# The MEG II experiment: status and perspectives

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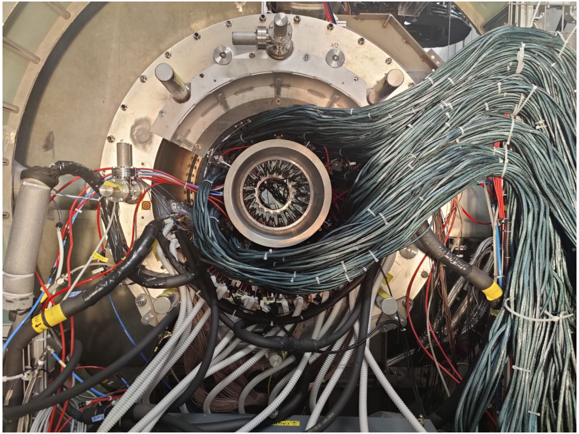
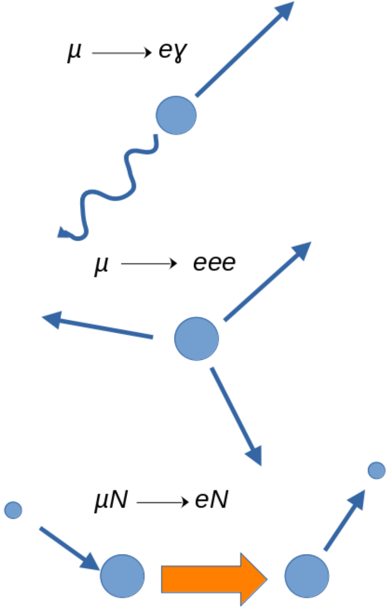
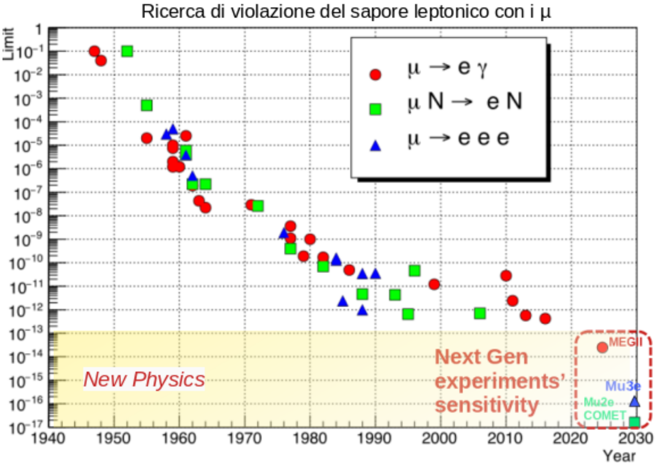
# Summary



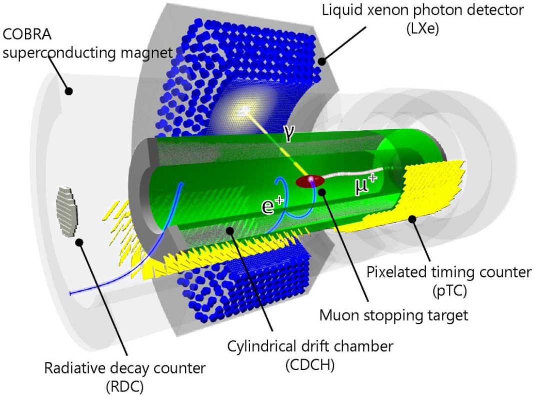
- The search for $\mu \to e^+\gamma$: the MEG II experiment
- Detector scheme of MEG II
- Analysis strategy
- The data taking and first Physics Results with 2021 data
- Other searches for cLFV @ MEG II

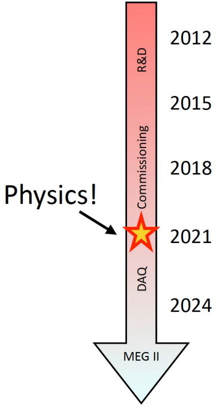
# The search for cLFV: history



# MEG II OVERVIEW



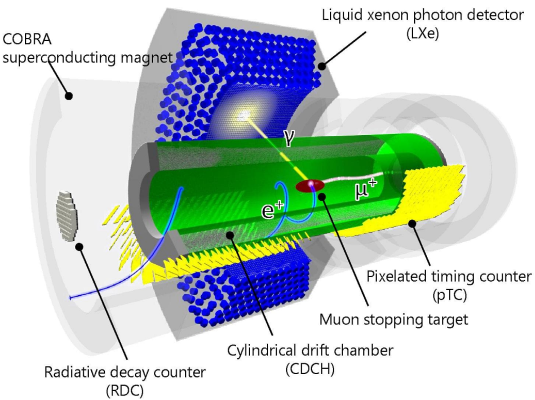

**MEG II Sensitivity in 2021**

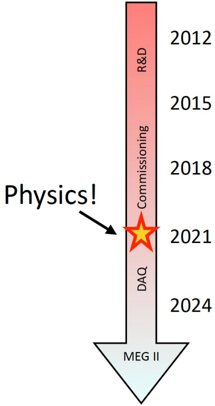
$BR(\mu \to e\gamma) < 8.8 \times 10^{-13}$ @ 90% CL (with 2021 dataset)

**MEG II goal**

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

# MEG II overview

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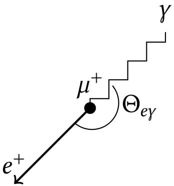
# EXPERIMENTAL SEARCH FOR $\mu \to e\gamma$

## Signal characteristics: Two-body decay




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

## Experimental background

a) muon radiative decay $\mu^+ \to e^+ \nu\bar{\nu}\gamma$

b) accidental coincidence between positrons and high energy $\gamma$ from bremsstrahlung, RMD, annihilation (dominant, $\sim 90\%$)

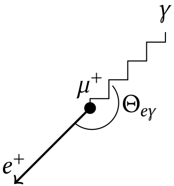
$$\mathcal{R}_{acc} = \overset{\text{Muon rate}}{\mathcal{R}_\mu^2} \cdot \overbrace{\delta t_{e\gamma} \cdot \left(\delta E_\gamma\right)^2 \cdot \left(\delta \Theta_{e\gamma}\right)^2 \delta E_e}^{\text{Experimental resolution}}$$

## Sensitivity determined by:

- Number of stopped muons: $SES \propto N_\mu^{-1}$
- experimental resolutions

# Experimental search for $\mu \to e\gamma$

## Signal characteristics: Two-body decay

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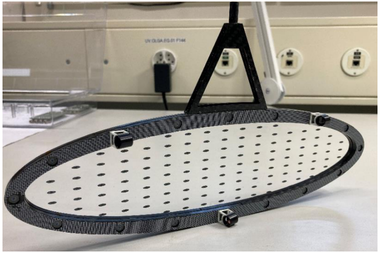
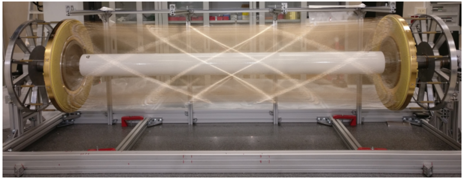
# MEG II: Muon beamline and target


