THE MEG-II EXPERIMENT

G.Gallucci on behalf of MEG-II collaboration

WIFAI 2025 : Workshop italiano sulla fisica ad alta intensità

Bari 11-14 November 2025

Outline

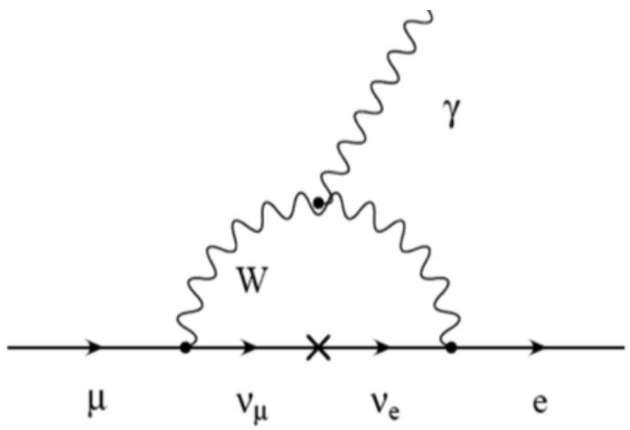
- Introduction to MEG-II Physics
- Muon beam
- MEG-II experiment at Paul Scherrer Institute (PSI)
- Latest MEG-II results
- Conclusions

Charged lepton flavor violation (cLFV)

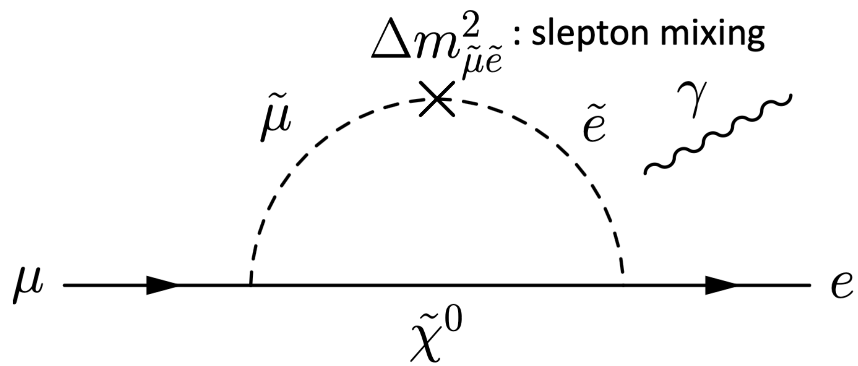
- The lepton flavor is conserved in the Standard Model (SM).
- In the nature the lepton flavor is not an exact symmetry, in the neutral sector is violated (neutrinos oscillations) but we never observed violation in charged sector.
- Observe a cLFV process is clear signature of physics beyond the SM (BSM).

No SM process for $\mu \to e + \gamma$
Even with ν oscillation:
B($\mu \to e + \gamma$) ~ 10^{-54}

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\boxed{\Delta m^2_{i1}}}{M_W^2}\right|^2 \simeq 10^{-54}$$



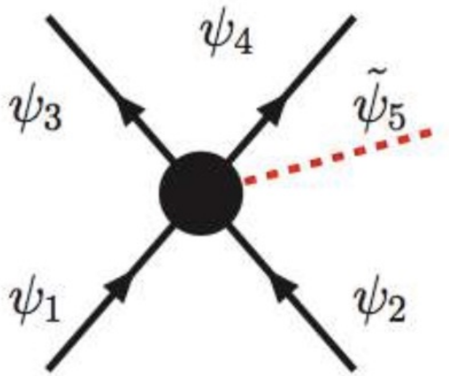
In BSM new particles
$\mu \to e + \gamma$ >> 10^{-54}
SM background free search!



Intensity frontier

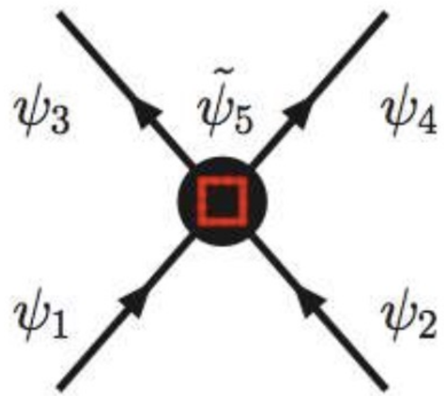
Intensity frontier is complementary to energy frontier
You can probe energy scale otherwise unreachable (E>1000 TeV)

Energy frontier



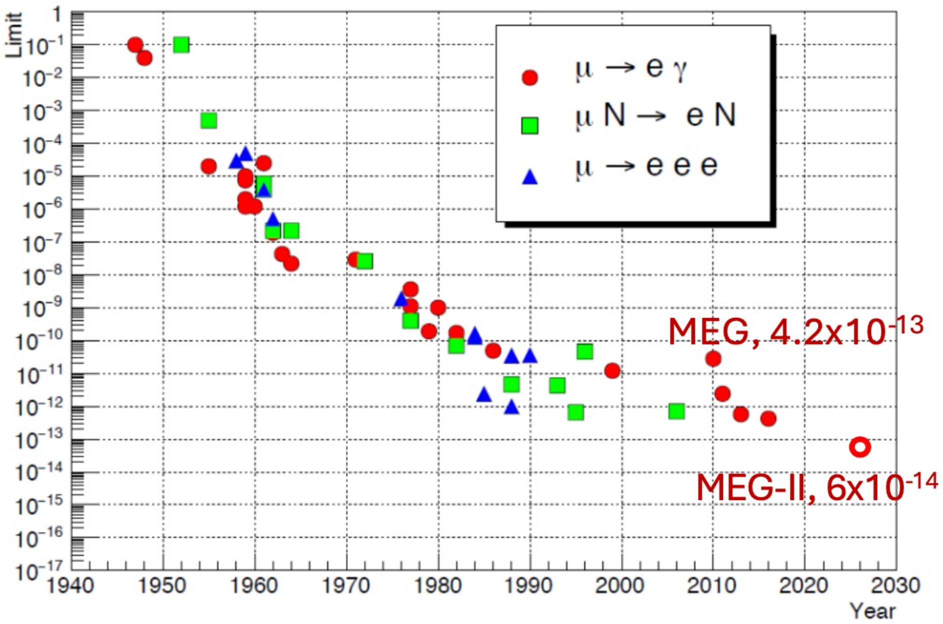
Real BSM particles

Precision and intensity frontier



Virtual BSM particles

Status and prospects of cLFV search with muons



(Riv. Nuovo Cimento 41 (2018) 71)

- In the near future improved sensitivities in all the so called "golden" muon channels;
- Strong complementarities among channels: the only way to reveal the mechanism responsible for cLFV;
- Probing energy scale otherwise unreachable at the energy frontiers;

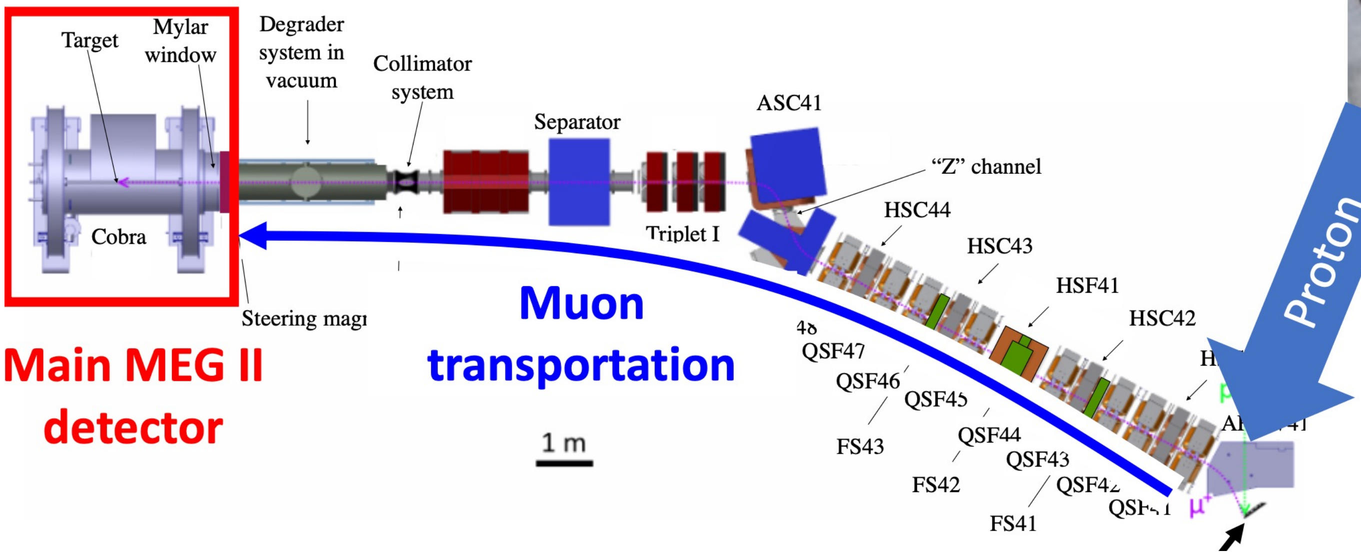
	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 6 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	few x 10^{-17}

MEG II goal: 6 x 10^{-14} sensitivity

PSI muon beam

The 590 MeV proton ring cyclotron of PSI delivers the most intense muon beam in the world:

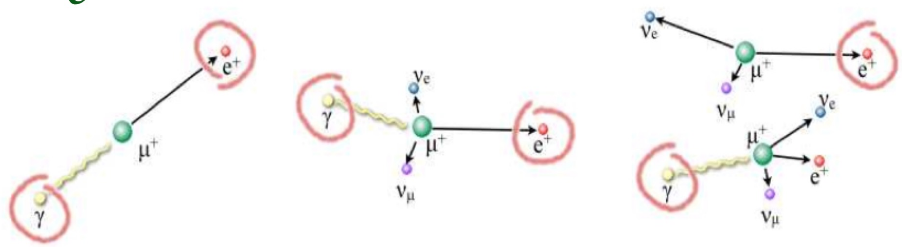
- Continuous (DC);
- Intense $\sim 10^8 \frac{\mu}{s}$;
- Low energy (28 MeV/c, from surface muons);



Proton ring cyclotron

$\mu \rightarrow e + \gamma$ process

signal *RMD* *Accidental*



signal	RMD	Accidental
$E_\gamma = 52.8$ MeV	$E_\gamma < 52.8$ MeV	$E_\gamma < 52.8$ MeV
$E_{e^+} = 52.8$ MeV	$E_{e^+} < 52.8$ MeV	$E_{e^+} < 52.8$ MeV
$\Theta_{e\gamma} = 180°$	$\Theta_{e\gamma} < 180°$	$\Theta_{e\gamma} < 180°$
$T_{e\gamma} = 0$ s	$T_{e\gamma} = 0$ s	$T_{e\gamma} \Rightarrow$ flat

Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to identify $\mu \rightarrow e + \gamma$ events.

