Joint Institute for Nuclear Research

SCIENCE BRINGS NATIONS TOGETHER

# Observation of structures at $\sim 17$ and $\sim 38$ MeV/c$^2$ in the $\gamma\gamma$ invariant mass spectra in pC, dC, and dCu collisions at $p_{lab}$ of a few GeV/c per nucleon


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# Abstract

The results of an analysis of the invariant mass spectra of photon pairs produced in *d*C, *p*C and *d*Cu interactions at momenta of 2.75, 5.5 and 3.83 GeV/*c* per nucleon respectively, are presented. Signals in the form of enhanced structures at invariant masses of about 17 and 38 MeV/$c^2$ are observed. The results of testing of the observed signals, including the results of the Monte Carlo simulation are presented. The test results support the conclusion that the observed signals are the consequence of detection of the particles with masses of about 17 and 38 MeV/$c^2$ decaying into a pair of photons

# Outline

- The experiment
- γγ invariant mass spectra
- The background estimations
- Check of the observed peaks
- Data simulation
- Conclusion

# Introduction

- A series of experiments on the production of photon pairs in the interactions of protons, deuterons and alpha particles with nuclei was carried out on the internal beams of the Nuclotron at JINR. The experiments were performed on a multichannel two-arm gamma spectrometer of the SPHERE setup (PHOTON-2 setup). The results of the first analysis on the production of eta mesons (selection of photons from different arms of the spectrometer) have been published in: Kh.U. Abraamyan et al., Phys. Rev. **C80**, 034001 (2009). [arXiv:0806.2790]
- At the suggestion of colleagues from Portugal, Eef van Beveren and George Rupp, the spectra of photon pairs in the region of invariant masses around 38 MeV/$c^2$ were analyzed in order to search for the E38 boson. The results of this analysis (photons from the same spectrometer arm) are published in:

Kh.U. Abraamyan et al. Check of the structure in photon pairs spectra at the invariant mass of about 38 MeV/$c^2$. EPJ Web of Conferences **204**, 08004 (2019).

# EXPERIMENT

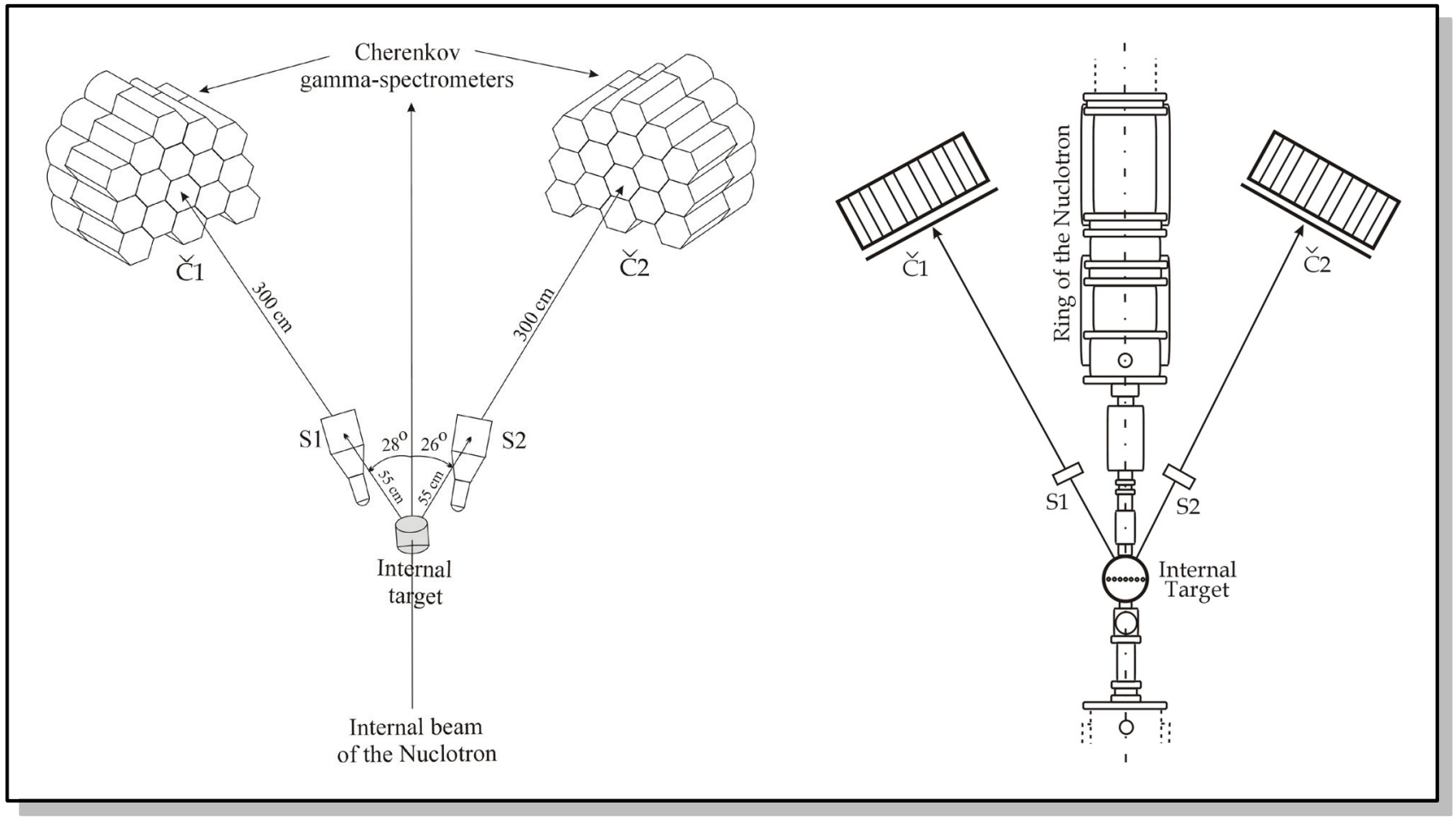
The data acquisition of production of neutral mesons and γ-quanta in pC, *d*C, and dCu interactions has been carried out with internal beams of the JINR Nuclotron.

The PHOTON-2 setup includes 32 γ-spectrometers of lead glass. The modules of the γ-spectrometer are assembled into two arms of 16 units. These modules in each arm are divided into two groups of 8 units. The output signals in each group are summed up linearly and after discrimination by amplitude are used in fast triggering. In this experiment, the discriminator threshold was at the level of 0.4 GeV. Triggering takes place when there is a coincidence of signals from two or more groups from different arms. (The block-scheme of electronic equipment is in sl. № 46.)

Detailed description of the experiments is in:

*Kh. U. Abraamyan et al., Phys. Rev. C* ***80****, 034001 (2009); arXiv:0806.2790.*

# PHOTON-2 setup (multichannel Cherenkov γ spectrometer of the SPHERE facility) on internal beams of the NUCLOTRON




Kh.U. Abraamyan et al., Instruments and Experimental Techniques **32**, 58 (1989); **39**, 775 (1996).

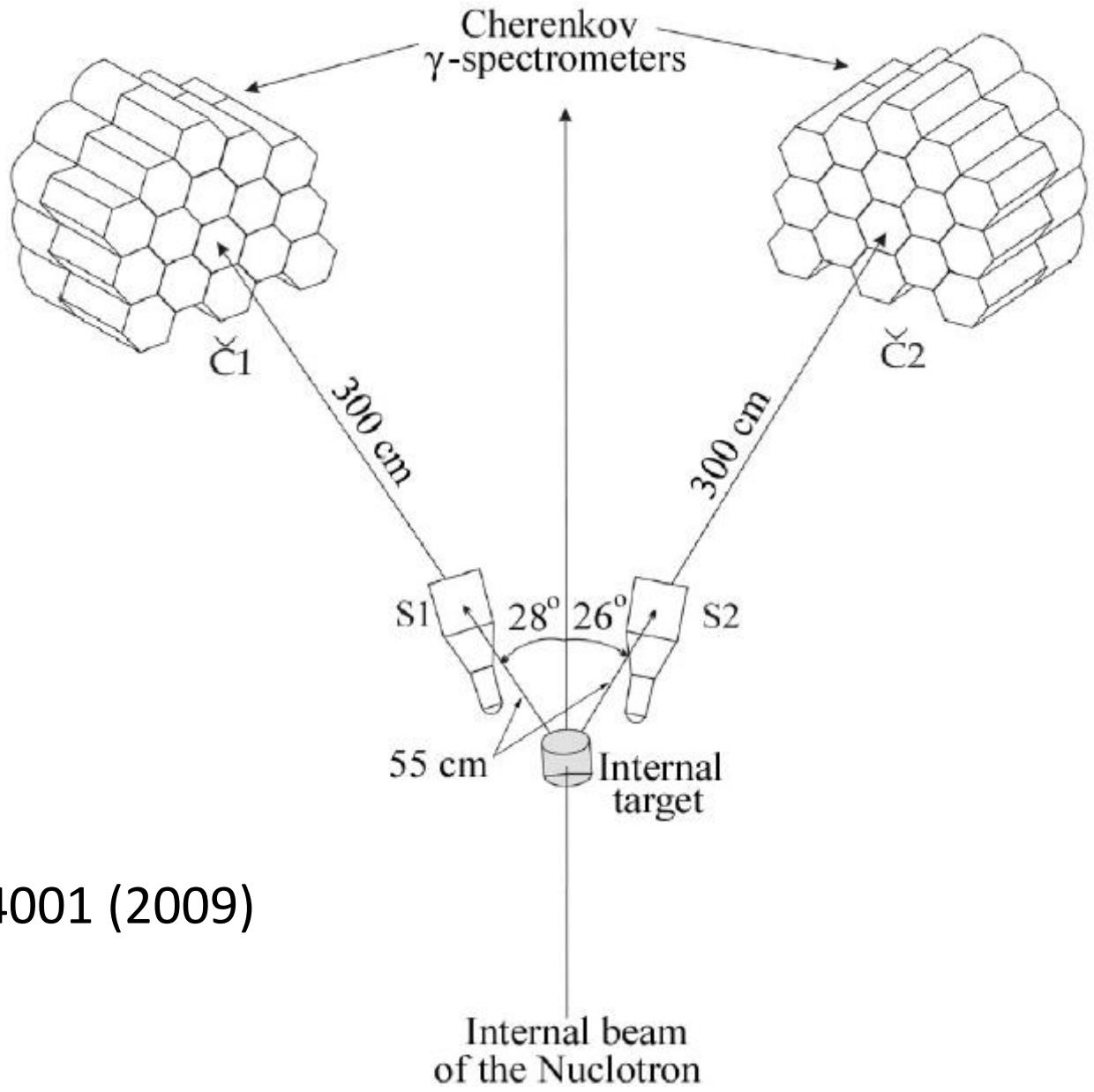
# Multichannel γ-spectrometer of the SPHERE setup (the PHOTON-2 setup) in experiments on the internal beams of the Nuclotron

$\check{C}1,\ \check{C}2$ –

*γ*-spectrometers of lead glass,

S1, S2 –

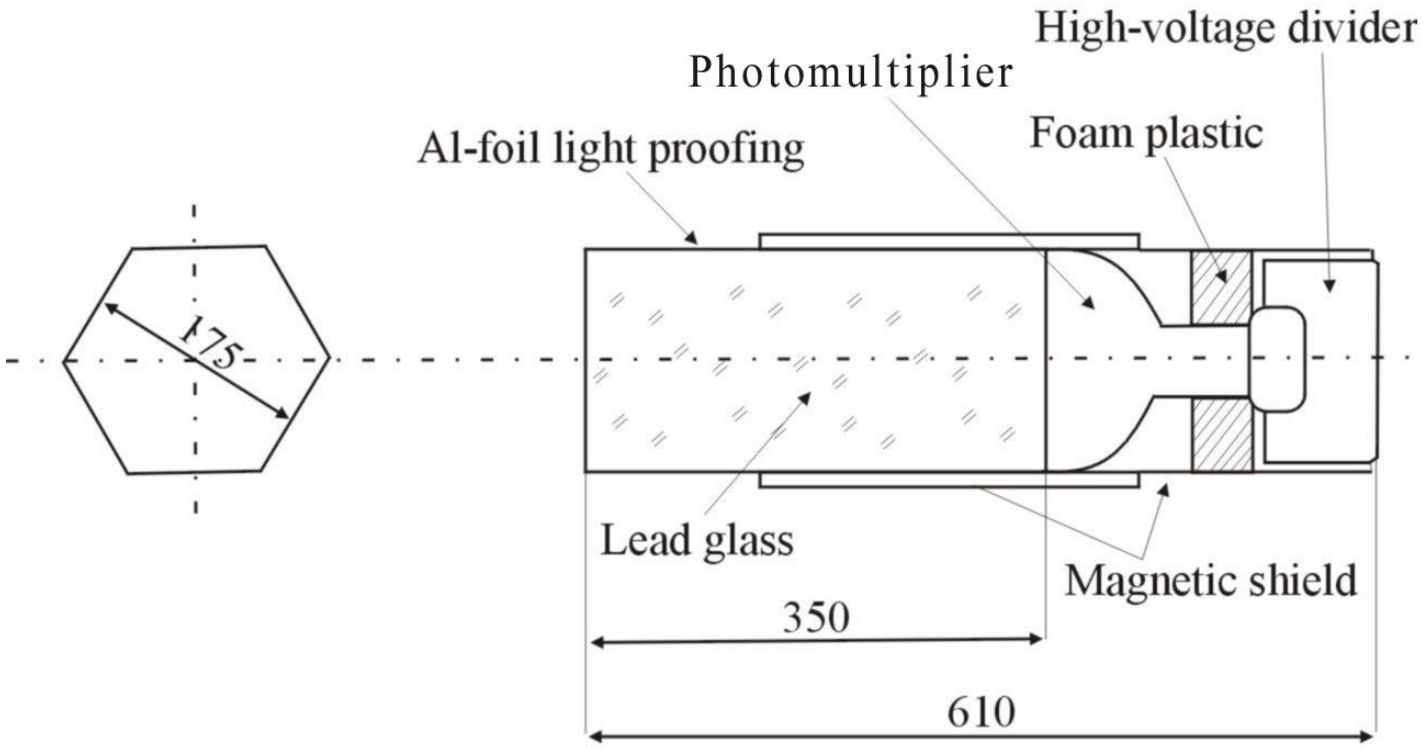
scintillation counters of 2 × 15 × 15 cm³.



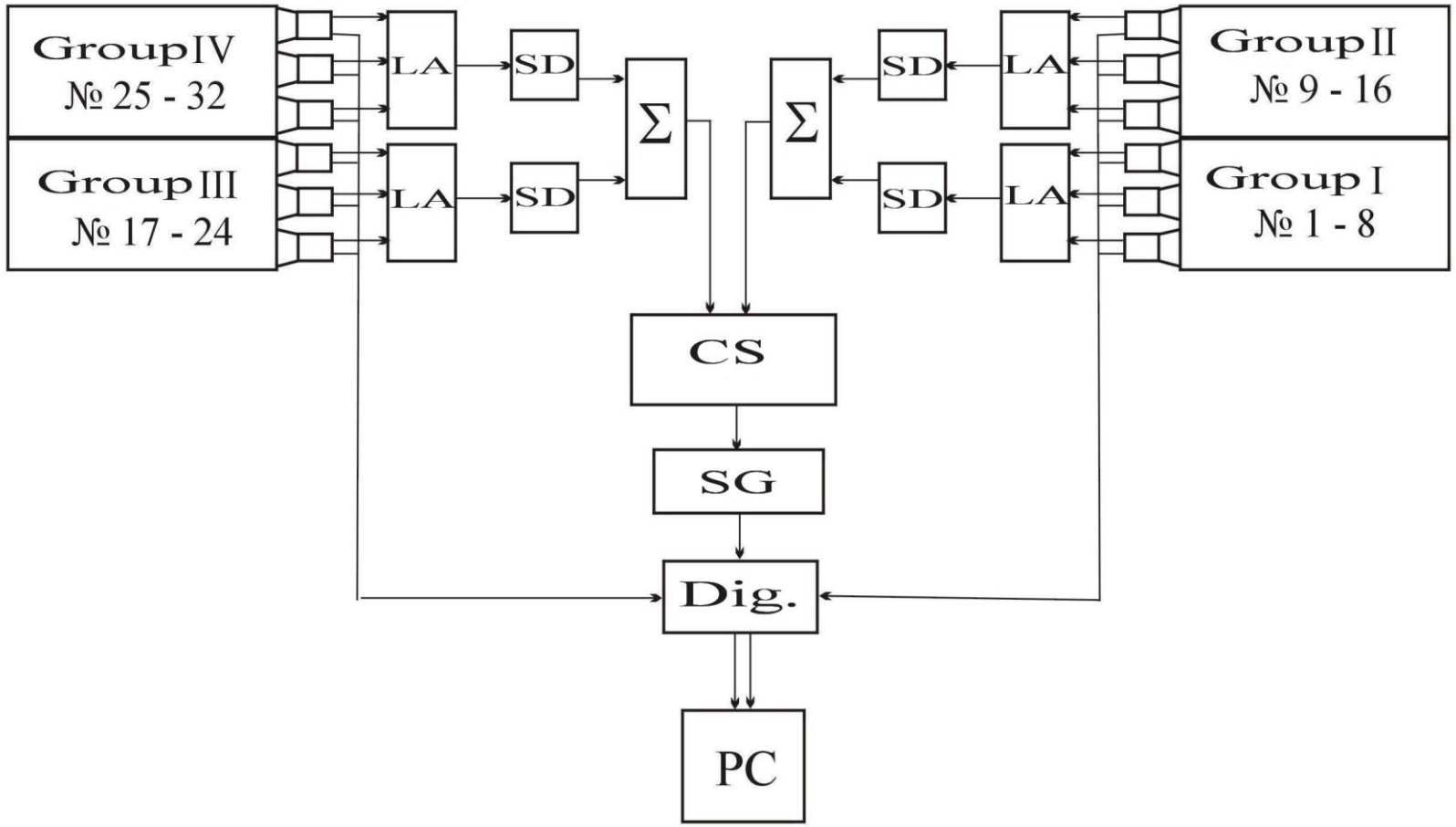

*A detailed description of the setup is in:*

Kh.U. Abraamyan et al., Phys. Rev. **C80**, 034001 (2009)
*arXiv:0806.2790.*

# A schematic drawing of a single module of the γ-spectrometer



# Block diagram of the electronic equipment of the PHOTON-2 setup

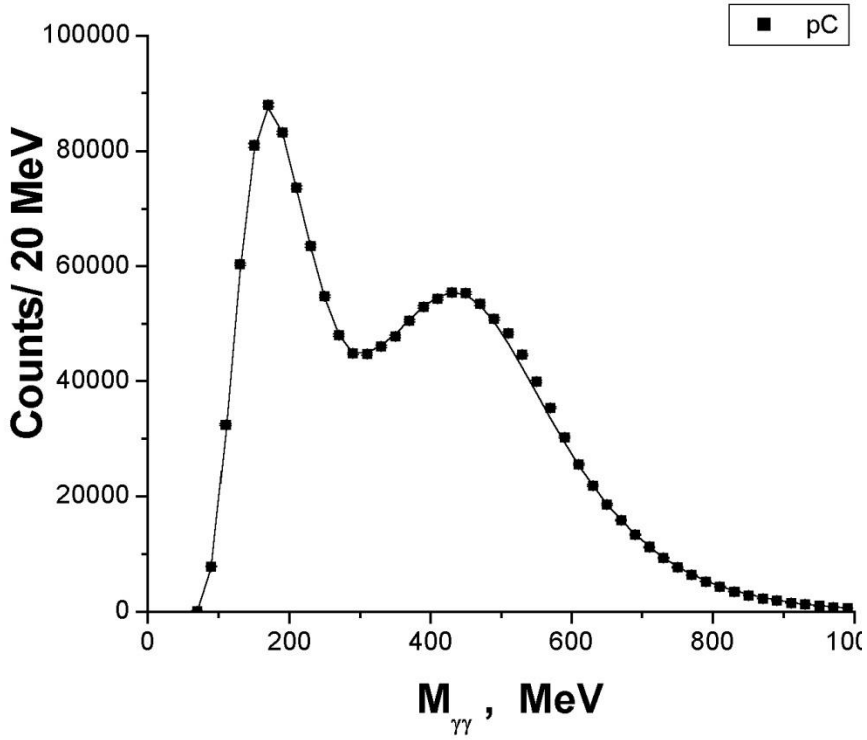


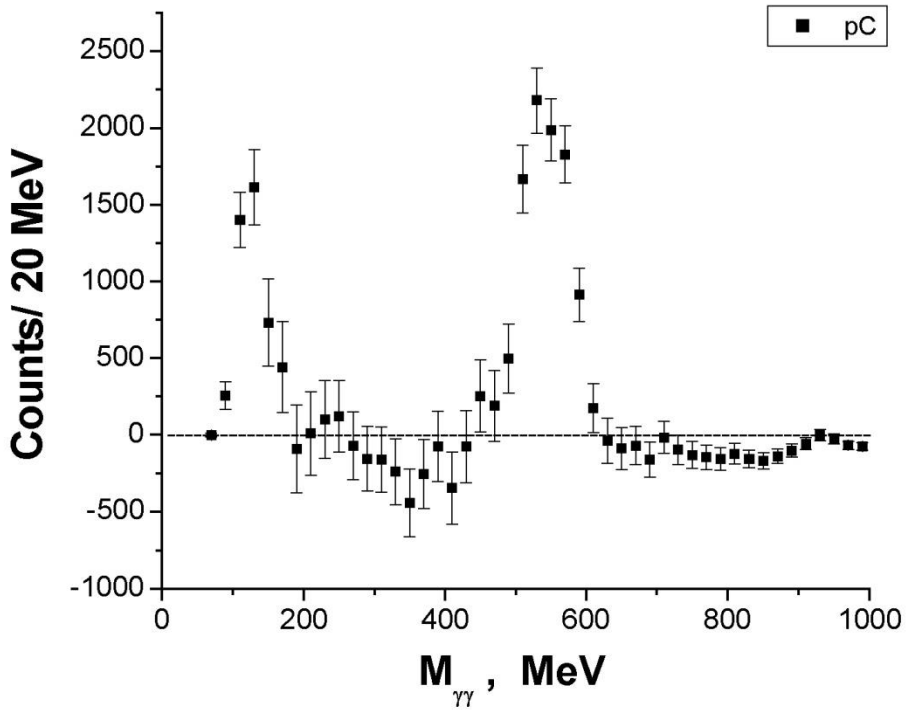
# The background estimation method

The so-called **event mixing method** was used to estimate the combinatorial background: a photon in one event from the first arm is combined with a photon in other events from the second arm.

The background **normalization** was carried out in two steps. First, the background is normalized to the total pair number. Naturally that at the event mixing the η-meson maximum is not reproduced disturbing the overall normalization. At the second step this shortcoming of the background estimate is corrected by an auxiliary factor obtained by iterating treatment of the resonance contribution to the spectrum.

Invariant mass distributions of γγ pairs without (left figure) and with (right figure) the background subtraction in the reaction *p*(5.5 Gev/c)+C, at minimal cuts: Eγ ≥ 50 MeV.

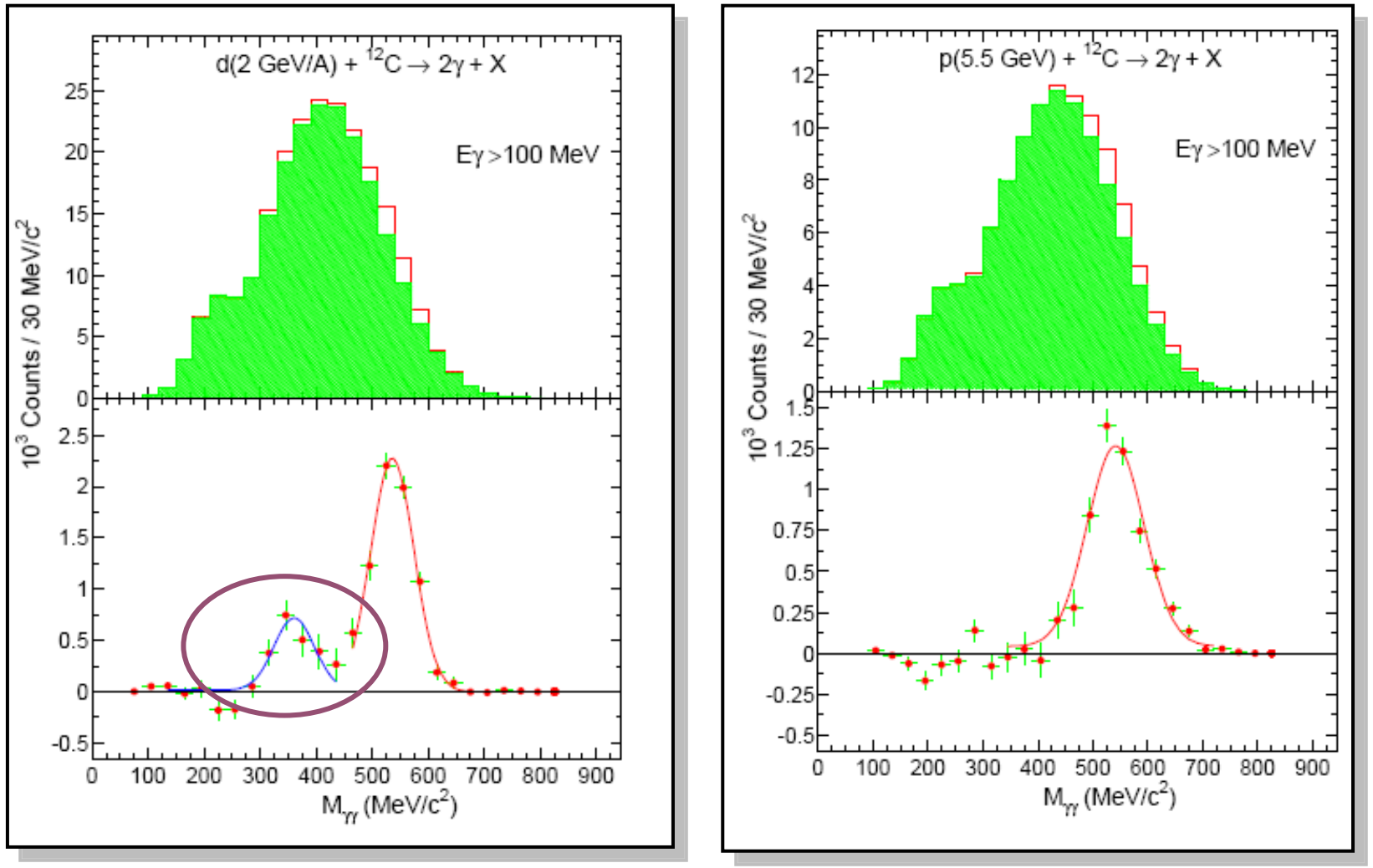





Abraamyan Kh.U. et al., Observation …

The first observation (nucl-ex/0607027; PR **C80**, 2009, p.034001).
Invariant mass distributions of γγ pairs without (upper panel)
and with (bottom panel) the background subtraction after the criteria (1)-(3).



# From the PDG



## OTHER LIGHT MESONS

NODE=MXXX015

### Further States

NODE=M300

OMITTED FROM SUMMARY TABLE

NODE=M300

This section contains states observed by a single group or states poorly established that thus need confirmation. Publications that exclude earlier claims in this section are listed under 'Other Related Papers.'

QUANTUM NUMBERS, MASSES, WIDTHS, AND BRANCHING RATIOS

**X(360)** $I^G(J^{PC}) = ?^?(?^{?+})$

NODE=M300K08

NODE=M300K08

| | MASS (MeV) | WIDTH (MeV) | EVTS | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|---|---|
| YOUR DATA | $360 \pm 7 \pm 9$ | $64 \pm 18$ | 2.3k | [1] ABRAAMYAN 09 | CNTR | 2.75 $d\,C \rightarrow \gamma\gamma X$ |

[1] Not seen in $pC \rightarrow \gamma\gamma X$ at 5.5 GeV/c.

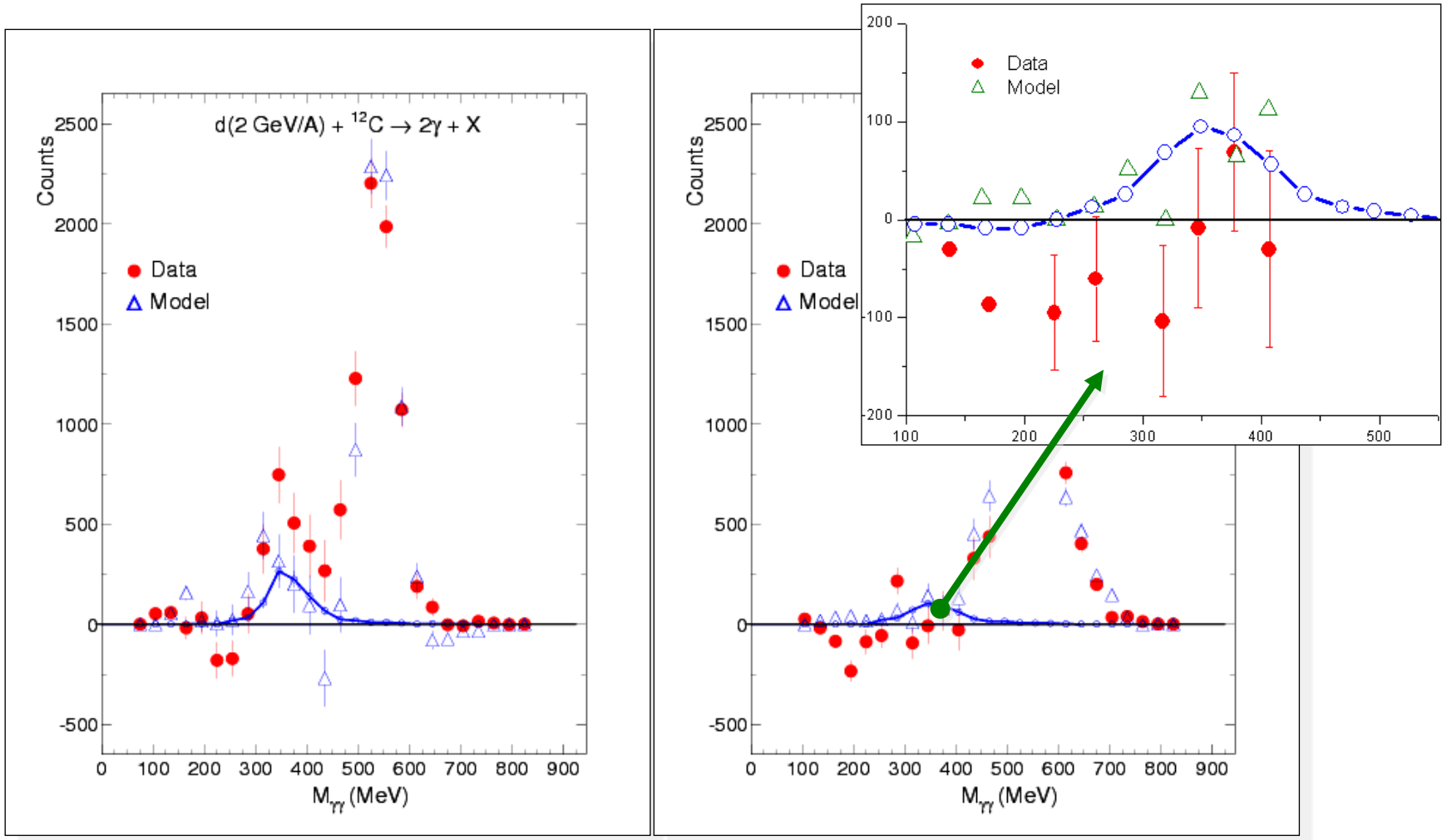
NODE=M300K08;LINKAGE=AB

**REFERENCES for Further States**

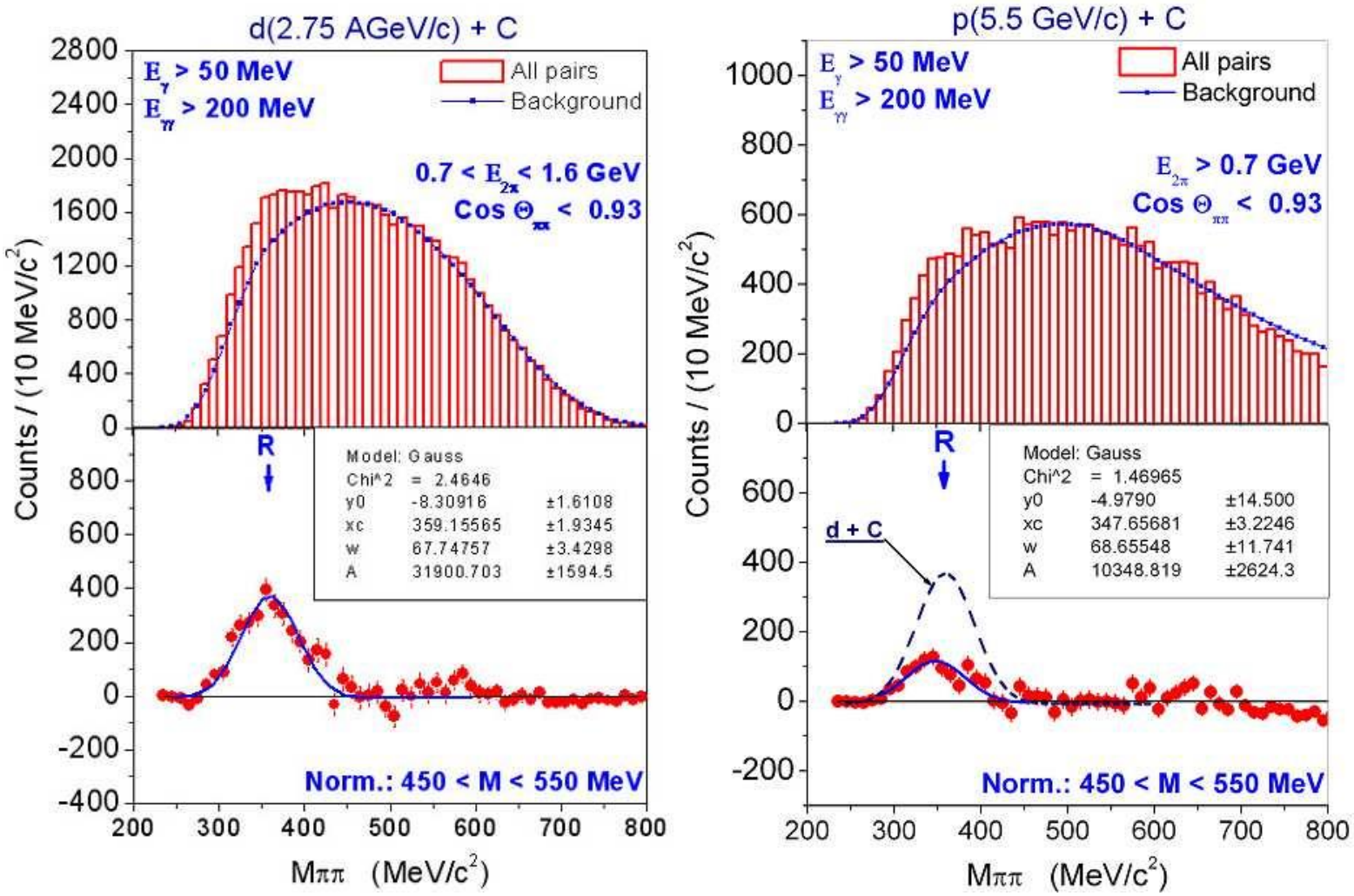
NODE=M300

| | | | | |
|---|---|---|---|---|
| YOUR PAPER | ABRAAMYAN 09 | PR C80 034001 | Kh.U. Abraamyan *et al.* | REFID=53100 |

The experimental (●) and simulated (Δ) data for the *d*(2 GeV/n)+C (left) and *p*(4.6 GeV)+C (right) reactions. The curves are contributions of $R \rightarrow \gamma\gamma$ decays.



# Check of the resonance structure at an invariant mass of pairs of γ-quanta and pairs of π°-mesons of about 360 MeV/c². Eur. Phys. J. A (2016) 52: 259.




The Invariant-mass distributions of π°π° pairs without (upper panels) and with (bottom panels) the background subtraction for the reactions d+C at 2.75 GeV/c per nucleon (left figure) and p+C at 5.5 GeV/c (right figure). The backgrounds are normalized to pair numbers in the interval: 450 < Mππ < 550 MeV/c2.

-------- Исходное сообщение --------
**Тема:** ArXiv:1203.4198
**Дата:** Thu, 17 May 2012 19:04:52 +0100
**От:** eef@teor.fis.uc.pt
**Кому:** Khachik Abraamyan <abraam@sunhe.jinr.ru>
**Копия:** George Rupp <george@ist.utl.pt>

Dear Dr. Khachik Abraamyan and collaborators,

It was a pleasant surprise to read your article on "Resonance structure in diphoton and two-neutral-pion systems in Deuterium-Carbon interactions" ArXiv:1203.4198.

I am sorry that I did not come across your 2006 work nucl-ex/0607027 before today.

Your result is spectacular as it does not seem to fit into any type of model for strong interactions and worth to offer you my congratulations.

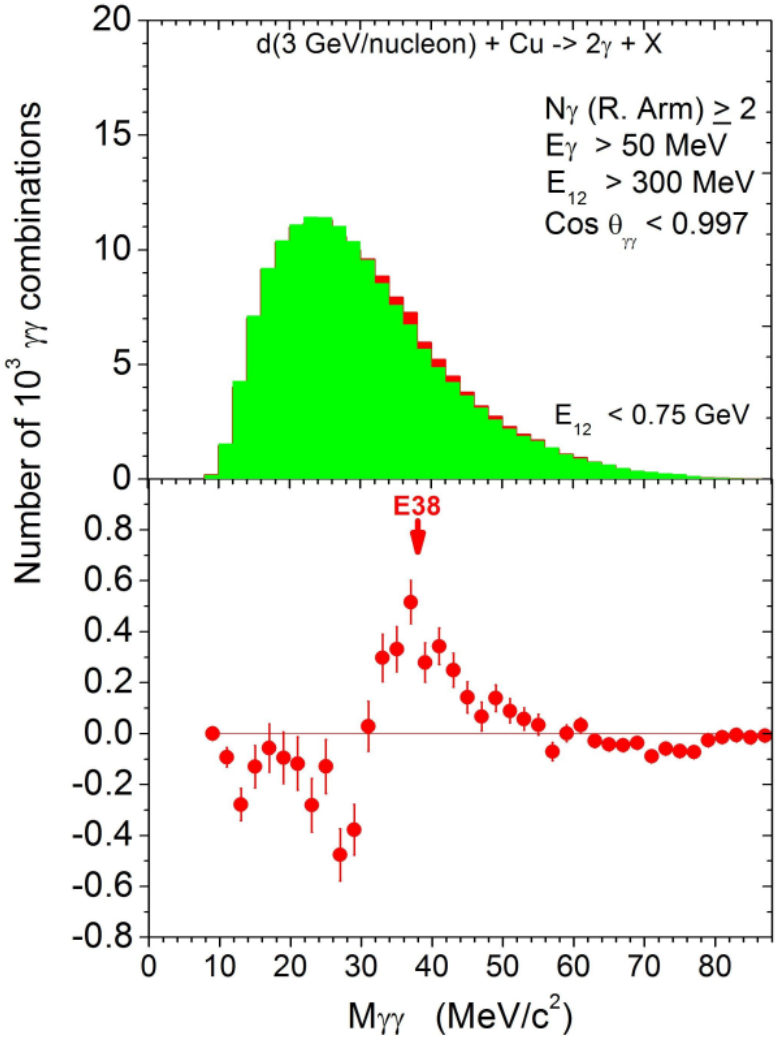
Do you yourself have an explanation for the resonance at 360 MeV?

