

# Resolution of SPD Detector in the Search of Dibarions with small energy excitations

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# Introduction

The modern theory of strong interactions admits the possibility of the existence of phase transitions into new forms of nuclear matter in strongly compressed atomic nuclei at relatively low temperatures. In fact, it implies that two nucleons cease to be nucleons and turn into a new state, which can be called a dibaryon.

There are some experimental indications that light dibaryons with energy excitations of a smaller than mass of the pion could be observed in the experiments of Yu. A. Troyan (Yu.A. Troyan, Foz. Elem. Chastits At Yadra 24,683(1993)).

Such phenomena can be observed in MPD, but large number of nucleons involved in that detector can greatly complicate interpretation of their data.

Some additional information can be found in (B.Kostenko, "Coherent Dibaryons", Baldin ISHEPP XXIV, September 2018).

## Introduction, Conditions of the study

So we are talking about  $X$  systems, produced in the reactions  $d + d^- \rightarrow d + X$  with consequent decay

$X^- \rightarrow p + n$ , with mass  $M_X = M_d + E_{exc}$  and  $E_{exc} < m_{\pi^0}$  mass.

Conditions of the study equivalent to the experiment Baldin et al., Communication of the JINR, Dubna 1979, 1-12397

- ▶ Momentum is 2.6 GeV/c, equivalent to 8.9 on fixed target
- ▶ Transferred momentum of unbroken deuteron  
 $t = -0.5(\text{GeV}/c)^2$
- ▶  $E_{exc}$  is taken as a fraction of  $\pi^0$  mass equal to 1/4, 1/2, 3/4 (or masses 1.90935, 1.9421, 1.97685 in GeV)
- ▶ All the collisions are taking place in central point of detector (coordinates  $x = y = z = 0$ ), deuteron and proton tracks and primary vertex are reconstructed and dibarion has zero decay width.
- ▶ SpdRoot is last version from master branch with some modifications. Vertex detector is DSSD.

# Introduction, Results of Baldin experiment

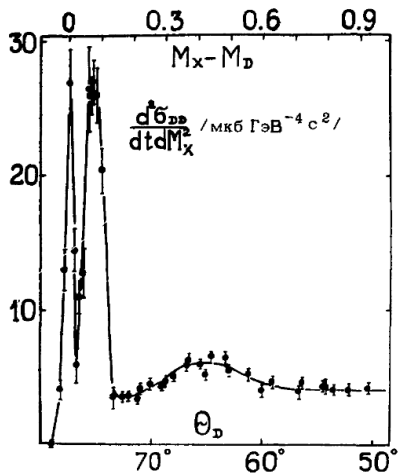


Рис.2. Зависимость двойного дифференциального сечения  $\frac{d^2 \sigma}{dt dM_x^2}$  процессов  $D + D \rightarrow M_x + D$  и  $N + D \rightarrow ND$  от угла эмиссии дейтрона отдачи при  $t \approx 0,5$  (ГэВ/с)<sup>2</sup>.

## What is Resolution?

Under the resolution we understand the width of the distribution(or a signal) of mass estimates of  $X$ . In electronics the width of any signal is characterized by so called FWHM(Full Width at Half Maximum) and if the signal is pure Gaussian, sigma of this Gauss is  $1.18 \cdot \sigma = 1/2FWHM$ . So we may specify the resolution as a  $\sigma$  of the Gaussian function approximating peak region of MX distribution.

**Peak region here is selected by eye and the quality of such a selection can be seen below in a number of figures.**

On the other hand we may use standard deviations(RMS). So we cite the resolution in both ways though we consider citing by  $\sigma$ 's preferable

