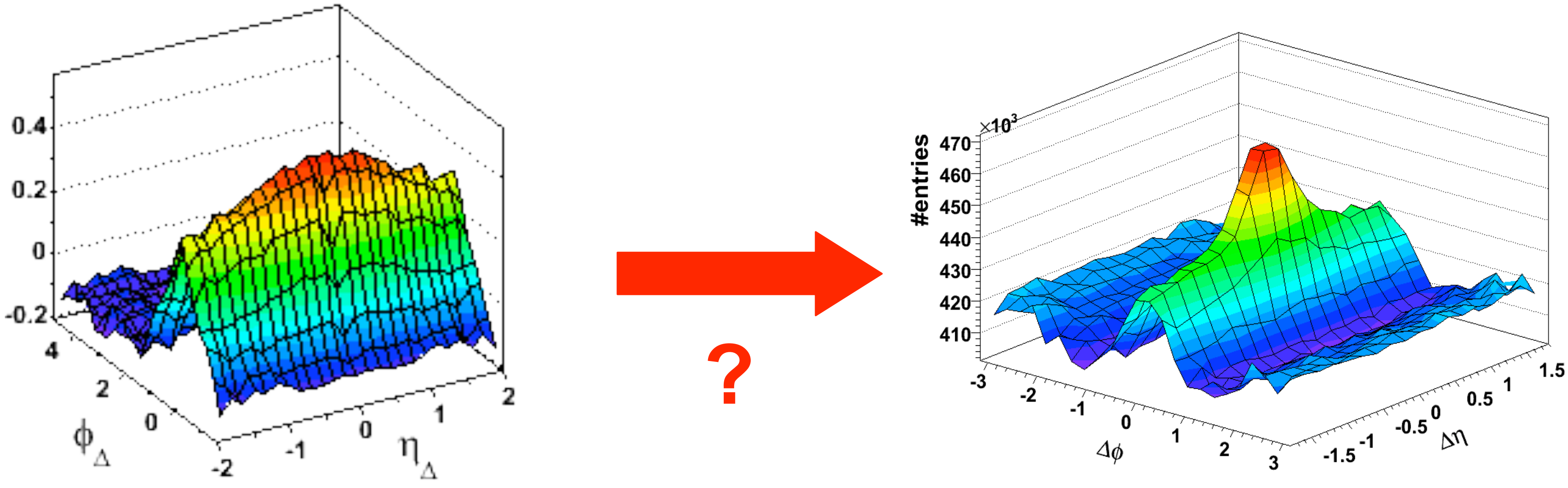
Soft Contribution to the Hard Ridge

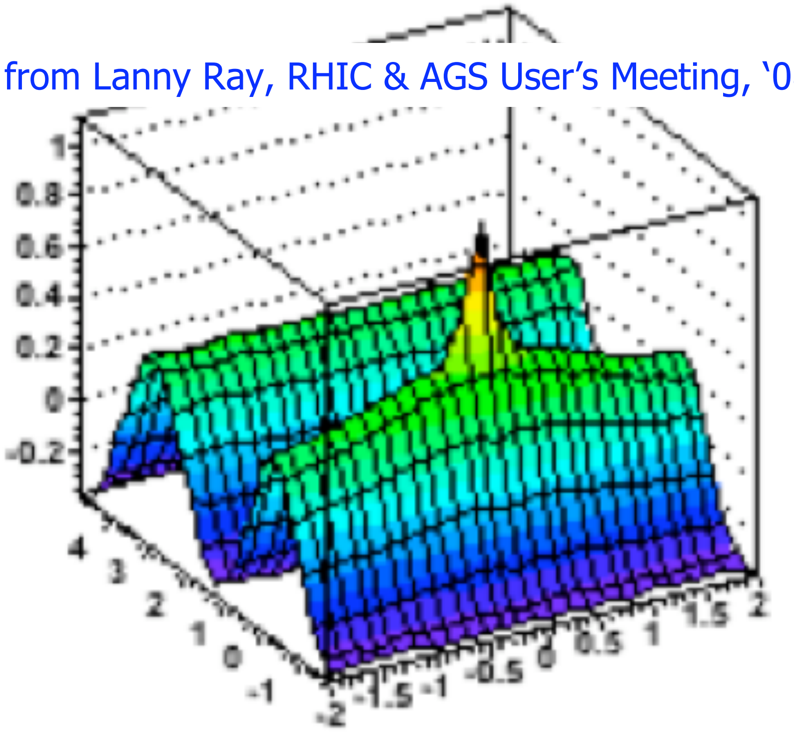


George Moschelli
Sean Gavin
DPF July 31, 2009
Wayne State University

Outline:

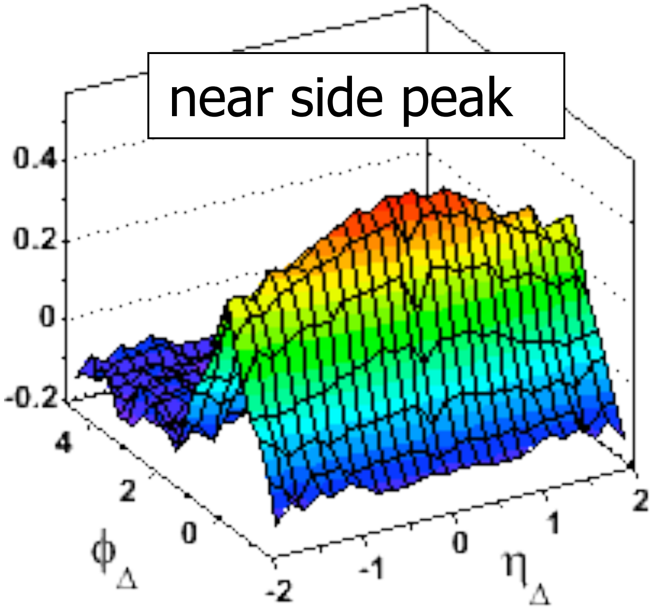
- The soft ridge and bulk correlations
- p_t dependence on bulk correlations
- Jet correlations with bulk
- Relative contribution of bulk- bulk and jet-bulk correlations
- Summary

STAR: Soft Ridge



from Lanny Ray, RHIC & AGS User’s Meeting, ‘08

- Correlation function with no p_t trigger ⇒ near side peak
- Rapidity width and amplitude increase with centrality
- Azimuthal width roughly constant


near side peak

Hard vs. Soft Ridge

hard ridge explanations -- jet interactions with matter

- N. Armesto, C.A. Salgado, U.A. Wiedemann, Phys. Rev. Lett. 93, 242301 (2004)
- P. Romatschke, Phys. Rev. C 75, 014901 (2007)
- A. Majumder, B. Muller, S. A. Bass, Phys. Rev. Lett. 99, 042301 (2007)
- C. B. Chiu, R. C. Hwa, Phys. Rev. C 72, 034903 (2005)
- C. Y. Wong, arXiv:0712.3282 [hep-ph]
- R. C. Hwa, C. B. Yang, arXiv:0801.2183 [nucl-th]
- T. A. Trainor, arXiv:0708.0792 [hep-ph]
- A. Dumitru, Y. Nara, B. Schenke, M. Strickland, arXiv:0710.1223 [hep-ph]
- E. V. Shuryak, Phys. Rev. C 76, 047901 (2007)
- C. Pruneau, S. Gavin, S. Voloshin, Nucl.Phys.A802:107-121,2008

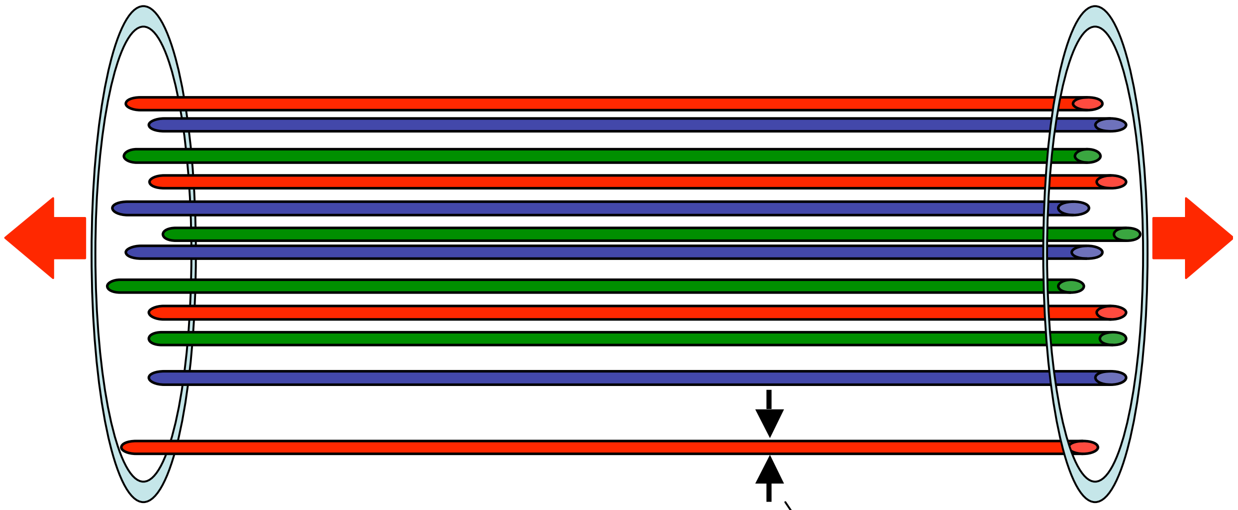
soft ridge -- similar but no jet -- collective behavior

- S. Gavin and M. Abdel-Aziz, Phys. Rev. Lett. 97, 162302 (2006)
- S. A. Voloshin, Phys. Lett. B 632, 490 (2006)
- S. Gavin and G. Moschelli, arXiv:0806.4366 [nucl-th]
- A. Dumitru, F. Gelis, L. McLerran and R. Venugopalan, arXiv:0804.3858 [hep-ph]
- S. Gavin, L. McLerran, G. Moschelli, arXiv:0806.4718 [nucl-th]
- F. Gelis, T. Lappi, R. Venugopalan, arXiv:0807.1306 [hep-ph]

