How to measure HBT?

PHENIX Focus Seminar

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- **Bose-Einstein correlations**
  - The HBT effect
  - Its use for us
- **Measuring correlations**
  - Method of measurement
  - Problems and solutions
- **Cuts, corrections**
- **Results**

A new look at the stars

- Intensity interferometry in radio astronomy
- Angular diameter of a main sequence star measured

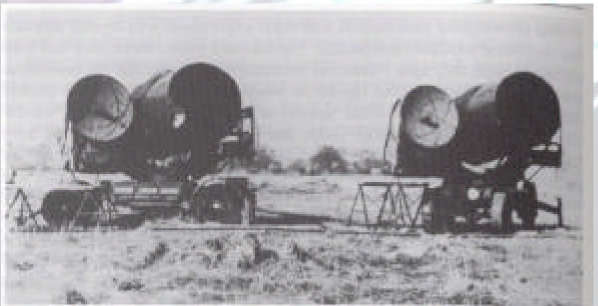
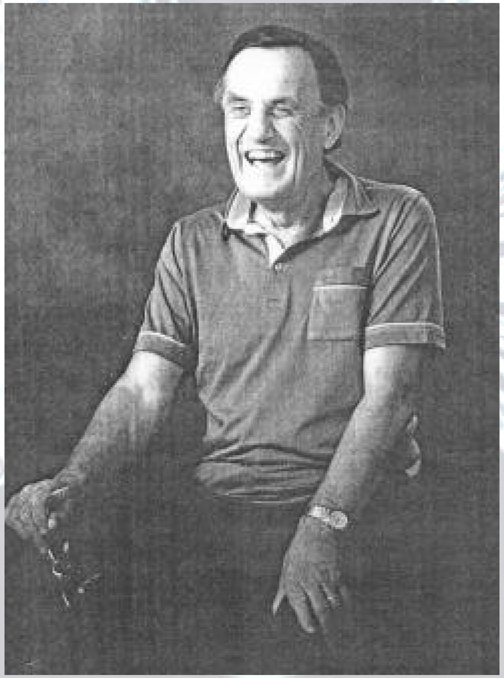
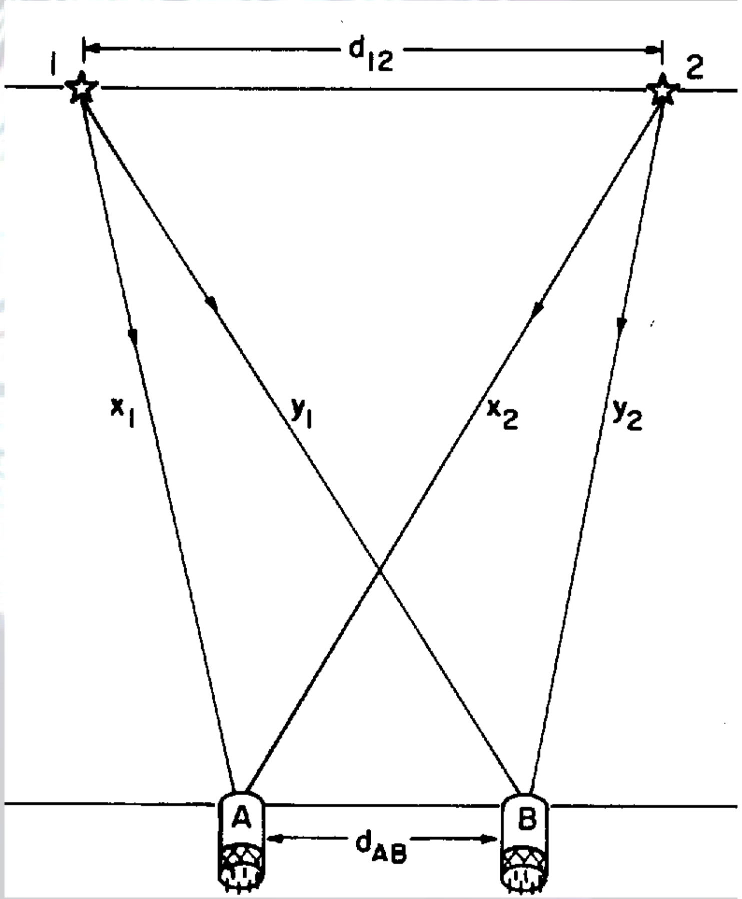


Figure 10.1 The first stellar intensity interferometer; the pilot model of the stellar intensity interferometer at Jodrell Bank in 1955. Two Army searchlights were used to make the first measurement of the angular diameter of a main sequence star (Sirius).



R. H. Brown



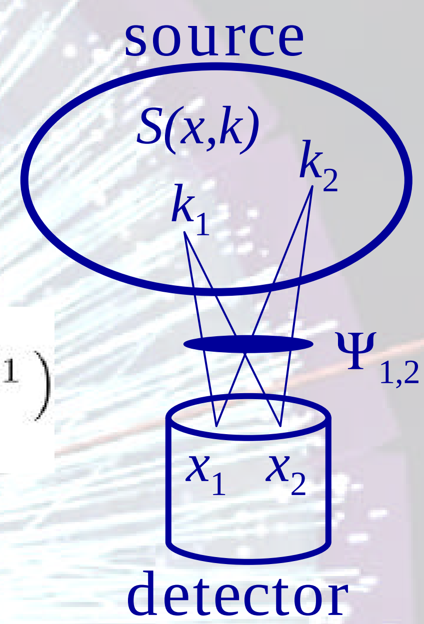
Hanbury Brown and Twiss

- **Engineers, worked in radio astronomy**
- **In fact two people: Robert Hanbury Brown and Richard Q. Twiss**
  - **Robert, Hanbury and Richard: all given names…**
- **„Interference between two different photons can never occur.”**
  P. A. M. Dirac, The Principles of Quantum Mechanics, Oxford, 1930
- **„In fact to a surprising number of people the idea that the arrival of photons at two separated detectors can ever be correlated was not only heretical but patently absurd, and they told us so in no uncertain terms, in person, by letter, in print, and by publishing the results of laboratory experiments, which claimed to show that we were wrong …”**
- **“I was a long way from being able to calculate, whether it would be sensitive enough to measure a star. To do that one has to be familiar with photons and as an engineer my education in physics had stopped far short of the quantum theory. Perhaps just as well, otherwise like most physicists I would have come to the conclusion that the thing would not work – ignorance is sometimes a bliss in science”**