- @Paul Scherrer Institute: 590 MeV proton cyclotron (up to 2.2 mA current). Protons impinge on a carbon target to produce muons and pions
- Dedicated accelerator line to select low momentum muons $p_\mu \approx 28$ MeV/c
- Most intense continuous muon beam in the world. For MEG II: $3 - 5 \times 10^7\ \mu^+/\mathrm{s}$

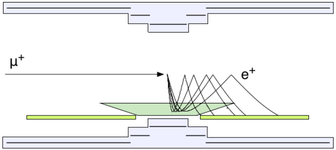


- Thin ($\approx 174$ µm) plastic target to stop muons at the center of the experiment
- Holes and markers for alignment and deformation monitoring → control systematics

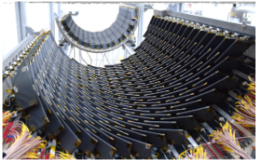
# MEG II: Spectrometer



Cylindrical Drift Chamber




COBRA superconducting magnet



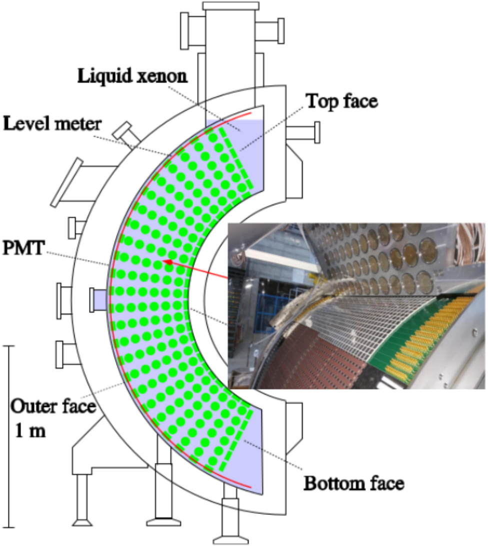
pixelated Timing Counter

- Single volume drift chamber. (Gas: 90:10 He:$C_4H_{10}$ + 1.5% isopropyl + 0.5% $O_2$)
- **1728 anode wires** (cell size ~ 7 mm)
- **Super light**: $d = 2.4 \times 10^{-4}\ X_0$
- Minimizes multiple scattering → **good angular and momentum resolution**

- gradient B field
- $|B| \in [0.05, 1.26]$ T
- track radius $\propto |\vec{p}|$
- reduces *occupancy*: MAX 3 turns, $|\vec{p}| < 45$ MeV out of acceptance

- Hyper segmented: **1024** scintillating tiles
- Fast response: use $t_e$ for trigger
- $< \sigma_{t_e} >= 38$ ps

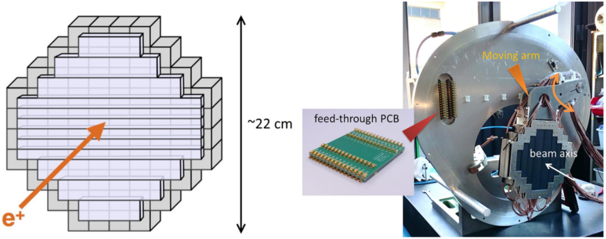
# MEG II: Liquid Xenon detector

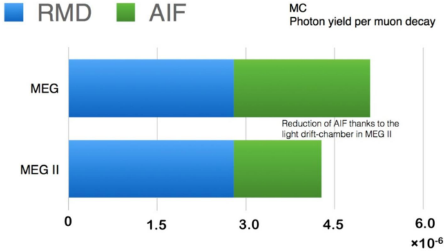



- Homogeneous photon detector ("C-shape")
- Xenon scintillation: High Light Yield (40 $\gamma$/keV), fast (4/22/40 ns) $\rightarrow$ **good time and energy resolution**
- Hyper-segmented read-out: > 4000 SiPMs + 700 PMTs $\rightarrow$ **good position resolution**
- Uniform performances of the detector

# MEG II: Radiative Decay Counter

- 76 LYSO crystals (energy measurement)
- 12 scintillating bars (time measurement)
- Located Downstream

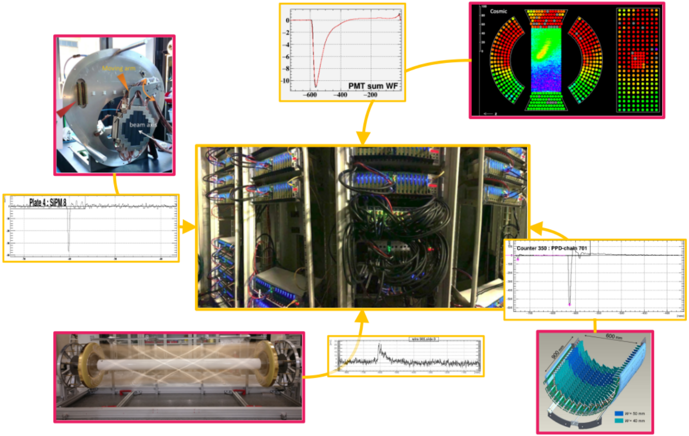



**AIF** Hyper-light tracker reduces the contribution from $e^+e^- \to \gamma\gamma$

**RMD** **RDC** will identify $e^+$ on-time with a $\gamma$ in the LXe, **improving background rejection**

# MEG II: Trigger & DAQ



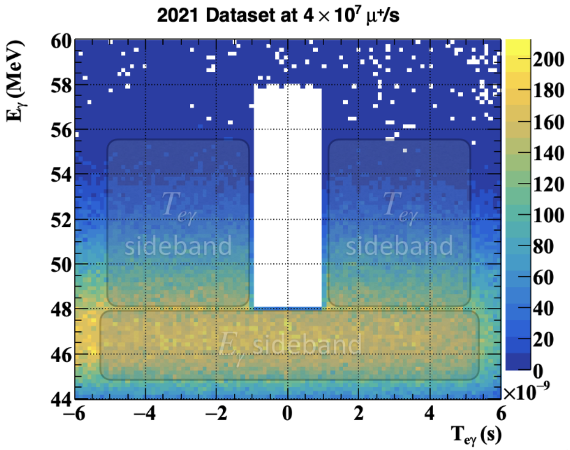

- Integrated Trigger & DAQ system.
- $>$ 9000 **waveforms** from detectors digitalized for offline reconstruction

## MEG II Trigger Logic

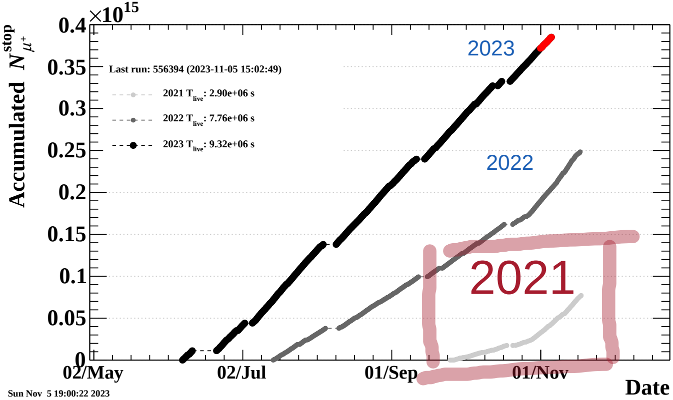
- $E_\gamma > 42$ MeV
- $-12.5$ ns $< \Delta T_{e^+\gamma} <$ 7 ns (2021)
- ”Direction match” (cut on $e\gamma$ relative angle)

# Analysis Strategy

- $BR(\mu \to e\gamma)$ extracted from a **Maximum Likelihood fit** in the signal region ($< 5\sigma$)
- Each event parameterized using 5 variables ($E_\gamma$, $E_e$, $t_{e\gamma}$, $\phi_{e\gamma}$, $\theta_{e\gamma}$) that discriminates signal and background
- Confidence intervals for the Number of $\mu \to e\gamma$ events estimated with the **Feldman-Cousins** strategy
- **Blind Analysis**: number of background events and PDF parameterization (RMD e Accidental) determined in the **side-bands** $E_\gamma$ and $t_{e\gamma}$



# MEG II data taking: Stopped Muons




- **Physics data taking** started in 2021
- In 2022: most muons stopped on target $N_\mu^{stop}$ in $\mu \to e\gamma$ search history
- In 2023: augmented $R_\mu = 4 \times 10^7$, data taking on-going

Data from 2021 run analyzed and presented here!

