Non-identical particle femtoscopy in heavy-ion collisions

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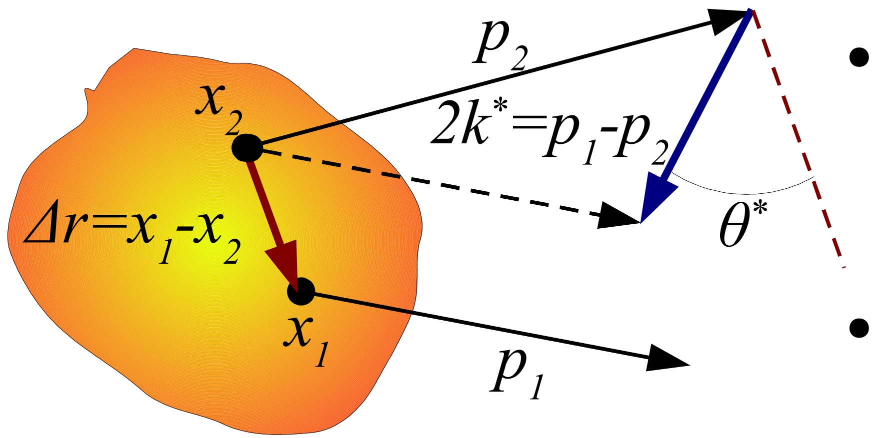
Outline

- Correlations through FSI
  - Pair wave-function from Coulomb and strong
  - Asymmetries in the correlation function
- Measuring the size and the asymmetry
- Origins of asymmetry
  - Time delay from resonance decays
  - Spatial asymmetry from radial flow
- Experimental results
  - Non-identical correlations from SPS
  - Results from RHIC
    - Complete coverage of pion, kaon and proton correlations
    - Same-mass particle-antiparticle correlations
    - Baryon-baryon correlations (see talk by H. Gos)
  - Measuring scattering lengths (see talk by F.Retiere)

Two particle wave function for non-identical particles



- We follow two particles emitted independently from the source and arriving at the detector (far away)
- Charged hadrons interact through Coulomb and strong forces:

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

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

$A_c(\eta)$ is the Gamow factor, F is the confluent hypergeometric function and G is the combination of the regular and singular s-wave Coulomb functions, f is the s-wave scattering amplitude.

- We will later analyze in detail the Coulomb interaction:

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

Femtoscopy definitions

- We start from simple definitions of single- and two-particle spectra:

$$P_1(\vec{p}) = E\frac{dN}{d^3p} = \int d^4x\, S(x,p)$$

$$P_2(\vec{p}_a,\vec{p}_b) = E_aE_b\frac{dN}{d^3p_a\, d^3p_b} = \int S(x_{1,}\, x_{2,}\, p_{1,}\, p_2)\, d^4x_1\, d^4x_2$$

expressed as integrals over source emission function.

- Then we define the correlation function:

$$C(\vec{p}_a,\vec{p}_b) = \frac{P_2(\vec{p}_a,\vec{p}_b)}{P_1(\vec{p}_a)\,P_1(\vec{p}_b)}$$

- Which can also be expressed through these integrals and the wave-function of the pair:

$$C(\vec{q},\vec{K}) = \frac{\int d^4x_1\, S(x_1,p_1)\, d^4x_2\, S(x_2,p_2)\left|\Psi_{\tilde{q}}^{S(+)}\right|^2}{\int d^4x\, S(x_1,p_1)\int d^4x\, S(x_2,p_2)}, \quad \boldsymbol{q} = \boldsymbol{p_1} - \boldsymbol{p_2}, \quad \vec{K} = (\vec{p}_1 + \vec{p}_2)/2$$

Details of Coulomb interaction

- We start from the Coulomb-only wave-function:

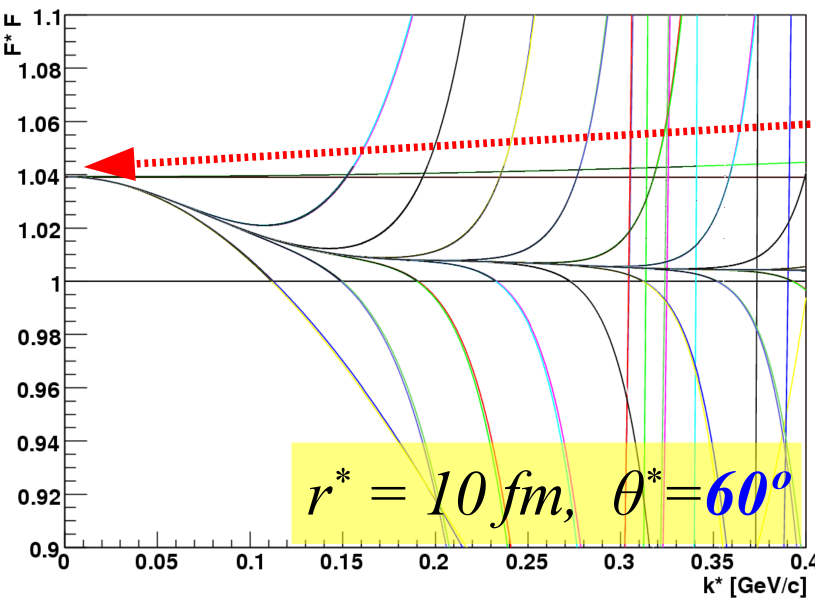
$$\Psi_{-\boldsymbol{k}^*}(\boldsymbol{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-i\boldsymbol{k}^*\boldsymbol{r}^*}F(-i\eta, 1, i\xi)\right]$$

- In particular the F function is of interest:

$$F(\alpha, 1, z) = 1 + \alpha z/1!^2 + \alpha(\alpha+1)z^2/2!^2 + \ldots$$

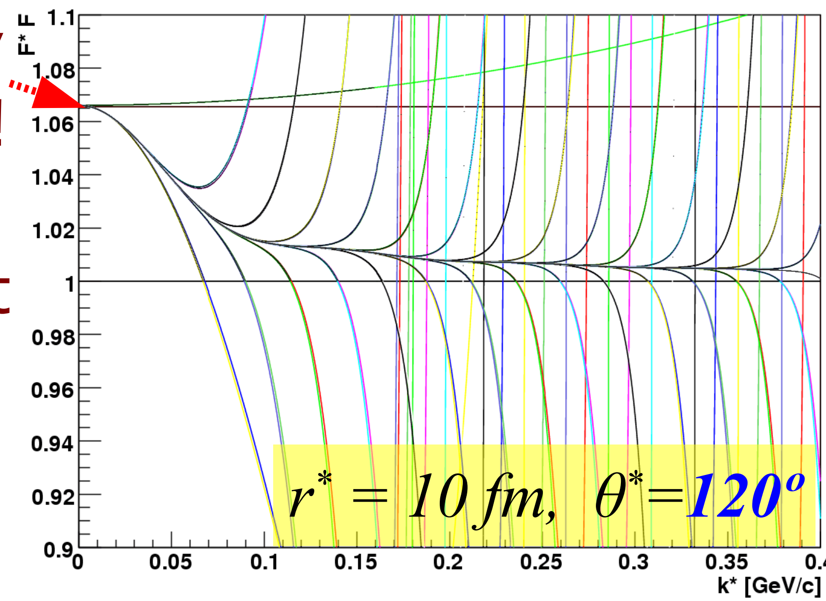
- In our case this is:

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



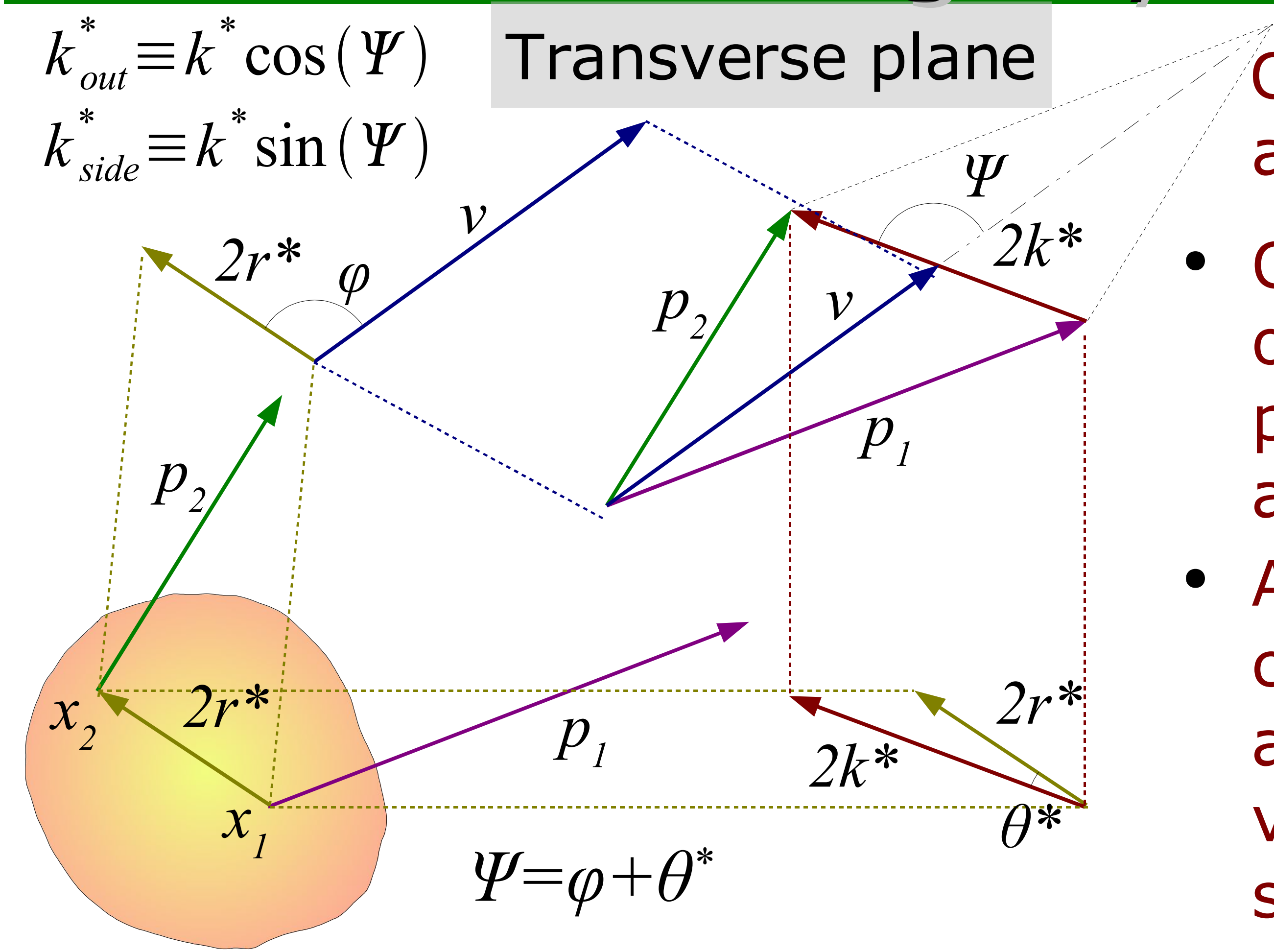
Asymmetry from angle!

