Institute for High Energy Physics of
NRC Kurchatov Institute

Analysis of the rare $K^+\to\pi^+\pi^-\pi^+\gamma$ decay at the CERN-NA62 experiment

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Motivation

1989

1997

2019

Бармин В.В. и др. Измерение вероятности распада $K^+\to\pi^+\pi^-\pi^+\gamma$ // ЯФ. 1989. Т. 50. С. 679

Barmin V.V et al. Measurement of the $K^+\to\pi^+\pi^-\pi^+\gamma$ decay probability. *Sov.J.Nucl.Phys.* 50 (1989) 421-423

$BR(K^+\to\pi^+\pi^-\pi^+\gamma) = (1{,}04\pm0{,}31)*10^{-4}$, $E_\gamma^* > 5$ MeV

7 events

PDG (2023):

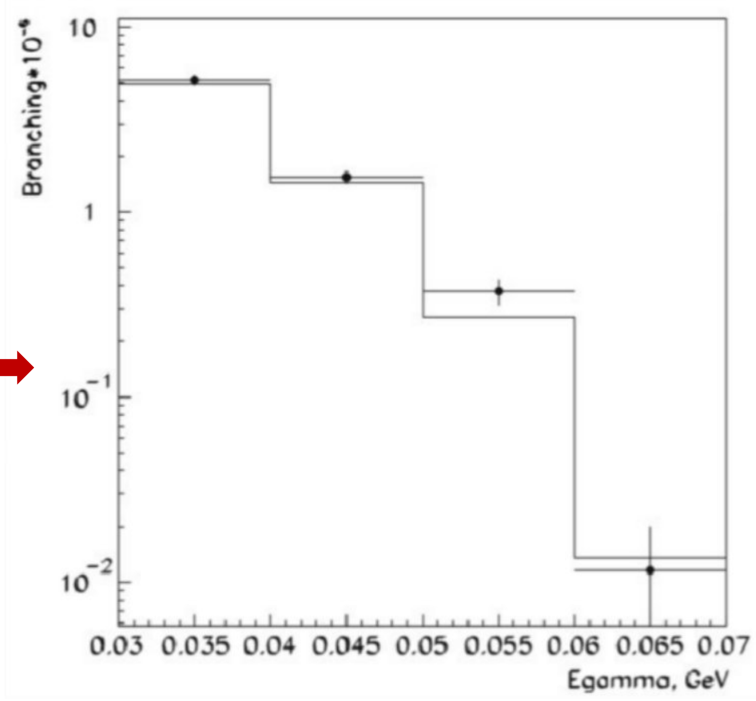
$BR(K^+\to\pi^+\pi^-\pi^+\gamma) = (1{,}04\pm0{,}31)*10^{-4}$, $E_\gamma^* > 5$ MeV

(Barmin et al., 1989)

D'Ambrosio, G., Ecker, G., Isidori, G. *et al.* $K \to \pi\pi\pi\gamma$ in chiral perturbation theory. *Z Phys C - Particles and Fields* **76**, 301–310 (1997). https://doi.org/10.1007/s002880050554

E_γ, MeV	$\frac{\Gamma_{GB}-\Gamma_{Low}}{\Gamma}$	BR
10–20	$-1.7\cdot10^{-3}$	$(4.36\pm0.04)\cdot10^{-5}$
20–30	$-4.8\cdot10^{-3}$	$(1.43\pm0.01)\cdot10^{-5}$
30–40	$-9.2\cdot10^{-3}$	$(4.93\pm0.05)\cdot10^{-6}$
40–50	$-1.5\cdot10^{-2}$	$(1.44\pm0.01)\cdot10^{-6}$
50–60	$-2.1\cdot10^{-2}$	$(2.69\pm0.03)\cdot10^{-7}$
60–70	$-2.8\cdot10^{-2}$	$(1.36\pm0.02)\cdot10^{-8}$
10–70	$-3.4\cdot10^{-3}$	$(6.46\pm0.06)\cdot10^{-5}$

$BR(K^+\to\pi^+\pi^-\pi^+\gamma)_{theor.} = (1{,}26\pm0{,}01)*10^{-4}$, $E_\gamma^* > 5$ MeV

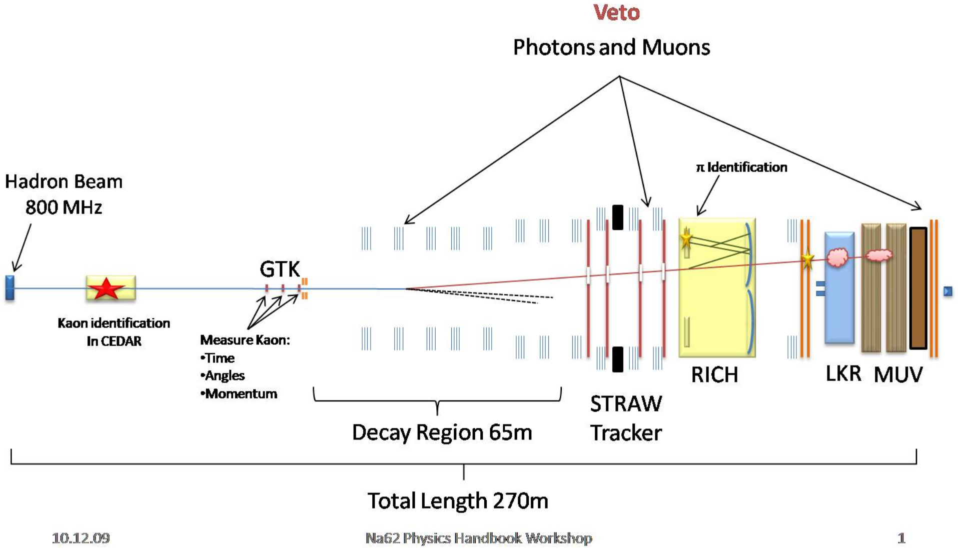


Shapkin, M.M. *et al.* Study of the decay $K^+\to\pi^+\pi^-\pi^+\gamma$ in the OKA experiment. *Eur. Phys. J. C* **79**, 296 (2019). 019-6797-1. https://doi.org/10.1140/epjc/s10052-019-6797-1

$BR(K^+\to\pi^+\pi^-\pi^+\gamma) = (0{,}71\pm0{,}05)*10^{-5}$, $E_\gamma^* > 30$ MeV

450 events

NA62 experiment



Goal of an experiment: research of an ultra-rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ to measure $|V_{td}|$ parameter of the CKM matrix with uncertainty of 10%.

- **CEDAR** - identification of beam kaons with a differential Cherenkov detector.
- **GTK** - determination of beam particles parameters with pixel detectors (beam intensity ~10^9 / 6 sec^{-1})
- **STRAW** - tracking detector based on drift ‘straw’ tubes, it registers tracks of decay products.
- **RICH** - Ring Imaging CHerenkov detector that separates pions from muons.
- **LKR-IRC-SAC-LAV** - photon veto (calorimetry system). **LKr** - a main gamma detector, an ionization detector, uses liquid krypton for work.
- **MUV** - muon veto (calorimeter+hodoscope).
- **CHOD** - scintillation hodoscope.

Experiment is ongoing since 2015.

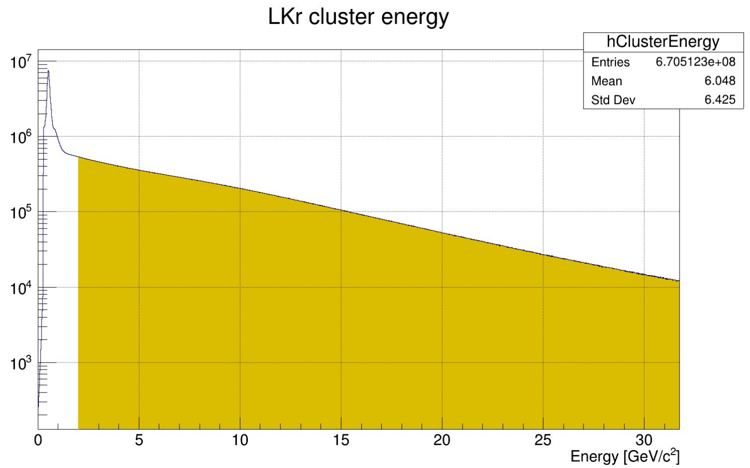
Events selection

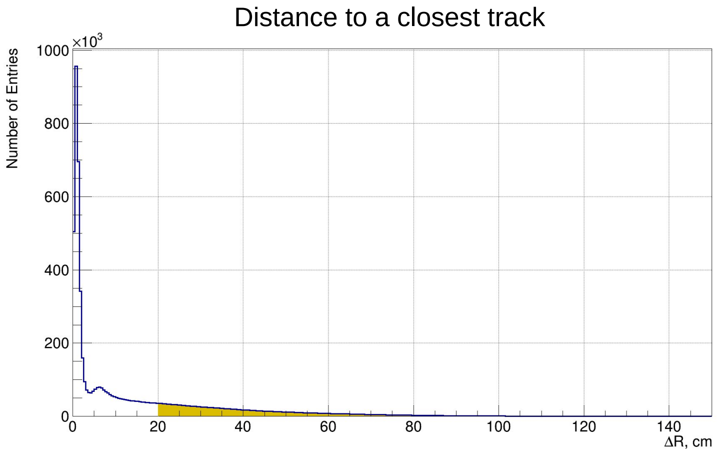
General cuts:

- «Multitrack» trigger to choose multitrack events: Ntracks >= 3
- Exactly one 3-track decay vertex
- Acceptance in STRAW and in a photon veto
- Total charge = +1
- For Cedar: NSectors >= 5
- GTK acceptance
- $105 < Z < 180$ m - a vertex is inside a decay volume

