COMET experiment. Simulation of the calorimeter triggering algorithm

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Outline

1. Introduction
2. Muon to electron conversion
3. The COMET experiment
4. Simulation of the calrimeter triggering algorithm

Introduction

- The discovery of a Higgs boson at the LHC in 2012 provided the missing piece in the Standard Model (SM) to explain electroweak symmetry breaking. However SM still has many unanswered questions: the lack of a dark-matter candidate, no explanation for the observed matter antimatter asymmetry in the Universe, does no account for neutrino oscillation phenomena, no quantum theory of gravity and etc.

- All these phenomena highlight the need for physics beyond the SM (BSM) and many of these models predict charged lepton flavour violation (CLFV).

Introduction

- In the SM, neutrinos are massless by construction, and all lepton numbers are conserved; in particular, the SM Lagrangian is invariant under a global $U(1)_e \times U(1)_\mu \times U(1)_\tau$ lepton field rotation.

$$L_e(e^-, \nu_e) = +1,\ L_\mu(\mu^-, \nu_\mu) = +1,\ L_\tau(\tau^-, \nu_\tau) = +1$$

$$L_e(e^+, \bar{\nu}_e) = -1,\ L_\mu(\mu^+, \bar{\nu}_\mu) = -1,\ L_\tau(\tau^+, \bar{\nu}_\tau) = -1$$

- Moreover, the total lepton number, $L_{total} = L_e + L_\mu + L_\tau$ is also a conserved quantity.
- The lepton flavor violation (LFV) among neutrino species has been experimentally confirmed with the discovery of neutrino oscillations. The observation of neutrino oscillations implies that neutrinos are massive, and that neutral lepton flavours are not conserved hence the SM must be modified so that charged lepton flavour violating (CLFV) can occur.

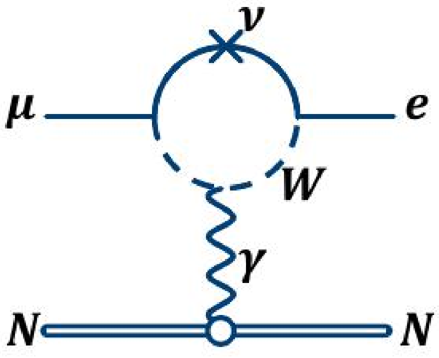
Introduction

Charged lepton flavor violating (CLFV) processes are not forbidden in the SM but extremely suppressed due to the tiny neutrino mass.

For example, in minimal extension of SM, in which Dirac masses for neutrinos are incorporated the rate for the neutrinoless conversion of muon to electron (μ-e conversion) are suppressed by the difference in mass between neutrino and W.

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left| U_{ej}\, U^*_{\mu j} \frac{m^2_{\nu_j}}{M^2_W} \right|^2 \simeq \mathcal{O}(10^{-55})$$

U - neutrino mixing matrix



SM $\mu - e$ conversion

Clearly, such a tiny value lies beyond the reach of any future experiment.

Thus, the observation of a CLFV signal would be a clear indication of new physics!

Muon to electron conversion

When a negative muon is stopped by some material, it is trapped by an atom, and a muonic atom is formed. After it cascades down energy levels in the muonic atom, the muon is bound in its 1s ground state. In SM the following processes are possible:

1. Muon decay in orbit (DIO)

$$\mu N \rightarrow e\nu\bar{\nu}N$$ (39% in Al)

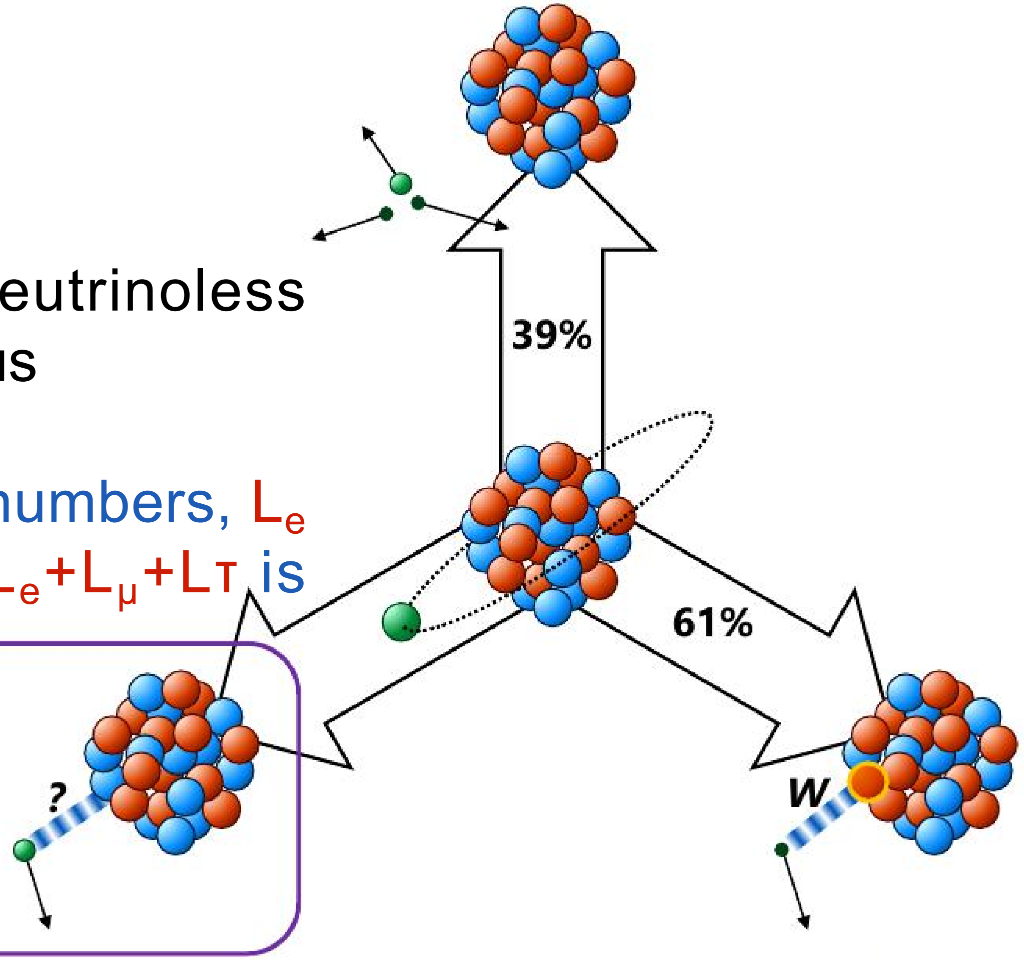
2. Nuclear muon capture

$$\mu N(Z) \rightarrow \nu N'(Z-1)$$ (61% in Al)

In the context of physics BSM, exotic process of neutrinoless conversion of muons into electrons in the field of a nucleus

$\mu^- + (Z,A) \rightarrow e^- + (Z,A)$ is expected.

This process violates the conservation of lepton flavor numbers, L_e and L_μ, by one unit, but the total lepton number $L = L_e + L_\mu + L_\tau$ is conserved.



Looking for the conversion:

$$\mu N \rightarrow eN$$

From $1s_\mu$ orbital: ***mono-energetic electron*** at 105MeV ($\approx m_\mu - B^{\mu}_{1s} - E_R$)

COMET Experiment

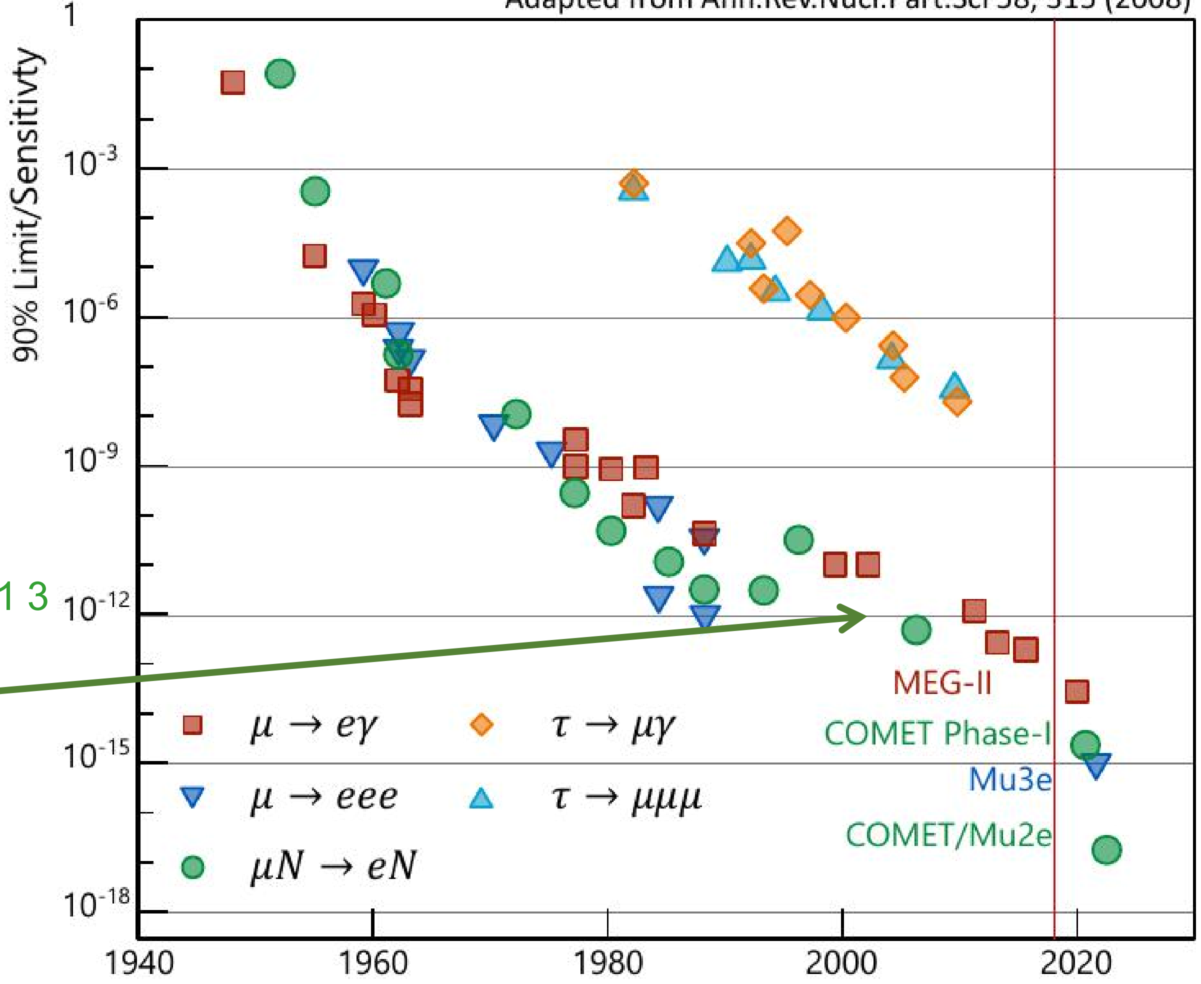
COMET -
COherent Muon to Electron Transition

search for μ−e conversion in the field of an aluminium nucleus, $\mu^- N \rightarrow e^- N$, with a single event sensitivity of 2.6×10^{-17}

Recent upper limit : 7 x 10^{-13} (SINDRUM-II at PSI)

Our COMET goal: improvement 10,000 !!!

