Non-identical particle correlations vs. pair velocity

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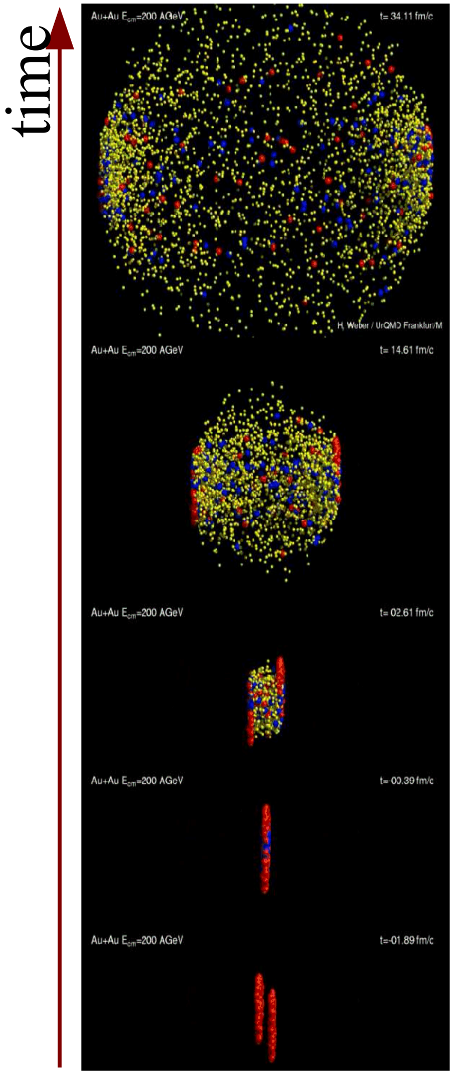
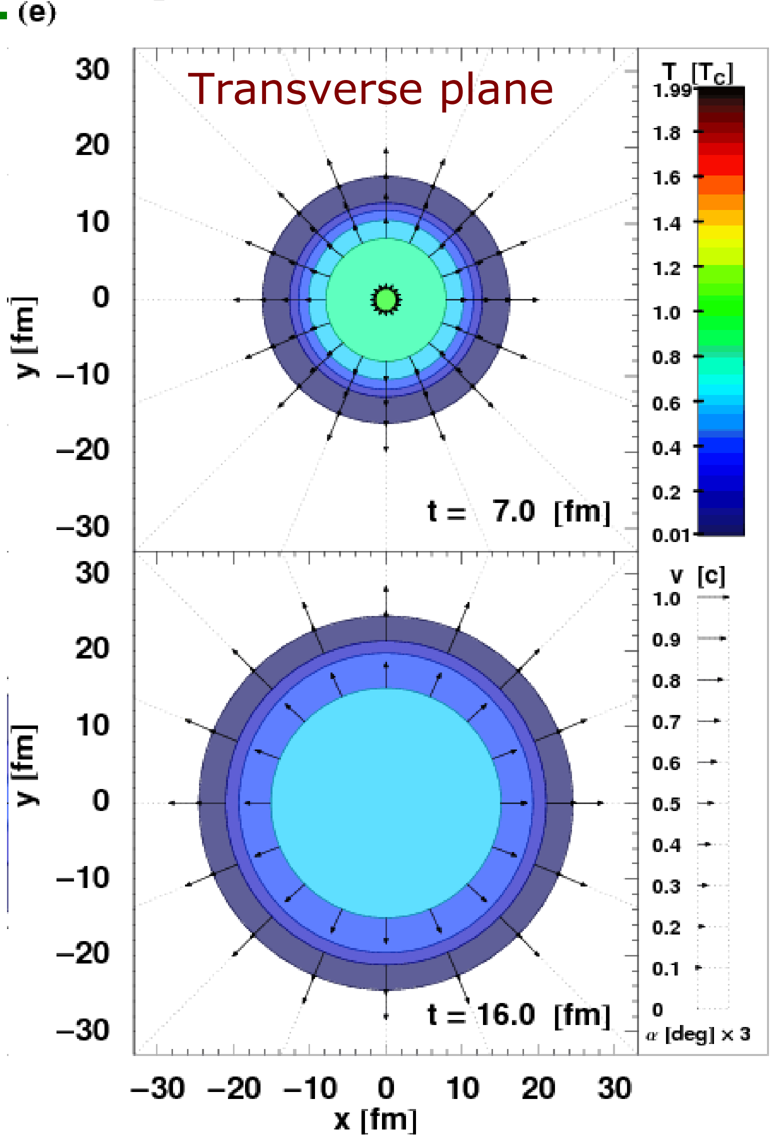
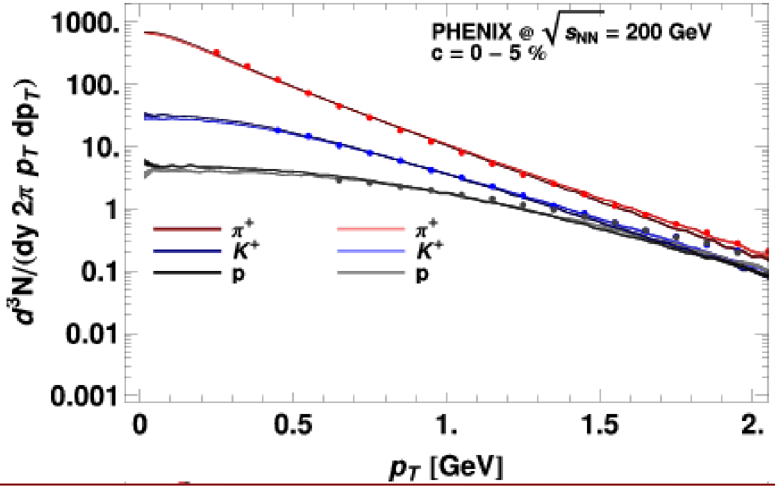
Heavy-ion collision evolution



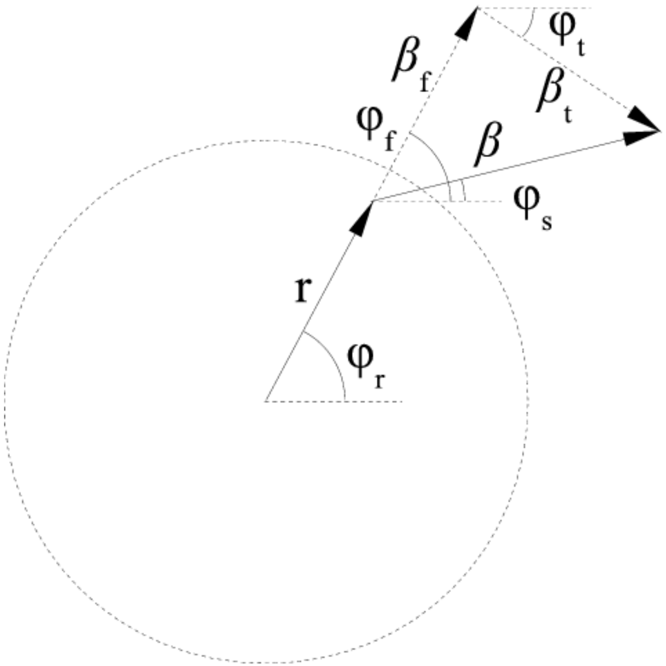


M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905

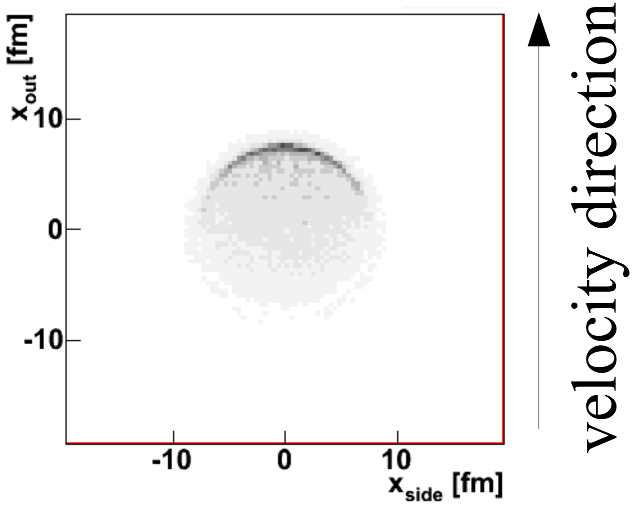
- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification

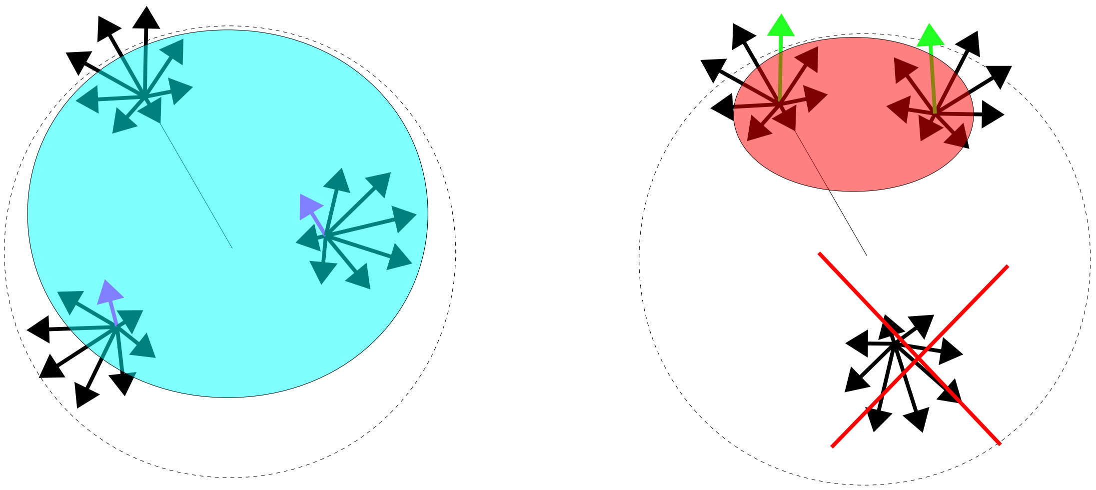


Thermal emission from collective medium

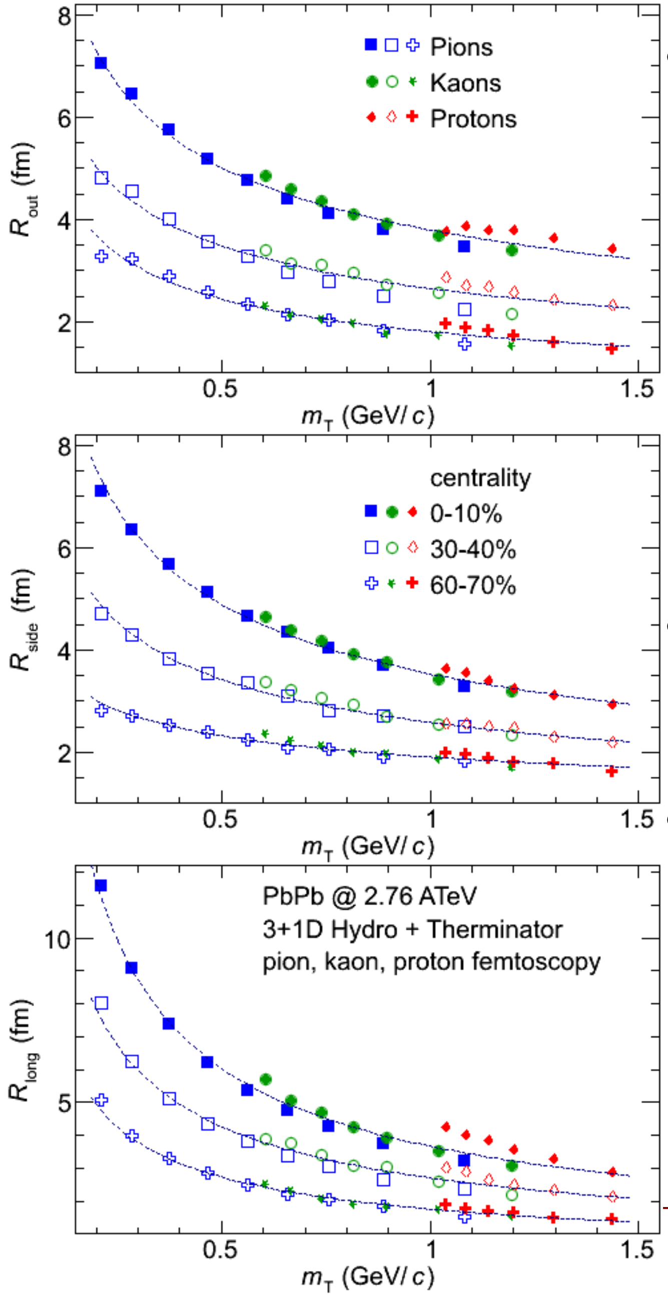


- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source





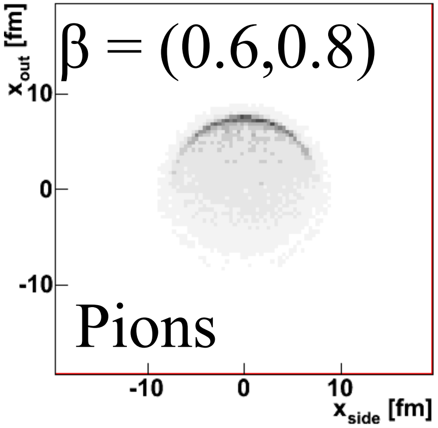
Consequences of flow

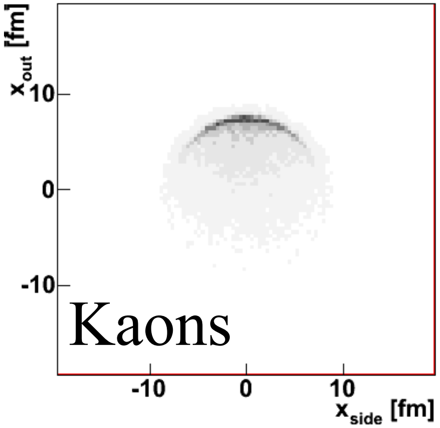


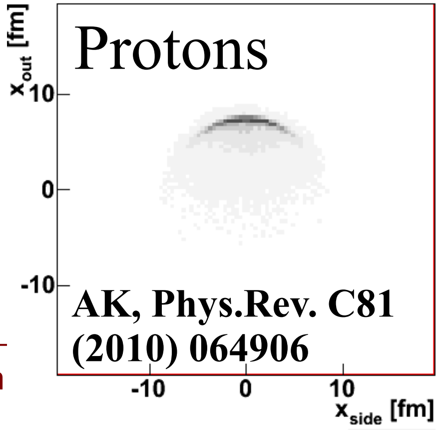
- "Collective" flow should apply to all particles
  - Ideal 1D hydro → m_T scaling for all particles
  - "Real" 3+1D hydro + viscosity (no rescattering) → approximate scaling in LCMS
  - Heavier/faster particles give smaller size of the system
- System size decrease – change of the second moment (width) of the emission function
- Increase of the first moment (emission asymmetry) with pair momentum and mass difference
  - Only for non-identical particles

AK, M.Gałażyn, P.Bożek;
Phys.Rev.C90 (2014) 6, 064914

Collectivity and emission asymmetry







AK, Phys.Rev. C81 (2010) 064906

- As particle mass (or p_T) grows, average emission point moves more "outwards" - origin of this "emission asymmetry" the same as m_T scaling
- Average emission points for primordial particles with same velocity but different mass:

Pions $\langle x^{\pi}_{out} \rangle$	Kaons $\langle x^{K}_{out} \rangle$	Protons $\langle x^{p}_{out} \rangle$
2.83 fm	4.47 fm	5.61 fm

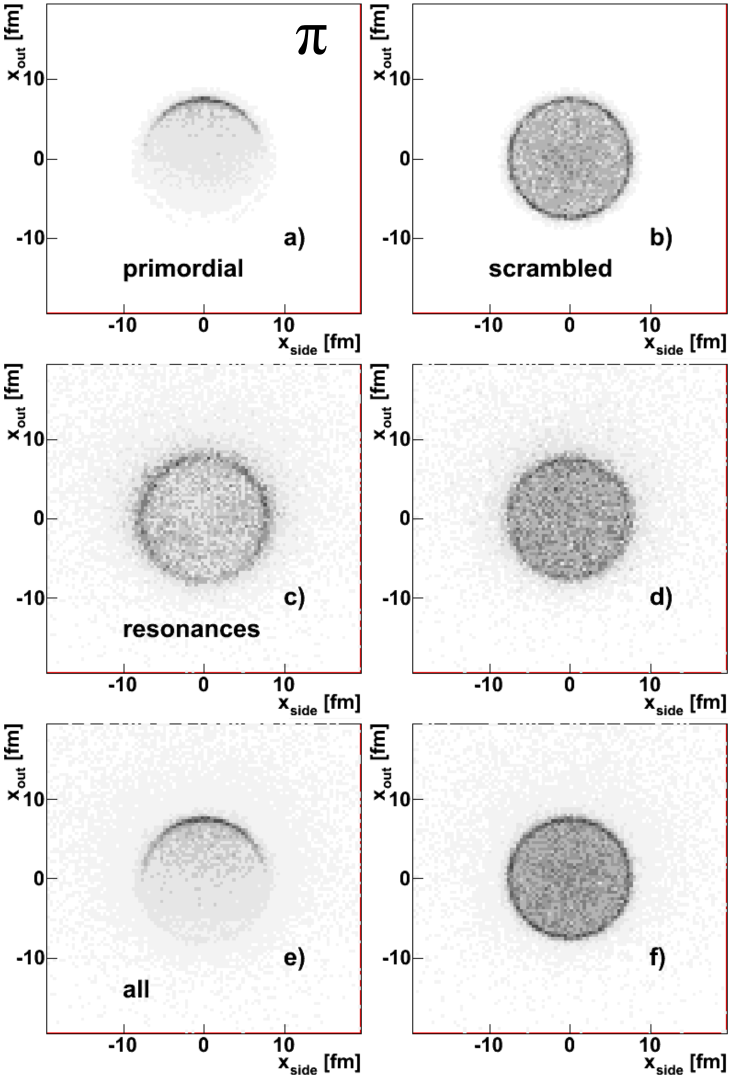
Asymmetry: $\langle r^{\pi K}_{out} \rangle \approx \langle x^{\pi}_{out} \rangle - \langle x^{K}_{out} \rangle$

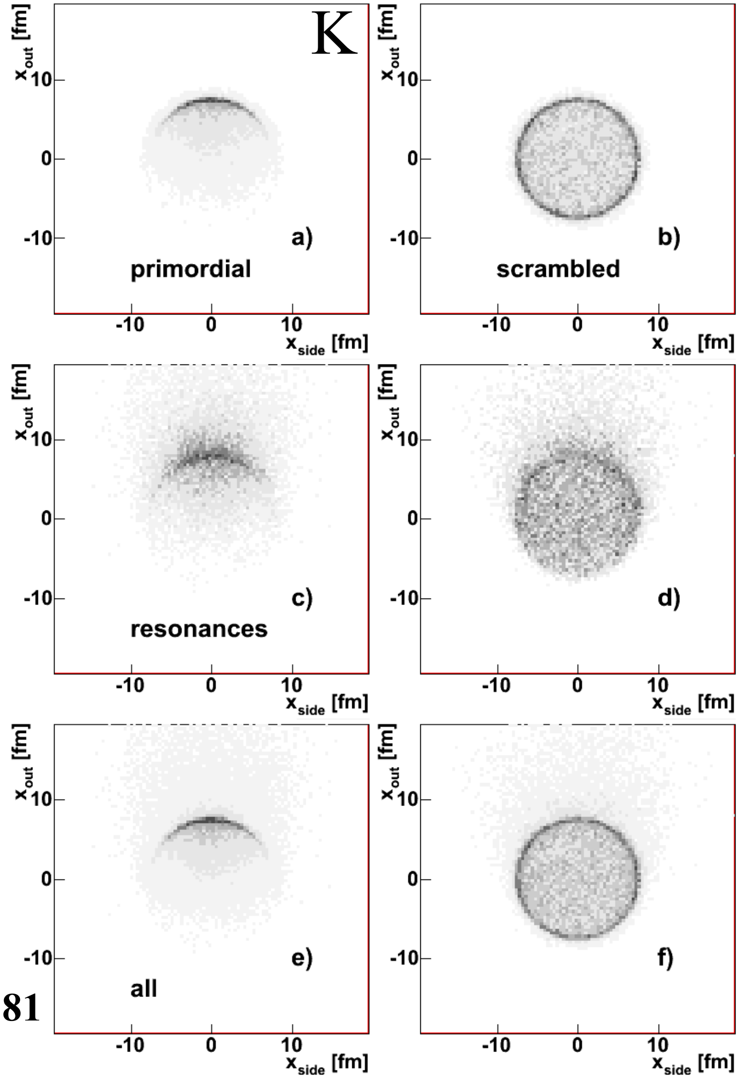
- When resonance decays included, asymmetry grows (also mostly a flow consequence)

Pions $\langle x^{\pi}_{out} \rangle$	Kaons $\langle x^{K}_{out} \rangle$	Protons $\langle x^{p}_{out} \rangle$
2.00 fm	5.54 fm	6.69 fm

Flow or resonances? Both!

