

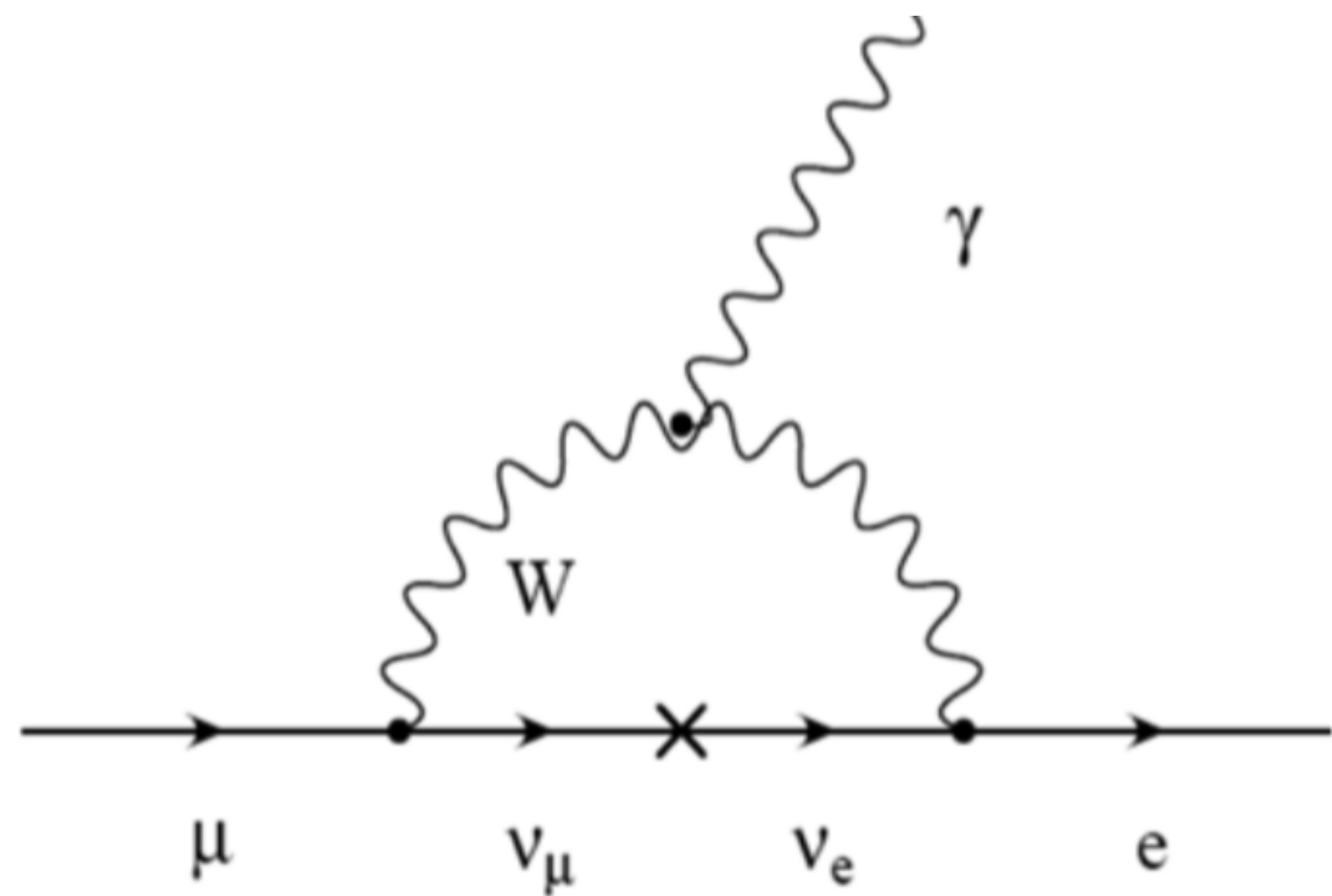
Status of the BSM searches with the MEG II apparatus



Luca Galli, INFN Sezione di Pisa
La Thuile 14-03-2025

cLFV = physics beyond SM

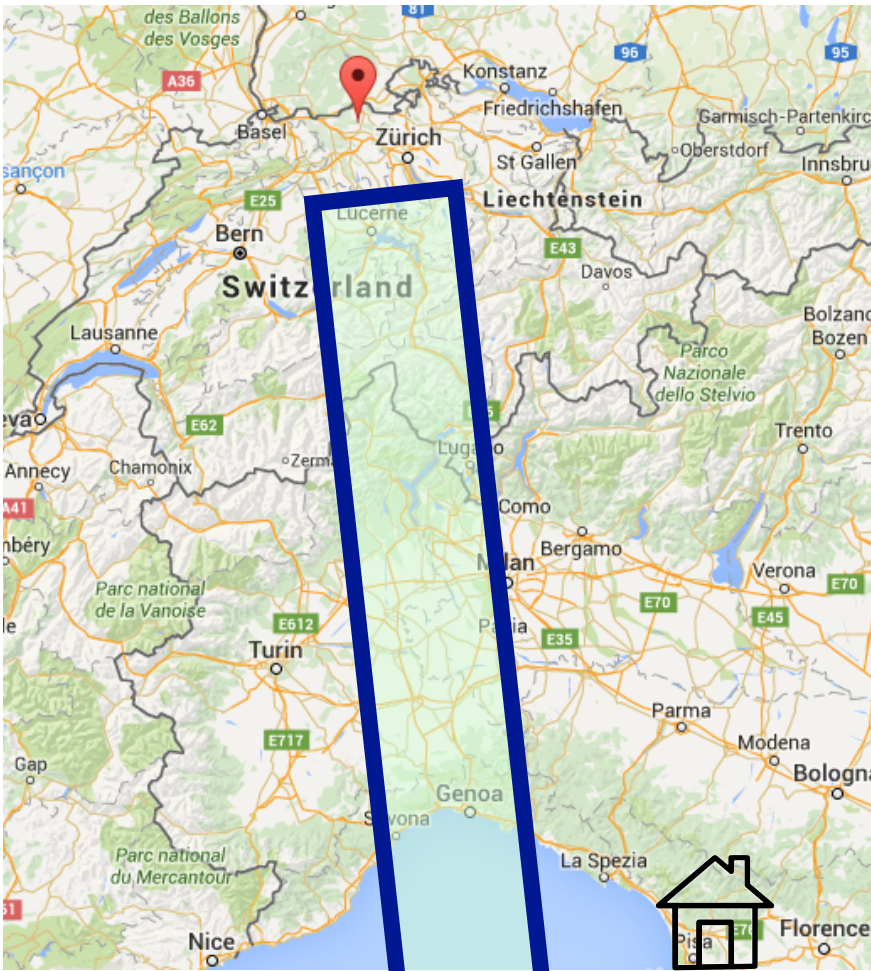
- $l \rightarrow l' + X$ ($X = \gamma, \dots, ee, \mu\mu, \text{others...}$)



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

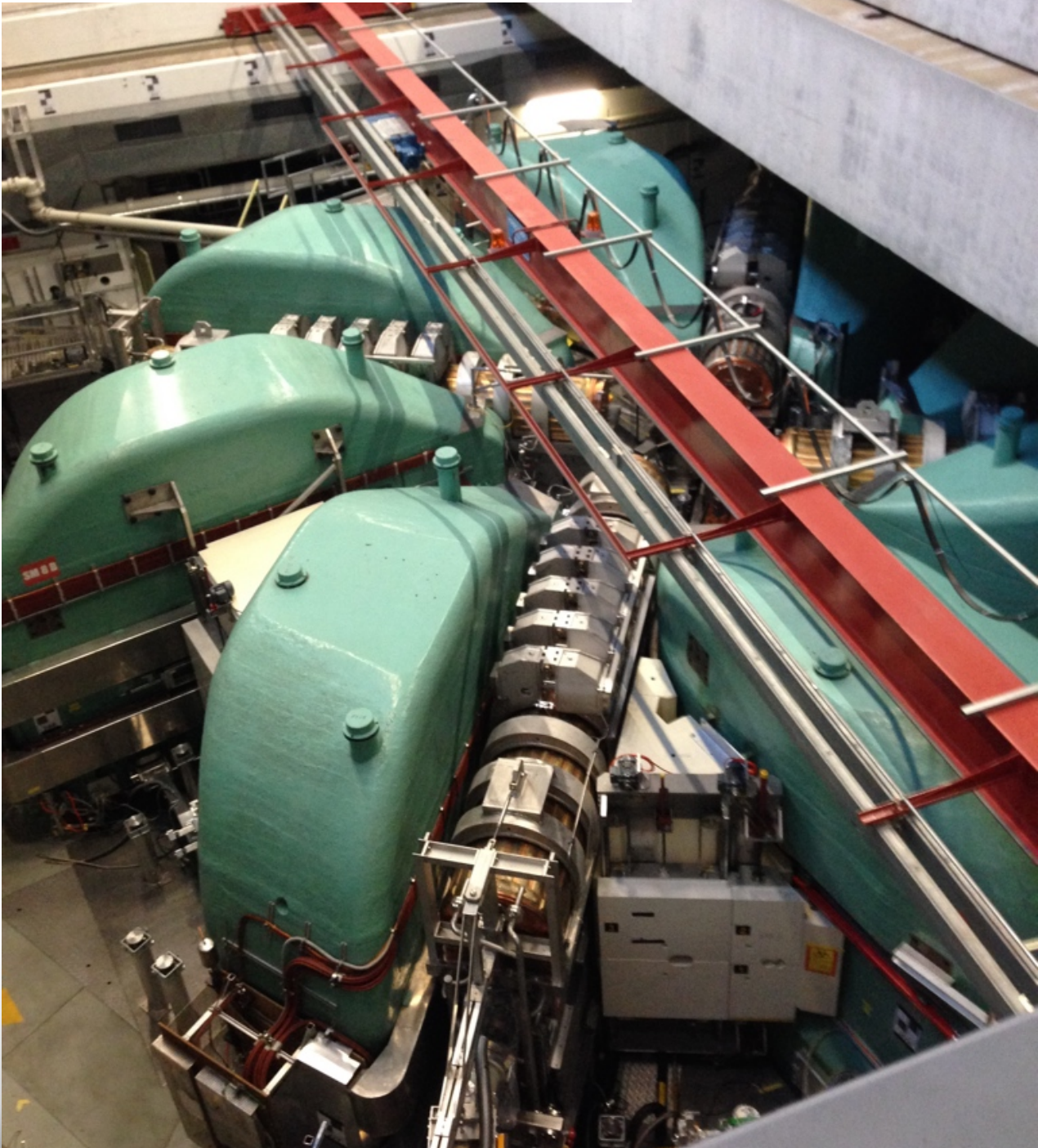
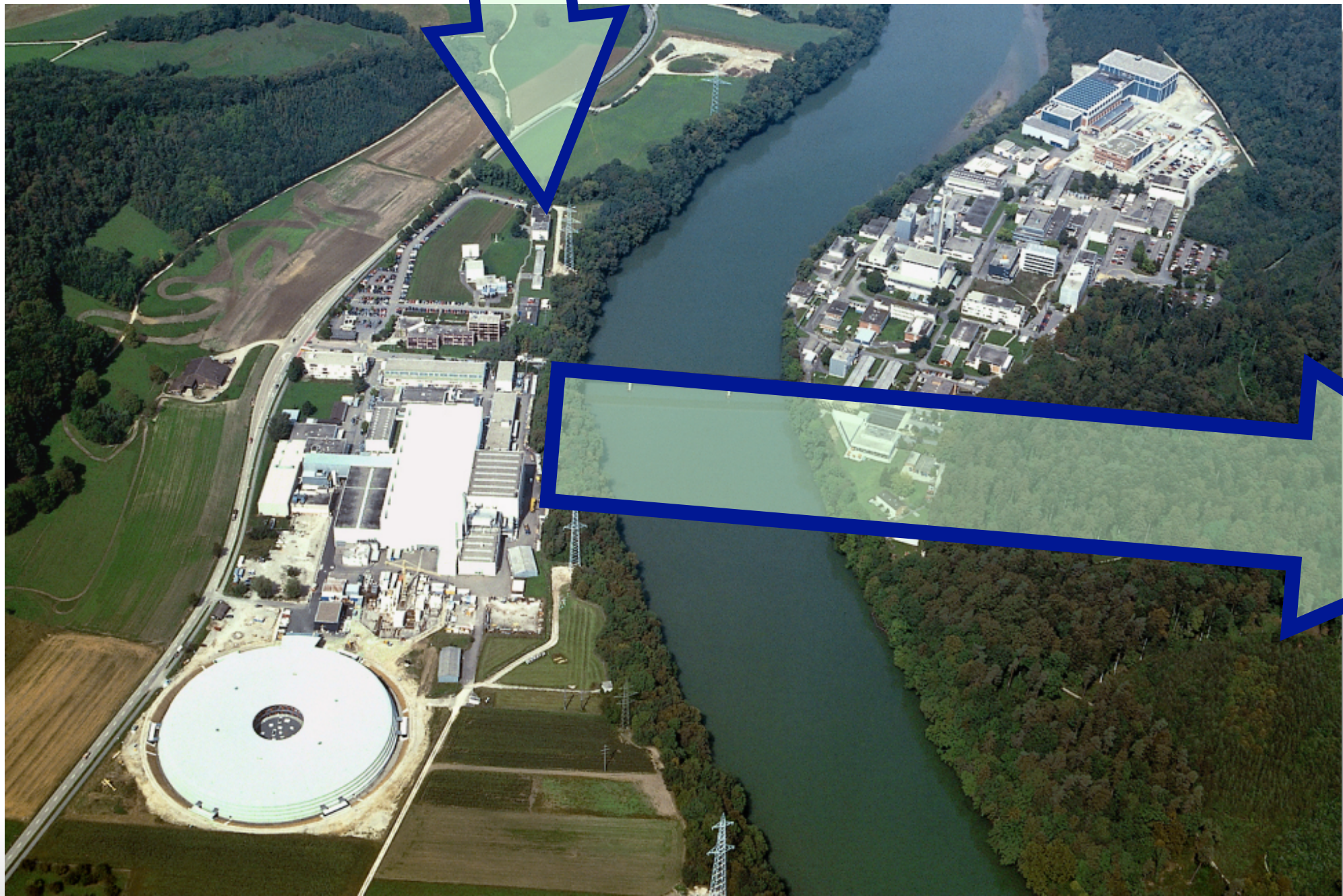
too small to be experimentally
accessible $\rightarrow$ portal to New Physics
extensively exploited in intensity
frontier searches
SM background free searches!

The MEG II experiment @PSI



MEG collaboration
~60 physicists from 12 institutes from 5 countries

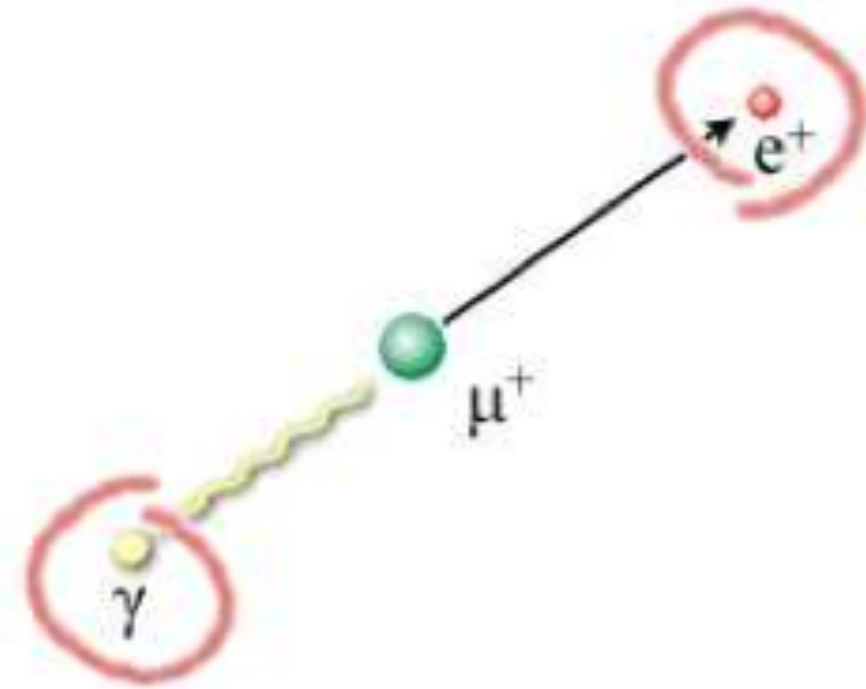
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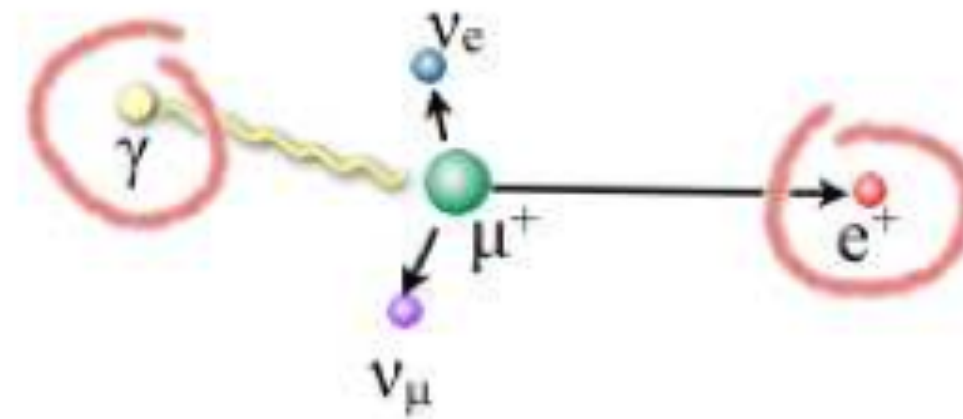
PSI Ring
Cyclotron

$\mu \rightarrow e\gamma$ search: signal and background

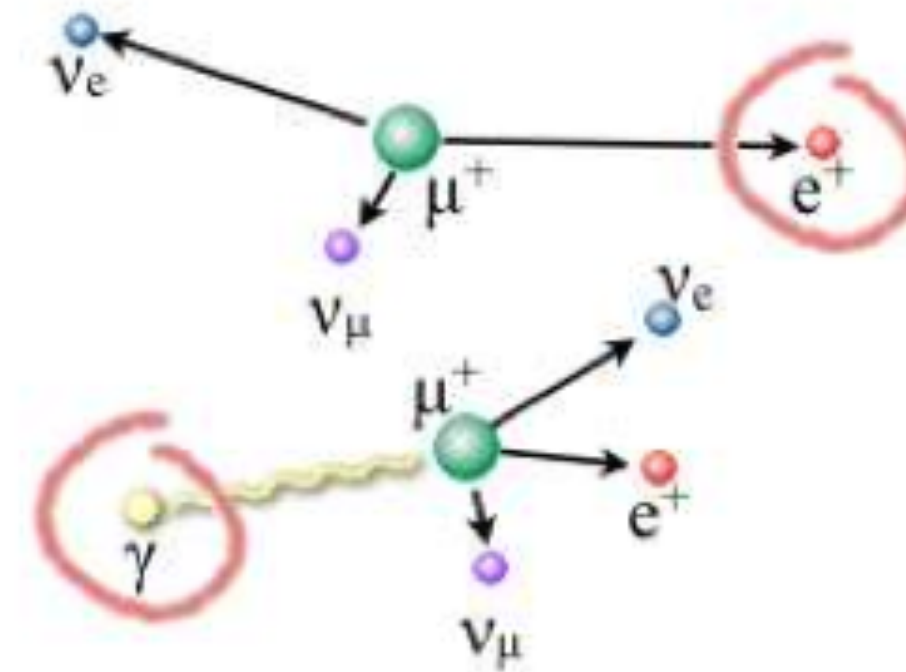
signal



RMD



Accidental



$E_\gamma = 52.8 \text{ MeV}$	$E_\gamma < 52.8 \text{ MeV}$	$E_\gamma < 52.8 \text{ MeV}$
$E_{e^+} = 52.8 \text{ MeV}$	$E_{e^+} < 52.8 \text{ MeV}$	$E_{e^+} < 52.8 \text{ MeV}$
$\Theta_{e\gamma} = 180^\circ$	$\Theta_{e\gamma} < 180^\circ$	$\Theta_{e\gamma} < 180^\circ$
$T_{e\gamma} = 0 \text{ s}$	$T_{e\gamma} = 0 \text{ s}$	$T_{e\gamma} \Rightarrow \text{flat}$

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

$$B_{acc} \propto R_\mu \Delta E_e \Delta E_\gamma^2 \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma}$$

$$B_{RMD} \approx 0.1 \cdot B_{acc}$$

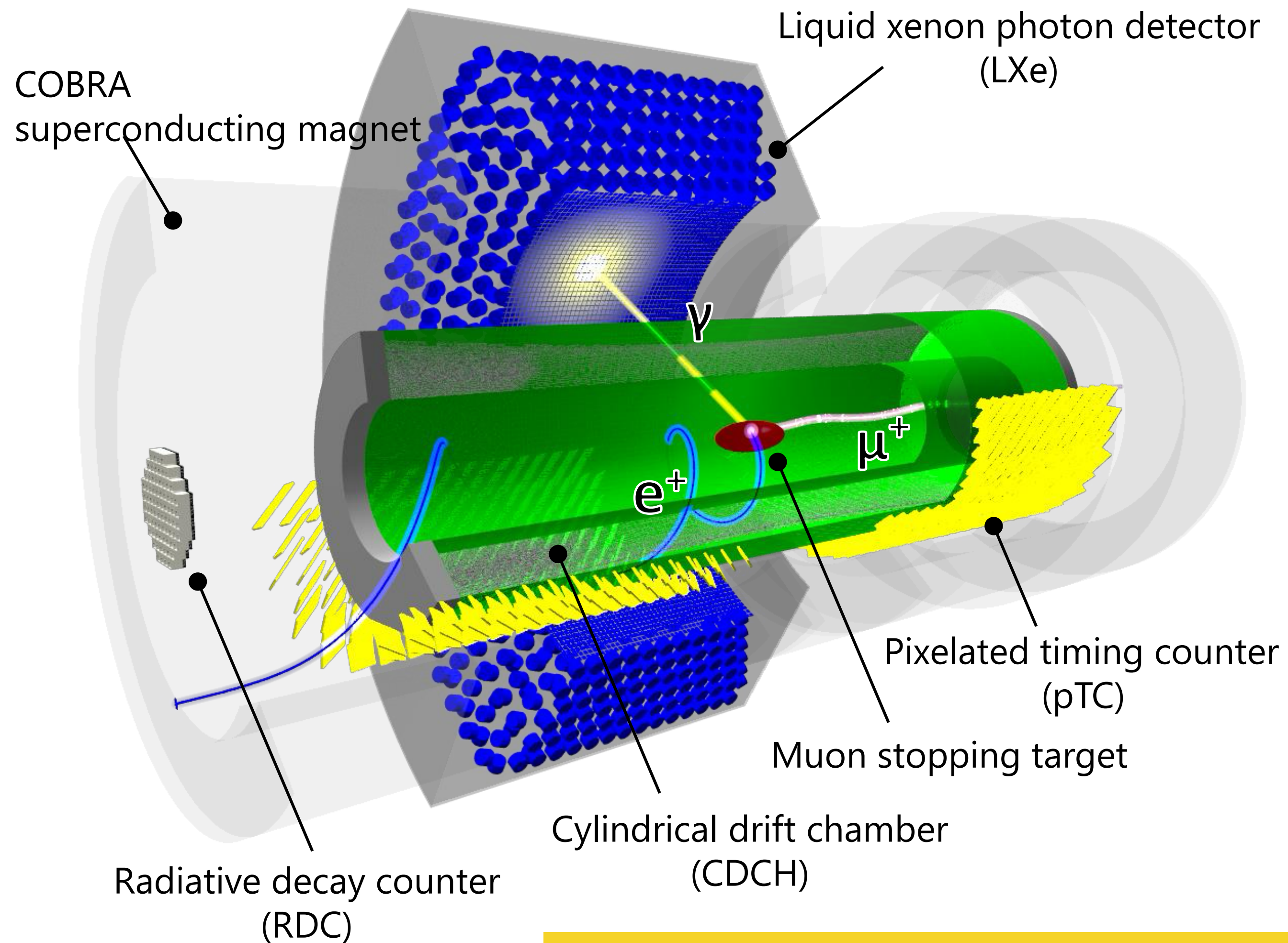
Keywords

- (1) **thin**: “low” energy
- (2) **fast**: high rate $\iff$ high intensity frontier
- (3) **stable**: precision measurement $\iff$ background rejection

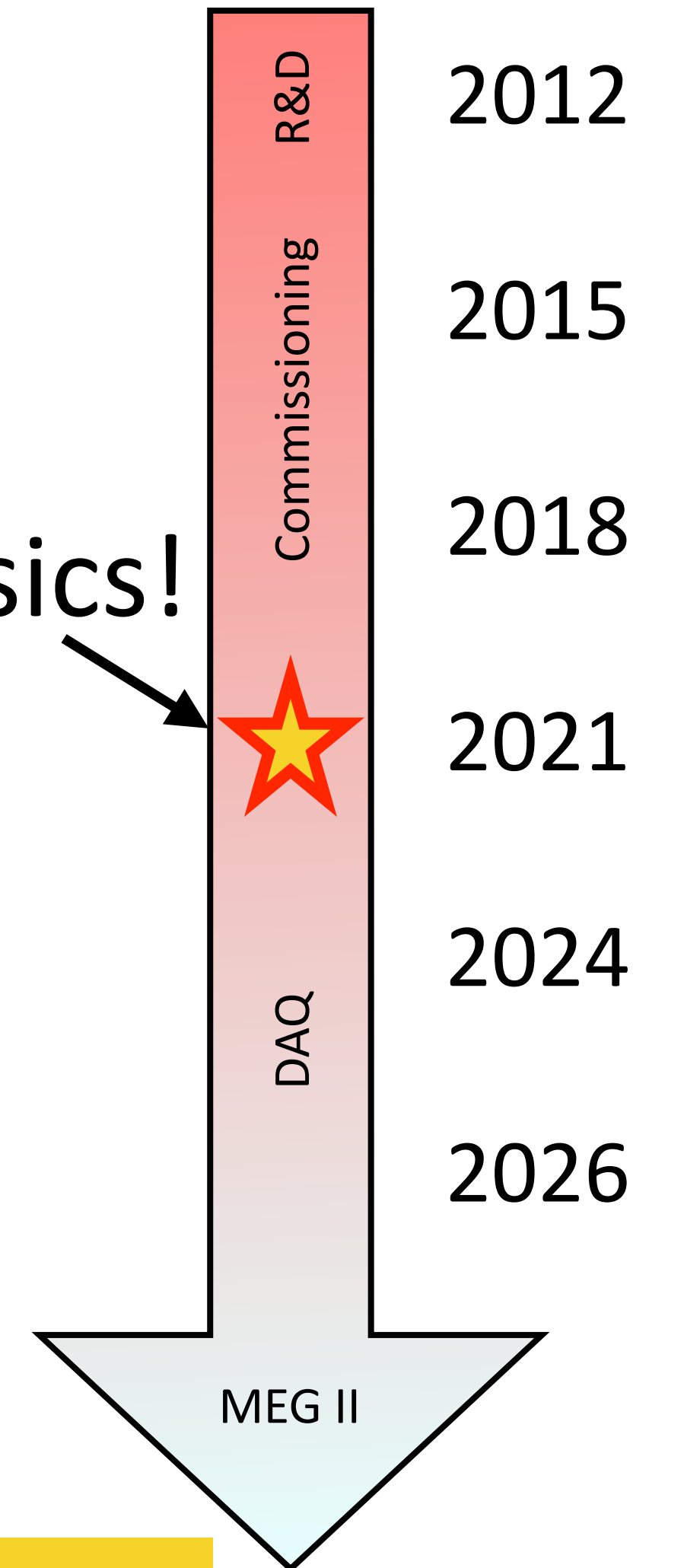
MEG II solutions

- . **μ beam stopped** on a 174 μ m BC400 target (1)
- . **non uniform solenoidal magnetic field** (2)
- . tracking with **ultra-thin drift chamber** (1) and timing with **plastic scintillators** (2)
- . **γ detection with LXe scintillator** (1+2)
- . **complete and redundant calibration** techniques (3)

