Long Range Correlations and Hydrodynamic Expansion

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I. Correlations: PHOBOS Data, Flux Tubes and Causality

II. Ridge: Transverse Flow, Blast Wave

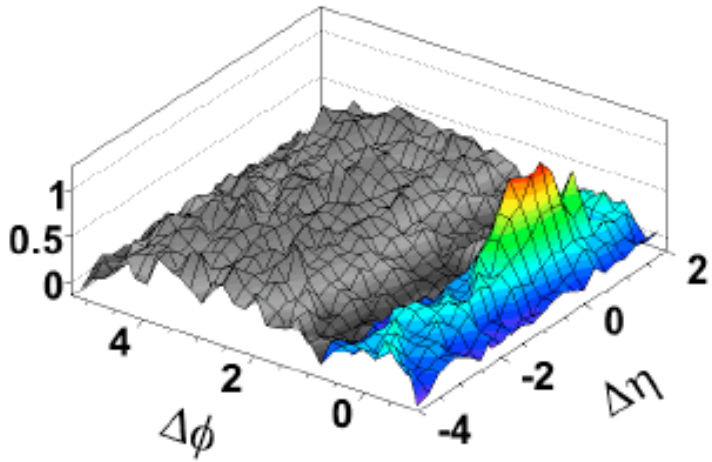
III. Glasma Flux Tubes

IV. STAR data: Au+Au and Cu+Cu

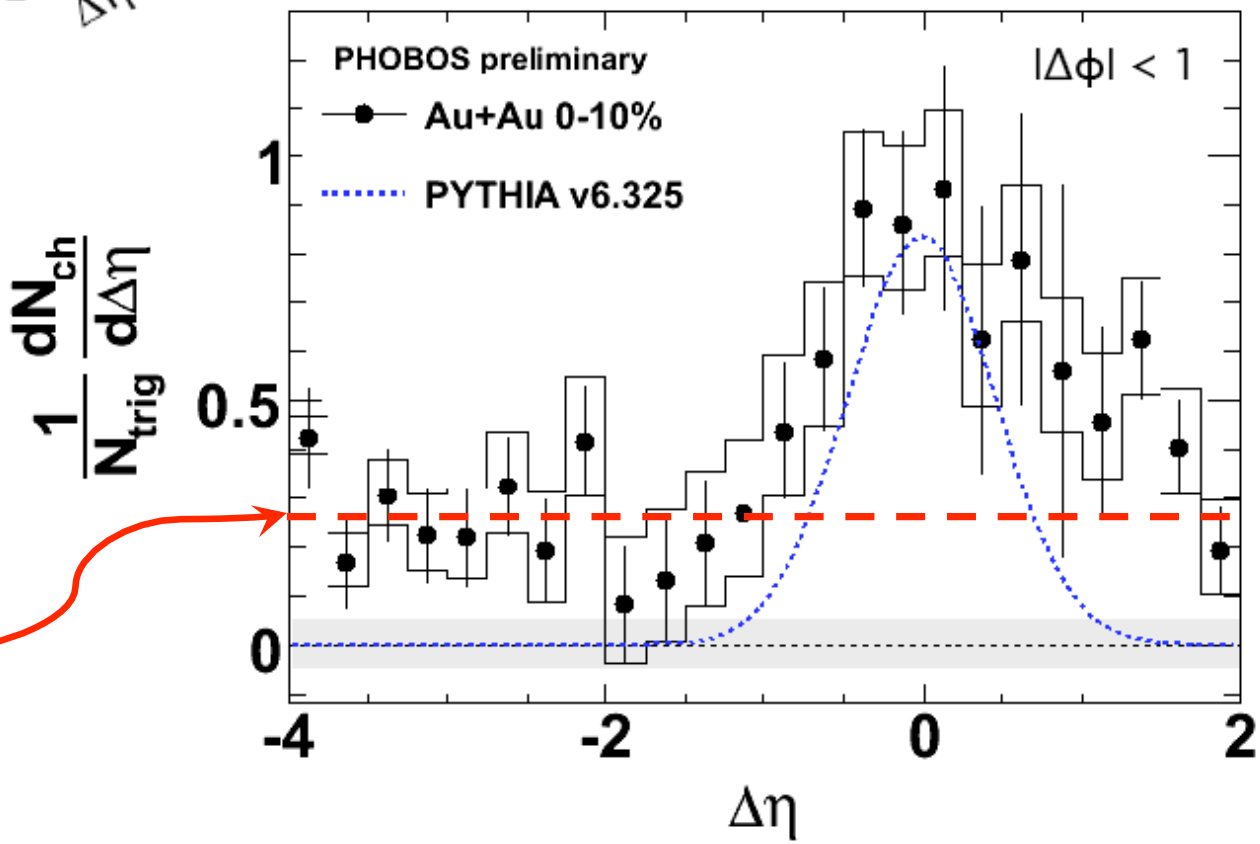
V. Questions:

- A. STAR Rapidity Dependence?
- B. How Robust is the Ridge?

