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Yu.A.Troyan*, A.V.Beljaev, A.Yu.Troyan, E.B.Plekhanov, A.P.Jerusalimov, S.G.Arakelian

*E-mail: atroyan@jinr.ru

The Search and Study of Low-Mass Scalar σ_0-meson in the reaction $np \rightarrow np\pi^+\pi^-$ at the Impulse of Neutron Beam $P_n = 5.20$ GeV/c

The investigation has been performed at the Veksler and Baldin Laboratory of High Energies, JINR.

Based on JINR preprint P1-2008-100

Introduction

This work continues a series of our works, devoted to the study of low-mass ($M<1.2 GeV/c^2$) resonances in the $\pi^+\pi^-$ - system.

Their existence can clarify the properties of low-lying scalar mesons (the so-called σ_0 - mesons),

whose investigation is important both

for the mechanism of realization of chiral symmetry for corresponding Lagrangians and

for an adequate description of an attractive part of the nucleon-nucleon interaction potential.

It was noted by dr. Pennington that light scalar mesons constitute Higgs sector of strong interactions that ensures finite masses of all kinds of light hadrons (with simultaneous disappearance of pi – meson mass)

To clarify these fundamental conceptions, it needs thorough studying of properties of σ_0-mesons and also investigation of their structure.

There are hundreds of works devoted to these problems, and we have no possibility to quote all of them. We send a reader to the review in PDG.

However this review of some theoretical works concerns the quark-gluon picture of the scalar mesons structure.

There σ_0-mesons are considered

as a construction of 2 or 4 quarks,
as glueballs,
as constracted of quarks into diquarks etc.

However there are some other conceptions of this problem.

Among them are

- –the predictions of series and properties of resonances from the point of view of multi-dimensional space (Archipov),
- –the predictions of series of resonances, obtained from formulas of quasi-classic quantization (Gareev),
- –the predictions of resonance series based on the McGregor model (Palazzi),
- –the search for properties of instant vacuum (Kochelev).

Such a large number of theoretical conceptions tell that the understanding of properties and structure of σ_0-mesons does not yet exist.

It may be explained first with the absence of experimental data in the region of masses less than 1 GeV/c^2.

The problem became more actual due to:

statistically abundant data obtained at the HADES spectrometer;
investigations of mixed phase planned in the LHE JINR [LHE];
some similar experiments planned in other accelerators in the world.

The low-mass σ_0-mesons can become a powerful tool to study of new state of matter. Predictions about varying of the σ_0-meson properties in intermediate conditions are obtained in some papers (Volkov).

Reaction $np \to np\pi^+\pi^-$

The study was carried out using the data obtained in an exposure of 1-*m* HBC of LHE (JINR) to a quasimonochromatic neutron beam with $\Delta P_n / P_n \approx 2.5\%, \Delta\Omega_n \approx 10^{-7}\,sterad.$ due to the acceleration of deuterons by synchrophasotron of LHE

The accuracy of the momenta of secondary charged particles from the reaction $np \to np\pi^+\pi^-$ are:

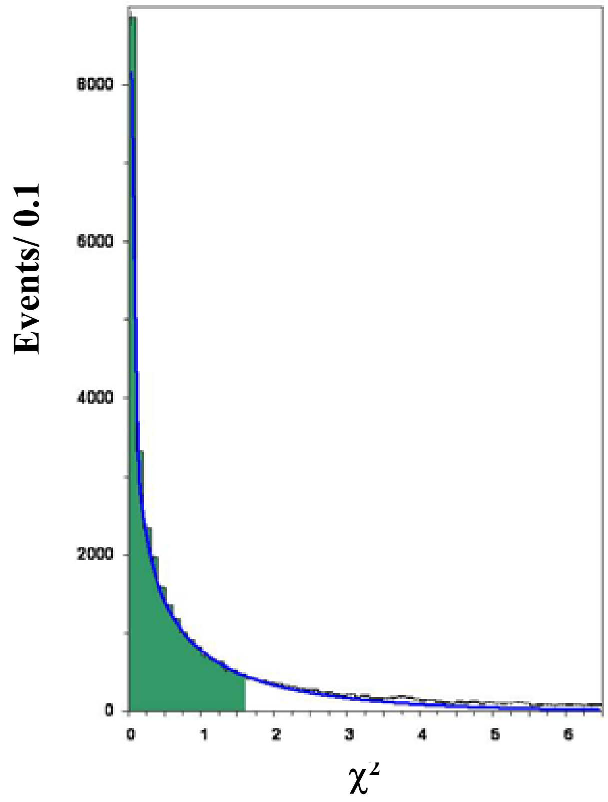
$\Delta P/P \approx 2\%$ for protons and $\Delta P/P \approx 3\%$ for π^+ and π^-.

The angular accuracy was $\leq 0.5°$.

The channels of the reactions were separated by the standard χ^2–method taking into account the corresponding coupling equations.

There is only one coupling equation for the parameters of the reaction $np \to np\pi^+\pi^-$ (energy conservation law) and the experimental χ^2–distribution must be the same as the theoretical χ^2–distribution with one degree of freedom.

np → npπ⁺π⁻ P_n = 5.20 GeV/c



The experimental (histogram) and the theoretical (curve) χ^2–distributions for the reaction $np \to np\pi^+\pi^-$.

One can see a good agreement between them up to $\chi^2 = 1.5$ and some difference for $\chi^2 > 1.5$.

As a result,

25650 events

were selected under the 4π geometry

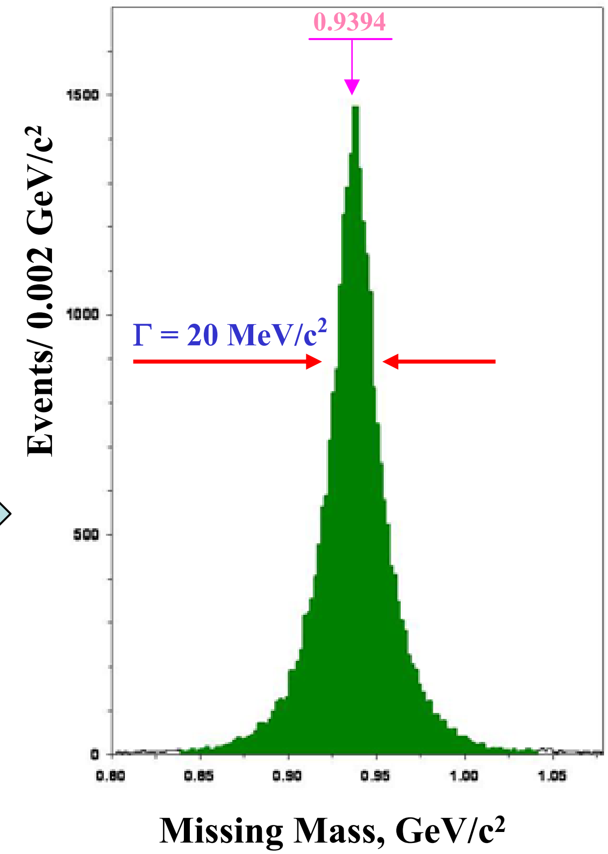
an admixture of other reactions practically is absent

The missing mass distribution for the events of $\chi^2 \leq 1.5$.