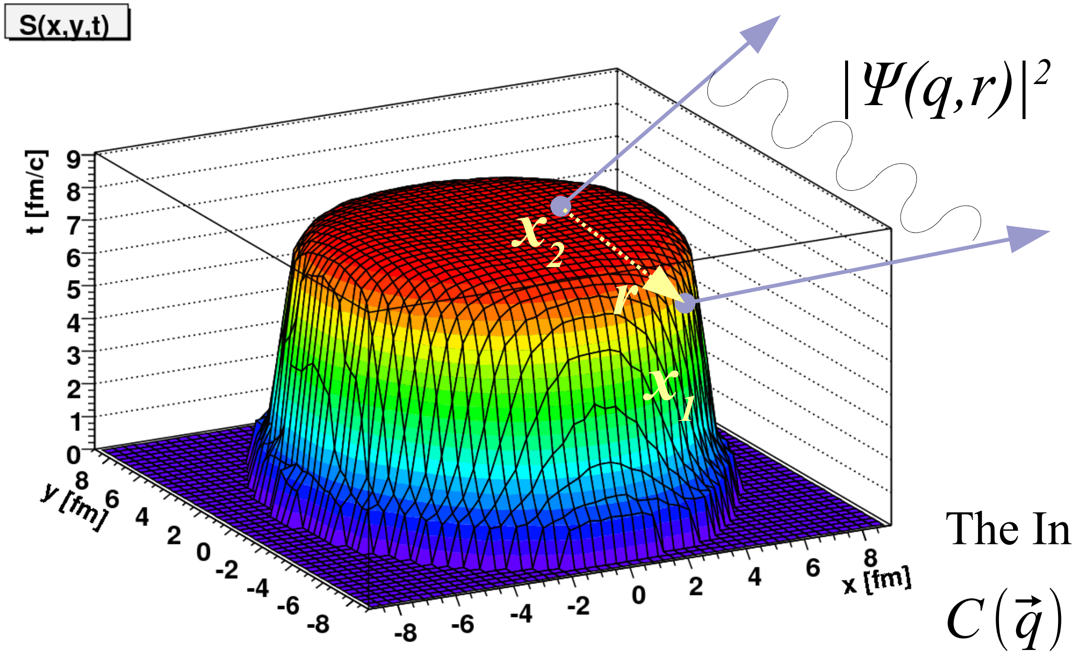
- Pions smeared by resonances
- Kaons pushed by flow of resonances

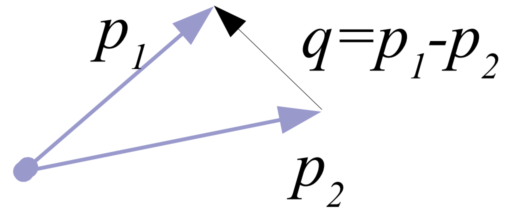




AK, Phys.Rev. C81 (2010) 064906

Measuring space-time extent: femtoscopy



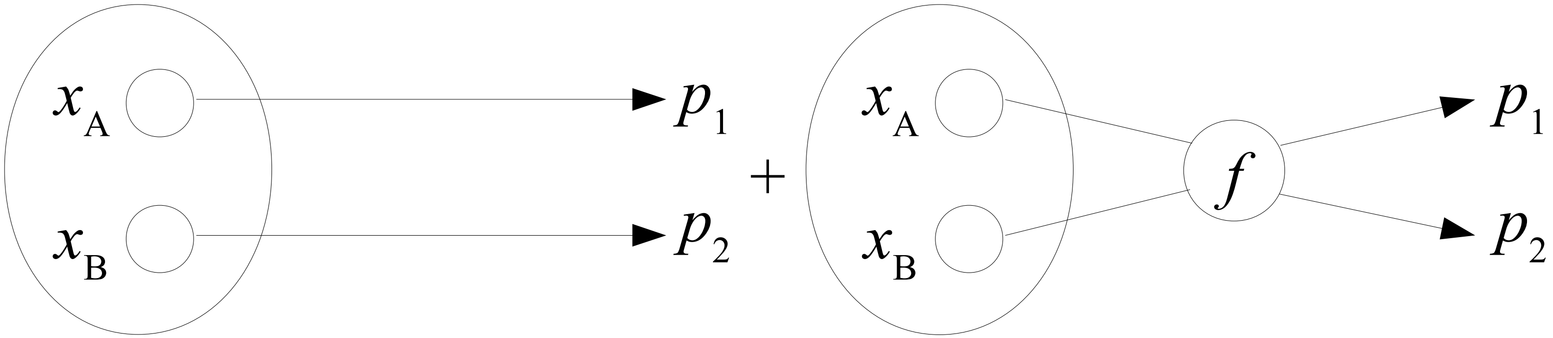


The Integral Equation for Correlation

$$C(\vec{q})=\int S(\boldsymbol{r})|\Psi(\vec{q},\boldsymbol{r})|^2 d^4 r=\langle|\Psi(\vec{q},\boldsymbol{r})|^2\rangle_{pairs}$$

- Use two-particle correlation, coming from the interaction Ψ (quantum statistics (HBT), coulomb and/or strong)
- Measure $C(q)$
- Try to invert the Koonin-Pratt eq. to gain information about S from known Ψ and measured C

Correlation – charged particles



$q = 2k^* = p_1 - p_2$

$r = x_A - x_B$

- Two charged particles interact via Coulomb and strong after their last scattering
  - This gives the final form of the wave-function, for pion-kaon pairs the Coulomb interaction dominates

$$\Psi_{-\mathbf{k}^*}(\mathbf{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-i\mathbf{k}^*\mathbf{r}^*}F(-i\eta,1,i\xi) + f_c(k^*)\tilde{G}(\rho,\eta)/r^*\right]$$

$$\xi = \mathbf{k}^*\mathbf{r}^* + k^* r^* \equiv \rho(1+\cos(\theta^*)),\ \ \rho = k^* r^*,\ \ \eta = (k^* a)^{-1},\ \ a = (\mu z_1 z_2 e^2)^{-1}$$

$$F(k^*, r^*, \theta^*) = 1 + r^*(1+\cos\theta^*)/a + (r^*(1+\cos\theta^*)/a)^2 + i k^* r^{*2}(1+\cos\theta^*)^2/a + \ldots$$

θ^* is an angle between separation r^* and relative momentum k^*

Simulations in Therminator2

- Used Therminator2 hydrodynamics + statistical hadronization model (includes pion and kaon generation as well as radial and elliptic flow)
  - Pb-Pb Collisions, 2.76 ATeV (parameters from ALICE data)
  - Centrality 0-10%, 10-20%, 20-30%, 30-40%, 40-50%
  - Separately for π^+K^-, π^-K^+, π^+K^+, π^-K^-
- Calculate two versions of correlations
  - Containing only purely femtoscopic correlation
  - Also affected by elliptic flow (and other global effects)
- Perform analysis for two ranges (low and high) of pair velocity

Calculation types

- Correlation function from integral relation:

$$C_{AB}(k^*)=\int S(p_A,x_A,p_B,x_B)|\Psi(k^*,r^*)|^2 d^4x_A d^4x_B \sim \langle|\Psi(k^*,r^*)|^2\rangle = \sum_{pairs}^{same}|\Psi(k^*,r^*)|^2 / \sum_{pairs}^{mixed} 1$$

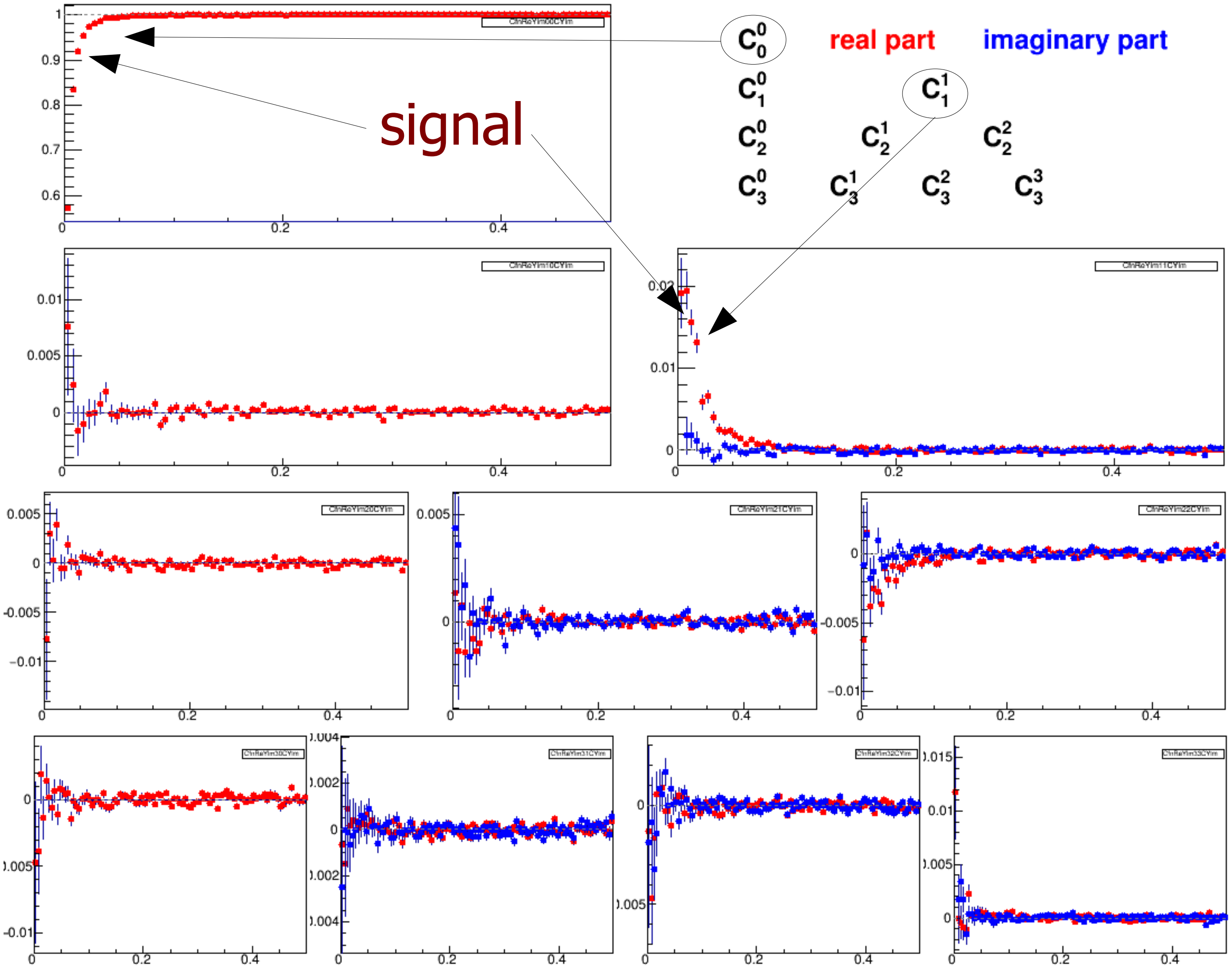
- Three histograms calculated:
  - Numerator (same-event pairs) N_{true} with "femto" weight $|\Psi(k^*,r^*)|^2$
  - Numerator (same-event pairs) N_{pure} no weight
  - Denominator D (mixed-event pairs) no weight
- In addition calculation done in two modes
  - THERMINATOR 2 generates events with event-plane at 0 degree in all events
  - Before histogram calculation each event can be rotated by random angle (as in reality). Two results produced: "rotated" and "flat"

