Transverse Momentum Fluctuations at RHIC

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I. **Fluctuations – nonequilibrium two-body correlations**

- p_t fluctuation observables.
- approach to equilibrium.
- initial and near-equilibrium fluctuations.
- Effects of Jets & Flow.

Systematic Case for Thermalization

clues: thermalized parton matter at RHIC?

- jets, energy loss – interacting partonic system
- flow – pressure due to thermalized partons
- particle ratios – local equilibrium in central collisions

wanted: more info on **phase space correlations**

- long range properties of correlation functions.
- fluctuations: simple way to characterize correlations.

Dynamic Fluctuations

dynamic = variance – thermal contribution Pruneau, Voloshin and Sean Gain

multiplicity N

$$R_{AA} = \frac{\langle N^2 \rangle - \langle N \rangle^2 - \langle N \rangle}{\langle N \rangle^2}$$

mean p_t

$$\langle \delta p_{t1} \delta p_{t2} \rangle \equiv \frac{1}{\langle N_{\text{pairs}} \rangle} \left\langle \sum_{\text{pairs } i \neq j} \delta p_{ti} \delta p_{tj} \right\rangle$$

$$\delta p_t \equiv p_t - \langle p_t \rangle$$

probe two-body correlations:

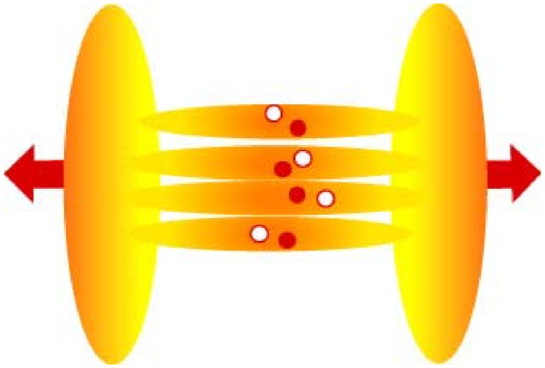
$$r(p_1, p_2) = n(p_1, p_2) - n(p_1) n(p_2)$$

$$R_{AA} \propto \iint r(p_1, p_2)$$

$$\langle \delta p_{t1} \delta p_{t2} \rangle \propto \iint \delta p_{t1} \delta p_{t2} \, r(p_1, p_2)$$

Time Scales

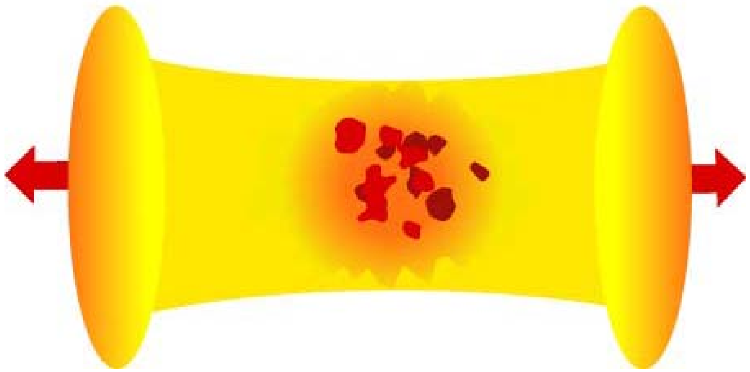
initially – string fragmentation



later – clumps, size $\sim \xi$

- local thermalization; time $\sim \nu^{-1}$

  scattering rate $\nu = \langle \sigma\, v_{rel} \rangle n$

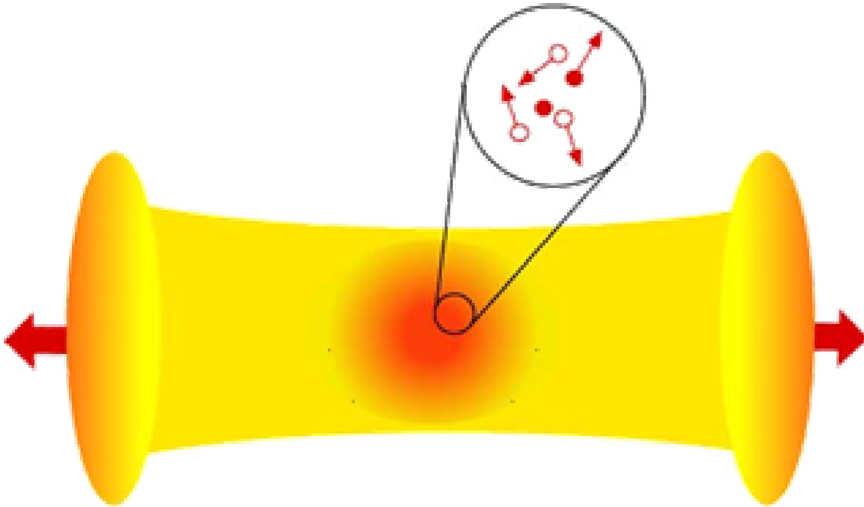


much later (if ever)