The distribution has the maximum at the value equal to the neutron mass with accuracy of 0.1 MeV/c^2, the width at the half-height $20 MeV/c^2$ and is symmetric about the neutron mass.

For more purity of data a small number of events with the missing masses out of green range were excluded.

np → npπ⁺π⁻ P_n = 5.20 GeV/c

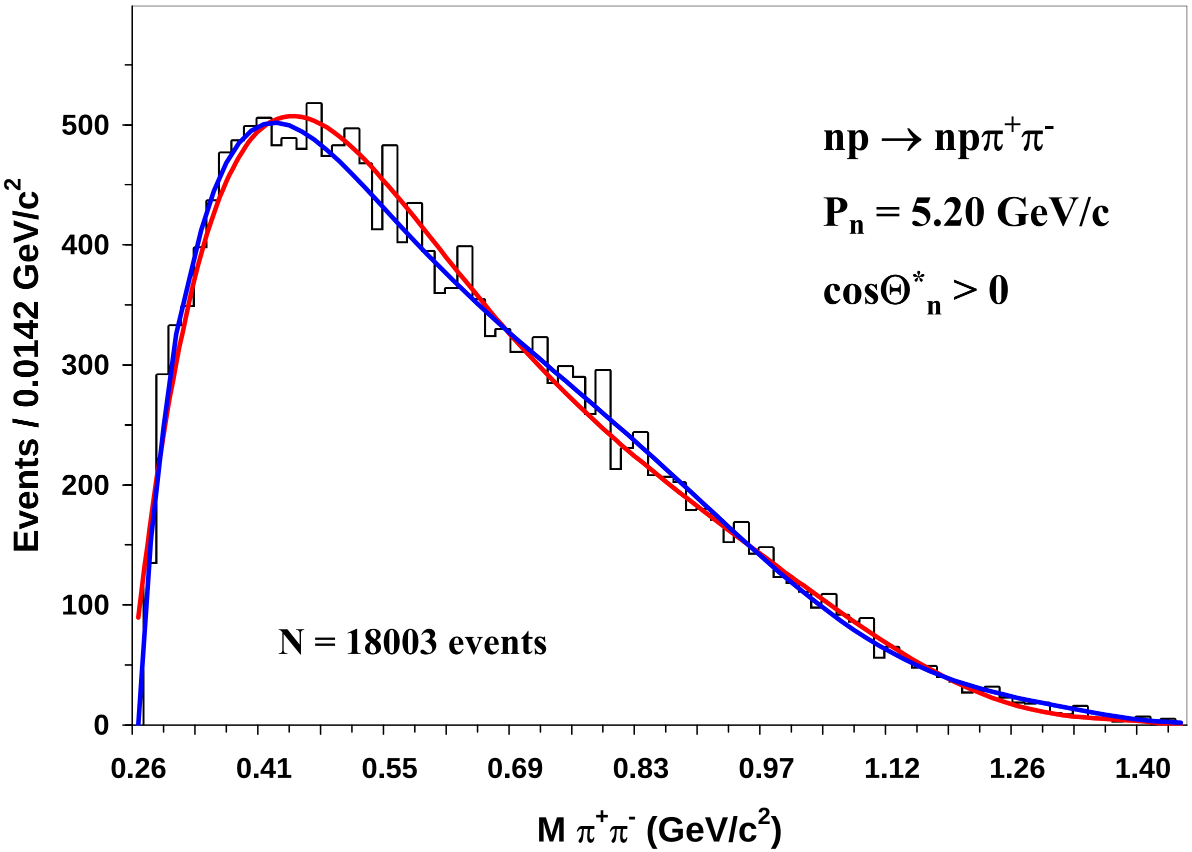


Earlier, we have already studied the reaction $np \to np\pi^+\pi^-$, and OPE-exchange with a dominated exchange of the charged π - meson has been shown to be the main mechanism of this reaction. It leads to a plentiful production (up to 70% of the total reaction cross section) of Δ^{++} and Δ^--resonances in the lower and upper vertices of the corresponding diagrams.

The OPE - exchange calculated by means of One Pion Reggezied Exchange model. OPER model contains the processes of N^* and Δ^* -resonances production and elastic $\pi\pi \to \pi\pi$ scattering.
In addition to the description of the reaction $np \to np\pi^+\pi^-$, the processes of the diffraction production of N^*_{1440}, N^*_{1520} and N^*_{1680} -resonances are used.

This OPE mechanism gives the main part into the events with neutron flying into the forward hemisphere.

The effective mass distribution of $\pi^+\pi^-$-combinations for the events with $\cos\Theta_n^* > 0$.
There are no such effects on this distribution.