Correlation function

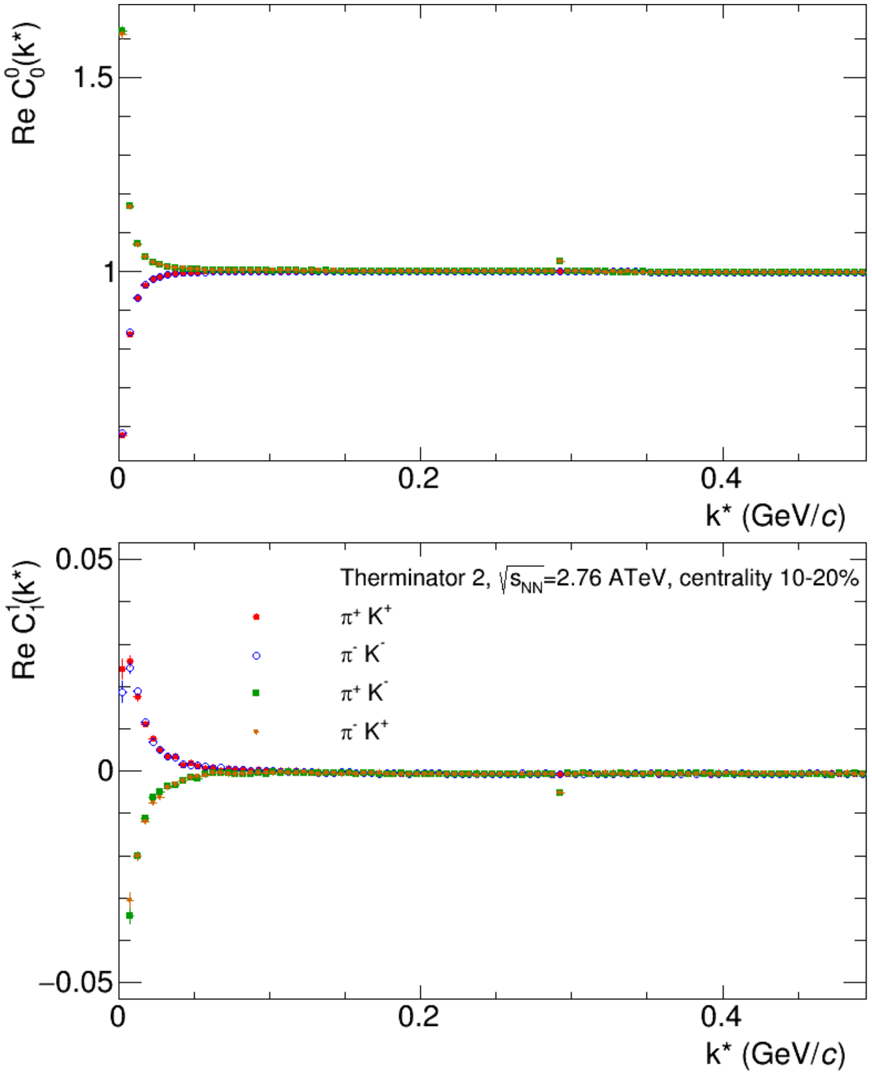
- From histograms two correlation functions determined:
  - “Realistic” or “true” $C_{\mathrm{true}} = N_{\mathrm{true}}/D$
  - “No Coulomb” or “pure” $C_{\mathrm{pure}} = N_{\mathrm{pure}}/D$
- Both calculated in “rotated” and “flat” mode
  - The “rotated” “true” calculation closest to “experimental” data. Possibly contains correlations in addition to “femto”, coming from global event correlation, especially related to reaction plane (elliptic flow ...)
  - In “flat” calculations the global correlation are present both in Numerator and Denominator, so they cancel in correlation
  - The “rotated” “pure” correlation contains baseline correlations, but no femto effect

Pion-kaon in 3D (spherical harmonics)

$$C_l^m(q)=\int C(\vec{q})\,Y_l^m(\cos(\theta),\varphi)\,d\varphi\,d\cos(\theta)$$



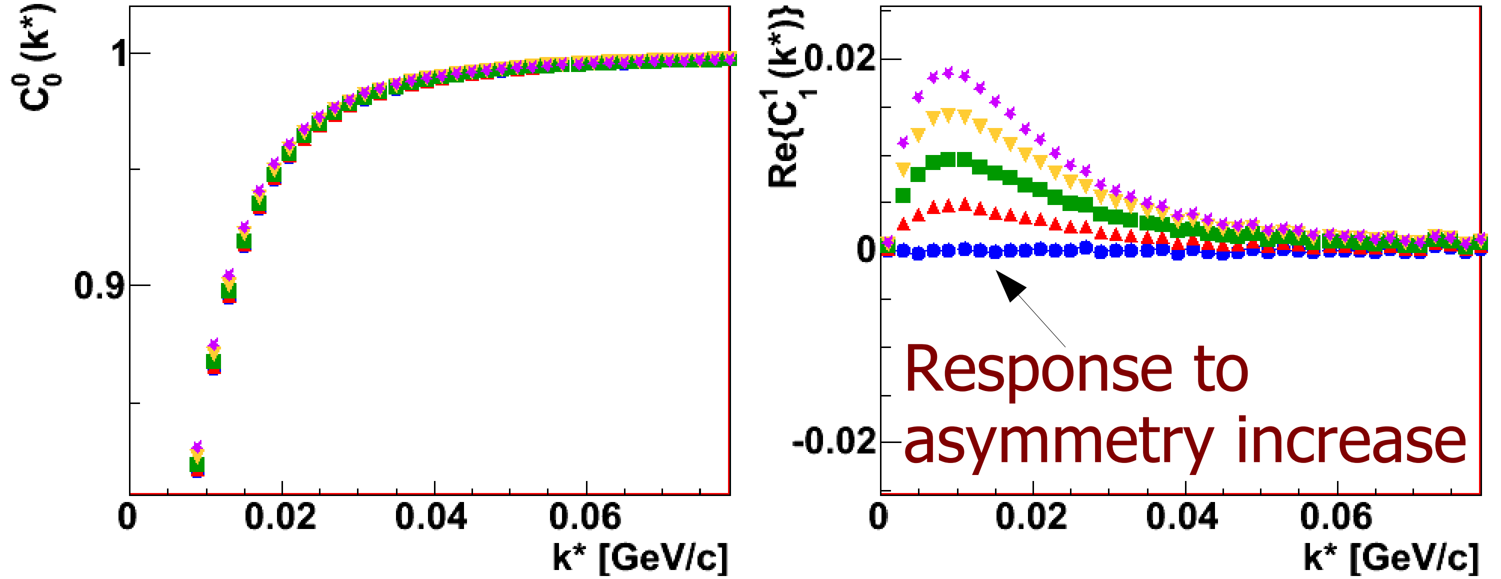
Pion-kaon correlation



- The pion-kaon correlation dominated by Coulomb (effect is quite narrow and opposite for same-sign and opposite-sign pairs)
- Only the l=0,m=0 and l=1,m=1 real components drawn, as they contain most of the interesting signal
- l=0,m=0 component sensitive to overall system size
- l=1,m=1 component sensitive to emission asymmetry
- Higher l – finer details of correlation – not analyze here

Sensitivity to emission asymmetries

$$\Re\{C_1^1\} \sim \int C(\varphi, \cos(\theta)) \cos(\varphi)\, d\varphi\, d\cos(\theta)$$



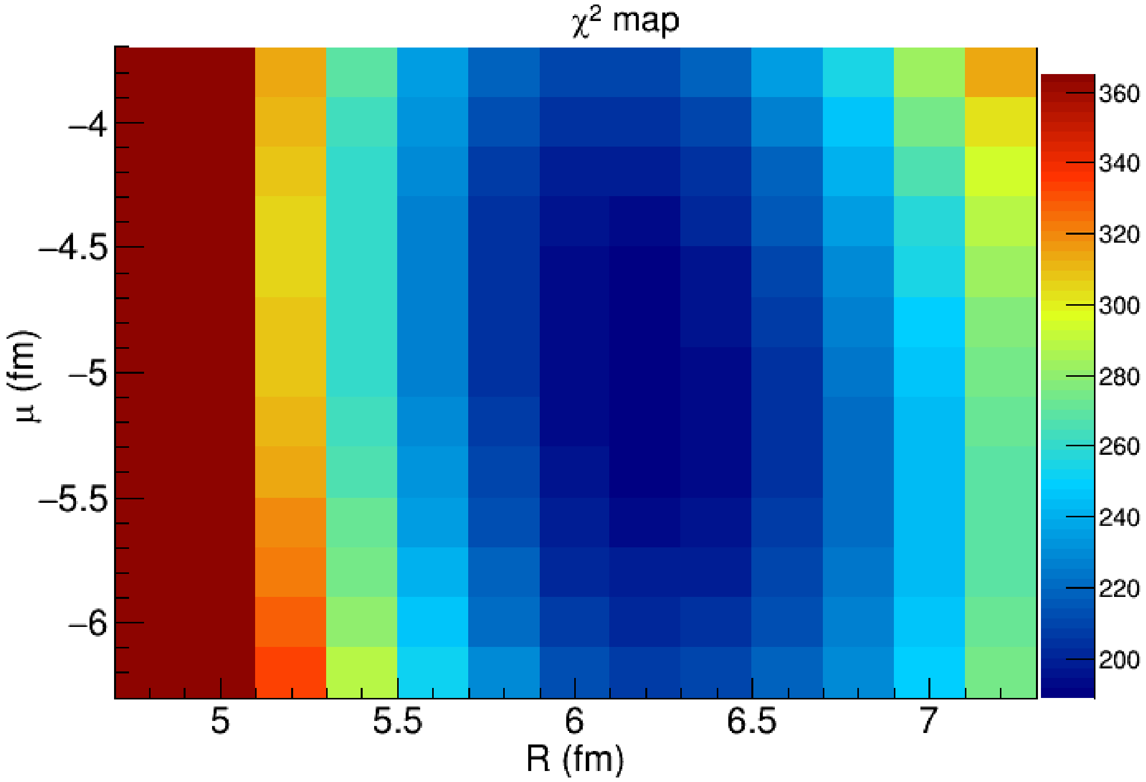
Response to asymmetry increase

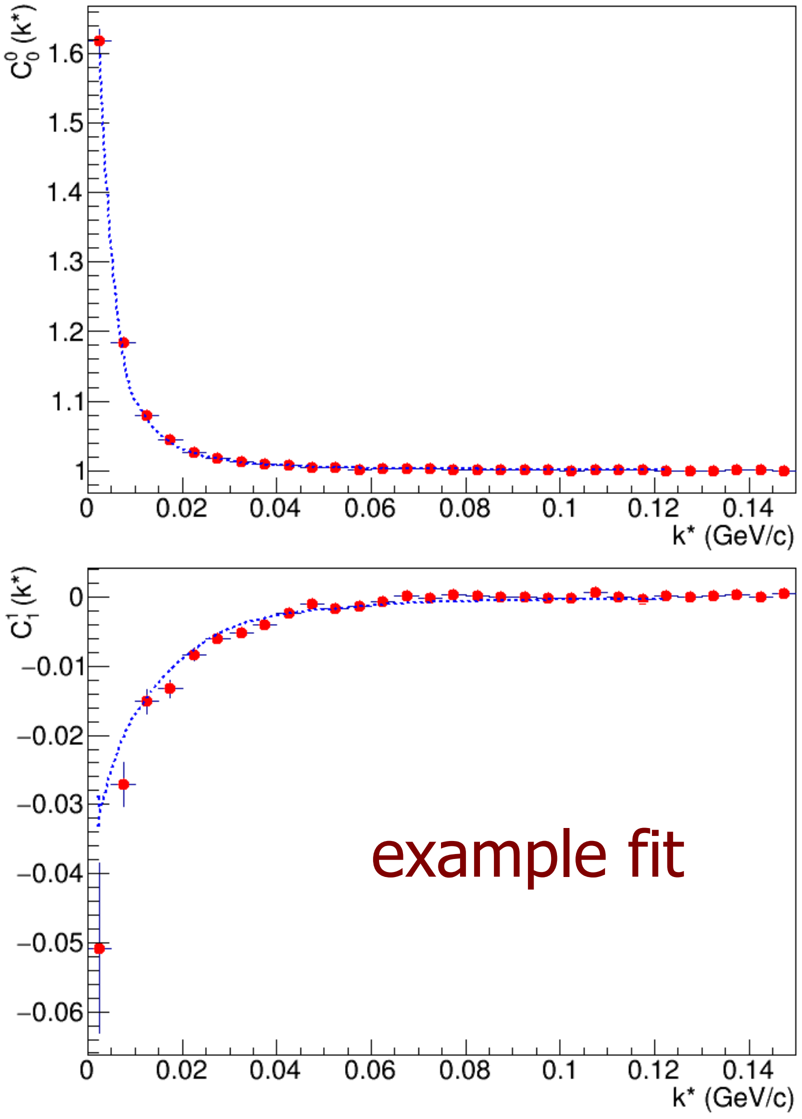
- Increasing emission asymmetry mainly affects Re$\{C_1^1\}$
- No asymmetry gives flat Re$\{C_1^1\}$
- Fitting the two components is able to extract asymmetry