Actually, I was browsing in Google through data for diphotons where I found your work. The reason is that I myself and my collaborator George Rupp are interested in diphoton data from 30 to 50 MeV (see arXiv:1202.1739 and arXiv:1204.3287).

Unfortunately, your lower limit is 100 MeV, but I wonder
whether that is a limitation of your setup at the JINR Nuclotron,
or that it could be lowered to 30 MeV.

Kind regards,
Eef van Beveren

*From the paper: Kh.U. Abraamyan et al. arXiv:1208.3829v1 [hep-ex]: Fig. 2.*
Invariant mass distribution of γγ pairs satisfying criteria (A) from the reaction *d*+Cu→γ+γ+X at 3.83 GeV/c per nucleon. The green histogram shows the background contribution. The bottom panel show the spectra after the background subtraction. The background is normalized to the total pair number.



EPJ Web of Conferences **204**, 08004 (2019) https://doi.org/10.1051/epjconf/201920408004
*Baldin ISHEPP XXIV*

# Check of the structure in photon pairs spectra at the invariant mass of about 38 MeV/$c^2$

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[2]Yerevan State University, 0025, Yerevan, Armenia
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**Abstract.** Results of analysis of the effective mass spectra of photon pairs produced in *d*C, *d*Cu and *p*C interactions at momenta of 2.75, 3.83 and 5.5 GeV/*c* per nucleon, respectively, are presented. A structure at effective mass of about 38 MeV/$c^2$ is observed. The results of testing the observed signal are presented. The test results support the conclusion that the observed signal is the consequence of detection of a particle with a mass of about 38 MeV/$c^2$ decaying into a pair of photons.

Mail

## Your work on E38, arxiv:1208.3829

DB **David Blaschke <david.blaschke@gmail.com>**
30.07.2020 7:06

Кому: Khachik Abraamyan; abraam@sunhe.jinr.ru Копия: Alexander Sorin

Dear Khachik jan,

...

I would like to point out that there is severe interest in this state because in the context of understanding the hypothetical X17 boson, there is a model that would explain both states, including the one at 38 MeV, see table 1 of

https://arxiv.org/pdf/2001.04864.pdf

The author, Cheuk-Yin Wong, is a good old friend of mine and has pointed out your result to me which he has included to a recent update of his work.

It seems to me that there could be some indication for the X17 state in your data too.
If that is true you should possibly revise your background analysis taking this state into account.

I am looking very much forward to hearing from you!

With best wishes,
David Blaschke

# Possibilities for detecting particles with low masses ($M < 20$ MeV/c²)

Triggering takes place when there is a coincidence of signals from two or more groups from different arms:

$$(D_1 + D_2) \times (D_3 + D_4) \ldots \qquad (1)$$

In order to studying the region of small invariant masses, we processed the data obtained in groups not participating in the trigger launch (thanks to the logical addition (see (1)), there are such groups in each event). The energies in such groups are not affected by the discriminator thresholds. Thus, the energy in such groups is arbitrary, starting from zero.

# Gamma's from the Groups outside the trigger

The figures on the second slide shows the sum of data for two groups that did not participate in the event triggering (after logical addition) (see (1), previous slide). Thus, the energy in the specified group could be arbitrary (without the influence of the discriminator thresholds)

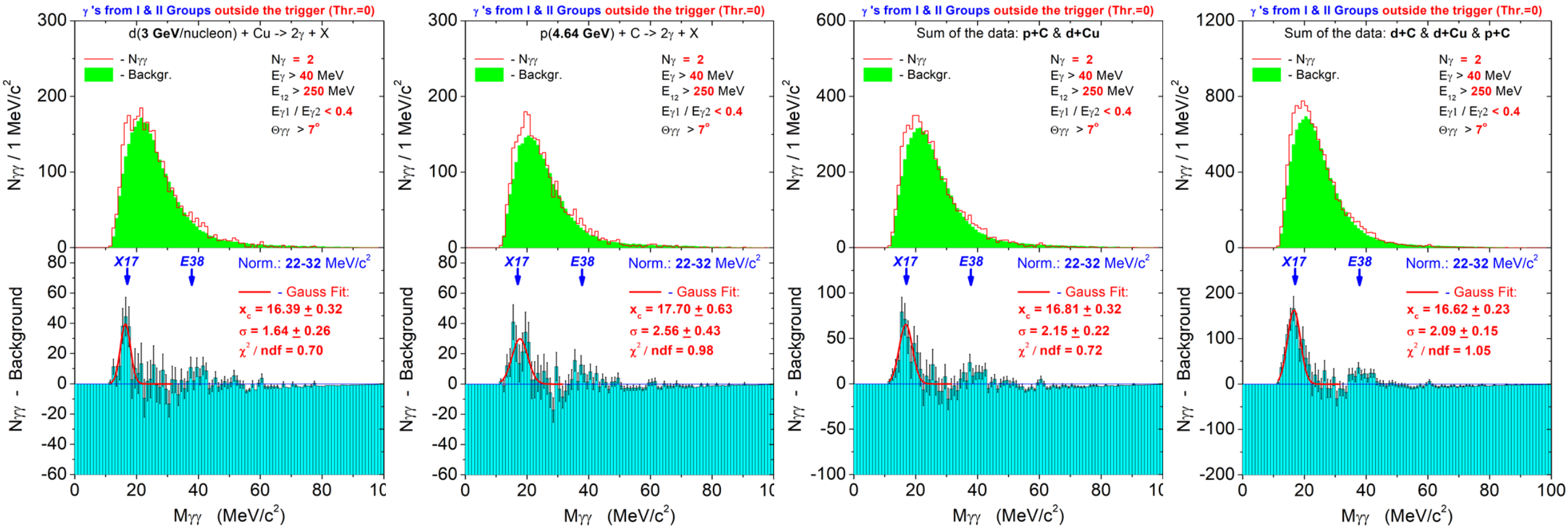
For searching for a signal from a particle with a mass of 17 MeV/c², the following selection criteria were used:

(i) the sum of the energies of photons in a pair, $E_{12} > 250$ MeV (effective detection of pairs at the setup geometry);

(ii) the ratio of the energies of photons in a pair, $E_{\gamma 1}/E_{\gamma 2} < 0.4$ (suppresses systematic errors due to violation of the energy-momentum conservation laws at the event mixing);

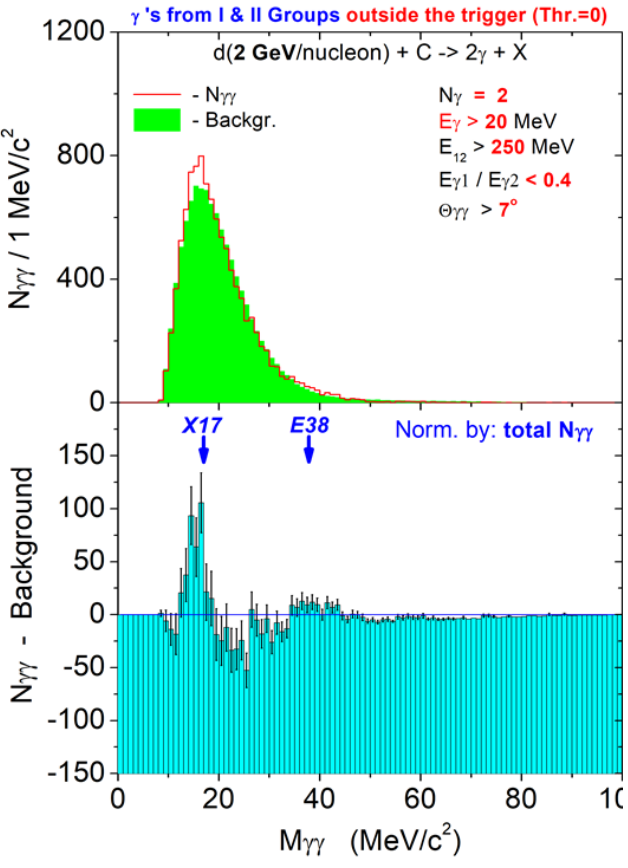
(iii) opening angle of photons in a pair, $\Theta_{\gamma\gamma} > 7°$ (suppresses systematic errors due to an excess of pairs with small opening angles at the event mixing).

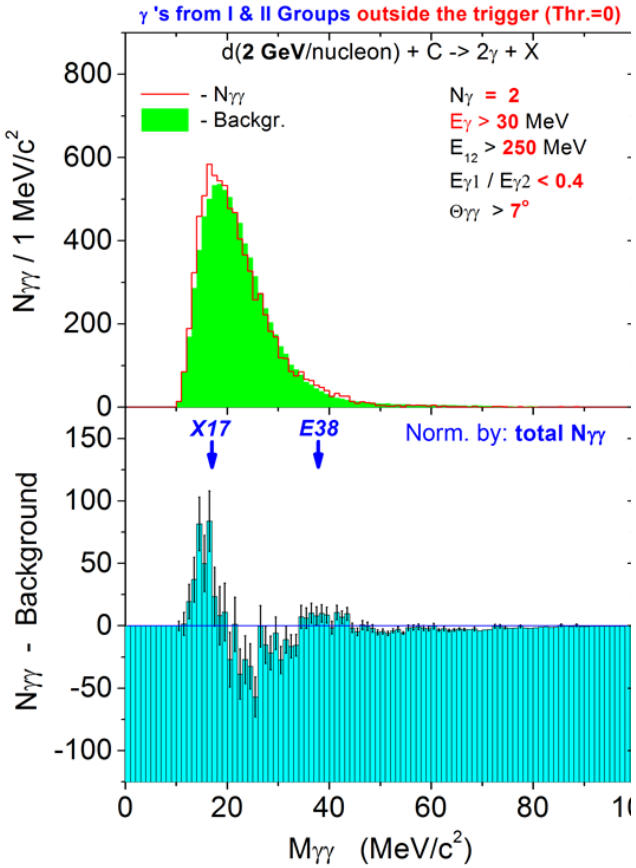
# Results of the search for a signal at an invariant mass of photon pairs of about 17 MeV/c²

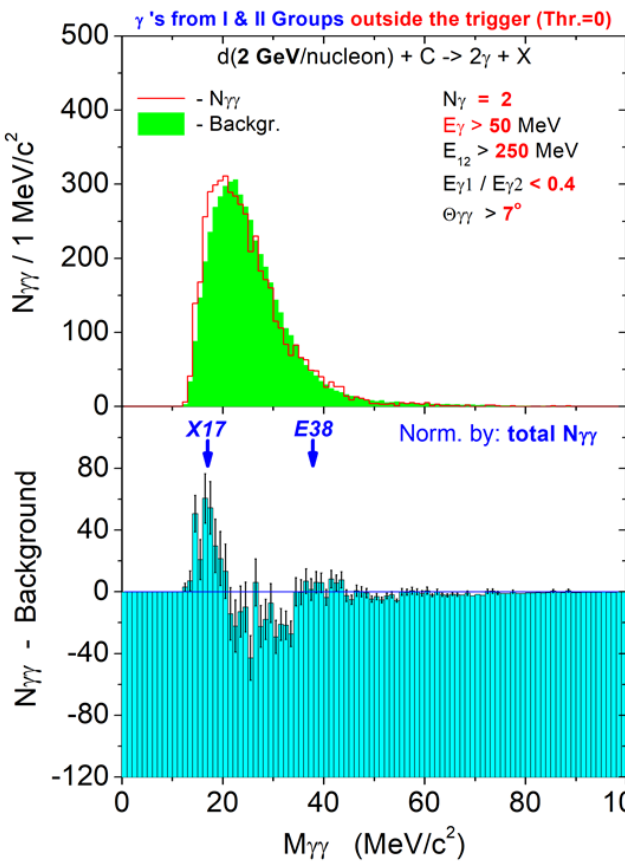


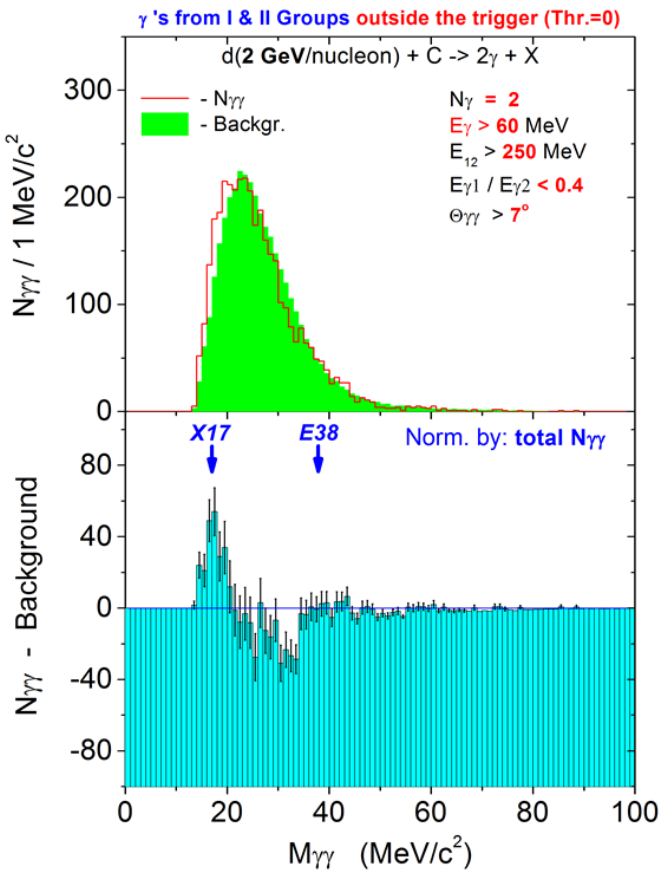

Invariant mass distributions of *γγ* pairs satisfying criteria (i)-(iii) without (upper panels) and with (bottom panels) the background subtraction obtained for the *d*+C, *d*+Cu and *p* + C reactions. The backgrounds are normalized by the numbers of pairs in the range (22, 32) MeV/c².

# CHECK OF THE OBSERVED PEAKS
## Different minimal energies of photons



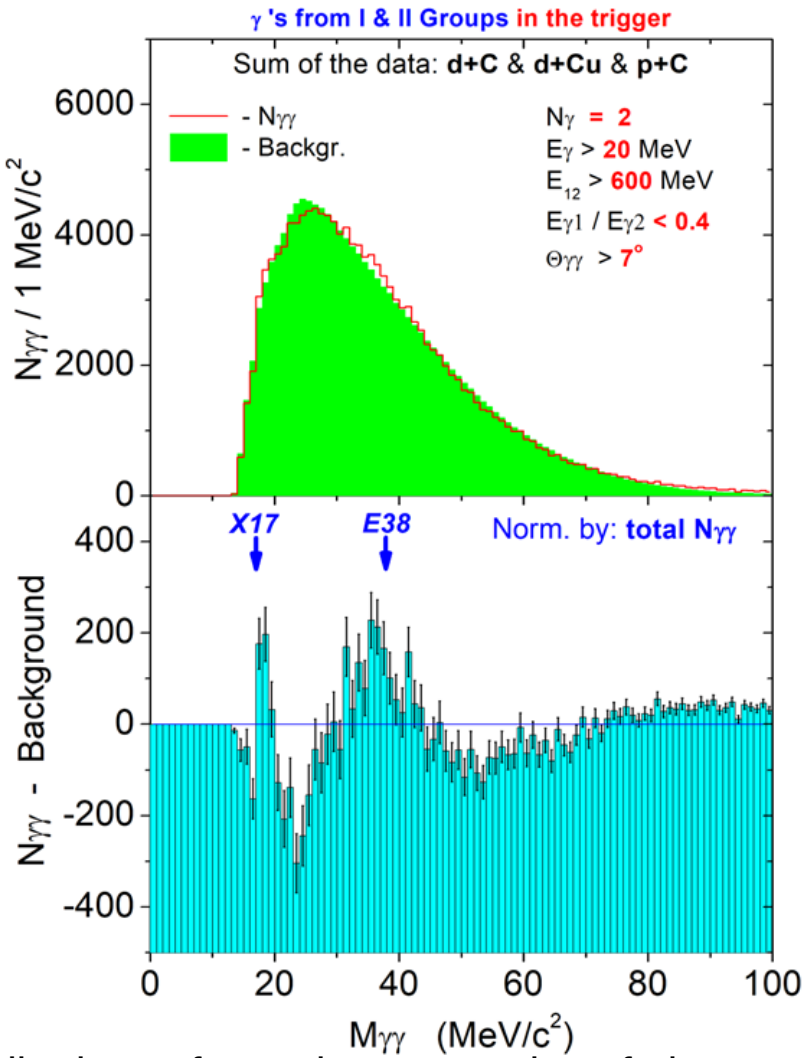

The same as in previous dlide, but at different minimal energies of photons: 20; 30; 50 and 60 MeV

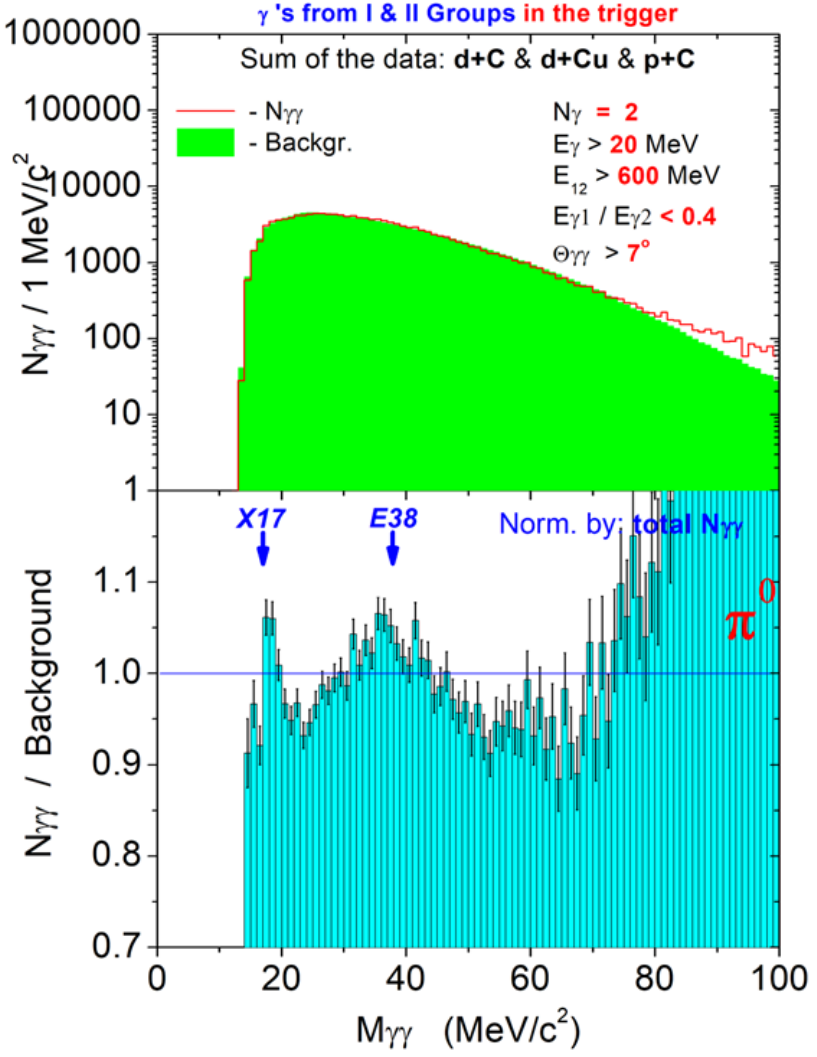
# Gamma's from the triggering Groups

Below are the results of an analysis of photon pairs detected only in one group participating in the launch of the facility. Thus, the sum of photon energies in these events are influenced by the discriminator thresholds (see above, (1)).
The next slide shows the invariant mass distributions of $\gamma\gamma$ pairs under the following conditions:

(1) the number of detected photons in the group, $N\gamma = 2$;
(2) the minimal energy of photons, $E\gamma Min = 20$ MeV;
(3) the sum of the energies of photons in a pair, $E_{12} > 600$ MeV (taking into account the discriminator thresholds);
(4) the ratio of the energies $E\gamma 1/E\gamma 2 < 0.4$ (suppresses systematic errors due to violation of the energy-momentum conservation laws at the event mixing);
(5) the opening angles of photons in a pair, $\Theta\gamma\gamma > 7°$.

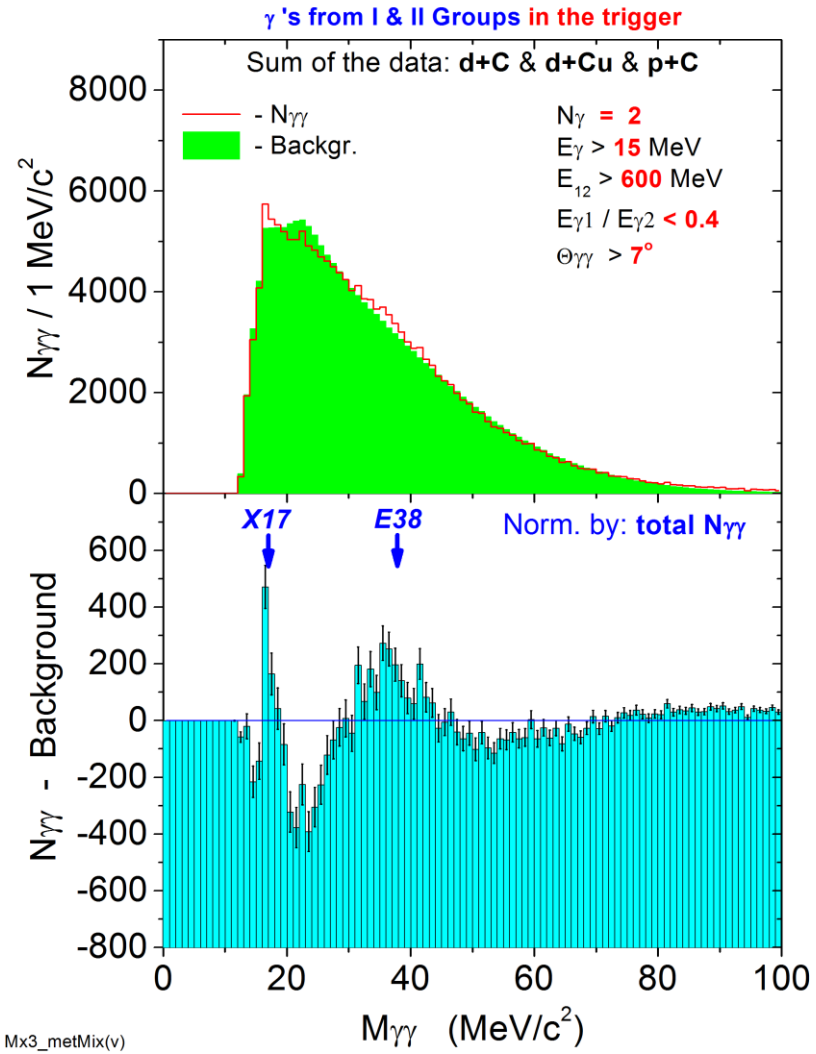
# Gamma's from the triggering Groups

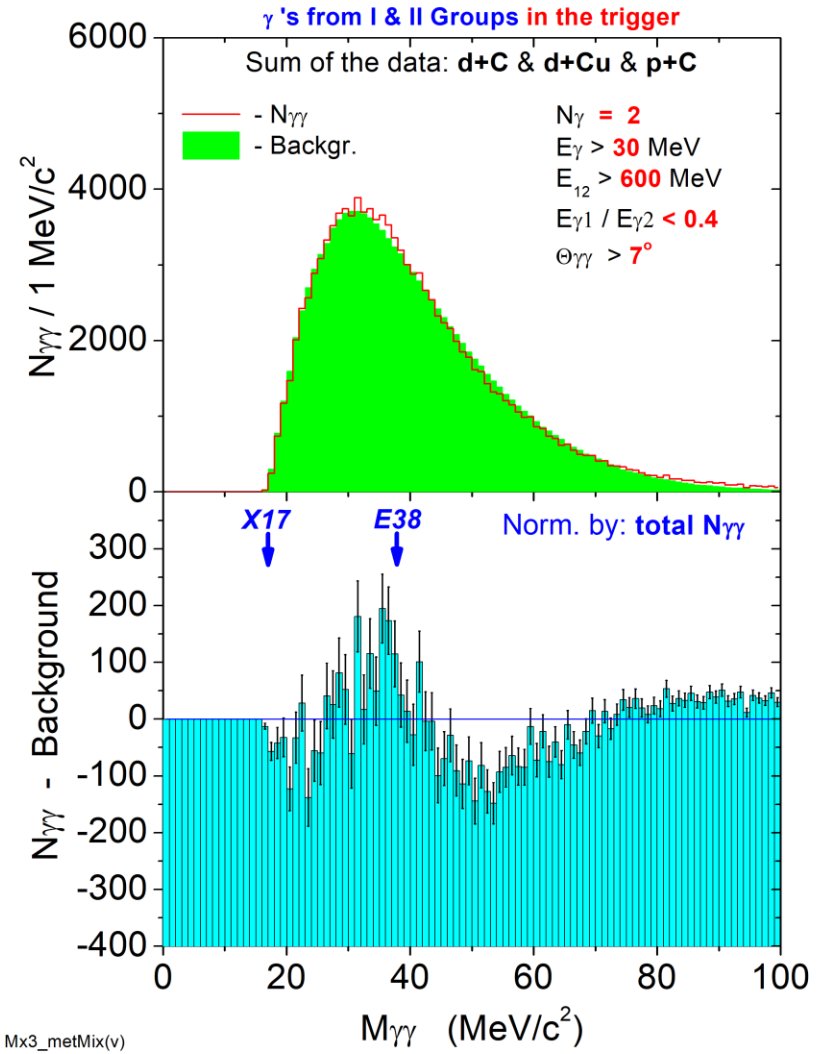



Invariant mass distributions of *γγ* pairs at energies of photons, Eγ > 20 MeV, without (upper panels) and with (bottom panels) the background subtraction obtained for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The backgrounds are normalized to the total pair numbers.

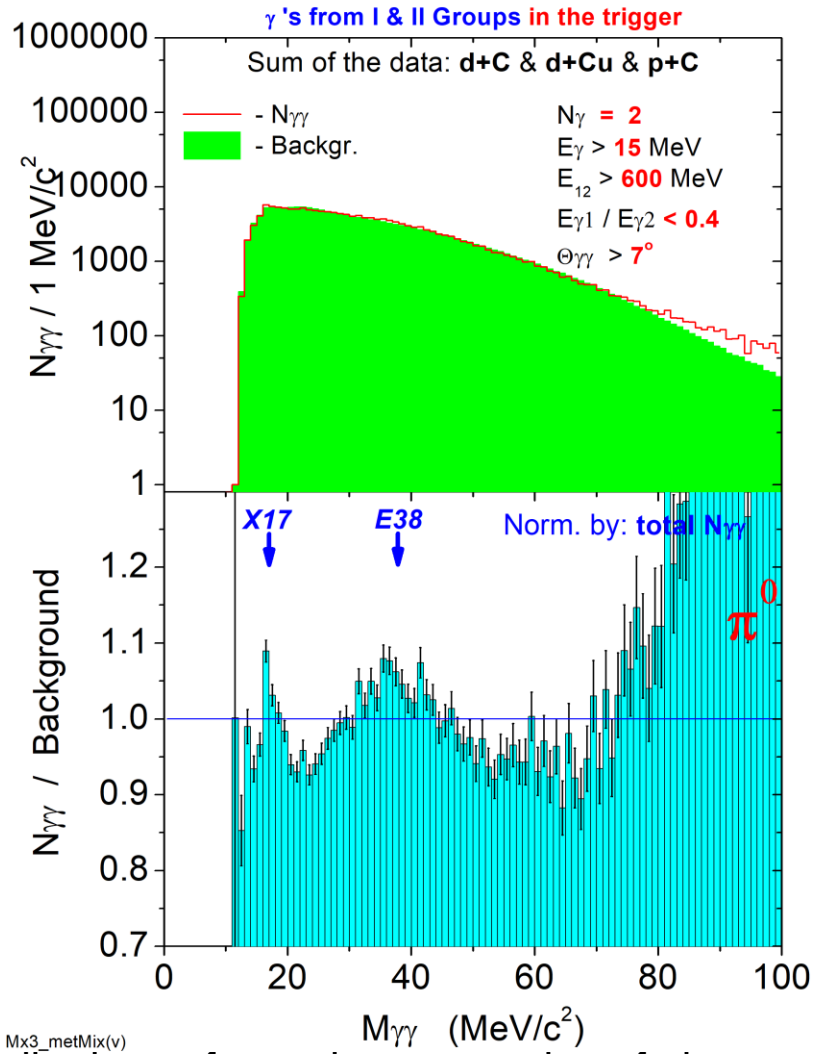
# The same as on the previous slide, but for Eγ > 15 and Eγ > 30 MeV

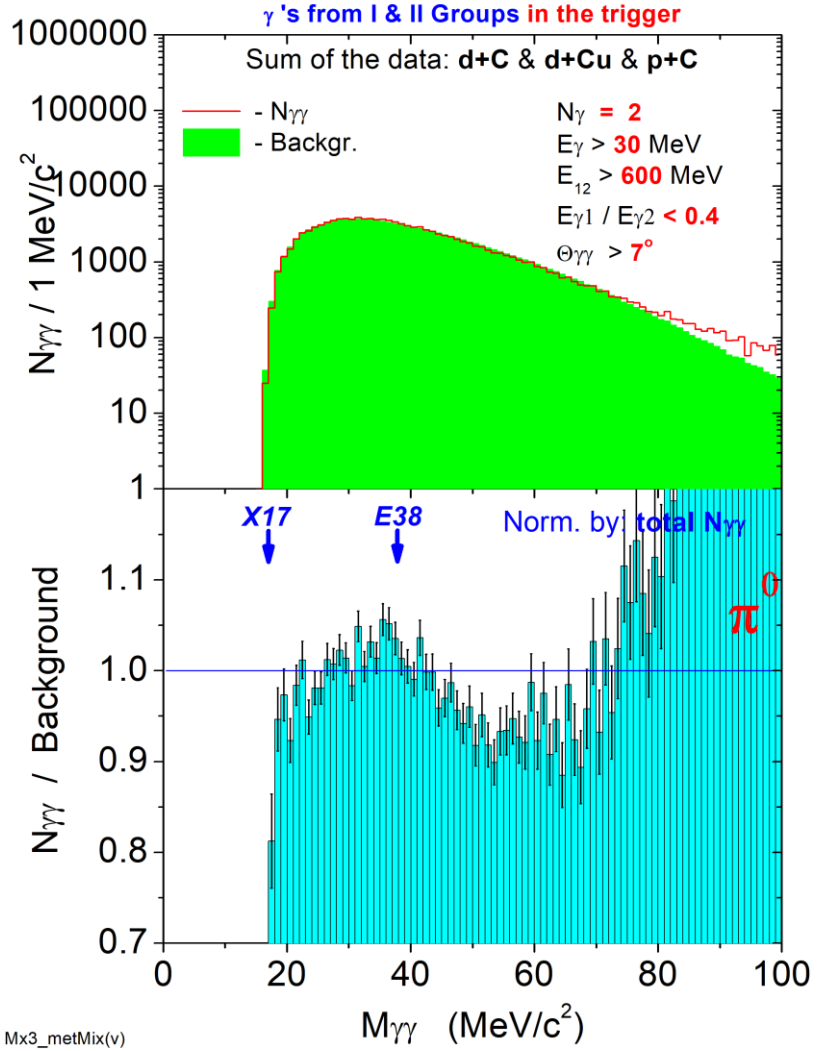



Invariant mass distributions of *γγ* pairs at energies of photons, Eγ > 15 MeV, (left) and Eγ > 30 MeV (right), without (upper panels) and with (bottom panels) the background subtraction obtained for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The backgrounds are normalized to the total pair numbers.

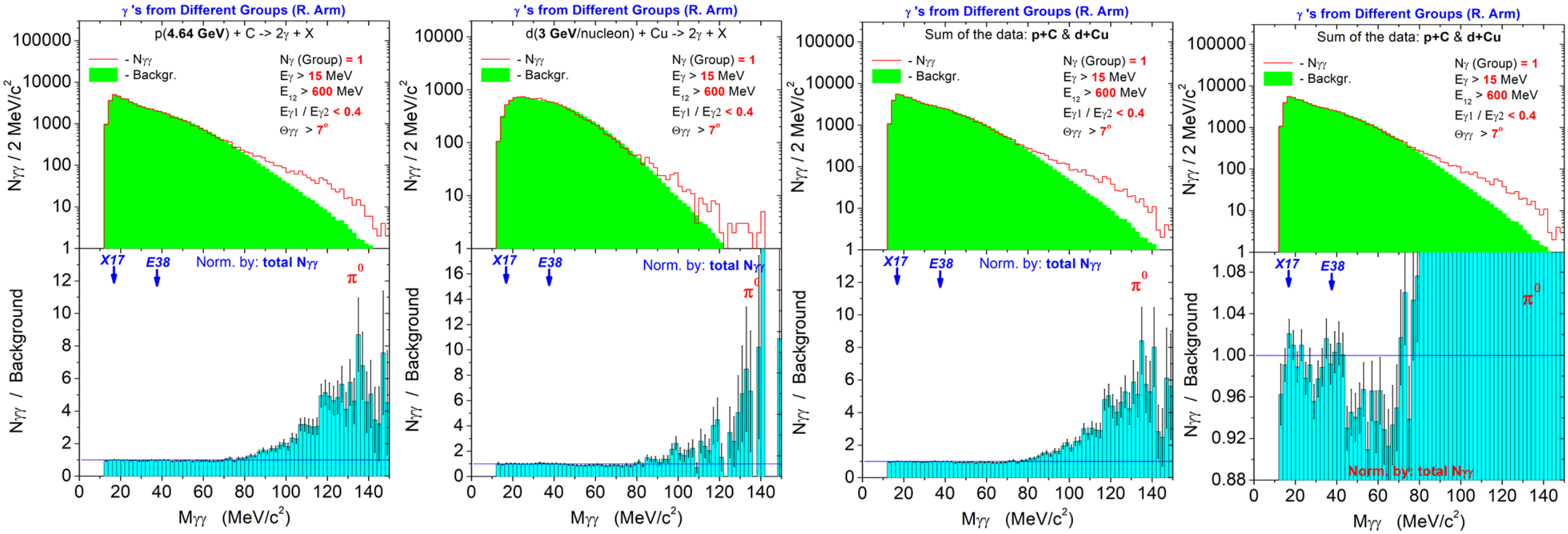
# The same as on the previous slide, but for the Nγγ/Background ratio




Invariant mass distributions of *γγ* pairs at energies of photons, Eγ > 15 MeV (left) and Eγ > 30 MeV (right), without (upper panels) and with (bottom panels) the background subtraction obtained for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The backgrounds are normalized to the total pair numbers.

# Gamma's from different Groups. Signals from the $\pi^0$-mesons



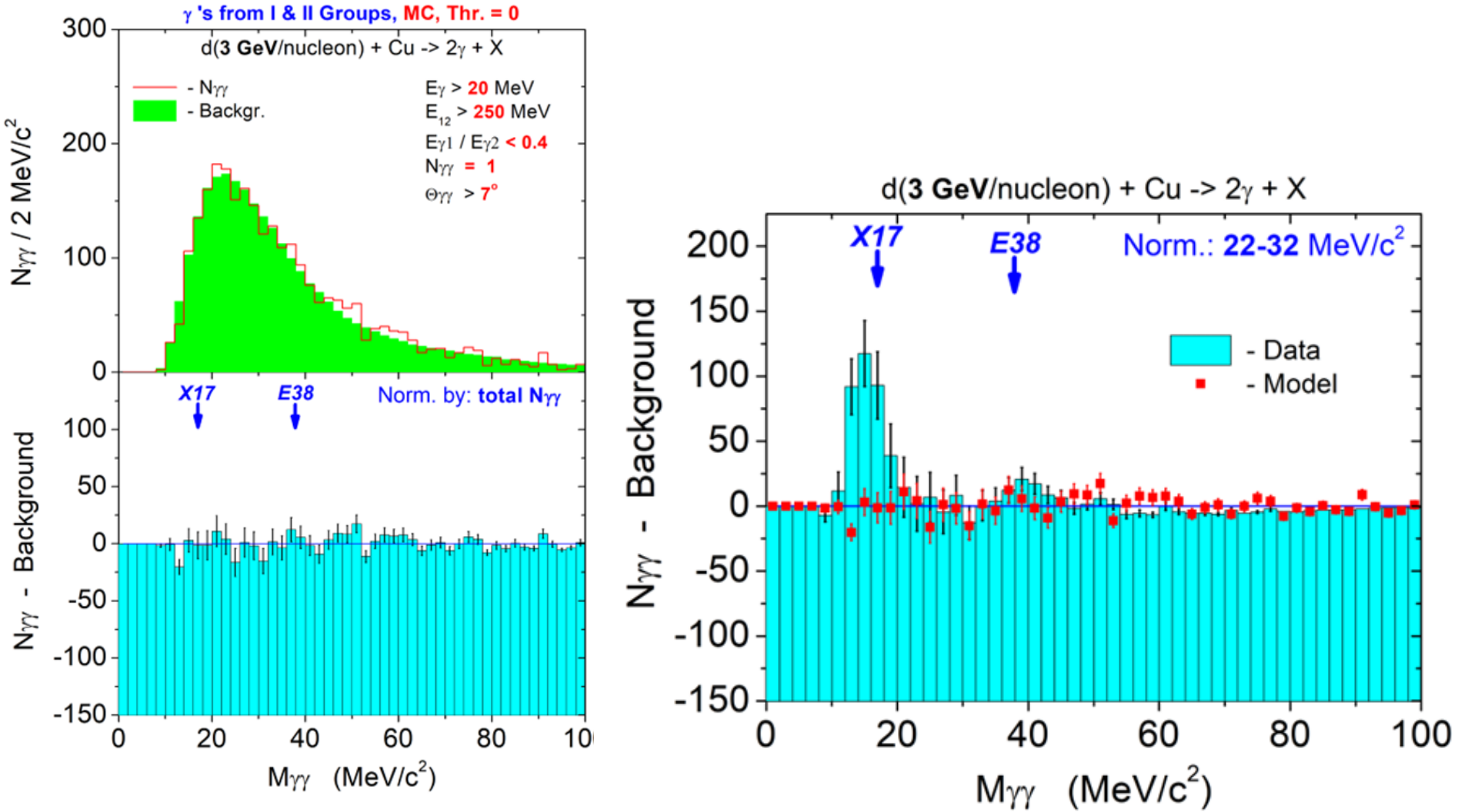

The *Nγγ* to the background ratio for photon pairs from different groups (Right arm) for the *d* + Cu and *p* + C reactions (left figures) and sum of these data at different scales.

# DATA SIMULATION

To simulate the *d* + Cu reaction we use a transport code. At high energies it is the Quark-Gluon String Model (QGSM) (N.S. Amelin, K.K. Gudima, and V.D. Toneev ) and at the energy of a few GeV the string dynamics is reduced to the earlier developed Dubna Cascade Model (DCM) (V.D. Toneev and K.K. Gudima) with upgrade of elementary cross sections involved (K. K. Gudima, S. G. Mashnik, and A. J. Sierk).

