3 particle correlations from Glasma flux tubes

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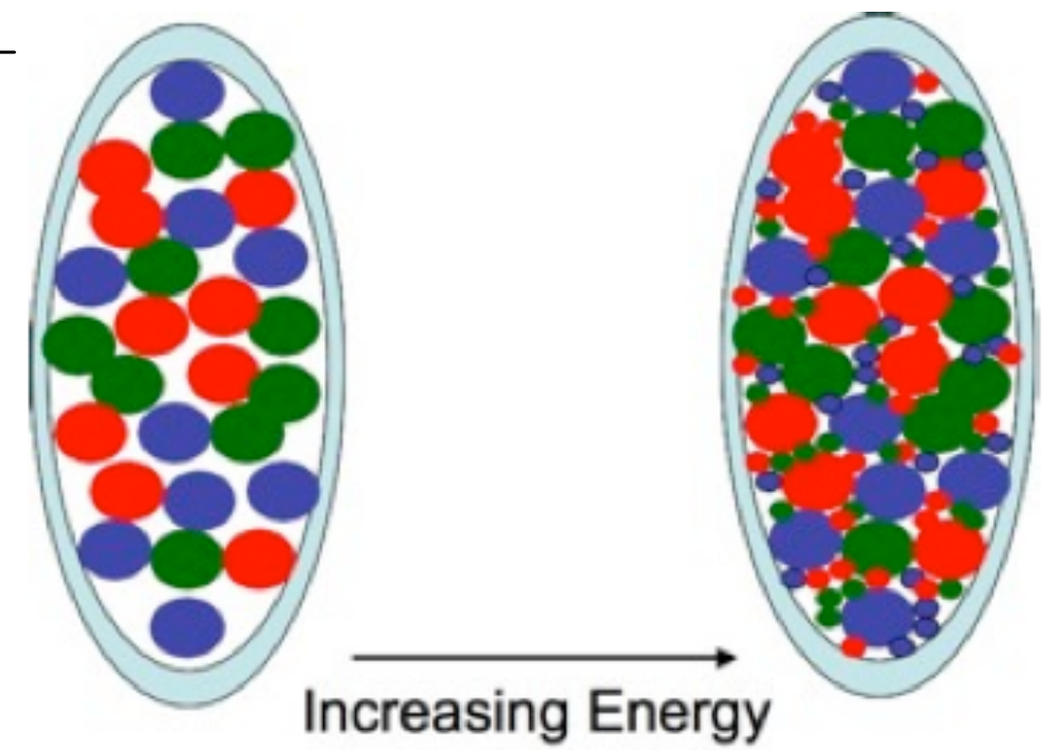
Contents

- The CGC and Glasma flux tubes
- Review of 2 particle correlation and the ridge
  - A. Dumitru, F. Gelis, L. McLerran, R. Venugopalan Nucl. Phys. A 810:91 (2008)
- 3 particle correlation and near side ridge
  - KD, D. Daniel Fernández-Fraile, R. Venugoplan arXiv:0902.4435

Color Glass Condensate

- Size of parton (gluon) $\frac{1}{k_\perp^2}$ $\quad \sigma \sim \alpha_s \frac{1}{k_\perp^2}$
- Size of Hadron: $S_\perp$
- Saturation: $\frac{dN}{dy}\sigma \sim S_\perp$

$$k_{\perp,\mathrm{max}}^2 \equiv Q_S^2 \sim \frac{\alpha_s}{S_\perp}\frac{dN}{dy}$$

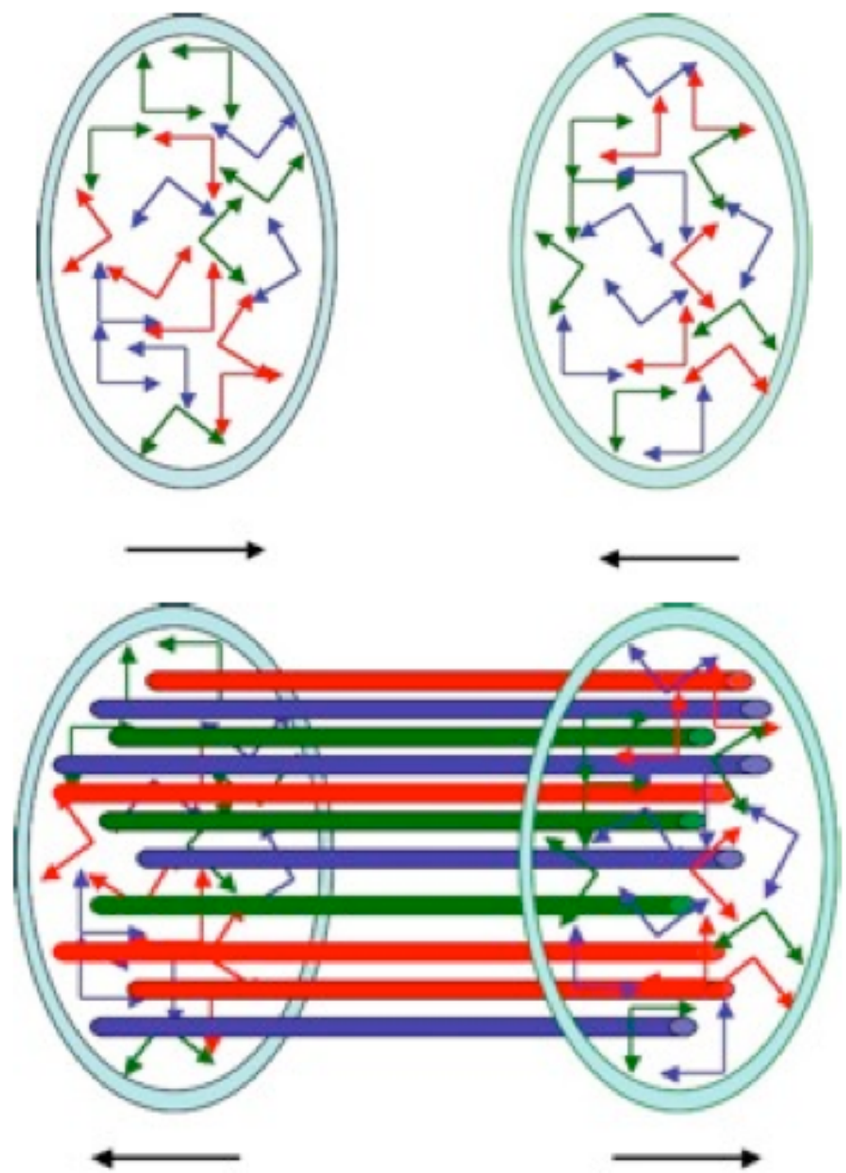


For a summary of the empirical evidence for the CGC: R.~Venugopalan, arXiv:0707.1867 [hep-ph].
Pictures: L.~McLerran, arXiv:0812.4989 [hep-ph].

Glasma Flux Tubes

D. Kharzeev, A. Krasnitz and R. Venugopalan, Phys. Lett. B545 (2002) 298
Lappi, McLerran, Nucl.Phys.A772:200-212,2006.

- Before
- After



$$N_{\text{f.t.}} \sim \alpha_s \frac{dN}{dy}$$

$$\sim 300 \text{ in Au-Au}$$

A. Kovner, L.D.McLerran and H. Weigert, Phys. Rev. D 52, 3809 (1995):

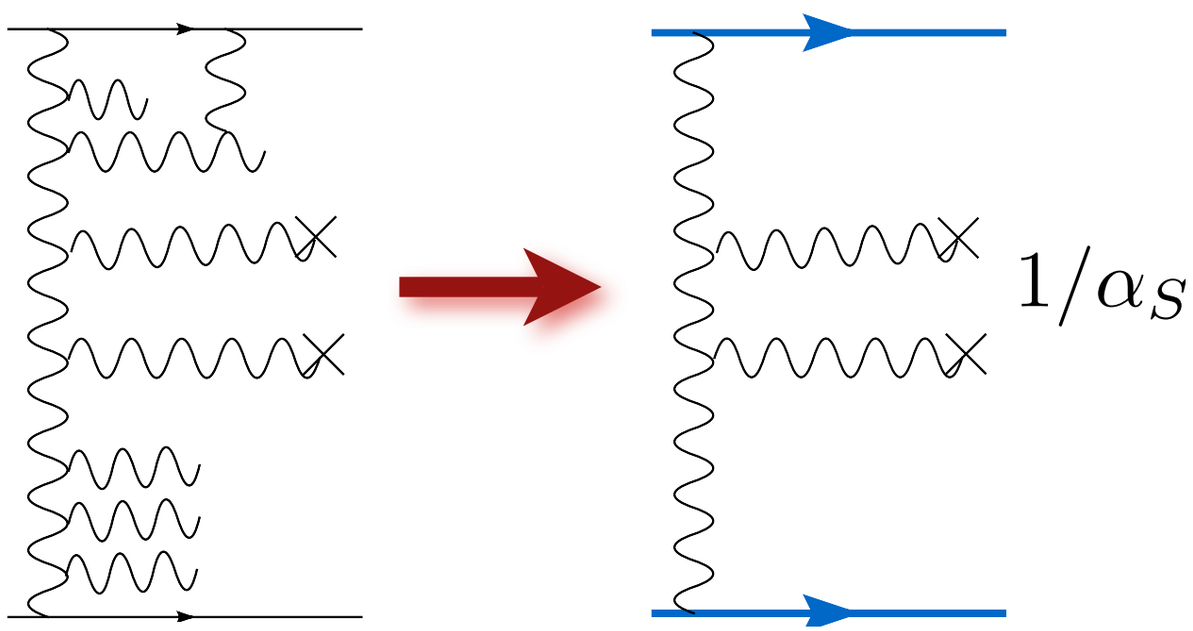
$$p^2 A^{\mu,a}(\mathbf{p}) = -i f_{abc} \frac{g^3}{2} \int \frac{d^2\mathbf{k}_\perp}{(2\pi)^2} L^\mu(\mathbf{p},\mathbf{k}_\perp) \frac{\tilde{\rho}_1^b(\mathbf{k}_\perp)\tilde{\rho}_2^c(\mathbf{p}_\perp - \mathbf{k}_\perp)}{\mathbf{k}_\perp^2 \left(\mathbf{p}_\perp - \mathbf{k}_\perp\right)^2}$$

