



NATIONAL SCIENCE CENTRE
POLAND



ALICE
A JOURNEY OF DISCOVERY

Studies of final state interactions via femtoscscopy in ALICE

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for the ALICE Collaboration



XII Polish Workshop on Relativistic Heavy-Ion Collisions
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4.11.2016

Femtoscscopy – beyond the system size

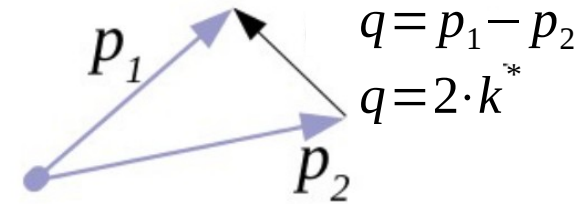
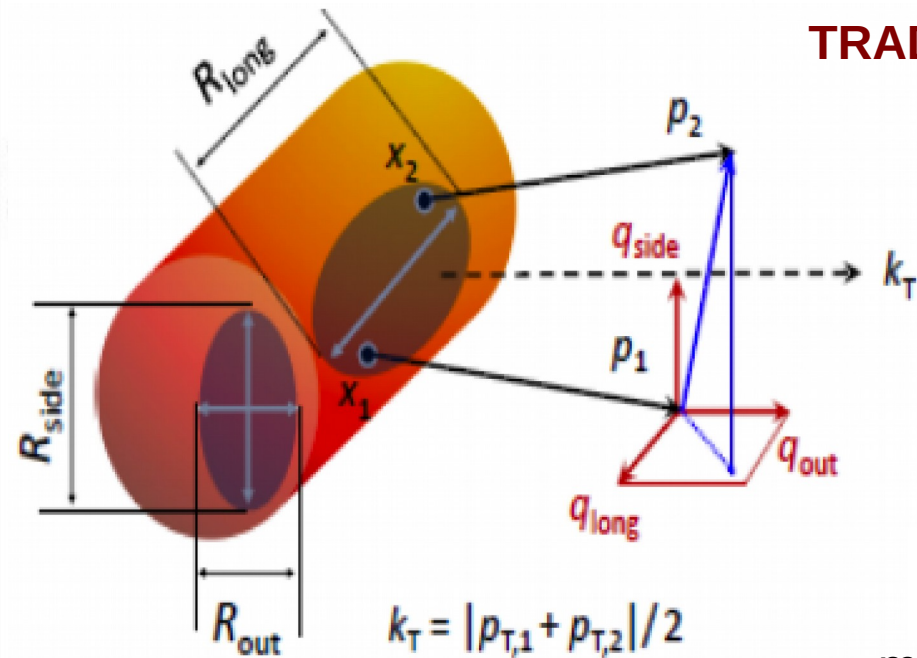
Correlations of baryons

$K_s^0 K^\pm$ correlations

Femtoscscopy technique

TRADITIONAL FORMALISM

Identical pions



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

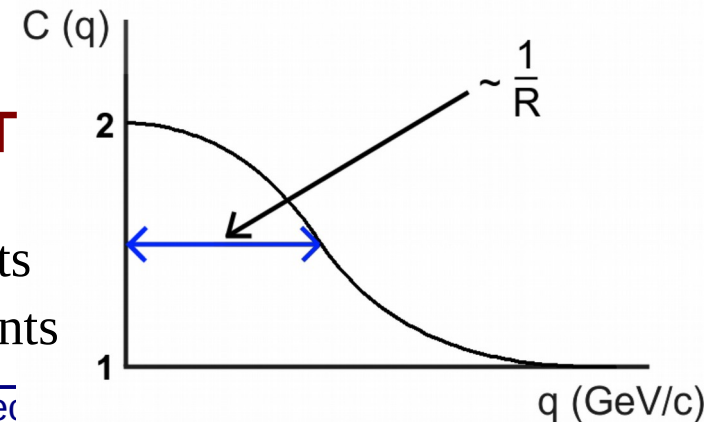
emission function
(source size/shape)

cross-section

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

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

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



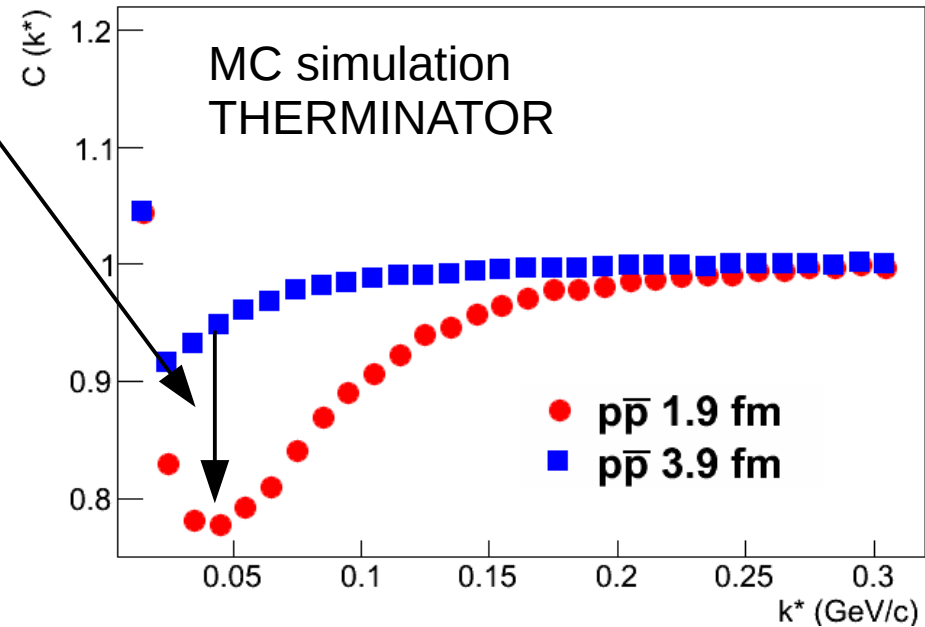
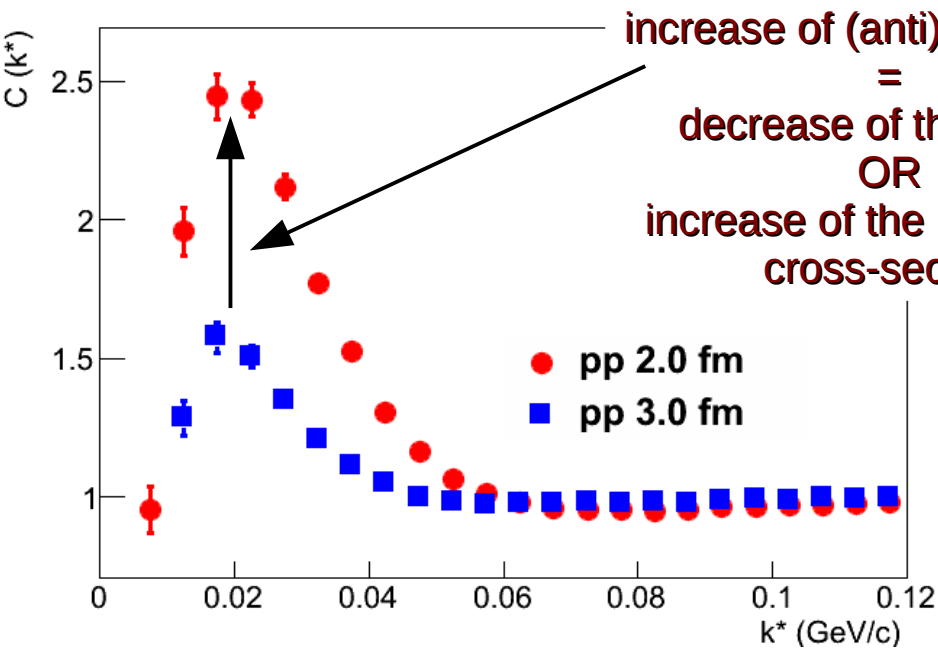
- The size (or sizes in 3D) R is referred to as the “**HBT radius**”

