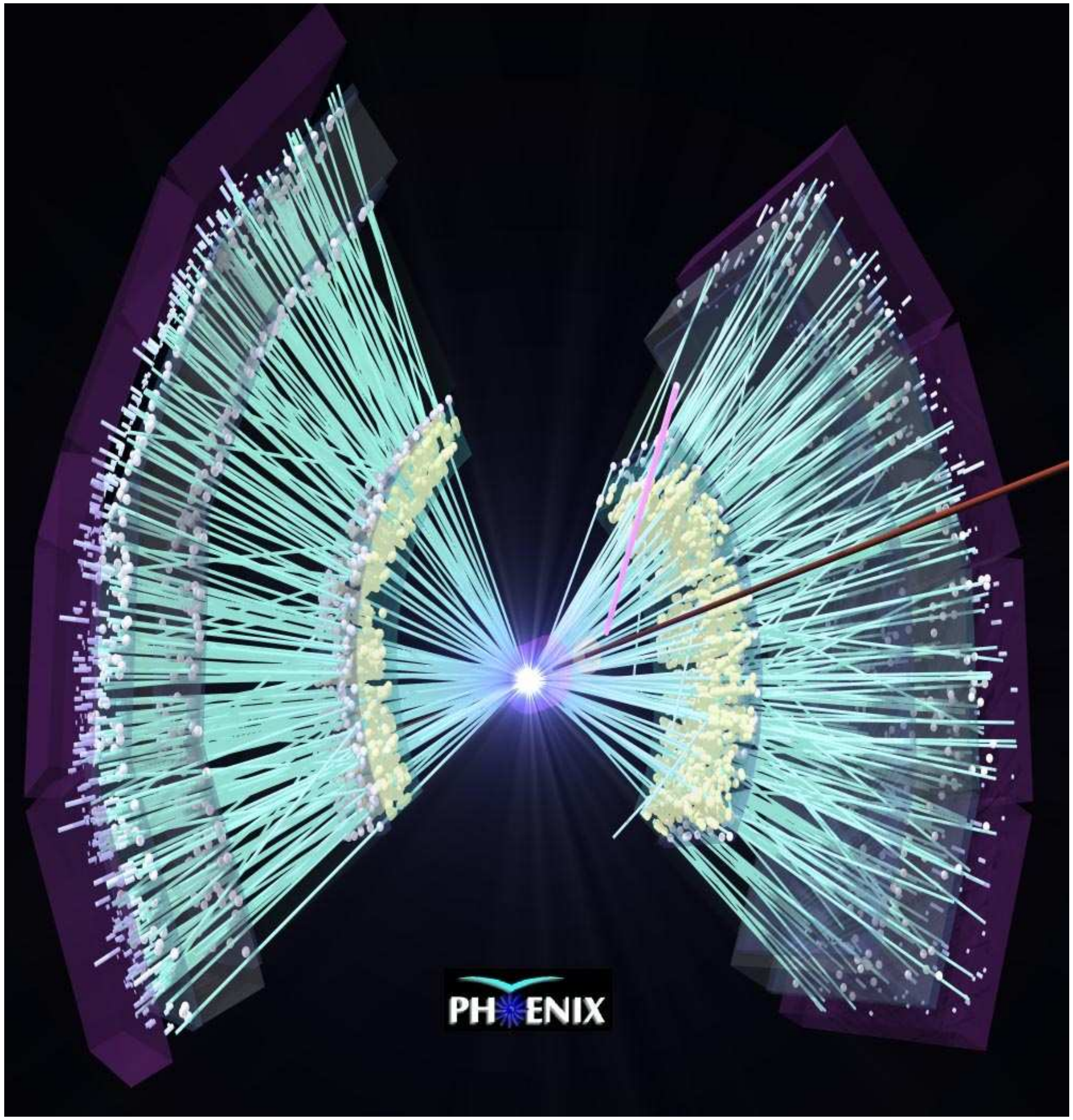
Global and Hadronic Observables in the PHENIX Experiment at RHIC

A Relativistic Heavy Ion Collision Census



Jeffery T. Mitchell (Brookhaven National Laboratory) for the PHENIX Collaboration

OUTLINE

A Relativistic Heavy Ion Collision Census

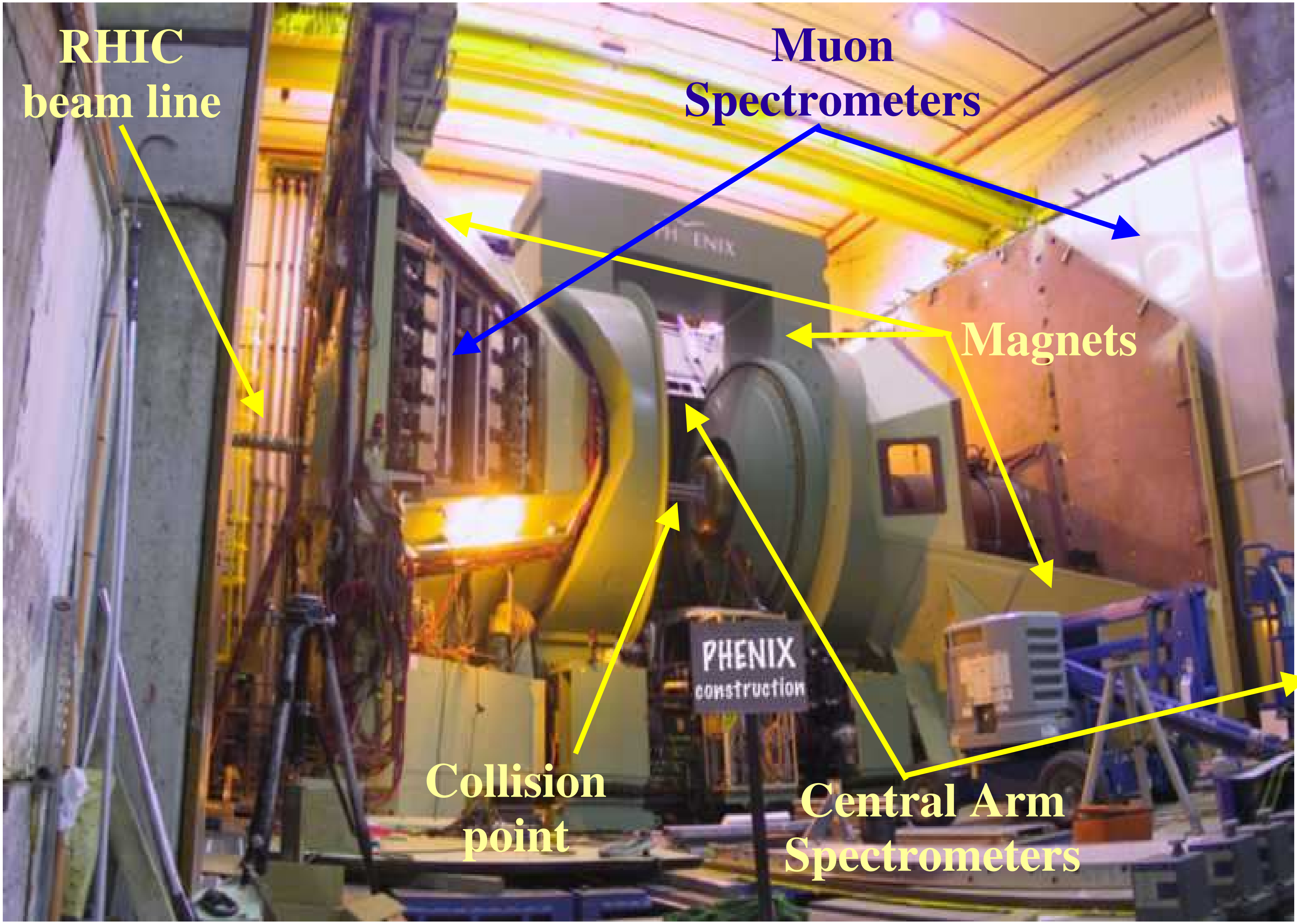
- **Population**
  - *Charged particle multiplicity*
- **(Transverse) Energy Production and Density**
- **Demographics and Diversity**
  - *Identified Particle Spectra*
- **Sizes**
  - *Hanbury-Brown Twiss Correlations*
- **Collective Movement**
  - *Elliptic Flow*
- **Fluctuations**
  - *Transverse momentum and charge*

The Census Bureau: PHENIX

Pioneering **H**igh **E**nergy **N**uclear **I**nteraction e**X**periment

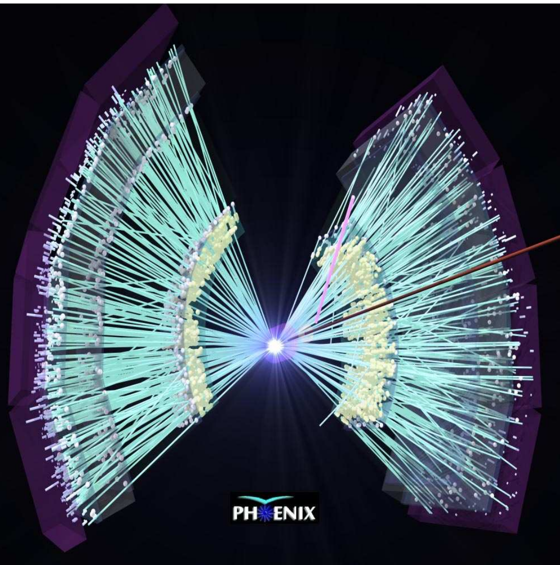
430 scientists from 12 countries

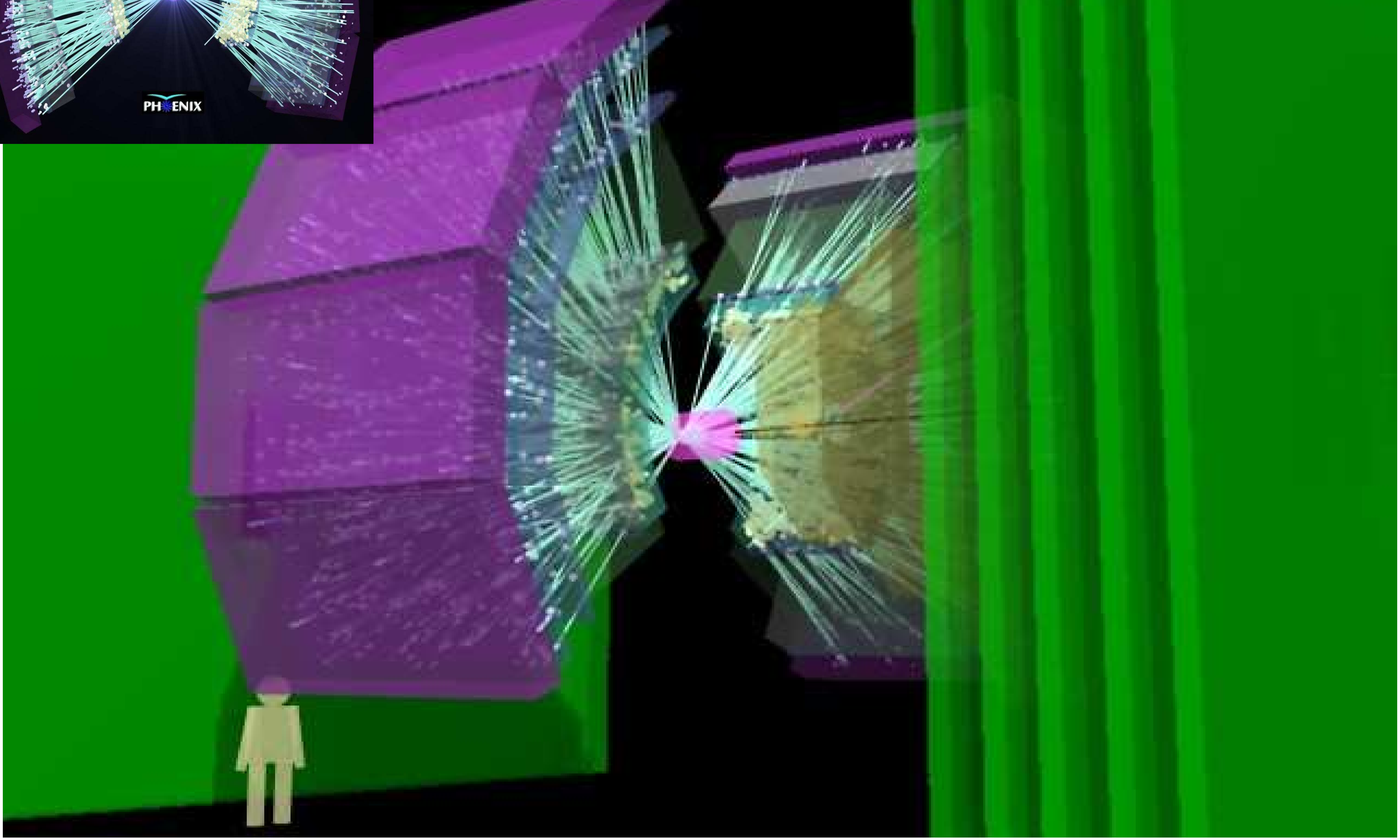
The Census Bureau: PHENIX



Taking The Census

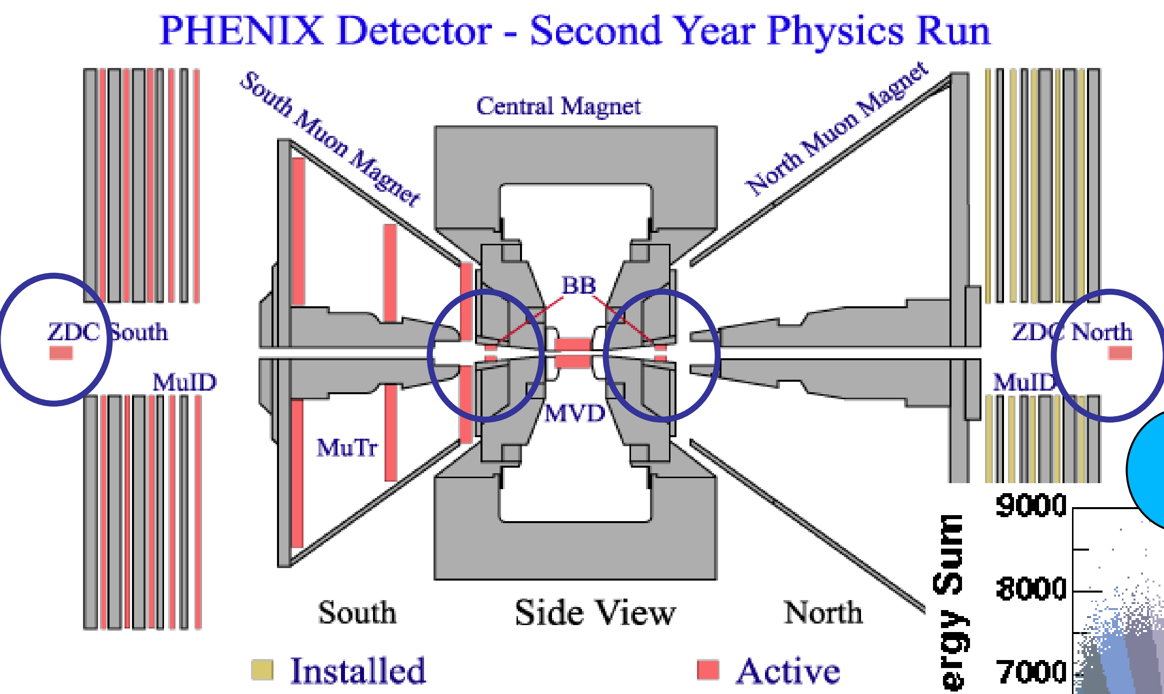
Over 300 tracks in a single head-on Gold-on-Gold Collision!



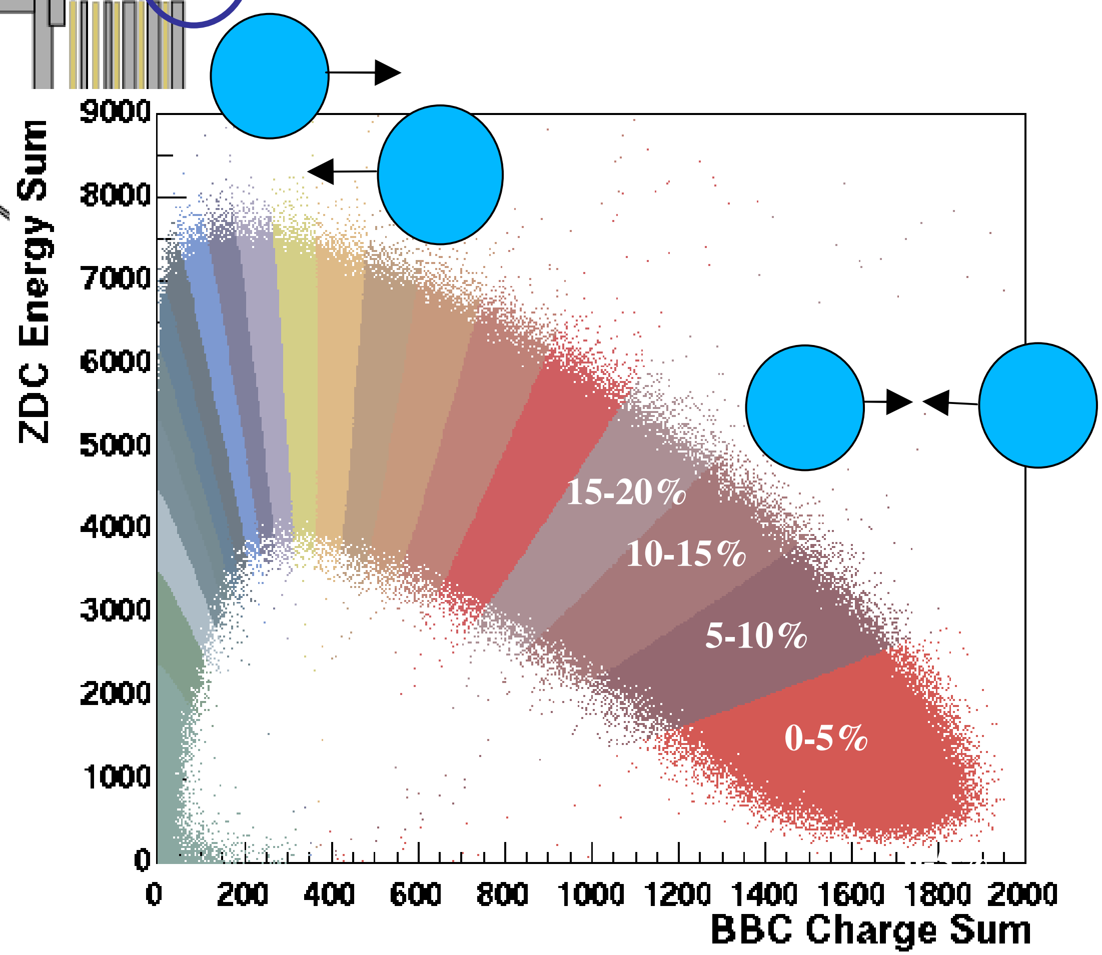


Jeffery T. Mitchell (BNL). 8th Wigner Symposium. NYC. 5/28/03

Population Sampling



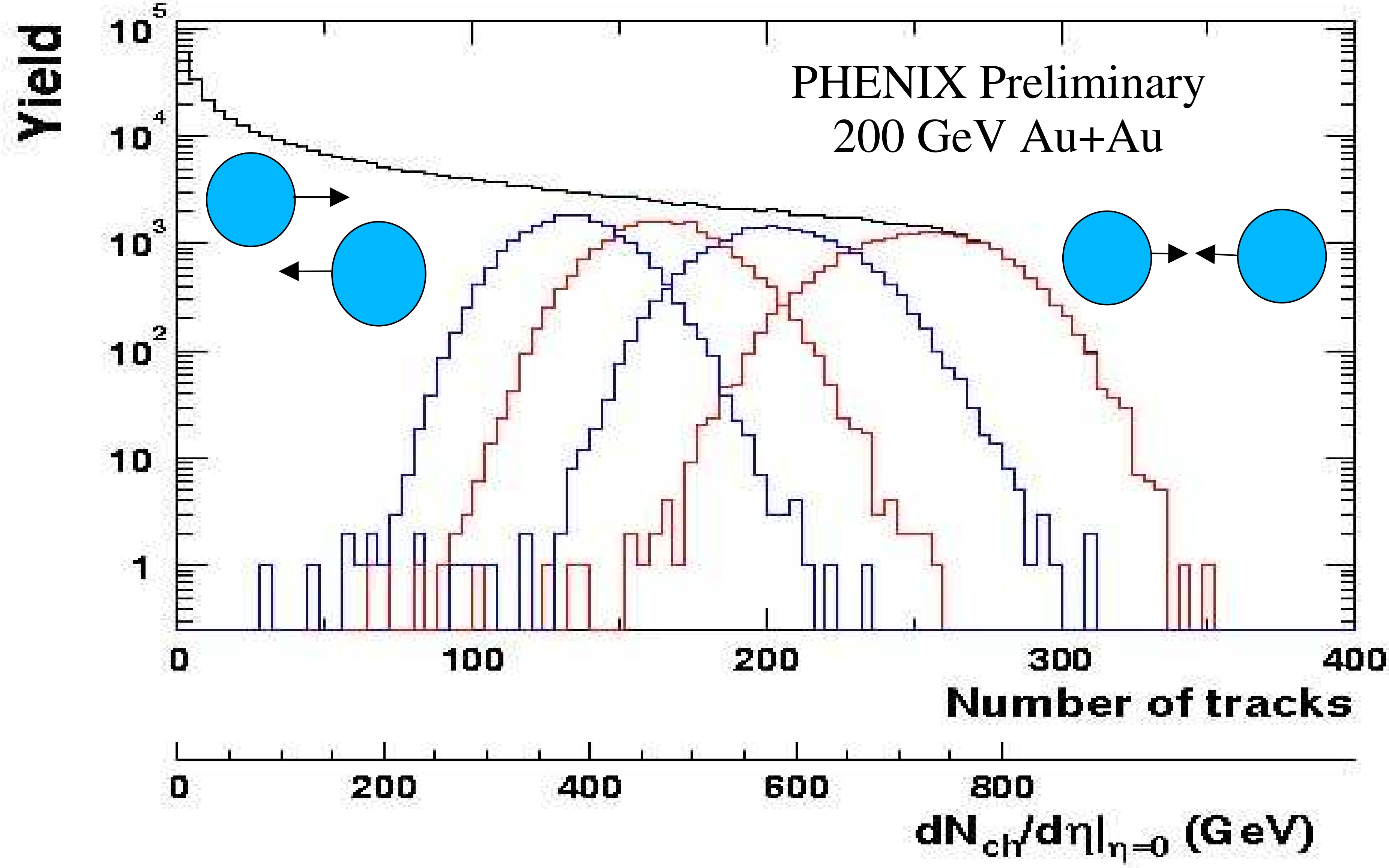
Urban "central" or
Rural "peripheral"?



