
West Ridge of Mt. Everest

Viscosity and the Soft Ridge at RHIC

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Ridge in 2-particle correlations with **no** jet tag

Claim: viscous hydro can explain this!

I. Soft ridge (no jet tag)

II. Transverse flow fluctuations in viscous hydro

III. Effect on transverse momentum correlations

IV. Rapidity + Azimuthal Correlation Data

V. Implications for "hard ridge"

SG + Abdel-Aziz, PRL 97, 162302 (2006)

SG + G. Moschelli, in progress

Pruneau, Voloshin + SG, NPA, in press

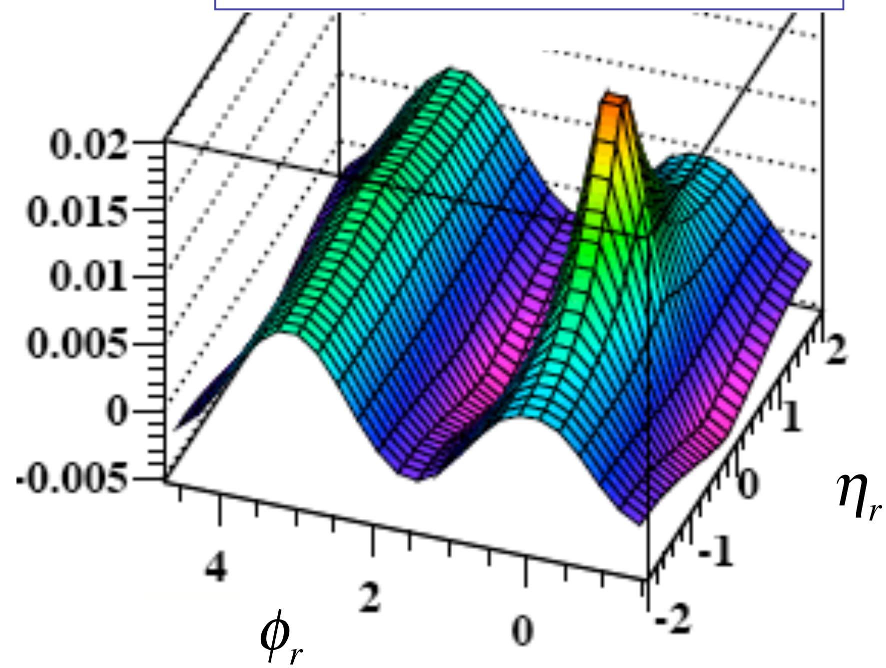
Momentum Correlation Landscape

STAR, J.Phys. G32 (2006) L37

soft ridge: near side peak

similar to **ridge** with jet tag

but at ordinary p_t scales
-- no jet tag



STAR p_t fluctuations

$$\Delta\sigma_{p_t:n} = \frac{1}{\langle N \rangle}\left\langle \sum_{pairs} \left(p_{ti} - \langle p_t \rangle\right)\left(p_{tj} - \langle p_t \rangle\right) \right\rangle \rightarrow \int (\text{correlation function})\, d\eta_r d\phi_r$$

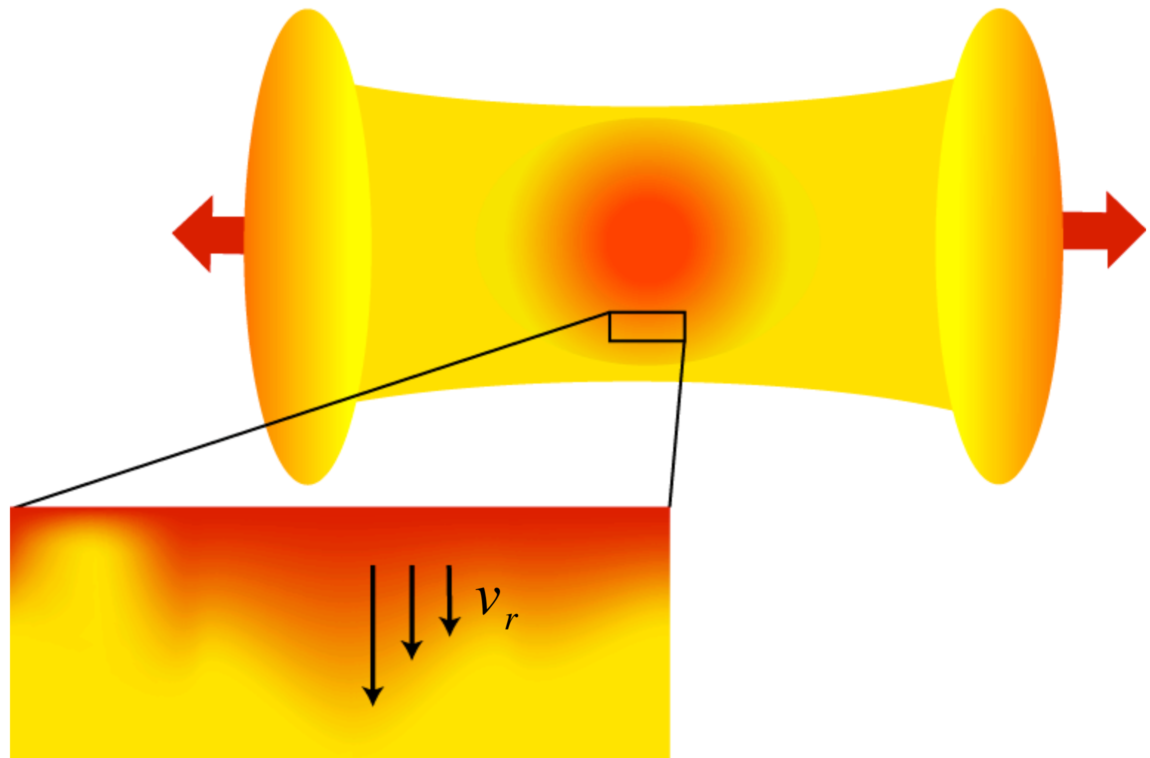
jet-like correlations from flow **-- Voloshin; Shuryak**
our aim: **hydro explanation for untagged correlations**