Experimental approach

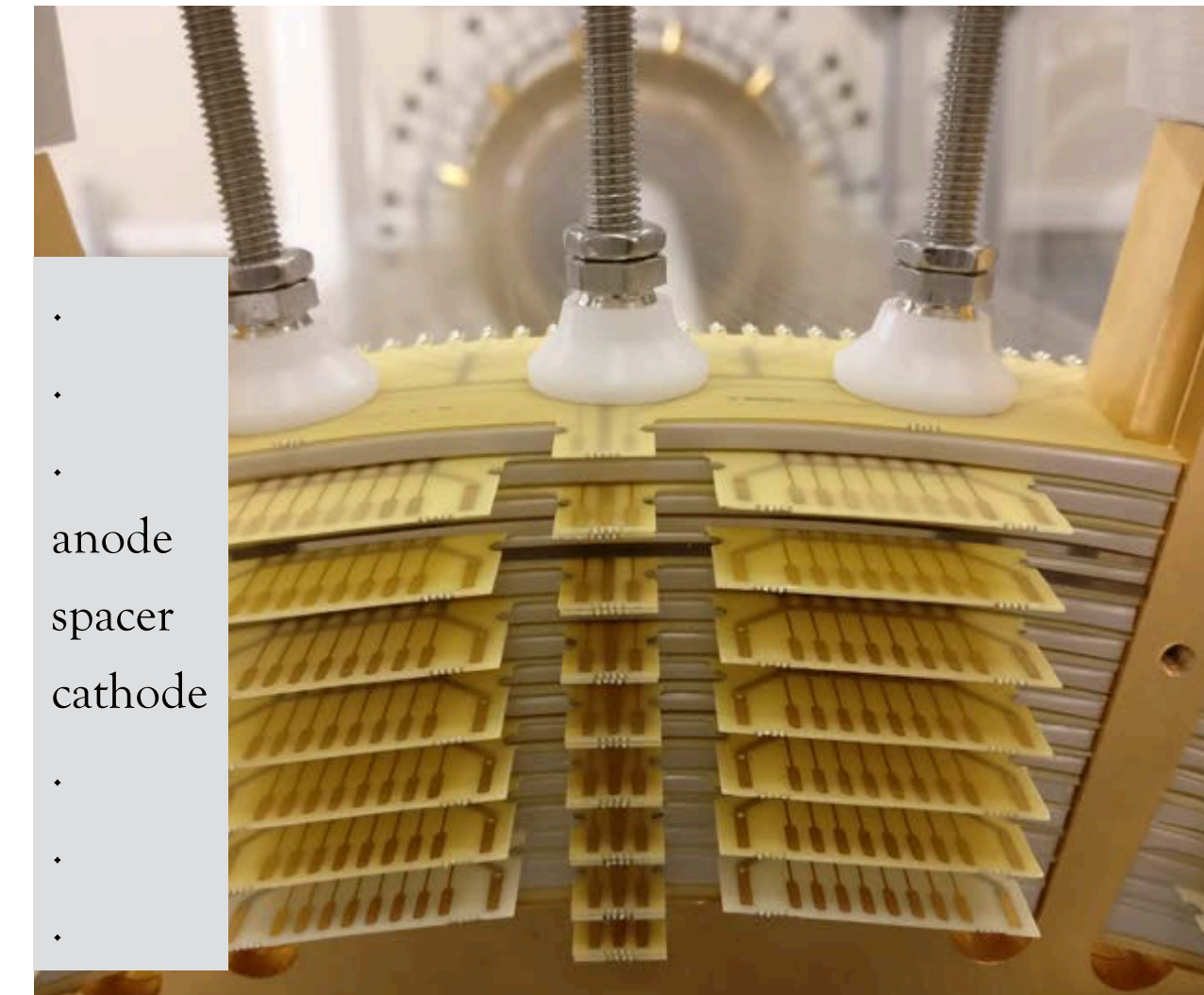
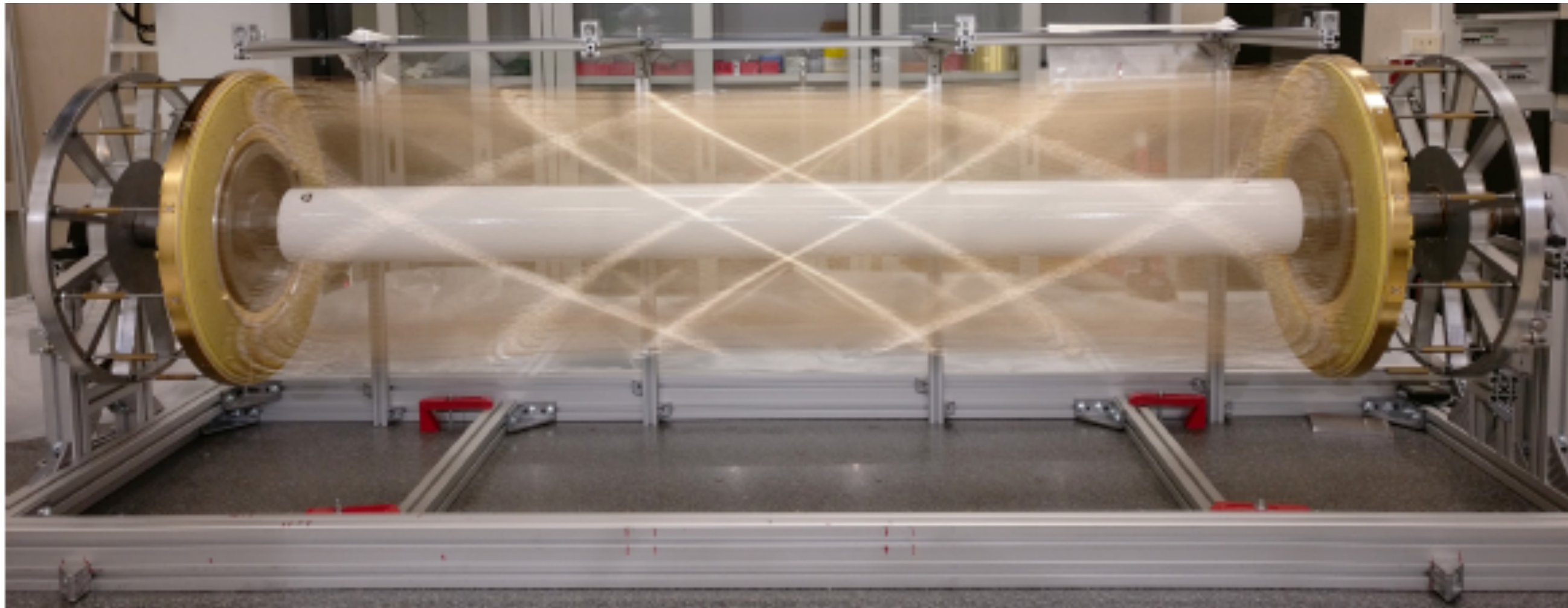


Physics!

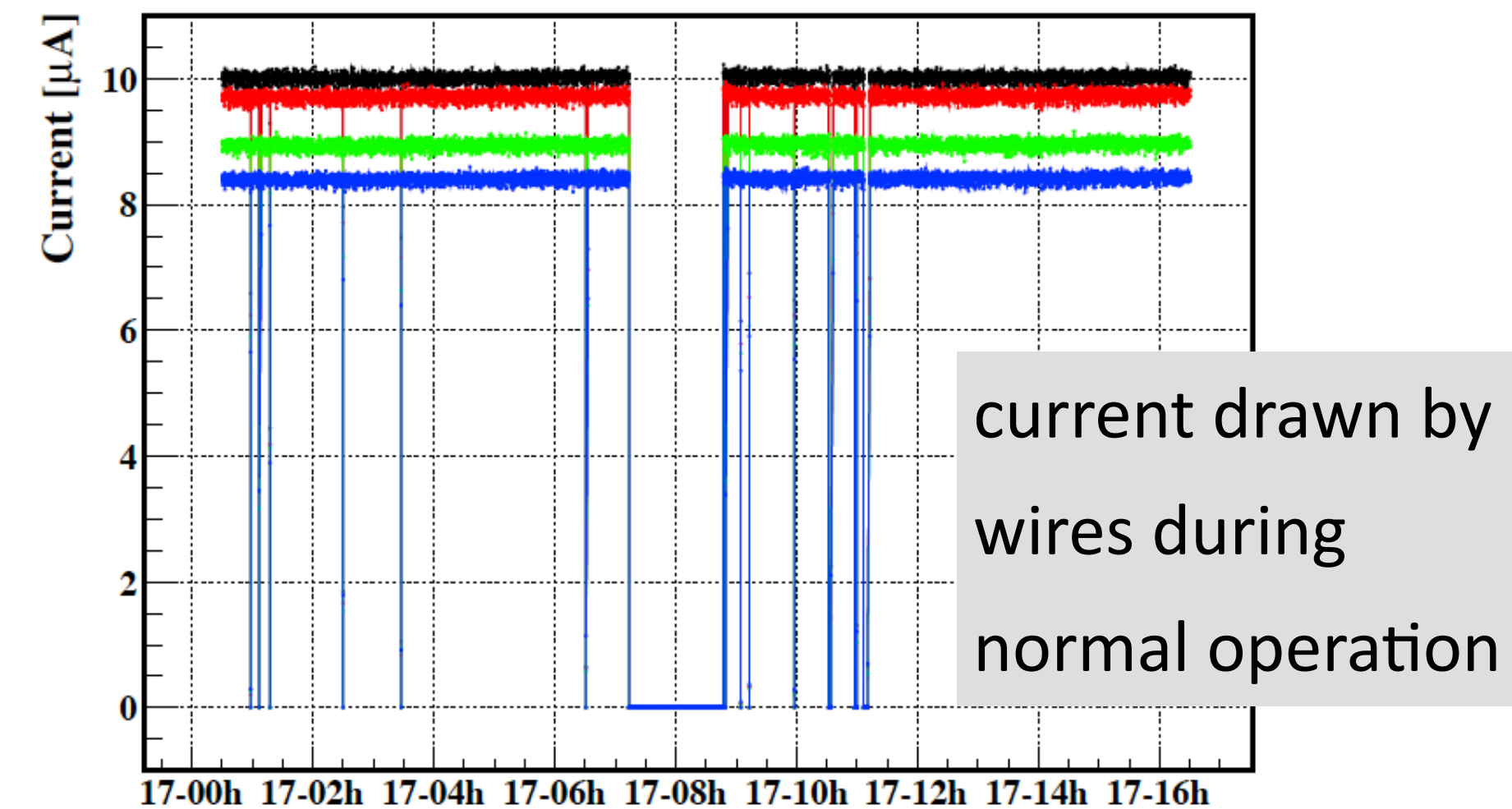


A. M. Baldini et al, The design of the MEG II experiment EPJC, 2018
K. Afanaciev et al, Operation and performance of the MEG II detector EPJC, 2023

CDCH detector



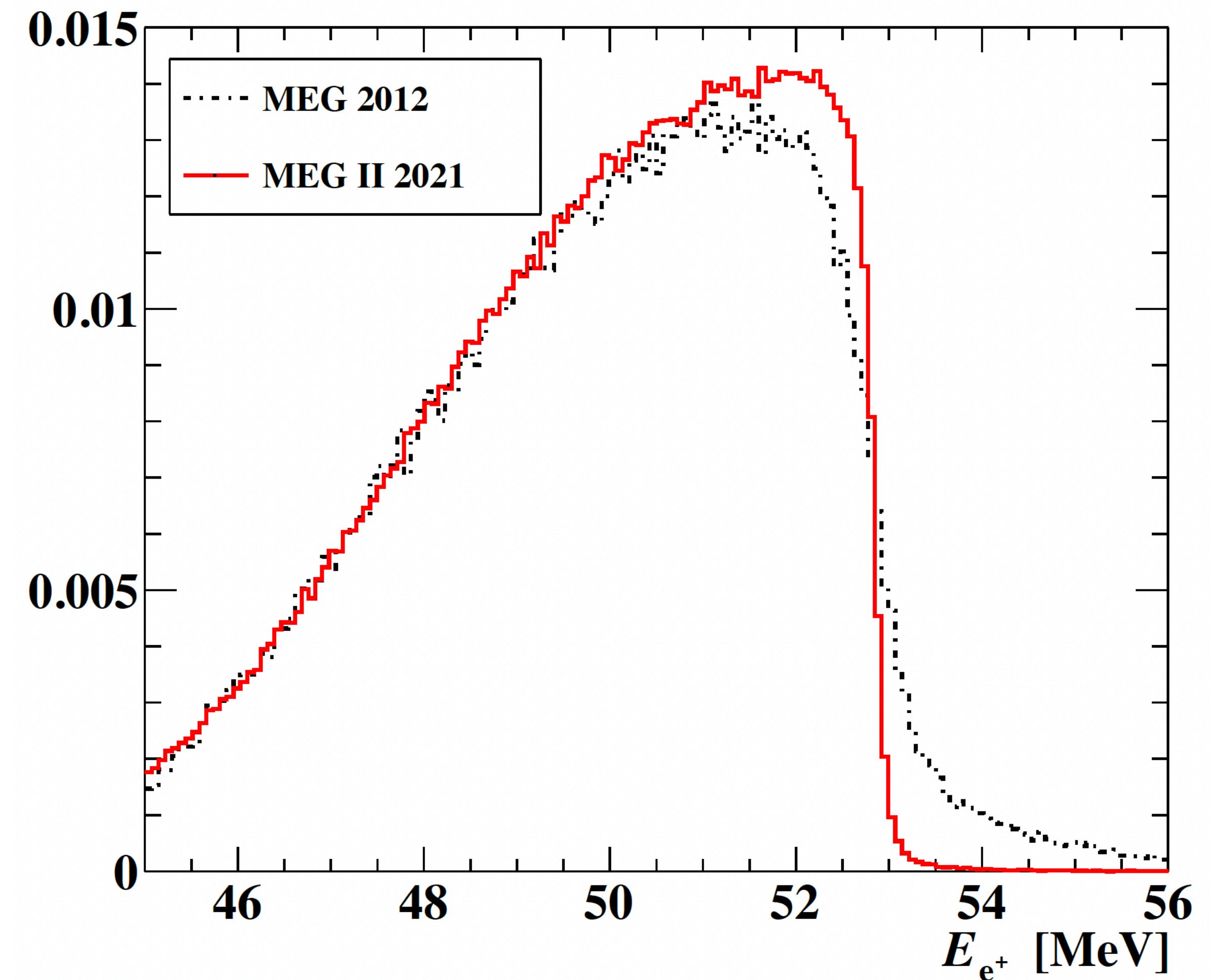
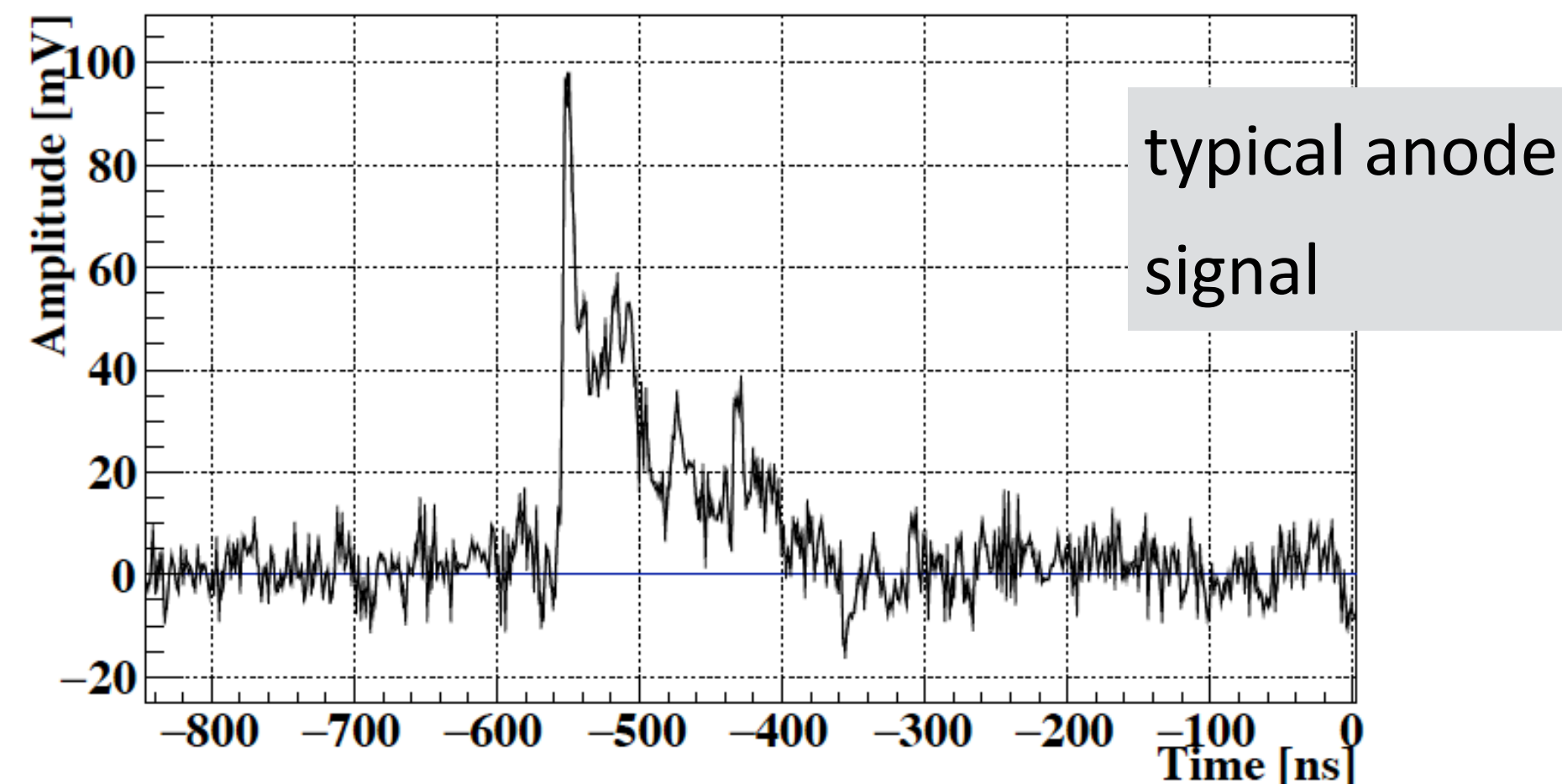
- **single** volume drift chamber
- **He-Isobuthane (90-10) low mass** gas mixture (*+ addition 1% isopropilic alcohol and ~0.5% oxygen or less*)
 - 2×10^{-3} *radiation length per track*
- **1728 anode** wires + **~10000 cathodes**
 - *anode: 20 μ m W/Au, cathode: 40/50 μ m Al/Ag*
 - *7 degree stereo angle*
- In **operation** since **late 2020** after 2 years of commissioning



CDCH performance

$$B_{acc} \propto R_{\mu} \Delta E_e \Delta E_{\gamma}^2 \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma}$$

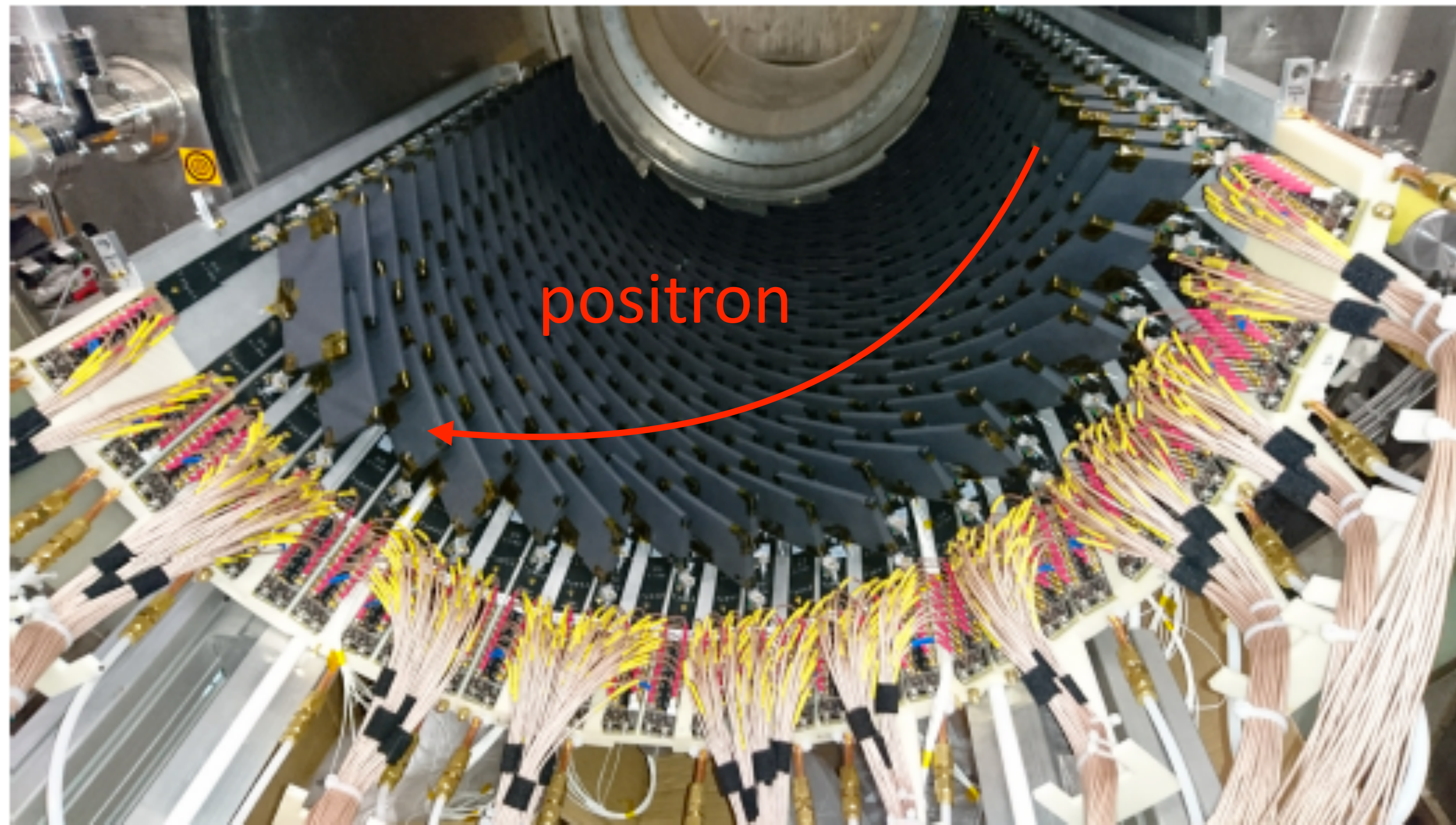
- Performance at MC level in most the variables
- *single hit resolution* $\sim 150\mu\text{m}$
- *momentum resolution* $\sim 90\text{keV}/c$ (core)
- *tracking efficiency* $\sim 75\%$ @ $3e7 \mu/s$



A. M. Baldini et al, Performances of a new generation tracking detector: the MEG II cylindrical drift chamber, EPJC 2024

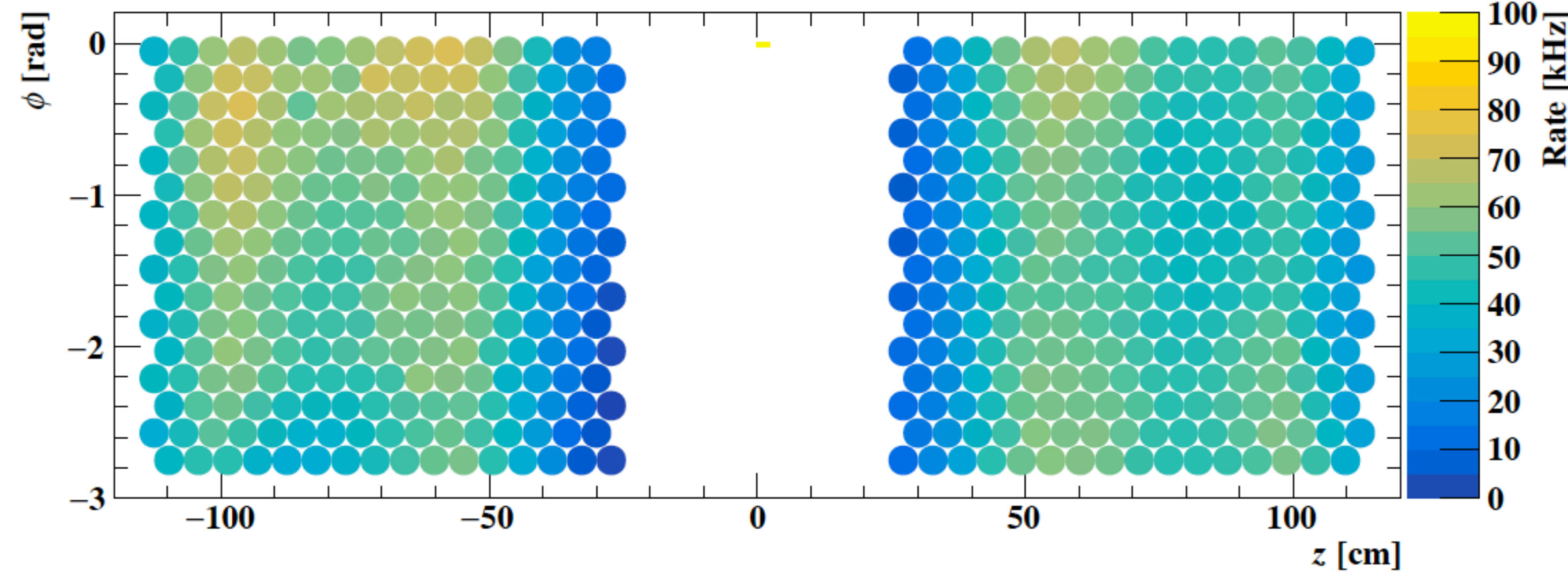
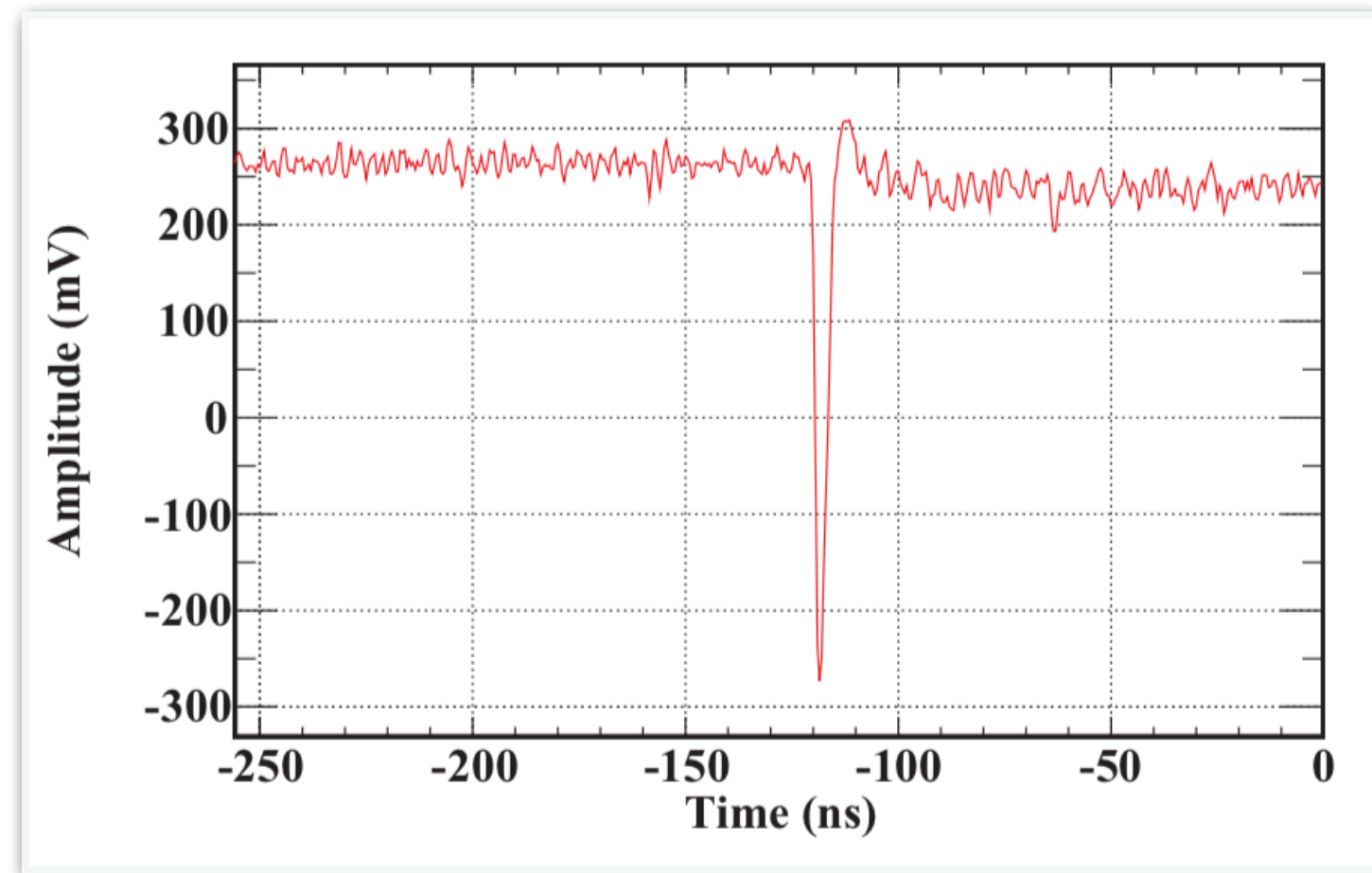
Pixelated Timing Counter detector

