The status of the MEG II experiment

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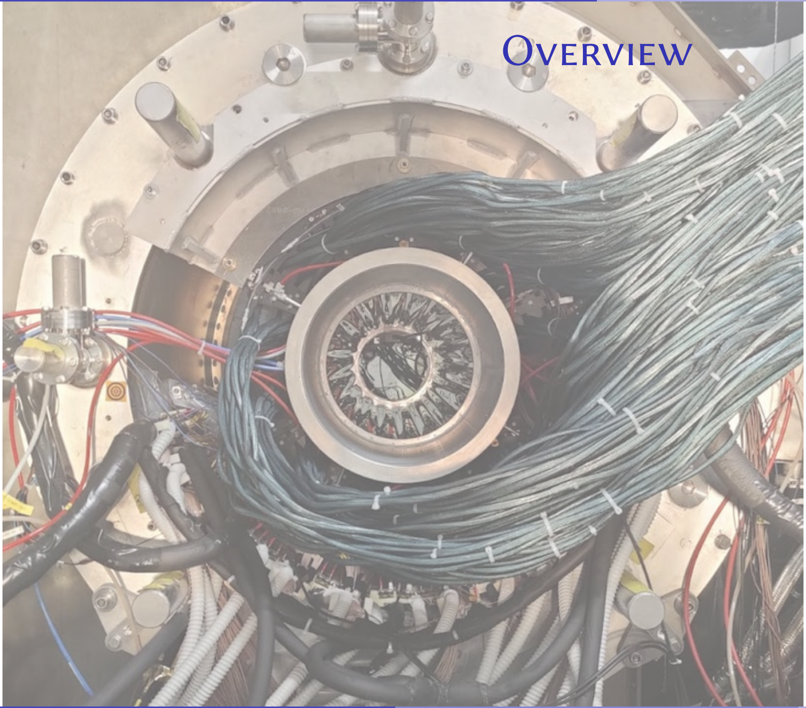


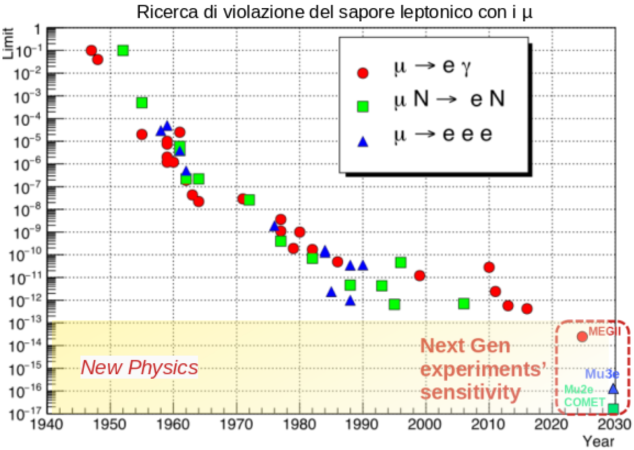
Overview

- The search for $\mu \to e\gamma$
- The concept of the MEG II experiment
- Status of the MEG II experiment after 2 years of data taking
- Sensitivity estimate
- Conclusions

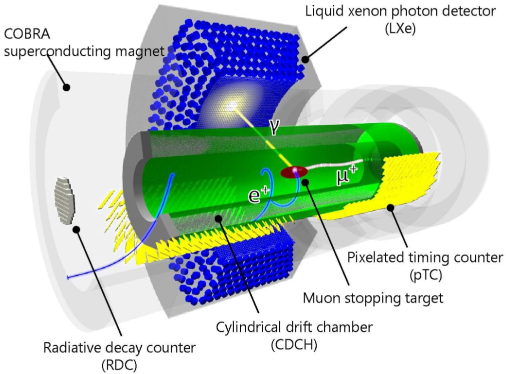
Searching for $\mu \to e\gamma$ & Co

cLFV: perfect channel to look for New Physics

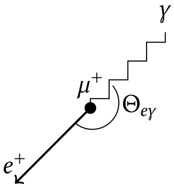
- No Standard Model background:
  - lepton flavor *almost* conserved
    $BR(\mu \to e\gamma) \lesssim 10^{-53-55}$
  - Any experimental evidence of cLFV
    $\equiv$ New Physics signal
- Most NP scenarios predict cLFV processes



MEG II overview



Two-body decay



- $E_{e^+} \approx 52.83$ MeV
- $E_\gamma \approx 52.83$ MeV
- $\Theta_{e^+\gamma} \equiv 180^\circ$
- $\Delta t_{e^+\gamma} \equiv 0$

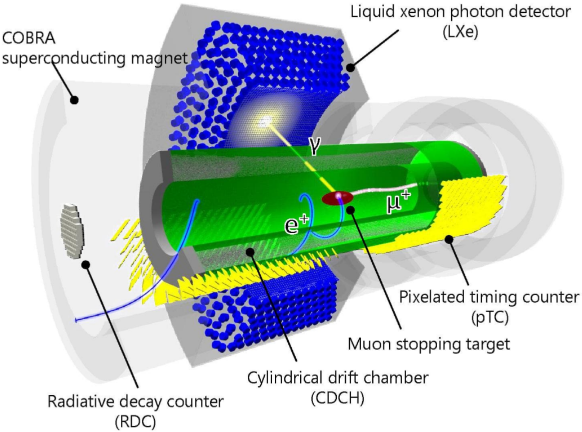
Sensitivity determined by:

- Number of stopped muons
- experimental background:
  a) muon radiative decay $\mu^+ \rightarrow e^+ \nu \bar{\nu} \gamma$
  b) accidental coincidence (dominant, $\sim 90\%$)

MEG II overview: upgrade & goals

MEG II goal for 2026

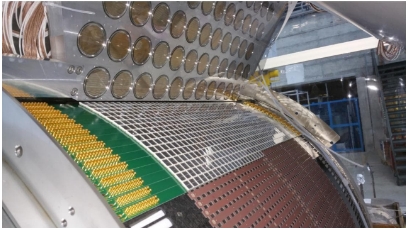
6×10^{-14} sensitivity, to overtake MEG final result: $BR(\mu \to e^+\gamma) \leq 4.2 \times 10^{-13}$



Project

- Most intense μ^+ continuous beam in the world @PSI: up to 10^8 μ^+/s
- Upgrade detectors for improved kinematic resolutions *by a factor 2*; reduce background sources:

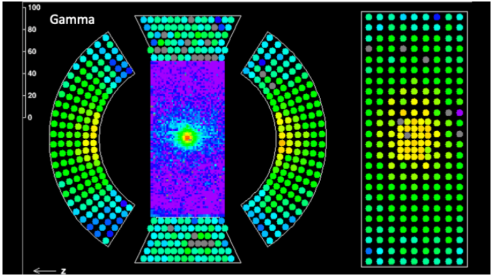
Liquid Xenon Detector



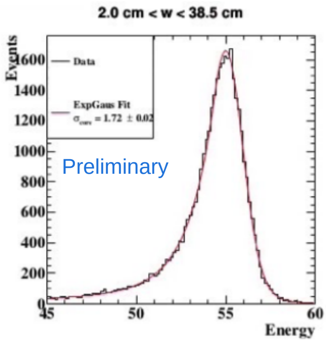
- Higher segmentation: > 4000 SiPMs + 700 PMT
- Better position and energy resolution
- lower material budget

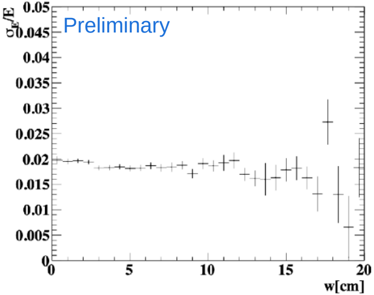
Calibration

- Regular monitoring of PDE & Light Yield & Gain
- Energy scale determined with:
  - γ from nuclear processes ($\mathcal{O}$(10 MeV)) using a *dedicated C-W accelerator*
  - *CEX reaction* $\pi^- p \to \pi^0 n$, $\pi^0 \to \gamma\gamma$ (55 and 83 MeV)



Liquid Xenon detector: performances

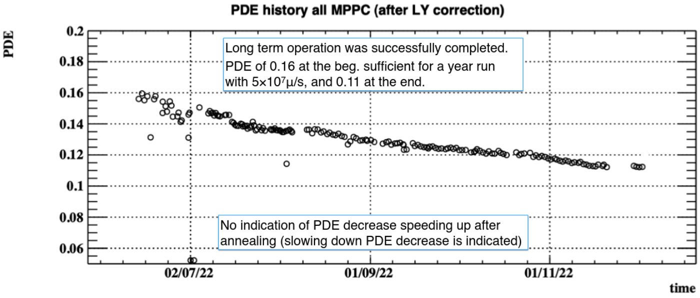


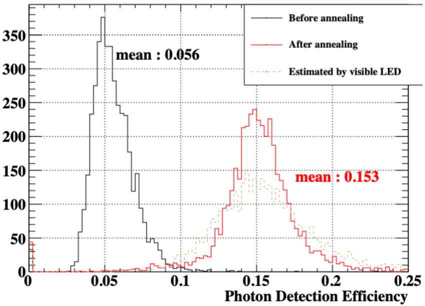


Preliminary

Quantity	Performance	agree w MC
Position resolution [mm]	2.4	✓
Energy resolution [%] ($w < 2$ cm / $w > 2$ cm)	2.0% / 1.7%	× (80% off)
Time resolution [ps]	65 ± 6	✓
Detection Efficiency [%]	64%	∼ (5% off)

Liquid Xenon detector: Maintenance



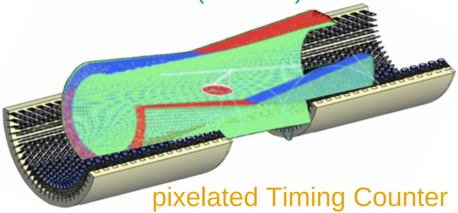


The degradation of SiPM's PDE after beam irradiation has been observed.
An annual annealing procedure is carried on to recover the PDE. The annealing is done heating the SiPM through Joule effect. The procedure has been succesfull in 2022.

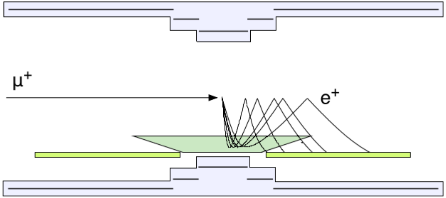
MEG II spectrometer

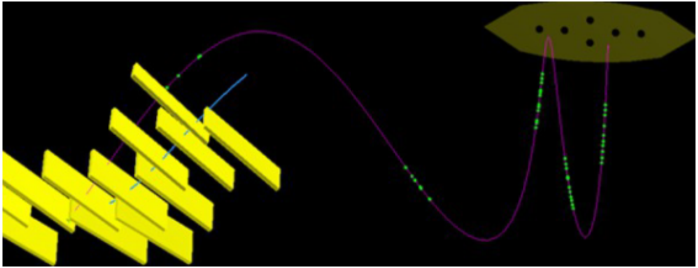
COnstant Bending Radius superconductive NON-SOLENOIDAL magnet

Cylindrical Drift Chamber (Tracker)

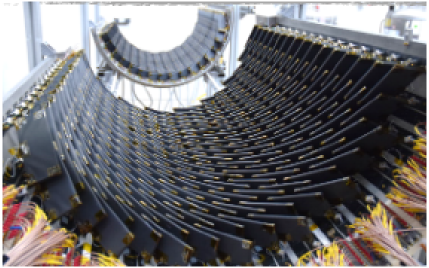


pixelated Timing Counter

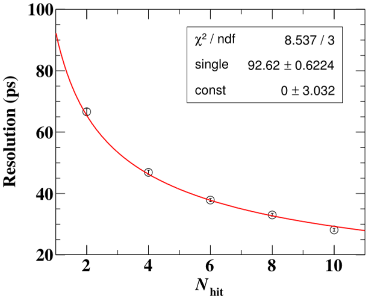




The pixelated Timing Counter



- Highly segmented timing detector (512 scintillating tiles)
- SiPM readout
- Improved e^+ timing resolution

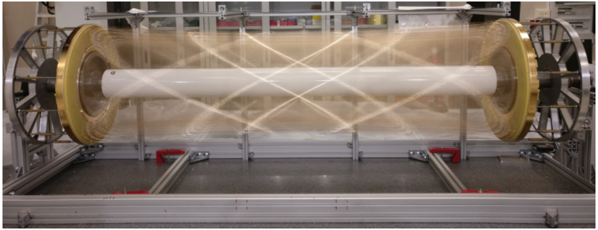


Timing resolution

Timing resolution compatible with design project

$$\sigma_t = \frac{\sim 90-100 \text{ ps}}{\sqrt{N_{hits}}}$$

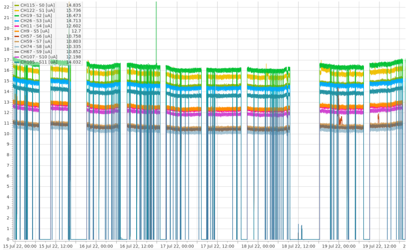
Cylindrical Drift Chamber

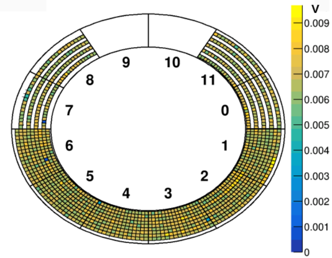


- Single volume ultra-light drift chamber
- mixture: 90:10 He : isobutane + 1.5% isopropanol + 0.5% O_2
- Highly segmented: 1728 anodes, $< 4 \times 4$ mm^2 drift cells
- Rejects e^+ with $E_{e^+} \lesssim 45$ MeV

Very stable operation conditions during 2021 and 2022 runs

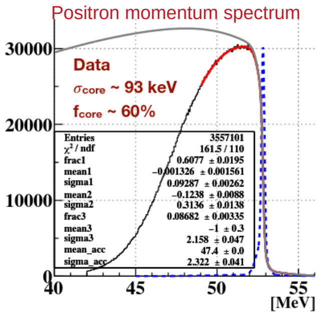
CDCH CURRENTS

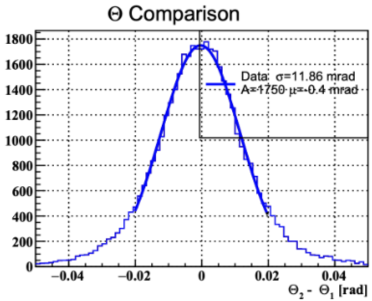




Low & homogeneous noise

CDCH: PERFORMANCES





Quantity	Resolution	agree with MC
p_{e^+}	90 keV/c	✓
ϕ_{e^+}	6.8 mrad	~ (10% off)
θ_{e^+}	7.1 mrad	~ (10% off)
z	1.85 mm	✓
ϵ_{e^+}	65%	~ (10% off)

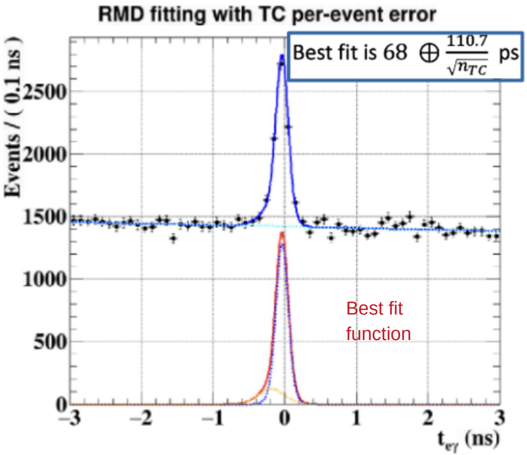
Calibrations & systematics search

- Iterative alignment
- Magnetic field corrections

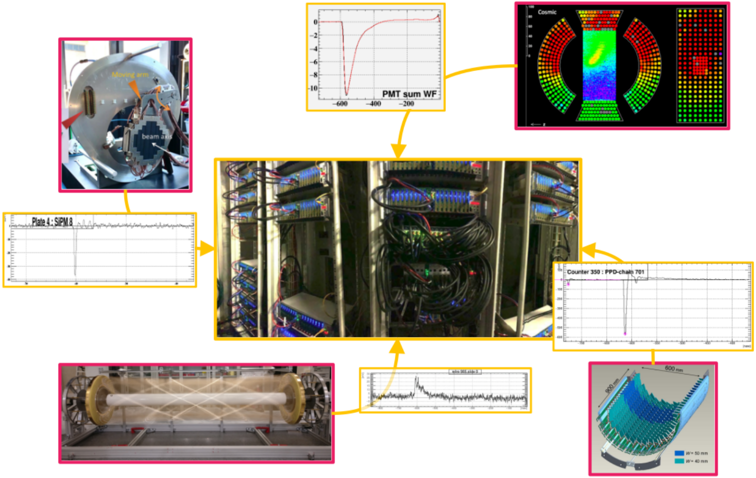
Resolution on $t_{e^+\gamma}$

Calibration

Use on-time e^+ - γ signal from $\mu \to e\nu\bar{\nu}\gamma$



MEG II Trigger & DAQ



- Integrated Trigger & DAQ system
- $>$ 9000 detectors' waveforms digitized and saved for offline reconstruction
- highly flexible

Trigger performances

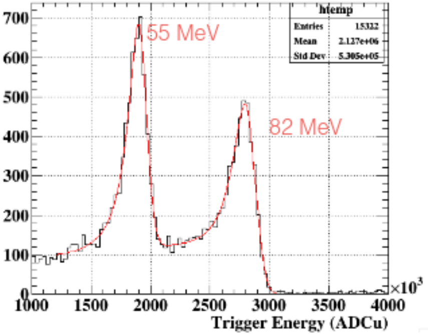


Figure: Photon energy spectra reconstructed online during CEX calibration using $\pi^0 \to \gamma\gamma$

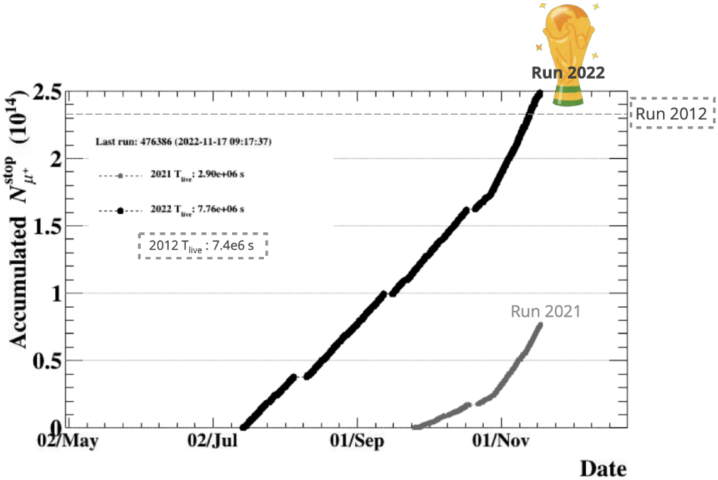
Trigger logic

- $E_\gamma > 42$ MeV
- $|\Delta T_{e^+\gamma}| = 7 - 12.5$ ns (2021), 7-11 ns (2022)
- Direction match

The trigger performances

- Online energy resolution $\sim 3 - 4\%$
- Overall trigger efficiency $\gtrsim 90\%$
- Trigger rate @$3 \times 10^7\ \mu^+/\text{s} \approx 20$ Hz

Estimate of stopped muons: N_μ^{stop}



What has been accomplished

- Physics data taking started in 2021
- In 2022: largest N_μ^{stop} in a single year in the history of MEG
- 2023 expected to be as good as 2022 (hopefully better)

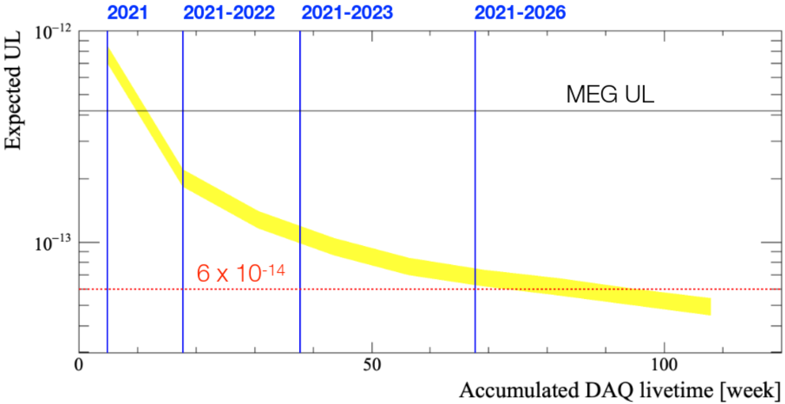
2021/2022 Analysis status

Quantity	MEG	MEG II 2021 (@ 3×10^7 μ^+/s)	MEG II proposal
$\sigma_{t_{e^+\gamma}}$	130 ps	78 ps × 1.6	84 ps
$\sigma_{E_\gamma}/E_\gamma$	1.7%/2.3%	1.7%/2.0%	1.0%/1.1%
σ_{x_γ}	5.0 mm	2.5 mm × 2	2.4 mm
ϵ_γ	63%	64%	69%
$\sigma_{p_{e^+}}$	360 keV/c	90 keV/c × 4	130 keV/c
$\sigma_{\theta_{e^+}}$	9.4 mrad	7.1 mrad × 1.3	5.3 mrad
ϵ_{e^+}	30%	65% ×2.2	70%

Results

Most resolutions are better *by a factor 2* in MEG II with respect with MEG → essential for background rejection!

Sensitivity estimate with 2021 and 2022 data



According to Monte Carlo simulations:

- With 2021 + 2022 data: best sensitivity to $\mu \to e\gamma$ decay $\sim 2 \times 10^{-13}$
- Goal sensitivity 6×10^{-14} is in MEG II's reach (data taking until 2026)

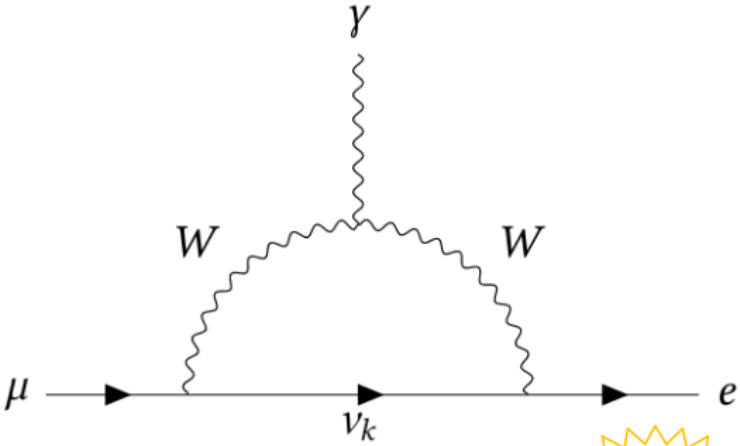
Conclusions

- MEG II experiment started collecting data since 2021… more than 3×10^{14} muons collected so far!
- Detectors have been almost fully calibrated and their performances evaluated on data
- With 2021 + 2022 data a new sensitivity for the search of $\mu \to e\gamma$ has been reached: big effort to publish results before 2024
- MEG II is likely to accomplish its project sensitivity goal of 6×10^{-14}

MEG II results will be a milestone on the road for cLFV search!

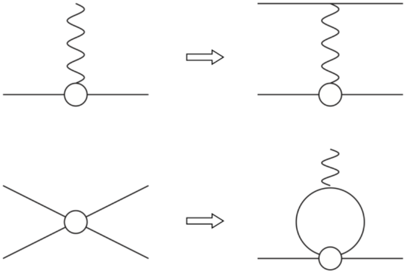
Thank you!

A possible contribution to $\mu \to e\gamma$



$$\mathrm{BR}(\mu \to e\gamma) \approx \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\overline{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{k=1,3} \frac{U_{\mu k}U^{*}_{ek}m^{2}_{\nu_k}}{M^{2}_{W}}\right|^{2} \approx 10^{-54} - 10^{-55}$$

$\mu \to e\gamma$ and other New Physics phenomena



In a *model independent* framework, where the 6-th order lagrangian cLFV operator can be ”4 fermion”-like or ”dipole”-like, all cLFV processes are connected

BR($\mu \to e\gamma$) vs $g-2$

Results on cLFV can help us understand also $g-2$ results

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \cdot \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \cdot \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

Background estimate

Accidental background

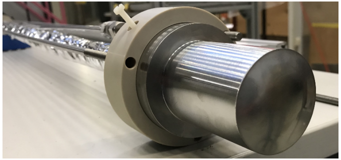
A positron and a photon of high energy coming from two different processes (RMD, annihilation in flight, bremsstrahlung...)

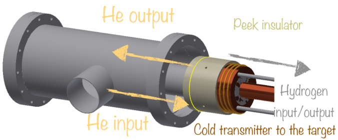
$$\mathcal{R}_{acc} = \mathcal{R}_{\mu}^2 \cdot \delta t_{e\gamma} \cdot \left(\delta E_{\gamma}\right)^2 \cdot \left(\delta \Theta_{e\gamma}\right)^2 \delta E_e$$

LXe calibration procedures

Process		Energy	Purpose
Charge exchange	$\pi^- p \to n\pi^0$ $\pi^0 \to \gamma\gamma$	55, 83 MeV	Energy scale
C-W accelerator	^{7}Li(p,γ)^{8}Be ^{11}B(p,γ)^{12}C	14.8, 17.6 MeV 4.4, 11.6, 16.1 MeV	Energy scale
α source	^{241}Am(α, γ)^{237}Np	4.6 MeV	PDE calibration
LED		UV light	Gain calibration
Cosmic rays	$\mu^{\pm}$	$\mathcal{O}(10^{2-3}$ MeV)	L-Y Monitor

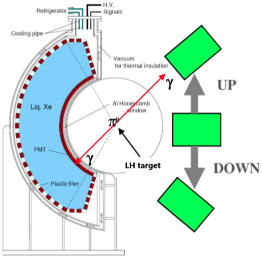
LXe calibration: CEX





$$\pi^- p \to n\pi^0$$

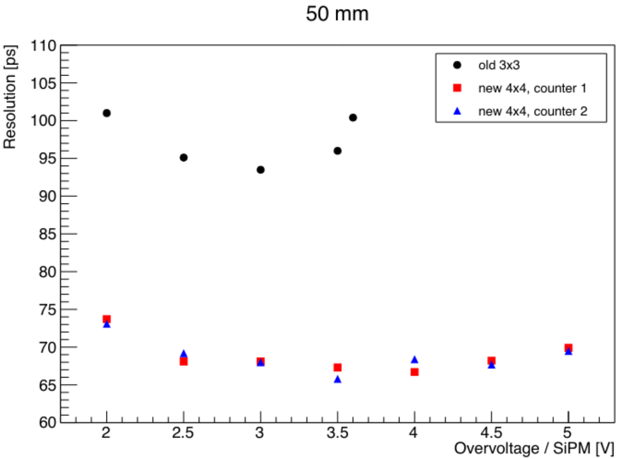
- tune MEG II beam line to select π^-
- p from a LH_2 target inserted at the center of COBRA



Trigger on anti-parallel γ using an auxiliary BGO detector:

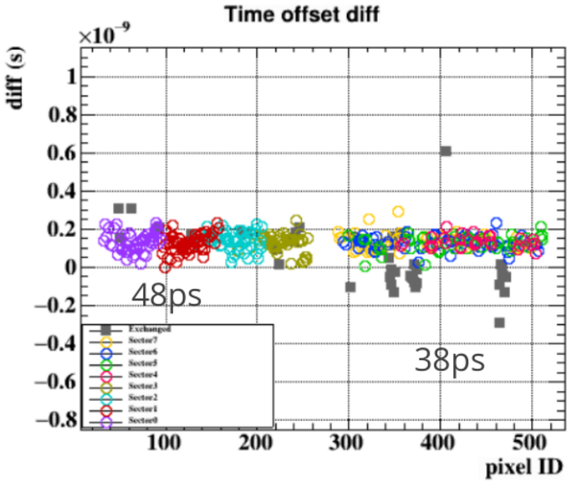
- 55 and 83 MeV lines for energy calibration
- time calibration from $\Delta_{\gamma\gamma}$ measurement

pTC: UPGRADE



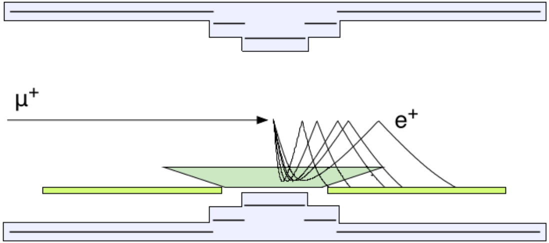
- aging effects on pTC tiles
- Replace most damaged scintillator tiles and SiPM
- New $4 \times 4\text{mm}^2$ SiPM for improved resolution

pTC calibration

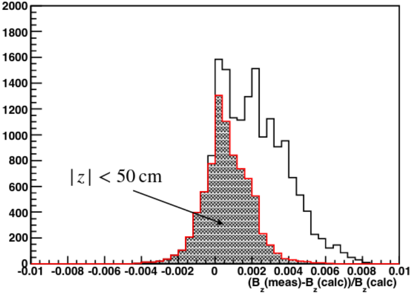


- Laser calibration of tiles timing in each module
- global calibration using e^+ time of flight from $\mu \to e\nu\bar{\nu}$ decay

COBRA Magnet

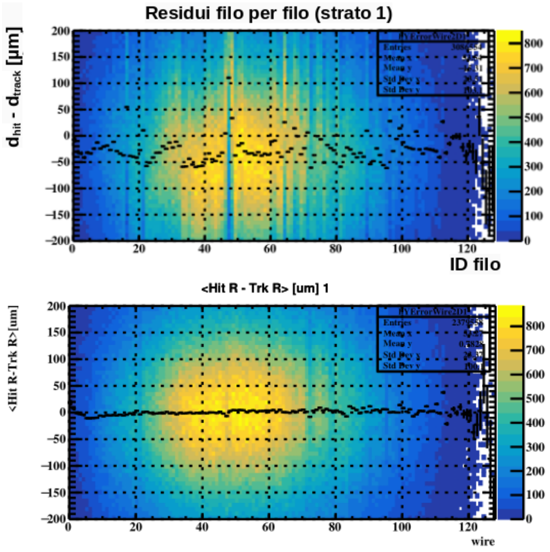


COnstant **B**ending **RA**dius superconductive magnet generates a non solenoidal gradient field with $|B|_{max} = 1.26$ T.



Two different maps for B field in tha analysis software: one based on a survey, one based on Maxwell equations. The agreement is at the *per mille* level

CDCH: ALIGNMENT



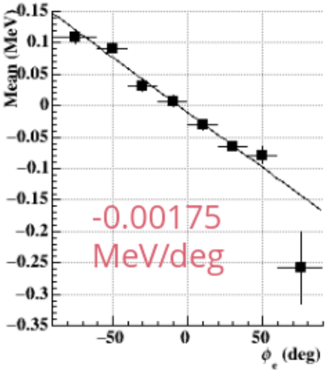
Method

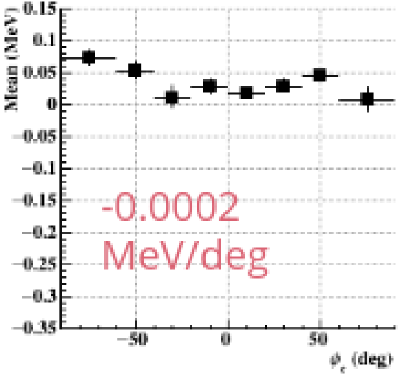
- Iterative alignment procedure to minimize $d_{track} - d_{hit}$ residuals using tracks from $\mu \to e\nu\overline{\nu}$ decay ✓
- MillePede alignment with cosmic tracks (ongoing)

Results

- $d_{track} - d_{hit}$ was 190 μm, now is 140 μm
- Improved angular and z resolutions

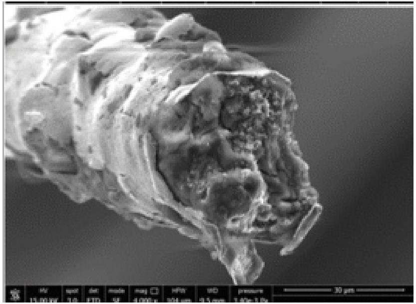
CDCH: COBRA tuning





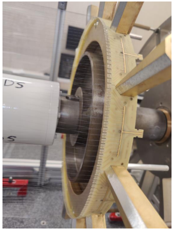
Data-driven tuning of CDCH position with respect to COBRA to correct for reconstruction asymmetries: $|x_{shift}| \sim |y_{shift}| \approx 100$ µm, $|z_{shift}| = 300$ µm

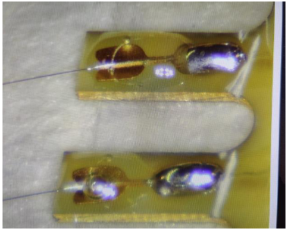
CDCH2



Lot of struggles with CDCH construction (wire breaking): a second, improved, cylindrical drift chamber is being built and may be installed in 2024

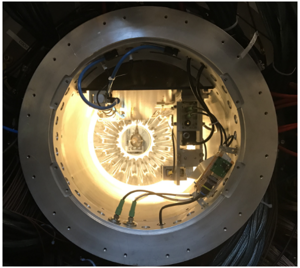
- Al(Ag) 40 µm cathode wires replaced with Al 50 µm cathode wires
- soldering and *glueing*
- 10 layers instead of 9

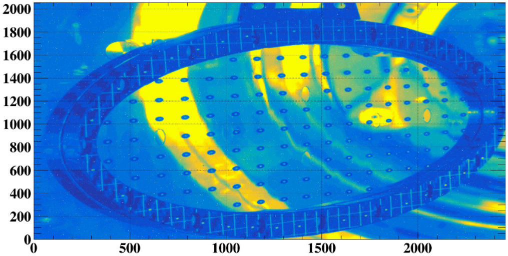




Target monitoring

Use cameras for constant monitoring of target position and **deformations**: this was the largest systematic error in MEG





Method's precision

$\sigma_z \approx 50\ \mu m$, $\sigma_x \approx \sigma_y \approx 10\ \mu m$