Experimental study of nuclear fusion reactions in a ptμ system (TRITON)

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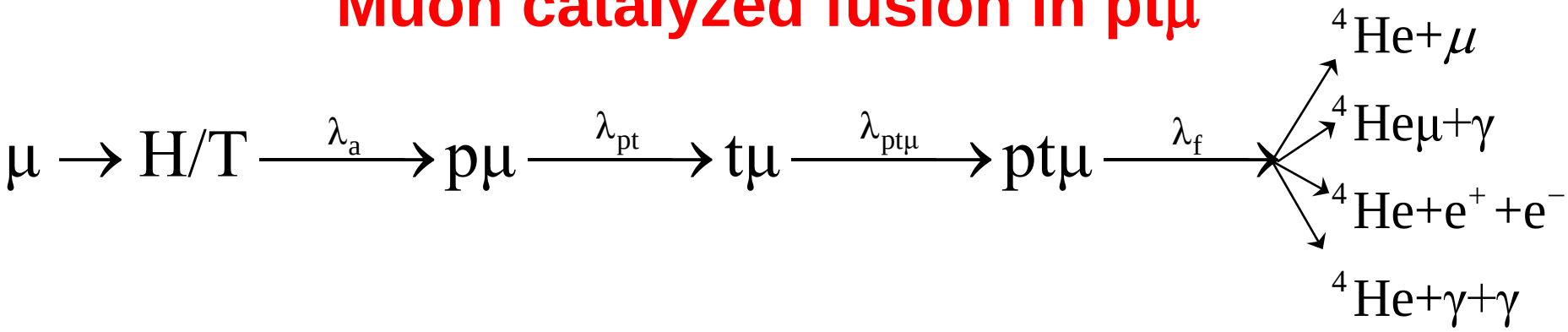
Muon catalyzed fusion in ptμ



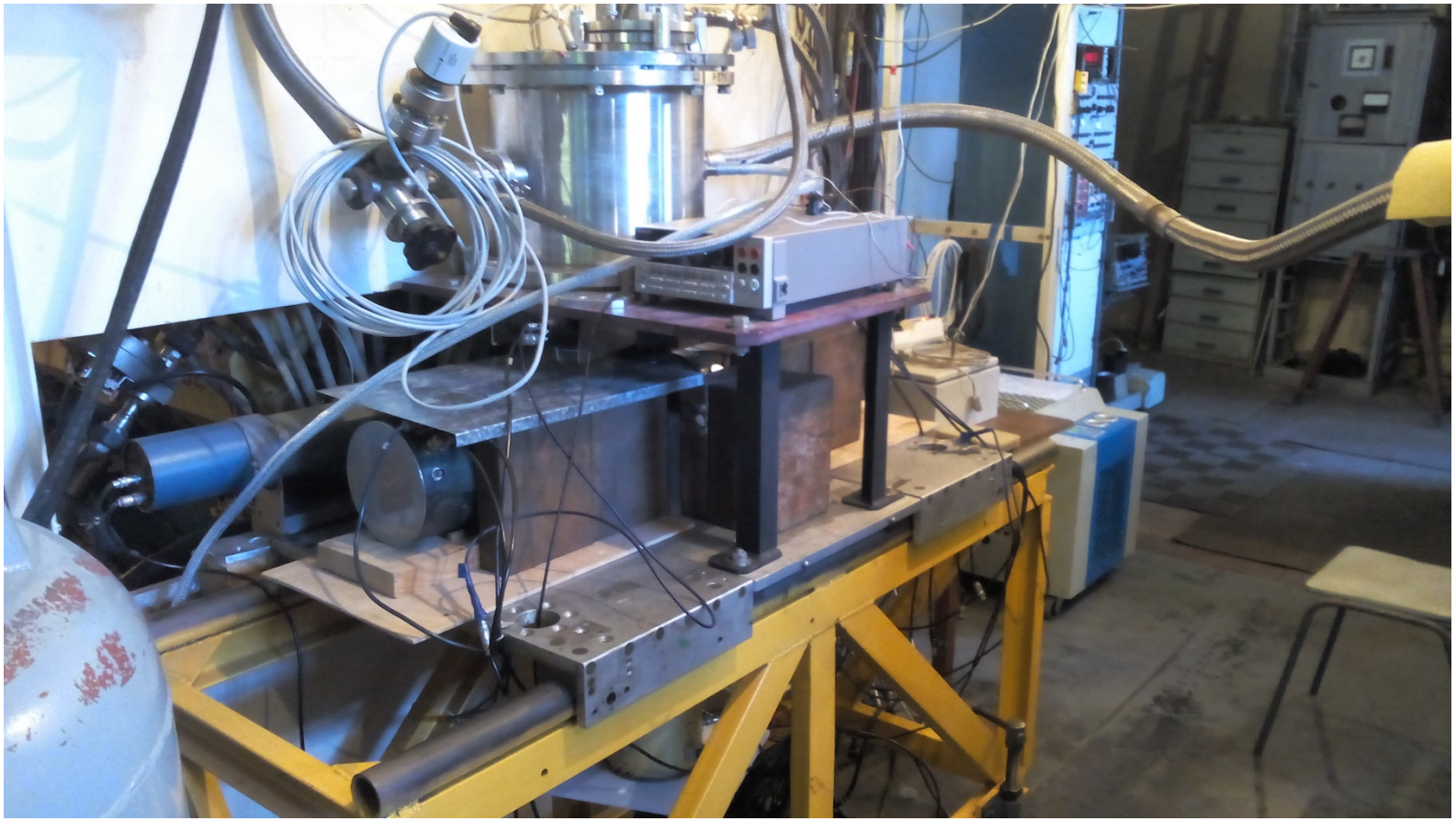
1. ptμ → ^{4}Heμ+γ+19.8 MeV,
2. ptμ → ^{4}He + μ+19.2 MeV,
3. ptμ → ^{4}Heμ+e^++e^-+ 18.8 MeV,
4. ptμ → ^{4}Heμ + γ+γ + 19.8 MeV.

TRITON installation

The experimental complex TRITON was created earlier in cooperation between the Russian Federal Nuclear Center (VNIIEF, Sarov) and the Laboratory of Nuclear Problems (JINR, Dubna).

Since 1996 the comprehensive measurements of muon catalysis parameters in **D/T** and **H/D/T** mixtures have been carried out by use of TRITON at the Phasotron in Dubna and were awarded the JINR First Prize.

The recent published results of experiments with muons in pure tritium (**t + t** $\rightarrow$ **^{4}He + n + n**) and deuterium (**d + d** $\rightarrow$ **^{4}He + γ).**



- The 50cc cryogenic target filled with liquid H/T mixture was exposed to the negative muon beam (10^4 s^{-1}, 100 MeV/c) of JINR Phasotron in 2016.
- Run-time duration is 270 h. (Thanks to PAC'16 for extension)
- The experiment is aimed at measuring the product yields of the pt-reactions: γ-quanta, conversion muons and e^+e^- pairs.

