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STUDY OF nn-INTERACTION IN nd- AND dd-REACTIONS

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NN-Interaction

pp and *np* Interaction

A huge amount of data on pp and np interactions has been accumulated. Careful analysis of these data led to constructing NN interaction potentials describing vast majority of experimental data.

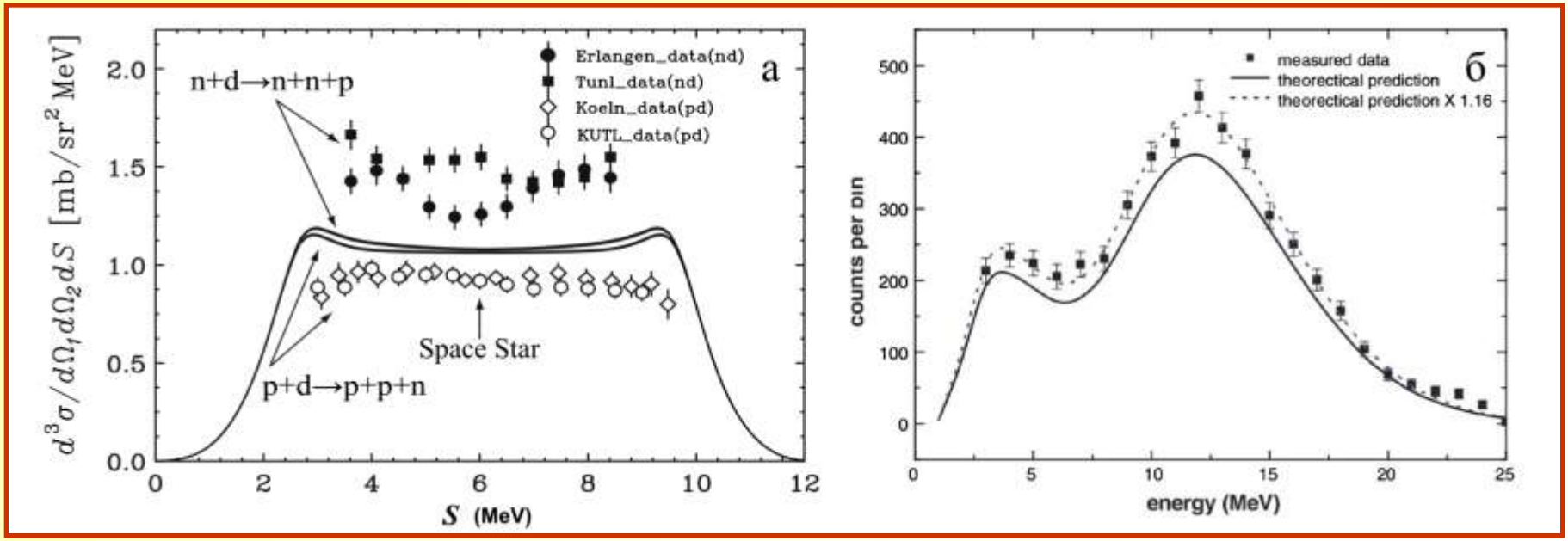
nn Interaction

The situation around neutron–neutron interaction is more ambiguous. Because of the absence of neutron target, data on this interaction are obtained primarily from reactions with two neutrons in the final state. But in many cases, there are serious discrepancies between available experimental data and the results of the current precise calculations on the basis of Faddeev equations.

Unresolved Problems in *Nd*-breakup

***nd*- and *pd*-breakup in SS-configuration**

***nn*-quasifree scattering**

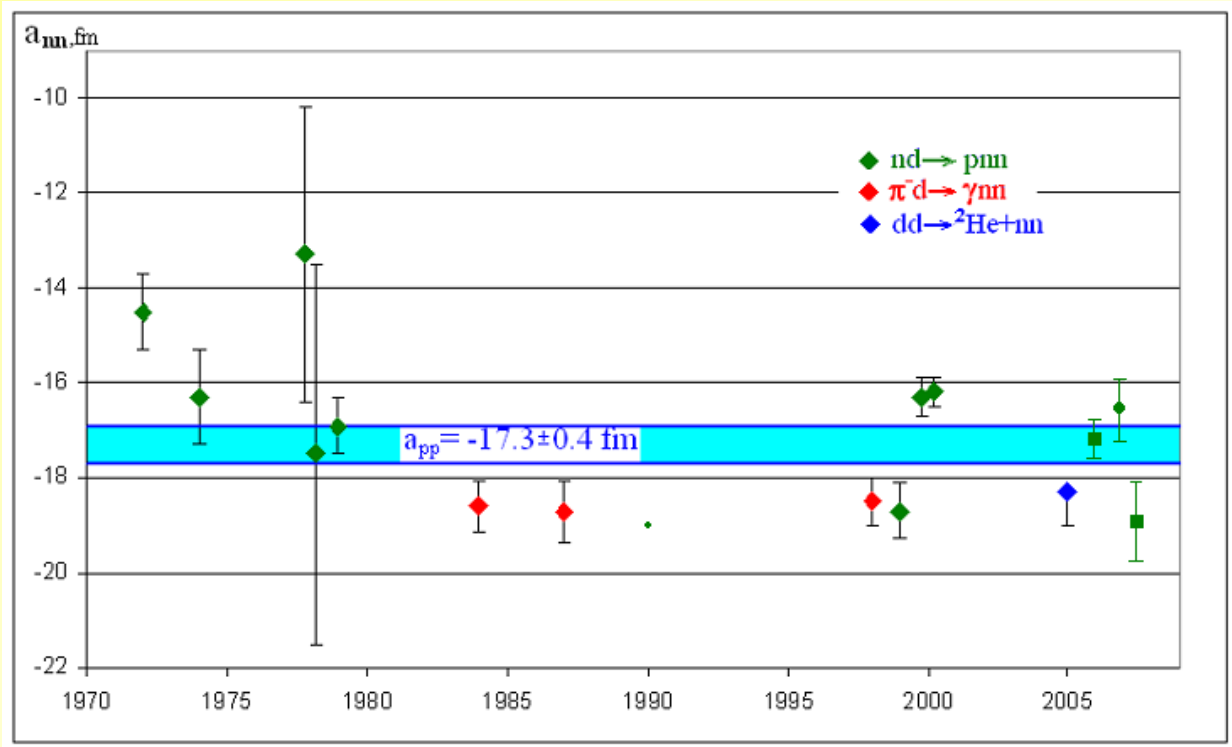


*Experimental CS for **pd-** and **nd-** breakup differ greatly while the theoretical CS are almost identical and do not agree with the experimental data*

*Experimental CS for **nn**-QFS exceed theoretical estimates by about 18%. At the same time, the theory describes well the CS obtained for **np** QFS*

The analysis performed by several authors showed that theoretical results remain quite stable using different standard NN-potentials and introducing modern three-nucleon forces

Data on proton-proton and neutron-neutron scattering lengths



The results obtained by now testify significant uncertainty of a_{nn} values, which are clustered near -16.3±0.4 (Bonn) and -18.5±0.4 fm (TUNL-LAMPF) so there is even uncertainty about the sign of the difference $a_{nn}-a_{pp}$, which is a measure of CSB in relative energy

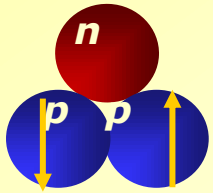
Neutron-proton scattering length is determined from the pp-scattering (a_{pp}= -17.3±0.4 fm), its accuracy is mainly connected with model-dependent corrections of Coulomb effects

^{3}He(ppn) and ^{3}H(nnp) Systems

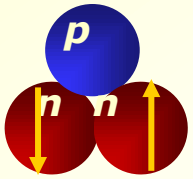
Two protons in ^{3}He are mainly in opposite spin states

Two neutrons in ^{3}H are also in a spin-singlet state

^{3}He



^{3}H

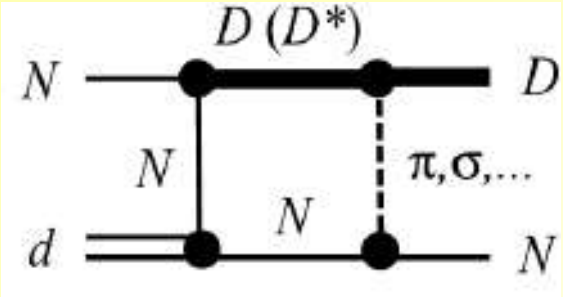


Strong discrepancies observed in Nd-breakup can be explained by a significant strengthening of *nn*- and *pp*-correlations of attractive character in the third nucleon field.

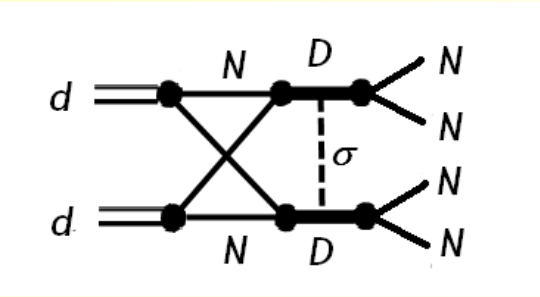
Dibaryon Model (Kukulin et al)

New mechanism arising in the Dibaryon Model: New force – meson exchange between the nucleon and dibaryon

N*d* or *t* (^{3}He)



dd* → D + D → *n*+*n*+*p*+*p

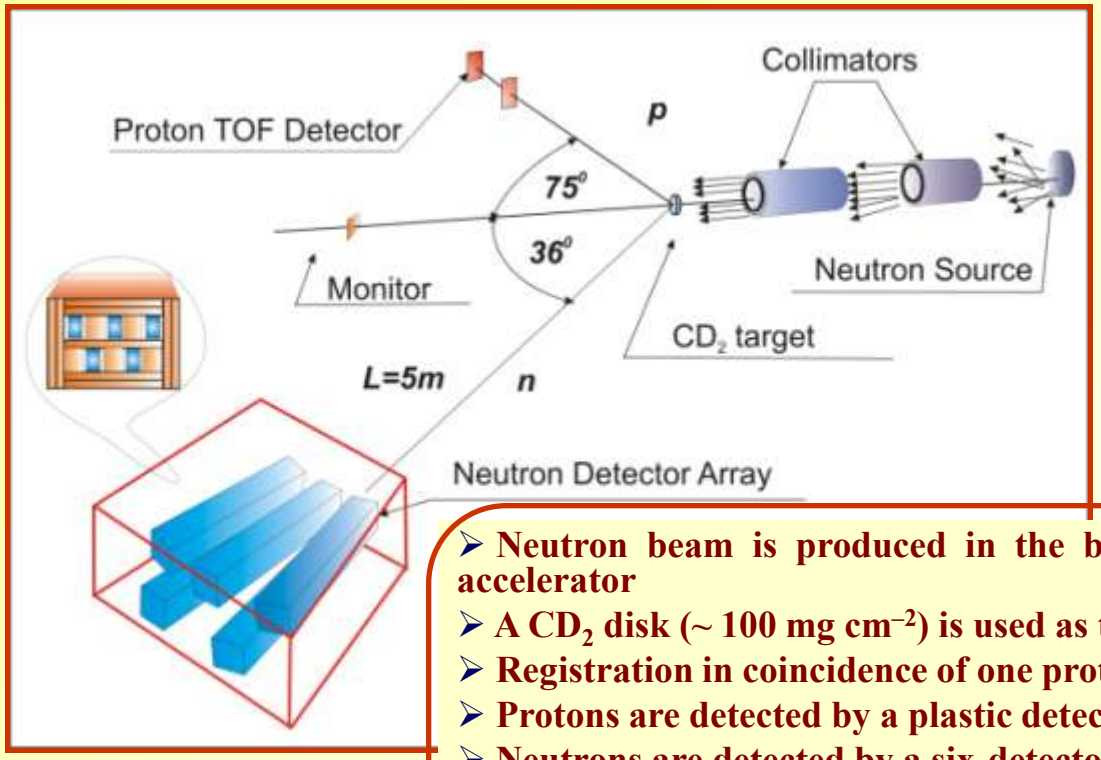


Our plans: study of *nd*→*p*+*nn*, *nt* →*d*+*nn* and *dd*→*pp*+*nn and* ….

In these reactions *nn*-correlated pair can be produced dynamically in the intermediate state. Thus, measured *nn*-correlation, in particular energy of *nn* virtual singlet state, may be different from those inherent for the free NN-systems.

Determination of *nn*-Virtual-State Energy and Scattering Length in $n + {}^2\mathrm{H} \rightarrow n + n + p$ Reaction