Fitting non-identical correlation

- Calculate numerically the correlation function for points on the (R,μ) grid, where source is defined in LCMS as:

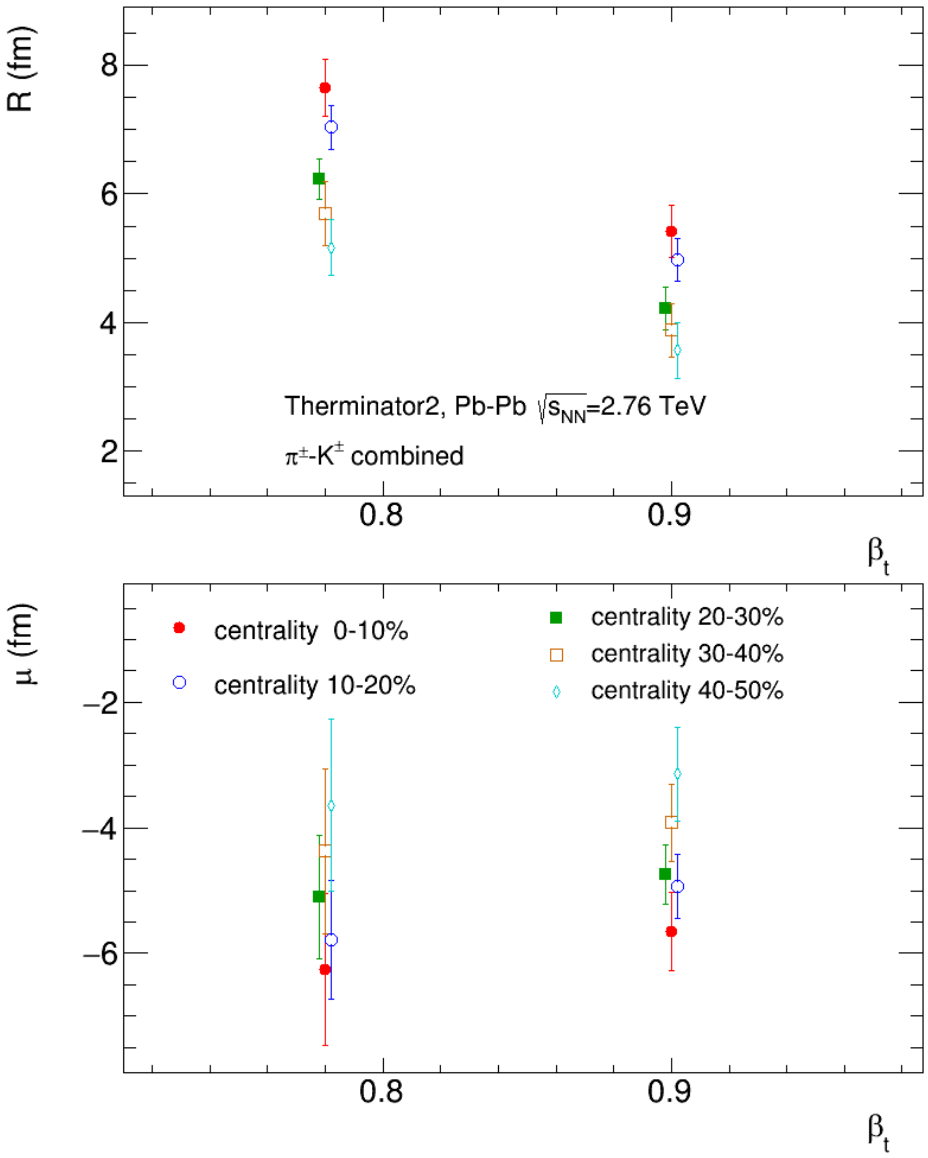
$$S(\vec{r})\sim\exp\left(-\frac{(r_{out}-\mu_{out})^2}{R^2}-\frac{r_{side}^{\;2}}{R^2}-\frac{r_{long}^{\;2}}{\alpha^2R^2}\right)$$





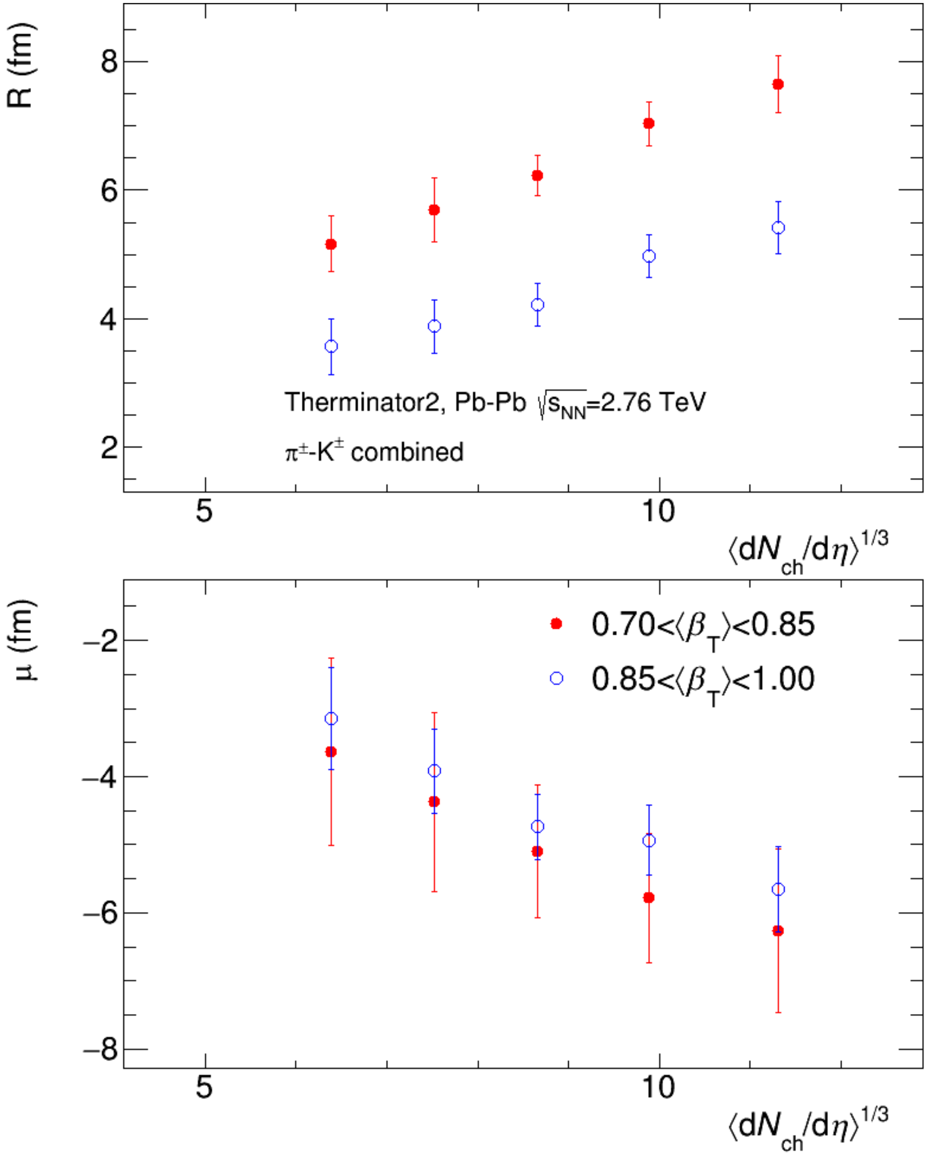
example fit

Fits vs. pair velocity



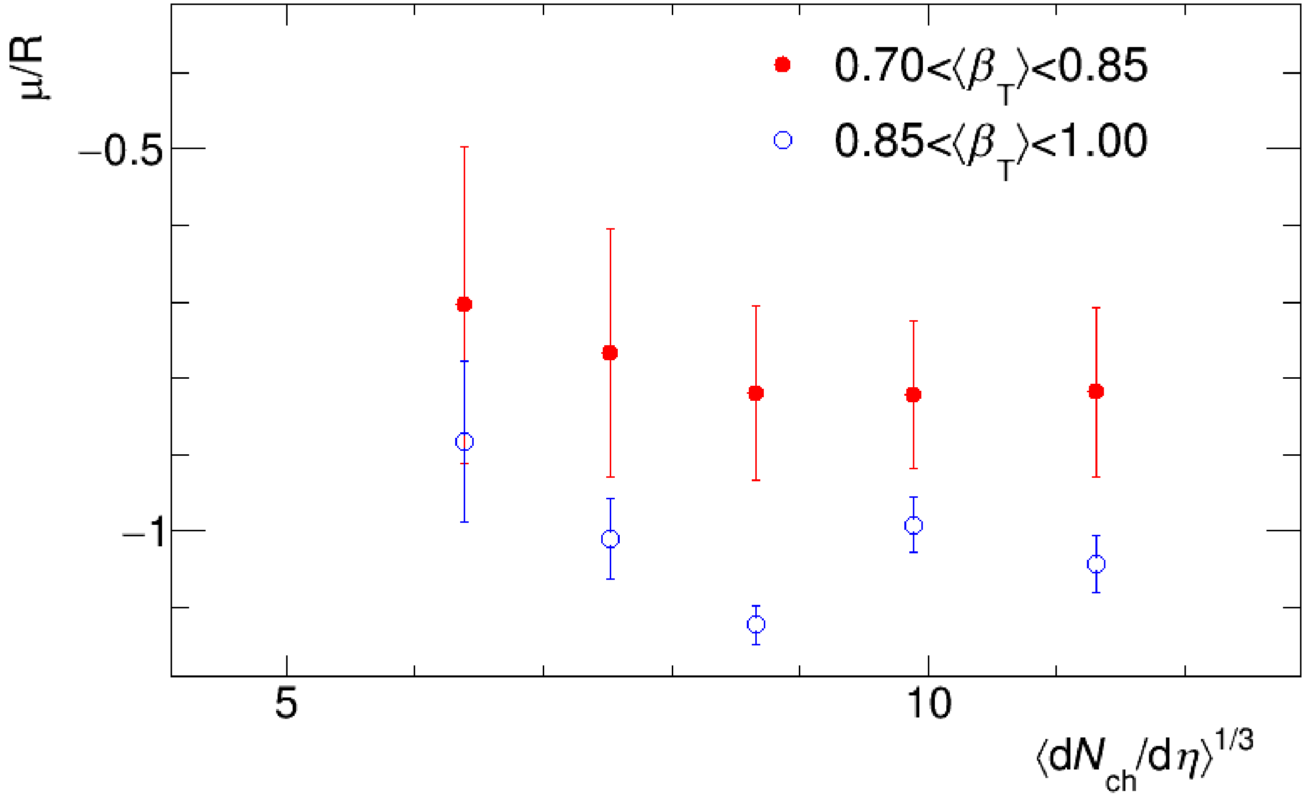
- Size of the system decreases with pair velocity – clear signature of collectivity
- Emission asymmetry is also clearly observed for both pair velocity intervals
- Both signatures of collectivity observed simultaneously
- Emission asymmetry falls less than the system size with event multiplicity

Centrality dependence



- Correlations show linear size dependence with cube root of multiplicity, similar to all identical-particle correlation analyses (pion, kaon, proton, 1D, 3D, etc.)
- Emission asymmetry also seems to linearly scale with multiplicity, regardless of pair velocity range

