Experimental Verification of the Exotic Six-Quark Hadron $d_1^*(1956)$ Production in the Process $pp \to pp\gamma\gamma$ Below the Pion Production Threshold.

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Villigen PSI
Switzerland

AUTHORS OF THE PROJECT

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Aims of the project

The project is aimed at solving one of the long-standing problems of QCD, namely, the problem of the existence of exotic hadrons that are more complex color singlet bound systems made up of quarks and antiquarks than ordinary (q^3 and $q\bar{q}$) hadrons. The primary goals of the project are the following:

1. To make crucial experimental verification of the existence of the exotic six-quark hadron $d^*_1(1956)$.

2. To determine more precisely its mass and its total width.

MOTIVATION

QCD admits the existence of exotic hadrons and, in particular, those with baryon number B=2 made up of six-quarks q^6. An important feature of such hadrons is that they may be composed of colored quark clusters separated in space $\Longrightarrow$ states with "hidden color"$\Longrightarrow$narrow resonances or even states bound with respect to strong interaction.

The experimental discovery of any such a hadron could have a big effect on our understanding of QCD and would provide valuable information for its stringent test. Moreover, the study of such qualitatively new type of nuclear matter could help elucidating mechanisms of confinement.

Most promising candidates for the exotic six-quark hadrons are low mass narrow dibaryon resonances not coupled to the *NN* channel, in particular those with zero strangeness. These are nonstrange, two-baryon hadrons with quantum numbers inaccessible to the systems built from two nucleons:

$$J^P = \begin{cases} 1^+, 3^+, 5^+, \ldots\ldots\ldots\ldots, \ \textbf{for}\ I = 1 \\ 0^\pm, 2^-, 4^-, \ldots\ldots\ldots\ldots, \ \textbf{for}\ I = 0 \end{cases}$$

They cannot be bound or resonant states of two color-singlet nucleons. In addition owing to small widths and masses they could hardly be interpreted as resonances in such two body systems as *NΔ* or *ΔΔ* or in the three body system πNN.

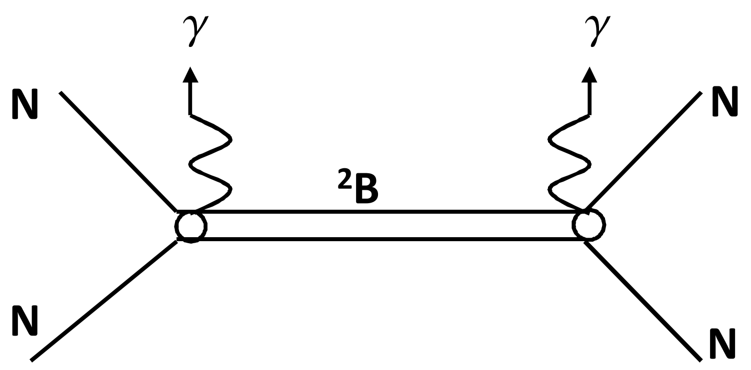
Experiment: Narrow dibaryon states have been searched for in a number of experiments, but none has provided any convincing evidence for their existence. Most of these searches were limited to dibaryons coupled to the *NN* channel and only a few were dedicated to the *NN*-decoupled dibaryon resonances. The situation with the latter, however, is not so definite. There is a series experimental data that strongly suggests the existence of the *NN*-decoupled nonstrange dibaryon with a mass of about 1956 MeV. But its existence has neither been conclusively confirmed nor definitely ruled out up to now.

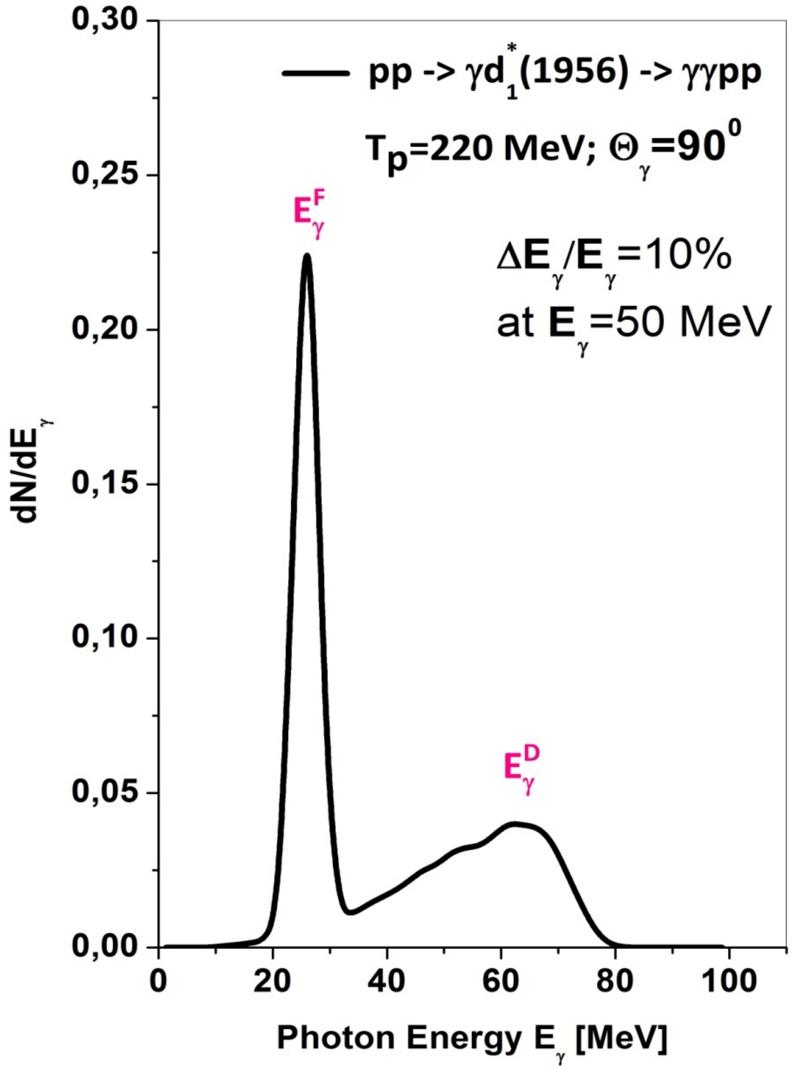
The main drawback of the methods used to search for the dibaryon resonances is a very large but not well enough determined background due to non-resonant processes of reactions used.

The authors of the project have proposed a new and, effective method of searching for nonstrange, *NN*-decoupled dibaryon resonances ^2B with masses $M_R \leq 2m_N + m_\pi$ which is free of such a drawback. S.B. Gerasimov and A.S. Khrykin (Mod. Phys. Lett. A, 8,(1993)2457).

The method consists in measuring the photon energy spectrum of the reaction $NN \rightarrow NN\gamma\gamma$ at incident energies below the pion production threshold detecting both photons in coincidence.

The method is based on the following idea. If the *NN*-decoupled dibaryons exists in nature, then the $NN \to NN\gamma\gamma$ process may proceed through the mechanism that directly involves the radiative excitation $NN \to \gamma\, ^2B$ and decay $^2B \to NN$ modes of these states. In *NN* collisions at energies below the pion production threshold these production and decay modes of the *NN*-decoupled dibaryon resonances with masses $M_R \leq 2m_N + m_\pi$ would be unique or dominant.





<u>The signature of this resonance mechanism</u> in the measured photon energy spectrum would be a narrow peak due to the radiative resonance formation and more broad one due to its radiative, three-body decay.

In the laboratory system the position of the narrow peak E_γ^F in the measured spectrum is determined as

$$E_\gamma^F = \frac{W^2 - M_R^2}{2(E - p \cdot \cos(\Theta_\gamma))},$$

where $W^2 = 2m_N(2m_N + T_N)$ is square of the invariant mass of the colliding NN system, $E = 2m_N + T_N$ is the total energy of this system, p is the momentum of incident nucleons, θ_γ is the angle of detected photons and M_R *is* the mass of the resonance.

The dependence of the position of the narrow peak on the kinetic energy of incident nucleons T_N is a very important feature of the given method and can be used for strict verification of the resonant origination of the measured photon energy spectrum.

The energy of the photons E_γ^D associated with the resonance decay in the rest frame of this resonance is determined by the mass of this resonance and the invariant mass M_{NN} of the final NN state:

$$E_\gamma^D = \frac{M_R^2 - M_{NN}^2}{2M_R}$$

The method has two important features: (1) it permits to scan the two baryon invariant mass in the region $2m_N \leq M_R \leq 2m_N + m_\pi$ with a high resolution; (2) there is only one background process that would compete with the resonance mechanism in question. This is the double NN-bremsstrahlung reaction. But this reaction is well enough understood and expected to have a small cross section.

The reaction $pp \to \gamma\gamma X$ is ideally suited for searching for the NN-decoupled dibaryon resonances, since the double pp-bremsstrahlung has extremely small cross section. Therefore, in an experiment registering two photons of the process $pp \to \gamma\gamma X$ in coincidence one can hope for a good signal-to-background ratio.

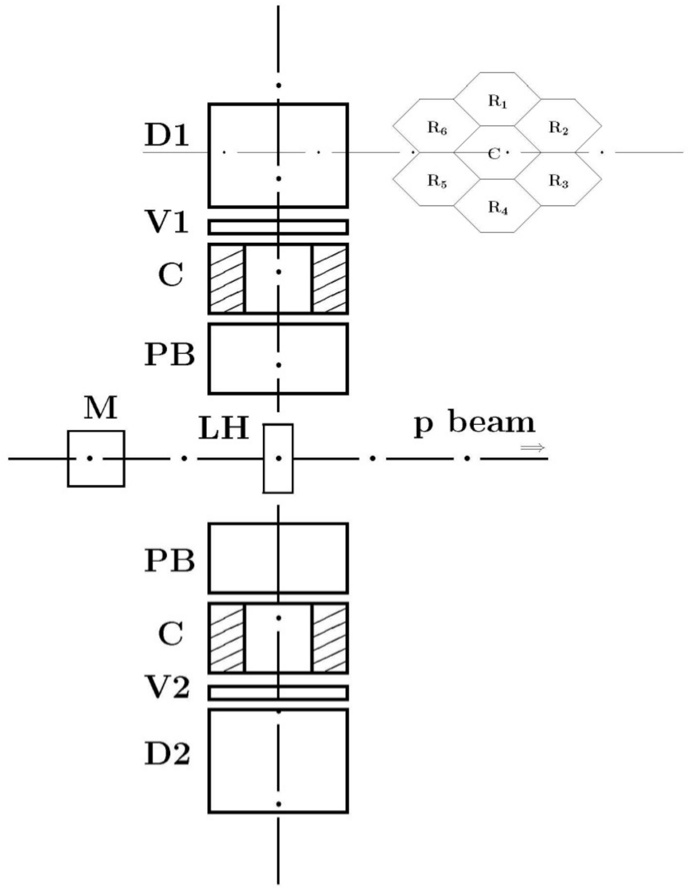
FIRST EVIDENCE FOR THE $d_1^*(1956)$

A.S. Khrykin et al., Phys.Rev. C64, 034002(2001)

Reaction : $pp \to \gamma\gamma X$

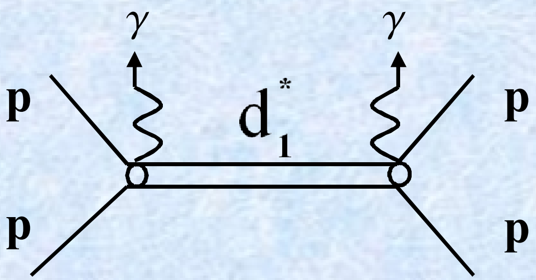
T_p=216 MeV; $\theta_\gamma = \pm 90^0$

The photon energy spectrum of the reaction was measured detecting two photon in coincidence.



