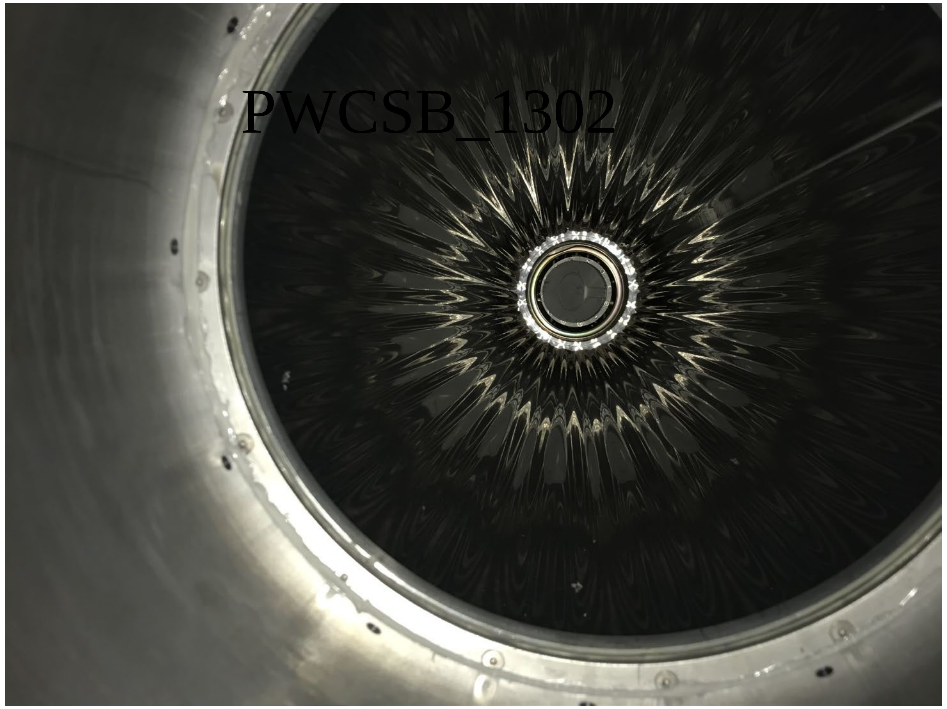
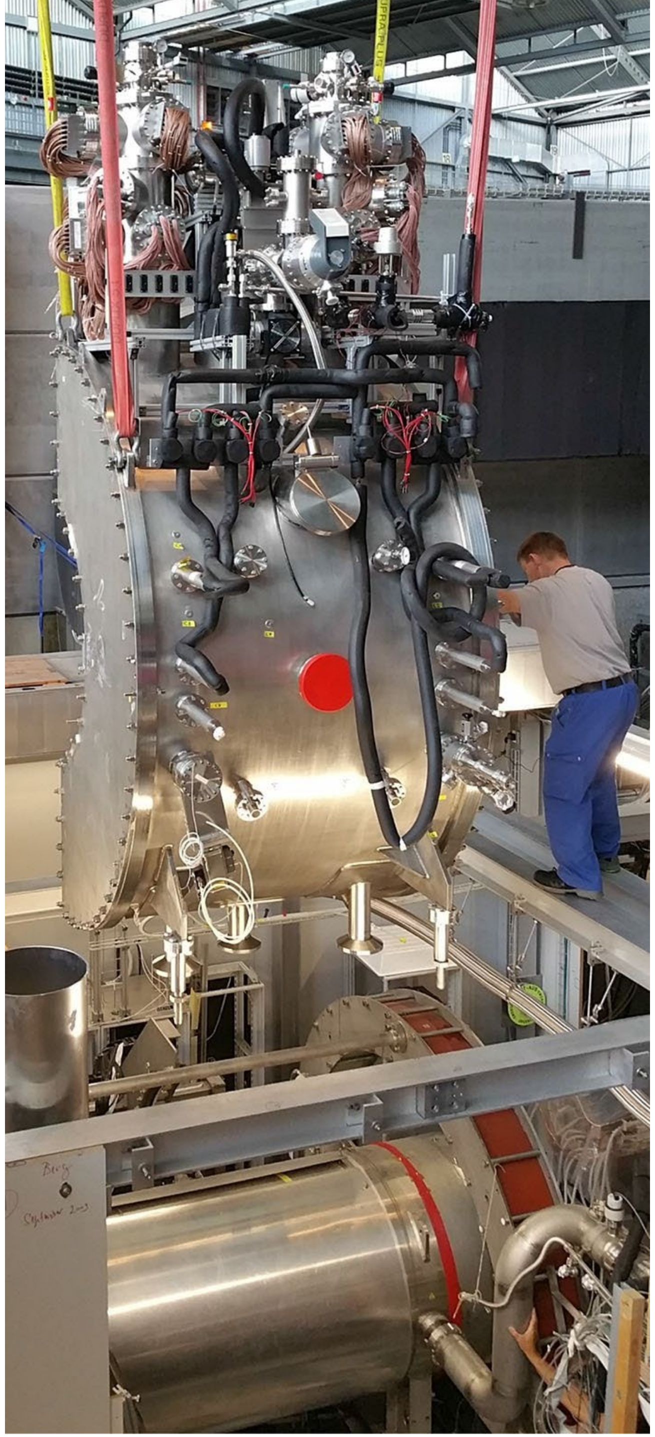
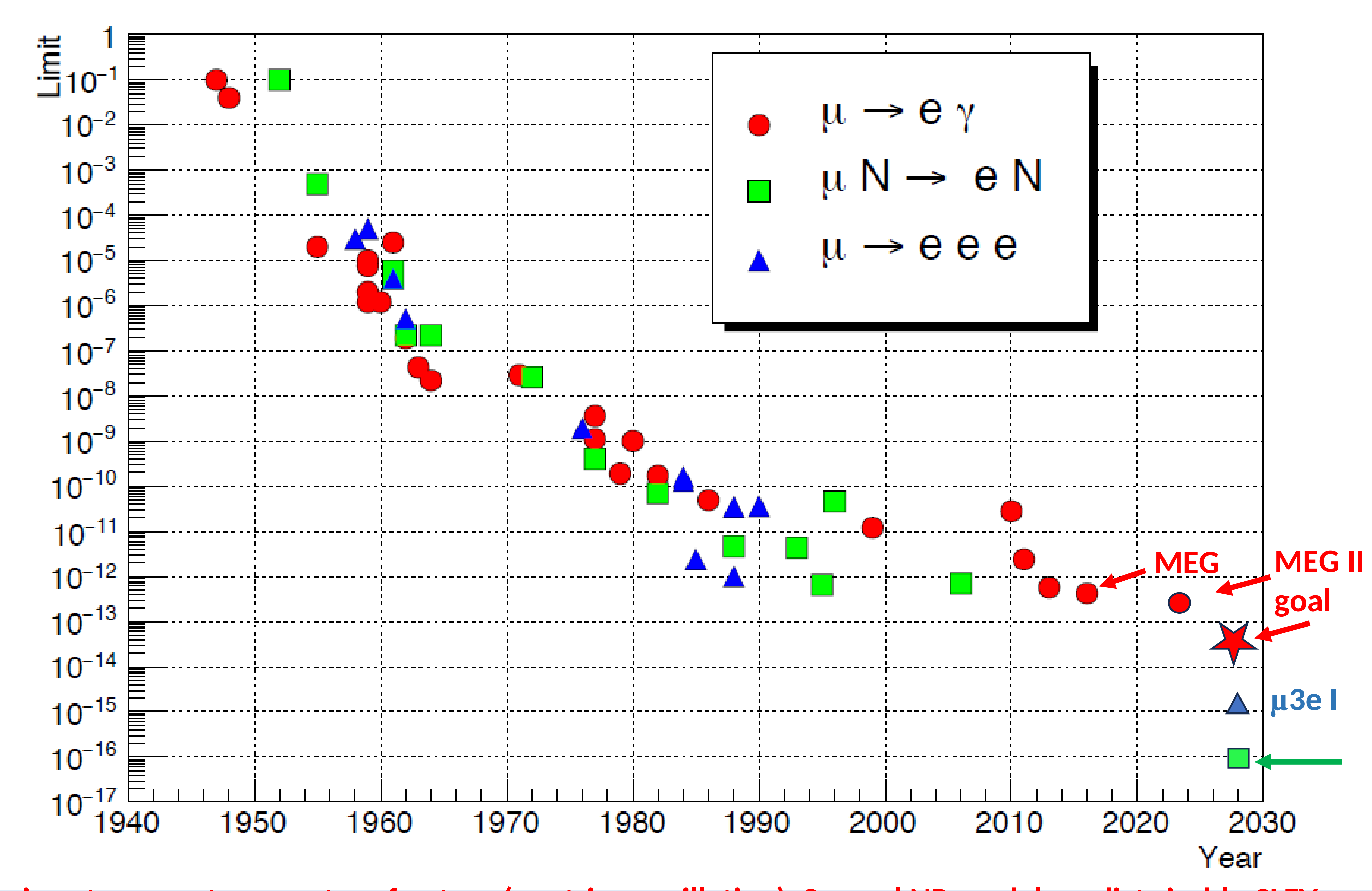
Updated result from $\mu^+ \rightarrow e^+\gamma$ search in MEG II and future projects





FLASY Rome
Jun 30th 2025
P.W. Cattaneo
INFN Pavia



Charged Lepton Flavor Violating (CLFV) processes involving muons

μ2e Run 1
COMET II

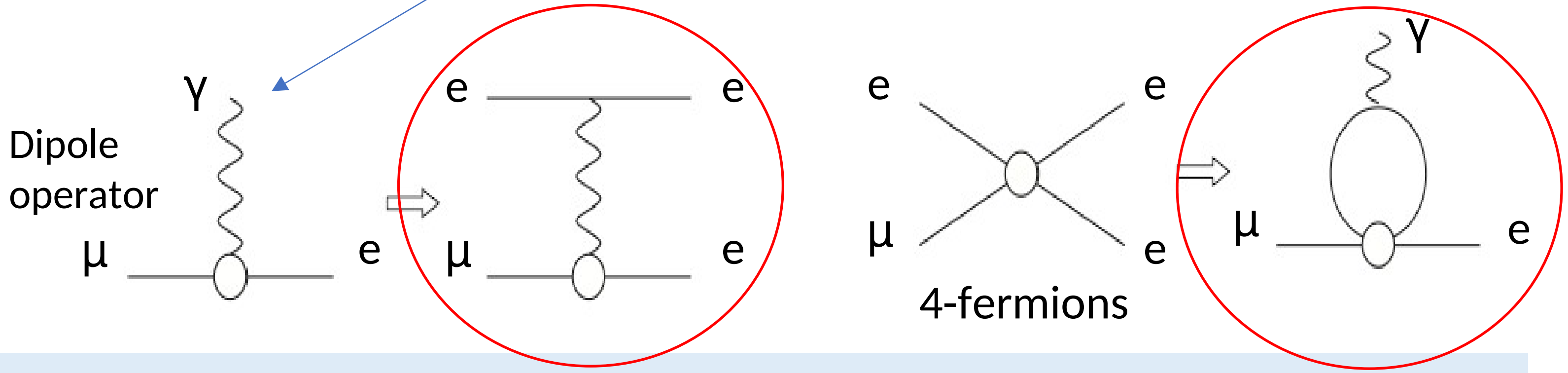
- **Flavor is not an exact symmetry of nature (neutrino oscillation). Several NP model predict sizable CLFV**
- **O(10^{-54}) in the SM (small neutrino masses) → If seen it would represent a clear sign of physics BSM**

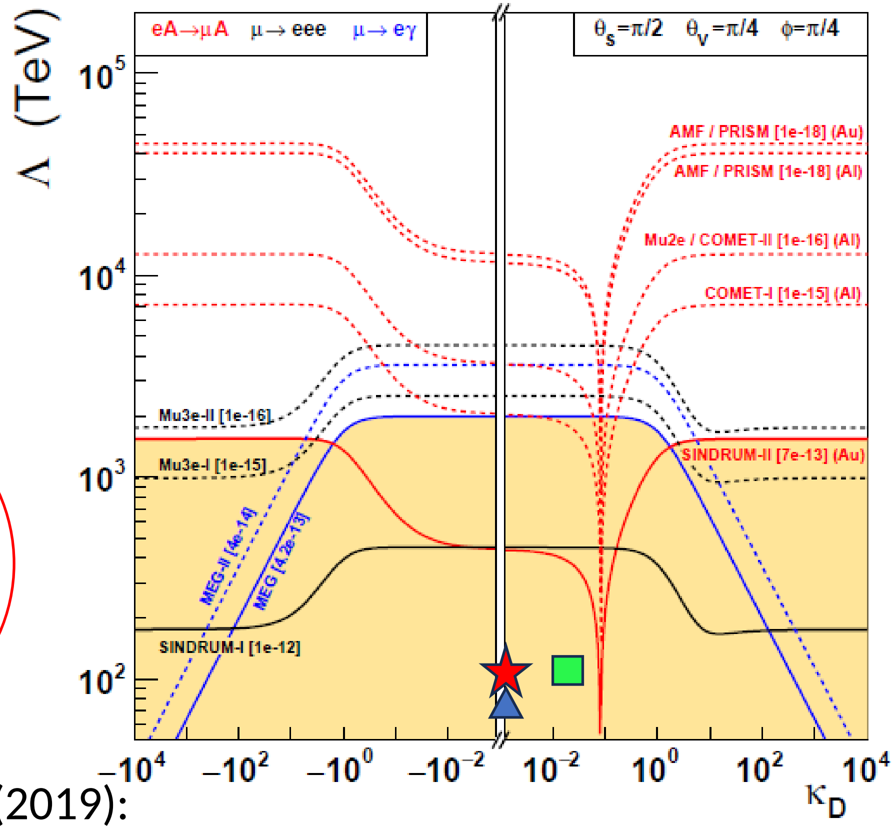
Effective Field Theory approach

S. Davidson, B. Echenard 2022

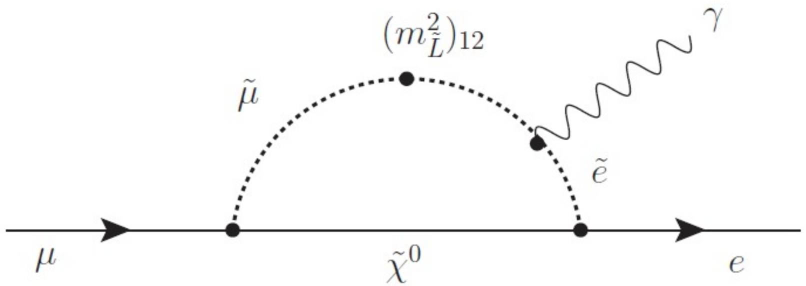
NP energy scale

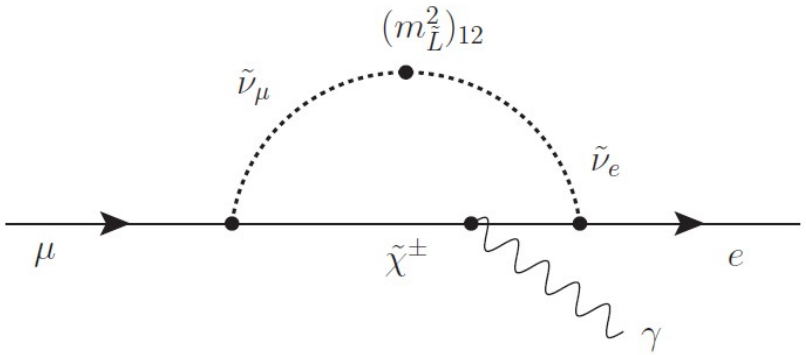
$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2}\Big[C_D(\bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re) + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re) + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight}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





Example: H. Baer, V. Baer, H. Serce: PHYSICAL REVIEW RESEARCH **1**, 033022 (2019):





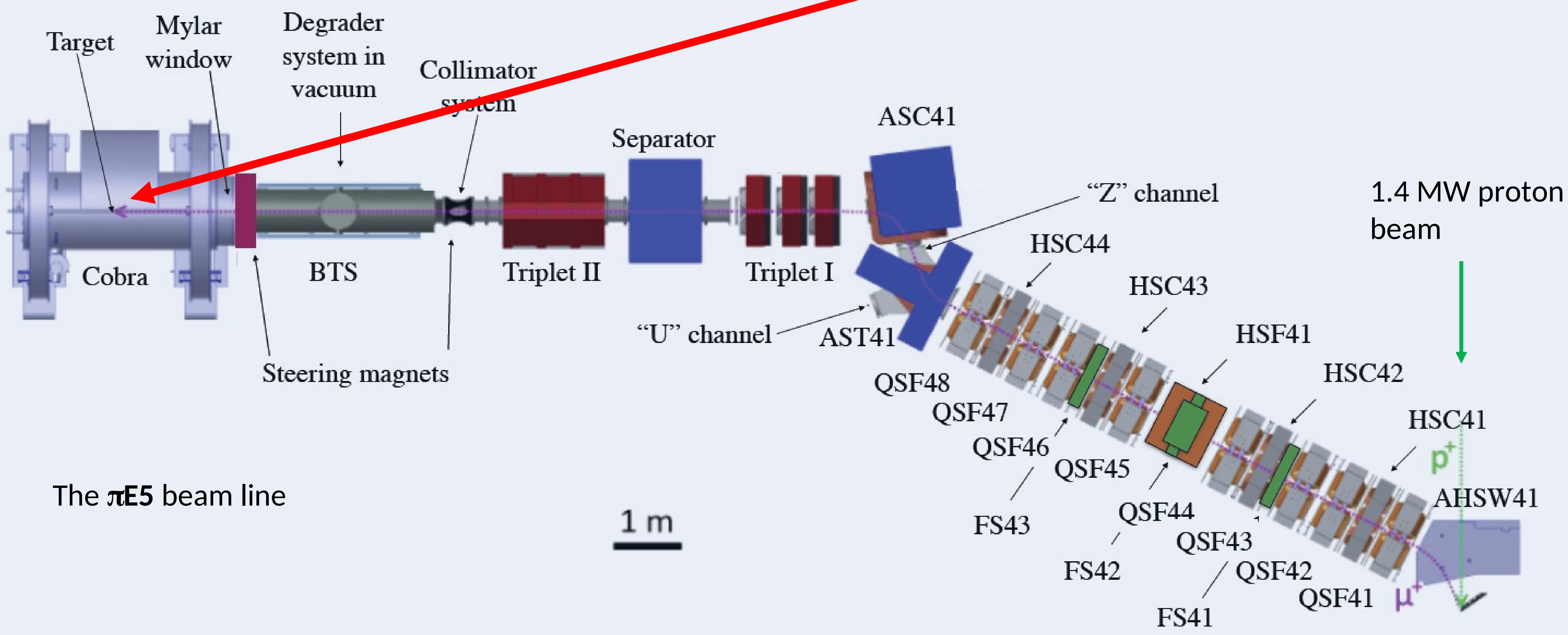
K_D parametrizes the relative magnitude of dipole and four-fermion coefficients

Implications of lepton flavor-violating processes within a supersymmetric seesaw framework in the three-extra-parameter nonuniversal Higgs model (NUHM3)

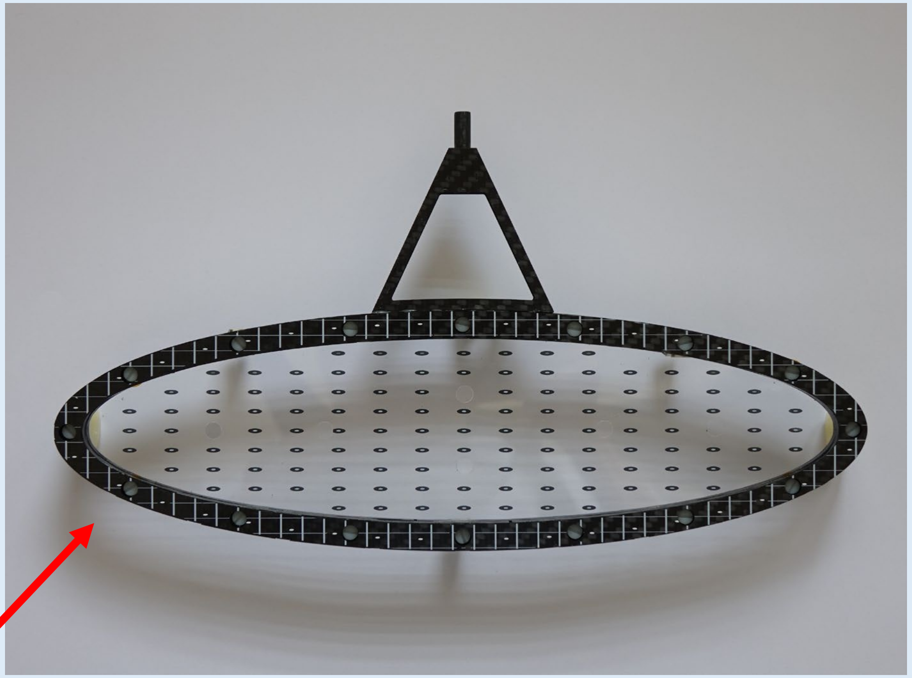
MEG II uses the πE5 beam line at Paul Scherrer Institut in Switzerland

Surface muon beam: p ≅ 28 MeV/c

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

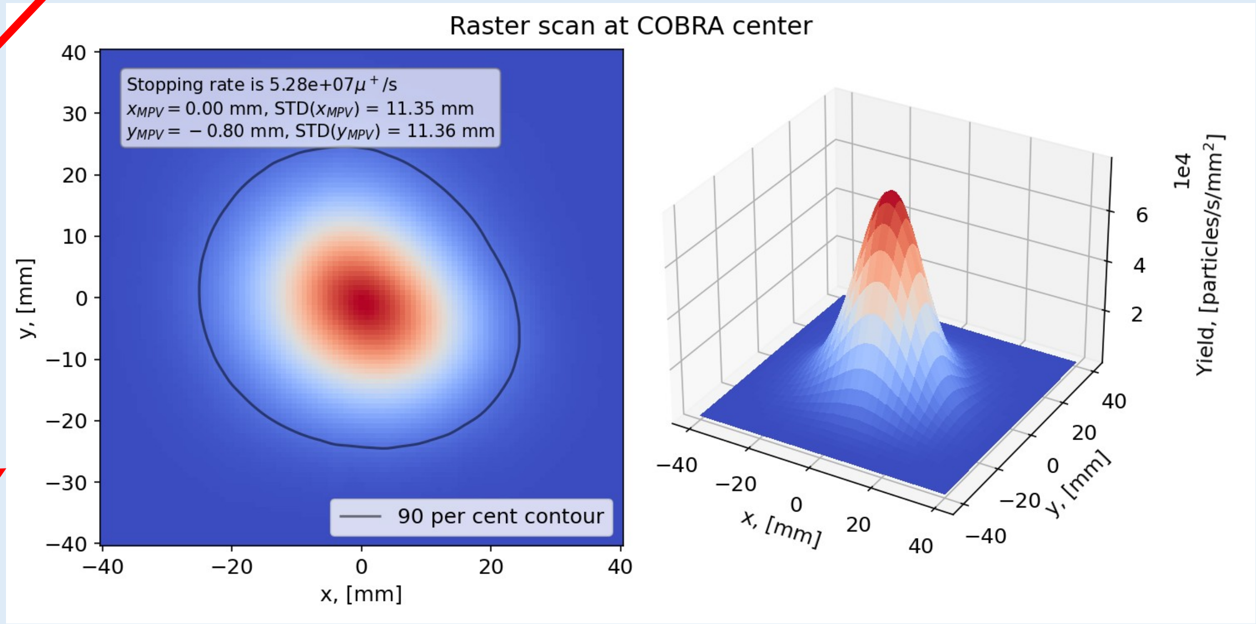


The πE5 beam line

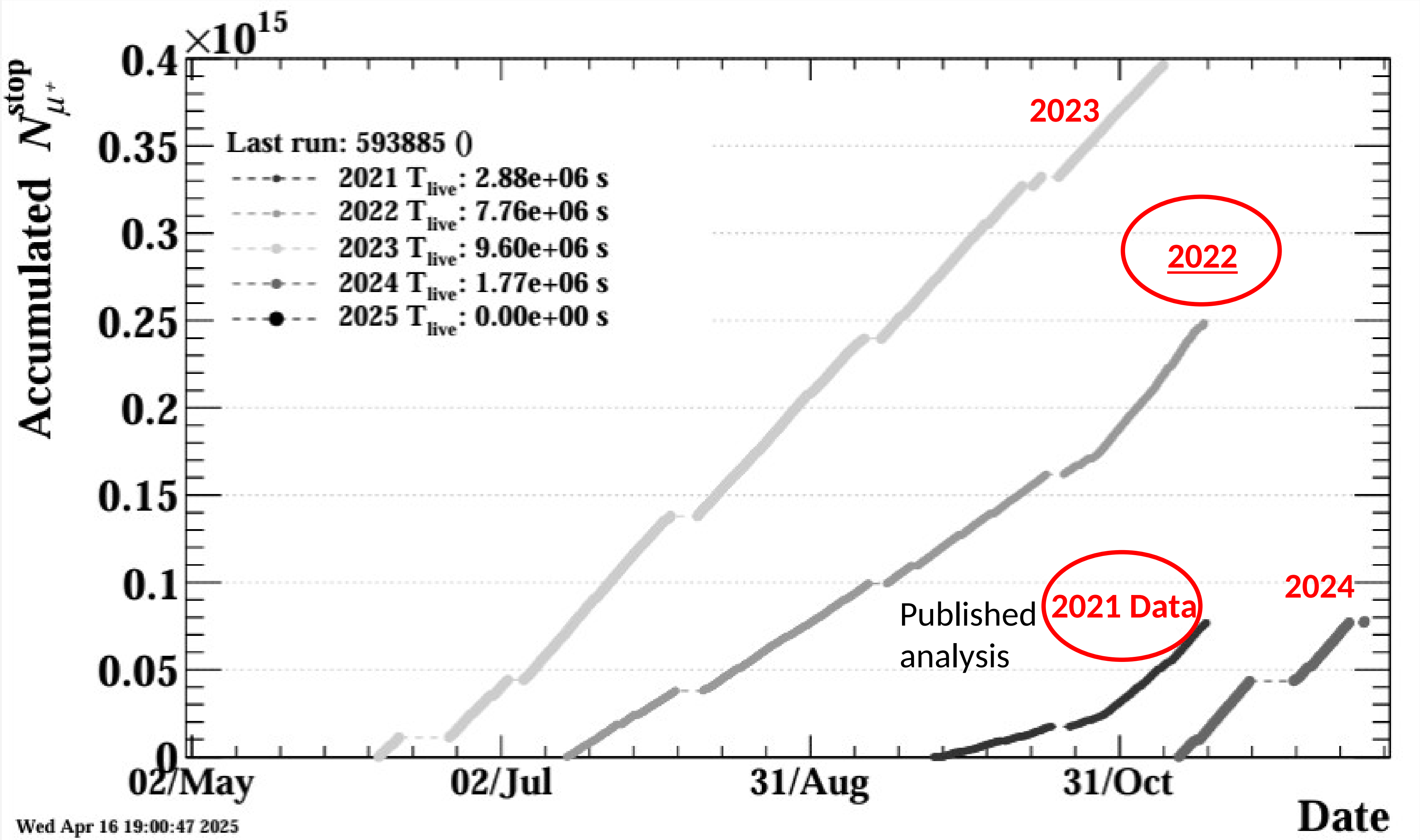


270 mm x 66 mm

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

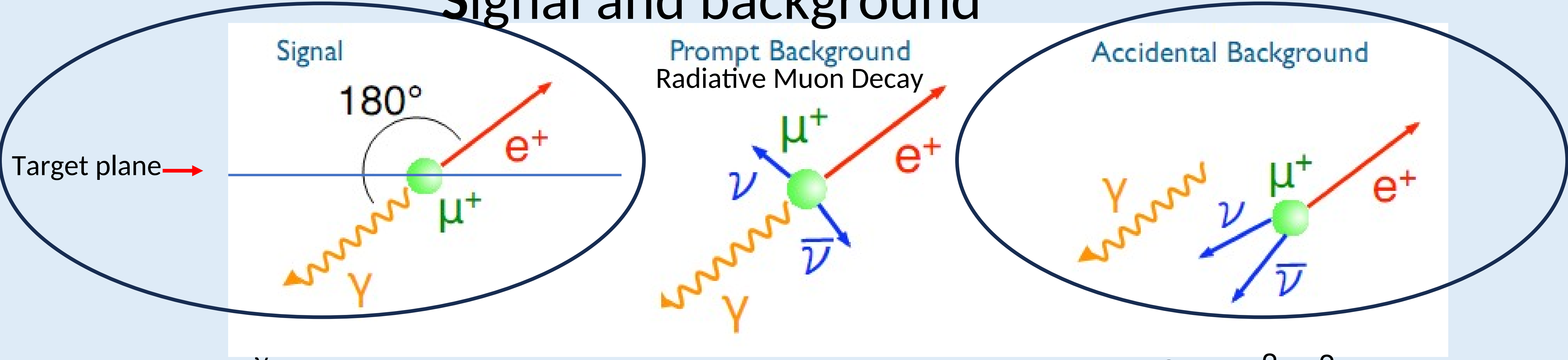


The muon beam profile at the target position is measured before start of data taking for stopping rates 2-5 x 10^7 μ^+/s



×10^15
Accumulated $N_{\mu^+}^{stop}$
Last run: 593885 ()
2021 T_{live}: 2.88e+06 s
2022 T_{live}: 7.76e+06 s
2023 T_{live}: 9.60e+06 s
2024 T_{live}: 1.77e+06 s
2025 T_{live}: 0.00e+00 s
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
02/May
02/Jul
31/Aug
31/Oct
Date
Wed Apr 16 19:00:47 2025
2023
2022
Published analysis
2021 Data
2024