Experimental installation:

1-3 – plastic counters,

BGO – BGO crystal,

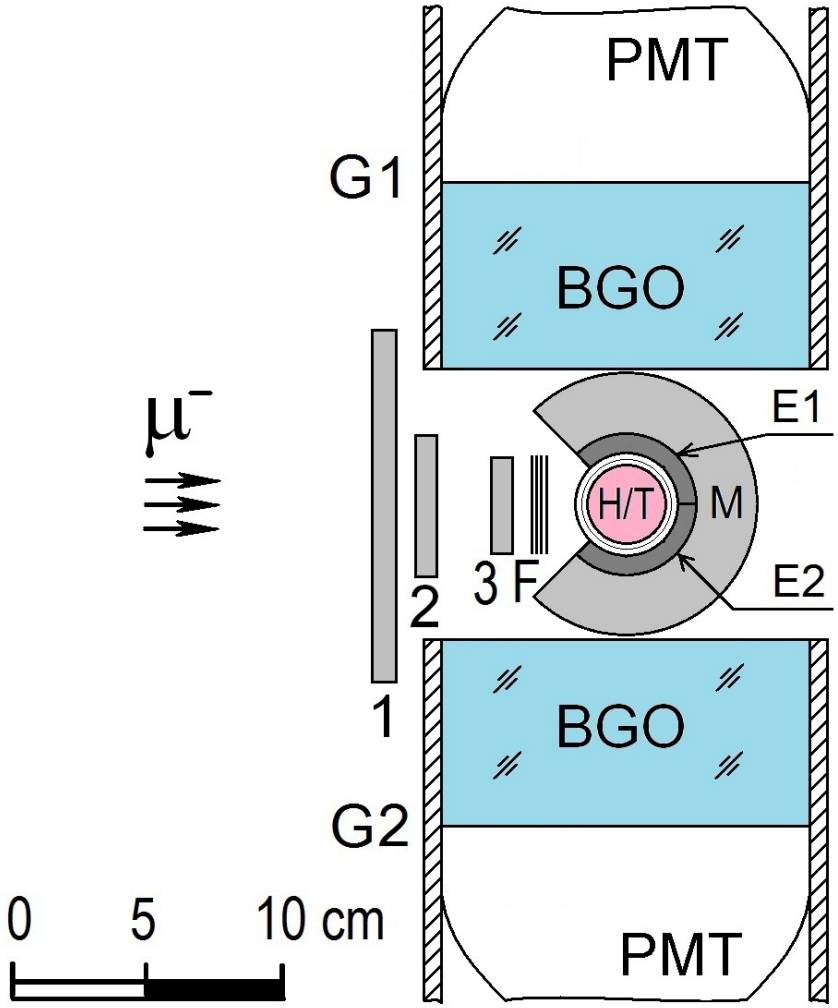
E1-E2 – electron telescope,

F – copper degrader,

G1-G2 – gamma-detector,

H/T – target,

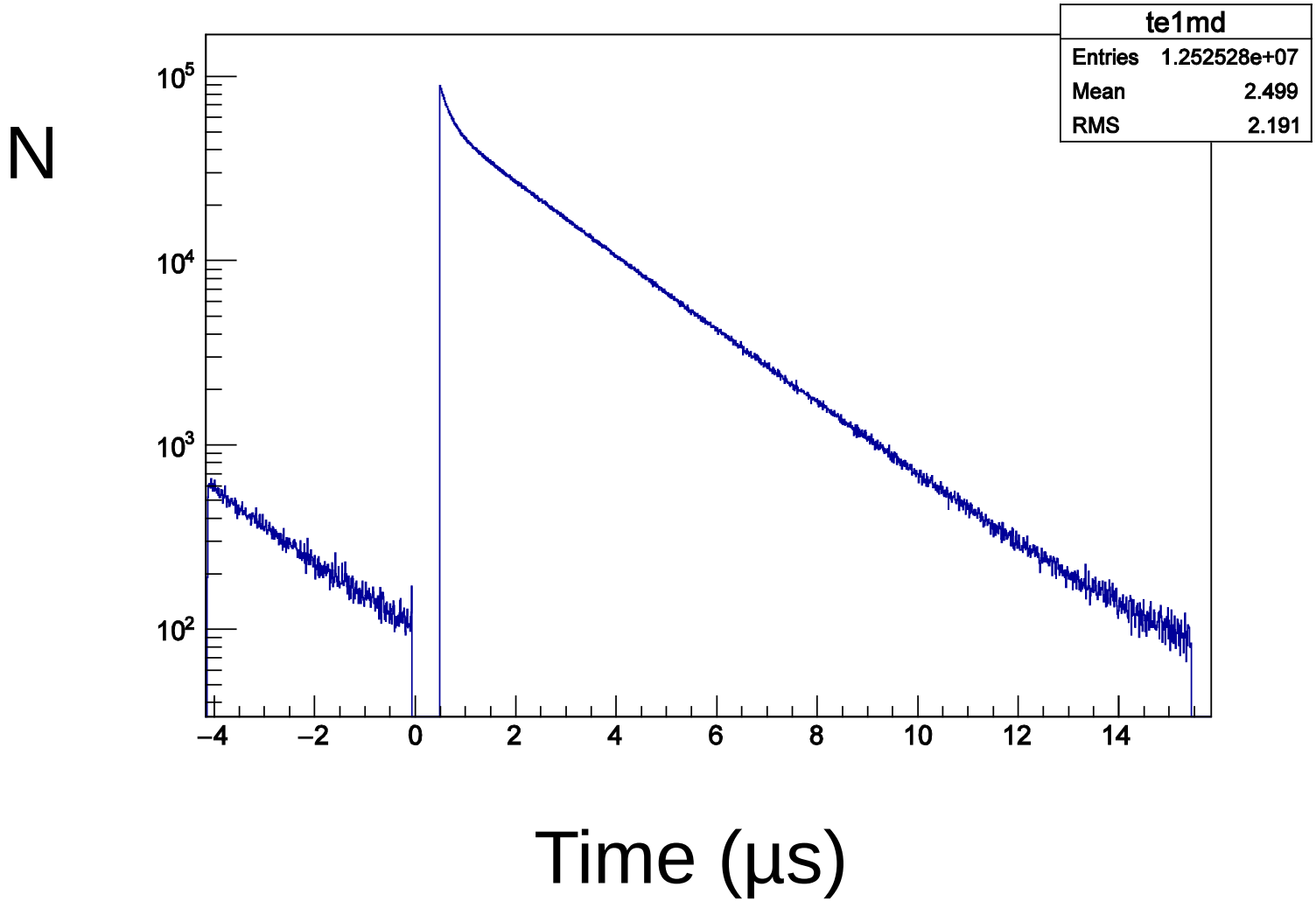
M – conversion muon detector



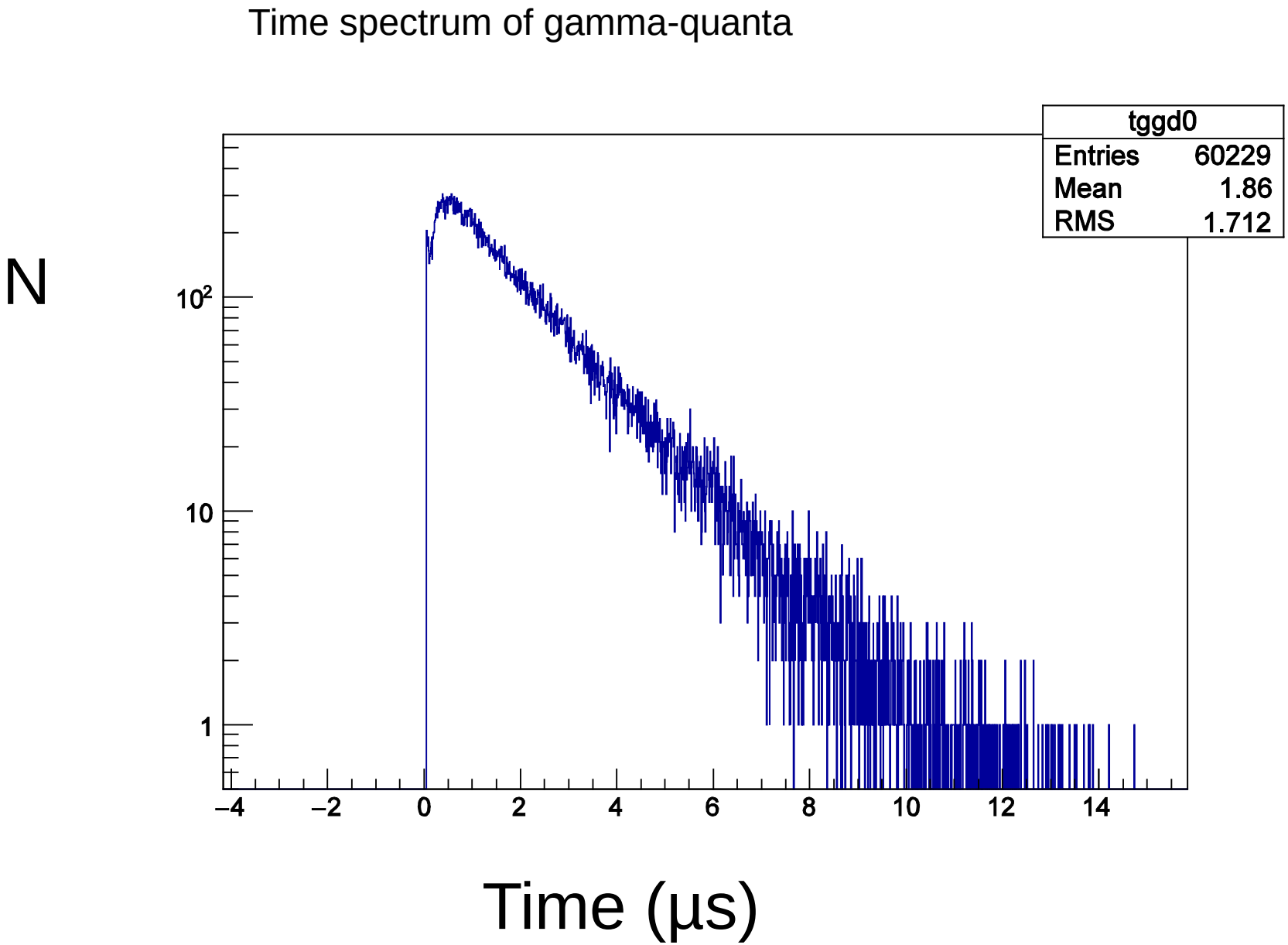
Experimental spectra

Time spectrum of μ-decay electron is used for normalization

$$N_e^{\text{total}}(t) = A_e \exp(-\lambda_e t) + k\, B_{\text{empty}}(t) + F$$

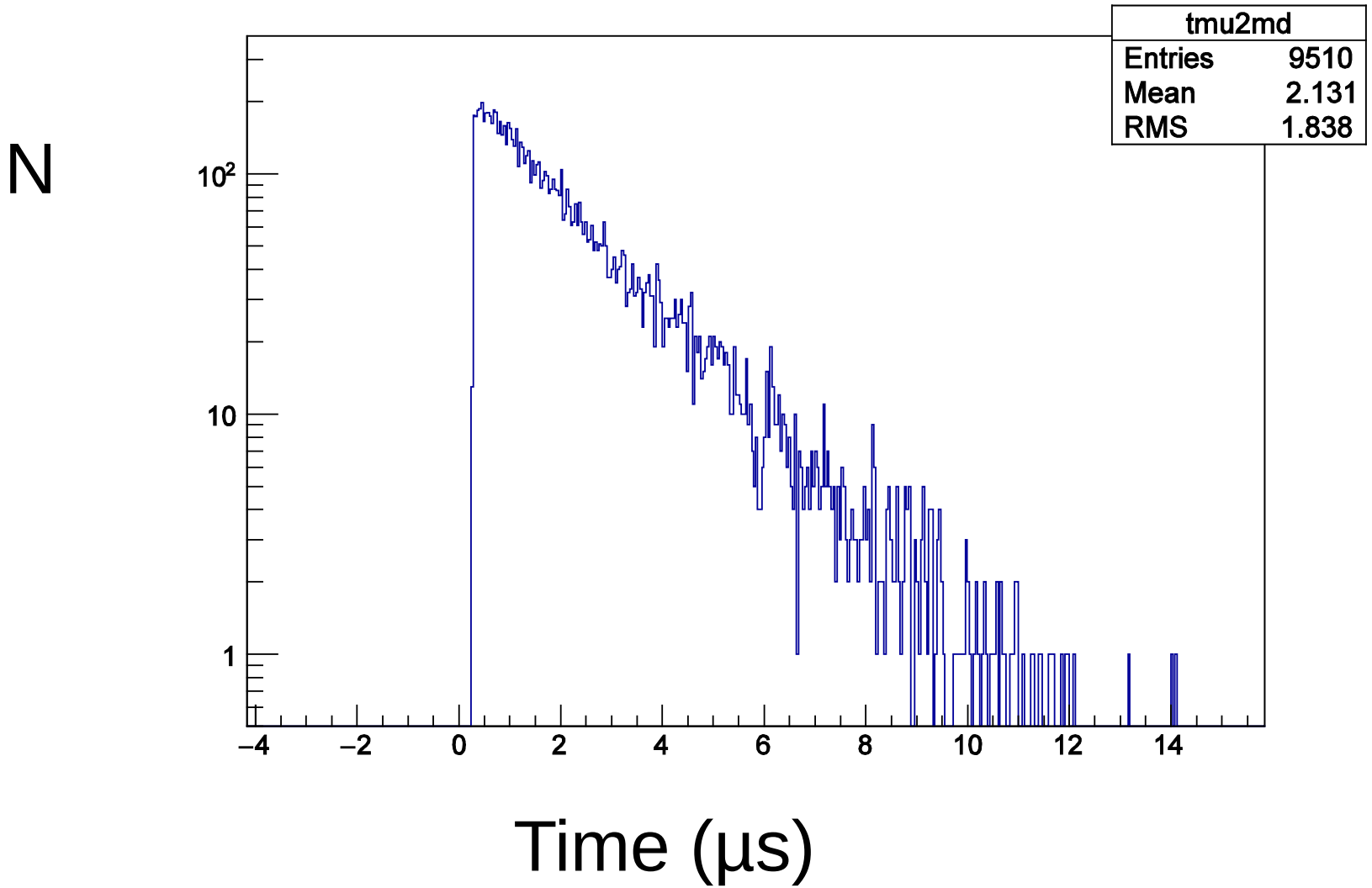


Experimental spectra:



Experimental spectra:

Time spectrum of conversion muons



Comparison of the rates of the nuclear reaction from the analysis of time spectra:

The preliminary results of TRITON experiment (2017)

λ_{pt}^{γ} (I_{pt}=1) = 0.065±0.004(stat) μs^{-1}(fusion rate)

λ_{pt}^{μ} (I_{pt}=0) = 0.11±0.01(stat) μs^{-1} (muon conversion rate)

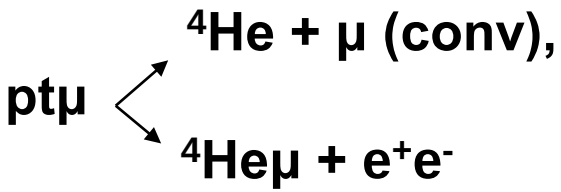
PSI results (Hartmann 1993)

λ_{pt}^{γ} (I_{pt}=1) = $0.067 \pm 0.002_{-0.002}^{+0.005}$ μs^{-1}(fusion rate)

λ_{pt}^{μ} (I_{pt}=0) = 0.15±0.02 μs^{-1} (muon conversion rate)

Registration of yields of paired particles

One of the goals of our experiment was detecting the yield of $\mathbf{e^+e^-}$ pairs, which were not observed in pt-fusion either in the PSI experiment with **ptμ** molecule



