First MEG II results

NuFact 2024 - The 25th international workshop on Neutrinos from Accelerators

September 16th - 21st, 2024, Argonne National Laboratories

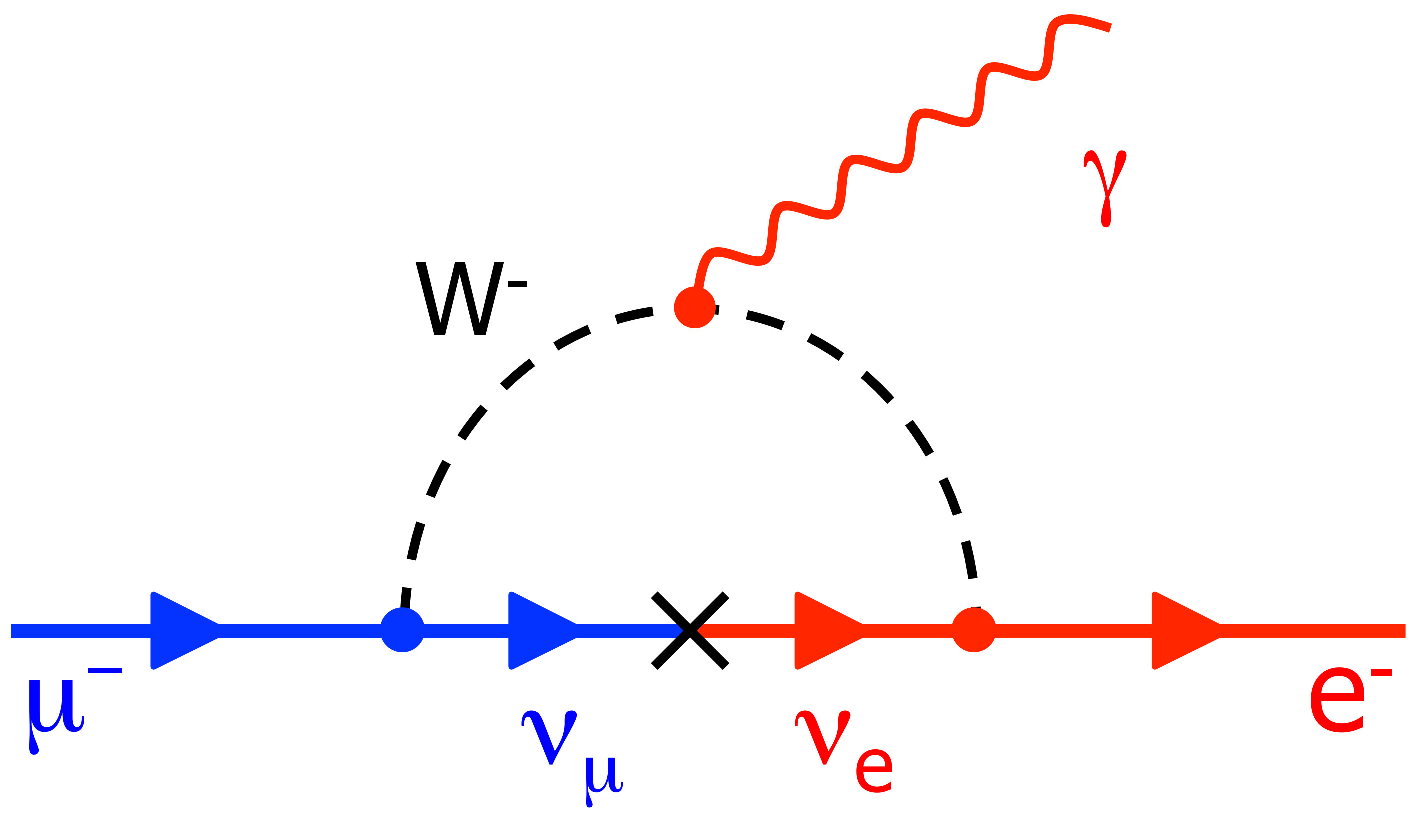
Matteo De Gerone - INFN Genova

Outline

- Why we are looking for $\mu\to e\gamma$ decay?
- The MEG II experiment: signal, background and experimental apparatus
- First results from MEG II
- Status and prospects

Intro: cLFV processes in muon decay

- In Standard Model even including ν oscillations charged Lepton Flavor Violating rates are expected to be too small to be observed.
  - As an example, $\mu \to e\gamma$ decay could be induced radiatively by neutrino mixing, but at a negligible level:



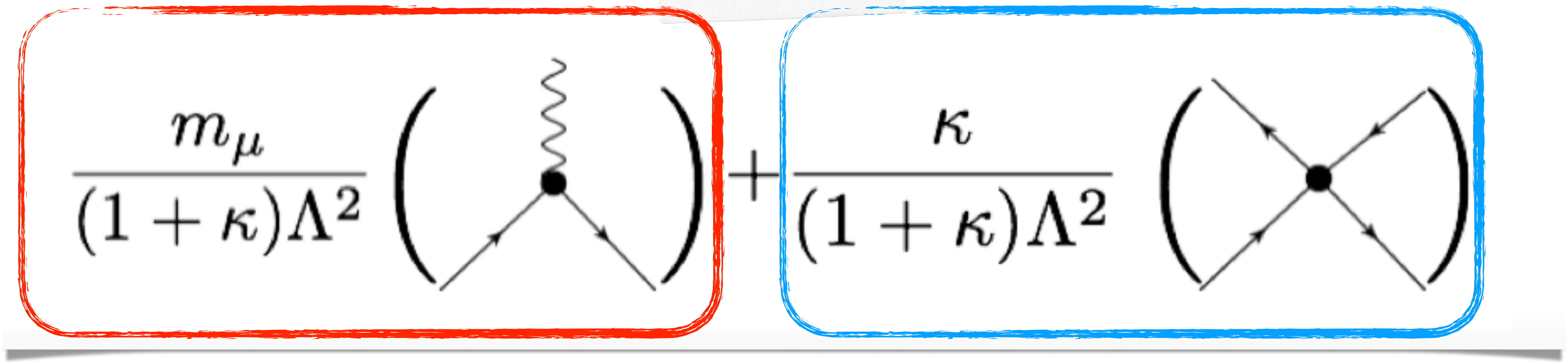
$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M_W^2}\right|^2 \simeq 10^{-52}$$

- Observation of a such a decay would be a clear indication of **New Physics**.
- A search motivated by many models Beyond Standard Model (SUSY, GUT…) which predict BR at measurable level (10^{-13} / 10^{-14}).

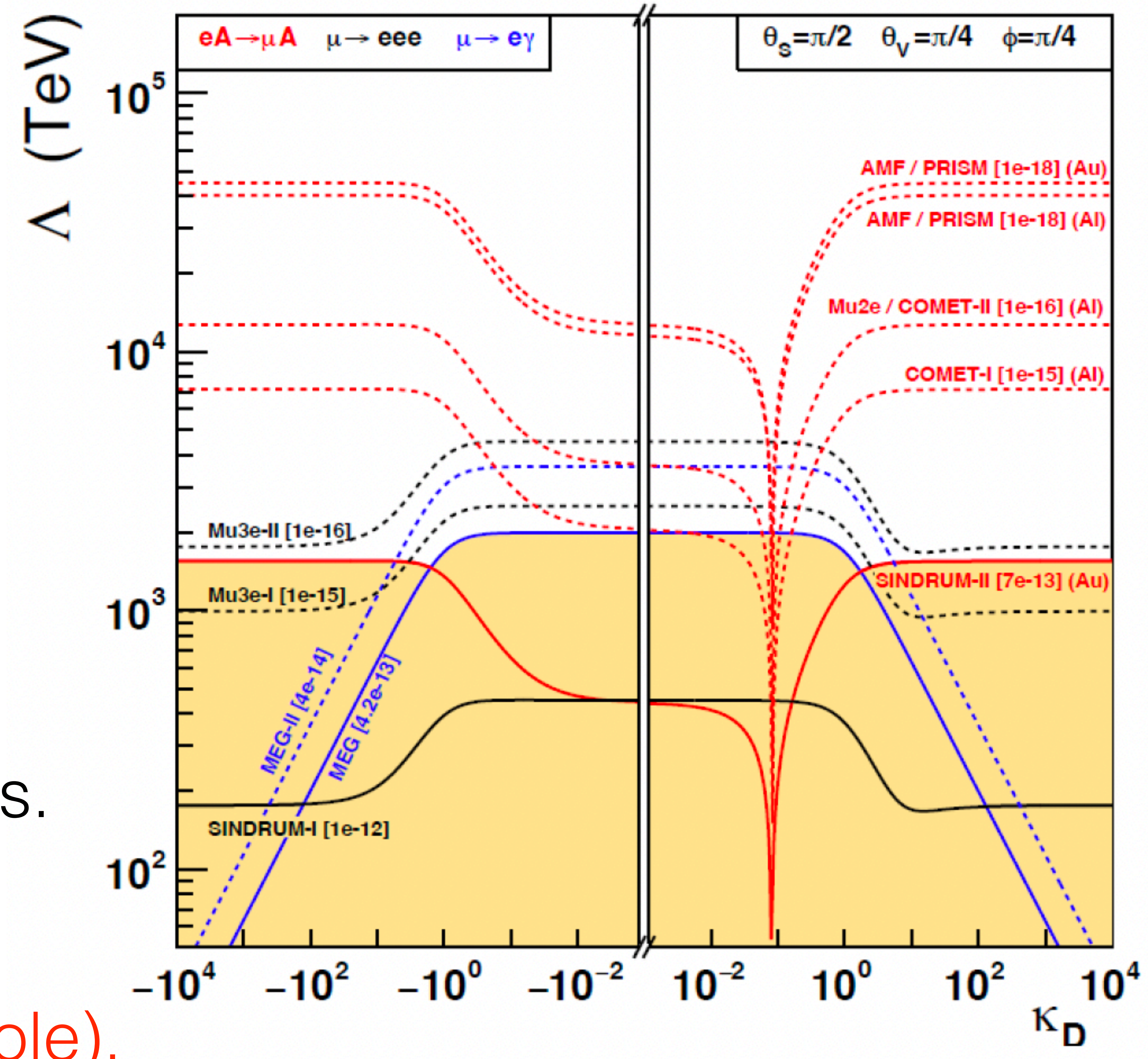
Why μ channel is a golden one?

- No background from SM processes.
- Very high intensities low energy muon beam are now available at meson factories and proton accelerators.
- μ life time allows for long beam transport.
- μ decays show simple kinematics with a clear signature (in a huge background).
  - 3 main channels:
    - **$\mu^+ \rightarrow e^+\gamma$**
    - $\mu^+ \rightarrow e^+e^+e^-$
    - $\mu^-N \rightarrow e^-N$ conversion
- All these channels should be (and they are) investigated, because there is a **strong complementarity** among them…

μ→e cLFV transition process: complementarity



- **Effective Lagrangian** as a function of new physics energy scale **Λ.**
- Contributions could come from:
  - **dipole transition like term** and
  - **4-fermion interaction like term.**
- Factor κ takes into account the weight of each terms.
- Depending on κ value, different channels will be enhanced.
- As an example, μ→eγ probe the k << 1 region (dipole), while μN→eN is (also) sensitive to 4 fermion operator…



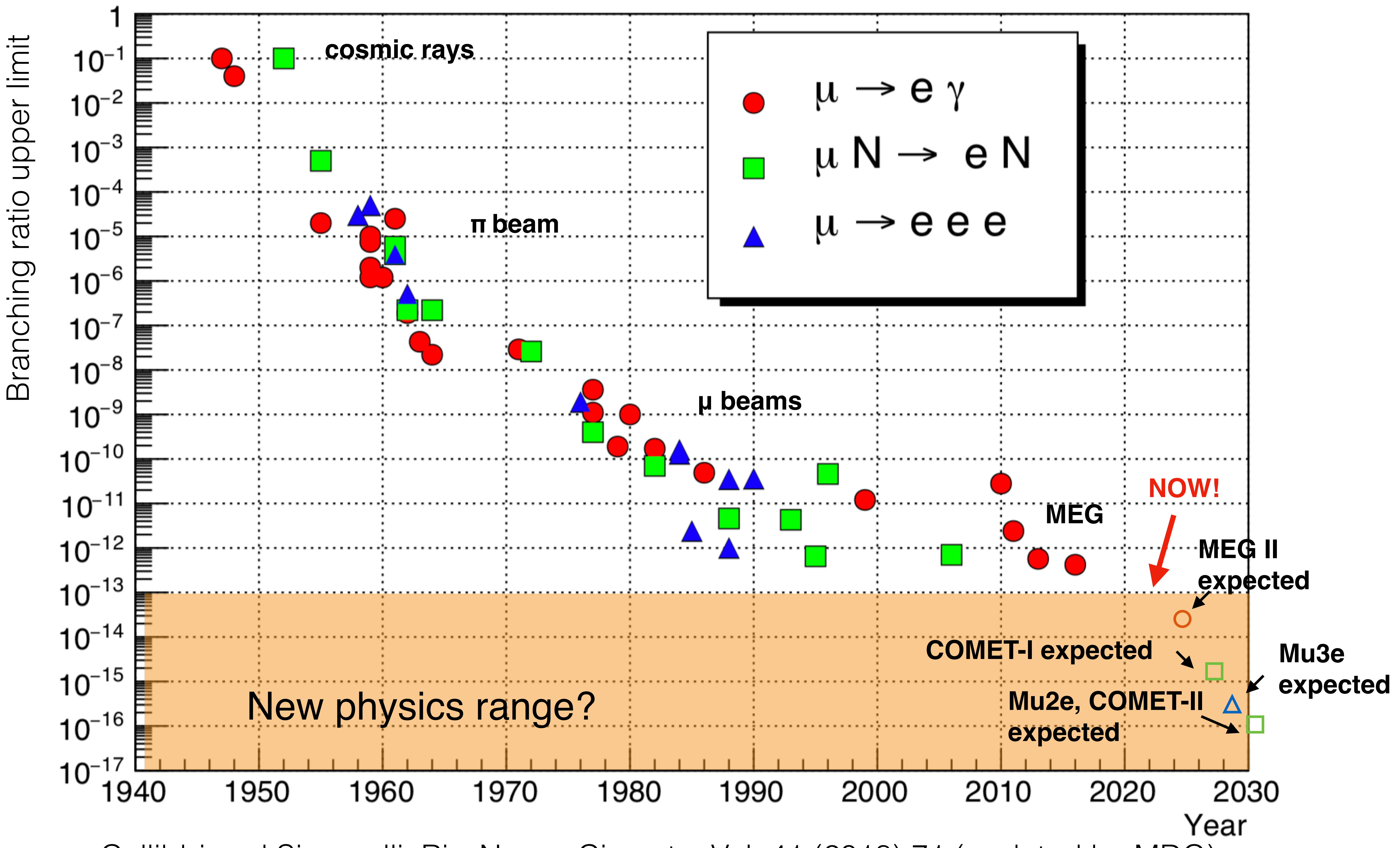
De Gouvea and Vogel, Prog. Part. Nuc. Phys. 71 (2013) 75-92

S. Davidson and B. Echenard, Eur. Phys. J. C 82 (2022) 9, 836

A closer look at the current experimental status

μ cLFV decays search is a more than 70 years long quest…

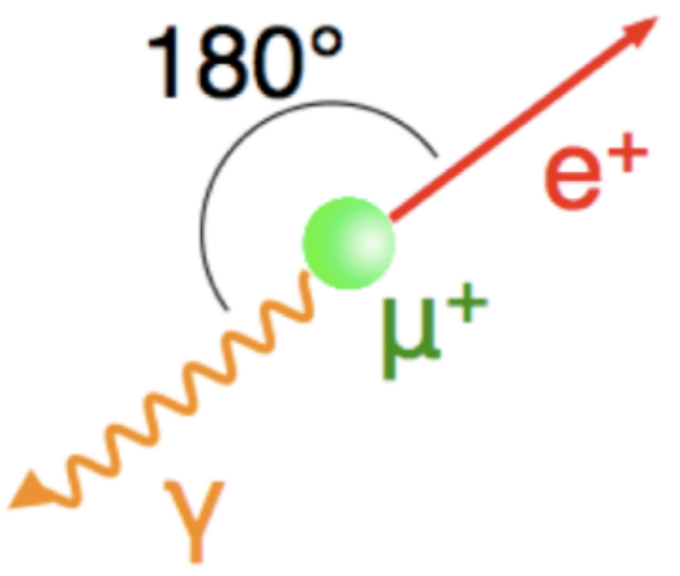
All μ decays channels are subject of running (or commissioning phase) experiments.
Among them, the μ→eγ search is the currently most advanced one: MEG took data in the period 2009 - 2013, while MEG II is just releasing its first results right now!