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

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**

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

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

- 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

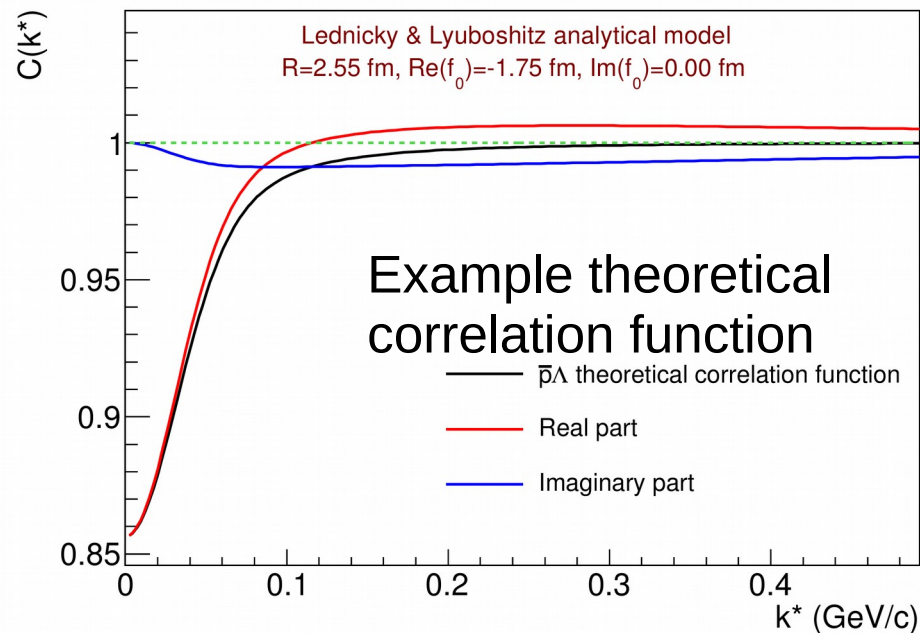
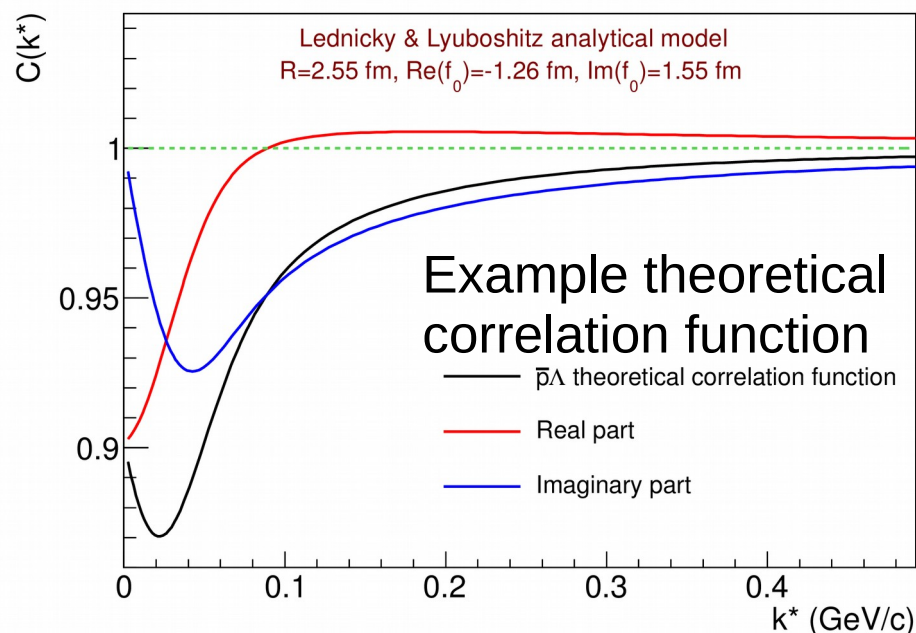
- The correlation function is finally characterized by **three parameters**:
 - radius R , scattering length f_0 , and effective radius d_0**

Cross-section σ (at low k^*) is simply: $\sigma = 4\pi |f|^2$

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

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

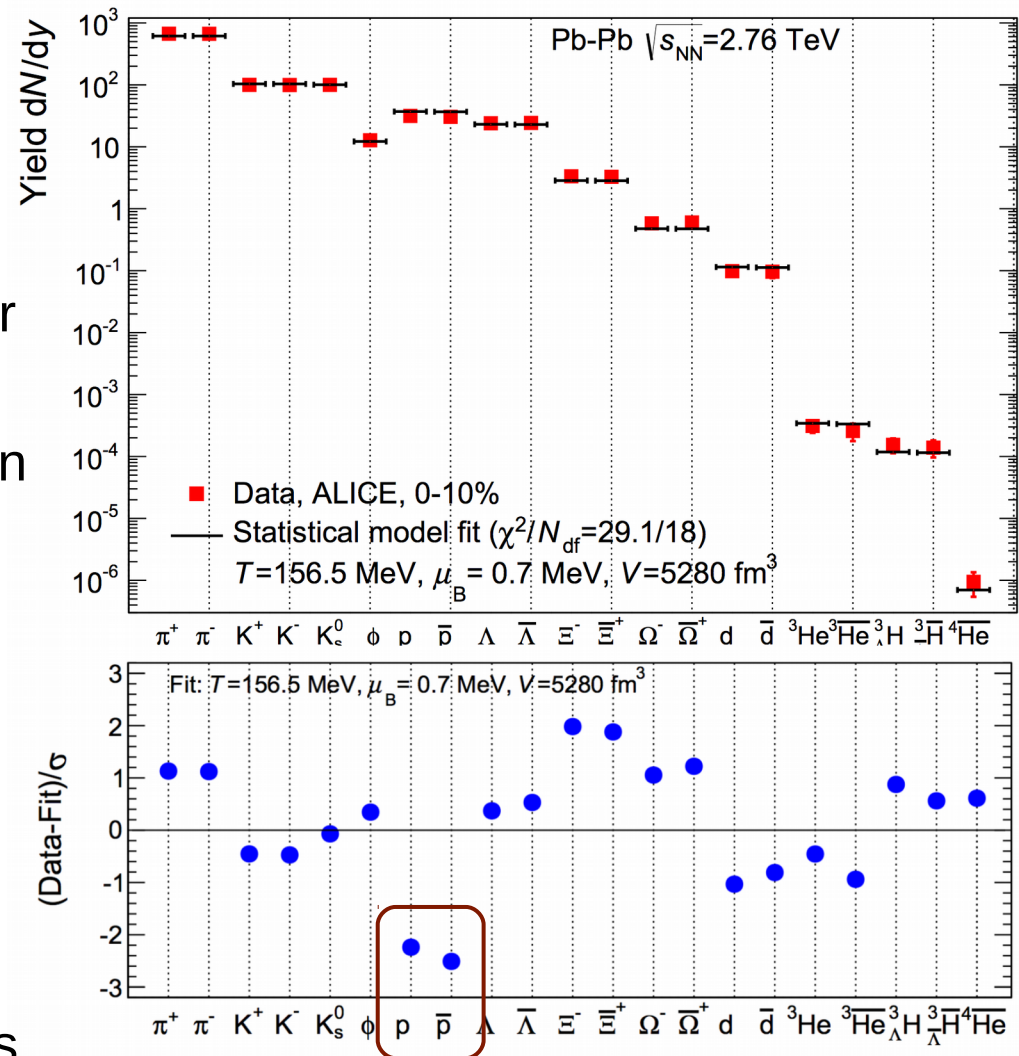
Correlation from Strong Interaction – $\bar{p}\Lambda$ example



