The MEG II experiment & perspectives on lepton physics at PSI

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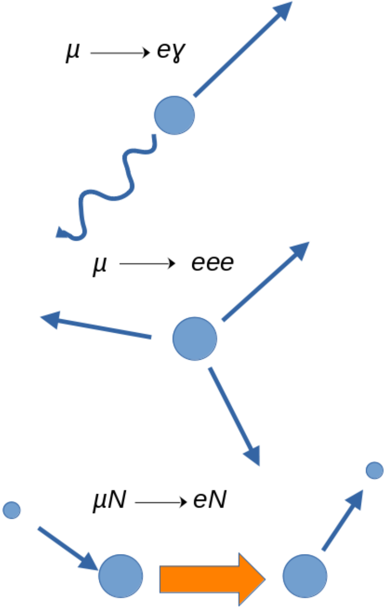
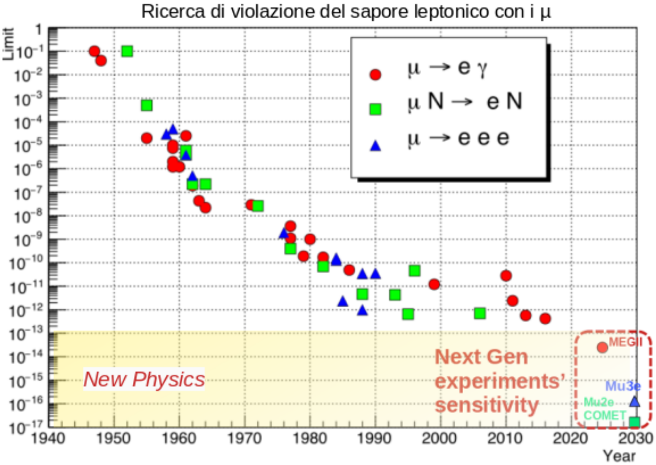
Summary

- charged Lepton Flavor Violating searches at PSI:
  - Present: MEG II status
  - Future: accelerator upgrade & new perspectives for future experiments
- A new method to search for the μ Electric Dipole Moment:
  - The muEDM experiment

The search for cLFV: history





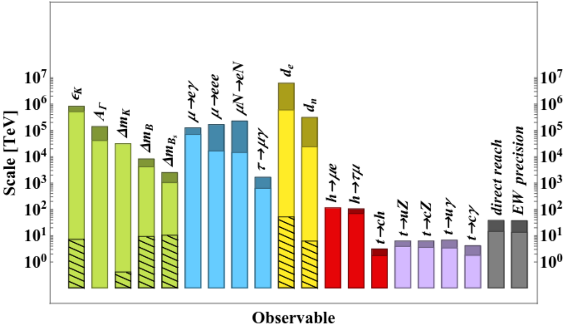
Beyond the Standard Model with cLFV

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) inducing cLFV processes.

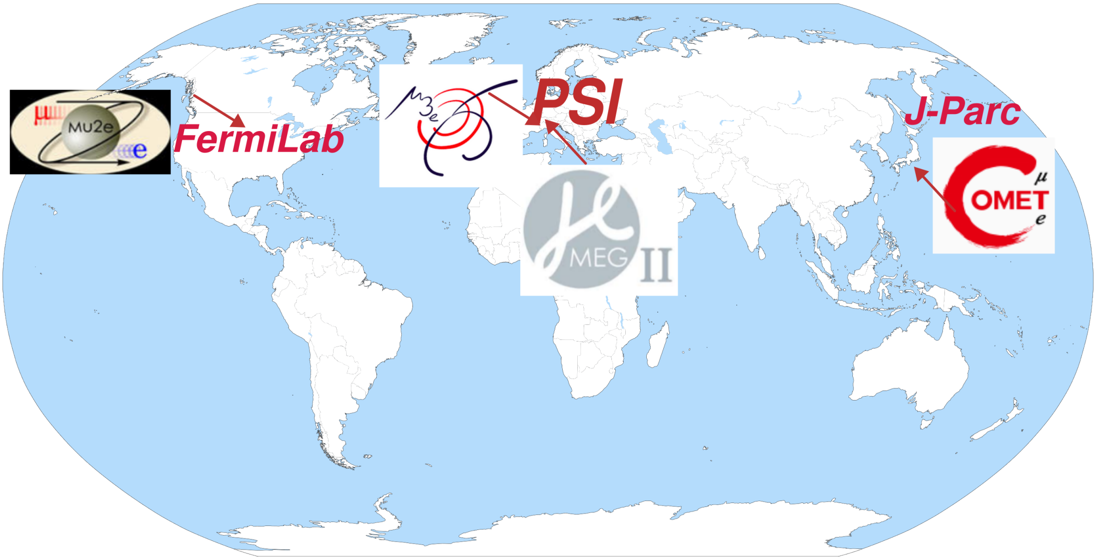
Effective Field Theory

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

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

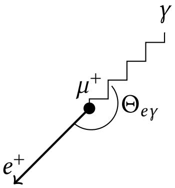


Experimental search for cLFV



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 $\mu^+ \to e^+ \nu \bar{\nu} \gamma$

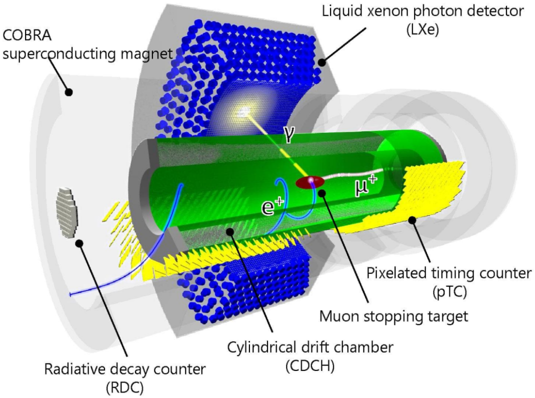
b) accidental coincidence between positrons and high energy γ from bremsstrahlung, RMD, annihilation (dominant, $\sim 90\%$)

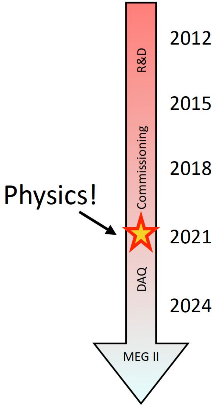
$$\mathcal{R}_{acc} = \overbrace{\mathcal{R}_\mu^2}^{\text{Muon rate}} \cdot \overbrace{\delta t_{e\gamma} \cdot (\delta E_\gamma)^2 \cdot (\delta \Theta_{e\gamma})^2 \, \delta E_e}^{\text{Experimental resolution}}$$

Sensitivity determined by:

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

MEG II overview





MEG II Coll., "The design of the MEG II experiment" (2018)