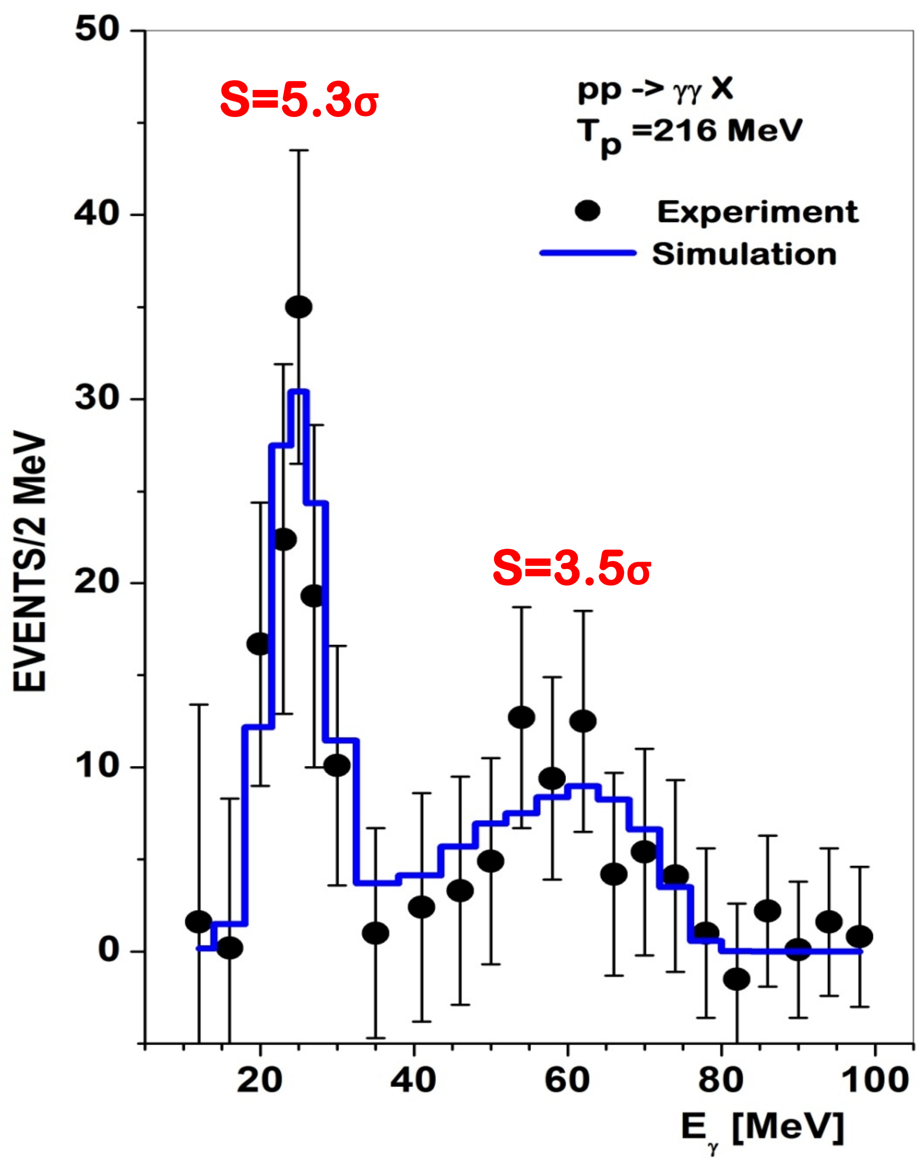
The behavior of the photon spectrum conforms to the signature of the *NN*-decoupled dibaryon resonance with a mass of about 1956 MeV, that we called $d_1^*(1956)$. **The total width of the narrow peak Γ_{tot} ~8 MeV.**

$$pp \rightarrow \gamma\, d_1^* \rightarrow \gamma\gamma pp$$



$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = 9.3 \frac{nb}{sr^2}$$

Isospin $d_1^*(1956)$ I=1 or 2



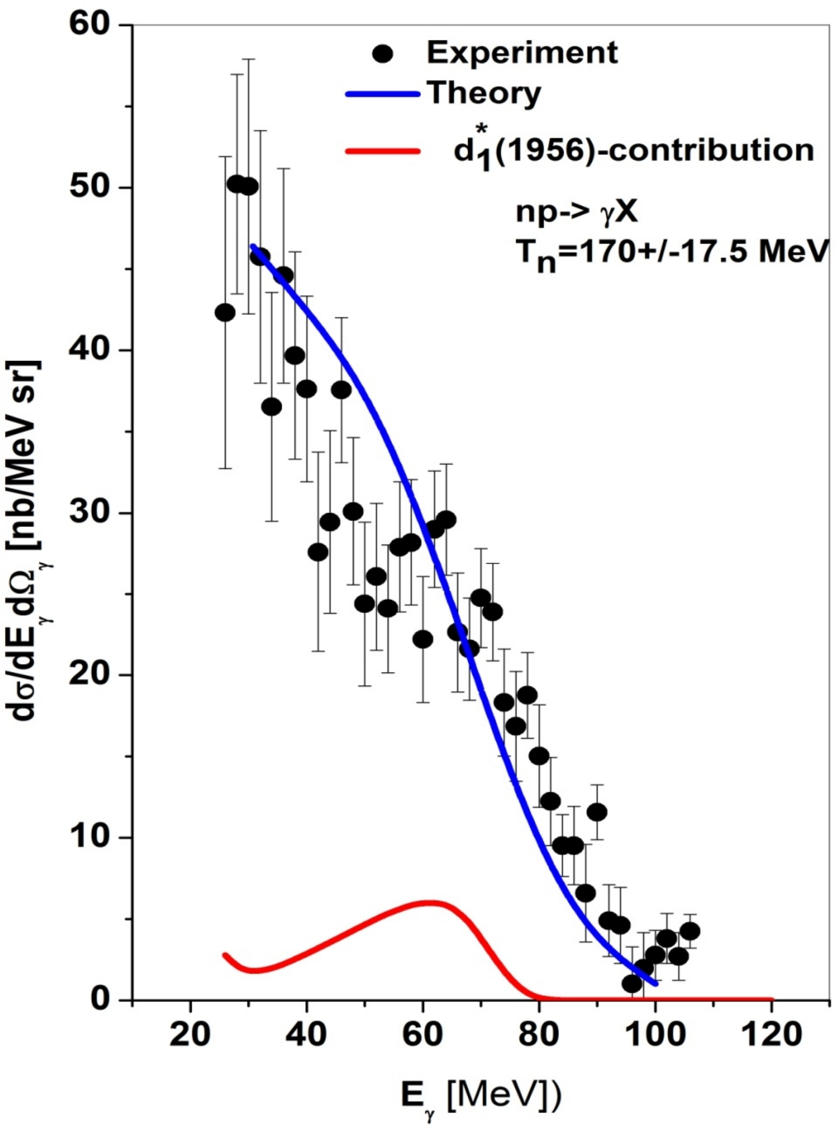
The existence of the $d_1^*(1956)$ entails the existence of a new mechanism of photon pair production in *NN* collisions that should be taken into account. Depending on experimental conditions of either experiment on a study of a photon emission process in *NN*, *NA* or *AA* collisions it can show up in measured single-(two-)photon energy or(and) two-photon invariant mass spectra .

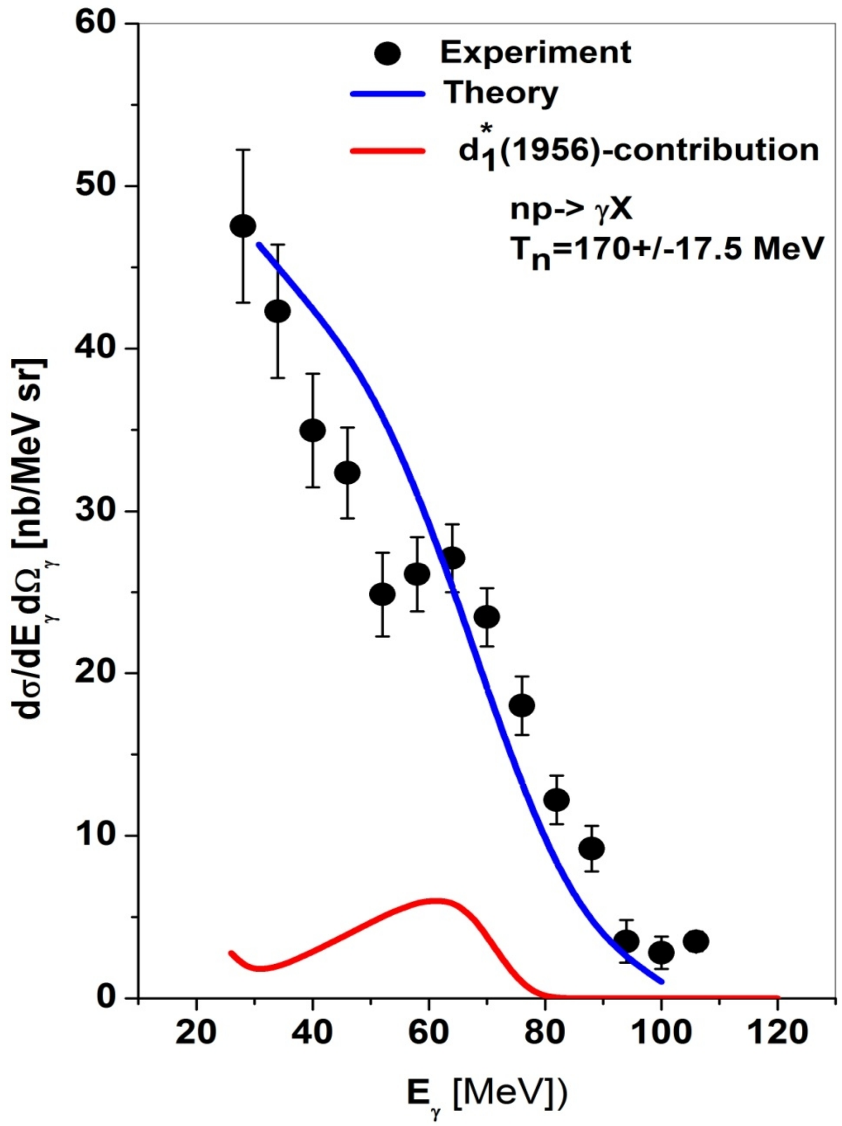
Further indications for $d_1^*(1956)$ resonance existence.

1. Indications for the $d_1^*(1956)$ existence in inclusive photon energy spectra of the reactions n+p -> γX, p+^{12}C ->γX, p+d -> γX.