Multi-particle production

F. Gelis, T. Lappi, R. Venugopalan, PRD 78, 054019(20) (2008).

- In leading log $\sum_n \alpha_s^n \ln^n \left(\frac{1}{x}\right)$

$$\left\langle \frac{dN_n}{d^2p_{\perp,1}dy_1 \cdots d^2p_{\perp,n}dy_n} \right\rangle = \int [d\rho_A d\rho_B] W_{y_{\rm beam}-Y}[\rho_A] W_{y_{\rm beam}+Y}[\rho_B] \times \frac{dN_{\rm LO}}{d^2p_{\perp,1}dy_1}(\rho_A,\rho_B) \cdots \frac{dN_{\rm LO}}{d^2p_{\perp,n}dy_n}(\rho_A,\rho_B)$$

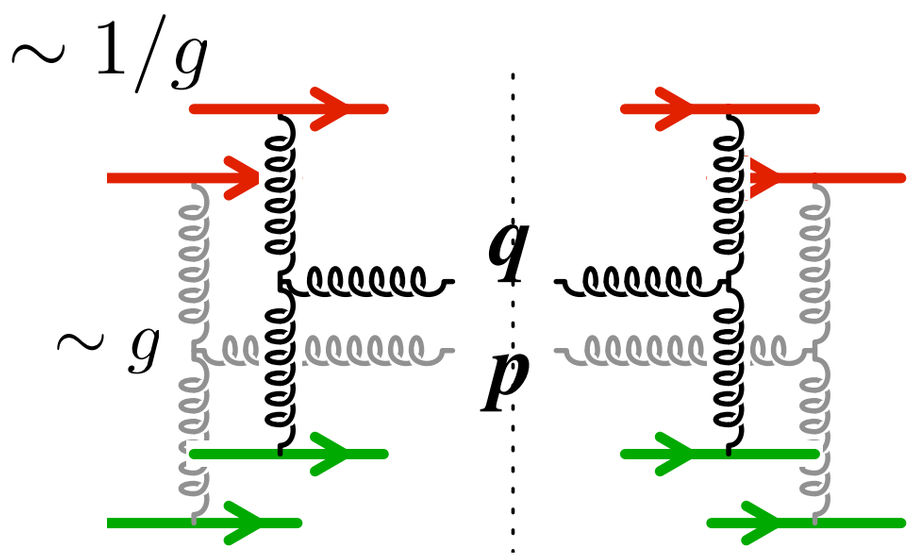


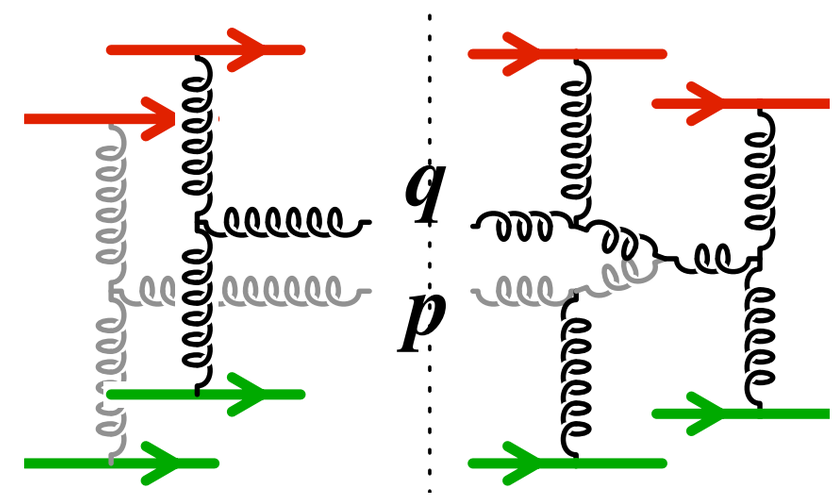
- Valid when $|y_i - y_j| \leq 1/\alpha_S$

Two Particle Correlation

- Definition of cumulant

$$C(\mathbf{p},\mathbf{q}) \equiv \left\langle \frac{dN_2}{dy_p d^2\mathbf{p}_\perp dy_q d^2\mathbf{q}_\perp} \right\rangle - \left\langle \frac{dN}{dy_p d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2\mathbf{q}_\perp} \right\rangle$$





- Classical Diagram

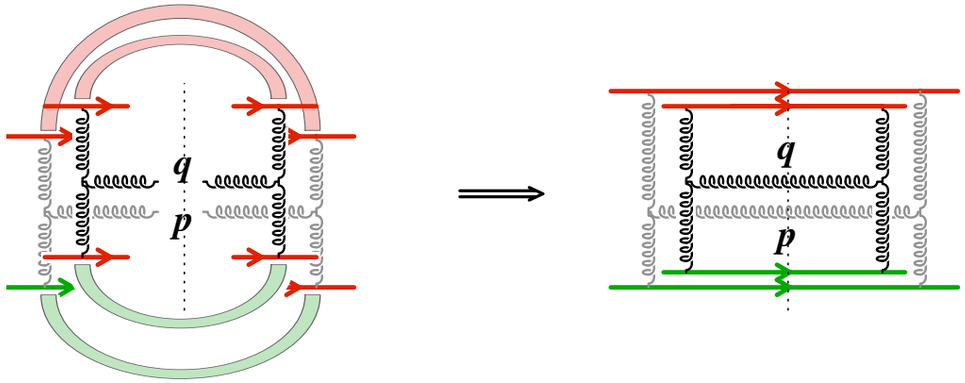
$$\sim \frac{1}{g^4}$$

- Quantum Correction

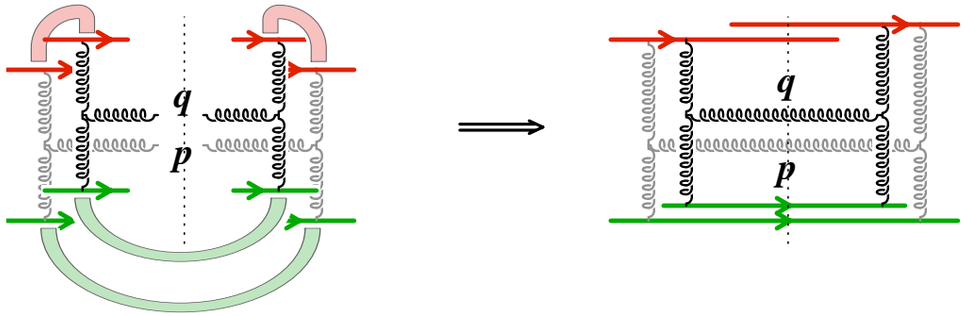
$$\sim \frac{1}{g^2}$$

Two Particle Correlation

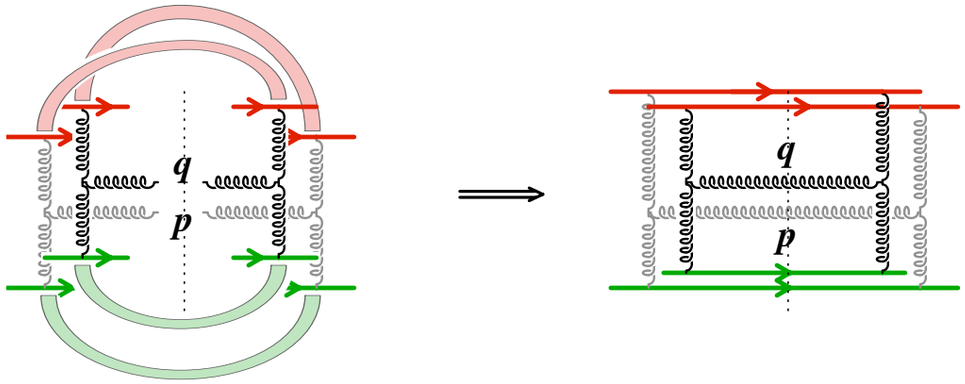
- Trivial Correlation



- Diffractive Diagram:



- Interference Diagram:

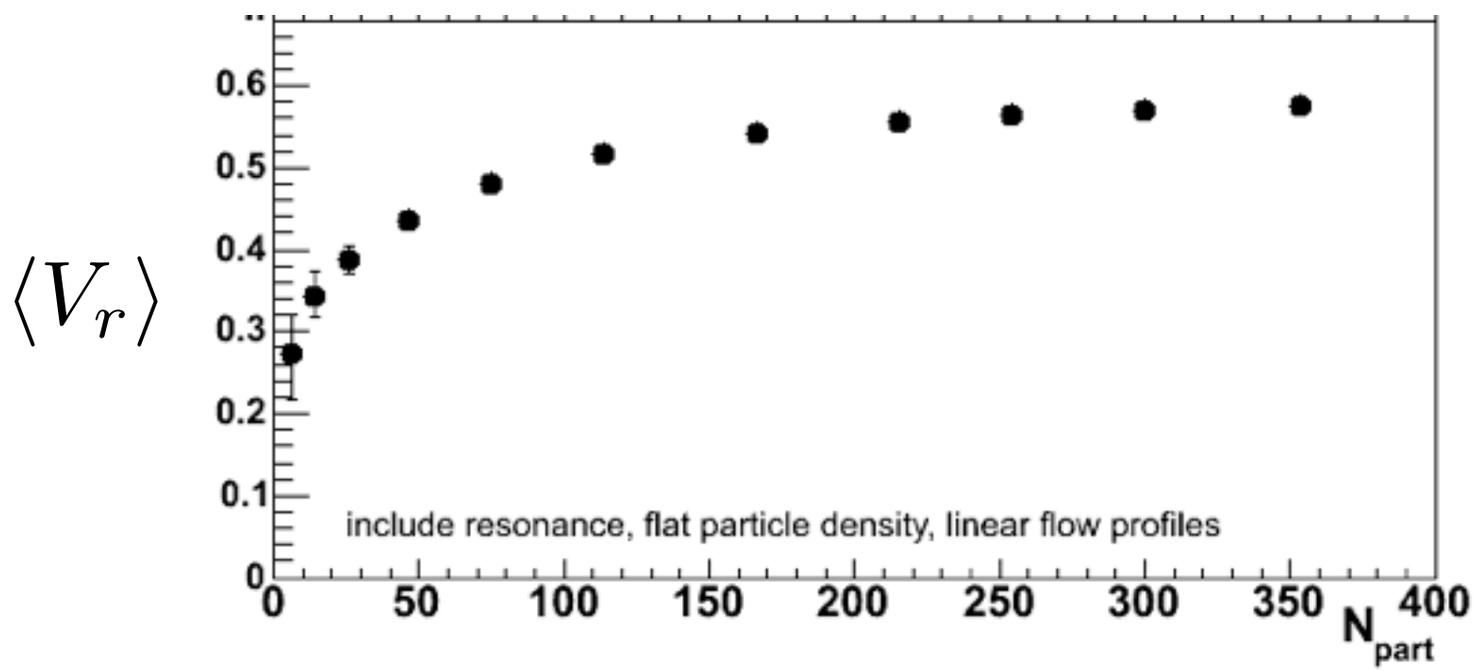


- Result: $$C(\mathbf{p},\mathbf{q}) = \kappa_2 \frac{1}{S_\perp Q_S^2} \left\langle \frac{dN}{dy_p d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2\mathbf{q}_\perp} \right\rangle$$

Radial Boost Model

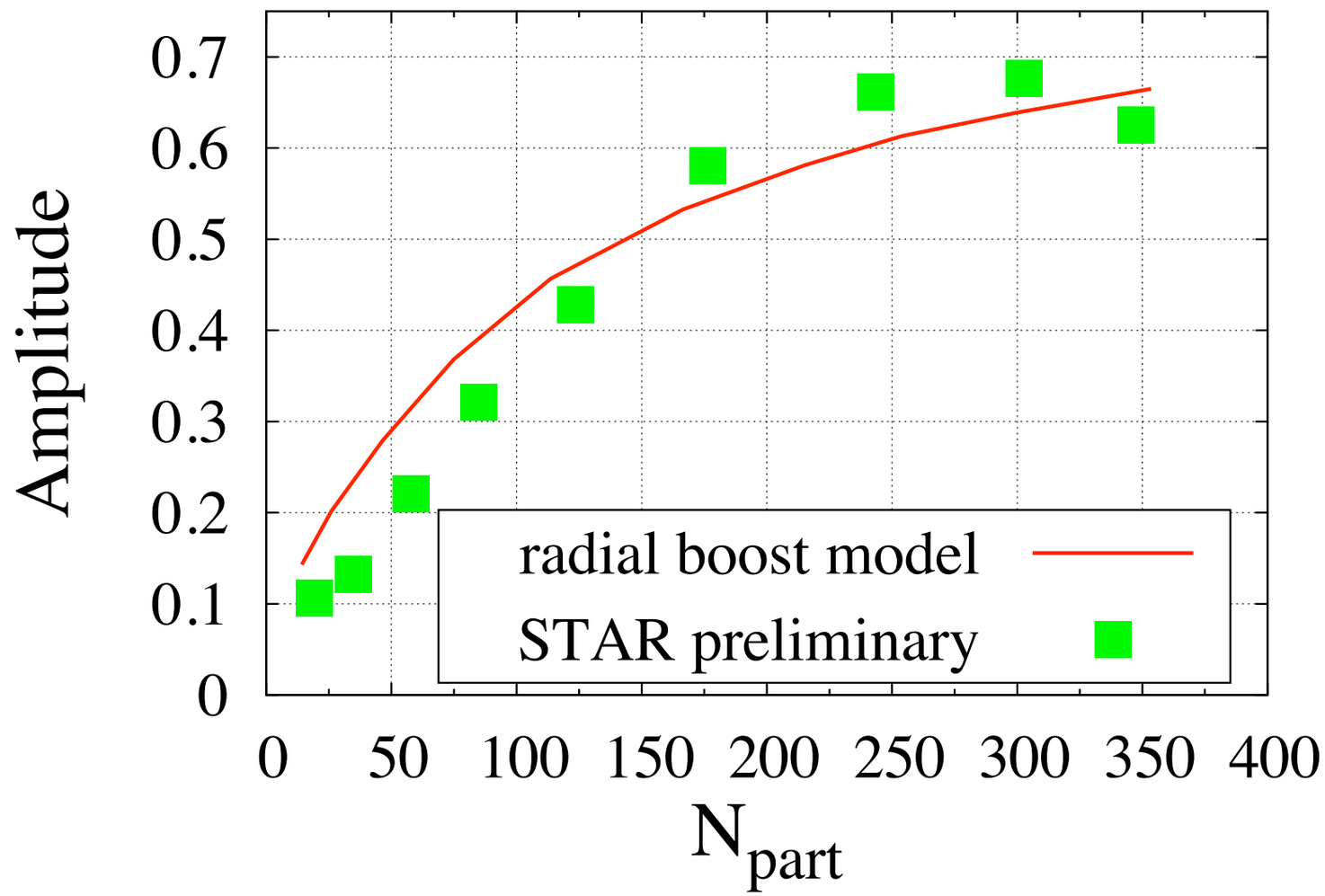
A, Kiyomichi [PHENIX]