PHOBOS: Long Range Correlations



$p_T^{trig} > 2.5$ GeV/c
$p_T^{assoc} \gtrsim 20$ MeV/c



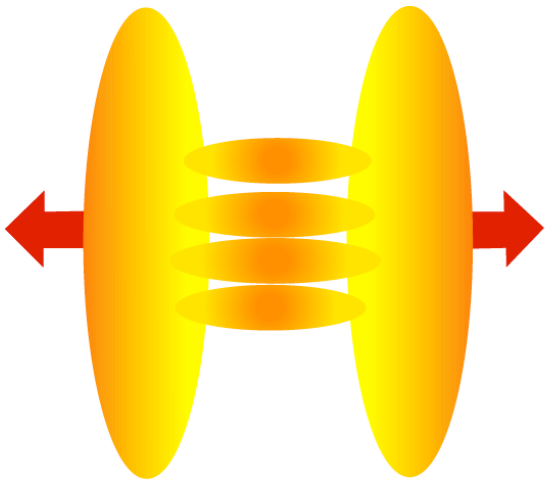
long range correlations

Flux Tubes ⇒ Long Range Correlations

flux tubes: longitudinal fields early on

Dumitru, Gelis, McLerran, Venugopalan, arXiv:0804.3858

fields → gluons + quarks

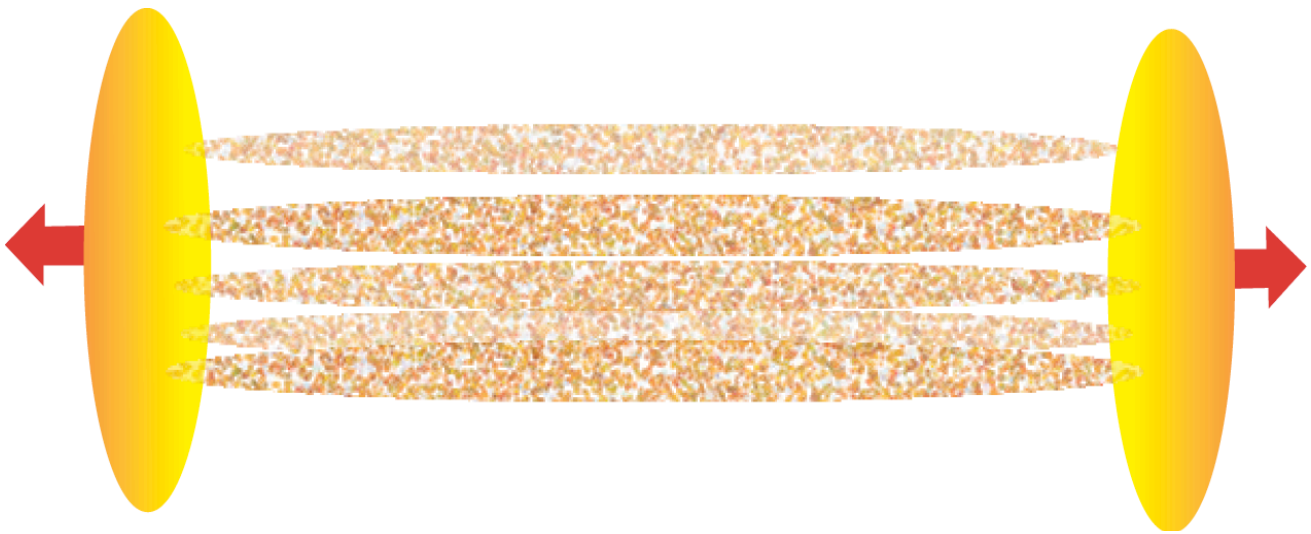


correlated partons from same flux tube

causally disconnected -- diffusion can't erase these correlations

Flux Tubes ⇒ Long Range Correlations

correlations: flux tube number and positions vary event by event



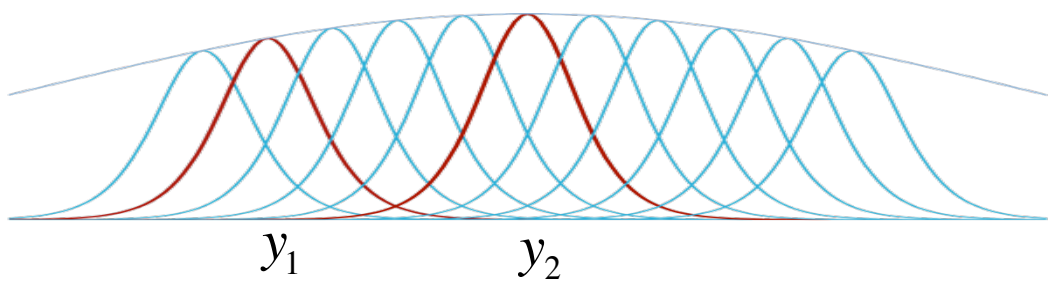
only initial-state correlations affect large intervals $\Delta y = y_1 - y_2$

diffusion can't erase correlations for

$$\Delta y > \left(2\nu / \tau_0\right)^{1/2}$$

kinematic viscosity

$$\nu = \eta / sT$$



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

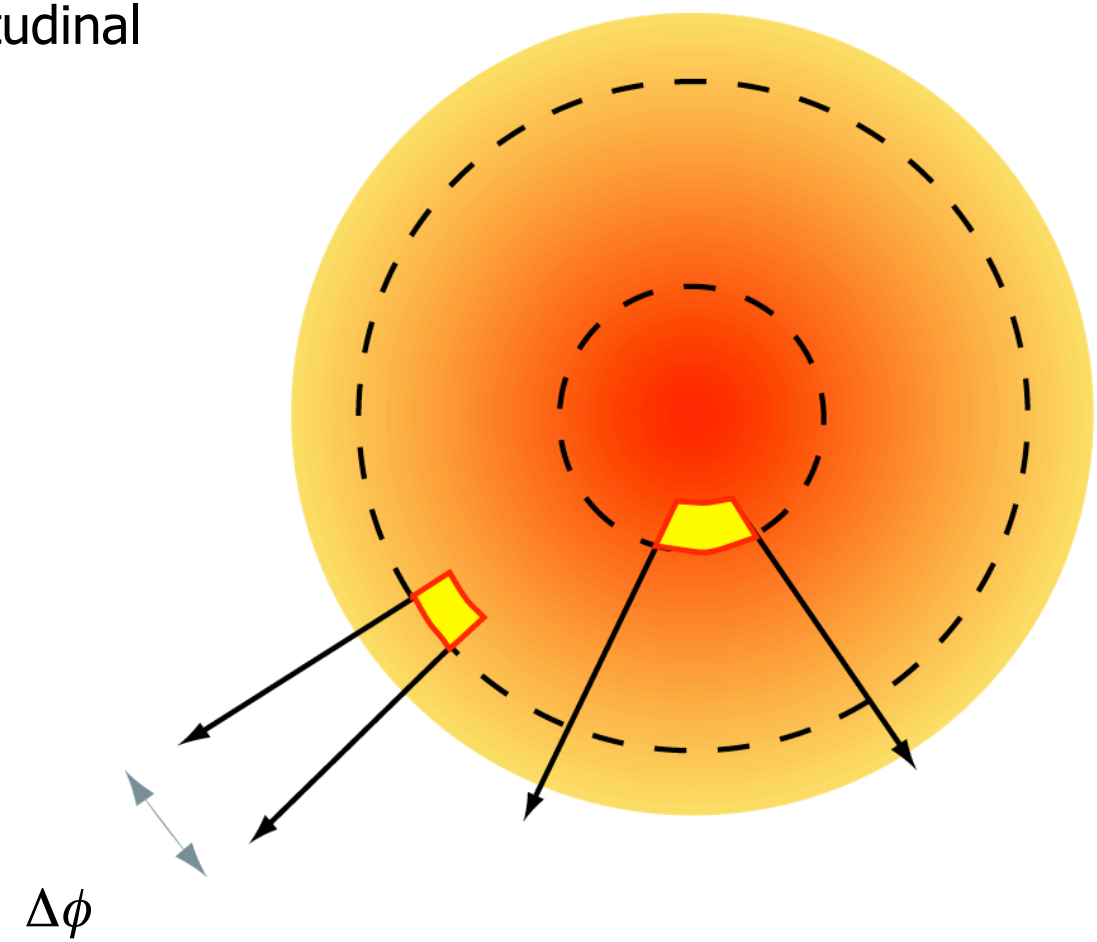
Transverse Flow ⇒ Near-Side ϕ Peak

bulk correlations - longitudinal string fragmentation

string position $\vec{r}$

transverse boost
thermalization and flow

$\vec{v}_t \sim \lambda \vec{r}$



flow ⇒ narrow opening angle

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

Voloshin; Pruneau, Gavin, Voloshin; Gavin, Moschelli, McLerran; Shuryak; Mocsy & Sorenson

Flow Works!

