AGS/RHIC User Meeting - June 2005

Probing Collision Dynamics with Fluctuation and Correlation Studies at RHIC

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Talk Outline

- Net Charge Fluctuations
- Transverse Momentum Fluctuations
- K/π Fluctuations (Proof of principle)

- Questions:
  - Smoking gun for QGP, phase transition ?
    - Threshold Effects with beam energy?
  - What can we learn about collision dynamics ?
    - Resonances
    - Radial Flow Velocity + Profile
    - Role of Jets ?
  - Issues
    - E, p conservation
    - HBT & Coulomb effects

Why Study E-by-E Fluctuations ?

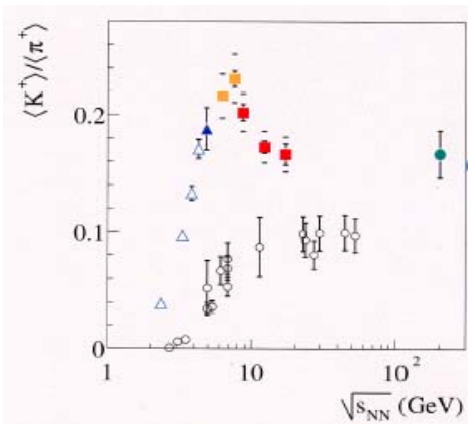
- Net Charge Fluctuations
  - Prediction by Jeon & Koch, PRL83 (99) 5435, + others)
  - Net charge fluctuations ***reduced*** in a QGP compared to a hadron or resonance gas.

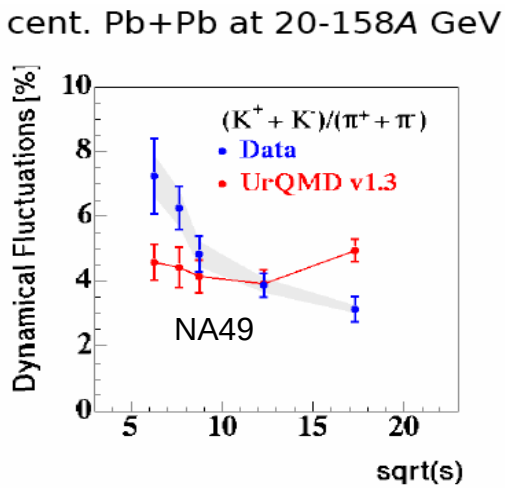
$$R = \frac{N_+}{N_-} \qquad D \equiv \langle N_{ch} \rangle \langle \delta R^2 \rangle = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{CH} \rangle} = 4 \varpi_Q$$

Model	D	$\nu_{+-,dyn}$
Poisson, Hadron Gas	4	0
Resonance Gas (Koch et al)	2.8	$-1.2/n_{ch}$
Quark Coalescence (Bialas)	3.33	$-0.7/n_{ch}$
QGP (Koch et al)	0.75	$-3.25/n_{ch}$
Lattice	1	$-3/n_{ch}$

- Momentum Fluctuations
  - Predictions by M. Stephanov *et al* PRL81 (98) 4816; S. Mrowczynski, PLB314 (93) 118.
  - Large Transverse Momentum Fluctuations
    - Sensitive to 1st order phase transition (QGP Droplets)
    - Sensitive to 2nd order phase transition Near critical point.

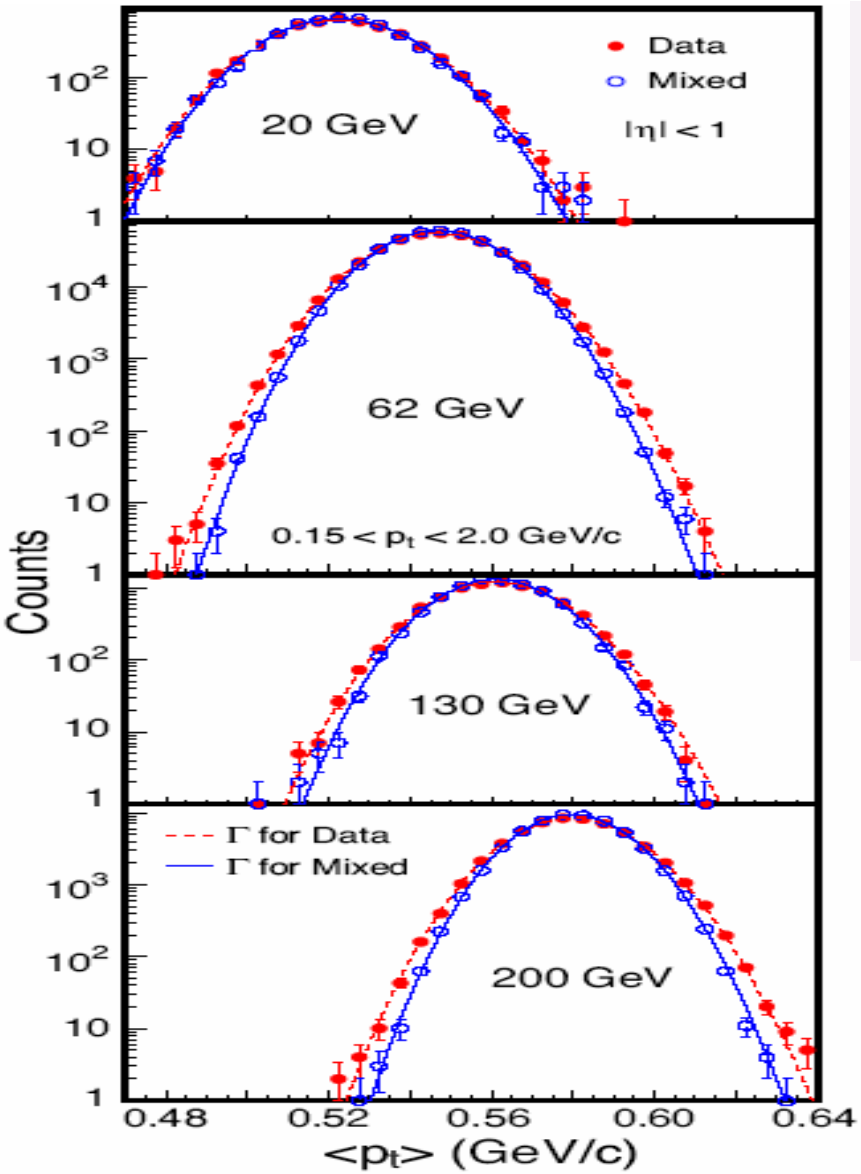
- Strangeness Fluctuations
  - Large strangeness fluctuations
    - QGP Droplets





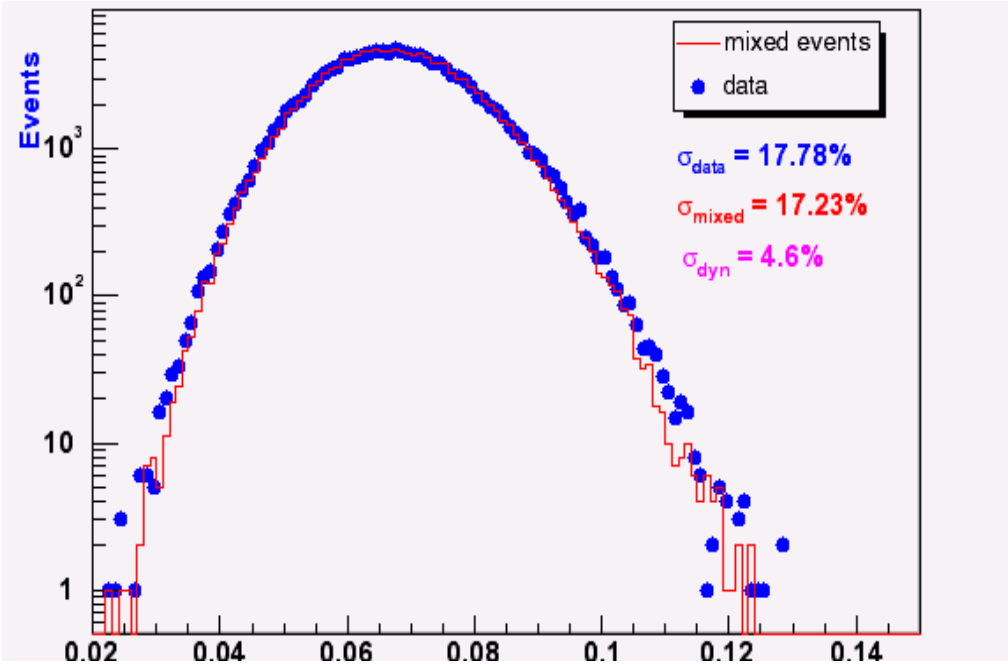
Event-by-event Fluctuations at STAR

G. Westfall *et al*



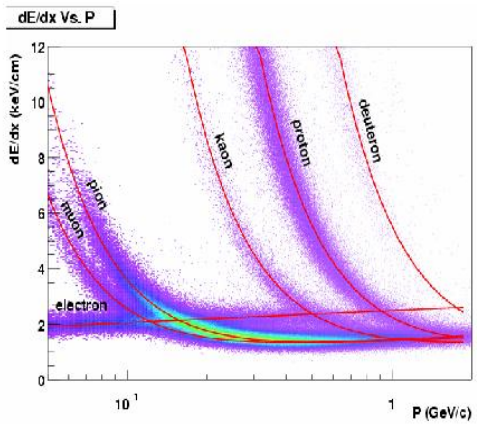
STAR Preliminary

Suprya Das, *et al.*



K/π

M. Anderson et al. NIMA499 (2003)



Anatomy of Fluctuations

2-particle distribution

1-particle distribution

Differential Observables

- **Two-Particle Correlation**: $C(\vec{p}_1, \vec{p}_2) = \rho_2(\vec{p}_1, \vec{p}_2) - \rho_1(\vec{p}_1)\rho_1(\vec{p}_2)$
- Probability to find a correlated pair: $R(\vec{p}_1, \vec{p}_2) = \dfrac{C(\vec{p}_1, \vec{p}_2)}{\rho_1(\vec{p}_1)\rho_1(\vec{p}_2)}$
- Distribution of associated particle per trigger $B(\vec{p}_1, \vec{p}_2) = \dfrac{C(\vec{p}_1, \vec{p}_2)}{\rho_1(\vec{p}_1)}$

Integral Observables

- **1-, 2-Particle Integrals** $\int d\vec{p}\,\rho_1(\vec{p}) = \langle n \rangle; \qquad \int d\vec{p}_1 \int d\vec{p}_2\, \rho_2(\vec{p}_1, \vec{p}_2) = \langle n(n-1) \rangle$
- Weighted Integrals: $\int w\rho_1(\vec{p})d\vec{p} = \langle w \rangle; \qquad \int\int w_1 w_2 \rho_2(\vec{p}_1, \vec{p}_2) d\vec{p}_1 d\vec{p}_2 = \langle w_1 w_2 \rangle$
- Variance: $Var(w) = \langle w^2 \rangle - \langle w \rangle^2$
- Covariance: $\langle \Delta w_1 \Delta w_2 \rangle = \langle w_1 w_2 \rangle - \langle w_1 \rangle \langle w_2 \rangle$
- Correlation Coefficient: $\tilde{R}_{1,2} = \dfrac{\int dy_1 \int dy_2 C(y_1, y_2)}{\int dy_1 \int dy_2 \rho_1(y_1)\rho_1(y_2)} = \dfrac{\langle n(n-1) \rangle - \langle n \rangle^2}{\langle n \rangle^2}$

Net Charge, and K/π Fluctuations

Instead of measuring the variance of a yield ratio,

$$r_{12} = \frac{n_1}{n_2} \quad \rightarrow \quad \frac{\langle (\Delta r_{12})^2 \rangle}{\langle r_{12} \rangle^2} \approx \frac{\langle (\Delta n_1)^2 \rangle}{\langle n_1 \rangle^2} + \frac{\langle (\Delta n_2)^2 \rangle}{\langle n_2 \rangle^2} - 2\frac{\langle \Delta n_1 \Delta n_2 \rangle}{\langle n_1 \rangle \langle n_2 \rangle}$$

Study the "dynamical fluctuations":

$$\boxed{\nu_{12,dyn} = \left\langle \left(\frac{n_1}{\langle n_1 \rangle} - \frac{n_2}{\langle n_2 \rangle} \right)^2 \right\rangle - \frac{1}{\langle n_1 \rangle} - \frac{1}{\langle n_2 \rangle} = \tilde{R}_{11} + \tilde{R}_{22} - 2\tilde{R}_{12}}$$

Side Note: $D \equiv \langle n_1 + n_2 \rangle \langle (\Delta r_{12})^2 \rangle$ $\qquad \frac{D}{4} \approx 1 + \frac{(\tilde{R}_{++} + \tilde{R}_{--} - 2\tilde{R}_{+-})\langle n_+ + n_- \rangle}{4}$