Reaction np→γX reaction at T_n=170±17.5 MeV , θ_γ=90^0 . The experiment was performed at the Saturn National Laboratory in Saclay. The experiment: F.Malek et al., PLB 266 (1991) 255. Theory : M.Schafer et al. Z. Phys. A 339, 391 (1991);

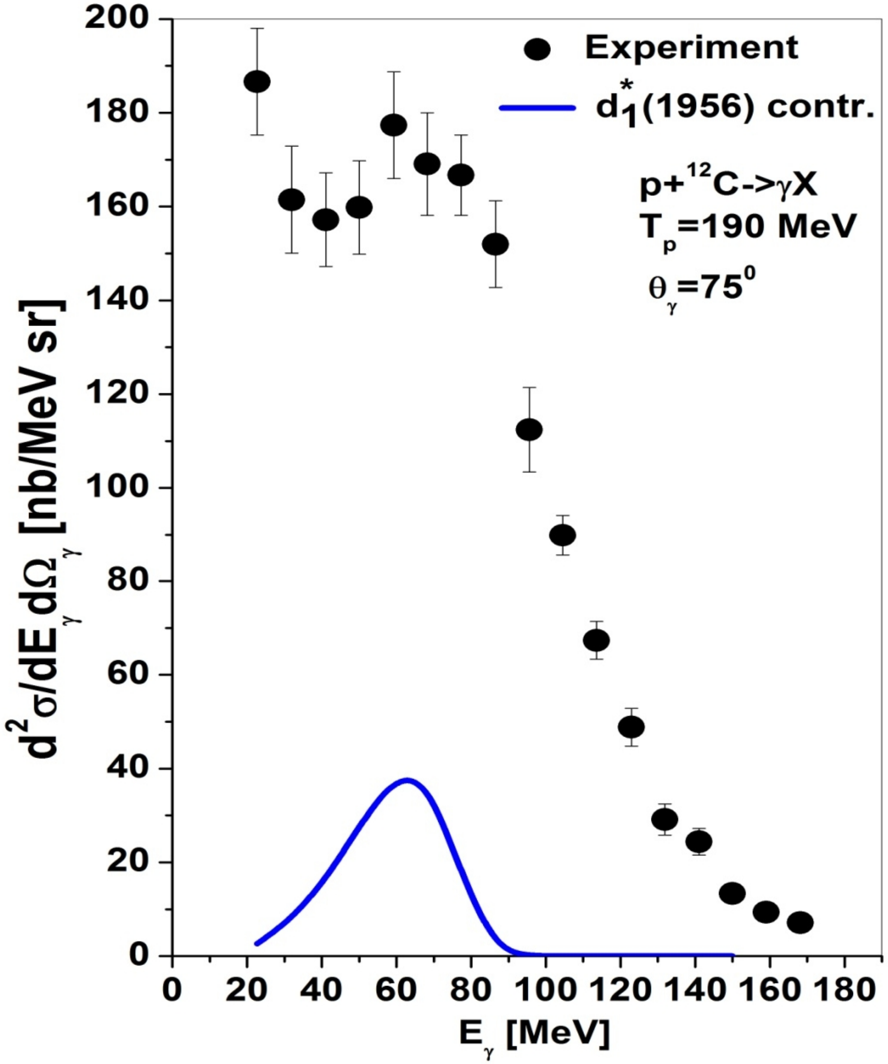
A.S. Khrykin, Nucl. Phys. A721, 625c (2003)



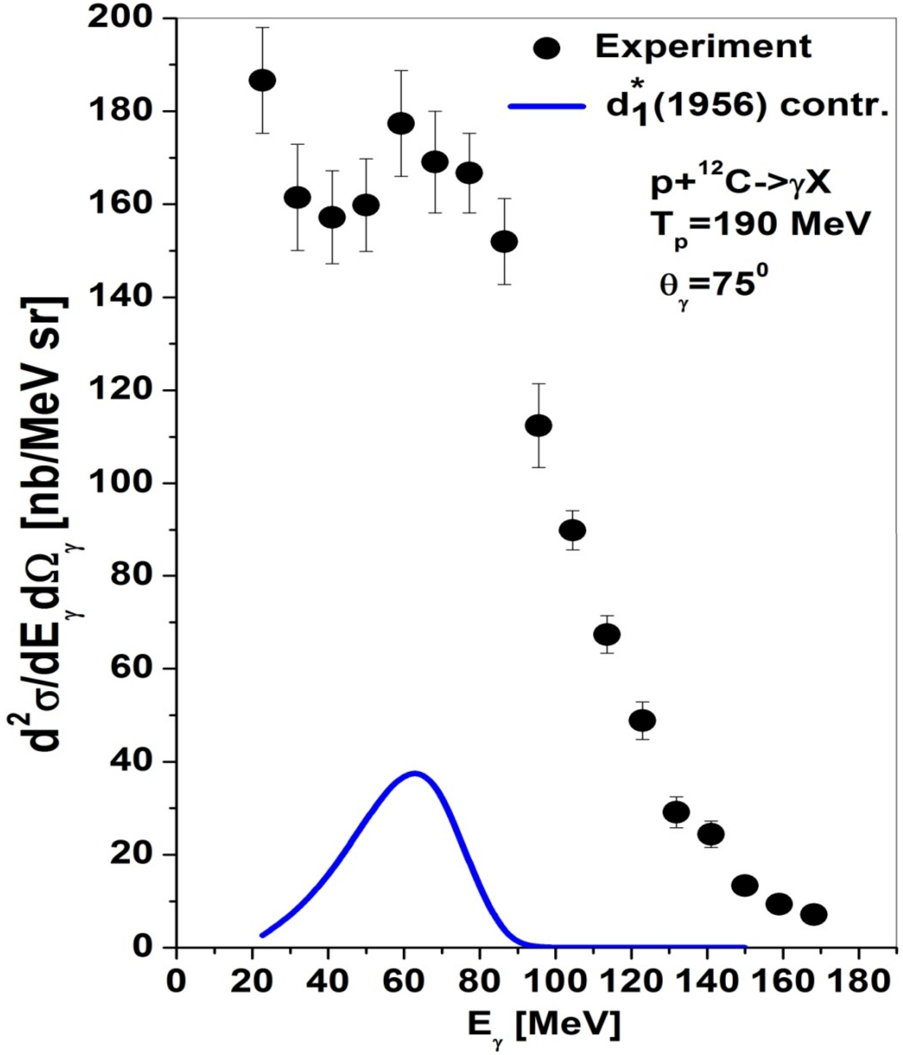


Inclusive photon spectrum for the $p + ^{12}C \rightarrow \gamma X$ reaction

Grenoble group, J.A. Pinston et al., Phys.Lett. B249, 402(1990)



KVI group, H. Lohner and the TAPS Collaboration, Acta Physica Polonica B, Vol.33,827(2002).



Indications in inclusive photon energy spectra of the reaction pd -> γX.

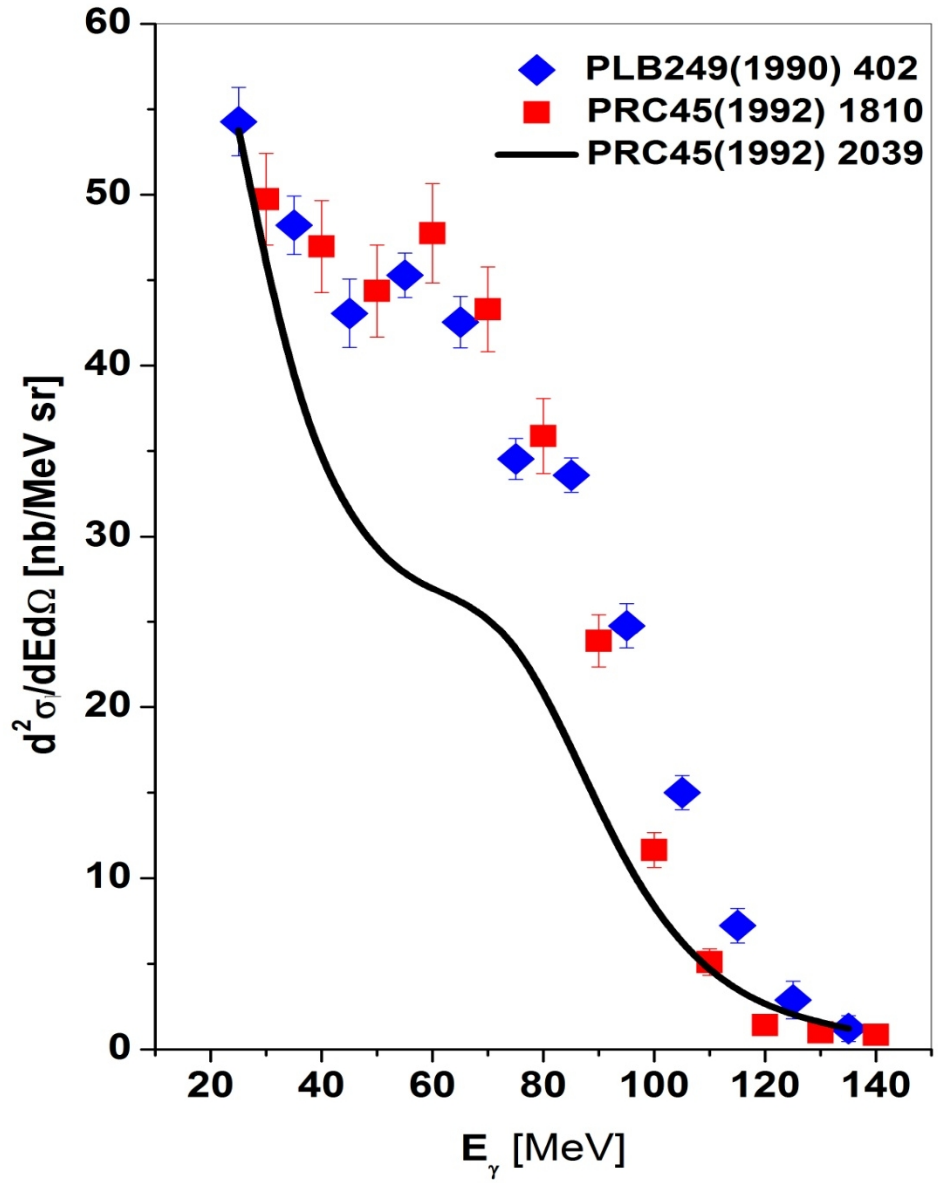
Reaction : $p+d \to \gamma X$

EXPERIMENTS:

Grenoble group
Orsay synchrocyclotron
T_p=200 MeV; $\theta_\gamma=90^0$
J.A. Pinston et al.,
Phys.Lett. B249, 402(1990)

Michigan State group
IUCF
T_p=195 MeV; $\theta_\gamma=90^0$
J. Clayton et al., Phys. Rev. C45, 1810 (1992).

Theory
K.Nakayama, PRC 45, 1992(2039)



Inclusive photon energy spectrum for the pd→γX reaction at 195 MeV.

A.S. Khrykin, Nucl. Phys. A721, 625c (2003)

Reaction : p+d→γX

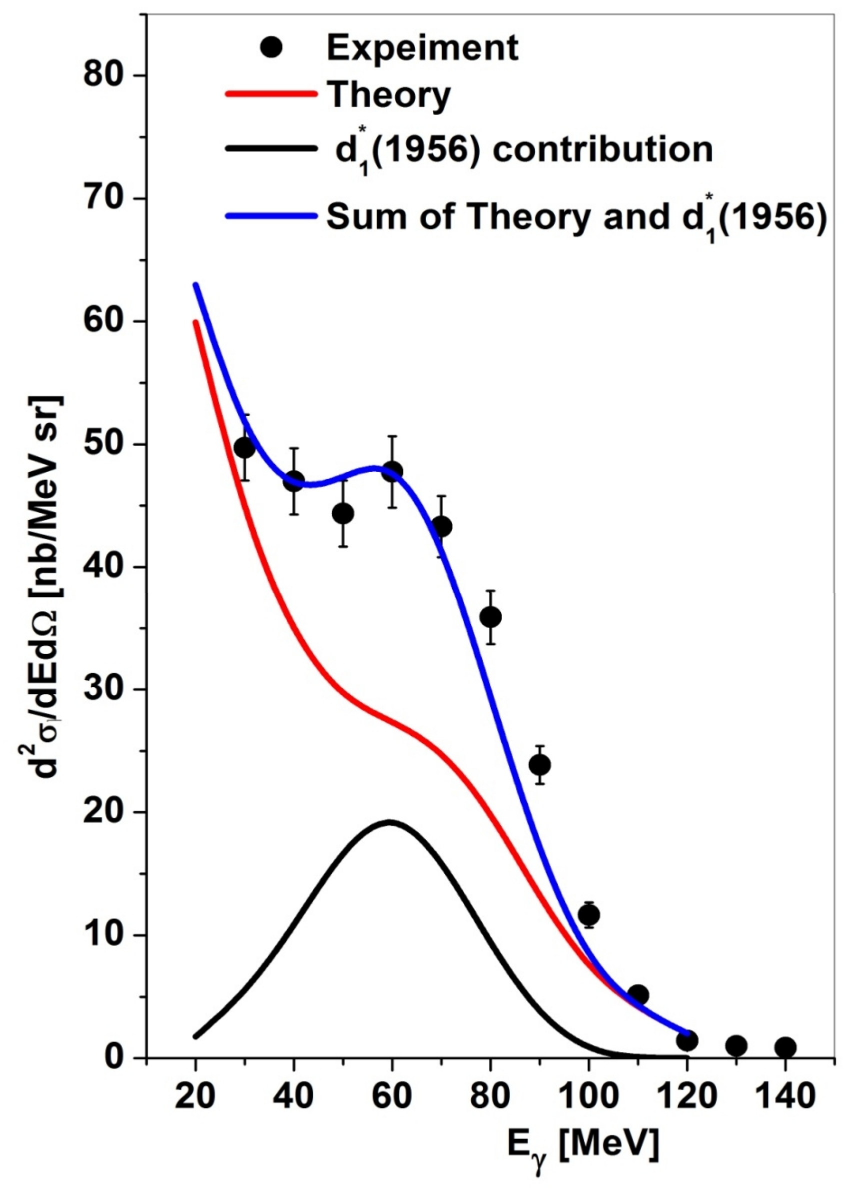
Experiment

T_p=195 MeV; θ_γ=90^0

J. Clayton et al., Phys. Rev. C45, 1810 (1992).

Theory

K.Nakayama, Phys.Rev. C45, 2039 (1992).