Flux Tubes and Glasma

- Flux Tubes: longitudinal fields early on

- Tubes→quarks+gluons



flux tube transverse size ~ $Q_s^{-1} \ll R_A$

- Correlation function:
  - Partons from the same tube are correlated
  - Correlations between tubes are negligible

$$c(\mathbf{x}_1, \mathbf{x}_2) \sim \mathcal{R}\,\delta(\vec{r}_{t,1} - \vec{r}_{t,2})$$

correlation strength

- Causally disconnected

Flux Tubes and Correlations

- Gluon rapidity density

  Kharzeev & Nardi:

$$\frac{dN}{dy} \propto \alpha_s^{-1}(Q_s) Q_s^2 R_A^2$$

- Correlation Strength

$$\mathcal{R} \propto \langle \#tubes \rangle^{-1} = (Q_s R_A)^{-2}$$

- Long range **Glasma** fluctuations scale the phase space density

$$\mathcal{R}\frac{dN}{dy} \propto \alpha_s^{-1}(Q_s^2)$$

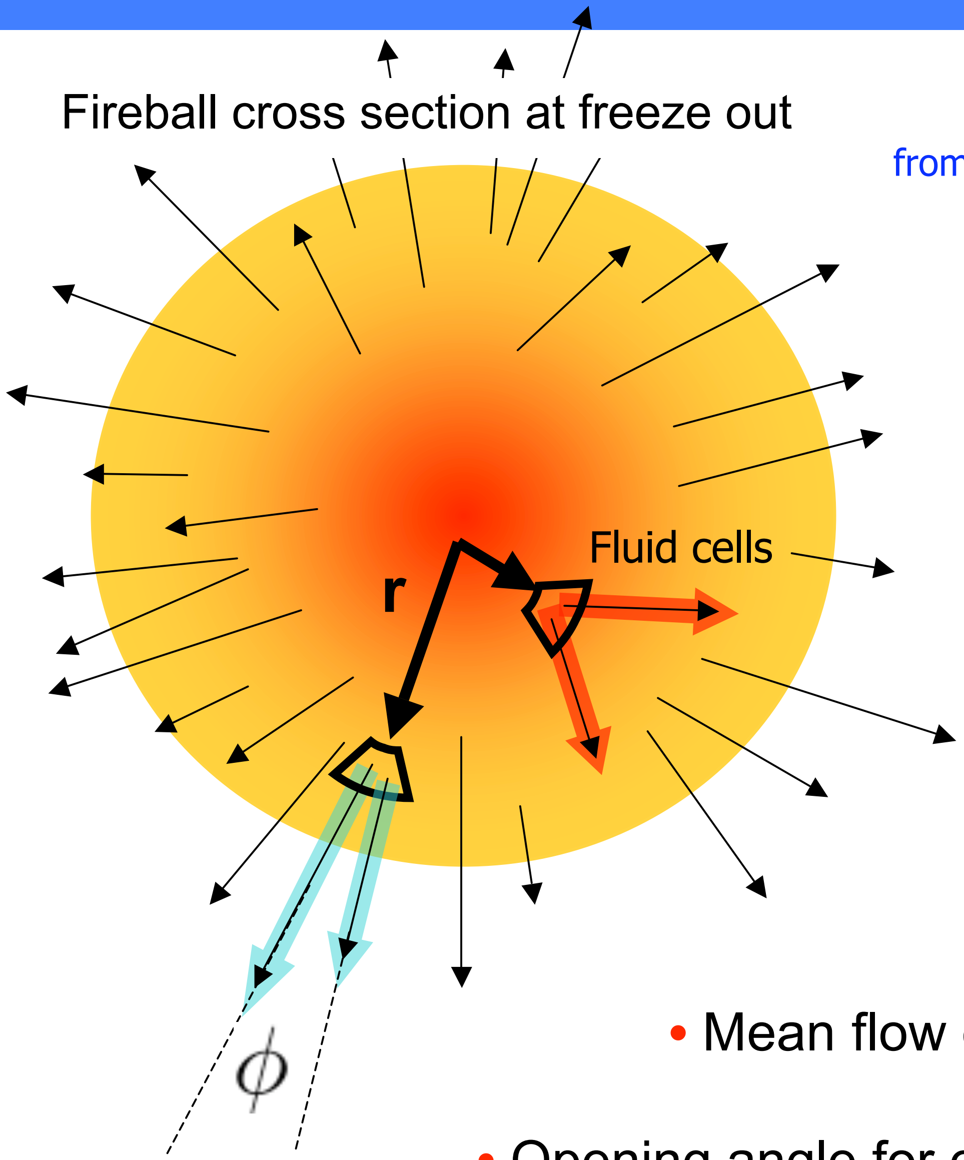
  Dumitru, Gelis, McLerran & Venugopalan;
  Gavin, McLerran & Moschelli

- Energy and centrality dependence of correlation strength

$$Q_s^2 \propto (\sqrt{s})^{1/3} (N_{part})^{1/3}$$

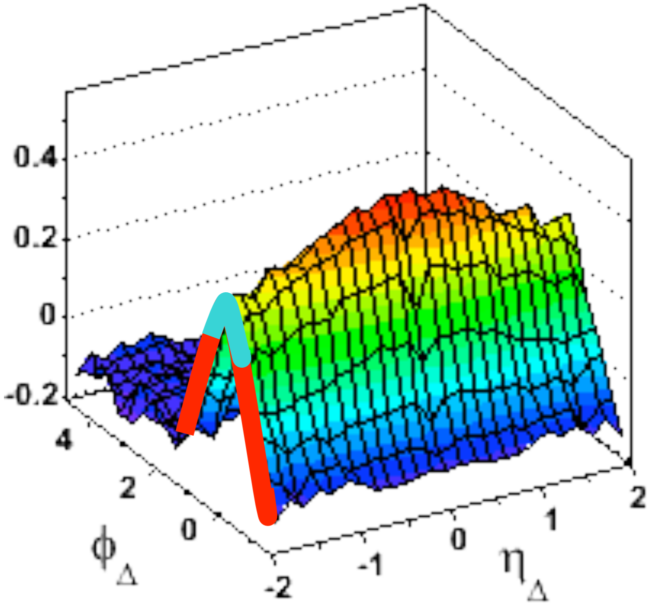
Flow and Azimuthal Correlations

Fireball cross section at freeze out



STAR soft ridge

from Lanny Ray, RHIC & AGS User's Meeting, '08



- Mean flow depends on position $\vec{v}_t \sim \lambda \vec{r}_t$
- Opening angle for each fluid element depends on **r** $\phi \sim v_{th}/v_t \propto (\lambda r_t)^{-1}$

Blast Wave and the Correlation Function

Schnedermann, Sollfrank & Heinz

- Single Particle Spectrum

$$\rho_1(\vec{p}) \equiv \frac{dN}{dyd^2p_t} = \int_{freezout} f(\vec{x},\vec{p})$$

$\gamma_t \vec{v}_t = \lambda \vec{r}$

A Hubble like expansion in used in a Boltzmann Distribution

- Correlation Function

$$\Delta\rho(\vec{p}_1,\vec{p}_2) \equiv pairs - (singles)^2$$

$$\Delta\rho(\vec{p}_1,\vec{p}_2) = \iint_{freezout} c(\vec{x}_1,\vec{x}_2) f(\vec{x}_1,\vec{p}_1) f(\vec{x}_2,\vec{p}_2)$$

- Normalization

$$\iint_{momenta} \Delta\rho = \iint_{positions} c = \langle N\rangle^2 \mathcal{R}$$

Glasma + Blast Wave

STAR measures:

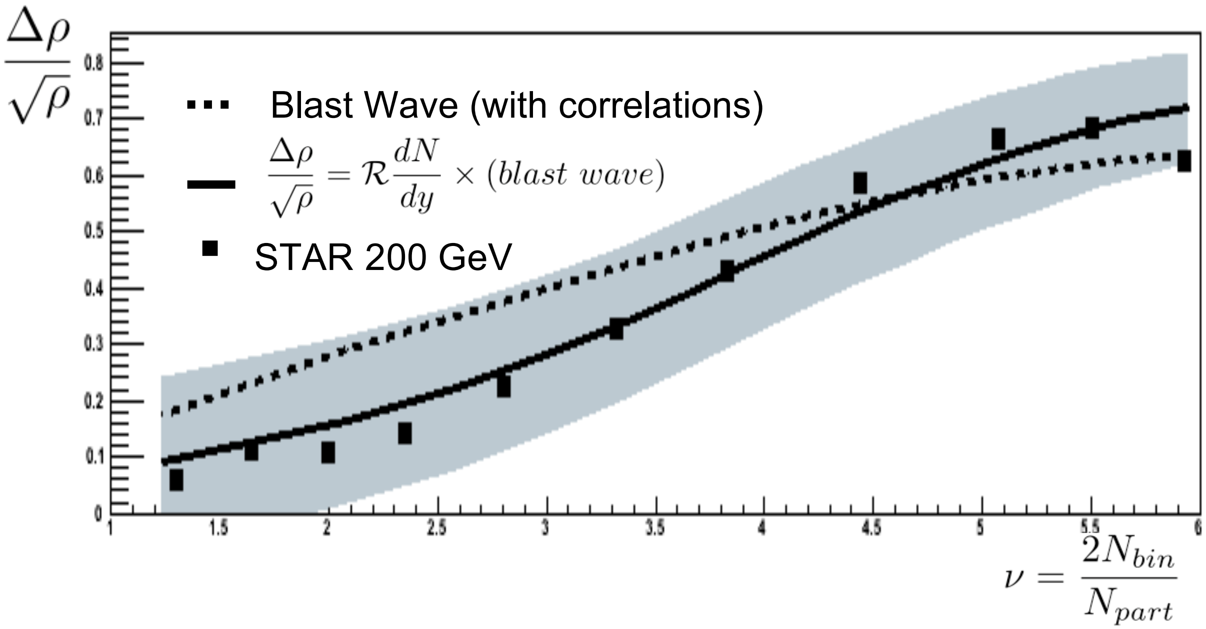
$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{\rho_2 - \rho_{2,mixed}}{\sqrt{\rho_{2,mixed}}}$$

We calculate:

$$\Delta\rho(\eta,\phi) = \iint\limits_{momenta} \Delta\rho(\vec{p}_1,\vec{p}_2)$$

$$\rho_{ref} = \iint\limits_{momenta} \rho_1(\vec{p}_1)\rho_1(\vec{p}_2)$$

Peak Amplitude Au-Au 200 GeV

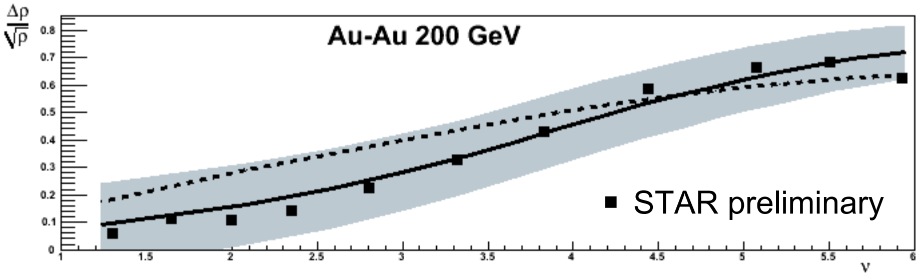


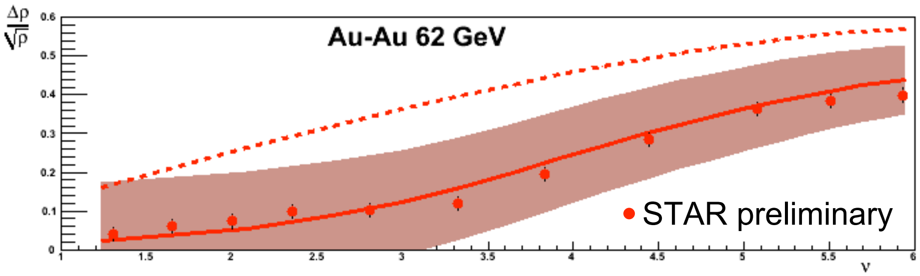
- BW scaled to fit 200 GeV
- v and T from Blast Wave