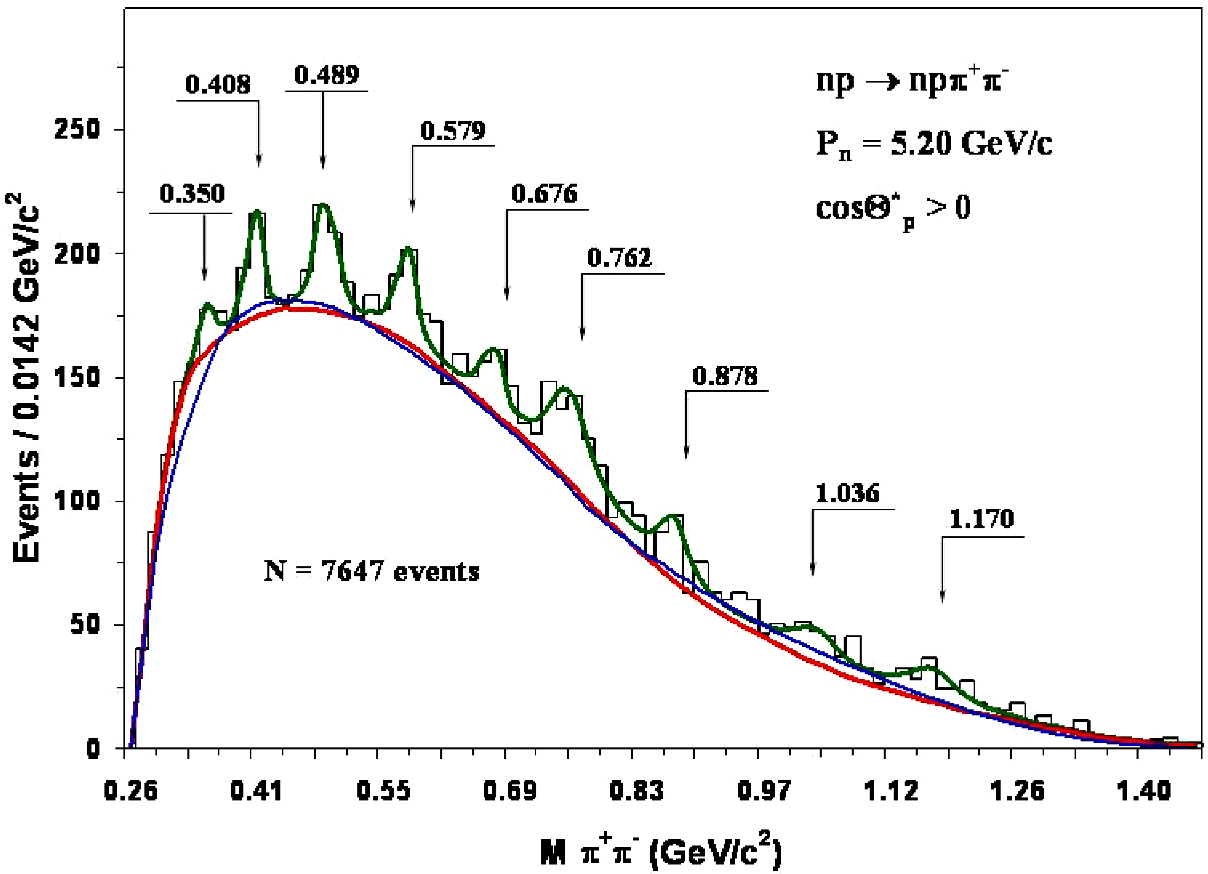


Red line - the superposition of Legendre polynomials up to 9th power.
Described this experimental distribution with $\overline{\chi^2} = 1.02 \pm 0.15$ **and** $\sqrt{D} = 1.51 \pm 0.11$

Blue line - the curve calculated by means of OPER model
Describes this experimental distribution with $\overline{\chi^2} = 1{,}07 \pm 0{,}15$ **and** $\sqrt{D} = 1{,}60 \pm 0{,}11$.

Therefore, it seems reasonable to study the resonances in the $\pi^+\pi^-$-system of the reaction $np \to np\pi^+\pi^-$ selecting the events on condition that $\cos\Theta_p^* > 0$.

The total contribution of the Δ^{++} and Δ^--resonances is not more than 17% for these events, and the background from resonance decays decreases greatly.



Green line - the superposition of Legendre polynomials background and 9 resonance curves taken in the Breit-Wigner form.
The experimental values of the resonance masses (obtained by fitting procedure) are shown by arrows.

BACKGROUNDS:

Red line - up to 9th power Legendre polynomials

Described the background with $\overline{\chi^2} = 0.97 \pm 0.24$ **and** $\sqrt{D} = 1{,}36 \pm 0{,}17$
The contribution of the background to this distribution is 89%.

Normalized to 100% of events in the plot (with resonance regions included) with $\overline{\chi^2} = 1.26 \pm 0.15$ **and** $\sqrt{D} = 1.59 \pm 0.11$ **(Confidence Level 9%).**

Blue line - calculated by means of OPER model

Described the background with $\overline{\chi^2} = 0{,}95 \pm 0{,}24$ **and** $\sqrt{D} = 1{,}45 \pm 0{,}17$.

Normalized to 100% of events in the plot (with resonance regions included) with $\overline{\chi^2} = 1{,}24 \pm 0{,}15$ **and** $\sqrt{D} = 1{,}87 \pm 0{,}11$. **(Confidence Level 11%).**

The mass distributions is approximated by an incoherent sum of the background curve taken in the form of a superposition of Legendre polynomials and by resonance curves taken in the Breight-Wigner form.

The requirements to the polynomial background curve are the following:

- **the errors of the coefficients must be not more than 50 % for each term of the polynomial;**
- **the polynomial must describe the experimental distribution after "deletion" of resonance regions with $\overline{\chi^2} \approx 1.0$ and $\sqrt{D} \approx 1.41$ (the parameters of χ^2–distribution with 1 degree of freedom).**

The results of approximation – Table 1

$M_{Res} \pm \Delta M_{Res}$, MeV/c^2	$\Gamma_{Res} \pm \Delta\Gamma_{Res}$, MeV/c^2	S.D.	σ μb
350 ± 3	11 ± 8	3.5	12 ± 6
408 ± 3	11 ± 8	3.5	12 ± 6
489 ± 3	20 ± 10	4.0	20 ± 8
579 ± 5	17 ± 14	3.8	18 ± 8
676 ± 7	11 ± 14	3.0	11 ± 6
762 ± 11	53 ± 33	6.1	26 ± 8
878 ± 7	30 ± 14	3.6	11 ± 5
1036 ± 13	61 ± 30	5.1	15 ± 5
1170 ± 11	65 ± 33	5.8	11 ± 4

<u>The first column</u> contains the experimental values of the resonance masses and their errors.
<u>The second column</u> contains the experimental values of the total width of the resonances.
<u>The third column</u> contains the statistical significances of the resonances, determined by formula: $S.D. = N_{Res.} / \sqrt{N_{back.}}$.
<u>The fourth column</u> contains the resonance cross-sections.
For the cross sections errors, we have taken into account the cross section error for the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20\, GeV/c$ $(\sigma_{np\to np\pi^+\pi^-} = (6.22 \pm 0.28)\, mb)$

The mass resolution function grows with increasing mass as: $\Gamma_{res}(M) = 4.2\left[\left(M - \sum_{i=1}^{2} m_i\right)/0.1\right] + 2.8$,

where: M – the mass of the resonance, m_i – the rest mass of the particles composing this resonance, M and m_i are in GeV/c^2; coefficients 4.2 and 2.8 are in MeV/c^2.

The true width of a resonance is obtained by formula: $\Gamma_{Res}^{true} = \sqrt{\left(\Gamma_{Res}^{exp}\right)^2 - \left(\Gamma_{res}\right)^2}$.