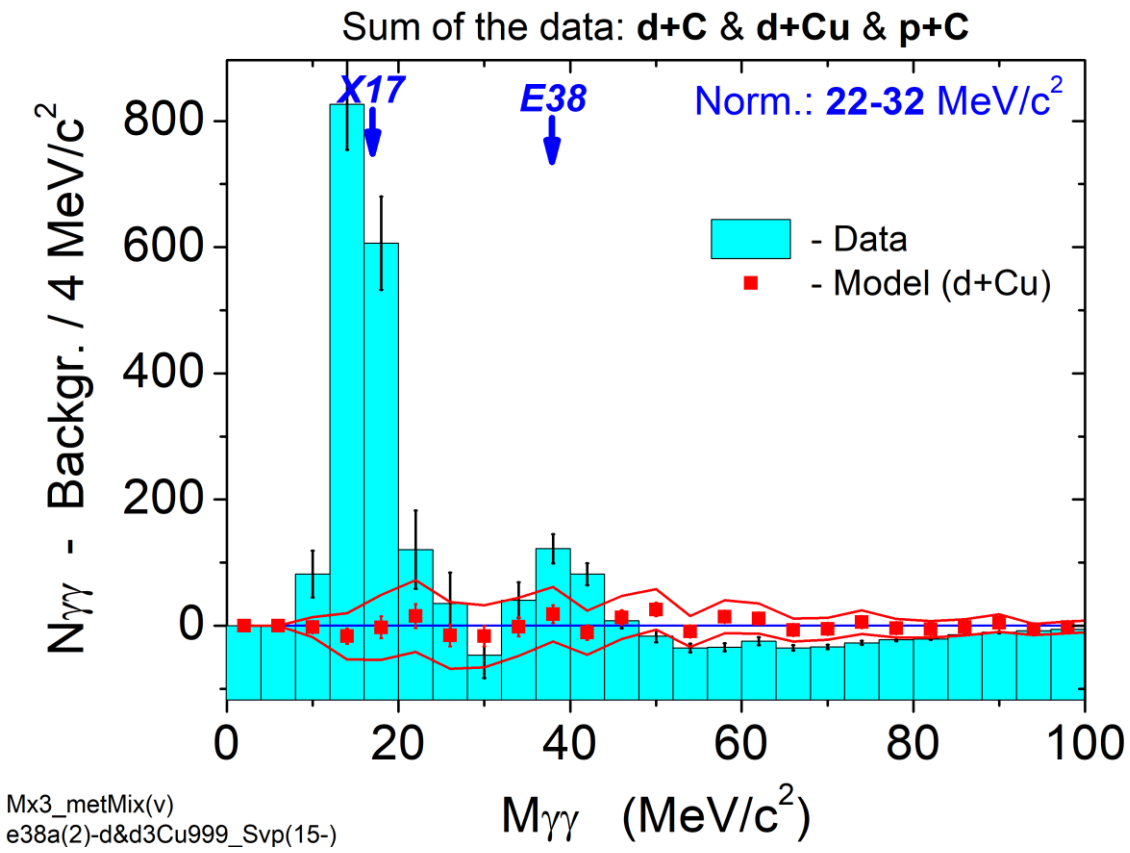
The following $\gamma$-decay channels are taken into account: the direct decays of $\pi^o$, $\eta$, $\eta'$ hadrons into two $\gamma$'s, $\omega \to \pi^o\gamma$, $\Delta \to N\gamma$ and the Dalitz decay of $\eta \to \pi^+\pi^-\gamma$, $\eta \to \gamma + e^+ + e^-$ and $\pi^o \to \gamma + e^+ + e^-$, the $\eta' \to \rho^o + \gamma$, the $\Sigma \to \Lambda + \gamma$, the $\pi N$ and $NN$-bremsstrahlung. One should note that in accordance with the HADES data, the $pn$-bremsstrahlung turned out to be higher by a factor of about 5 than a standard estimate and weakly depends on the energy. This finding, being in agreement with the result of Ref. L.P. Kaptari and B. K¨ampfer, Nucl. Phys. **A764**, 338 (2006)., allowed one to resolve the old DLS puzzle [E.L. Bratkovskaya and W. Cassing, Nucl. Phys. **A807**, 214 (2008) ]. This enhancement factor is included in our calculations. Tests of this model in detail are described in Ref. Kh.U. Abraamyan et al., Phys. Rev. **C80**, 034001 (2009); *arXiv:0806.2790.*

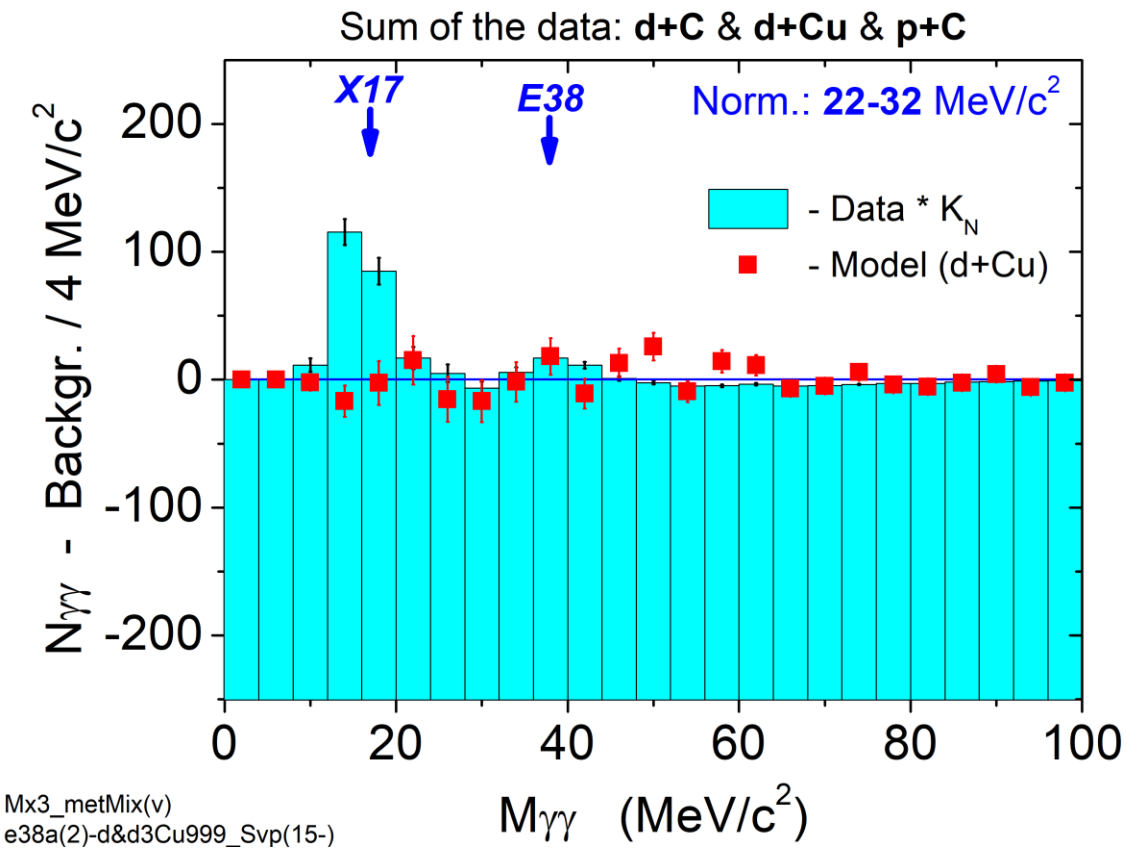
# Estimates of systematic errors in the combinatorial background




The result of processing the simulated data by the same method as experimental data, for the *d*(3 GeV/n) +Cu reaction (left) and comparison of the experimental and simulated spectra after the backgrounds subtraction (right). The backgrounds are normalized by the numbers of pairs in the range (22, 32) MeV/$c^2$. The selection criteria are in the figure.

# Estimates of systematic errors in the combinatorial background




The same as in the previous slide (right figure), but for the sum of the spectra (after the backgrounds subtraction), obtained in three experiments (indicated in the figure). The curves indicate the interval of ± 3 standard statistical errors in the simulated data. On the right figure, for the most stringent verification of the signals, the experimental data (in the left figure) were multiplied by a factor *K'n = N model* (22 < *Mγγ* < 32 *MeVc²*) / *N Exper.*(22 < *Mγγ* < 32 *MeV/c²*).

A more rigorous quantitative verification of the signal at 38 MeV/$c^2$ (with the participation of K.Gudima and Ch.Austin) was given in:

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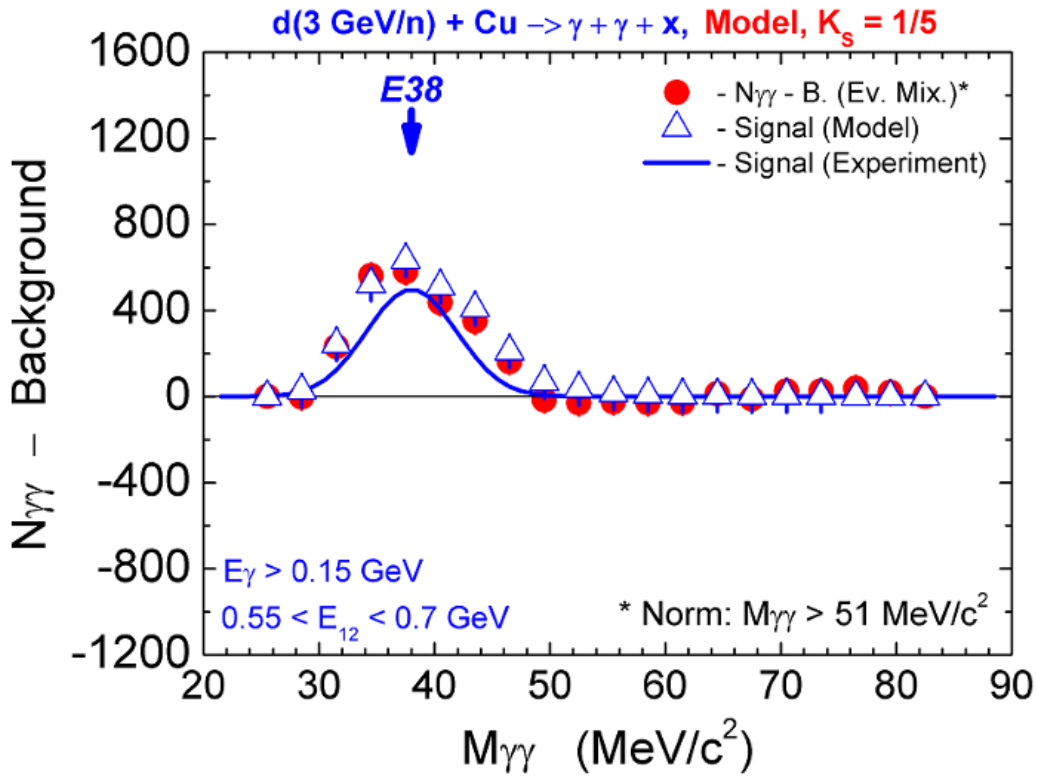
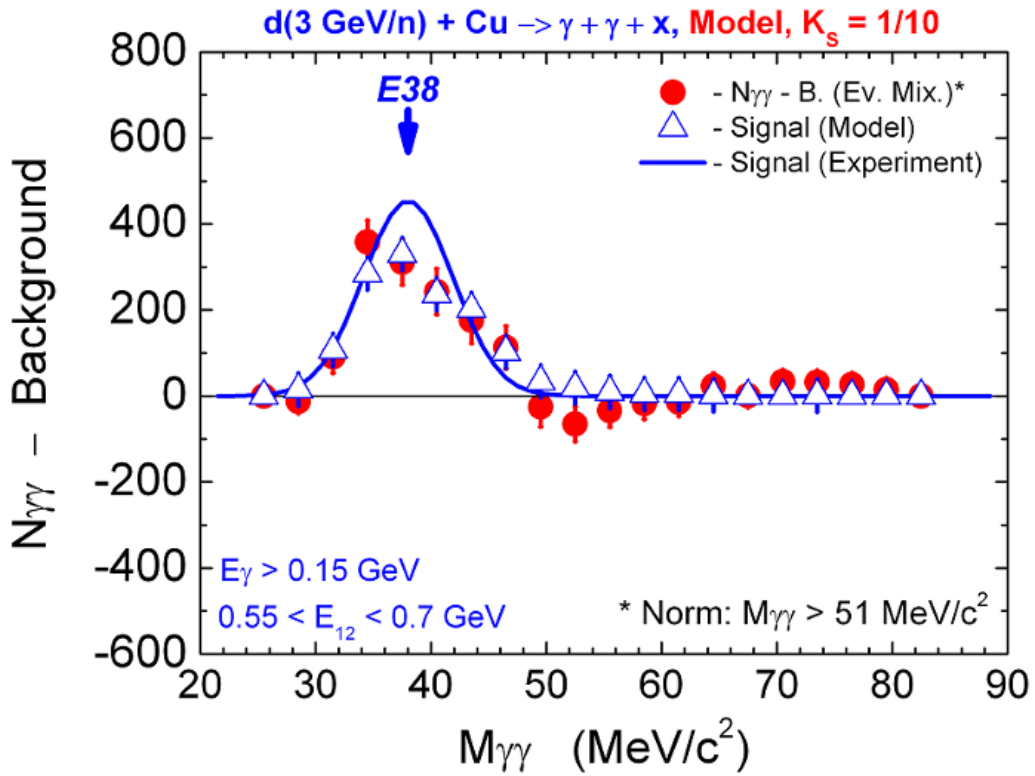
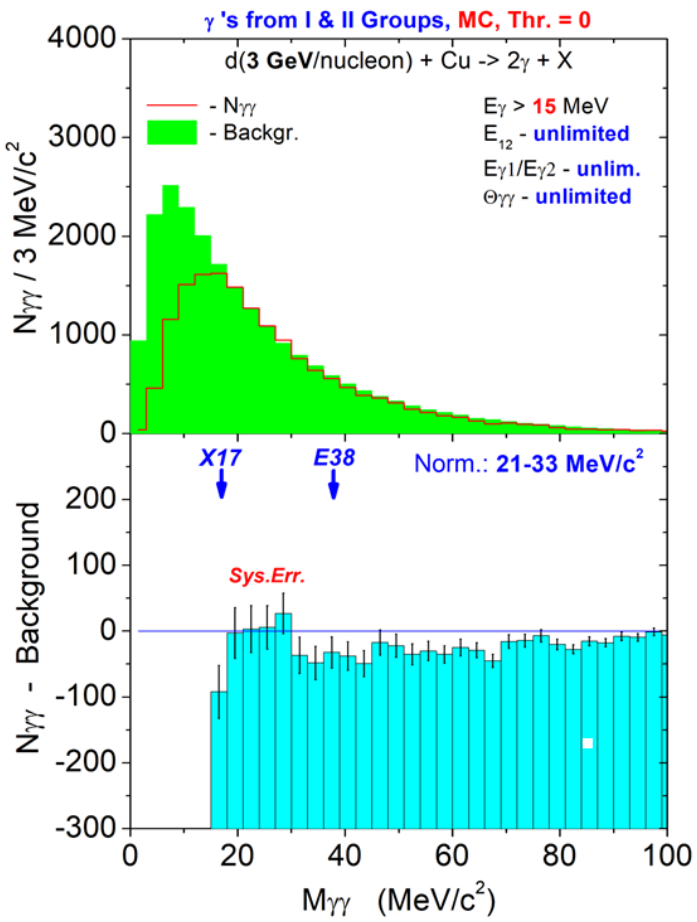
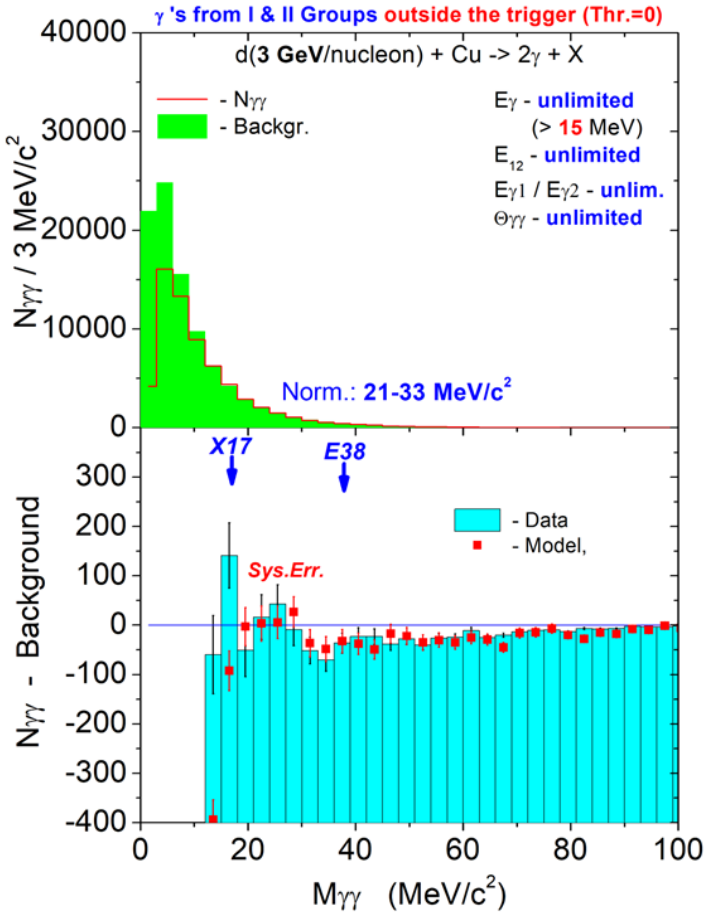



Invariant mass distributions (per 3 MeV/$c^2$) of γγ pairs from the decay of E(38) under the real experimental conditions: 4 - pairs γγ, selected by means of labels of photons applied in the model; • - the result of processing the simulated data with the method applied to the experimental data. The curves are the experimental signal after the background subtraction (Gaussian approximation) proportional to the number of *d* + Cu events containing a pair of γγ in the required energy range. The signal in the simulated data reduced by a factor *Kṣ* = 1/5 (among the events, containing a photon from the decay of E(38), each 5th event was taken) (left figure) and by a factor *Kṣ* = 1/10 (right figure) .

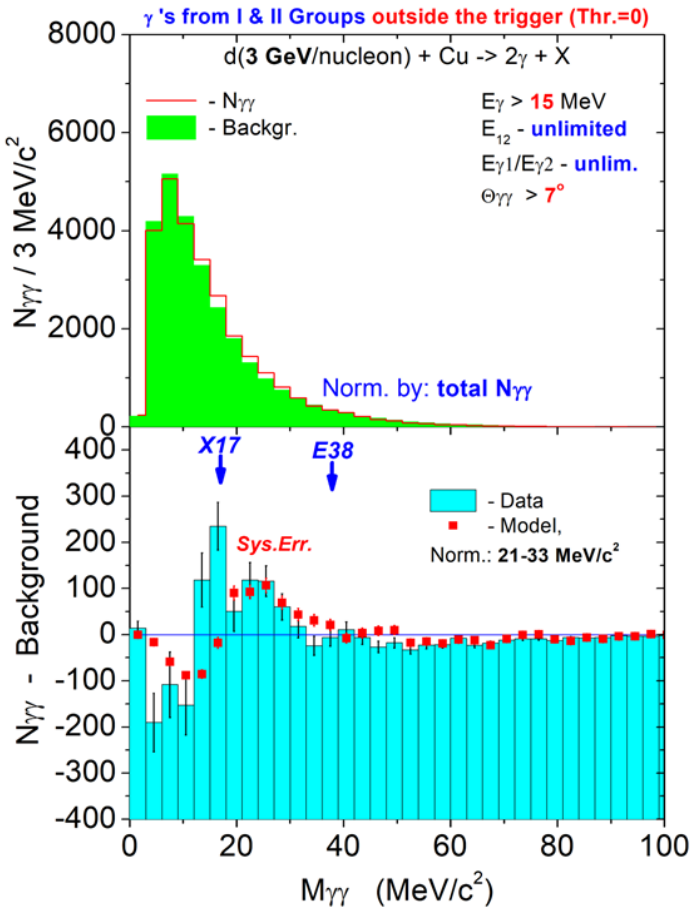
# No cuts. Systematic errors

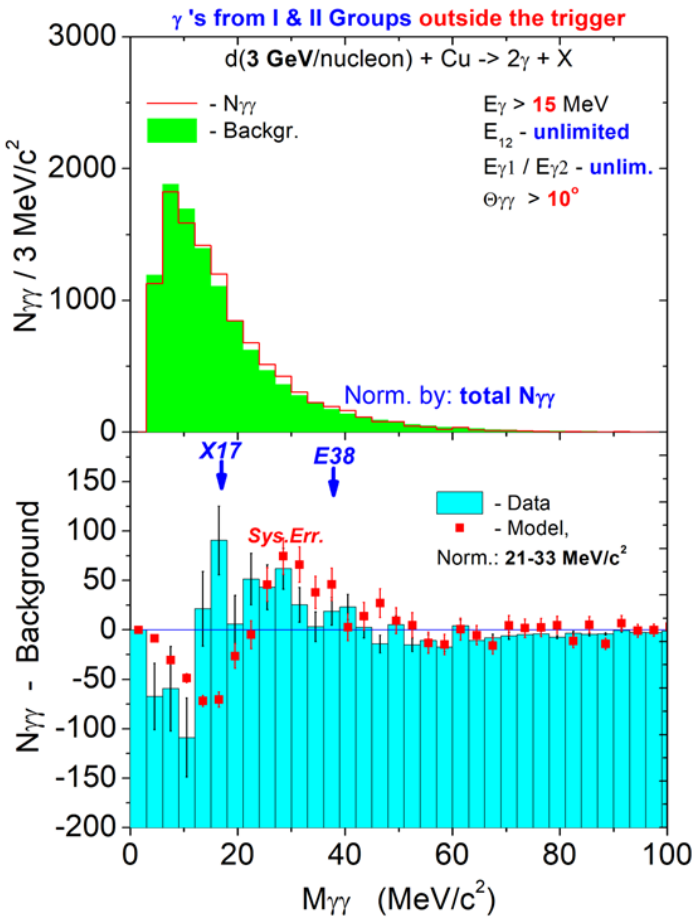



The result of processing the simulated data by the same method as experimental data, for the *d*(3 GeV/n) +Cu reaction (left) and comparison of the experimental and simulated spectra after the backgrounds subtraction (right) **at the minimum selection conditions**. The backgrounds are normalized by the numbers of pairs in the range (21, 33) MeV/$c^2$.

# No cuts. Systematic errors



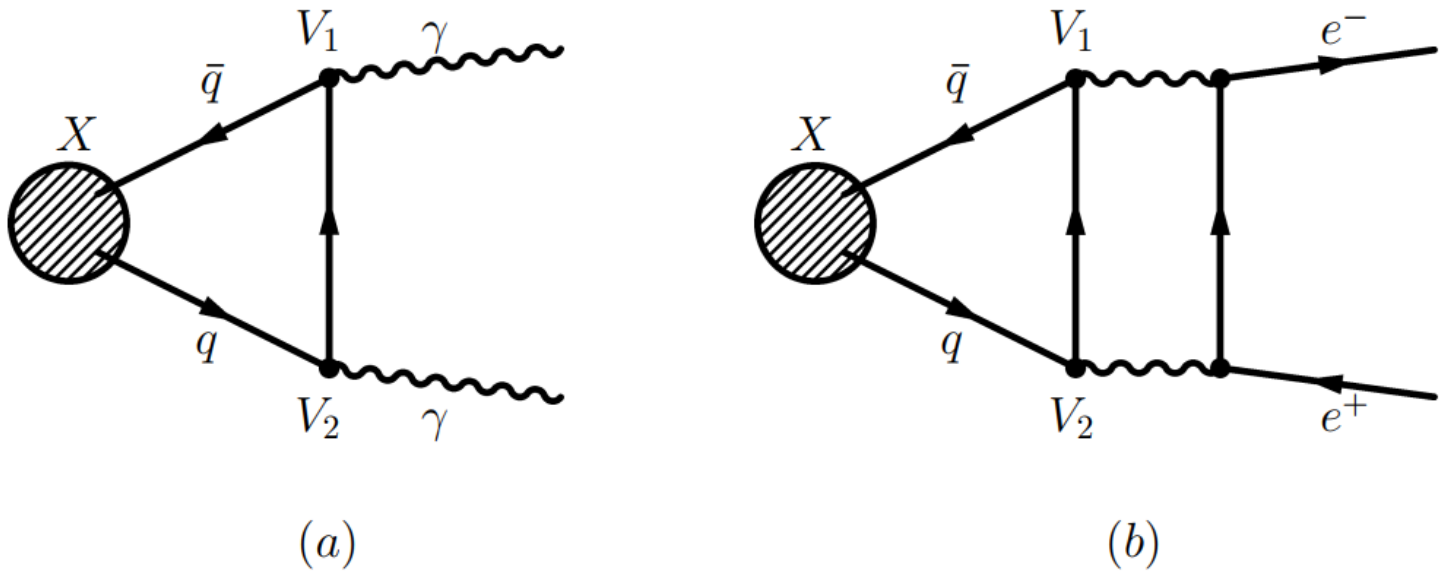




The same as in the previous slide, but after cuts by the opening angle: **Θγγ > 7°** (left figure) and **Θγγ > 10°** (right figure). The backgrounds are normalized to the total pair numbers in the spectra. The spectra after the backgrounds subtraction in the experimental and simulated data are normalized by the numbers of pairs in the range (21, 33) MeV/$c^2$.

# CONCLUSION

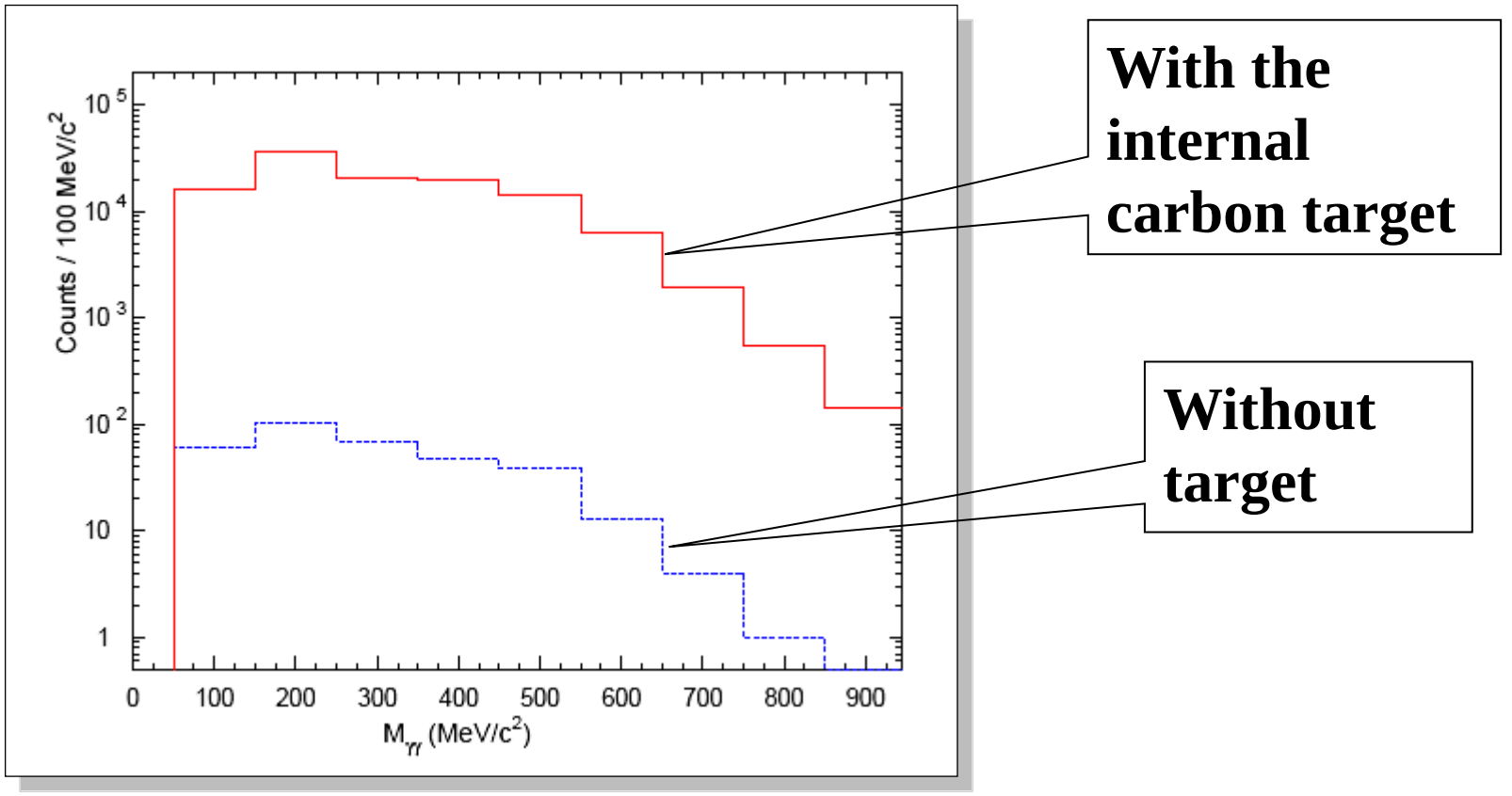
- Along with $\pi^0$ mesons, signals in the form of enhanced structures at invariant masses of about 17 and 38 MeV/$c^2$ are observed in the reactions $p$+C→ $\gamma$ +$\gamma$ +$x$, $d$+C → $\gamma$ +$\gamma$ +$x$ and $d$ + Cu → $\gamma$ + $\gamma$ + $x$ at momenta 5.5 GeV/c, 2.75 GeV/c and 3.83 GeV/c per nucleon, respectively. The results of testing of the observed signals, including the results of the Monte Carlo simulation support the conclusion that the observed signals are the consequence of detection of the particles with masses of about 17 and 38 MeV/$c$2 decaying into a pair of photons.
- In view of the many theoretical possibilities, it is of great to confirm the occurrence of X17 at different initial conditions and from different decay channels. The decay of both channels is in agreement with the composite picture of $X$17 and $E$38 (see the second slide).

Decay of the QED meson X into a $\gamma\gamma$ pair (a), and an $e^+e^-$ pair (b).
[*C. Y. Wong, Open string QED meson description of the X17 particle and dark matter, JHEP, **08**, 165 (2020)*].
The our experiment corresponds to the decay in Figure (a) while the ATOMKI experimental observation corresponds to the decay by Figure (b)



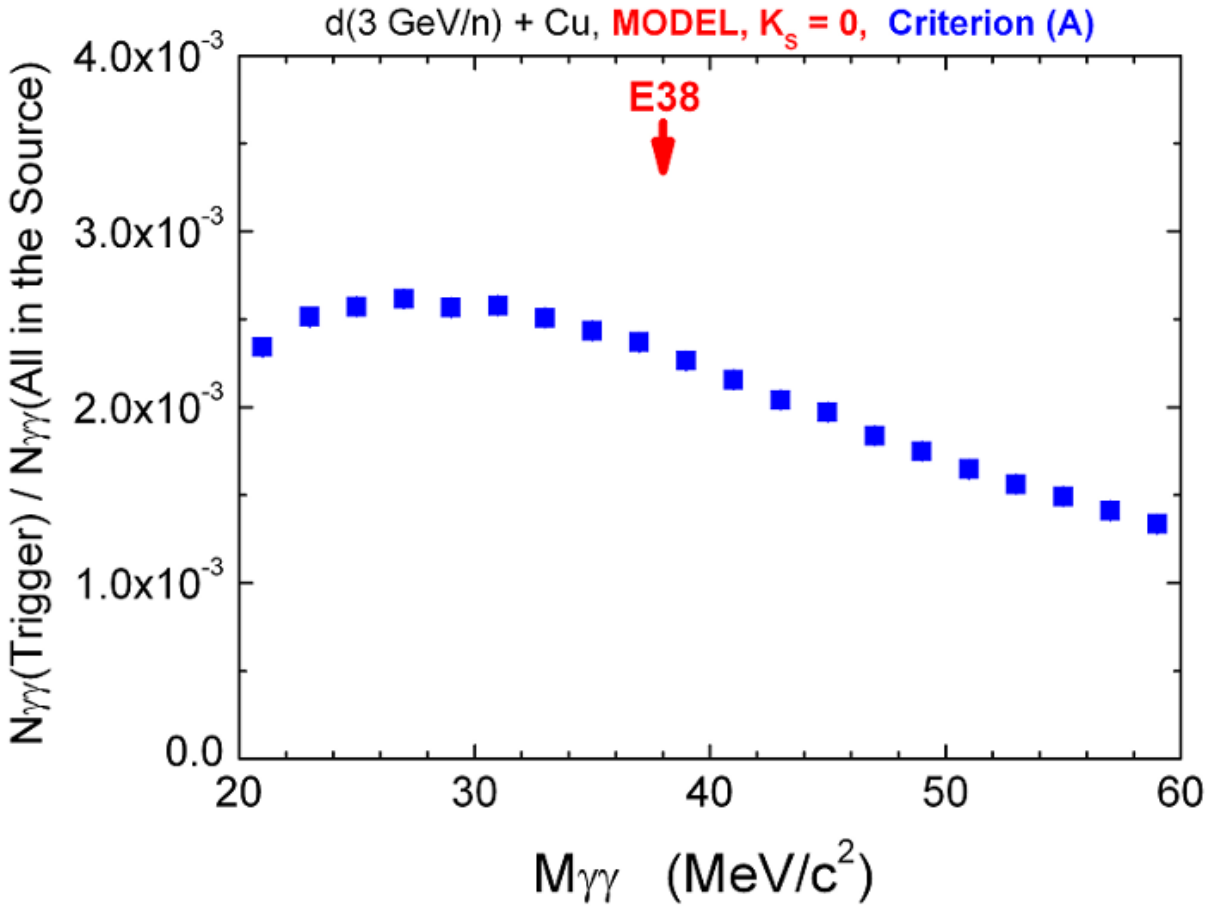
# Thank you!

Invariant mass distributions of γγ pairs in two different runs of measurement under condition Eγ ≥ 50 MeV: with the empty target (dashed histogram) and with the internal carbon target (solid histogram) in the reaction *d*C → γ +γ +X at 2.75 GeV/c per nucleon.



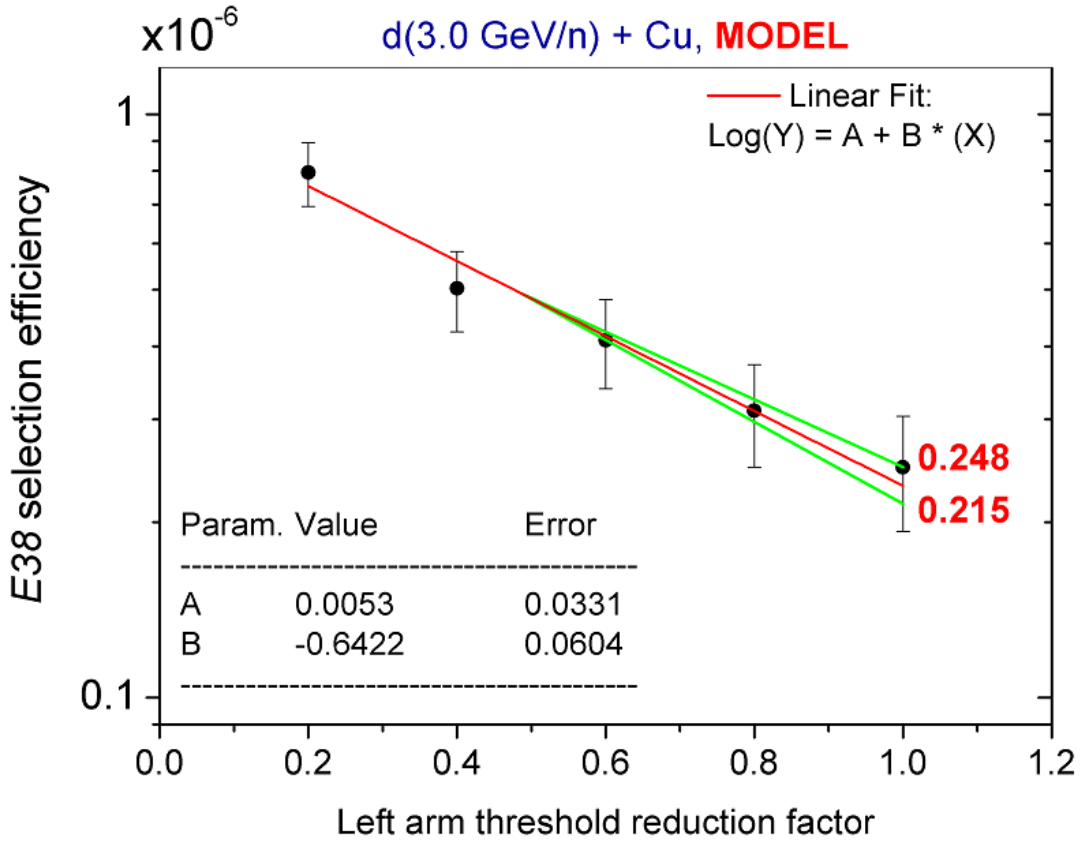
# The relative efficiencies of $\gamma\gamma$-pairs detection and selection.

EPJ Web of Conferences **204**, 08004 (2019) **204**, 08004 (2019)




The ratio of the number of triggered γγ pairs under real experimental conditions (at *E*γ > 50 MeV (criterion (A))) on the total number in the simulated source, depending on the effective mass (per 2 MeV/*c*2) of γγ pairs for the Model after excluding the events with γγ pairs from the E(38) boson. In this analysis, the coincidence with the Left arm is not required (i.e. triggering takes place when there is a signal from one or two groups from the Right arm).