Akio Kiyomichi, PHENIX

- ~10% uncertainty from BW
- uncertainty from Q_s greatest in peripheral collisions

Energy and System Dependence





Au-Au data from Lanny Ray, RHIC & AGS User's Meeting, '08

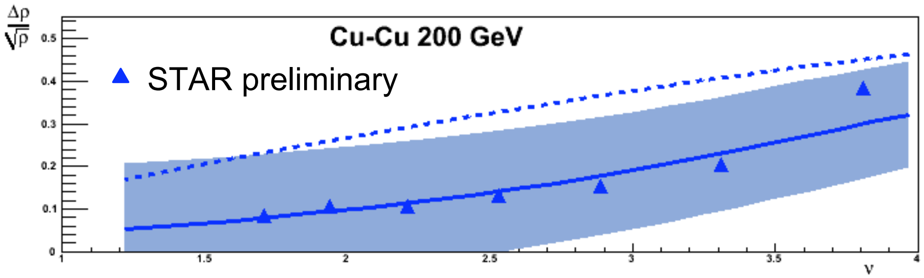
- Dashed lines from Blast Wave

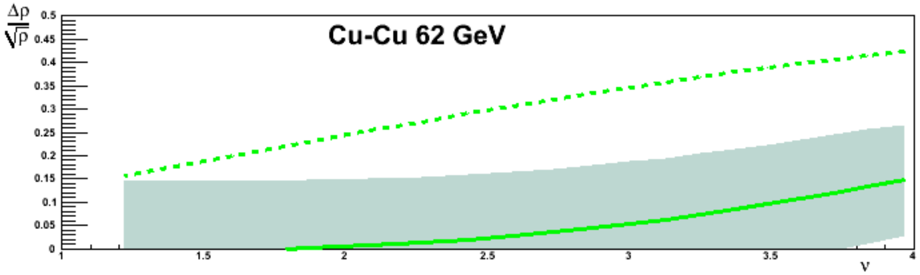
Centrality and some energy dependence on blast wave parameters (v and T)

- CGC adds energy and centrality dependence and now system dependence

- Theoretical Cu-Cu centrality and BW parameterizations follow Au-Au

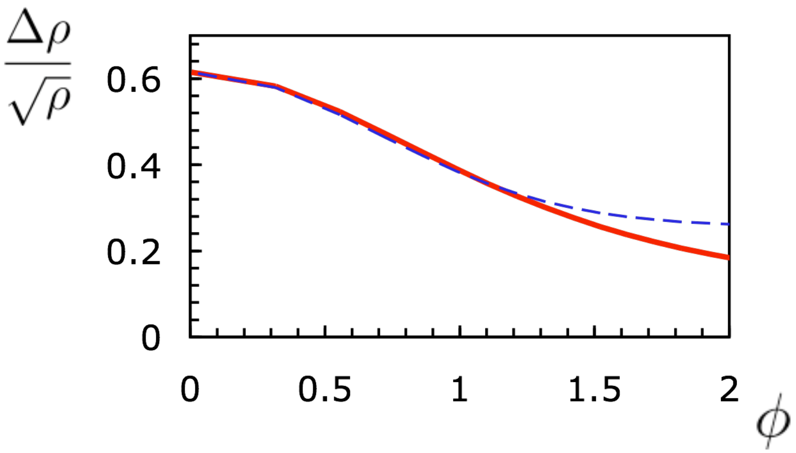
Cu-Cu 200 GeV data from Chanaka DeSilva





Angular Correlations

- Fit using Gaussian + offset

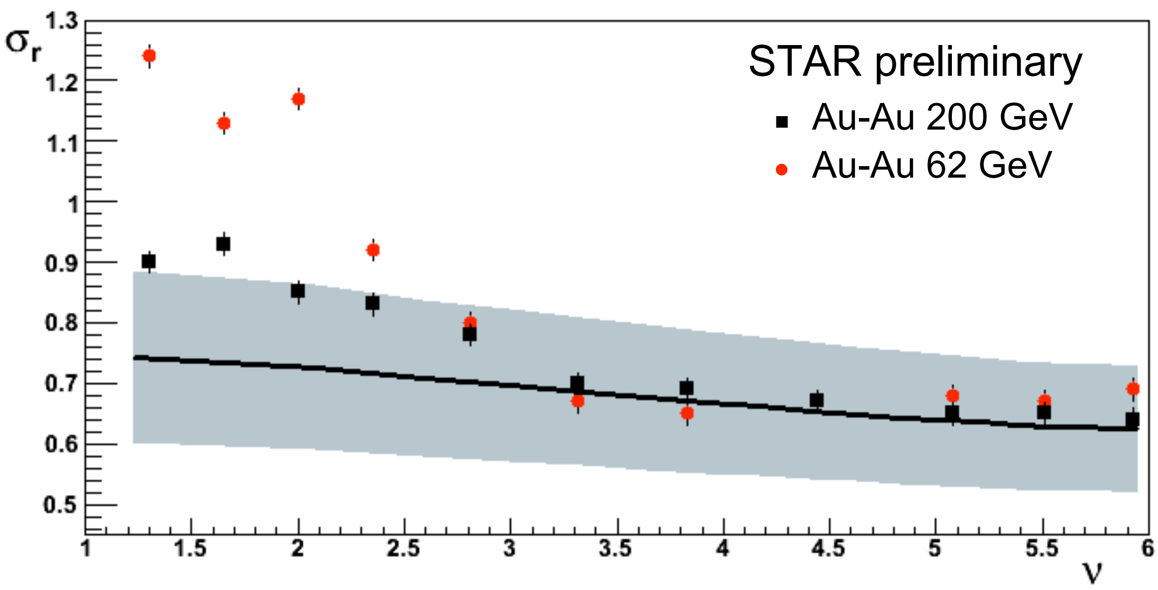


- Range: $-\pi/2 < \phi < \pi/2$

- Error band: 20% shift in fit range

- Computed angular width is approximately independent of energy

Peak ϕ Width



Cu-Cu Angular Correlations

- Fit using Gaussian + offset
- Range: $-\pi/2 < \phi < \pi/2$
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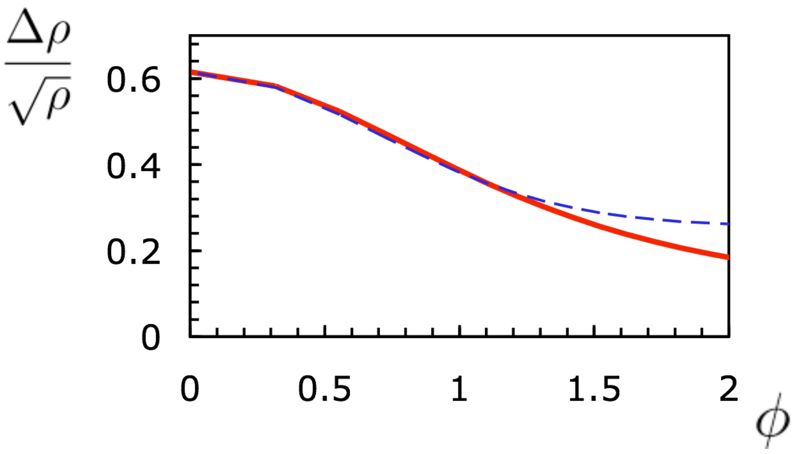
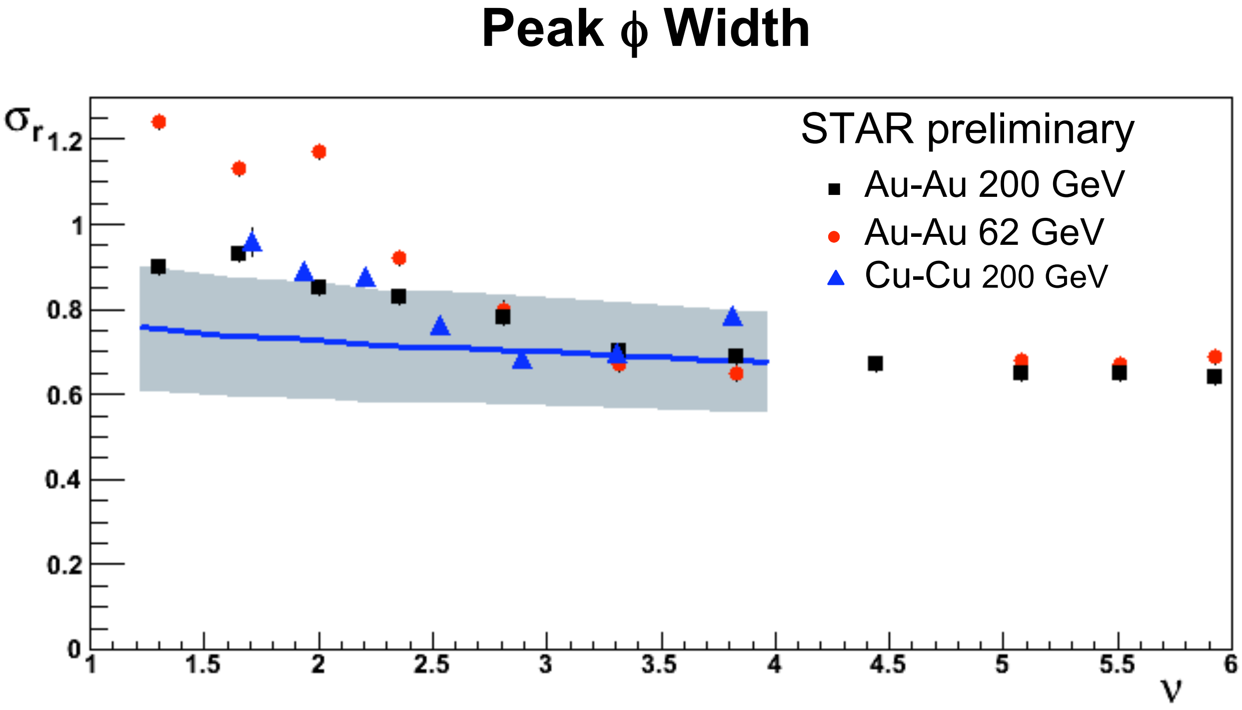
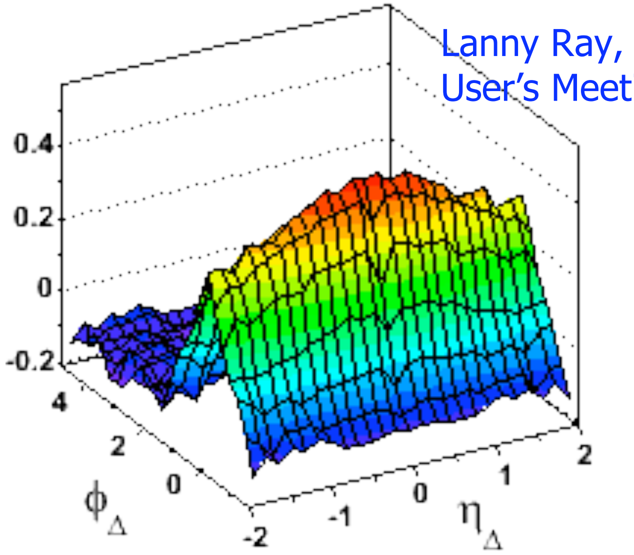
- Computed angular width is approximately independent of energy