Behavior at low k^* well described by 1st term



Accessing asymmetry

$$k^*_{out} \equiv k^* \cos(\Psi)$$
$$k^*_{side} \equiv k^* \sin(\Psi)$$



$$\Psi = \varphi + \theta^*$$

$$\cos(\Psi) = \cos(\varphi)\cos(\theta^*) + \sin(\varphi)\sin(\theta^*)$$

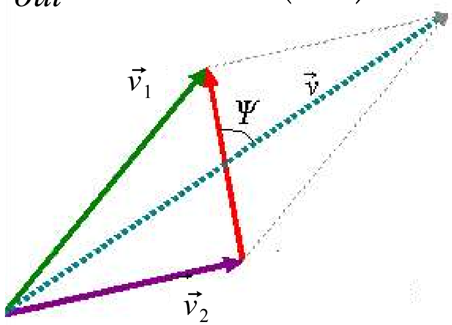
$$sign\langle\cos(\Psi)\rangle = sign\langle\cos(\varphi)\rangle\, sign\langle\cos(\theta^*)\rangle$$

Only particle momenta are measured

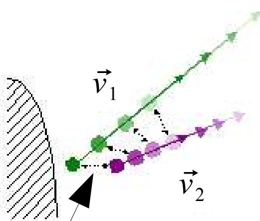
- One selects pairs basing on the angle Ψ between pair relative k^* and average v momenta
- Angles Ψ and θ^* are connected through φ - angle between pair velocity and space separation
- Can analyze with respect to any direction, not only v (“out”)

The asymmetry analysis

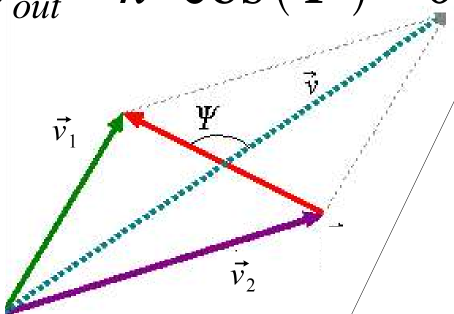
$k^{*}_{out} \equiv k^{*} \cos(\Psi) > 0$



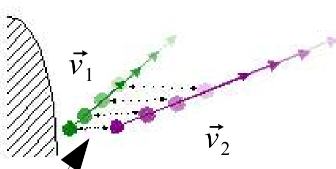
$\cos(\Psi) > 0$



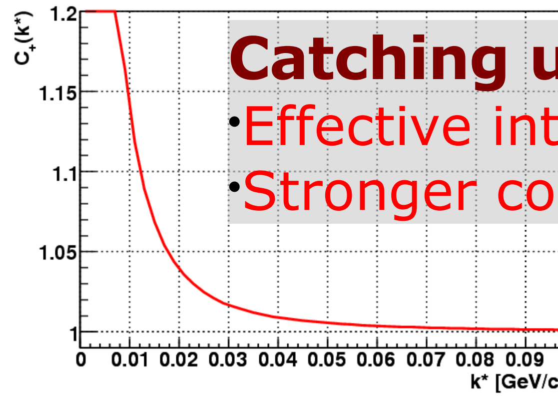
$k^{*}_{out} \equiv k^{*} \cos(\Psi) < 0$



$\cos(\Psi) < 0$



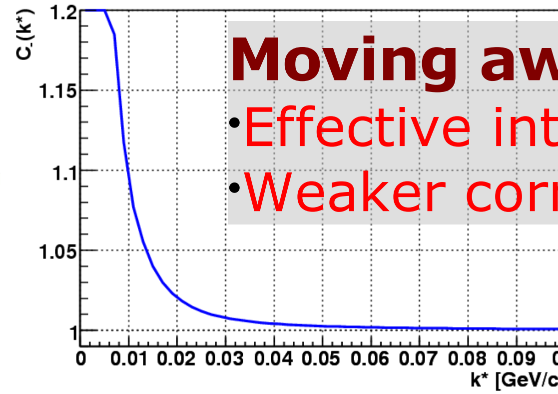
$\cos(\varphi) < 0 \Leftrightarrow \vec{r}^{*} \| \vec{v} < 0$



Catching up

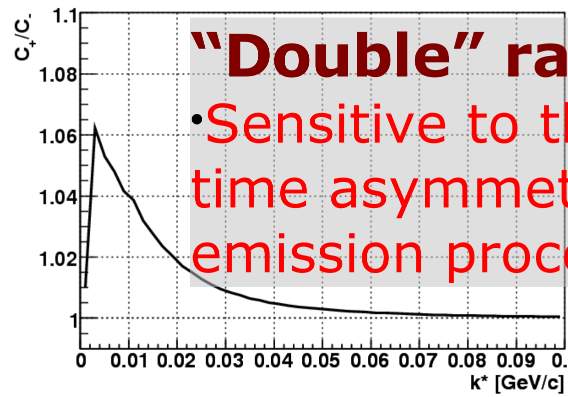
- Effective interaction time longer
- Stronger correlation

R.Lednicky, V. L.Lyuboshitz, B.Erazmus, D.Nouais, Phys.Lett. B373 (1996) 30.



Moving away

- Effective interaction time shorter
- Weaker correlation



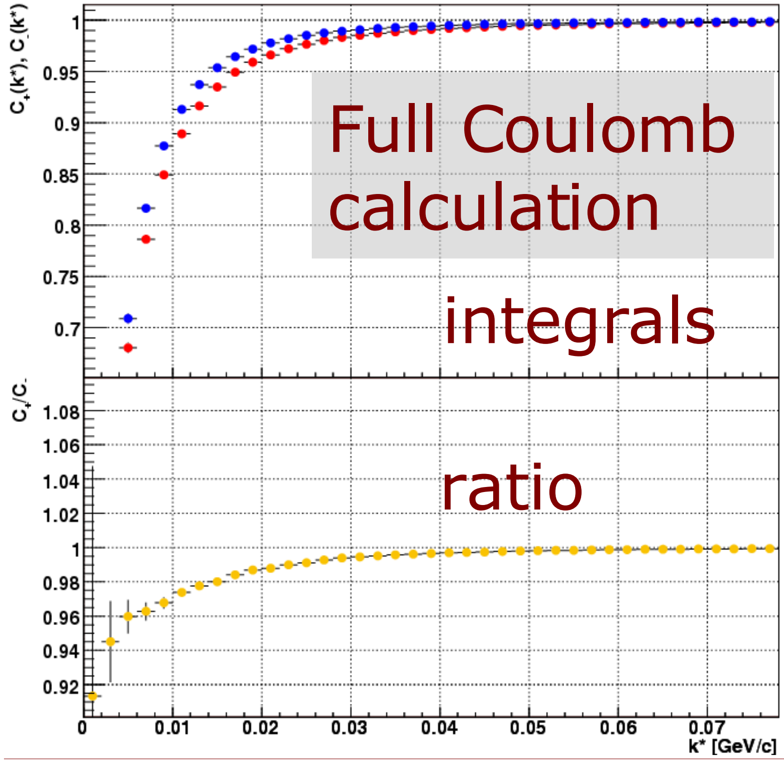
"Double" ratio

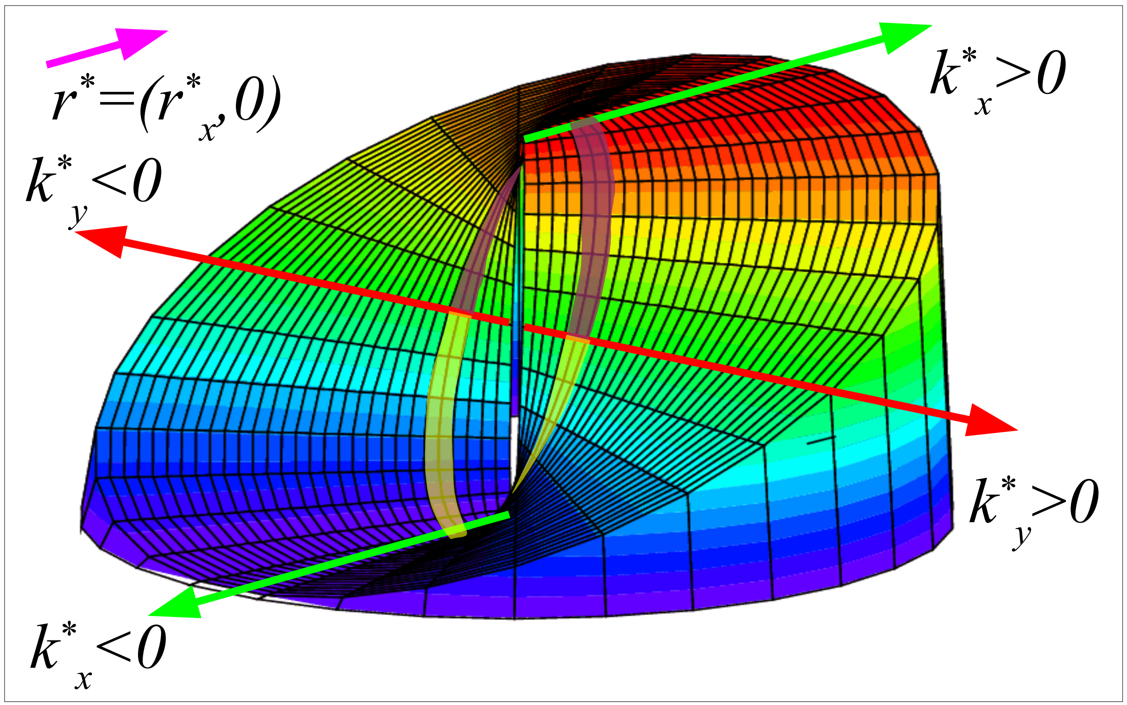
- Sensitive to the space-time asymmetry in the emission process