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

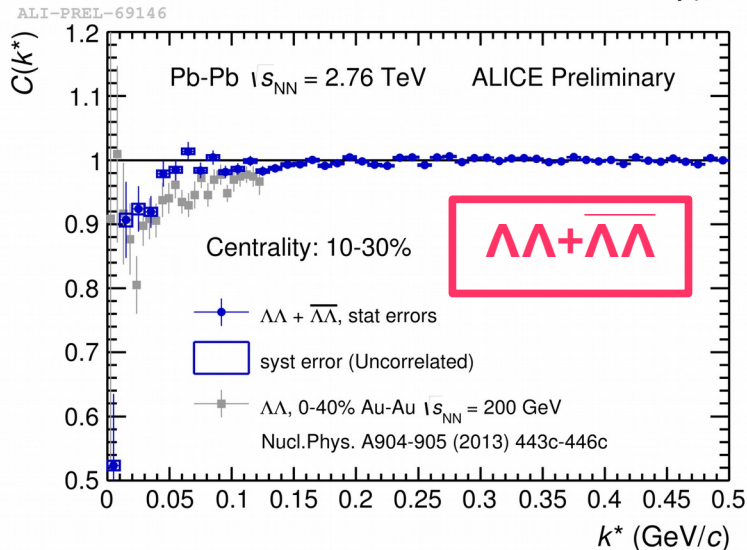
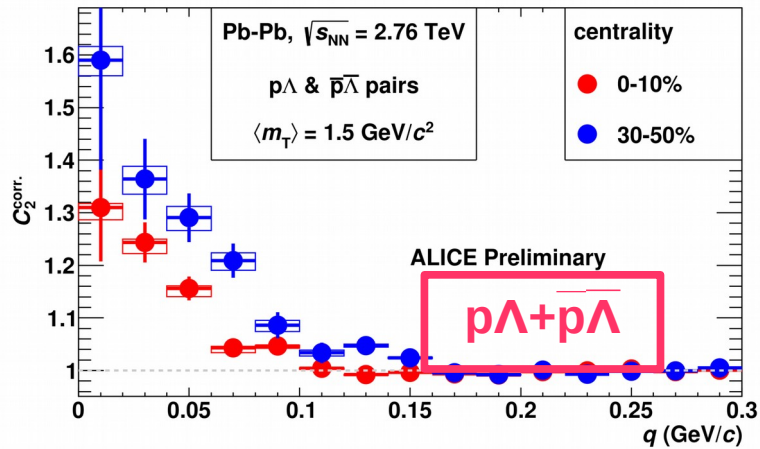
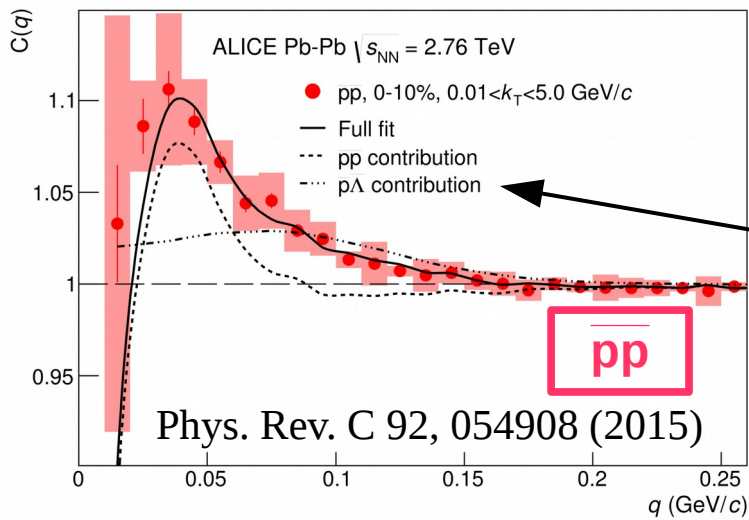
What are the potential applications?

- **Input to models with rescattering phase:** UrQMD (PRC 89, 054916 (2014))
 - annihilation cross-sections only measured for pp, pn, and pd pairs – UrQMD currently **guesses** it for other systems from pp 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** (SQM 2016, Benjamin Dönigus)
- **Hypernuclear structure theory** (Nucl.Phys. A914 (2013) 377-386)
- **Neutron star equation of state** (Nucl.Phys. A804 (2008) 309-321)