Are the soft and hard ridges related?

Soft Ridge



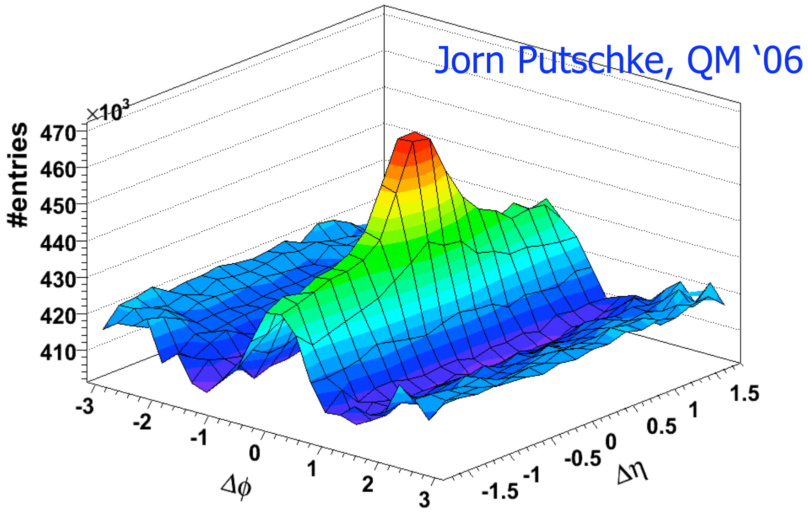
Lanny Ray, RHIC & AGS User's Meeting, '08

Correlated pairs for all p_t

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}}$$

?

Hard Ridge



Jorn Putschke, QM '06

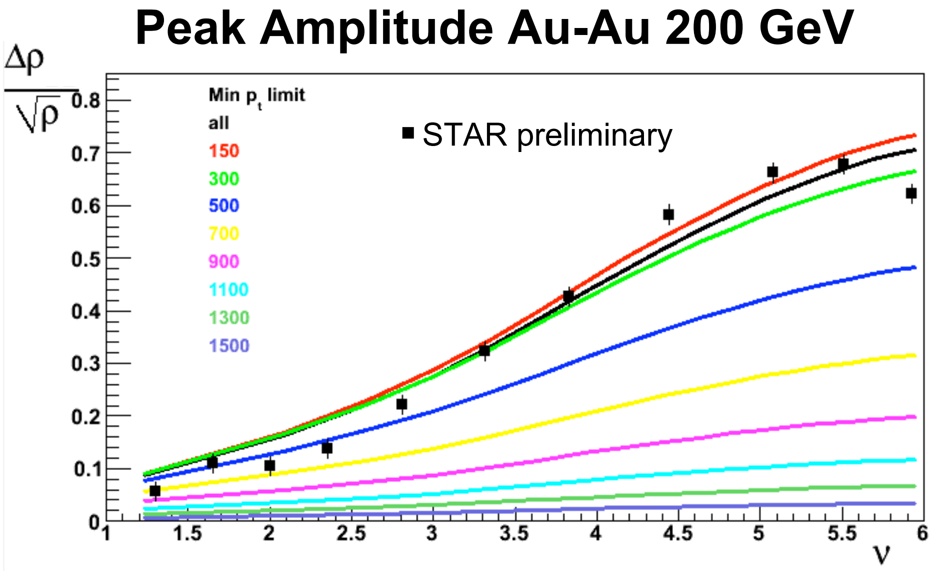
Yield of associated particles per jet trigger

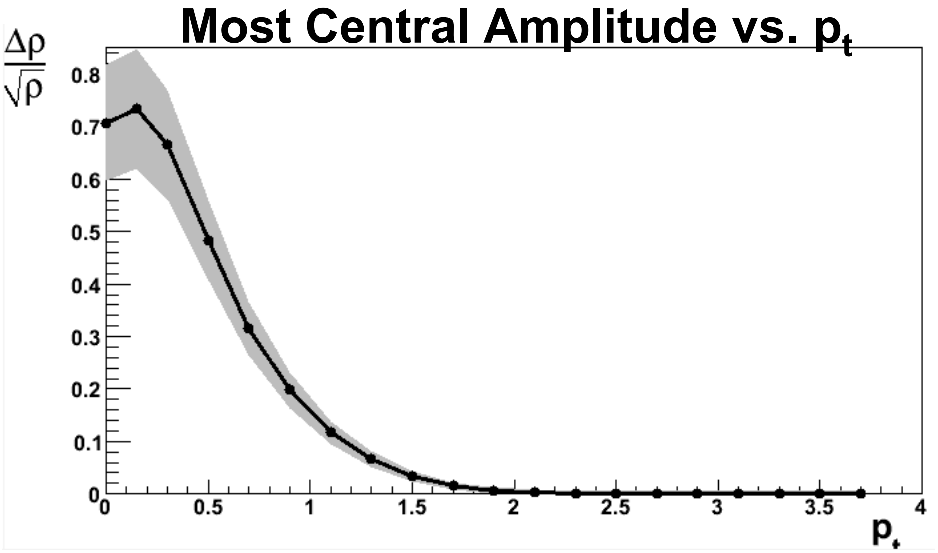
$3 < p_{t,trigger} < 4$ GeV

$2 \text{ GeV} < p_{t,assoc.}$

- Soft Ridge: no trigger, pairs not separated by p_t
- Hard Ridge: only high p_t particles, trigger and associated in different ranges
- Look for a change in the soft ridge as the minimum p_t range is increased

Soft Ridge vs. p_t



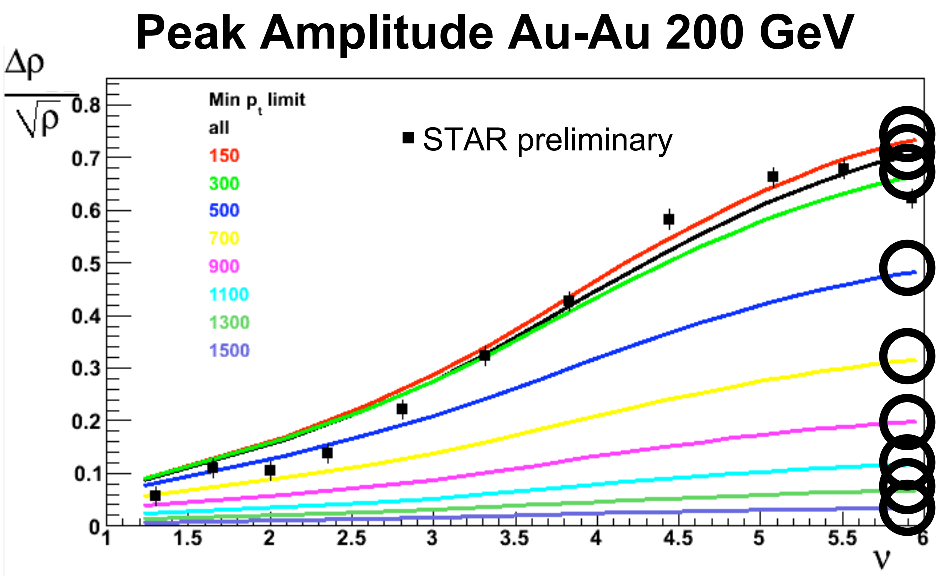


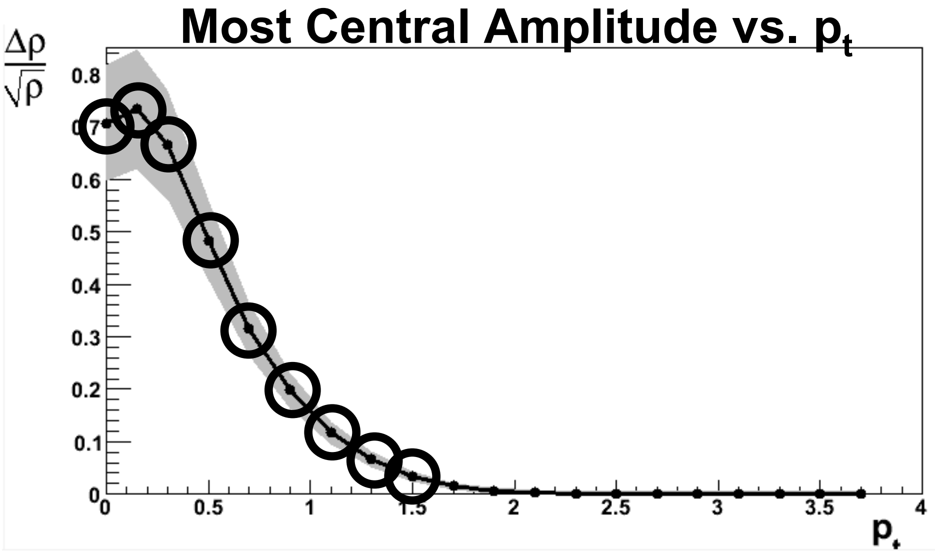
$$\left(\frac{\Delta\rho}{\sqrt{\rho_{ref}}}\right)_{p_t>p_{t,min}} = \frac{\iint\limits_{p_{t,min}} \Delta\rho(\vec{p}_{t1},\vec{p}_{t2})}{\left\{\iint\limits_{p_{t,min}} \rho_{1(\vec{p}_{t1})}\rho_{1(\vec{p}_{t2})}\right\}^{1/2}}$$

- Increase the lower p_t limit of the soft ridge calculation toward the hard ridge range.
- As the lower p_t limit is increased less particles are available for correlations.