- Highly segmented detector
 - *Two sectors made of 256 scintillation tiles each*
 - **Bicron BC422** read by **Advansid SiPM**
 - *Time by averaging the tiles hit by a positron*
 - **8 tiles on average** for **signal positrons**
 - *Laser can be injected in most of the tiles for time calibration and monitoring*

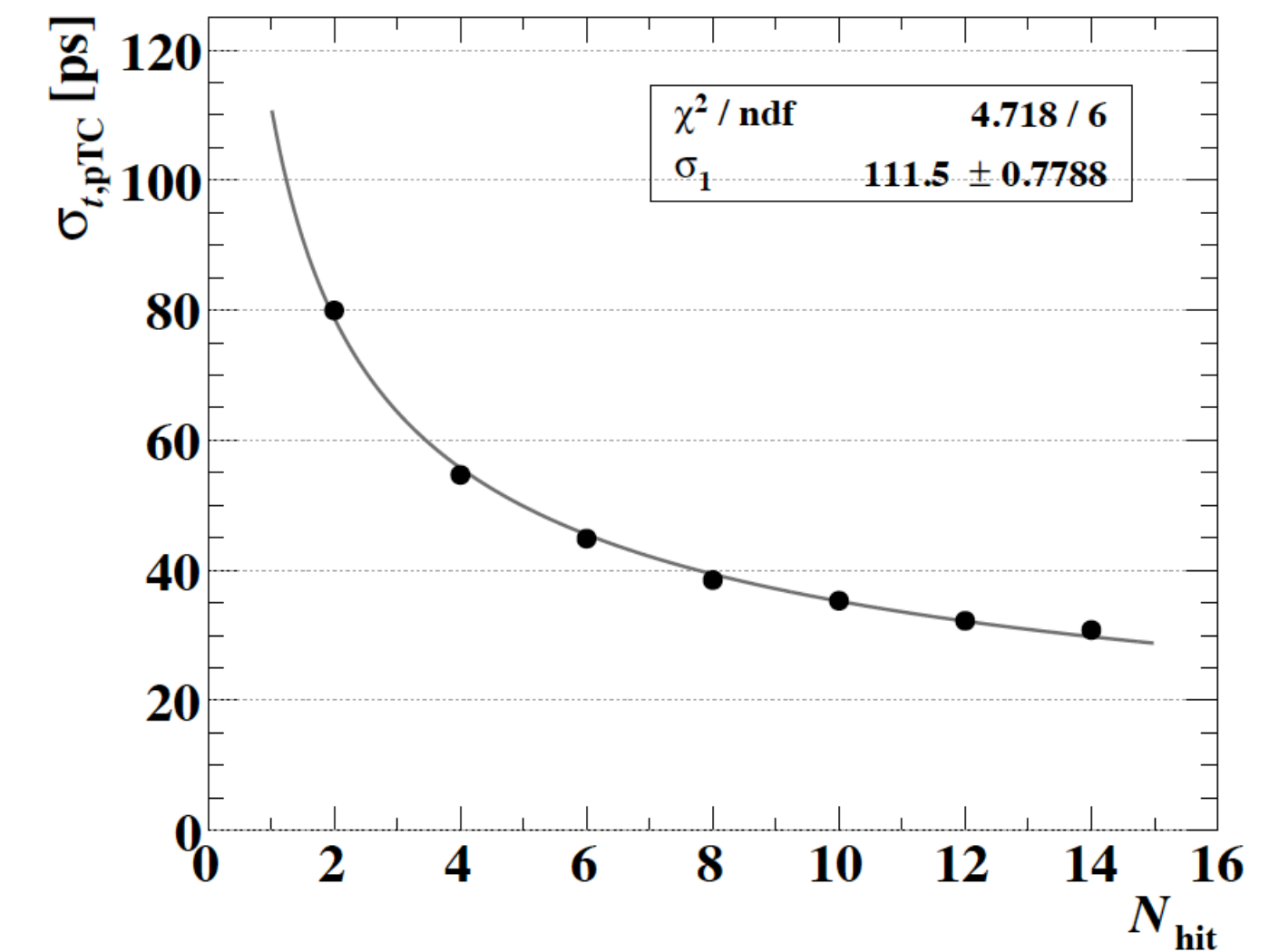


pTC performance

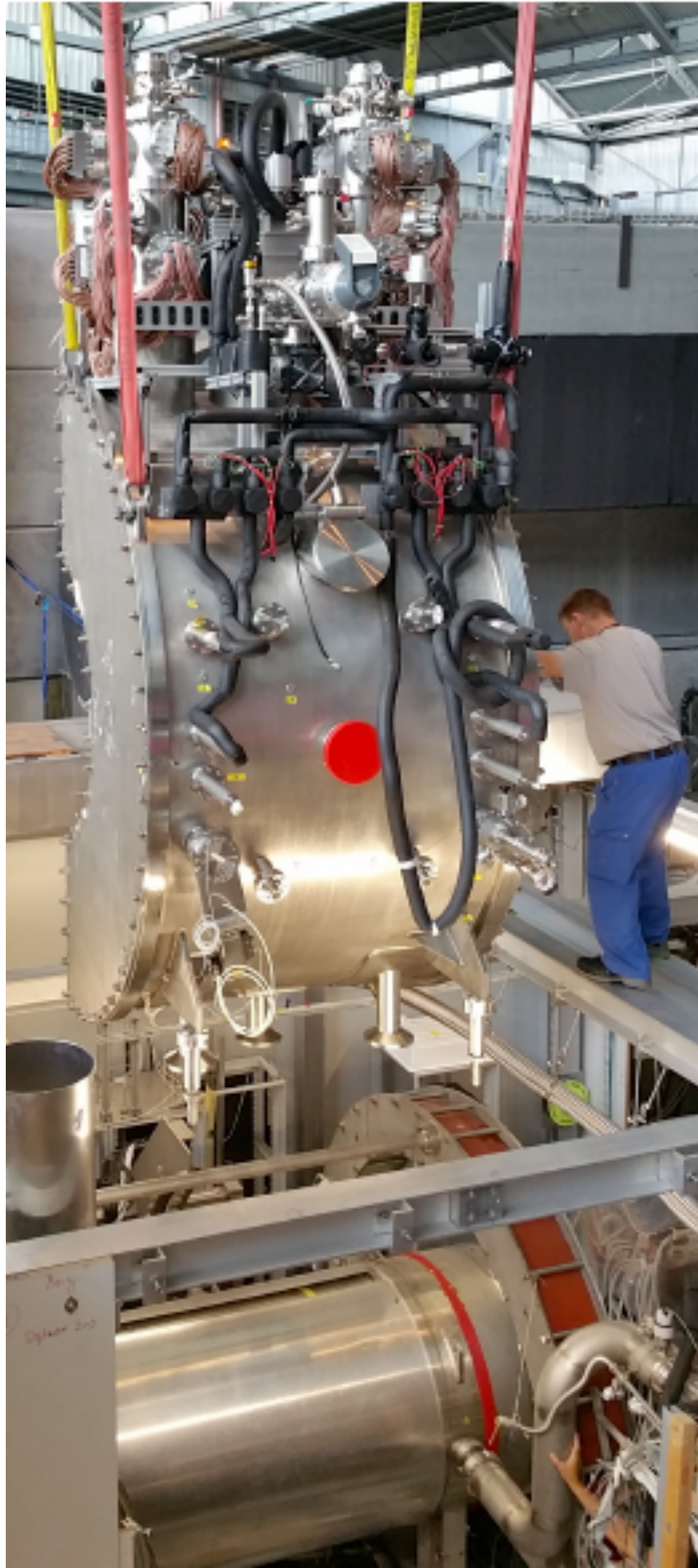
$$B_{acc} \propto R_{\mu} \Delta E_e \Delta E_{\gamma}^2 \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma}$$



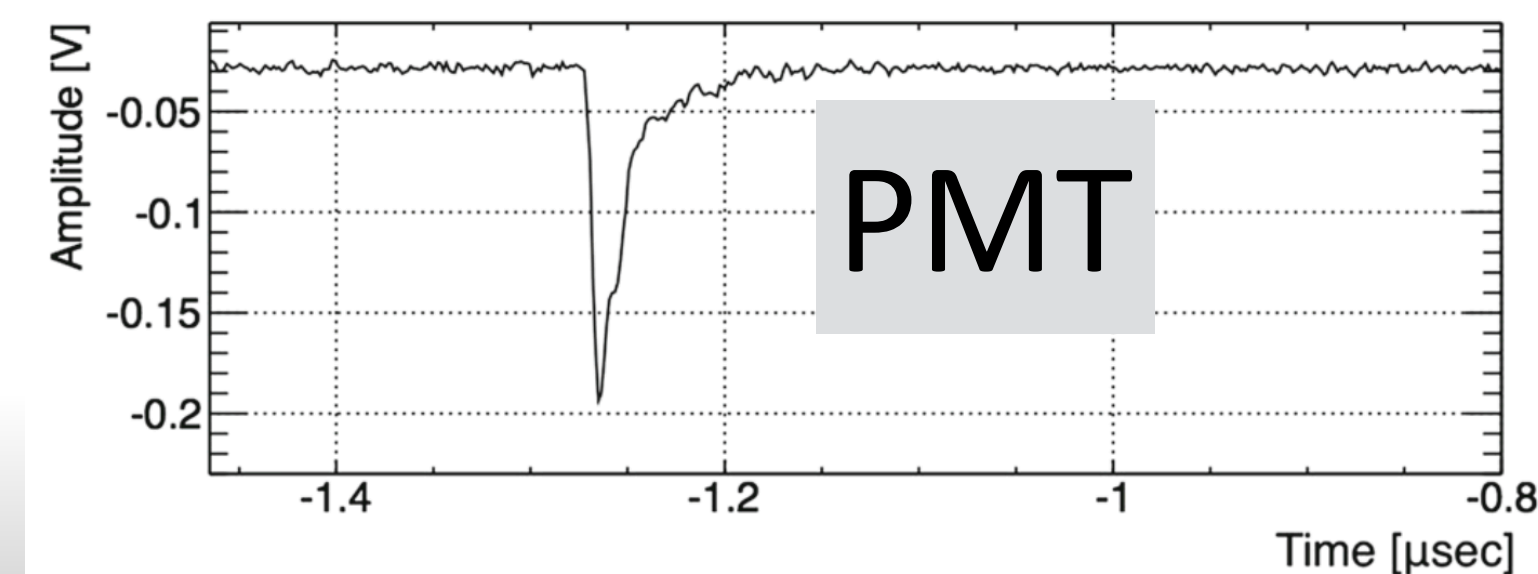
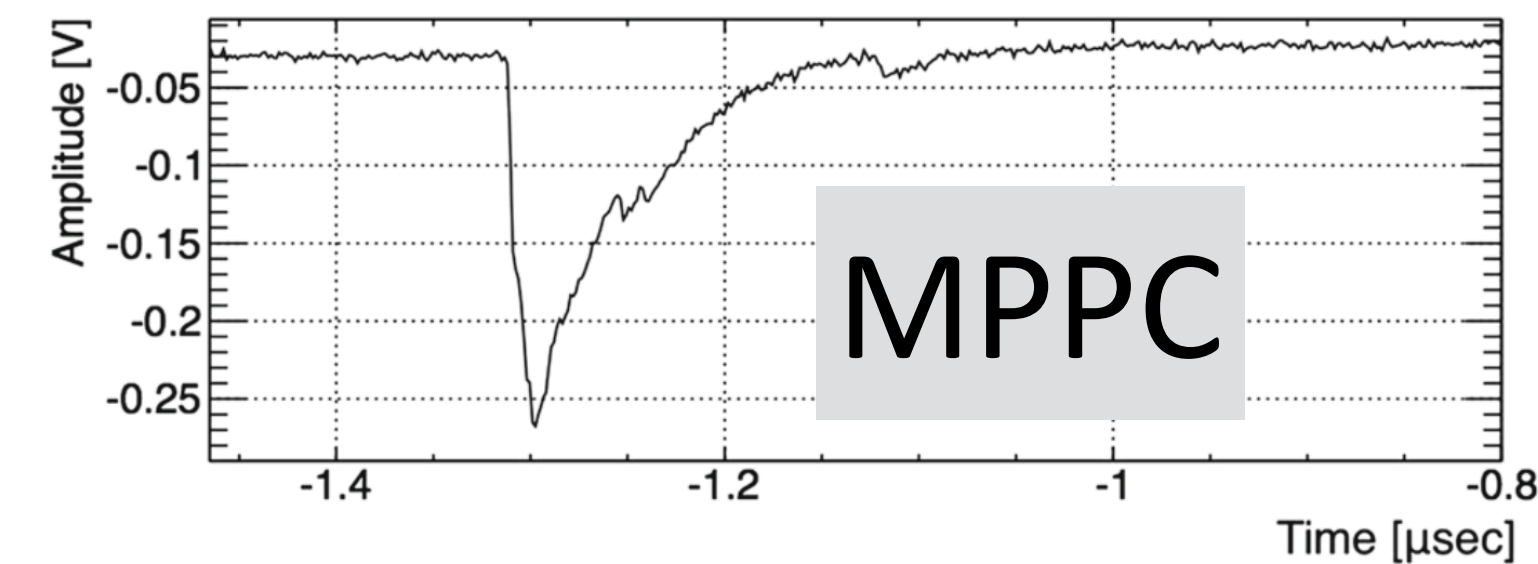
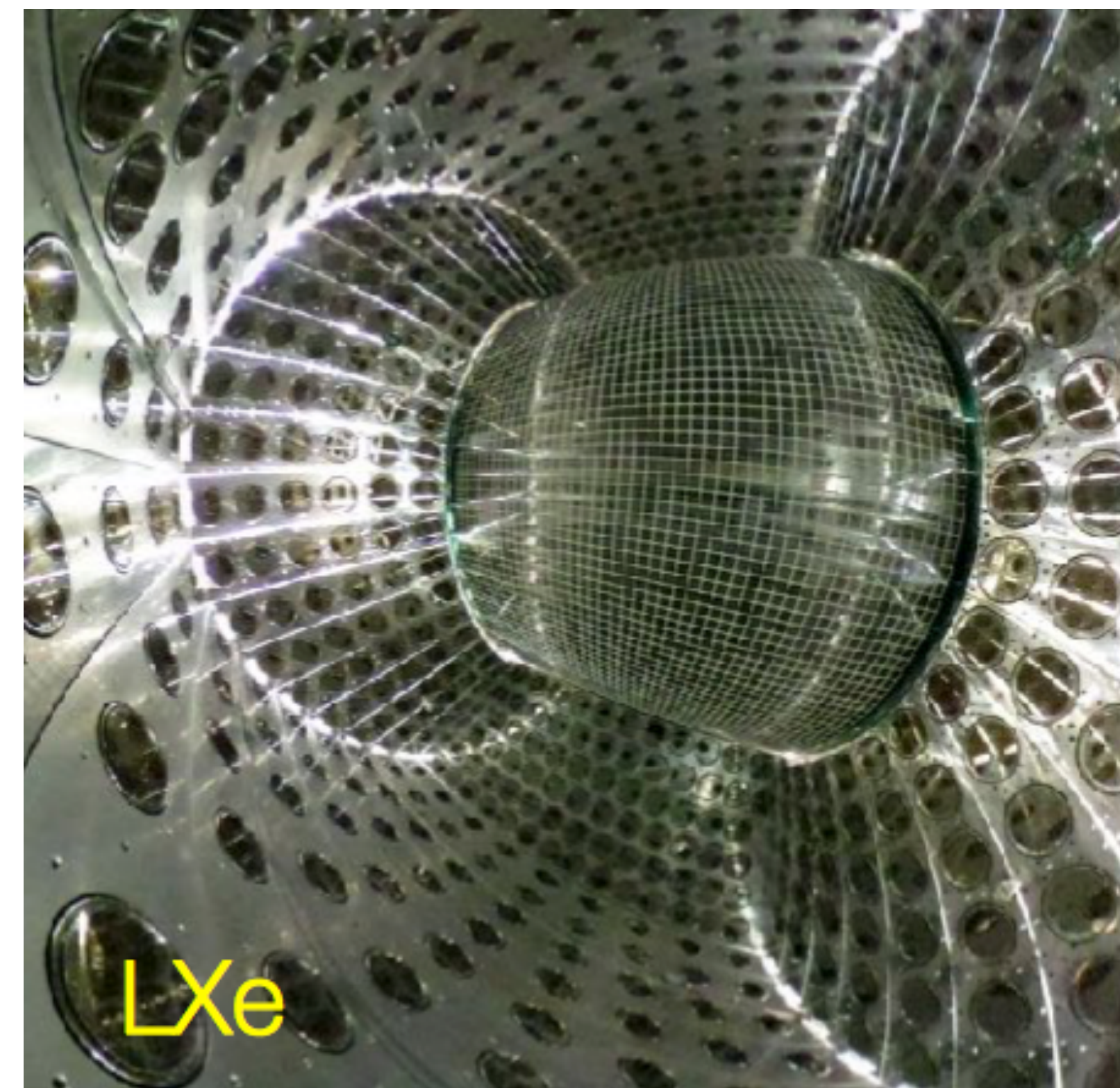
- **Stable detector operation**
- **Tile rates in agreement with expectation**
- **Time resolution of about 30ps for signal positrons**



LXe detector



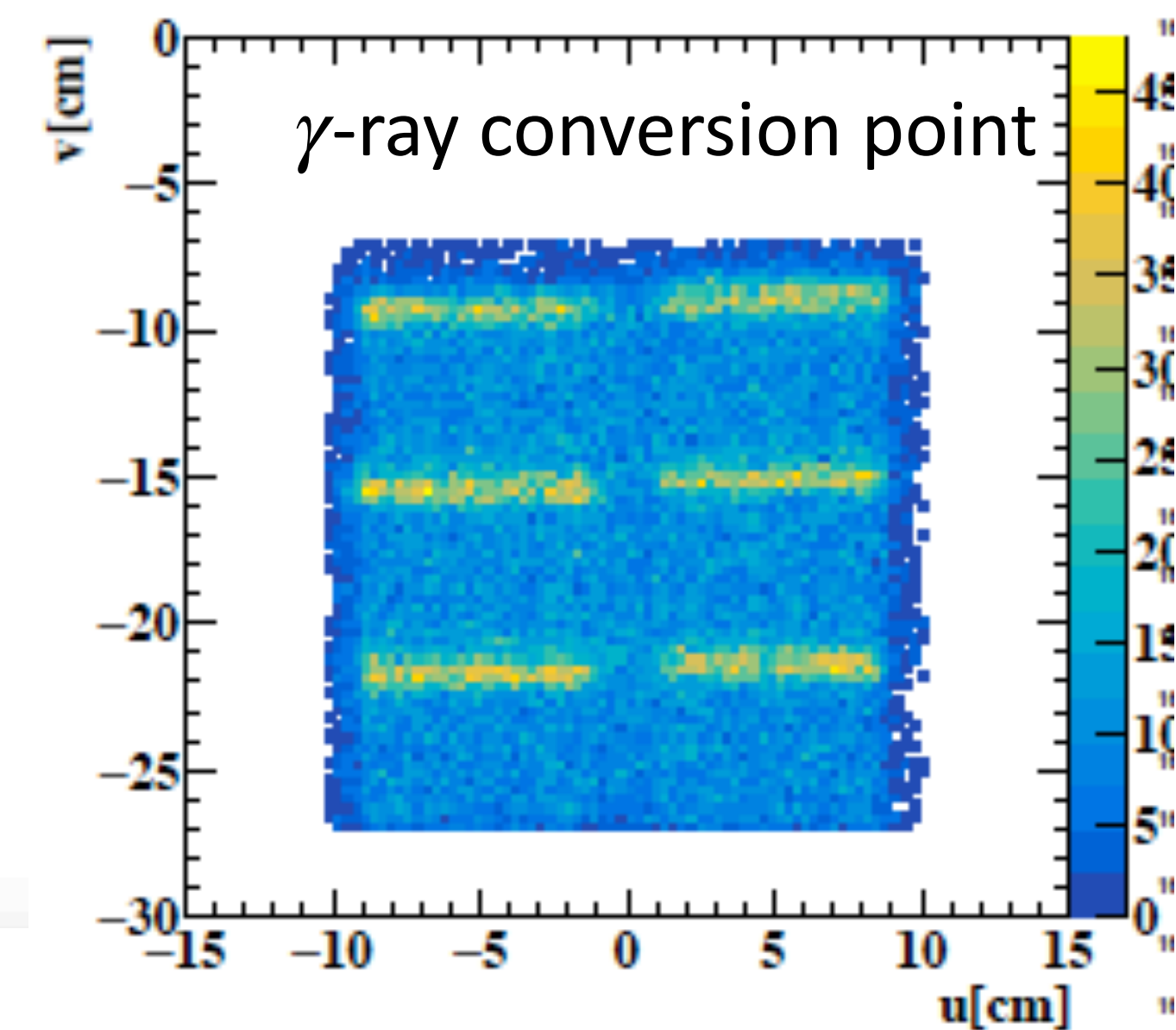
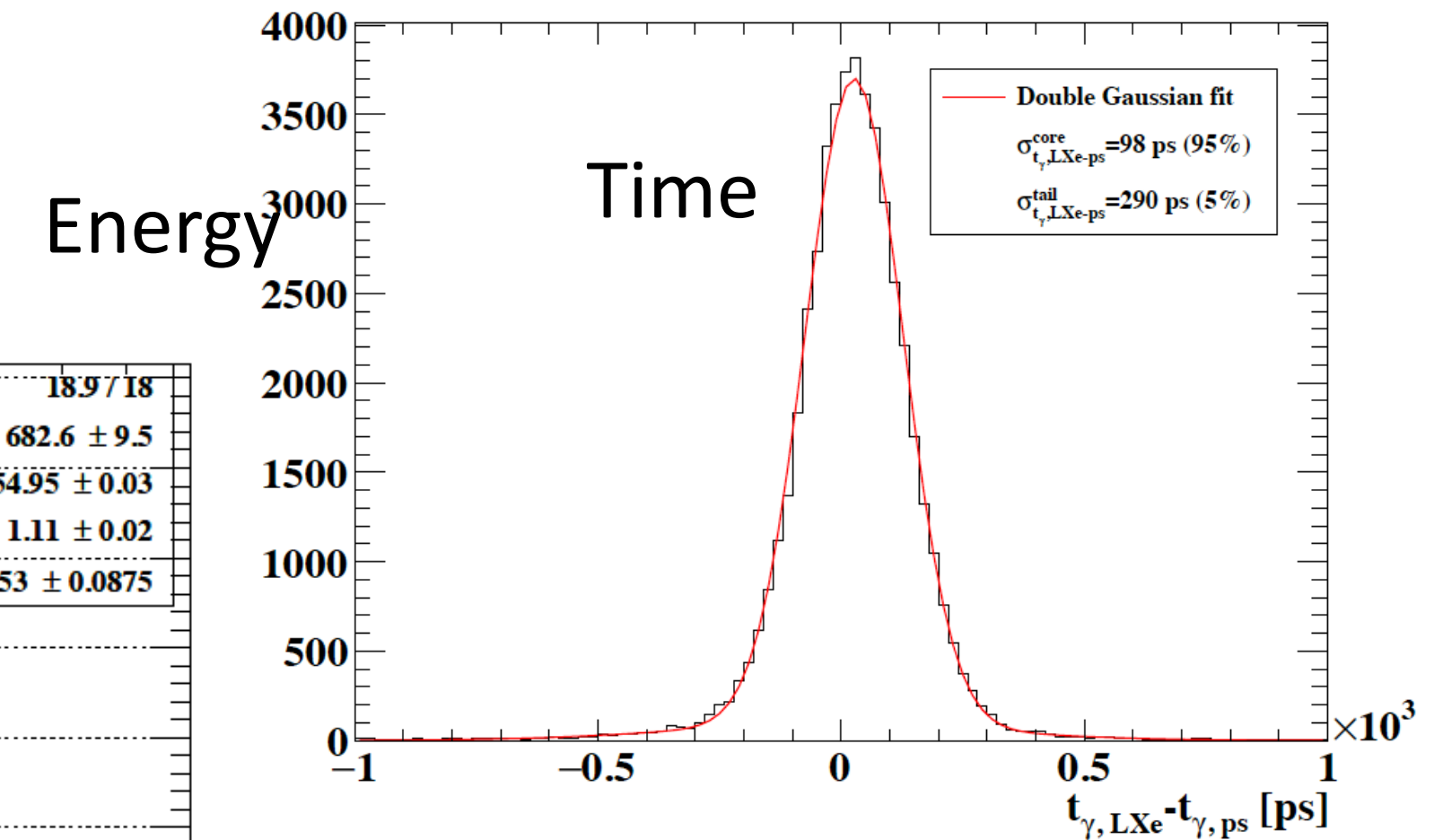
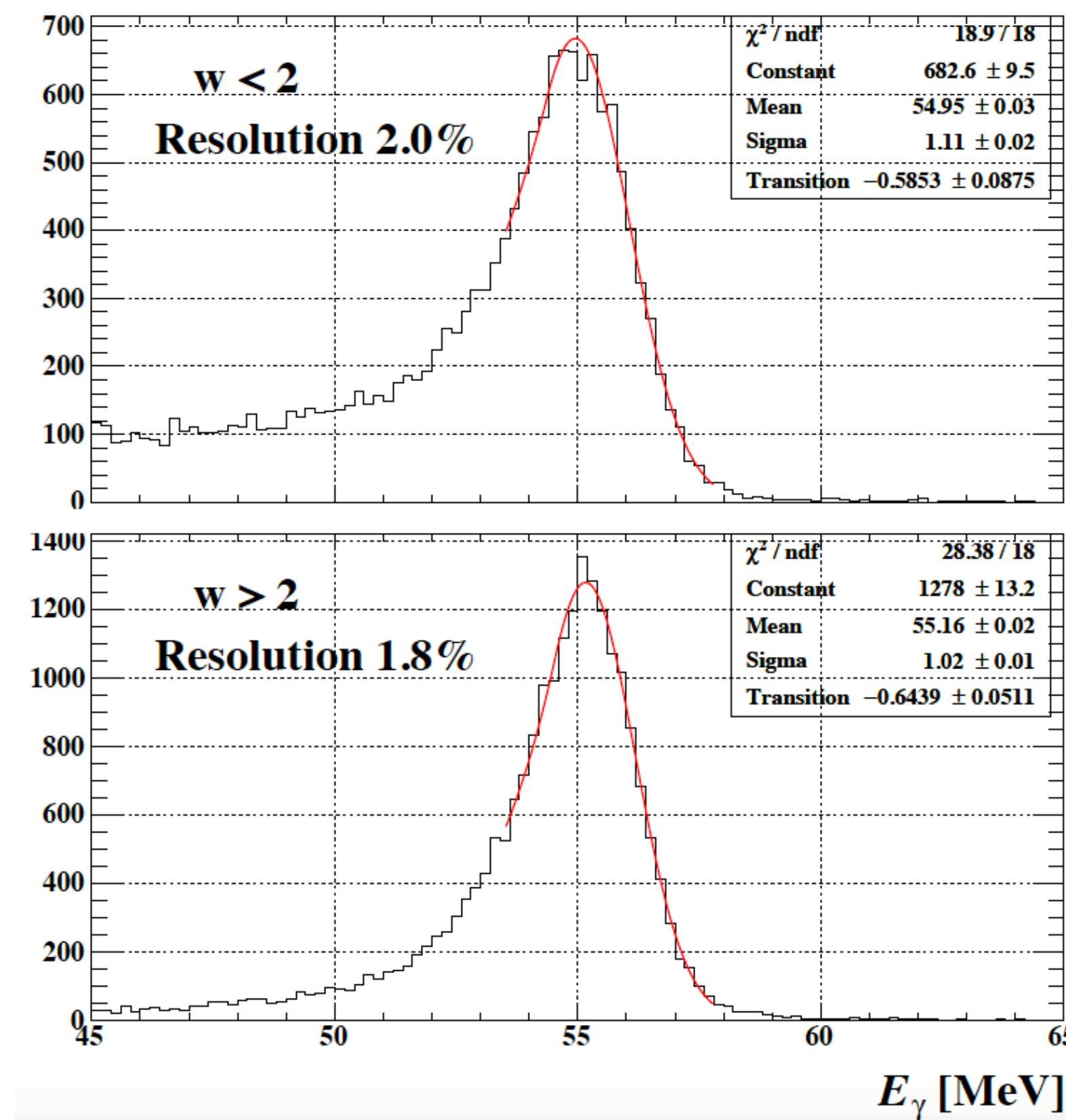
- homogenous volume of LXe
- *LXe as scintillator*
 - bright: 40 photons/keV
 - fast: 4/22/40 ns
- *VUV MPPC replacing PMTs in the inner face*
- 4092 channels instead of 216!!
- uniform response in particular for shallow events