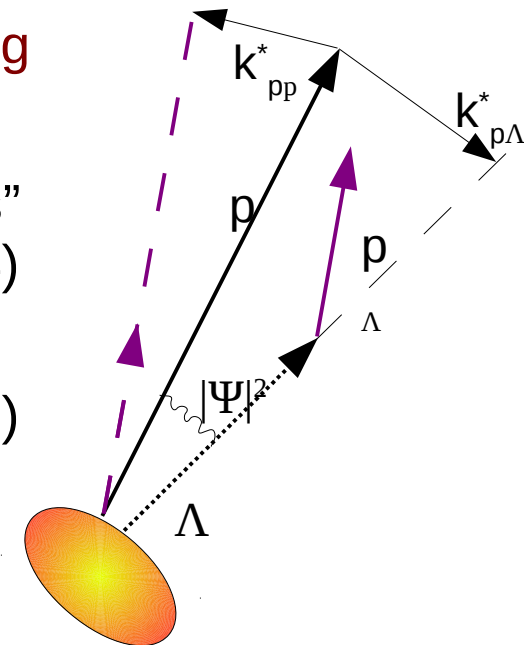


A. Andronic, SQM 2016
 Wed, Plenary 11:00

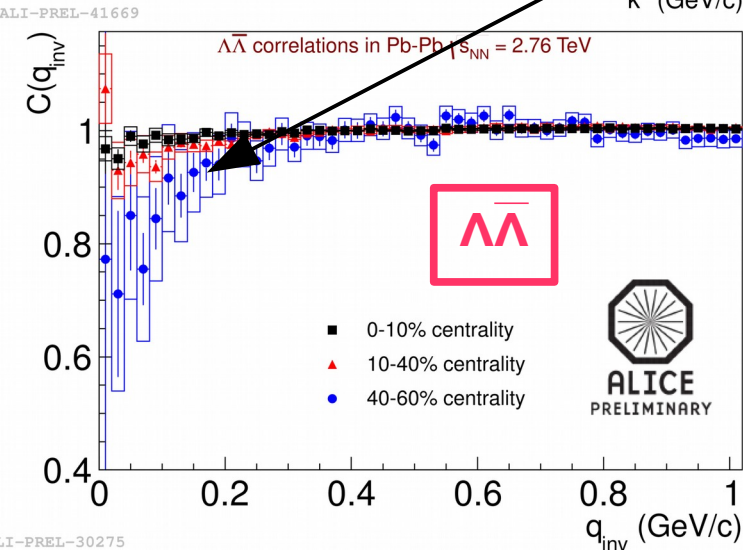
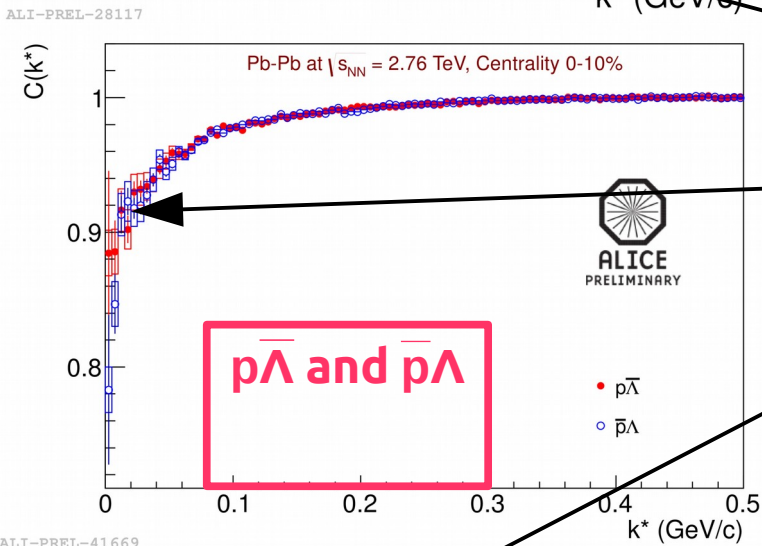
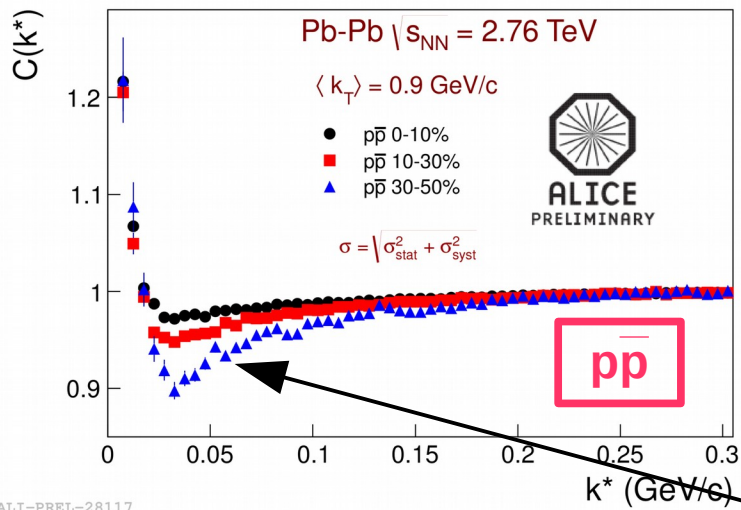
Baryon-baryon correlations



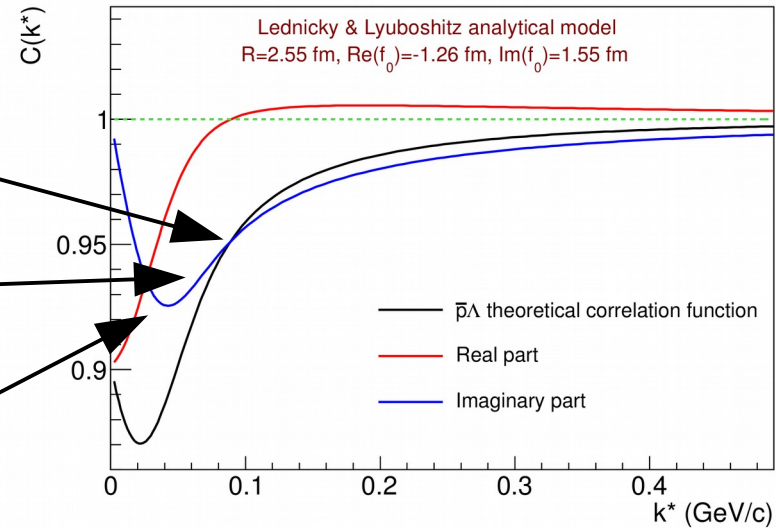
- Analysis of experimental data is complicated by the presence of **residual correlations**
- Weak decay baryons have momentum in similar direction as parent – decay momentum is small with respect to the baryon mass (e.g. $\Lambda \rightarrow p$: 101 MeV/c)
- The femtoscopic correlation of the parent 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

Femtoscscopy – beyond the system size

Correlations of baryons

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

Motivation for $K_s^0 K^\pm$ 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 $K_s^0 K_s^0$ and $K^\pm K^\pm$
 - Coulomb FSI – $K^\pm K^\pm$
 - **Strong FSI – $K_s^0 K_s^0$ (via $f_0(980)/a_0(980)$ resonances)**
- **Why are $K_s^0 K^\pm$ 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)