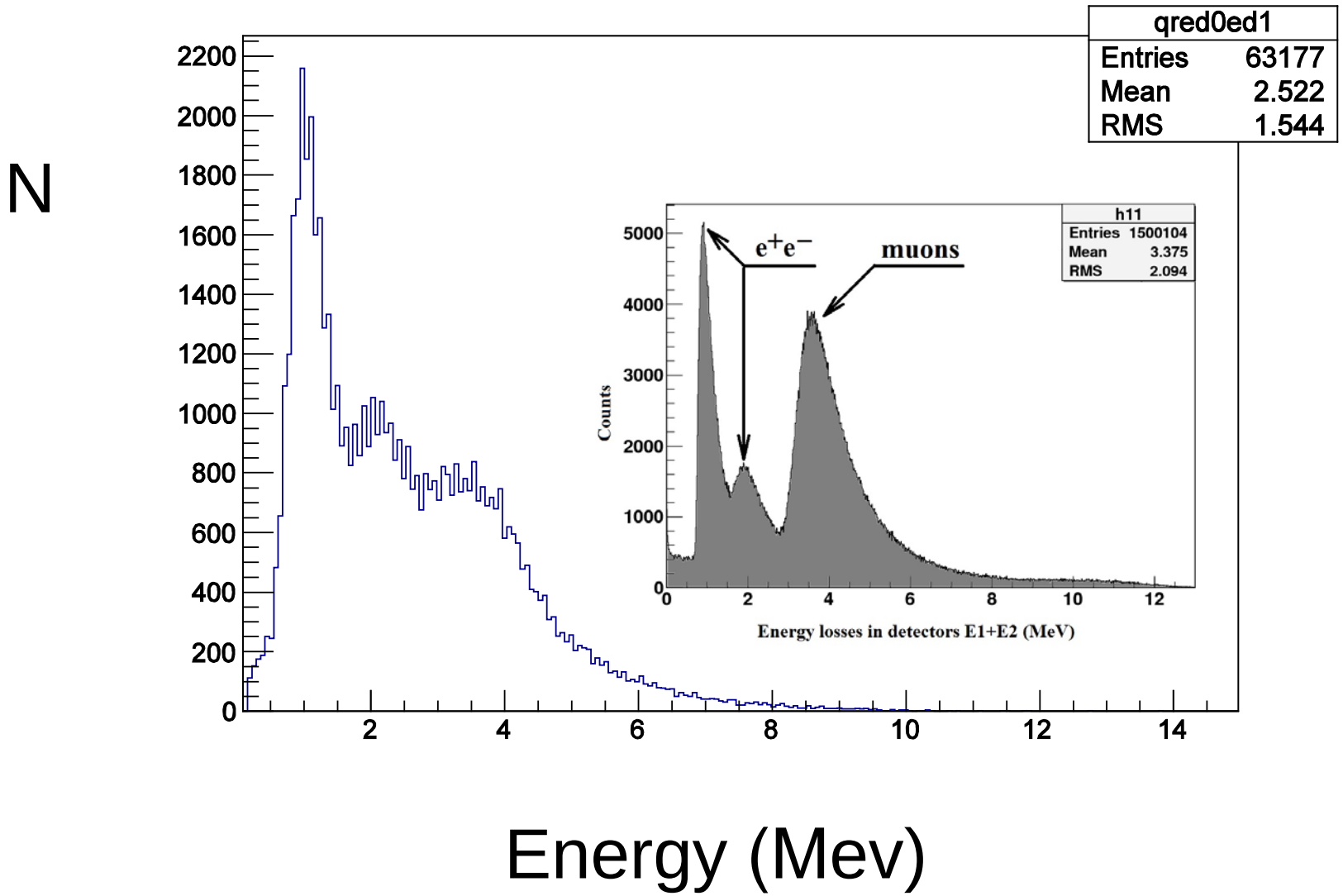
or in beam-target experiments.

The ratio of the yield of pairs to the output of conversion muons

$$R = \frac{Y_{\mu}}{Y_{e^+e^-}} = 0.73 \quad \text{(theory)}$$

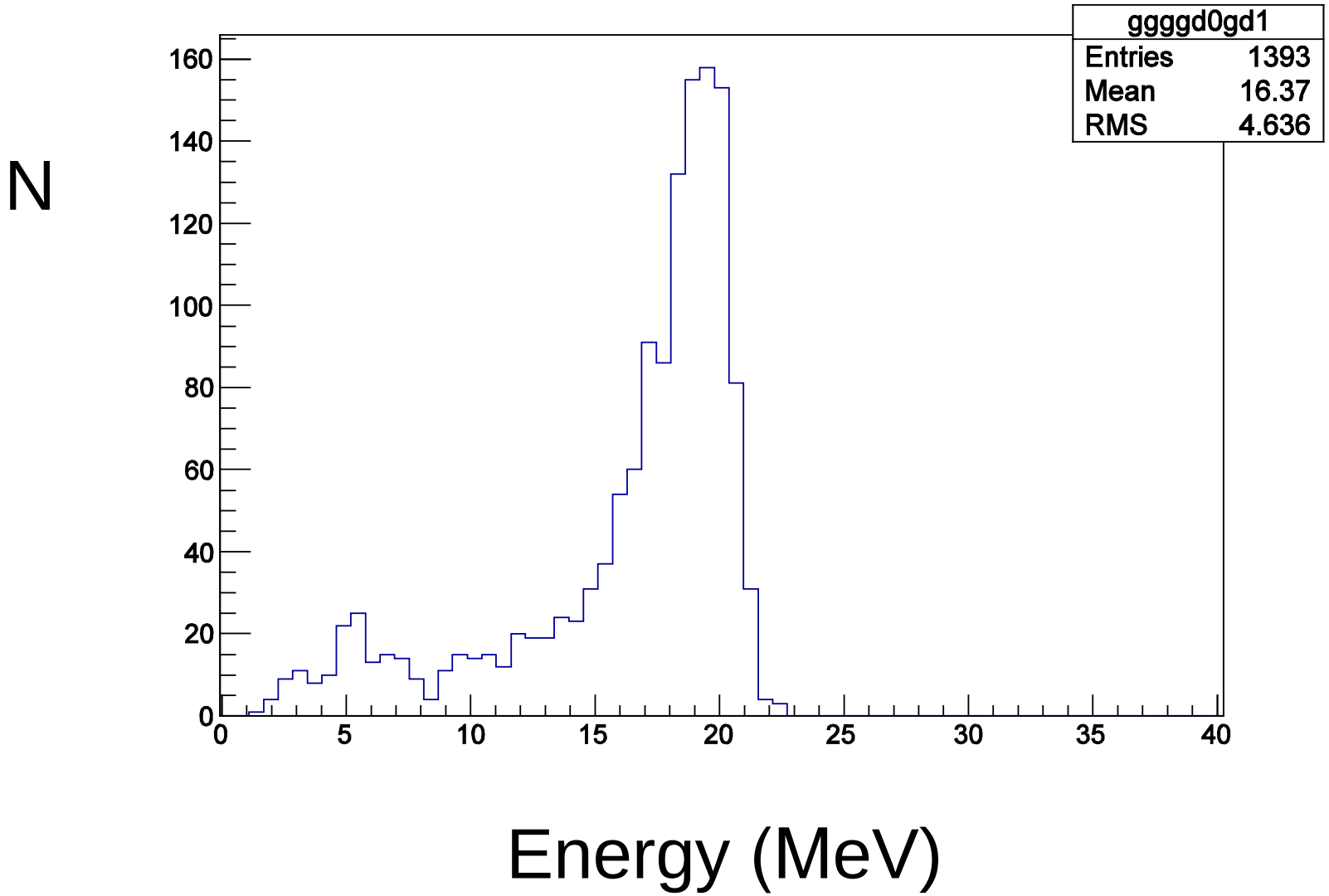
Experimental spectra (paired charged particles):