Background comes from:

- the radiative decay of muon (RDM) -> Physics Background
- from uncorrelated events (Michel, RDM, on-flight annihilation) → Accidental background.

Accidental background is dominant and determined by beam rate and resolutions.

How to reach MEG-II goals:

- High statistics, to be more sensitive to signal
- High resolution to rejecting background

- More sensitive to the signal...

high statistics

$$SES = \frac{1}{R \times T \times A_g \times \varepsilon(e^+) \times \varepsilon\,(\text{gamma}) \times \varepsilon(\text{TRG}) \times \varepsilon(\text{sel})}$$

Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

- More effective on rejecting the background...

high resolutions

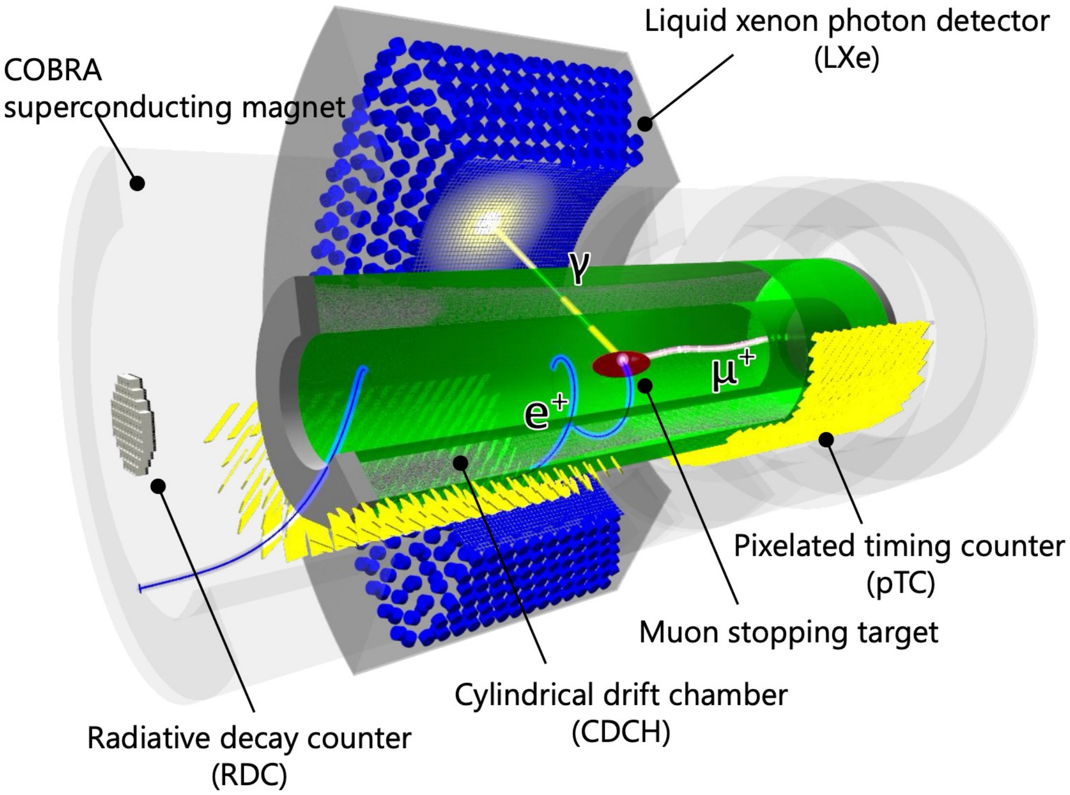
$$B_{acc} \sim R \times \boxed{\Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta\Theta_{egamma})^2}$$

Positron Energy resolution
Gamma Energy resolution
Relative timing resolution
Relative angular resolution

MEG-II experiment

MEG

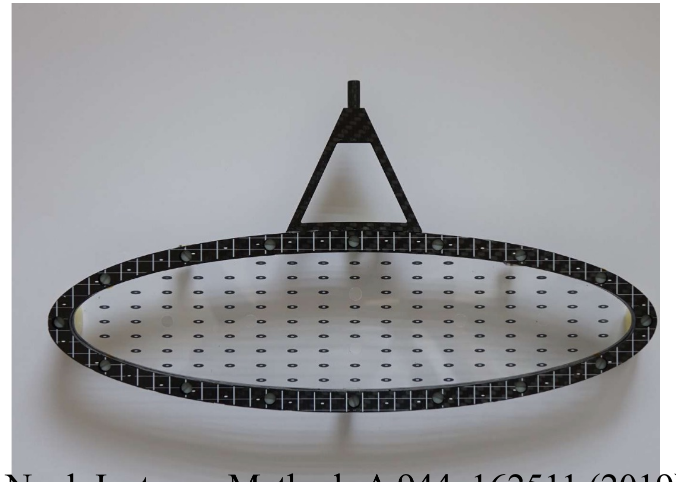
- μ beam stopped on a target;
- non uniform solenoidal magnetic field;
- tracking with ultra-thin Drift Chamber and timing with plastic scintillators;
- γ detection with liquid xenon;
- complete and redundant calibrations techniques;



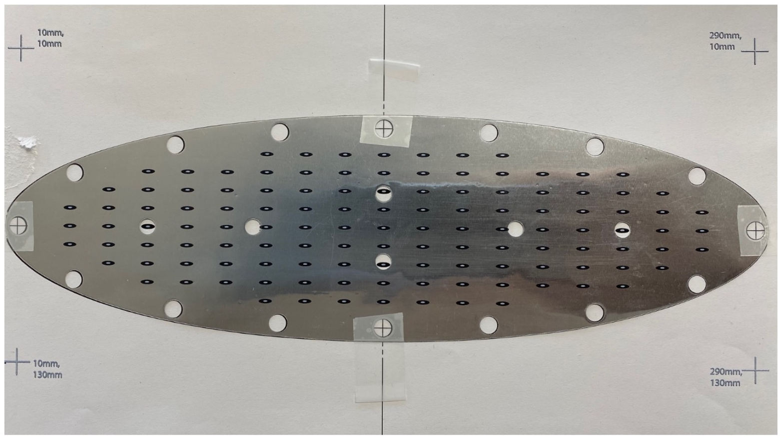
Muon stopping target

BC400 174μm thick (cf. MEG 205μm), 66mm height, 15° slanted, carbon fiber frame

- Displacement/deformation of target should be < 0.5mm
- Dominant systematic error (5% in BR) of MEG
- Six holes - systematic checks by e+ tracking
- NEW: photogrammetric survey by two cameras good within 100μm normal to the target plane



Nucl. Instrum. Methods A 944, 162511 (2019); Rev. Sci. Instrum. 92(4), 043707 (2021)



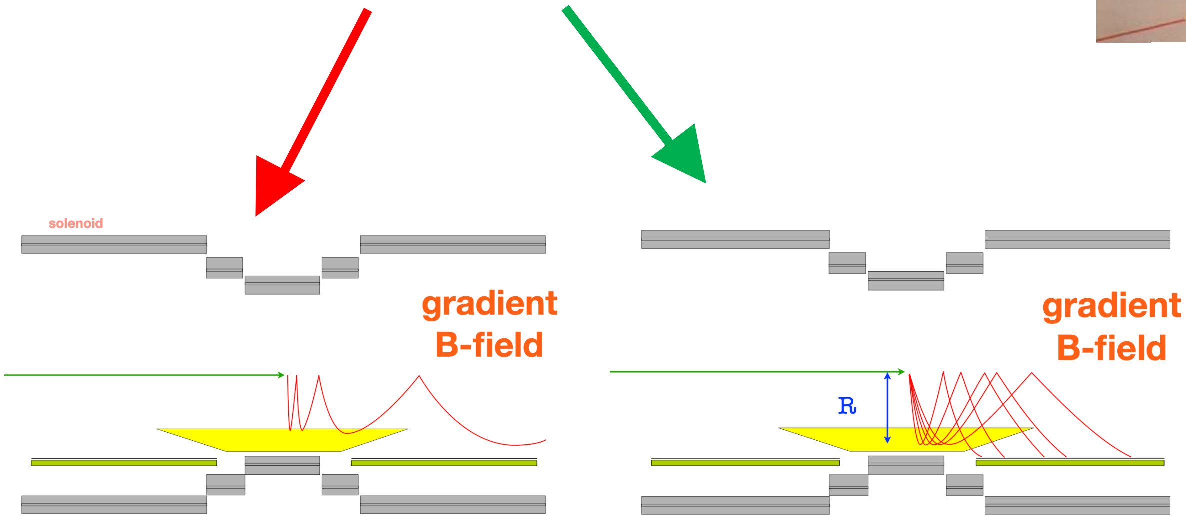
In 2025 data taking run:

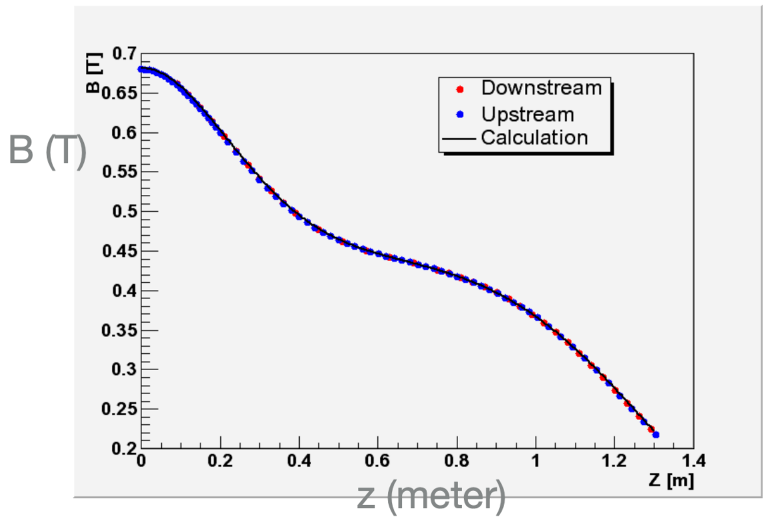
- Target of ~100μm of Berillium
- Stopping power comparable to BC400
- Better heat resistance, less deformation during run.