Signal and background



$\theta^{e\gamma} = 180$

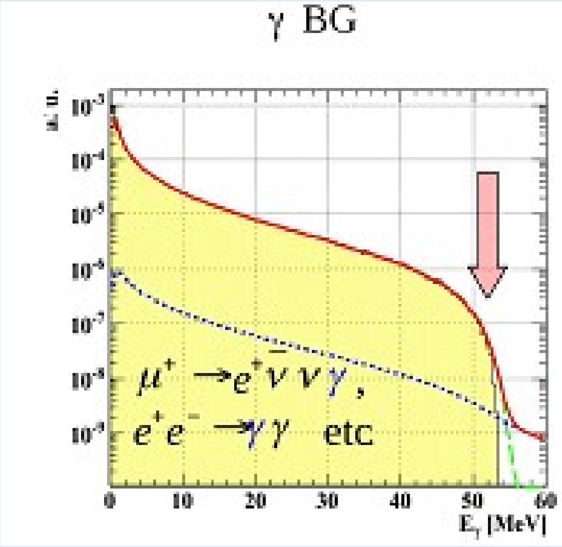
$E_{e^+} = E_\gamma = 52.8$ MeV

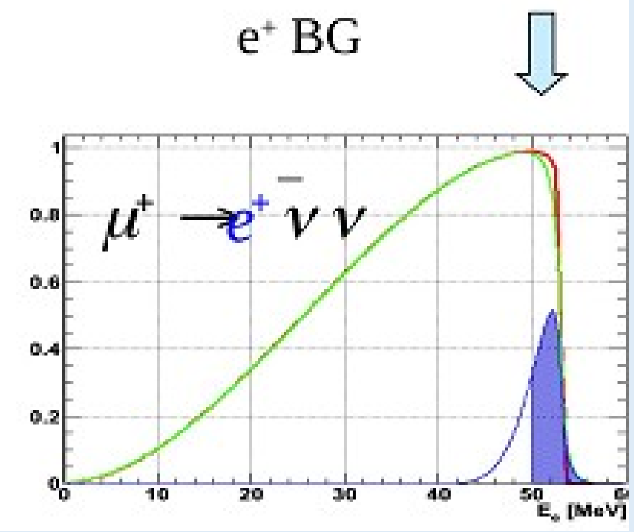
$t_{e+} = t_\gamma$

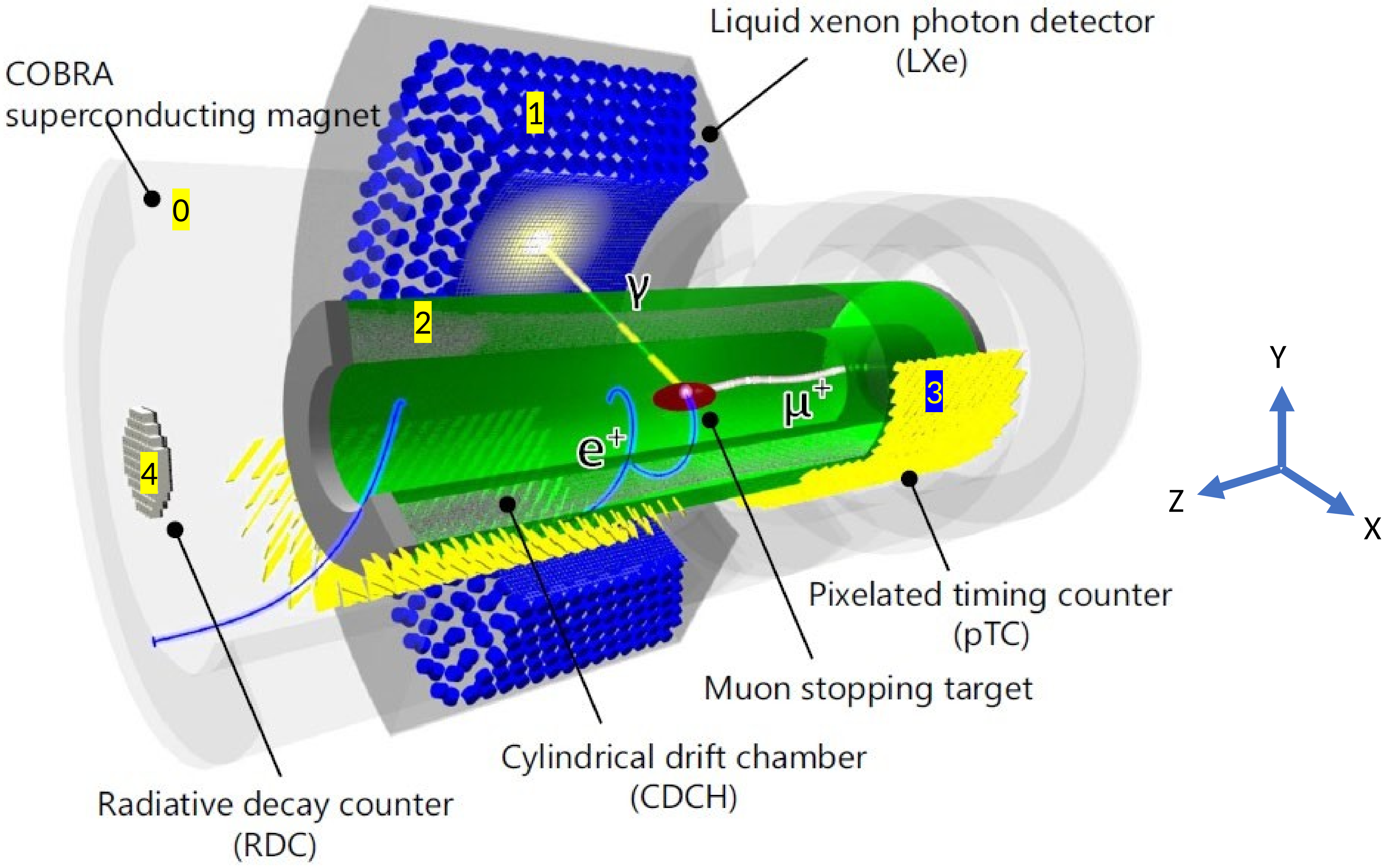
$N_{acc} \propto R_\mu^2 \sigma_{\Delta t} \sigma_{\Delta\theta}^2 \sigma_{E_\gamma}^2 \sigma_{E_{e^+}}$

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

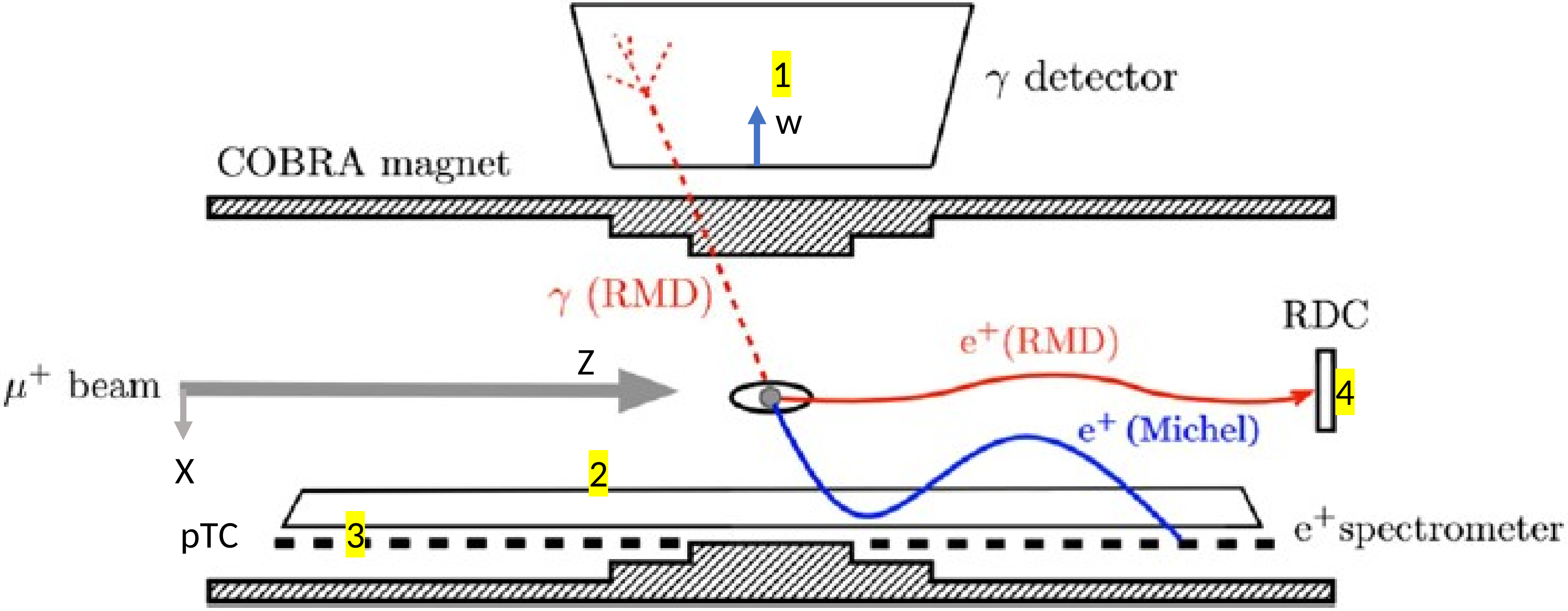
Detectors resolutions are crucial to keep it under control







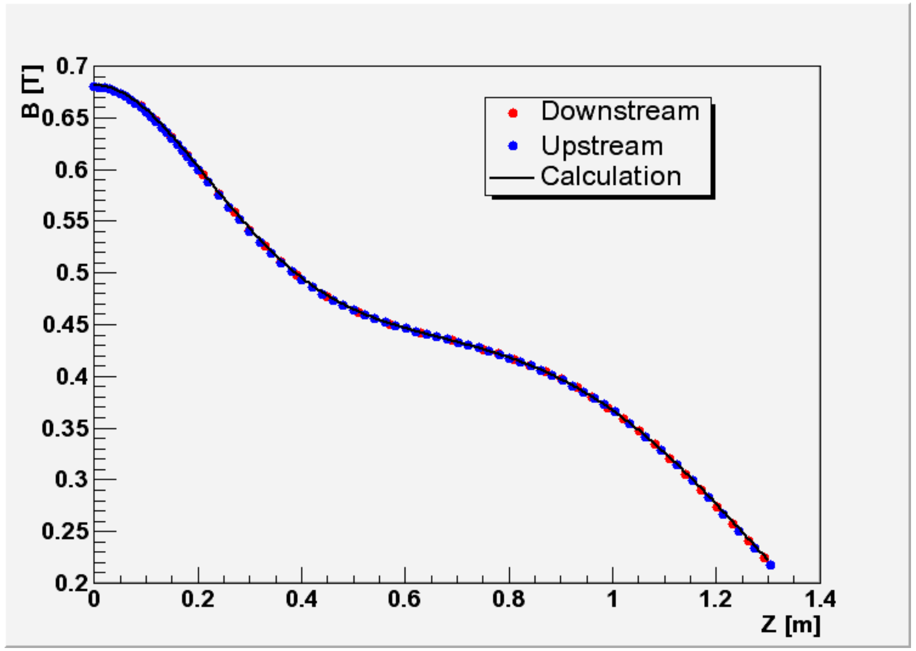
Liquid xenon photon detector
(LXe)
COBRA
superconducting magnet
0
1
2
3
4
γ
e+
μ+
Y
Z
X
Pixelated timing counter
(pTC)
Muon stopping target
Cylindrical drift chamber
(CDCH)
Radiative decay counter
(RDC)

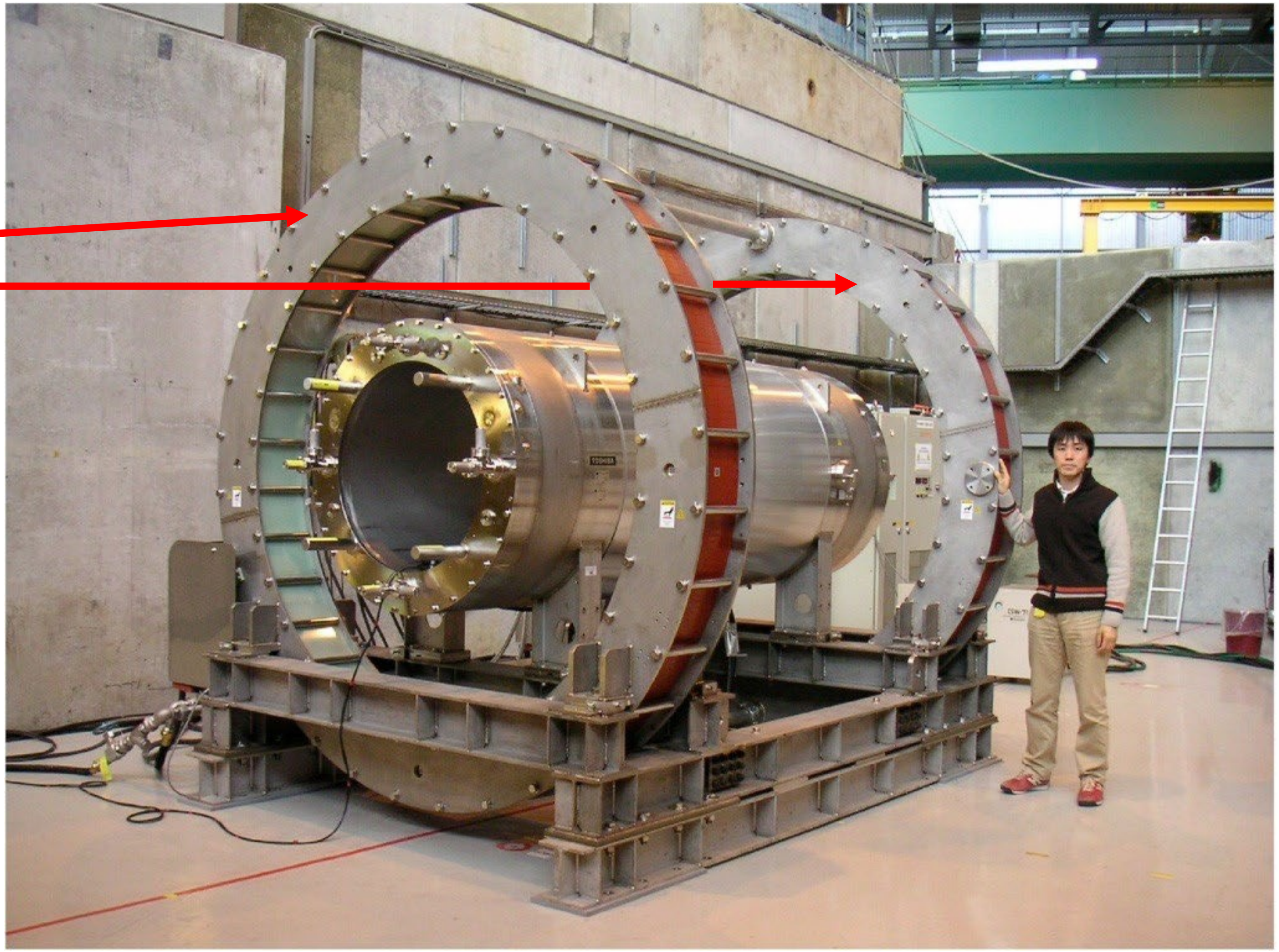

γ detector
1
w
COBRA magnet
γ (RMD)
RDC
e+(RMD)
Z
μ+ beam
4
e+ (Michel)
X
2
pTC
3
e+spectrometer

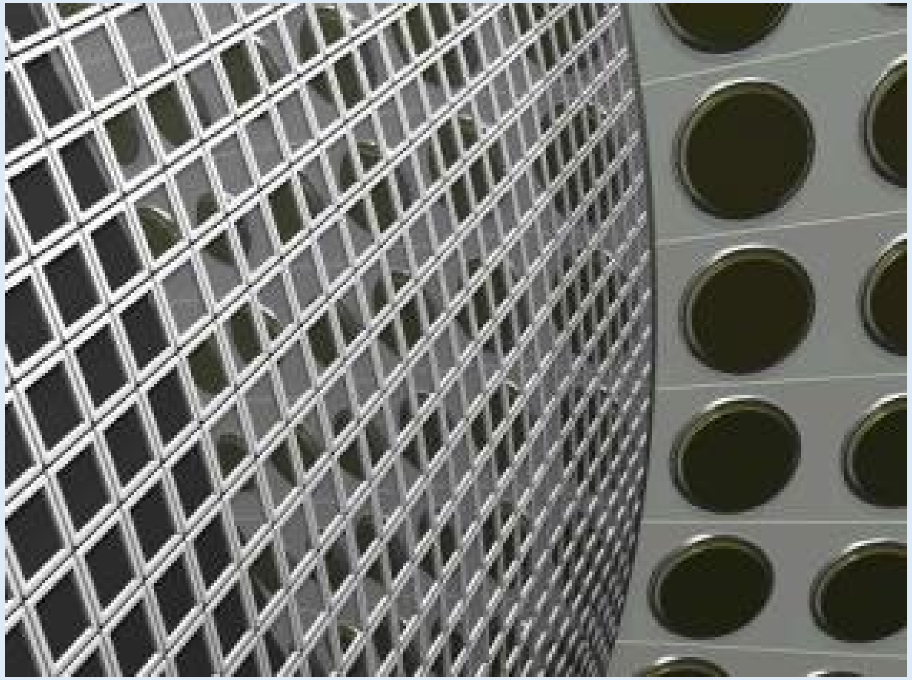
The COBRA magnet: 0

Thin-wall SC solenoid with a gradient magnetic field:
1.27 T center – 0.49 T both ends

Compensating coils

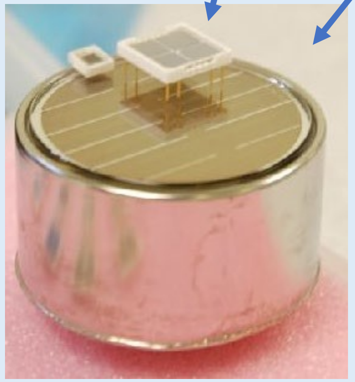


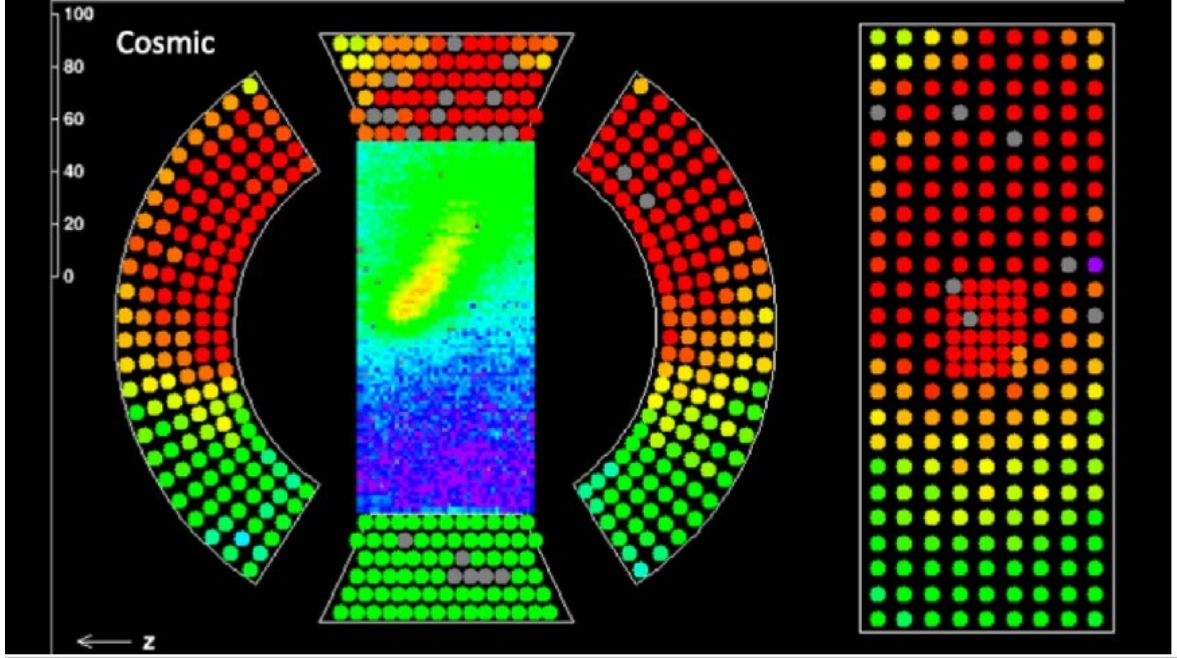


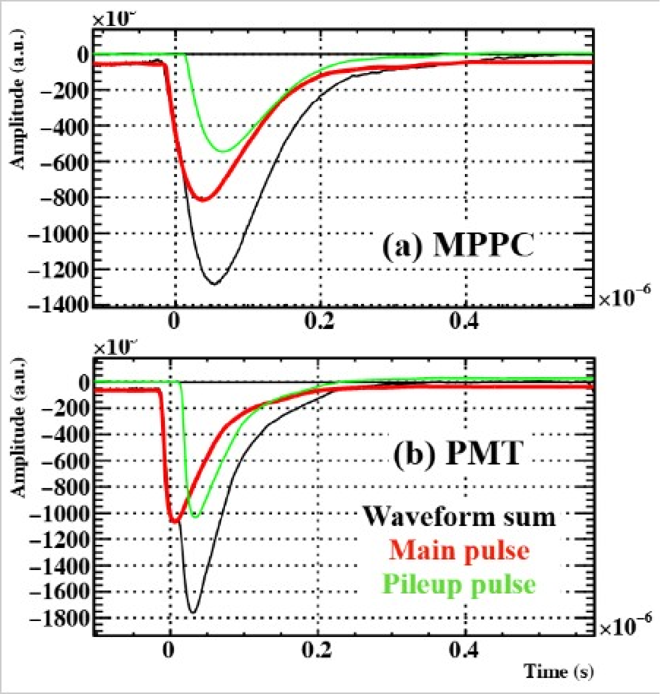


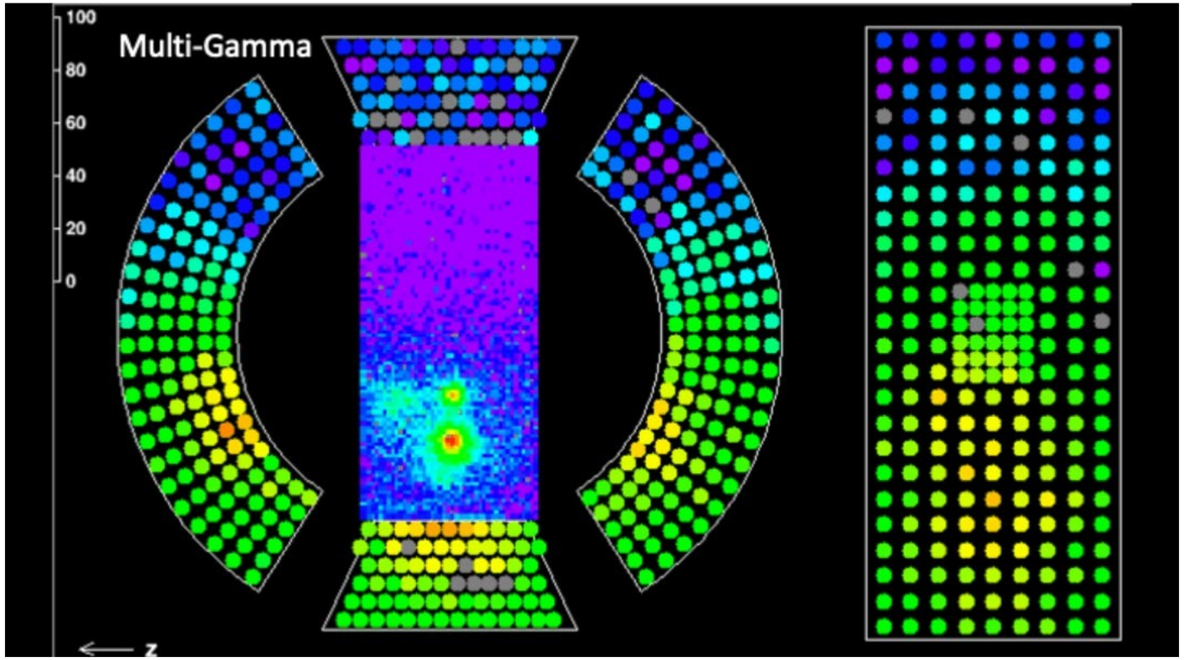
1: LXe

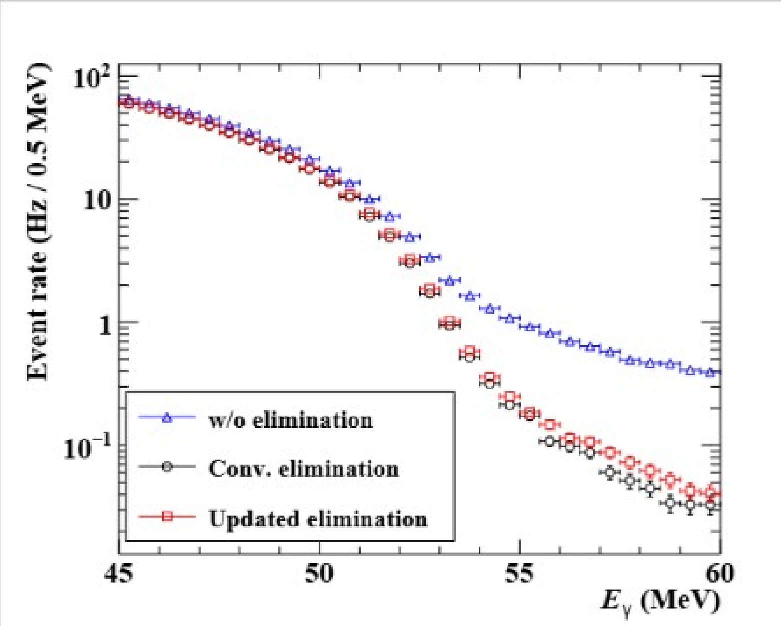
LXe γ–detector (800 liters) read by ≈ 4000 UV-sensitive 12mm x 12mm SiPMs (MPPC) on the γ–entrance face and by ≈ 600 2'' PMTs on the others




Cosmic
100
80
60
40
20
0
← z


Amplitude (a.u.)
(a) MPPC
×10^{-6}
(b) PMT
Waveform sum
Main pulse
Pileup pulse
Time (s)


Multi-Gamma
100
80
60
40
20
0
← z


Event rate (Hz / 0.5 MeV)
w/o elimination
Conv. elimination
Updated elimination
E_γ (MeV)

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 CEX

Energy & time calibration at signal energy

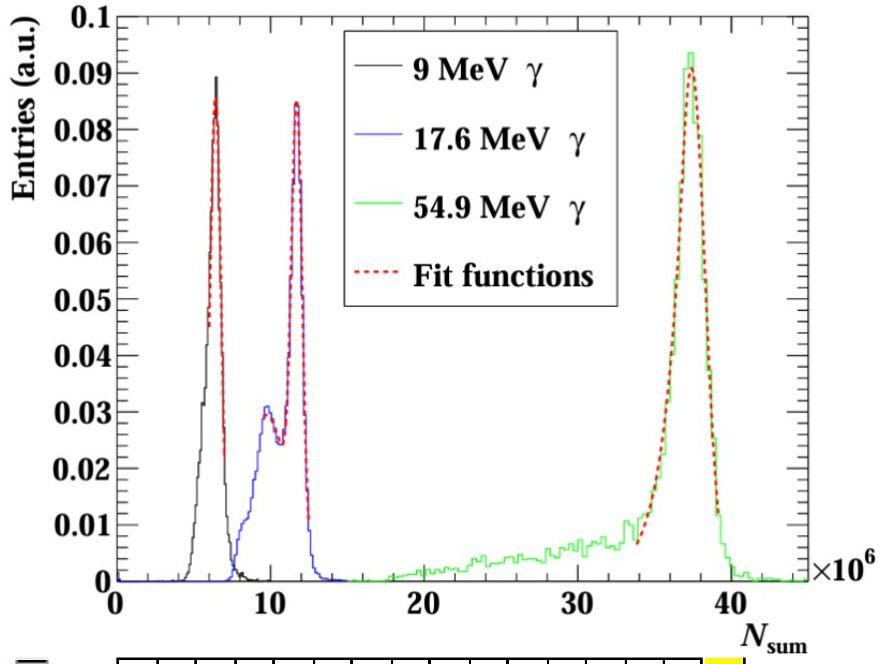
$$\pi^- p \rightarrow \pi^0 n$$
$$\pi^0 \rightarrow \gamma\gamma$$