Using the correlation effect in θ^{*} and a selection on Ψ we are analyzing angle φ thus probing the space asymmetry of the source

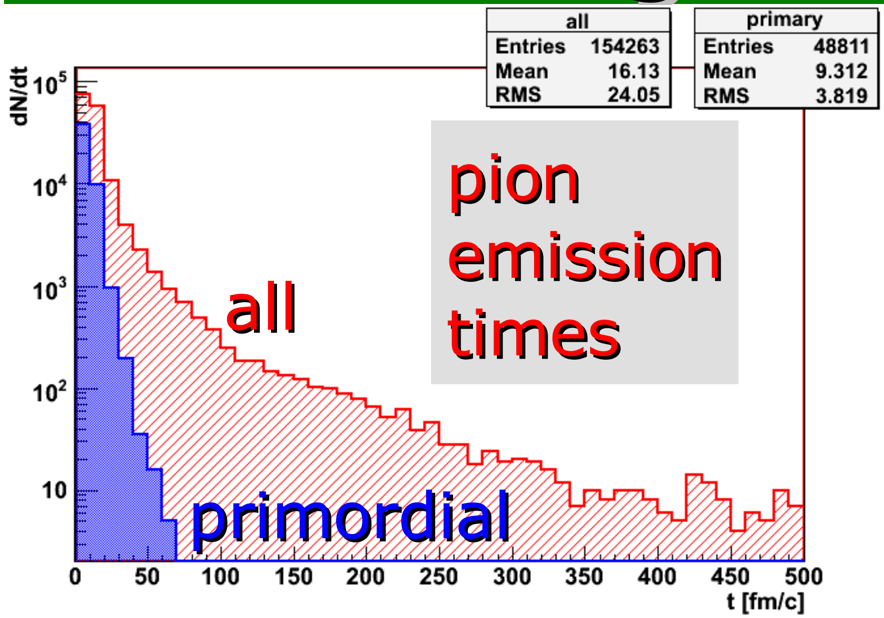
Discontinuity

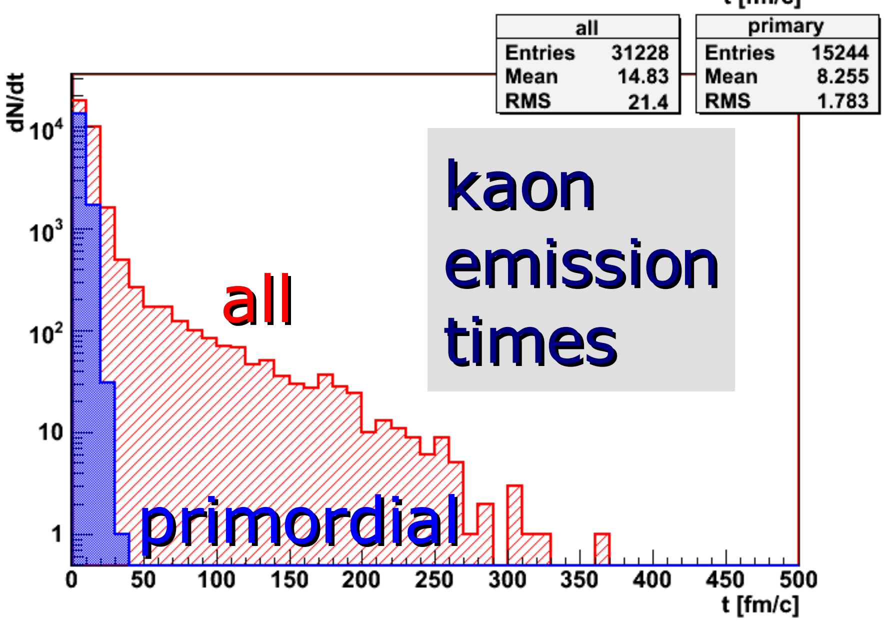
- The $r^*(1+\cos(\theta^*))$ term introduces not only asymmetry but also discontinuity of the size $2r^*$ in the interaction at $k^*=0$.
- Full model calculation shows that correlation functions for $k^*_x>0$ and $k^*_x<0$ do not come to the same value at $k^*=0$.





Origins of asymmetry

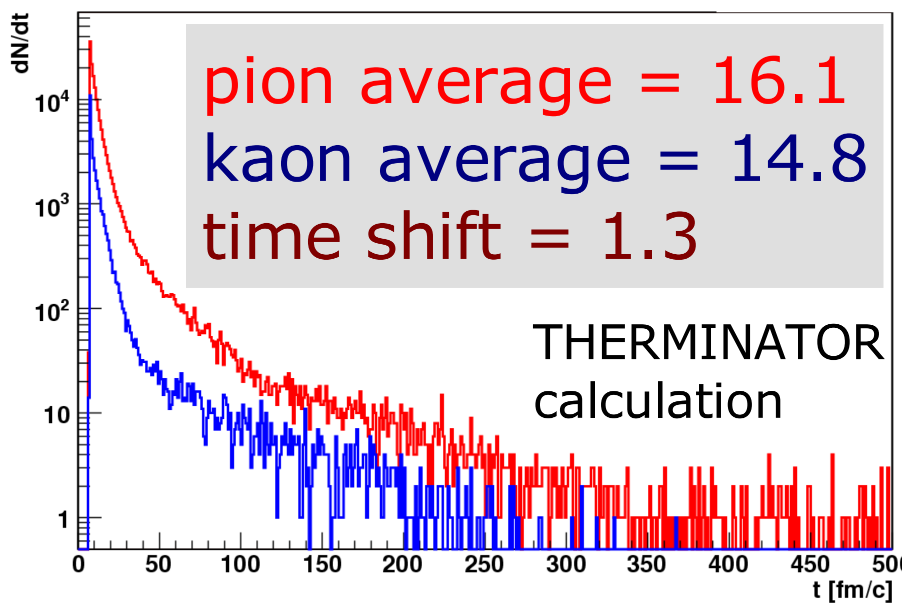




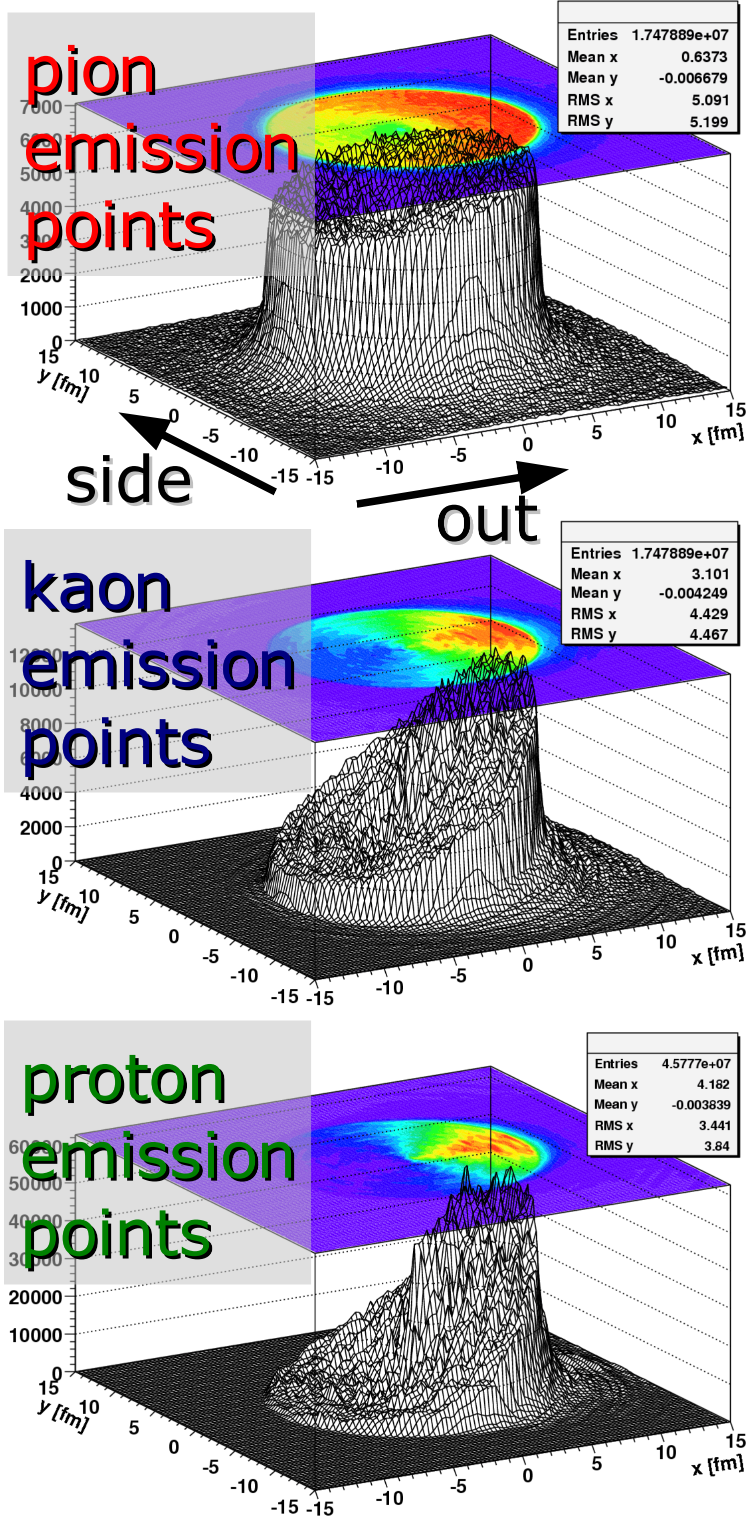
- Measures asymmetry in pair rest frame is a combination of time and space shifts in source frame

$$\langle r^*_{out} \rangle = \gamma \left(\langle r_{out} \rangle - \beta_t \langle \Delta t \rangle \right)$$

- In heavy-ion collisions one expects difference in emission time from resonance decays



Space asymmetry from flow



THERMINATOR calculation

- Transverse momentum of particles is composed of the thermal (randomly distributed) and flow (directed "outwards") components
- With no flow average emission point is at center of the source and the length of homogeneity is the whole source
- Flow makes the source smaller ("size"-p correlation) AND shifted in outwards direction (x-p correlation)
- For particles with large mass thermal motion matters less – they are shifted more in "out" direction. The difference is measured as emission asymmetry.