<p_t> Fluctuations

$$\boxed{\langle \Delta p_{t,1} \Delta p_{t,2} \rangle = \frac{1}{N_{event}} \sum_{k=1}^{N_{event}} \frac{C_k}{N_k (N_k - 1)}}$$

where

$$C_k = \sum_{i=1}^{N_k} \sum_{j=1, i \neq j}^{N_k} \left(p_{t,i} - \langle \langle p_t \rangle \rangle \right) \left(p_{t,j} - \langle \langle p_t \rangle \rangle \right)$$

$$\langle \langle p_t \rangle \rangle = \left(\sum_{k=1}^{N_{event}} \langle p_t \rangle_k \right) / N_{event}$$

$$\langle p_t \rangle_k = \left(\sum_{i=1}^{N_k} p_{t,i} \right) / N_k$$

Useful Properties

- Independent Particle Production (Poisson):

$$C(\vec{p}_1, \vec{p}_2) = \rho_2(\vec{p}_1, \vec{p}_2) - \rho_1(\vec{p}_1)\rho_1(\vec{p}_2) = 0$$

$$\Rightarrow \qquad R = 0$$

$$\nu_{12,dyn} = 0$$

$$\left\langle \Delta p_{t,1} \Delta p_{t,2} \right\rangle = 0$$

- Superposition of M "N+N" collisions without re-scattering of secondaries:

$$\rho_1^{\{N_c\}}(y) = M\rho_1^{\{1\}}(y)$$

$$\rho_2^{\{N_c\}}(y_1, y_2) = M\rho_2^{\{1\}}(y_1, y_2) + M(M-1)\rho_1^{\{1\}}(y_1)\rho_1^{\{1\}}(y_2)$$

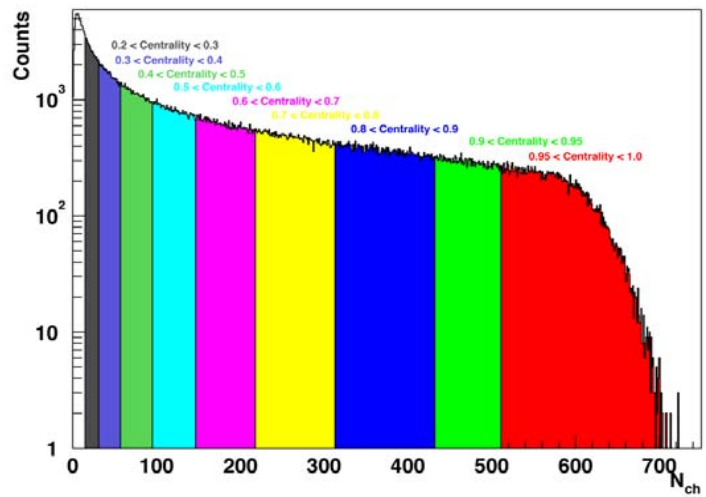
$$R^{\{N_c\}} = \frac{M\rho_2^{\{1\}}(y_1, y_2) + M(N_c - 1)\rho_1^{\{1\}}(y_1)\rho_1^{\{1\}}(y_2) - M^2\rho_1^{\{1\}}(y_1)\rho_1^{\{1\}}(y_2)}{M^2\rho_1^{\{1\}}(y_1)\rho_1^{\{1\}}(y_2)} = \frac{R^{\{1\}}}{M}$$

$$\boxed{\nu_{+-,dyn}^{\{M\}} = \frac{\nu_{+-,dyn}^{\{1\}}}{M} \qquad \left\langle \Delta p_{t,1} \Delta p_{t,2} \right\rangle^{\{M\}} = \frac{\left\langle \Delta p_{t,1} \Delta p_{t,2} \right\rangle^{\{1\}}}{M}}$$

- Robustness
  - Independent of detection efficiency

Data Sets - STAR

- Au + Au
  - $s_{NN}^{1/2}$ = 20, 62, 130, 200 GeV
  - Collision Centrality Determination based on all charged particle multiplicity $|\eta|<0.5$.
    - Centrality slices 0-5%, 5-10%, 10-20 %, …
    - Use Glauber model/MC to estimate the corresponding number of participants.

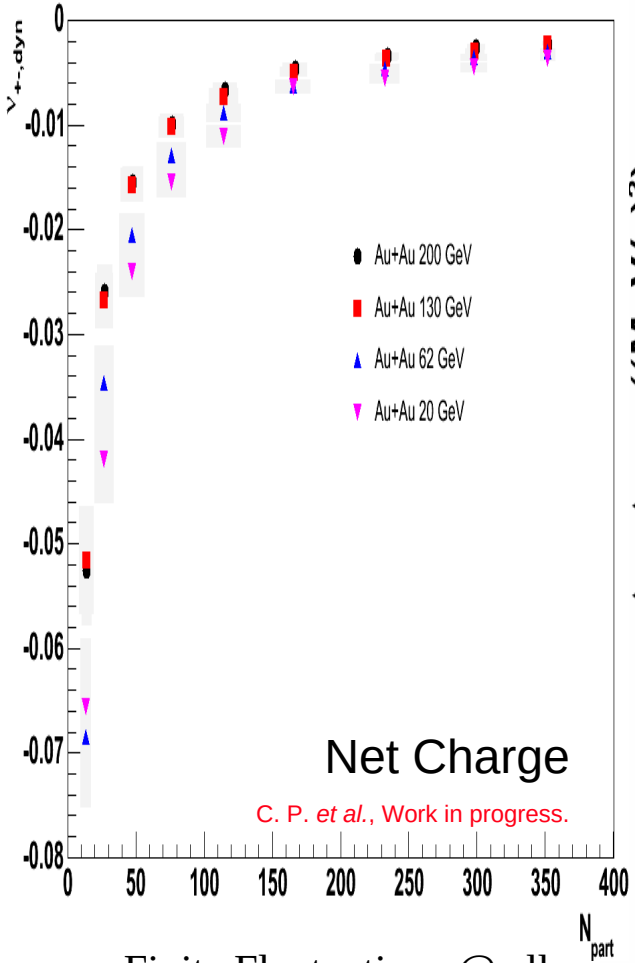


  - Events analyzed for $|z_{vertex}|<MAX$.
  - DCA < DCA_{MAX} cm.
  - Track quality $N_{hit}>15$; $N_{fit}/N_{hit}>0.5$.
  - Fluctuations studied in finite rapidity, p_t, and azimuthal ranges.

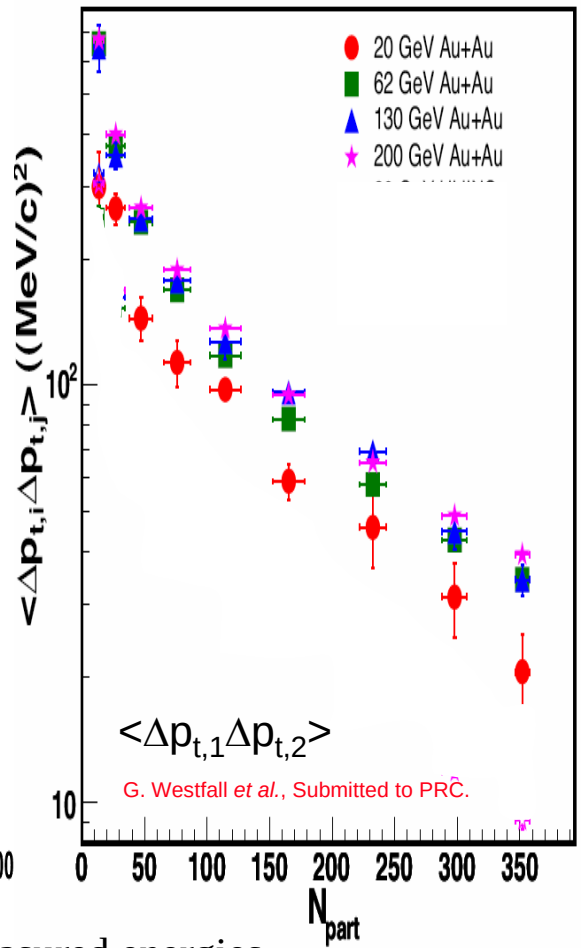
Dynamical Fluctuations in Au + Au Collisions

STAR Preliminary

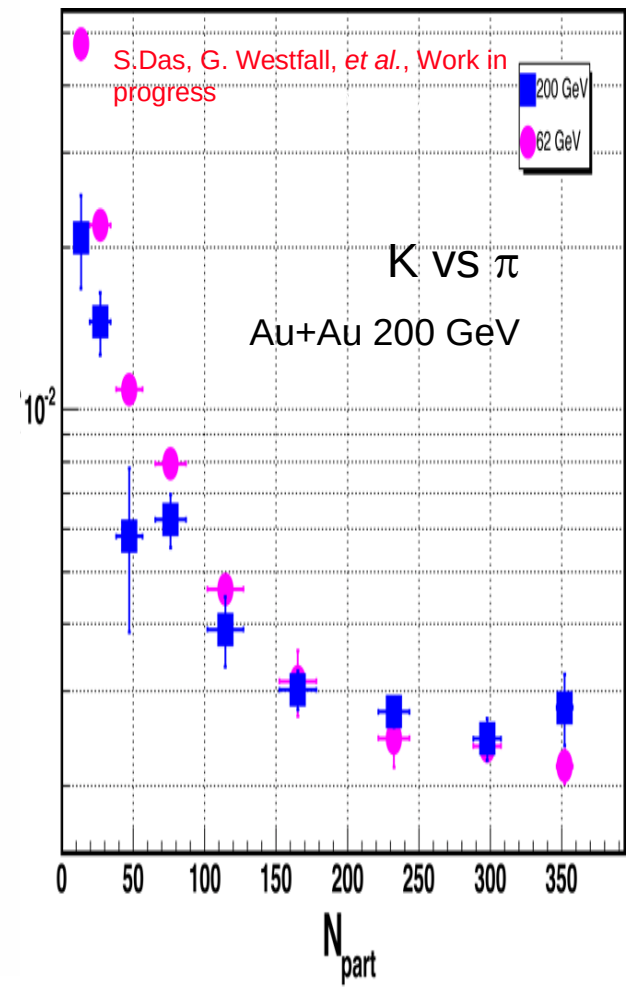
|η|<0.5; 0.2 < p_t < 5.0 GeV/c



|η| < 1.0; 0.15< p_t< 2.0 GeV/c

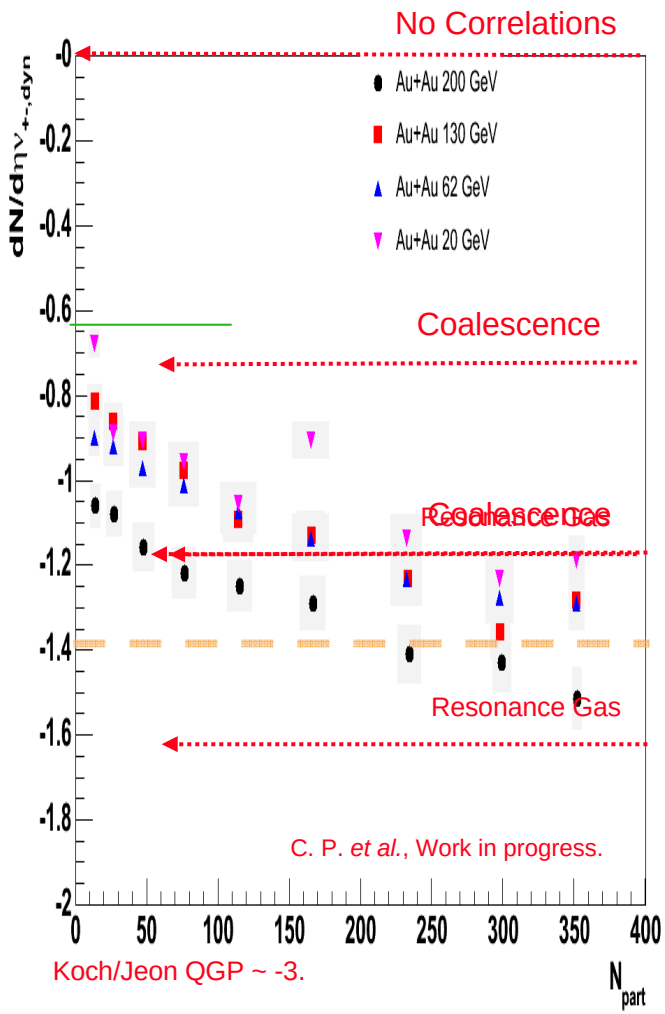


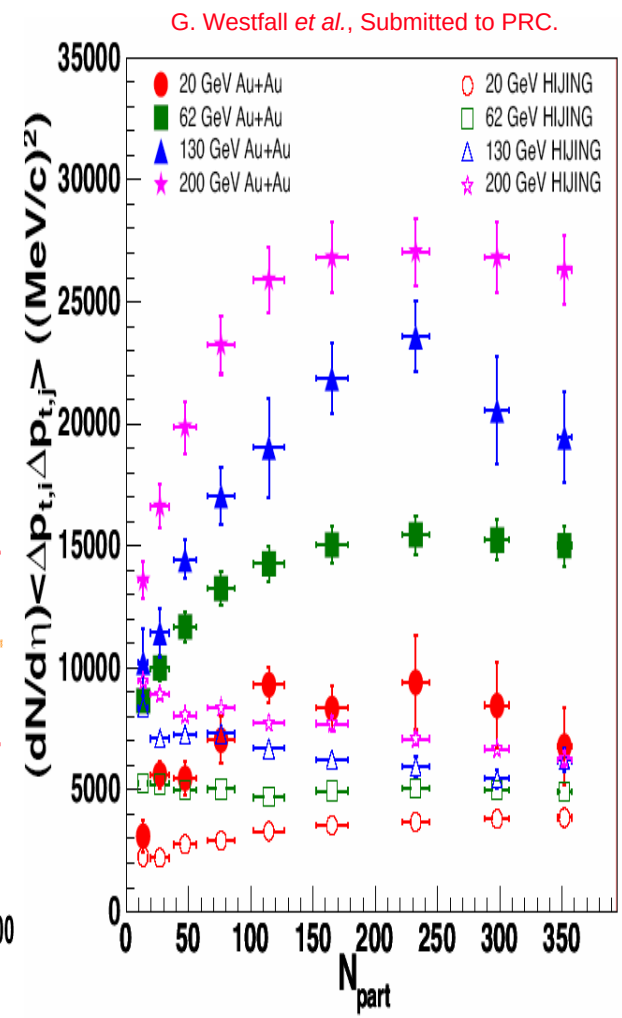
|η|<0.5;

