Femtoscopy of the initial state geometry fluctuations

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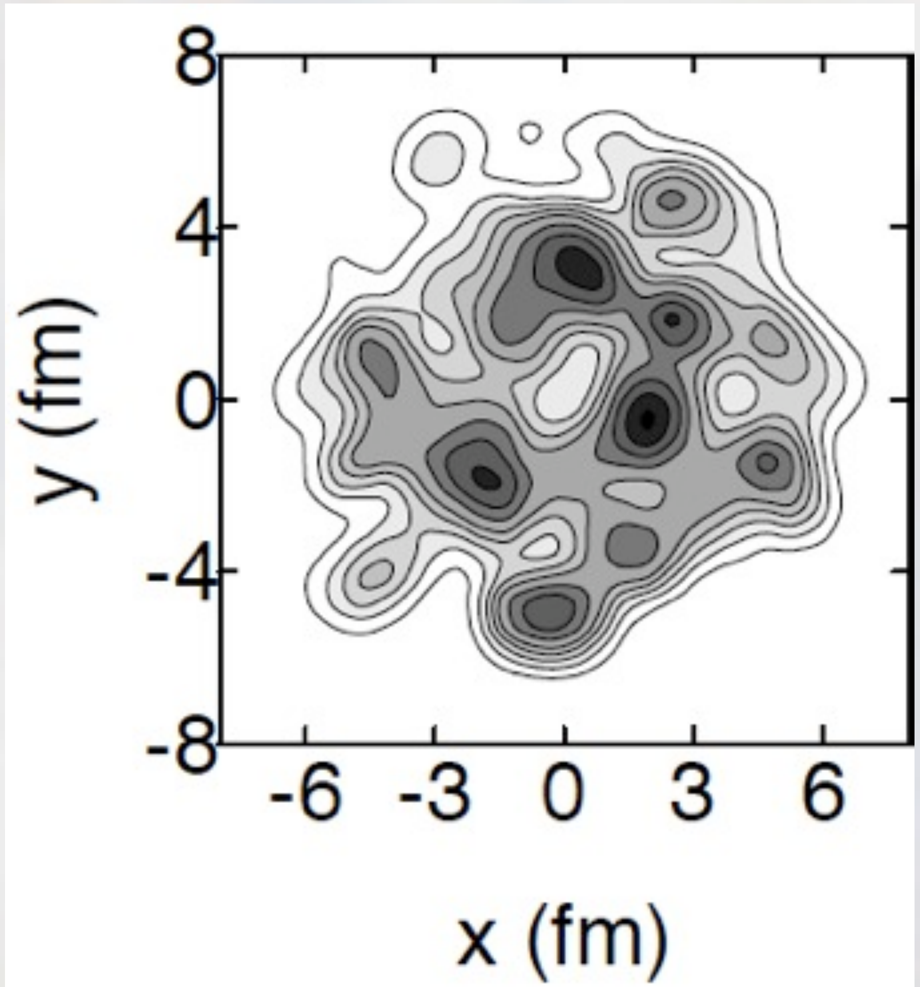
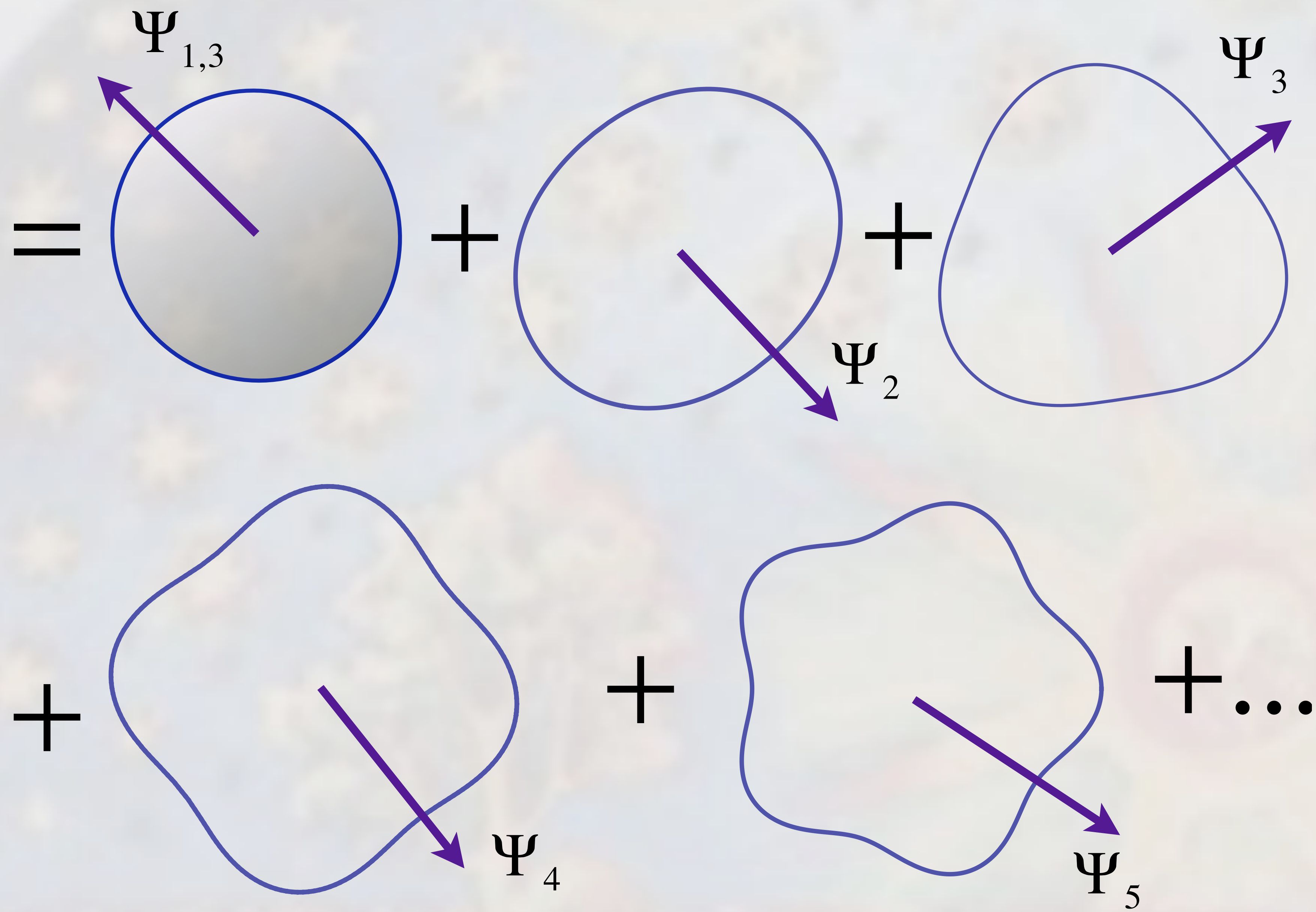
- Fluctuation in the initial conditions ➔ different harmonics flow
- Can we “see” the triangular shape? quadrangular?
- Blast wave simulations
- AMPT results
- What is next
- Conclusions

Density decomposition



Yogiro Hama,[1] Rone Peterson G. Andrade,[1] Frédérique Grassi,[1] Wei-Liang Qian,[1] Takeshi Osada,[2] Carlos Eduardo Aguiar,[3] and Takeshi Kodama[3]

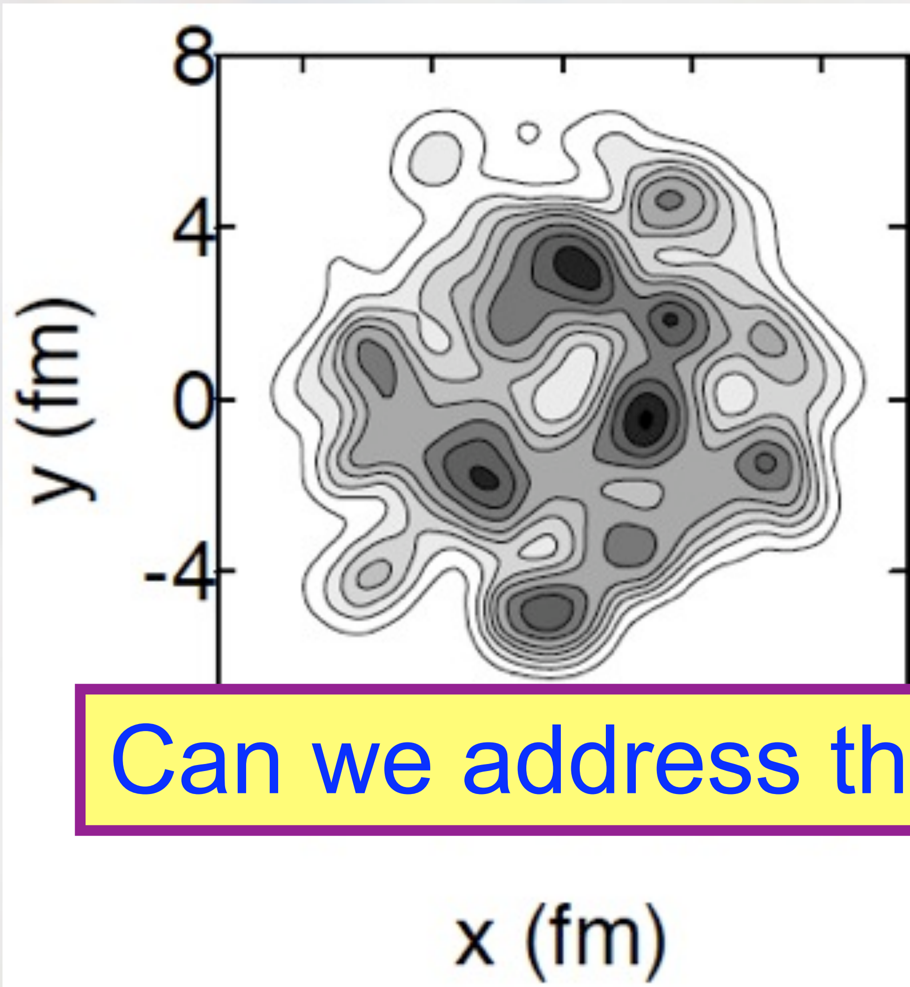


$$\int \mathrm{d}^2 x\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \rho(x) = \rho(\boldsymbol{k}) \,,$$

arXiv:1010.1876v1 [nucl-th] 9 Oct 2010

Derek Teaney and Li Yan

Density decomposition



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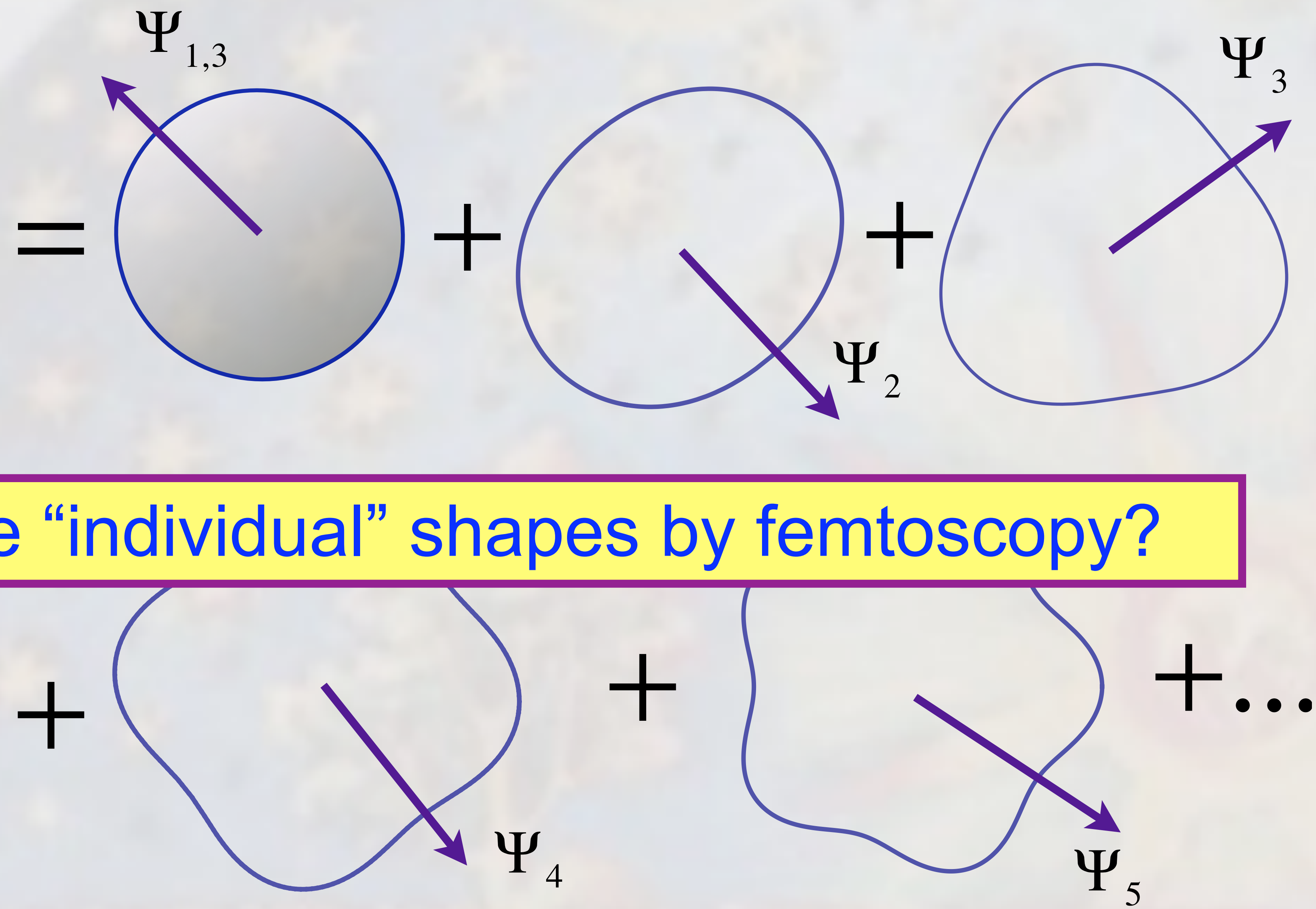


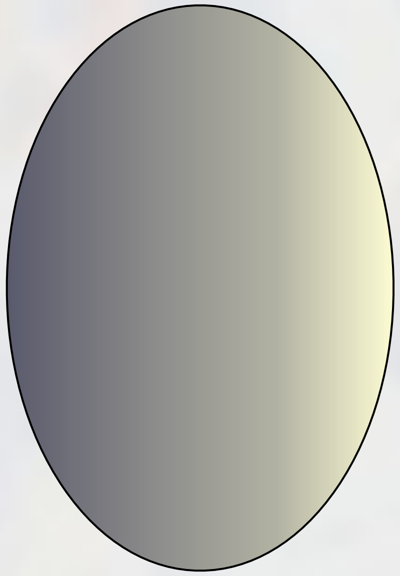
Can we address the "individual" shapes by femtoscopy?

$$\int d^2x\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \rho(x) = \rho(\boldsymbol{k}),$$

arXiv:1010.1876v1 [nucl-th] 9 Oct 2010

Derek Teaney and Li Yan

Source from different directions



S. A. Voloshin and W. E. Cleland, Phys. Rev. C **53**, 896 (1996) [arXiv:nucl-th/9509025];Phys. Rev. C **54**, 3212 (1996) [arXiv:nucl-th/9606033].

