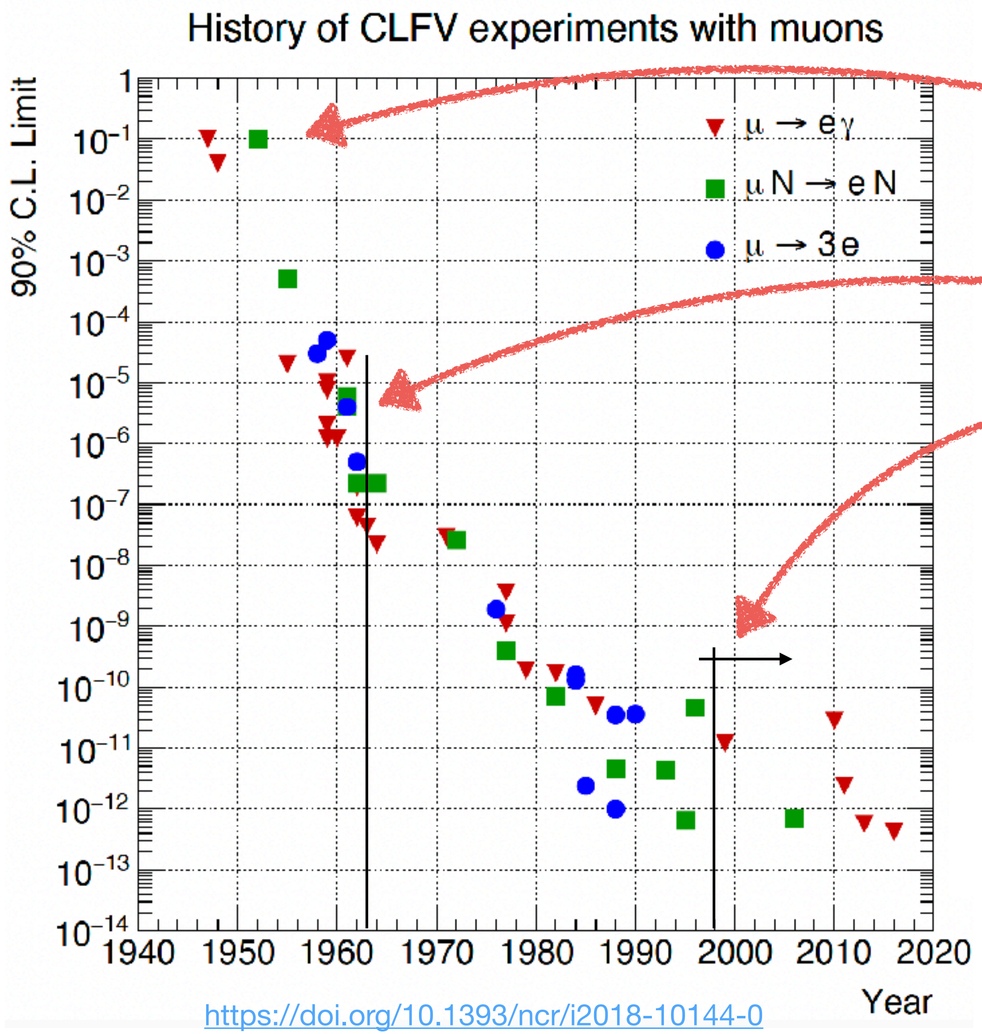


Frontiers of muon LFV searches

Marco Francesconi, INFN Napoli

JPS Symposium, Tokyo University, 14th September 2026

Historic intro to CLFV

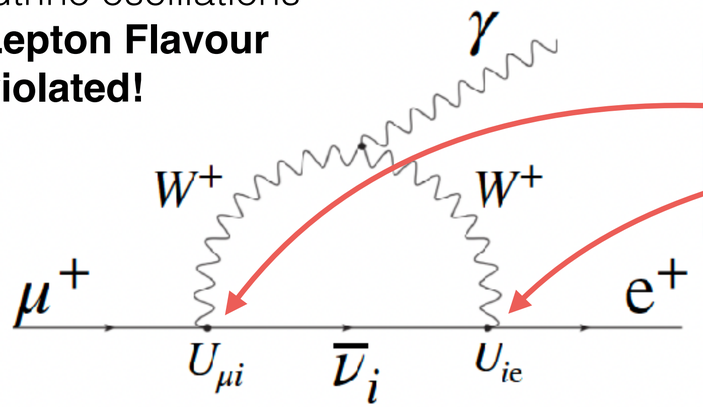


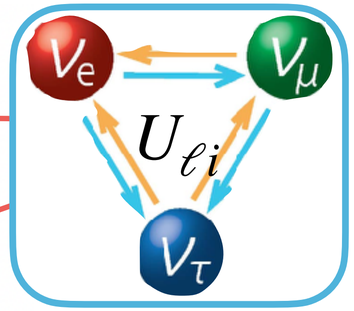
Lepton flavour shaped the Standard Model

… from the initial experiments with cosmic rays:
μ is not an excited electron!

… to the first experiments with stopped π beam:
key to the $\overline{\nu}_\mu \neq \overline{\nu}_e$ hypothesis

… but after neutrino oscillations
we know that **Lepton Flavour symmetry is violated!**





$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=1}^{3} U_{\mu i} U_{ei}^{*} \frac{m_i^2}{m_W^2} \right|^2 \approx 10^{-55 \leftrightarrow -50}$$

Beyond experimental reach:

any CLFV observation is sign of new physics

Muon processes with ≥ 2 final state particles

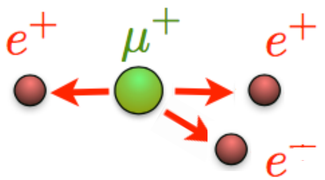
$\mu^+ \to e^+\gamma$ **and** $\mu^+ \to e^+e^-e^+$**: lots of similarities**

Signal with peculiar topology



$\mu^+ \to e^+\gamma$

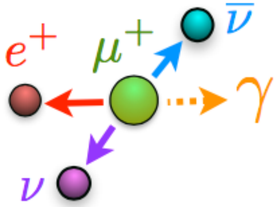
- mono-energetic
- back-to-back
- **time coincidence**



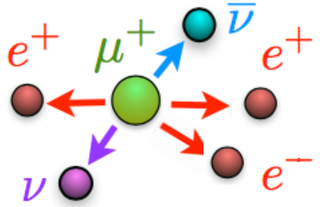
$\mu^+ \to e^+e^-e^+$

- $\sum E_i = m_\mu$
- $\sum \vec{p_i} = 0$
- **time coincidence**

Irreducible background



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

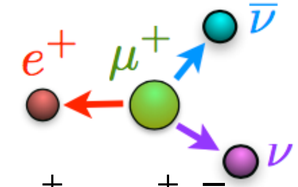


$\mu^+ \to e^+\nu\bar{\nu}e^+e^-$

$$\propto R_\mu \, \mathrm{BR}(\mu \to \dots)$$

only relevant at kinematic endpoint

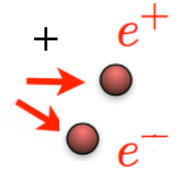
Accidental coincidence



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



From $\mu^+ \to e^+\nu\bar{\nu}\gamma$
or Annihilation in flight



From $\mu^+ \to e^+\nu\bar{\nu}e^+e^-$
or Bhabba scattering

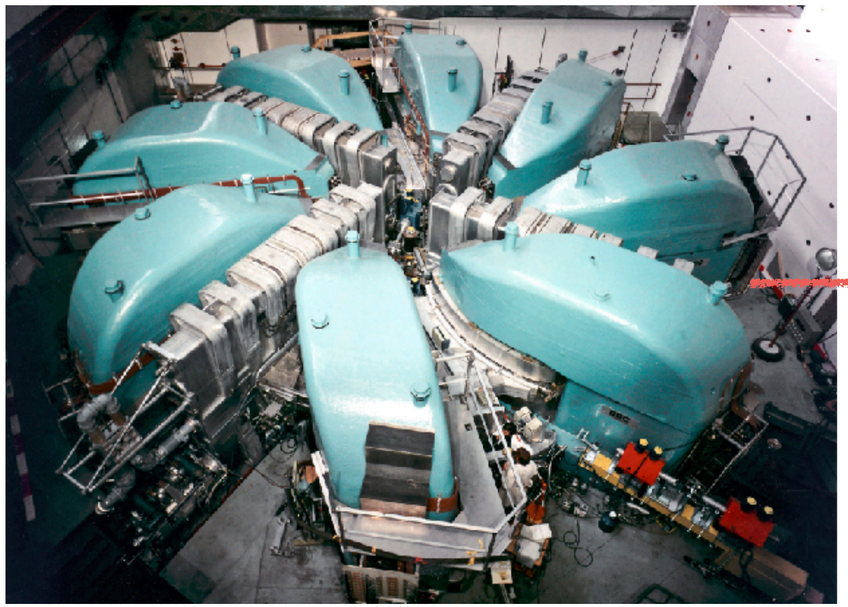
$$\propto R_\mu^2 \Delta T_{e\gamma}$$

dominant at high beam rates

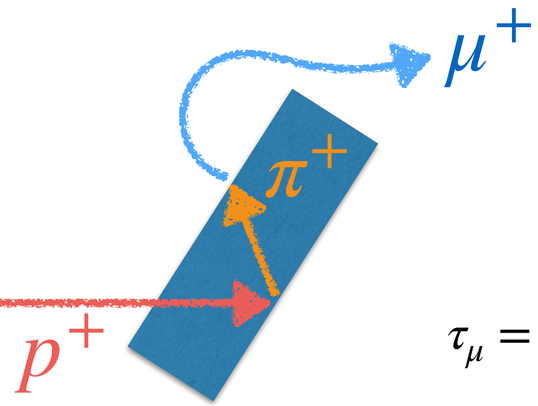
Fast detectors with **high granularity** to cope with particle rate

Focus on **continuous muon beams**: limit instantaneous intensity → limit accidental rate

Continuous muon beams



PSI HIPA proton cyclotron



Muon beams by π^+ from proton interaction with target

Maximum capture yields for μ^+ from decays **on target surface**, with fluencies up to $10^8\ \mu/s$

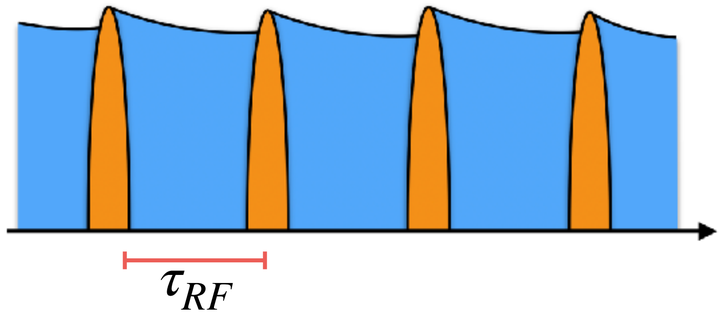
$\tau_\mu = 2.2\ \mu s$ → beam delivery to dedicated experiments far from production target

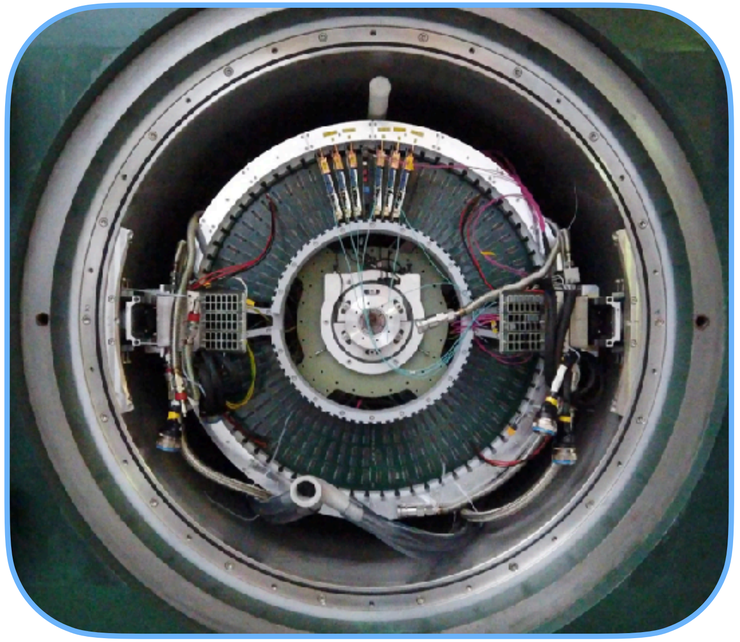
To cope with accidental background, peak R_μ should be minimised

Continuous beams preferred over bunched beams

PSI RF is 80 MHz

$\tau_\pi \approx \tau_{RF} = 25\ ns$





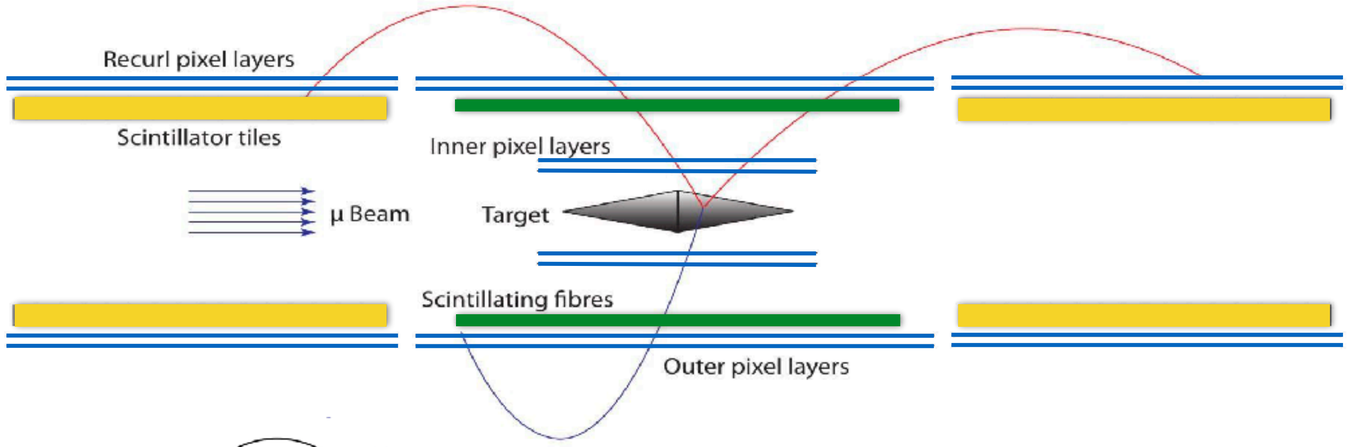
$$\mu^+ \to e^+ e^- e^+$$

The Mu3e experiment



The Mu3e experiment

Main difficulty: need to record all tracks $|\vec{p}| < m_\mu/2$ and reconstruct them



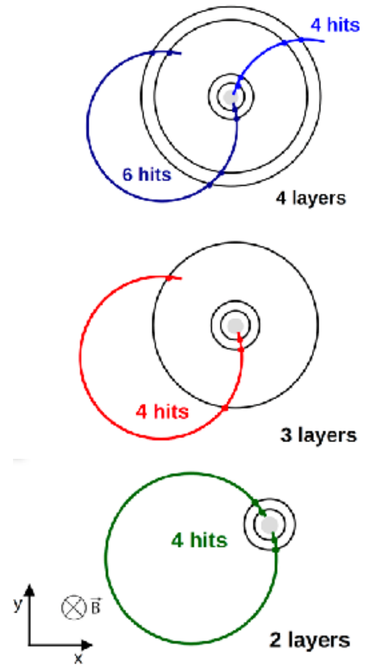
Solution: HVMAPS 6-layer $50\ \mu m$-tick **pixel tracker**

+

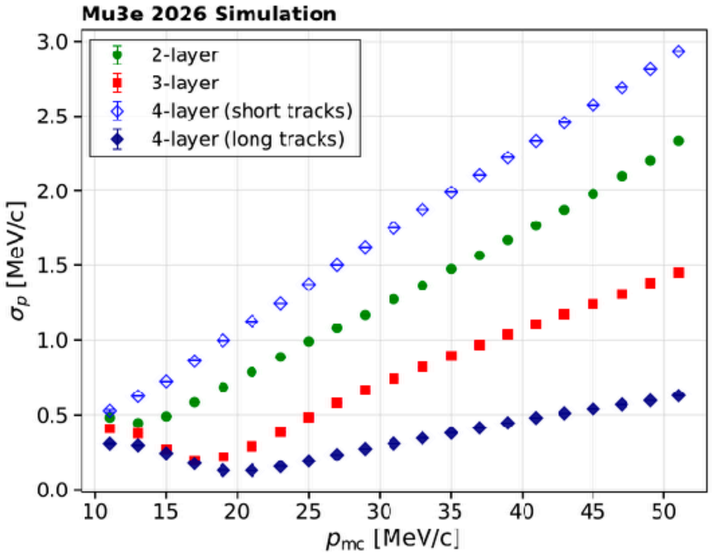
scintillating **fibres** and **tiles** for timing