# The E(38) detection and selection efficiency versus the energy threshold reduction factor for the Left Arm of the Spectrometer



Mail

## inquiry on E38 particle

CW **Cheuk-Yin Wong <wongcyor@gmail.com>**
30.07.2020 6:48

Кому: abraamyan@jinr.ru

x17v4.pdf
697,34 КБ

07/29/2020 (To. Prof. Khachik Abraamyan, abraamyan@jinr.ru)

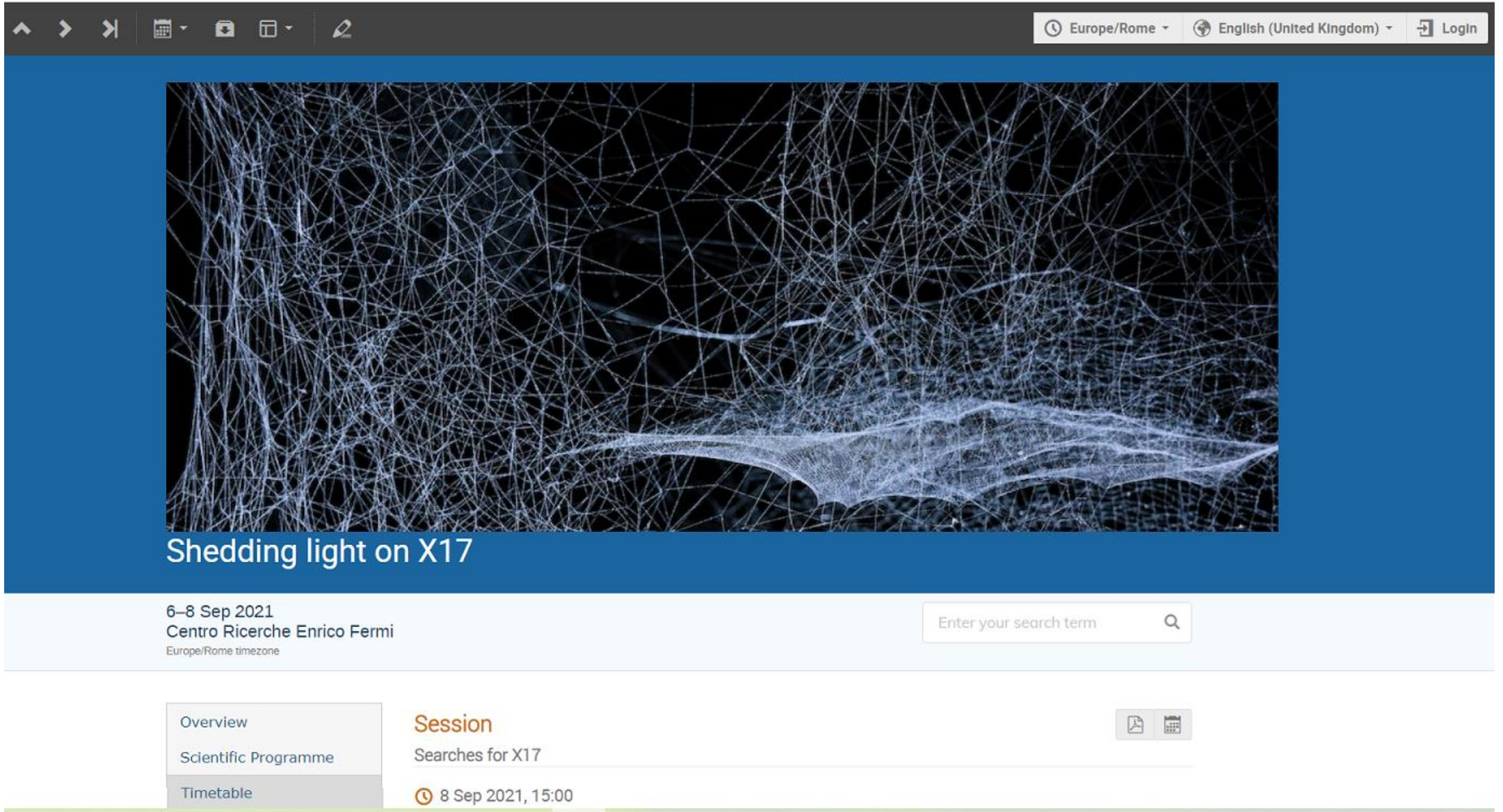
Dar Prof. Abraamyan,

(2) Is it possible for you to go to the invariant mass region of 10-20 MeV region where another boson state, the X17 state at 17 MeV, is predicted to occur? You may need to lower your E12 value. I would expect that the yield for such a boson state is much greater than the yield for the E38 state, but the background may also be greater.

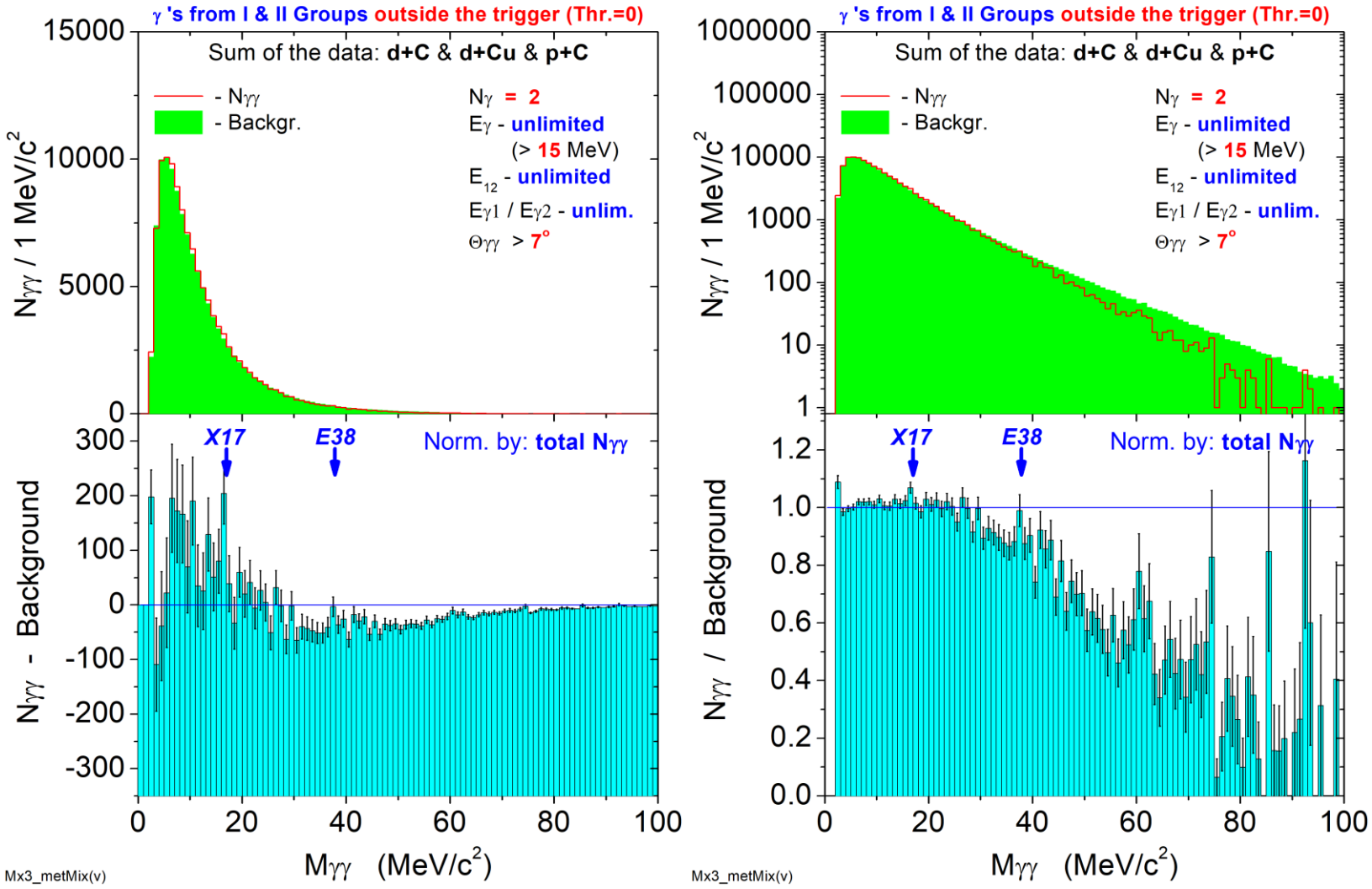
Best regards!

Cheuk-Yin Wong
Distinguished Senior Physicist
Physics Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831

https://agenda.infn.it/event/26303/sessions/20094/#20210908

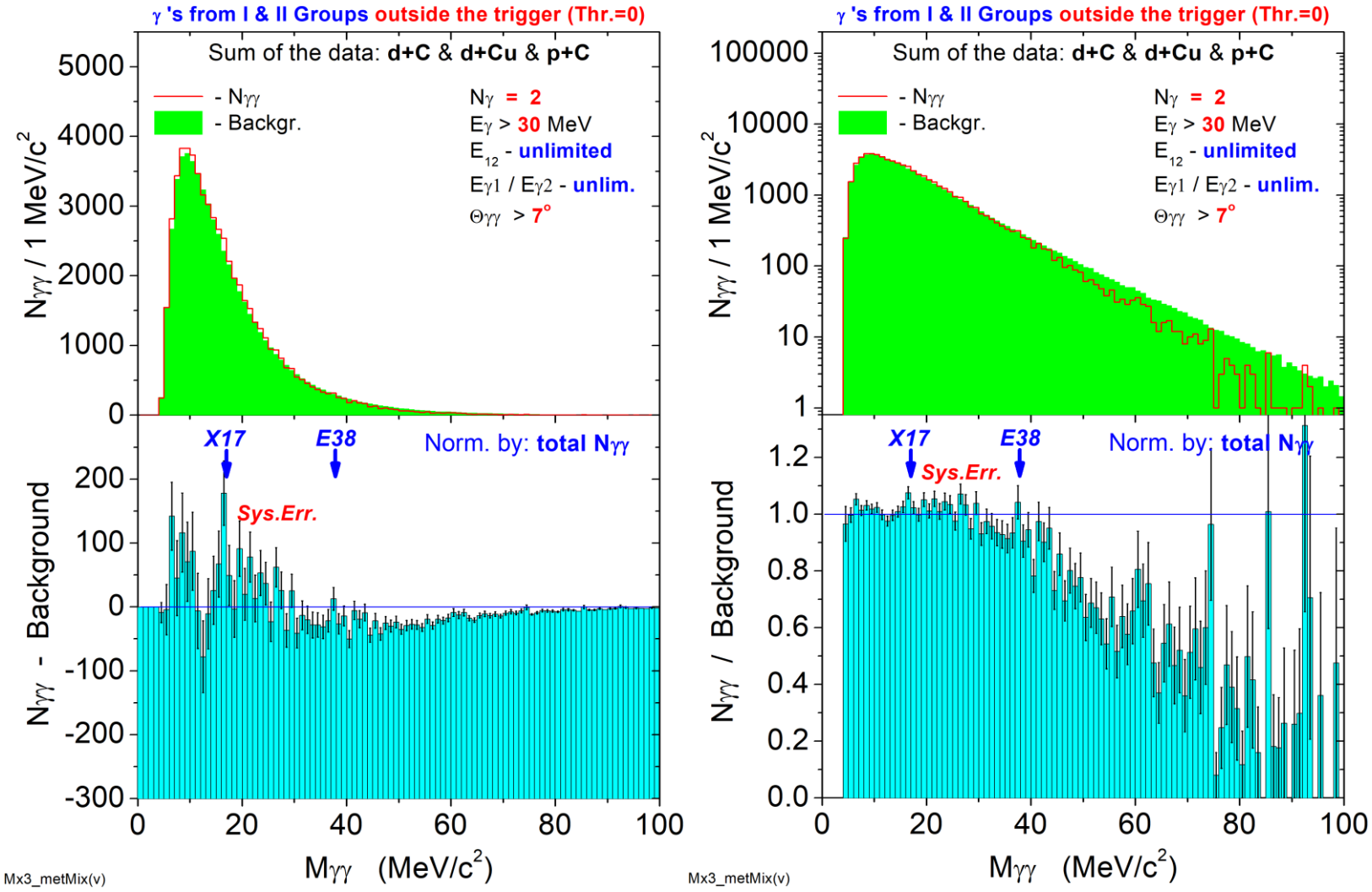


# Influence of the used criteria
# 2) No cuts + Θγγ > 7°



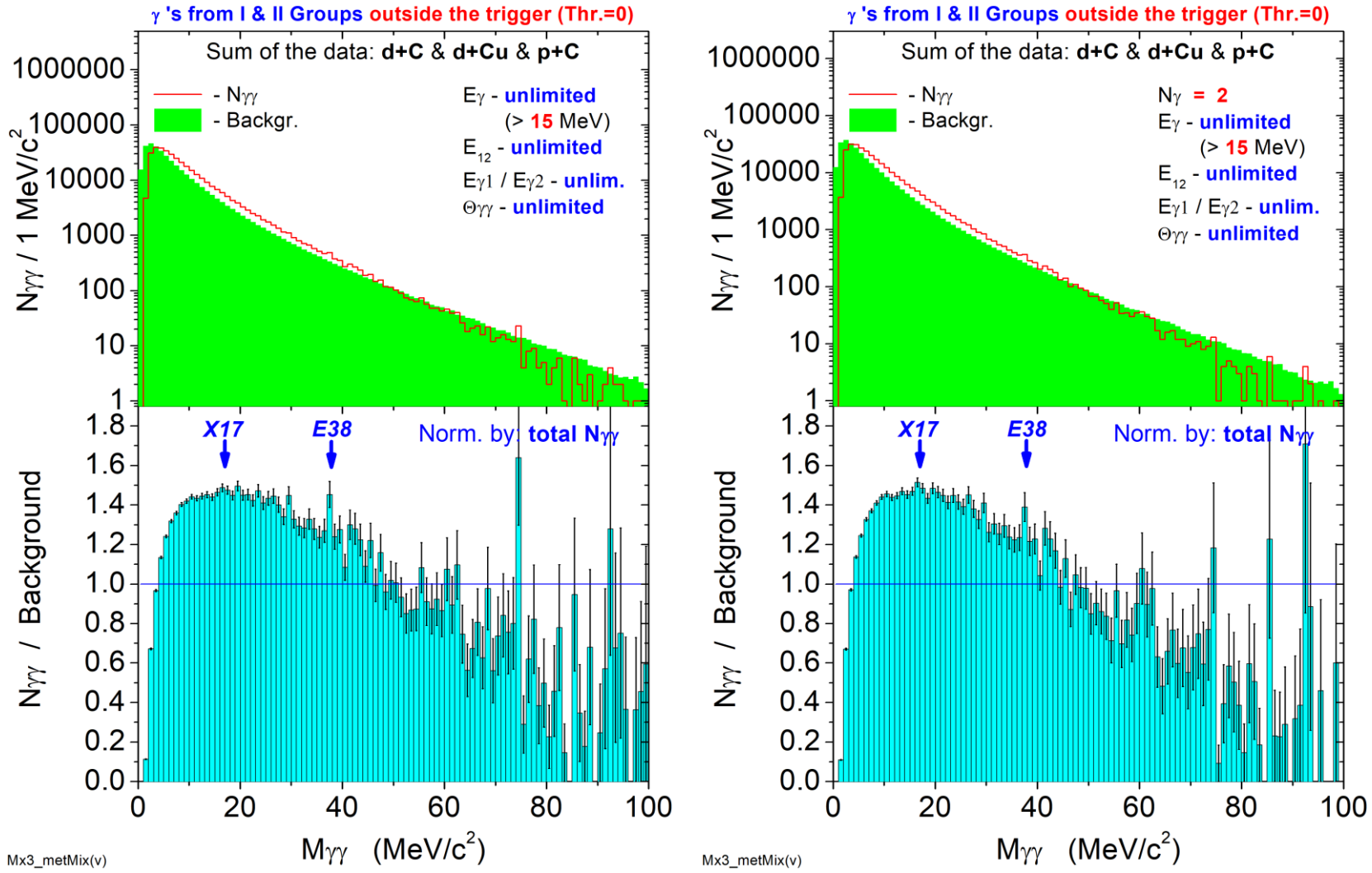

The *Nγγ* to the background ratio for photon pairs from from the Groups outside the trigger for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The backgrounds are normalized to the total pair numbers.

# Influence of the used criteria
# 3) No cuts + Θγγ > 7° + Eγ > 30 MeV



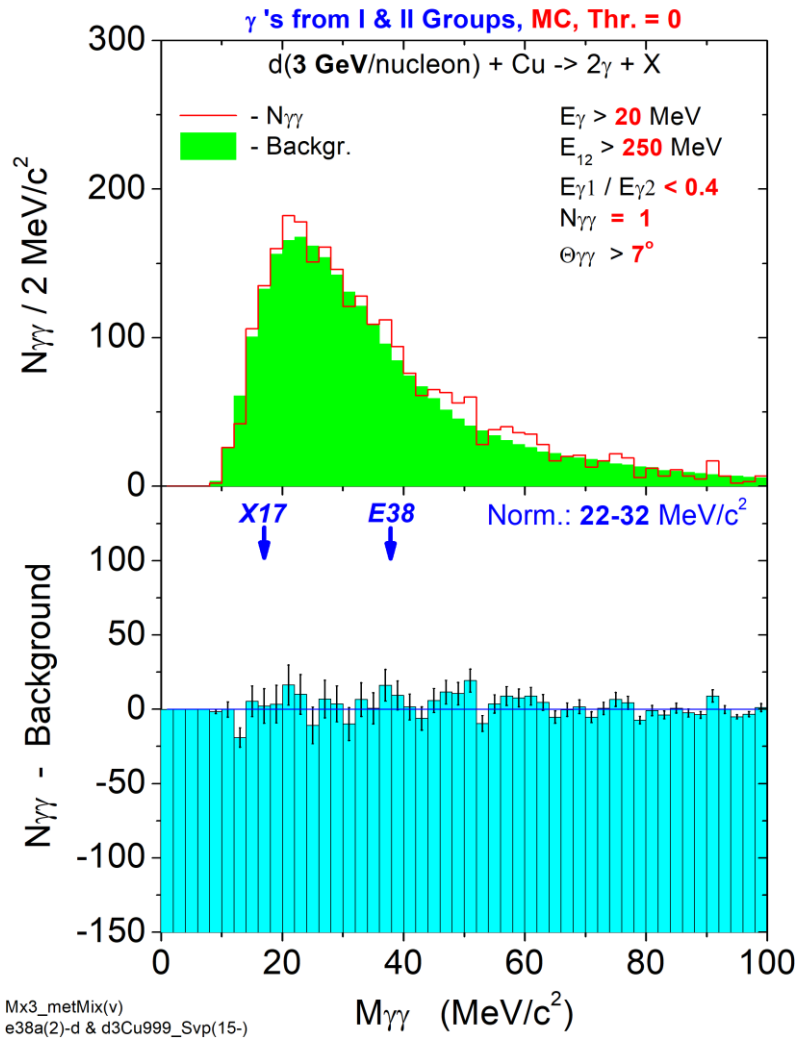

The *Nγγ* to the background ratio for photon pairs from from the Groups outside the trigger for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The backgrounds are normalized to the total pair numbers.

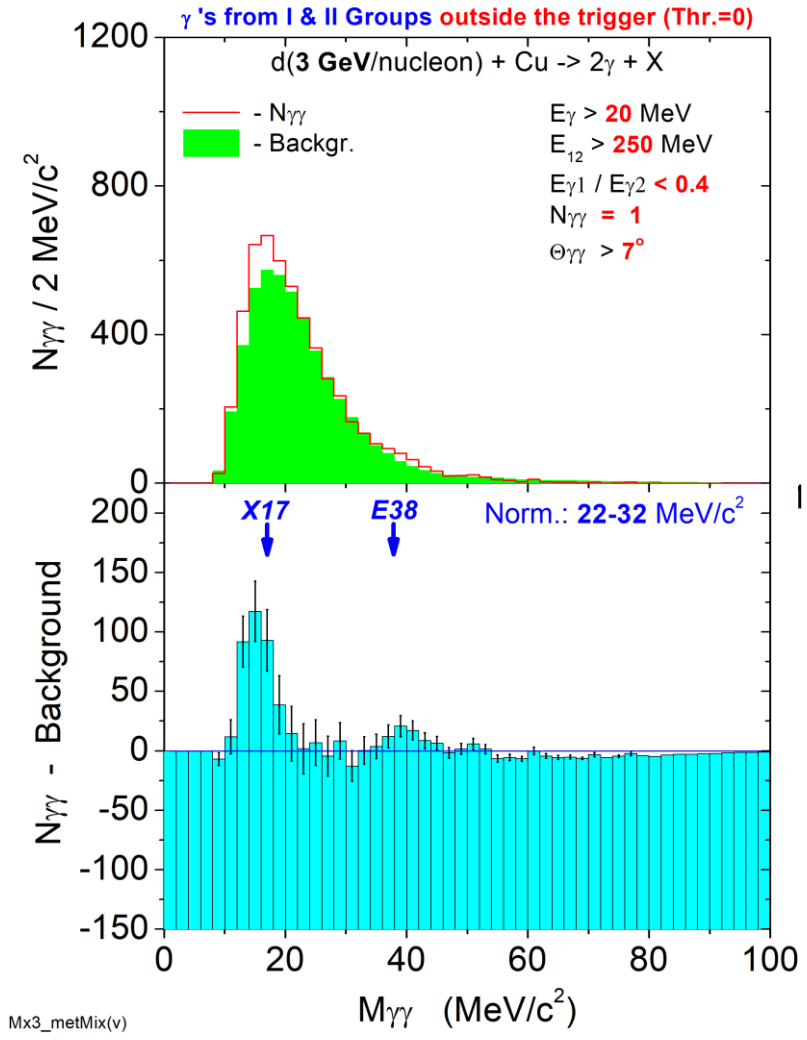
# Influence of the used criteria
# 1) No cuts

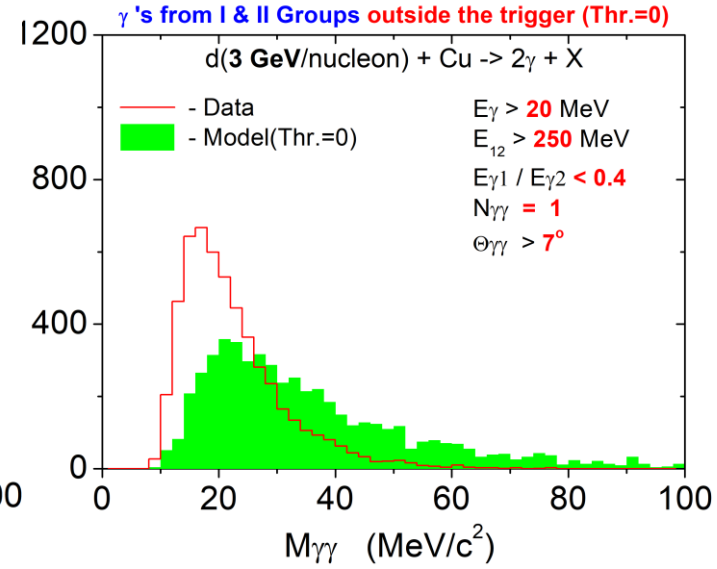



The *Nγγ* to the background ratio for photon pairs from the Groups outside the trigger for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The backgrounds are normalized to the total pair numbers.

# Estimates of systematic errors in the combinatorial background

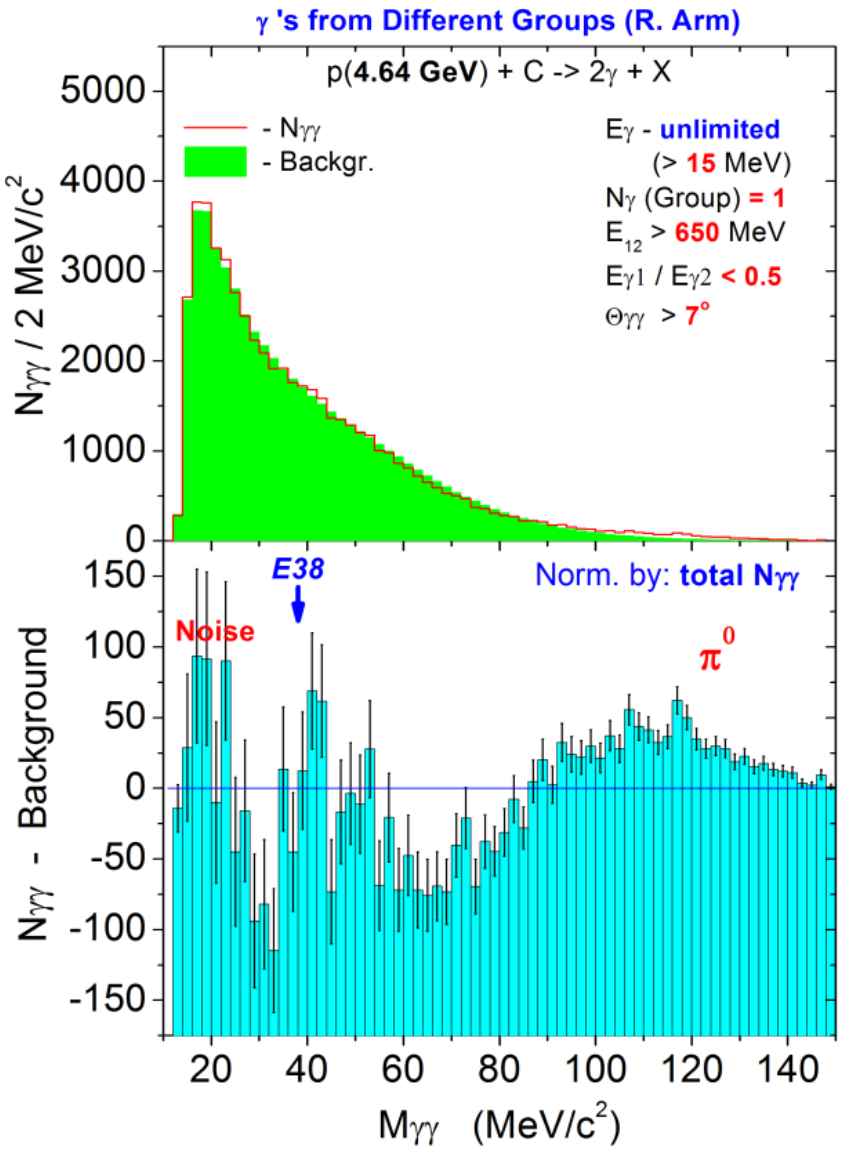


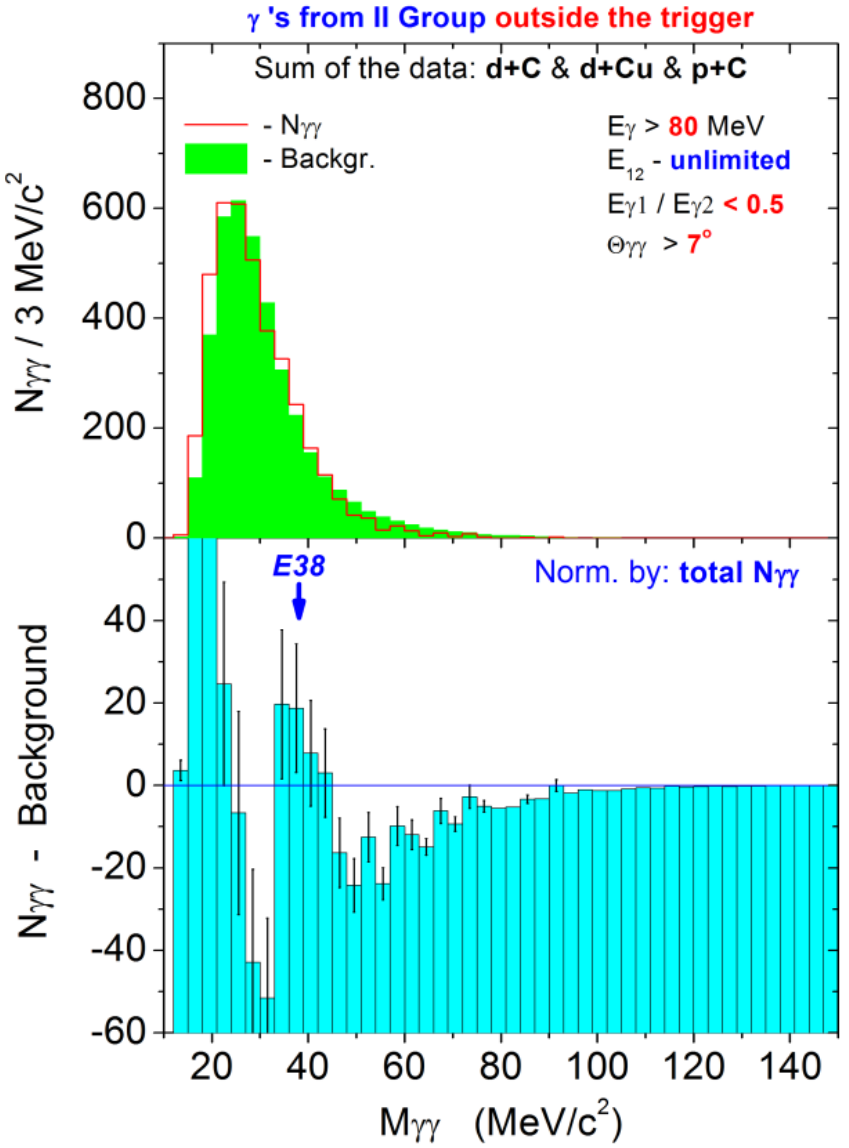




The results of processing the simulated data by the method which was applied to the experimental data (i.e., the difference of the combinatorial spectrum and the background obtained by the event mixing method. The selection criteria are in the pictures.

# Проверка структуры при инвариантной массе пар γ-квантов 38 МэВ/c². Новости.

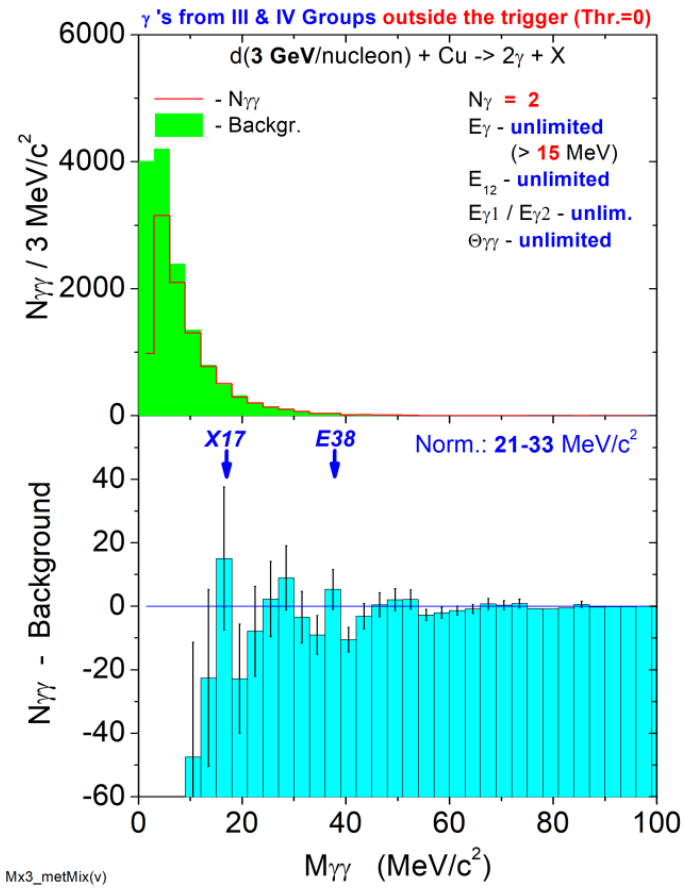


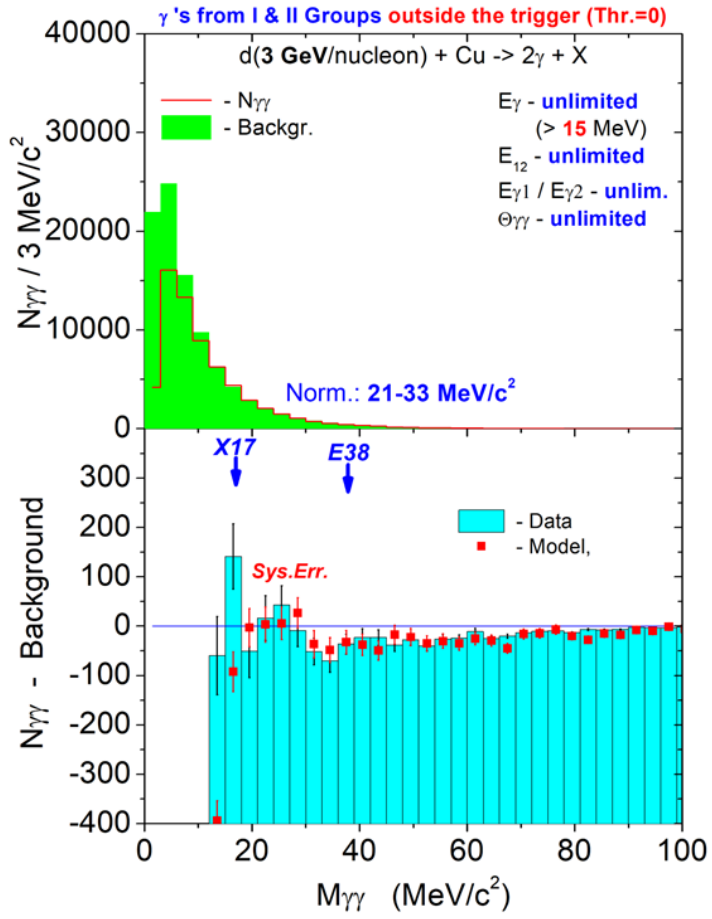

February 01, 2020



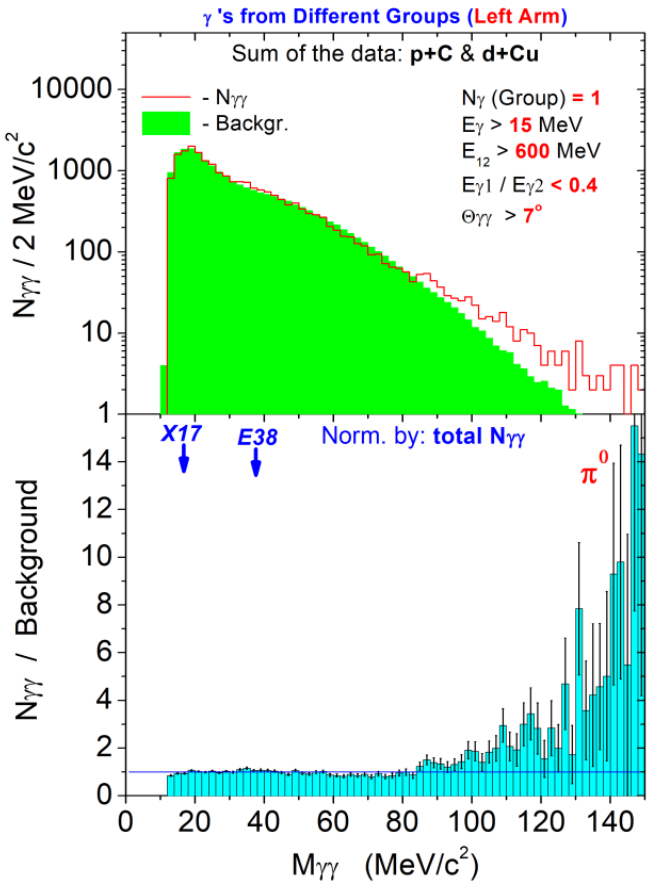

February 29, 2020

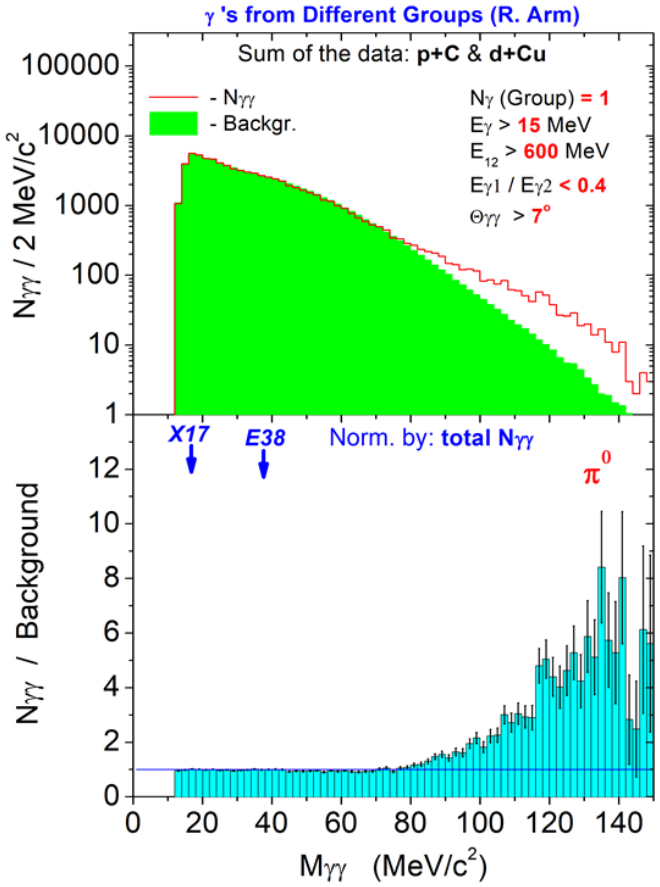
Invariant mass distributions of $\gamma\gamma$ pairs at the minimum selection conditions (no cuts), for the reaction $d$ + Cu → $\gamma$ + $\gamma$ + $x$ at 3.8 GeV/c per nucleon obtained in the **Left Arm** (left figure) and in the **Right Arm** (right figure). The backgrounds are normalized by the numbers of pairs in the range (21, 33) MeV/$c^2$.



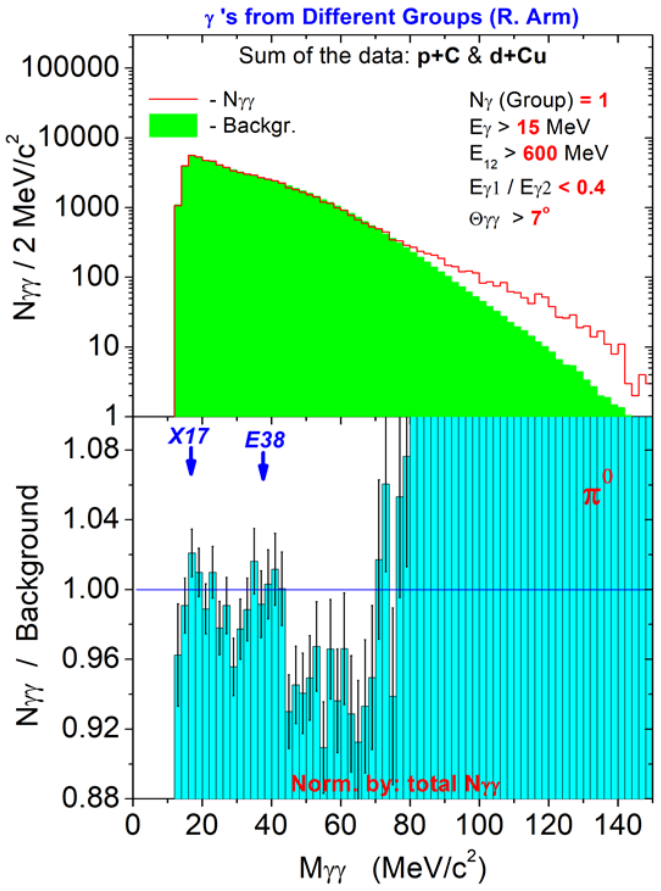



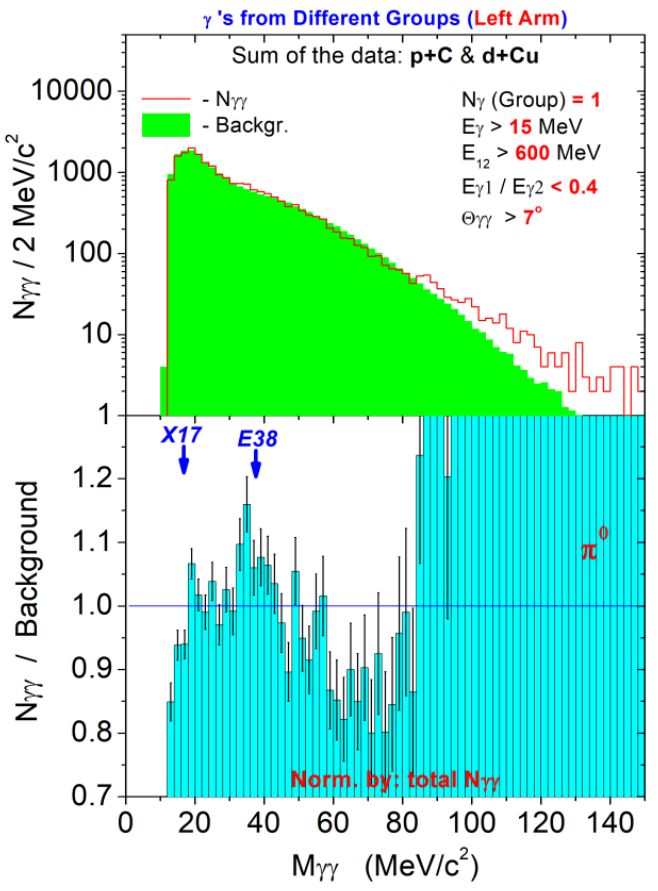
The *Nγγ* to the background ratio for photon pairs from different groups for the *d* + Cu and *p* + C reactions obtained in the **Left Arm** (left figure) and in the **Right Arm** (right figure).