Transverse Flow $\rightarrow p_t$ Fluctuations

small variations in radial flow in each event

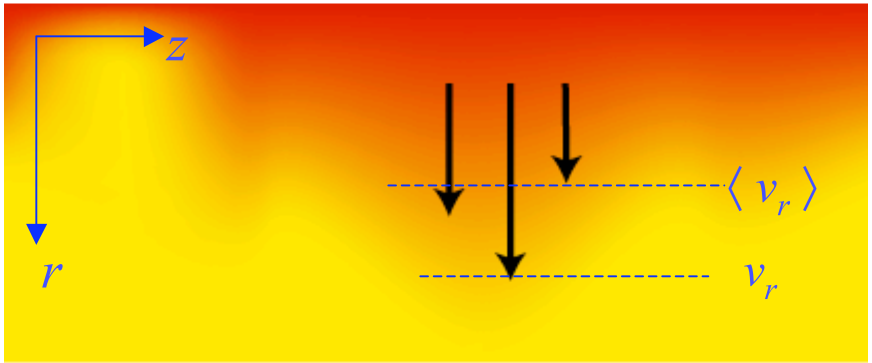
neighboring fluid elements flow past one another
$\Rightarrow$ viscous friction

shear viscosity drives velocity toward the average



motivation: **damping of radial flow fluctuations $\Rightarrow$ viscosity**

Evolution of Fluctuations



momentum current

small fluctuations

$$g_t \equiv T_{0r} - \langle T_{0r} \rangle$$

diffusion equation for momentum current

$$\frac{\partial}{\partial t} g_t = \frac{\eta}{sT} \nabla^2 \left(g_t + \text{noise} \right)$$

shear viscosity η, entropy density s, temperature T

fluctuations $\rightarrow$ Langevin noise

diffusion + transverse flow

$$\frac{\partial g_t}{\partial \tau} + \langle \vec{v}_r \rangle \cdot \vec{\nabla}_t g_t + g_t \frac{\partial \langle v_r \rangle}{\partial r} = \frac{\eta}{sT} \nabla^2 (g_t + \text{ noise}), \qquad v_r \ll 1$$

Hydrodynamic Momentum Correlations

SG + Abdel-Aziz, PRL 97, 162302 (2006)

momentum flux density correlation function

$$r_g = \langle g_t(x_1) g_t(x_2) \rangle - \langle g_t(x_1) \rangle \langle g_t(x_2) \rangle$$

$\Delta r_g = r_g - r_{g,eq}$ **satisfies diffusion equation (no noise)**

observable:

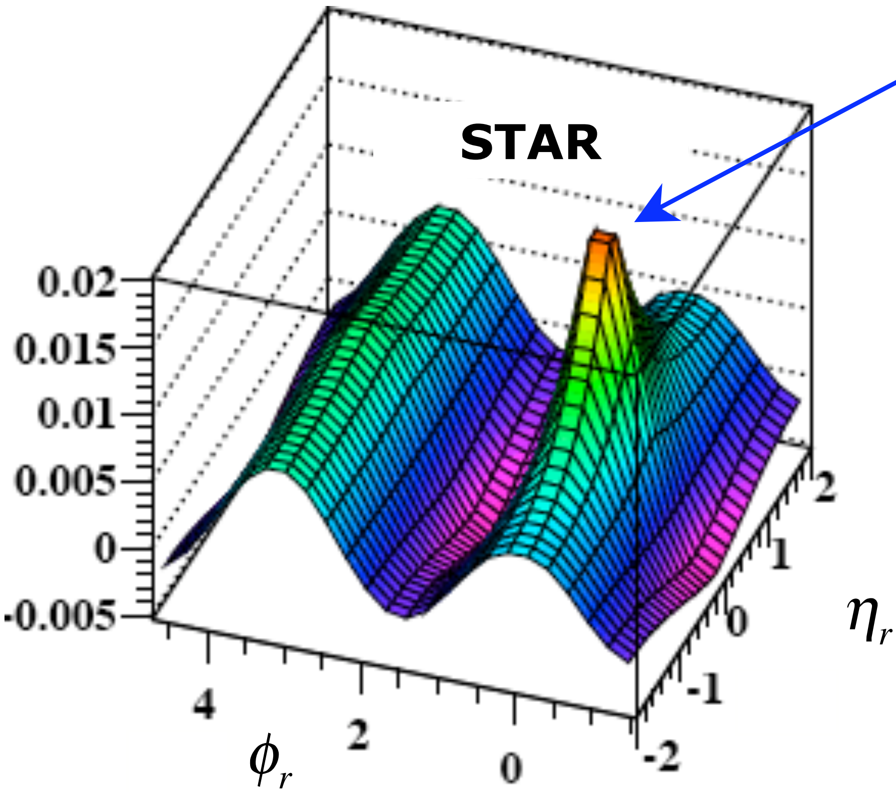
$$C = \frac{1}{\langle N \rangle^2} \left\langle \sum_{\text{pairs}} p_{ti} p_{tj} \right\rangle - \langle p_t \rangle^2 = \frac{1}{\langle N \rangle^2} \int \Delta r_g \, dp_1 dp_2$$