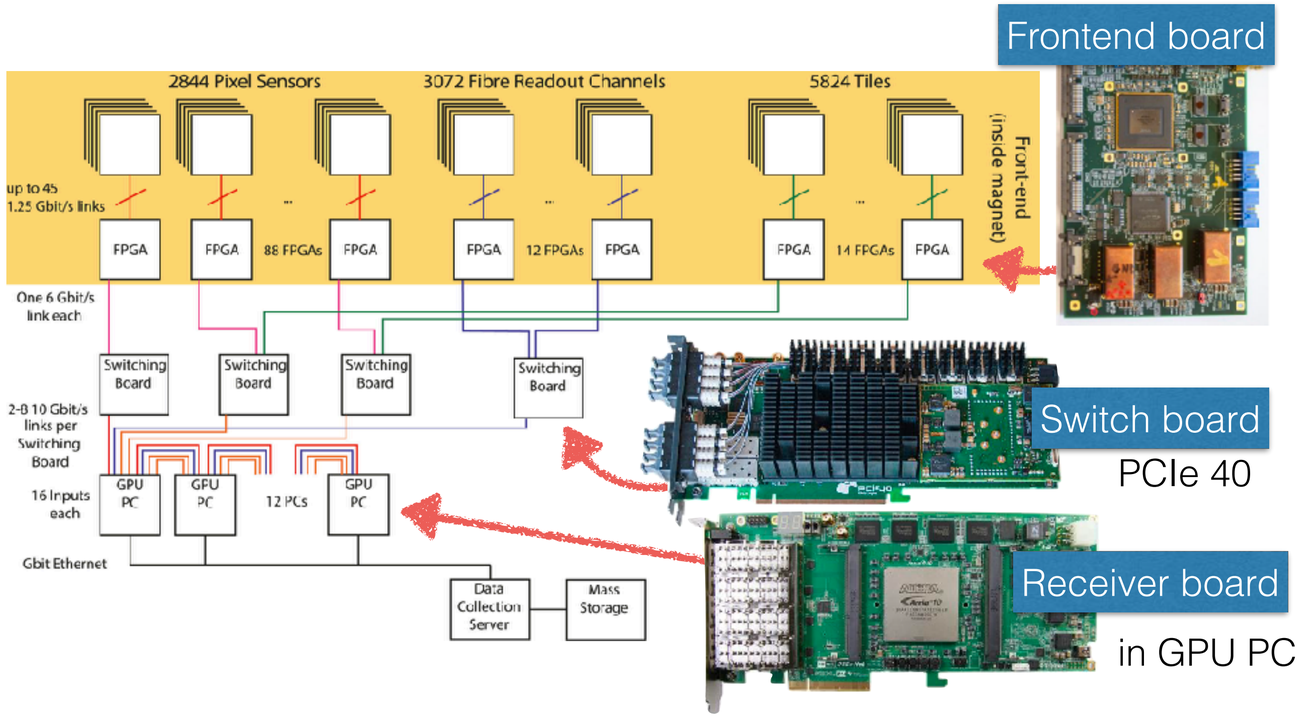
+

steaming DAQ with full event reconstruction and filtering

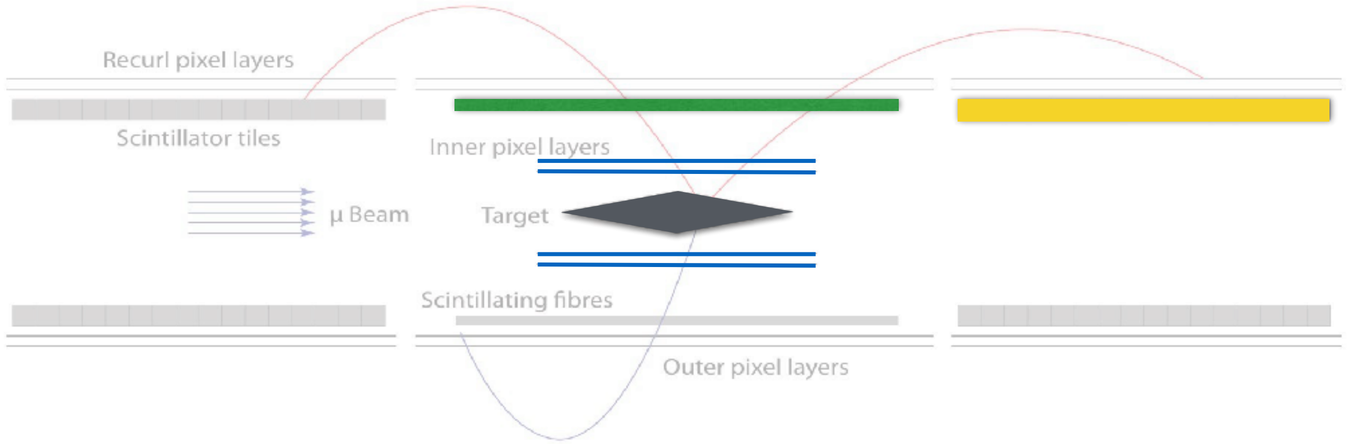


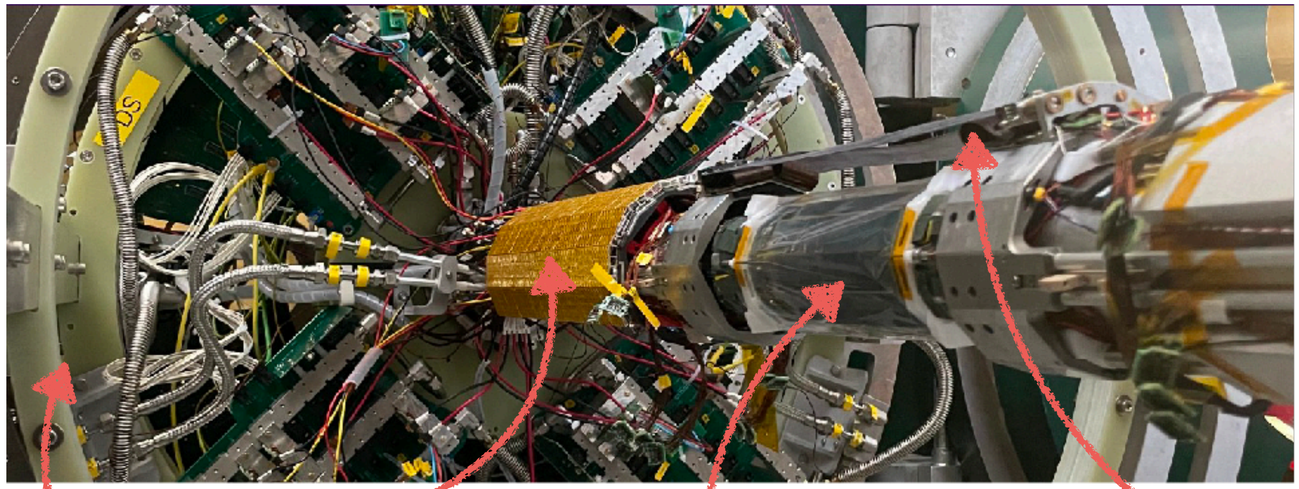
Exploit recurring tracks to improve momentum resolution





Mu3e 2025 beam time results



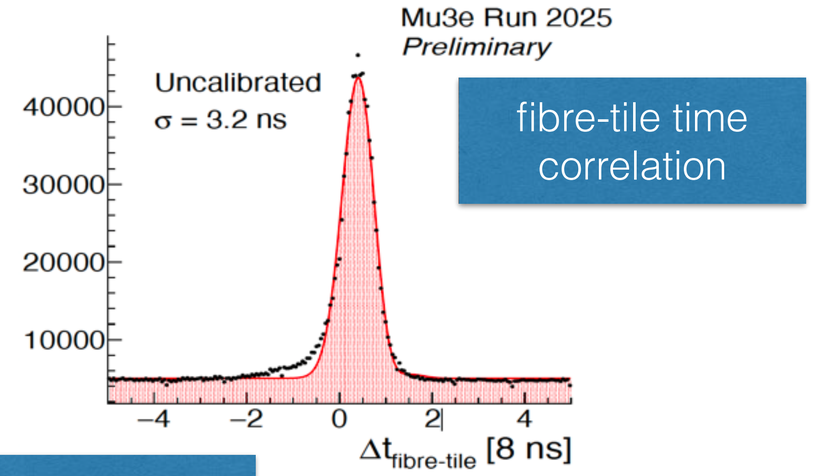


3/7 upstream tiles

1/6 fibres assemblies

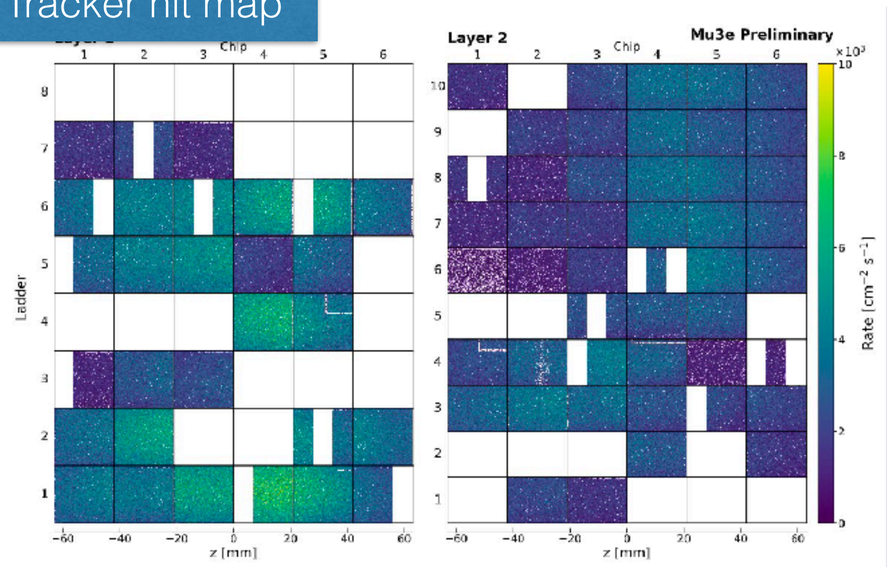
1T solenoid magnet

Full internal tracker



fibre-tile time correlation

Tracker hit map

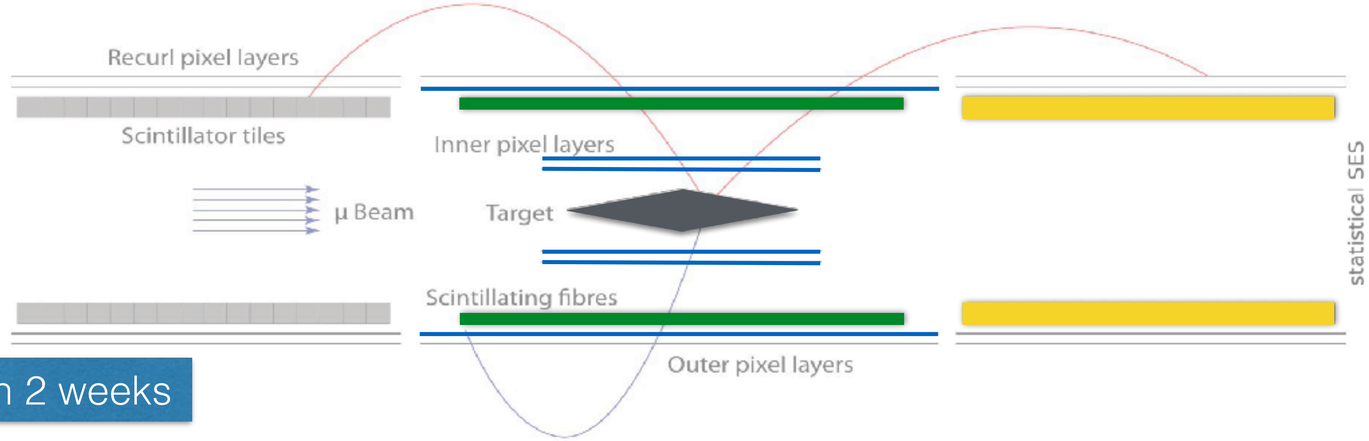


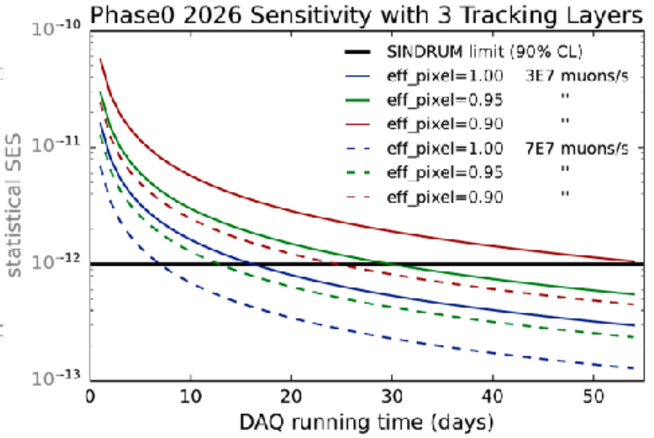
Mu3e short term perspectives

This year: **Phase 0**

New $70\,\mu m$-tick vertex
Outer pixel layer 3
Full fibres
Full downstream tiles
PC Farm in operation

Could surpass SINDRUM in 2 weeks

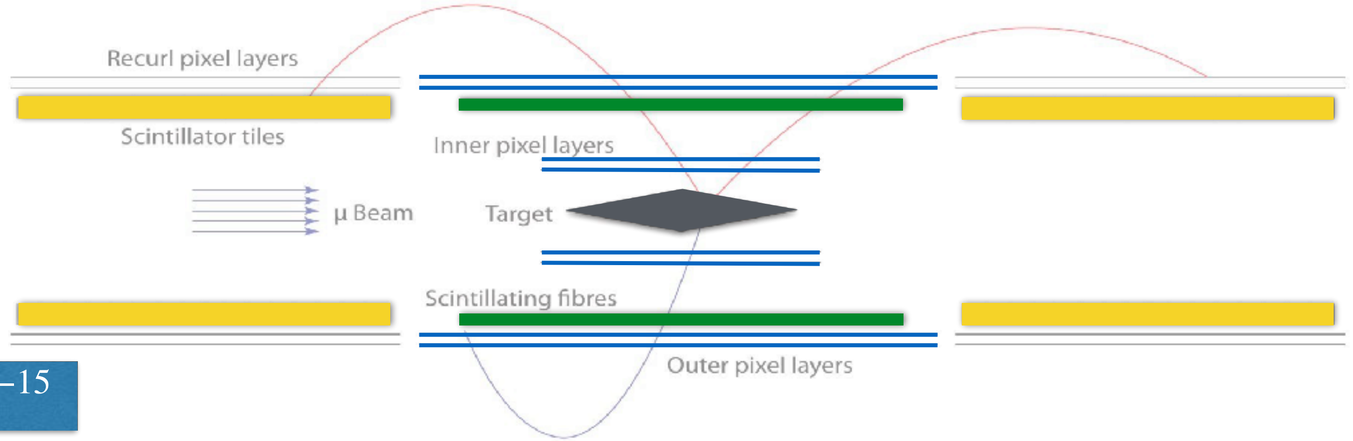


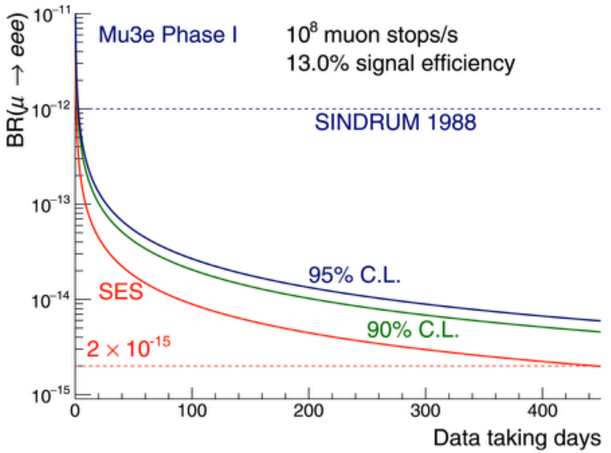


Run 2027: **Phase I**

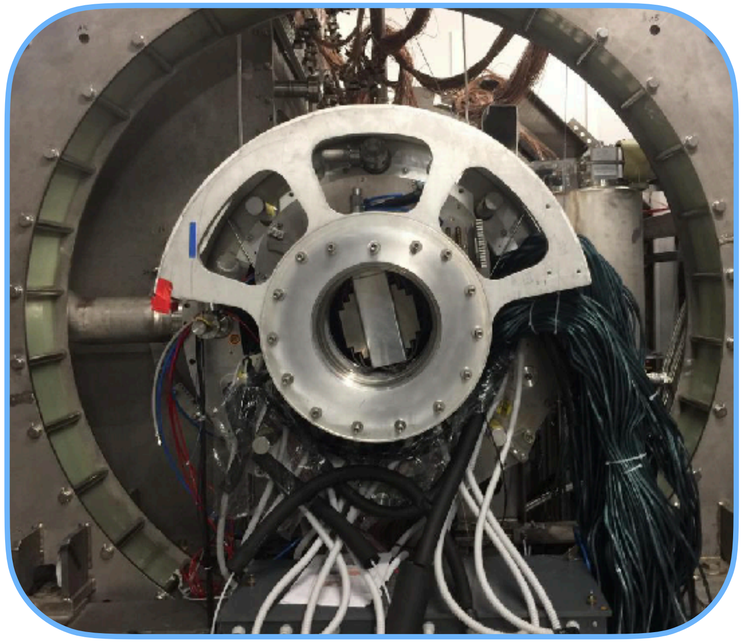
Outer pixel layer 4
Full upstream tiles

Sensitivity down to $2 \cdot 10^{-15}$





Beyond 2028, **Phase II**, depends on PSI accelerator schedule
Final design goal $< 10^{-16}$



