Source size measurements in the $e^3He(^4He) \to e'p\Lambda X$ reaction

(For CLAS collaboration)

K. Mikhailov,[1,*] A. Stavinsky,[1] A. Vlassov,[1] B. Kerbikov,[1] and R. Lednicky[2]

[1] *Institute of Theoretical and Experimental Physics, Moscow, 117218, Russia*

[2] *Joint Institute for Nuclear Research, Dubna, Moscow Region, 141980, Russia* [†]

Proton-lambda correlations at small relative momentum q were studied in the $e^3He(^4He) \to e'p\Lambda X$ reaction at $E_0 = 4.7(4.46)$ GeV using the CLAS detector at Jefferson Lab. The enhancement of the correlation function at small q was found to be in qualitative agreement with theoretical expectations provided the emission region size parameter r_0 about 1 fm and the $p\Lambda$ scattering length. The exprimental correlation function is compartible with the P-matrix fit of the hyperon-nucleon data. Small relative momentum proton-lambda correlations both for ^{3}He (^{4}He) target and for electro-production reaction was studied for the first time.

I. INTRODUCTION

It was shown by Wang and Pratt [1] that proton-Lambda correlations also can be used for source size study. They found that an enhancement to the pΛ correlation function at low relative momentum allow one to infer the size of the emitting source. The inferred lambda source parameters may provide valuable information because lambdas are strangeness carrying baryons. In some case pΛ correlations might be more sensitive than pp correlations, because of pΛ system has no repulsive Coulomb interaction.

In [2] we already reported data on two-proton correlations at small relative momentum q were studied in eA(^{3}He, ^{4}He, ^{12}C, ^{56}Fe)$\to e'ppX$ reactions. In the study [2] the correlations at small relative momentum (femtoscopy) was applied to study the space-time characteristics of the process in which particles are produced in the kinematic region forbidden to interactions

*Konstantin.Mikhailov@itep.ru

†Institute of Physics ASCR, Na Slovance 2, 18221 Prague 8, Czech Republic

with a single motionless nucleon (so called “cumulative processes”) [3–5]. The measured reaction size for He nuclei proved to be $r_0 \simeq 1fm$.

Kinematical restriction for pΛ system production is even stronger than for pp system. Even for electron interaction with ^{3}He(^{4}He) as a whole the threshold energy transfer should be more then 1 GeV. The study of the small relative momenta correlations for such process appears to be particularly promising. Here we report data on pΛ correlations at small relative momenta in $e^3He(^4He) \to e'p\Lambda X$ reaction, for an incident electron energy of 4.7 (4.46) GeV. The enhancement of the correlation function at small q was found to be in qualitative agreement with theoretical expectations provided the emission region size parameter r_0 about 1 fm. There is the P-matrix description of our experimental data. The corresponding values of the scattering length and effective range both average on the spin states are $a = -2.44$ fm, $r = 2.64$ fm.

Measured $p\Lambda$ correlation function is affected by both residual correlation from $p\Sigma^0$, $\Lambda\Lambda$ correlations [6] and pp correlations for misidentified Λ background. Both effects play significant role for high energy heavy ion collisions at RICH and LHC. Lately there was very interesting results obtained from STAR on pΛ correlations in central $Au+Au$ collisions as $\sqrt{s_{NN}}$=200 GeV which [7]. The so-called the residual correlations was discussed in this paper.

At CLAS, $\Lambda\Lambda$ and $p\Sigma^0$ pair production are next order of the magnitude effects with respect to $p\Lambda$ pair production due to the strong kenimatical restrictions. It provides the possibility to extract and evaluate pp correlation background for $p\Lambda$ correlation. This is an important methodical aspect for high energy heavy ion femtoscopy.

II. DATA SAMPLE AND REACTION IDENTIFICATION

The measurements were performed with the CEBAF Large Acceptance Spectrometer (CLAS) [8] in Hall B at the Thomas Jefferson National Accelerator Facility. The CLAS detector is a six-sector toroidal magnetic spectrometer. The detection systems consist of drift chambers to determine the trajectories of charged particles [9], scintillation counters to measure time of flight [10], Cerenkov counters to distinguish between electrons and pions [11], and electro-magnetic shower calorimeters to identify electrons and neutrons [12]. The CLAS was triggered on scattered electrons detected in the calorimeter with energies above 1 GeV.

Run conditions are described in detail in Ref. [13]. Only events with at least two detected protons within momentum interval 0.3-2.0 GeV/c and at least one negative pion within momentum interval 0.1-0.7 GeV/c were accepted. Misidentifying of electrons, negative pion's or protons was negligible. Λ's were identified by decay into $p\pi^-$. Pairs of tracks hitting a single scintillator were excluded from our analysis because they have ambiguous time-of-flight values.

To reduce target wall events from eHe ones we tuned up the vertex cut using empty target run. The contribution of target wall in the selected events was less 1.5%.

The invariant mass distribution of proton-pion pair for combined statistics of both reaction $e^3He \rightarrow e'pp\pi^-X$ and $e^4He \rightarrow e'pp\pi^-X$ are shown on Fig. 1. All proton-pion combinations in an event were included in the analysis. There are two types of contribution in this figure. First is when both a proton and a pion are from lambda decay. And the second is when both a proton or a pion are direct particles. We will call first one *lambda* contribution and second one call *direct* contribution. The pairs from Λ decay generate a Λ-peak which is clearly seen at the right position on Fig. 1. The other pairs demonstrate smooth phase space dependence. And this contribution under the Λ-peak is not negligible.

To reduce *direct* contribution according strangeness conservation we apply two cuts: on the transferred energy $(\nu - \nu_{min}) > 0.8\ GeV$, and on the missing mass $M^2_{mis} > 2.1\ GeV^2$. Here ν_{min} is the transferred energy according to strangeness conservation in the strong interactions and M_{mis} is the missing mass for reaction under study. The value 0.8 GeV for the transferred energy cut was chosen as a compromise between *direct* contribution reduction and *lambda* contribution saving.