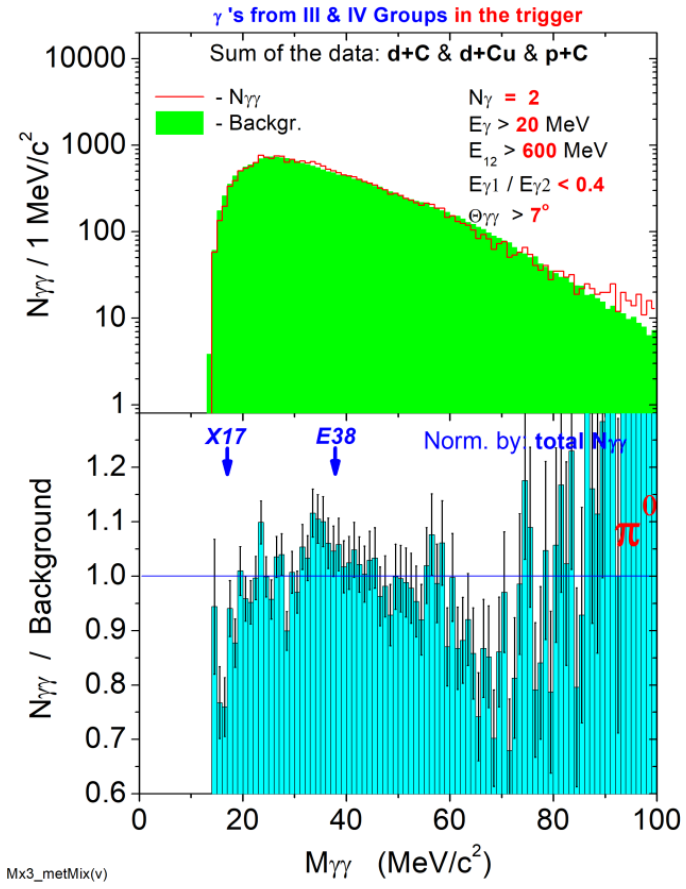



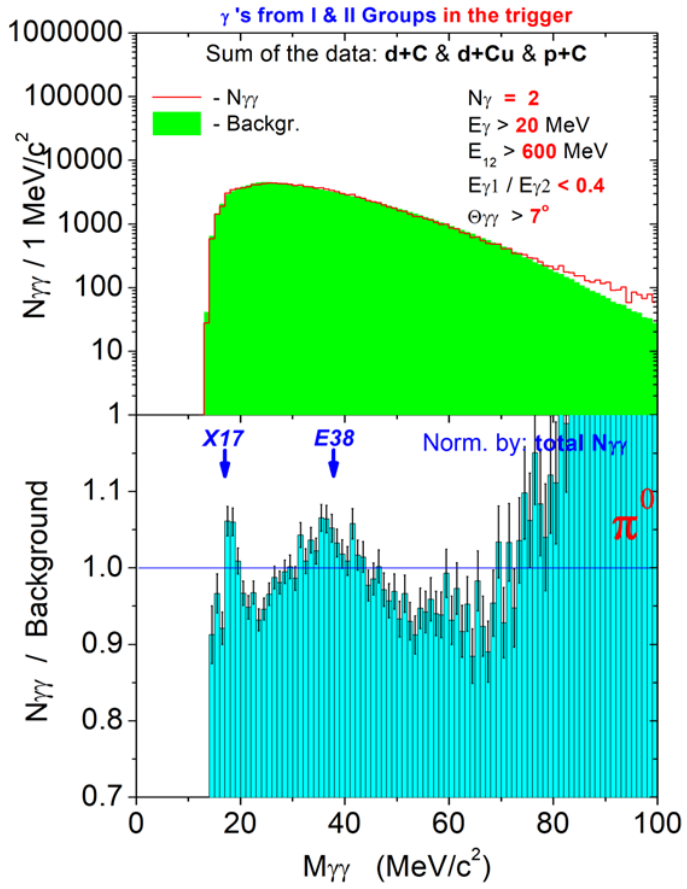
# The same as in the previous slide, but at another scale



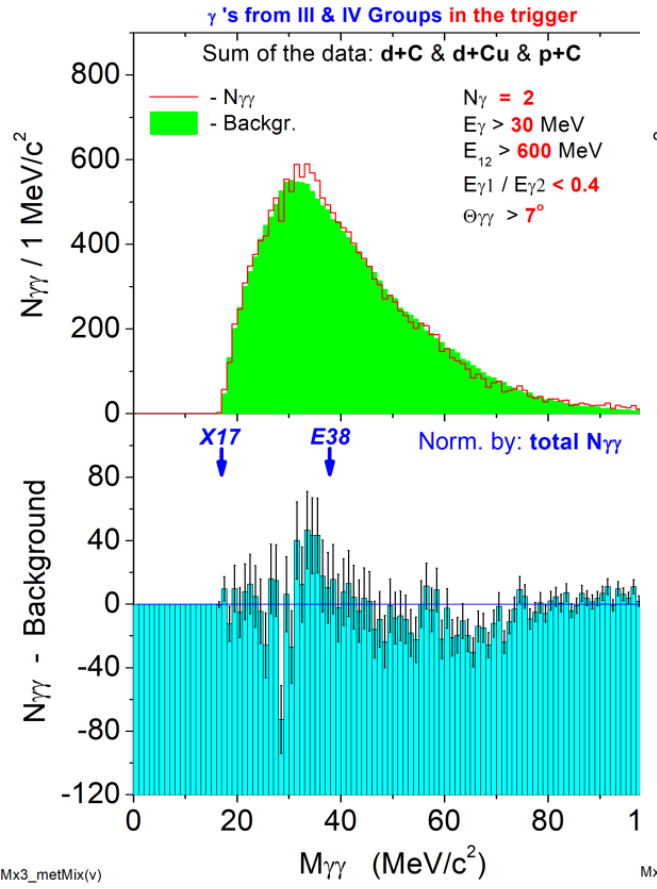



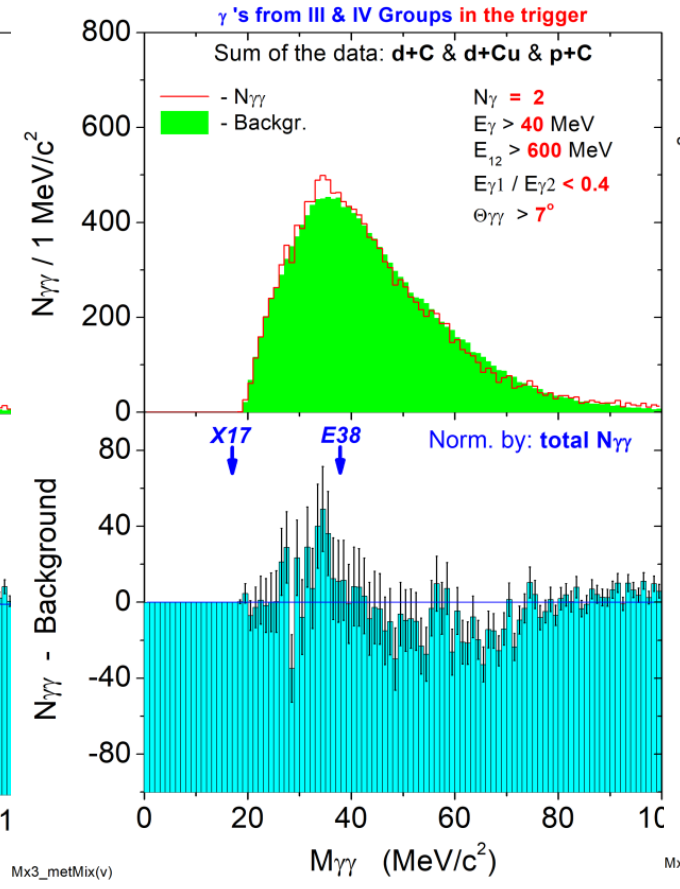
Invariant mass distributions of $\gamma\gamma$ pairs satisfying criteria (1)-(5) (*shown in the figure*) without (upper panels) and with (bottom panels) the background subtraction obtained for the *d*+C, *d*+Cu and *p* + C reactions obtained in the **Left Arm** (left figure) and in the **Right Arm** (right figure). The backgrounds are normalized to the total pair numbers in the spectra.

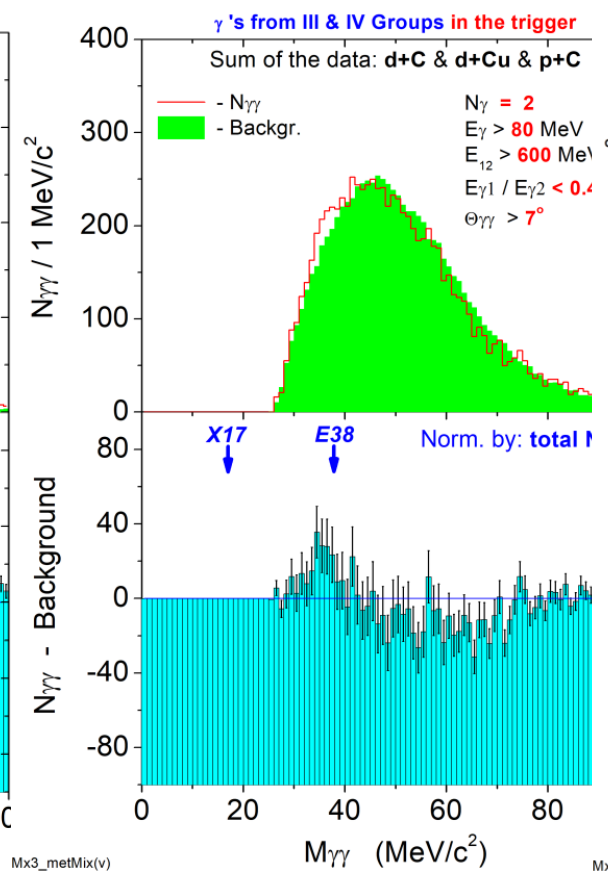


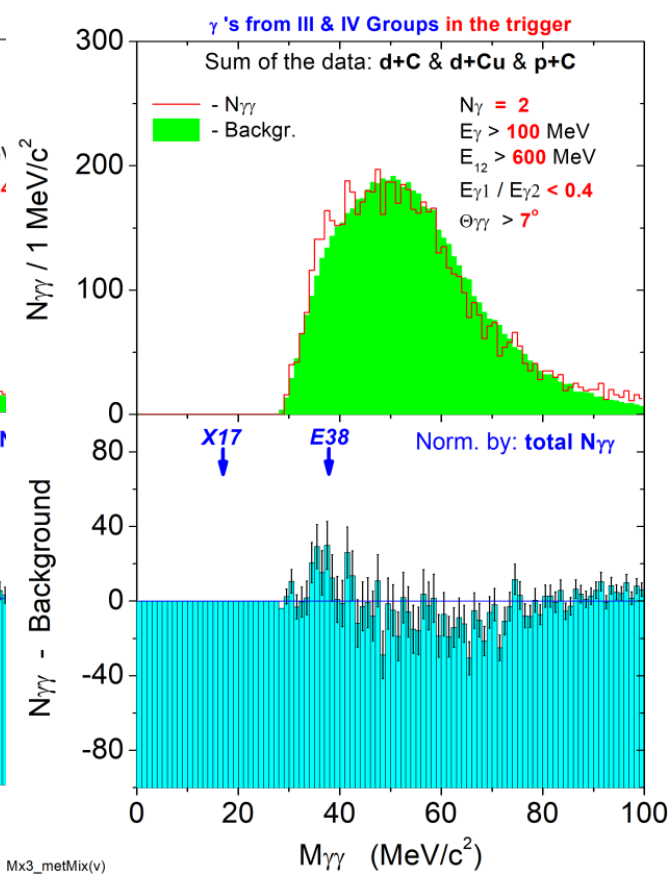



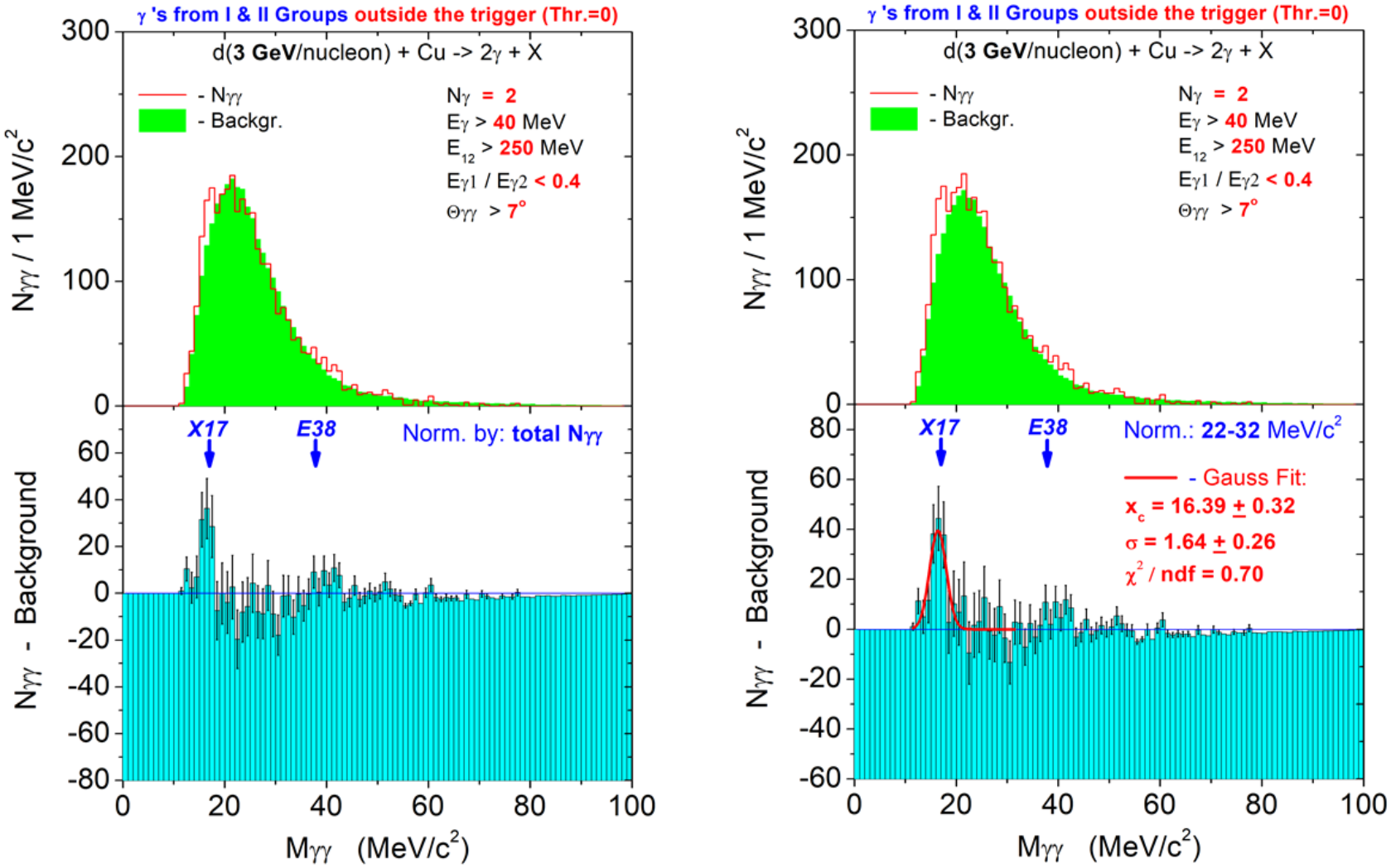
As can be seen from previous slide, the signal from X17, which is visible (as a relief) in the data obtained in the Right Arm is practically not visible in the data from the Left Arm (due to the low statistics): the signal "sinks" in statistical errors. With such a selection (data in triggering Groups subject to the threshold of the discriminators), a signal from E38 is visible. It is weak, "ragged", but withstands the stability test with a significant shift of the full spectrum (with background) (see Figures below).



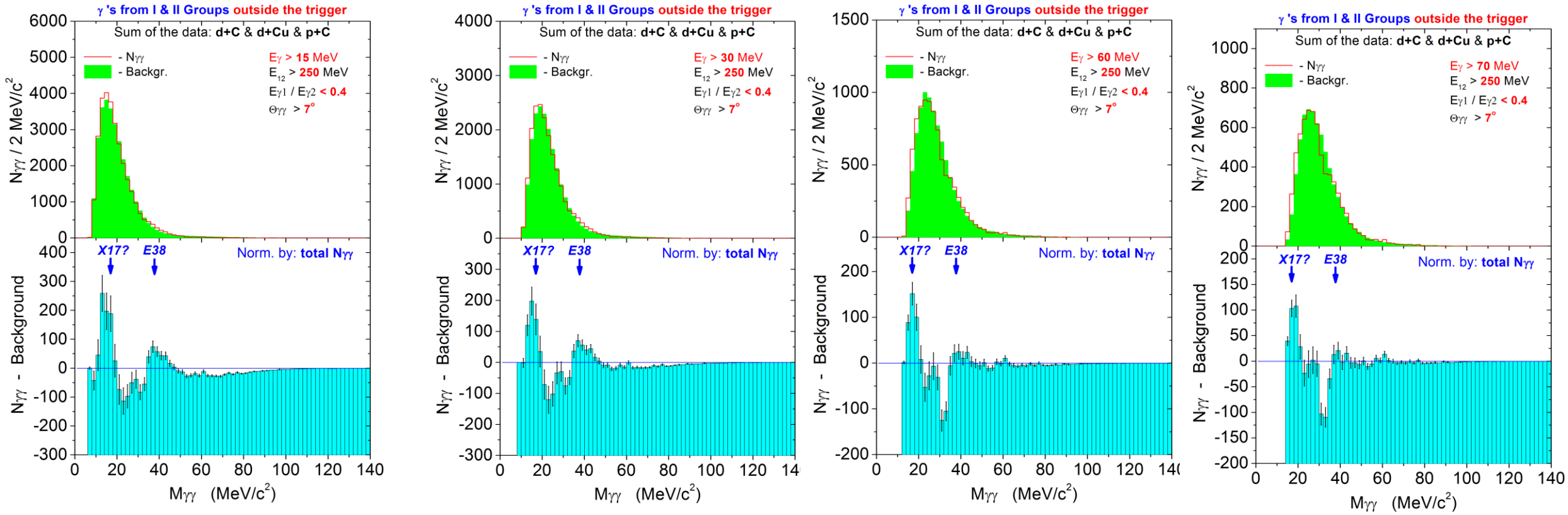





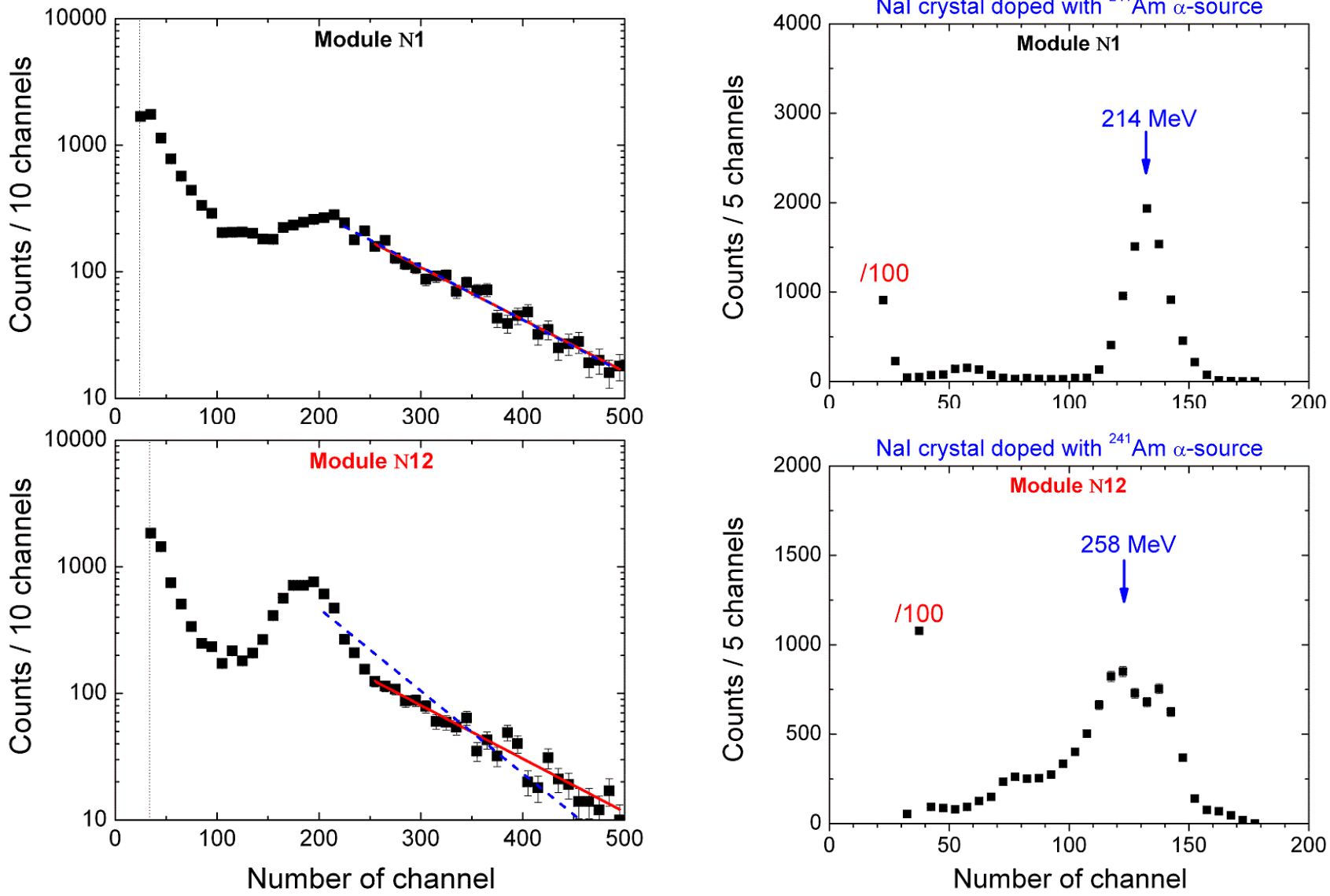

Распределения по эффективной массе пар γγ до (верхние панели) и после (нижние панели) вычитания фона, в группах, не участвовавших в запуске триггера. Фон нормирован по полному числу пар в спектре (левый рисунок) и по числу пар в области (22, 32) МэВ/с²

# Предварительные результаты поиска сигнала при инвариантной массе пар γ-квантов около 17 МэВ/c².



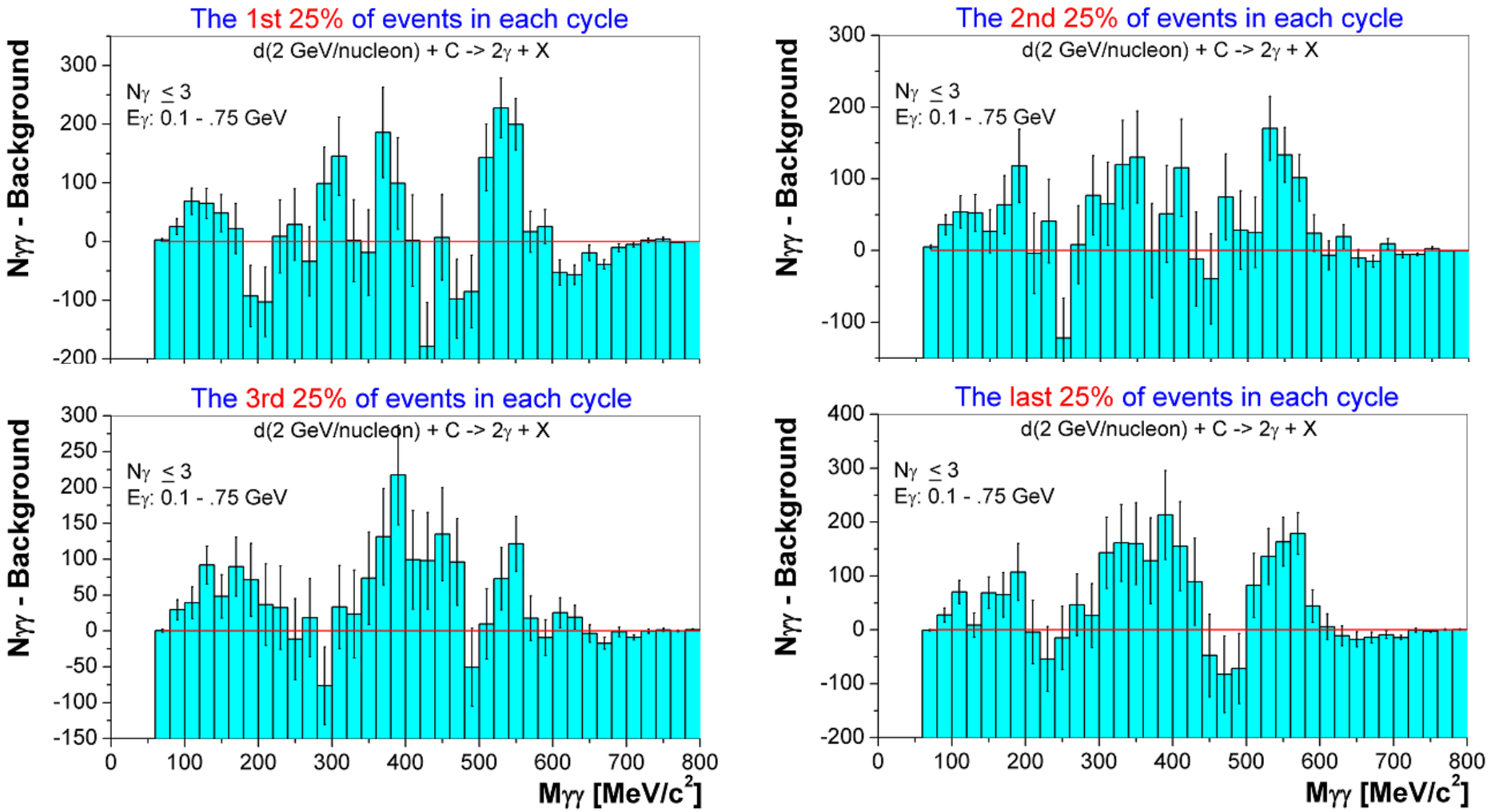

Invariant mass distributions of *γγ* pairs satisfying criteria (i)–(iii), for different minimal energies of photons, without (upper panels) and with (bottom panels) the background subtraction obtained for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The backgrounds are normalized to the total pair numbers.

Analysis of the operation of individual modules, after which some modules were excluded in order **to exclude deterioration in the amplitude resolution**: amplitude spectra (left) and spectra from the NaI crystals doped with $_{241}Am$ sources in separate modules in the *d(3.0 GeV/n)*+Cu experiment



# Проверка резонансной структуры при инвариантной массе пар γ-квантов и пар π°-мезонов около 360 МэВ/$c^2$.

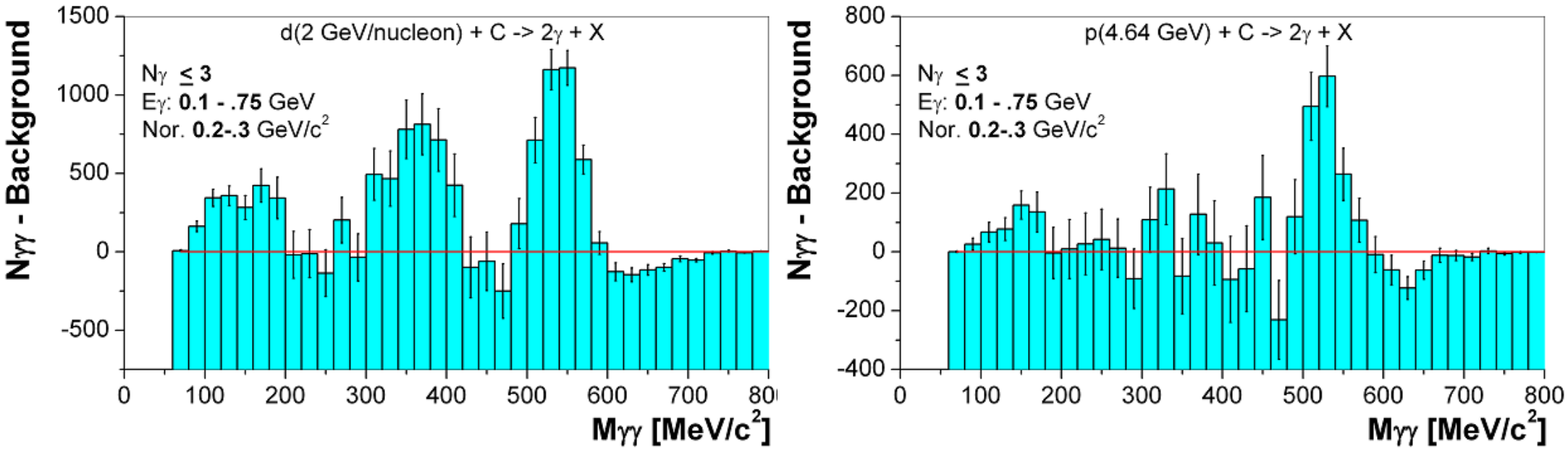
EPJ Web of Conferences **138**, 04006 (2017)




The invariant mass distributions of γγ pairs satisfying criteria (i)-(ii) (see Sl. 26) in the reactions *d*(2 *GeV*/*n*) + *C* → γ + γ + *X* after the background subtraction, in the events recorded in different intervals of accelerator cycle. The backgrounds are normalized to pair numbers in the interval: 200 < *M*γγ < 300 MeV/*c*.

# Проверка резонансной структуры при инвариантной массе пар γ-квантов и пар π°-мезонов около 360 МэВ/c².

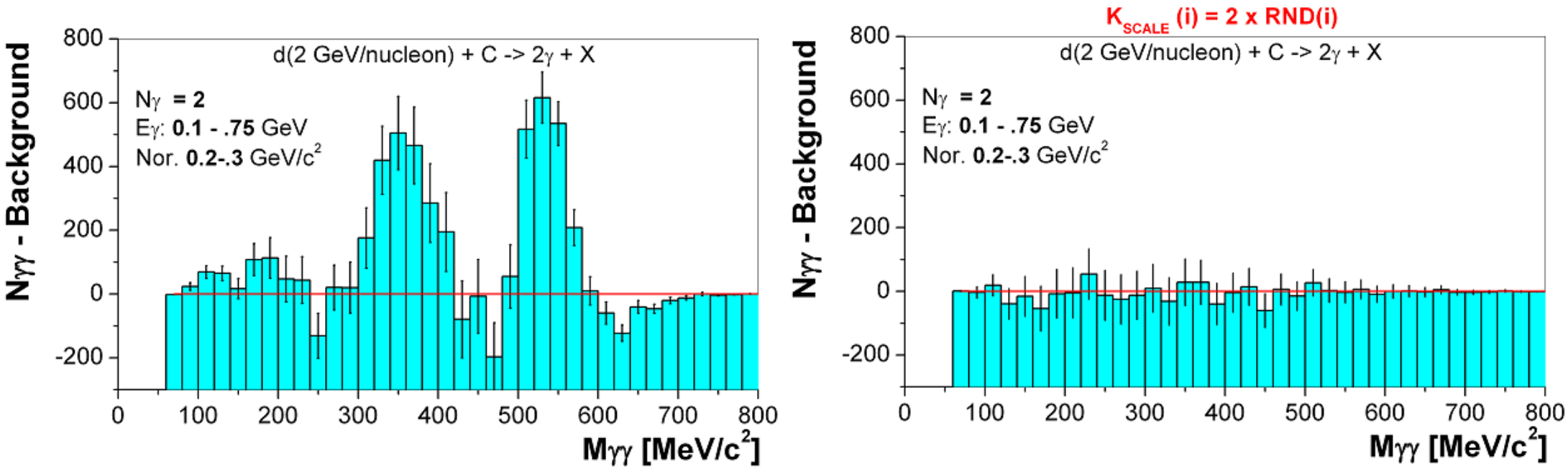
EPJ Web of Conferences **138**, 04006 (2017)




The invariant mass distributions (per 20 MeV/c²) of γγ pairs satisfying criteria:
(i) the number of photons in an event, *N*γ ≤ 3 (the events of each type (one of the photons in the left arm and two on the right, etc.) were analysed separately, the results were summarized);
(ii) the energies of photons, 100 < *E*γ < 750 MeV,
in the reactions d(2 GeV/n)+C → γ+γ+X (left figure) and p(4.6 GeV)+C → γ+γ+X (right figure) after the background subtraction. The backgrounds are normalized to pair numbers in the interval: 200 < Mγγ < 300 MeV/c².

# Проверка резонансной структуры при инвариантной массе пар γ-квантов и пар π°-мезонов около 360 МэВ/c².

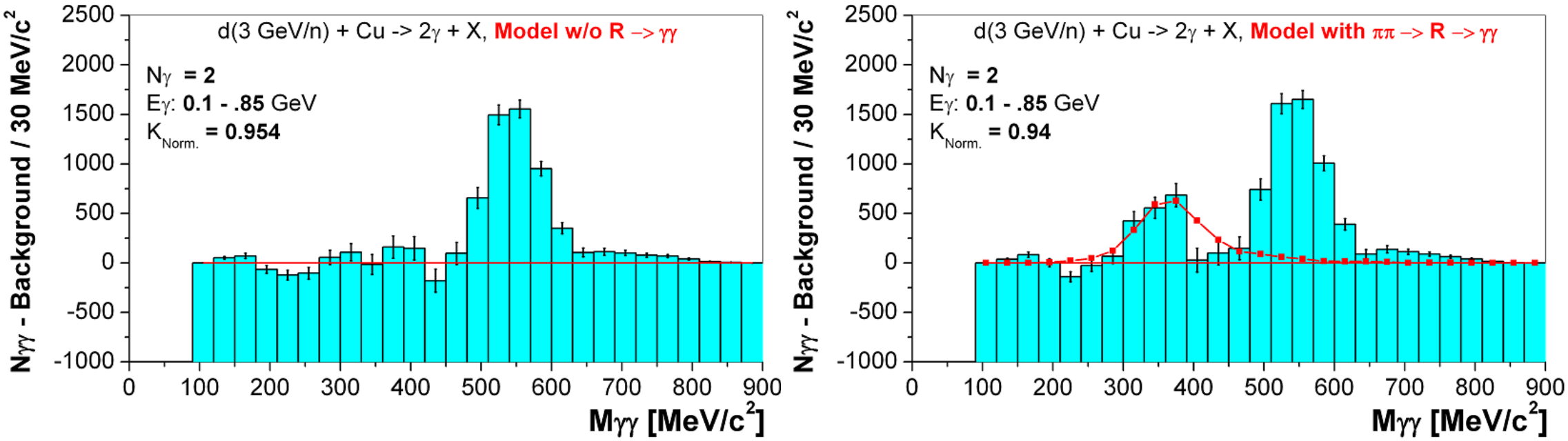
EPJ Web of Conferences **138**, 04006 (2017)




Invariant mass distributions (per 20 MeV/c²) of γγ pairs in the reactions d(2 GeV/n) + C → γ + γ + X after the background subtraction, at the number of photons in an event, Nγ = 2 and at the energies of photons, 100 < E γ < 750 MeV (left figure), and the same but after a "miscalibration" of the modules by the introduction of chaotic coefficients in the range 0÷2: Ei → Ei ·2·RND(i), (where Ei is the energy in the i-th module, RND(i) are random numbers) (right figure). Here, the average of results obtained after the introduction of 6 different sets of random numbers is shown. The backgrounds are normalized to pair numbers in the interval: 200 < Mγγ < 300 MeV/c².

# Проверка резонансной структуры при инвариантной массе пар γ-квантов и пар π°-мезонов около 360 МэВ/с².

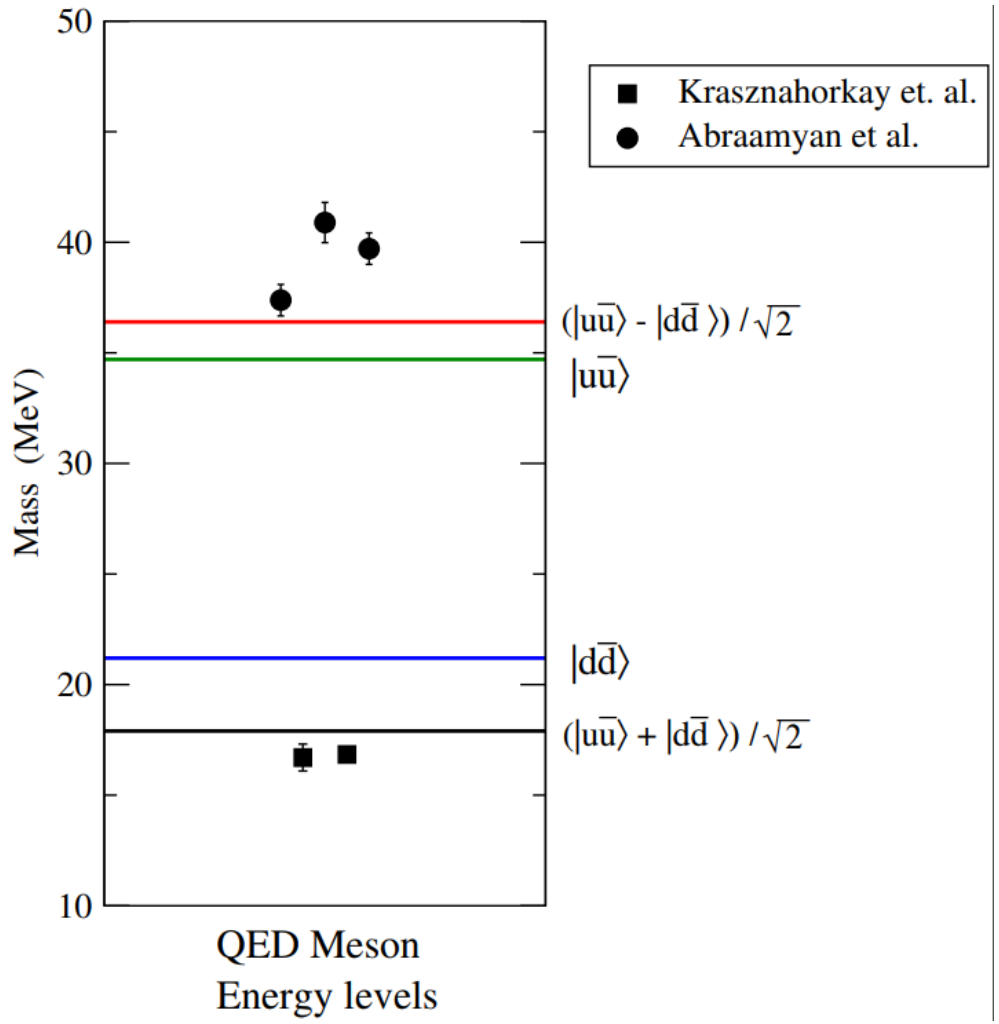
EPJ Web of Conferences **138**, 04006 (2017)



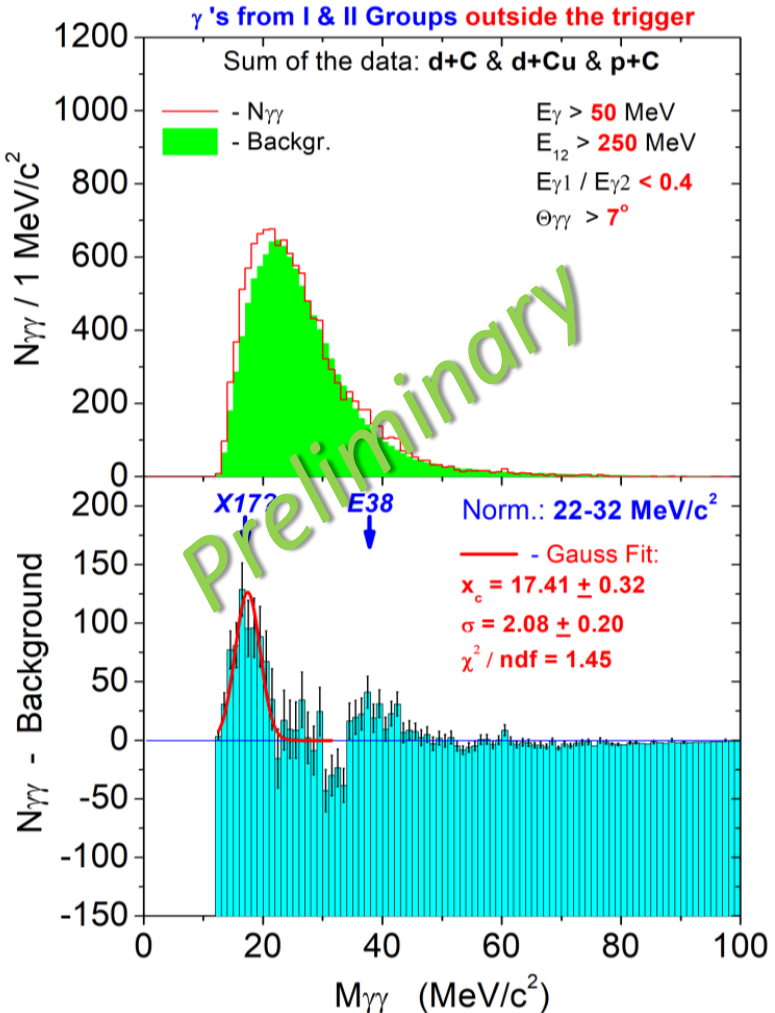

Invariant mass distributions of γγ pairs from the *d*(3 *GeV*/*n*)+Cu reaction after the background subtraction, at the number of photons in an event, *N*γ = 2 and at the energies of photons, 100 < *E*γ < 850 MeV, without (left figure) and with the reaction π + π → *R* → γ + γ (right figure), under the real experimental conditions. The spectra are the result of processing the simulated data with the method which was applied to the experimental data. The contribution of photon pairs from the resonance decay (selected with the help of labels of photons applied in the model) is shown by the solid line. The auxiliary factors *KNorm* of the backgrounds normalization (see below) are given in the figures.