Radius extraction

- For identical particle correlation functions, a static, Gaussian, single-particle emission function is assumed:

$$S(x,K) \sim \exp\left(-\frac{x_1^2}{2R_{out}^2} - \frac{x_2^2}{2R_{side}^2} - \frac{x_3^2}{2R_{long}^2}\right)$$

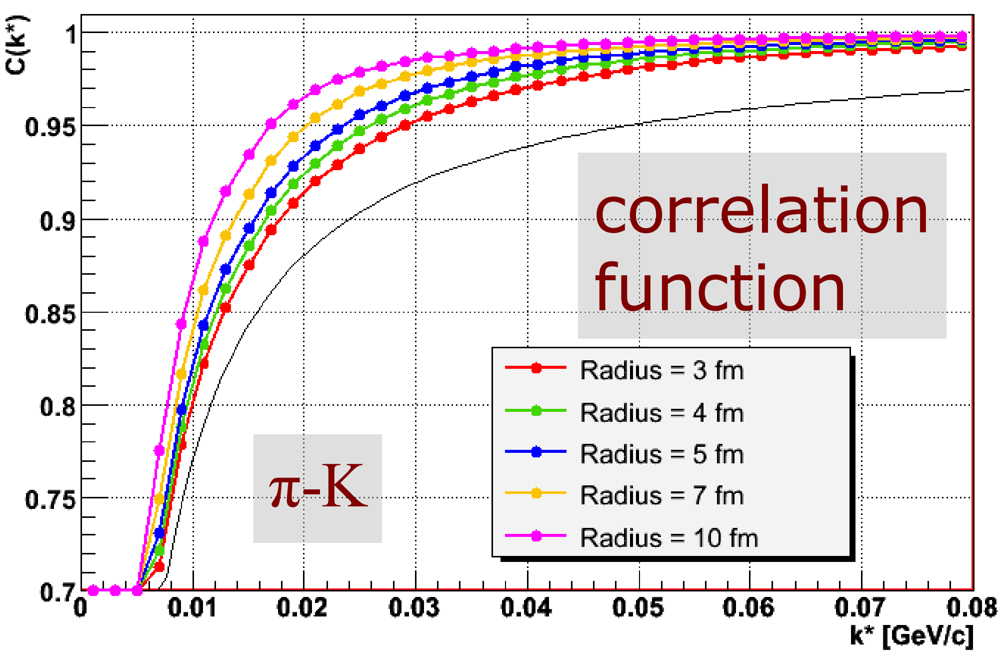
- The integration then gives:

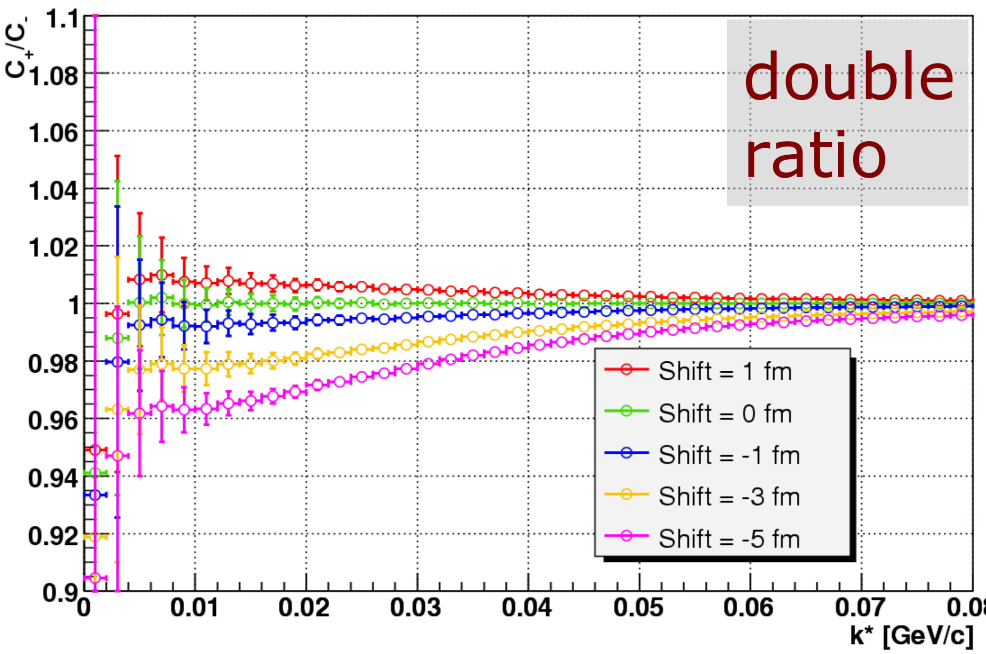
$$C(\vec{q}) = 1 + \lambda \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)$$

- and the so-called "HBT radii" are obtained
- This procedure cannot be applied for non-identical particle correlations, for several reasons:
  - It uses wave-function symmetrization and neglects FSI
  - Analytic form of the FSI can be drastically different for different pair systems
  - One must deal with two-particle emission function

Sensitivity to size and shift

- Coulomb correlation function shows sensitivity to the source size both in width and height of the effect (unlike identical particle correlations, where only width is affected)
- The "double ratio" shows monotonic sensitivity to the shift in average emission points



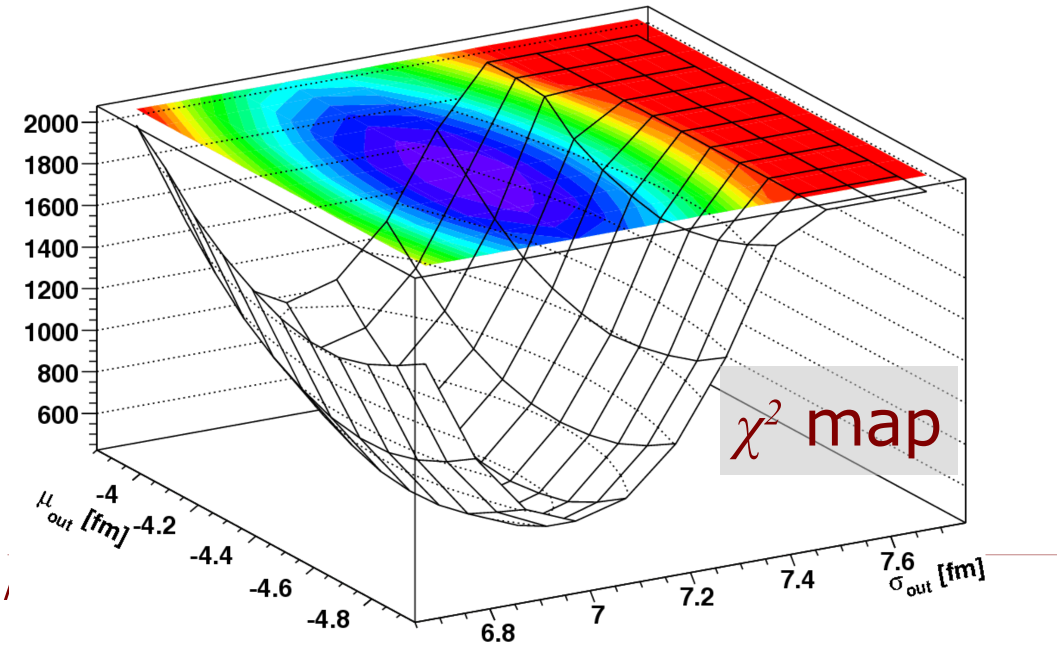


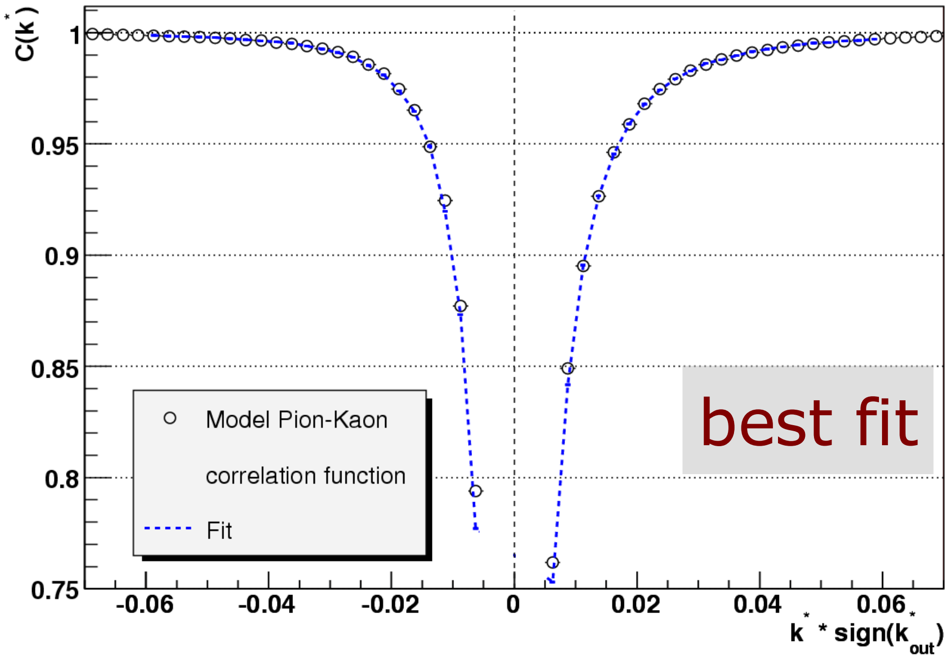
CorrFit – numerical integration of the emission function