Bose-Einstein correlations

- **Two plane-waves:** $$\Psi_1 = \mathrm{e}^{-ik_1x_1}$$ $$\Psi_2 = \mathrm{e}^{-ik_2x_2}$$
- **Bosons: need for symmetrization**

$$\Psi_{1,2} = \frac{1}{\sqrt{2}}(\mathrm{e}^{-ik_1x_1}\mathrm{e}^{-ik_2x_2} + \mathrm{e}^{-ik_1x_2}\mathrm{e}^{-ik_2x_1})$$



- **Spectrum:** $$N_1(k_1) = \int S(x_1,k_1)|\Psi_1|^2 \mathrm{d}x_1$$

  S(x,k) is the source distribution

- **Two-particle spectrum (momentum-distribution):**

$$N_2(k_1,k_2) = \int S(x_1,k_1)S(x_2,k_2)|\Psi_{1,2}|^2 \mathrm{d}x_1 \mathrm{d}x_2$$

Approximations: Plane-wave, no multiparticle symmetrization, thermalization …

How can we use this?

- **Now the invariant correlation function**
  - Depends on relative and average momenta

$$C_2(k_1,k_2)=\frac{N_2(k_1,k_2)}{N_1(k_1)N_1(k_2)}\simeq 1+\left|\frac{\tilde{S}(q,K)}{\tilde{S}(0,K)}\right|^2$$

$$q=k_1-k_2, K=0.5(k_1+k_2)$$

- **Uses Fourier-transformed of the source**

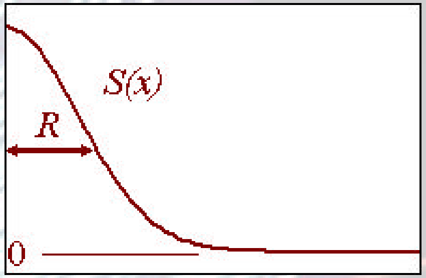
$$\tilde{S}(q,K)=\int \mathrm{d}x S(x,k)\mathrm{e}^{iqx}$$

- **We can figure out something about the source!**
  - In fact, for long times, this was the ONLY tool for mapping the source-function, and it is still unique today
- **Note: let us drop the average momentum dependence**

Again, what brings us all this?

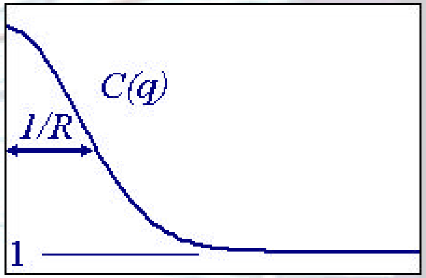
- **If the source is approximated with Gaussian:**

$$S(x) \sim \exp\left(-\frac{r_x^2}{2R_x^2} - \frac{r_y^2}{2R_y^2} - \frac{r_z^2}{2R_z^2}\right)$$



- **Then the correlation function is also Gaussian:**

$$C(q) - 1 \sim \exp\left(-q_x^2 R_x^2 - q_y^2 R_y^2 - q_z^2 R_z^2\right)$$



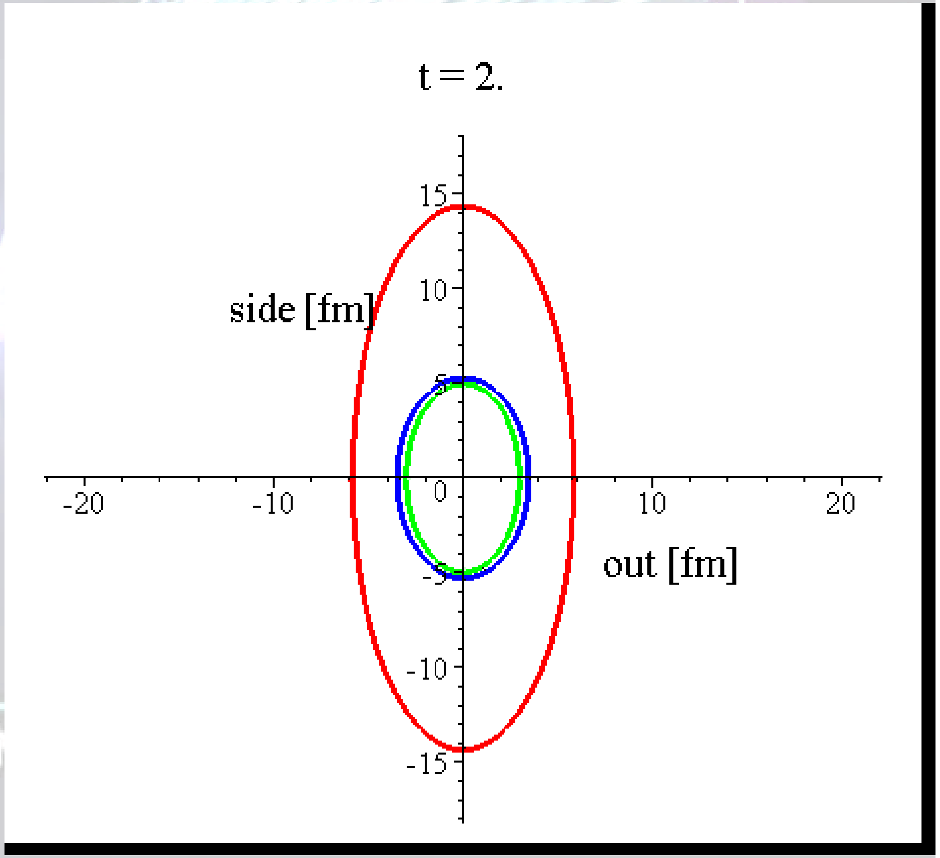
- **These radii are the so-called HBT radii**
  - If transformed to the out-side-long system (not invariant)
    - Out: direction of the mean transverse momentum of the pair
    - Side: orthogonal to out
    - Long: beam direction

$$C(q) = 1 + \lambda \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2\right)$$

