Two-baryon correlations in heavy-ion collisions at the LHC

Jai Salzwedel (Ohio State University)
For the ALICE Collaboration

Abstract

In heavy-ion collisions produced at the LHC a significant number of baryons is emitted in each collision. Two-particle correlations of those baryons carry important information about the emitting source and the interaction between them.

At low relative momentum femtoscopic correlations arise, which are sensitive to the homogeneity lengths of the system. Hydrodynamic models predict that these will decrease with increasing transverse mass of the pair. Such decrease is universally reported for pions, including at the LHC. Baryons, having a much larger mass, allow to significantly extend the range of measured m_{T}. The results of baryon femtoscopy would put a strong constraint on such predictions.

Femtoscopic correlations between baryons arise mostly due to the strong interaction, which is not precisely known for some baryon pair types. Most interesting are baryon-antibaryon potentials, which have a significant contribution from annihilation channels. These processes may have an impact on single-particle spectra and should be investigated as one of the possible sources of the small proton yield at the LHC.

Analysis of proton correlations

35 million Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV registered by the ALICE experiment have been analysed. Tracks were reconstructed with the Time Projection Chamber (TPC); (anti-)protons were identified with the TPC and the Time-of-Flight detector in $\eta < |0.8|$. Protons had $p_{\mathrm{T}} > 0.5$ GeV$/c$. Primary tracks were selected based on the Distance of Closest Approach to the primary vertex (DCA): less than 0.1 cm in the transverse plane and 2.0 cm in the beam direction. The distributions of the DCA in the transverse plane from data and AMPT simulations are shown in Fig. 1.

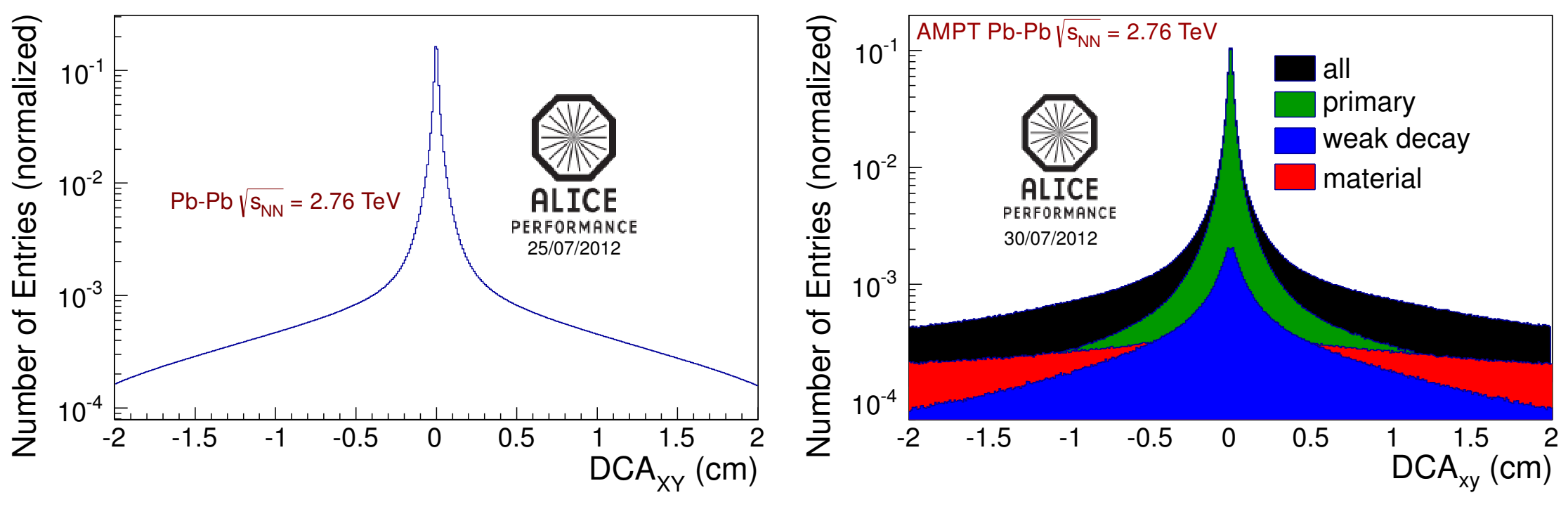

Figure 1 : DCA distributions for the data (left) and AMPT (right)

Particles from the same event were grouped into pairs to form the signal, from two different events to form a mixed background. Pair cuts have been used to account for fake low-q pairs (splitting) and two-track inefficiency (merging). Signal was divided by the background to form the correlation function.

Two-proton correlation functions

The correlation for pairs of (anti)protons (Fig. 2, 3) is a combination of Fermi-Dirac statistics, Coulomb and Strong Final State Interactions (FSI). A distinct maximum for $q_{\mathrm{inv}} \approx 40$ MeV$/c$ [1] is seen. Correlation effect increases for more peripheral events indicating that the size of the emitting source increases with event multiplicity.