- One starts from two-particle emission function, which includes a possibility of non-zero mean separation (shift):

$$S(\vec{r},\vec{K}) \sim \exp\left(-\frac{(r_{out}-\mu_{out})^2}{\sigma_{out}^2}-\frac{r_{side}^2}{\sigma_{side}^2}-\frac{r_{long}^2}{\sigma_{long}^2}\right), \quad \text{or} \quad S(\vec{r},\vec{K}) \sim \exp\left(-\frac{(r^*_{out}-\mu_{out})^2}{\sigma_{out}^2}-\frac{r^{*\,2}_{side}}{\sigma_{side}^2}-\frac{r^{*\,2}_{long}}{\sigma_{long}^2}\right)$$

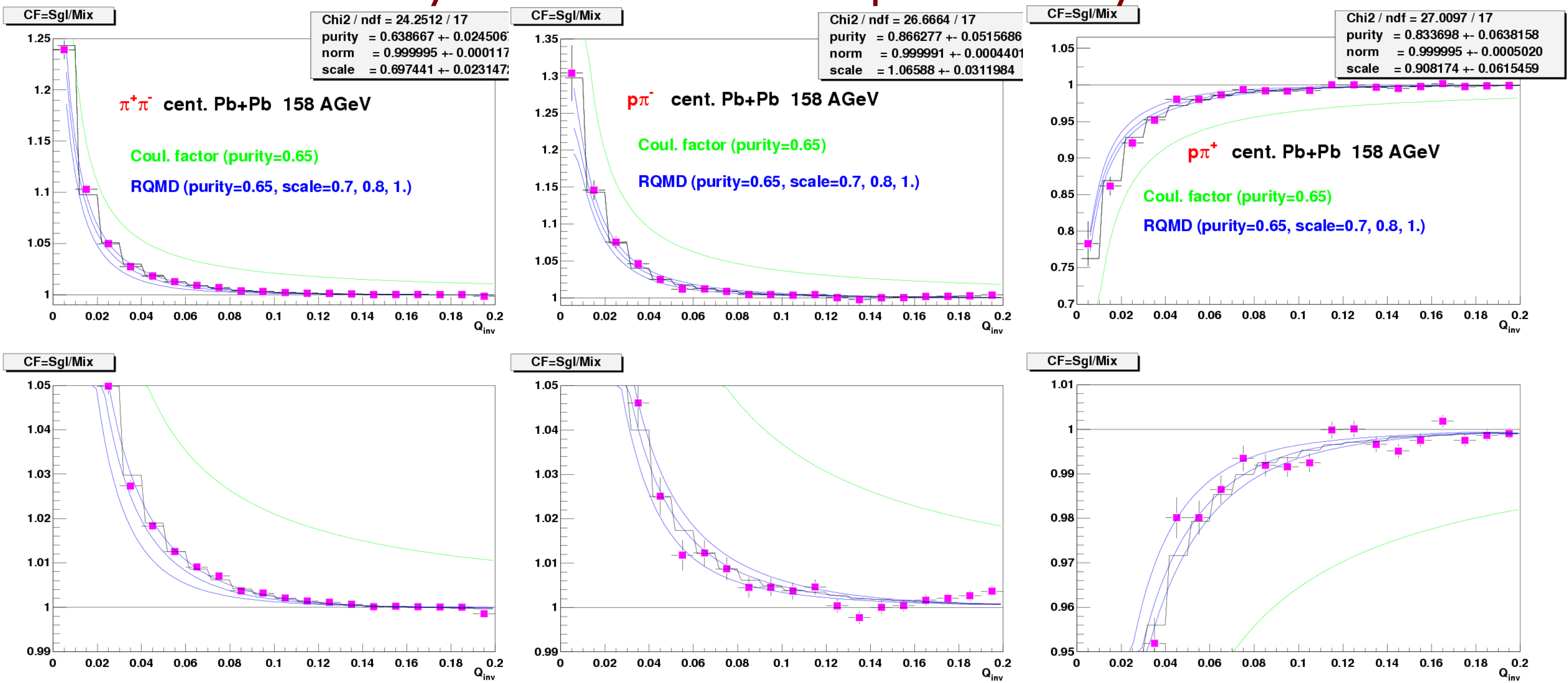
- Then one numerically integrates it with particle momenta taken from the experiment, assuming a range of values of source radii. Best-fit radii are selected by finding which calculated CF describes the experimental one best





Results from SPS

- First results on non-identical particle correlations in high-energy heavy-ion collisions
- R. Lednicky NA49 note – not published yet



Pion-Kaon correlation functions

- Correlation functions show expected correlation pattern
- Functions for same charge combinations are in very good agreement
- The agreement within the charge combination points to a very similar K^+ and K^- emission mechanism

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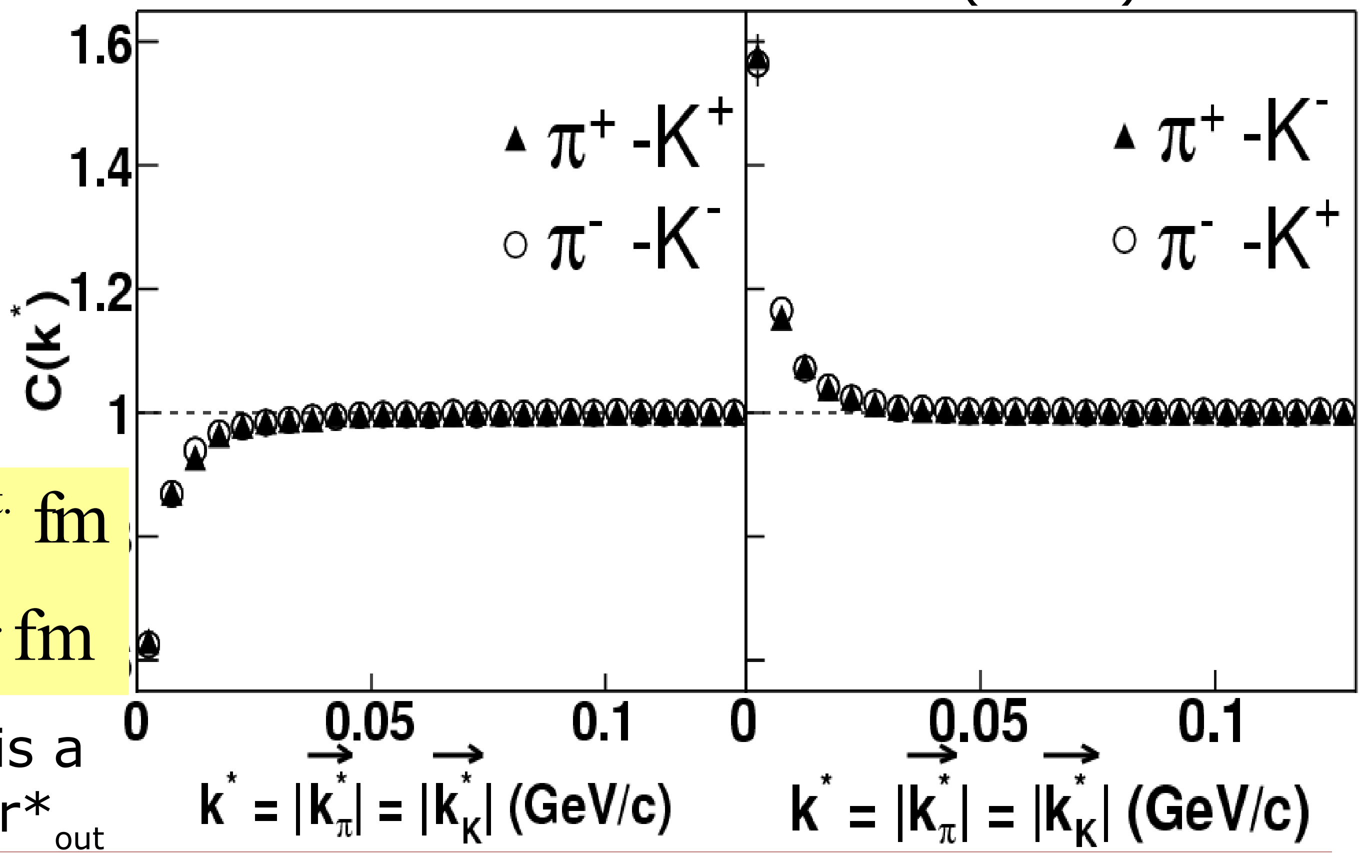
130 AGeV