Adapted from Ann.Rev.Nucl.Part.Sci 58, 315 (2008)



Time evolution of the accuracy increasing of the existing and prospective experiments searching for the CLFV processes

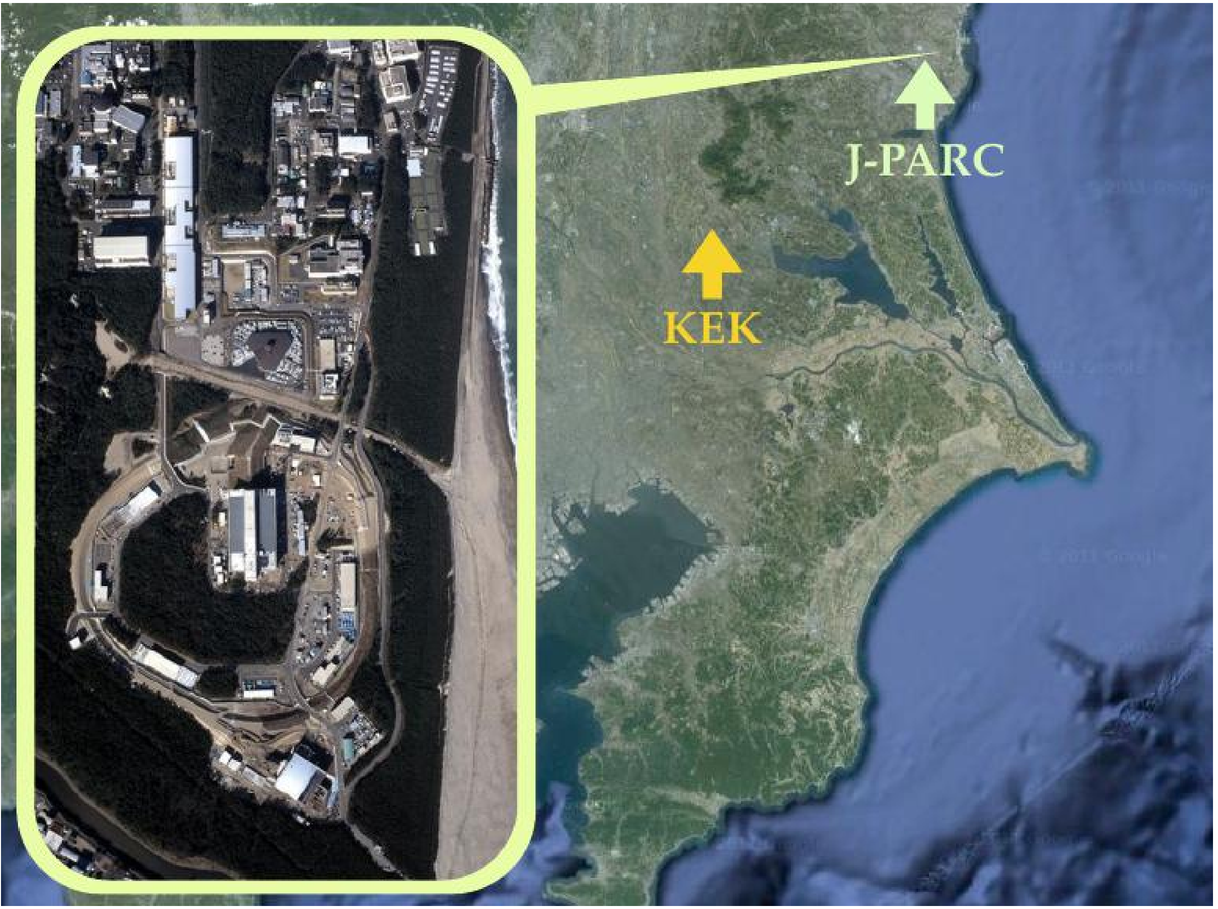
COMET Collaboration

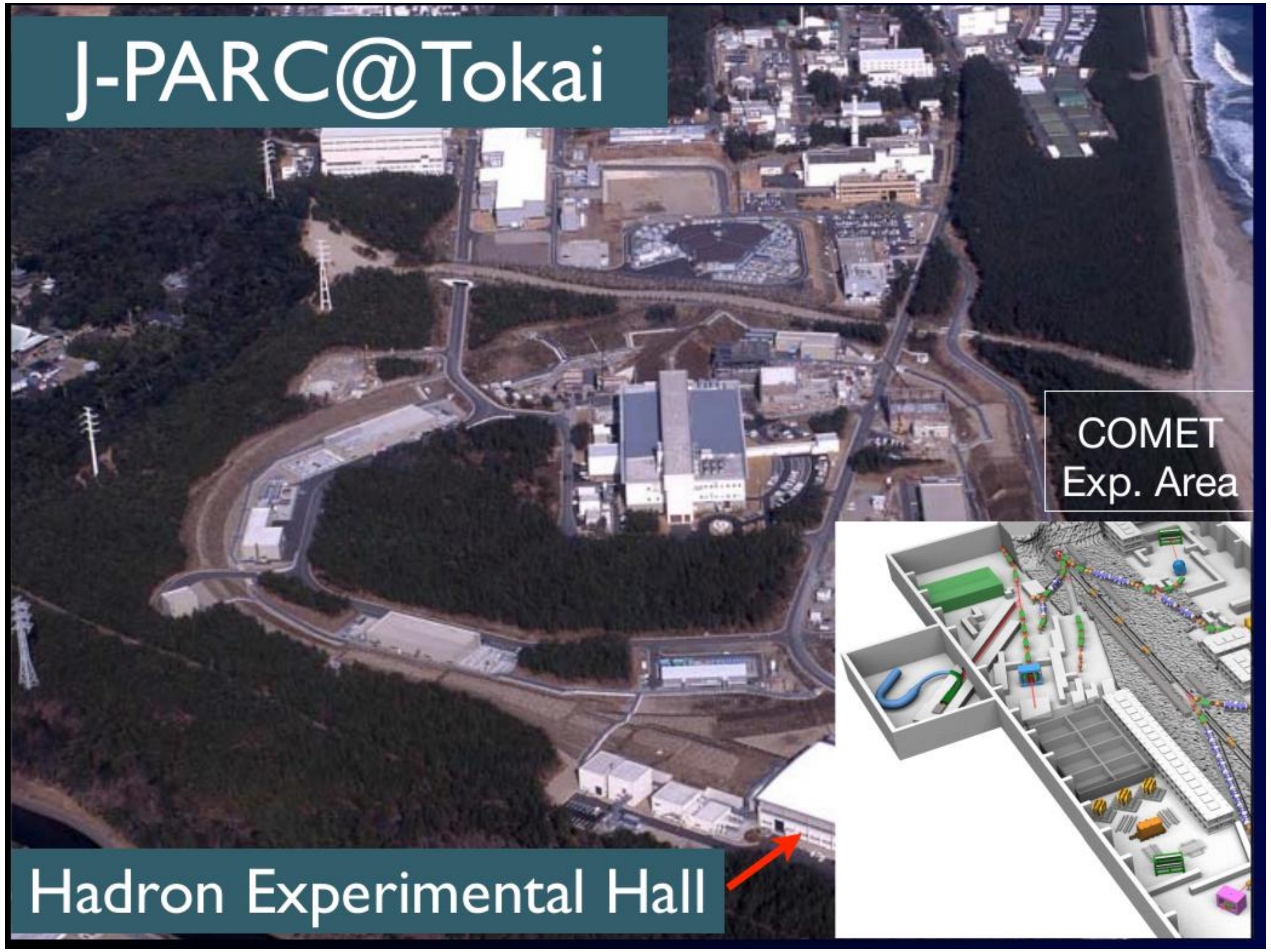
The COherent Muon to Electron Transition: (COMET) Experiment – the world wide collaboration

The O(200) participants from 39 institutes of 16 countries.

COMET experiment

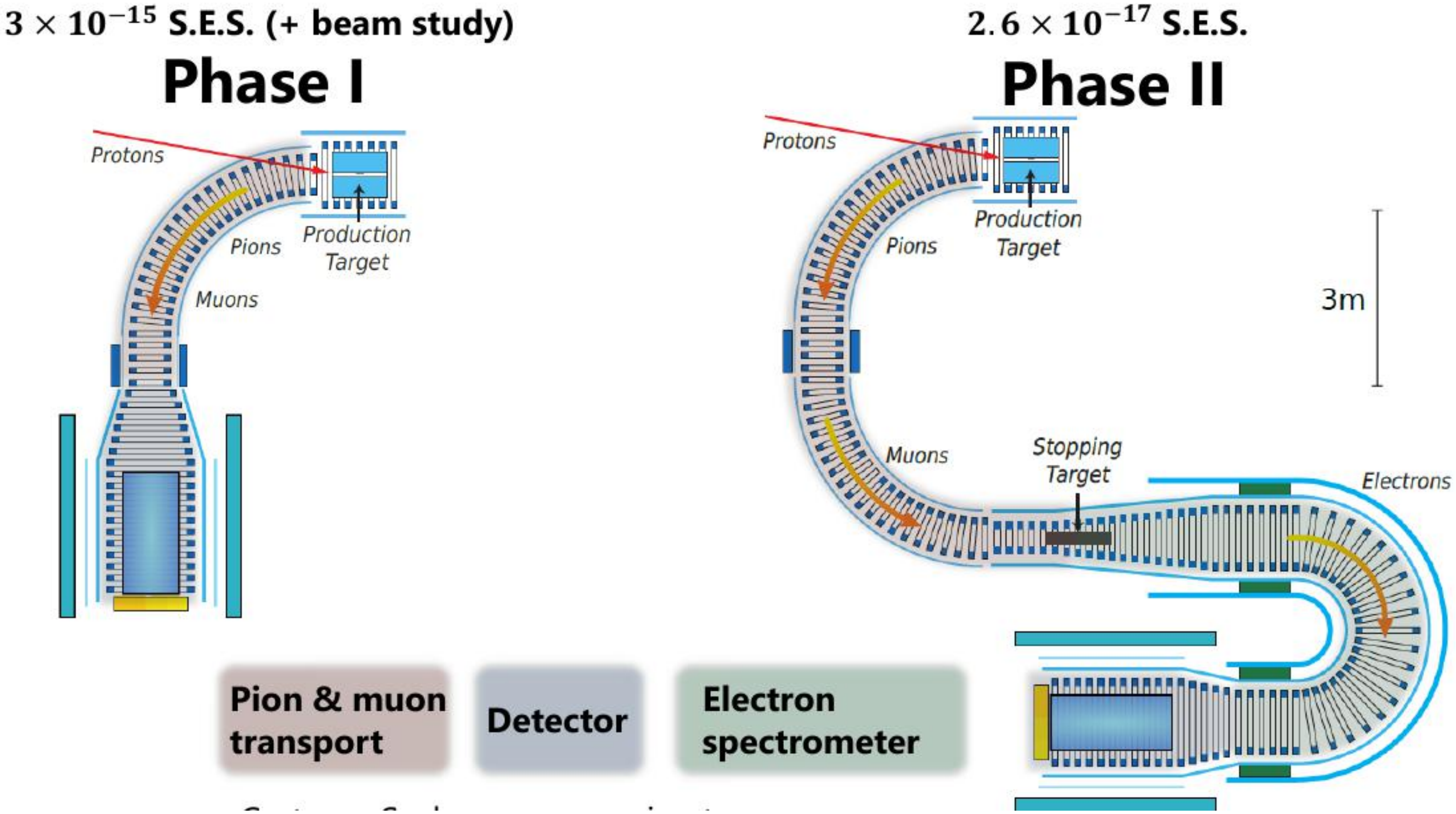
COMET experiment will be carried out at the Japan Proton Accelerator Researcn Complex (J-PARC) in Tokai, Japan.