Callibbi and Signorelli, Riv. Nuovo Cimento, Vol. 41 (2018) 71 (updated by MDG)

μ→eγ decay: signal and background

Signal

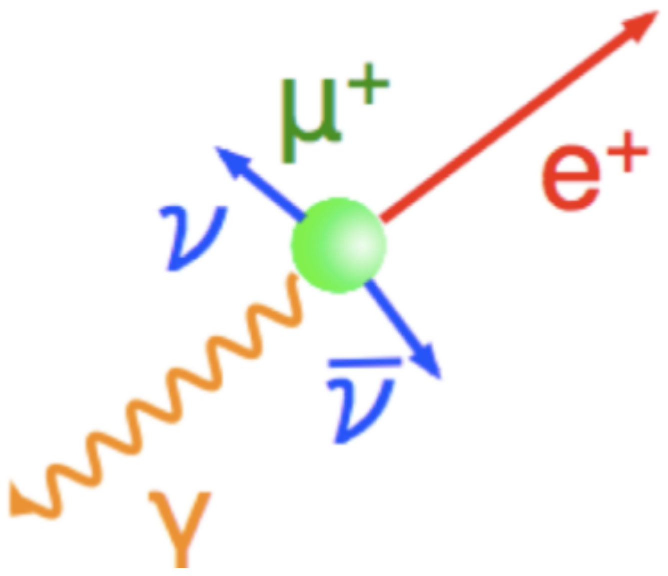


2 bodies final state

$$E_\gamma = E_e = \frac{m_\mu}{2} = 52.8 MeV$$
$$\Delta t_{e\gamma} = 0$$
$$\theta_{e\gamma} = \phi_{e\gamma} = 180°$$

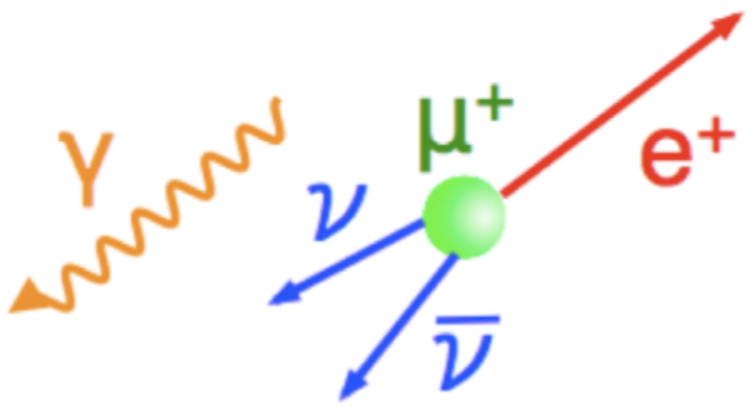
Background

Correlated



radiative μ decay

Accidental



Michel decay +
γ from other processes

$$R_{rad} \simeq R_\mu \times BR(\mu \to e\nu\bar{\nu}\gamma)$$
$$R_{acc} \simeq R_\mu^2 \sigma^2(E_\gamma)\sigma^2(\Omega_{e\gamma})\sigma(t_{e\gamma})\sigma(E_e)$$

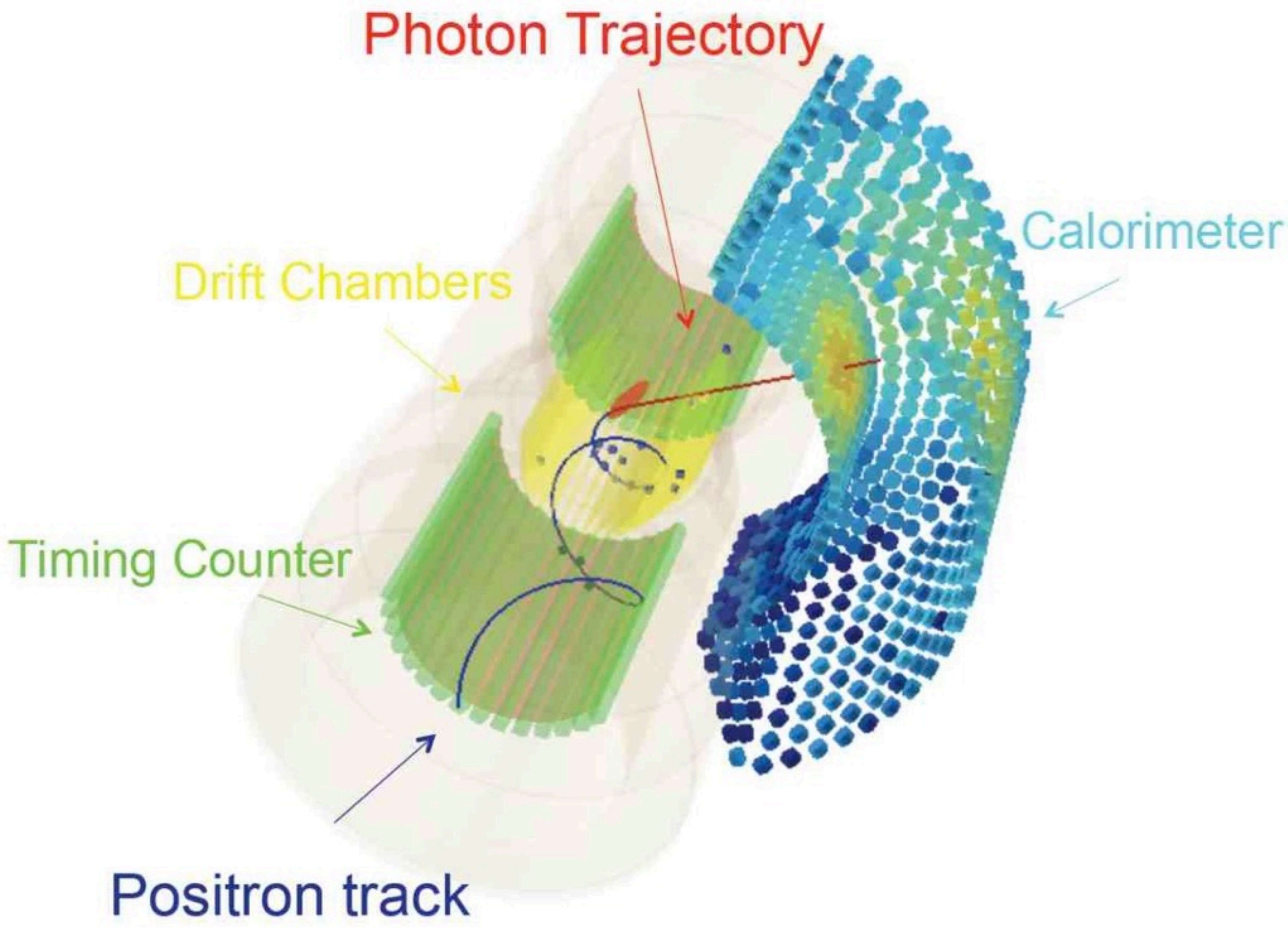
The accidental background dominates and grows as R^2.

$\mu \to e\gamma$ decay: status before MEG II results…

- The current best upper limit on BR($\mu \to e\gamma$) was set by MEG experiment with the analysis of the data collected in 2009 - 2013:
  - **BR($\mu \to e\gamma$) < 4.2 10^{-13} @90% CL.**

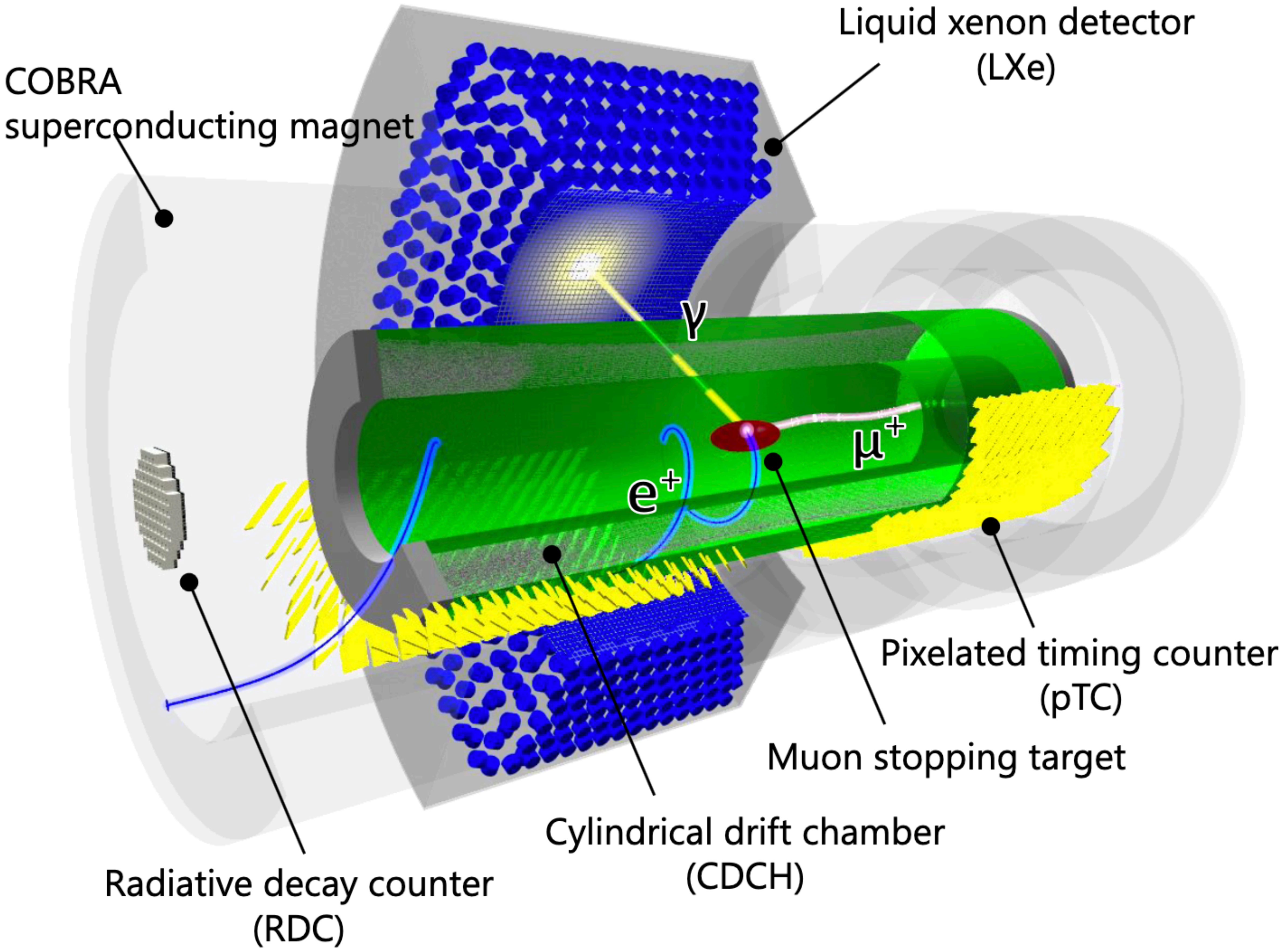
- Since 2013, an intense upgrade work was done on the main detectors, in order to gain at least 1 order of magnitude in sensitivity, down to ~ 5 10^{-14} → **MEG II**

- **MEG II is now running and taking physics data since 2021.**



MEG II detector: a general view

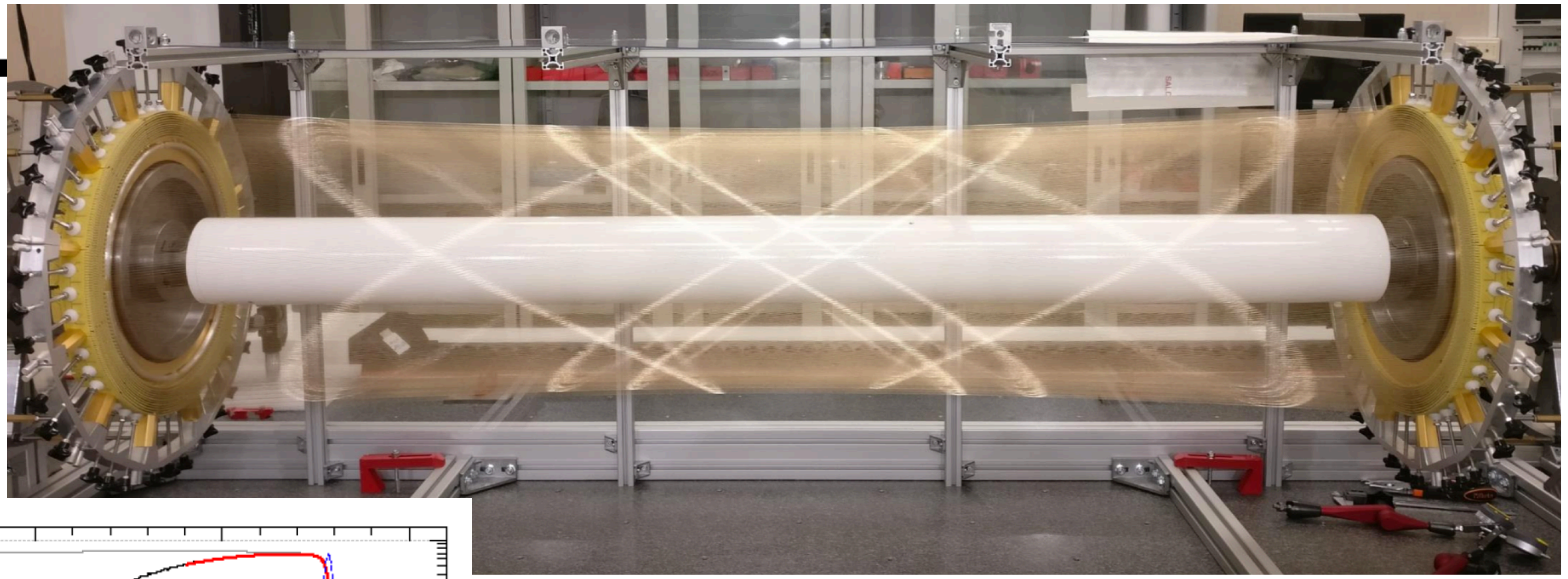
- The MEG II experiment is placed at the Paul Scherrer Institute (PSI), where the world's most intense **low energy μ DC beam** (up to 5×10^7 μ/s) is focused and stopped on a **thin plastic target** inside a **superconductive solenoid magnet (COBRA).**
- Positron momentum is measured by a **Cylindrical Drift Chamber system** placed inside magnetic field, then time is reconstructed by a **pixelated Timing Counter** (plastic scintillator + SiPM tiles).
- γ time and momentum reconstructed in a **Liquid Xenon Calorimeter**
- **Radiative muon decay counter** tags high energy γ by detecting low energy e^+.
- **High efficient trigger and DAQ** integrated in a single, compact system (WaveDREAM).