The correlation in the Beam-Beam Counter charge sum and Zero Degree Calorimeter Energy sum effectively selects impact parameter, or centrality.

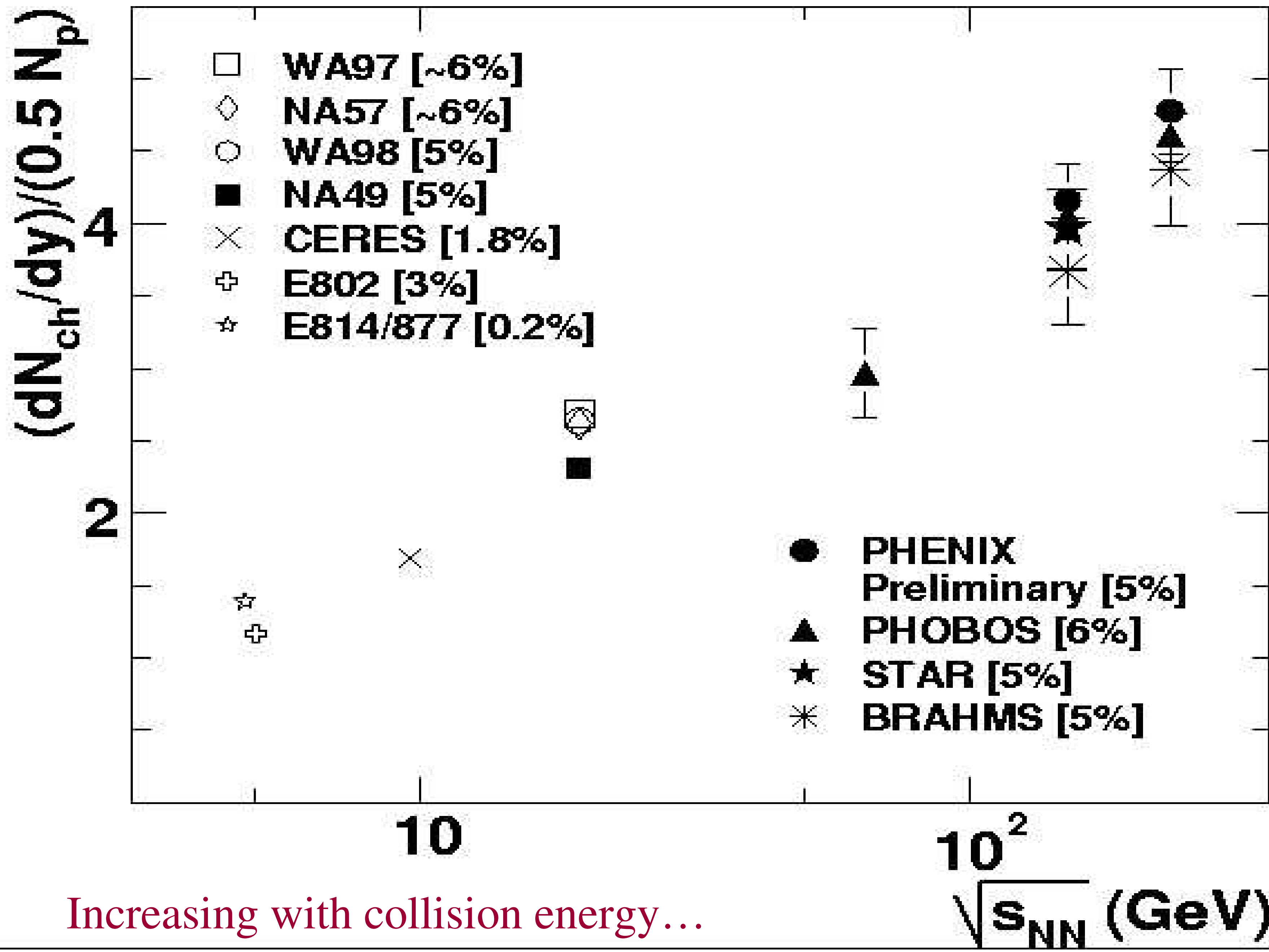
Population Distributions

Let's start by simply counting the number of charged particles produced (multiplicity)



Sasha Milov

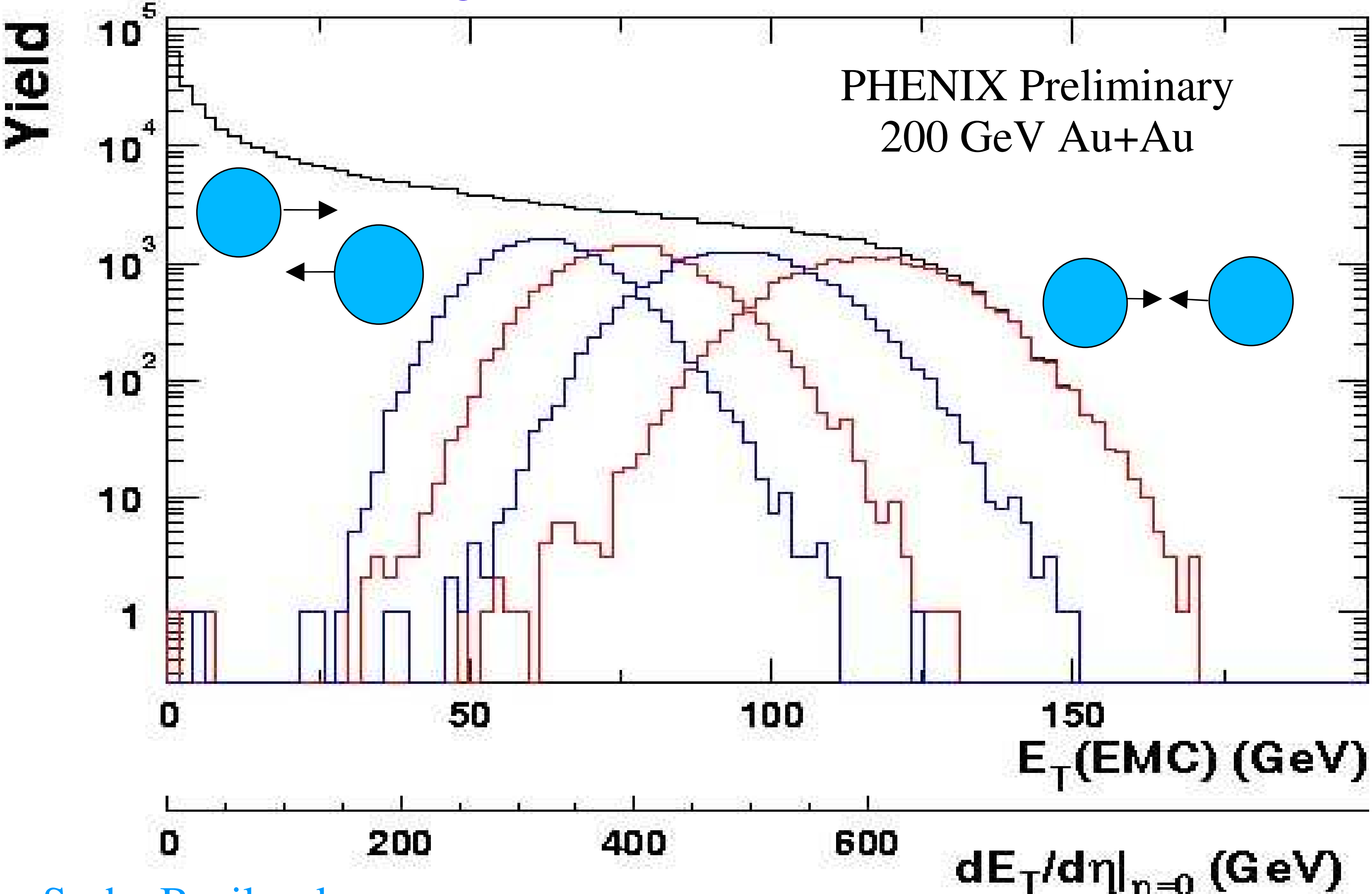
Population Growth



Increasing with collision energy…

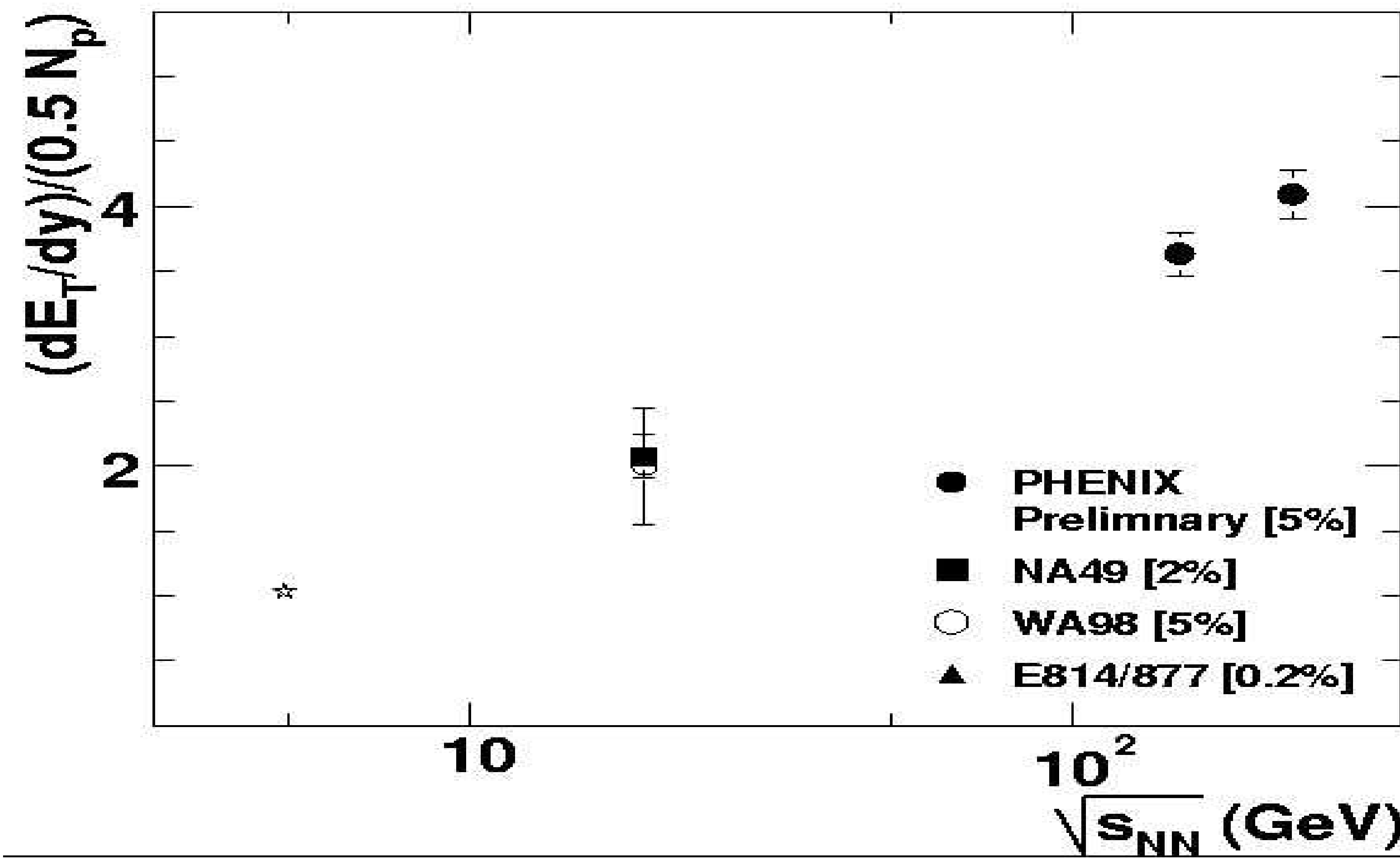
Transverse Energy Production

We can also measure the total amount of transverse energy produced using the PHENIX calorimeters



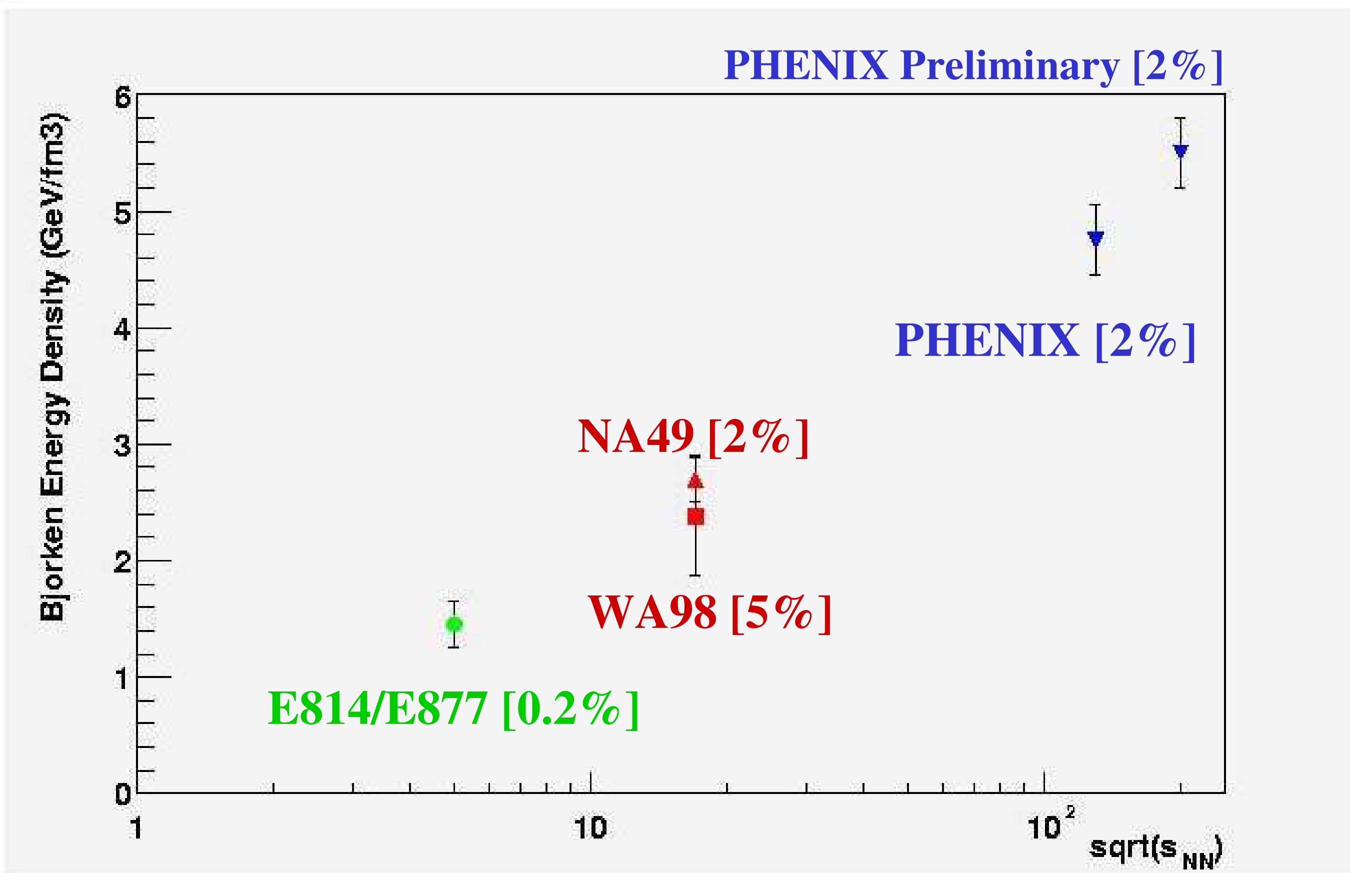
Sasha Bazilevsky

Transverse Energy Production Growth



Increasing with collision energy…

Energy Density Growth

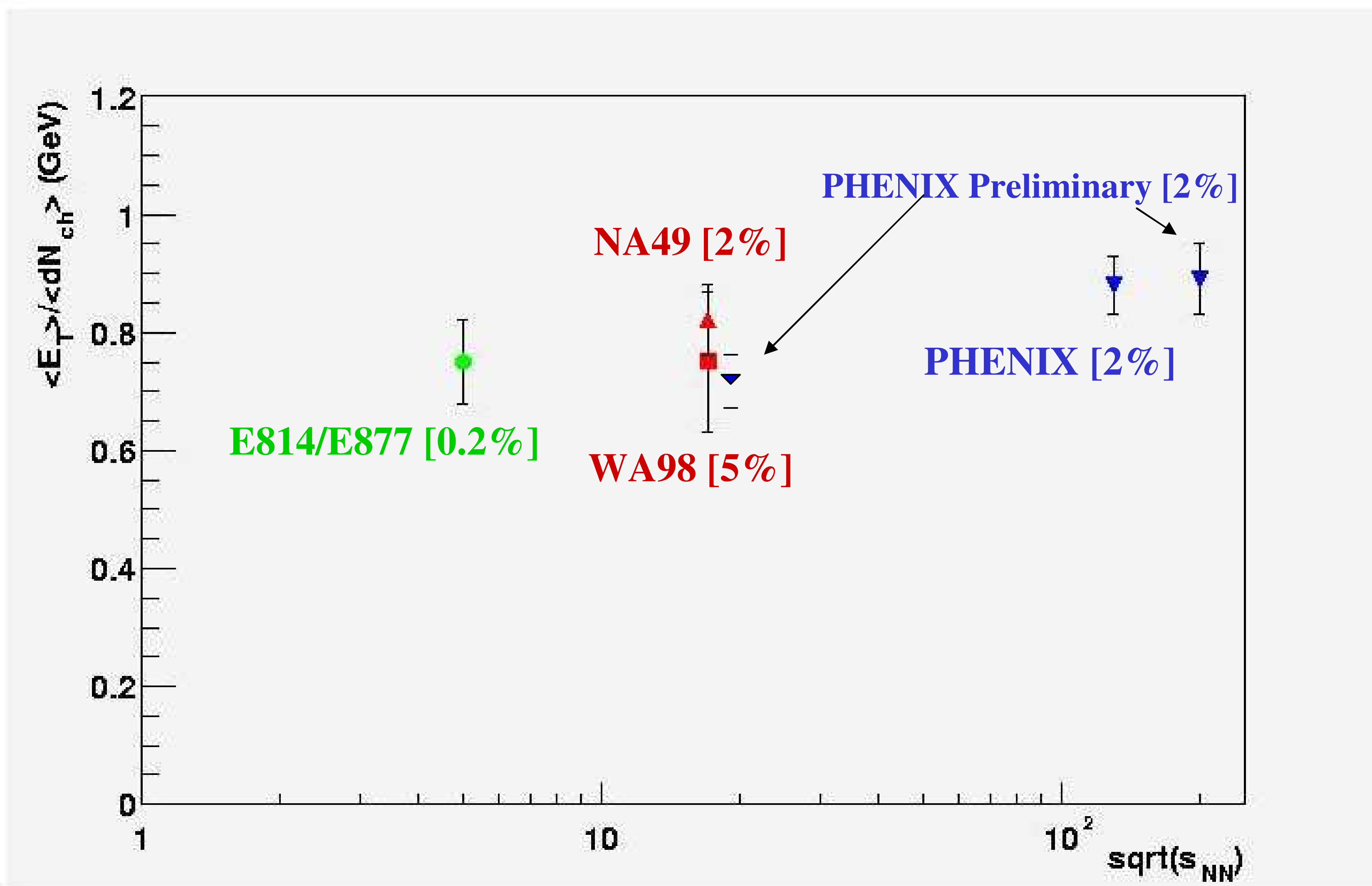


Extracting the (Bjorken) energy density

$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$

For the 2% most central 200 GeV Au+Au collisions, e ~ 5.5 GeV/fm^3, or more than **30** times more dense than normal nuclear matter!

