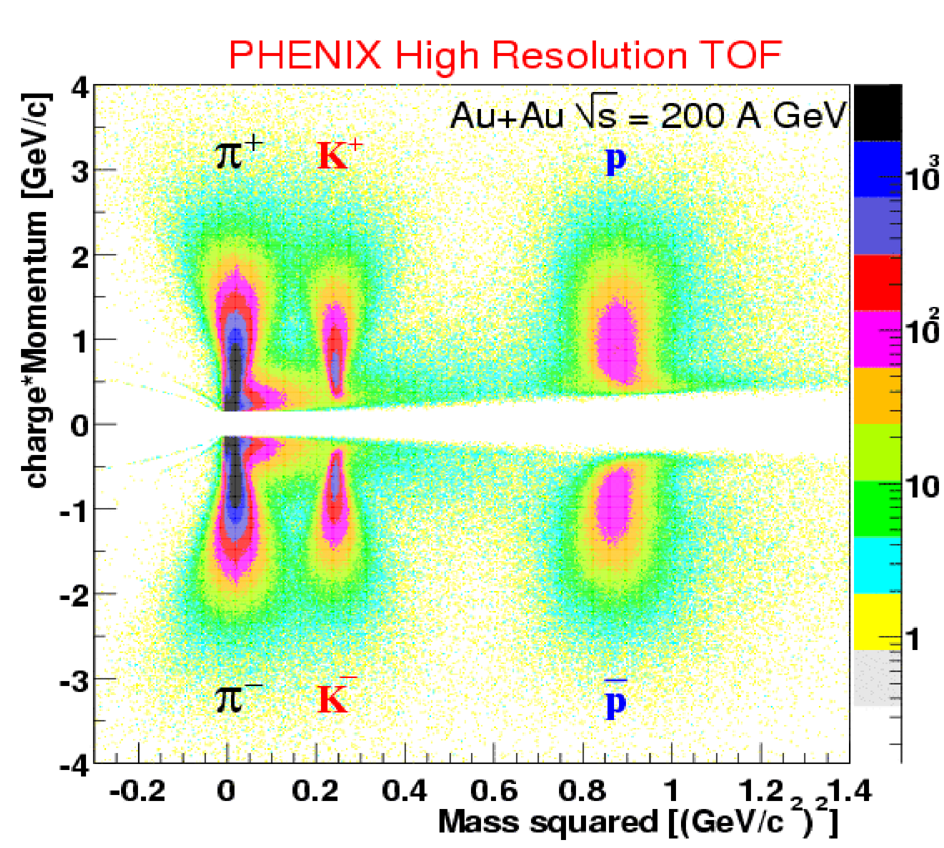


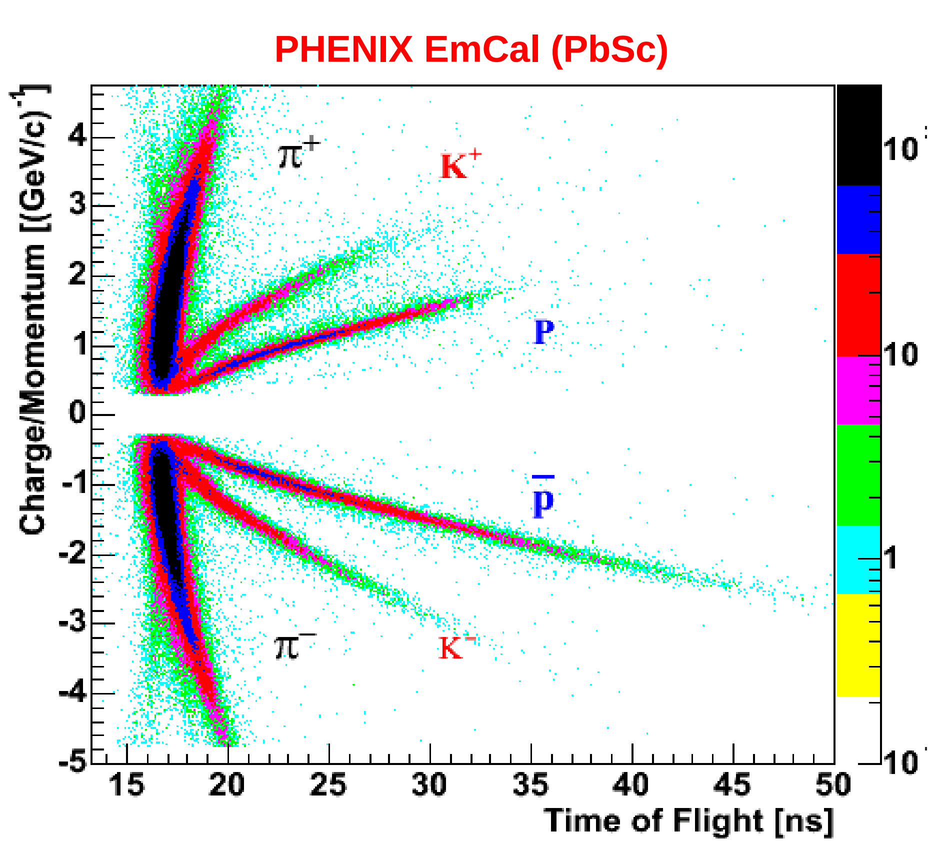


Measurement: Charged Hadron Spectra



Charged hadron identification in PHENIX





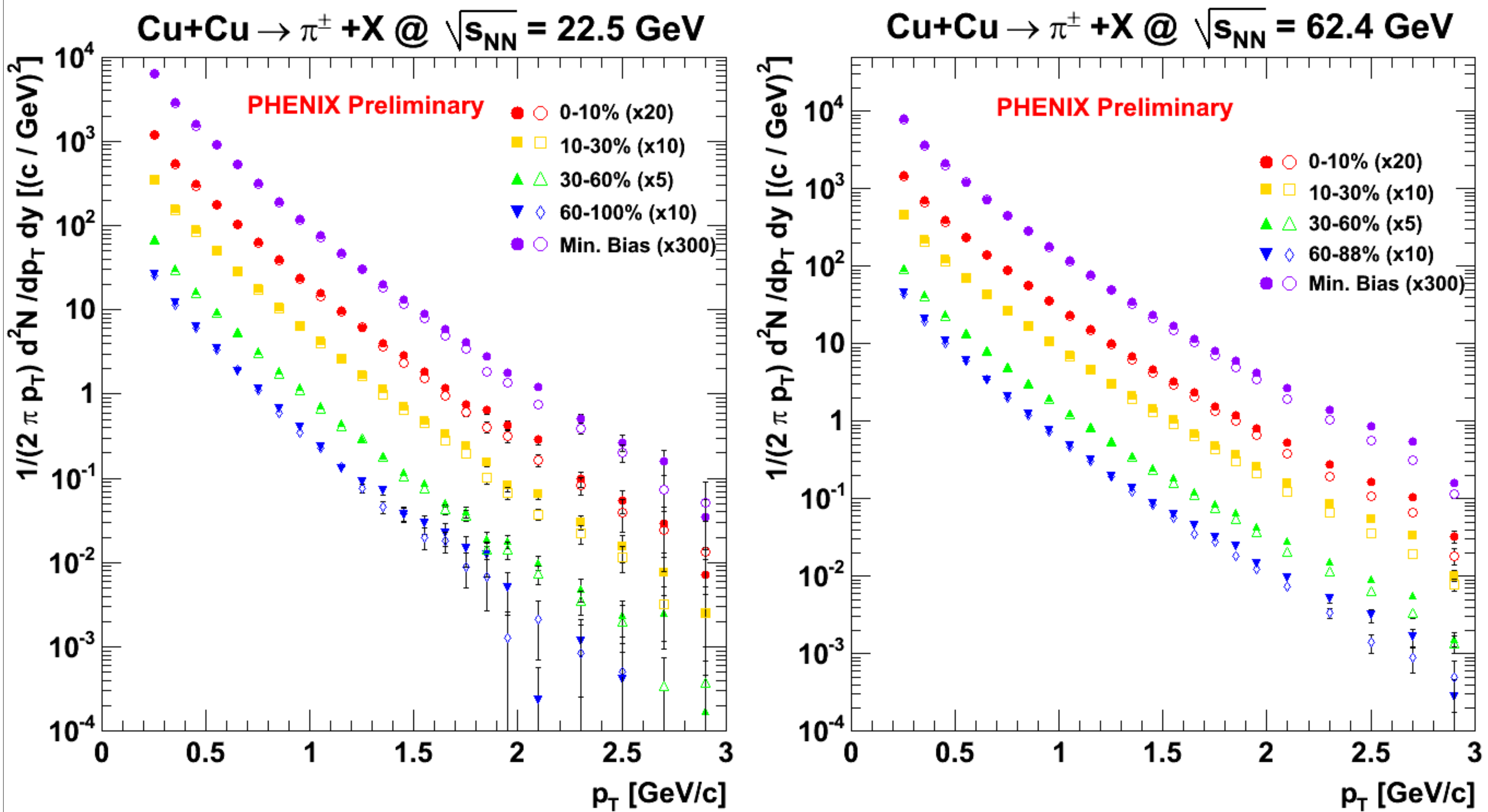
Time of Flight

- π/K separation ~ 3 GeV/c
- K/p separation ~ 5 GeV/c

Electromagnetic Calorimeter

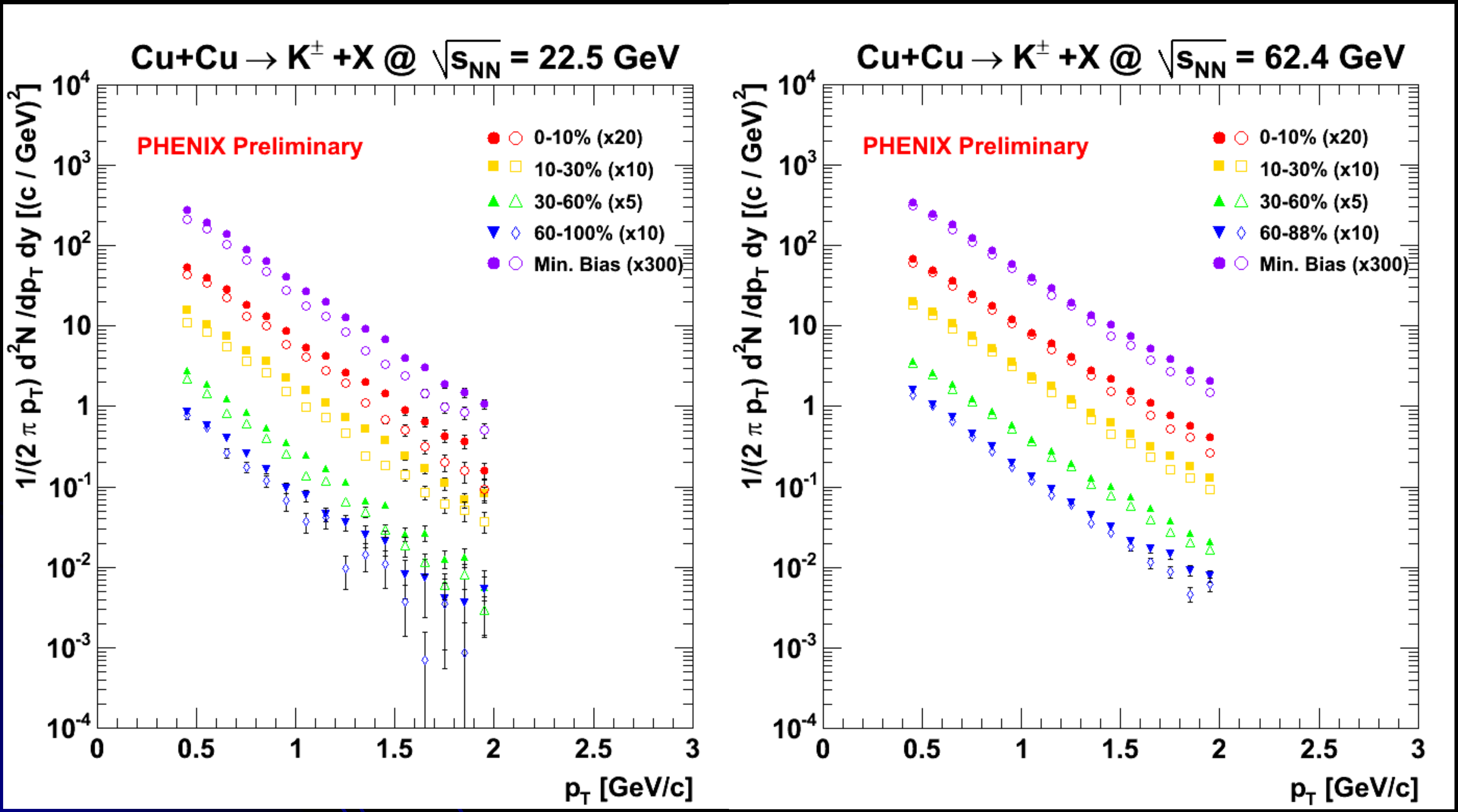
- π/K separation ~ 1 GeV/c
- K/p separation ~ 2 GeV/c