- Correlation amplitude for the most central collision plotted vs. the lower p_t limit.

Soft Ridge vs. p_t





$$\left(\frac{\Delta\rho}{\sqrt{\rho_{ref}}}\right)_{p_t>p_{t,min}} = \frac{\iint_{p_{t,min}} \Delta\rho(\vec{p}_{t1},\vec{p}_{t2})}{\left\{\iint_{p_{t,min}} \rho_{1(\vec{p}_{t1})}\rho_{1(\vec{p}_{t2})}\right\}^{1/2}}$$

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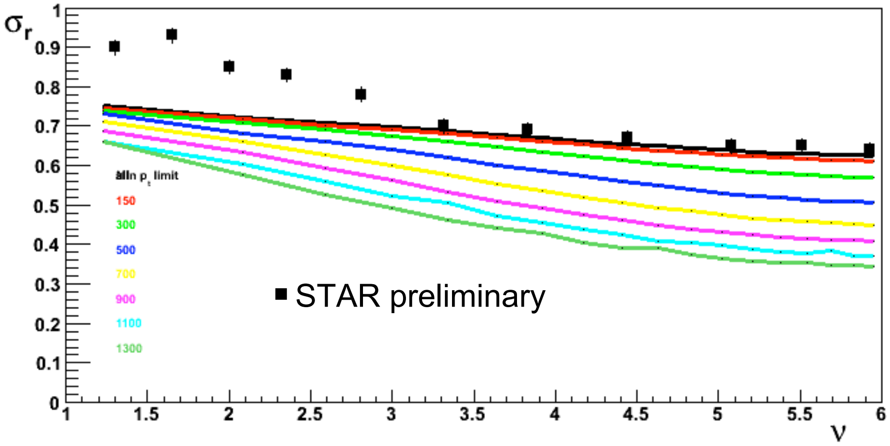
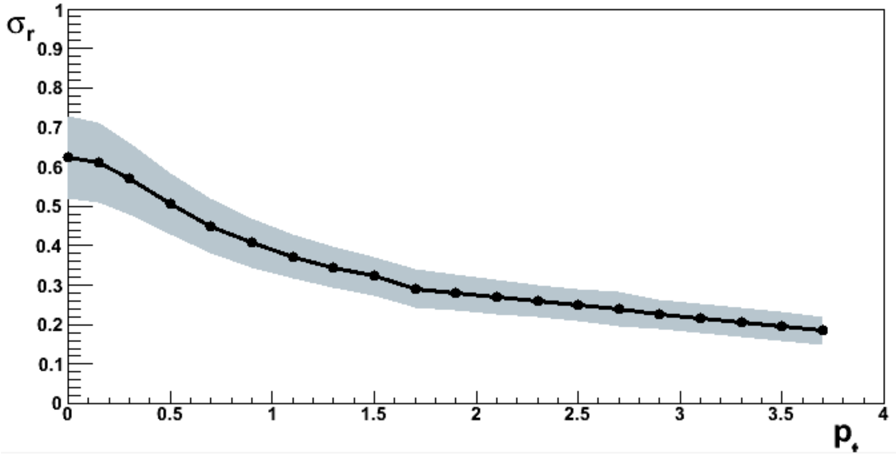
Soft Ridge vs. p_t



Peak φ Width Au-Au 200 GeV

Angular width from

$$\left(\frac{\Delta\rho}{\sqrt{\rho_{ref}}}\right)_{p_t>p_{t,min}}$$

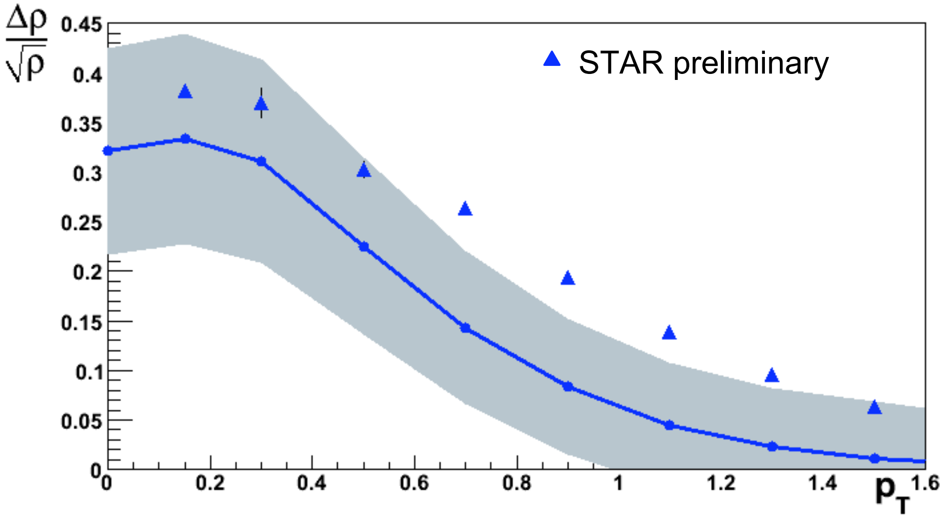


Most Central φ Width vs. p_t

- Higher p_t particles received a larger radial push ⇒ narrower relative angle.

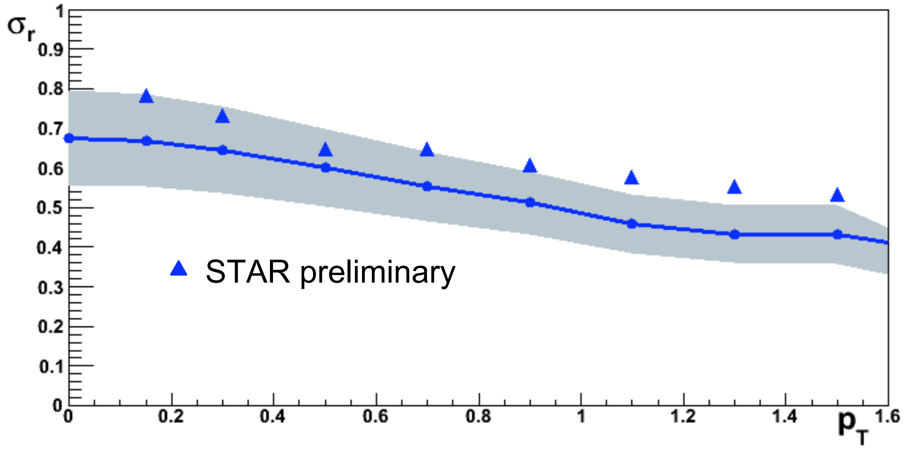
Cu-Cu Soft Ridge vs. p_t

Cu-Cu 200 GeV Most Central Amplitude vs. p_t



- Bulk correlations alone cannot explain the data at higher p_t
- The contribution from Jet-Bulk and Jet-Jet correlations should have an increasing effect with p_t

Cu-Cu 200 GeV Most Central ϕ Width vs. p_t



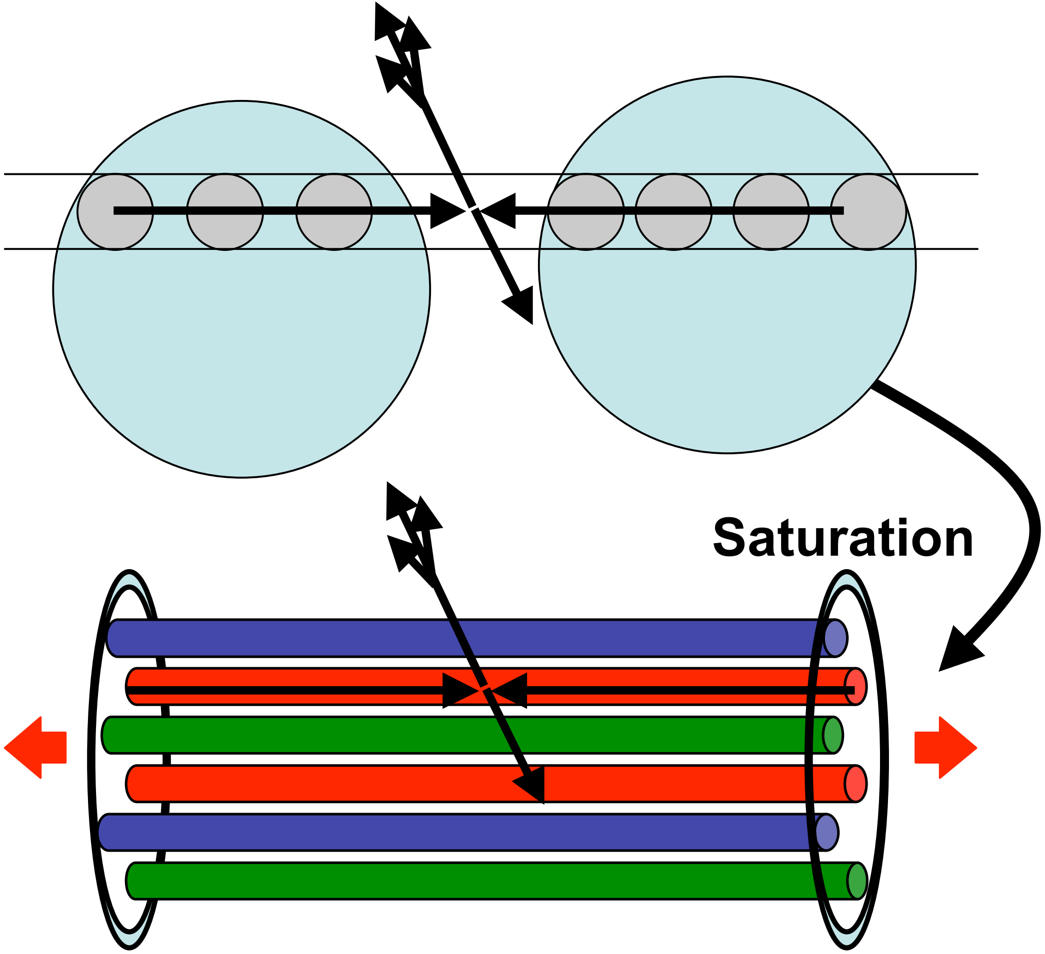
- The azimuthal width narrows with increasing p_t
- Jet contributions should force the correlation width to approach the jet correlation width