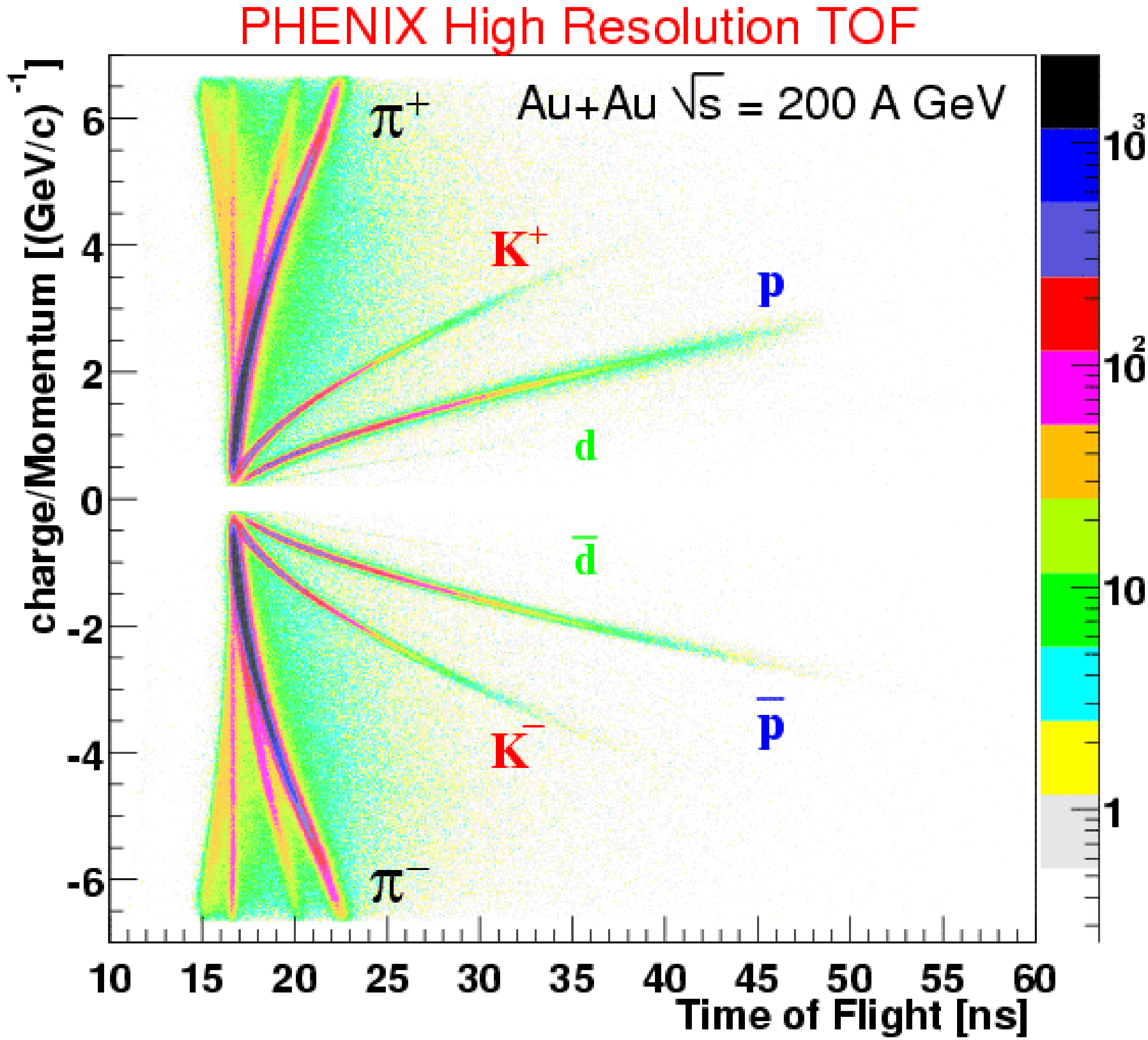
Transverse Energy - to - Multiplicity Growth?



No significant growth seen → Extra energy is going into particle production.

Population Diversity

Identifying Particle Types



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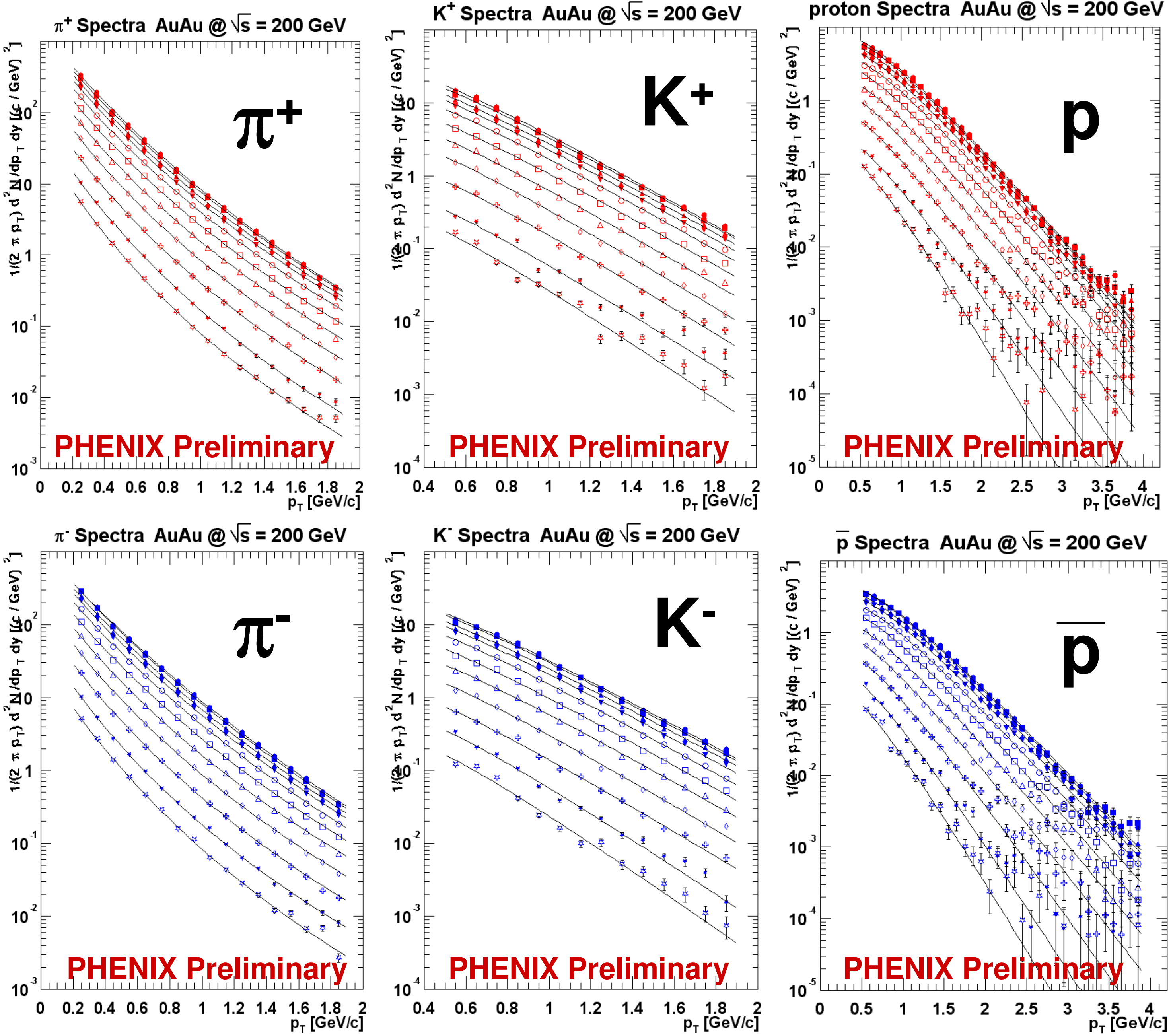
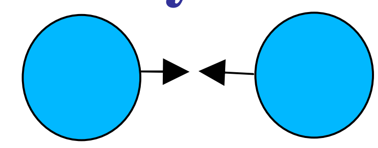
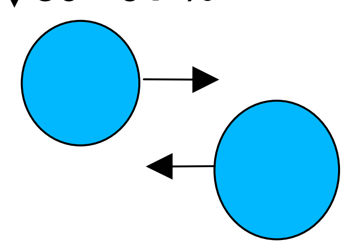
Identified Particle p_T Distributions vs. Centrality





centrality

- 0 - 5 %
- 5 - 10 %
- 10 - 15 %
- 15 - 20 %
- 20 - 30 %
- 30 - 40 %
- 40 - 50 %
- 50 - 60 %
- 60 - 70 %
- 70 - 80 %
- 80 - 91 %

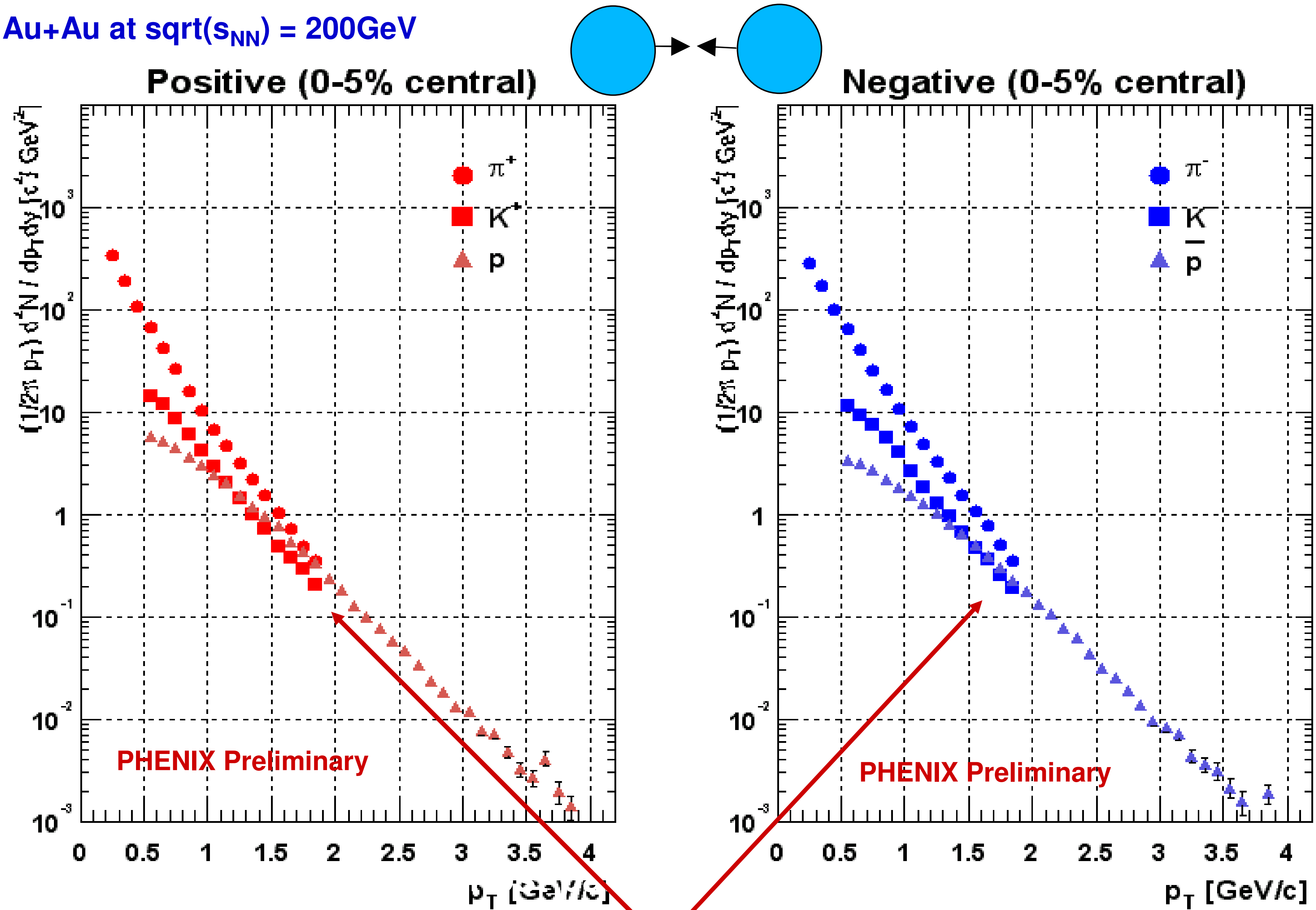


Shapes:
- **Pions: Power law**
- **Kaons: m_T exponential**
- **Protons: Boltzmann function**

Tatsuya Chujo, Julia Velkovska, Akio Kiyomichi

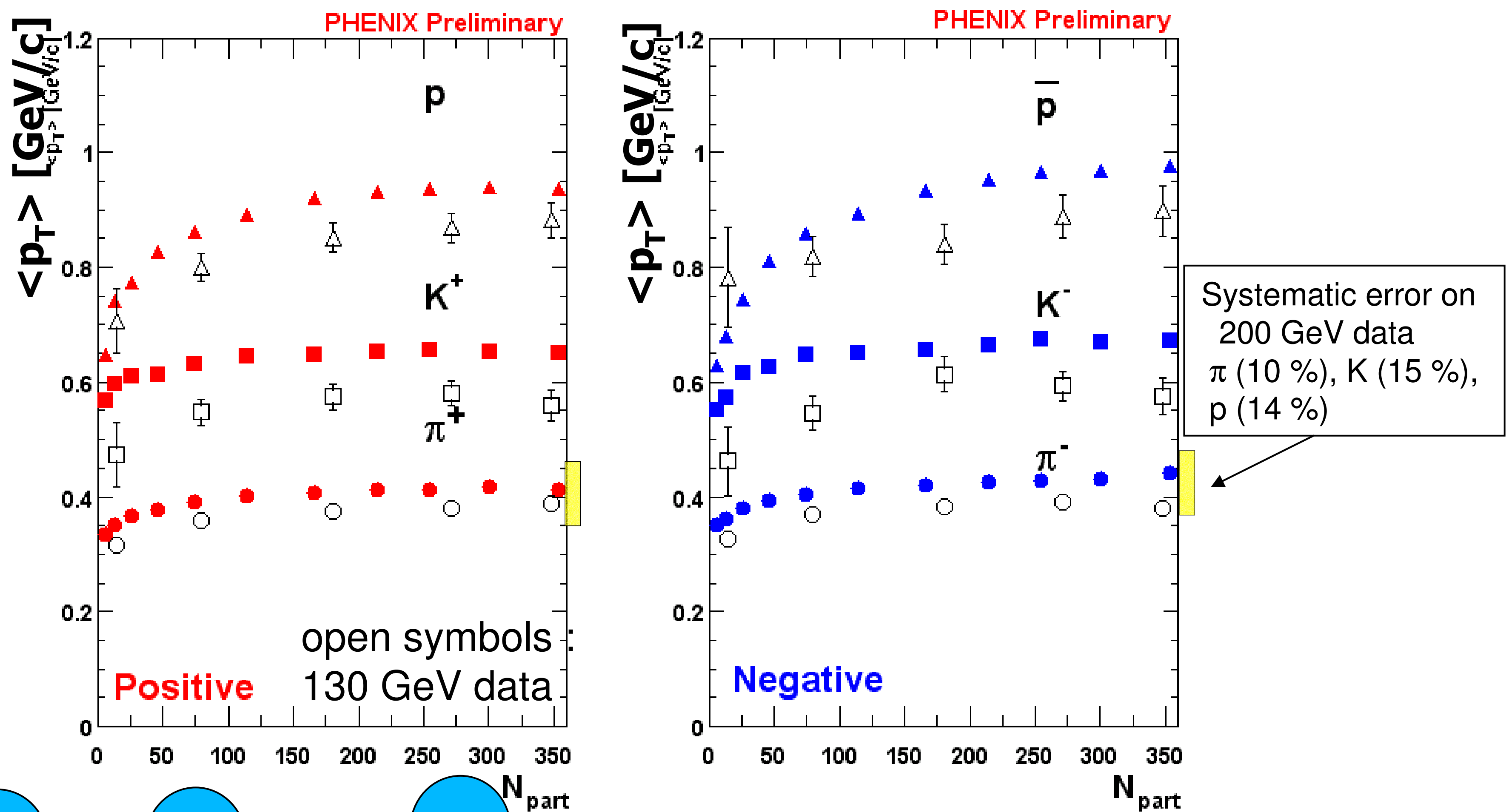
Population Demographics: Identified Particle Spectra

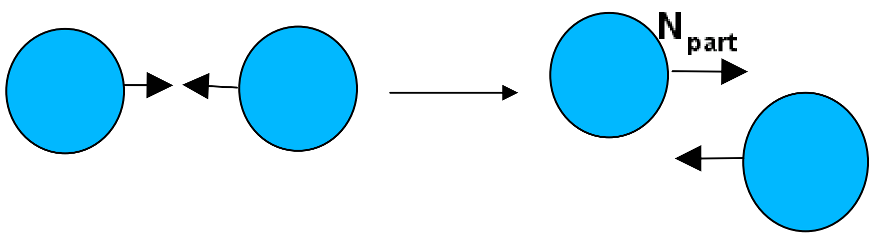
Au+Au at sqrt(s_{NN}) = 200GeV



Note: The proton yield is comparable to the pion yield @ 2 GeV.

$<p_T>$ vs. Centrality ($N_{participants}$)



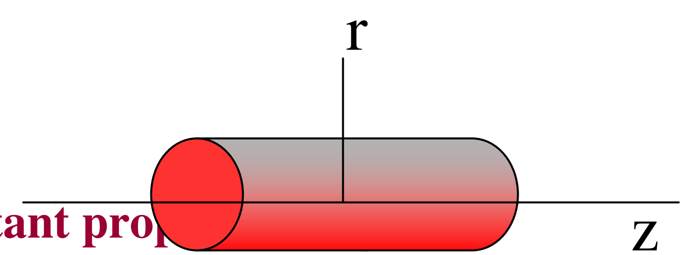


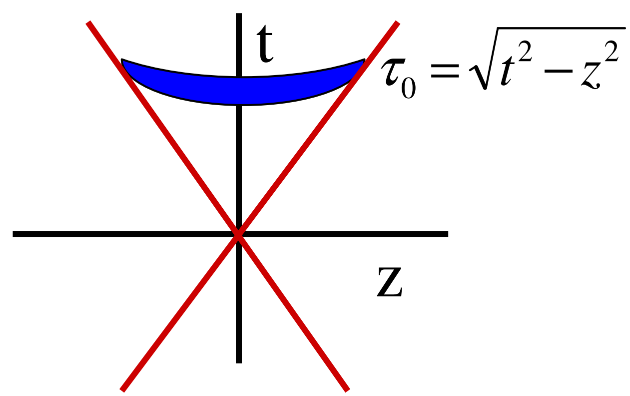
- **Increase of $<p_T>$ as a function of N_{part}.**
  Tends to saturate in the order π < K < proton (pbar)
- **This is consistent with a hydrodynamic expansion picture.**

A Simple Hydrodynamic Model for the Particle Emission Source

Model by Wiedemann, Scotto, and Heinz , Phys. Rev. C 53, 918 (1996)
E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48, 2462 (1993)

•FFluid elements each in local thermal equilibrium move in space-time with hydrodynamic expansion.
–NNo temperature gradients
•BBoost invariance along collision axis z.
•IInfinite extent along rapidity y.
•CCylindrical symmetry with radius r.
•PParticle emission in a hyperbola of constant pro
•SShort emission duration, t_0 < 1 fm/c

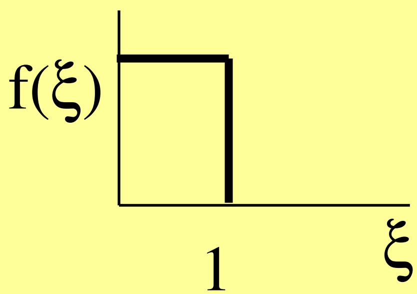




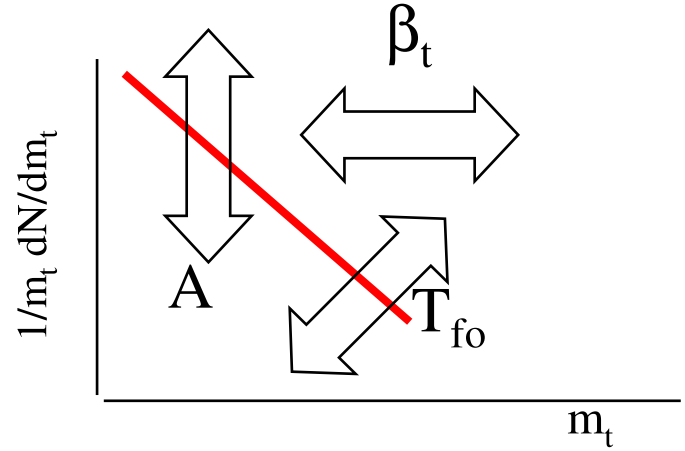
Reproducing the Shape of the Single Particle Spectra

Radial position on freeze-out surface
$\xi = r/R$

Particle density distribution $f(\xi)$ is independent of ξ



Shape of spectra is important

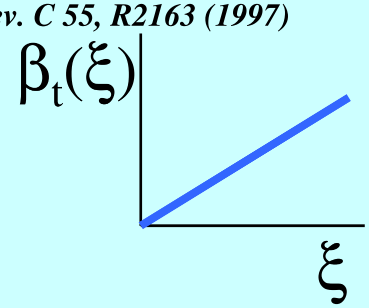


Parameters:

- normalization A
- freeze-out temperature T_{fo}
- surface velocity β_T

Linear flow profile $\beta(\xi) = \beta_T \xi$
$\langle \beta_T \rangle = 2\beta_T/3$

S. Esumi, S. Chapman, H. van Hecke, and N. Xu, Phys. Rev. C 55, R2163 (1997)

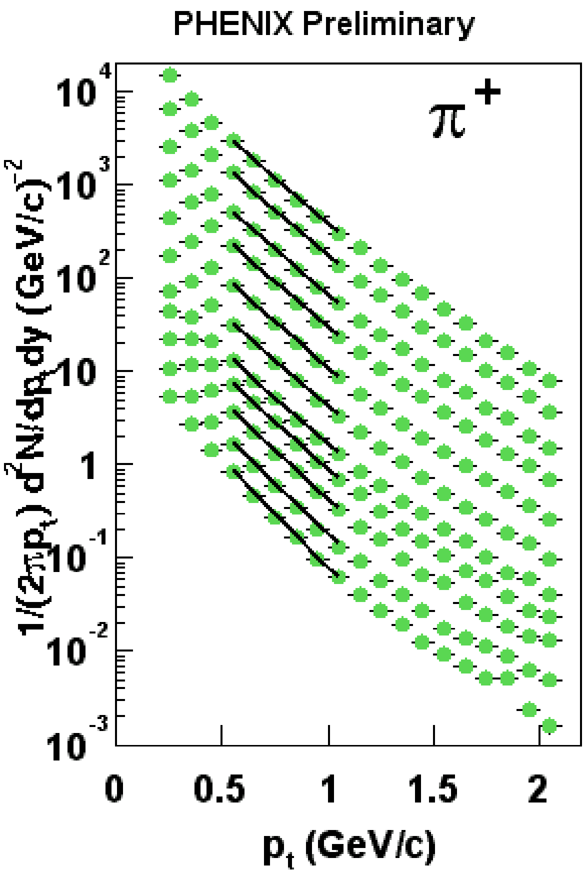


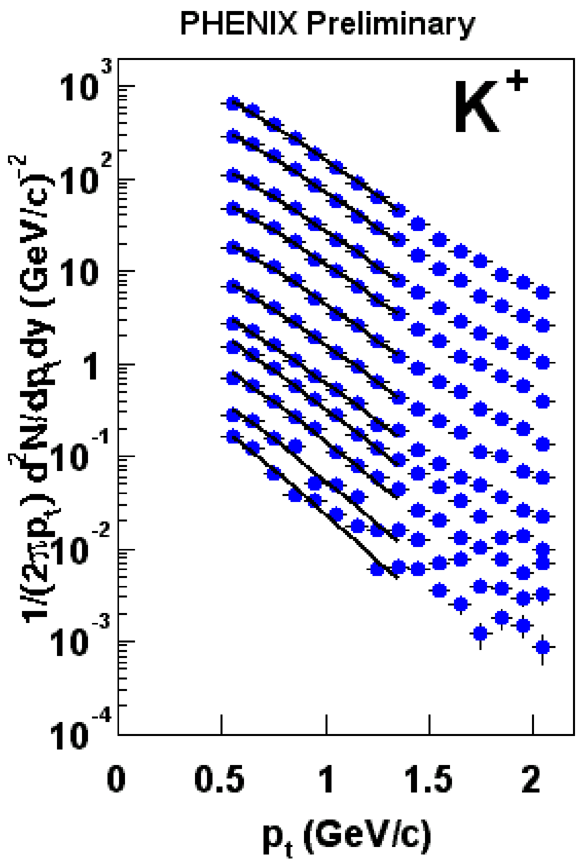
Fit range chosen to:

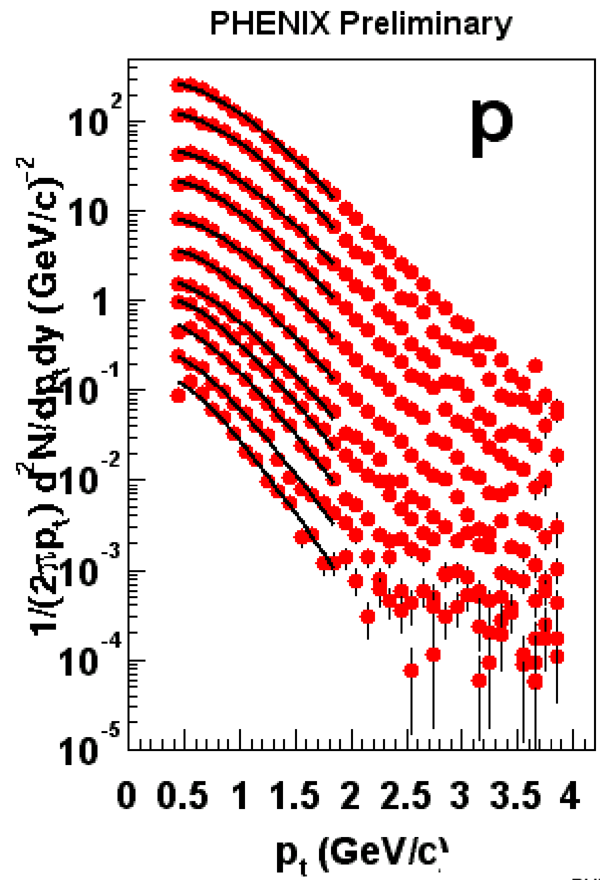
a) Minimize contributions from hard processes
$(m_t - m_0) < 1$ GeV

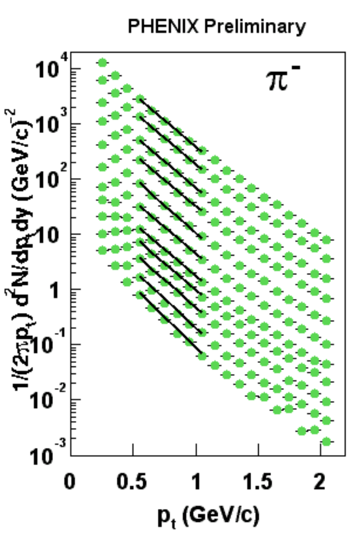
b) Exclude π resonance region
$p_T < 0.5$ GeV/c

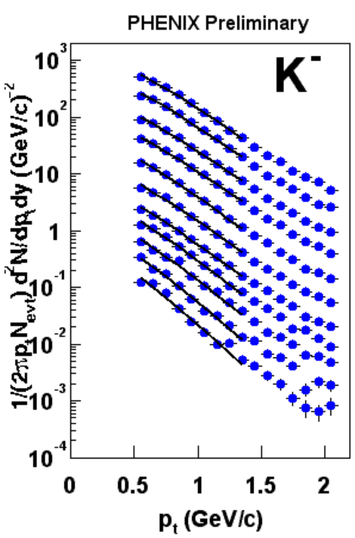
Fitting the Transverse Momentum Spectra





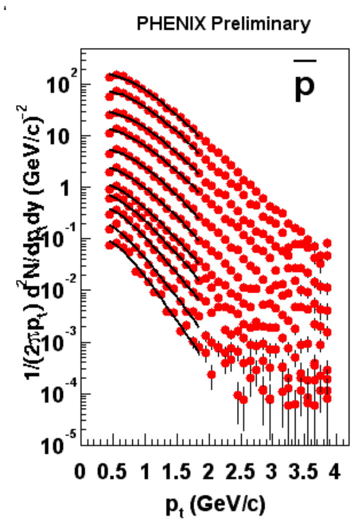






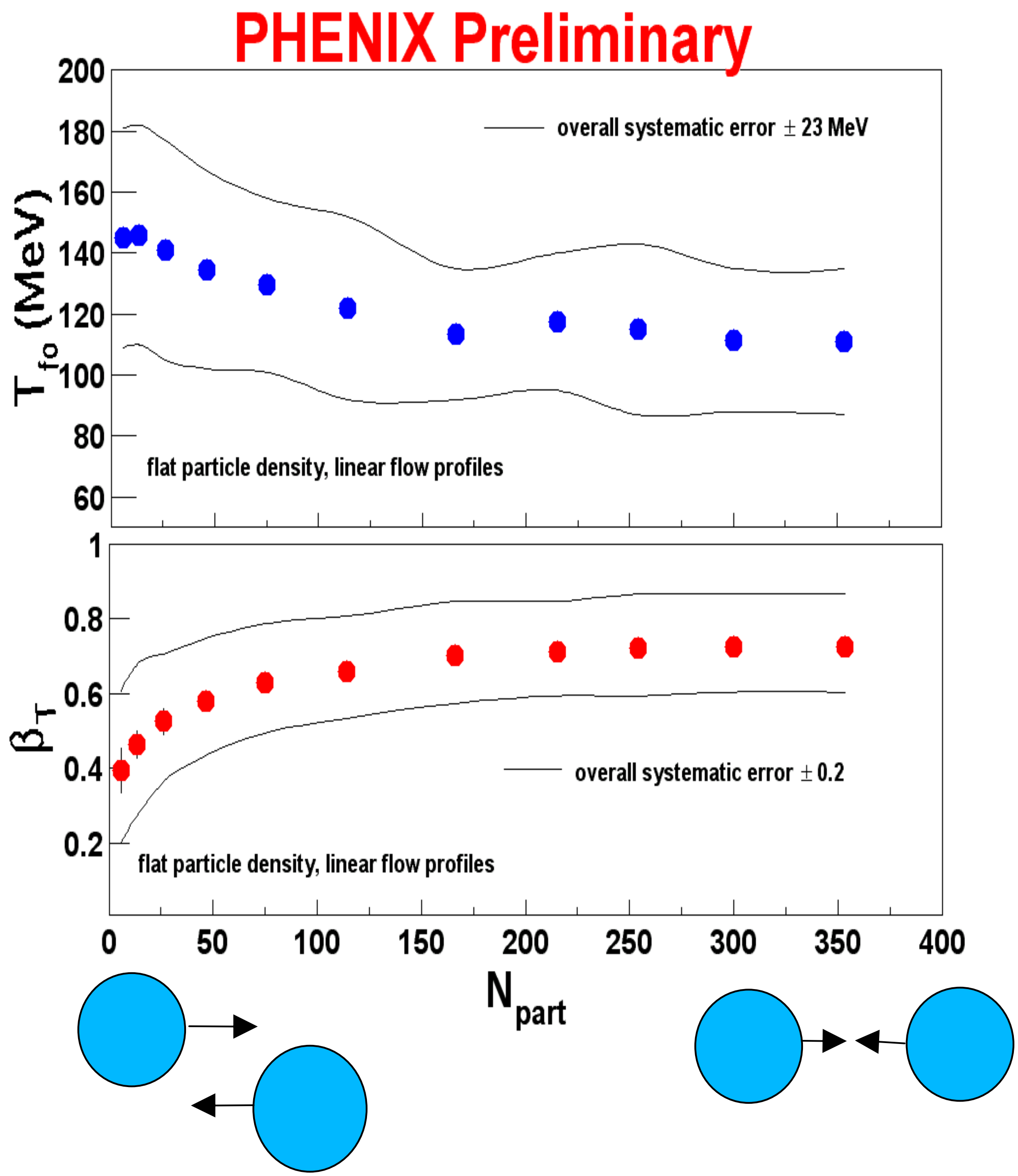
- Simultaneous fit in range $(m_t - m_0) < 1$ GeV is shown.
- The top 5 centralities are scaled for visual clarity.
- Similar fits for negative particles.

Jane Burward-Hoy



Population Characteristics - The Fit Results: The Parameters T_{fo} and β_T vs. N_{part}

- Expansion parameters in each centrality
- Overall systematic uncertainty is shown.
- A trend with increasing N_{part} is observed:
  - $T_{fo}\downarrow$ and $\uparrow\ \beta_T$
- Saturates at mid-centrality



Particle Emission Source Sizes:

Hanbury-Brown Twiss (HBT) Correlations

Some models predict that the source size will become larger and the duration time will become longer in the presence of a QGP phase

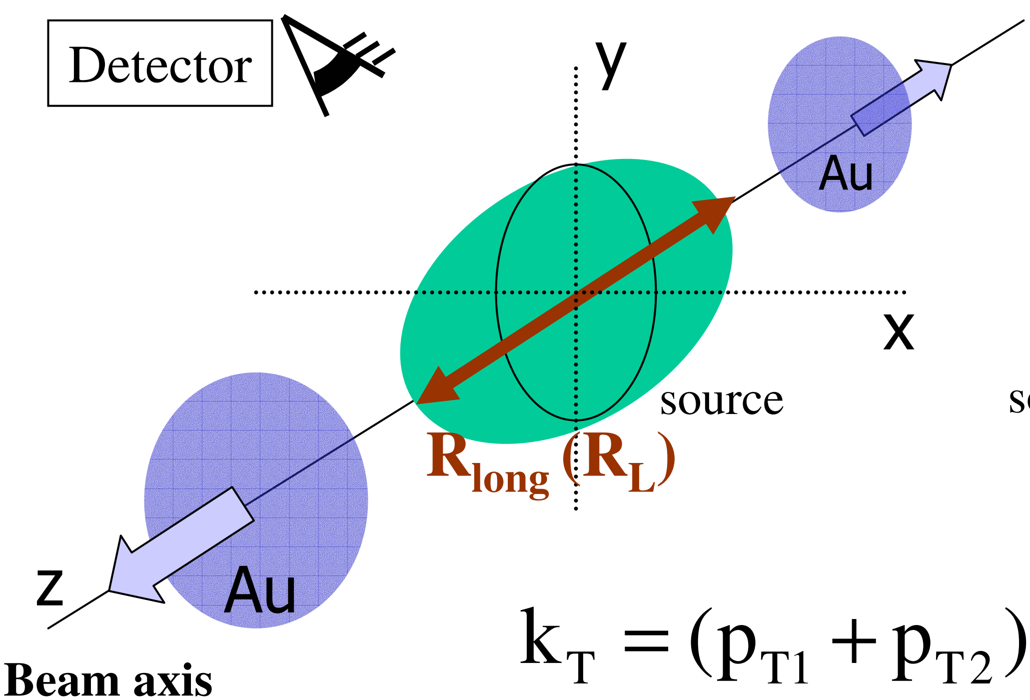
Bertsch-Pratt source radii

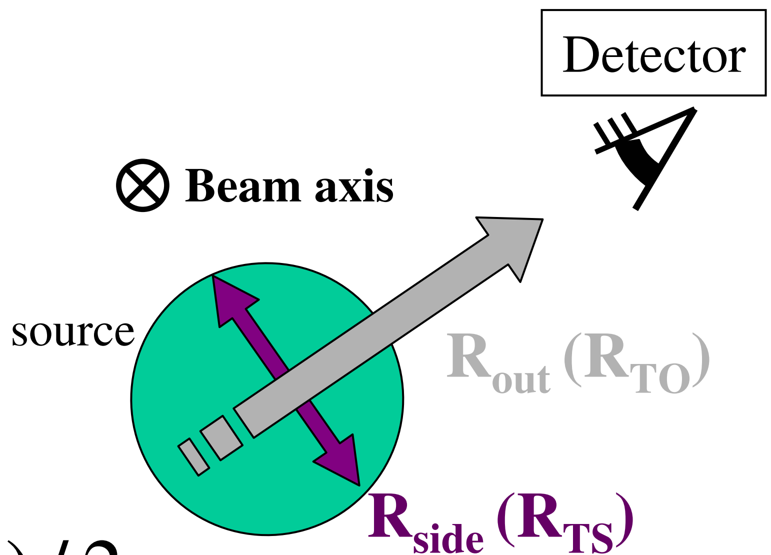
$$C_2 \equiv 1 + \lambda \exp\left(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2\right)$$