RQMD Au+Au 11.4 GeV/nucleon $3.0<b<6.0$ fm
$0.14<p_t<0.25$ GeV. $2.7<y_{\rm lab}<3.2$

	$+x$	$-x$	$+y$	$-y$
$\langle x\rangle$	4.9	-0.5	1.6	1.7
$\langle y\rangle$	-0.2	-0.2	3.0	-3.0
$\langle z\rangle$	11.2	9.2	9.9	9.3
$\langle t\rangle$	19.7	16.7	18.2	17.3
$\langle x^2\rangle-\langle x\rangle^2$	12.8	17.4	17.6	15.8
$\langle y^2\rangle-\langle y\rangle^2$	19.1	16.6	16.9	17.1
$\langle z^2\rangle-\langle z\rangle^2$	69.4	61.1	68.7	66.2
$\langle t^2\rangle-\langle t\rangle^2$	92.3	92.2	98.0	99.1

	$+x$	$-x$	$+y$
$\langle xy\rangle-\langle x\rangle\langle y\rangle$	0.2	0.0	0.1
$\langle xz\rangle-\langle x\rangle\langle z\rangle$	9.3	1.6	7.3
$\langle xt\rangle-\langle x\rangle\langle t\rangle$	12.2	-7.1	5.3
$\langle yz\rangle-\langle y\rangle\langle z\rangle$	-2.4	-2.1	4.7
$\langle yt\rangle-\langle y\rangle\langle t\rangle$	-1.6	-3.0	9.3
$\langle zt\rangle-\langle z\rangle\langle t\rangle$	72.8	68.4	74.7

The system looks different from different directions

HBT: how it works

$$C(\mathbf{q},\mathbf{P}) \approx 1 + \frac{\int d^4x_1 d^4x_2\, S(x_1,\mathbf{P}/2) S(x_2,\mathbf{P}/2) e^{-i\mathbf{q}[\mathbf{V}(t_1-t_2)-(\mathbf{r}_1-\mathbf{r}_2)]}}{\left[\int d^4x\, S(x,\mathbf{P}/2)\right]^2} =$$

$$1 + \frac{\left[\int d^4x\, S(x,\mathbf{P}/2) e^{-i\mathbf{q}[\mathbf{V}t-\mathbf{r}]}\right]^2}{\left[\int d^4x\, S(x,\mathbf{P}/2)\right]^2} \approx 1 + \lambda \exp[-\sum_{i,j} R_{ij}^2 q_i q_j]$$

$$\mathbf{P} = (\mathbf{p}_1 + \mathbf{p}_2)/2; \qquad \mathbf{q} = (\mathbf{p}_1 - \mathbf{p}_2)$$

$$(p_1 + p_2)(p_1 - p_2) = 0$$
$$Eq_0 - \mathbf{Pq} = 0$$
$$q_0 = \mathbf{Pq}/E = \mathbf{Vq}$$

Femtoscopy measures particle separation at the moment the second particle is produced

Gaussian source -> Gaussian correlation function

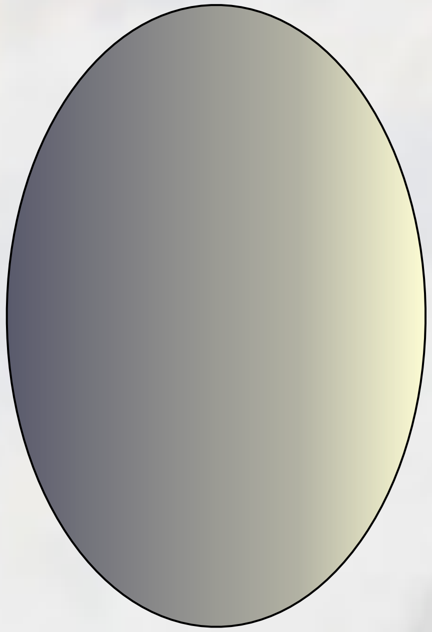
$$R_{ij}^2 = \left\langle \left(\Delta x_i - V_i \Delta t\right)\left(\Delta x_j - V_j \Delta t\right) \right\rangle$$

$$\Delta x_i = x_i - \langle x_i \rangle$$

Review: M. A. Lisa, S. Pratt, R. Soltz and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. **55**, 357 (2005) [arXiv:nucl-ex/0505014].

AzFemto

S. A. Voloshin and W. E. Cleland, Phys. Rev. C **53**, 896 (1996) [arXiv:nucl-th/9509025];Phys. Rev. C **54**, 3212 (1996) [arXiv:nucl-th/9606033].



	$+x$	$-x$	$+y$	$-y$
$\langle x\rangle$	4.9	-0.5	1.6	1.7
$\langle y\rangle$	-0.2	-0.2	3.0	-3.0
$\langle z\rangle$	11.2	9.2	9.9	9.3
$\langle t\rangle$	19.7	16.7	18.2	17.3
$\langle x^2\rangle-\langle x\rangle^2$	12.8	17.4	17.6	15.8
$\langle y^2\rangle-\langle y\rangle^2$	19.1	16.6	16.9	17.1
$\langle z^2\rangle-\langle z\rangle^2$	69.4	61.1	68.7	66.2
$\langle t^2\rangle-\langle t\rangle^2$	92.3	92.2	98.0	99.1

	$+x$	$-x$	$+y$
$\langle xy\rangle-\langle x\rangle\langle y\rangle$	0.2	0.0	0.1
$\langle xz\rangle-\langle x\rangle\langle z\rangle$	9.3	1.6	7.3
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$$R_{ij}^2 = \left\langle \left(\Delta x_i - V_i \Delta t\right)\left(\Delta x_j - V_j \Delta t\right)\right\rangle$$

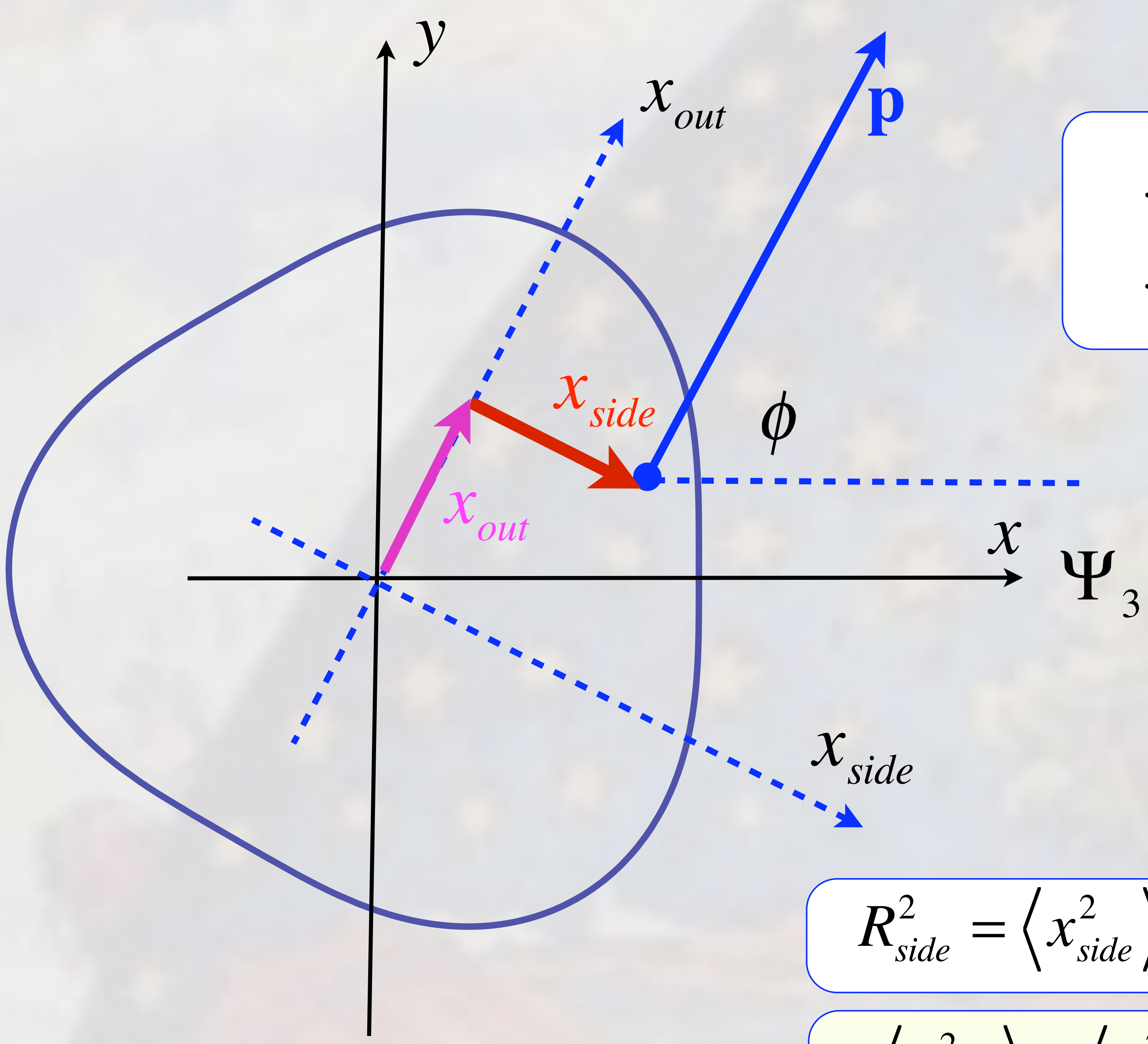
	R_x^2	R_y^2	R_z^2	R_{xy}^2	R_{xz}^2	R_{yz}^2
$x+$	16.9	19.1	12.6	0.8	-1.5	-1.0
$x-$	25.3	16.6	11.8	-1.1	3.3	1.2
$y+$	17.6	24.0	12.9	-1.9	2.7	0.6
$y-$	15.8	24.8	14.7	2.8	1.2	-0.2

How to do a bit better, see

Hardtke D, Voloshin SA. *Phys. Rev. C* 61: 024905 (2000)

(and a slide in "extras")

Side-out-long (Bertsch-Pratt system)

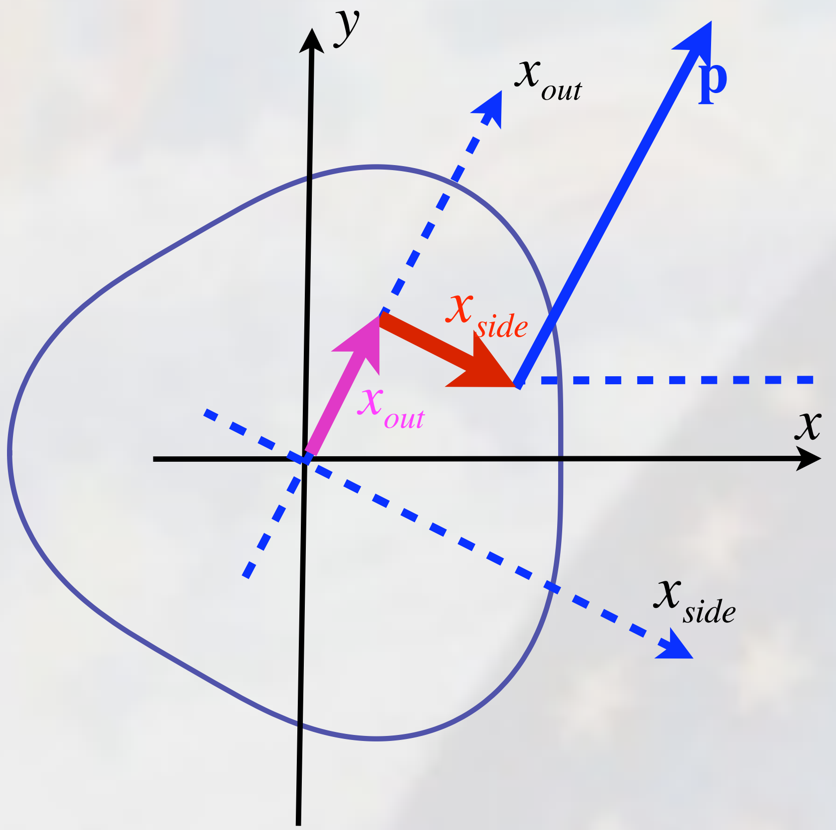


$$x_{side} = -x\sin\phi + y\cos\phi$$
$$\tilde{x}_{out} = x\cos\phi + y\sin\phi - V_t t$$

$$R^2_{side} = \left\langle x^2_{side} \right\rangle,\ R^2_{out} = \left\langle \Delta\tilde{x}^2_{out} \right\rangle,\ R^2_{side-out} = \left\langle x_{side}\tilde{x}_{out} \right\rangle$$

$$\left\langle x^2_{side} \right\rangle = \left\langle x^2 \right\rangle \sin^2\phi + \left\langle y^2 \right\rangle \cos^2\phi - \left\langle xy \right\rangle \sin 2\phi$$