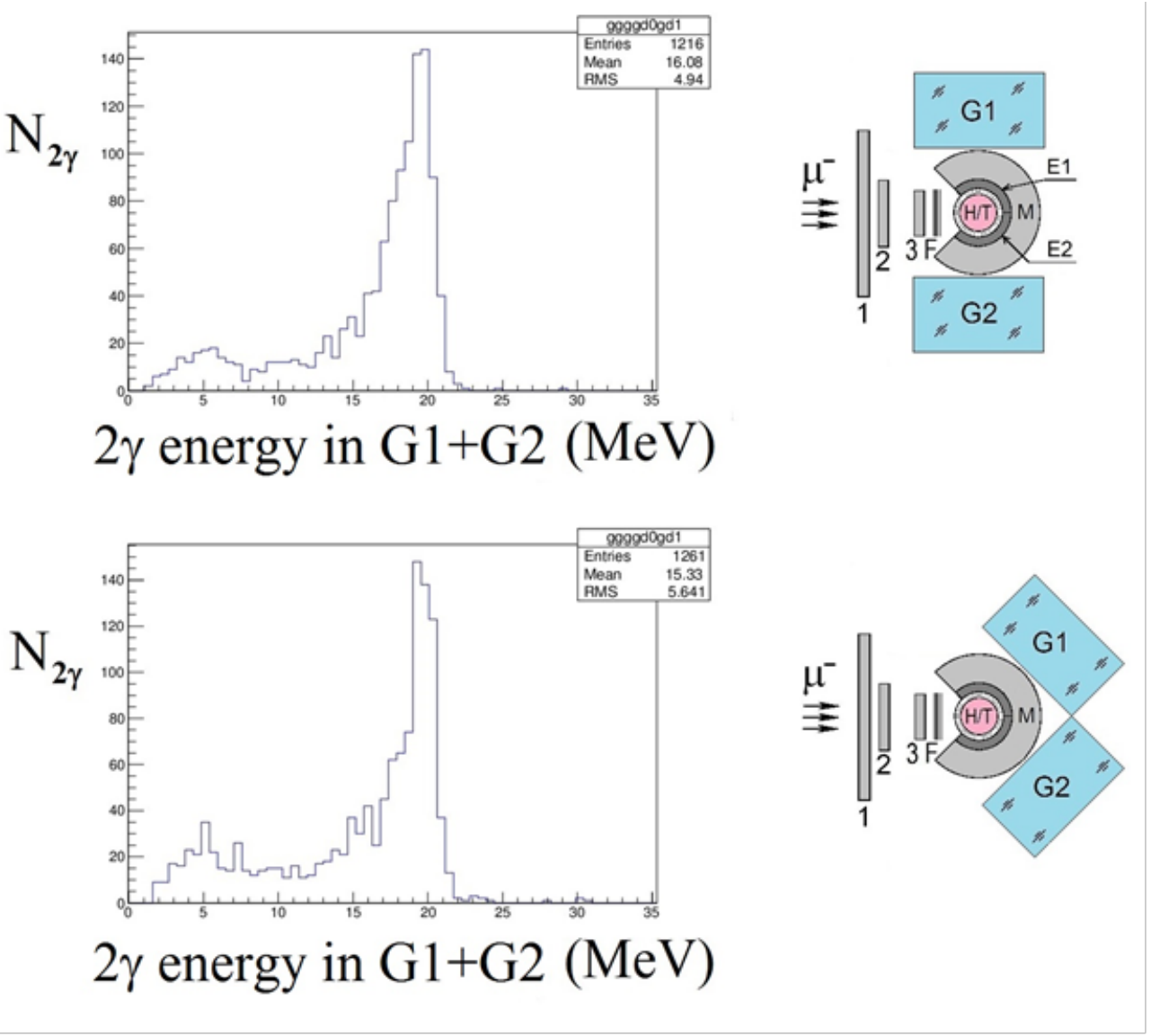
Sum energy spectrum of conversion muon and electron-positron pairs in electron telescope E1+E2



Experimental spectra (paired neutral particles):

Sum energy spectrum of gamma-quanta pairs in detectors G1+G2





2γ-yield of pt-reaction at tritium concentration c_t = 0.08% on the same statistics for two different relative positions of gamma detectors: a relative angle of 180 degrees (top), 110 – (bottom).

Registration of e^+e^- pairs and pairs of gamma quanta from pt-fusion

For the first time the channel of pt-reaction with electron-positron pair output

$$pt\mu \rightarrow {}^4He\mu + e^+ + e^- + 18.79\ MeV$$

was observed. The general statistics collected on the TRITON installation in 2016 is about **15 thousand** events.

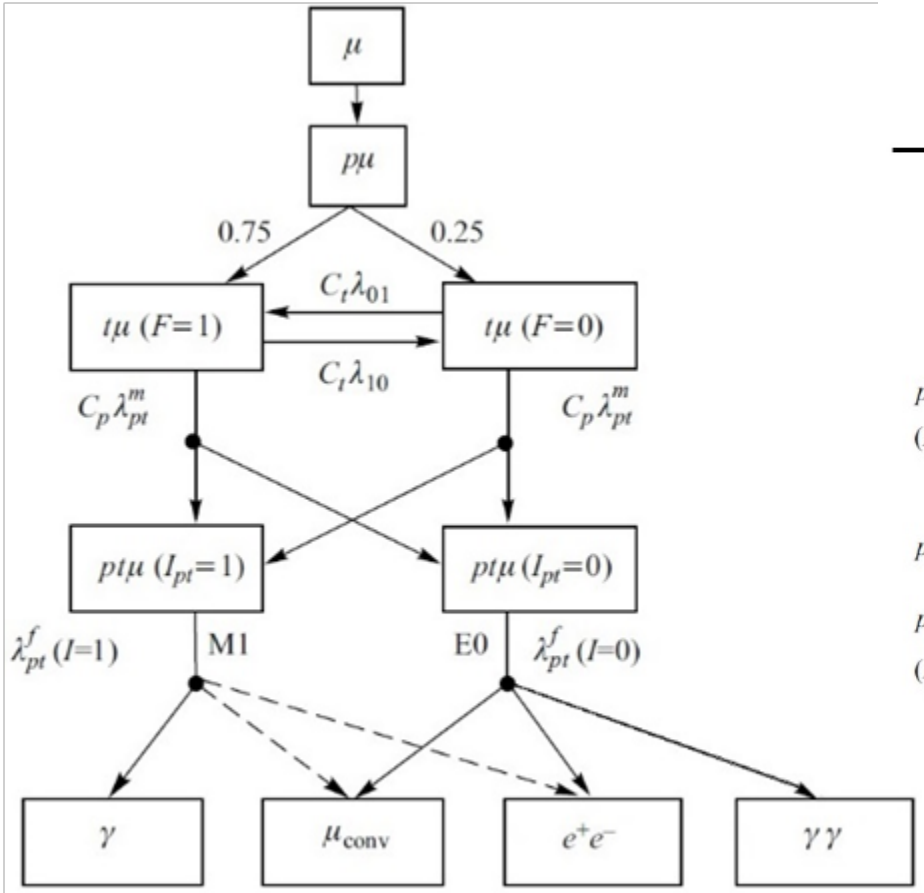
Also the reaction channel with output of two gamma quanta

$$pt\mu \rightarrow {}^4He\mu + 2\gamma + 19.82\ MeV\ (E_{\gamma 1} + E_{\gamma 2} \geq 19.77\ MeV)$$

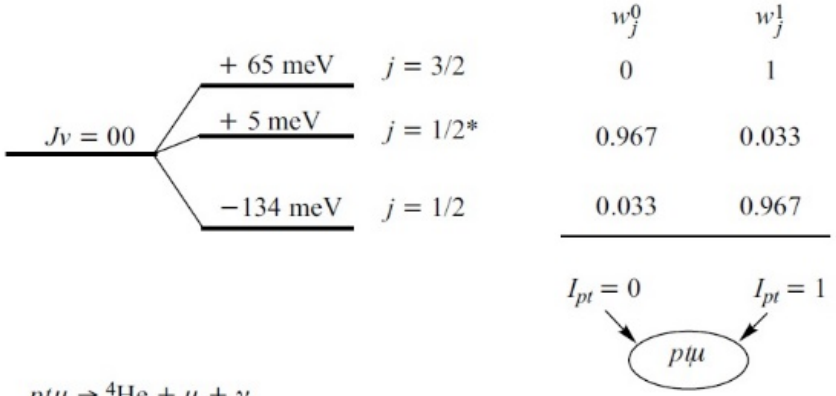
was registered. The general statistics is about **3 thousand** registered double events that satisfy the selection criteria for gamma quanta simultaneously recorded in each of two gamma detectors.

Measurements with different geometry of the installation in November 2016 (gamma detectors were first set at a relative angle of 180, then 110 degrees) do not give a convincing evidence of the angular correlation between γ-quanta in 2γ-pair.

The package of computing programs on the basis of Monte Carlo method, allowing simulations of numerous muon atomic and molecular processes accompanying μCF was developed.