We have tried to estimate the quantum numbers

for the observed resonances in $\pi^+\pi^-$-system

The distributions of emission angles
of π^+ - meson
in the helicity coordinate system
(subtracted background)
are described by a sum of
even-power Legendre polynomial
with maximum power being equal to 2J,
where spin of the resonance $\geq$ J

The most probable spin values
for these resonances are equal to 0

No corresponding signal in the $\pi^-\pi^0$-system
from the reaction $np \to pp\,\pi^-\pi^0$
No corresponding signal in the $\pi^-\pi^-$ -system
from the reaction $np \to pp\pi^+\pi^-\pi^-$
which also have been studied by us

The isotopic spin values
for these resonances are equal to 0

Taking into account
Generalized Pauli`s principle for 2 π -system

↓

peculiarities observed in our experiment
have the quantum numbers
$I^G(J^{PC}) = 0^+(0^{++})$
and may be identified as σ_0 –meson

Intensification of the Effect

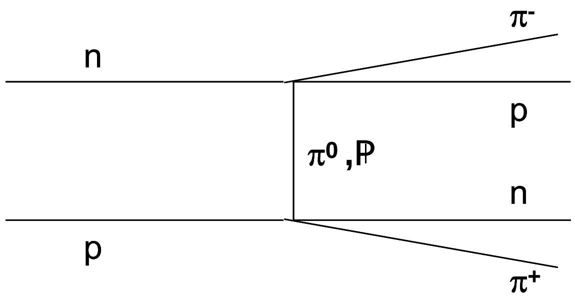
To intensify the effect, we have used an additional criterion of events selection – namely on the variable

$$X^*_{\pi^+\pi^-} = \left(P^*_{\parallel\pi^+} + P^*_{\parallel\pi^-}\right) \Big/ P^*_{\pi\,\max}$$

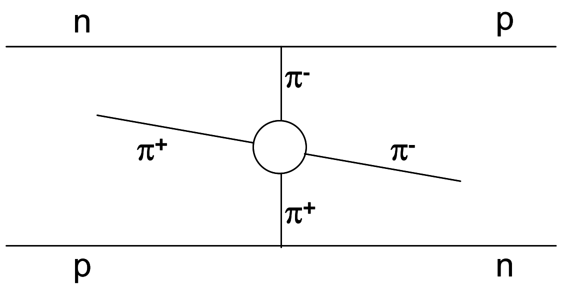
where: $P^*_{\parallel\pi^{+(-)}}$ - experimental value of the longitudinal component of $\pi^+(\pi^-)$ in general c.m.s.,

$P^*_{\pi\,\max}$ - maximum possible value of π-meson momentum for given event in general c.m.s.

Since the application of the criterion $\cos\Theta^*_p > 0$
the main background arises due to OPE diagram
where the exchange is π^0 – meson (1)
and due to the process of diffraction production
(Pomeron exchange).
The process $\pi^- p \to \pi^0 n$ (charge exchange process)
plays the basic part in these diagrams.
There are no peculiarities in the cross section of this process
except the maximum at $M_{p\pi^-} = 1236 MeV/c^2$.



(1)



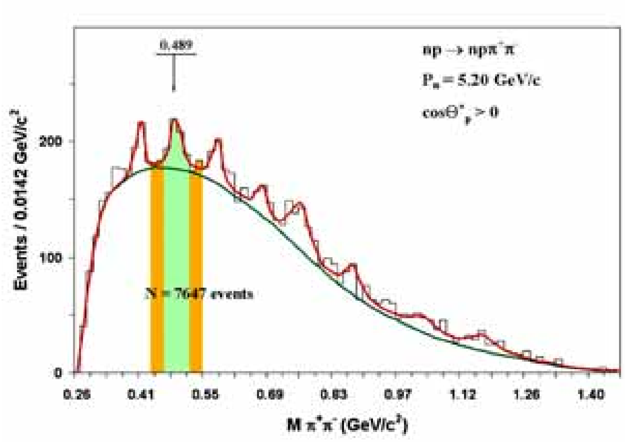
(2)

The diagrams of the type (2) become more important.
This diagram was earlier vastly masked
by diagrams of the charged meson exchange

π^+ and π^- are equitable in diagrams (2),
therefore it is possible to expect that effect will arise in $\pi^+\pi^-$ - scattering,
$\pi^+\pi^-$ - system will be close to symmetric (in $X^*_{\pi^+\pi^-}$ - variable) relative to $X^*_{\pi^+\pi^-} \approx 0$.

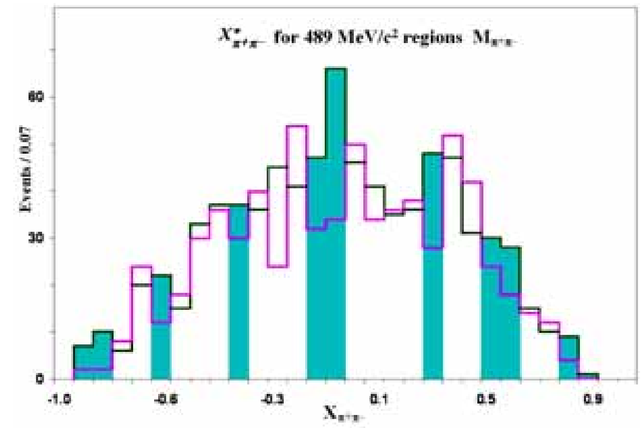
Let us consider the application of $X^*_{\pi+\pi-}$ variable to intensify the resonance effect at the mass of 489 MeV/c^2.

The similar procedure was used for other studied effects.



