Status of MEG-II and future plans

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(on the behalf of MEG collaboration)

MPP2025, Liverpool

Outlook

- Theoretical issues
- The experiment
- $\mu \rightarrow e\gamma$ search, latest results
- Future plans
- Other "exotic" channels
- Conclusions

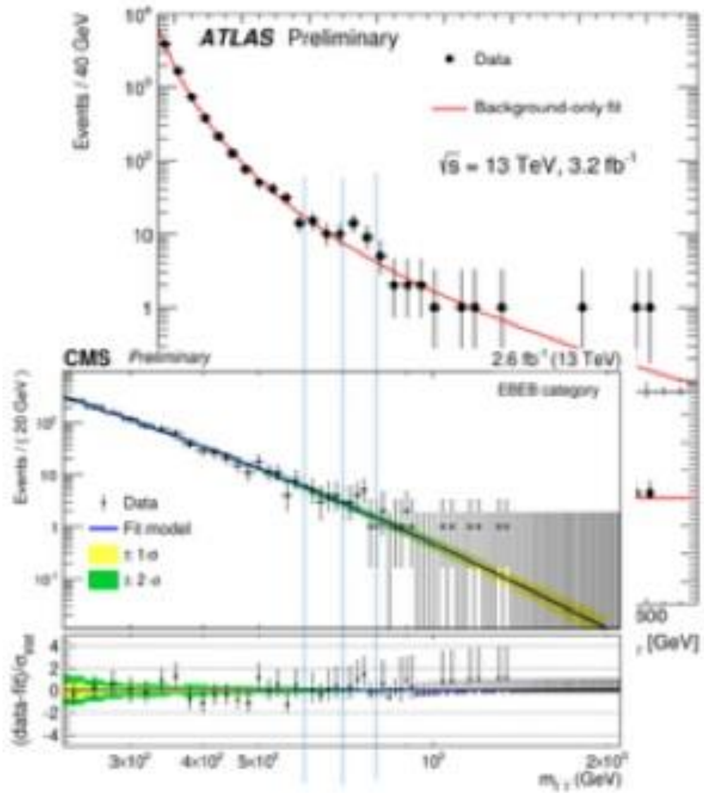
Theoretical issues

- cLFV as a probe of New Physics
- SUSY predictions
- Complementarity & redundancy

Experimental approaches to NP

Energy frontier

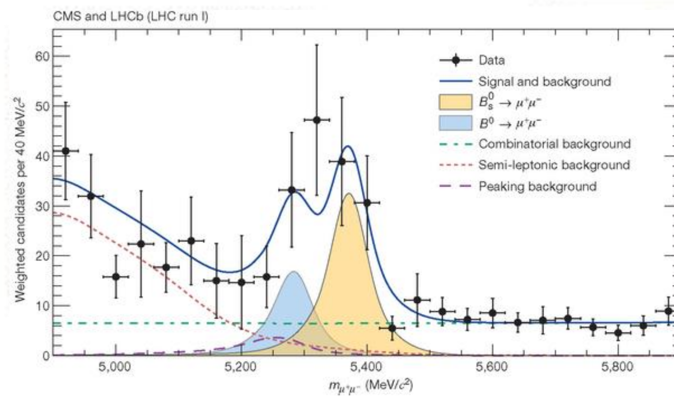
- search for direct production of new particles in the extended sector of the theory

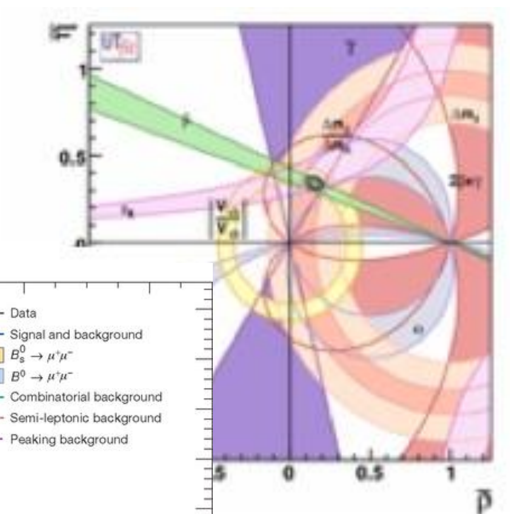


Intensity frontier

- deviations at lower energies from SM predictions due to diagram loops involving new particles
  - hadron flavour physics
  - neutrino physics
  - proton decay

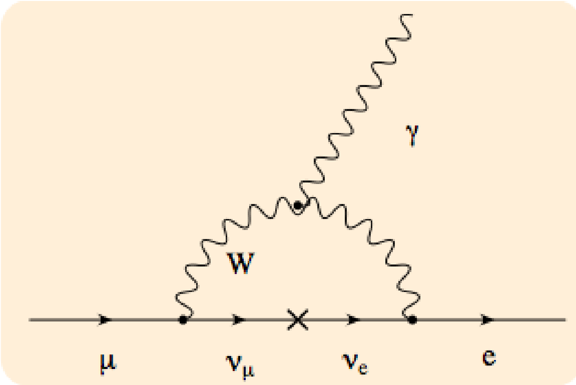
  and also
  - charged lepton flavour violation (cLFV)





cLFV in the SM and beyond

- SM: Dirac ν-oscillations ⇒ flavour mixing in the leptonic sector (PMNS matrix)



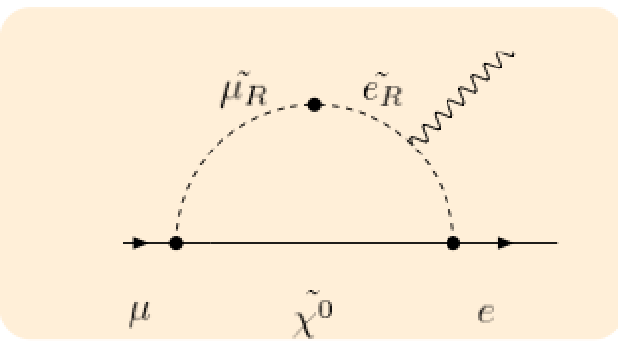
$$\frac{\Gamma(\mu\rightarrow e\gamma)}{\Gamma(\mu\rightarrow e\nu\bar{\nu})}\approx\left(\frac{\alpha}{2\pi}\right)\sin^2 2\theta_\oplus\left(\frac{\Delta m^2}{M_W^2}\right)^2\approx 10^{-55}$$

S.M. Bilenky, S.T. Petcov, B.Pontecorvo
Phys. Lett. B67 (1977)309

need of new Physics at higher mass scale ➔ SUSY

SM-background free!

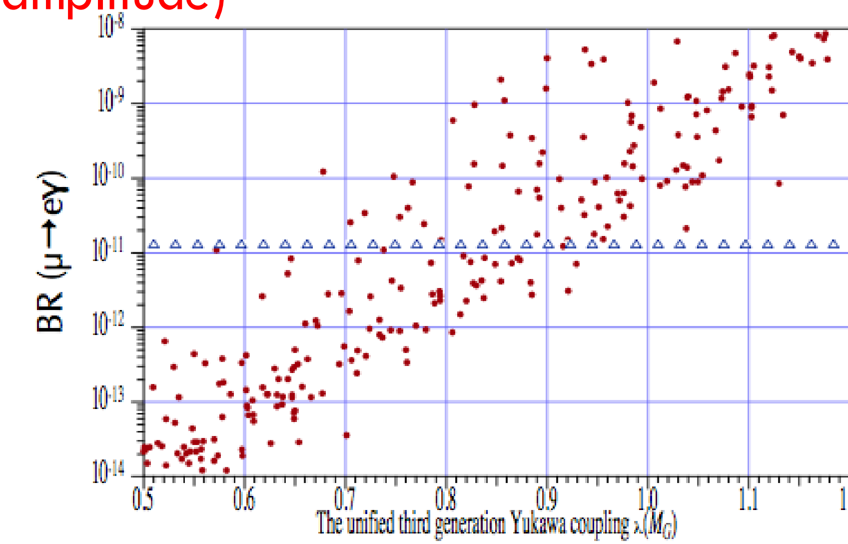
- SUSY: contributions from mixing in the High Energy sector of the theory (the heavier the mass, the higher the amplitude)



R. Barbieri *et al.*, Nucl. Phys. B445(1995) 215

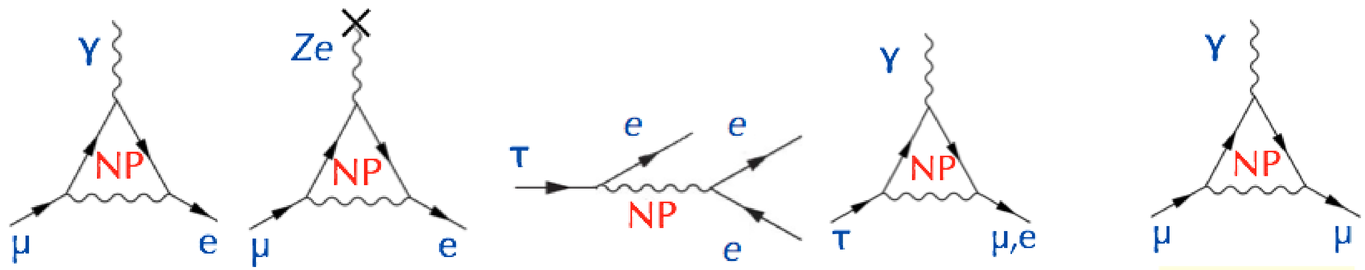
A. Masiero *et al.* Nucl. Phys. B649 (2003) 189

L. Calibbi *et al.* Phys. Rev. D74 (2006) 116002



cLFV golden channels

- arising from new lepton-lepton coupling $y_{ij}\bar{l}_i F^{\mu\nu} l_j \sigma_{\mu\nu}$
  (additional contribution to μN→eN amplitude due to Z-exchange)