nd Breakup Reaction
Setup for Determination *nn*-Scattering Length



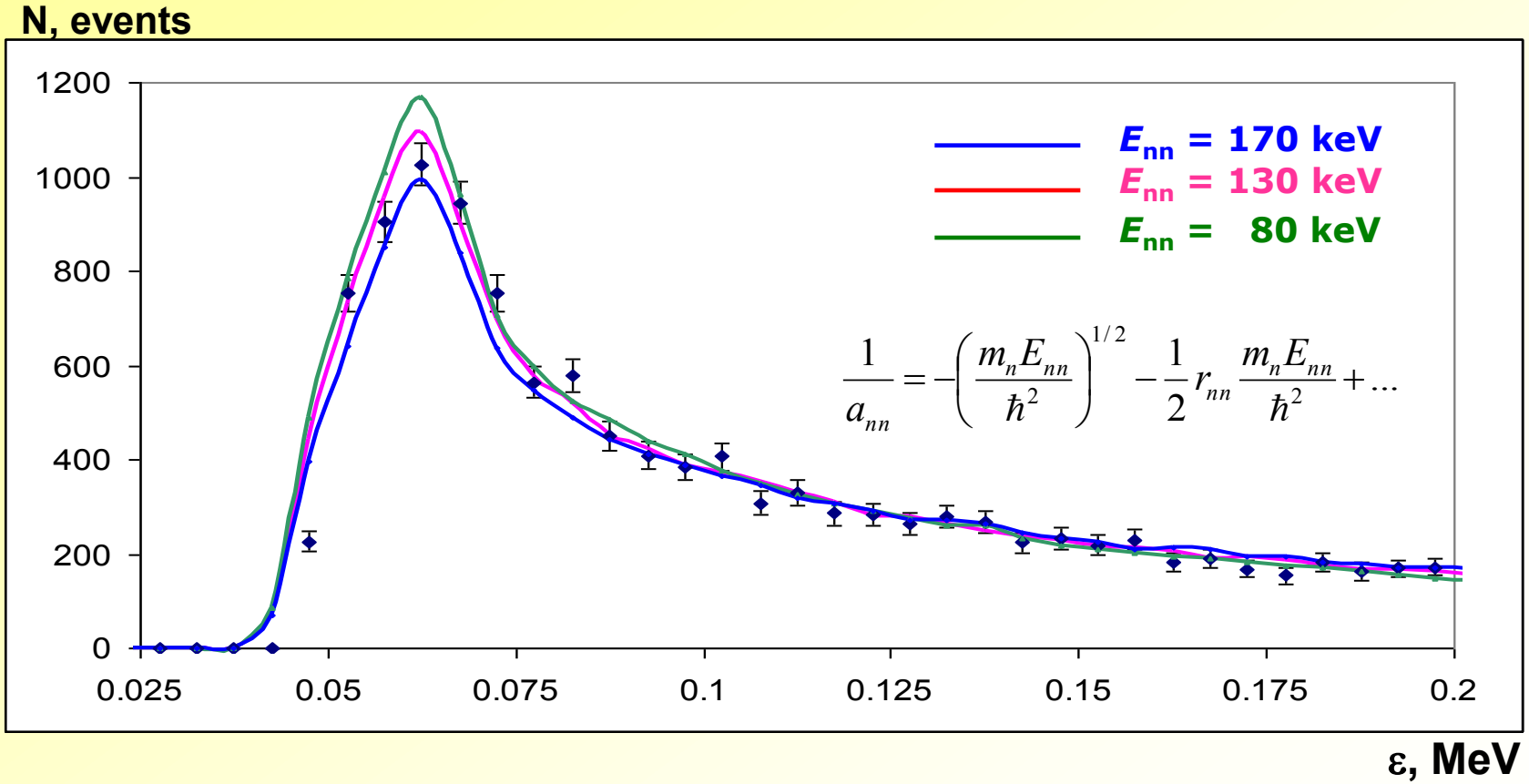
FSI

$$\varepsilon=(E_{n1}+E_{n2}-2(E_{n1}E_{n2})^{1/2}\cos\Delta\Theta)/2$$

$$\frac{dN}{d\varepsilon}_{WM}=\frac{\sqrt{\varepsilon}}{\varepsilon+E_{nn}}$$

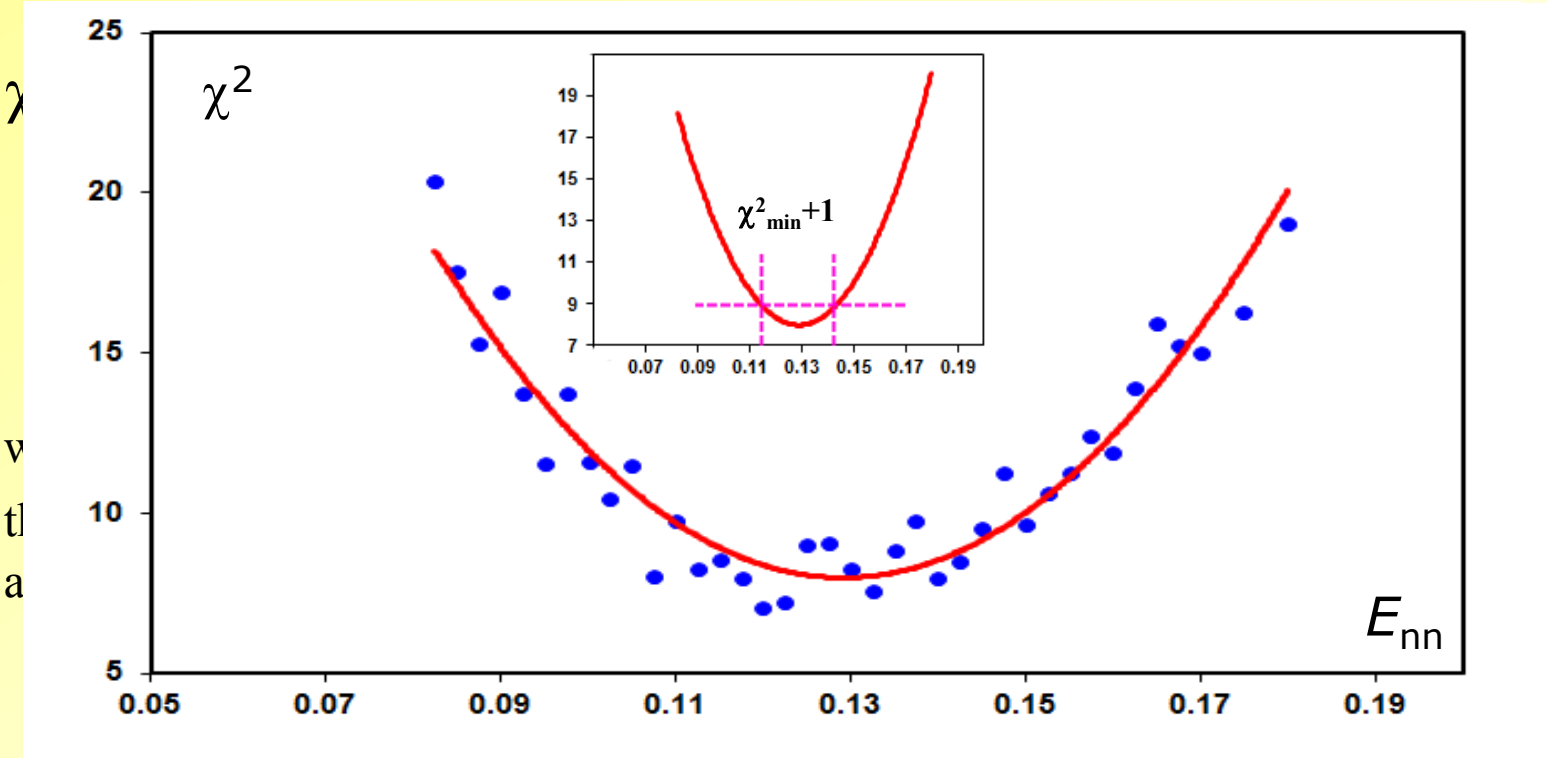
- **Neutron beam is produced in the beam stop of INR proton accelerator**
- **A CD_2 disk (~ 100 mg cm^{-2}) is used as the scattering target.**
- **Registration in coincidence of one proton and two neutrons**
- **Protons are detected by a plastic detector located at 75°±6°**
- **Neutrons are detected by a six-detector hodoscope at 30°-42°**
- **Energies of secondary neutrons are determined by a TOF technique**
- **Incident neutron energy and Θ_p are reconstructed from kinematics**

Experimental and simulated dependences N(ε) for various values of E_{nn} ; ΔΘ= 6°, E_0 = 40 ± 5 MeV



The best fit is obtained for E_{nn} = 129 ± 14 keV.

Determination of E_{nn} from χ^2 versus E_{nn} curve $\Delta\Theta = 6^o$; $E_0 = 40 \pm 5$ MeV



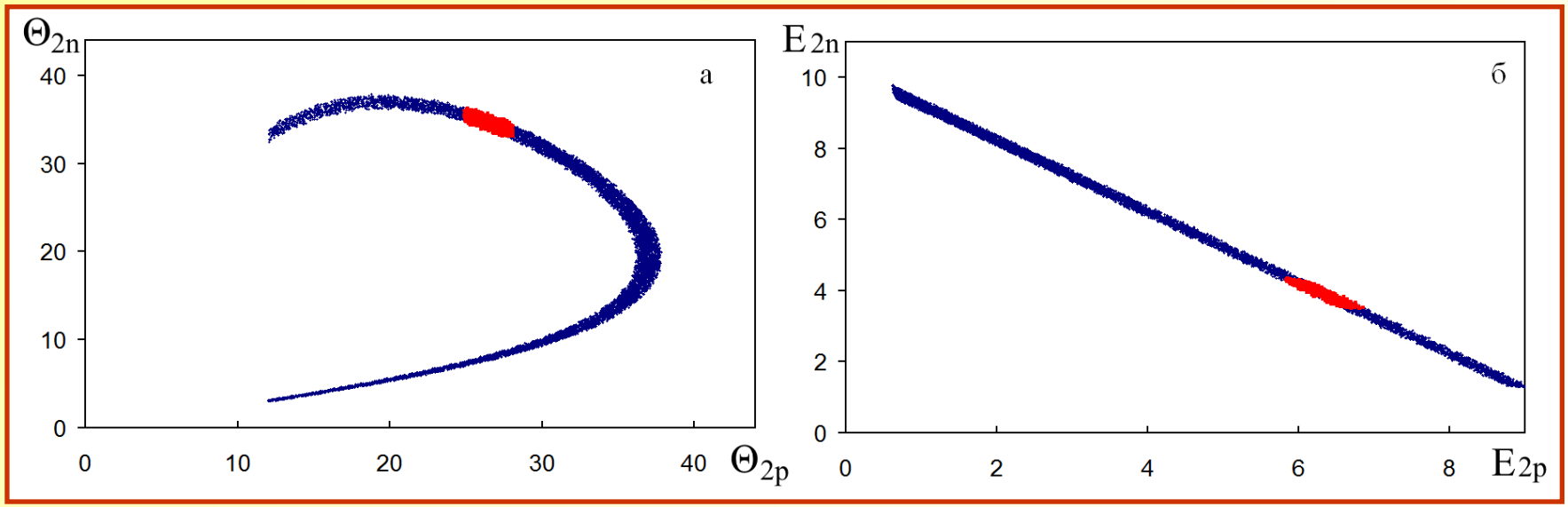
The values of $\chi^2(E_{nn})$ are approximated by a quadratic polynomial.
The minimum of the curve determines E_{nn}.

Statistical uncertainty ΔE_{nn} is given as $\Delta E_{nn} = \left|E_{nn}(\chi^2_{min}) - E_{nn}(\chi^2_{min}+1)\right|$

E_{nn} = 129 ± 14 keV → a_{nn} = -16.6 ± 0.9 fm

Determination of *nn*-Virtual-State Energy and Scattering Length in $d + {}^2\mathrm{H} \rightarrow (nn)^S + (pp)^S \rightarrow n+n+p+p$ Reaction

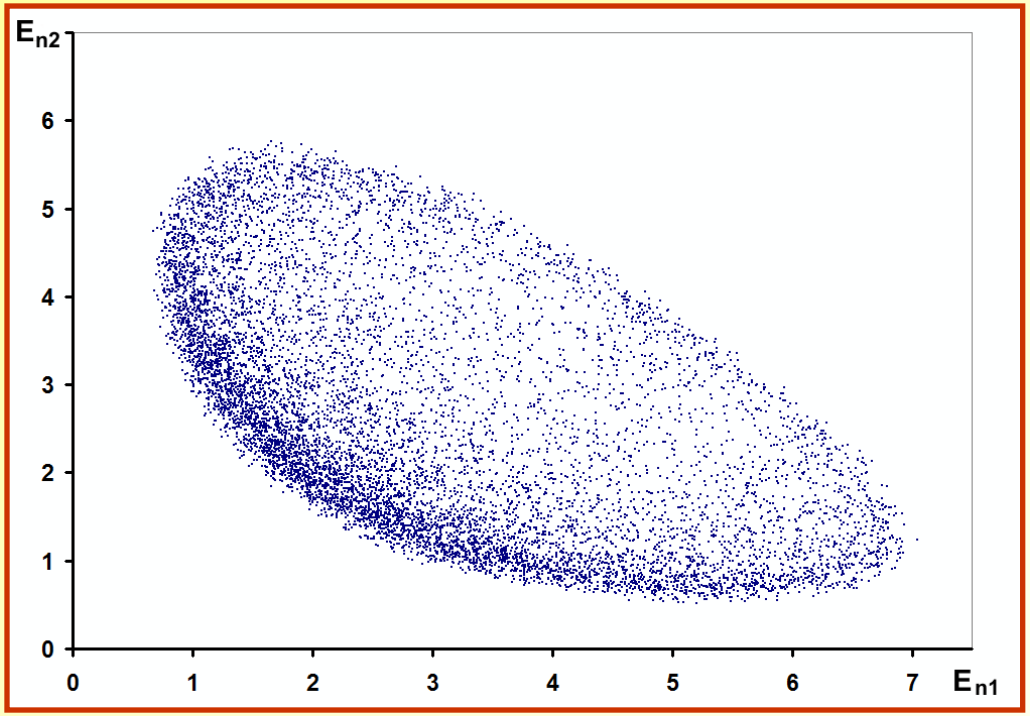
Simulation of $d + {}^2\mathrm{H} \rightarrow {}^2n^s + {}^2p^s$ Reaction; $E_d = 15$ MeV



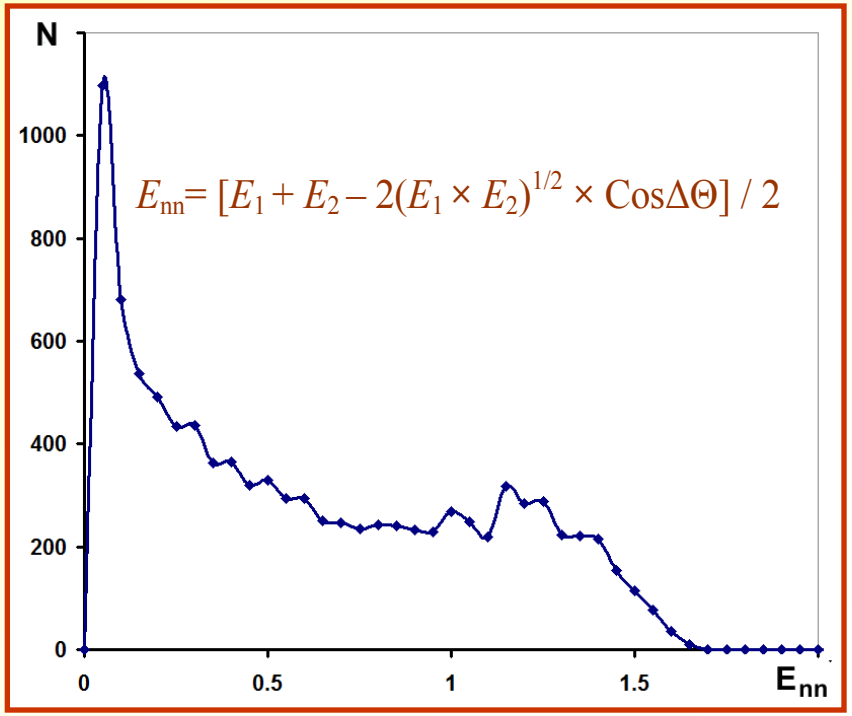
Output parameters: $\Theta_{p1}=\Theta_{p2}=27°$; $\Theta_n=36°$ (red areas)
Corresponding energies: $E({}^2p)$~6 MeV; $E({}^2n)$~4 MeV

Simulation of $d + {}^2H \rightarrow n + n + p + p$ Reaction: $E_d = 15$ MeV, $\Theta_{p1} = 27^o$, $\Theta_{p2} = 27^o$, $\Theta_{n1} = 36^o$

E_{n1} vs E_{n2}



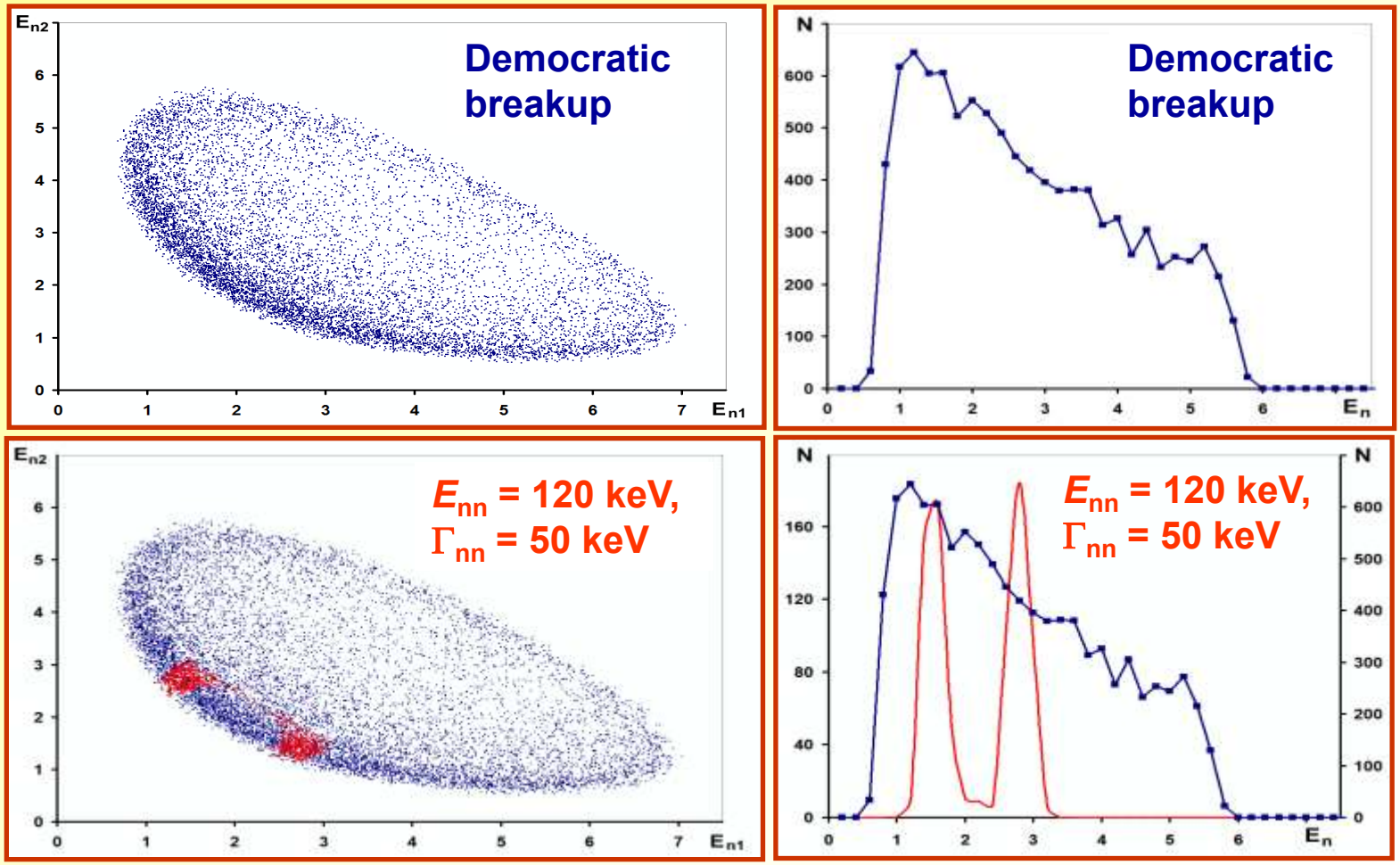
E_{nn} Spectrum



For democratic breakup two neutrons can have a relative energy in the range 0 - 1.8 MeV

Simulation of $d + {}^2\mathrm{H} \rightarrow n + n + p + p$ Reaction:

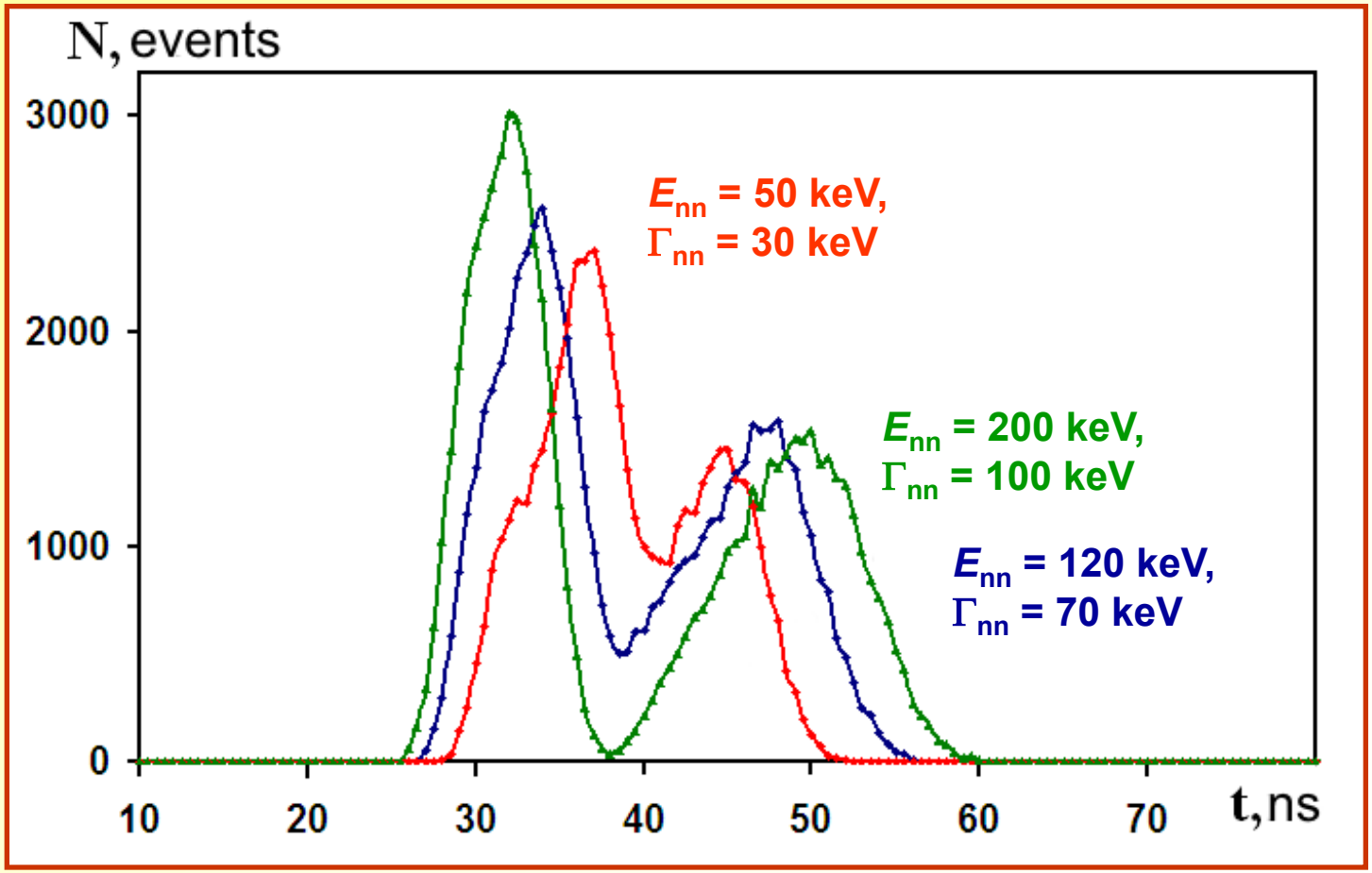
E_{n1} vs E_{n2} $\qquad$ E_{nn} Spectrum



This structure in spectrum is due to the fact that to reach detector, installed at angle of emitting *nn*-system in two-body reaction, may only breakup particles emitted in c.m. system in forward or in backward direction

Simulation of $d + {}^2\mathrm{H} \rightarrow n + n + p + p$ Reaction:

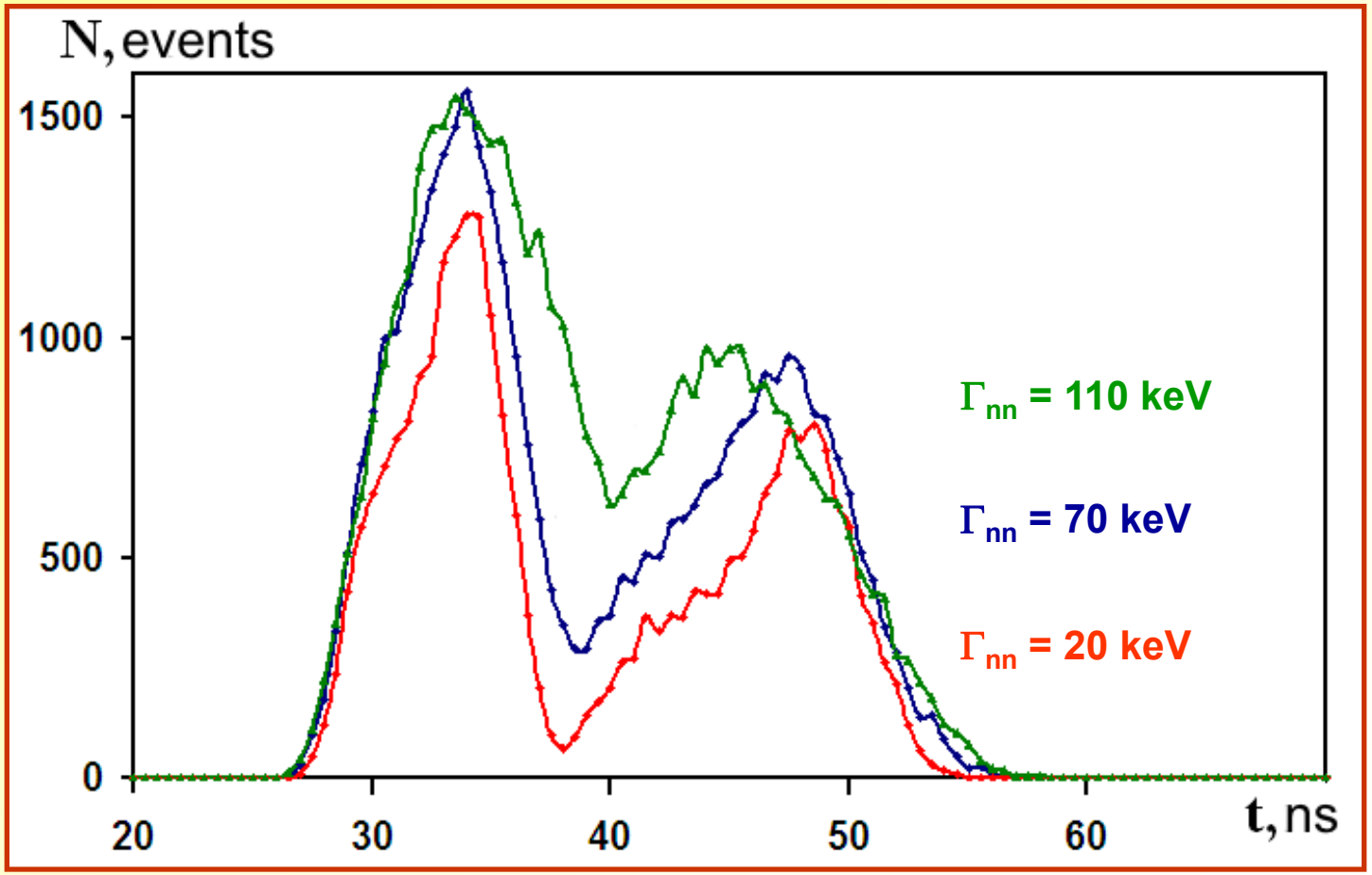
Different Energies of Singlet State



The distance between peaks depends on the excitation energy (excess mass of two-nucleon system over the sum of masses of its constituents)

Simulation of $d + {}^2\mathrm{H} \rightarrow n + n + p + p$ Reaction:

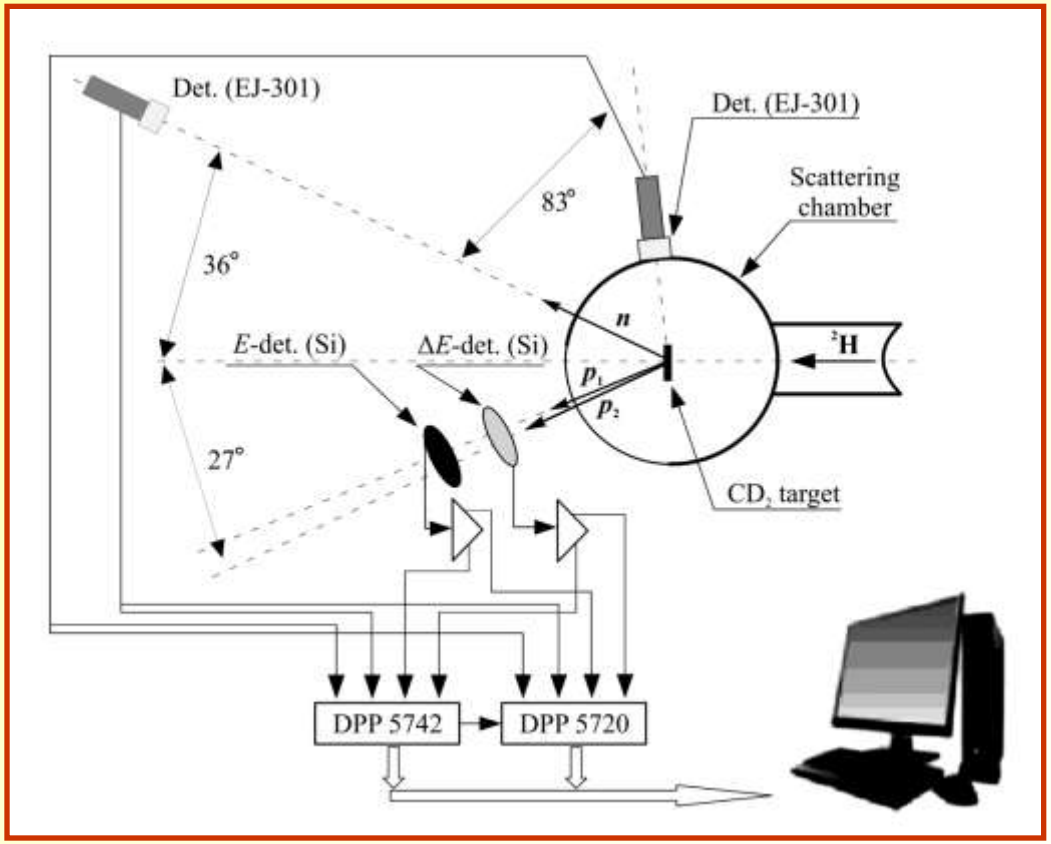
Different Widths of Singlet State; E_{nn} = 120 keV



One can see that the shape of the spectra is sensitive to the value of the singlet state energy and width, that will allow us to determine the best fit to the experimental data using simulation results

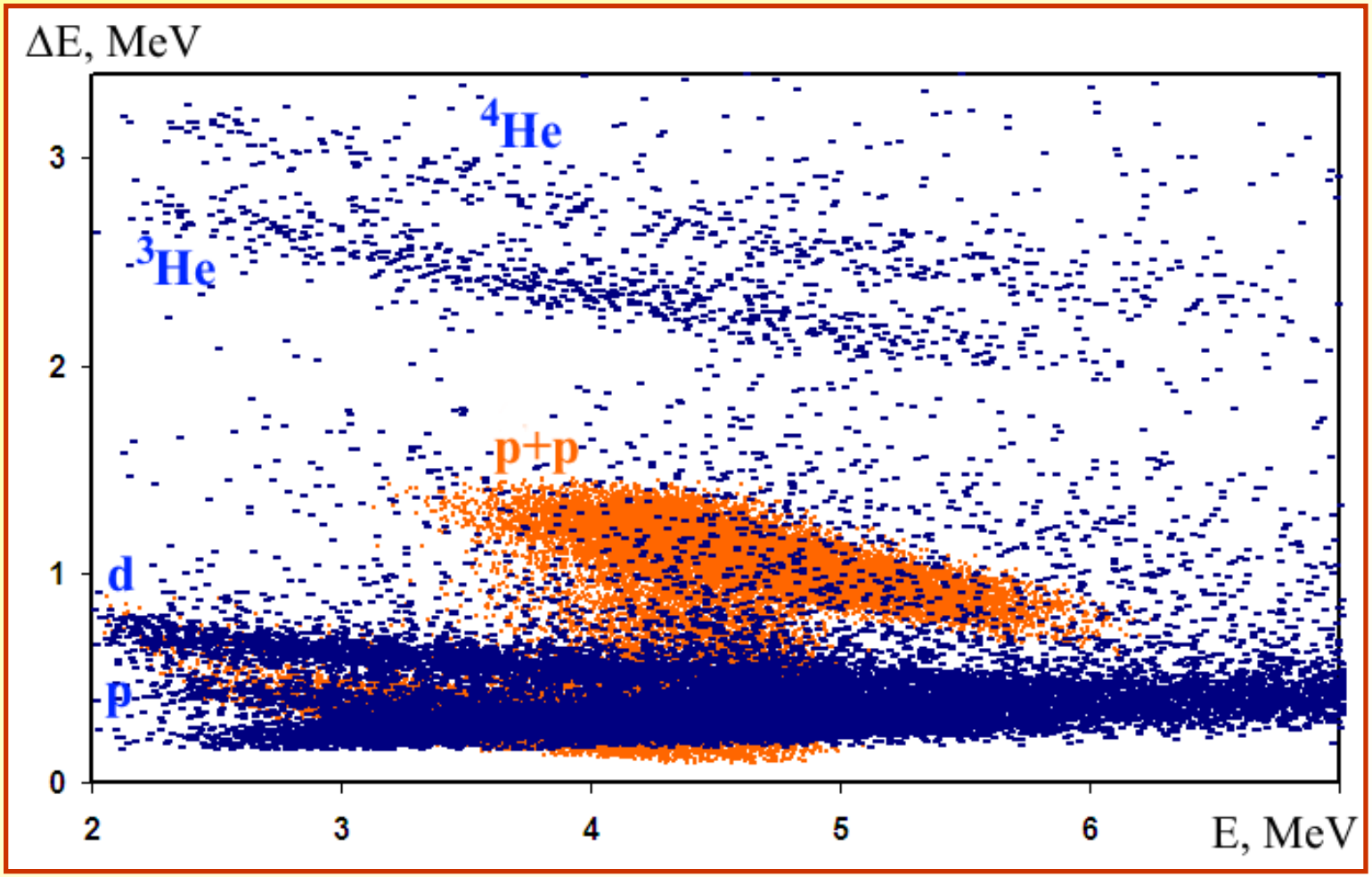
The shape of the peaks is sensitive to the value of the singlet state energy and width, that will allow us to determine the best fit to the experimental data using simulation results

Experimental: Setup for Study $d + {}^2\mathrm{H} \rightarrow p+p+n+n$ Reaction @ $E_d = 15$ MeV



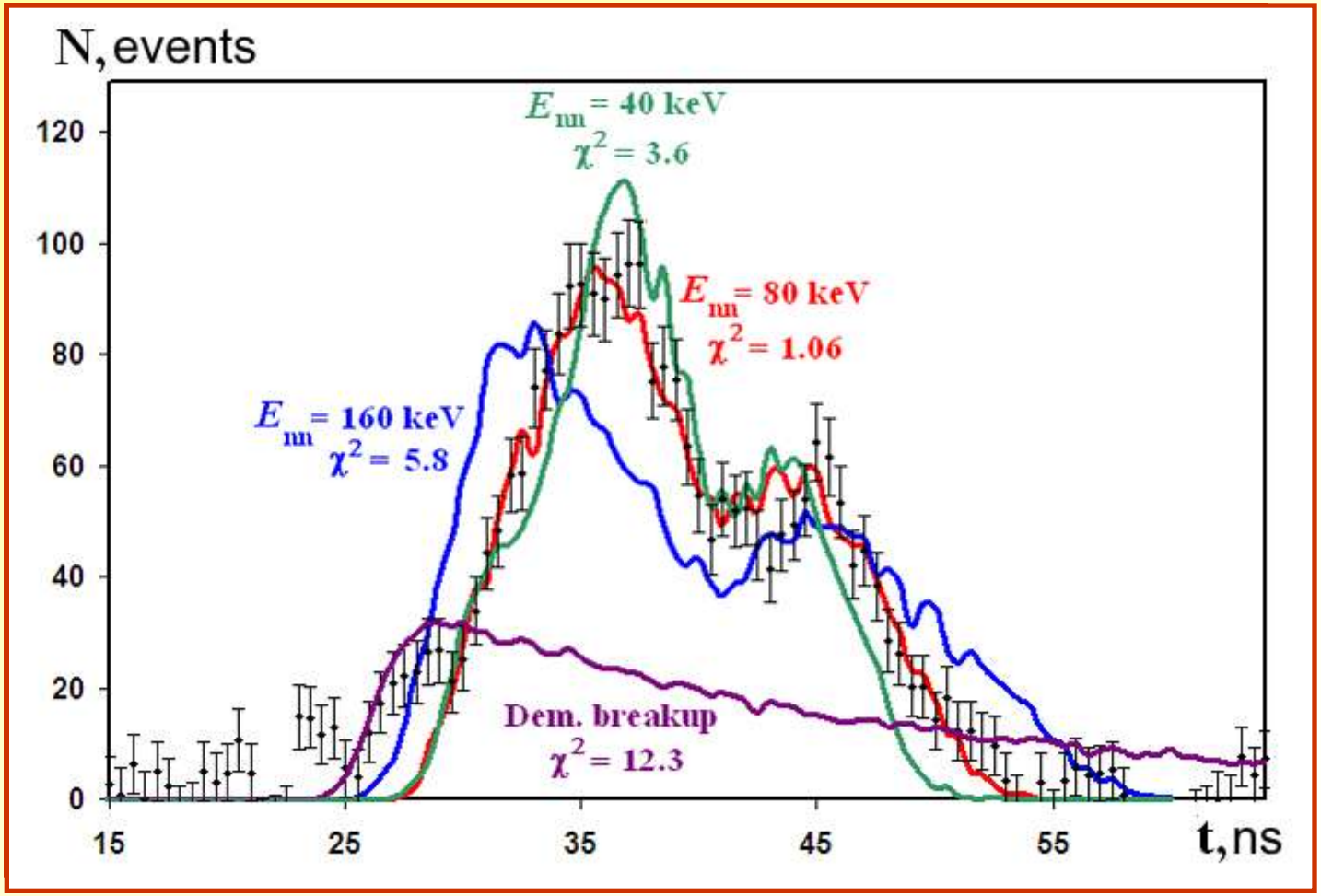
Conditions: 15 MeV deuteron beam of U120 cyclotron of SINP MSU
CD_2-target
p- and n-detectors are set at angles of ^{2}p and ^{2}n emitting
both protons are detected in one ΔE-E telescope
n-detector at 83° was used for timing calibration in dd → ^{3}He+n reaction