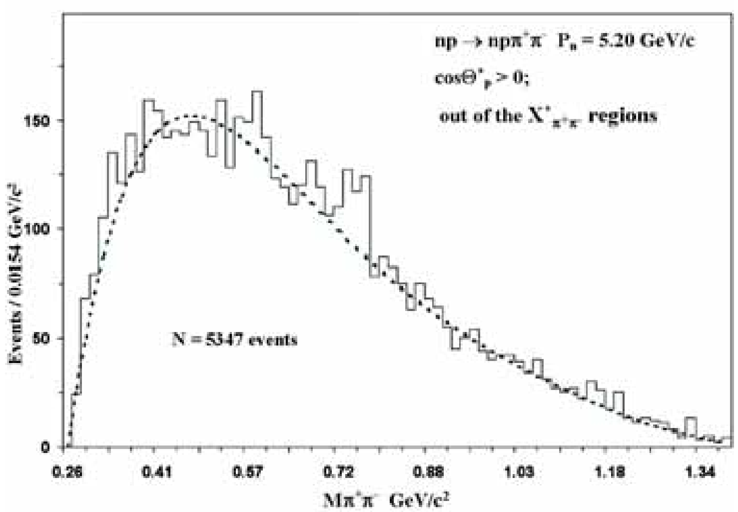
The resonance (green) and the background (orange) regions of masses

One can see that the resonance events get to some regions of $X^*_{\pi^+\pi^-}$ with more probability than background one



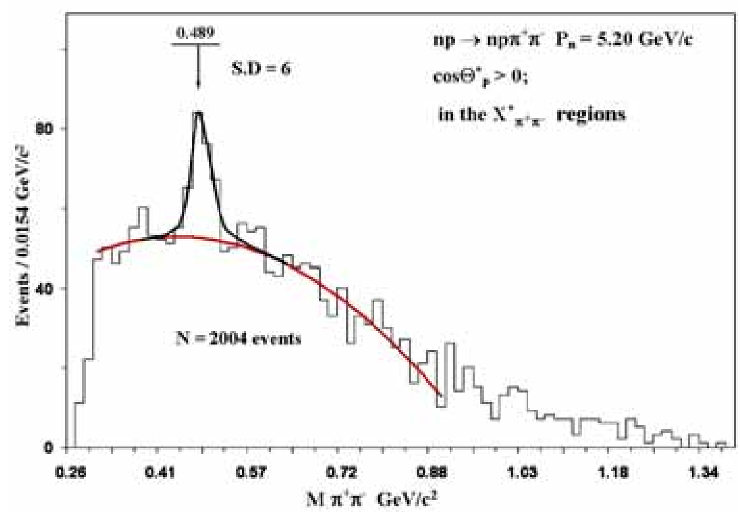
$X^*_{\pi^+\pi^-}$ distributions for the resonance (green) and the background regions of masses

It is possible to significantly decrease a part of background to the resonance due to selection of bands on $X^*_{\pi^+\pi^-}$ where the probability for resonance events is larger than for the background one.



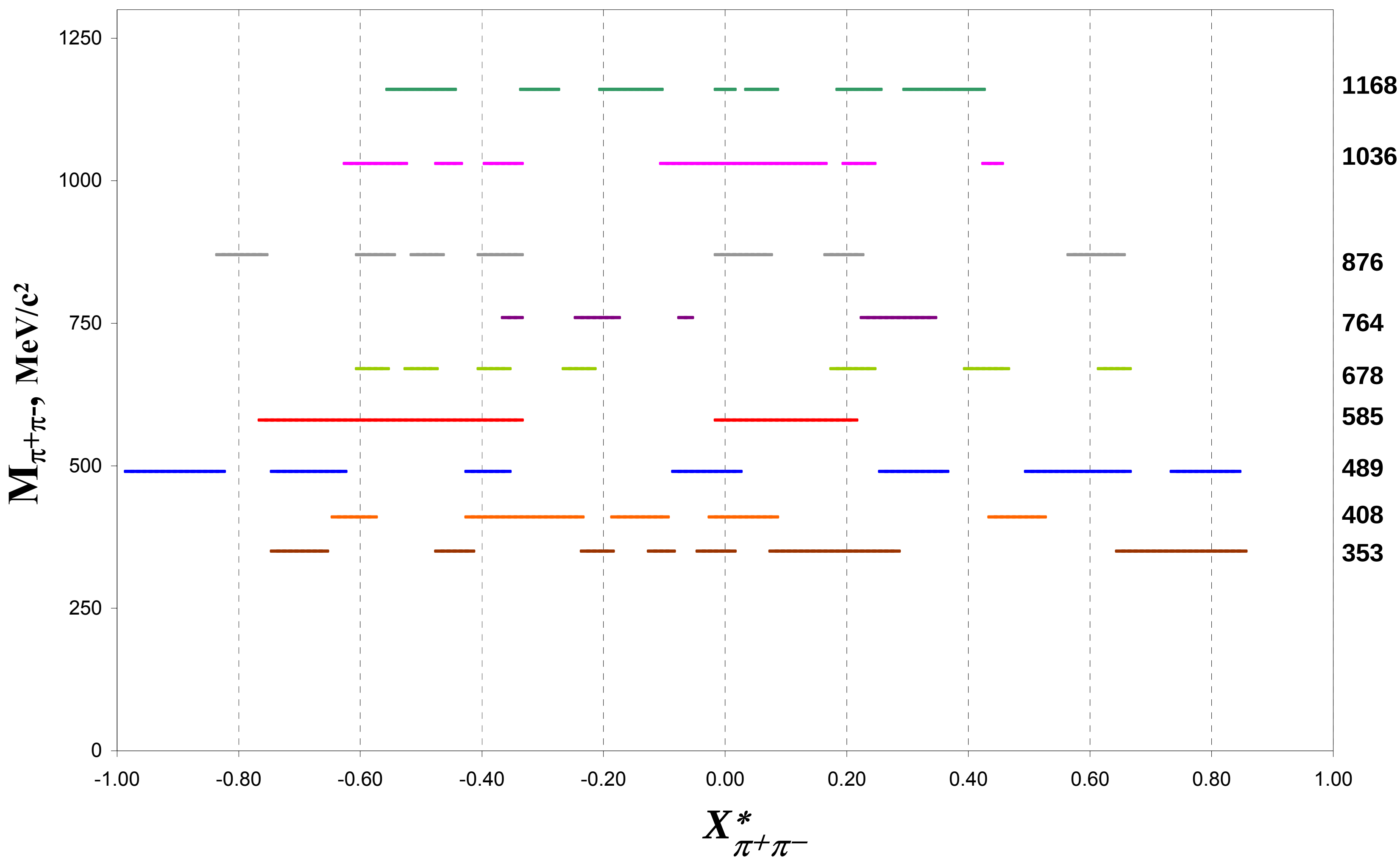
The total absence of effect at the mass of 489 MeV/c^2

The strong increase of effect at the mass of 489 MeV/c^2. S.D.=6.