Jet Correlations with Flux Tubes

- Likelihood of having a jet depends on nuclear density (which depends on transverse position) and the momentum of colliding partons

- Low momentum fraction partons form CGC and tubes after the collision

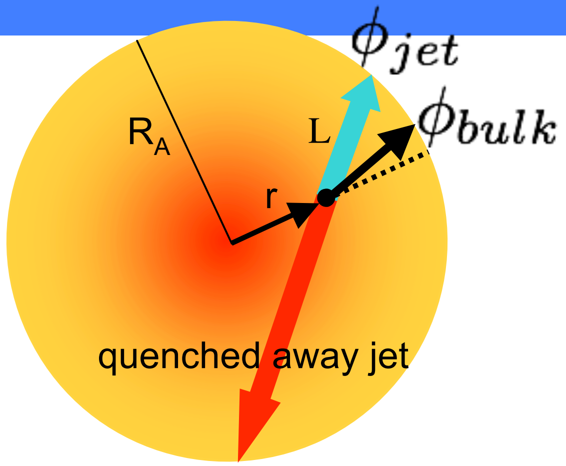
- Correlations between a hard interaction and a tube at the same radial position



correlation function:

$$c(\mathbf{x}_1,\mathbf{x}_2) \sim \mathcal{R}_{JB}\,\delta(\vec{r}_{t,jet} - \vec{r}_{t,tube})$$

Quenching + Flow



E. Shuryak, Phys. Rev. C 76, 047901 (2007)

- Surviving jets tend to be more radial, due to quenching.
- Jet path

$$L(r,\phi_{jet}) = \sqrt{R_A^2 - r^2\sin^2(\phi_{jet})} - r\cos(\phi_{jet})$$

- Survival probability $$S(\vec{x_1},\vec{x_2}) = e^{\frac{-L(r,\phi_{jet})}{\rho\sigma}}$$

- Production probability $$P_{prod}(r) \propto \left(1 - \frac{r^2}{R^2}\right)$$

- Jet Distribution $$f(\vec{x},\vec{p}) = \frac{A}{p^n} P_{prod}(r) S(r,\phi_{jet})$$

Jets and the Correlation Function

- Jet-Bulk Correlations

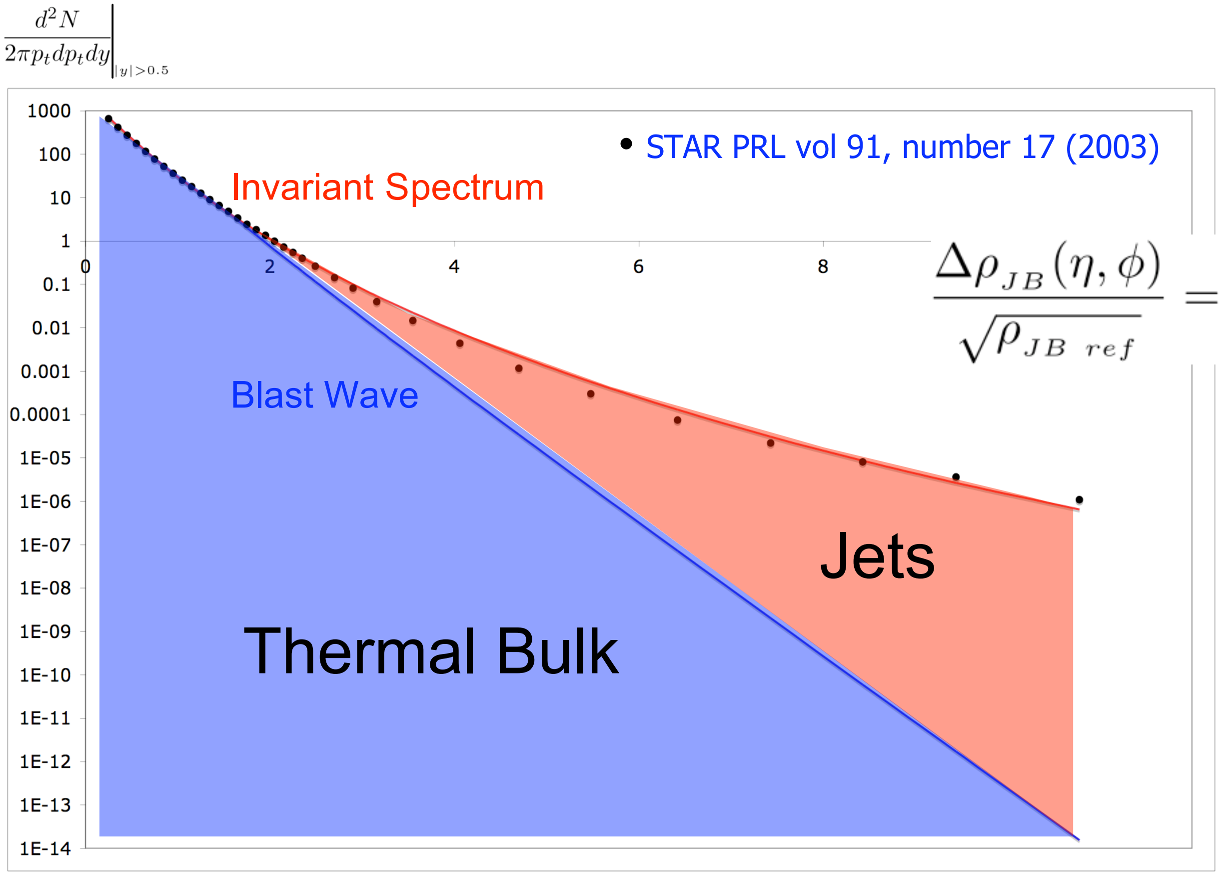
$$\Delta\rho_{JB}(\vec{p}_1, \vec{p}_2) \equiv (\text{pairs}) - (\text{Jet singles})(\text{Bulk singles})$$

$$\Delta\rho_{JB}(\vec{p}_1, \vec{p}_2) = \iint_{freezout} c_{JB}(\vec{x}_1, \vec{x}_2) f_J(\vec{x}_1, \vec{p}_1) f_B(\vec{x}_2, \vec{p}_2)$$

- Normalization

$$\int_{momenta} \Delta\rho_{JB} = \int_{positions} c_{JB} = \langle N_J \rangle \langle N_B \rangle \mathcal{R}_{JB}$$

Two Contributions



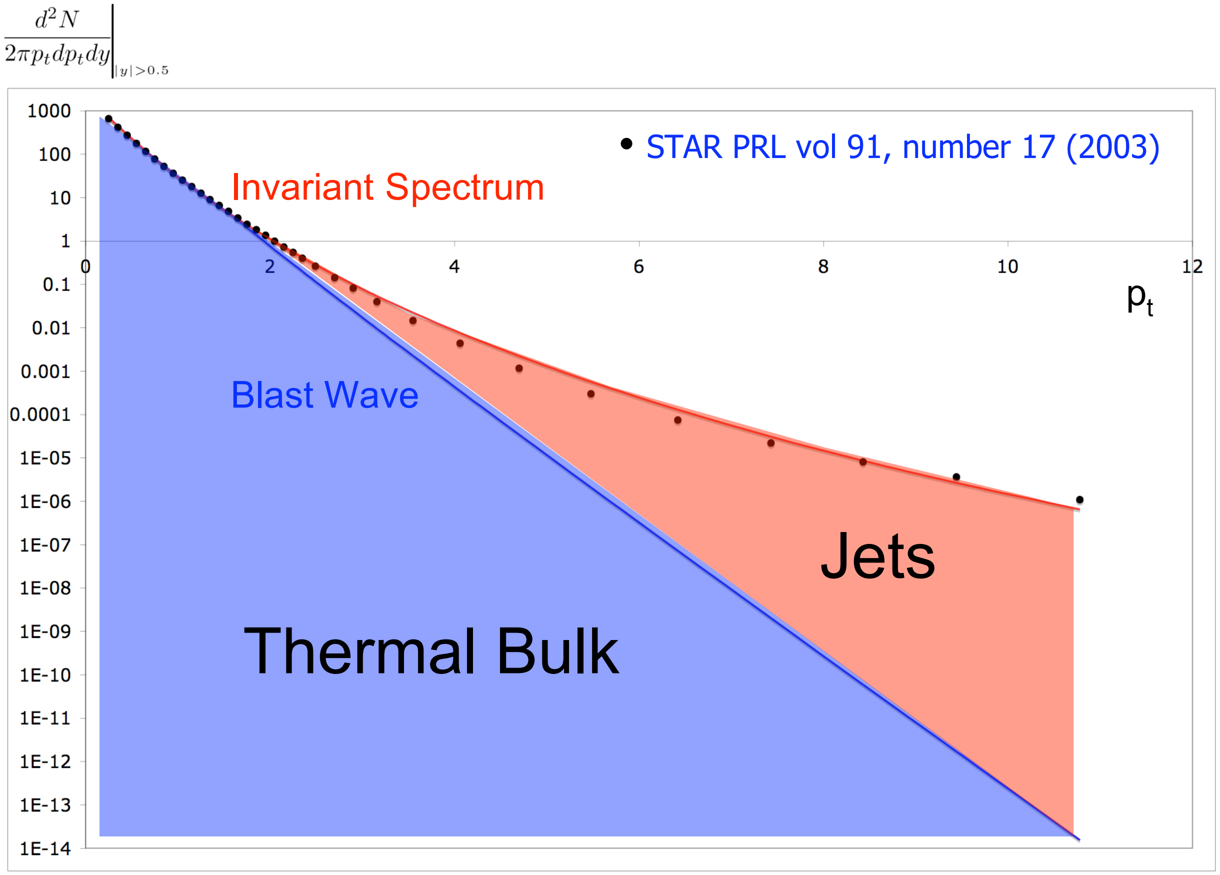
$$\frac{\Delta\rho_{JB}(\eta,\phi)}{\sqrt{\rho_{JB\ \ ref}}} = \left(\frac{\int \Delta\rho_{JB}(\vec{p}_{t1},\vec{p}_{t2})}{\int \rho_{1J}(\vec{p}_{t1}) \int \rho_{1B}(\vec{p}_{t2})}\right)\mathcal{R}\frac{dN_J}{dy}$$

“Jet-Bulk” correlations

$$\frac{\Delta\rho_{BB}(\eta,\phi)}{\sqrt{\rho_{BB\ \ ref}}} = \left(\frac{\int \Delta\rho_{BB}(\vec{p}_{t1},\vec{p}_{t2})}{\int \rho_{1B}(\vec{p}_{t1}) \int \rho_{1B}(\vec{p}_{t2})}\right)\mathcal{R}\frac{dN_B}{dy}$$