Cobra magnet

A thin-wall super conducting solenoid with a gradient magnetic field (1.27T centre - 0.49T both ends).
Two effects:

1. Positrons transversly emitted are quickly swept out (reduced crowing of tracker);
2. Constant bending radius independent of emission angles;

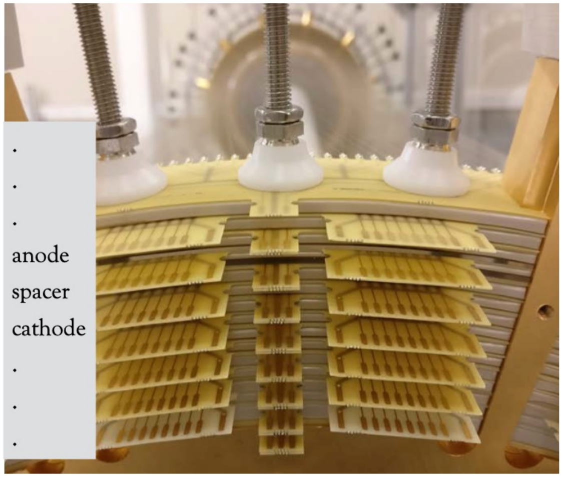


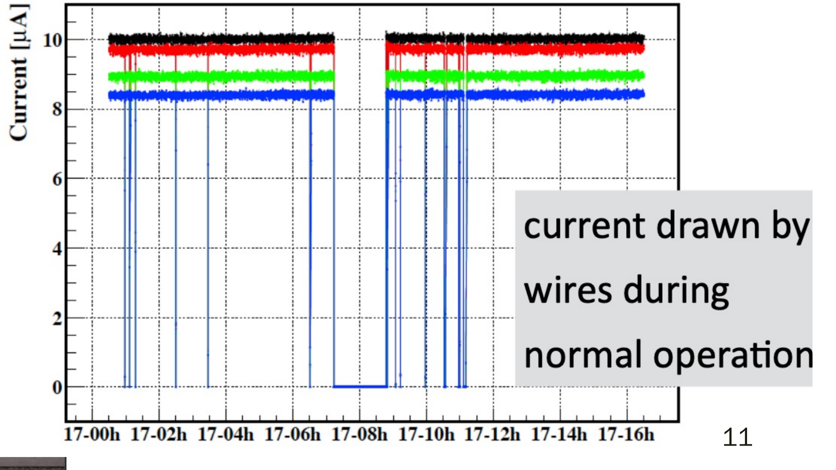


CDCH detector

Single volume drift chamber:

- Low material (1.58×10^{-3} X_0 for turn);
- ~2 m long and radius of 12-29 cm;
- He-Isobuthane (90-10) low mass gas mixture (+ 1% isopropylic alcohol and ~0.5% oxygen or less to stabilize currents);
- 9 layers of drift cells of 6 – 9 mmø with stereo angles of 6.0 - 8.5°, high-density readout (2 – 3 cells / cm2);
- 1728 anode wires + 10000 cathodes (anode: 20µm W/Au, cathode: 40/50 µm Al/Ag)
- innermost cells at > 1MHz for 5×10^7 μ/sec, max occupancy ~25%

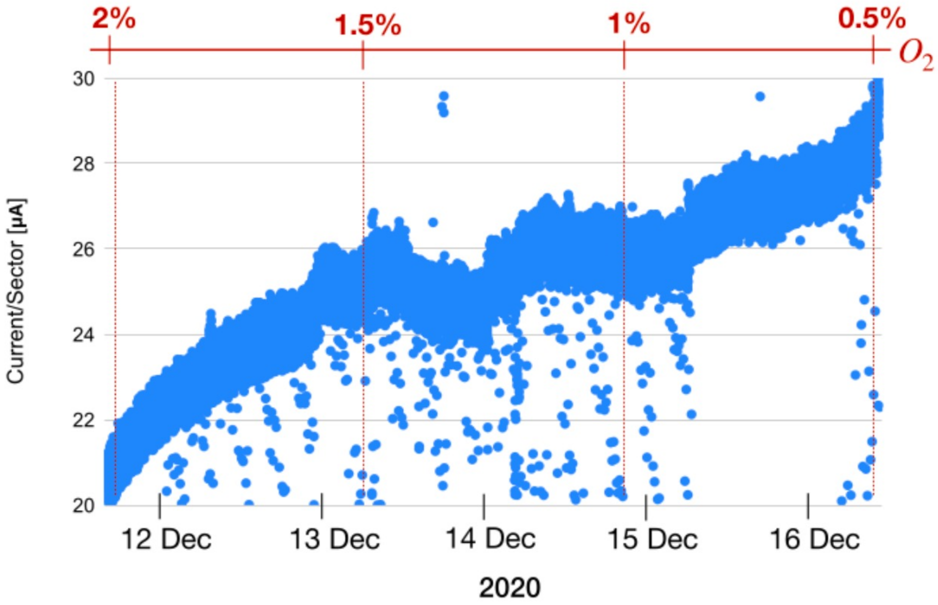




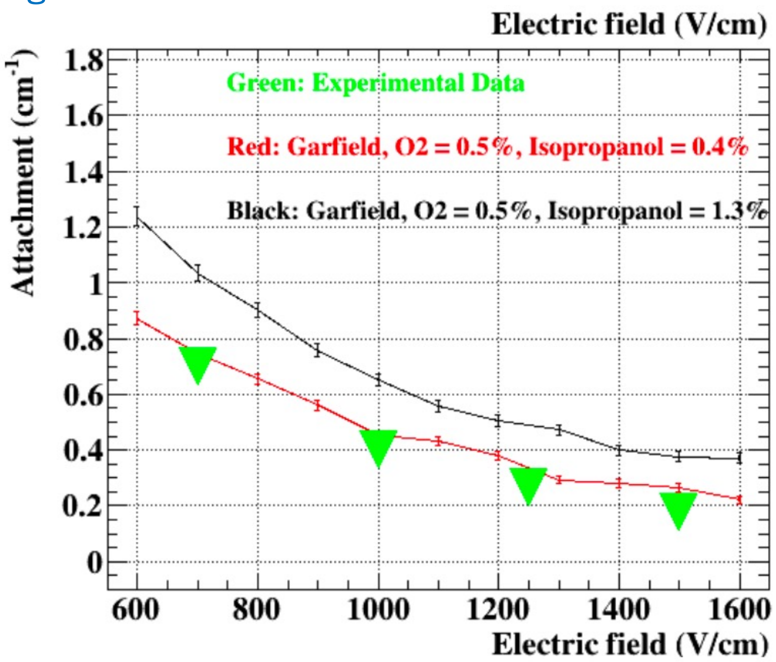
Hint about gas mixture

The adding of small quantity of oxygen and isopropanol stabilizes the chamber working without degrading its performances. The electron attachment on oxygen due to the 3-body de-excitation can be evaluated using Garfield++ by modifying the treatment of this process in the Garfield routine dedicated to oxygen; this requires to pass by hand
the gas mixture and the experimental values of attachment probability for all gases.

Current as function of oxygen fraction

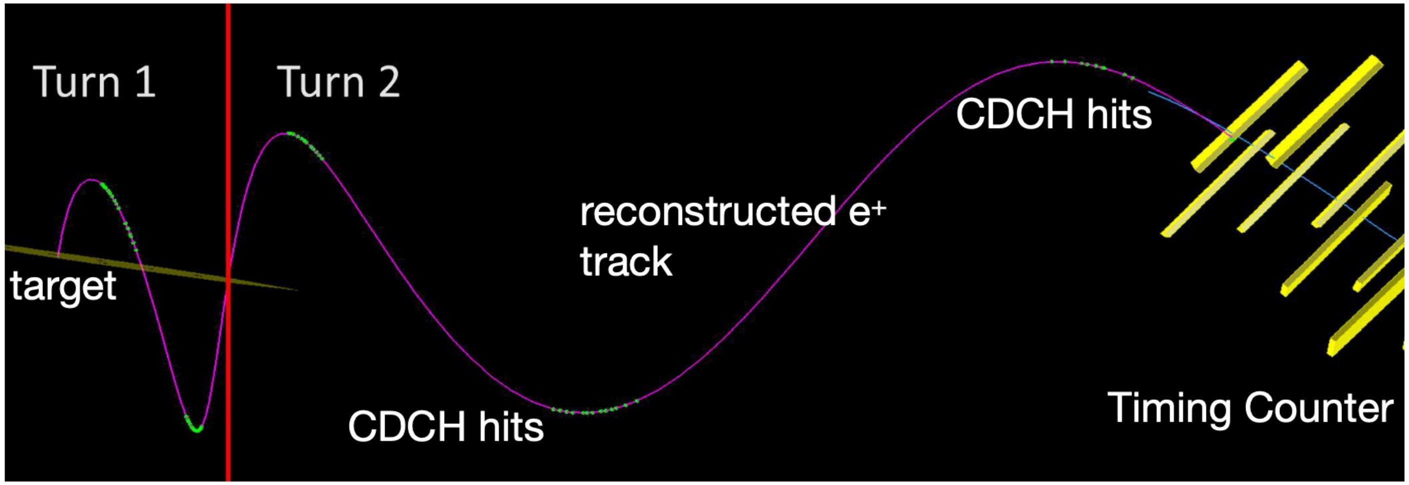


Agreement between data and Garfield simulation using correct three-body attachments and gas mixture



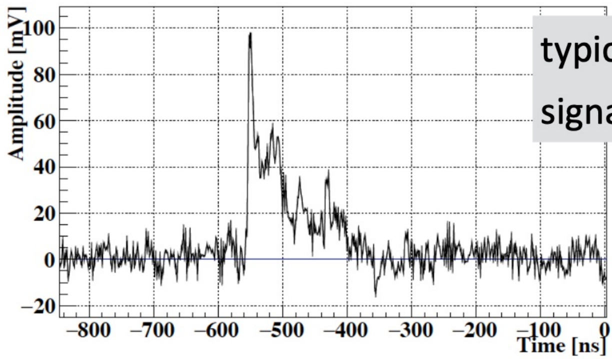
Paper submitted to JINST; arXiv number 2511.07082.