$$\mu^+ \to e^+\gamma$$

The MEG II experiment



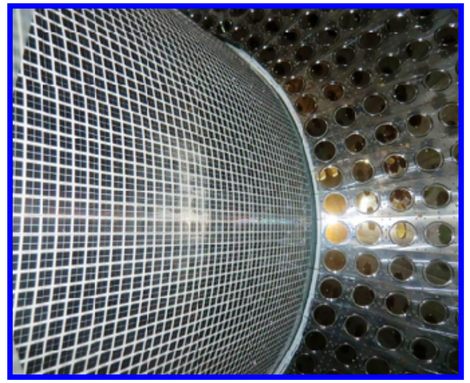
The MEG II experiment

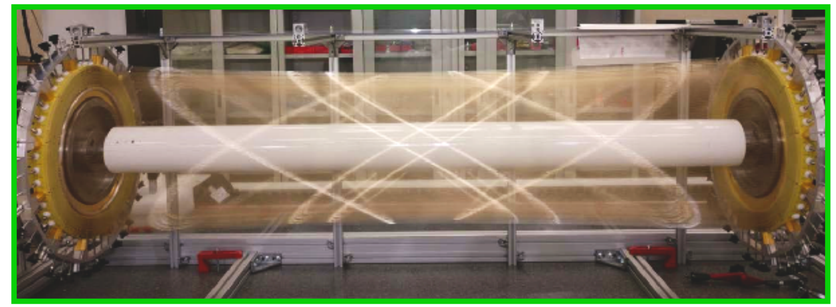
LXe

Scintillation detector

4092 MPPCs
+ 668 PMTs

$E_\gamma, T_\gamma, \Theta_\gamma$





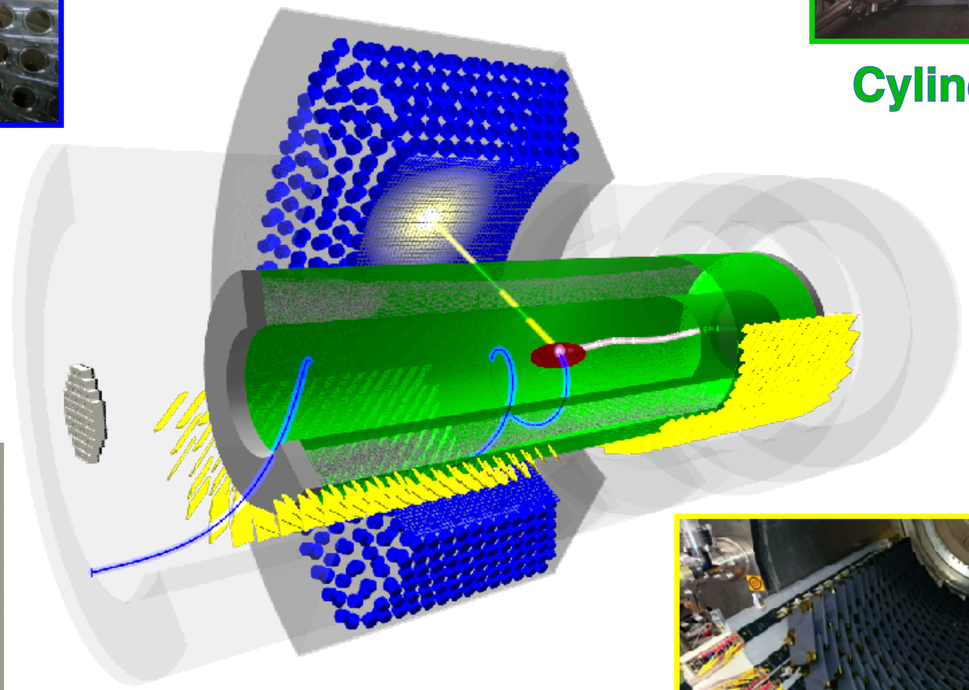
Cylindrical Drift Chamber

1728 **square drift cells**

Gas: He:IsoButane:IsoPropyl Alcool:O_2

> 60 hits/track in non-solenoidal $\vec{B}$ field

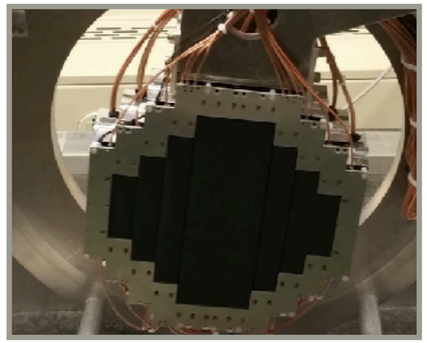
E_e, Θ_e



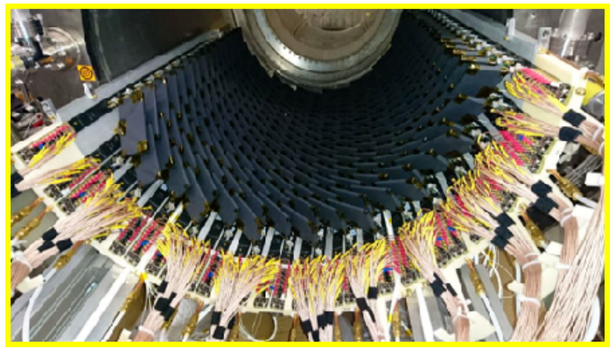
RDC

Plastic + LYSO scintillators

Detects low energy e^+ associated with high energy γ from $\mu \to e\nu\bar{\nu}\gamma$



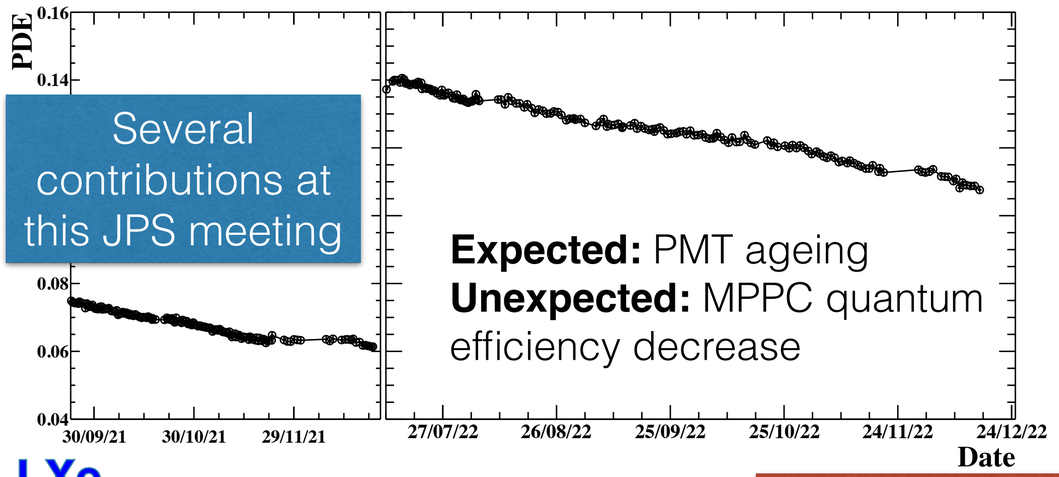
Timing counter



512 **scintillator tiles** with SiPM readout

T_e

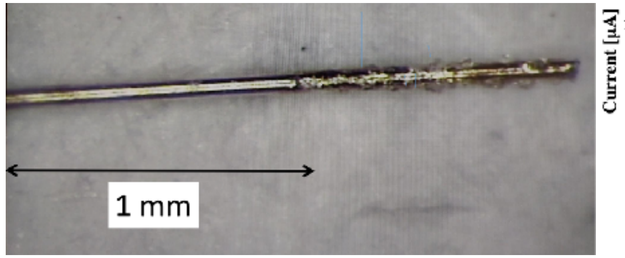
MEG II detector challenges

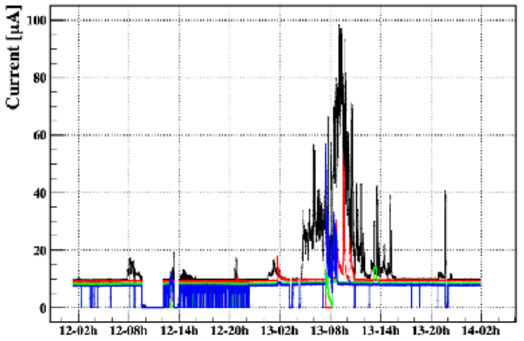


Several contributions at this JPS meeting

Expected: PMT ageing
Unexpected: MPPC quantum efficiency decrease

LXe





Expected: huge wire density
Unexpected: wire breaking, high currents in operation

Cylindrical Drift Chamber

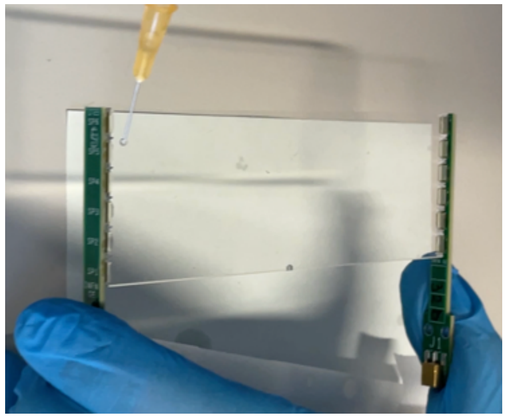
All challenges addressed: stable operation since 2021

TDAQ

Expected: higher channel count with GHz digitisation, HV and frontend gain
Unexpected: part procurement, noise hunting



Timing counter

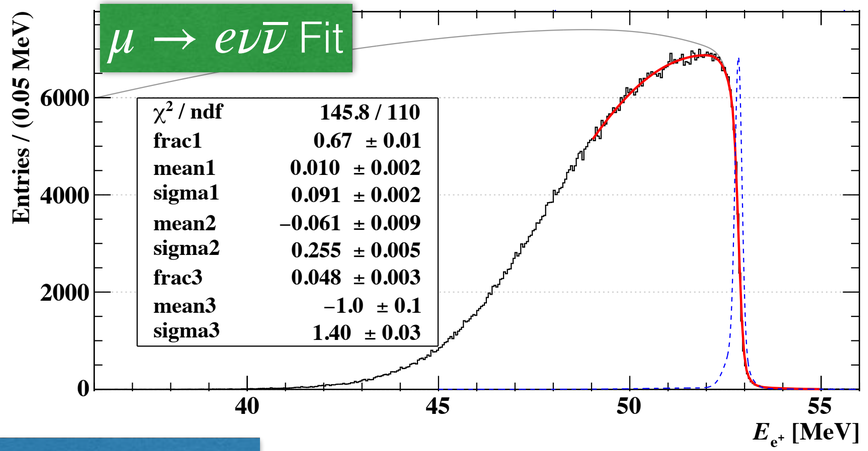


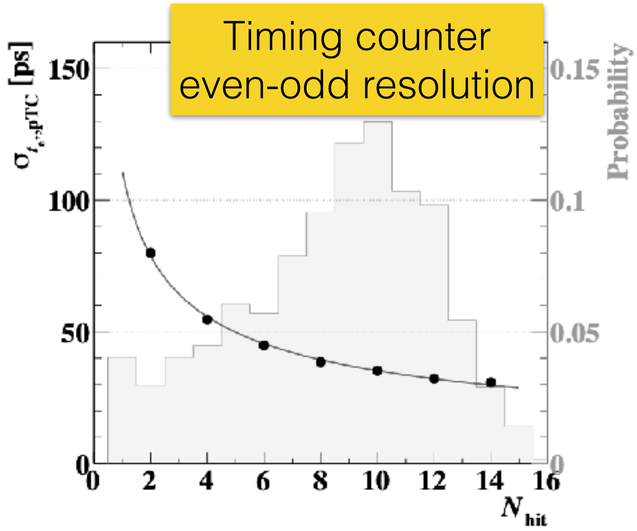
Expected: PMT→SiPM, HV and external gain
Unexpected: new counter for radiation damage, noise hunting in new electronics

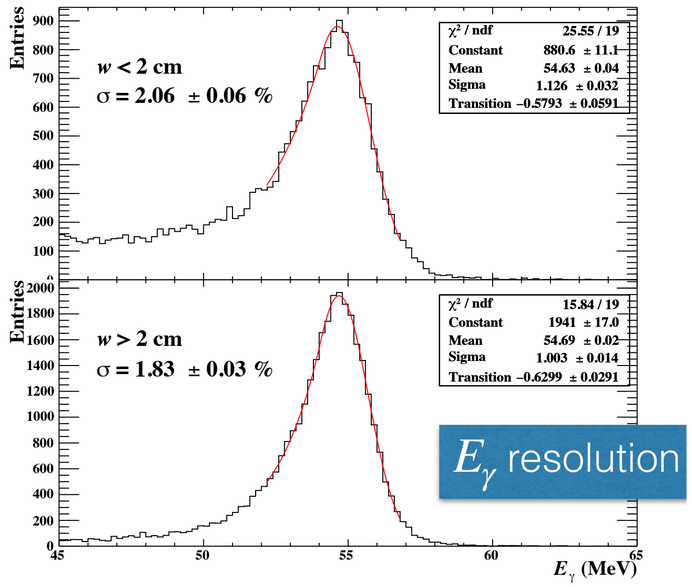
Detector performances

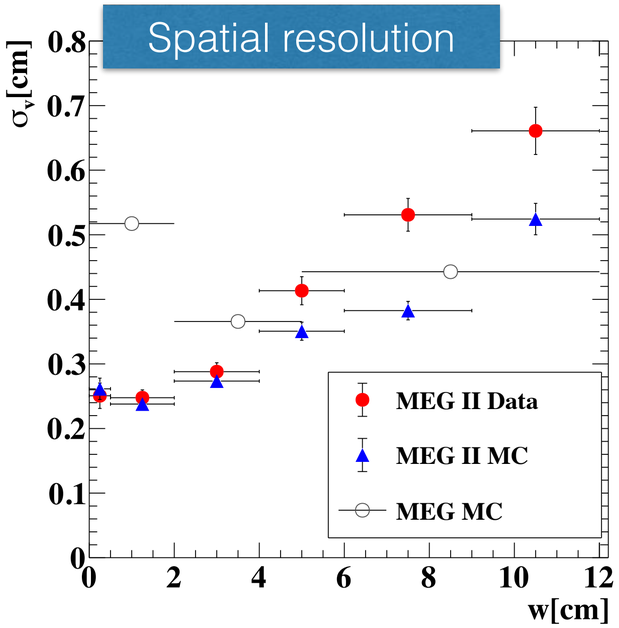
Spectrometer (**DCH** + **TC**) reached design performances:

- Fit of $\mu \to e\nu\overline{\nu}$
  - E_e **resolution,** 84 keV (core)
- **Track timing**
  - Single counter resolution 112 ps
  - Combining ~10 hits $\sigma(T_e) = 43$ ps





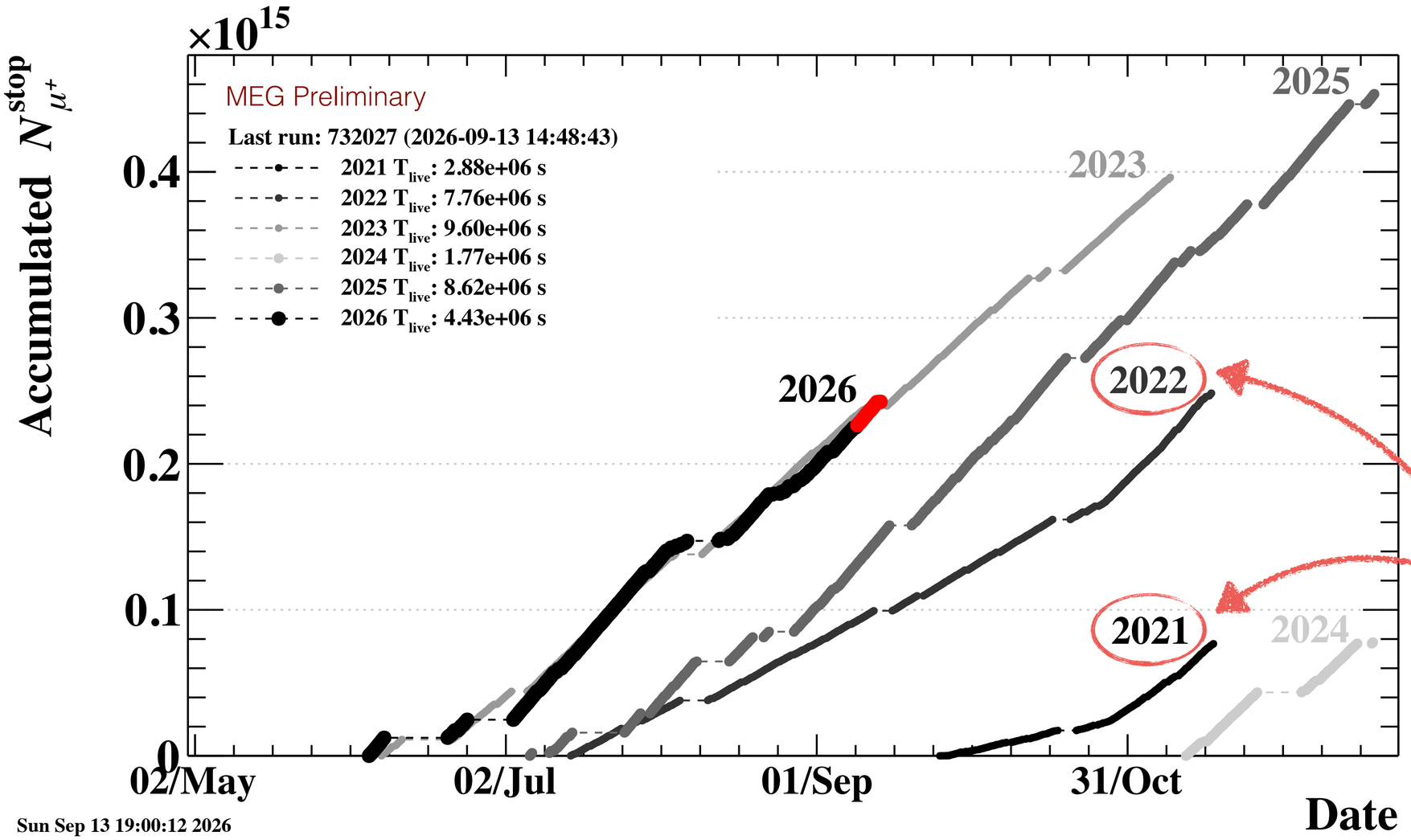




LXe detector affected by photosensors PDE decrease

- E_γ **resolution 1.9-2.4%** @52.8MeV
  - measured yearly with pion charge exchange reaction
  - depends on conversion depth
- **Spatial resolution** ~2.5 mm
  - dedicated data taking with collimator
  - big improvement for shallow events w.r.t. MEG I PMTs

Data taking runs

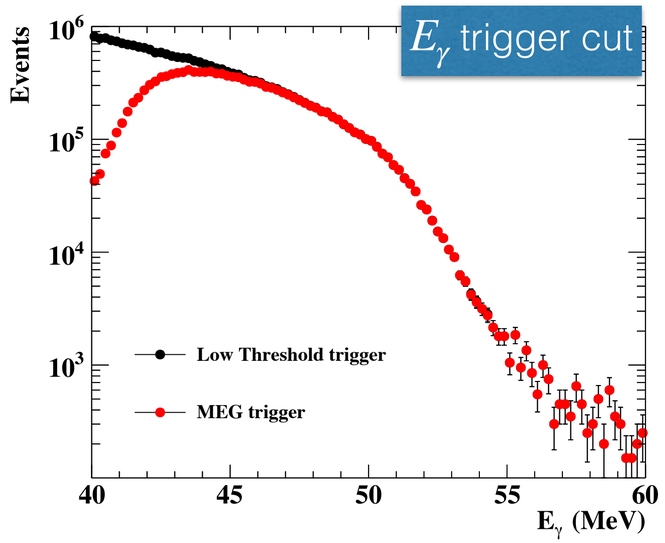


DAQ time limited by beam availability and other users

2021-2022: beam intensity scans
2023: $4 \cdot 10^7 \mu/s$
2024:PSI cryoplant problem
2025: intensity increased to $5 \cdot 10^7 \mu/s$
2026: PSI shutdown for cooling