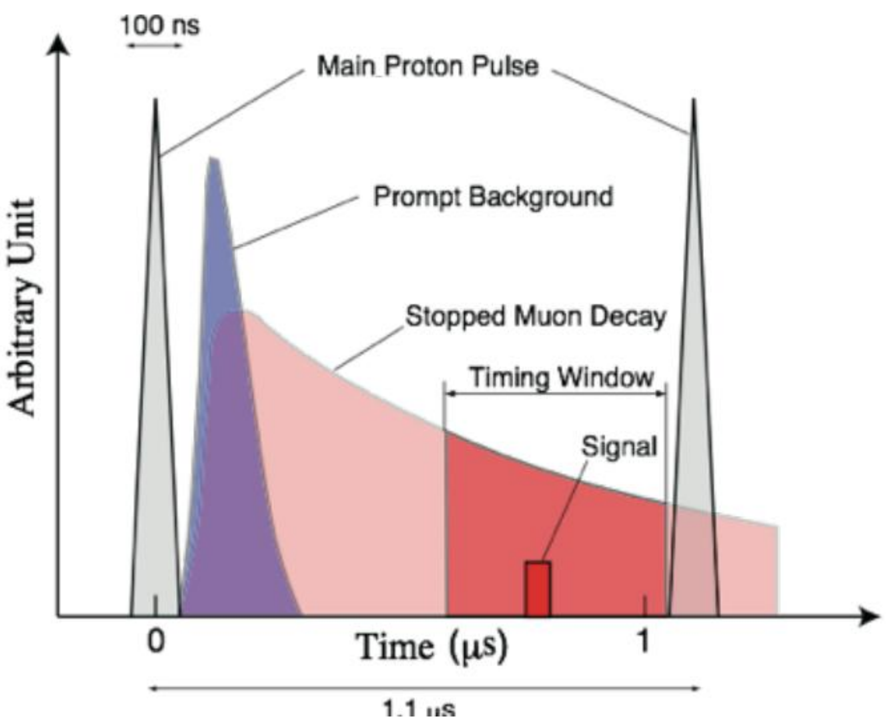




COMET experiment

The COMET experiment will be carried out using a two-staged approach.





The idea – use the pulse beam and look for the delayed electron from muon capture on nucleus

Goal of COMET PHASE-I

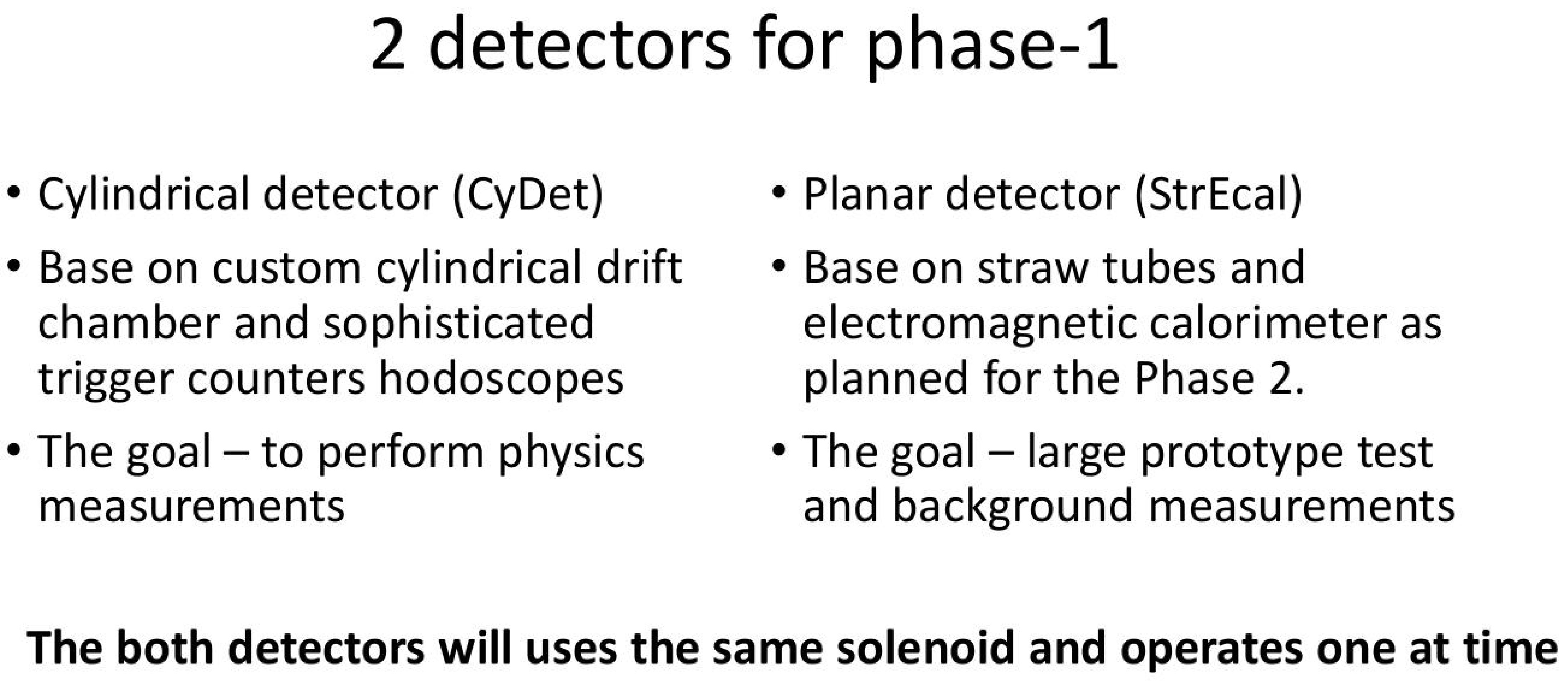
1. Search for μ-e conversion

- **a search for μ-e conversion at the intermediate sensitivity which would be 100-times better than the present limit (SINDRUM-II). The primary COMET Phase-I detector for searching for the neutrinoless μ−e conversion signals is a cylindrical drift chamber.**

2. Background study for the full COMET (Phase-II)

- **Direct measurement of potential background for the full COMET experiment using prototypes of the Phase-II straw tracker and the electron calorimeter.**

COMET PHASE-I



2 detectors for phase-1

- Cylindrical detector (CyDet)
- Base on custom cylindrical drift chamber and sophisticated trigger counters hodoscopes
- The goal – to perform physics measurements

- Planar detector (StrEcal)
- Base on straw tubes and electromagnetic calorimeter as planned for the Phase 2.
- The goal – large prototype test and background measurements

The both detectors will uses the same solenoid and operates one at time

Slide: Dmitry Grigoriev at ICHEP2018

COMET PHASE-I

To reach a required sensitivity we should obtain is a very intensive muon beam

$$BR(\mu^- + Al \rightarrow e^- + Al) = 3.1\times10^{-15}$$

$$B(\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}}$$

N_μ - number of stopping muons in the stopping target

f_{cap} - fraction of muon captute = 0,6 for Al

f_{gnd} =0,9 - fraction of μ−e conversion to the ground state in the final state

$A_{\mu-e}$ = 0,041- detector acceptance

- To achieve SES=3×10^{-15} , Nμ = 1.5×10^{16} is needed.
- By using the muon yield per proton of 4,7 × 10^{-4} a total number of protons on target of 3.2×10^{19} is needed.
- With the proton beam current of 0.4 μA, running time is 1.26×10^{7} seconds (~146 days)

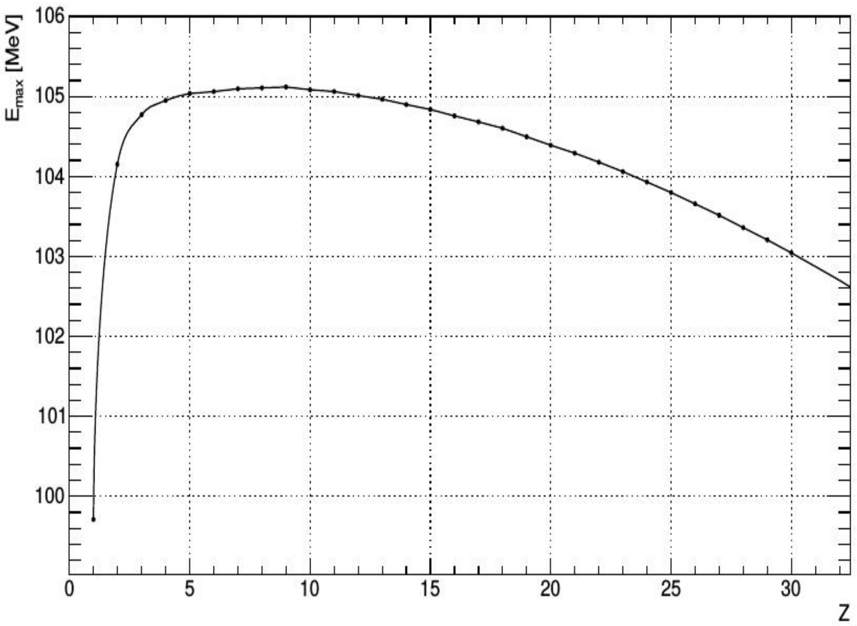
1,2x10^{9} muons per second in the stopping target !

