NATIONAL SCIENCE CENTRE POLAND

Studies of final state interactions via femtoscopy in ALICE

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Strangeness in Quark Matter 2016
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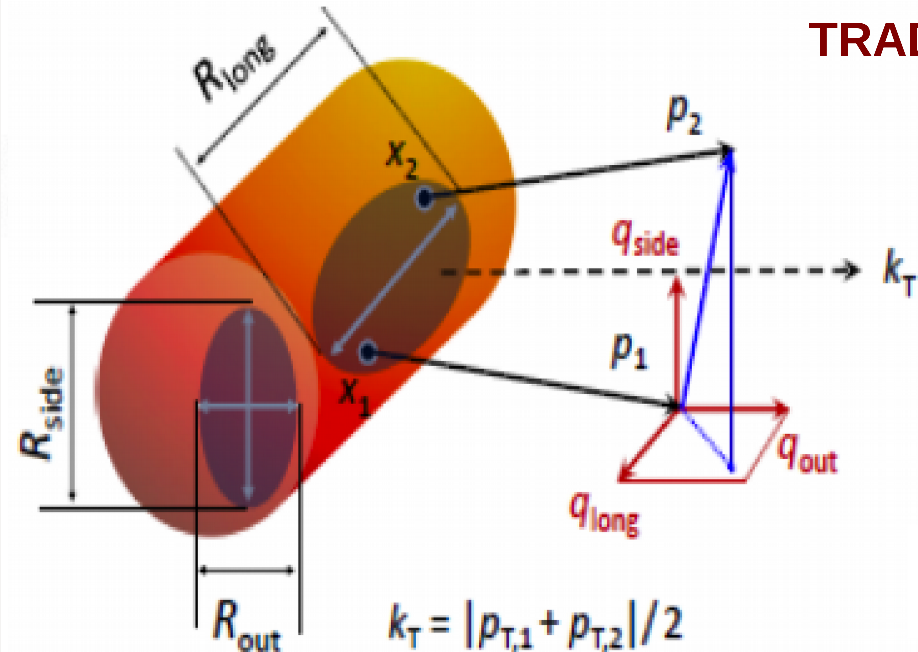
Femtoscopy – beyond the system size

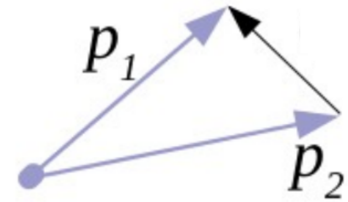
Correlations of baryons

$K^0_s K^\pm$ **correlations**

Femtoscopy technique



TRADITIONAL FORMALISM
Identical pions



$q = p_1 - p_2$

$q = 2 \cdot k^*$

The Koonin-Pratt formula
(S.E. Koonin, PLB70 (1977) 43; S.Pratt et al., PRC42 (1990) 2646)

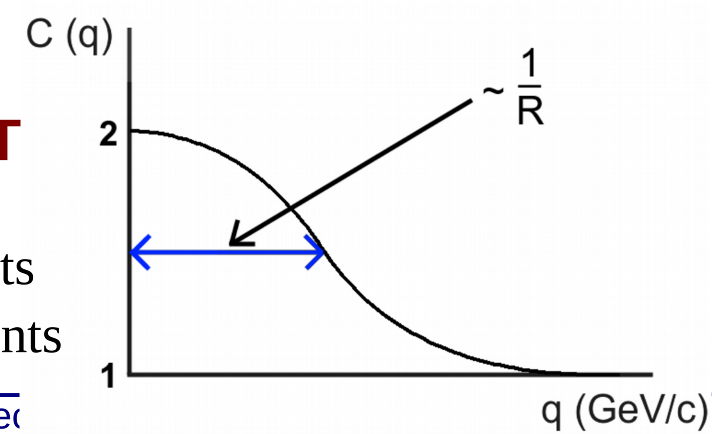
$$C(\vec{q}) = \int S(\vec{r}) |\Psi(\vec{q}, \vec{r})|^2 d^4 r$$

measured correlation — emission function (source size/shape) — cross-section

$$S(\vec{r}) \sim \exp\left(-\frac{r_{out}^2}{4R_o^2} - \frac{r_{side}^2}{4R_s^2} - \frac{r_{long}^2}{4R_l^2}\right)$$

$$|\Psi(\vec{q}, \vec{r})|^2 = 1 + \cos(\vec{q}\vec{r})$$

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



- The size (or sizes in 3D) *R* is referred to as the "**HBT radius**"

$A(\vec{q})$ – same events

$B(\vec{q})$ – mixed events

- In the experiment: $C(\vec{q}) = A(\vec{q}) / B(\vec{q})$

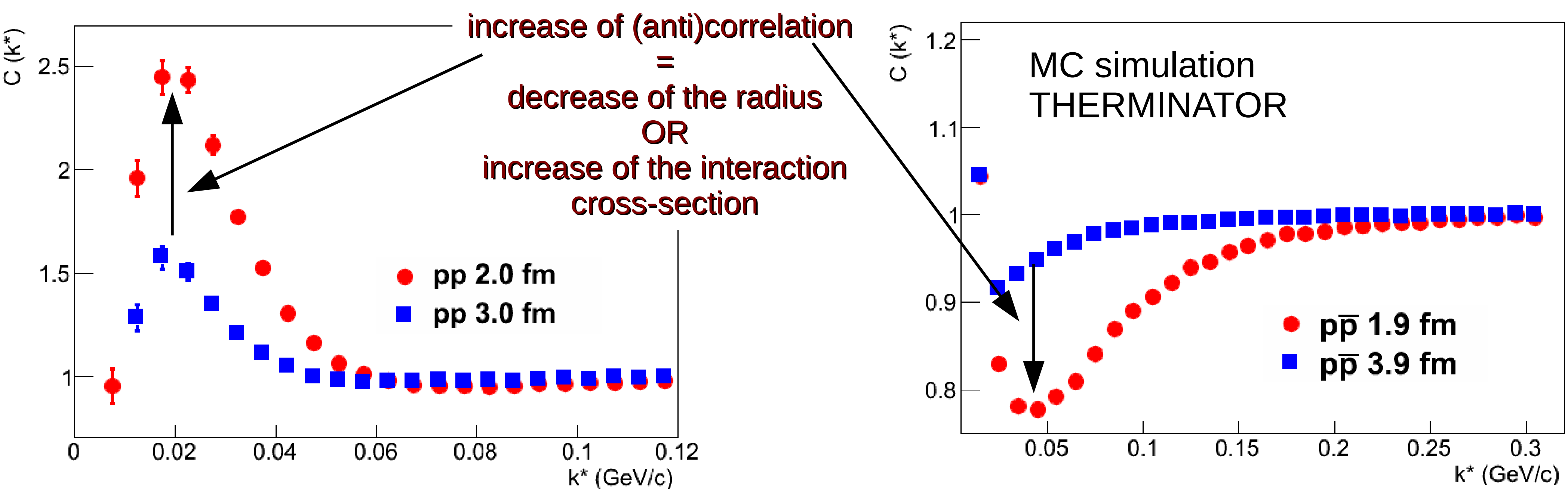
Going beyond the system size

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

measured correlation

emission function
(source size/shape)

cross-section



Correlation from Strong Interaction

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

measured correlation

emission function (source size/shape)

cross-section

$$\Psi = \exp(-i \vec{k}^* \vec{r}) + f \frac{\exp(ik^* r)}{r}$$ s-wave scattering approximation

$$f^{-1} = \frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^*$$ effective range approximation

- If only Strong Final State Interaction (FSI) the result of integration:

$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{R} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} R} \right) + \frac{2 \Re f^S(k^*)}{\sqrt{\pi} R} F_1(2k^* R) - \frac{\Im f^S(k^*)}{R} F_2(2k^* R) \right]$$

Lednicky, Lyuboshitz, Sov. J. Nucl. Phys., 35, 770 (1982)

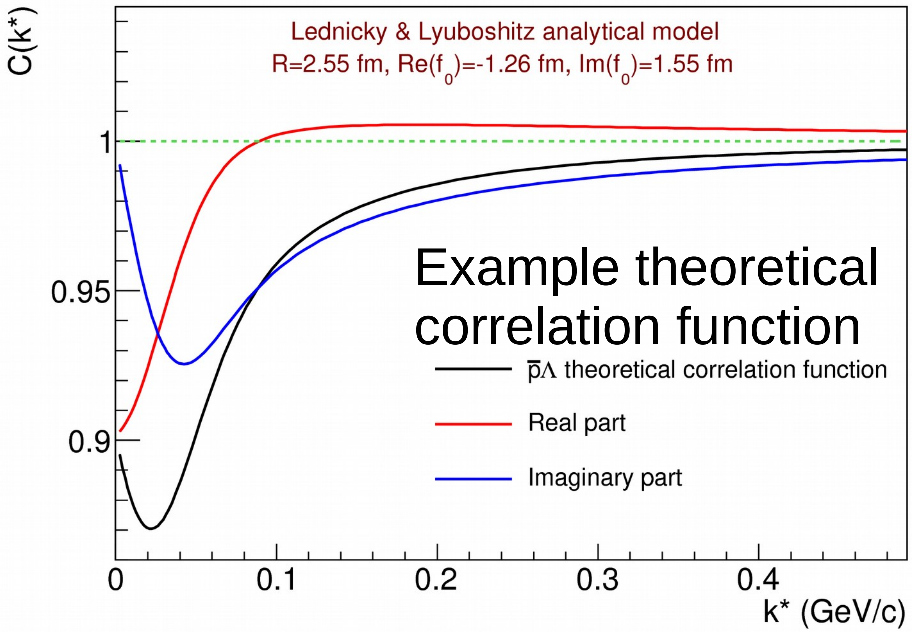
where ρ_S are the spin fractions

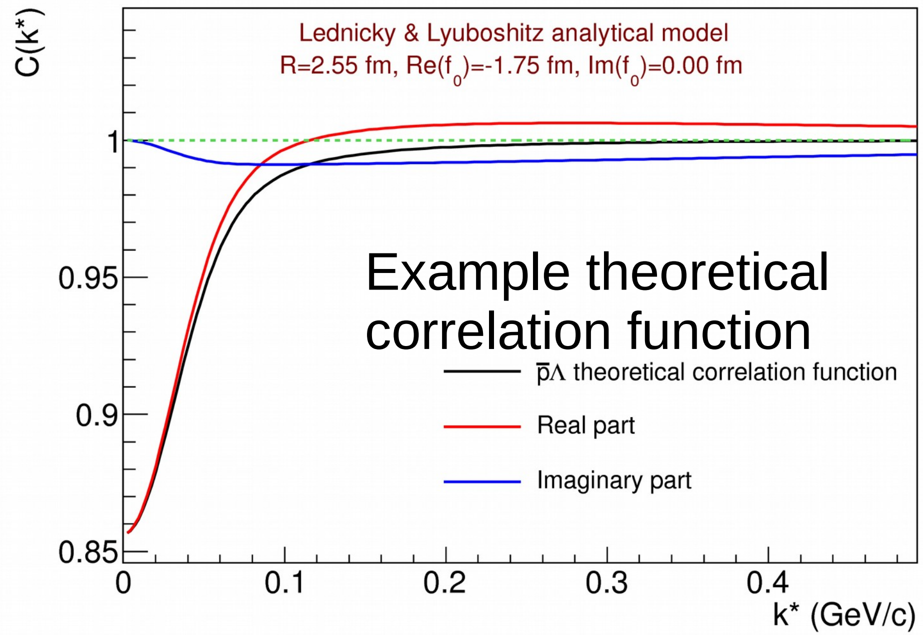
- The correlation function is finally characterized by **three parameters**:
  - **radius** R, **scattering length** f_0, and **effective radius** d_0
  - **Cross-section** σ (at low k^*) **is simply:** $\sigma = 4\pi |f|^2$