- **Not necessarily reflecting the geometrical size**
  - Take a hydro model of an expanding ellipsoid…

Physics motivation

- **Predictions for R_{out}/R_{side}:**
  - S. Pratt: For strong first order phase transition R_{out}»R_{side}
  - Gyulassy: Prediction for RHIC: R_{out}»R_{side}, sign for QGP
  - Hydro, parton cascade: $R_{out} \approx R_{side}$
- **Exact hydro result:**
  - Thermal and geometrical radii determine correlation radii



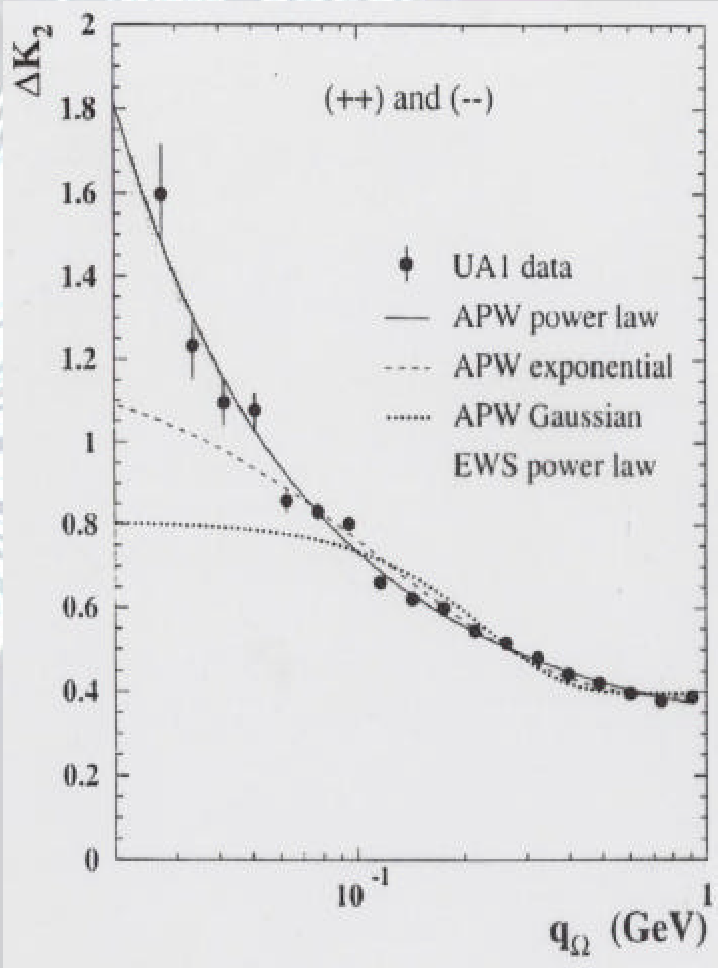
Correlation radii

Geometrical radii

Thermal radii

Non-gaussian distributions

- **Of course, the source does NOT have to be Gaussian**
  - Non-Gaussian tails
  - Low-*q* bins
- **One can check, if the correlation function is really Gaussian or not**
- **The Gaussian assumption can potentially cause results to be meaningless**



How does all this look in practice?

- **First, let us go into the q_{inv} space** $q_{inv} = |k_1 - k_2|^2$
- **Calculate the actual and background distributions**
  - Actual pair: both particles are from the ***same event***
  - Background pair: particles from can be from ***mixed events***
  - Distribution: how many pairs did we have in that q_{inv} specific bin

$$A(q_{inv}) = \sum_{\text{actual pairs}} \delta_{\Delta q}\left(q_{inv} - q_{inv}(k_1, k_2)\right)$$

$$B(q_{inv}) = \sum_{\text{mixed pairs}} \delta_{\Delta q}\left(q_{inv} - q_{inv}(k_1, k_2)\right)$$

- **Then, the correlation function will be:**

$$C(q_{inv}) = \frac{A(q_{inv})}{B_{\text{normalized}}(q_{inv})}$$

- **Still, one has to be careful**
  - Loop over every pair? What kind of events can be mixed?

Problems and solutions

- **Background pair mixing**
  - Loop over every pair: LSF will throw you out…
    - Take only e.g. as much background pairs, as actuals
  - Make a buffer with a few events for every
    - Centrality
    - Vertex position
- **Actual pairs**
  - Cut duplicated (ghost) tracks
    - Separation in EMC: dr_{EMC}
    - Separation in DCH: $d\phi$ and dz
  - Need more than one particle per event…
    - Statistics needed
    - Published result: charged pions, PPG021

Problems and solutions

- **Cut on spatial separation: information may be lost**
  - Correction via Monte Carlo simulation
- **There is a correlation due to Coulomb-interaction**
  - Two-body Coulomb-problems is solved, so:

$$K = \frac{\int |\Psi^C_{1,2}(x_1, x_2)|^2 S(x_1) S(x_2) \mathrm{d}x_1 \mathrm{d}x_2}{\int |\Psi^0_{1,2}(x_1, x_2)|^2 S(x_1) S(x_2) \mathrm{d}x_1 \mathrm{d}x_2}$$