Performance

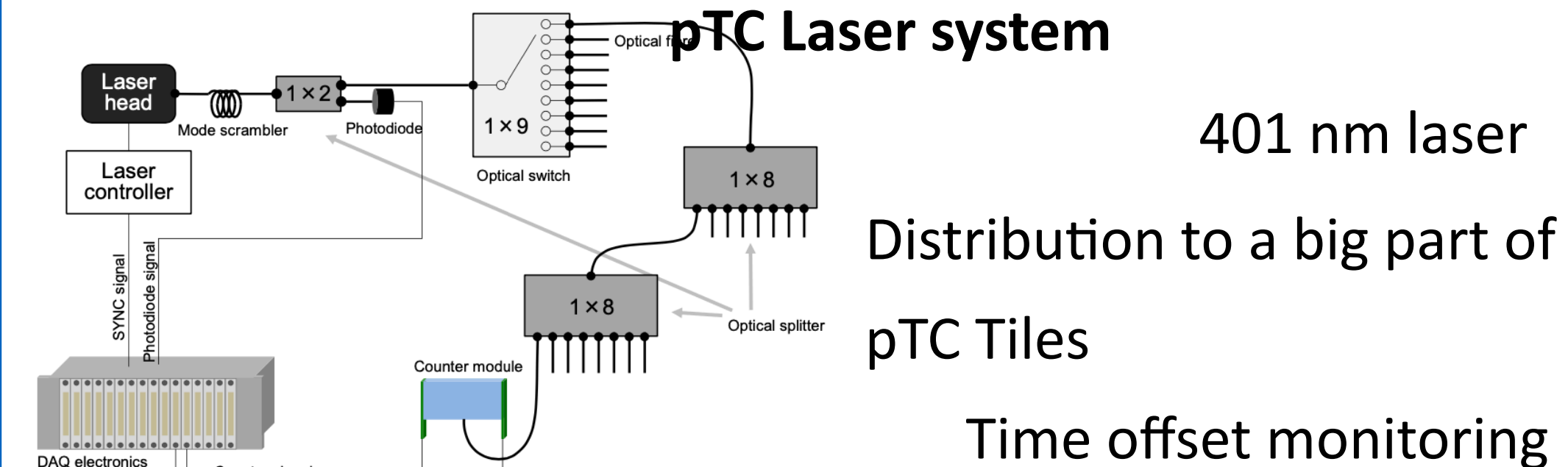
$$B_{acc} \propto R_{\mu} \Delta E_e \Delta E_{\gamma}^2 \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma}$$

- Stable detector operation
- Energy resolution 1.8%-2% @55MeV
 - measured with dedicated calibration run
- Time resolution ~65ps
- Position resolution 2.5mm-4mm
- Observed MPPC PDE degradation with integrated beam time
- annealing tested successfully and run every year in the beam shut down period





Energy calibration line :

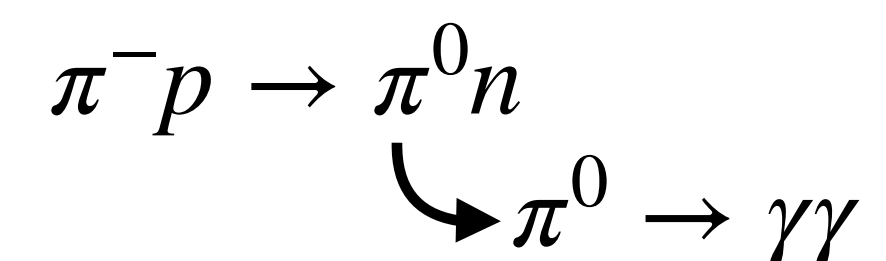


Localised energy deposit (40 μm range in LXe)

For detection efficiency
monitoring calibration

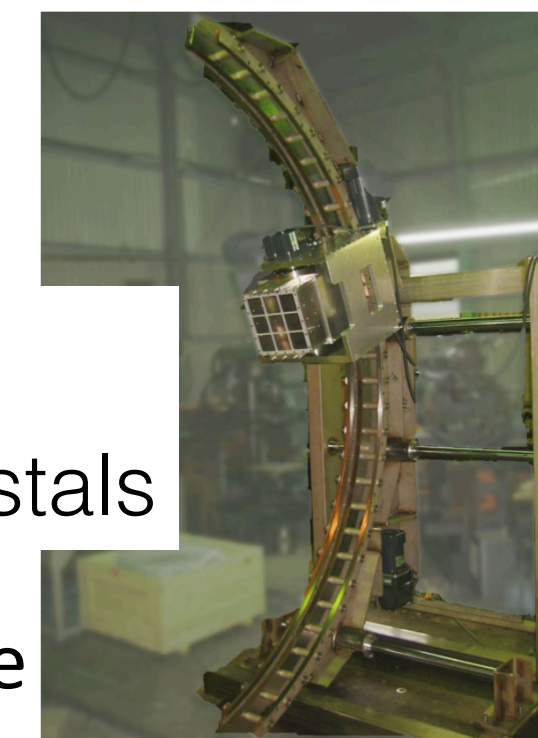
Charge Exchange reaction

Energy & time calibration at signal energy



Movable
array of BGO Crystals

Energy in 55-83 MeV range



Other calibrations

Drift chamber:

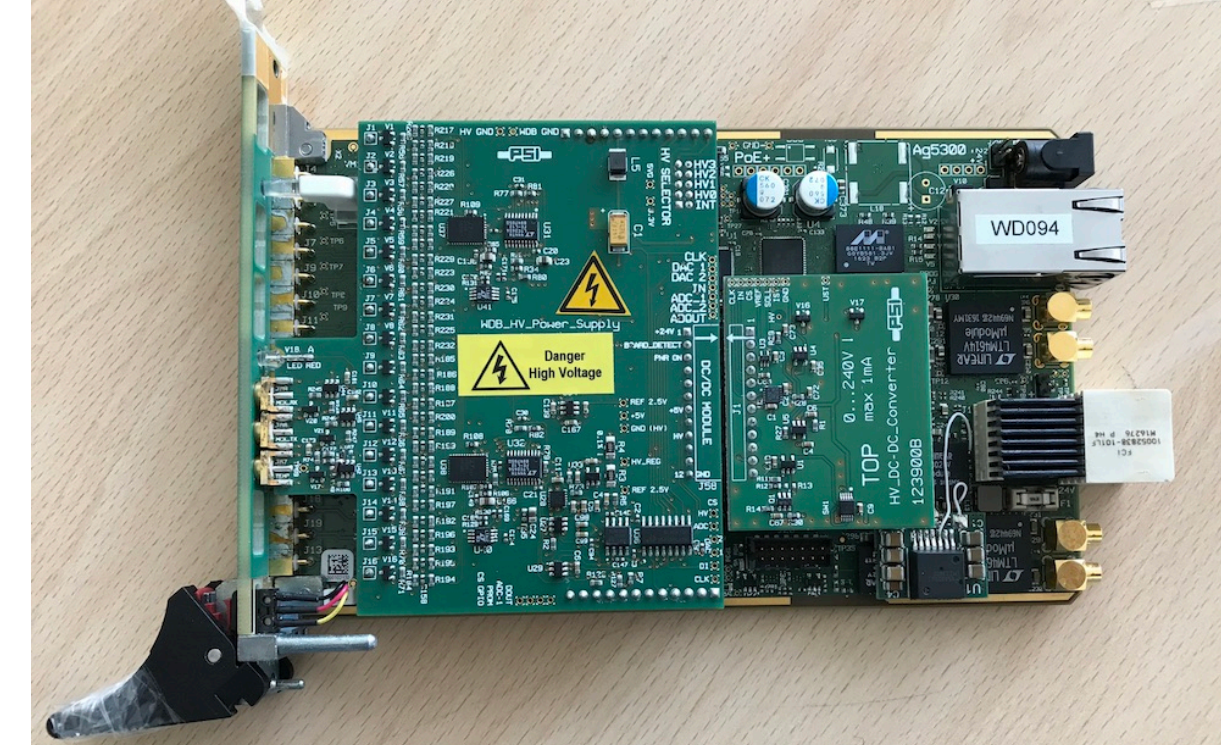
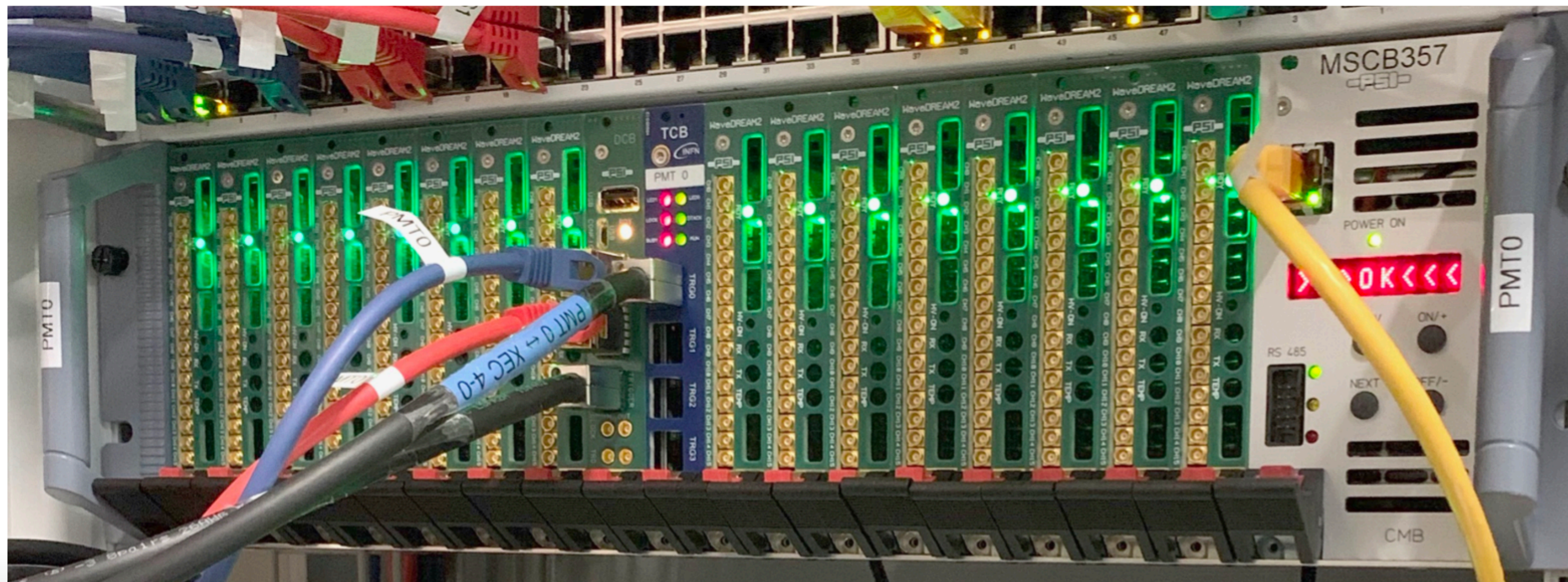
- Cosmic rays
- B-field mapping

Liquid Xenon detector:

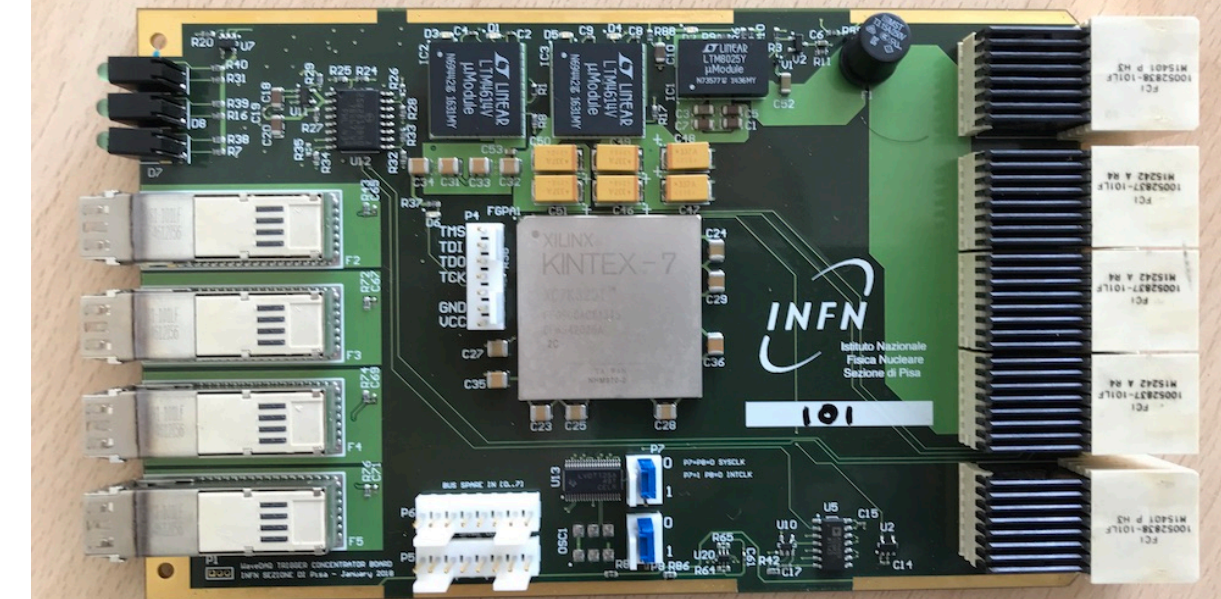
- LED
- Neutron-Nicke γ (9 MeV)
- ^{57}Co X-Ray position survey

TDAQ electronics: WaveDAQ

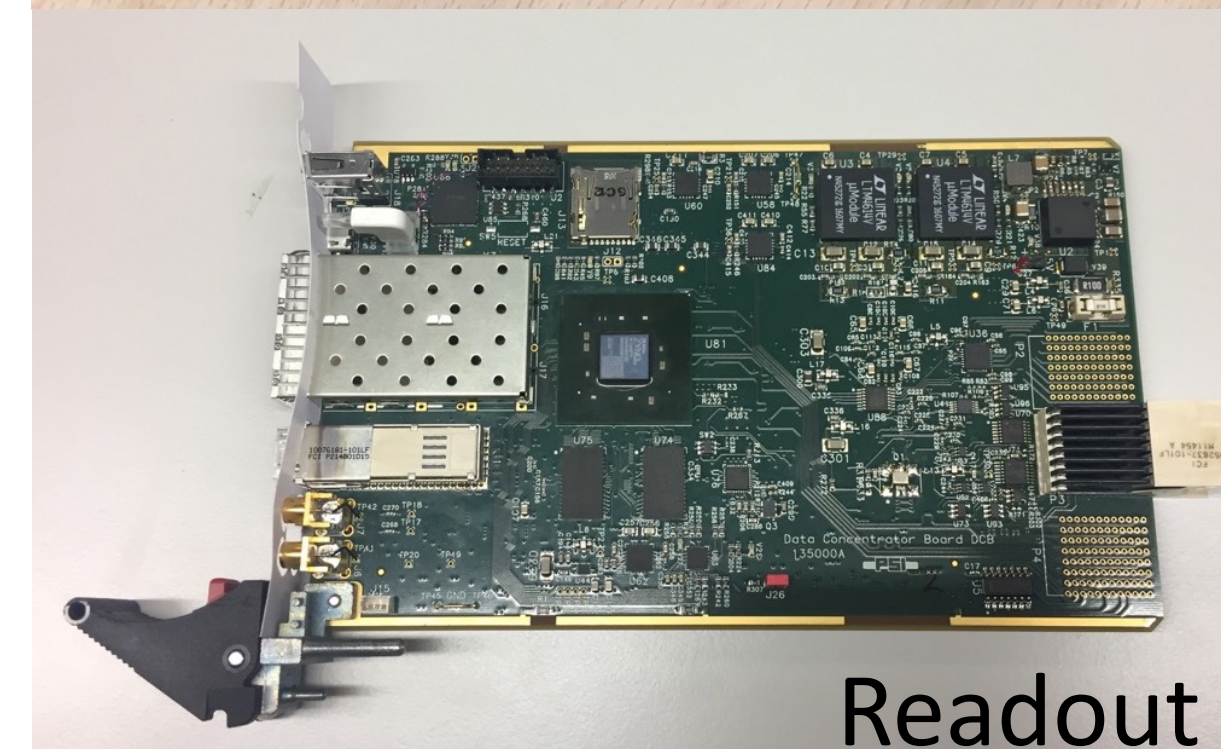
- Full custom
- Trigger and DAQ integrated
 - *waveform digitiser @GSPS with DRS chip*
 - intrinsic **time resolution** better than **10ps**
 - **SiPM power supply and amplification** included
 - *Complex FPGA based trigger with latency <450ps*
 - *up to 10 Gb/s DAQ throughput (50 Hz)*