Indications for the $d_1^*(1956)$ existence in two-photon invariant mass spectra of the reactions p p -> $\gamma\gamma$pp and p^{12}C -> $\gamma\gamma$X.

$$\mathbf{M}_{\gamma\gamma}^{2} = 2 * \mathbf{E}_{\gamma}^{F} * \mathbf{E}_{\gamma}^{D}(1 - \cos(\text{И}_{12}))$$

Exclusive pp→pp$\gamma\gamma$ reaction

A.S.Khrykin and S.B.Gerasimov, in : *Proc. of the MENU2007,* IKP, Forschungentrum Juelich, Germany, September 10-14, 2007, edited by H. Machner and S. Krewald, eConf C070910(2008),250.

Experiment

CELSIUS-WASA *Collaboration*
Bashkanov et al. Int. Jour. of Mod. Phys. A20,554(2005); hep-ex/0406081

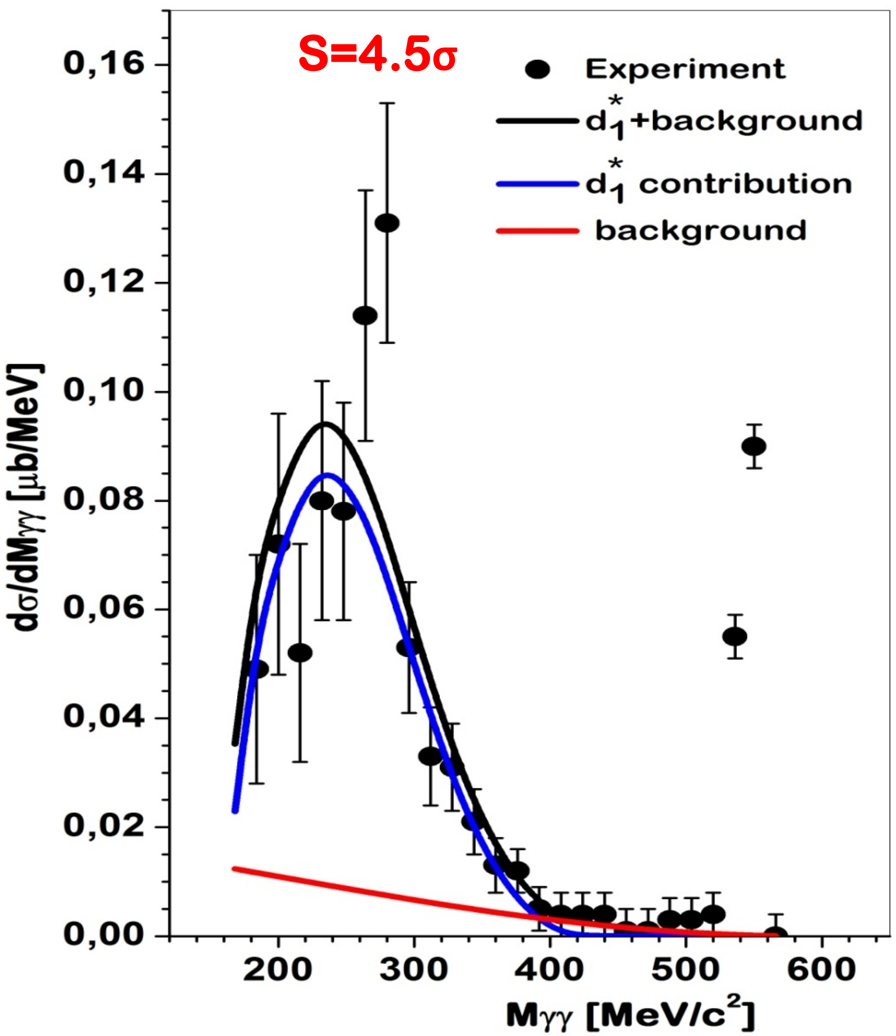
pp→pp$\gamma\gamma$

The two-photon invariant mass spectra of the reaction were measured at two energies:
T_p=1.36 GeV and T_p=1.2 GeV

St.sign.= $N_S/(N_S+2N_B)^{1/2}$: 4.5σ & 3.5σ

Calculations: $|M(NN\rightarrow \gamma d_1^* \rightarrow pp\ \gamma\gamma|^2$
$\Longrightarrow \sim(E_\gamma^F \bullet E_\gamma^D)^2$
$M^2_{\gamma\gamma}=(k_1+k_2)^2=2E_{\gamma1} * E_{\gamma2} *(1-\cos\theta_{12})$

χ^2=1.1/dof



Inclusive p+ $^{12}C \rightarrow \gamma\gamma X$ reaction

Experiment

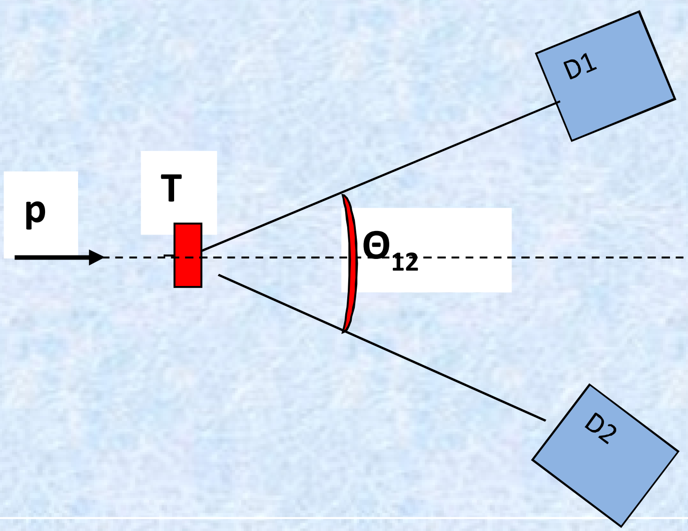
Reaction: p+ $^{12}C \rightarrow \gamma\gamma X$

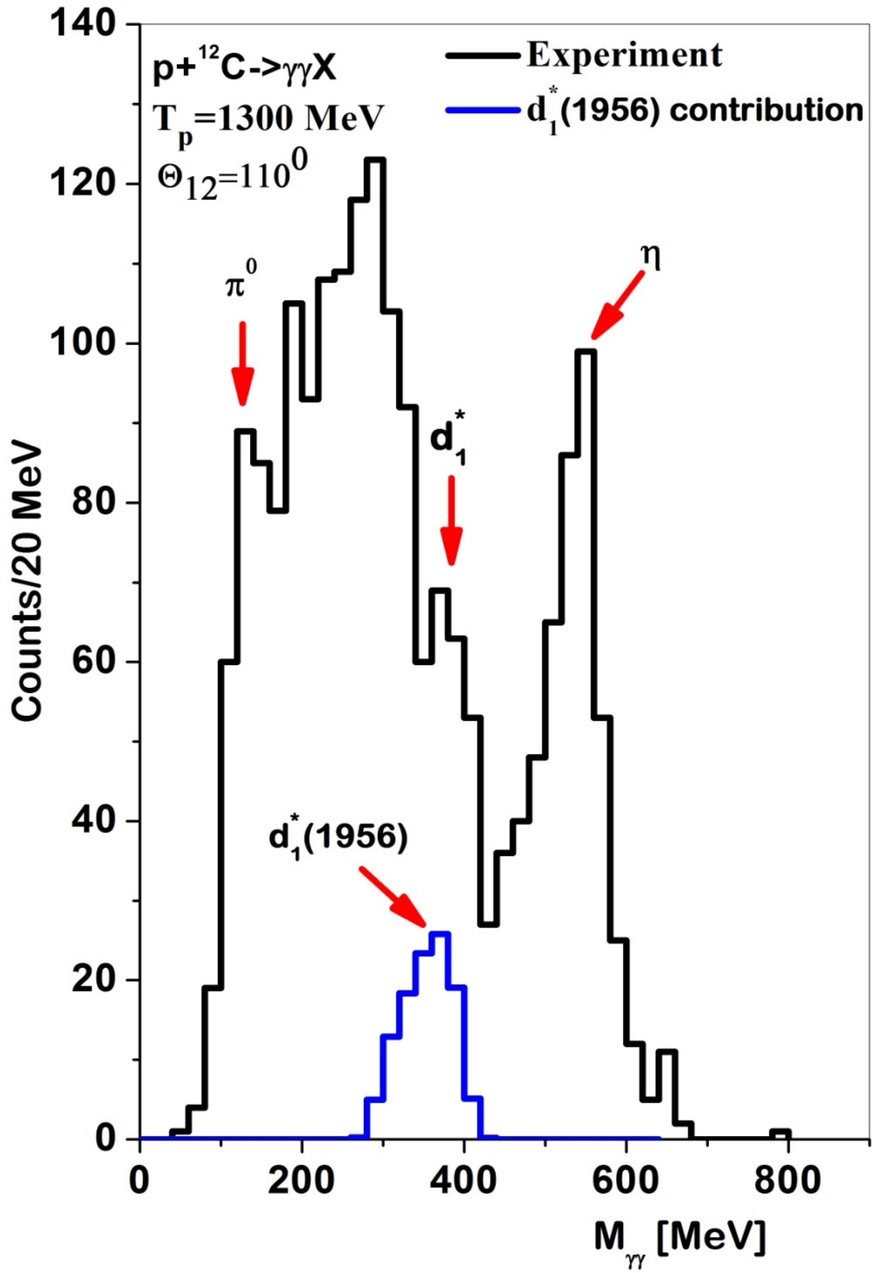
T_p=1300 MeV

PINOT Spectrometer $\theta_{12}=110^0$

Exp. Data: C.De Olivera Martins et al.