Main Background

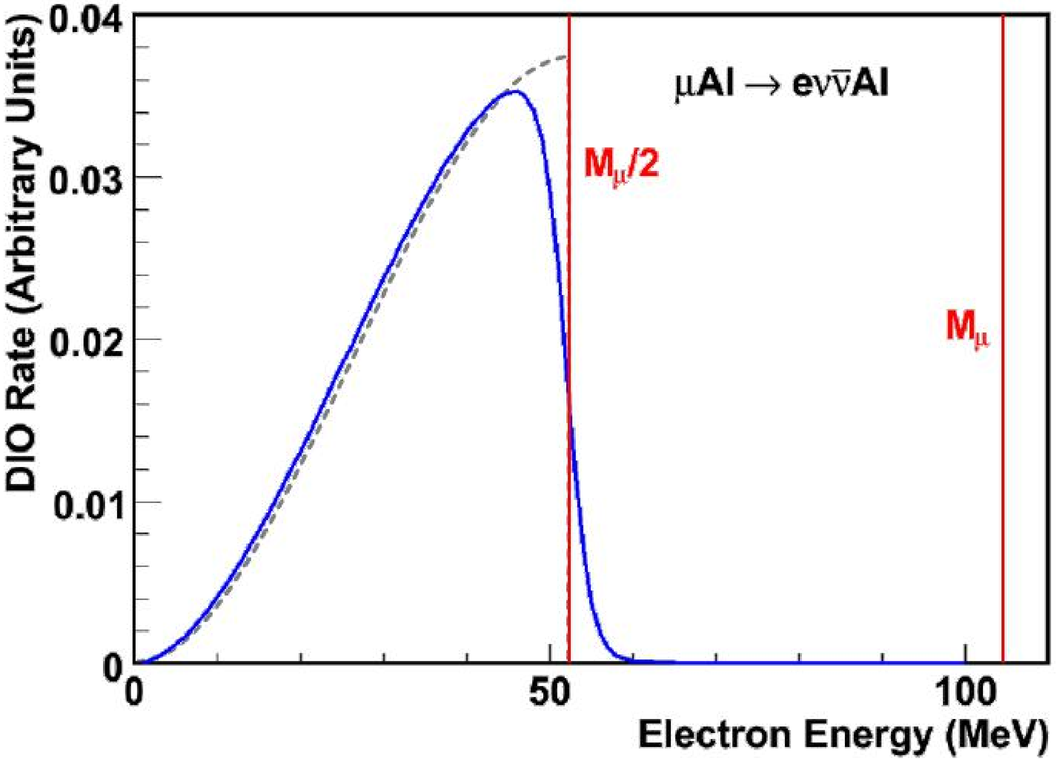
- **Muon Decay in Orbit** , $\mu^- + N \to e^-\nu_\mu\overline{\nu}_e + N$

- The energy spectrum of electrons produced by muons decaying in free space has cuts off at Mμ/2=52.8 MeV

- In the case a muonic atom, recoil against the nucleus allows the electron energy to exceed the kinematic limit of the free muon decay (leads to tail up to 105 MeV).



DIO endpoint energy as a function of atomic number.



Main Background

Muon Decay in Orbit → **Solution: Momentum resolution!**

In order to reduce the DIO contribution down to O(10^{-16}), the lower side of the momentum region for μ−e conversion signals should be above about 103.6 MeV for aluminium.

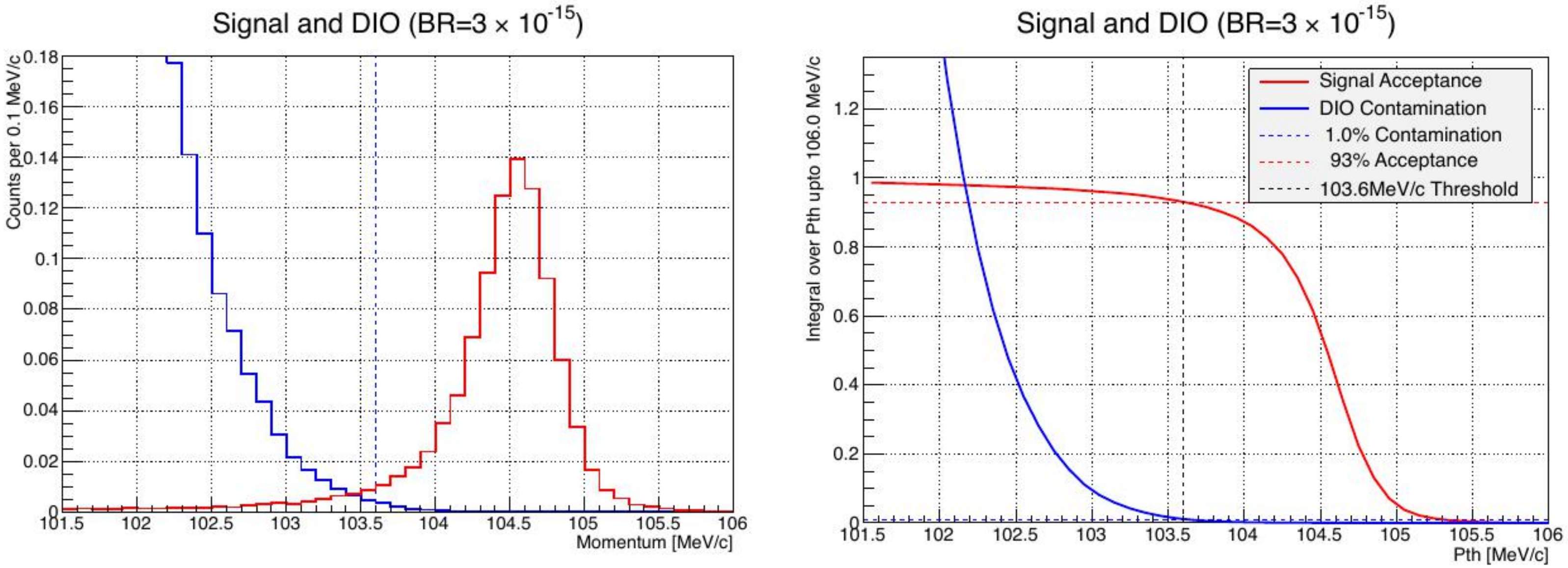
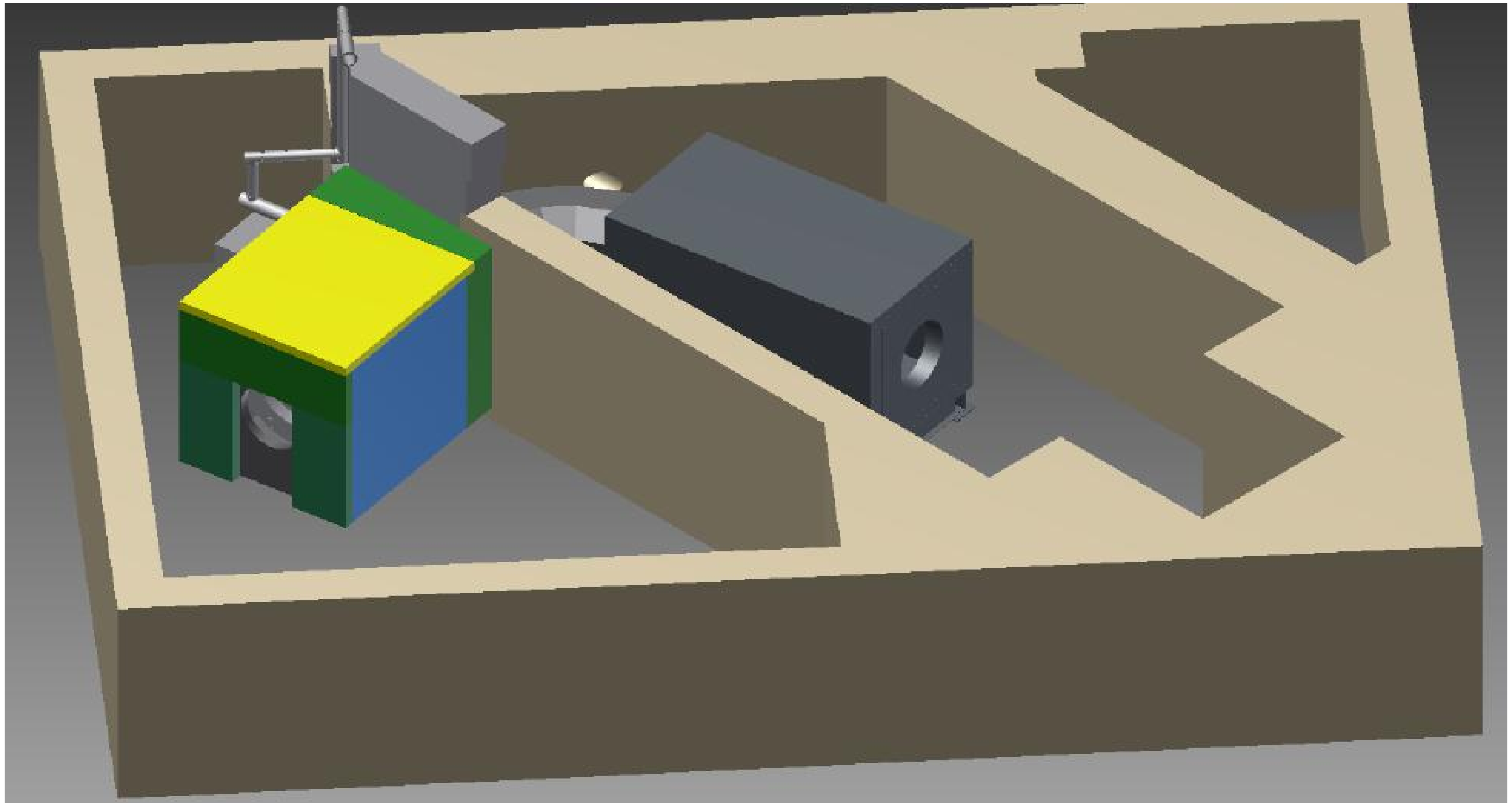


Figure 13.2: *Left: The momentum distributions for the reconstructed $\mu - e$ conversion signals and reconstructed DIO events. The vertical scale is normalized such that the integral of the signal curve is equal to one event. This assumes a branching ratio of $B(\mu N \to eN) = 3.1 \times 10^{-15}$. Right: The integrated fractions of the $\mu - e$ conversion signals and DIO events as a function of the lower bound of the integration range. The momentum window for signals is selected to be from 103.6 MeV/c to 106 MeV/c, yielding a signal acceptance of 0.93.*

Backgrounds

1. **Cosmic ray** induced backgrounds are one of the most important backgrounds. CR muons can decay in flight or interact with the materials around the area of the muon-stopping target producing signal-like electrons in the detector region.

- Solution: the Cosmic Ray Veyo system consits of 4 layers of scintillator strips covers detection region