Digitiser

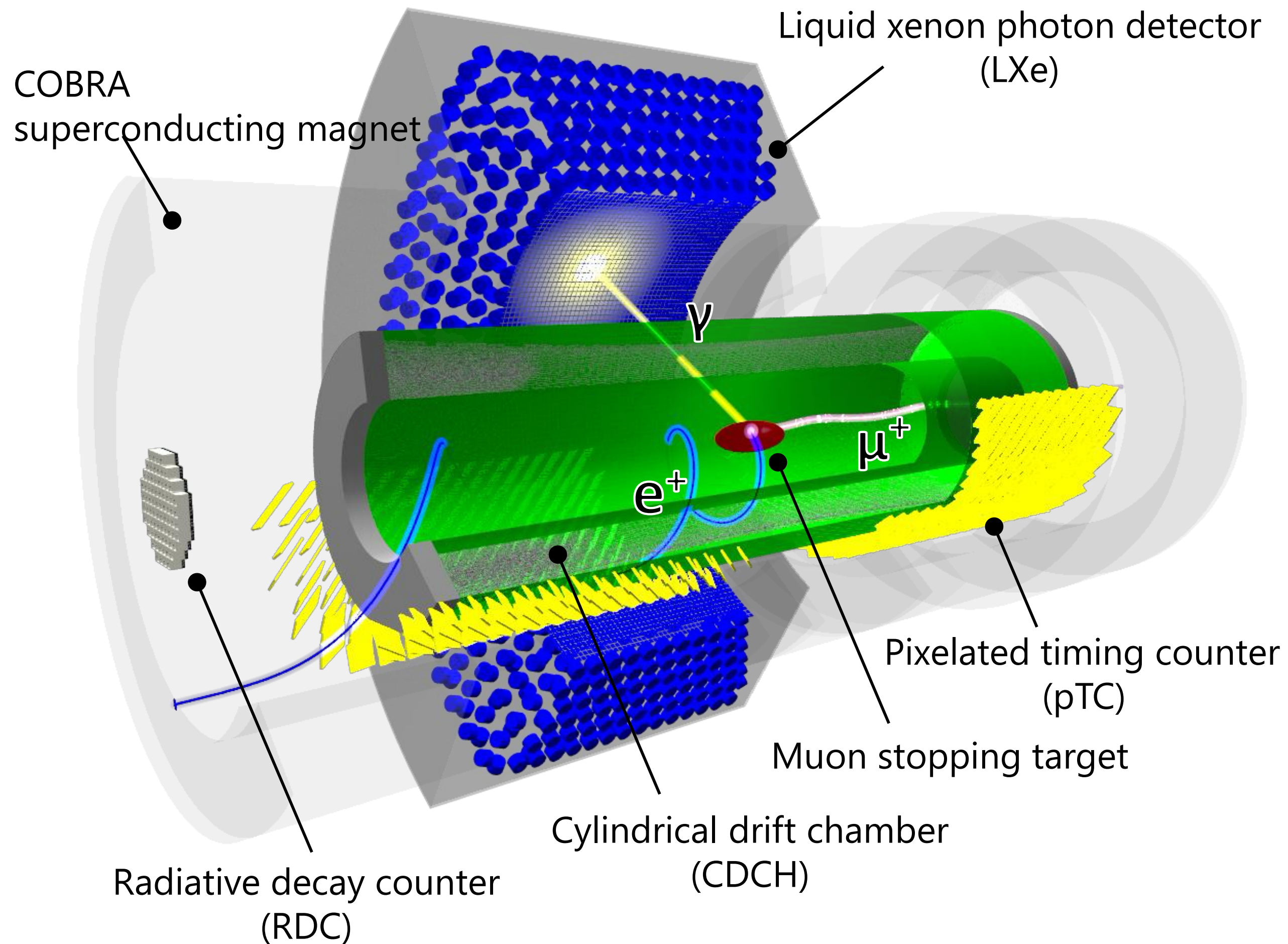


Trigger

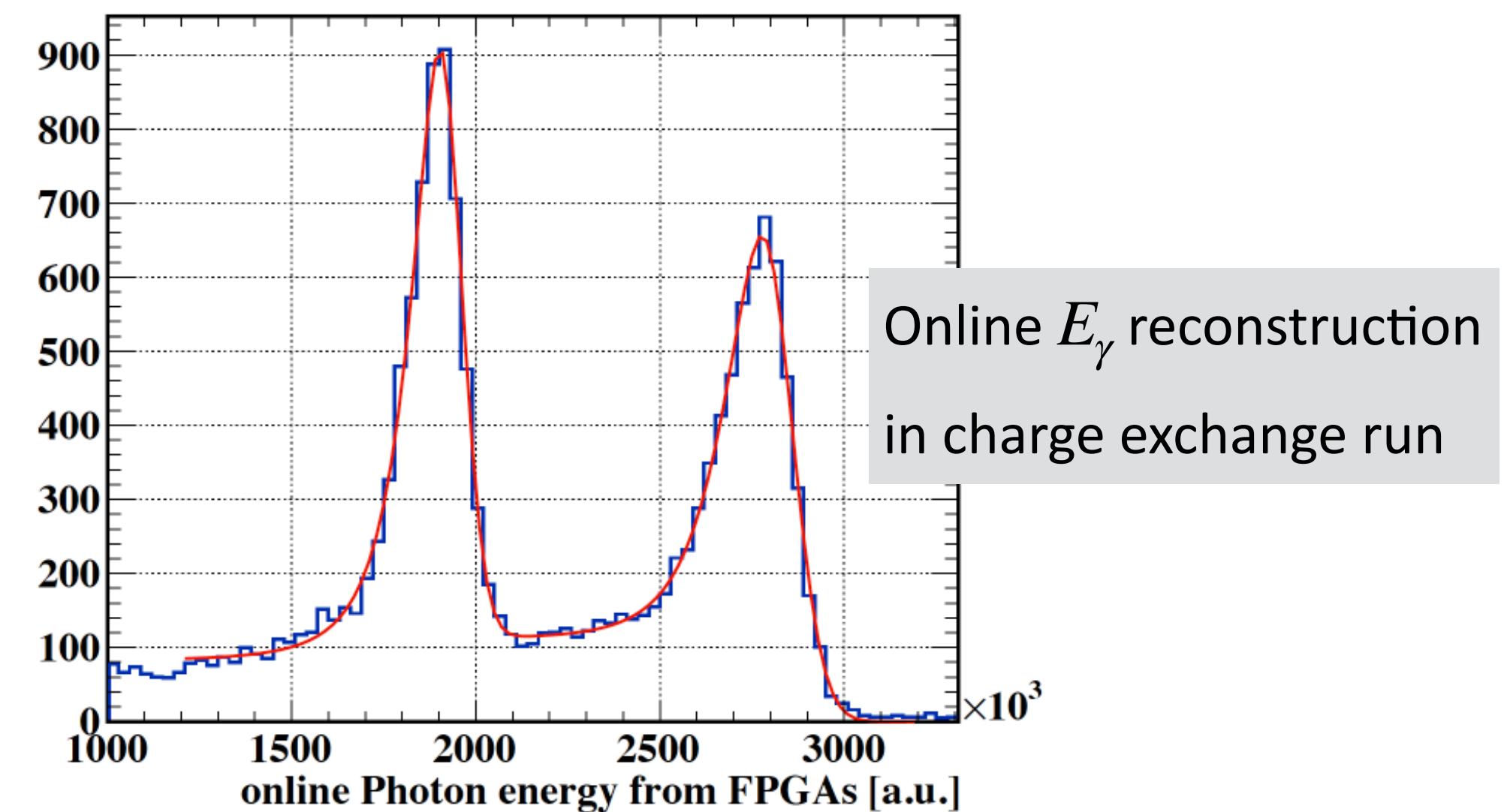


Readout

MEG trigger logic

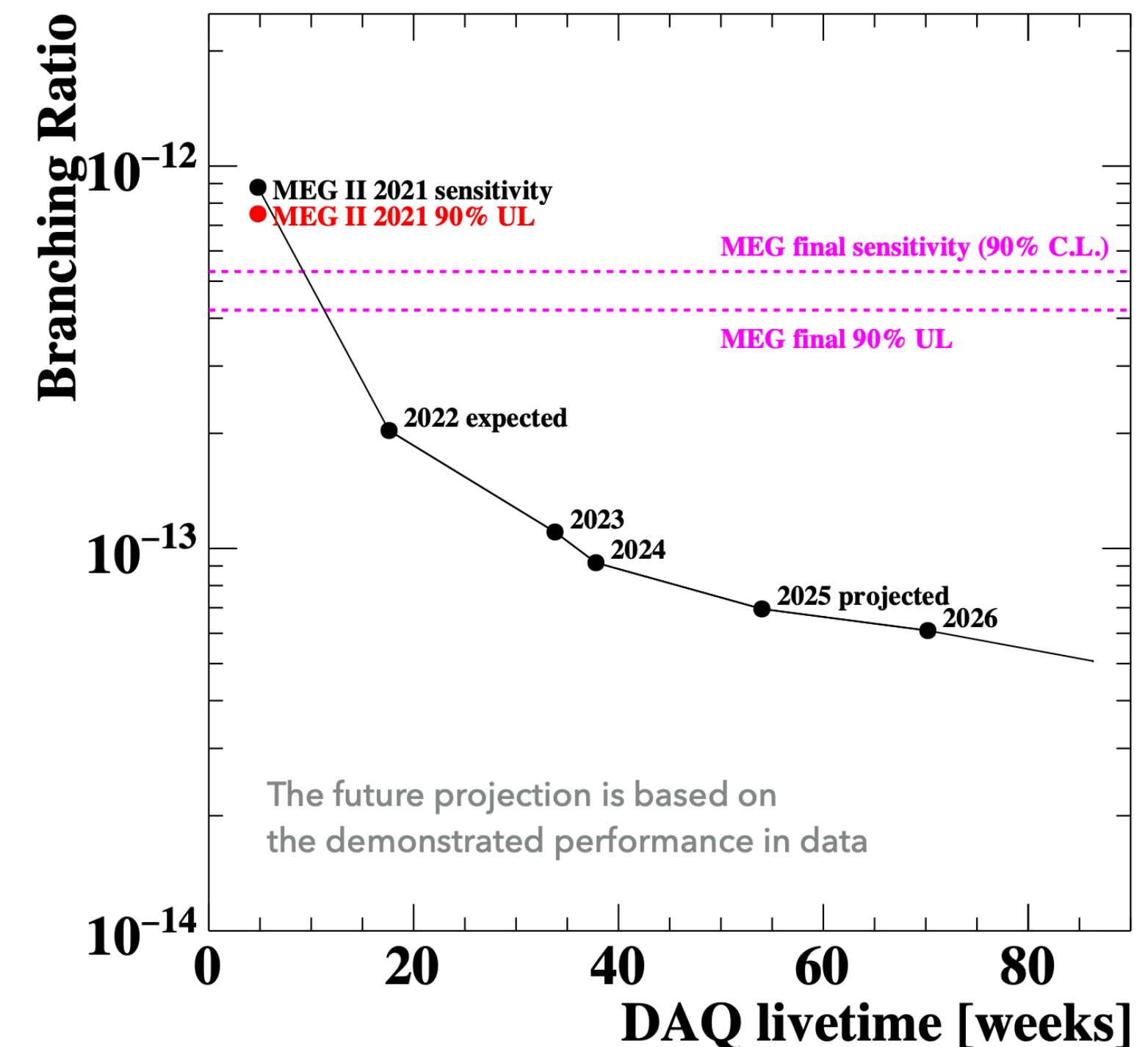
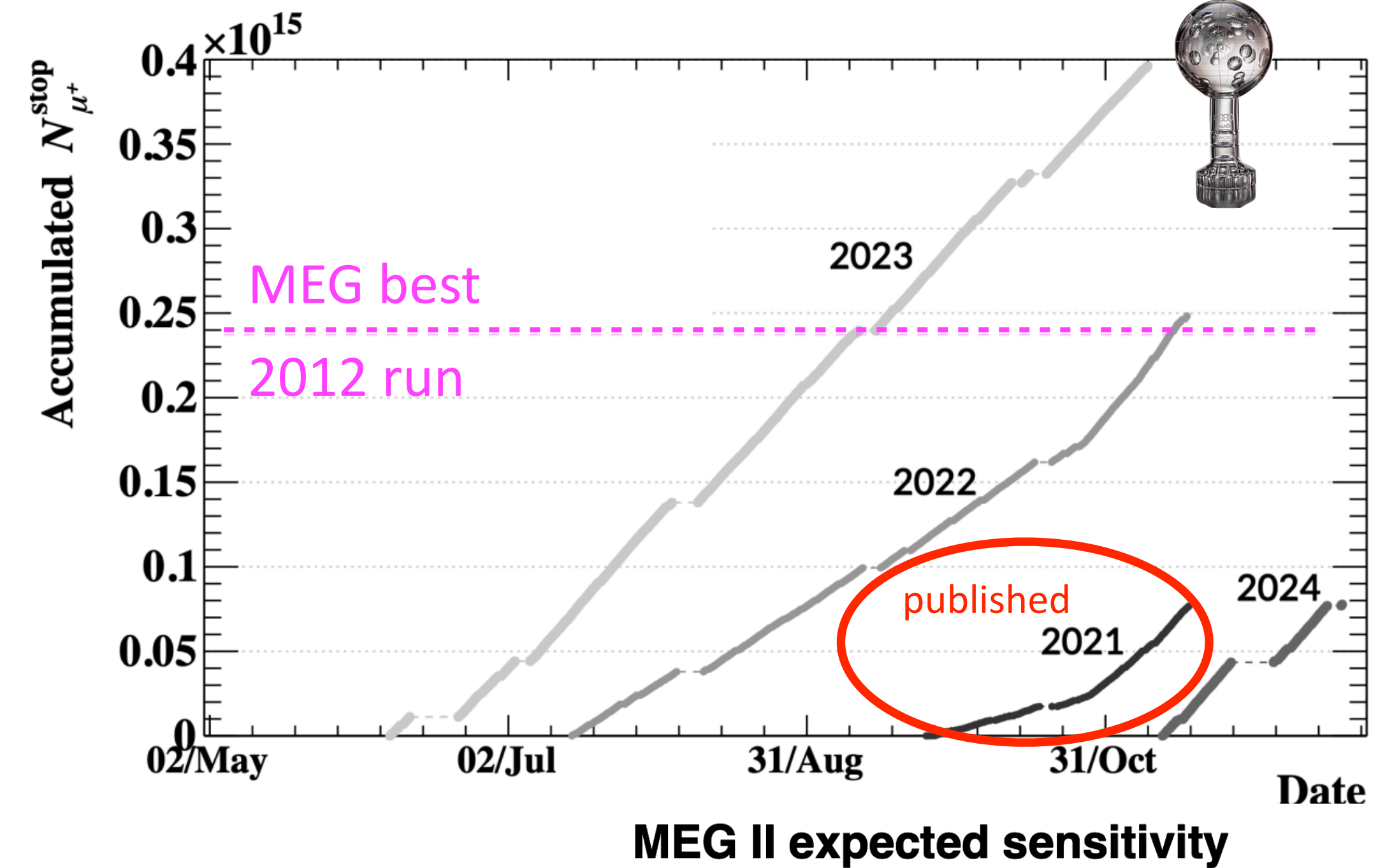


- $E_\gamma > \text{threshold} (\sim 40\text{-}44 \text{ MeV})$
- $|T_{e\gamma}| < \text{time window} (\sim 10\text{-}12.5 \text{ ns})$
- Direction match condition: $e\gamma$ hit positions correlation
- *From $O(10^7) \mu \text{ decays/s} \rightarrow \sim 10 \text{ Hz trg rate}$*



MEG II logbook

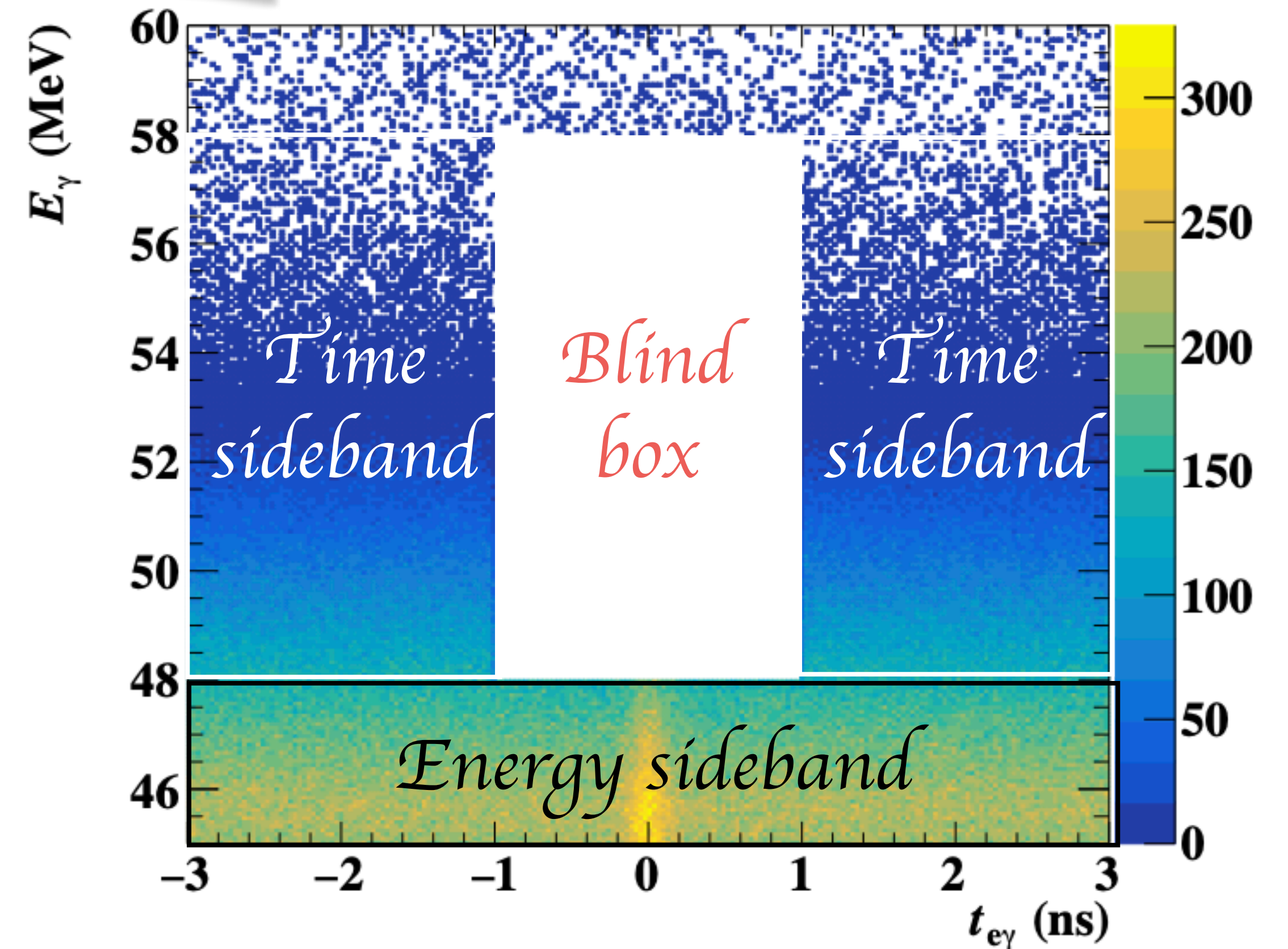
- **2021:** First physics run, mostly @ $3e7 \mu/s$
- **2022:** First long data collection, mostly @ $3e7 \mu/s$
 - *~4 times 2021 statistics*
 - *analysis in a well advanced phase*
- **2023:** Longest run un MEG history
 - *beam intensity @ $4 \cdot 10^7 \mu/s$ (and from now on)*
- **2024:** statistics similar to 2021 due to external conditions
- We plan in **2025** and **2026** long DAQ periods as in 2023
 - *this will guarantee to reach goal sensitivity*



Data analysis

$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) = \frac{N_{\text{sig}}}{k}$$

- Decided to extract CL to $\mathcal{B}(\mu \rightarrow e \gamma)$ from a **likelihood analysis** in a **wide signal box**
- Each **event** is described mostly in terms of **5 kinematic variables**: $x_i = (E_\gamma, E_e, t_{e\gamma}, \phi_{e\gamma}, \theta_{e\gamma})$
- resolutions and PDFs evaluated on data outside the signal box
 - signal box closed until analysis is fixed*
- Use of sidebands
 - accidental background from Left and Right $T_{e\gamma}$ sidebands*
 - Radiative Muon Decay (RMD) studied in the E_γ sideband*

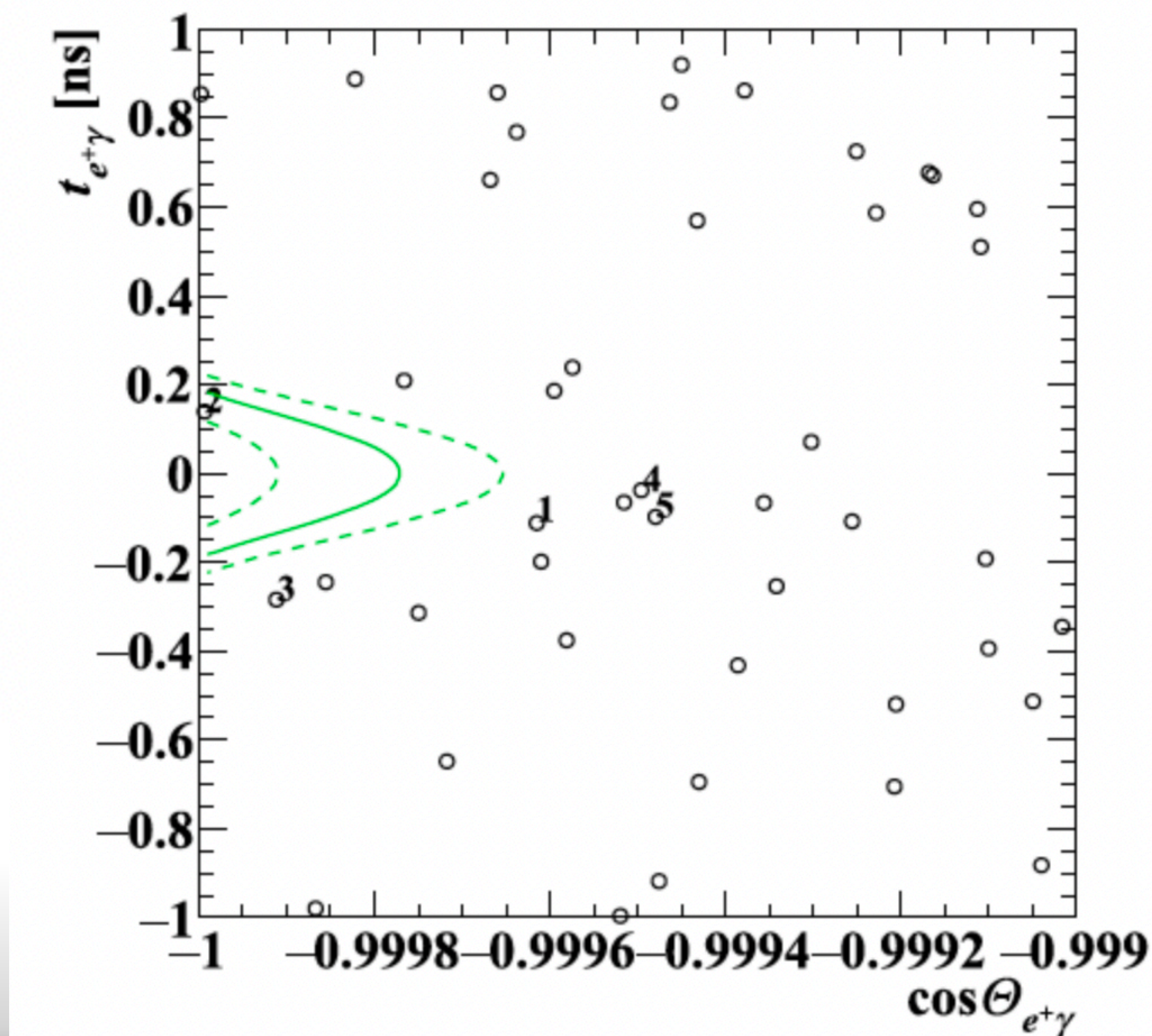
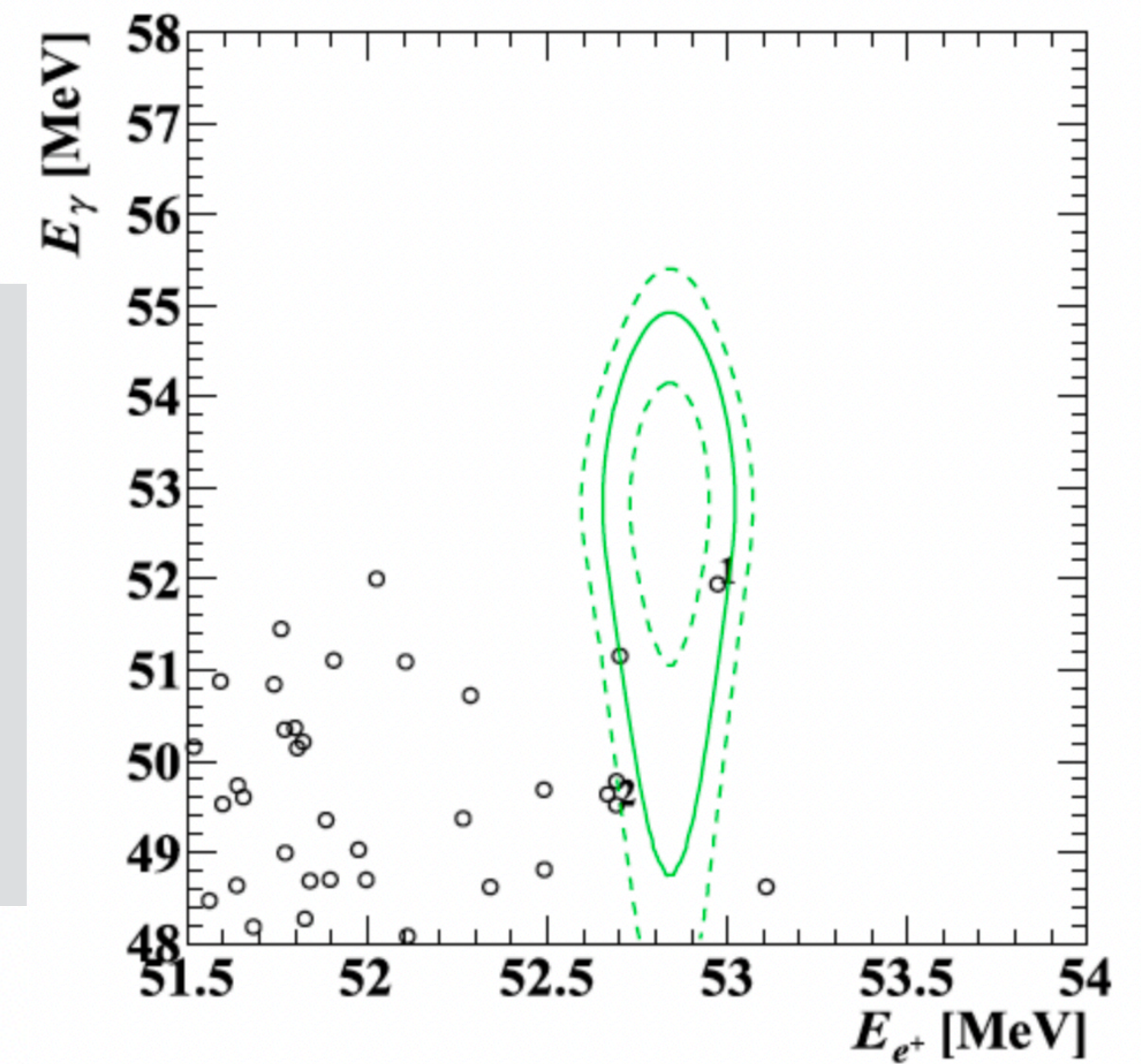
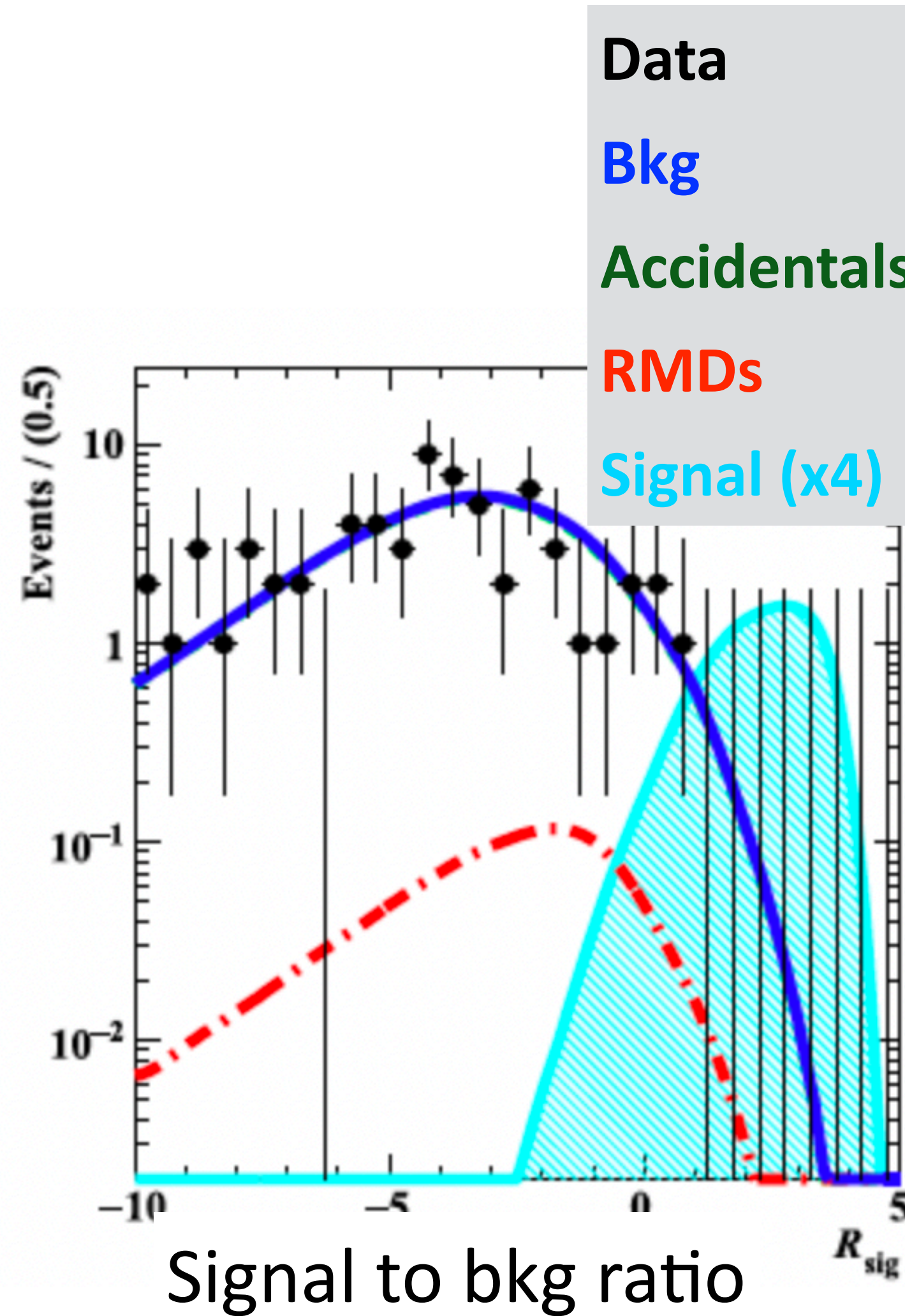


**Normalisation by
counting positrons**

$$k_{\text{michel}} = \frac{N_{\text{Michel}}}{BR(\mu \rightarrow e \nu \nu)} \cdot \frac{\epsilon_{\text{trg0}}}{\text{Presacling}_{\text{trg0}}} \cdot \frac{\text{Prescaling}_{\text{trg21}}}{\epsilon_{\text{trg21}}} \cdot \frac{\epsilon_{\text{signal}}}{\epsilon_{\text{michel}}} \cdot \epsilon_\gamma \cdot \epsilon_{\text{sel}}$$

MEG II 2021 result (+ MEG)

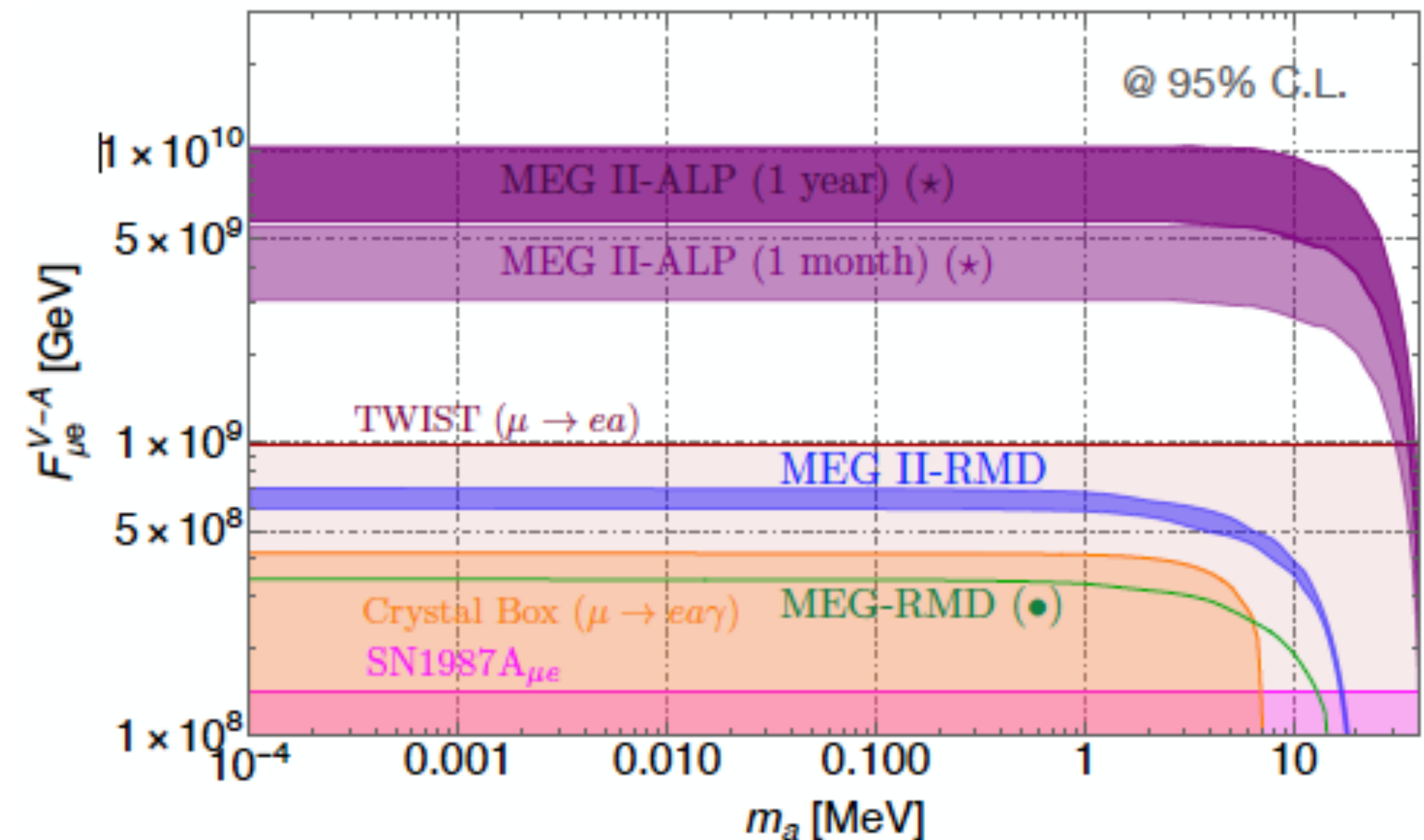
- No signal evidence
- Run 2021 result
 - *sensitivity*: $BR(\mu \rightarrow e\gamma) < 8.8 \cdot 10^{-13}$ @90%CL
 - *result*: $BR(\mu \rightarrow e\gamma) < 7.5 \cdot 10^{-13}$ @90%CL
- Combination with MEG - **new limit**
 - $BR(\mu \rightarrow e\gamma) < 3.1 \cdot 10^{-13}$ @90%CL