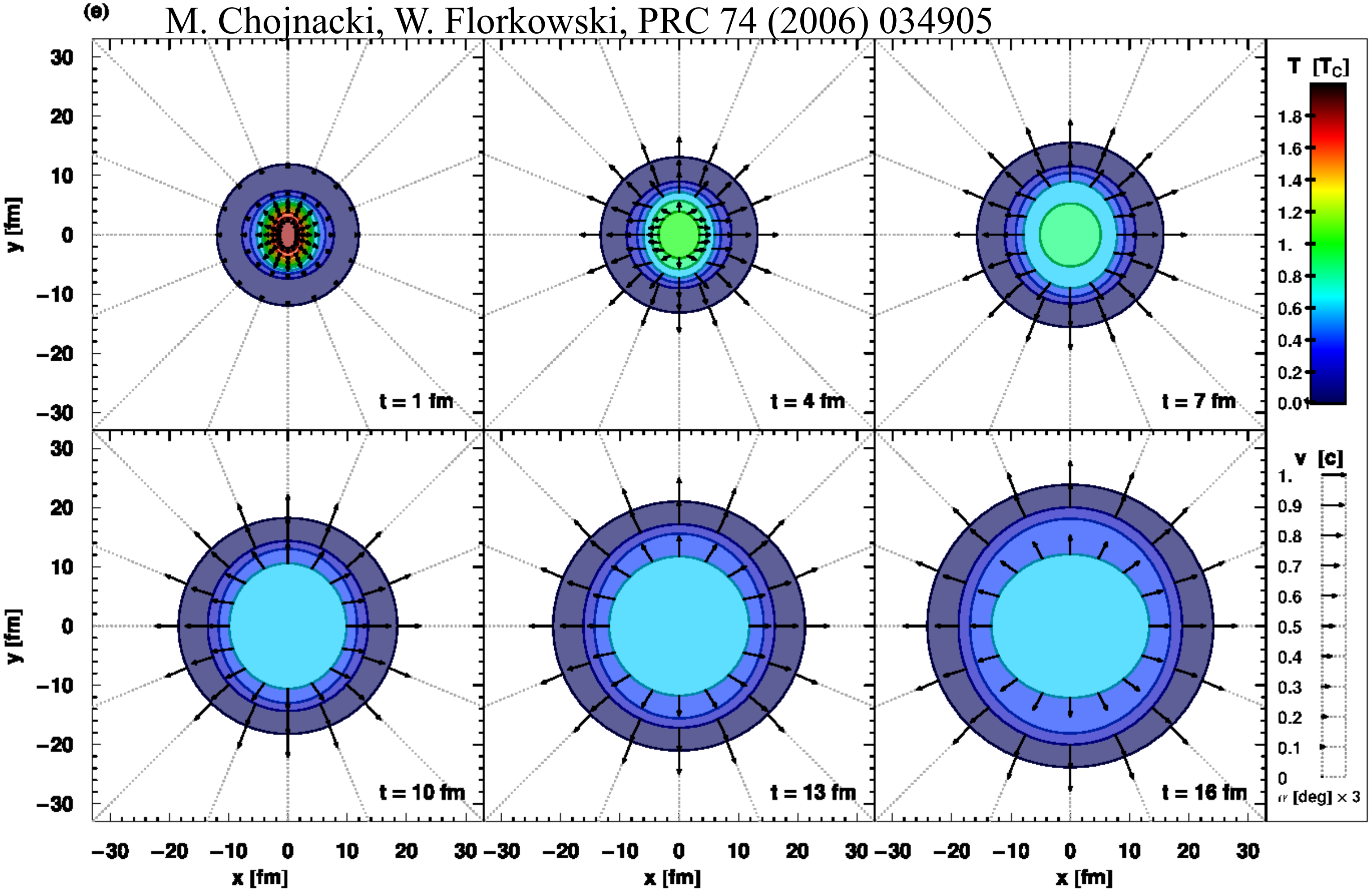
Scaled asymmetry



- Emission asymmetry scaled with system size:
  - Relatively constant with multiplicity – may be smaller at peripheral collisions
  - Grows with pair velocity

Creation of elliptic flow

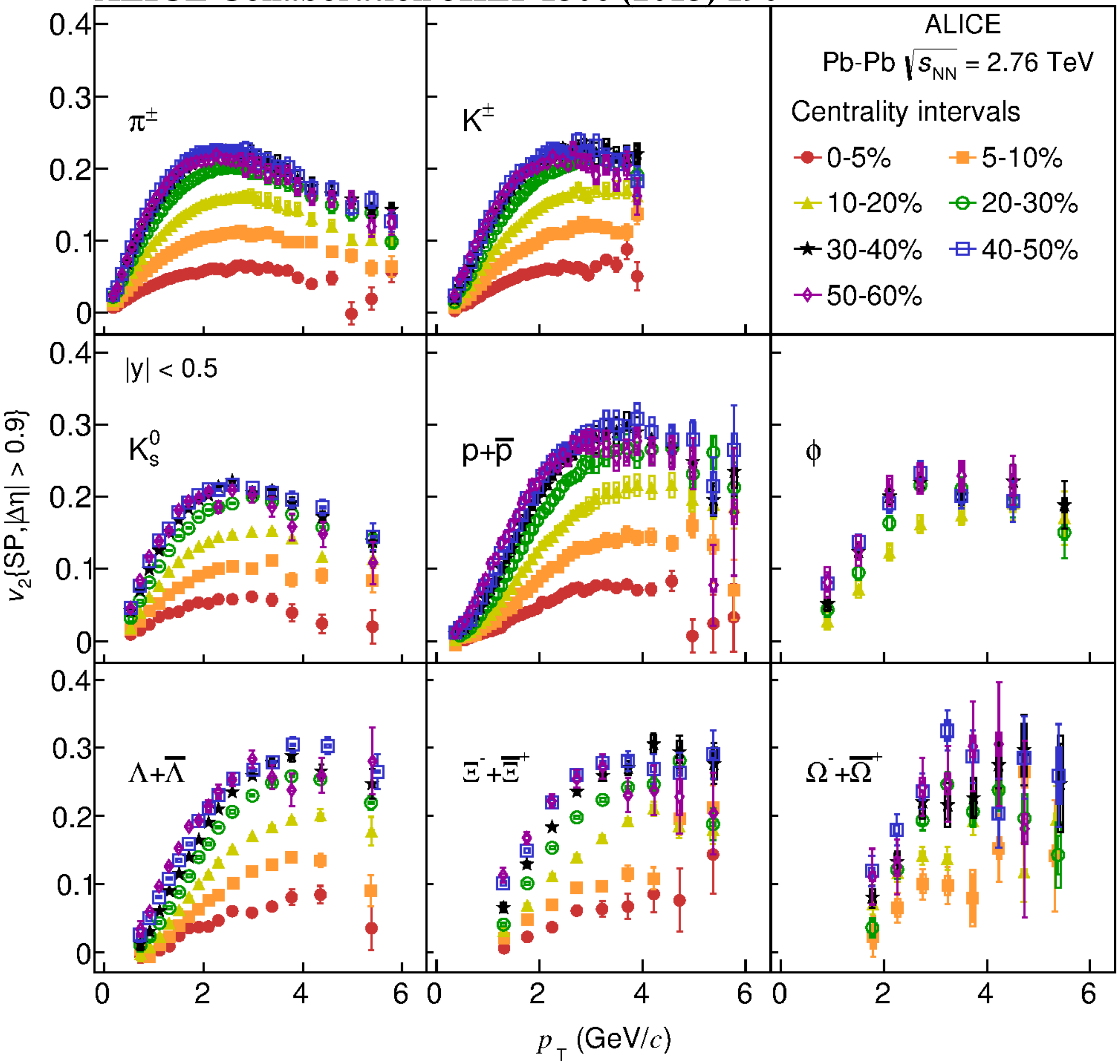
M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905



- In non-central collisions initial overlap region is of ellipsoidal shape, resulting in strong in-plane density gradients and development of azimuthally asymmetric (elliptic) flow