“Bulk-Bulk” correlations

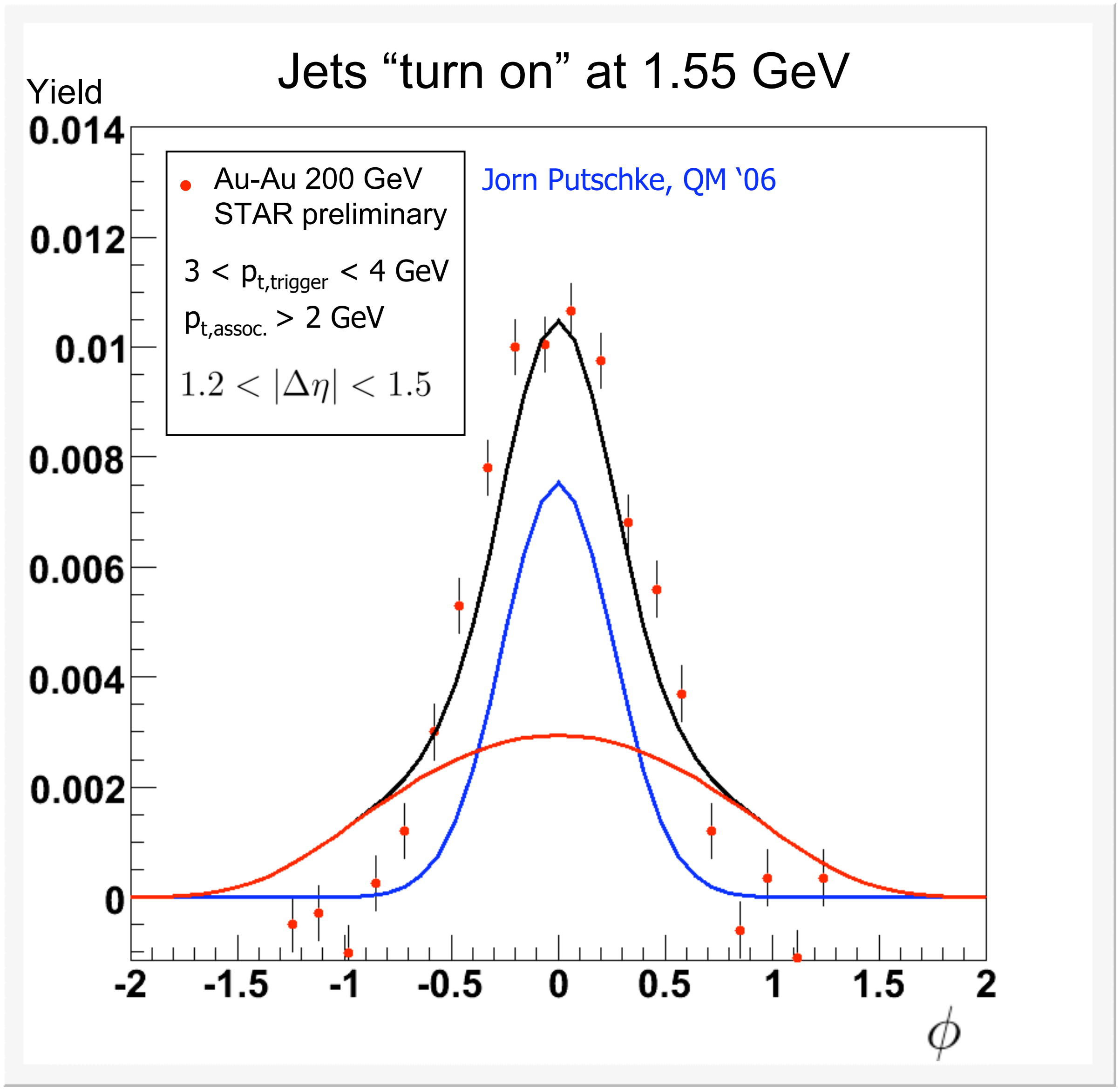
Two Contributions



- Both the Bulk-Bulk and Jet-Bulk contributions are weighted by the fraction of bulk or jet particles to the total.

$$\frac{\Delta\rho(\eta,\phi)}{\sqrt{\rho_{ref}}} = \frac{\Delta\rho_{BB}(\eta,\phi)}{\sqrt{\rho_{BB\ ref}}}\left(\frac{Bulk}{fraction}\right) + \frac{\Delta\rho_{JB}(\eta,\phi)}{\sqrt{\rho_{JB\ ref}}}\left(\frac{Jet}{fraction}\right)$$

Hard Ridge

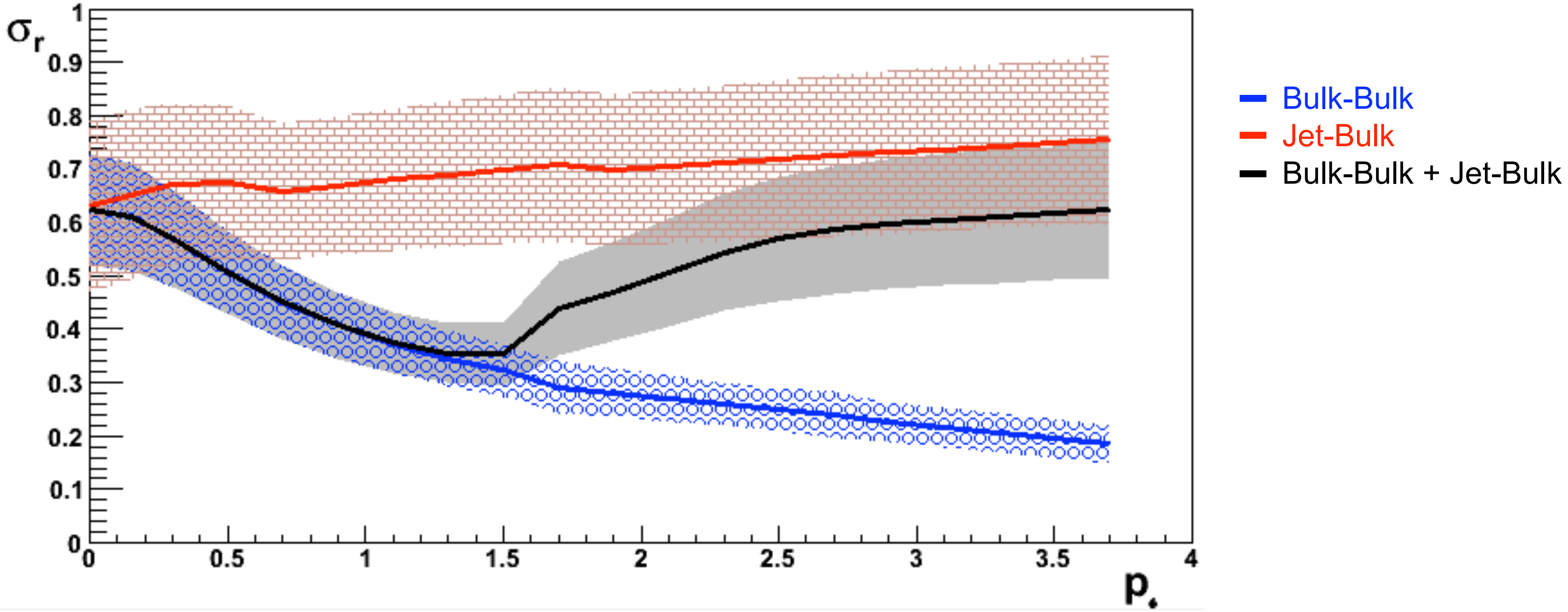

Jets “turn on” at 1.55 GeV

Jorn Putschke, QM ‘06

▬ Bulk-Bulk Yield
▬ Jet-Bulk Yield
▬ Bulk-Bulk + Jet-Bulk Yield

- Bulk-Bulk correlations still significant, but too narrow.
- Jet-Bulk correlations too wide.
- Bulk-Bulk + Jet-Bulk fits amplitude and width
- The choice of the starting energy for jets affects both the bulk and jet fractions
- Yield is a different observable

Azimuthal Width



- Broad angular width from quenching alone (Shuryak)
- Narrow width from flow alone (Gavin, McLerran, Moschelli)
- The jet contribution becomes more significant with increasing p_t
- Width of the combination seems to work

Angular width from

$$\left(\frac{\Delta\rho}{\sqrt{\rho_{ref}}}\right)_{p_t>p_{t,min}}$$

Summary

Bulk correlations are a nontrivial contribution to the hard ridge

- Glasma provides energy, centrality, and system dependence
- Angular width from flow and jet quenching
- Experimental study is needed
    - p_t dependence of soft ridge: Chanaka DeSilva
    - A common observable between the hard and soft ridge could help

Jet Correlation Strength

$$\mathcal{R} = \frac{\langle N(N-1)\rangle - \langle N\rangle^2}{\langle N\rangle^2}$$

Pruneau, Gavin, Voloshin
Phys.Rev. C66 (2002) 044904

$$\langle N_B\rangle = \beta\langle N\rangle$$

$$\langle N_J\rangle = \alpha\langle N\rangle$$

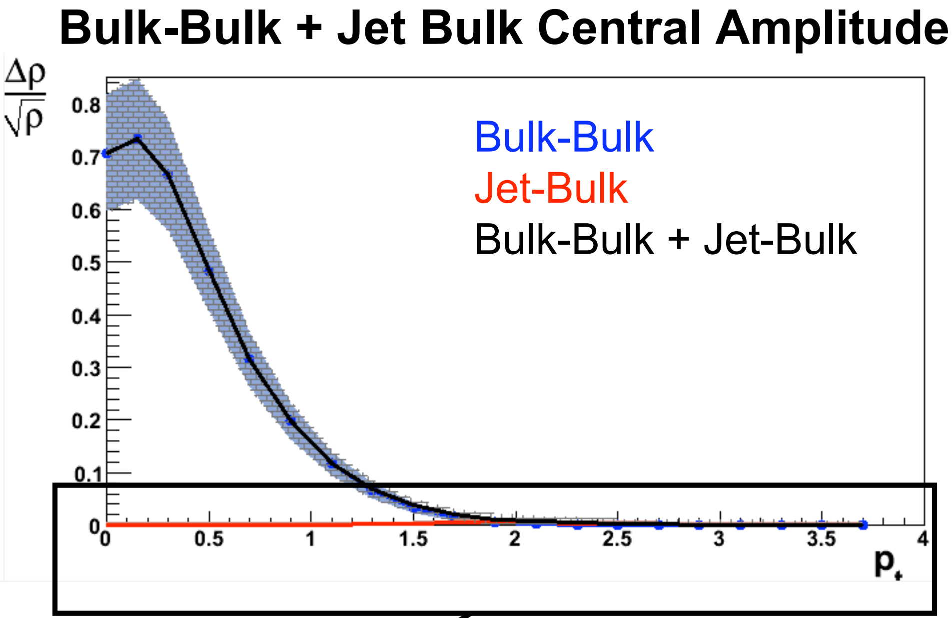
$$\langle N_J N_B\rangle = \alpha\beta\langle N(N-1)\rangle$$

