The latest results of the MEG II experiment

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on behalf of the MEG collaboration

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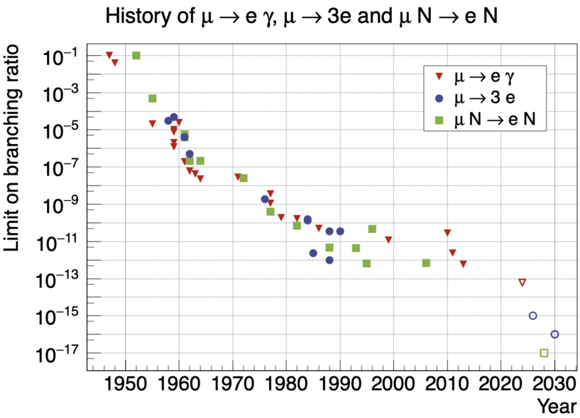
G.A. 858199

Charged Lepton Flavor Violation

- even though it is predicted by SM with neutrino oscillations ...

$$\mathcal{B} \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \approx 10^{-54}$$

... it is heavily suppressed $\rightarrow$ **Any observation would be a clear sign of new physics**



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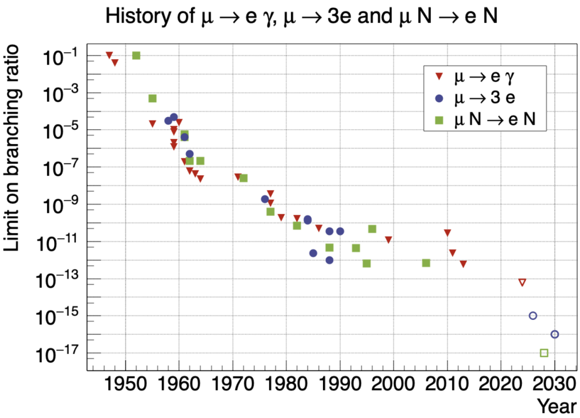
$$\mathcal{B} \propto \frac{1}{\Lambda^4}$$

... **Probe extreme energy scales ($>$ 1000 TeV)**



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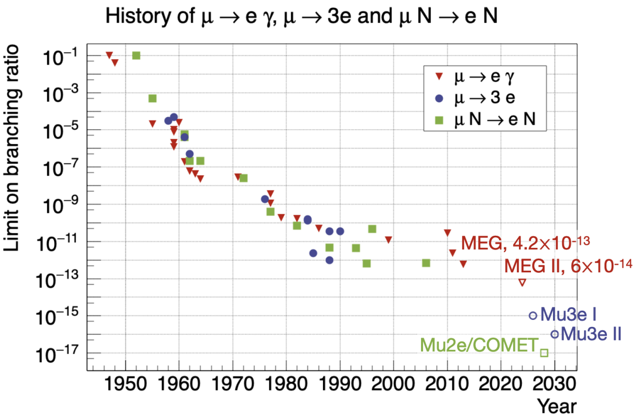
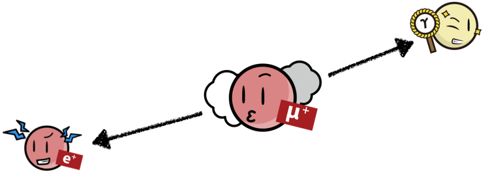


The MEG decay

The signal features:

- a positron and a gamma with the same timing



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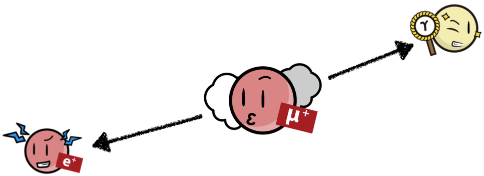

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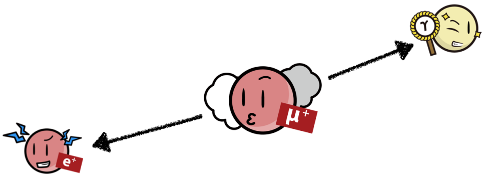

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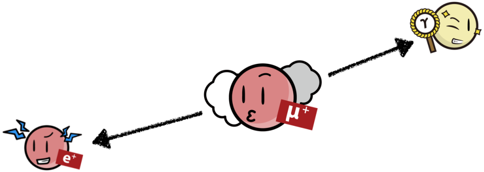
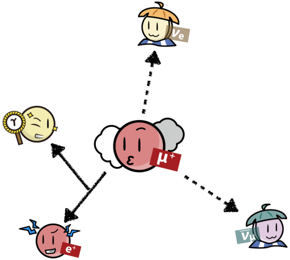


Backgrounds

Physical

Missing energy from neutrinos: **need excellent momentum and energy resolution**.



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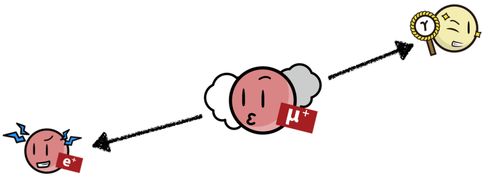

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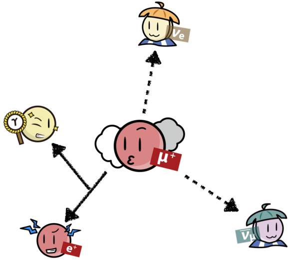

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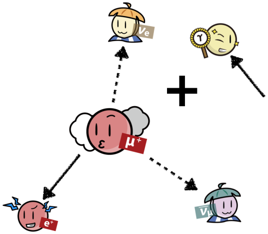
Particles from different processes: **need excellent timing resolution**.



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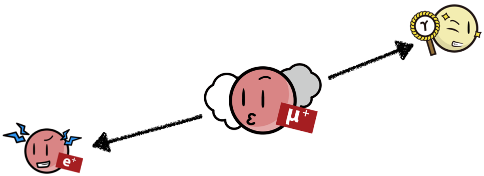

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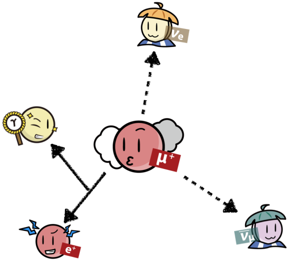

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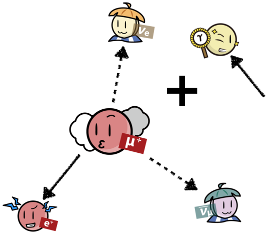
DC muon beams are preferred.



MEG detection

We aim to a sensitivity of $\mathcal{B} = 6 \times 10^{-14}$, ten times better than MEG [1]. The event selection and the analysis are based on 5 kinematic variables:

- E_γ: photon energy (52.8 MeV)
- E_{e+}: positron energy (52.8 MeV)
- $t_{e+\gamma}$: relative timing
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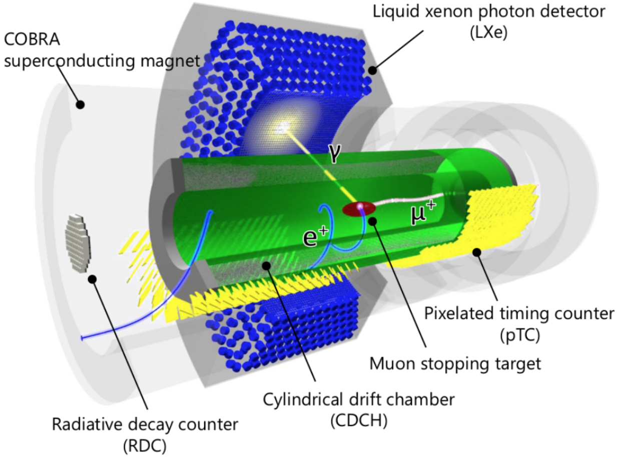

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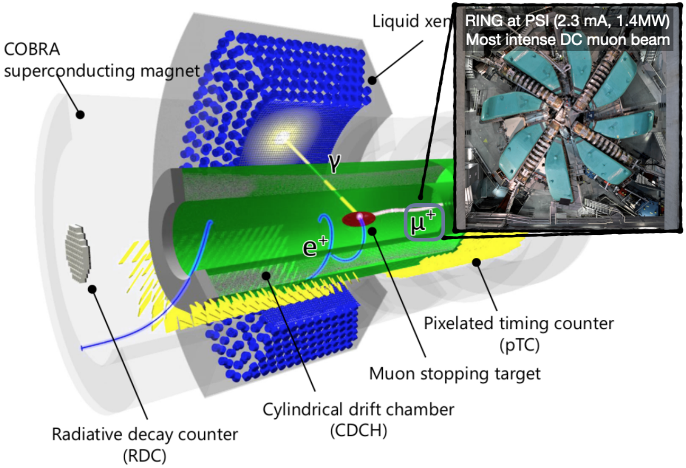

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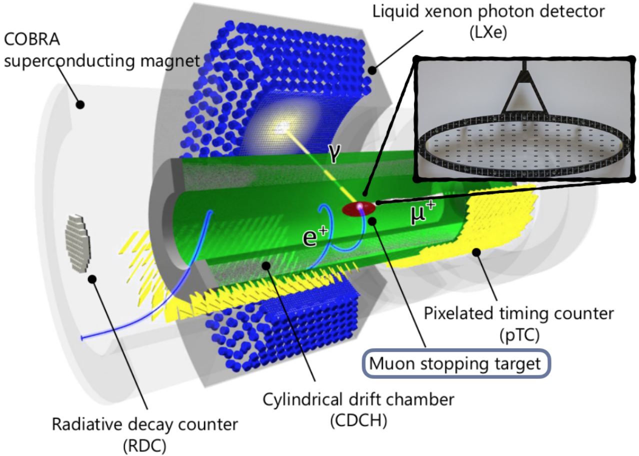