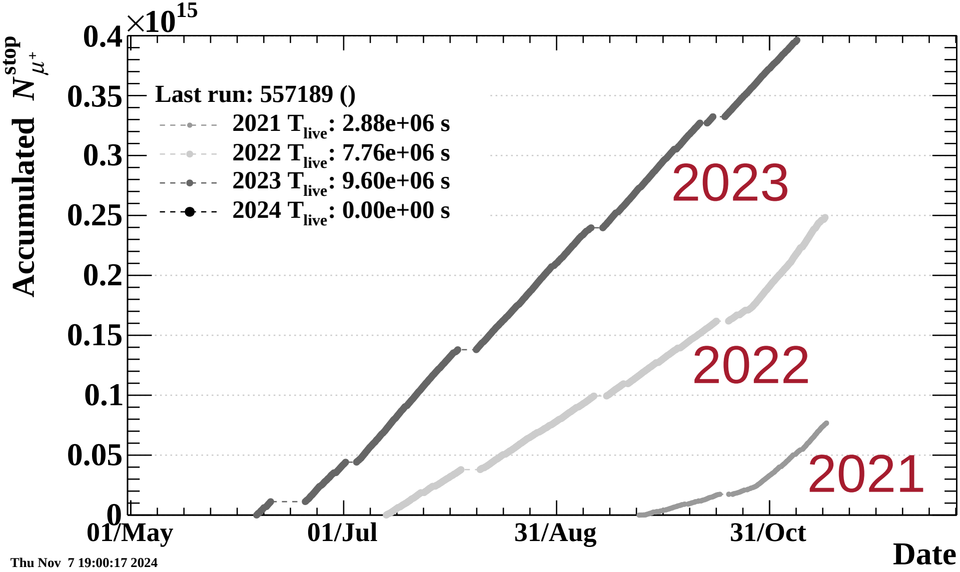
MEG II Results with 2021 dataset

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

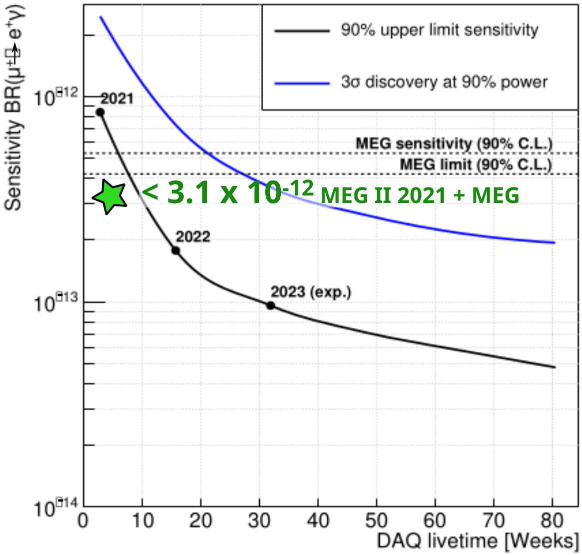
MEG II goal

6×10^{-14} sensitivity

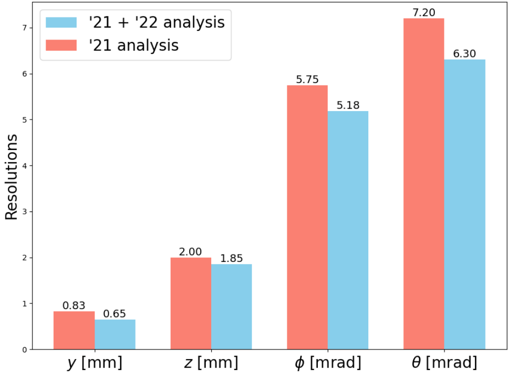
MEG II data taking status



MEG II perspectives

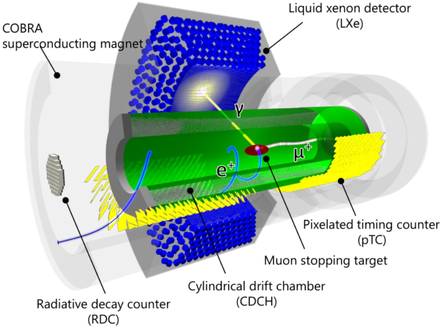


- Best BR($\mu^+ \to e^+\gamma$) limit with combination of 2021 MEG II dataset + MEG results
- 2022 statistics = ×3 2021
- Boost in sensitivity also from **analysis improvements**

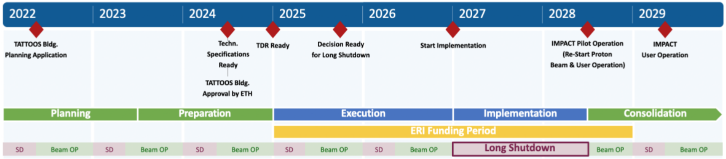


MEG II schedule

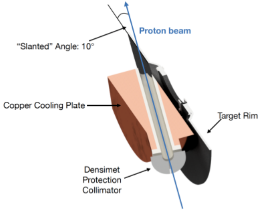
- Physics data taking for 2024 ongoing
- Analysis of 2021 + 2022 data coming soon:
  - Detectors calibrated
  - Likelihood fit function built
  - Preparing for unblinding
- And more from the search for other exotic processes:
  - ALPs search $\mu \to e a \gamma$: talk by E. G. Grandoni
  - X17 search: first results presented here by Hicham Benmansour

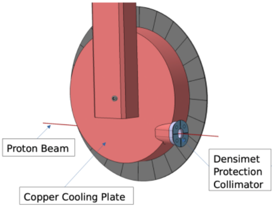


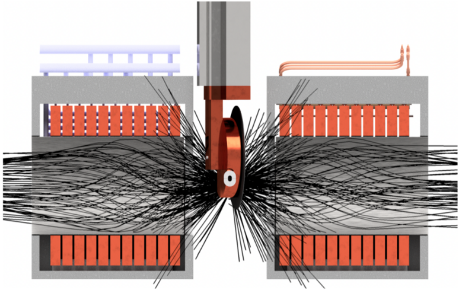
PSI muon facility upgrade: HiMB



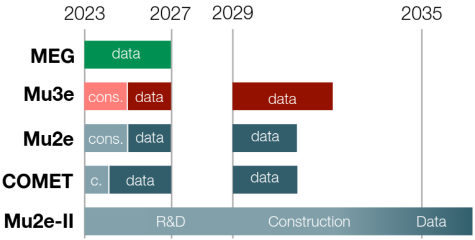
- Upgrade of μ^+ production target & transport beam lines
- **Goal:** $\mathcal{O}(10^8\ \mu^+/s) \to \mathcal{O}(10^{10}\ \mu^+/s)$
- PSI Long Shutdown scheduled for Jan. 2027 → 2028

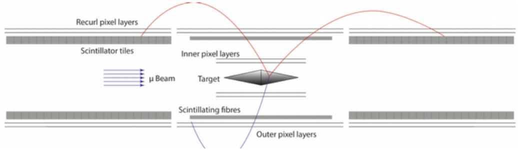






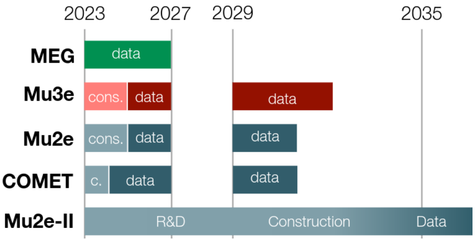
$\mu \to e\gamma$ VS $\mu \to 3e$ & $\mu N \to eN$

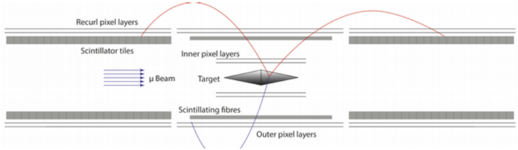


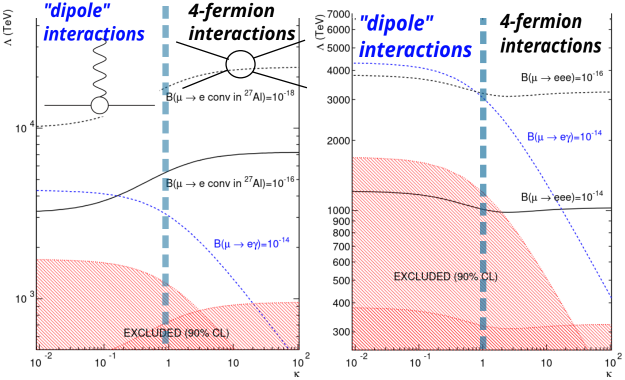


- Mu3e Phase-II will exploit the new HiMB facility to get to a final sensitivity of $\mathrm{BR}(\mu \to eee) \lesssim 10^{-16}$

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





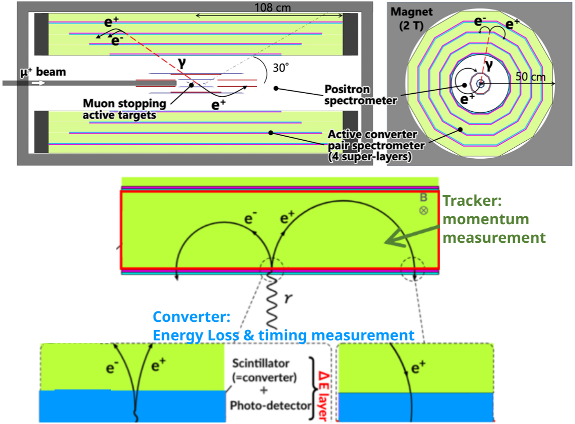


PDG, "Tests of Conservation Laws" (2024)

- Mu3e Phase-II will exploit the new HiMB facility to get to a final sensitivity of $\mathrm{BR}(\mu \to eee) \leq 10^{-16}$
- Different cLFV processes are sensitive to different NP observables

R&D for future $\mu \to e\gamma$ experiments

Future $\mu \to e\gamma$ experiments call for new technologies to improve the sensitivity