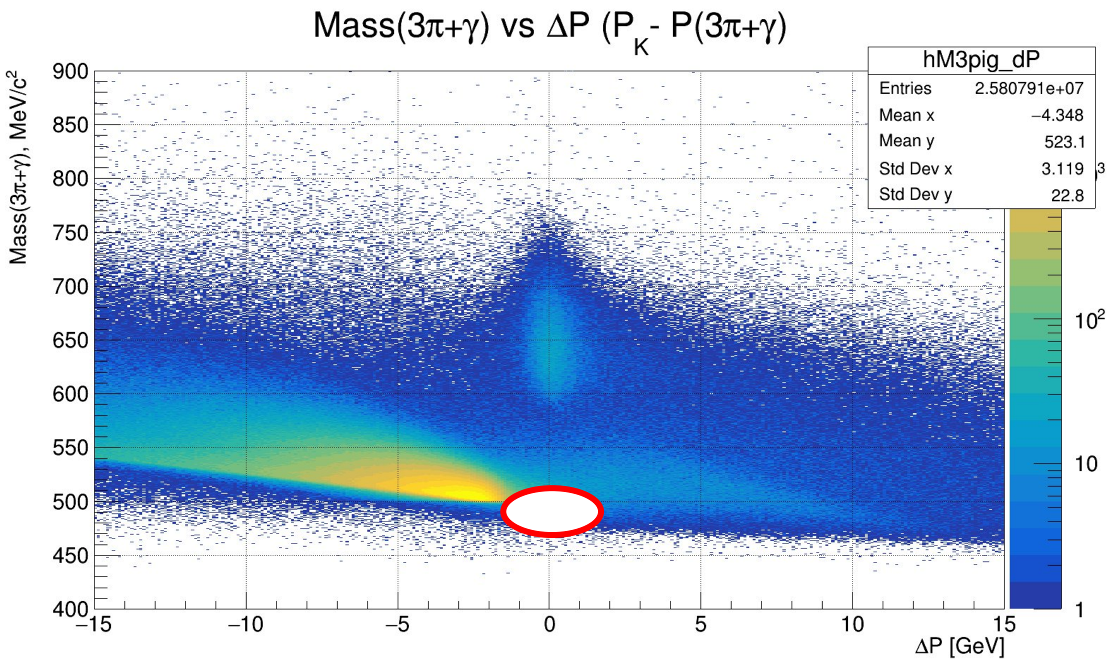
For each LKr cluster:

- $|time_{LKr} - time_{Cedar}| < 4$ ns
- Cluster energy > 2000 MeV
- Distance to tracks >= 20 cm
- $|P_{3pig} - P_k| < 2$ GeV
- No dead cells within 20 mm from a cluster
- Cluster energy in a kaon rest frame > 10 MeV

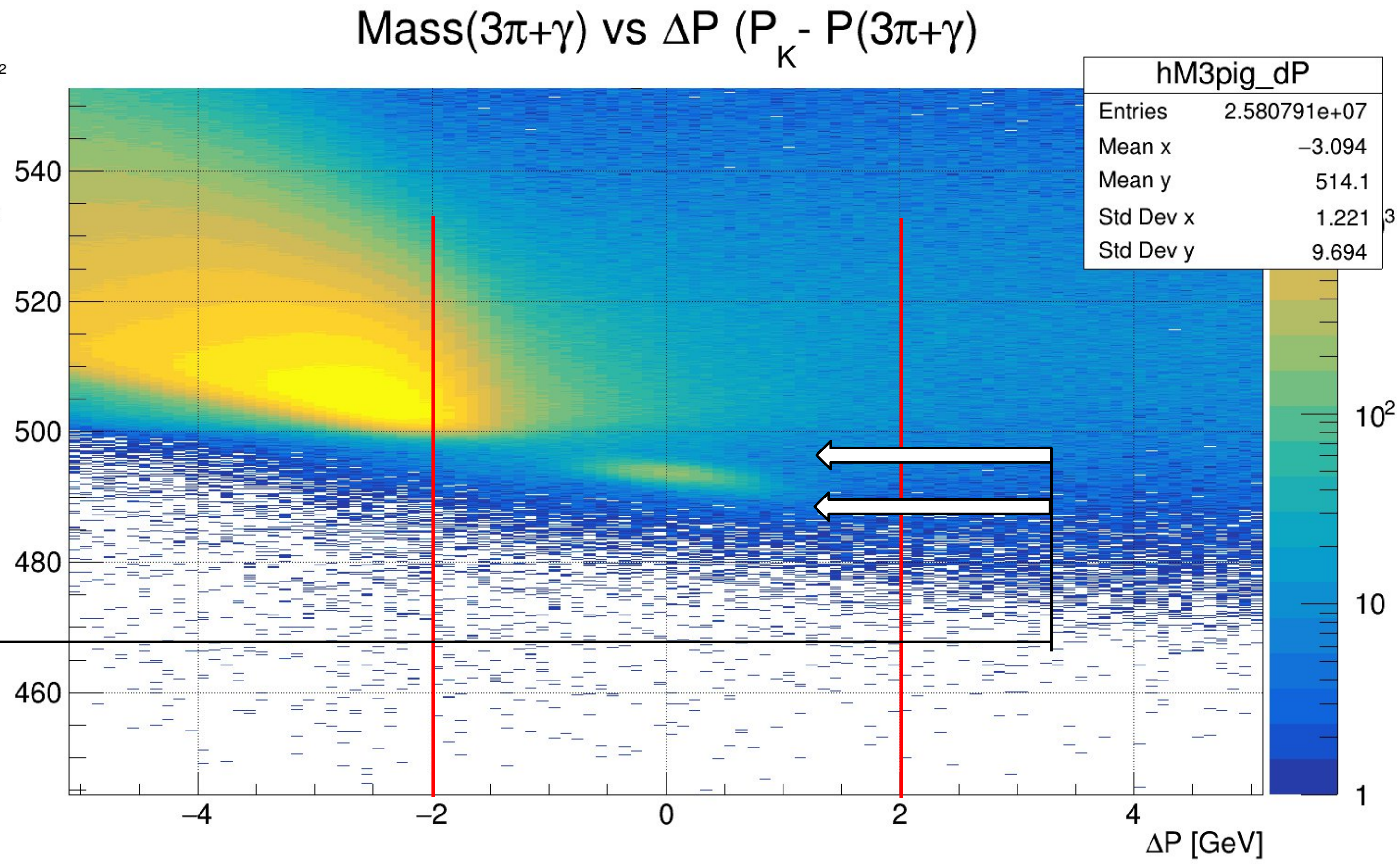




Events selection

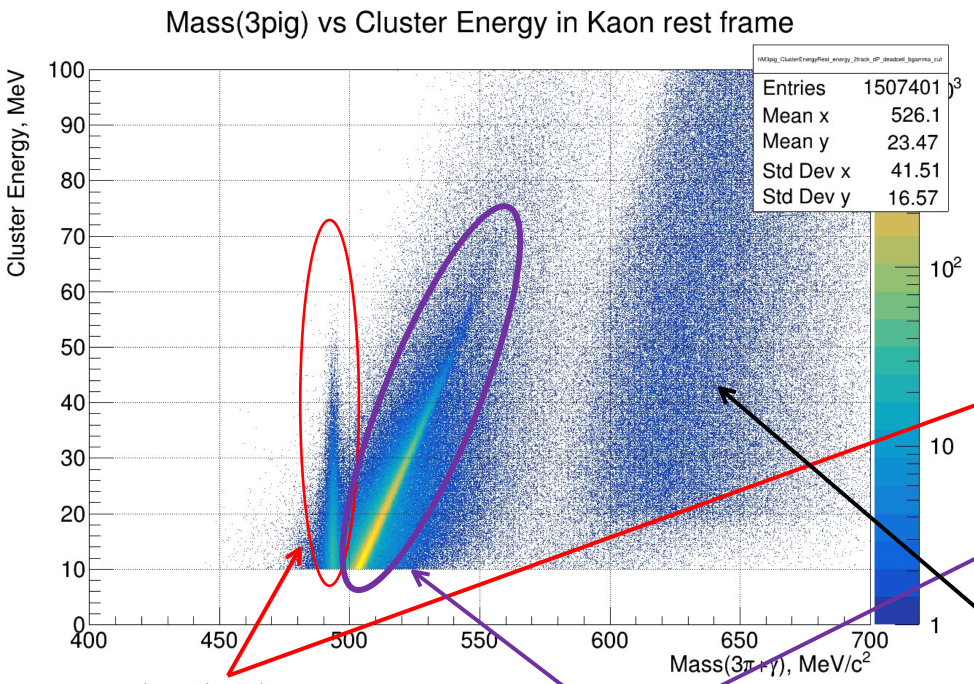


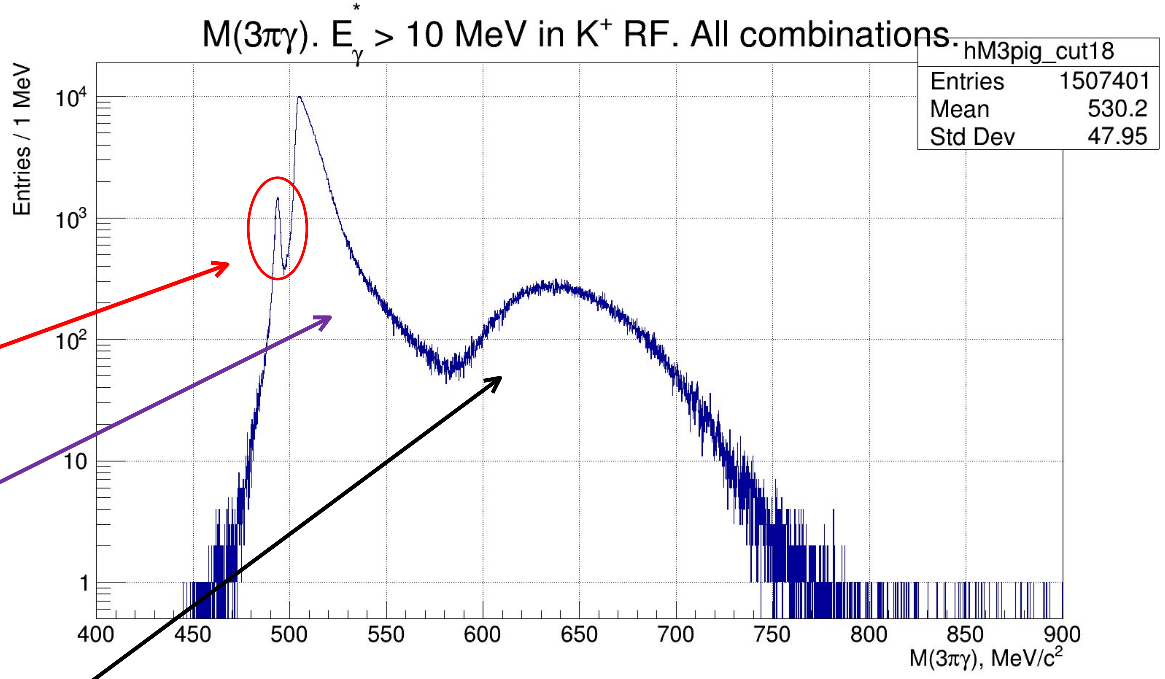
Selection condition: $|P_{3pig}\text{-}P_k| < 2$ GeV