Measurement: p_T spectra for pions



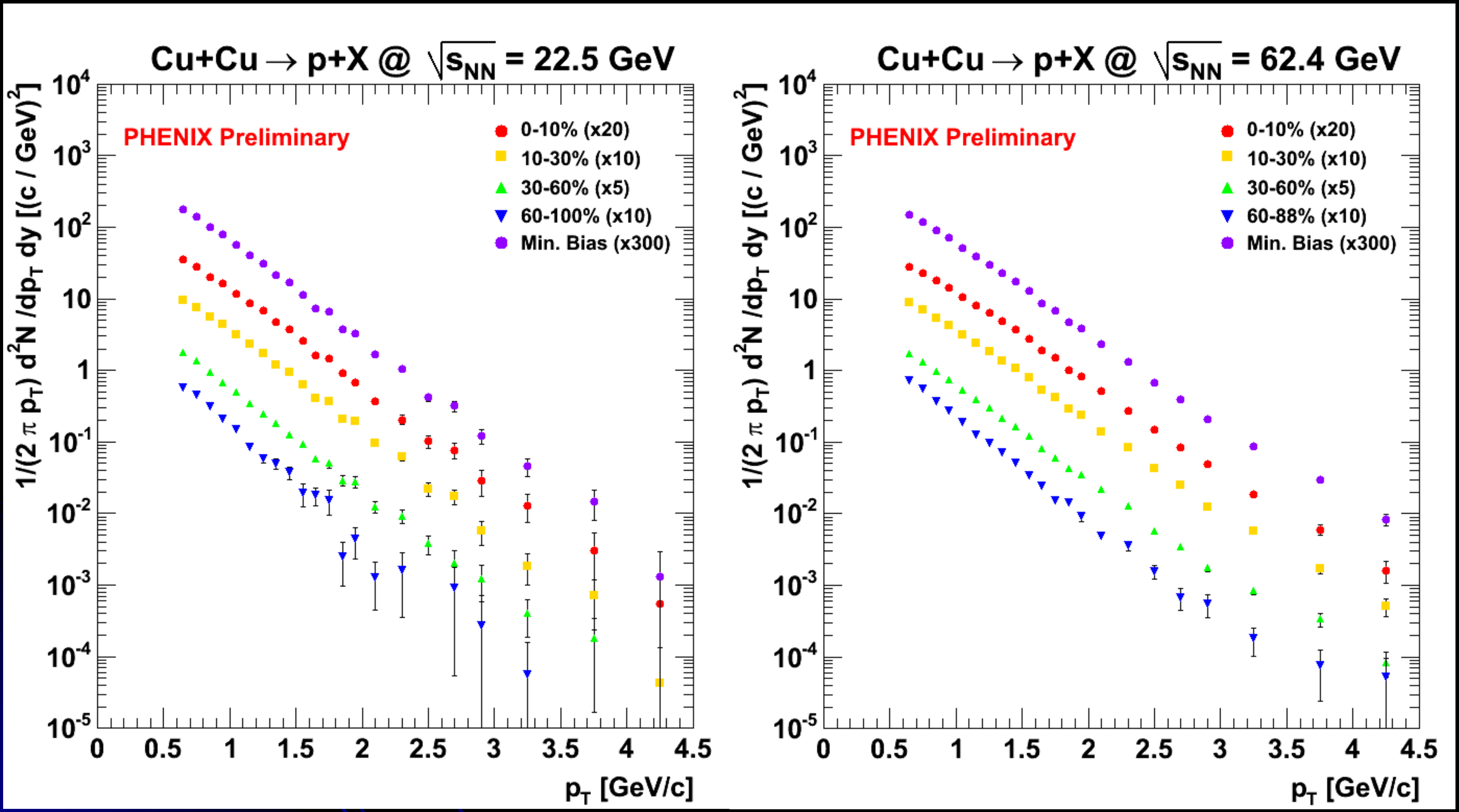
Filled symbols : π^+
Open symbols : π^-

Measurement: p_T spectra for kaons



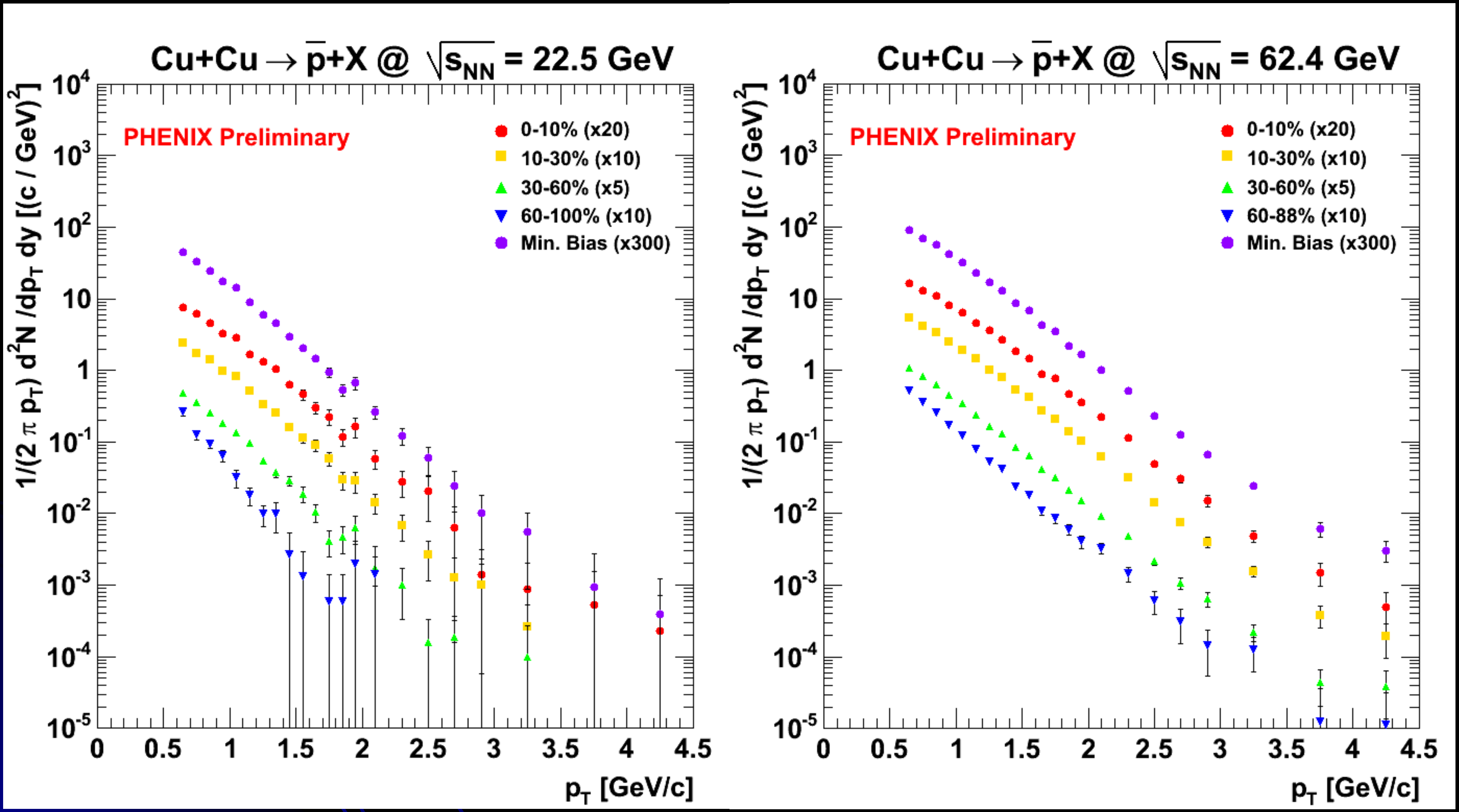
Filled symbols : K^+
Open symbols : K^-

Measurement: p_T spectra for protons



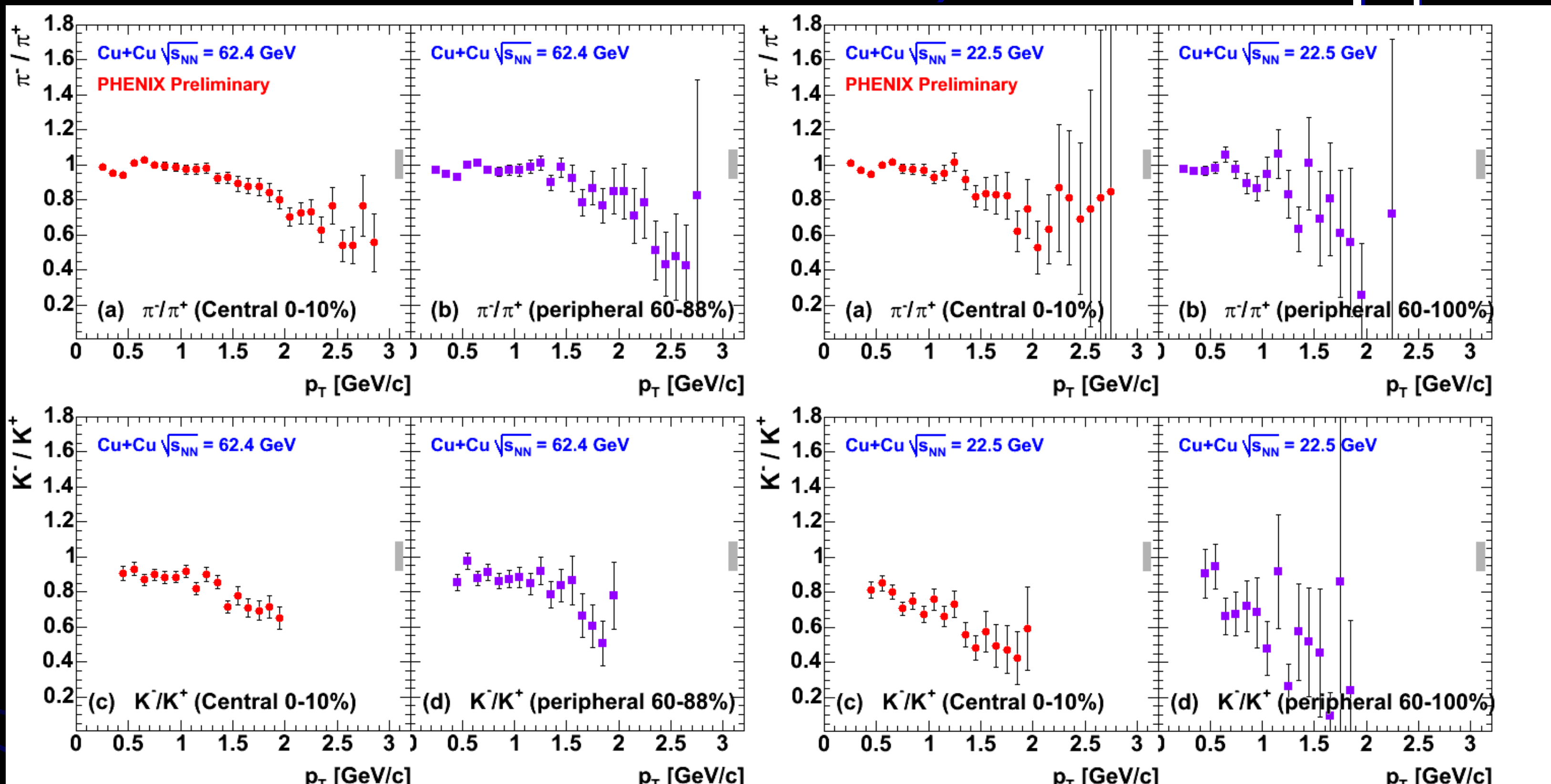
* No weak decay feed-down correction applied

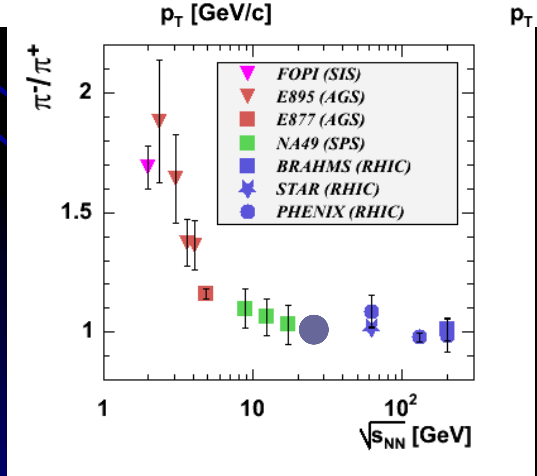
Measurement: p_T spectra for antiprotons