Braz. Jour. Of Phys. V.31, 533(2001)





Inclusive p+ $^{12}C \rightarrow \gamma\gamma X$ reaction

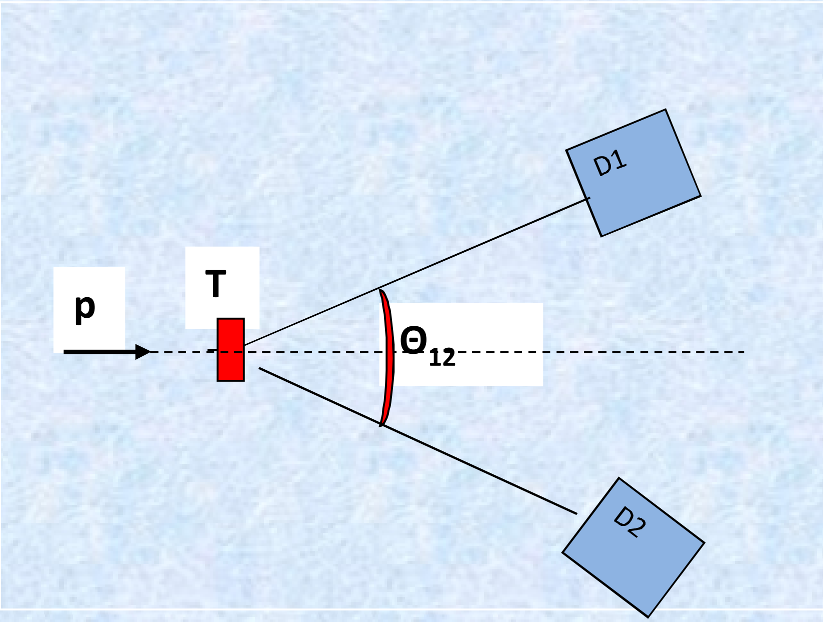
Experiment

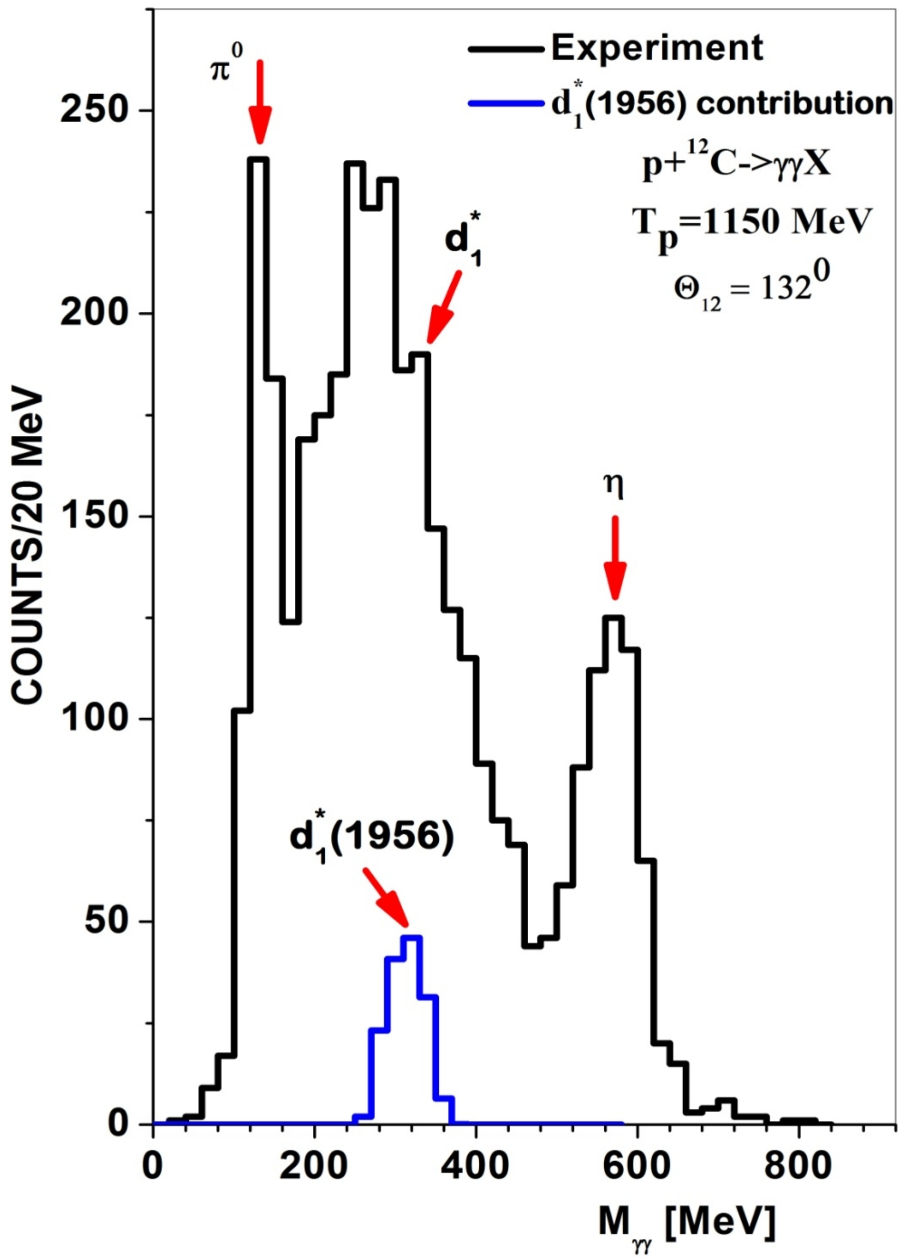
Reaction: p+ $^{12}C \rightarrow \gamma\gamma X$

T_p=1150 MeV

PINOT Spectrometer θ_{12}=132^0

Exp. Data: E.Chiavassa et al.,Europhys. Lett. V.41, p. 365(1998)





Presented experimental results strongly suggest the existence of the exotic six-quark state $d_1^*(1956)$. However, we believe that in order to draw the firm conclusion about its existence it is necessary to carry out additional improved experimental investigations.

Proposed Experiment

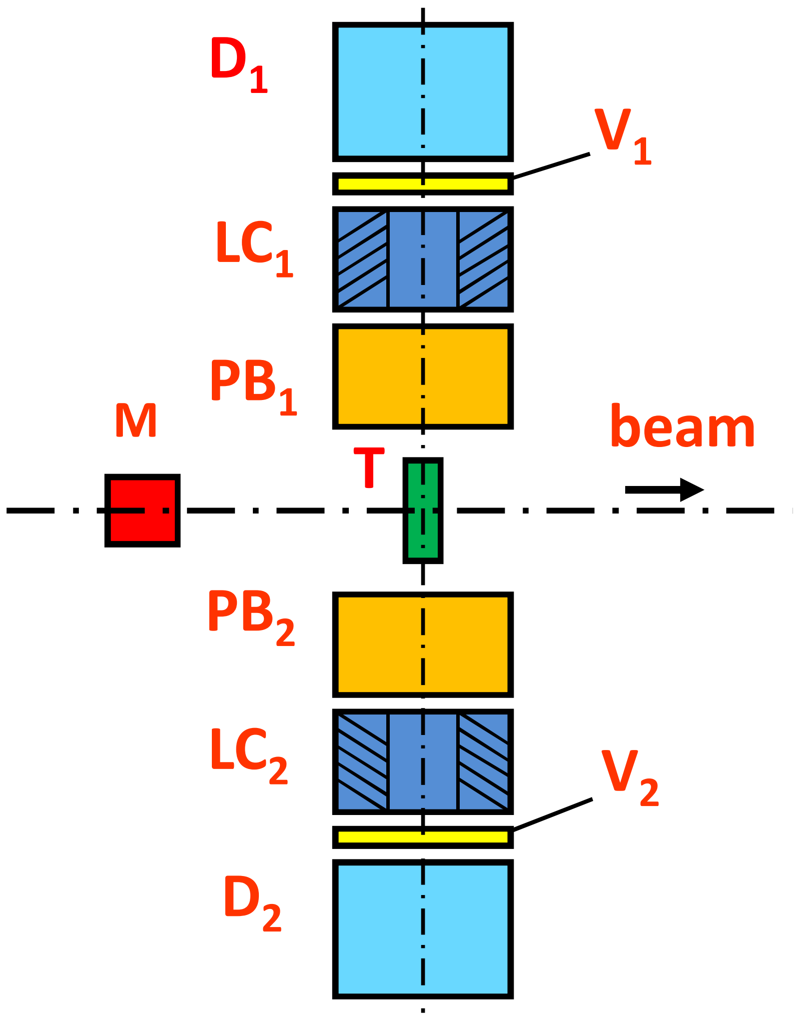
To make a robust experimental test of the existence of the *NN*-decoupled dibaryon resonance $d_1^*(1956)$ we intend to perform high-precision measurements of the energy spectra of photons emitted at $\pm 90^0$ from the process $pp \to pp\gamma\gamma$ for two different proton beam energies T_p, namely, 220 and 250 MeV.

If the d^*_1 resonance really exists then it should reveal itself in both these spectra as a narrow γ-peak associated with its formation in *pp* collisions and a more broad γ-peak due to its radiative three-particle decay. In addition, since the position of the narrow γ-peak in a spectrum depends on the incident proton energy then positions of such a peak in the measured spectra should be shifted relative one another by $\Delta E_\gamma = E_\gamma(T_{p1}) - E_\gamma(T_{p2})$ where $E_\gamma(T_p)$ is determined by the equation

$$E_\gamma(T_p) = \frac{W^2 - M_R^2}{2(E - p \cdot \cos(\theta_\gamma))}$$

The measured spectra will also enable us to determine more precisely its mass and its total width.

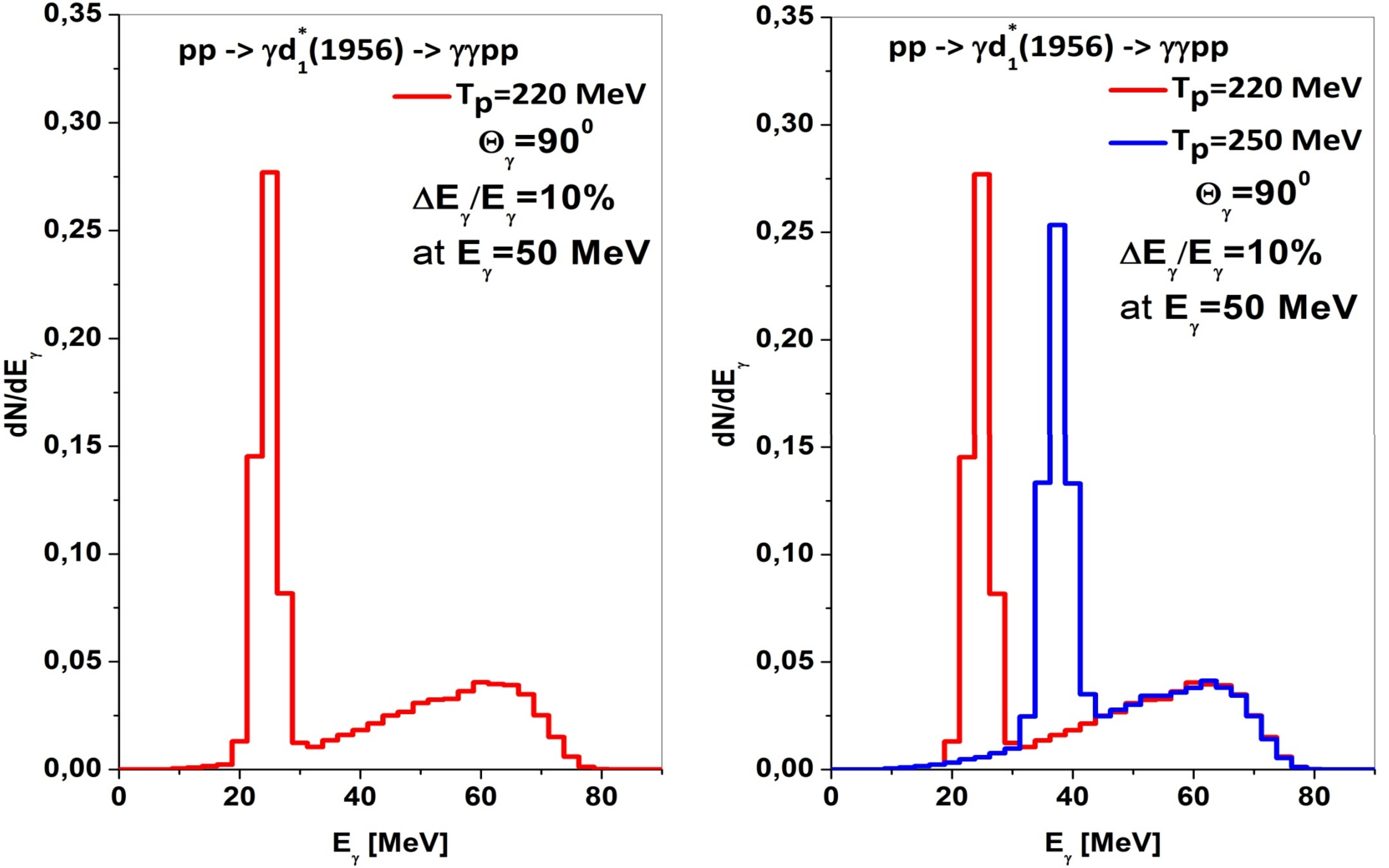
Principal scheme of the experimental setup