STAR measured:

$$\Delta\sigma_{p_t:n} = \frac{1}{\langle N \rangle} \left\langle \sum_{i \neq j} (p_{ti} - \langle p_t \rangle)(p_{tj} - \langle p_t \rangle) \right\rangle$$

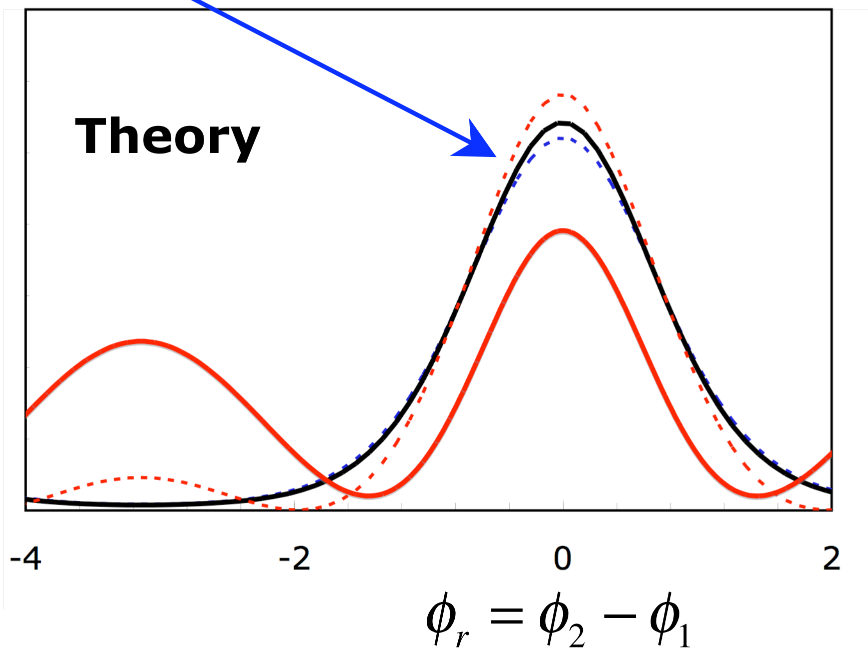
$$= \langle N \rangle C - \langle p_t \rangle^2 \text{ (multiplicity fluctuations)}$$

Momentum Correlation Landscape



near side peak

S.G. + G. Moschelli
in progress



Soft Ridge: Centrality Dependence

near side peak

- pseudorapidity width $\sigma \to \sigma_\eta$
- azimuthal width σ_ϕ

centrality dependence:

path length $\sim 2n_{bin}/n_{part}$

rapidity broadening:

viscous diffusion $\Rightarrow 1/4\pi < \eta/s < 0.32$

SG + Abdel-Aziz, PRL 97, 162302 (2006)

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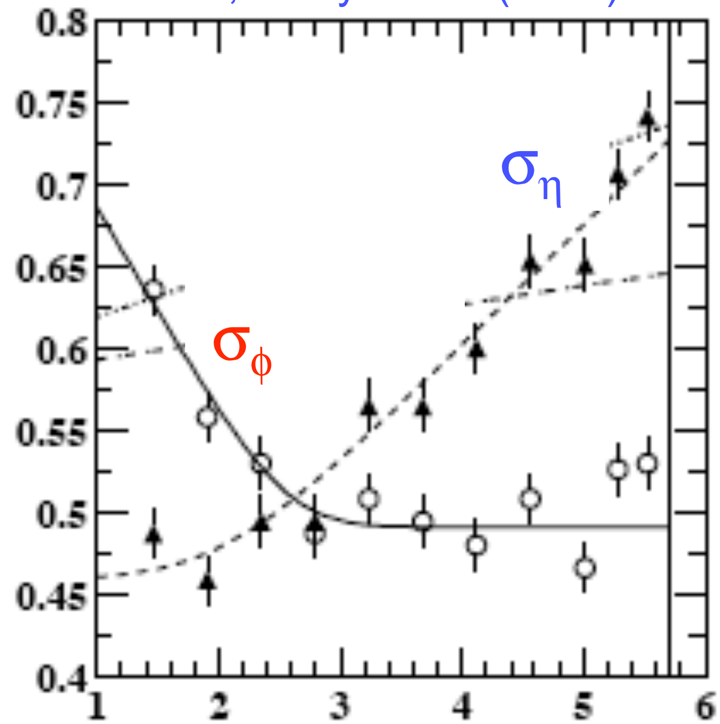
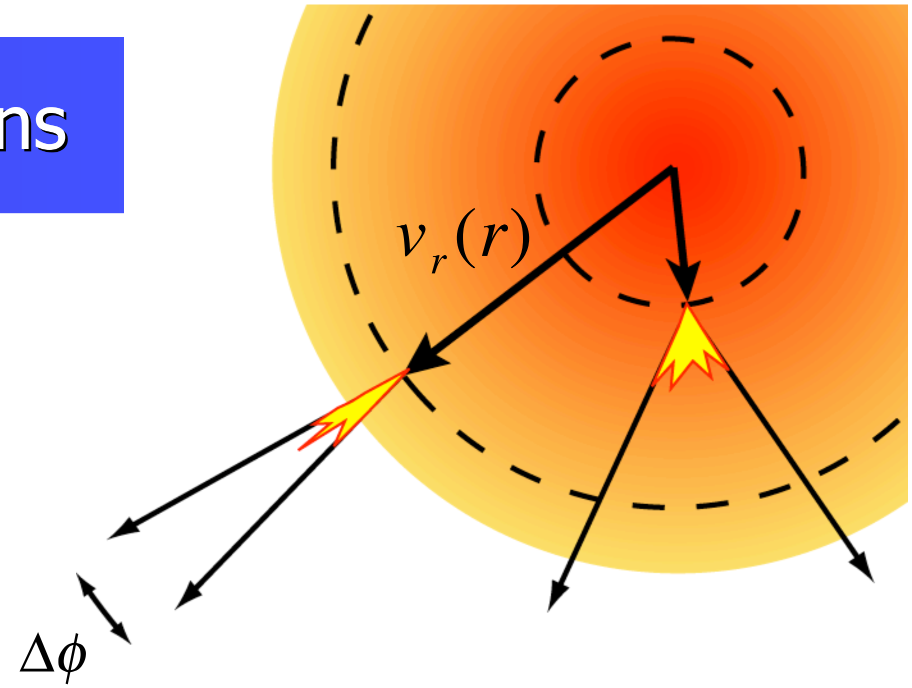