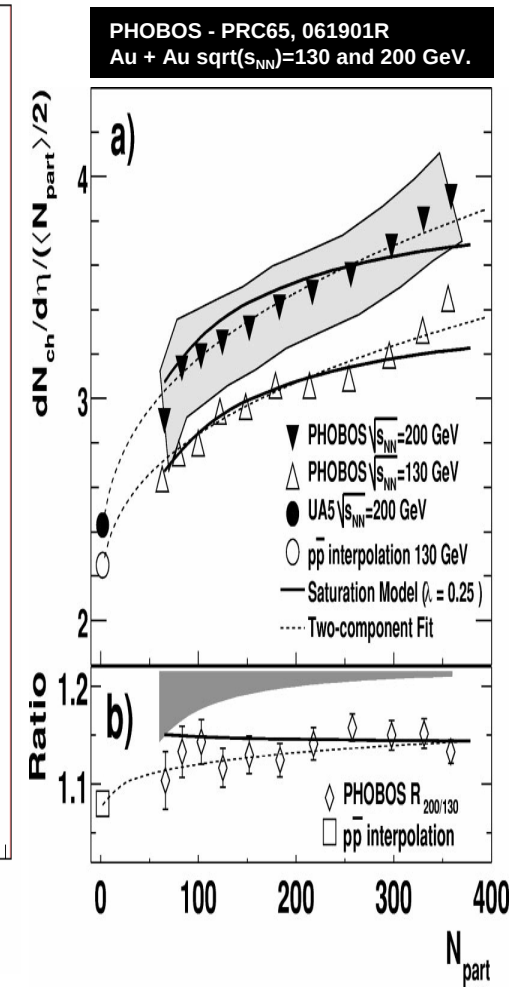


- Finite Fluctuations @ all measured energies.
- Increased dilution with increasing N_{part}
- Energy dependence ?

QGP Signature? 1/N Scaling?



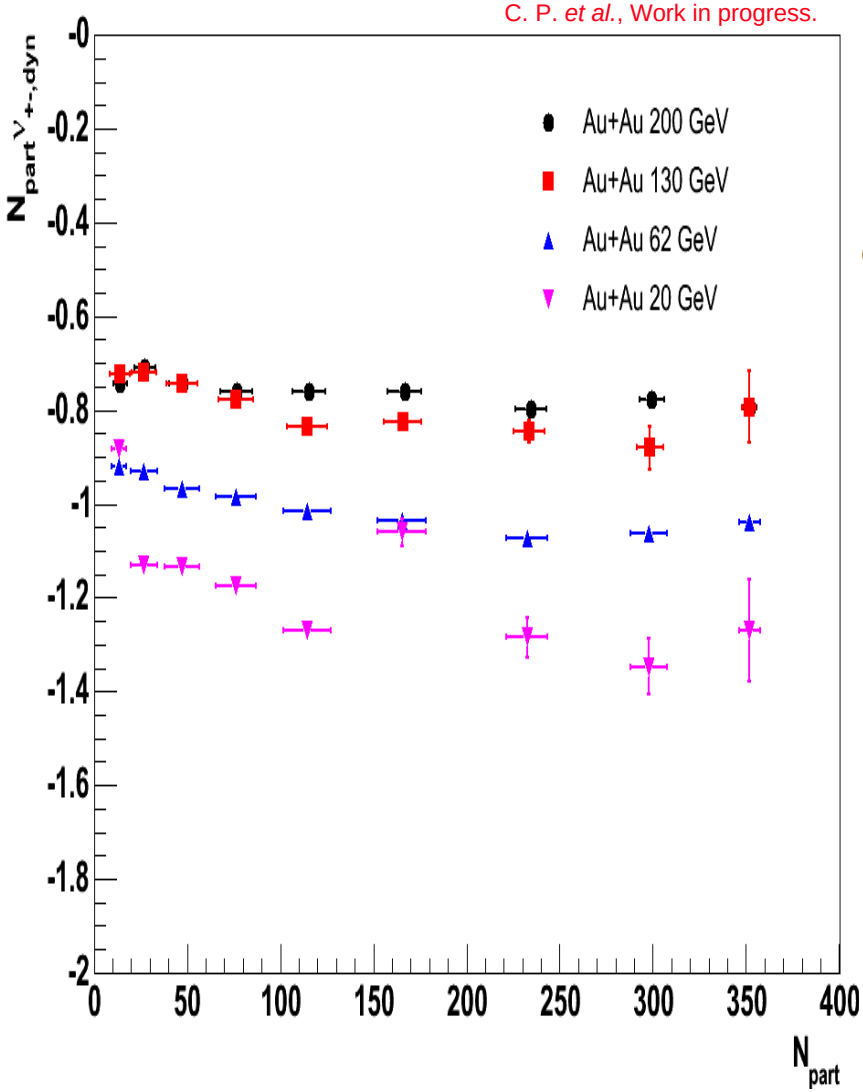




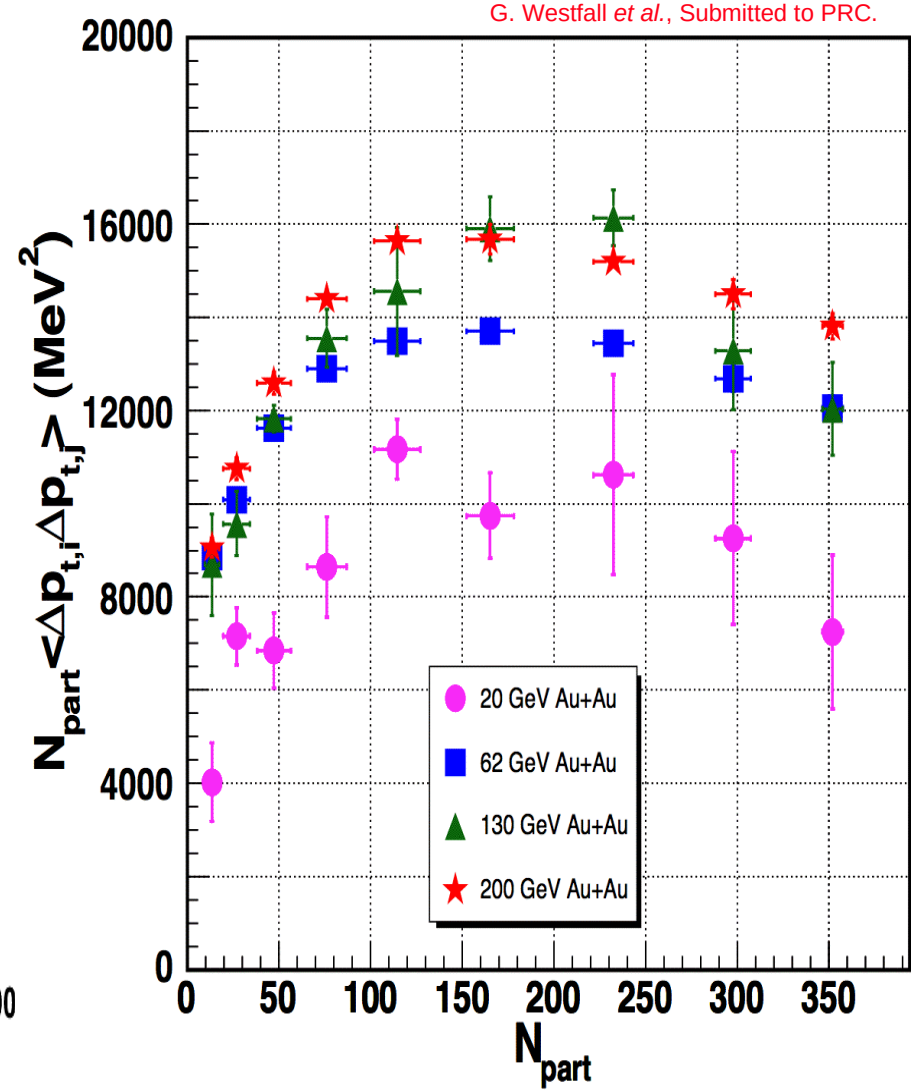
- Finite Centrality Dependence
- Magnitude of net charge "compatible" with resonance and coalescence models.
- Disagreement with HIJING "predictions".
- Note $dN/d\eta/(N_{part}/2)$ changes with N_{part}.

$1/N_{part}$ Scaling?

C. P. *et al.*, Work in progress.



G. Westfall *et al.*, Submitted to PRC.



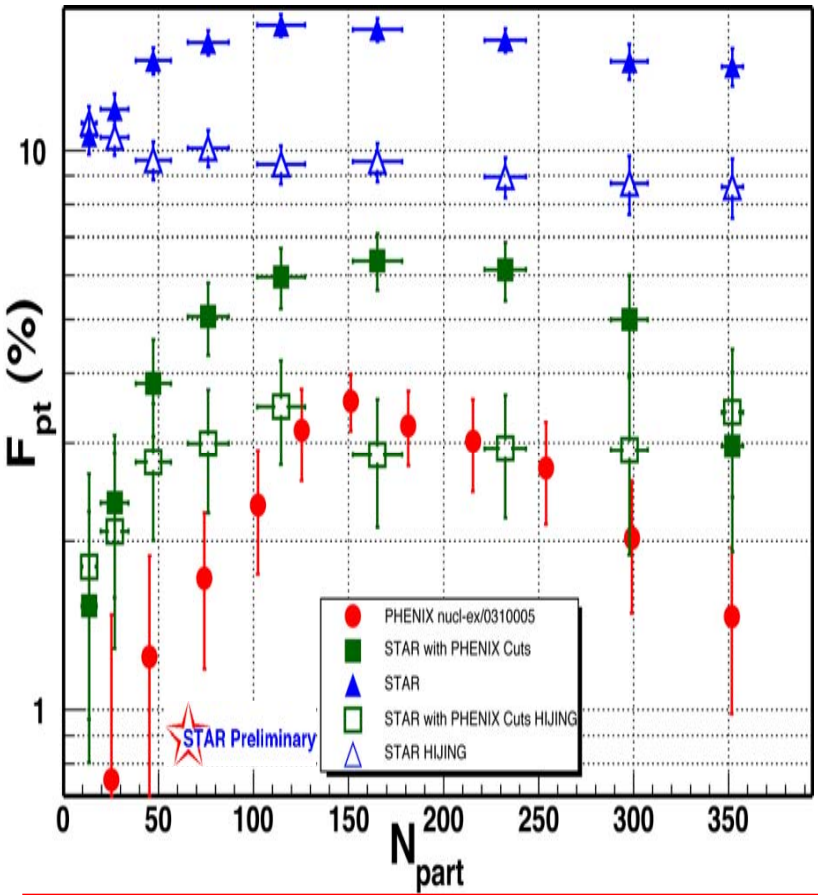
Comparison to PHENIX, F_{pt}

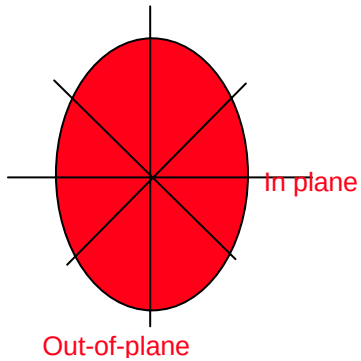
PHENIX 130 GeV Au+Au; STAR 200 GeV Au+Au

$$\omega_T = \frac{\sigma_T}{\mu_T}$$

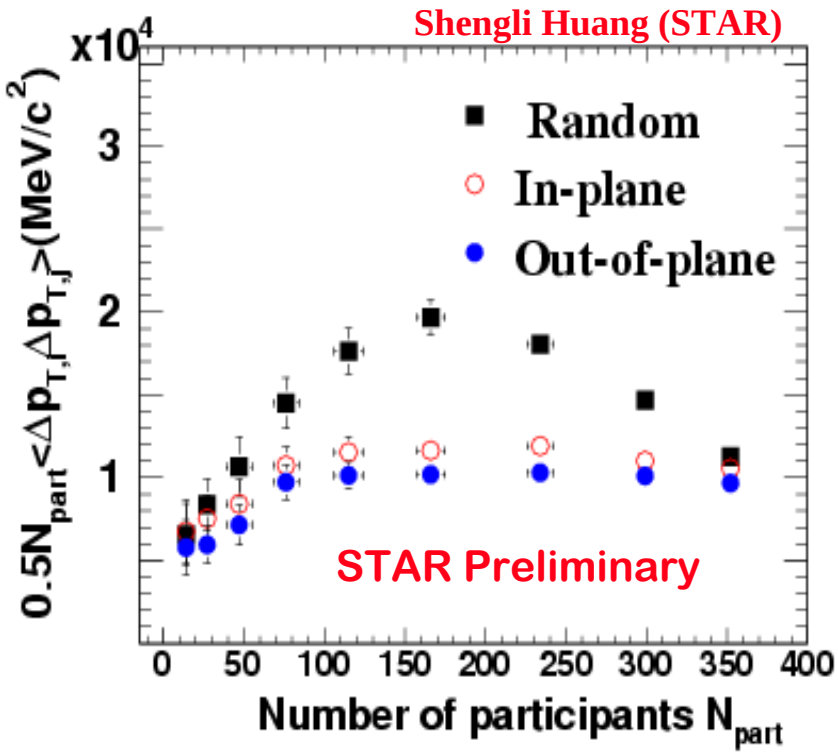
$$F_{pt} = \frac{\omega_{T,real} - \omega_{T,mixed}}{\omega_{T,mixed}} = \frac{\sigma_{T,real} - \sigma_{T,mixed}}{\sigma_{T,mixed}}$$