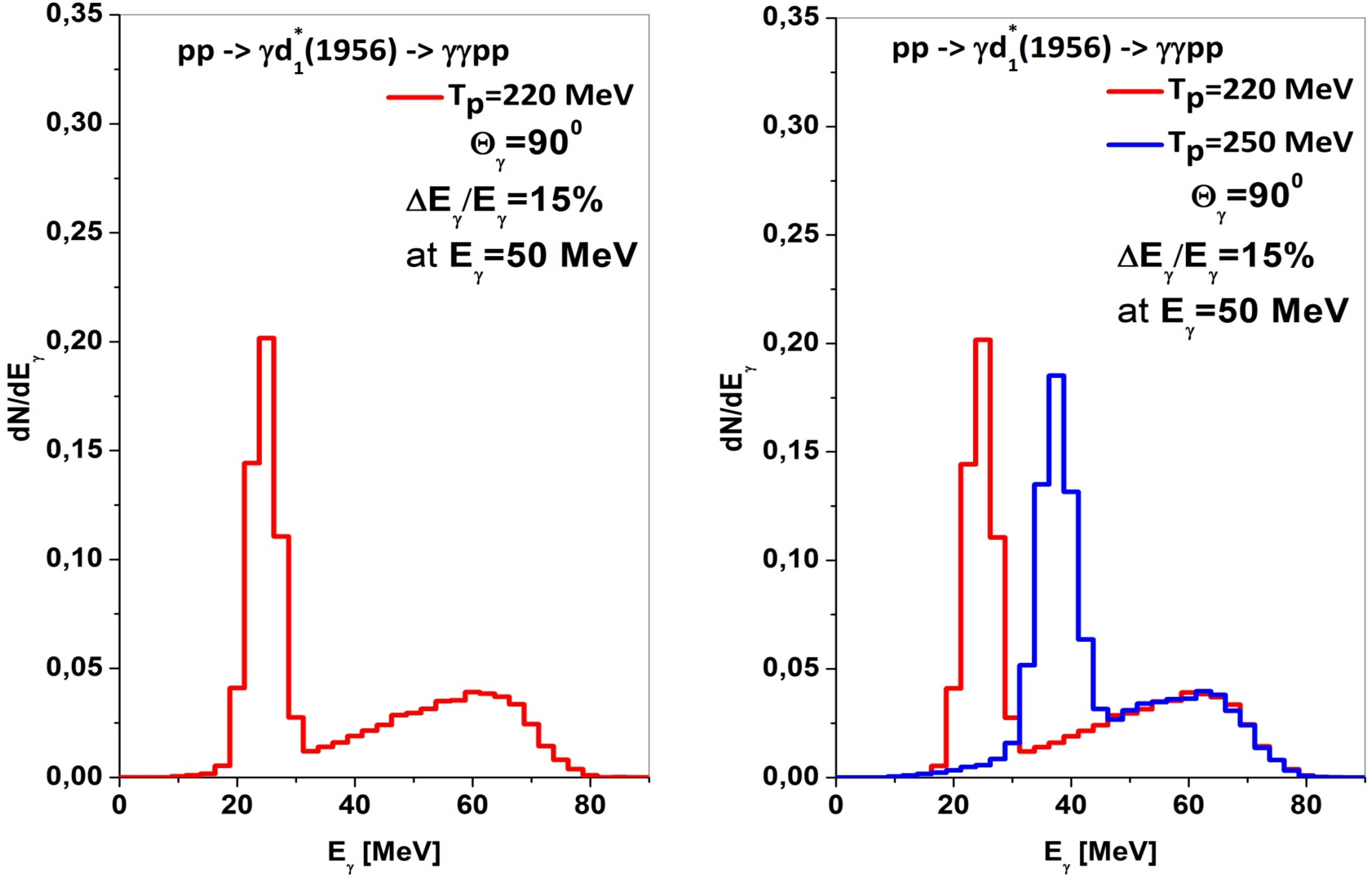
Basic arrangement of the experimental setup. **The proton beam aproaches from the left. *M* is the monitor of the incident beam, *T* is the target, D_1 and D_2 are the γ ray detectors, V_1 and V_2 are the plastic scintillators, LC_1 and LC_2 are the lead collimators, and PB_1 and PB_2 are the polyethylene bars.**

We plan to mount this setup in the PIF area of the PROSCAN area at PSI.

What we'll expect to observe.



What we'll expect to observe.



Measuring time estimation.

The proposed experimental program includes measurements of the photon energy distributions of the reaction $pp \to pp\gamma\gamma$ at two different incident proton energies for both the target filled with liquid hydrogen and the empty one. We intend to collect about 1.0• 10^3 events (photon pairs) for each spectrum measured at one incident proton beam energy. The time *T* of measurement of the γ-ray energy spectrum can be estimated by the following formula:

$$T = \frac{N}{\frac{d^2\sigma}{d\Omega_{\gamma 1} d\Omega_{\gamma 2}} \cdot I \cdot n \cdot \Delta\Omega_1 \cdot \Delta\Omega_2},$$

where *N* is number of events, $d^2\sigma/d\Omega_{\gamma 1}\, d\Omega_{\gamma 2}$ is the cross sections of the reaction, *I* is the intensity of the proton beam, n is the density of nuclei in the target, $\Delta\Omega_{\gamma 1}$ and $\Delta\Omega_{\gamma 2}$ are the solid angles covered by the γ-detectors. Assuming, that *I*=6.0• 10^9 protons/sec, *n*=2.13•10^{23} 1/cm^2, $\Delta\Omega_{\gamma 1} = \Delta\Omega_{\gamma 2}$ = 30 msr and the cross section $d^2\sigma/d\Omega_{\gamma 1}\, d\Omega_{\gamma 2}$ =9.0 nb/sr^2 we can obtain $T \simeq$ 30 h. Taking into account the fact, that approximately the same time is needed for the measurement with the empty target we can obtain that the total time of the measurement of the γ-ray energy spectrum at one incident proton energy will be about 60 h. Thus the total measuring time of the proposed experiment is about 120 h.

Thank you for your attention!

Indications for the $d_1^*(1956)$ existence in the DLS dielectron invariant mass spectra of the reactions $\mathbf{pp \to e^+e^-X}$ and $\mathbf{AA \to e^+e^-X}$.

A new mechanism for dielectron production in NN collisions.

A.S. Khrykin, "On a Missed Mechanism of Dielectron Production in Nucleon-Nucleon Collisions " in Proceedings of the 12TH INTERNATIONAL CONFERENCE ON MESON-NUCLEON PHYSICS AND THE STRUCTURE OF THE NUCLEON (MENU 2010), Virginia, (USA), 31 May–4 June 2010, AIP Conference Proceedings Volume 1374, p410-413.

DLS Measurements: $A+A \rightarrow e^+e^-X$ for C+C and Ca+Ca at 1.04 A GeV $\Longrightarrow$
Substantial Excess of the e^+e^- pair yield in the mass region $0.2 < M_{ee} < 0.6$ GeV

HADES Measurements: $A+A \rightarrow e^+e^-X$ spectra for C+C collisions at 1A and 2A GeV. The DLS finding was confirmed.

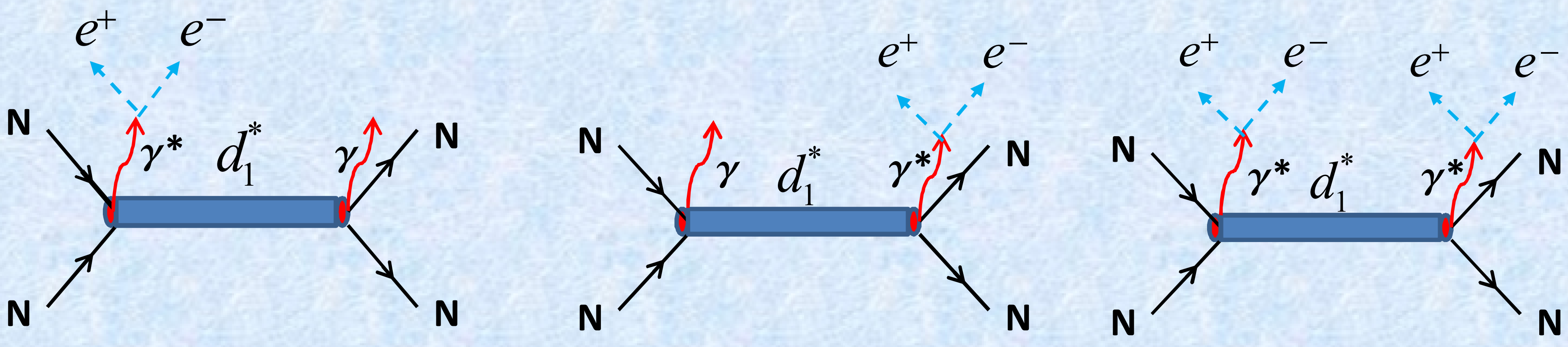
Conventional mechanisms of dielectron production at 1-2 GeV per nucleon:

- Dalitz decay of the π^0- , η-, and ω mesons and baryon resonances Δ(1232), N^*(1520),…
- Direct decay of the π^0-, ρ-, and ω- mesons
- Bremsstrahlung in NN and $\pi\pi$ collisions
- Pion annihilation

Up to now there is no clear conception of the origin of such an excess.

If the resonance d_1^* (1956) really exists then together with its formation (decay) channel with a real photon the same channels with a virtual, massive photon should also take place. Conversion of such photons into e^+e^- pairs would give rise to a new source of dielectrons.

Dibaryon mechanism for dielectron production in NN Collisions



The kinematical region for a photon mass overlaps with that where the shortage of dielectrons of interest was observed.

We decided to examine whether a new source NN→ $\gamma^* d^*_1$(1956)→ $e^+e^- d^*_1$ can supply the observed shortages of e^+ e^- pairs in the DLS data in the mass region 0.2< M_{ee} < 0.6 GeV.

$$NN \longrightarrow \gamma^* \boldsymbol{d}_1^*(1956) \longrightarrow e^+e^- \boldsymbol{d}_1^*(1956)$$

$p_a + p_b = p_1 + p_2 + p_3$

$p = p_a + p_b$, p_a- and p_b- the four momenta of colliding nucleons,
$p^2 = s$ – the total energy of the colliding nuclens inc.m.s.