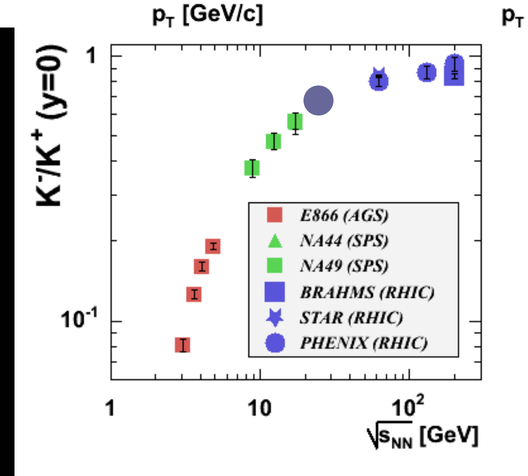


*** No weak decay feed-down correction applied**

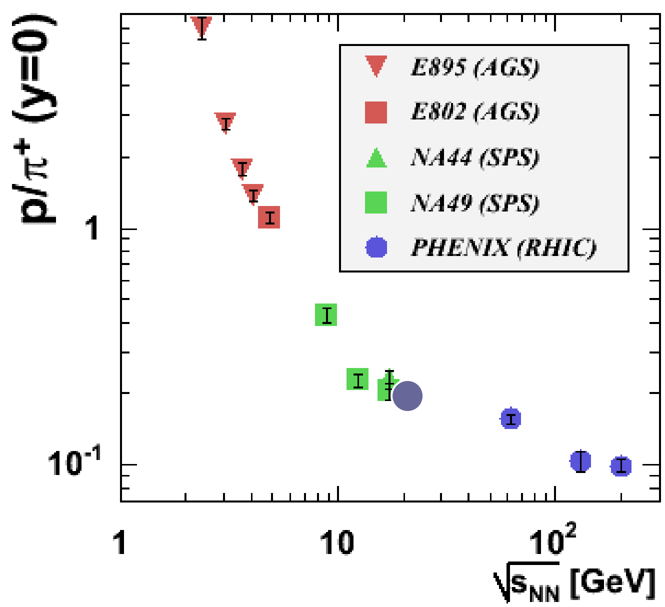
Measurement: π^-/π^+, K^-/K^+ vs. p_T

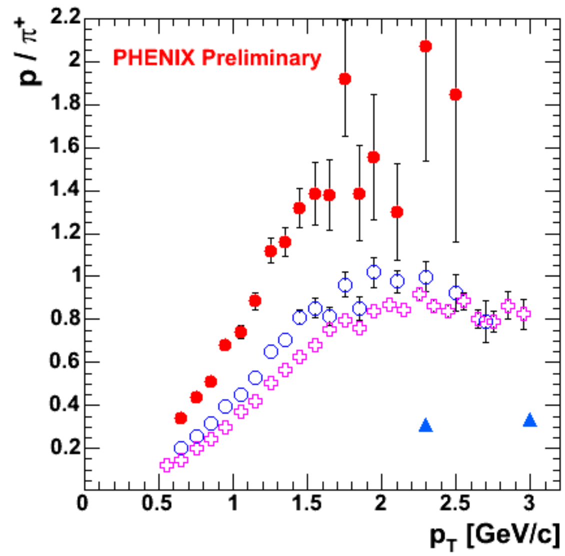


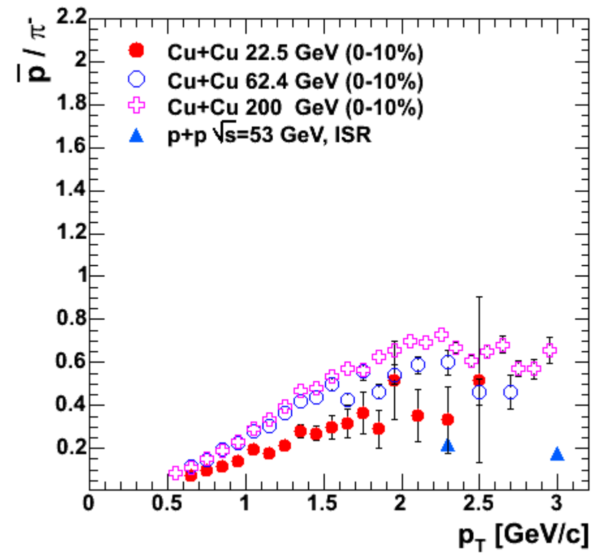




Measurement: p/π Ratios

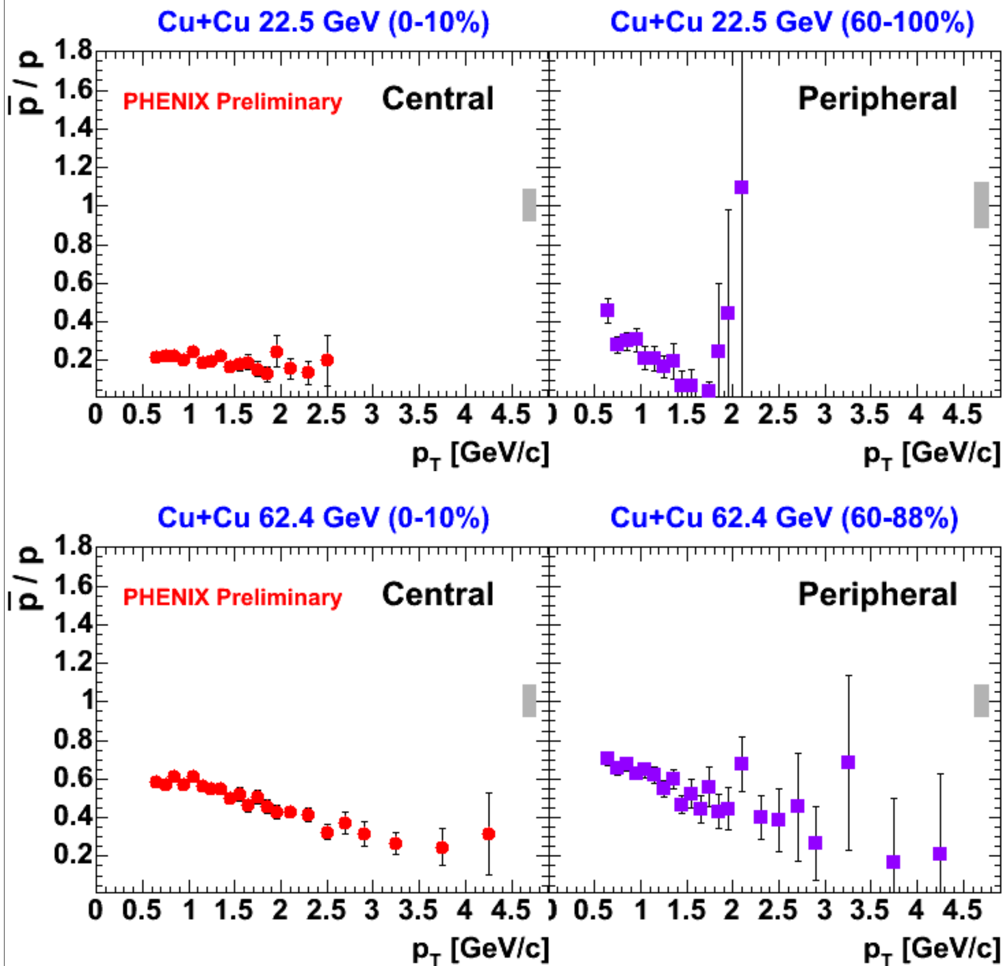


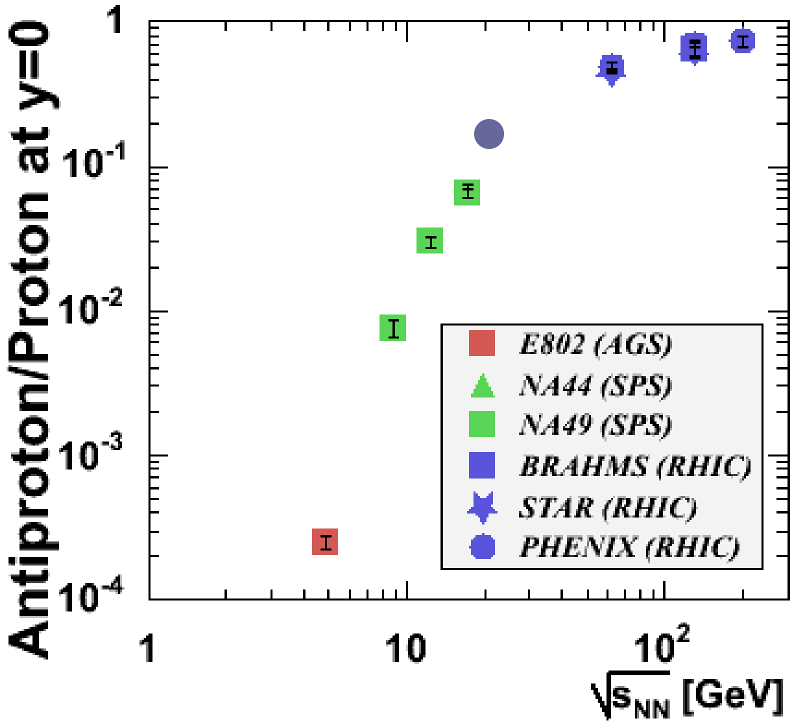




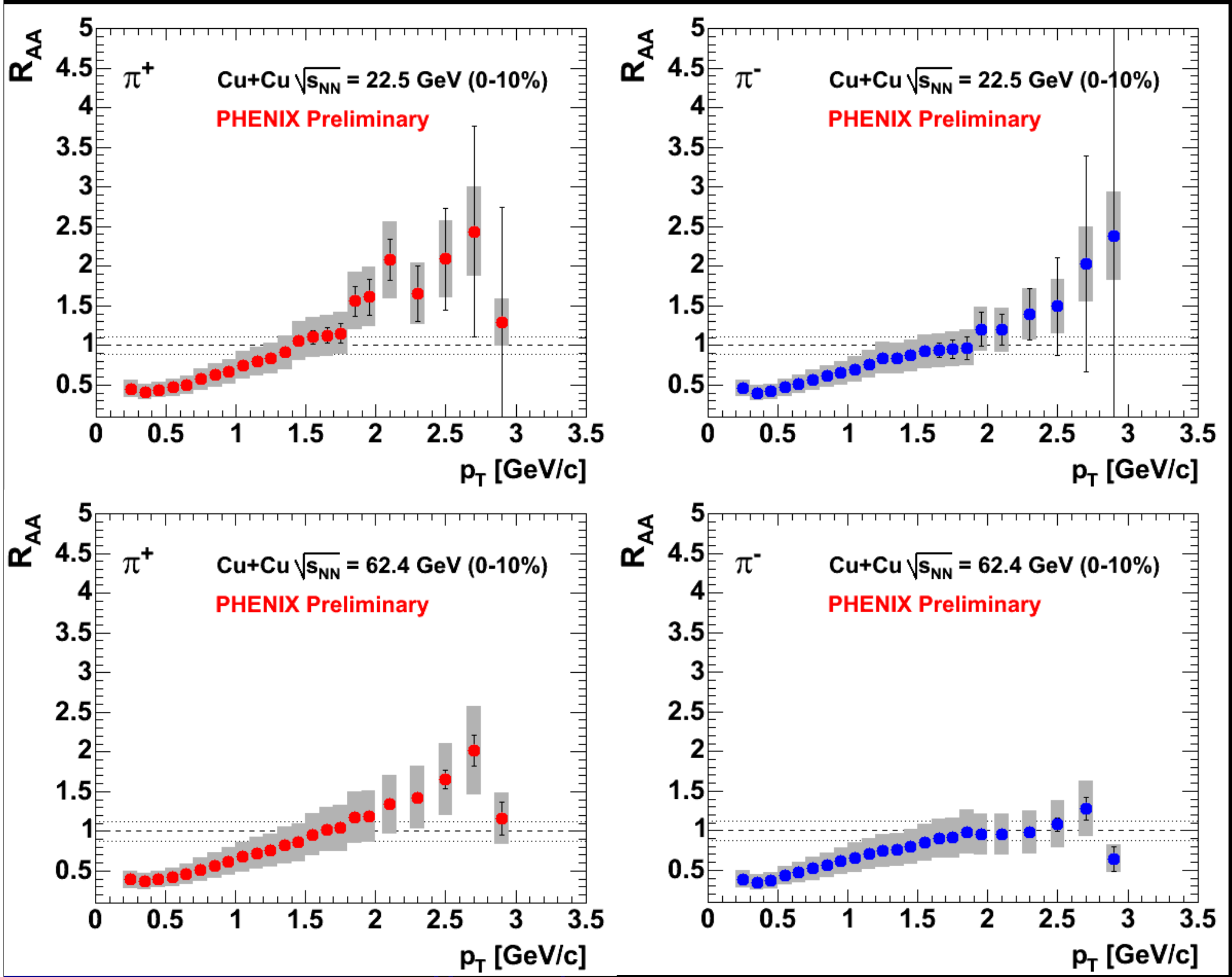
- **p/π^+ ratio** : increasing as a function of $\sqrt{s_{NN}}$.
- **$\bar{p}/\pi^-$ ratio** : decreasing as a function $\sqrt{s_{NN}}$.
  - Cu+Cu 22.5 GeV central data reaches the p+p values.

Measurement: pbar/p ratio vs. p_T





Measurement: R_{AA} for pions



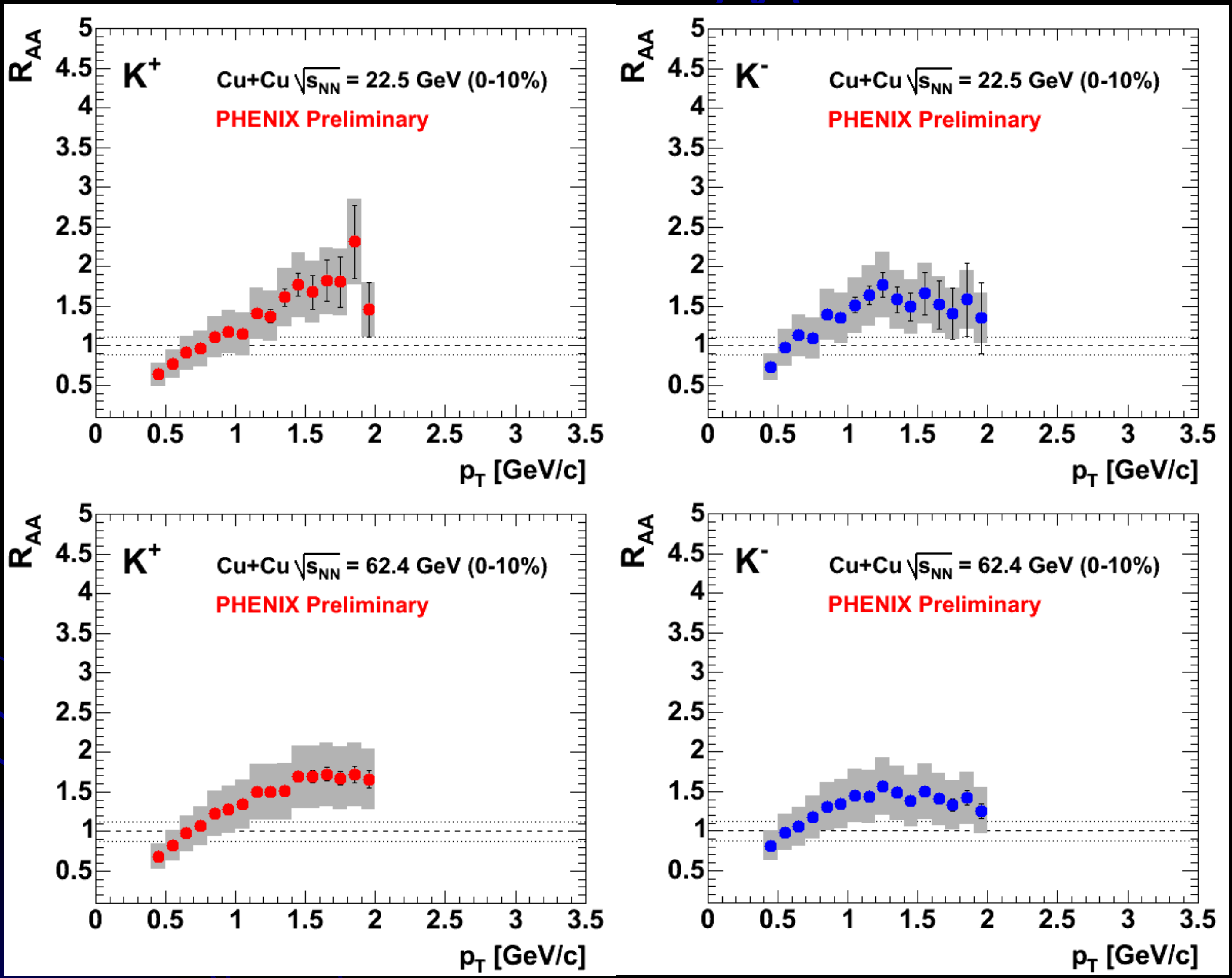
- p+p reference: global fit of pion data at $\sqrt{s}$ ~23 GeV (D. d'Enterria).

Error notations:

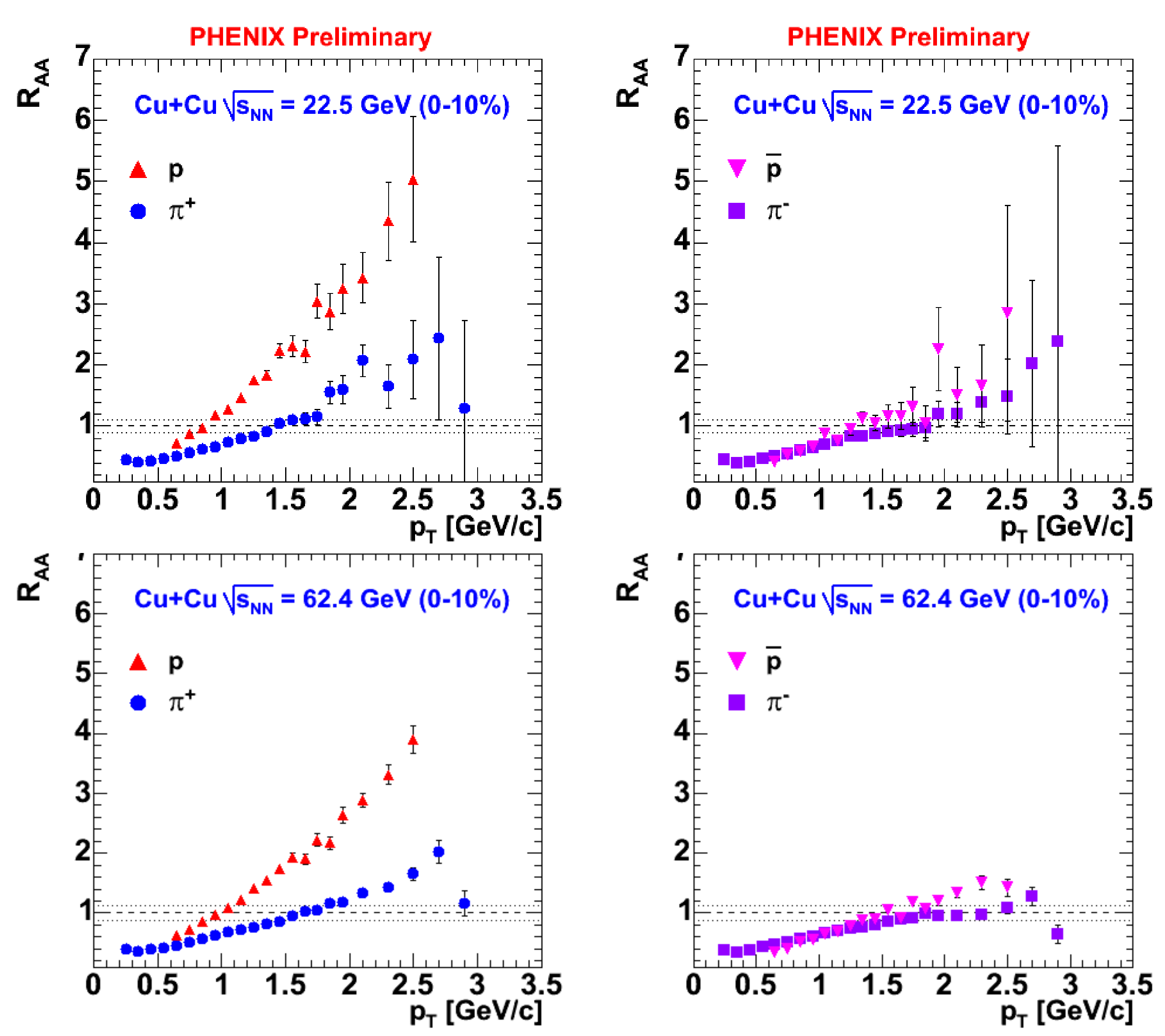
- Error bars: statistical error for Cu+Cu spectra
- Gray boxes:
  1) sys. error for p+p reference.
  2) sys. error for Cu+Cu spectra.
- Lines: N_{coll} error (1σ.)

- p+p reference: global fit of pion data at $\sqrt{s}$ ~62 GeV.
- nucl-ex/ nucl-ex/0411049, D. d'Enterria.