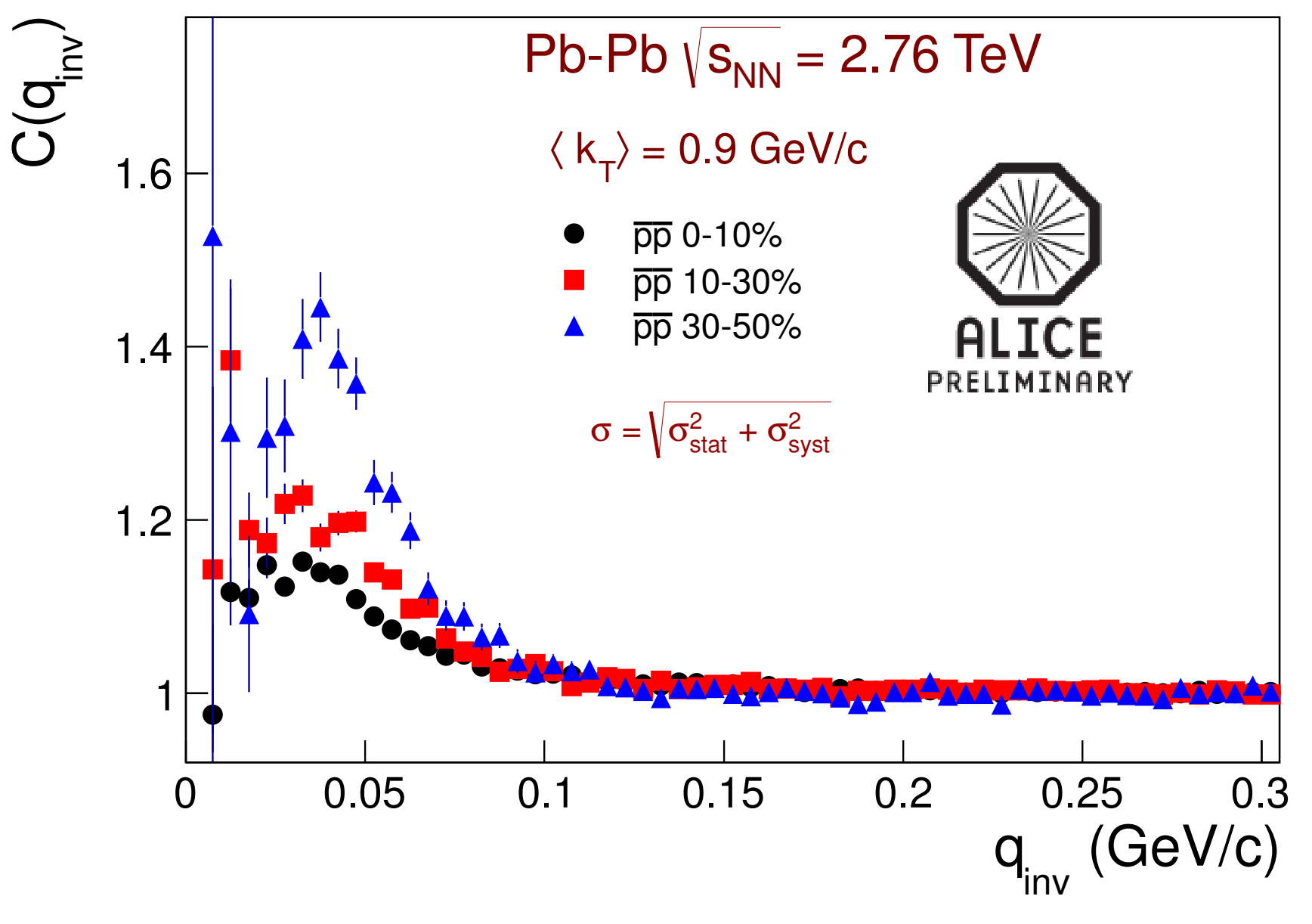

Figure 2 : $\bar{\mathrm{p}}\bar{\mathrm{p}}$ correlation functions for the $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb.

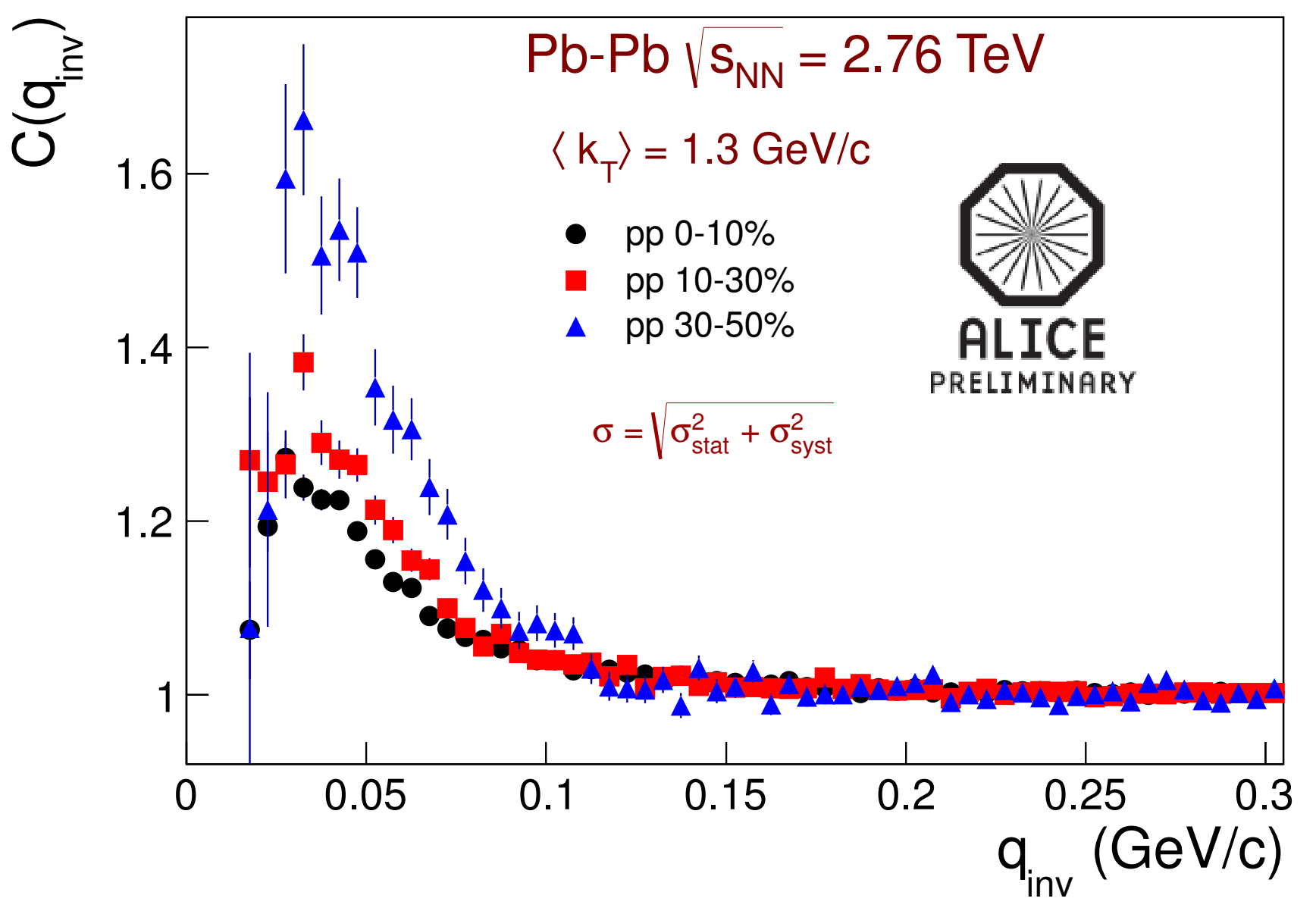

Figure 3 : pp correlation functions for the $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb.

Proton-antiproton correlations (Fig. 4) show a maximum for the low relative momentum from Coulomb attraction, then a wide minimum caused by the annihilation part of the strong FSI. The femtoscopic effect is wide comparing to pp, providing a better statistical handle on system size. The baseline at large values of q is flat, indicating the absence of wide non-femtoscopic structures.