- Correlation is flat in Δη and Δϕ
- Radial flow will correlate particles in Δϕ



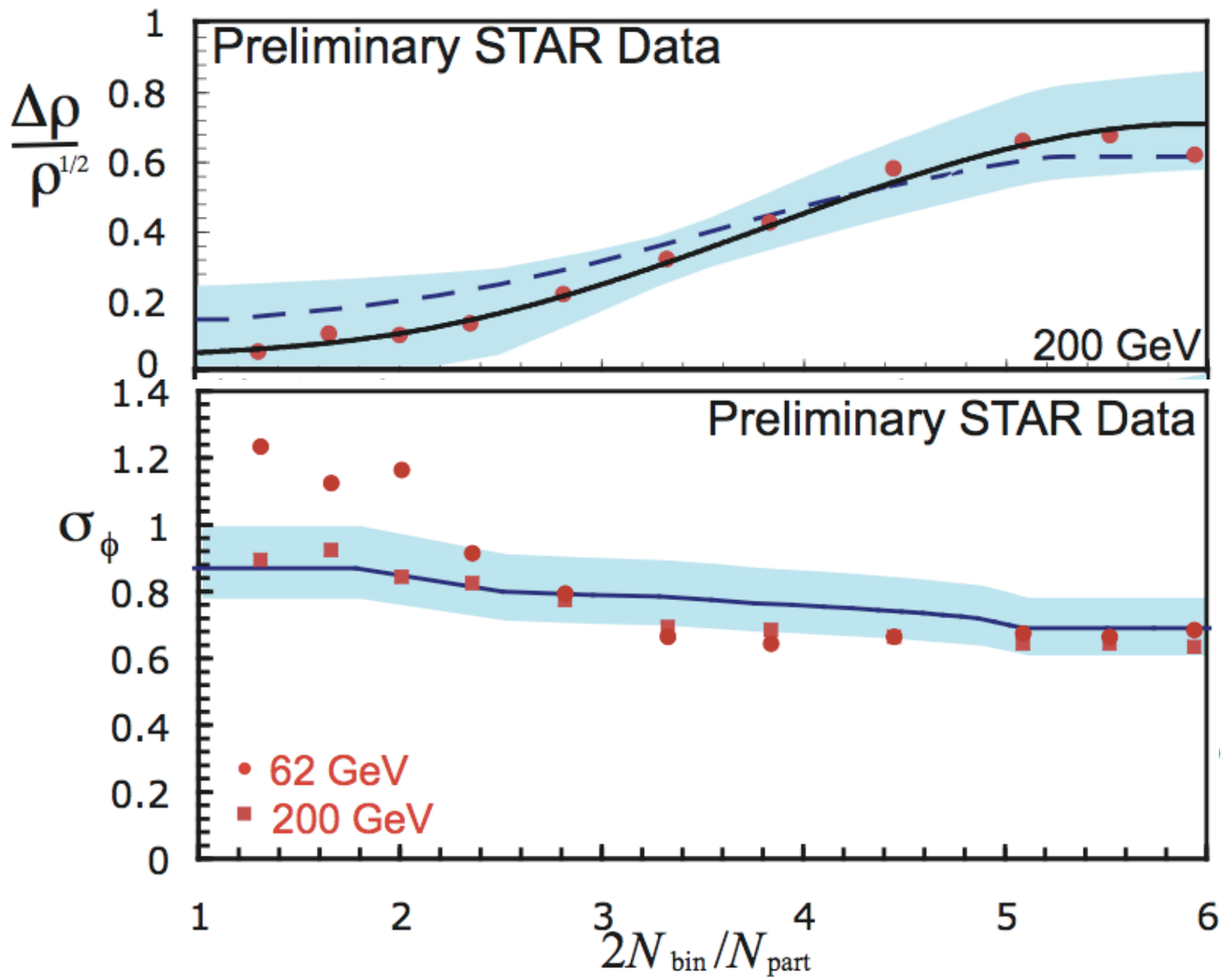
Model Comparison I

- Dumitru, Gelis, McLerran, Venugopalan
- One fit parameter for total amplitude



Model Comparison II

- Gavin, McLerran, Moschelli

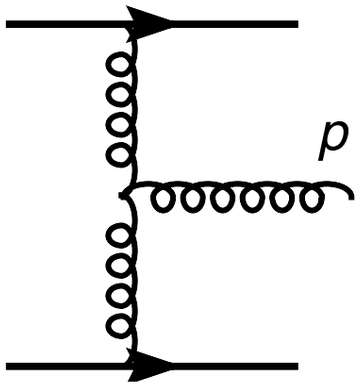


Three Particle Correlation

- Definition of 3 particle cumulant

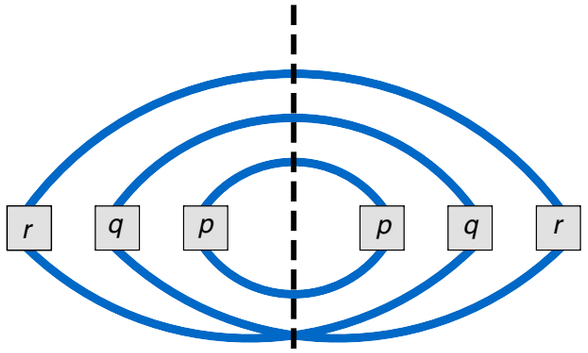
$$
\begin{aligned}
C(\mathbf{p},\mathbf{q},\mathbf{r}) \equiv & \left\langle \frac{dN_3}{dy_p d^2\mathbf{p}_\perp dy_q d^2\mathbf{q}_\perp dy_r d^2\mathbf{r}_\perp} \right\rangle \\
- & \left\langle \frac{dN_2}{dy_p d^2\mathbf{p}_\perp dy_q d^2\mathbf{q}_\perp} \right\rangle \left\langle \frac{dN}{dy_r d^2\mathbf{r}_\perp} \right\rangle - \left\langle \frac{dN_2}{dy_q d^2\mathbf{q}_\perp dy_r d^2\mathbf{r}_\perp} \right\rangle \left\langle \frac{dN}{dy_p d^2\mathbf{p}_\perp} \right\rangle \\
- & \left\langle \frac{dN_2}{dy_p d^2\mathbf{p}_\perp dy_r d^2\mathbf{r}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2\mathbf{q}_\perp} \right\rangle + 2 \left\langle \frac{dN}{dy_p d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2\mathbf{q}_\perp} \right\rangle \left\langle \frac{dN}{dy_r d^2\mathbf{r}_\perp} \right\rangle
\end{aligned}
$$

- Some Notation: $\boxed{p}$ =

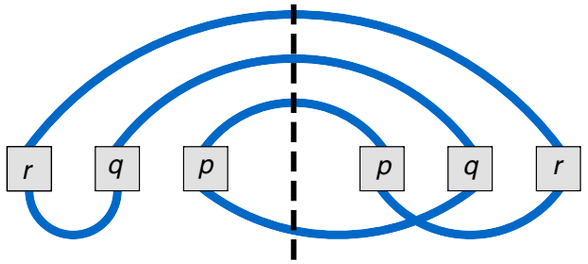


Three Particle Correlation

- Trivial Correlation

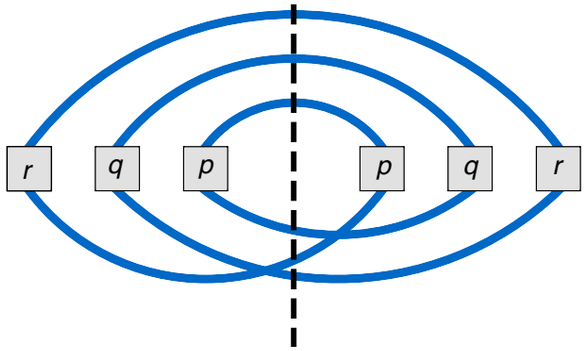


- Diffractive Diagram:



$\times 12$

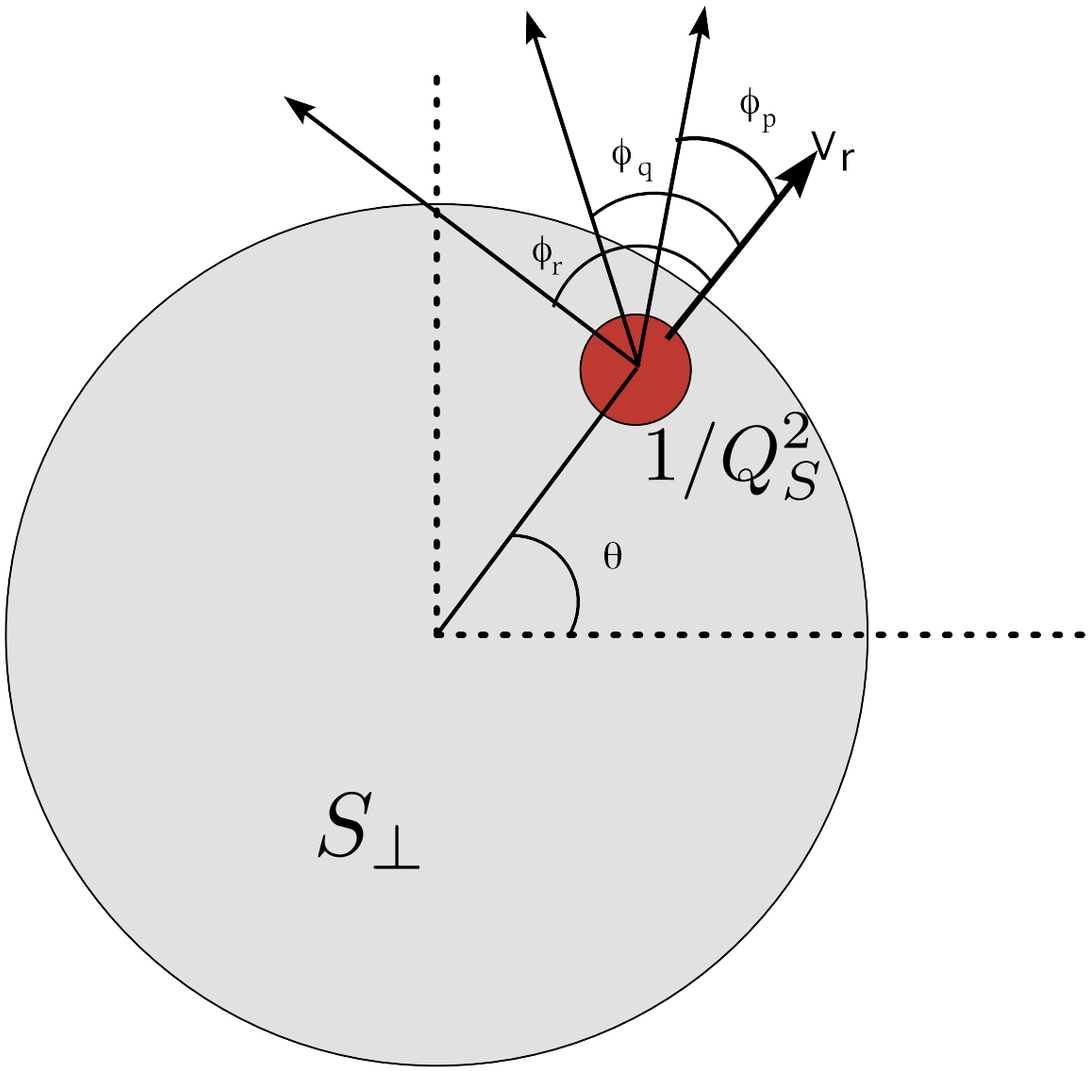
- Interference Diagram:



$\times 4$

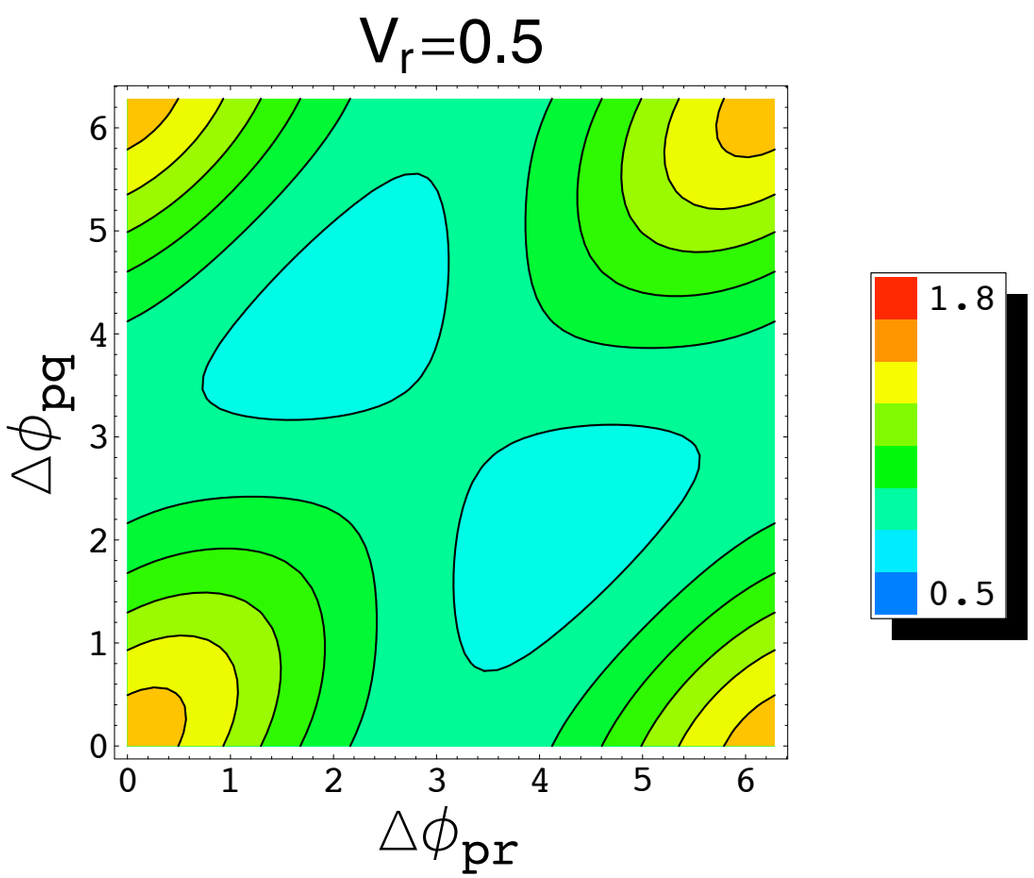
- Result: $C(\mathbf{p},\mathbf{q},\mathbf{r}) = \kappa_3 \frac{1}{S_\perp^2 Q_S^4} \left\langle \frac{dN}{dy_p d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2\mathbf{q}_\perp} \right\rangle \left\langle \frac{dN}{dy_r d^2\mathbf{r}_\perp} \right\rangle$