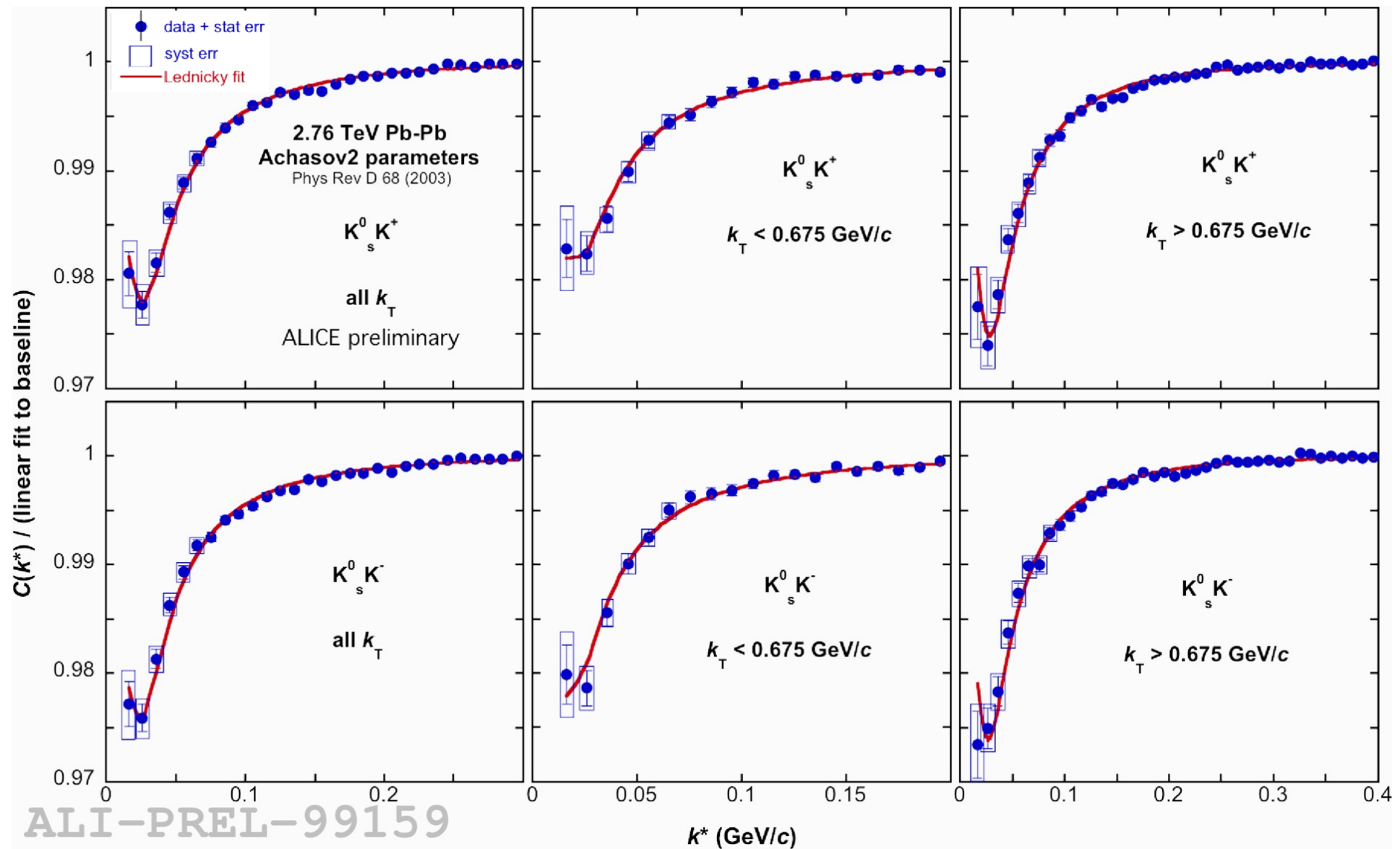
- Correlation of mesons is described by a version of Lednicky analytic formula, where:

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

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

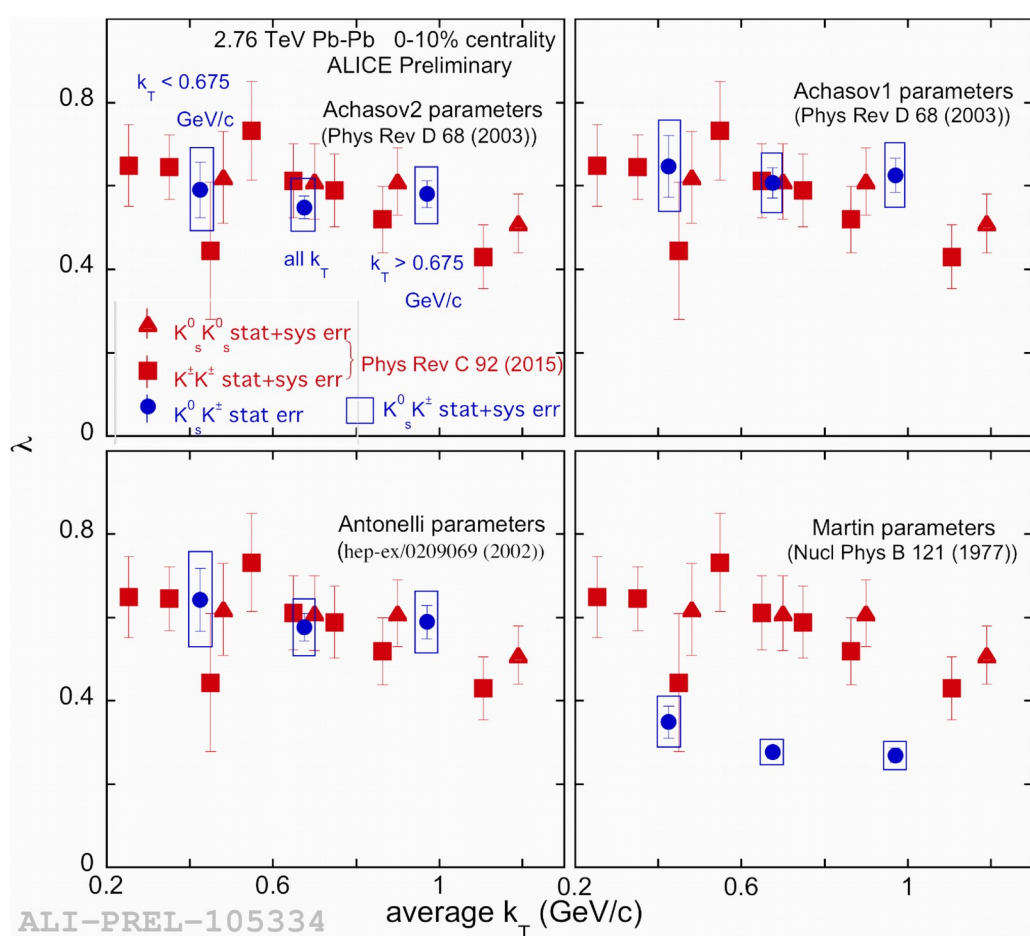
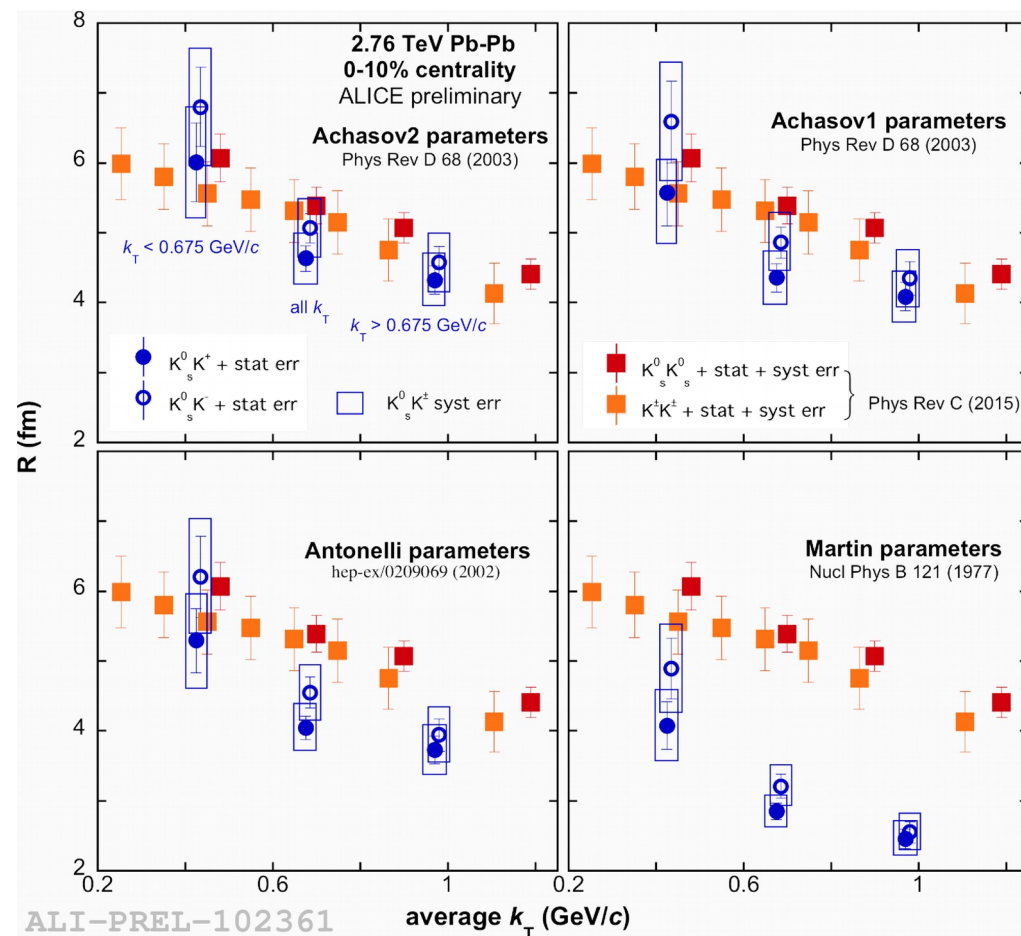
	m_{a_0}	$\gamma_{a_0 \rightarrow K \bar{K}}$	$\gamma_{a_0 \rightarrow \pi \eta}$	Reference
“Martin”	0.974	0.3330	0.2220	Nucl. Phys. B 121, 514 (1977)
“Antonelli”	0.985	0.4038	0.3711	arXiv: hep/ex-0209069 (2002)
“Achasov1”	0.992	0.5555	0.4401	Phys. Rev. D 68, 014006 (2003)
“Achasov2”	1.003	0.8365	0.4580	Phys. Rev. D 68, 014006 (2003)