In LCMS frame

The duration time

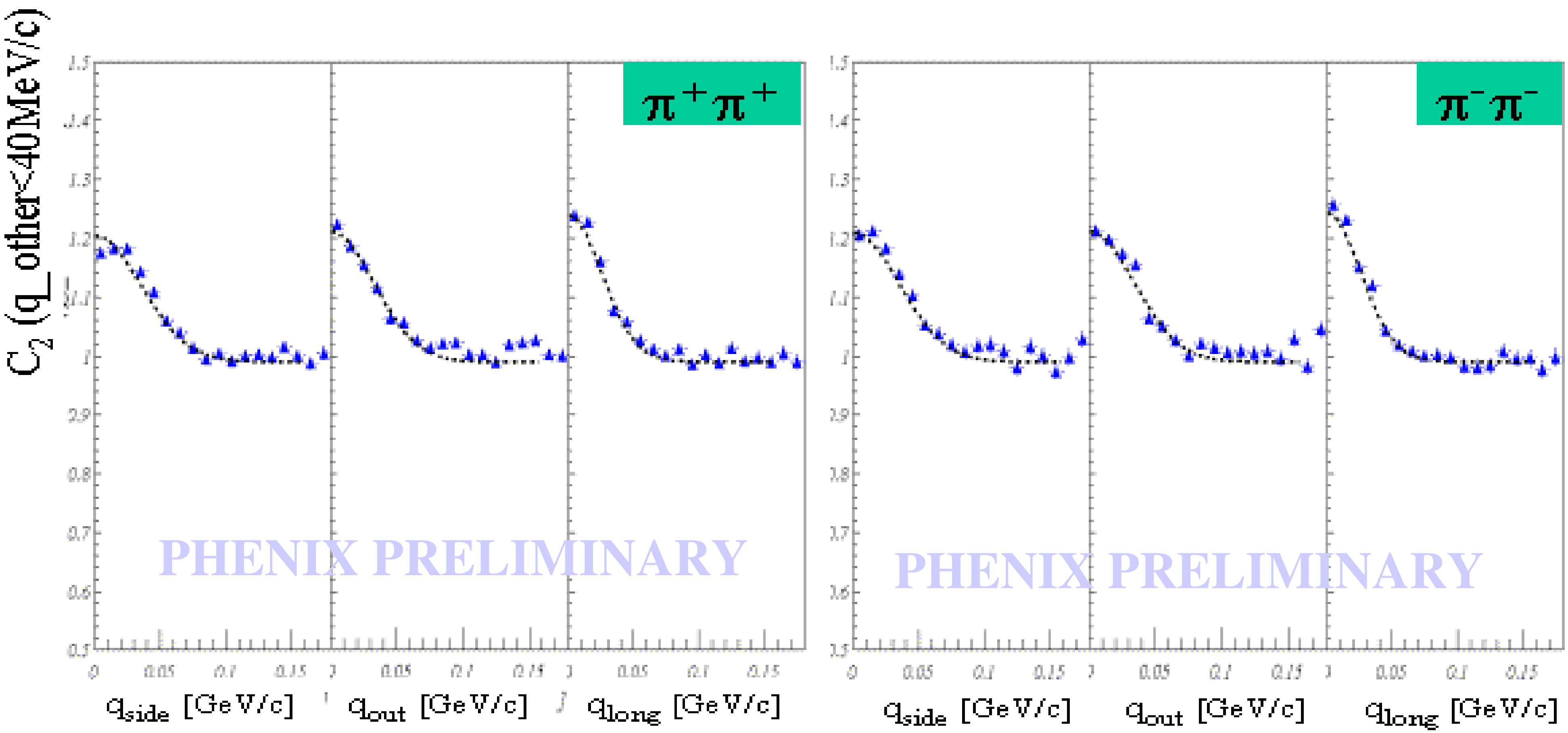
$$\Delta\tau = \sqrt{R_{TO}^2 - R_{TS}^2} / \beta$$





$$k_T = (p_{T1} + p_{T2}) / 2$$

3-D correlation results for charged pions



200 GeV Au+Au、Top 30% Centrality, $0.2<k_T<2.0$GeV/c, $\langle k_T \rangle=0.46$GeV/c

$\lambda = 0.397 \pm 0.015$
$R_{side} = 4.40 \pm 0.12$
$R_{out} = 3.73 \pm 0.12$ [fm]
$R_{long} = 4.82 \pm 0.15$

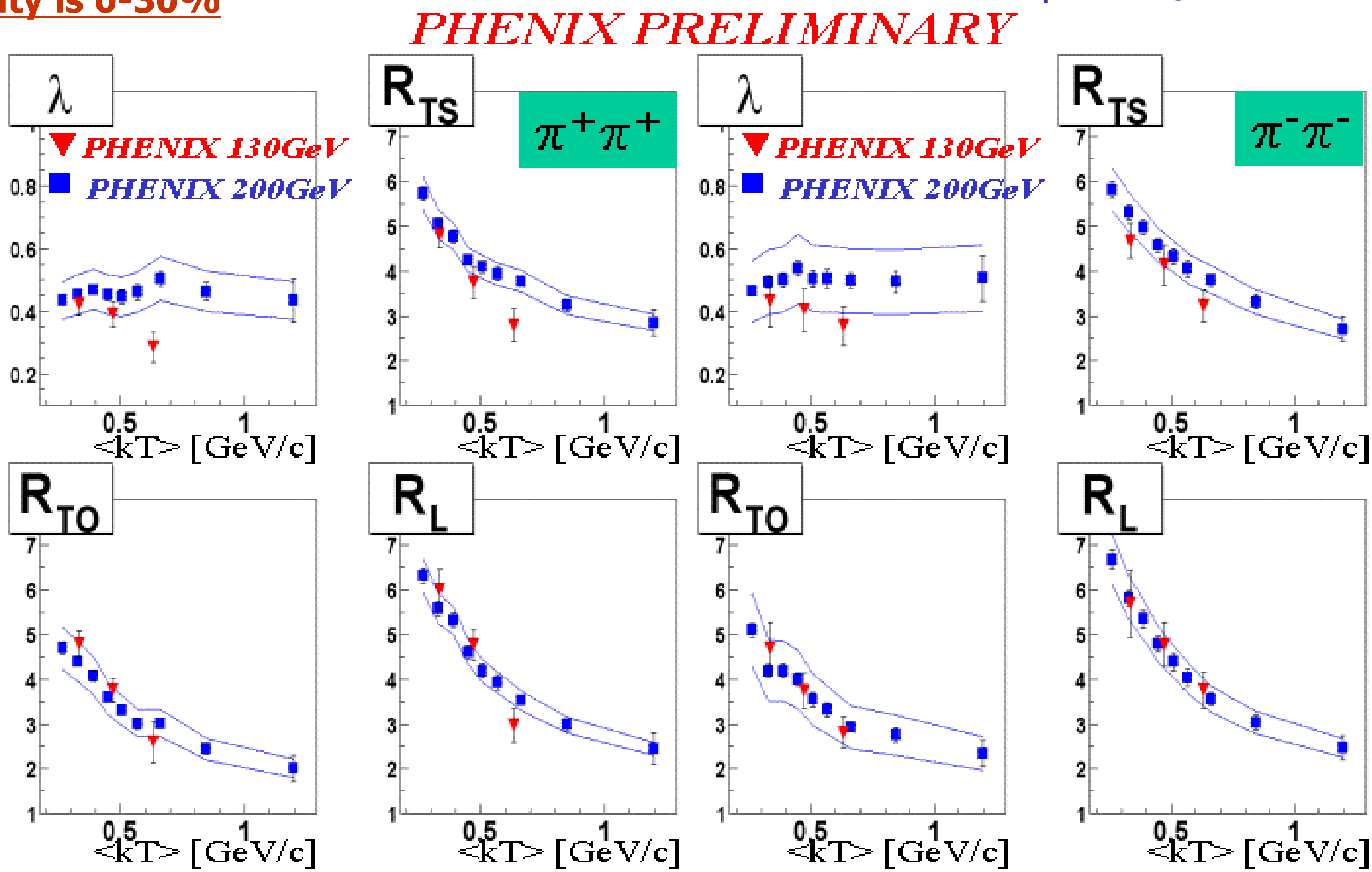
$\lambda = 0.434 \pm 0.018$
$R_{side} = 4.58 \pm 0.14$
$R_{out} = 3.88 \pm 0.14$ [fm]
$R_{long} = 5.24 \pm 0.18$

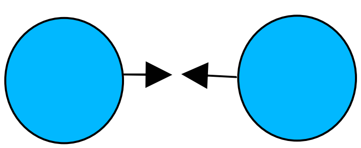
Akitomo Enokozino, Steve Johnson, Ron Soltz, Mike Heffner

k_T dependence of the Radii

Centrality is 0-30%

k_T : average momentum of pair



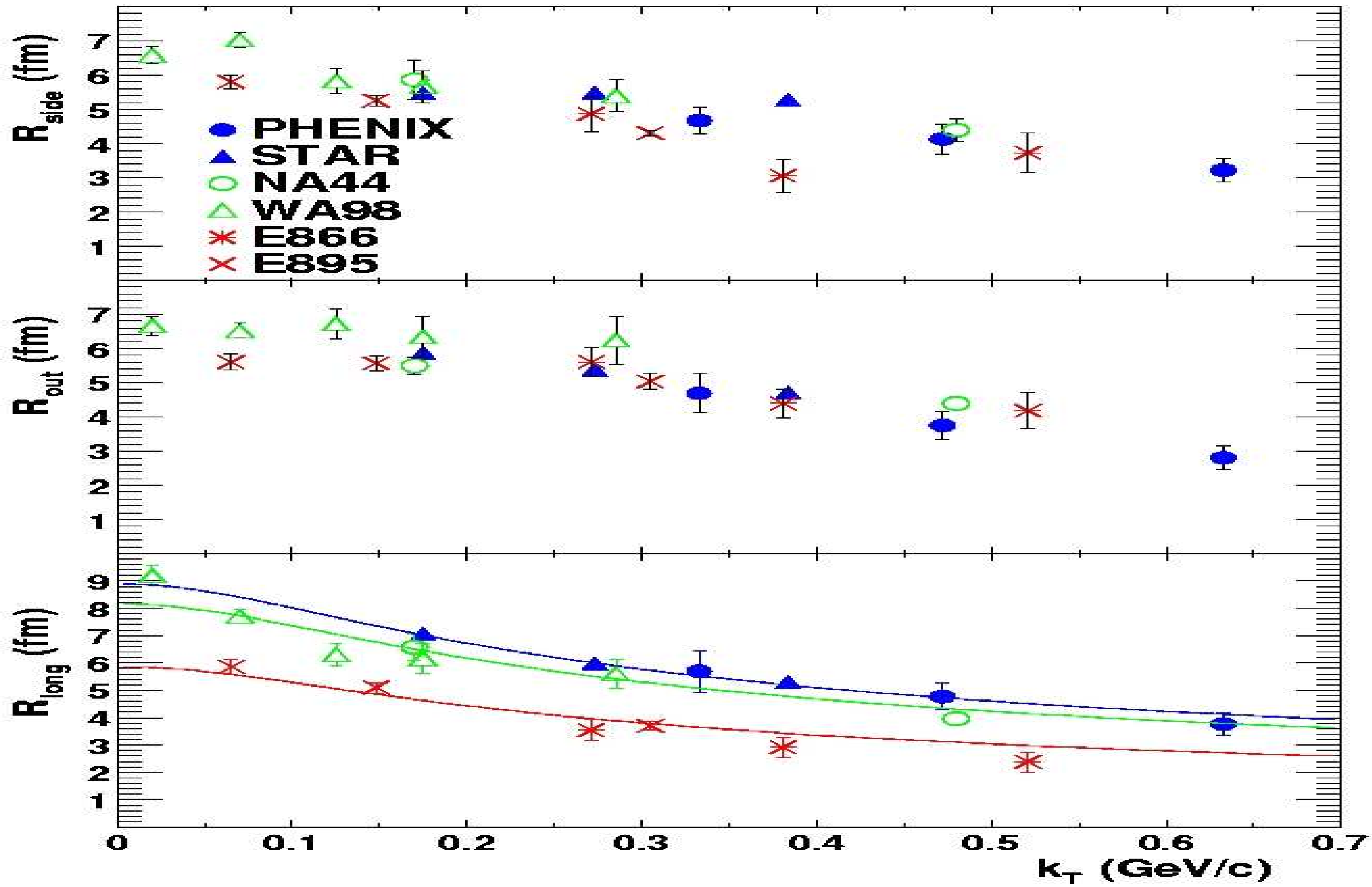


- Broad $\langle k_T \rangle$ range : 0.2 - 1.2 GeV/c
- All Radius parameters decrease as a function of k_T

  ⇒ consistent with collective expansion picture.
- Stronger k_T - dependence in R_{long} has been observed.

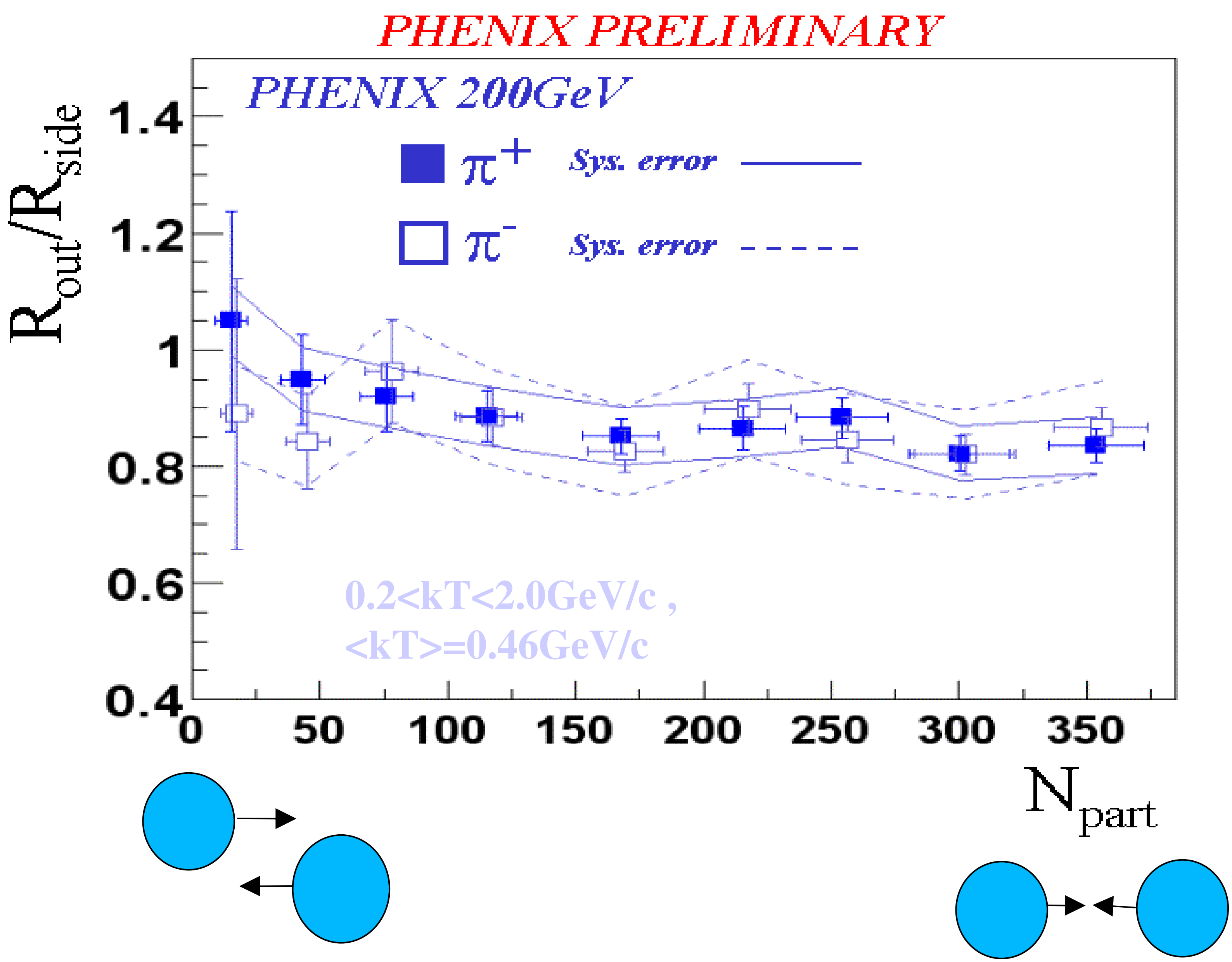
Source Size Evolution

The HBT Puzzle



R_{out}, R_{side}, and R_{out}/R_{side} changes little with collision energy while R_{long} is increasing.

Centrality dependence of R_{out}/R_{side}



Using spectra information to constrain HBT fits…

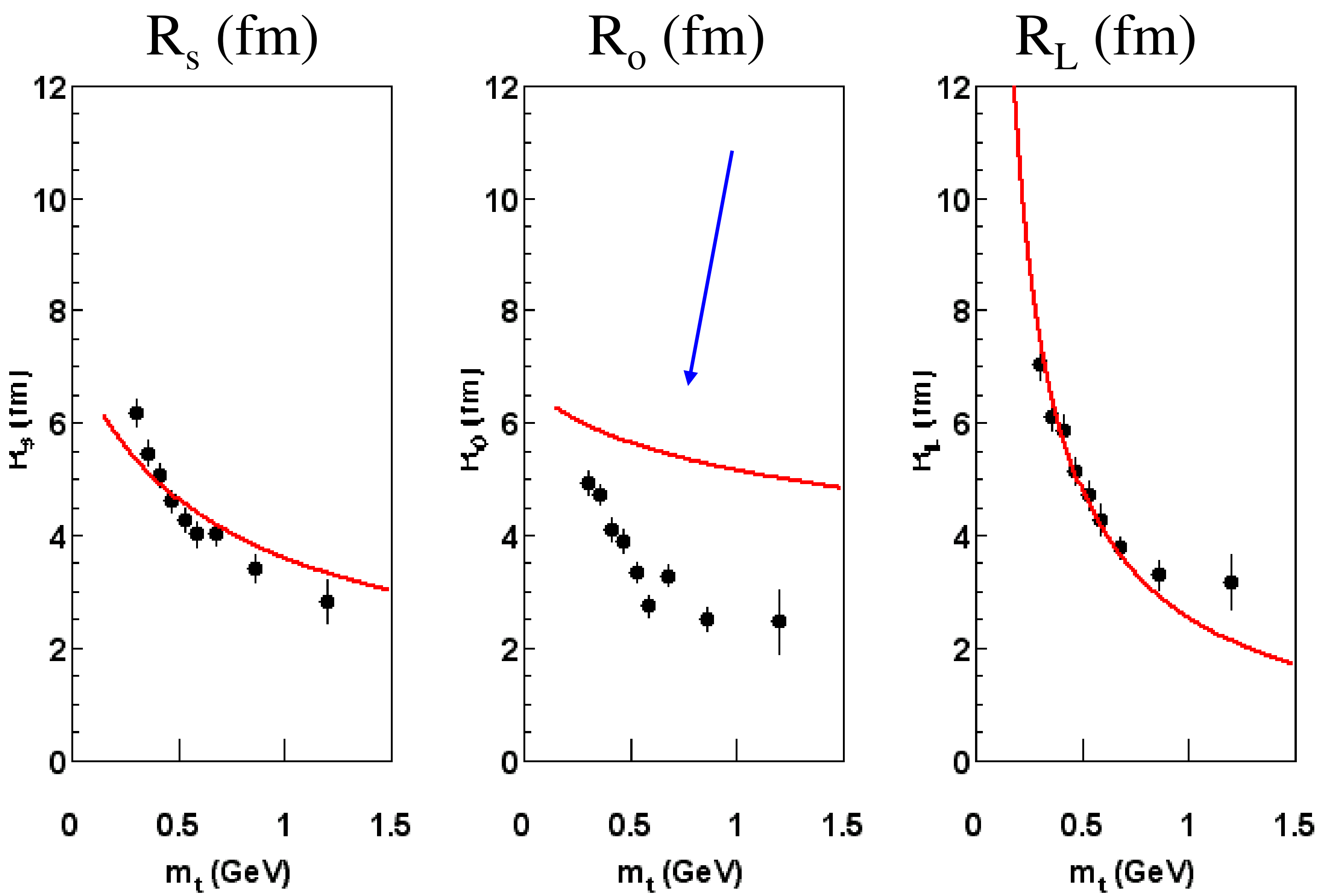
Back to the hydrodynamic model

From the spectra (systematic errors):
$\beta_T = 0.7 \pm 0.2$ syst. $T_{fo} = 110 \pm 23$ syst. MeV

