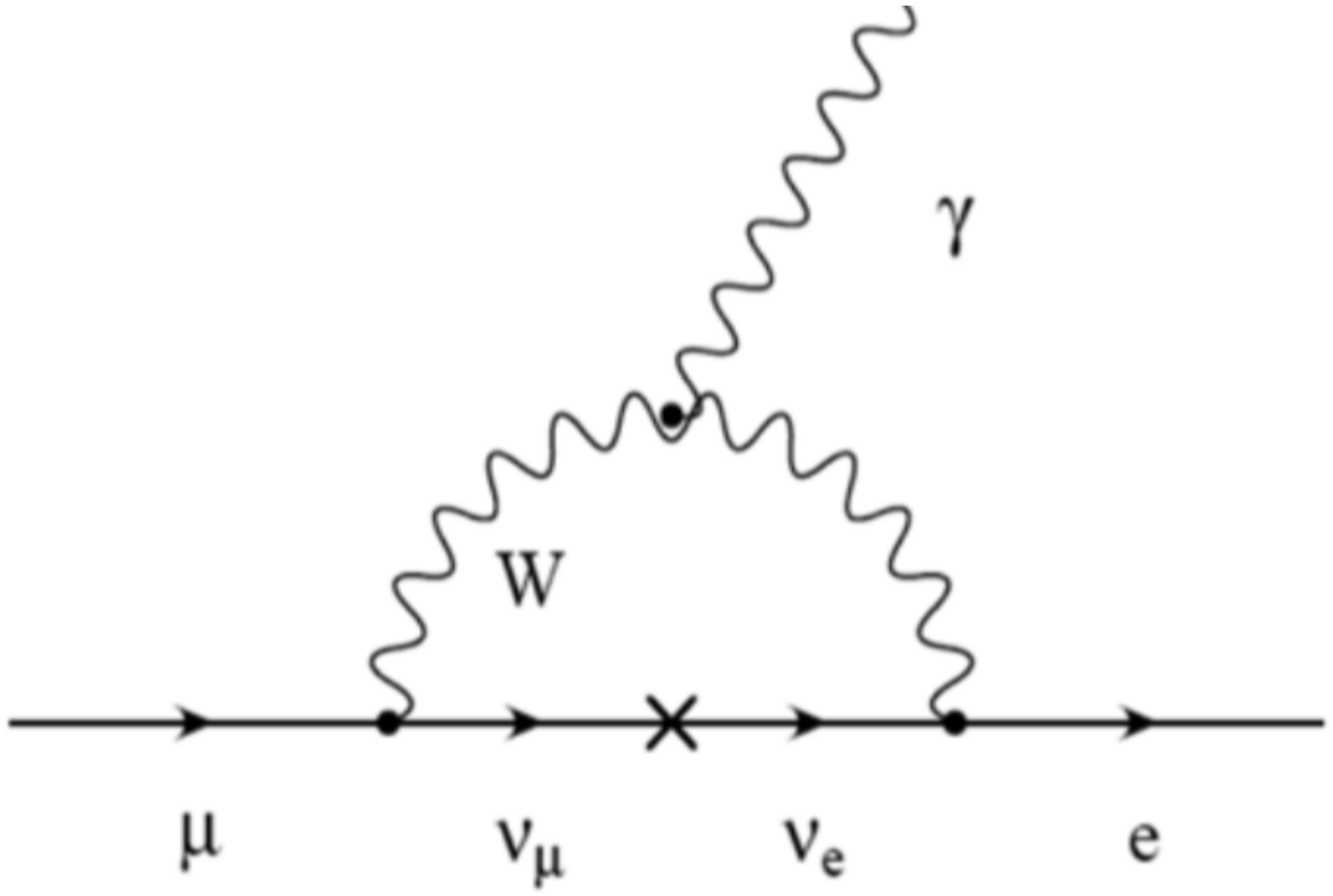
Status of the BSM searches with the MEG II apparatus

Luca Galli, INFN Sezione di Pisa
Phi to Psi 09-06-2026

cLFV = physics beyond SM

- l → l' + X (X = γ, " " , ee, μμ, others…)