CDCH performances



- Single hit resolution ~150 μm;
- momentum resolution 89keV/c (core);
- tracking efficiency ~65% @3e7 μ/s;

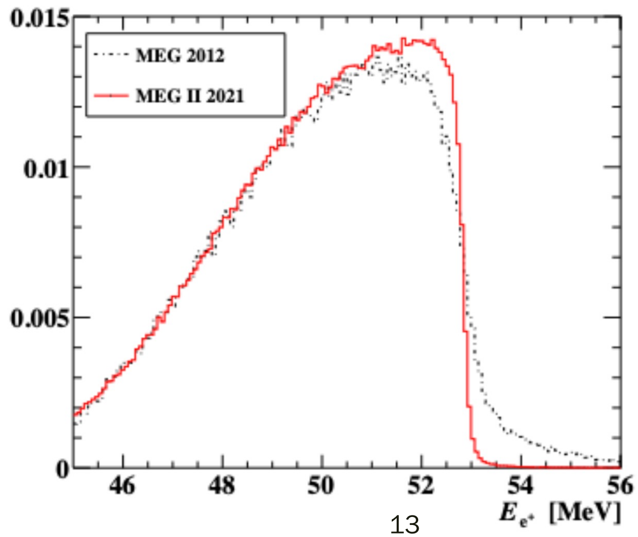
Current performance at MC level in most the variables



typical anode signal

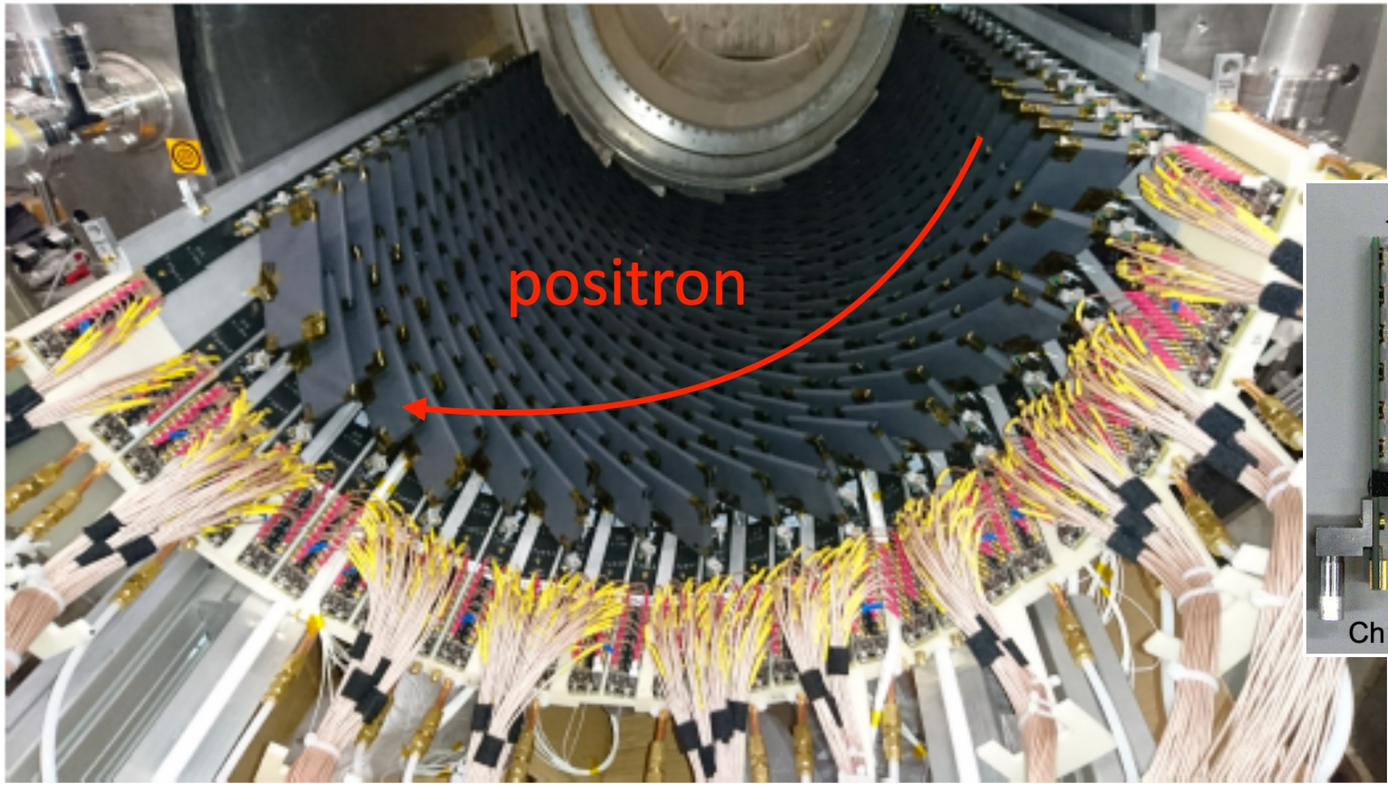
CDCH alignment:

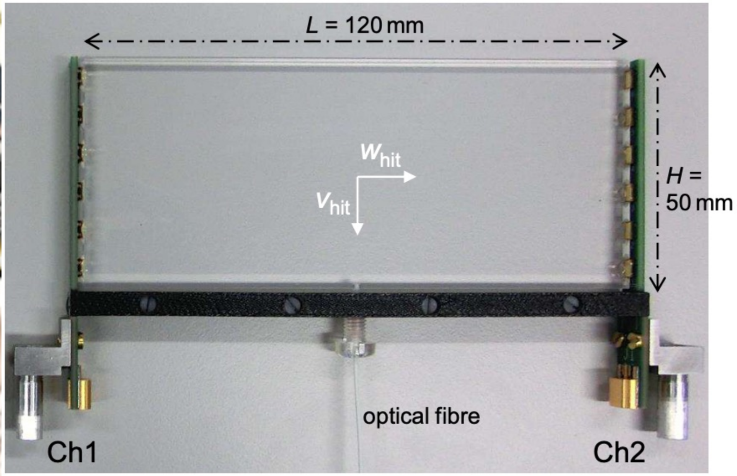
- Michel positrons;
- Survey measurements;
- Magnetic field map;
- Target holes reconstruction;
- Cosmic rays (alignment with photon detector)./



Pixelated Timing Counter detector (pTC)

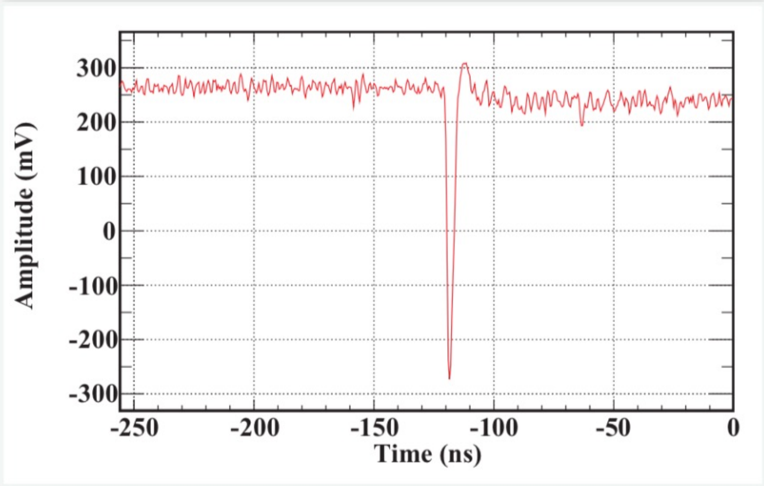
- Highly segmented detector;
- Two sectors, each made of 256 scintillator tiles of Bicron BC422 (120x50x5 mm^3);
- Each tile is read from 2 array of 6 SiPM (AdvanSiD 3x3 mm^2);
- Time by averaging the tiles hit by a positron, 8 tiles hit on average for signal positrons;
- Laser can be injected in most of the tiles for time calibration and monitoring.

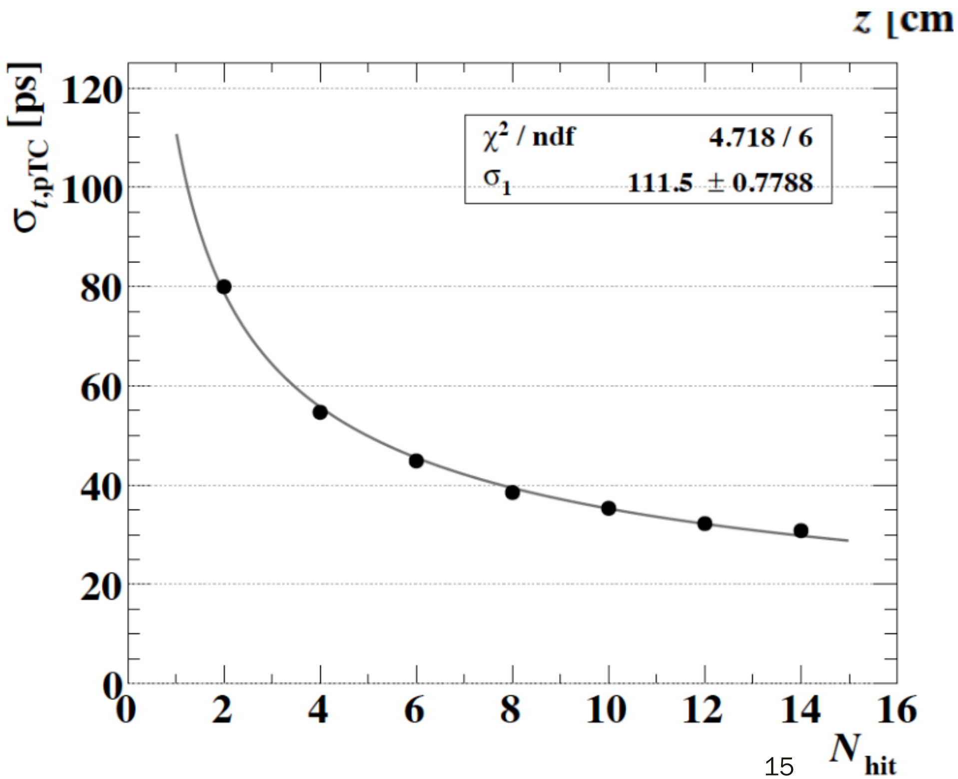




Timing counter performances

- Very stable detector operation;
- Tile rates in agreement with expectations;
- Time resolution of ~ 30ps for signal positrons.