Scheme of the MC processes in H/T mixture



$pt\mu \rightarrow {}^4\mathrm{He} + \mu + \gamma$ $\quad {}^3S_1 \rightarrow {}^1S_0$ (M1)

($I_{pt} = 1$)

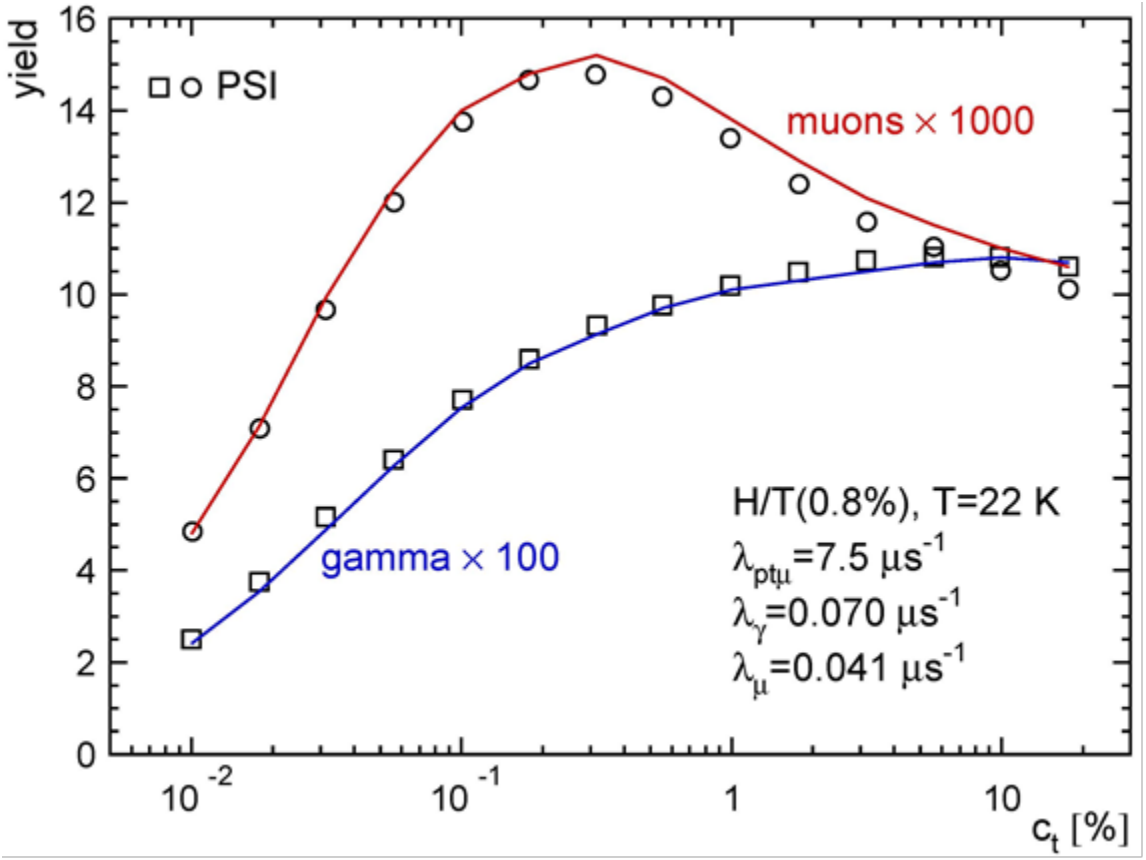
$pt\mu \rightarrow {}^4\mathrm{He} + \mu_{conv}$

$pt\mu \rightarrow \mu\, {}^4\mathrm{He} + e^+ + e^-$ $\quad {}^1S_0 \rightarrow {}^1S_0$ (E0)

($I_{pt} = 0$)

Hyperfine structure of $pt\mu$ ground state

The dependences, obtained by two different (PSI and our) calculating programs of kinetics modelling the μCF processes, are in quite good agreement.



Yields for conversion muons (circles) and γ emissions (squares) in pt fusion as a function of tritium concentration c_t (PSI, 1993). Respectively, red and blue curves correspond to results of our MC simulations at fixed parameters (presented on plot).

CONCLUSIONS

1. The channel with the output of electron-positron pairs as well as the channel with the output of a pair of gamma quanta were detected in experimental investigation of pt-fusion nuclear reactions;

2. The obtained results confirm theoretical predictions of Ya.B. Zel'dovich and S.S. Gershtein (1960) on the output products of nuclear reactions in cold hydrogen isotope mixtures caused by muons.

3. The preliminary analysis of data and obtained rates of observed pt-fusion reactions with the yield of single gamma quanta and muon conversion agree well with results and conclusions of PSI experiment (1993).

Thanks for attention

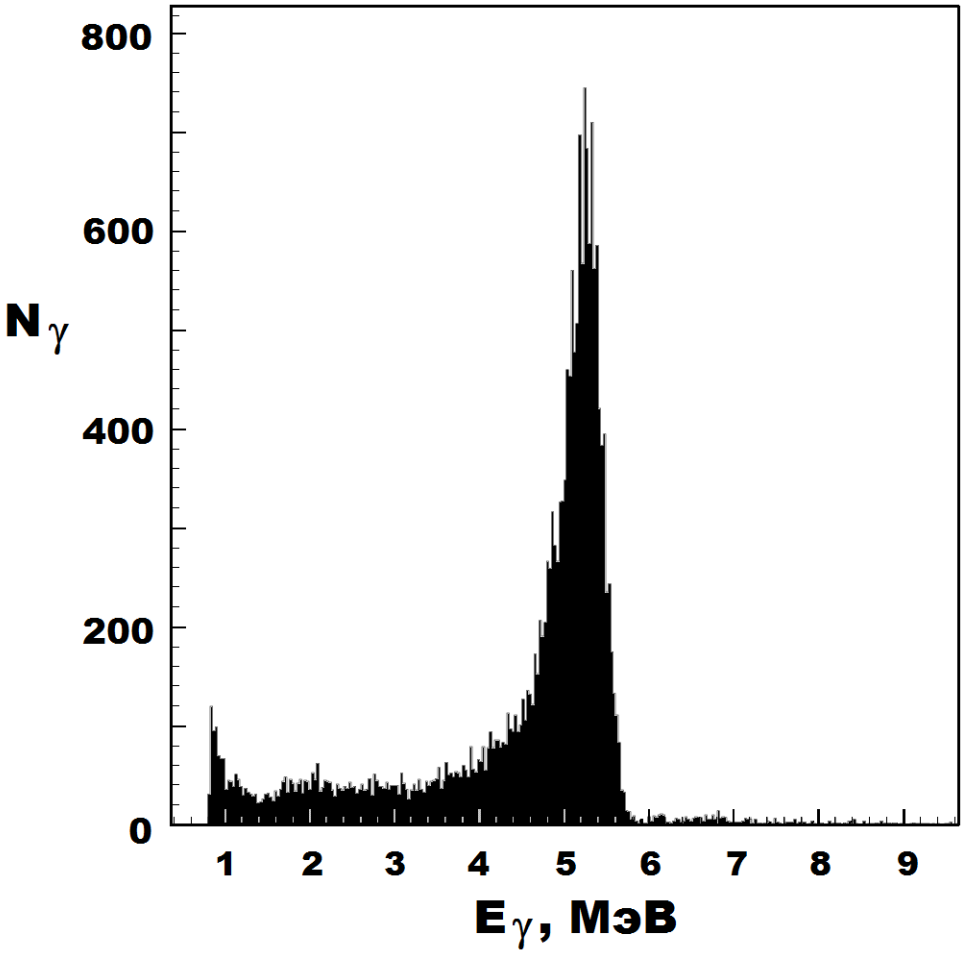
Additional slides below

2013 - The experimental equipment was adjusted on a muon beam with a target filled with liquid hydrogen with a natural deuterium concentration

The experimental energy spectrum of gamma quanta from the reaction

$pd\mu \rightarrow {}^{3}He\mu+\gamma+5.5$ MeV

was obtained.



Criteria for selecting experimental events:

• e_d1 is the coincidence signal $(E1+E2)\cdot M$, responsible for the muon stop in the target;

• $e_d2 = (\bar{E}1 + \bar{E}2)\cdot M\cdot(G1+G2)$ means conversion muon decay in detector M.

Marker x notes the fusion reaction products: γ, e^-e^+ or conversion muon. The appropriate signals are the following:

• $x=\gamma$: $(\bar{E}1+\bar{E}2)\cdot\bar{M}\cdot G$, the decay electron selected as e_d1;

• $x=\mu$: the coincidence signal $(E1+E2)\cdot M$, and e_d2 for the electron from muon decay;

• $x=e^-e^+$: $(E1+E2)\cdot M$, and e_d1 corresponds to detection of at least one particle of the pair;

• $E1\cdot E2\cdot M$, and the subsequent e_d1 corresponds to simultaneous detection of both particles of the pair with their coincidence in time.