The regions of samples on $X^*_{\pi^+\pi^-}$ for various mass regions (for the corresponding resonsnces)

$X^*_{\pi^+\pi^-}$ Vs $M_{\pi^+\pi^-}$

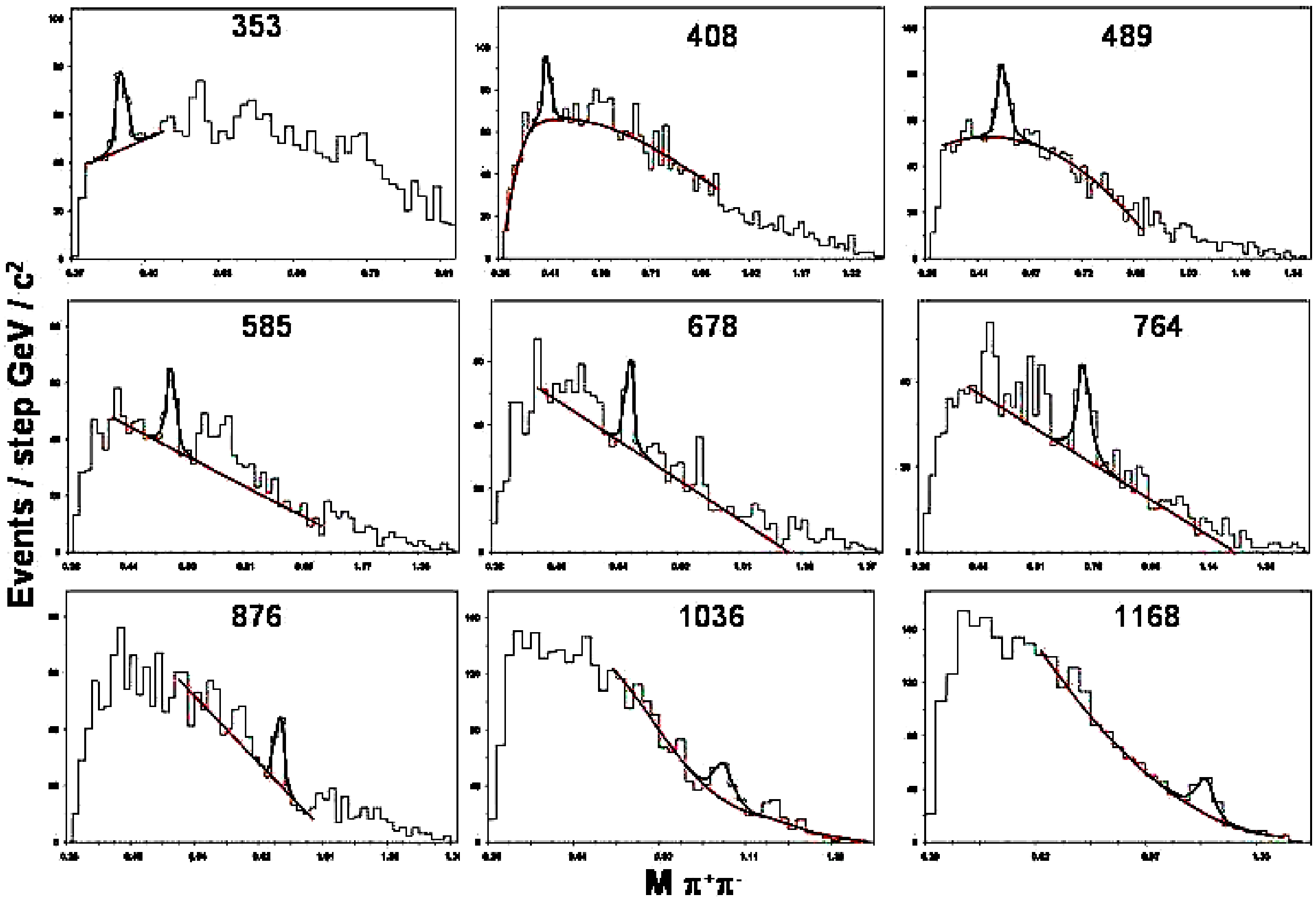


Some of the $X^*_{\pi^+\pi^-}$ regions are overlapping for different resonances.

This observation is taken into account at the construction of the background curves for the distributions of the resonance effective masses.

The distributions of $M_{\pi^+\pi^-}$ after useing the criterion $X^*_{\pi^+\pi^-}$ for all our observed resonances.

The background and resonance (Breigt-Wigner) curves are shown.



	$M_{Res}+\Delta M_{Res}$ MeV/c^2	$\Gamma_{Res}+\Delta\Gamma_{Res}$ MeV/c^2	S.D.
1	353 ± 6	12 ± 8	5.5
2	408 ± 5	16 ± 6	5.0
3	489 ± 4	28 ± 13	6.0
4	585 ± 6	19 ± 7	5.4
5	678 ± 3	18 ± 9	5.5
6	764 ± 18	53 ± 18	6.9
7	876 ± 4	28 ± 10	6.8
8	1036 ± 10	60 ± 16	6.4
9	1168 ± 11	70 ± 16	7.5

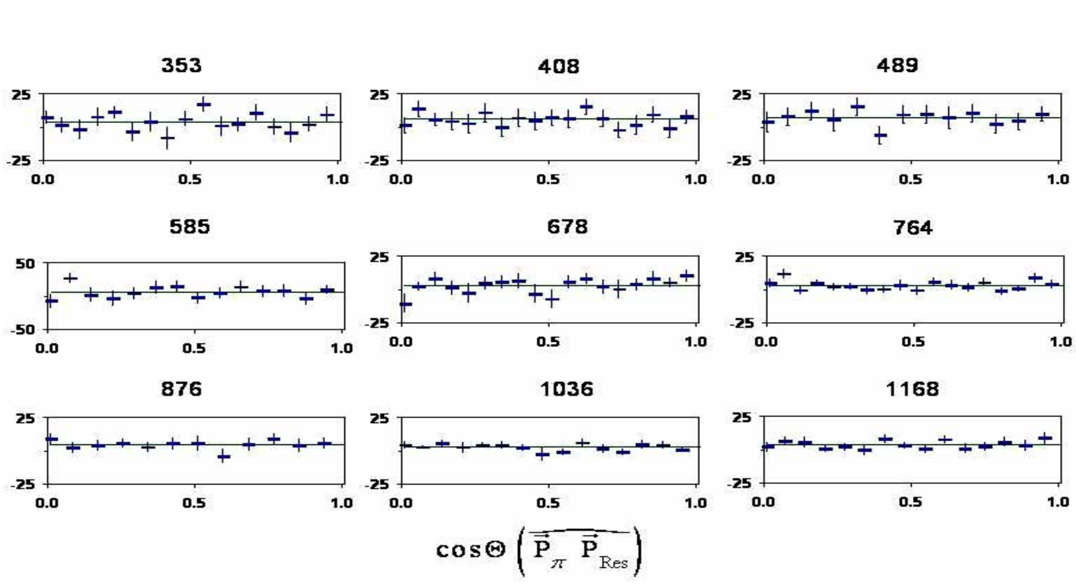
The values of the resonances masses and widths are close to the values shown in Table 1. The values of S.D. significantly increase and are not less than 5 everywhere

The use of the $X^*_{\pi^+\pi^-}$ criterion decreases strongly the level of the background for each effect not distorting the resonance characteristics.