$$F_1(z) = \int_0^z x e^{x^2 - z^2} / z \, dz$$

$$F_2(z) = (1 - e^{-z}) / z$$

Correlation from Strong Interaction – $\bar{p}\Lambda$ example

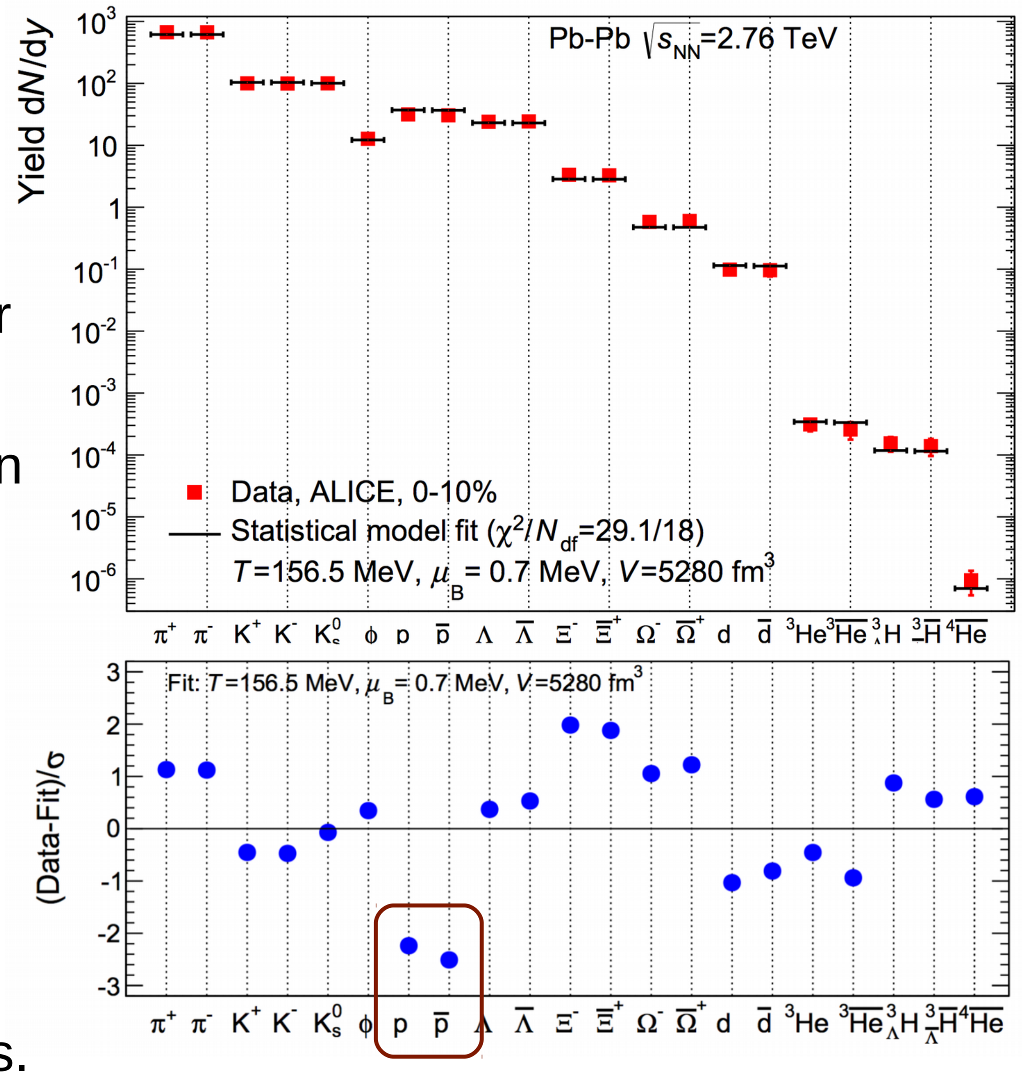




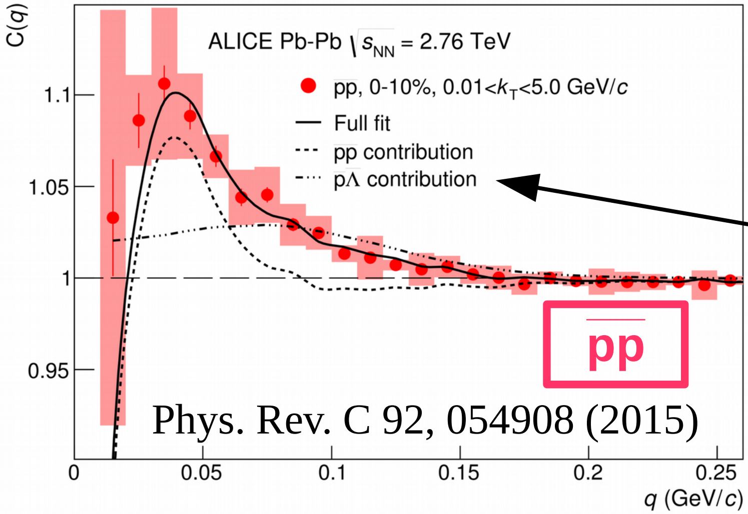
- Real and imaginary part of scattering length have **distinctively different contributions**
- Contribution from Re(f_0) is either positive or negative but **very narrow** (up to 100 MeV/c) in k^*
- The Im(f_0) accounts for baryon-antibaryon annihilation and produces a **wide** (hundreds of MeV) **negative correlation**

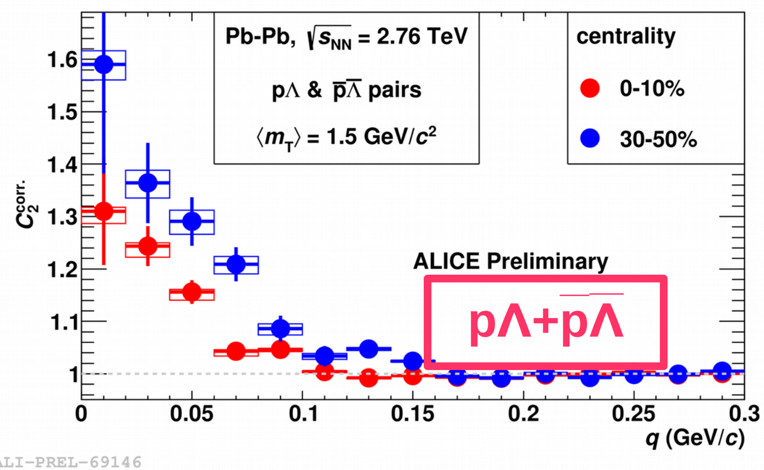
What are the potential applications?

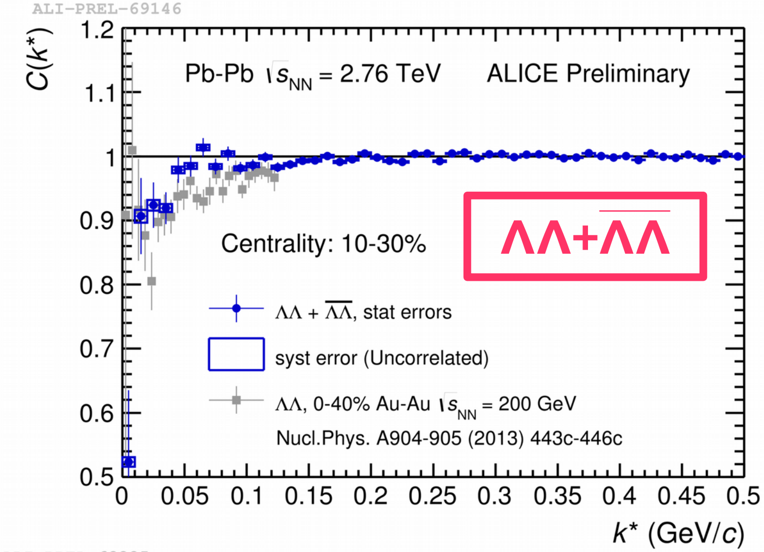
- Input to models with rescattering phase: UrQMD (PRC 89, 054916 (2014))
  - annihilation cross-sections only measured for $p\bar{p}$, $p\bar{n}$, and $p\bar{d}$ pairs – UrQMD currently **guesses** it for other systems from $p\bar{p}$ pairs
  - should help us to answer the question on deviations of baryon yields from thermal model expectations
- Structure of baryons/search for CPT violation (STAR, Nature 527, 345-348 (2015))
- Search for H-dibaryon (see next ALICE talk by Benjamin Dönigus – this session)
- Hypernuclear structure theory (Nucl.Phys. A914 (2013) 377-386)
- Neutron star equation of state (Nucl.Phys. A804 (2008) 309-321)