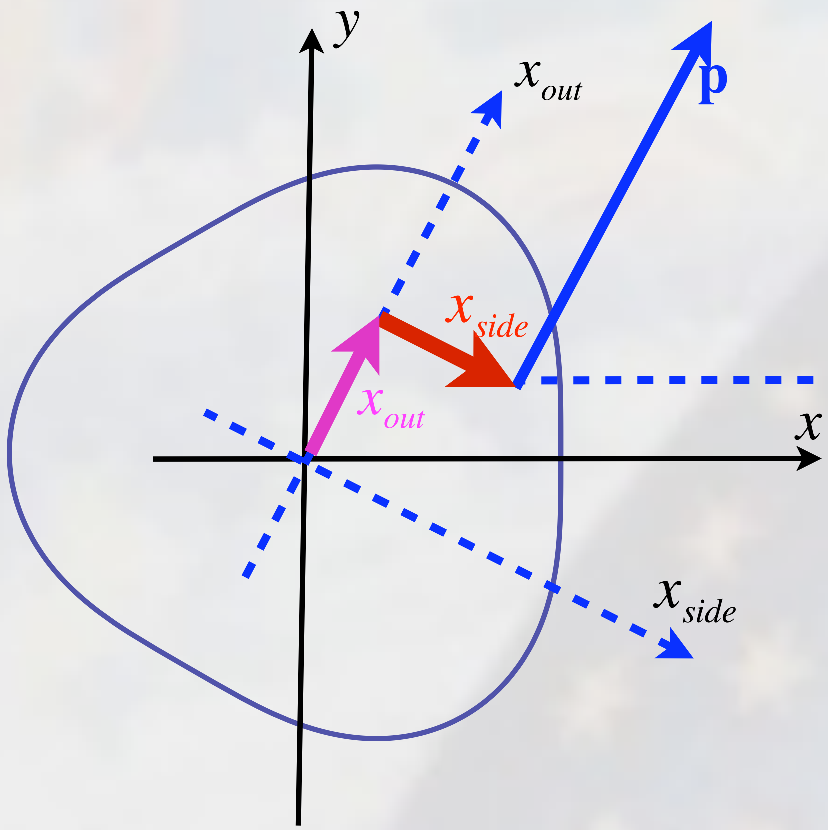
Stationary and expanding sources



Stationary source:
no higher order anisotropy in Gaussian approximation
4-th harmonic - modulations appear only in $\langle x^4 \rangle$
3-rd harmonic - modulations appear only in $\langle x^6 \rangle$

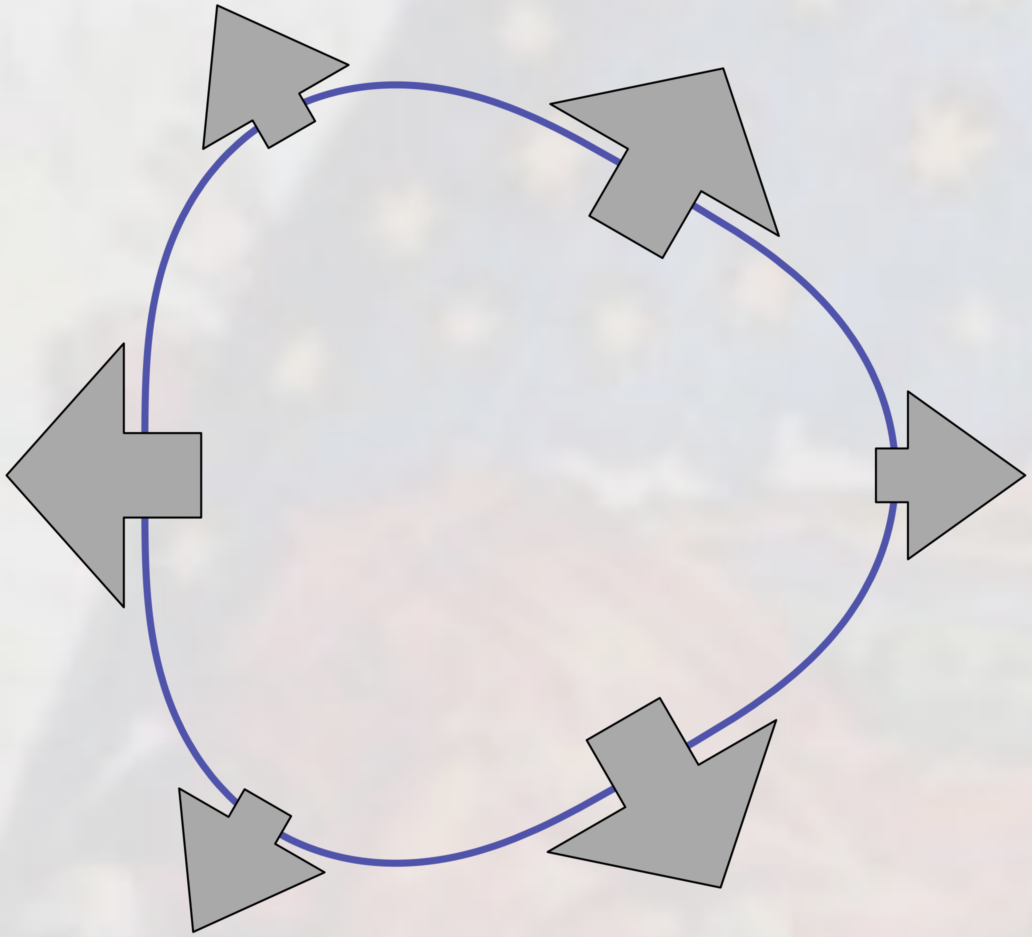
$$\langle x_{side}^2 \rangle = \langle x^2 \rangle \sin^2\phi + \langle y^2 \rangle \cos^2\phi - \langle xy \rangle \sin 2\phi$$

Stationary and expanding sources



Stationary source:
no higher order anisotropy in Gaussian approximation
4-th harmonic - modulations appear only in $\langle x^4 \rangle$
3-rd harmonic - modulations appear only in $\langle x^6 \rangle$

$$\left\langle x_{side}^2 \right\rangle = \left\langle x^2 \right\rangle \sin^2\phi + \left\langle y^2 \right\rangle \cos^2\phi - \langle xy \rangle \sin 2\phi$$

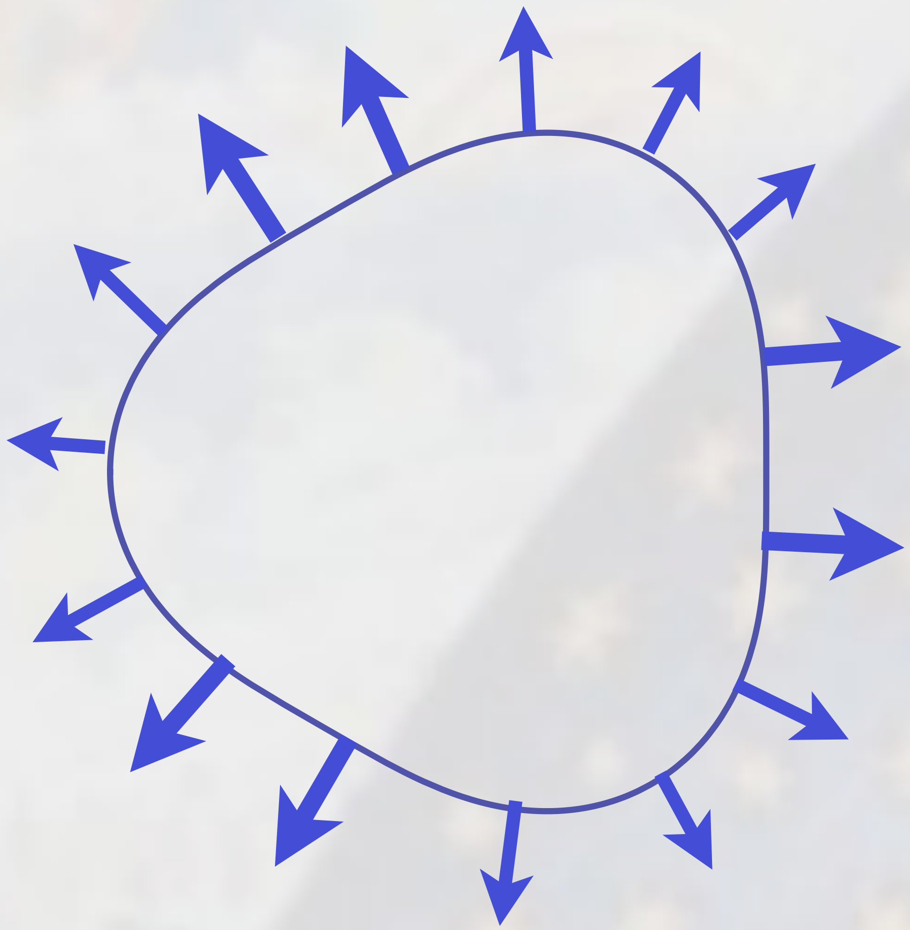


Can expansion lead to nontrivial *R(ϕ)* dependence?
Yes, several effects:
- variation in the “blast wave” velocity
- variation in velocity gradients in “side” direction

$$R_{out}^2 = \left\langle \left(\Delta x_{out} - V_t \Delta t \right)^2 \right\rangle$$

$$R_{long} \propto \frac{v_{therm}}{dv_z / dz}$$

Blast wave model

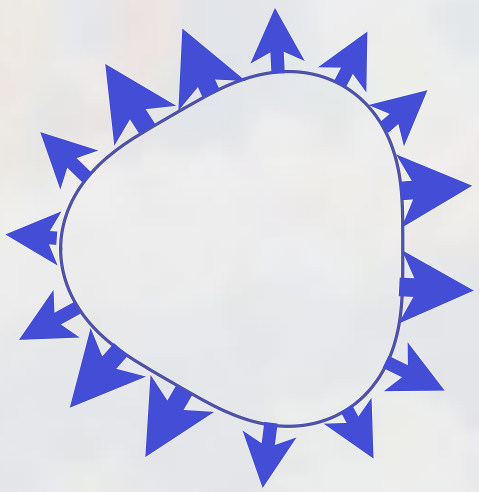


Expansion velocity is perpendicular to the surface, instantaneous freeze-out at constant temperature T=100 MeV , and linear transverse rapidity profile with $\rho_{t,max} = 0.9$ $\quad (\langle v_t \rangle \approx 0.7, \quad \langle p_t \rangle_\pi \approx 0.40$ GeV).

$$r_{max}(\phi) = R\,[1 - a_{space}\cos(n\phi)]$$

$$\rho_t(r,\varphi) = \rho_{t,\,max}\frac{r}{r_{max}(\phi)}[1 + a_{boost}\cos(n\phi)]$$

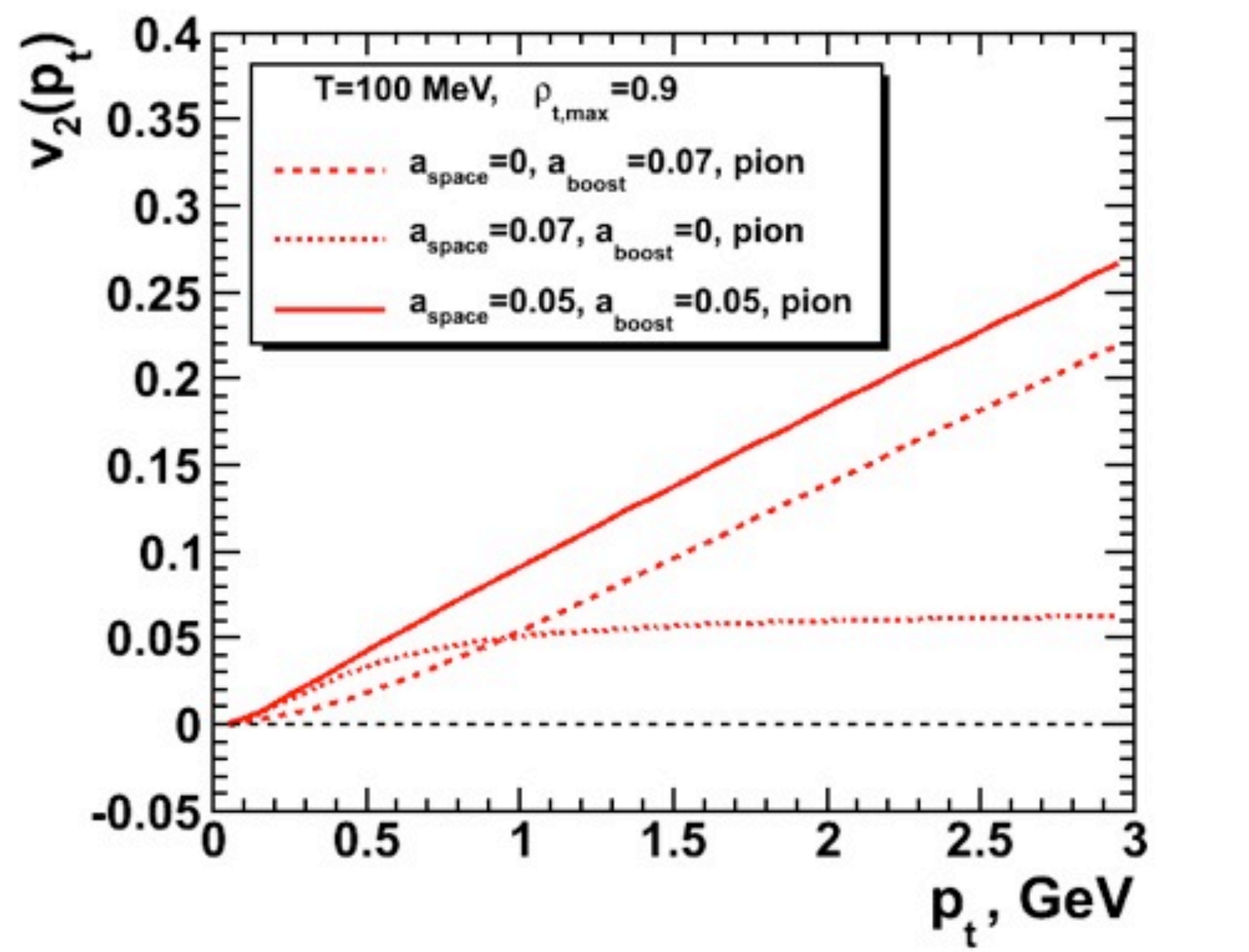
Blast wave model. “Fixing” a’s.