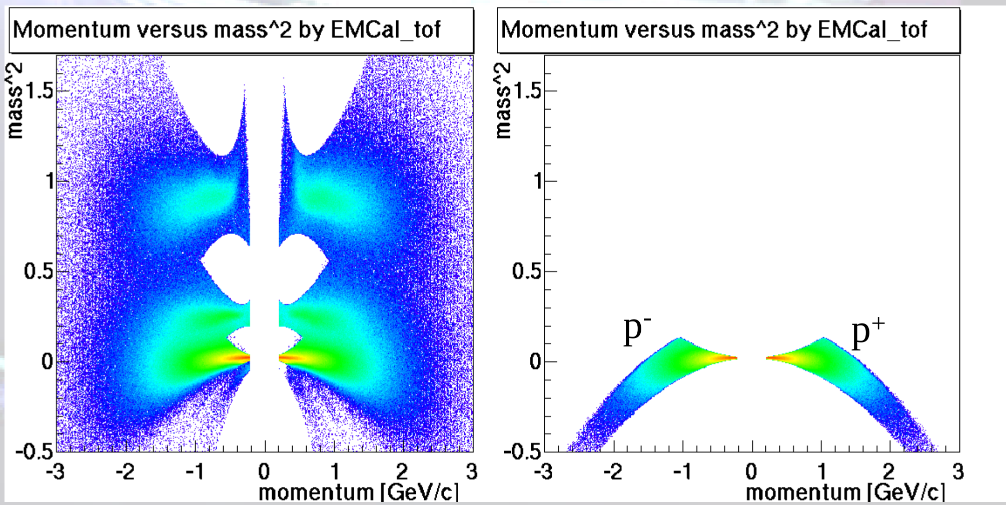
- **What if the source is not Gaussian?**
  - Just fit with a more general function, eg. Levy
  - There are other methods, but time limitations also…

Goals of the analysis

- **To establish a correlation function for identical particles**
  - Positive and negative pions, separately
- **Project it into the one dimensional q_{inv} space**
- **Look at its shape in the out, side and longitudinal directions also**
- **Make the necessary corrections**
- **Determine HBT radii**
- **Published result: PPG021**

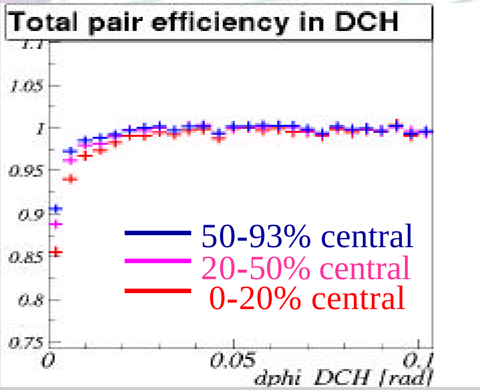
Let us start: PID

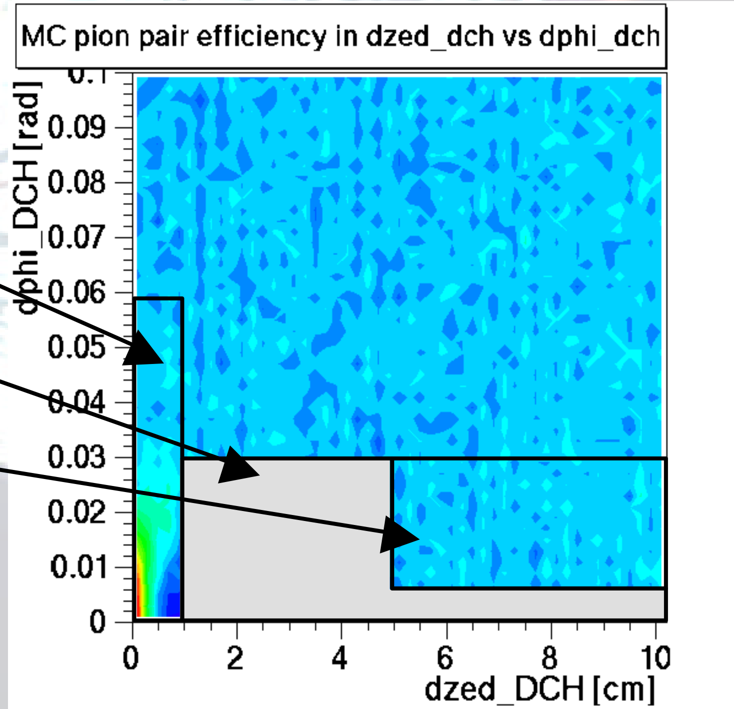
- **Track selection: the usual stuff**
  - z_{vertex} < 30 cm.
  - p_t : 0.2 to 2.0 GeV / c
  - DCH quality: 63 or 31.
  - West EMC: 0-2 sectors
  - EMC time of flight < 60 ns
  - Matching cut at west EMC < 2*s*
- **Particle ID:**
  - Is pion within 1.5*s*
  - Is not kaon by 2.5*s*
- **51M p^+ and 58M p^-**