Measurement: R_{AA} for kaons

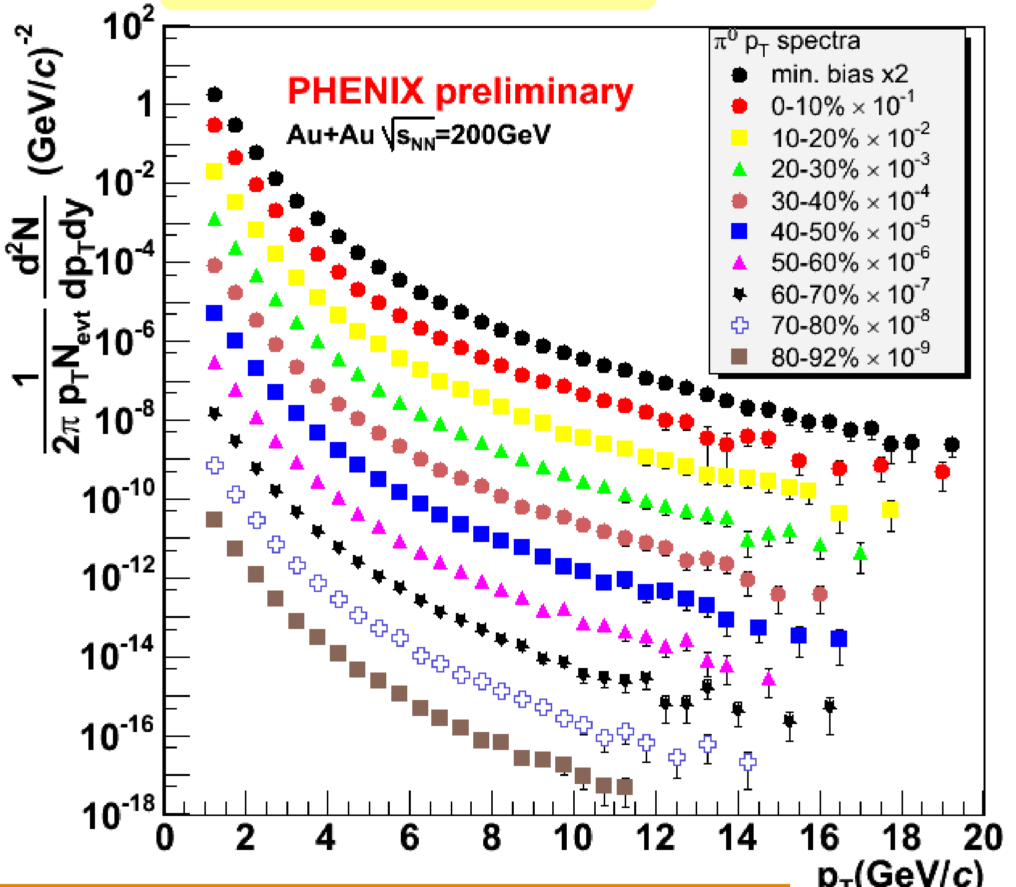


Measurement: p,π R_{AA}



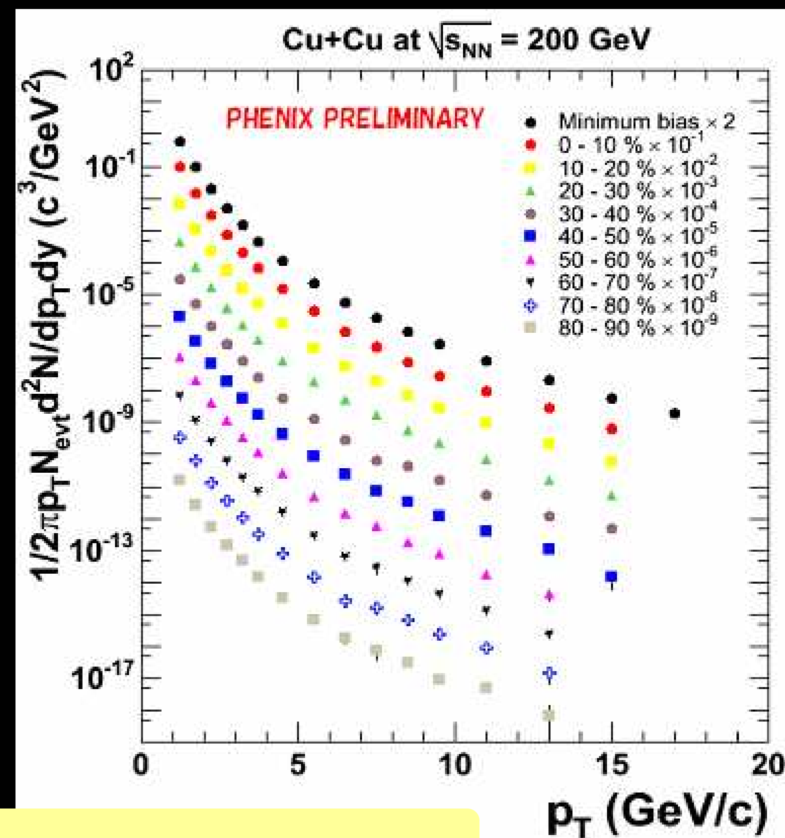
Measurement: π^0 p_T Spectra

New Run4 Data



Au+Au 200 GeV
Luminosity 241μb-1 (sampled)
1.5B events

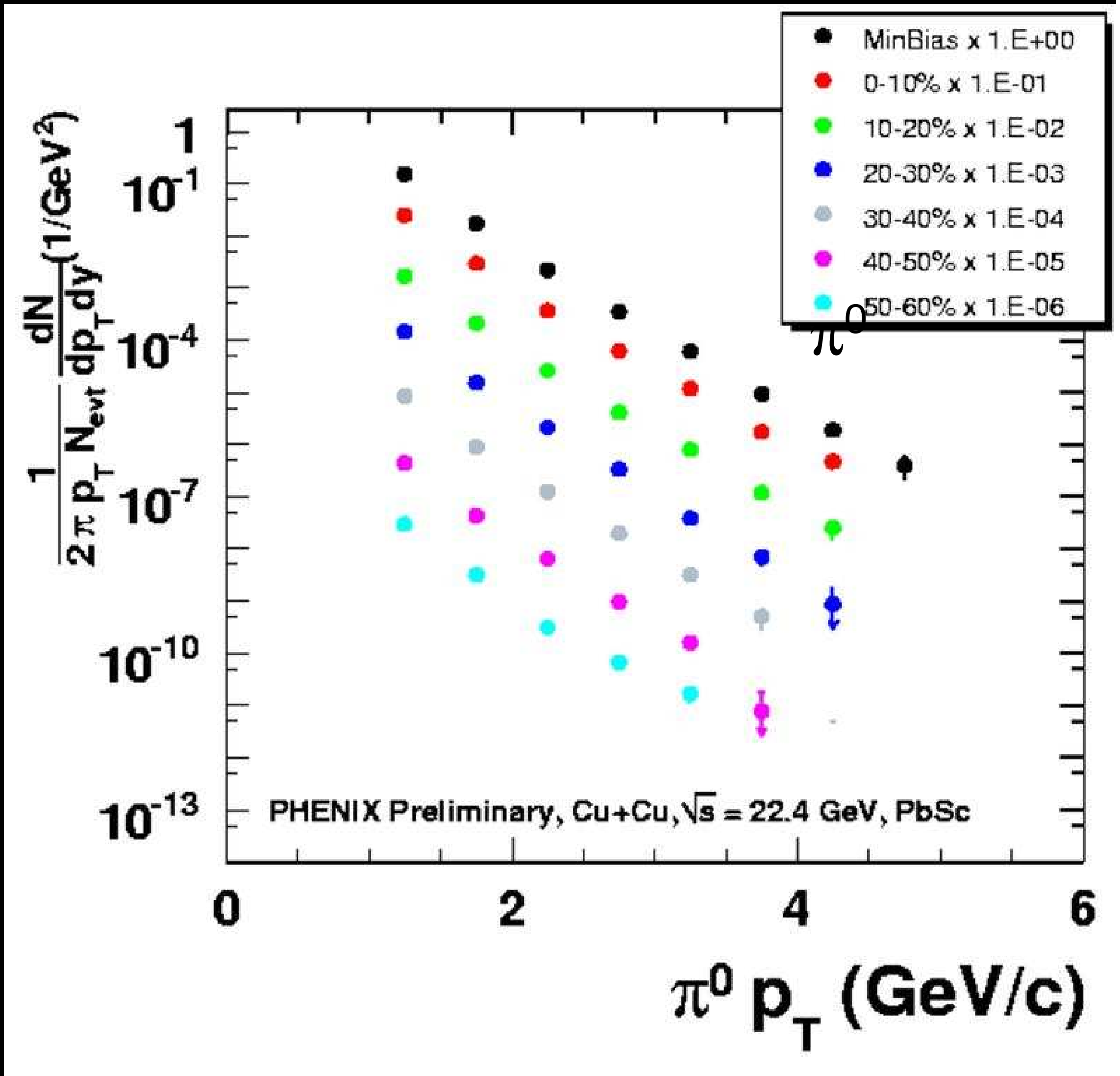
Cu+Cu 200 GeV
2.2 B sampled



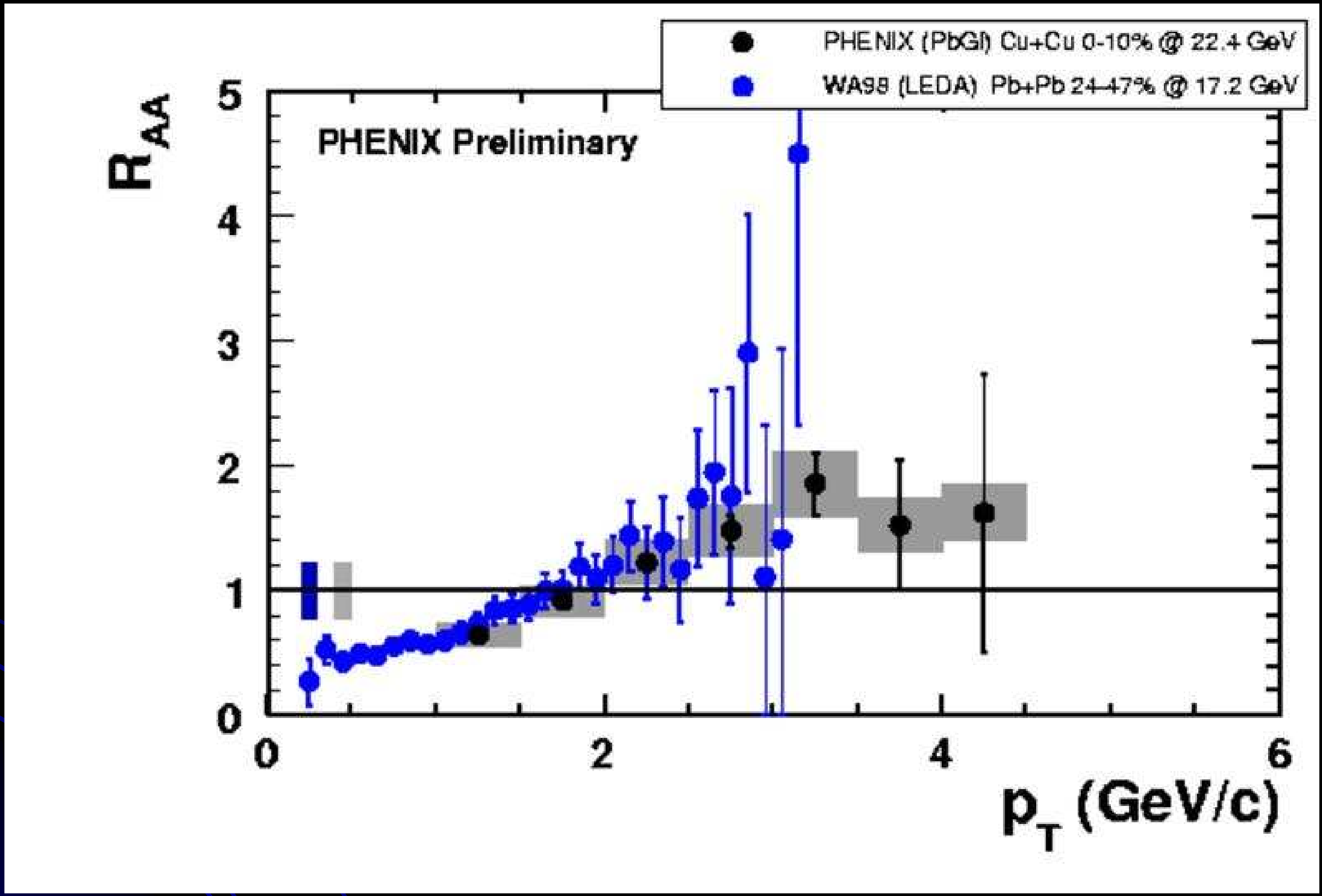
New Run5 Data

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



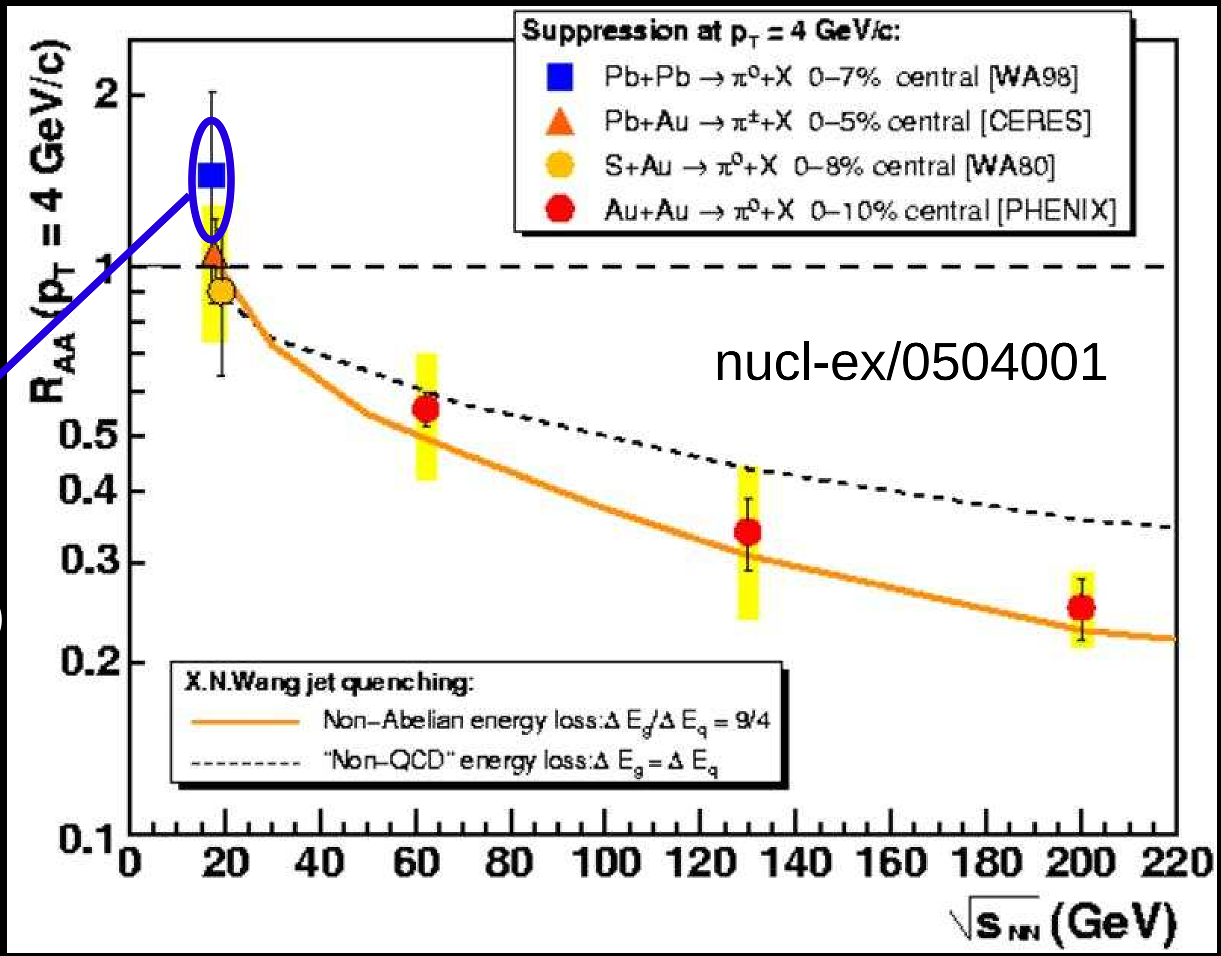
Measurement: π^0 R_{AA}



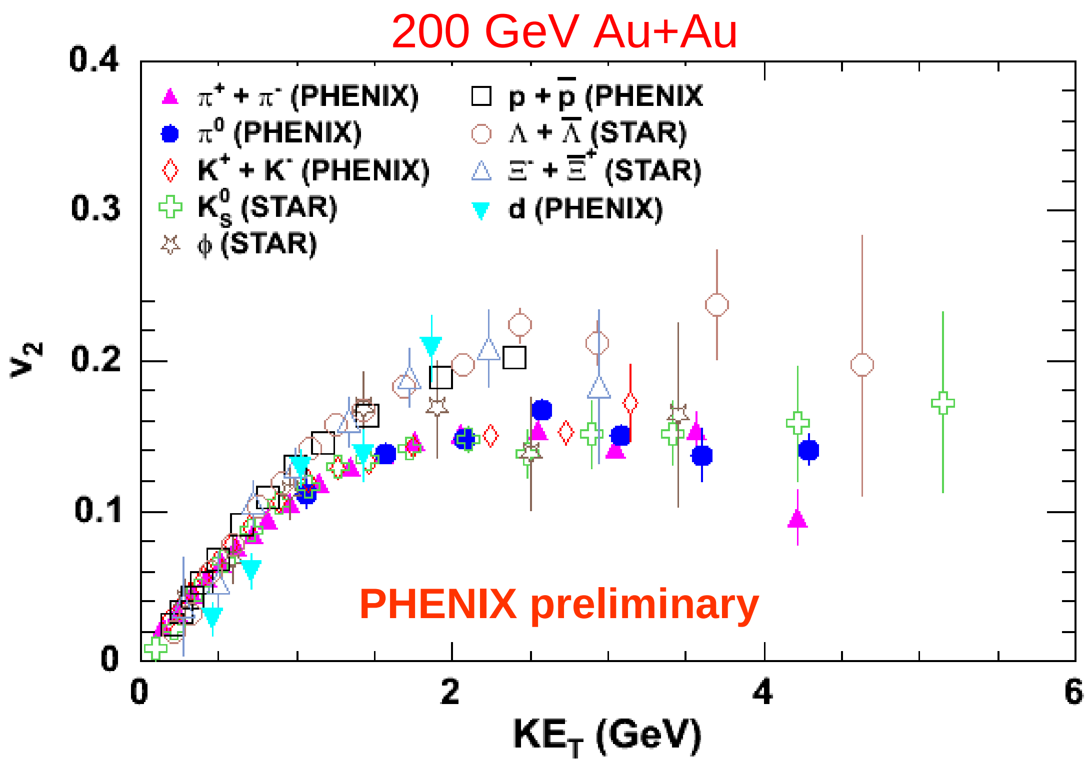
Similar N_{part} (WA98 : 132, PHENIX: 140)
same behaviour

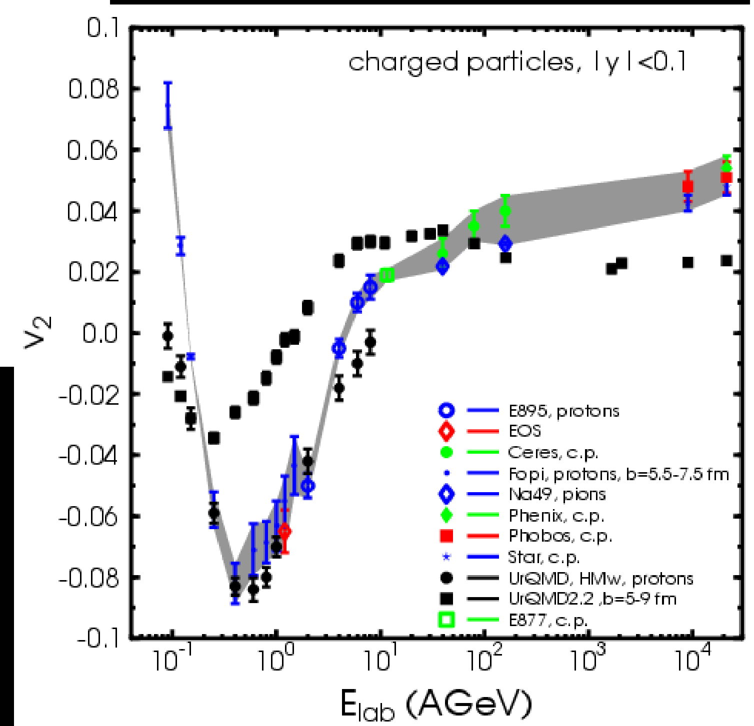
Measurement: π^0 R_{AA}

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



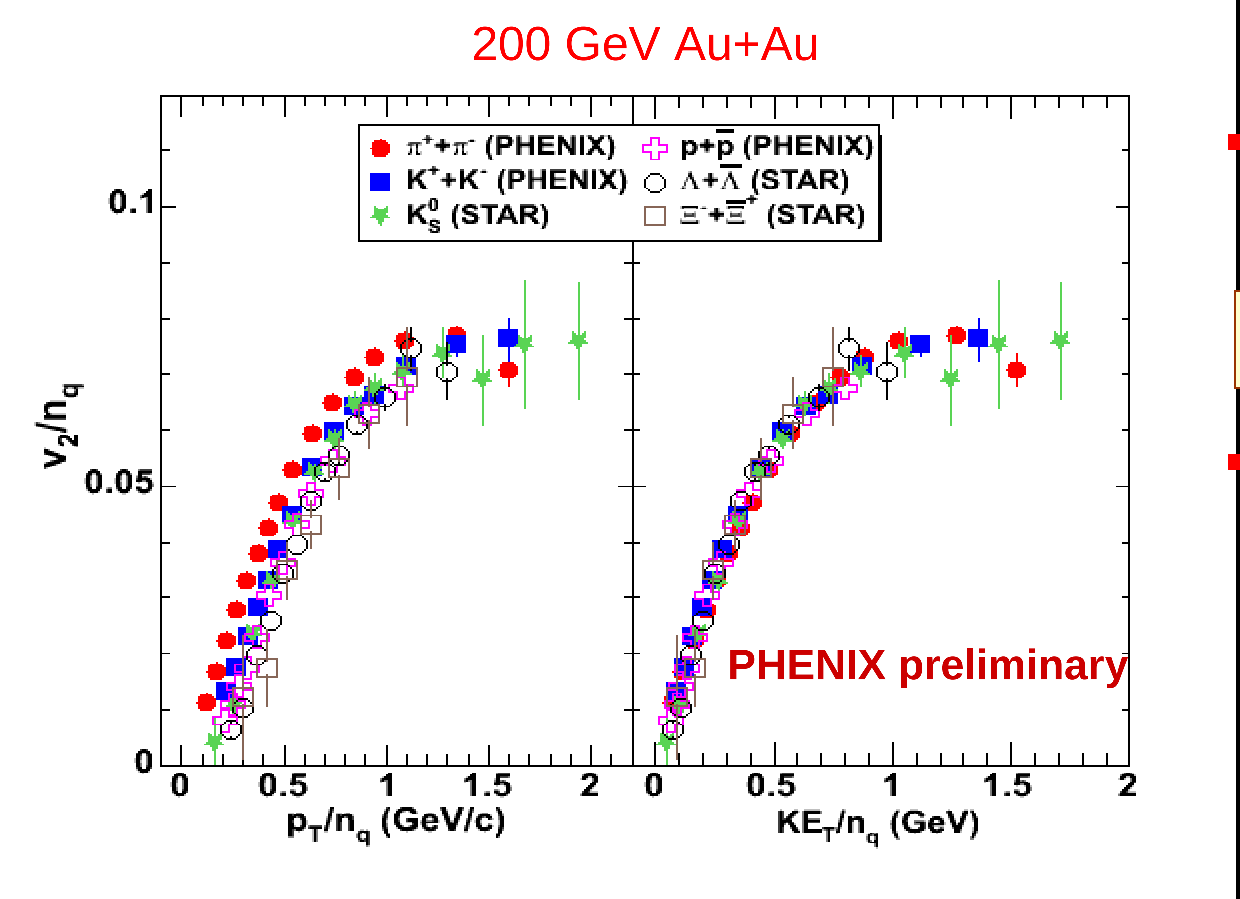
Measurement: v_2





- 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

$$v_2^h(KE_T) = n v_2^p(KE_T / n)$$

- 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

Fluctuations and Critical Exponents

- A useful tool in the search for the QCD critical point is the observation of critical behavior through fluctuations and correlations.
- Near a phase transition, thermodynamic quantities (compressibility, heat capacity, correlation length) diverge. The divergence follows a power-law behavior described by a critical exponent. For example, γ is the critical exponent for compressibility and typically has a value of ~1.2:

$$\frac{k_T}{k_T^c} = A^{'}\left(\frac{T - T_c}{T_C}\right)^{-\gamma}$$

- All systems should exhibit a universal behavior near the phase transition. Experimentally, many fluids exhibit this behavior.