Signal region: 490-497 MeV

Selection result

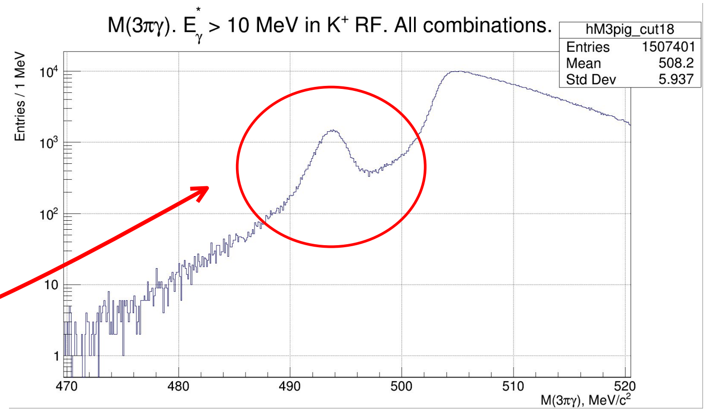




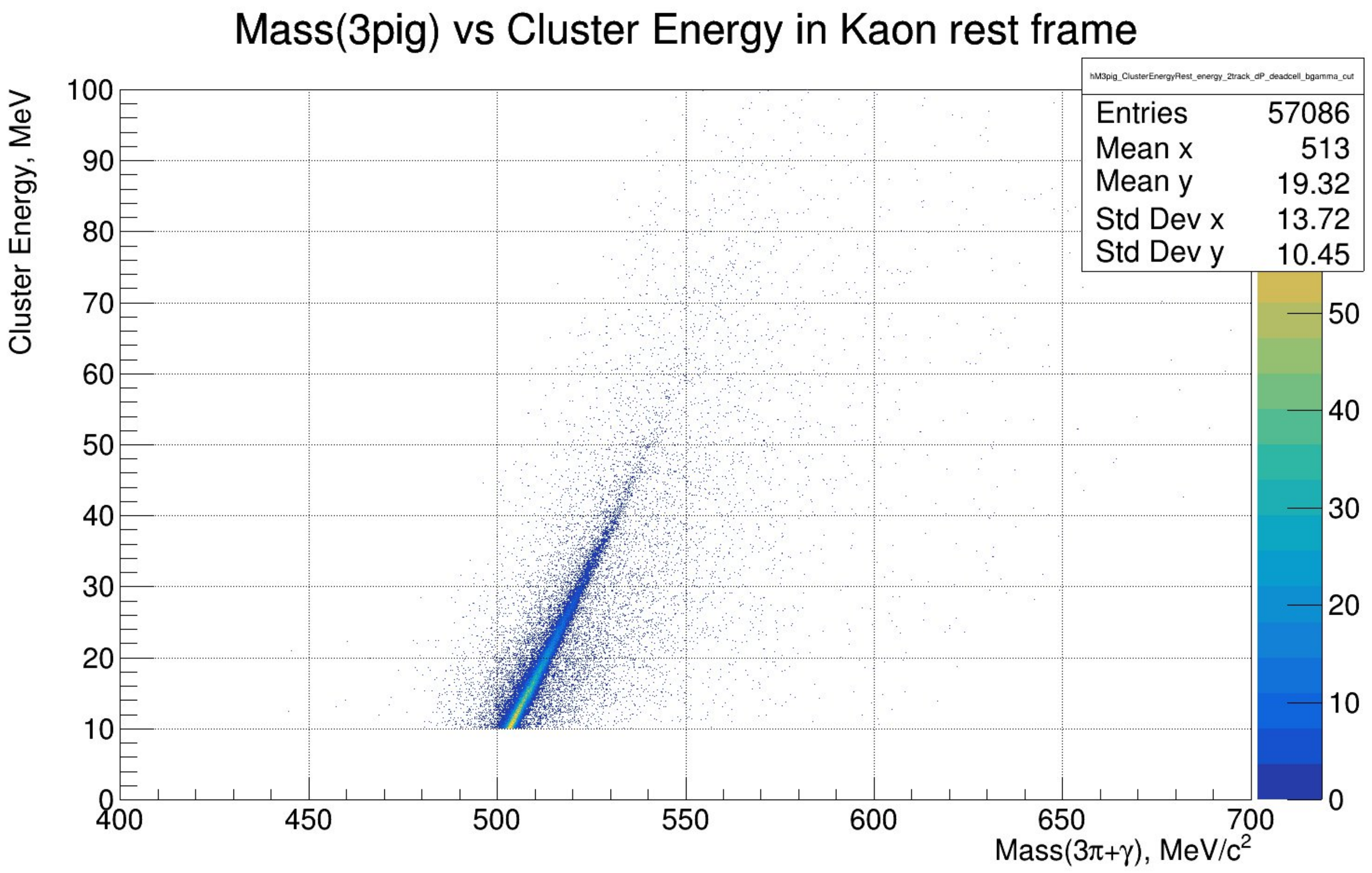
$K^+ \rightarrow \pi^+\pi^-\pi^+\gamma$

$K^+ \rightarrow \pi^+\pi^-\pi^+$

$K^+ \rightarrow \pi^+\pi^0 \rightarrow \pi^+e^+e^-\gamma$



MC (main background)



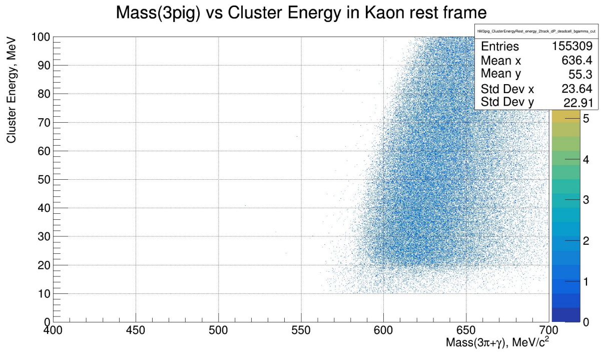
$K^+ \to \pi^+\pi^-\pi^+$

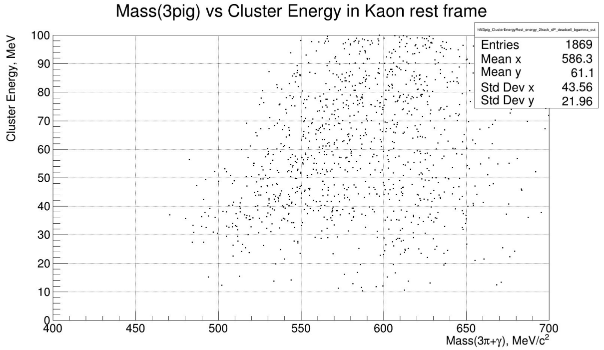
$N_{samples} = 200M$

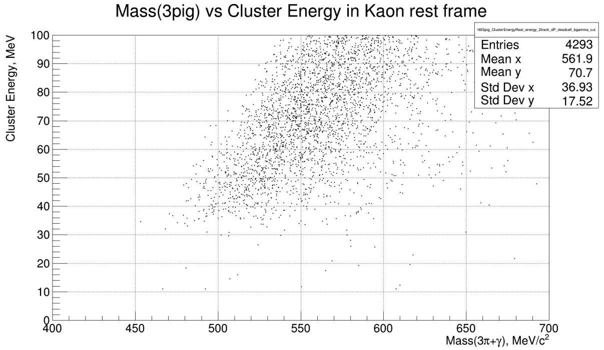
Acceptance: 2.25e-06

BR = 0.05583 ± 0.0024

MC (minor backgrounds)