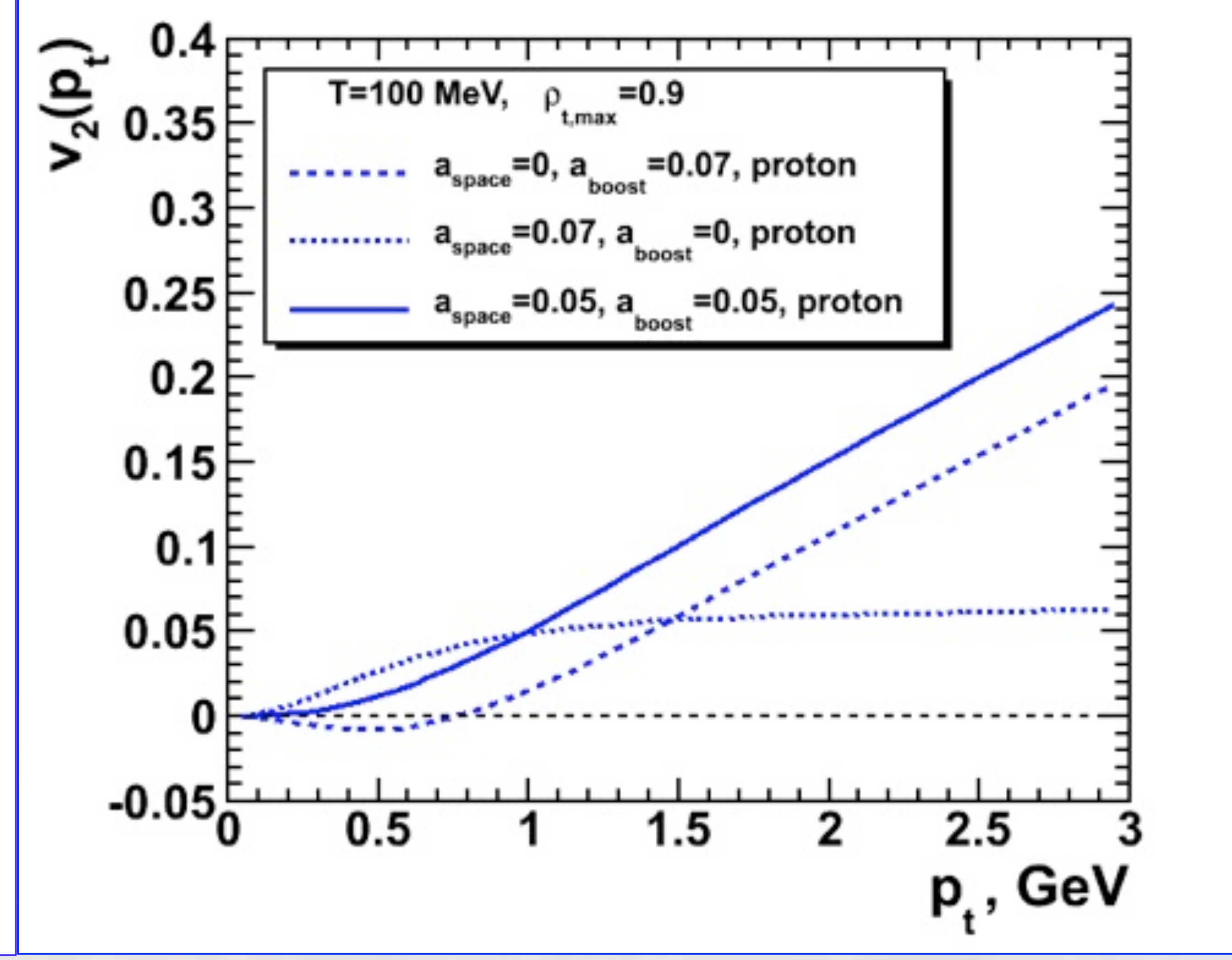
$$r_{max}(\phi) = R\,[1 - a_{space}\cos(n\phi)]$$

$$\rho_t(r,\varphi) = \rho_{t,\,max}\,\frac{r}{r_{max}(\phi)}[1 + a_{boost}\cos(n\phi)]$$

Pion

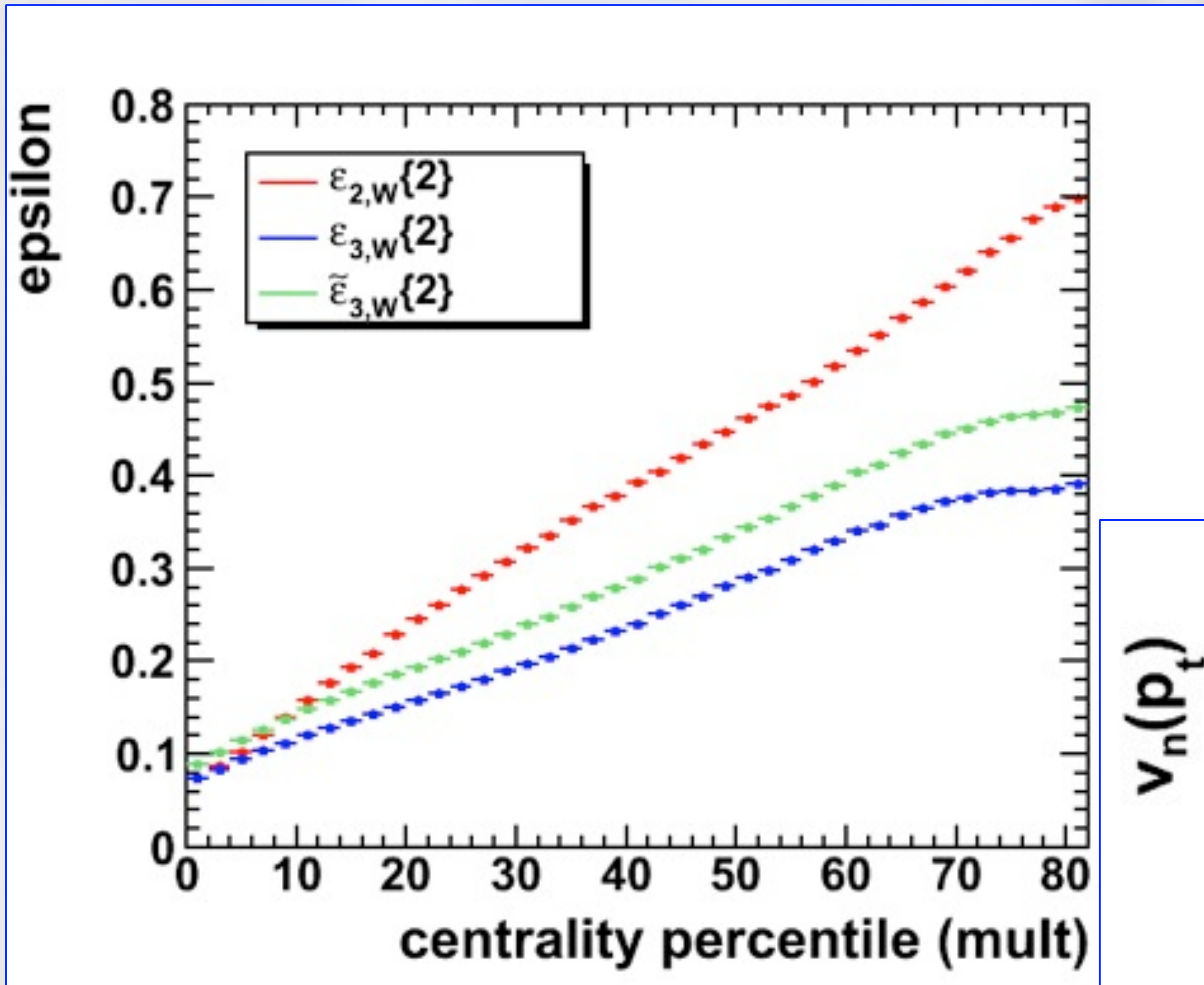


Proton



Note the “mass splitting” dependence on spatial eccentricity!

Eccentricities in MC Glauber model



$$\varepsilon_2 = \langle r^2 \cos(2\phi) \rangle / \langle r^2 \rangle$$

$$\varepsilon_3 = \langle r^2 \cos(3\phi) \rangle / \langle r^2 \rangle$$

$$\tilde{\varepsilon}_3 = \langle r^3 \cos(3\phi) \rangle / \langle r^3 \rangle$$

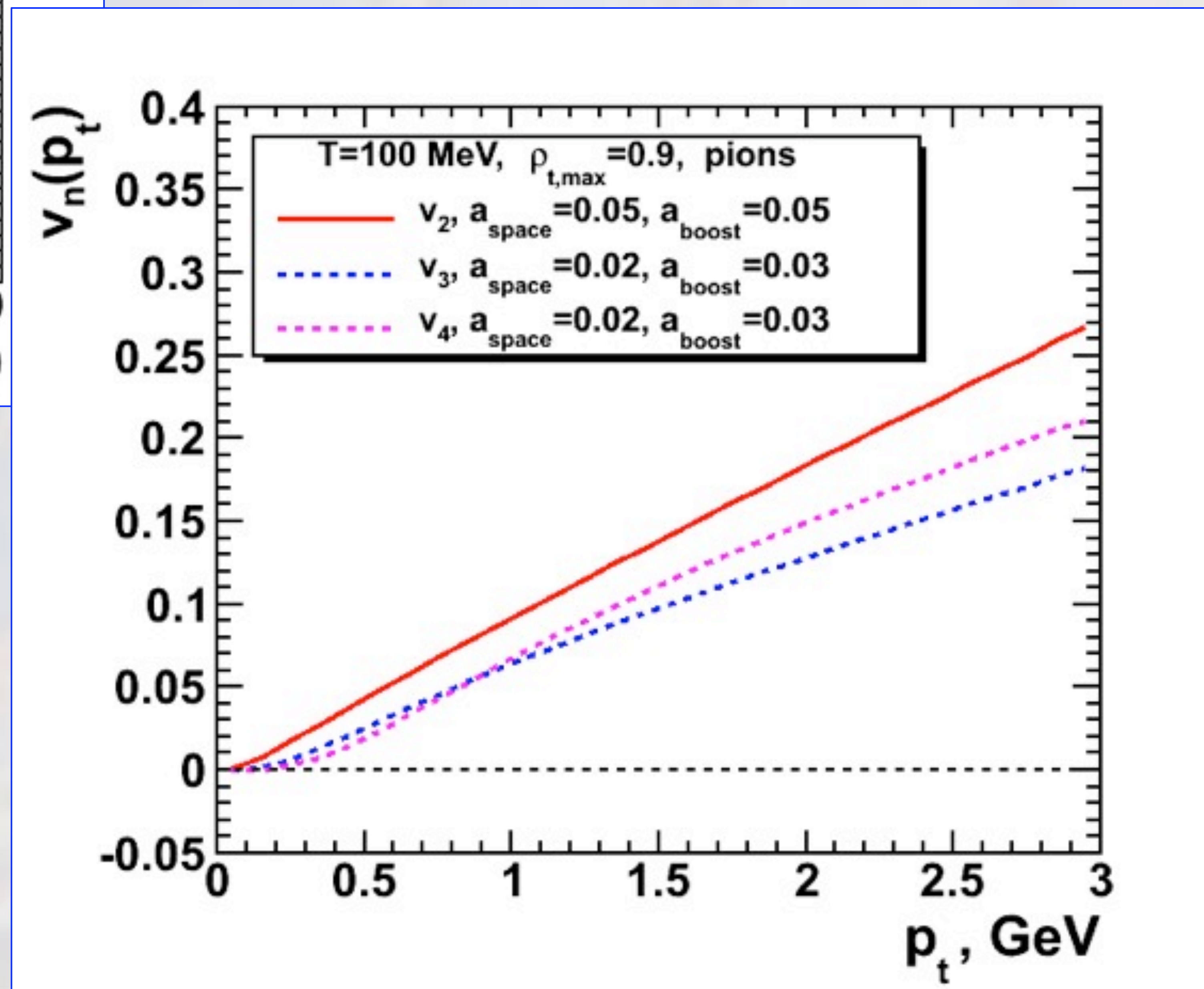
$$r(\phi) = r_0 [1 + a_{space} \cos(n\phi)]$$