- Background grows as (beam rate)^2: higher sensitivity @ higher beam rates only if resolutions improve!
- R& D from MEG II and Mu3e collaborators
- **tracking *à la Mu3e***: pixels (< 50 µm thickness) to cope with high rates
- **photon reconstruction**: pair conversion
  - active LYSO converter: Energy resolution $\frac{\Delta E}{E} < 0.4\%$ $\sigma_t < 40$ ps timing. Very promising results from prototype tests
  - Radial-TPC for e^+e^- tracking: R&D ongoing for readout with cylindrical MPGD

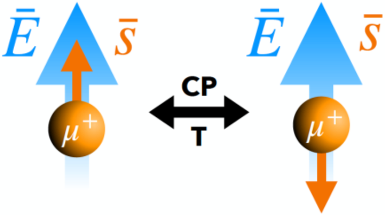
Sensitivity BR($\mu \to e\gamma$) $\lesssim 10^{-15}$

Conclusions about cLFV searches at PSI

- **MEG II experiment:**
  - The analysis for 2021 + 2022 data is almost completed
  - This will be the most sensitive result for $\mu \to e\gamma$ experiments
  - Data taking is continuing and even newer results are behind the corner: stay tuned!
- **Future cLFV experiments at PSI:**
  - HiMB upgrade will open a new era for $\mu \to e\gamma$ and $\mu \to eee$ experiments
  - The (italian) cLFV community is working to be ready and exploit these new possibilities

Searching for the μ electric dipole moment

A permanent EDM requires T violation,
equivalently CP violation by the CPT Theorem.



$$H_\mu^{EDM} \overset{\beta\to 0}{\propto} d_\mu \bar{\sigma}\cdot\bar{E}$$

Hamiltonian EDM term is CP violating

SM Prediction: $d_\mu^{SM} = 1.4\times 10^{-38}\, e\,.\,\mathrm{cm}$ (Yamaguchi & Yamanaka, 2020)

$$d_e \leq 1.1\times 10^{-29} e\,.\,\mathrm{cm} \overset{LFU}{\Longrightarrow}{?}\; d_\mu \leq \frac{m_\mu}{m_e} d_e = 1.6\times 10^{-27} e\,.\,\mathrm{cm}$$

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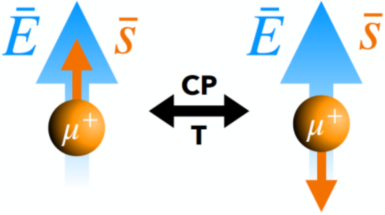

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Status Report of the search for the muon electric dipole moment to INFN

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R. Appleby, I. Bailey
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C. Chavez Barajas, T. Bowcock, J. Price, N. Rompotis, T. Teubner, G. Venanzoni, J. Vossebeld
UL: University of Liverpool, Liverpool, United Kingdom

R Chislett, G. Hesketh
UCL: University College London, London, United Kingdom

N. Berger, M. Köppel[1], A. Kozlinsky, M. Müller[1], F. Wauters
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F. Trillaud
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B. Märkisch
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A. Baldini, F. Cei, M. Chiappini, A. Driutti, L. Galli, G. Gallucci, M. Grassi, A. Papa, A. Venturini[1], B. Vitali[1]
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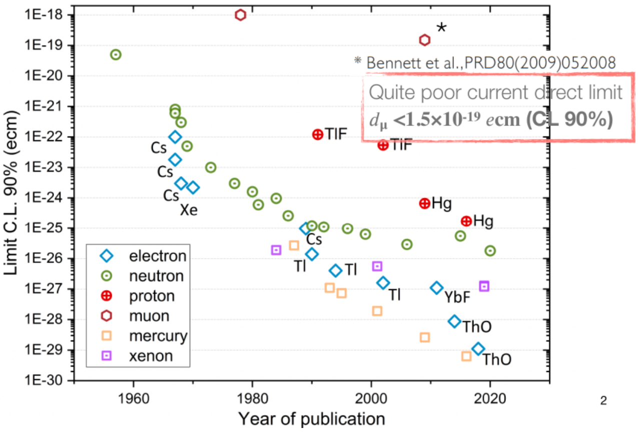
SJTU: Shanghai Jiao Tong University and Tsung-Dao Lee Institute, Shanghai, China

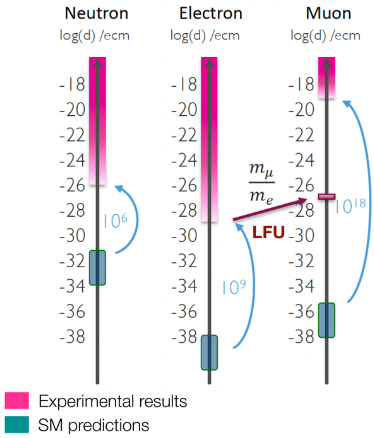
A. Adelmann, C. Calzolaio, R. Chakraborty, M. Daum, A. Doinaki[12], C. Dutsov, W. Erdmann, D. Höhl,[12], T. Hume,[12], M. Hildebrandt, H.C. Kästli, A. Knecht, K.Z. Michielsen[12], L. Morvaj, D. Reggiani, D. Sanz-Beccera, P. Schmidt-Wellenburg[3]
PSI: Paul Scherrer Institut, Villigen, Switzerland

K. Kirch[4]
ETHZ: ETH Zürich, Switzerland

L. Caminada[4], A. Crivellin[4]
UZ: University of Zürich, Zürich, Switzerland

Searching for μ electric dipole moment





The frozen spin technique

ω_a = "(g - 2)" precession

$$\vec{\Omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\frac{\vec{\beta}\times\vec{E}}{c}\right)\right]$$

$$+\frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right]$$

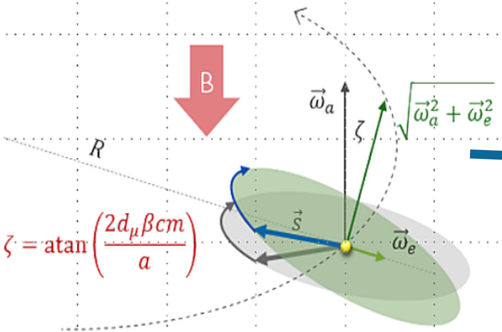
ω_e = EDM precession

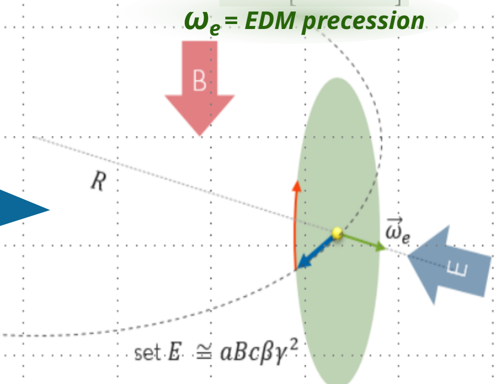
$$E_f \approx \frac{g-2}{2}Bc\beta\gamma^2$$

$$\vec{\Omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\frac{\vec{\beta}\times\vec{E}}{c}\right)\right]$$

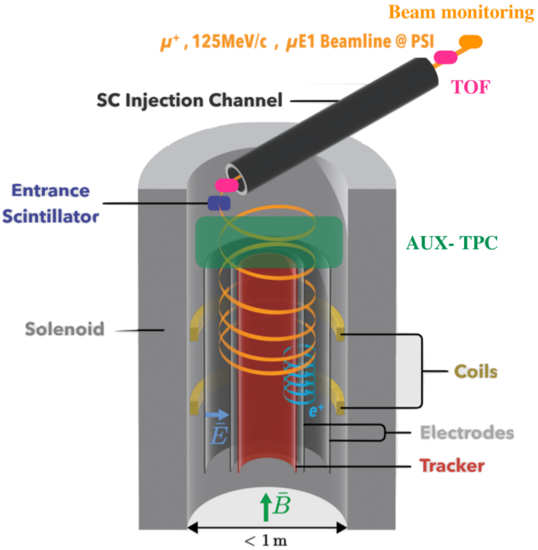
$$+\frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right]$$