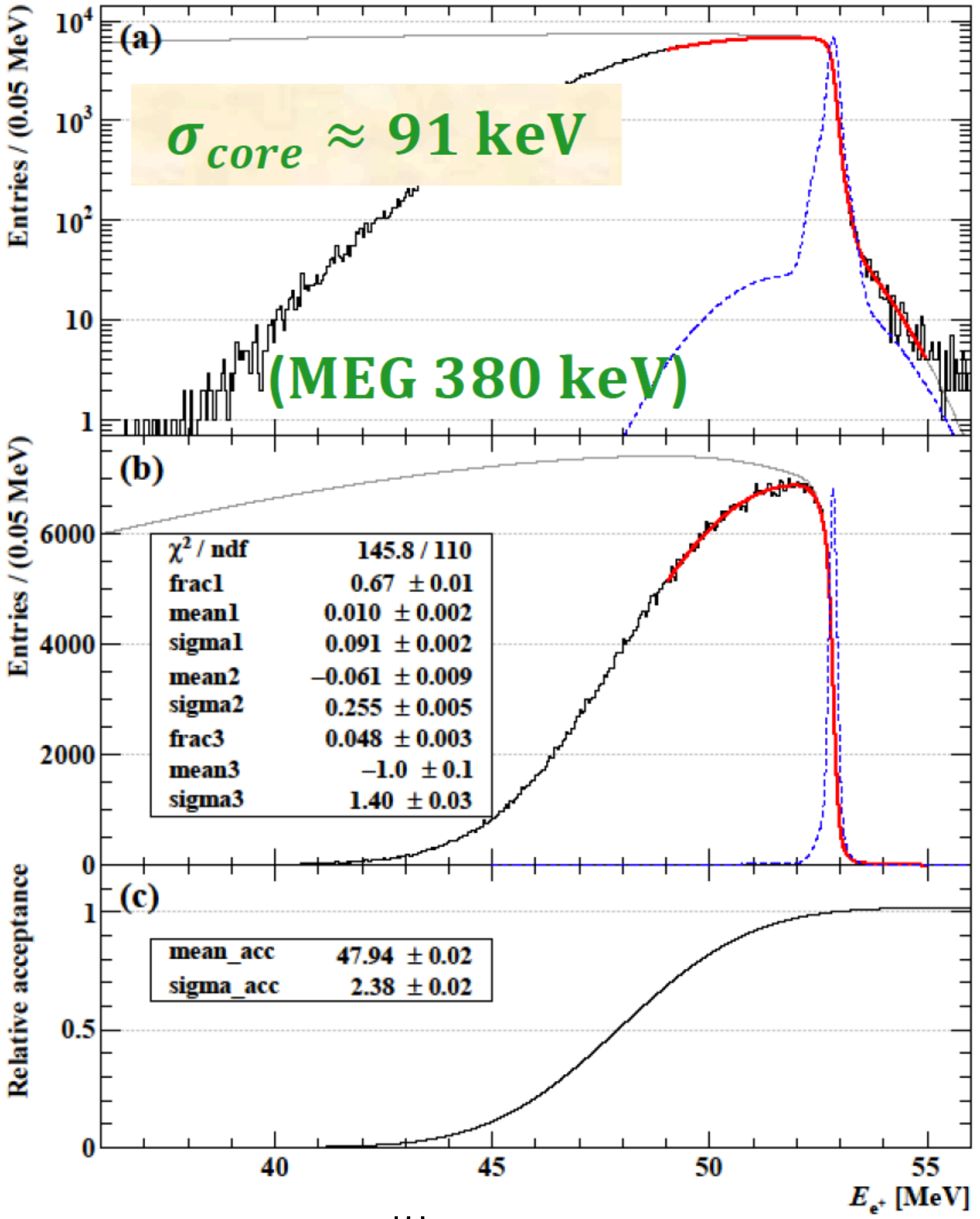


EPJ C 84:190 (2024)

MEG II detector: cylindrical drift chamber

- **Single volume, stereo U-V views** chamber, 7-8° stereo angle with almost squared (7 x 7 mm^2) drift cells;
- **He - Isobutane 90:10 mixture +** traces of **additives** (O^2, isopropyl alcohol);
- >1700 anode wires (20 um Au + W), >10000 cathode and guard wires (40 - 50 um Ag-plated Al wires).
- After some initial delay due to the hard technological challenges, **it reached outstanding performances** in run conditions since 2020.



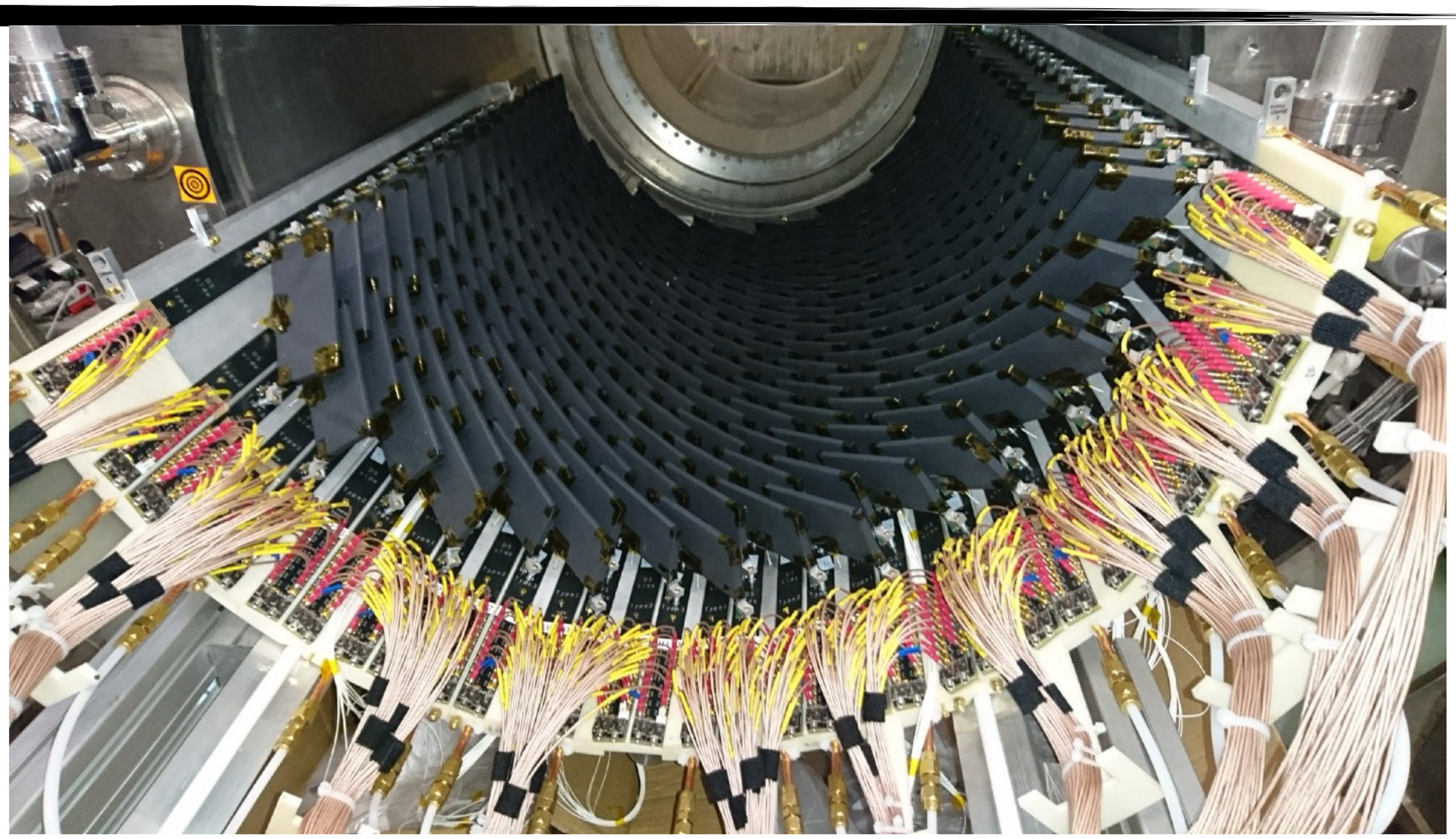


Eur. Phys. J. C (2024) **84**: 473

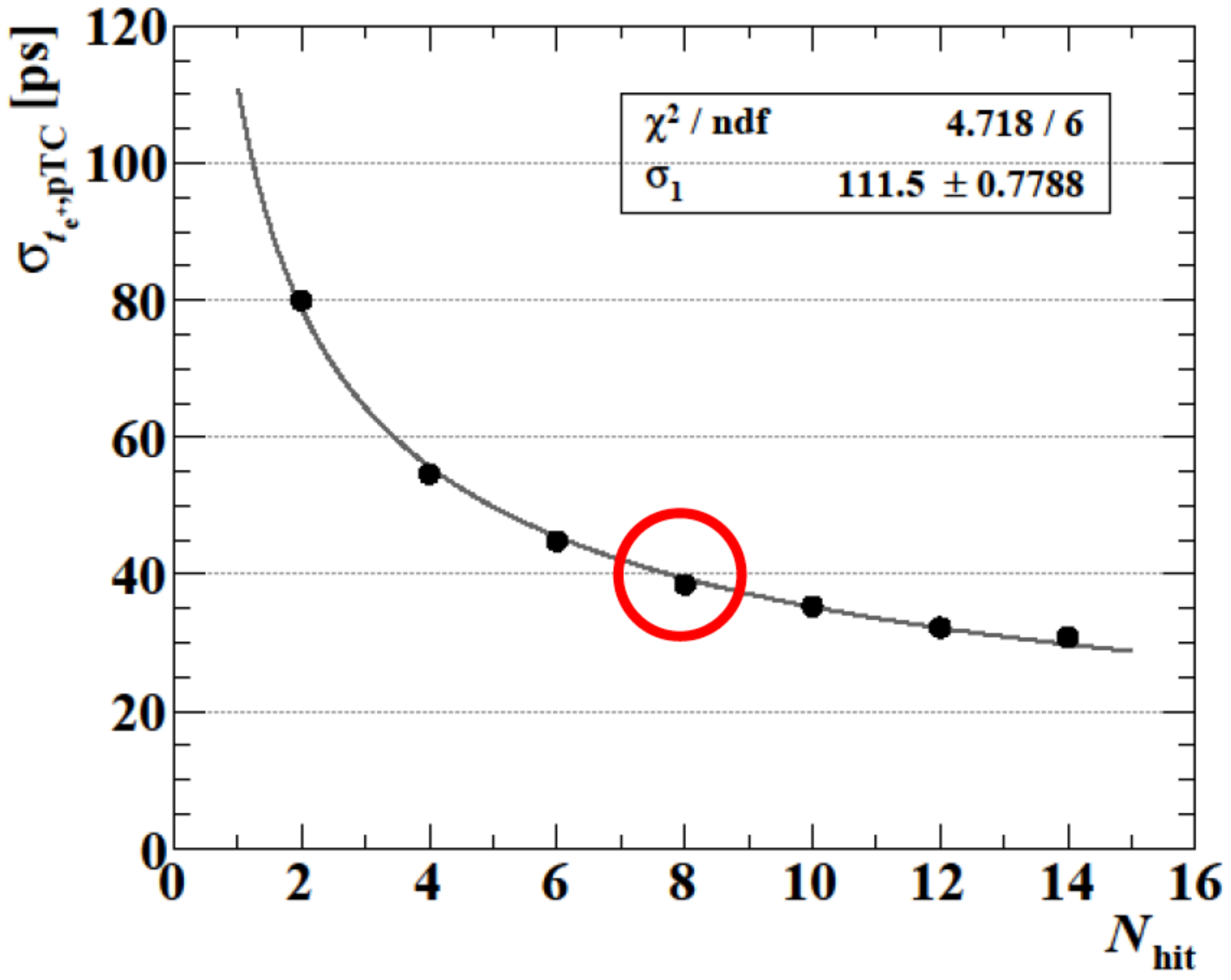
- **40 - 60 fitted hits for signal e^+;**
- **single hit reso 120 um;**
- **momentum reso < 100 keV.**

MEG II detector: pixelated Timing Counter

- Two sectors made by **256 scintillating tiles** (pixels), **equipped with a dual-side readout** based on array of SiPM;
- positron **time is obtained by combining single pixel measurements** (~ 8 hit pixels for signal positrons).
- An optical fiber system distributes **synchronous laser pulse to each pixel for calibration purposes** (inter-timing, stability, etc).
- Stable operation since 2017. Minor deterioration due to radiation damage has been fixed with annual maintenance work and with a "refurbishment" made in 2023 (~ 100 brand new pixels were installed).