Hydrodynamics

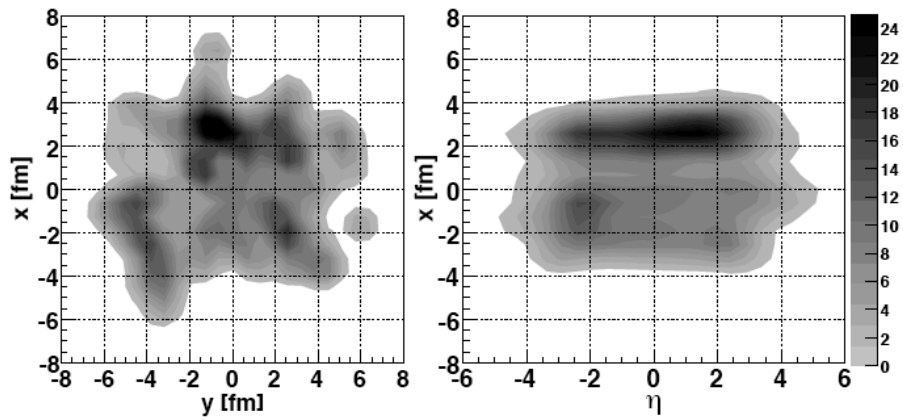
Takahashi, Tavares, Qian, Grassi, Hama, Kodama, Xu

Phys. Rev. Lett. 103, 242301 (2009)

see also:

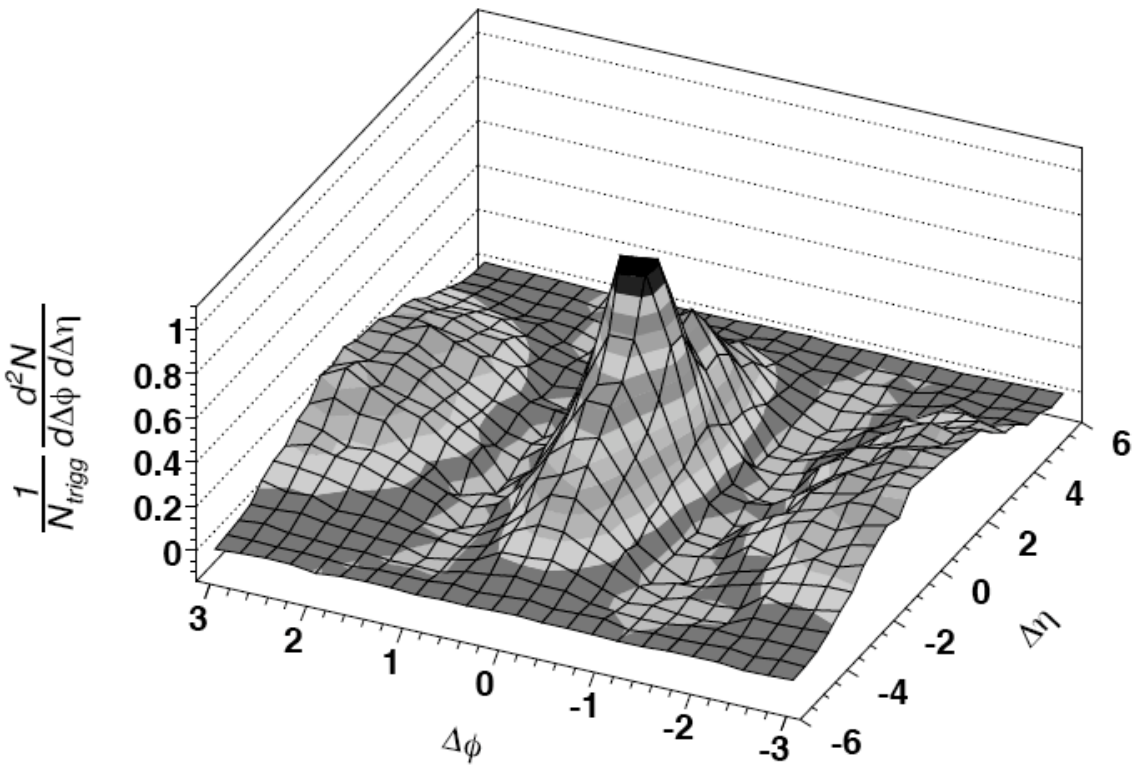
Werner, Karpenko, Pierog, Bleicher, Michailov

arXiv:1004.0805

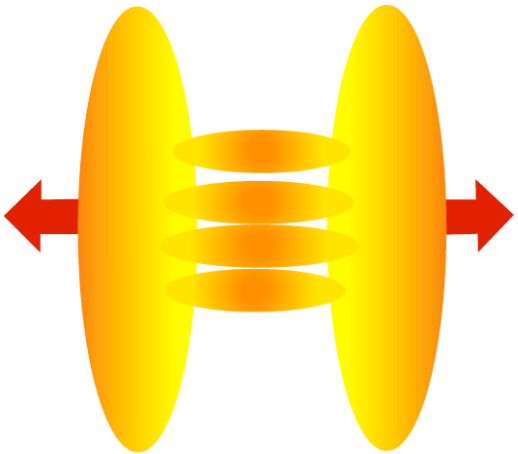


correlations
NEXUS strings

transverse boost
SPHERIO hydro



Flux Tubes in Glasma



N_{FT} flux tubes

gluon rapidity density

$$\frac{dN}{dy} = \frac{\text{gluons}}{\text{tube}} \times \langle N_{FT} \rangle \propto \alpha_s^{-1}(Q_s) \langle N_{FT} \rangle$$

fluctuations in the number of flux tubes

$$R = \frac{Var(N) - \langle N \rangle}{\langle N \rangle^2} \propto \frac{1}{\langle N_{FT} \rangle}$$

long range glasma fluctuations

$$R \frac{dN}{dy} \propto \alpha_s^{-1}(Q_s)$$

Dumitru, Gelis, McLerran & Venugopalan;
SG, McLerran & Moschelli

Glasma + Blast Wave ⇒ Ridge Height

pair correlation function -- Cooper Frye freeze out

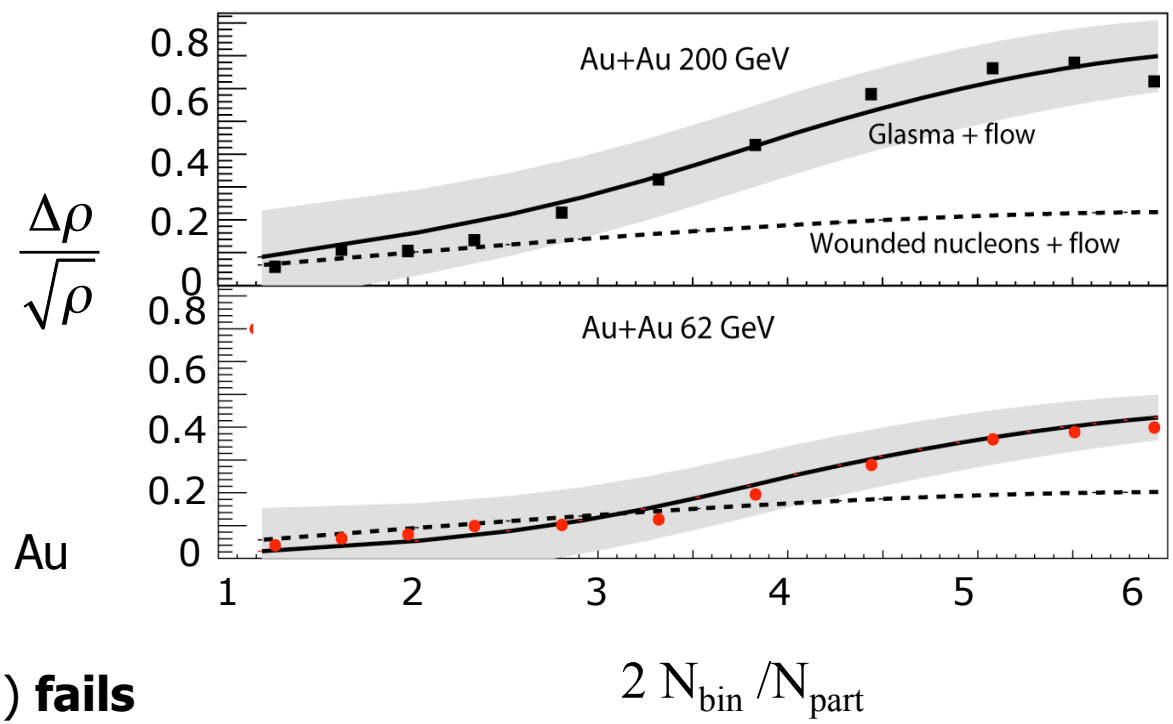
$$\Delta\rho \equiv \text{pairs} - (\text{singles})^2 \quad \propto \iint_{\text{freezeout surface}} f(p_1,x_1) f(p_2,x_2) c(x_1,x_2)$$