The upper histogram on Fig. 1 is the mass of all $p\pi^-$ pairs (without cuts). The medium histogram on Fig. 1 presents $p\pi^-$ pairs if both cuts on the transferred energy and on the missing mass are applied. The difference between pairs without cuts and with cuts is shown by lower histogram on Fig. 1. After applying these two cuts *lambda* contribution to *direct* contribution ratio for identified Λ for combined statistics of both reaction $e^3He \rightarrow e'pp\pi^-X$ and $e^4He \rightarrow e'pp\pi^-X$ is increased from 0.74 to 0.99 while only 9% of Λ's are lost.

The whole statistics $({}^3He +{}^4He)$ in the invariant mass interval $1.1135 < M_{p\pi^-} < 1.1175 GeV$ is number p-π^- pairs from Λ is 6376, number direct p-π^- 6427 and the total number of p-π^- pairs is 12804.

After all selections the transferred energy ν is between 1.5 and 4.5 GeV with mean value

3.03 GeV. The Q^2 is between 0.6 and 5 $(GeV/c)^2$ with mean value 1.4 $(GeV/c)^2$.

III. CORRELATION FUNCTION.

The measured correlation function ($R_{p\Lambda}(q) = \frac{N_r(q)}{N_m(q)}$) has been defined as the ratio of the measured distribution of the three-momenta difference of the two particles to the reference one obtained by mixing particles from different events of a given class, normalized to unity at sufficiently large relative momenta [14]. Here $q = |\vec{q}|$, $\vec{q} = (\vec{p_p} - \vec{p_\Lambda})$- is momentum difference between proton and Λ in $p\Lambda$-pair reference frame, all proton-pion pars within Λ invariant mass region are considered as Λ with momentum $\vec{p_\Lambda} = (\vec{p_p} + \vec{p_\pi})$, N_r and N_m are the numbers of $p\Lambda$ pairs from the real events and those combined from protons and lambdas taken from different (i.e. mixed) events, respectively.

The measured $p\Lambda$ correlation function is shown in Fig. 2. All experimental cuts are applied. The correlation function shows a pronounced enhancement in the small relative momenta q. There is a slow dependence of the correlation function on q (at $q \geq 0.2GeV/c$. The same dependence was for proton-proton correlation for reaction $eHe \rightarrow\ e'\ p\ p\ X$ in our previous paper [2]. This correlations (so-called long-range correlations(LRC)) arise mainly from momentum conservation for real events which is not a requirement for mixed pairs. LRC cause a smooth increase of R with q, which reflects the fact that due to momentum conservation the probability of two particles emitted in the same direction is smaller than that of two particles emitted in opposite directions.

Empirically, LRC can be parametrized by $R \propto \exp(b \cos\psi)$, in which ψ is the angle between the two particles and b is a constant [15]. Practically, accounting for such a week dependence of the correlation function on q is usually taken into account by introducing into data fit a factor $(1 + const \cdot q^2)$ [2]. The corrected on LRC proton-lambda correlation functions is shown on Fig. 3. Indeed, both uncorrected and corrected for LRC correlation functions (Fig. 2 and Fig. 3 respectively) clearly show the enhancement of the correlation function at small q.

The decay momentum for $\Lambda \rightarrow p\pi^-$ (0.101GeV/c) is relatively small. Small relative momenta region for p-Λ system corresponds to small relative momenta region for primordial proton and proton from Λ-decay. It means that in study of p-Λ correlations at small relative momenta one must take into account close-track efficiency for proton pairs in the reaction

$eHe \to e'pp\pi^- X$ when the $p\pi$ pair mass close to M_Λ.

The ability to detect two tracks with a small relative momentum is limited because both particles hit the same or neighboring detector cells. A detailed study of the close-track efficiency $\varepsilon(q)$ has been done in Ref. [16]. We apply close-track efficiency correction for pair of protons in the same manner as in [2]. The close-track efficiency for measured correlation function is shown by the line on Fig. 3. It is not large and much more smooth compaired to the proton-proton corrections [2].

The calculation p-Λ correlation function will be according to formula

$$R_{p\Lambda+pp\pi} = \eta \cdot R_{p\Lambda} + (1-\eta) \cdot R_{pp\pi} \ , \qquad (1)$$

where $\eta \simeq 0.5$ is the ratio of Λ-pairs to $p\pi^-$-pairs when $M_{p\pi} \sim M_\Lambda$. $R_{p\Lambda+pp\pi}$ is the measured correlation function which is a combination of both $p\Lambda$ and $pp\pi$ correlation functions.

To measure $p-p\pi$ correlation itself (from *direct* contribution) we used three different experimental methods. First is $p-p\pi^-$ correlation function for events when $M_{p\pi^-}$ is out of Λ-peak ($M_{p\pi^-} < M_\Lambda$ or $M_{p\pi^-} > M_\Lambda$). We used two mass interval: $1.1055\ GeV < M_{p\pi^-} < 1.1135\ GeV$ and $1.1175\ GeV < M_{p\pi^-} < 1.1255\ GeV$. Second is $p-p\pi^+$ correlation function for the events when $M_{p\pi^+}$ is out of Λ-peak with the same mass intervals as for $p-p\pi^-$ correlation function. And the third is $p-p\pi^+$ correlation function for events when $M_{p\pi^+}$ is in the Λ-peak. We used the same mass interval as for $p-\Lambda$ correlation function ($1.1135\ GeV < M_{p\pi^-} < 1.1175\ GeV$). The three $p-p\pi$ correlation function are shown on Fig. 4. We can conclude that all three methods are in agreement within statistical errors.

Methodically second method and third method are very close to each other. To see how $p-p\pi$ correlation can affect on final $p\Lambda$ correlation function we use three variants of $p-p\pi$ correlation function measurements. First is $p-p\pi^-$ correlation function for the out of Λ-peak in $M_{p\pi^-}$. Second is average $p-p\pi^+$ correlation function for the out of Λ-peak in $M_{p\pi^+}$ and for the in of Λ-peak in $M_{p\pi^+}$. And third is average of $p-p\pi^-$ and $p-p\pi^+$ correlation functions.