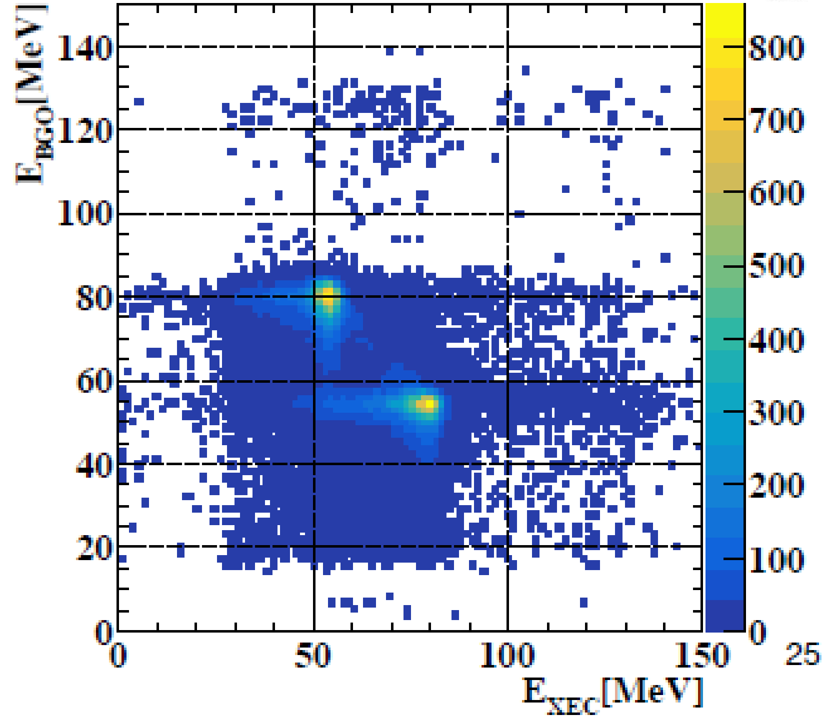
Movable array of BGO Crystals

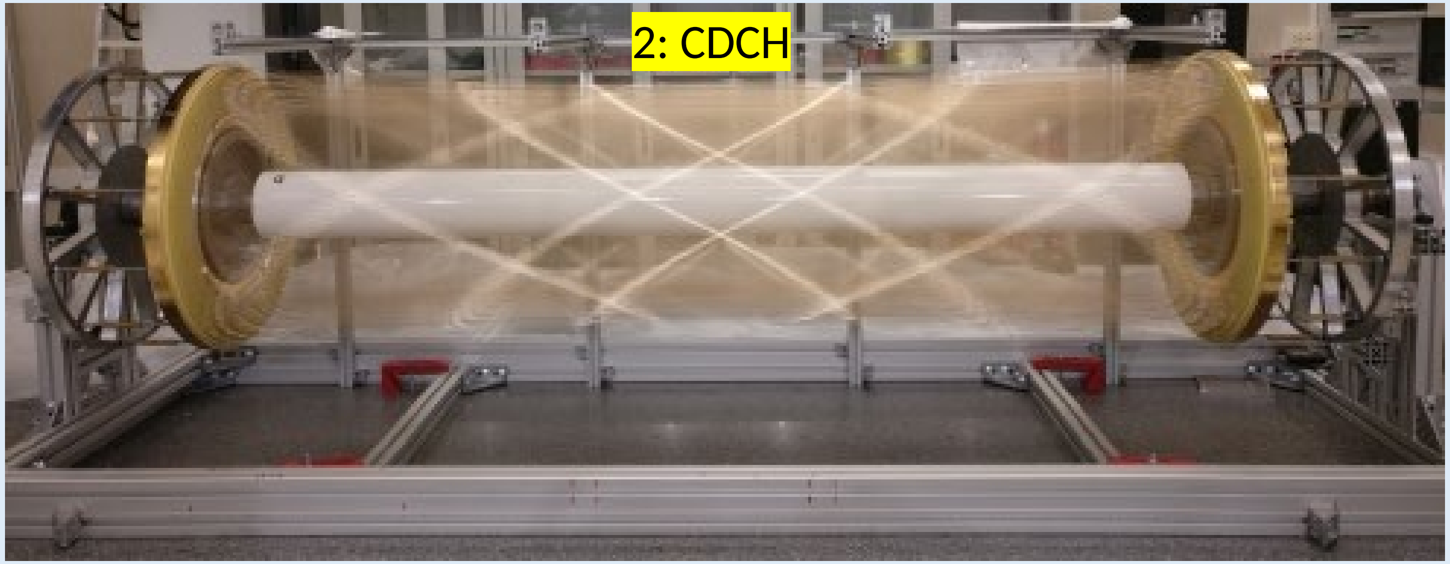
Energy in 55-83 MeV range

Once per year

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





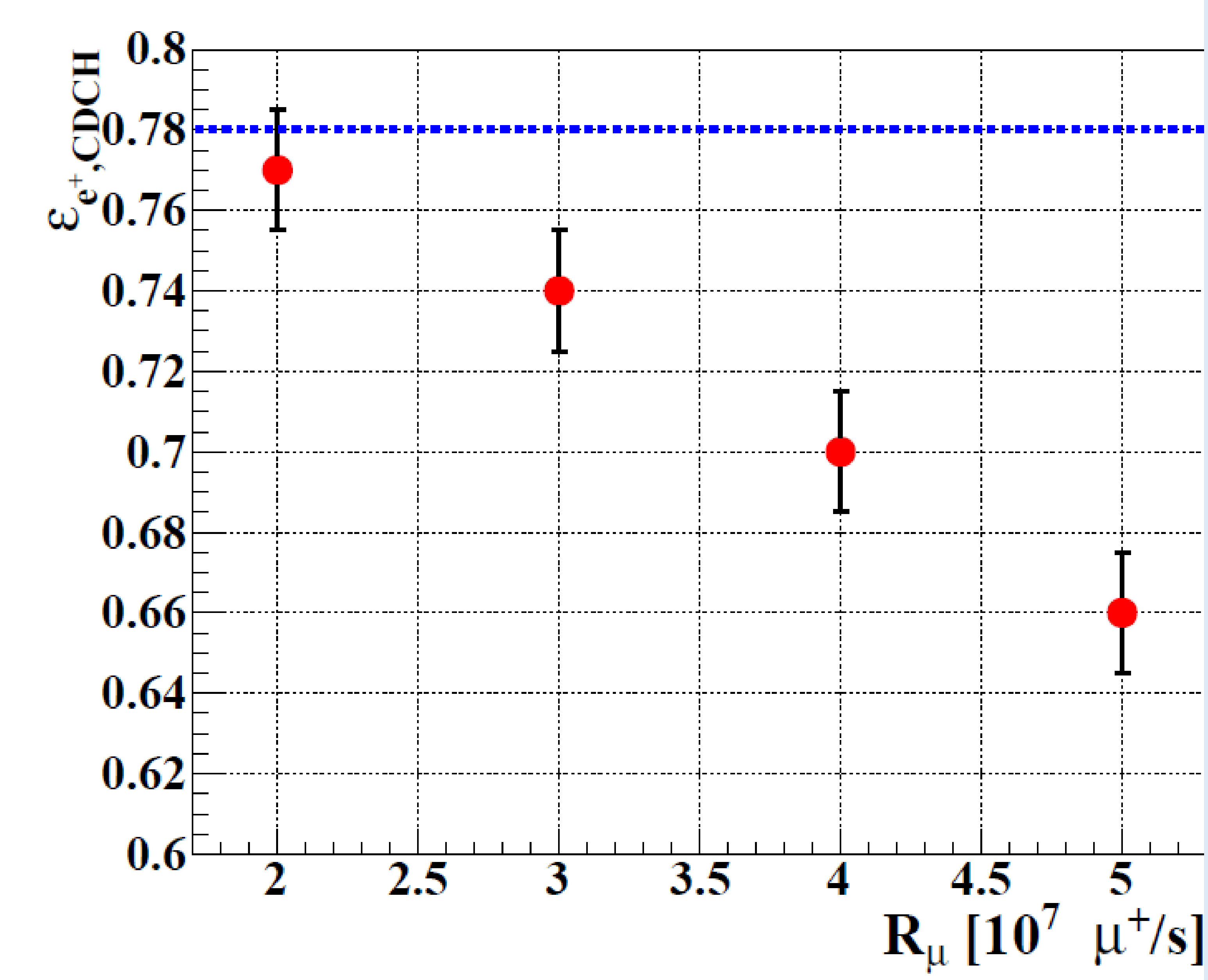


1.9 m x .5 m Φ

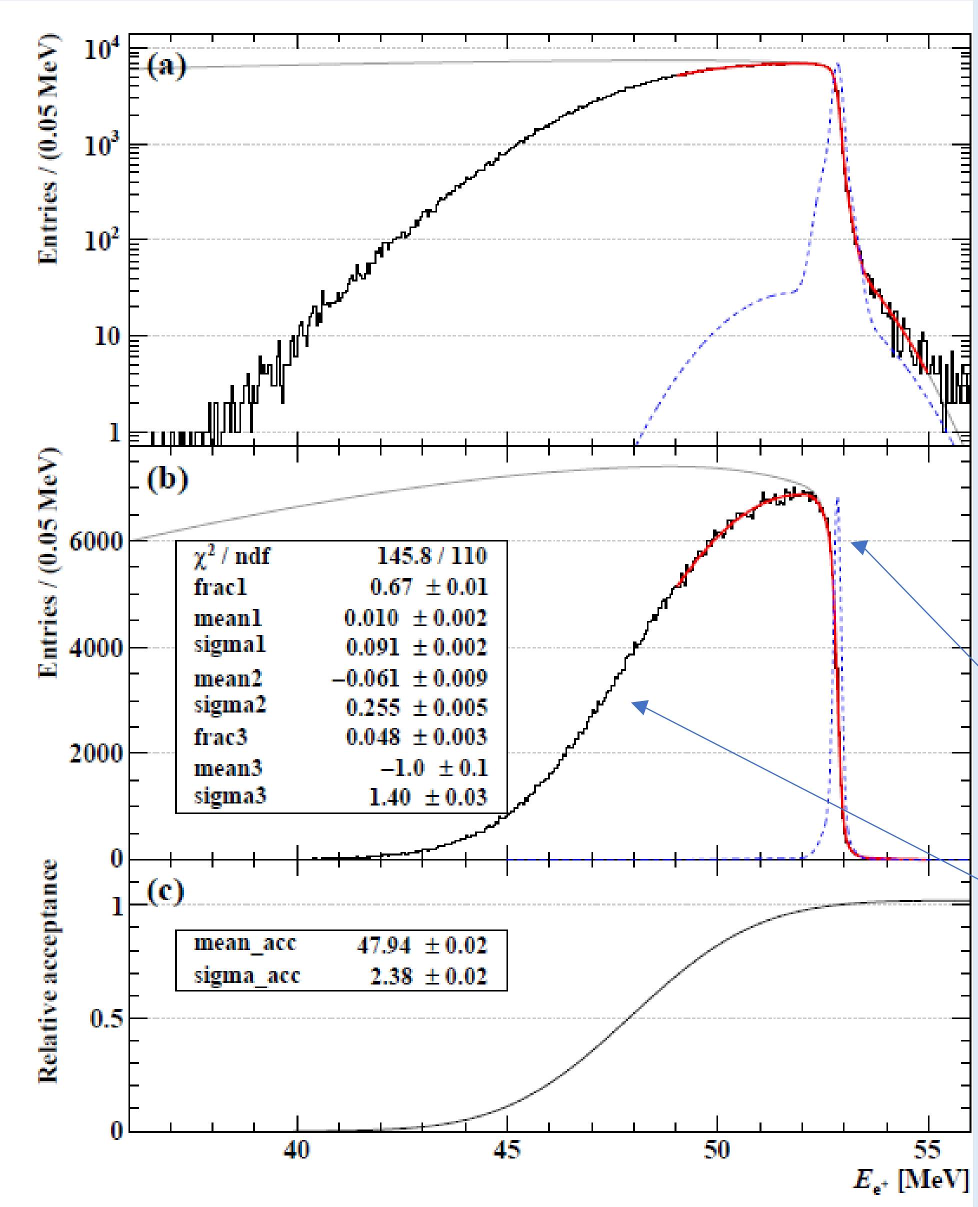
- u,v anodes **stereo** (7 degrees) configuration for improved position reconstruction along the beam axis (Z)
- Almost squared cells with **6 mm** sides: 9 layers
- Roughly 1700 anodes Au/Ti 20 µm and 1 0,000 Ag/Al 40/50 µm cathodes
- He-Isobuthane (90-10) low mass gas mixture **(+ addition of 1% isopropilic alcohol and ~0.5% oxygen)**
- 1.5x10^{-3} rad.length X_0 per track (instead of 2x10^{-3} X_0 of MEG)
- Working properly since late 2020

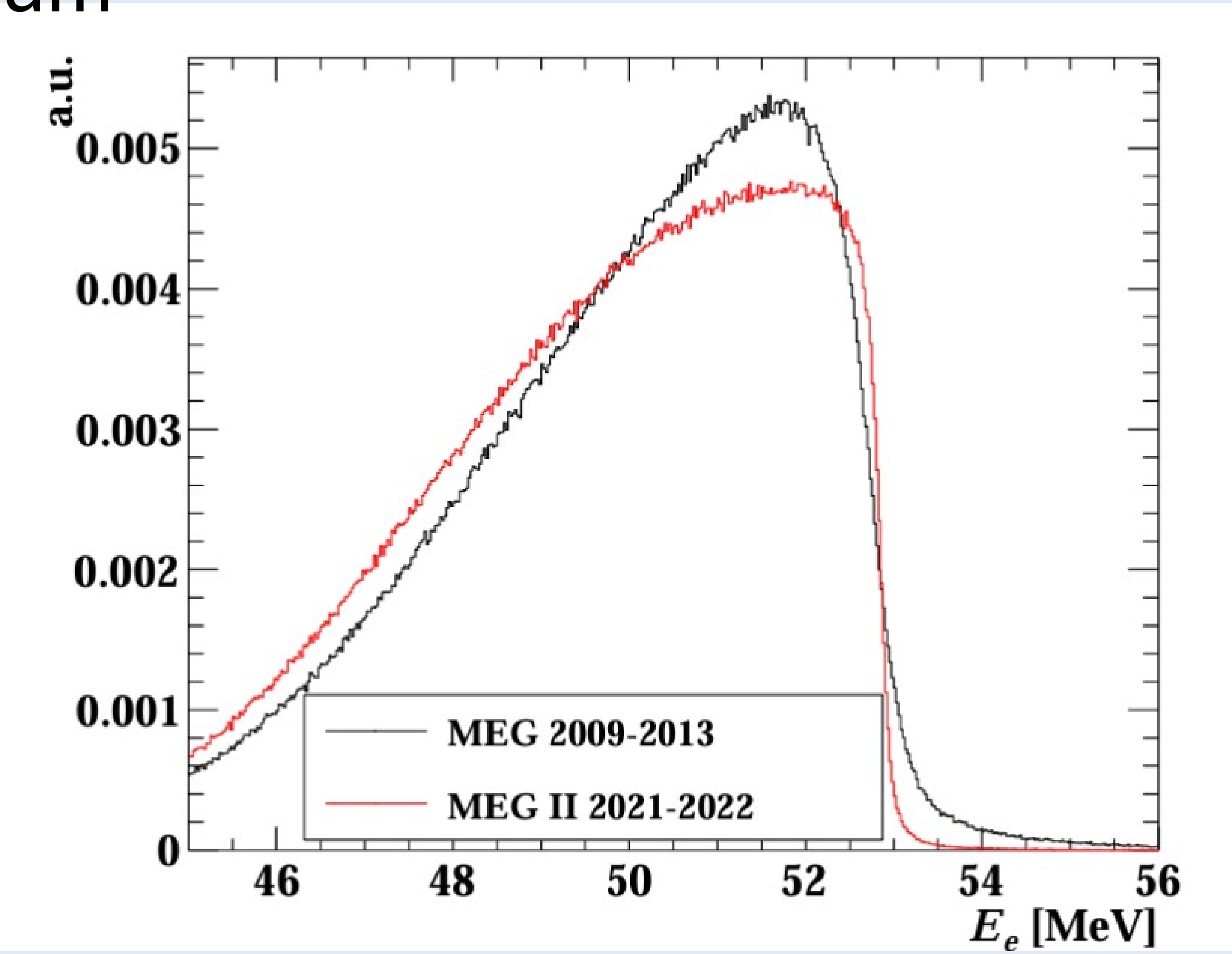
A backup chamber with different (bare Al5056) cathodes has been wired and will soon be delivered to PSI

The CDCH positron efficiency



The positron spectrum

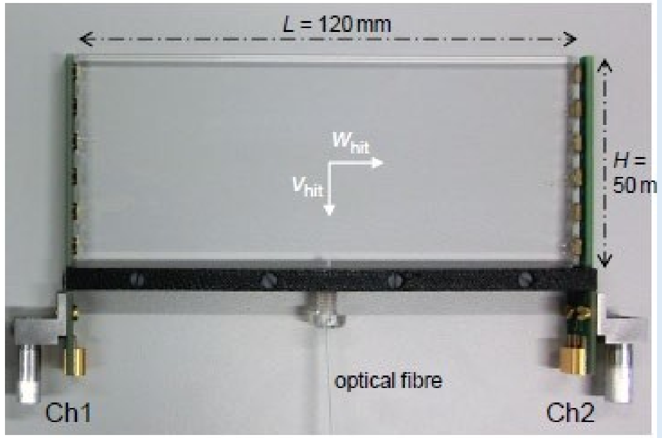




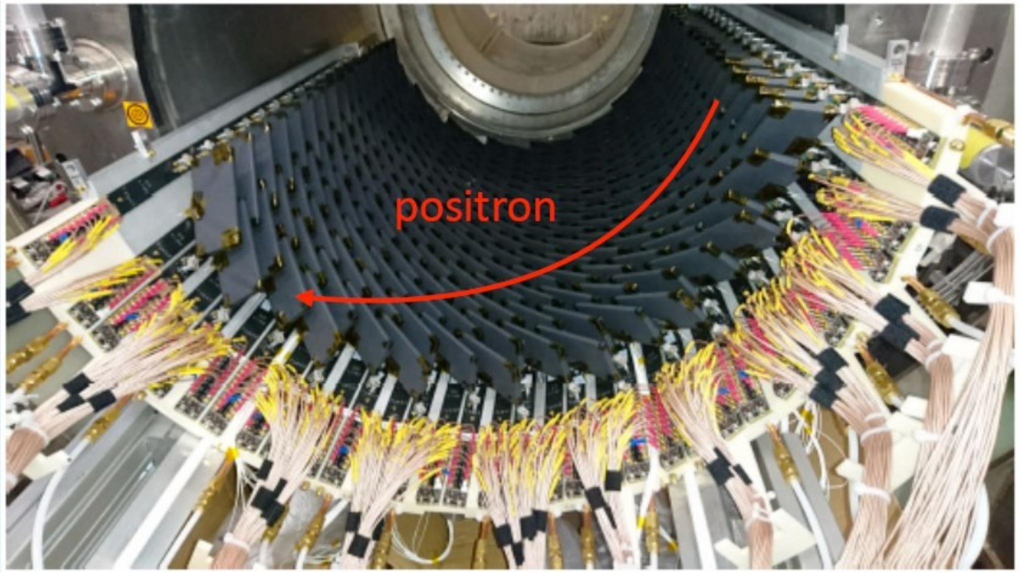
Very good (90 KeV) positron energy resolution from fit to the michel spectrum

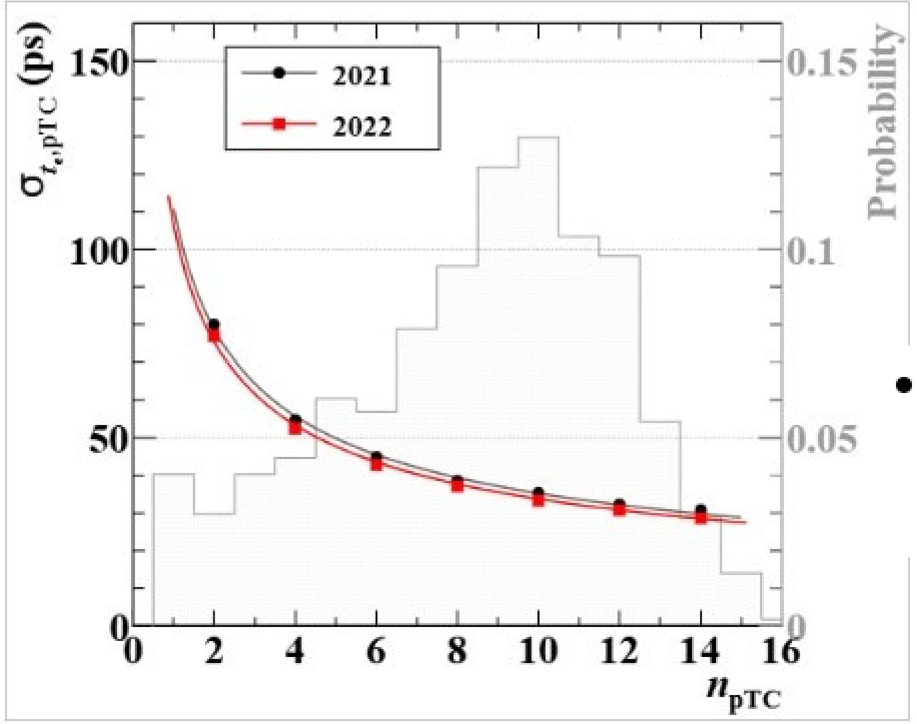
Theoretical spectrum ⊕ Acceptance ⊕ Resolution = Experimental

3: pixelated Timing Counter



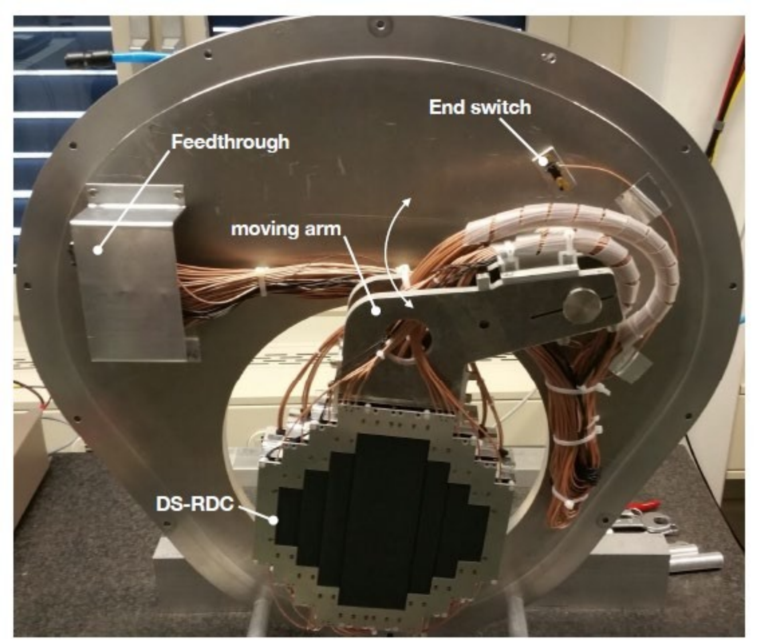
- Two sectors made of 256 scintillating BC422 tiles read by Advansid SiPMs
- Time obtained by averaging the tiles hit by a positron: 8 tiles on average for signal positrons
- A laser system is used for calibrations and monitoring

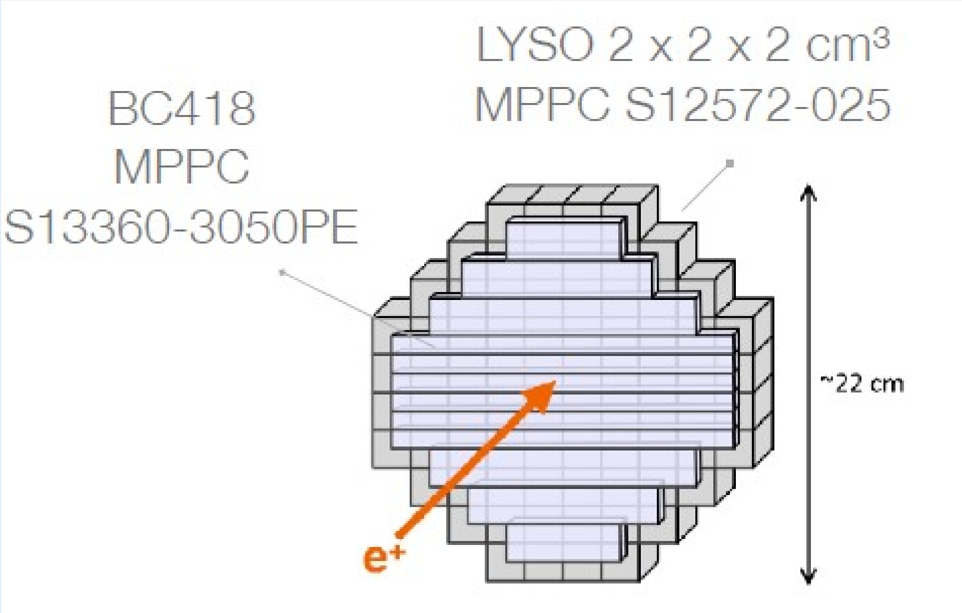




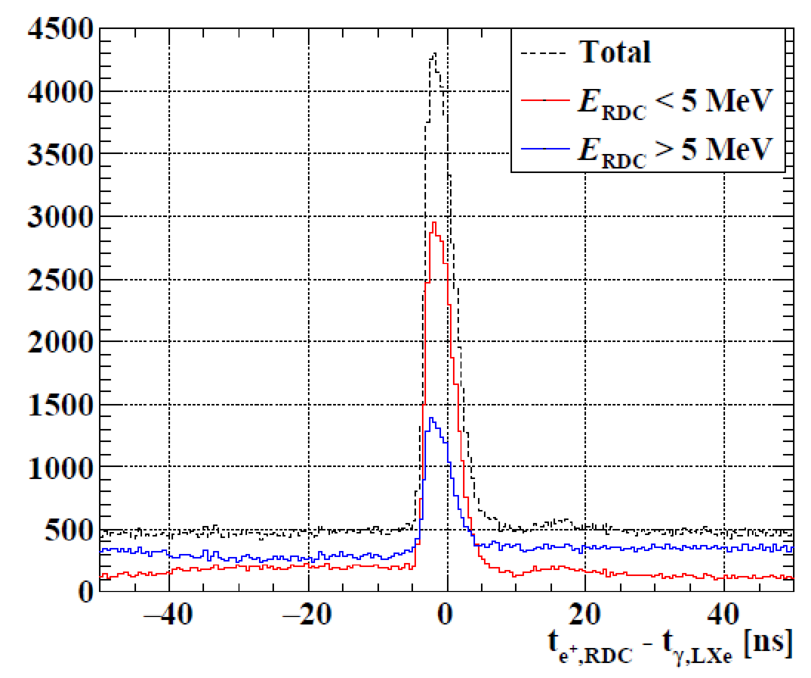
- Single-counter resolution
  - 2021: 112 ps
  - 2022: 106 ps

4: Radiative Decay Counter





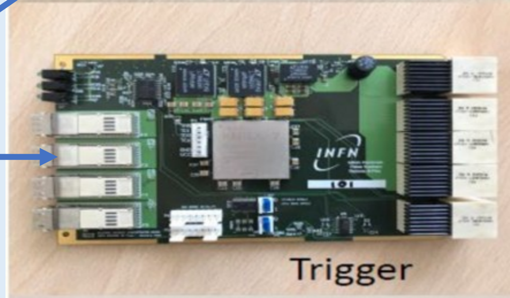
- Tag γ in LXe from RMD associated to a low energy positron
- Low e^+ positrons: plastic scintillator for timing and LYSO for energy measurement

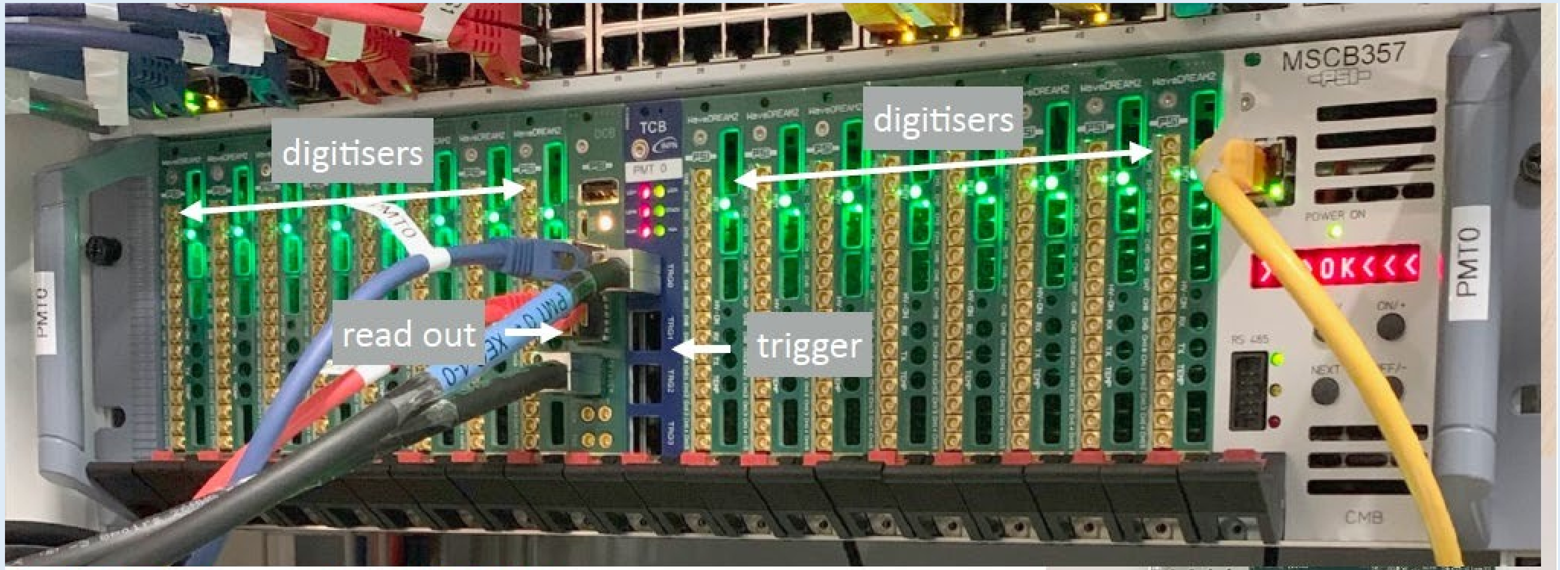


Most coincidences with LXe associated to low energy positrons

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)





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/ 7.2	8.4/9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.74/2.0	1.1/2.5
$E_\gamma(\%)$ (w<2 cm)/(w>2 cm)	1.7/1.7	2.4/1.9 (2.1/1.8)	2.4/1.8
$u_\gamma, v_\gamma, w_\gamma$, (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	62	63
ε_{e^+}	65	67	30
ε_{TRG}	≈99	91(88)	

(2021 in parenthesis)

Analysis Strategy

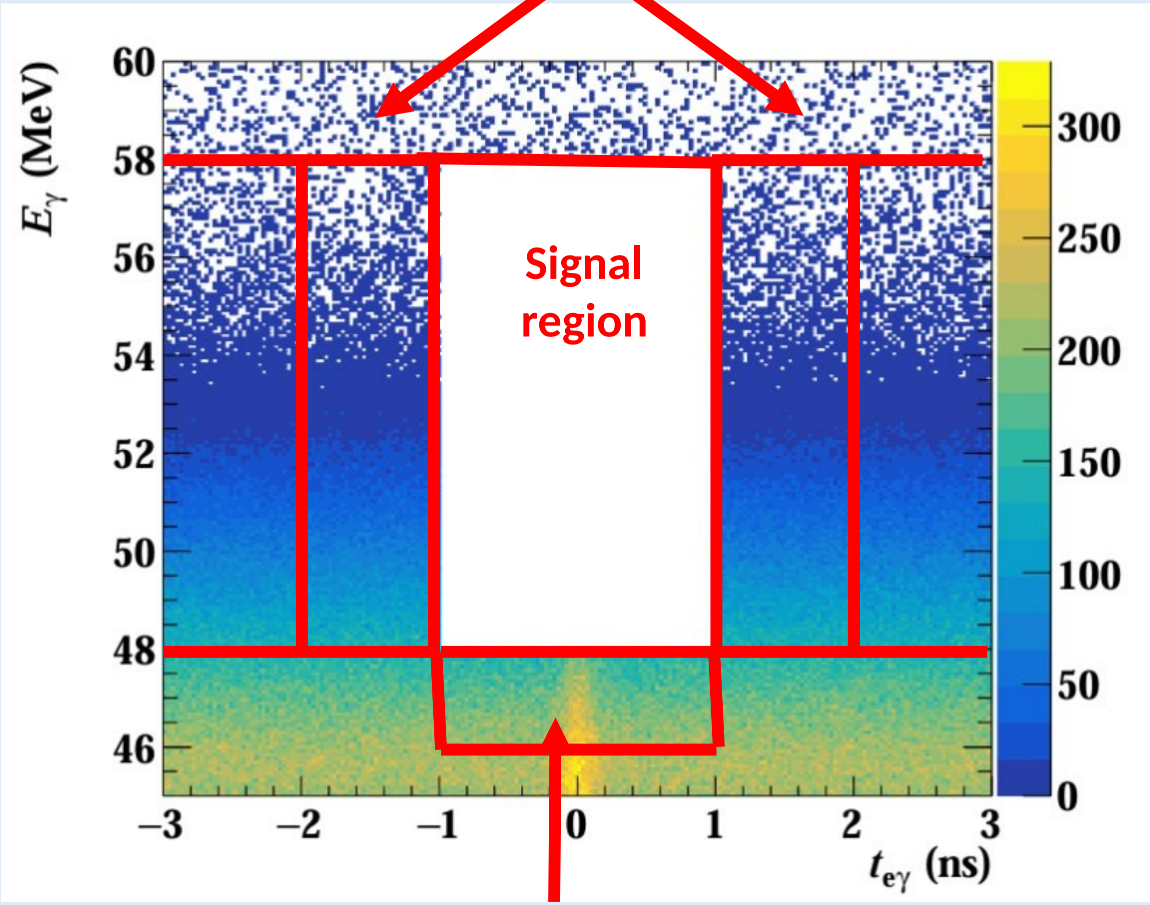
We blind events in the signal region and use the other events (**S**ide**B**ands), plus Simulation and Calibrations, to evaluate **P**robability **D**istribution **F**unctions to be used in a likelihood fit.

$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm ACC}, x_{\rm T}) = \frac{e^{-(N_{\rm sig}+N_{\rm RMD}+N_{\rm ACC})}}{N_{\rm obs}!} C(N_{\rm RMD}, N_{\rm ACC}, x_{\rm T}) \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S(\vec{x_i}) + N_{\rm RMD} R(\vec{x_i}) + N_{\rm ACC} A(\vec{x_i}) \right)$$

PDFs

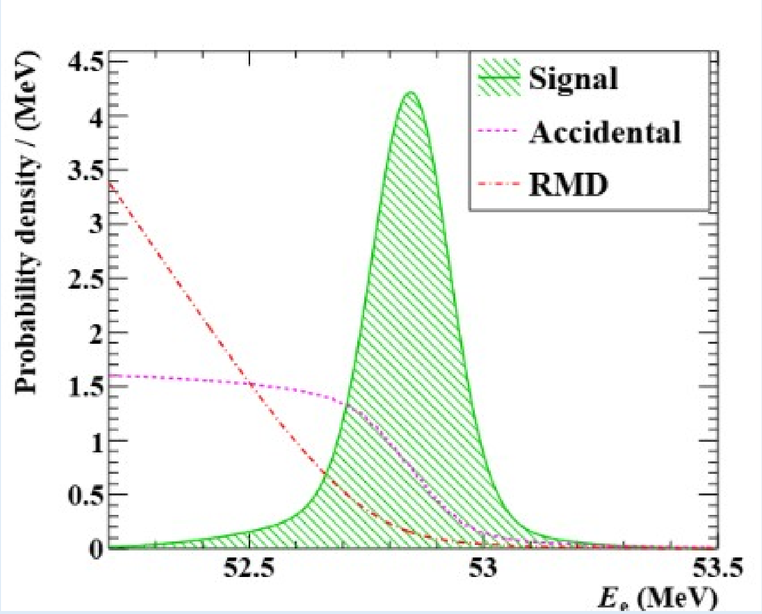
$$x_i = \{E_\gamma, E_{\rm e^+}, t_{\rm e^+\gamma}, \theta_{\rm e^+\gamma}, \phi_{\rm e^+\gamma}\}$$

Timing Sidebands



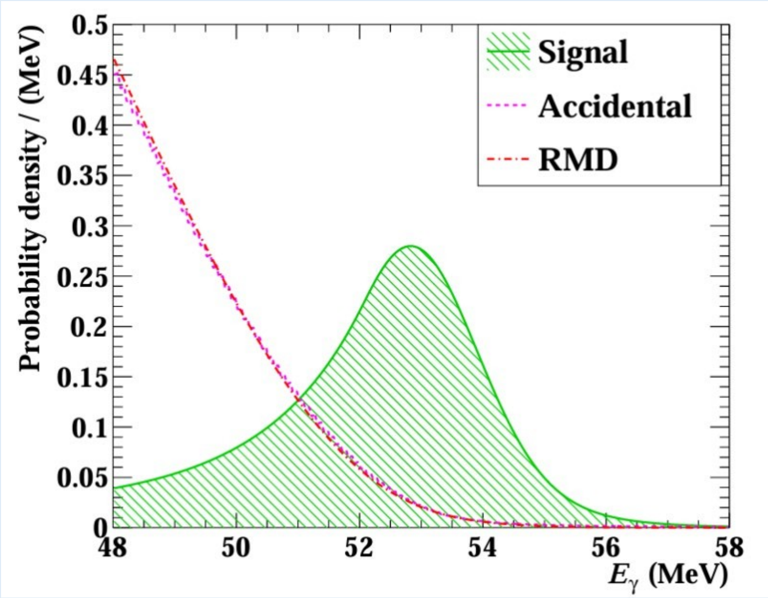
Energy Sideband

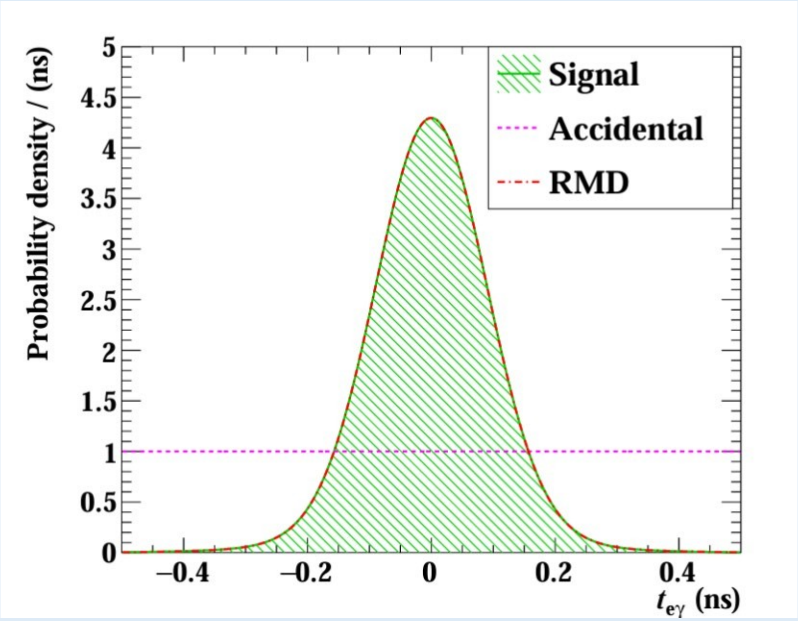
NRMD and NACC are in the signal region are constrained by the events measured in the sidebands

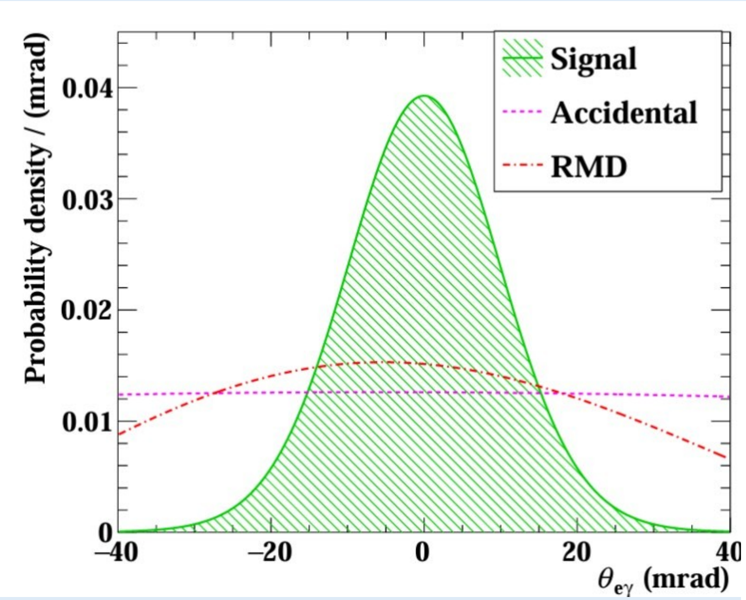


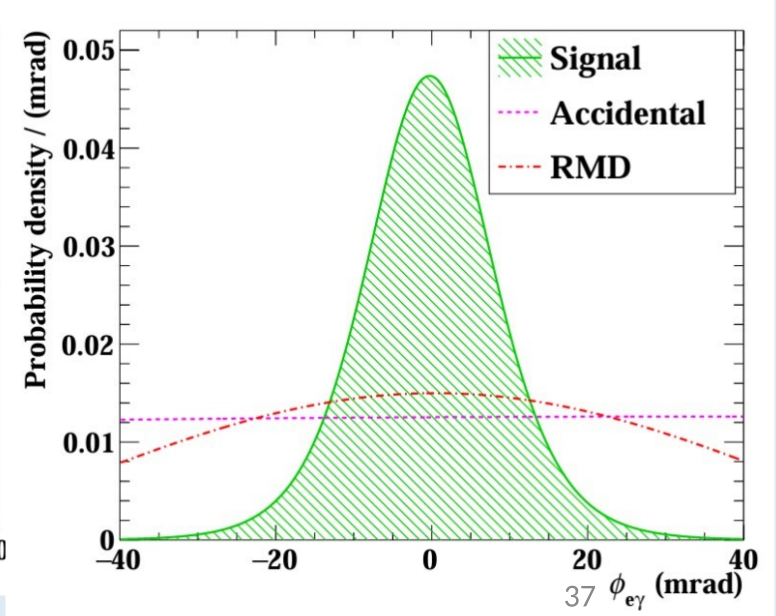
Probability **D**istribution **F**unctions

Calibrations, Sidebands, MC

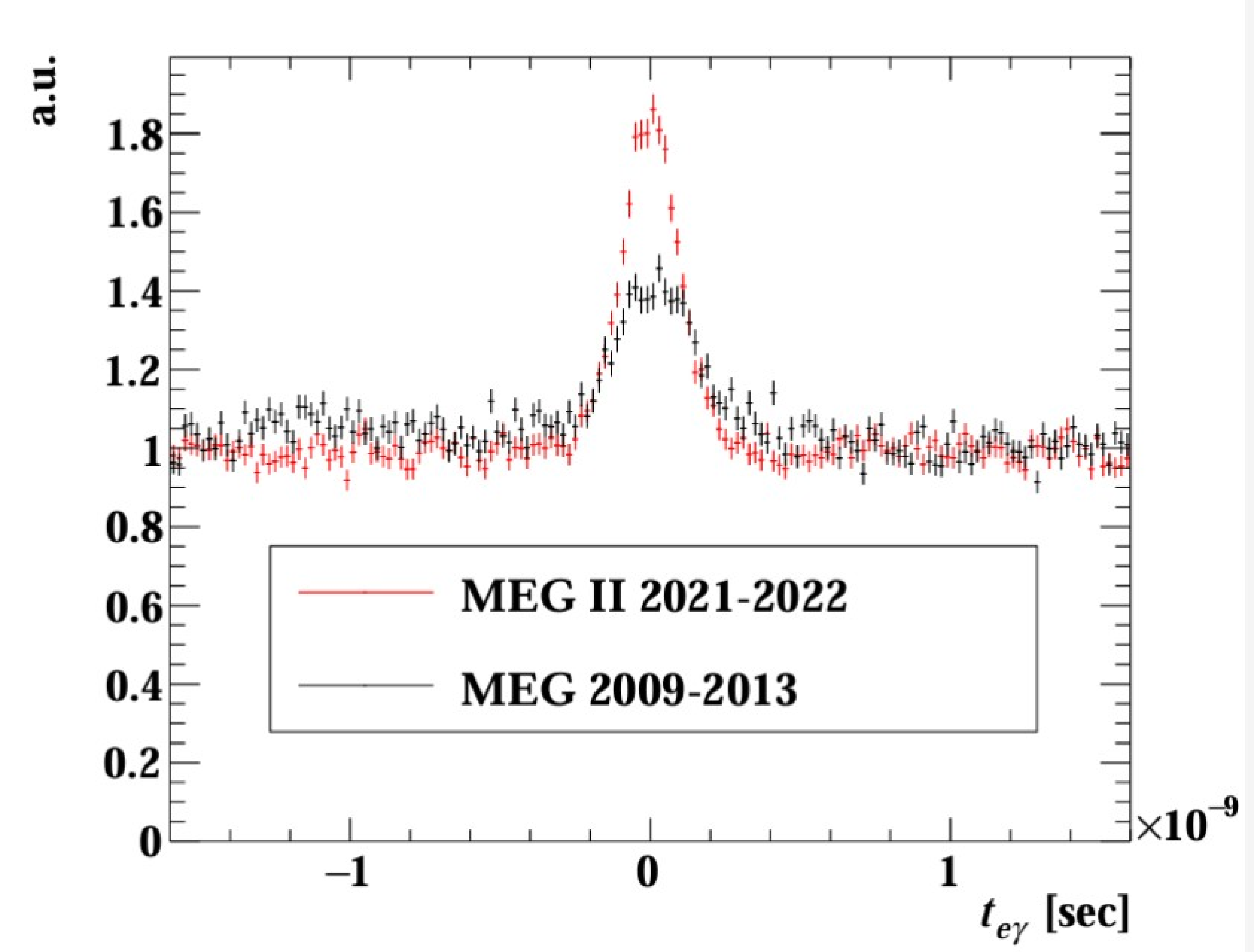




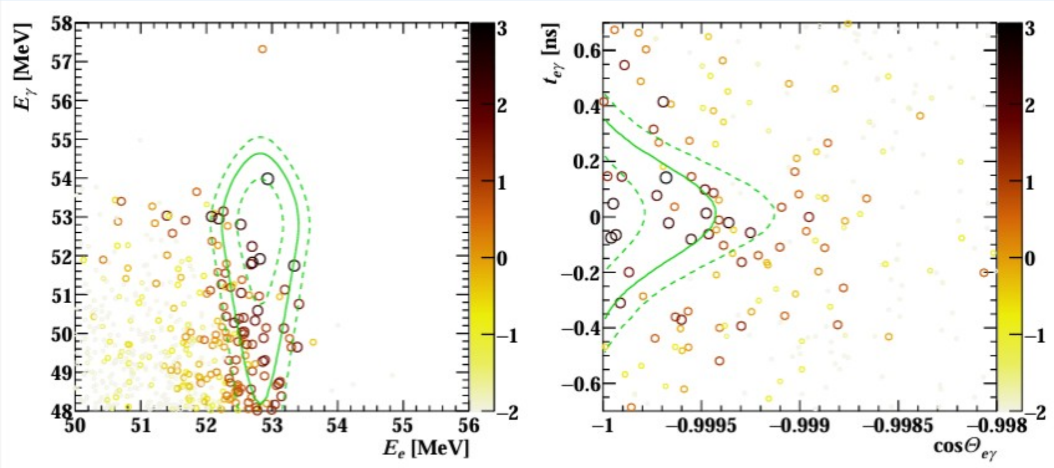




Radiative muon decays in MEG II data (Energy SideBand): a crucial check for a μ→eγ experiment – Same topology of possible signal events

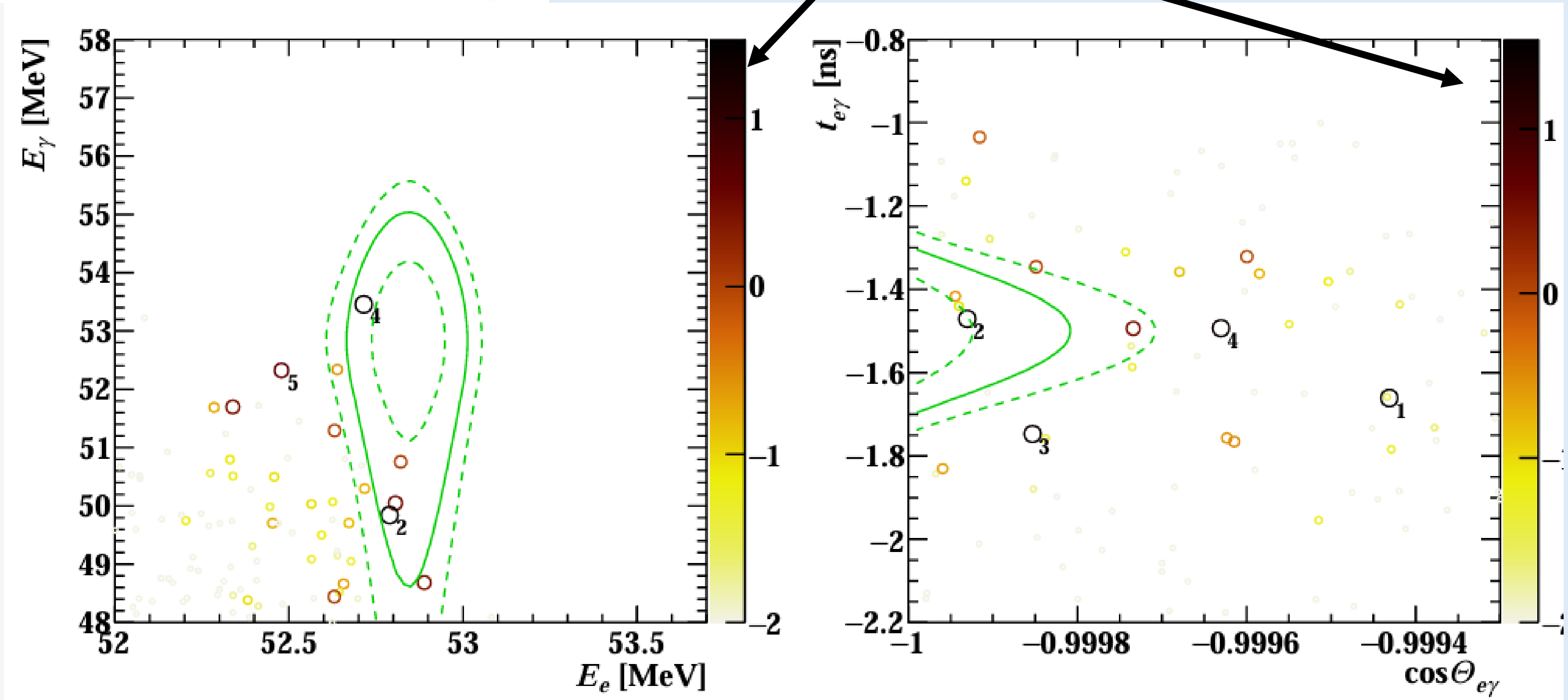


MEG final ($S_{90} = 5.3 \times 10^{-13}$)



2021 + 2022 data
One timing sideband
(-2 ns,-1 ns)

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

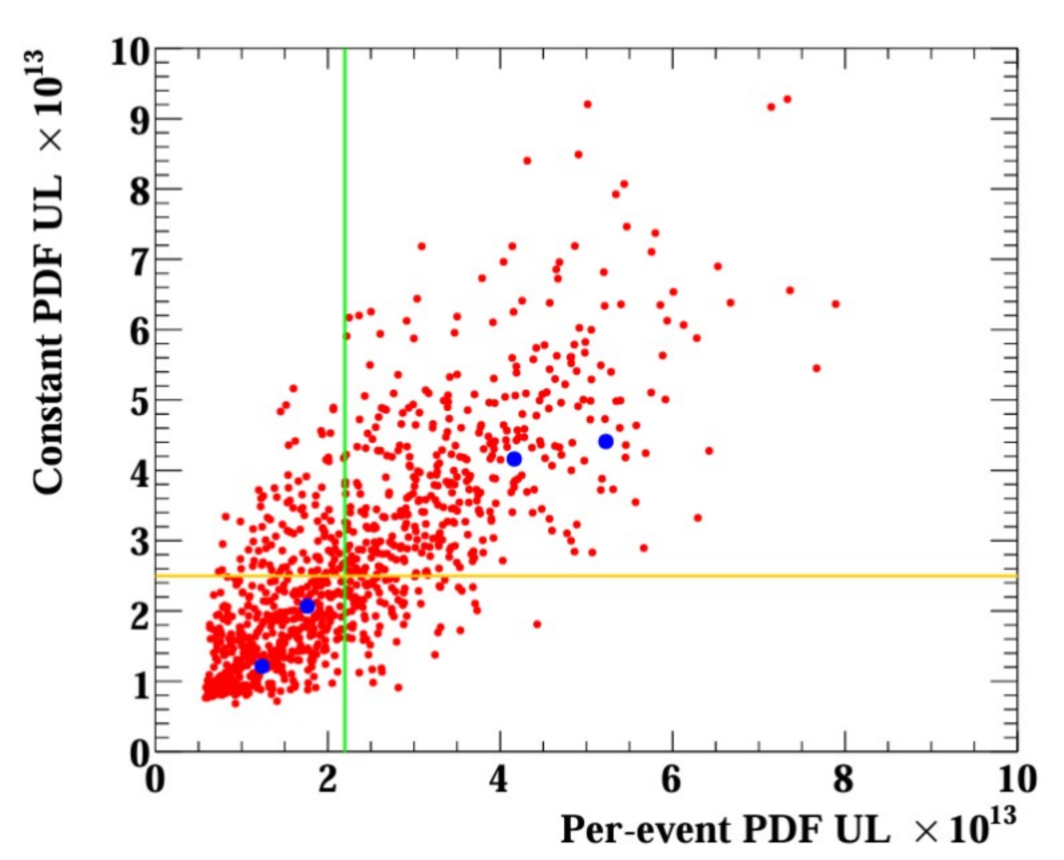


cosΘeγ < −0.9995 and |teγ-1.5| < 0.2 ns

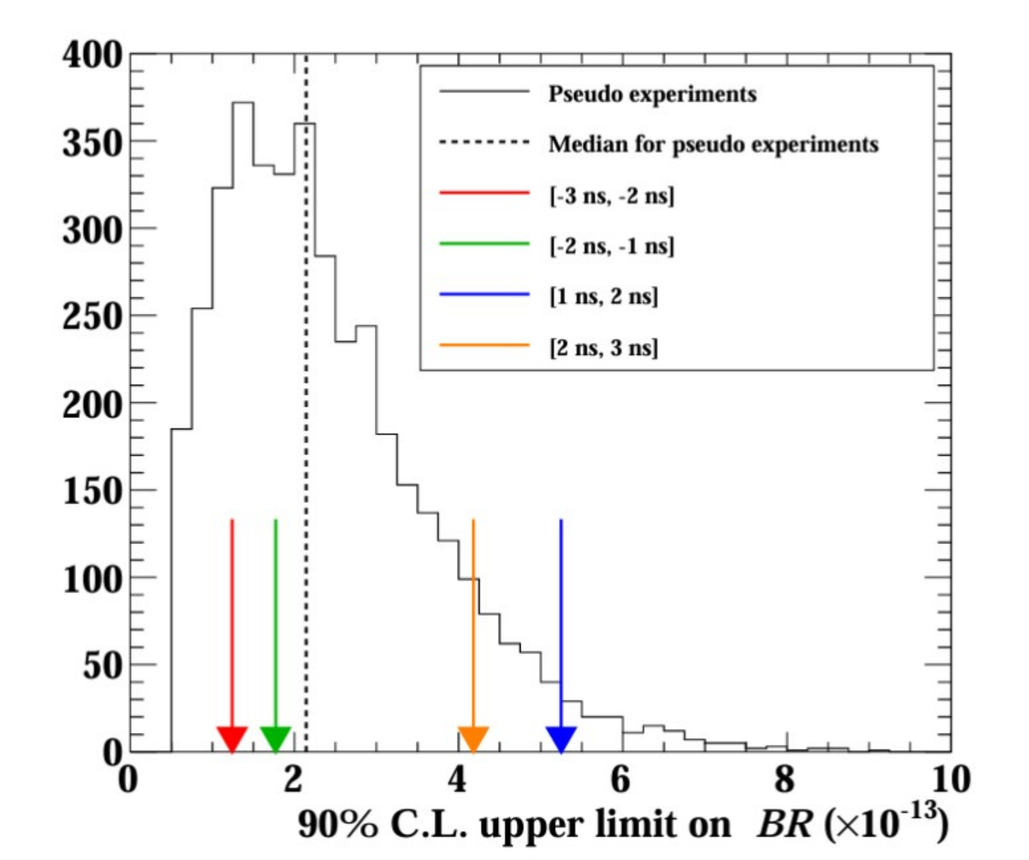
49.0 < Eγ < 55.0 MeV and 52.5 < Ee < 53.2 MeV

90% Confidence Levels computed according to the Feldman Cousins Prescriptions based on the Likelihood previously described

Two independent analyses:
constant and per event PDFs must match on **NULL toy MC (red dots)** and **side bands (blue dots)** before opening the blind box

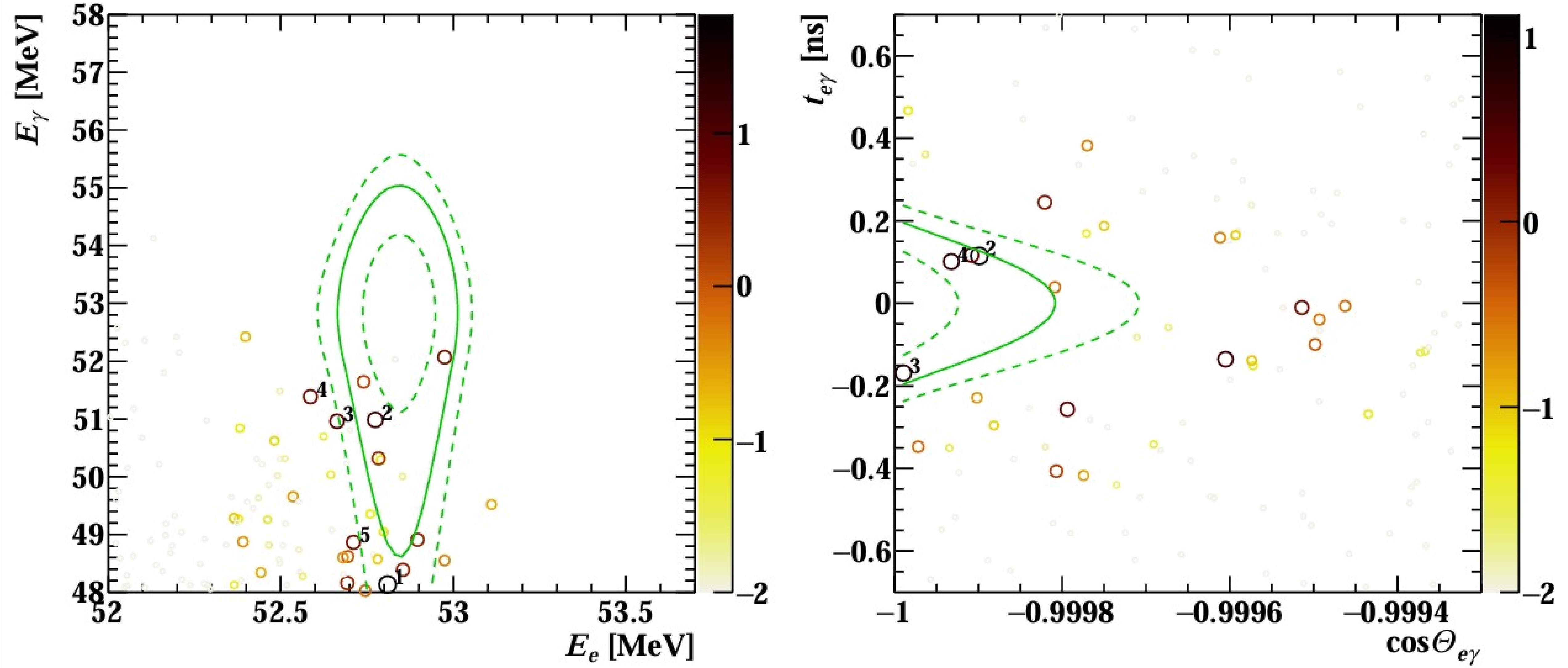


Projection on the per event (x)-axis



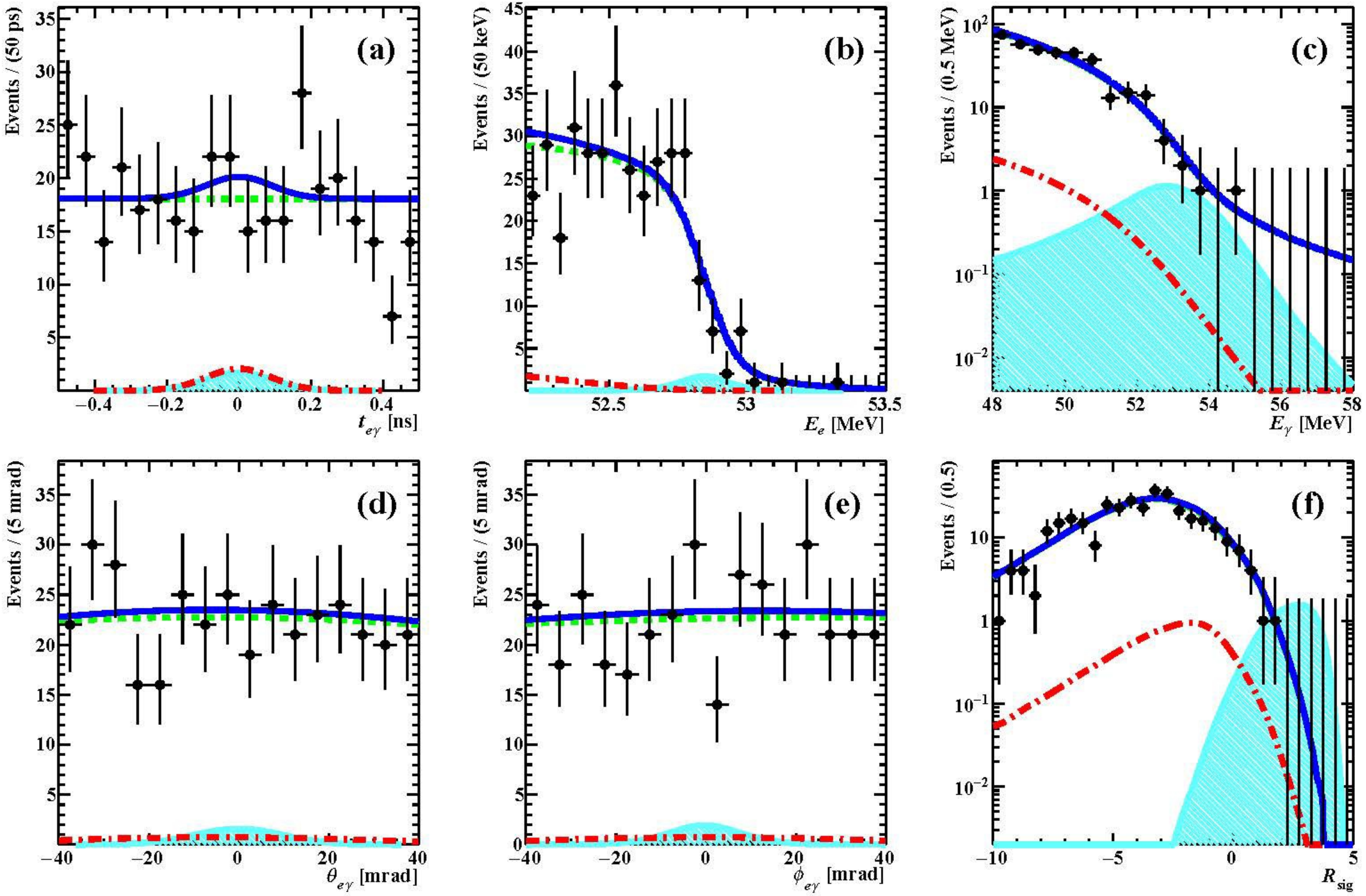
Sensitivity (S_{90}): median on the UL on the null toy experiments = 2.2x10^{-13}

Opening the Signal Region



$\cos\Theta_{e\gamma} < -0.9995$ and $|t_{e\gamma}| < 0.2$ ns

$49.0 < E_\gamma < 55.0$ MeV and $52.5 < E_e < 53.2$ MeV



Likelihood fit: Best Fit B_{fit} =-3.8 x 10^{-13}

MEG II Present result
2021 + 2022

Best Fit B_{fit} = -3.8 x 10^{-13}

Upper Limit (90% CL) B_{90} = 1.5 x 10^{-13}

arXiv:2504.15711 [hep-ex]

Previous Result
Combined MEG II 2021 & MEG

B_{90}= 3.1 x 10^{-13}

Eur.Phys.J.C 84 (2024) 3, 216

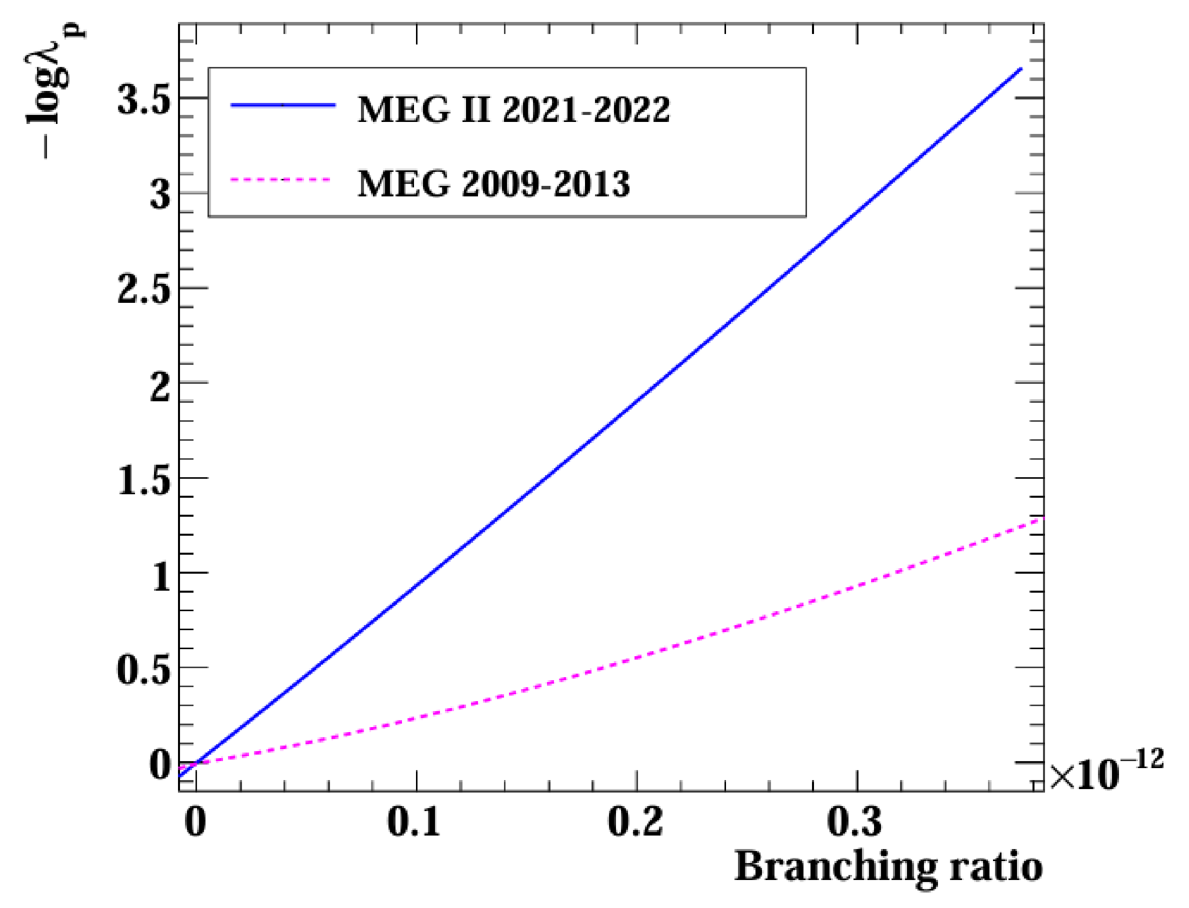
arXiv:2310.12614 [hep-ex]

MEG final

Eur.Phys.J.C 76 (2016) 8, 434

arXiv:1605.05081 [hep-ex]

B_{90}= 4.2 x 10^{-13}



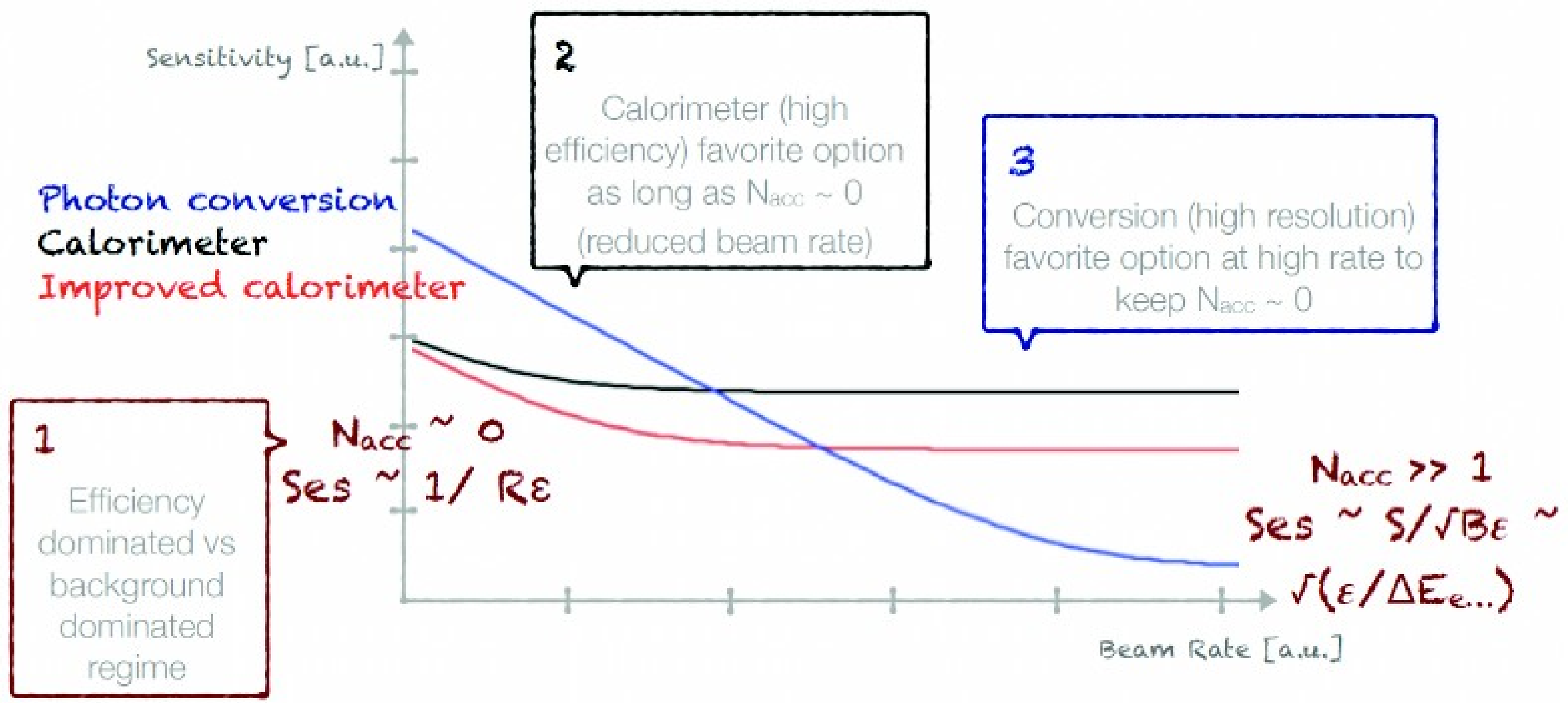
High Intensity Muon Beam

An upgrade of the PSI muon beamlines is foreseen during the 2027-2028 long shutdown to bring muon intensity up to 10^{10} μ^+/s in the new experimental areas
—> can we exploit it?

MEGII runs at R_μ=4-5x10^7 μ^+/s and the intensity R_μ=2x10^8 μ^+/s is available.

$$B_{acc} \propto R_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta \Theta_{e\gamma})^2 \cdot (\delta \Theta_\gamma)^2 \quad (2)$$

To exploit high R_μ high positron tracking efficiency must be retained.
High Eγ is required as well as high angular resolution (small MS)


Sensitivity [a.u.]
Photon conversion
Calorimeter
Improved calorimeter
2
Calorimeter (high efficiency) favorite option as long as Nacc ~ 0 (reduced beam rate)
3
Conversion (high resolution) favorite option at high rate to keep Nacc ~ 0
1
Efficiency dominated vs background dominated regime
Nacc ~ 0
Ses ~ 1/ Rε
Nacc >> 1
Ses ~ S/√Bε ~ √(ε/ΔEe...)
Beam Rate [a.u.]

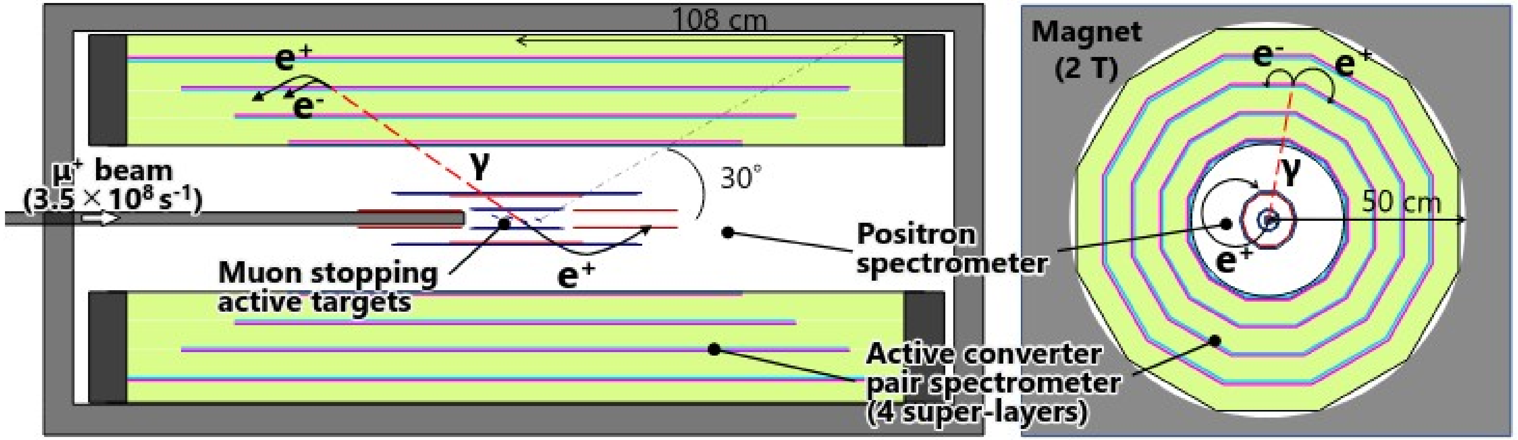


Figure 16: Possible layout of $\mu \to e\gamma$ experiment with photon conversion spectrometer.

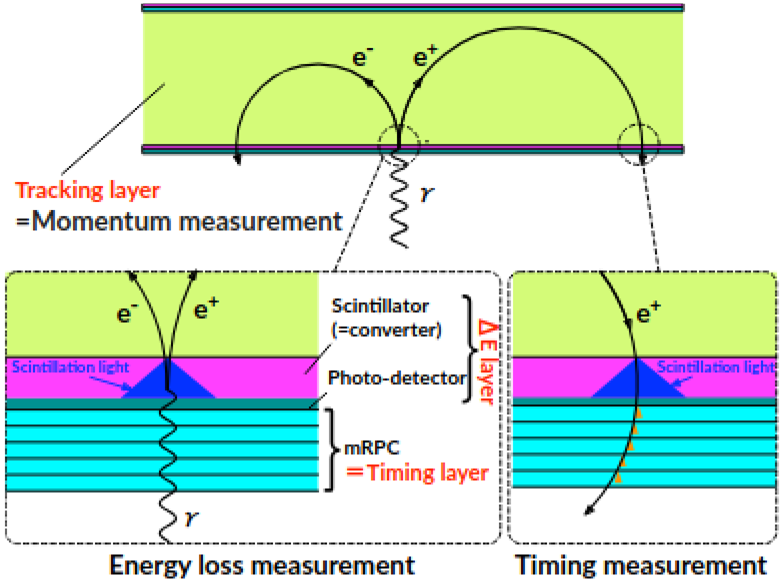
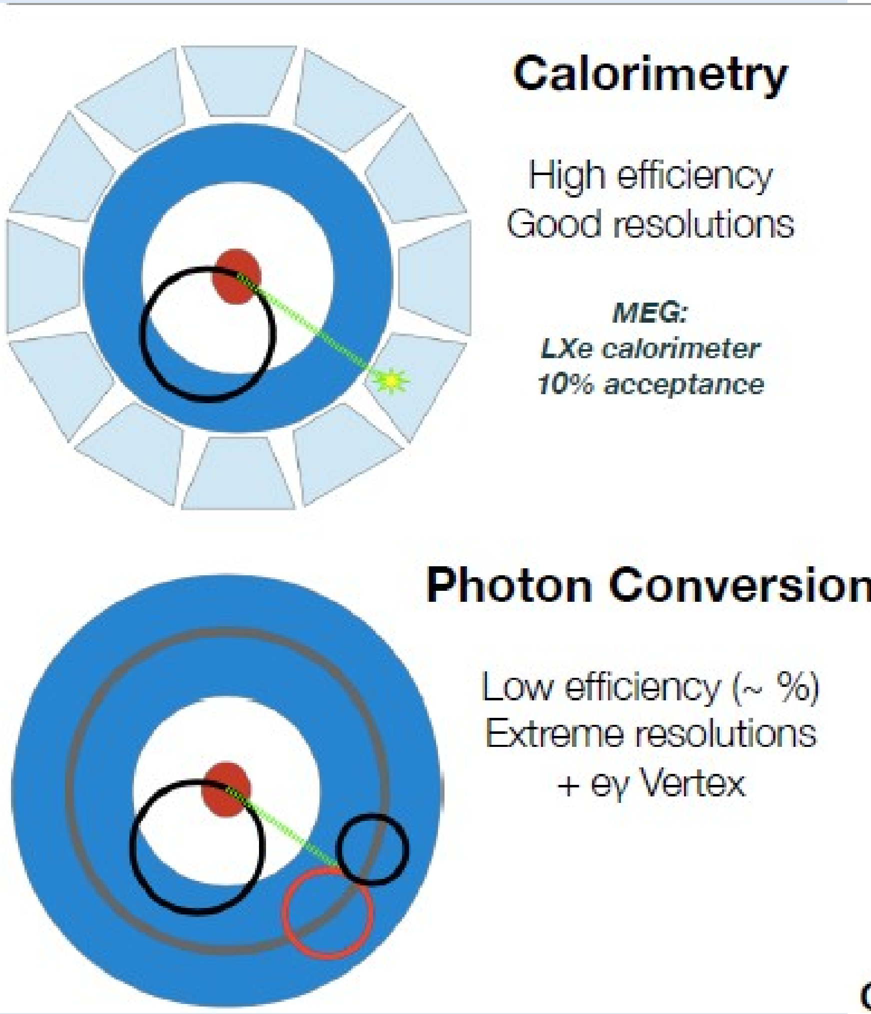
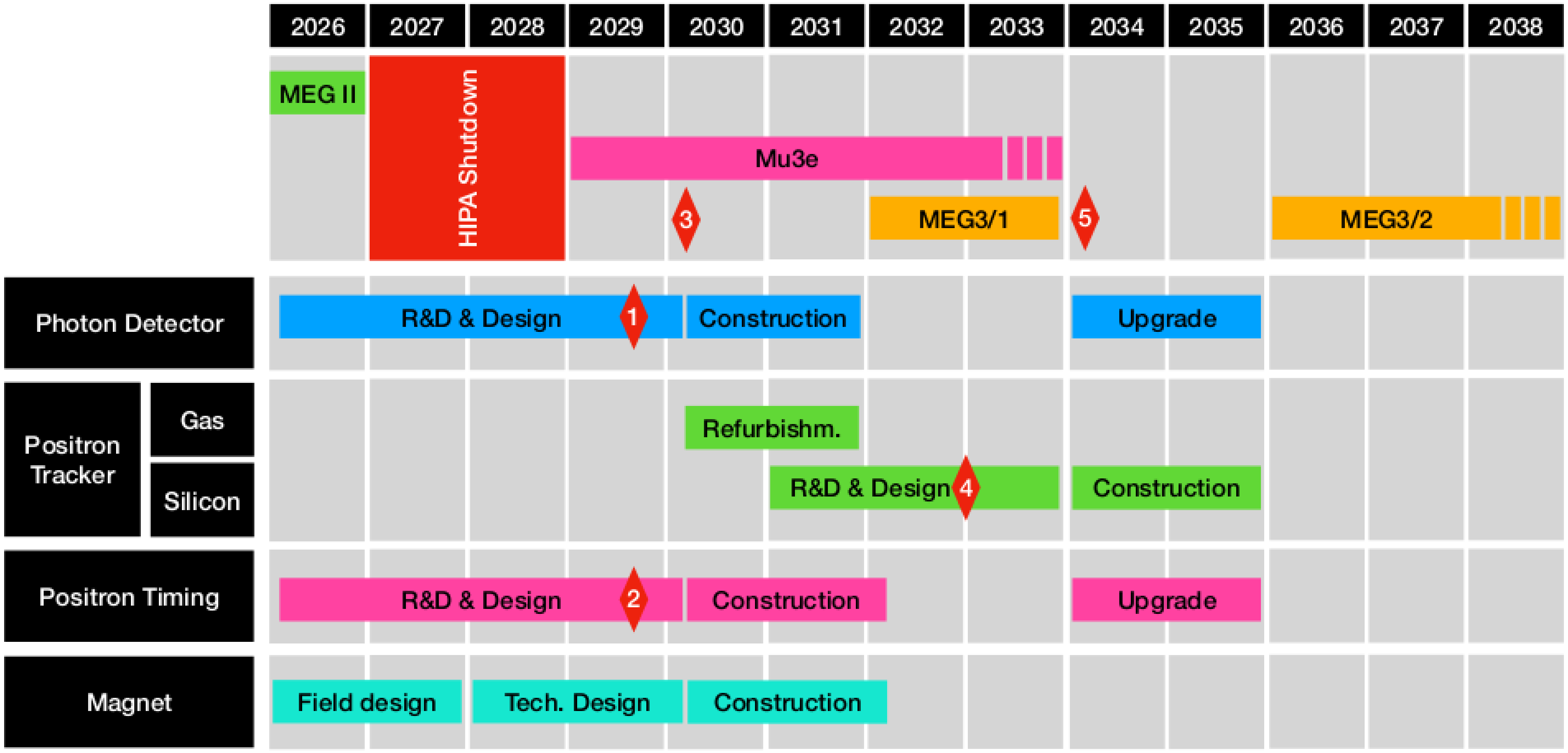


Figure 15: Possible structure of the active conversion spectrometer.





♦1: Photon converter proof of principle (CEX with converter + tracker in the MEG COBRA magnet)

♦2: Decision about positron timing technology

♦3: phase-I approval by PSI and funding agencies

♦4: Decision about positron tracker technology for phase-II

♦5: phase-II approval by PSI and funding agencies

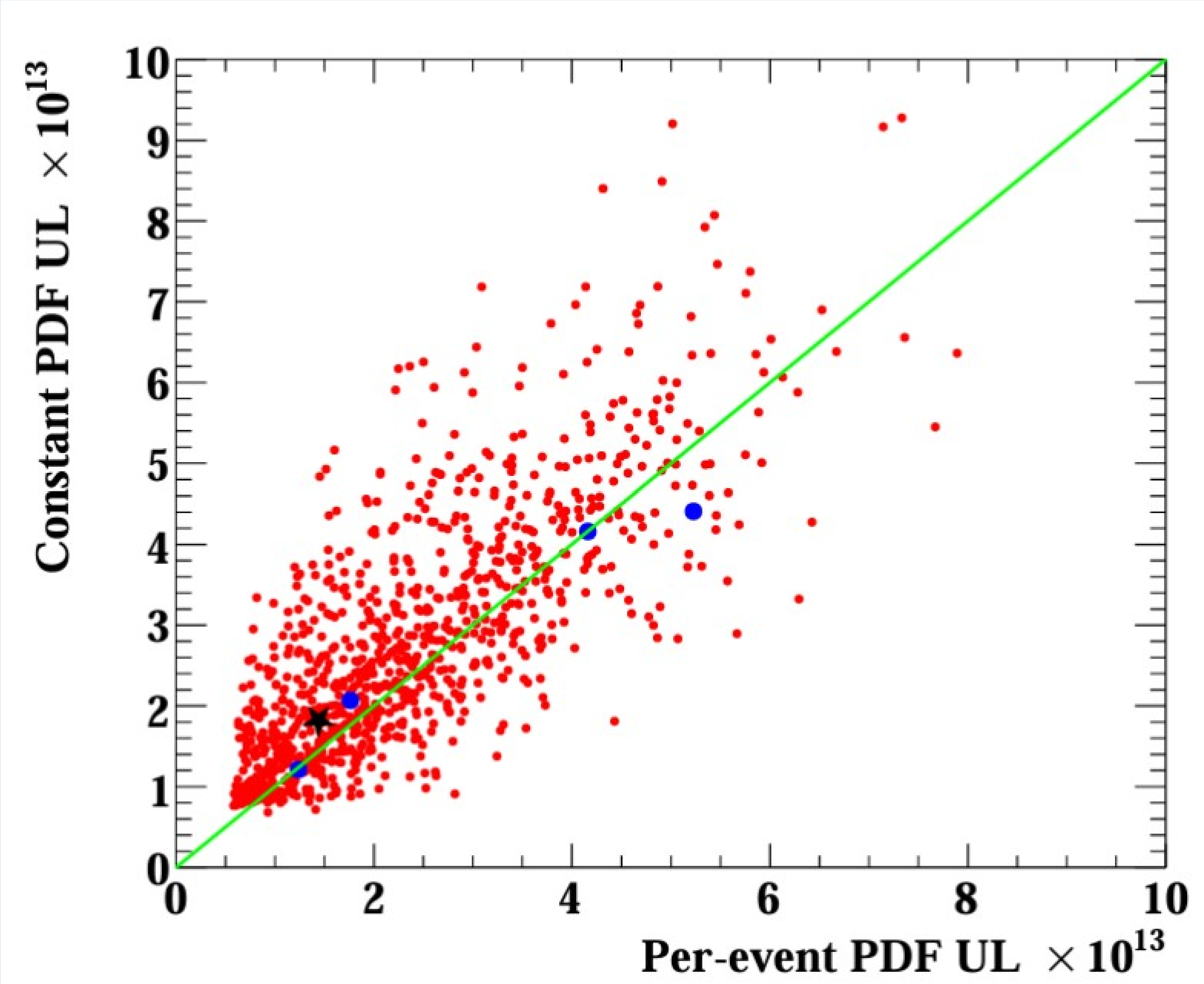
Summary

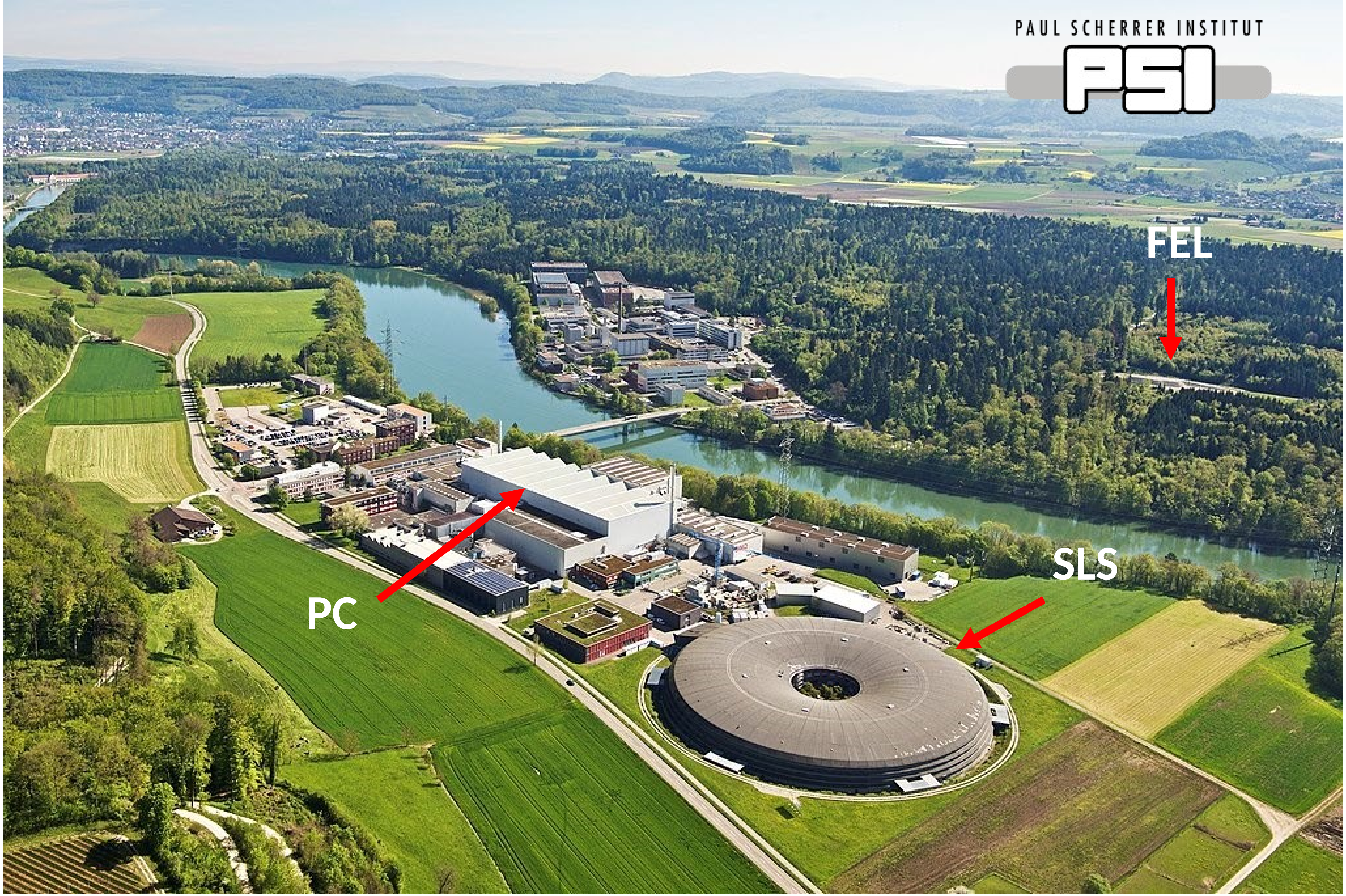
- MEG II has been taking data since 2021 and aims at improving the sensitivity to μ→eγ by an order of magnitude in the B.R. wrt MEG
- Result from 2021+2022 : **B_{90}=1.5 x10^{-13}**
- Possibly improve analysis algorithms & maybe increase beam rate to maximize sensitivity
- Data taking will continue until 2026 to reach the final goal
- Design of a future μ→eγ experiment for the HIMB project at PSI ongoing

- Thank you very much for your attention

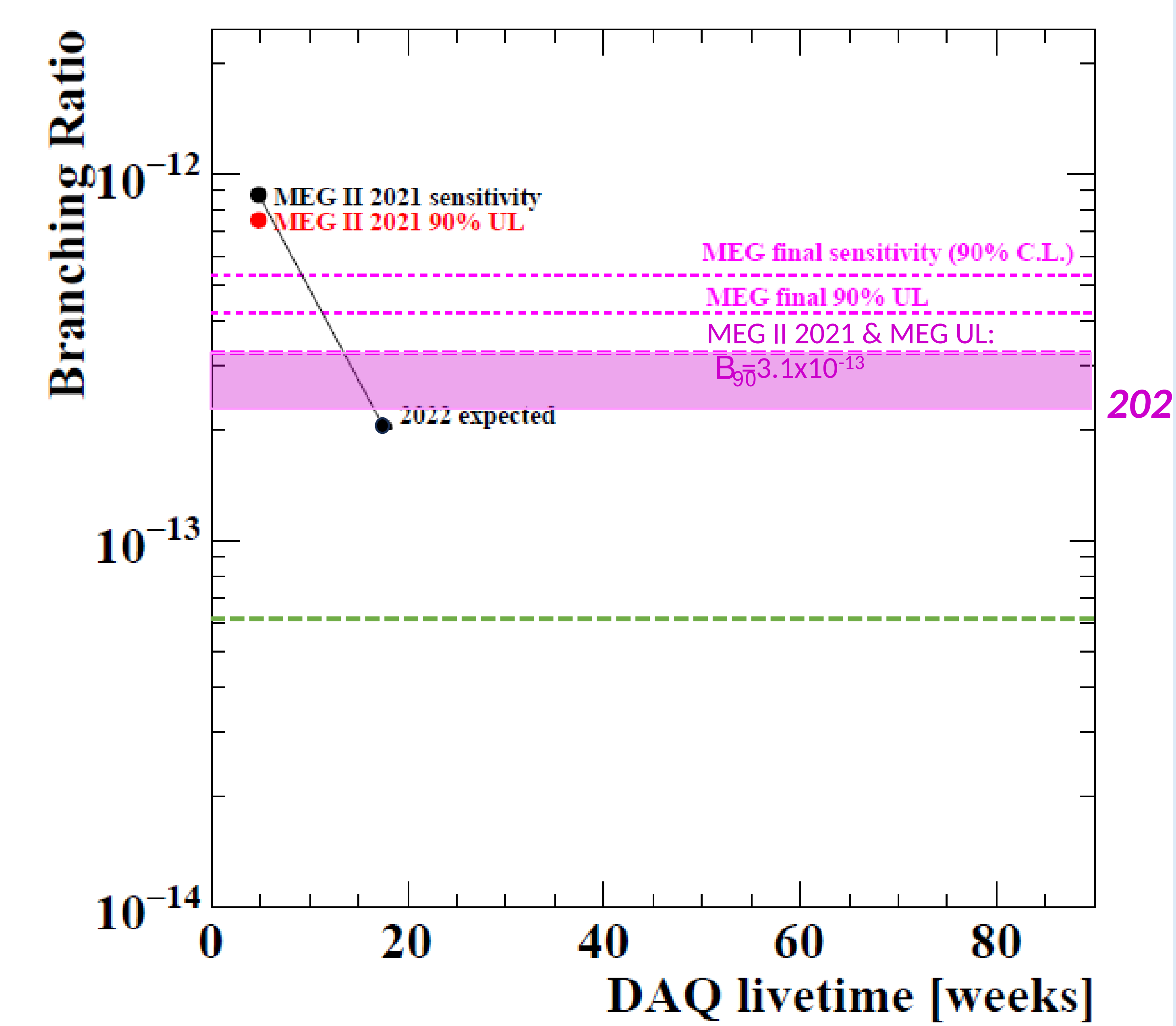
Backup

A posteriori check




PAUL SCHERRER INSTITUT
PSI
FEL
SLS
PC

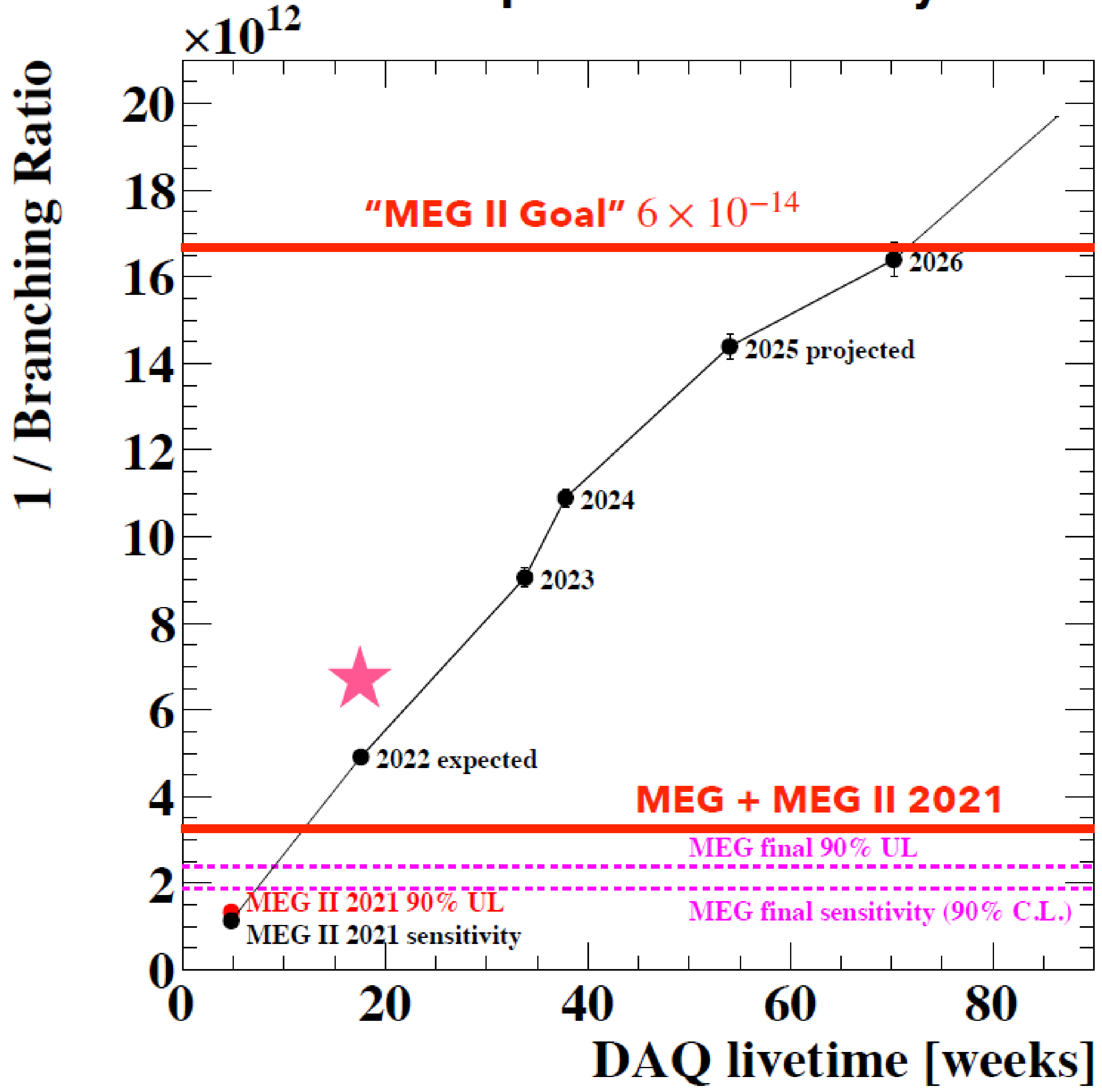
Sensitivity



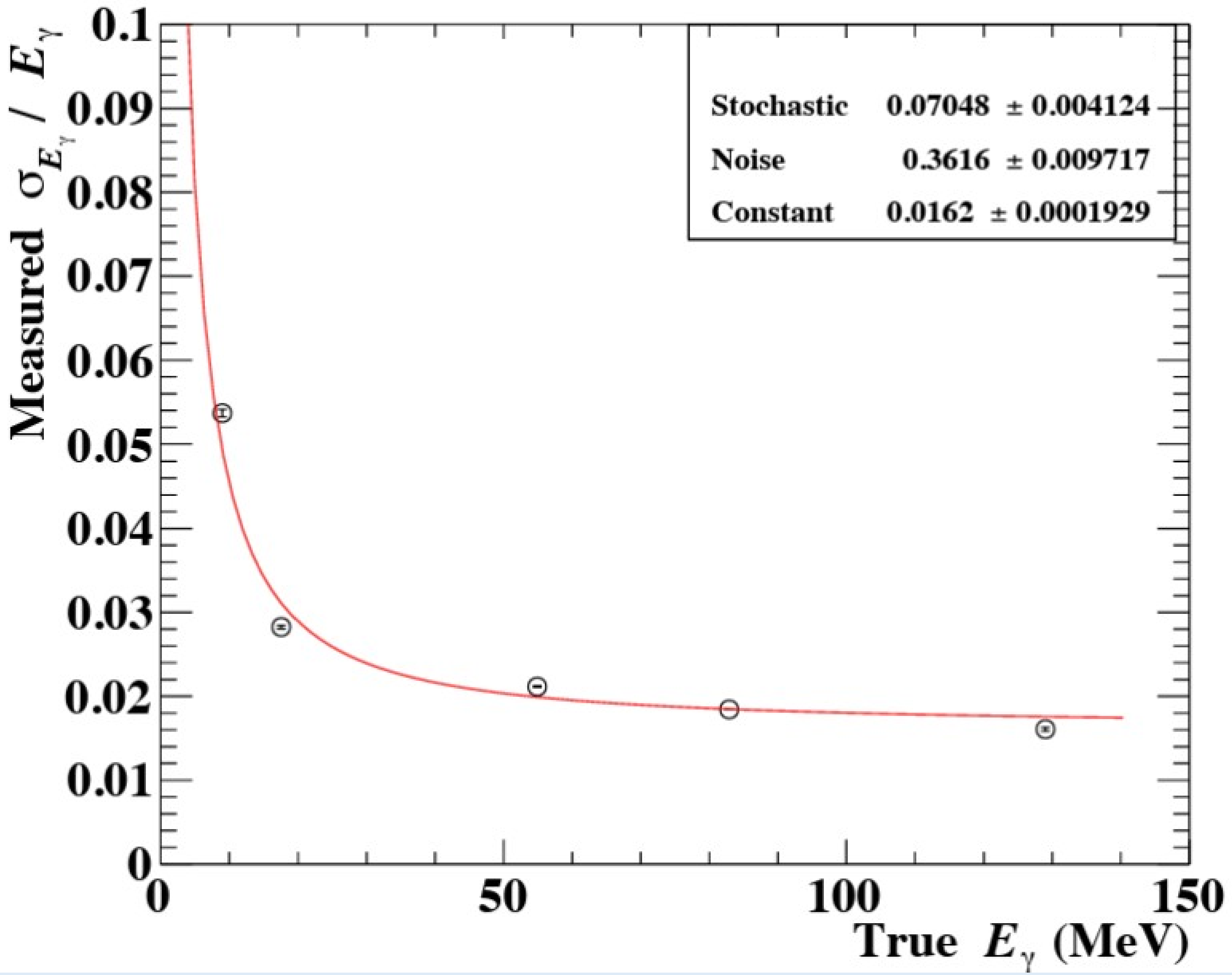
2021+2022 **S_{90}=2.2x10^{-13}**

MEG II goal:
S_{90}=6x10^{-14}

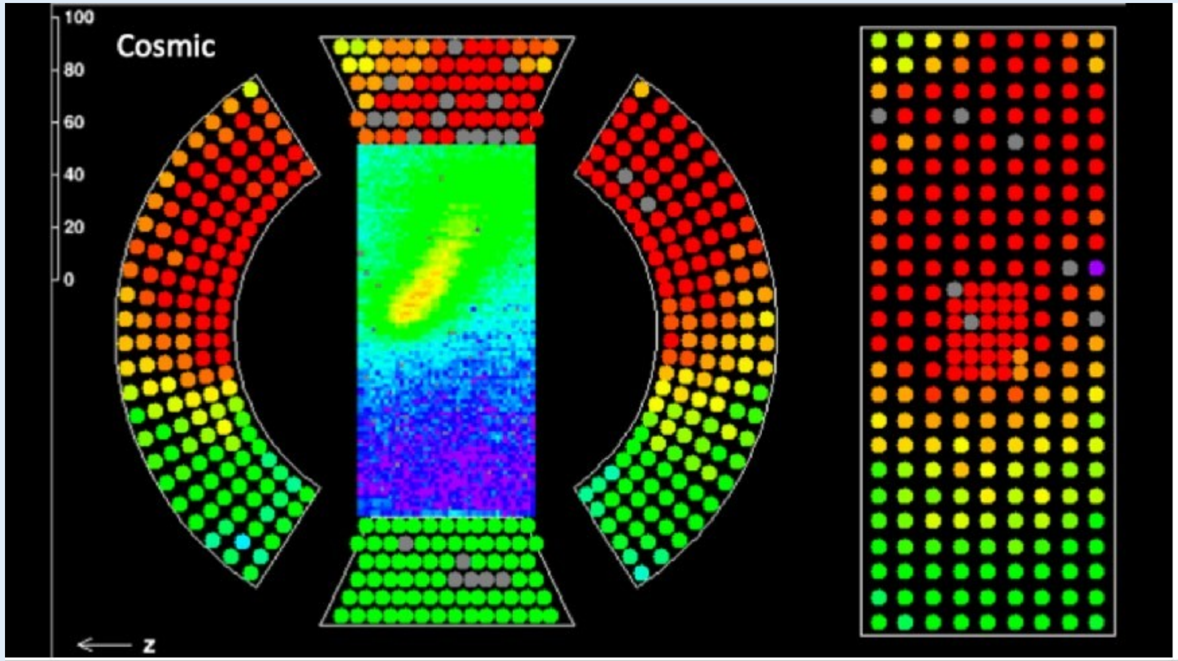
MEG II expected sensitivity

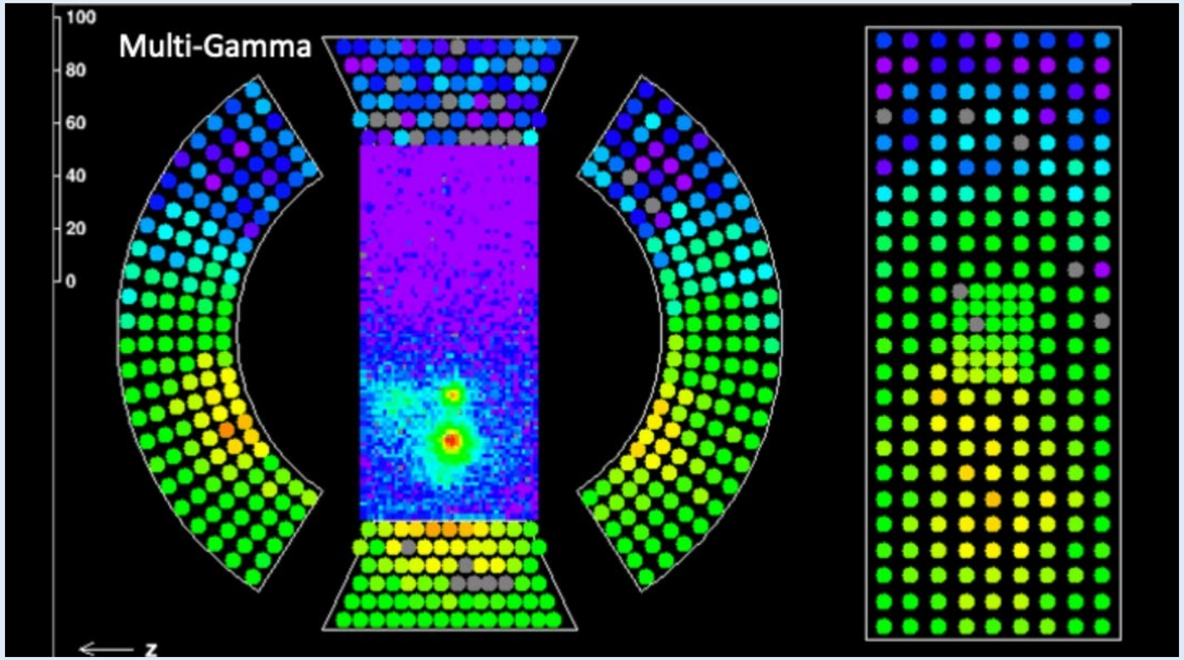


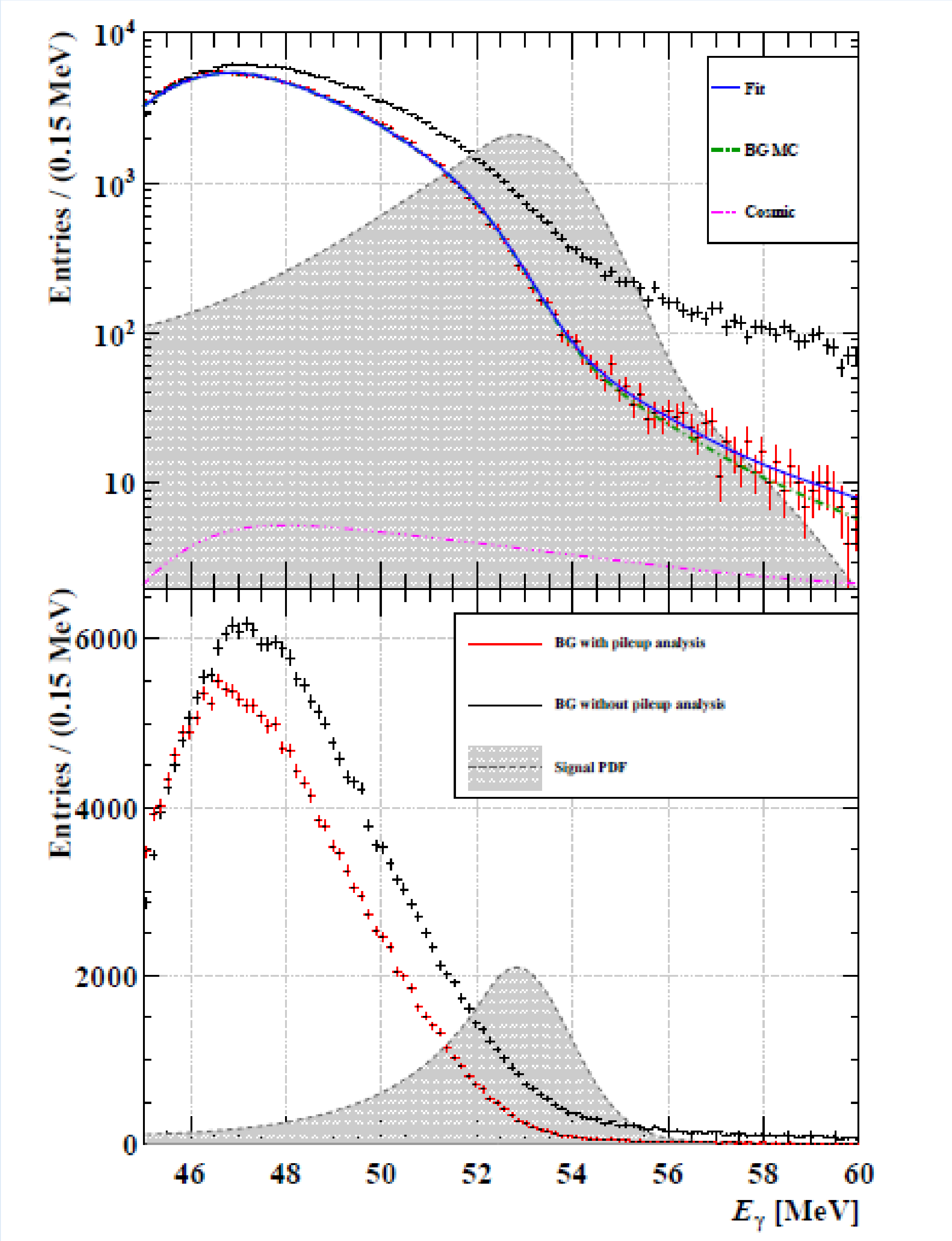
Resolution



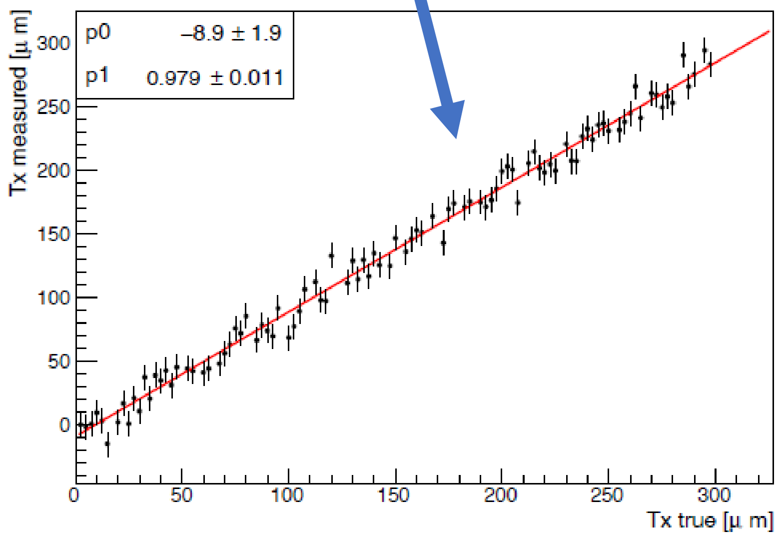
Stochastic 0.07048 ± 0.004124
Noise 0.3616 ± 0.009717
Constant 0.0162 ± 0.0001929
Measured $\sigma_{E_\gamma} / E_\gamma$
True E_γ (MeV)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
50
100
150

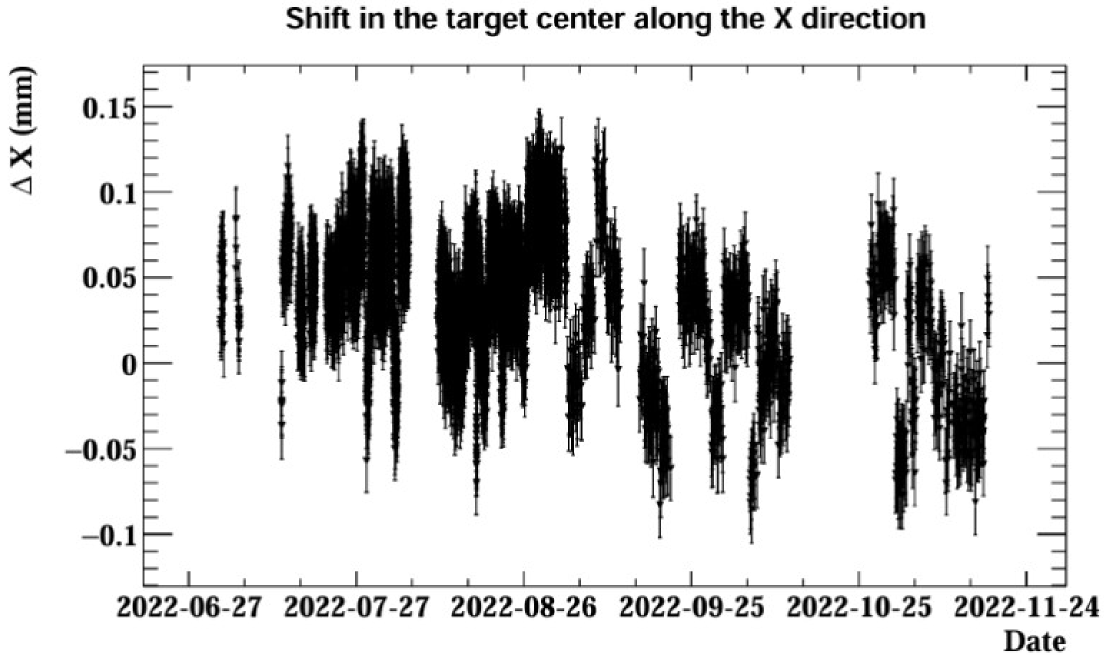

Cosmic
100
80
60
40
20
0
z

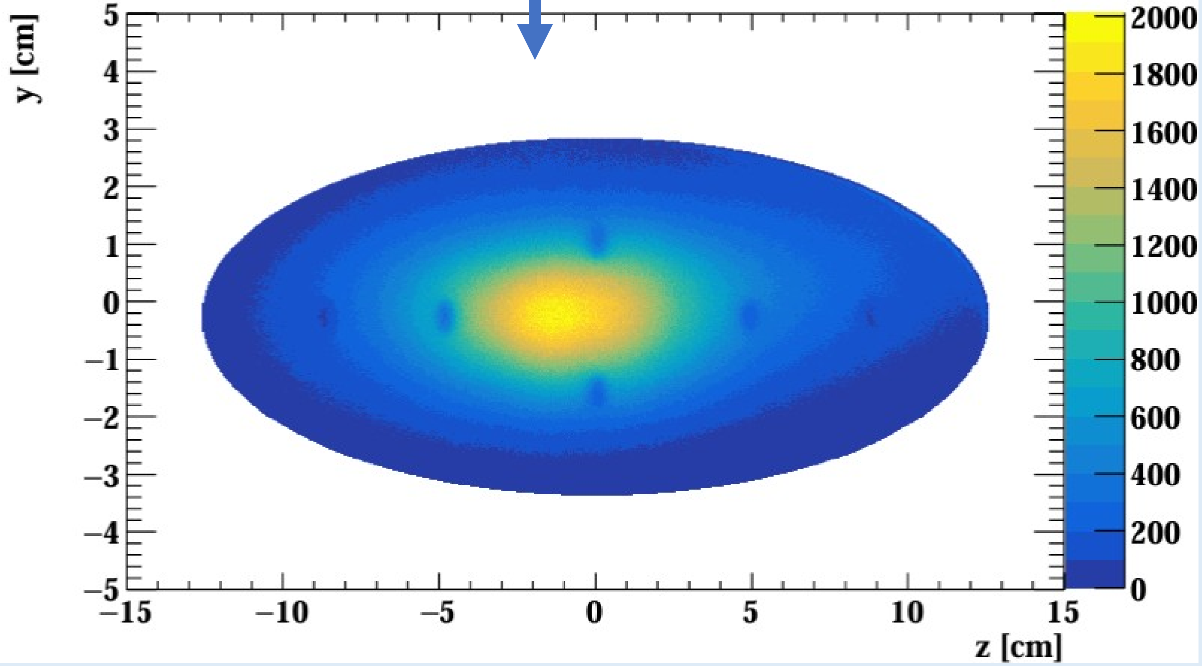

Multi-Gamma
100
80
60
40
20
0
z


Entries / (0.15 MeV)
10^4
10^3
10^2
10
Fit
BG MC
Cosmic
Entries / (0.15 MeV)
6000
4000
2000
0
BG with pileup analysis
BG without pileup analysis
Signal PDF
46
48
50
52
54
56
58
60
E_γ [MeV]

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







Normalization: Michel events simultaneously measured with the normal MEG trigger

$$N_{e\gamma} = BR(\mu^+ \rightarrow e^+\gamma) \cdot k$$

K = 1 / S.E.S.

where:

$$k \equiv N_{e\nu\nu} \times \left[\frac{f_S}{f_M}\right] \times \left[\frac{\varepsilon(TRG = MEG \mid e^+\gamma)}{\varepsilon(TRG = Michel \mid track \cap e_m^+ \cap TC)}\right] \times A(\gamma \mid track) \cdot \varepsilon(\gamma) \cdot Psc(Mtr)$$

$$f_S \equiv A(DC) \cdot \varepsilon(track, p_e > \text{Pcut} \mid DC) \cdot \varepsilon(TC \mid p_e > \text{Pcut})\big|_S$$

$$f_M \equiv \pi\pi \big|_M$$

pre-scaling O(10^7)

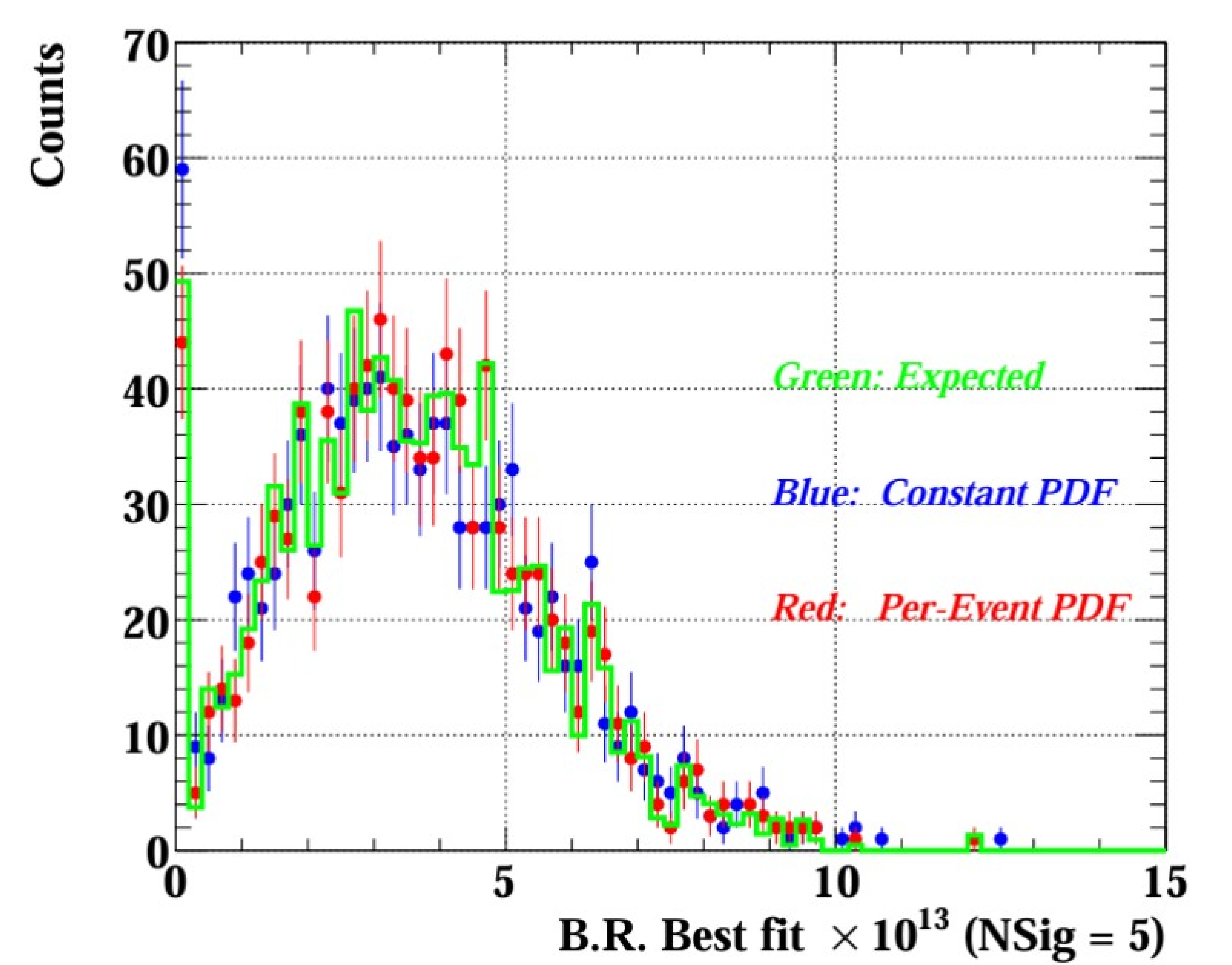
-Independent of instantaneous beam rate

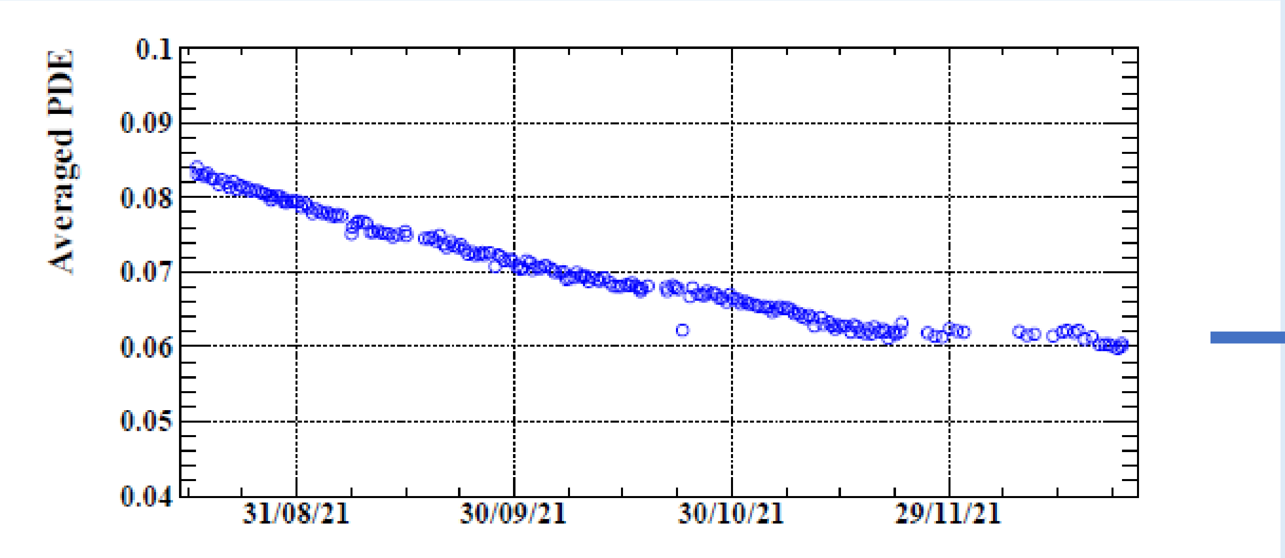
- Nearly insensitive to positron acceptance and efficiency factors associated with DCH and TC

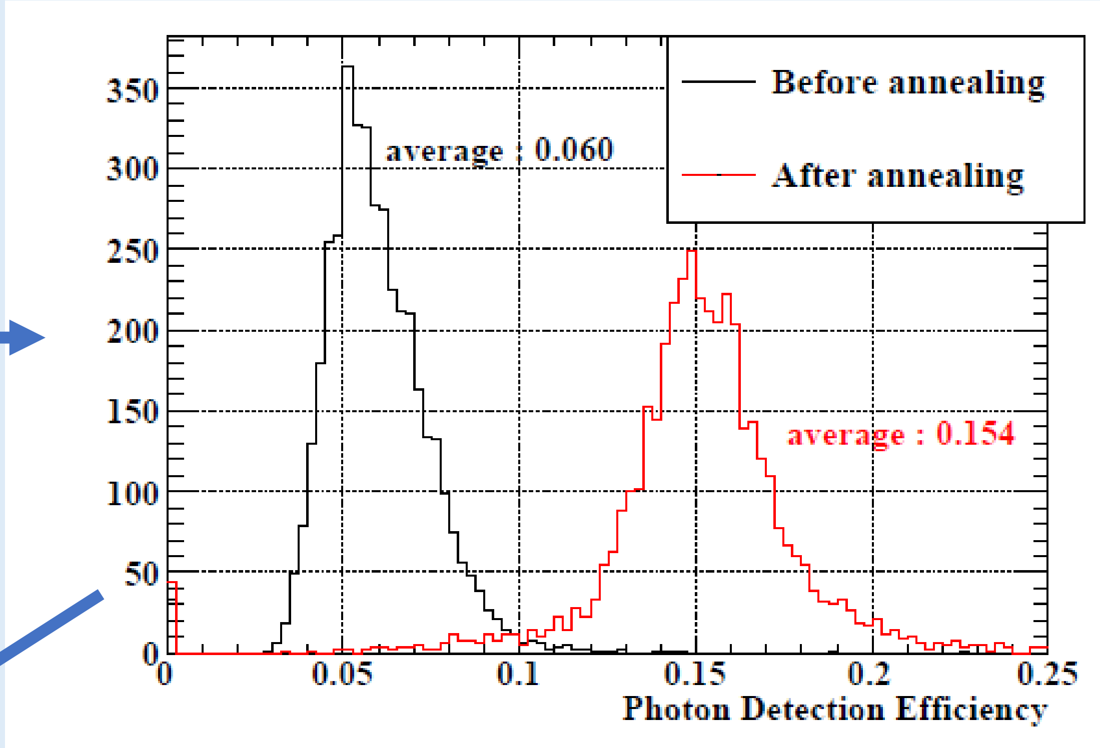
Systematic uncertainty

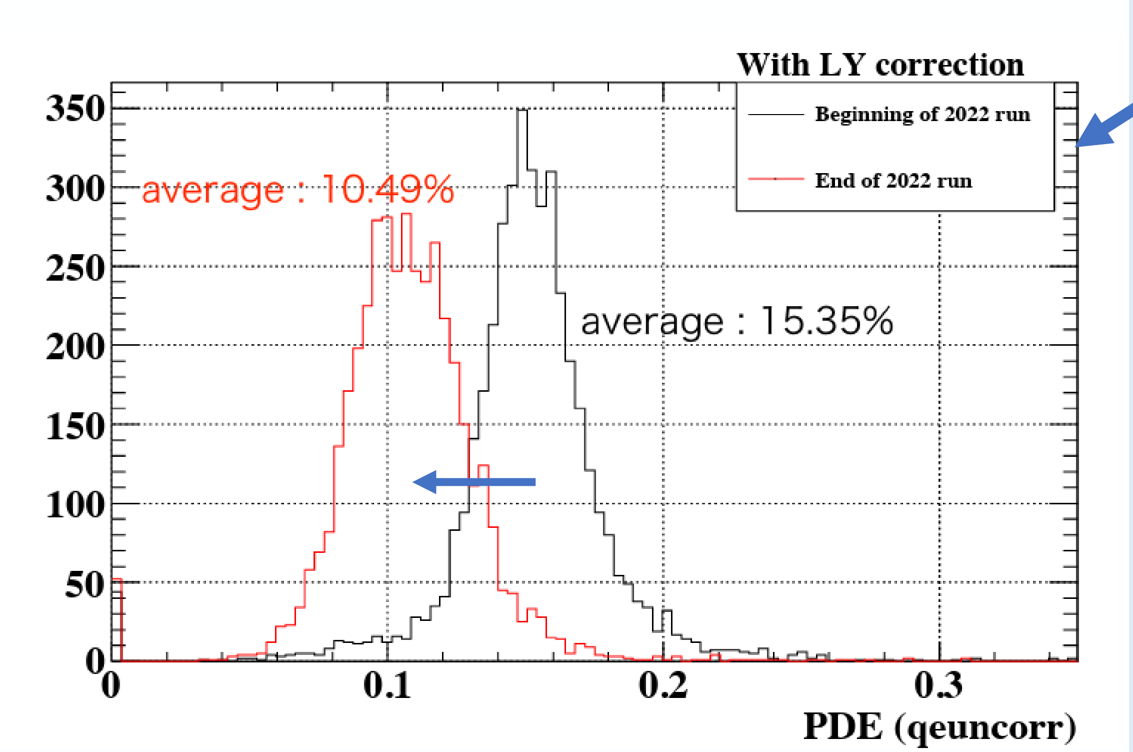
Source	Uncertainty	Impact on limit
Angle uncertainty	50 μm for CDCH-target alignment 400 μm for CDCH-XEC alignment	1.4 %
EGamma uncertainty	0.2 % for energy scale	1.0 %
Normalisation uncertainty	5 % for k	0.4 %
EPositron uncertainty	6 keV for energy scale	0.1 %
Time uncertainty	4 ps for offset	<0.1 %
RDC uncertainty	Ignorable statistical uncertainty	<0.1 %

Inserting 5 events in a sample of the same size of the experimental one





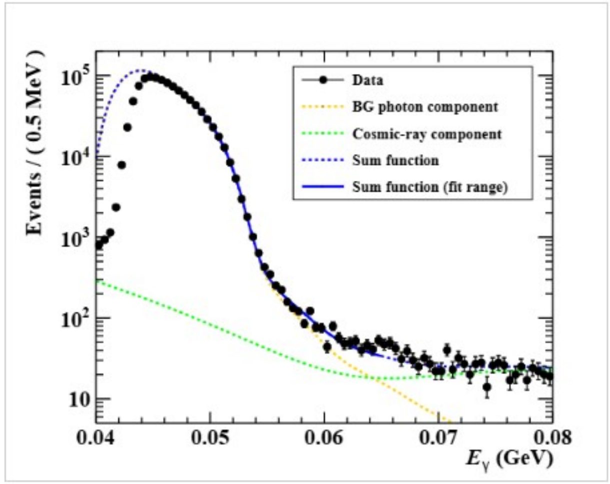


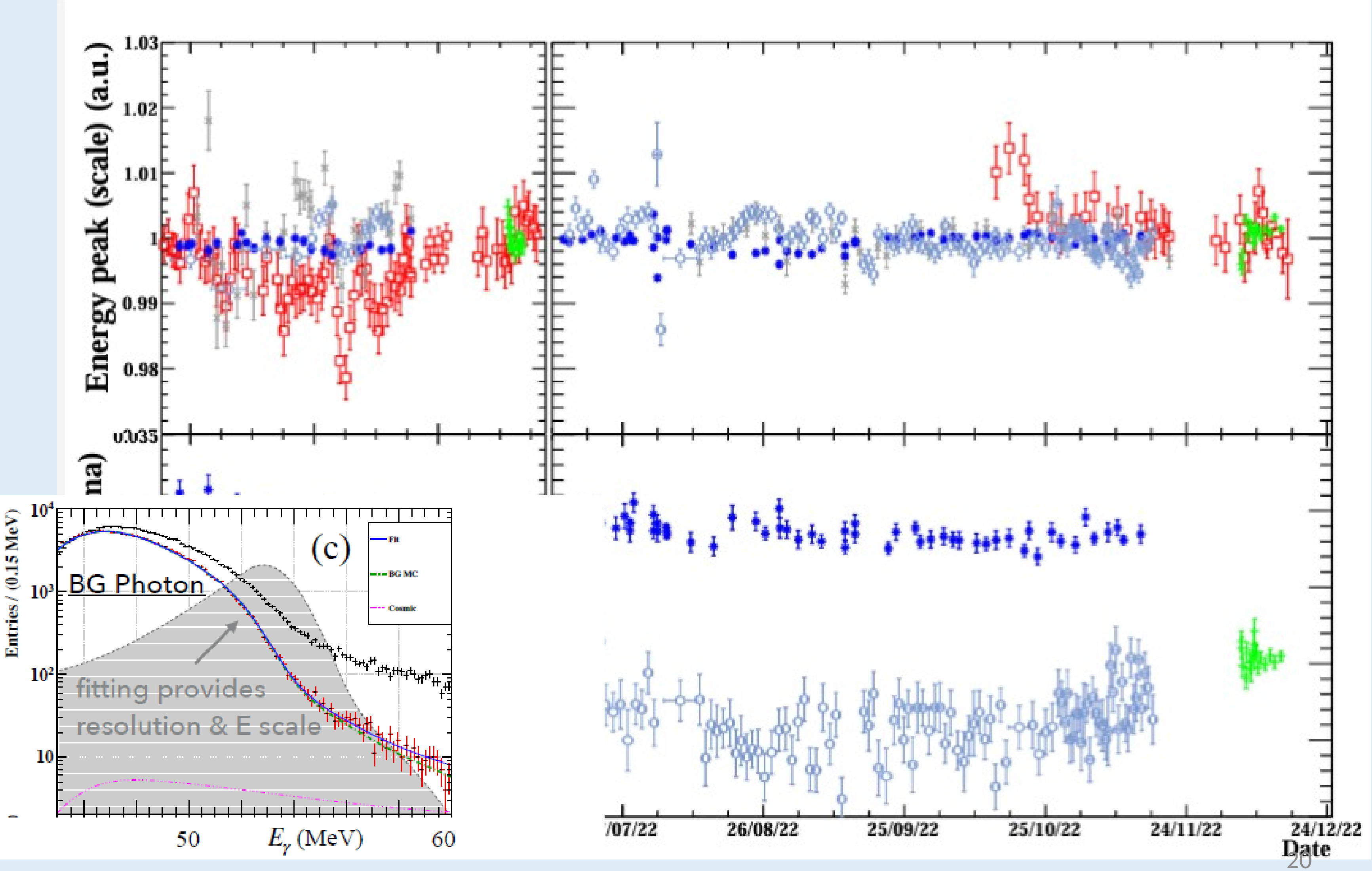


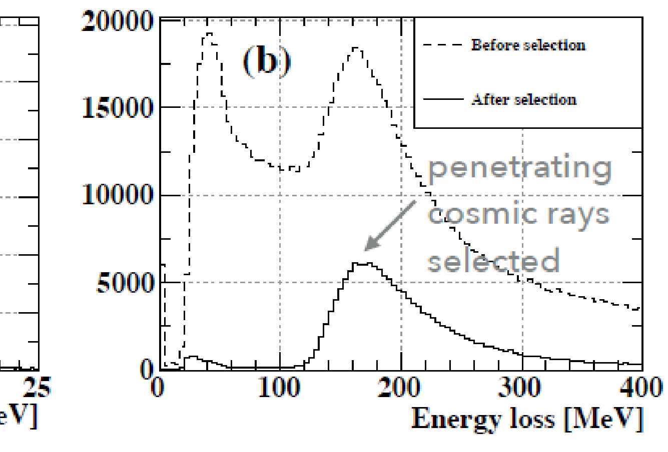
SiPMs annealing: can be performed once per year O(1÷2 month)

Stability of E_γ reconstruction

Background spectrum fit



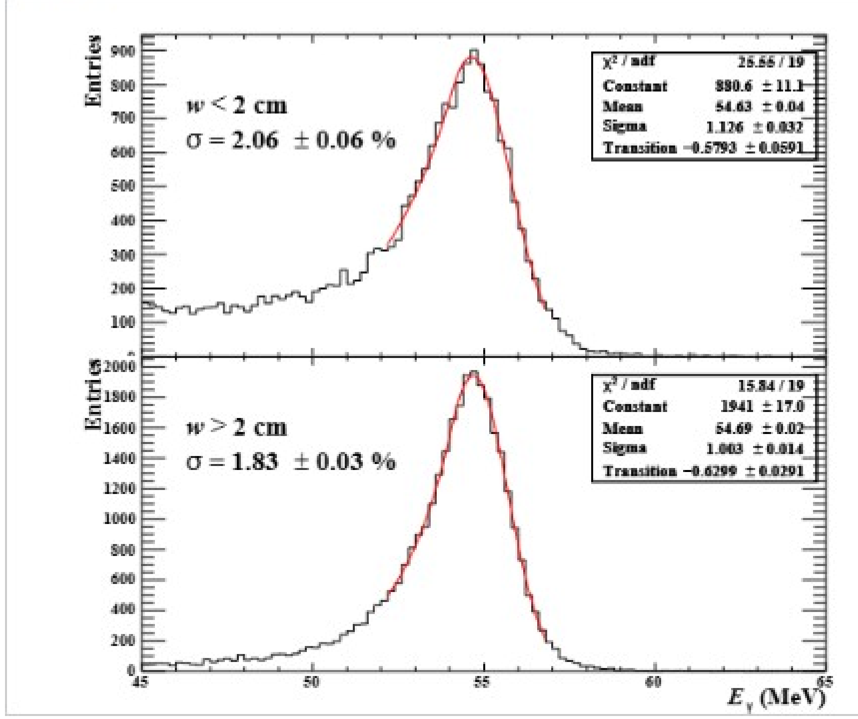




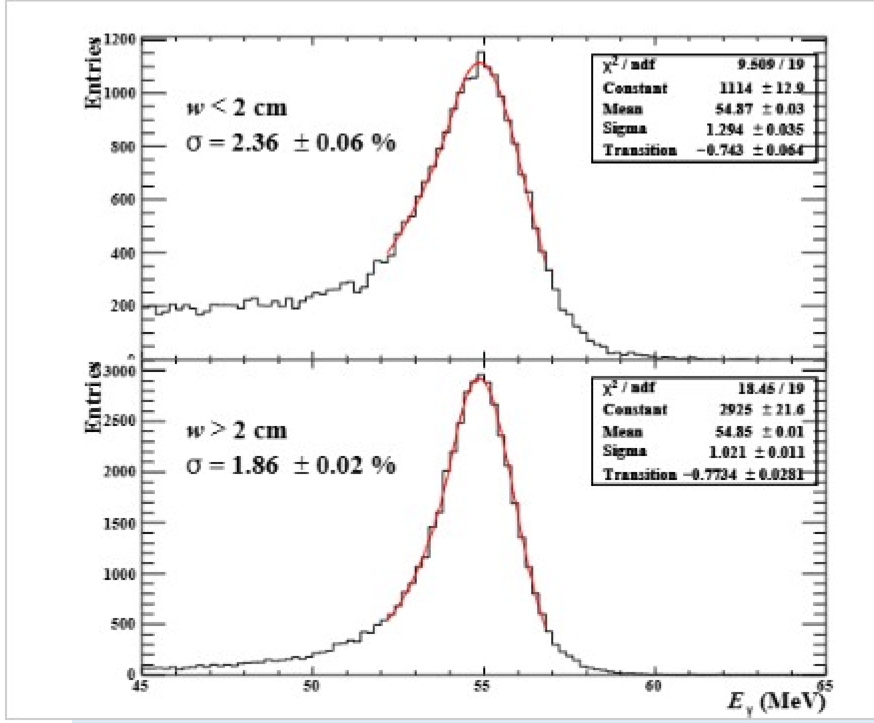
E_γ Probability Distribution Function

CEX reaction

2021



2022

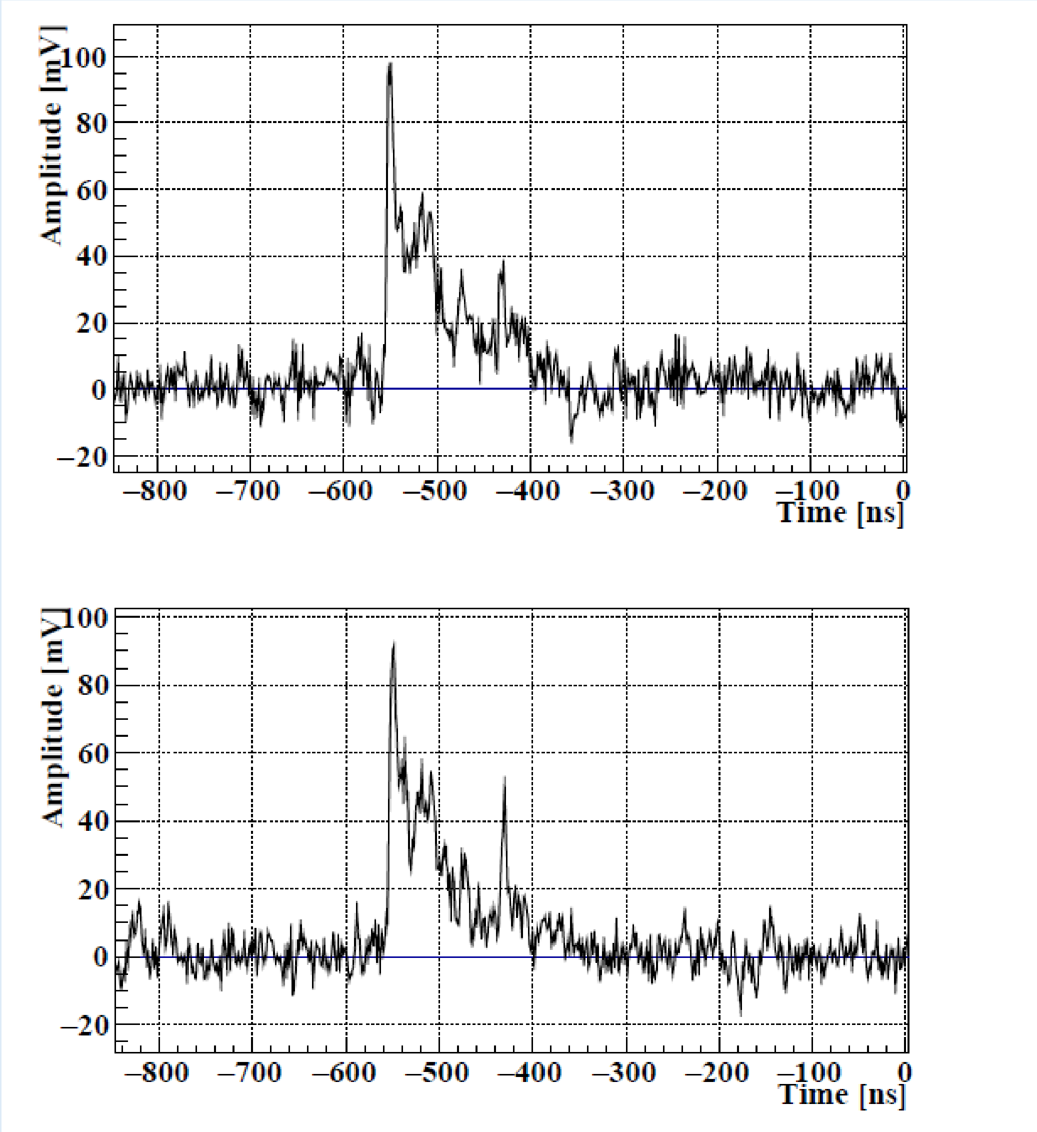


Energy resolution

55 MeV γ

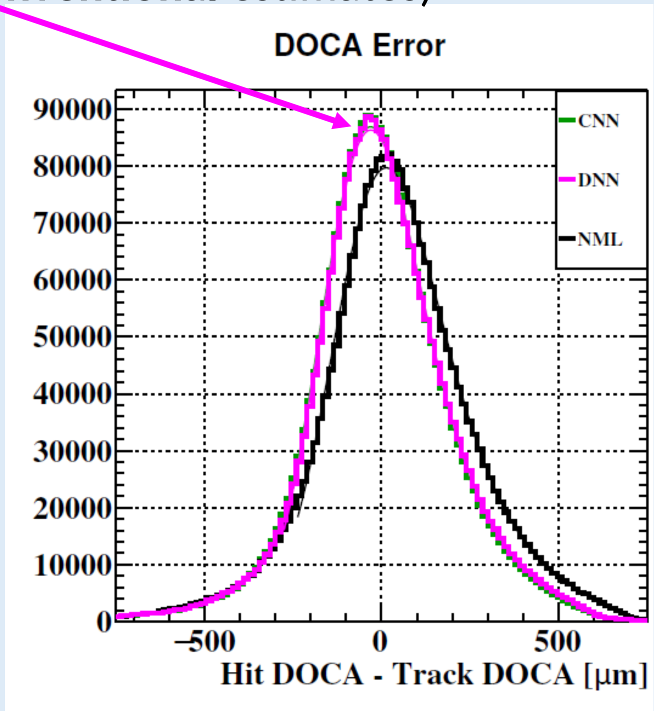
	MEG II 2021	MEG II 2022	MEG
w < 2 cm	2.1 %	2.4 %	2.4 %
w > 2 cm	1.8 %	1.9 %	1.8 %

Examples of waveforms: 1.2 GHz

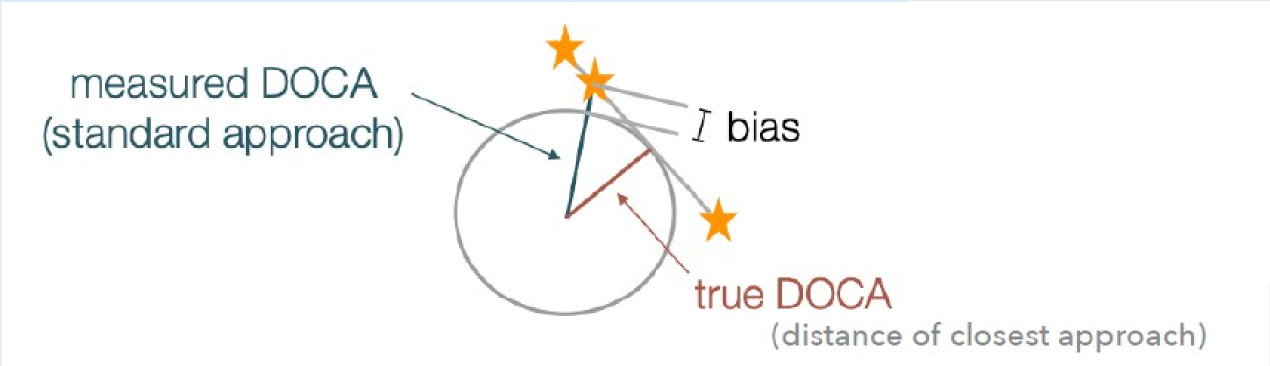


X 4 amplification in FE electronics

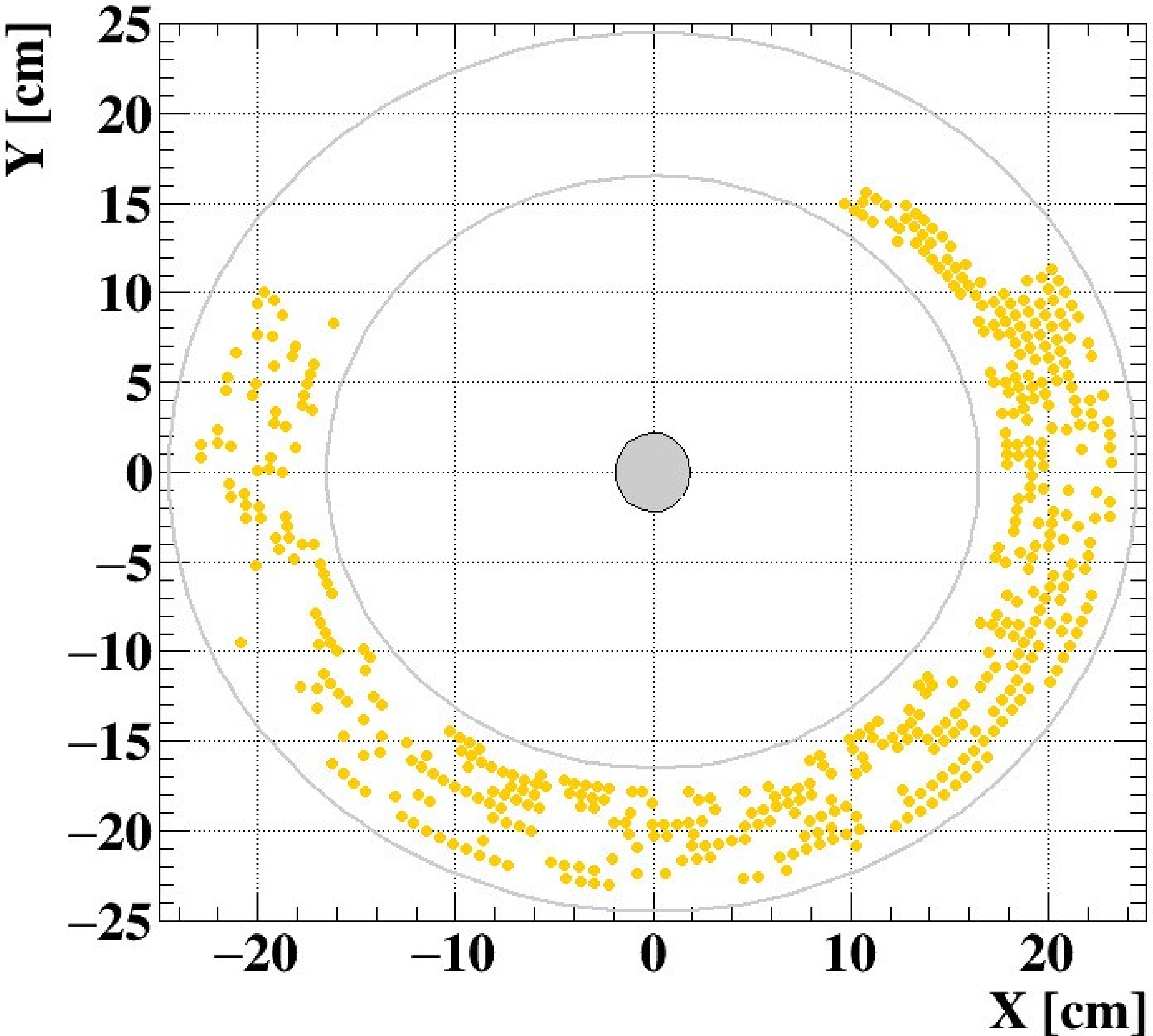
NN DOCA estimates take into account several clusters (differently from **conventional** estimates)

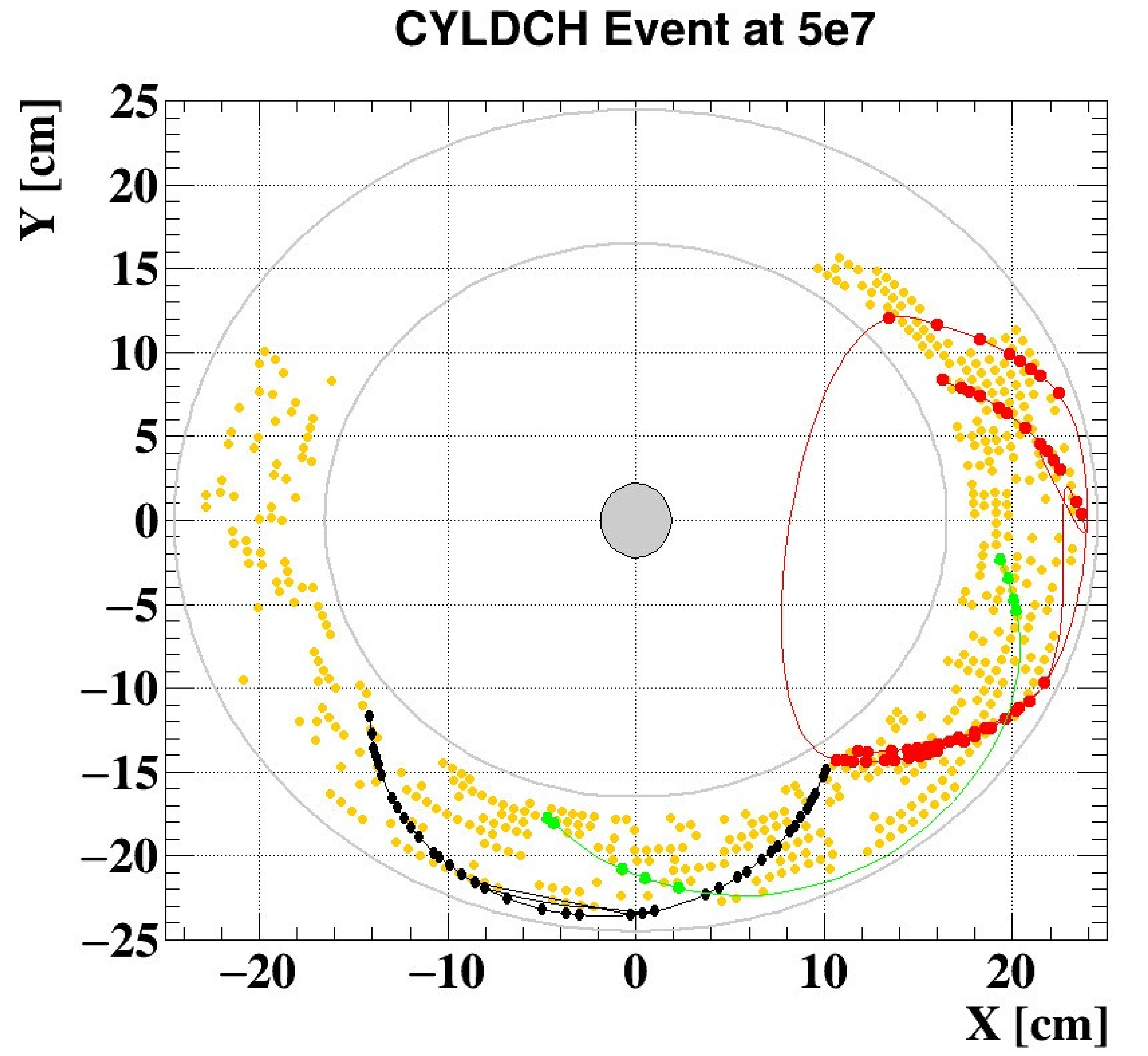


σ = 115 μ



CYLDCH Event at 5e7




CYLDCH Event at 5e7
Y [cm]
X [cm]
25
20
15
10
5
0
−5
−10
−15
−20
−25
−20
−10
0
10
20

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

Alternative alignment (Millepede for wires with sag) using CR: trying using both alignements

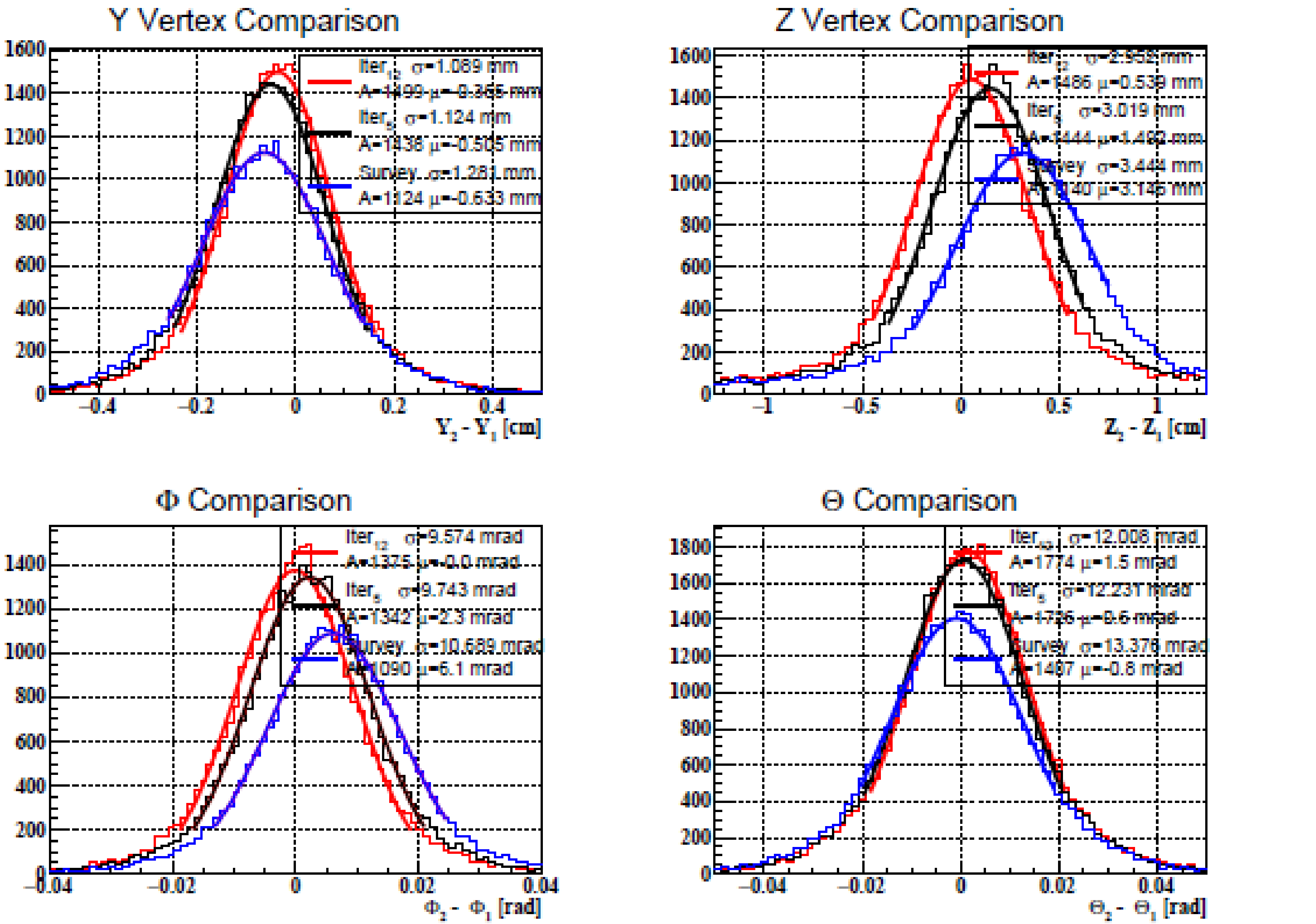
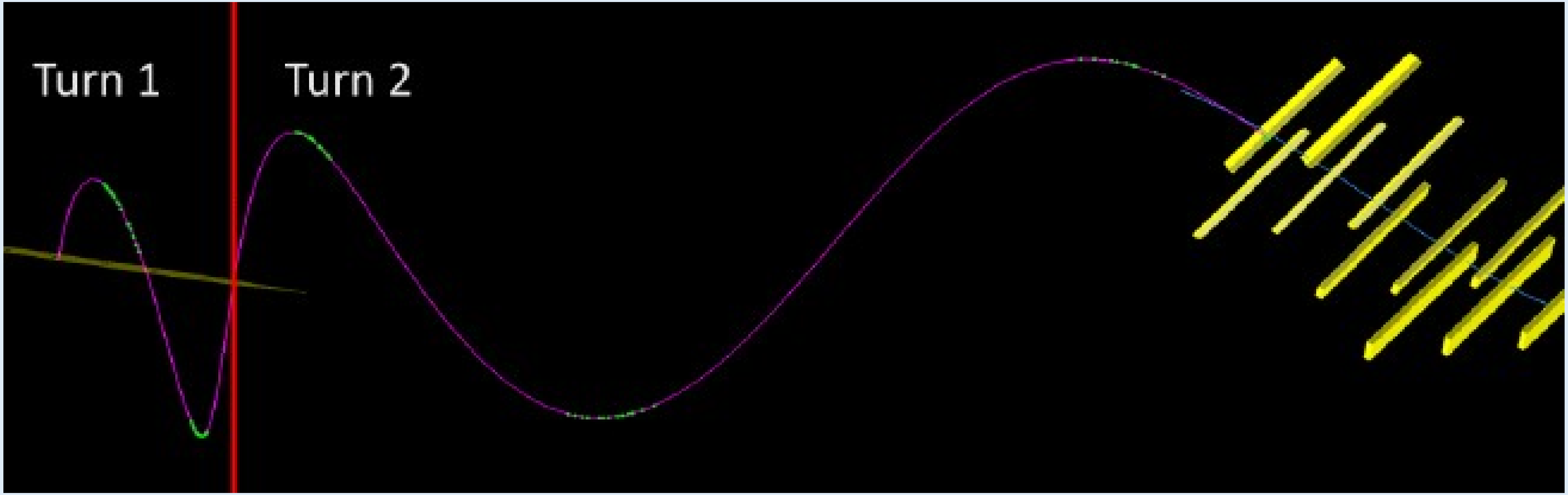
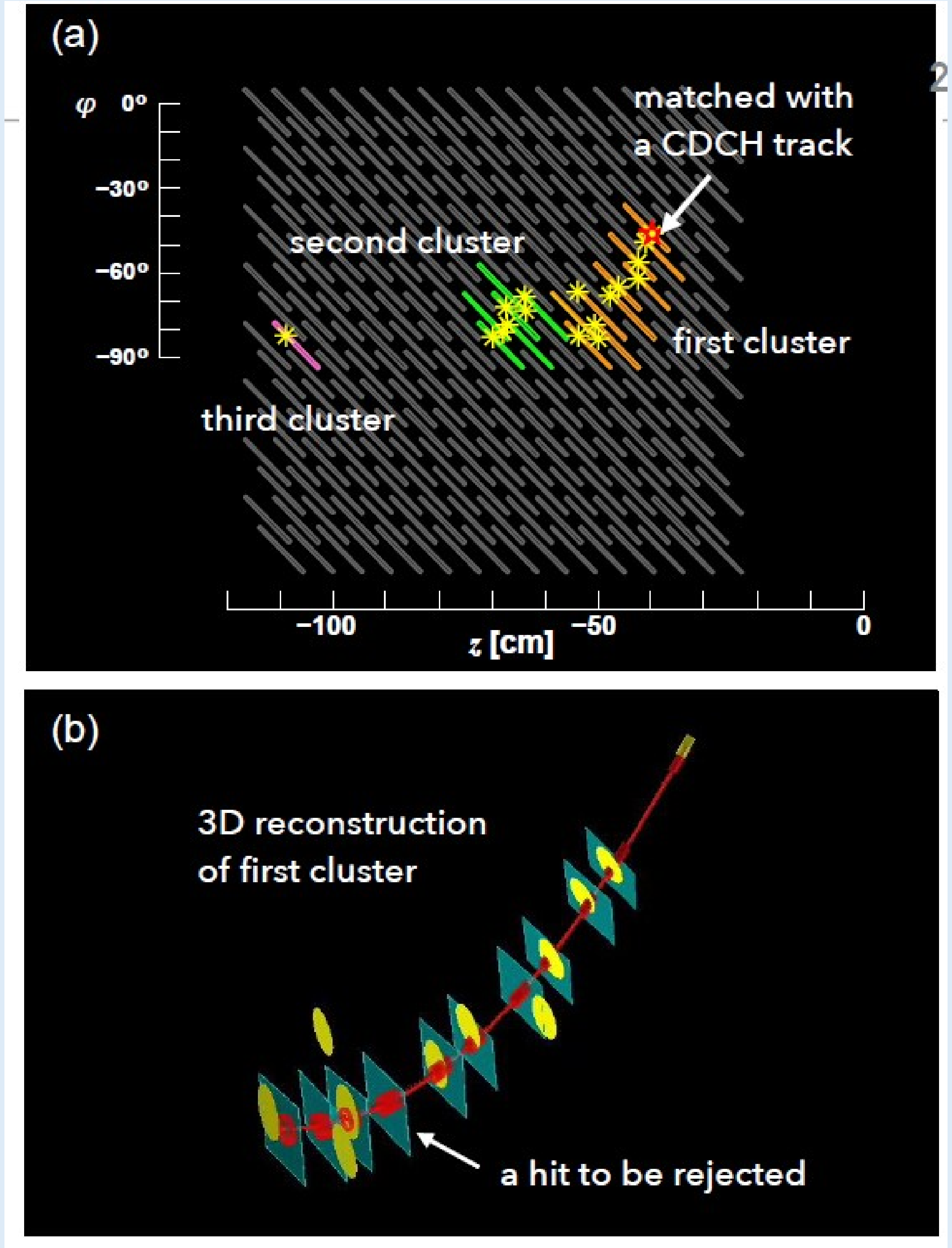


Figure 13. The double-turn analysis results for the positron kinematic

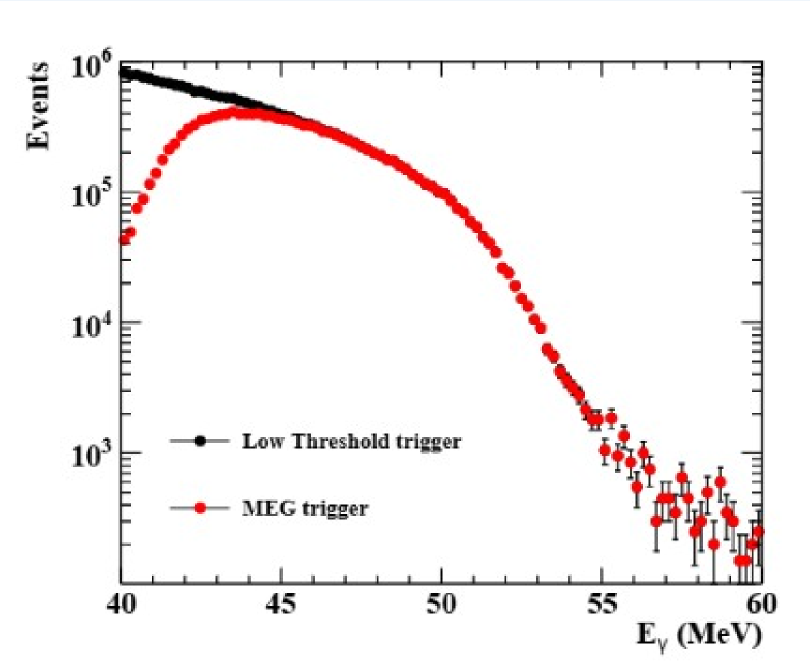
Positron tracks passing twice through the target are used to determine position and angle resolutions

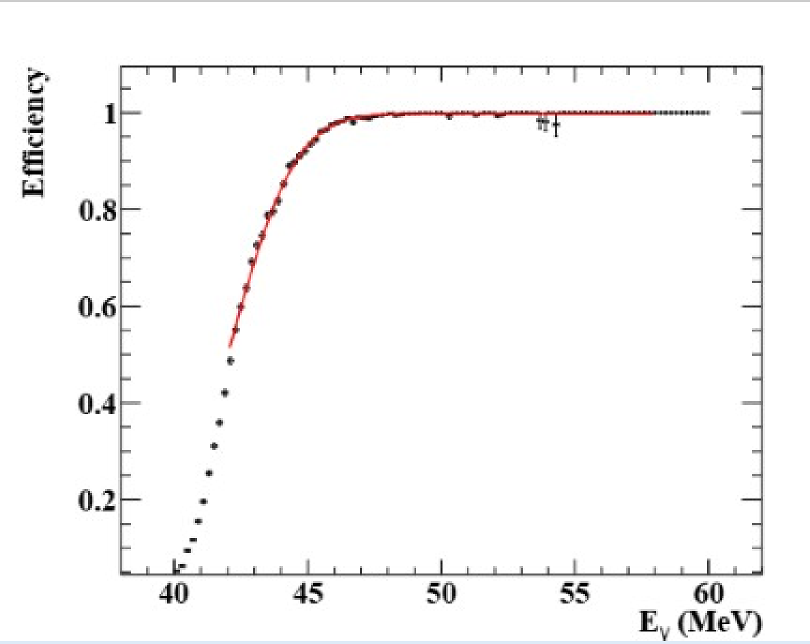


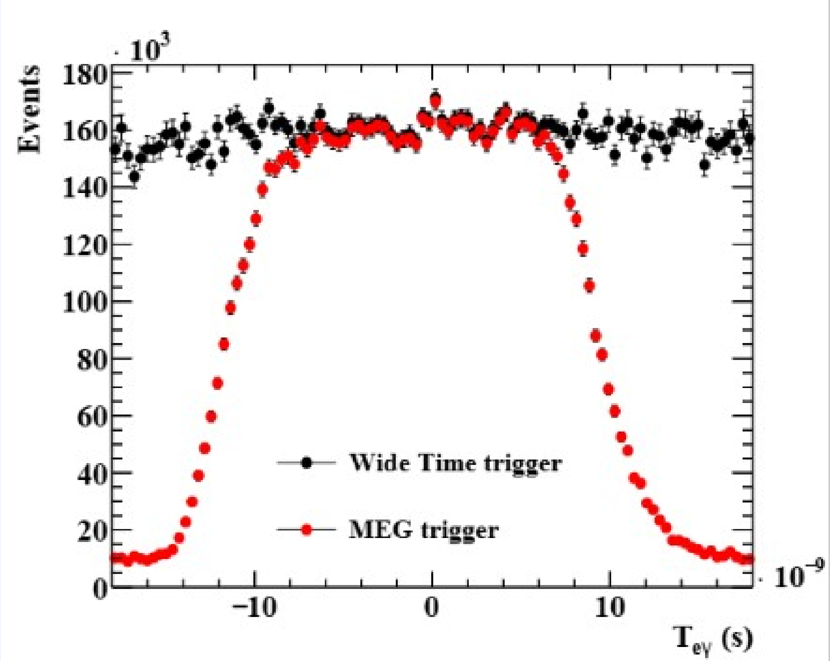
- Identification of clusters of tiles
- Matching with CDCH tracks
- Δt(tiles) ~15 ps: Laser system + tracking
- T~10–15 °C for minimizing dark current due to radiation damage
- Worst tiles (80) substituted in 2024 after 3 years of data taking

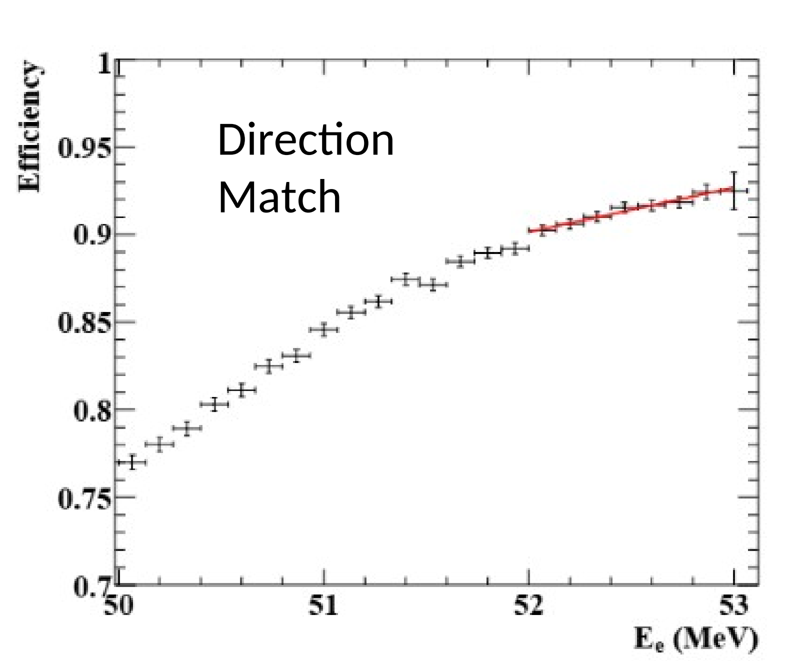


Trigger efficiency



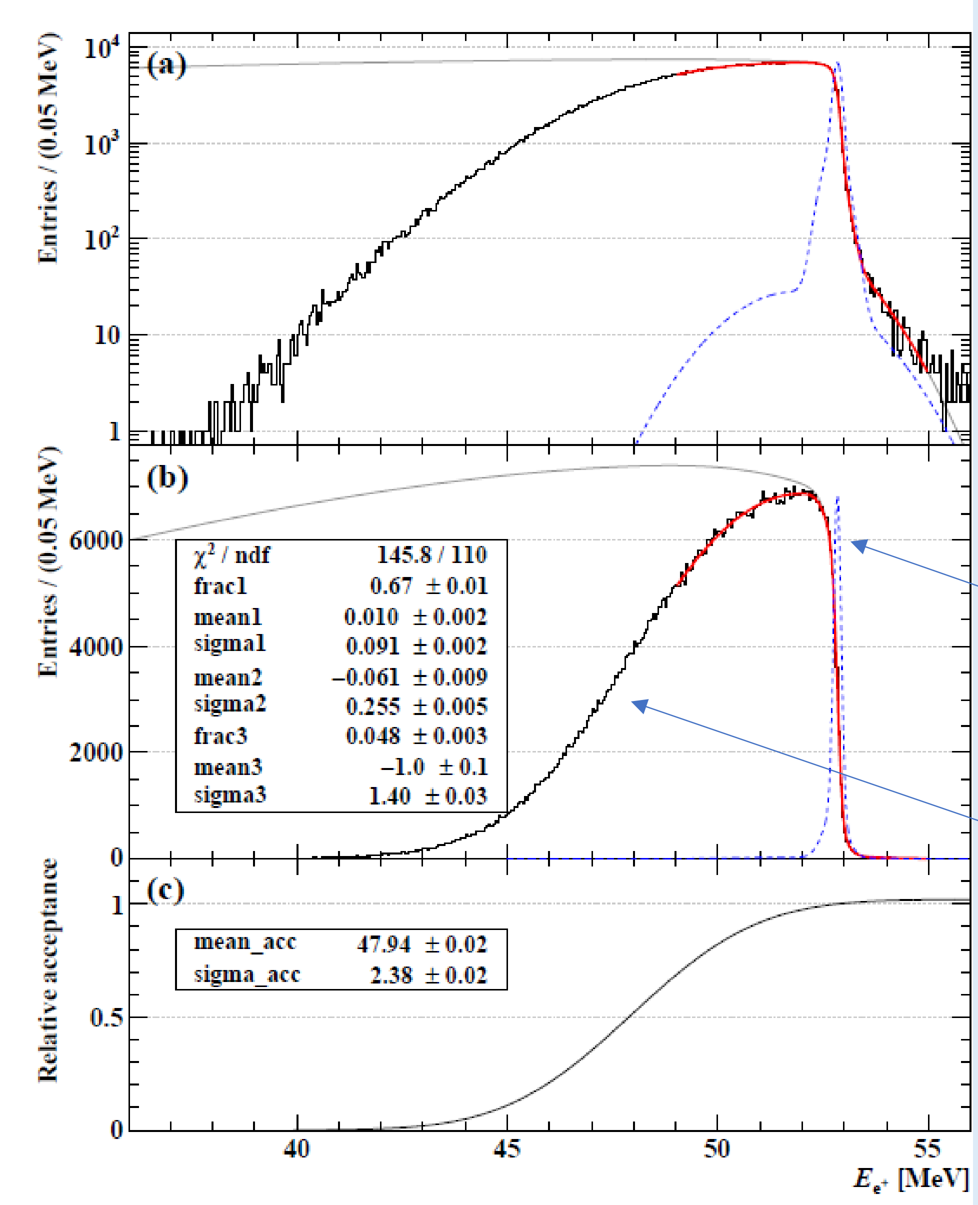


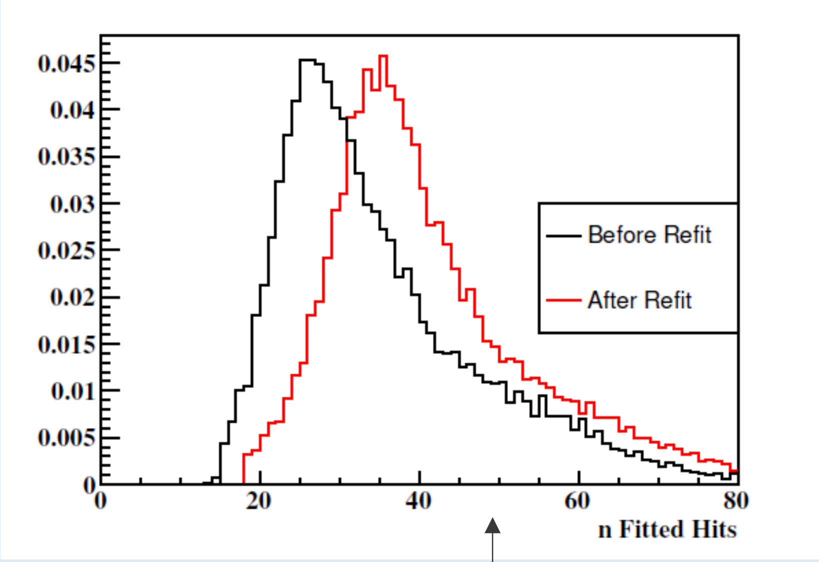




$$\varepsilon_{\mathrm{TRG}} = \varepsilon_{E_\gamma} \times \varepsilon_{T_{e^+\gamma}} \times \varepsilon_{\mathrm{DM}} \approx (80$$

88%	2021
91%	2022





- 40 hits/track in average (red curve)
- Very good (90 KeV) positron energy resolution from fit to the michel spectrum

Theoretical spectrum ⊕ Acceptance ⊕ Resolution = Experimental