G. Westfall (STAR), QM'04





Shengli Huang (STAR)



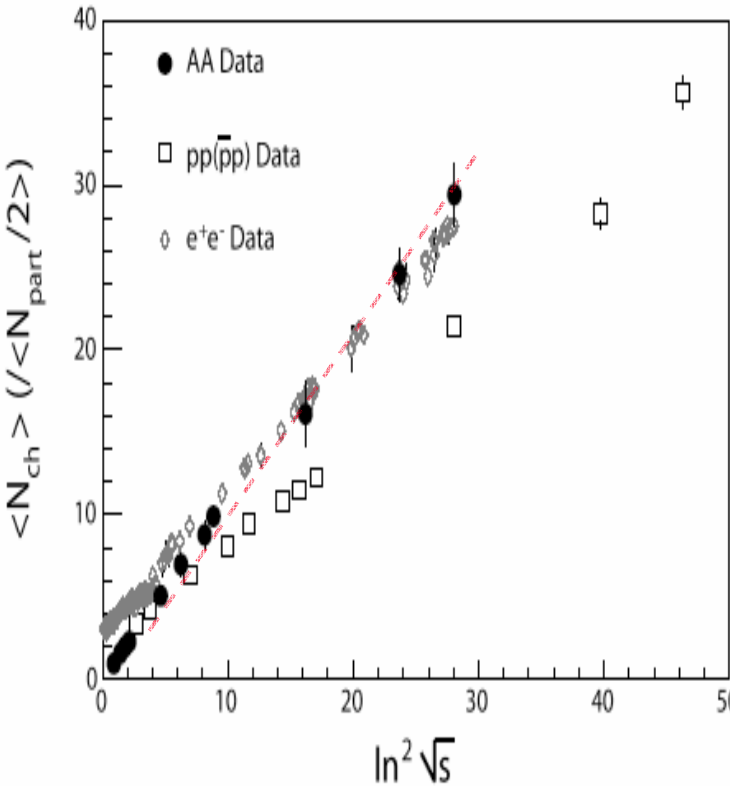
STAR Cut : $|\eta| < 1.0$; $\Delta\phi = 360°$; $0.1 < p_t < 2$ GeV

STAR with
PHENIX Cuts: *$|\eta| < 0.35$; $\Delta\phi = 2x90°$; $0.2 < p_t < 2$ GeV*

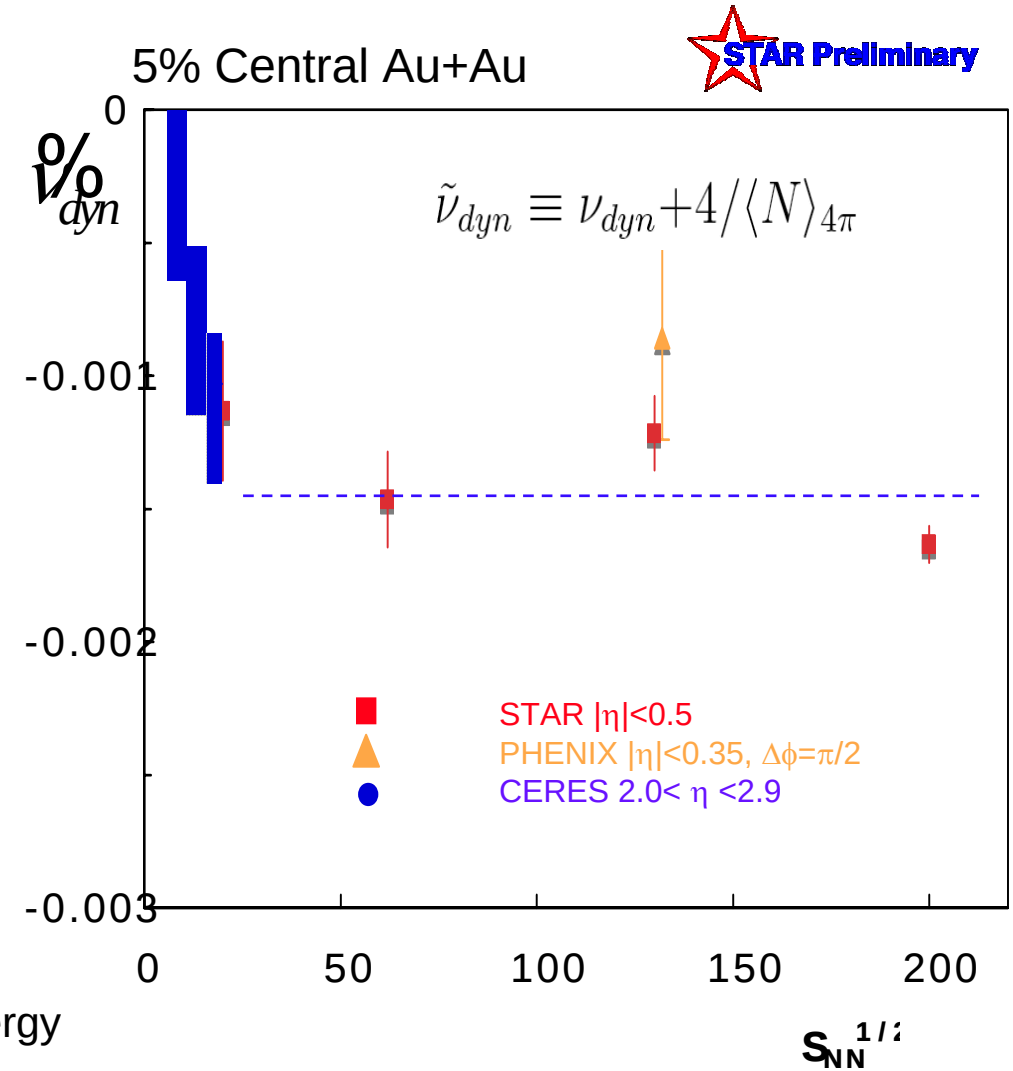
Net Charge Fluctuations - Beam Energy Dependence

Need to correct for charge conservation effects!

W. Busza, et al., Phobos, nucl-ex 0410035



5% Central Au+Au

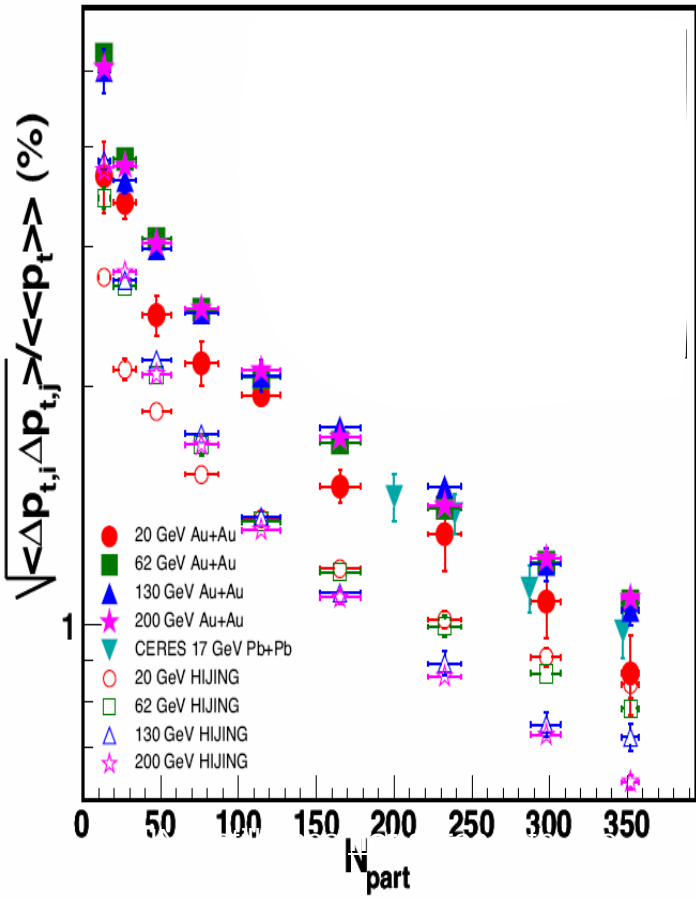


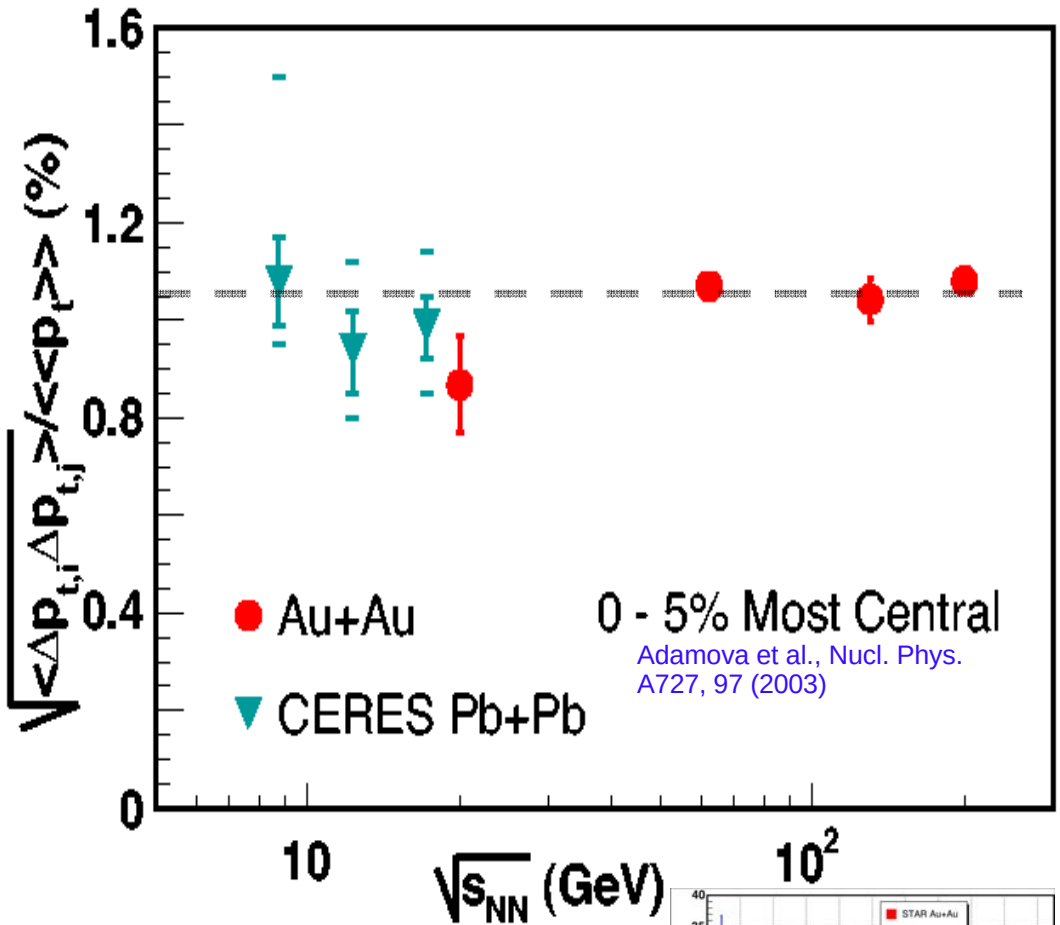
$N_{ch,tot}$(200,5%) ~ 5092
$N_{ch,tot}$(130,5%) ~ 3900
$N_{ch,tot}/N_{part}$~"constant" at a given energy