Experimental ΔE-E Plot and Simulated Plot for Two-Proton Events



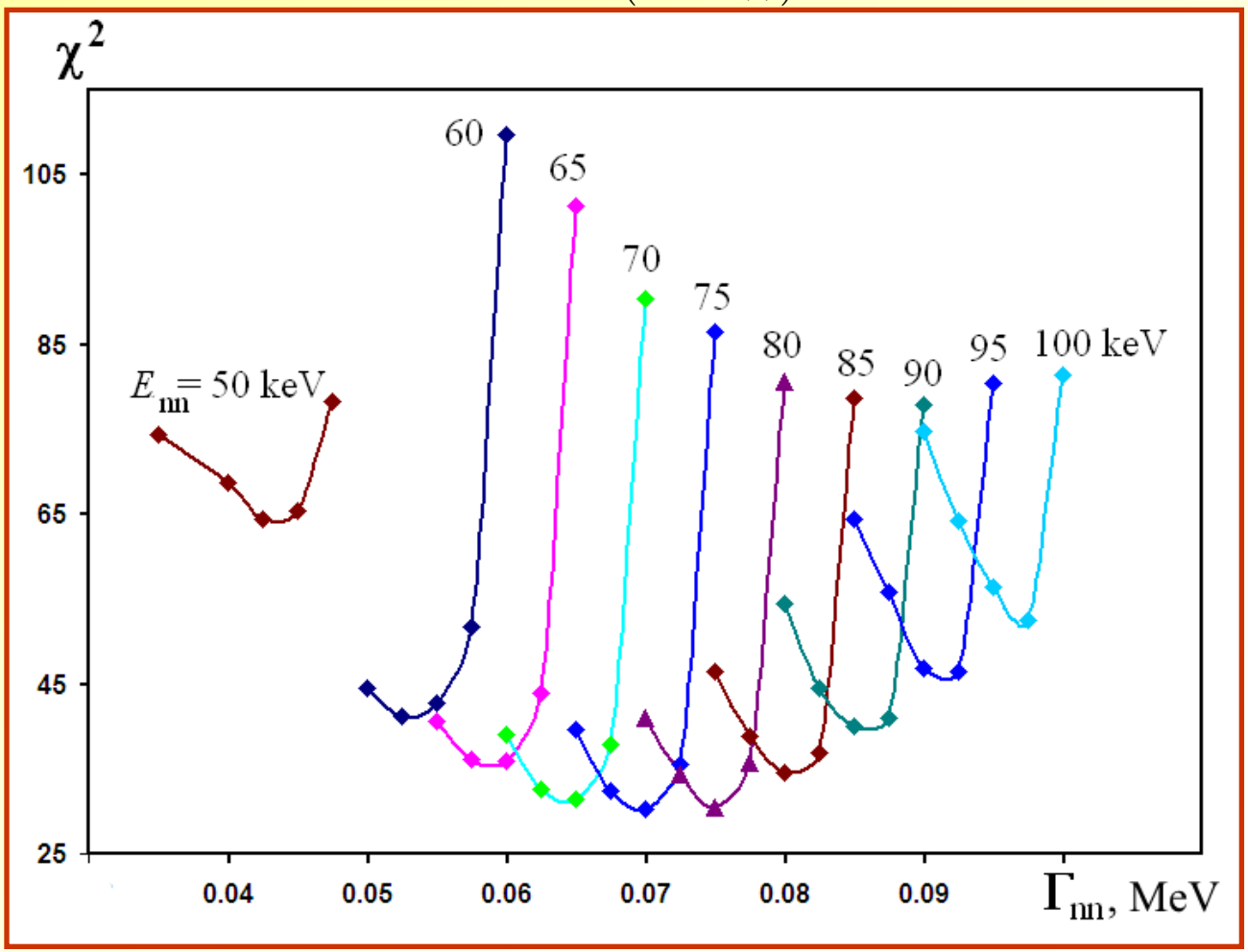
Selecting events on p+p region and determining the neutron time of flight for these events we obtained neutron timing spectrum

Experimental: Neutron Time-of-flight Spectrum **vs Simulated**

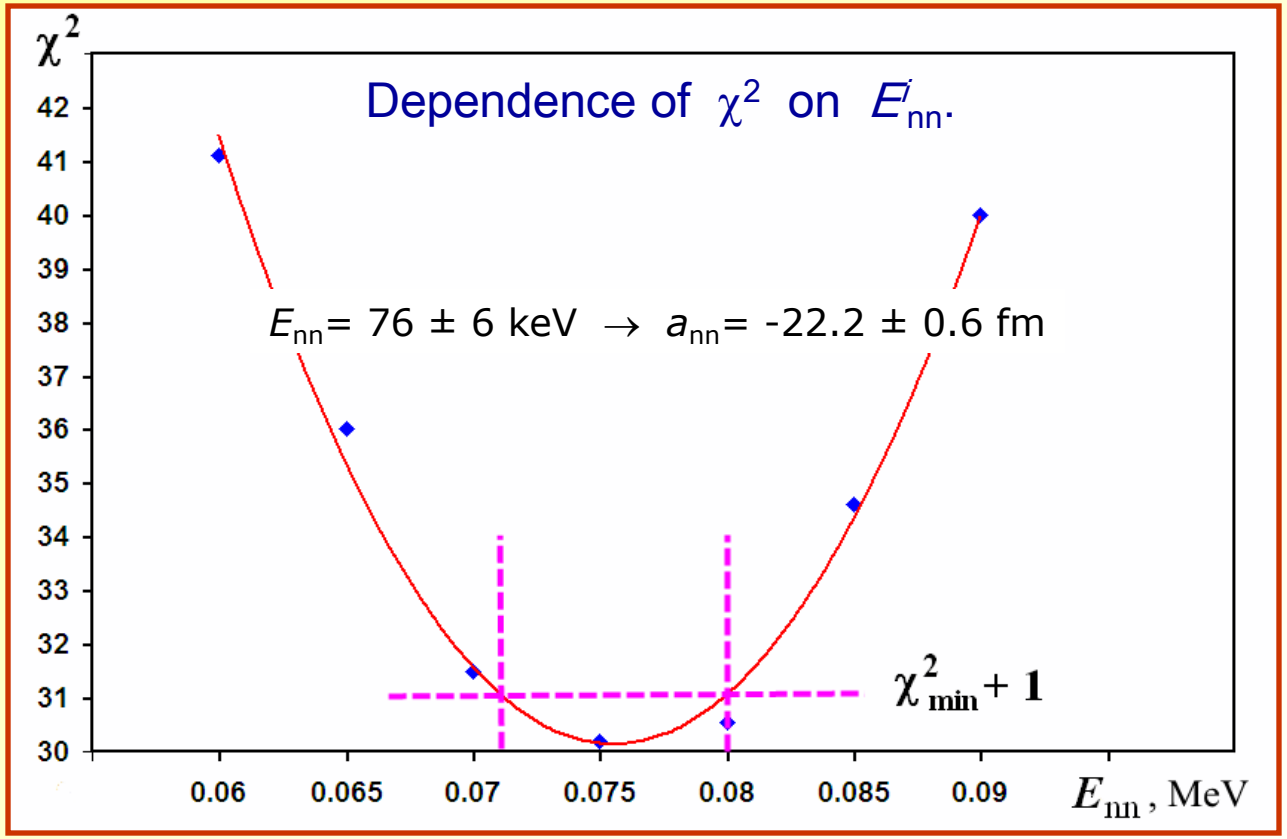


χ^2-Fitting on Γ_{nn} for Different E_{nn}

$$\chi^2(E_{nn},\Gamma_{nn}) = \sum_t \frac{\left(N^{th}_{E_{nn},\Gamma_{nn}}(t) - AN^{\exp}(t)\right)^2}{\left(\Delta N^{\exp}(t)\right)^2}$$



χ^2-Fitting over E_{nn}



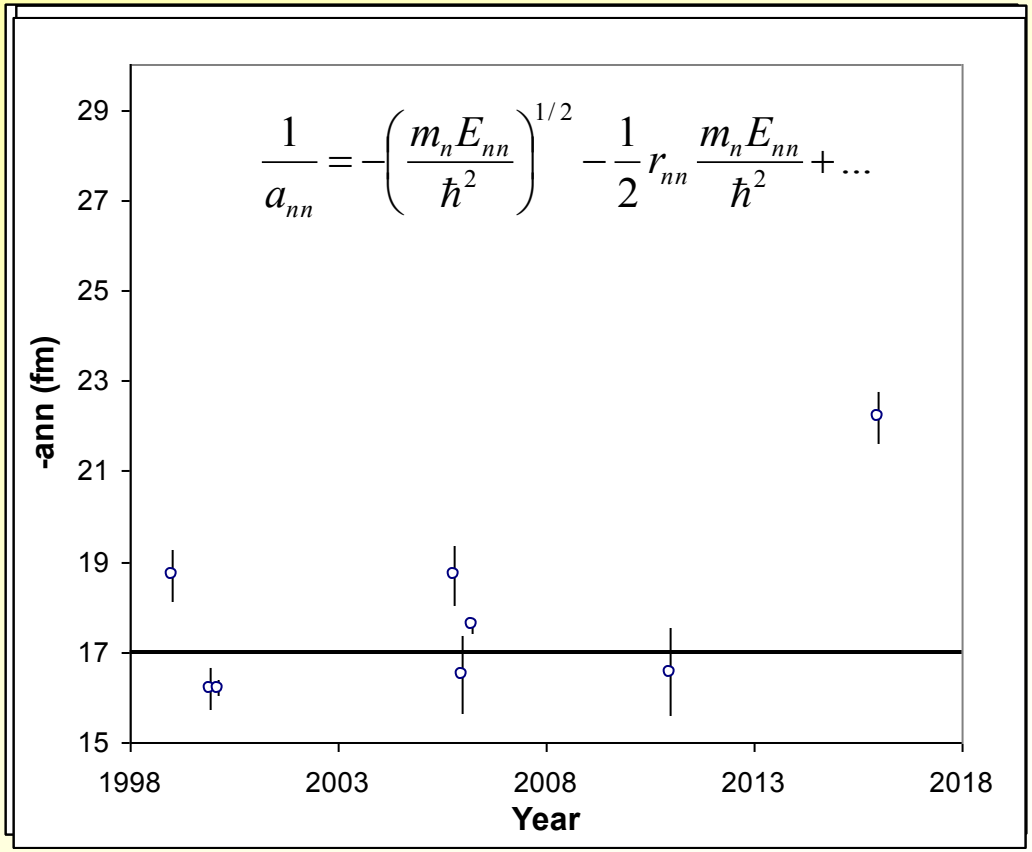
To determine E_{nn} the dependence of minimum value on Enn was fitted by a quadratic polynomial. The minimum value of χ^2 determines the most probable value of the quasibound state energy.

Error in determining E_{nn} is given as $\Delta E_{nn} = \left| E_{nn}(\chi^2_{\min}) - E_{nn}(\chi^2_{\min} + 1) \right|$

The minimum value of the polynomial is achieved at E_{nn} = 76 keV, ΔE_{nn} = ± 6 keV

Analysis of a_{nn} data obtained in nd- and dd-breakup

$$R \approx \tau * c * \sqrt{\frac{(E_1 + Q)(M_3 + M_4) - E_1 M_1}{M_3 M_4}}$$



For each experiment we introduced parameter R which corresponds to distance between *nn* pair and proton (or diproton in dd experiment) for arbitrary time interval

nclusions

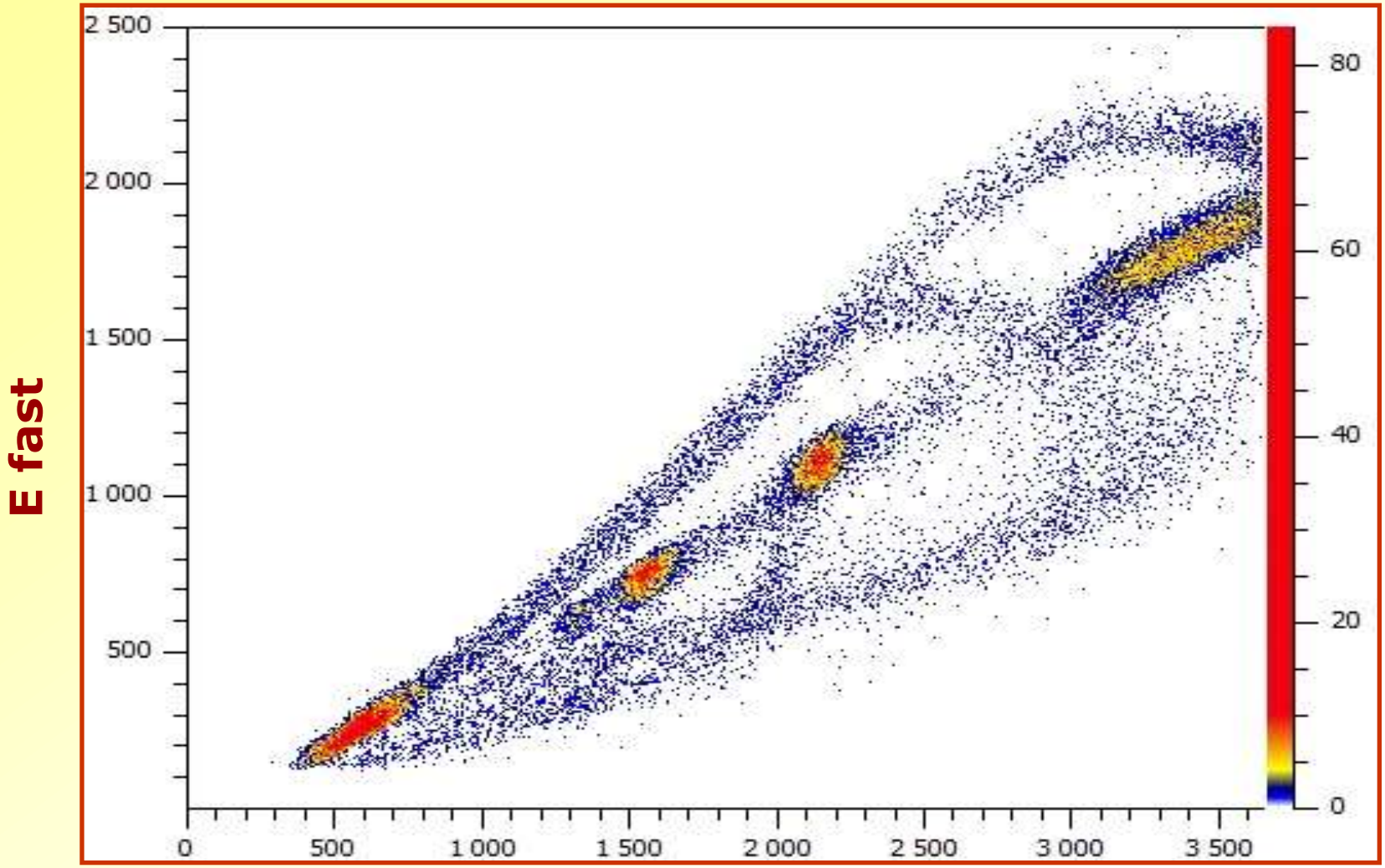
ering length a_{nn} has been
ally complete *nd* breakup

fm and E_{nn} = 129 ± 14 keV
were obtained performing the shape analysis of the FSI dependence of reaction yield on relative energy of *nn* pair.