**Cheuk-Yin Wong <wongcyor@gmail.com>**
31.12.2020 20:17

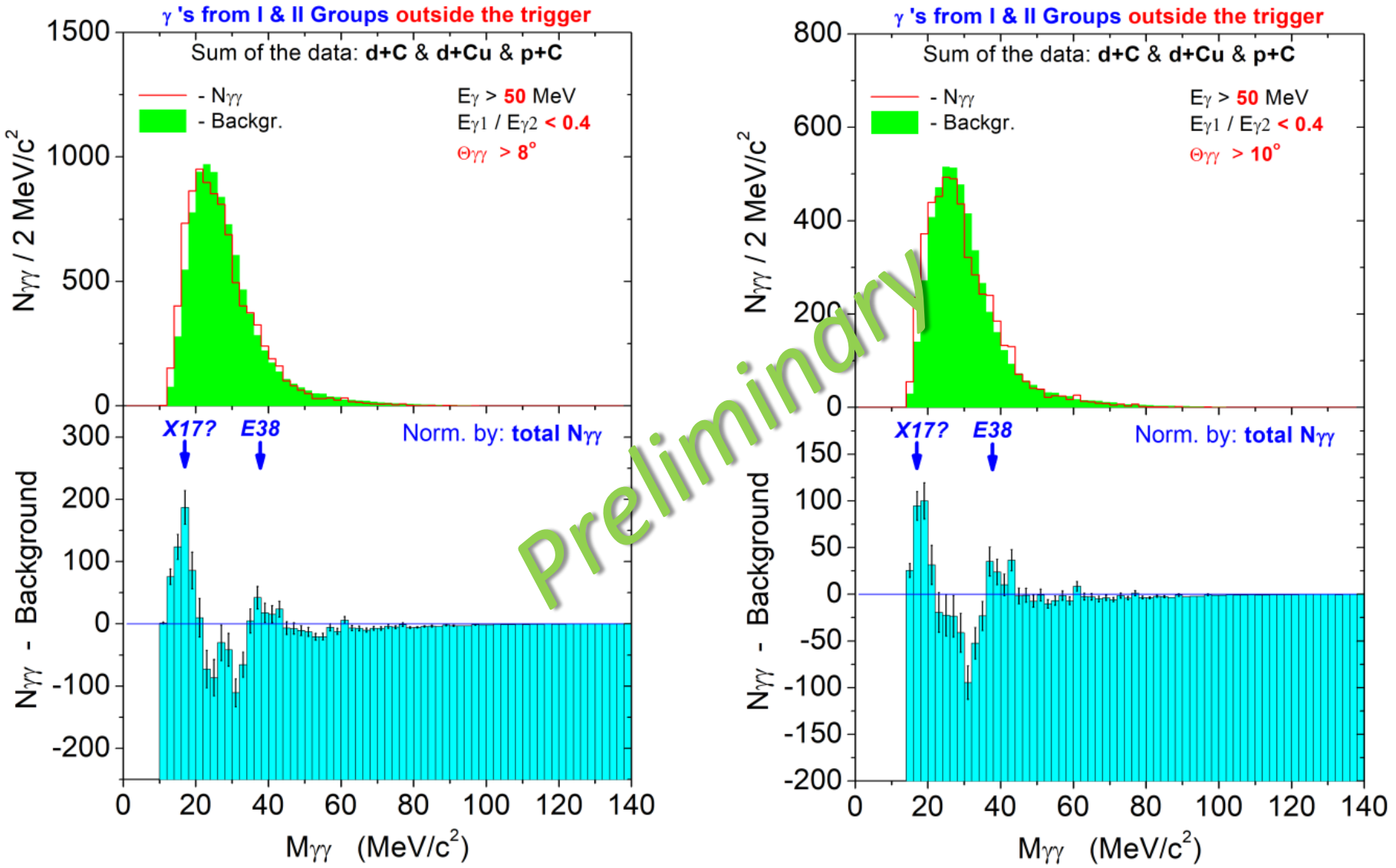
Кому: abraamyan Копия: Alexander Sorin; David Blaschke



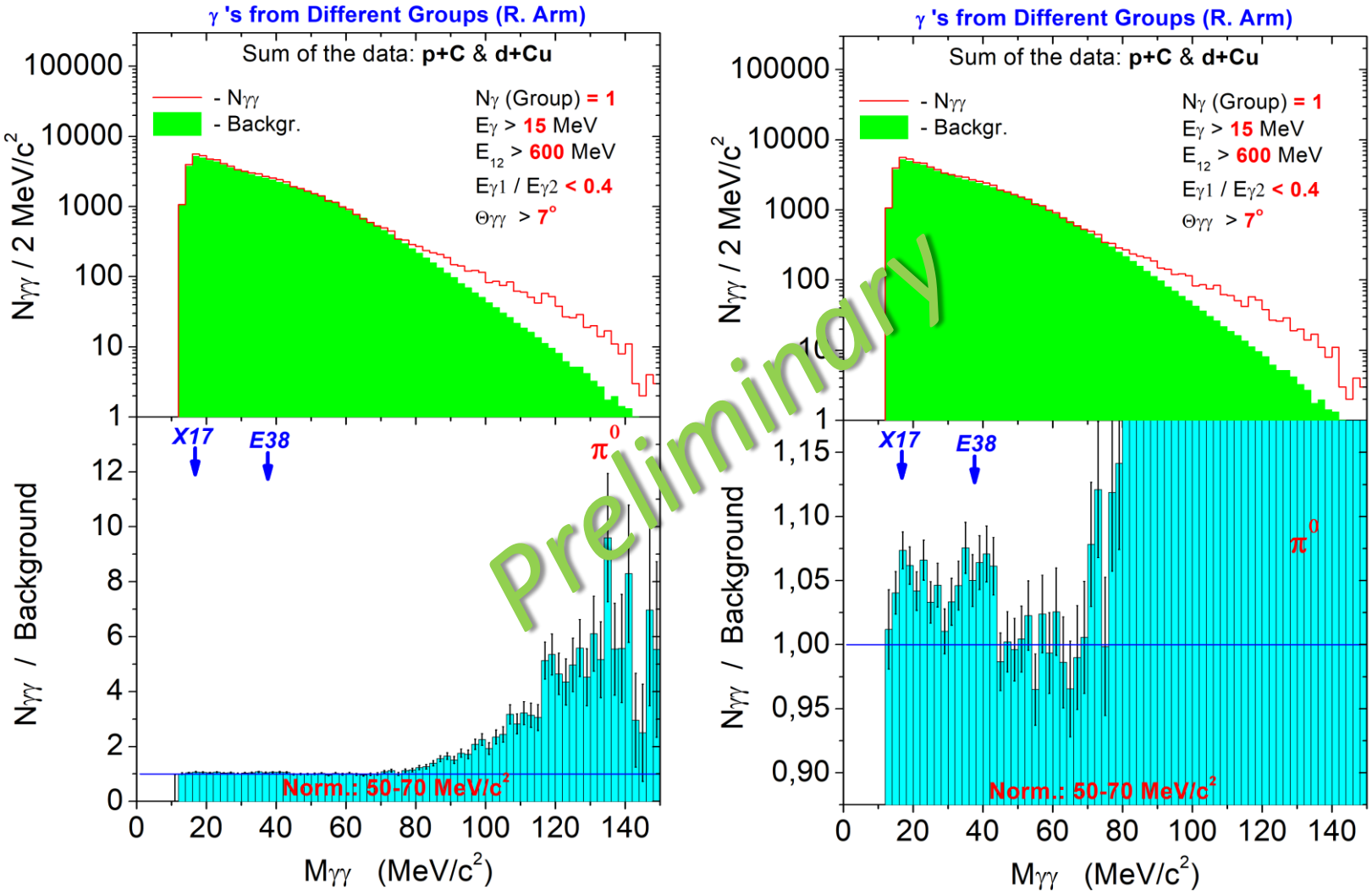
Invariant mass distributions of *γγ* pairs satisfying criteria (i)–(iii), at the energies of photons, Eγ > 50 MeV, without (upper panel) and with (bottom panel) the background subtraction obtained for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The background is normalized to pair numbers in the interval: 22 < Mγγ < 32 MeV/c2. The curve is the Gaussian approximation of experimental points in the interval 12 ÷ 32 MeV/c2. The main parameters of the Gaussian are shown in the figure. Normalization factor of the Gaussian (total number of pairs after the background subtraction), A=659.4 ± 79.8.



**Different levels of selection for the opening angles of γγ pairs**



Invariant mass distributions of *γγ* pairs satisfying criteria (i)–(iii), at the energies of photons, Eγ > 50 MeV, without (upper panel) and with (bottom panel) the background subtraction obtained for the reactions *d*(2.0 GeV/n)+C, *d*(3.0 GeV/n)+Cu and *p*(4.64 GeV)+C. The background is normalized to pair numbers in the interval: 22 < Mγγ < 32 MeV/c$^2$.



# Required statistics

$$n_\sigma = \frac{N_R}{\Delta N_R} > 3.$$

$$\Delta N_R = \sqrt{N_{\gamma\gamma}} \Rightarrow N_{\gamma\gamma} = n_\sigma^2 / \tau^2,$$

*where* $\tau = N_R / N_{\gamma\gamma}$ ($\approx$ the signal - to - background ratio).

The statistics necessary for reliable extraction of the signal ($n_\sigma \geq 5$),

$$N_{\gamma\gamma} \geq 25/\tau^2 \quad (\textit{at least}, N_{\gamma\gamma} > 10/\tau^2). \qquad \textbf{(1)}$$

# The luminosity of the internal deuteron beam with a momentum of 2.75 GeV/c per nucleon

The luminosity was estimated using the following formula:

$$L = \frac{N_{Inter./\sec}}{\sigma(d+C)}$$

where

$$N_{Inter./\sec} \approx \frac{1}{6} \cdot 10^9 \text{ int } ./\sec$$

is the number of interactions per second,

$$\sigma(d+C) \approx 500\ mb$$

is the cross section of *dC*-interactions.

As a result, the luminosity can be estimated as:

$$L \approx 3 \cdot 10^{32}\ cm^{-2} \cdot s^{-1}.$$

# Проверка резонансной структуры при инвариантной массе пар γ-квантов и пар $\pi^o$-мезонов около 360 МэВ/$c^2$.

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**Different parts of the collected statistics**

The purpose of this analysis is to show different appearances of the signal at low (for a given signal-to-background ratio) statistics. In particular, this allows to explain the lack of appearance of the signal in other experiments (TAPS, WA80 ) and make predictions for possible appearances of the signal in upcoming experiments.
To create conditions, in terms of statistics similar to those of the experiment on TAPS (see also our analysis of this experiment in [Phys. Rev. C **80**, 034001 (2009)]), we divided the statistics recorded in the reaction d(2.0 GeV/n)+C into 19 parts. Each part was analysed separately, under the conditions shown in Sl. 27. The spectrum in Sl. 27 contains a total of 189864 selected ($N\gamma = 2$) events. The number of pairs after the background subtraction in the range of 300-420 MeV/$c^2$ (in the vicinity of the resonance mass), is 2386 ± 280. Thus, the expected average number of pairs after the background subtraction in the above indicated range, for the each part is 126 ± 64, i.e. 2 standard deviations. In our experiment, each of these spectra is a result of ~ $10^{11}$ d(2.0 GeV/n)+C interactions. Some results of this analysis are shown below.

# Проверка резонансной структуры при инвариантной массе пар γ-квантов и пар π°-мезонов около 360 МэВ/c².

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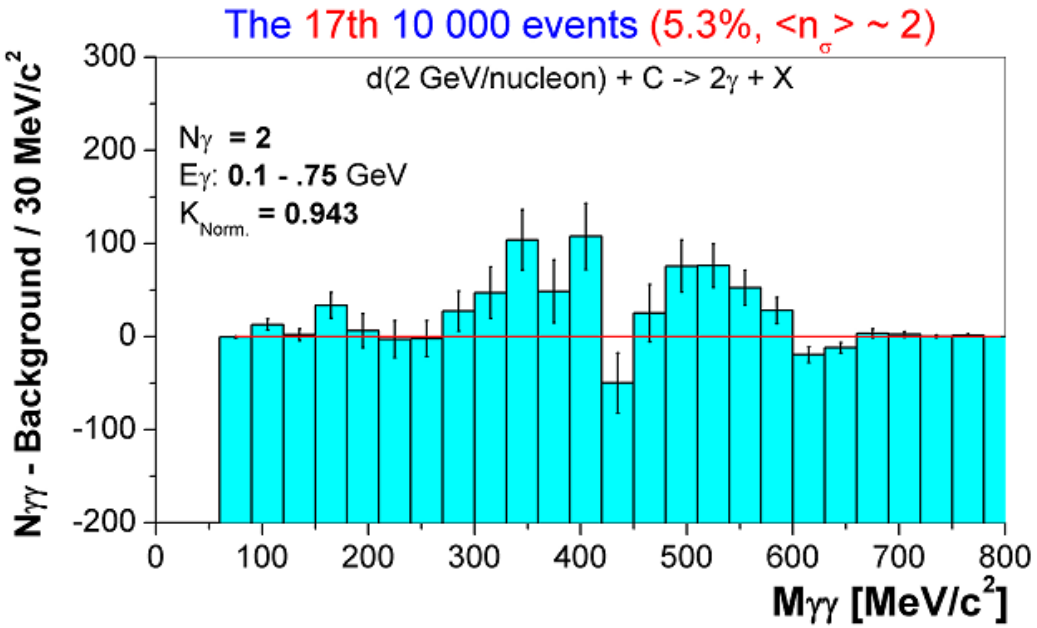
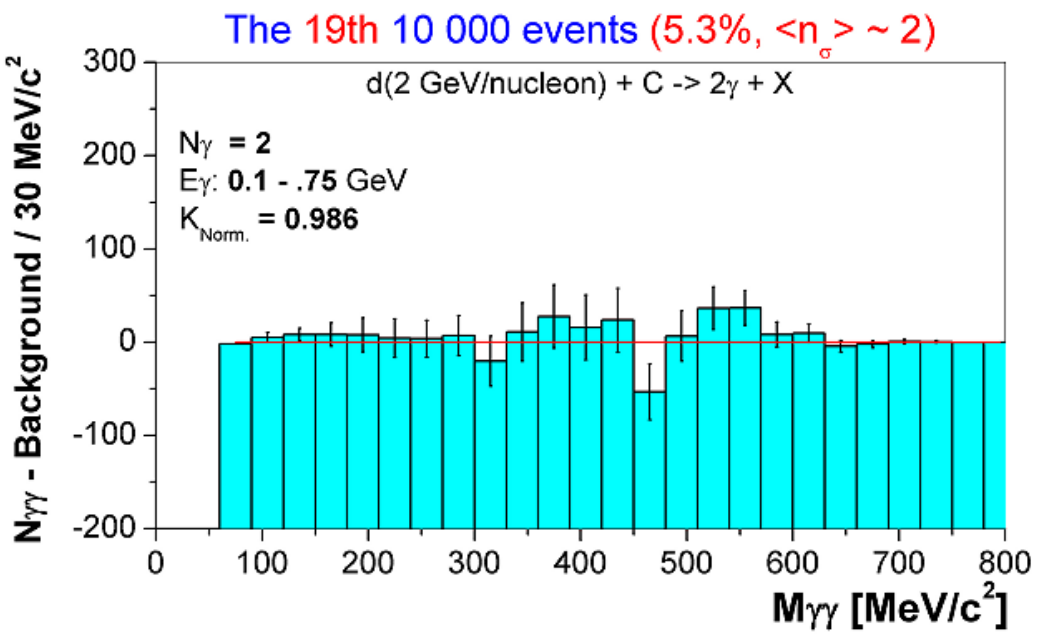
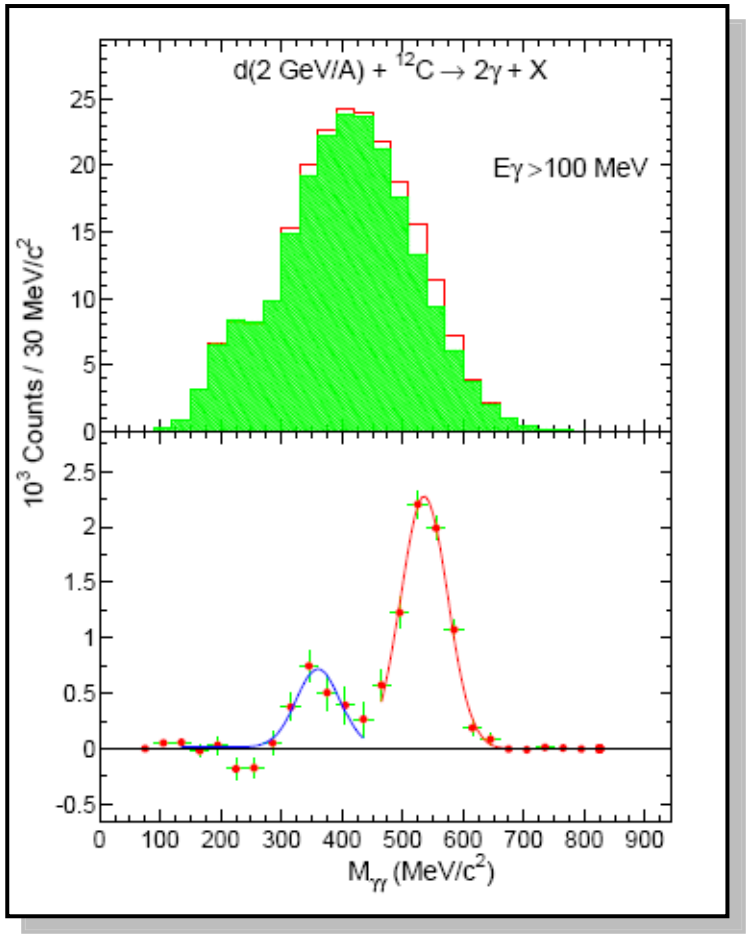
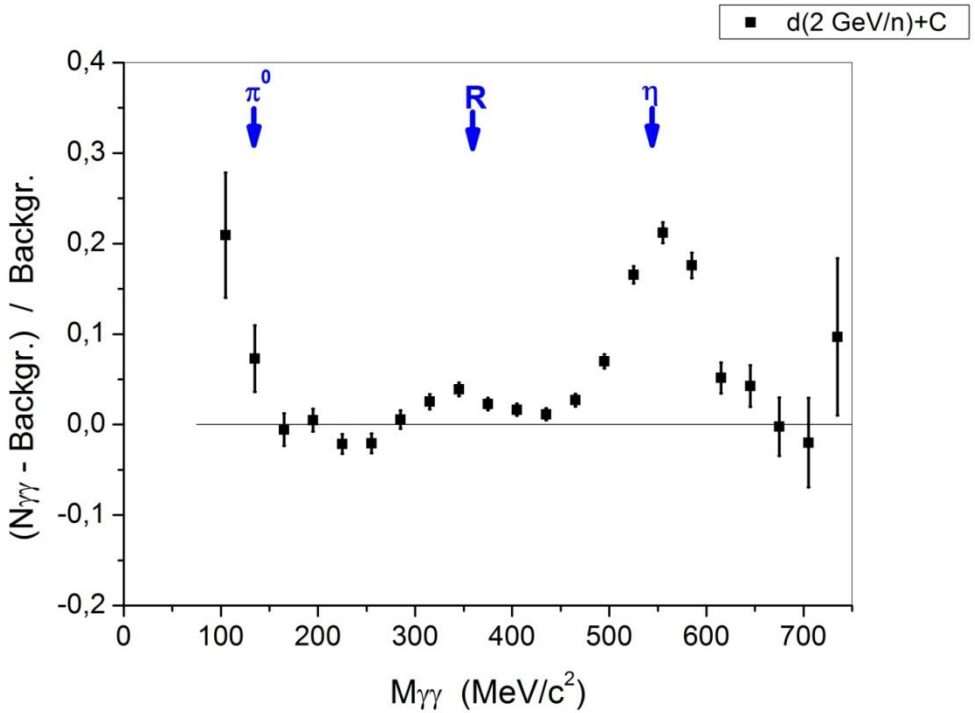


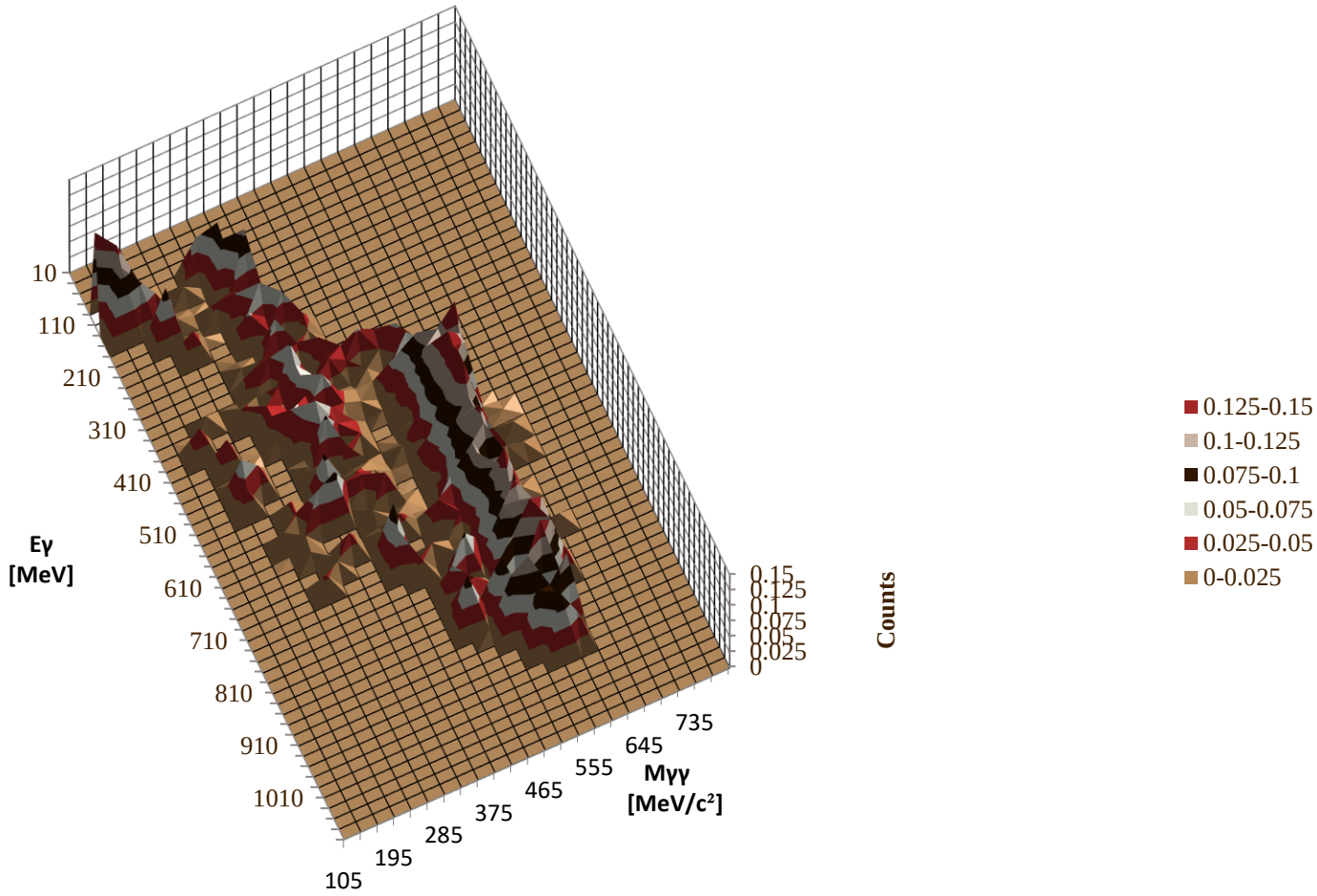

Invariant mass distributions of γγ pairs in the reaction *d*(2 *GeV*/*n*) + *C* → γ + γ + *X* after the background subtraction, under the same conditions as in figure 3, for different parts of the statistics collected in this experiment. The auxiliary normalization factors *KNorm* are given in the figures.

# From checks of the enhancement (signal from $\pi^0$)

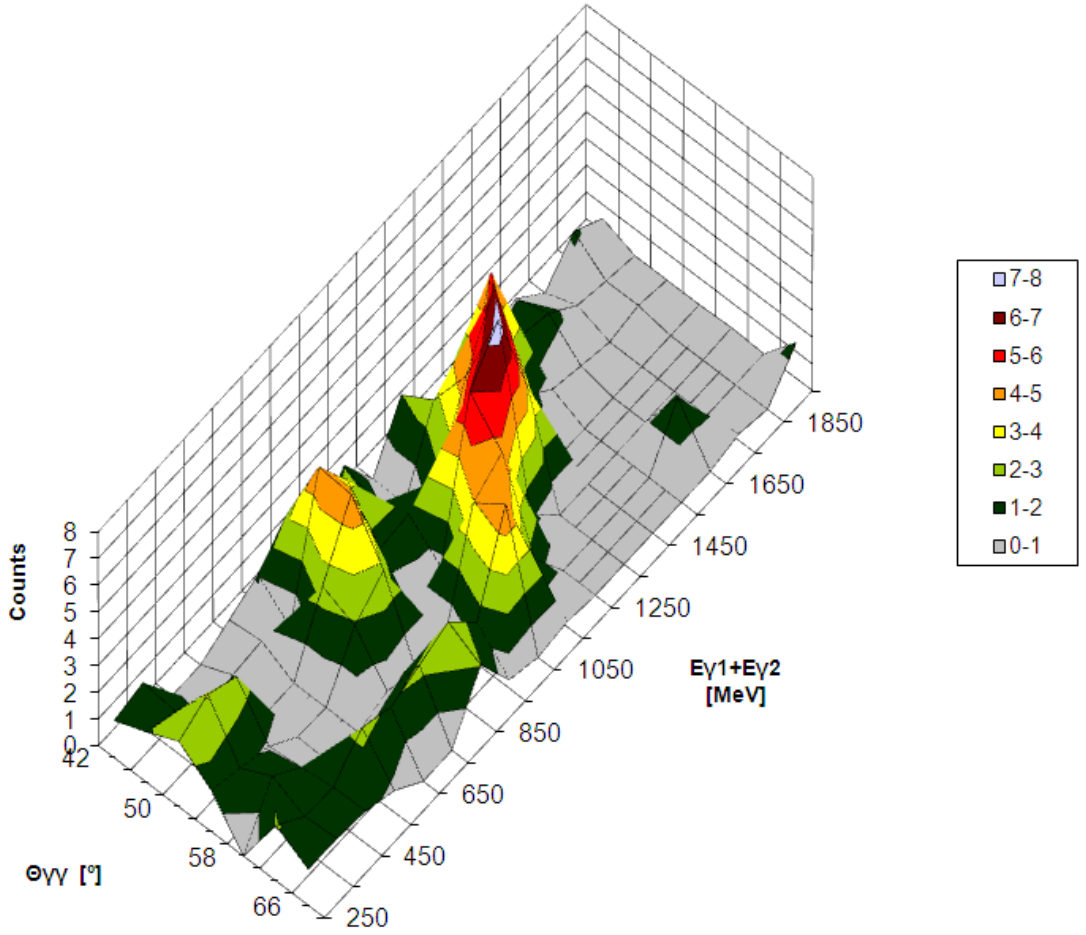


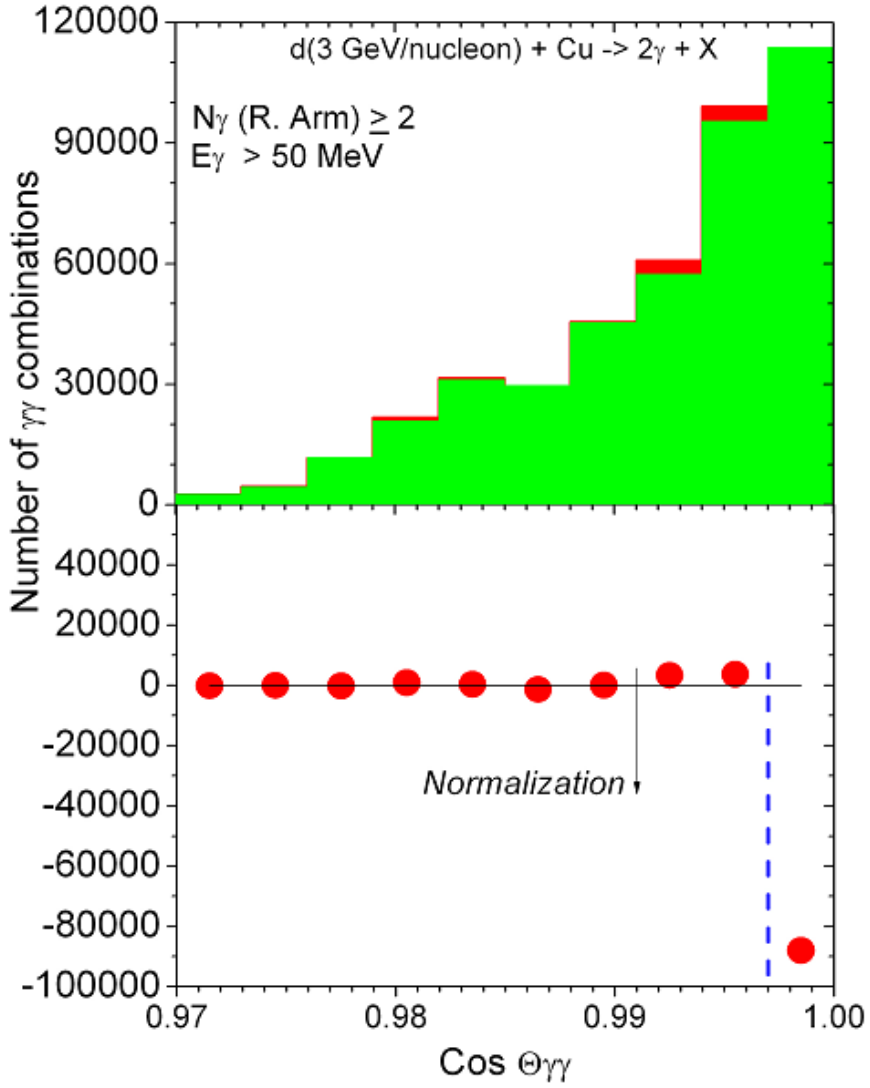



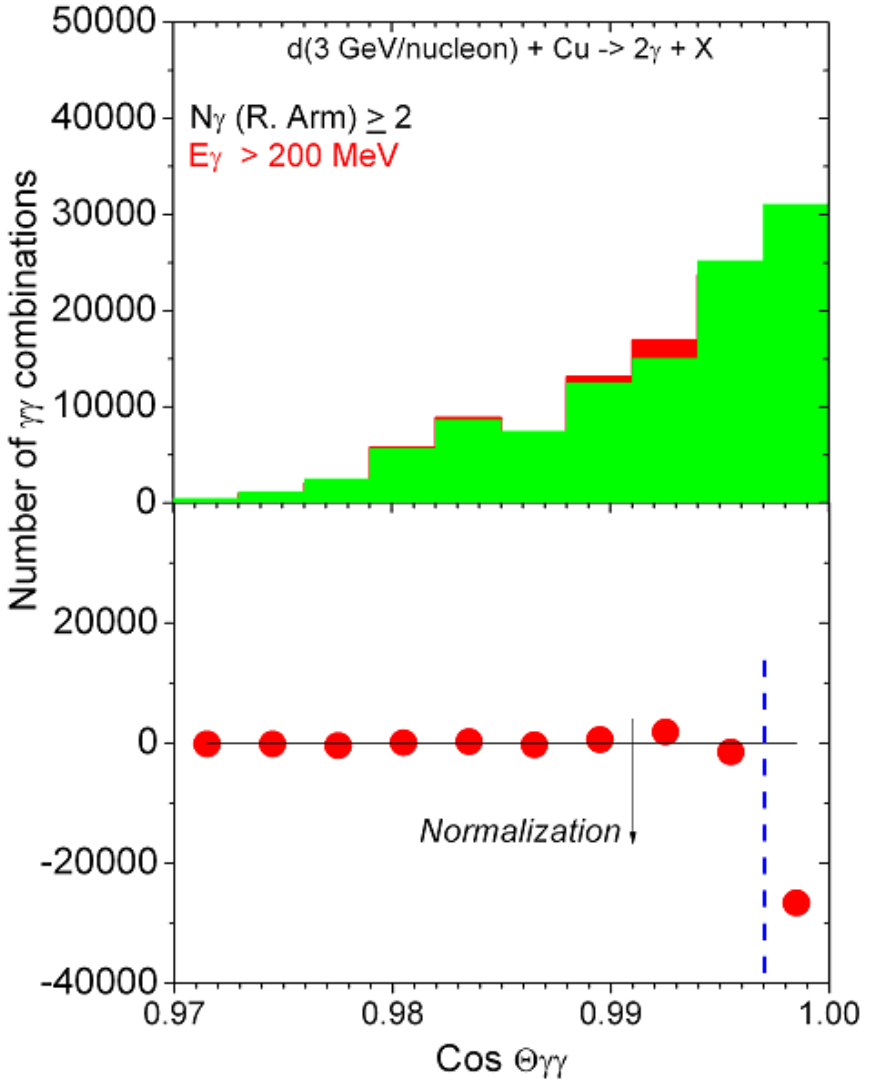
The two-dimensional distribution of the magnitude $(N_{\gamma\gamma} - B)/N_{\gamma\gamma}$ on the invariant mass of the pairs and the energies of photons in the pair (showing Nγγ – B > 200).