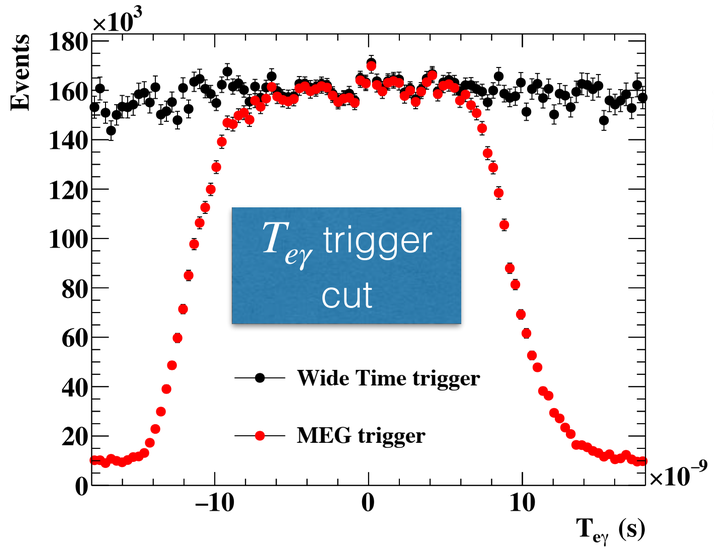
~1/4 of statistics analysed (2021+2022)

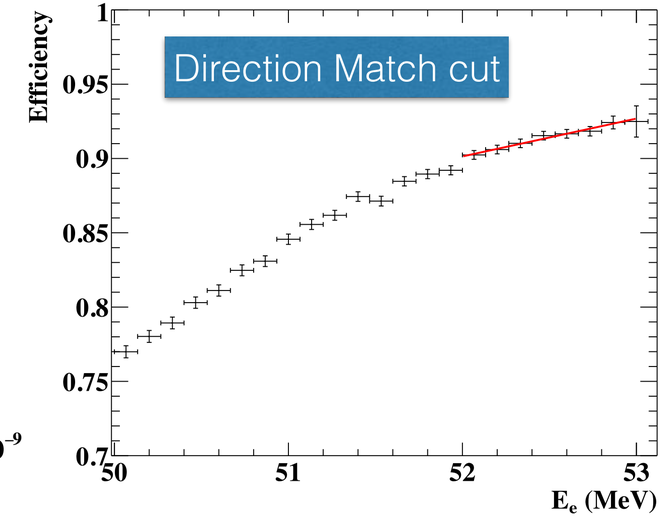
Event selection and normalisation



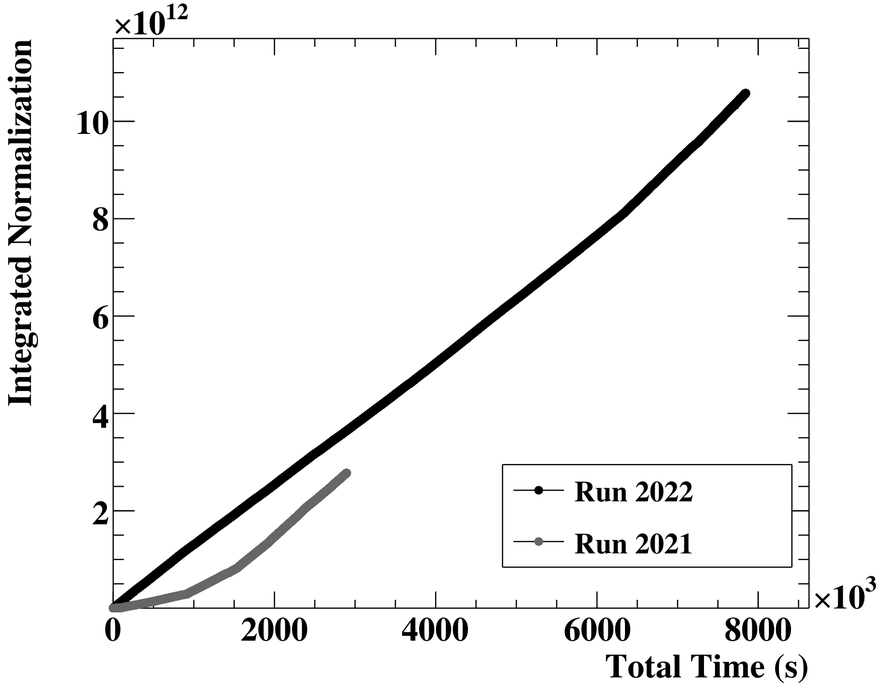
Three selections at trigger level:

1. Photon energy
   - weighted sum of LXe photosensors
2. Time coincidence
   - difference between TC and LXe hits
   - without track length compensation
3. Geometrical cut "Direction Match"
   - lookup table of TC and LXe channels designed for $\mu \to e\gamma$ events



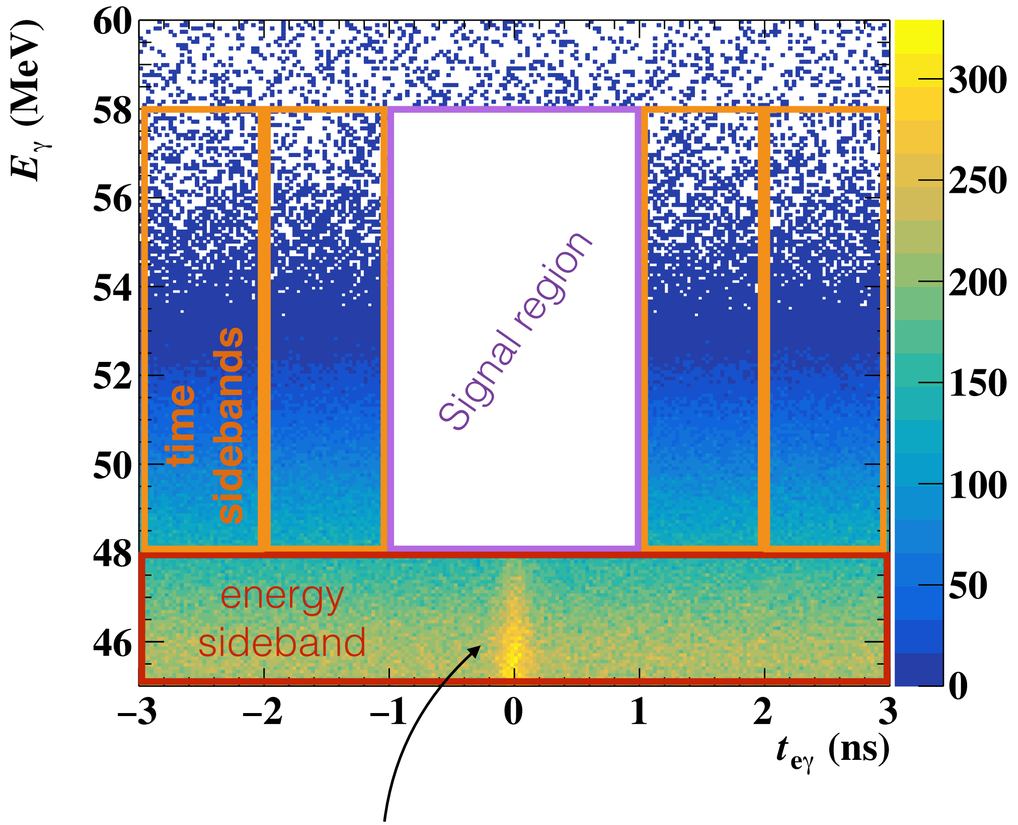


Normalization to $\mu^+ \to e^+\nu\bar{\nu}$ using a prescaled trigger



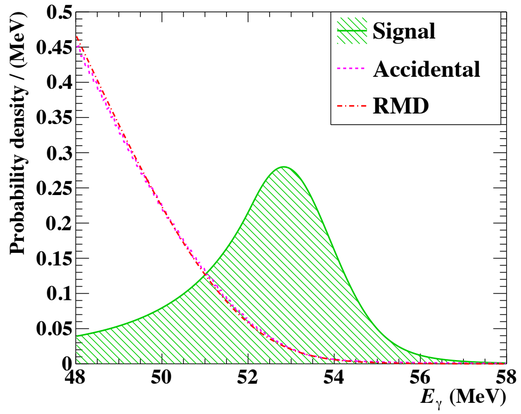
Blinding box and fit strategy

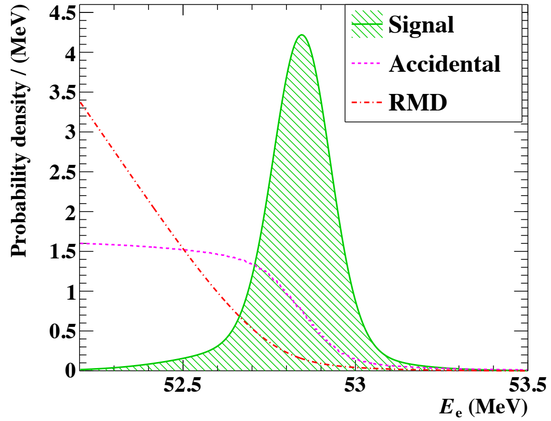
Automatic blinding of data in the $E_\gamma - T_{e\gamma}$ plane

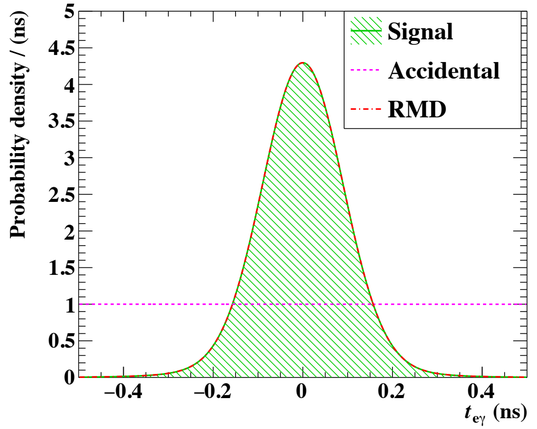


$\mu \to e\nu\bar{\nu}\gamma$ sample, complemented with low-intensity data

Data-driven extraction of observable PDFs from sidebands and calibration data







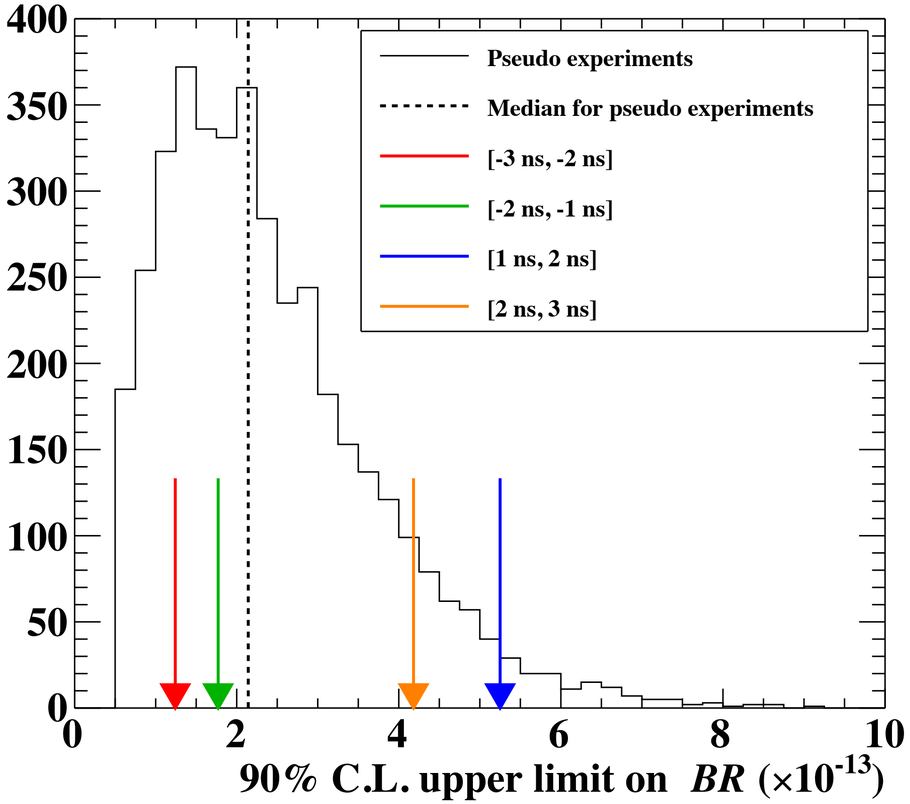
Observables

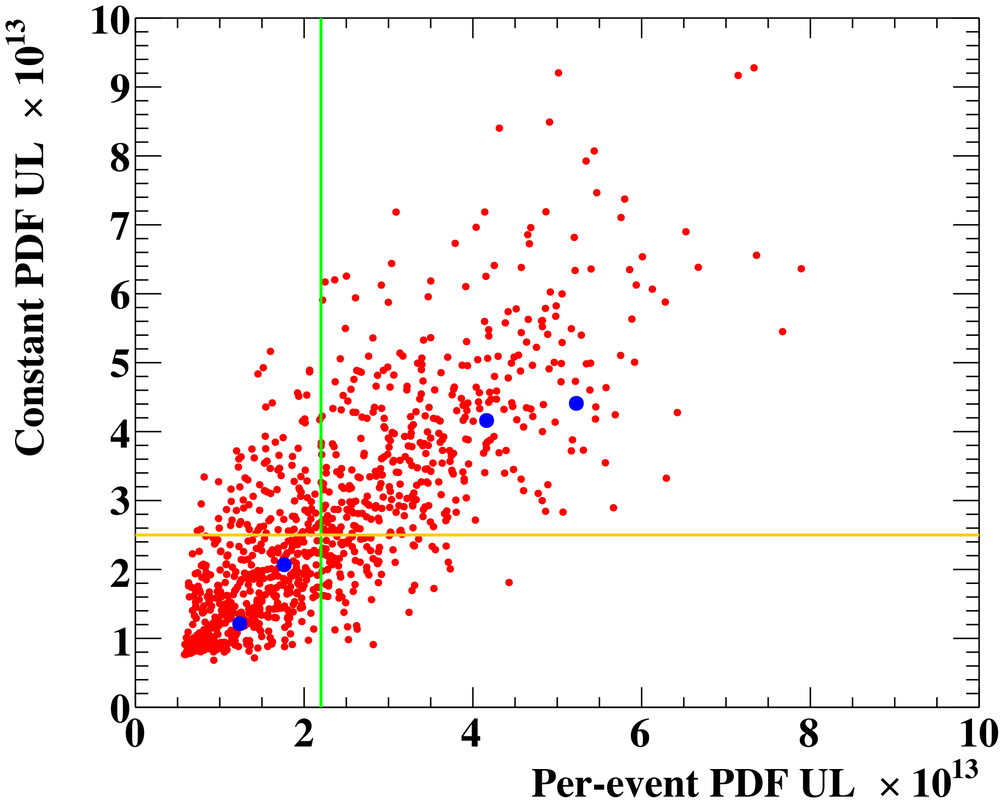
$\vec{x} = \{E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}, n_{pTC}, t_{RDC}, E_{RDC}\}$

Each PDF includes event by event parametrisation
es.: resolutions from event reconstruction

2021+2022 Sensitivity

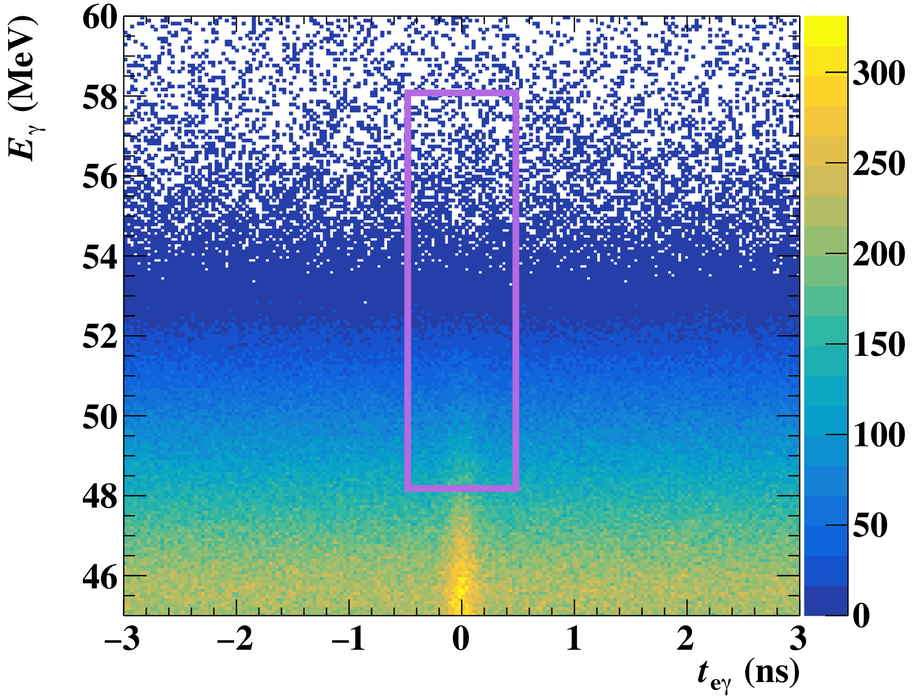
Feldman Cousin approach: sensitivity computed as median of null-signal Toy experiments validated with the four time sidebands

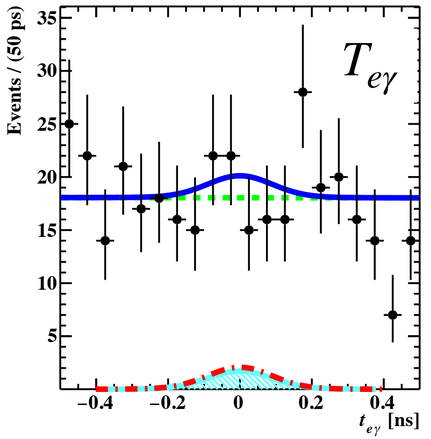


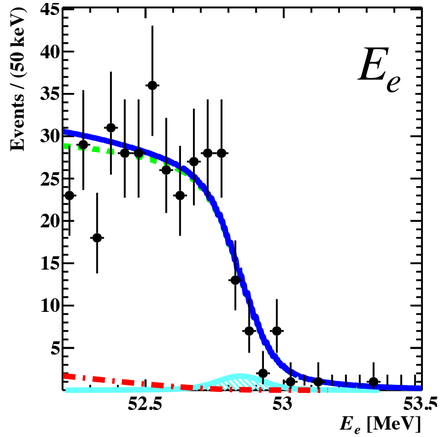


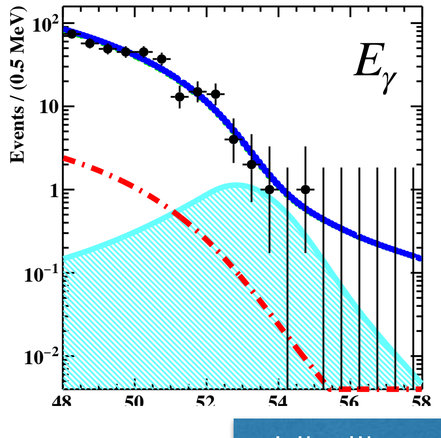
Per-event PDF analysis compared with independent Constant PDF before unblinding