centrality, $2n_{bin}/n_{part}$

azimuthal narrowing: viscous diffusion + transverse and elliptic flow

Flow ⇒ Azimuthal Correlations



mean flow depends on position

blast wave $\vec{v}_r \sim \lambda \vec{r}$

opening angle for each fluid element depends on r

$$\Delta\phi \sim v_{th}/v_r \sim (\lambda r)^{-1}$$

correlations:

$$\Delta r_g(p_1,p_2) = \iint_{x_1,x_2} f(p_1,x_1) f(p_2,x_2) \Delta r_g(x_1,x_2)$$

gaussian spatial $r(x_1, x_2)$:

- σ_t -- width in $\vec{r} = \vec{r}_{t2} - \vec{r}_{t1}$
- Σ_t -- width in $\vec{R} = (\vec{r}_{t1} + \vec{r}_{t2})/2$

momentum distribution:

$$f = e^{-\gamma(E - \vec{p}\cdot\vec{v})/T}$$

⇒

$$\sigma_\phi{}^2 = \langle \Delta\phi^2 \rangle \propto \lambda^{-2}(\Sigma_t^2 - \sigma_t^2/4)^{-1}$$

Measured Flow Constrains Correlations

diffusion + flow for correlations

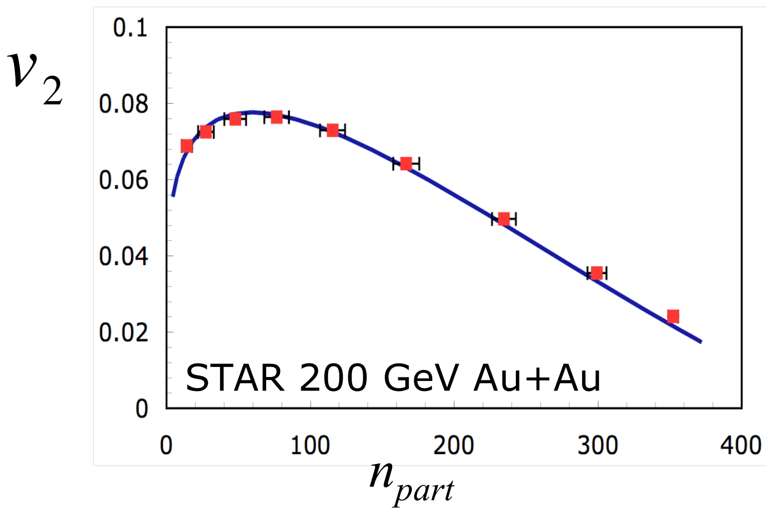
$$\frac{\partial g_t}{\partial \tau} + \vec{v}_r \cdot \vec{\nabla}_t g_t + g_t \frac{\partial v_t}{\partial r} = \frac{\eta}{sT} \nabla^2 g_t \rightarrow \Sigma_t(\tau),\ \sigma_t(\tau)$$

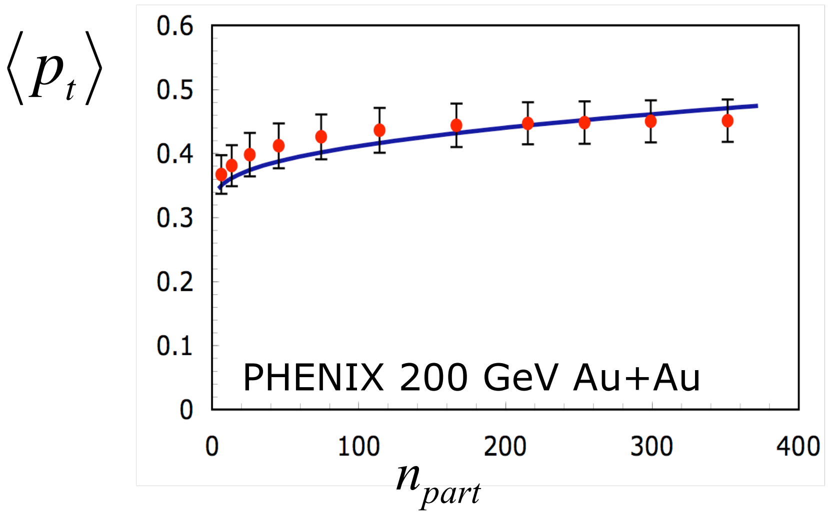
radial plus elliptic flow:
"eccentric" blast wave