- blast wave → $f(p,x)$
- scale factor to fit 200 GeV only
- Glasma energy dependence

$$R\, dN/dy \propto \alpha_s^{-1}(Q_s)$$

STAR Data, J.Phys. G35 (2008) 104090

SG, McLerran, Moschelli et al. PRC 79 (2009) 051902



Glasma Q_s dependence: 200 GeV Au +Au ⇒ 62 GeV, Cu+Cu

wounded nucleon model (dashed) **fails**

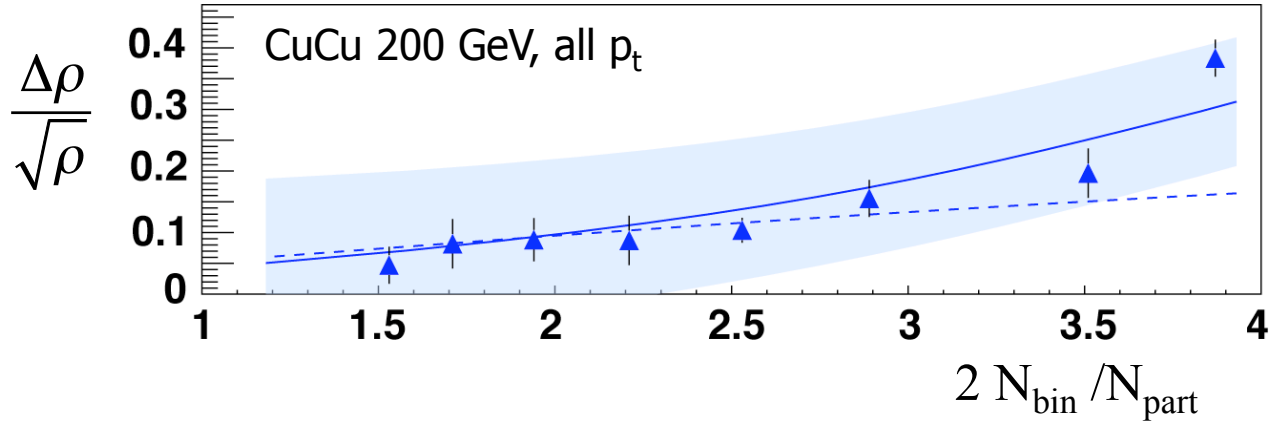
Peak Amplitude of the Soft Ridge

STAR data, preliminary

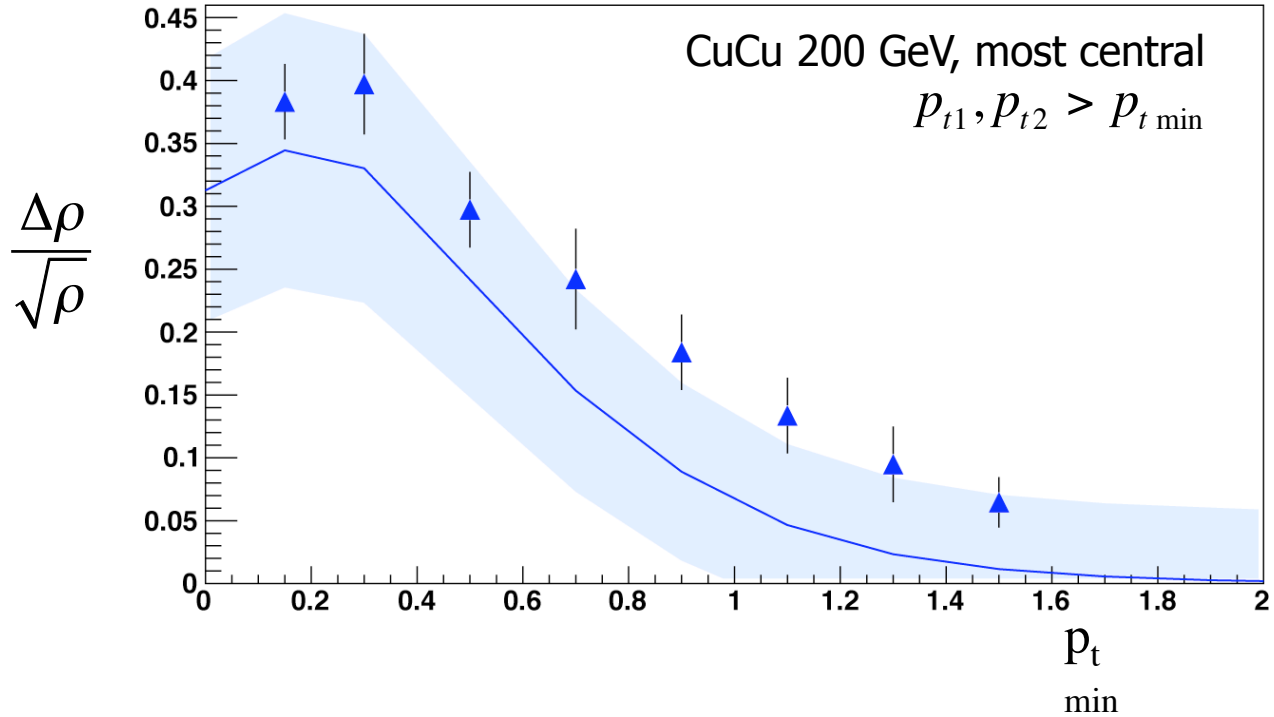
Moschelli & SG

Ridge amplitude vs. Centrality, all p_t

→ L. Ray's talk



Ridge amplitude for $p_{t1}, p_{t2} > p_{t\,\min}$

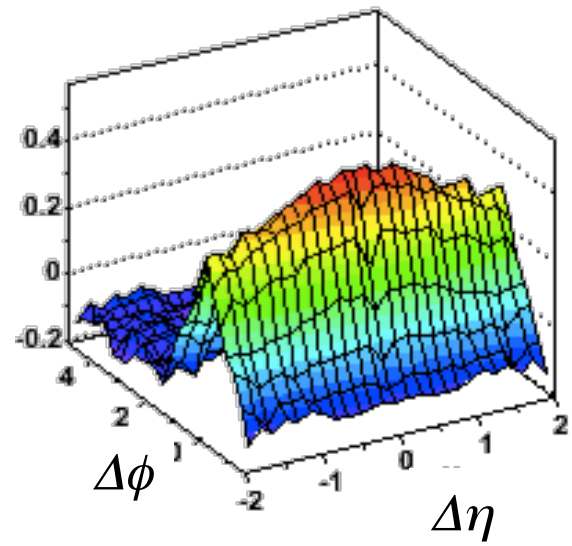


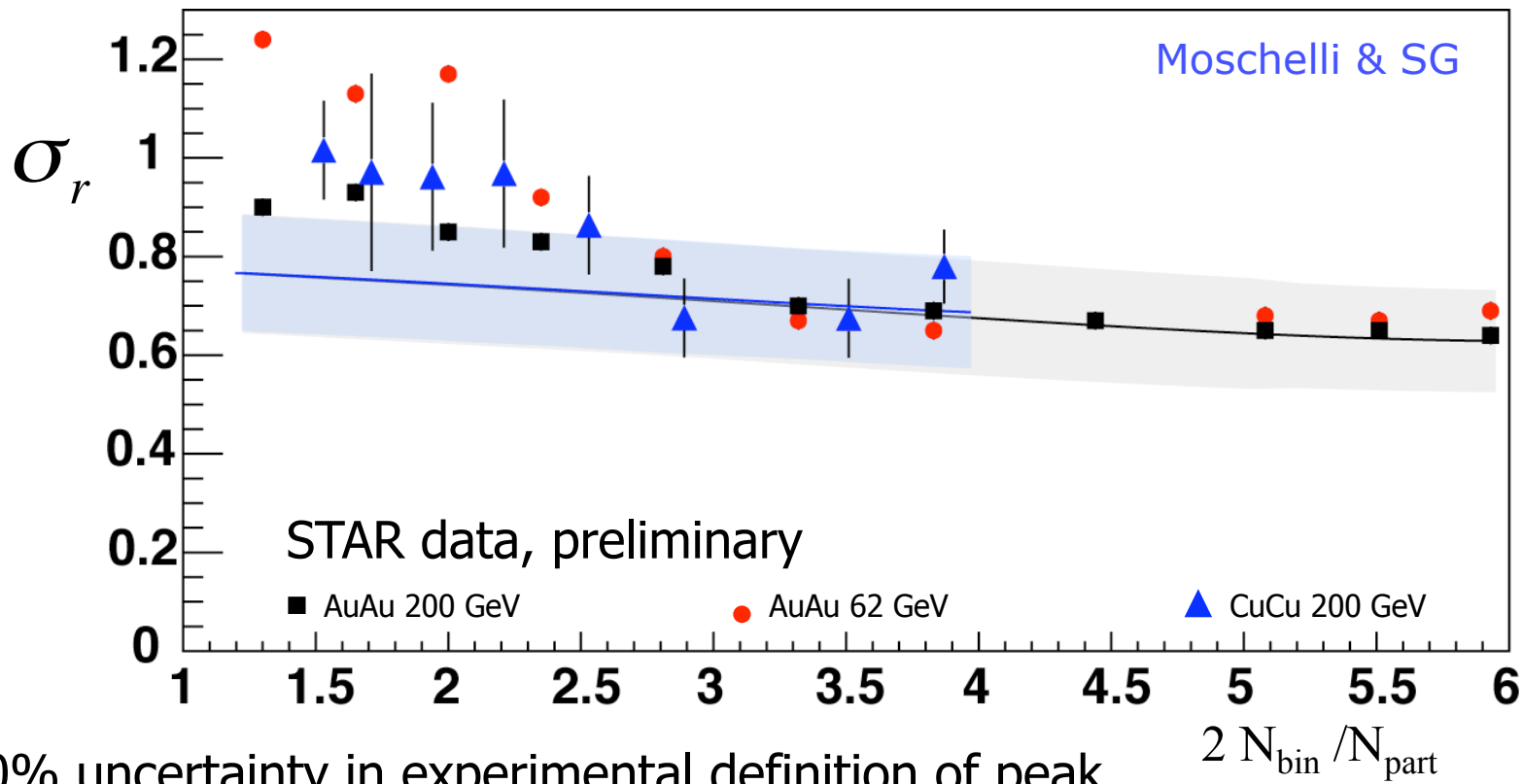
Amplitude decreases for higher $p_{t\,\min}$