The distributions of the emission angles of π^+ - mesons from the resonance decay (in the helicity coordinate system).

These distributions are obtained subtracting the corresponding background curves for intense effects using all the criteria.

All distributions are isotropic



Therefore, the most probable spin values for these resonances are equal to 0.

Comparison to other experiments

The experiment where the so-called ABC-effect was observed.
It is the peak at the mass of 350 MeV/c^2 that was found in various nuclear reactions.

We have observed such effect in the reaction
$np \rightarrow d\pi^+\pi^-$ - **at** $P_n = (1{,}73 \pm 0{,}04)\, GeV/c$
in the system of $\pi^+\pi^-$ **- mesons**
at the mass of $Ì_{\pi^+\pi^-} \approx 400 MeV/c^2$.

	$M_{Res} \pm \Delta M_{Res}$, MeV/c^2
1	353 ± 6
2	408 ± 5
3	489 ± 4
4	585 ± 6
5	678 ± 3
6	764 ± 18
7	878 ± 4
8	1036 ± 10
9	1168 ± 11

PDG - data

$f_0(600)$ BREIT-WIGNER MASS OR K-MATRIX POLE PARAMETERS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
(400–1200) OUR ESTIMATE				
513±32	[22] MURAMATSU	02	CLEO	$e^+e^- \approx$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$478^{+24}_{-23}\pm17$	AITALA	01B	E791	$D^+ \rightarrow \pi^-\pi^+\pi^+$
$563\pm^{+58}_{-20}$	[23] ISHIDA	01		$\Upsilon(3S) \rightarrow \Upsilon\pi\pi$
555	[24] ASNER	00	CLE2	$\tau^- \rightarrow \pi^-\pi^0\pi^0\nu_\tau$
540±36	ISHIDA	00B		$p\bar{p} \rightarrow \pi^0\pi^0\pi^0$
750± 4	ALEKSEEV	99	SPEC	1.78 $\pi^- p_{polar} \rightarrow \pi^-\pi^+ n$
744± 5	ALEKSEEV	98	SPEC	1.78 $\pi^- p_{polar} \rightarrow \pi^-\pi^+ n$
759± 5	[25] TROYAN	98		5.2 $np \rightarrow np\pi^+\pi^-$
780±30	ALDE	97	GAM2	450 $pp \rightarrow pp\pi^0\pi^0$
585±20	[26] ISHIDA	97		$\pi\pi \rightarrow \pi\pi$
761±12	[27] SVEC	96	RVUE	6–17 $\pi N_{polar} \rightarrow \pi^+\pi^- N$
~ 860	[28,29] TORNQVIST	96	RVUE	$\pi\pi \rightarrow \pi\pi, K\bar{K}, K\pi, \eta\pi$
1165±50	[30,31] ANISOVICH	95	RVUE	$\pi^- p \rightarrow \pi^0\pi^0 n$, $\bar{p}p \rightarrow \pi^0\pi^0\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$
~ 1000	[32] ACHASOV	94	RVUE	$\pi\pi \rightarrow \pi\pi$
414±20	[27] AUGUSTIN	89	DM2	

The resonance peculiarity was found in dC-interactions at the momentum of 2.75 MeV/c per nucleon in the effective mass spectrum of 2γ at the mass $M_{\gamma\gamma}$=350 MeV/c^2 (Abraamyan)

There were found the effects at the $M_{\gamma\gamma}$=350 MeV/c^2 in 2-m propane bubble chamber.
The peaks in the momentum distribution of γ's can be explained under the assumption that resonances produced at the masses of $M_{\gamma\gamma}$=350 MeV/c^2 decay into 2 γ's

**The scalar pole was found by PWA of K^0_s – mesons decay into 2 π – mesons and 4 leptons at the mass of 489 MeV/c^2.
But the width of the resonance is very large.**

As well the pole in the decay $D^+ \rightarrow \pi^+\pi^+\pi^-$ was observed in the system of $\pi^+\pi^-$ at the mass of 478 MeV/c^2.

Phenomenological description of the scalar resonances series

both our observed resonances and the data presented in PDG

The analysis of all data shows that the distance between resonances varies in a rather complicated manner. It leads to an idea about the existence of several trajectories describing the augmentative masses of resonances.

We have constructed 4 resonances series
Whose values were determined
M_0^i **- the initial excitations**
x^i **- the excitations of clusters**
***i* is number of series**

The following form was taken for the approximation:

$$M_n = M_0 + x\frac{n(n+1)}{2} \quad (1)$$

where,

M_0 **– initial excitation of the trajectory;**
***x* – parameter of the excitation,**
***n* – number of the resonance on the trajectory**

The term of the form $\frac{n(n+1)}{2}$ arises because of the sum of the natural numbers from *1* to *n*

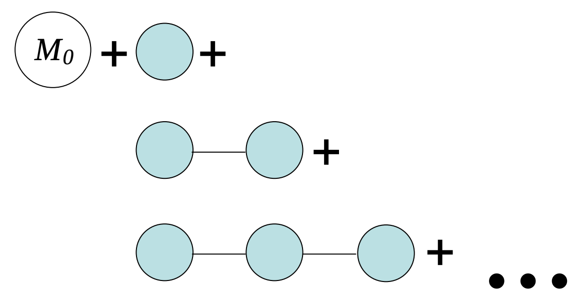
traject 1 $M_n = 305 + 120\frac{n(n+1)}{2}$					
n	n(n+1)/2	M_n(cal)c	M	±	ΔM(exp)
0	0	305			
1	1	425	408	±	5
2	3	665	678	±	3
3	6	1025	1036	±	10
4	10	1505	1505	±	6
5	15	2105	2103	±	8

traject 2 $M_n = 350 + 136\frac{n(n+1)}{2}$					
n	n(n+1)/2	M_n_calc	M_exp	±	ΔM_exp
0	0	350	353	±	6
1	1	486	489	±	4
2	3	758	764	±	18
3	6	1166	1168	±	11
4	10	1710	1724	±	7
5	15	2390	2330	±	20

traject 3 $M_n = 420 + 158\frac{n(n+1)}{2}$					
n	n(n+1)/2	M_n_calc	M_exp	±	ΔM_exp
0	0	420	408	±	5
1	1	578	585	±	6
2	3	894	876	±	4
3	6	1368	1370	±	
4	10	2000	1992	±	16

traject 4 $M_n = 485 + 170\frac{n(n+1)}{2}$					
n	n(n+1)/2	M_n_calc	M_exp	±	ΔM_exp
0	0	485	489		4
1	1	655	678	±	3
2	3	995	980	±	10
3	6	1505	1505	±	6
4	10	2185	2189	±	13

Therefore the mass of the n[th] - resonance can be presented schematically in the form of the sum of the series excited by the force *x*



Sum all series we get the form (1).