$$\varepsilon_n \approx 2 a_{space}$$

$$\tilde{\varepsilon}_3 \approx 5 a_{space} / 2$$

Assume that during the expansion period eccentricities decrease about 4 times

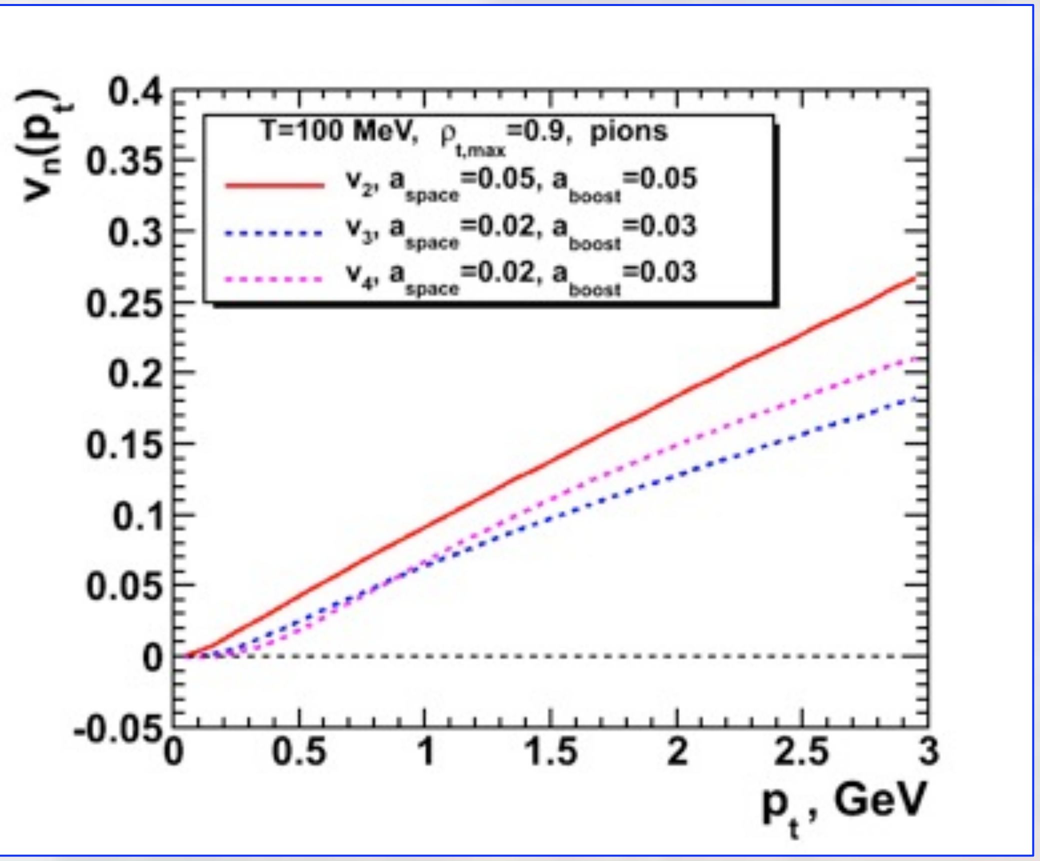
Consider centrality ~ 15%

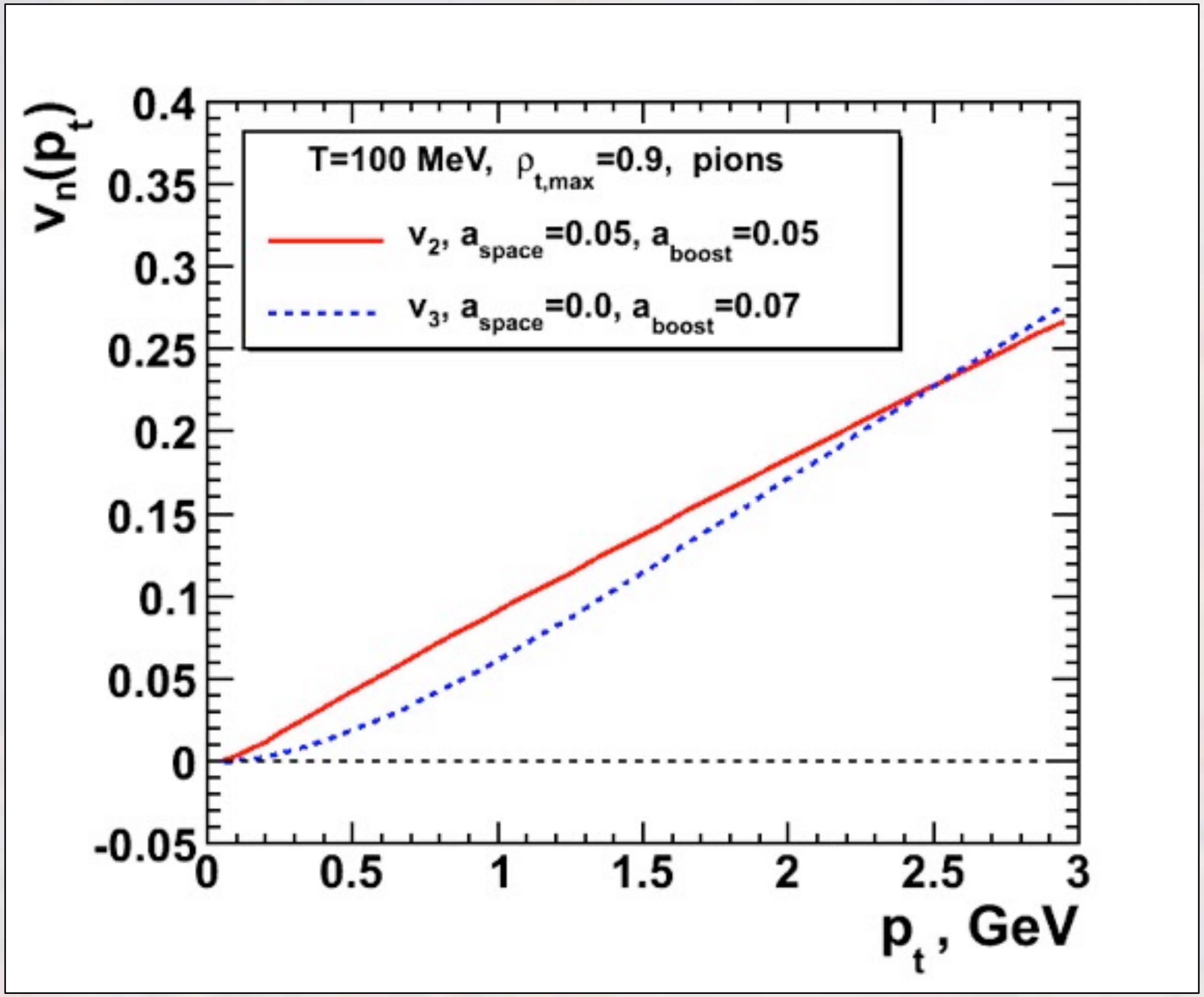


An "exotic" case?

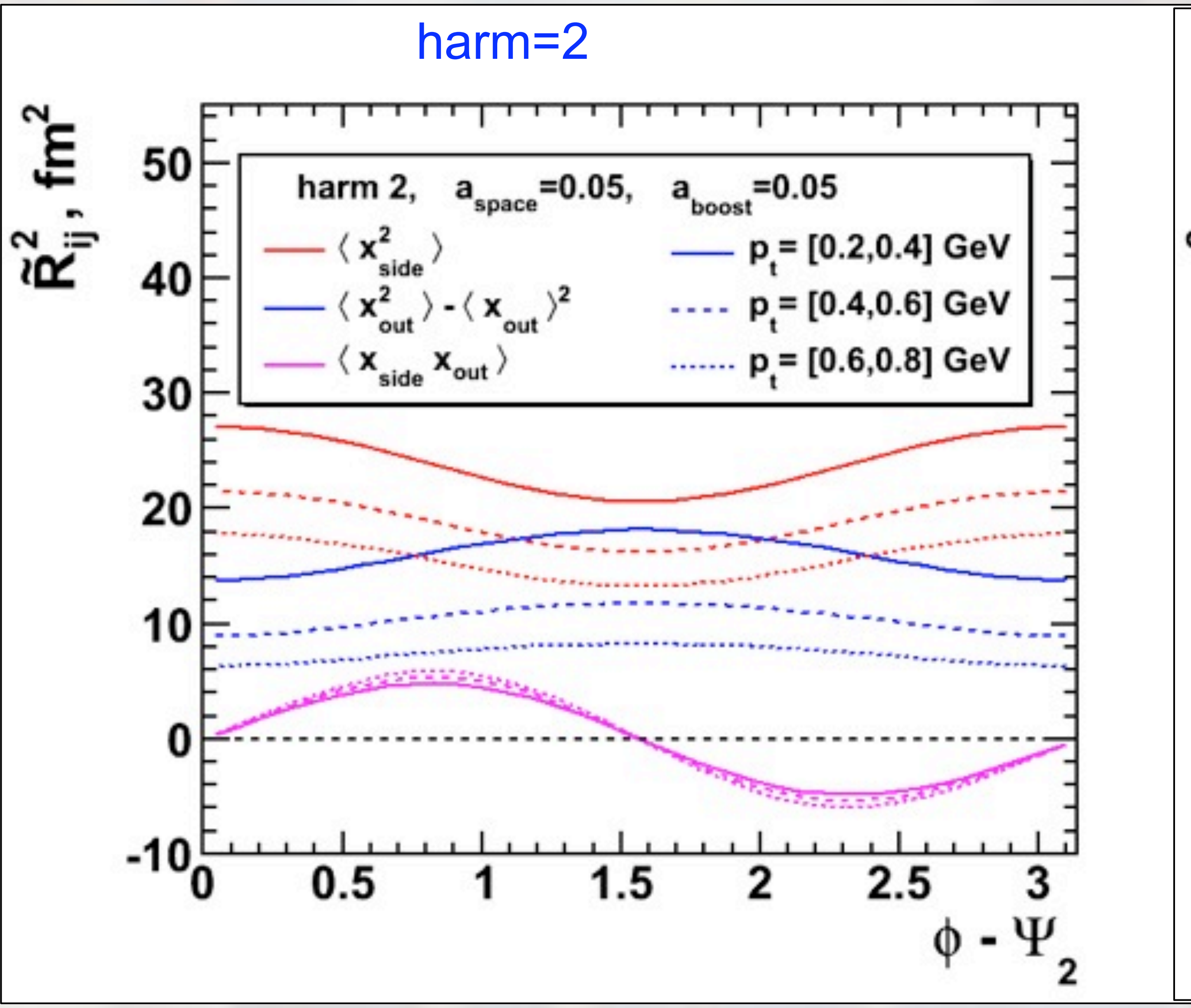
For $a_{boost}^{(3)} > a_{boost}^{(2)}$ and $a_{space}^{(3)} < a_{space}^{(2)}$