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



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

Results of the fits



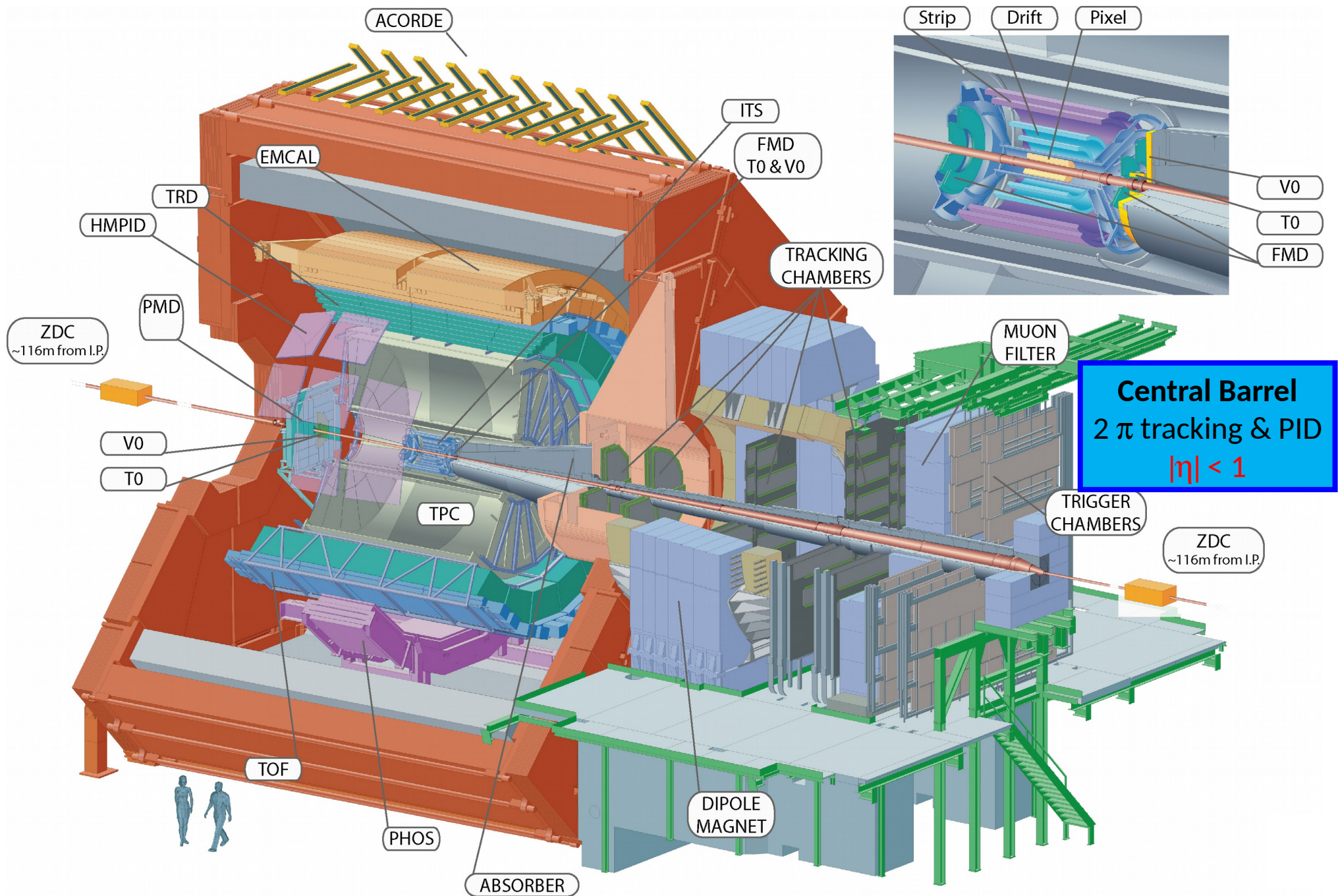
- “Achasov” parameter fits give best agreements with $K_s^0 K_s^0$ and $K^\pm K^\pm$ results
- “Antonelli” parameter fits are somewhat lower
- “Martin” parameter fits much lower
- **Present results favor higher $a_0(980)$ parameters**

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!)
- **$K^0_s K^\pm$ 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