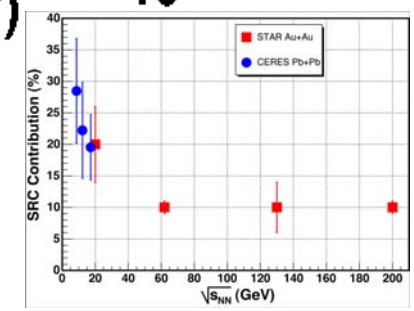
Possible "Threshold" Effect at lowest SPS/CERES energy.

p_t Fluctuations - Beam Energy Dependence

G. Westfall *et al.*, Submitted to PRC.

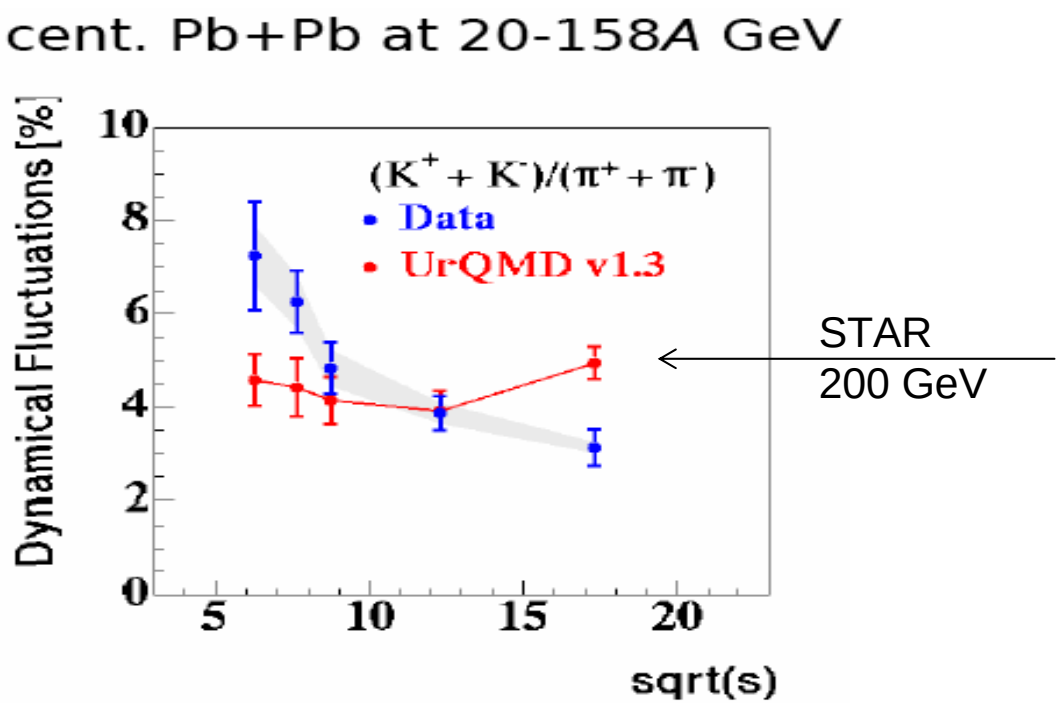






$<\Delta p_t,\Delta p_t>^{1/2}$ scaled by $<p_t>$ exhibits small or no beam energy dependence.

K/π Fluctuations Beam Energy Dependence



STAR Preliminary

Experiment	Ratio type	σ_{data}	σ_{mixed}	σ_{dyn}
STAR	K/π	17.78%	17.23%	4.6%±0.025
STAR	K^+/π^+	24.29%	24.10%	3.06%±0.066
STAR	K^-/π^-	24.81%	24.55%	3.61%±0.055

Supriya Das et al, work in progress

What Can We Learn About Reaction Dynamics ?

- Thermalization
- Role of resonance production
- Collective Flow
- Jets
- etc

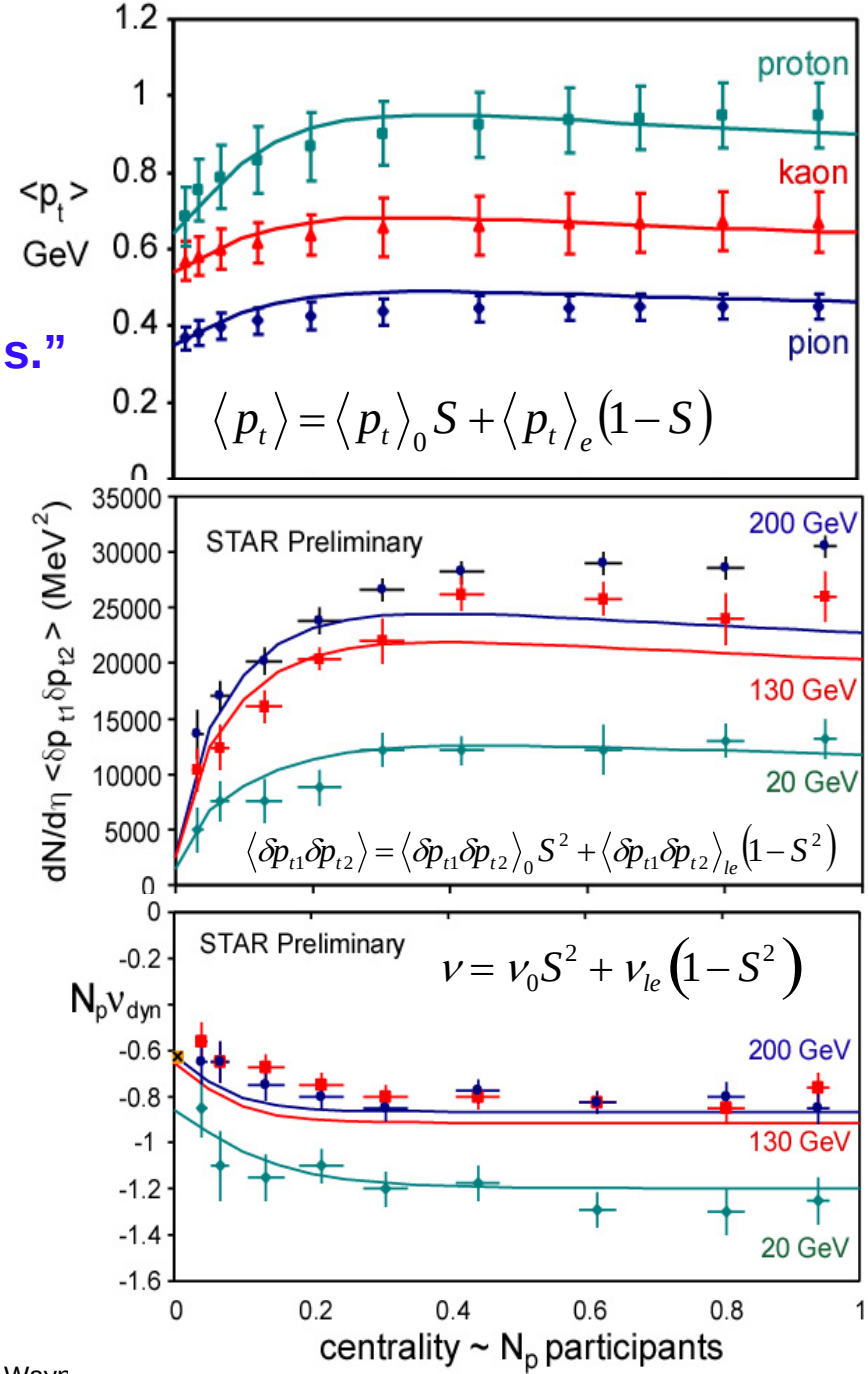
Thermalization

S. Gavin, Nucl. Dyn 2004.

"Partial thermalization describes trends."

- Solves Boltzmann equation
- Parameterize particle correlations
  - Spatial
  - Rapidity
  - Momentum

$$\langle \delta p_{t1} \delta p_{t2} \rangle_e \approx \frac{\langle p_t \rangle^2 R_{AA}}{1 + R_{AA}} F(\xi / R_t)$$

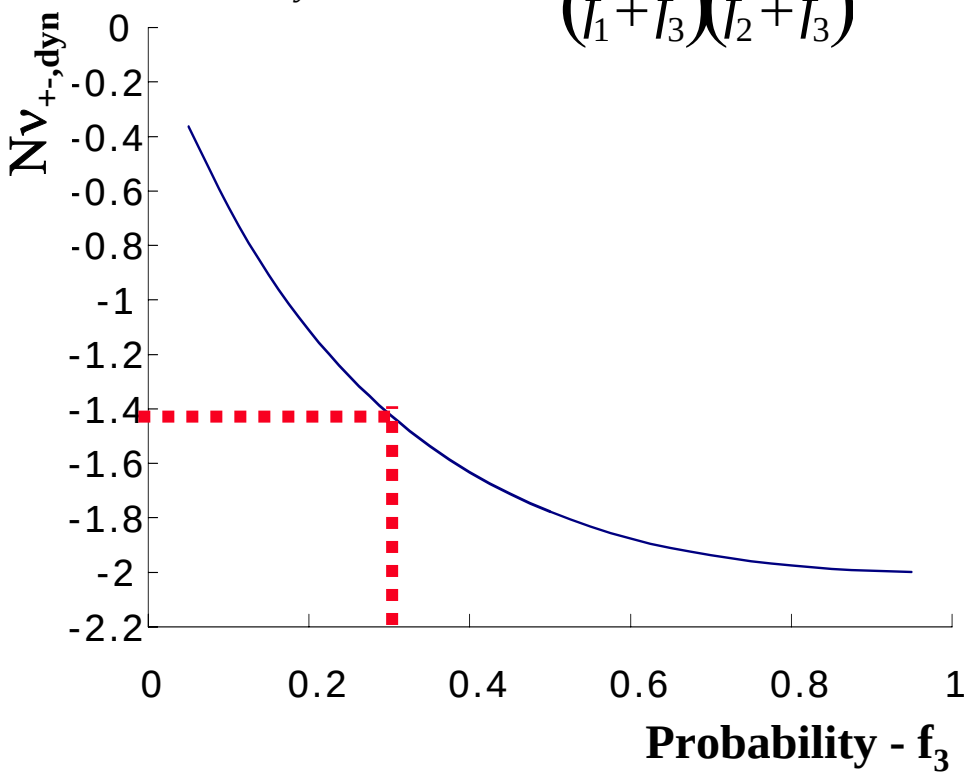


Resonance Contributions - An Example

$$P(n_1,n_2,n_3) = \frac{N!}{n_1!n_2!n_3!} f_1^{n_1} f_2^{n_2} f_3^{n_3}$$

$$G(t_+,t_-;N) = (f_1 e^{t_+} + f_2 e^{t_-} + f_3 e^{t_+ + t_-})^N$$

$$N\nu_{+-,dyn}(\pi^+,\pi^-,\rho^0) = \frac{-2f_3}{(f_1+f_3)(f_2+f_3)}$$

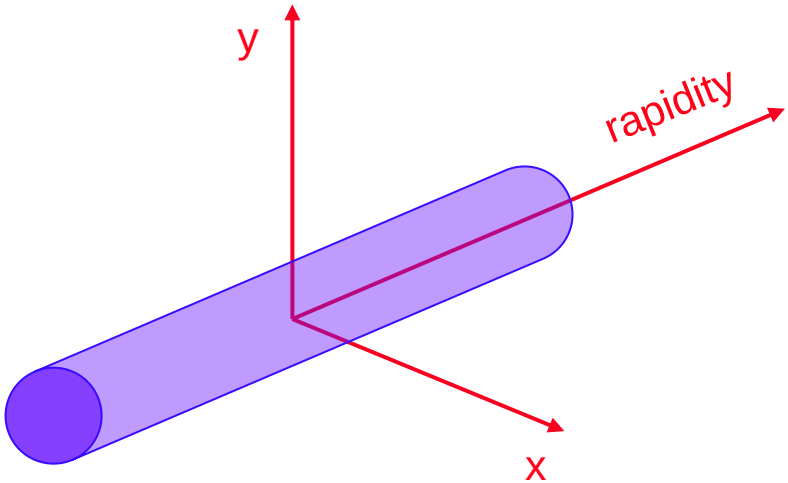


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

STAR, PRL92 (2004) 092301

$\rho/\pi \sim 0.17$
k^o_s/π ~ 0.12
~ 0.08 effective
with DCA < 3cm.
Resonances $/\pi \geq 0.3$

Particle Correlations in "Elementary" NN-collision.