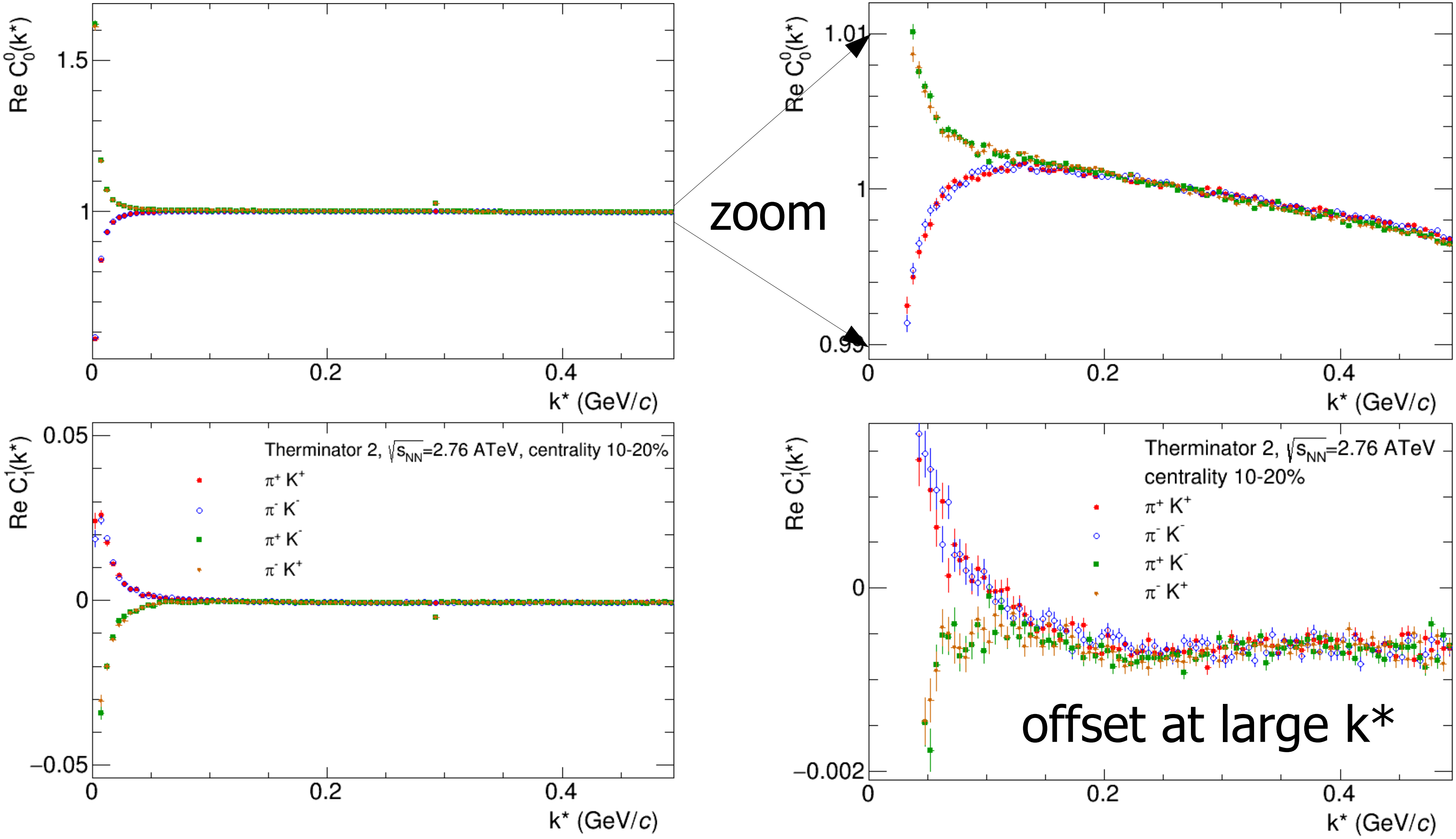
Elliptic flow

ALICE Collaboration JHEP 1506 (2015) 190



- For all particles elliptic flow increases with momentum

Functions including elliptic flow

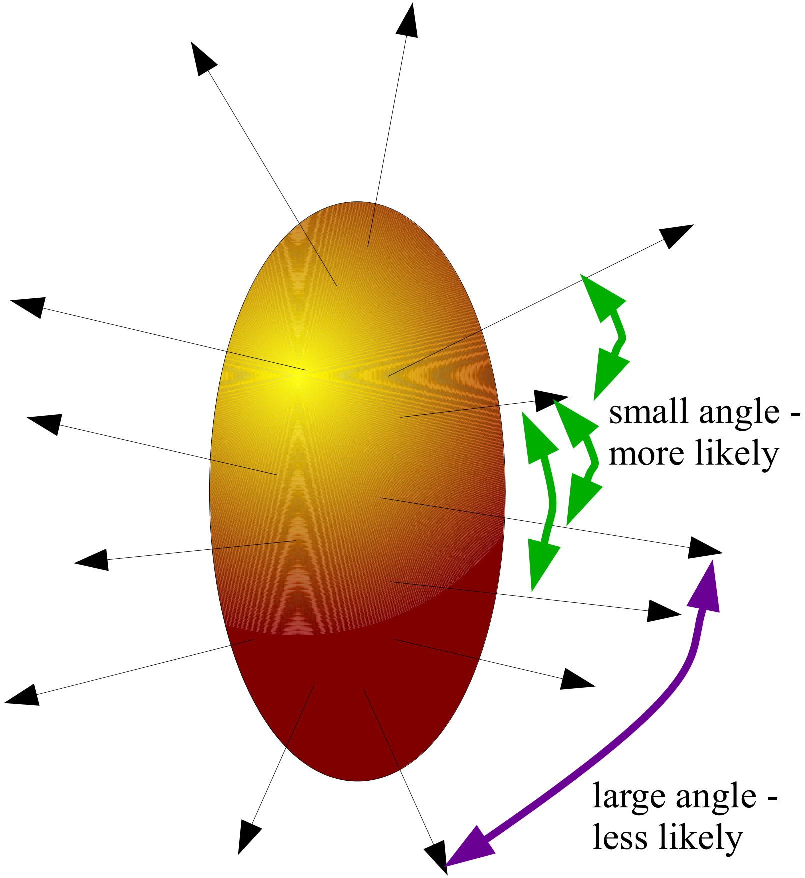


offset at large k*

- Significant additional correlation from elliptic flow in C_0^0 and C_1^1

Background from elliptic flow

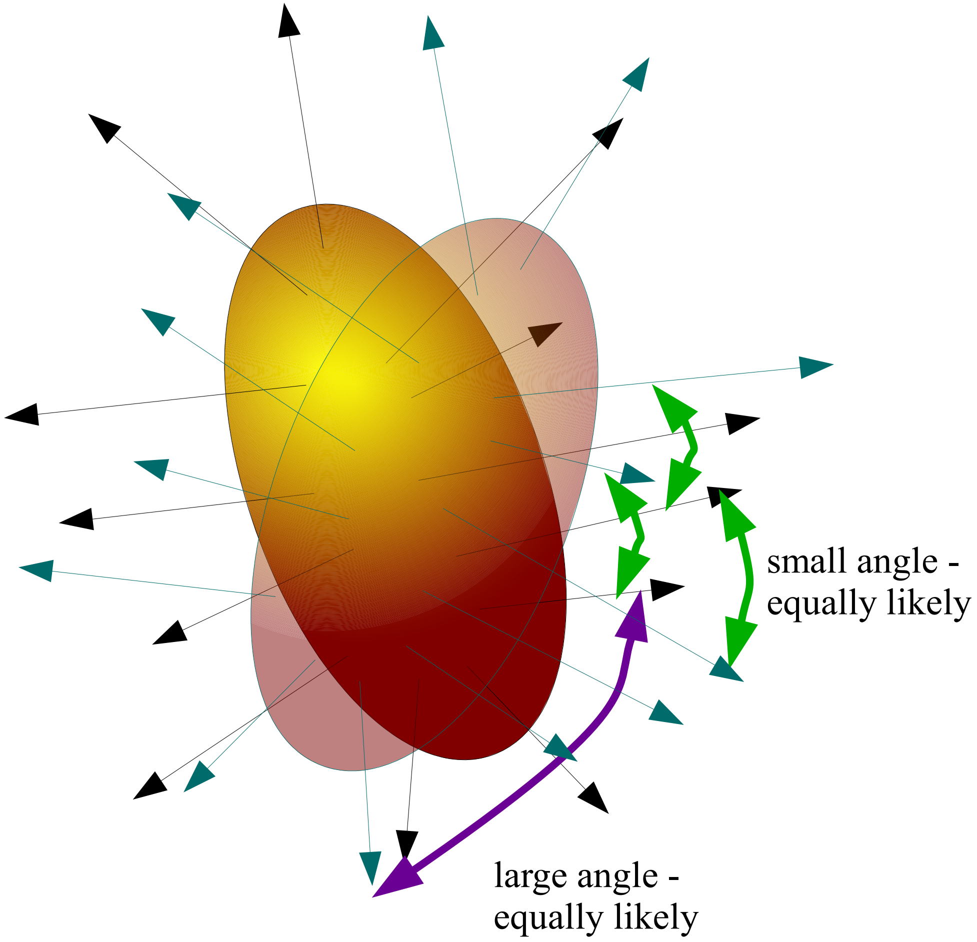
- Same event (signal)



small angle - more likely

large angle - less likely

- Mixed events (background)



small angle - equally likely

large angle - equally likely

- In “mixed” sample large-k* pair are relatively enhanced (resulting in negative correlation function slope)

Model correlation correction

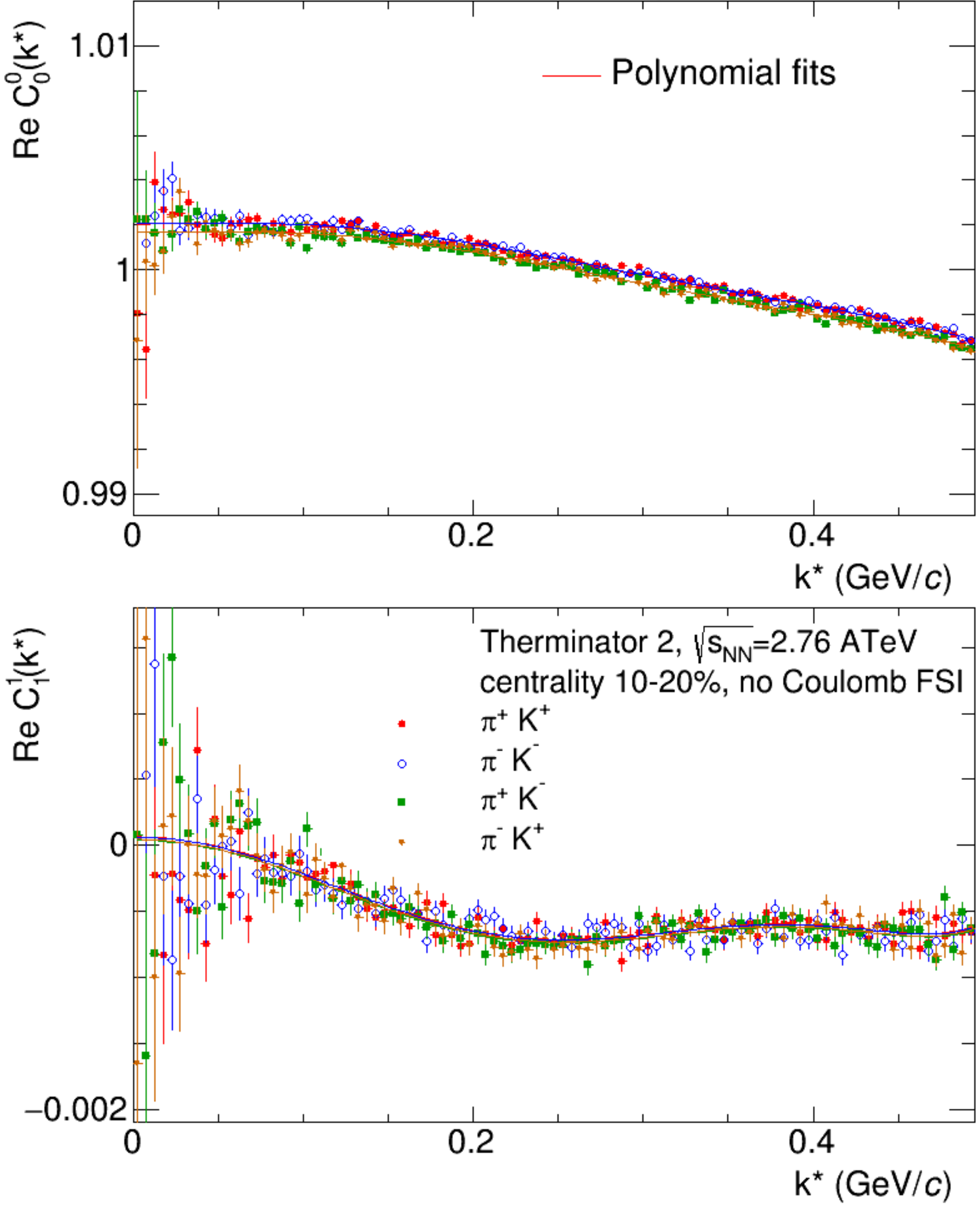
- Assumption: background effect additive to femto correlation
- Proposed correction method:
  - Determine the background function B, by fitting "baseline" correlation (with no femto)
  - Correct the {0,0} component of the full function with:

$$C^0_{0,corr} = C^0_{0,true} - \left(B^0_0 - 1\right)$$

  - Correct the Re{1,1} with:

$$C^1_{1,corr} = C^1_{1,true} - B^1_1$$

Separating elliptic flow contribution



- Function can be calculated with elliptic flow effects only
- Background is identical for all charge pair combinations – can be reliably estimated
- Shape of background is not trivial – cannot be simply “guessed” from the non-femtoscopic region
- 6-th order polynomial seems to be enough to fully capture the background features