Pair cuts, efficiency correction

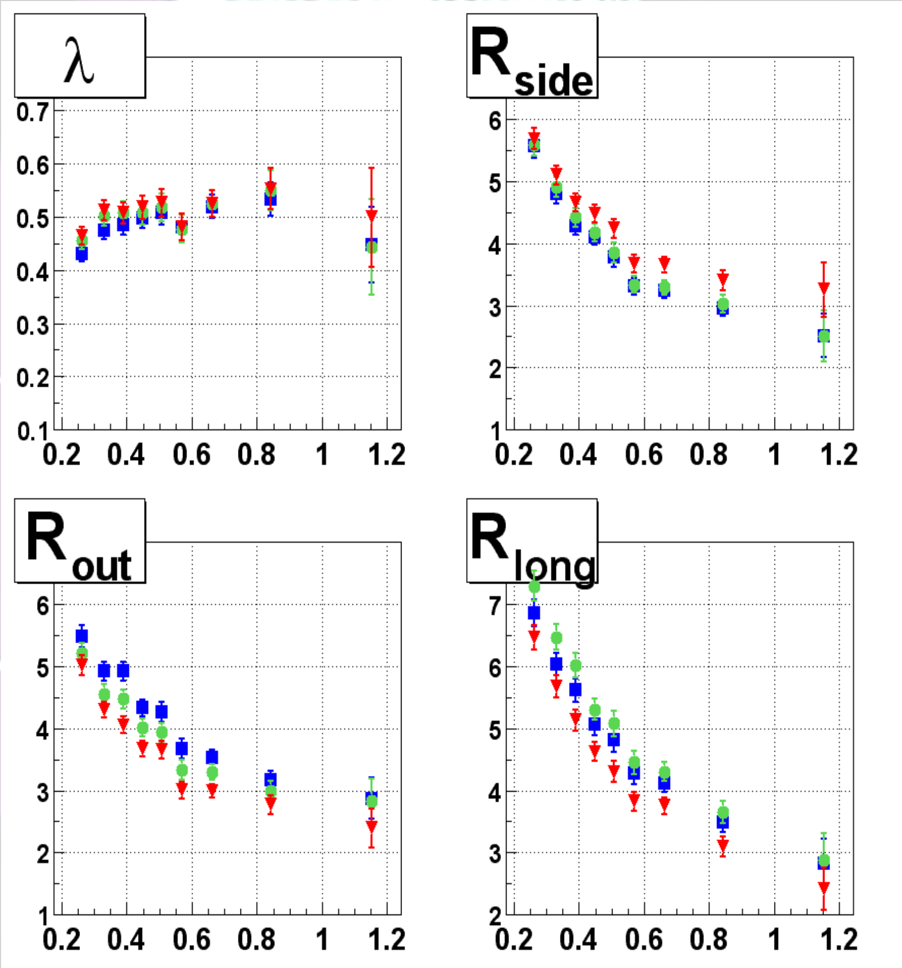
- **Pair cut needed to sort ghost tracks out**
- **A cut on track separation in *dz*, *d*f and *dr***
- **Remove 'bad' regions with efficiency map**
  - Un-ghosting cut
    - *dz*<1cm and *d*φ<0.06
  - Significant inefficiency cut
    - (*dz*<5cm and *d*φ<0.03) or *d*φ<0.005
  - Other regions: correct on inefficiency



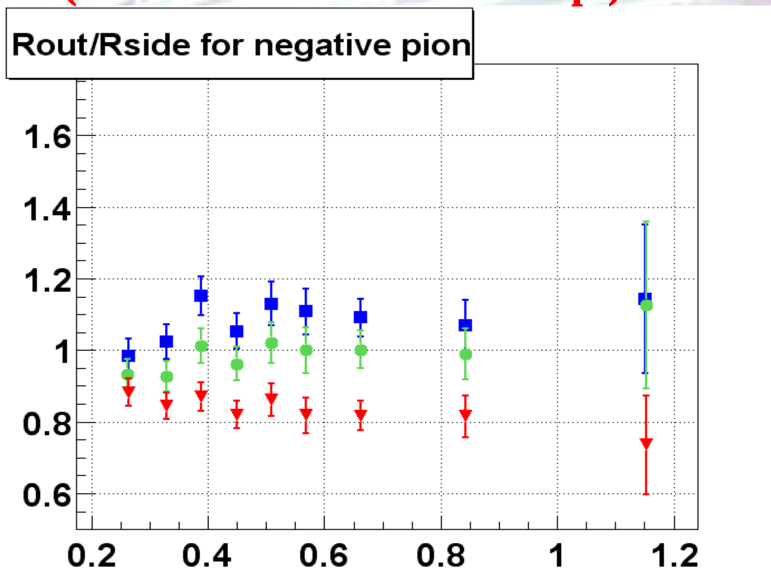


Effect of pair cuts and corrections

- **Have a look at how this all changes the results**



- ■ **Results with an old (not accurate) pair correction for the 1st manuscript**
- ● **Results with the new (more accurate) pair correction**
- ▼ **Results with the new (more accurate) pair correction + dφ>0.005 (Results in the 2nd manuscript)**