Example: Multiplicity Fluctuations

- In the Grand Canonical Ensemble, particle number (multiplicity) fluctuations can be related to the compressibility:

$$\left(\sigma^2/\mu\right)/\mu = 1/k_{NBD} + 1/\mu = \frac{k_B T}{V} k_T$$

- Again, the critical exponent for compressibility is represented by the symbol γ and is described by

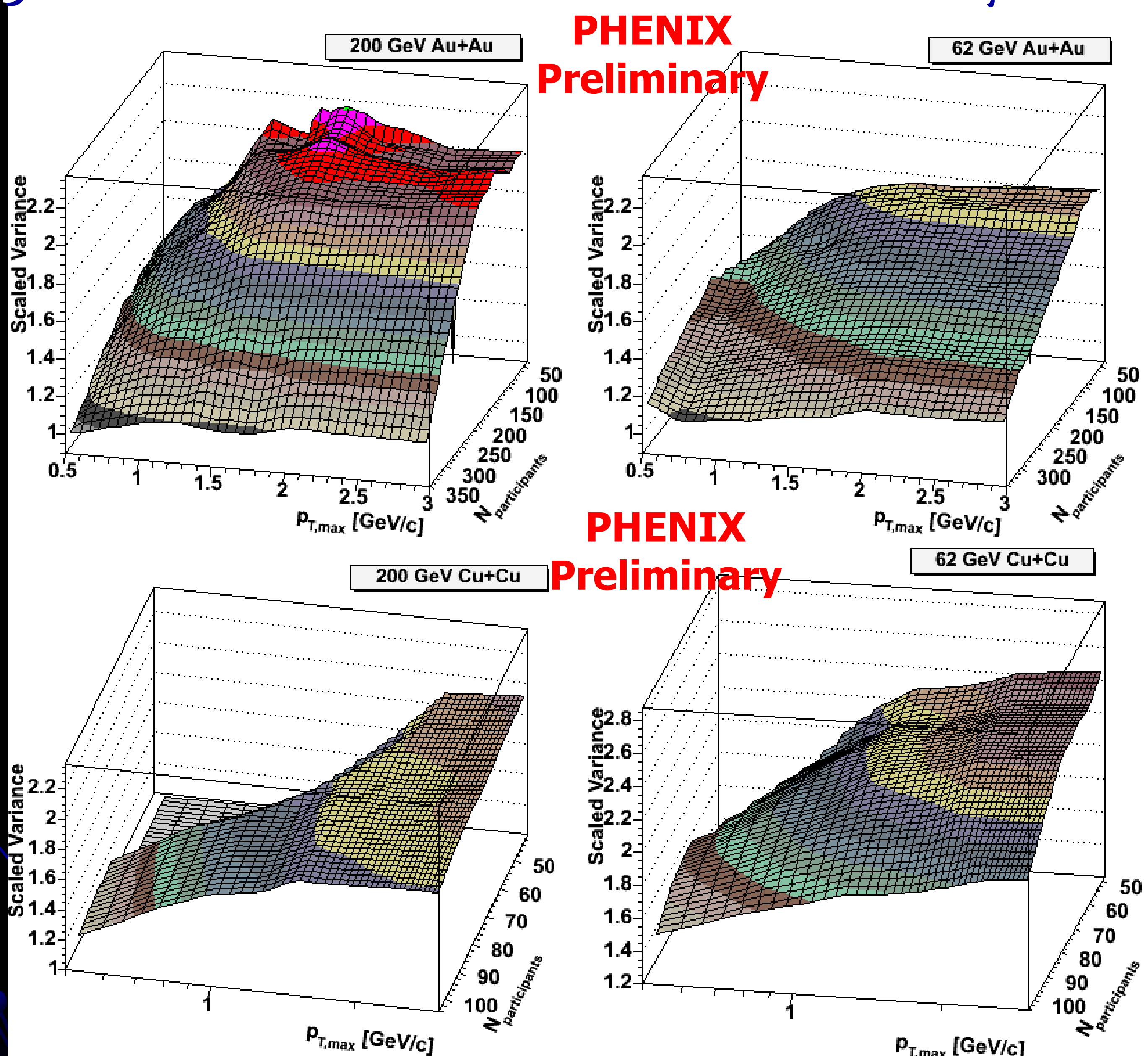
$$\frac{k_T}{k_T^c} = A^{'}\left(\frac{T - T_c}{T_C}\right)^{-\gamma}$$

- This gives (A=constant, T=Temperature, V=volume)

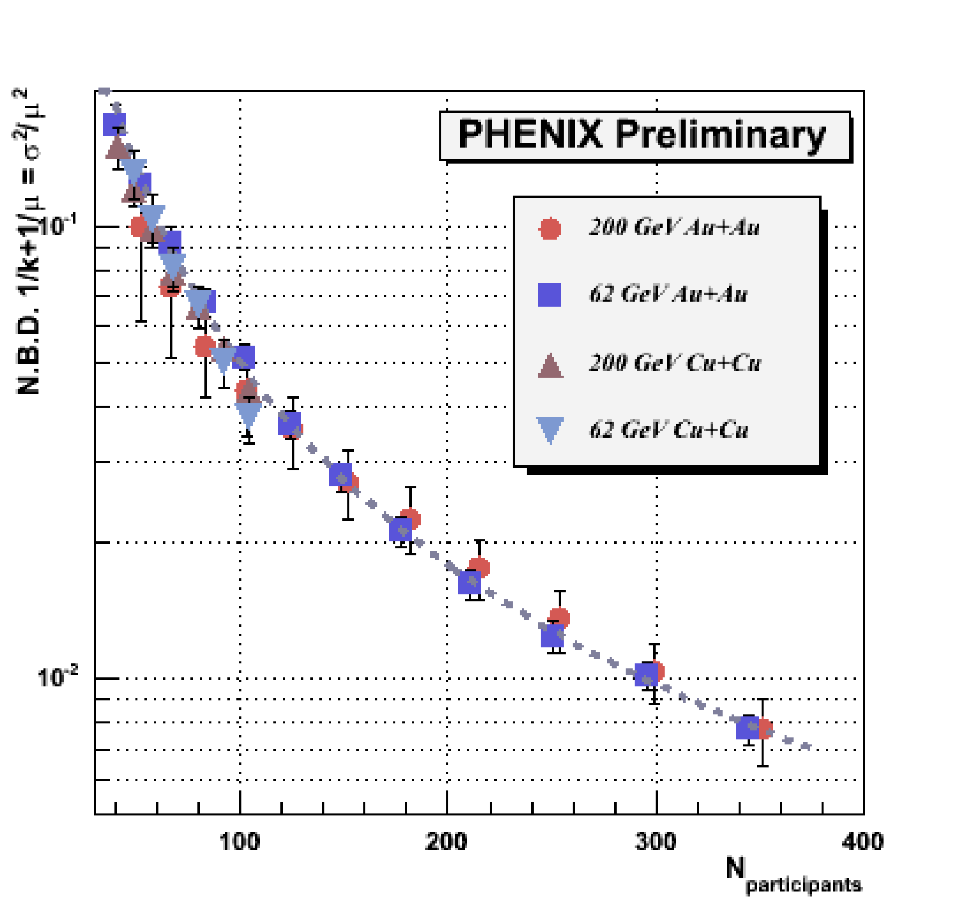
$$\left(\sigma^2/\mu\right)/\mu = A\left(\frac{T}{V}\right)\left(\frac{T - T_c}{T_C}\right)^{-\gamma}$$

A Survey of Scaled Variance, σ^2/μ

- Inclusive charged hadron fluctuations.
- $0.2 < p_T < p_{T,max}$ GeV/c
- These values are corrected to remove the contribution due to impact parameter (geometrical) fluctuations and projected to 2π in azimuth.
- The Poissonian (random) limit is 1.0.
- Large non-random fluctuations are observed that increase with p_T and decrease with centrality, although the p_T-dependence is relatively weak, unlike $<p_T>$ fluctuations.



Measurement: Multiplicity Fluctuations



Inclusive charged hadron multiplicity fluctuations.

All points extracted from a fit to a Negative Binomial Distribution.

All points are corrected to remove contributions due to geometry fluctuations within a centrality bin.

All points are corrected for efficiency and occupancy and projected to 2π azimuthal acceptance.

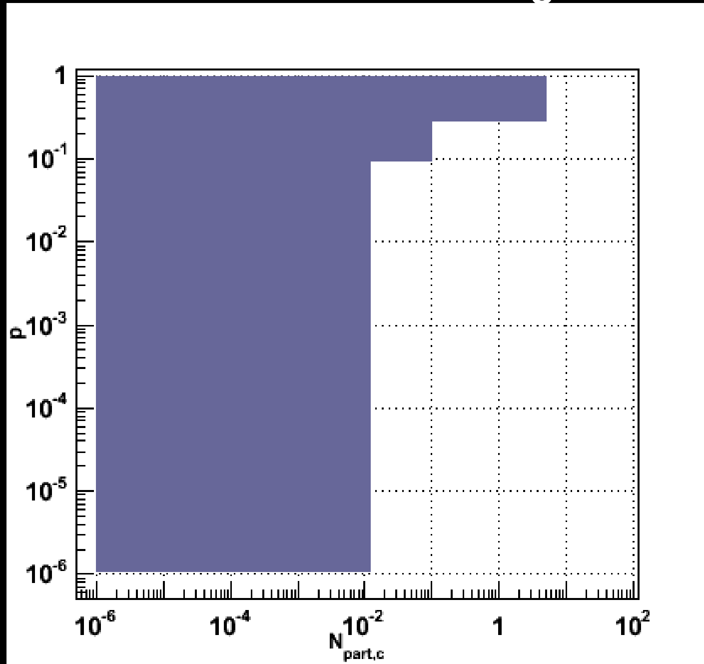
All species lie on a universal curve.

The curve is a power law.

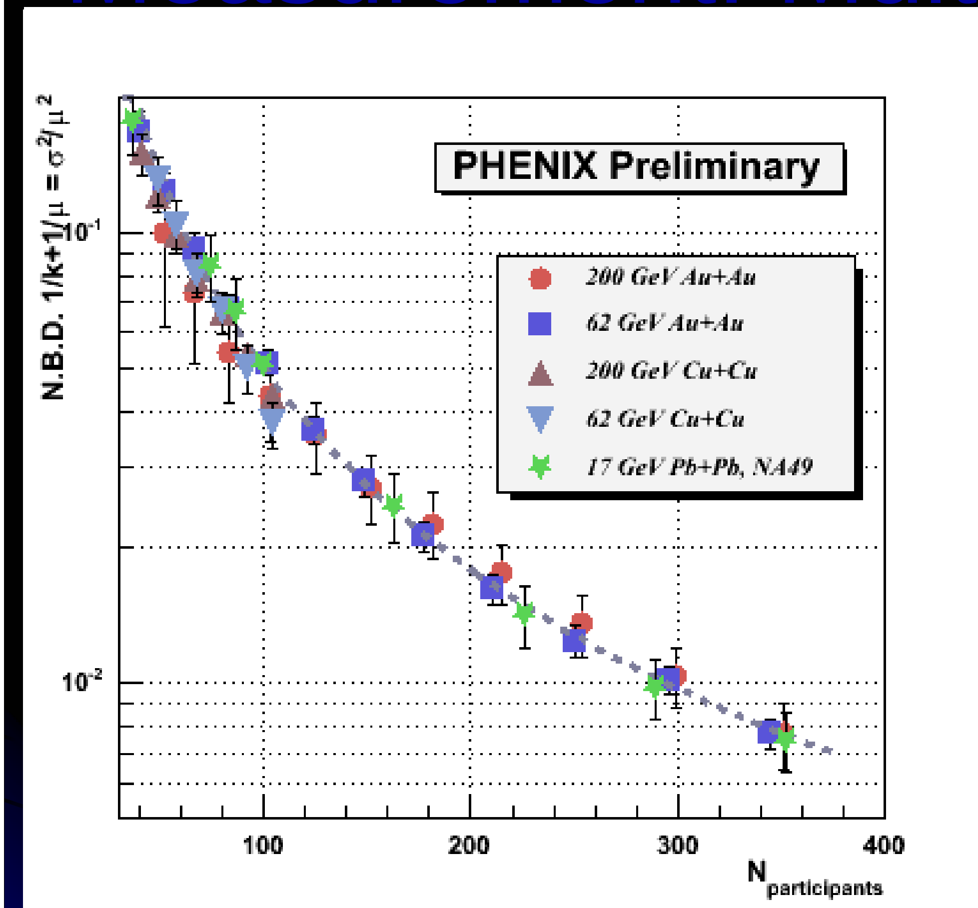
Assuming that the temperature varies with $N_{participants}$ as:

$$T \propto N_{part}^{p}$$

The exponent γ is consistent with the value of [1.1-1.2] at the 95% confidence level over the following range:



Measurement: Multiplicity Fluctuations



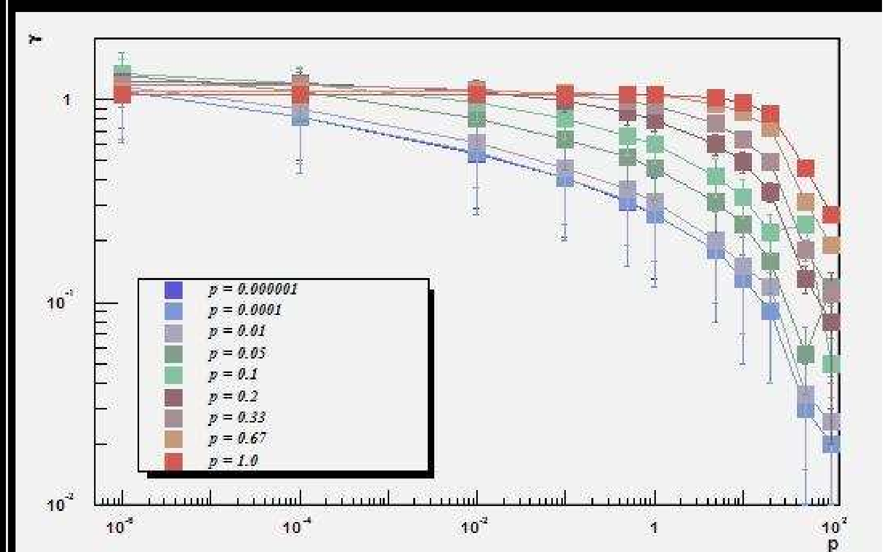
All species lie on a universal curve.

The curve is a power law.

Assuming that the temperature varies with $N_{participants}$ as:

$$T \propto N_{part}^{p}$$

The exponent γ varies as a function of $N_{part,c}$ and p as shown below. All fits pass a 90% confidence level χ^2 test.



NA49 data (17 GeV Pb+Pb) fall upon the same universal curve!

Measurement: <p_T> Fluctuations

Fluctuations in event-by-event <p_T> are related to temperature fluctuations in the system. Hence, they can probe the heat capacity of the system.