It should be noted that $R_{pp\pi} \neq 1$ and consistent with pp-correlation function measured in [2] smeared out by adding pion momenta. Statistical errors in $R_{pp\pi}$ two times better then one for combined measured $R_{p\Lambda+pp\pi}$.

Fig. 5 shows derived proton-lambda correlation function $R_{p\Lambda}(q)$ corrected for close-track efficiency $\varepsilon(q)$, "long-range" correlations(LRC), and direct $p - p\pi$ contribution. Statistical and systematic errors have been added in quadrature. The data in Fig. 5 are averaged over proton and Λ momenta as well as over ν and Q^2. The average correlation effect over $0 < q_{p\Lambda} < 0.180 GeV/c$ is equal 2.33 ± 0.45 which corresponds to 2.96 standard deviation from unit (without correlation effect).

The proton and Λ momentum resolution within the selected kinematic range is estimated to be $\delta p/p \sim 2$ %. Since δp is typically much smaller than the width of the effects under study, the measured correlation functions are only slightly smeared out by the momentum resolution. The momentum resolution corrections were estimated by applying the smearing procedure n times to the measured CF and then extrapolating the results to $n = -1$. This correction proved to be negligible.

IV. DATA ANALYSIS.

A. The source size

The two-particle correlation function at small k^*-values is basically given by the square of the wave function of the corresponding elastic transition $ab \to ab$ averaged over the distance $\mathbf{r}^*$ of the emitters in the two-particle c.m. system and over the particle spin projections [17]:

$$\mathcal{R}(\mathbf{p}_1, \mathbf{p}_2) \doteq \langle |\psi^{S(+)}_{-\mathbf{k}^*}(\mathbf{r}^*)|^2 \rangle$$
$$\doteq 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 + \frac{2\Re f^S(k^*)}{\sqrt{\pi} r_0} F_1(Qr_0) - \frac{\Im f^S(k^*)}{r_0} F_2(Qr_0) \right], \quad (2)$$

where $F_1(z) = \int_0^z dx e^{x^2 - z^2}/z$ and $F_2(z) = (1 - e^{-z^2})/z$ and ρ_S is the emission probability of the two particles in a state with the total spin S; we assume the emission of unpolarized particles, i.e. $\rho_0 = 1/4$ and $\rho_1 = 3/4$ for pairs of spin-1/2 particles. The analytical expression in Eq. (2) corresponds to the Gaussian $\mathbf{r}^*$-distribution:

$$d^3N/d^3\mathbf{r}^* \sim \exp(-\mathbf{r}^{*2}/4r_0^2). \quad (3)$$

The mean-square radius r_{rms} is equal $\sqrt{3} r_0$. It implies a small radius of the FSI interaction as compared with the characteristic separation of the emitters in the two-particle c.m. system. The non-symmetrized wave function describing the elastic transition can then be approximated by a superposition of the plane and spherical waves, the latter being dominated by the s-wave,

$$\psi^{S(+)}_{-\mathbf{k}^*}(\mathbf{r}^*) \doteq \exp(-i\mathbf{k}^*\mathbf{r}^*) + f^S(k^*)\frac{\exp(ik^*r^*)}{r^*}. \quad (4)$$

The s-wave scattering amplitude

$$f^S(k^*) = \frac{\eta^S \exp(2i\delta^S) - 1}{2ik^*} = (1/K^S - ik^*)^{-1}, \quad (5)$$

where $0 \leq \eta^S \leq 1$ and δ^S are respectively the elasticity coefficient and the phase shift, K^S is a function of the kinetic energy, i.e. an even function of k^*. In the effective range approximation,

$$1/K^S \doteq 1/a^S + \frac{1}{2}d^S k^{*2}, \quad (6)$$

where a^S and d^S are respectively the s-wave scattering length and effective radius at a given total spin S; in difference with the traditional definition of the two-baryon scattering length, we follow here the same sign convention as for meson-baryon or two-meson systems.

One can introduce the leading correction $\mathcal{O}(|a^S|^2 d^S/r_0^3)$ to the correlation function in Eq. (2) to account for the deviation of the wave function (4) from the true solution inside the range of the two-particle strong interaction potential [17]:

$$\Delta\mathcal{R}(\mathbf{p}_1, \mathbf{p}_2) = -(4\sqrt{\pi}r_0^3)^{-1}\sum_S \rho_S |f^S(k^*)|^2 d^S(k^*), \quad (7)$$

where the function $d^S(k^*) = 2\Re d(K^S)^{-1}/dk^{*2}$; $d^S(0)$ is the effective radius.

It should be noted that the two particles are generally produced at non-equal times in their c.m. system and that the wave function in Eq. (2) should be substituted by the Bethe-Salpeter amplitude. The latter depends on both space ($\mathbf{r}^*$) and time (t^*) separation of the emission points in the pair rest frame and at small $|t^*|$ coincides with the wave function ψ^S up to a correction $\mathcal{O}(|t^*/mr^{*2}|)$, where m is the mass of the lighter particle. It can be shown that the equal-time approximation in Eq. (2) is usually valid better than to few percent even for particles as light as pions [17, 18].

The K^S-function and the low energy scattering parameters are real in the case of only one open channel as in the near threshold $p\Lambda$ scattering. For $p\Lambda$ system, we use the values from [1] $a^0 = 2.88$ fm, $a^1 = 1.66$ fm, $d^0 = 2.92$ fm and $d^1 = 3.78$ fm (the same values were used in STAR experimental paper [7]).