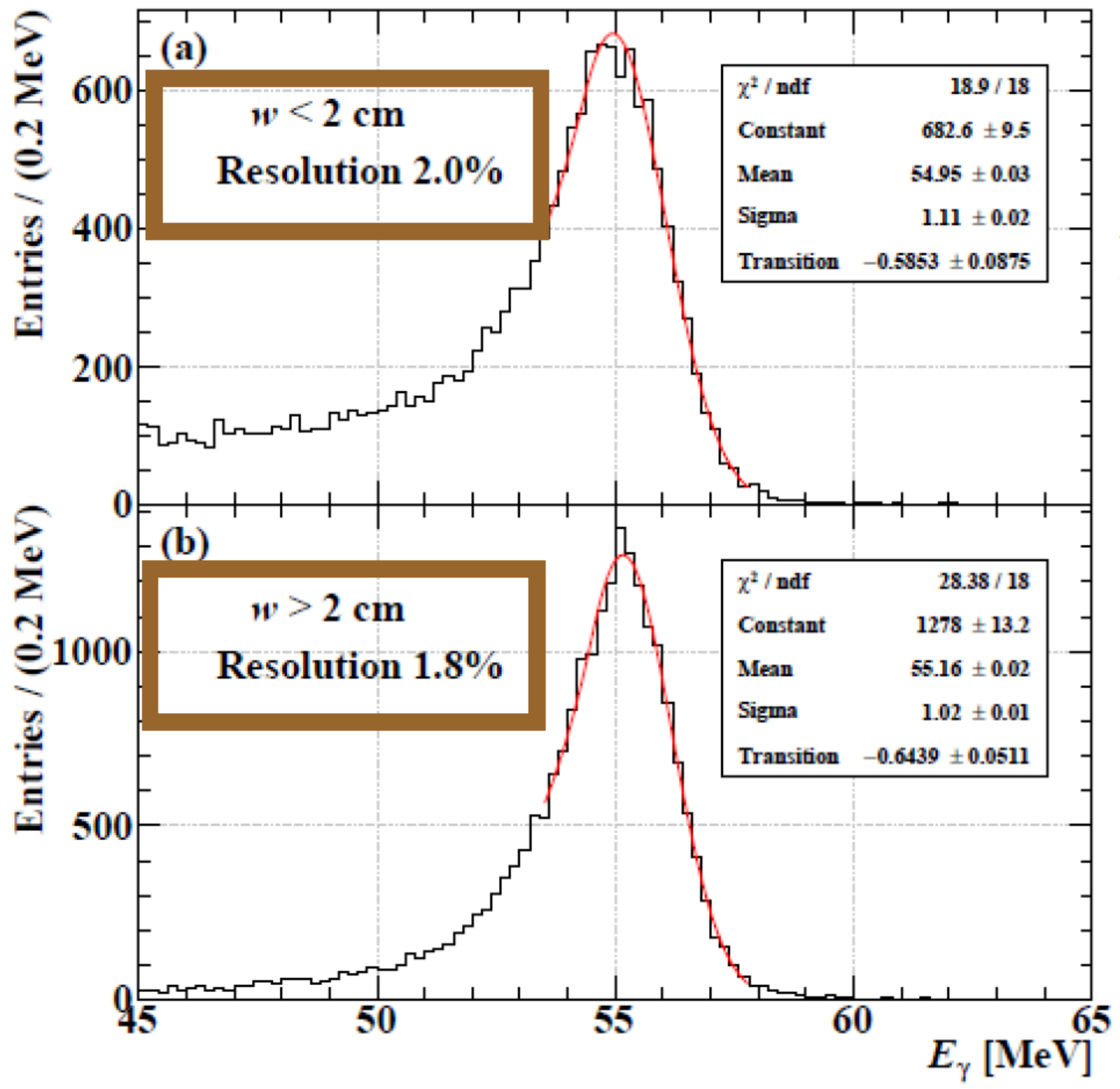
NIM A **1046**(2023) 167751

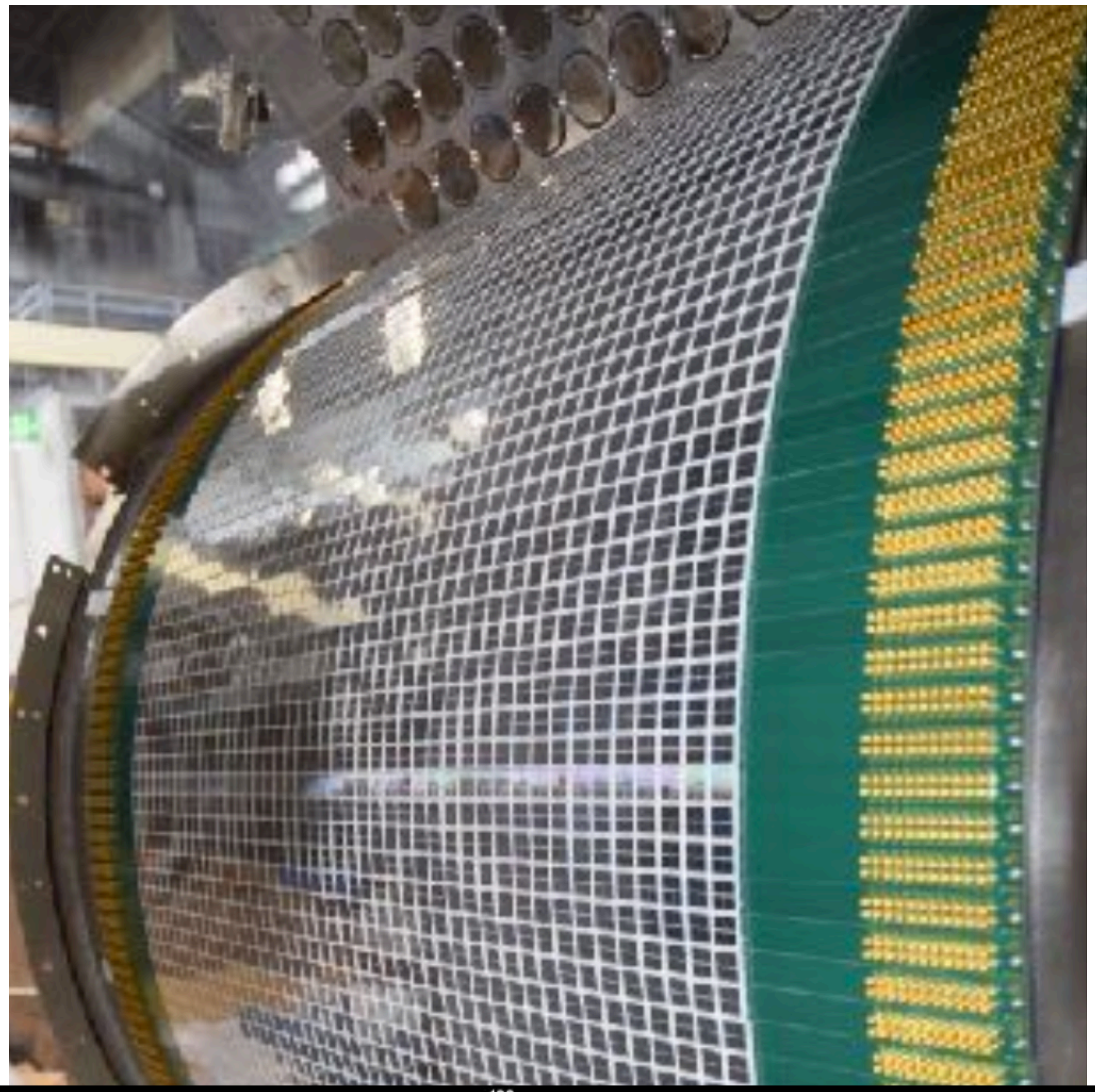


- **~110 ps single counter reso in MEG experimetal conditions.**
- **~35 ps reso on signal positrons**

MEG II detector: the LXe calorimeter

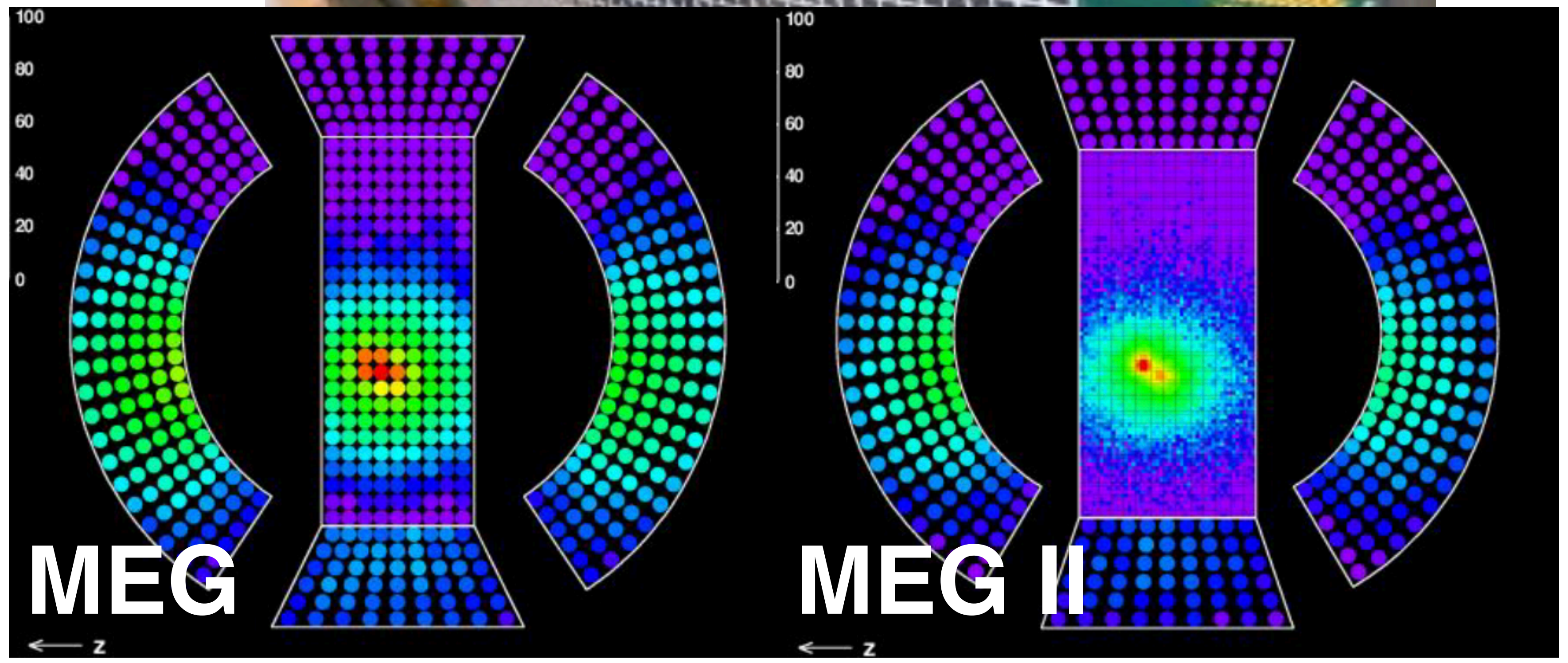
- Upgraded from MEG experiment:
- Higher granularity on front face: **216 PMTs have been replaced with 4092 12 x 12 mm² UV sensitive SiPM.**
- Enlarged acceptance and detection efficiency;
- **better pile-up rejection**;
- **increased resolutions** on photon interaction point, timing and energy.
- **Several calibration tools have been developed** (from MEG experiment) for constant performances monitoring





@55MeV:

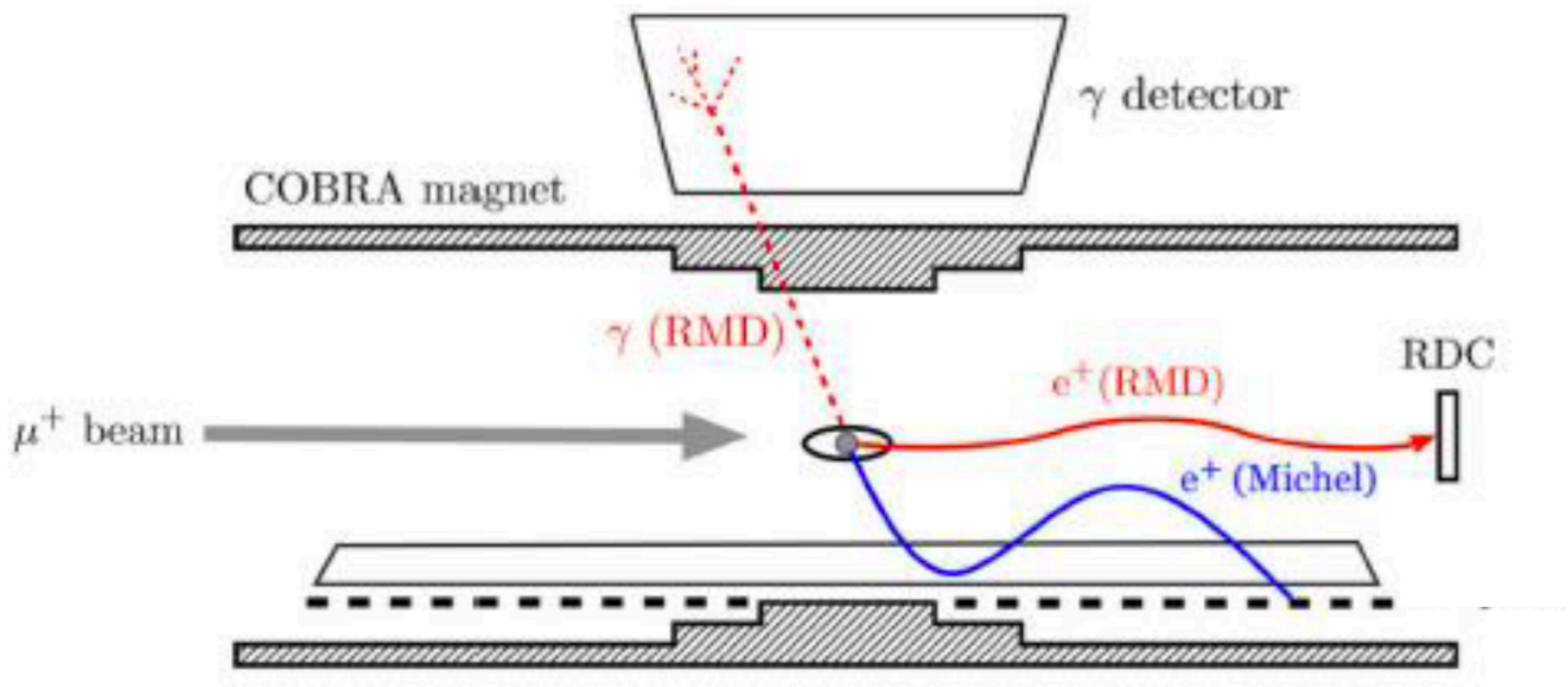
- **2% resolution on events with w < 2 cm**
- **1.8% resolution on events with w > 2 cm**



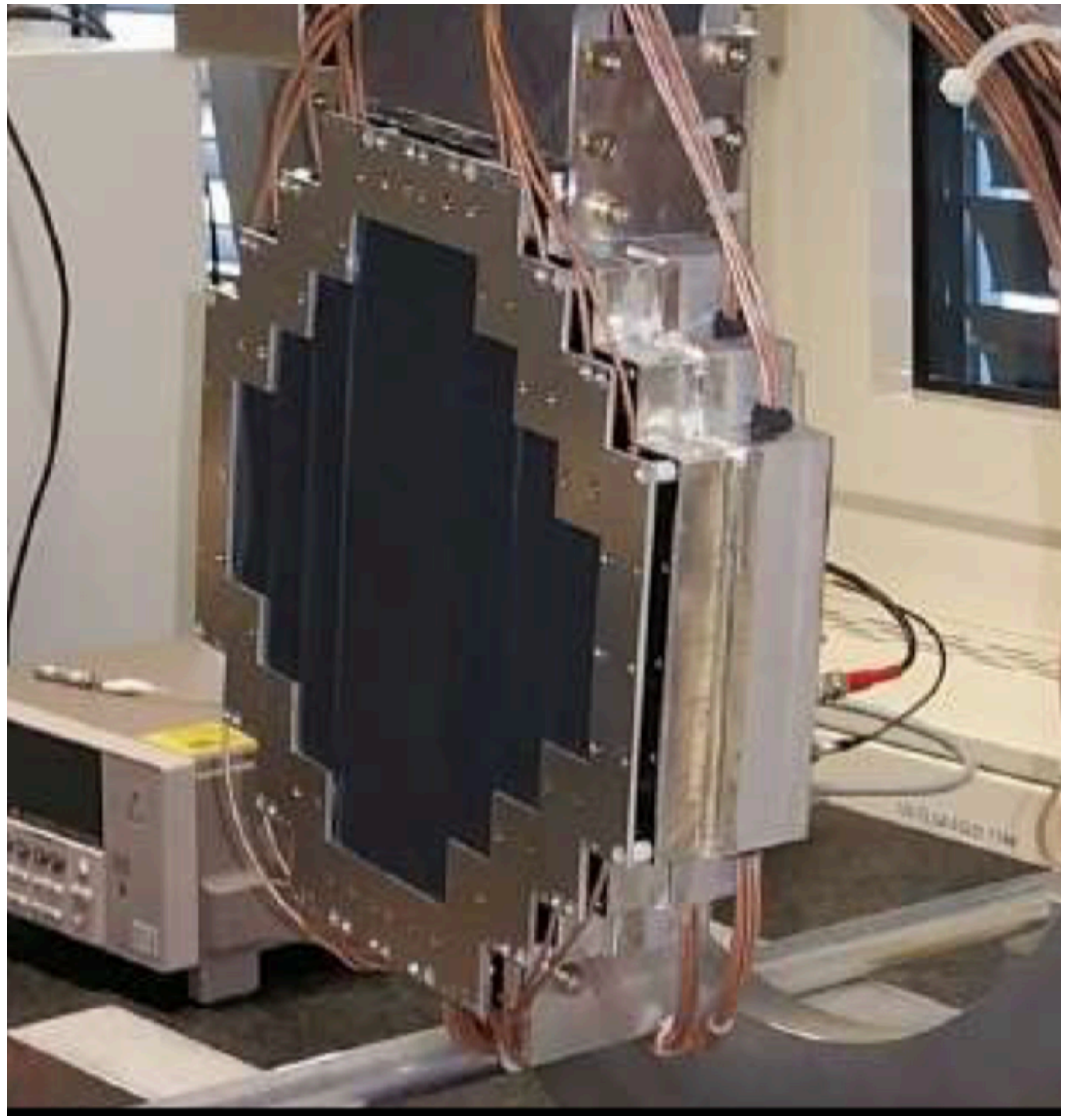
NIM A1046(2023) 167720)

MEG II detector: RMD counter

- A **brand new auxiliary detector** not present in MEG.
- Designed to **reconstruct low momentum positrons for RMD photons tagging.**



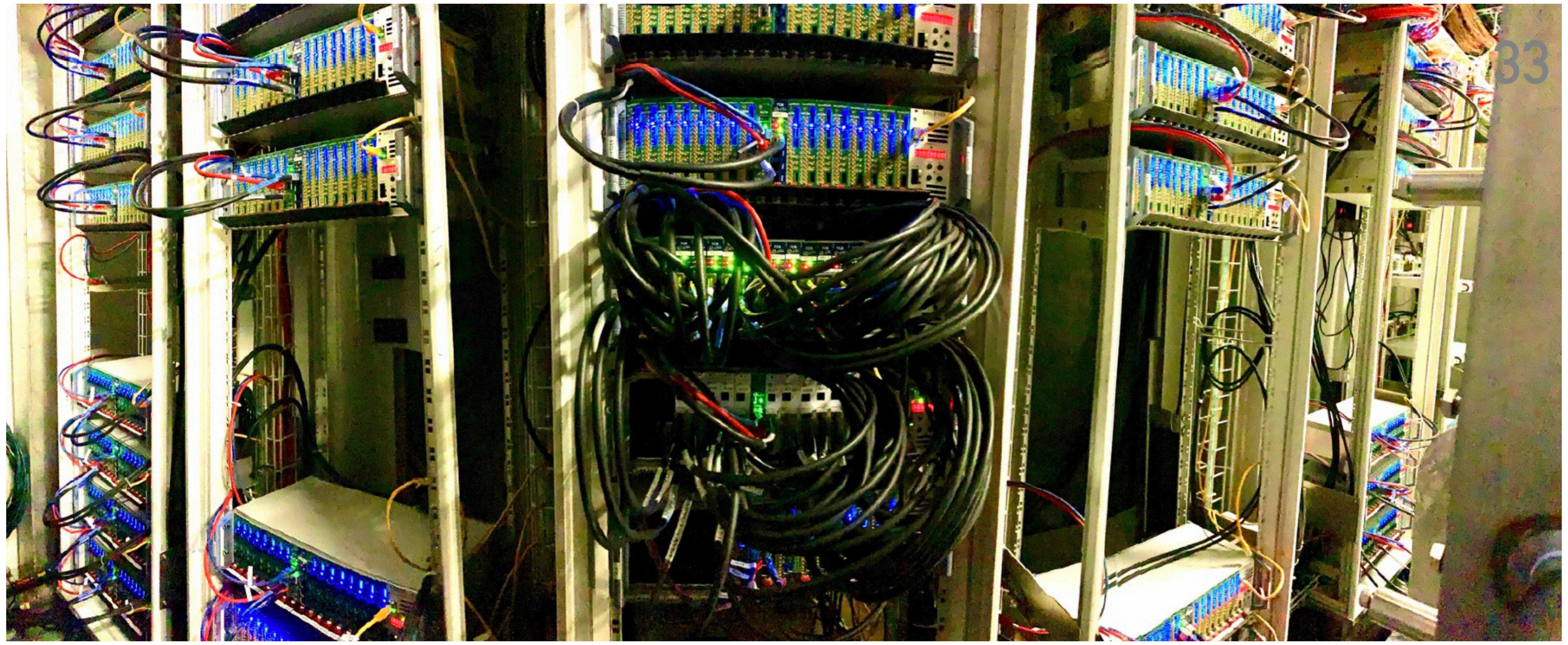
- **LYSO and plastic scintillator pixel read out by SiPM arrays.**
- Expected **improvement in sensitivity ~ 7%.**



Proc. Phys. **212**(2017) 82–86)

MEG II detector: trigger and DAQ system

- **Full waveform recording @1.4 GSPS with custom designed digitizing board** based on Domino Ring Sample (DRS) chip.
- Custom made **high efficient trigger** system for fast and efficient (>99%) event selection based on:
  - LXe total detected charge → **E_γ > 40 MeV;**
  - pTC - LXe relative timing → **$\Delta T_{e\gamma}$ < 11 ns;**
  - pTC - LXe fast topological information - almost **back to back reconstruction** based on look-up table.