ω_e = EDM precession





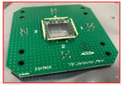
MUEDM EXPERIMENT

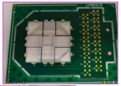


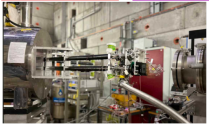
- **Goal Phase I** (before HiPA upgrade): demonstrate the *frozen spin technique*
  - μ^+ with 28 MeV/c momentum; detection rate $\sim$ 300 e^+/s
  - **Goal sensitivity** $\sigma(|d_\mu|) \leq 3 \times 10^{-21}$ $e\cdot$ cm
- **Goal Phase II** (after HiPA upgrade):
  - μ^+ with 125 MeV/c momentum; detection rate $\sim 10^5$ e^+/s
  - **Goal sensitivity** $\sigma(|d_\mu|) \leq 6 \times 10^{-23}$ $e\cdot$ cm

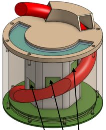
MUEDM PRECURSOR

Beam monitoring/Entrance/TOF/
Muon Chamber

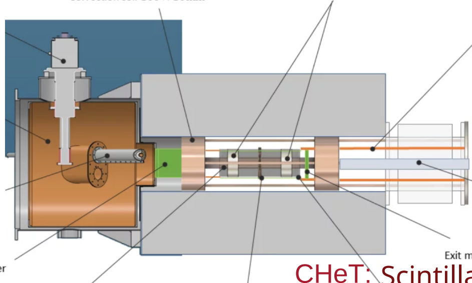




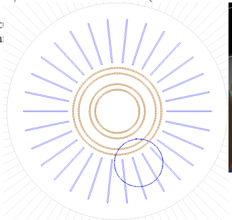


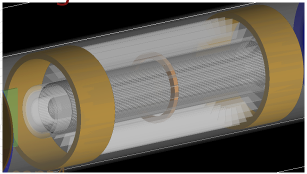


- R&D completed
- Ready for final construction

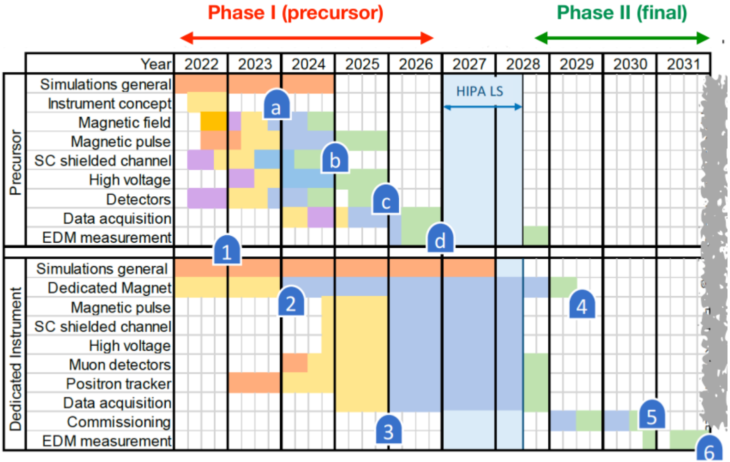


CHeT: Scintillating fibers tracker





muEDM status & perspectives



- Simulations
- Conception/Design
- Prototyping
- Acquisition/Assembly
- Tests/Measurements

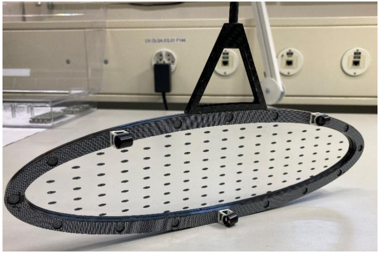
1	Full proposal for both phases to CHRISP committee
2/a	Magnet call for tender / precursor design fix
b	Precursor ready for assembly/commissioning
3/c	Technical design report / frozen spin demonstration
d	First data for precursor muEDM
4	Magnet delivered, characterized and accepted
5	Successful commissioning / start of data taking
6	End of data acquistion for muEDM

muEDM proposal submitted to INFN CSN1, *sub iudice* approval to be discussed December '24

Thank you for your attention

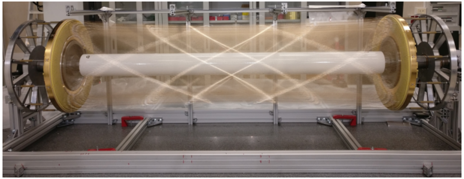
MEG II: Muon beamline and target

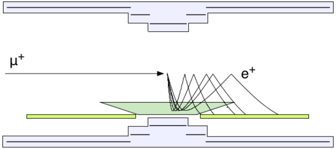
- @Paul Scherrer Institute: 590 MeV proton cyclotron (up to 2.2 mA current). Protons impinge on a carbon target to produce muons and pions
- Dedicated accelerator line to select low momentum muons $p_\mu \approx 28$ MeV/c
- Most intense continuous muon beam in the world. For MEG II: $3 - 5 \times 10^7\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

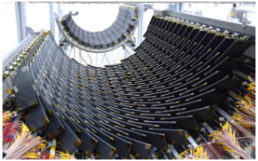


- Thin (≈ 174 µm) plastic target to stop muons at the center of the experiment
- Holes and markers for alignment and deformation monitoring → control systematics

MEG II: Spectrometer





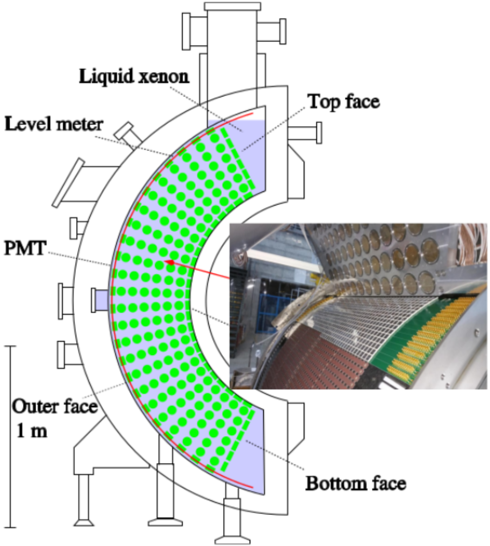


- Single volume drift chamber. (Gas: 90:10 He:C_4H_{10} + 1.5% isopropyl + 0.5% O_2)
- **1728 anode wires** (cell size ~ 7 mm)
- **Super light**: $d = 2.4 \times 10^{-4}\ X_0$
- Minimizes multiple scattering → **good angular and momentum resolution**

- 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

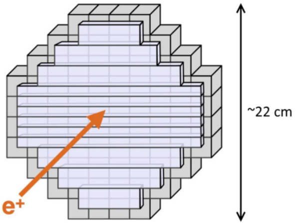
MEG II: Liquid Xenon detector

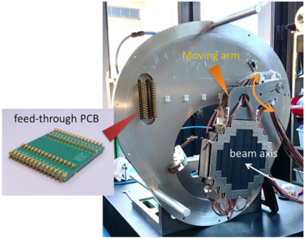


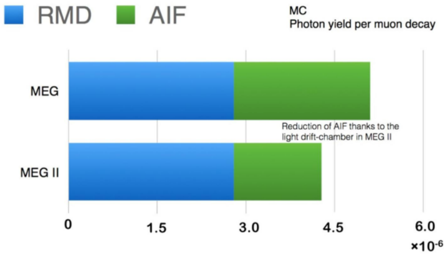
- Homogeneous photon detector ("C-shape")
- Xenon scintillation: High Light Yield (40 γ/keV), fast (4/22/40 ns) → **good time and energy resolution**
- Hyper-segmented read-out: > 4000 SiPMs + 700 PMTs → **good position resolution**
- Uniform performances of the detector