- flow between clumps →

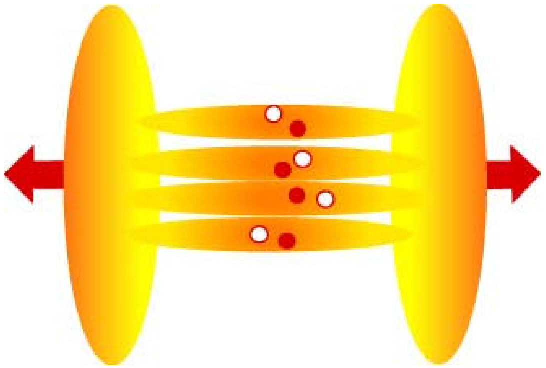
  homogeneity

- diffusion time $t_{diff} \sim \nu\xi^2$



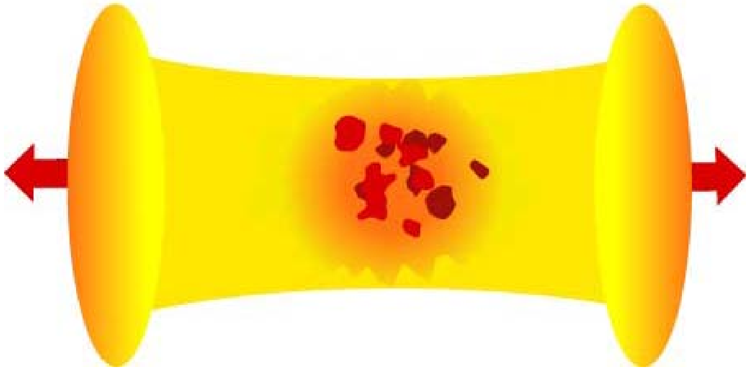
Fluctuation Sources

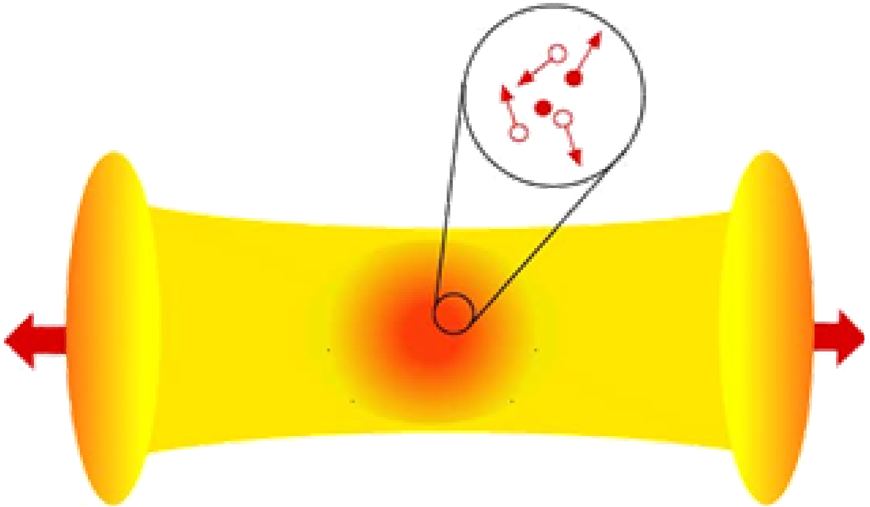
dynamic fluctutations ~ $(\text{strings})^{-1}$



dynamic fluctutations ~ $(\text{clumps})^{-1}$

-- larger? depends on clump size





statistical fluctuations ~ $(\text{particles})^{-1}$

dynamic fluctuations **vanish**

Approach to Equilibrium

Boltzmann Equation for phase space density $f(x,p)$

$$\frac{\partial f}{\partial t} + \vec{v}_{\vec{p}} \cdot \vec{\nabla} f = -\nu \left(f - f^{e} \right)$$

approximation: relaxation time ν^{-1}

Bjorken scaling: $$f = f_0(p_z', p_t, s) S(t, t_0) + \int_{t_0}^{t} f^{e}(p_z', p_t, s) S(t, s) \nu \, ds$$

Baym; Gavin; B. Zhang & Gyulassy

where $p_z' = p_z(t/t_0)$

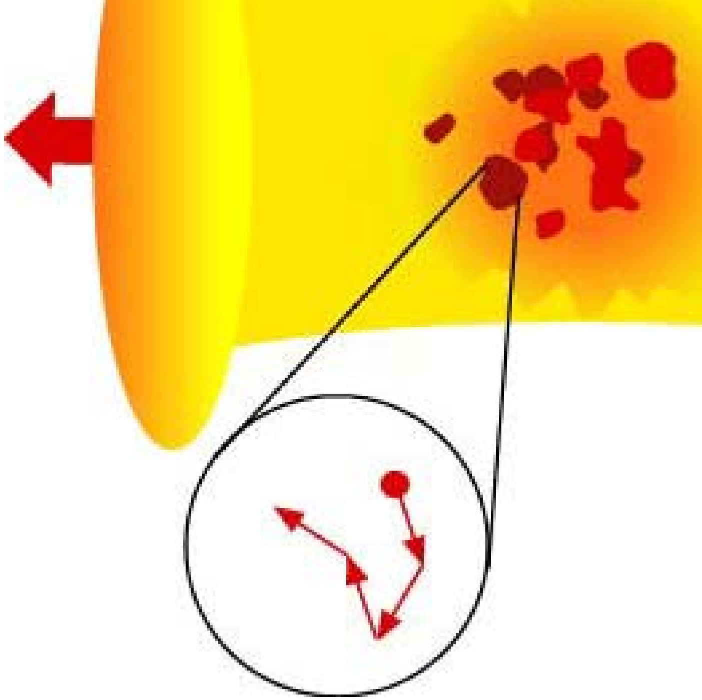
survival probability –
chance of no scattering

$$S(t, t_0) = e^{-\int_{t_0}^{t} \nu \, ds}$$

$$\langle p_t \rangle = \langle p_t \rangle_0 S + \langle p_t \rangle_e (1 - S)$$

$$\langle p_t \rangle_e \propto \left(\frac{\tau_0}{\tau_F} \right)^{\gamma}$$

Partial Thermalization



random walk – n collisions

$$\langle p_t^{\,2} \rangle = \langle p_t^{\,2} \rangle_0 + \kappa (n-1)$$

collision: many walkers bouncing off each other – energy conservation limits p_t increase