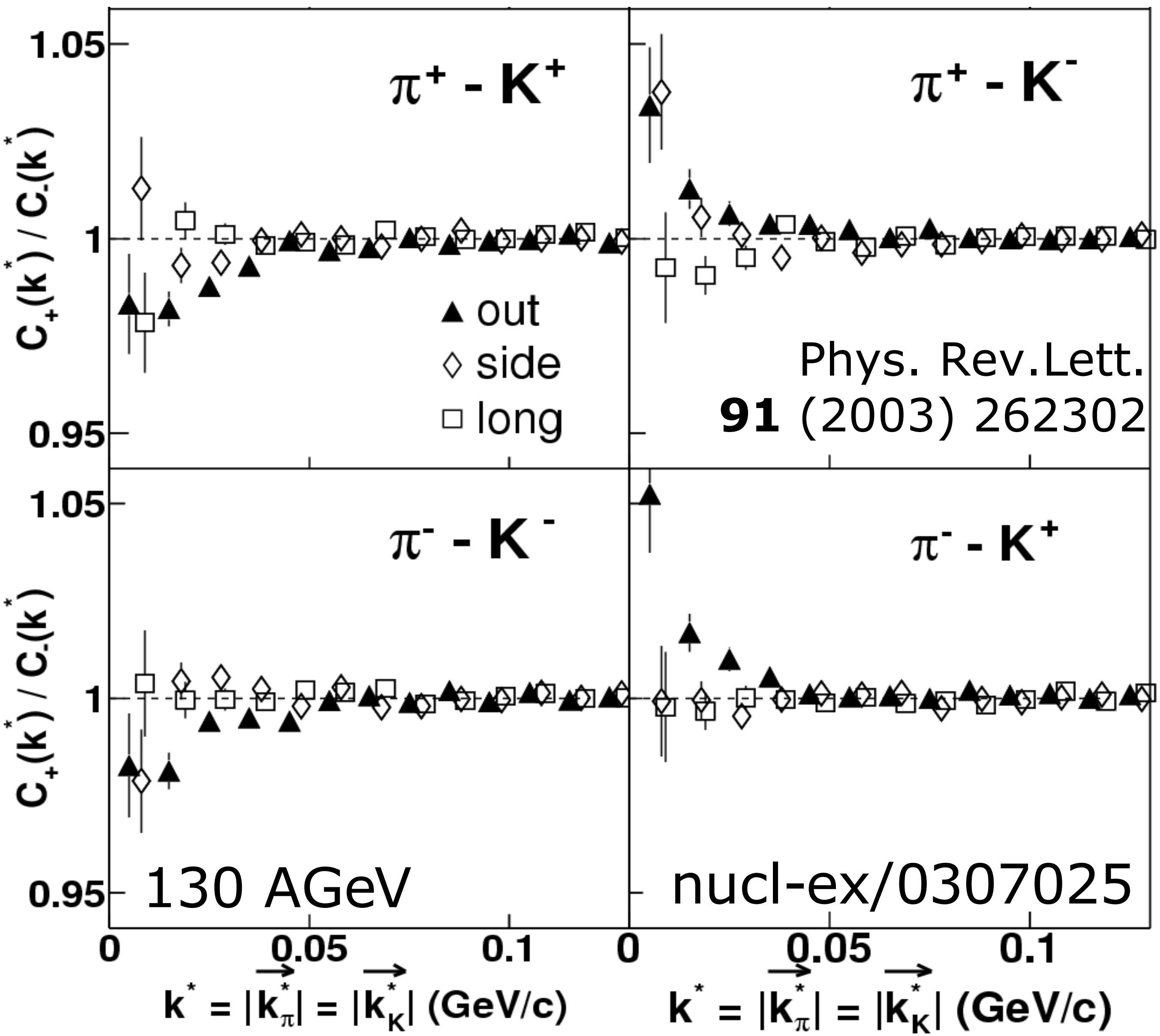


Sigma: **12.5** ± **0.4** $^{+2.2\ \text{syst.}}_{-3.0\ \text{syst.}}$ fm

Mean: **-5.6** ± **0.6** $^{+1.9\ \text{syst.}}_{-1.3\ \text{syst.}}$ fm

Fit assumes source is a gaussian in r^*_{out}

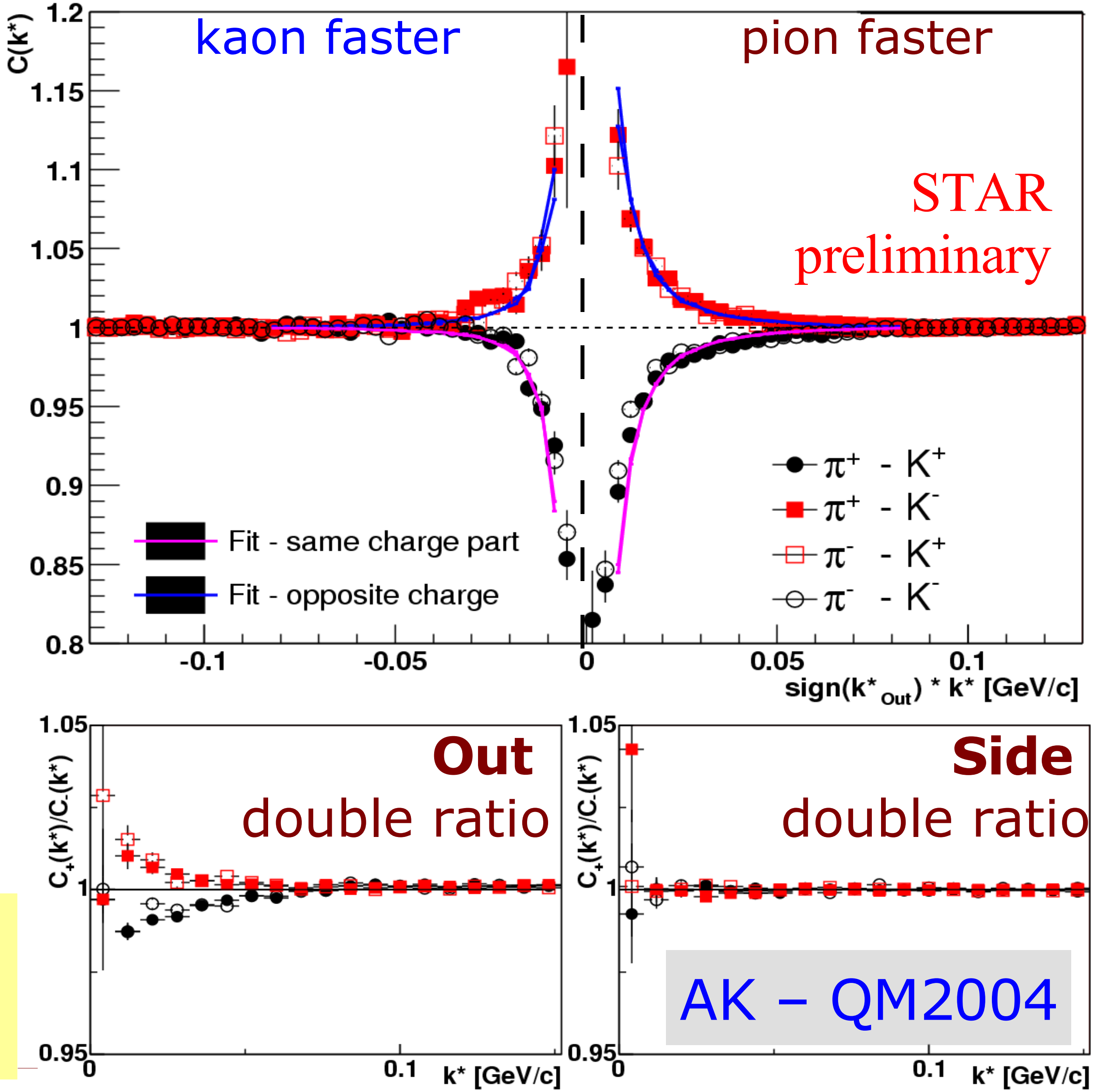
Double ratios



- Clear deviation from unity for Out – sign of asymmetry: pions are emitted closer to the center and/or later
- Side and Long – flat as expected (cross-check)
- Side is a very good test for experimental issues

Pion-Kaon at 200 AGeV

- Good agreement for same-charge combinations
- Clear emission asymmetry signal consistent with 130 GeV data
- Significant contribution of e^+e^- contaminating the Side double ratio removed



Sigma: **12.9** $\pm$ **0.3** $^{+1.2\ \text{syst.}}_{-1.3\ \text{syst.}}$ fm

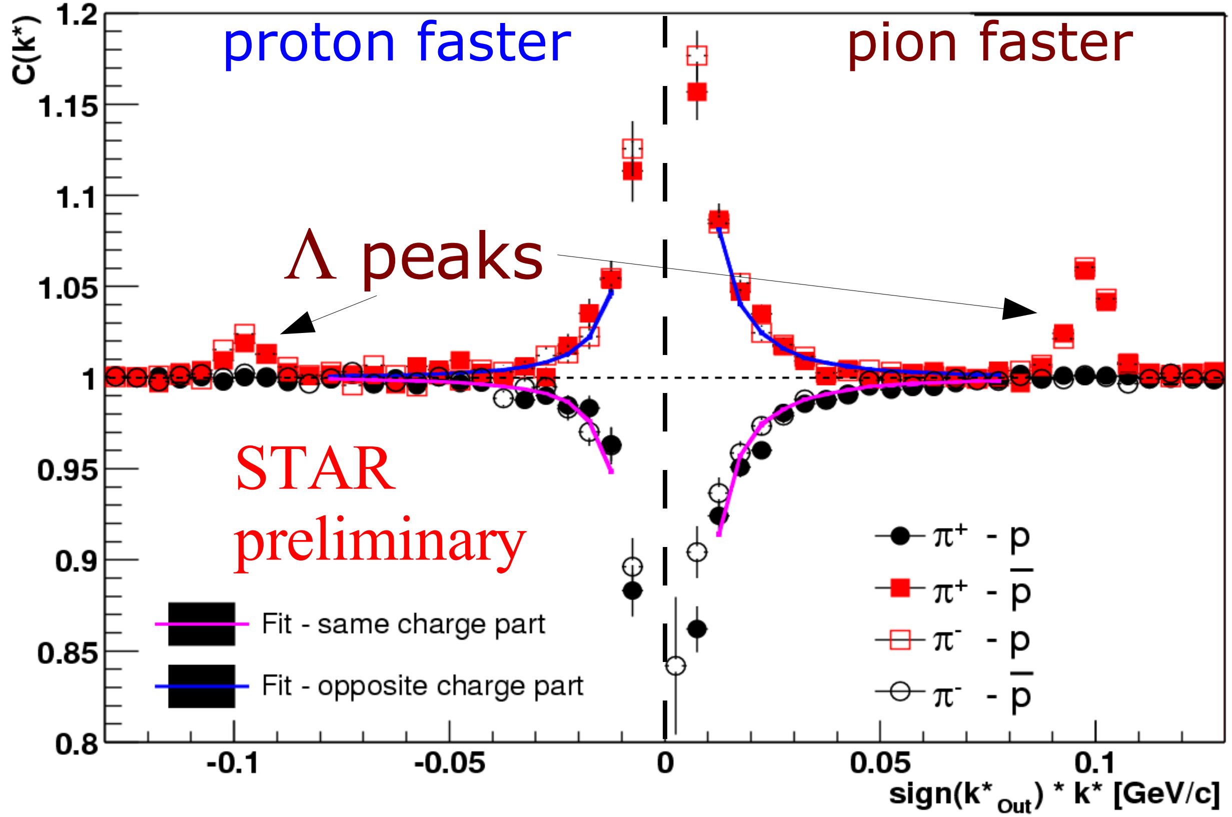
Mean: **-4.9** $\pm$ **0.8** $^{+0.9\ \text{syst.}}_{-1.2\ \text{syst.}}$ fm