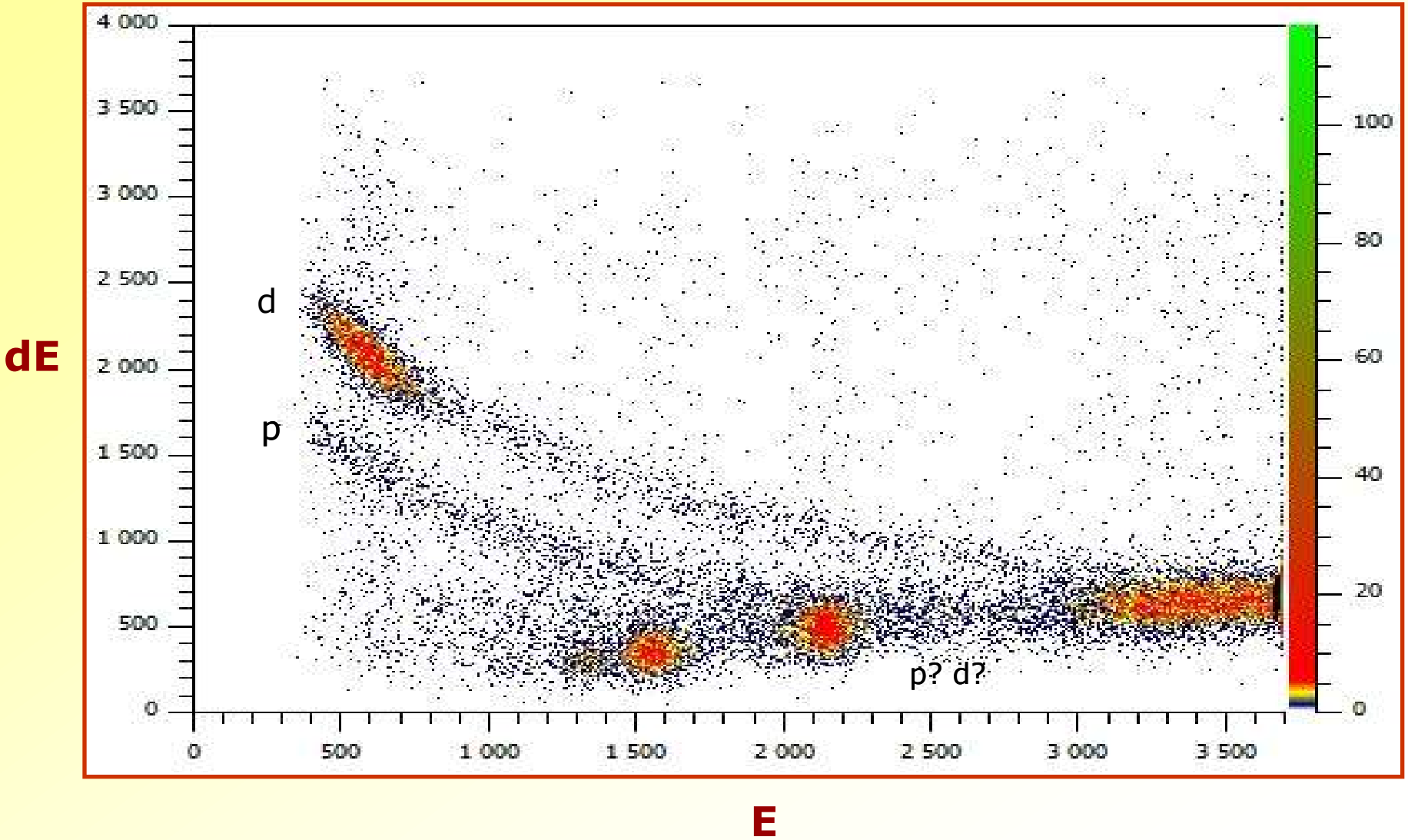
- For the first time, in $d+{}^2\mathrm{H} \rightarrow {}^2n^S + {}^2p^S \rightarrow n+n+p+p$ reaction the energy of virtual state of ${}^2n$-system and nn-scattering length were determined - E_{nn} = 76 ± 6 keV; a_{nn} = -22.2 ± 0.6 fm.
- The obtained values of scattering lengths were compared with experimental values of ${}^1S_0$ *nn*-scattering length obtained in *nd*-breakup reaction.
- One can conclude that the difference in the scattering lengths obtained under different kinematic conditions can be explained by the influence of 3N-forces depending on the relative velocity between the *nn*-pair and the charged fragment.

Thank you!

2D-Plot E-E_{fast}



Experimental 2D-plot ΔE-E

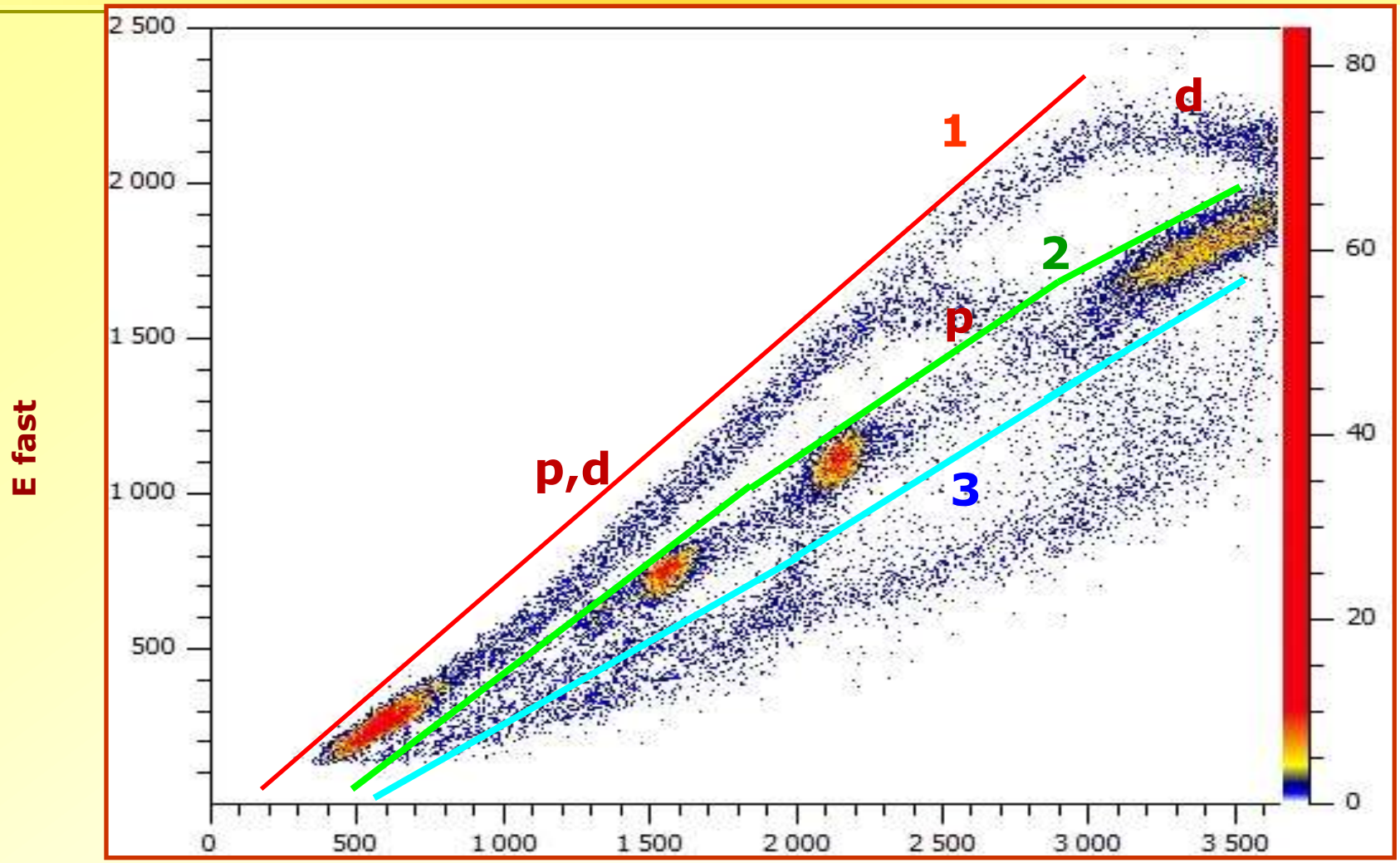


Summary

- We investigated $d+{}^2\mathrm{H} \rightarrow {}^2n^S + {}^2p^S \rightarrow n+n+p+p$ reaction, passing through a formation in the intermediate state of dineutron and diproton singlet pairs.
- For the first time, in a kinematically complete experiment the energy virtual state of 2*n*-system is determined.
- The energy of the state is determined by comparing the experimental TOF spectrum of neutrons from breakup of this state with simulated spectra depending on this energy.
- The obtained value $E_{nn} = 76 \pm 6$ keV was compared with experimental values of ${}^1S_0$ *nn*-scattering length obtained in *nd*-breakup reaction.
- One can conclude that the difference in the scattering lengths obtained under different kinematic conditions can be explained by the influence of 3N-forces depending on the relative velocity between the *nn*-pair and the charged fragment.

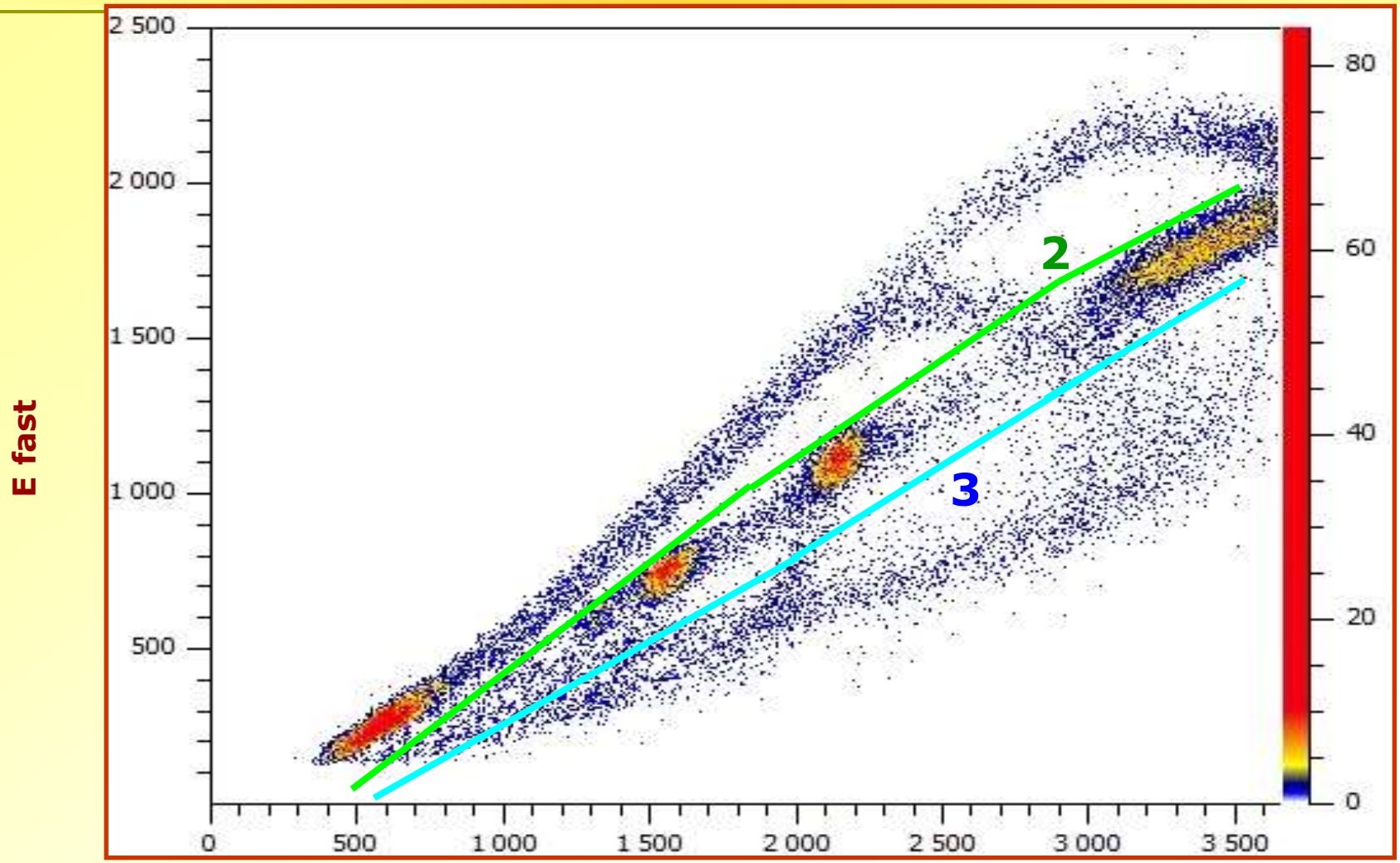
Experimental 2D-plot E-Ef (400 μm)

1-2 – полное поглощение, 2-3 - пролет

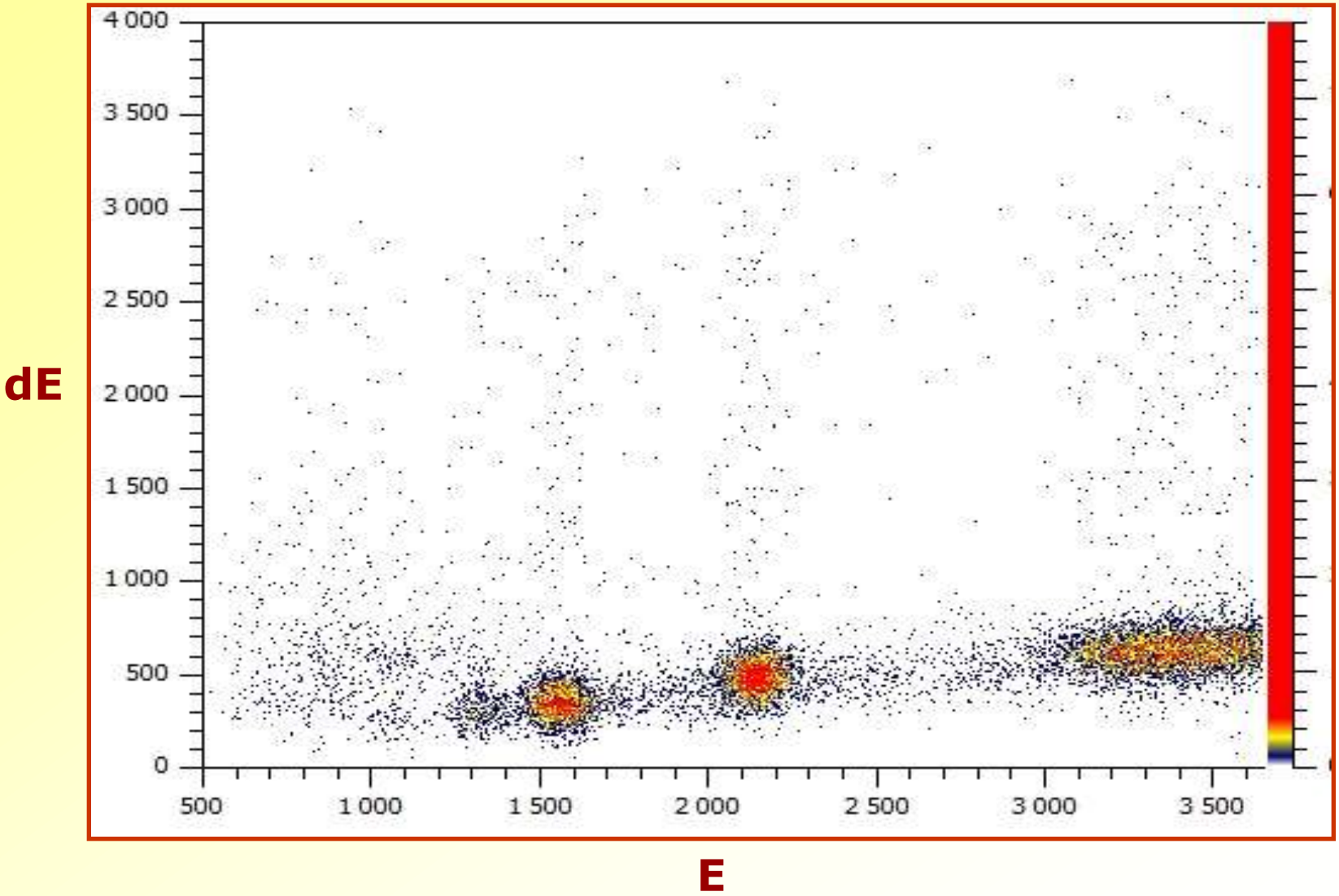


Experimental 2D-plot E-Ef (400 μm)

1-2 – полное поглощение, 2-3 - пролет

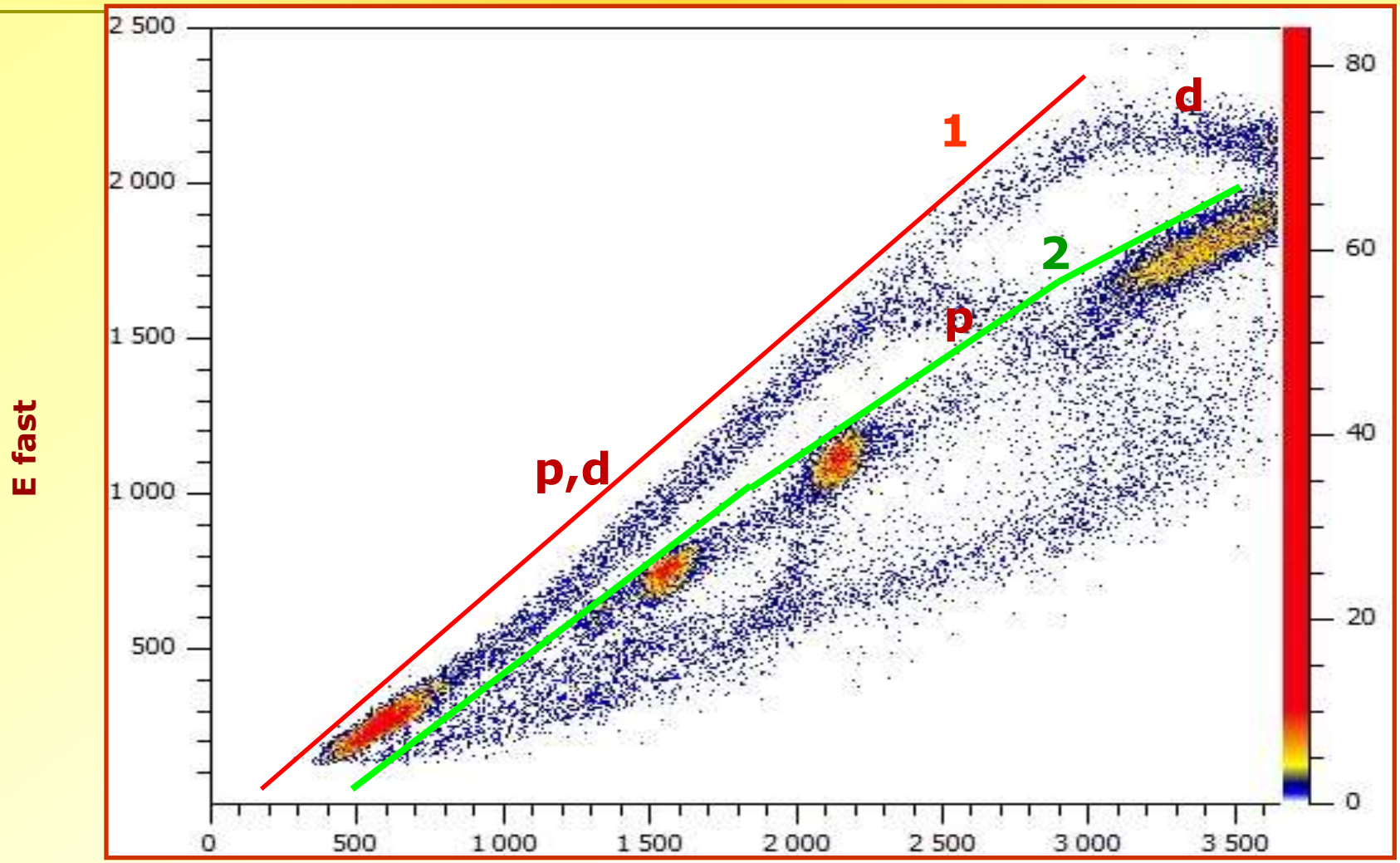


ΔE-E: пролетный локус (2-3)