Produced particles are correlated due to:

- **Local charge(s) conservation,**
- **Resonances,**
- **Fluctuations in number of produced "strings", e.g. number of qq-collisions.**

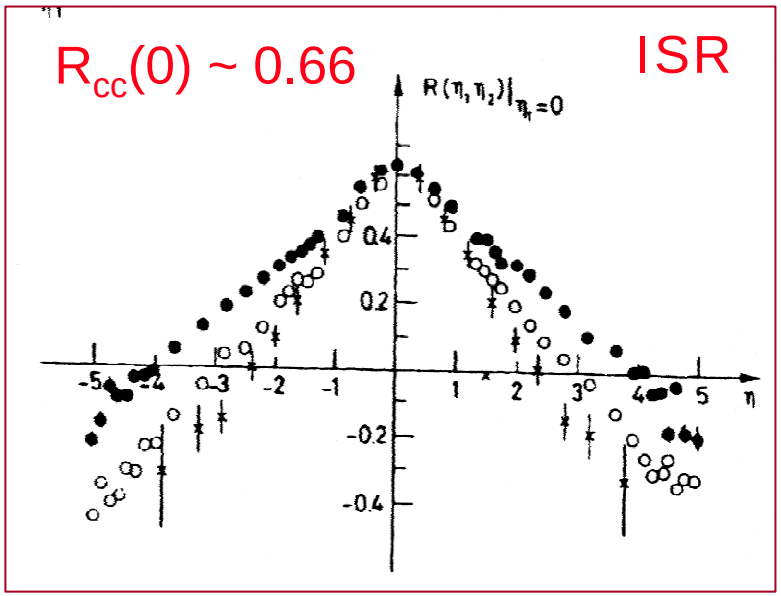
$$R(y_1, y_2) = \frac{C(y_1, y_2)}{\rho_1(y_1)\rho_1(y_2)}$$

$$C(y_1,y_2) = \rho_2(y_1,y_2) - \rho_1(y_1)\rho_1(y_2)$$

$$B(y_1, y_2) = \frac{C(y_1, y_2)}{\rho_1(y_1)}$$

$$\int dy\, \rho_1(y) = \langle n \rangle$$

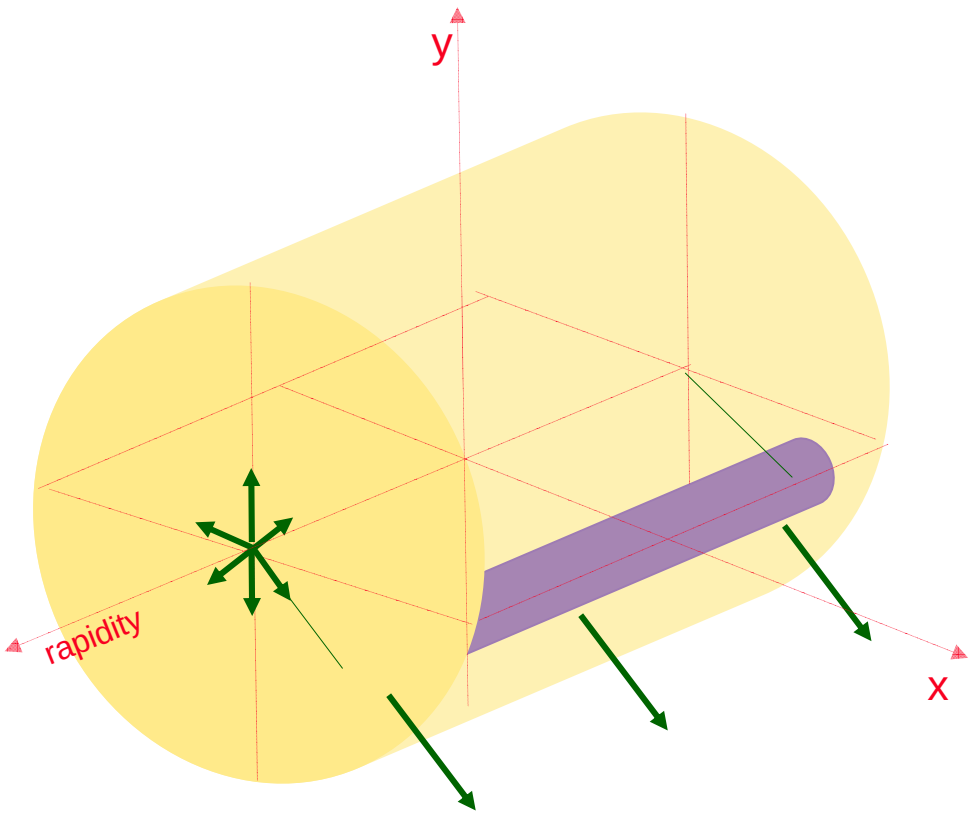
$$\int dy_1 \int dy_2 \rho_2(y_1, y_2) = \langle n(n-1) \rangle$$



The probability to find a particle at mid-rapidity is about 60% larger if a particle has been already detected.

$$\langle n(n-1) \rangle \approx 1.6 \langle n \rangle^2$$

Particle Correlations in A+A ⊕ Radial flow



Hypothesis:

All particles produced in the same NN-collision or "qq-string" subject to

- Same transverse/radial "push".
  - Same radial direction + magnitude

Consequences:

- Induced correlations in phi
- Induced position-momentum correlation in AA
- not present in N+N
- Induced p_t correlations.

Specifics

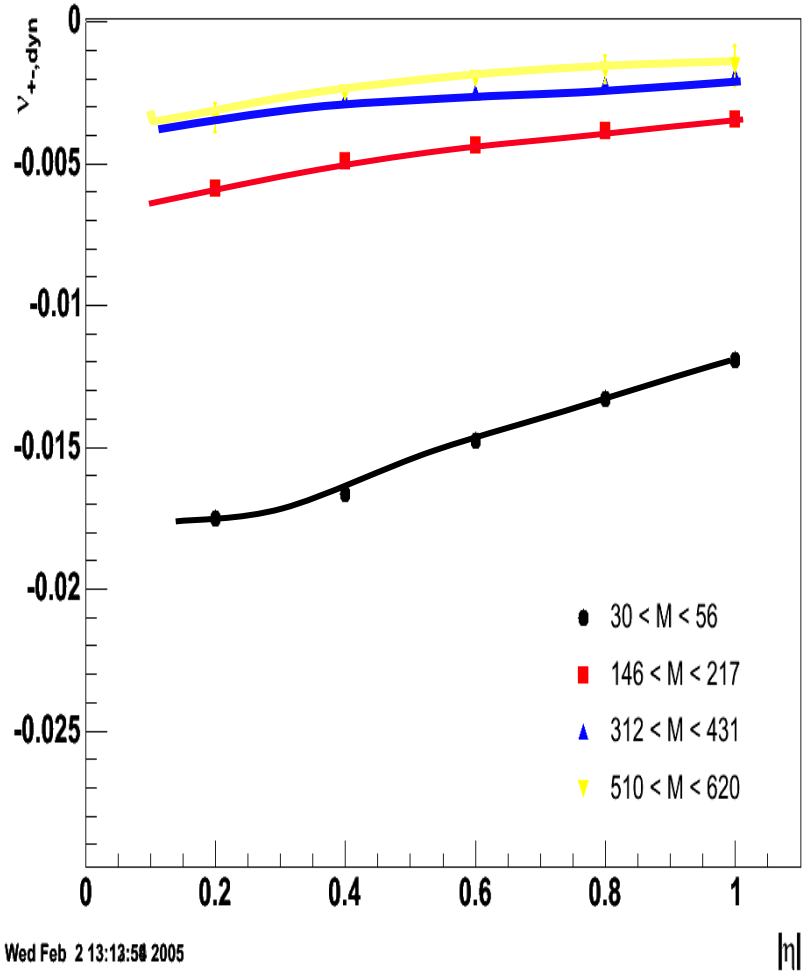
- Long range rapidity correlations
  - Narrow in ϕ and wide in η, charge independent
- Stronger 2-particle p_t correlation in narrow ϕ bins
- Narrowing of the charge balance function
  - Increase in mt & decrease in rapidity separation

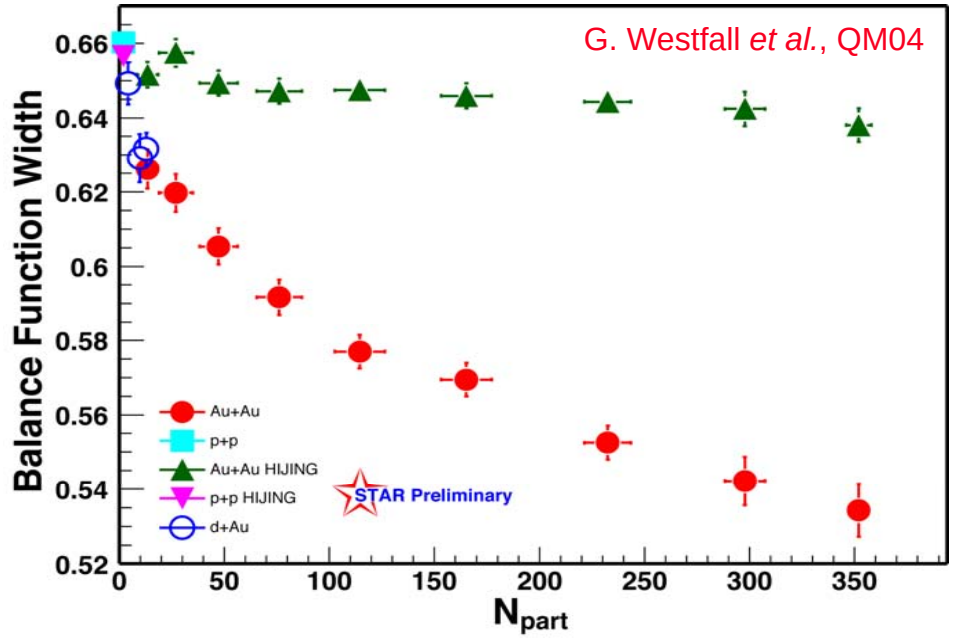
$$\Delta p_z \approx m_t \sinh(\Delta y)$$

  - Similar to S. Pratt et al, "late hadronization scenario"
- Increase in Charge correlations in ϕ.
  - Azimuthal Balance function
- Correlation observables all evolving with centrality (radial flow)

Longitudinal Correlations

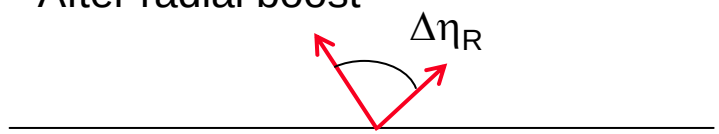
Au + Au @ 200 GeV





Before radial boost

After radial boost



$$\Delta\eta_R < \Delta\eta$$

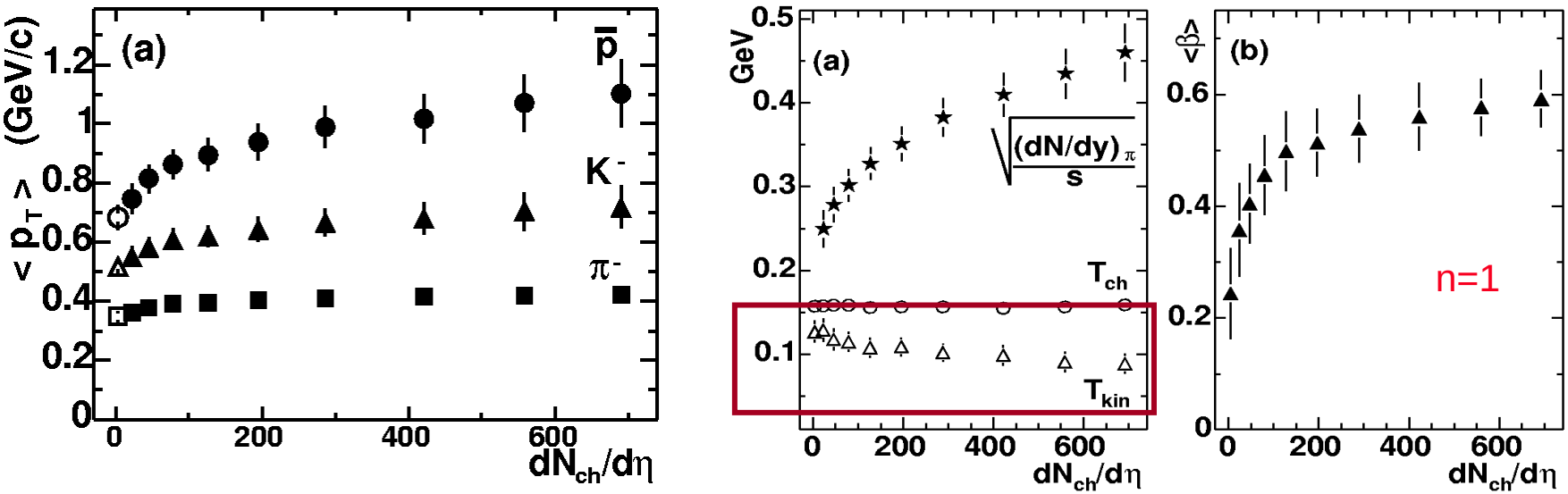
RADIAL FLOW

DELAYED HADRONIZATION ???