The Setup

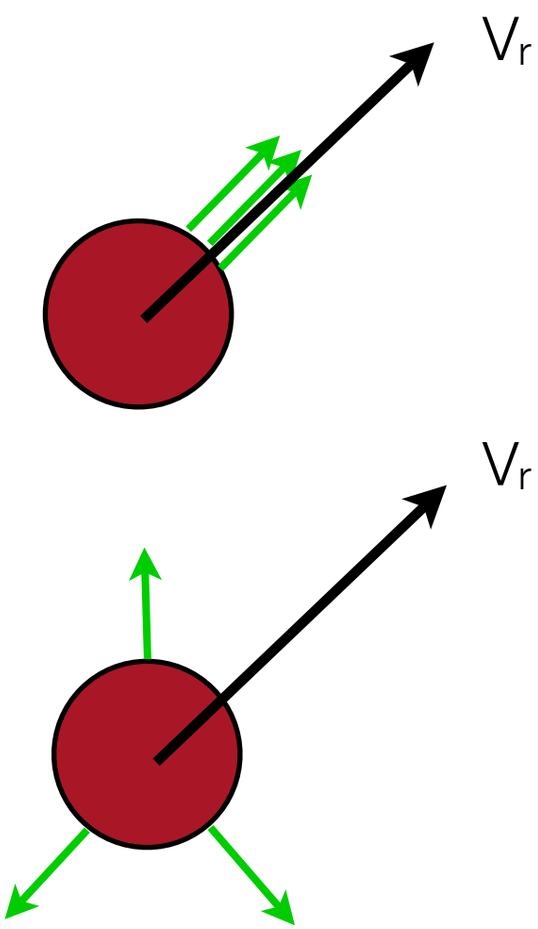


Azimuthal Dependence

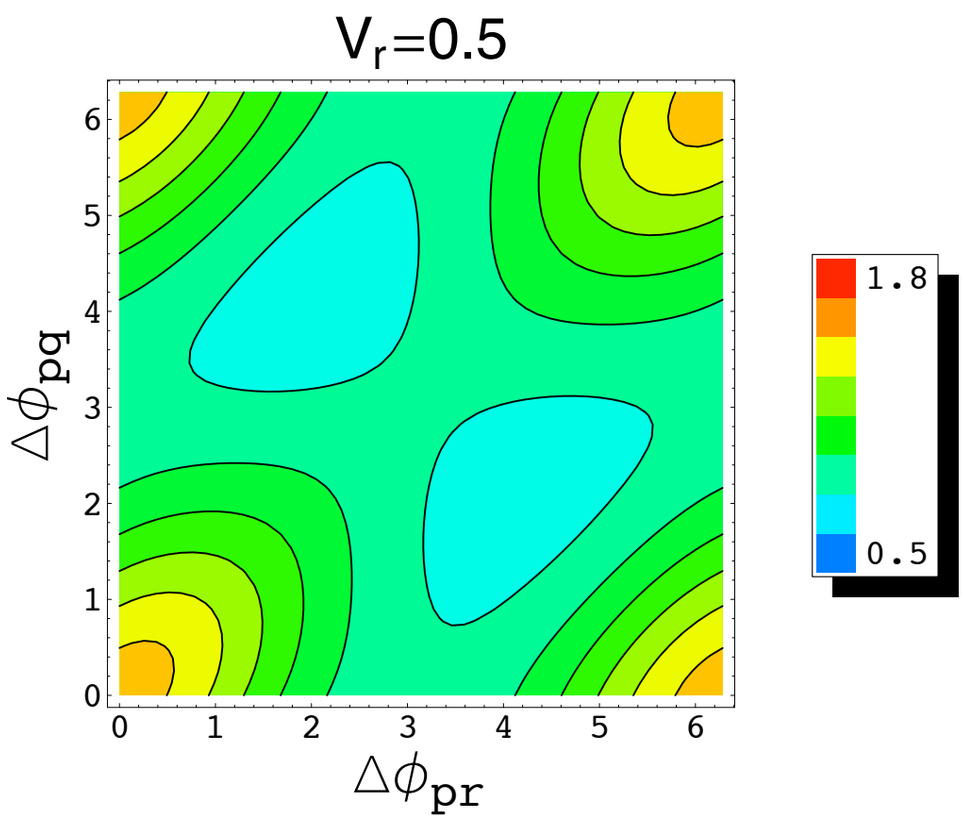
$$\overline{C}_3(\Delta\phi_{pq}, \Delta\phi_{pr}) = \frac{\kappa_3}{S_\perp^2 Q_s^4} \mathcal{A}(\Delta\phi_{pq}, \Delta\phi_{pr}, \zeta_B)$$