Boltzmann equation ⇒ $$\langle p_t^{\,2} \rangle = \langle p_t^{\,2} \rangle_0 S + \langle p_t^{\,2} \rangle_e (1-S)$$

Survival probability: $S = e^{-N_{scat}} \approx (\tau_0 / \tau_F)^{\alpha}$ $\alpha = \sigma v_{rel} n_0 \tau_0$

few collisions $\langle p_t^{\,2} \rangle_e - \langle p_t^{\,2} \rangle_0 \sim \kappa$ many collisions – saturates at $\langle p_t^{\,2} \rangle_e$

Nonequilibrium $\langle p_t \rangle$

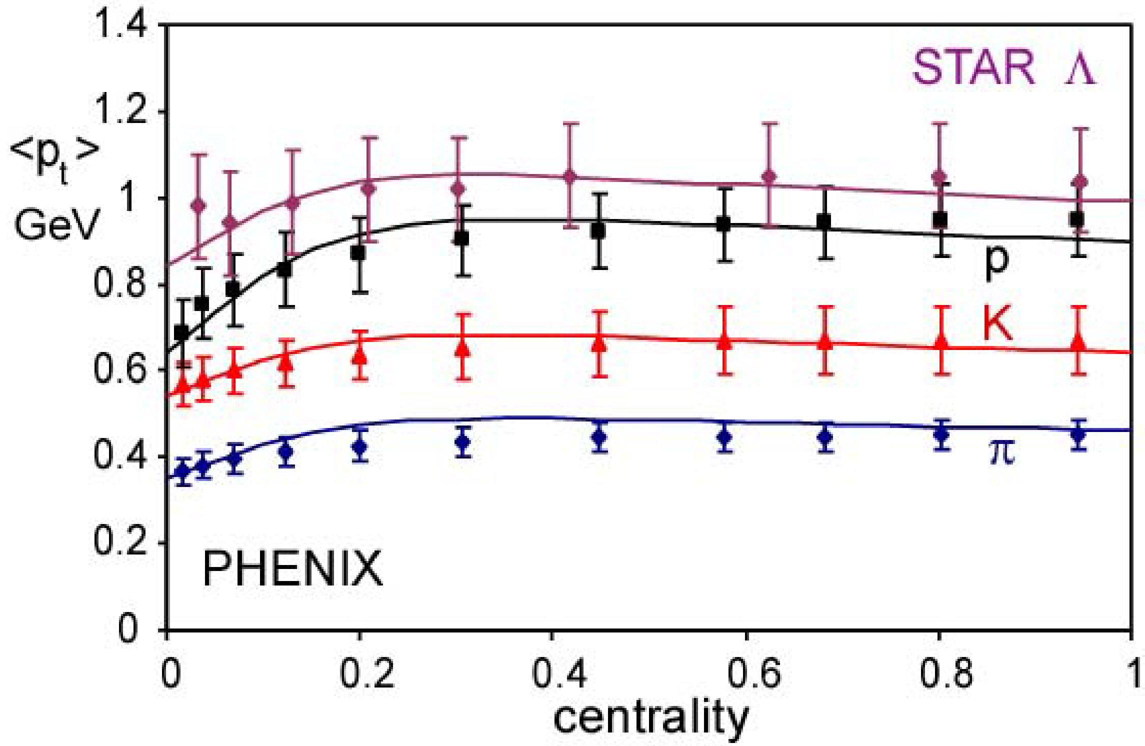
more participants $N \Rightarrow$ longer lifetime $\Rightarrow$ smaller survival probability S

$$\langle p_t \rangle = \langle p_t \rangle_0 S + \langle p_t \rangle_e (1 - S)$$

S. Gavin, Phys.Rev.Lett. 92 (2004) 162301

- centrality dependence

$$\tau_F \propto N^x, \alpha \propto N^y$$



$\tau_F(0) = 6$ fm, $\tau_0 = 1$ fm, $T_0 = 450$ MeV
$\alpha(0) = 4$, $\gamma = 0.15$, $x = 1$, $y = 1/2$

Nonequilibrium Dynamic Fluctuations

Boltzmann equation with Langevin noise $\Rightarrow$ phase-space correlations $\Rightarrow$ dynamic fluctuations

simple limits:

independent initial and near-local equilibrium correlations

$$\left\langle \delta p_{t1} \delta p_{t2} \right\rangle = \left\langle \delta p_{t1} \delta p_{t2} \right\rangle_0 S^2 + \left\langle \delta p_{t1} \delta p_{t2} \right\rangle_{le} \left(1 - S^2\right)$$