MEG II: Radiative Decay Counter

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



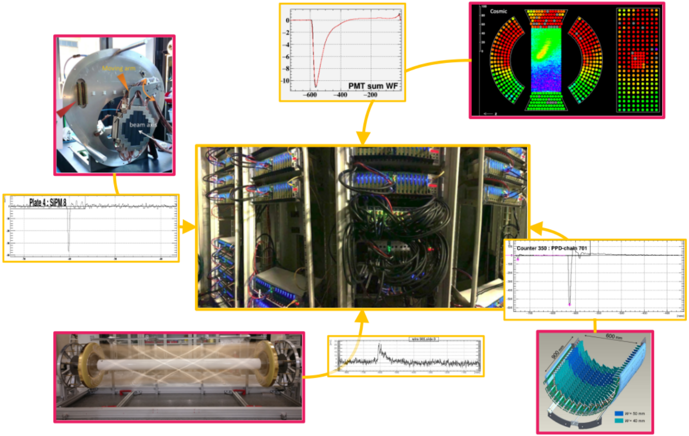




AIF Hyper-light tracker reduces the contribution from $e^+e^- \to \gamma\gamma$

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

MEG II: Trigger & DAQ



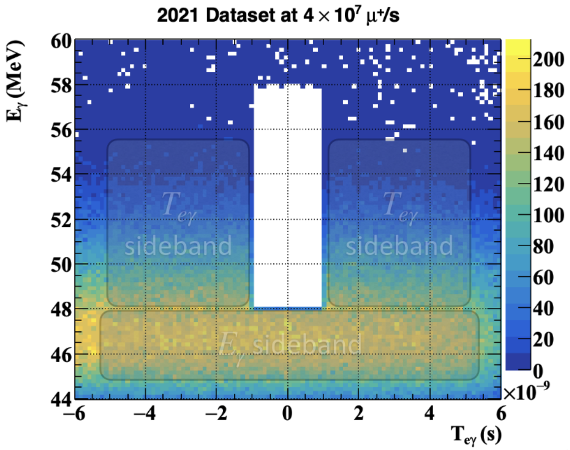
- Integrated Trigger & DAQ system.
- $>$ 9000 **waveforms** from detectors digitalized for offline reconstruction

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_γ, 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_γ and $t_{e\gamma}$

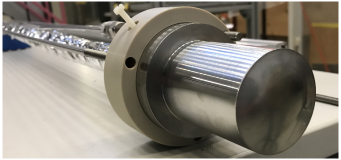


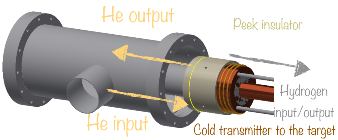
Liquid Xenon Detector calibration

- 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)

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

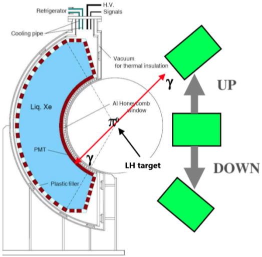
LXe calibration: CEX





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

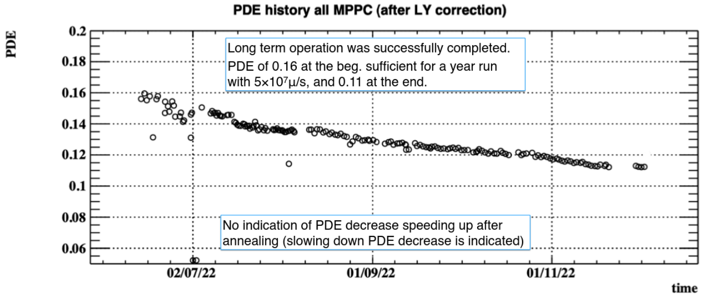
- tune MEG II beam line to select π^-
- p from a LH_2 target inserted at the center of COBRA

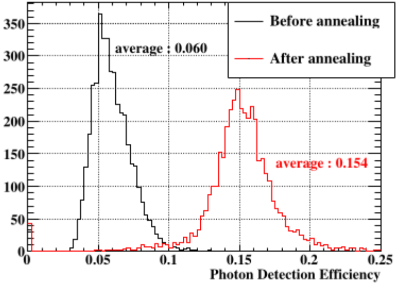


Trigger on anti-parallel γ using an auxiliary BGO detector:

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

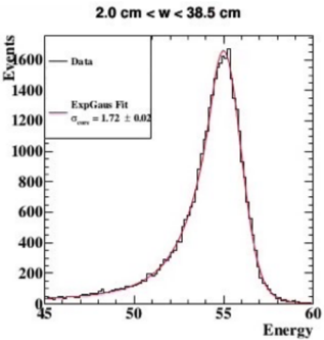
Liquid Xenon detector: Maintenance

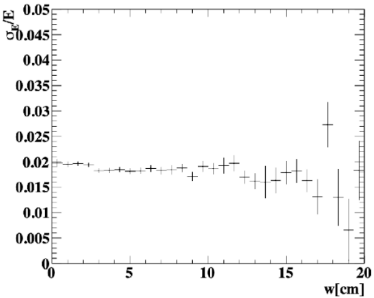




The degradation of SiPM's PDE after beam irradiation has been observed.
An annual annealing procedure is carried on to recover the PDE. The annealing is done heating the SiPM through Joule effect. The procedure has been succesfull in 2022.

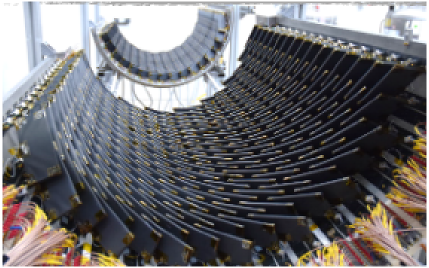
Liquid Xenon detector: performances



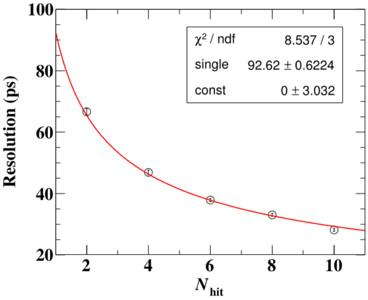


Quantity	Performance	agree w MC
Position resolution [mm]	2.4	✓
Energy resolution [%] ($w < 2$ cm / $w > 2$ cm)	2.0% / 1.7%	× (80% off)
Time resolution [ps]	65 ± 6	✓
Detection Efficiency [%]	64%	~ (5% off)

The pixelated Timing Counter



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

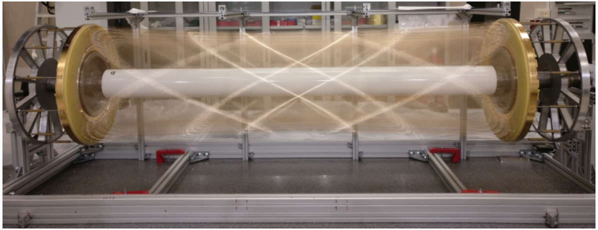


Timing resolution

Timing resolution compatible with design project

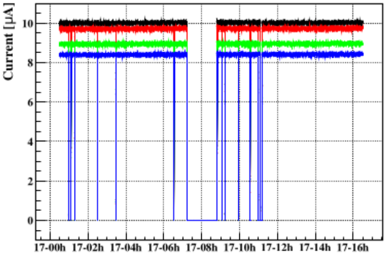
$$\sigma_t = \frac{\sim 90\text{–}100 \text{ ps}}{\sqrt{N_{hits}}}$$

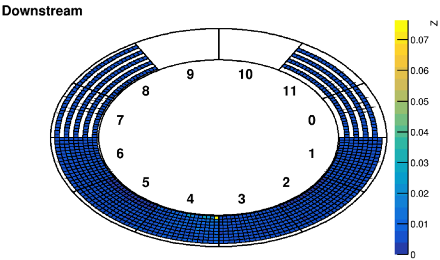
Cylindrical Drift Chamber



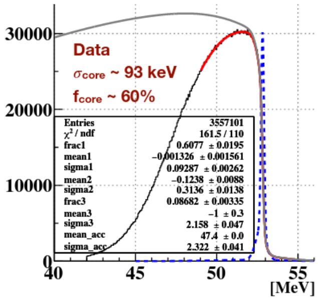
- Single volume ultra-light drift chamber
- mixture: 90:10 He : isobutane + 1.5% isopropanol + 0.5% O_2
- Highly segmented: 1728 anodes, $< 4 \times 4$ mm^2 drift cells
- Rejects e^+ with $E_{e^+} \lesssim 45$ MeV

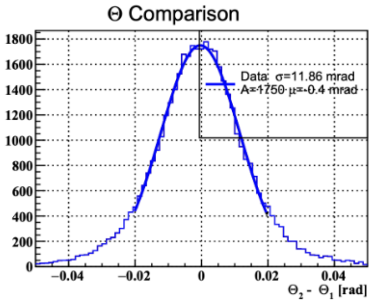
Very stable operation conditions during 2021 and 2022 runs