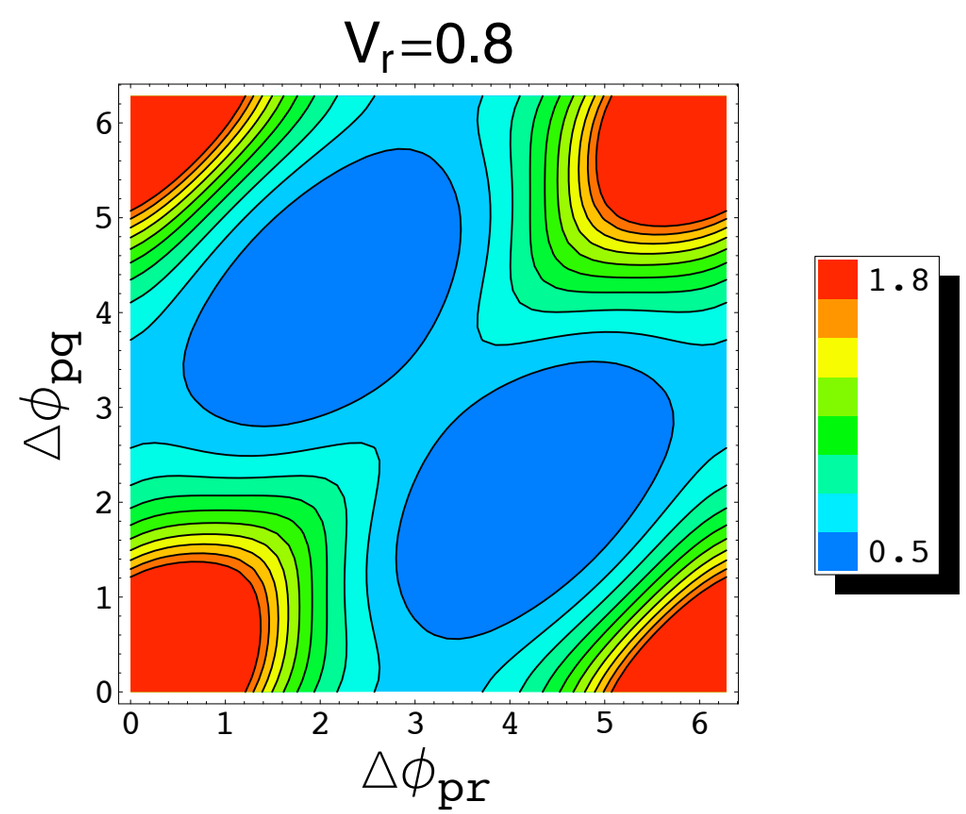


- Maximum
- Minimum



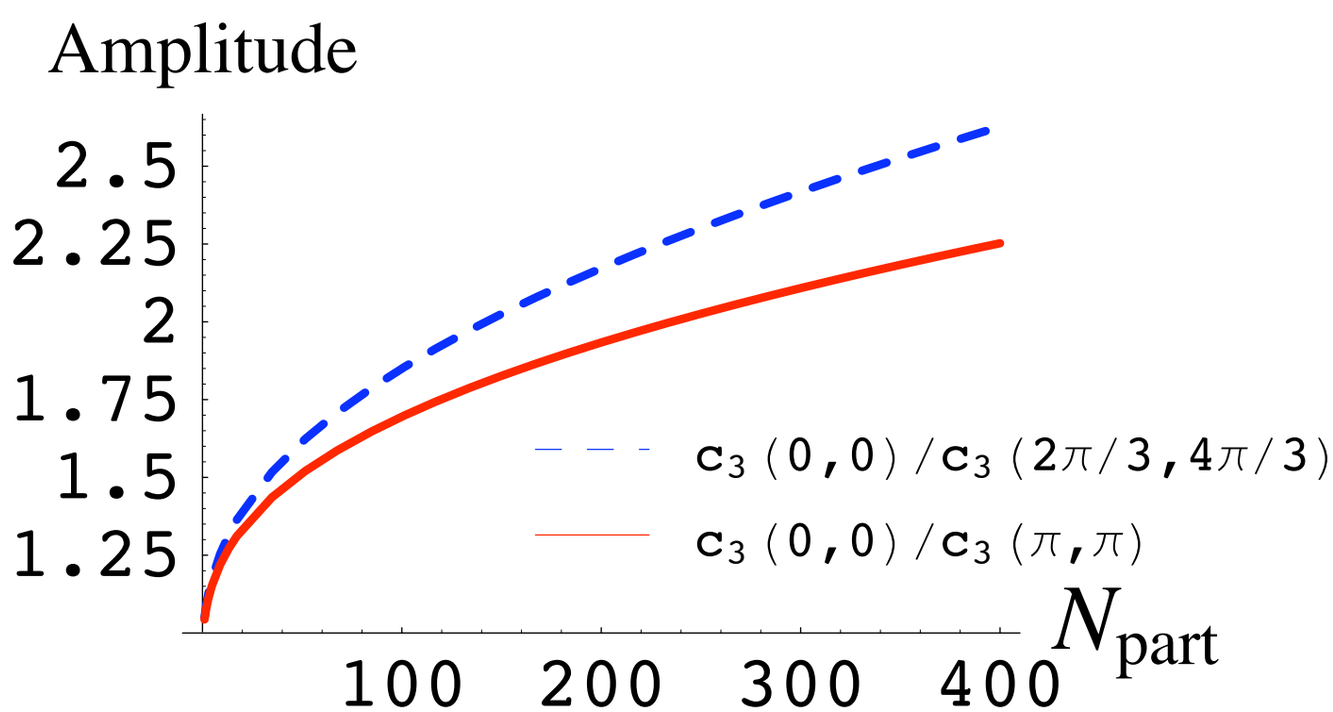
Azimuthal Dependence





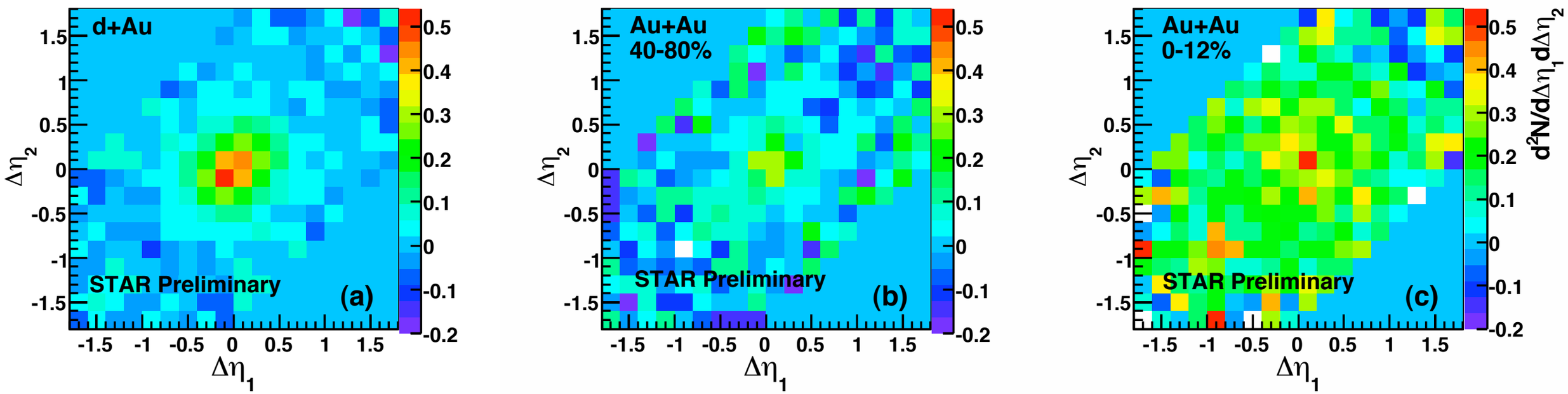
“Ridge” amplitude in 3 particle correlations

- No Free Parameters
- A direct measure of $\langle V_r \rangle$
  - No dependence on κ_3, α_s or N_{part}



Rapidity Dependence

- d+Au Au+Au (40%80%) Central Au+Au

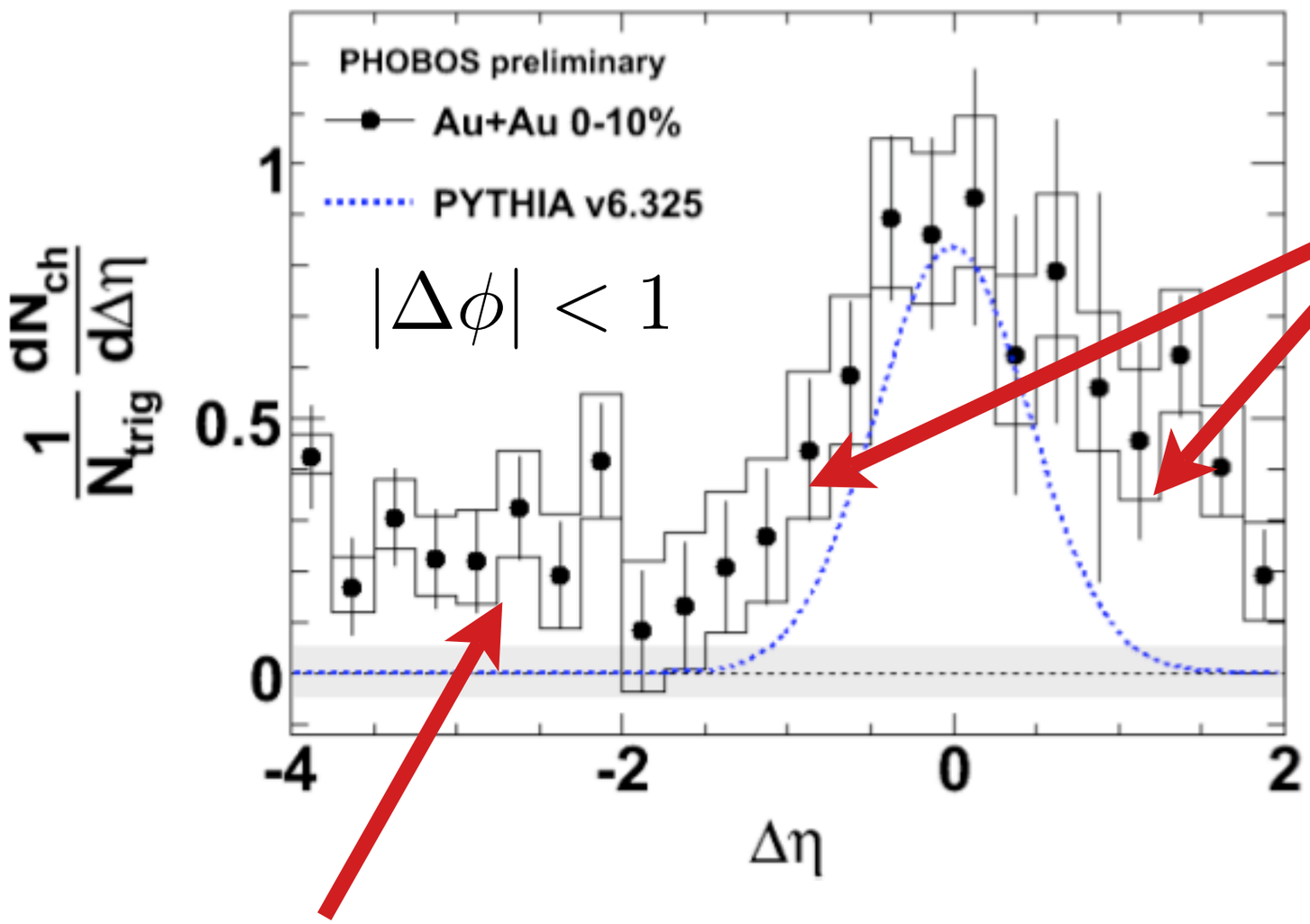


- We see a jet peak sitting on top of a flat plateau in central collisions

$$\Delta\eta_{\mathrm{max}} \sim 1.5$$

Long range rapidity correlations

- B. Alver [PHOBOS Collaboration], J. Phys. G 35, 104080 (2008).

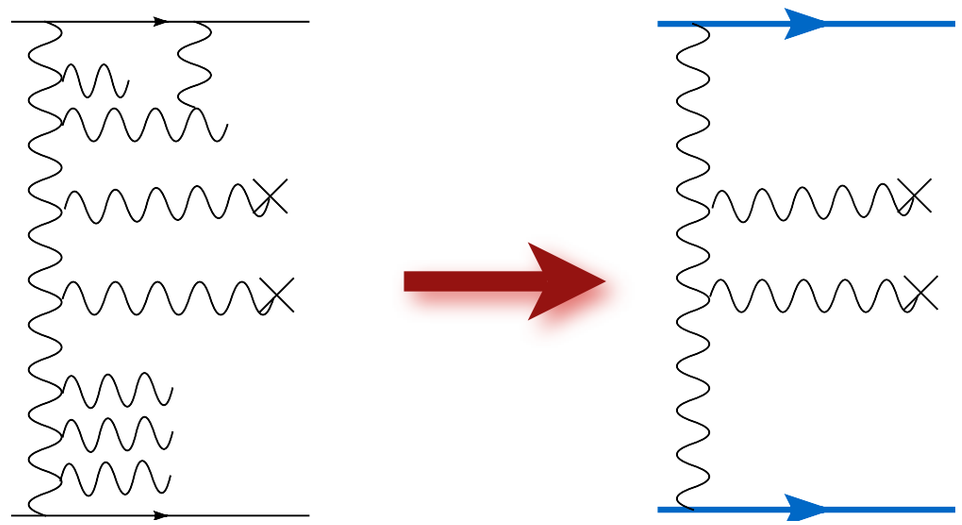


Same ridge as seen by STAR?