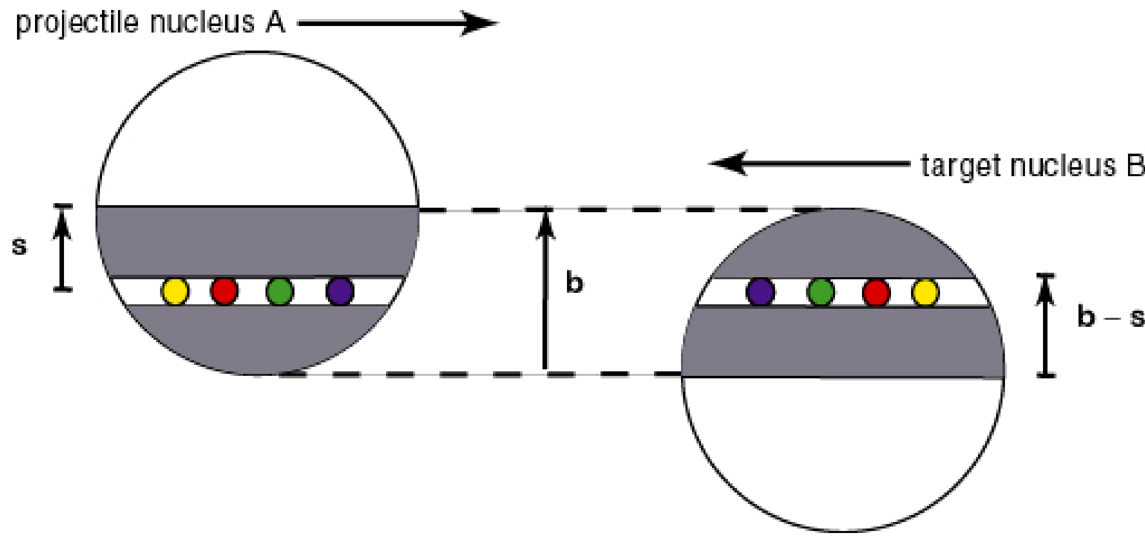
same centrality dependence of S

Initial Fluctuations

AA collision:

***M* participant nucleons**

$\rightarrow$ independent strings



multiplicity $\propto M$

variance $R_{AA} \propto M^{-1}$

$$\langle \delta p_{t1} \delta p_{t2} \rangle \equiv \frac{1}{\langle N(N-1) \rangle} \left\langle \sum_{i \neq j} \delta p_{ti} \delta p_{tj} \right\rangle$$

$$\langle N(N-1) \rangle = \langle N \rangle^2 (1 + R_{AA})$$

$$\langle \delta p_{t1} \delta p_{t2} \rangle \approx \frac{2 \langle \delta p_{t1} \delta p_{t2} \rangle_{pp}}{M} \left(\frac{1 + R_{pp}}{1 + R_{AA}} \right)$$

ISR data $\rightarrow \langle \delta p_{t1} \delta p_{t2} \rangle_{pp}$; HIJING R_{pp}, R_{AA}

Near Local Equilibrium Correlations

single particle phase space distribution:

$$f(p,x) = e^{-(E-\vec{p}\cdot\vec{v})/T(x)}, \qquad \vec{v} << 1$$

particle correlations

$$\mathcal{P}^e(x_1, p_1, x_2, p_2) = f(p_1, x_1) f(p_2, x_2) A$$

$$A(x_1, p_1, x_2, p_2) = r(x_1, x_2)$$

density correlations

Fluctuations Near Equilibrium

correlations from non-uniformity – more likely to find particles near "hot spots" → spatial correlation function

$$\langle \delta p_{t1} \delta p_{t2} \rangle_e \propto \iint \delta T(x_1) \delta T(x_2)\, r(x_1, x_2)\, dx_1 dx_2$$

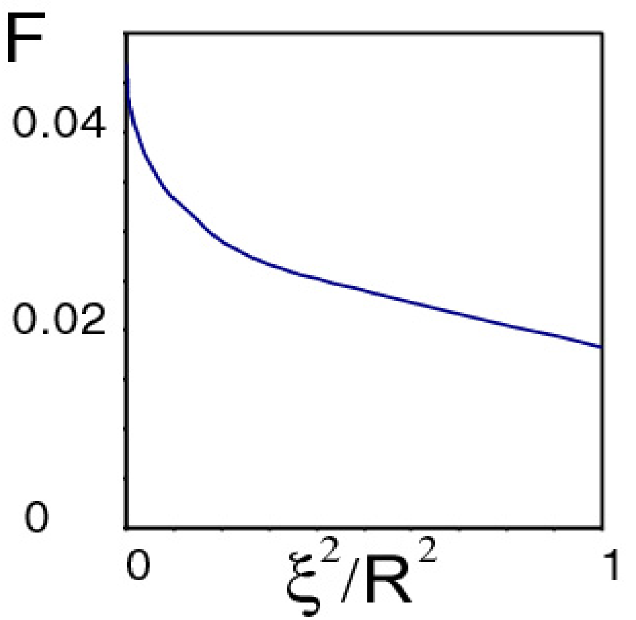
assume:

- longitudinal Bjorken expansion up to freeze out time
- independent longitudinal and transverse d.o.f.
- $\delta p_t \propto \delta T(x)$ independent of rapidity
- gaussian densities, correlation function

obtain:

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

transverse size R_t, correlation length ξ



Nonequilibrium Fluctuations

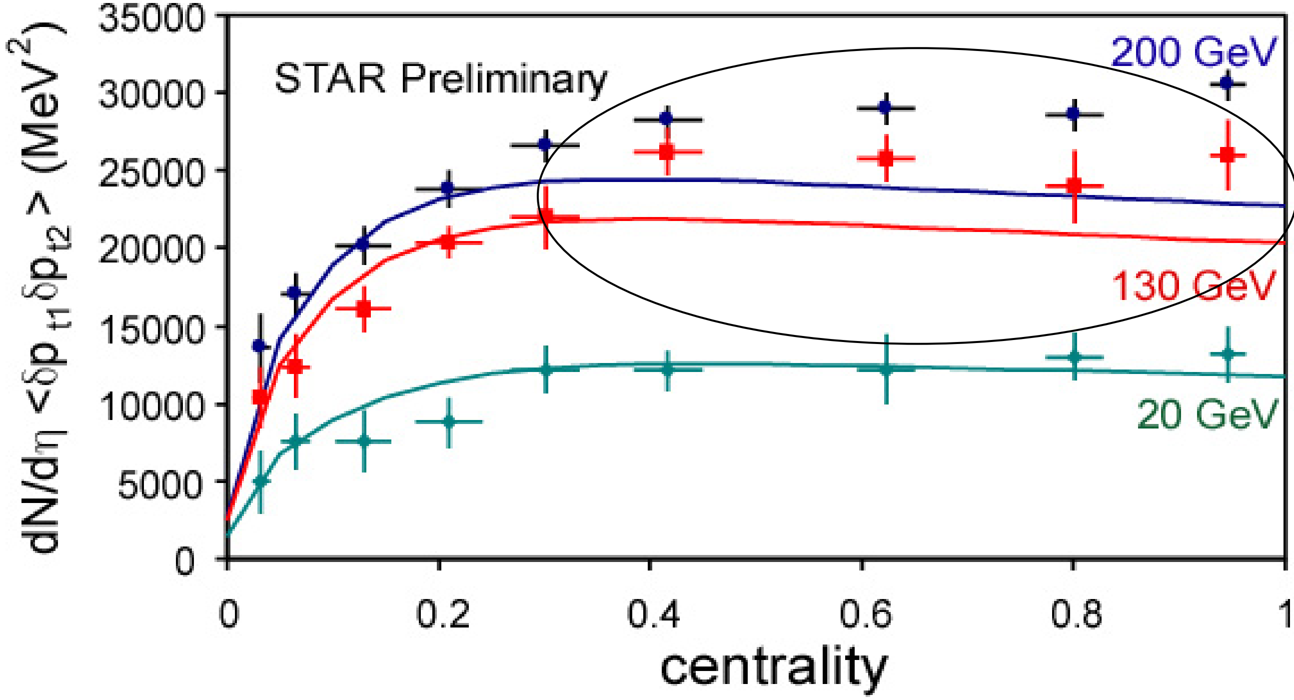
S. Gavin, Phys.Rev.Lett. 92 (2004) 162301

initial fluctuations – wounded nucleons

near equilibrium correlation length

ξ ~ 1 fm; R $\propto$ $N^{1/2}$

survival probability S vs.centrality from $\langle p_t \rangle$ data



energy $\rightarrow$ multiplicity $N \rightarrow$ scattering $\alpha \propto N$, number variance $R_{AA} \propto N^{-1}$

FIND: partial thermalization describes trends.

Deviation in central collisions at highest energies – **JETS/and or FLOW**?