For a more reliable identification of the registered experimental events and the background suppression, one should put certain timing limitations, usual in MC experiments:

$$t(e_d1)-t(\mu)>0.5\ \mu\text{s}, \qquad t(e_d1,2)=t_x+(0.5{-}4.5)\ \mu\text{s}$$

Carrying out the experiment

During the period May 10-16 and November 14-24, 2016, measurements were taken of the mu-catalysis of the nuclear p + t synthesis reaction at the DLNP Phasotron.

Duration of the data taking was 270 hours.

The concentration of tritium in the “Liquid hydrogen target” was 0.8% in the May run and 0.08% in the November run.

In the November run, two exposures were carried out with different geometries for the location of gamma detectors relative to the target.

Procedure for determining the yield in the reaction' channel

The number of detected events for each sort (y) of the fusion products is

$$N_y = N_\mu \cdot Y^0(y) \cdot \mathrm{eff}(y),$$

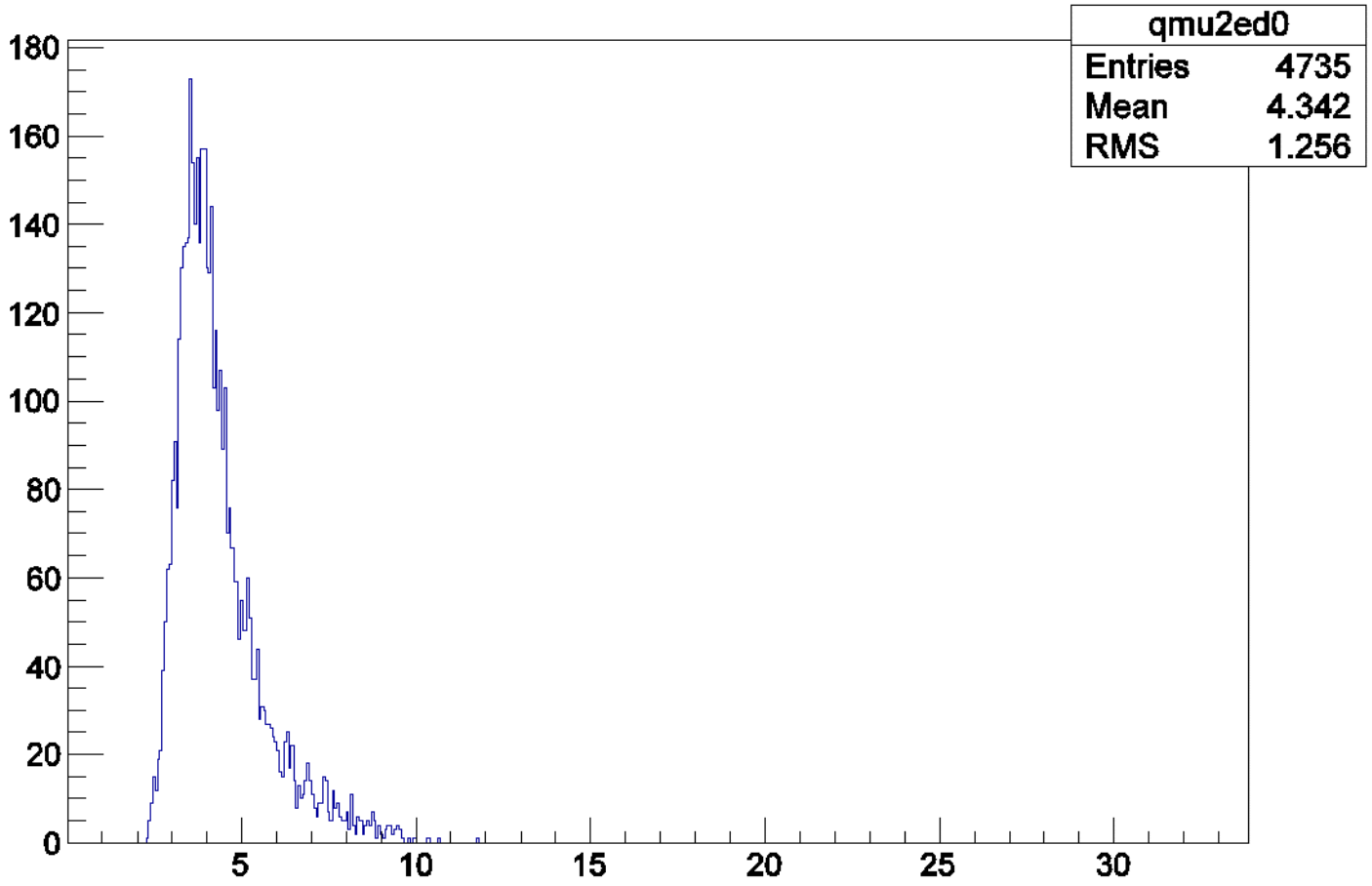
where $Y^0(y)$ is the absolute yield and $\mathrm{eff}(y)$ are the detection efficiencies:

$$\mathrm{eff}(\gamma) = \epsilon(\gamma) \cdot \epsilon(e_d 1) \cdot f_t, \quad \mathrm{eff}(\mu) = \epsilon(\mu) \cdot \epsilon(e_d 2) \cdot f_t,$$
$$\mathrm{eff}(\text{pairs } 1) = \epsilon(\text{pairs } 1) \cdot \epsilon(e_d 1) \cdot f_t, \quad \mathrm{eff}(\text{pairs } 2) = \epsilon(\text{pairs } 2) \cdot \epsilon(e_d 1) \cdot f_t.$$

A detailed description of the experimental procedure developed at the preparation stage is contained in the work: [L.N. Bogdanova, et al., "Experimental study of nuclear fusion reactions in a ptμ system", Physics of Particles and Nuclei Letters 9, No.8 (2012) 605].

Experimental spectra:

Conversion muon in E1



Nuclear Instruments and Methods in Physics Research A 334 (1993) 437–446
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

An electron–positron pair spectrometer for high energy decays of nuclei

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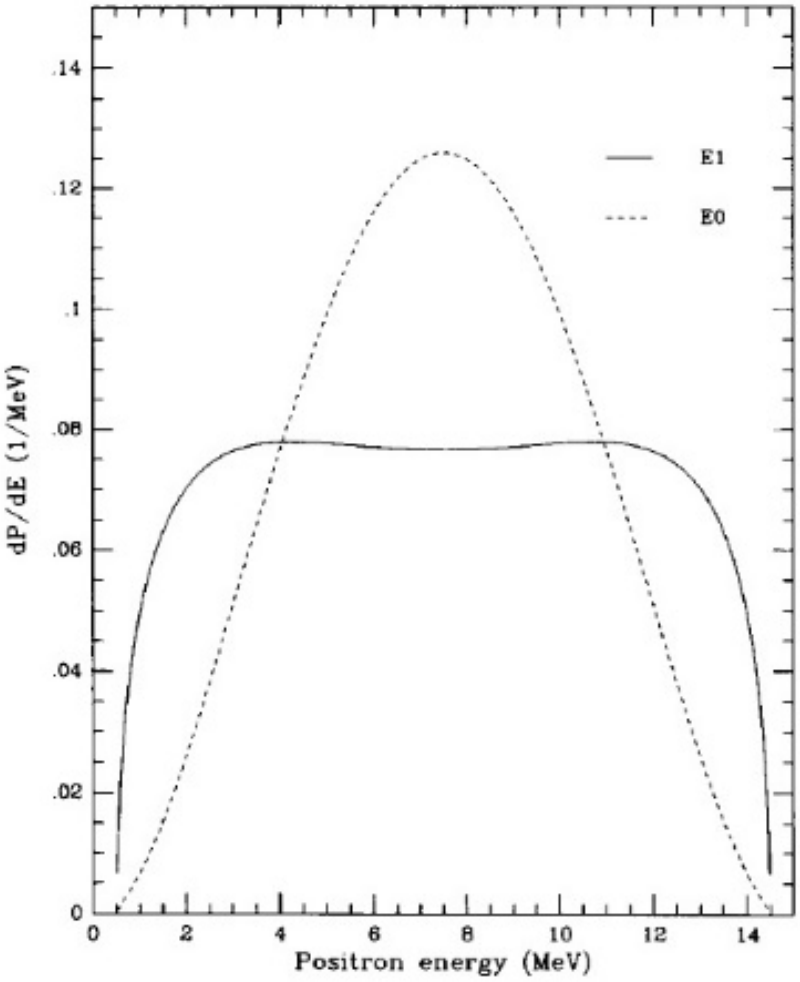


Fig. 3. Positron energy distribution for 15 MeV E0 and E1 transitions.