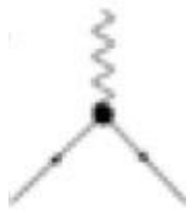


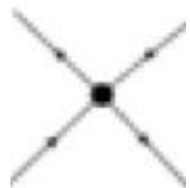
	$\mu \to e\gamma$	$\mu^- \mathcal{N} \to e^- \mathcal{N}$	$\mu \to eee$	$\tau \to \mu\gamma$ $\tau \to e\gamma$	$(g-2)_\mu$
Predictions (norm. to μ→eγ)	1	$\frac{Z\alpha}{\pi}$	$\alpha_{e.m.}$	$\left(\frac{m_\tau}{m_\mu}\right)^{2\div4}$	$3\cdot10^{-9}\sqrt{\frac{\mathcal{B}_{\mu e\gamma}}{3\cdot10^{-13}}}$
Current limits	1.5×10^{-13} (MEG-II, 2025)	4.7×10^{-12} 7.0×10^{-13} (SINDRUMII, 2006)	1.0×10^{-12} (SINDRUM, 1988)	$(3.3\div4.5)\times10^{-8}$ (B-factories, 2010)	(?±?)$\times10^{-11}$ (FNAL,WP2025, HVP, …)
Future sensitivity	5×10^{-14} (MEG-II)	6×10^{-17} (Comet, Mu2e)	$O(10^{-16})$ (Heidelberg, PSI)	$O(10^{-9})$ (Belle-II)	→ 8σ (?) (FNAL, JPARC)

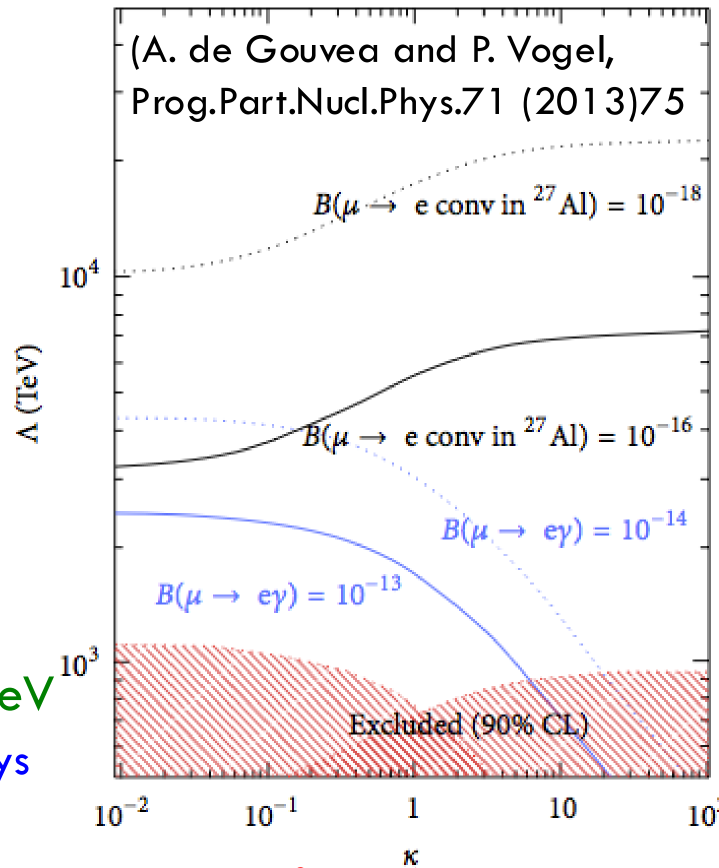
cLFV in effective theories

$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(\mathcal{K}+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\mathcal{K}}{(\mathcal{K}+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

- effective lagrangian as a function of
  - NP energy scale Λ
  - dimensionless parameter *k* due to the relative strength of
    - dipole transition (dominant at *k*≪1)
      $$\frac{B(\mu\mathcal{N}\to e\mathcal{N})}{B(\mu\to e\gamma)} \approx 10^{-2}$$
    - four-fermion interaction (preferred at *k*≫1) μ→e conversion favoured







- cLFV is sensitive to NP scale up to $\Lambda \approx 10^4$ TeV (three orders of magnitude as large as nowadays direct searches)

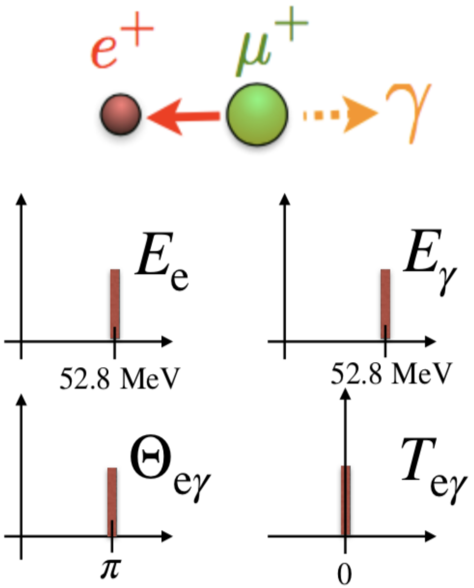
➔ cLFV processes provide complementary and redundant info on New Physics

The MEG experiment

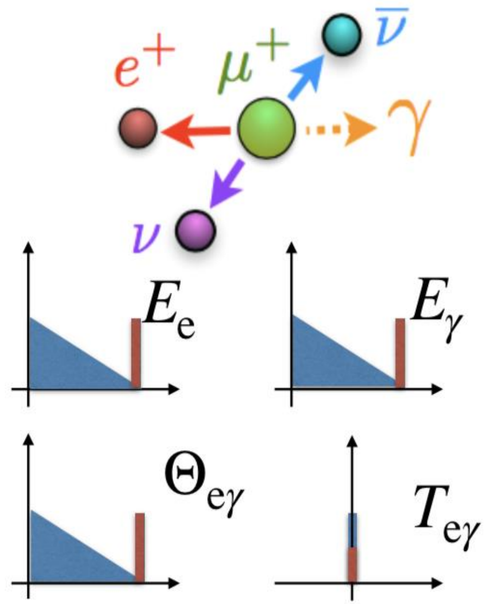
- Signature & background
- Detector upgrade
- Performances

Signal & background

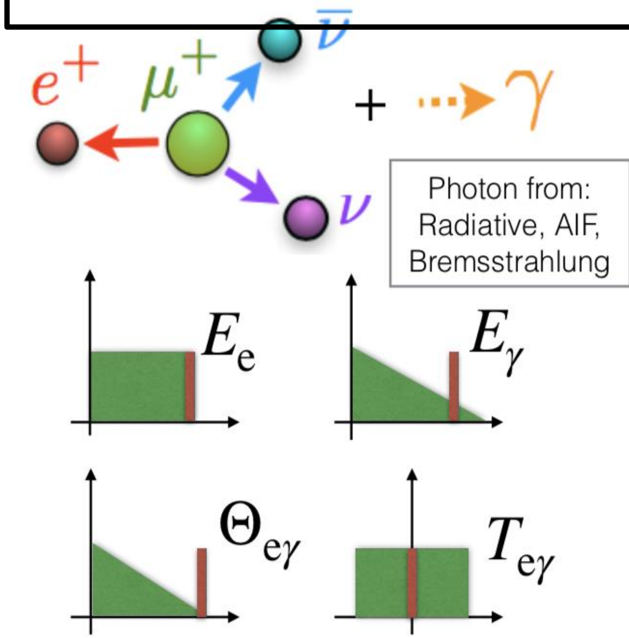
Signal



Physics background



Accidental background



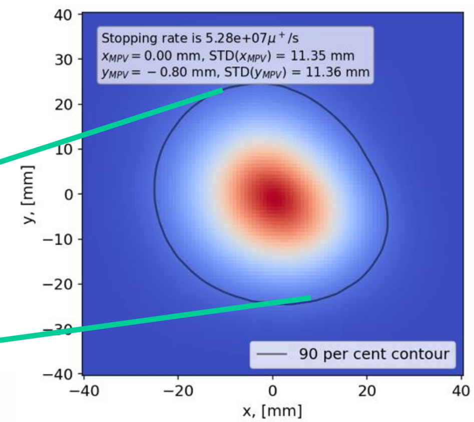
$$\Gamma_{rad} = \Gamma_\mu \mathcal{B}(\mu \to e\nu\bar{\nu}\gamma | \Delta E_\gamma, \Delta E_e, \Theta_{e\gamma})$$

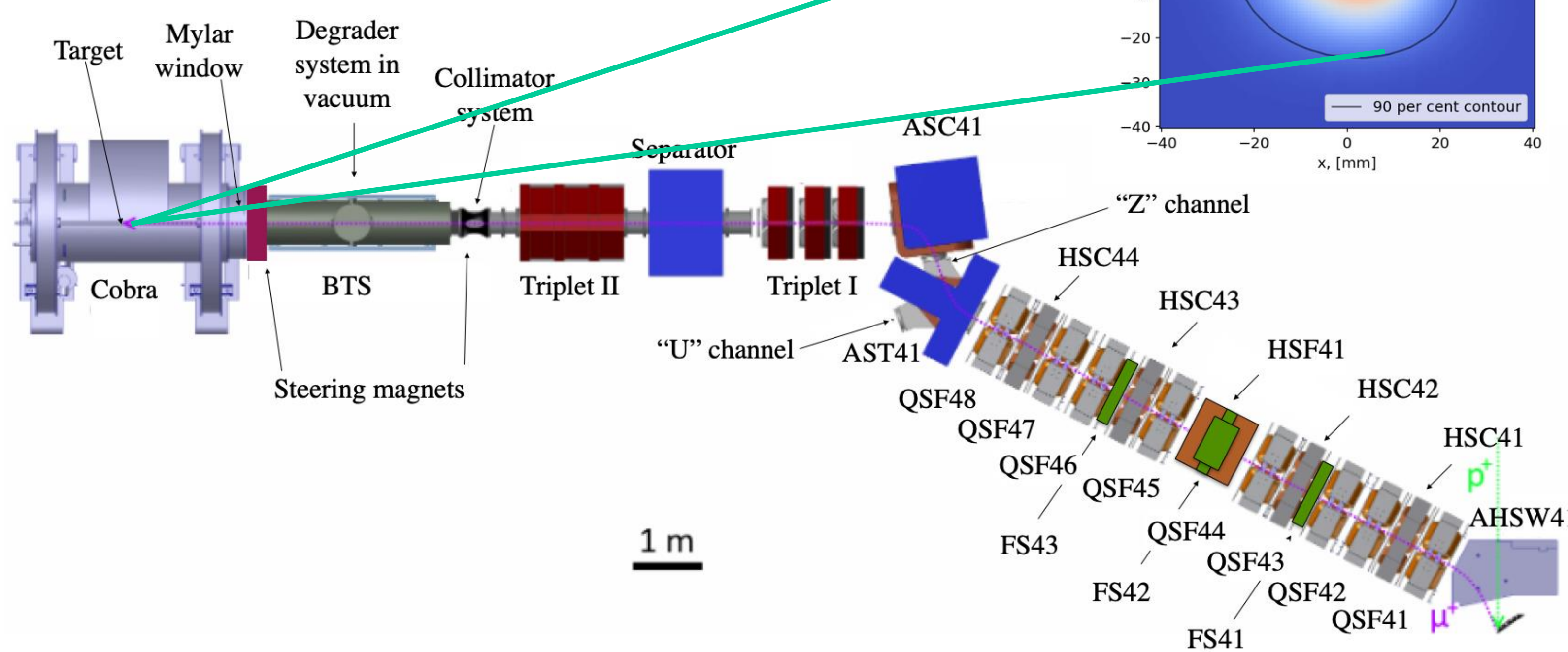
$$\Gamma_{acc} \approx \Gamma_\mu^2 \, \Delta E_\gamma^2 \, \Delta E_e \, \Theta_{e\gamma}^2 \, \Delta t_{e\gamma}$$

given the experimental resolution, this dominates at higher muon rates

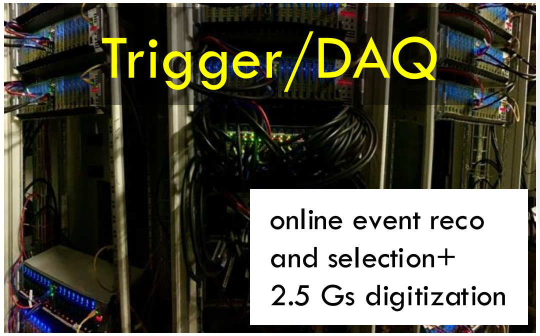
The muon beam line

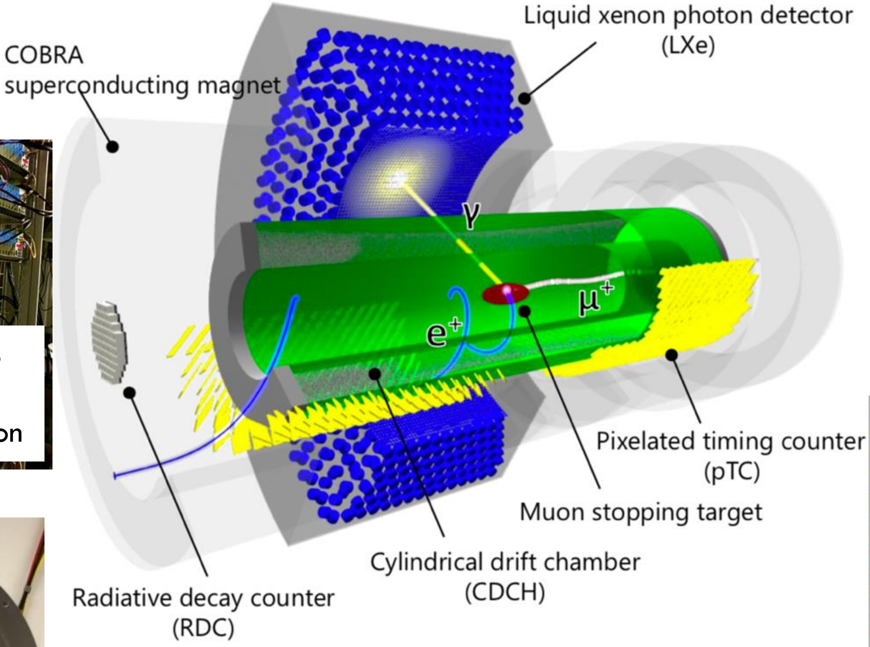
- Same beam as MEG-I (πE5), capable of delivering $> 10^8 \mu^+/s$ (p = 28 MeV/c)
  - limited so far to $5 \times 10^7/s$ (so as to take pileup and aging under control)
- Muon stopped on a 170 µm-thick (~0.004 X_0) target
  - spot size $\sigma_x = \sigma_y = 1.1mm$

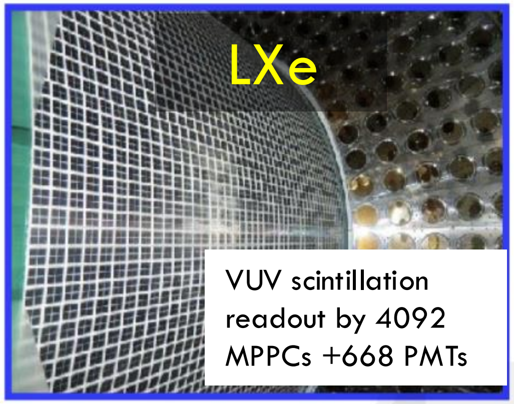


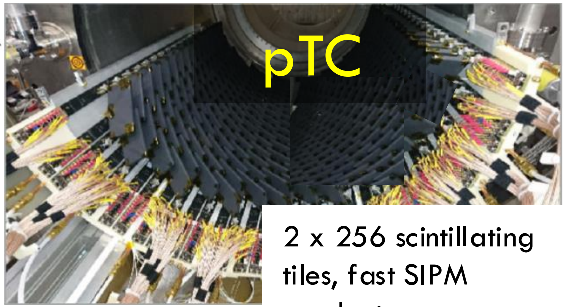


The upgraded detector

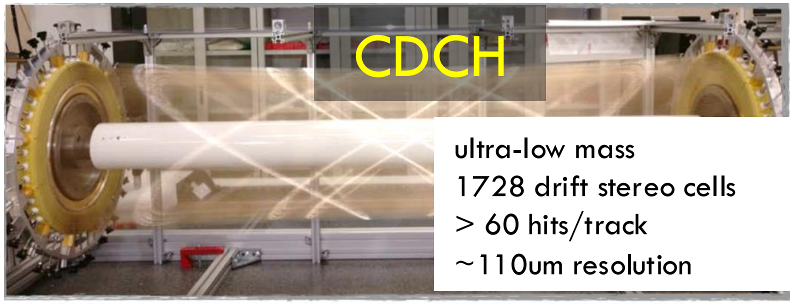








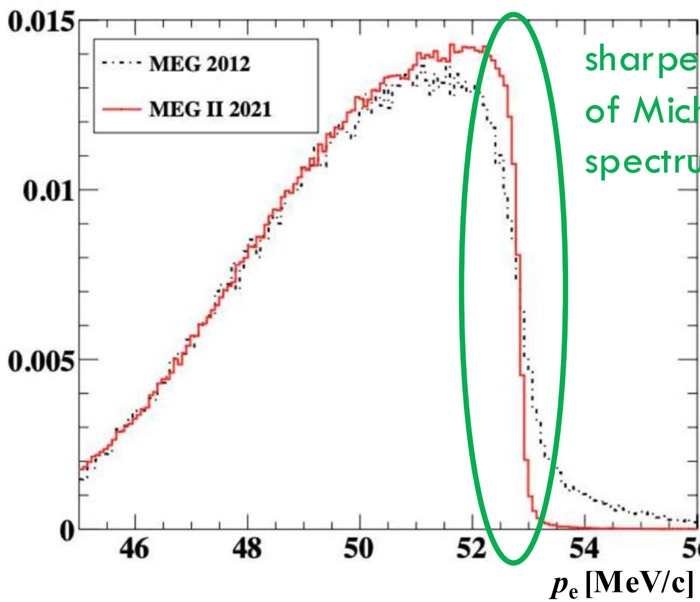
2 x 256 scintillating tiles, fast SIPM readout



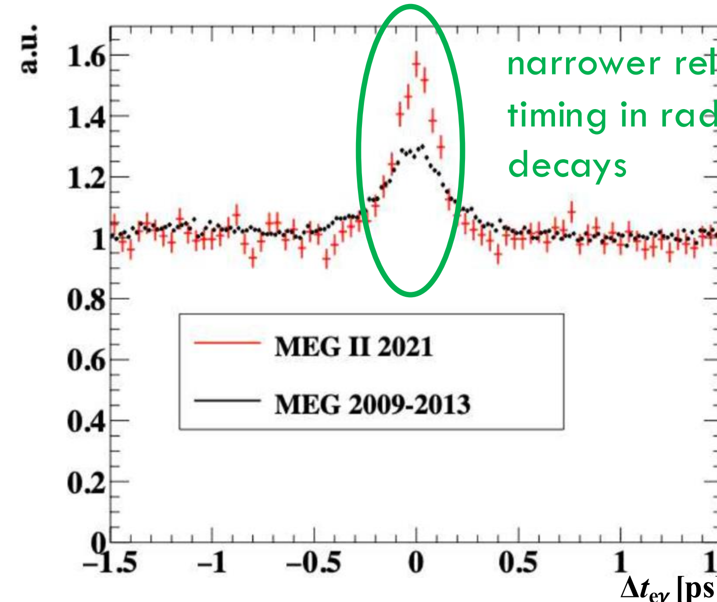
- For further details, please refer to our technical paper (EPJ C84 (2024) 190)

Performance enhancement

Observable	MEG-I	MEG-II (proposal)	MEG-II (2022)
$\sigma(p_e)$ (keV/c)	320	110	89
$\sigma(\theta_e, \phi_e)$ (mrad)	9.4, 8.7	5.0, 5.0	3.8, 6.2
$\sigma(y_e, z_e)$ (mm)	1.2, 2.4	0.7, 1.2	0.61, 1.76
ε_e (%)	30	70	67
$\sigma(E_\gamma)$ (keV) (deep/shallow)	90/130	55/60	100/130
$\sigma(u_\gamma, v_\gamma)$ (mm)	5, 5,	2.4, 2.4	2.5, 2.5
ε_γ (%)	63	70	63
$\Delta t_{e\gamma}$ (ps)	122	84	78



sharper edge of Michel spectrum



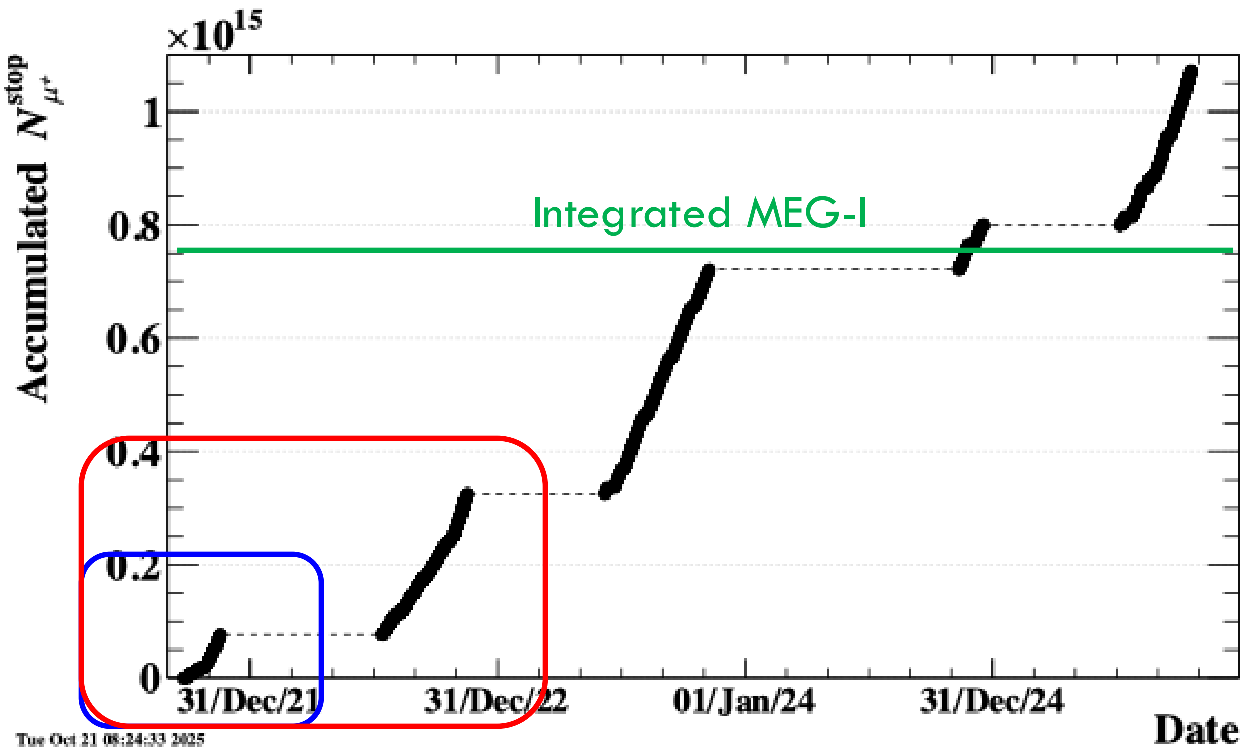
narrower relative timing in radiative decays

$\mu \rightarrow e\gamma$ search, latest results

- Data summary
- Analysis strategy
- Sensitivity projection vs. time

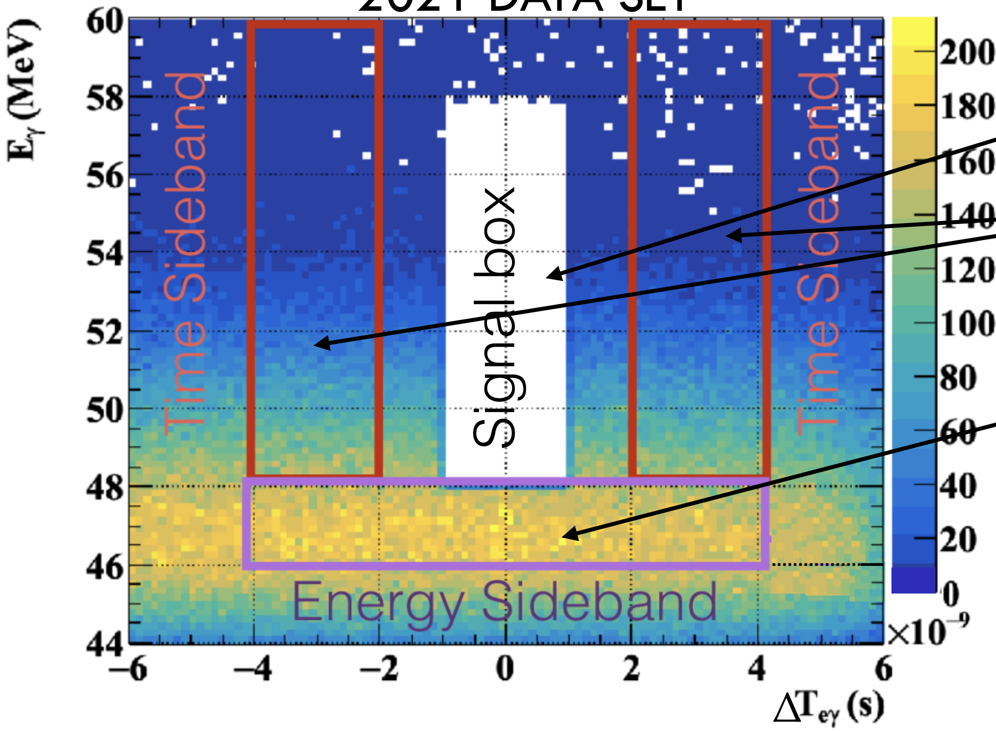
Integrated “luminosity” in MEG-II

- 2021: results published (combined with MEG full dataset) (EPJ C84 (2024) 216)
- 2022: “ “ (“ “ 2021 run) (EPJ C85 (2025) 1177)
- 2023: long and stable run, analysis ongoing
- 2024: short run (LHe shortage due to PSI cryoplant failure)
- 2025: run ongoing (with crossed fingers …)



Analysis strategy

- likelihood blind analysis strategy
  - blinding observables: E_γ and $\Delta t_{e\gamma}$



data-driven pdfs as functions of observables

$\vec{x}_i = (p_e, E_\gamma, \theta_{e\gamma}, \phi_{e\gamma}, \Delta t_{e\gamma})_i$

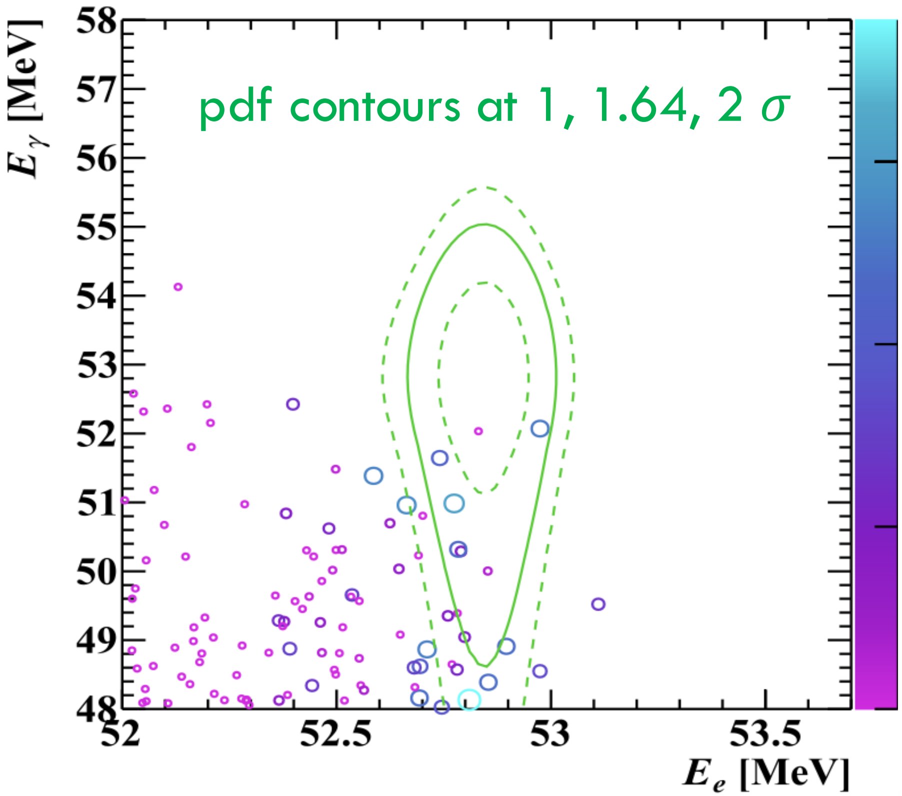
- signal: from detector response function
- accidental: from event distribution in time sidebands
- RD: from RD energy sideband data distribution and trigger simulation

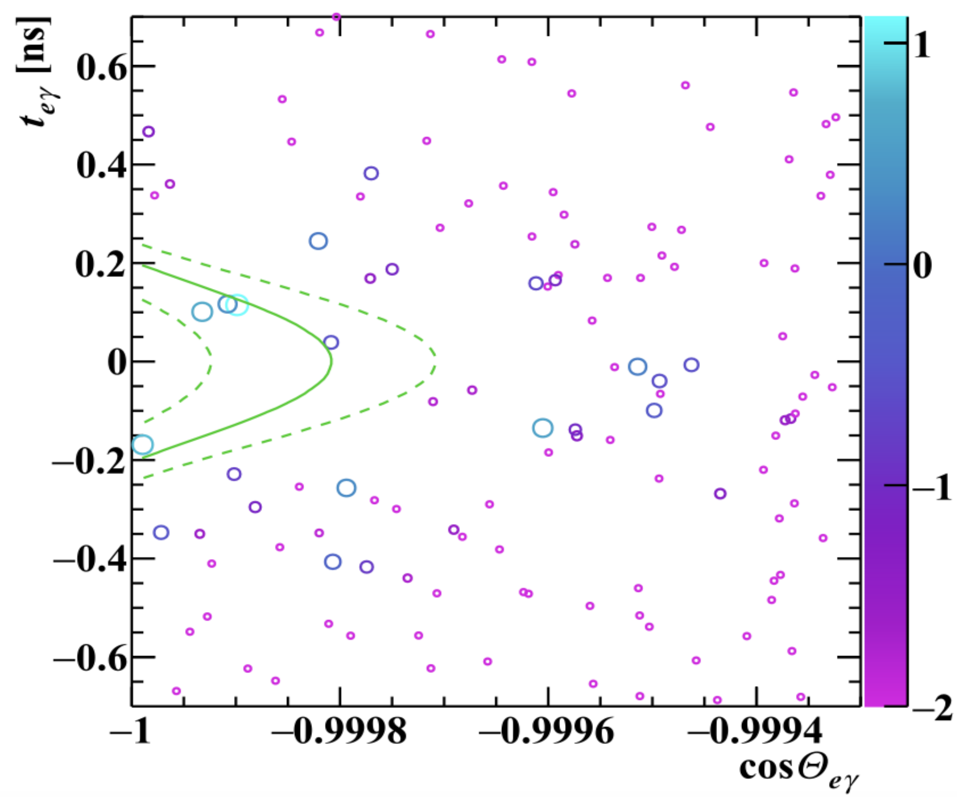
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm ACC}, x_{\rm T}) = \frac{e^{-(N_{\rm sig}+N_{\rm RMD}+N_{\rm ACC})}}{N_{\rm obs}!} C(N_{\rm RMD}, N_{\rm ACC}, x_{\rm T}) \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} \boxed{S(\vec{x}_i)} + N_{\rm RMD} \boxed{R(\vec{x}_i)} + N_{\rm ACC} \boxed{A(\vec{x}_i)}\right),$$

Event distribution (2021-2022)

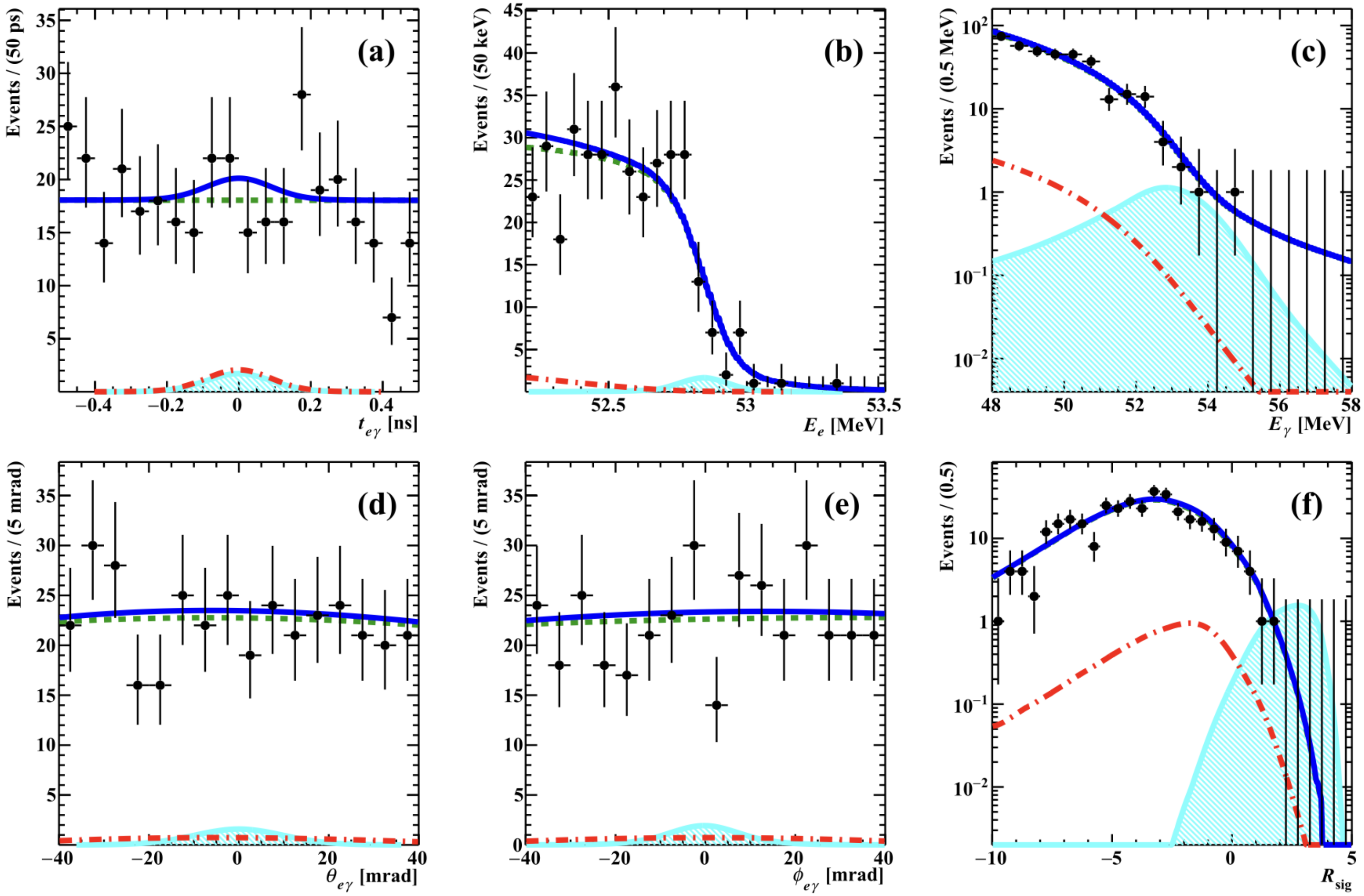
- No excess over expected background observed so far
  - events in (E_e, E_γ), $(\Theta_{e\gamma}, \Delta t_{e\gamma})$ scatter plots ranked by

$$R_{sig} = \log 10\left(\frac{S(\vec{x}_i)}{f_{RMD}R(\vec{x}_i) + f_{ACC}A(\vec{x}_i)}\right)$$





Best fit and results



- • Data
- \- Total exp
- \- RMD
- \- ACC
- \- SIG ULx4

Likelihood fit provides

$N_{OBS} = 357$

$N_{ACC} = 357 \pm 19$

$N_{RMD} = 0 \pm 0.8$

compatible with sideband estimates

$N_{ACC} = 364 \pm 10$

$N_{RMD} = 10.1 \pm 1.7$

Normalization & systematics

Normalization

$$\mathcal{B}(\mu \to e\gamma) = \frac{N_{sig}}{k}$$

- normalization factor k = $(SES)^{-1}$
  - i.e. k is the number of muon decays in detector acceptance (folded by efficiencies)
- obtained by independent counts of
  - pre-scaled single positron triggers
  - radiative decays in the energy sideband
- combined (as of 2022 run)

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

Systematics

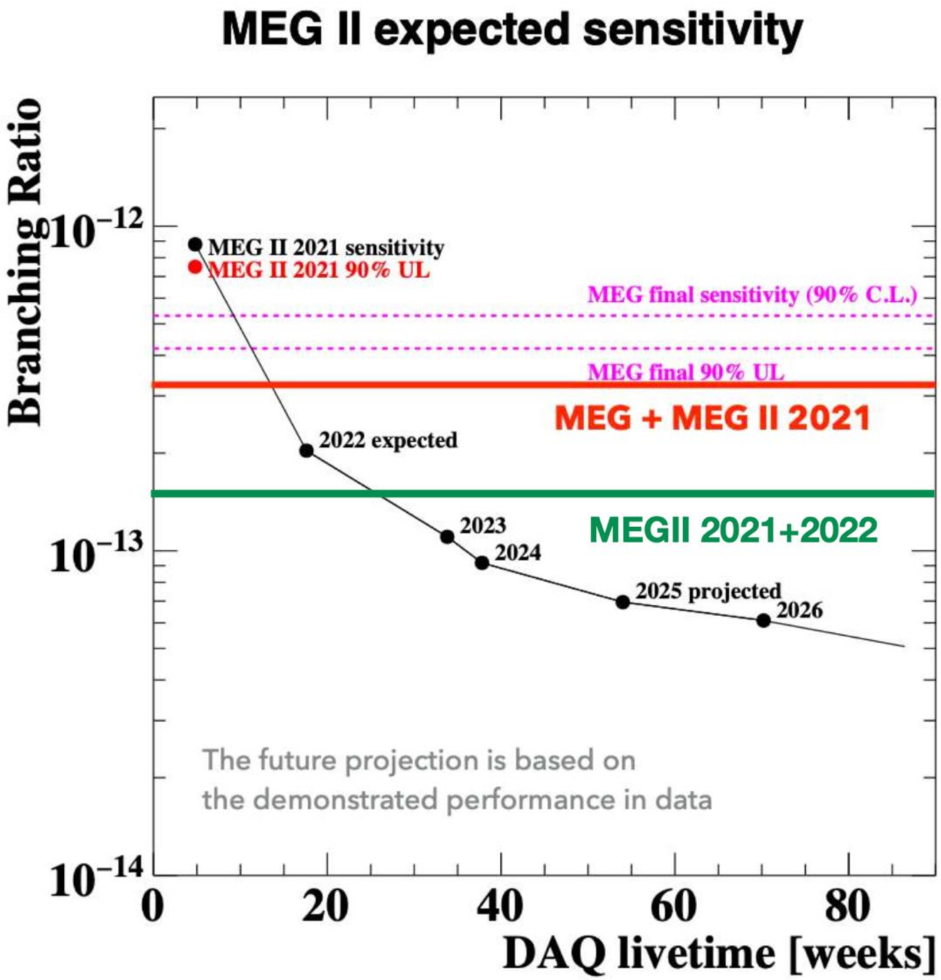
- major sources
  - magnet-detector alignment
  - energy scale calibration
  - normalization
- uncertainty budget

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 %

- overall effect on sensitivity ~ 3%
  - used to be 13% in MEG-I

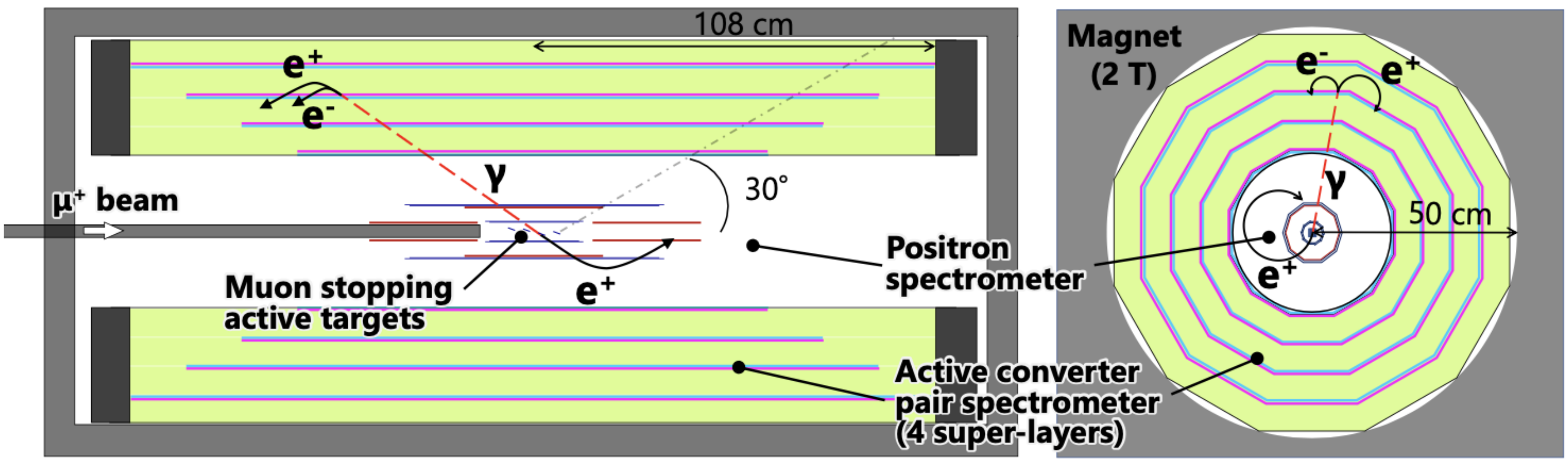
MEG-II, present and (near) future

- Results (based on 2021+2022 data)
  - $B(\mu \to e\gamma)$ sensitivity
    @ 90% CL = 2.2×10^{-13}
  - Upper limit
    = 1.5×10^{-13}
    (2.4 times better than MEG-I with only 8 months data taking)
- Projection (up to the end of 2026 run)
  - final expected sensitivity
    = 6×10^{-14}



What next?

- Study group for “Future $\mu \rightarrow e\gamma$ experiments” been established
  input to European Strategy for Particle Physics submitted (http://arxiv.org/abs/2503.22461v1)
- New detector concept conceived to cope with much higher HIPA intensity
- Both e^+ and γ-detectors embedded in the same (higher acceptance) magnetic spectrometer
  - inner side: silicon pixel detectors equipped with HVMAPS (similar approach as Mu3e) for positron tracking
  - outer side: pair production in active γ-converters (LYSO?) so as to compensate for energy straggling



Other “exotic” searches

- X_{17}
- ALPs

X_{17} (i.e. Atomki anomaly)

- Who ordered that?

  (see A.J. Krasznahorkay et al., PRL 116 (2016) 042501)

  – excess of e^+e^- pairs in Atomki in $^7Li(p,e^+e^-)^8B$
    - observed at E_p=1030 keV (Q=18.1 MeV)
    - no evidence at E_p= 440 keV (17.6 MeV)

  – interpreted as a production of a X boson (mediator of the fifth force?) with m_X = 16.95 MeV and $\Gamma(X)/\Gamma(\gamma)$= 6×10^{-6}

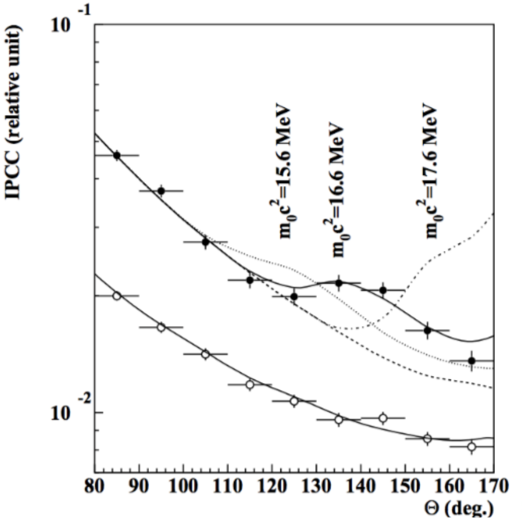
  – same anomaly seen in $^3H(p,e^+e^-)^4He$ and $^{11}B(p,e^+e^-)^{12}C$ (PRC 104 (2021) 044003, PRC 106 (2022) L061601)

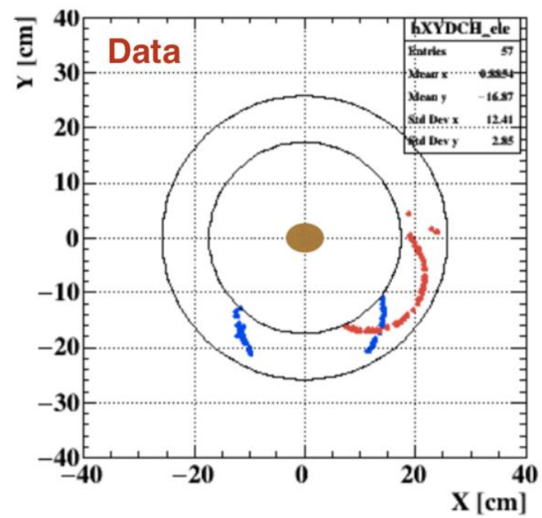
- MEG-II capability

  – reproduced by using CW accelerator (usually a facility for calibration) to deliver protons to a dedicated Li-target

  – signal: e^+e^- reconstructed in the magnetic spectrometer with downscaled magnetic field, wider acceptance and better pair invariant mass resolution ($\sigma(m_{ee})$ = 540 keV)

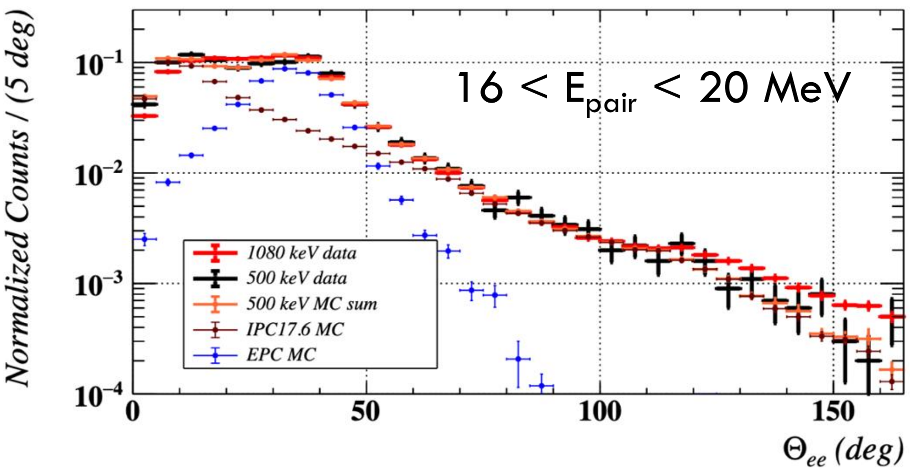
  – background: internal (IPC) or external (EPC) pair conversion

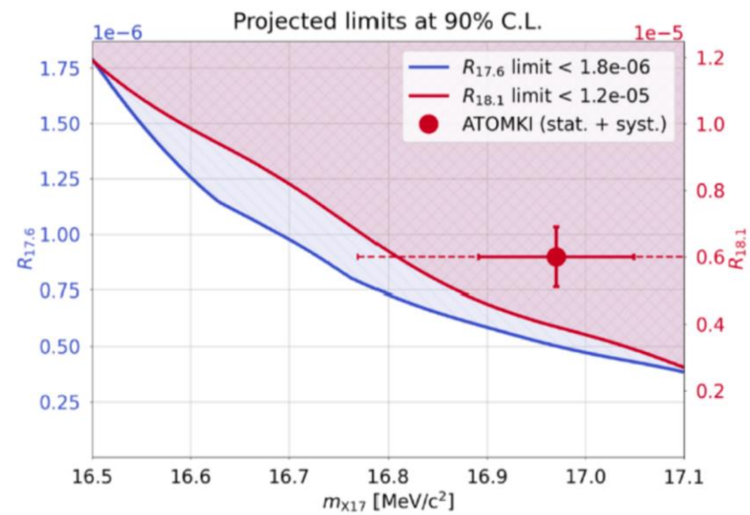




X_{17}, data and results

- Data set
  - 4 weeks in February 2023 at the same proton energy (E_p = 1030 keV)
  - excitation of both ^{8}Be resonances (17.6, 18.1 MeV) due to ~25% H_2^+ beam content
  - 75 Mevents collected, 500 kevents with reconstructed e^+e^- pairs





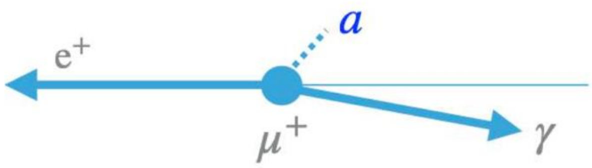
  - angular distribution compatible with the background for both resonances → exclusion plot
  - published results still compatible with Atomki results at ~1.5σ (~6% probability) (EPJ C85 (2025)763)
  - results from PADME collaboration compatible with background as well, with a most significant deviations (~2σ) at $\sqrt{s} \approx$ 16.9MeV (F. Bossi et al., JHEP 11 (2025) 007)
  - plans to continue X_{17} data taking during the next HIPA shutdown 2026 with pure 18.1 MeV sample

Search for $\mu \to e a \gamma$

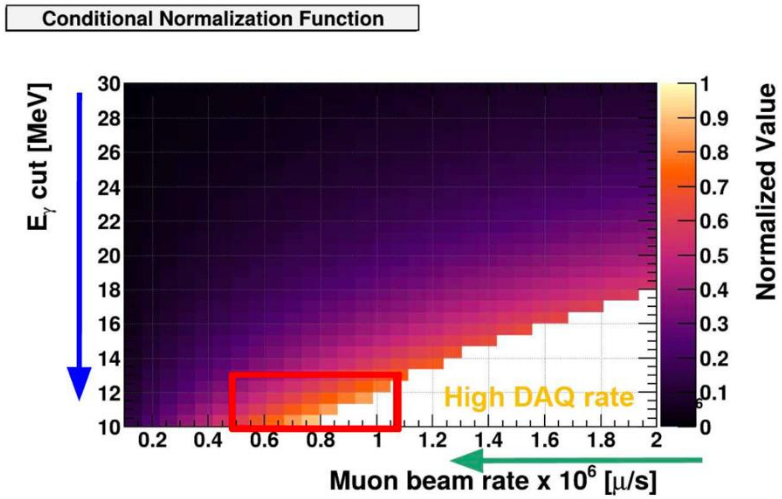
- Predicted in several Beyond Standard Model scenarios

  a = ALP = axion-like particle (i.e. pseudo Goldstone boson from spontaneous symmetry breaking of global symmetries) following suggestions from

  Jho, Knapen & Redigolo, JHEP 10 (2022) 029)

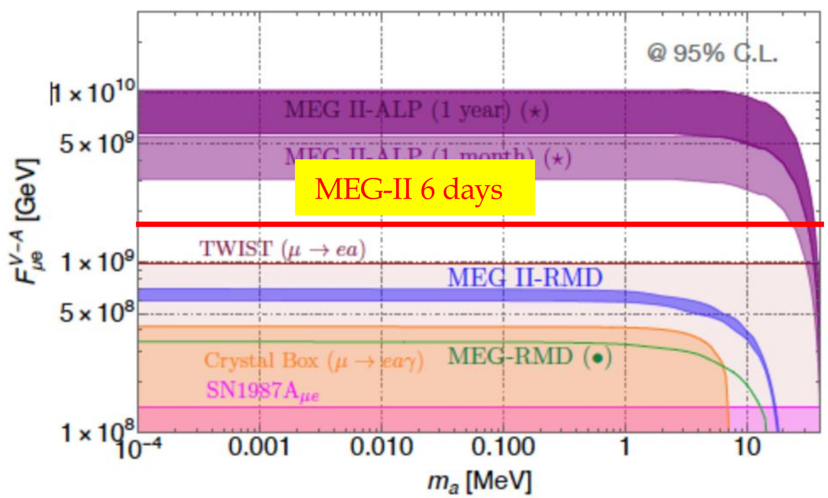


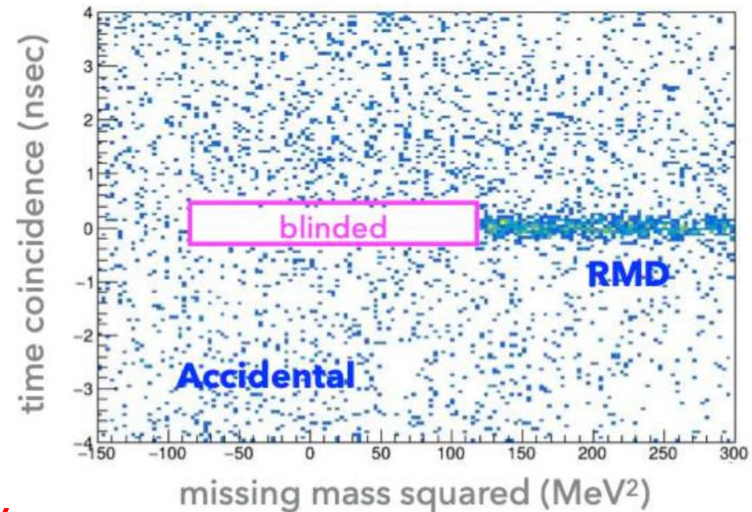
- Signature
  - 3-body decay ($e^+ + \gamma +$ invisible)
    (very similar to radiative muon decays)
  - simultaneous e^+ and γ detection
  - looser momentum/energy cuts ($E_\gamma > 10$ MeV)
  - no angular correlation required
  - ➔ need to operate the beam at quite lower intensi ($\lesssim 10^6$/s) in order to keep the trigger rate at c tolerable level

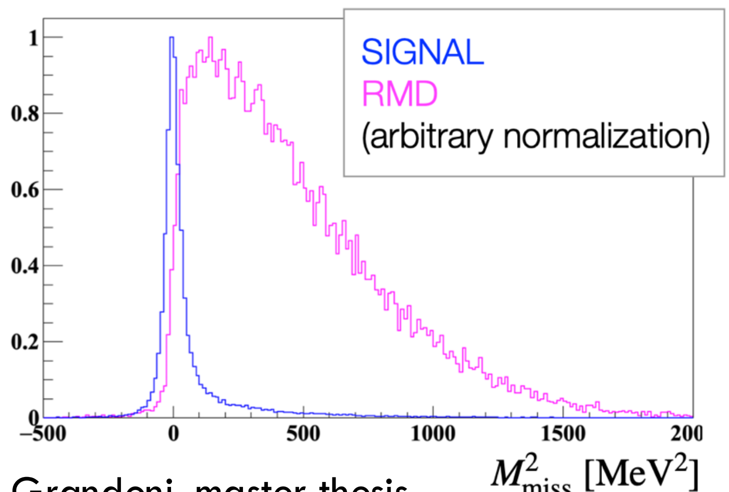


Data set and analysis strategy

- 6-days run at 10^6/s intensity cumulated in 2021+2022
- search for
  - timing coincidencies
    → accidental background suppression
  - peaked missing mass distribution
    → RMD background suppression
- sensitivity (based on toy-MC): 1.13×10^9 GeV







E.G. Grandoni, master thesis

Conclusions

- $\mu \to e\gamma$
  - MEG-II latest results (based on 2021+2022) are consistent with null result and set an upper limit at 1.5×10^{-13} (@90% CL) to the branching ratio
  - analysis of 2023 data and 2025 run ongoing so as to reach (with 2026 run) a sensitivity of 6×10^{-14} (10 times as low as former MEG-I limits)
- Exotics
  - X_{17} : no excess seen over background, still 1.5 σ compatibility with Atomki
    new run envisaged after 2026 shutdown
  - ALP: dedicated 6d-run at low intensity, should be able to push sensitivity down to current TWIST limit
- Still vast discovery potential…

  … so please, stay tuned!

Backup slides

Likelihood fit

- Frequentist approach based on Feldman-Cousins prescriptions with profile likelihood ratio ordering

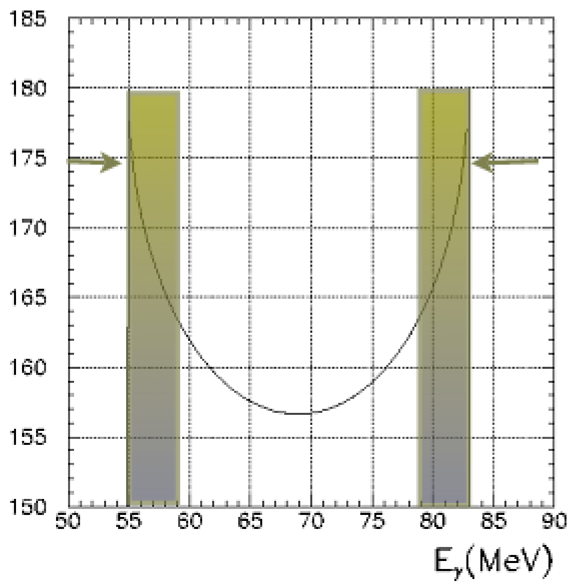
$$\mathcal{L}(\vec{x}_1, ..., \vec{x}_n, R_\diamond, A_\diamond|, \hat{S}, \hat{R}, \hat{A}) = \frac{e^{-\hat{N}}}{\hat{N}} e^{-\frac{1}{2}\frac{(A_\diamond - \hat{A})^2}{\sigma_A^2}} e^{-\frac{1}{2}\frac{(R_\diamond - \hat{R})^2}{\sigma_R^2}} \prod_{i=1}^{N} (\hat{S}s(\vec{x}_i) + \hat{R}r(\vec{x}_i) + \hat{A}a(\vec{x}_i))$$