A. Andronic, SQM 2016
Wed, Plenary 11:00

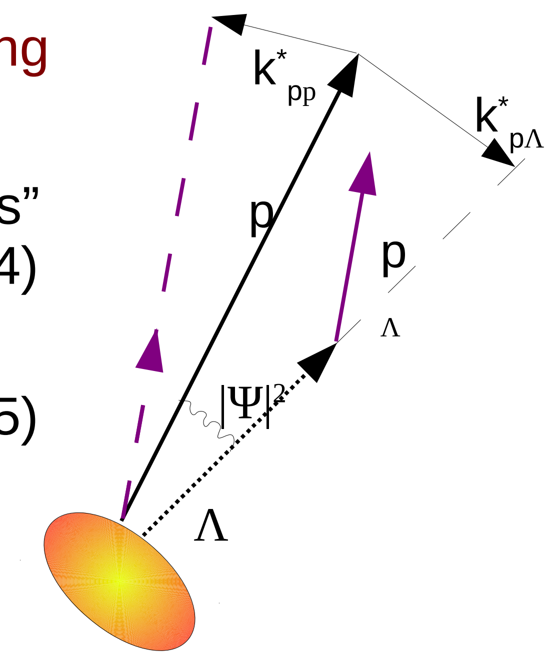




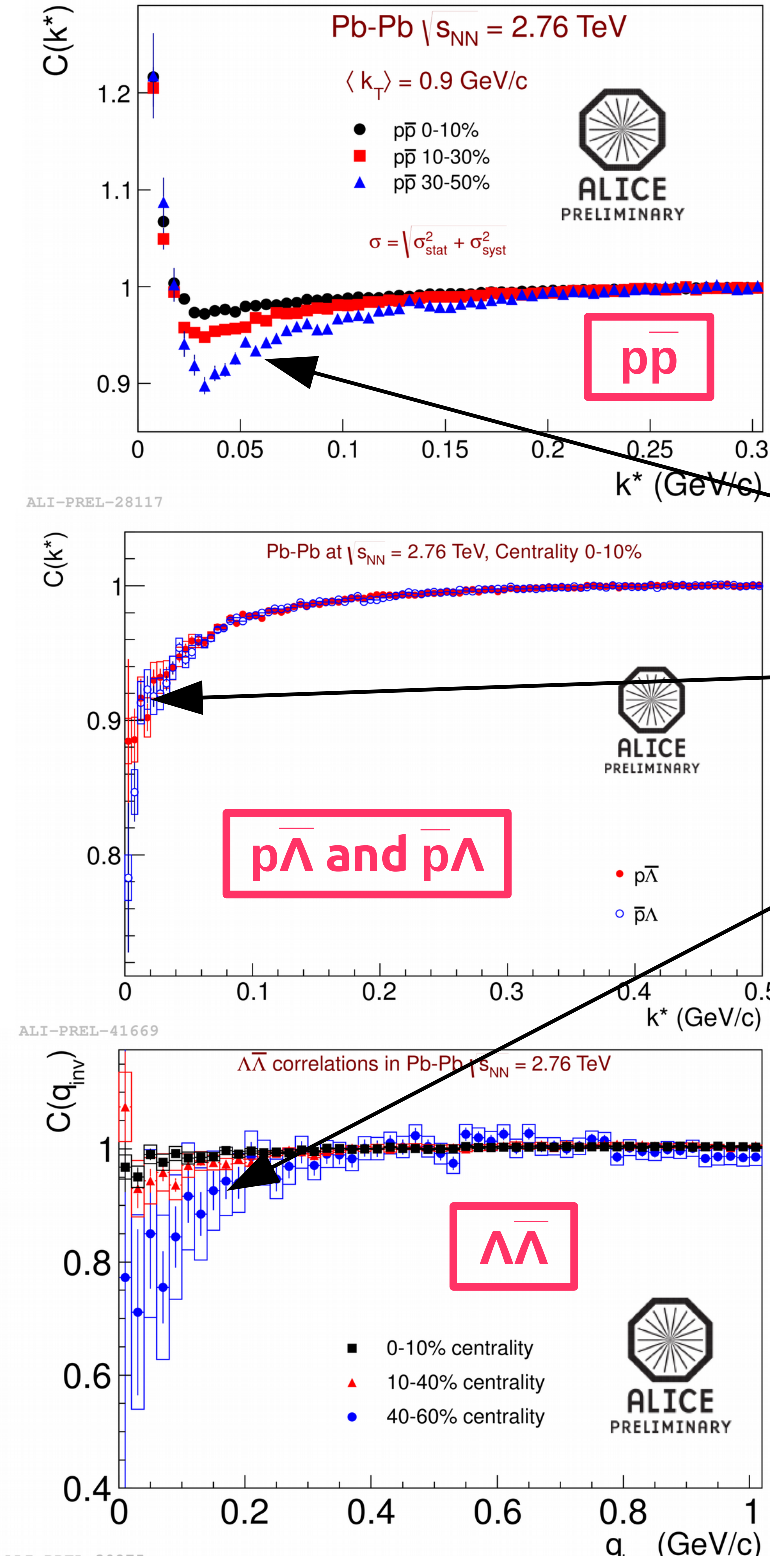


Baryon-baryon correlations

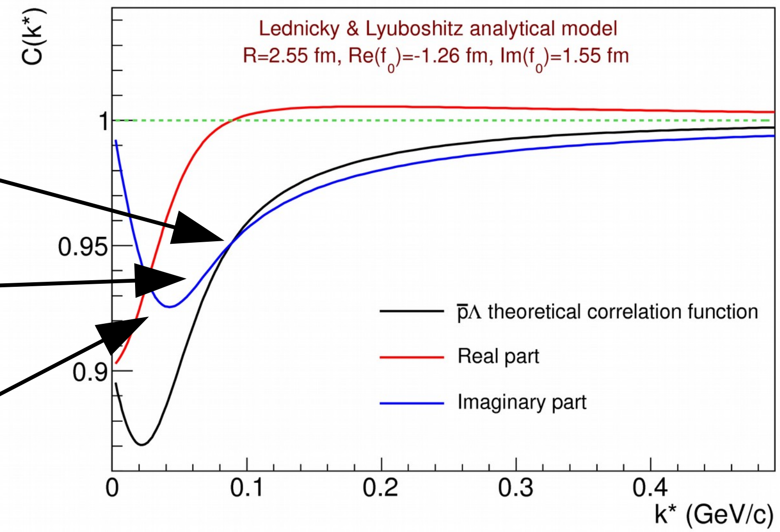
- Analysis of experimental data is complicated by the presence of **residual correlations**
- Weak decay baryons have momentum in similar direction as parent – decay momentum is small with respect to the baryon mass (e.g. Λ → p: 101 MeV/c)
- The femtoscopic correlation of the parent pair is smeared by the decay, but can still be significant
- Two approaches accounting for them:
  - "Transformed residuals" PRC 89, 054916 (2014)
  - "Gaussian residuals" PRC 92, 034910 (2015)



Baryon-antibaryon correlations



- All measured baryon-antibaryon pairs exhibit significant **wide anticorrelation** → as in the "Lednicky" formula



- **Conclusion:** cross-sections, including annihilation, should be measurable
- **Next steps**: fit all correlation functions (taking into account residual correlations) and extract f_0 and d_0 parameters

Femtoscopy – beyond the system size

Correlations of baryons

$K^0_s K^{\pm}$ **correlations**

Motivation for $K^0_sK^\pm$ analysis

- Identical kaon femtoscopy, similarly to pions, has been used to study space-time characteristics of the source
- ALICE has measured identical kaon systems in both pp and Pb-Pb (PLB 717 (2012) 151-161; PRD 87, 052016 (2013); PRC 92, 054908 (2015))
- Which sources of correlations are present in these systems?
  - Quantum Statistics (QS) – both $K^0_sK^0_s$ and $K^\pm K^\pm$
  - Coulomb FSI – $K^\pm K^\pm$
  - **Strong FSI –** $K^0_sK^0_s$ **(via** $f_0(980)/a_0(980)$ **resonances)**
- **Why are** $K^0_sK^\pm$ **pairs interesting?**
  - only Strong FSI:
    - $f_0(980)$ resonance is isospin = 0 → no $f_0(980)$ strong interaction
    - $a_0(980)$ **resonance is isospin = 1 as is the kaon pair → only** $a_0(980)$ **strong interaction present**

