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Dalitz plot analysis of the $pp \to pK^+\Lambda$ reaction to extract N*-resonances, cusp and FSI contributions

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The $pp \to pK^+\Lambda$ reaction has been measured exclusively with the COSY-TOF detector at 2.95 GeV/c beam momentum. The Dalitz plot shows contributions of hyperon nucleon final state interaction (FSI), N* - resonances and the so called cusp effect. This is a coupled channel effect at the $p\Sigma^0$ production threshold and it manifests itself as an enhancement in the $p\Lambda$ subsystem. To separate the different contributions, the Dalitz plot is fitted with a modified ISOBAR model, which takes into account the N*-resonances, the $p\Lambda$-final-state interaction and the cusp effect on an amplitude level and which allows interferences between the different terms. A first fit is shown, which describes the data well. To extract physics properties the model will be improved (e.g. description of cusp effect with Flatte formalism). New data measured at 2.7 GeV/c beam momentum, where the relative contribution of the cusp effect is found to be much smaller, will be fitted with the same model.

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1. Introduction

The $pp \to pK^+\Lambda$ reaction has been studied at different beam energies with the COSY-TOF detector (for recent work see [1, 2]). From these measurements one observes different reaction mechanisms. These are the hyperon nucleon final state interaction (FSI), N*-resonances and the so called cusp effect. This is a coupled channel effect at the $p\Sigma^0$ production threshold and it manifests itself as an enhancement in the $p\Lambda$ subsystem [3].

To obtain information of the different contributions, the Dalitz plot is fitted with a modified ISOBAR model [4] which will be described in detail later. This fit needs a Dalitz plot with high resolution and statistics, which can be achieved with the COSY-TOF detector.

2. Experimental Setup

The COSY-TOF detector is situated at one of the external beam lines of the Jülich COoler SYnchroton COSY and is shown in Figure 1 together with the different detector components and an event example of the $pp \to pK^+\Lambda \to pK^+(p\pi^-)$ reaction. The detectors are inside a 3 m long vacuum vessel of 2.5 m diameter.

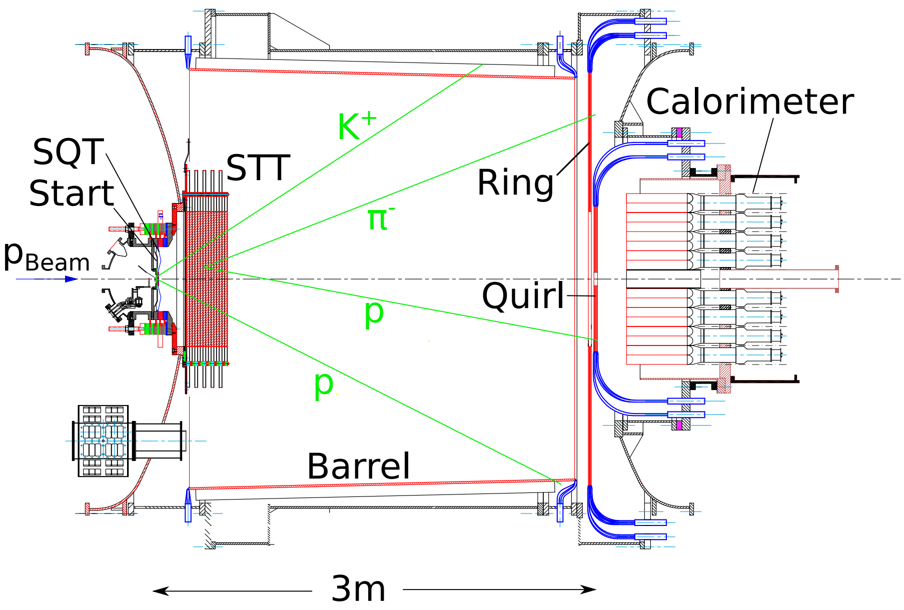

Figure 1: A schematic picture of the COSY-TOF detector together with the different detector subsystems and an example event of the $pp \to pK^+\Lambda \to pK^+(p\pi^-)$ reaction.

The proton beam from the accelerator hits a liquid hydrogen target, which is a cylinder of 6 mm diameter and 4 mm length with 0.9 μm thick hostaphan foil at its ends. The produced charged particles of the $pp \to pK^+\Lambda \to pK^+(p\pi^-)$ reaction are registered by different detector subsystems for tracking and time-of-fight measurements. The subsystems consist of scintillator detectors (start, ring, quirl, barrel and calorimeter) which provide the signals for the TOF measurement. For tracking information a silicon quirl detector (SQT) and a straw tube tracker (STT) are used.