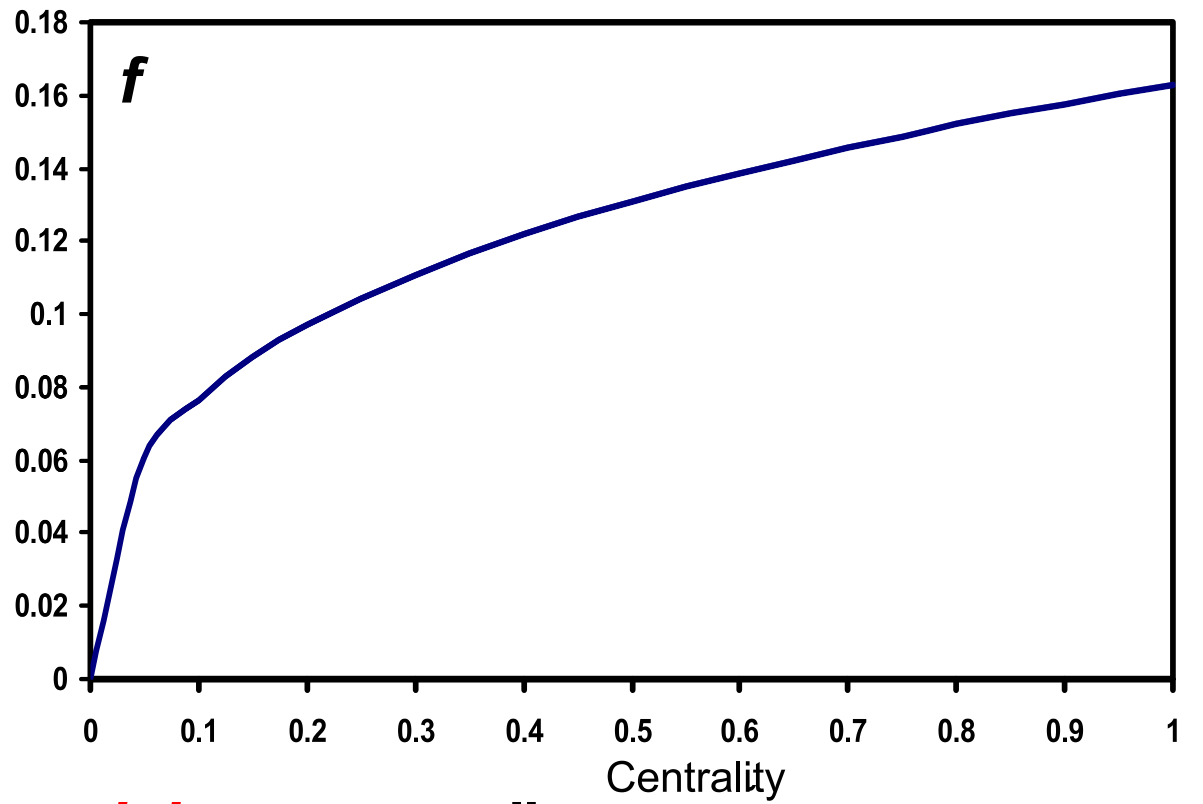
Effect of Jets

$$f = \frac{hard\ production}{soft\ production}$$

D. Kharzeev, M. Nardi, Phys. Lett. B507 (2001) 121-128

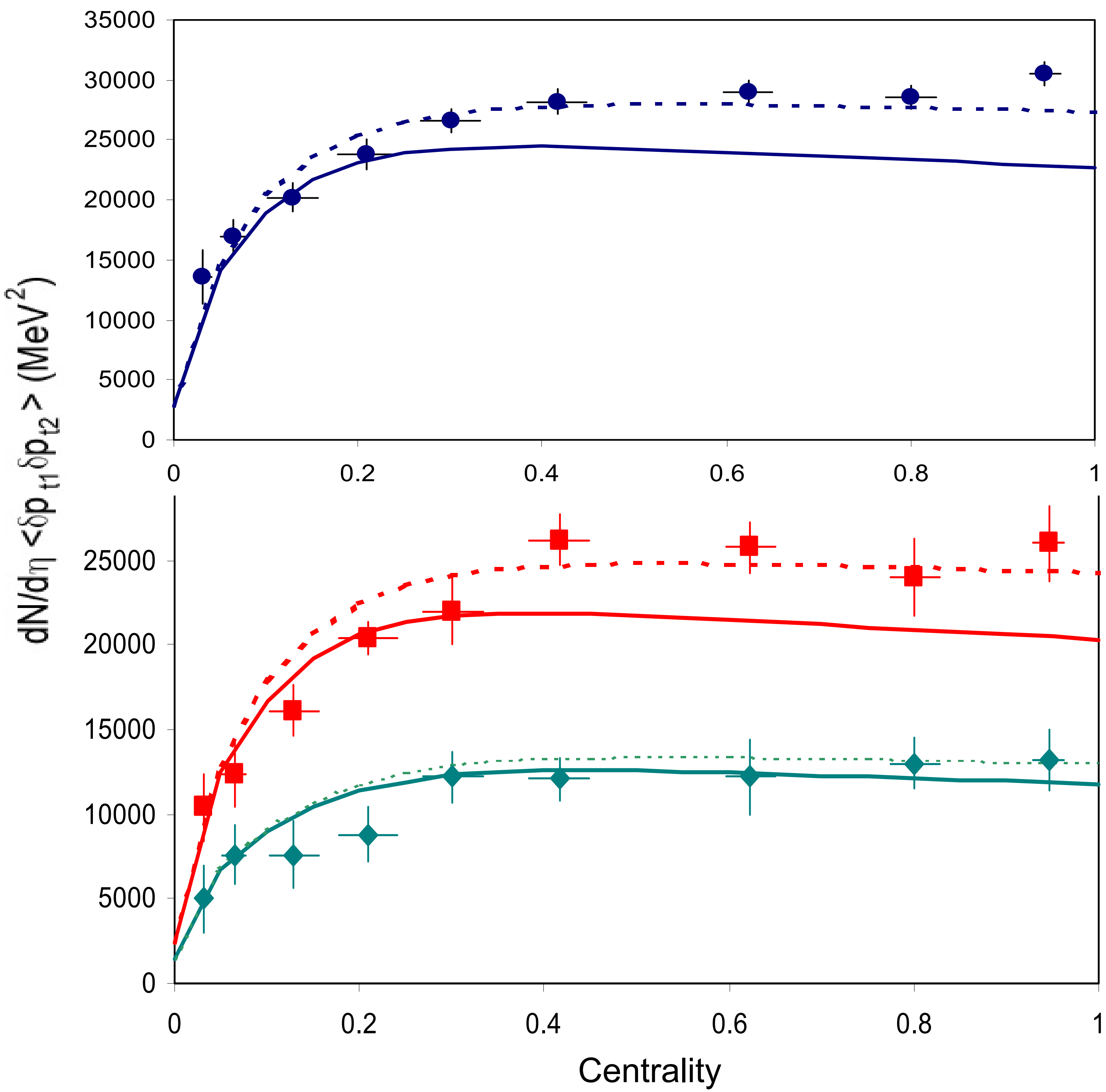
$$\Delta p \propto k_h\ n(x)\,\Delta x$$