Gauss with mean = 0 and  $\sigma$ :

$$\exp(-0.5(x/\sigma)^2) = 1 \text{ at } x = 0$$

$$\exp(-0.5(x/\sigma)^2) = 1/2 \text{ at } x = \pm 1.18\sigma$$

# Generator

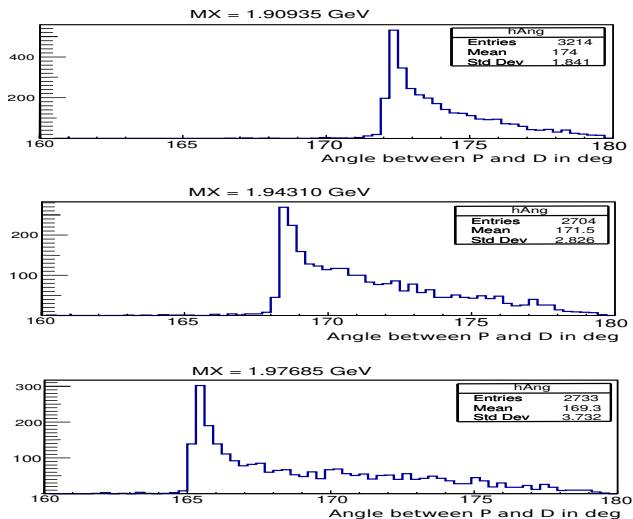


Figure: Angles(in  $^{\circ}$ ) in Collider System between proton and deuteron for  $MX$ , used in this study



# Modification of SpdRoot software

Two modifications were performed : in a track fitting and in Tof processing.

## ► Track Fitting

Earlier, Fit parameters were being obtained in first hit of the track. For the events when primary vertex was found its coordinates were added as additional hit to track hits and track was refitted to get Parameters at the vertex. These modifications were done by V. Andreev and the details of the realization were presented in his talk (see

*https :*

*//indico.jinr.ru/event/3782/contributions/21070/attachments : /15740/26671/Andreev\_24May\_2023.pdf)*

## ► Tof modifications

The aim of this is to get length and time of flight of each particle from primary vertex to its hitting point in Tof detector. Necessary modifications were done by A. Ivanov and also were presented in his talk(*https :*

*//indico.jinr.ru/event/3721/contributions/20660/attachments : /15128/25571/Ivanov.A.V\_18.04.2023.pdf)*

# Processing and fitting Event samples

After reconstruction of event, we have the following observables

1. Three momenta of deuteron and proton
2. Length and time of flight for deuteron and proton

Certainly the estimation should be done according to Maximum Likelihood Method and Total Likelihood Function is the production of 3 Likelihood functions

$$L_{tot} = L_{(Tof_d - Tof_p)} \cdot L_{\vec{p}_d} \cdot L_{\vec{p}_p} \quad (1)$$

Here  $L_{(Tof_d - Tof_p)}$  is Likelihood function for the difference of ToF's for deuteron and proton and we should say few words about it. If we measured the time of event origin then for ToF of deuteron we would have the following expression :

$$Tof_d = (t_d^m - l_d/v_d) \quad (2)$$

Here  $t_d^m$  - measured tof of deuteron,  $l_d, v_d$  - flight length and velocity of deuteron. But as was said above we do not have event origin time and consequently  $t_d^m$ . We can say the same words about

$$Tof_p = (t_p^m - l_p/v_p)$$

. On the other hand ToF system of Spd is measuring the time of their hits and we have the difference  $Tof_d - Tof_p$  and use it at the parameters estimation. We may write for  $L_{(Tof_d - Tof_p)}$  the following:

$$L_{(Tof_d - Tof_p)} \approx \exp(-1/2 \cdot ((Tof_d^m - Tof_p^m)/\sigma_{dif})^2) \quad (3)$$

here  $\sigma_{dif} = \sqrt{2} \cdot \sigma_{tof}$ , where  $\sigma_{tof}$  is the error of tof measurement equal to 60ps.

## Processing and fitting Event samples, continued, 1

$L_{\vec{p}_d}$  and  $L_{\vec{p}_p}$  are due to the measurements from VD+Straw(Track Detectors - TD). So for  $L_{\vec{p}_d}$  we have

$$L_{\vec{p}_d} \approx \exp\left(-1/2 \cdot (\vec{p}_d^t - \vec{p}_d^m) \cdot Cov_d^{-1} \cdot (\vec{p}_d^t - \vec{p}_d^m)^T\right) \quad (4)$$

$\vec{p}_d^t$  and  $\vec{p}_d^m$  respectively - three vectors of deuteron momentum(parameters to be found) and their estimates. The latter and  $Cov_d^{-1}$  are found by GenFit2 during reconstruction.