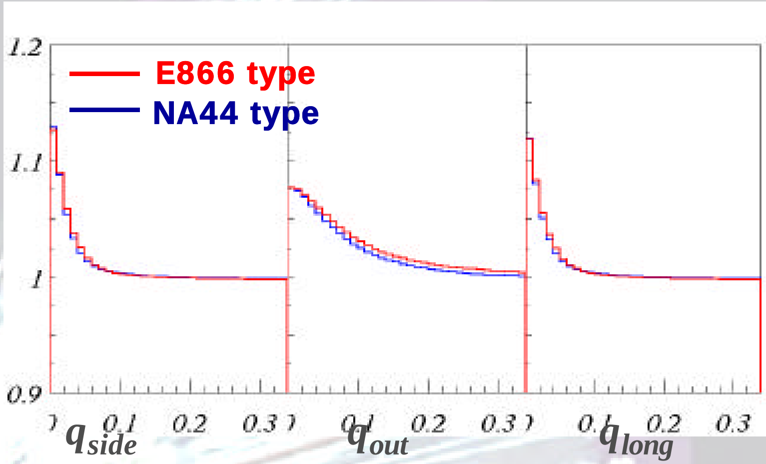


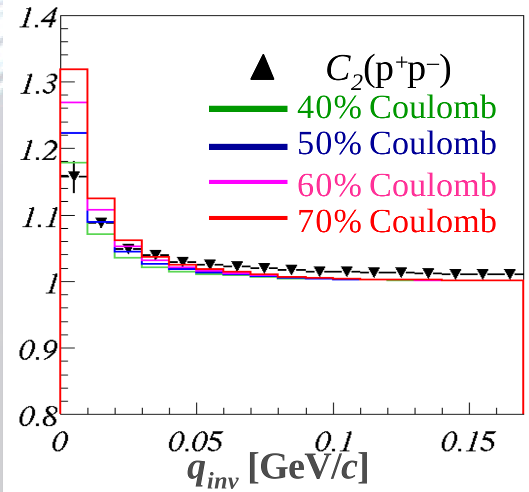
Coulomb-correction

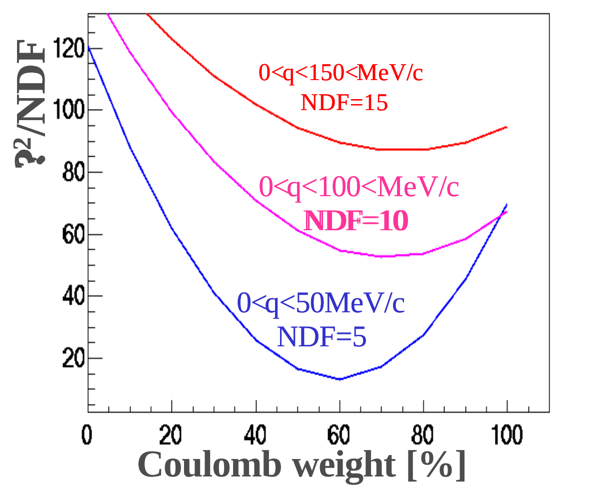
- **Now comes the Coulomb-correction ☹ (10 PPG talks)**
- **Repulsive Coulomb-interaction makes peak smaller**
- **Unlike-sign charged particles**
  - no Bose-Einstein correlation
  - Attractive Coulomb-interaction
  - Other effects? Non-Coulomb-interacting regions?
- **Let's take only a fraction of the Coulomb-correction**
- **Reasonable method: Core-halo picture**
  - Core: hot, dense, hydrodynamically evolving: interact
  - Halo: decay products of long lived resonances: no interaction

Variations

- **E866 method and NA44 method**
- **Both assume a 3D Gaussian source**
- **They are consistent**
- ***C_2* of unlike-signed particles**
- **What fraction of Coulomb-correction describes it the best?**
- **Check c^2**

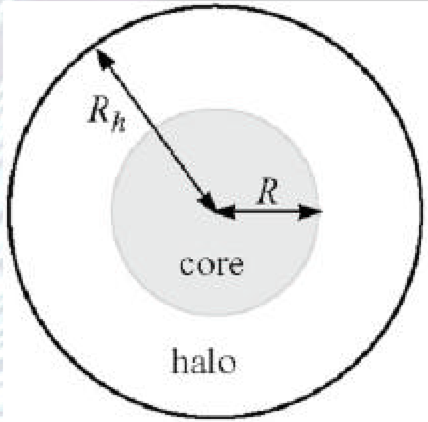






Core-halo picture

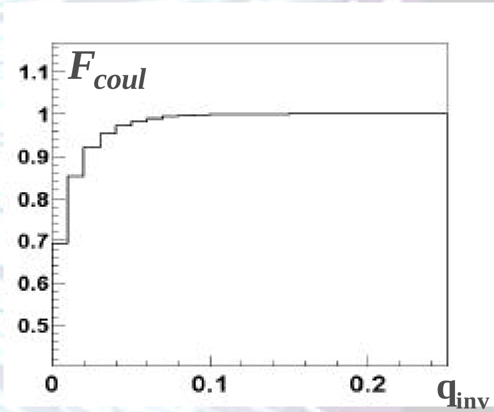
- **Particles in the core Coulomb-interact**
- **Rare halo, no Coulomb interaction**



- **Coulomb-correction is to be done only for the core part**
- **Sinyukov's fitting method:**

$$C_2^{\text{raw}} = C_2^{\text{core}} + C_2^{\text{halo}} = \lambda'(1+G)F + (1-\lambda')$$

$$F = \omega(F_{\text{Coul}} - 1) + 1$$



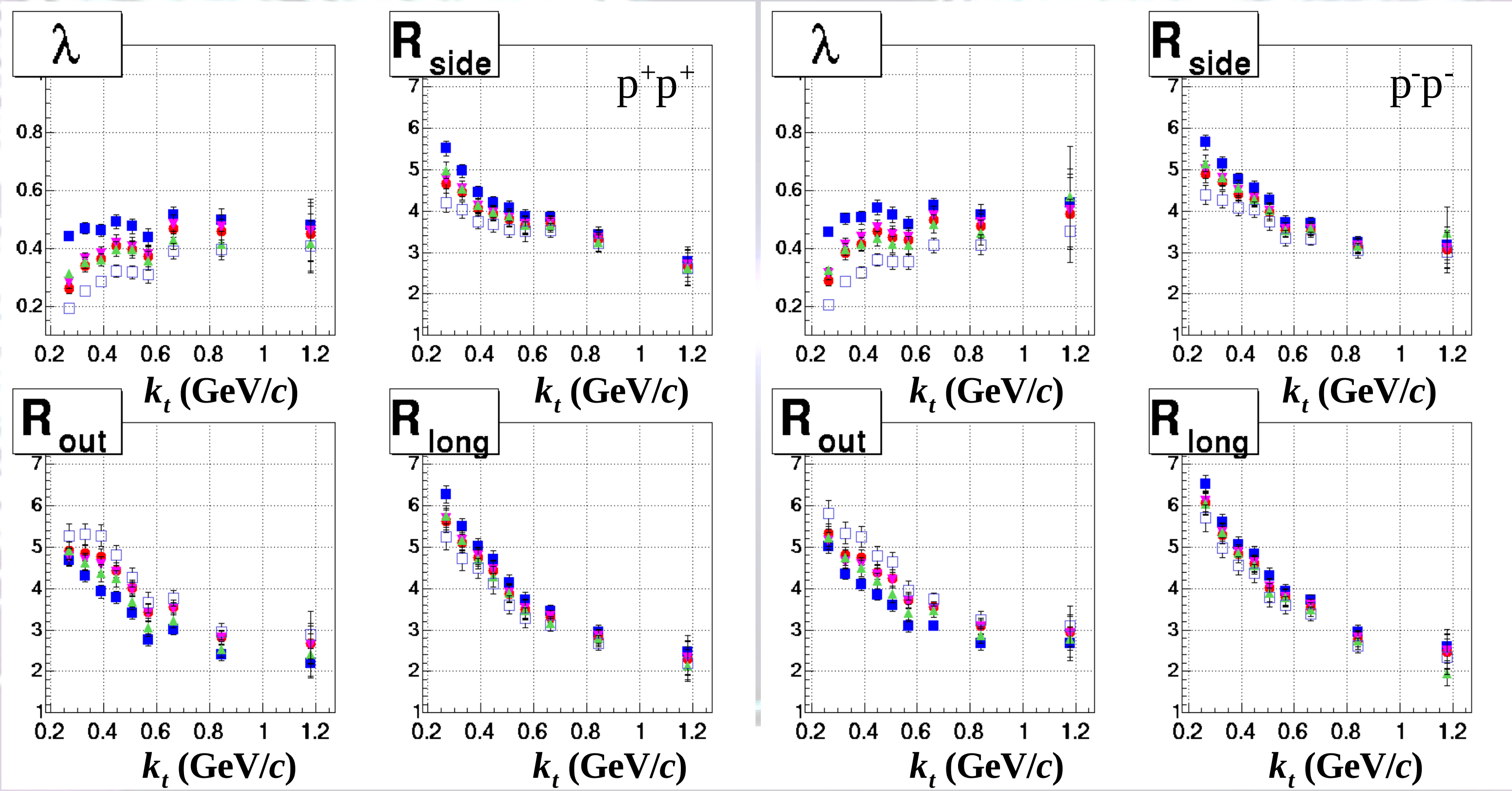
- w=l/l' **accounts for smearing due to finite momentum resolution**
  - This can be calculated via MC simulations…
- **There are more advanced techniques…**