$K^+ \to \pi^+\pi^0 \to \pi^+e^+e^-\gamma$

$N_{samples}$ = 20M

Acceptance: 0,000

BR = (2.427 ± 0.073)e-3

$K^+ \to \pi^+\pi^0 e^+e^-$

$N_{samples}$ = 20M

Acceptance: 6.49e-07

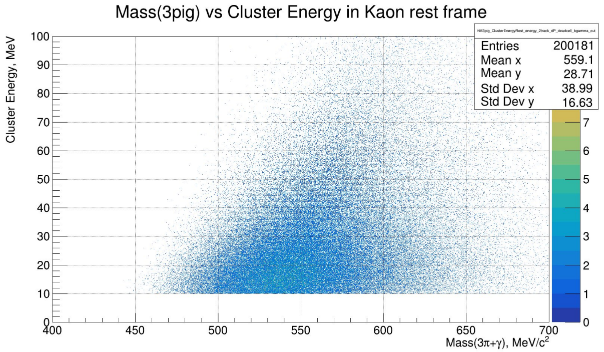
BR = (4.24 ± 0.14)e-6

$K^+ \to \pi^+\pi^0\pi^0 \to \pi^+\pi^0e^+e^-\gamma$

$N_{samples}$ = 100M

Acceptance: 1.20e-06

BR = (4.132 ± 0.269)e-4



$K^+ \to \pi^+\pi^-e^+\nu$

$N_{samples}$ = 100M

Acceptance: 4.68e-05

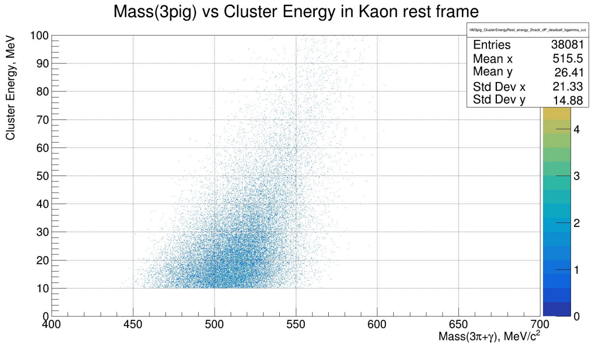
BR = (4.247 ± 0.024)e-5

$K^+ \to \pi^+\pi^-\mu^+\nu$

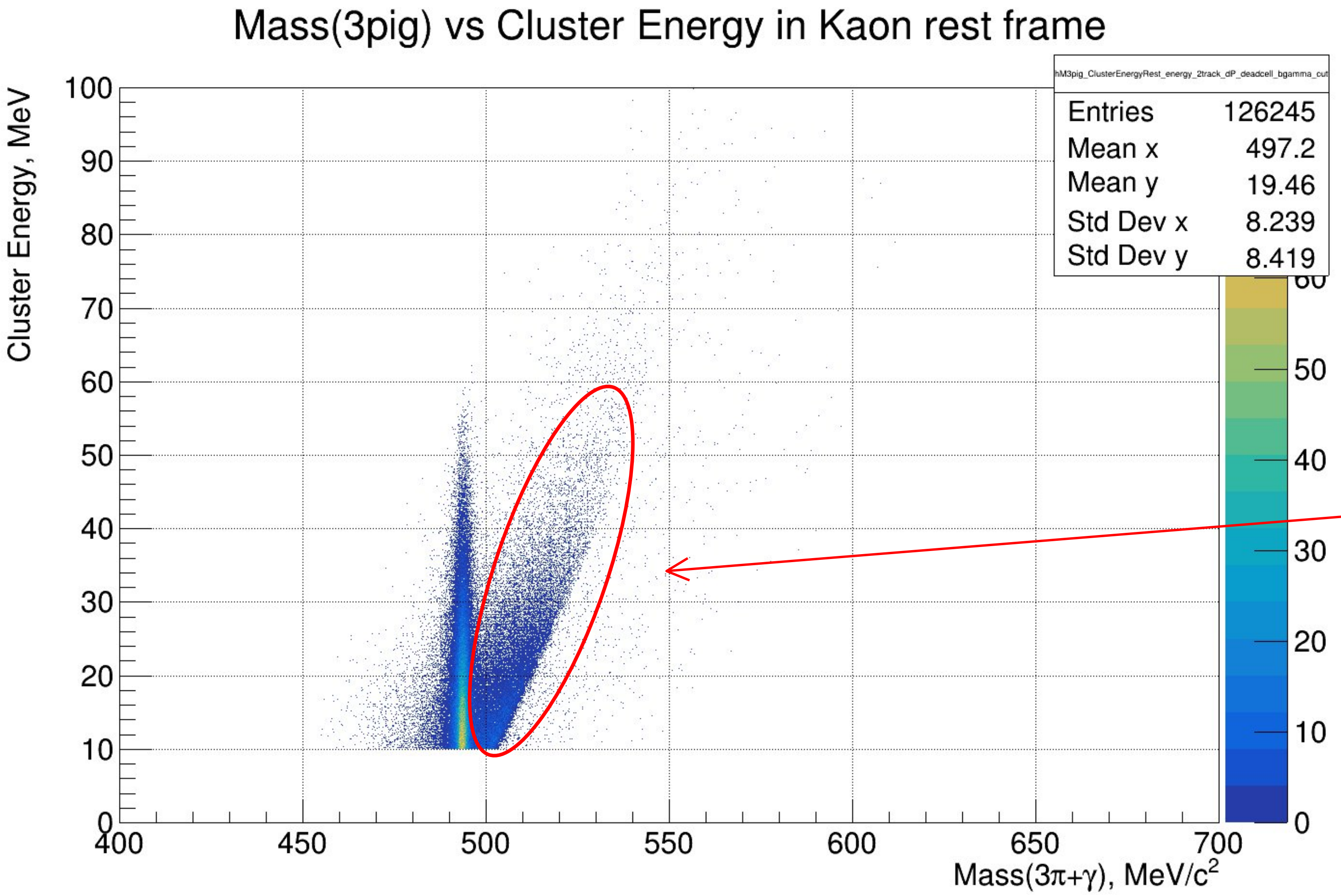
$N_{samples}$ = 10M

Acceptance: 4.34e-4

BR = (1.4 ± 0.9)e-5



MC (signal)



$K^+ \rightarrow \pi^+\pi^-\pi^+\gamma$

$N_{samples}$ = 10M

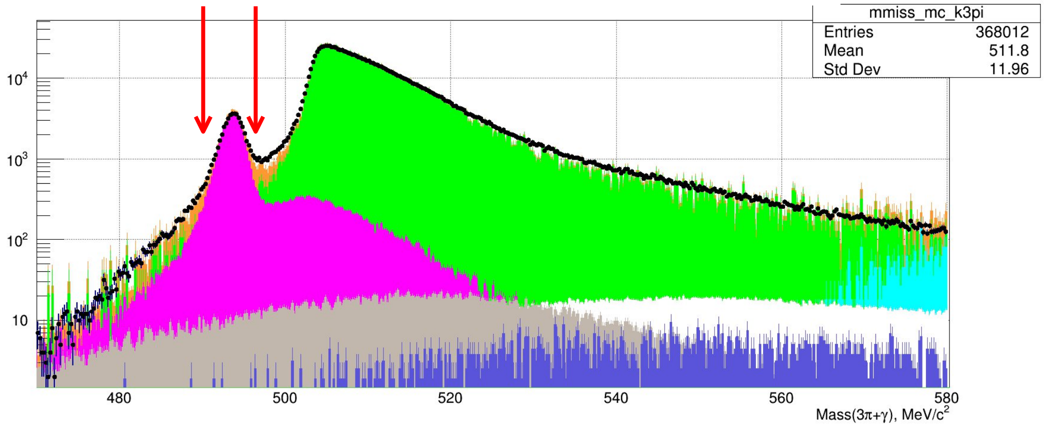
Acceptance: 0.67%

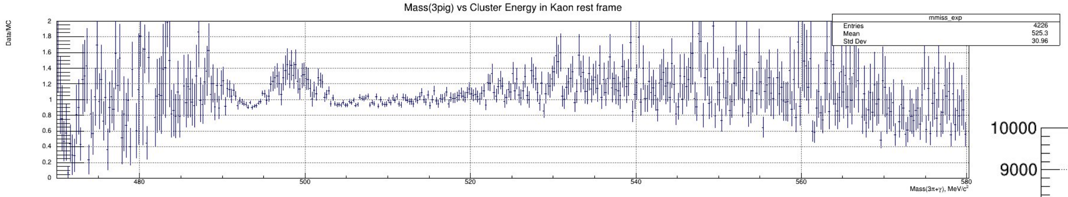
BR = *to be measured...*

Inelastic interactions between pions and setup elements that produce an extra photon?

Fitting MC and data

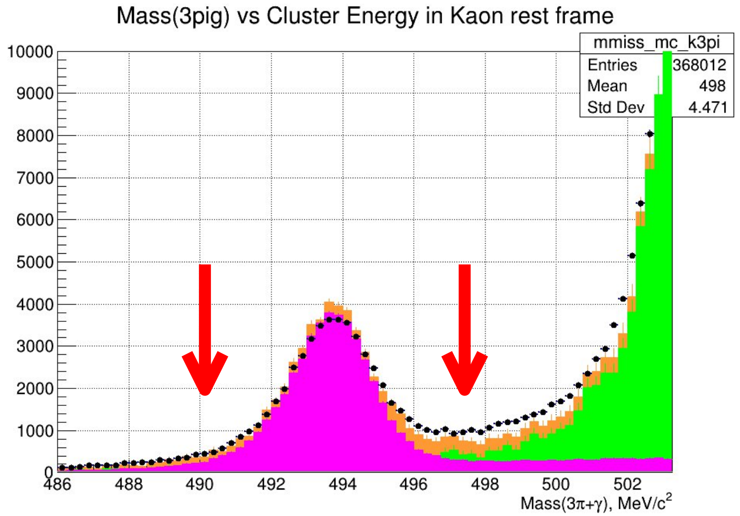
M3pig distribution



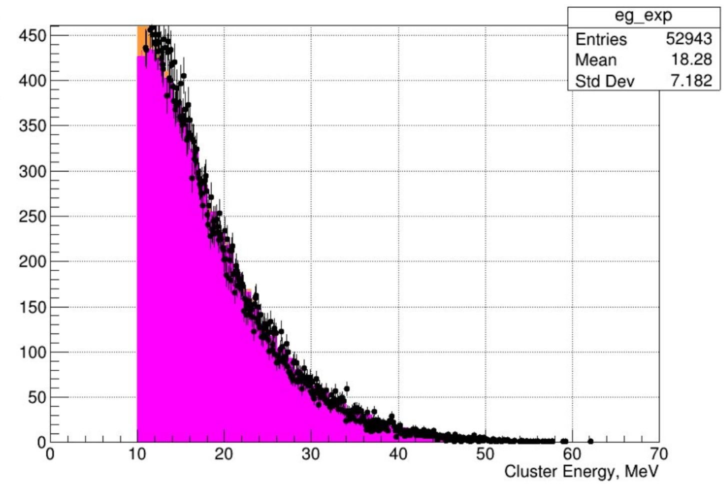


- Data
- $K^+ \to \pi^+\pi^-\pi^+\gamma$
- $K^+ \to \pi^+\pi^-\pi^+$
- $K^+ \to \pi^+\pi^0 \to \pi^+ e^+ e^- \gamma$
- $K^+ \to \pi^+\pi^0 e^+ e^-$
- $K^+ \to \pi^+\pi^0\pi^0 \to \pi^+\pi^0 e^+ e^- \gamma$
- $K^+ \to \pi^+\pi^- e^+ \nu$
- $K^+ \to \pi^+\pi^- \mu^+ \nu$

M3pig distribution



Cluster energy in a signal region
(MC is only K3pig)



$10\ \text{MeV} < E^*_\gamma < 70\ \text{MeV}$

Signal events: 52943 ± 230

Normalization

Normalizing decay: $K^+ \to \pi^+\pi^-\pi^+$.