2021+2022 Fit

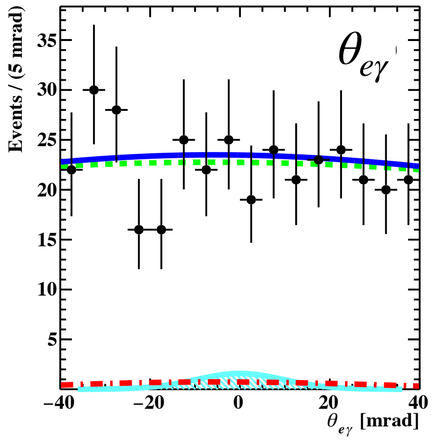


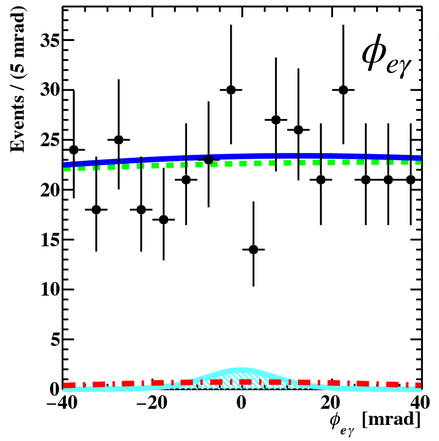




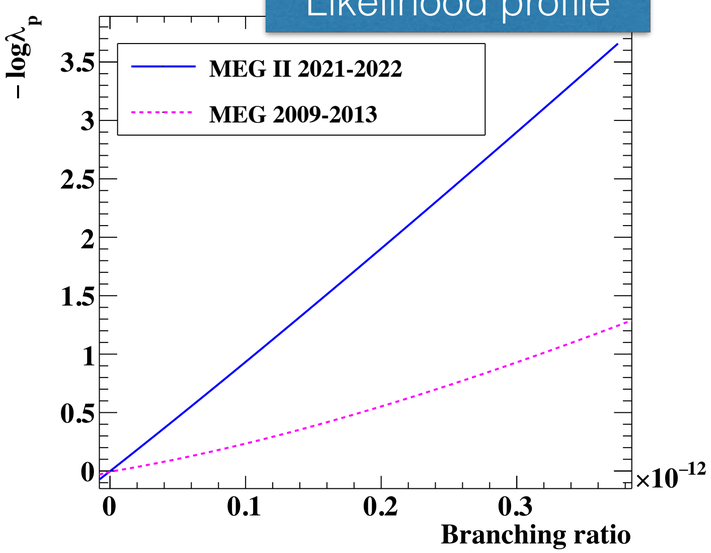


Accidentals
RMD
Signal UL x4





Likelihood profile



No excess

negative best fit $N_{sig} = -5.01 \pm 0.22$

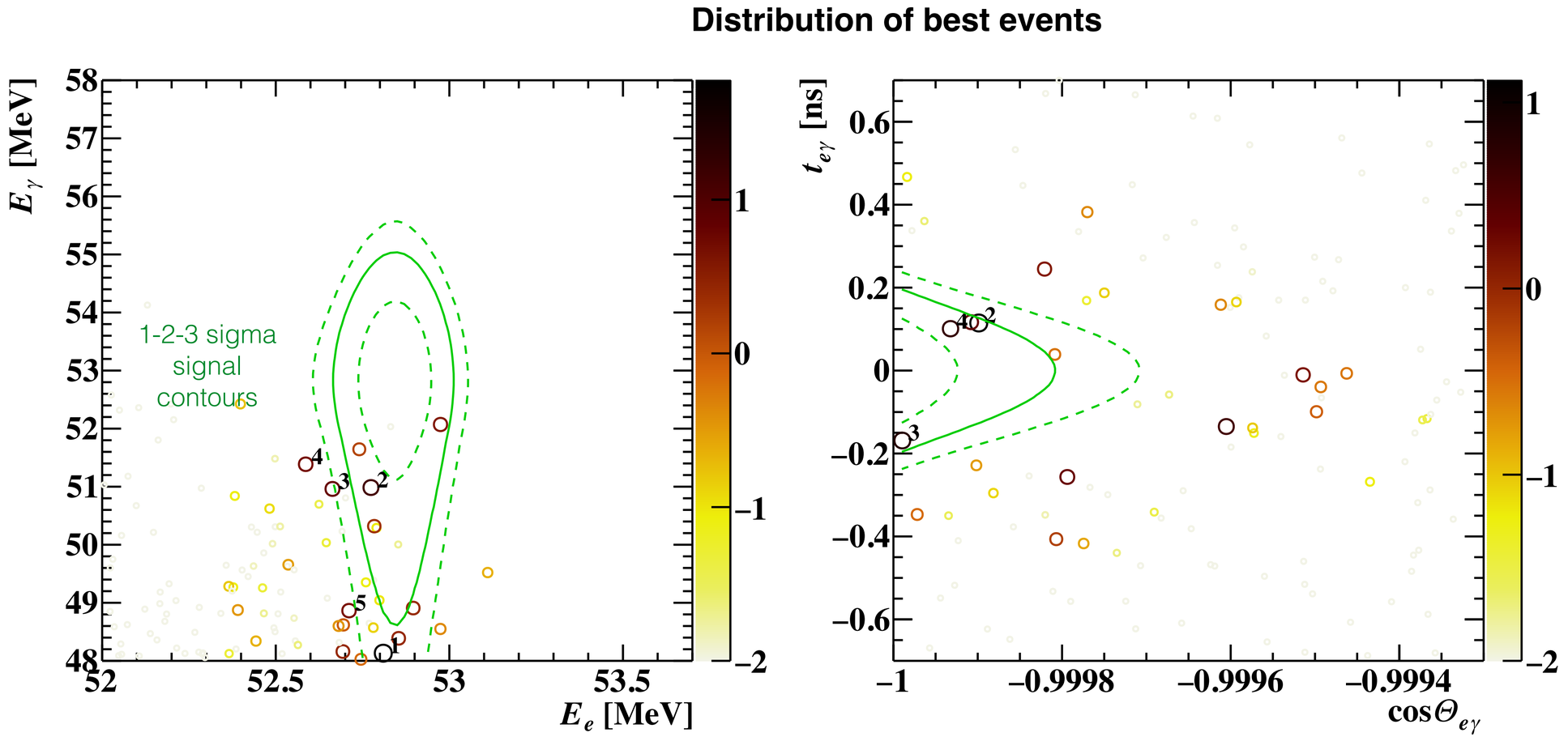
With positive constraint:

$$N_{sig} = 0.00 \pm 0.73, N_{Acc} = 360.94 \pm 8.85, N_{RMD} = 9.67 \pm 1.60$$

compatible with expectations from sidebands

$BR(\mu \to e\gamma) < 1.5 \cdot 10^{-13}$ @90%CL

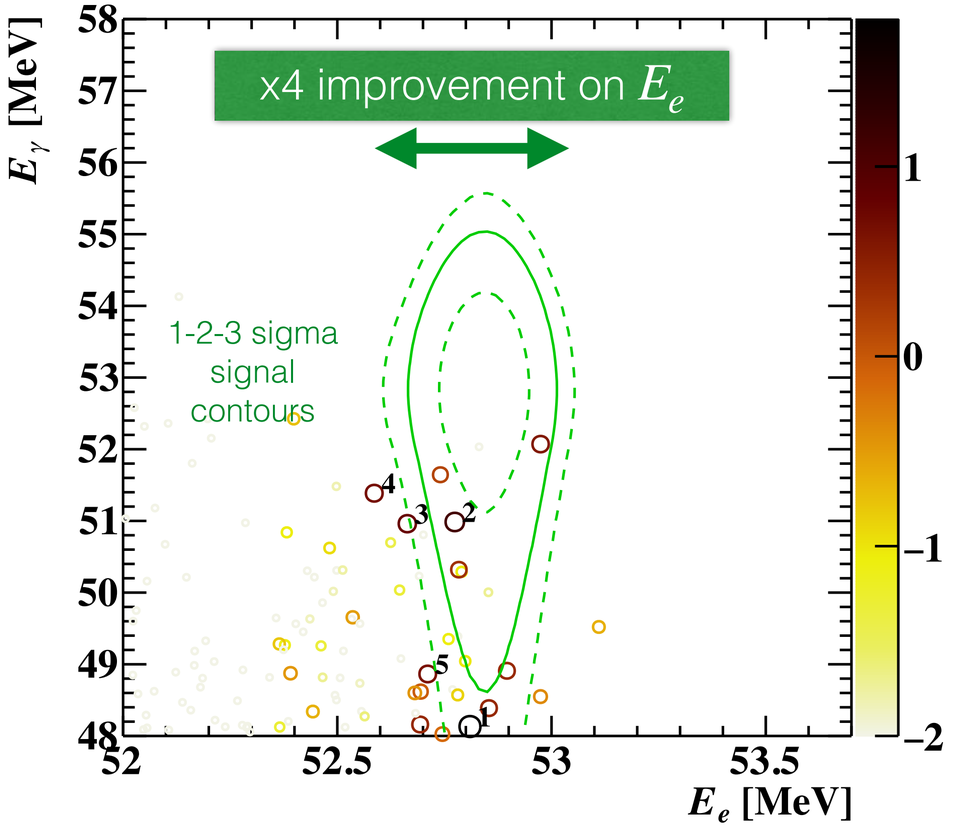
Ranked events

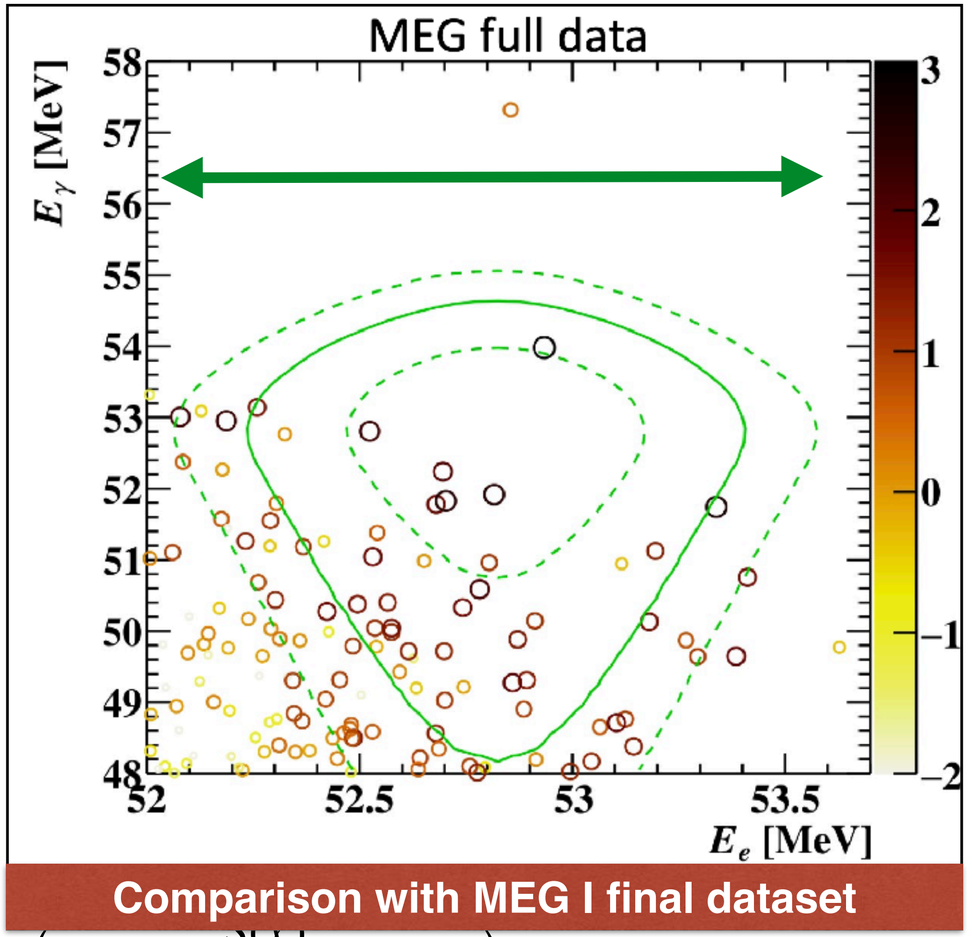


Ranked by $R_{sig} = \log_{10}\left(\frac{S(\vec{x})}{f_{RMD}R(\vec{x}) + f_{ACC}A(\vec{x})}\right)$

Ranked events

Distribution of best events



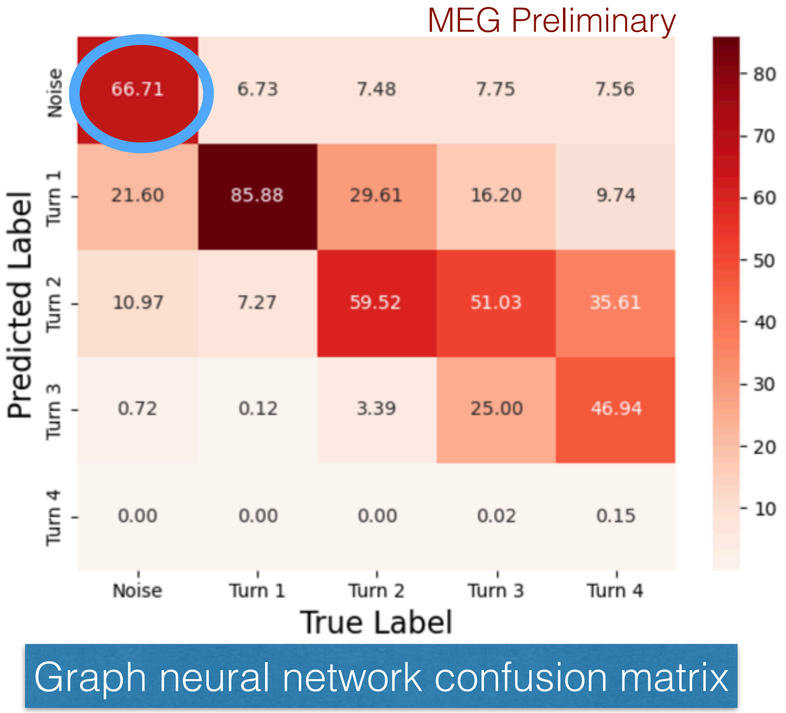


Comparison with MEG I final dataset

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

Analysis improvements

Since publication of 2021+2022 efforts focussed on **improving reconstruction**
Mainly through **ML algorithms**, example on **CDCH track** recognition:

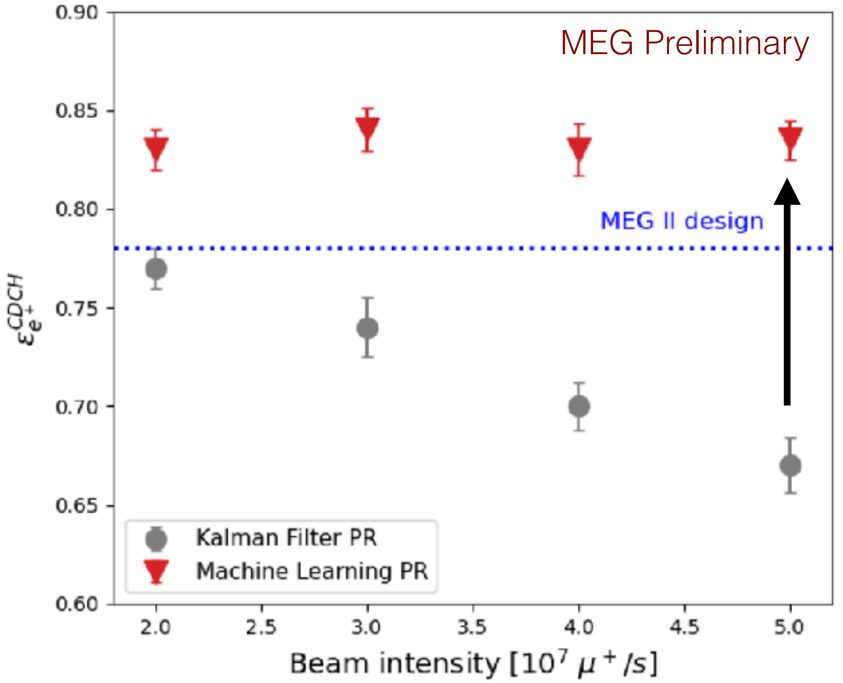


Graph neural network confusion matrix

Same Kaman Filter for track seeding but reduce the noise by ML tagging

Both **GNN** and **Transformer** implemented and combined to identify candidates

Default pattern recognition for next reprocessing

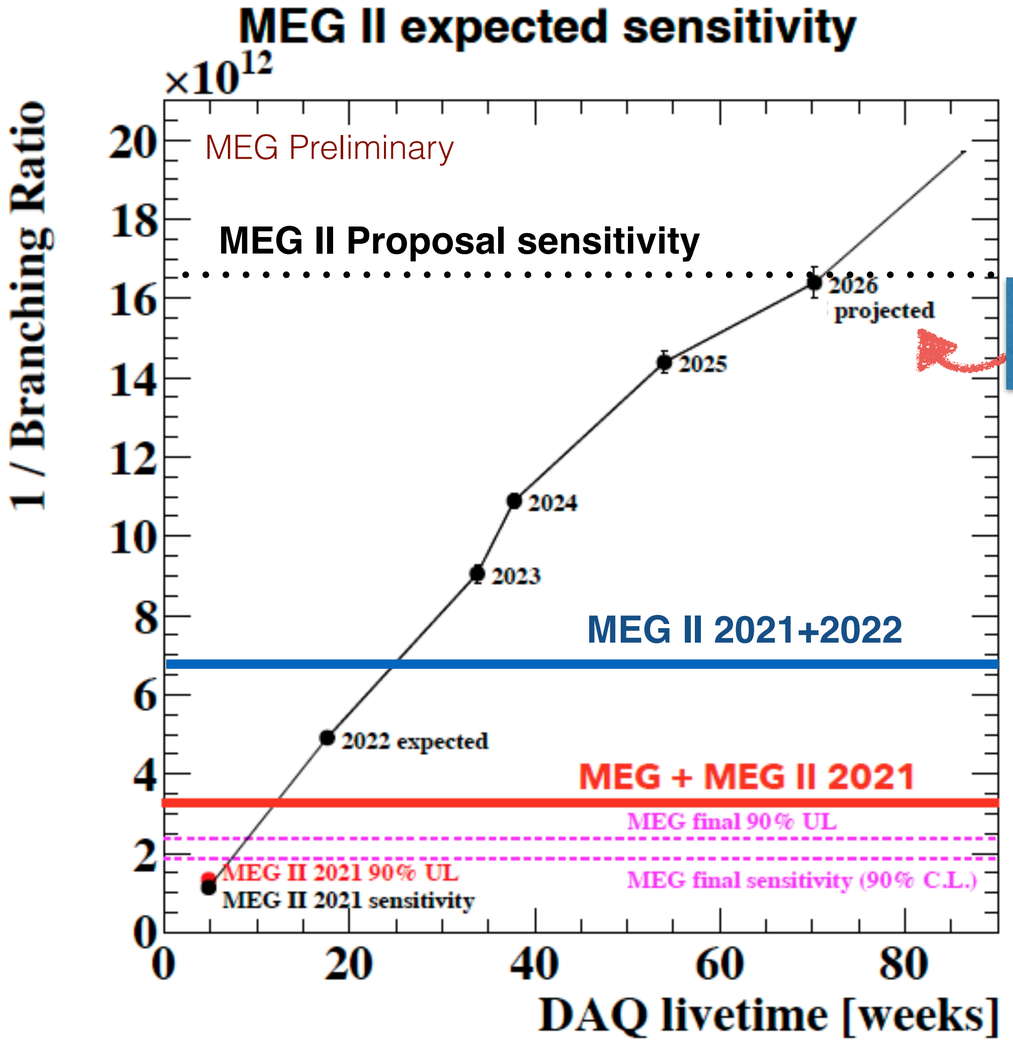


Results, just on CDCH side:

- 10% increment in already taken data
- Since 2024 R_μ increased to $5 \cdot 10^7 \mu/s$ (DAQ max)

Similar studies ongoing for the LXe
Two contributions on Wednesday at Calorimeter section

Sensitivity projection for the full dataset



2021+2022 sensitivity estimate with larger datasets

does not include analysis improvements nor detector performance degradations

Might be less, only fraction of requested time was granted

Sensitivity scales with inverse of DAQ time:

MEG II analysis is expected to remain background free

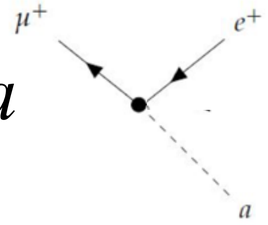
Expects to reach the experiment sensitivity goal of $6 \cdot 10^{-14}$ by the end of this year run (next week!)

Not only $\mu \to e\gamma$: dark sector physics searches

Investigating a new EFT including a **neutral scalar particle** a

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{\partial_\mu a}{2f_a}\bar{e}\gamma^\mu(C_V + C_A\gamma^5)\mu + h.c.$$

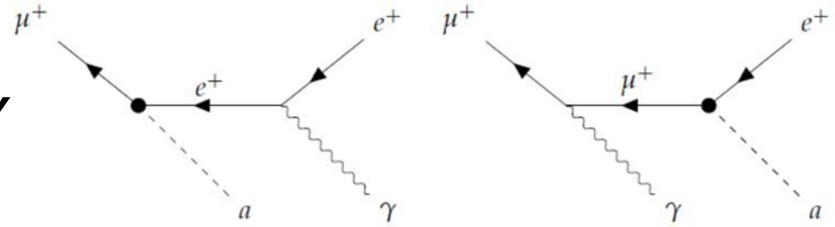
$\mu^+ \to e^+ a$



Signature:
monochromatic e^+

To be identified on top of $\mu \to e\nu\bar{\nu}$
MEG II not competitive with upper limit by TWIST experiment

$\mu^+ \to e^+ a\gamma$



Signature:
$e^+ - \gamma$ pair + missing energy

Main source of background is $\mu \to e\nu\bar{\nu}\gamma$

Dedicated data taking to increase acceptance:

- Lower E_γ cut
- Remove Direction Match
- Reduce beam intensity

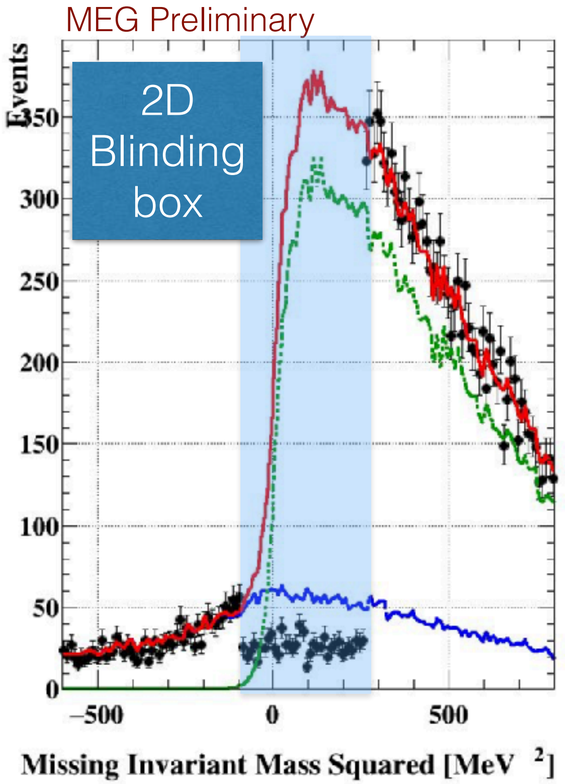
Much lower direct upper limit by CrystalBox experiment

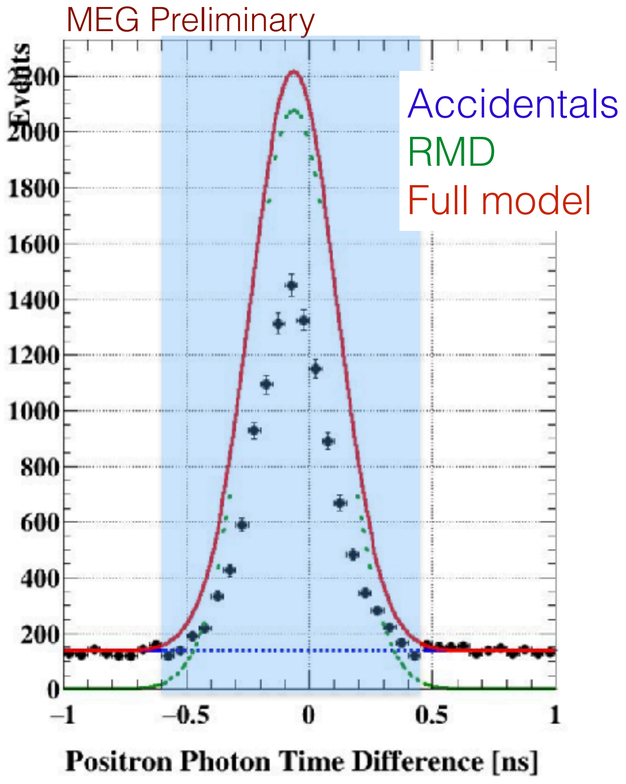
Not discussed here:

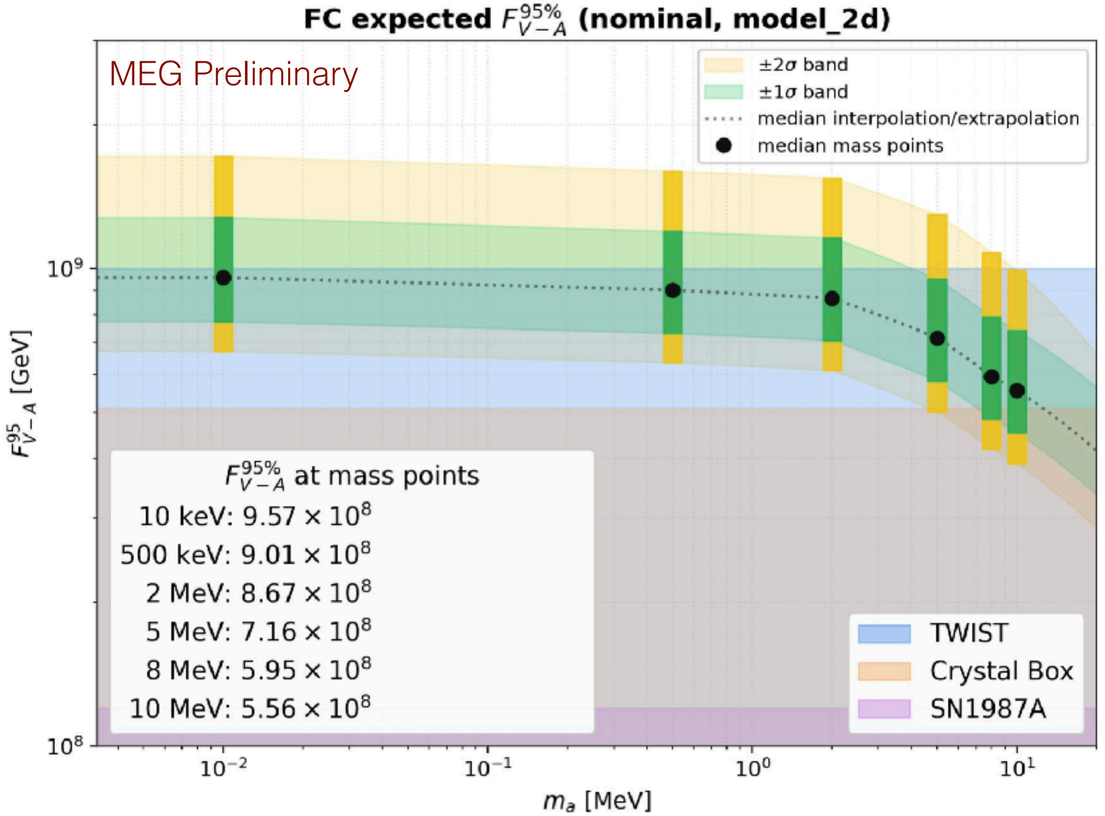
$\mu^+ \to e^+\chi\bar{\chi}$ with a massive neutral fermion χ

$\mu \rightarrow e a \gamma$ sensitivities

Analysis strategy: 2D fit in $m^2_{miss} - T_{e\gamma}$ plane



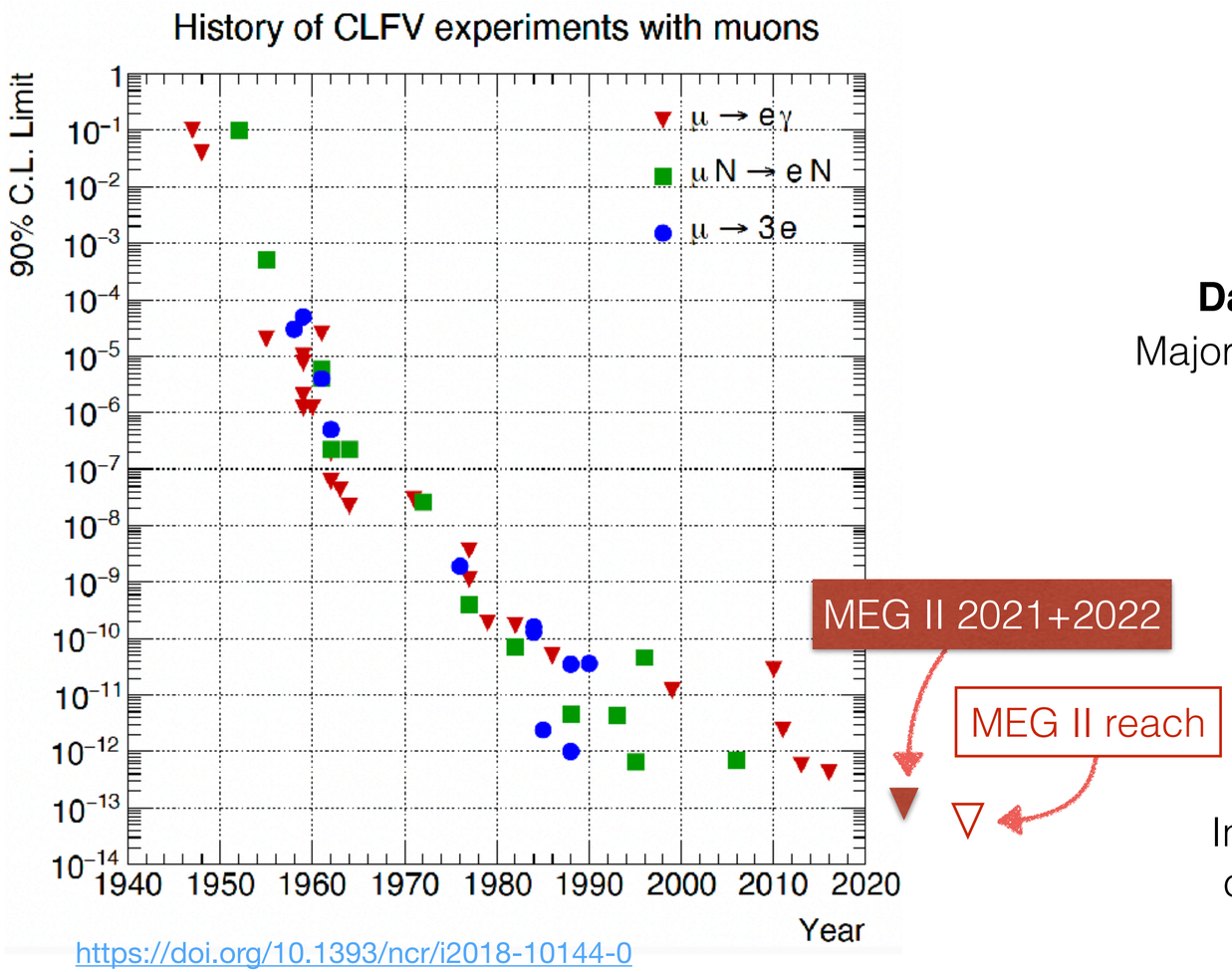




Using low-intensity datasets, improve on CrystalBox and competitive with TWIST upper limit

Analysis spinoff: measurement of $\mu \rightarrow e\nu\bar{\nu}\gamma$ down to $E_\gamma \geq 10\ MeV$

Conclusions



https://doi.org/10.1393/ncr/i2018-10144-0

MEG II set the **most stringent upper limit on a CLFV process** using 2021+2022 datasets:

$BR(\mu \to e\gamma) < 1.5 \cdot 10^{-13}$ @90%CL

with a sensitivity of $2.2 \cdot 10^{-13}$

Data collections ends this month, with ~ x4 dataset

Major developments in software to profit from ML techniques

Goal sensitivity of $6 \cdot 10^{-14}$ in reach!

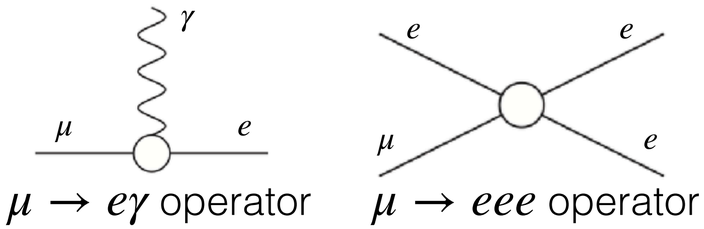
"Exotic" physics channels being investigated, stay tuned!

In parallel, efforts in R&D for a future $\mu \to e\gamma$ experiment capable to exploit the new high intensity facilities being constructed

Backup

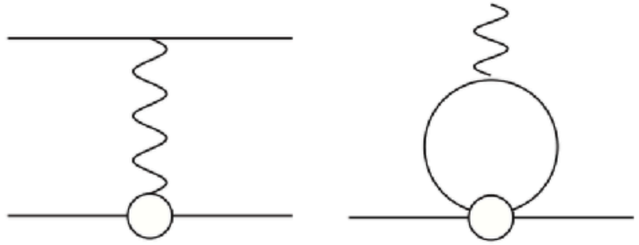
Measurements and physics reach

Measurement predictions mix several operators



$\mu \to e\gamma$ operator $\mu \to eee$ operator

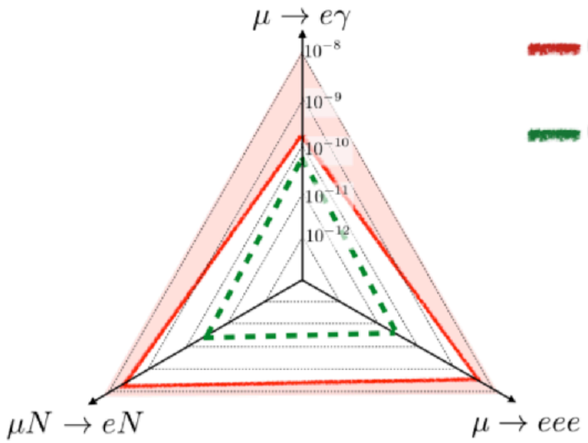
through loop diagrams



Effective field theory is used to compare all BSM operators $O_\alpha^{(n)}$ with dimensions $n \geq 5$

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{\Lambda}\sum_\alpha C_\alpha^{(5)} O_\alpha^{(5)} + \frac{1}{\Lambda^2}\sum_\alpha C_\alpha^{(6)} O_\alpha^{(6)} + \dots$$

For a fixed Λ (1TeV), constraints the strength of a particular operator



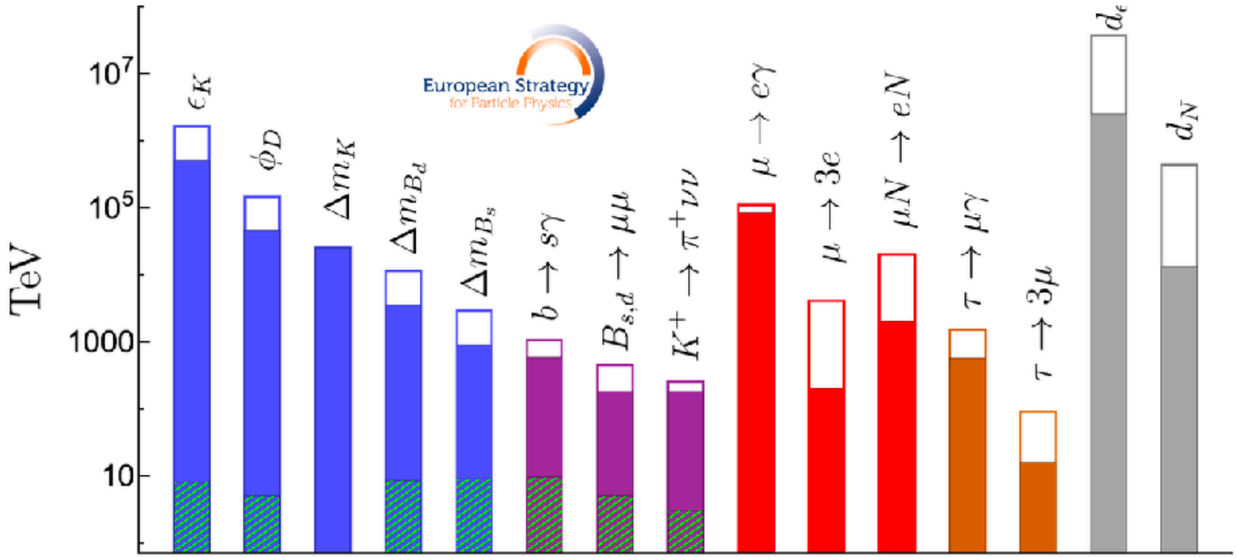
$C_{e\gamma}^{\mu e}$ from present limits

$C_{e\gamma}^{\mu e}$ from future experiments

Multiple channels are needed to identify the source in case of observation

https://doi.org/10.1393/ncr/i2018-10144-0

Setting $C_\alpha = 1$ gives the exploitable scale of new physics Λ

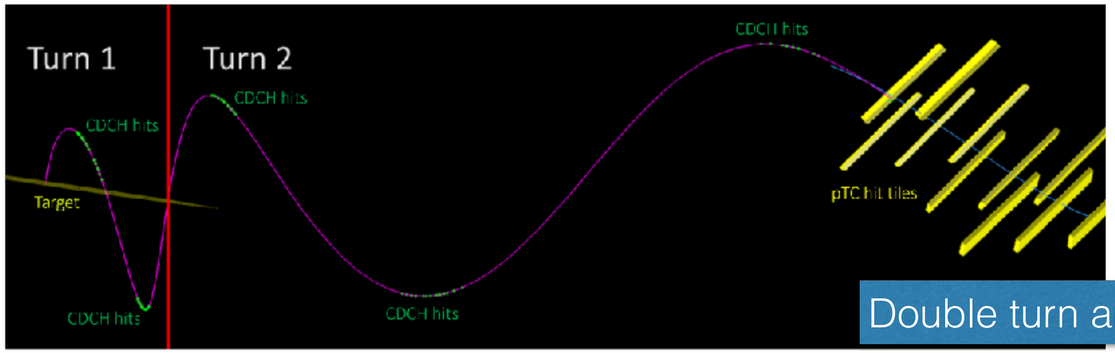


https://doi.org/10.17181/CERN.35CH.2O2P

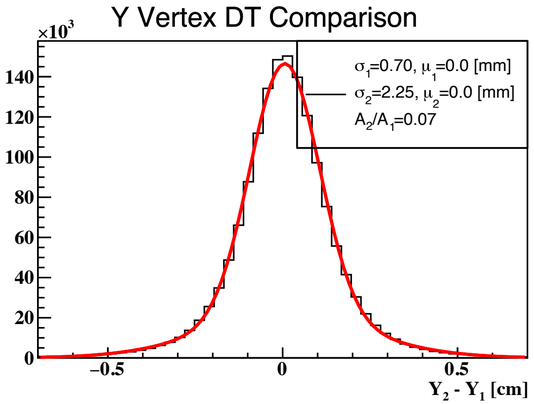
Detector performances (e^+)

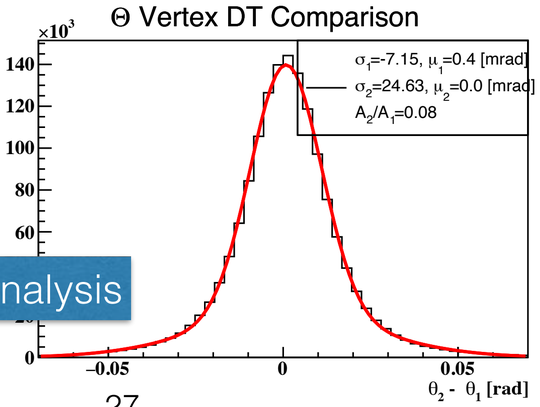
After lots of problems on drift chamber, reached design resolutions:

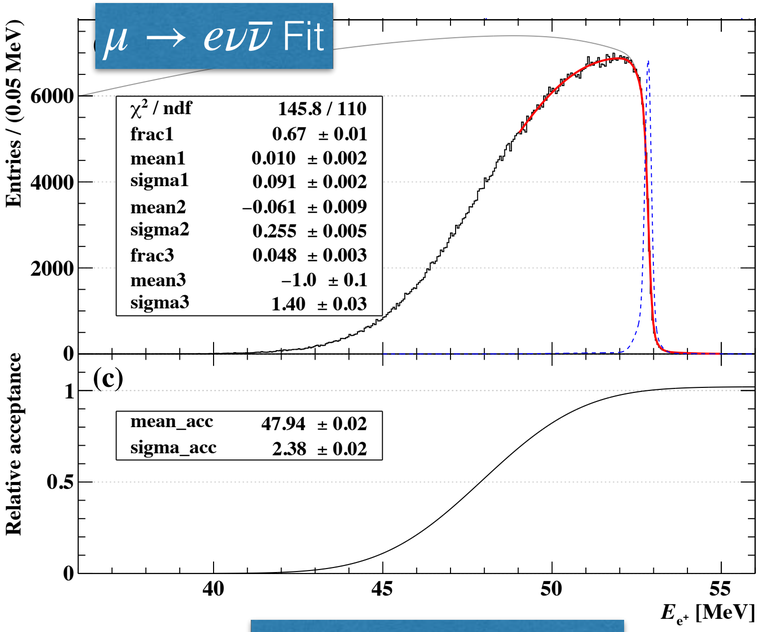
- Single hit resolution ~ $160\ \mu\mathrm{m}$
- Fit of $\mu \to e\nu\bar{\nu}$
  - E_e **resolution,** $84\ \mathrm{keV}$ (core)
  - Spectrometer acceptance
  - Momentum scale
- Double Turn analysis
  - **Angular resolutions**
    $\sigma(\phi_e) = 5.3\ \mathrm{mrad}$, $\sigma(\theta_e) = 6.3\ \mathrm{mrad}$
- **Track timing**
  - Single counter resolution $112\ \mathrm{ps}$
  - Combining ~10 hits $\sigma(T_e) = 43\ \mathrm{ps}$

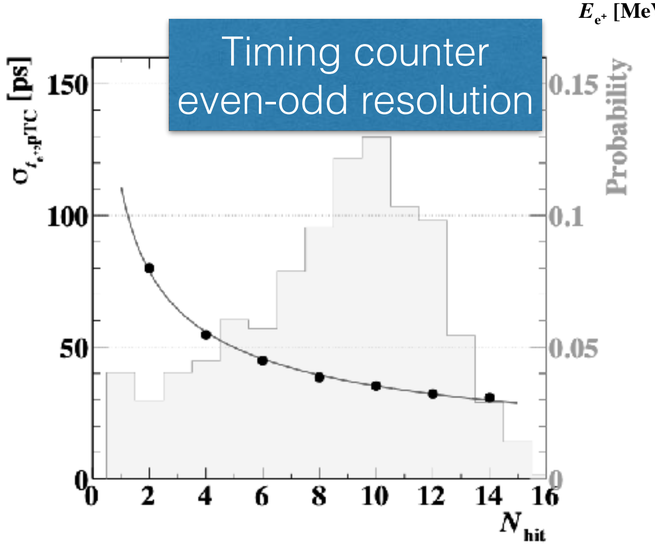


Double turn analysis



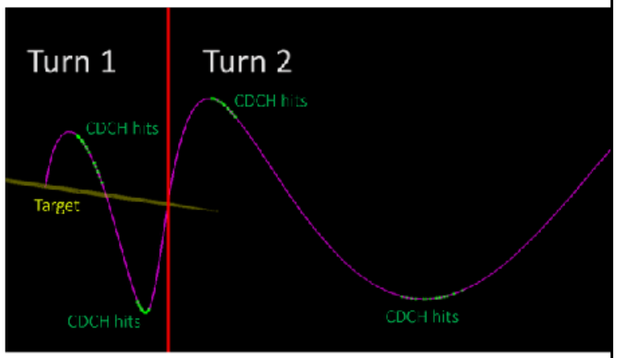


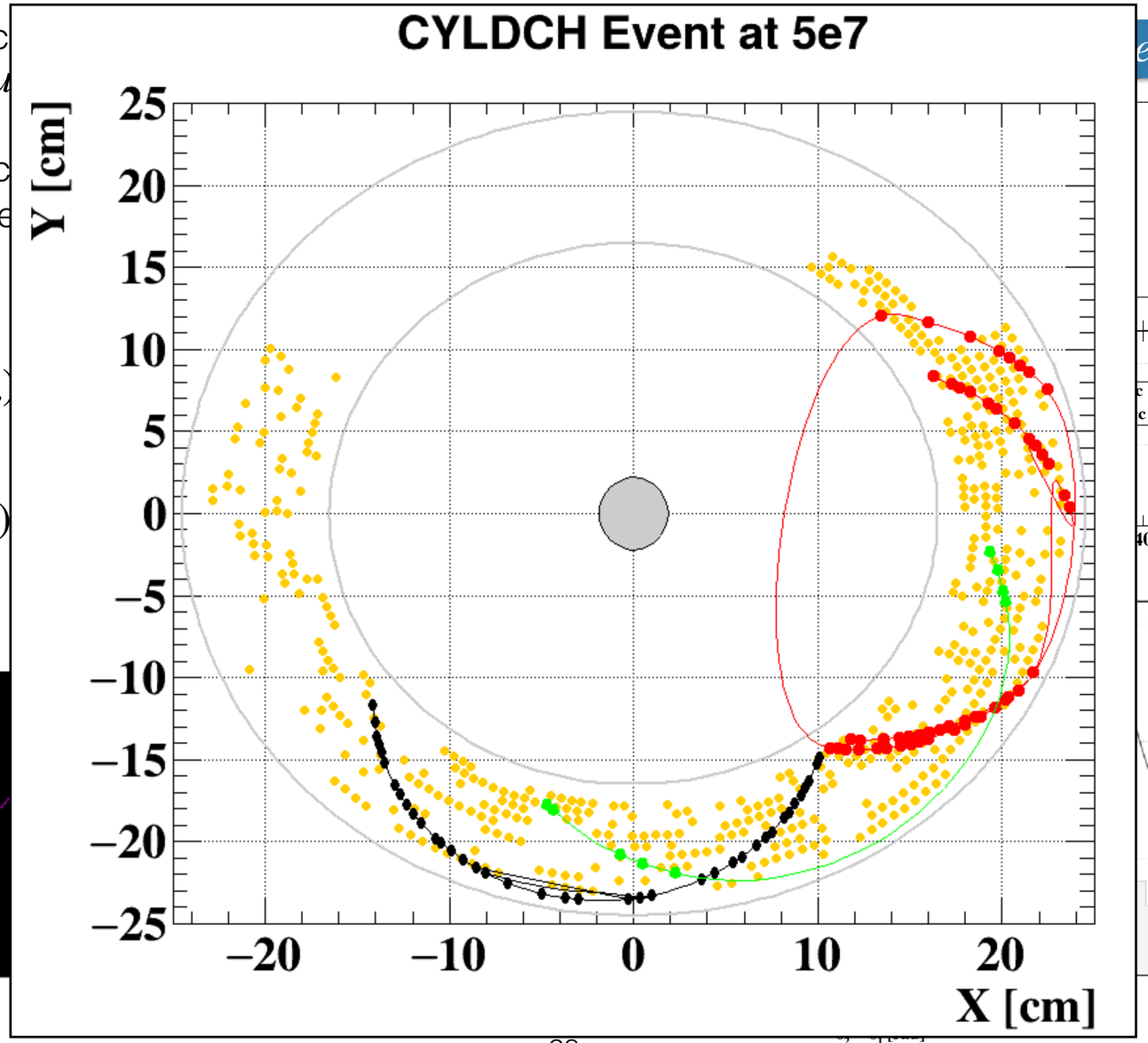


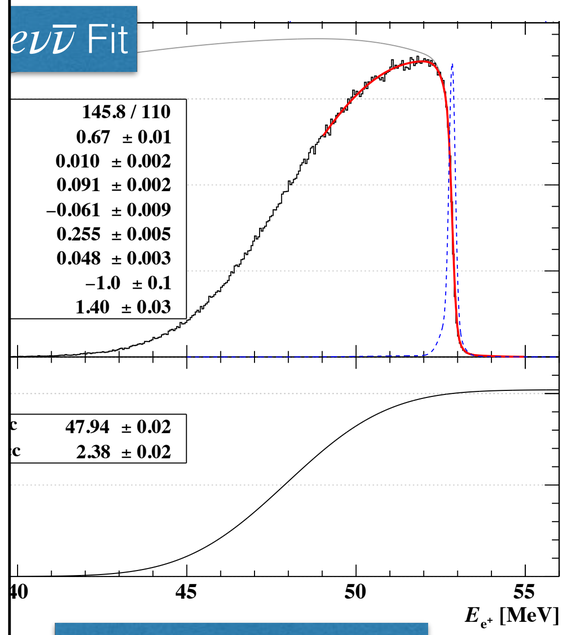


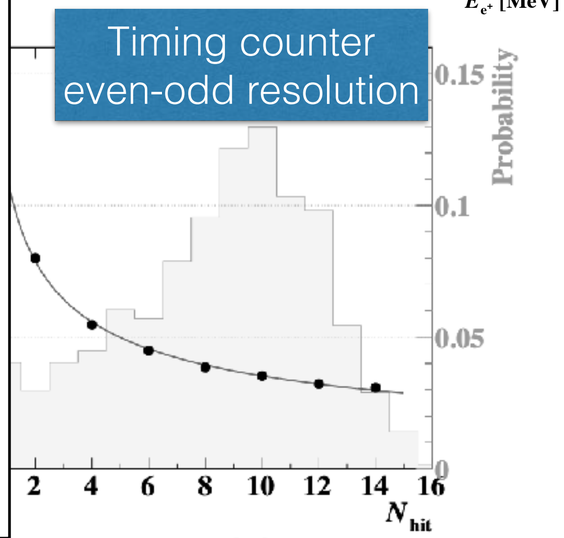
Detector performances (e^+)

After lots of problems on drift c
- Single hit resolution ~ 160 μ
- Fit of $\mu \to e\nu\bar{\nu}$
  - E_e **resolution,** 84 keV (c
  - Spectrometer acceptance
  - Momentum scale
- Double Turn analysis
  - **Angular resolutions**
    $\sigma(\phi_e) = 5.3$ mrad, $\sigma(\theta_e$
- **Track timing**
  - Single counter resolution
  - Combining ~10 hits $\sigma(T_e)$





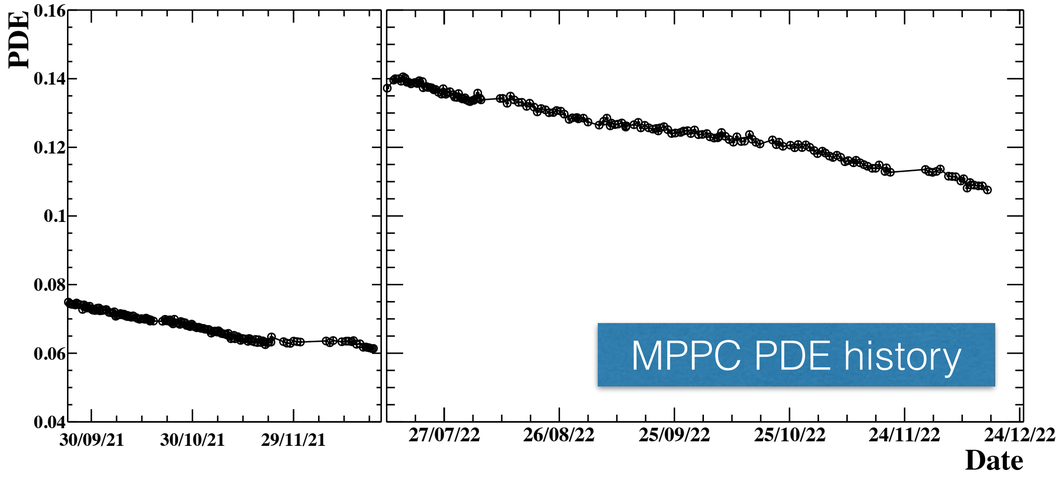


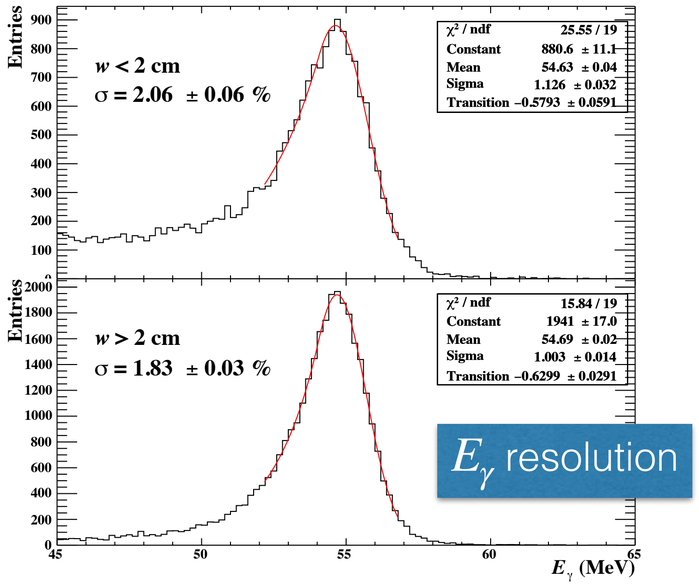


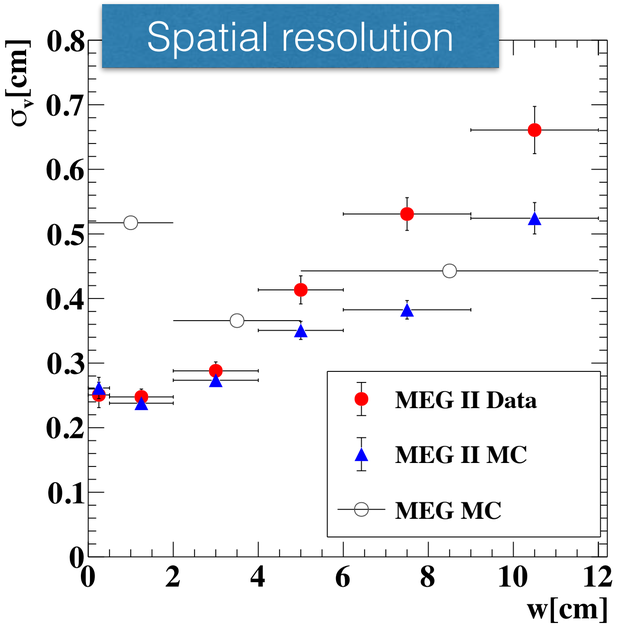
Detector performances (γ)