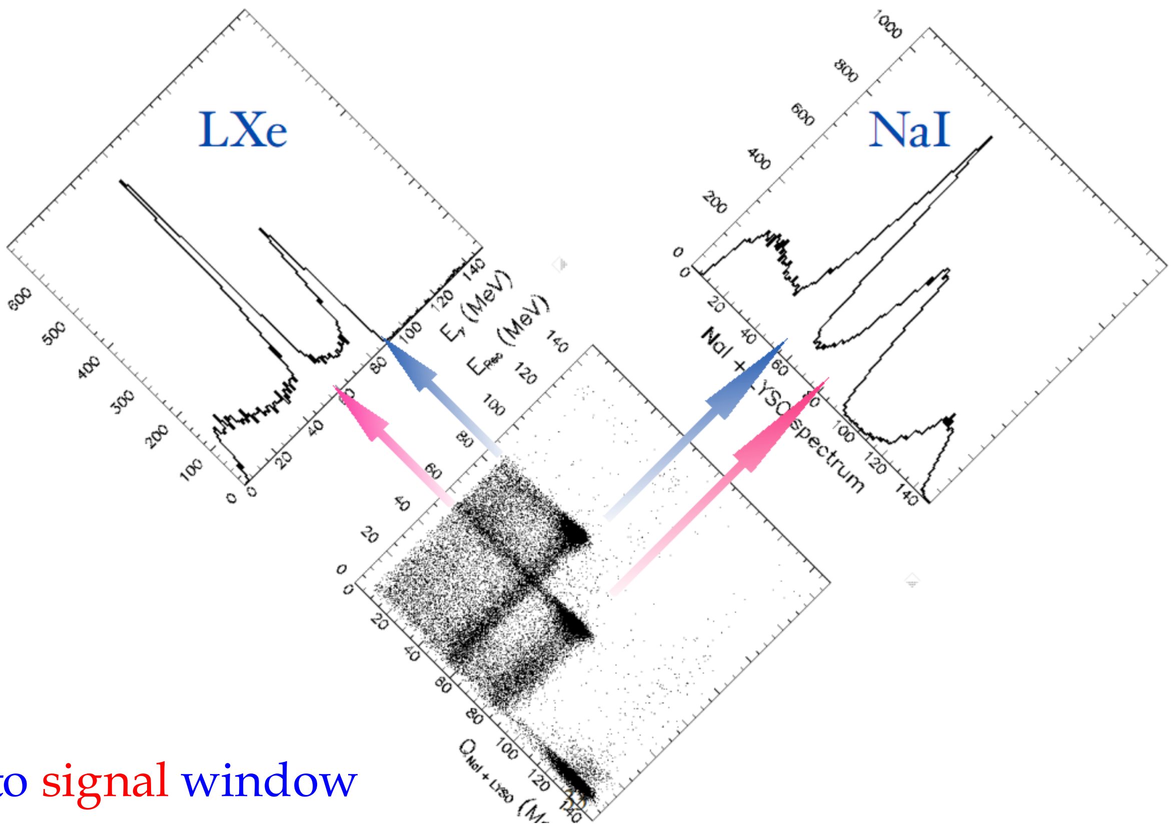
$$LR_p(N_{\rm sig}) = \frac{\max_{N_{\rm BG}, N_{\rm RMD}} \mathcal{L}(N_{\rm sig}, N_{\rm BG}, N_{\rm RMD})}{\max_{N_{\rm sig}, N_{\rm BG}, N_{\rm RMD}} \mathcal{L}(N_{\rm sig}, N_{\rm BG}, N_{\rm RMD})}.$$

- Observables
  - kinematics ($\vec{x}_i$)
  - event counts in the sidebands R , A
- Parameters
  - number of signal and background events
  - nuisance parameters added to take systematics into account

γ from π-CEX

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



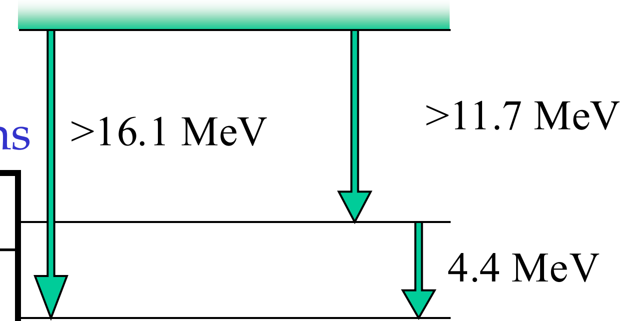


- E_γ = 55 (83) MeV ➔ close to signal window
- liquid H-target
- beam polarity and settings to be changed as well

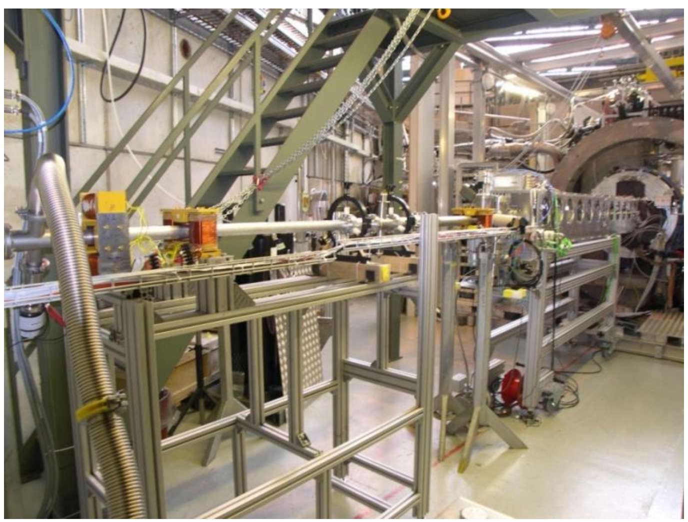
  → to be used quite seldom (~1/year)

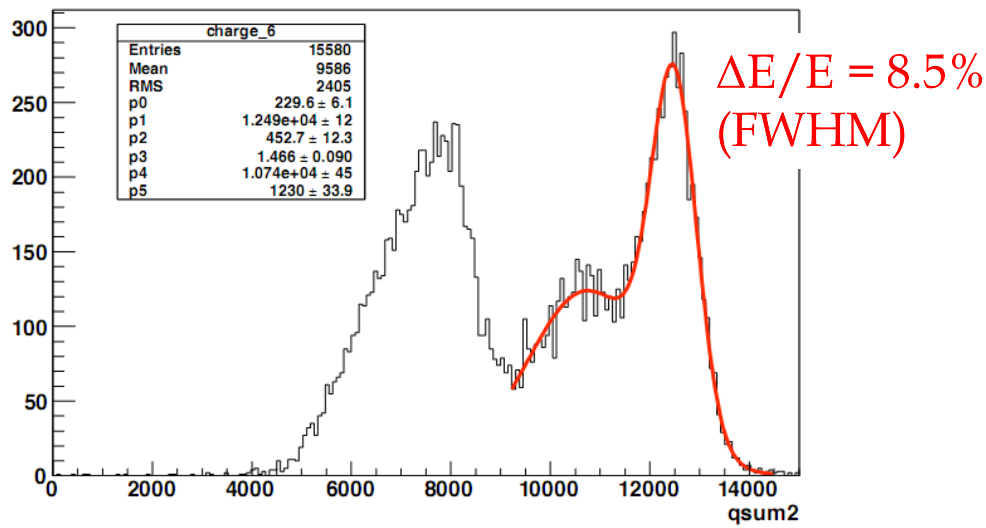
(p,γ) reactions

- Makes us of a Cockcroft-Walton accelerator to deliver tunable-energy protons to a $Li_2B_4O_7$ target
  - Li: high rate, higher energy photon
  - B: two (lower energy) time-coincident photons

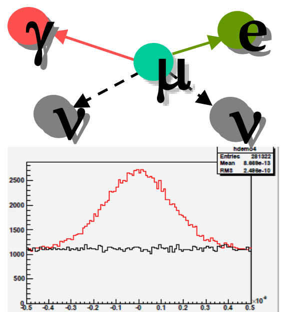


Reaction	E_{res}	σ_{res}	***γ-lines***
Li(p,γ)Be	440 keV	5 mb	(17.6, 14.6) MeV
B(p,γ)C	163 keV	$2\ 10^{-1}$ mb	(4.4, 11.7, 16.1) MeV





Calibration tools



Lower beam intensity < 10^7

Is necessary to reduce pile-ups

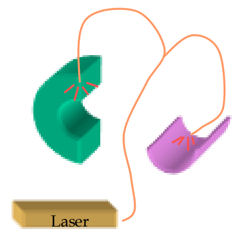
Better σ_t, makes it possible to take data with higher beam intensity

A few days ~ 1 week to get enough statistics

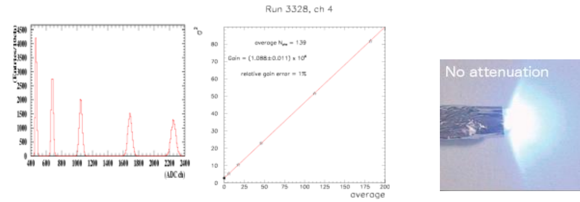
Laser

(rough) relative timing calib.

< 2~3 nsec



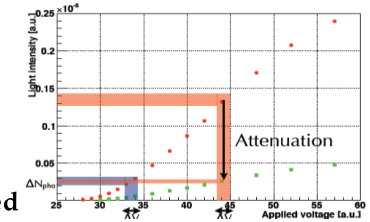
LED



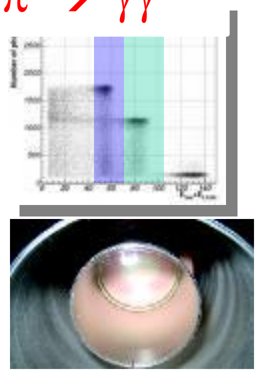
PMT Gain

Higher V with light att.

Can be repeated frequently



$\pi^0 \rightarrow \gamma\gamma$



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

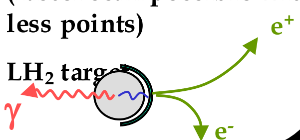
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

$\pi^- + p \rightarrow \gamma + n$ (129MeV)

10 days to scan all volume precisely

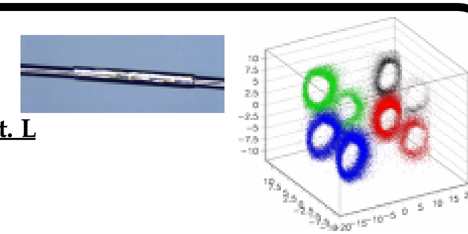
(faster scan possible with less points)

LH_2 targ



MEG detector standard calibrations

alpha

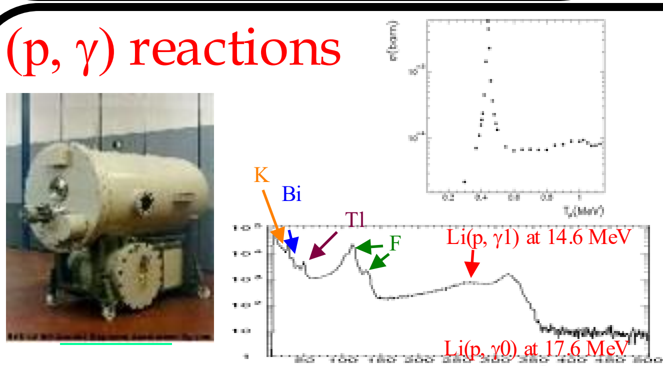


PMT QE & Att. L

Cold GXe

LXe

(p, γ) reactions



Li(p,γ)Be

LiF target at COBRA center

17.6MeV γ

~daily calib.

Can be used also for initial setup

(n,γ) on Ni

Neutron pulsed generator to induce (n, γ)