All final state particles can be reconstructed very precisely and so the delayed hyperon decay can be applied for a clear signature of the reaction because it is clearly separated from the primary vertex. This allows to suppress background processes like $pp \to pp\pi^-\pi^+$ nearly quantitatively. Already from the event geometry the $pp \to pK^+\Lambda$ reaction is kinematically completely determined. With the information of the Λ decay vertex and the known masses of all particles the system has two overconstraints for a kinematic fit. This reduces physical background from the $pp \to pK^+\Sigma^0$ reaction. Because of the good track resolution from the STT the implementation of the time-of-flight measurement into the kinematic fit is not neccessary and would not improve the resolution significantly.

Another feature of the detector is the full 4π acceptance for the forward boosted particles of the $pK^+\Lambda$ reaction and the complete azimuthal and polar symmetry, which reduces systematic uncertainties from inefficiencies of the components.

3. Data

The Dalitz plot from data measured at 2.95 GeV/c beam momentum is shown in Figure 2. The kinematic fit results in $\sim$ 42000 events from 6 days measurement with a reconstruction efficiency of $\sim$ 20 % [10]. The resolution of the $p\Lambda$ invariant mass is $\sigma = 1.1\,\mathrm{MeV/c^2}$ which is a factor of $\sim$ 3 better than in previous COSY-TOF measurements without the STT detector. The distribution clearly deviates from a homegeneous occupation of the available phase space and shows at low $p\Lambda$ invariant mass an enhancement coming from $p\Lambda$ final state interaction and an enhancement at the $p\Sigma^0$ threshold (blue line) from the cusp effect. The green and purple lines indicate the pole position of the 1650 MeV and 1720 MeV N*-resonances, respectively.

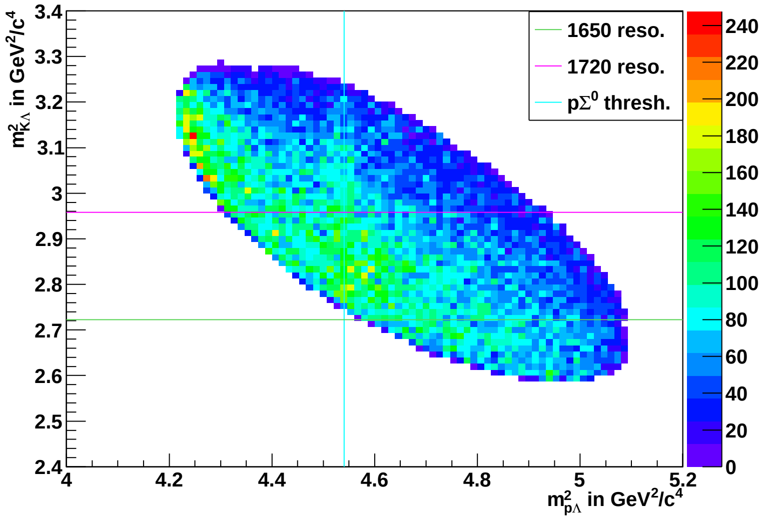

Figure 2: Acceptance corrected Dalitz plot from the data measured at $p_{\mathrm{beam}} = 2.95\,\mathrm{GeV/c}$. Green line: pole position of the 1650 MeV resonance, purple line: pole position of the 1720 MeV resonance, blue line: $p\Sigma^0$ threshold.

4. Model

The measured Dalitz plot is fitted with a modified ISOBAR model [4] to extract physics properties like the contribution of different N*-resonances. Taking into account the N*-resonances, the $p\Lambda$-final-state interaction and the cusp effect on an amplitude level the differential cross section is described by[1]

$$\frac{d^2\sigma}{dm^2_{p\Lambda}\,dm^2_{K\Lambda}} = P \cdot \left| \left(\sum_{\mathtt{R}} (C_{\mathtt{R}} \cdot A_{\mathtt{R}}(m^2_{K\Lambda})) + C_{\mathtt{N}} \cdot A_{\mathtt{N}} + C_{\mathtt{Cusp}} \cdot A_{\mathtt{Cusp}}(m^2_{p\Lambda}) \right) \cdot \left(1 + C_{\mathtt{FSI}} \cdot A_{\mathtt{FSI}}\right) \right|^2.$$