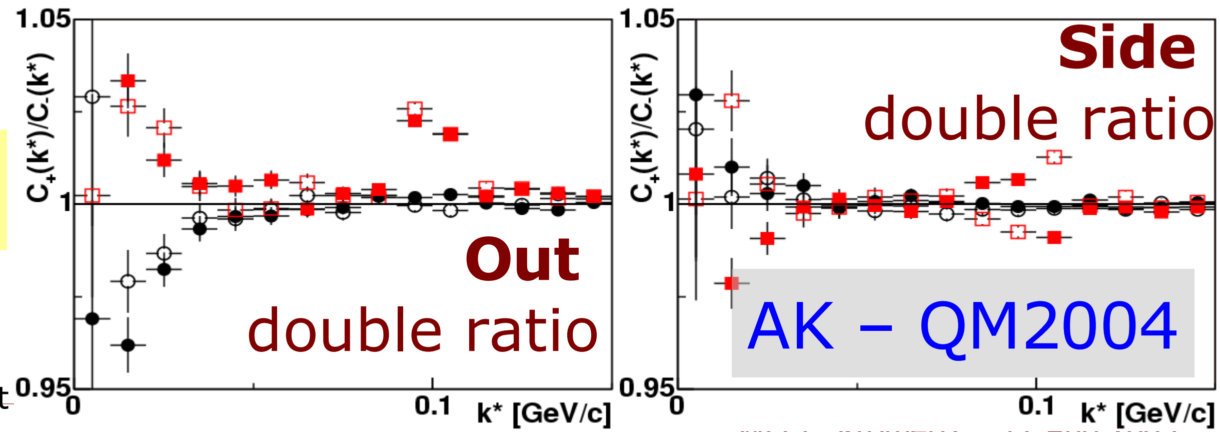
Pion-Proton 130 AGeV

- Good agreement for identical and non-identical charge combinations
- Asymmetry also for meson-barion system again pion emitted closer to the center and/or later, consistent with radial flow scenario

Mean: $\mathbf{-7.4 \pm 0.9}\ ^{+1.9\ \text{syst.}}_{-3.4\ \text{syst.}}$ fm

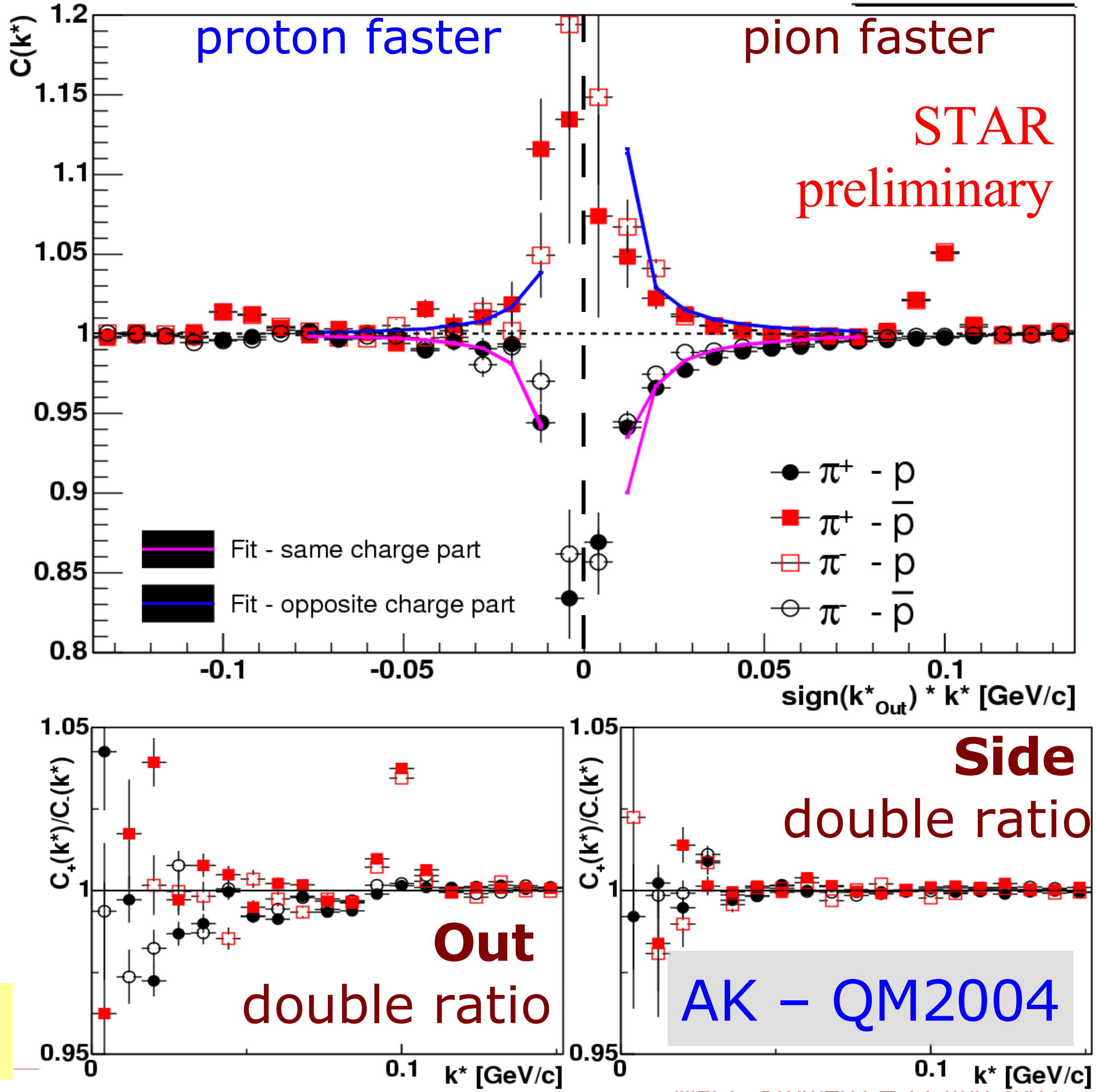
Fit assumes source is a gaussian in r^*_{out}





Pion – Proton at 200 AGeV

- Good agreement for same-charge combination pairs
- Systematic error influenced by the agreement between different charge combinations
- e^+e^- contamination more significant for 200 AGeV data



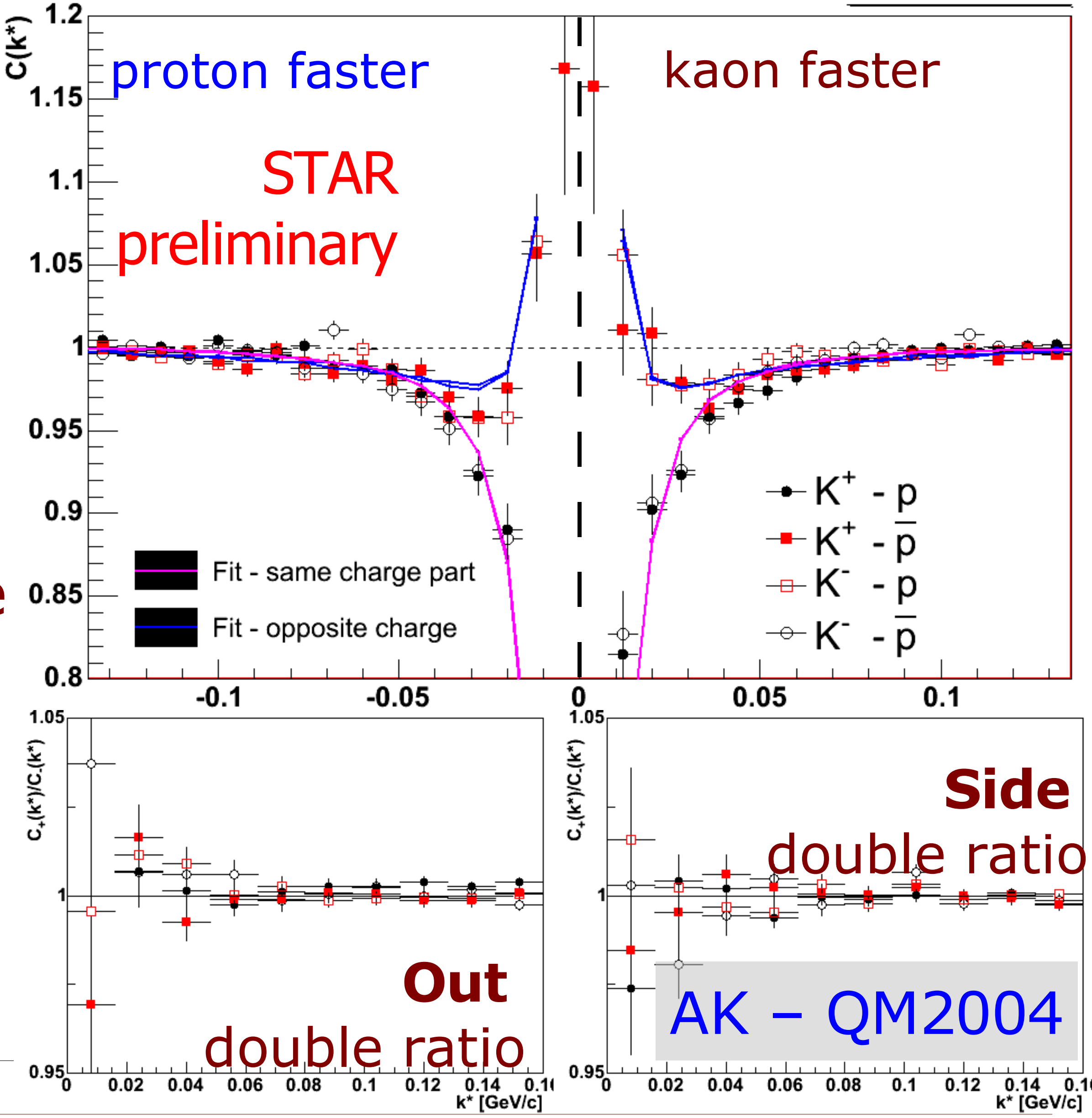
Mean: $\mathbf{-6.0 \pm 1.5}^{+3.0\text{ syst.}}_{-5.5\text{ syst.}}$ fm

Kaon-Proton at 200 AGeV

- Good agreement between functions for like and unlike sign, even though there is a significant strong interaction
- Time difference has opposite sign than space asymmetry, producing a negligible shift

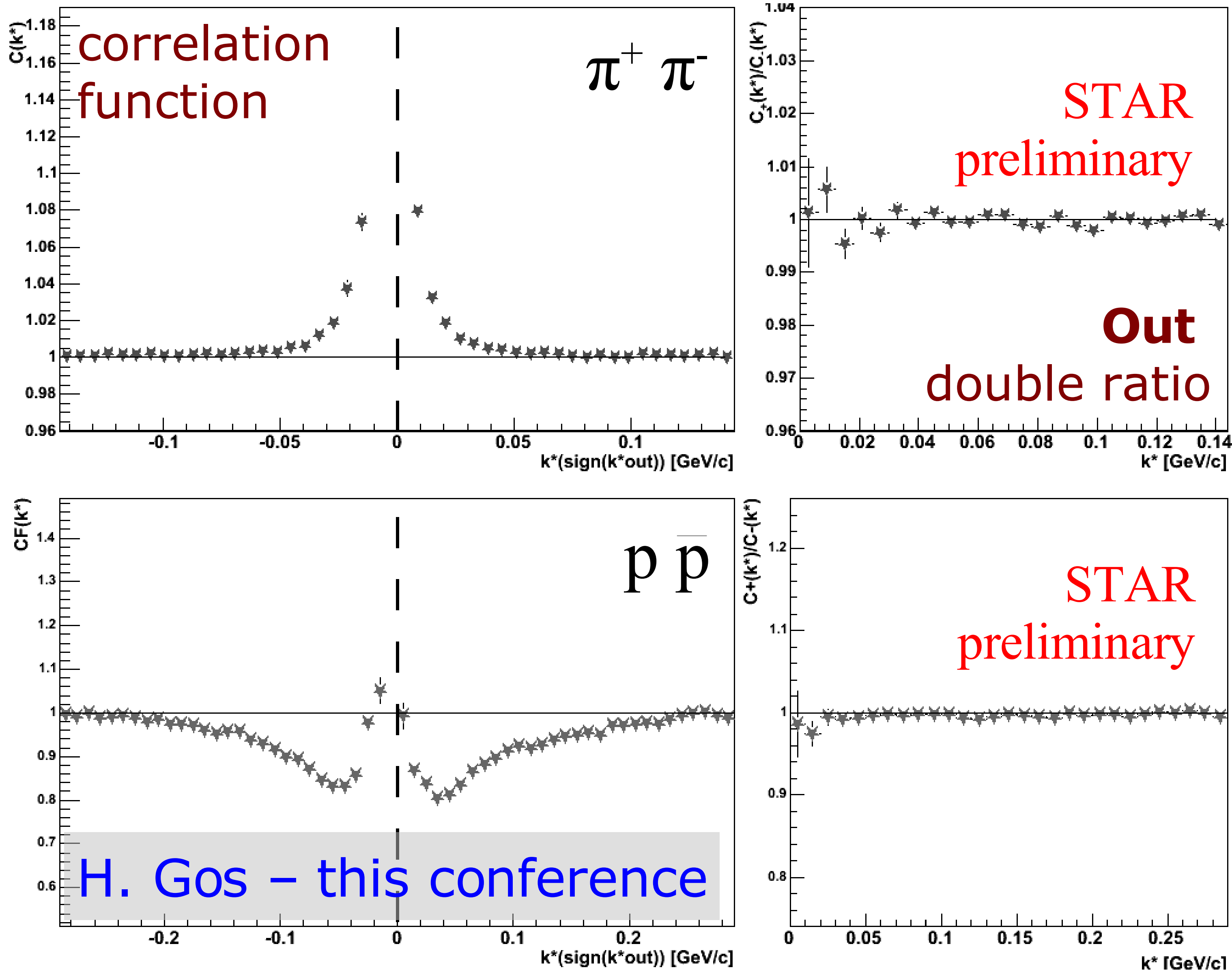
Sigma: **9.8** ± **0.4** $^{+1.6\ \text{syst.}}_{-0.6\ \text{syst.}}$ fm

Mean: **1.0** ± **0.9** $^{+0.6\ \text{syst.}}_{-1.2\ \text{syst.}}$ fm



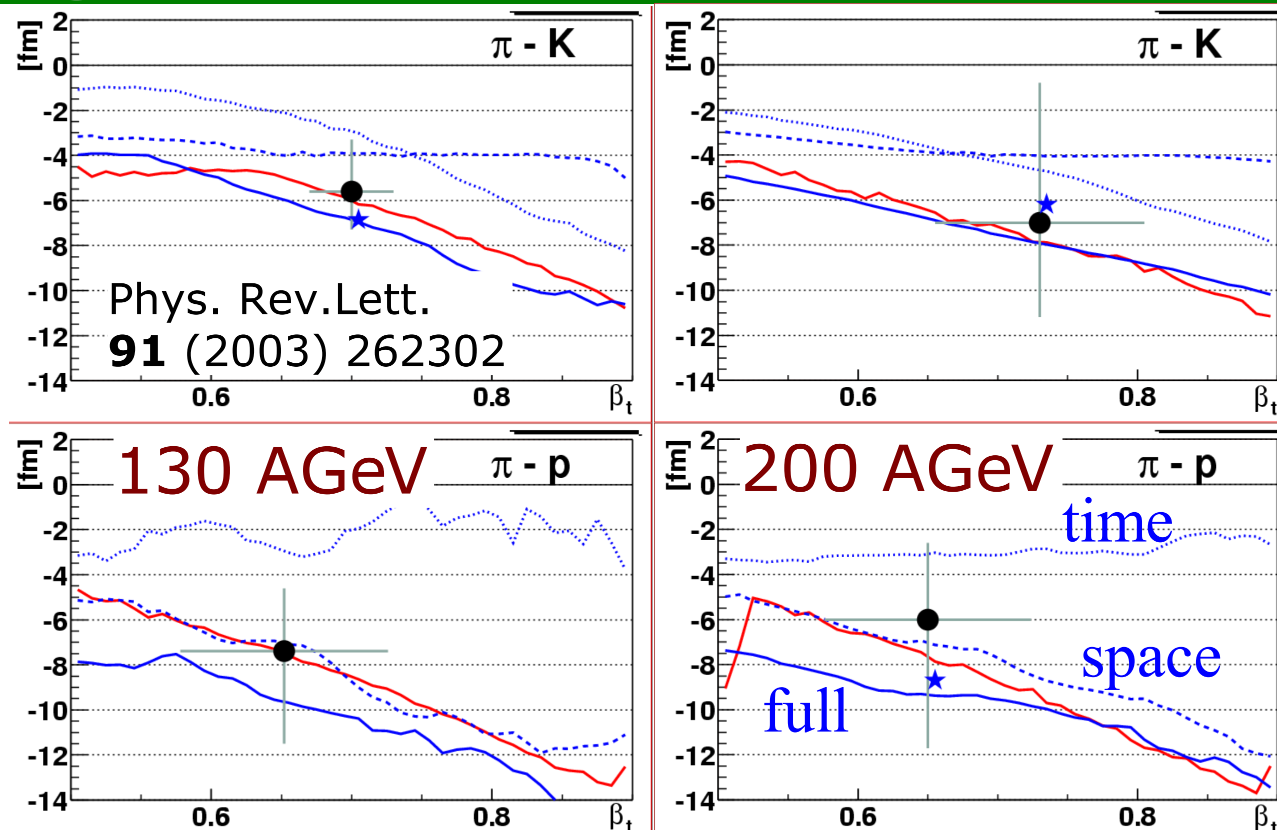
Particle-antiparticle double ratios

- Same mass particle-antiparticle correlations show no asymmetry, both for pions (Coulomb dominated) and protons (strong dominated)
- Also consistent with flow



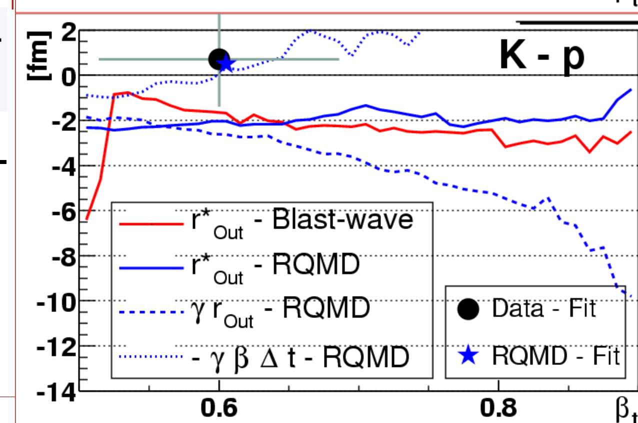
Comparing models to data

- We do see space-momentum correlations:
  - Data and blast-wave consistent
  - RQMD needs flow to reproduce data
- Time difference can explain small asymmetry for K-p
- Fair comparison: same fitting for RQMD and data



Blast-wave: nucl-th/0312024
F. Retiere, M. Lisa

	130 AGeV	200 AGeV
Temperature	104 MeV	100 MeV
Flow intensity	0.9	1.0 .
System radius	12.9 fm	13.0 fm
Evolution time	8.9 fm/c	10.0 fm/c
Emission duration	0.002 fm/c	3.5 fm/c



Summary

- Non-identical particle correlations exploit FSI dependance on source size and asymmetries to probe the space-time characteristics of the source
- They provide a qualitatively new piece of information - the shifts in average emission points/times
- All data analyzed so far support the picture of strong radial flow in relativistic heavy-ion collisions – a first observation of "x-p" correlations, complementing the "size-p" correlations measured by HBT
- Time differences play an important role and their realistic estimation is neccessary