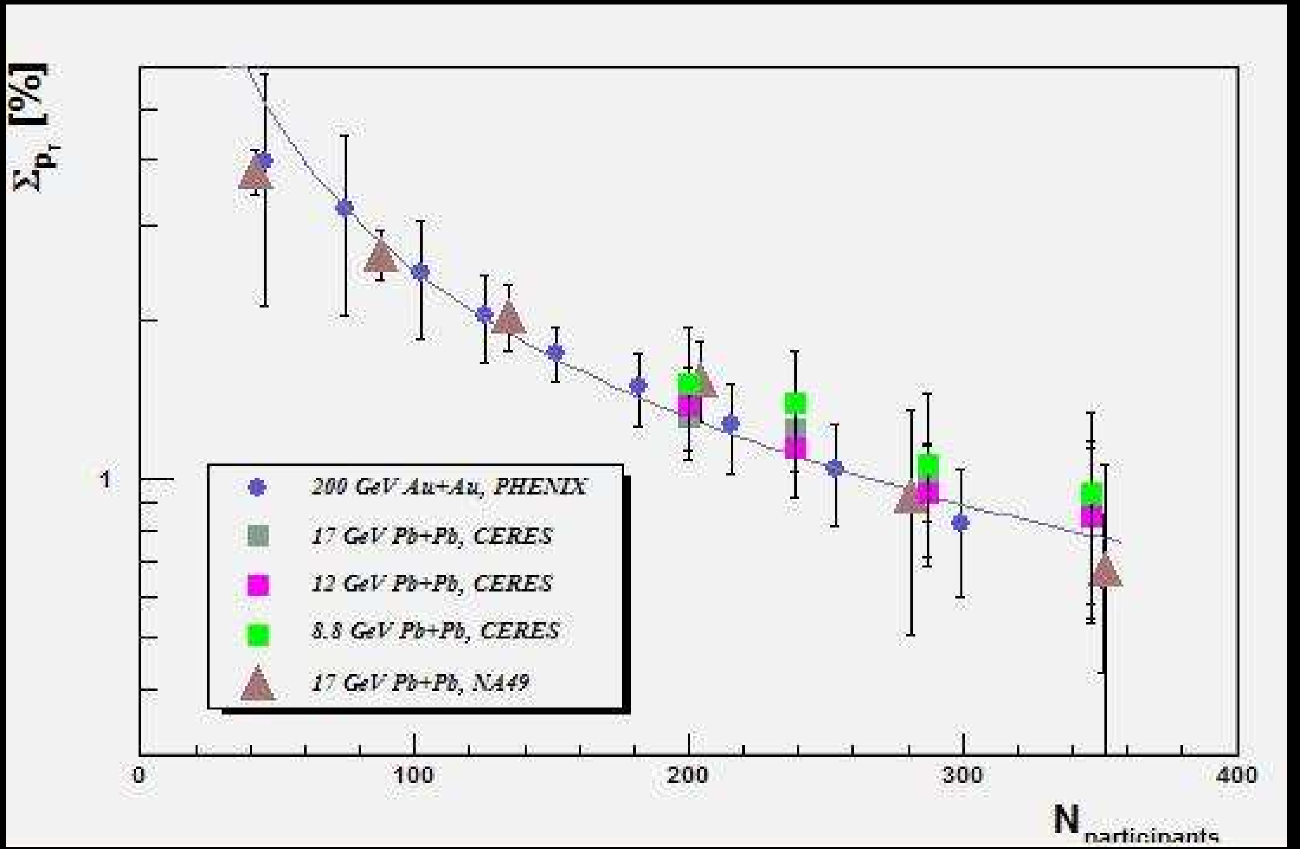
Contributions due to hard scattering should be much reduced at low energy.

For constant volume, the critical exponent for the heat capacity, α, could be extracted by varying sqrt(s_{NN}).

Unfortunately, simulations show that PHENIX sensitivity to temperature fluctuations is much reduced at low energy due to the small acceptance.

Σ_{pt} = (event-by-event p_T variance) – (inclusive p_T variance)/(mean multiplicity per event) normalized by the inclusive mean p_T.

Random expectation, Σ_{pt} = 0.0.



When plotted in terms of the Σ_{pT} variable, SPS and RHIC data fall on a universal curve which can be described by a power law function of N_{part}.

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

Calorimetry:

Rejection of Dalitz/Conv.

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

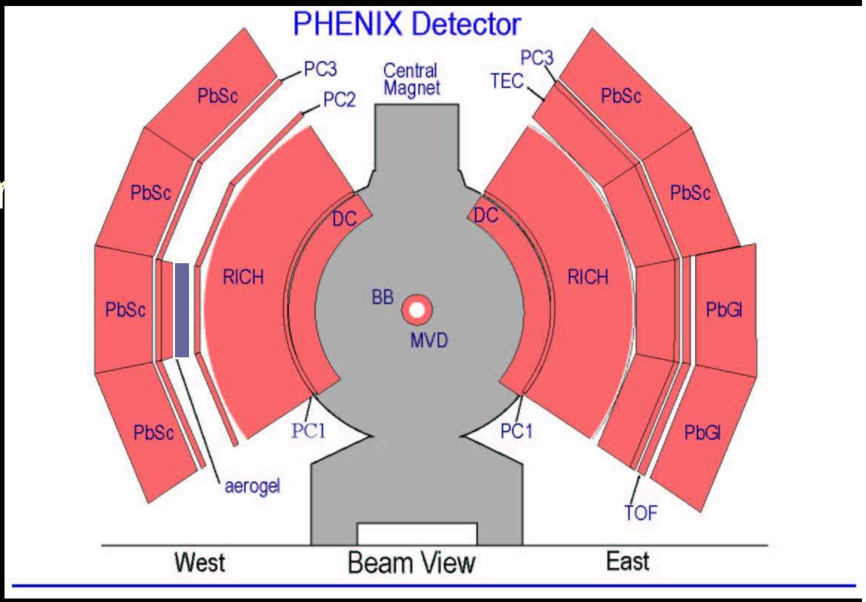
γ/π° coverage to very fwd

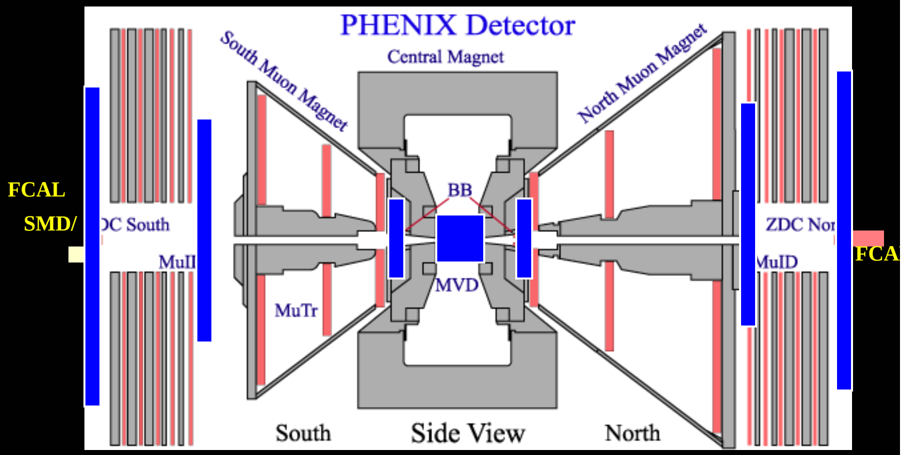
Event Characterization:

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

Data Acquisition:

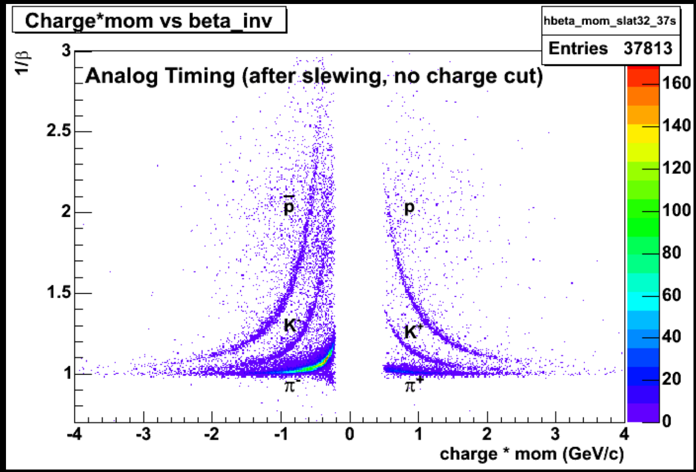
- DAQ Upgrade

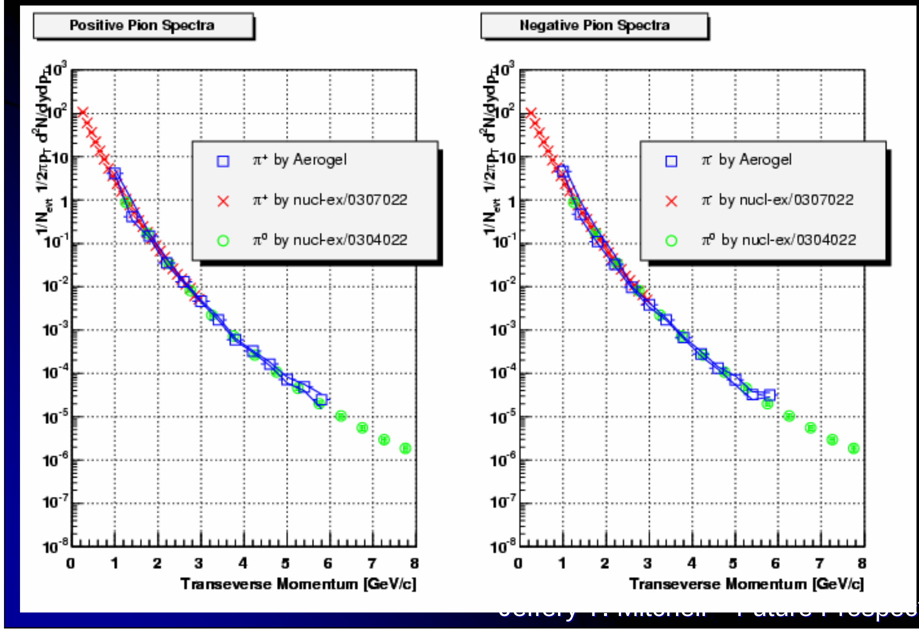


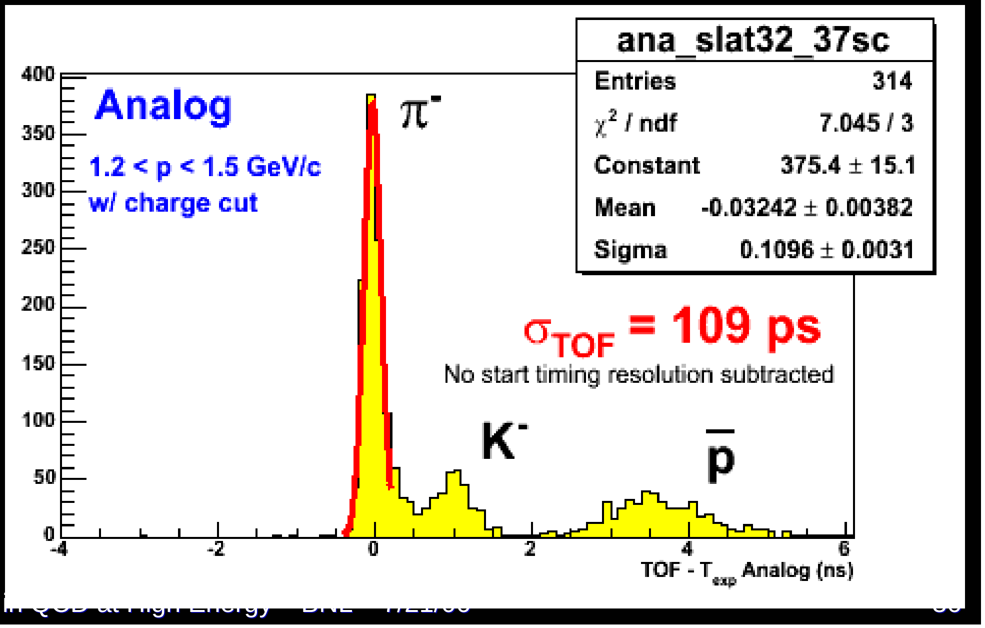


Extended PID: AGEL + TOF-W

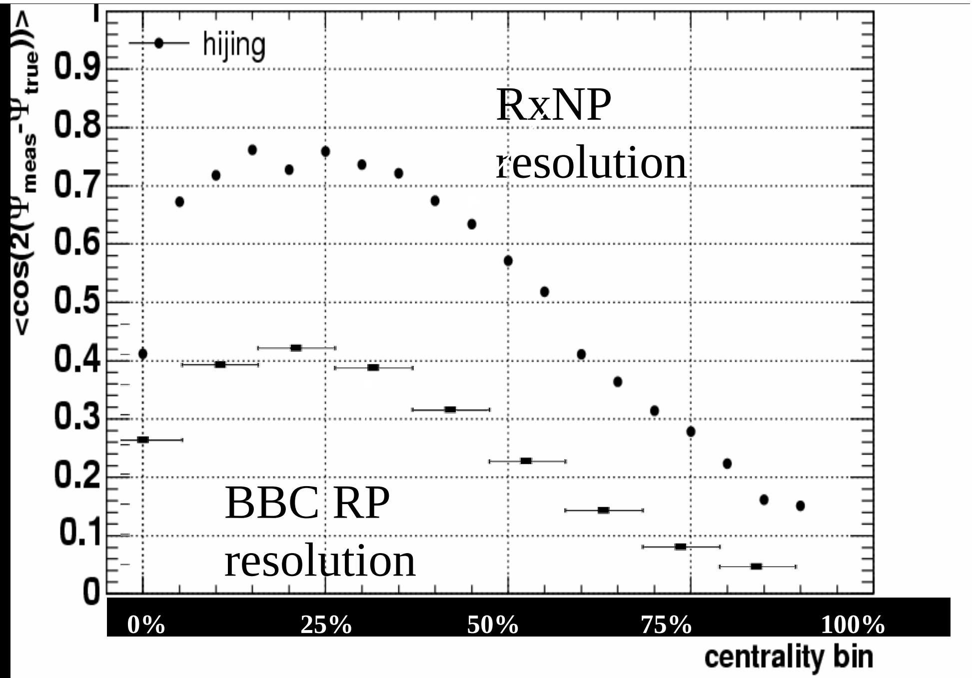
- "An aerogel and time-of-flight system to provide complete π/K/p separation for momenta up to ~10 GeV/c."
- Project well underway
  - Aerogel completely installed (first physics results now available)
  - TOF-W ('Time-Of-Flight-West')
    - Partial funding: J. Velkovska (Vanderbilt) OJI
    - Prototypes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



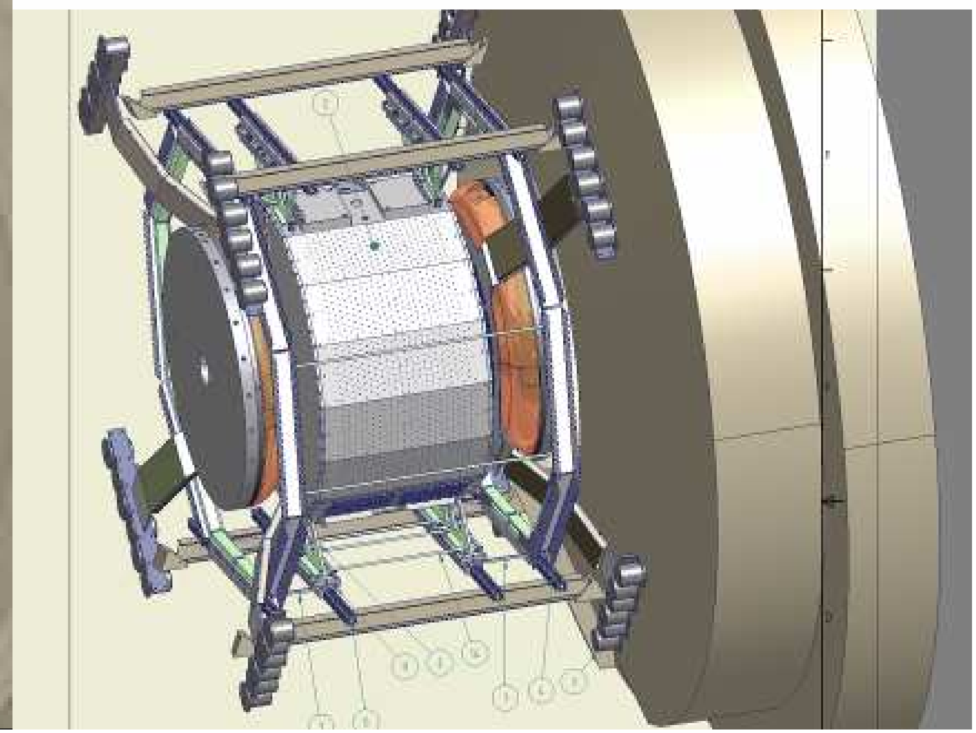




Reaction Plane Det (RxNP)



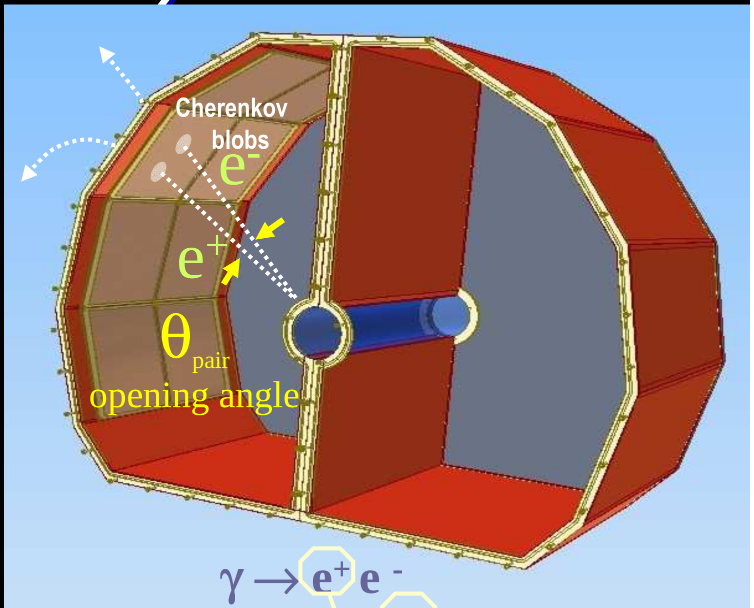
- Scintillator paddles with lead converter at $1<|\eta|<3$
  - Measure reaction plane
    - resolution better by factor 2
  - Trigger counter for low energy running, where η is reduced from beam energy



Hadron-Blind Detector (HBD)