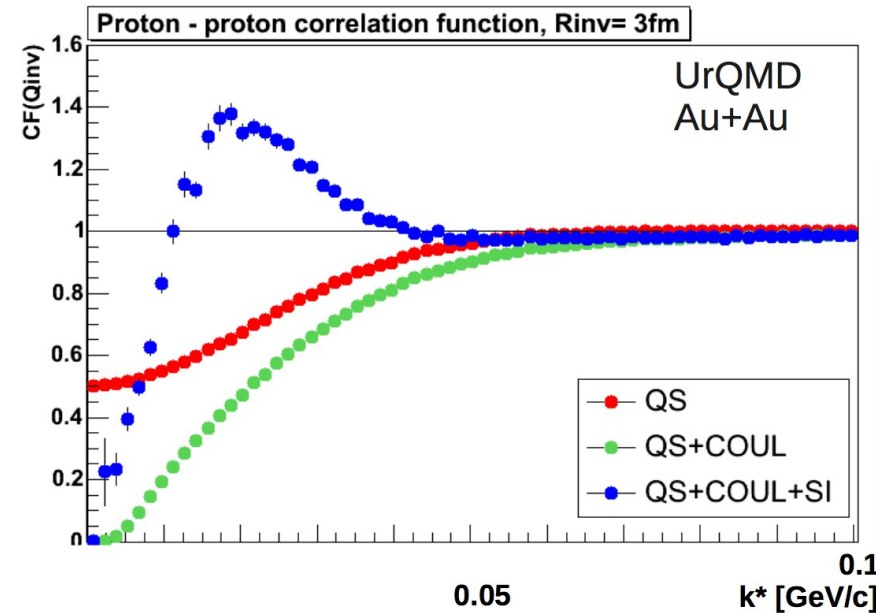


Status of baryon femtoscopy in ALICE

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

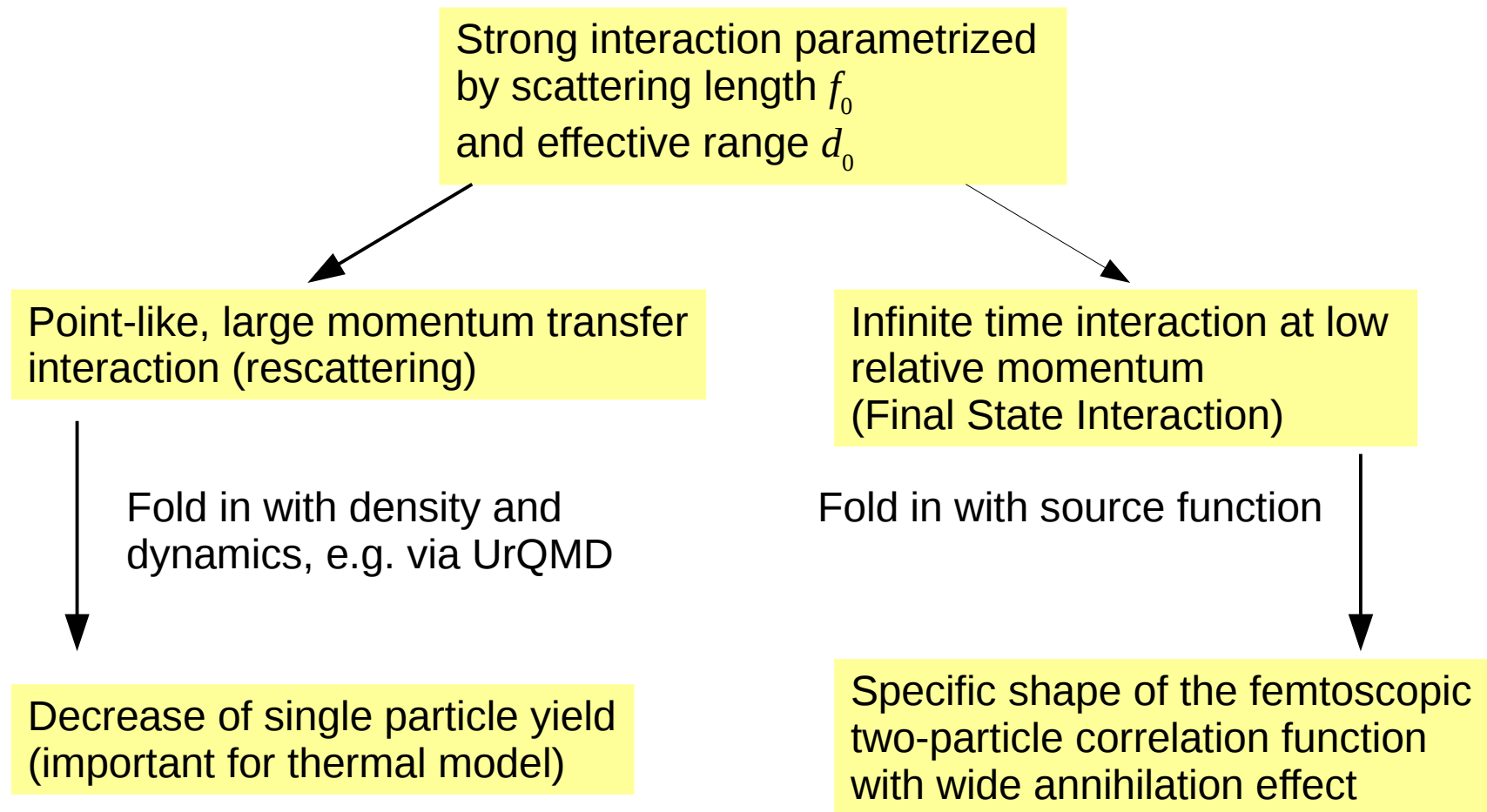
- Which sources of correlations are present?

- Quantum Statistics (QS) – pp , \overline{pp}
- Coulomb Final State Interactions (FSI) – pp , \overline{pp} and $p\overline{p}$
- **Strong FSI – all systems**



H. Zbroszczyk, Ph.D. thesis

Annihilation vs. yields and femtoscopy



- 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

Search for potential CPT symmetry breaking

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

S. Ulmer¹,
Y. Matsuda

LETTER

STAR

doi:10.1038/nature15724

Invariance
formation¹
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fundament
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Measurement of interaction between antiprotons

The STAR Collaboration*

One of the primary goals of nuclear physics is to understand the force between nucleons, which is a necessary step for understanding the structure of nuclei and how nuclei interact with each other. Rutherford discovered the atomic nucleus in 1911, and the large body of knowledge about the nuclear force that has since been acquired was derived from studies made on nucleons or nucleon pairs. Although antinuclei up to antihelium-4 have been discovered and their masses measured, little is known directly about the nuclear force between antinucleons. Here, we study antiproton pair correlations among data collected by the STAR experiment at the Relativistic Heavy Ion Collider (RHIC)³, where gold ions are collided with a centre-of-mass energy of 200 GeV per nucleon pair. Antiprotons are abundantly produced in such collisions, thus making it feasible to study details of the antiproton-antiproton interaction. By applying a technique similar to Hanbury Brown and Twiss intensity interferometry⁴, we show that the force between two antiprotons is attractive. In addition, we report two key parameters that characterize the corresponding strong interaction: the scattering length and the effective range of the interaction. Our measured parameters are consistent within error with the corresponding values for proton-proton interactions. Our results provide direct information on the interaction between two 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 theories³, 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 (\bar{d}), and ³He and $\bar{3}\text{He}$ 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 (time of flight)²³ detector to measure the time t_{TOF} needed by each track to traverse the detector. The combined ITS and TPC information is used to determine the track length (L) and the rigidity (p/z , where p is the momentum and z the electric charge in units of the elementary charge e) of the charged particles in the solenoidal 0.5 T magnetic field of the ALICE central barrel (pseudorapidity $|\eta| < 0.8$). On the basis of these measurements, we can extract the squared mass-over-charge ratio $\mu_{\text{TOF}}^2 \equiv (m/z)_{\text{TOF}}^2 = (p/z)^2 [(t_{\text{TOF}}/L)^2 - 1/c^2]$. The choice of this variable is motivated by the fact that μ^2 is directly proportional to the square of the time of flight, allowing to better preserve its Gaussian behaviour.