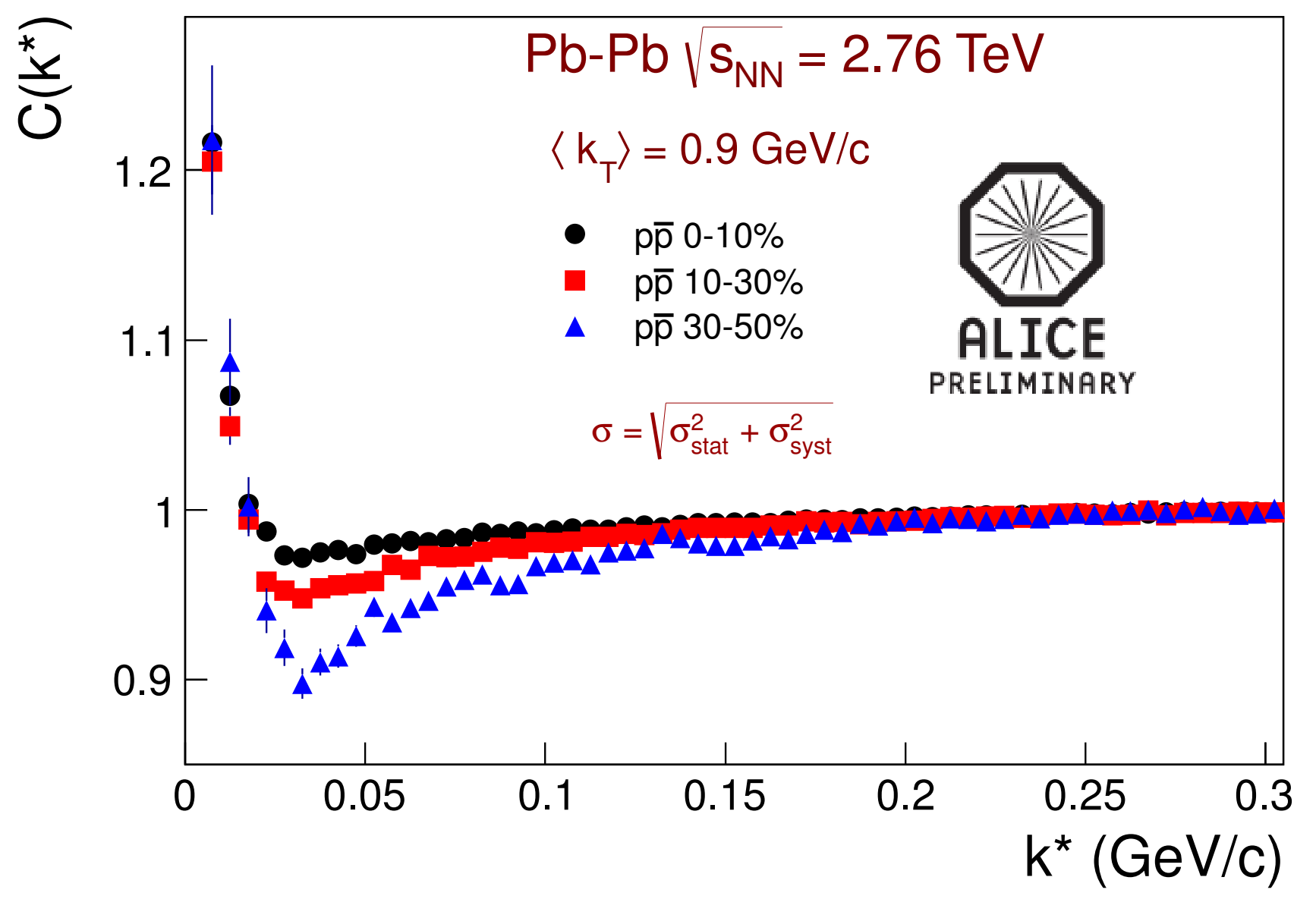

Figure 4 : $\mathrm{p\bar{p}}$ correlation functions for the $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb.

Fitting the baryon correlations

The Coulomb and Quantum Statistics for pp pairs give the correlation effect below unity. The Strong interaction is positive but has limited width - similar to a resonance peak. The excess between data and the theoretical pp curve around 50 MeV$/c$ of k^* cannot be explained by the pp wave function (Fig. 5).

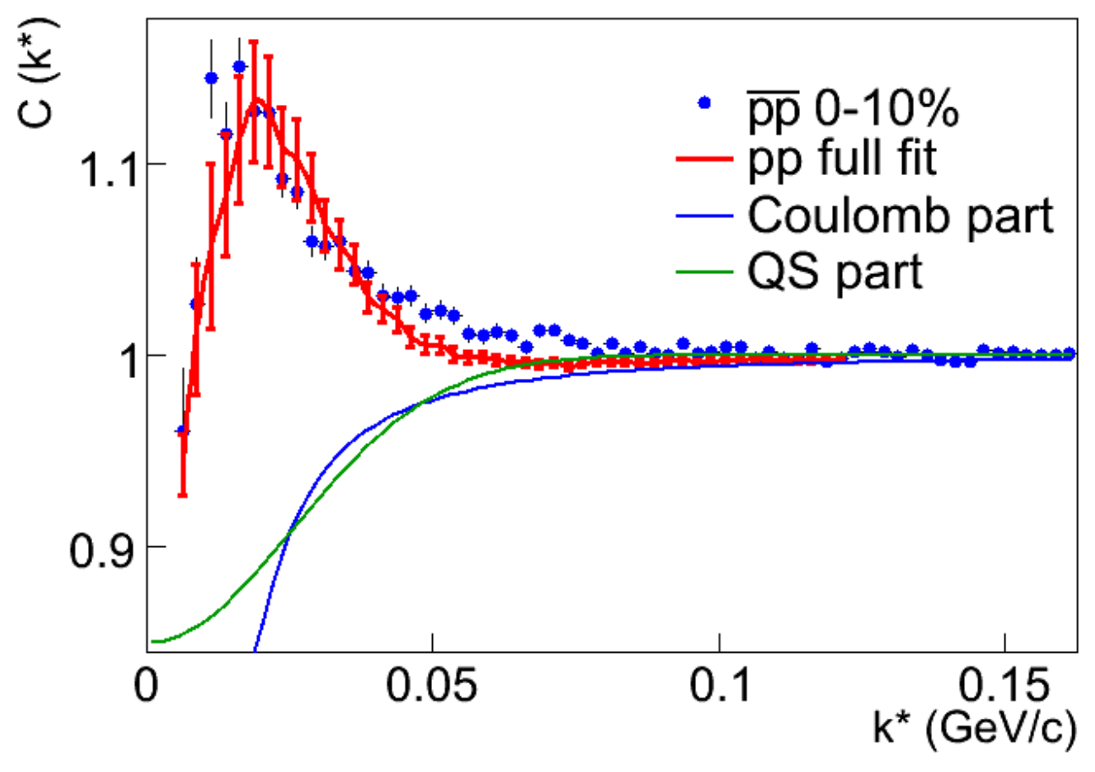

Figure 5 : Comparison of experimental correlation functions and fit obtained with `CorrFit` [2]. Contribution of Coulomb repulsion and QS are also shown [3].