Motivation for $K^0_s K^\pm$ analysis

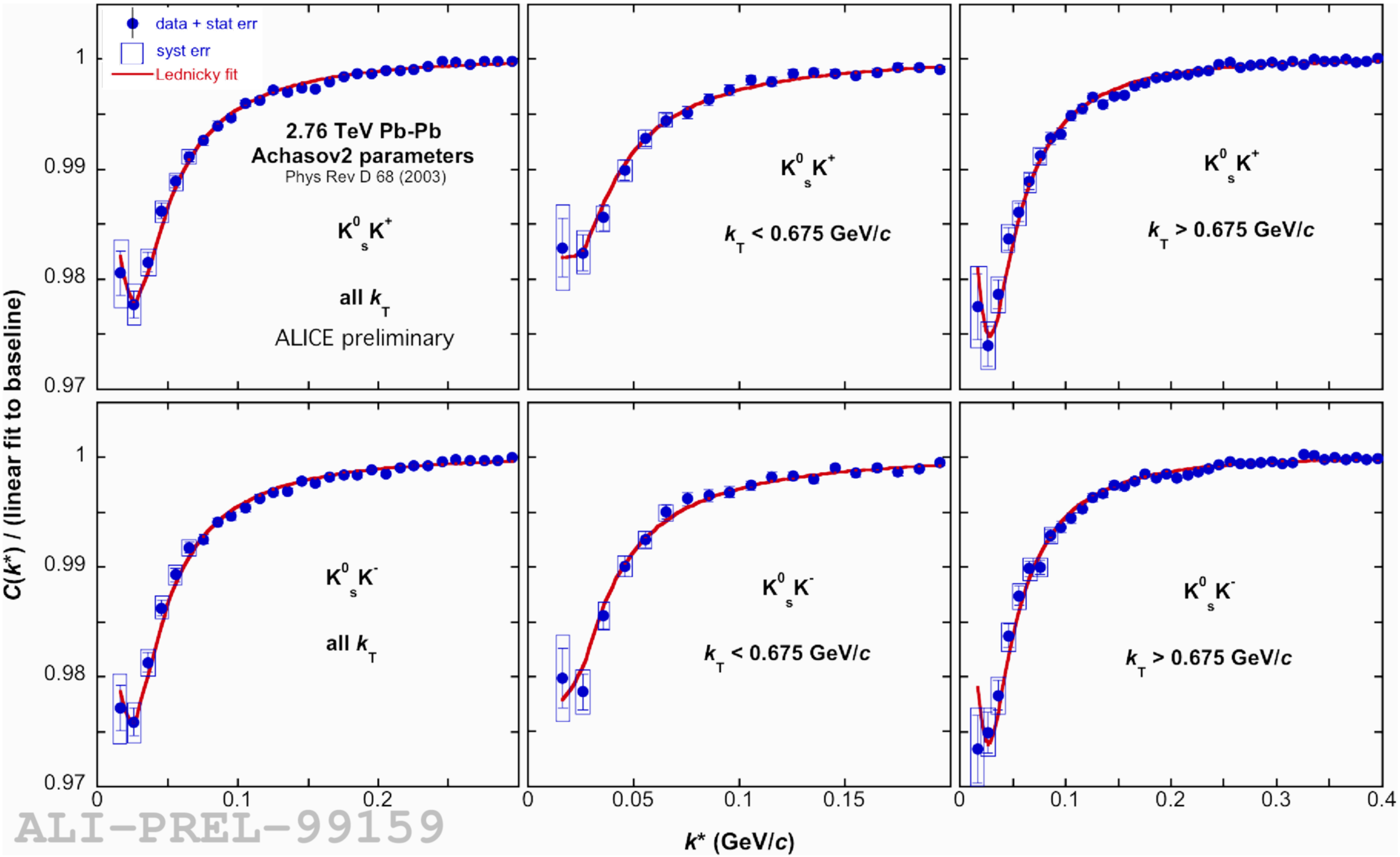
- Study the properties of the $a_0(980)$ resonance:
  - extract R using only the $a_0(980)$ decay strong interaction:
  - check published $a_0(980)$ decay coupling parameters and mass
  - the $a_0(980)$ is considered a candidate for a **tetraquark state** e.g. E. Santopinto and G. Galata, PRC 75, 045206 (2007)
- Correlation of mesons is described by a version of Lednicky analytic formula, where:

$$f(k^*) = \frac{\gamma_{a_0 \to K\bar{K}}}{m_{a_0}^2 - s - i\gamma_{a_0 \to K\bar{K}} k^* - i\gamma_{a_0 - \pi\eta} k_{\pi\eta}}$$

- $a_0(980)$ mass and coupling parameters (in GeV) extracted from model fits to Φ decay experiments:

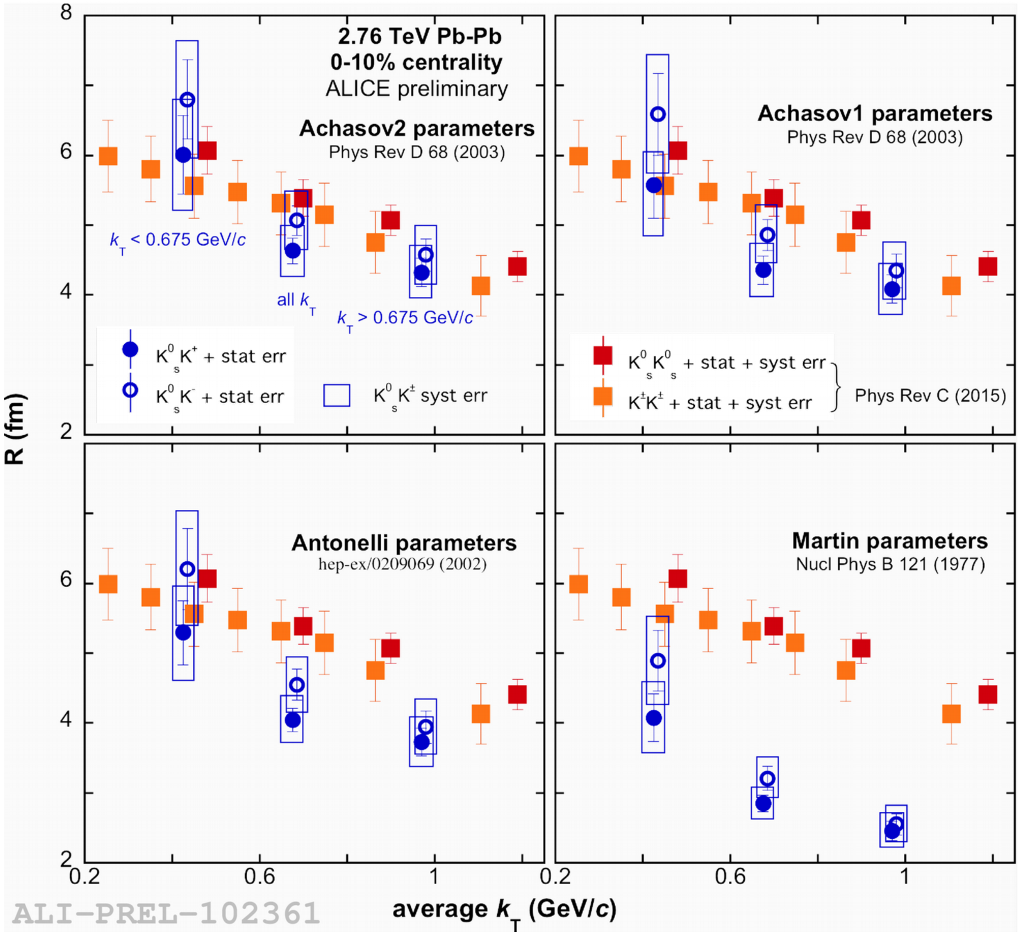
	m_{a0}	$\gamma_{a0 \to K\bar{K}}$	$\gamma_{a0 \to \pi\eta}$	Reference
“Martin”	0.974	0.3330	0.2220	Nucl. Phys. B 121, 514 (1977)
“Antonelli”	0.985	0.4038	0.3711	arXiv: hep/ex-0209069 (2002)
“Achasov1”	0.992	0.5555	0.4401	Phys. Rev. D 68, 014006 (2003)
“Achasov2”	1.003	0.8365	0.4580	Phys. Rev. D 68, 014006 (2003)