CDCH: PERFORMANCES



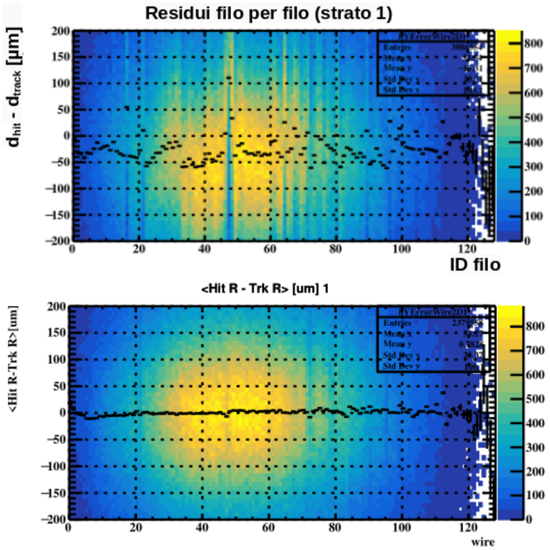


Quantity	Resolution	agree with MC
p_{e^+}	90 keV/c	✓
ϕ_{e^+}	6.8 mrad	$\sim$ (10% off)
θ_{e^+}	7.1 mrad	$\sim$ (10% off)
z	1.85 mm	✓
ϵ_{e^+}	65%	$\sim$ (10% off)

Calibrations & systematics search

- Iterative alignment
- Magnetic field corrections

CDCH: ALIGNMENT



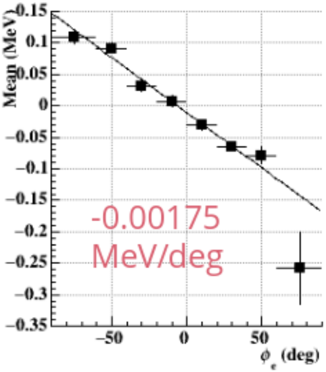
Method

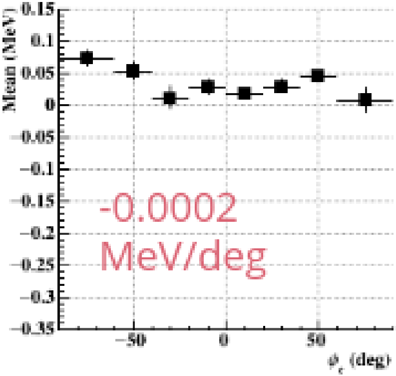
- Iterative alignment procedure to minimize $d_{track} - d_{hit}$ residuals using tracks from $\mu \to e\nu\overline{\nu}$ decay ✓
- MillePede alignment with cosmic tracks (ongoing)

Results

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

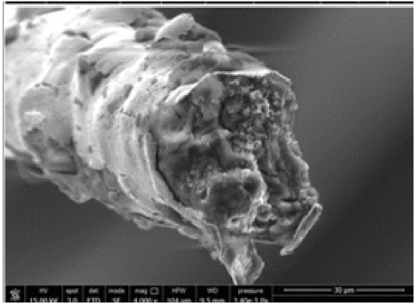
CDCH: COBRA TUNING





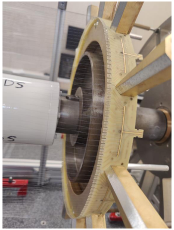
Data-driven tuning of CDCH position with respect to COBRA to correct for reconstruction asymmetries:
$|x_{shift}| \sim |y_{shift}| \approx 100\ \mu\text{m}$, $|z_{shift}| = 300\ \mu\text{m}$

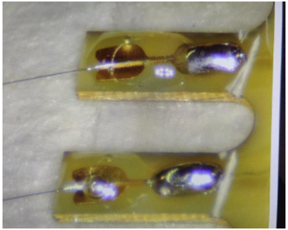
CDCH2



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

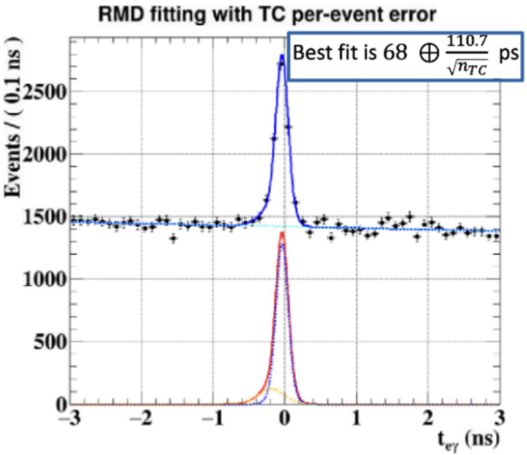




Resolution on $t_{e^+\gamma}$

Calibration

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



Trigger performances

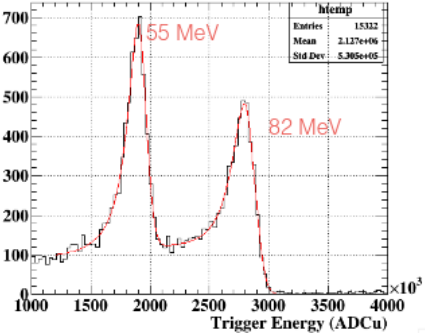


Figure: Photon energy spectra reconstructed online during CEX calibration using $\pi^0 \to \gamma\gamma$

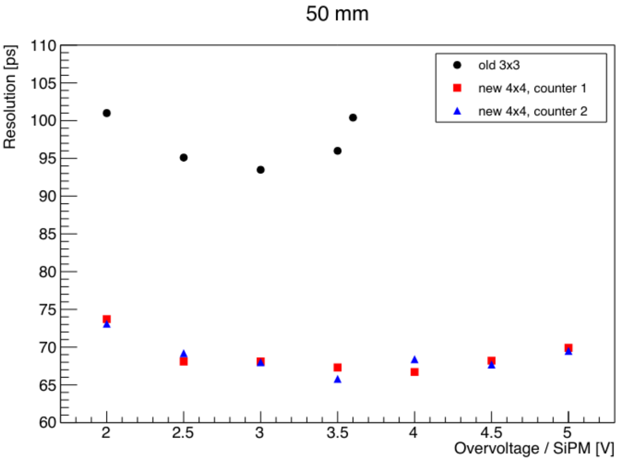
Trigger logic

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

The trigger performances

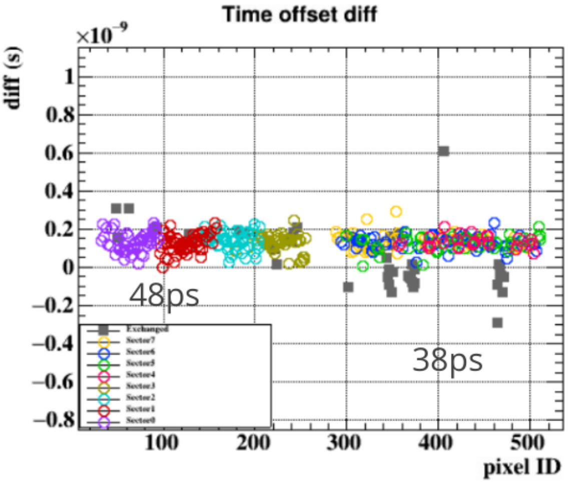
- Online energy resolution $\sim 3 - 4\%$
- Overall trigger efficiency $\gtrsim 90\%$
- Trigger rate @3×10^7 μ^+/s ≈ 20 Hz

pTC: UPGRADE



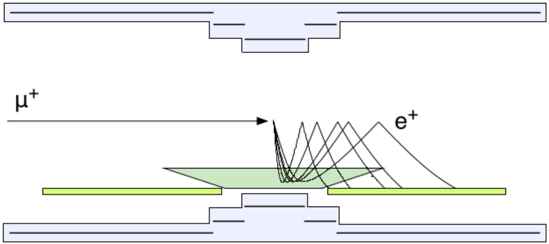
- aging effects on pTC tiles
- Replace most damaged scintillator tiles and SiPM
- New $4 \times 4\text{mm}^2$ SiPM for improved resolution

pTC calibration

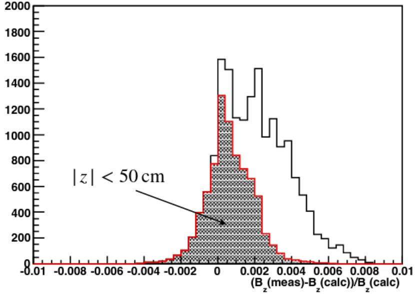


- Laser calibration of tiles timing in each module
- global calibration using e^+ time of flight from $\mu \to e \nu \overline{\nu}$ decay

COBRA Magnet



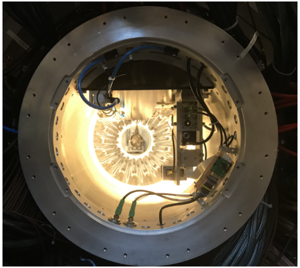
COnstant **B**ending **RA**dius superconductive magnet generates a non solenoidal gradient field with $|B|_{max} = 1.26$ T.