Heinz et al.

$$\vec{v}_r = \varepsilon_x(\tau)\, x\hat{x} + \varepsilon_y(\tau)\, y\hat{y}$$

constraints: flow velocity, radius from measured v_2, $\langle p_t \rangle$ vs. centrality





Rapidity and Azimuthal Trends

G. Moschelli + S.G., *in progress*

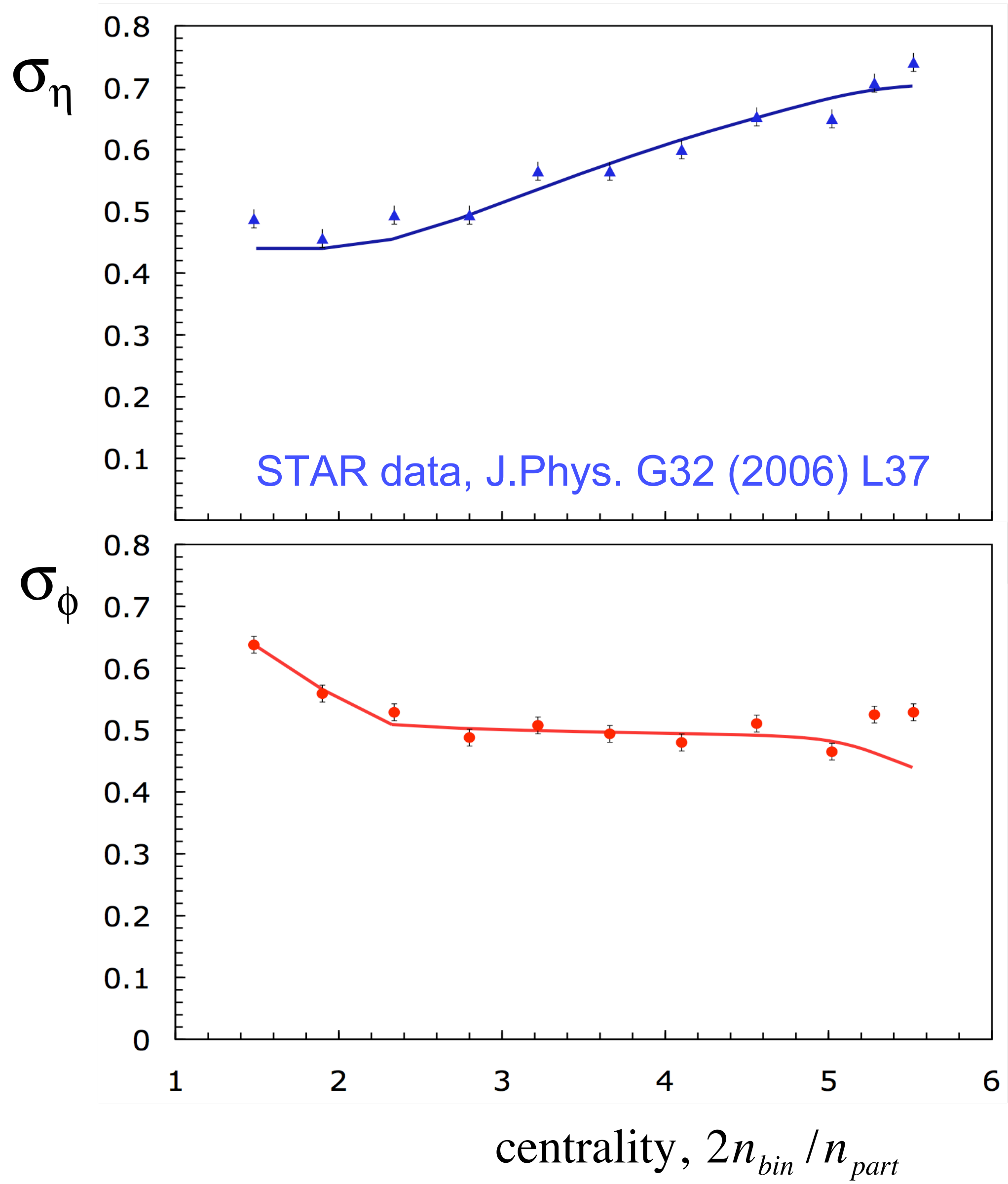
rapidity width:

- viscous broadening, $\eta/s \sim 1/4\pi$
- assume local equilibrium for all impact parameters

azimuthal width:

- flow dominates
- viscosity effect tiny

agreement with data easier if
we ignore peripheral region
-- nonequilibrium?



Summary: what can we learn from the soft ridge?