The high precision of the TOF detector, which determines the arrival time of the particle with a resolution of 80 ps (ref. 20), allows us to measure a clear signal for (anti-)protons, (anti-)deuterons and

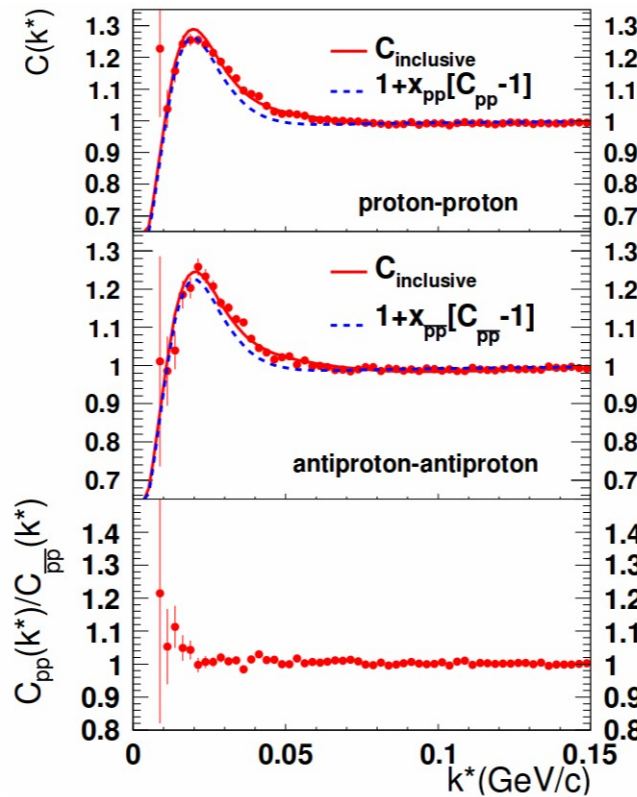
Au-Au: pp and pp correlations @ STAR

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

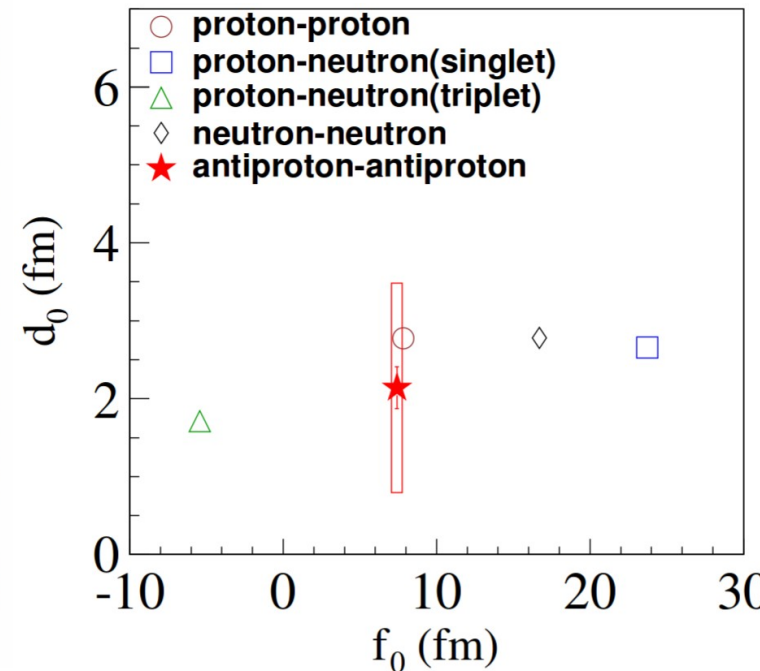
- Exactly the same methodology was used by STAR to measure pp interaction (Nature paper)

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

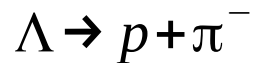


STAR Collaboration
Nature 527,345-348 (2015)



Residual correlations in pp

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

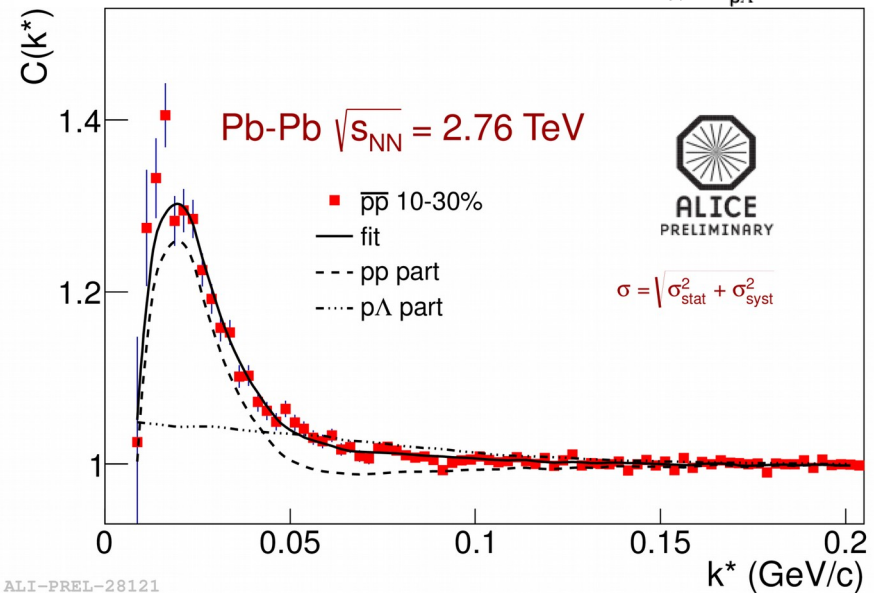
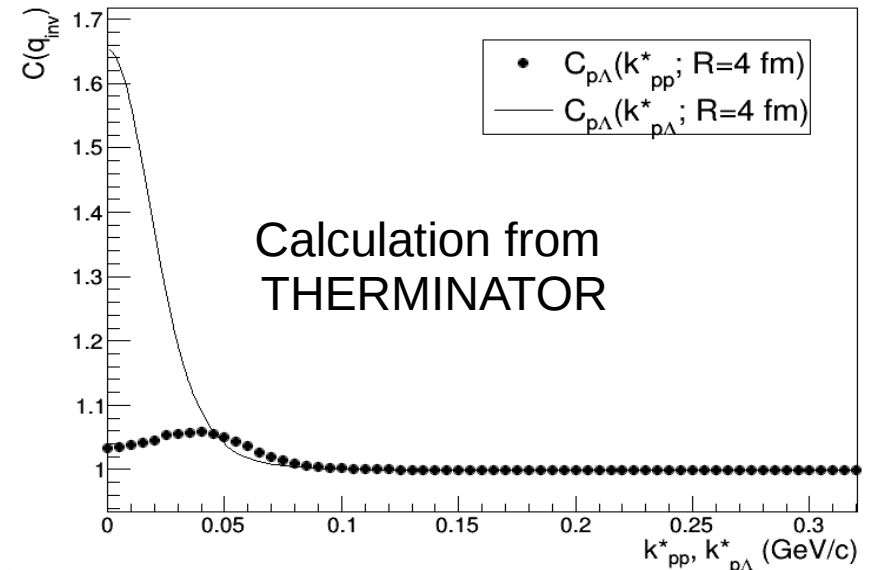


- Fitting function is a combination of theoretical pp and p Λ functions:

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

- 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)



ALI-PREL-28121

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