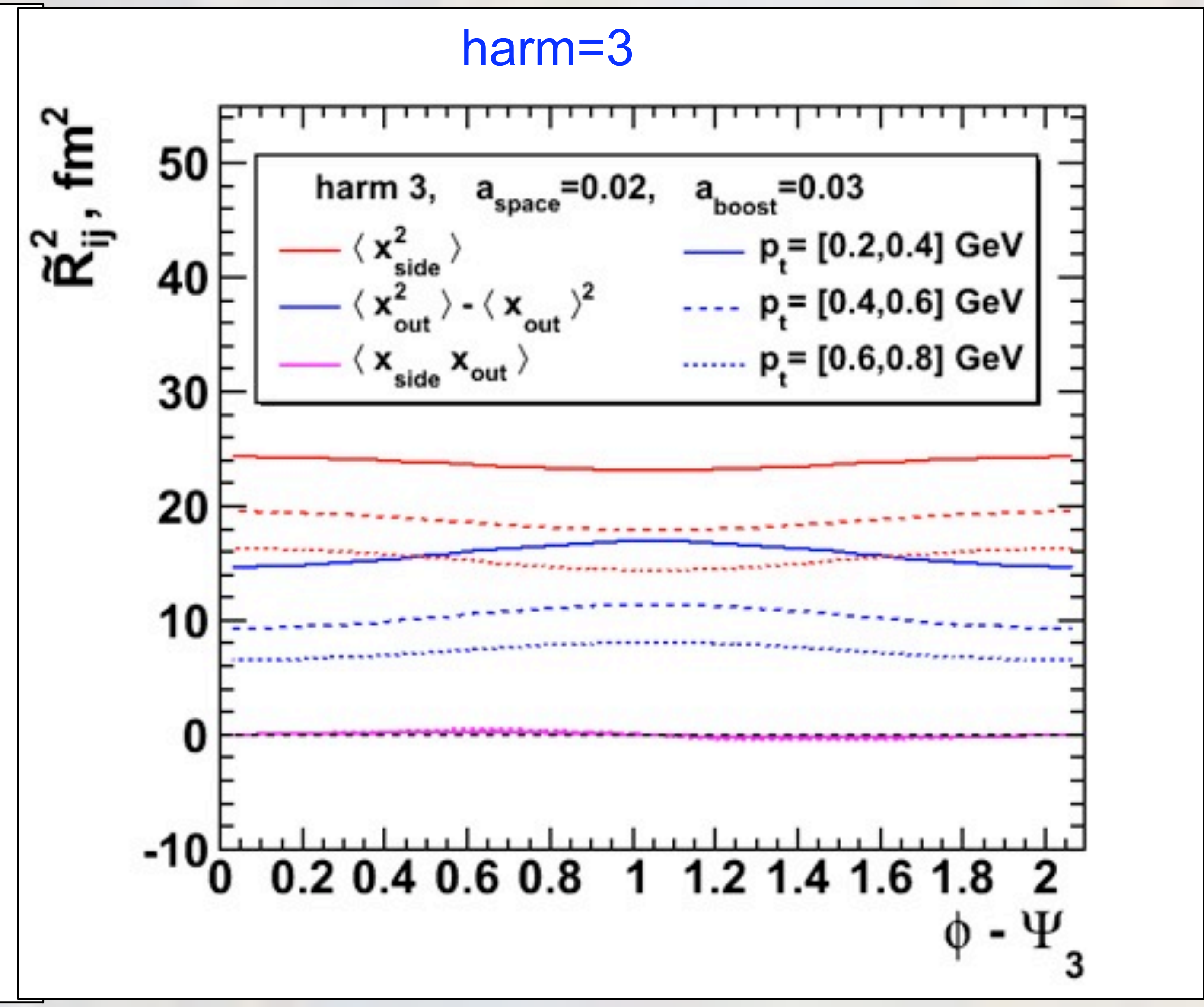
v_3 can become larger than v_2





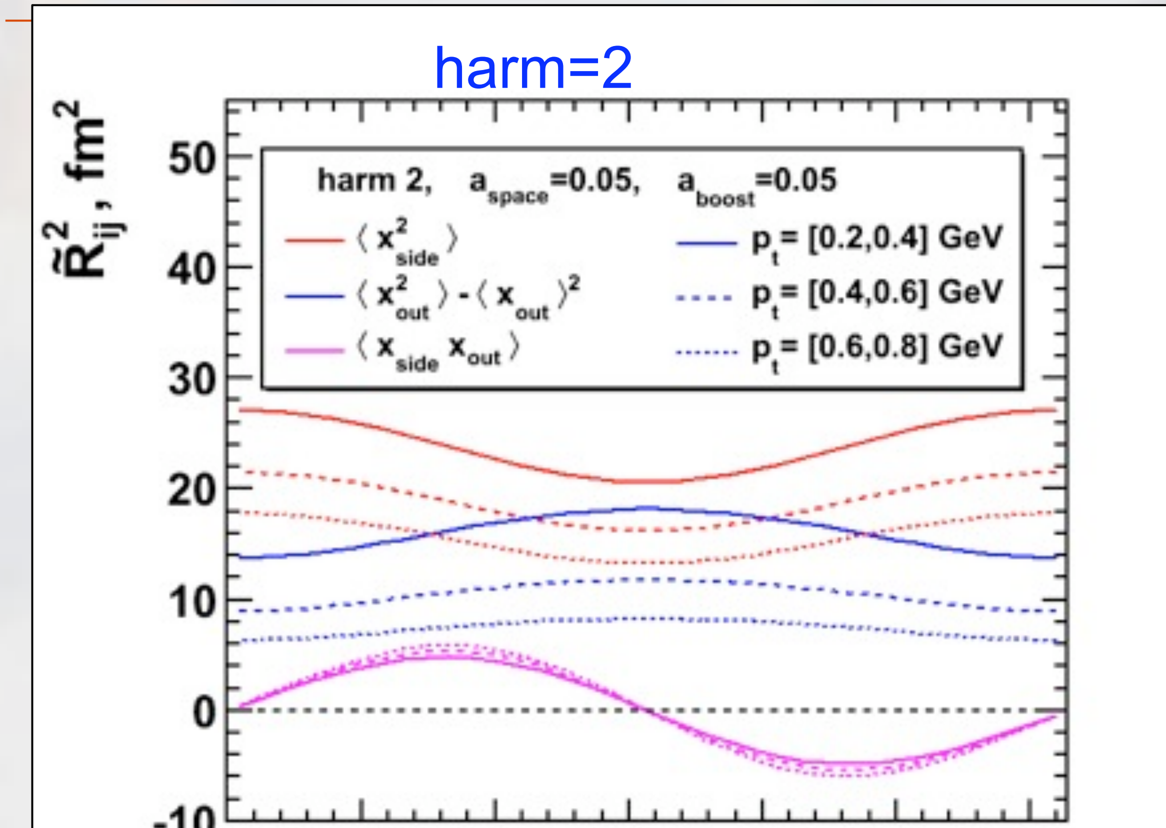
Second and third harmonics

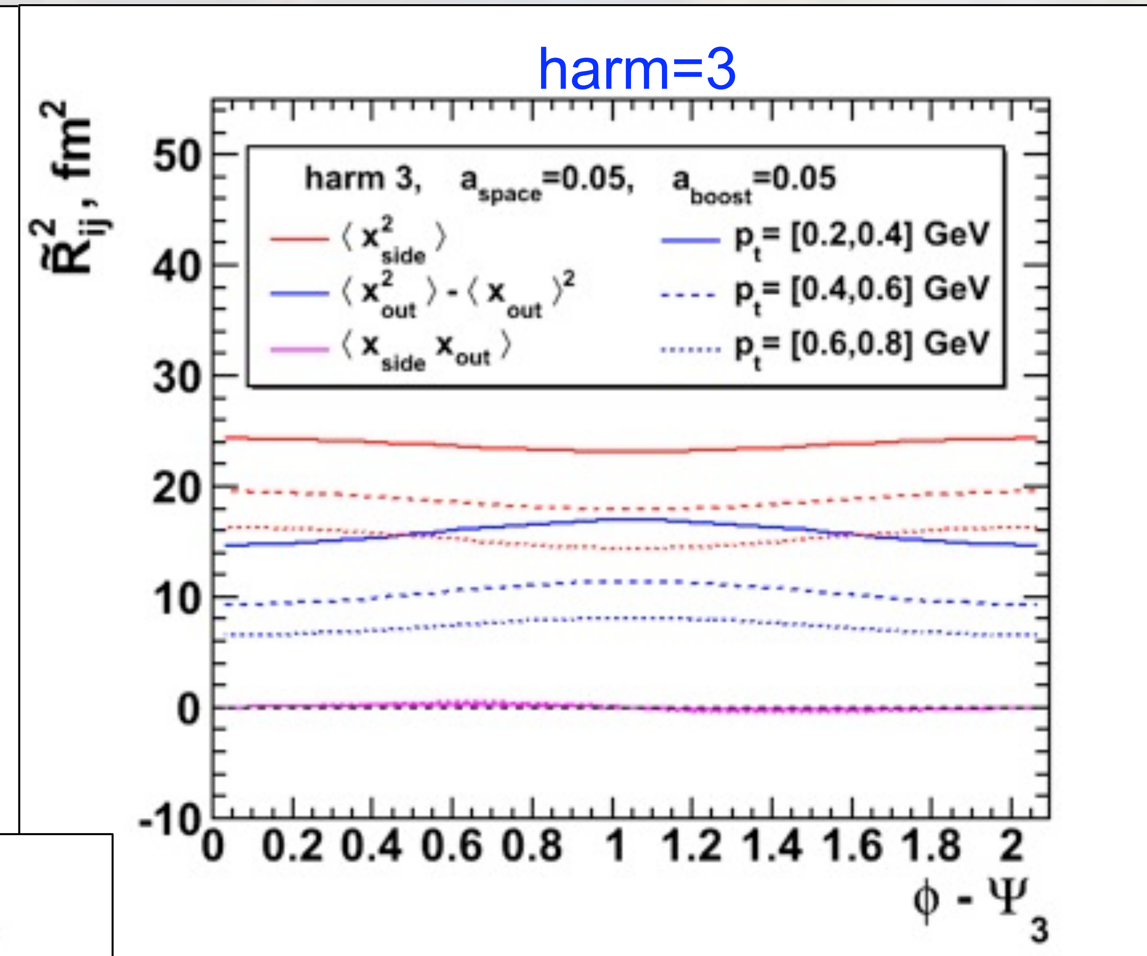


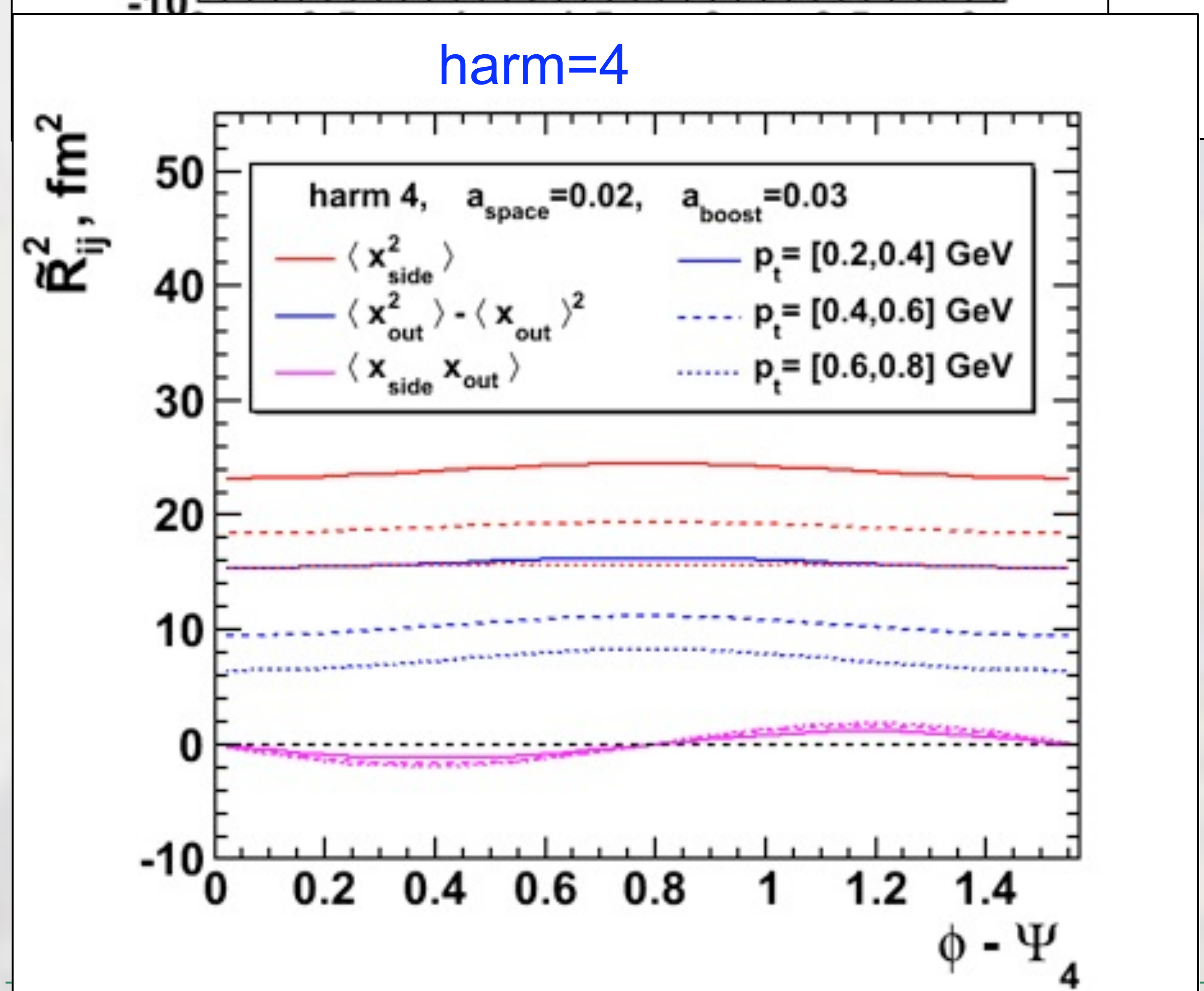


Very weak side-out correlations in the third harmonic

studying quadrangular shape...



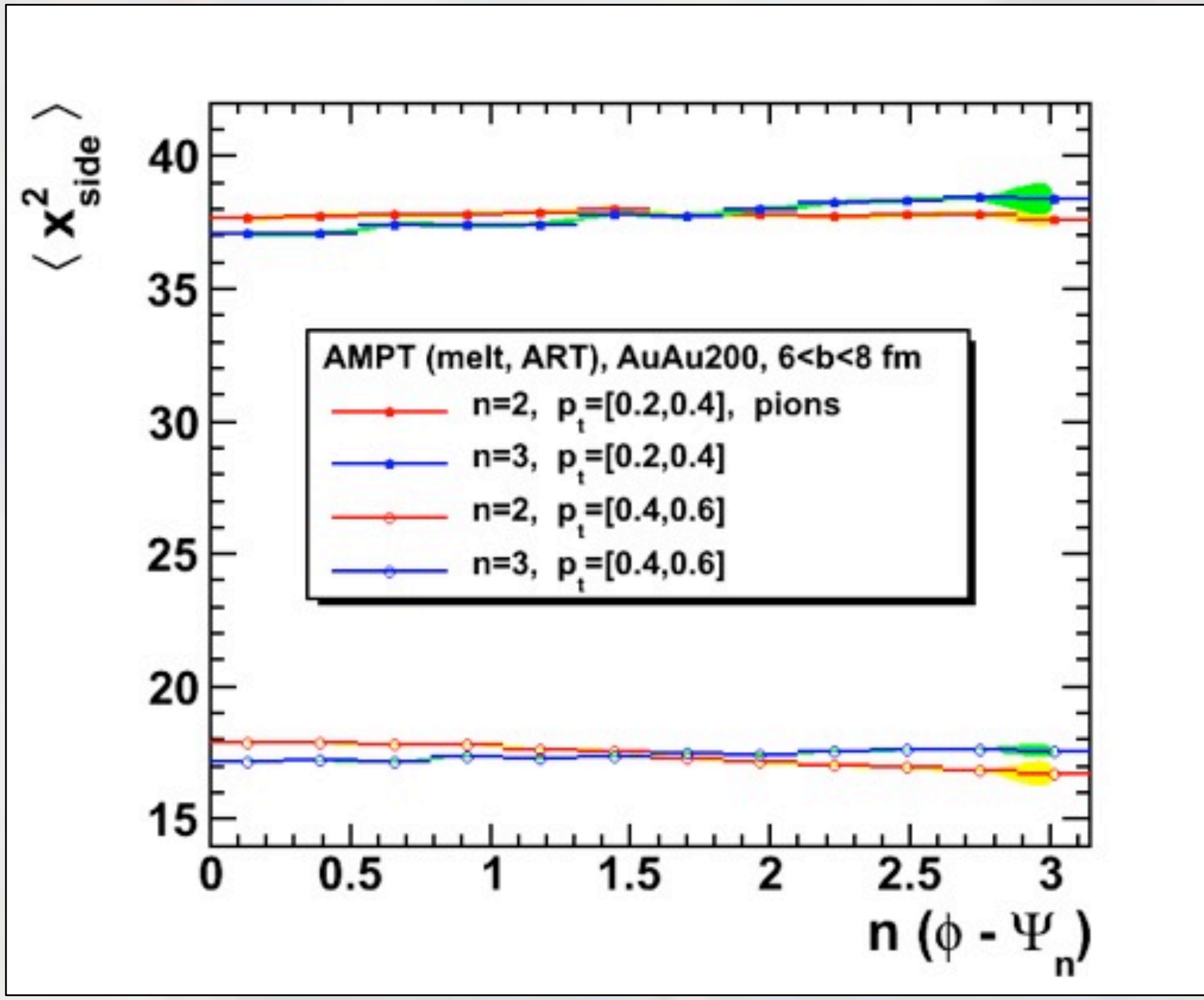


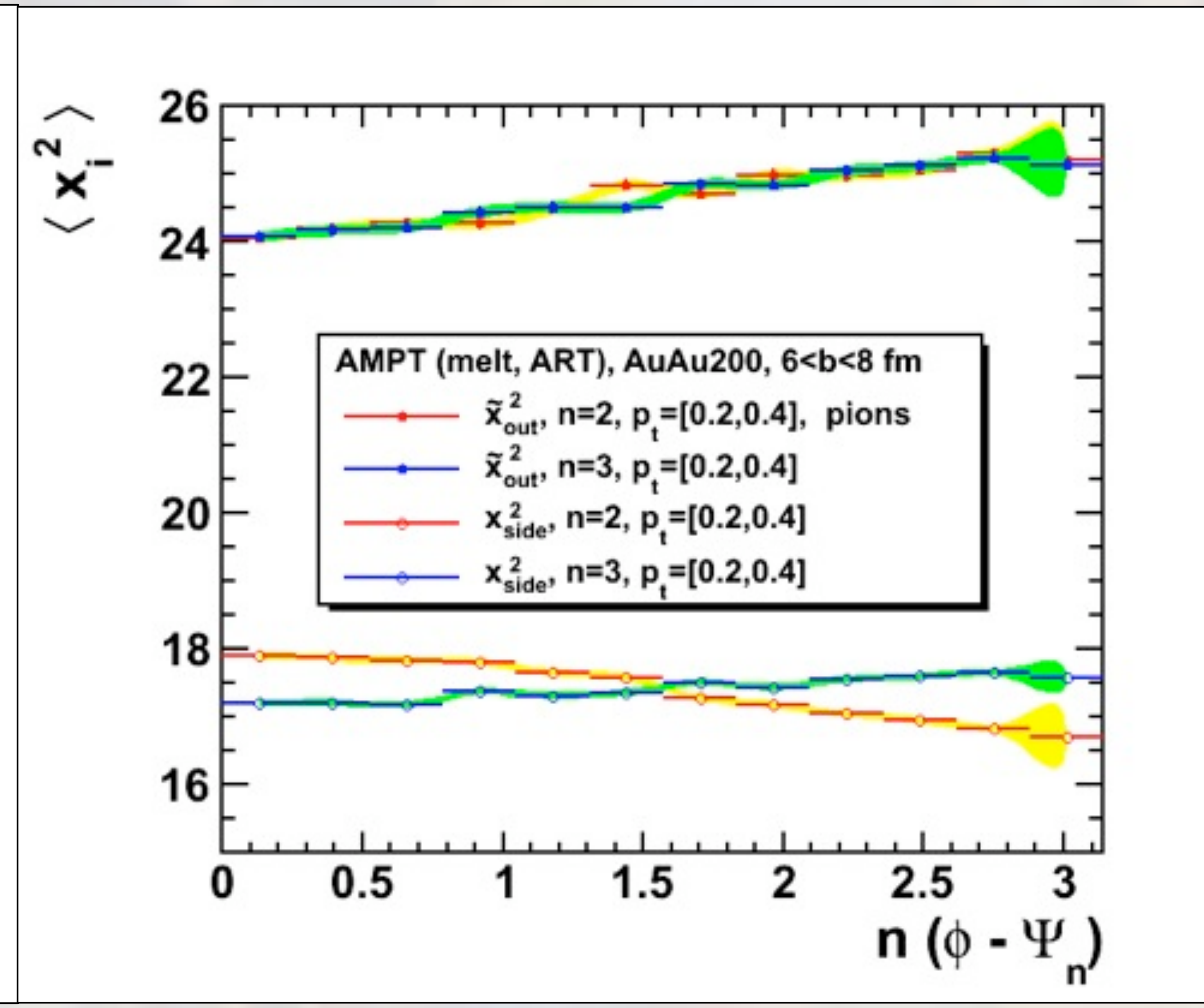


Even (?) harmonics have stronger side-out correlations?