The curves in Fig. 5 correspond to $r_{\rm RMS} = 1.5$ fm ($r_0 = 0.85 \pm 0.25 fm$). We neglect here the emission duration which is effectively absorbed in the parameter $r_{\rm RMS}$. Since the contemporary theoretical approaches do not consider the relation between extracted source-size parameters and the real value of R at large q, both correlation functions and the theoretical curves are normalized to unity for $q > 0.2$ GeV/c. Theory predicts [17, 19] that the enhancement of R at small q is inversely related to the measured size parameter. For large $r_{\rm RMS}$ values, the correlation function is mainly determined by the solution of the scattering problem outside the range of the strong interaction potential, and is therefore independent of the actual form of the potential, provided that it correctly reproduces the scattering amplitudes [17, 20].

Calculated curve is in reasonable agreement with data. Measured source size proved to be consistent with one for semi-inclusive two proton electro-production reaction for ^{3}He and ^{4}He target at approximately the same initial energy [2].

Experimental systematic errors on $r_{\rm RMS}$ arise mainly from uncertainty in the direct $p-p\pi$ contribution ($\approx 10\%$ with respect to statistical errors), $\Sigma \to \Lambda\gamma$ contribution($\approx 20\%$) [21], close-track efficiency correction ($\approx 5\%$), the correction for long-range correlations ($\approx 5\%$), and the correction for momentum resolution ($\approx 2\%$).

B. The P-matrix approach to the Λp FSI

Ten years ago the data set on low energy YN interaction available at that time was successfully described [22, 23] within the framework of the Jaffe-Low P -matrix [24]. The P–matrix establishes the connection between the scattering data and the multi-quark states. From that point of view the coupled $\Lambda N - \Sigma N$ channels with $I = 1/2$, $J^P = 0^+$ are particularly interesting. It has been known for a long time that a pole exists near the $\sum^+ n$ threshold in the $^3S_1$ hyperon-nucleon scattering amplitude [25] -[28]. There has been a good deal of controversy concerning the position of this pole and its nature [28], [29]-[32]. The P-matrix analysis performed in [22, 23] favors the identification of this structure with the $SU(3)$ partner of the deuteron. Such a pole may be called a $\sum N$ bound state and a Λp resonance, or an unstable bound state according to the classification of Ref. [30]. The genuine six-quark state [33, 34] can not be responsible for the structure near the $\sum N$ threshold since the corresponding pole moves away from the physical region when the coupling between the quark and hadronic channels is turned on [22, 23].

We applied the P-matrix analysis of the YN interaction to the new CLAS data on Λp

correlation near threshold. The P-matrix approach was reformulated in the spirit of the Migdal-Watson FSI theory[35]. The energy region where the resulting equations can be applied is not as wide as the applicability region of the original P-matrix. We were not permitted to use our approach up to the $\sum N$ threshold. However our present study confirms the conclusions made in [22, 23] on the location and the nature of the pole near the $\sum N$ threshold since the new CLAS data will be rather accurately described by the set of the P-matrix parameters obtained in [22]. The correlation function $R_{p\Lambda}(\varepsilon)$ calculated according to P-matrix [24] analysis of the YN interaction is presented in Fig. 6. Corresponding scattering length and effective radius are $a = 2.44$ fm, $d = 2.64$ fm. The agreement with the experimental data is reasonable.

V. SUMMARY

Being summarized small relative momentum correlations between proton and Λ produced in eHe interactions at 4.5-4.7 GeV have been investigated. For He nuclei in electro-production reaction was done for the first time.

The data clearly show a narrow structure in the correlation function in the region of small relative momenta ($q < 0.2$ GeV/c), which is in qualitative accordance with theoretical expectations.

The important $p - p\pi$ correlations were studied. It was shown that $p - p\pi$ pairs in the region of $M_{p\pi}$ M_Λ are correlated. The measured proton-Λ correlation function was corrected on $p - p\pi$ correlations.

Source size for strangeness production reaction proved to be consistent with one measured in semi-inclusive two proton production reaction.

The experimental proton-lambda correlation function is compatible with the P-matrix fit of the hyperon-nucleon data.

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Измерение размеров источника протона и лямбда в реакции $e^3He(^4He) \to e'p\Lambda X$

К.Михайлов, А. Ставинский, А. Власов, Б. Кербиков, Р. Ледницкий

В работе изучены узкие корреляции пар протон-лямбда в реакции $e^3He(^4He) \to e'p\Lambda X$ при энергии пучка электронов 4.7 ГэВ. Работа выполнена на установке CLAS в лаборатории Джефферсона (США). Наблюдаемый корреляционный эффект в области малых относительных импульсов согласуется с теоретическим описанием в рамках модели независимых источников. Измеренный размер области излучения пар протонв и лямбда оказался масштаба 1 фм. Экспериментальная корреляционная функция согласуется с теоретическим описанием в рамках P-матричного подхода к гиперон-нуклонному взаимодействию в конечном состоянии. Корреляции протон-лямбда пар в электророждении на ядрах ^3He и ^4He были имерены впервые.