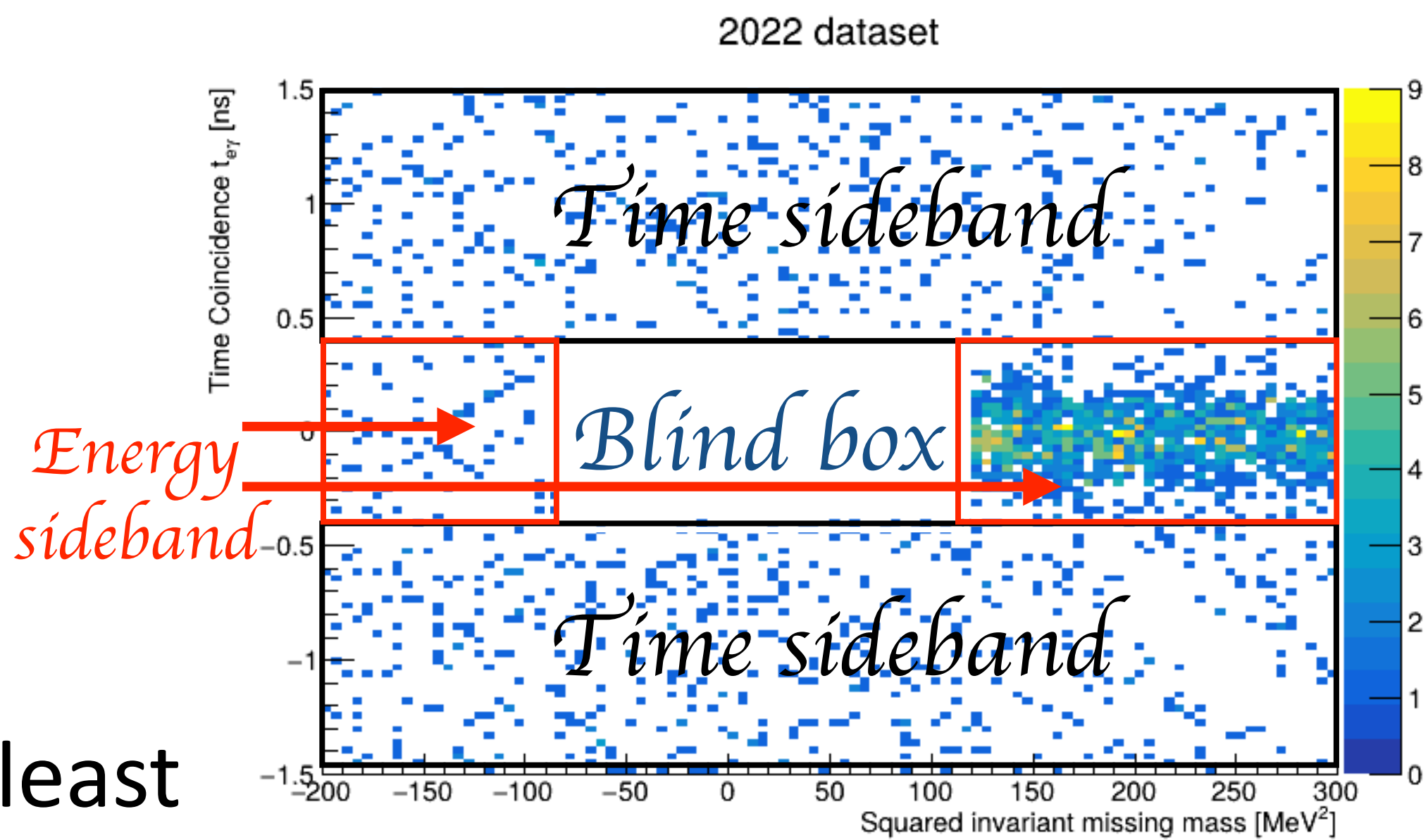
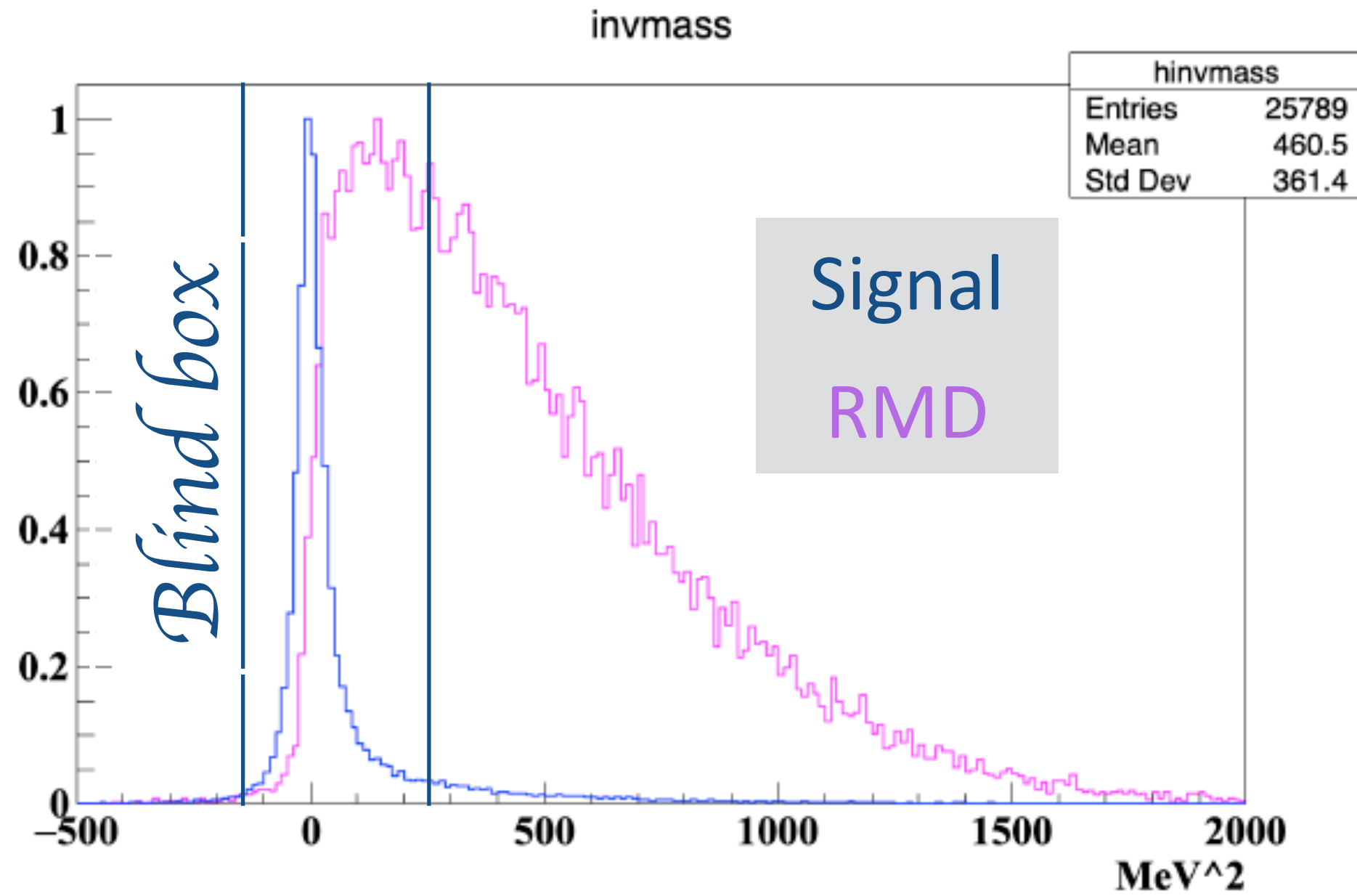
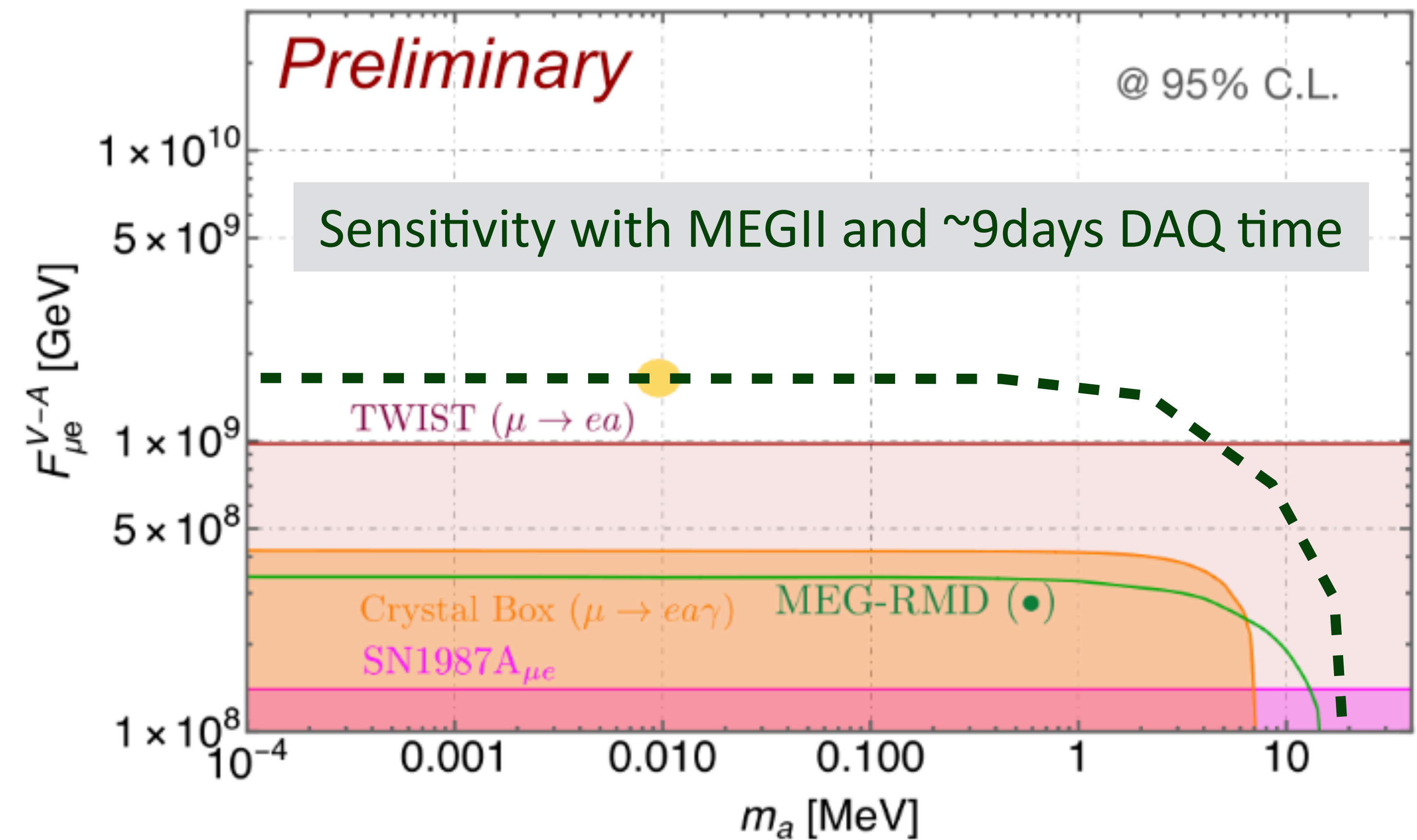
K. Afanaciev et al, A search for $\mu \rightarrow e\gamma$ with the first dataset of the MEG II experiment EPJC, 2023

What about $\mu \rightarrow e a \gamma$?

- 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 triggered
 - Gamma energy threshold close to 15 MeV
 - beam intensity and DAQ time needed
 - $\sim 10^6 \mu/s$ as in case of initial detector calibration



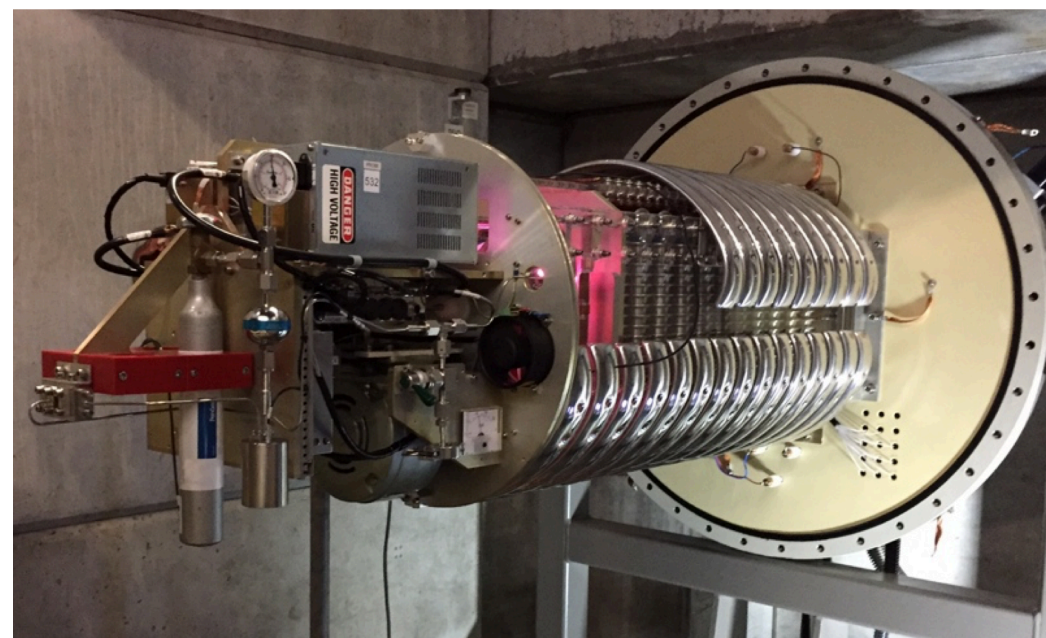
ALP search in MEG II



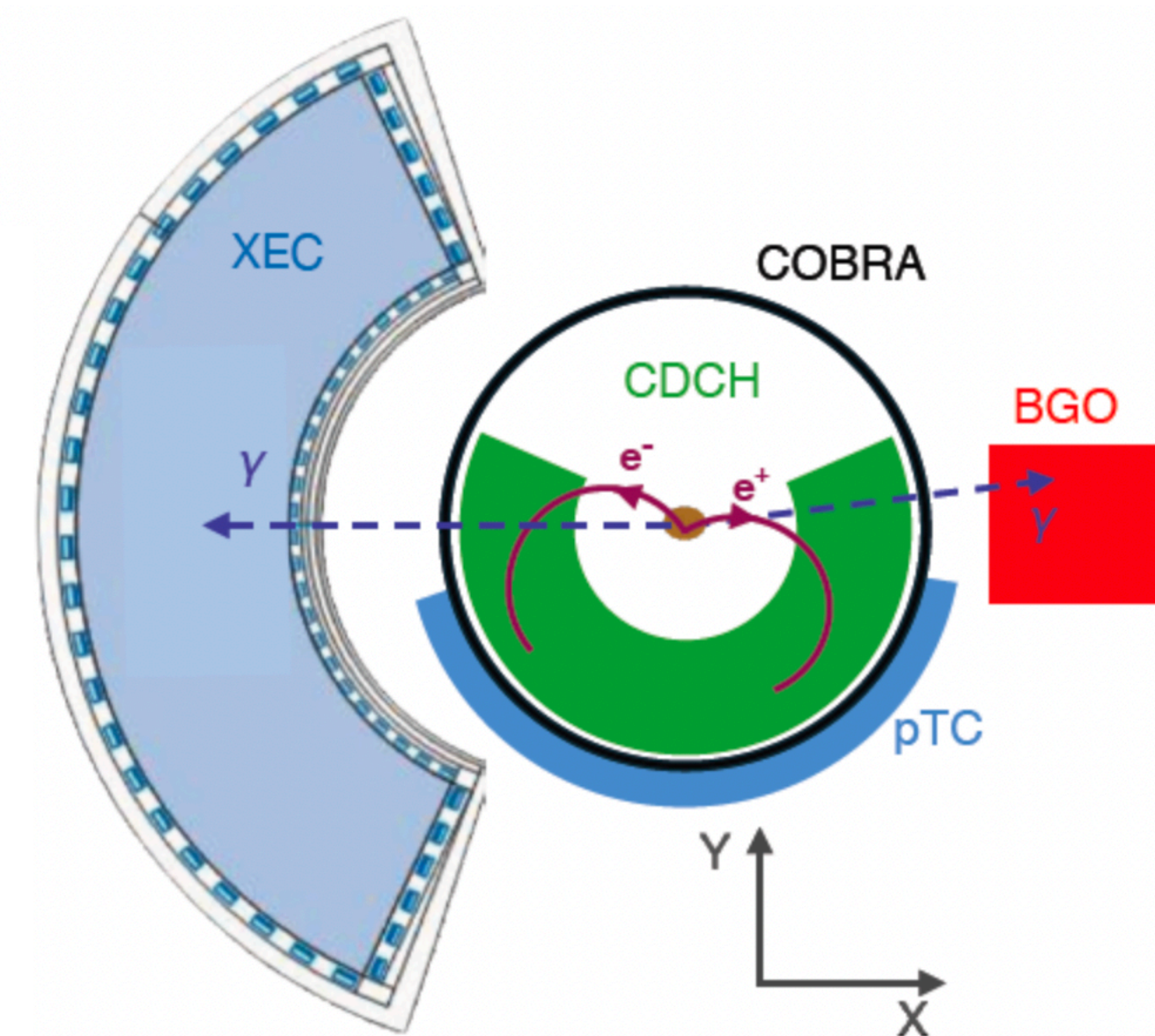
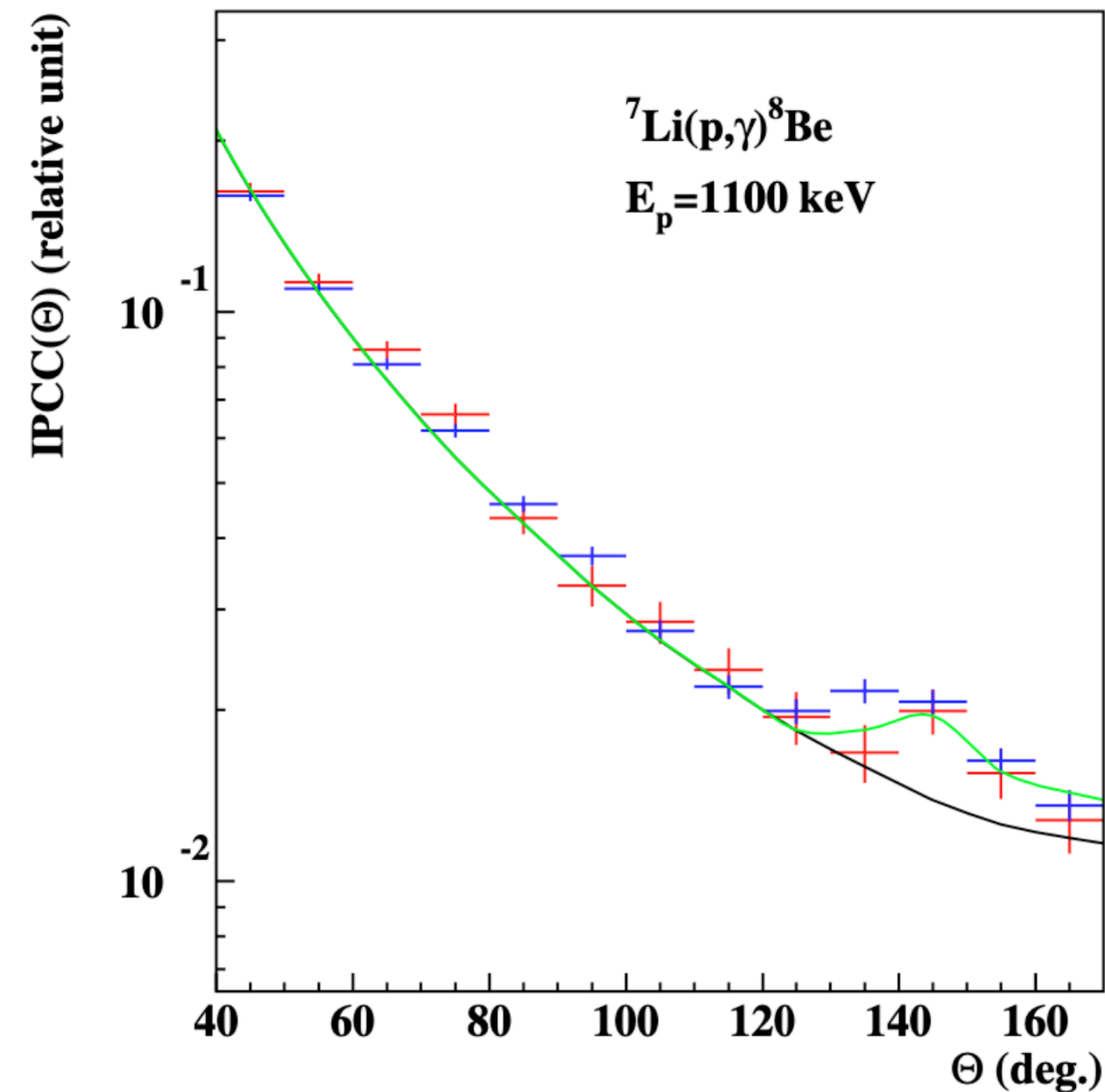
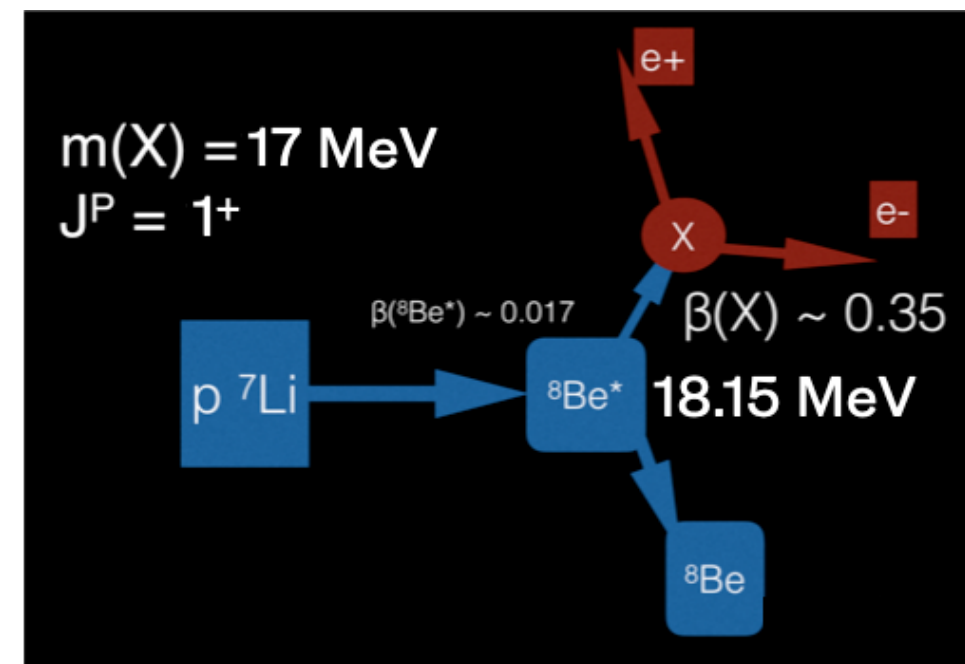
- MEG II plans accumulate O(15 days) of DAQ at least

Other physics: X(17 MeV) Boson

- **Anomaly** in the process $(p, {}^7\text{Li}) {}^8\text{Be}^*$ 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 $\sim 500\text{keV}$ instead of 1MeV**