Result of Coulomb-correction

- **Let us look at how the results vary**

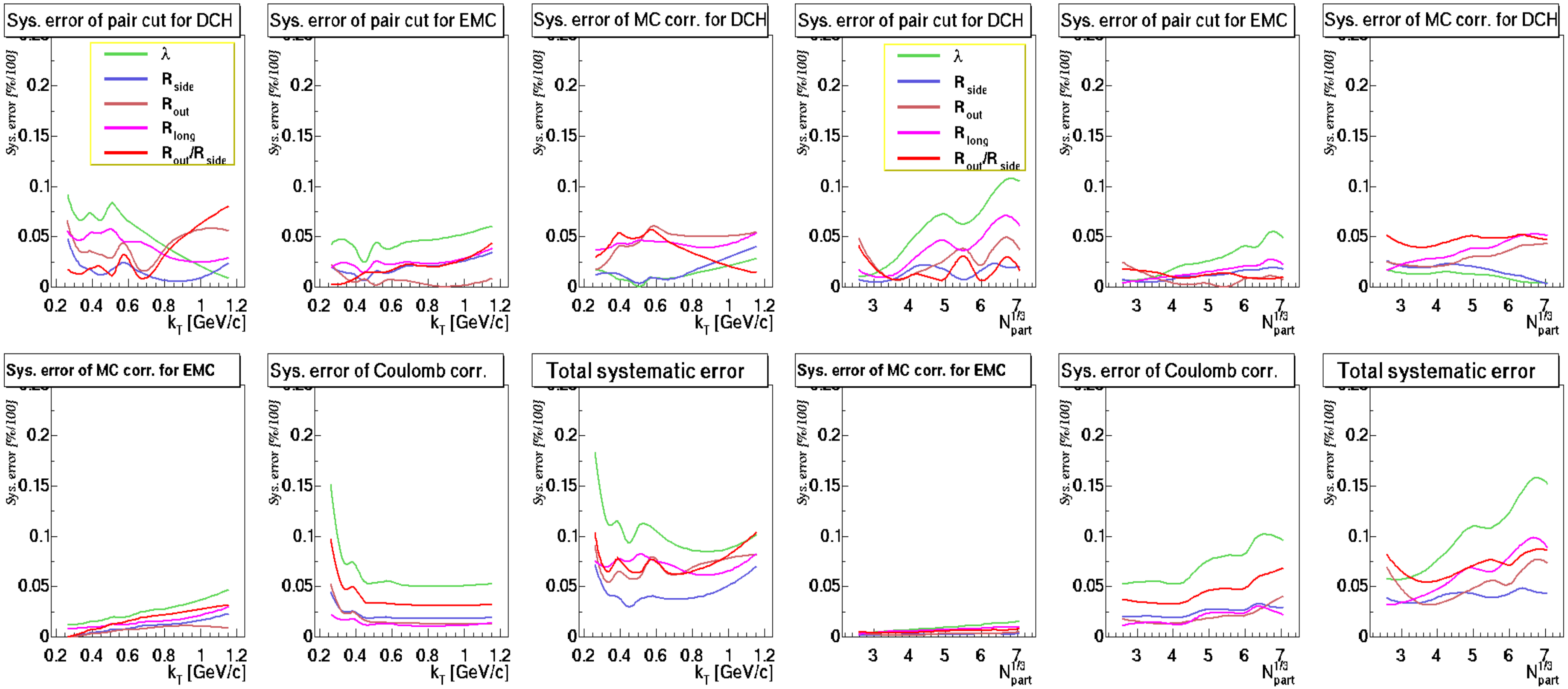
■ Full Coulomb　□ No Coulomb　● Sinyukov's fit: w=1