Selection efficiency:

$$\mathrm{eff}_{3\pi\gamma} = \frac{\text{MC (selected, all cuts)}}{\text{MC gen}}$$ - K3pig selection efficiency

$$\mathrm{eff}_{3\pi} = \frac{\textit{MC (selected, no cluster cuts)}}{\textit{MC gen}}$$ - K3pi selection efficiency

$N_{3\pi\gamma} = p_0 / \mathrm{eff}_{3\pi\gamma}$ - initial events' number estimation

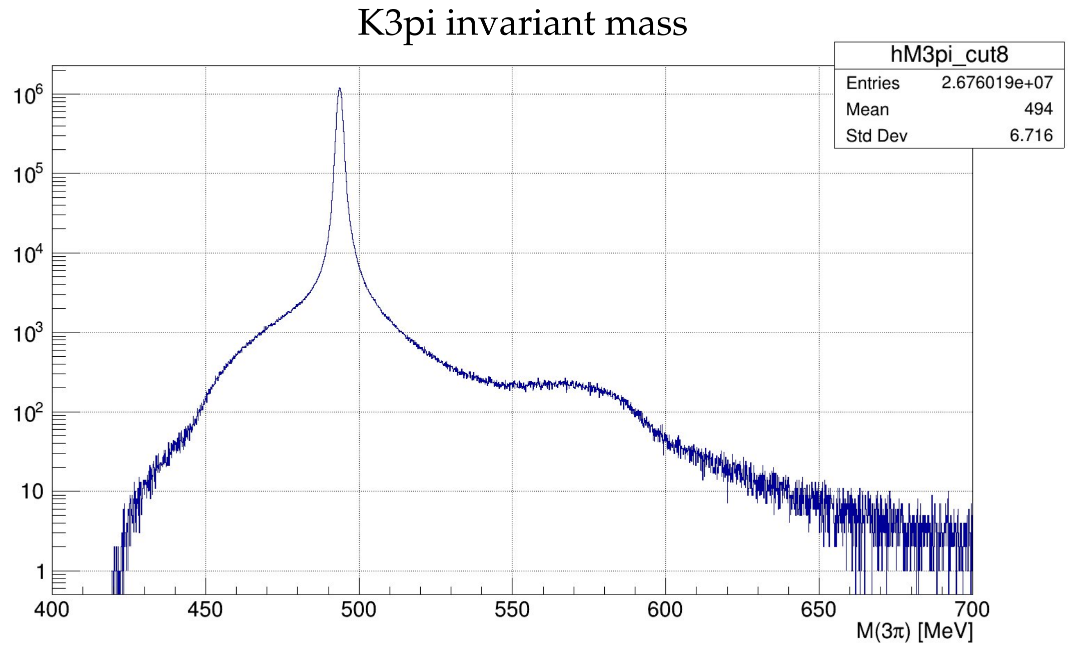
$N_{3\pi} = N_{\text{data selected, no cluster cuts}} / \mathrm{eff}_{3\pi}$

$$BR(3\pi\gamma) = BR(3\pi) \cdot \frac{N_{3\pi\gamma}}{N_{3\pi}}$$ - K3pig branching

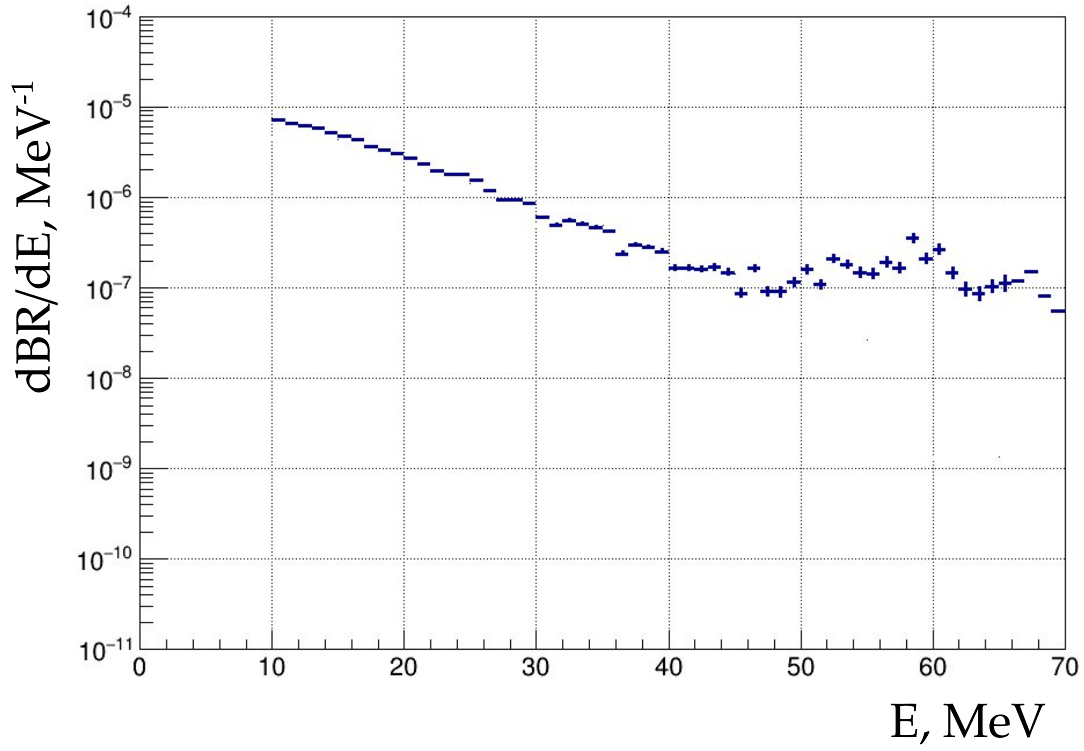
Selection of $K \to 3\pi$:

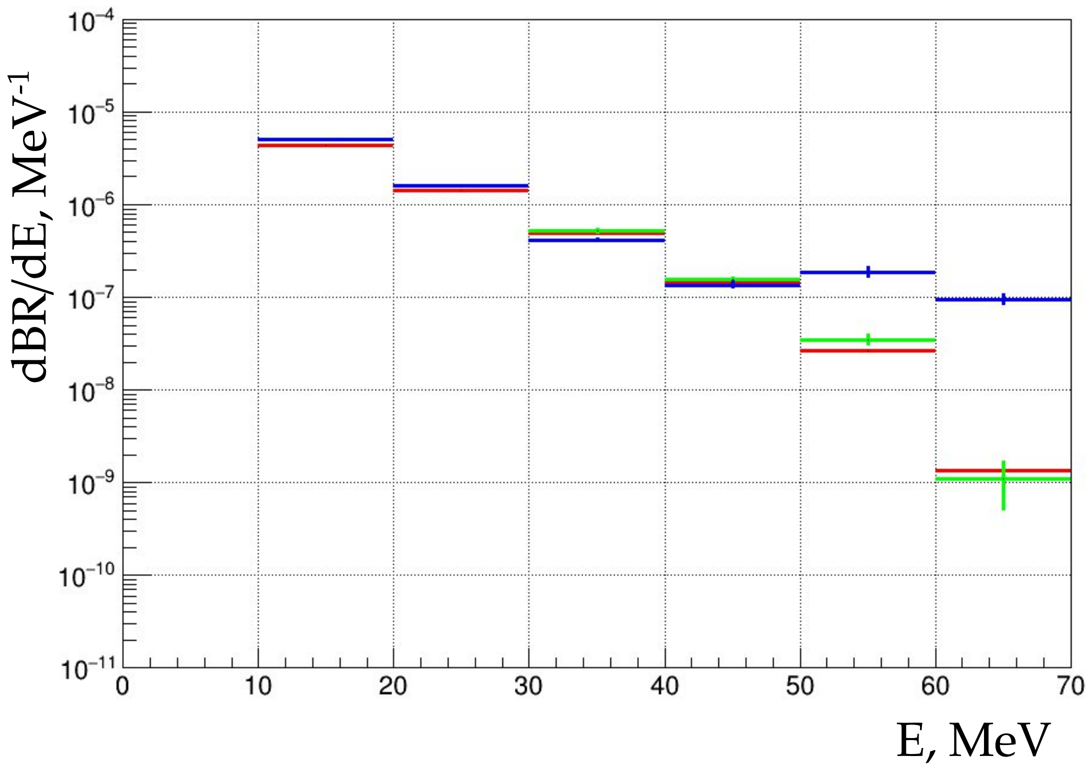
- «Multitrack» trigger to choose multitrack events: Ntracks >= 3
- Exactly one 3-track decay vertex
- Acceptance in STRAW and in a photon veto
- Total charge = +1
- For Cedar: NSectors >= 5
- GTK acceptance
- $105 < Z < 180$ m - a vertex is inside a decay volume

In other words, we use the same cuts except cluster cuts



Branching estimation (preliminary)