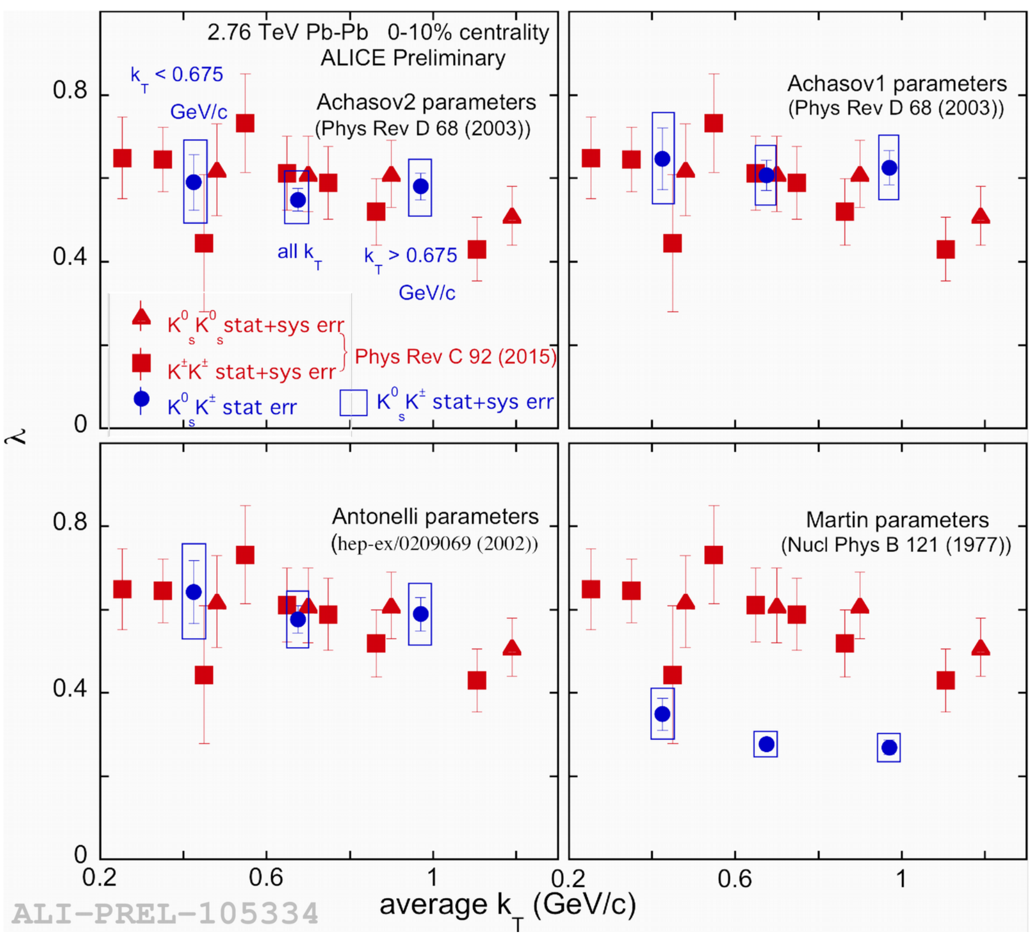
Measured correlation functions $C_{raw}(k^*)$/(linear fit)



- The $a_0(980)$ final state interaction gives **excellent** fits to data!

Results of the fits





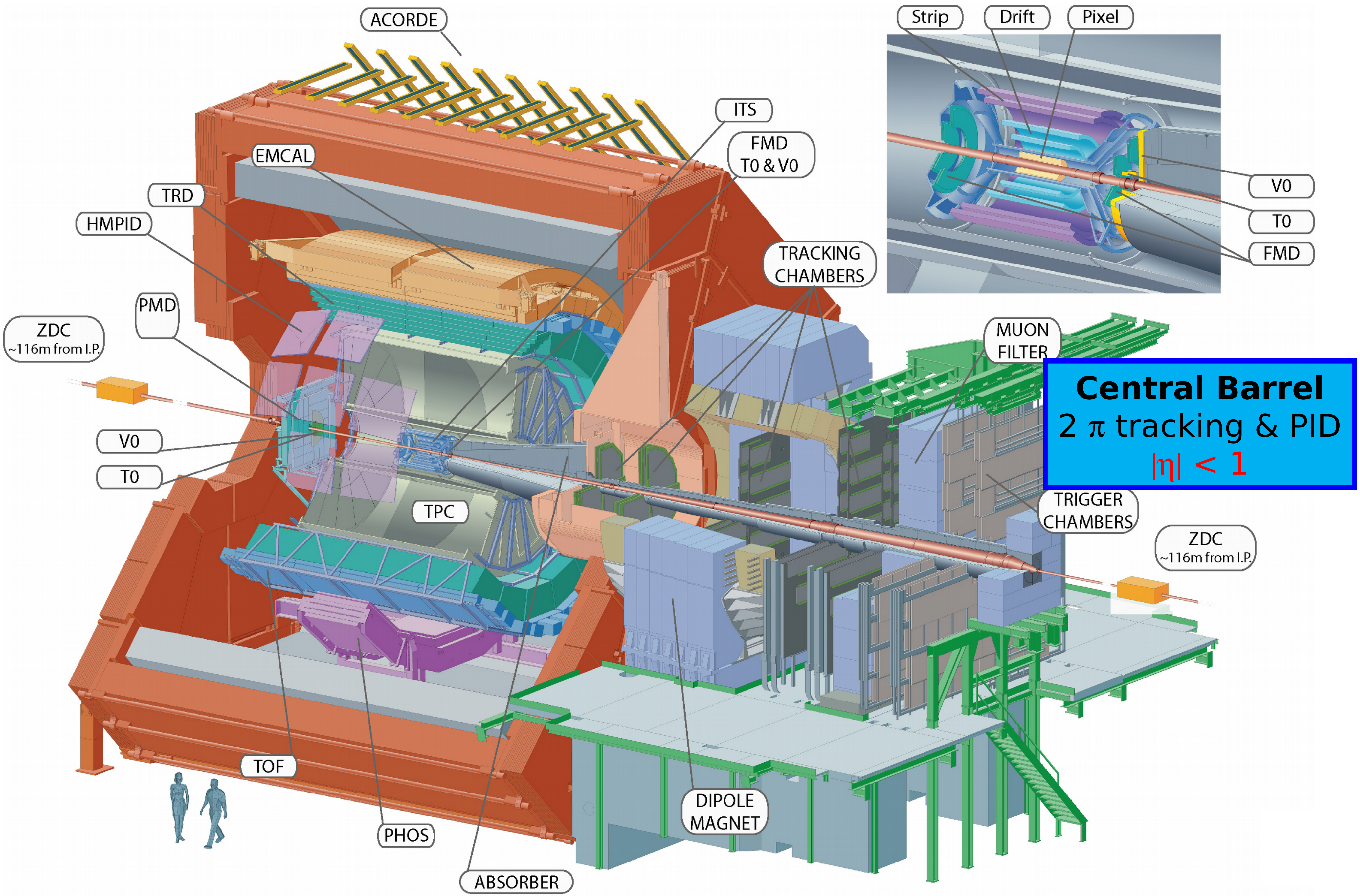
- "Achasov" parameter fits give best agreements with $K^0_sK^0_s$ and $K^\pm K^\pm$ results
- "Antonelli" parameter fits are somewhat lower
- "Martin" parameter fits much lower
- **Present results favor higher** $a_0(980)$ **parameters**

Summary

- **Correlations of baryons reveal interesting features** and baryons in general seem to be of great importance (recent Nature publications):
  - Unique experimental environment at RHIC and LHC → "baryon-antibaryon pair factories"
  - Correlation functions sensitive to strong interaction potential, including annihilation
  - Residual correlations complicate the analysis (but they contain interesting physics as well!)
- **$K^0_sK^{\pm}$ femtoscopic correlations measured for the first time:**
  - $a_0(980)$ FSI gives excellent description of the signal
  - No difference wrt identical kaons if larger mass and coupling $a_0(980)$ parameters used ("Achasov1" and "Achasov2") - e.g. "$a_0(1000)$" favored over "$a_0(980)$"


THANK YOU!