▲ 50% Coulomb　▼ Sinyukov's fit: w from MC



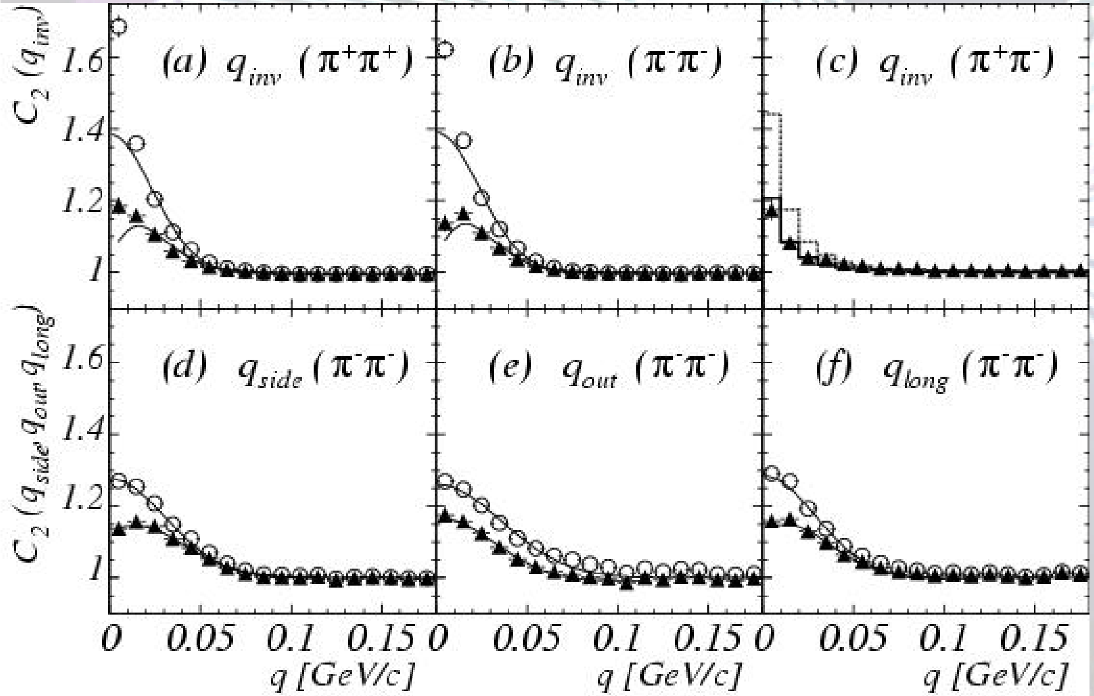
Systematic errors

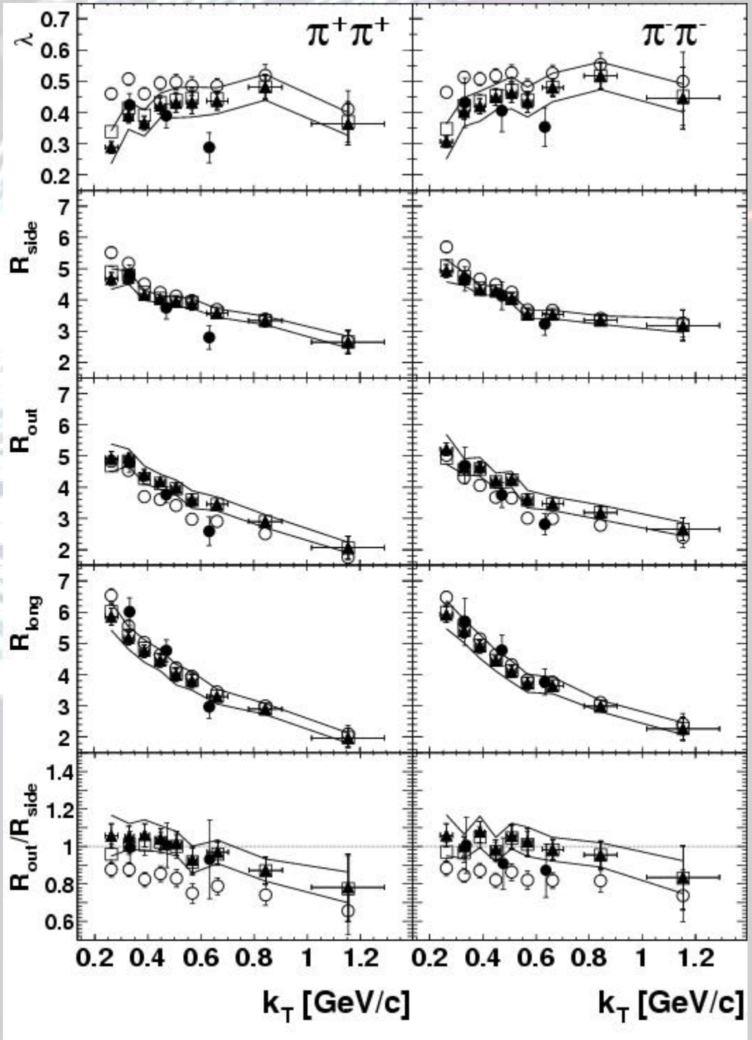
- **Pair cuts, efficiency corrections, Coulomb corrections**
- **Depending on centrality and k_t**



Published PHENIX results

- **Correlation function versus q_{inv}, q_{out}, q_{side}, q_{long}**
- **HBT radii versus centrality …**
- **… and versus k_t**





Summary

- **Measure background and actual pair distributions**
  - 1D or 3D: q_{inv} or q_{out}, q_{side} and q_{long}
- **Make pair cuts**
  - Elimination of ghost tracks
  - Correct on efficiency via simulations
- **Make Coulomb corrections**
  - Core-halo picture
  - Partial correction
- **Determine errors and ready!**

Interesting new directions

- **Azimuthally sensitive HBT (STAR, PHENIX)**
- **Source imaging (PHENIX)**
- **Multiparticle correlations (STAR, PHENIX)**
- **Non-identical correlations (STAR)**
- **Rapidity dependent HBT (PHOBOS)**
- **Photon HBT (STAR)**
- **Non-Gaussian features**

  S. Hegyi, T. Csörgo, W. A. Zajc, L3, STAR, ...
- **Pion lasers**

  S. Pratt, Q.H. Zhang, J. Zimányi, U. Heinz, Yu. Sinyukov...
- **Mass-modification, squeezing**

  M. Asakawa, T. Csörgo, M. Gyulassy, Y. Hama, S. Padula, ...
- **Search for axial UA(1) symmetry restoration using $l(p_t)$**

  S. Vance, T. Csörgo, D. Kharzeev