Analogously for proton

$$L_{\vec{p}_p} \approx \exp\left(-1/2 \cdot (\vec{p}_p^t - \vec{p}_p^m) \cdot Cov_p^{-1} \cdot (\vec{p}_p^t - \vec{p}_p^m)^T\right) \quad (5)$$

$\vec{p}_p^t, \vec{p}_p^m, Cov_p^{-1}$  have the same meaning explained above but for proton

So, number of observables is 7, number of parameters(Three Momenta of deuteron and proton to be found) is 6

# Fit

Fitting was done by Fumili code(S.N. Sokolov, I.N. Silin,Preprint JINR D-810,Dubna). Originally it was written in FORTRAN and rewritten later in C by V. Kurbatov. Here it is used in the application of KinFit(V.Kurbatov, "Kinematical Fitting Technique", Spd Collaboration Meeting, October 2019).

There are three methods of constrained minimization(To be short methods are named more or less arbitrarily):

1. Lagrange's multiplier method
2. Minimization with Heavy Term
3. Minimization with the change of parameter increments

Lagrange's multiplier method(J.P. Berge,F.T. Solmitz,H.D. Taft,Rev. Sci. Instr. 32(1961)538) is the first one where constraint fitting in the particle physics was proposed. It is named after Lagrange who proposed the method for finding the extreme of the functions of many variables with the constraints.

## Fit, Continued 1

Second method was proposed by V.I. Moroz (V.I. Moroz, JINR, P-1958, 1965), when bubble chambers were one of the main instruments in particle physics and it is related with the use of Fumili proposed earlier.

Finally third method was proposed (Nucl. Instr. and Meth. **A345**(1994)346) in 1994. The idea is very simple: using the constraint functions we can express some of parameter increments thru the other ones, effectively decreasing the number of free parameters by quantity of constraint functions, that is

$n_f = n_p - n_c$ . Here  $n_f$  - the number of free parameters (used in the iteration procedure),  $n_p$  - the total number of parameters,  $n_c$  - the number of constraint functions. The last and the second methods were extensively used in ANKE data processing system (COSY).

**By opinion of V. Kurbatov last method may be a good candidate for implementation of constraint fitting in SpdRoot system.** Here 2-nd method was used due to its quick realization!

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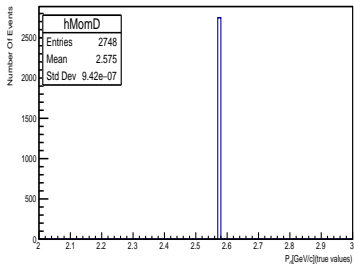
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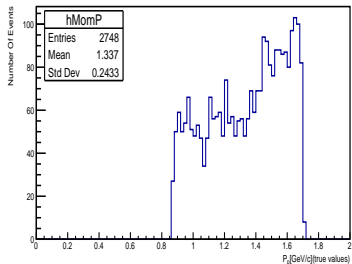
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# Fitting Results

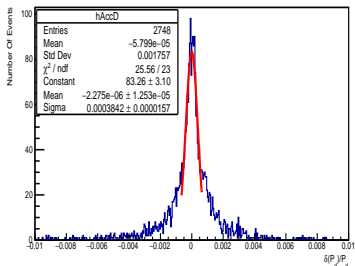
True Values Of Deuteron Momentum in a final state ,MX = 1.94310[GeV]



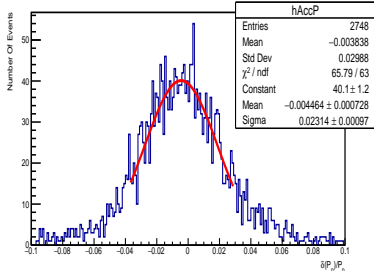
True Values Of Proton Momentum in a final state ,MX = 1.94310[GeV]



Accuracy Of Deuteron Momentum Reconstruction,MX = 1.94310[GeV]



Accuracy Of Proton Momentum Reconstruction,MX = 1.94310[GeV]





# Methods for the Dibarion Mass estimations - 3 Options

Using TD we can measure 3-momentum of deuteron -  $\vec{p}_d$ , or its 4-vector  $P_d^4$ . On the other hand we know mass of the reaction( mass of two colliding deuterons), let denote its 4-vector as  $M_R^4$ . Then we may try to see dibarions just by calculating missing mass:

$$M_X = (M_R^4 - P_d^4).M() \quad (6)$$

If the resolution of TD were sufficiently high( below we show it as the result of the simulation), we would see some peaks in missing mass distribution. We did it in our analysis and let us call it as an Option 1.