P is a normalization constant to the total cross section σ_{tot}. Two N*-resonances ($S_{11}(1650\text{ MeV})$ and $P_{13}(1720\text{ MeV})$) which have a non vanishing two star branching ratio into $K\Lambda$ [5] are taken into account. Their shapes are described by relativistic Breit-Wigner amplitudes which depend on the squared invariant mass of $K\Lambda$ ($m^2_{K\Lambda}$) and correspond to the $A_{\mathtt{R}}$ terms in the equation. Their parameters for mass and width are the average values from the Particle Data Group 2004 [5] used in the prior analyses of COSY-TOF data [1, 6]. The $C_{\mathtt{N}}A_{\mathtt{N}}$ term describes uniform population of phase-space with a non-resonant background. Its amplitude $A_{\mathtt{N}}$ is set to 1. The $p\Lambda$-final-state interaction amplitude $A_{\mathtt{FSI}}$ is characterized by an ansatz using an effective range expansion [7]. The values for the scattering length and effective range parameters are taken from the Juelich YN-model with parameter set $\tilde{A}$ [8]:

$$\begin{aligned} a_s &= -2.04\,\text{fm} \ , \ r_s = 0.64\,\text{fm} \quad \text{(singlet part)} \\ a_t &= -1.33\,\text{fm} \ , \ r_t = 3.91\,\text{fm} \quad \text{(triplet part)} \\ \tilde{a} &\approx -1.51\,\text{fm} \ , \ \tilde{r} \approx 3.09\,\text{fm} \quad \text{(averaged)} \end{aligned}$$

These values are chosen because they are used in the former Dalitz plot analyses [1, 6]. For first quantitative studies the cusp effect is implemented like the N*-resonances with a relativistic Breit-Wigner amplitude depending on the $m^2_{p\Lambda}$ and the peak position at the $p\Sigma^0$ threshold. The selection of the corresponding width is an important issue and an open question.

The fitting procedure is done with MINUIT and ROOT. The model is fit with the variables $C_{\mathtt{R}}$, $C_{\mathtt{N}}$, $C_{\mathtt{FSI}}$ and $C_{\mathtt{Cusp}}$. Since the model does not respect the kinematic limits, the function value is set to zero outside of the allowed region of the Dalitz plot.

5. Results

The corresponding Dalitz plot of the fit of the model to the measured data at $2.95\,\text{GeV/c}$ beam momentum is shown in Figure 3. The relative contributions of the two N*-resonances are given by this fit to be $C_{N^*(1650)}/C_{N^*(1720)} \sim 2/1$. The best result[2] of the fit has been obtained by assuming the width of the cusp to be $30\,\text{MeV/c}^2$. The structure of the data in the Dalitz plot as well as in the projection on the $m^2_{p\Lambda}$ axis (see Figure 4) is described well by the fit with a reduced $\chi^2 = 1.8$.

[1] the model corresponds to the already used model in COSY-TOF analyses [1, 6] extended with cusp part
[2] lowest χ^2

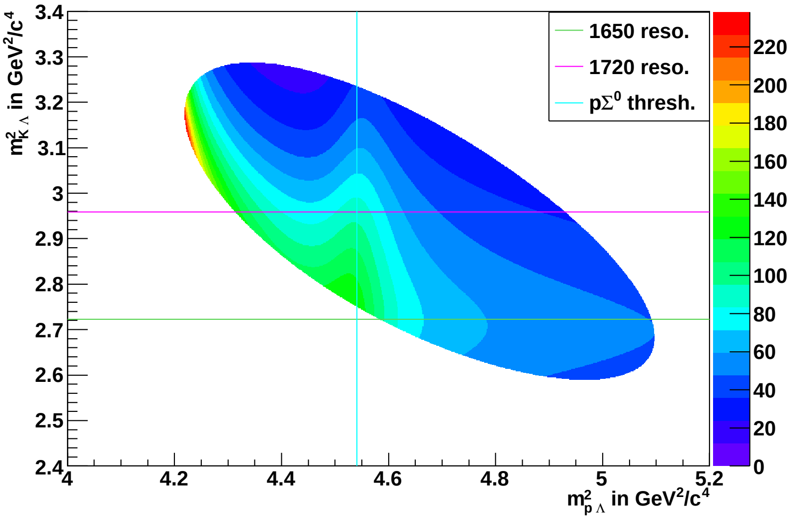

Figure 3: Fit to the Dalitz plot with a cusp width of 30 MeV. Green line: pole position of the 1650 MeV resonance, purple line: pole position of the 1720 MeV resonance, blue line: $p\Sigma^0$ threshold.