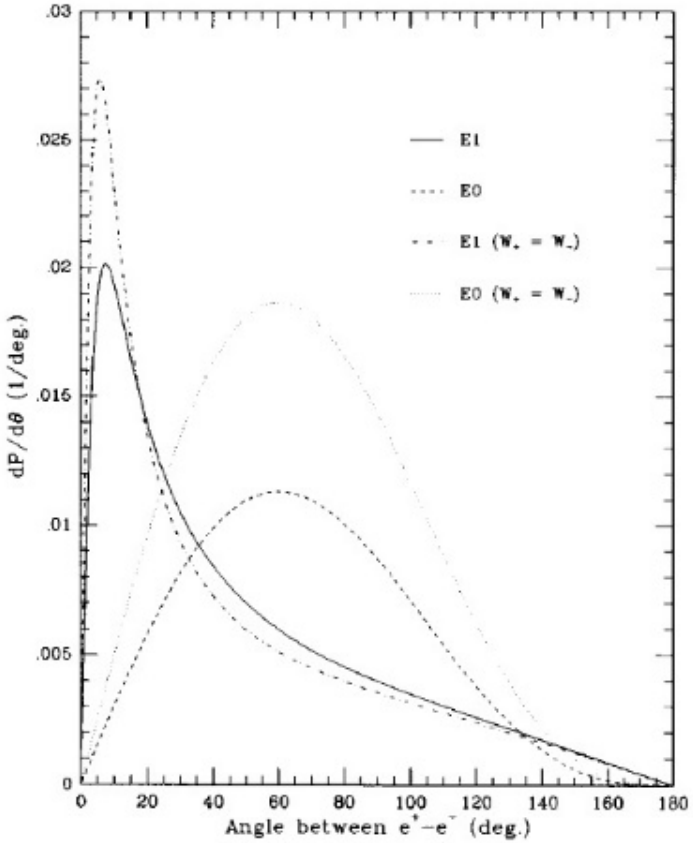
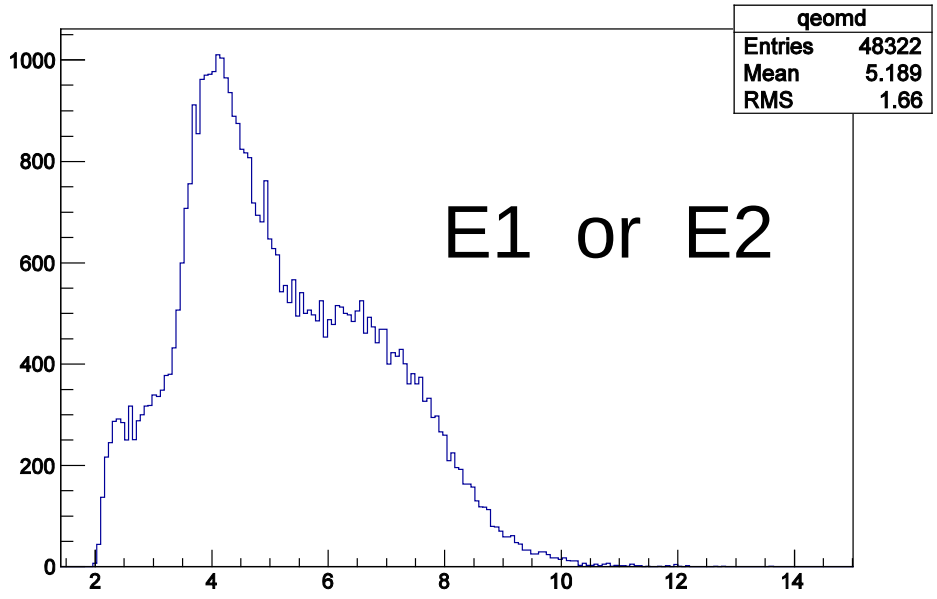
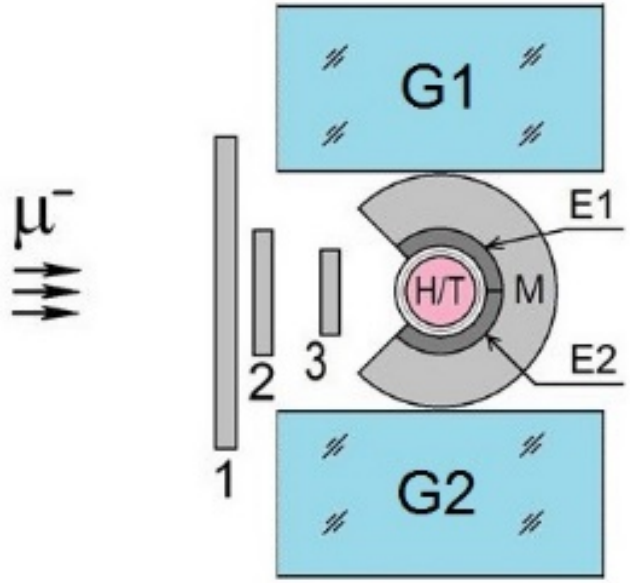


Fig. 4. The e^+–e^- angular correlation for a 15 MeV E0 and E1 transition. Also indicated is the strong effect which a requirement of equal energy sharing has on the angular correlations. The normalization of the curves is such that the two E1 curves have equal areas and the E0 curves are obtained assuming transition probabilities equal to the respective E1 transitions.

Spectra in M(E1,E2): pdμ, ptμ→ $e^+ + e^-$

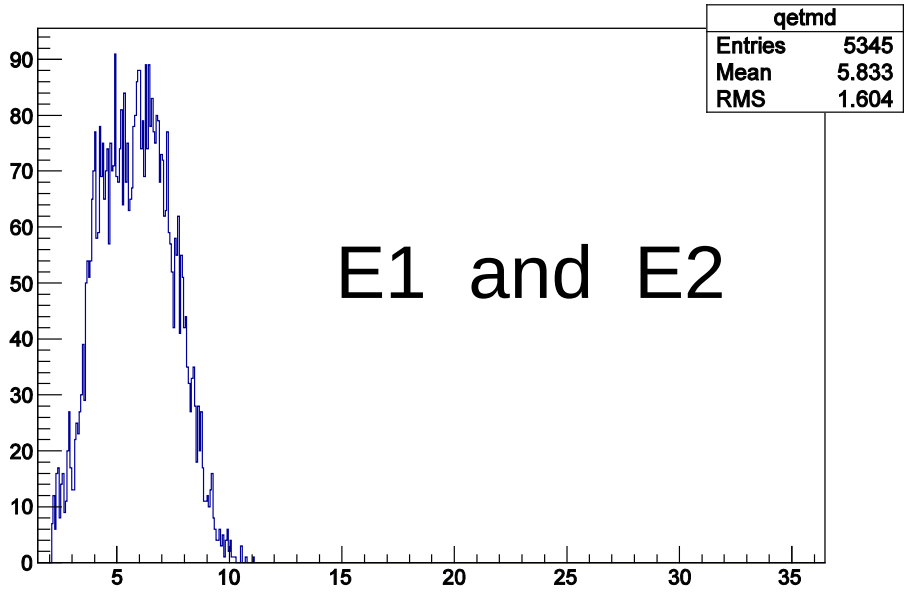




C_t = 0

N (E1 or E2) = 4194

N (E1 and E2) = 53



C_t = 0,8

N (E1 or E2) = 48322

N (E1 and E2) = 5345

C_t=0,08

N (E1 or E2) = 46618

N (E1 and E2) = 4868

Electron telescope E1 - E2 make-up

Plastic fiber light-guide gathering light :