## 2021 data

$\approx 7 \times 10^{13}$ muons stopped on target in 2 months, varying beam intensity $2 - 5 \times 10^7$ $\mu$/s

# 2021 Analysis status

| Quantity | MEG | MEG II 2021 (@ $3 \times 10^7$ $\mu^+$/s) | MEG II proposal |
|---|---|---|---|
| $\sigma_{t_{e^+\gamma}}$ | 130 ps | 78 ps $\times$ 1.6 | 84 ps |
| $\sigma_{E_\gamma}/E_\gamma$ | 1.7%/2.3% | 1.8%/2.0% | 1.0%/1.1% |
| $\sigma_{x_\gamma}$ | 5.0 mm | 2.5 mm $\times$ 2 | 2.4 mm |
| $\epsilon_\gamma$ | 63% | 62% | 69% |
| $\sigma_{E_{e^+}}$ | 360 keV/c | 89 keV $\times$ 4 | 130 keV/c |
| $\sigma_{\theta_{e^+}}$ | 9.4 mrad | 7.1 mrad $\times$ 1.3 | 5.3 mrad |
| $\sigma_{\phi_{e^+}}$ | 8.7 mrad | 4.1 mrad $\times$ 2.1 | 3.7 mrad |
| $\epsilon_{e^+}$ | 30% | 67% $\times$2.2 | 65% |
| $\epsilon_{TRG}$ | 97% | 80% | 99% |

### Results

Most resolutions are better *by a factor 2* in MEG II with respect with MEG → essential for background rejection!
See pre-print of the MEG II detector paper at https://arxiv.org/abs/2310.11902

# MEG II Normalization

$$\mathrm{BR}(\mu \to e\gamma) = \hat{N}_{e\nu}/N_\mu$$

$N_\mu$ is measured with two methods:

- counting number of detected positrons from $\mu \to e\nu\bar{\nu}$ decay:

$$N_\mu = \frac{N_e}{f_E^{e\nu\bar{\nu}}} \times \frac{\epsilon_{e\gamma}}{\epsilon_e^{e\nu\bar{\nu}}} \times \frac{\epsilon_{TRG}^{e\gamma}}{\epsilon_{TRG}^{e\nu\bar{\nu}}} \times \mathcal{A}_{GEO} \times \epsilon_\gamma \times P^{e\nu\bar{\nu}}$$

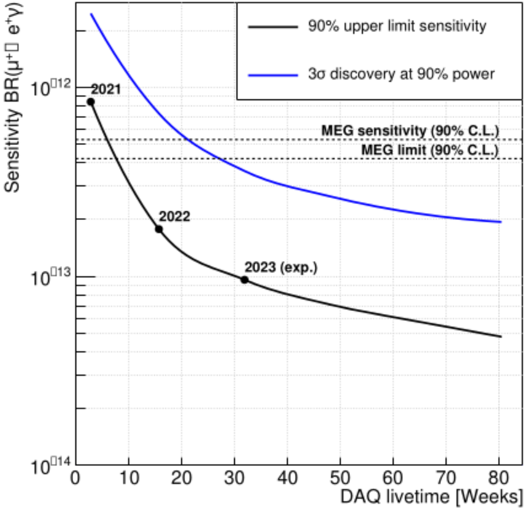
- From sideband fits to the number of RMD decays

$$N_\mu = \frac{N_e}{\mathrm{BR}(e\nu\bar{\nu}\gamma)} \times \frac{\epsilon_e^{e\gamma}}{\epsilon_e^{e\nu\bar{\nu}\gamma}} \times \frac{\epsilon_{TRG}^{e\gamma}}{\epsilon_{TRG}^{e\nu\bar{\nu}\gamma}} \times \frac{\epsilon_\gamma^{e\gamma}}{\epsilon_\gamma^{e\nu\bar{\nu}\gamma}}$$

Two methods are compatible: $N_\mu = (2.64 \pm 0.12) \times 10^{12}$

# Sensitivity estimate

Sensitivity = median of the distribution of 90% Upper Limit from 1000 Monte Carlo Toy experiments

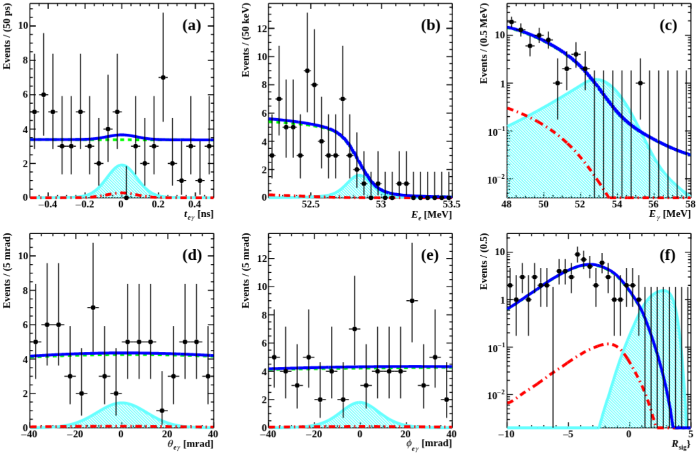



- 2021: $8.8 \times 10^{-13}$ sensitivity: **unblinding done September 1st, 2023**
- With 2021 + 2022 data:
  best sensitivity to $\mu \to e\gamma$ decay BR $\sim 2 \times 10^{-13}$
- Goal sensitivity $6 \times 10^{-14}$ is in MEG II's reach ($\sim$ 70 weeks of DAQ)

# 2021 Analysis Results

## No evidence for $\mu \to e^{+}\gamma$ decay

$\mathrm{BR}(\mu \to e\gamma) < 7.5 \times 10^{-13}$ @90% CL (systematic effects ~ 5%)