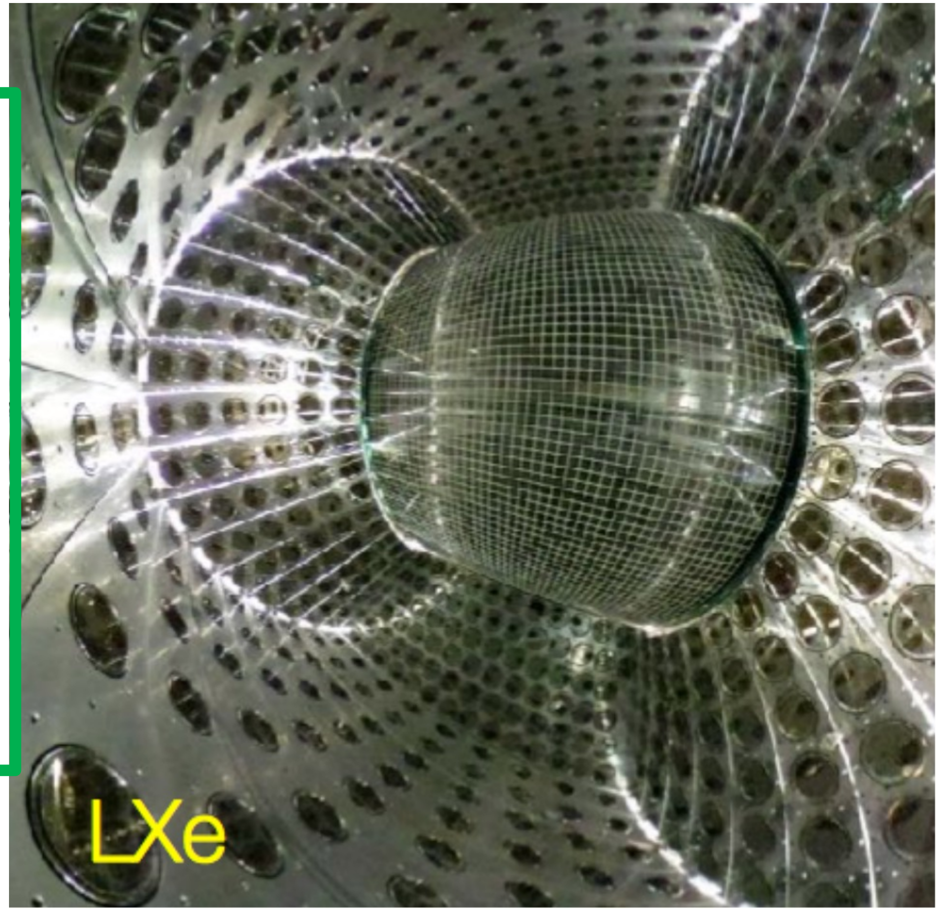


Liquid xenon calorimeter

- Homogenous volume of 2,7 ton of LXe (~900 l);
- Gas/liquid circulation system to purify xenon from water and oxygen;
- High light yield: 40 photons/keV;
- Very fast: 4/22/40 ns

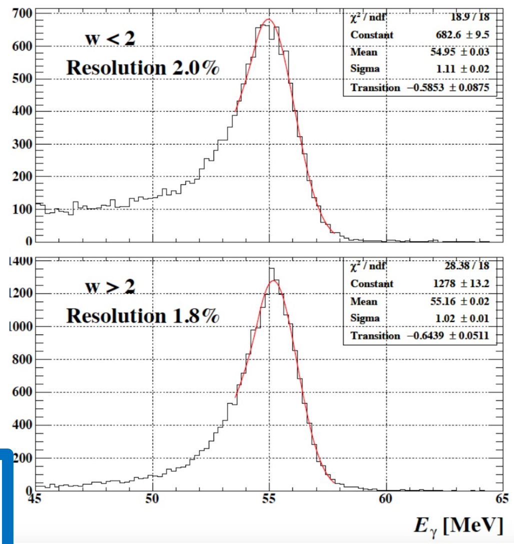
Readout with:

- 4,092 MPPCs (15x15mm2) on inner face;
- 668 2” PMTs on other faces;

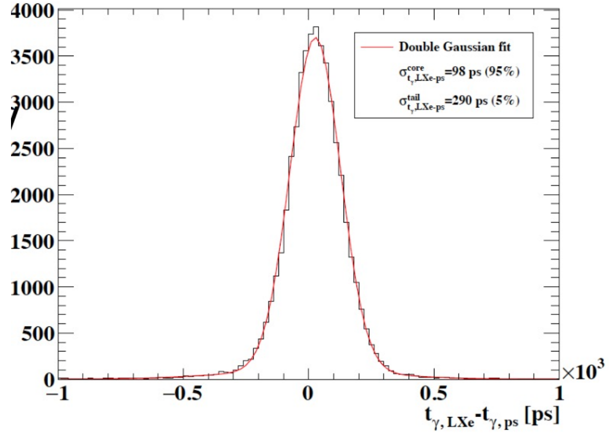


Liquid xenon calorimeter performances

ENERGY

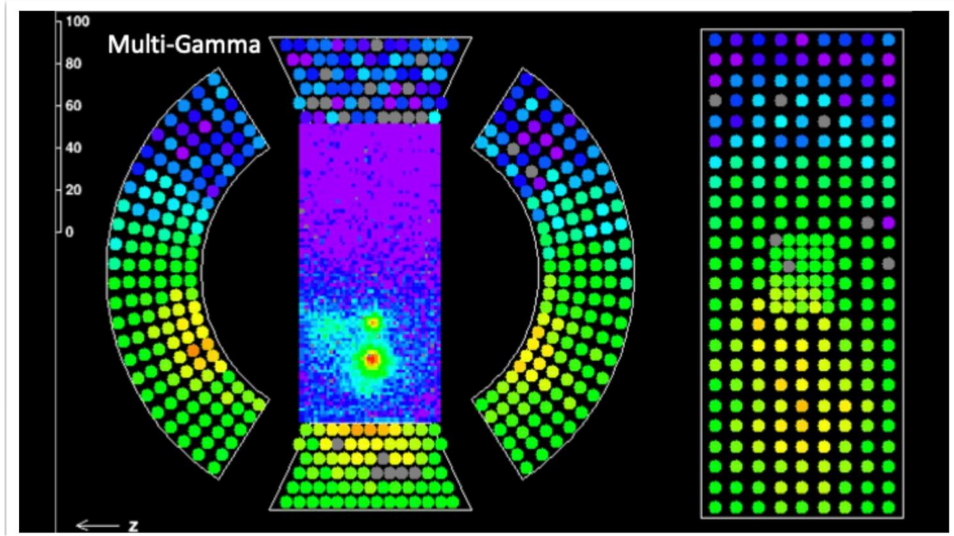


TIME



- Energy resolu,on 1.8%-2% @52.8MeV measured with dedicated charge exchange run;
- Time resolution ~40 ps;
- Position resolution 2.5mm - 4mm;

We observed MPPC PDE degradation with integrated beam. Annealing tested successfully and run every year in the beam shut down period.



Detectors calibrations

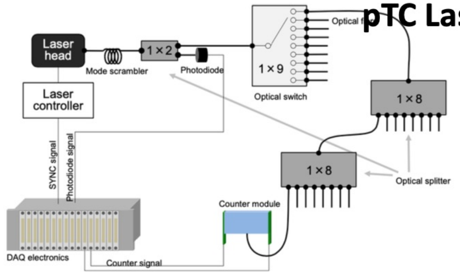
Calibrations are essential to follow the minimum variations of detectors and monitor behaviour and resolutions

C-W proton accelerator

Up to 1 MeV proton on $LiBO_4$ target

Energy calibration line :

$$p\ {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}\ \gamma(17.6\ \mathrm{MeV})$$



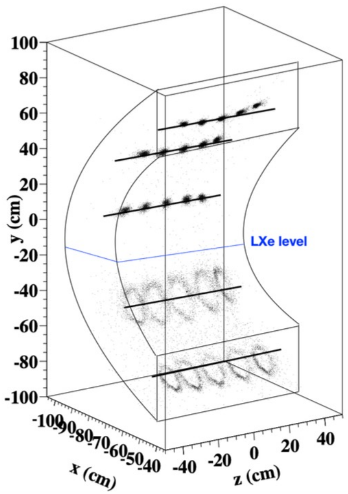
pTC Laser system

401 nm laser

Distribution to a big part of pTC Tiles

Time offset monitoring

α particle sources in Liquid Xenon



25 point-like sources on wires

Localised energy deposit

(40 μm range in LXe)

For detection efficiency monitoring calibration

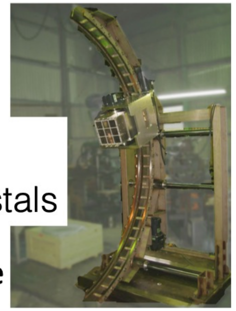
Charge Exchange reaction

Energy & time calibration at signal energy

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

Movable array of BGO Crystals

Energy in 55-83 MeV range



Other calibrations

Drift chamber:

- Cosmic rays
- B-field mapping

Liquid Xenon detector:

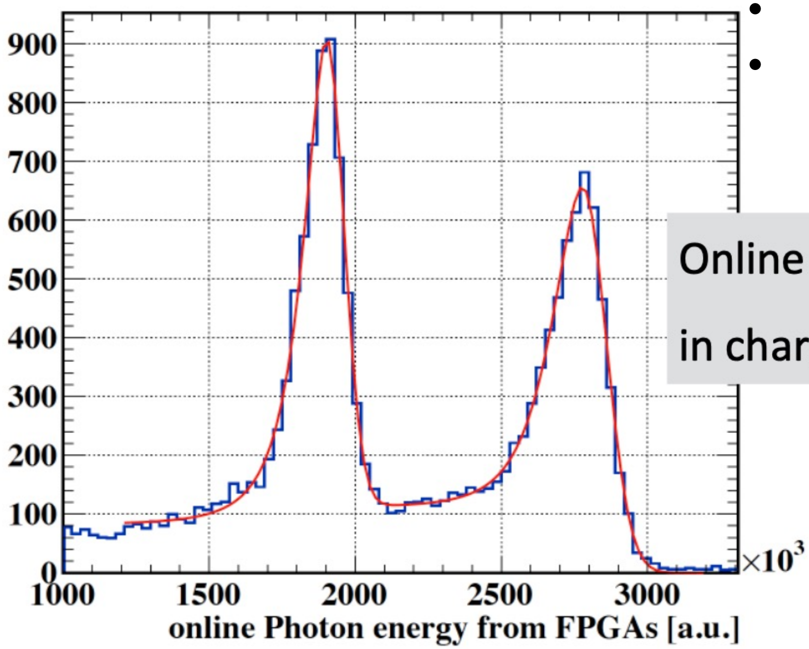
- LED
- Neutron-Nicke γ(9 MeV)
- ^{57}Co X-Ray position survey

Trigger and DAQ

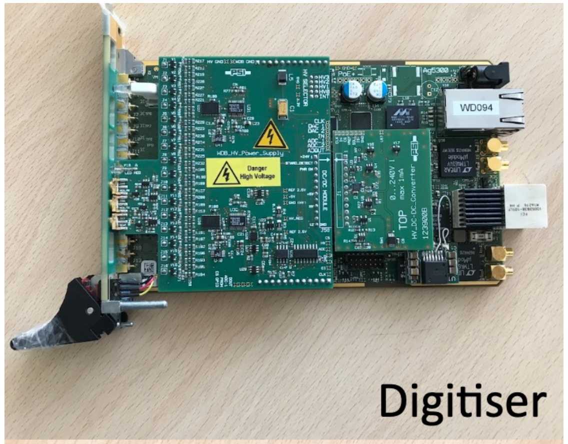
- ❑ Electronic boards are full custom.
- ❑ Trigger and DAQ are integrated
- ❑ Waveform digitiser @GSPS with DRS chip
- ❑ SiPM power supply and amplification included
- ❑ Complex FPGA based trigger with latency <450ps
- ❑ up to 10 Gb/s DAQ throughput (50 Hz)

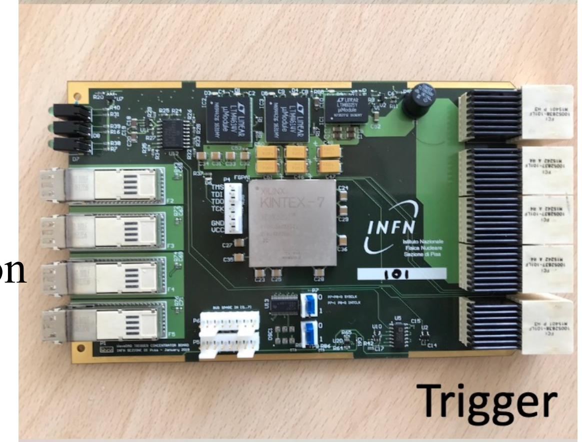
Trigger logic:

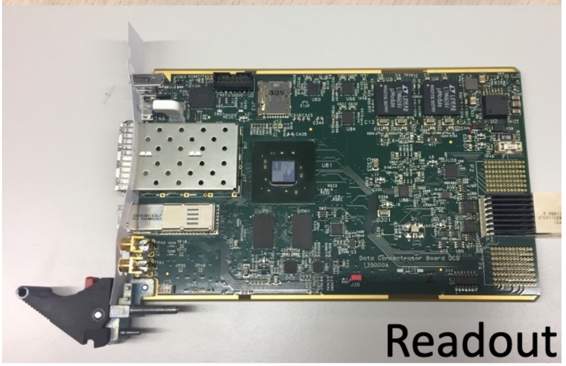
- $E_\gamma >$ ~40-44 MeV
- $T_{e\gamma} <$ time window (~10-12.5ns)
- Direction match condition : hits from positron and gamma position correlated (using a lookup table).



Online E_γ reconstruction in charge exchange run





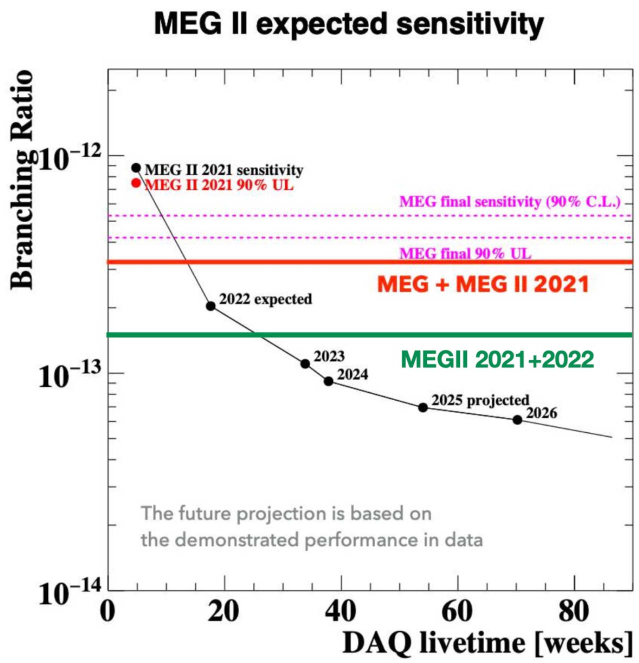


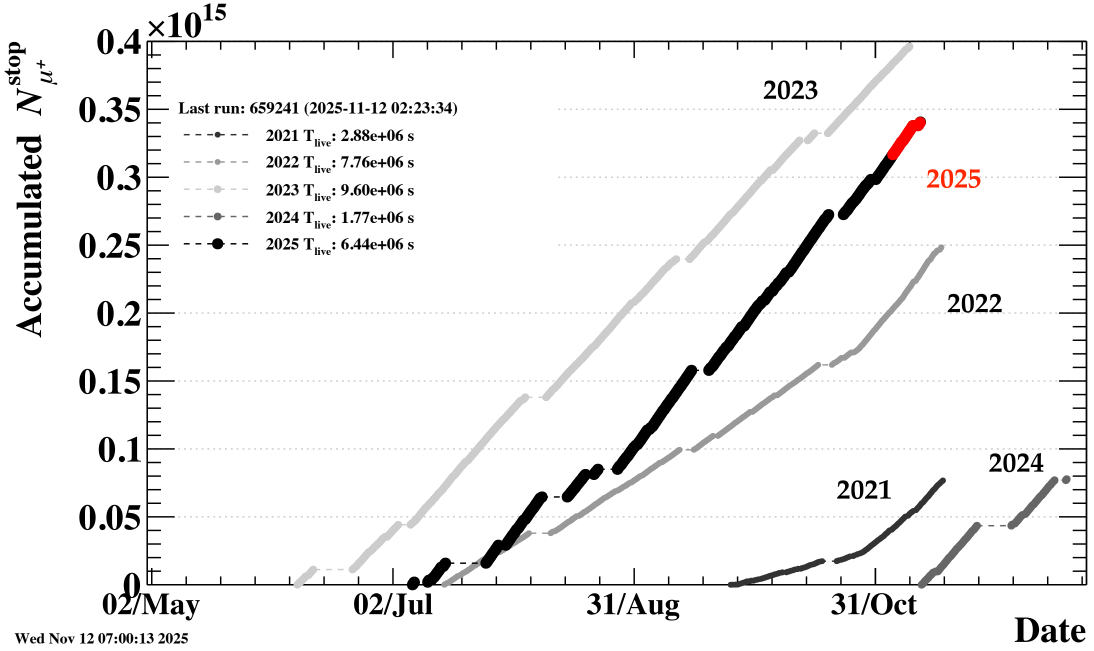
Summary of performance of MEG-II

Resolution	**MEG**	**MEG II data 2022 (2021)**
E_e (keV)	320	**89**
θ_e (mrad)	9.4	**3.8**
ϕ_e (mrad)	8.7	**6.2**
z_e/y_e (mm) core	2.4/1.2	**1.76/0.61**
E_γ(%) (w<2 cm)/(w>2 cm)	2.4/1.7	**2.4(2.0)/1.9(1.8)**
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	**2.5/2.5/5.0**
$t_{e\gamma}$ (ps)	122	**78**
Efficiency (%)		
Trigger	≈ 99	**91 (88)**
Gamma-ray	63	**63**
Positron	30	**67**