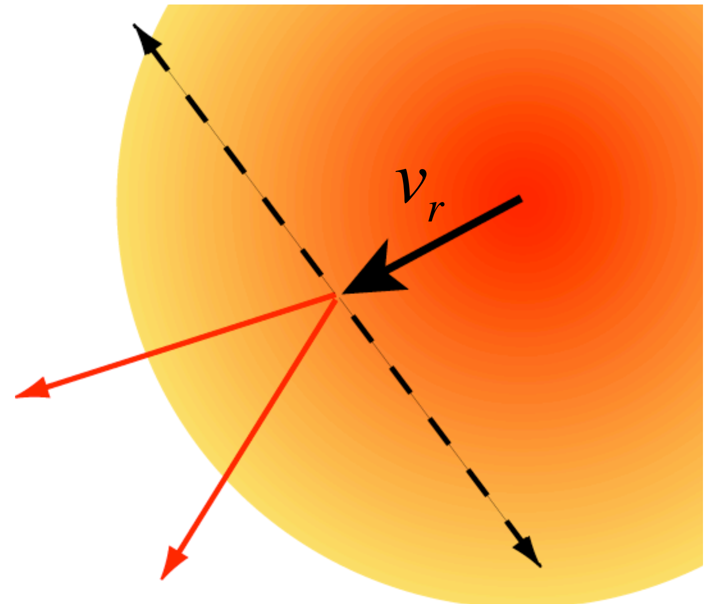
viscous hydro can explain two-particle correlations

- azimuthal and rapidity correlations **explained**
- **very small** $\eta/s \sim 1/4\pi$

does the jet cause the jet-tag ridge?

- **soft ridge:** ridge-like feature without jet tag
- **correlation:** jet tag and transversely-expanding fluid both fly outward
- **correlation ≠ causation**

Hard Ridge: Transverse Flow?



any effect of transverse flow on jets ⇒ ridge-like structure

C. Pruneau, S. Voloshin + S.G., Nucl Phys A to be published

PYTHIA + transverse boost

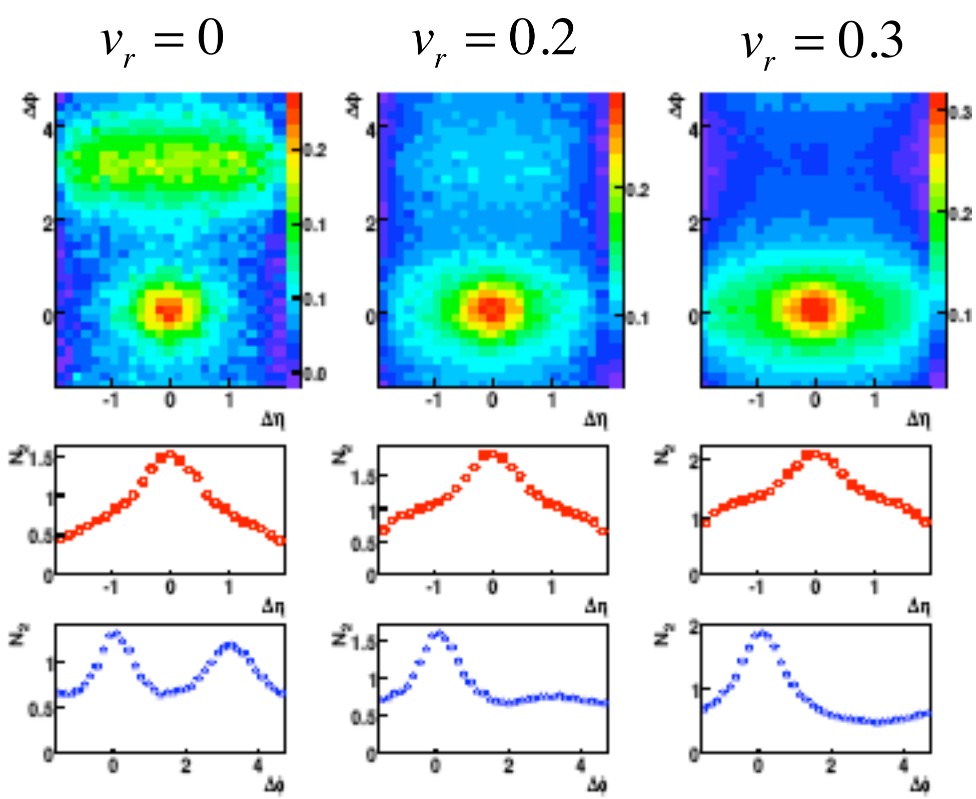
- jet tag particle 3 < pt < 20 GeV
- associates 0.2 < pt < 1 GeV

flow-like effects for jets?

- Cronin (pA, dA, leptons)
- radial color fields

  Fries, Kapusta + Li

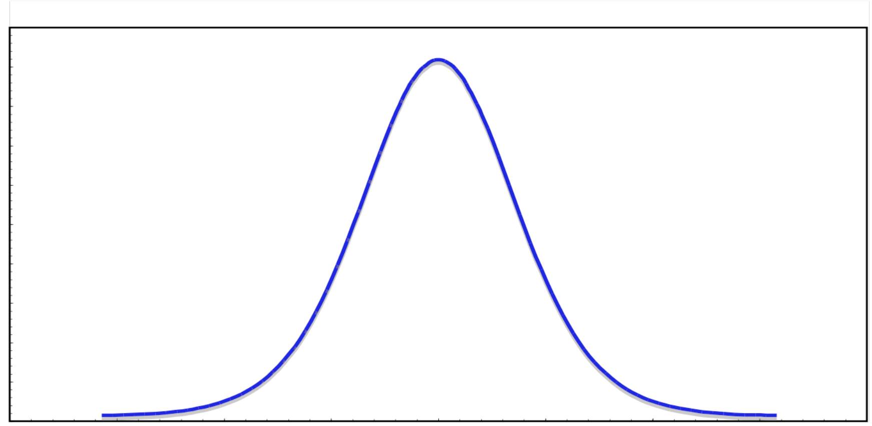
further clues from 3 particle correlations



Azimuthal Correlations from Flow

transverse flow: narrows angular correlations

- no flow $\Rightarrow \sigma_\phi = \pi/\sqrt{3}$
- $\sigma_\phi \propto 1/v_{rel}$