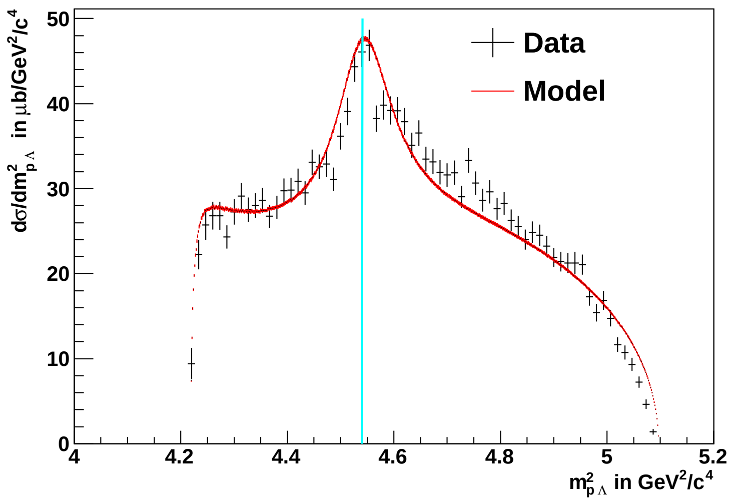

Figure 4: Yield of the data and model (red line) as function of the $m^2_{p\Lambda}$. The light blue line indicates the $p\Sigma^0$ threshold. The fit of the model is rescaled so that the integral yield corresponds to the total cross section.

6. Outlook

Since the data is not complete symmetric around the $p\Sigma^0$ threshold a Breit-Wigner amplitude is not the optimal choice to describe the cusp. It is planned for the future to use a more sophisticated description of the cusp like a Flatte function [9].

Furthermore data at another beam momentum (2.7 GeV/c) is available to study the relative contributions and their energy dependence. The new data has four to five times higher statistics compared to the data at presented here. The contribution of the cusp effect is found to be much weaker in the new data as can be seen in Figure 5 (left), which shows the Dalitz plot of these data. Only in the projection to the $m^2_{p\Lambda}$ axis (Figure 5 right) some small enhancement at the $p\Sigma^0$ threshold is visible.

Additionally, a measurement is planned at a beam momentum higher than 3.15 GeV/c at the end of 2012, which will give more information on the energy dependence of the reaction mechanism in $pp \to pK^+\Lambda$.

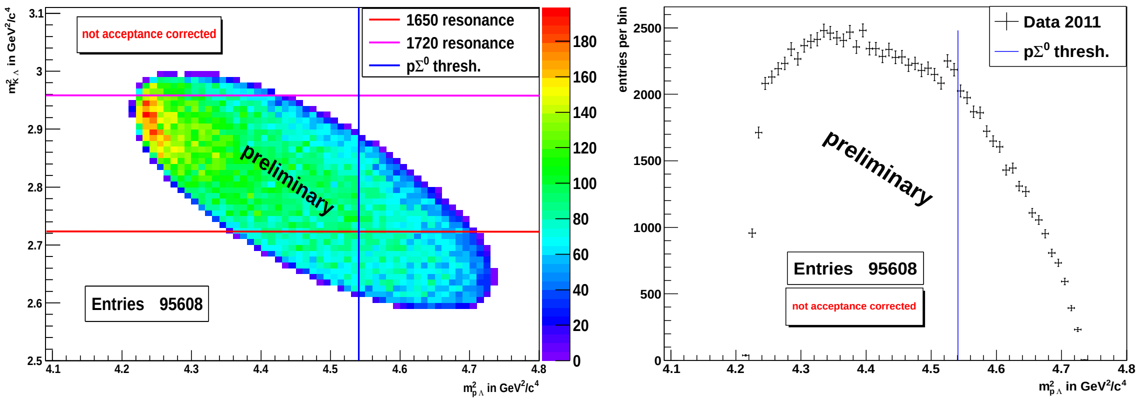

Figure 5: Left: Preliminary Dalitz plot from the data measured at $p_{\text{beam}} = 2.7\,\text{GeV/c}$ (not acceptance corrected). Red line: pole position of the 1650 MeV resonance, purple line: pole position of the 1720 MeV resonance. **Right:** Projection of the preliminary Dalitz plot to the $m^2_{p\Lambda}$ axis. In both pictures the blue line indicates the $p\Sigma^0$ threshold.

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