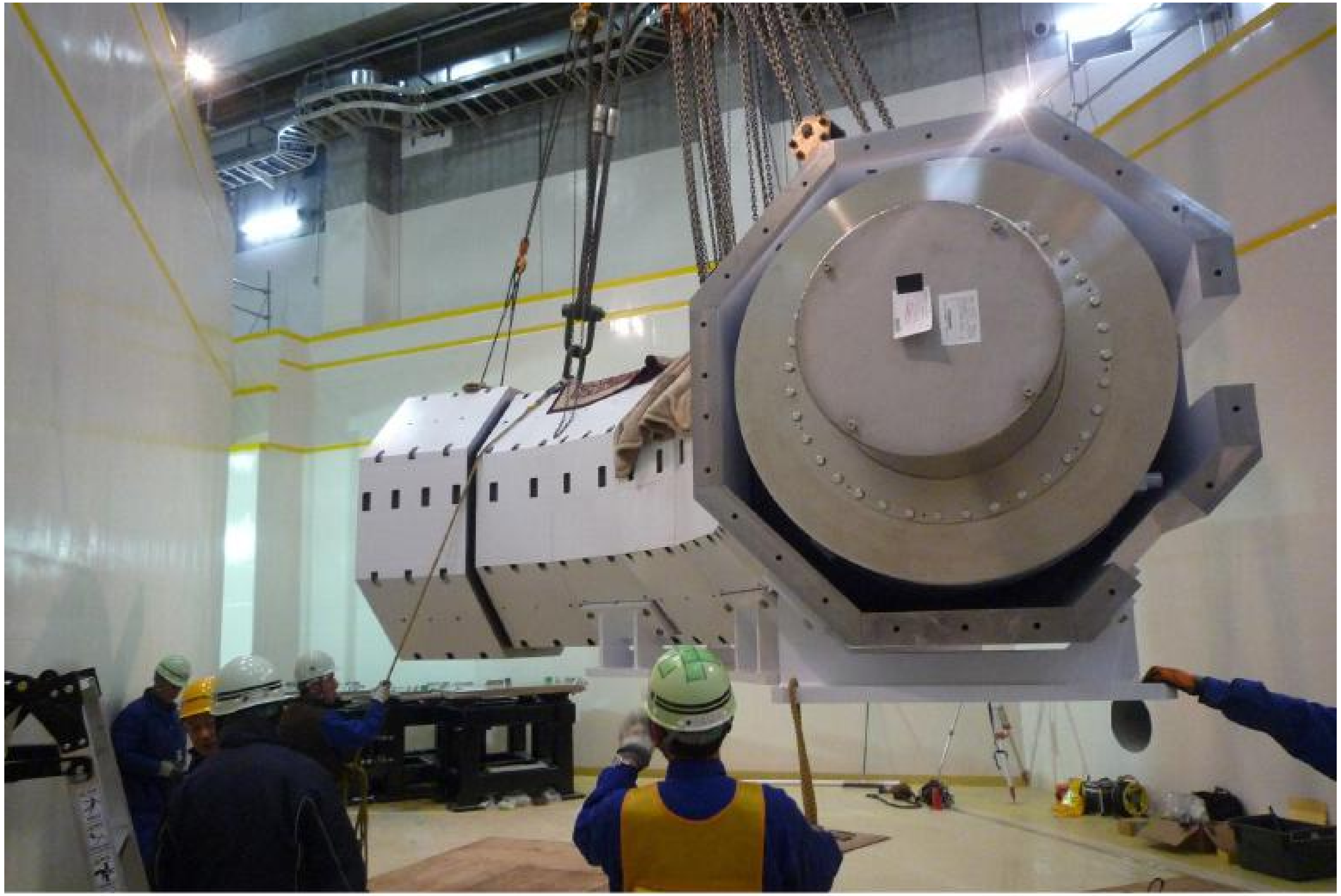


COMET preparation status

- Construction of the COMET building is completed!
- The dedicated beamline is designed and under construction now.

COMET preparation status

Main part of COMET transport solenoid is already installed in the COMET hall



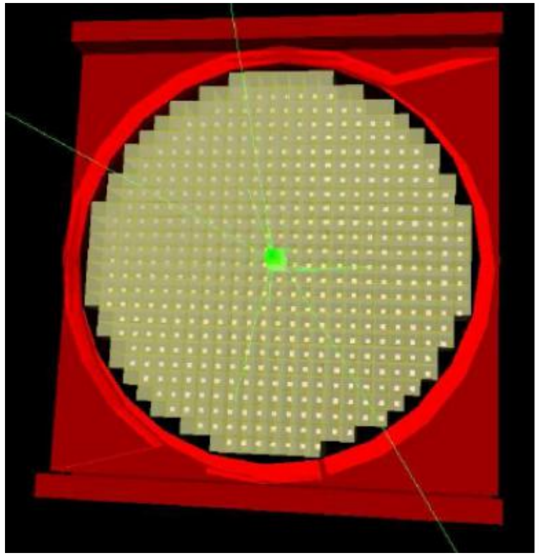
Summary. Part I

- CLFV would give the best opportunity to search for BSM. (So far, no BSM signals at the LHC.)
- Muon to electron conversion could be one of the important CLFV processes in terms of theoretical and experimental points of view
- The COMET experiment is a search for μ^--e^- conversion at J-PARC with sensitivity of O(-17) which is four orders of magnitudes better than the present limit.
- We're ready for the COMET Phase-I. The commissioning will start at the end of 2019!!!

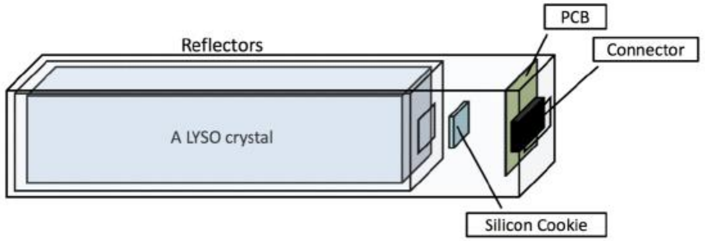
Electromagnetic calorimeter (ECAL)

The main requrements is
- energy resolution of better than 5% at 105 MeV
- a cluster position resolution of better than 1 cm.

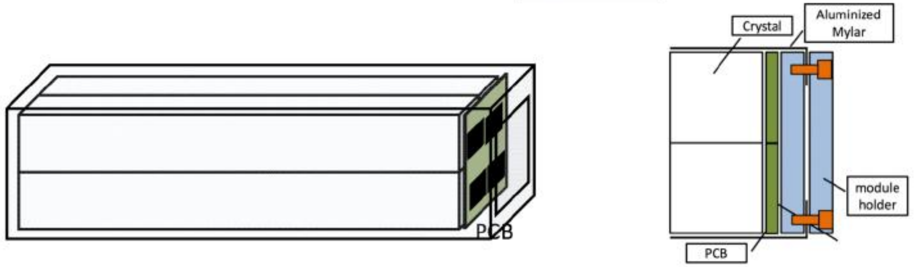
The crystals need to have a good light yield, and fast response and decay times to reduce pileup. High segmentation is required to reduce pileup and provides good position information. High segmentation is required to obtain sufficient spatial resolution and also allows for reducing pile-up. The ECAL will be built of LYSO crystals which have a $2 \times 2\ \mathrm{cm}^2$ cross-section and whose length is 12 cm, corresponding to 10.5 radiation lengths. The basic unit of the ECAL is a 2 × 2 crystal module.



(a) 1 crystal



(b) 2x2 module
4 crystals



ECAL trigger

Trigger is a system that uses criteria to rapidly decide which events to keep when only a small fraction of the total can be recorded

Good energy resolution

ECAL trigger: Requirements

High signal selection efficiency

High reduce the rate of background events

Trigger algorithm

ECAL trigger is based on a simple algorithm which uses the total deposited energy of cluster above a minimum energy threshold.

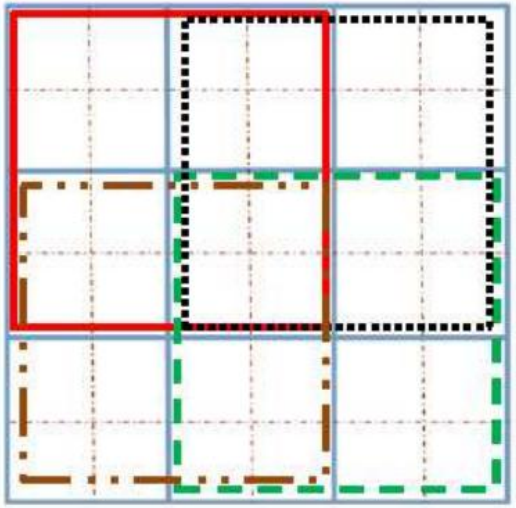
Competition, What algorithm for selecting a cluster is best?

based on

Single trigger cell (the trigger cell with the maximum energy deposition)

2×2 trigger cells

Floating window are summed up over all possible combinations of 2×2 trigger cells, as it is shown in Figure. Then the cluster with the maximal sum of energy depositions is selected.

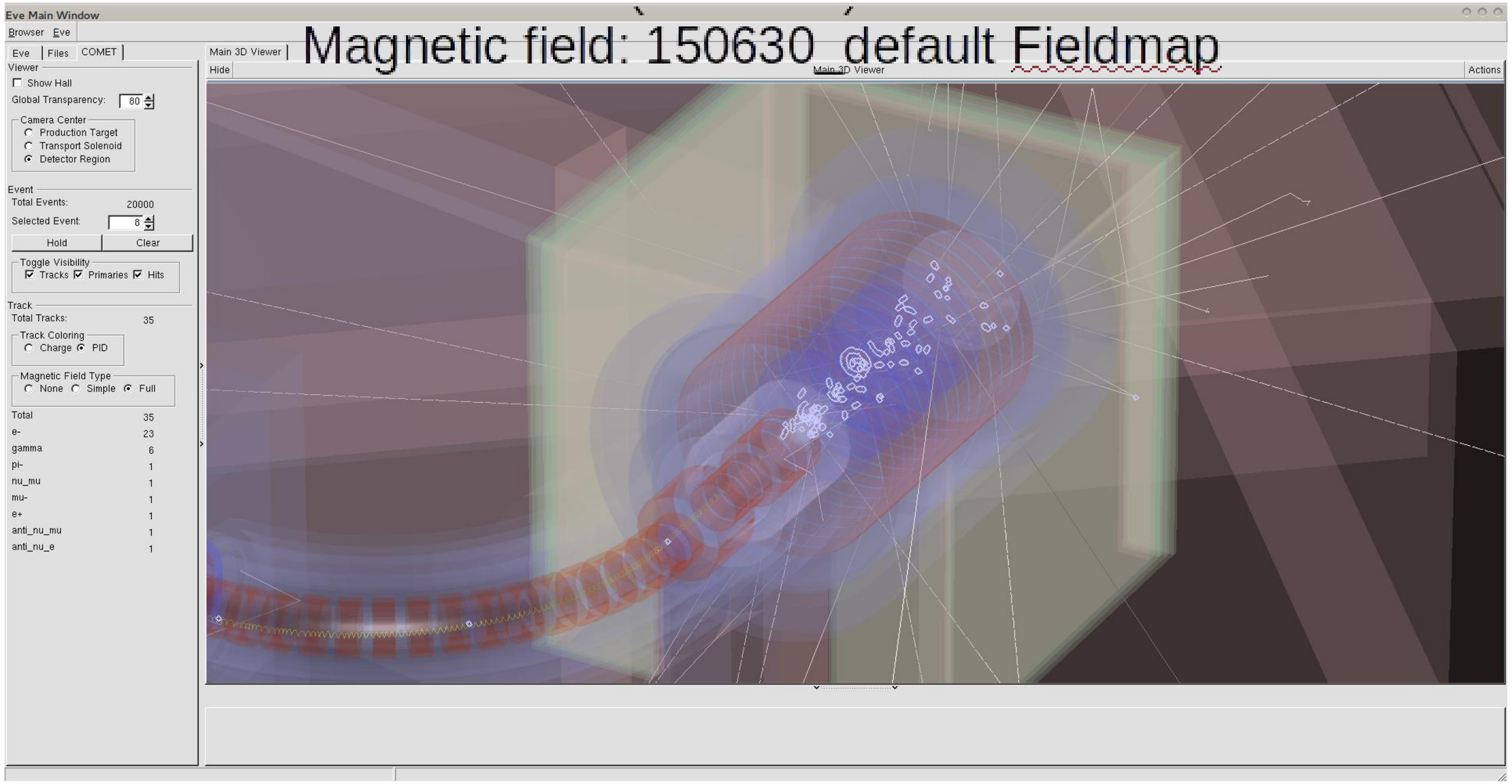


Simulation Model

- The simulation was done using ICEDUST software.

<u>Signal event simulation</u>

- At the simulation a point-like isotropic source of monoenergetic electrons with the momentum of 105 MeV/c and $-25^o < \Theta < 25^o$ was used. One million electron events around the muon-stopping target were simulated.



Magnetic field: 150630_default Fieldmap

Viewer
☐ Show Hall
Global Transparency: 80
Camera Center
○ Production Target
○ Transport Solenoid
● Detector Region

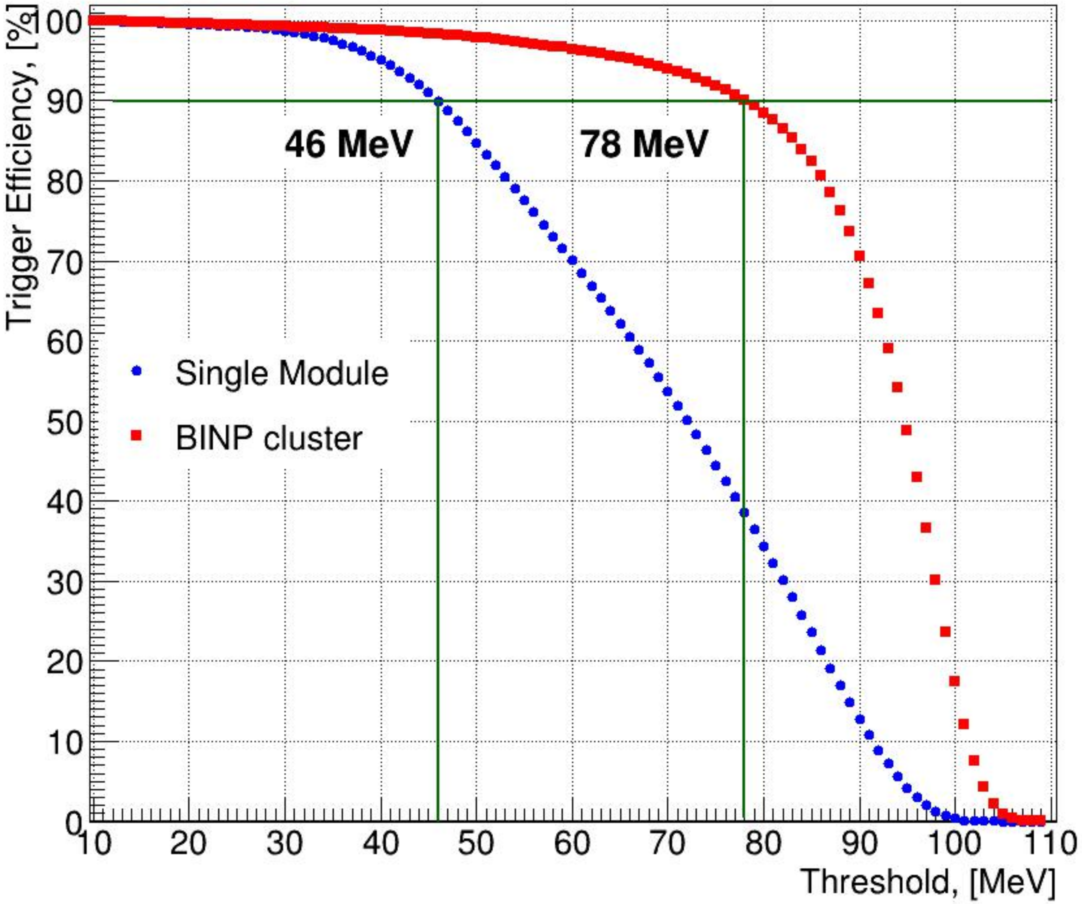
Event
Total Events: 20000
Selected Event: 8
Toggle Visibility
☑ Tracks ☑ Primaries ☑ Hits

Track
Total Tracks: 35
Track Coloring
○ Charge ● PID
Magnetic Field Type
○ None ○ Simple ● Full

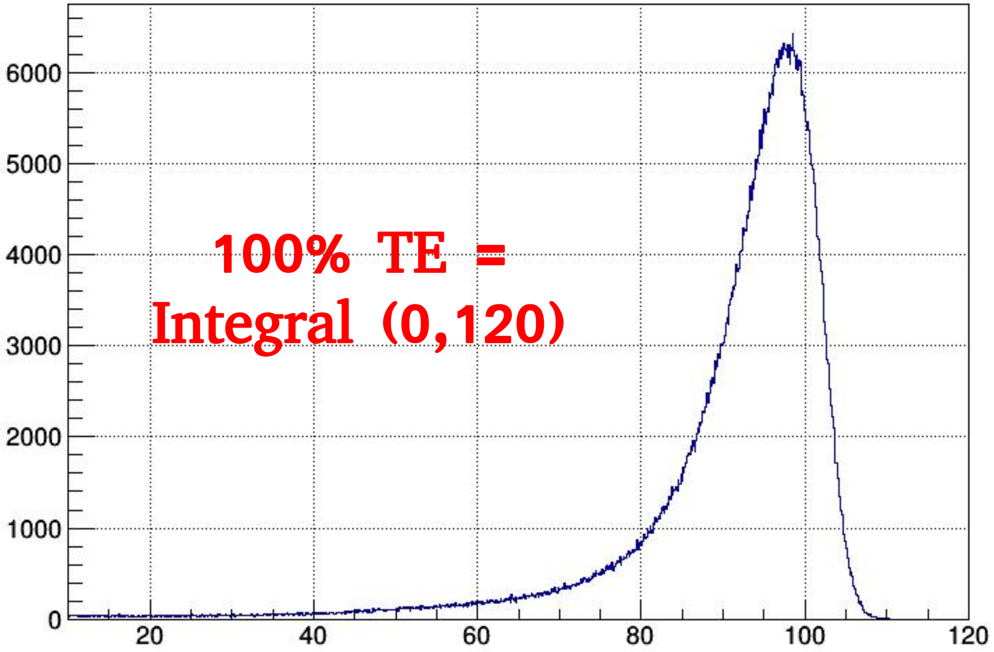
Total	35
e-	23
gamma	6
pi-	1
nu_mu	1
mu-	1
e+	1
anti_nu_mu	1
anti_nu_e	1

Trigger efficiency

Trigger efficiency (TE) is defined as the fraction of signal events with energy above the chosen trigger threshold.



The behavior of trigger efficiency as a function of the threshold imposed on the reconstructed energy for each cluster sizes

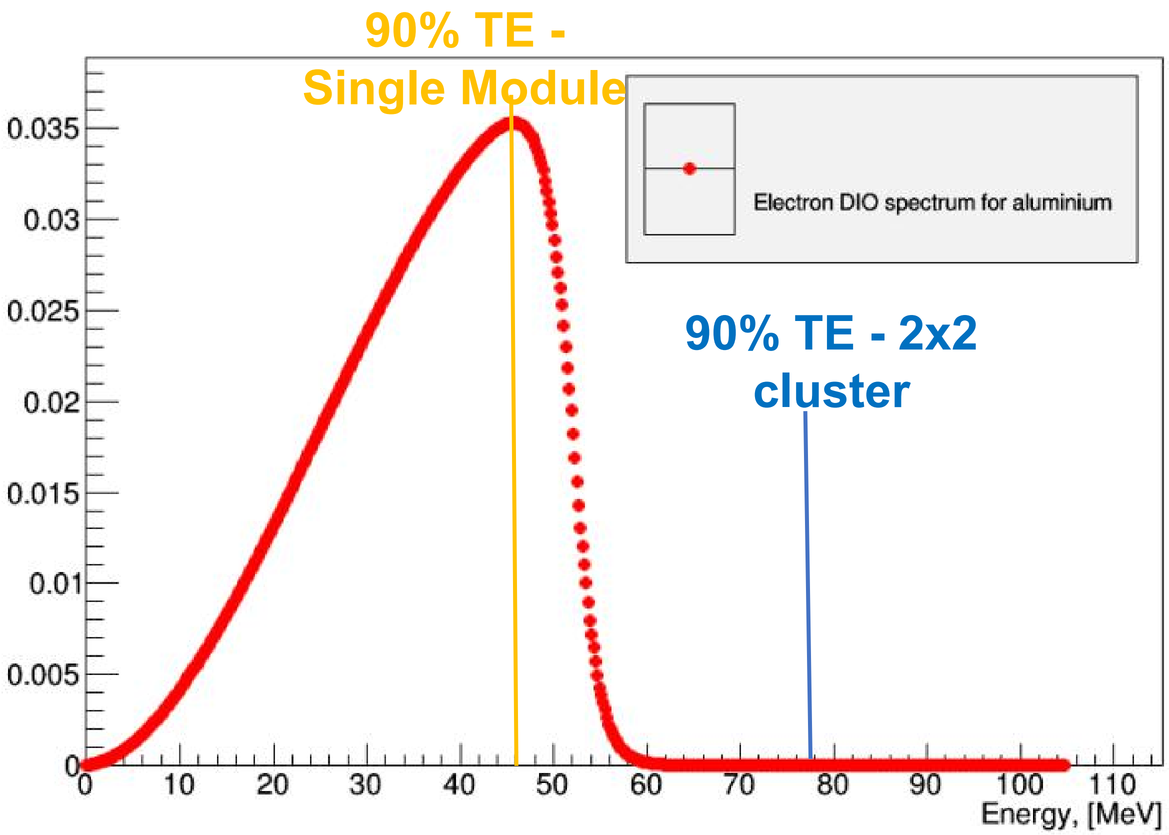


100% TE = Integral (0,120)

90% trigger efficiency on signal events corresponds a threshold of ~ 78 MeV for 2x2 trigger cells and ~46 MeV - single trigger cell.

DIO spectrum

The main background process which deposits large energy in the calorimeter is the DIO electrons. Moreover, the high-energy tail of the electron spectrum in muon decay in orbit constitutes a background for conversion search.



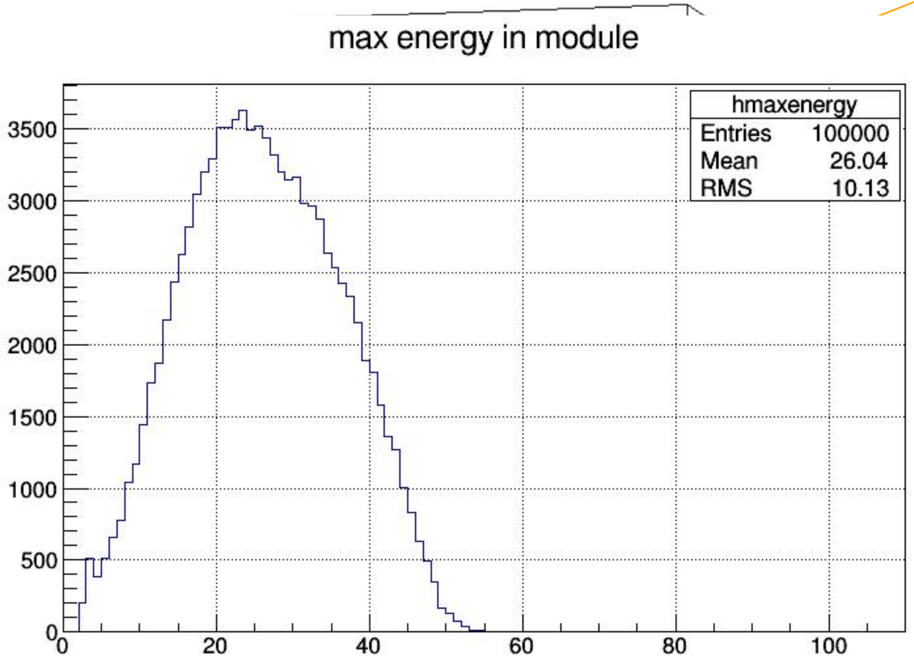
Since the DIO electron energy spectrum strongly falls at ~ E>60 MeV then it is very important to have an ECAL trigger with high efficiency at high threshold energy.
In the opposite case with decreasing trigger threshold energy the surviving DIO rate quickles increases.

Trigger threshold should provide a compromise between reducing the DAQ acquisition rate and an high efficiency on the signal.

DIO rejection factor. Single Module

The estimation of the trigger response on DIO eletrons.

100 thousand DIO electrons were generated (by putting a discrete values of spectrum into SimG4 macro file) around the muon target. Since I used the full region of the DIO spectrum (from 0 to 105 MeV) hence the tail of the spectrum was not generated due to a low probability.



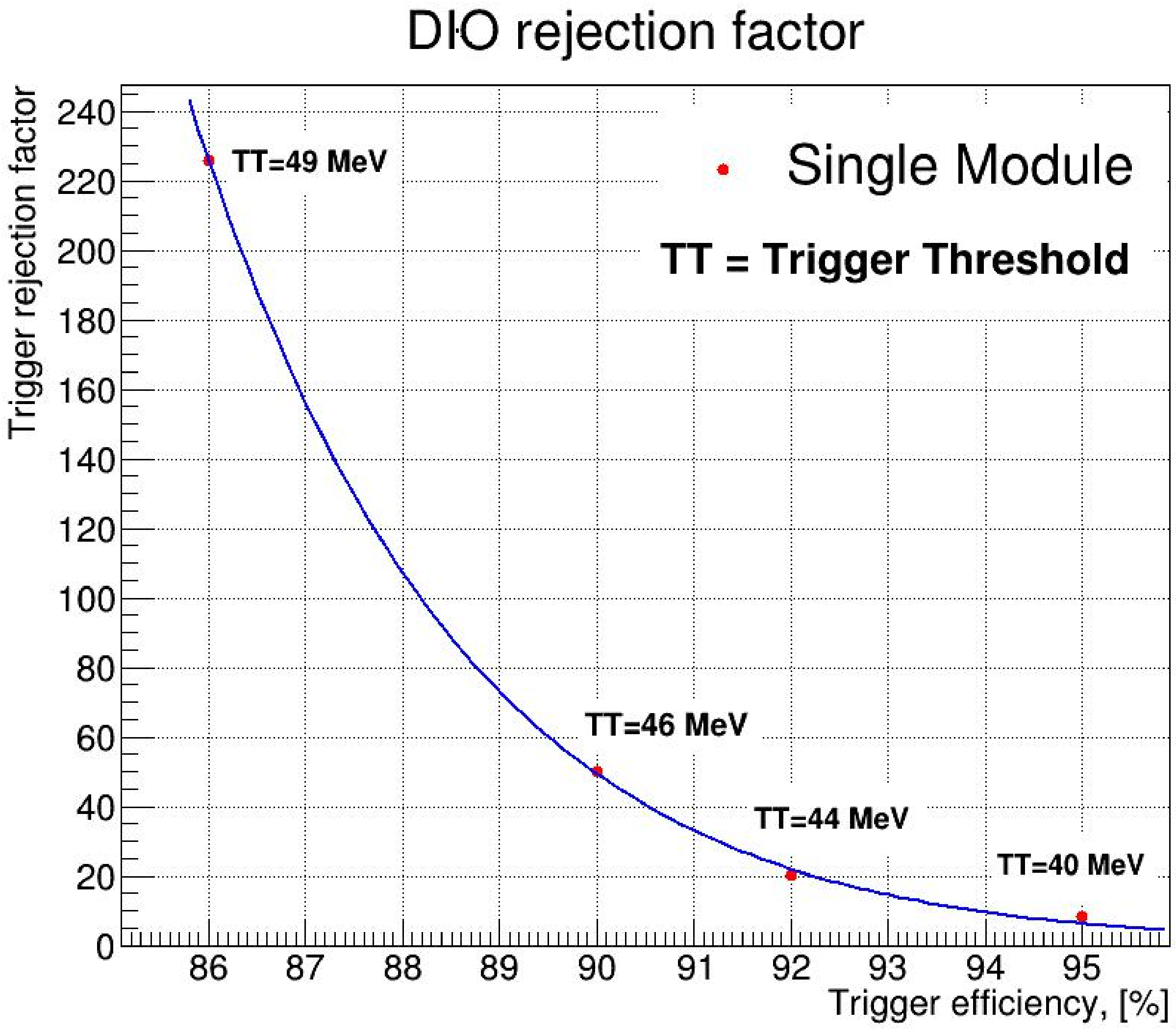
Based on the energy spectrum of deposited energy for a single module, the DIO rejection factor estimated as the ratio of the integrals:

DIO rejection factor =

Integral(start point, end point) / Integral(Threshold, end point)

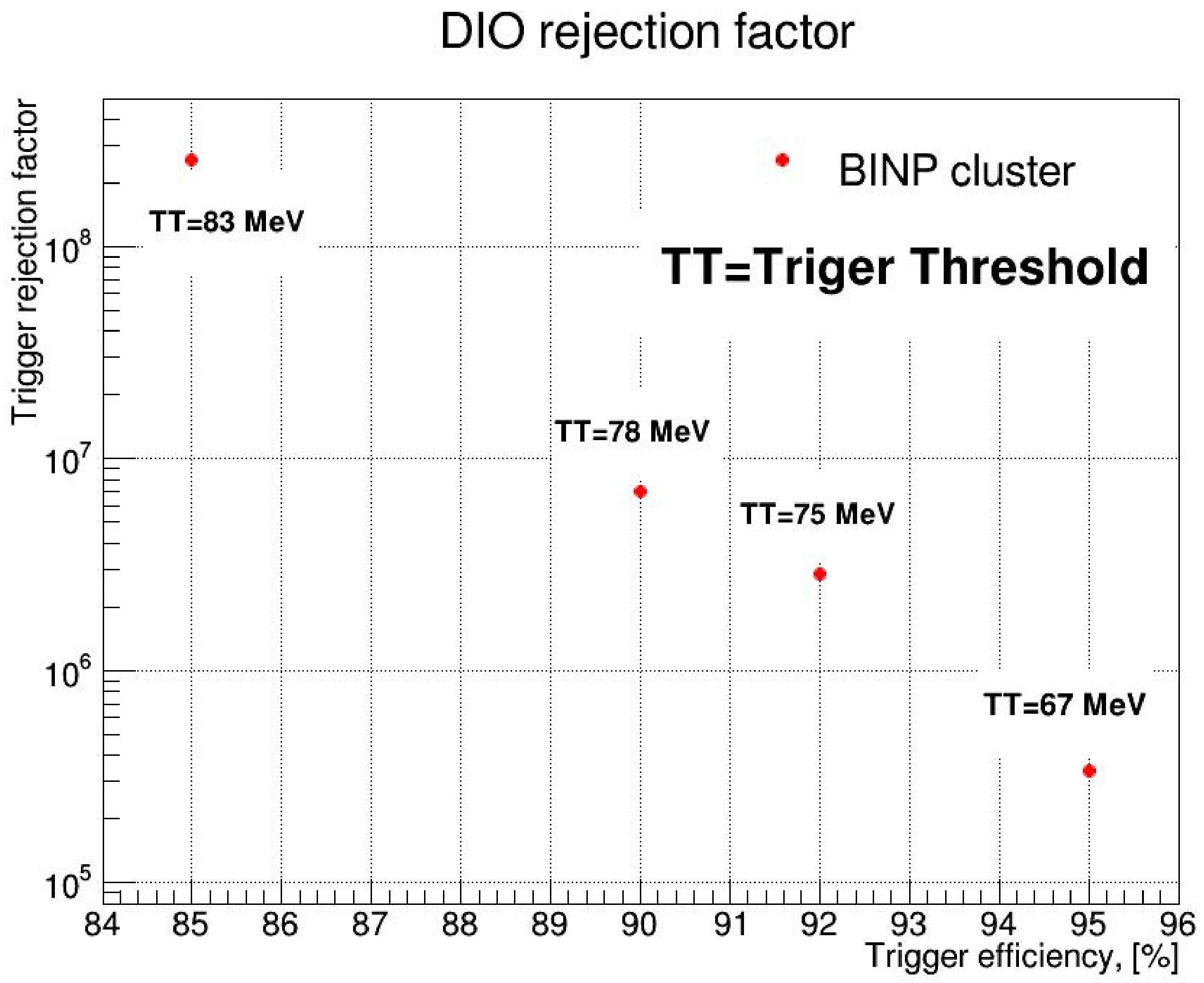
Such a scheme has been applied to each threshold energy.

DIO rejection factor. Single Module



DIO rejection factor is 50 for 90% trigger efficiency on signal event.
In other words, such a trigger pass 2% of all DIO events!!!

DIO rejection factor. BINP cluster



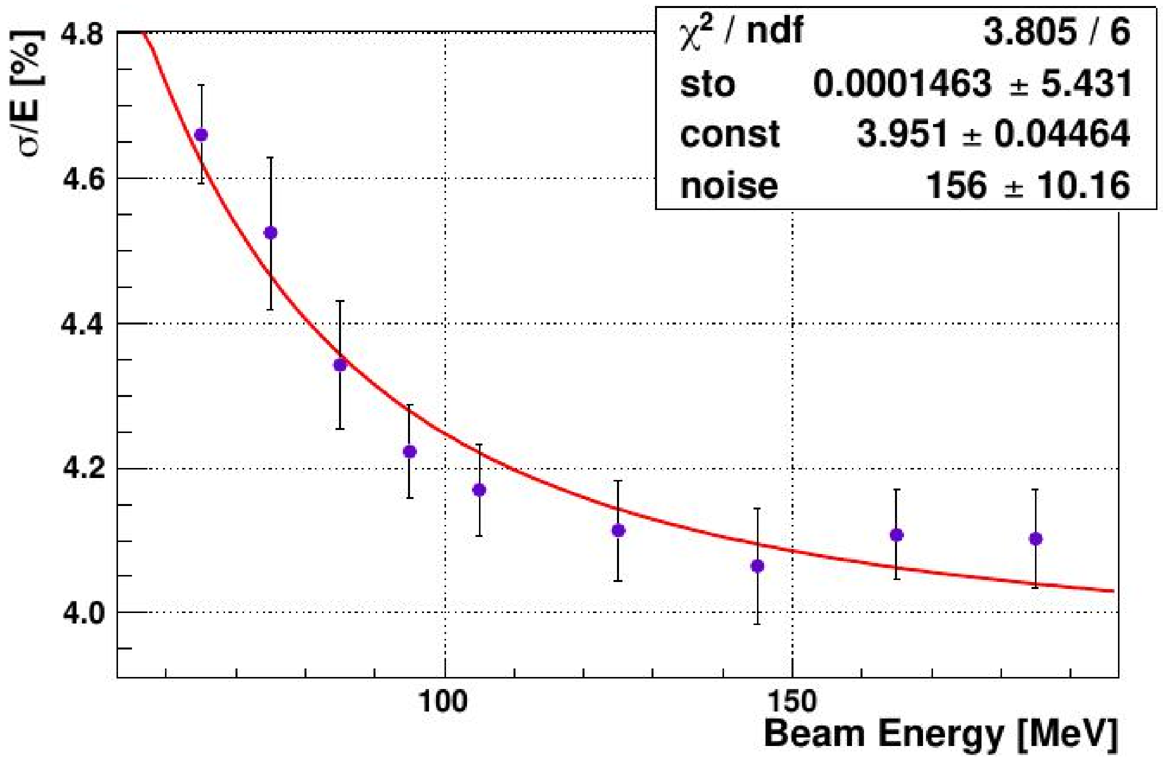
DIO rejection factor is 10^{6} for 90%-93% trigger efficiency on signal event.