bands: uncertainty of blast wave parameters and Q_s extrapolated from AuAu

Angular Width of the Soft Ridge

near side $\Delta\phi$ width decreases with increasing centrality



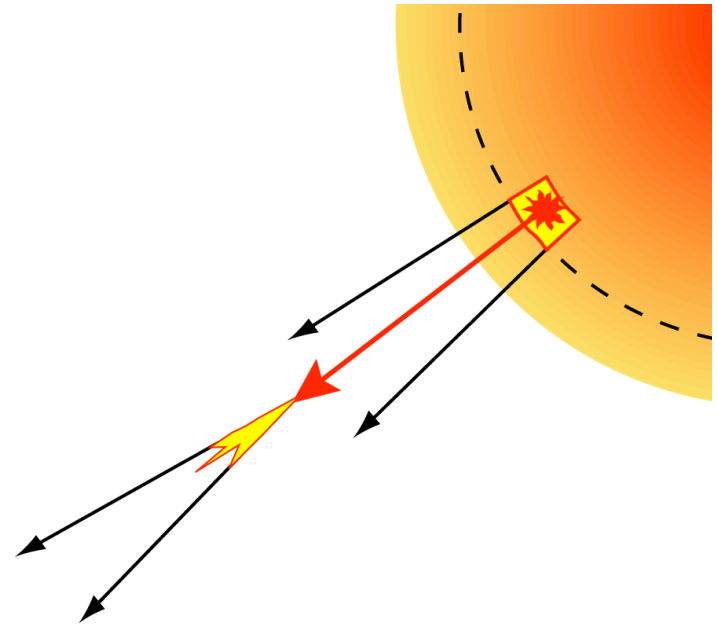


bands: 20% uncertainty in experimental definition of peak

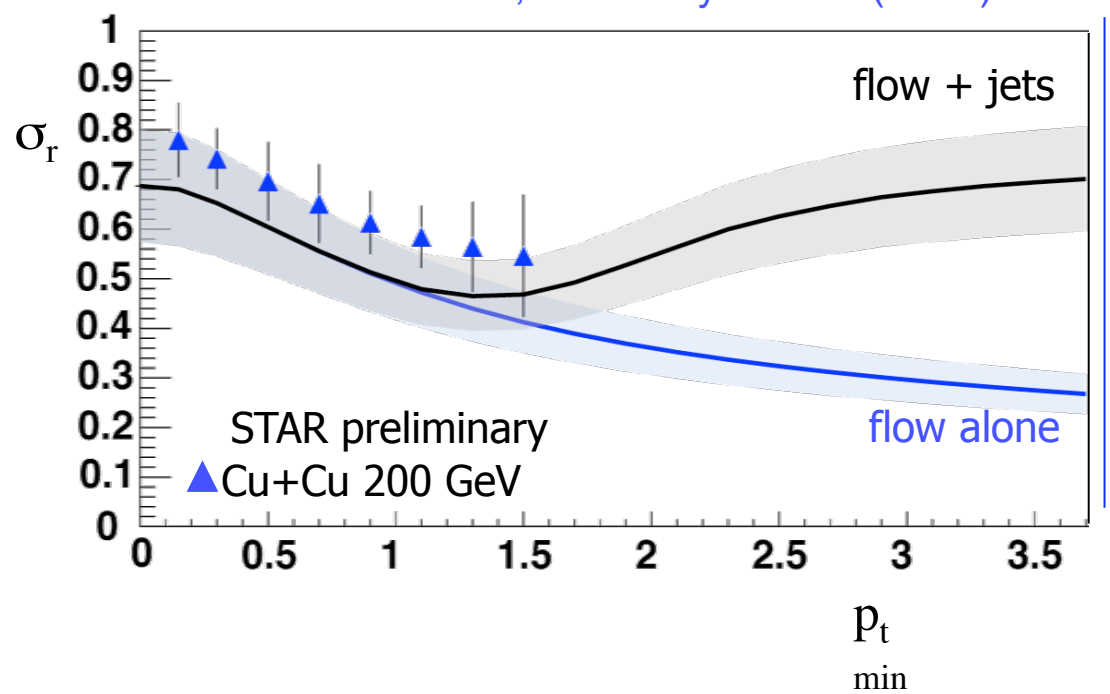
Ridge: from Soft to Hard

STAR $\Delta\rho$ with low p_t cutoff

- Hard: Jets + quenching
- Bulk: Glasma + flow
- Bulk - Hard correlations



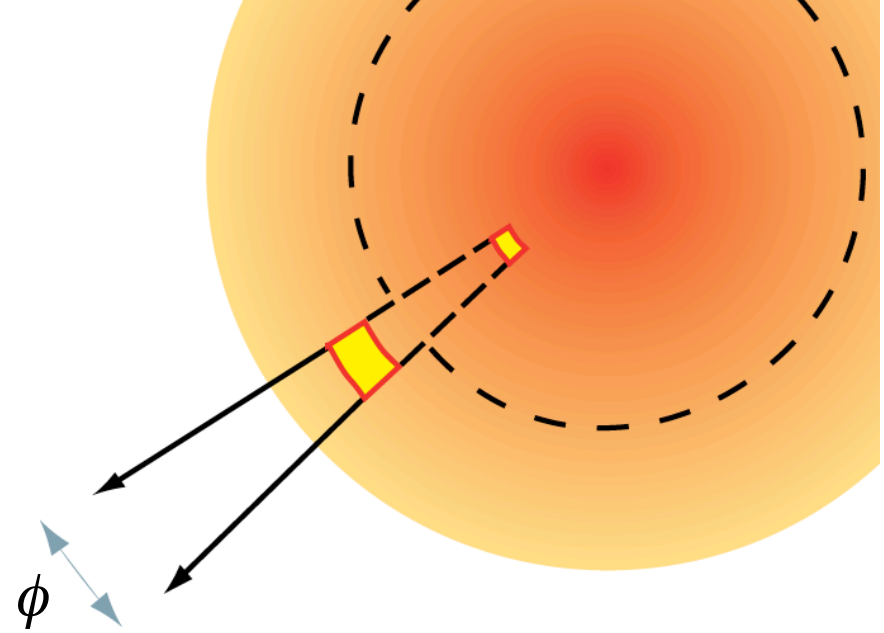
G. Moschelli & SG, Nucl. Phys. A836 (2010) 43



Jet quenching ⇒ near side bias may explain hard ridge

Shuryak, Phys Rev C76, 047901,2007

The Ridge is Robust



Correlations in relative ϕ, not position

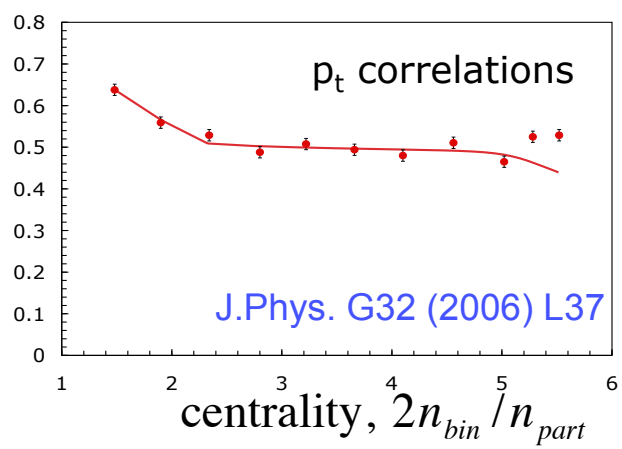
- flow ⇒ most particles move radially
- pythia + small radial boost → ridge

NEXSPERIO: ideal hydro ⇒ ridge
→ F. Grassi's talk

Can diffusion (multiple scattering) drive correlated particles to $|\phi_1 - \phi_2| > \pi$

- radial flow
- viscous diffusion
- Langevin noise

azimuthal ridge width



SG, G. Moschelli, J.Phys.G35 (2008) 104084;

Pang et al., Phys.Rev.C81 (2010) 031903

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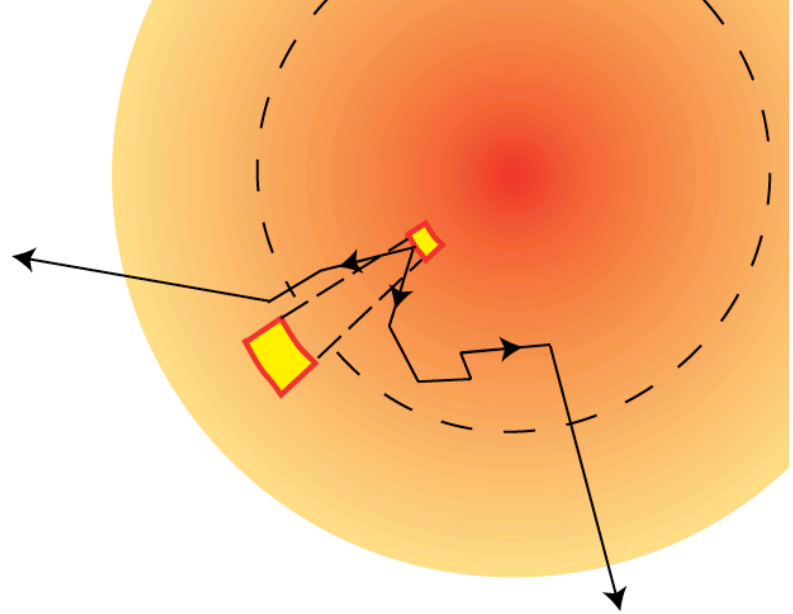

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- flow $\Rightarrow$ most particles move radially
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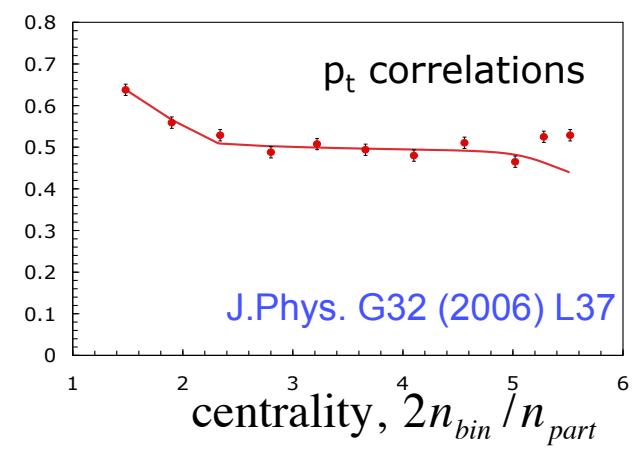


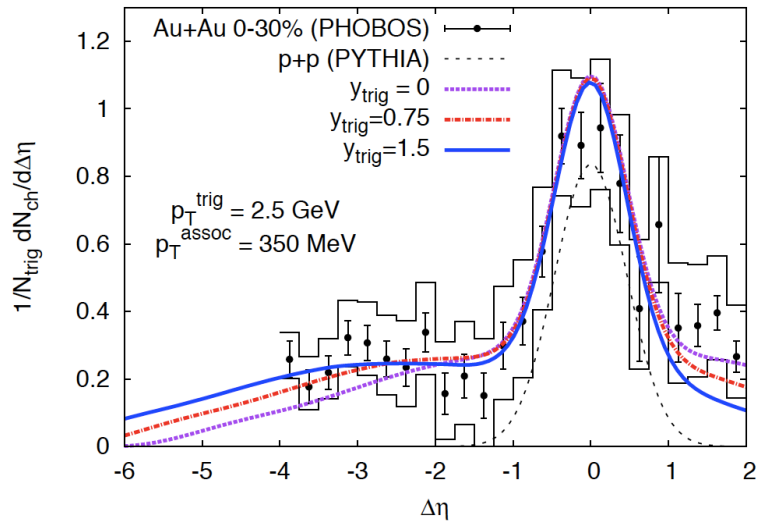
SG, G. Moschelli, J.Phys.G35 (2008) 104084;

Pang et al., Phys.Rev.C81 (2010) 031903

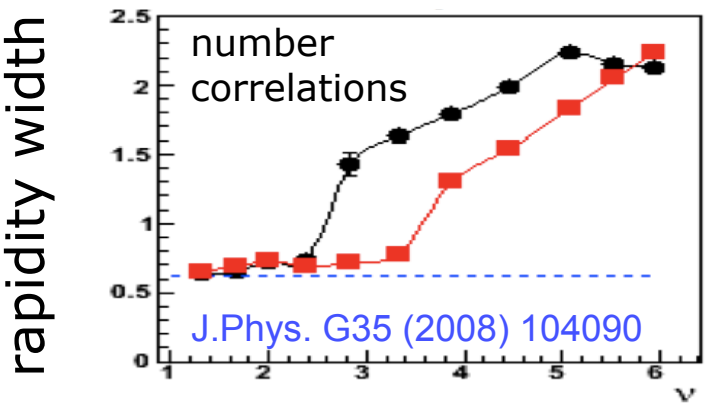
Rapidity Dependence

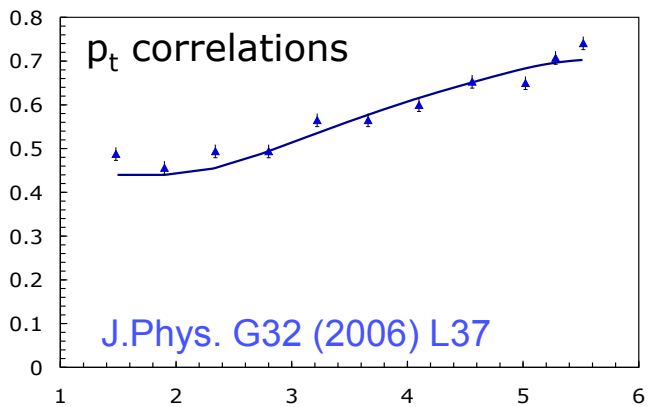
CGC long range correlations
explain PHOBOS triggered ridge

Dusling, Gelis, Lappi, Venugopalan
arXiv:0911.2720



Question: what about STAR centrality dependence?





- why does rapidity width increase with centrality?
- why are number and p_t correlations so different?

viscous diffusion can account for p_t correlations

SG & Abdel-Aziz, PRL 97 (2006) 162302; G. Moschelli, J.Phys.G35:104084,2008

Summary: the Ridge, the Glasma, and Radial Flow

Long range correlations ⇒ new info on particle production

- PHOBOS covers large rapidity interval → isolate CGC contribution
- STAR measurements $|\eta| < 1$ interesting implications

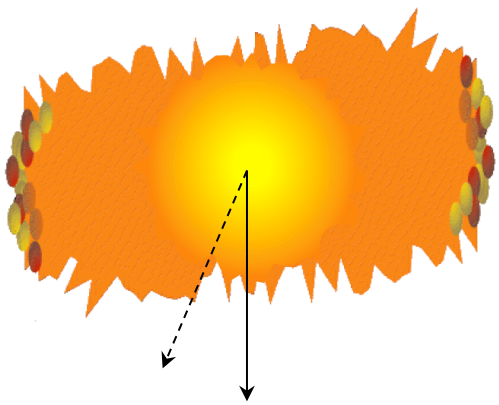
Blast wave + Glasma describes height and azimuthal width of both Hard and Soft Ridge

- blast wave fixed by single particle spectra
- Glasma fixed by dN/dy and 200 GeV Au+Au
- Predict energy, centrality, system size and p_t dependence

Azimuthal width vs. $p_{t\,min}$ can distinguish flow from jets

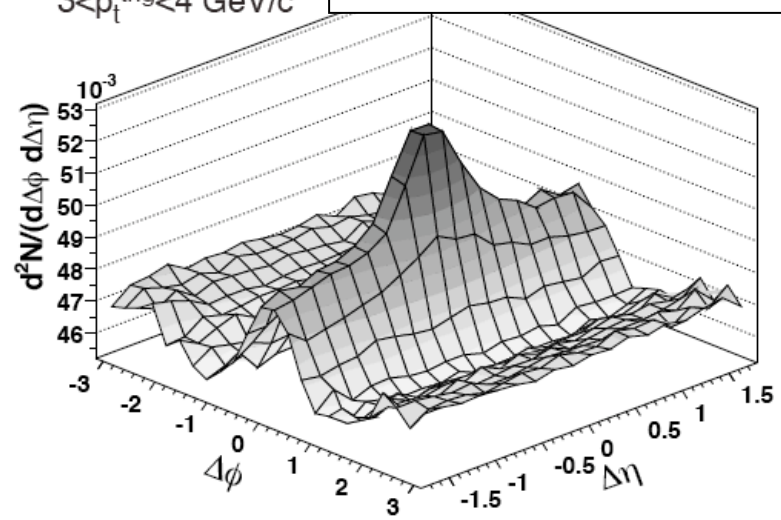
Hard Ridge: Jet + Associated Particles

high p_t trigger - measure yield of associated particles

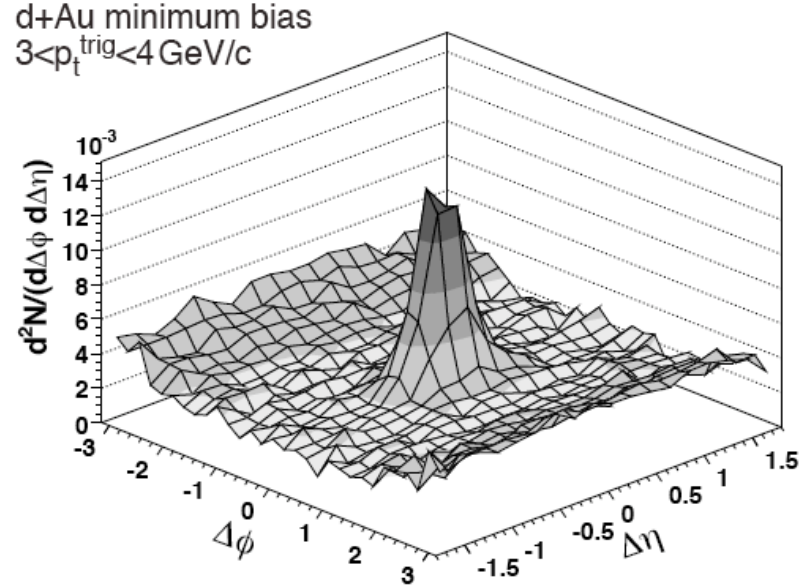


Au+Au central
$3<p_t^{trig}<4$ GeV/c

STAR: arXiv:0909.0191



d+Au minimum bias
$3<p_t^{trig}<4$ GeV/c



hard ridge: near side peak

- peaked near $\Delta\phi = 0$
- broad in $\Delta\eta$

Soft Ridge: Untriggered Correlations

two particle correlations with no jet tag

STAR: arXiv:0806.2121

measure:

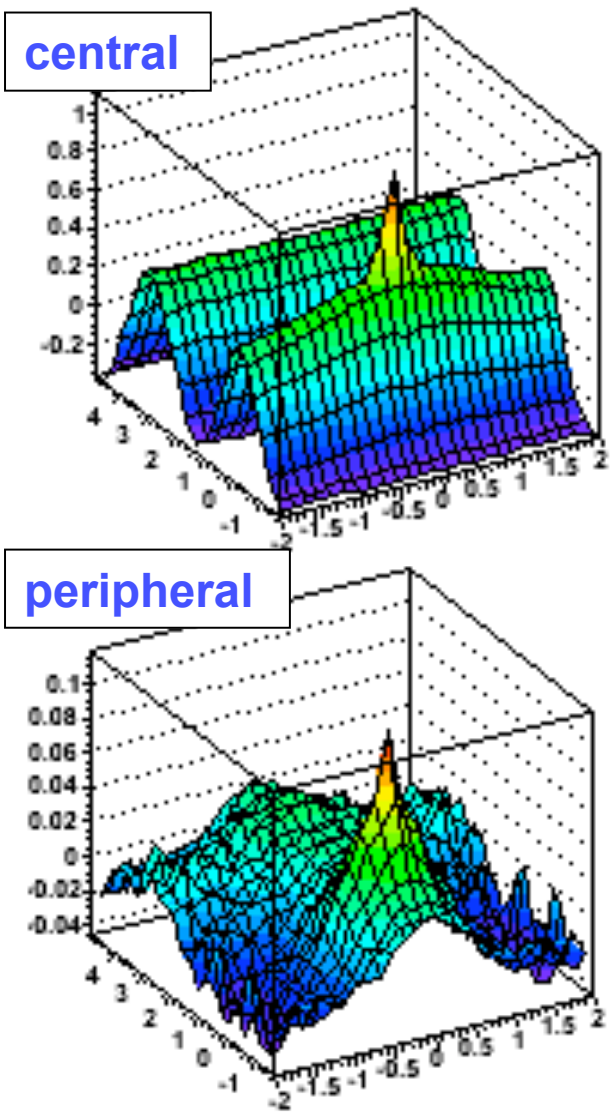
$$\frac{\Delta\rho(\eta,\phi)}{\sqrt{\rho_{ref}}} = \frac{\text{pairs} - (\text{singles})^2}{\text{singles}}$$

soft + hard ridges similar

- peaked near $\Delta\phi = 0$
- broad in $\Delta\eta$

common features

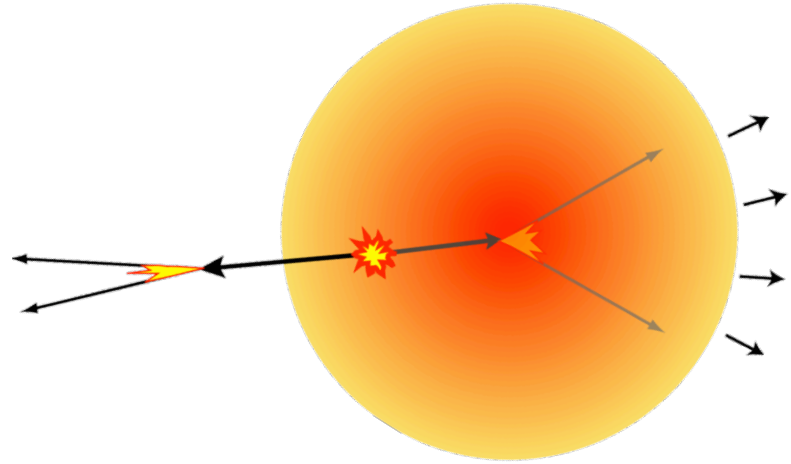
- $\Delta\eta$ width increases with centrality
- peripheral ~ proton+proton



Hard Ridge

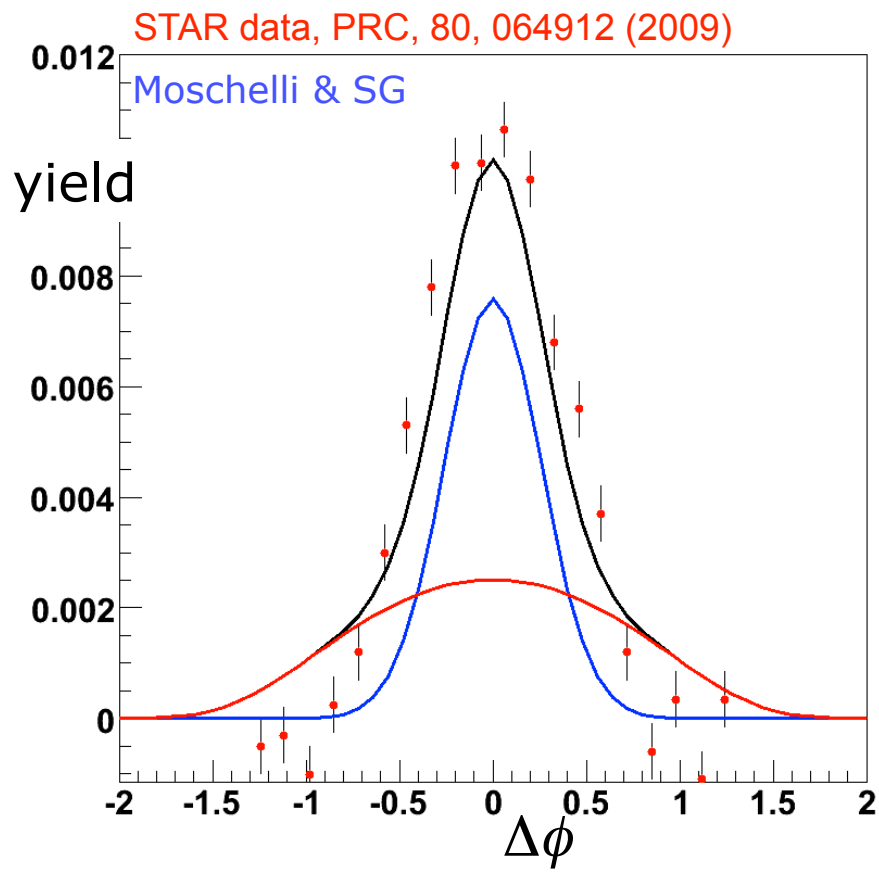
Jet quenching ⇒ near side bias may explain hard ridge

Shuryak, Phys Rev C76, 047901,2007



Compute yield of associated particles and and angular shape

- dN/dp_t constrains jet fraction
- jet scale $\propto Q_s$; take $1.5\ \mathrm{GeV}$



Find: jets plus flow fits hard ridge

~ 60% flow for $3\ \mathrm{GeV} < p_{t,\mathrm{trigger}} < 4\ \mathrm{GeV}$, $2\ \mathrm{GeV} < p_{t,\mathrm{assoc}} < p_{t,\mathrm{trigger}}$