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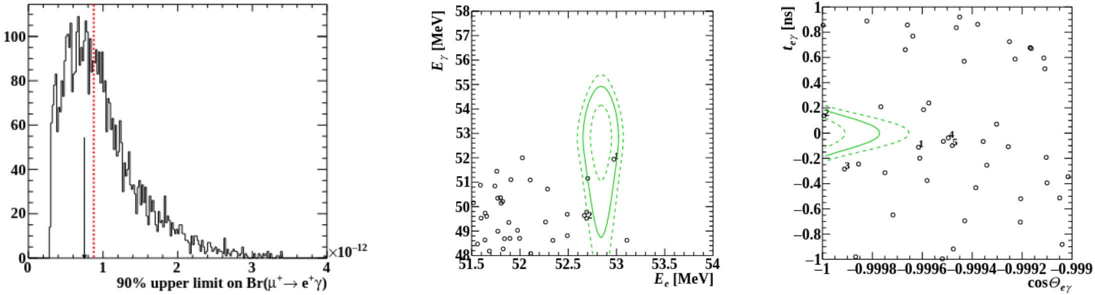
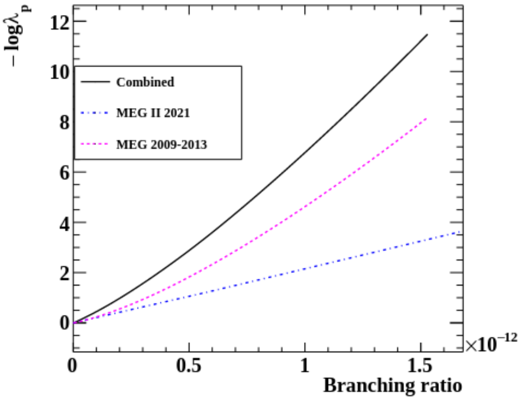


# Combination of MEG and MEG II results



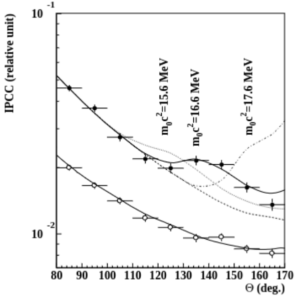

**New limit on BR($\mu \to e\gamma$)**

Combining MEG and MEG II experimental results it is possible to extract more stringent limits:

$$BR(\mu \to e\gamma) < 3.1 \times 10^{-13} \text{ @90\% CL}$$

# Physics beyond $\mu \to e\gamma$: X Boson search

From ATOMKI 2016 paper (1504.01527)

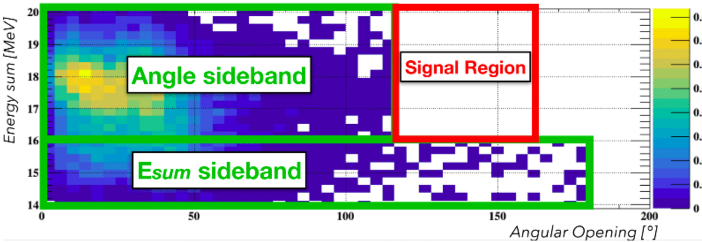



- Analysis of $^7$Li$(p, e^+e^-)^8$Be (Atomki Collaboration, 2016) → evidence for a new resonance compatible with an hypotetical new particel X of mass ≈ 17 Mev/c$^2$
- Evidence for a similar structure also from other experiments
- Many dedicated experiments to validate these results: PADME, MEG II and more

## Physics data taking in 2023 @ MEG II

- 4 weeks of DAQ with Cockroft-Wolton proton accelerator $E_p$=1.080 MeV. 2 μm LiPON target
- 300k $e^+e^-$ pairs tracked
- Blinded Likelihood Analysis to search for a resonance in angular and energy distribution of $e^+e^-$

From H. Benmansour talk @ EPS2023



# Physics beyond $\mu \to e\gamma$: ALP search

## Axion-Like Particles

$$\mathcal{L}_{ALP} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}\sum_f c_f \overline{\psi_f}\gamma^\mu \psi_f + h.c.$$

- **ALP** are pseudo Goldston bosons coming from spontaneous breaking of global simmetries: predicted in many BSM theories, with very large parameter space
- Candidate to solve **strong-CP problem**, **dark matter**, **explain flavor**, etc...
- Can induce cLFV: **search for** $\mu \to ea$**,** $\mu \to ea\gamma$ experimentally feasible

## $\mu \to ea\gamma$ search @ MEG II

As proposed by D. Redigolo et al. (`http://dx.doi.org/10.1007/JHEP10(2022)029`), MEG II could put new limits on the search for axion-like particles with masses < 10 MeV searching for $\mu^+ \to e^+ a\gamma$ signals inside its data

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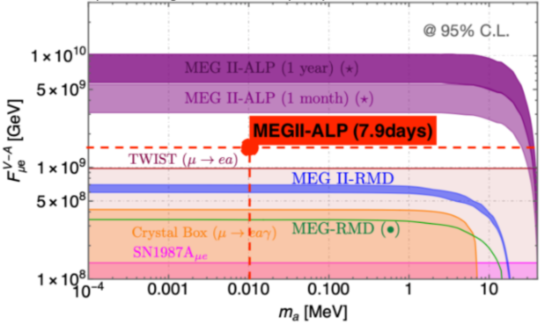
# ALP search @ MEG II: future prospects

**From E. G. Grandoni Master's Thesis:**
***Studio di sensibilità del decadimento cLFV μ → eaγ nell'esperimento MEG II***
Modified from http://dx.doi.org/10.1007/JHEP10(2022)029




- Full Monte Carlo studies confirmed that MEG II experiment can be sensitive to $mu^+ \to e^+ a\gamma$ cLFV channel (E.G.Grandoni Master's Thesis)
- Good sensitivity with few weeks of data taking @$1 \times 10^6\ \mu^+/s$ → new space of parameters explorable with $\sim$ 1 week of dedicated data taking
- Data at low beam intensity ($1 \times 10^6\ \mu^+/s$) already available in MEG II: data analysis on-going

# The Future of MEG II

- MEG II experiment started collecting data in 2021…more than $7 \times 10^{14}$ muons collected so far!
- With 2021 + 2022 data: sensitivity BR($\mu \to e\gamma$) improved by a **factor 2** → a new measurement on this fundamental process
- MEG II results with 2021 data are available at https://arxiv.org/pdf/2310.12614.pdf
- Combination of 2021 data analysis' results with MEG final results puts new limits on BR$(\mu \to e\gamma) < 3.1 \times 10$
- MEG II is likely to accomplish its project sensitivity goal of $6 \times 10^{-14}$
- Experimental measures for other New Physics searches are being conducted @ MEG II:
  - The analysis of the X17 data sample is in advanced status
  - preliminary studies on $\mu \to ea\gamma$ demonstrate that with a dedicated data taking new results are not far away!

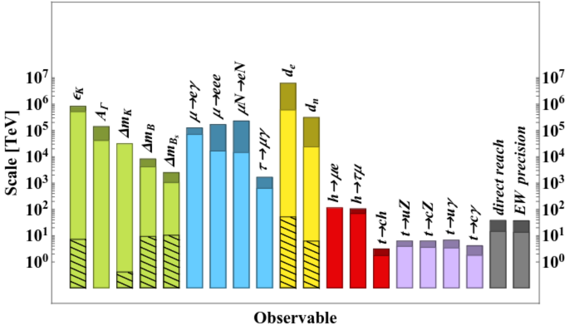
# Beyond the Standard Model with cLFV

Many Standard Model puzzles are linked to the flavor and lepton sector: mass ordering, origin of the flavor, dark matter, Grand Unification... In general, New Physics will always manifest itself (at some level) in inducing cLFV processes.