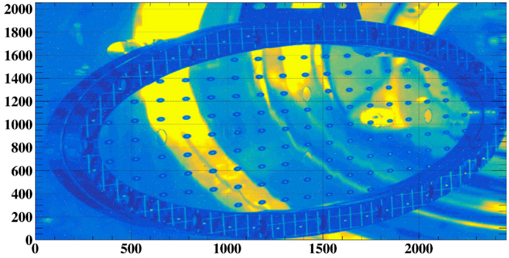


Two different maps for B field in tha analysis software: one based on a survey, one based on Maxwell equations. The agreement is at the *per mille* level

Target monitoring

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

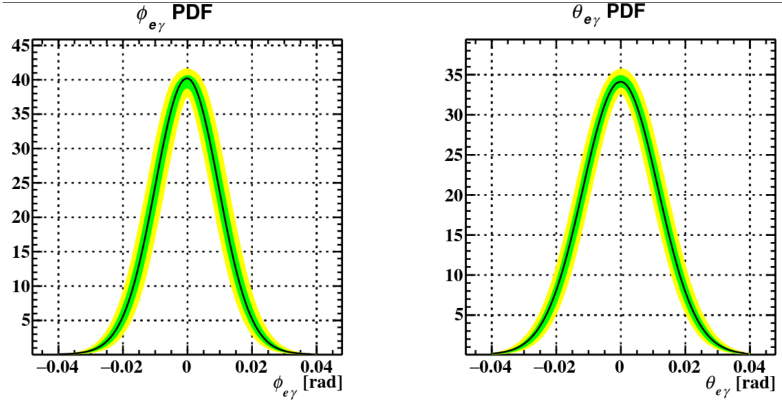




Method's precision

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

Systematics in the analysis



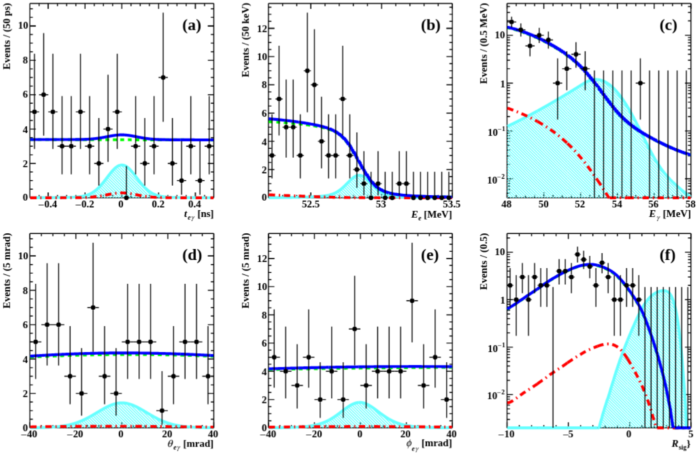
Larger systematics (accounting for 5% loss in sensitivity) are:

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

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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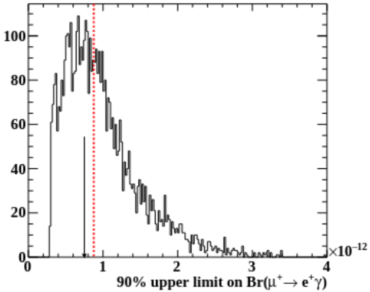
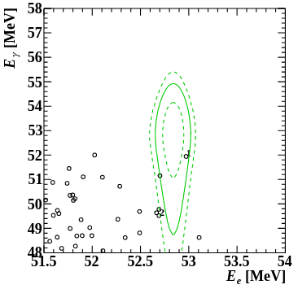
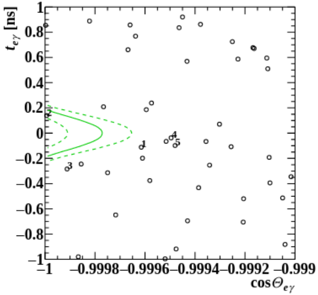
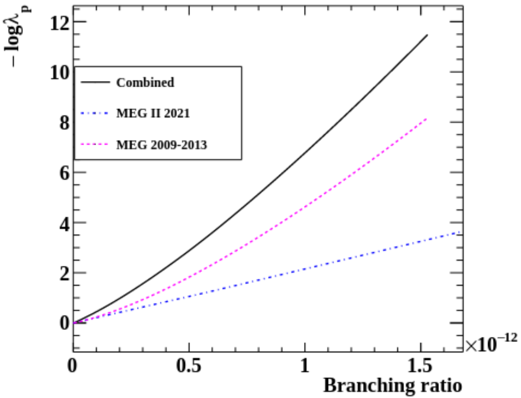






Combination of MEG and MEG II results

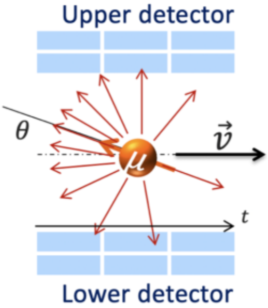


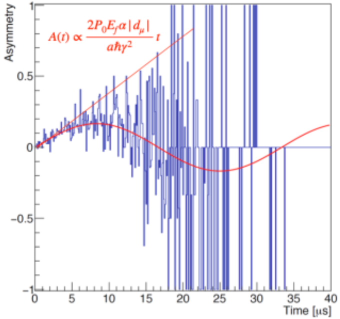
New limit on BR($\mu \to e\gamma$)

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

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

Analysis strategy



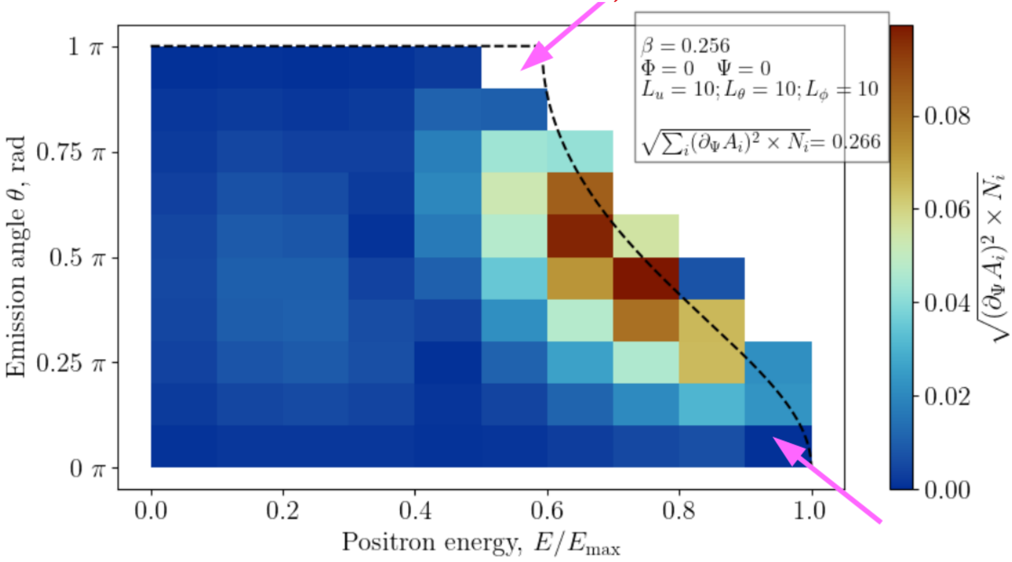


- P_0 = initial muon polarisation
- E_f = electric field in the lab frame
- N = number of observed decays
- τ_μ = muon lifetime
- α = mean decay asymmetry (~ 0.3)
- a = anomalous magnetic moment
- γ = gamma factor of the muon

$$A(t) = \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)} \propto \frac{2P_0E_f\alpha|d_\mu|}{a\hbar\gamma^2}t$$