Xin-Nian Wang. arXiv:nucl-th/045029



$$\delta T(x) \propto \delta n(x)$$ "***work in progress***"

$$\langle \delta p_{t1} \delta p_{t2} \rangle \approx \left[1 - f^2 \left(1 - \left(\frac{k_h}{k_s} \right)^2 \right) \right] \langle \delta p_{t1} \delta p_{t2} \rangle_{no\ \ jets}$$



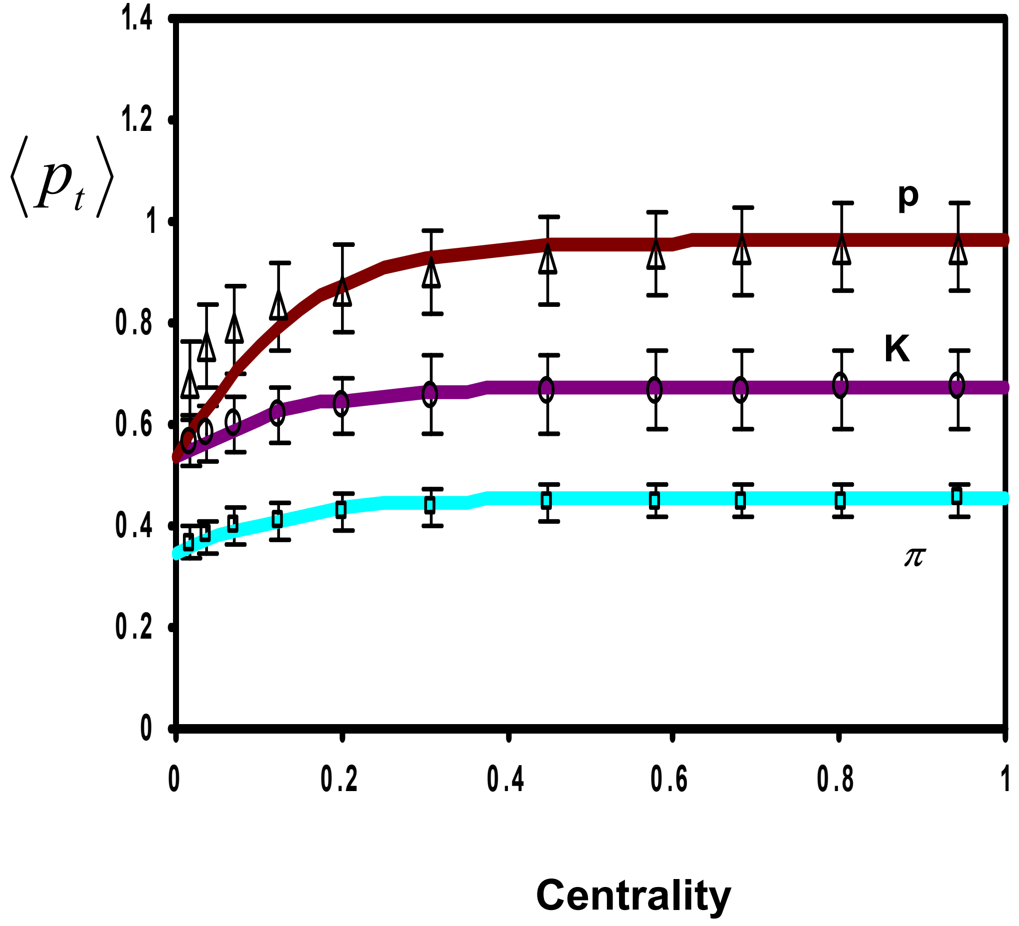
35000
30000
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
dN/dη <δp t1δp t2> (MeV2)
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
1
Centrality

Effect of Flow

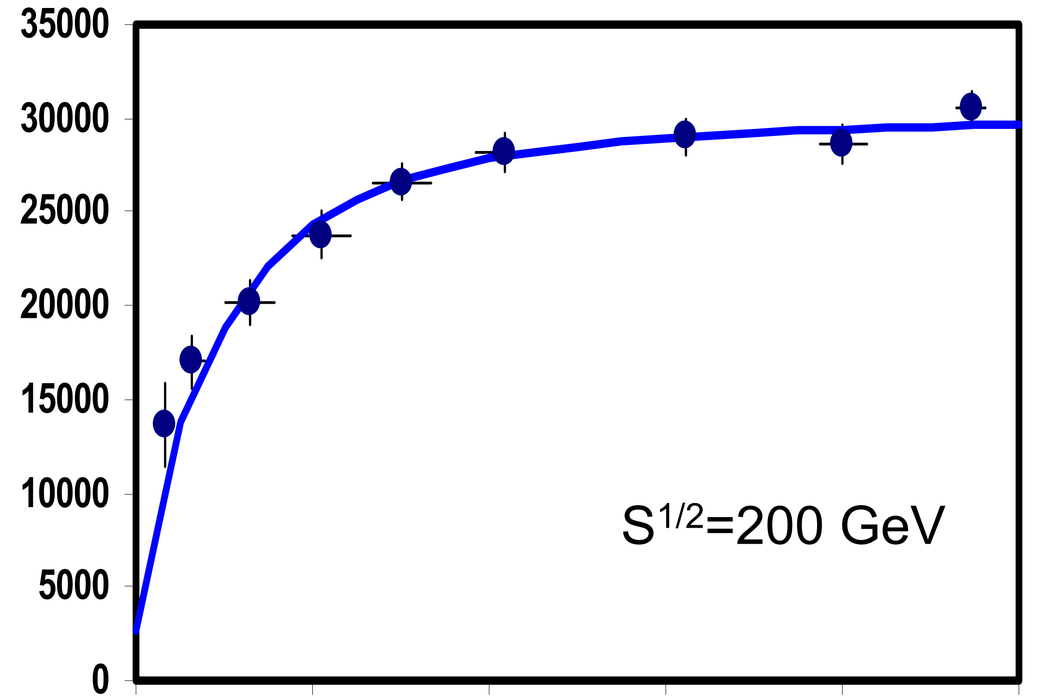
$$\langle \beta \rangle = 0.45 \pm 0.1$$