Fourth harmonic:
out and side radii go “in phase” !
side-out -- also in different phase to n=2 and 3

AMPT_melt_afterART

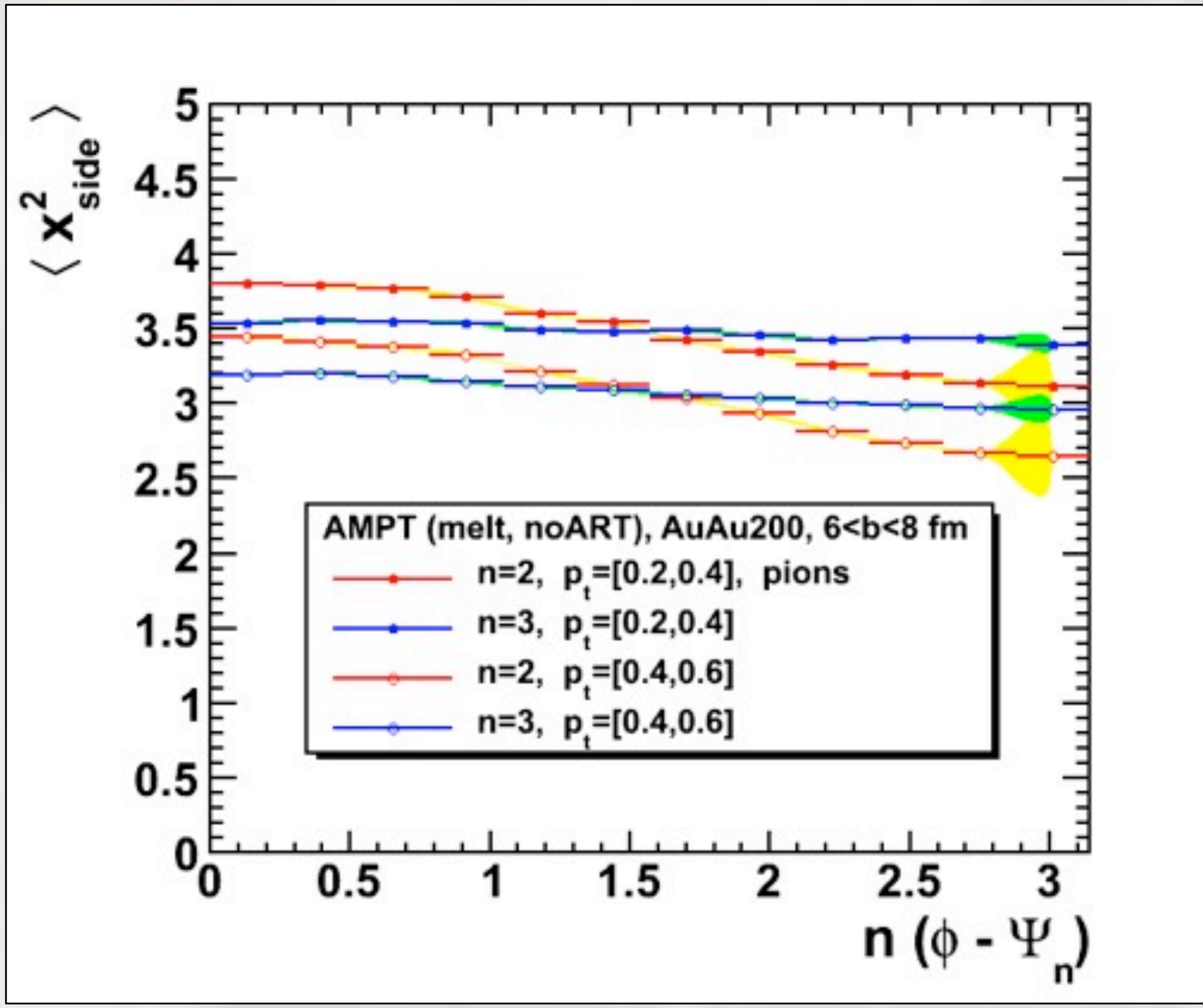


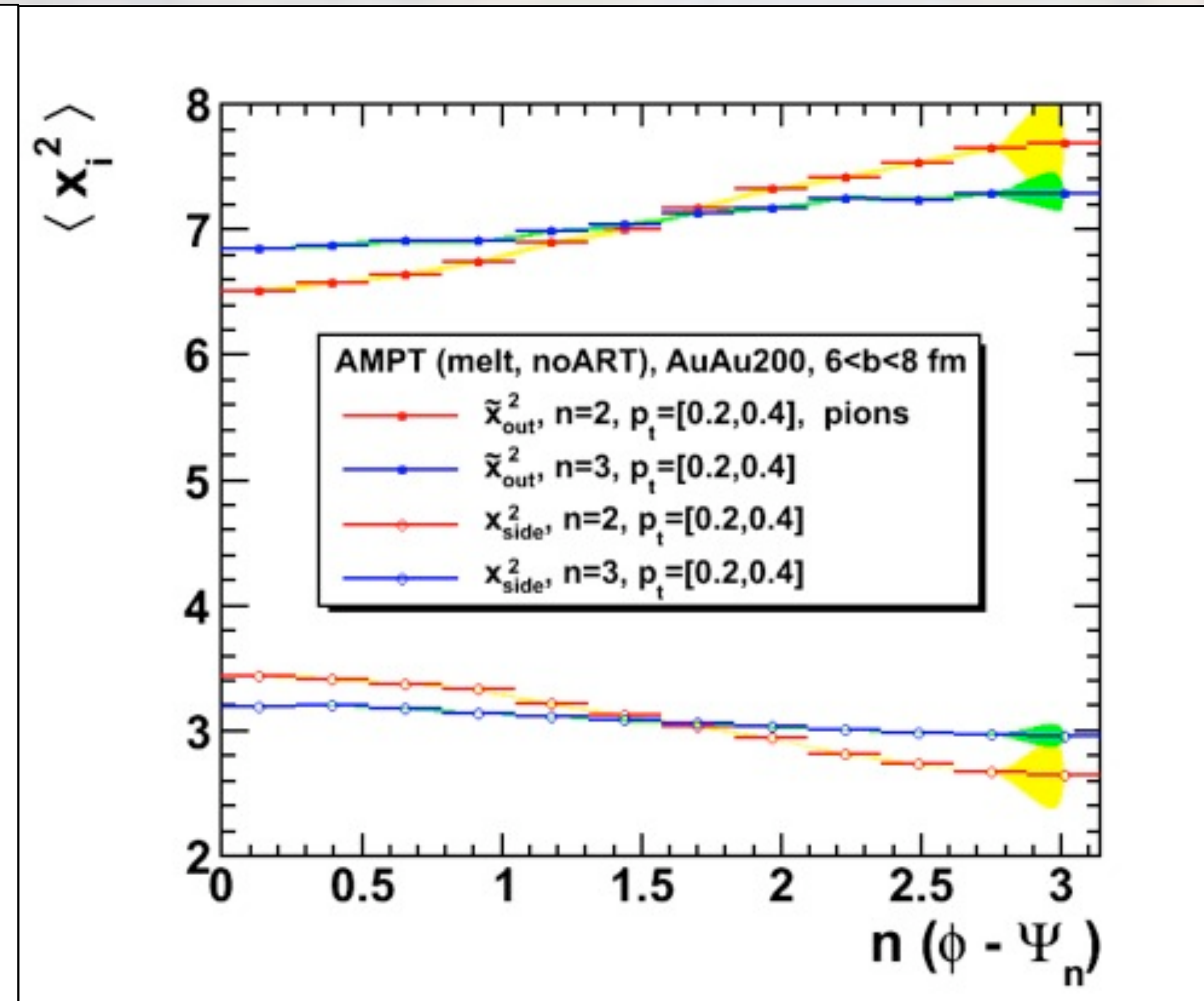


In this study, unlike as in the "blast wave" simulation, no true symmetry plane was not used. The magnitude of modulations is affected by the reaction plane resolutions.

Note unusual azimuthal dependence for harm=3 R_{out} (in phase with R_{side})

AMPT_melt_beforeART





Compare modulation to STAR measurements

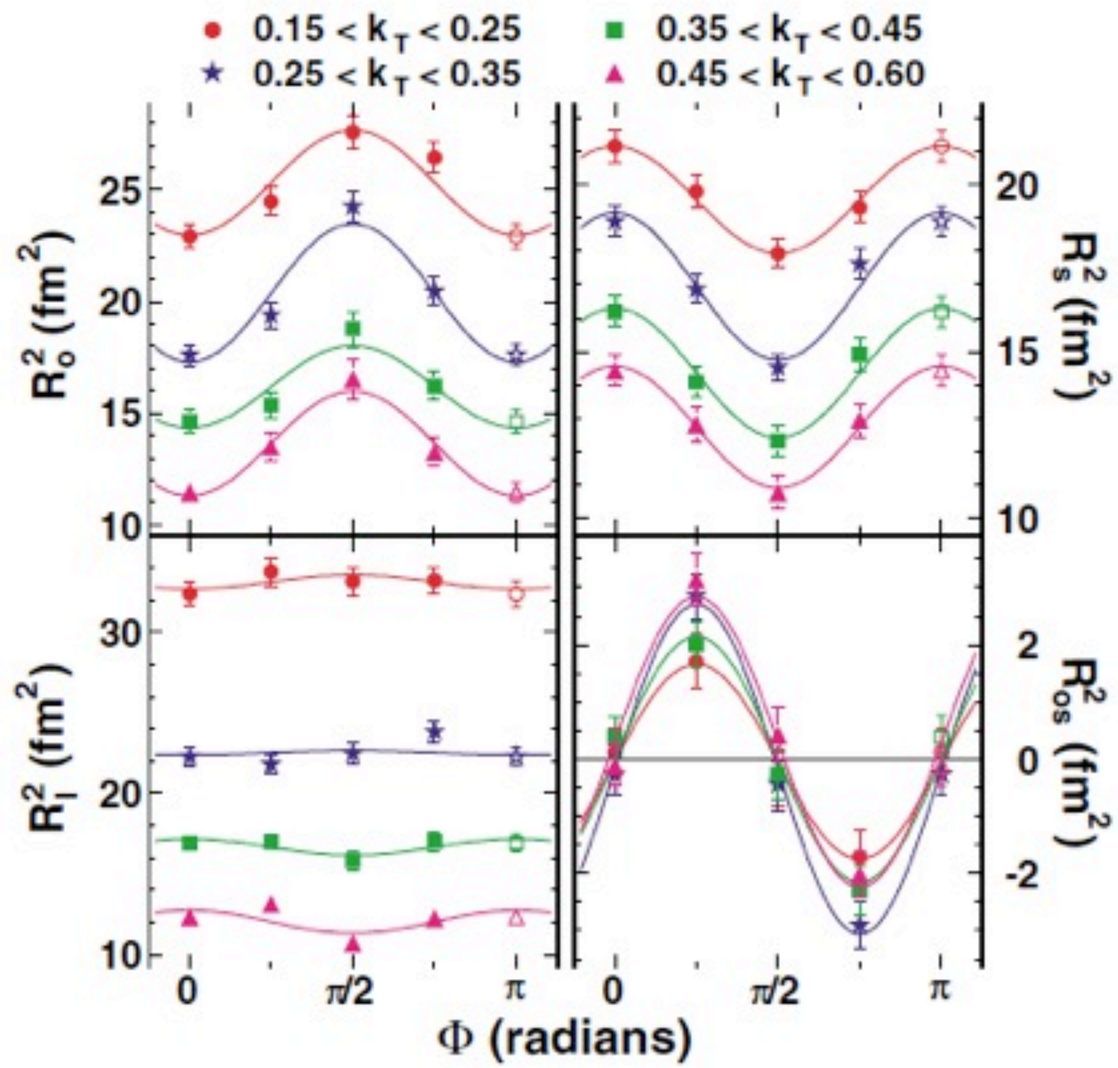
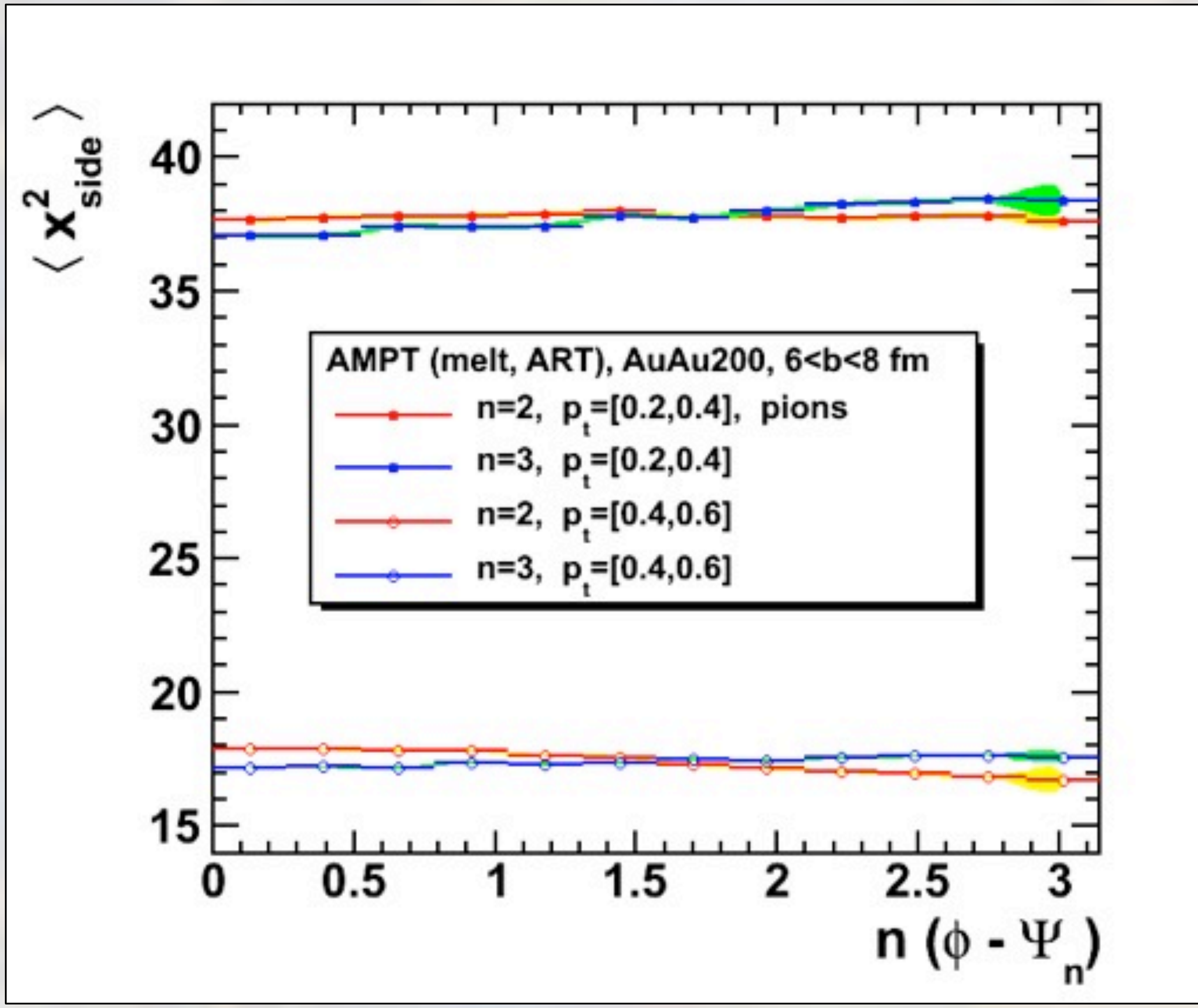


FIG. 2 (color online). Squared HBT radii relative to the reaction plane angle for four k_T (GeV/c) bins, 20%–30% centrality events. The solid lines show allowed [24] fits to the individual oscillations.