The significant influence of residual correlations may be a possible explanation since feed-down from weak decays cannot be neglected in high-energy heavy-ion collisions. Because of the low decay momentum of Λ decay into p and π^- with respect to the mass of proton, femtoscopic correlations between a Λ and a primary proton might still be detected for a pair consisting of a primary proton and the proton from Λ. The method of simultaneous fitting of pp ($\mathrm{\bar{p}\bar{p}}$, $\mathrm{p\bar{p}}$) and $\mathrm{p}\Lambda$ ($\mathrm{\bar{p}}\bar{\Lambda}$, $\mathrm{p}\bar{\Lambda}$) correlations was proposed. It is assumed that residual correlations coming from $\mathrm{p}\Sigma^+$ system are negligible, due to a known small cross-section for this system. Hence, the experimental correlation function were fitted with the formula:

$$C_{meas}(k^*_{pp}) = 1 + \lambda_{pp} \cdot (C_{pp}(k^*_{pp}; R) - 1) + \lambda_{p\Lambda} \cdot (C_{p\Lambda}(k^*_{pp}; R) - 1),$$

where:

- λ_{pp}, $\lambda_{p\Lambda}$ - parameters which describes the relative number of pp pairs where both particles are primary (λ_{pp}) and pairs where one particle is primary, the other is a product of Λ decay ($\lambda_{p\Lambda}$),
- R - radius
- $C_{pp}(k^*_{pp}; R)$ - theoretical proton-proton correlation function for given R (Gaussian source assumed), obtained from `CorrFit` [2],
- $C_{p\Lambda}(k^*_{pp}; R) = \sum_{k^*_{p\Lambda}} C_{p\Lambda}(k^*_{p\Lambda}) T(k^*_{pp}, k^*_{p\Lambda})$ - theoretical $\mathrm{p}\Lambda$ correlation function for given R obtained from Lednicky's model (decay kinematics taken into account (Fig. 6)) [3],
- $T(k^*_{pp}, k^*_{p\Lambda})$ - transformation factors related to Λ decay kinematics, calculated with `THERMINATOR` [4].

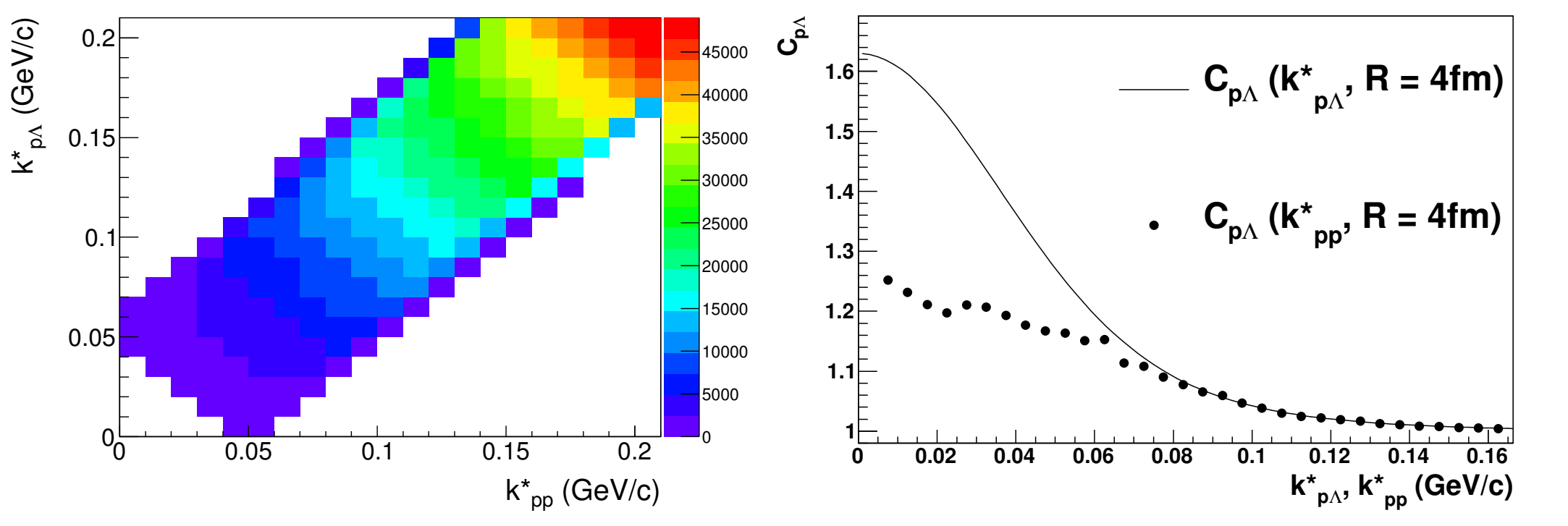

Figure 6 : Example of the transformation of $C_{p\Lambda}(k^*_{p\Lambda}) \to C_{p\Lambda}(k^*_{pp})$.

In the fit obtained with this method, the contribution from pp ($\mathrm{\bar{p}\bar{p}}$) correlations describes the maximum at $k^* \approx 20$ MeV$/c$, and the wide correlation effect, is reproduced by residual correlations from $\mathrm{p}\Lambda$ (Fig. 7).