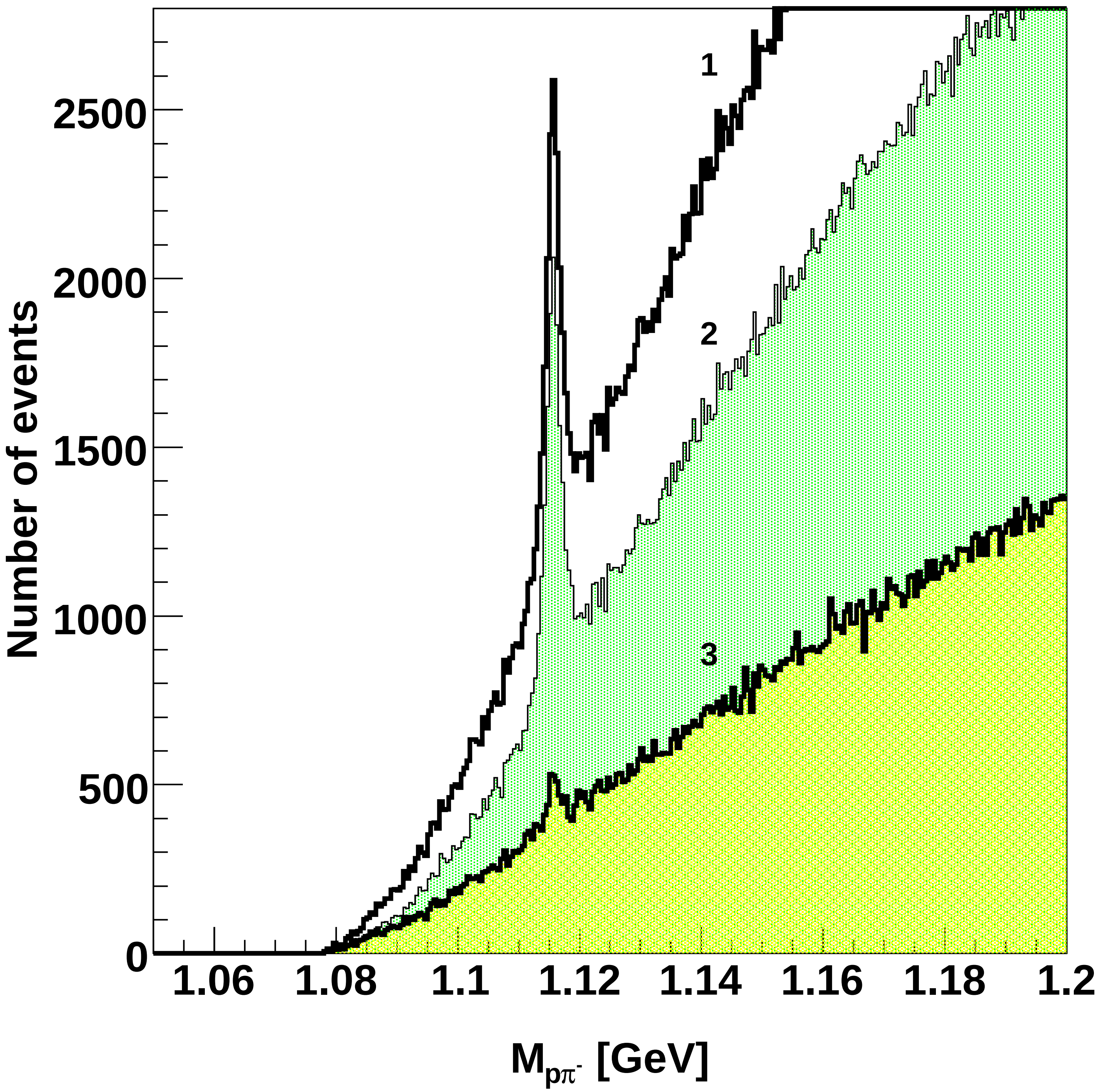

Fig. 1: The p-π^- pairs invariant mass distribution for $e^3He(^4He) \rightarrow e'pp\pi^-X$ reaction. Upper histogram(1) -all pairs, medium(2)-pairs rejected by the cut $\nu - \nu_{min} > 0.8$ GeV, and the missing mass cut $M^2_{mis} > 2.1$ GeV^2. Lower - the difference between (1) and (2).