S. Voloshin, nucl-th/0312065

Model of Transverse radial expansion

STAR, PRL 92, 112301 (2004)



Blast wave parameterization of the source at freeze-out: $d^3n/d^3p \sim e^{-E/T}$

Schnedermann, Sollfrank, Heinz, PRC 48, 2462 (1993)

$$\frac{Ed^3n}{d^3p} \propto \int_0^R r dr \int dy_s\, d\varphi_s\, m_t \cosh(y-y_s)\exp[-\frac{m_t\cosh(y-y_s)\cosh(\rho_t)-p_t\sinh(\rho_t)\cos(\varphi-\varphi_s)}{T}]$$

$$\frac{d^3n}{dy\,d^2p_t} \propto \int_0^R r dr\, m_t K_1(\beta_t) I_0(\alpha_t); \quad \beta_t \equiv \frac{m_t}{T}\cosh(\rho_t); \quad \alpha_t \equiv \frac{p_t}{T}\sinh(\rho_t)$$

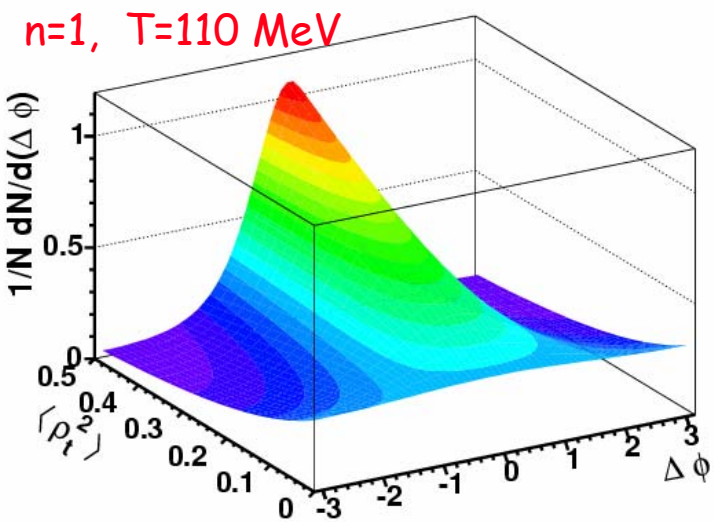
$$\langle \delta p_{t,1}\delta p_{t,2}\rangle = \frac{\int d\rho_t d\phi_b\, \rho_t^{2/n-1} \int d\mathrm{p}_{t,1} \int d\mathrm{p}_{t,2}(\delta p_{t,1}\delta p_{t,2}) m_{t,i} K_1(\beta_{t,1}) e^{\alpha_{t,1}\cos(\phi_b-\phi_1)} m_{t,2} K_1(\beta_{t,2}) e^{\alpha_{t,2}\cos(\phi_b-\phi_2)}}{\int d\rho_t d\phi_b\, \rho_t^{2/n-1} \int d\mathrm{p}_{t,1} \int d\mathrm{p}_{t,2} m_{t,1} K_1(\beta_{t,1}) e^{\alpha_{t,1}\cos(\phi_b-\phi_1)} m_{t,2} K_1(\beta_{t,2}) e^{\alpha_{t,2}\cos(\phi_b-\phi_2)}}$$

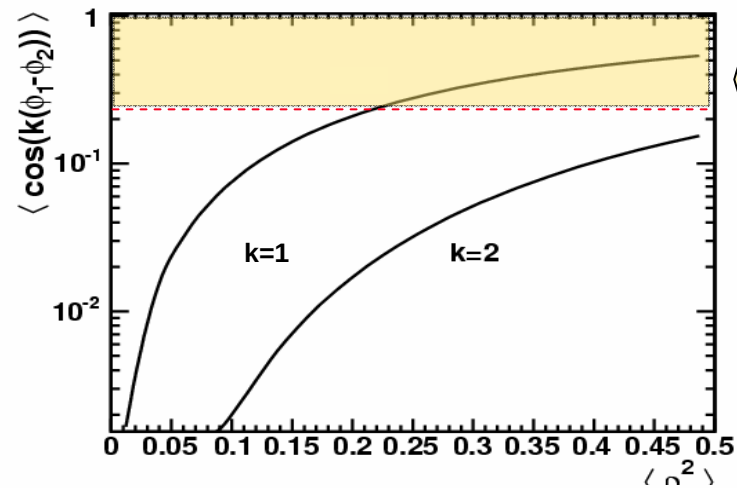
Hypotheses:
Uniform source density for r<R.
Unique Temperature, T,
Velocity profile: $v_t \quad r^n$

S. Voloshin, nucl-th/0312065

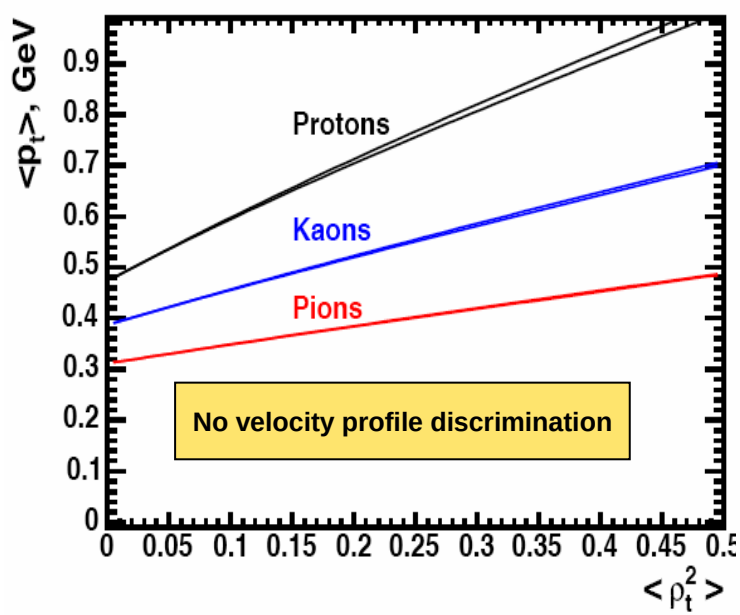
Correlations Induced by Radial Flow

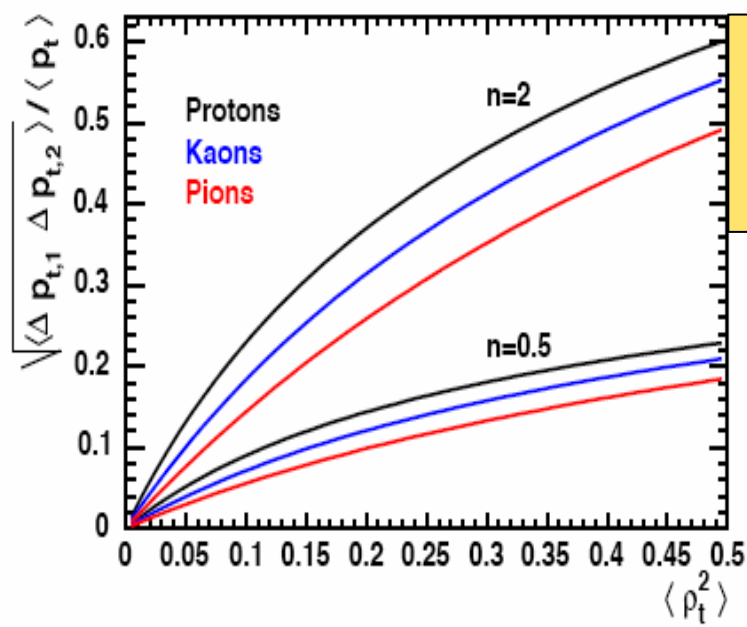
No dilution factor and No momentum conservation effects included





Excluded based on estimates non flow contributions to v_2



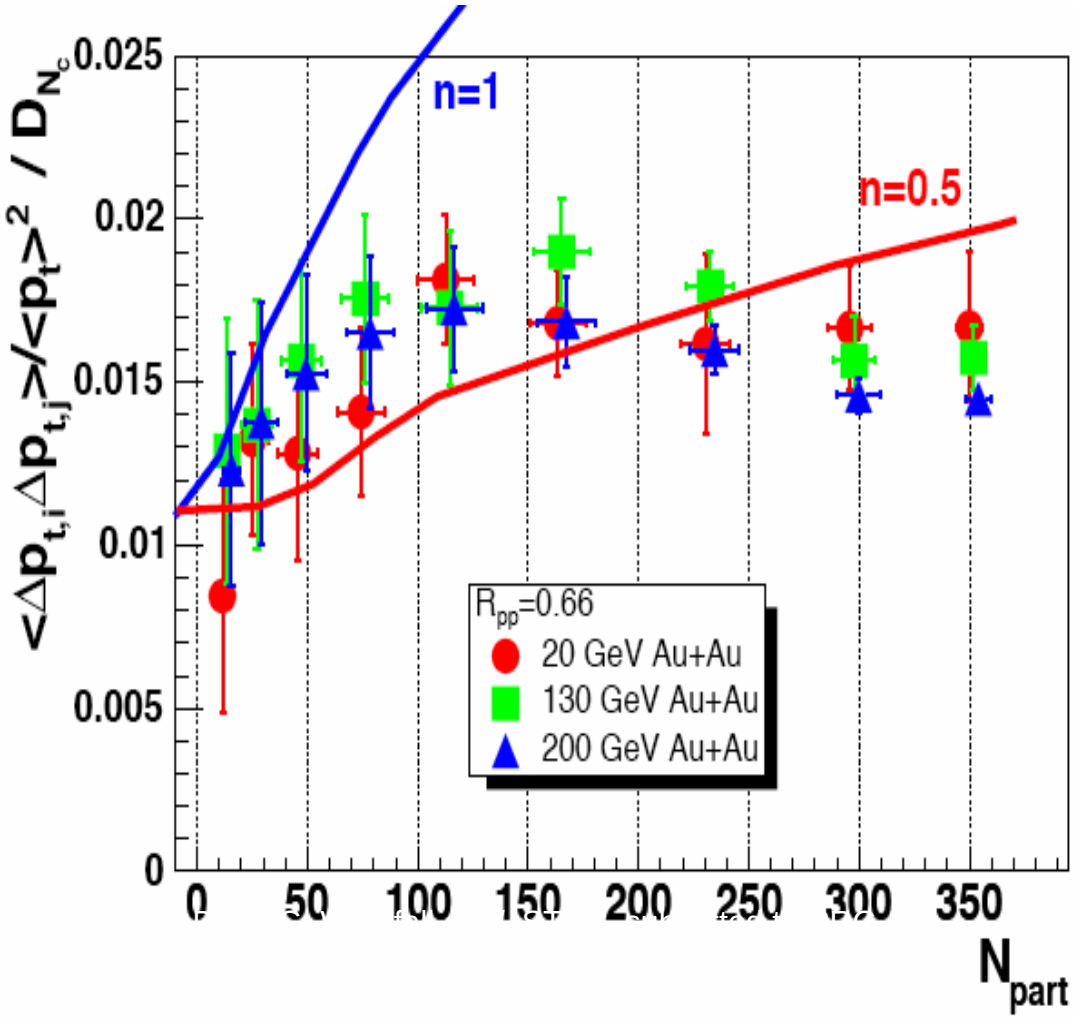


Good velocity profile discrimination

$v_t \quad r^n$

Transverse Momentum Correlations

Scale $<\Delta p_{t,1}\Delta p_{t,2}>$, divide by $<<p_t>>^2$ and number of participants.
Compare to Blastwave calculation by S. Voloshin



Caveats:

- **Neglecting Diffusion,**
- **Finite Thermalization Time**
- **Used "simple" Spatial Source Profile**
- **Simple N_{coll} Scaling**

$$\left\langle \delta p_{t,1}\delta p_{t,2}\right\rangle_{AA} = D_{N_{coll}}\left\langle \delta p_{t,1}\delta p_{t,2}\right\rangle_{NN}$$

$$D_{N_{coll}} = \frac{\left\langle n(n-1)\right\rangle_{NN}}{(N_{coll}-1)\left\langle n\right\rangle_{NN}^2 + \left\langle n(n-1)\right\rangle_{NN}}$$

v_n t r

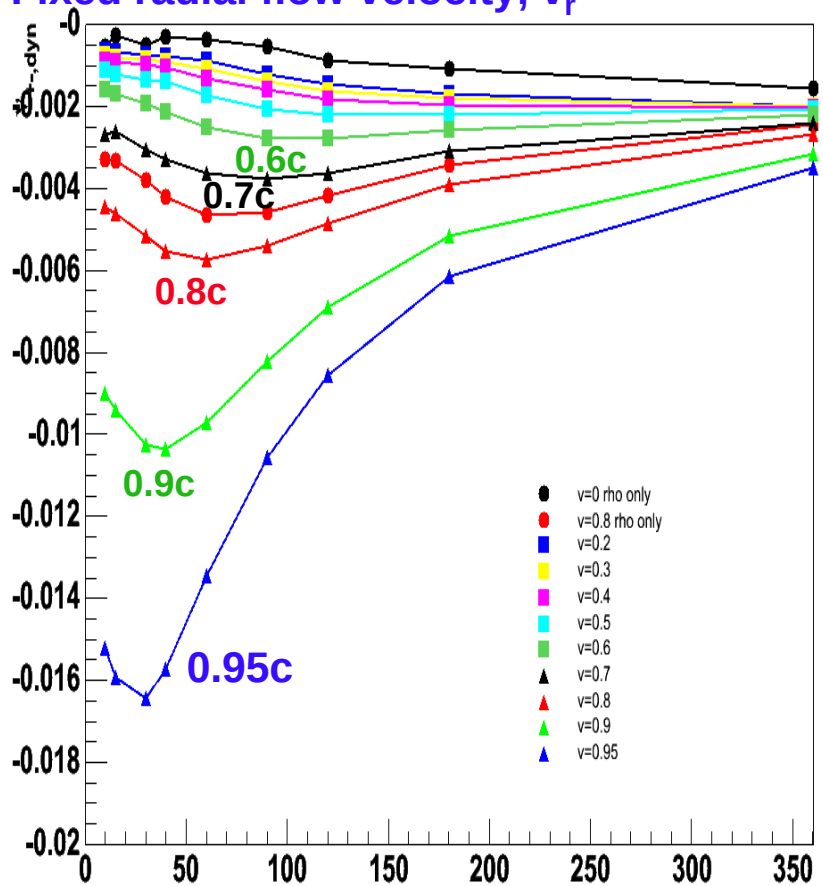
Effect of radial flow on Net Charge Azimuthal Correlations Monte Carlo Toy Model

Multinomial production of π^+, π^-, ρ^0, K^0.