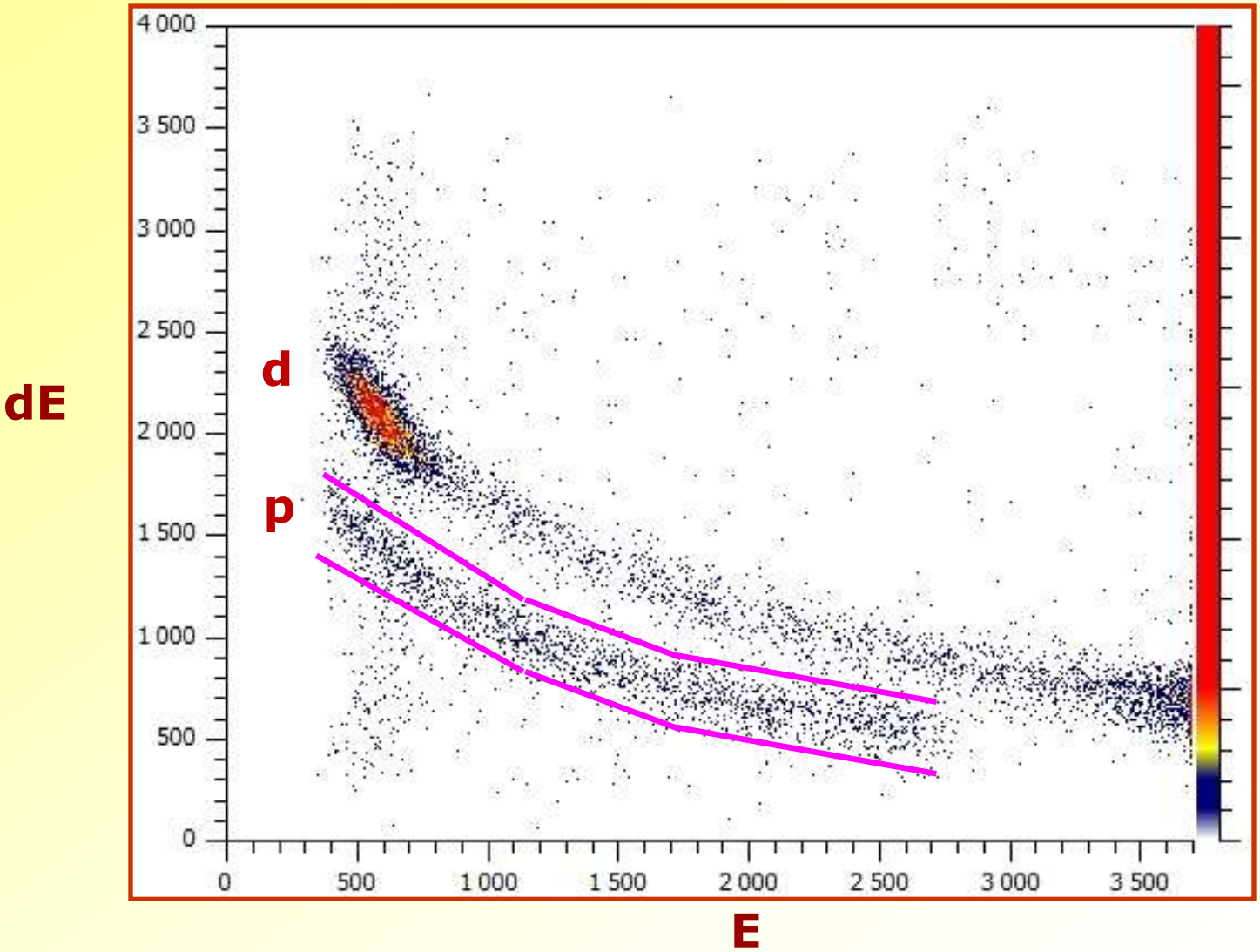


Experimental 2D-plot E-Ef (400 μm)

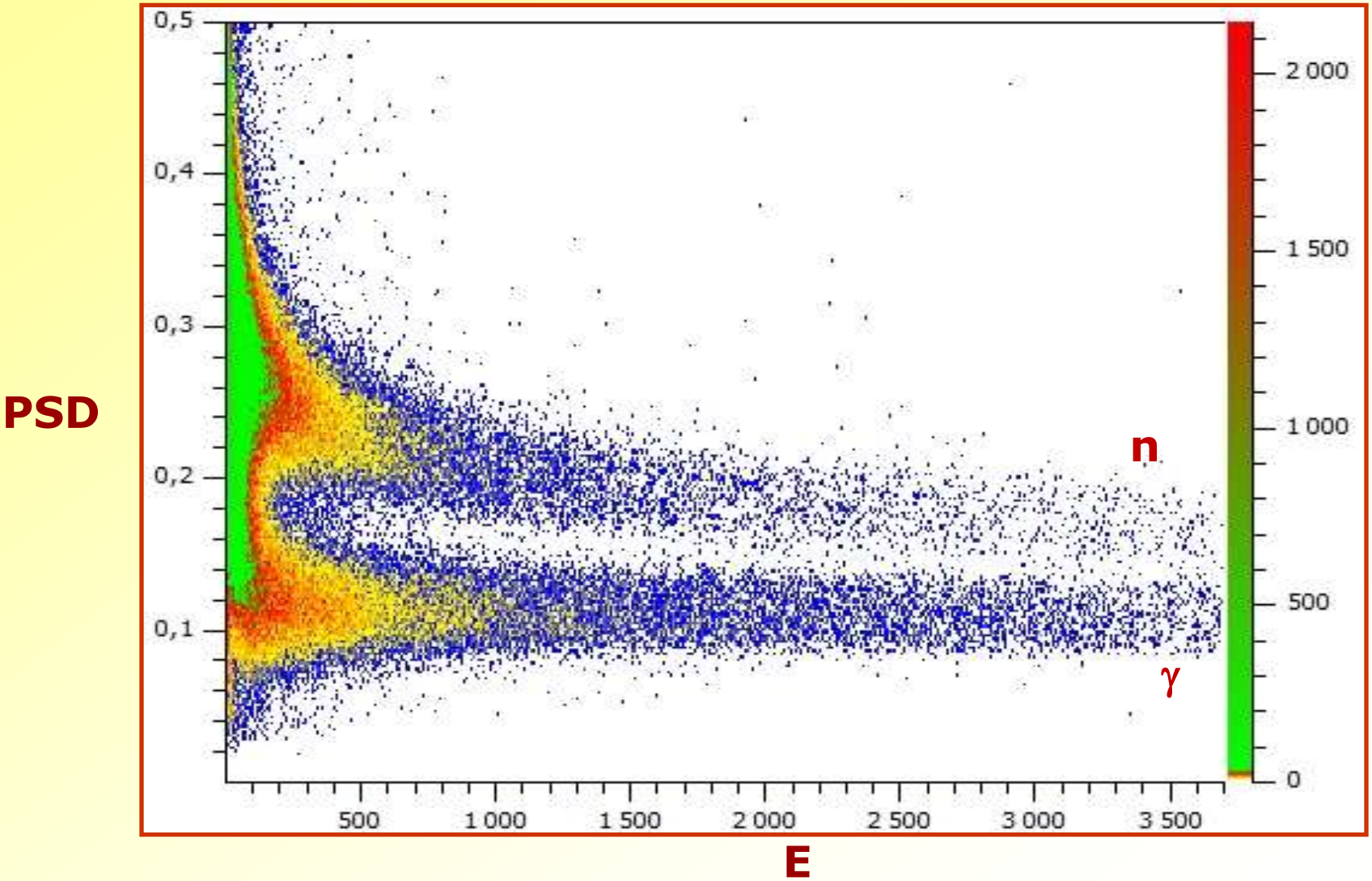
1-2 – полное поглощение, 2-3 - пролет



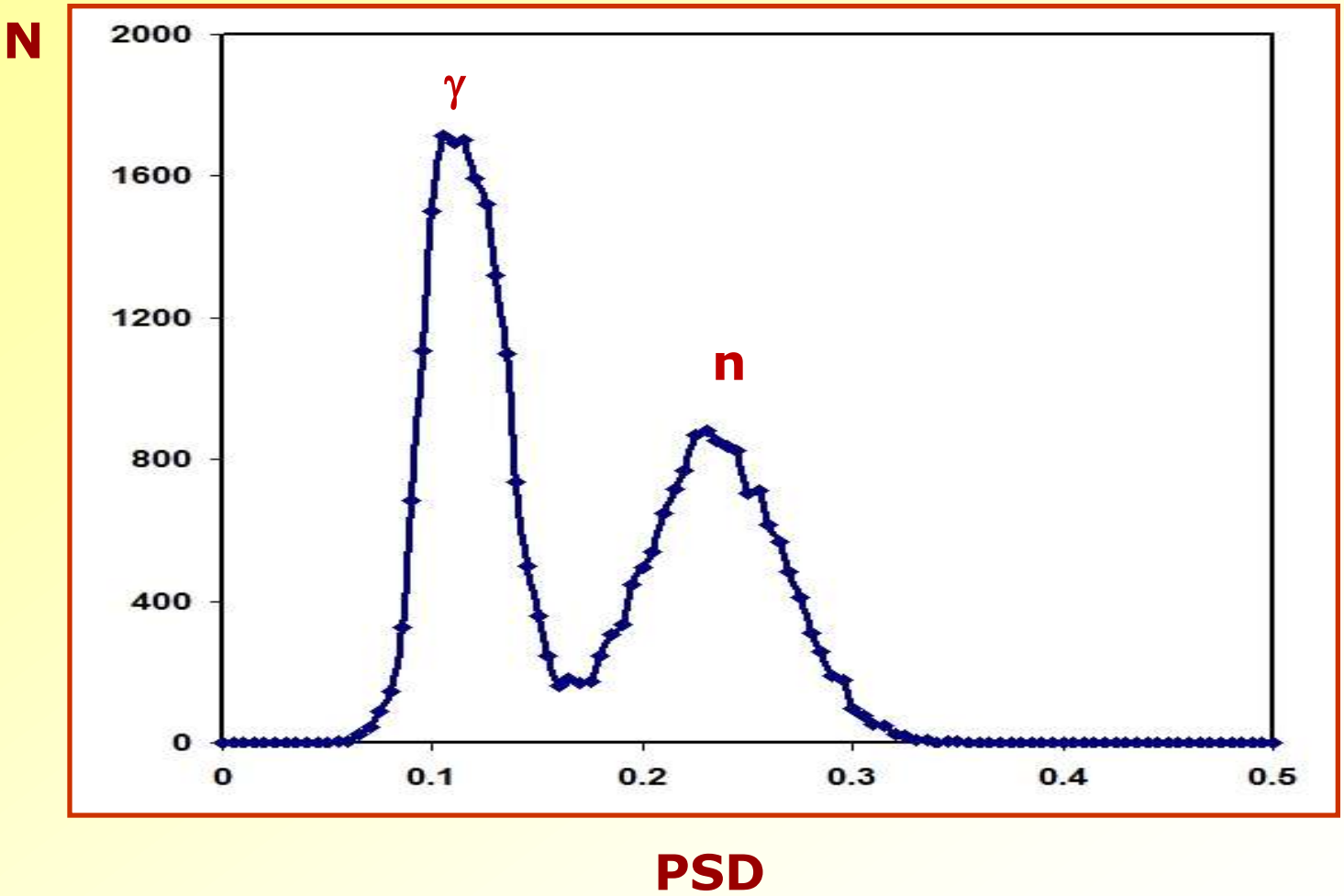
dE-E: полное поглощение (1-2)



PSD: n-γ разделение (EJ-301)



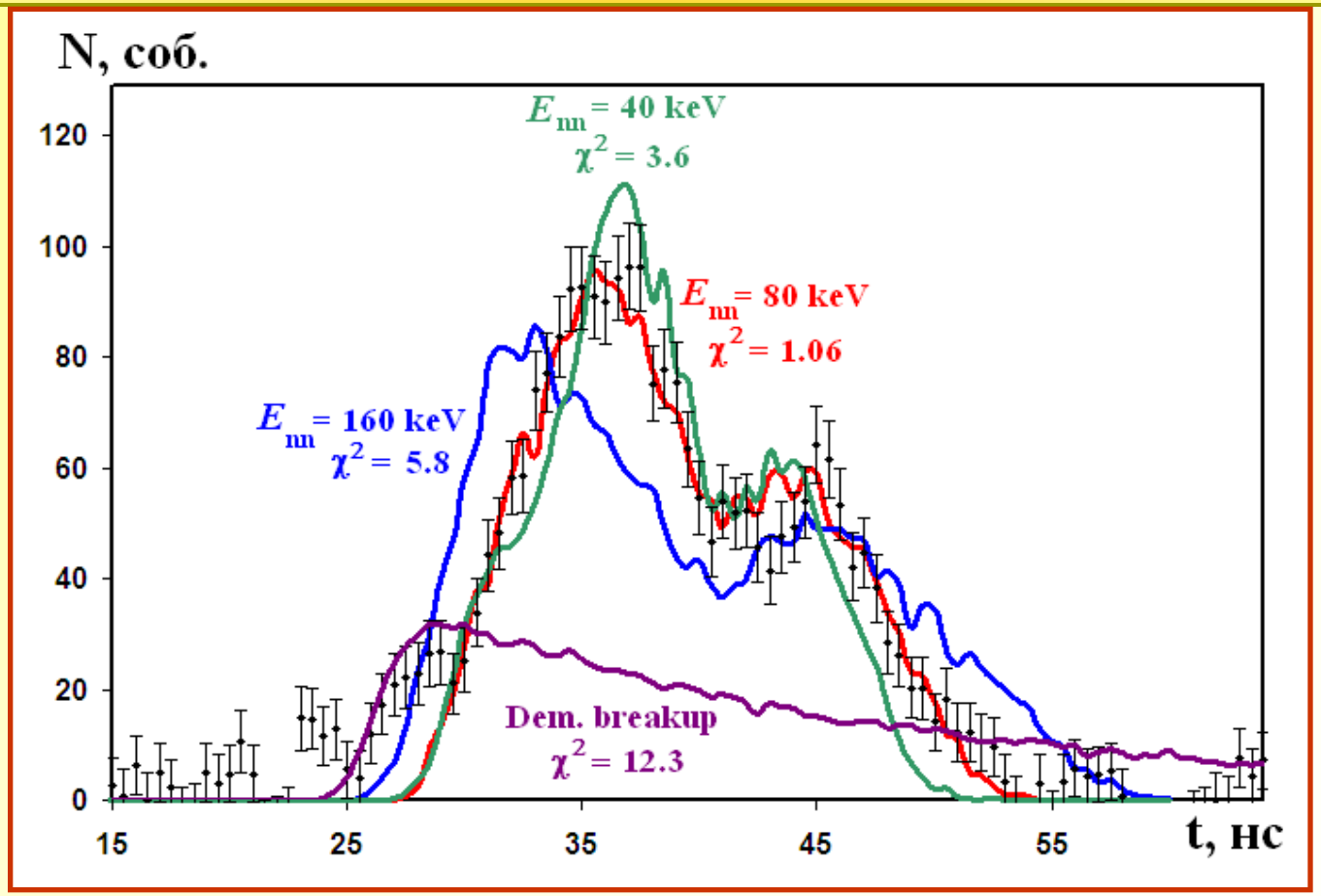
PSD - Spectrum



Предварительные результаты по эксперименту dp→ppn

- Проведено моделирование реакции dp→ppn
- Отлажена детектирующая система (ΔE-E и n-детекторы)
- Отлажена методика выделения p+n событий
- Начат набор статистики