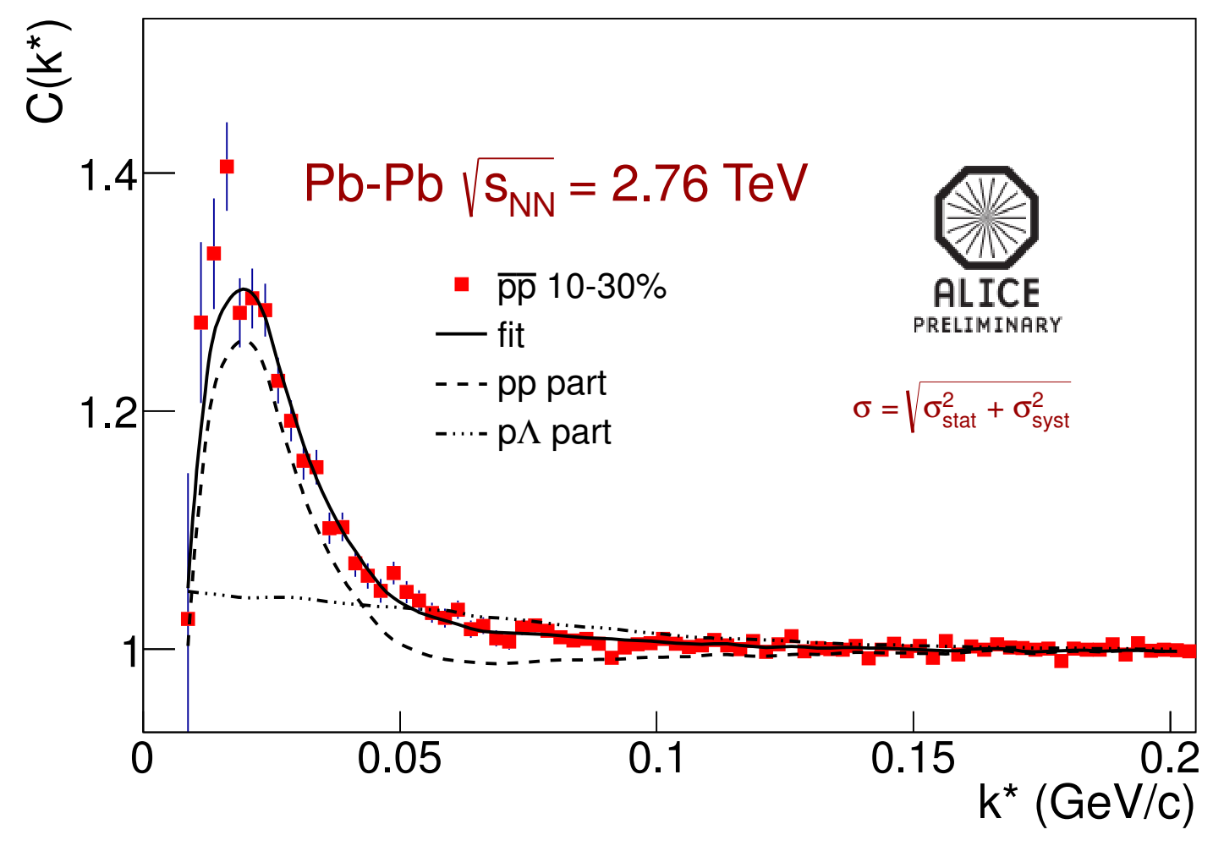

Figure 7 : Results of fitting the $\mathrm{\bar{p}\bar{p}}$ correlation function. The contribution of the theoretical pp and $\mathrm{p}\Lambda$ correlation functions scaled by factors related to the relevant fractions of pp pairs are shown with dashed and dotted-dashed lines, respectively.

An analogous method was used to extract the radii from $\mathrm{p\bar{p}}$ correlation functions (Fig. 8).

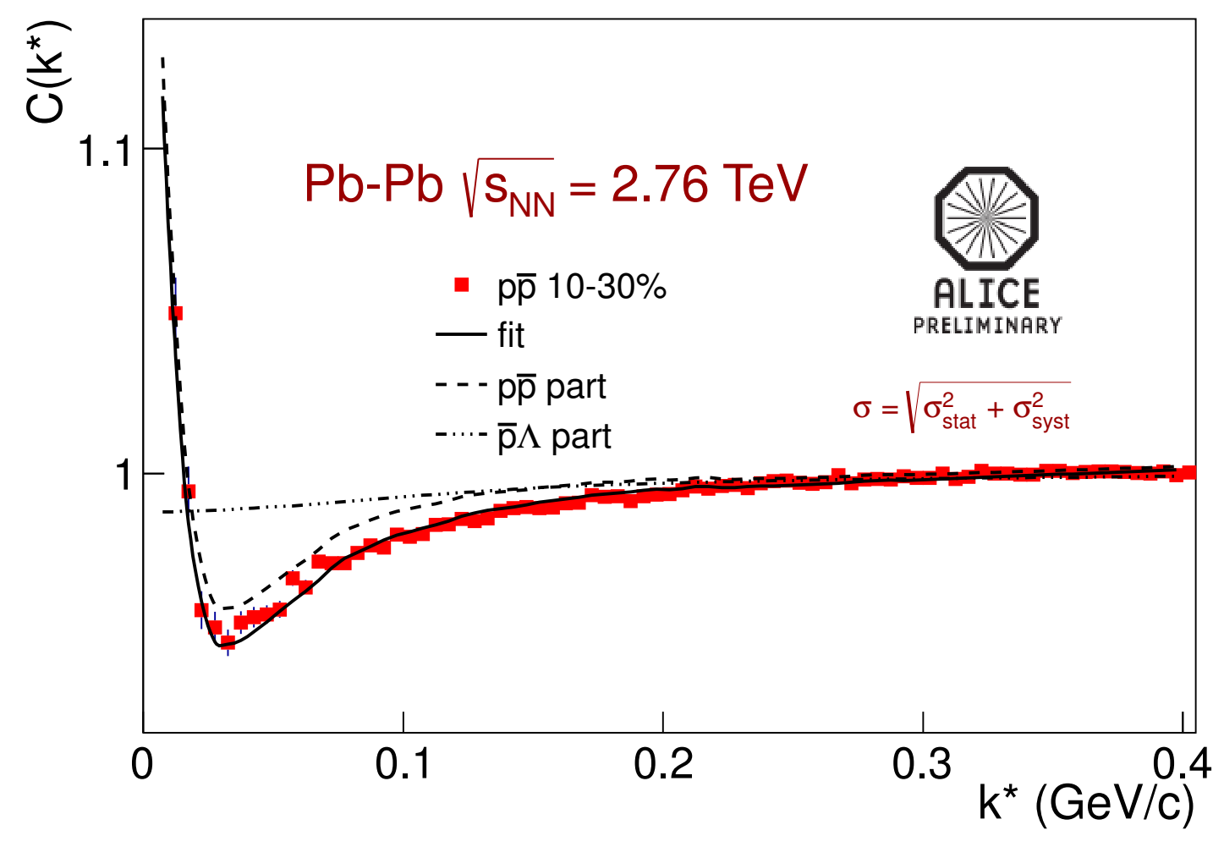

Figure 8 : Results of fitting the $\mathrm{p\bar{p}}$ correlation function. The contribution of the theoretical $\mathrm{p\bar{p}}$ and $\mathrm{\bar{p}}\Lambda$ correlation functions scaled by factors related to the relevant fractions of $\mathrm{p\bar{p}}$ pairs are shown with dashed and dotted-dashed lines, respectively.