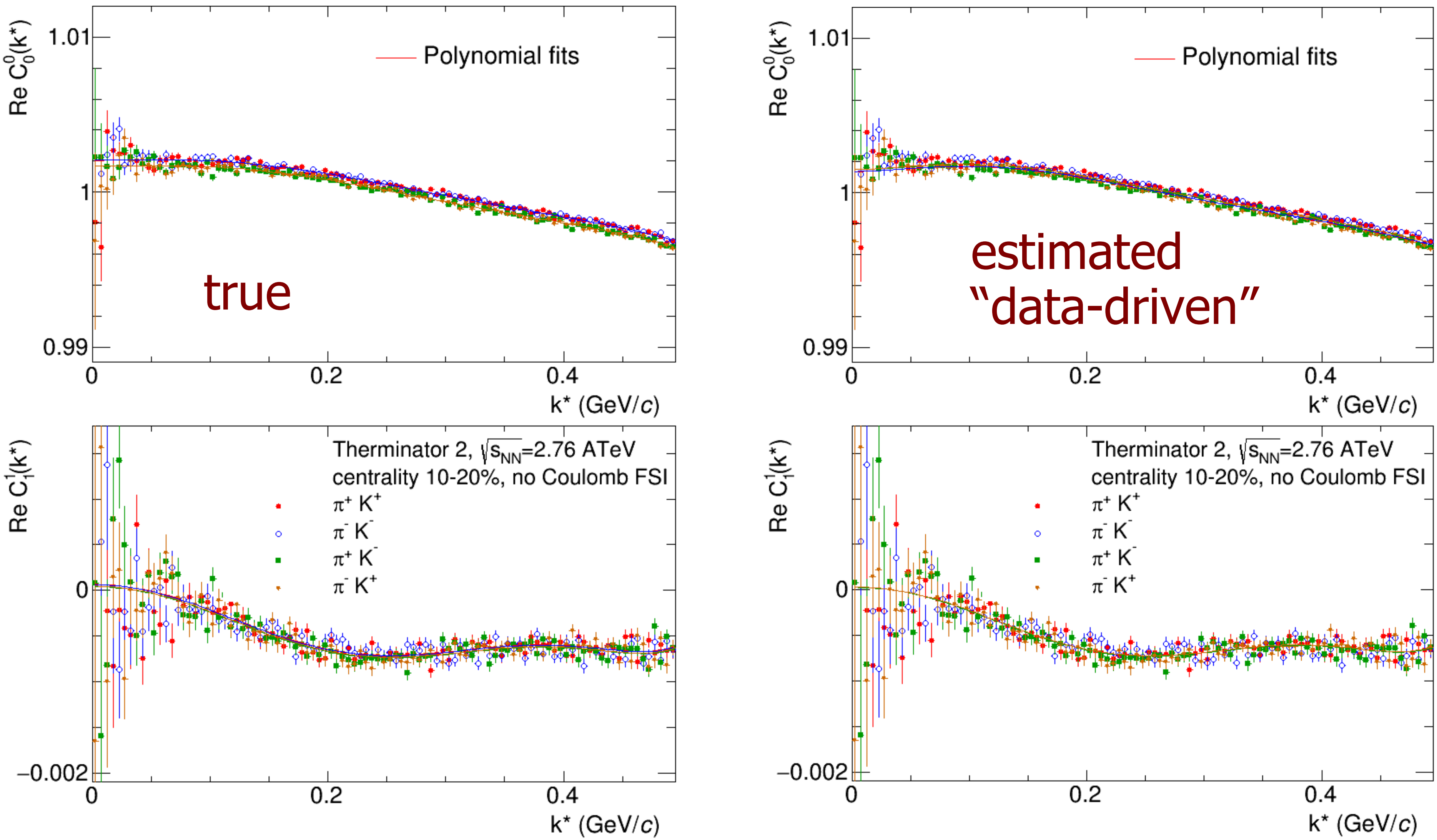
Correcting experimental function

- In real data "baseline" correlation not available
- But: "full" correlation available for same- and opposite-sign
  - Extrapolation from beyond femto region not possible
  - Assumption: Background is common for all charges
  - In addition: "femto" effect for same-sign is approximately the inverse of opposite-sign (not strictly correct, but good enough?)
  - Determine B, with minimizes (for the sum of all same/opposite-charge combinations):

$$\chi^2 = \sum_{k^*} \sum_{\pm\pm} \left[(C_{SS} - B) - (1/(C_{OS} - B)) \right] / \sigma^2$$

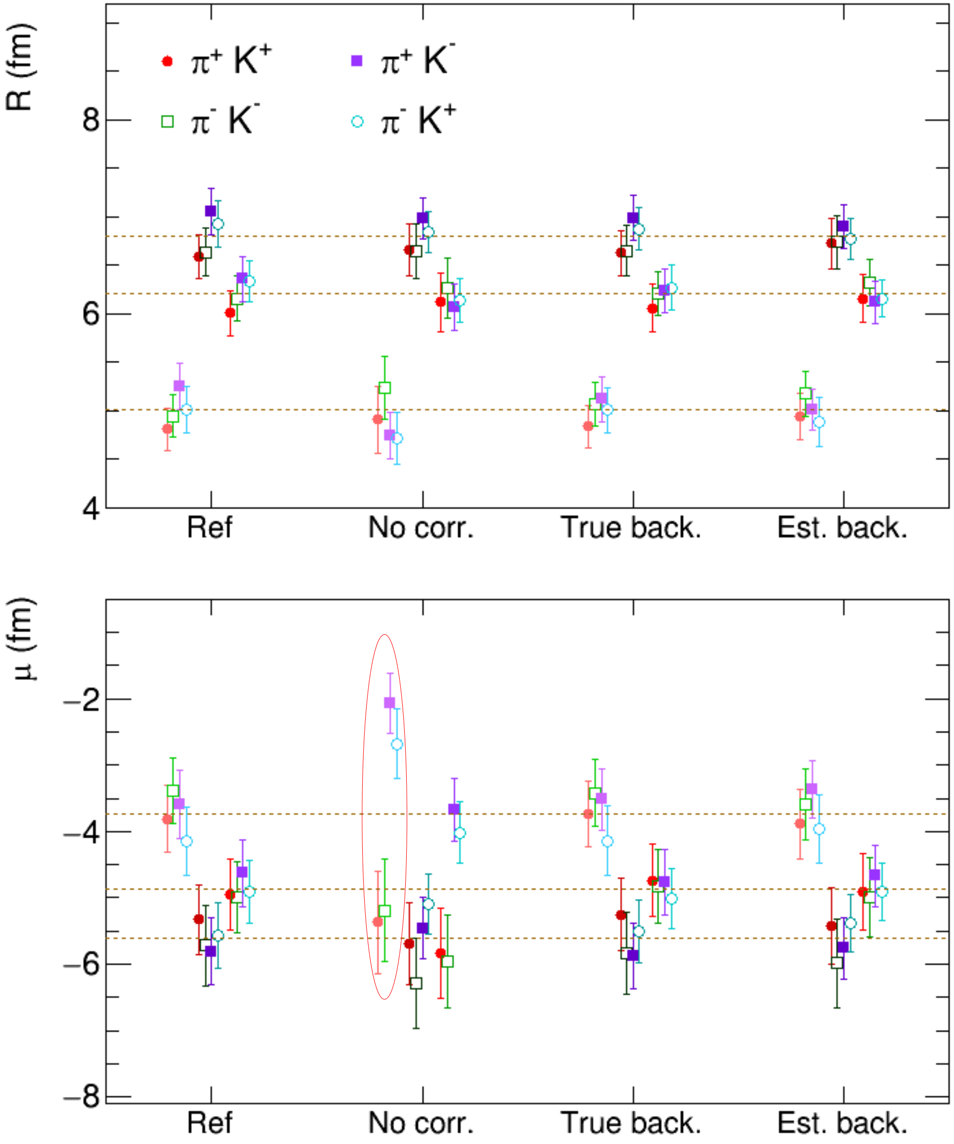
  - Then correct the same way as before

Background fitted to full function



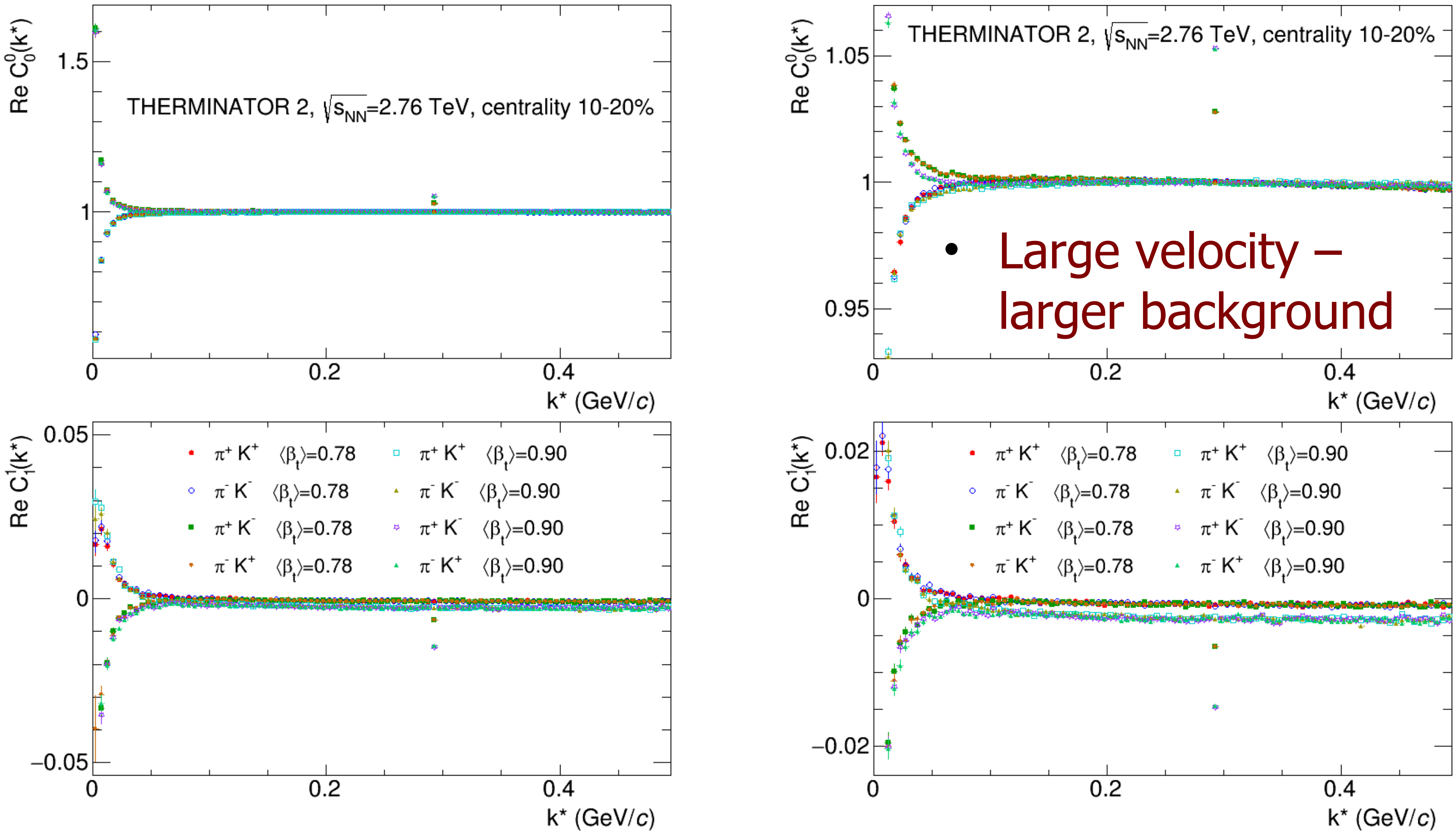
- Comparison of “baseline” and background fitted to “data”

Correction for the background



- Correlation function fits
  - Fit to “pure” functions gives reference value
  - If no correction for the effect is done, results are strongly affected
  - We can use the simulations to fully remove the background – then fit becomes compatible with reference fits
  - The model is not necessary to estimate the correction – it can also be based on data alone and fit is still correct

Calculations vs. pair velocity



- Large velocity – larger background

- Dependence on pair velocity of signal and background

Summary

- Pion-kaon correlations an unique way to analyze the collectivity in heavy-ion collisions
- Addition of pair velocity dependence combines two signatures of collectivity in one analysis
- Relative asymmetry increase and total size decrease observed for high velocity, first time both effects seen together.
- Elliptic flow identified as possible source of non-femtoscopic correlations
- Effect seen and corrected for with dedicated procedure
- Analysis vs. pair velocity shows large background for high velocity, in agreement with expectations