Long range collimated correlation
Diminished?

Long range rapidity correlations

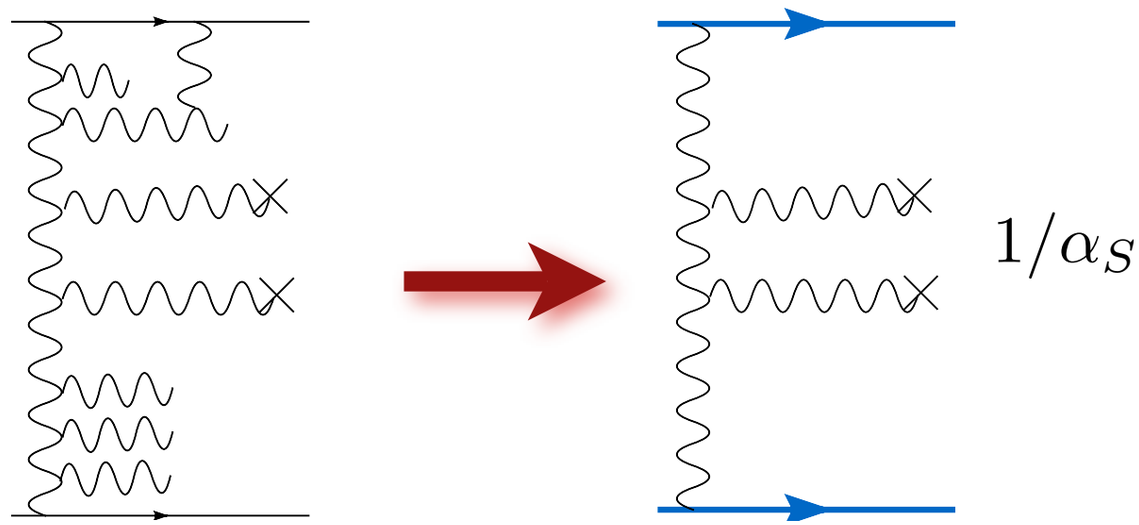
$$\left\langle \frac{d^2N}{d^2p_{\perp,1}dy_1 d^2p_{\perp,2}dy_2} \right\rangle = \int [d\rho_A d\rho_B] W^A_{y_{\rm beam}-y_1} W^B_{y_{\rm beam}+y_2} \frac{dN_{\rm LO}}{d^2p_{\perp,1}dy_1} \frac{dN_{\rm LO}}{d^2p_{\perp,n}dy_n}$$



$1/\alpha_S$

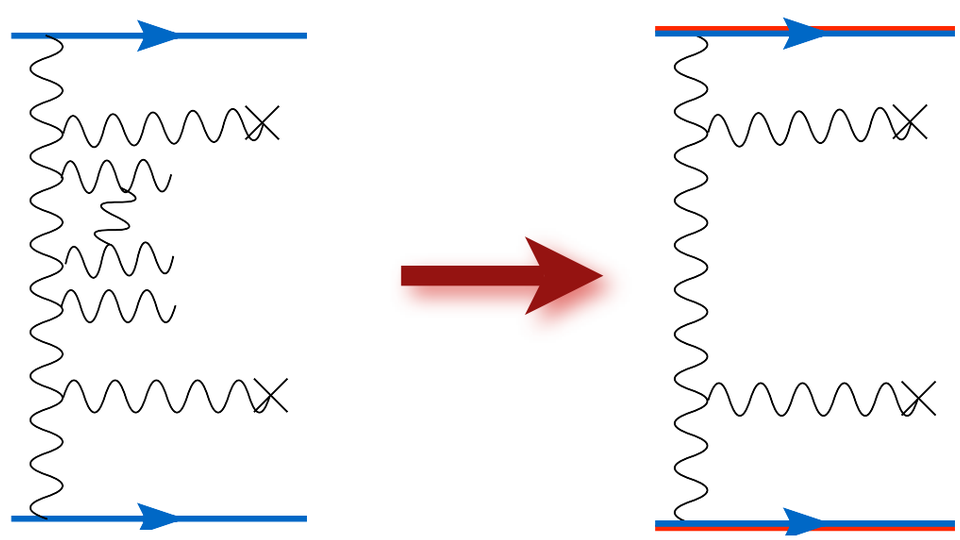
Long range rapidity correlations

$$\left\langle \frac{d^2N}{d^2p_{\perp,1}dy_1 d^2p_{\perp,2}dy_2} \right\rangle = \int [d\rho_A d\rho_B] W^A_{y_{\rm beam}-y_1} W^B_{y_{\rm beam}+y_2} \frac{dN_{\rm LO}}{d^2p_{\perp,1}dy_1} \frac{dN_{\rm LO}}{d^2p_{\perp,n}dy_n}$$



F. Gelis, T. Lappi and R. Venugopalan, High energy factorization and long range rapidity correlations in the Glasma, arXiv:0810.4829 [hep-ph]

$$\left\langle \frac{d^2N}{d^2p_{\perp,1}dy_1 d^2p_{\perp,2}dy_2} \right\rangle = \int [d\rho_A d\rho_B d\rho_A d\rho_B] W^A_{y_{\rm beam}-y_1} W^B_{y_{\rm beam}+y_2} \mathcal{G}_{y_1,y_2}\mathcal{G}_{y_2,y_1} \frac{dN_{\rm LO}}{d^2p_{\perp,1}dy_1} \frac{dN_{\rm LO}}{d^2p_{\perp,n}dy_n}$$



Future Work

- Non-perturbative solution of classical YM eqns.
  - In progress for 2 particle: Srednyak, Lappi, Venugopalan
- Improved treatment of hydrodynamic flow and hadronization
- Long range rapidity correlations

Conclusions

- Simple geometric pictures of the strength of correlations

$$\overline{C}_2 \sim \frac{\kappa_2}{S_\perp Q_S^2} \qquad \overline{C}_3 \sim \frac{\kappa_3}{(S_\perp Q_S^2)^2}$$

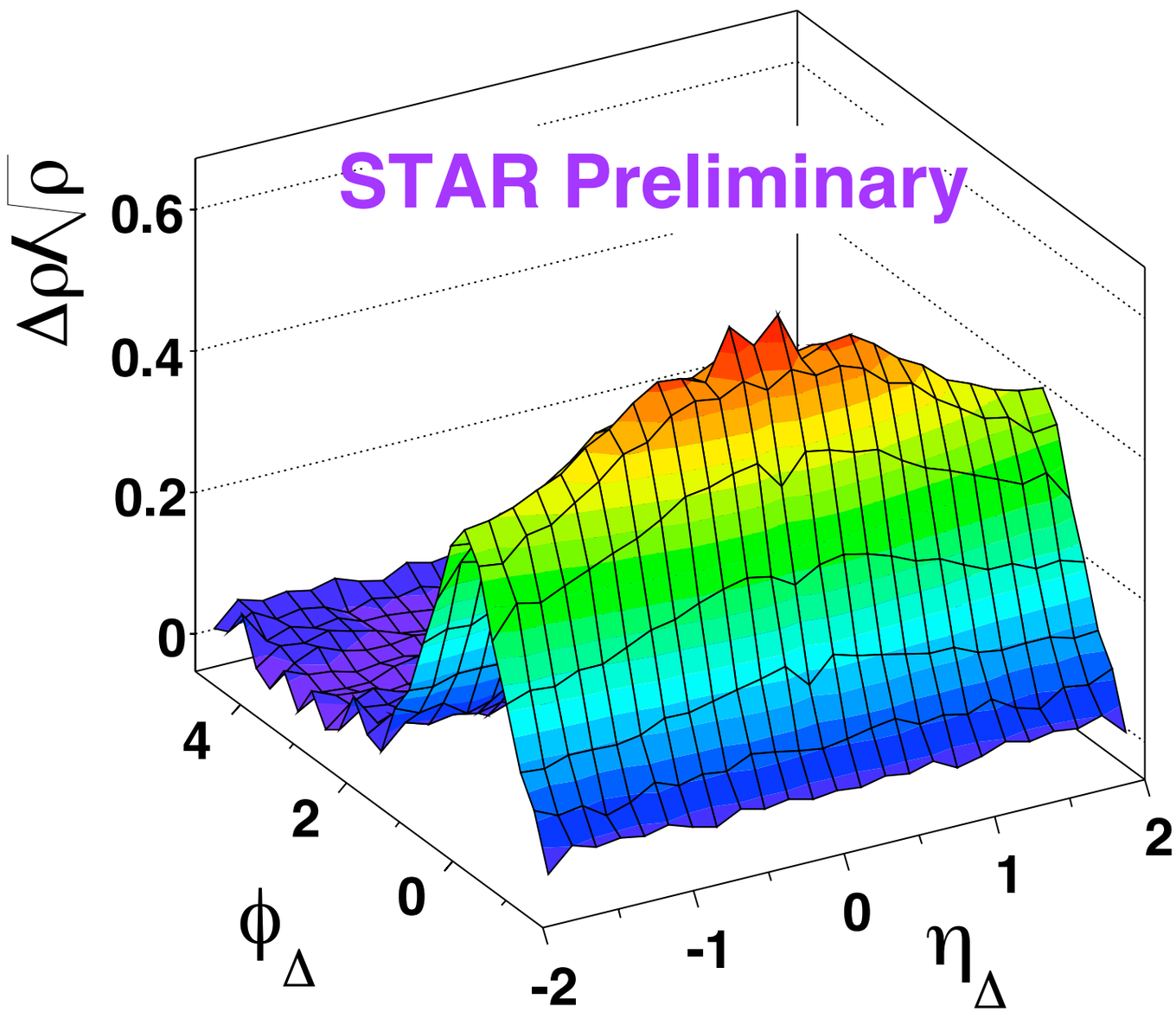
$$\kappa_2 \sim 4 \qquad \kappa_3 \sim 1.5$$