Radii vs. centrality

Fig. 9 shows the expected trend of the increase of the R_{inv} with event multiplicity for all combinations of proton pairs. Radii calculated for two k_{T} ranges are within the systematic uncertainty.

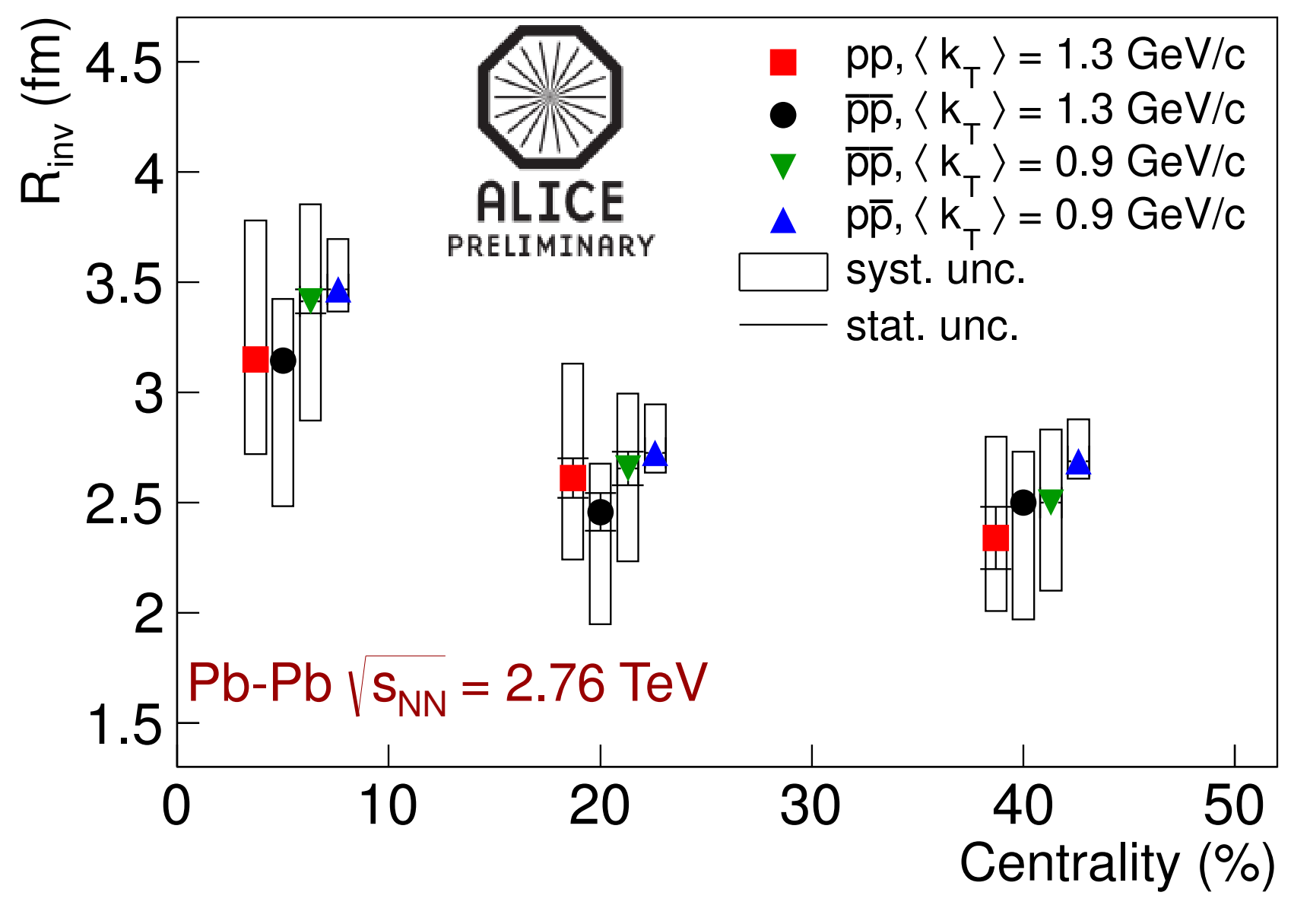

Figure 9 : Centrality dependence of the fitted radii from proton femtoscopy. Statistical (lines) and systematic (boxes) uncertainties are shown.

m_{T} scaling with different masses

In the hydrodynamic model, approximate m_{T} scaling of the radii calculated in the Longitudinally Co-Moving System is observed (Fig. 10). At the same time, there is no such scaling for the radii calculated in the Pair Rest Frame. It results from the kinematics, therefore one can try to recover the m_{T} scaling with an approximate formula relating 1D sizes in LCMS and PRF.

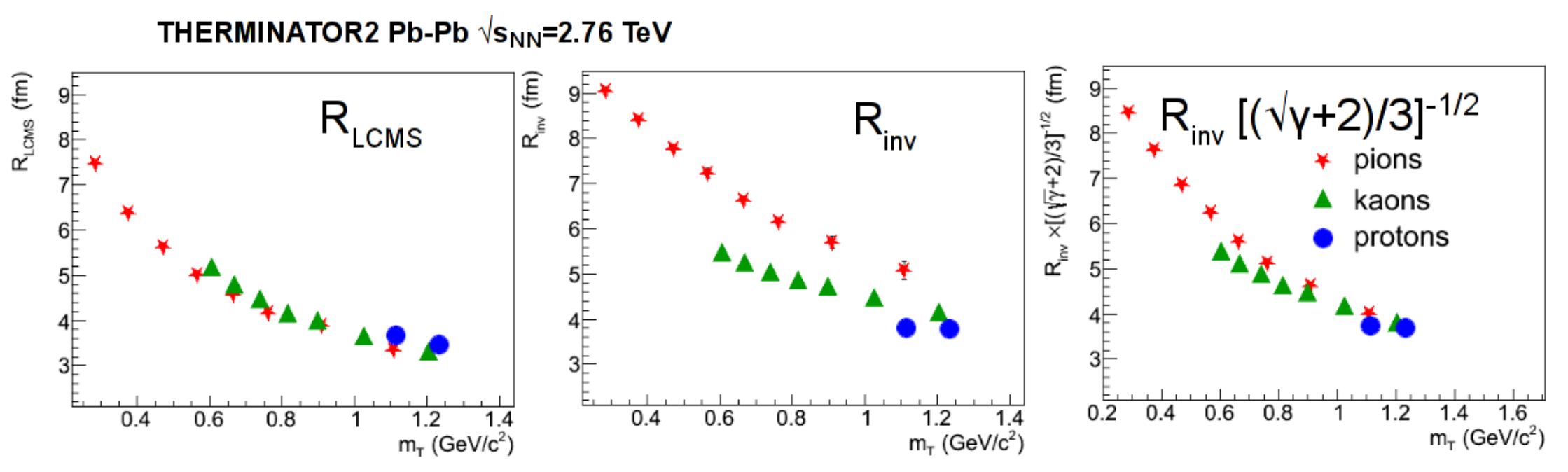

Figure 10 : Transverse mass dependence of the radius calculated in LCMS (left panel), the radius calculated in PRF (middle panel) and the radius calculated in PRF scaled by kinematic factor (right panel). Results were obtained with `THERMINATOR` [4]