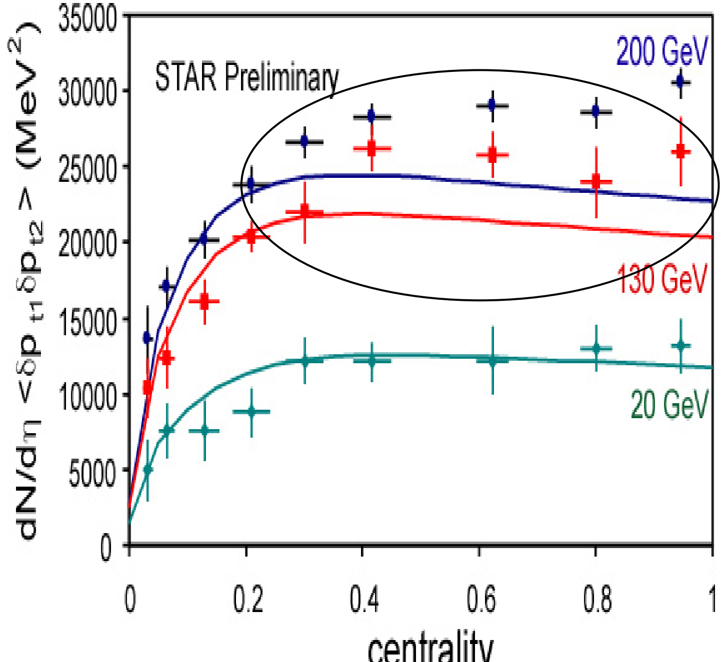
Olga Barannikova, nucl-ex/0403014

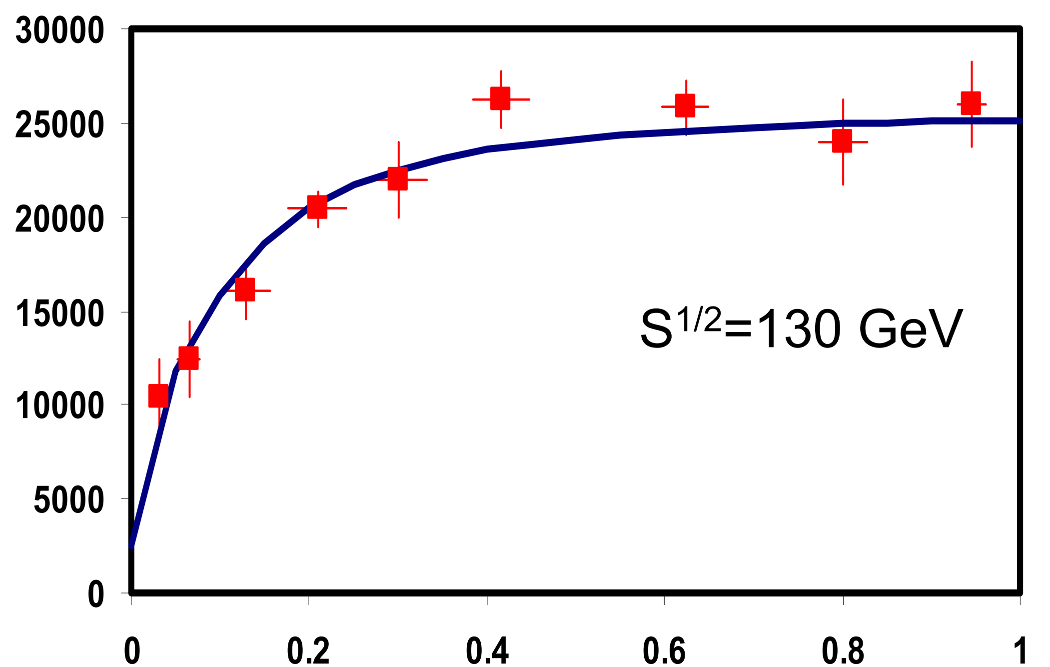
$$\langle p_t \rangle = \langle p_t \rangle_0 S + \langle p_t \rangle_e \left(\frac{1+\beta}{1-\beta} \right)^{\frac{1}{2}} (1-S)$$



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







Summary

1- Flow and jet can affect the fluctuation studies of $\langle p_t \rangle$

2- Centrality dependence of the fluctuations, seems to be the same as the $\langle p_t \rangle$