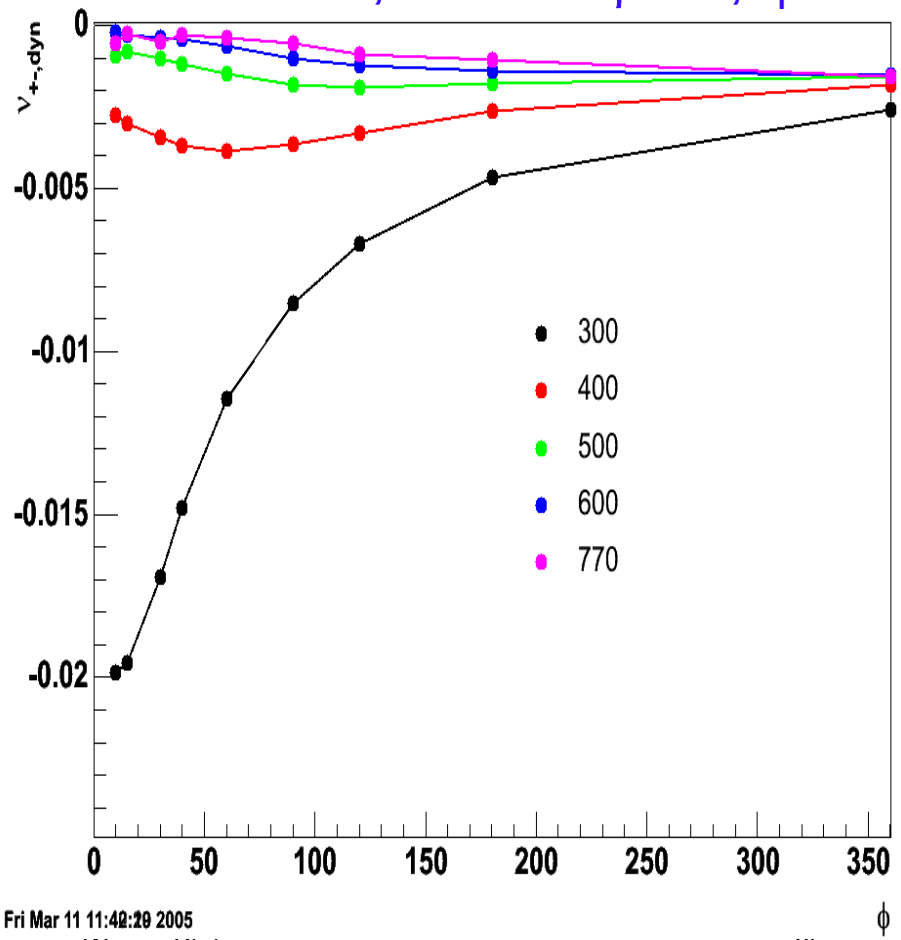
$$P(n_{\pi^+}, n_{\pi^-}, n_\rho, n_{K_s^o}; N) = \frac{N!}{n_{\pi^+}!\, n_{\pi^-}!\, n_\rho!\, n_{K_s^o}!} f_1^{n_{\pi^+}} f_2^{n_{\pi^-}} f_3^{n_\rho} f_4^{n_{K_s^o}}$$

Isotropic source; Maxwell Boltzman Dist.; T = 0.18 GeV;

Fixed radial flow velocity, v_r

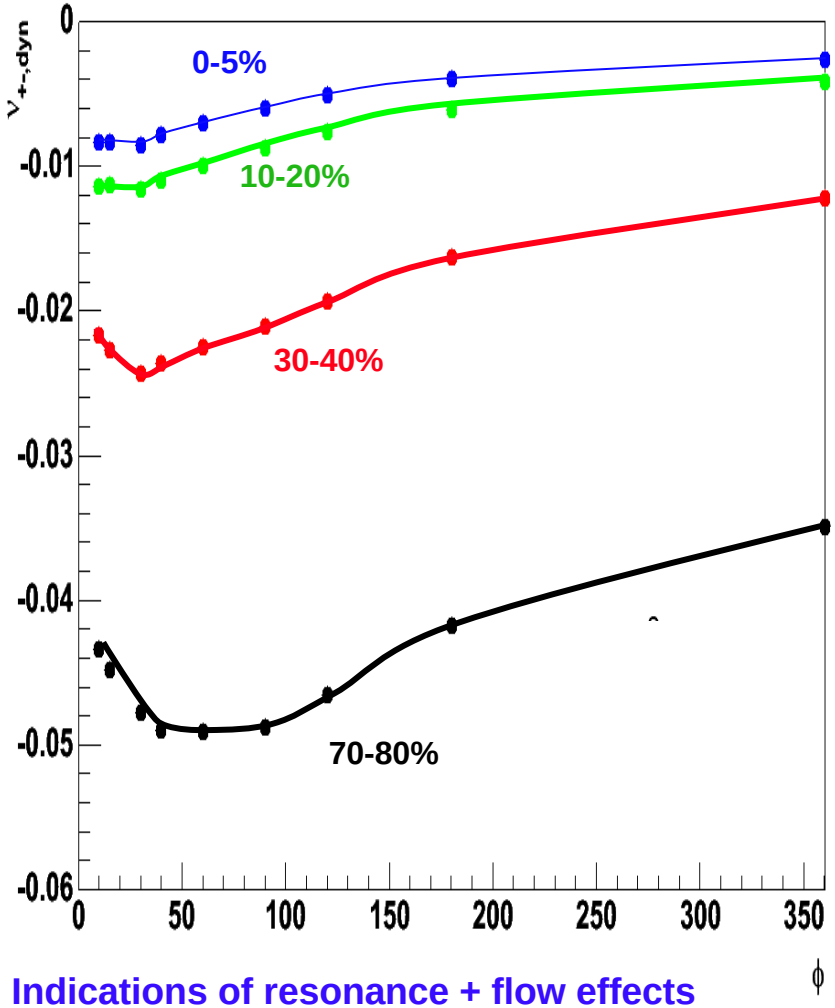


No K^o, Low mass ρ or σ, v_r = 0.



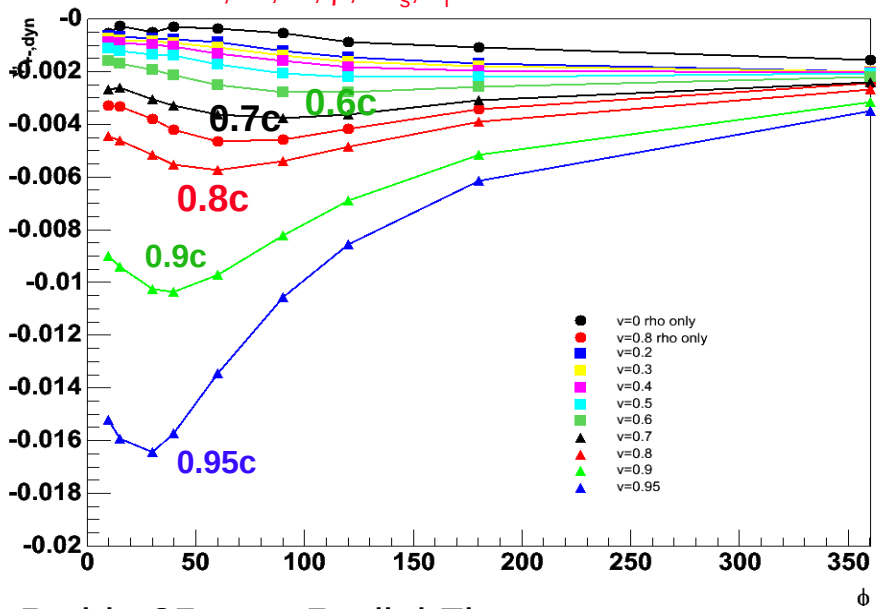
Net Charge - Azimuthal Dependence

Au+Au @ $s_{NN}^{1/2}$ = 62 GeV

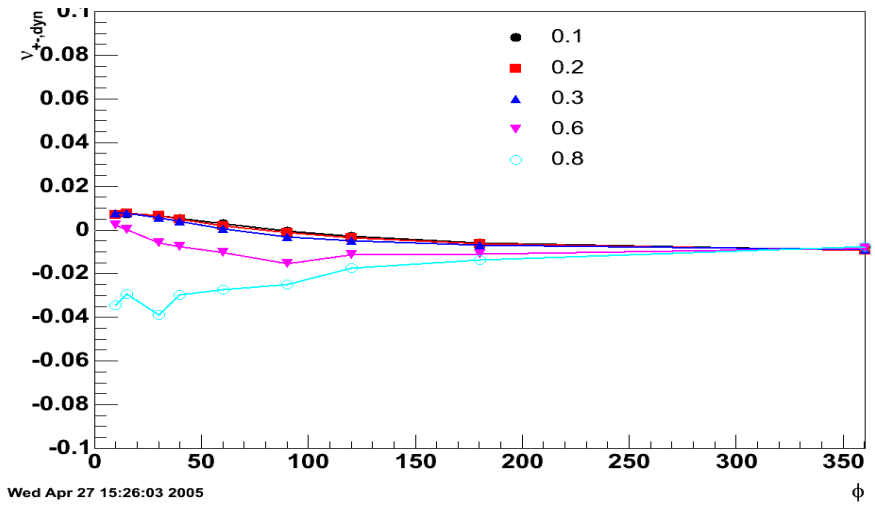


Resonance Gas - Toy Model

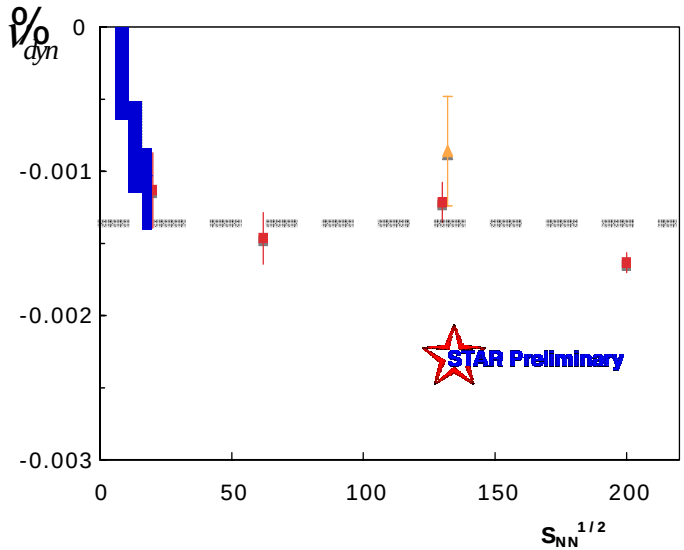
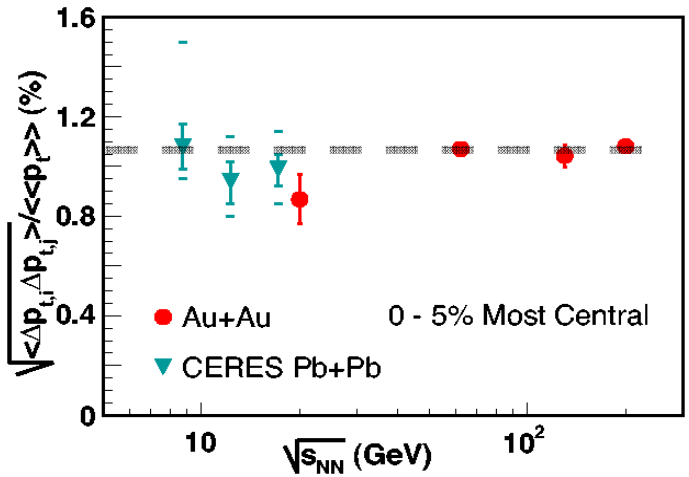
T=0.18 GeV; π^+, π^-, ρ, K^0_s, v_r as shown



Pythia 25 pp + Radial Flow



Indications of resonance + flow effects
Interpretation requires detailed model comparisons

Summary

- Net Charge fluctuations
  - No smoking gun for reduced fluctuations as predicted by Koch *et al*.
  - No beam energy dependence
  - Bulk of observed correlations likely due to resonance decays.
  - Sensitivity to radial flow.
- P_t fluctuations
  - No smoking gun for large fluctuations.
  - No beam energy dependence.
  - Sensitivity to radial velocity profile
- K/π Yield fluctuations
  - Super-poissonian
  - No beam energy dependence ?
- Suggestion:
  Bulk correlation properties invariant with beam energy $15 < s^{1/2}_{NN} < 200$ GeV ?