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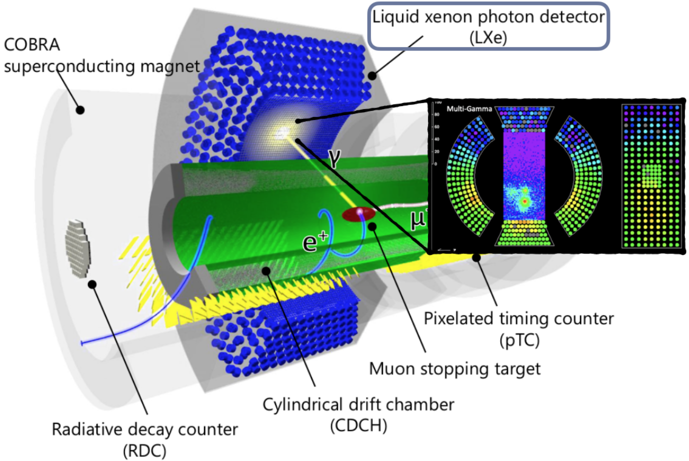

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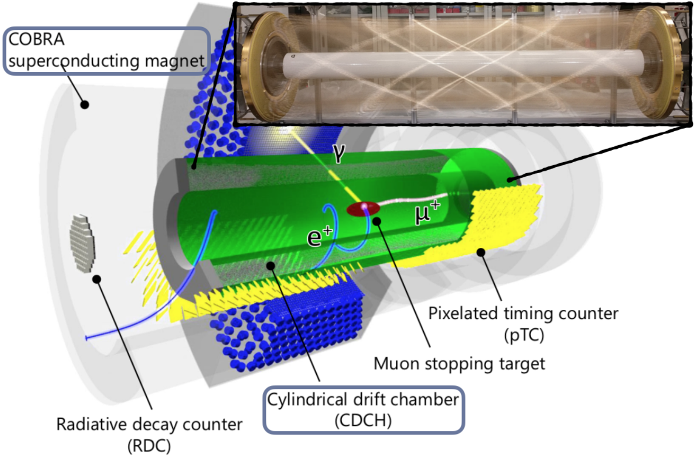

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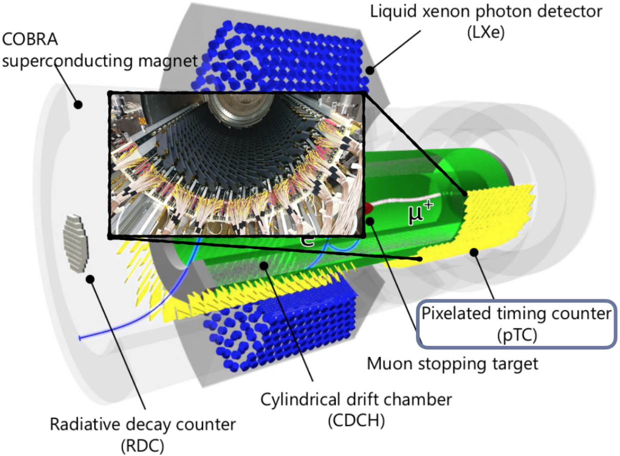

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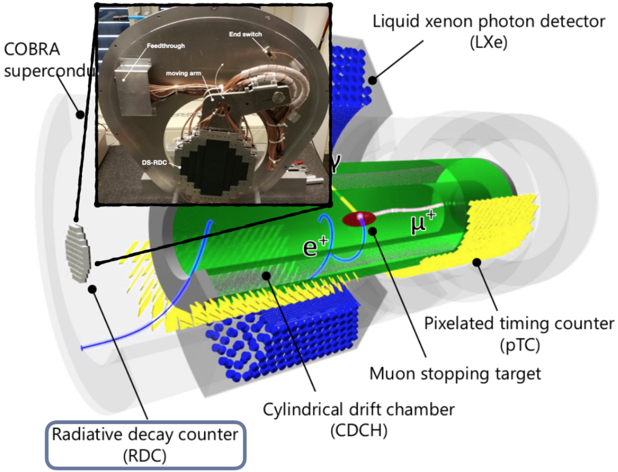

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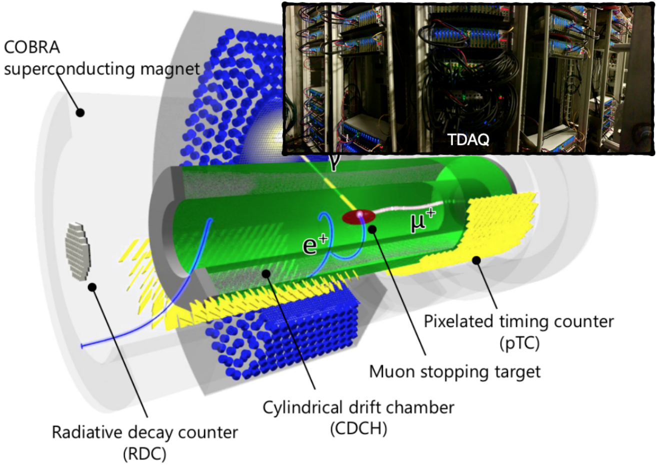
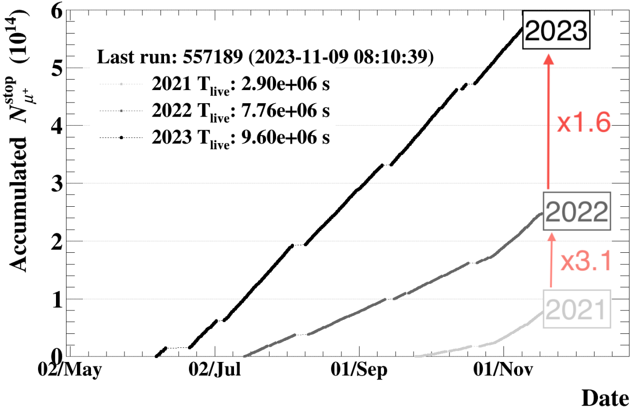
~ 9000 **channels with full waveform digitization.**



Collected data

- 2021: first physics run with optimized detector operation $\rightarrow$ **published**
- 2022: stable DAQ with optimal detector conditions $\rightarrow$ **analysis ongoing**
- 2023: longest physics run



Detector performances in 2021 [1]

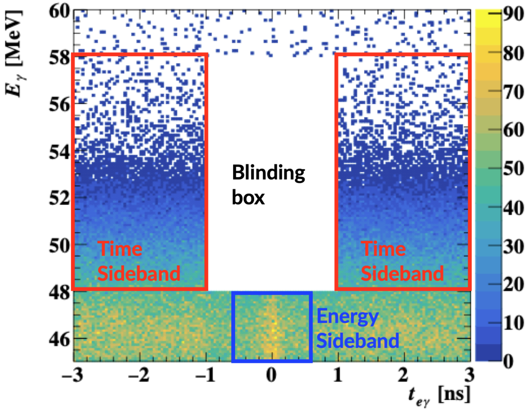
	MEG	MEG II
Resolutions		
δE_{e^+} [keV]	380	89
$\delta \theta_{e^+}$ [mrad]	9.4	7.2
$\delta \phi_{e^+}$ [mrad]	8.7	4.1
$\delta z_{e^+}/\delta y_{e^+}$ [mm]	2.4/1.2	2.0/0.74
δE_γ ($w > 2$ cm/$w < 2$ cm) [%]	2.4/1.7	2.0/1.8
$\delta u_\gamma/\delta v_\gamma/\delta w_\gamma$ [mm]	5/5/6	2.5/2.5/5.0
$\delta t_{e^+\gamma}$ [ps]	122	78
Efficiencies [%]		
Trigger	$\simeq$ 99	$\simeq$ 80
Photon	63	63
e^+ (tracking $\times$ matching)	30	67

Analysis approach

- blinding box: $48\,\text{MeV} < E_\gamma < 58\,\text{MeV}$, $|t_{e^+\gamma}| < 1\,\text{ns}$
- accidentals are studied in the time sidebands
- RMDs are studied in the energy sideband
- unbinned maximum likelihood analysis in the signal region to estimate $\mathcal{N}_S$:

$$48\,\text{MeV} < E_\gamma < 58\,\text{MeV},$$
$$52.2\,\text{MeV} < E_{e^+} < 53.5\,\text{MeV},$$
$$|\phi_{e^+\gamma}| < 40\,\text{mrad}, \ |\theta_{e^+\gamma}| < 40\,\text{mrad},$$
$$|t_{e^+\gamma}| < 0.5\,\text{ns}$$

- Two independent analyses: one with a per-event PDF and two angular observables $\theta_{e\gamma}$, $\phi_{e\gamma}$; one with constant PDFs and one angular observable $\Theta_{e\gamma}$.



$$\mathcal{L}(\mathcal{N}_S, \mathcal{N}_{RMD}, \mathcal{N}_{ACC}, x_T) = \frac{e^{-(\mathcal{N}_S, \mathcal{N}_{RMD}, \mathcal{N}_{ACC})}}{\mathcal{N}_{obs}!} C(\mathcal{N}_{RMD}, \mathcal{N}_{ACC}, x_T) \times \prod_{i=1}^{\mathcal{N}_{obs}} (\mathcal{N}_S S(\vec{x_i}) + \mathcal{N}_{RMD} R(\vec{x_i}) + \mathcal{N}_{ACC} A(\vec{x_i})))$$