$\pi^+\pi^+$

$R = 9.6 \pm 0.2$ fm

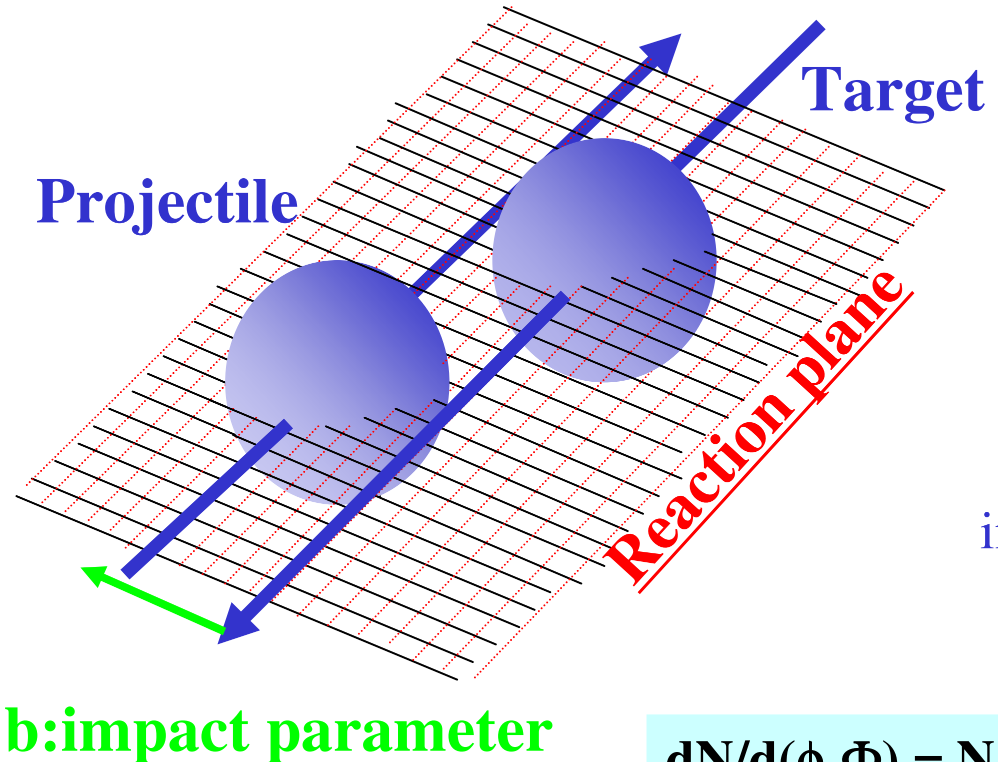
$\tau_0 = 13 \pm 2$ fm/c

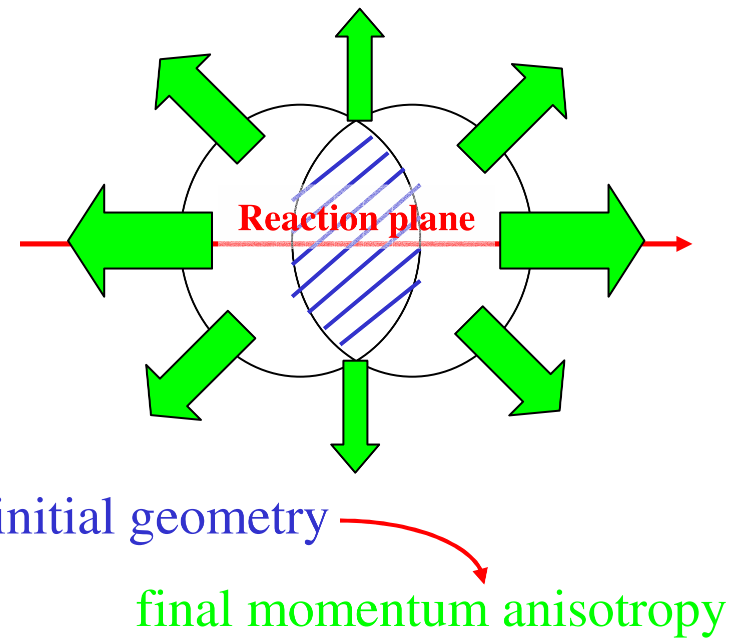


- Most 10% central positive pion HBT radii (similar result for negative pion data).
- Systematic uncertainty in the data is 8.2% for R_s, 16.1% for R_o, 8.3% for R_L.

Jane Burward-Hoy

Population Mass Movement: Elliptic Flow





$$dN/d(\phi-\Phi) = N\,(1 + \Sigma\, 2v_n' \cos(n(\phi-\Phi)))$$

ϕ : azimuthal angle for measured particles

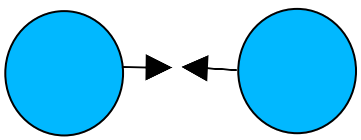
Φ : reaction plane angle

v_n' : raw anisotropy parameter

$v_n = v_n'/F$: corrected anisotropy parameter

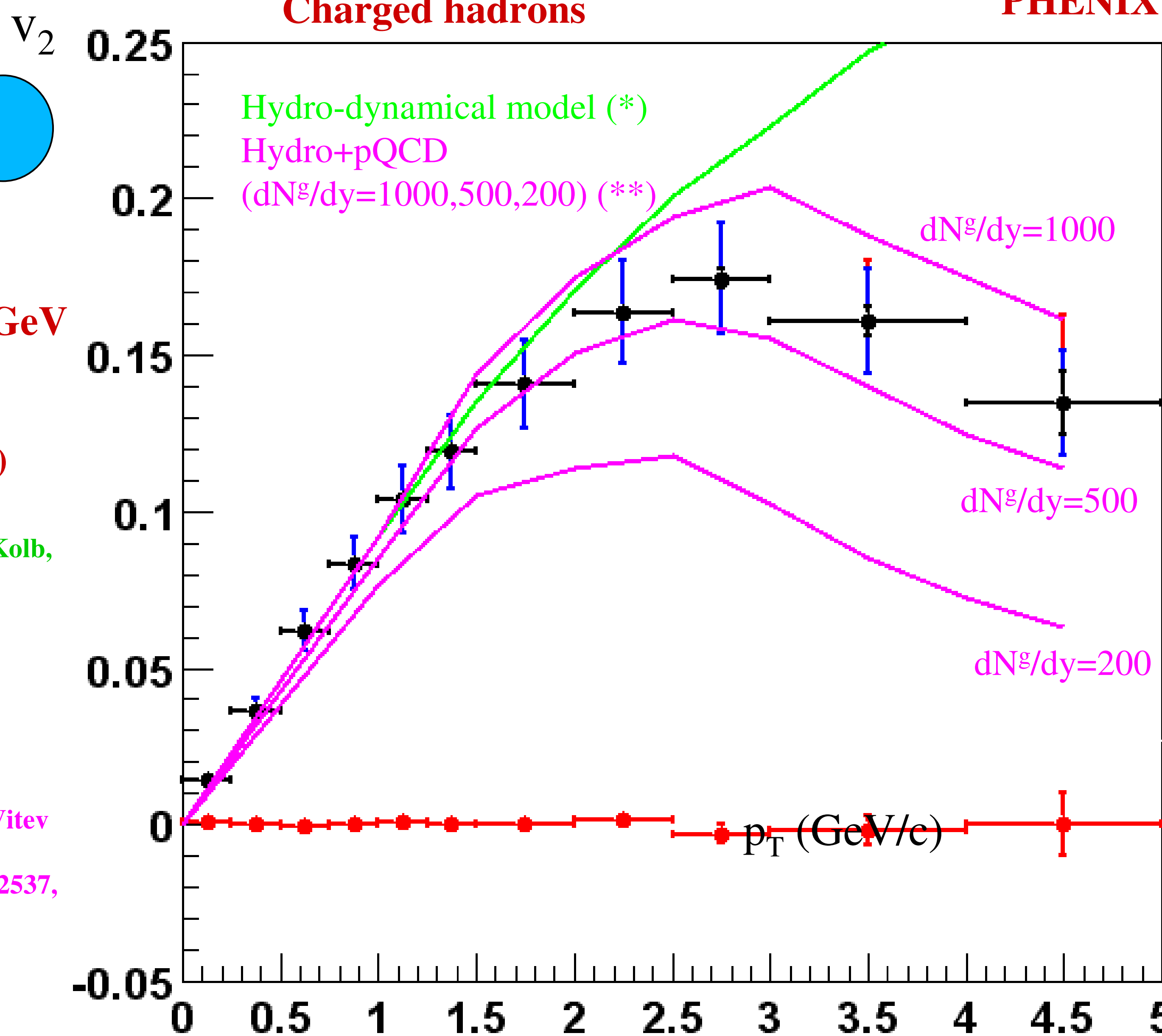
F : reaction plane resolution

Elliptic Flow vs transverse momentum



reaction plane based analysis
Charged hadrons

PHENIX Preliminary



Au+Au at $\sqrt{s_{NN}}$=200GeV

min. bias

(r.p. |η|=3~4)

(*) P.Huovinen, P.F.Kolb, U.W.Heinz, P.V.Ruuskanen and S.A.Voloshin, Phys. Lett. B503, 58 (2001)

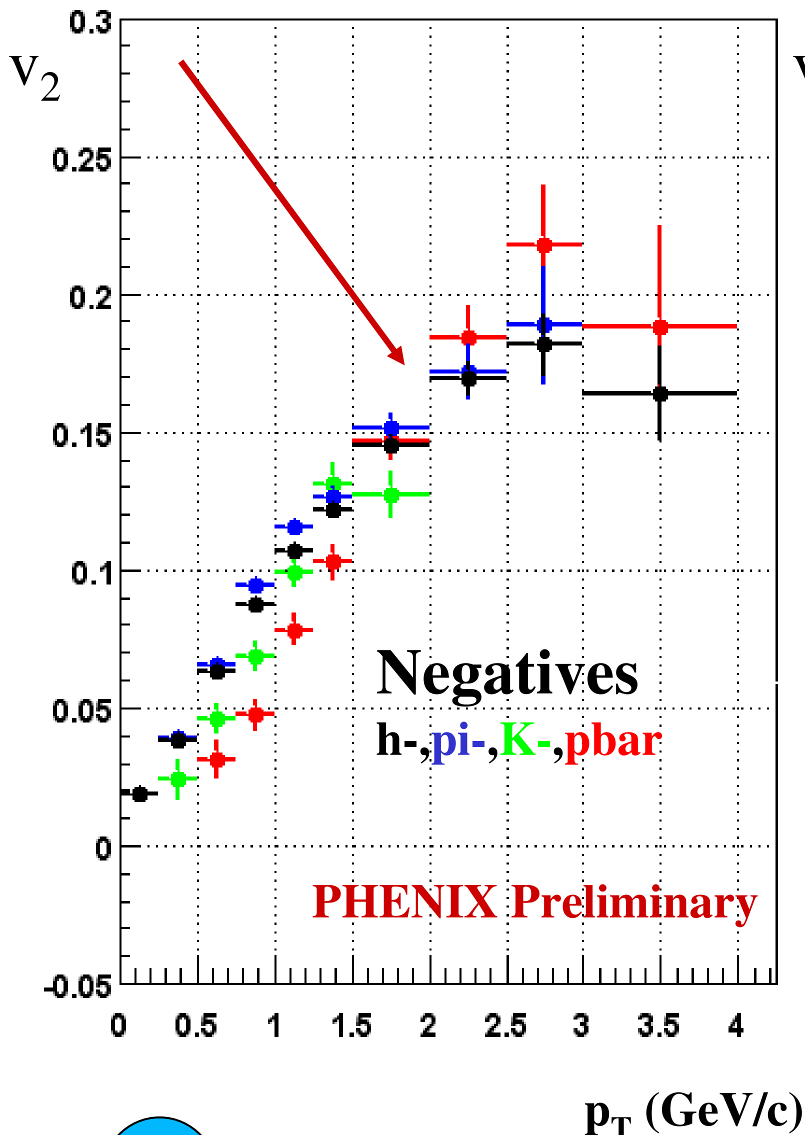
(**) M.Gyulassy, I.Vitev and X.N.Wang, Phys. Rev. Lett. 86, 2537, (2001)

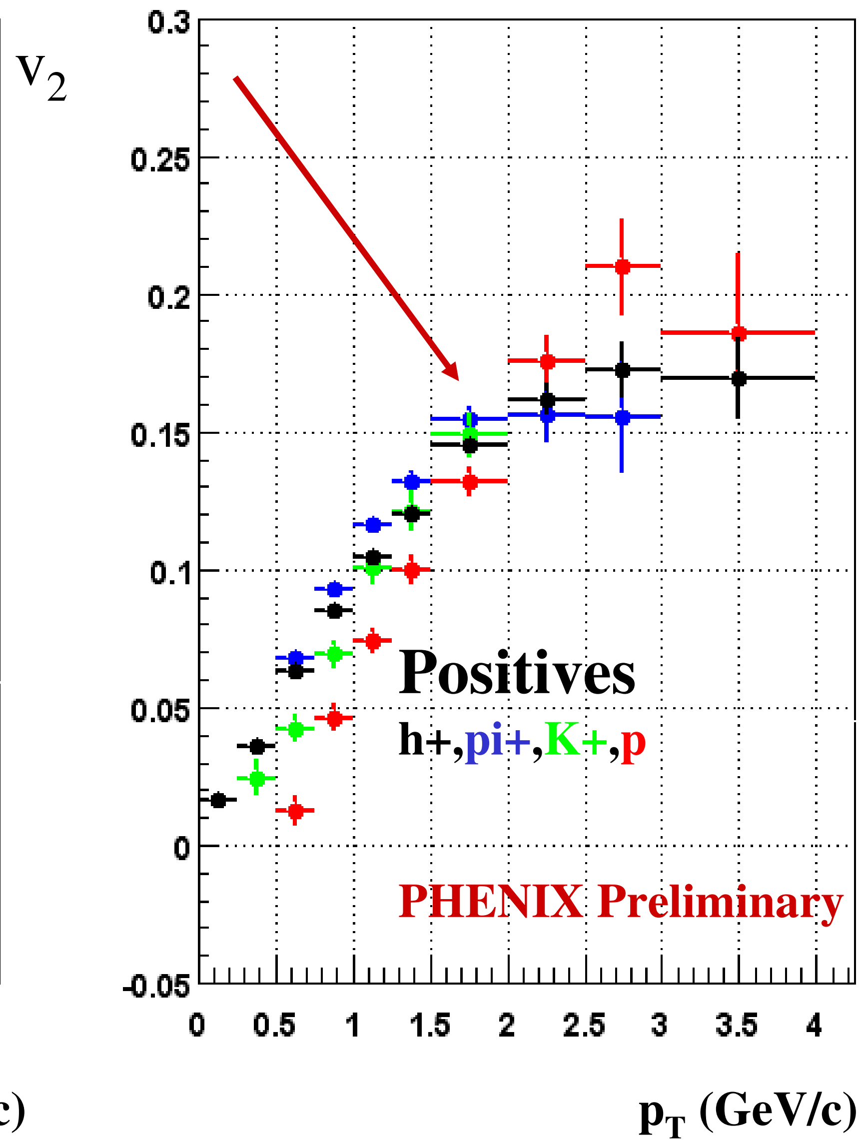
Shinichi Esumi

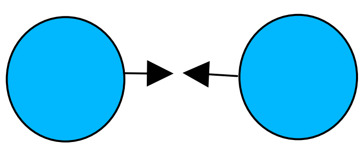
Jeffery T. Mitchell (BNL). 8th Wigner Symposium. NYC. 5/28/03

Elliptic Flow of identified hadrons

Au+Au at sqrt(s_{NN})=200GeV   min. bias   r.p. |η|=3~4





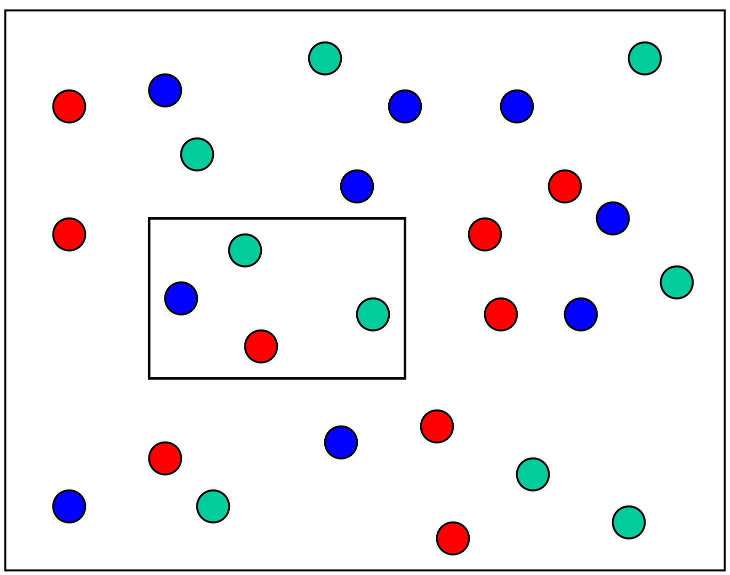


Note: The Protons cross the pions at ~1.5 GeV/c

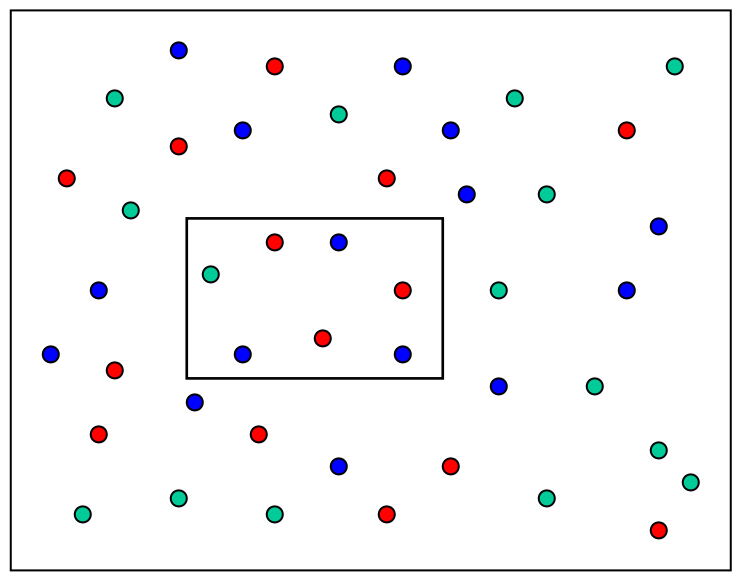
Net charge fluctuations

Proposed ~ 3 years ago: Fluctuations in net charge and net baryon number significantly reduced if a QGP is formed in the collisions
Asakawa, Heinz, Müller PRL 85(2000)2072; Jeon&Koch PRL 85(2000)2076

Fractional electric charges (q = ± 1/3, 2/3) of the quarks ==> Charges more evenly spread in a plasma ==> Reduced net charge fluctuations in a small region of phase-space



”hadron-gas”



”quark-gluon plasma”

Net Charge Fluctuation Measures and Results

Charged particle multiplicity

$$n_{ch} = n_+ + n_-$$

Net charge

$$Q = n_+ - n_-$$

Define:

$$v(Q) \equiv Var(Q)/\langle n_{ch} \rangle$$

For stochastic emission, $v(Q) = 1$
Globally, one expects $v(Q) = 0$ – charge conservation

If we observe a fraction p of all produced particles ⇒
$v(Q) \propto (1 - p)$ from global charge conservation

Joakim Nystrand

For the 10% most central collisions, $|\eta|<0.35$, $p_T > 200$ MeV/c, $\Delta\varphi=\pi/2$:

$v(Q) = 0.965 \pm 0.007(\text{stat.}) - 0.019$ (syst.) $\sqrt{s_{nn}} = 130$ GeV

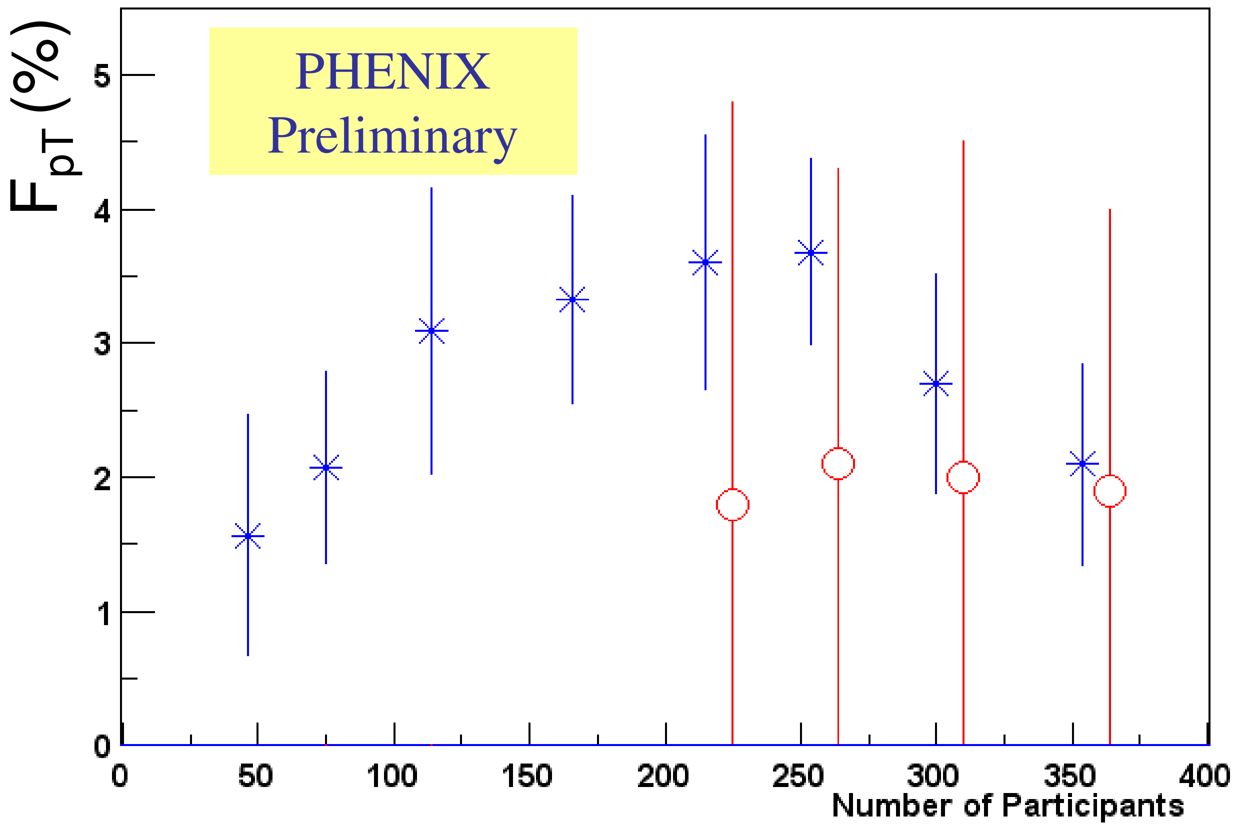
$v(Q) = 0.969 \pm 0.006(\text{stat.}) \pm 0.020$ (syst.) $\sqrt{s_{nn}} = 200$ GeV (PRELIMINARY)

Systematical error estimated from GEANT simulations (reconstruction efficiency and contribution from background tracks), and by comparing the results for the 2 arms (200 GeV).