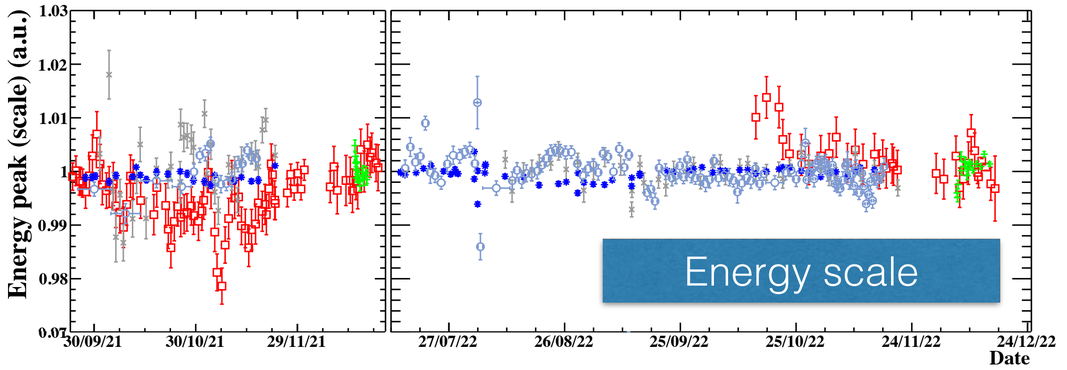
Performances affected by photosensors PDE decrease

- Annealing partially recovers
  - closely followed by **calibration tools**
- E_γ **resolution 1.9-2.4%** @52.8MeV
  - measured yearly with pion charge exchange reaction
  - depending on conversion depth
- **Spatial resolution** ~ 2.5 mm
  - dedicated data taking with collimator
  - big improvement for shallow events w.r.t. MEG I PMTs









Calorimeter calibration tools

3/week

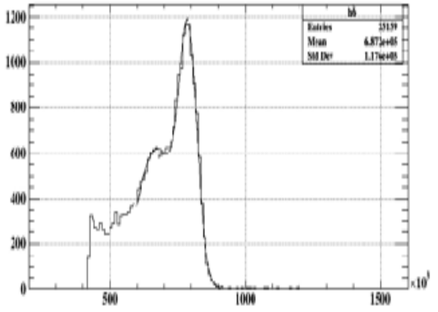


Cockroft-Walton proton accelerator

up to 1MeV on $LiBO_4$ target

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

energy calibration line &
uniformity monitoring



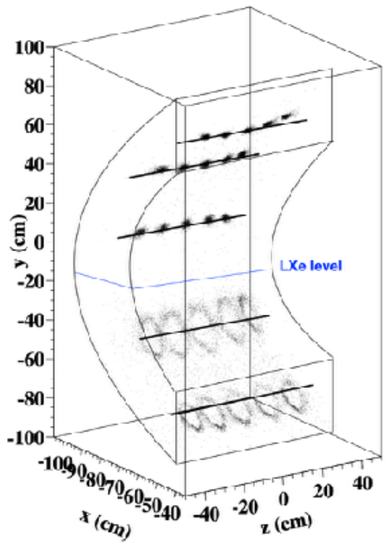
Other calibrations

- LED
- AmBe $\gamma(4.4\ MeV)$
- Neutron-Nickel $\gamma(9\ MeV)$
- Cosmics
- Collimated ${}^{60}Co$ X-Ray source

Daily

α-particle sources in LXe

lattice of 25 sources at known locations



Very localised deposit (range= $40\ \mu m$)

Calibration of photosensors QE



1/year

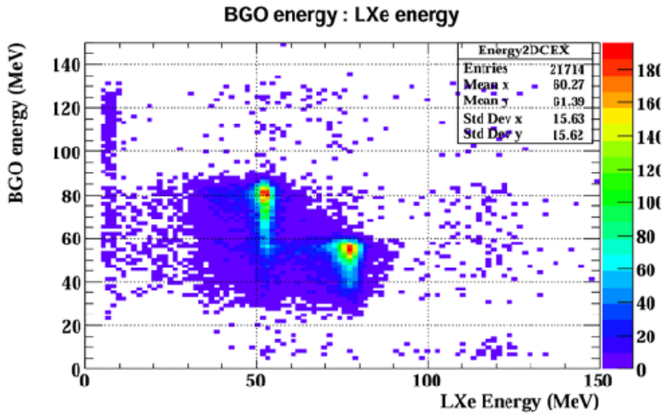
Charge exchange reaction

π^- beam on LH_2 target

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

π^0 production by capture at rest

$55 - 92\ MeV$ photons



Back-to back selection with ancillary calorimeter

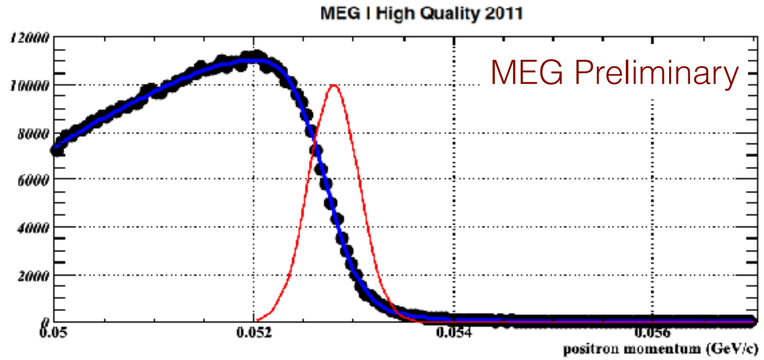
"Monocromatic" $55\ MeV$ photons

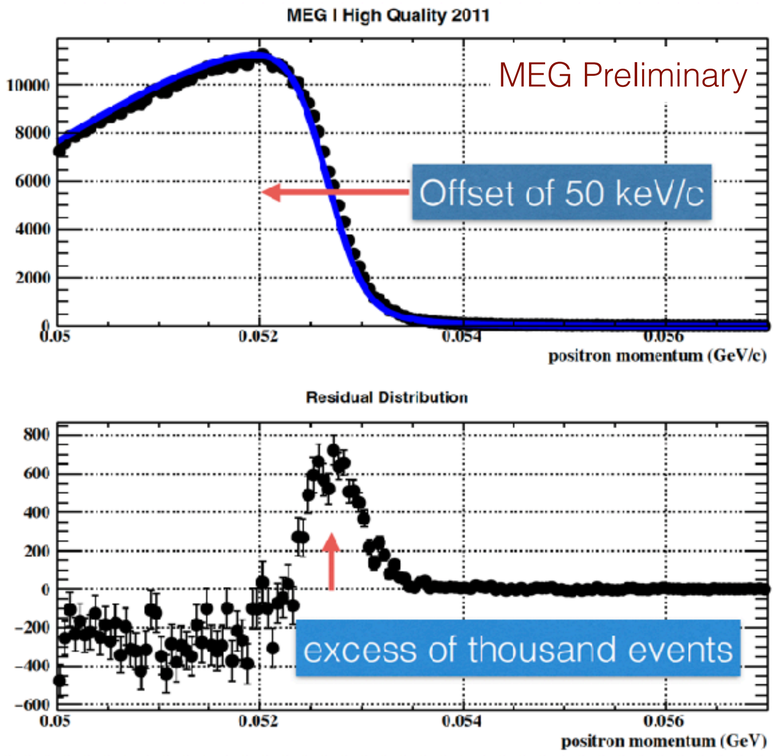


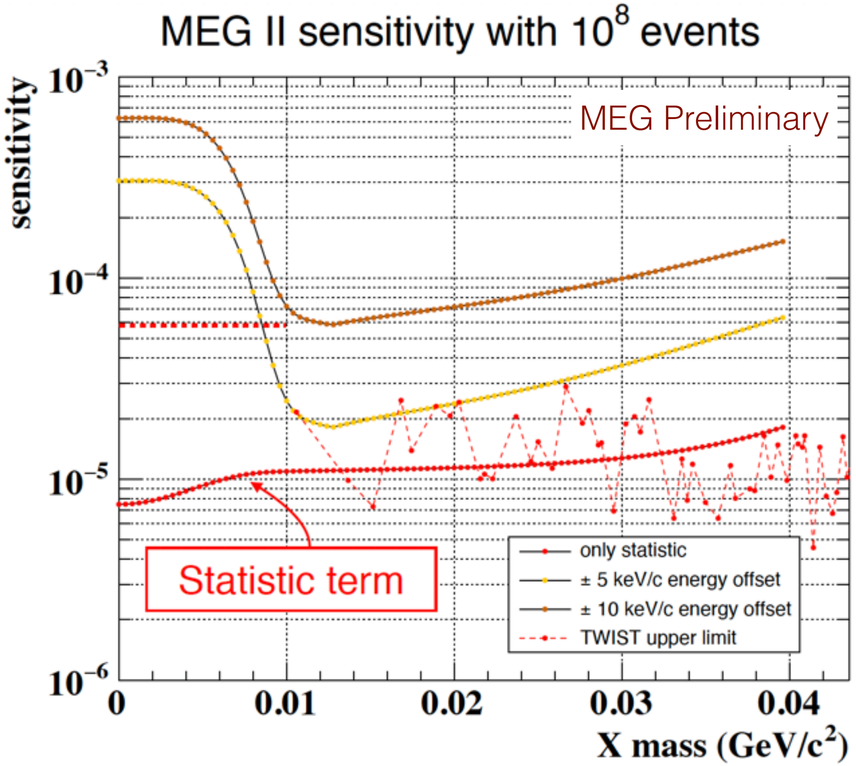
$\mu \to ea$ sensitivities

Signal: monochromatic positron, approaching $\mu \to e\gamma$ energy when $m_a \ll m_\mu$

Measurement limited by precision of kinematic endpoint





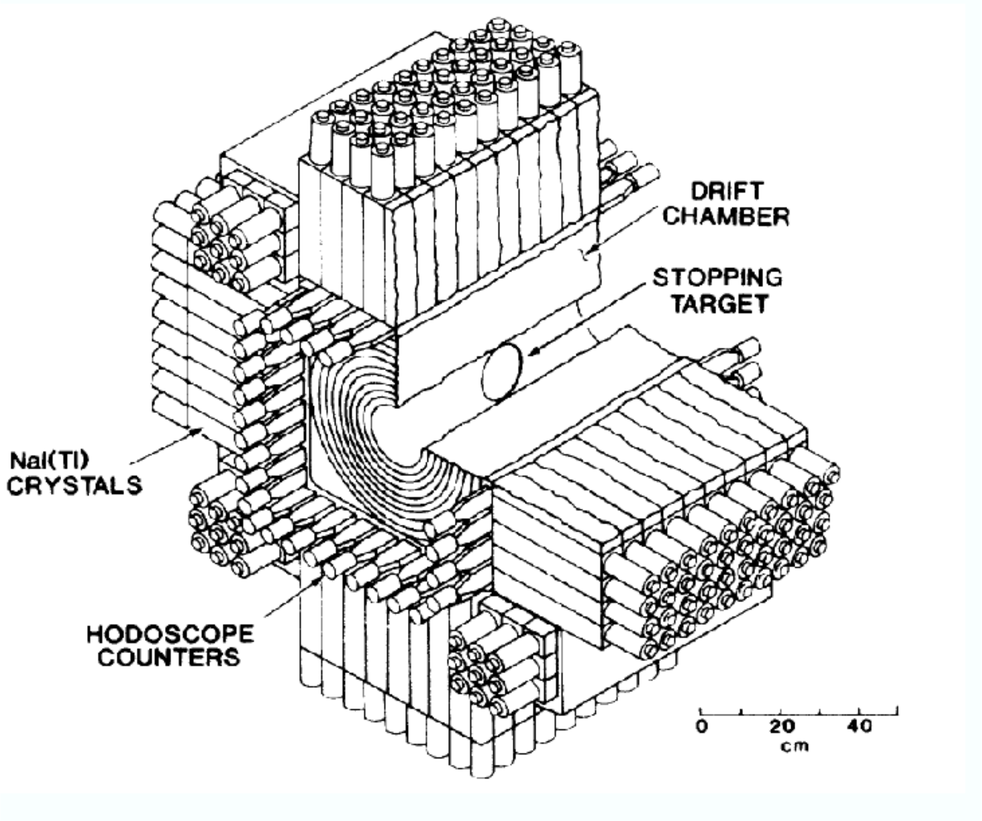


Not competitive with TWIST upper limit

Two ways to detect photons

Crystalbox Experiment @LAMPF (1988)

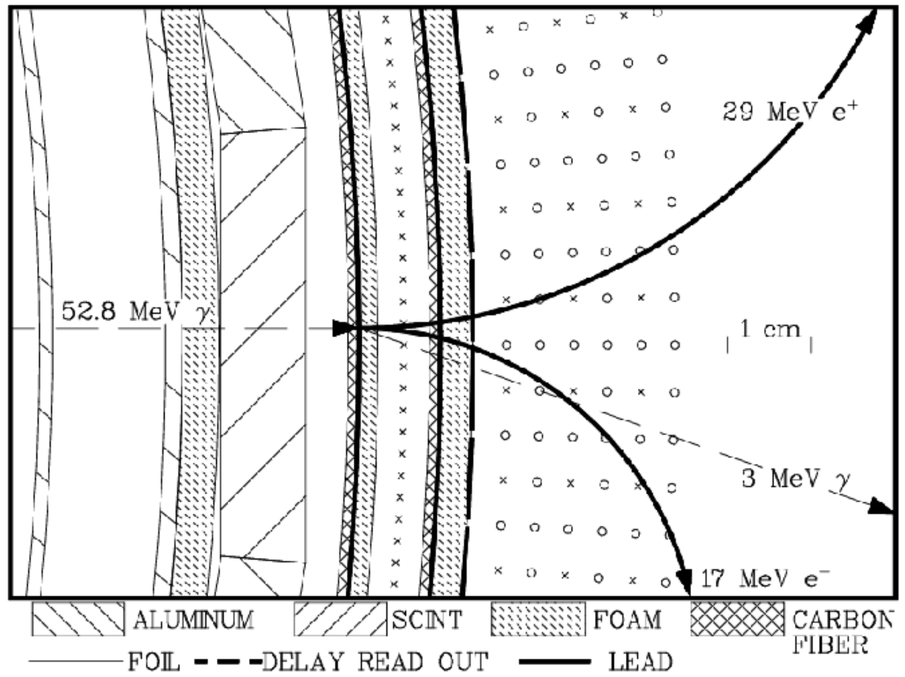
Calorimetria con cristalli NaI, nessun campo magnetico



$$BR(\mu \to e\gamma) \leq 4.9 \cdot 10^{-11}$$

MEGA @LAMPF (2001)

Conversione coppia + spettrometro



$$BR(\mu \to e\gamma) \leq 1{,}2 \cdot 10^{-11}$$

References

Calibbi, Signorelli, **Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction,** https://arxiv.org/pdf/1709.00294
EPPS update, ***group,*** **Physics Briefing Book,** https://arxiv.org/abs/2511.03883
Luca Galli talks, **GGI School Theory meets experiment: "the high intensity frontier of particle physics"**, https://www.ggi.infn.it/showevent.pl?id=464

The MEG Collaboration, **The design of the MEG II experiment**, https://arxiv.org/pdf/1801.04688
The MEG Collaboration, **Operation and performance of the MEG II detector**, https://arxiv.org/pdf/2310.11902
The MEG Collaboration, **New limit on the μ+→e+γ decay with the MEG II experiment**, https://arxiv.org/pdf/2504.15711

L.Dispoto et al, **Transformer-based approach to enhance positron tracking performance in MEG II,** https://arxiv.org/abs/2512.19482
A.Venturnini, **The MEG II Drift Chamber and the Search for Rare Muon Decays: Performance and Implications for Recent Experimental Results,** *PhD thesis,* https://etd.adm.unipi.it/t/etd-04072026-222514/
A.Grandonii, **Probing CLFV ALPs with the MEG2 experiment,** *ICHEP 2026 Conference, https://indico.cern.ch/event/1522800/contributions/6982926/attachments/3322115/5948000/ICHEP2026.pdf*

The study group for future $\mu^+ \to e^+\gamma$ *experiments*, **Letter Of Intent for a future** $\mu \to e\gamma$ **experiment at the High Intensity Muon Beam facility at PSI**, https://arxiv.org/abs/2504.18831

Andrè Schöning, **Status of the Mu3e Experiment**, *BVR57 PSI user meeting,* https://indico.psi.ch/event/17196/contributions/61397/attachments/32888/66440/Mu3e_BVR57_2026.pdf
Tomasi Kar, **The Mu3e Experiment**, *CLFV 2026 conference,* https://agenda.infn.it/event/49750/contributions/293657/attachments/151679/232335/TkarRome.pdf