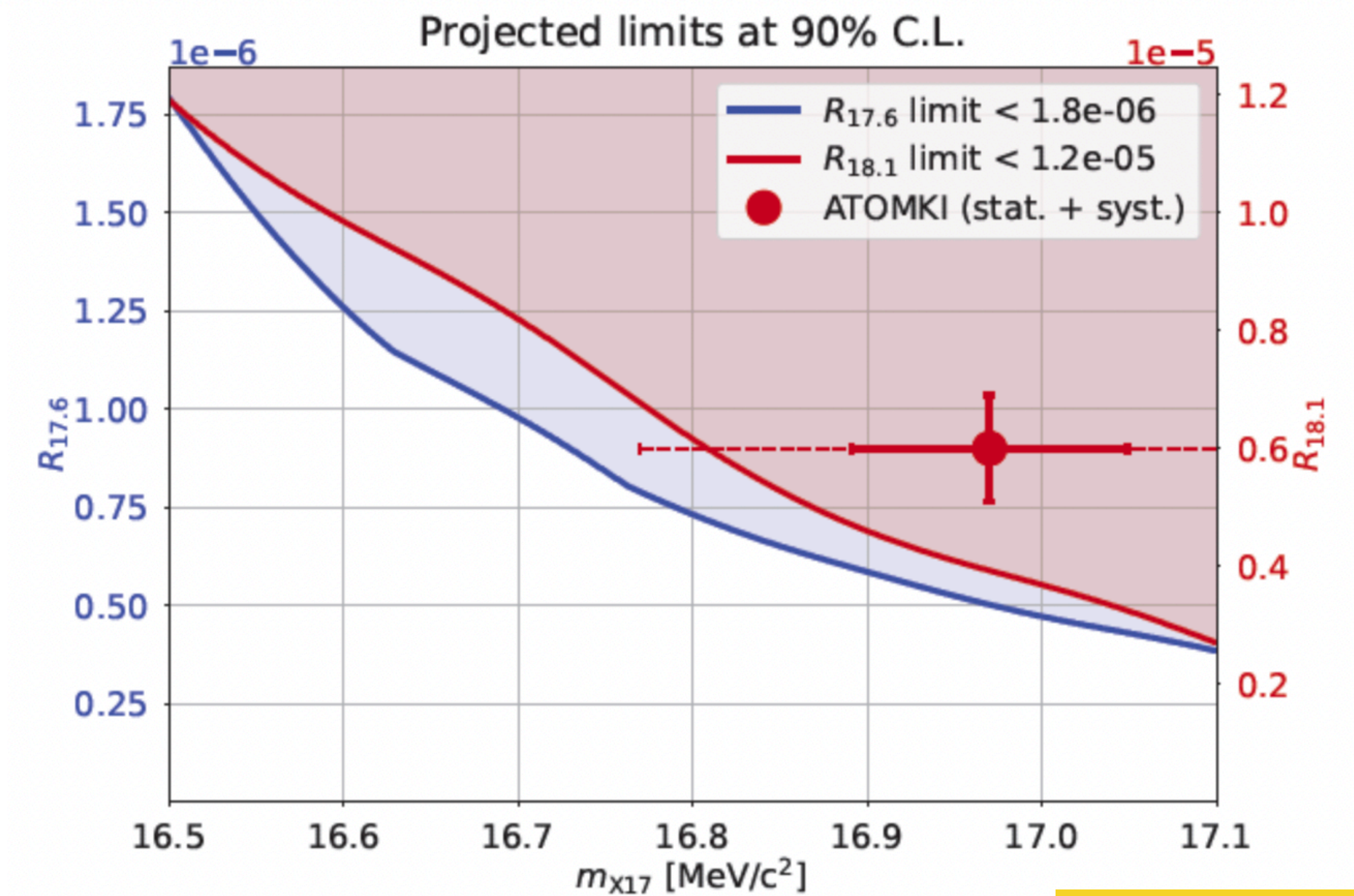
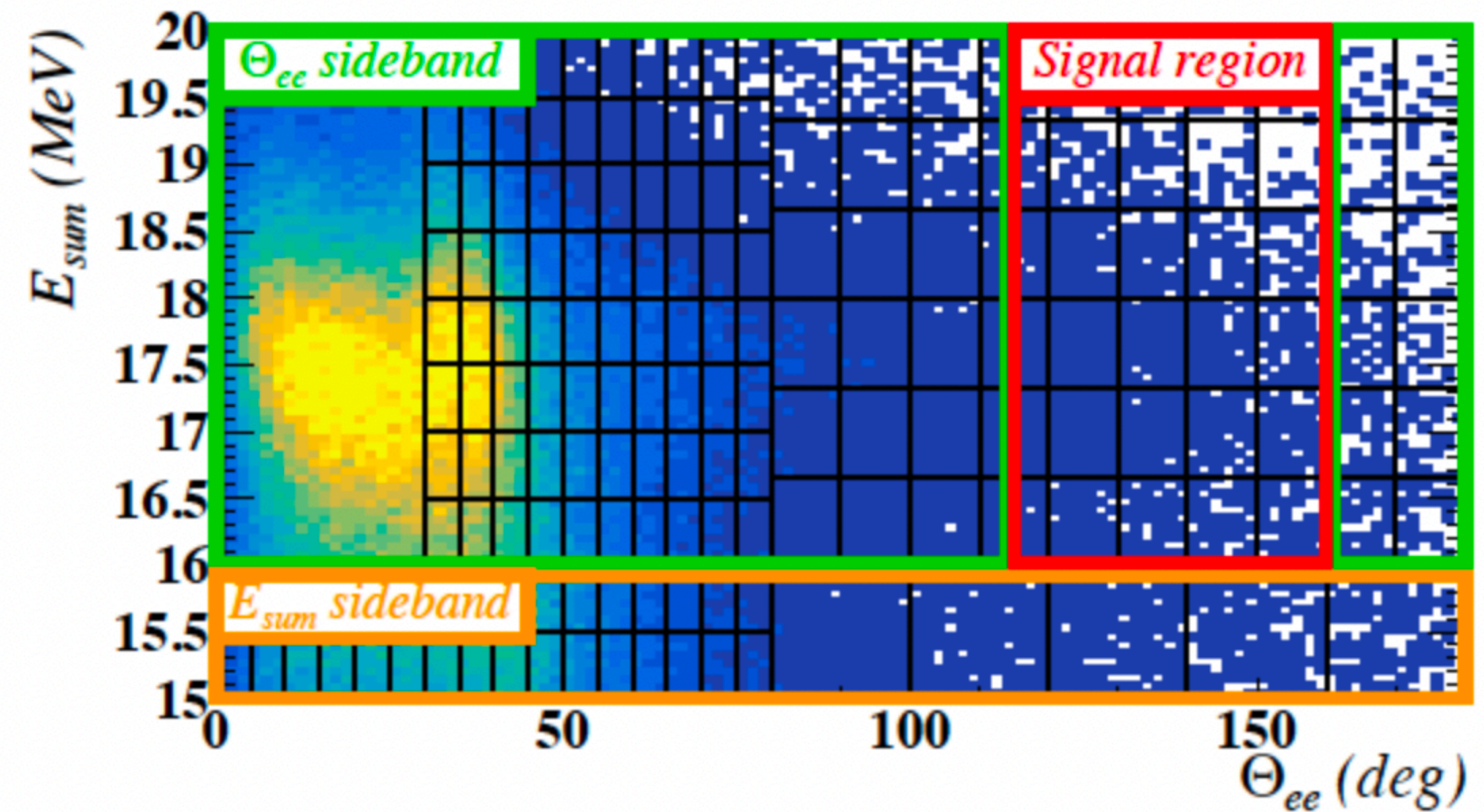


from slide 13...



“Our” result on X17

- Combined fit on the energy sum of the electron and positron 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



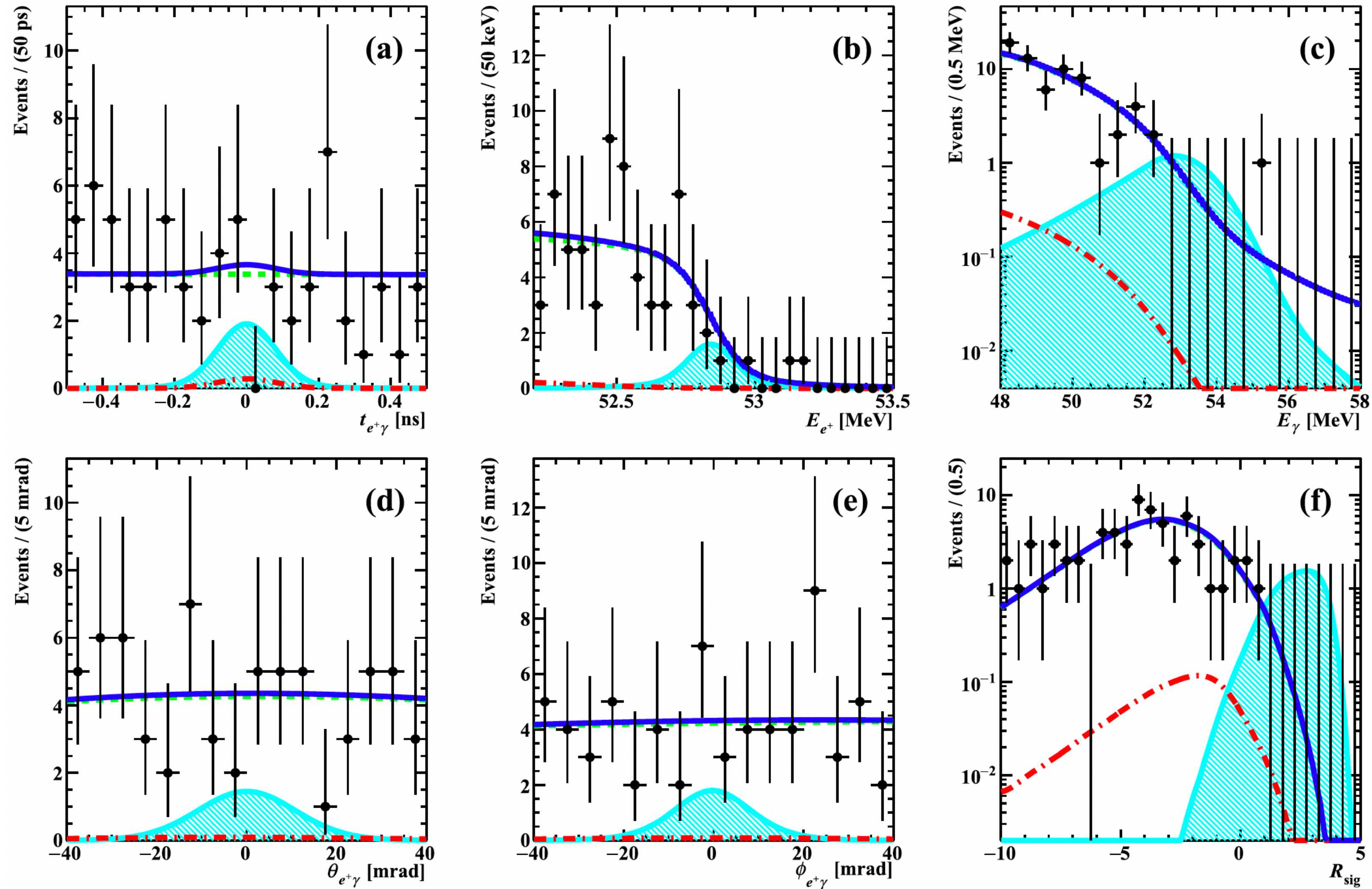
arXiv:2411.07994v1

Conclusions

- **cLFV with muons features a unique opportunity to discover physics beyond the standard model**
- **MEG II collecting physics data from 2021**
 - *goal sensitivity: 6×10^{-14} by taking data until 2026*
 - *first result with 2021 data combined with MEG data: $BR(\mu \rightarrow e\gamma) < 3.1 \times 10^{-13}$ @90%CL*
 - *We are about to unblind 2021+2022 data: stay tuned!*
 - **Sensitivity $\sim 2 \times 10^{-13}$**
- **a full physics program, with also exotic channels, looks just behind the corner!**

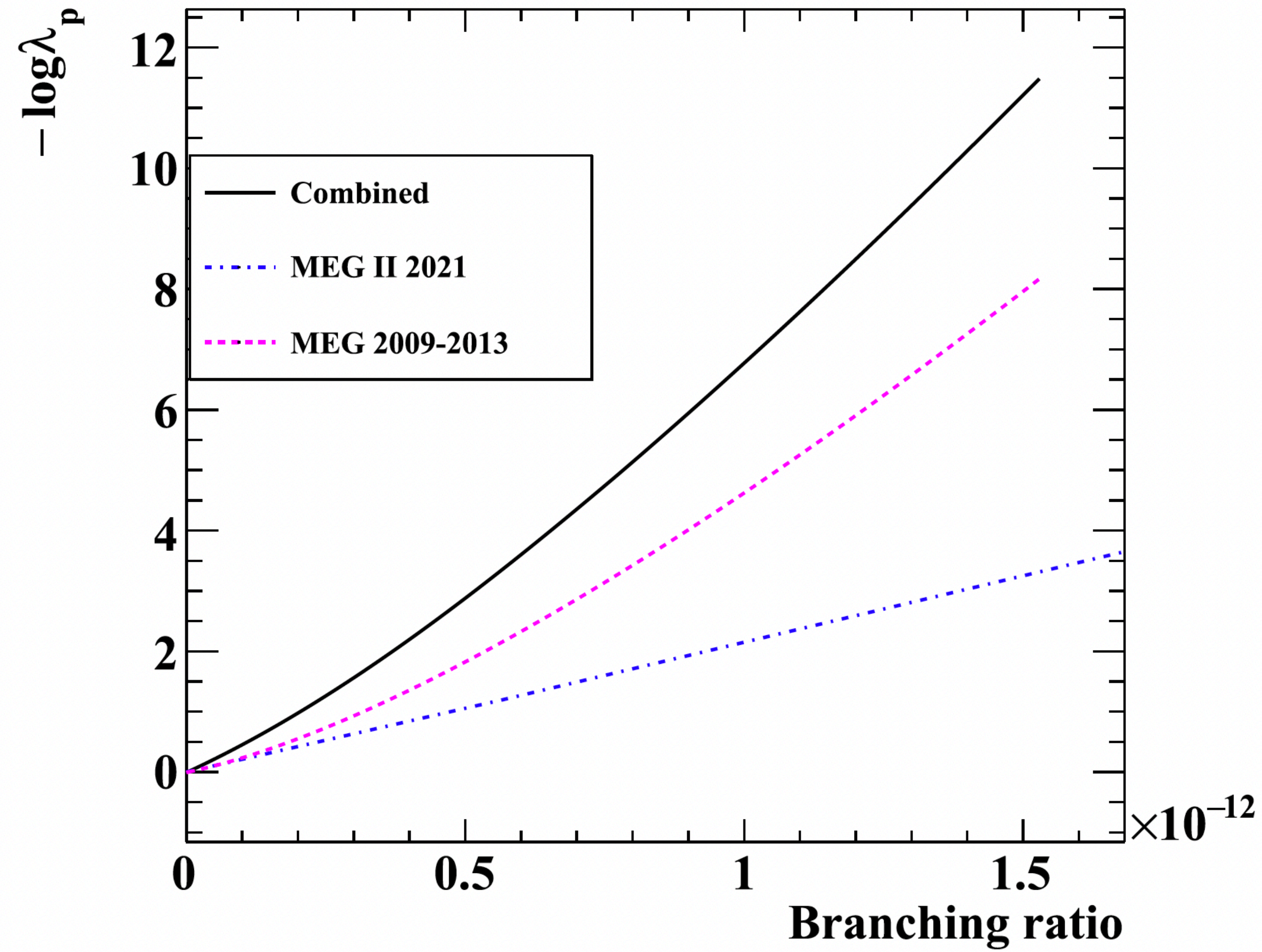
**Thanks for
your
attention!**

Fit on 2021 data



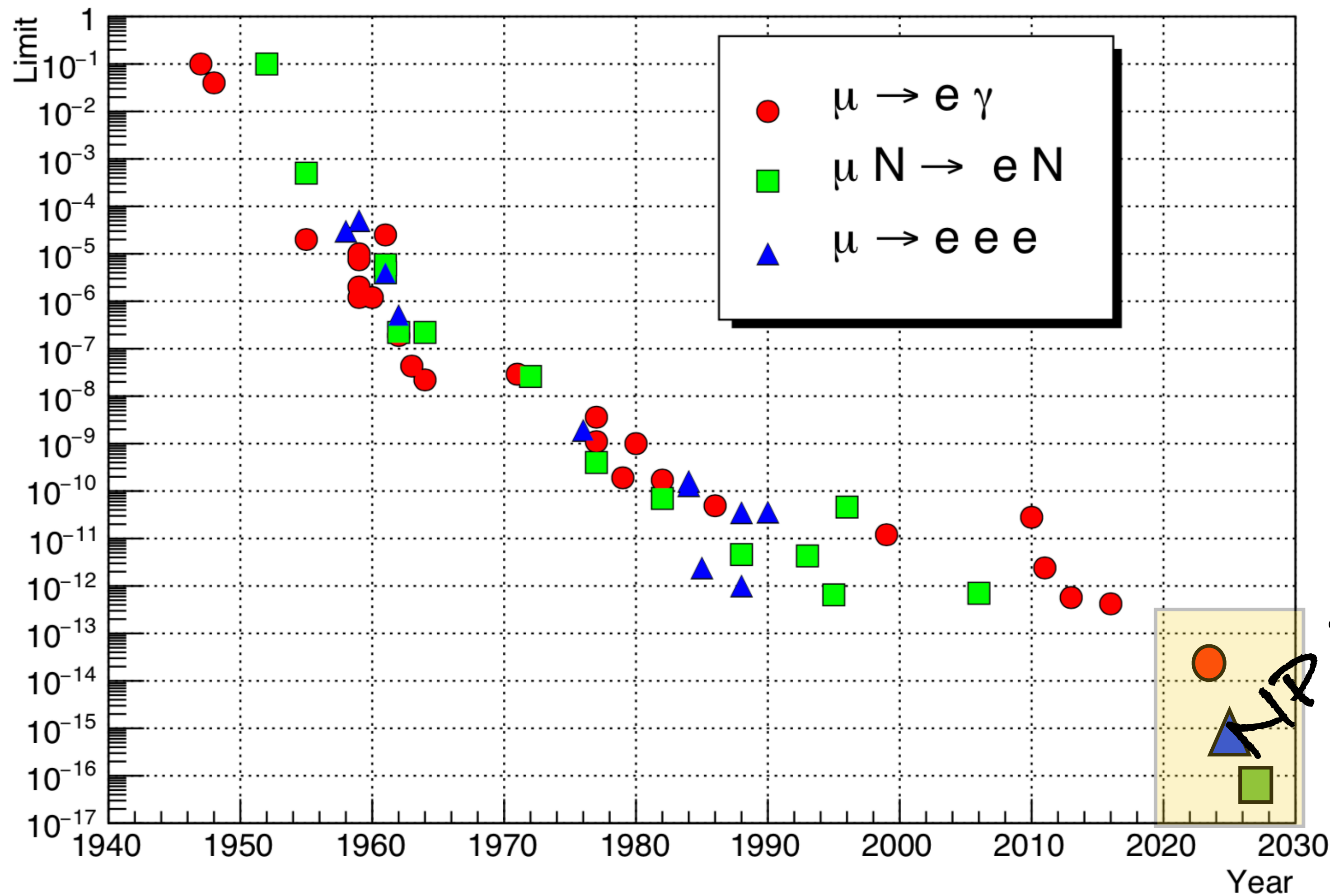
Data
 Bkg
 Accidentals
 RMDs
 Signal (x4)

Combination with MEG

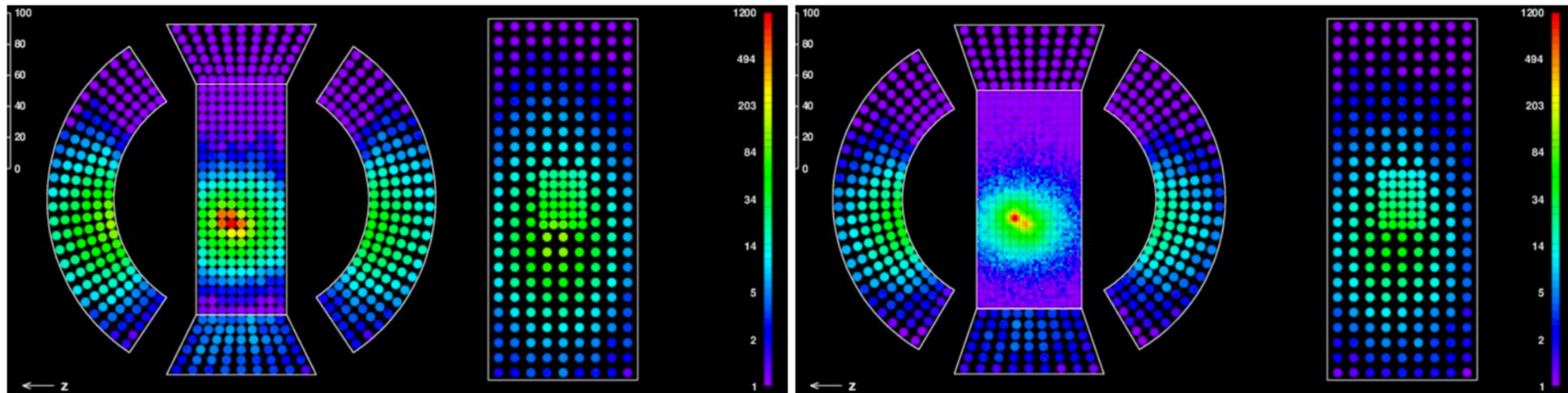


cLFV in 10 years

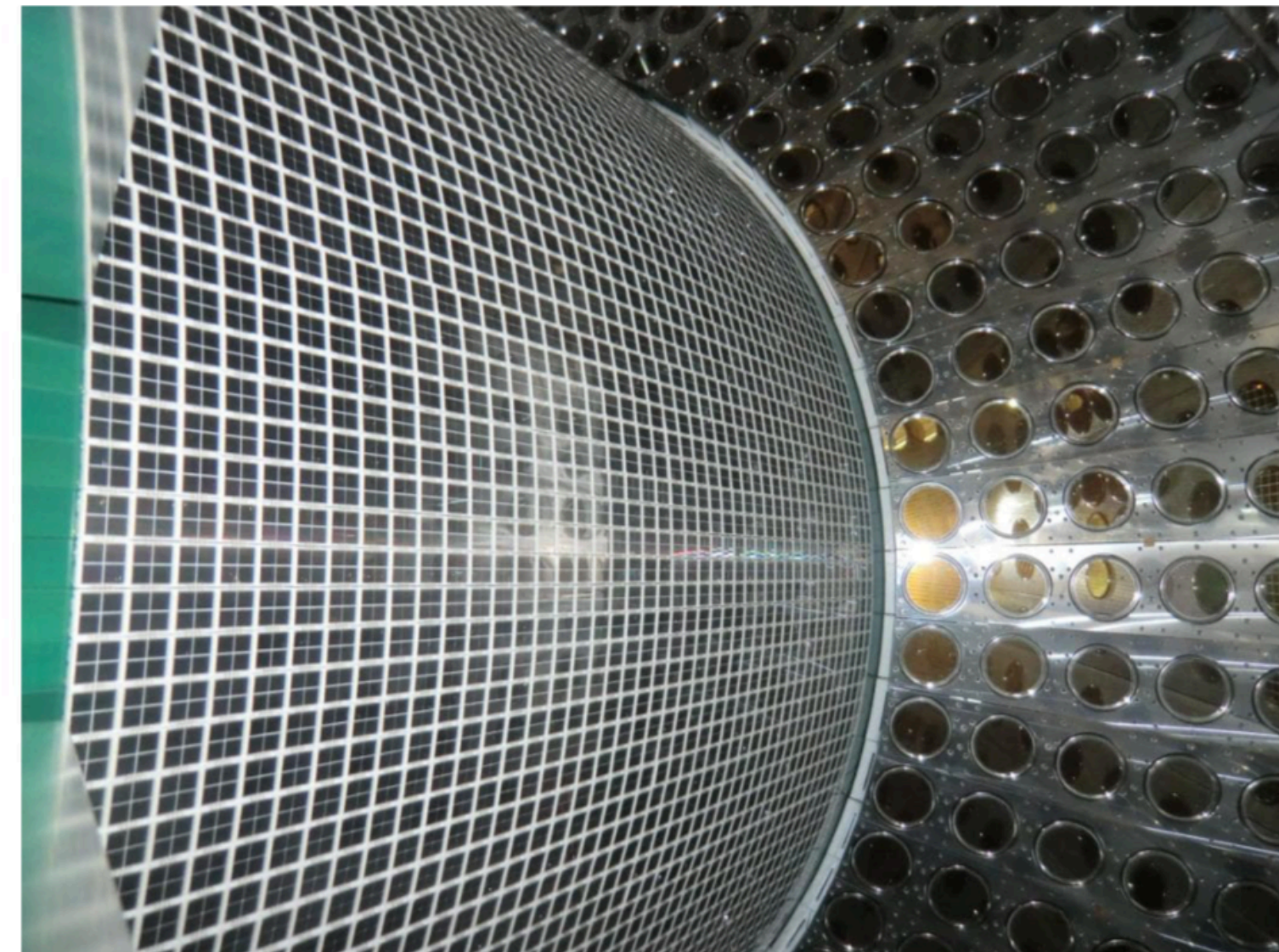
Calibbi and Signorelli, Riv. N. Cimento, 2017



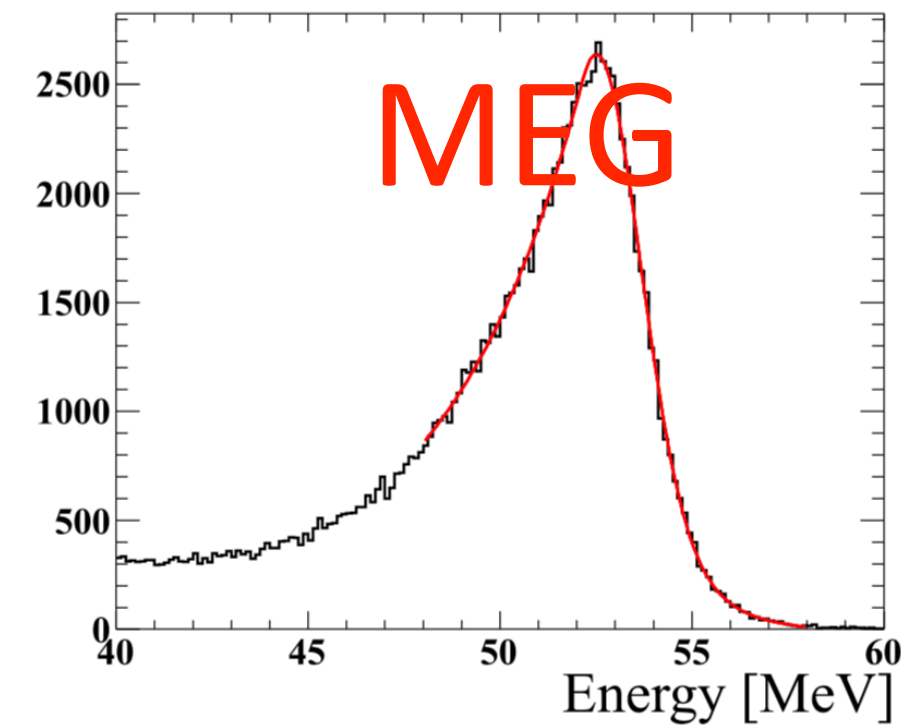
LXe detector



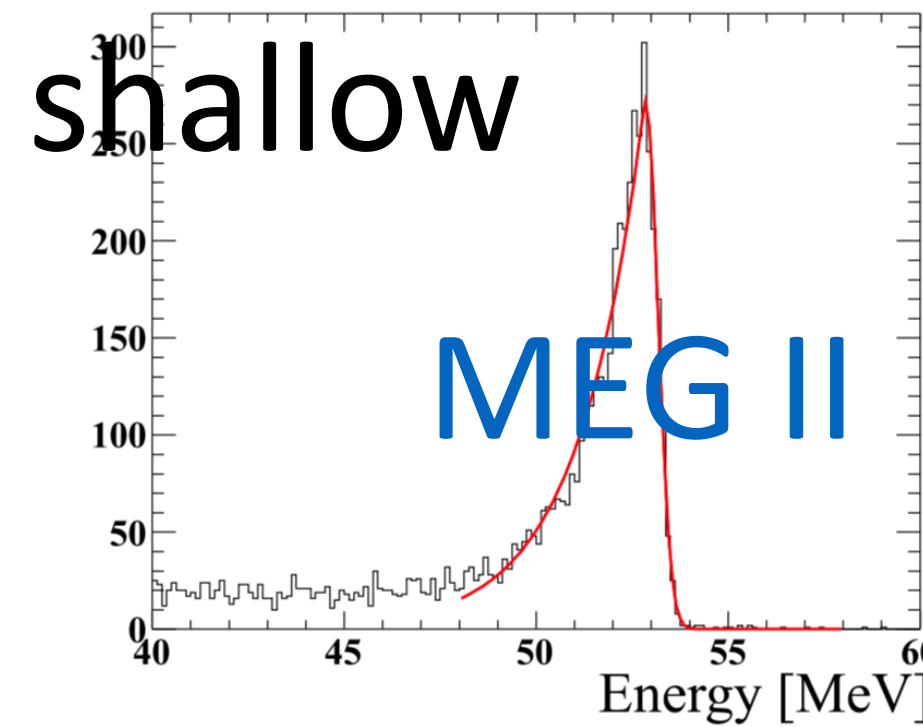
- LXe based homogenous detector
 - *bright: 40 photons/keV*
 - *fast: 4/22/40 ns*
- VUV MPPC replacing PMTs in the inner face
 - *4192 channels (instead of 216 as in MEG!!)*
 - *uniform response in particular for shallow events*