Fluctuations in Event-by-Event Average Transverse Momentum

$$\omega = \frac{\sqrt{\mathrm{Var}(p_T)}}{< p_T >} \qquad F_{p_T} = \omega_{data} - \omega_{random} \Big/ \omega_{random}$$

F_{pt} represents the fraction of non-random fluctuations with respect to a mixed event baseline.



* AuAu 200 GeV, preliminary

o AuAu 130 GeV, published

Maximum for semi-central collisions.

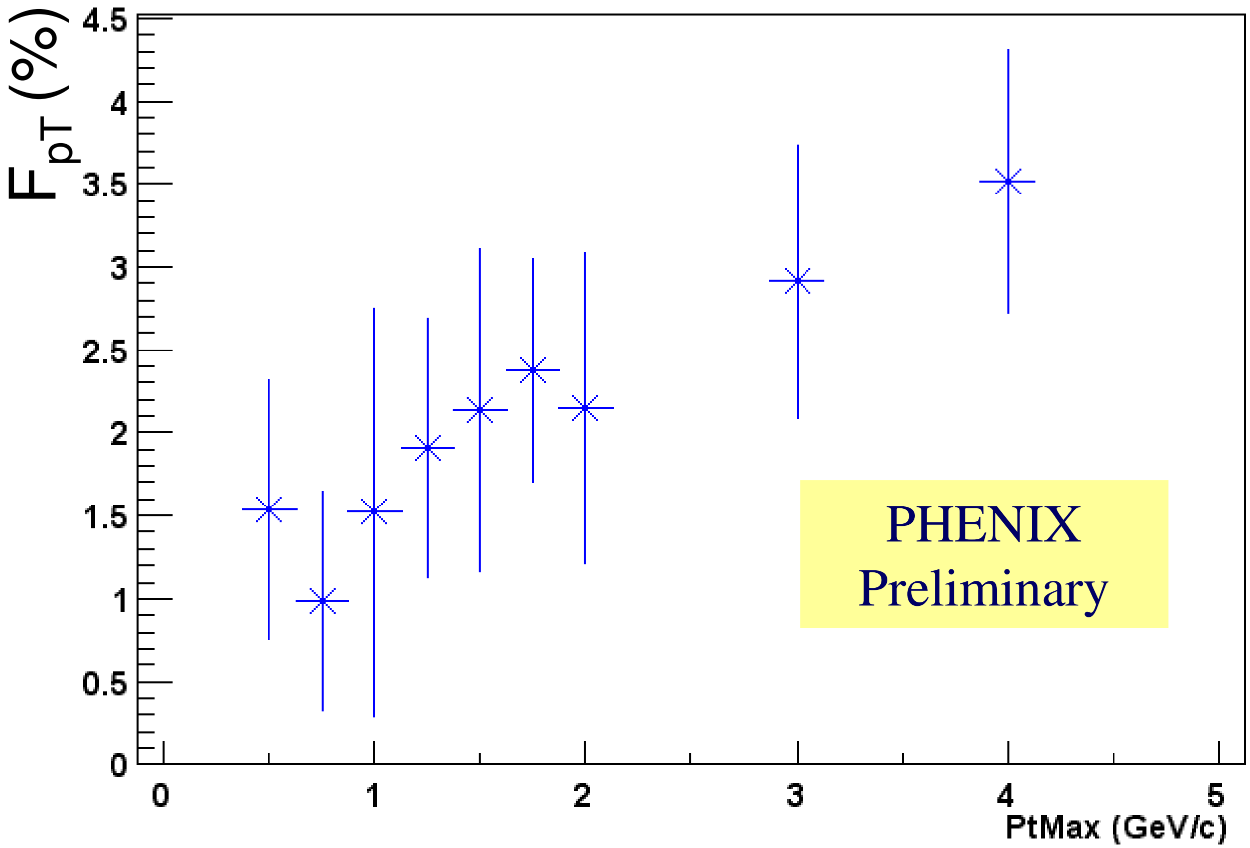
F_{pT} related to ϕ_T:

$$\phi = F_{p_T}\, \sigma_{random} \sqrt{< N >}$$

Jeffery Mitchell

PHENIX

The fluctuation magnitude tends to increase as the p_T range used to calculate $<p_T>$ is extended to higher values.



F_{pT} vs. P_T range
$(0.2<p_T<p_{T,\,max})$

A Hint of Something New

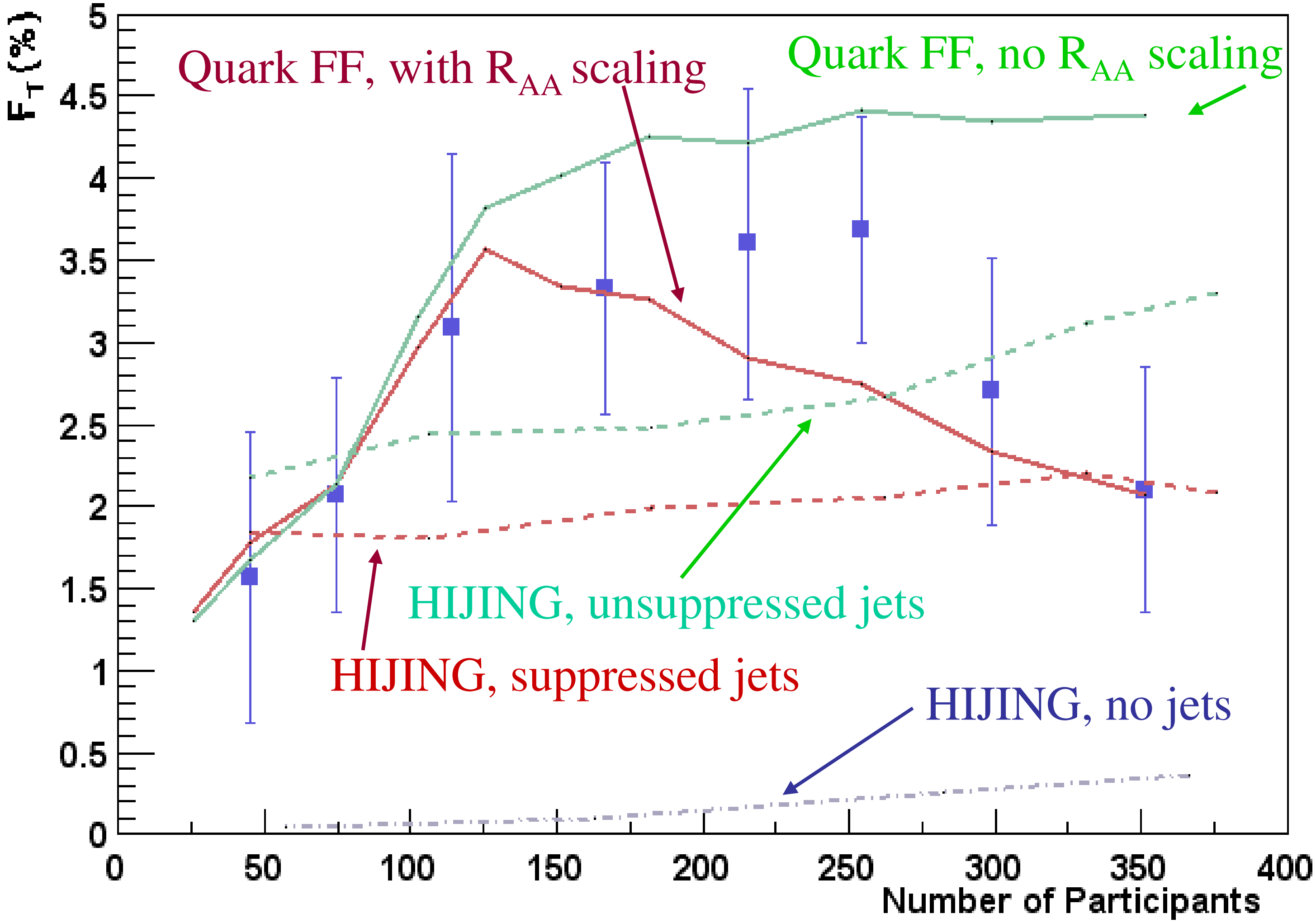
NOTE: The non-random fluctuations are being introduced primarily by high p_T particles.

A simulation of elliptic flow shows that there is a negligible contribution due to that effect.

Explaining the Source of the Excess Fluctuations

Observed signal is not consistent with temperature fluctuations due to a phase transition.

HIJING 1.3 filtered through PHENIX acceptance



Observed signal is consistent with jets suppressed by the preliminary PHENIX R_{AA} values.

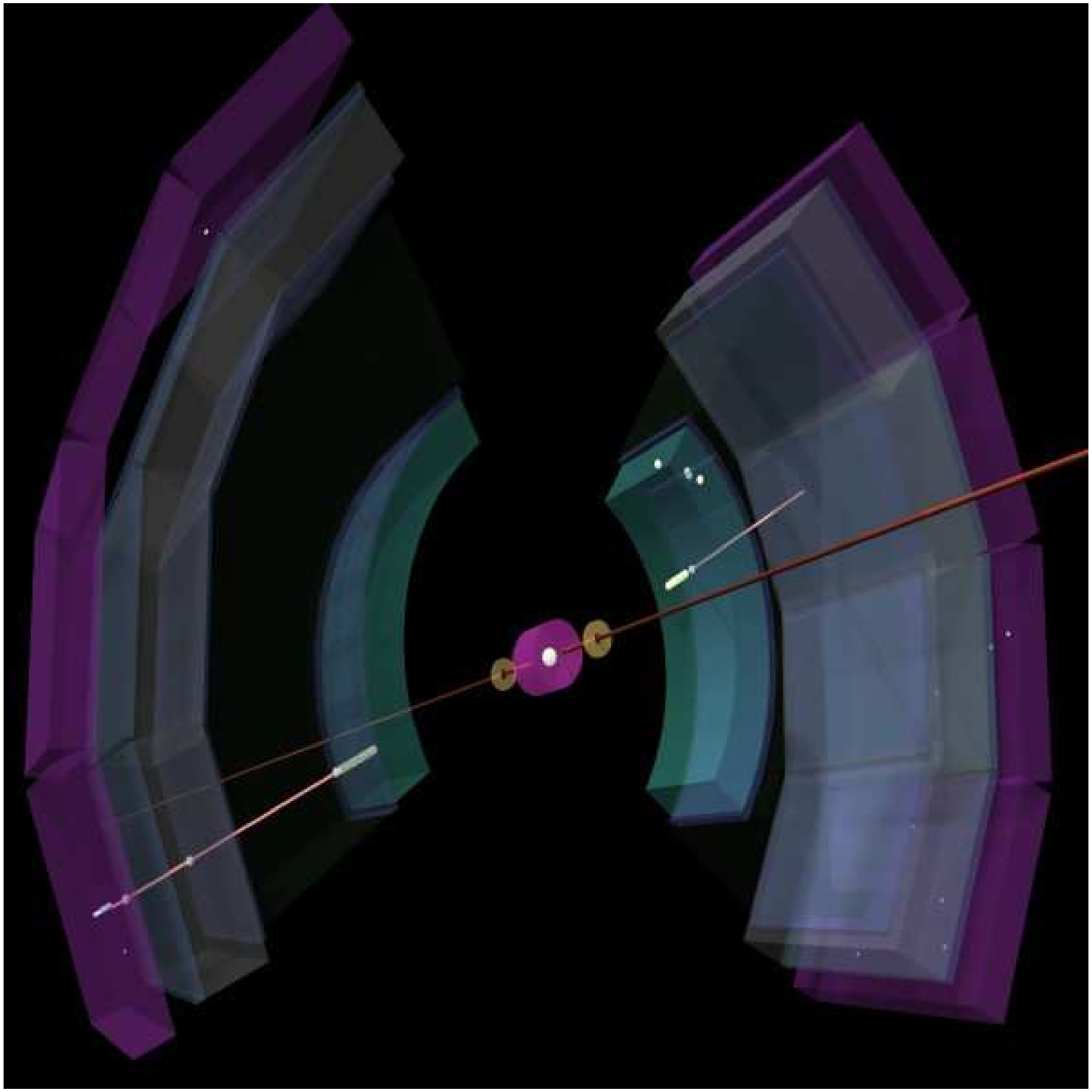
A Simple Model:

- **Throw inclusive spectra and <N> distributions to match data.**
- **Define hard collision probability (P_{hard}) vs. p_T from data excess over m_T exponential fit.**
- **For hard collisions, generate jets by sampling the fragmentation function (FF).**
- **Calculate F_T.**
- **The only adjusted parameter vs. centrality is P_{hard} scaled by measured R_{AA}.**

PHENIX Census Conclusions

- **Population, (transverse) energy production, and density**
  - *Monotonically increasing with collision energy. High energy density achieved.*
- **Demographics and Diversity**
  - *Consistent with hydrodynamical model expectations. Many protons at high p_T.*
- **Sizes**
  - *Source sizes are large, but duration time is short*
- **Collective Movement**
  - *Only consistent with hydrodynamics below p_T ~2 GeV/c. Protons flow more at high p_T.*
- **Fluctuations**
  - *No excess charge fluctuations seen. Excess $\langle p_T \rangle$ fluctuations seen are consistent with a predominant jet source.*

Synopsis: "Thermal"-like properties at low p_T. Maybe something new observed at high p_T.



The PHENIX census is still underway.
Stay tuned for many more results soon!

Auxiliary Slides Follow…

Simultaneous Fit Conclusions

- Expansion measured from spectra depends on N_{part}.
  - Saturates to constant for most central.
- Used simple profiles for the expansion and particle density distribution
  - Linear velocity profile
  - Flat particle density
- Within this hydro model, no common source parameters could be found for spectra and all HBT radii simultaneously.

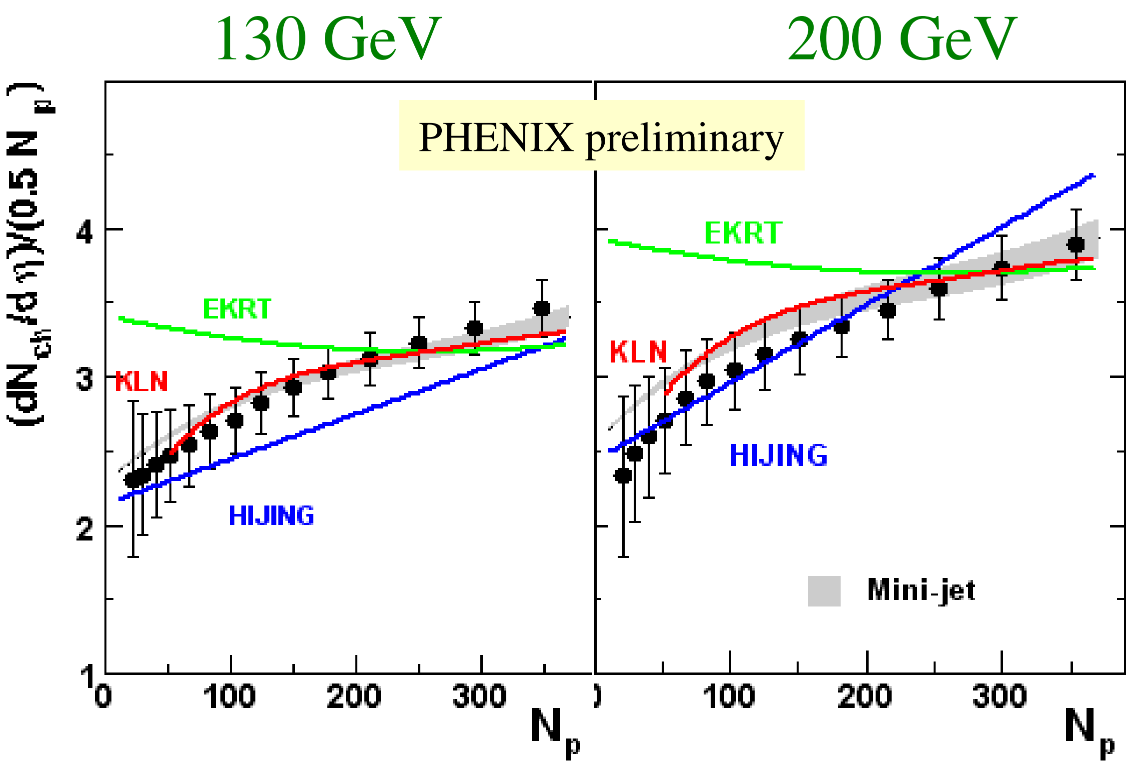
For the most peripheral spectra:
$\beta_T = 0.5 \pm 0.2$ syst. ($<\beta_T> = 0.3 \pm 0.2$ syst.)
$T_{fo} = 135 \pm 23$ MeV

… to the 5% spectra
$\beta_T = 0.7 \pm 0.2$ syst. ($<\beta_T> = 0.5 \pm 0.2$ syst.)
$T_{fo} = 110 \pm 23$ MeV

R_s prefers $\eta_T > 1.0$ and $T_{fo} < 50$ MeV

R_o prefers $\eta_T > 1.4$ and $T_{fo} > 100$ MeV

Nch: Comparison to theory



HIJING
X.N.Wang and M.Gyulassy,
PRL 86, 3498 (2001)

Mini-jet
S.Li and X.W.Wang
Phys.Lett.B527:85-91 (2002)