ALICE experiment

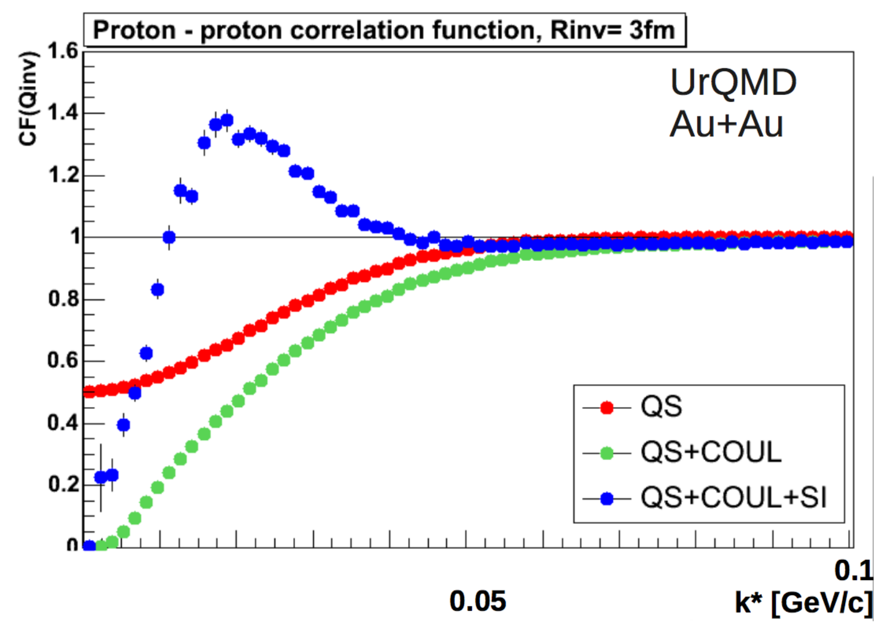


Central Barrel
2 π tracking & PID
$|\eta| < 1$

Status of baryon femtoscopy in ALICE

- ALICE PID capabilities allow us to measure a number of baryon pairs:
  - Baryon-baryon femtoscopy:
    - identical proton femtoscopy (pp and $\bar{p}\bar{p}$) – already published
      Phys. Rev. C 92, 054908 (2015)
    - $p\Lambda$, $\bar{p}\bar{\Lambda}$, $\Lambda\Lambda$, and $\bar{\Lambda}\bar{\Lambda}$ femtoscopy – preliminary results available
  - Baryon-antibaryon femtoscopy ($p\bar{p}$, and $p\bar{\Lambda}$, $\bar{p}\Lambda$, and $\Lambda\bar{\Lambda}$) – preliminary results available
  - Analysis of heavier baryons (eg. $p\Xi$) – in progress

- Which sources of correlations are present?
  - Quantum Statistics (QS) – pp, $\bar{p}\bar{p}$
  - Coulomb Final State Interactions (FSI) – pp, $\bar{p}\bar{p}$ and $p\bar{p}$
  - **Strong FSI – all systems**



H. Zbroszczyk, Ph.D. thesis

Annihilation vs. yields and femtoscopy

Strong interaction parametrized by scattering length f_0 and effective range d_0

Point-like, large momentum transfer interaction (rescattering)

Fold in with density and dynamics, e.g. via UrQMD

Decrease of single particle yield (important for thermal model)

Infinite time interaction at low relative momentum (Final State Interaction)

Fold in with source function

Specific shape of the femtoscopic two-particle correlation function with wide annihilation effect

- Measured cross-sections (f_0 and d_0 parameters) can be supplied to UrQMD for a realistic calculation of the decrease of baryon yield
- **Currently UrQMD uses theory guesses for most baryon-antibaryon potentials!**

Are (anti)baryons important? YES

LETTER

BASE experiment

OPEN

doi:10.1038/nature14861

nature

High-precision comparison of the antiproton-to-proton charge-to-mass ratio

Search for potential CPT symmetry breaking

S. Ulmer[1],
Y. Matsud

LETTER

STAR

doi:10.1038/nature15724

Invariance
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Measurement of interaction between antiprotons

The STAR Collaboration*

One of the primary goals of nuclear physics is to understand t
force between nucleons, which is a necessary step for understandi
the structure of nuclei and how nuclei interact with each oth
Rutherford discovered the atomic nucleus in 1911, and the lar
body of knowledge about the nuclear force that has since be
acquired was derived from studies made on nucleons or nucl
Although antinuclei up to antihelium-4 have been discovere
and their masses measured, little is known directly about t
nuclear force between antinucleons. Here, we study antiprot
pair correlations among data collected by the STAR experimer
at the Relativistic Heavy Ion Collider (RHIC)[3], where gold io
are collided with a centre-of-mass energy of 200 gigaelectronvo
per nucleon pair. Antiprotons are abundantly produced in su
collisions, thus making it feasible to study details of the antiproto
antiproton interaction. By applying a technique similar to Hanbu
Brown and Twiss intensity interferometry[4], we show that the for
between two antiprotons is attractive. In addition, we repo
two key parameters that characterize the corresponding stro
interaction: the scattering length and the effective range of t
interaction. Our measured parameters are consistent within erro
with the corresponding values for proton–proton interactions. O
results provide direct information on the interaction between tw
antiprotons, one of the simplest systems of antinucleons, and
are fundamental to understanding the structure of more-compl

nature physics

ALICE

LETTERS

PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NPHYS3432

OPEN

Precision measurement of the mass difference between light nuclei and anti-nuclei

ALICE Collaboration†

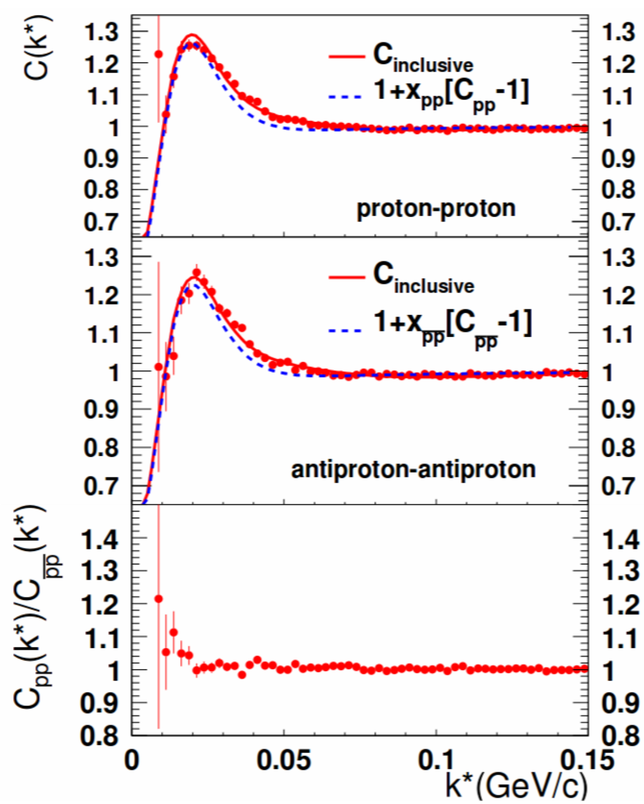
The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons[1,2]. The extension of such measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories[3], but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons (d) and anti-deuterons ($\overline{d}$), and ^{3}He and $^3\overline{He}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment)[4] detector in Pb-Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirms

and specific energy loss (dE/dx) measurements, and the TOF (tim
of flight)[23] detector to measure the time t_{TOF} needed by each trac
to traverse the detector. The combined ITS and TPC information i
used to determine the track length (L) and the rigidity (p/z, where
is the momentum and z the electric charge in units of the elementar
charge e) of the charged particles in the solenoidal 0.5 T magneti
field of the ALICE central barrel (pseudo-rapidity $|\eta| < 0.8$). On
the basis of these measurements, we can extract the squared mass
over-charge ratio $\mu^2_{TOF} \equiv (m/z)^2_{TOF} = (p/z)^2 [(t_{TOF}/L)^2 - 1/c^2]$. The
choice of this variable is motivated by the fact that μ^2 is directl
proportional to the square of the time of flight, allowing to bette
preserve its Gaussian behaviour.
The high precision of the TOF detector, which determines th
arrival time of the particle with a resolution of 80 ps (ref. 20), allow
us to measure a clear signal for (anti-)protons, (anti-)deuterons and