$p_1(E_1, \vec{p}_1), p_2(E_2, \vec{p}_2)$ **and** $p_3(E_3, \vec{p}_3)$ **-the four momenta of dielectrons and resonance.**

$$\frac{dy}{dM} = \frac{(2p)^4}{f} \int \prod_{i=1}^{3} \frac{d^3\,\vec{p}_i}{2E_i(2p)^3} |\mathcal{M}|^2 \text{д}(p - \sum_{i=1}^{3} p_i) \bullet \text{д}(M - M(\vec{p}_1, \vec{p}_2))$$

$$f = 4\sqrt{(p_a p_b)^2 - m_a^2 m_b^2}$$

M- ***the invariant mass of the*** **e^+e^- - pair**

$|\mathcal{M}|^2$ – ***the matrix element for the transition NN*** $\rightarrow e^+e^-d_1^*$

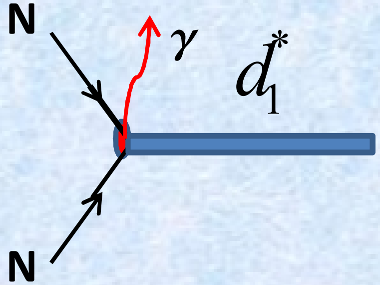
$$\mathcal{M} = \frac{e^2}{k^2} j^M J_M, \quad j_M =< e^+e^- \left| j \right| 0 > , \; J_M = (J_0, \vec{J}) =< d_1^* \left| J_M \right| NN >$$

$$\vec{J} = \vec{J}_T + \vec{J}_L$$

$$\left|\mathcal{M}\right|^2 = \frac{1}{4}\frac{e^4}{M^4}\frac{1}{2m_e^2}\{M^2\left|\vec{J}_T\right|^2 - \left|\vec{J}_T\vec{q}_T\right|^2 + \frac{M^2}{k_0^2}(1 - \frac{M^2}{k_0^2}\left|\vec{J}_L\vec{q}_L\right|^2)$$

$$- 2\left|\vec{J}_L\vec{q}_L\right|\left|\vec{J}_T\vec{q}_T\right|\}, \quad k = (k_0,\vec{k}) = p_1 + p_2, \; q = (q_0,\vec{q}) = p_1 - p_2$$

O. Scholton et al. PRC71,034005(2005)

$\boldsymbol{J^P(d_1^*)} = 0^-$ **the vertex** 

$1^- \xrightarrow{M1} 0^-$ **is magnetic in structure**

$$\left|\mathcal{M}_E\right|^2 = e^2\left|\vec{J}_T\right|^2 = C\cdot(p_a\cdot k)(p_b\cdot k)$$

Hadronic current for the magnetic transition is transverse, $\vec{J}_L = 0$

$$|\mathcal{M}|^2 = \frac{1}{4}\frac{e^4}{M^2}\frac{1}{2m_e^2}\left(|\vec{J}_T|^2 - \frac{1}{M^2}|\vec{J}_T\vec{q}_T|^2\right) \cong \frac{1}{4}\frac{e^4}{M^2}\frac{1}{2m_e^2}|\vec{J}_T|^2$$

$$\left|\mathcal{M}_{NN\to e^+e^-d_1^*}\right|^2 = \frac{N}{M^2}|\mathcal{M}_E|^2|F(M^2)|^2$$

$$|F(M^2)|^2 = \frac{m_c^4 - m_c^2\Gamma_c^2}{(m_c^2 - M^2)^2 + m_c^2\Gamma_c^2}$$

N-is the normalization constant

The calculations $\Longrightarrow$ Monte Carlo method. Event generator $\Longrightarrow$ GENBOD. It used to randomly generate four momenta of the outgoing particles of the explored reaction. The probabilty of any event has been given its weight:

$$WT = \left|\mathcal{M}_{NN\to e^+e^-d_1^*}\right|^2$$

Energy resolution: by procedure of a spectrum smearing with a Gaussian distribution with the corresponding σ.

$$\frac{\sigma_{tot}^{ee}}{\sigma_{tot}^{\gamma}} = \frac{\alpha}{\pi}\left[\frac{2}{3}\ln\left(\frac{\Delta M}{m_e}\right) - \frac{5}{9} + \frac{1}{3}I_1 + O\left(\left(\frac{m_e}{\Delta M}\right)^2\right)\right],\ I_1 \approx 1$$

B.E.Lautrup and J.Smith, PRD3,1122(1971)

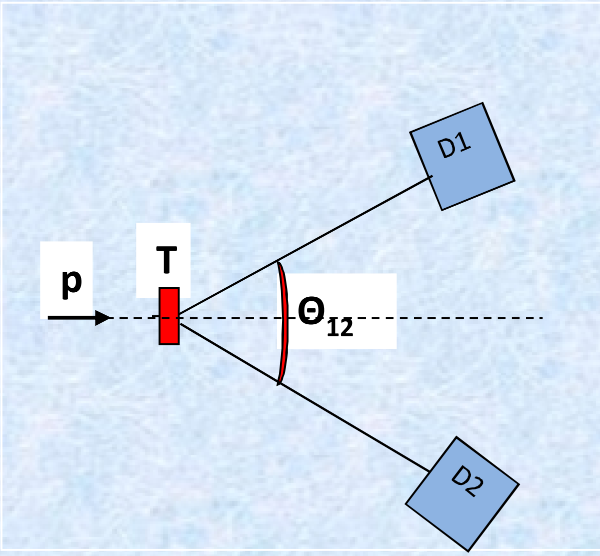
Contribution of the $pp \to e^+e^-d_1^*$ mechanism to the DLS $pp \to e^+e^-X$ data

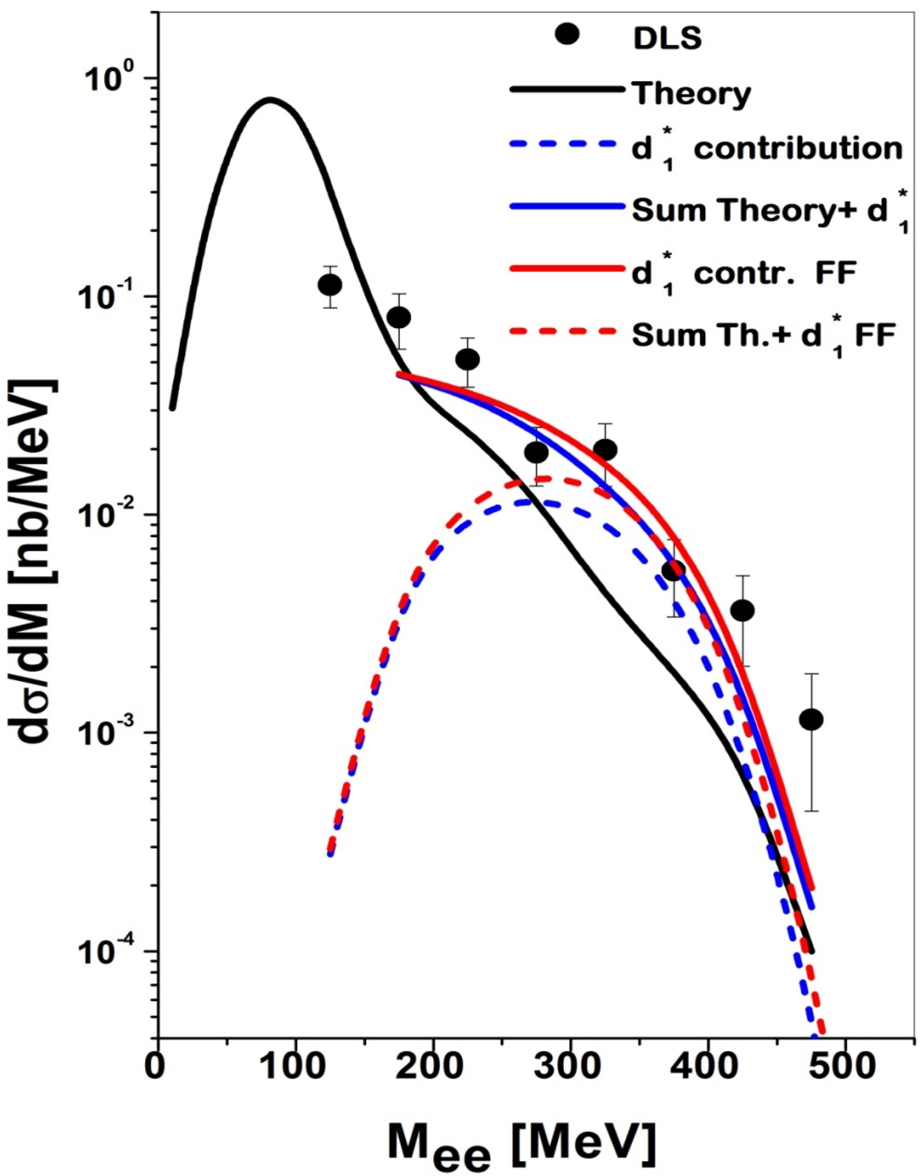
DLS data:W.K.Wilson et al.,Phys.Rev. C **57**, 1865(1998)
Theoretical data:Amand Faessler et al.,J.Phys. G **29**, 603(2003)