Taking this approximation into account, ALICE results from pion, kaon and proton femtoscopy scale with the transverse mass (Fig. 11). Such a tendency enhances the picture of the strongly-interacting system created in heavy-ion collision.

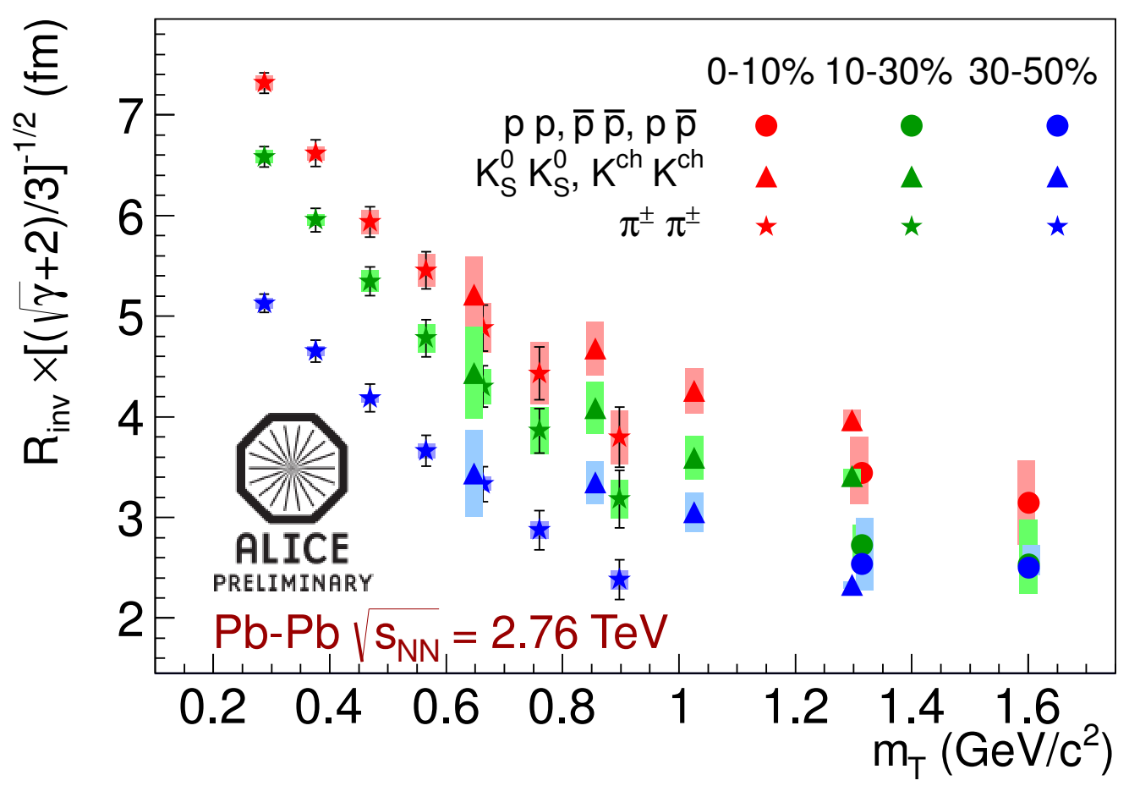

Figure 11 : m_{T} dependence of the radius parameter extracted from correlations of pions, charged kaons, neutral kaons and protons.

Λ femtoscopy

We also present the measurements of $\Lambda\bar{\Lambda}$ correlations in in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV registered by the ALICE experiment. The motivation for Λ baryon femtoscopy is to complement previous studies, as well as to probe the little-understood strong interactions of these baryons.

Λ ($\bar{\Lambda}$) candidates were extracted by identifying daughter tracks using TPC and TOF detectors. The signal quality was estimated using a ratio of real and background counts in the invariant mass spectra (left panel of Fig. 12). The background was estimated using a fourth order polynomial. The number of real Λ was then estimated by counting the bin content and subtracting the background. The signal quality was found to be $real/(real + background) \approx 0.82$. Two-track effects were taken into account. As an example, the average separation of daughter tracks was studied revealing the effects of splitting and merging (right panel of Fig. 12).