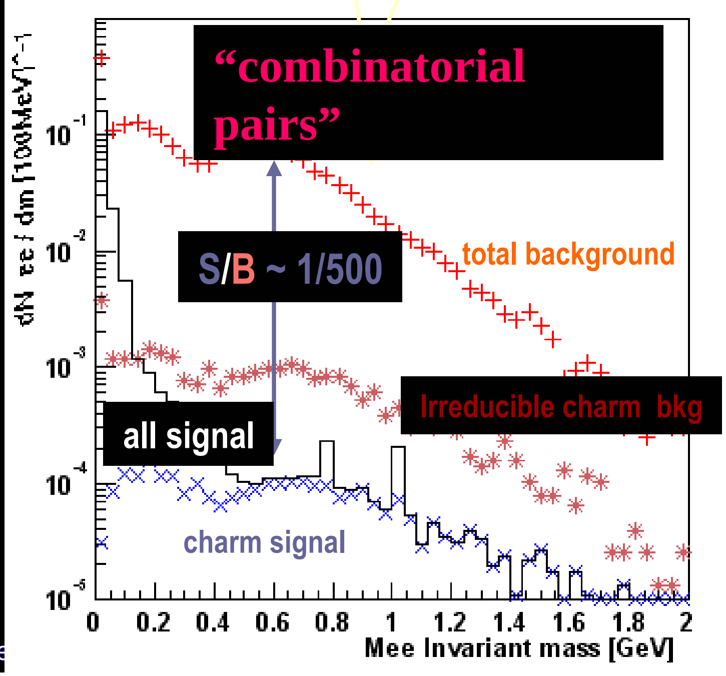
- "A hadron-blind detector to detect electrons from near the vertex."
- Dalitz rejection via opening angle
  - Identify electrons in field free region
  - Veto electrons with partner
- HBD: a novel detector concept:
  - windowless CF4 Cherenkov detector
  - 50 cm radiator length
  - CsI reflective photocathode
  - Triple GEM with pad readout
  - reverse bias → hadron blind
  - 2x135° in ϕ and $|\eta| < 0.45$
- Construction 2005-2006, Installation in 2006 (4-6 weeks from now)
  - Funding provided by DOE, NSF, Weizmann, Stony Brook
  - R&D completed

partner positron needed for rejection



$\gamma \rightarrow e^+ e^-$

$\pi^0 \rightarrow \gamma\ e^+ e^-$



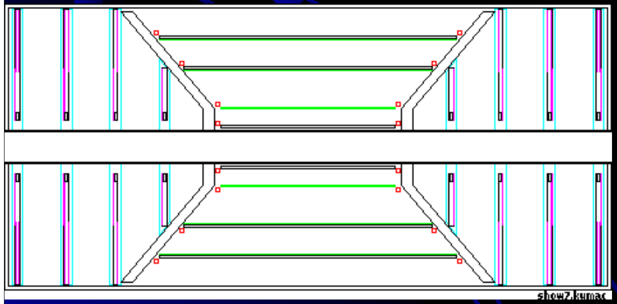
Silicon Tracker

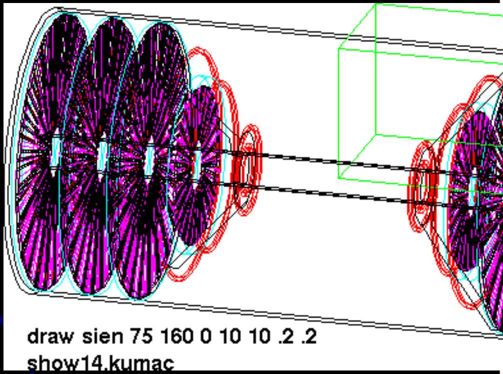
- "A vertex detector to detect displaced vertices from the decay of mesons containing charm or bottom quarks."
  - ~$3M committed by RIKEN
  - MIE proposal submitted to DOE Aug-04:
    - DOE Cost & Schedule review May, 2006
    - Total Project Cost = $4.6M
    - In President's Budget for FY07
    - Very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

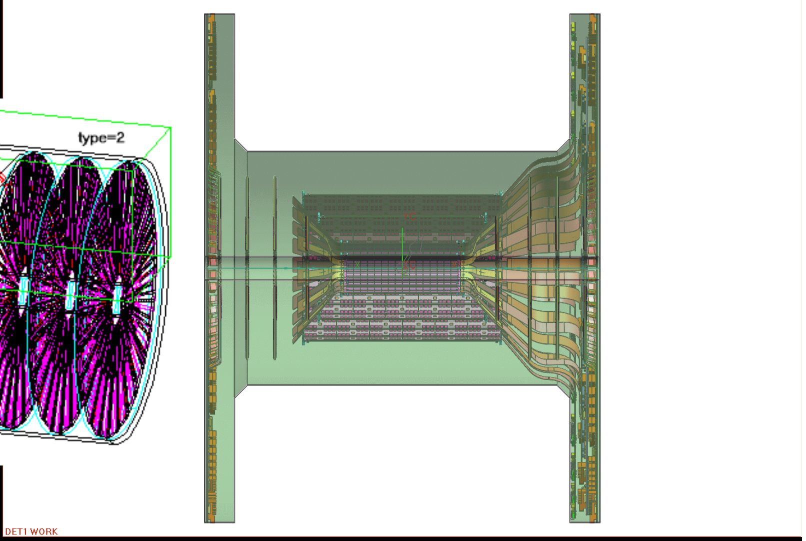
$|\eta|<1.2$
$\phi \sim 2\pi$
$z \sim \pm$ 10 cm

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



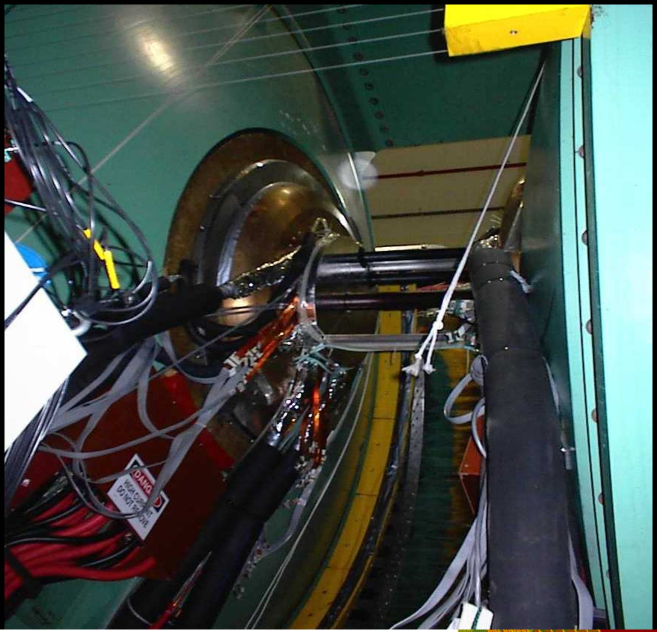




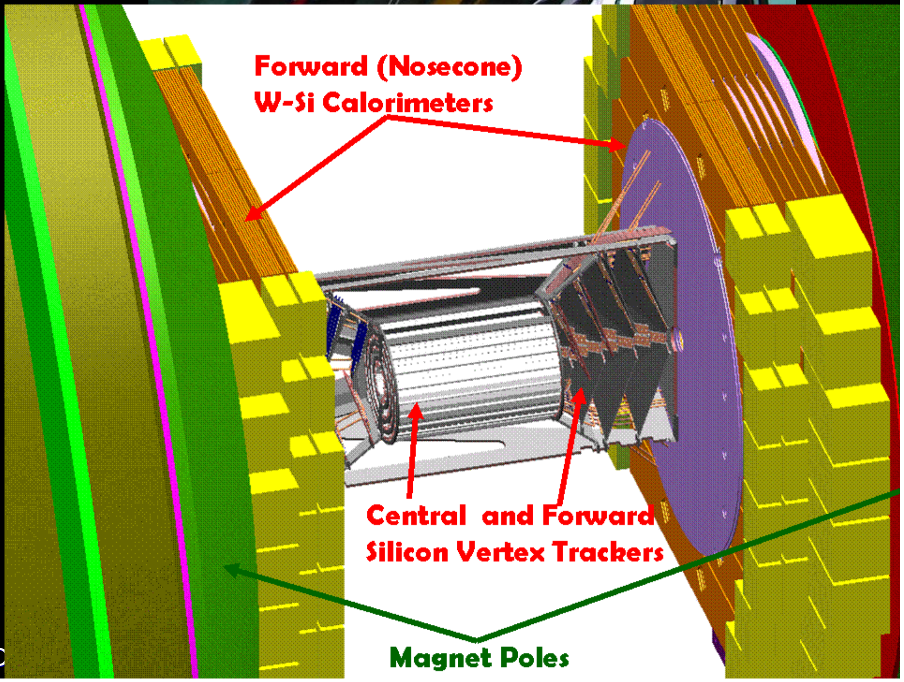
Nosecone Calorimeter (NCC)

- "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

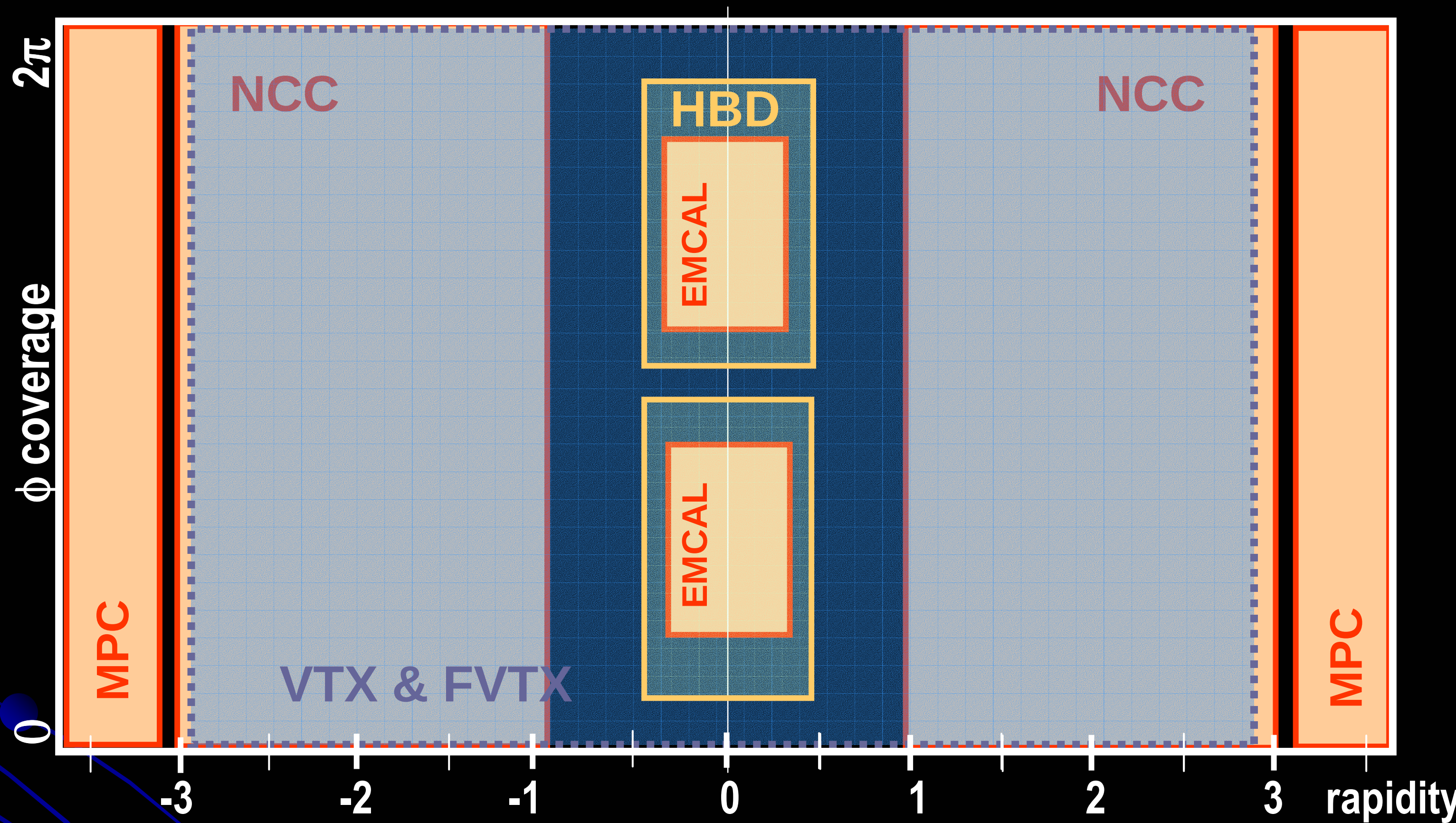
$0.9 < \eta < 3.0$
10 X Acceptance of Central Arms



- 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



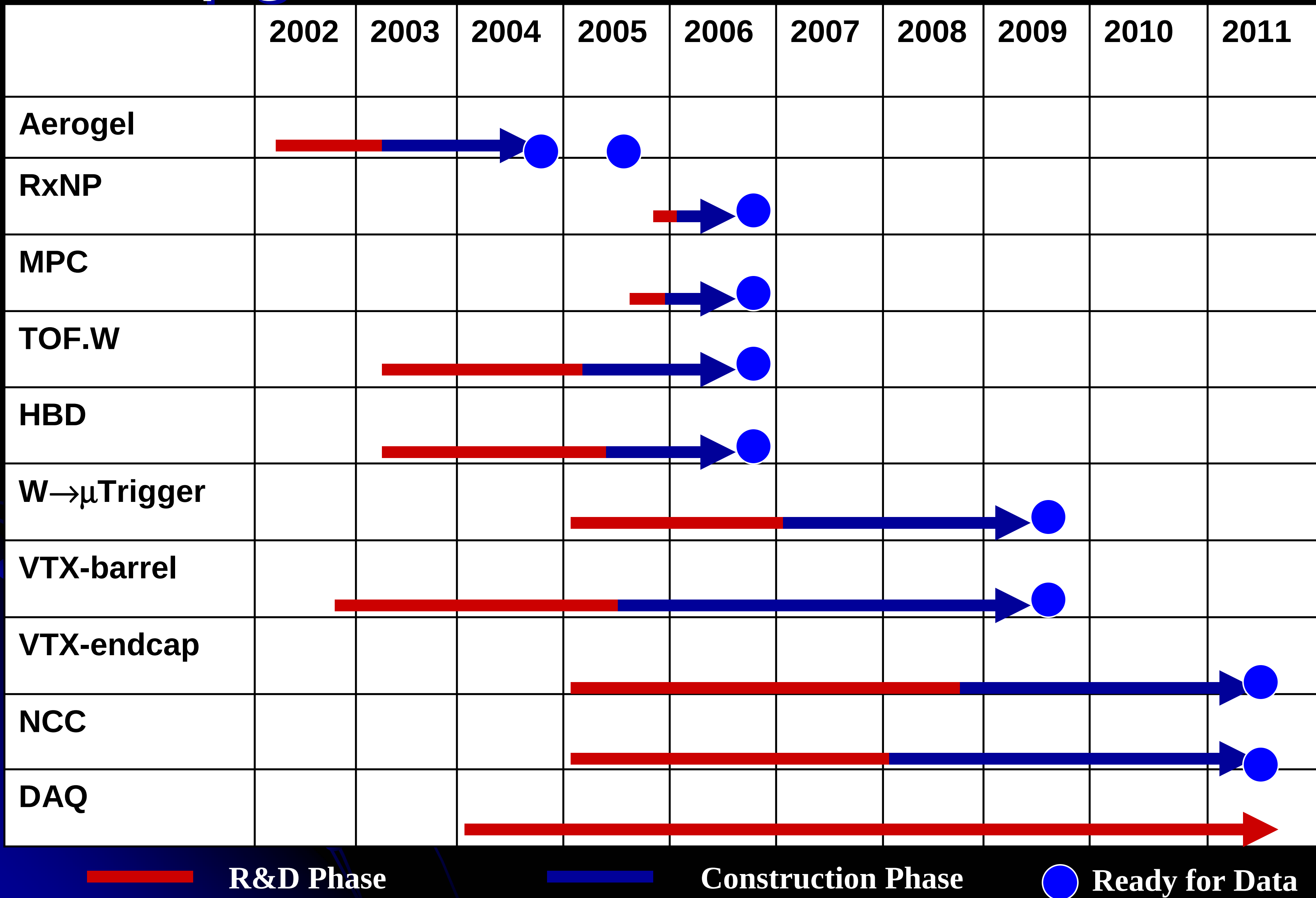
(i) π^0 and direct γ with combination of all electromagnetic calorimeters

(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



Conclusions

- There is much interest in a RHIC low energy scan program.
- 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 cover all the bases, it would be nice to complete the program with:
  - Enough energy steps with sufficient statistics to map out any 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/or d+Au data at each energy in order to reduce any systematic errors in measuring baseline distributions – very important for R_{AA} measurements.
- Estimated time for a 3σ correlation function critical exponent measurement (η): 18 days at 20 GeV

- University of São Paulo, São Paulo, Brazil
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- Peking University, Beijing, P. R. China
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- Eövös Loránd University (ELTE), Budapest, Hungary
- Banaras Hindu University, Banaras, India
- Bhabha Atomic Research Centre (BARC), Bombay, India
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- Kyoto University, Kyoto, Japan
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- RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan
- RIKEN – BNL Research Center, Japan, located at BNL
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- Korea University, Seoul, 136-701, Korea
- Myong Ji University, Yongin City 449-728, Korea
- System Electronics Laboratory, Seoul National University, Seoul, South Korea
- Yonsei University, Seoul 120-749, Korea
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- Kurchatov Institute, Moscow, Russia
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- Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Vorob'evy Gory, Moscow 119992, Russia
- Saint-Petersburg State Polytechnical Univiversity, Politechnicheskayastr, 29, St. Petersburg, 195251, Russia