MEG-II physics runs summary

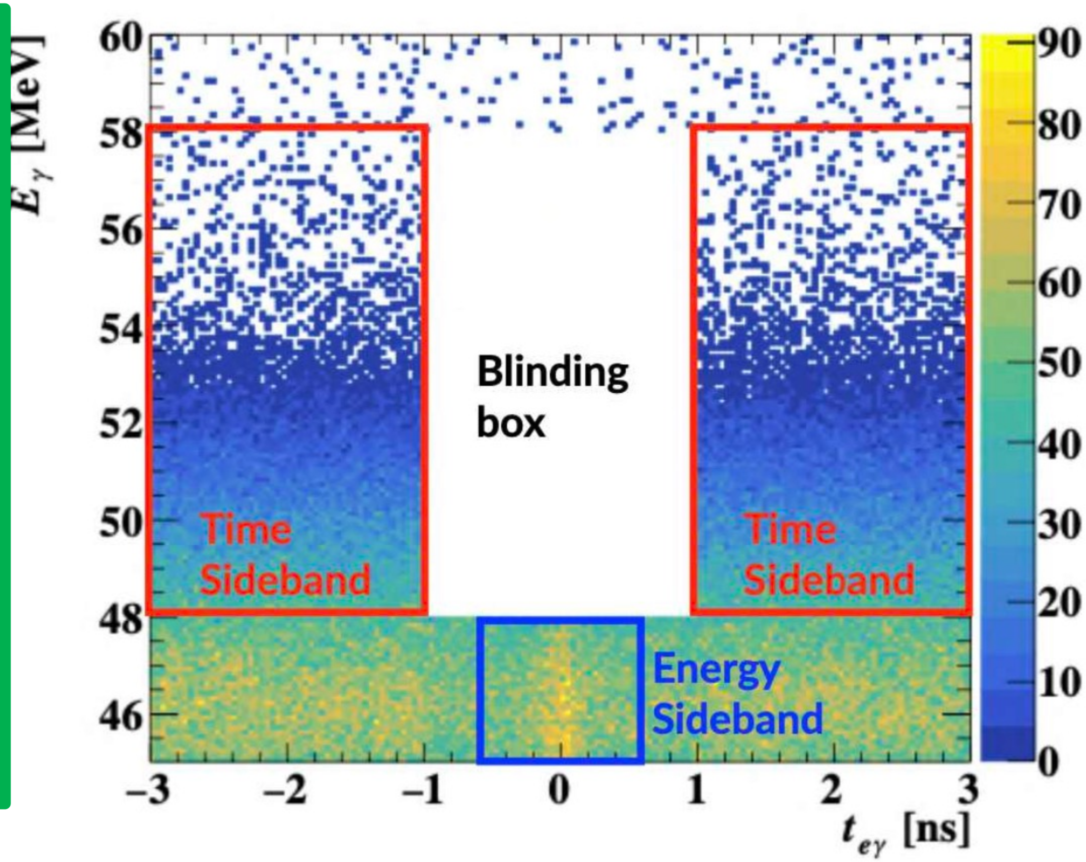
- 2021: first physics run with the full detector first result of MEGII published (Eur. Phys. J. C84 (2024) 216);
- 2022: long and stable run in optimal conditions (3 times 2021 statistics) ;
- 2023: largest statistics ever acquired data analysis ongoing (> 4 times 2021 statistics);
- 2024: ~5 months in standby due to technical problem at PSI;
- 2025: Ongoing since beginning of July;
- 2026: the last data taking run.





MEG-II Data Analysis (1)

- CL to B ($\mu \rightarrow e\gamma$) from a likelihood analysis in a wide signal box;
- Each event has 5 kinematic variables (E_γ, E_e, $t_{e\gamma}$, $\varphi_{e\gamma}$, $\theta_{e\gamma}$);
- The signal region is blinded ($48 < E_\gamma < 58$ MeV, $|t_{e\gamma}| < 1$ ns;
- Resolutions and PDFs evaluated on data outside the signal box;
- Use of sidebands for background evaluation:
  - accidental background from left and right time sidebands;
  - radiative muon decay studied in energy sideband;
- Maximum likelihood analysis to estimate N_{sig}



MEG-II Data Analysis (2)

Normalisation

$$\mathscr{B}(\mu^+ \to e^+\gamma) = \frac{N_{\mathrm{sig}}}{k}$$

- **Normalisation factor k**

  = # effectively measured muons (=1/SES)

- **Two independent methods**
  - Counting Michel positrons
    - Pre-scaled Michel positron trigger
    - Include positron efficiency and beam rate instability
  - Counting RMD events
    - RMD events in energy sideband
- **Combined normalisation factor**

  $(1.35 \pm 0.07) \times 10^{13}$

Systematics

- **Major sources for systematics**
  - Detector alignment
  - E_γ scale
  - Normalisation
- **Effect on sensitivity ~3%**
  - Better controlled than MEG (~13%)

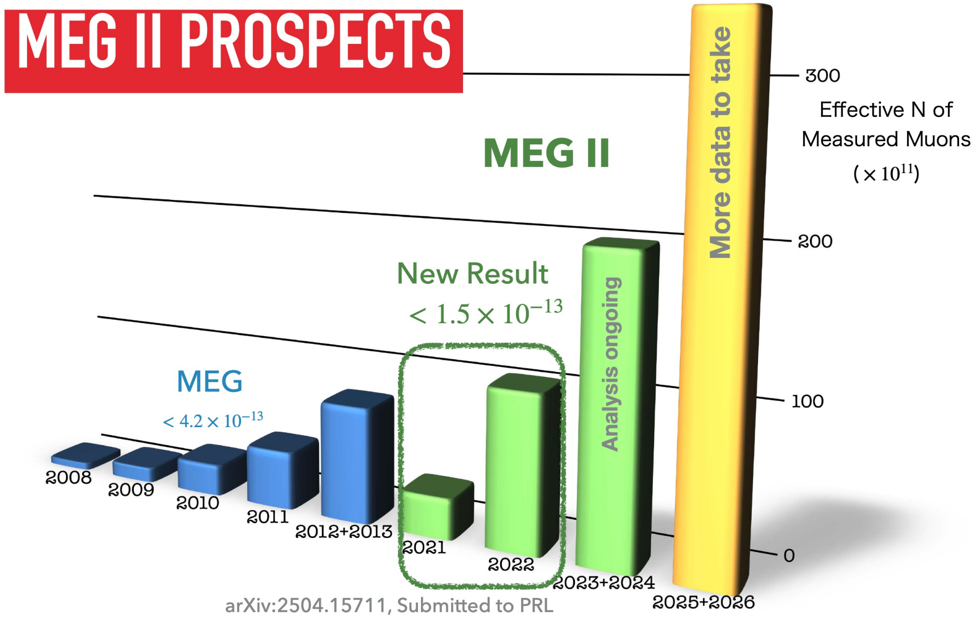
Parameter	Impact on sensitivity
$\phi_{e\gamma}$ uncertainty	1.1 %
E_γ uncertainty	0.9 %
$\theta_{e\gamma}$ uncertainty	0.7 %
Normalization uncertainty	0.6 %
$t_{e\gamma}$ uncertainty	0.1 %
E_e uncertainty	0.1 %
RDC uncertainty	< 0.1 %

The 90% C.L. upper limit based on 2021+2022 data is: BR($\mu \to e + \gamma$) = 1.5×10^{-13}

Eur.Phys.J.C 85 (2025) 10, 1177

Conclusions

- cLFV with muons features a unique opportunity to discover physics beyond the standard model;
- MEGII started data taking since 2021 and the detectors showed resolutions and efficiencies close or better than the design;
- A new upper limit on the $\mu \to e + \gamma$ decay has been set based on the 2021+2022 data: B (90% CL) < 1.5 10^{-13};
- Analysis ongoing on the 2023-2024 data;
- Continue to take data in 2025-2026 to reach the sensitivity goal of 6×10^{-14} ;

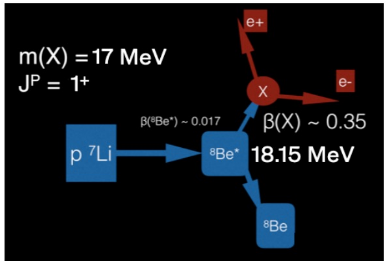


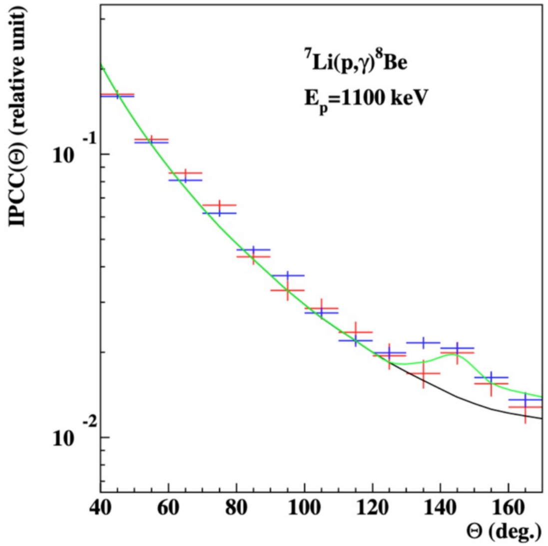
Thanks for your attention!

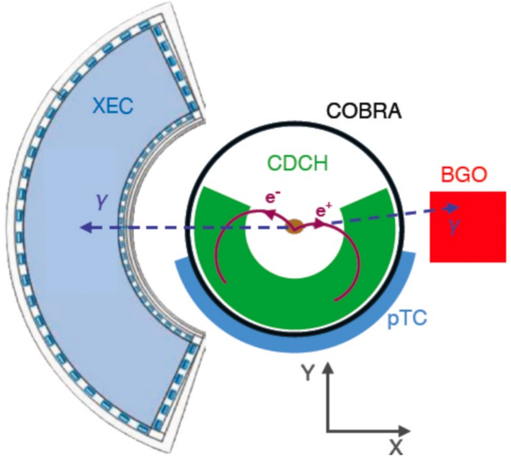
Backup

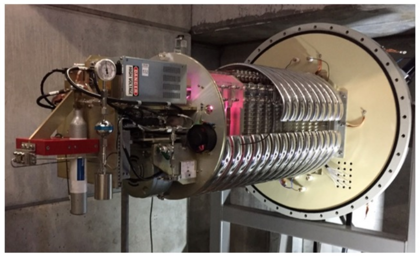
Other physics: X(17 MeV) Boson

- **Anomaly** in the process (p,7Li)8Be* measured by **Atomki experiment**
  - *can be **replicated** by **MEG II***
    - **CW accelerator** used to LXe calibration
    - **tracking of e⁺e⁻** with **drift chamber** at **reduced magnetic field**
      - **similar** angular resolution
      - **improved** invariant mass resolution ~500keV instead of 1MeV





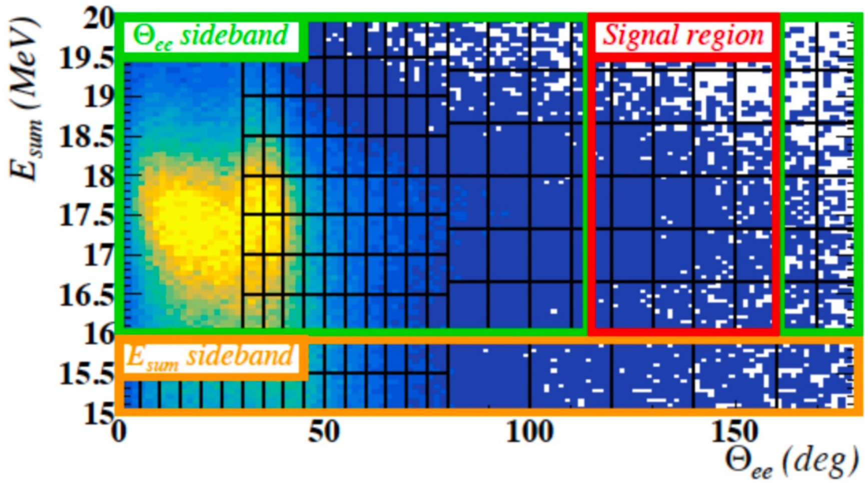


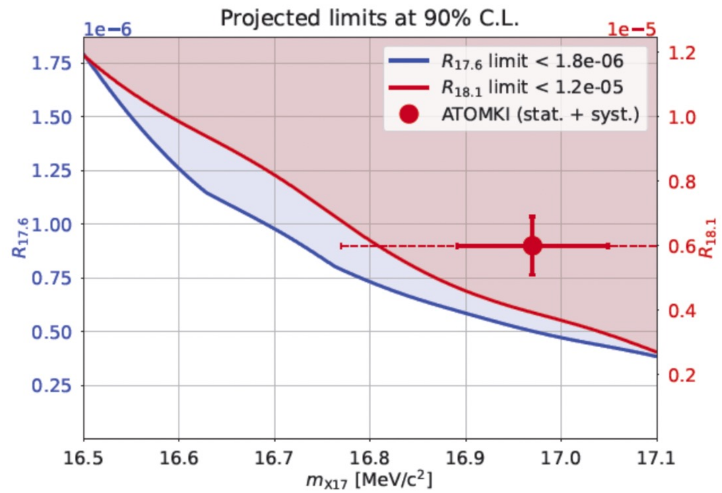


from slide 12...

“Our” result on X17

- **Combined fit** on the **energy sum** of the electron and position and their **relative angle**
- **Best fit** on X17 signal is **0 events** with an **expectation of 100 events**
  - *our result is **incompatible** with **ATOMKI** result **at 94%***
- We are **preparing** for a **new DAQ** campaign with **improved beam** and thinner **target**

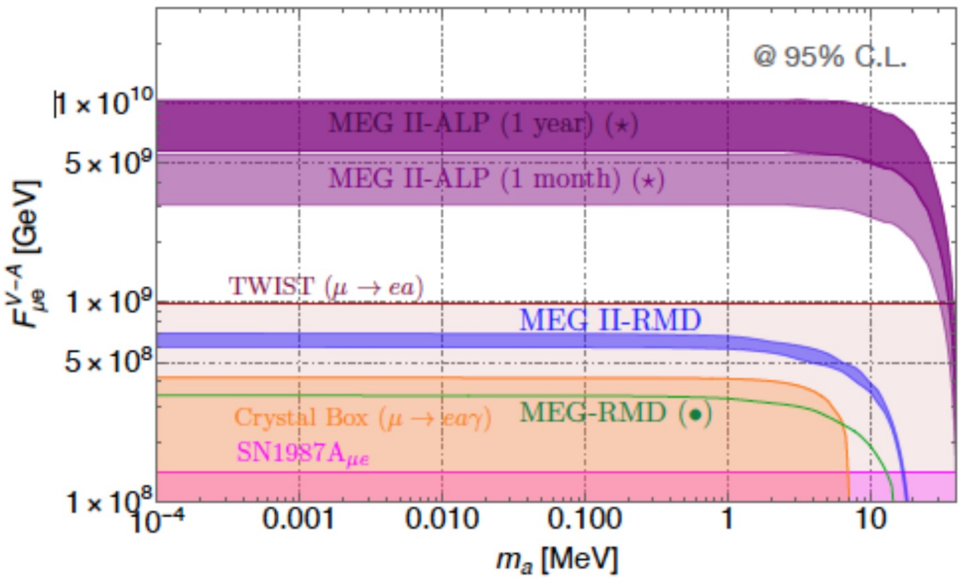




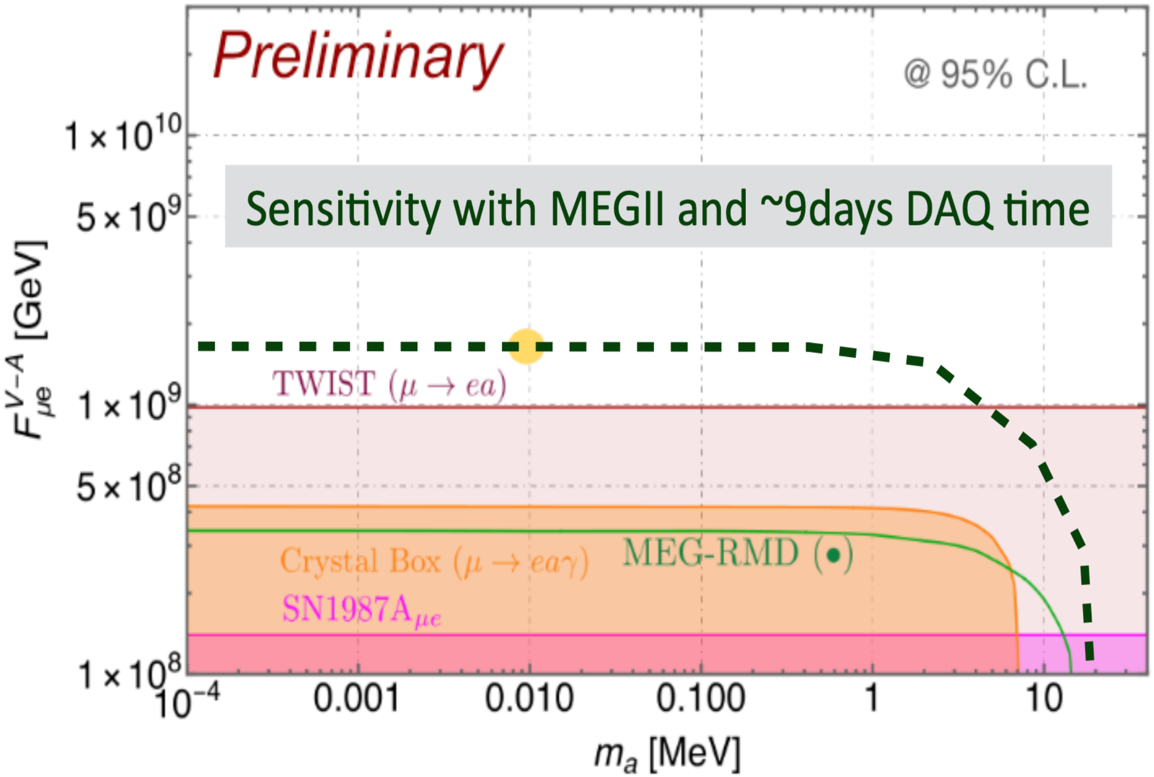
What about $\mu \rightarrow ea\gamma$?

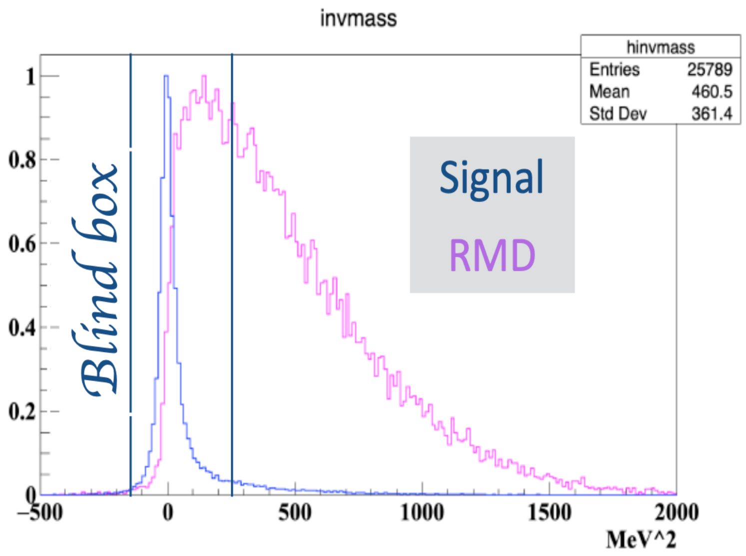
arXiv:2203.11222v1

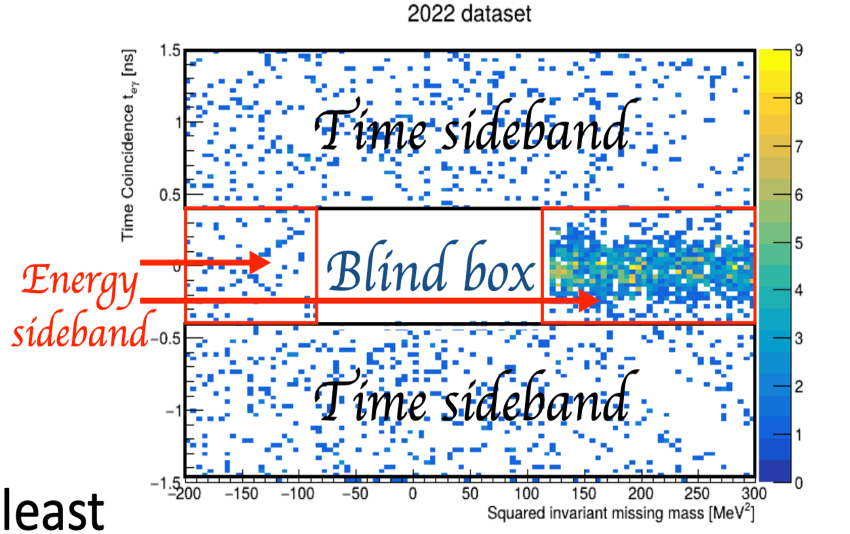
- **Boost** from discussions among **MEG II group** and **D. Redigolo**
  - *Can **MEG-II** be **competitive** w.r.t. **TWIST**?*
  - ***how** can we **increase sensitivity**?*
    - **dedicated trigged**
      - Gamma energy **threshold** close to **15 MeV**
    - **beam intensity** and **DAQ time needed**
      - ***~10⁶ μ/s** as in case of initial **detector calibration***



ALP search in MEG II







- MEG II plans accumulate O(15 days) of DAQ at least