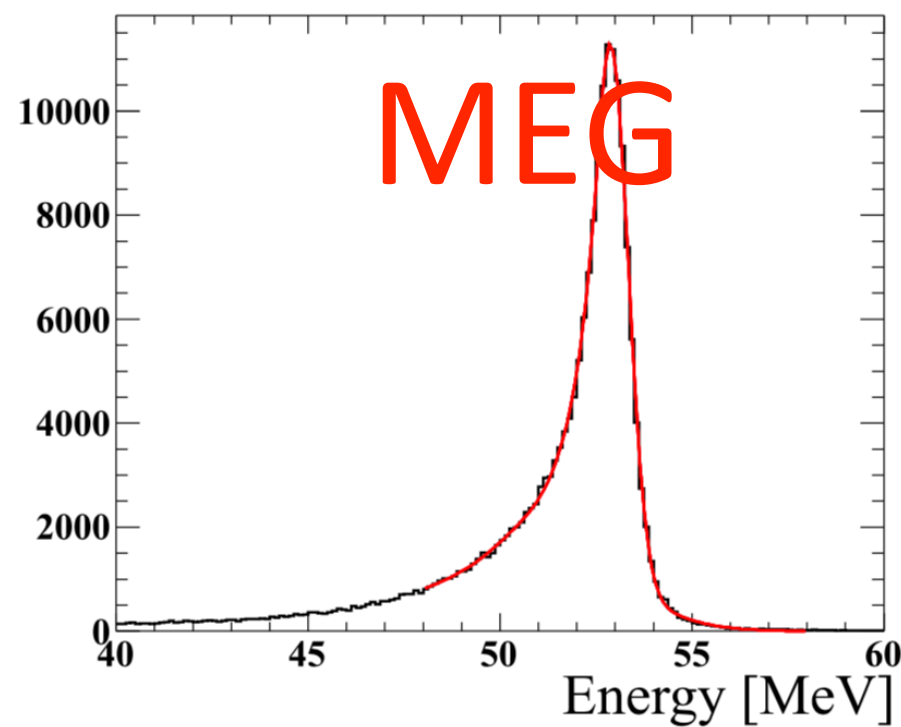
Performance improvement



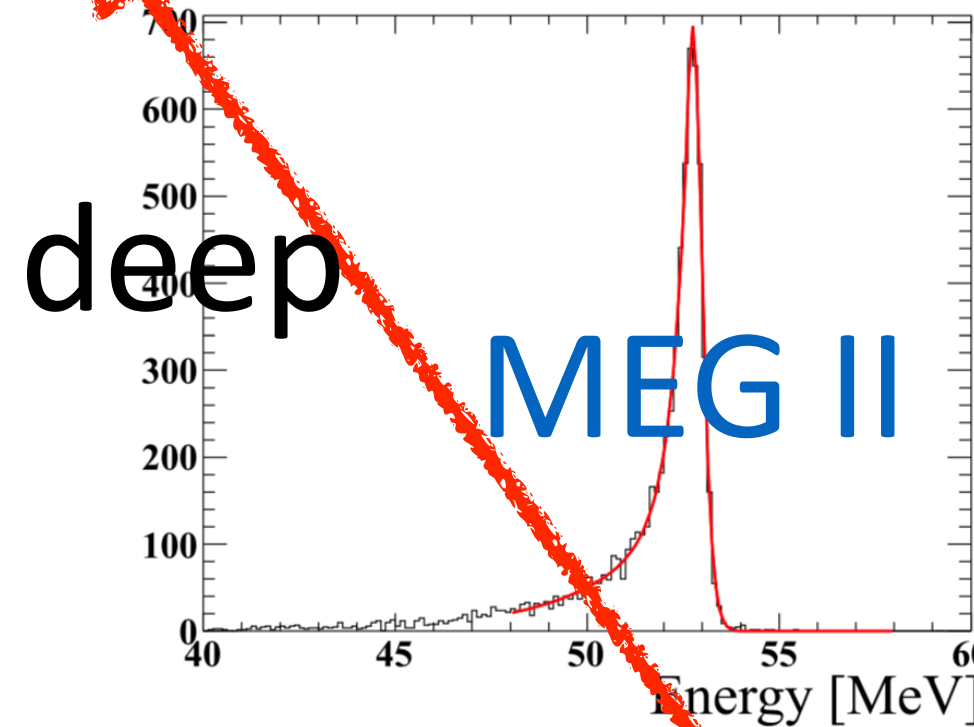
(a) MEG ($w < 2$ cm)



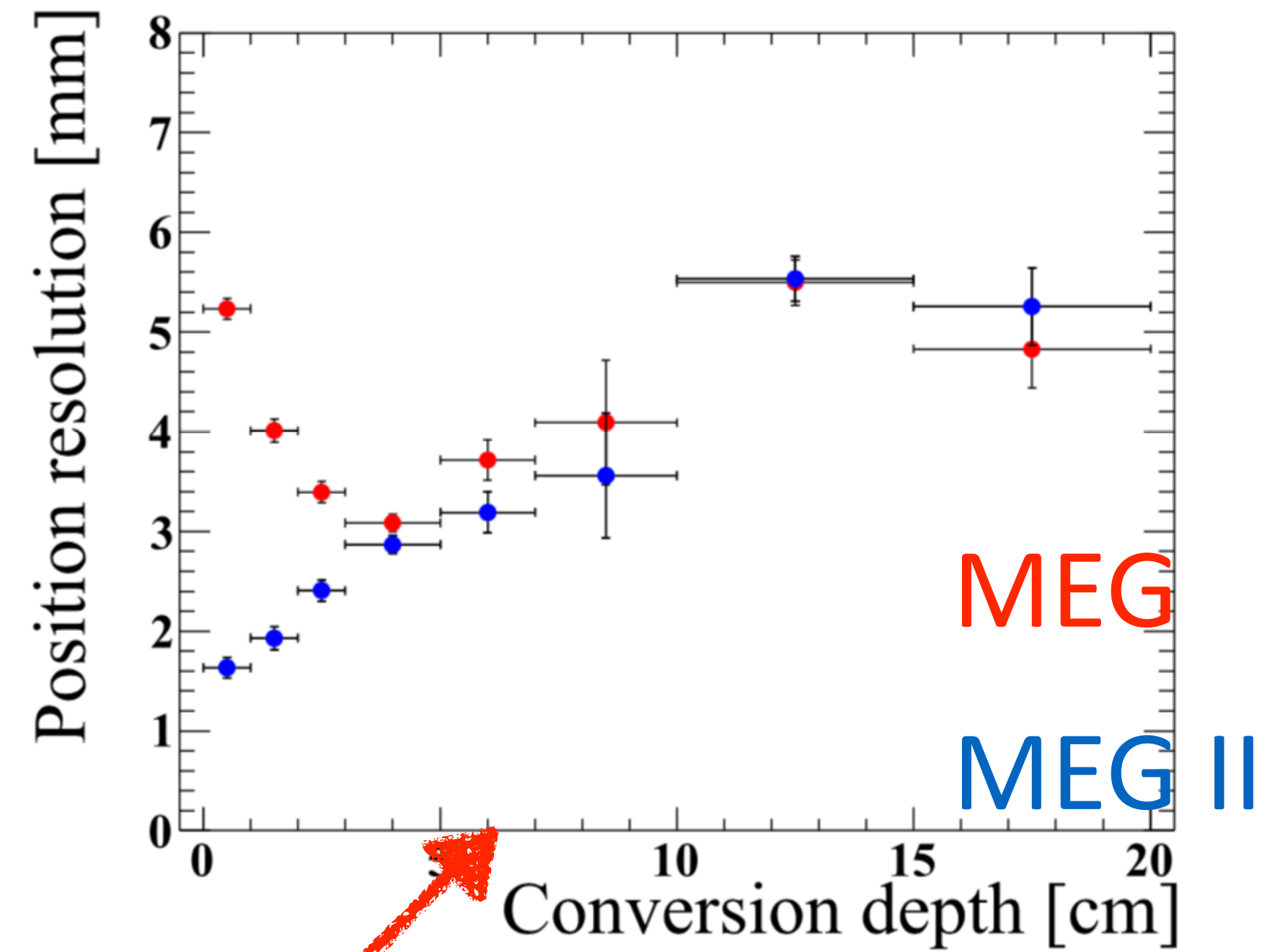
(b) MEG II ($w < 2$ cm)



(c) MEG ($w \geq 2$ cm)



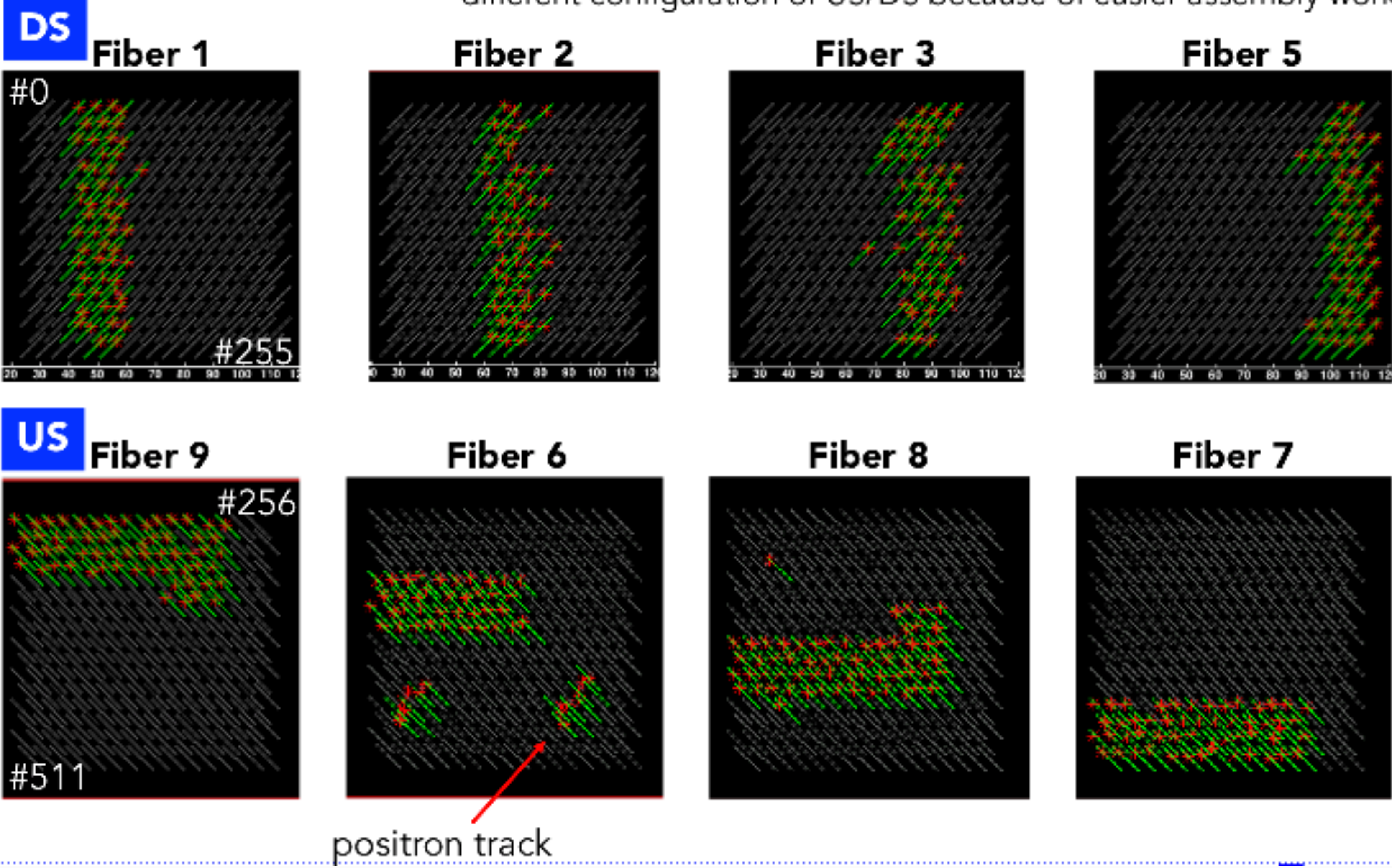
(d) MEG II ($w \geq 2$ cm)



$$B_{acc} \propto R_{\mu} \Delta E_e \Delta E_{\gamma}^2 \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma}$$

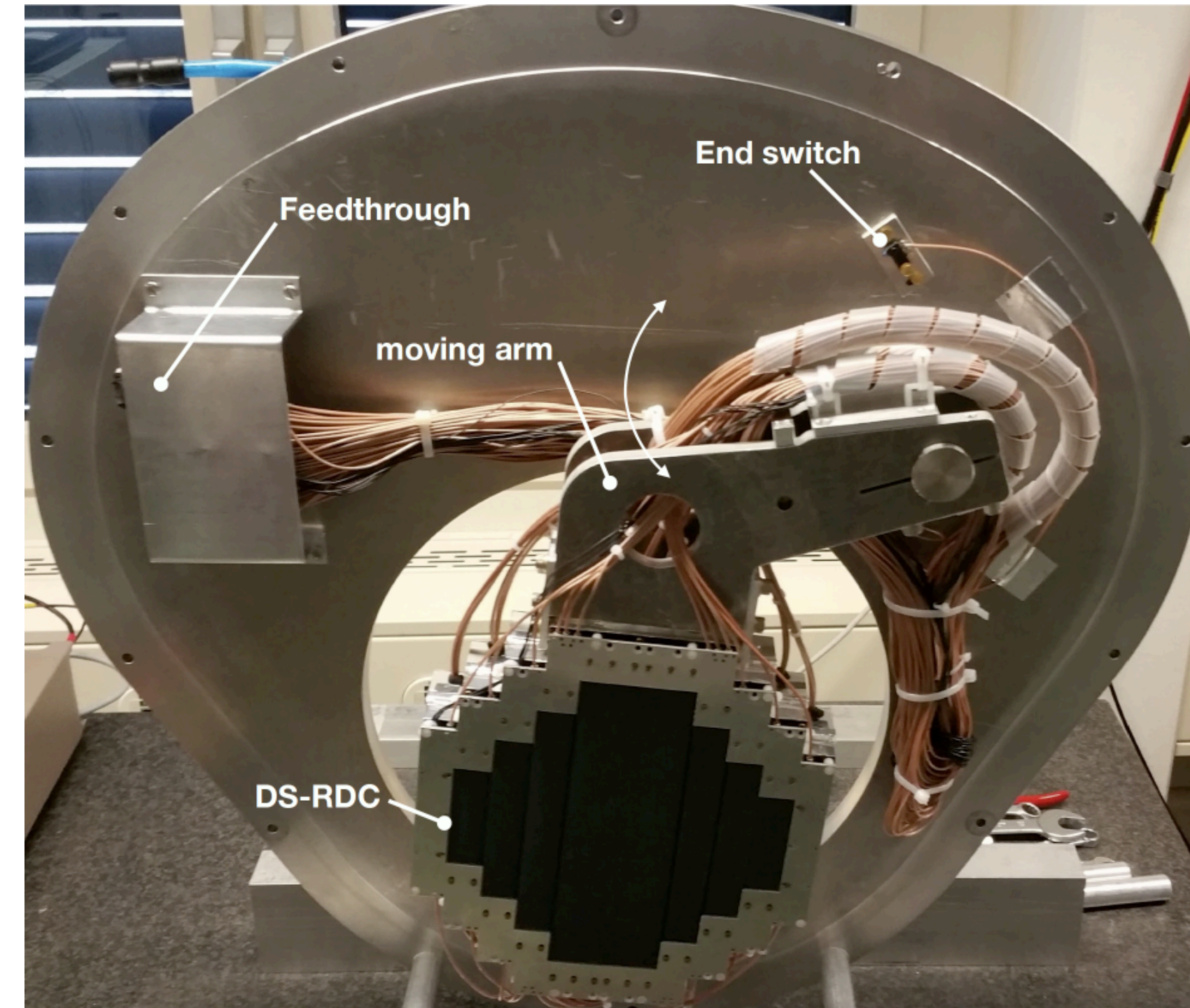
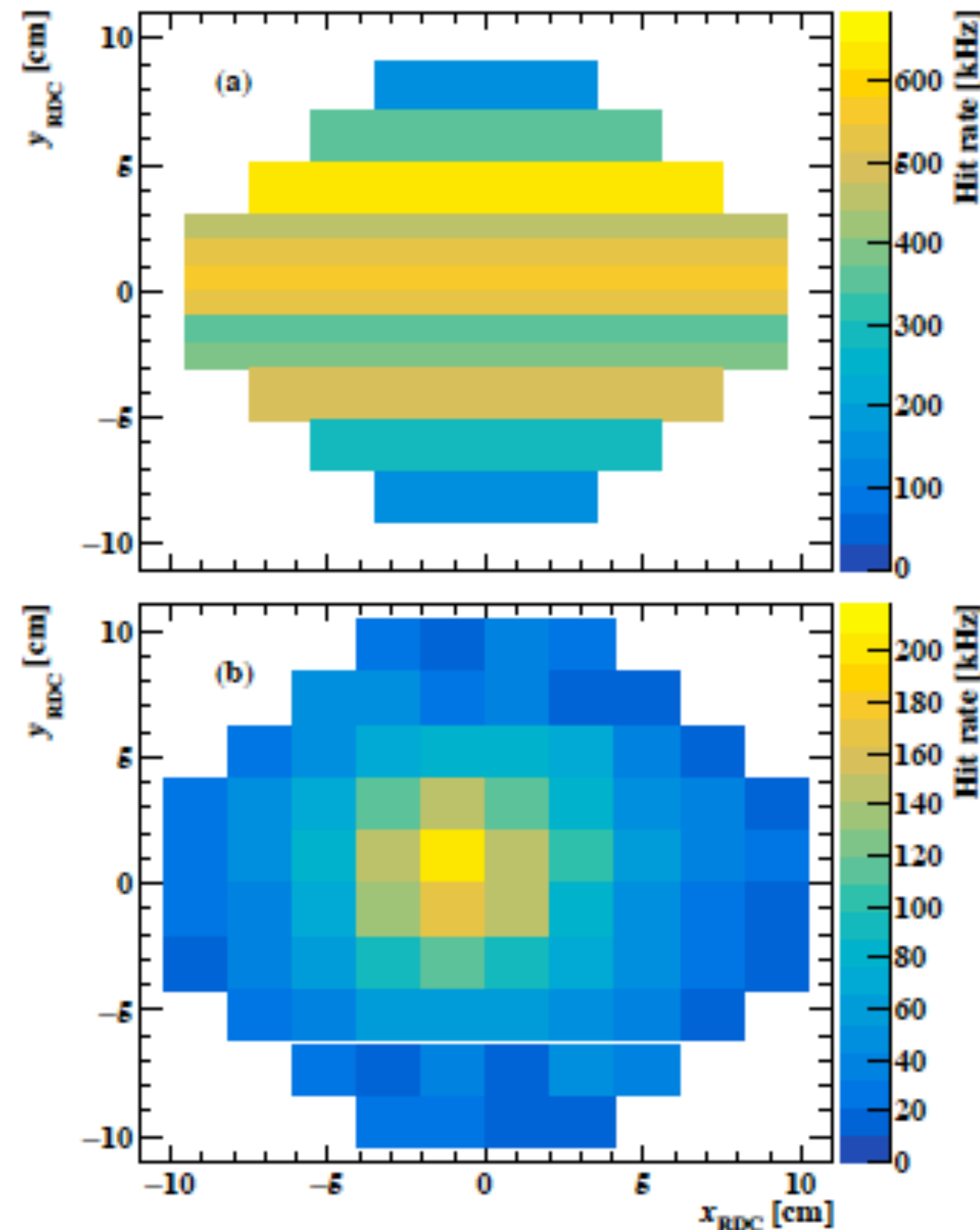
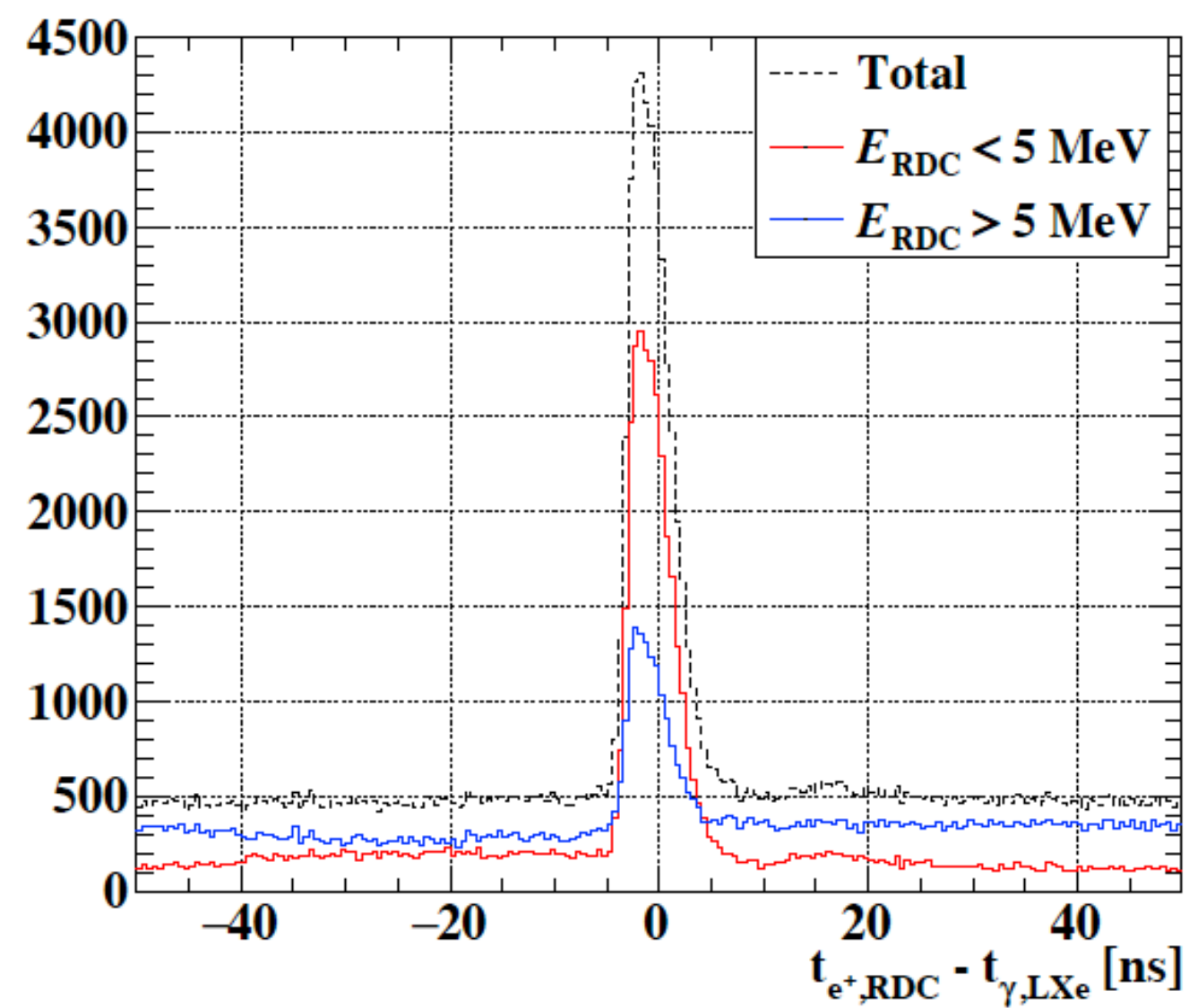
Calibration with laser

*different configuration of US/DS because of easier assembly work.

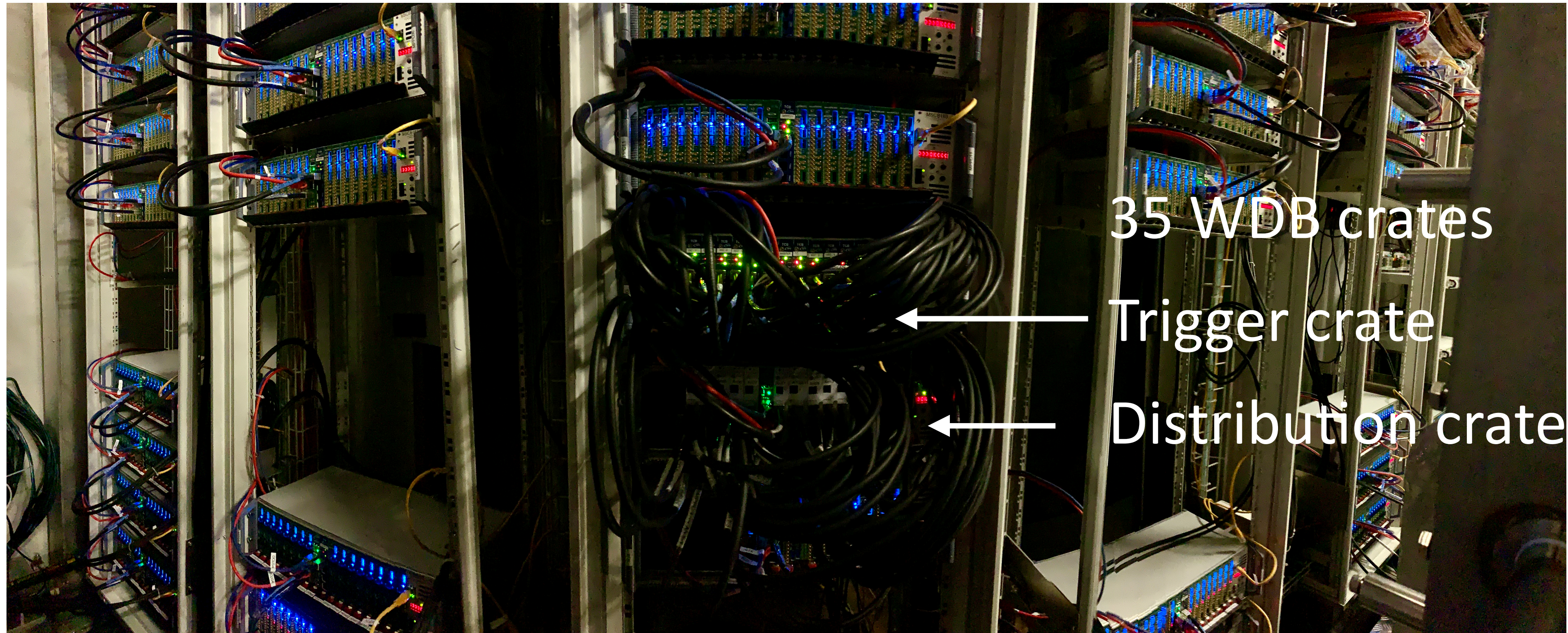


Radiative Decay Counter

- Tags BG γ -rays from muon **radiative** decays by detecting **low energy positrons**
 - **(a) scintillation tile** in the front for **timing**
 - **(b) LYSO cube** for **energy** measurement
- Sensitivity improved by 15%



TDAQ system



TDAQ electronics

- Full custom
- Trigger
- waveform
- SiPM
- Compliance
- up to 10 Gb/s DAQ throughput (50 Hz)