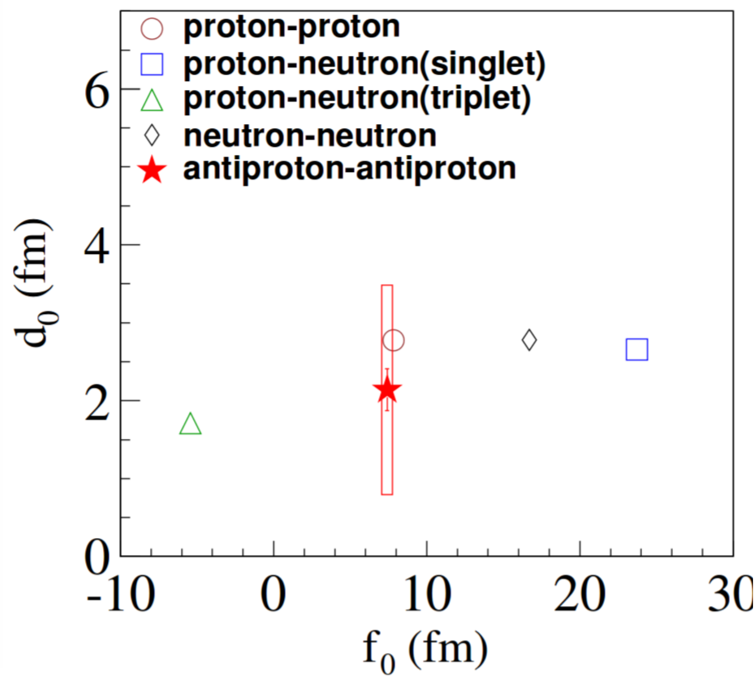
Au-Au: pp and $\overline{pp}$ correlations @ STAR

Figure 4 presents the first measurement of the antiproton-antiproton interaction, together with prior measurements for nucleon-nucleon interactions. Within errors, the f_0 and d_0 for the antiproton-antiproton interaction are consistent with their antiparticle counterparts – the ones for the proton-proton interaction. Our measurements provide parameterization input for describing the

- Exactly the same methodology was used by STAR to measure $\overline{pp}$ interaction (Nature paper)
- **Conclusions:**
  - LHC and RHIC are "baryon-antibaryon pair factories" - unique opportunities
  - Both ALICE and STAR, with their perfect PID, are the only experiments where such measurements are possible



STAR Collaboration
Nature 527,345-348 (2015)



Residual correlations in pp

- The excess about 50 MeV/c in k* is explained by residual correlations, from main decay channel leading to protons:

$$\Lambda \rightarrow p + \pi^{-}$$

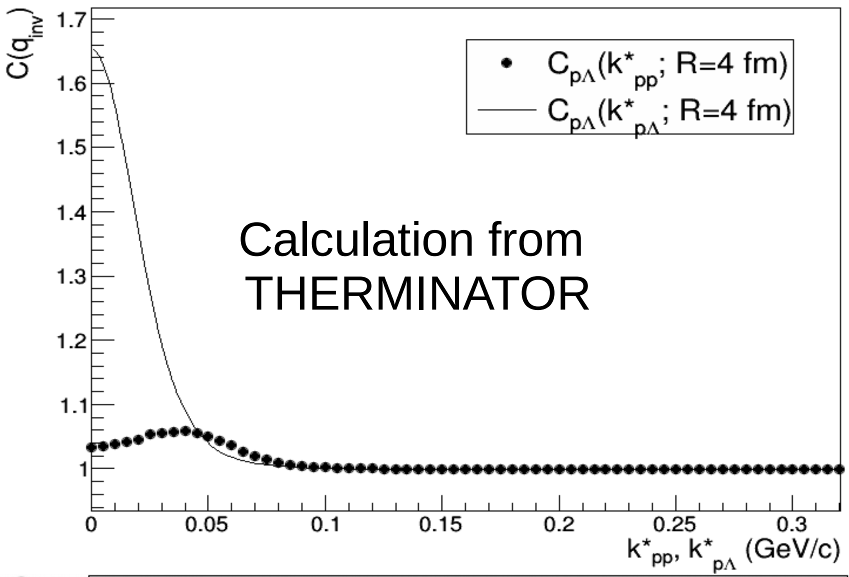
- Fitting function is a combination of theoretical pp and pΛ functions:

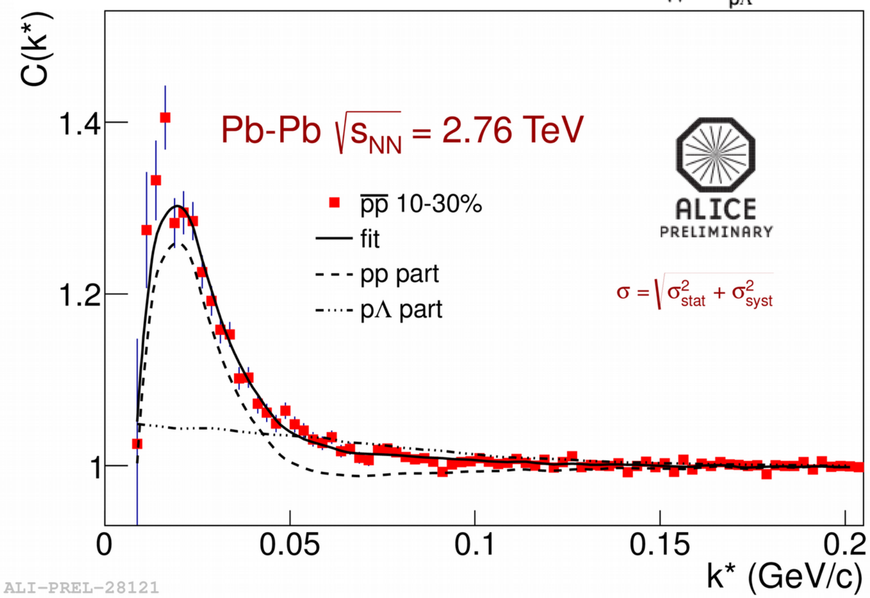
$$C_{meas}(k^*) = 1 + \lambda_{pp}(C_{pp}(k_{pp}; R) - 1) + \lambda_{p\Lambda}\left(\int C_{p\Lambda}(k_{p\lambda}; R) T(k_{p\lambda}, k_{pp}) - 1\right)$$

- Assume Gaussian source, $R_{pp}/R_{p\Lambda}$ ratio, decay kinematics taken into account.

- Results with RC effect taken into account published in:

Phys. Rev. C 92, 054908 (2015)





Residual correlations in pp – transformation matrix

- The transformation matrix T from parent pair k^* to the daughter pair k^* determined by random decay, bound by decay momenta
- When only one particle decays, it has a rectangular shape, for pairs when both particles decay it is smeared more

F. Wang, S. Pratt; Phys. Rev. Lett. 83, 3138 (1999)
Adam Kisiel, M. Szymański, H. Zbroszczyk, Phys.Rev. C89 (2014) 054916