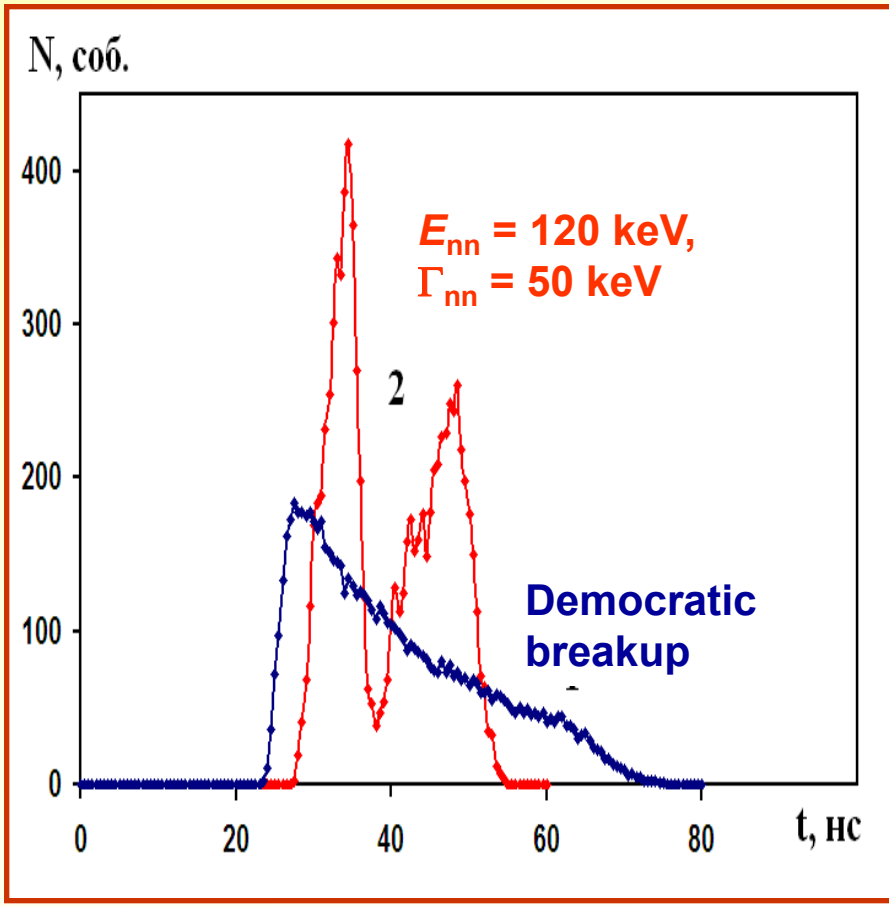
Experimental Spectrum vs Simulated



Analysis: Fitting Procedure

Simulation of $d + {}^2\mathrm{H} \rightarrow n + n + p + p$ Reaction:

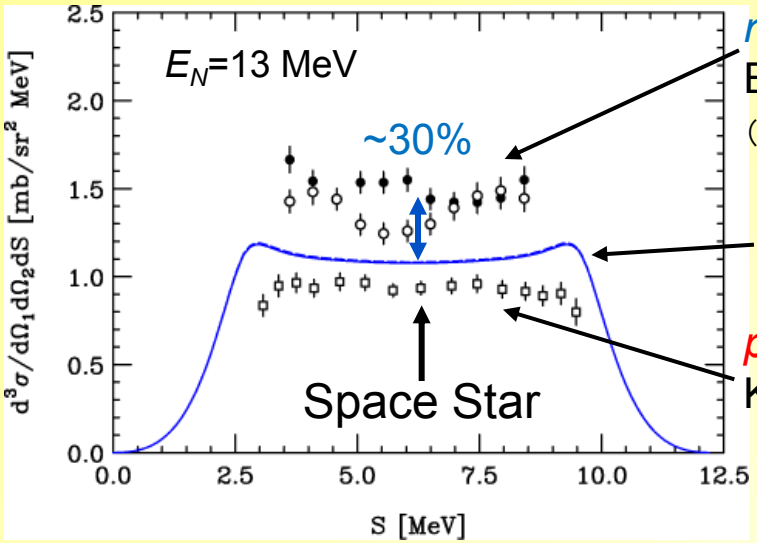
Democratic vs Quasibound state



Simulated time-of-flight spectra of neutrons: 1 – for events of democratic breakup, 2 – for events with E_{nn} = 120 keV, Γ_{nn} = 50 keV. Neutron time-of-flight base 0.79 м.

Space Star (SS) Anomaly

- SS Anomaly was first found in 1989 in *nd* breakup reaction at 13 MeV.



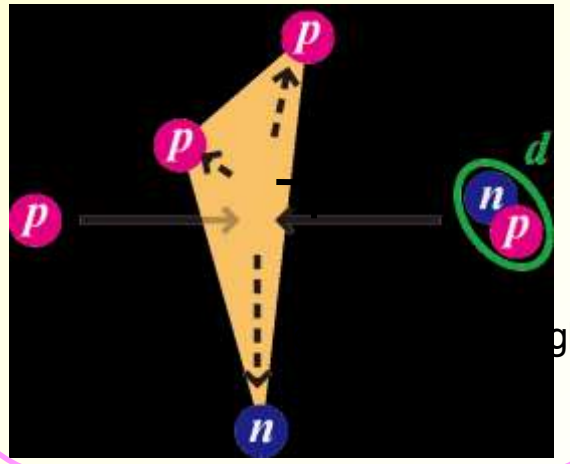
nd exp.
Erlangen & TUNL
(●)(1989) (○)(1996)

nd calc.

pd exp.
Koeln (1991)

J.STRATE *et al.*, Nucl. Phys. A**501** (1989) 51
H.R.Setze *et al.*, Physics Letters B**388** (1996) 229
G.RAUPRICH *et al.*, Nucl. Phys. A**535** (1991) 313

Space Star
(c.m. system)



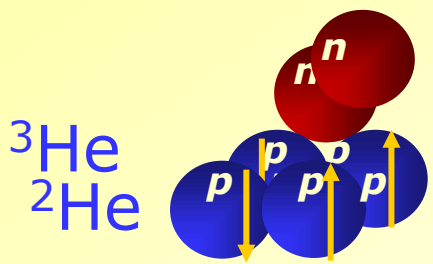
gle

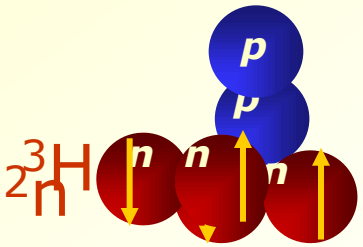
- In Star configuration, outgoing 3 nucleons have the same energy and form an equilateral triangle.
- In Space Star (SS), the star plane is perpendicular to the beam axis in c.m. system.

The Search for *NN*-Correlations in 3*N*-Systems

In ^{3}He neutron causes a correlation of two protons leading to an appearance of quasibound $^1S_0$ diproton state

In ^{3}H proton causes a correlation of two neutrons leading to an appearance of quasibound $^1S_0$ dineutron state

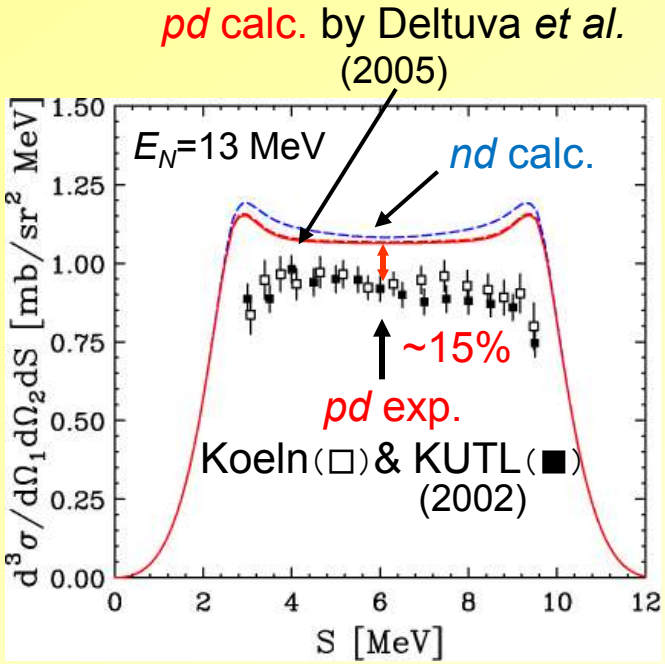


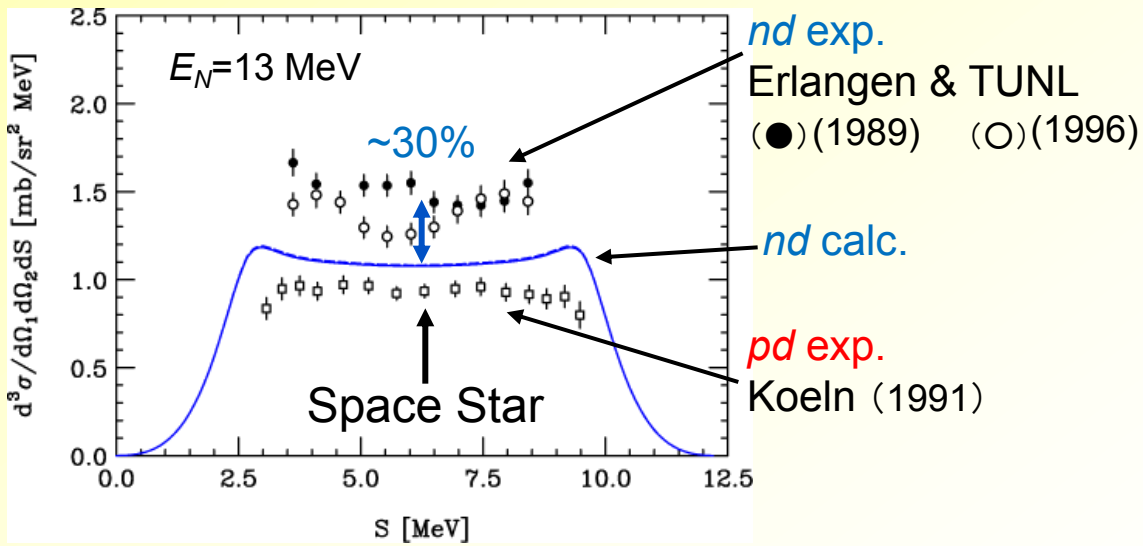


Removal of proton from *^{3}H* and/or neutron from *^{3}He* provide conditions advantageous for *NN*-correlations to search

Space Star (SS) Anomaly in *pd* breakup

- *pd* calc. were made by Deltuva *et al*. and by Ishikawa.

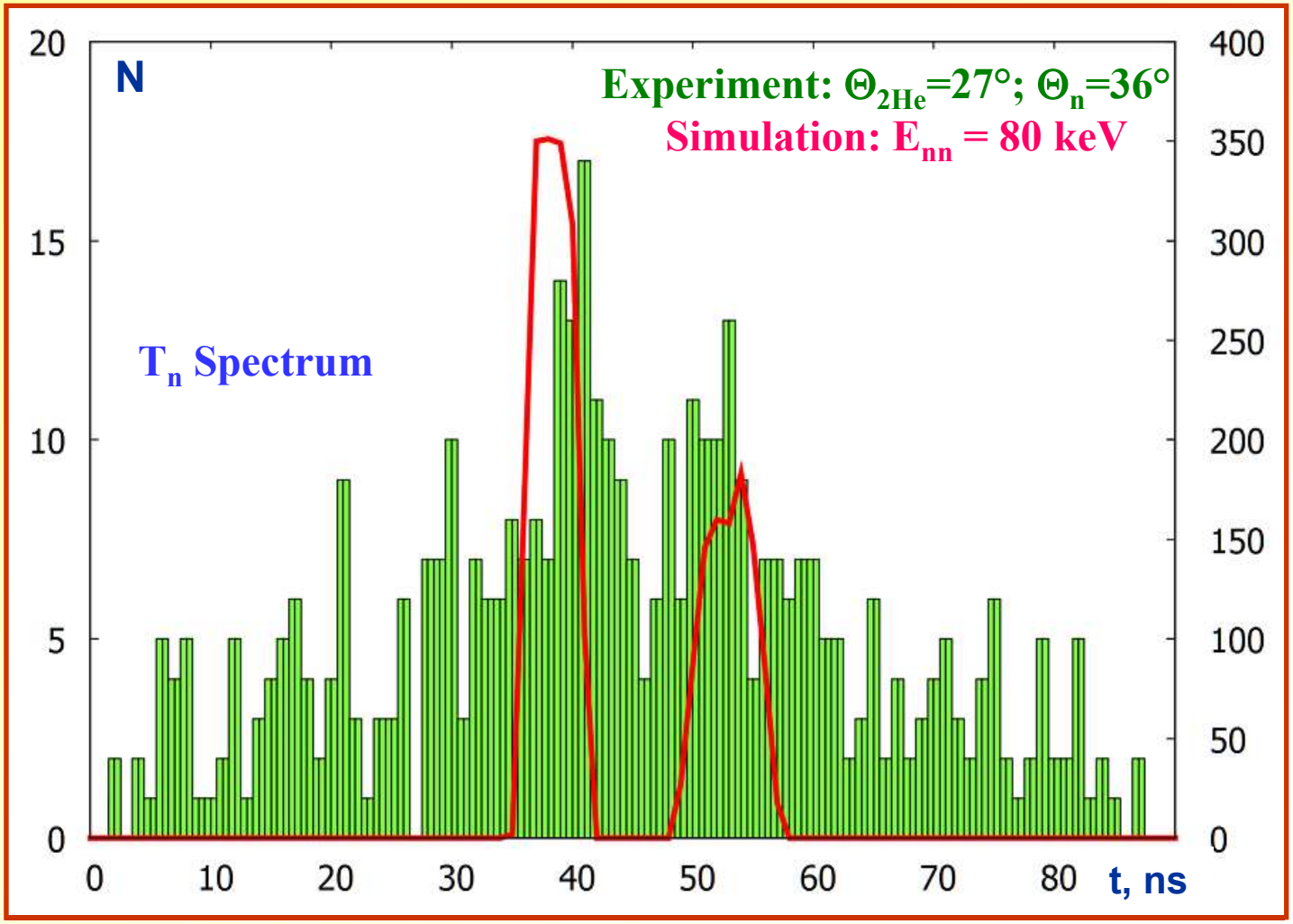




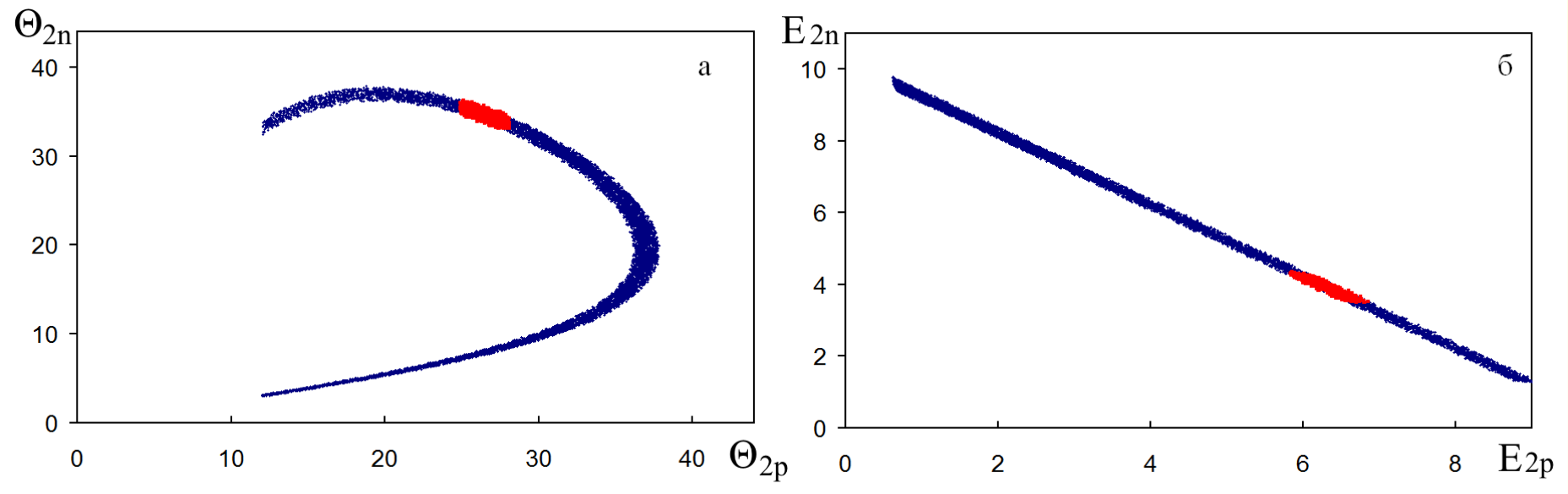
A.Deltuva et al., PRC72,054004 (2005)
J.STRATE *et al.*, Nucl. Phys. A**501** (1989) 51
H.R.Setze *et al.*, Physics Letters B**388** (1996) 229
G.RAUPRICH *et al.*, Nucl. Phys. A**535** (1991) 313

- At *pd* SS, exp. cross section is smaller than *pd* calc.
- At *nd* SS, exp. cross section is larger than *nd* calc.