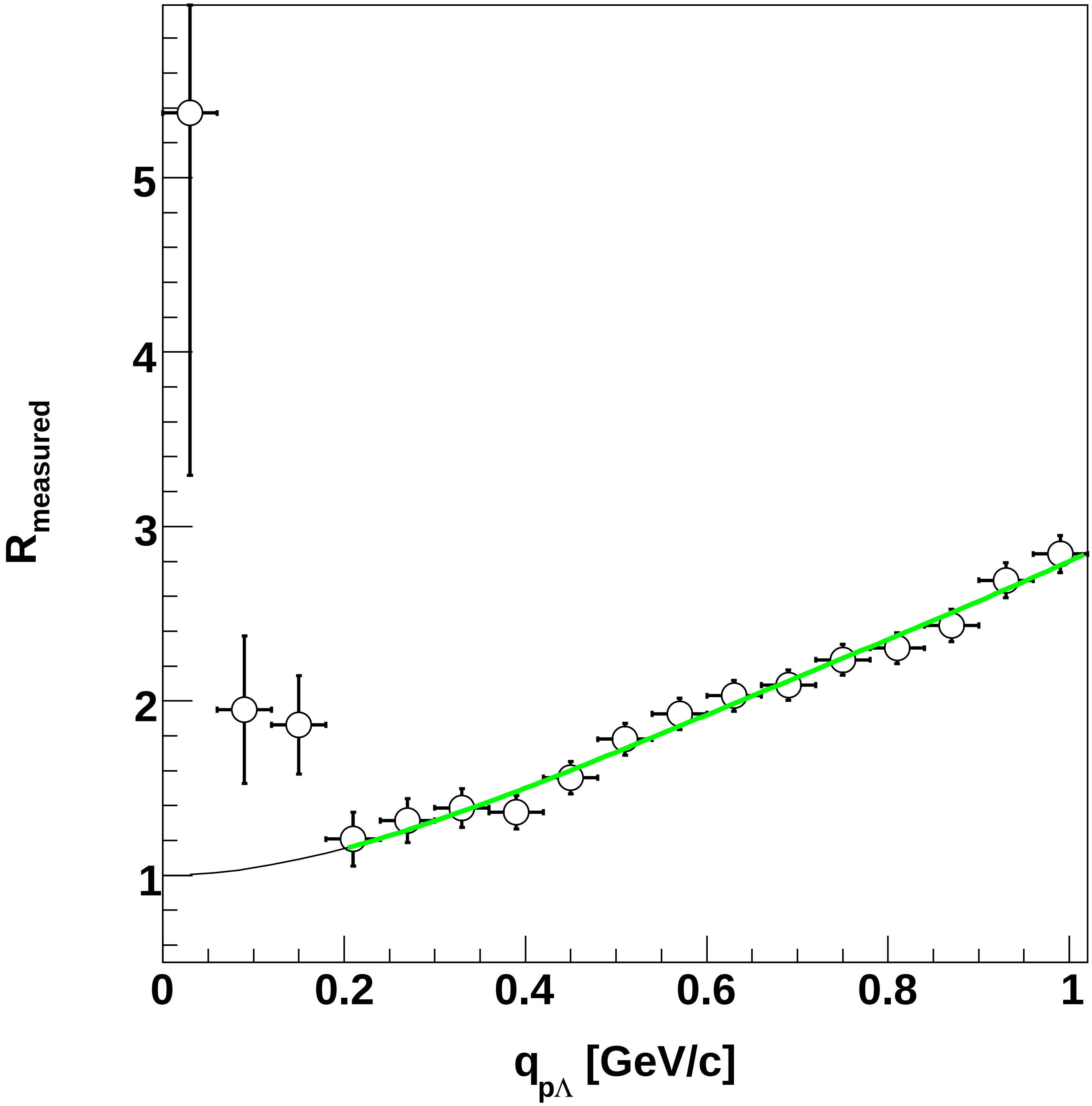

Fig. 2: Measured correlation function. The curve shows corrections on long-range correlation.

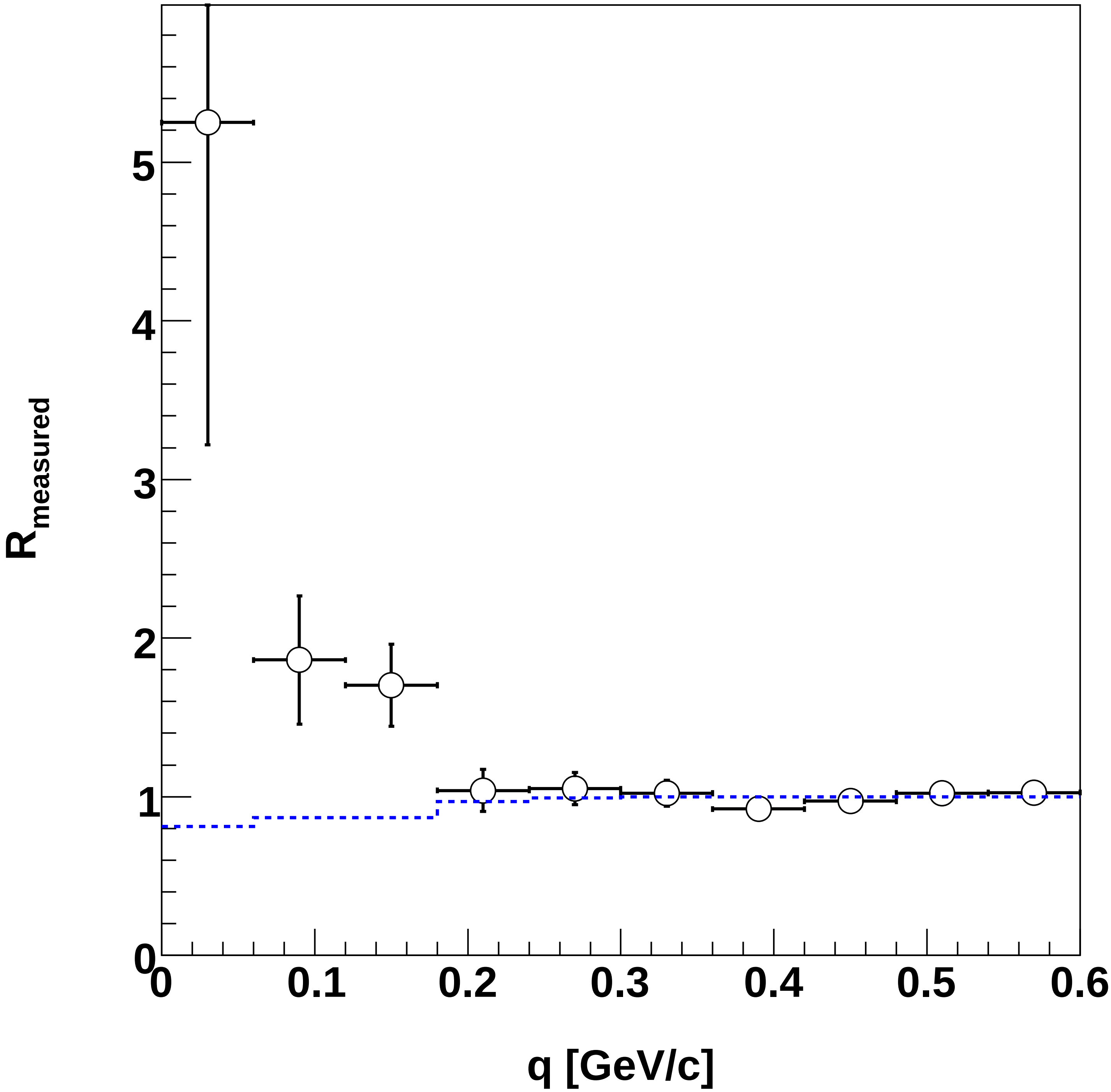

Fig. 3: The measured correlation function which is corrected on long-range correlation (open cycles). The dashed line corresponds to the close track efficiency.