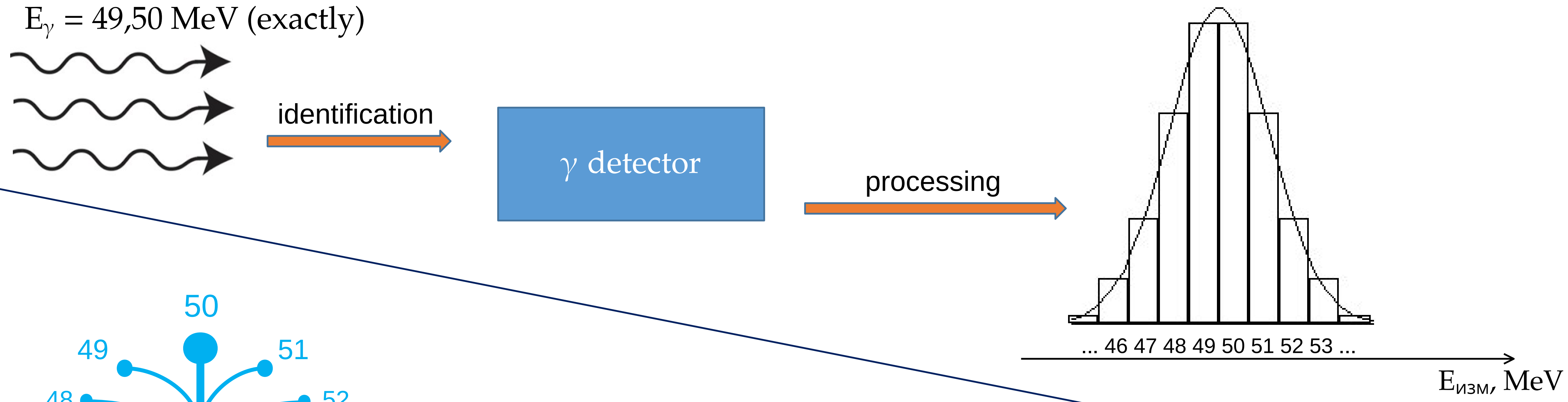


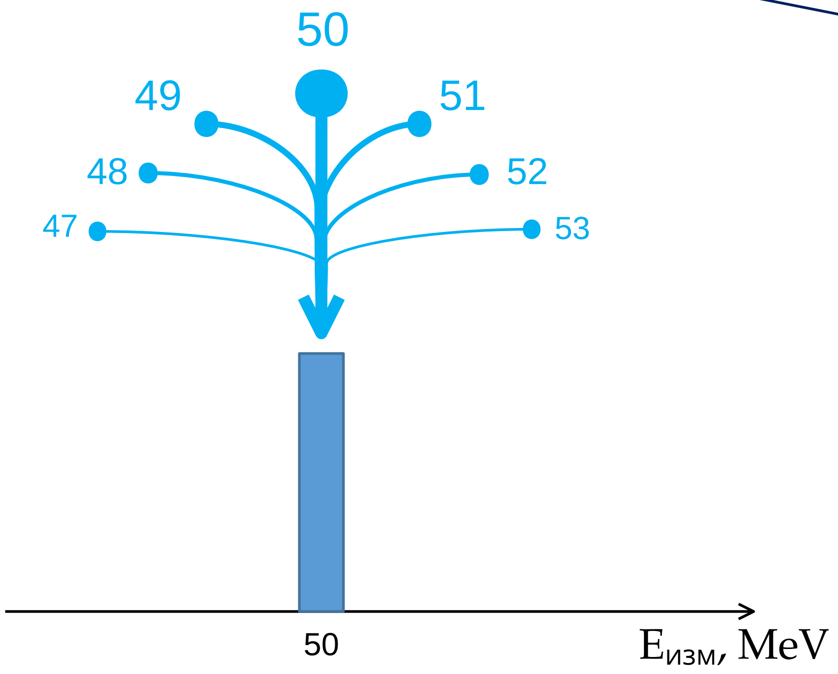


- – D’Ambrosio, ChPT
- – Shapkin, OKA
- – this, NA62

E > 10 MeV		E > 30 MeV	
D’Ambrosio:	BR = (6,46 ± 0,06)*10^{-5}	Shapkin:	BR = (0,71 ± 0,05)*10^{-5}
This:	BR = (6,39 ± 0,23)*10^{-5}	This:	BR = (0,60 ± 0,02)*10^{-5}

Unfolding procedure (theory)





While being processed, a signal unavoidably corrupts due to a resolution limit and random errors. A goal of **unfolding procedure** is to reconstruct an initial signal analytically.

Unfolding procedure (theory)

$[E_L, E_R]$ - signal range. Let's divide it into pieces: $[E_L=E_1, E_2, ..., E_n=E_R]$.

Let E be a true energy of the photon, E' is a result of processing. Therefore $P(E'|E)$ is a probability for some signal E to be registered as E'.

According to the Bayes' theorem,

$$\mathrm{P}(E_i|E') = \frac{P(E'|E_i)\cdot P(E_i)}{\sum_{l=1}^{n} P(E'|E_l)\cdot P(E_l)} \tag{1}$$

Also, if one observes $n(E')$ signal events, they can be assigned to the initial cause as

$$\tilde{n}(E_i) = n(E')\cdot P(E_i|E') \tag{2}$$

Considering that there is a range of observable signals $\{E'_i\}$, there can be written a *smearing matrix* that describes a migration of values based on (1):

$$\mathrm{P}(E_i|E'_j) = \frac{P(E'_j|E_i)\cdot P(E_i)}{\sum_{l=1}^{n} P(E'_j|E_l)\cdot P(E_l)} \tag{3}$$

Unfolding procedure (theory)

$$P(E_i|E'_j) = \frac{P(E'_j|E_i) \cdot P(E_i)}{\sum_{l=1}^{n} P(E'_j|E_l) \cdot P(E_l)} \tag{3}$$

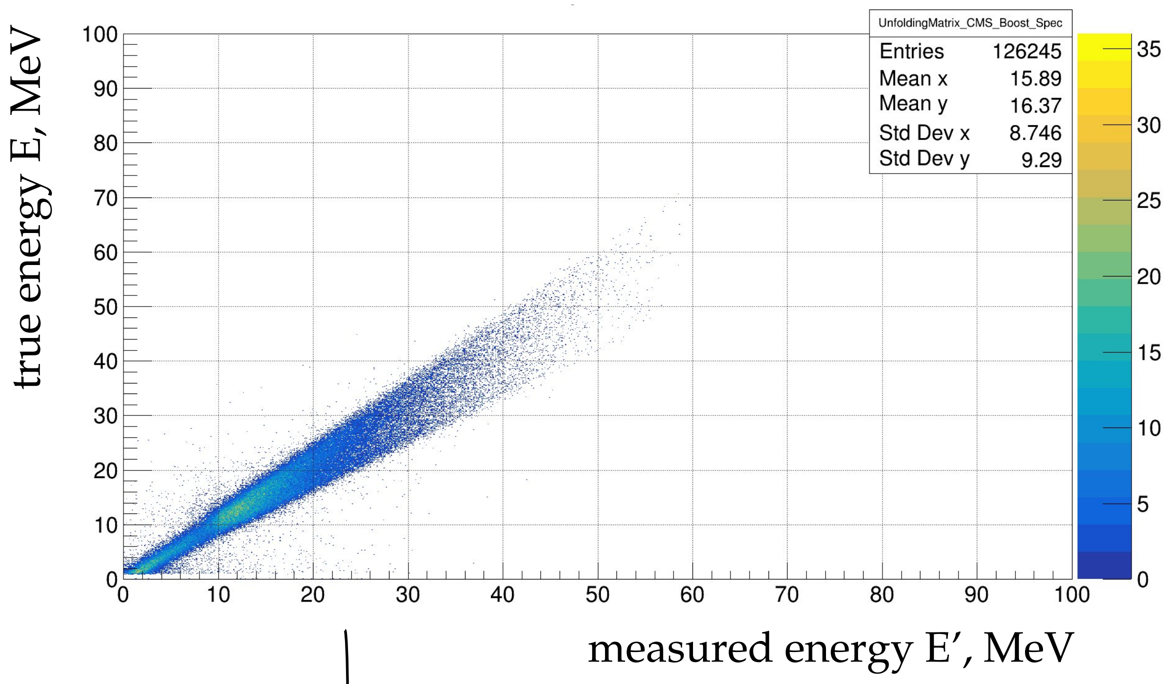
We keep in mind that $\sum_i P(E_i) = 1$ and $\sum_i P\left(E_i|E'_j\right) = 1$. Finally, we get a full number of initial events:

$$\tilde{N}(E_i) = \sum_j n(E'_j) \cdot P(E_i|E'_j) \tag{4}$$

$P(E_i|E'_j)$ form a *matrix of unfolding* that makes it possible to reconstruct the initial distribution of a signal.

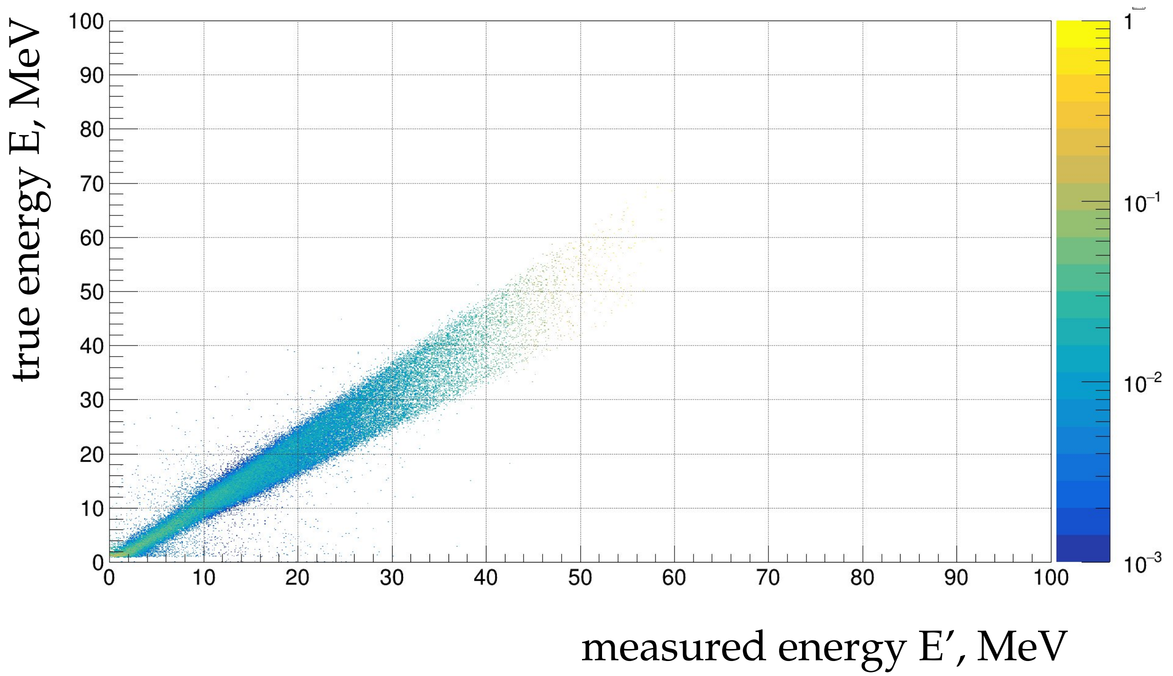
Unfolding procedure (realization)

Let's use our MC. We may get true values $\{E_i\}$ from *mctrue* and $\{E'_i\}$ are results of an analysis.