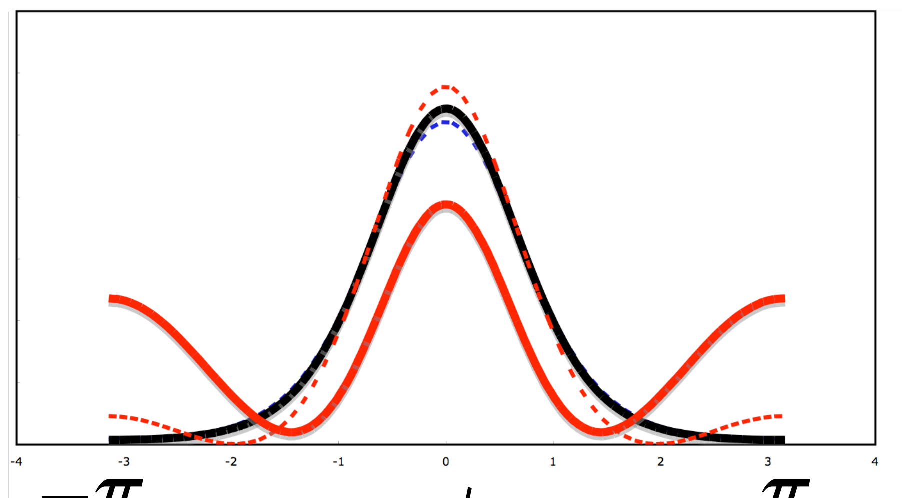
elliptic flow:

- v_2 contribution
- STAR subtracted

momentum conservation:

- $\propto \sin\phi$; subtracted

  Borghini, et al



viscous diffusion:

- increases spatial widths Σ_t and σ_t
- $\sigma_\phi \propto (\Sigma_t^2 - \sigma_t^2/4)^{-1/2}$

Uncertainty Range

we want: $$C = \frac{1}{\langle N\rangle^2}\left\langle \sum_{i\neq j} p_{ti}p_{tj}\right\rangle - \langle p_t\rangle^2$$

STAR measures: $$\langle N\rangle \Delta\sigma_{p_t:n} = \left\langle \sum_{i\neq j}\left(p_{ti}-\langle p_t\rangle\right)\left(p_{tj}-\langle p_t\rangle\right)\right\rangle$$

$$= \int dx_1 dx_2 \left[\Delta r_g(x_1,x_2) - \langle p_t\rangle^2 \Delta r_n(x_1,x_2)\right]$$

momentum density correlations

density correlations

density correlation function

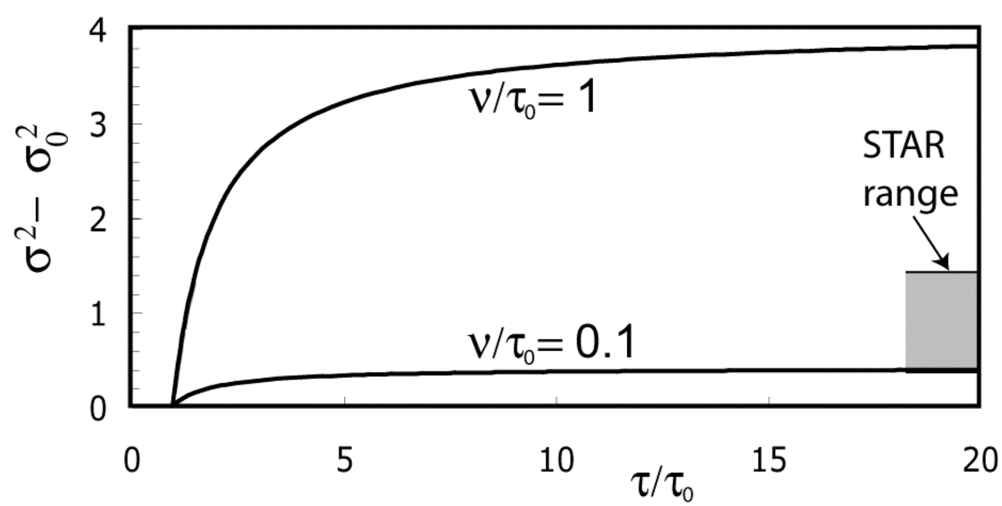
$\Delta r_n = r_n - r_{n,eq}$ may differ from Δr_g

maybe $\sigma_n \approx 2\sigma_*$

STAR, PRC 66, 044904 (2006)

uncertainty range $\sigma_* \le \sigma \le 2\sigma_*$

$\Rightarrow 0.08 \le \eta/s \le 0.3$



Covariance ⇒Momentum Flux

covariance $$C = \frac{1}{\langle N \rangle^2} \left\langle \sum_{\text{pairs } i \neq j} p_{ti} p_{tj} \right\rangle - \langle p_t \rangle^2$$

unrestricted sum: $$\sum_{\text{all} i,j} p_{ti} p_{tj} = \int p_{t1} p_{t2} dn_1 dn_2$$

$$= \int dx_1 dx_2 \left(\int dp_1\, p_{t1} f_1 \right) \left(\int dp_2 p_{t2} f_2 \right)$$

$$\left.\begin{array}{l} dn = f(x,p) dp dx \\ g_t(x) = \int dp\ p_t \Delta f(x,p) \end{array}\right\}$$

$$\rightarrow \int g(x_1) g(x_2) dx_1 dx_2$$

correlation function: $$r_g = \langle g_t(x_1) g_t(x_2) \rangle - \langle g_t(x_1) \rangle \langle g_t(x_2) \rangle$$

$$\int r_g dx_1 dx_2 = \left\langle \sum p_{ti} p_{tj} \right\rangle - \langle N \rangle^2 \langle p_t \rangle^2 = \left\langle \sum p_{ti}{}^2 \right\rangle + \langle N \rangle^2 C$$

C =0 in equilibrium ⇒ $$C = \frac{1}{\langle N \rangle^2} \int (r_g - r_{g,eq}) dx_1 dx_2$$

Current Data?