On the other hand Spd is measuring also  $P_p^4$  and the difference  $Tof_d - Tof_p$ . If in addition to the information about the deuteron and proton from TD system we add  $Tof_d - Tof_p$  we can try to find the other estimates of deuteron and proton momenta and then analyze missing mass distribution, calculating it by the same formula 6. Let us call it as an Option 2.

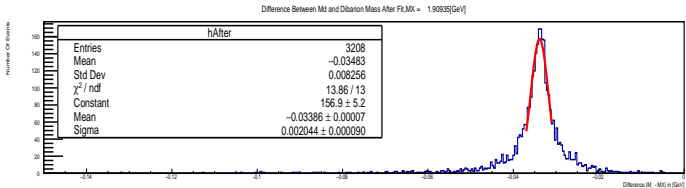
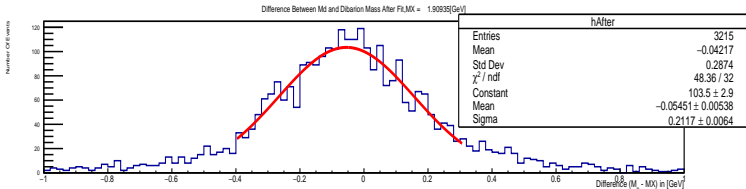
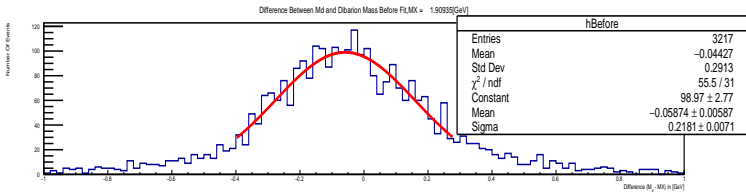
Finally, we know that except of registered deuteron and proton there is unregistered neutron.

We may require the fulfillment of the following equation 7:

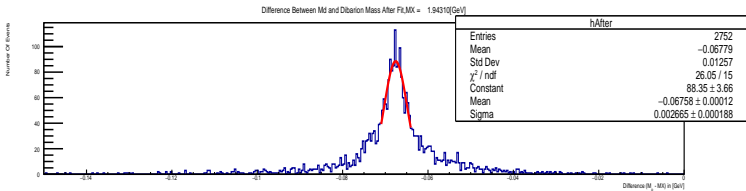
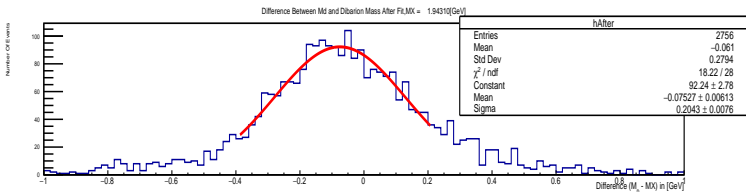
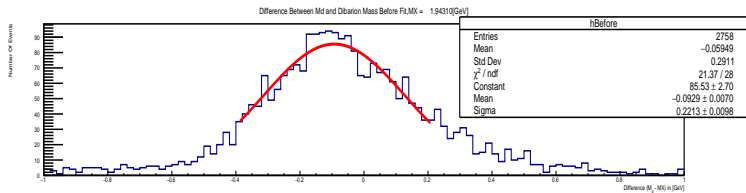
$$M_n^2 = (M_R^4 - P_d^4 - P_p^4).M2() \quad (7)$$

We should do so called constraint fit, in other words we should find momenta of deuteron and proton by maximizing joint Likelihood function 1 with addition of the constraint in the form of missing mass equation 7. Here  $M_n^2$  is square of neutron mass. We call it as an **Option 3**.