DLS Experiment

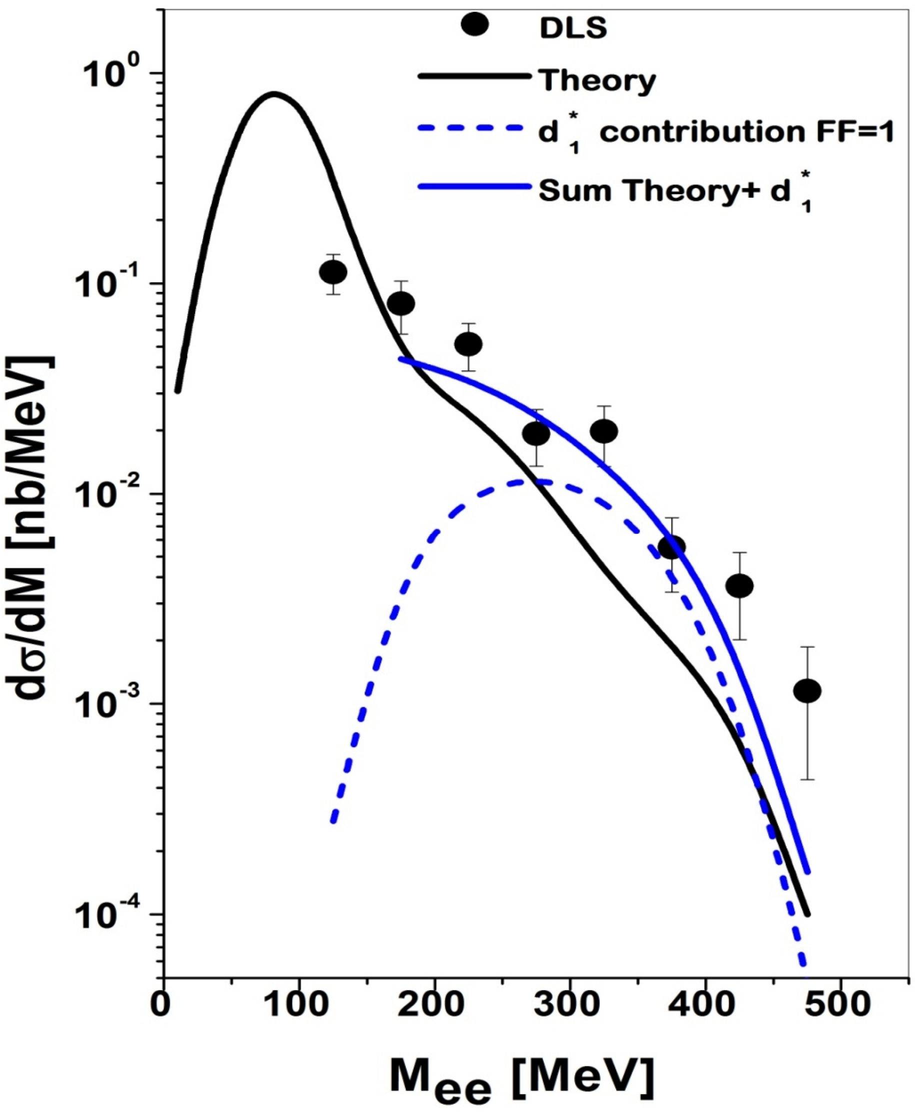
Reaction: $p+p \rightarrow e^+ e^- X$

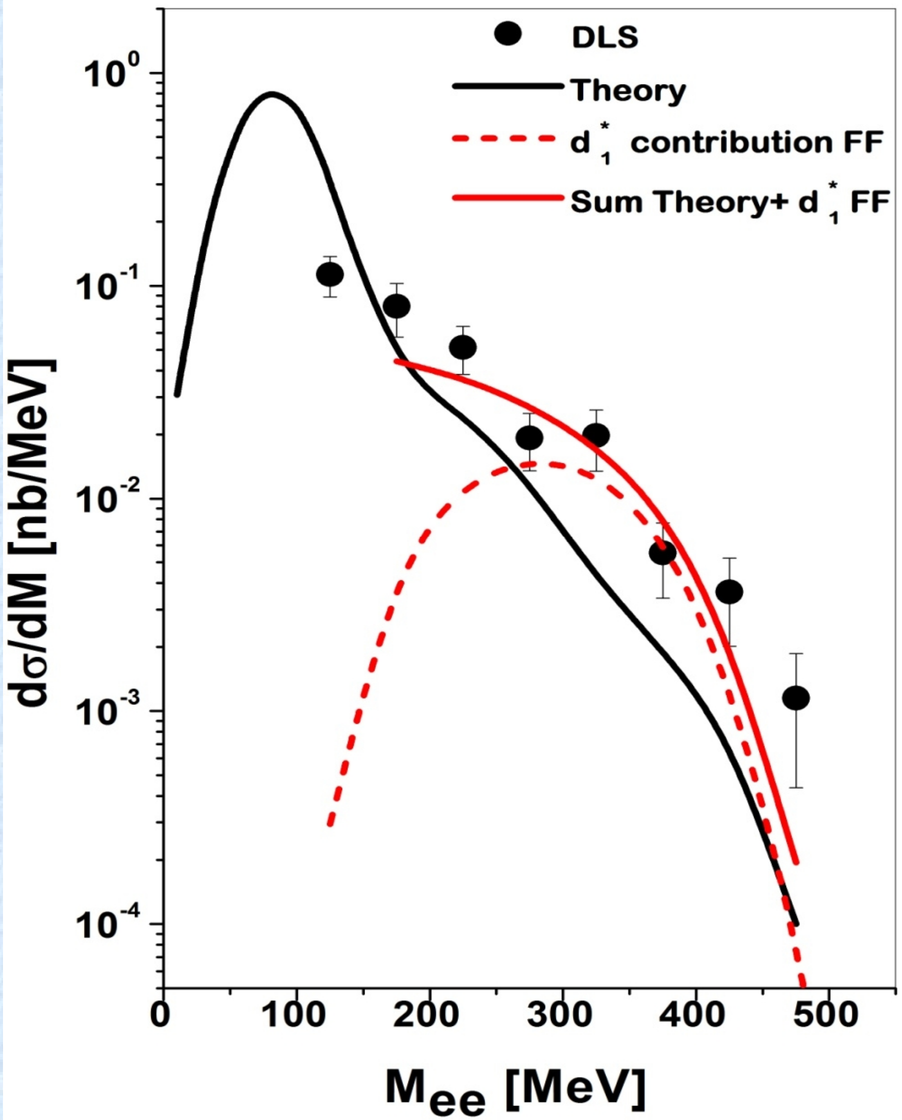
T_p=1.04 GeV





DLS data:W.K.Wilson et al.,Phys.Rev. C **57**, 1865(1998)
Theoretical data:Amand Faessler et al.,J.Phys. G **29**, 603(2003)





DLS data:R.J.Porter et al.,Phys.Rev.Lett. **79**, 1229(1997)
Theoretical data:E.L.Bratkovskaya et al.,Nucl.Phys. **A634**,168(1998)

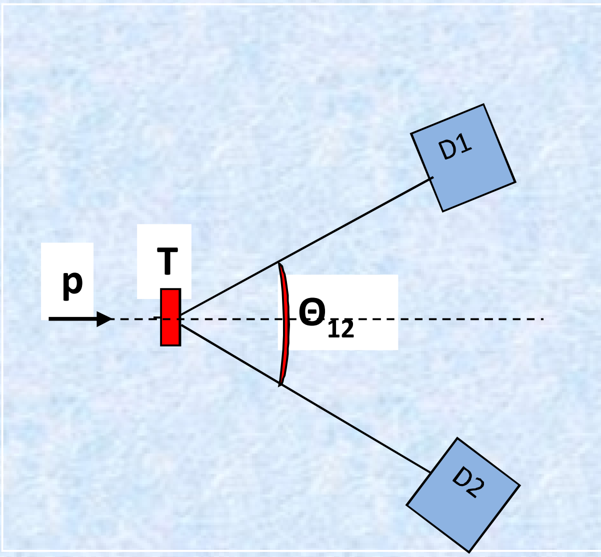
DLS Experiment

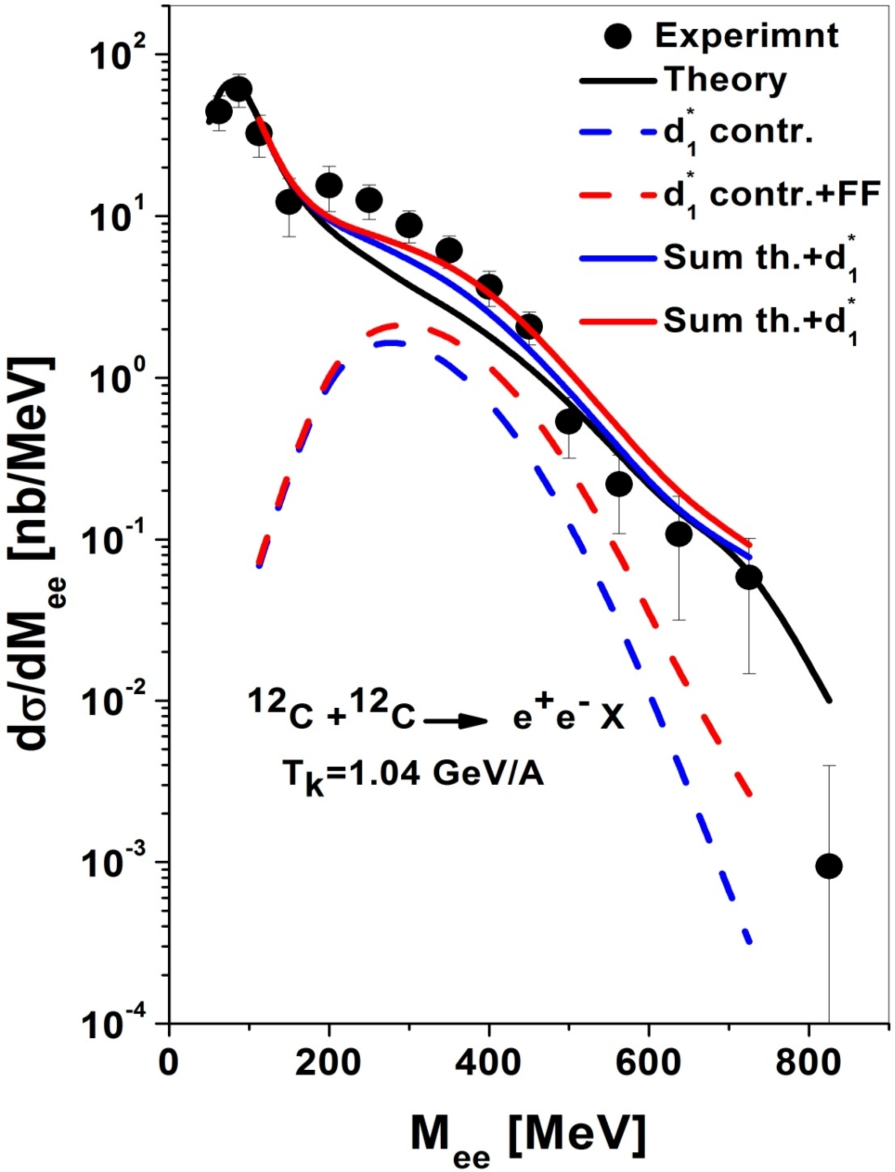
Reaction: $^{12}C + ^{12}C \rightarrow e^{+} e^{-} X$

T=1.04 GeV/A

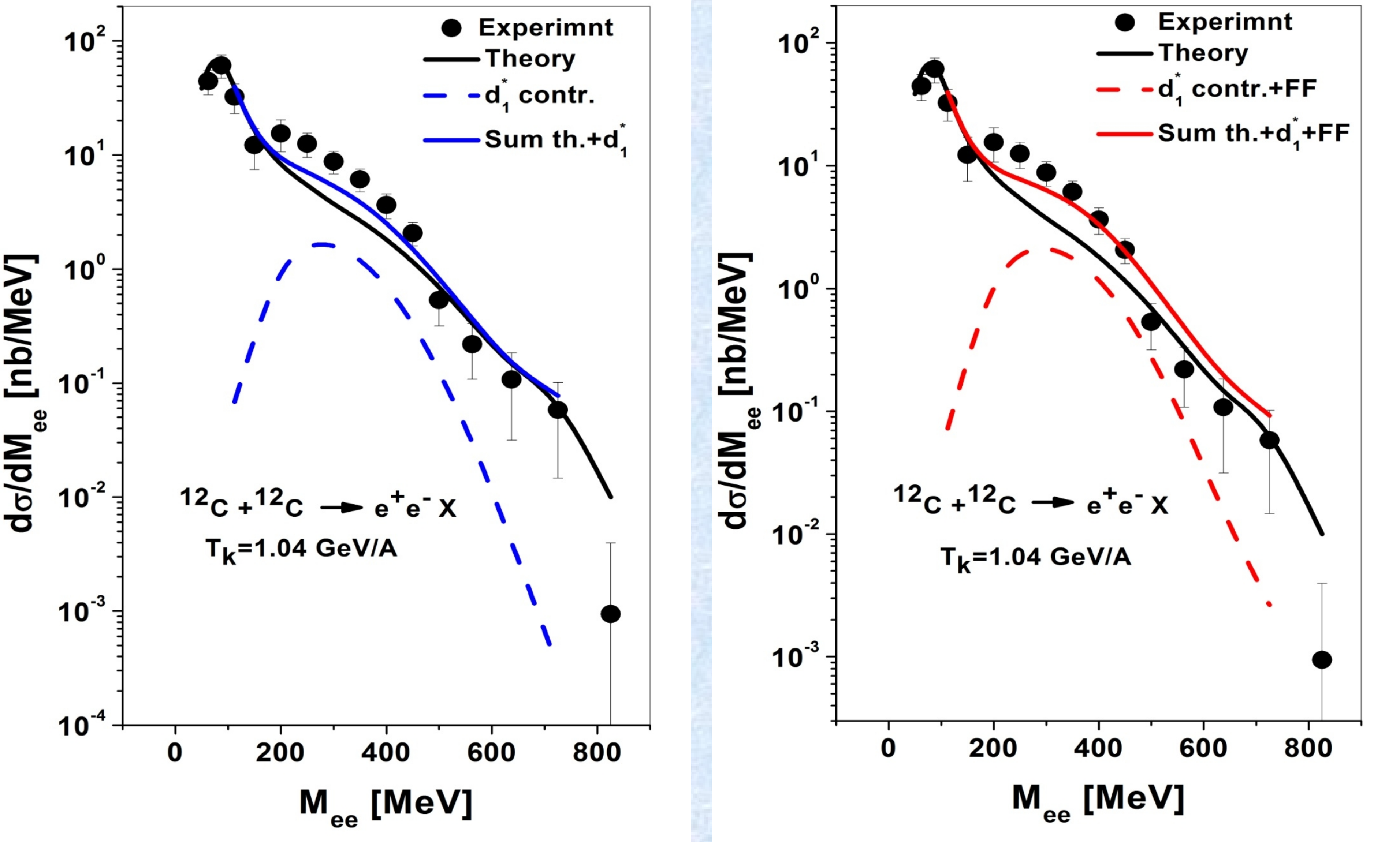
Mass resolution ДM/M = 10%

Filter v4.1p, CNWF:O.Benhar et al.,
Phys. Lett. **B177**,135(1986)





DLS data:R.J.Porter et al.,Phys.Rev.Lett. **79**, 1229(1997)
Theoretical data:E.L.Bratkovskaya et al.,Nucl.Phys. **A634**,168(1998)



Why the Celsius-Wasa Collaboration did not find the dibaryon signal in their pp $\rightarrow pp\gamma\gamma$ data at 310 MeV?

pp$\rightarrow\gamma$pp at T_k=310 MeV

H.Calen et al., Phys. Lett. B427, 248(1998).

To remove the γ-background due to the pp$\rightarrow\pi^0$pp $\rightarrow\gamma\gamma$pp process $\gamma\gamma$events also were collected. From these events were removed those connected with the π^0 – decay to search for the d^*_1

Two-photon inv. mass spectra were calculated for the **pp$\rightarrow\gamma d^*_1$(1956) $\rightarrow pp\gamma\gamma$** and **pp$\rightarrow pp\pi^0\rightarrow pp\gamma\gamma$** channels of the reaction **pp$\rightarrow$ pp$\gamma\gamma$** for the geometry and kinematic of the experiment PLB427,248 (1998).

So,all events (at least most of them) associated with the d^*_1(1956) were removed!