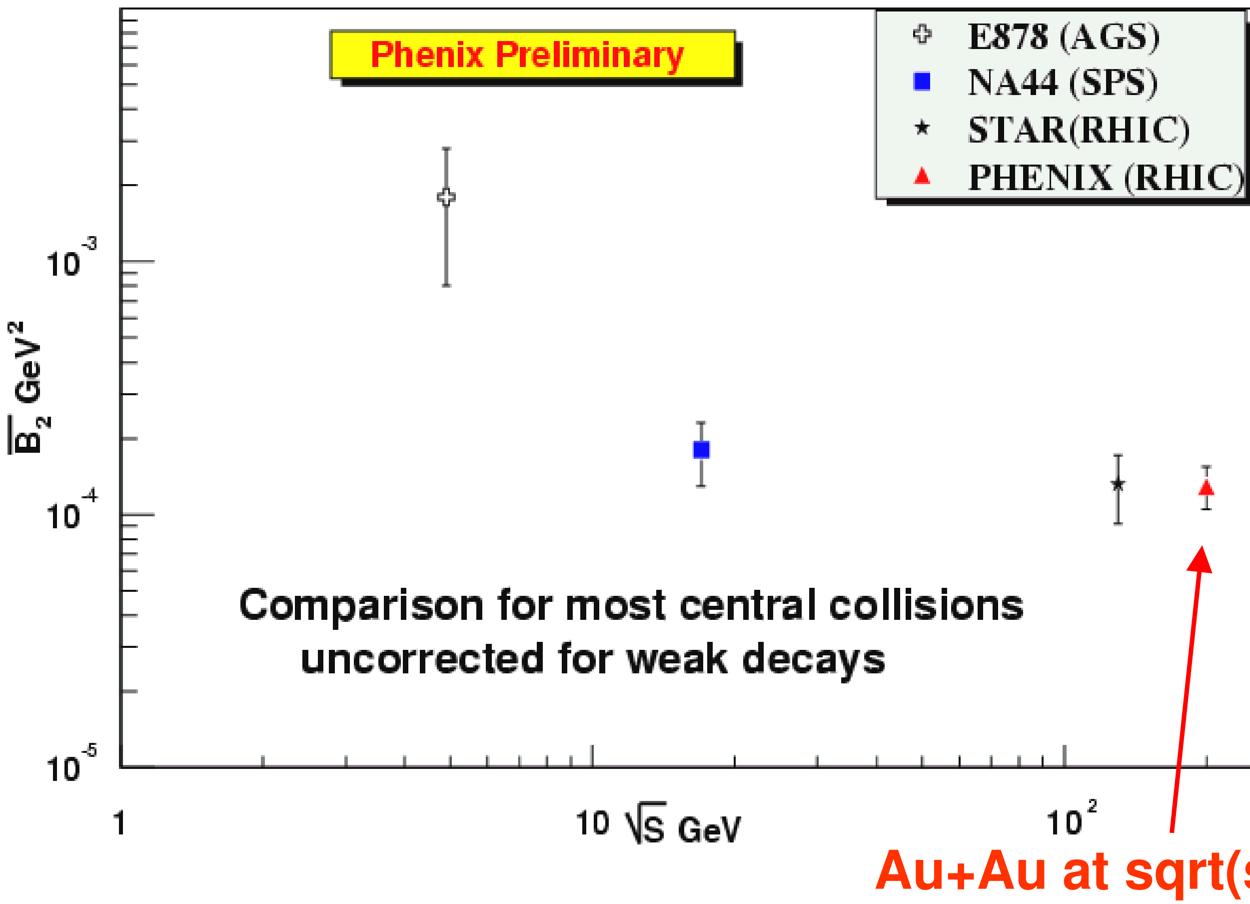
EKRT
K.J.Eskola et al,
Nucl Phys. B570, 379 and
Phys.Lett. B 497, 39 (2001)

KLN
D.Kharzeev and M. Nardi,
Phys.Lett. B503, 121 (2001)
D.Kharzeev and E.Levin,
Phys.Lett. B523, 79 (2001)

✓ Mini-jet and KLN: describe data well
✓ HIJING: not too bad

PHENIX

Coalescence model for anti-deuteron

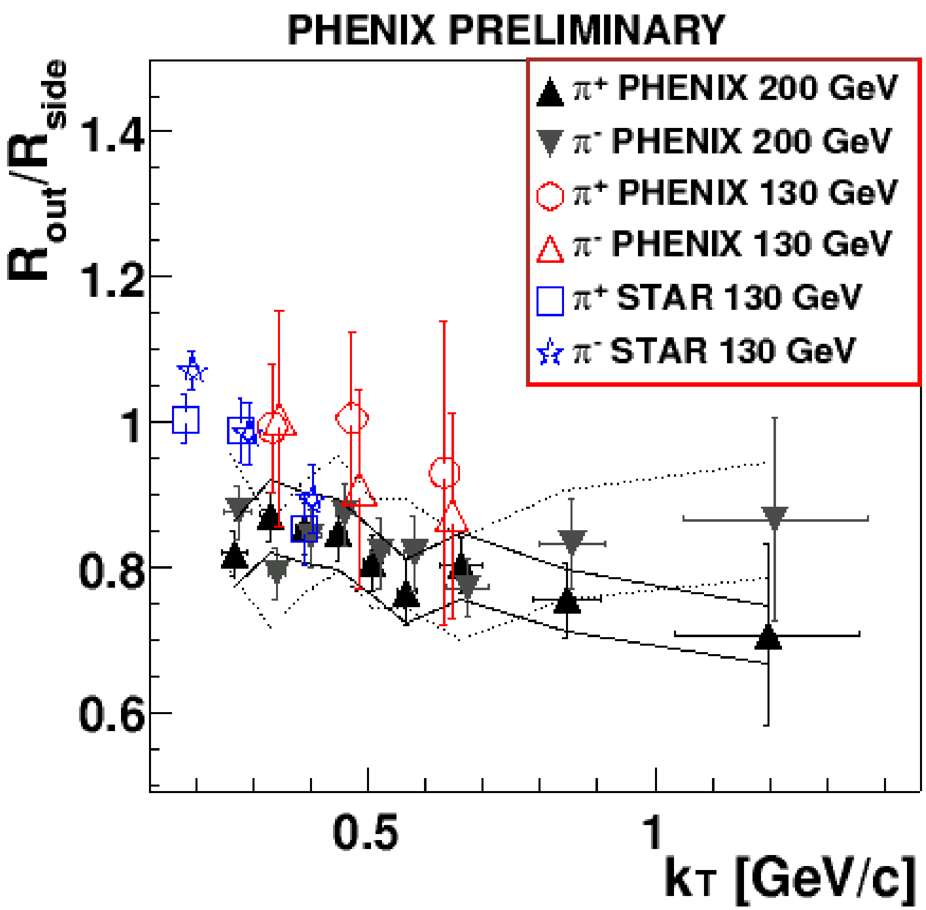


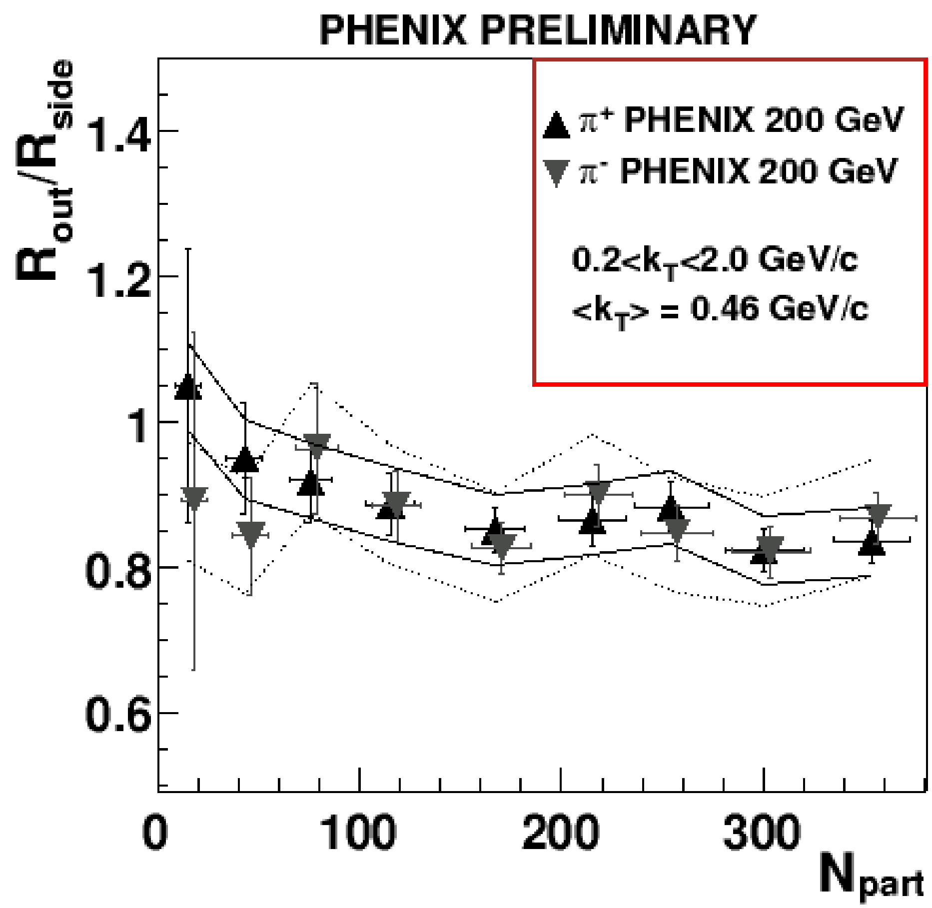
$1/B_2$ QV

$$E_d \frac{d^3N_d}{dp_d^3} = B_2 (E_p \frac{d^3N_p}{dp_p^3})^2$$

- Weak beam energy dependence from SPS to RHIC.
- Similar behavior has been observed in pion HBT correlations.

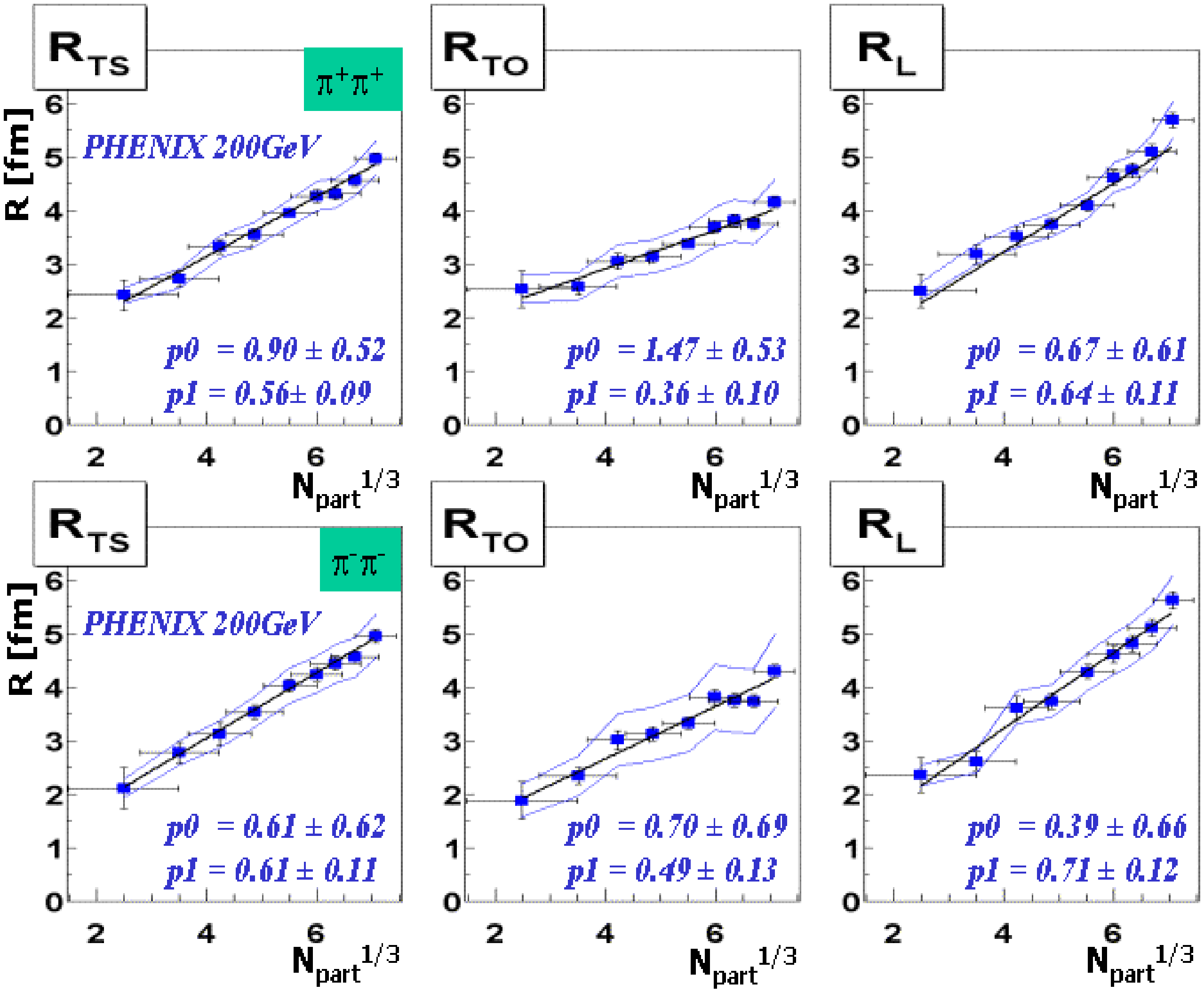
PHENIX Run-2 Preliminiary





Centrality dependence of source radii

PHENIX PRELIMINARY 0.2<kT<2.0GeV/c, <kT>=0.46GeV/c

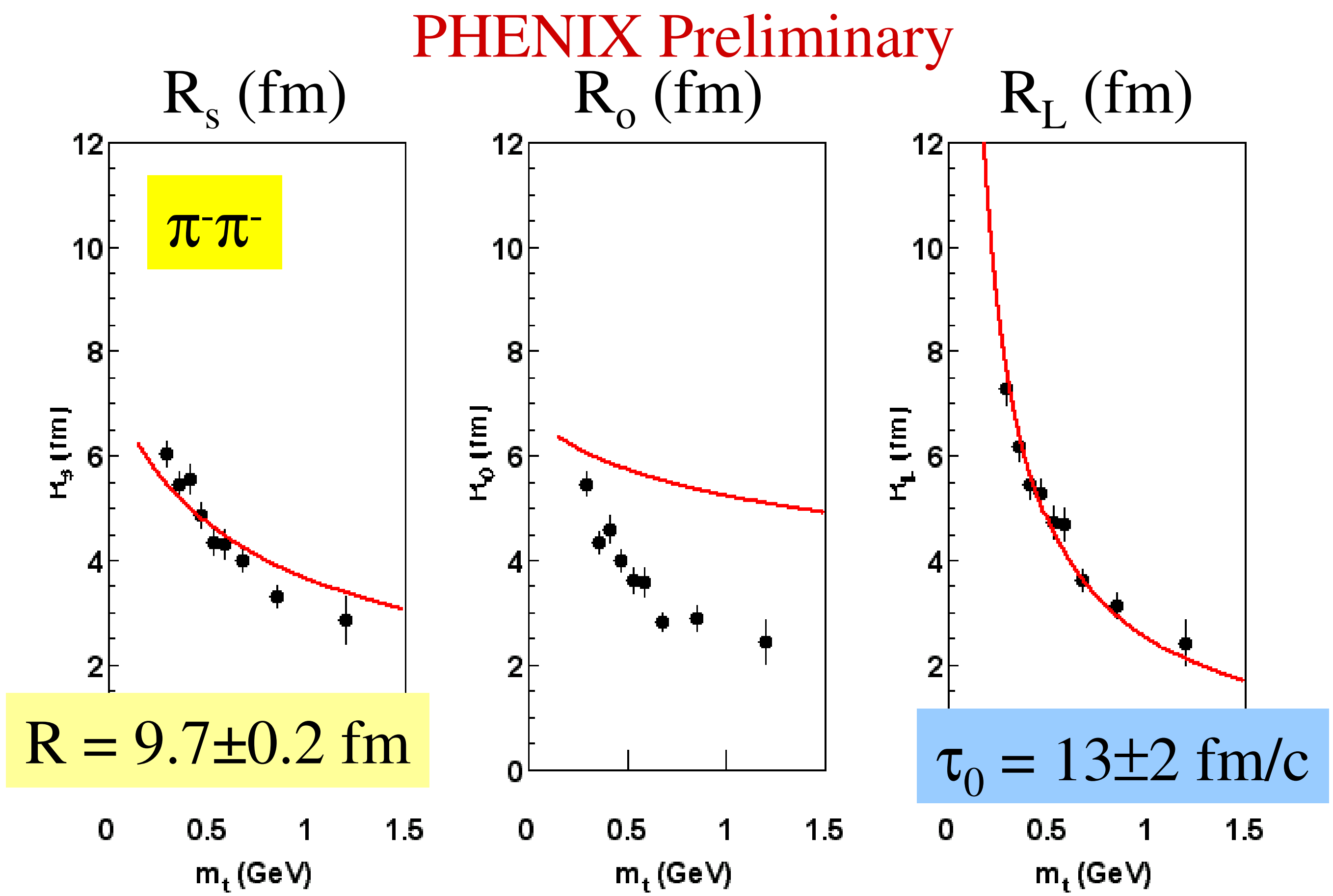


Fit with $p0+p1*N_{part}$^1/3

R_{long} increases rapidly with the N_{part} than R_{out}.

Using spectra information to constrain HBT fits…

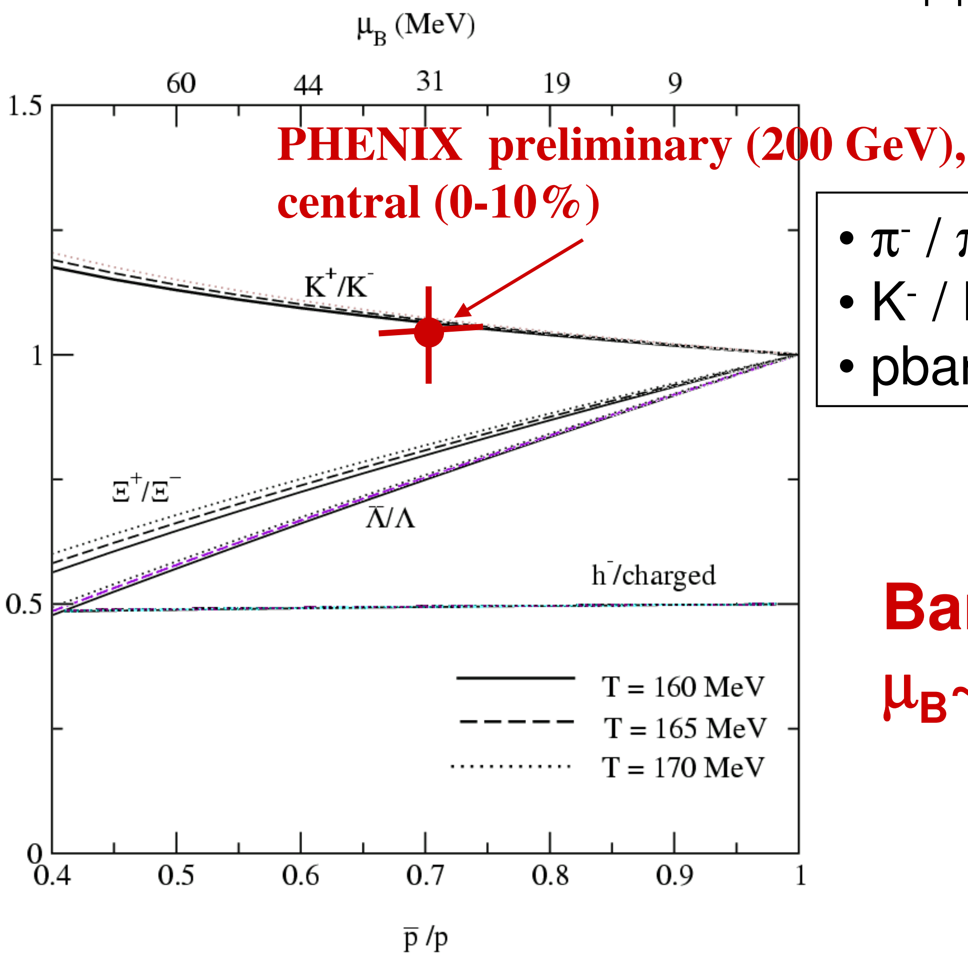
From the spectra (systematic errors):
$\beta_T = 0.7 \pm 0.2$ syst. $T_{fo} = 110 \pm 23$ syst. MeV



- 10% central negative pion HBT radii.
- Systematic uncertainty in the data is 8.2% for R_s, 16.1% for R_o, 8.3% for R_L.

Estimate of Baryon Potential

Statistical thermal model hep-ph/0002267 F.Becattini et al.



- $\pi^- / \pi^+ = 1.02 \pm 0.02$ (stat) $\pm$ 0.1 (sys)
- $K^- / K^+ = 0.92 \pm 0.03$ (stat) $\pm$ 0.1(sys)
- pbar / p = 0.70 ± 0.04 (stat) $\pm$ 0.1(sys)

Baryon chemical potential
$\mu_B \sim$ 30MeV