STAR measures rapidity width of p_t fluctuations J.Phys. G32 (2006) L37

$$\Delta\sigma_{p_t:n} = \frac{1}{\langle N \rangle}\left\langle \sum_{i\neq j}\left(p_{ti}-\langle p_t\rangle\right)\left(p_{tj}-\langle p_t\rangle\right)\right\rangle$$

find width σ_* increases in central collisions

- most peripheral $\sigma_* \sim 0.45$
- central $\sigma_* \sim 0.75$

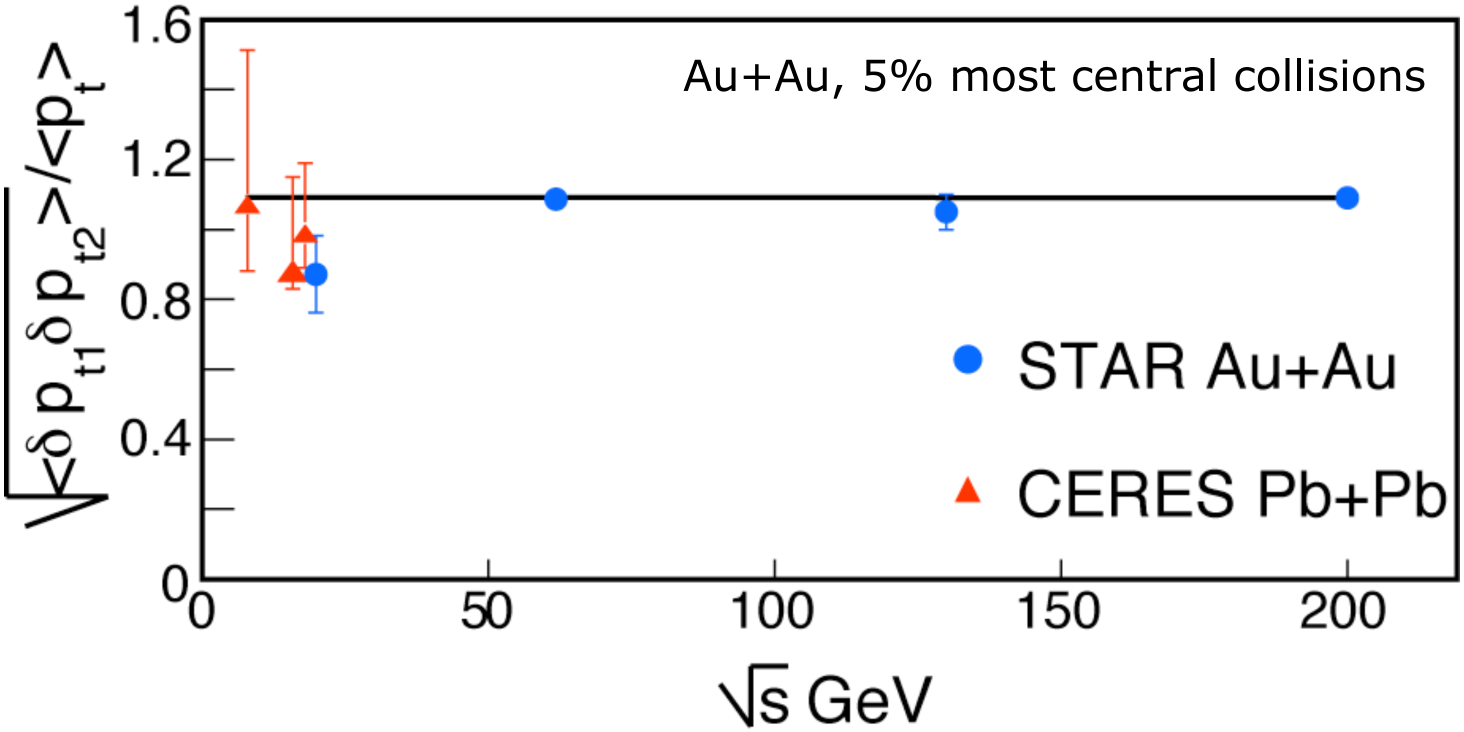
naively identify σ_* with σ (strictly, $\Delta\sigma_{p_t:n} = \langle N \rangle C + \text{corrections}$)

$$\sigma^2_{central} - \sigma^2_{peripheral} = 4\nu\left(\frac{1}{\tau_{f,p}} - \frac{1}{\tau_{f,c}}\right)$$

but maybe $\sigma_n \approx 2\sigma_*$ STAR, PRC 66, 044904 (2006)

uncertainty range $\sigma_* \leq \sigma \leq 2\sigma_*$ $\Rightarrow$ $0.08 < \eta/s < 0.3$

p_t Fluctuations Energy Independent



sources of p_t fluctuations: thermalization, flow, jets?

- central collisions ⇒ thermalized
- energy independent bulk quantity ⇒ jet contribution small