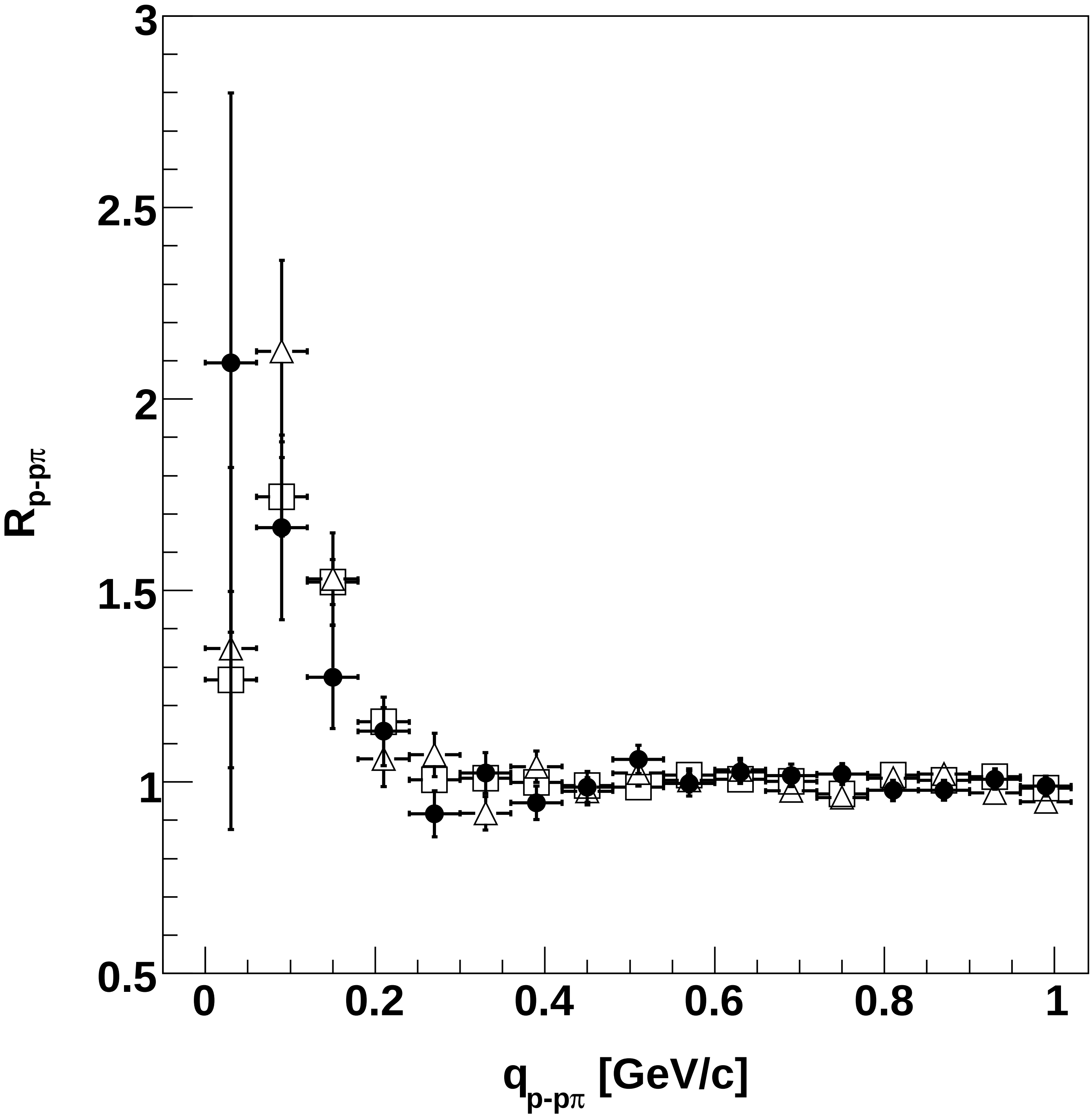

Fig. 4: Comparison of $p - p\pi$ correlation functions which are measured by three different methods. Symbols: cycles correspond to $p - p\pi^-$ correlation function for events when $M_{p\pi^-}$ is out of Λ-peak ($M_{p\pi^-} < M_\Lambda$ or $M_{p\pi^-} > M_\Lambda$), open squares correspond to $p - p\pi^+$ correlation function for the events when $M_{p\pi^+}$ is out of Λ-peak, open triangles correspond to $p - p\pi^+$ correlation function for events when $M_{p\pi^-}$ is in the Λ-peak.

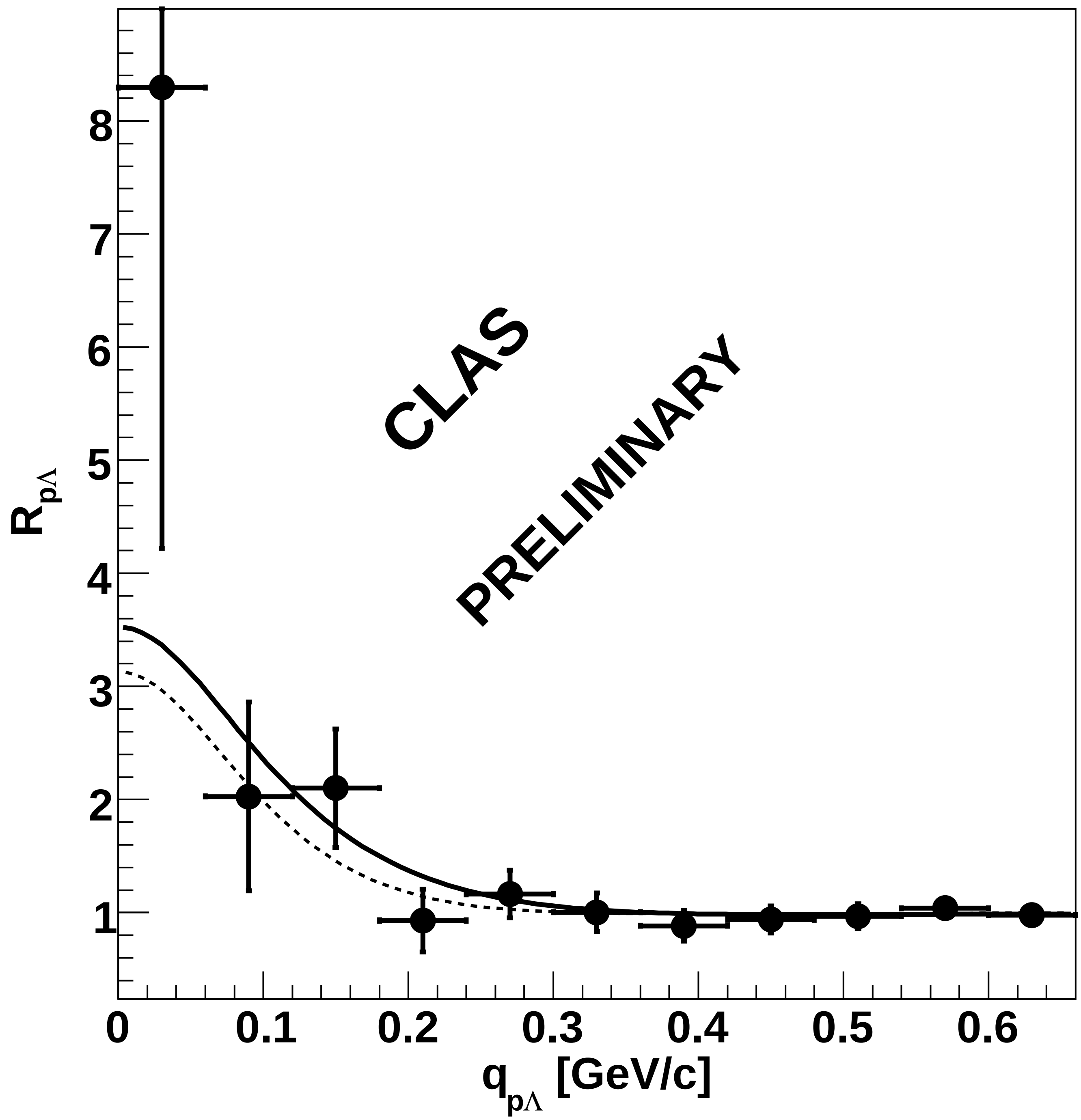

Fig. 5: The derived proton-Λ correlation function $R_{p\Lambda}$. Corrections for close-track efficiency, "long-range" correlations, and direct $p-p\pi$ contribution are applied. Solid curve corresponds to the sorce size parameter $r_0 = 0.85fm$. The dahsed curve corresponds to $r_0 = 1.2fm$

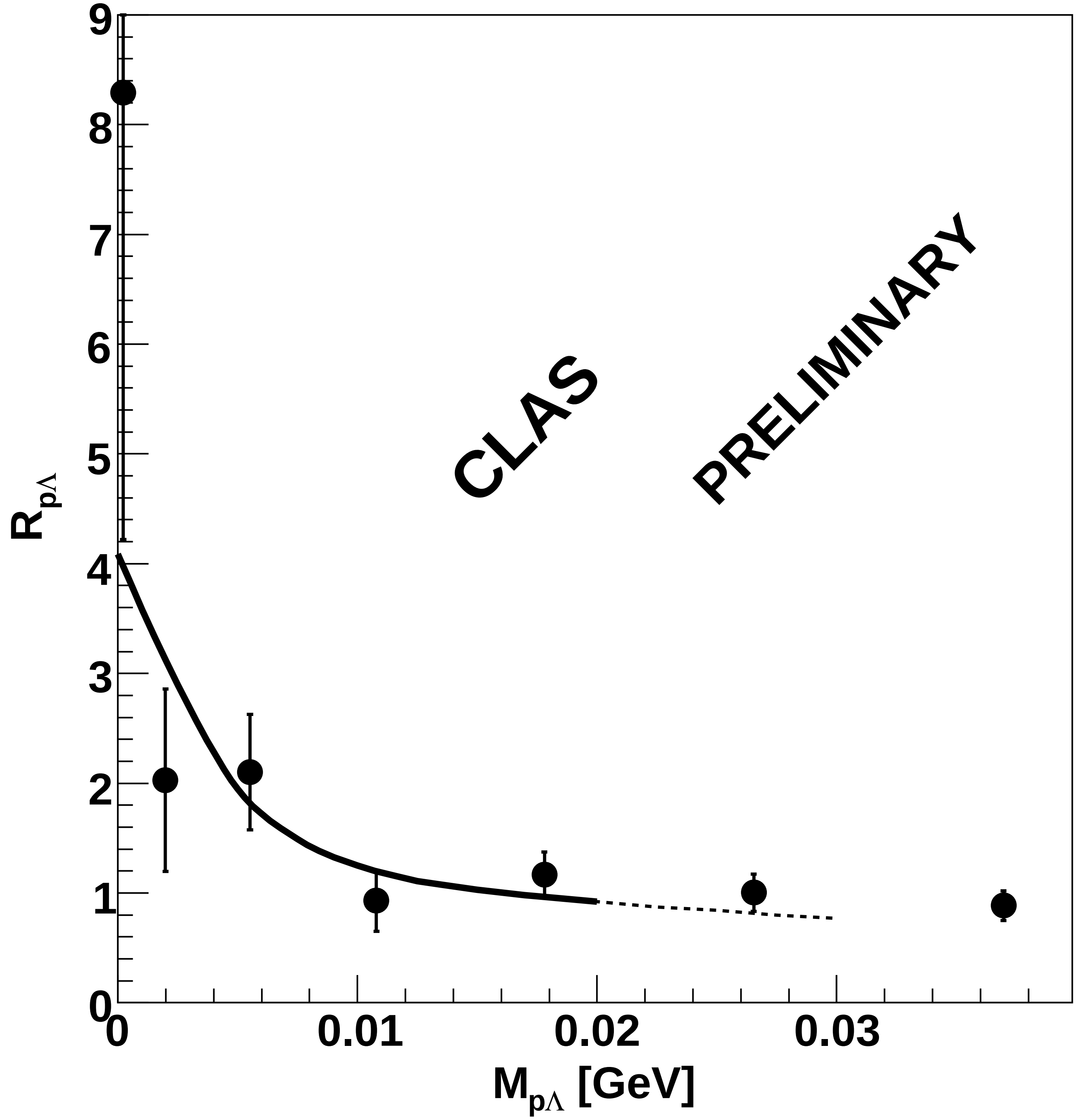

Fig. 6: The proton-Λ experimental correlation function versus the invariant mass of proton and lambda. The curve is the description of the experimental data by P-matrix approach (solid part corresponds to the region where P-matrix decsription is legitimate to the standard effective range approximation for the Migdal-Watson theory).