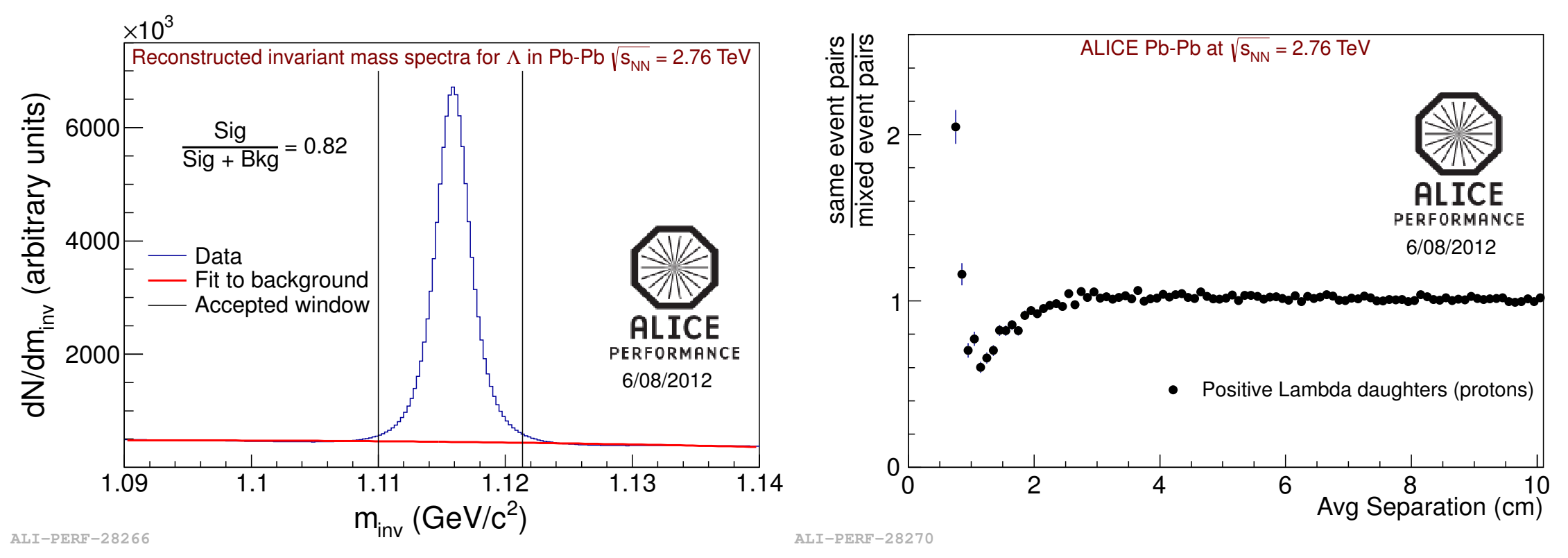

Figure 12 : Invariant mass distribution for reconstructed Λ's baryons (left panel). Correlation function vs. average separation distance in the TPC for proton daughters of Λ's (right panel).

As one can see in Fig. 13, $\Lambda\bar{\Lambda}$ correlation functions for three different centralities ranges show clear suppression at low relative momentum. It is consistent with annihilation in the strong FSI between baryons and antibaryons. The strength of the correlation effect increases with more peripheral events, an indication that the emitting source size is shrinking for those events.

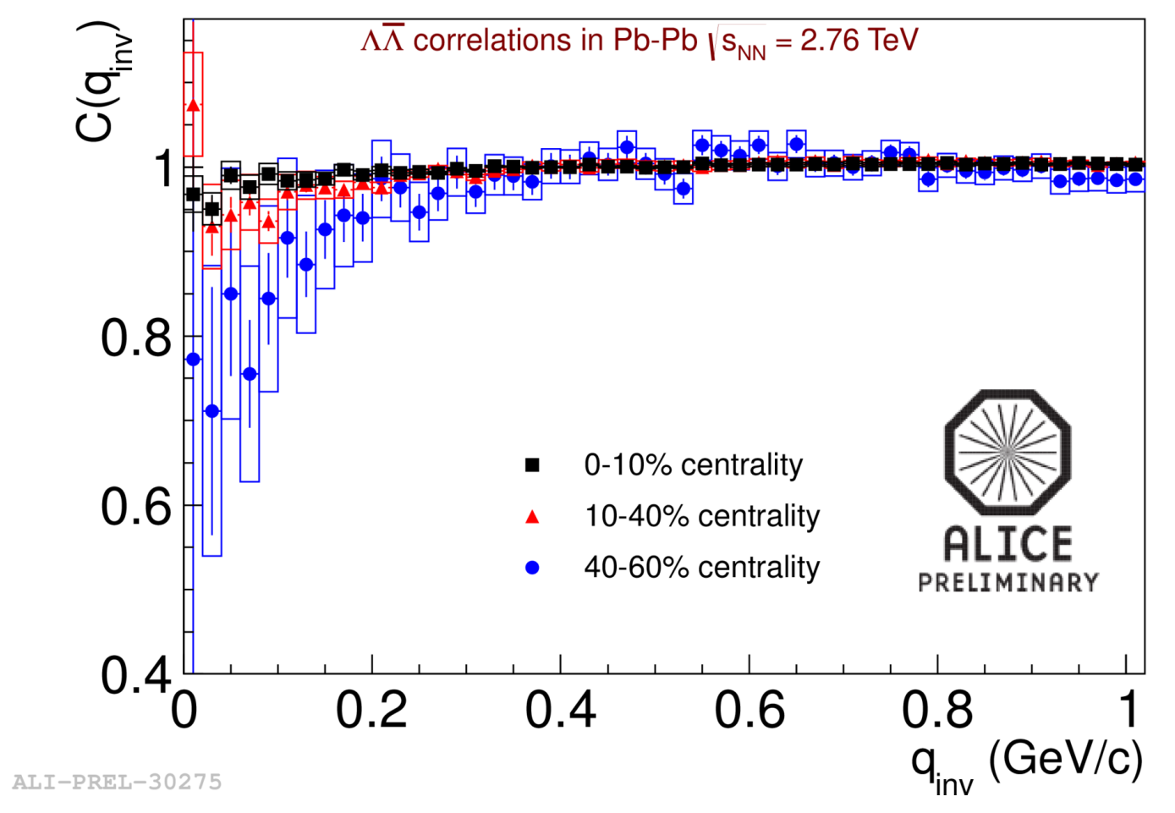

Figure 13 : $\Lambda\bar{\Lambda}$ correlation functions for the $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb.

Summary

Correlations of $\Lambda\bar{\Lambda}$ as well as all combinations of pairs of protons and antiprotons have been measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV in the ALICE experiment. The femtoscopic parameters for the radius of the proton source are extracted from one-dimensional pp, $\mathrm{\bar{p}\bar{p}}$ and $\mathrm{p\bar{p}}$ correlation functions. The fit includes final-state interactions and quantum statistics for identical pairs of (anti)protons. What is more, the fit takes into account residual correlations coming from $\mathrm{p}\Lambda$ system. Two-proton correlations show an increase of the radius with increasing multiplicity.

Observed significant annihilation in baryon-antibaryon correlations may be responsible for the decrease of proton yields at LHC energies with respect to chemical models.

m_{T} scaling of femtoscopic radii for pions, kaons and protons confirm the picture of strongly-interacting system created in heavy-ion collisions.

References

[1] Lednicky, R., Lyuboshitz, V. L.: *Final State Interaction Effect on Pairing Correlations Between Particles with Small Relative Momenta*; Sov.J.Nucl.Phys. 35 (1982) 770

[2] Kisiel, A.: *CorrFit - a program to fit arbitrary correlation functions*; Nukleonika 49;Suppl 2:s81-s83 (2004)

[3] Lednicky, R.: *Finite-size effects on two-particle production in continuous and discrete spectrum*; Phys.Part.Nucl. 40 (2009) 307-352

[4] Kisiel, A., Taluc, T., Broniowski W., Florkowski, W.; *THERMINATOR: THERMal heavy-IoN generATOR*; Comput.Phys.Commun. 174 (2006) 669-687