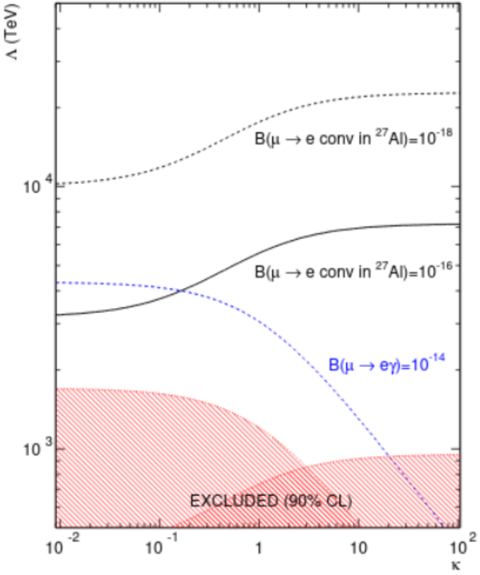
## Effective Field Theory

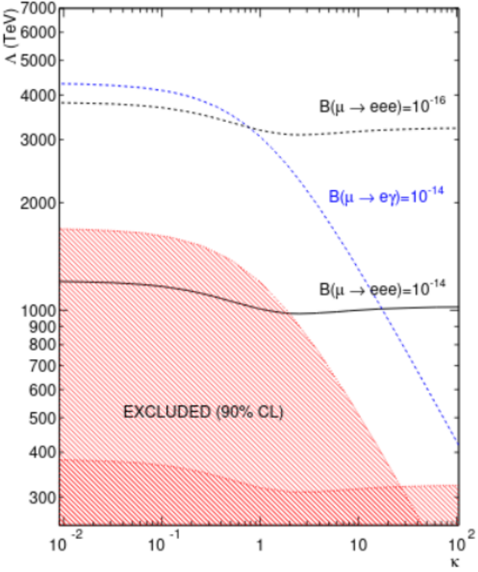
$$\mathcal{L}_{BSM} = \mathcal{L}_{SM} + C^{(5)}\frac{\mathcal{O}^{(5)}}{\Lambda} + \sum_i C_i^{(6)} \frac{\mathcal{O}_i^{(6)}}{\Lambda^2}$$

- cLFV processes sensitive to $\mathcal{O}^{(6)}/\Lambda^2$ operators (dipole or 4-fermions)
- Probing very high energy scale for $\Lambda$ in a very pure way (no suppression from other phenomena), complementary to other searches at colliders

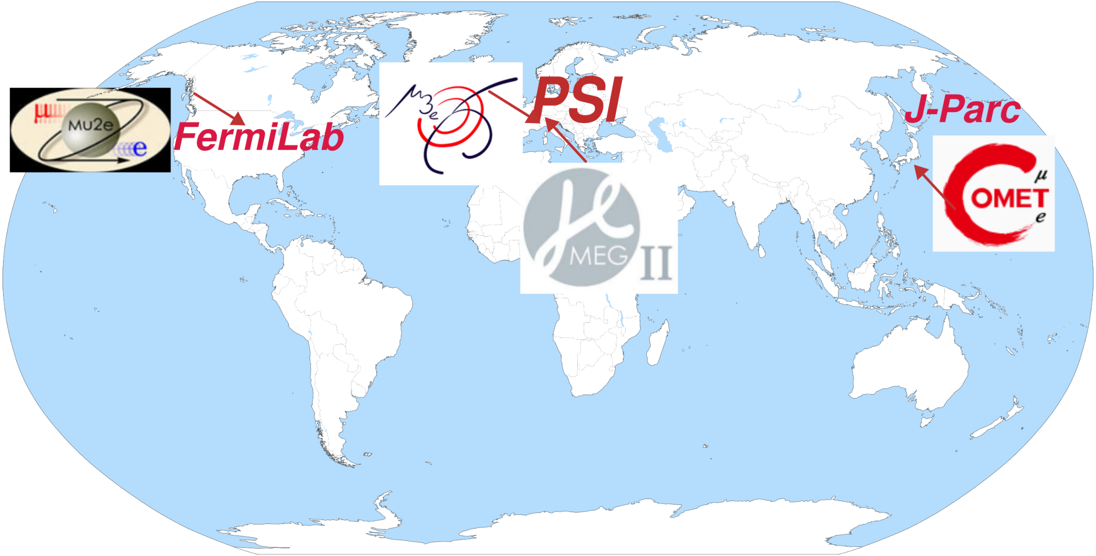


# $\mu \to e\gamma$ VS $\mu \to 3e$ & $\mu N \to eN$



# Experimental search for cLFV

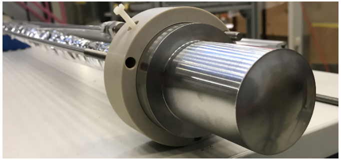


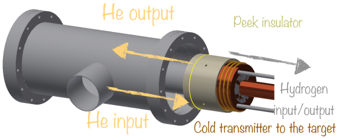
# Liquid Xenon Detector calibration

- Regular monitoring of PDE & Light Yield & Gain
- Energy scale determined with:
  - $\gamma$ 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)

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

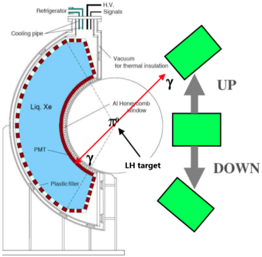
# LXe calibration: CEX






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

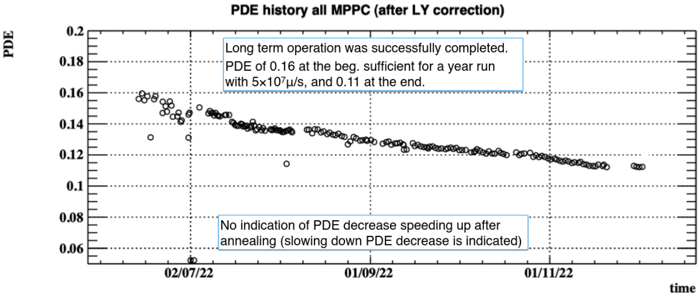
- tune MEG II beam line to select $\pi^-$
- $p$ from a $LH_2$ target inserted at the center of COBRA

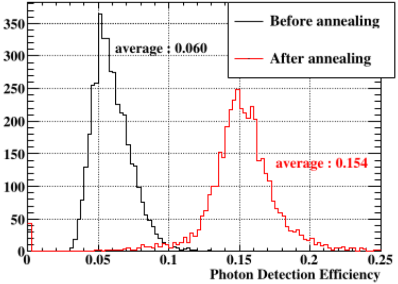



Trigger on anti-parallel $\gamma$ using an auxiliary BGO detector:

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

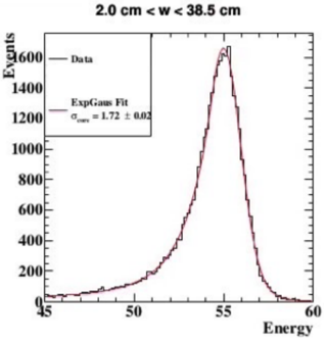
# Liquid Xenon detector: Maintenance

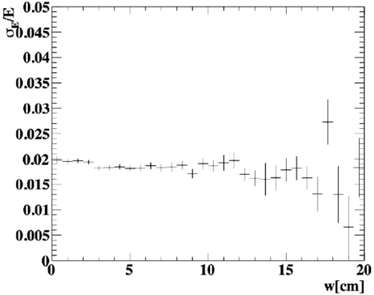



The degradation of SiPM's PDE after beam irradiation has been observed.
An annual annealing procedure is carried on to recover the PDE. The annealing is done heating the SiPM through Joule effect. The procedure has been succesfull in 2022.