The two-dimensional distribution of the magnitude $(N_{\gamma\gamma} - B)/\sqrt{N_{\gamma\gamma}}$ on the total energy of pairs and the opening angles of photons in the pair

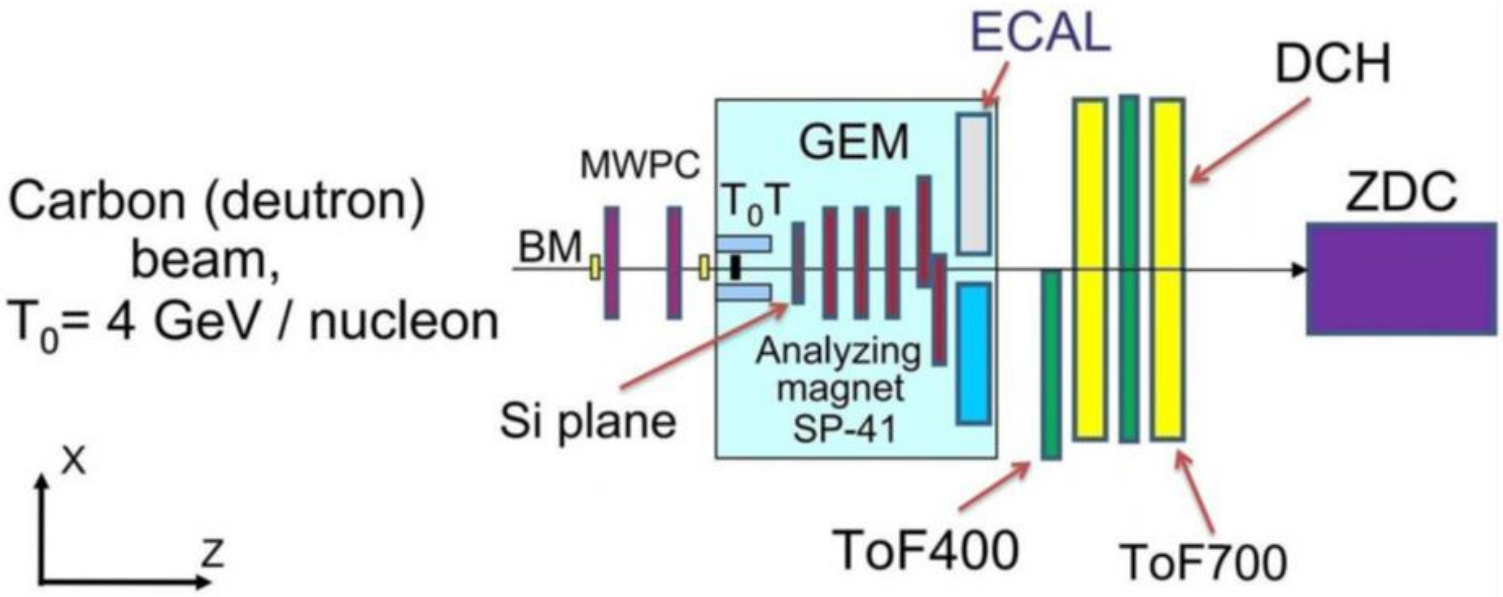





Результат влияния систематических ошибок при малых углах на установки СФЕРА. При cosθ близком к единице возникает резкий провал, который проявляется при смешивании событий. Порог 50 МеВ(левый рисунок), порог 200 МеВ(правый рисунок)

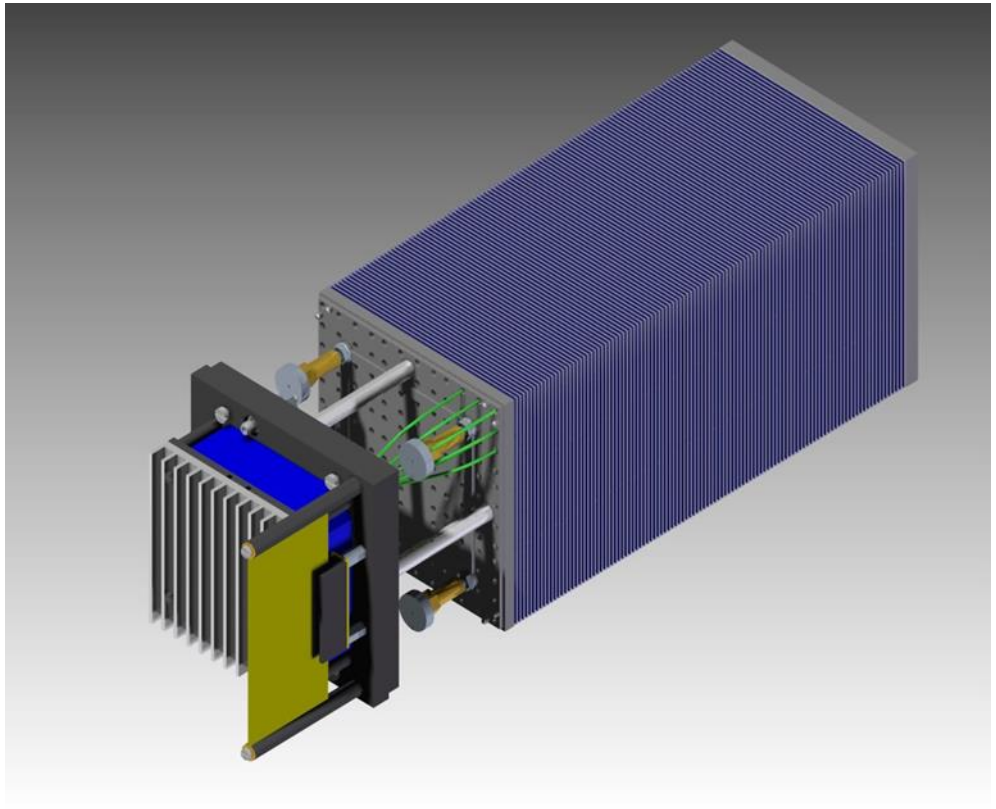
# Schematic drawing of the location of the Electromagnetic Calorimeter on the BM@N setup

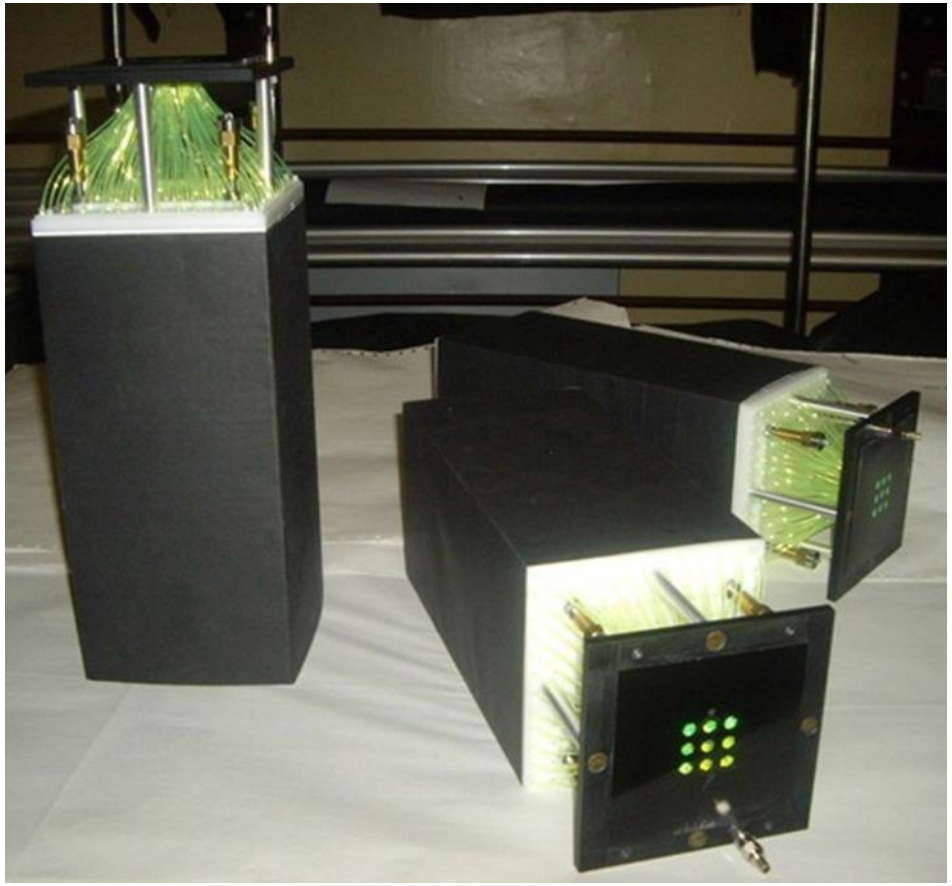



***DCH*** – дрейфовые камеры
***ToF400*** – времяпролетный детектор (x400)
***ToF700*** – времяпролетный детектор (x700)
***ECAL*** – электромагнитный калориметр
***ZDC*** – адронный калориметр
***T₀T*** – T₀ + Trigger

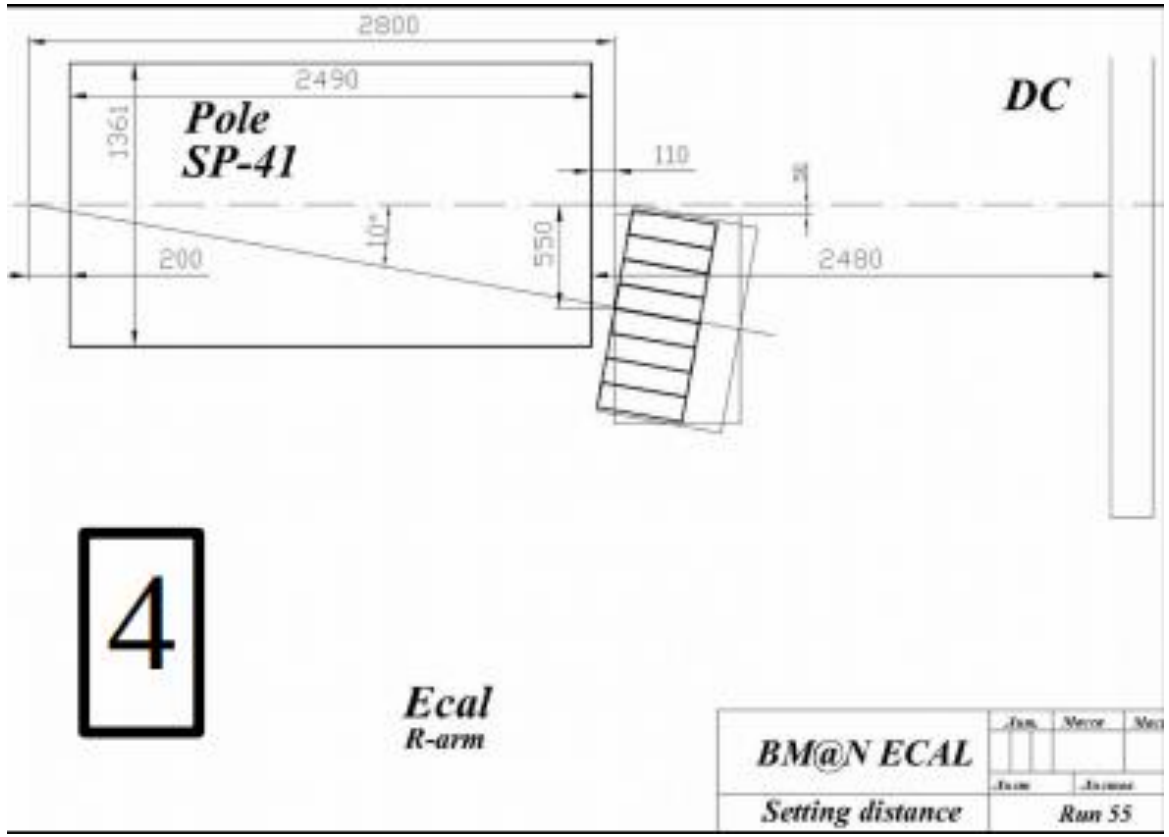
***Si plane*** – кремневый детектор
***GEM*** – газо-электронный умножитель
***BM*** – beam monitors
***MWPC*** – координатная камера
***SP-41*** – дипольный магнит

# Schematic and general view of a single cell of the calorimeter

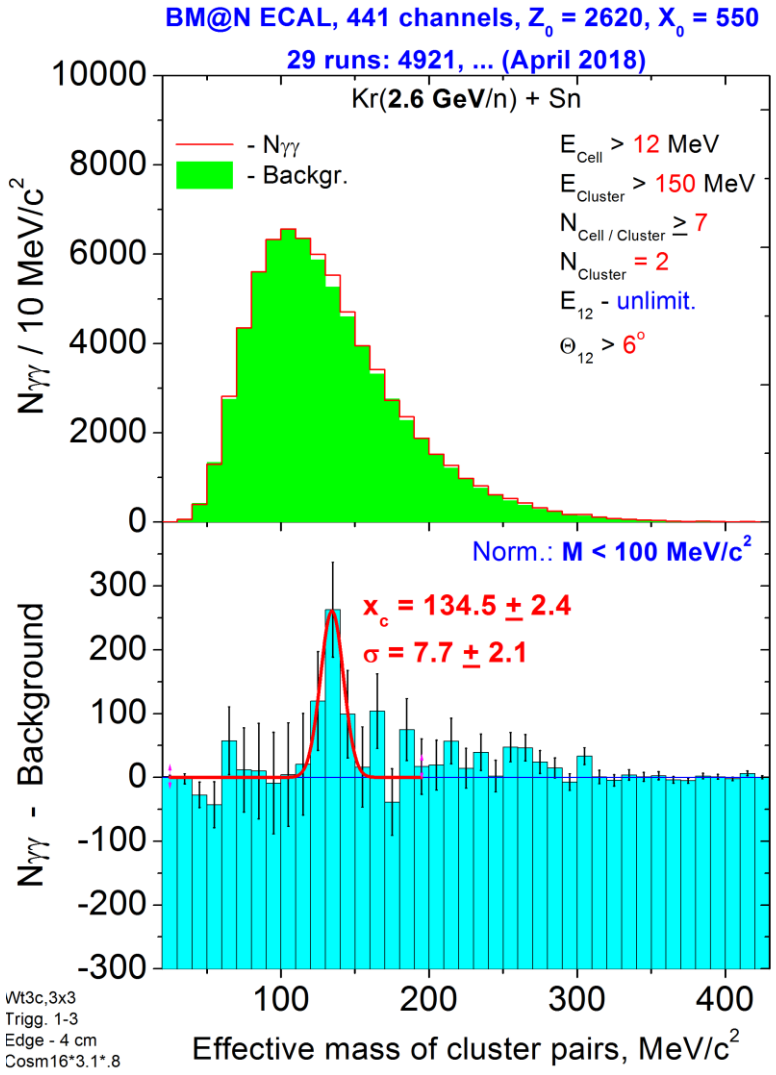




# Effective mass distributions of photon pairs (pairs of clusters) in the reaction Kr (2.6 GeV / nucleon) + Sn




Location of the ECAL in the 55th run of the Nuclotron, on a beam of Kr nuclei with an energy of 2.6 GeV per nucleon, using a tin target.



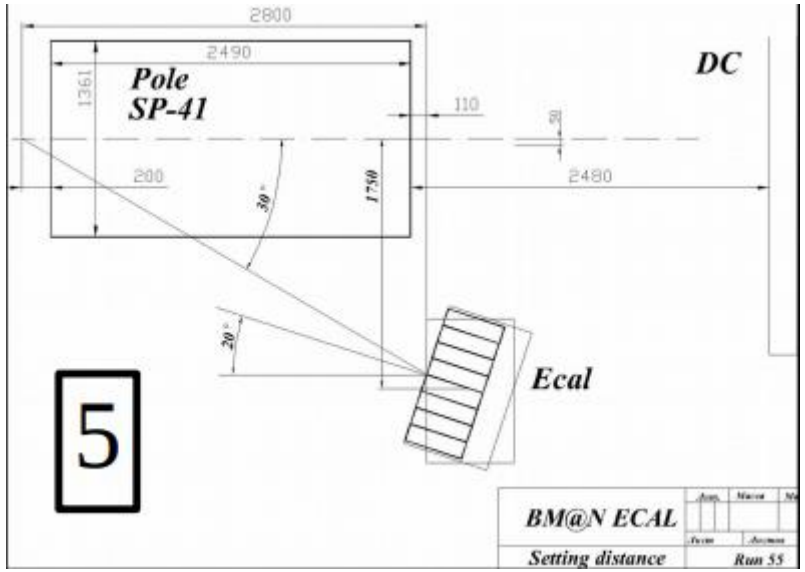
# The background estimation

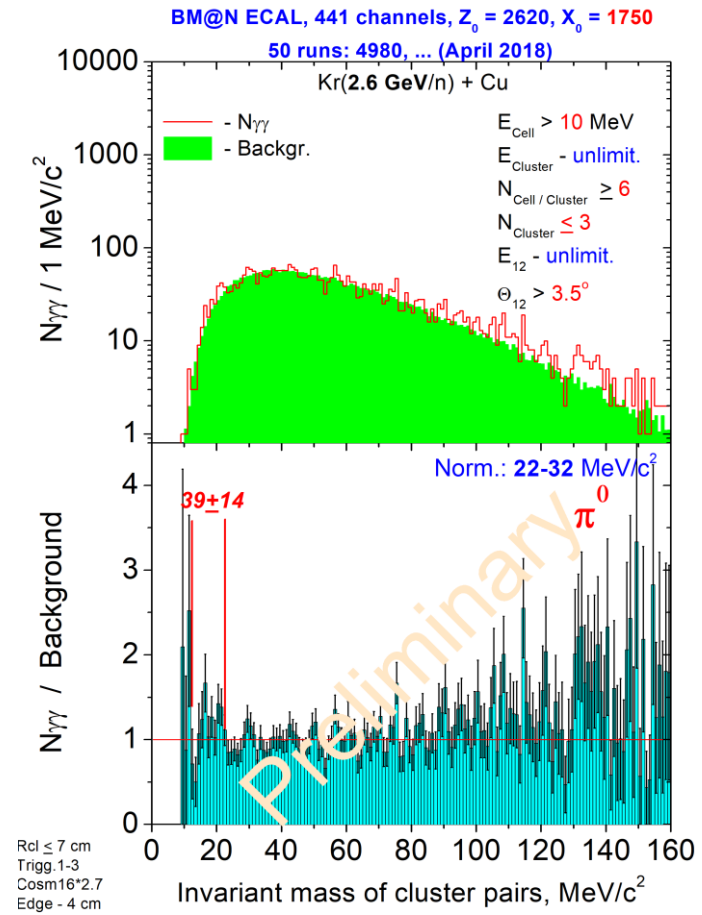
To see a possible structure of the invariant mass spectra, a background should be subtracted.

The so-called event mixing method was used to estimate the combinatorial background: a photon in one event from the Right arm of the Calorimeter is combined with photon in other events from the same arm.

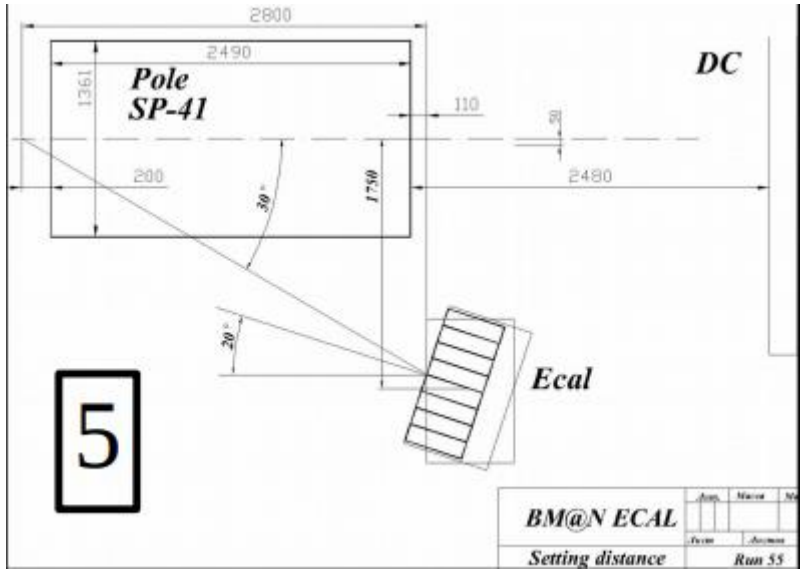
In the mixing are involved events in which there are two or more photons satisfying the criteria applied to clusters and to the pairs of clusters.

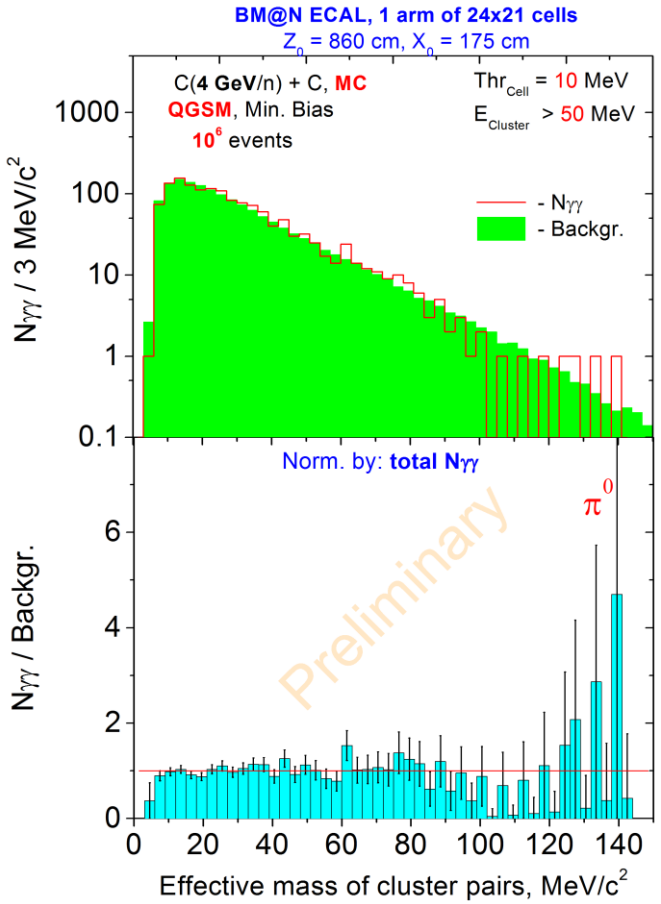
Invariant mass distribution of photon pairs (pairs of clusters) in the reaction Kr (2.6 GeV/nucleon) + Sn, under minimal selection conditions (shown in the figure). The top shaded histogram shows the background contribution. The background obtained using the event mixing method and normalized to the number of pairs in a range of masses 22-32 MeV/$c^2$. Bottom panel shows the ratio of number of pairs to the background.



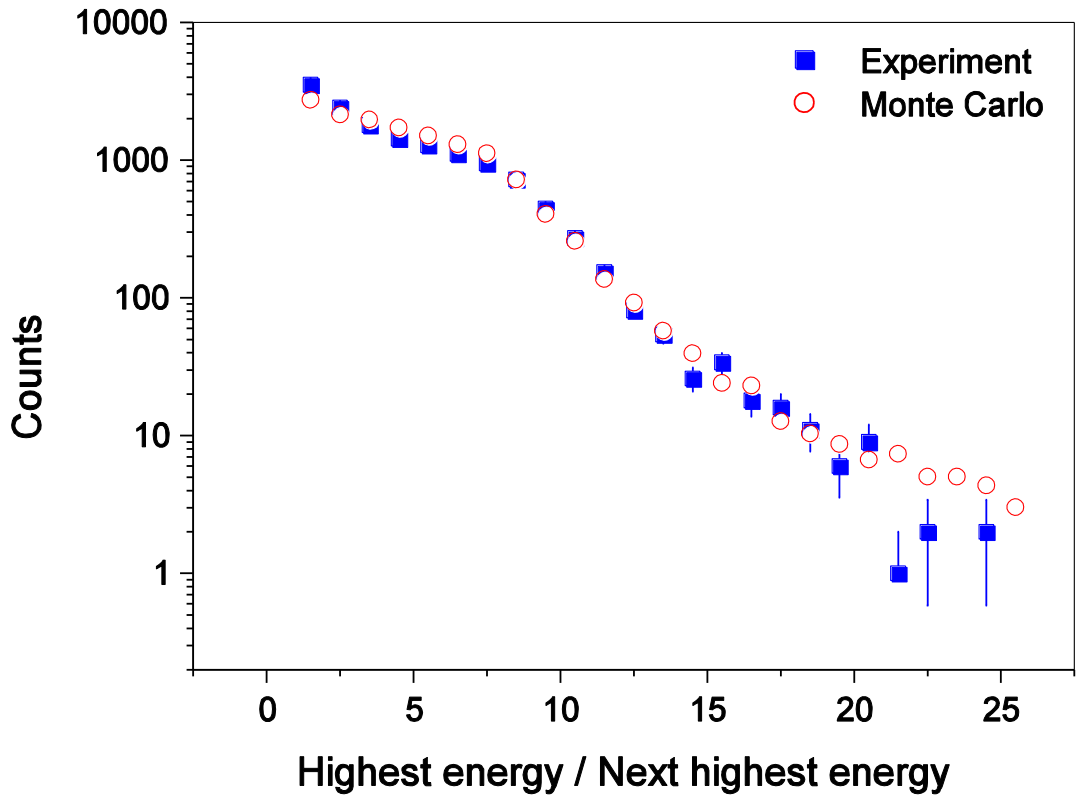



Invariant mass distribution of photon pairs (pairs of clusters) in the reaction C(4 GeV/nucleon) + C - results of Monte Carlo simulation (Model QGSM), for the distance of ECAL from the target 860 cm. The top shaded histogram shows the background contribution. The background obtained using the event mixing method and normalized to the total pair number. Bottom panel shows the ratio of number of pairs to the background.

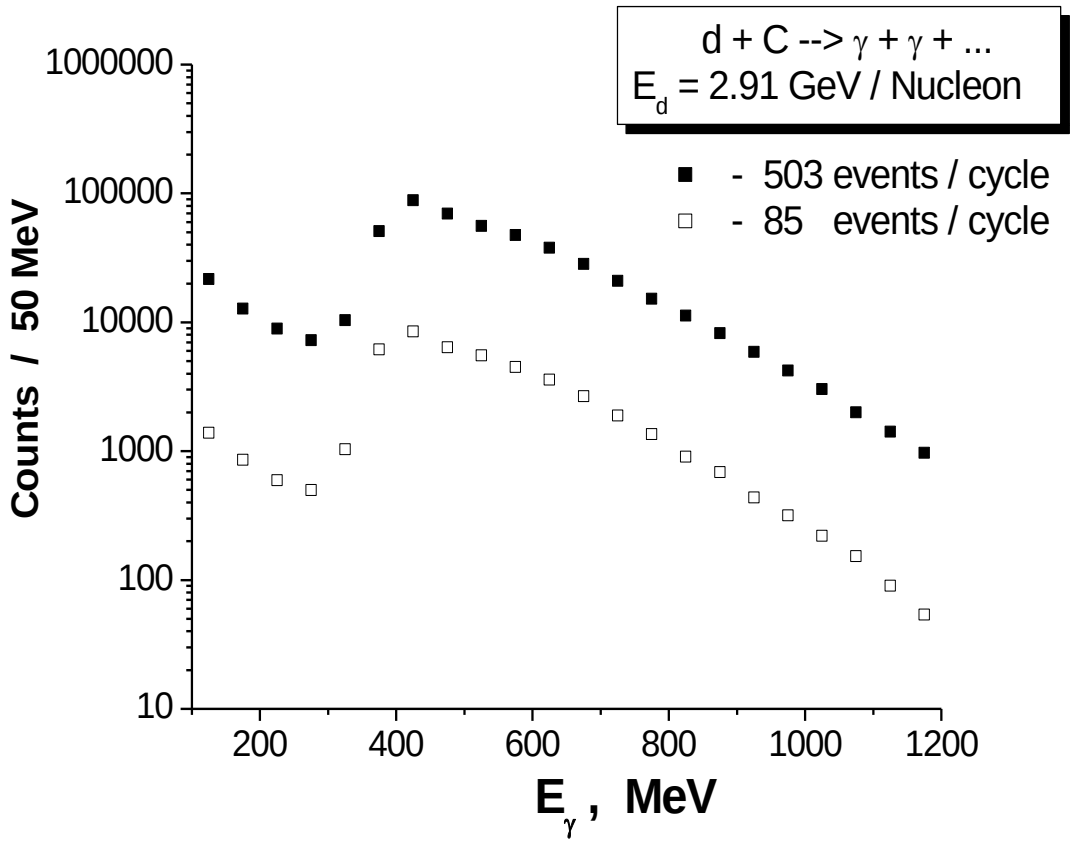


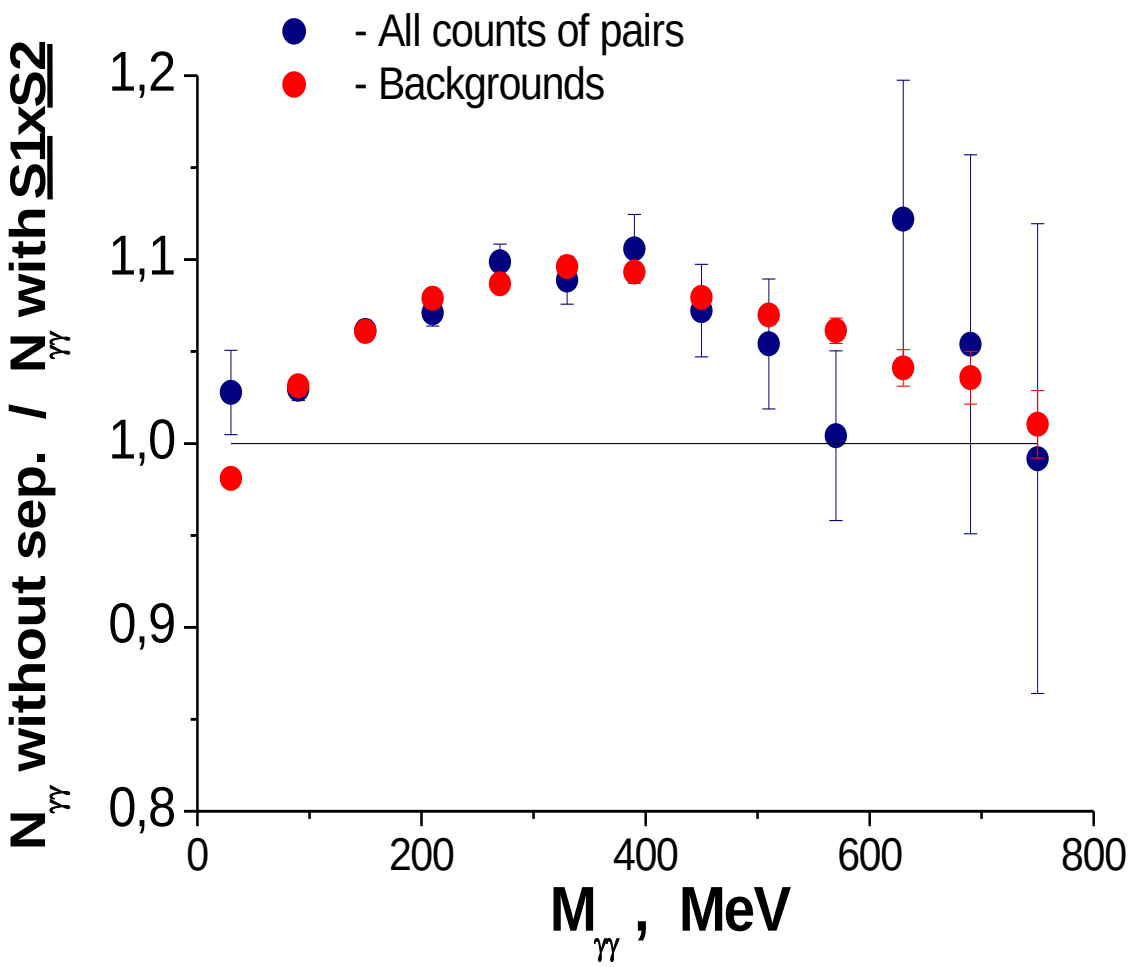
Отношение энергии в центральном (с максимальной энергией) модуле на вторую по величине энергию в модулях. Квадратиками обозначены экспериментальные данные, кружочками представлены данные, полученные с помощью моделирования методом Monte Carlo. Нормировка по полному числу γ-квантов.



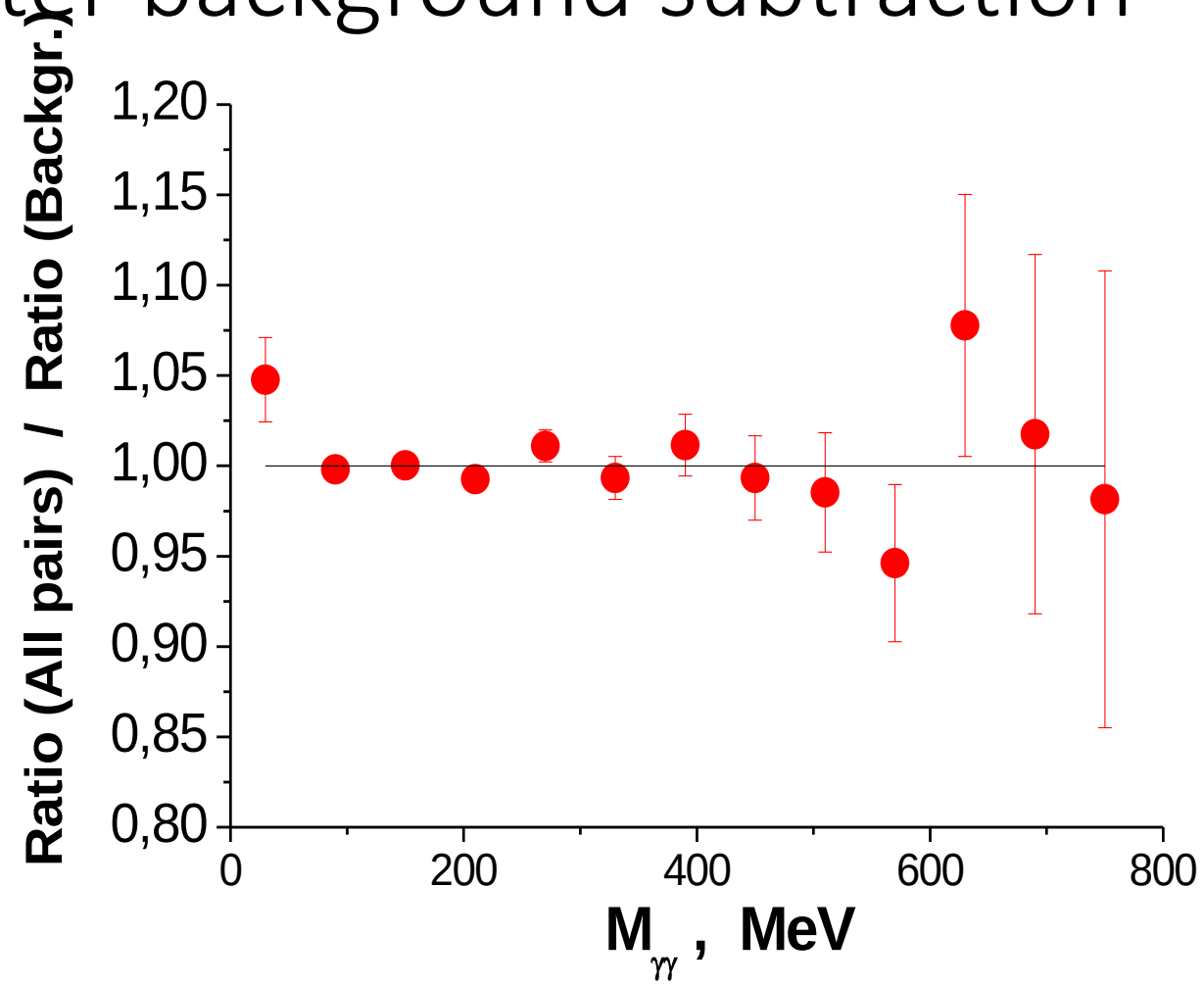
# Энергетическое распределение фотонов



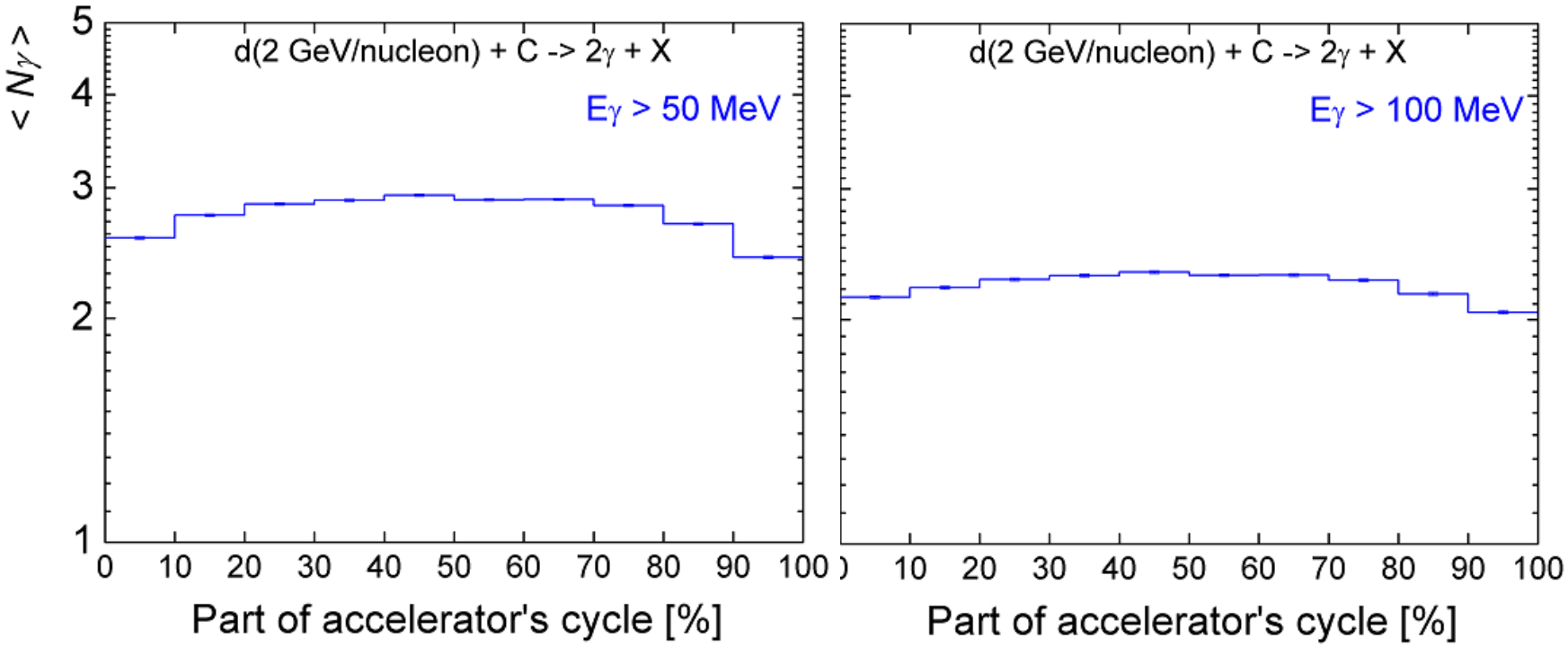
# Charged particles contribution



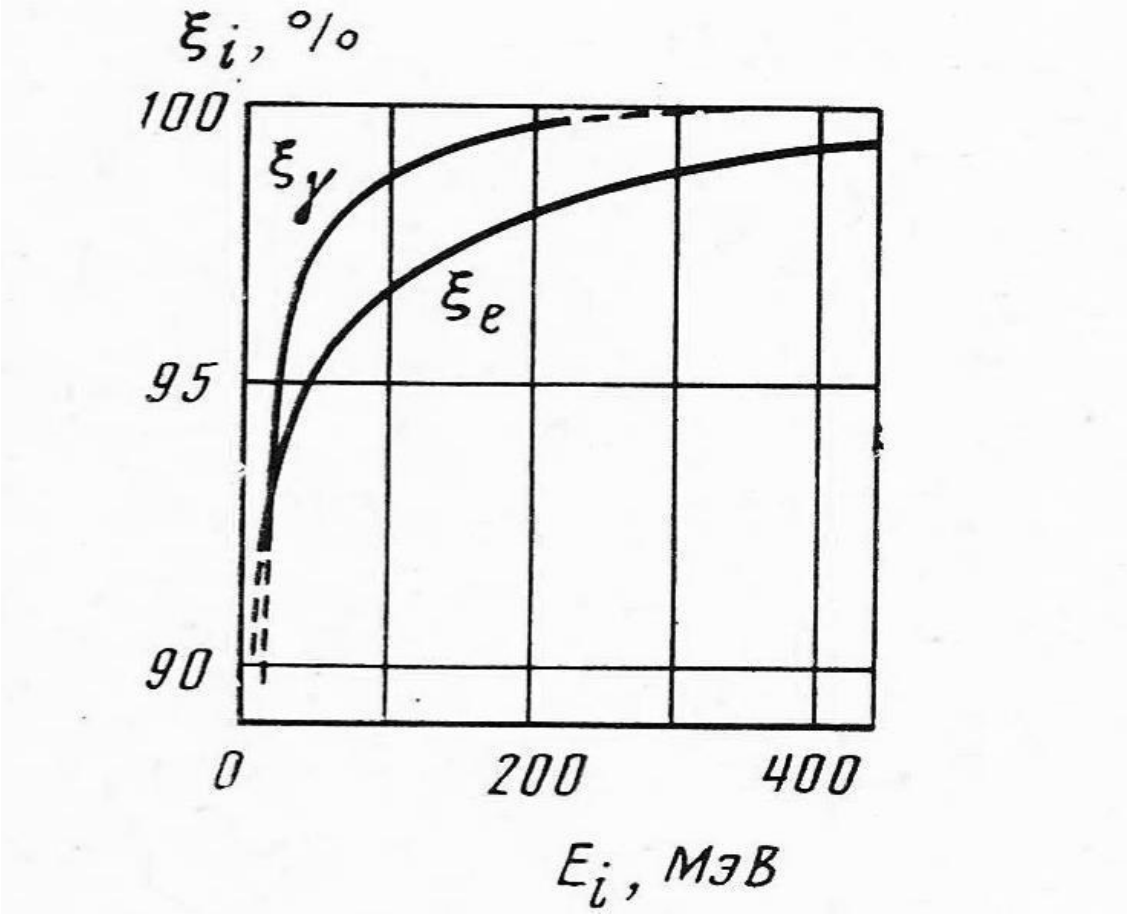
# Charged particles contribution after background subtraction



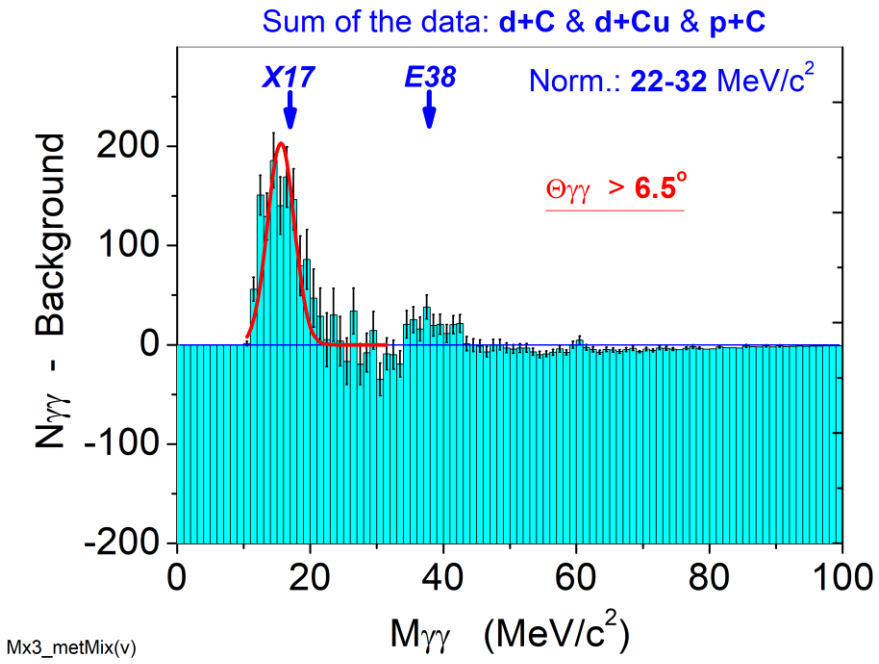
The mean number of detected photons in an event, recorded in different intervals of accelerator cycle, with a minimum energy of photons, Eγmin = 50 MeV (left) and Eγmin = 100 MeV (right).