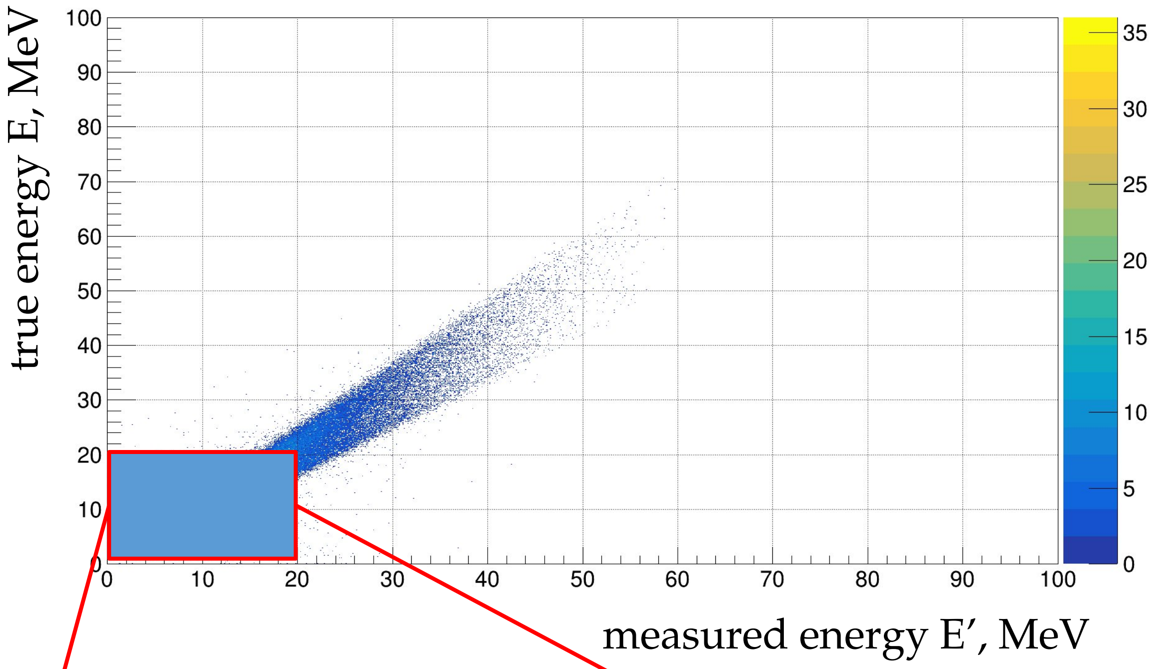


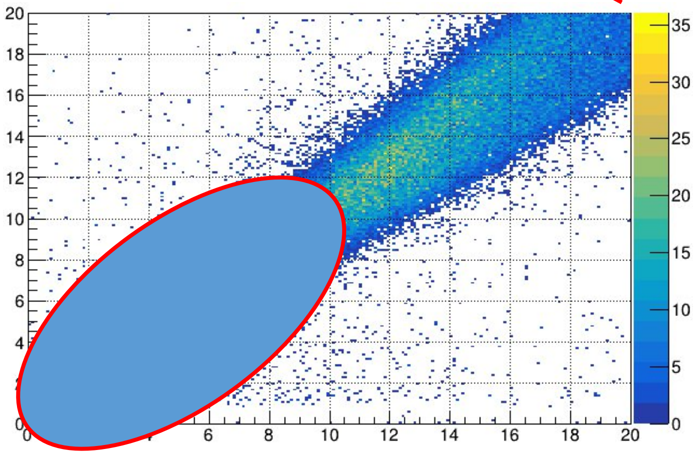
To get a matrix that we need, each column should be normalized by 1.

This is a $P(E_i|E'_j)$ plot:

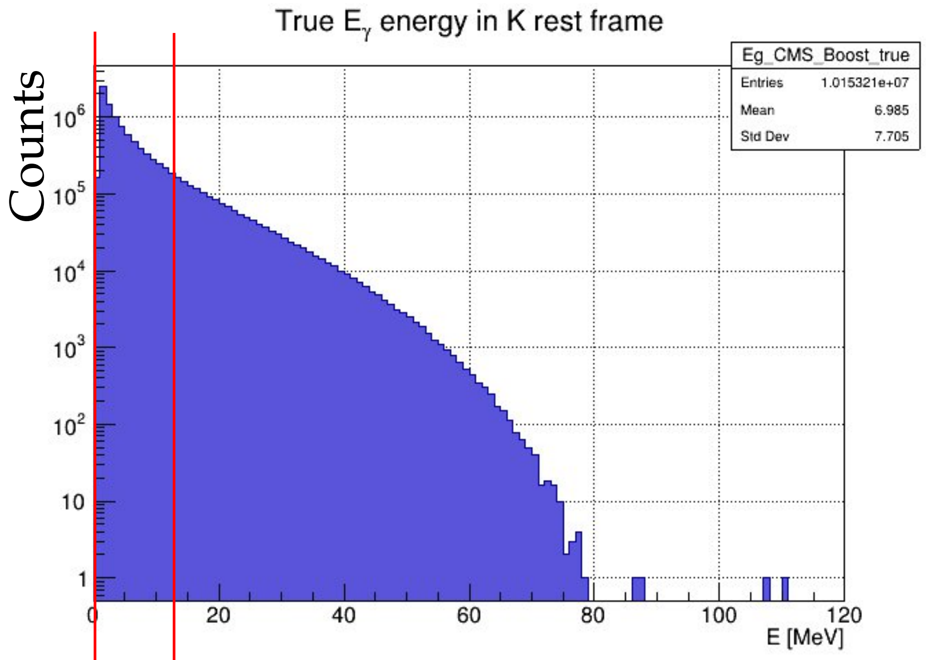


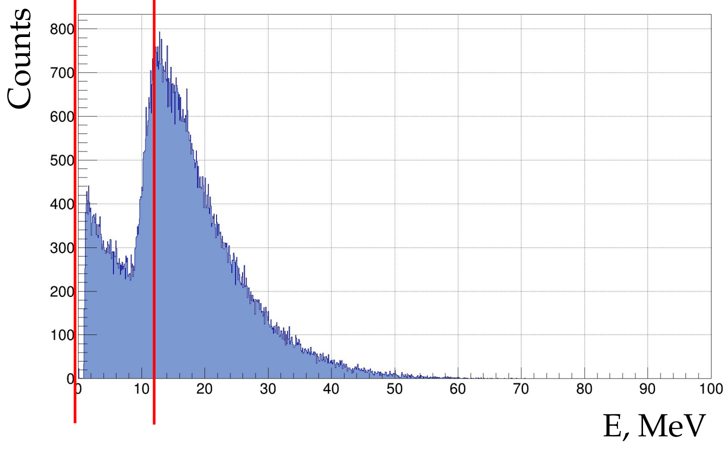
Unfolding procedure (realization)



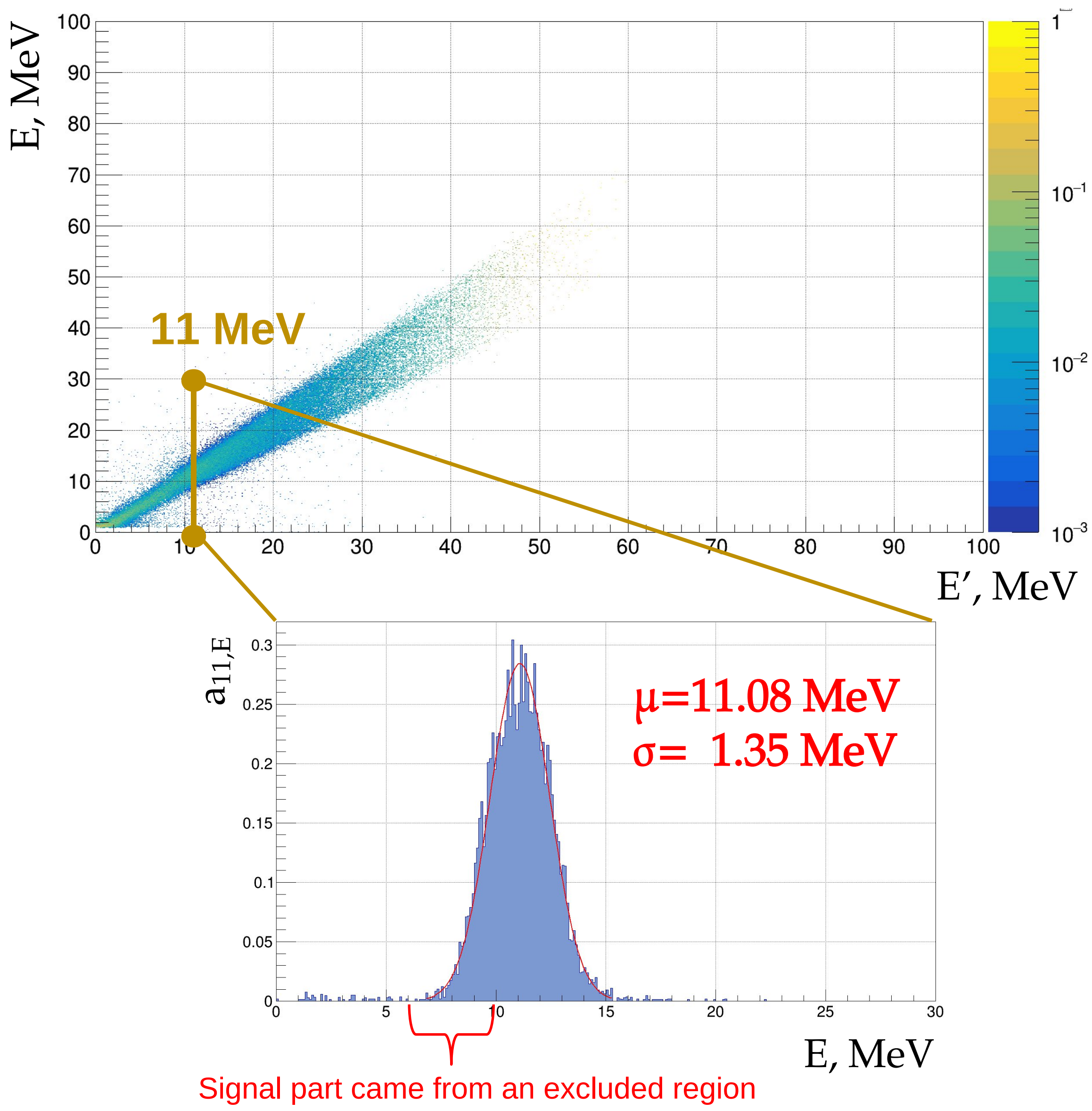


E_{γ} < 10 MeV region was excluded from an analysis. But photons from that region still can affect left end of a distribution.