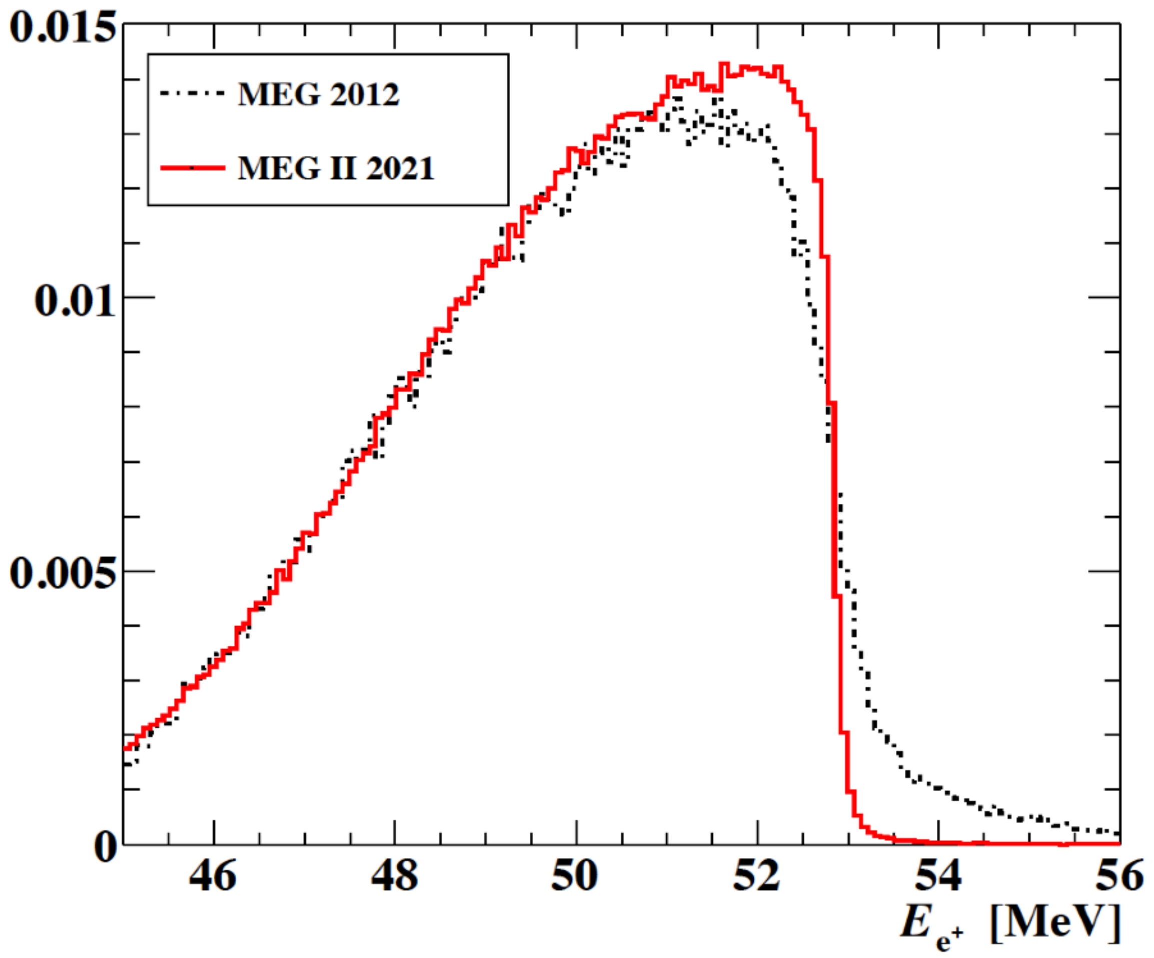


NIM A **1045**, 167542 (2023)

- **~ 9000 channels, trigger rate ~ 10 - 30 Hz depending on muon beam intensity.**
- **Online E_γ reso : 2.5 %**
- **Online $T_{e\gamma}$ reso < 2 ns.**

MEG II performances summary

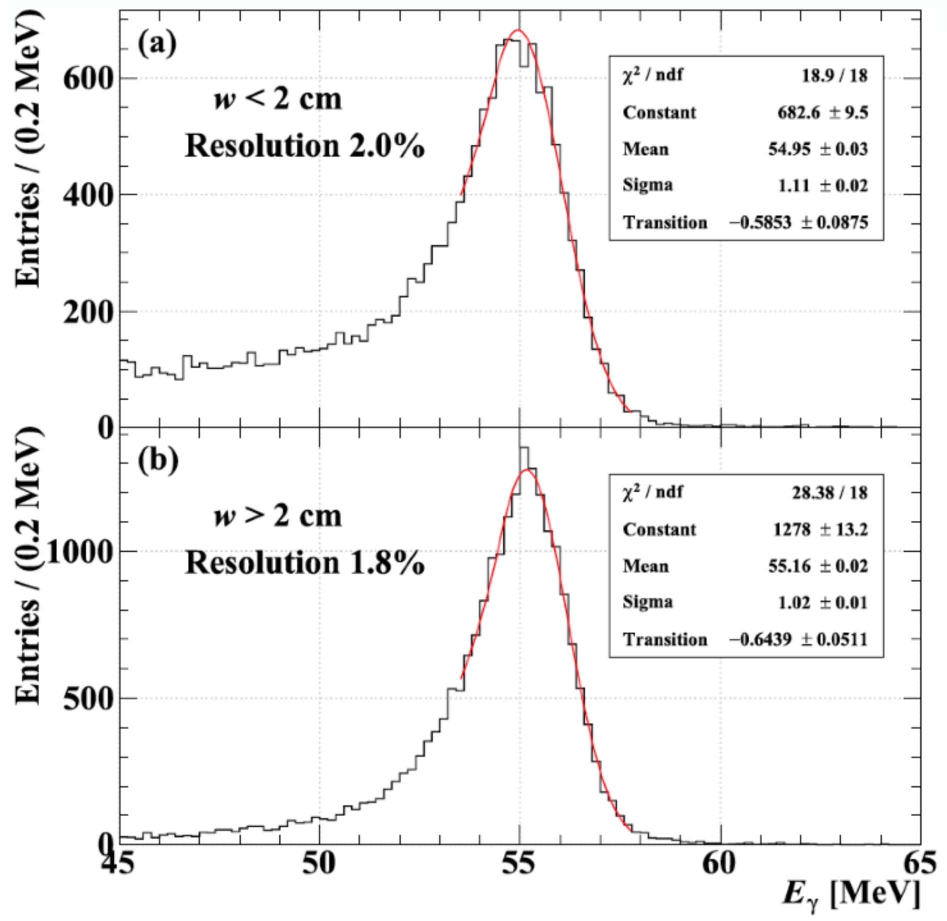
Positron tracking



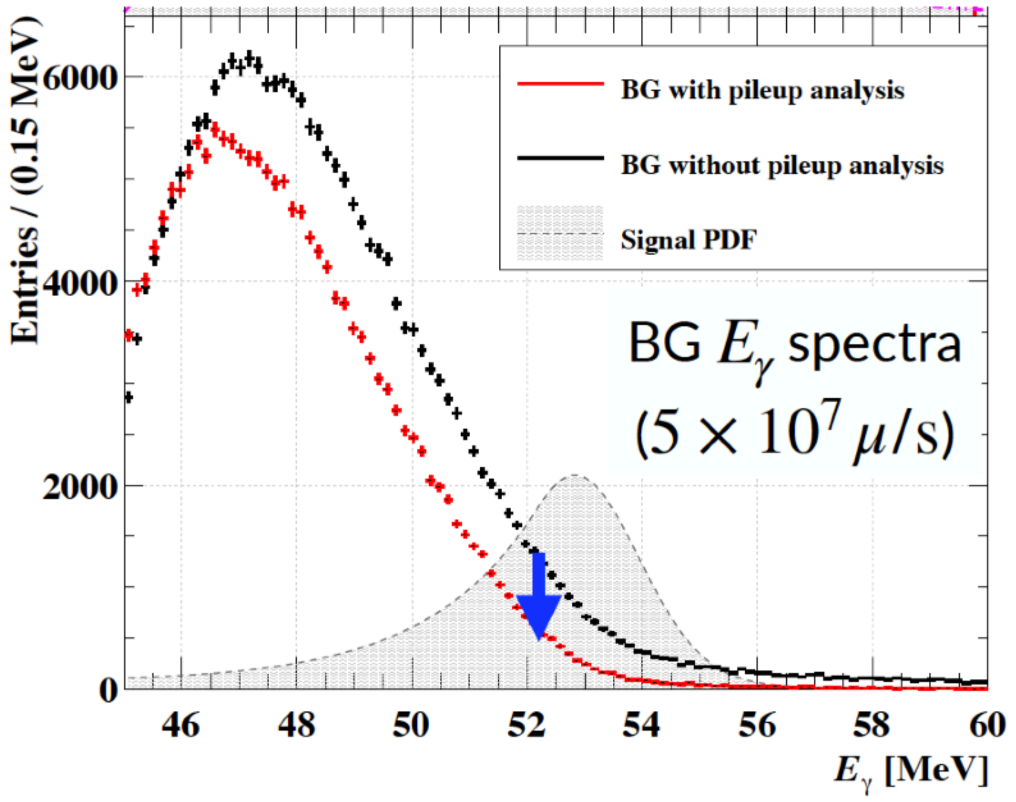
- Energy resolution: **90** keV
  (↔ 320 keV@MEG)
- Efficiency: **67 %** @ $3 \times 10^7 \mu/s$
  (↔ 30 % @MEG)

Photon energy

Energy resolution

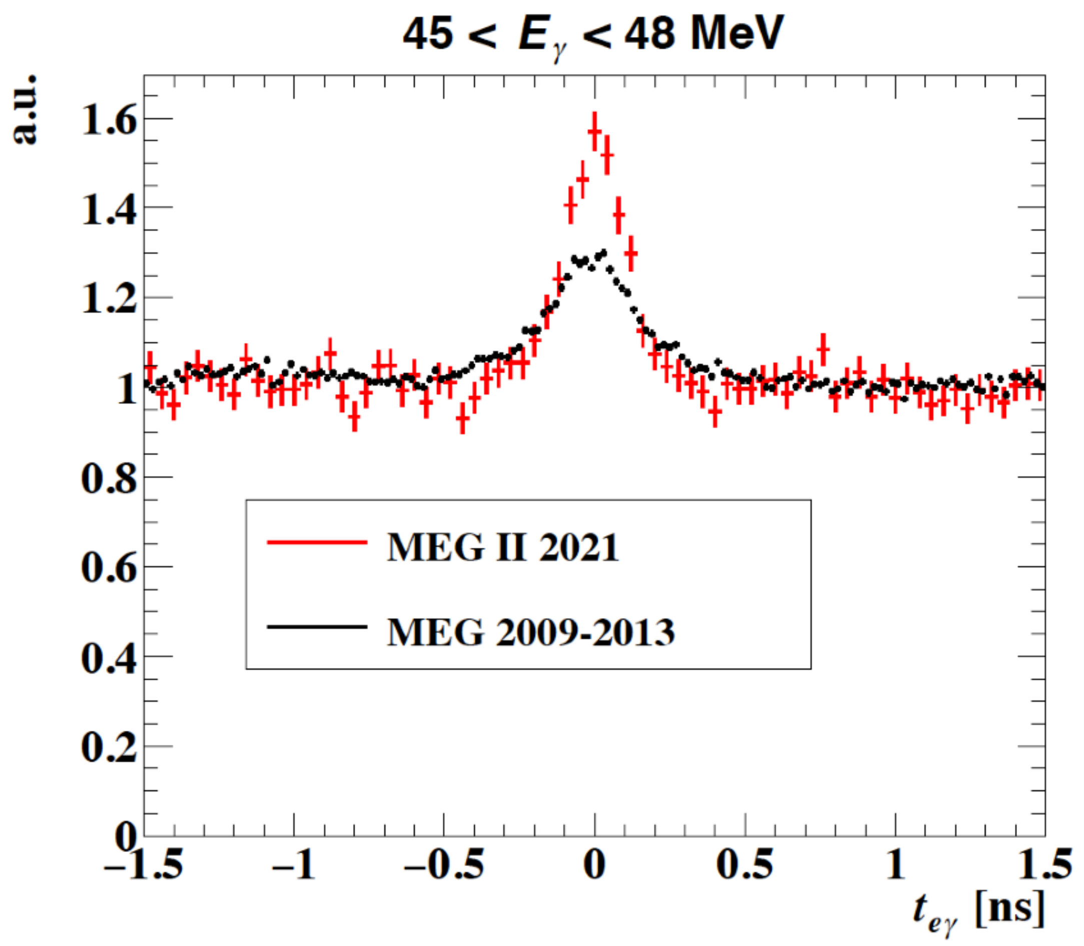


Pileup analysis



- High-granularity and uniform readout by MPPCs
- Energy resolution: **2.0%/1.8% for (conv. depth: <2cm/>2cm)**
- **Pielup BG reduction by 35%** at 48-58MeV $(5 \times 10^7 \mu/s)$

Relative timing



- Overall resolution: **84** ps
  (↔122 ps@MEG)