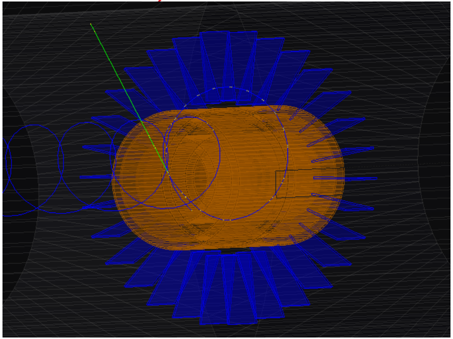
$$\sigma(|d_\mu|) = \frac{d|d_\mu|}{d\bar{A}}\sigma(\bar{A}) \sim \frac{a\hbar\gamma}{2P_0E_f\sqrt{N}\tau_\mu\alpha}$$

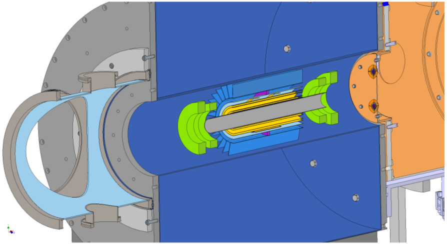
Analysis strategy



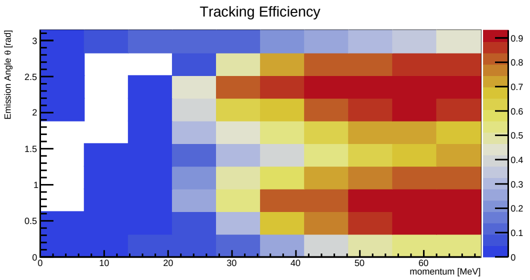
CHeT detector: project

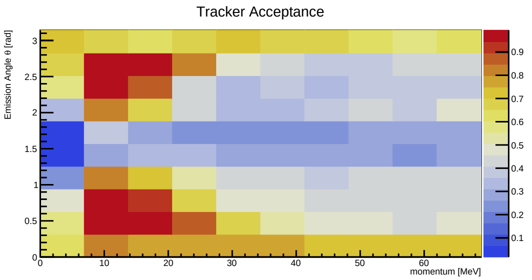
- **g - 2 measurement**: radial planes formed with two orthogonal layers of 500 µm scintillating fibers
- **muEDM measurement**: 4 cylinders made from stereo arrangement of scintillating fibers layers

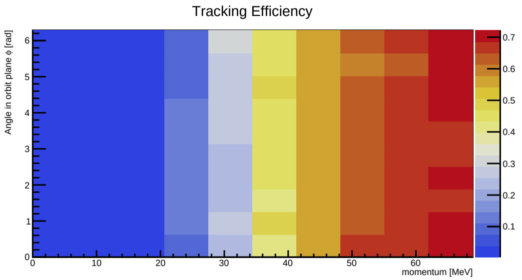


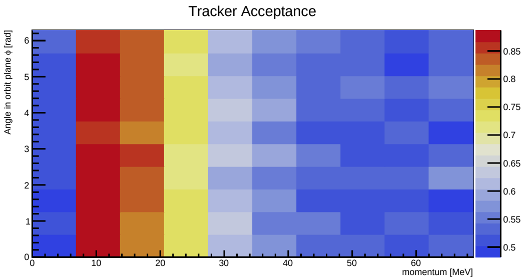


CHeT detector: simulations

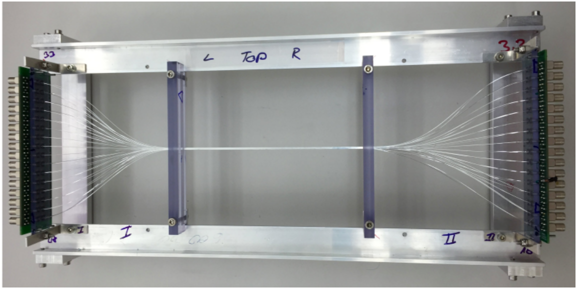






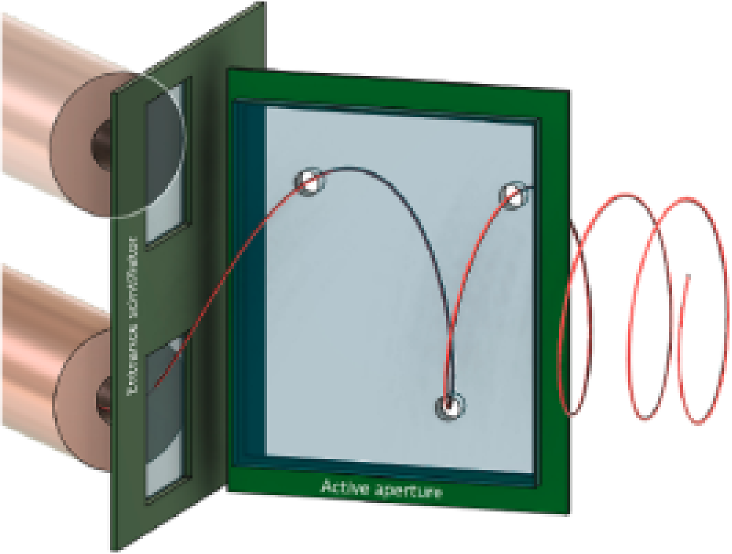


CHeT detector: prototype

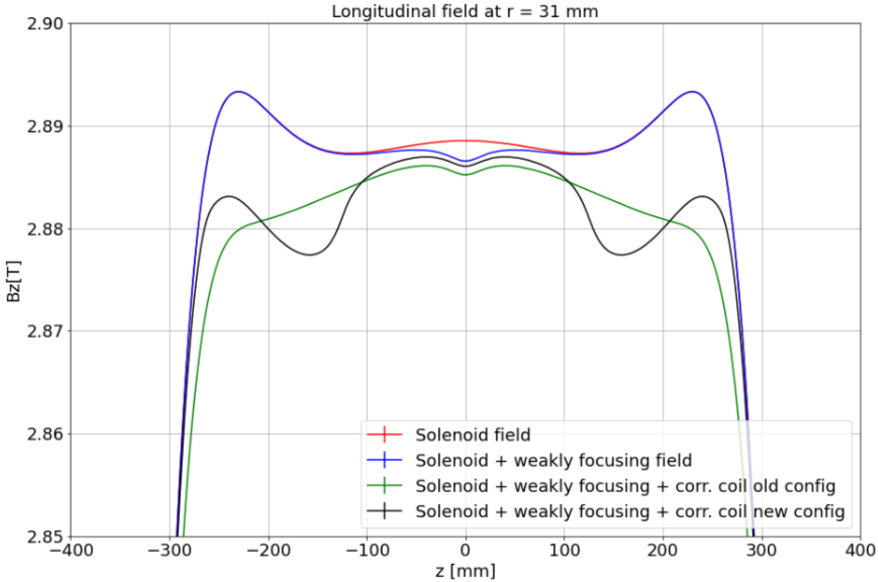


	Single layer	Double layer	Triple layer	Array
ε_{AND} [%] (1.5 phe)	34 ± 1	52 ± 1	67 ± 1	88.0 ± 0.3
ε_{OR} [%] (1.5 phe)	79 ± 1	93 ± 1	97 ± 1	97.5 ± 0.2
ε_{AND} [%] (0.5 phe)	72 ± 1	89 ± 1	95 ± 2	95.8 ± 0.2
ε_{OR} [%] (0.5 phe)	96 ± 1	99 ± 1	98 ± 1	98.3 ± 0.2

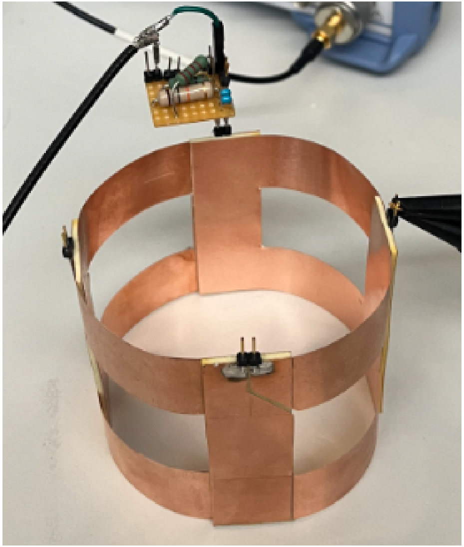
ENTRANCE DETECTOR



Magnetic field



Kicker



Electrodes