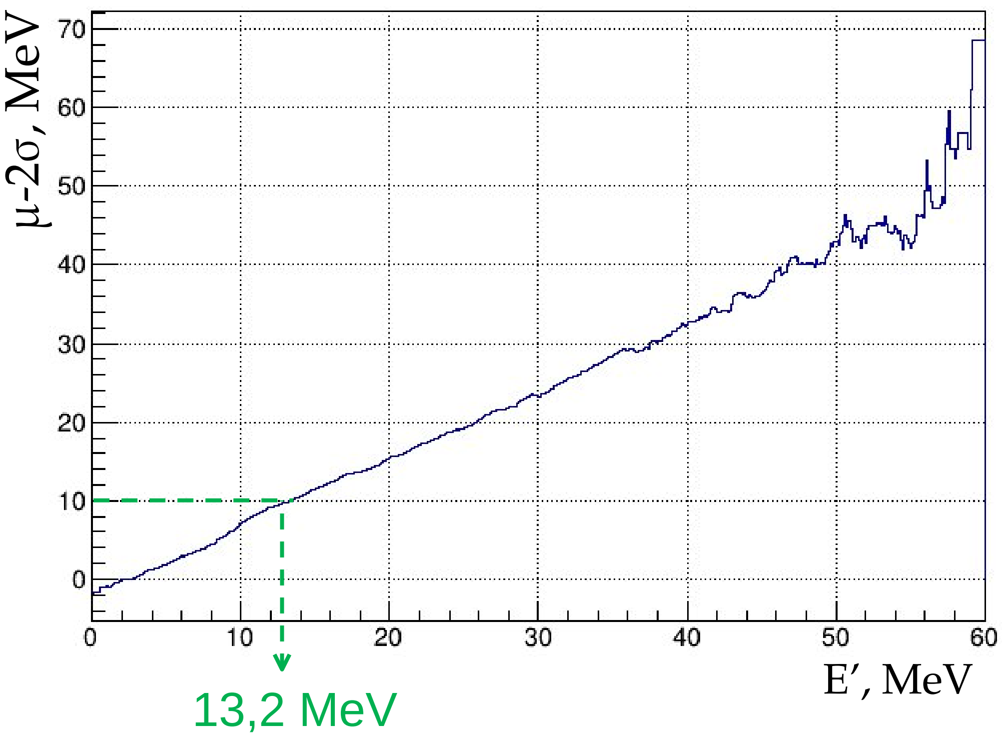


Unfolding procedure (realization)



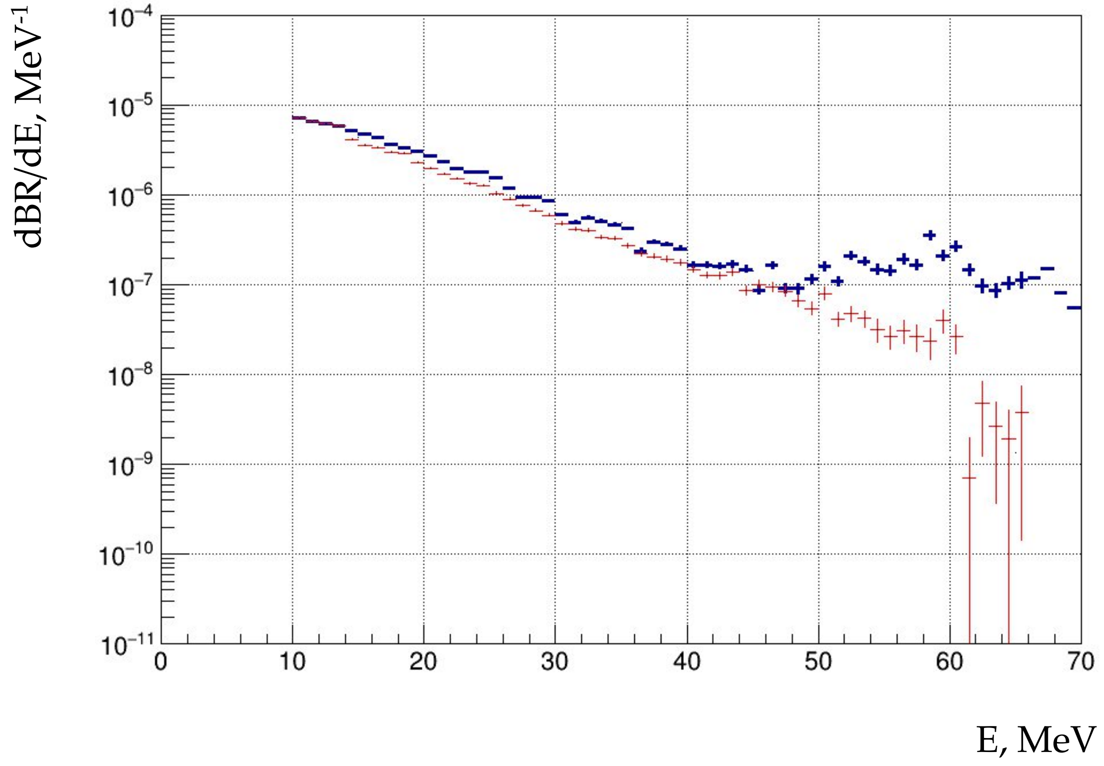
I decided not to use unfolding in a region that is affected by excluded photons (E_γ < 10 MeV).

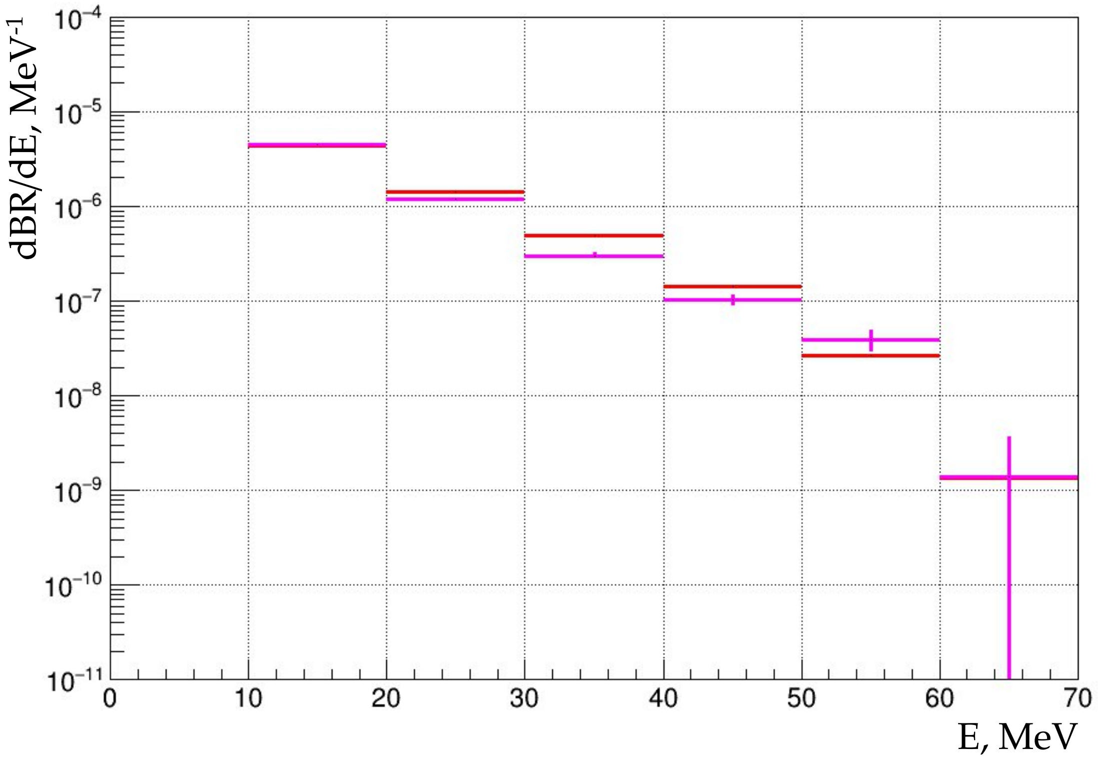
Selection condition: **μ-2σ > 10 MeV.**



Result: unfolding is applied to E ≥ 14 MeV only

Braching (after unfolding, preliminary)





- – D'Ambrosio, ChPT
- – this, NA62
- – this, NA62, <u>final result</u>

<u>E > 10 MeV</u>

D'Ambrosio: BR = $(6{,}46 \pm 0{,}06) * 10^{-5}$

This: BR = $(6{,}39 \pm 0{,}21) * 10^{-5}$

Thank you for your attention!

TOC: