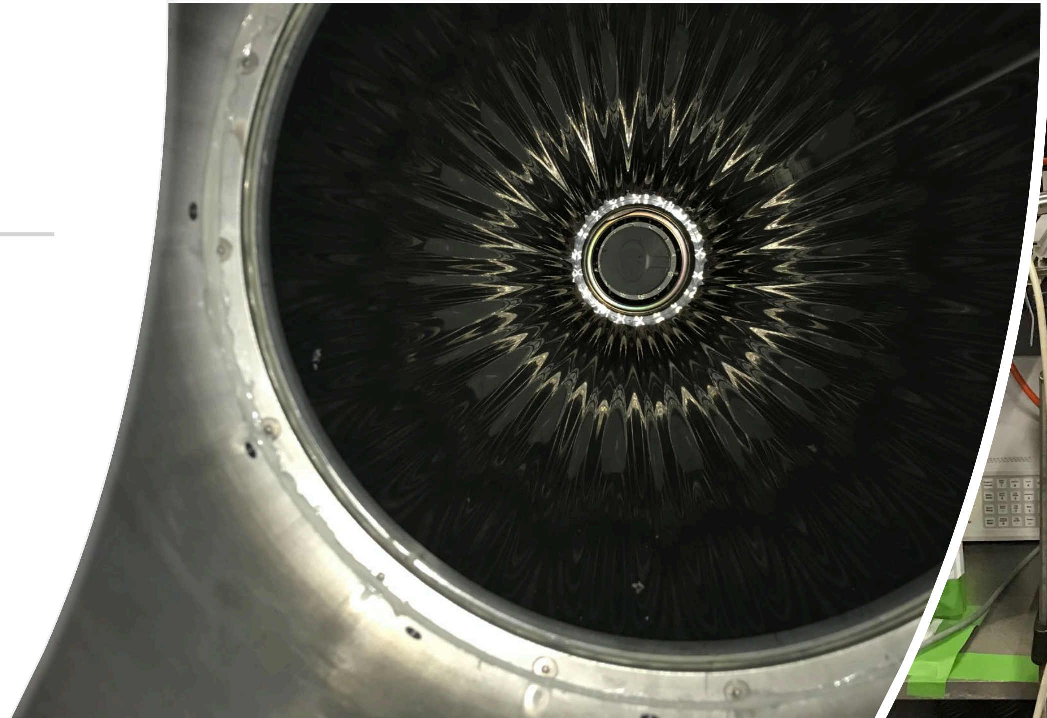
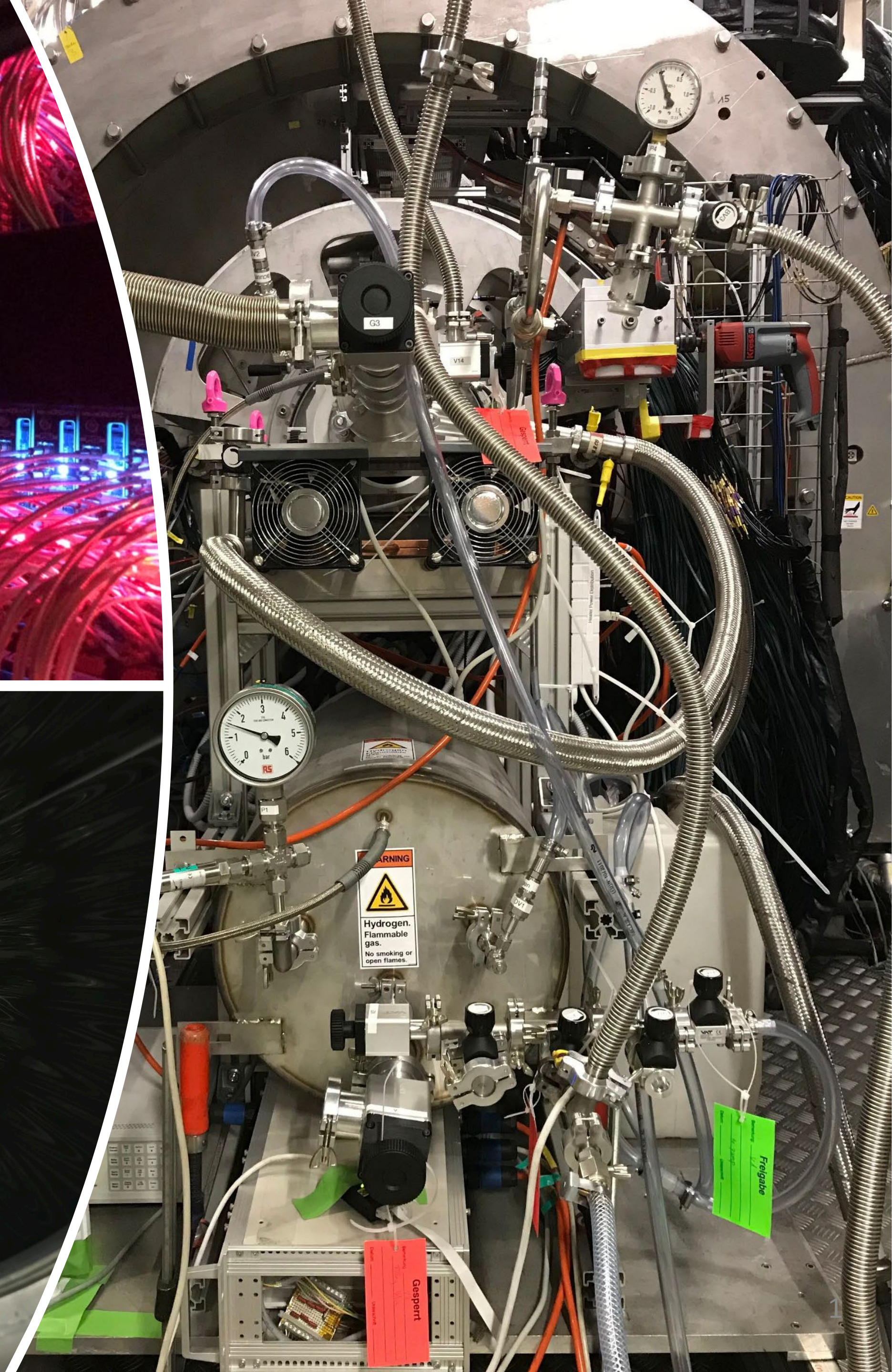
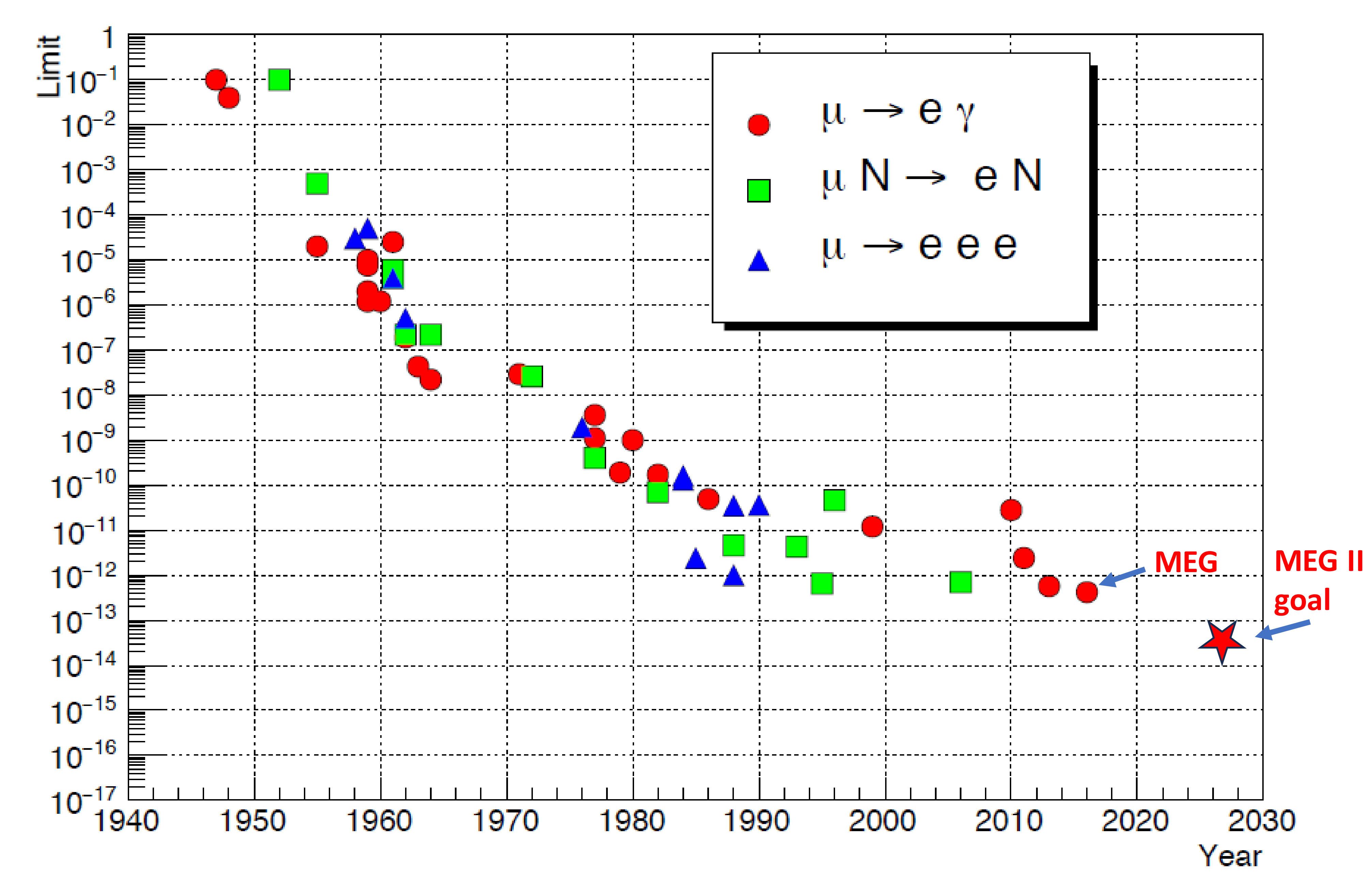
MEG II Status and future plans

Liverpool
November 10th 2023
A. M. Baldini
INFN Pisa







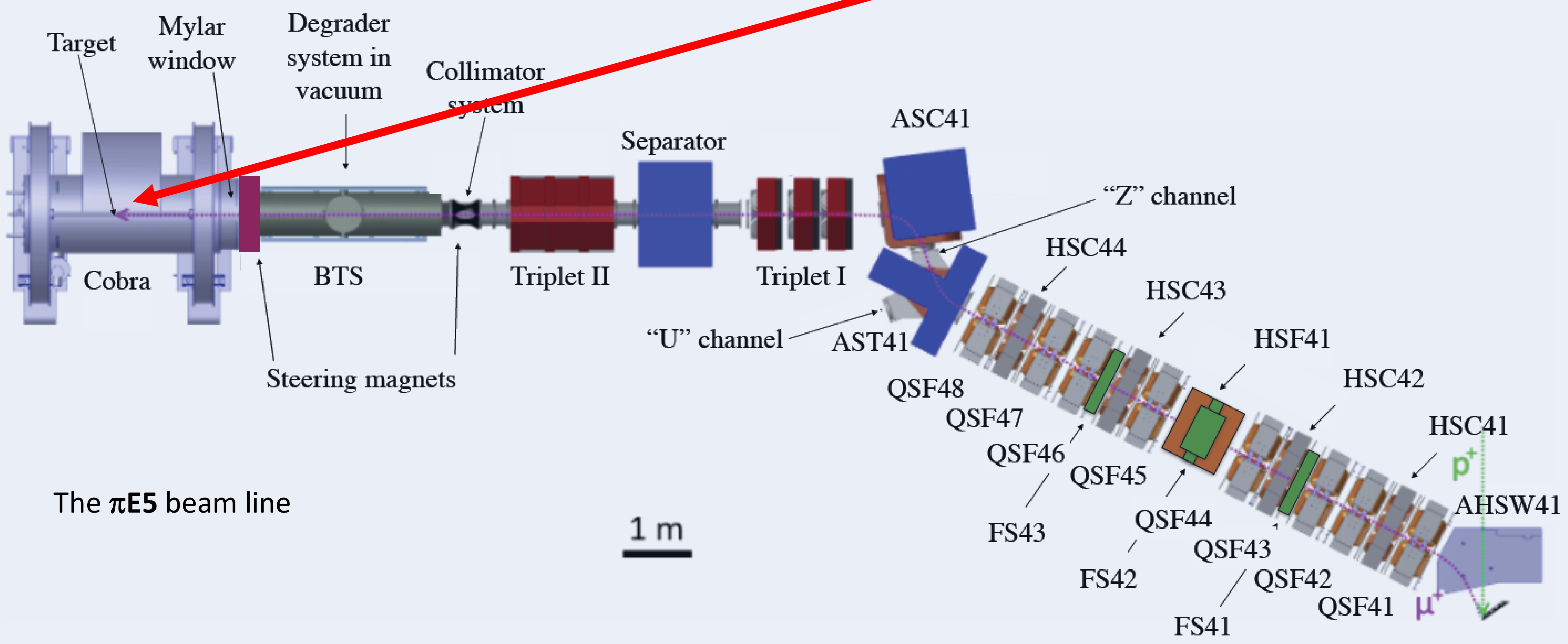
Charged Lepton Flavor Violation (CLFV)

$O(10^{-54})$ in the SM → If seen it would represent a clear sign of physics BSM

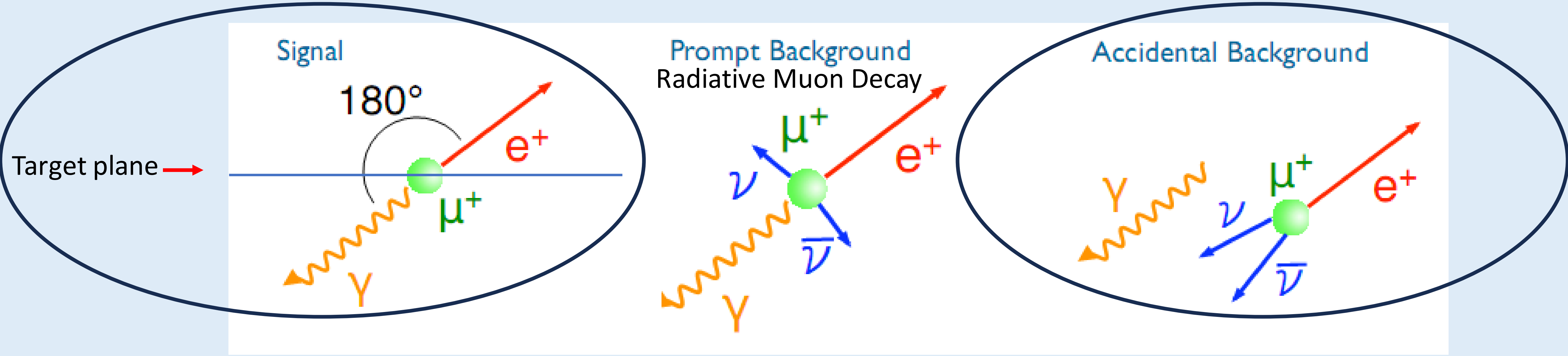
MEG II uses the **πE5** beam line at Paul Scherrer Institut in Switzerland

Surface muon beam: p ≅ 28 MeV/c

Up to 2.32x10^{8} μ/sec 2.2 mA can be trasported into the magnet (COBRA) of the experiment



The **πE5** beam line

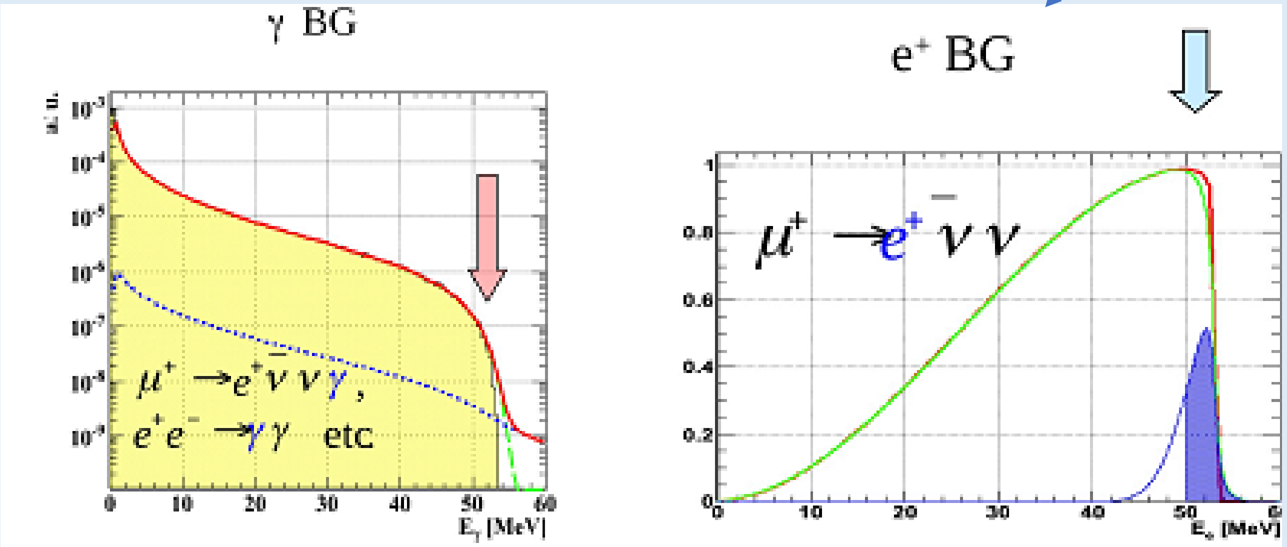


$\theta_{e\gamma}=180$

$E_{e^+}=E_\gamma=52.8$ MeV

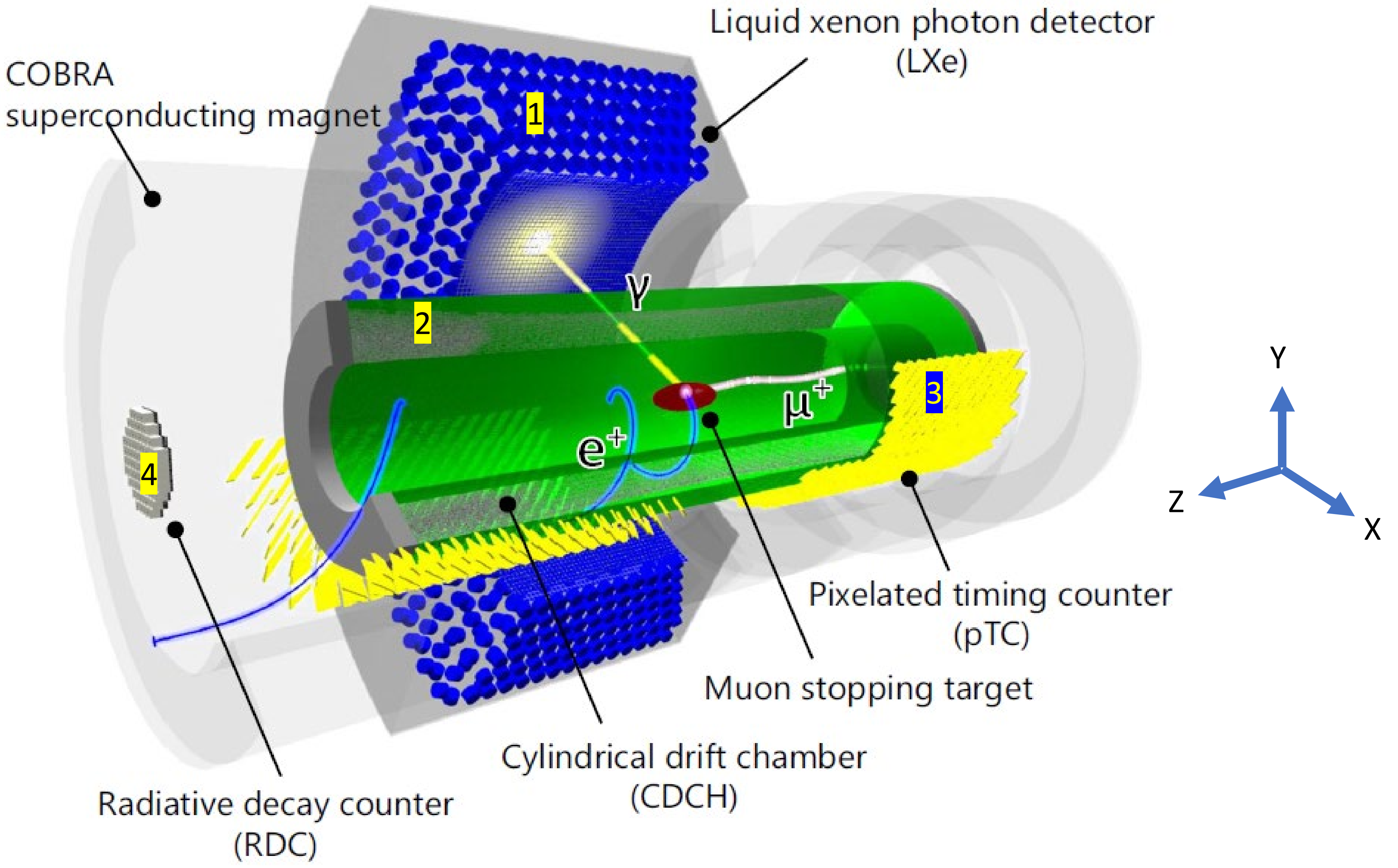
$t_{e^+}=t_\gamma$

$N_{acc} \propto R_\mu^2\, \sigma_{\Delta t}\, \sigma_{\Delta\theta}^2\, \sigma_{E_\gamma}^2\, \sigma_{E_{e^+}}$

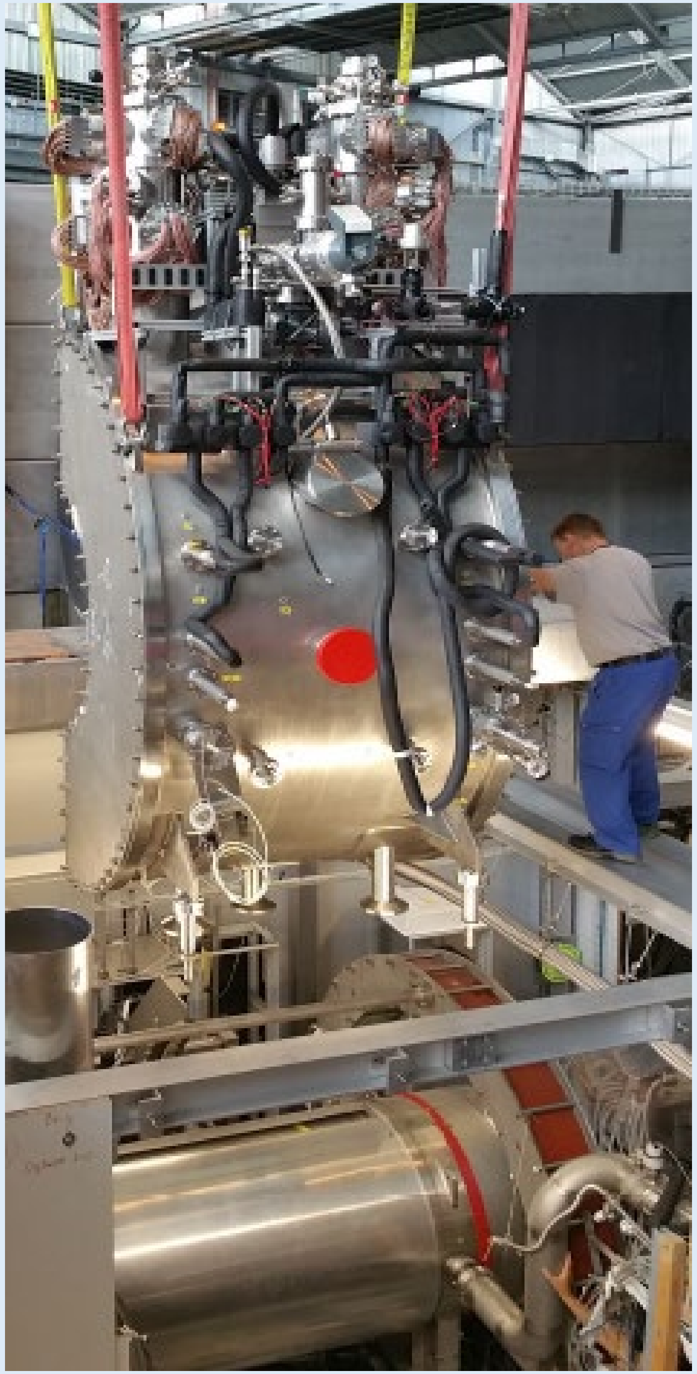


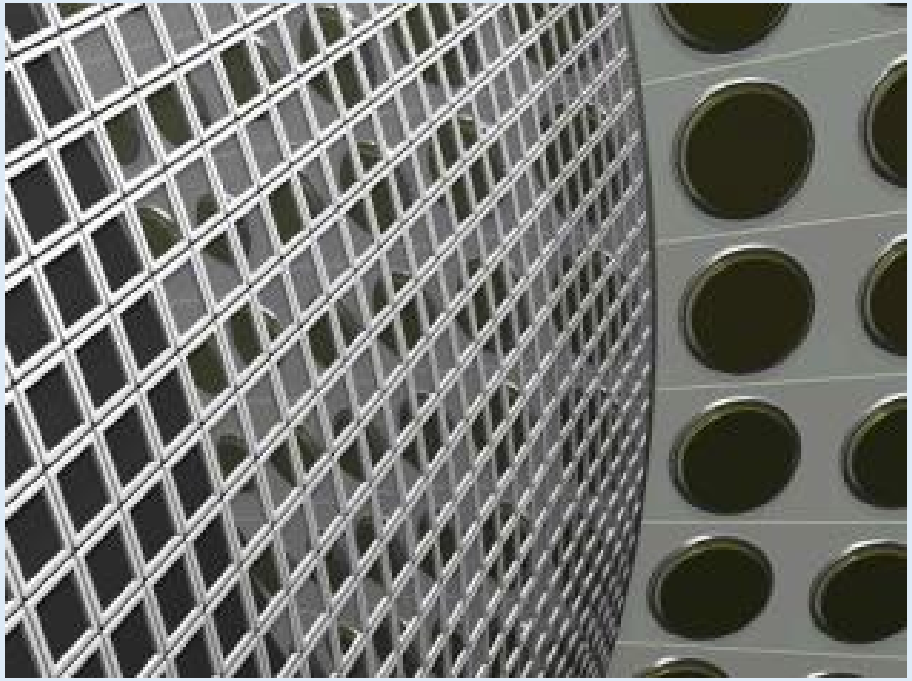
At large muon intensities background is by far dominated by the accidental component

Detectors resolutions are crucial to keep it under control



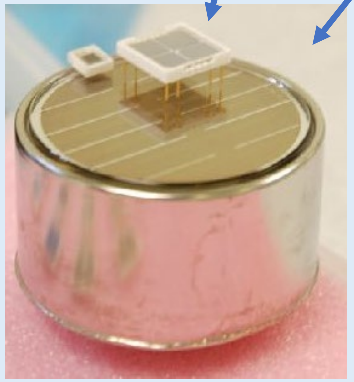
Liquid xenon photon detector
(LXe)
COBRA
superconducting magnet
1
γ
2
3
μ+
e+
4
Y
Z
X
Pixelated timing counter
(pTC)
Muon stopping target
Cylindrical drift chamber
(CDCH)
Radiative decay counter
(RDC)

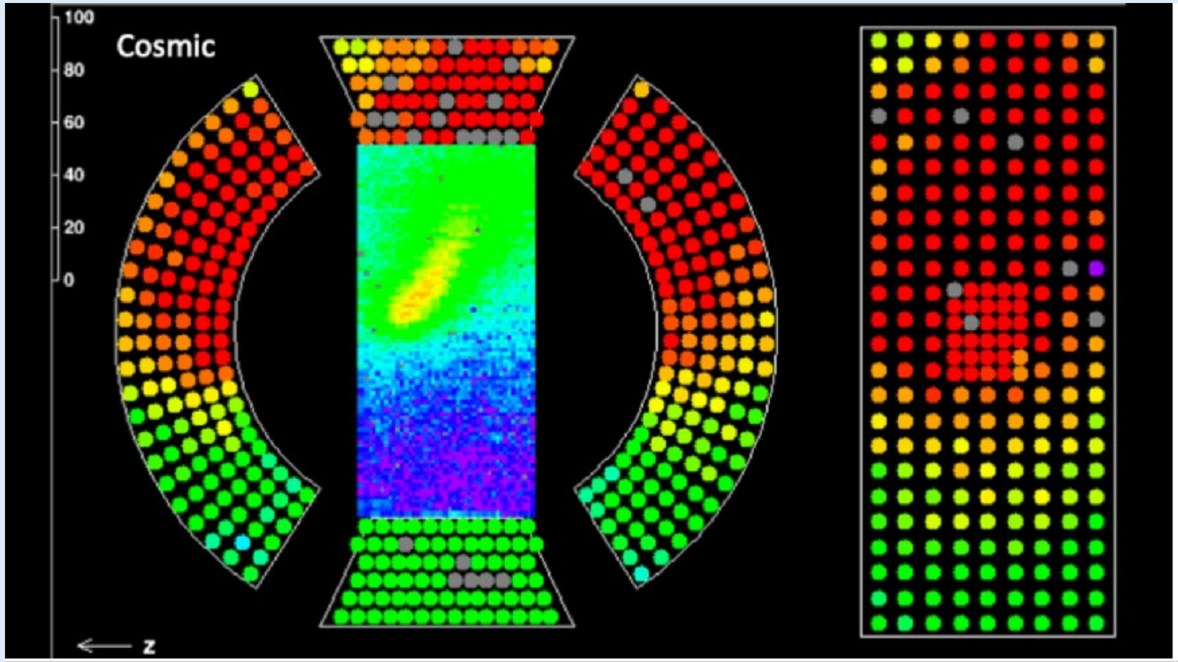


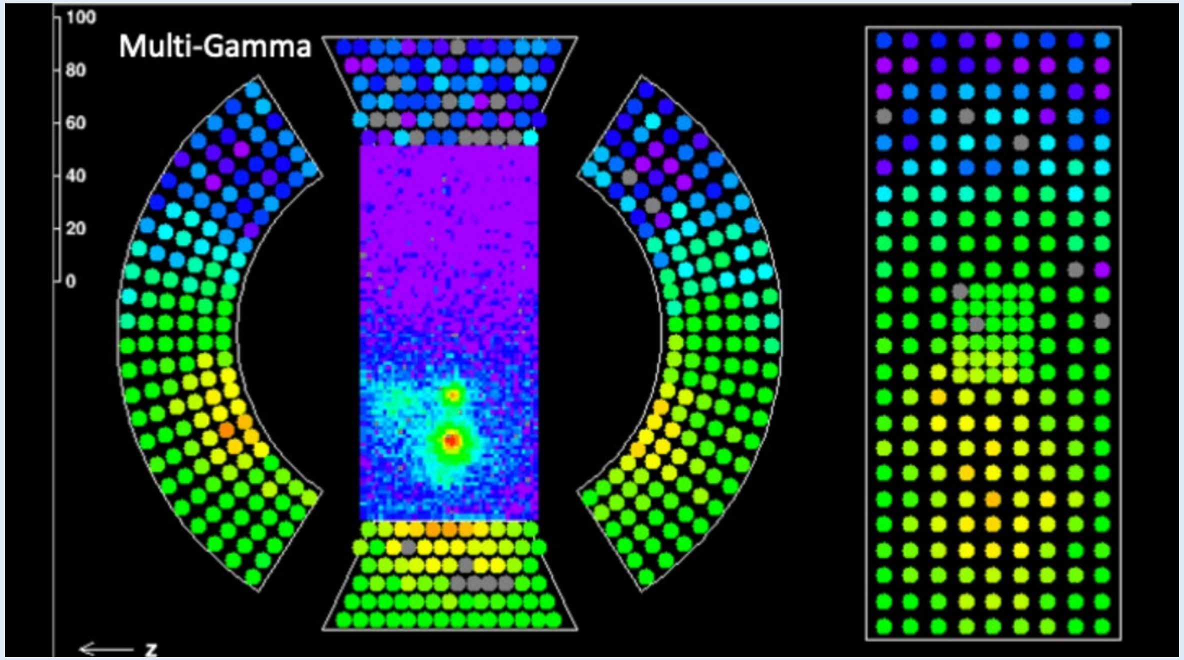


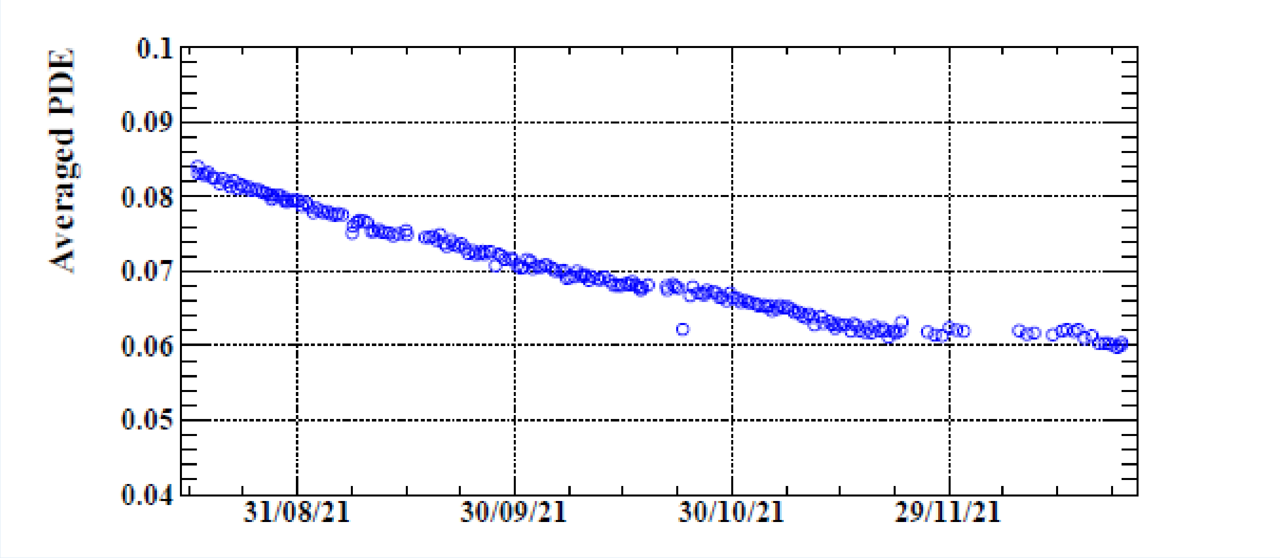
1: LXe

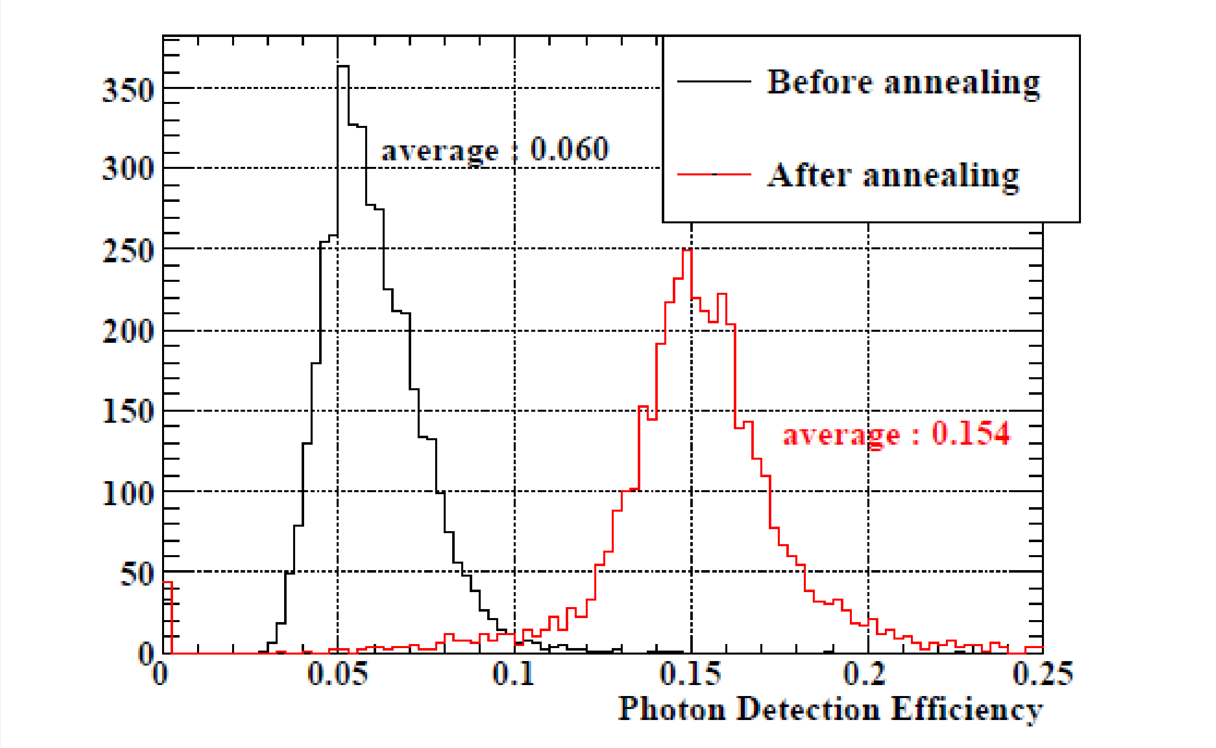
LXe γ–detector (800 liters) read by ≈ 4000 UV-sensitive 12mm x 12mm SiPMs (MPPC) on the γ–entrance face and by ≈ 600 2'' PMTs on the others




Cosmic
100
80
60
40
20
0
z


Multi-Gamma
100
80
60
40
20
0
z





SiPMs annealing: can be performed once per year O(1 month)

C-W proton accelerator

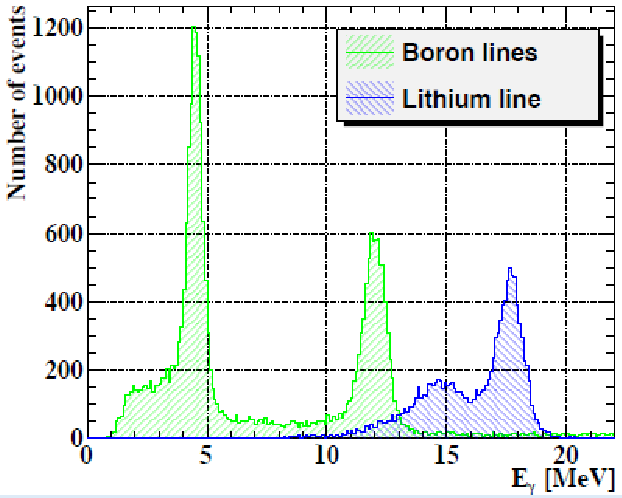
Up to 1 MeV proton on $LiBO_4$ target

Energy calibration line :

$$p\ {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}\ \gamma(17.6\ \mathrm{MeV})$$

XEC-pTC time alignment with line :

$$p\ {}^{11}\mathrm{B} \rightarrow {}^{12}\mathrm{C}\ \gamma(11.6\ \mathrm{MeV})\ \gamma(4.4\ \mathrm{MeV})$$



Three times a week

Charge Exchange reaction

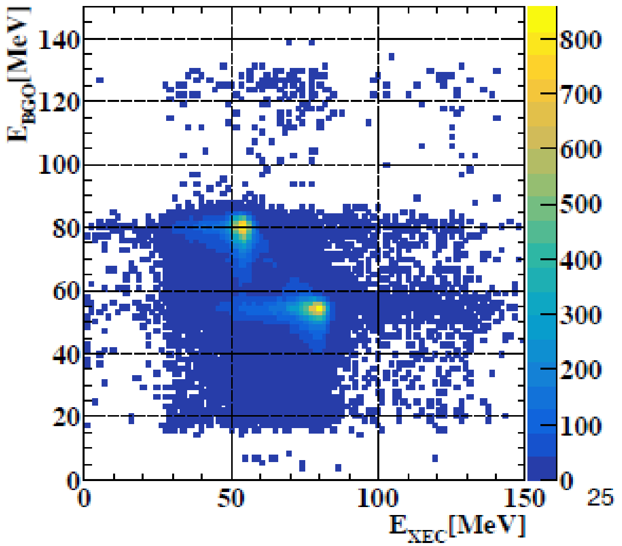
Energy & time calibration at signal energy

$$\pi^{-} p \rightarrow \pi^{0} n$$
$$\pi^{0} \rightarrow \gamma\gamma$$

Movable array of BGO Crystals

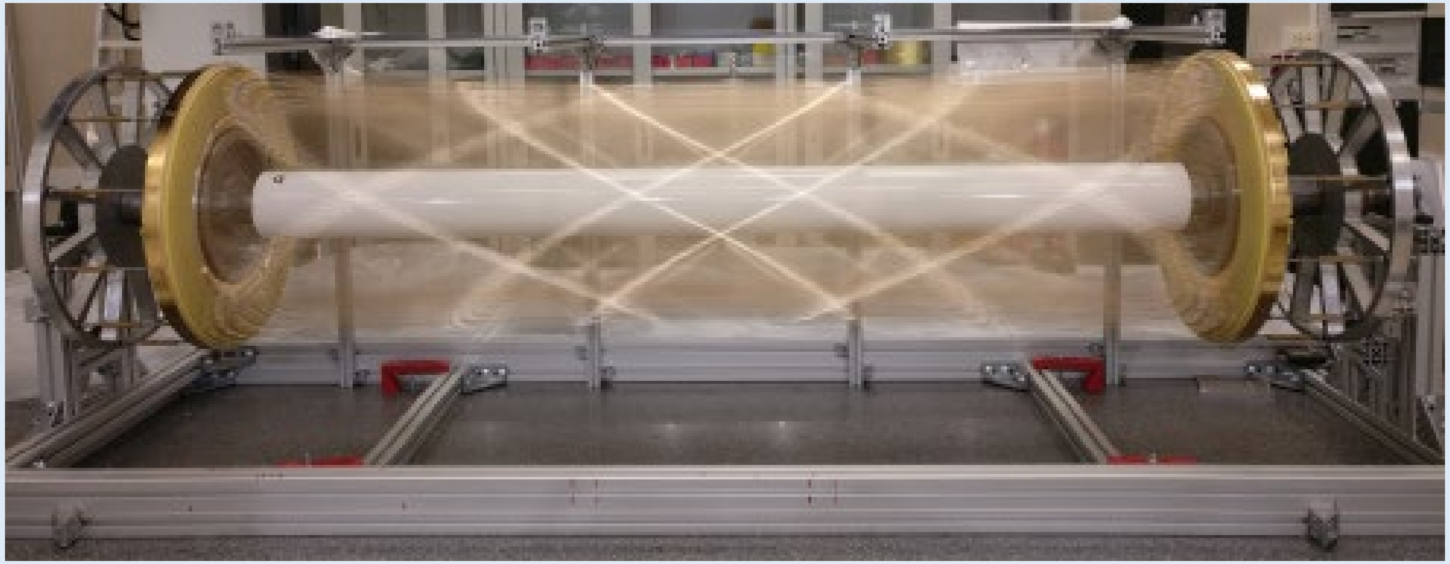
Energy in 55-83 MeV range

Data from the **first** Physics Run2021



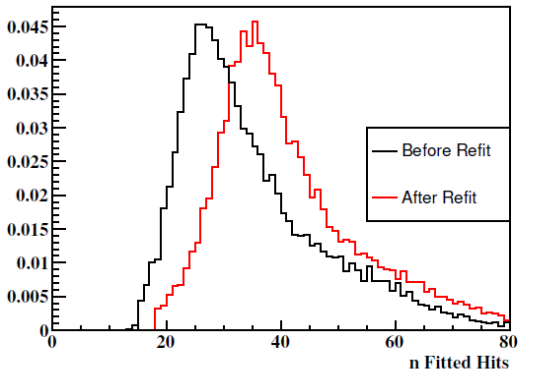
Once per year

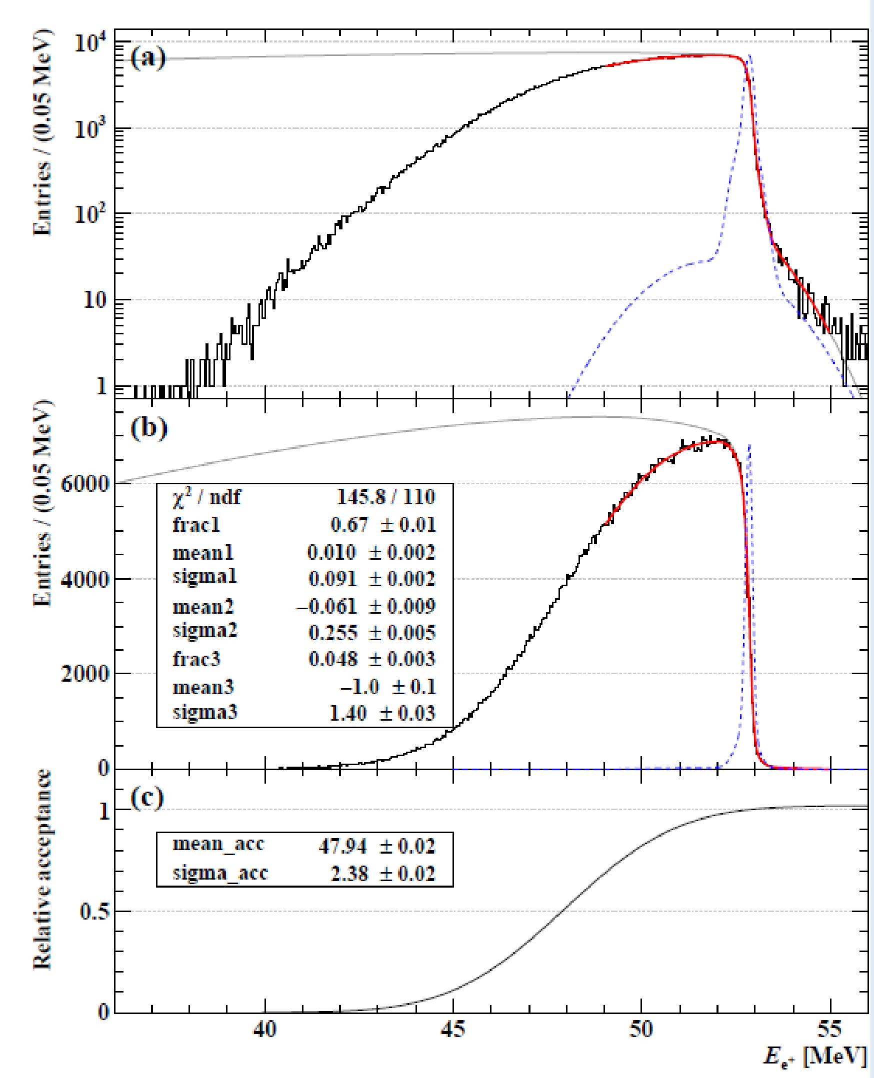
+ LEDs, Alpha sources on wire, n-generator (9 MeV from absorption in Ni)



2: CDCH

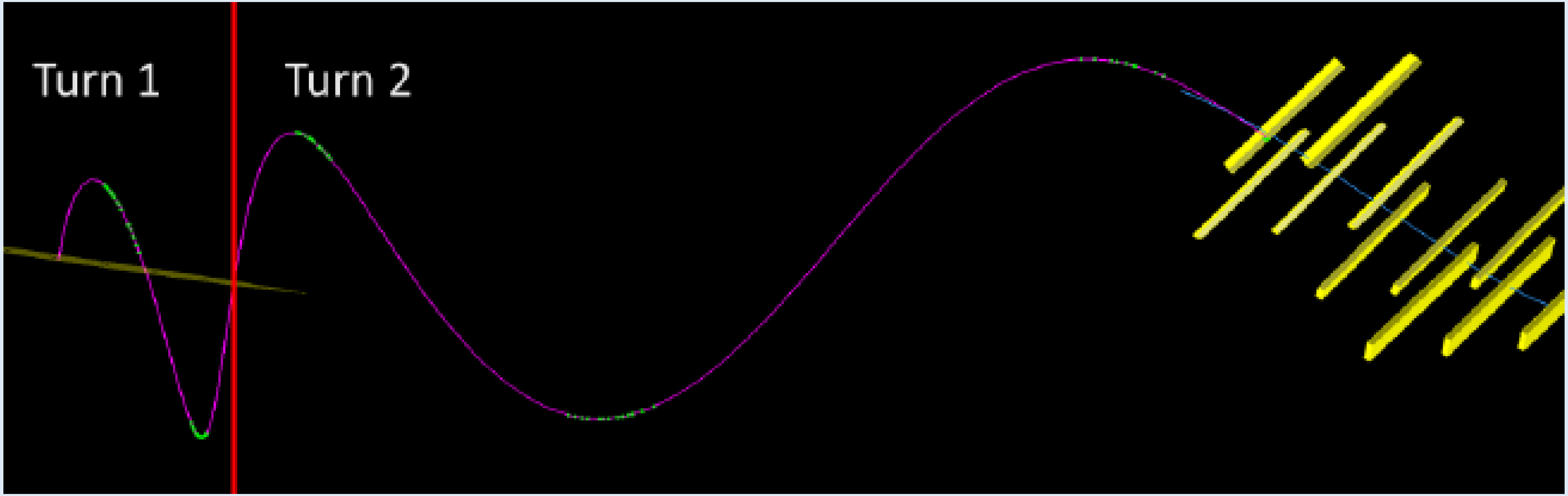
- u,v anodes stereo (7 degrees) configuration for improved position reconstruction along the beam axis
- Almost squared cells with 6 mm sides
- Roughly 1700 anodes (Au/Ti 20 μ) and 10,000 Ag/Al 40/50 μ cathodes
- He-Isobuthane (90-10) low mass gas mixture (+ addition of 1% isopropilic alcohol and ~0.5% oxygen)
- 1.5×10^{-3} rad.length per track (instead of 2×10^{-3} of MEG)
- Working properly since late 2020





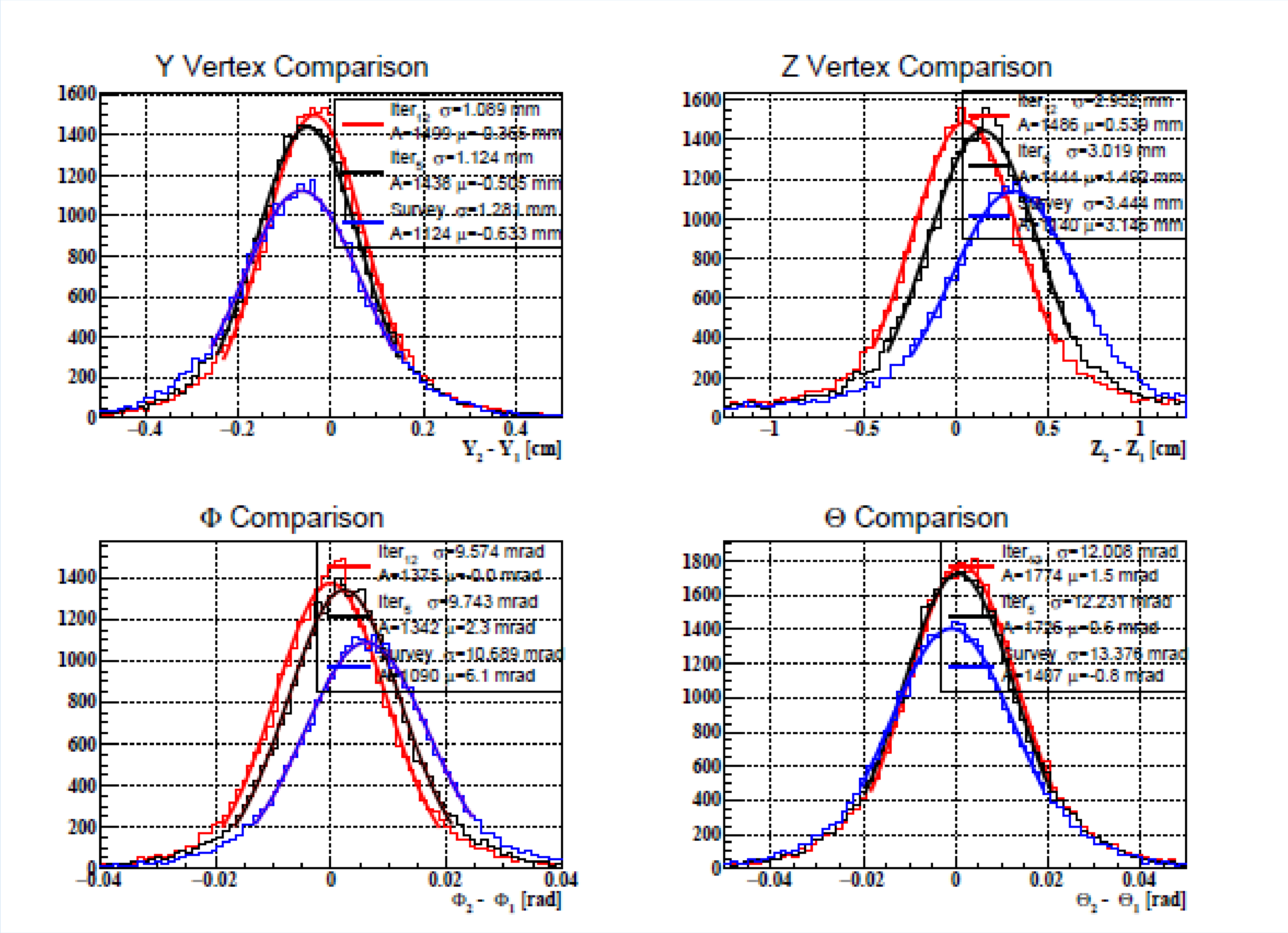
A backup chamber with different (bare Al5056) cathodes will be available in 2024

Positron tracks passing twice through the target are used to determine position and angle resolutions



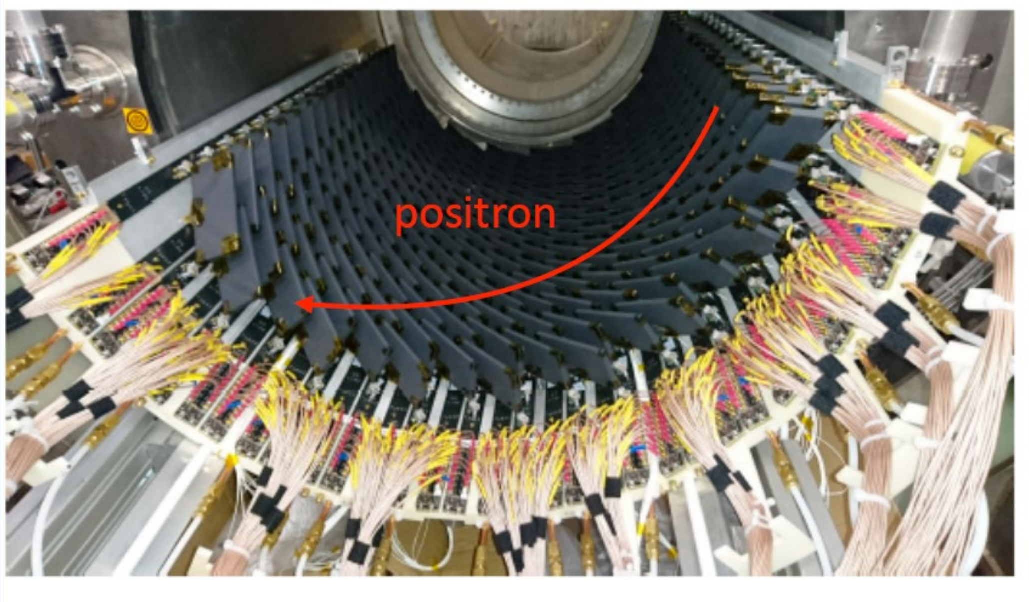
- Survey alignment
- Iterative alignment after 5 steps
- After 12 steps

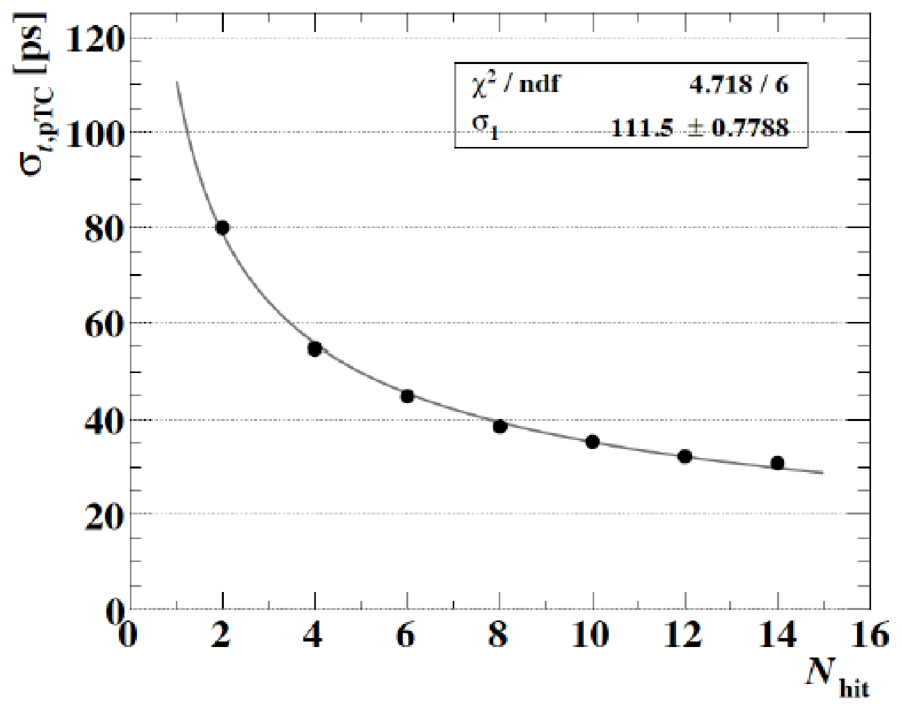
Alternative alignment (Millepede for wires with sag) being developed



3: pixelated Timing Counter

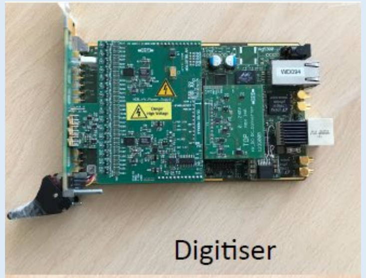
- Two sectors made of 256 scintillating BC422 tiles read by Advansid SiPMs
- Time obtained by averaging the tiles hit by a positron: 8 tiles on average for signal positrons
- A laser system is used for calibrations and monitoring

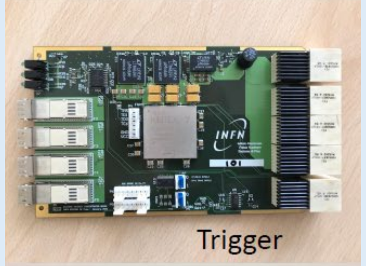


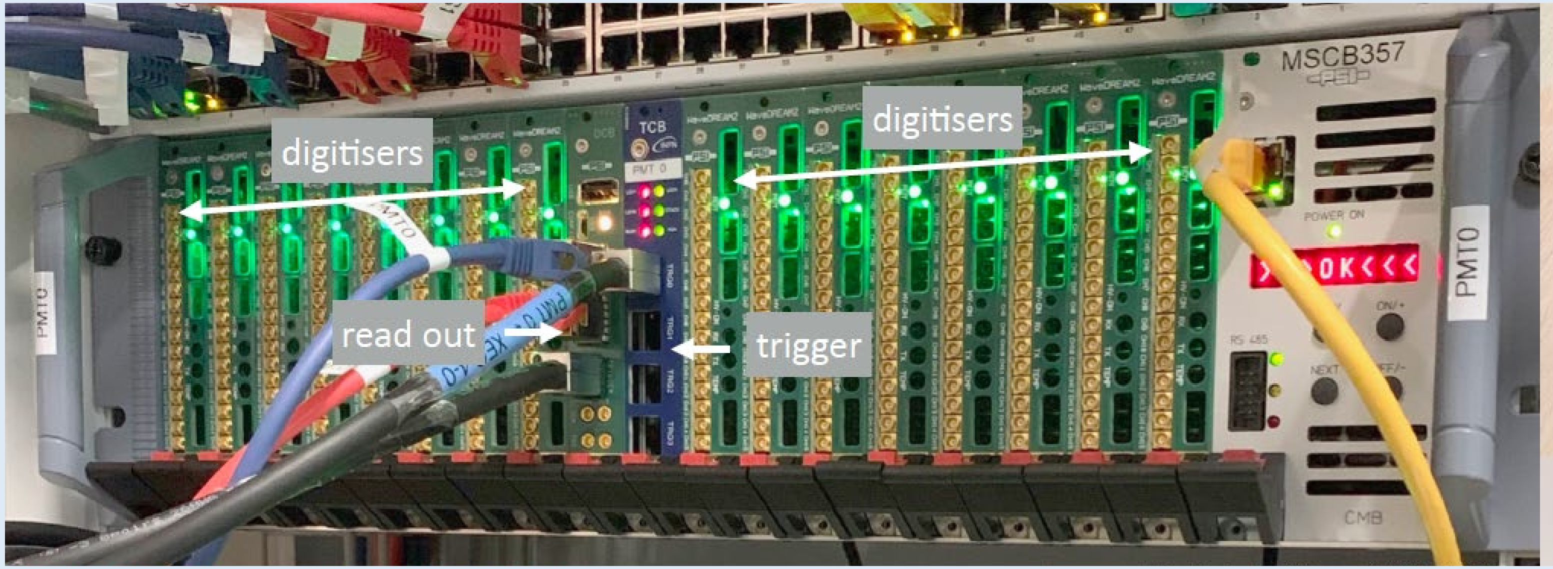


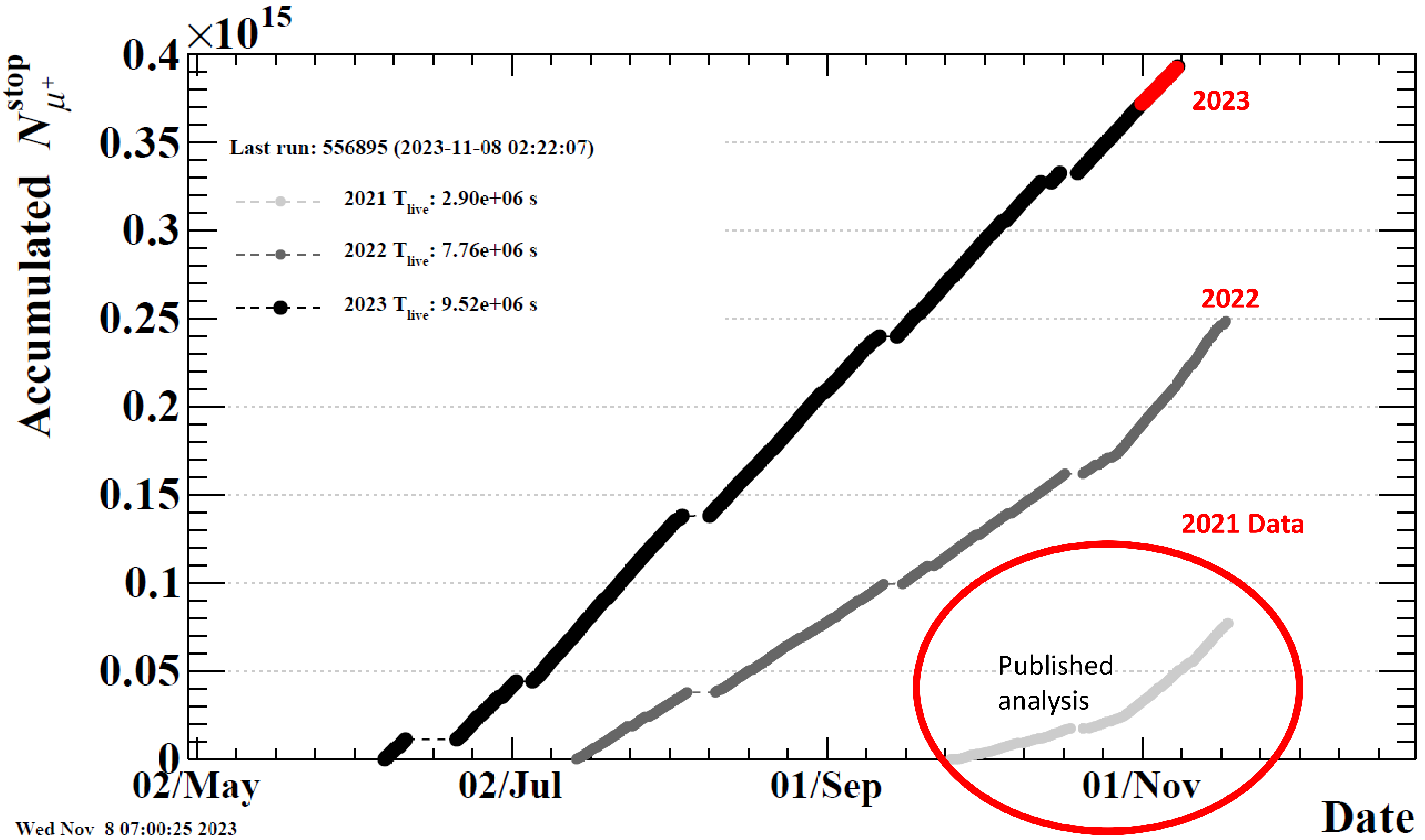
Trigger and Data Acquisition

- Trigger and DAQ are integrated and accomplished with full custom boards and crates
- Waveform digitizer (GSPS) with DRS chip with SiPM power supply and amplification included
- Complex FPGA based trigger with latency <450ps based on E_{γ}, Δt(LXe-pTC) and e-γ direction match
- up to 10 Gb/s DAQ throughput (50 Hz)
- All readout channels available in March 2021 (previously 10% of the cannels)









$\times 10^{15}$
Accumulated $N_{\mu^+}^{stop}$
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Last run: 556895 (2023-11-08 02:22:07)
2021 T_{live}: 2.90e+06 s
2022 T_{live}: 7.76e+06 s
2023 T_{live}: 9.52e+06 s
2023
2022
2021 Data
Published analysis
02/May
02/Jul
01/Sep
01/Nov
Date
Wed Nov 8 07:00:25 2023

Detector's performances

MEG II

PDF parameters	Foreseen	Achieved	MEG
E_{e^+} (keV)	100	89	330
ϕ_{e^+}, θ_{e^+} (mrad)	3.7/6.7	4.1/7.1	8.4/9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.75/1.85	1.1/2.5
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.0/1.8	2.4/1.7
$u_\gamma, v_\gamma, w_\gamma$, (mm)	2.4/2.4/5.0	2.5/2.5/5.0	5/5/6
$t_{e^+\gamma}$ (ps)	70	78	122
Efficiency (%)			
ε_γ	69	63	63
ε_{e^+}	65	65	30
ε_{TRG}	≈99	82	

Analysis Strategy

We blind events in the signal region and use the other events (**S**ide**B**ands), plus Simulation and Calibrations, to evaluate **P**robability **D**istribution **F**unctions to be used in a likelihood fit.

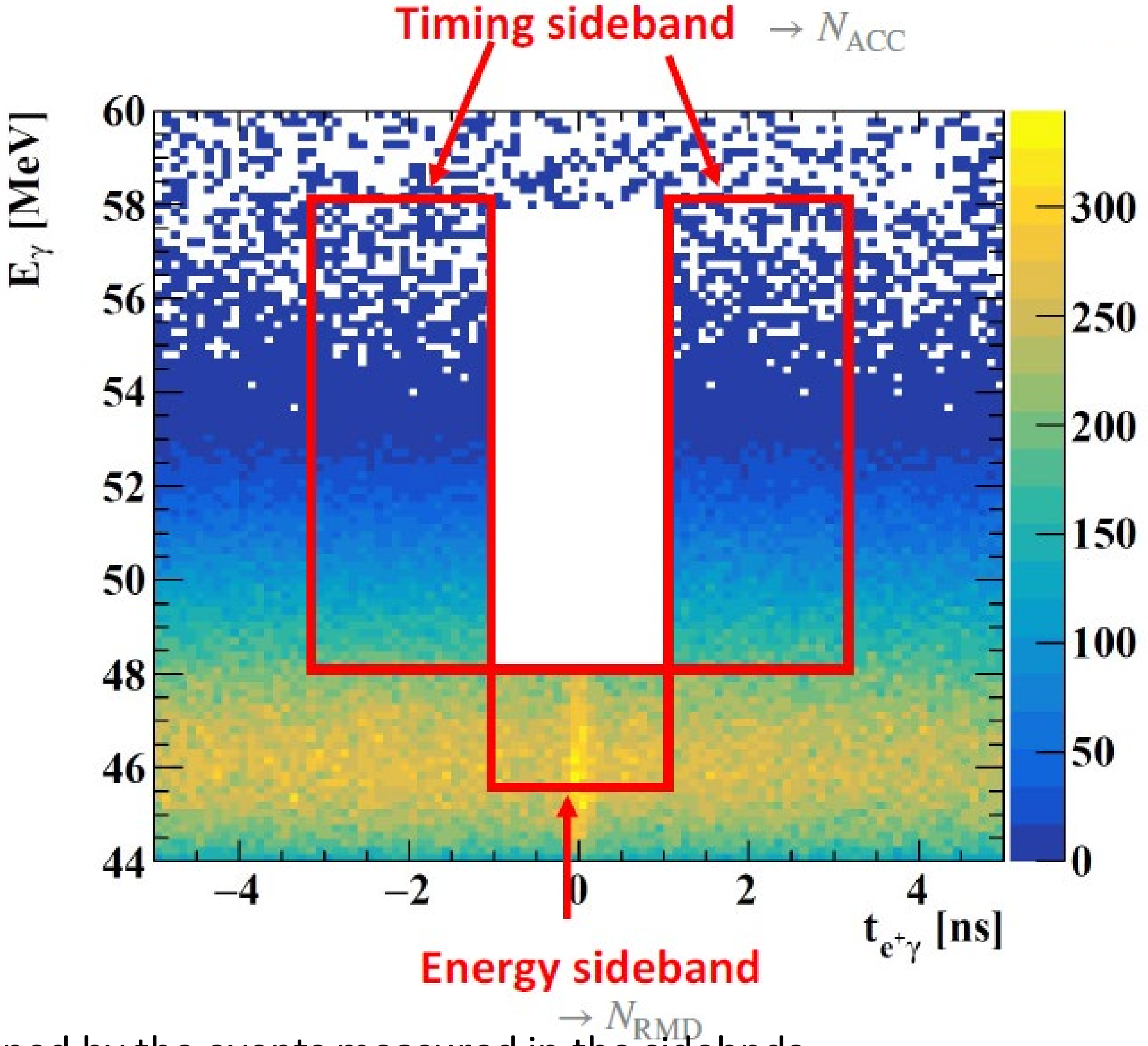
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm ACC}, x_{\rm T}) =$$

$$\frac{e^{-(N_{\rm sig}+N_{\rm RMD}+N_{\rm ACC})}}{N_{\rm obs}!} C(N_{\rm RMD}, N_{\rm ACC}, x_{\rm T}) \times$$

$$\prod_{i=1}^{N_{\rm obs}} (N_{\rm sig} S(\vec{x_i}) + N_{\rm RMD} R(\vec{x_i}) + N_{\rm ACC} A(\vec{x_i}))$$

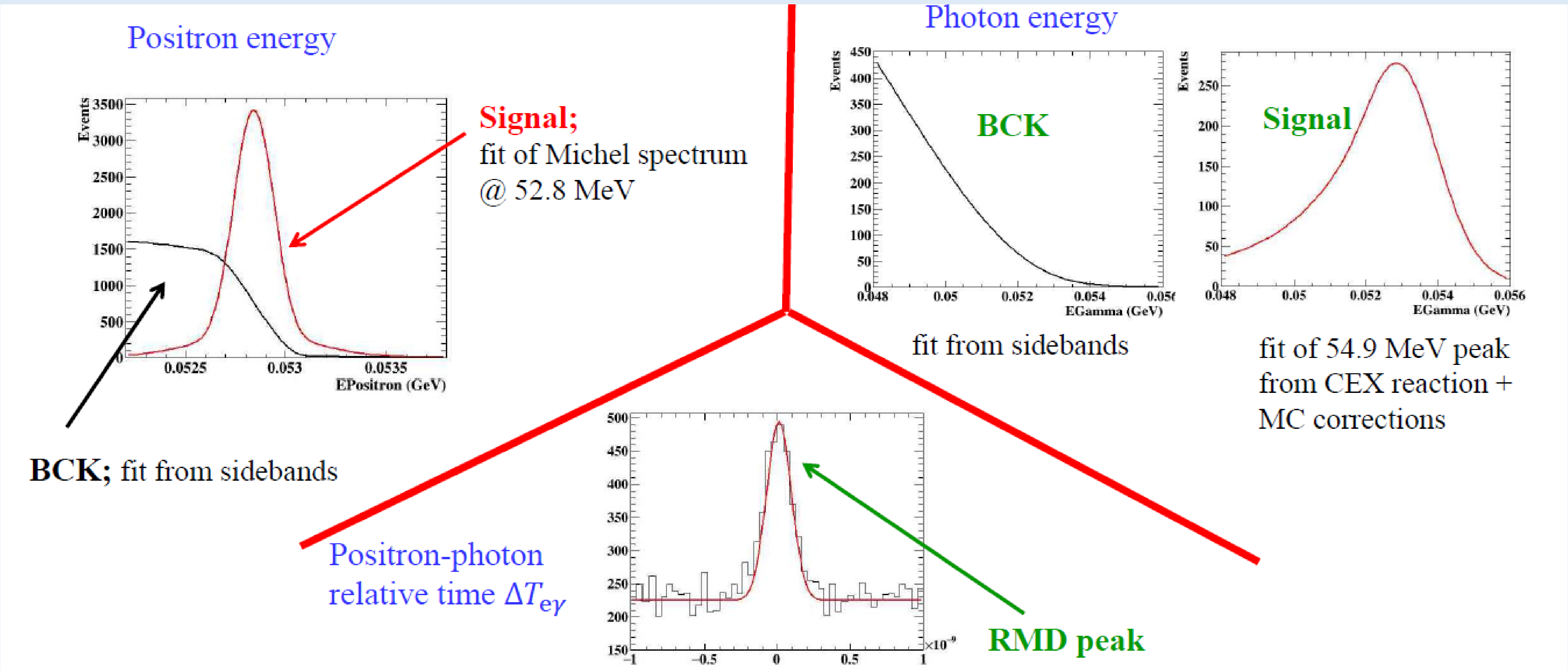
PDFs

$$x_i = \{E_\gamma, E_{e^+}, t_{e^+\gamma}, \theta_{e^+\gamma}, \phi_{e^+\gamma}\}$$



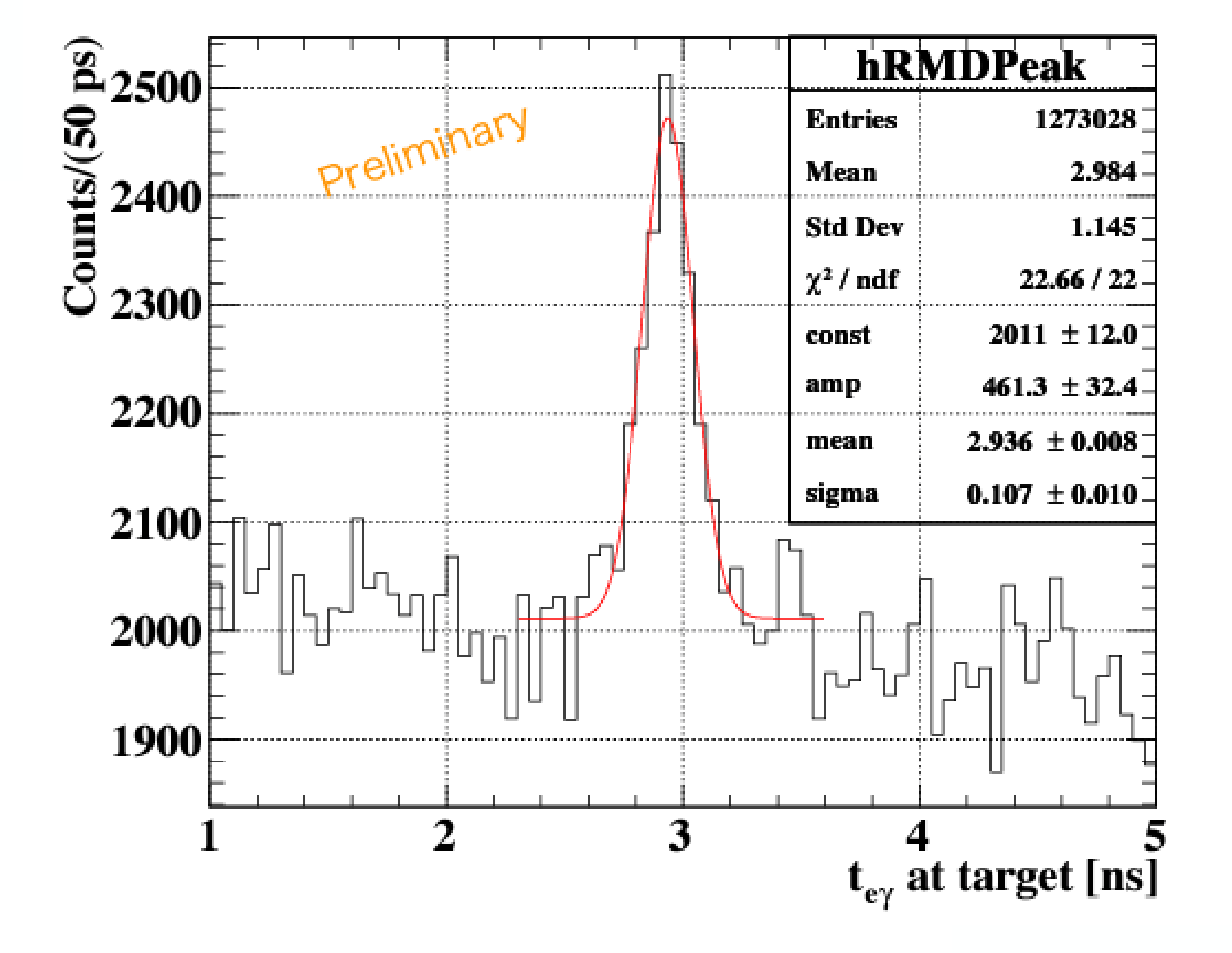
NRMD and NACC are in the signal region are constrained by the events measured in the sidebnds

Probability Distribution Functions

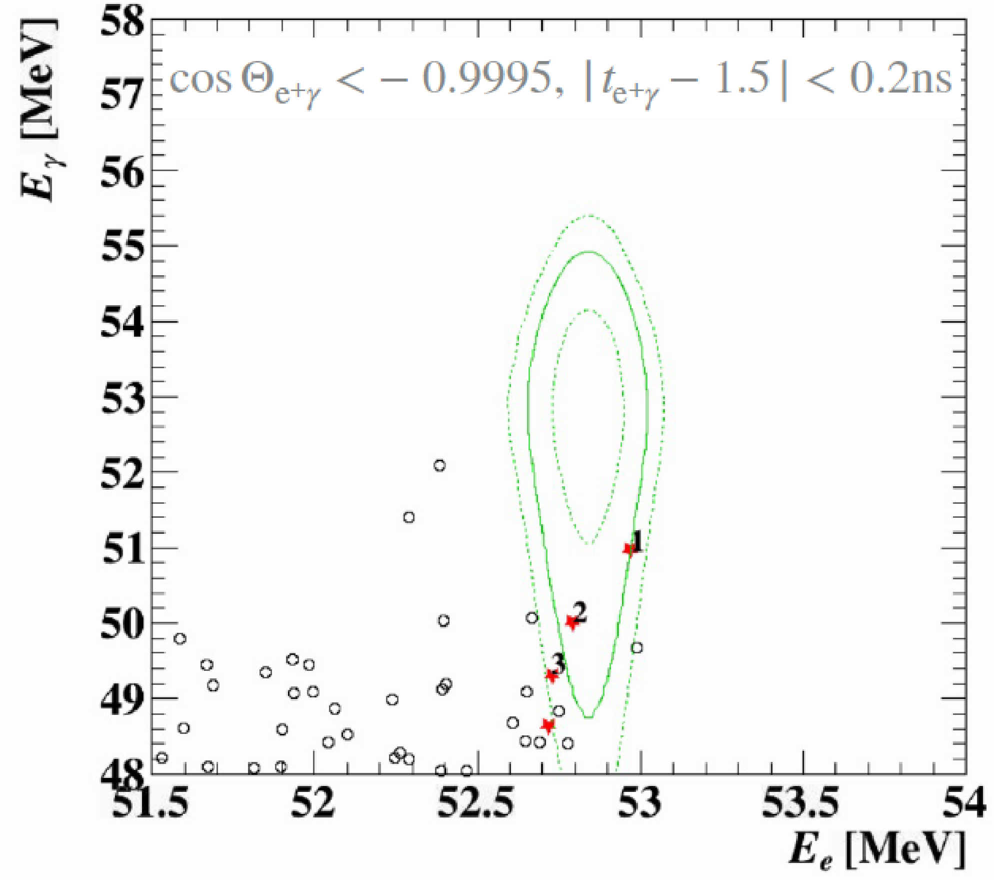


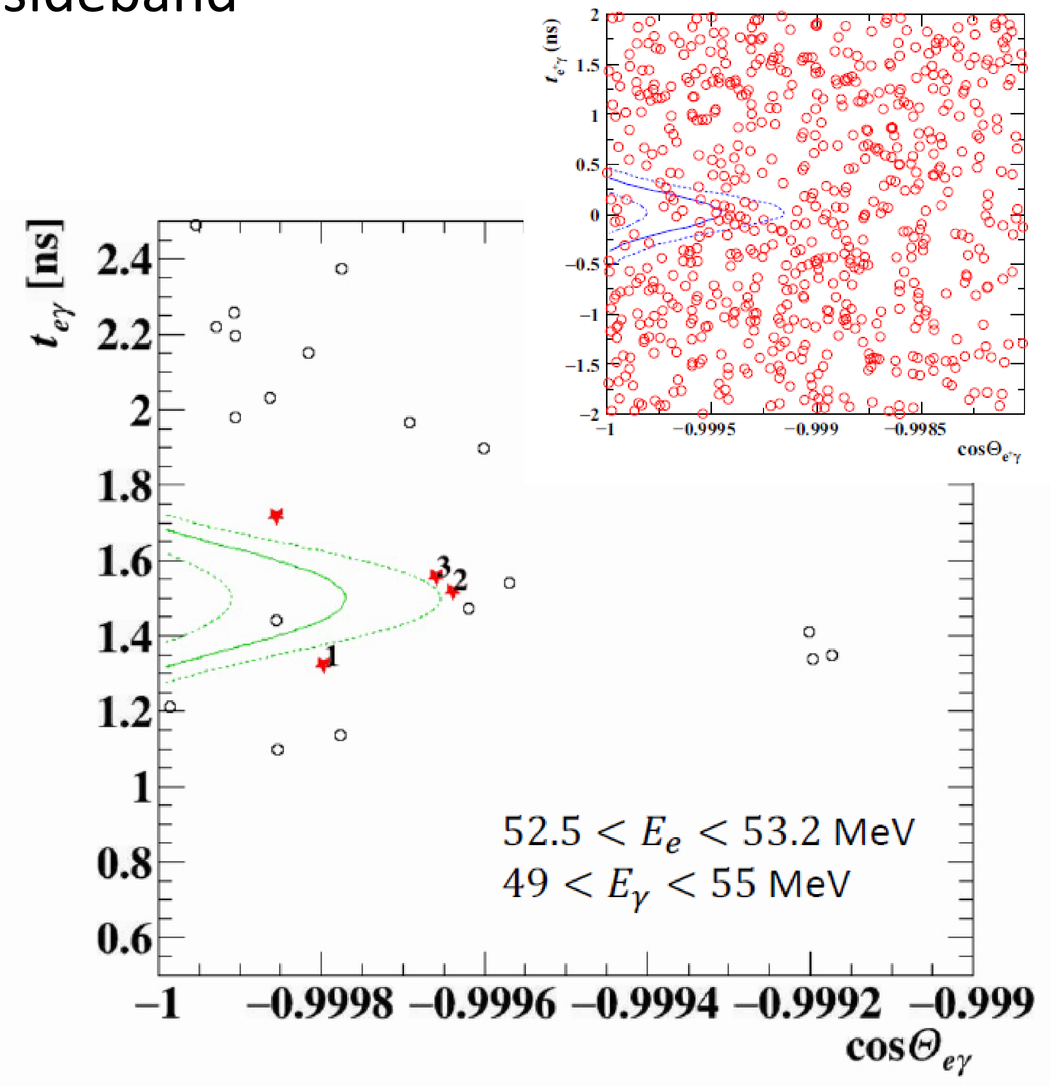
Remind that BCK (background) is mostly accidental

Radiative muon decays in MEG II data (Energy SideBand): a crucial check for a $\mu \rightarrow e\gamma$ experiment – Same topology of possible signal events

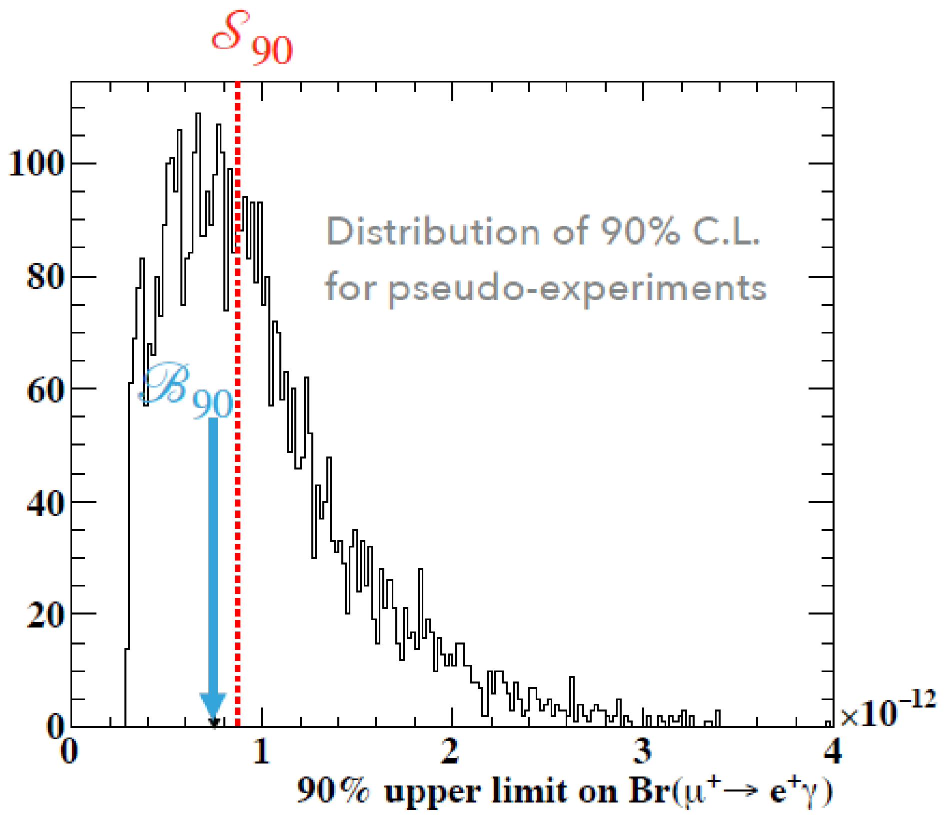


One timing sideband

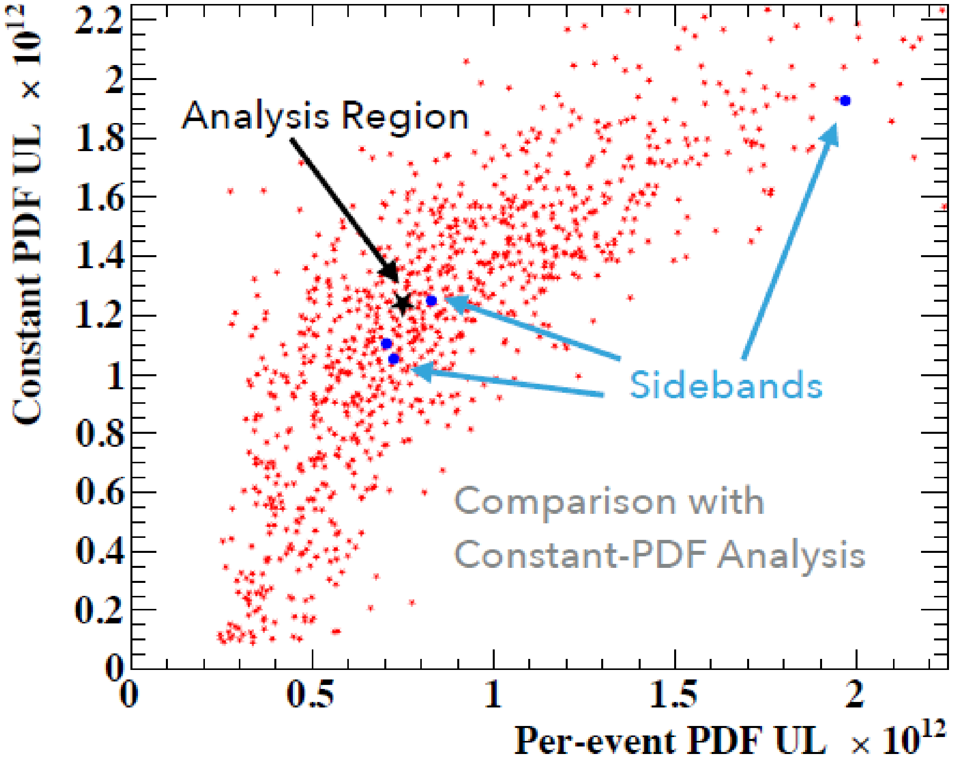




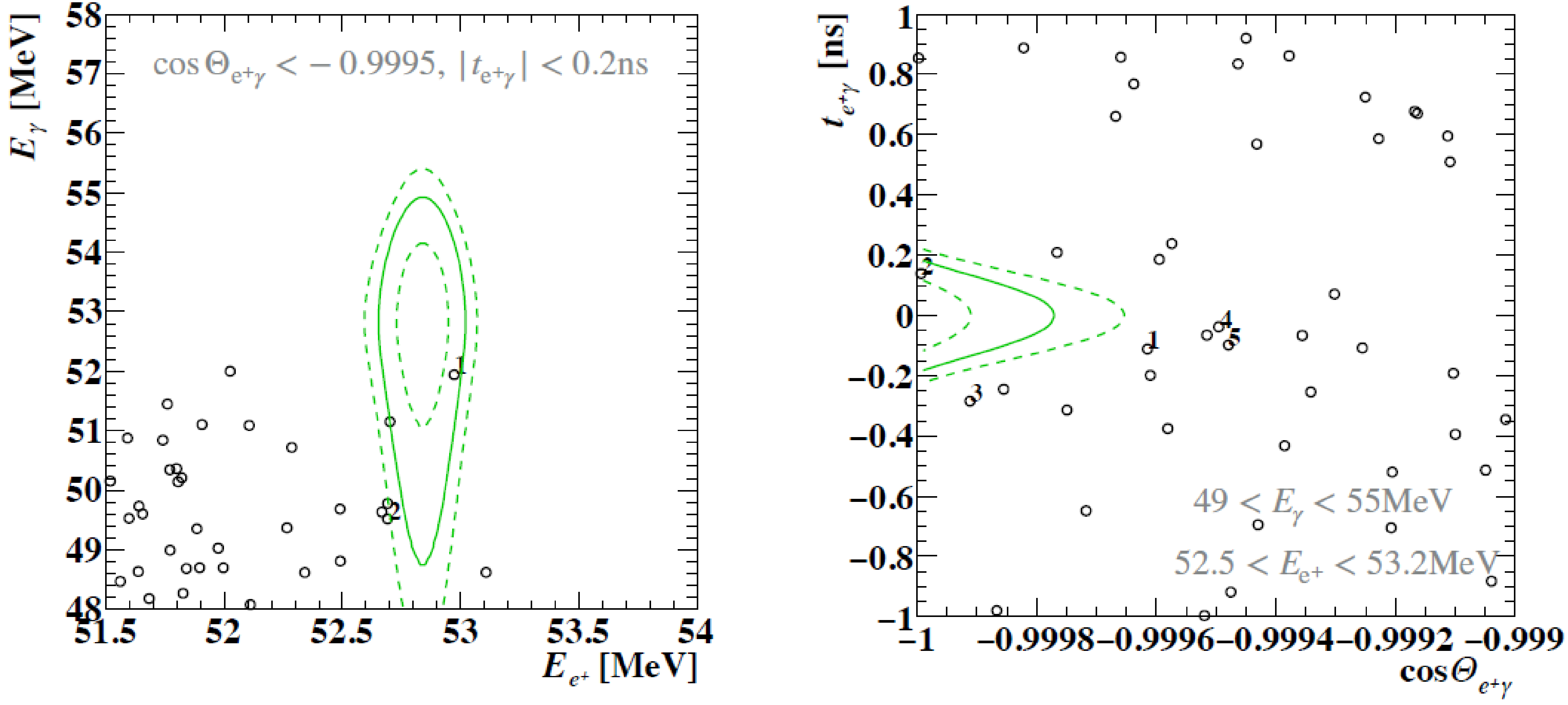
Sensitivity $\mathcal{S}_{90}$, defined as median of distributions of 90% C.L. upper limits for an ensemble of pseudo-experiments with null-signal, is $\underline{8.8 \times 10^{-13}}$. cf. MEG 5.3×10^{-13}



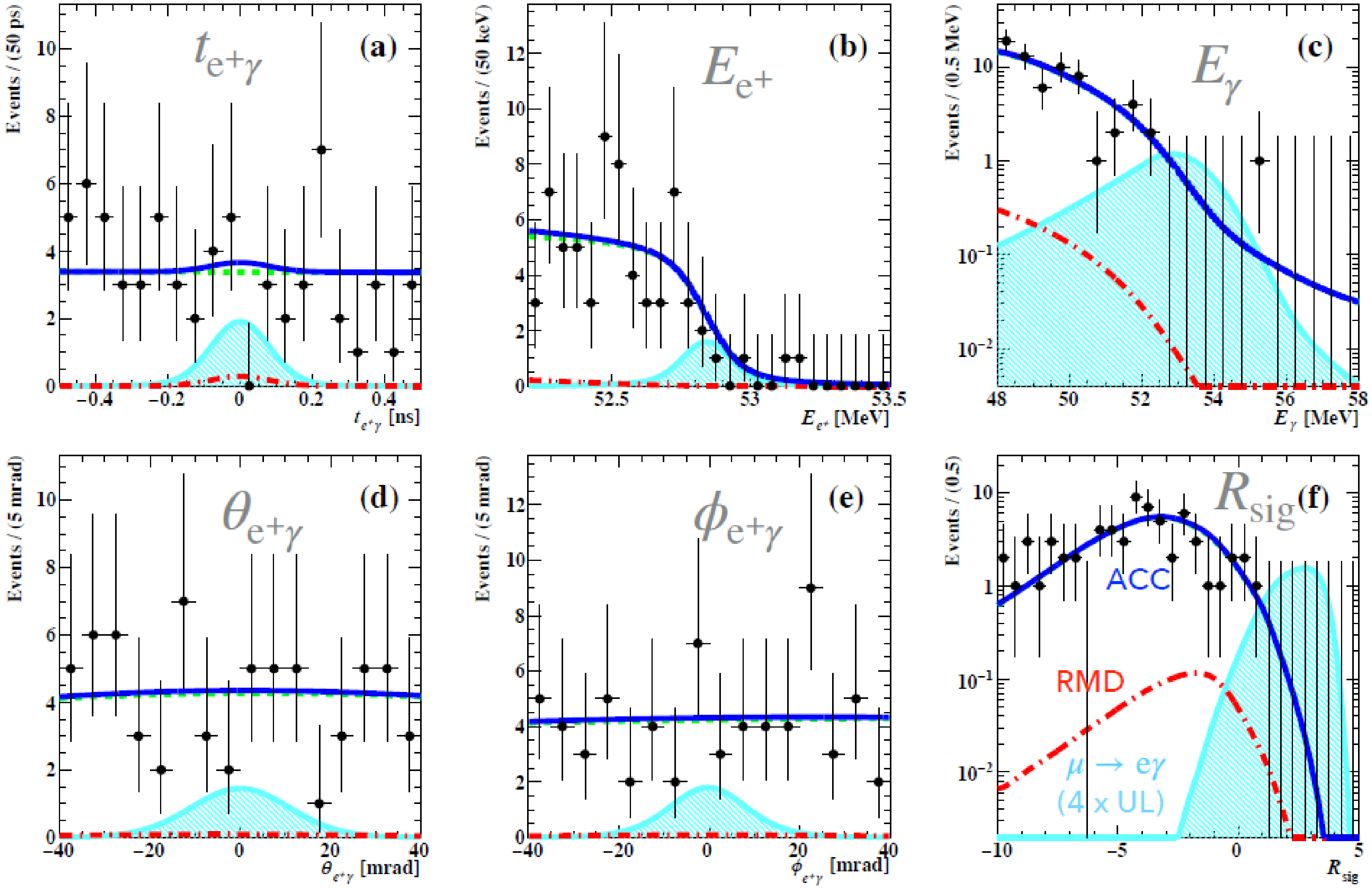
Two independent analyses: constant and per event PDFs must match on toy MC and side bands before opening the blind box



Unblinded data - arXiv :2310.12614v2 [hep-ex] 20 Oct 2023 Submitted to EPJC



Likelihood fit



(f) Relative signal likelihood

$$R_{\rm sig} = \log_{10}\left(\frac{S(x_i)}{f_{\rm RMD}R(x_i) + f_{\rm ACC}A(x_i)}\right)$$

$f_{\rm RMD} = 0.02,\ f_{\rm ACC} = 0.98$

- Confidence interval for $N_{\rm sig} > 0$
  - à la Feldman-Cousins
  - Best fit branching ratio $\mathscr{B}_{\rm fit}$

$$\mathscr{B}_{\rm fit} = -1.1 \times 10^{-16}$$

- 90% C.L. upper limit of branching ratio:

$$\mathscr{B}_{90} = 7.5 \times 10^{-13}$$

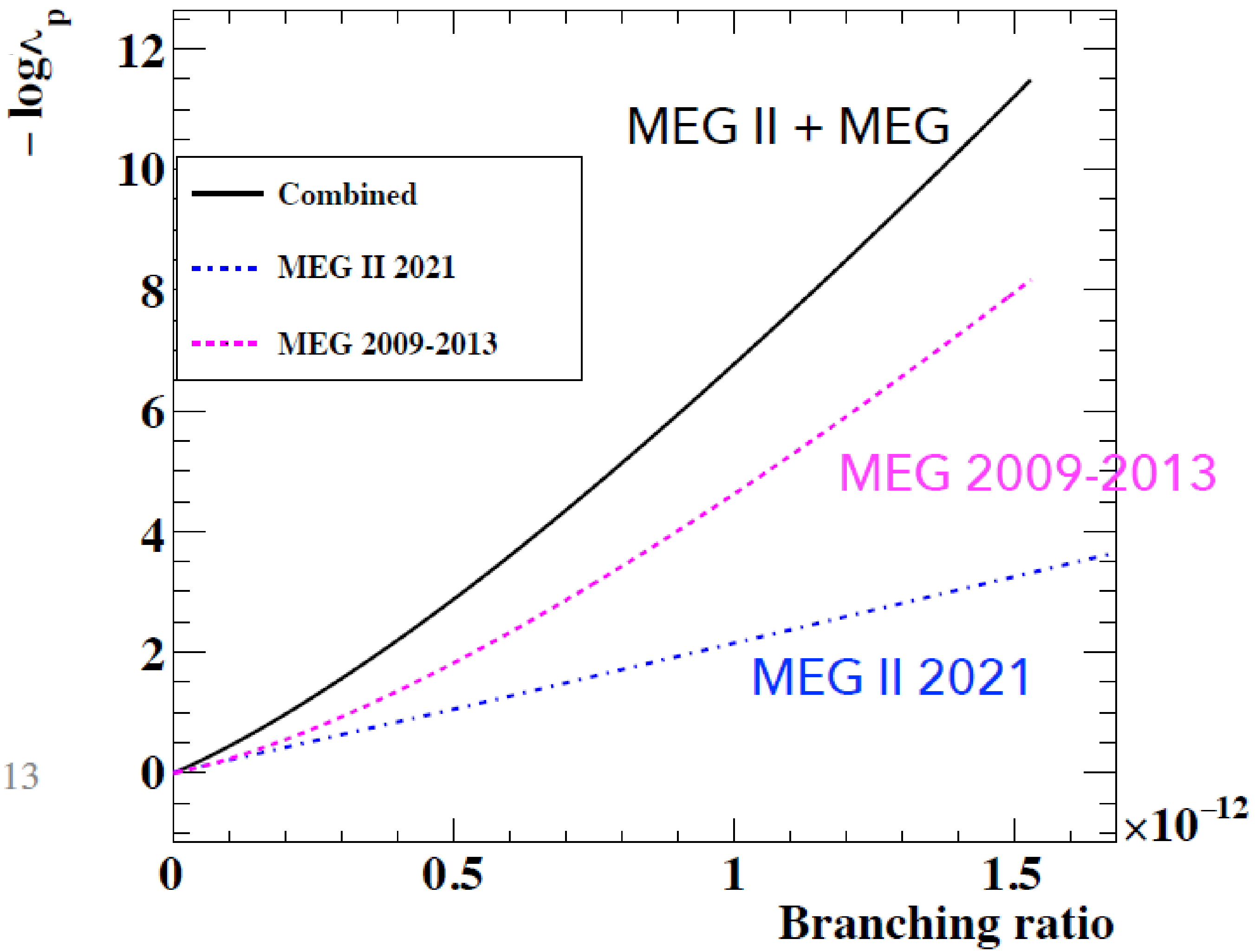
MEG: $\mathscr{B}_{90} = 4.2 \times 10^{-13}$

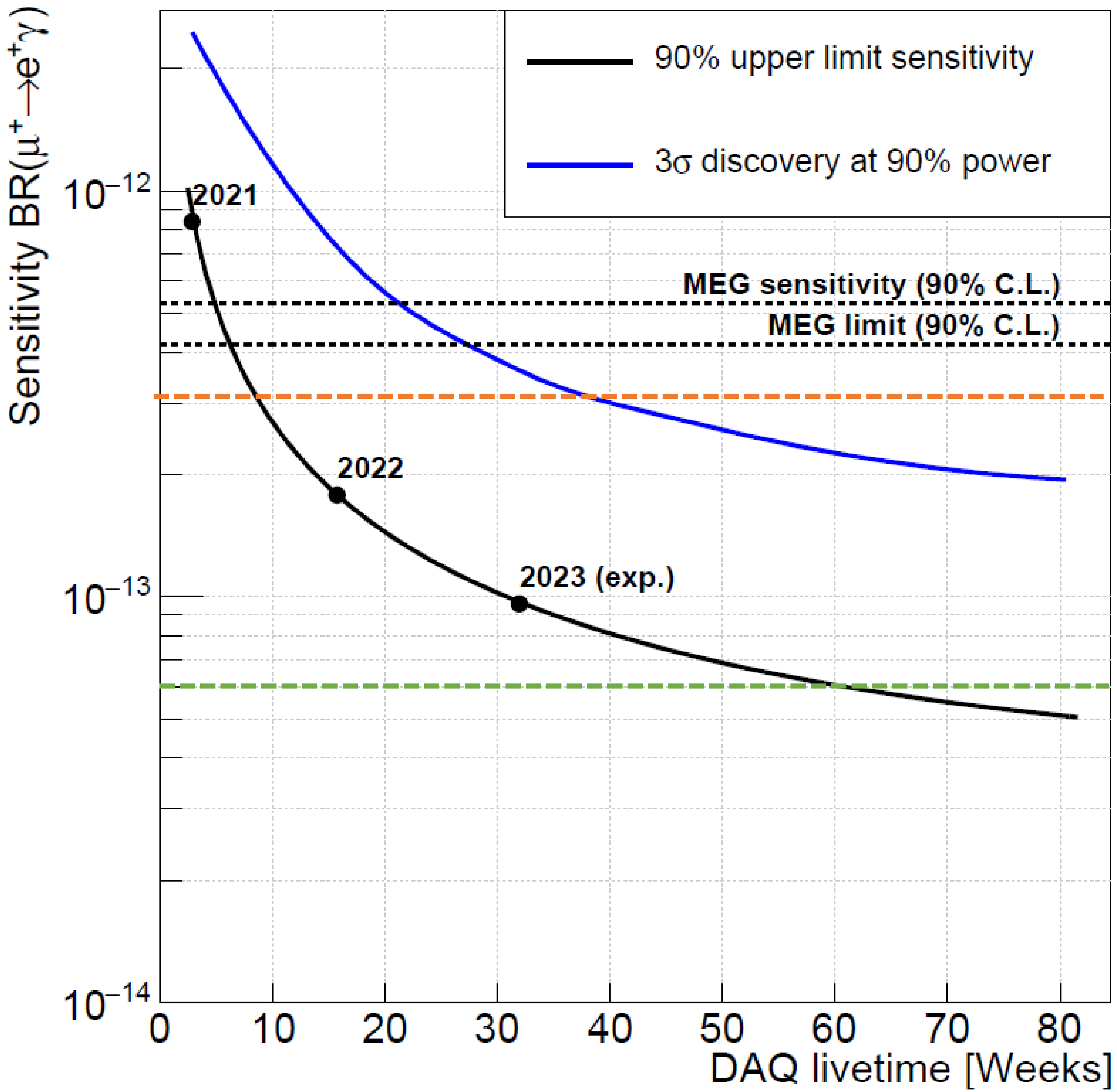
- MEG II + MEG combined:

$$\mathscr{B}_{90} = 3.1 \times 10^{-13}$$

combined sensitivity: $\mathscr{S}_{90} = 4.3 \times 10^{-13}$

Profile Likelihood





New best UL:
$\mathscr{B}_{90}$=3.1x10^{-13}

MEG II goal:
$\mathscr{S}_{90}$=6x10^{-14}

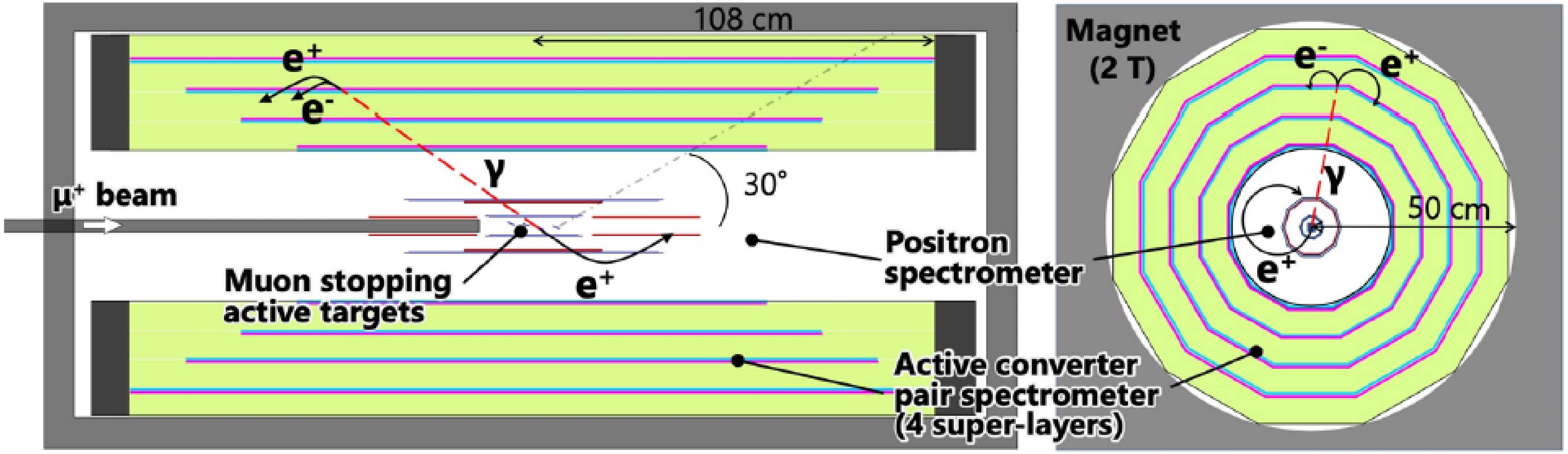
A future $\mu \rightarrow e\gamma$ search at PSI?

- The PSI accelerator will shut down for two years in 2027-2028 to implement a new **H**igh **I**ntensity **M**uon **B**eam (HIMB): $I=10^{10}$ muons/s

- No official plan of the MEG collaboration for a third phase of MEG

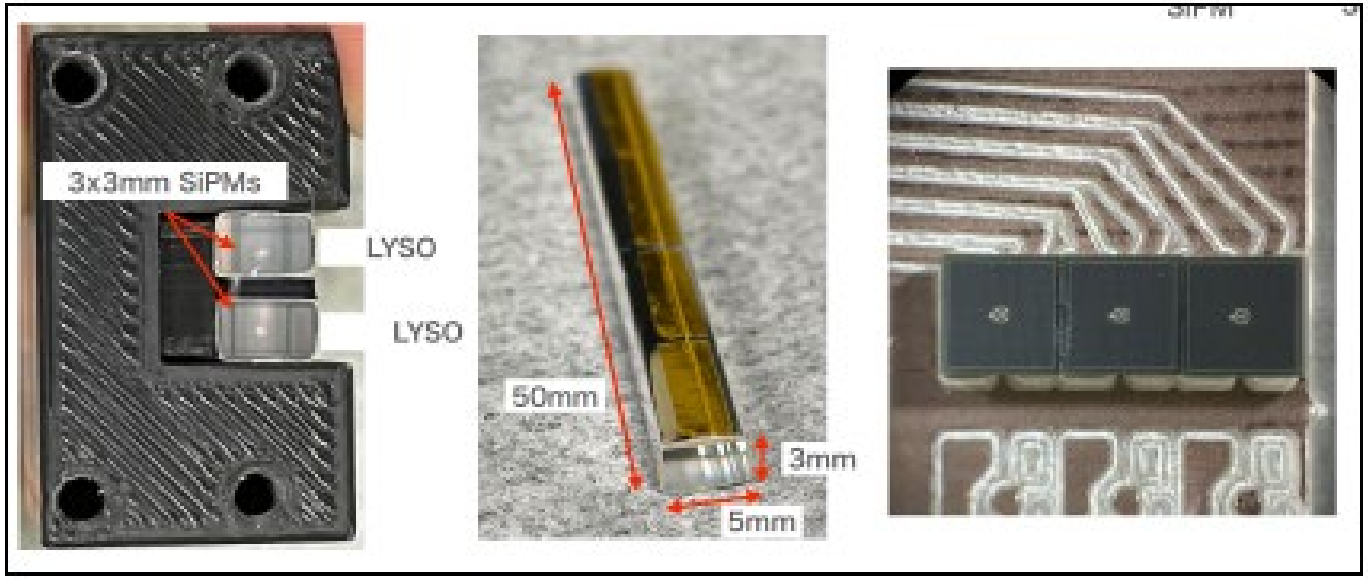
- A working group of MEG and Mu3e collaborators are holding meetings for a possible common future project for the search of $\mu \rightarrow e\,\gamma$ in order to exploit the muon beam intensity increase to gain one further order of magnitude w.r.t. the MEG II goal

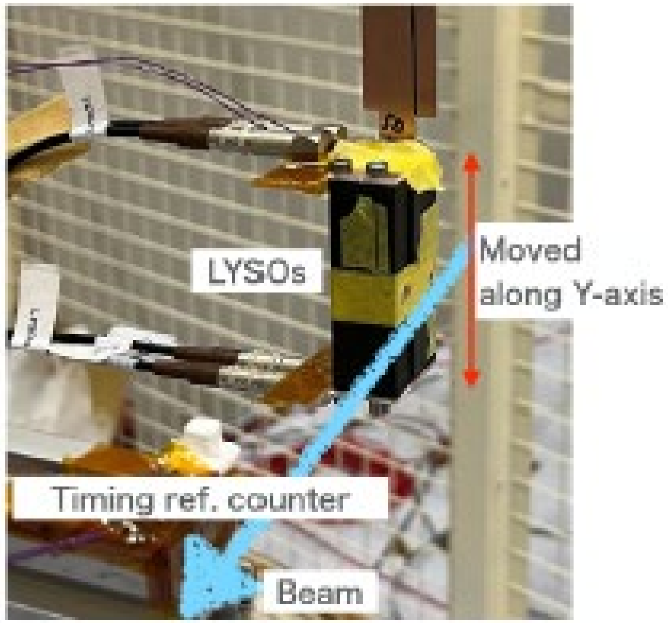
Conceptual design — Silicon tracker + Conversion



The use of a pair spectrometer may give an improvement of a factor 3-4 w.r.t. the MEG II energy resolution (~1 MeV) : the loss of efficiency due to the small photon conversion probability can be compensated by improved fiducial solid angle coverage, multiple conversion layers and the higher beam intensity

An active converter is necessary to minimize energy resolution due to loss fluctuations: W. Ootani Tokyo University





A crystal calorimeter option (LYSO) is still kept in consideration (A. Papa - Pisa Univ. & PSI) despite large surfaces imply high costs

A central positron spectrometer based on Silicon HV-MAPS (Mu3e) with reduced thickness (25 μ) could reach momentum resolutions < 80 KeV/c (A. Schöning: Heidelberg Univ.) in strong magnetic fields+ high rate capability

A gaseous detector (MEG like or a radial TPC) is foreseen for tracking pairs in the external photon detector (F. Renga – Roma1 INFN)

Summary

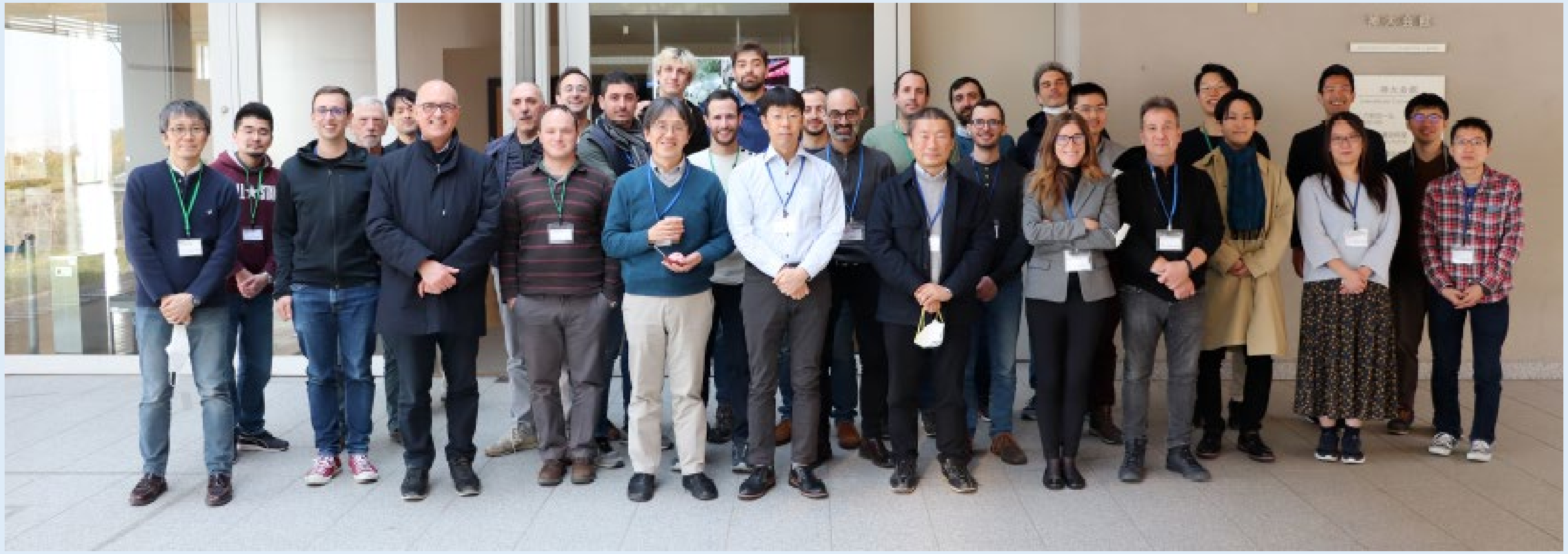
- MEG II has been taking data since 2021 and aims at improving the sensitivity to $\mu \rightarrow e\gamma$ by an order of magnitude in the B.R.

- First result from the 2021: BR< 7.5×10^{-13} and BR <3.1×10^{-13} when combined with the final (2016) MEG result

- Will finalize the 2022 data analysis in about half a year

- Data taking will continue until 2026 to reach the final goal

- Thank you for your attention

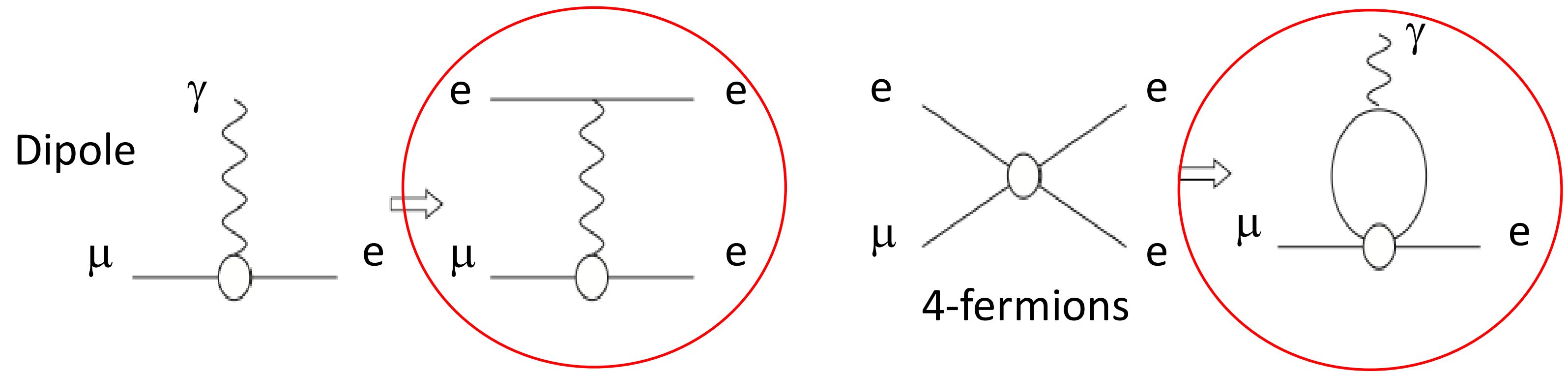


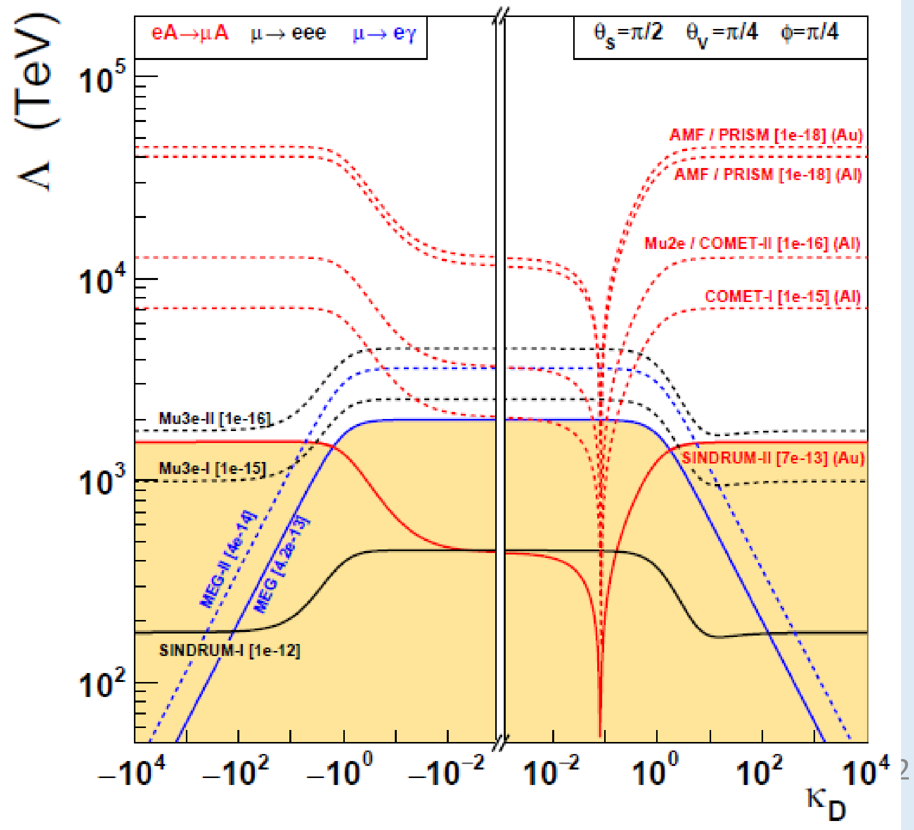
Backup

Effective Field Theory approach (a recent paper)

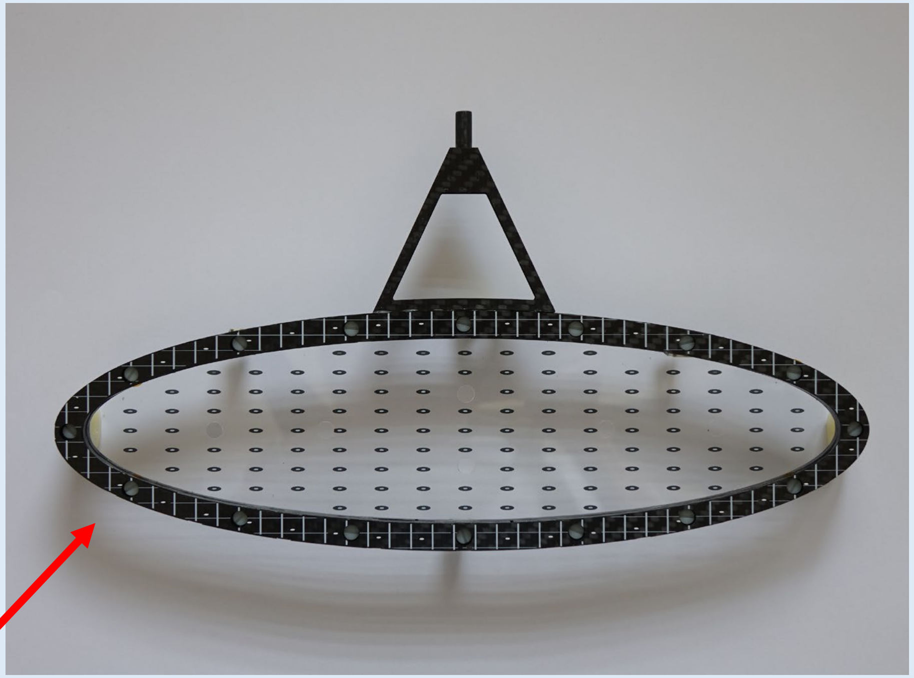
S. Davidson, B. Echenard 2022

$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2}\Big[C_D(\overline{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\overline{e}P_R\mu)(\overline{e}P_Re) + C_{VR}(\overline{e}\gamma^\alpha P_L\mu)(\overline{e}\gamma_\alpha P_Re)$$
$$+ C_{VL}(\overline{e}\gamma^\alpha P_L\mu)(\overline{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big]$$

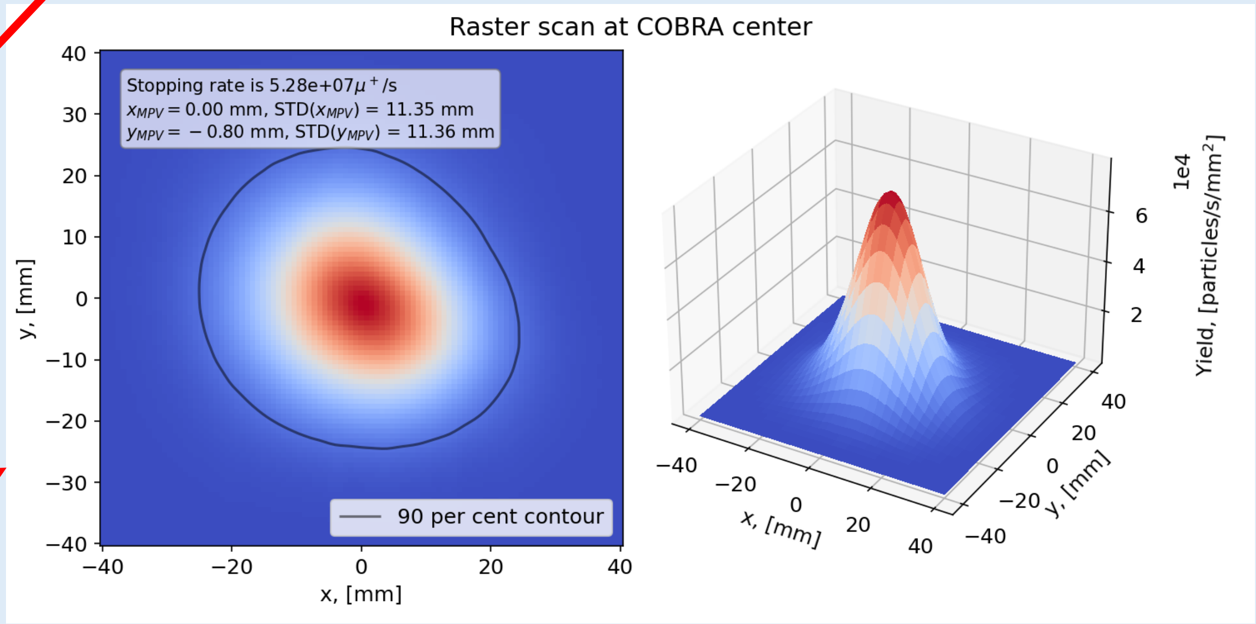




K_D parametrizes the relative magnitude of dipole and four-fermion coefficients



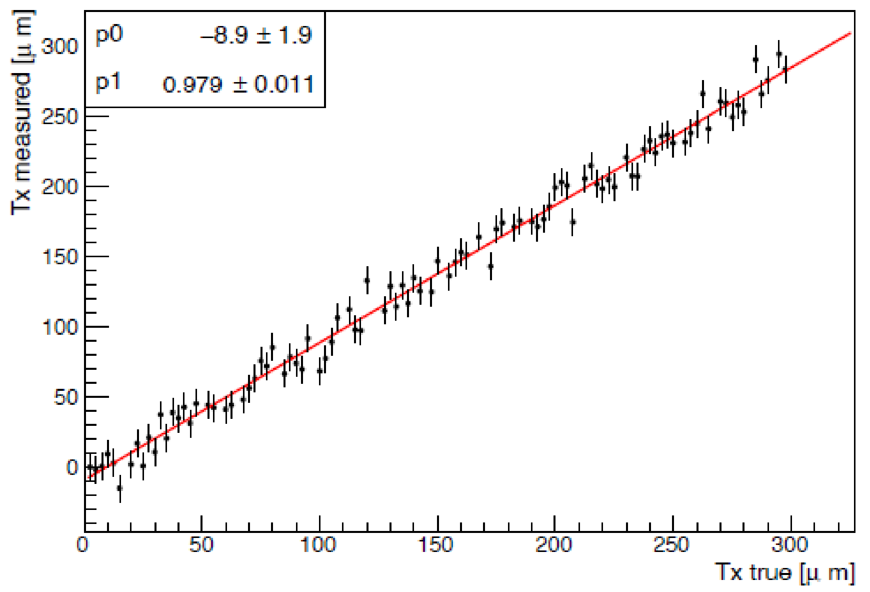
270 mm x 66 mm

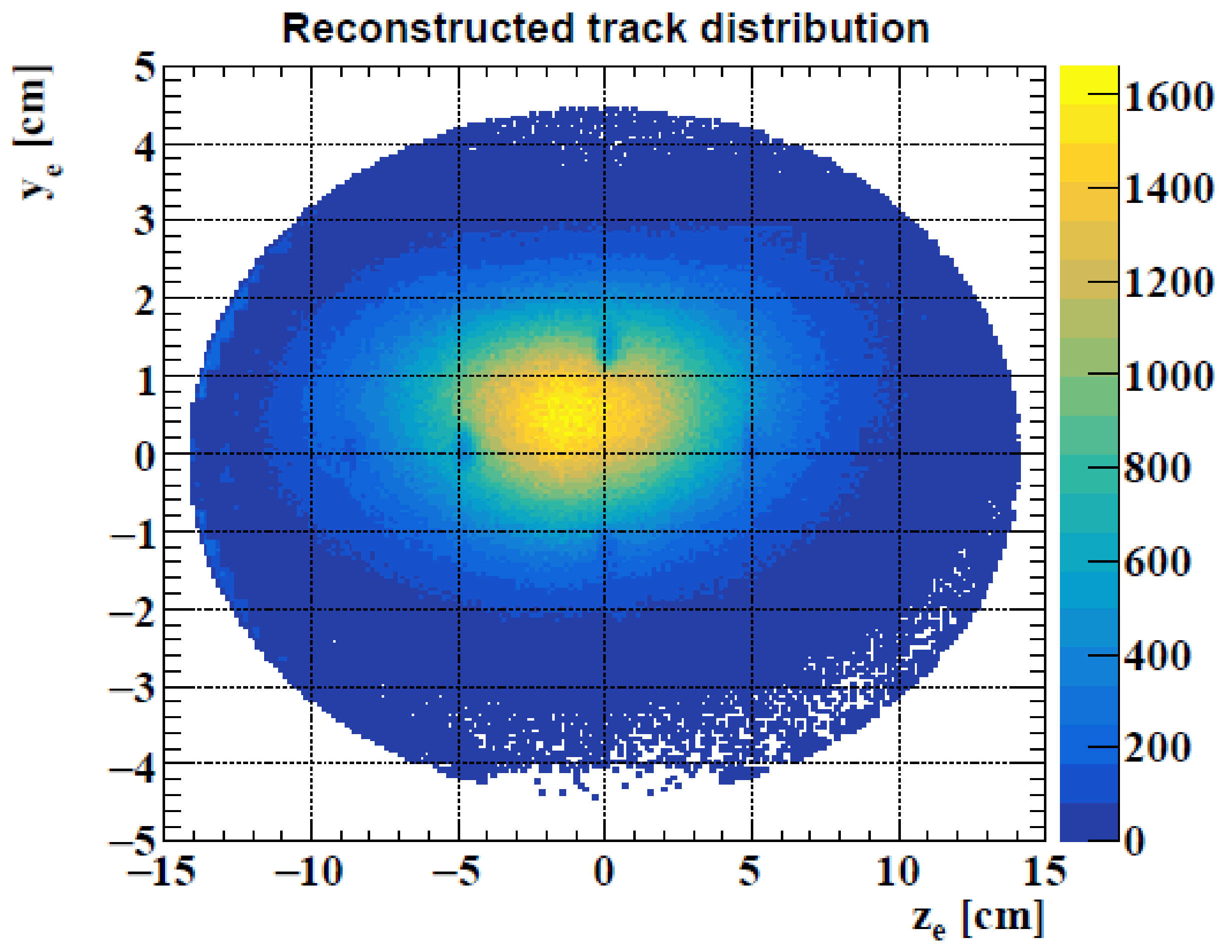


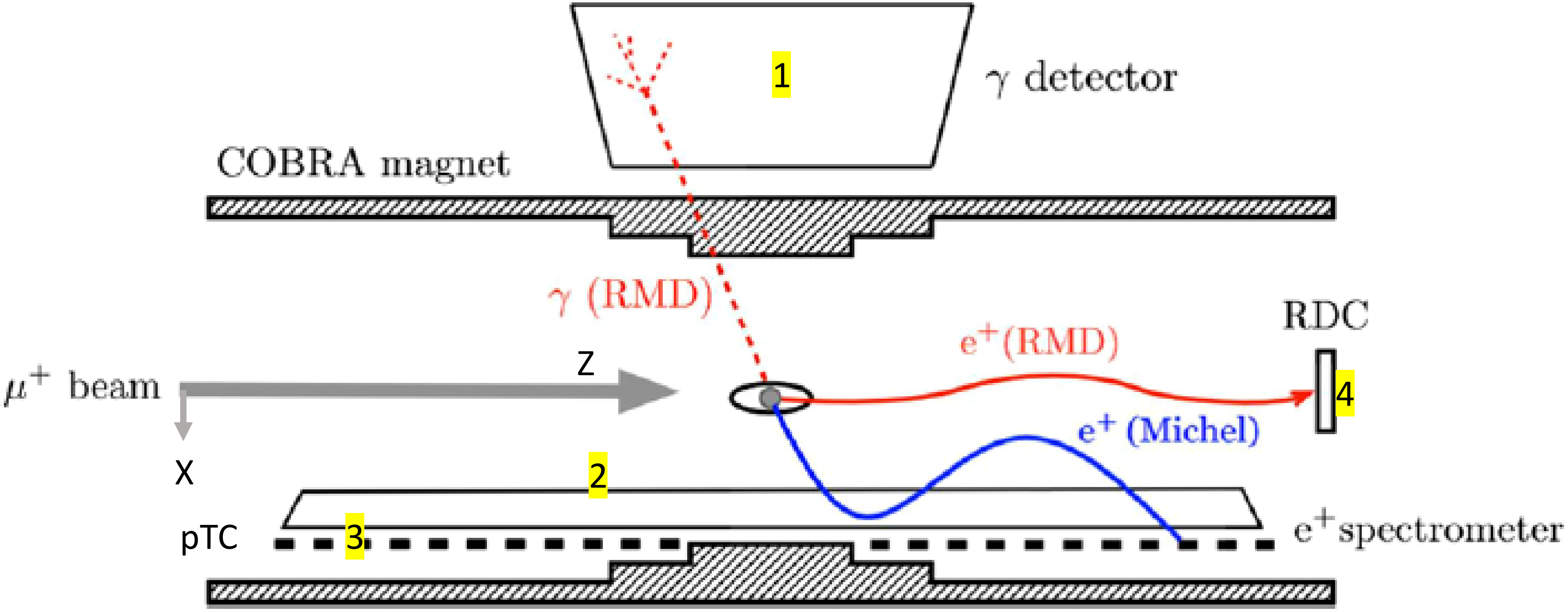
Muons are stopped in a slanted BC400 170 μm thick target with 6 holes and a pattern of dots (photographed by a camera) to continuously monitor the shape and position of the foil

The muon beam profile at the target position is measured before start of data taking for stopping rates 2-5 x 10^7 μ/s

Target position and deformations are checked by means of off-line reconstruction and on-line Camera measurements

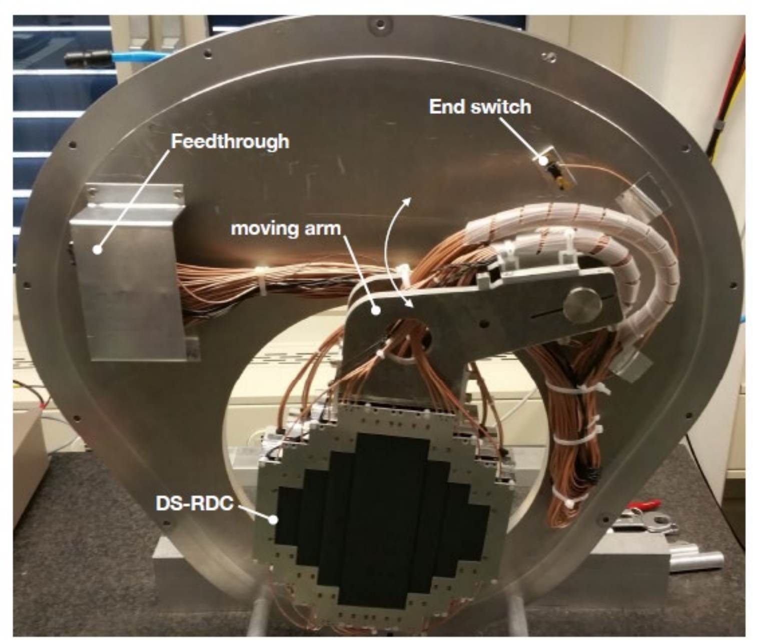


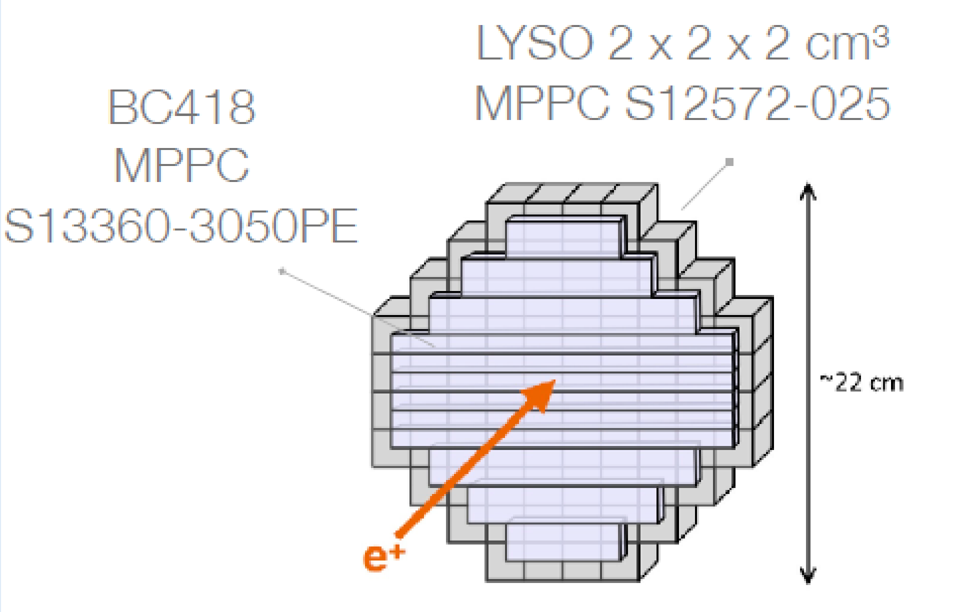




γ detector
1
COBRA magnet
γ (RMD)
RDC
e+(RMD)
μ+ beam
Z
4
e+ (Michel)
X
2
pTC
3
e+spectrometer

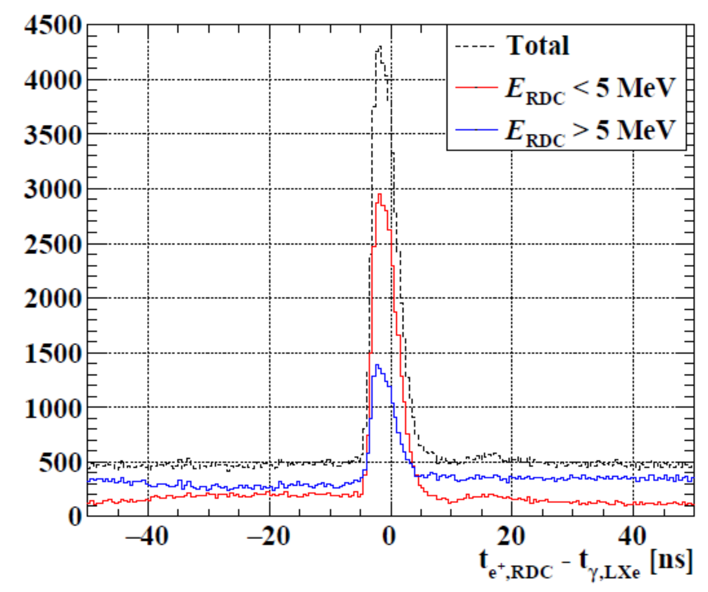
4: Radiative Decay Counter



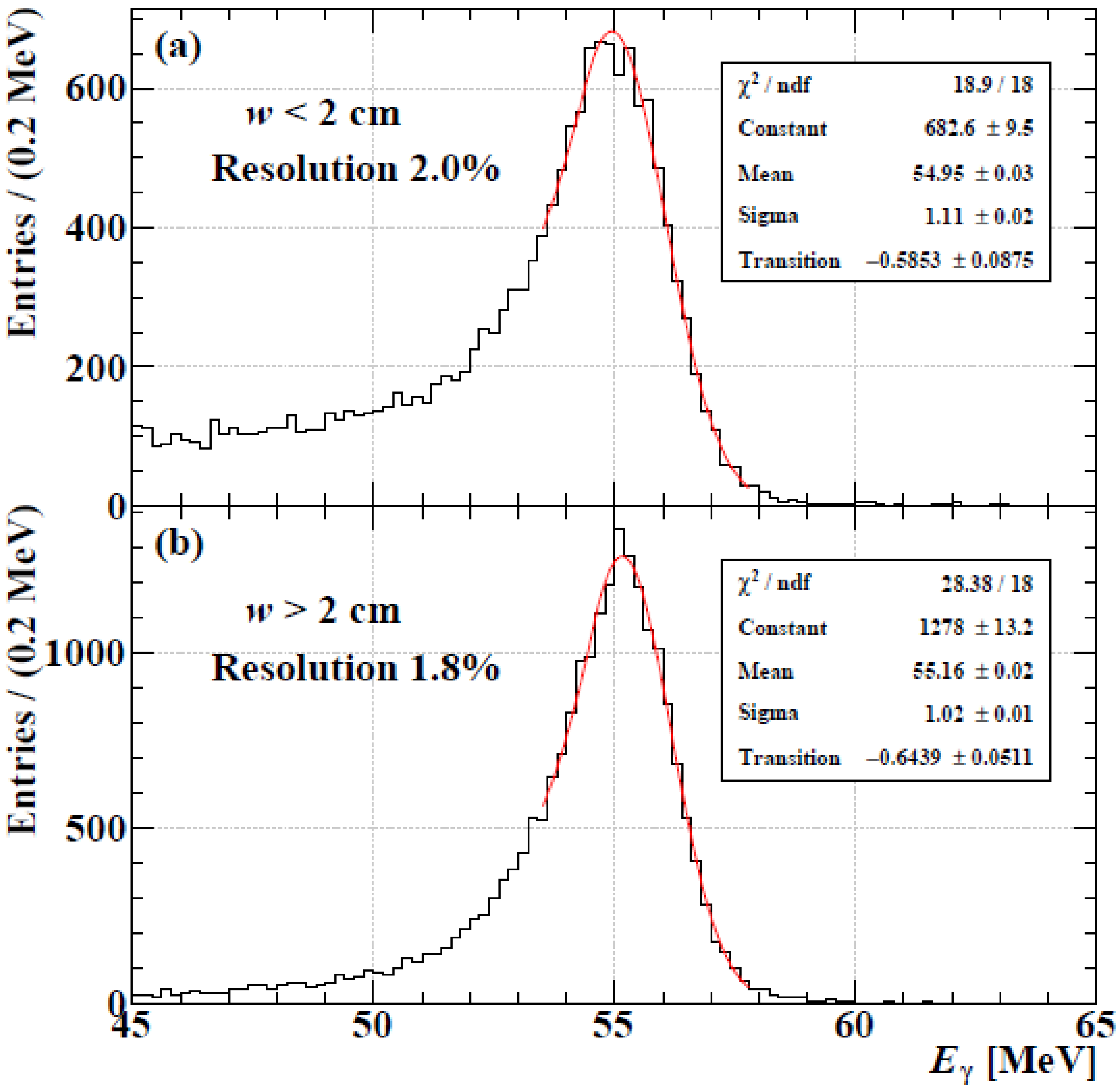


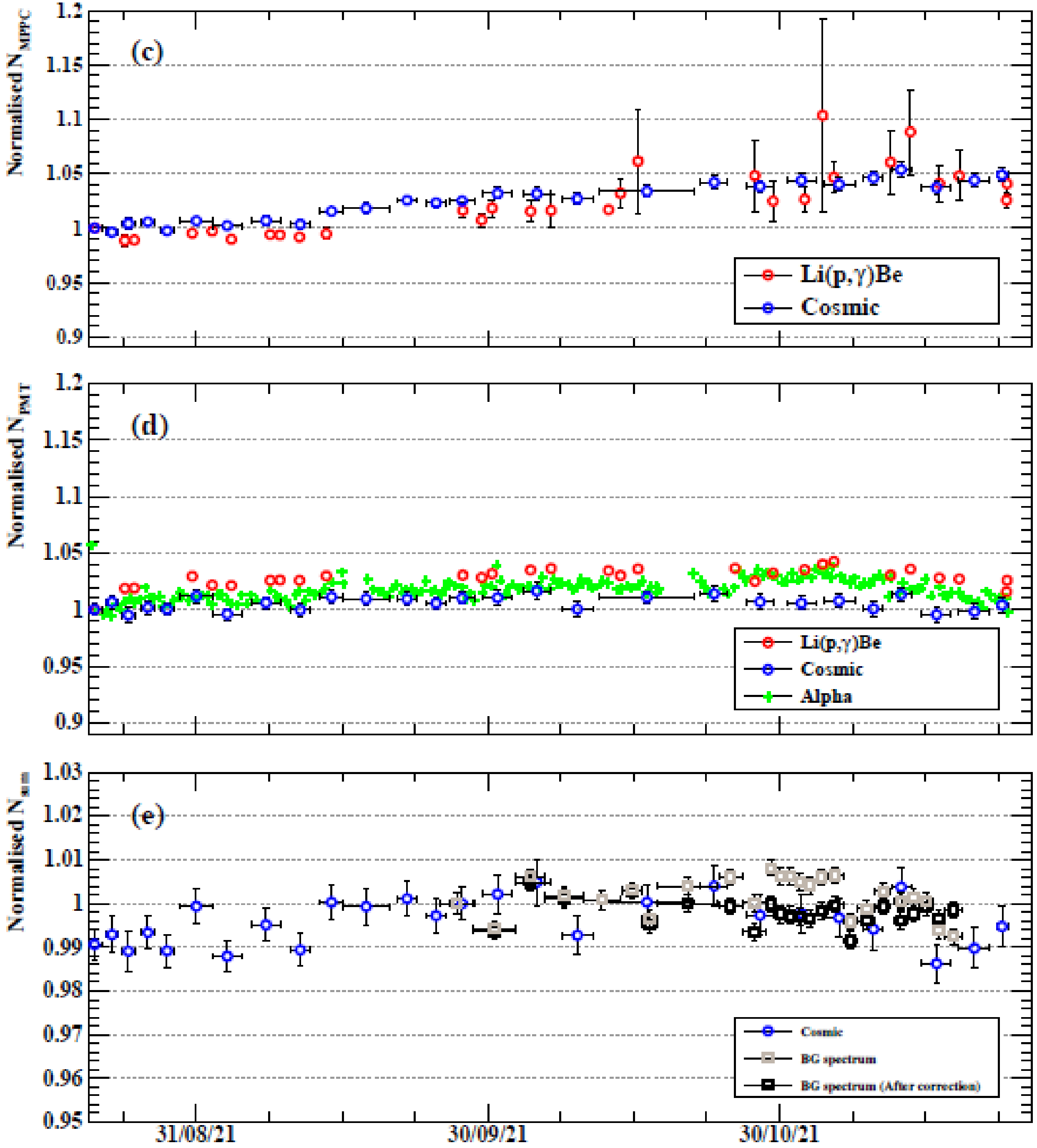
- Tag γ in LXe from RMD associated to a low energy positron

- Low e^+ positrons: plastic scintillator for timing and LYSO for energy measurement

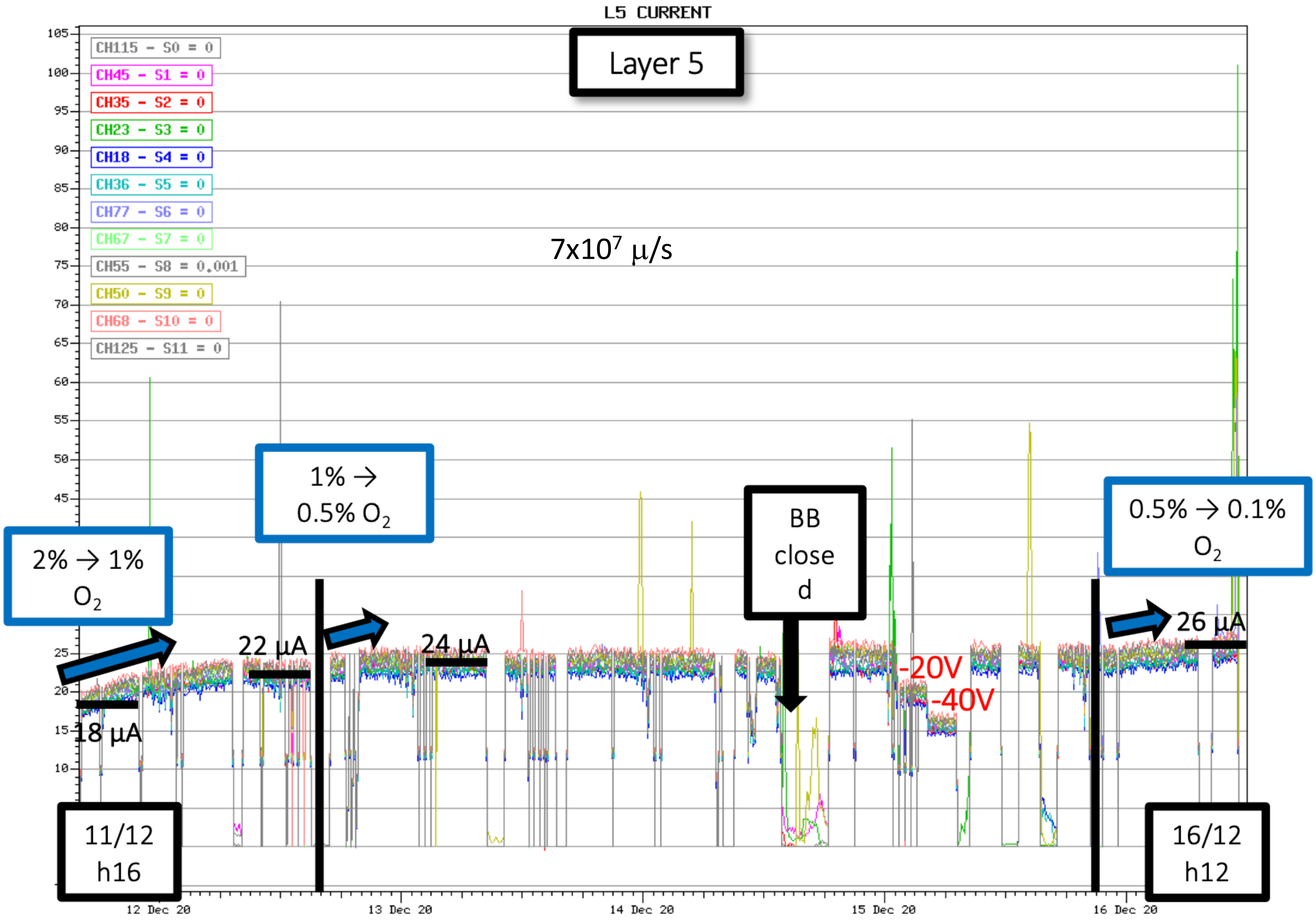


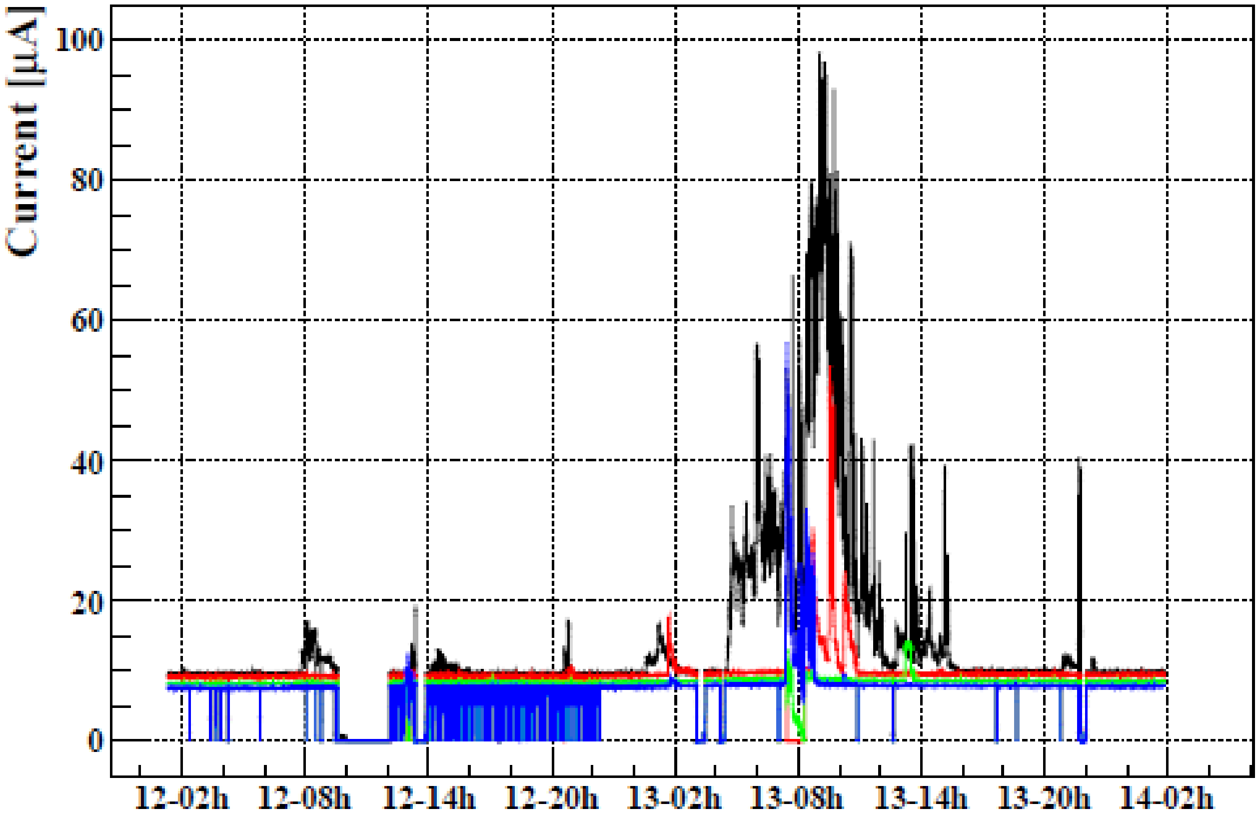
Most coincidences with LXe associated to low energy positrons


(a)
w < 2 cm
Resolution 2.0%
χ² / ndf 18.9 / 18
Constant 682.6 ± 9.5
Mean 54.95 ± 0.03
Sigma 1.11 ± 0.02
Transition −0.5853 ± 0.0875
(b)
w > 2 cm
Resolution 1.8%
χ² / ndf 28.38 / 18
Constant 1278 ± 13.2
Mean 55.16 ± 0.02
Sigma 1.02 ± 0.01
Transition −0.6439 ± 0.0511
Entries / (0.2 MeV)
0
200
400
600
500
1000
45
50
55
60
65
Eγ [MeV]

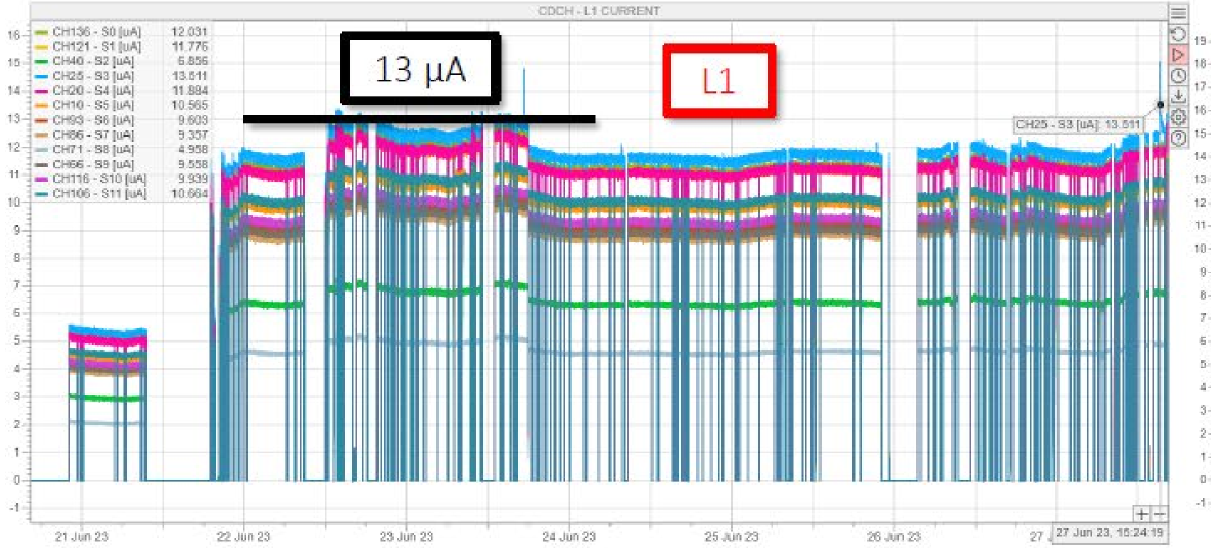


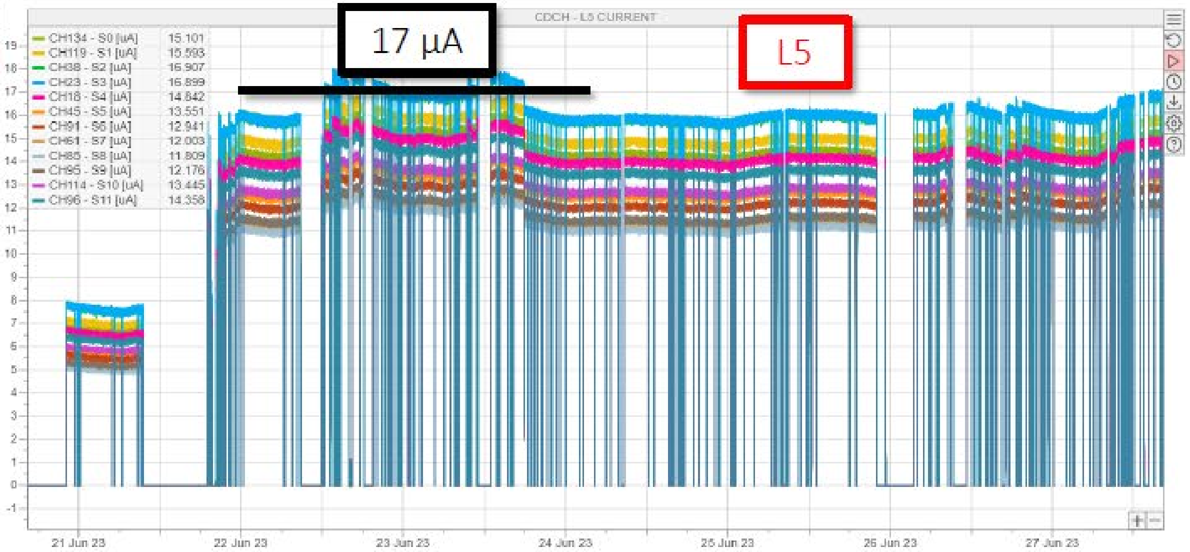
Normalised N_{MPPC}
(c)
Li(p,γ)Be
Cosmic
Normalised N_{PMT}
(d)
Li(p,γ)Be
Cosmic
Alpha
Normalised N_{sum}
(e)
Cosmic
BG spectrum
BG spectrum (After correction)
31/08/21
30/09/21
30/10/21

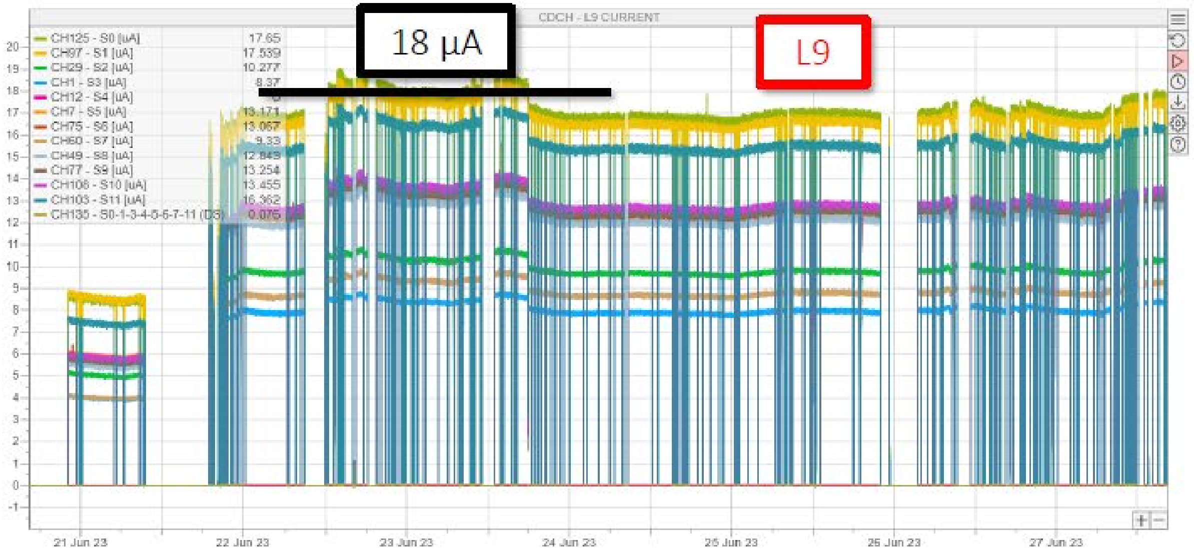

L5 CURRENT
Layer 5
CH115 - S0 = 0
CH45 - S1 = 0
CH35 - S2 = 0
CH23 - S3 = 0
CH18 - S4 = 0
CH36 - S5 = 0
CH77 - S6 = 0
CH67 - S7 = 0
CH55 - S8 = 0.001
CH50 - S9 = 0
CH68 - S10 = 0
CH125 - S11 = 0
7x10^7 μ/s
2% → 1% O2
1% → 0.5% O2
BB close d
0.5% → 0.1% O2
18 μA
22 μA
24 μA
26 μA
-20V
-40V
11/12 h16
16/12 h12
12 Dec 20
13 Dec 20
14 Dec 20
15 Dec 20
16 Dec 20

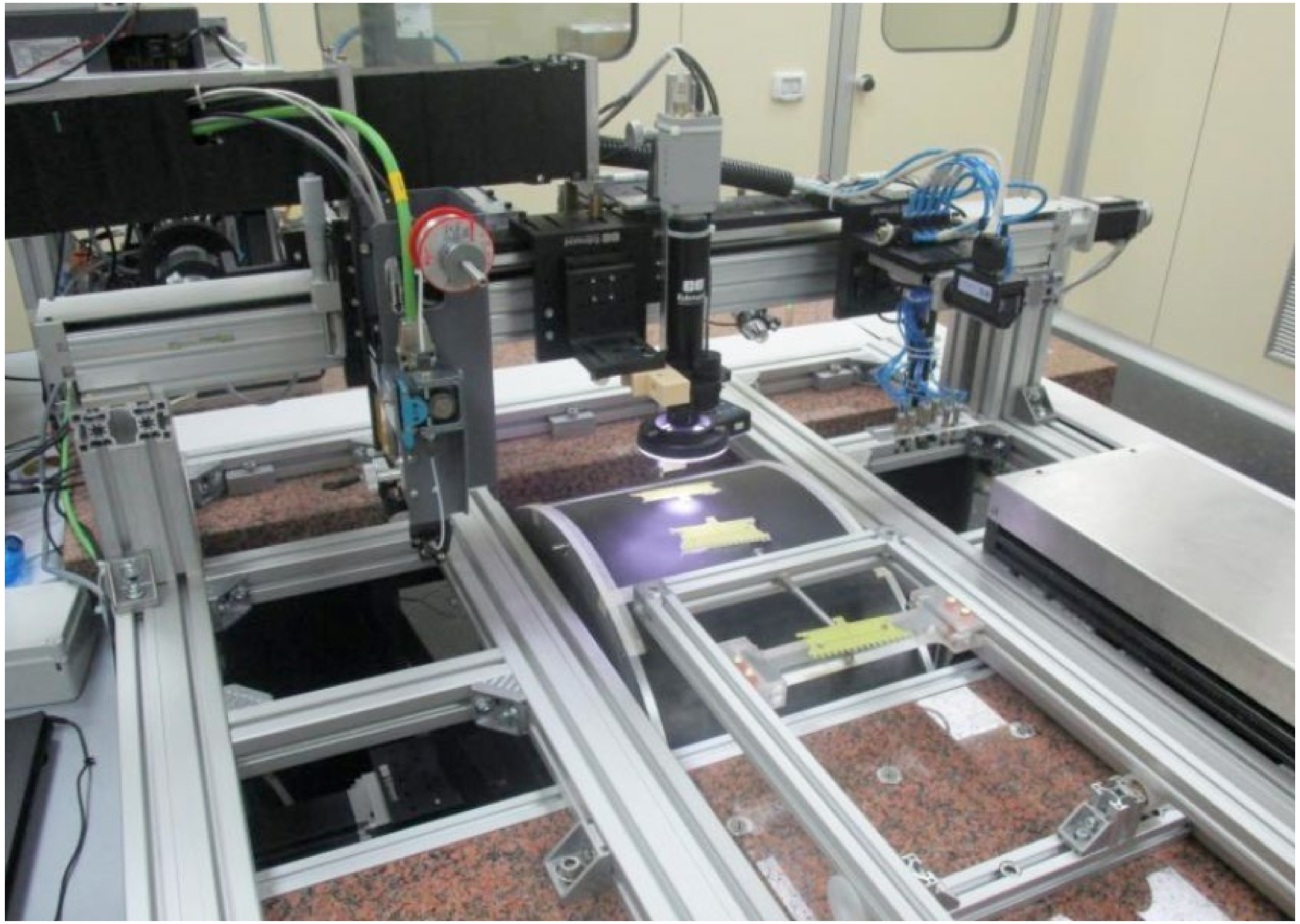

Current [μA]
100
80
60
40
20
0
12-02h
12-08h
12-14h
12-20h
13-02h
13-08h
13-14h
13-20h
14-02h

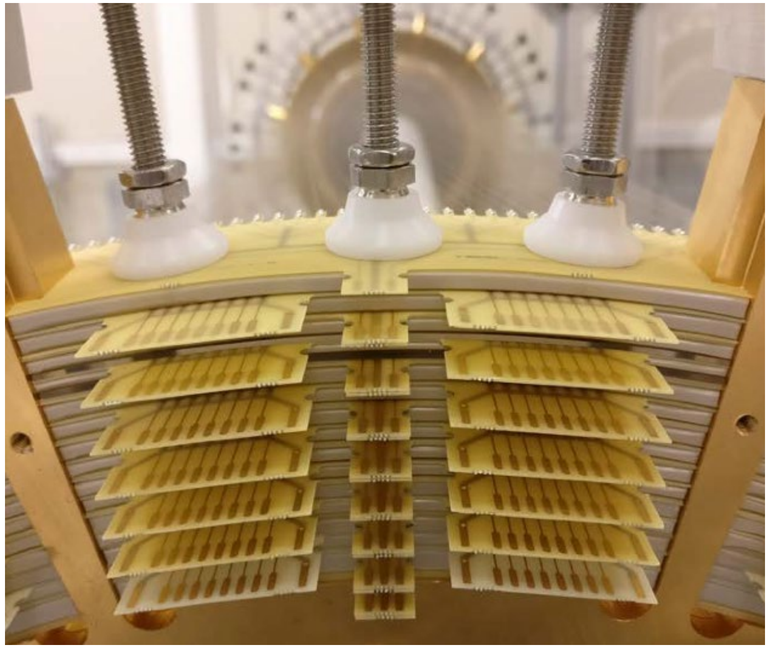
CDCH current stability

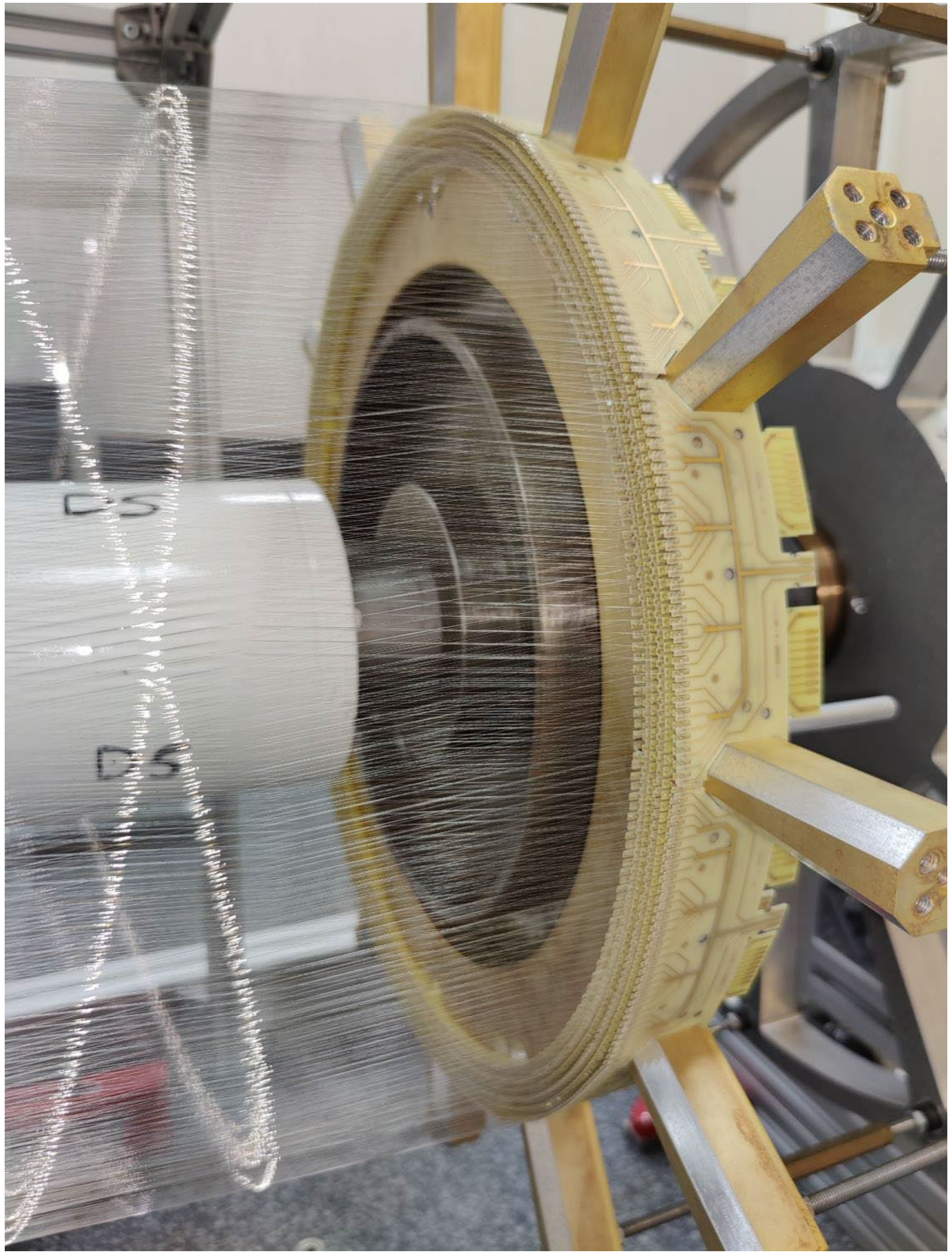


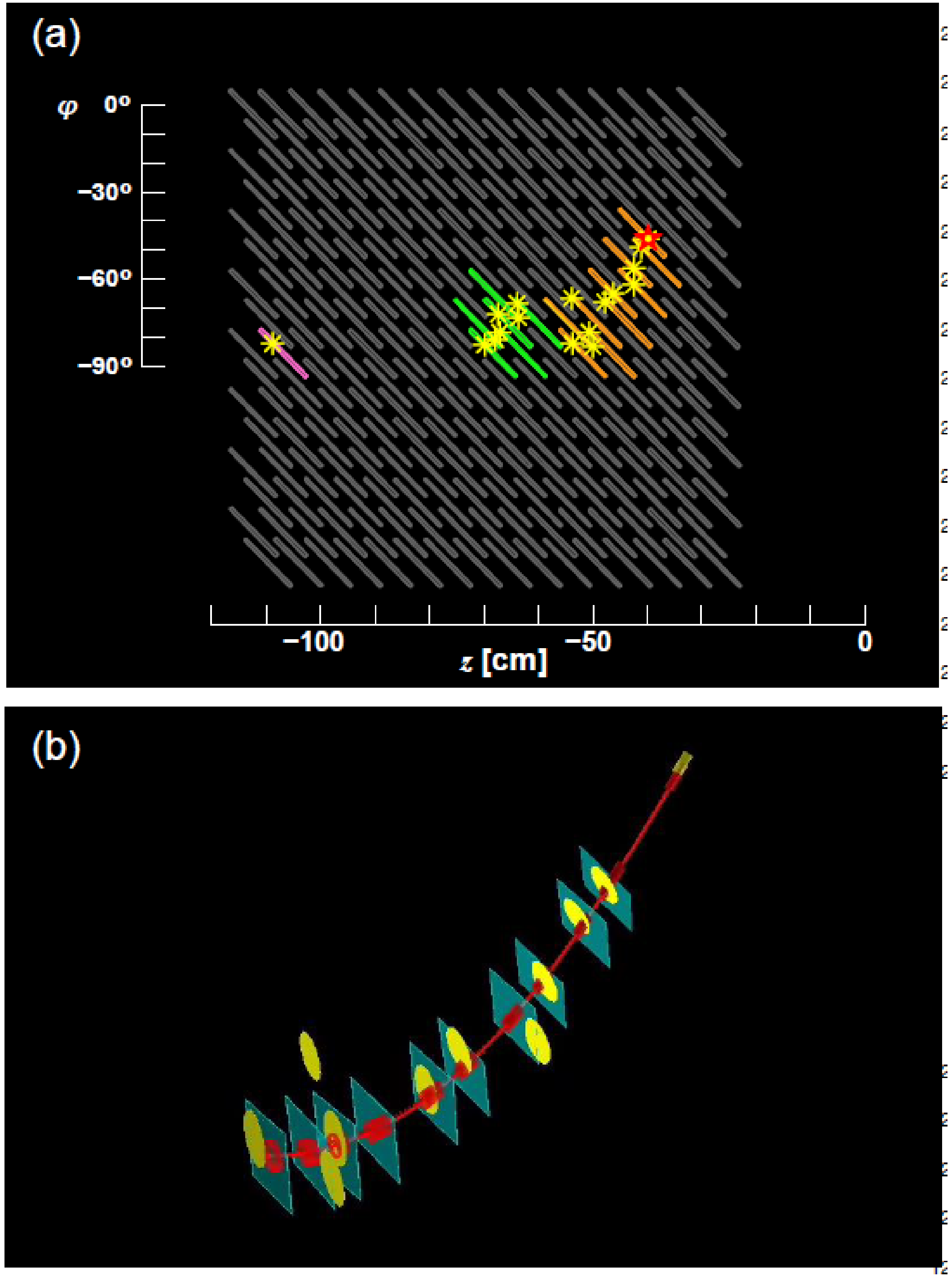


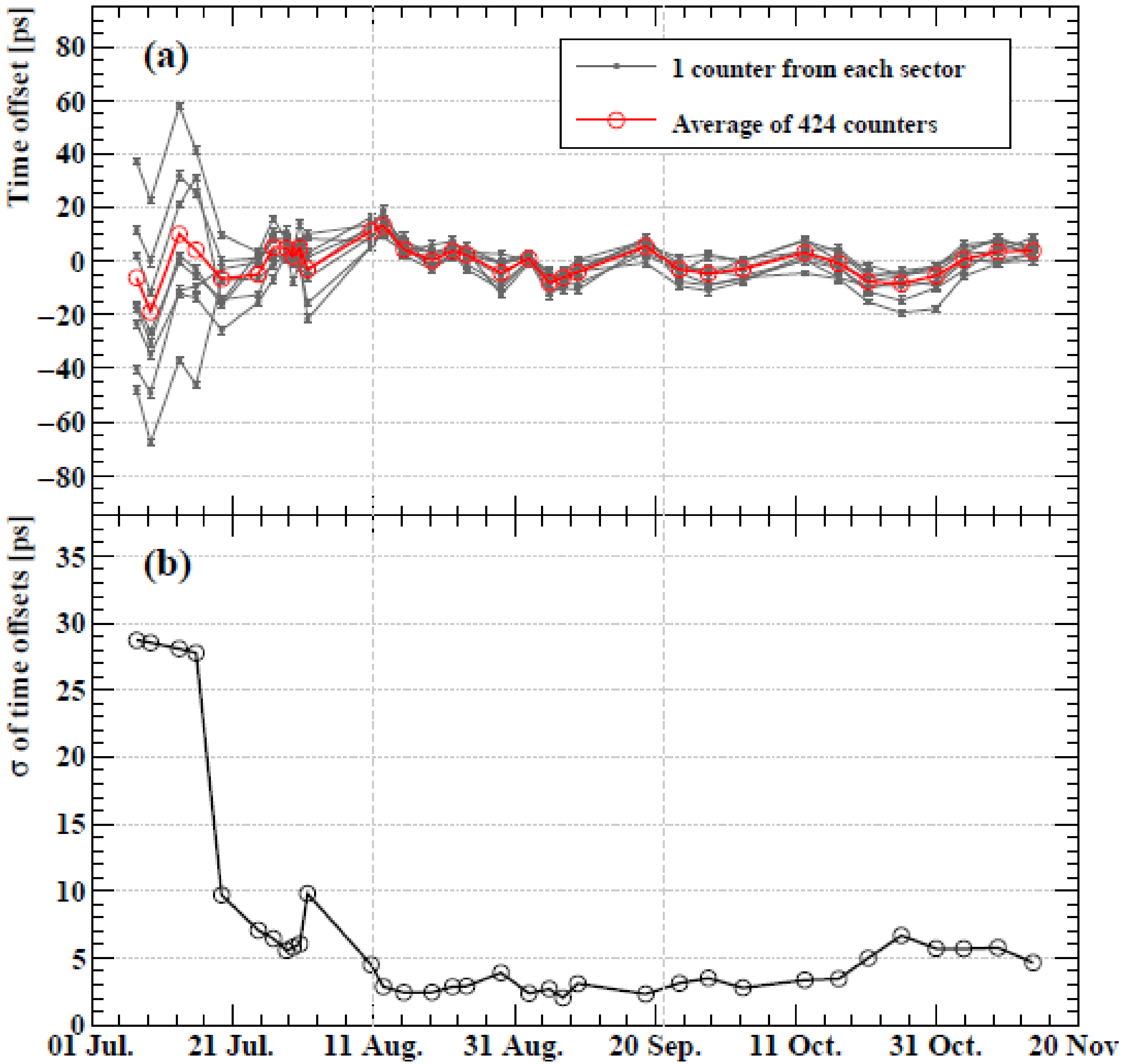






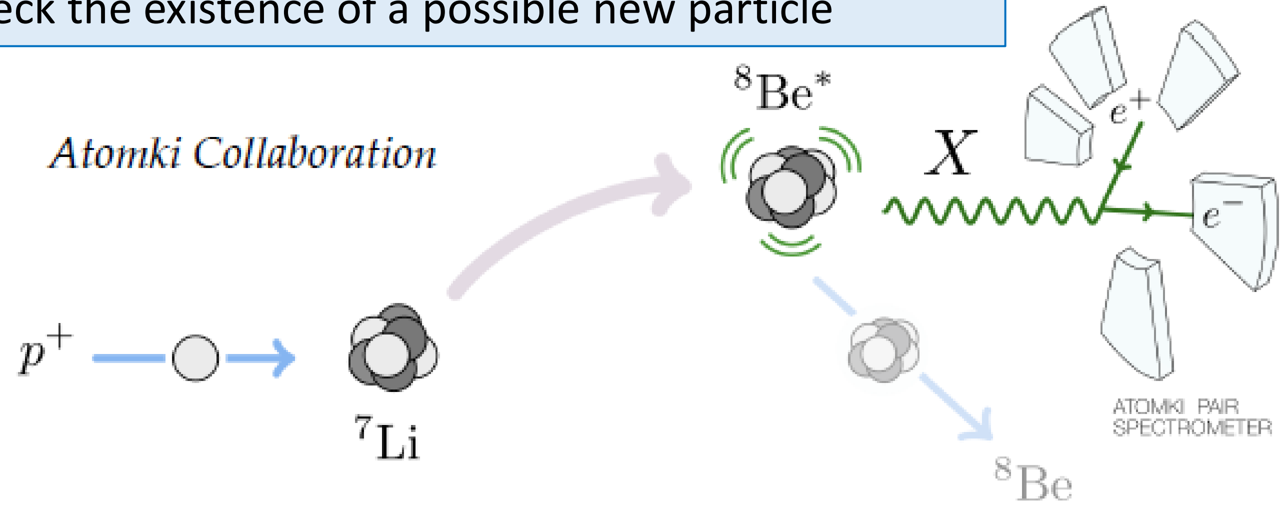

DS
DS


(a)
φ
0º
−30º
−60º
−90º
−100
−50
0
z [cm]
(b)



(a)
1 counter from each sector
Average of 424 counters
Time offset [ps]
80
60
40
20
0
−20
−40
−60
−80
(b)
σ of time offsets [ps]
35
30
25
20
15
10
5
0
01 Jul.
21 Jul.
11 Aug.
31 Aug.
20 Sep.
11 Oct.
31 Oct.
20 Nov

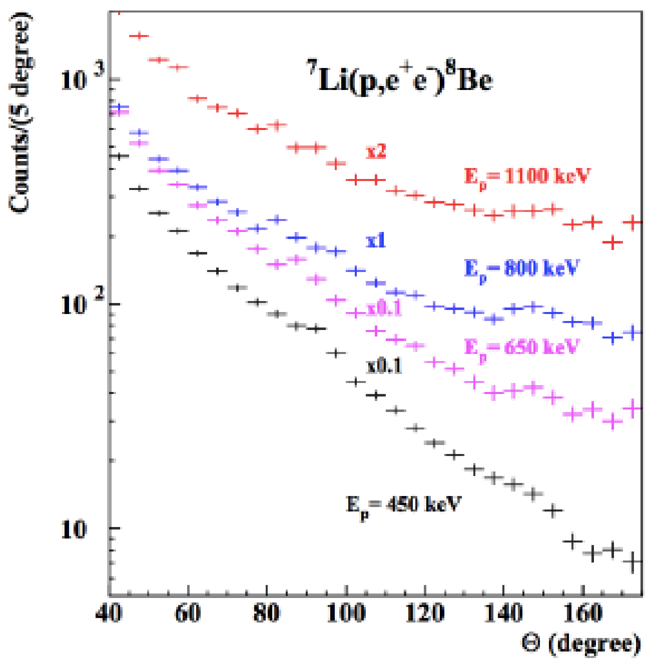
Check the existence of a possible new particle

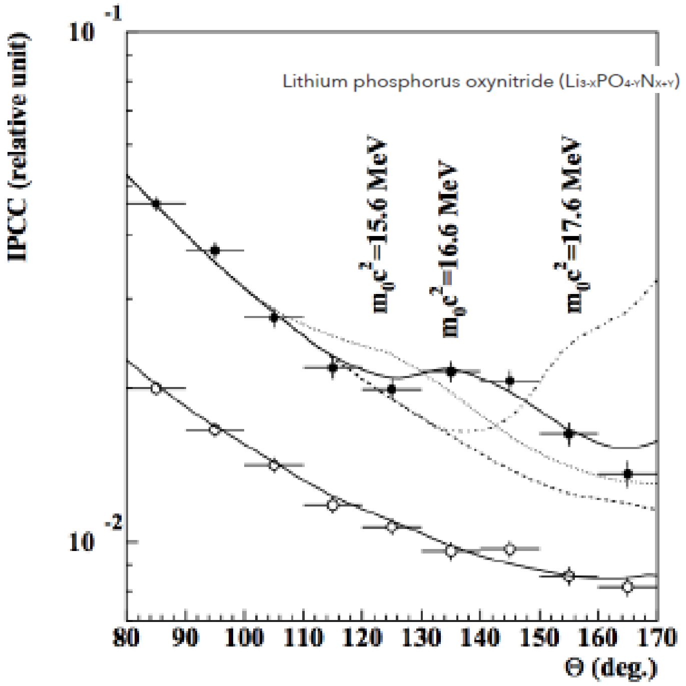


$^7\mathrm{Li}(p,e^+e^-)^8\mathrm{Be}$ studied at

$E_p =$ 450, 650, 800, 1100 keV

e+/e- energy sum and angular correlation Θ



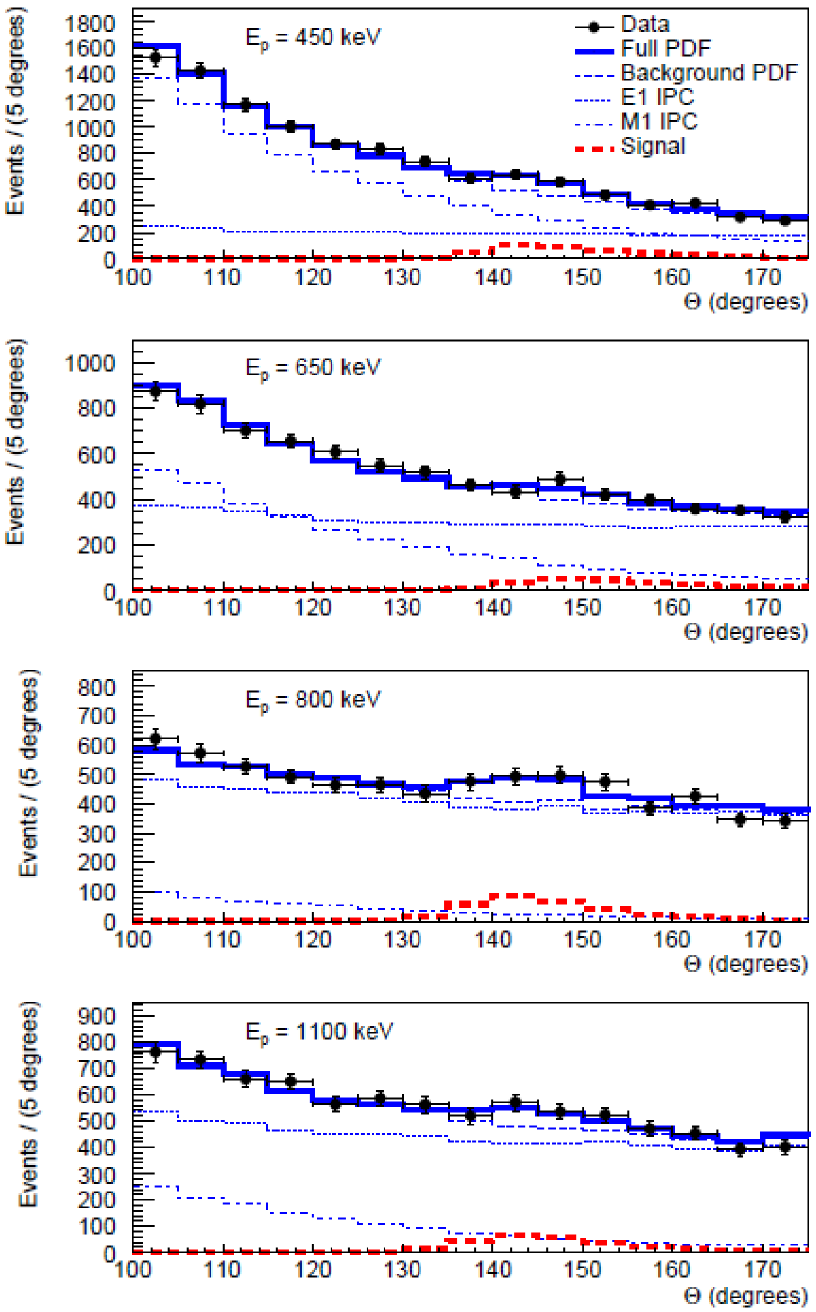


- Internal Pair Conversion (IPC) distribution shows excess at Θ~140° at several beam energies

decay of a light particle

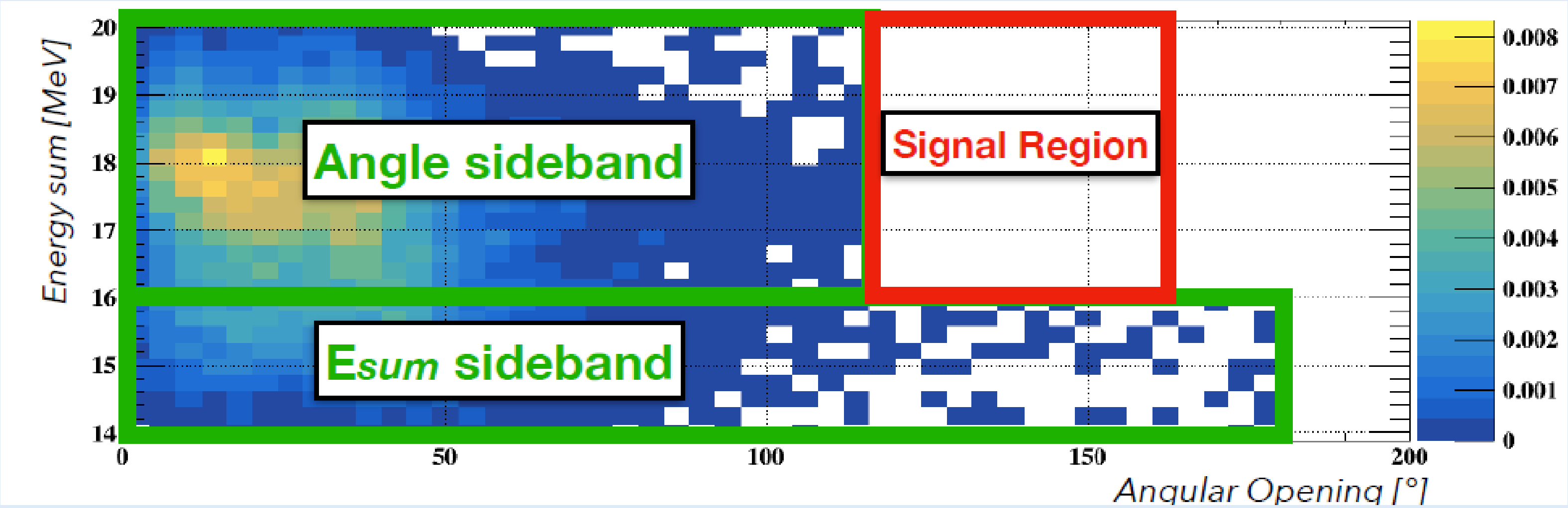
best fit $m_X = 16.95\ \mathrm{MeV}/c^2$, $BR(X) = 6\times10^{-6}$

arXiv:2205.07744 Phys. Rev. Lett. 116, 042501

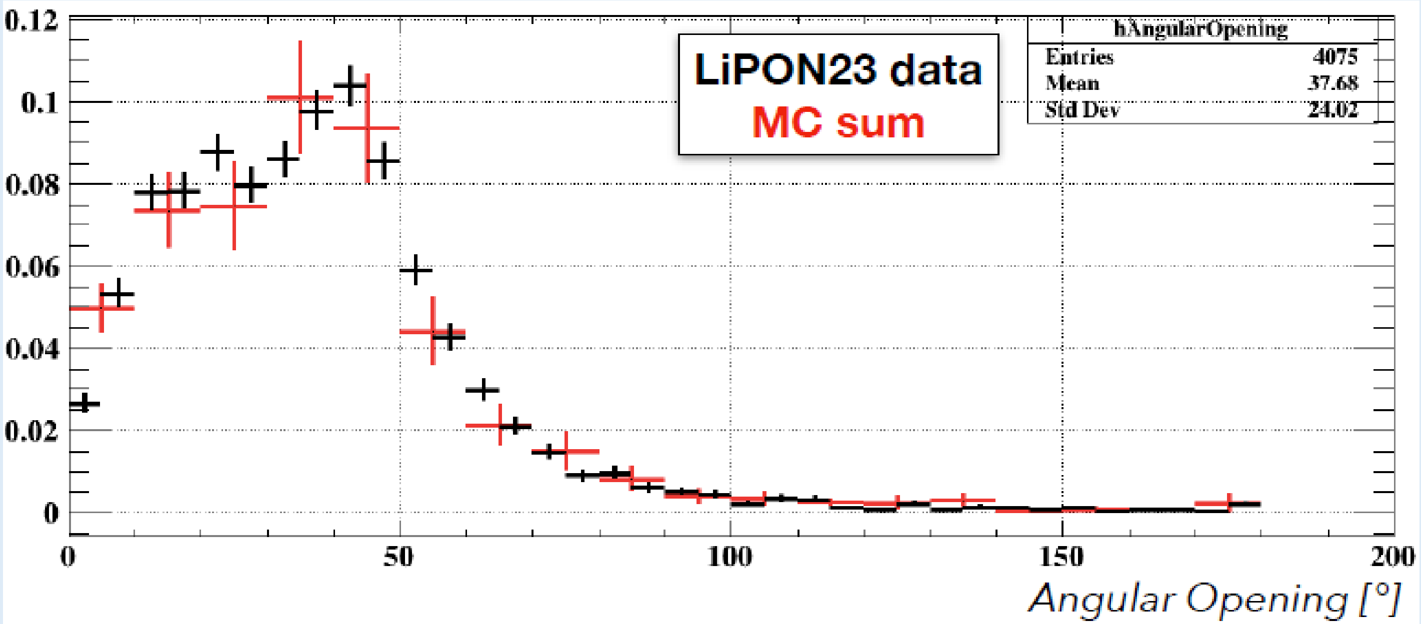


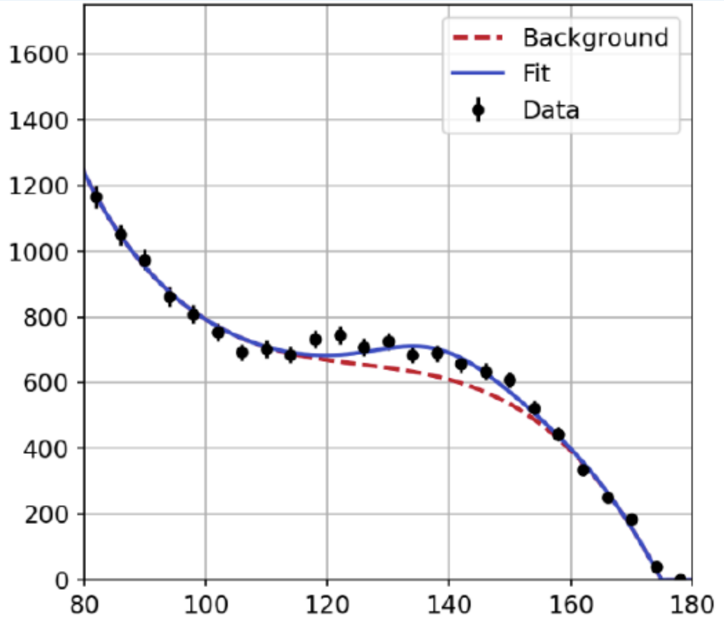
E_p = 450 keV
Data
Full PDF
Background PDF
E1 IPC
M1 IPC
Signal
E_p = 650 keV
E_p = 800 keV
E_p = 1100 keV
Events / (5 degrees)
Θ (degrees)

Analysis in an advanced state



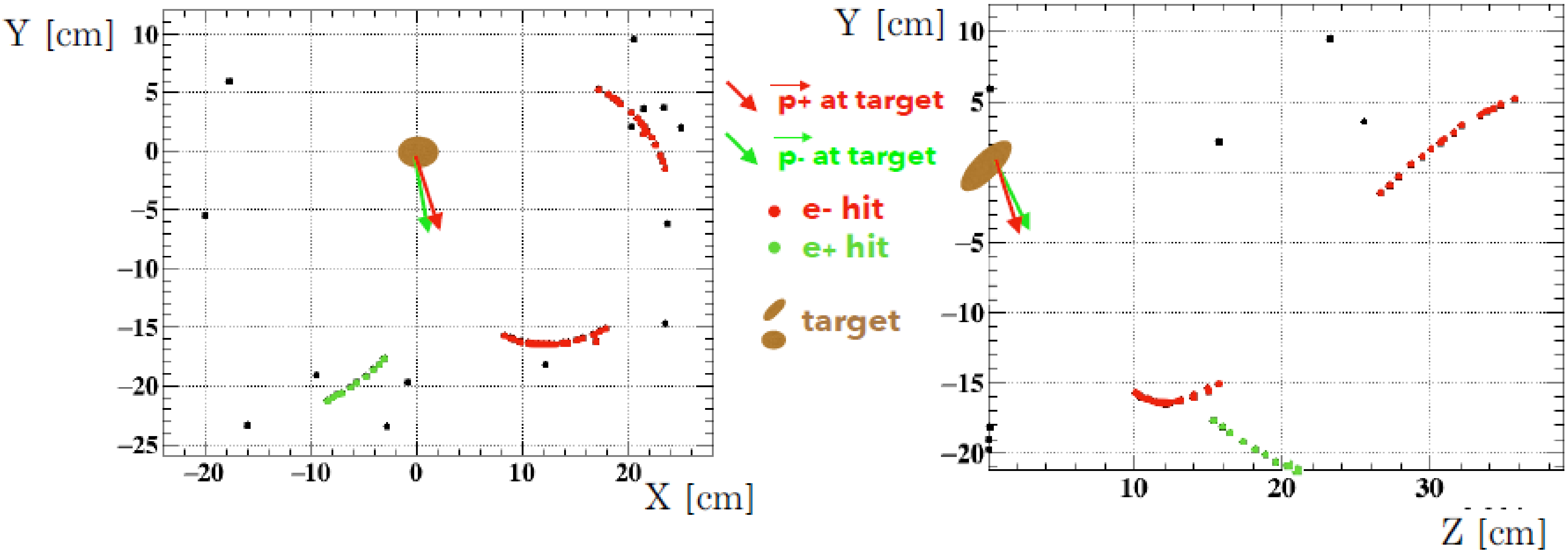
2023 signal estimate





- MEG-II only reconstructs e+. Procedure was adapted for e- as well.

LiPON event



- 400 μm-thickness carbon fiber vacuum chamber to minimize multiple scattering
- Main target for physics run

→ 2 μm LiPON(*) on 25 μm copper substrate (by PSI)

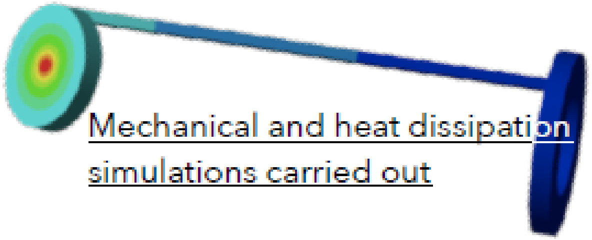
- For gamma detectors calibration

→ 5 μm LiF on 10 μm copper substrate (by INFN Legnaro)

- Target-supporting and heat-dissipating copper structure attached to CW nose

Li distribution in target under investigation

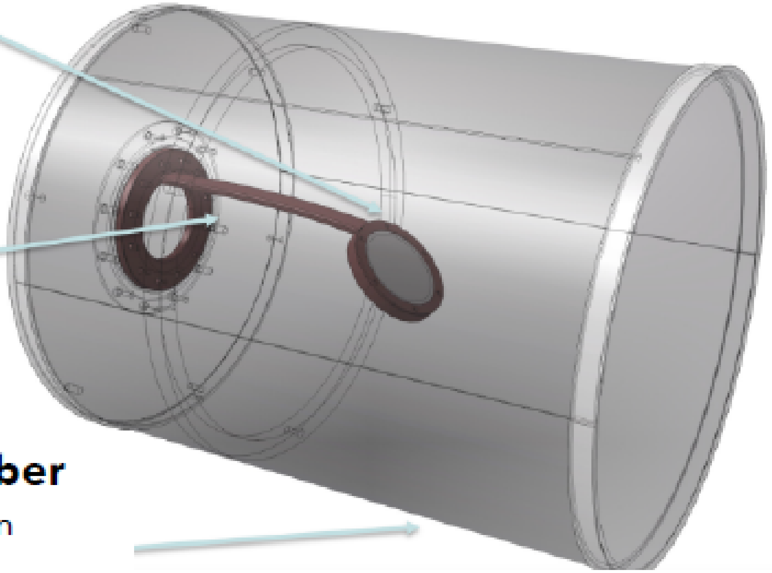
B field x0.15 wrt MEG (0.2T at center)



Mechanical and heat dissipation simulations carried out

Li target
at COBRA center
45° slant angle

Target arm
Cu for heat dissipation



Carbon fiber vacuum chamber
Thickness: 400 μm, Diameter: 98 mm
Length: 226 mm

(*) Lithium phosphorus oxynitride ($Li_{3-x}PO_{4-y}N_{x+y}$)

Exotica: Search for μ➔eaγ

J. High Energ. Phys. **2022**, 29 (2022)

- Exploit the optimal γ detection MEG II properties to increase the sensitivity to μ➔ea
- Need to make ad hoc runs with different trigger configurations