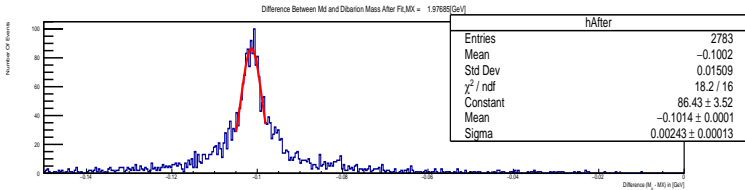
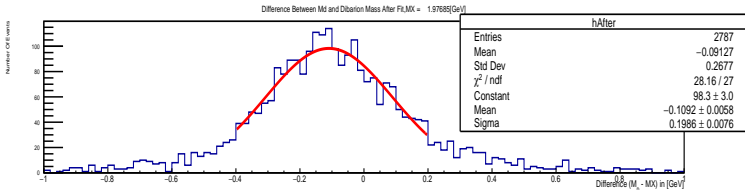
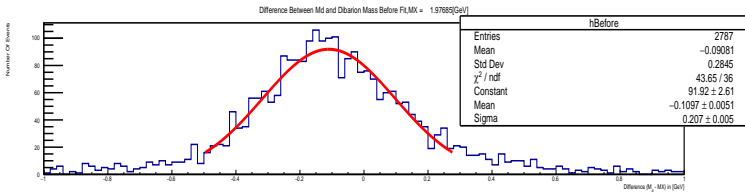
# Resolution for $E_{exc} = m_{\pi^0}/4$ in different Options



# Resolution for $E_{exc} = m_{\pi^0}/2$



# Resolution for $E_{exc} = 3/4m_{\pi^0}$



## The resolution of MX in a different Options

In three figures before we show histograms, demonstrating the distributions of MX obtained in different Options. Three distributions are shown in each picture. As you can see each distribution has a peak and near it we may select some region, where the distribution is practically Gaussian. By solid line we show the fit of such a regions by Gaus. Regions were selected by eye. Then we can do the comparison of the widths by its  $\sigma$ 's. On the other hand there are standard deviations(RMS), which also may characterize the widths of distributions. If we compare the results in Option2 and Option 3, we may say that for these three MX

- ▶ in terms of  $\sigma$ 's the width of MX distribution in the Option 3 in  $\approx 75 - 100$  times less than in Option 2
- ▶ in terms of RMS the width of MX distribution in the Option 3 in  $\approx 17 - 30$  times less than in Option 2

# The resolution of MX in a different Options, continued 1

Fit in so called Option2 is a fit,taking into account all the information about event, but without constraint,fit in Option3 - the same but with addition of the constraint. In a table 1 we show the results of fitting in all the Options and RMS of distributions(in parentheses near fit results). Remember that the regions for a fitting are selected by eye!

$M_d - MX$	Option1(RMS)	Option2(RMS)	Option3(RMS)
-0.0338	$-0.05874 \pm 0.2181(0.2913)$	$-0.0545 \pm 0.2117(0.2874)$	$-0.0339 \pm 0.0020(0.0083)$
-0.0675	$-0.0929 \pm 0.2213(0.2911)$	$-0.0753 \pm 0.2043(0.2794)$	$-0.0676 \pm 0.0027(0.0126)$
-0.1013	$-0.1097 \pm 0.2070(0.2845)$	$-0.1092 \pm 0.1986(0.2677)$	$-0.1014 \pm 0.0024(0.0151)$

**Table:** The results of fitting( $M_d - MX$ ) in all the Options in the form mean  $\pm \sigma$  for all MX's. RMS is shown in parenthesis .Everything in GeV

## Concluding Remarks

- ▶ The resolution of Spd detector in the search of dibarions at the process  $d + d^- \rightarrow d + X$ ,  $M_d < MX < M_d + m_{\pi^0}$  under simplified assumptions looks very optimistic, the resolution is  $\approx 2 - 3 \text{ MeV}$  in the dibarion mass. Such amazing resolution is achieved by the using kinematical fitting technique, giving improvement  $\approx 75 - 100$  times in terms of  $\sigma$ 's compared with the estimation parameters without this technique.
- ▶ It deserves the starting of the planning **real** experiment with the attempt to answer many questions, some of them below
- ▶ At which Collider Momentum to do such a study?
- ▶ Which kinematical region (in a final state) is more promising for the search ?
- ▶ How to identify (select) the reaction  $d + d^- \rightarrow d + p + n$ ?
- ▶ And ..., et cetera