$$\mathcal{R}_{JB} = \frac{\langle N_J N_B\rangle - \langle N_J\rangle\langle N_B\rangle}{\langle N_J\rangle\langle N_B\rangle}$$

$$= \frac{\alpha\beta\langle N(N-1)\rangle - \alpha\beta\langle N\rangle\langle N\rangle}{\alpha\beta\langle N\rangle\langle N\rangle}$$

$$\Rightarrow \boxed{\mathcal{R}_{JB} = \mathcal{R}}$$

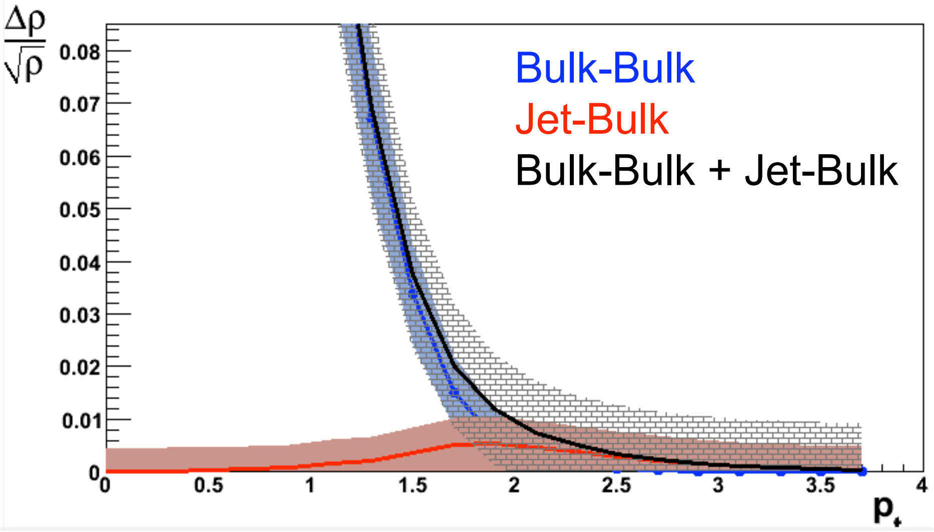
Amplitude vs. p_t



Bulk-Bulk + Jet Bulk Central Amplitude vs. p_t

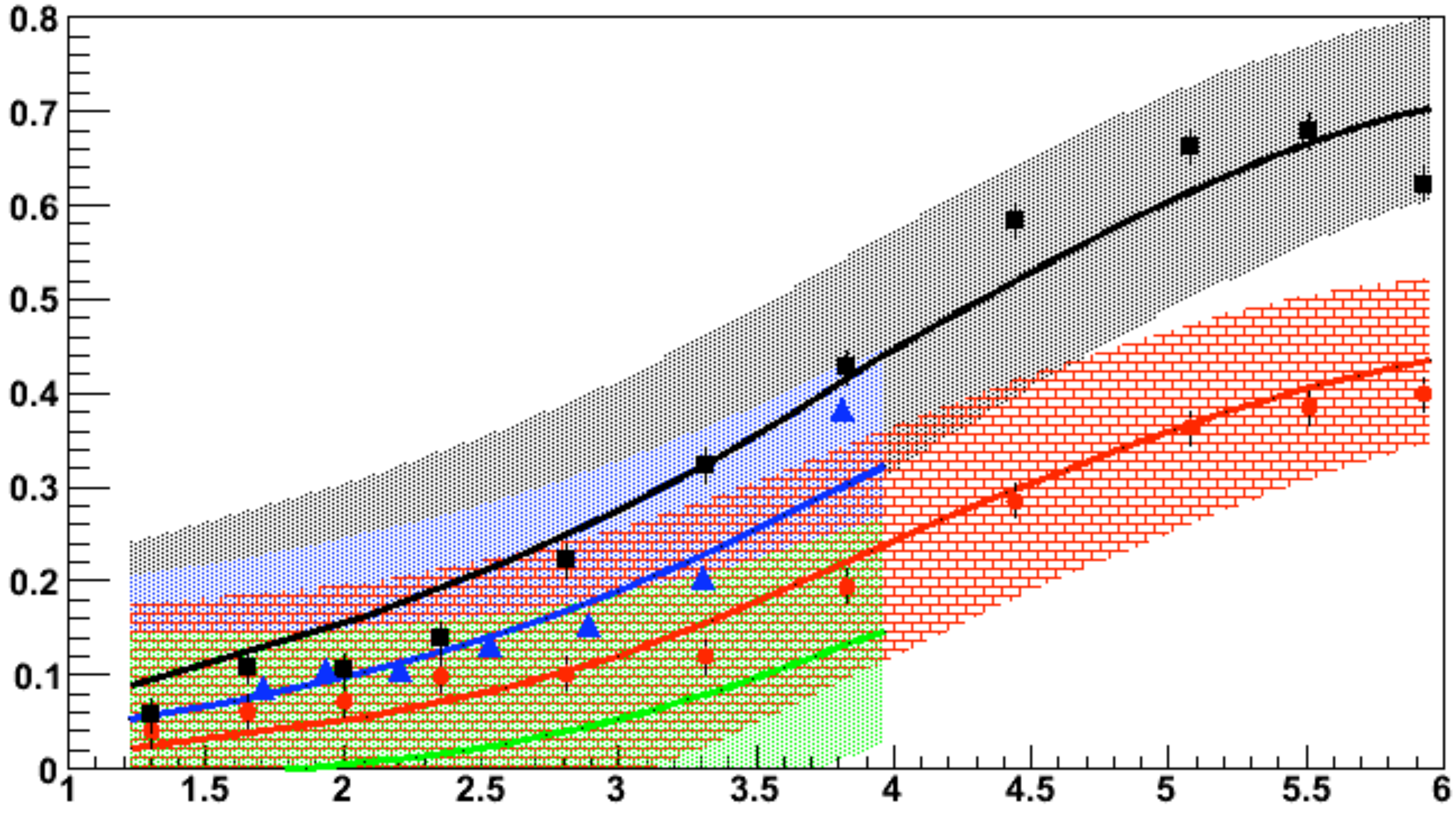
- Bulk correlations dominate because soft particles dominate the spectrum at low p_t

- ~10% error from BW; Glasma errors are at a minimum since saturation is strongest in central collisions

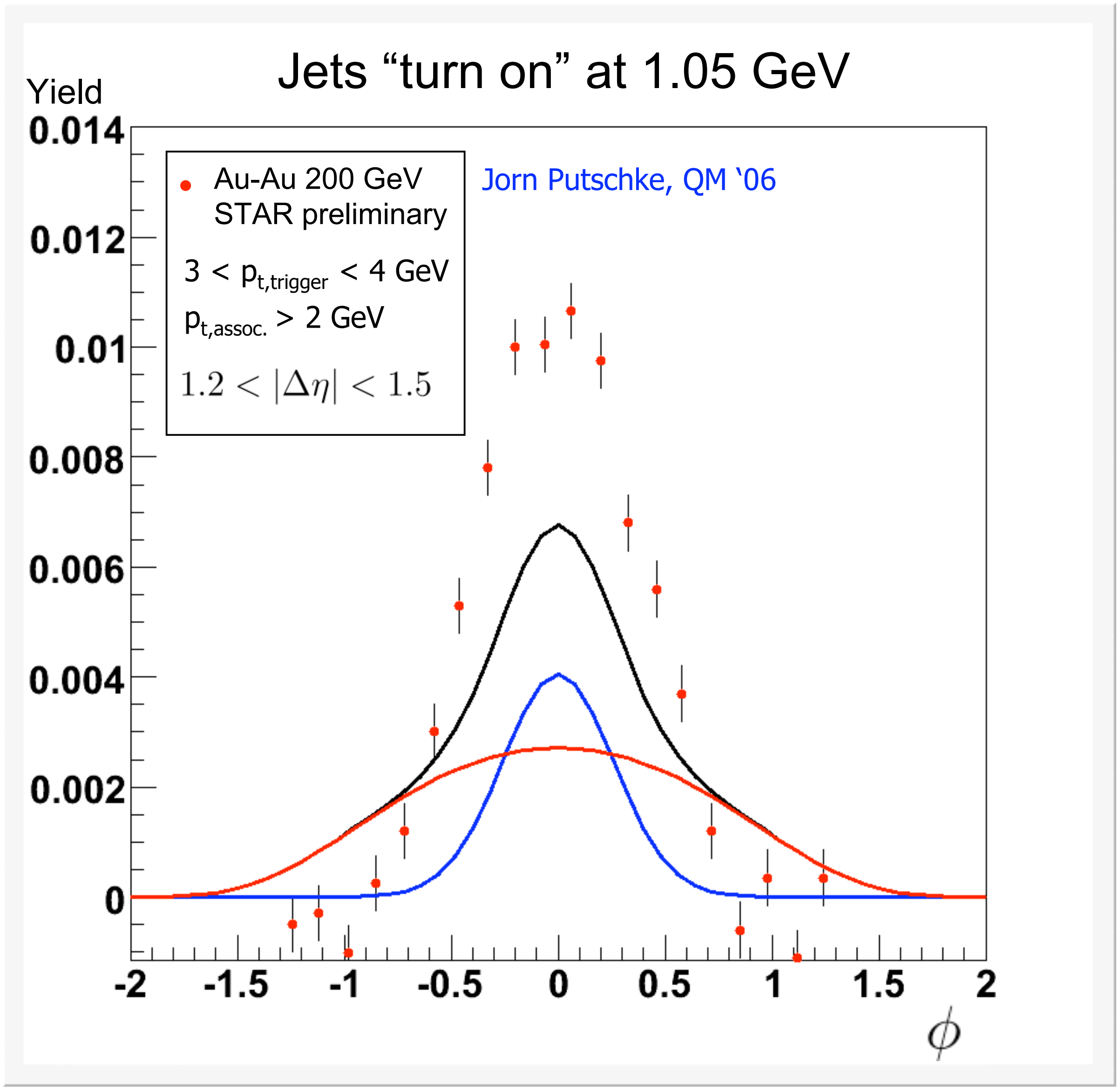


- The jet contribution becomes more significant at high p_t

Amplitude Comparison



Hard Ridge



▬ Bulk-Bulk Yield
▬ Jet-Bulk Yield
▬ Bulk-Bulk + Jet-Bulk Yield