Our Preliminary Results of $d+D \rightarrow {}^2He+2n$ Neutron TOF Spectrum @ TOF Base 1 m

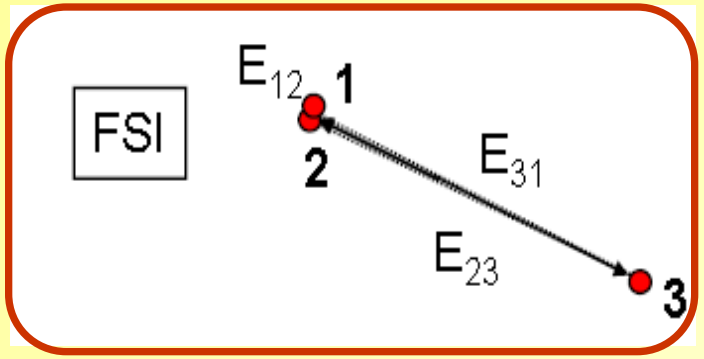


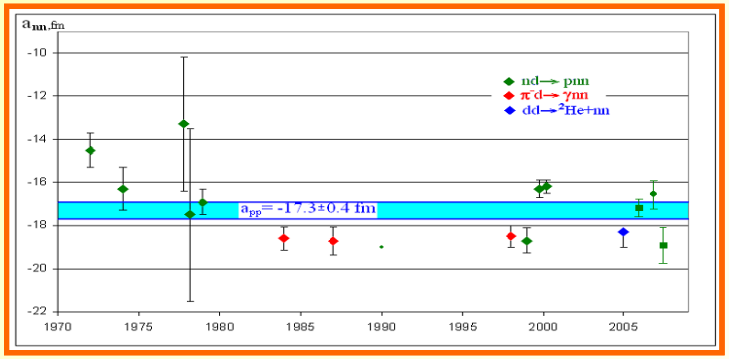
The Search for NN-Correlations

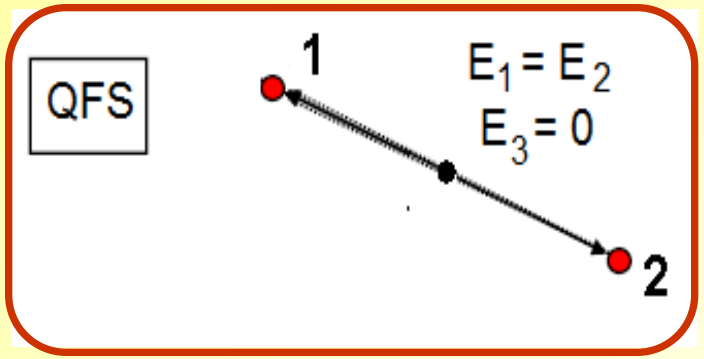


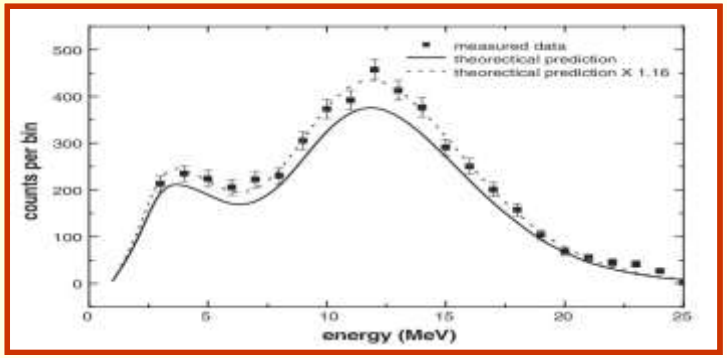
Результаты кинематического моделирования реакции $d + 2H \rightarrow {}^2n^s + {}^2p^s$ – двумерные диаграммы Θ_{2n}-Θ_{2p} (а) и E_{2n}-E_{2p} (б), где Θ_{2n} и Θ_{2p} – углы вылета, а E_{2n} и E_{2p} – энергии двухнейтронной и двухпротонной систем. Красные области соответствуют вылету системы ${}^2p^s$ под углом 27° ± 1.5°

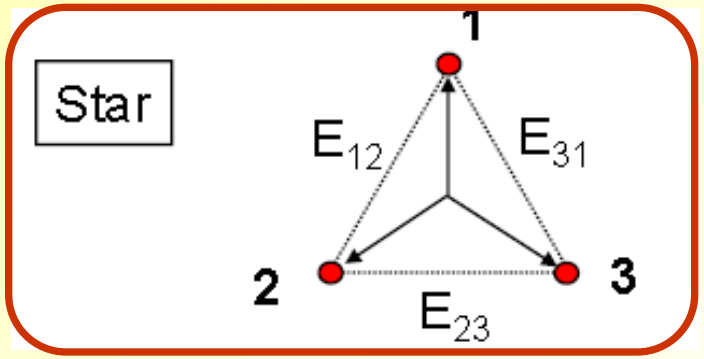
nd-breakup configurations and unresolved problems

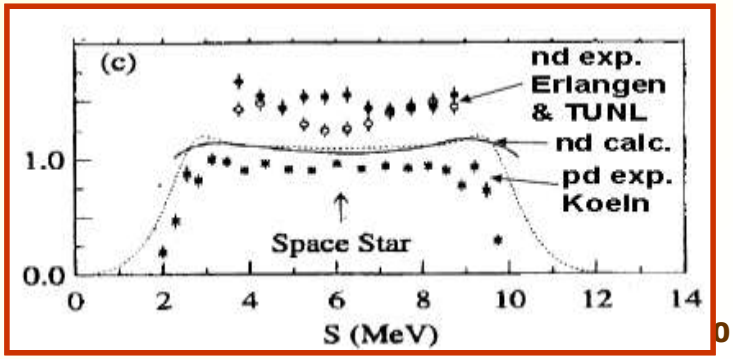








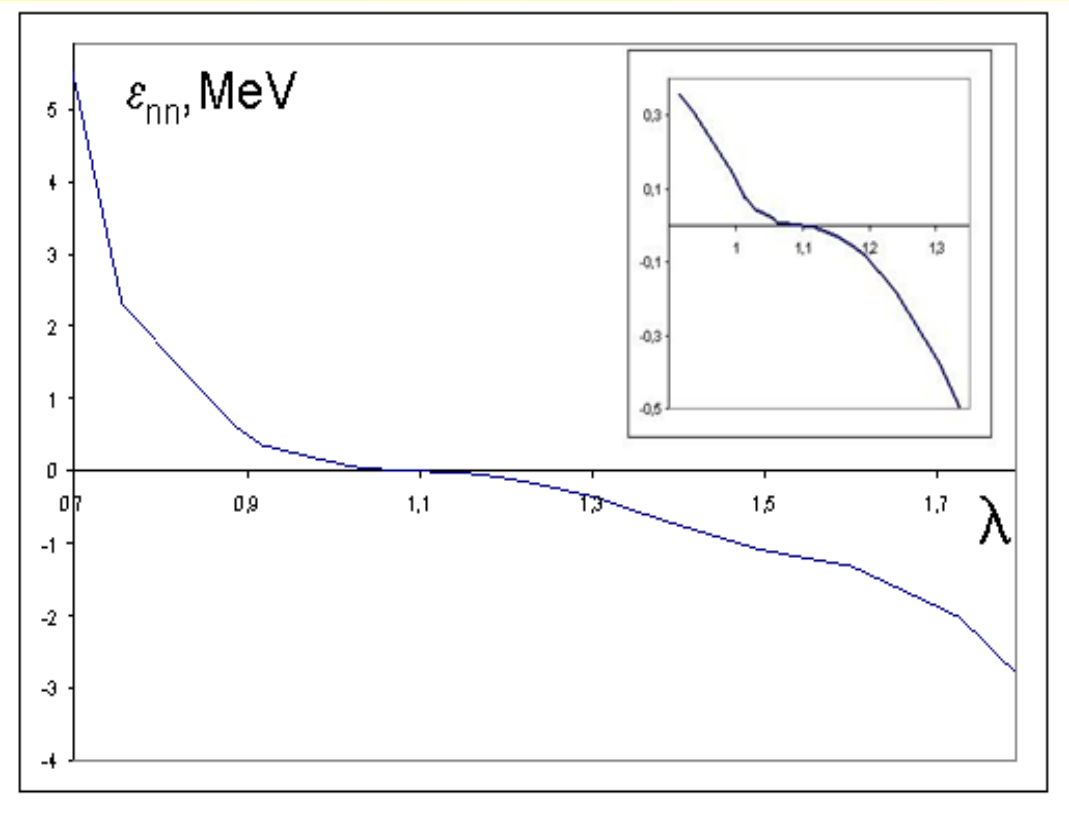




Modification of $^1S_0$ nn force

H. Witala & W. Gloeckle suggested

$$V_{nn}(^1S_0) = \lambda \times V_{CDBonn}(^1S_0)$$



λ	ϵ_{nn} [MeV]	a_{nn} [fm]	r_{eff} [fm]
0.9	-	-8.25	3.12
1.0	-	-18.80	2.82
1.19	-0.099	+21.69	2.39
1.21	-0.144	+18.22	2.35
1.3	-0.441	+10.95	2.20
1.4	-0.939	+7.87	2.07

H. Witala & W. Gloeckle, Phys. Rev. C83, 034004 (2011)

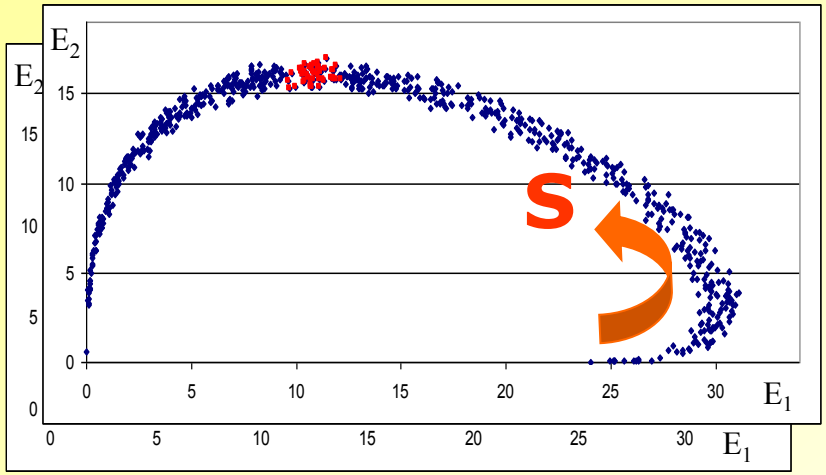
- λ=1.08

No arguments for this modification

X.C.Ruan *et al.*, Phys. Rev. C 75, 057001 (2007)

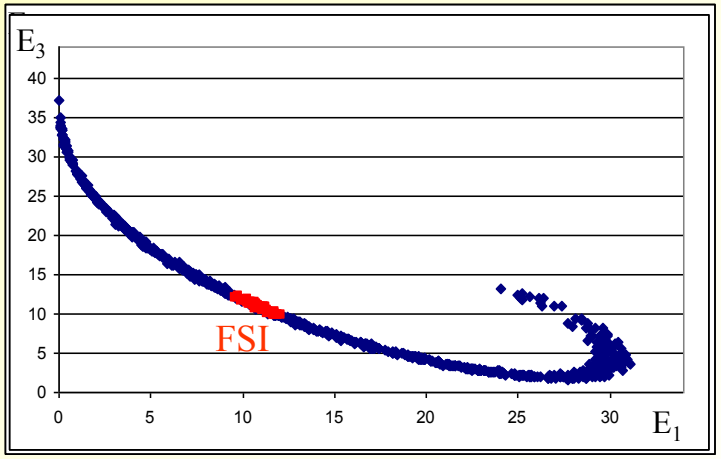
Kinematical curves for FSI geometry in *nd*-breakup
$E_0 = 40 \pm 5$ MeV, $\Theta n1 = -36^o$, $\Theta p = 75^o$

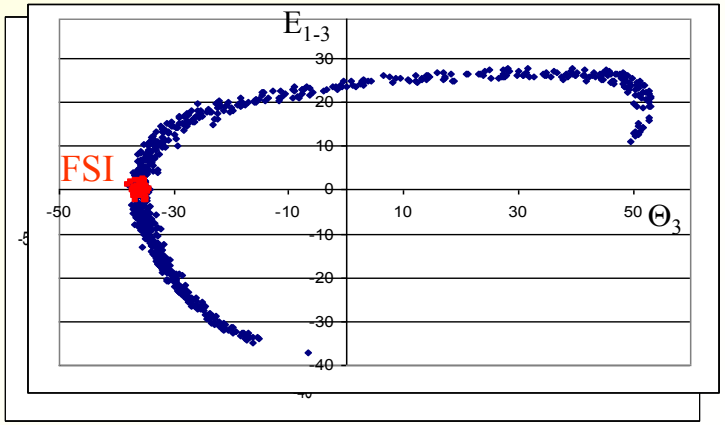
1-neutron, 2-proton



FSI

1-neutron 3-neutron





$E_{13}=\varepsilon= (E_1 + E_2 - 2(E_1E_2)^{1/2}\cos\Delta\Theta)/2$

$0, \Theta_1 \approx \Theta_2$

3N Faddeev equation

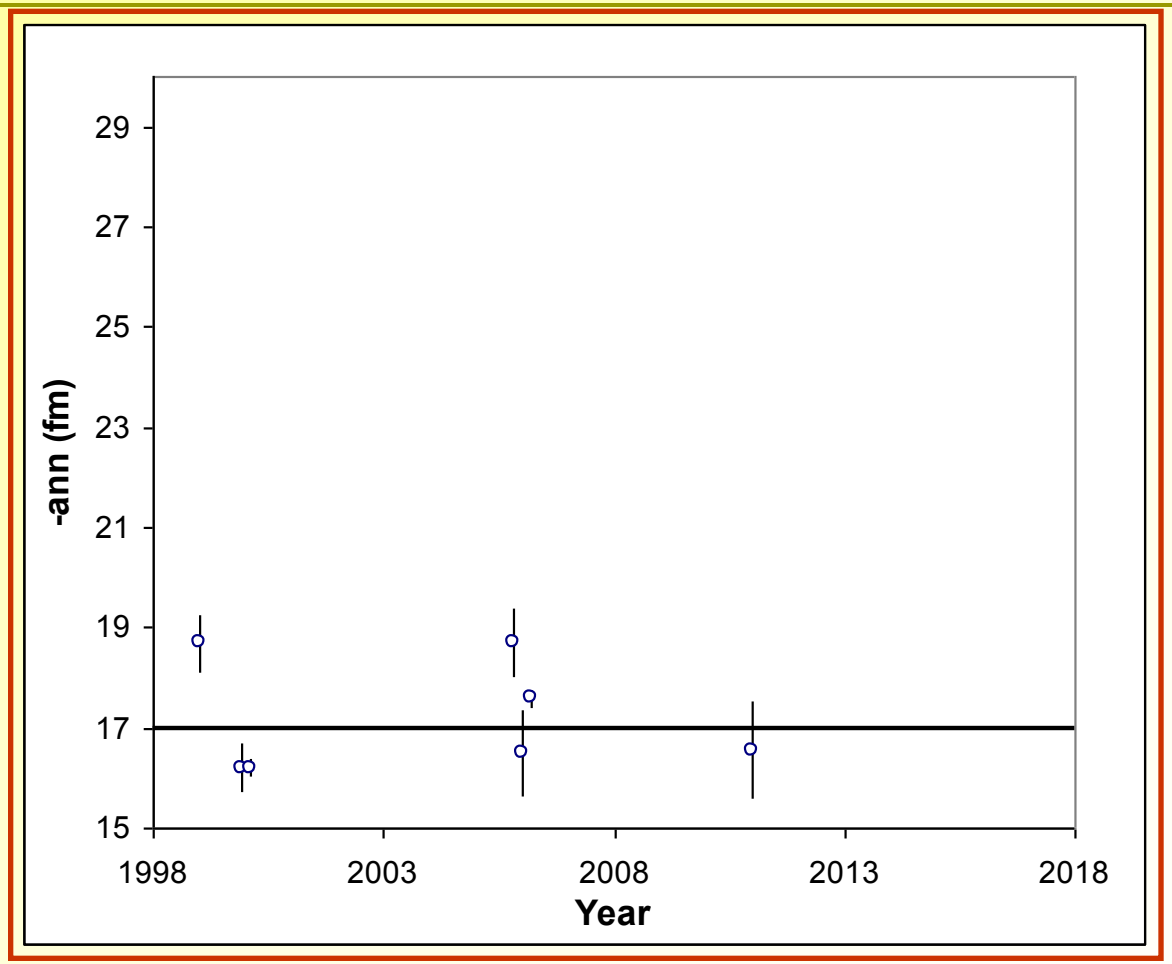
$$\frac{d\sigma}{d\Omega_1 d\Omega_3 dS}$$

WM-approximation

$$\frac{dN}{d\varepsilon}_{WM} = \frac{\sqrt{\varepsilon}}{\varepsilon + \varepsilon_0}$$

INR RAS 2012

nn- и pp -длины рассеяния



Charge Independence and Charge Symmetry of Nuclear Forces

pp and *np* Interaction

A huge amount of data on pp and np interactions has been accumulated. Careful analysis of these data led to constructing NN interaction potentials describing vast majority of experimental data.

nn Interaction

The situation around neutron–neutron interaction is more ambiguous. Because of the absence of neutron target, data on this interaction are obtained primarily from reactions with two neutrons in the final state. But in many cases, there are serious discrepancies between available experimental data and the results of the current precise calculations on the basis of Faddeev equations.