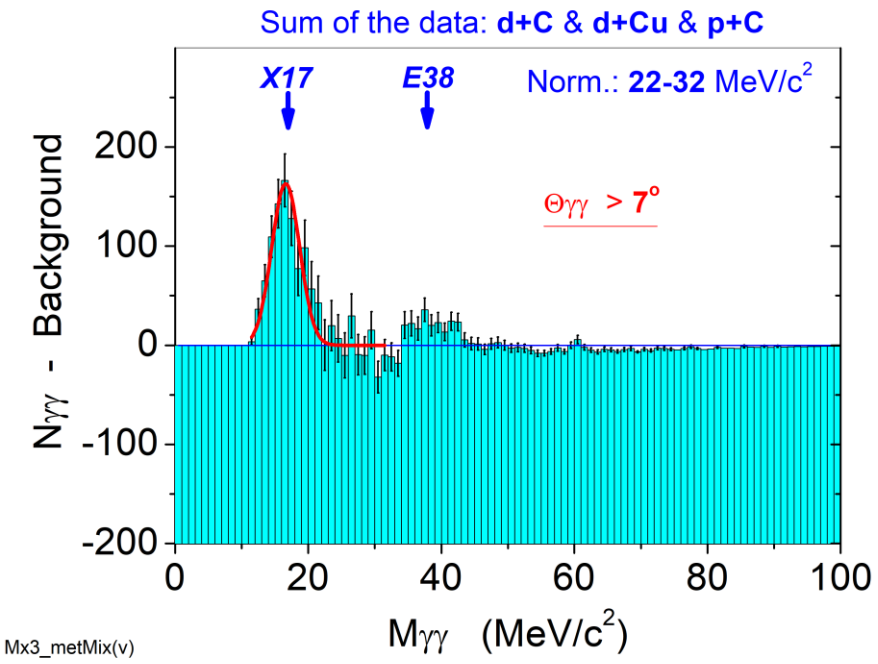


Dependence of the **linearity coefficient** of the γ-spectrometer on the energies of electrons and γ-quanta (from the paper: Kh. U. Abraamyan et al., Prib. Tekh. Eksp. **1**, 57 (1989) [Instruments and Experimental Techniques **32**, 58 (1989)).



Invariant mass distributions of *γγ* pairs satisfying criteria: Eγ > 40 MeV, $E_{12}$> 250 MeV, after the background subtraction obtained for the *d*+C, *d*+Cu and *p* + C reactions at different levels of cutoff in the **opening angles** of photons The backgrounds are normalized by the numbers of pairs in the range (22, 32) MeV/c².



# The results of approximation of the spectra of invariant masses of photon pairs after subtraction of the background, by the Gaussian function, at different levels of cutoff in the opening angle of photons

## Θγγ > 6.5°

*Parameters*

| | | Value | Standard Error |
|---|---|---|---|
| Dn | y0 | 0 | 0 |
| | xc | 15.59316 | 0.3408 |
| | w | 4.01606 | 0.39028 |
| | A | 1022.73161 | 135.81183 |
| | sigma | 2.00803 | |
| | FWHM | 4.72855 | |
| | Height | 203.18954 | |

Reduced Chi-sqr = 3.00817607017
COD(R^2) = 0.76212045150244
Iterations Performed = 12
Total Iterations in Session = 12
Fit converged - tolerance criterion satisfied.
Some parameter values were fixed.
sigma, FWHM, Height are derived parameter(s).

*Statistics*

| | Dn |
|---|---|
| Number of Points | 22 |
| Degrees of Freedom | 19 |
| Reduced Chi-Sqr | 3.00818 |
| Residual Sum of Squares | 57.15635 |
| Adj. R-Square | 0.73708 |
| Fit Status | Succeeded(100) |

## Θγγ > 7°

*Parameters*

| | | Value | Standard Error |
|---|---|---|---|
| Dn | y0 | 0 | 0 |
| | xc | 16.61814 | 0.22864 |
| | w | 4.18877 | 0.29564 |
| | A | 856.20624 | 74.64059 |
| | sigma | 2.09439 | |
| | FWHM | 4.93191 | |
| | Height | 163.09153 | |

Reduced Chi-sqr = 1.05369599059
COD(R^2) = 0.88059654822854
Iterations Performed = 8
Total Iterations in Session = 8
Fit converged - tolerance criterion satisfied.
Some parameter values were fixed.
sigma, FWHM, Height are derived parameter(s).

*Statistics*

| | Dn |
|---|---|
| Number of Points | 21 |
| Degrees of Freedom | 18 |
| Reduced Chi-Sqr | 1.0537 |
| Residual Sum of Squares | 18.96653 |
| Adj. R-Square | 0.86733 |
| Fit Status | Succeeded(100) |

## Θγγ > 7.5°

*Parameters*

| | | Value | Standard Error |
|---|---|---|---|
| Dn | y0 | 0 | 0 |
| | xc | 17.03783 | 0.24181 |
| | w | 4.10897 | 0.36726 |
| | A | 728.3959 | 69.83491 |
| | sigma | 2.05449 | |
| | FWHM | 4.83795 | |
| | Height | 141.44064 | |

Reduced Chi-sqr = 1.15923520492
COD(R^2) = 0.85612455701405
Iterations Performed = 12
Total Iterations in Session = 12
Fit converged - tolerance criterion satisfied.
Some parameter values were fixed.
sigma, FWHM, Height are derived parameter(s).

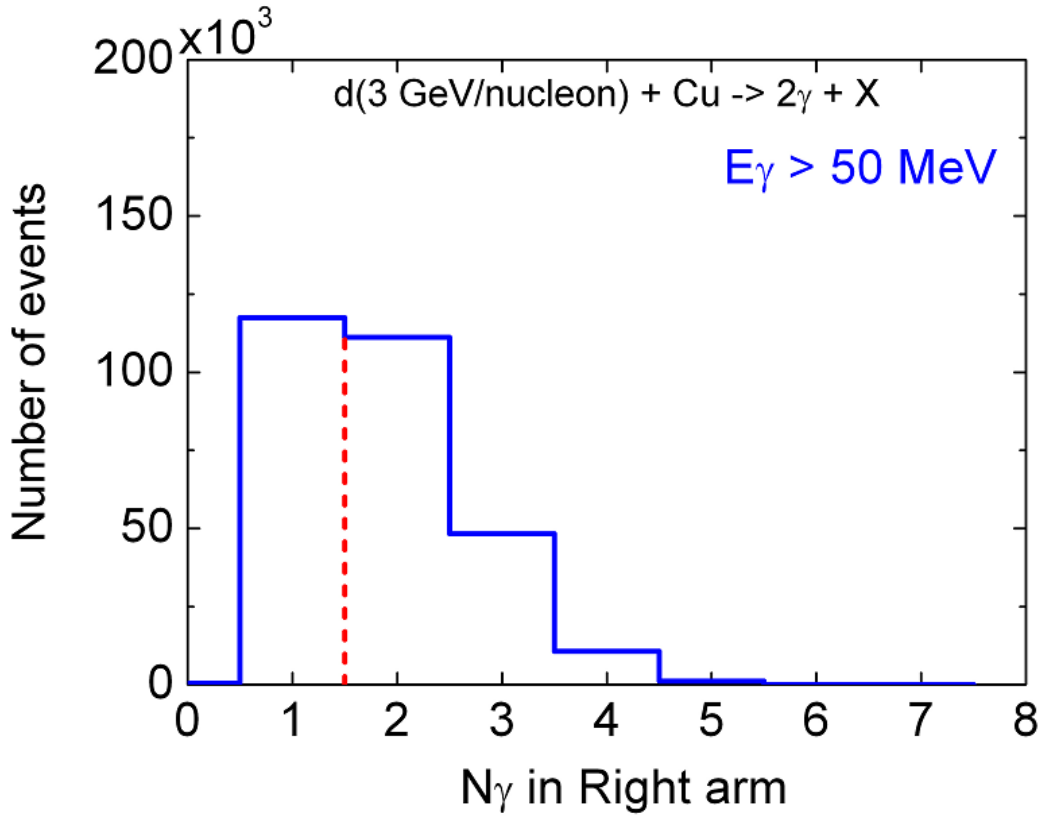
*Statistics*

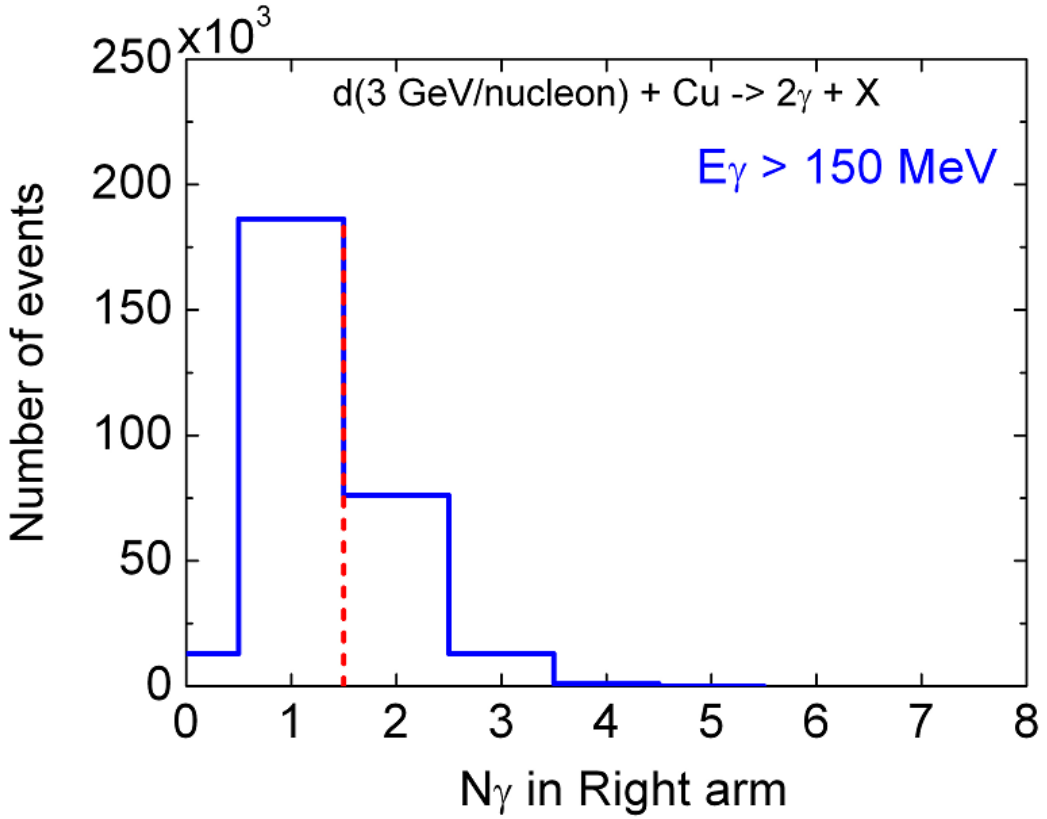
| | Dn |
|---|---|
| Number of Points | 20 |
| Degrees of Freedom | 17 |
| Reduced Chi-Sqr | 1.15924 |
| Residual Sum of Squares | 19.707 |
| Adj. R-Square | 0.8392 |
| Fit Status | Succeeded(100) |

# The basic parameters of the lead glass hodoscope

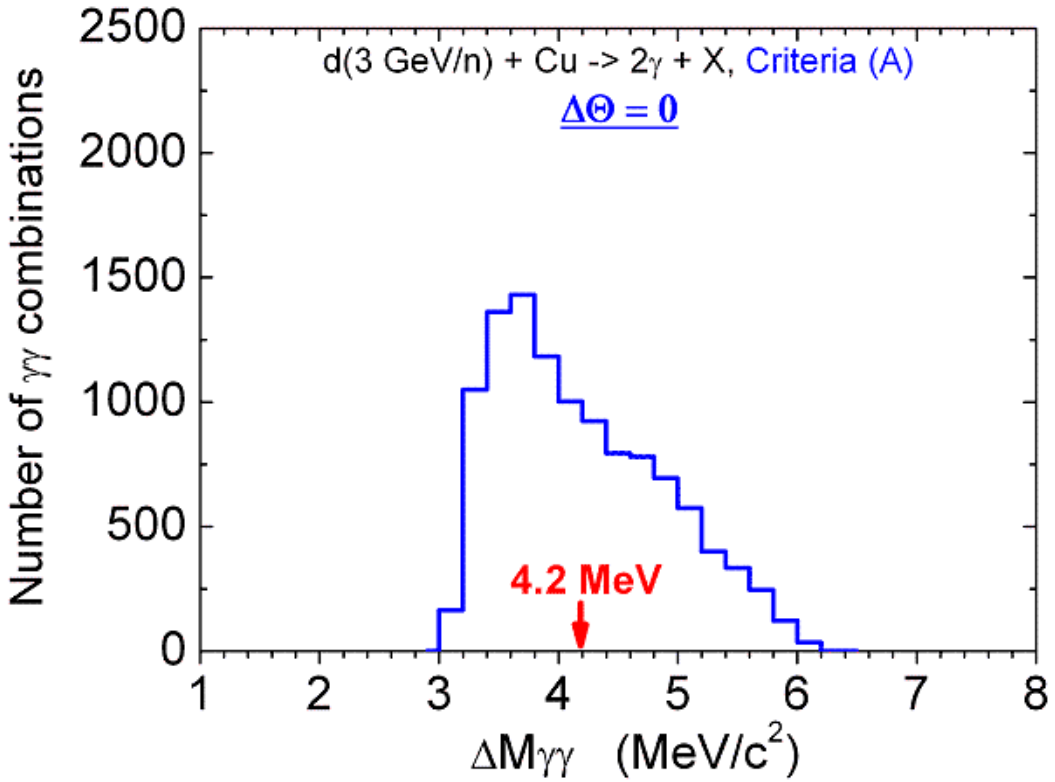
| | |
|---|---|
| Number of lead glasses | 32 TF-1, total weight 1422 kg |
| Module cross section | r = 9 cm of insert circumference |
| Module length | 35 cm, 14 R.L. |
| Spatial resolution | 3.2 cm |
| Angular resolution | 0.6◦ |
| Energy resolution | (3.9 / *pE* + 0.4)%, *E* [GeV] |
| Gain stability | (1-2)% |
| Dynamic range | 50 MeV - 6 GeV |
| Minimum ionizing signal | 382 ± 4 MeV of the photon equivalent |
| Total area | 0.848 $m_2$ |

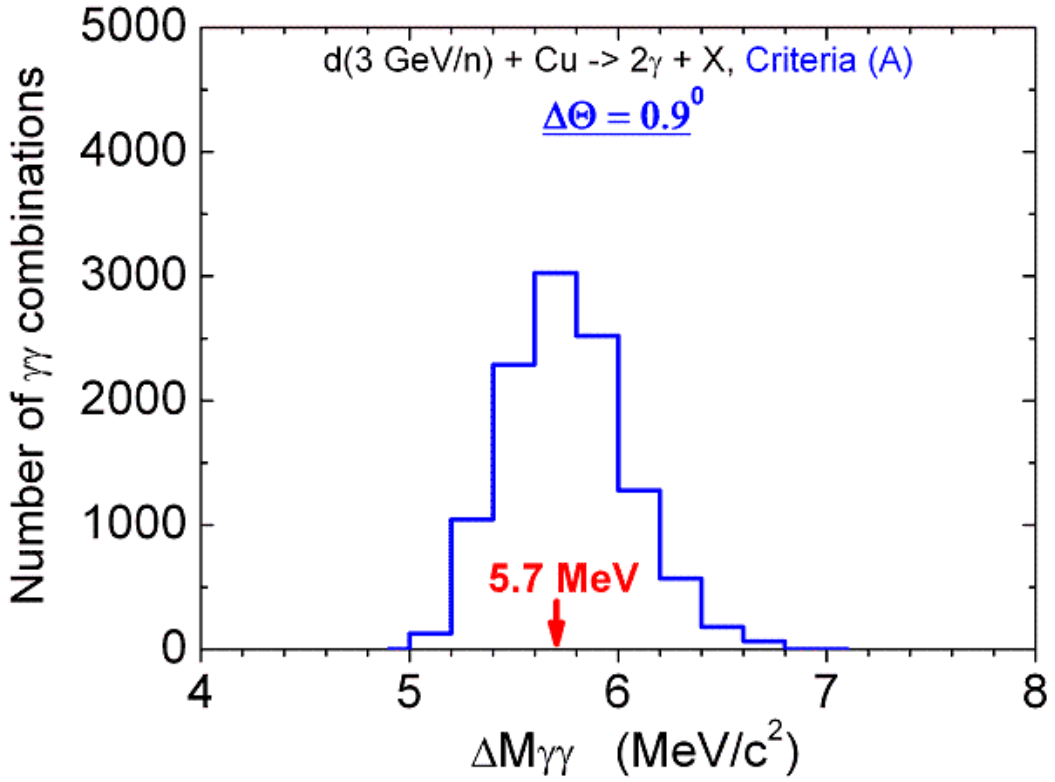
# Numbers of detected photons in the Right arm of the γ-spectrometer at a minimal energy of photons of 50 MeV (left figure) and 150 MeV (right figure)



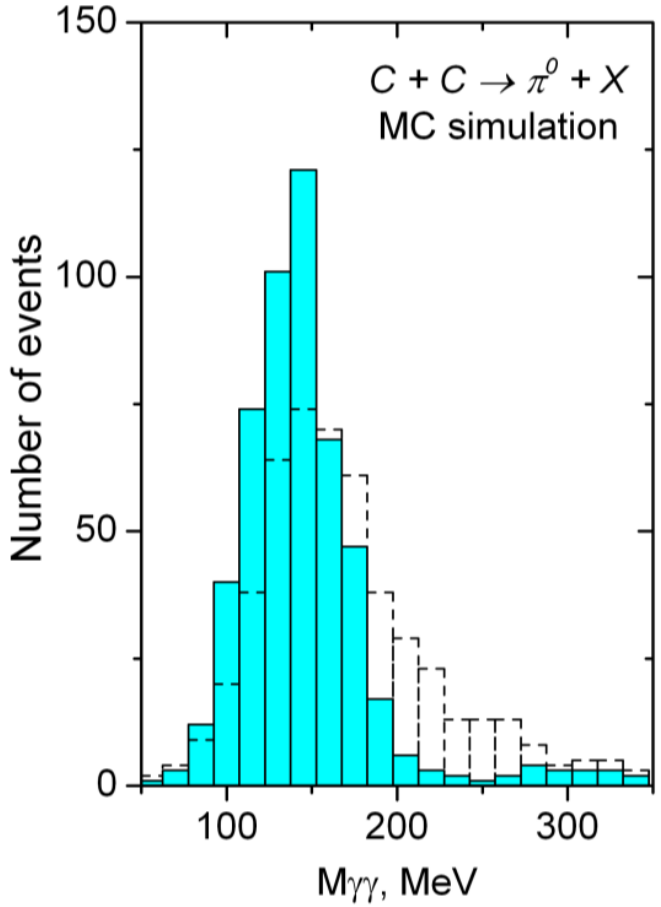



Distributions of calculated value of Δ*Mγγ* for photon pairs selected from the Right arm of the *γ*-spectrometer, under the Criteria (A), for the vicinity of the E(38) mass: 36 < *Mγγ* < 40 MeV/*c*2, at ΔΘ = 0 (left figure) and at the maximum value of ΔΘ = 0.9◦ (right figure).



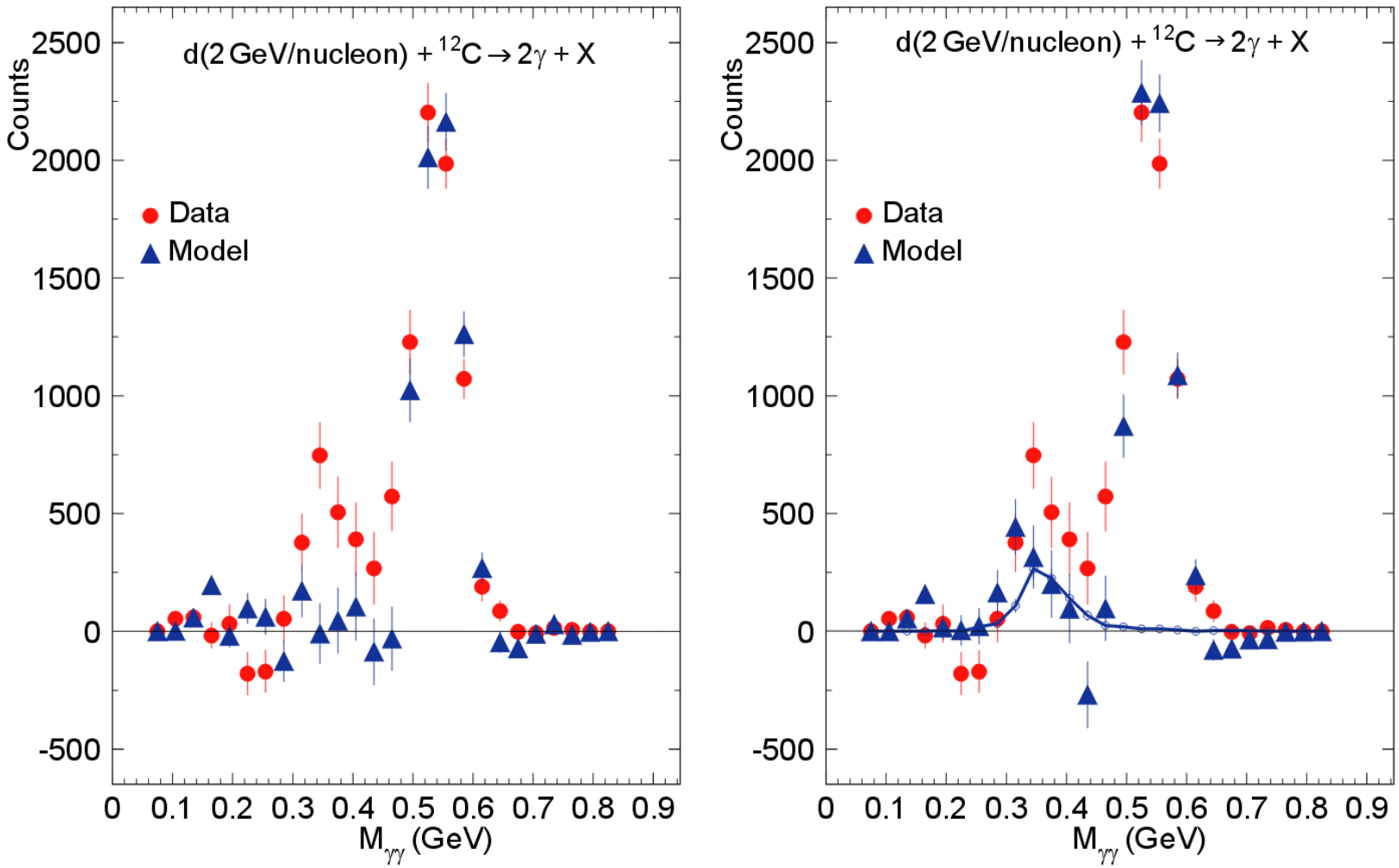



Распределение по инвариантной массе пар γγ от распада π0 мезонов, промоделированных с учетом реальных условий эксперимента в реакции C+C→π0+x при импульсе 4.5 ГэВ/с на нуклон. Сплошная гистограмма – спектр при отсутствии наложений (исключены при помощи меток, примененных в модели), пунктирная гистограмма – полный спектр с учетом наложений. Нормировка спектров по полному числу пар γγ



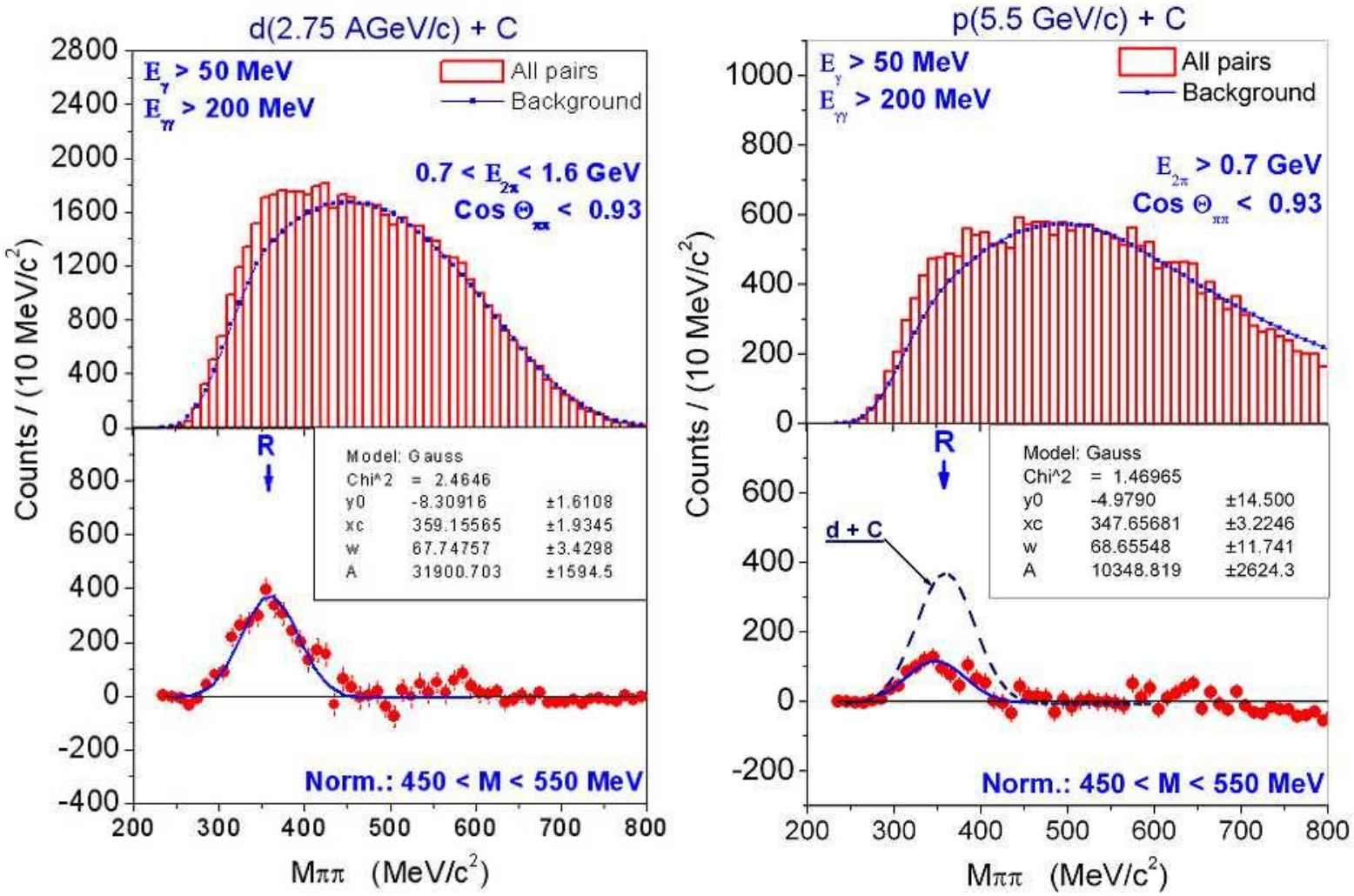
# Проверка резонансной структуры при инвариантной массе пар γ-квантов и пар π°-мезонов около 360 МэВ/c².

Eur. Phys. J. A (2016) **52**: 259.



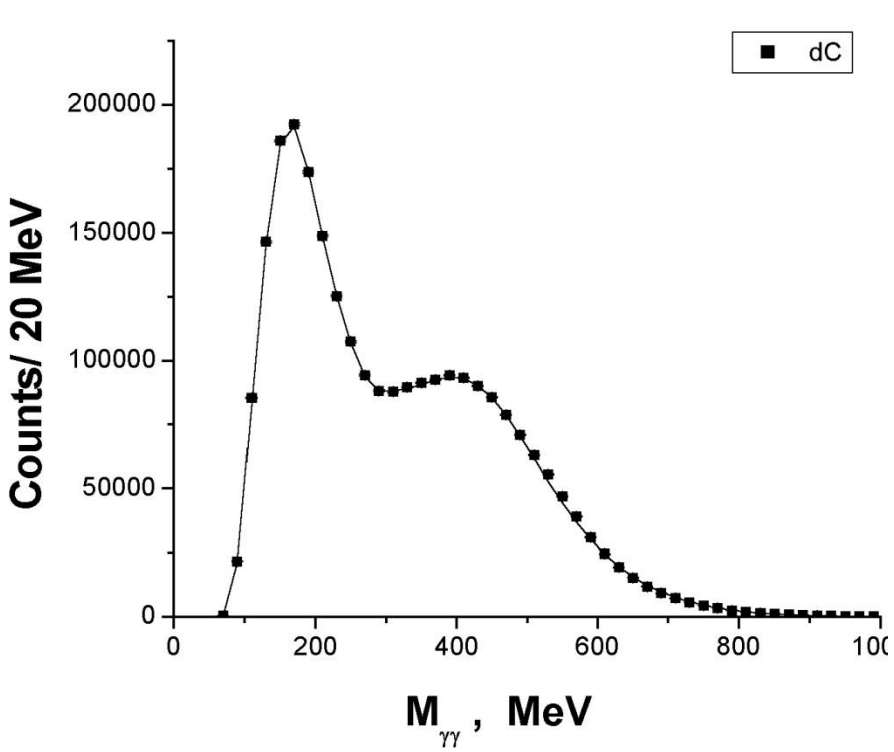

The invariant-mass distribution of γγ pairs from the d+C reaction after the background subtraction. Both experimental (● ) and simulated points are obtained under the same conditions.

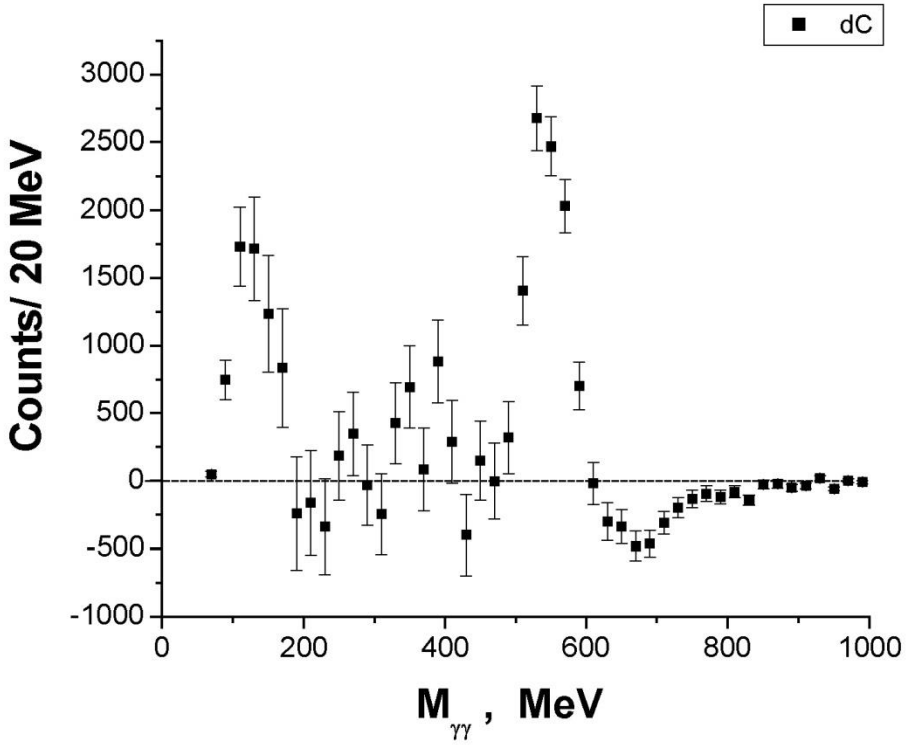
# Проверка резонансной структуры при инвариантной массе пар γ-квантов и пар π°-мезонов около 360 МэВ/c². Eur. Phys. J. A (2016) 52: 259.




The Invariant-mass distributions of π°π° pairs without (upper panels) and with (bottom panels) the background subtraction for the reactions d+C at 2.75 GeV/c per nucleon (left figure) and p+C at 5.5 GeV/c (right figure). The backgrounds are normalized to pair numbers in the interval: 450 < Mππ < 550 MeV/c2.

Invariant mass distributions of γγ pairs without (left figure) and with (right figure) the background subtraction in the reaction *d*(5.5 Gev/c)+C, at minimal cuts: Eγ ≥ 50 MeV.



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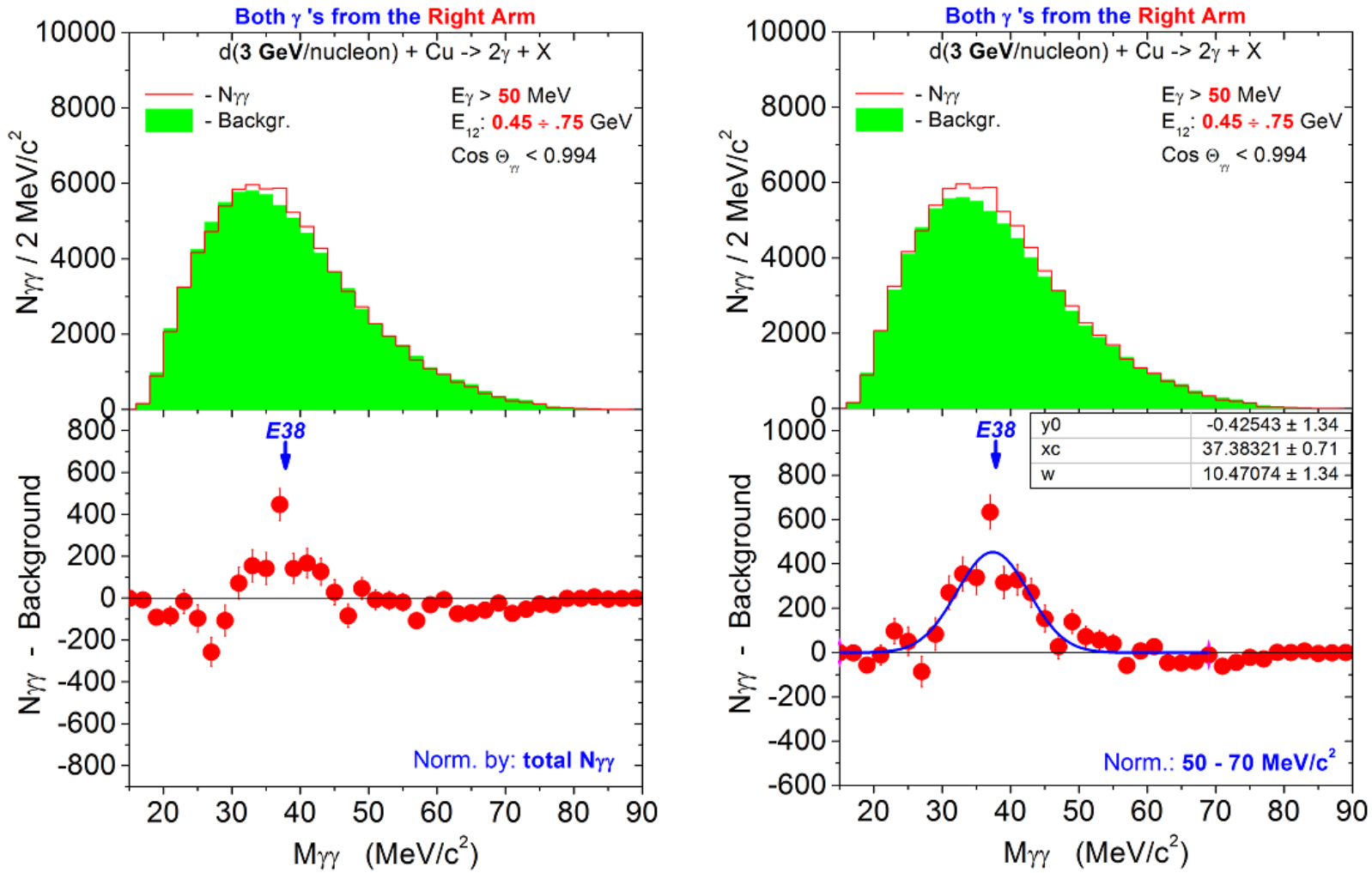
# Проверка структуры при инвариантной массе пар γ-квантов 38 МэВ/$c^2$.

EPJ Web of Conferences **204**, 08004 (2019)




Invariant mass distributions of γγ pairs satisfying criteria (i)-(iii) (criteria (A)) without (upper panels) and with (bottom panels) the background subtraction obtained for the reaction *d* + Cu ! γ + γ + *X* at 3.83 GeV/c per nucleon. The top shaded histograms show the background contribution. The background is normalized to the total pair number (left) and to the number of pairs in a range of masses 50 - 70 MeV/*c*2 (right). The curve is the Gaussian approximation of the experimental points in the range (14; 70) MeV/*c*2

# Optimal conditions for X17

In order to study the region of small invariant masses, we processed the data obtained in groups not participating in the trigger launch (thanks to the logical addition (see (1), previous slide), there are such groups in each event). To collect sufficient statistics, we processed the data obtained in several experiments.

(i) the number of detected photons in the group, $N\gamma = 2$;
(ii) the minimal energy of photons, $E\gamma Min = 40$ MeV;
(iii) the sum of the energies of photons in a pair, $E12 > 250$ MeV (effective
detection of pairs at the setup geometry);
(iv) the ratio of the energies $E\gamma 1/E\gamma 2 < 0.4$ (suppresses systematic errors due to violation of the energy-momentum conservation laws at the event mixing);
(v) the opening angles of photons in a pair, $\Theta\gamma\gamma > 7^o$.