2021 analysis - Normalisation

Normalization factor k = number of effectively measured muons (= 1/SES):

$$\mathcal{B}(\mu^+ \to e^+\gamma) = \frac{\mathcal{N}_S}{k}$$

It is estimated by two independent methods:

Counting Michel positron:

$$k_{\text{Michel}} = (2.55 \pm 0.13) \times 10^{12}$$

Counting RMD events in energy sidebands:

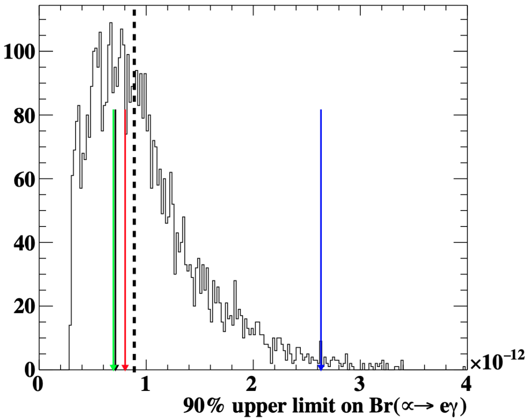
$$k_{\text{RMD}} = (3.1 \pm 0.11(\text{stat}) \pm 0.3(\text{syst})) \times 10^{12}$$

Combined factor: $(2.64 \pm 0.12) \times 10^{12}$

2021 analysis - Sensitivity

Sensitivity $\mathcal{S}_{90} = 8.8 \times 10^{-13}$:

- Median of the $90\,\%$ UL distribution for pseudo experiments with null-signal hypothesis
- ULs observed in four fictitious analysis windows in the timing sidebands are consistent with the sensitivity
- already approaching full MEG sensitivity (5.3×10^{-13})



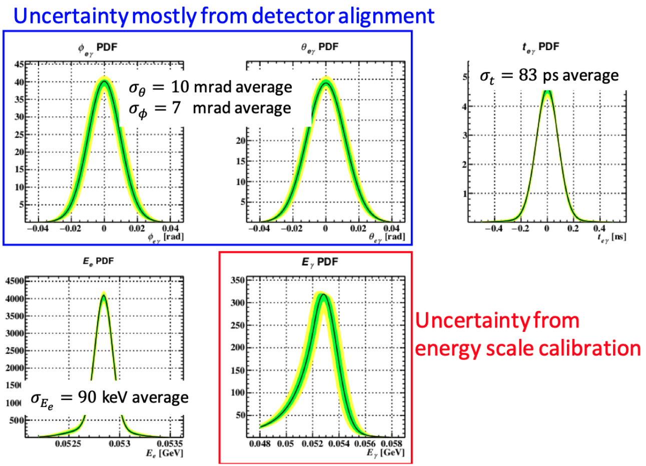
2021 analysis - Systematics

Major sources of systematics:

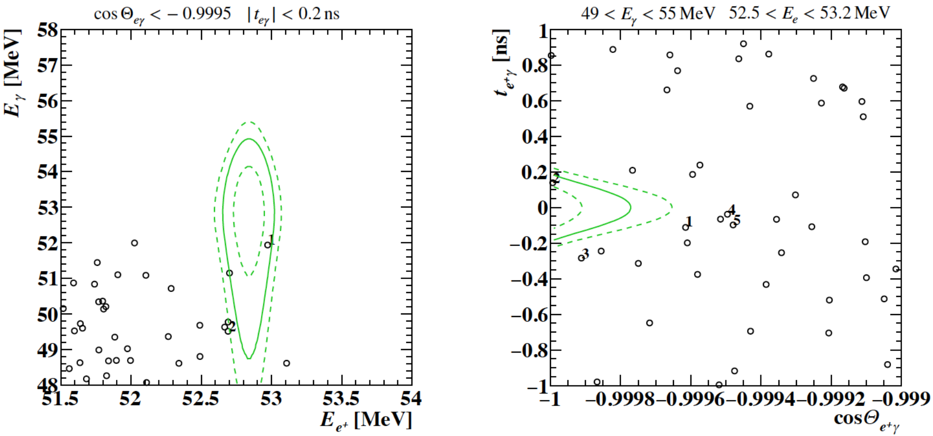
- Detector alignment
- E_γ scale
- Normalisation

Effect on sensitivity $\sim 4\,\%$ ($\sim 13\,\%$ in MEG)

Parameter	Impact on sensitivity
$\phi_{e\gamma}$ uncertainty	$1.1\,\%$
E_γ uncertainty	$0.9\,\%$
$\theta_{e\gamma}$ uncertainty	$0.7\,\%$
Normalization uncertainty	$0.6\,\%$
$t_{e\gamma}$ uncertainty	$0.1\,\%$
E_e uncertainty	$0.1\,\%$
RDC uncertainty	$< 0.1\,\%$



2021 analysis - Event distribution after unblinding

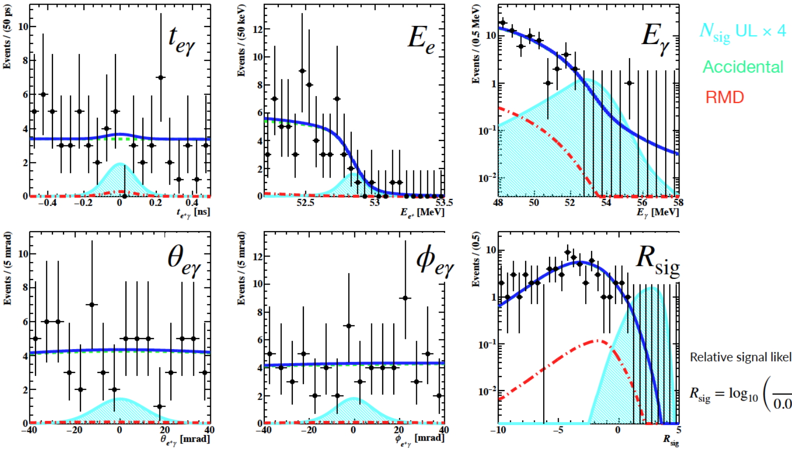


PDF contours (1, 1.64, 2 σ)

No excess of events around the signal region

2021 analysis - Likelihood fit

Projection of fit results



Relative signal likelihood

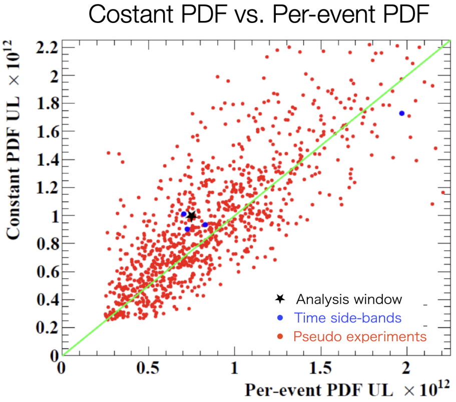
$$R_{sig} = \log_{10}\left(\frac{S}{0.02R + 0.98A}\right)$$

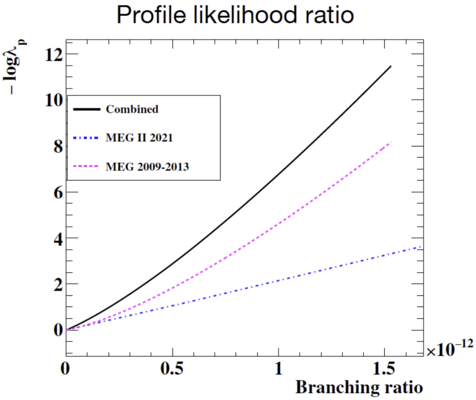
Best fit $N_{sig} = -2.9 \times 10^{-4}$ ($\mathscr{B} = -1.1 \times 10^{-16}$)

2021 analysis - Confidence Interval

The Confidence Interval is computed with a full frequentist approach and likelihood ratio ordering:

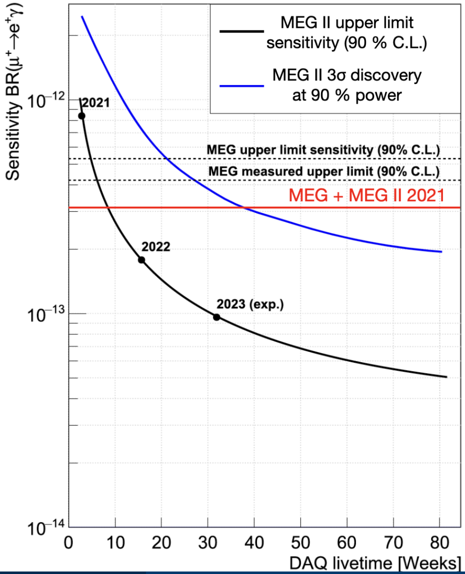
- 2021 analysis: $\mathcal{B}(\mu^+ \to e^+\gamma) < 7.5 \times 10^{-13}$ (90 % C.L.)
- 2021 analysis + MEG combined: $\mathcal{B}(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13}$ (90 % C.L.)





Conslusions and prospects

- in the first 7-week data-taking of 2021 we achieved $60\,\%$ of MEG total sensitivity between 2009 and 2013
- the combined MEG and MEG II results provides the most stringent limit to date [2]
- 2021 run represents only $11\,\%$ of the total data
- we expect to finalize 2022 analysis soon



Thank you for your attention!

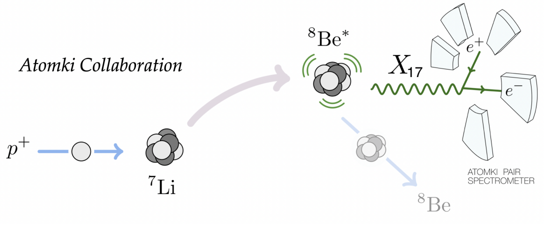
Resources

[1] K. Afanaciev et al. “Operation and performance of the MEG II detector”. In: *The European Physical Journal C* 84.2 (Feb. 2024), p. 190. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-024-12415-3. URL: https://doi.org/10.1140/epjc/s10052-024-12415-3.

[2] K. Afanaciev et al. “A search for $\mu^+ \to e^+\gamma$ with the first dataset of the MEG II experiment”. In: *The European Physical Journal C* 84.3 (Mar. 2024), p. 216. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-024-12416-2. URL: https://doi.org/10.1140/epjc/s10052-024-12416-2.

Back-up

Exotic channels with the MEG II detector: X17

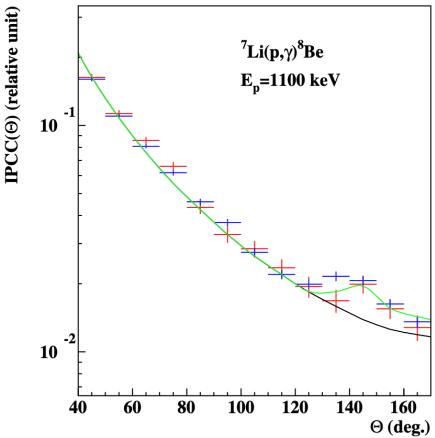


In 2016 the ATOMKI collaboration found an excess in the $^7\mathrm{Li}(\mathrm{p}, \mathrm{e}^+\mathrm{e}^-)^8\mathrm{Be}$ reaction: an excess of event is found in the internal pair conversion (IPC).

Excess was attributed to a light boson:

- $m_{X17} = 16.98\,\mathrm{MeV}/c^2$
- $\mathrm{BR}(X17/\gamma) = 6 \times 10^{-6}$

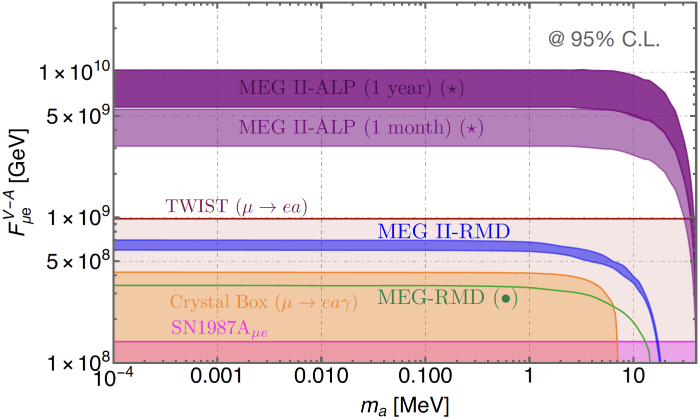
We had one month of data taking in early 2023 and we are close to unblinding.



Exotic channels with the MEG II detector: ALPs

Look for ALPs in $\mu^+ \to e^+\gamma a$. We had already a limited dedicated data taking (~1 week) with optimized trigger settings.

We're preparing for the blinded analysis.



The muon beam

Where to go?

- DC muon beams are ideal for coincidence experiments to minimize the accidental background.
- To reach sensitivities of $\mathcal{O}(10^{-14})$ you need to measure $\mathcal{O}(10^{14})$ decays $\rightarrow$ **high intensity.**

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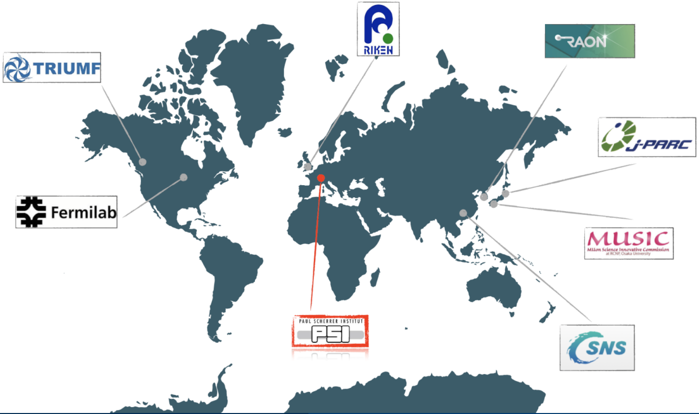
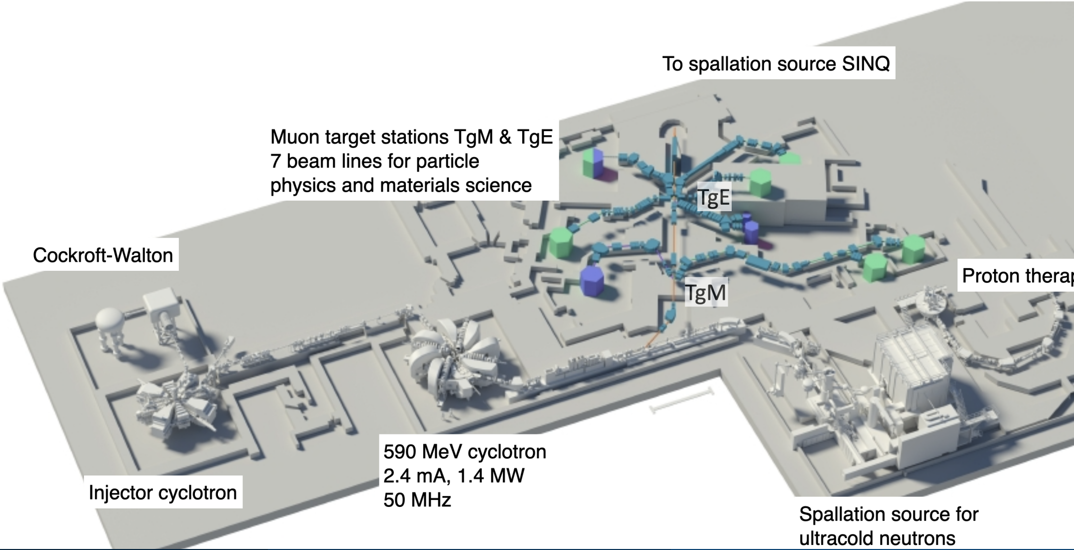
PSI is the place to go.



The High Intensity Proton Accelerator facility



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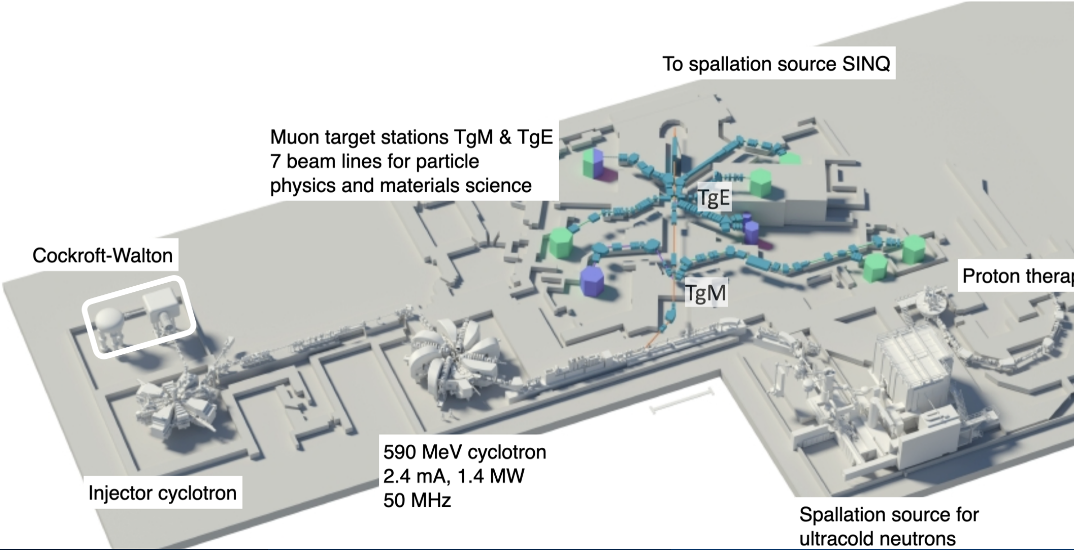

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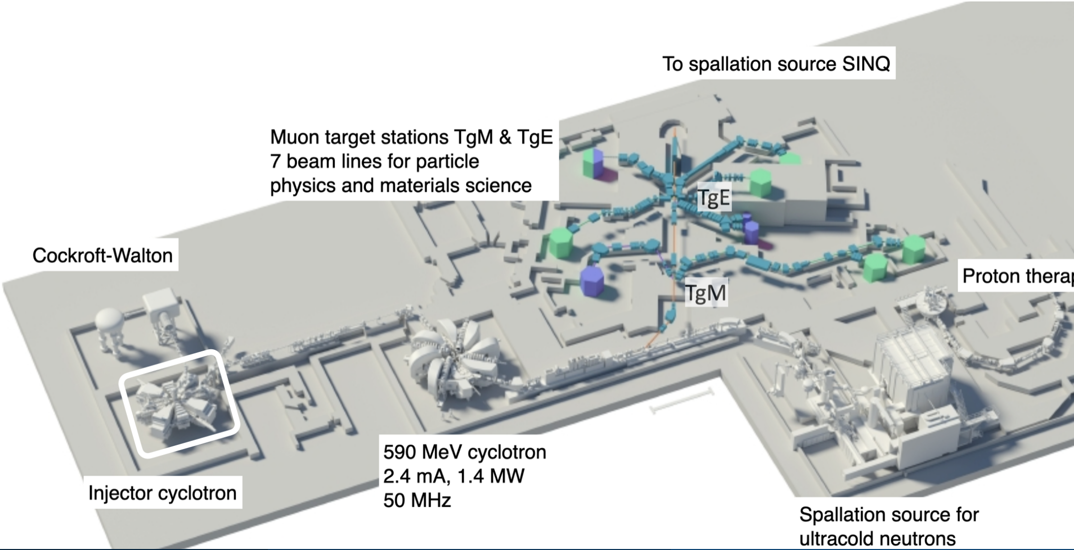

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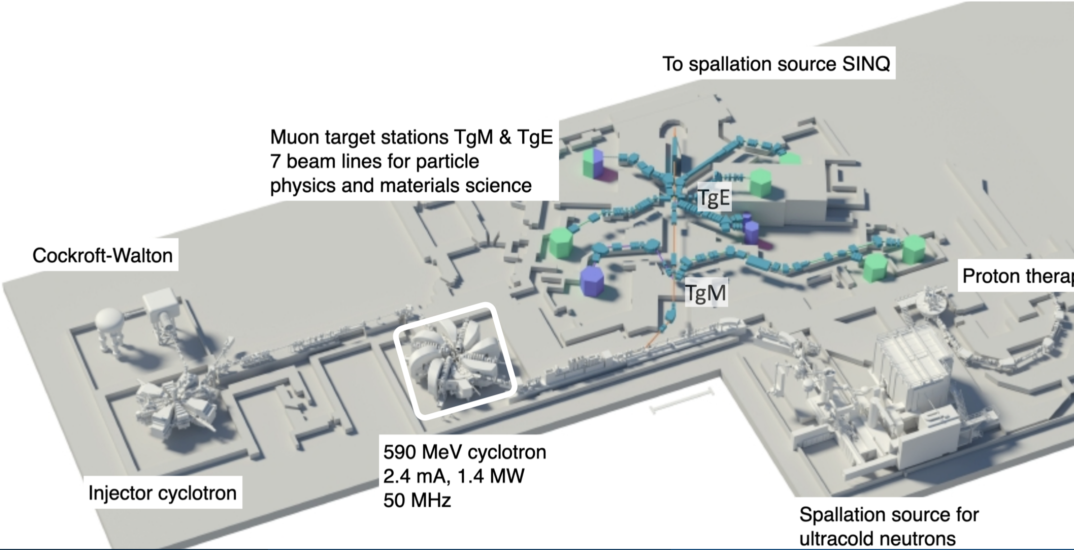

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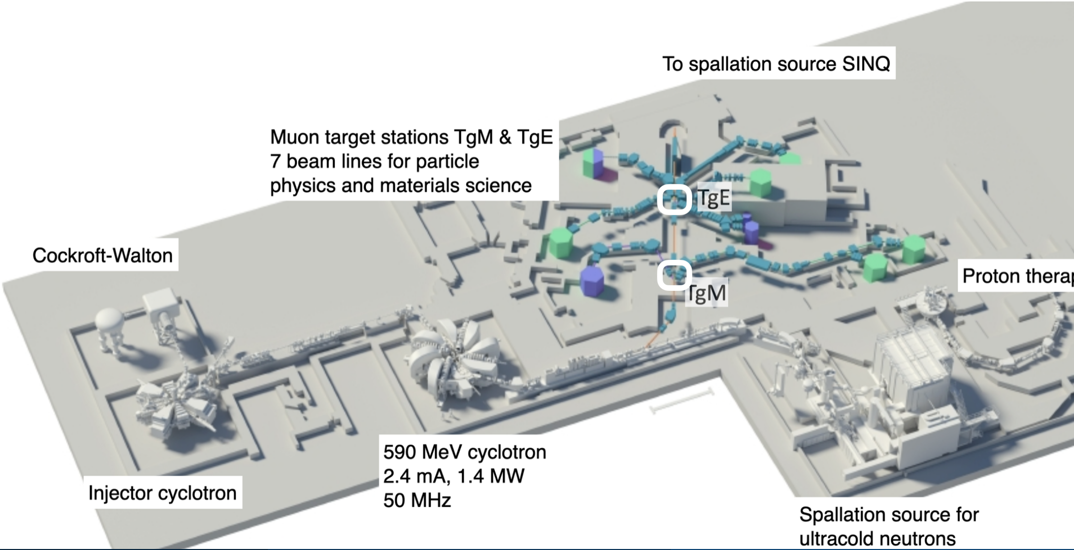
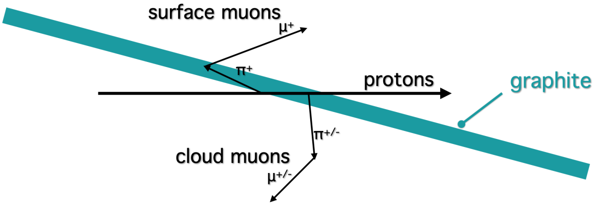


Muon production

The protons impinge on the targets, producing pions that decay in muons. Depending on where they are created, we classify:

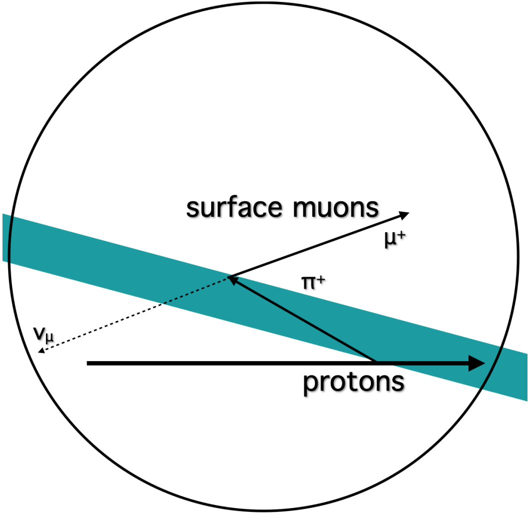
- Surface and sub-surface muons (5 - $30\,\mathrm{MeV/c}$): pion decay at rest.
- Cloud muons: pion decay in flight.



Due to the high intensity and low momentum, the most interesting muons for many experimental applications are surface muons as they can be stopped in low material budget targets.

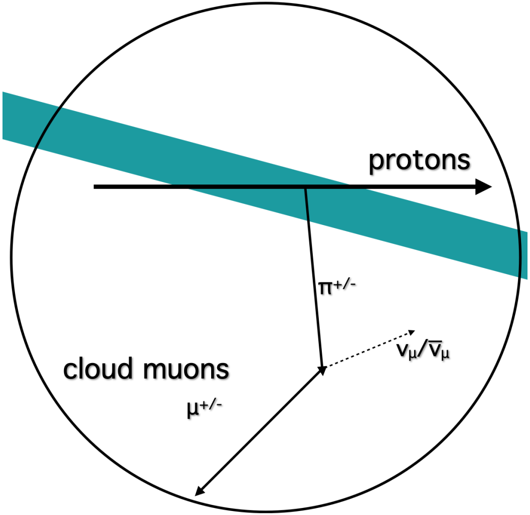
Muon production

- **Surface and sub-surface muons (5 - $30\,\mathrm{MeV/c}$): pion decay at rest.**



Muon production

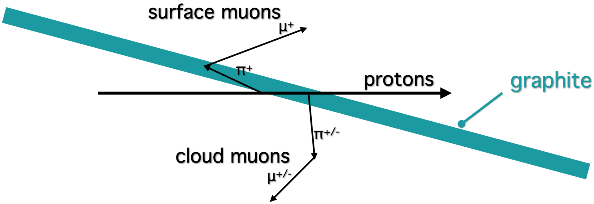
- **Cloud muons: pion decay in flight.**



Muon production

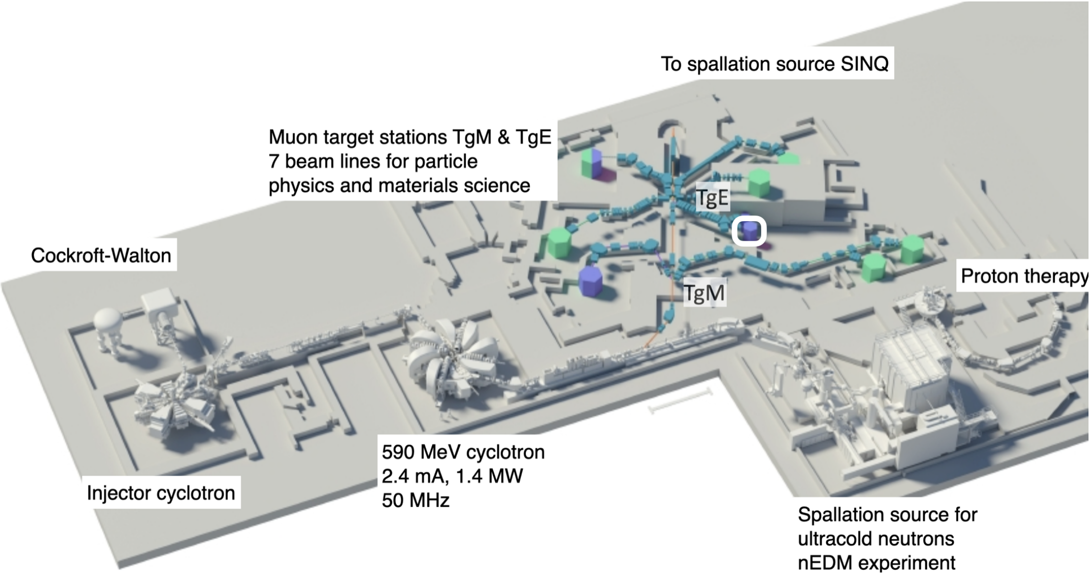
The protons impinge on the targets, producing pions that decay in muons. Depending on where they are created, we classify:

- Surface and sub-surface muons (5 - $30\,$MeV/c): pion decay at rest.
- Cloud muons: pion decay in flight.

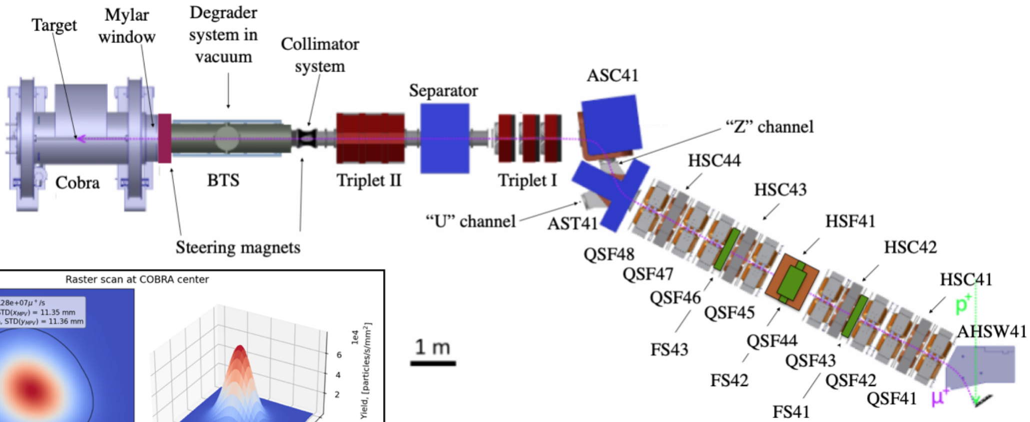


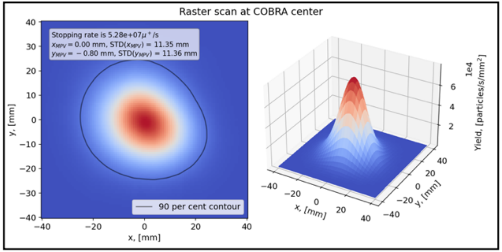
Due to the high intensity and low momentum, the most interesting muons for many experimental applications are surface muons as they can be stopped in low material budget targets.

The High Intensity Proton Accelerator (HIPA) facility



The πE5 beamline

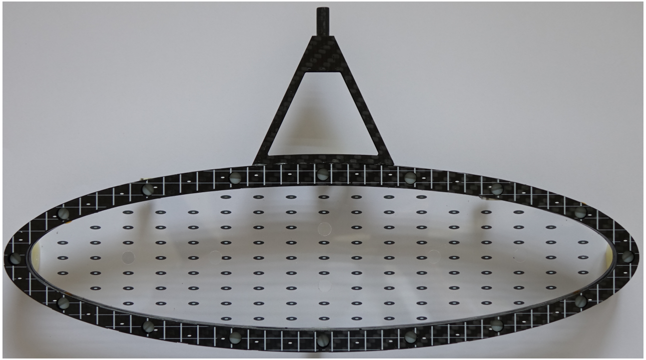




$>10^8$ μ^+/s can be delivered to the experiment

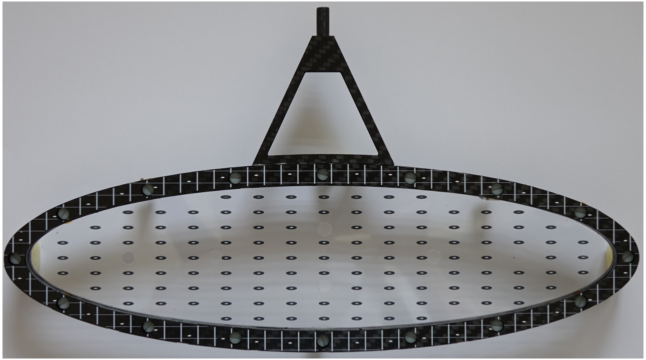
Stopping target

- reduce accidental background by distributing muon stops over a large surface



Stopping target

- reduce accidental background by distributing muon stops over a large surface
- reduce material budget for decay products

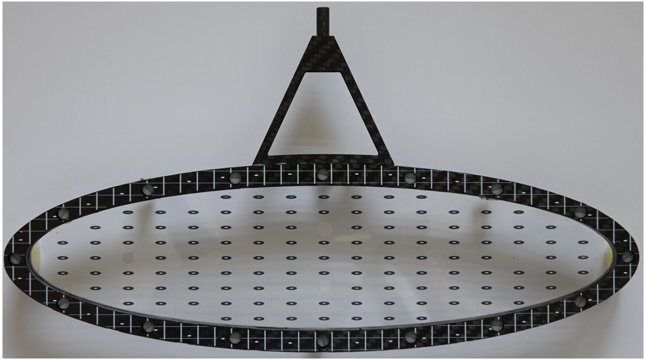


Stopping target

- reduce accidental background by distributing muon stops over a large surface
- reduce material budget for decay products

→ **slanted target**:

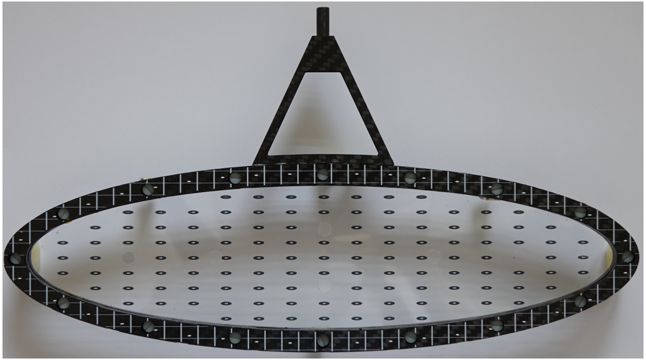
- 174 µm thick BC400
- $28\,\mathrm{cm} \times 8\,\mathrm{cm}$ ellipsis
- $86.6\,\%$ stopping efficiency



Stopping target

Displacement/deformation should be < 0.5 mm:

- dominant systematic error in MEG ($5\,\%$ in the branching ratio)
- 6 holes to monitor the target through e^+ vertices
- photogrammetric survey by two cameras, detect deformations down to $100\,\mu m$



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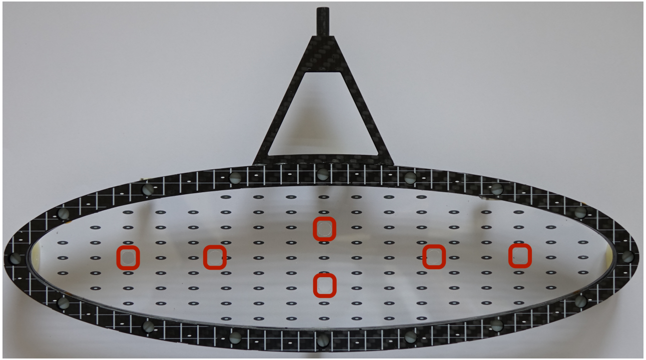

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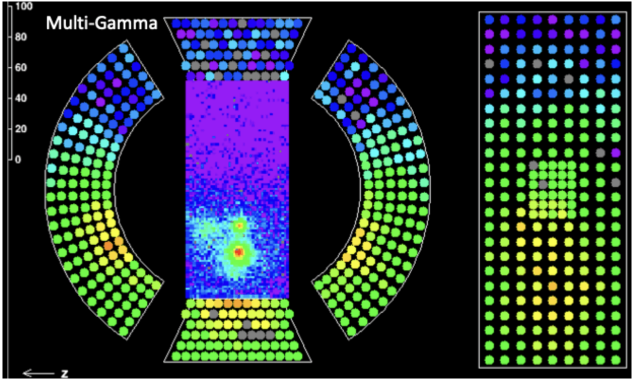
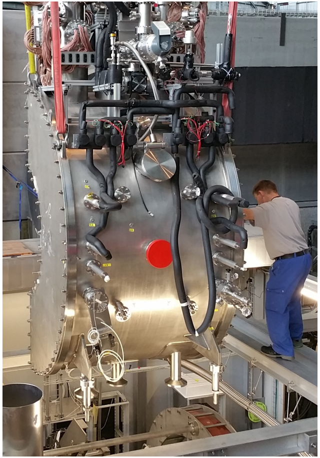
The liquid XEnon Calorimeter (XEC)

- 4092 MPPCs
- 668 PMTs
- 900 L liquid xenon





XEC calibrations

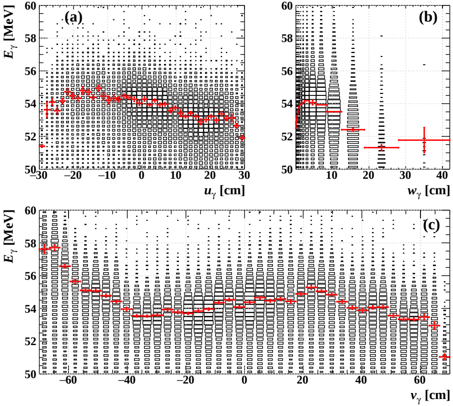
Periodic calibration routine (demanding):

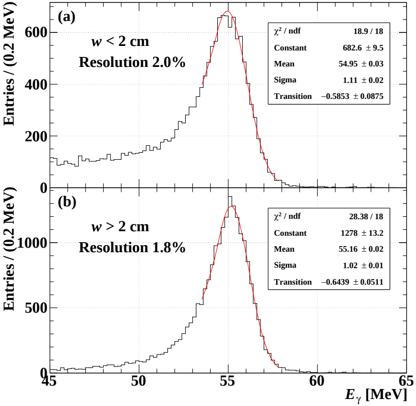
- radiative muon decay - energy scale, continuously
- LED (UV) - PMT/MPPC gains, daily
- radioactive source $\rightarrow$ $^{241}\mathrm{Am}(\alpha,\gamma)^{237}\mathrm{Np}$ (4.4 MeV) - energy scale daily
- cosmic rays - energy scale & uniformity, daily
- dedicated CW accelerator $\rightarrow$ $^{7}\mathrm{Li}(\mathrm{p},\gamma)^{8}\mathrm{Be}$ (17.6 MeV) - energy scale & PDE, 3 times per week
- neutron generator $\rightarrow$ $^{58}\mathrm{Ni}(\mathrm{n},\gamma)^{59}\mathrm{Ni}$ (9 MeV) - energy scale, 3 times per week
- $\pi^{-}\mathrm{p} \rightarrow \pi^{0}\mathrm{n}$ (55, 83, 129 MeV) - absolute energy scale, annually

XEC calibrations

They allow to monitor temporal variations in the performances, detector uniformity and energy resolution.

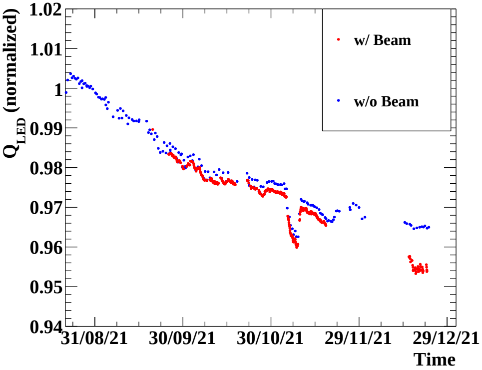
- energy scale uncertainty → 0.4 %
- detector resolution → 2.0 %

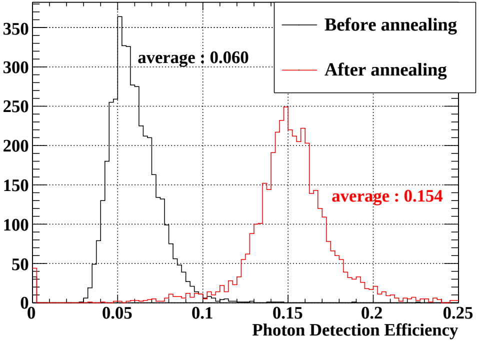




MPPC radiation damage

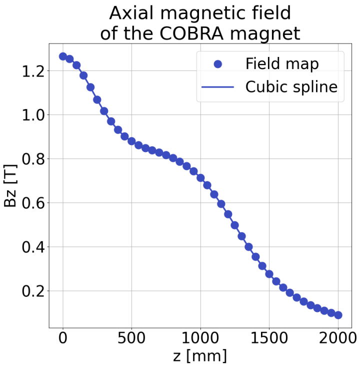
We see a decrease of the MPPC PDE with time through the run → recovery by Joule annealing (28 h / patch ∼ 2 months in total).





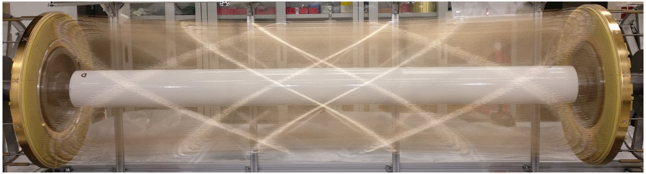
The COnstant Bending RAdius magnet COBRA

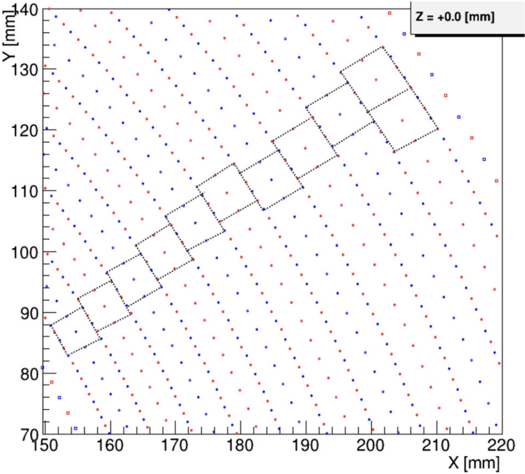
- thin SC magnet
- gradient magnetic field to bend positrons with radius independent on the emission angle



The Cylindrical Drift CHamber CDCH

- 1728 gold-plated tungsten wires ($20\,\mu m\varnothing$, anodes)
- 13560 silver plated aluminum wires ($40/50\,\mu m\varnothing$, cathodes)
- $\sim 7^\circ$ criss-cross stereo angle for z determination
- helium-isobutane (90-10) gas mixture
  (+ $1\,\%$ isopropyl alcohol and $0.5\,\%$ oxygen)
- $1.58 \times 10^{-3}\, X_0/e^+$−turn





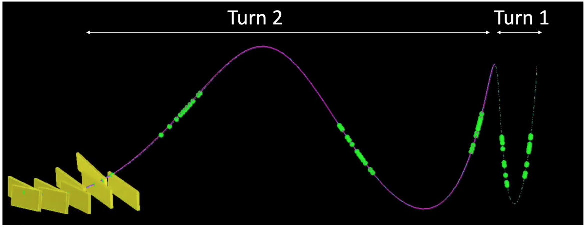
The Cylindrical Drift CHamber CDCH - performances

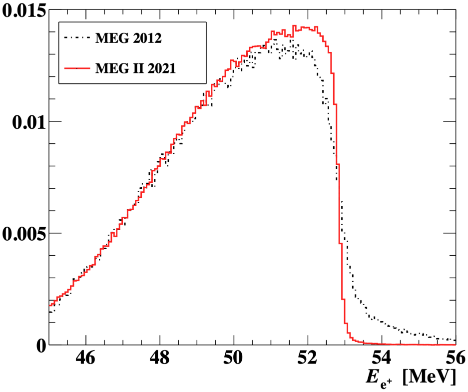
The resolutions are obtained through:

- double-turn analysis
- Michel edge fit

Performances in 2021:

- energy resolution: 89 keV (380 keV in MEG)
- efficiency @ 3×10^7 μ^+/s: 67 % (30 % in MEG)





The Cylindrical Drift CHamber CDCH - alignment

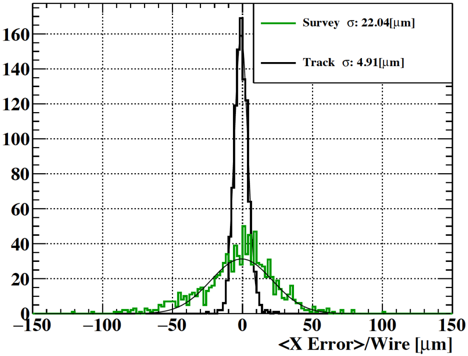
Major systematic effect. Need to evaluate the CDCH wire alignment and the relative alignment to the magnet, the target and to the XEC.

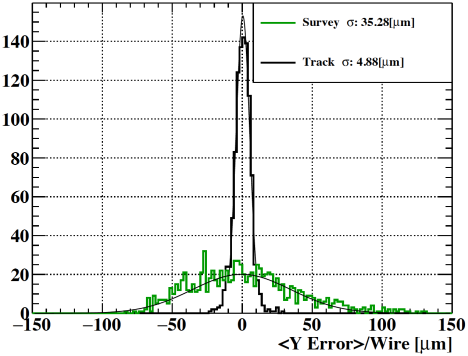
The Cylindrical Drift CHamber CDCH - alignment

Major systematic effect. Need to evaluate the **CDCH wire alignment** and the relative alignment to the magnet, the target and to the XEC.

Wire alignment

Optical survey (residuals $22 - 35\,\mu m$) → refined by relative alignment with Michel positron tracks (residuals $< 5\,\mu m$).



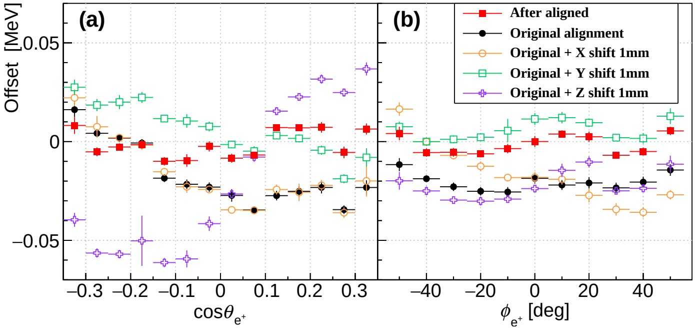


The Cylindrical Drift CHamber CDCH - alignment

Major systematic effect. Need to evaluate the CDCH wire alignment and the relative alignment to **the magnet**, the target and to the XEC.

CDCH-COBRA alignment

The nominal alignment introduces a dependence of the positron energy scale to the emission angle. → **align by minimising such effect**.

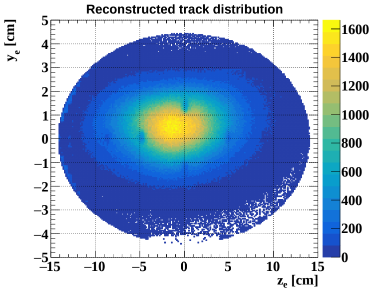


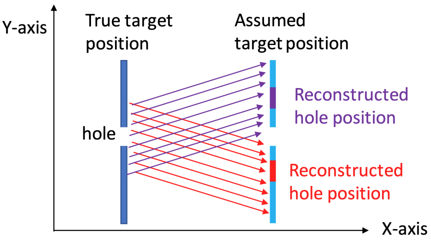
The Cylindrical Drift CHamber CDCH - alignment

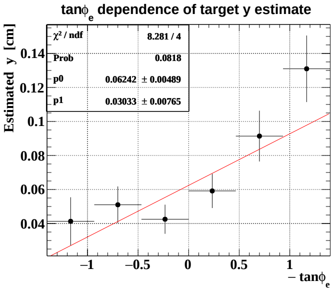
Major systematic effect. Need to evaluate the CDCH wire alignment and the relative alignment to the magnet, **the target** and to the XEC.

CDCH-target alignment

A misalignment in the reconstructed hole horizontal position results in a dependence of its reconstructed vertical position on the positron emission angle.





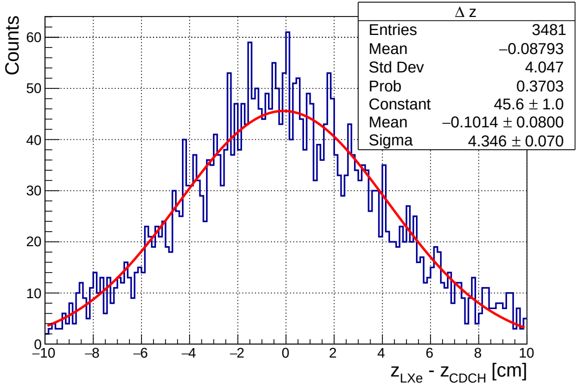


The Cylindrical Drift CHamber CDCH - alignment

Major systematic effect. Need to evaluate the CDCH wire alignment and the relative alignment to the magnet, the target and to the **XEC**.

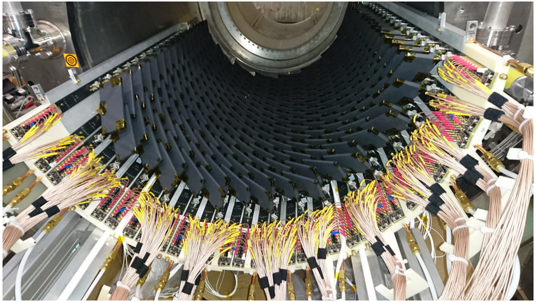
CDCH-XEC alignment

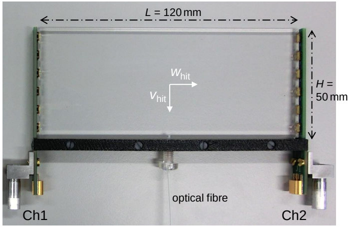
The alignment is done with cosmic rays crossing both detectors.

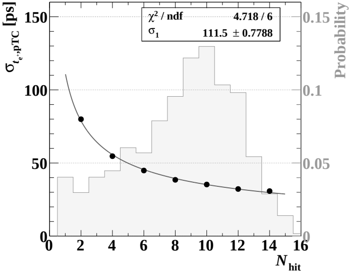


The pixelated Timing Counter (pTC)

- 256 plastic scintillating tiles
- single tile resolution ~ 100 ps
- on average 9 tiles per event are hit $\rightarrow \sim 37$ ps (65 ps in MEG)
- inter-calibration ~ 15 ps through track reconstruction and laser pulsing through optical fibres

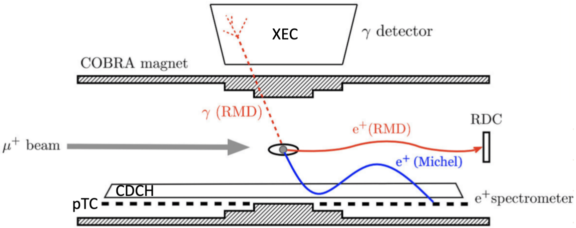


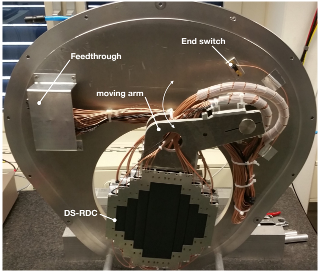


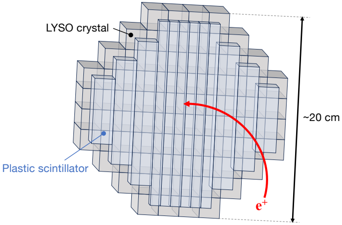


The Radiative Decay Counter (RDC)

- to tag high energy γ with low energy positrons ($\epsilon \sim 14\,\%$)
- plastic tiles for timing + LYSO crystal for energy
- $7\,\%$ improvement on sensitivity



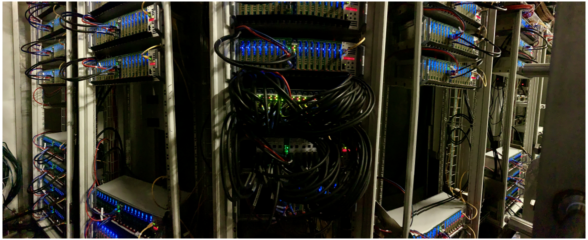


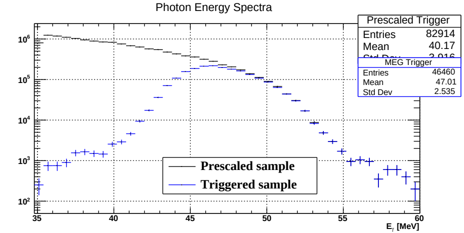


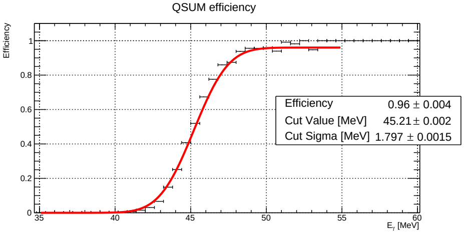
Trigger and Data AQuisition system

Trigger and DAQ are integrated in a single system for 8591 channels (4 times MEG):

- reconstruction is done based on the full waveform information
- trigger based on fast response detector (pTC and XEC):
  1. photon energy, $\epsilon = 96\,\%$
  2. time coincidence, $\epsilon = 94\,\%$
  3. direction match $\epsilon = 88.5\,\%$
- trigger efficiency $= 80\,\%$ in 2021



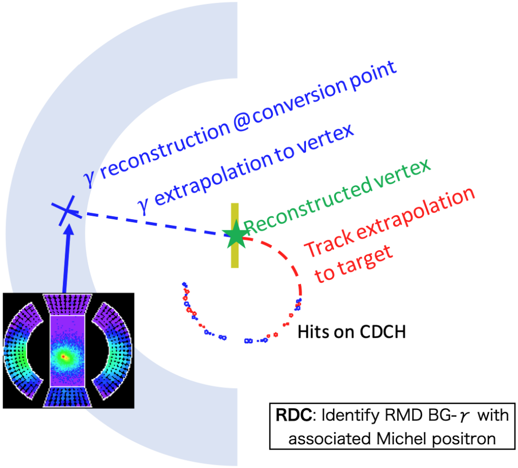




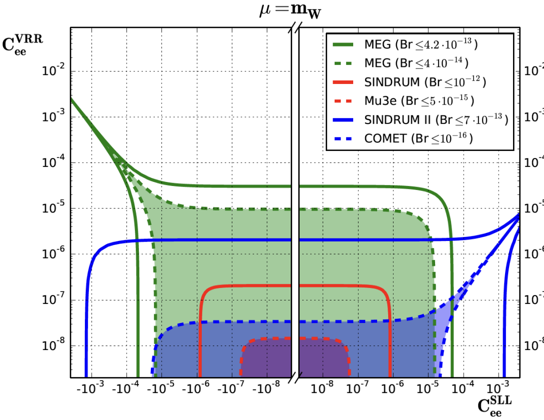
Analysis approach

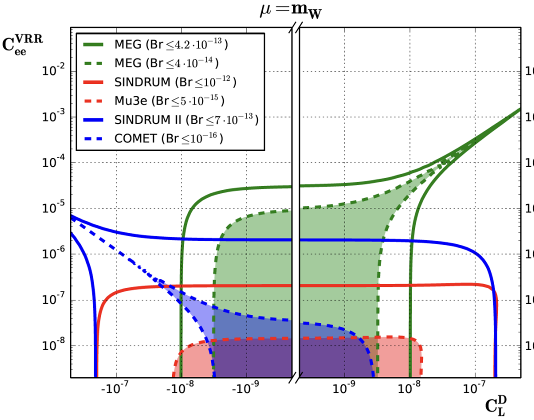
In addition to the kinematic variables, the RDC veto and the number of pTC tiles hits are included in the analysis:

- XEC, CDCH, pTC: E_γ, E_{e+}, $t_{e+\gamma}$, $\theta_{e+\gamma}$, $\phi_{e+\gamma}$
- RDC: $t_{RDC-XEC}$, E_{RDC}



cLFV complementarity





The Cylindrical Drift CHamber CDCH - hit-detection

Tracking efficiency improved by $26\,\%$ by combining two hit-finding algorithms ($53\,\% \rightarrow 67\,\%$).