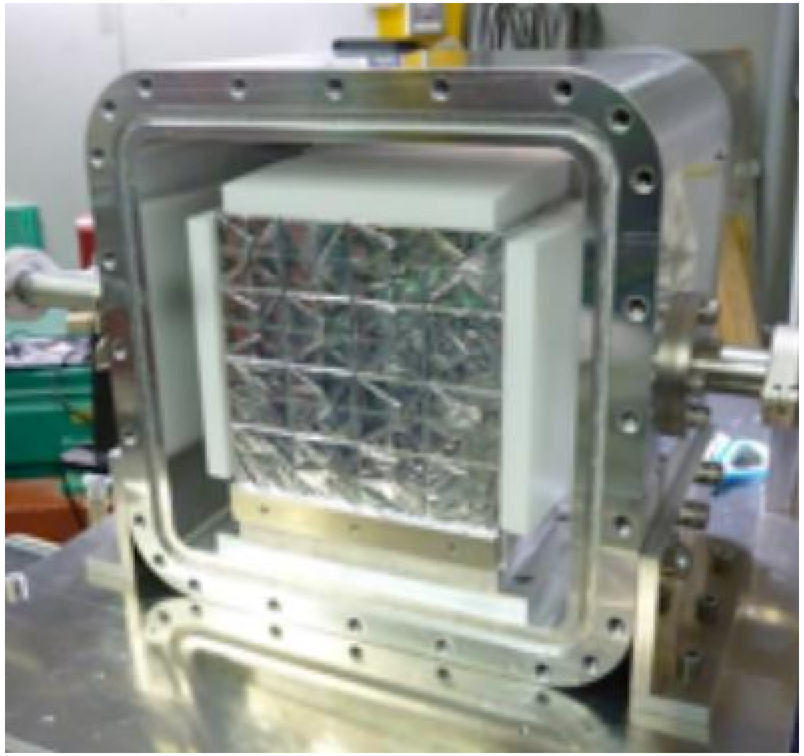
Test Beam

The electronics prototype with proposed logic was verified by test-bench measurements and electron beam experiments.

Test beam: ECAL prototype consits of 64 crystsals

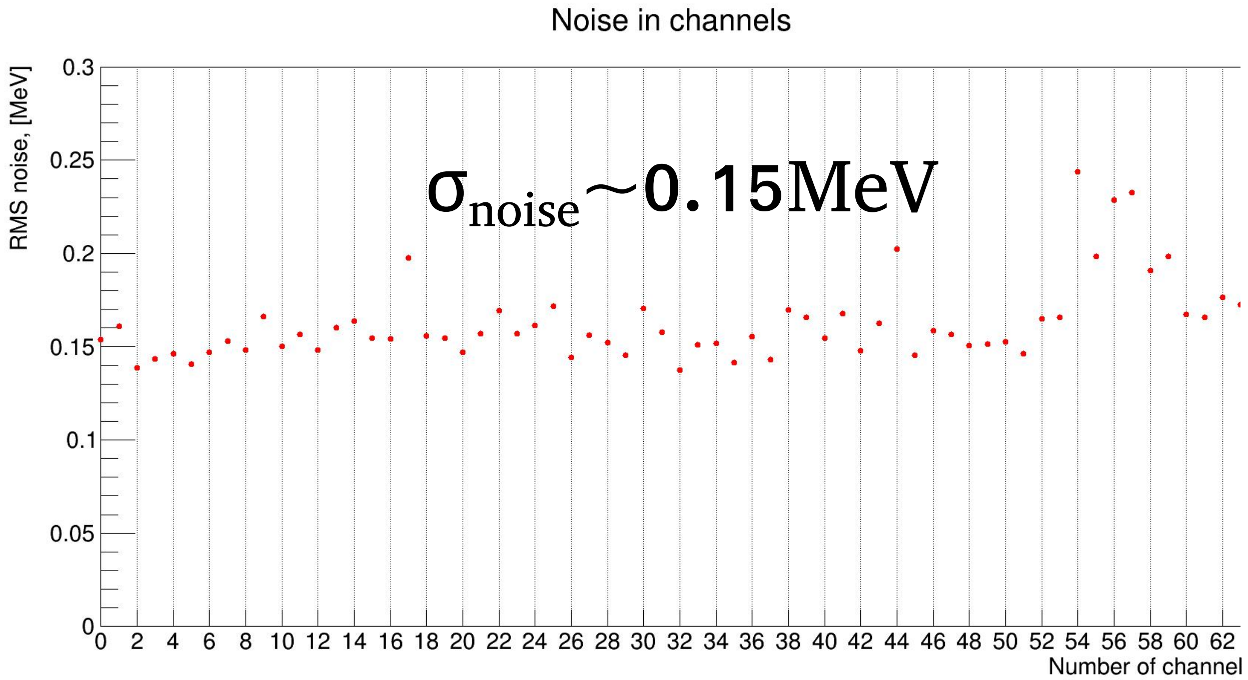
- **Momentum scan to evaluate energy resolution**
  - ✦ 65, 75, 85, 95, 105, 125, 145, 165,185 MeV/c electron beam



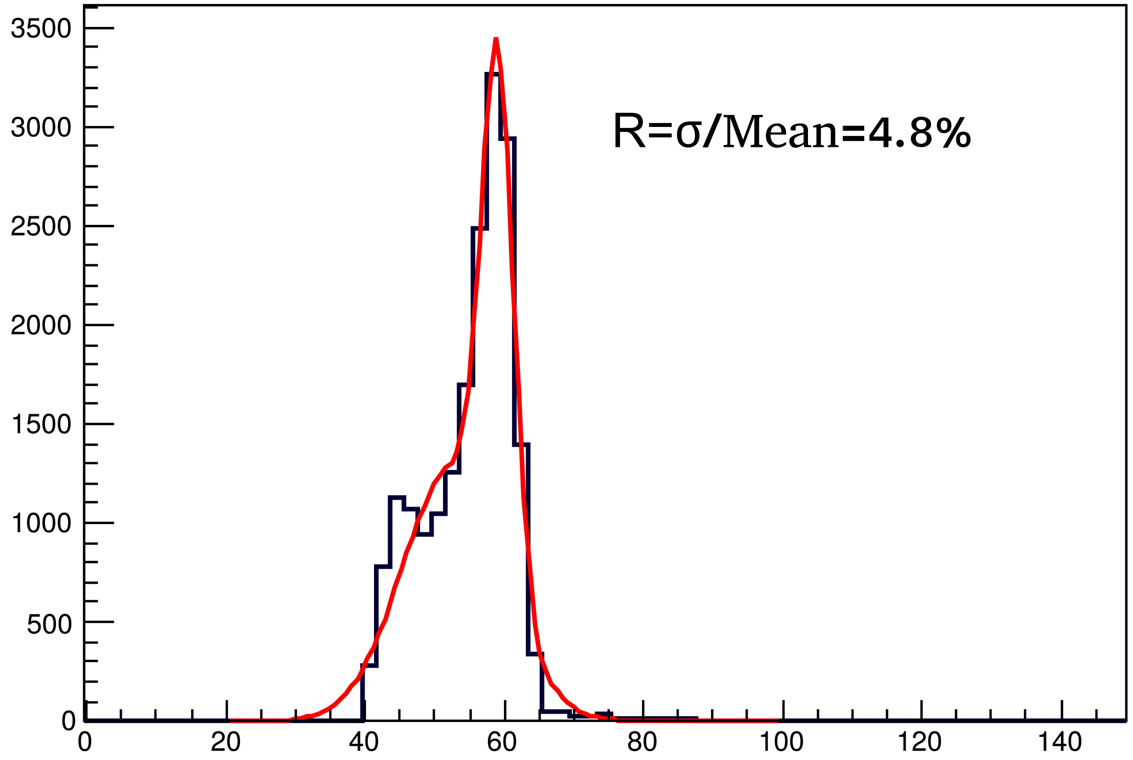


Test Beam. Trigger energy resolution

Trigger system energy resolution less 5% for signal events!


Noise in channels

$\sigma_{noise} \sim 0.15\,\mathrm{MeV}$


R=σ/Mean=4.8%

Conclusion. Part2

On the basis of the Monte-Carlo simulation results a signal processing algorithm for determination in real time of the energy deposited by incident particles has been developed and implemented in the created electronics prototype of the trigger system for an electromagnetic calorimeter of the COMET experiment.

The electronics prototype was verified by electron beam experiments. The obtained results satisfy the key requirement of the calorimeter the energy resolution in real time is better than 5% for the signal electron energy

DIO rejection factor. BINP cluster

In the case of BINP cluster the analysis was slightly different.

1. 100 thousands electron events with an energy equal to the threshold energy around the muon-stopping target were simulated. The Gaussian fit to the energy spectrum to get σ.
2. The part of the DIO spectrum from start point = threshold -1,5•σ MeV to end point = 104,5 MeV was generated. Since electrons with energy less the threshold energy can be selected by trigger (due to the energy resolution).
3. DIO rejection factor = 1/ (F*P),

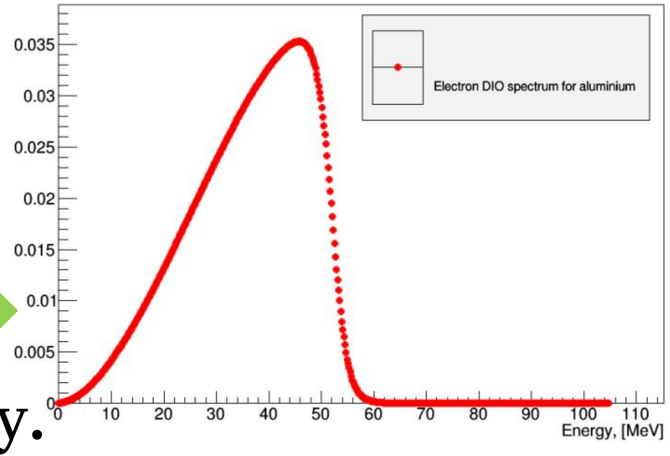
where F is number of events are selected by trigger with a given threshold energy.

F is determined from the the energy spectrum of deposited energy for the BINP cluster as follows:

$$F = \frac{\text{Integral (threshold, 105 MeV)}}{\text{Integral (threshold-1.5*}\sigma\text{, 105 MeV)}}$$

P is a probability of generated region of the DIO spectrum

$$P = \frac{\text{Integral (threshold-1.5 * }\sigma\text{, 105 MeV)}}{\text{Integral (0, 105 MeV)}}$$



Such a scheme has been applied to each threshold energy.