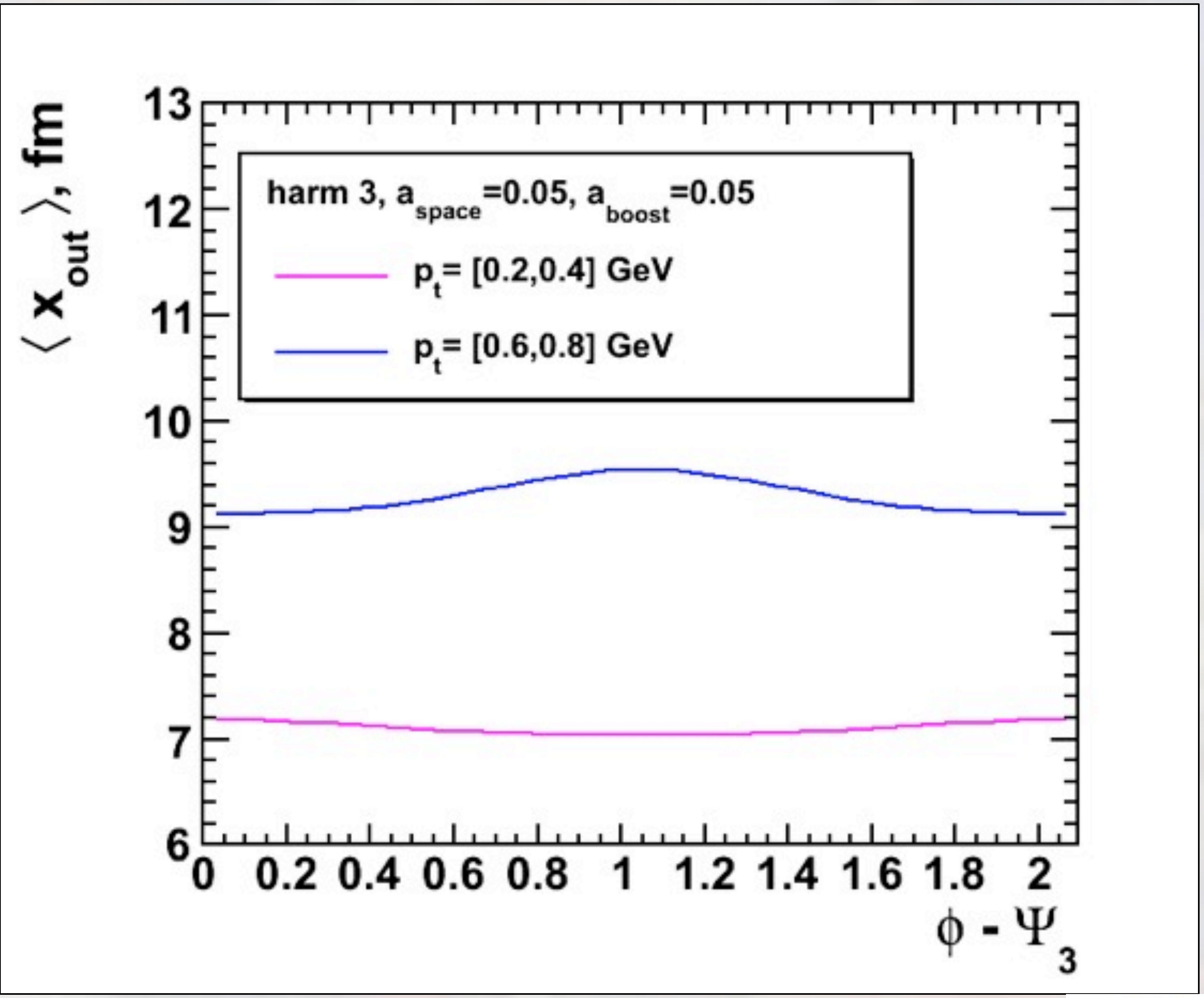
Adams J, el al. *Phys. Rev. Lett.* 93:012301 (2004)



Stronger correlation in data compared to AMPT?

Non-identical particle correlations

S. Voloshin, R. Lednicky, S. Panitkin and N. Xu, Phys. Rev. Lett. **79**, 4766 (1997) [arXiv:nucl-th/9708044].



$$\mathbf{v} \equiv \mathbf{p}_1/E_1 - \mathbf{p}_2/E_2$$

$$\tilde{\mathbf{r}}_{12} \approx (\mathbf{r}_1 - \mathbf{r}_2) - \mathbf{V}(t_1 - t_2)$$

$$\mathbf{k}^* = \mathbf{p}_\pi = -\mathbf{p}_p$$

$$k_i^* > 0 \text{ and } k_i^* < 0$$

$$R_i^{(+)} \text{ and } R_i^{(-)}$$

$$\frac{R_i^{(+)}}{R_i^{(-)}} \approx \frac{a + 2\langle r^* \rangle + 2\langle \mathbf{r}^* \mathbf{k}^*/k^* \rangle^{(+)}}{a + 2\langle r^* \rangle + 2\langle \mathbf{r}^* \mathbf{k}^*/k^* \rangle^{(-)}}$$

$$\approx \frac{1 + 2\langle \mathbf{r}^* \rangle \langle \mathbf{k}^*/k^* \rangle^{(+)}/a}{1 + 2\langle \mathbf{r}^* \rangle \langle \mathbf{k}^*/k^* \rangle^{(-)}/a} \approx 1 + 2\langle \mathbf{r}^* \rangle_i/a$$

Higher harmonics femtoscopy. Summary.

QUARK MATTER ANNECY 2011

- Stationary sources: no azimuthal dependence fro higher harmonic shape except small variation in deviation from Gaussian shape.
- With radial flow, radii variations become clear in Gaussian radii. Observable effects are within reach of the experiment
- Variation are very sensitive to the final shape eccebtricity as well as to modulations in the expansion velocity
- Significant double order components in the BW are visible in some parameter space
- AMPT simulations support BW observations, but needed more work to interpret the results.

EXTRA SLIDES

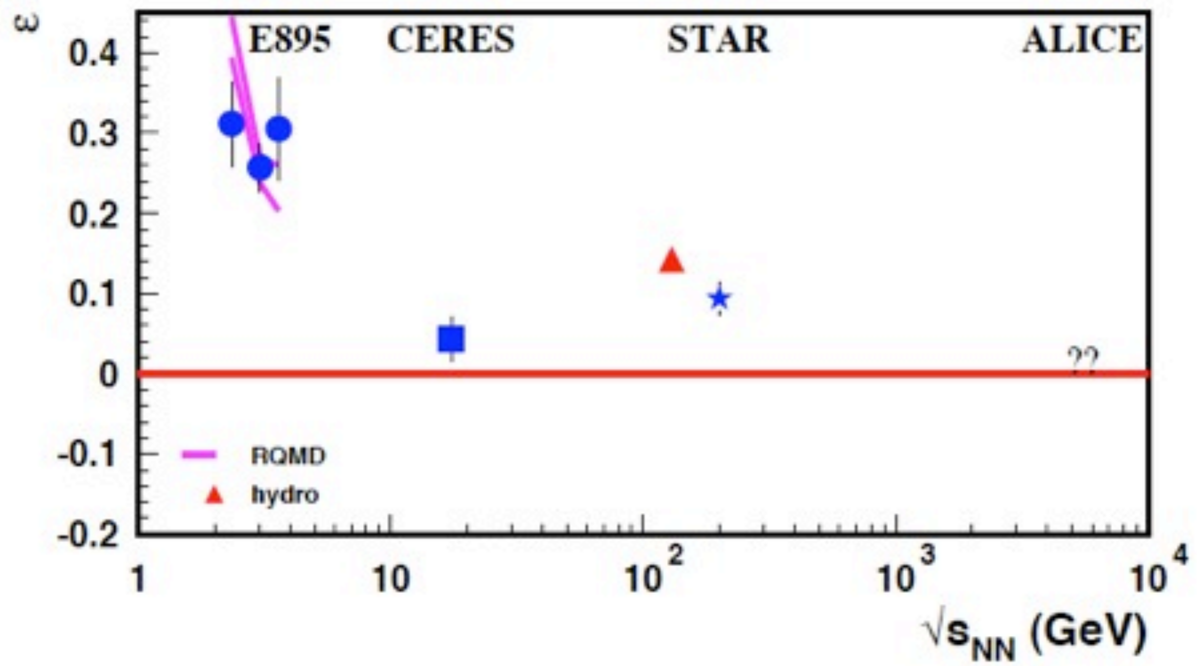


Fig. 11 The transverse spatial freezeout anisotropy ε as a function of collision energy, for mid-central ($\sim 10-30\%$) heavy ion collisions. Round sources correspond to $\varepsilon = 0$; $\varepsilon > 0$ indicates an out-of-plane-extended source. Measurements at the AGS (104), SPS (105) and RHIC (106) are compared with RQMD transport model calculations at the low energies; hydrodynamic calculations (107) at RHIC and the LHC are indicated.

Michael Annan Lisa and Scott Pratt

arXiv:0811.1352v3 [nucl-ex] 2 Oct 2009

$$\varepsilon \equiv \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2},$$

From distributions to HBT radii

Hardtke D, Voloshin SA. *Phys. Rev. C* 61: 024905 (2000)

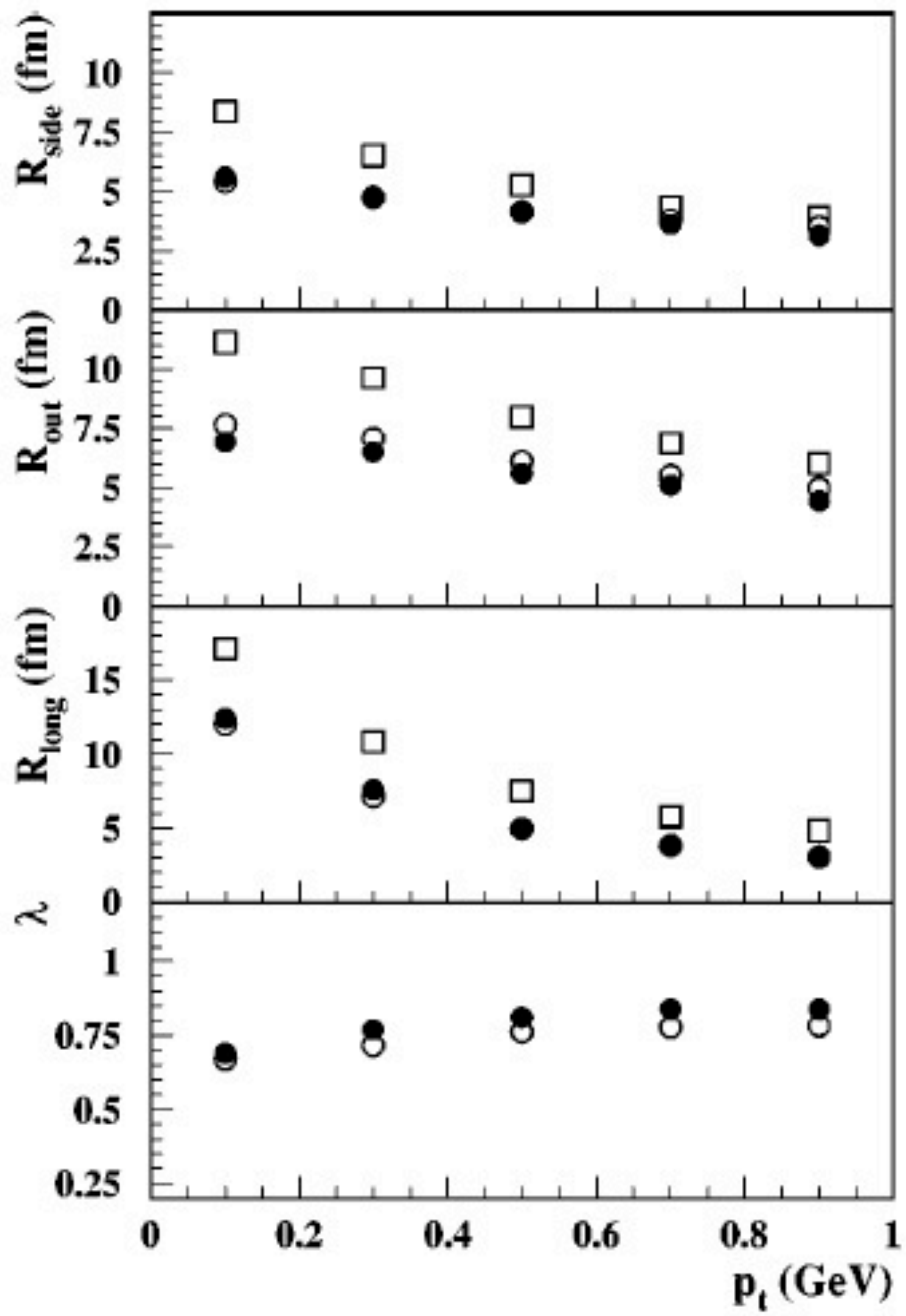


FIG. 2. The fitted HBT radius parameters (solid circles), single-particle rms deviations (open squares), and the sigma of the Gaussian fit two-particle position difference distribution (open circles) as a function of p_t for R_{side}, R_{out}, and R_{long}. The rapidity range is $|y|<0.5$. The bottom plot shows the lambda parameter determined from the fit to the correlation function (solid circles) and from the two particle position difference distribution.