Phenomenological description of the scalar resonances series

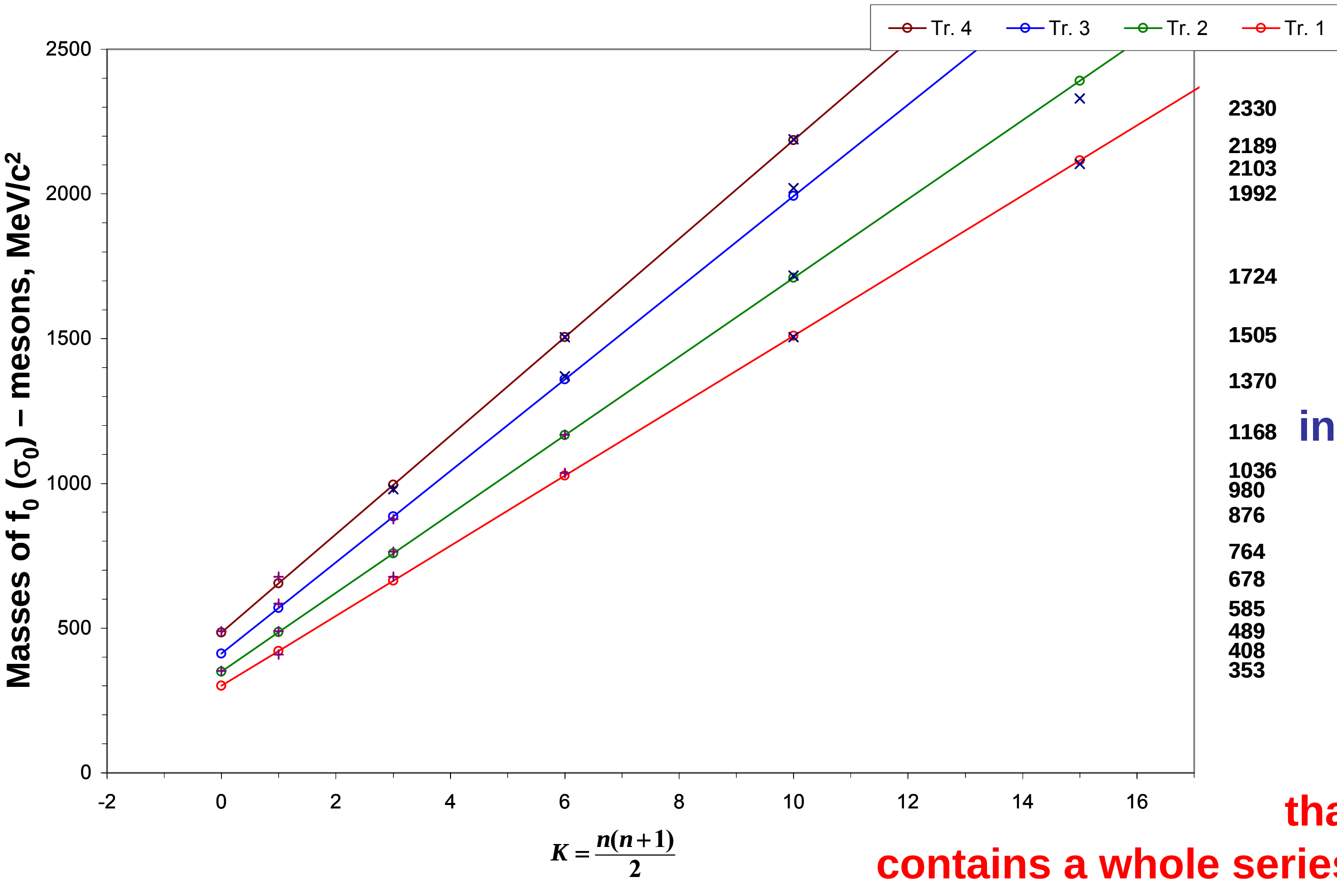
both our observed resonances and the data presented in PDG

The constructed trajectories are shown in Fig, where

the value $K = \frac{n(n+1)}{2}$ **is plotted on abscissa, the masses of** $f_0(\sigma_0)$ **– mesons are plotted on ordinate axis**

our data are pointed as +, data from PDG as x. The experimental values are shown to the right in the figure.

The values of the experimental errors are less than the sizes of markers



In the tables and in Fig one can see very good coincidence between the calculation by the formula (1) and experimental data in the whole range of $\pi^+\pi^-$ - masses from threshold (280 MeV/c^2) up to the mass of 2400 MeV/c^2.

Therefore it is possible to think that the resonance of the number *n* contains a whole series of cluster excitations and gives the total excitation of the scalar field.

Conclusion

- We have observed the series of resonances in the system $\pi^+\pi^-$ mesons from the reaction $np \to np\pi^+\pi^-$ at $P_n = (5.20 \pm 0.12)\, GeV/c$ that have the quantum numbers of σ_0 – meson $0^+(0^{++})$ and the masses in the range of $M \le 1200\, MeV/c^2$.

  The data about such resonances are practically absent.
- The widths of the observed peculiarities are sufficiently small.

  It sharply contradicts to the experimental data processed by PWA that give the widths equal to some hundreds MeV/c^2.

  We could not observe such wide resonances in our experiment.
- The statistical significance is sizeable $(\ge 5S.D.)$ due to the criterion $\cos\Theta_p^* > 0$ and selection of events for corresponding (for each effect) ranges of $X^*_{\pi^+\pi^-}$
- The resonances are evidently produced in the scattering of π^+ on π^- - mesons.

  And at the same time, it is accompanied by a well-ordered excitation of scalar fields.
- The study of σ_0 – mesons in a hot and dense matter will give much information about the properties of this matter.

  Therefore the study of σ_0 –mesons is extremely important both for NICA/MPD project and for experiments with nuclear beams at all accelerators of the world.

Acknowledgement

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THANK YOU
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