Significant improvements over MEG

MEG II performances summary

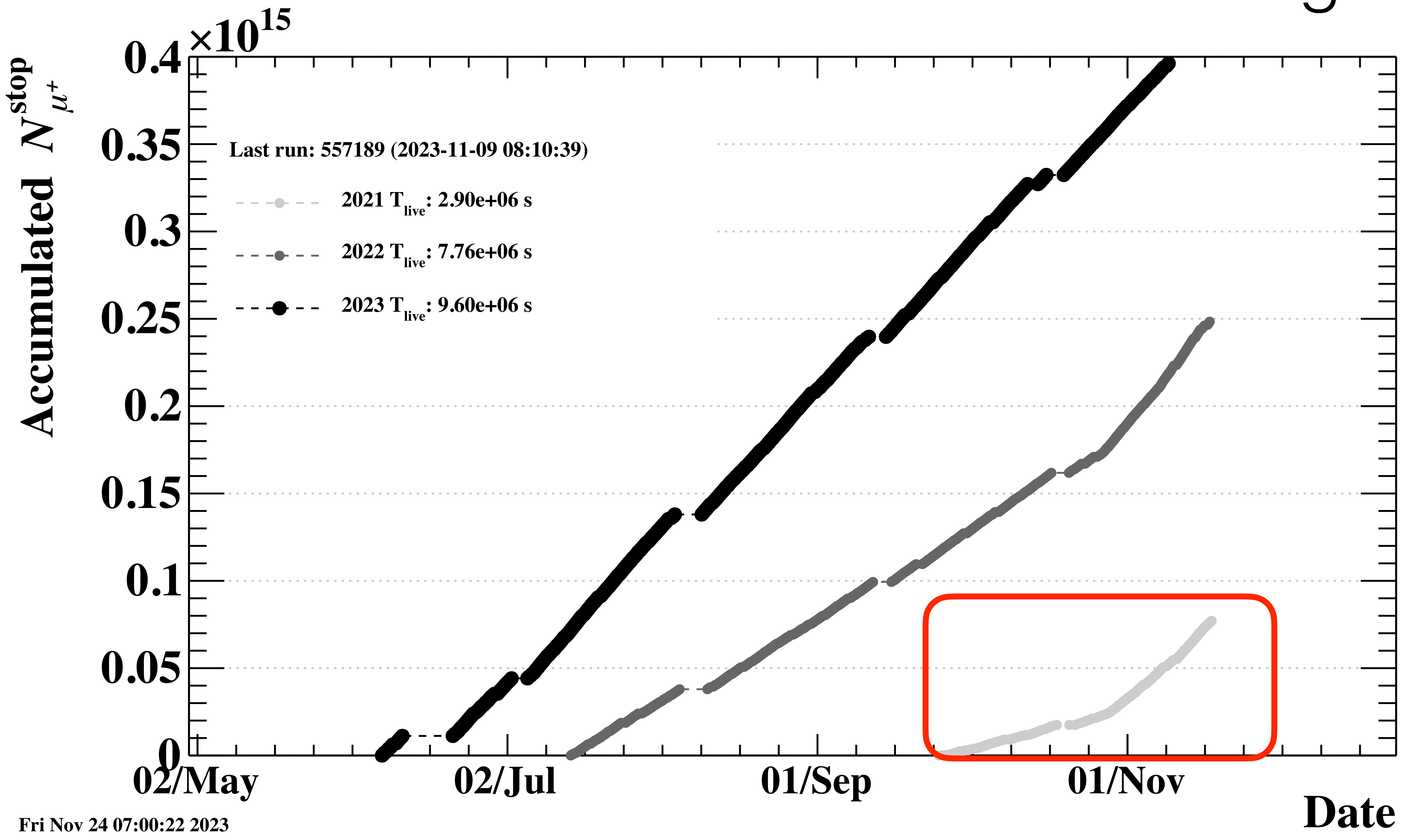
Resoluition	MEG performance	MEG II achieved value with this work
E_e (keV)	320	90
θ_e (mrad)	9.4	7.2
ϕ_e (mrad)	8.7	4.1
z_e/y_e (mm) core	2.4/1.2	2.0/0.7
E_γ(%) (w<2 cm)/(w>2 cm)	2.4/1.7	2.0/1.8
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.5/2.5/5
$t_{e\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	≈ 99	~ 80 → to be improved from 2022 onward (>90%)
Gamma-ray	63	62
Positron	30	67

Significant improvements over MEG

Thanks to this stunning performances, with the analysis 2021 run MEG II has reached in 7 weeks of data taking 60% of the full (2009 - 2013) MEG sensitivity.

MEG II physics data taking status

MEG II is stably taking physics data since 2021



2023 (currently the longest MEG II run)

2022 (first "long" stable MEG II run)

2021→ this talk (almost reached MEG sensitivity)

2024 not yet started (due to a HW fail at PSI cryo plant -> not MEG related…)

MEG II analisys: normalization and systematics

Normalization

- Normalization factor **k = number of effectively measured μ**
- **Meaning: BR = N_{sig} / k**
- 2 independent methods:
  - **Counting Michel positrons**
    - Pre-scaled Michel positron trigger
    - Include positron efficiency and beam rate instabilities
  - **Counting RMD events**
    - From RMD events in energy sidebands
- Combined normalization factor (2021 run):
  - $(2.64 \pm 0.12) \times 10^{12}$.

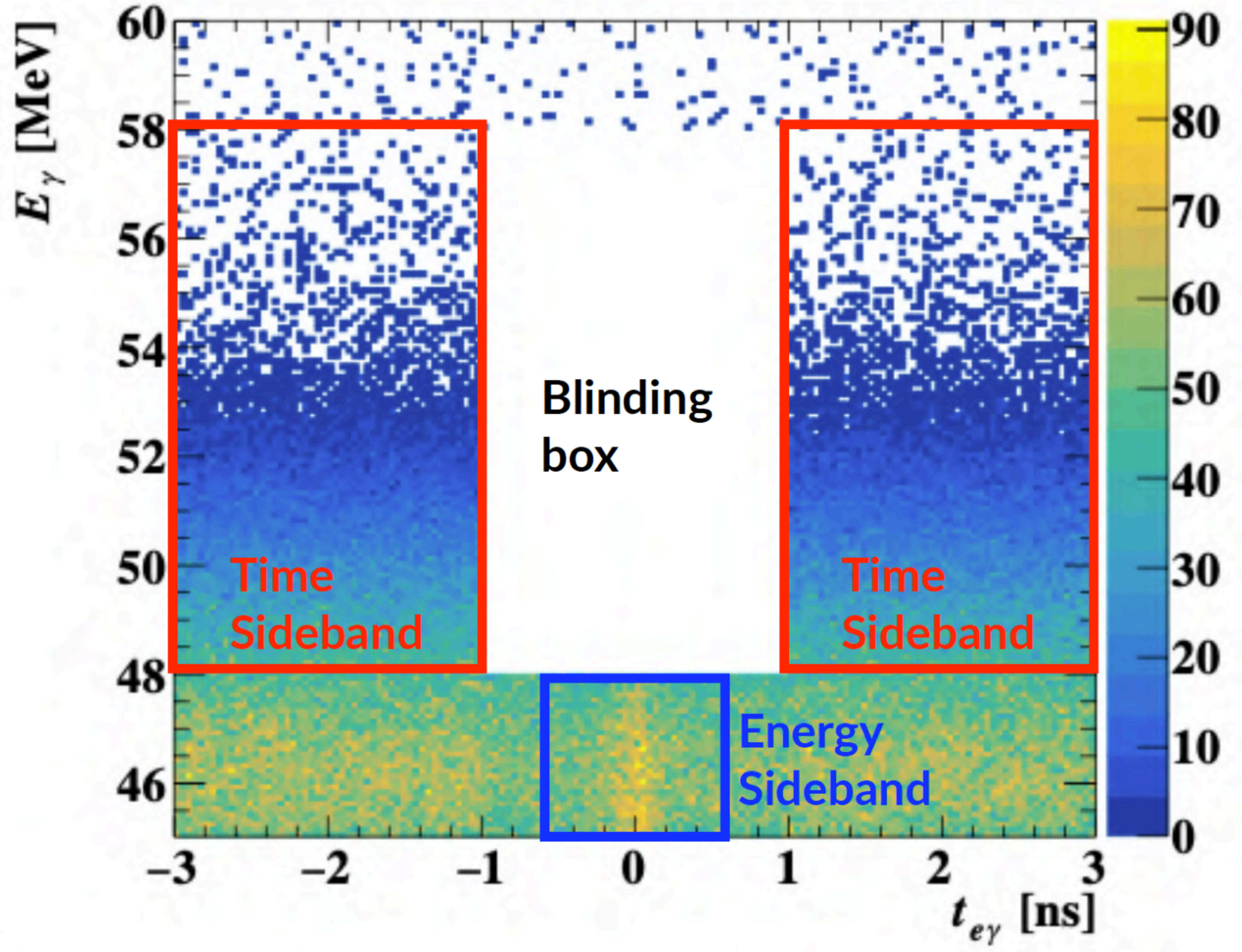
Systematics

- Major sources for systematics:
  - Detector alignment
  - E_γ scale
  - Normalization
- Effect on sensitivity ~ 4%
  - In MEG was estimated to be ~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 %

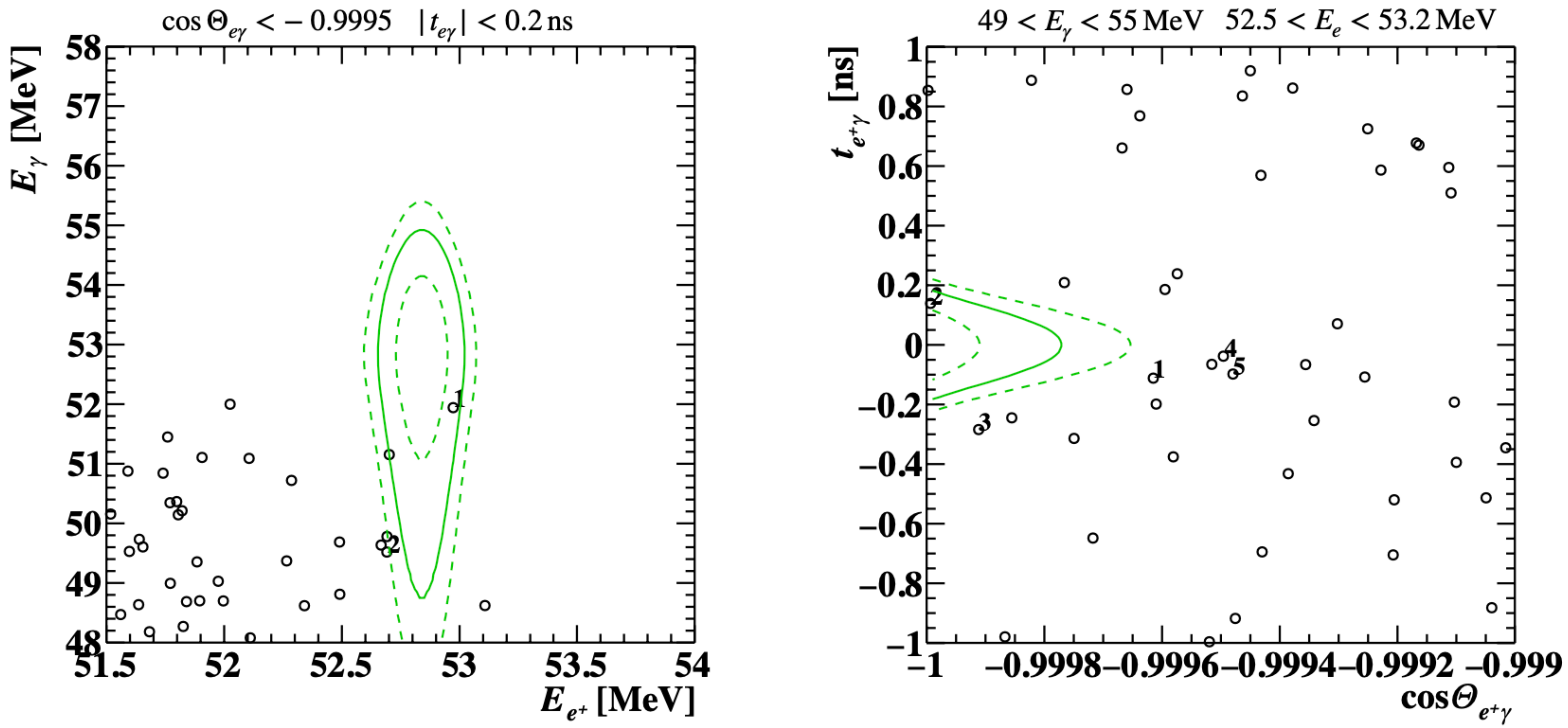
MEG II analysis: strategy

- The $\mu \to e\gamma$ decay is fully characterized by 5 observables: $\mathbf{T_{e\gamma}}$, $\mathbf{E_\gamma}$, $\mathbf{E_e}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$.
- We perform a **blind analysis**:
  - Blind box: $48 < E_\gamma < 58$ MeV, $|T_{e\gamma}|<1$ns
  - **BG study in the sidebands:**
    - Accidental BG in time sidebands
    - RMD in energy sideband.
- **Maximum likelihood fit to extract N_{sig}, N_{RMD}, N_{acc}**
- **Two independents analysis developed:**
  - Per-events PDFs with separate angular observables $\theta_{e\gamma}$, $\phi_{e\gamma}$ (reference one).
  - Constant PDFs with single angular observable (crosscheck).



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

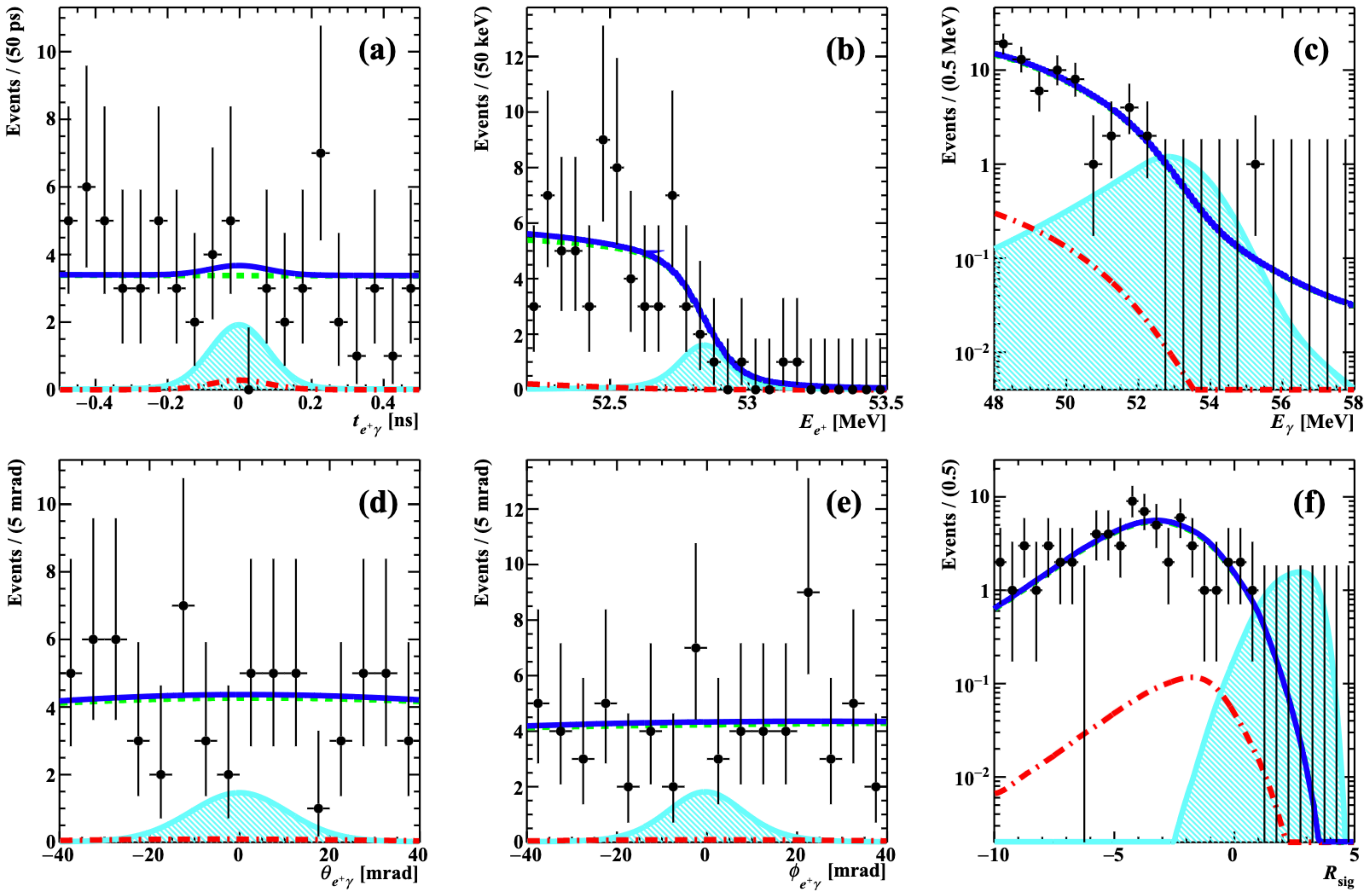
MEG II analysis: unblinding



PDF contours (1, 1.64, 2σ)