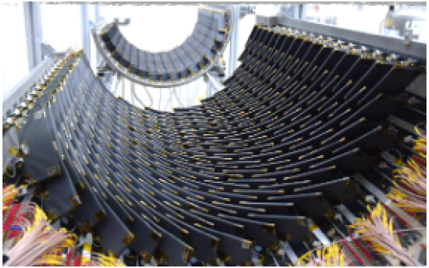
# Liquid Xenon detector: performances




| 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] | $65 \pm 6$ | ✓ |
| Detection Efficiency [%] | 64% | ∼ (5% off) |

# The pixelated Timing Counter

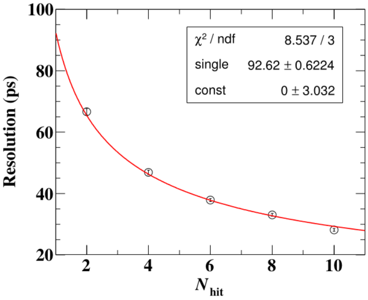


- Highly segmented timing detector (512 scintillating tiles)
- SiPM readout
- Improved $e^+$ timing resolution

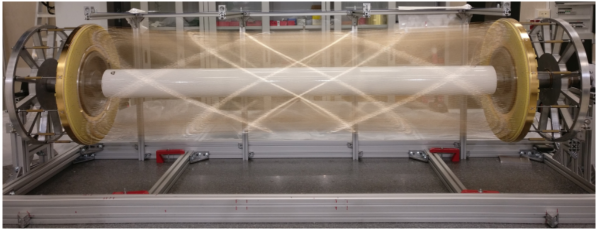
**Timing resolution**

Timing resolution compatible with design project

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

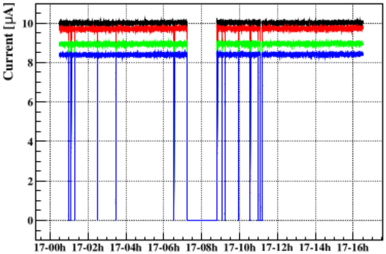


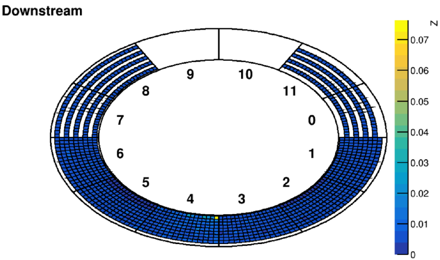
# Cylindrical Drift Chamber



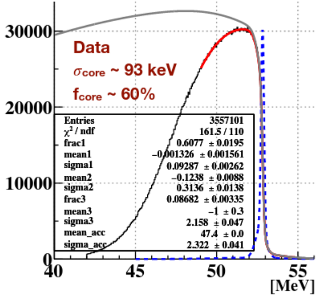
- Single volume ultra-light drift chamber
- mixture: 90:10 He : isobutane + 1.5% isopropanol + 0.5% $O_2$
- Highly segmented: 1728 anodes, $< 4 \times 4\ \text{mm}^2$ drift cells
- Rejects $e^+$ with $E_{e^+} \lesssim 45$ MeV

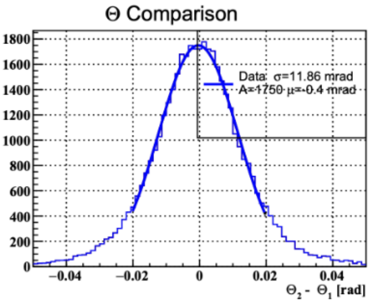
Very stable operation conditions during 2021 and 2022 runs



# CDCH: PERFORMANCES



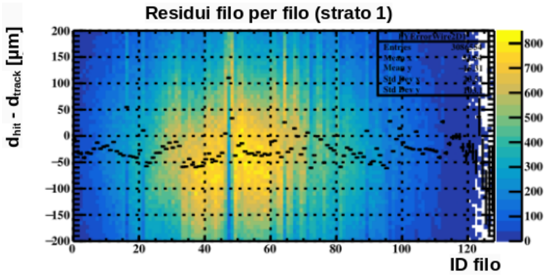



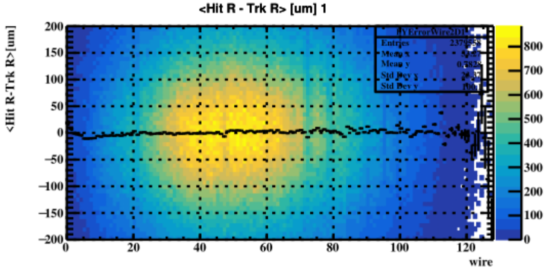

| Quantity | Resolution | agree with MC |
|---|---|---|
| $p_{e^+}$ | 90 keV/c | ✓ |
| $\phi_{e^+}$ | 6.8 mrad | $\sim$ (10% off) |
| $\theta_{e^+}$ | 7.1 mrad | $\sim$ (10% off) |
| $z$ | 1.85 mm | ✓ |
| $\epsilon_{e^+}$ | 65% | $\sim$ (10% off) |

## Calibrations & systematics search

- Iterative alignment
- Magnetic field corrections

# CDCH: ALIGNMENT



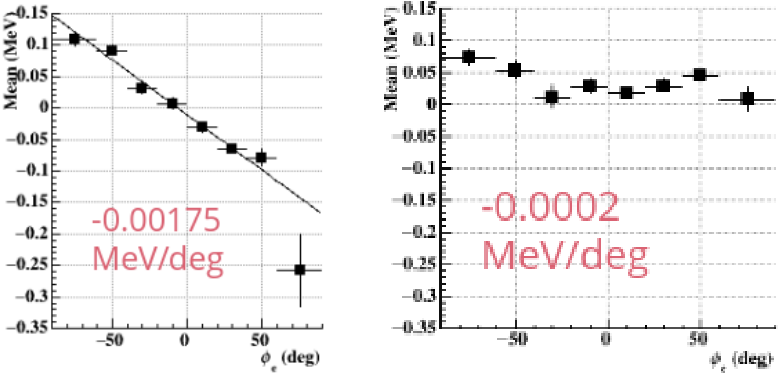

## Method

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

## Results

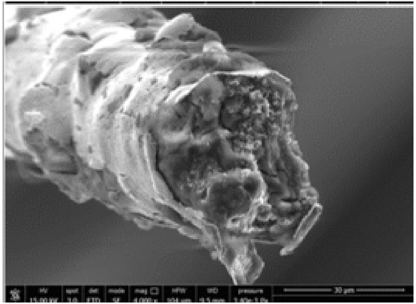
- $d_{track} - d_{hit}$ was 190 µm, now is 140 µm
- Improved angular and $z$ resolutions

# CDCH: COBRA TUNING



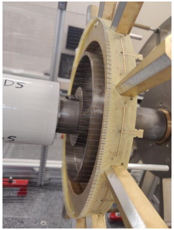

Data-driven tuning of CDCH position with respect to COBRA to correct for reconstruction asymmetries: $|x_{shift}| \sim |y_{shift}| \approx 100$ µm, $|z_{shift}| = 300$ µm

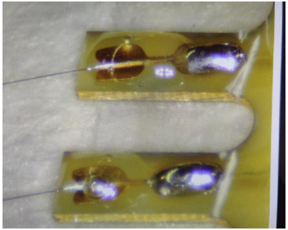
# CDCH2



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

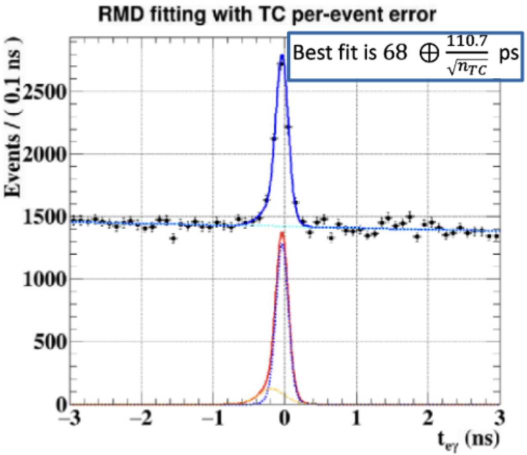




# Resolution on $t_{e^+\gamma}$

## Calibration

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



# Trigger performances

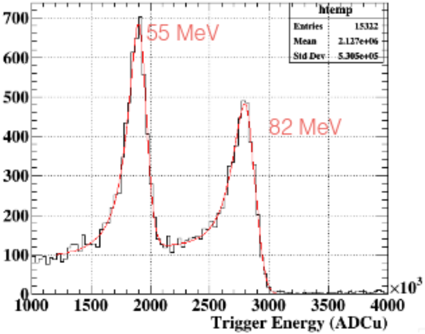



Figure: Photon energy spectra reconstructed online during CEX calibration using $\pi^0 \to \gamma\gamma$

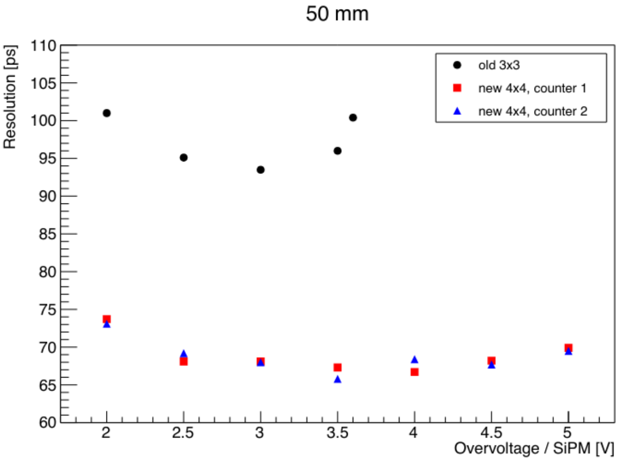
## Trigger logic

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

## The trigger performances

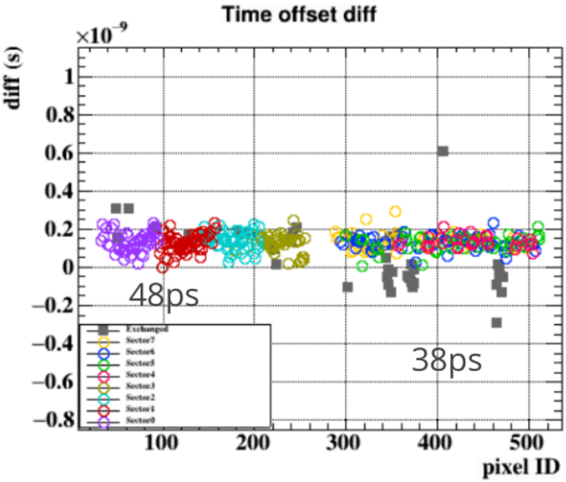
- Online energy resolution $\sim 3 - 4\%$
- Overall trigger efficiency $\gtrsim 90\%$
- Trigger rate @$3 \times 10^7$ $\mu^+/s \approx 20$ Hz

# pTC: UPGRADE



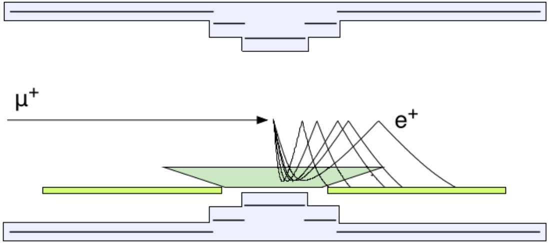

- aging effects on pTC tiles
- Replace most damaged scintillator tiles and SiPM
- New $4 \times 4mm^2$ SiPM for improved resolution

# pTC calibration

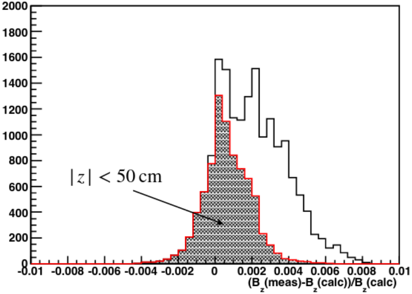



- Laser calibration of tiles timing in each module
- global calibration using $e^+$ time of flight from $\mu \to e\nu\bar{\nu}$ decay

# COBRA MAGNET



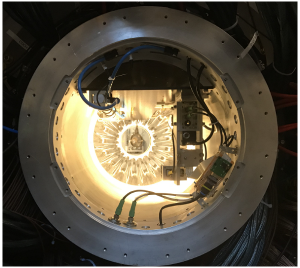

**CO**nstant **B**ending **RA**dius superconductive magnet generates a non solenoidal gradient field with $|B|_{max} = 1.26$ T.

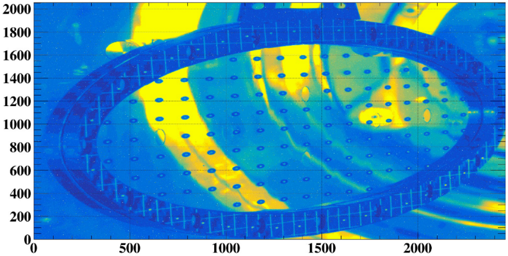



Two different maps for B field in tha analysis software: one based on a survey, one based on Maxwell equations. The agreement is at the *per mille* level

# Target monitoring

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

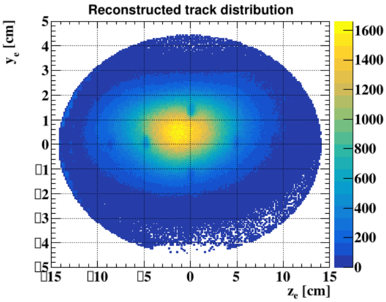


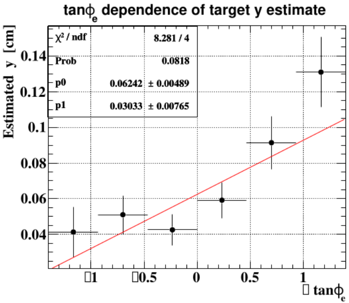


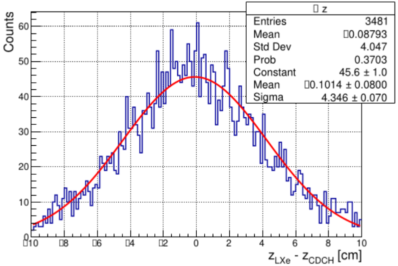

**Method's precision**

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

# Target and CDCH - LXe alignment

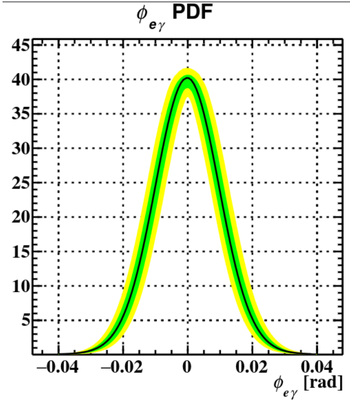


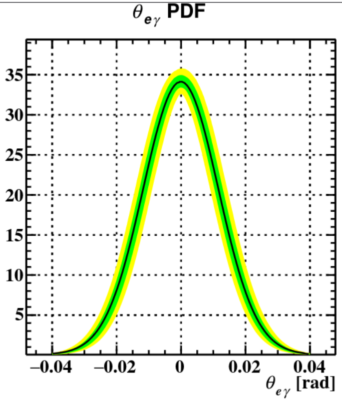




- Cosmic rays event for CDCH - LXe alignment
- Dedicated cosmic reconstruction
- $\Delta z = -1.0 \pm 0.8$ mm

# Systematics in the analysis

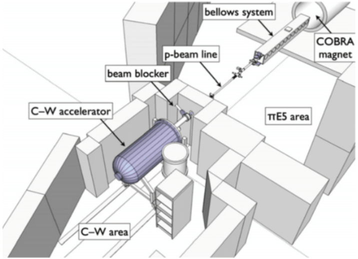


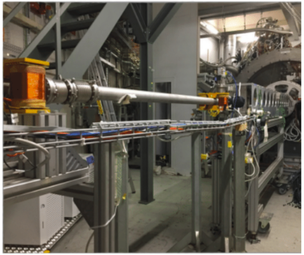



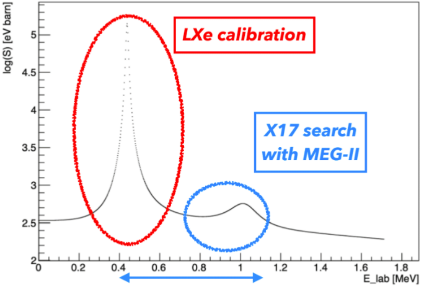

Larger systematics (accounting for 5% loss in sensitivity) are:

- Target and CDCH - LXe misalignment
- Photon energy scale
- Normalization

# X17 SEARCH: CW

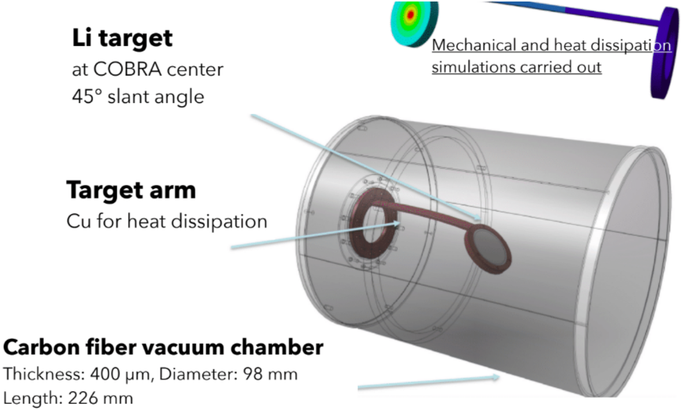





From H. Benmansour talk at EPS2023

# X17 SEARCH: TARGET




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

From H. Benmansour talk at EPS2023

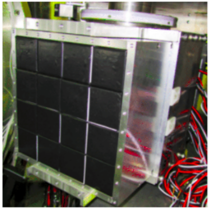
# X17 search: auxiliary detectors

From H. Benmansour talk at EPS2023

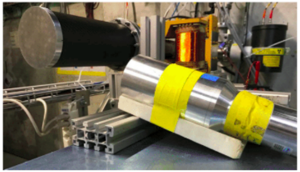
- Two additional gamma detectors

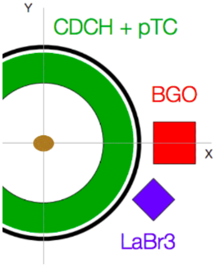
→ Stability monitoring → Signal normalisation → Daily monitoring

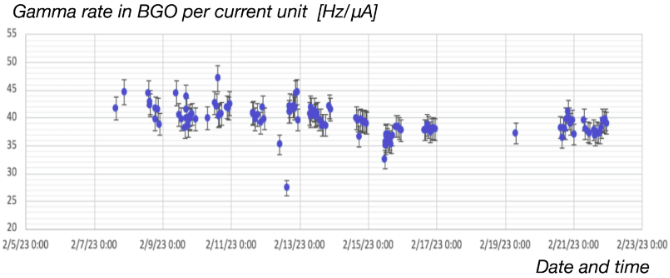
Bismuth Germanate (BGO) crystal matrix (4x4)



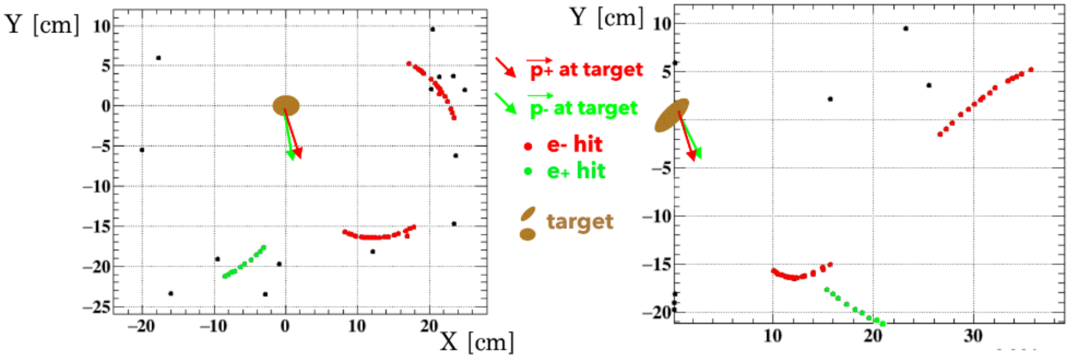
Lanthanum Bromide (LaBr3) crystal





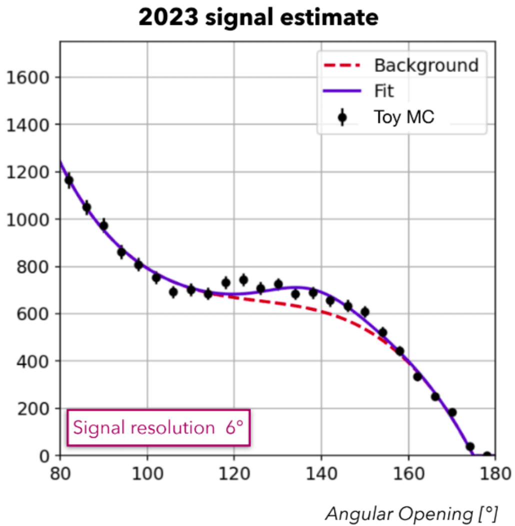



# X17 SEARCH: $e^+e^-$ TRACKING




From H. Benmansour talk at EPS2023

# X17 SEARCH: ANGULAR RECONSTRUCTION




From H. Benmansour talk at EPS2023