PHENIX

13 Countries; 62 Institutions; 550 Participants*

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- Brookhaven National Laboratory (BNL), Upton, NY 11973, USA
- University of California - Riverside (UCR), Riverside, CA 92521, USA
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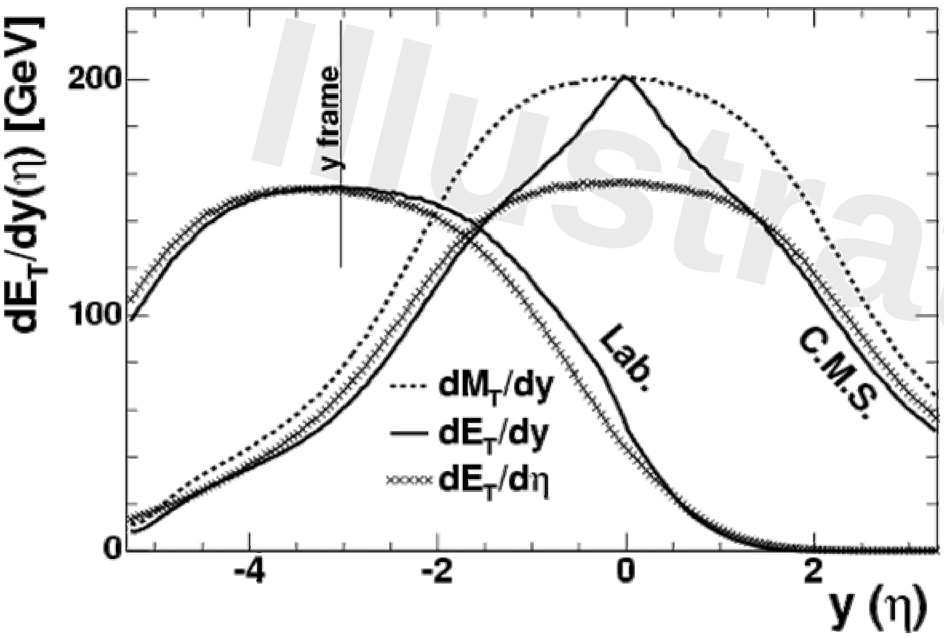
*as of March 2005

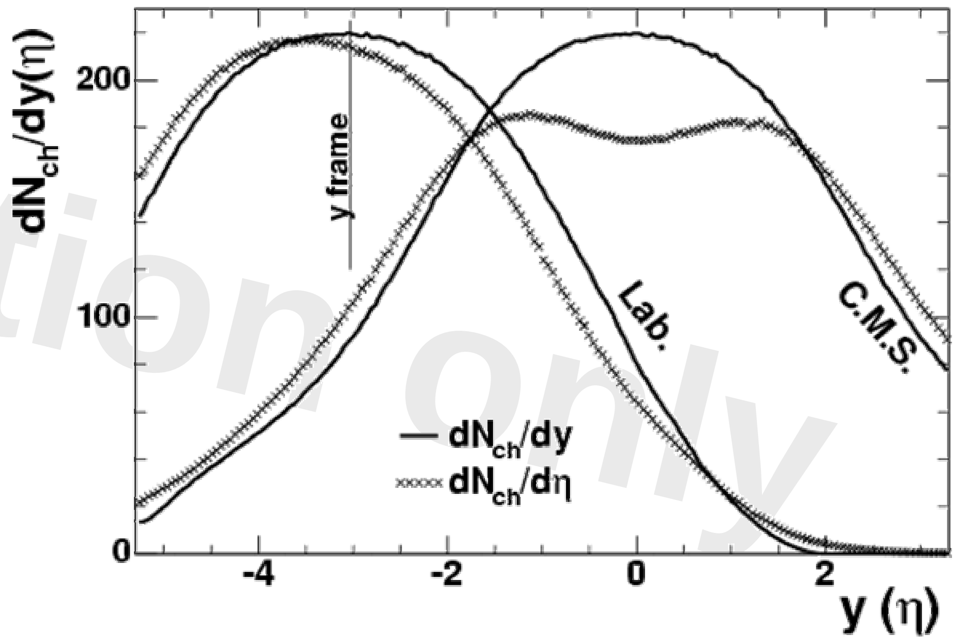
Thanks to those who contributed directly to this presentation…

- Martin Purschke
- Alexander Milov
- Tatsuya Chujo
- Christian Klein-Bosing
- Christoph Baumann
- Henner Buesching
- Hiroshi Masui
- Michael Issah
- Tamas Csorgo
- Bill Zajc
- Mickey Chiu
- Peter Steinberg
- … and many more

Auxiliary Slides

Recalculation between systems.



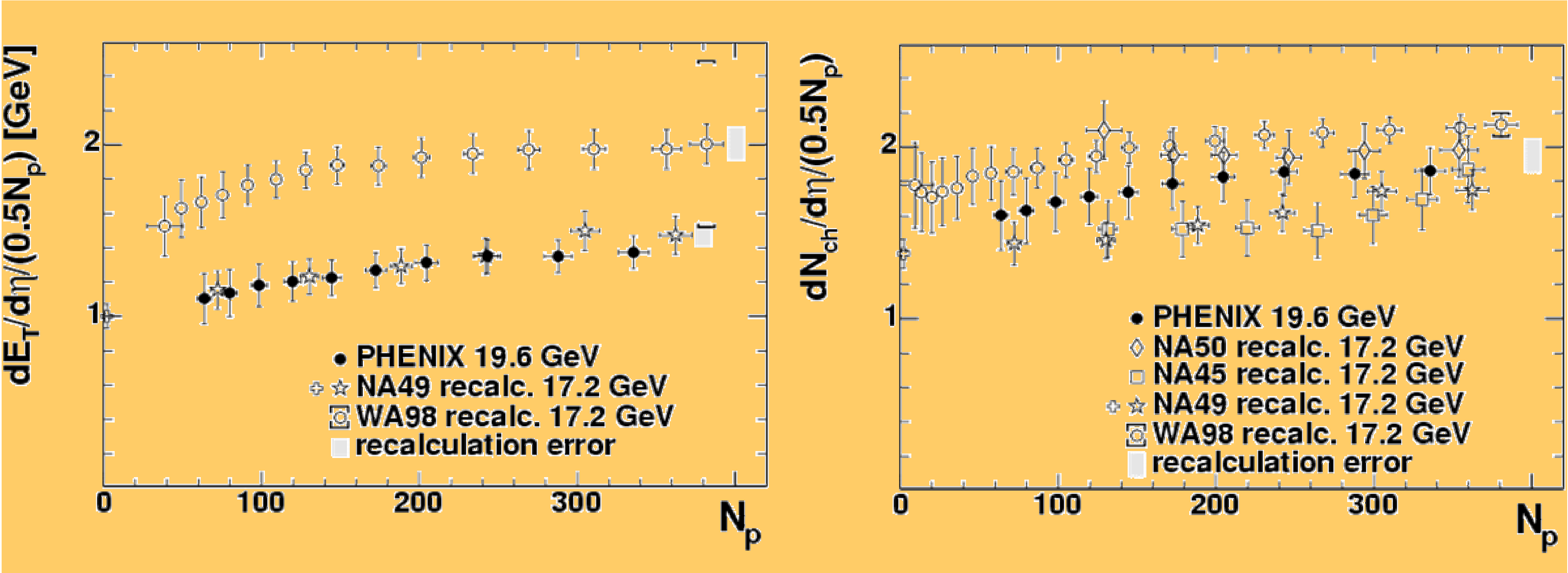


- In C.M.S.:
  - At Mid-Rapidity: $E_T \sim m_T$
  - $dE_T/dy \approx 1.25\ dE_{T/}d\eta$
- In Lab:
  - $dm_T/dy \approx 1.25\ dE_T/dy$
  - $dE_T/dy \approx dE_T/d\eta$

- In C.M.S.:
  - $dN_{ch}/dy \approx 1.25\ dN_{ch/}d\eta$
- In Lab:
  - $dN_{ch}/dy \approx 1.04\ dN_{ch}/d\eta$

- Recalculation parameters are “rather” independent on energy
- A systematic error of 5% is assigned to any recalculated value

Comparison to other SPS results.



- Good agreement between PHENIX measurements at 19.6 GeV and SPS measurements at 17.2 GeV in both measured values.
- SPS spread of the data is larger than RHIC, but the same averaging should be possible to reduce the systematic errors.

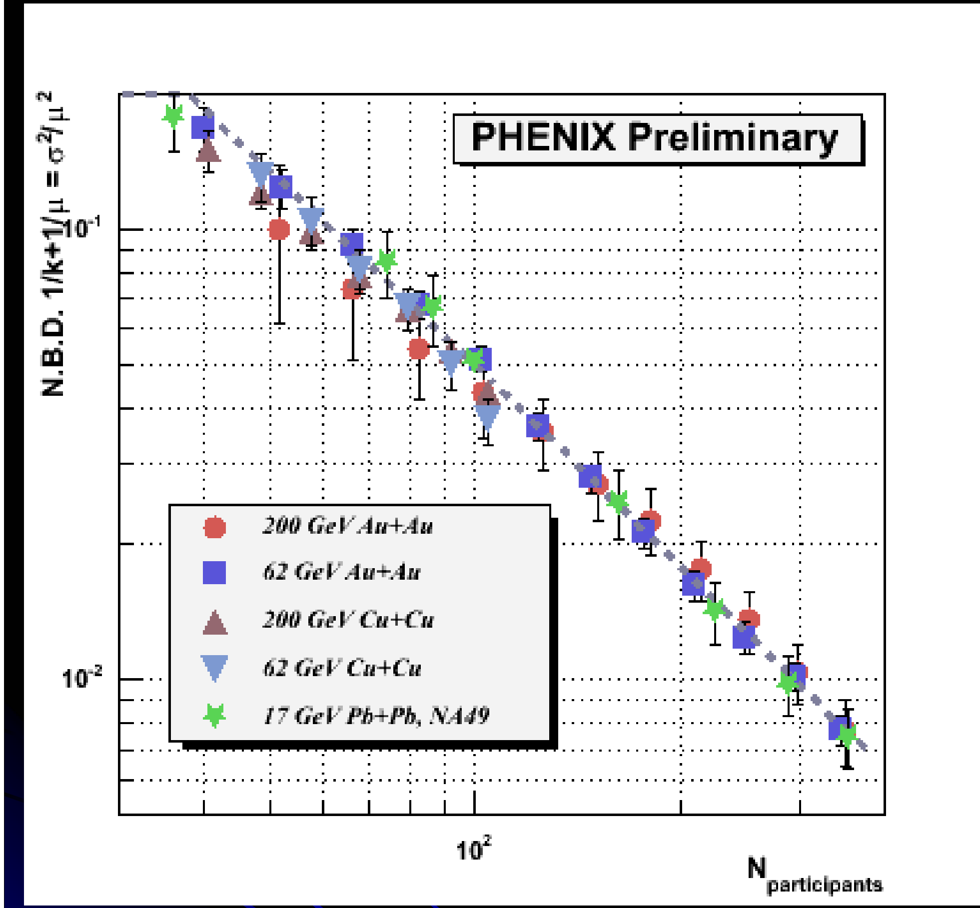
PHENIX Upgrades Physics Capabilities

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	ΔG/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

Measurement: Multiplicity Fluctuations



Inclusive charged hadron multiplicity fluctuations.

All points extracted from a fit to a Negative Binomial Distribution.

All points are corrected to remove contributions due to geometry fluctuations within a centrality bin.

All points are corrected for efficiency and occupancy and projected to 2π azimuthal acceptance.

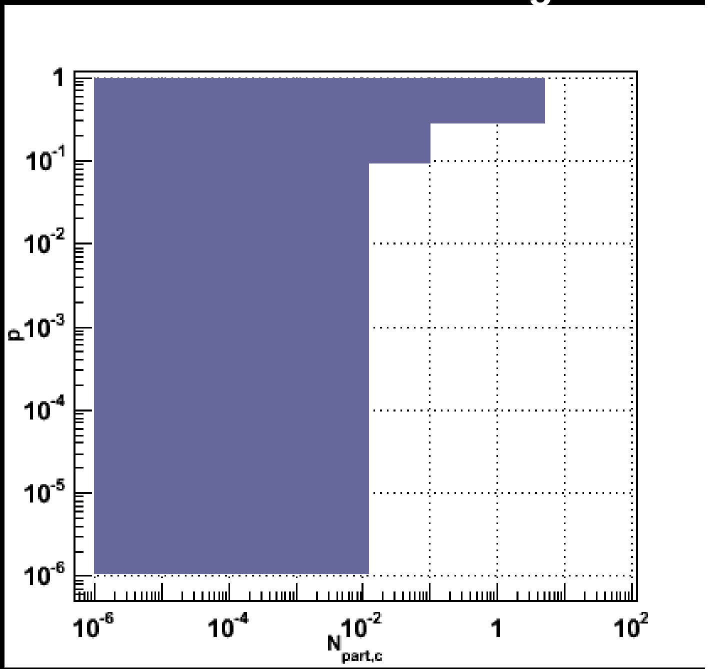
All species lie on a universal curve.

The curve is a power law.

Assuming that the temperature varies with $N_{participants}$ as:

$$T \propto N_{part}^{p}$$

The exponent γ is consistent with the value of [1.1-1.2] at the 95% confidence level over the following range:



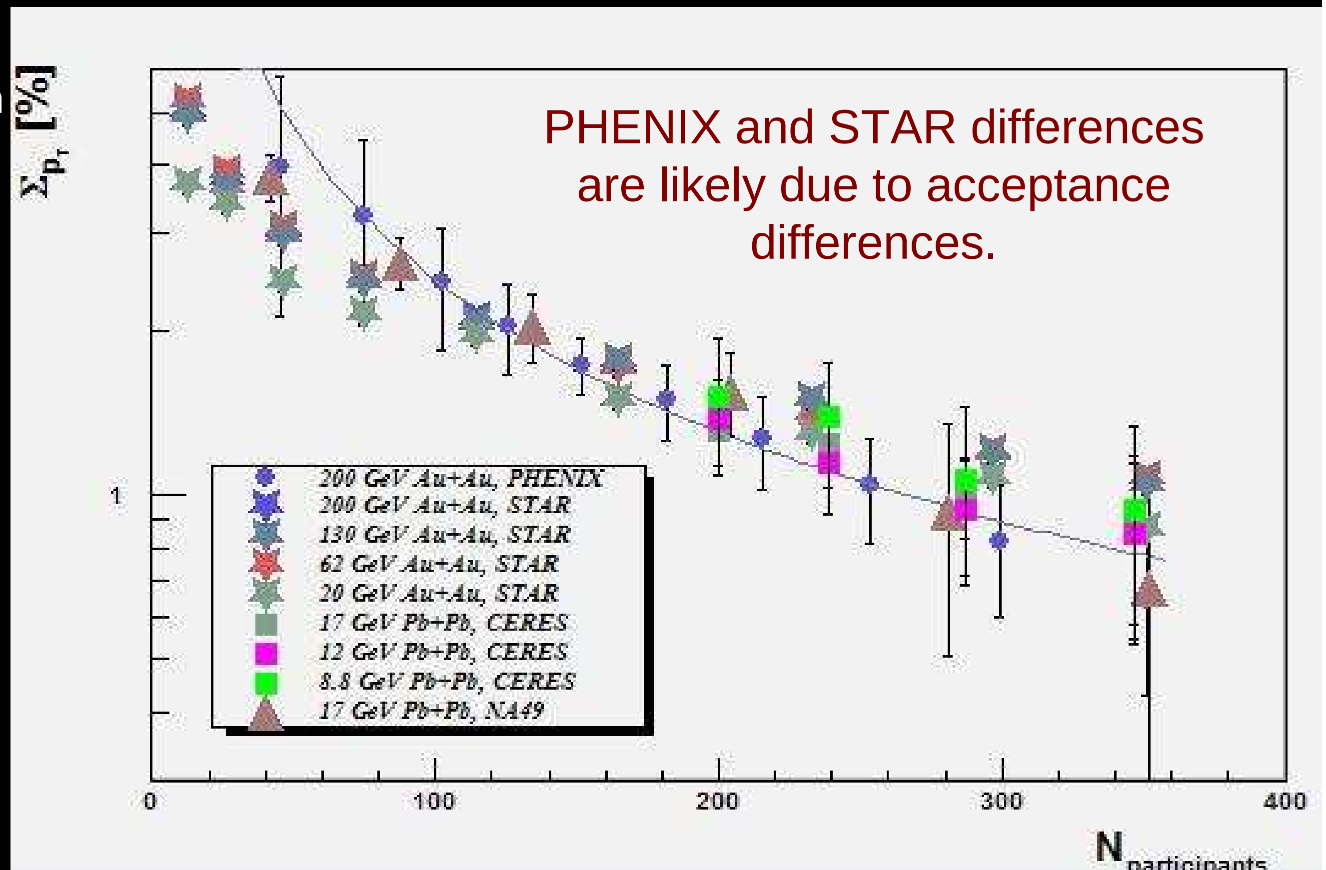
Measurement: $\langle p_T \rangle$ Fluctuations

Fluctuations in event-by-event $\langle p_T \rangle$ are related to temperature fluctuations in the system. Hence, they can probe the heat capacity of the system.

Contributions due to hard scattering should be much reduced at low energy.

For constant volume, the critical exponent for the heat capacity, α, could be extracted by varying sqrt(s_{NN}).

Unfortunately, simulations show that PHENIX sensitivity to temperature fluctuations is much reduced at low energy due to the small acceptance.



When plotted in the proper variable, SPS and RHIC data fall on a universal curve which can be described by a power law function of N_{part}.