- correlation flat in rapidity

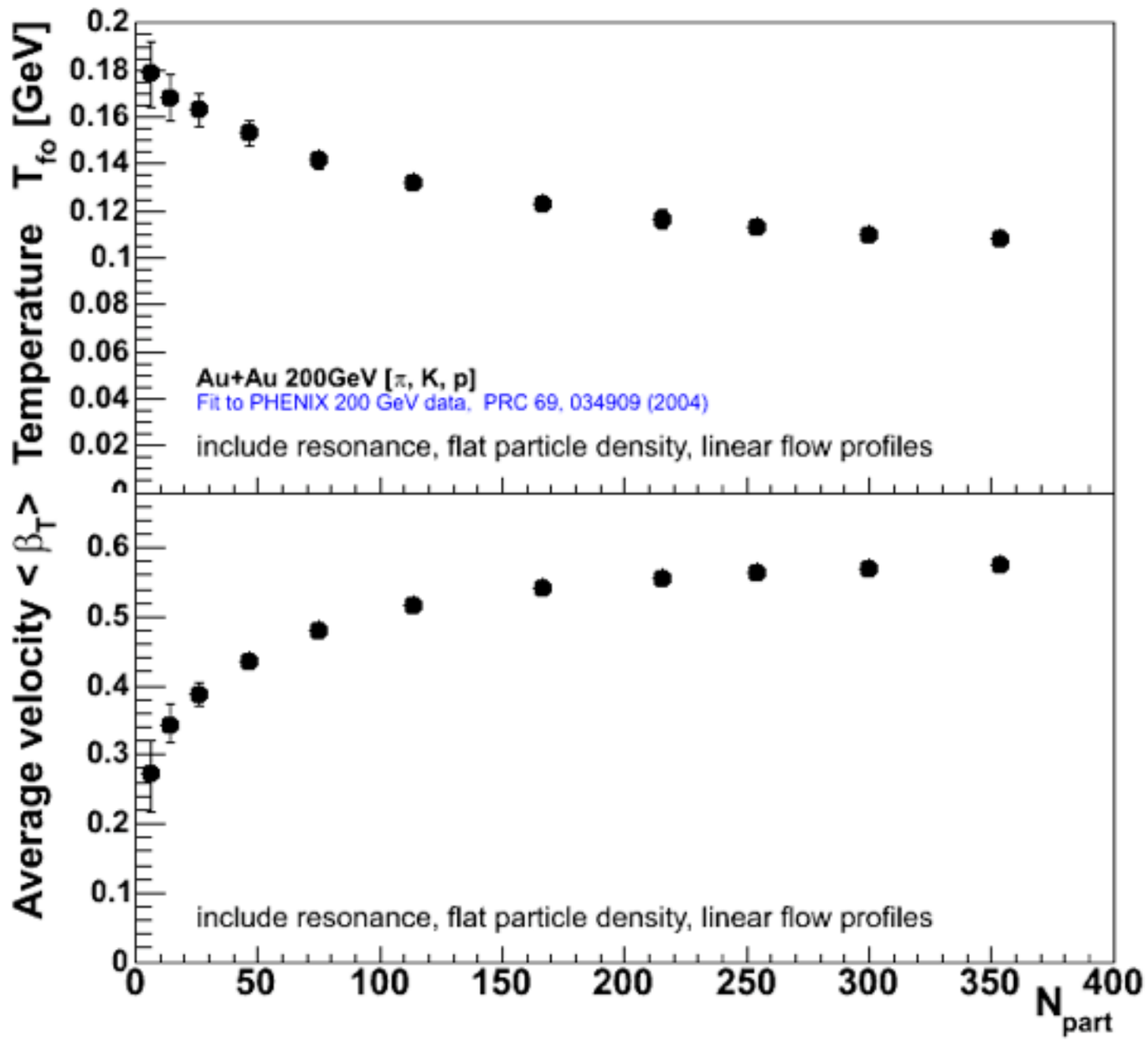
- radial flow lead to non-trivial azimuthal correlations
  - extraction of $\langle V_r \rangle$ from centrality dependence

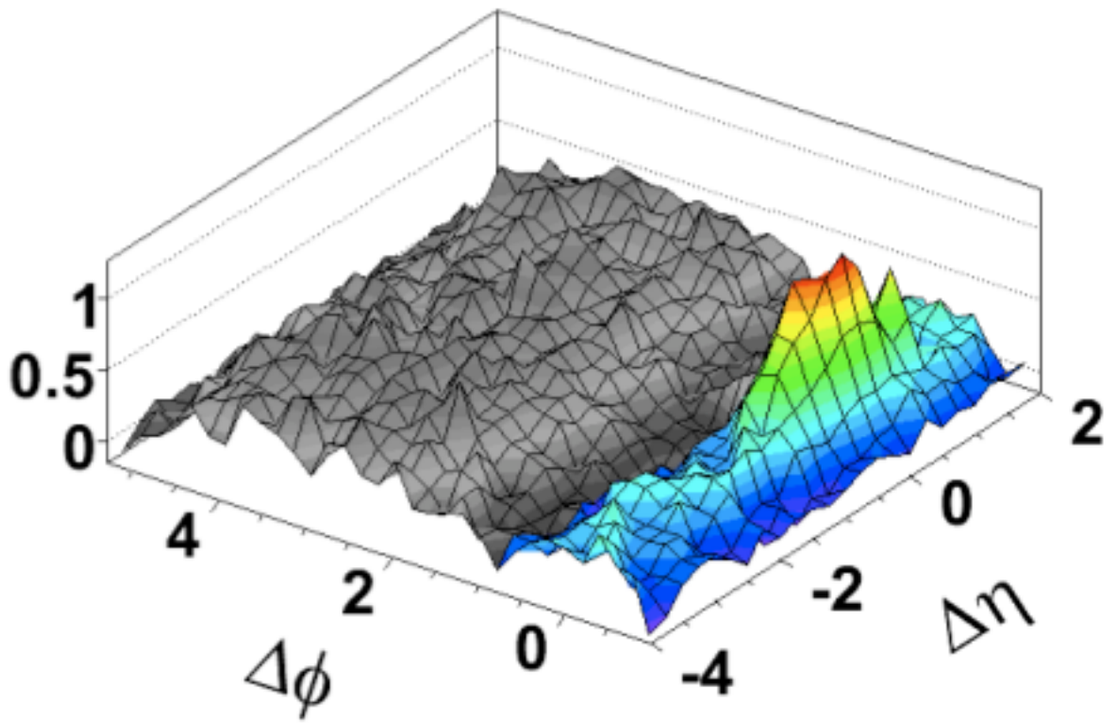
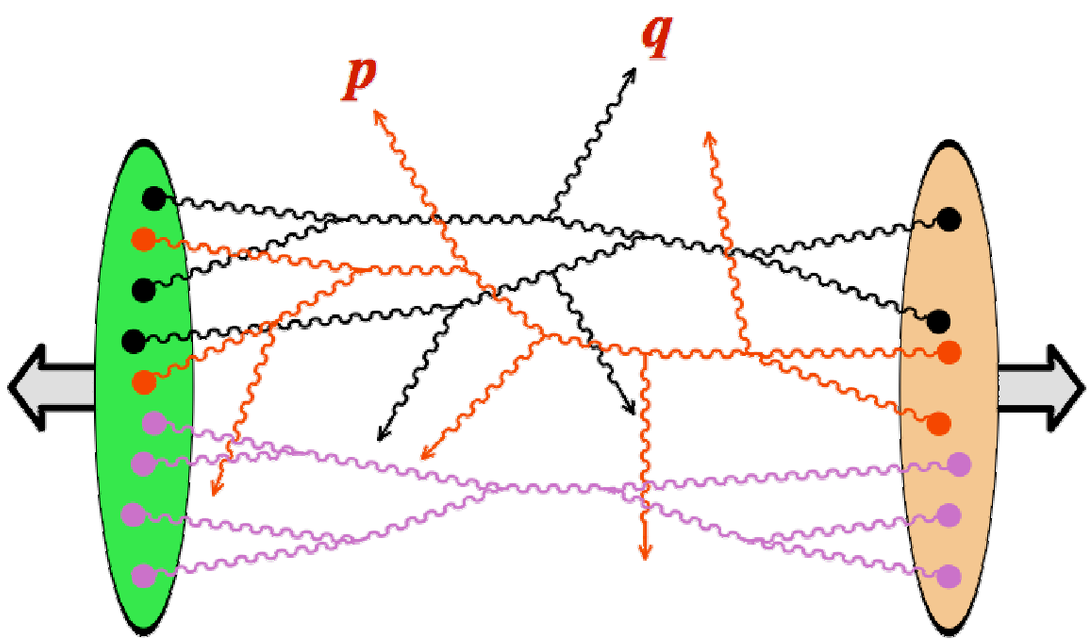
Backup

The Ridge


STAR Preliminary
$\Delta\rho/\sqrt{\rho}$
0.6
0.4
0.2
0
4
2
0
ϕ_Δ
-2
-1
0
1
2
η_Δ

Blast Wave Parameters




1
0.5
0
4
2
0
Δφ
-4
-2
0
2
Δη

- From talk of Raju Venugopalan