No excess of events over expected background around signal region

MEG II result: 2021 data analysis



Opening the box

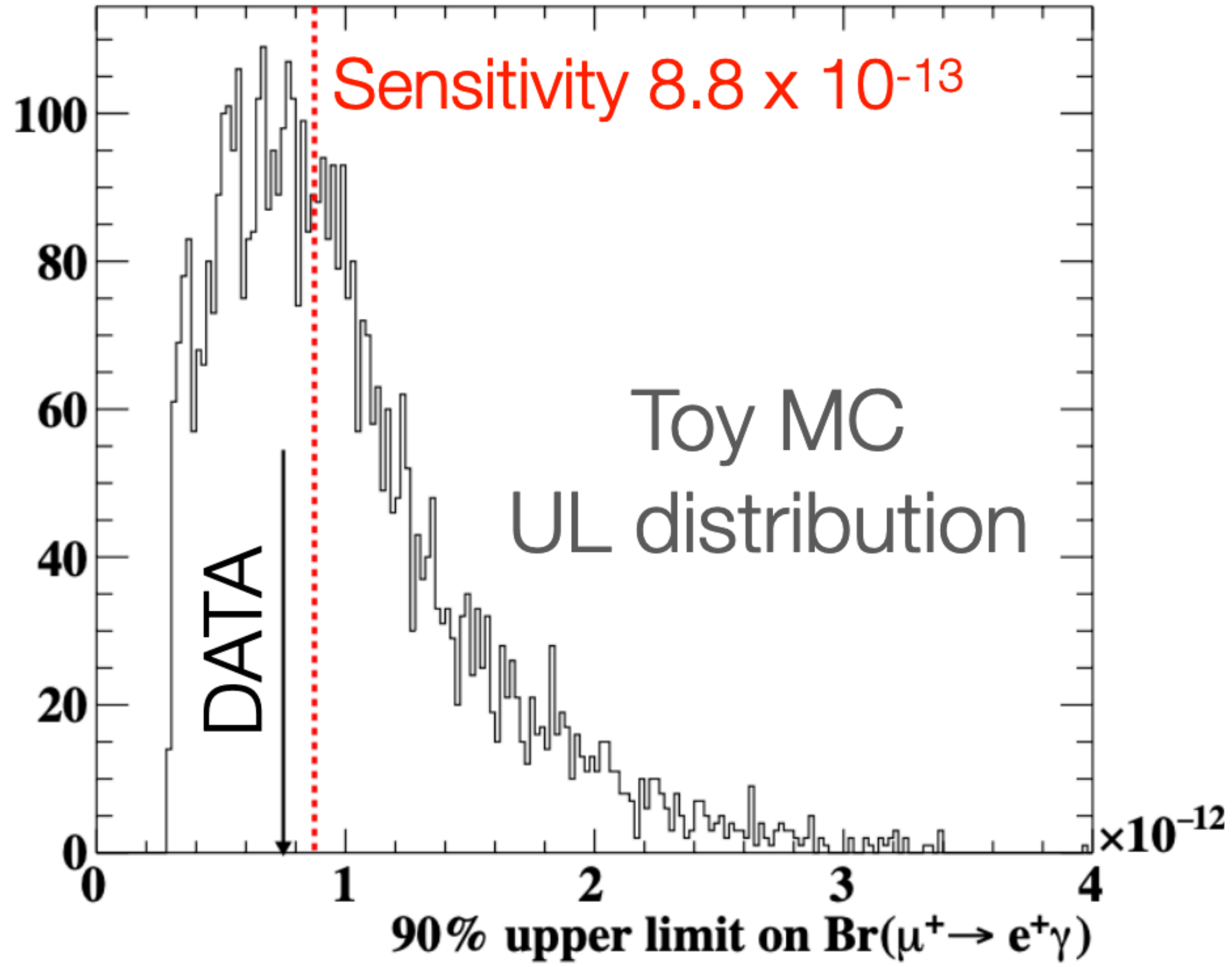
EPJ C (2024) 84:216

$N_{obs} = 66$

$N_{ACC}^{exp} = 68.0 \pm 3.5$

$N_{RMD}^{exp} = 1.2 \pm 0.2$

$N_{sig} < 2$



BR(μ→eγ) < 7.5 10^{-13} @90% CL

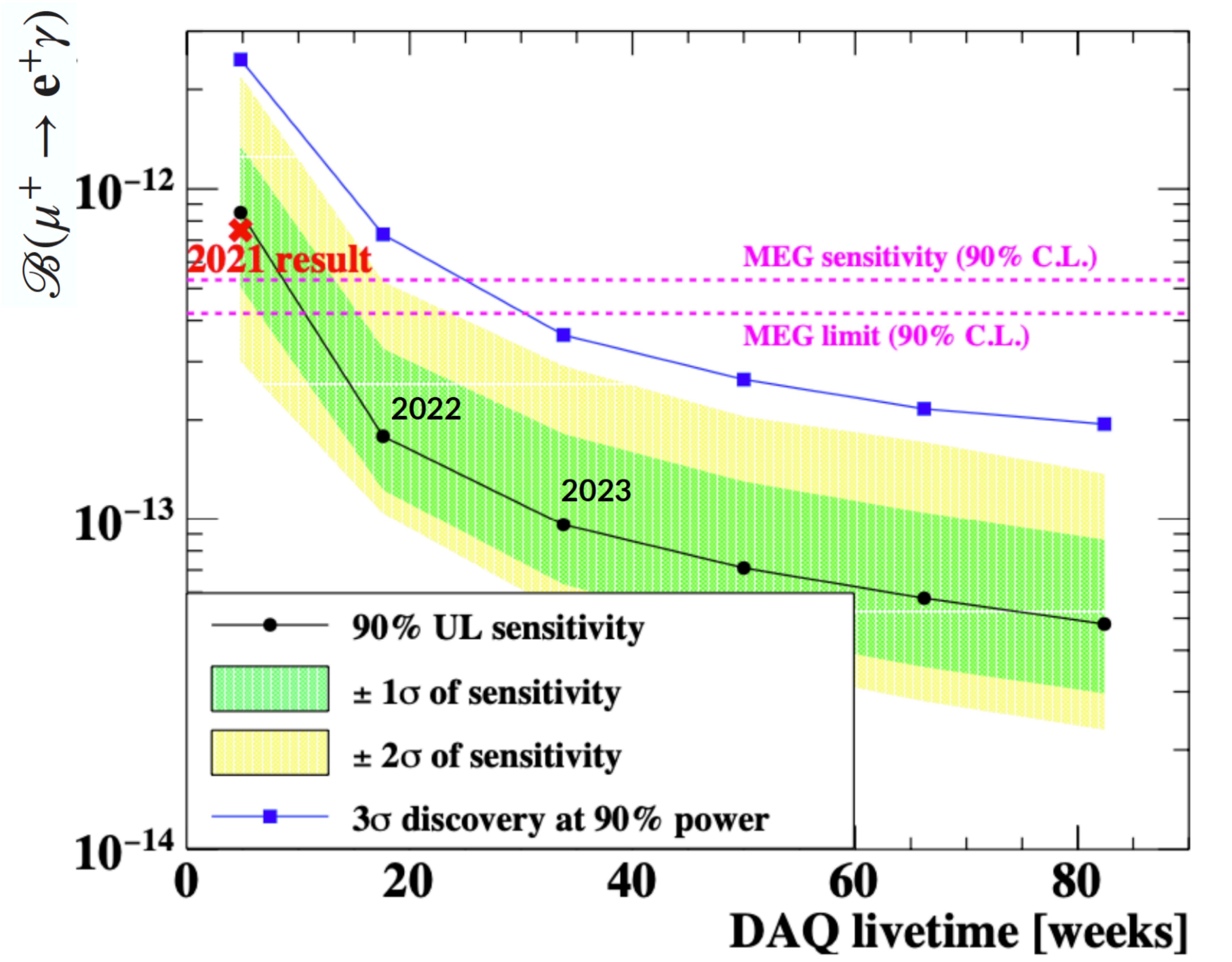
(MEG best result: BR(μ→eγ) < 4.2 10^{-13})

MEG II status and prospect

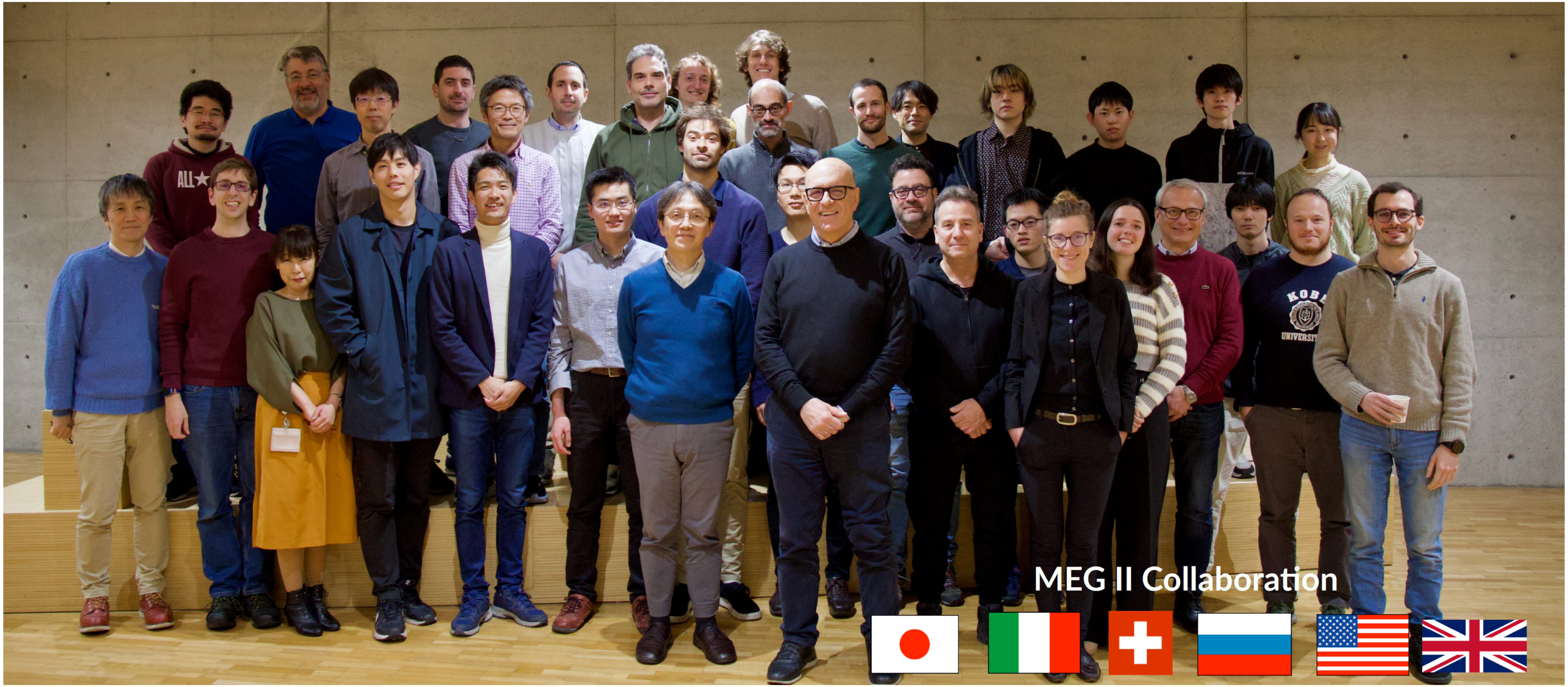
- The first 7-week data in 2021 achieved a sensitivity of ~60% of the full MEG dataset.
  - **$BR(\mu \to e\gamma) < 7.5 \times 10^{-13}$ @90% CL**
- Combining **MEG + MEG II results** we obtain the most stringent limit on the branching ratio of $\mu \to e\gamma$:
  - **$BR(\mu \to e\gamma) < 3.1 \times 10^{-13}$ @90% CL**

MEG II status and prospect

- 2022 and 2023 data analysis is on-going.
- A x10 data sample already acquired → **we expect to explore the 10^{-14} sensitivity region!**
- 2024 run expected to be already started but delayed for some (PSI) technical issues.
- Physics run will continue until PSI accelerator will be shut down for a major upgrade in 2027, to reach a sensitivity of 6 x 10^{-14}
- **New results are coming soon, stay tuned!**



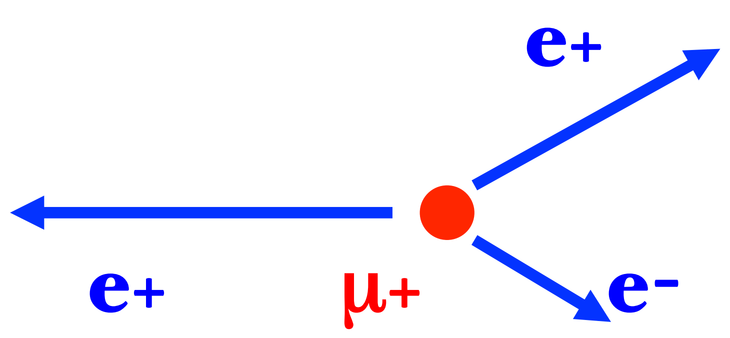
Thanks for your attention!



Back up slides

$\mu \to eee$ decay: signal and background

Signal

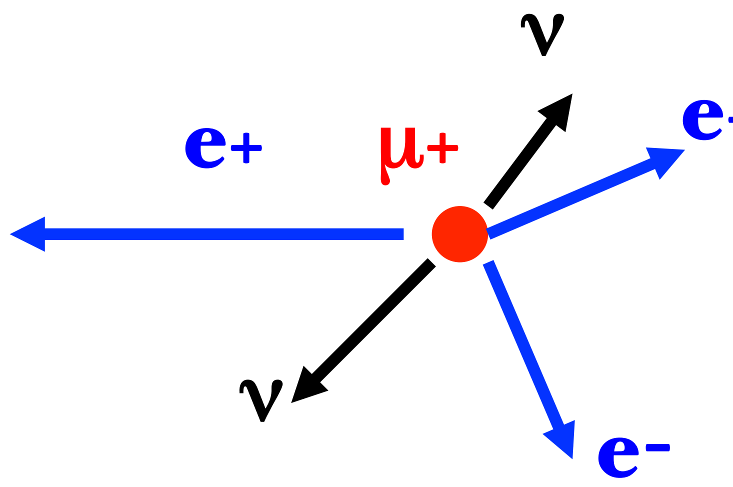


Event reconstruction:

- μ invariant mass
- $\sum p_i = 0$
- vertexing
- time coincidence

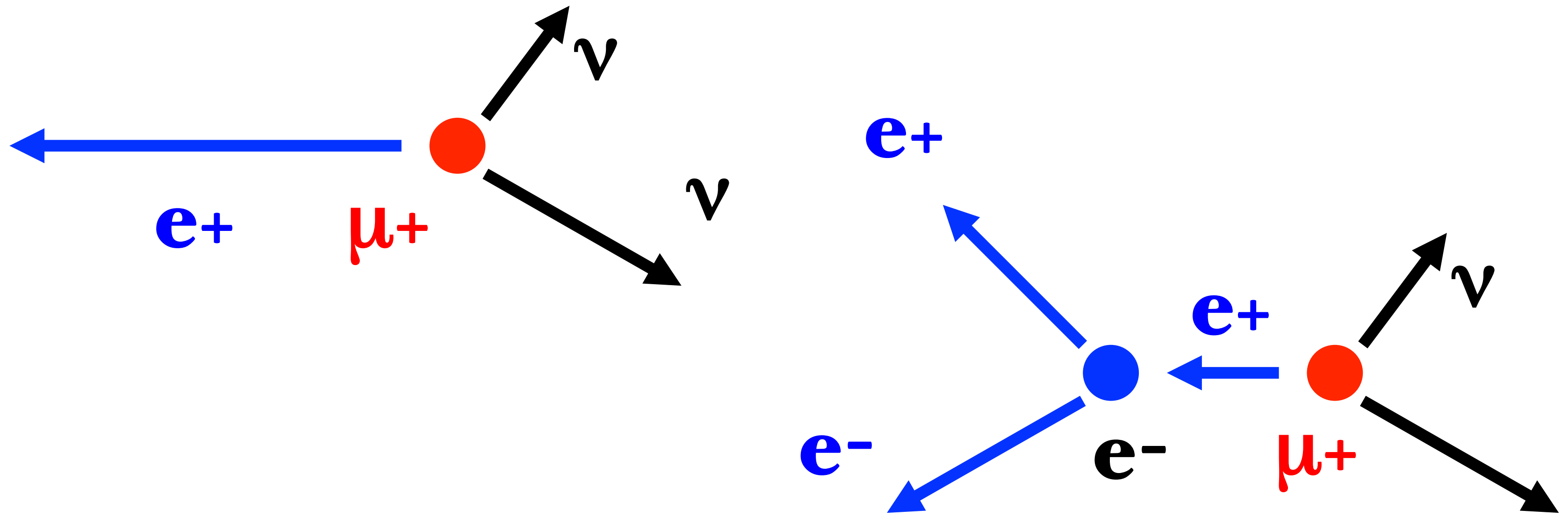
Background

Correlated



Radiative μ decay with
γ internal conversion

Accidental

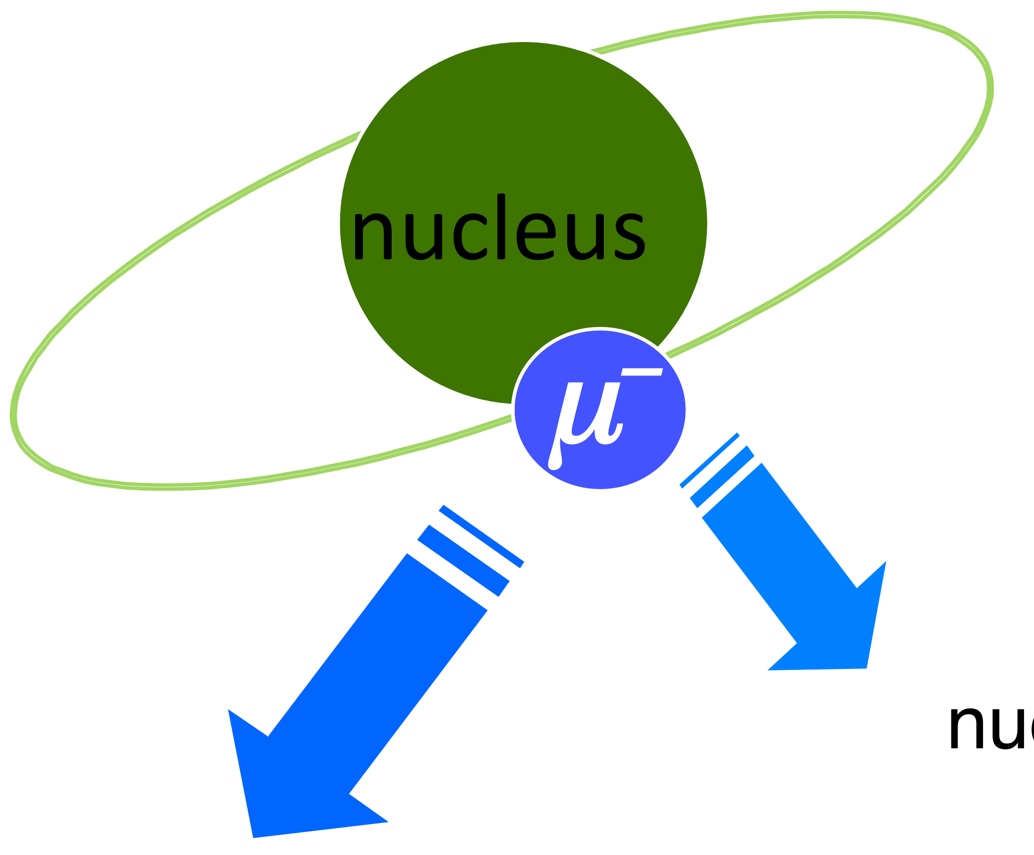


Standard Michel decay +
e^+e^- pair from Bhabha scattering

Correlated background ~ (R_μ)
Accidental background ~ $(R_\mu)^2$

As in MEG, the accidental background dominates and grows as R^2.

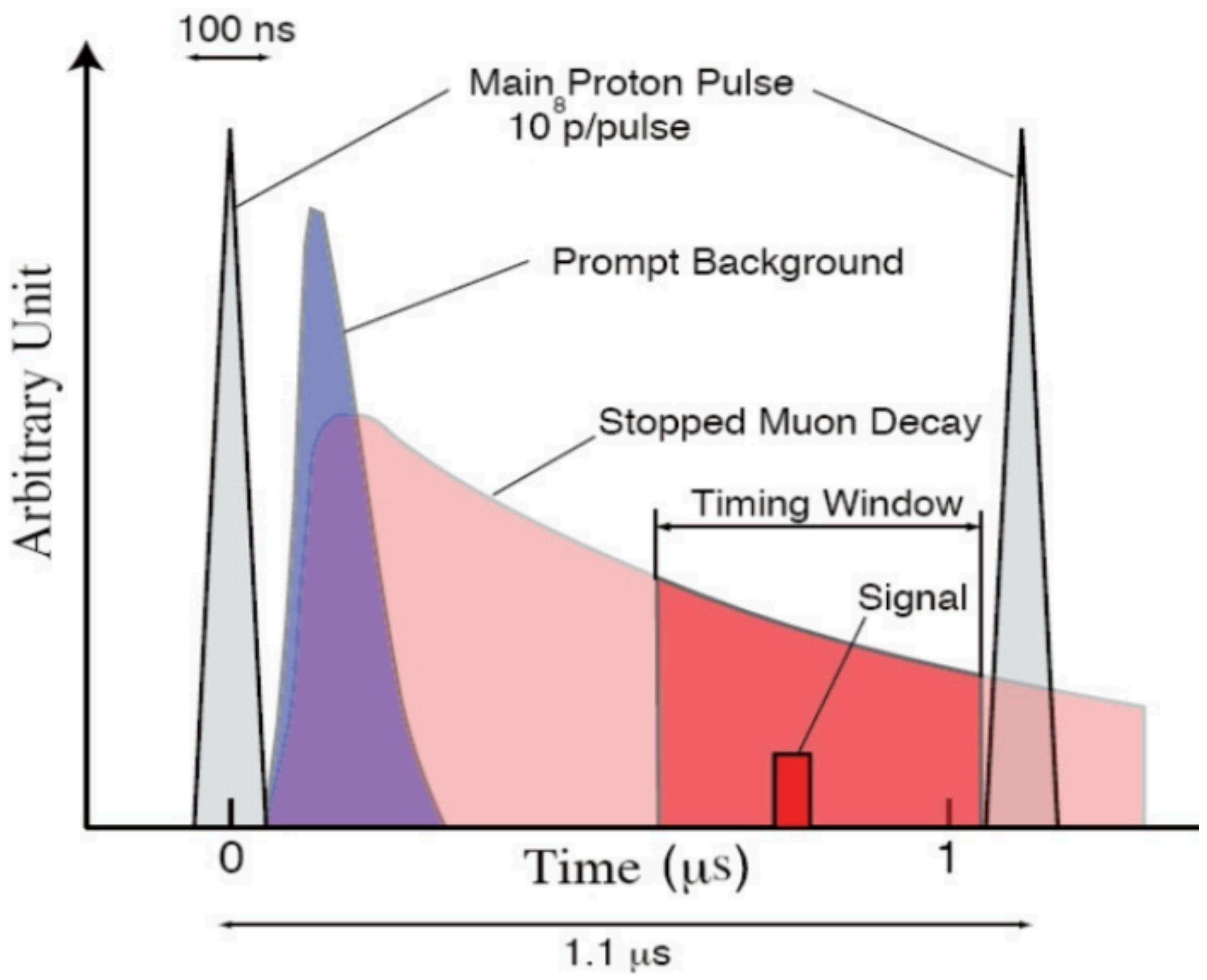
μ→e conversion: signal and background



Background:

- Intrinsic:
  - μ decay in orbit
- Beam related background:
  - Radiative π capture + contaminations

Neutrino-less conversion of a μ^- into an e^- in the field of a nucleus.
Signal: **single monoenergetic e^-, $E_e \sim E_\mu - B_\mu - E_{rec} \sim 105$ MeV**
Only one particle in final state: **no accidental background.**



μ decay: current experiments

All main muon LFV decay channels are currently subject of dedicated high resolution experiments, in different advance phases:

- **$\mu^+ \to e^+\gamma$: MEG II is taking data since 2021 and is publishing its first results**
  - Today's topic!

- **$\mu^+ \to e^+e^+e^-$: Mu3e collaboration is developing detector @PSI.**

- **$\mu^-N \to e^-N$ conversion**
  - **COMET @J-PARC and Mu2e @FermiLab are close to the end of development phase.**

Beam considerations

In **coincidence based experiments like μ→eγ and *μ*→eee, the accidental background is is proportional to R_μ^2** and it is the dominant one.
⇒ **a continuous beam is the proper choice.**

⇒ most intense DC μ beam is available at Paul Scherrer Institute

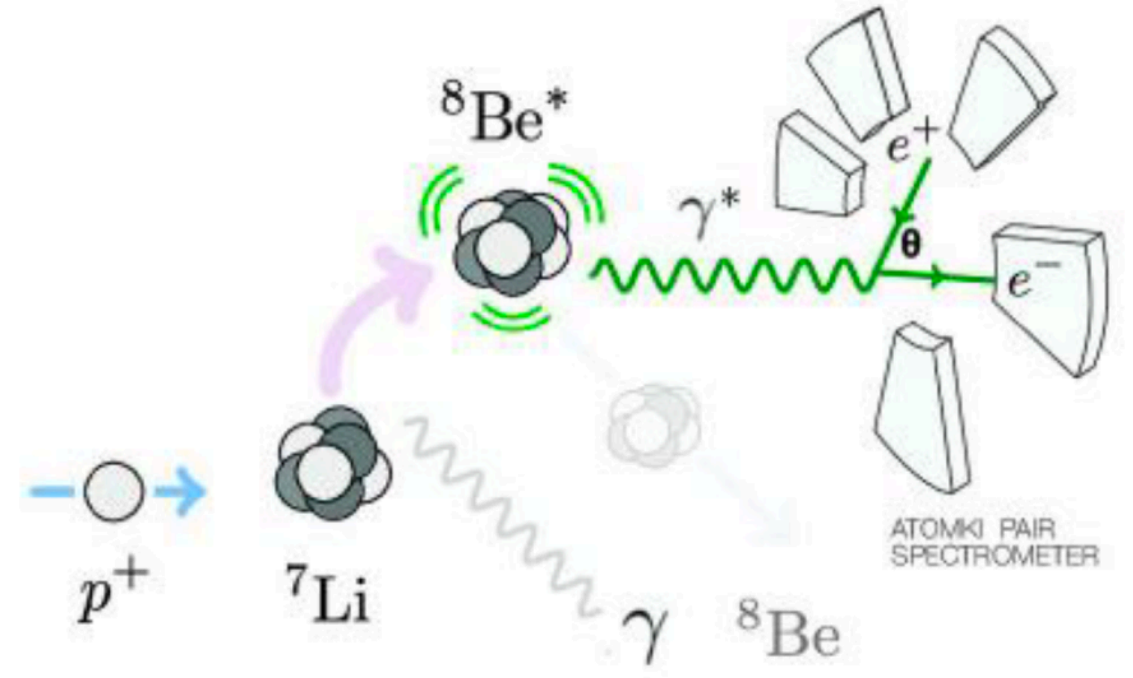
Conversely, **in μ-e conversion experiments there is only one particle in the final state.** Accidental BG is not an issue and instantaneous **beam rate can be pushed**
⇒ **pulsed beam can be used**. (J-PARC, FNAL)

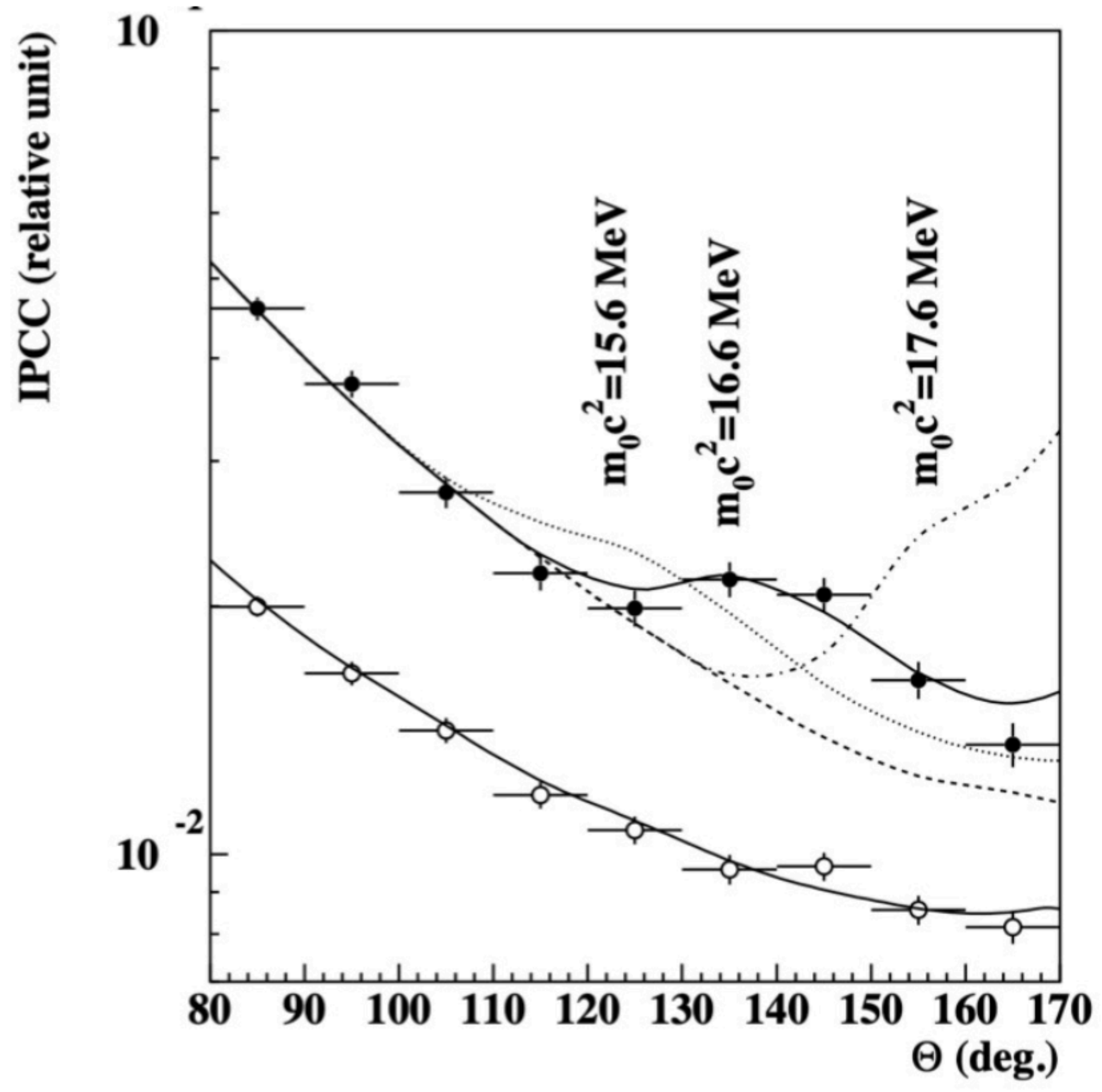
Nevertheless, beam related BG could be an issue. Proper beam handling is needed.
⇒ **more complicated beam transport line to reduce background.**

Search for signal at delayed time.

Other "exotic" searches: X17 boson

- In 2016 the ATOMKI experiment reported an excess in the angular distribution of **e^+e^-** pairs in an inelastic interaction of protons on a Li target. This excess can be interpreted as due to the production of a **17 MeV** boson (X17), mediator of an hypotethical fifth force.
- In MEG II we can search for X17 by using:
  - Dedicated runs with reduced magnetic field
  - CDCH + pTC detectors for e^+e^- reconstruction, using an extended tracking code to search for two opposite charge particles;
  - CW accelerator proton beam on a dedicated target;
  - LXe calorimeter for photon tagging
  - Analisys of first dedicated DAQ will be released soon!





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Other “exotic” searches: axion like particles

- Search for μ→eaγ (a = axion like particle).
- 3 bodies decay → needs a completely different analysis and DAQ strategy w.r.t. μ→eγ:
  - search for a peak in invariant mass distribution;
  - much lower energy cut ~ 10MeV;
  - release back to back e+γ topology;
  - reduce beam intensity (down to 10^6 μ/s)
- Main background is given by RMD…