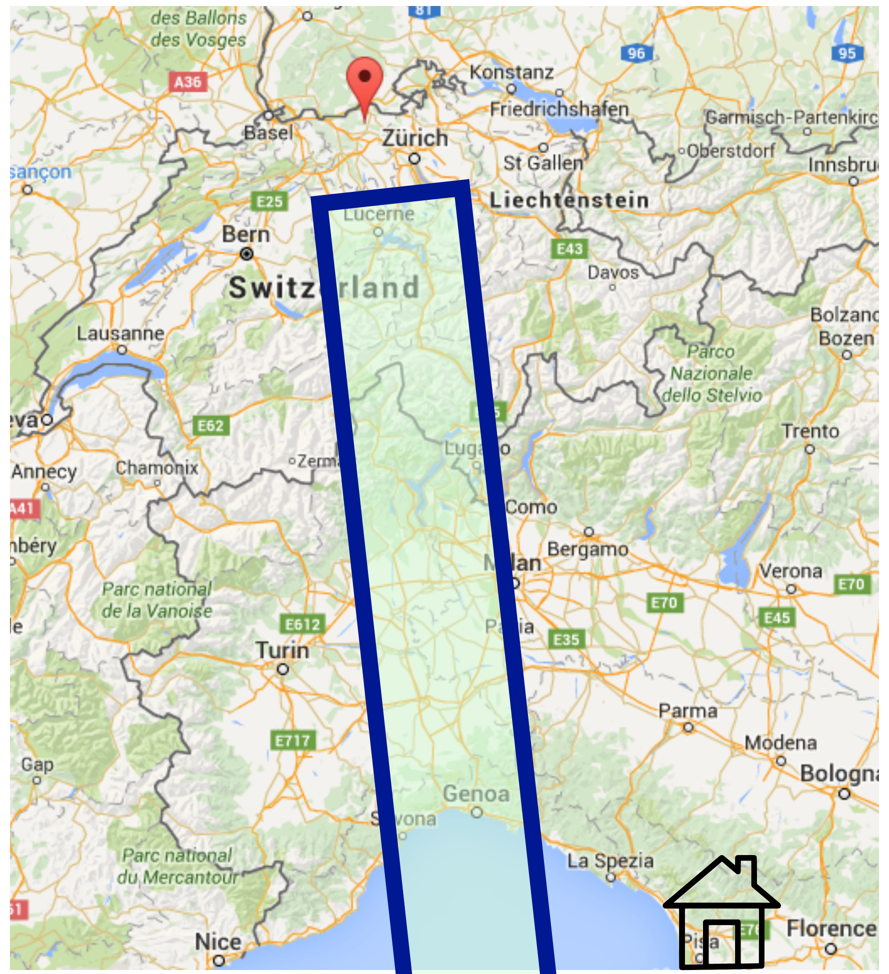
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W} \right|^2 \simeq 10^{-54}$$

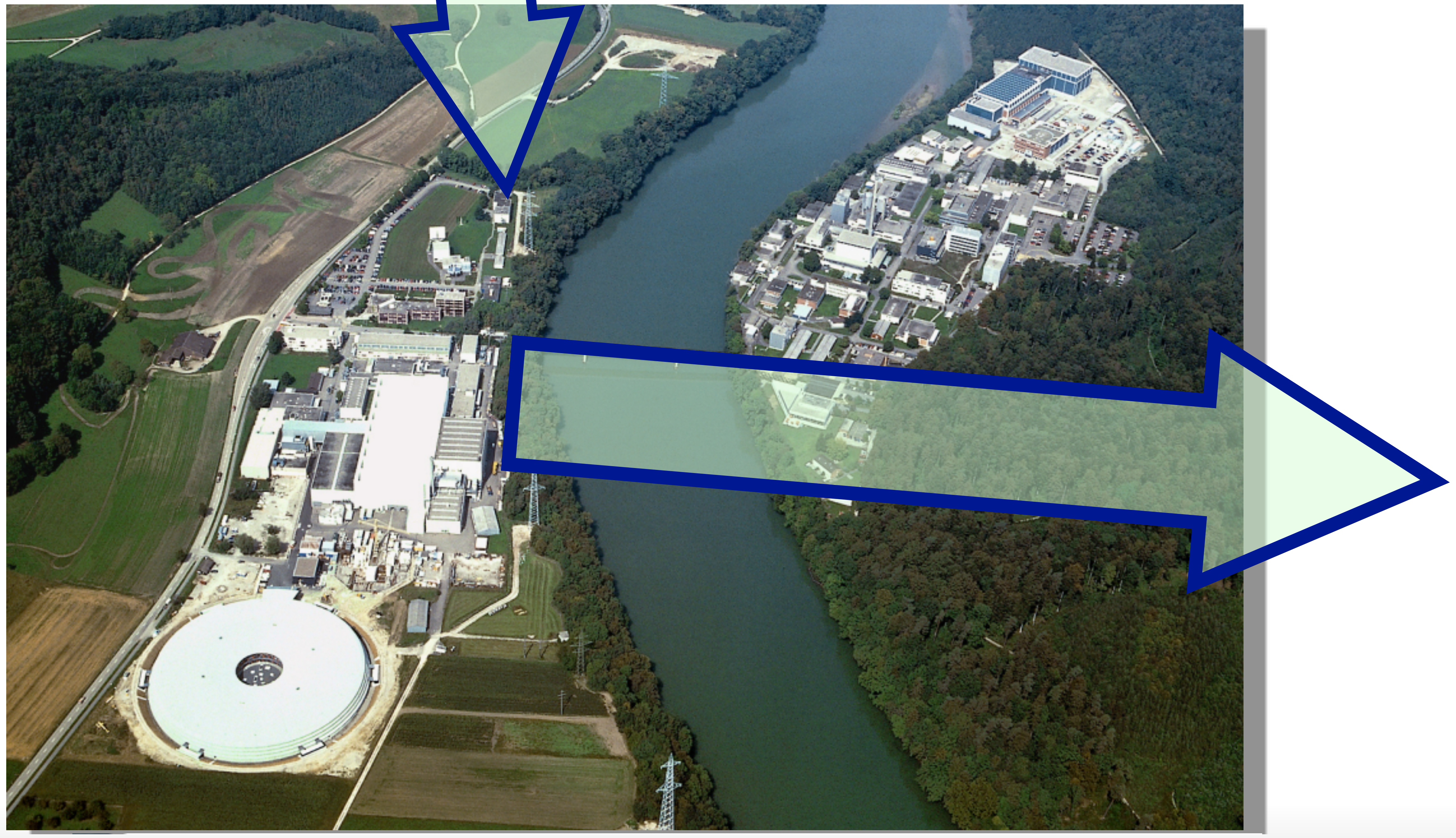
too small to be experimentally accessible → portal to New Physics

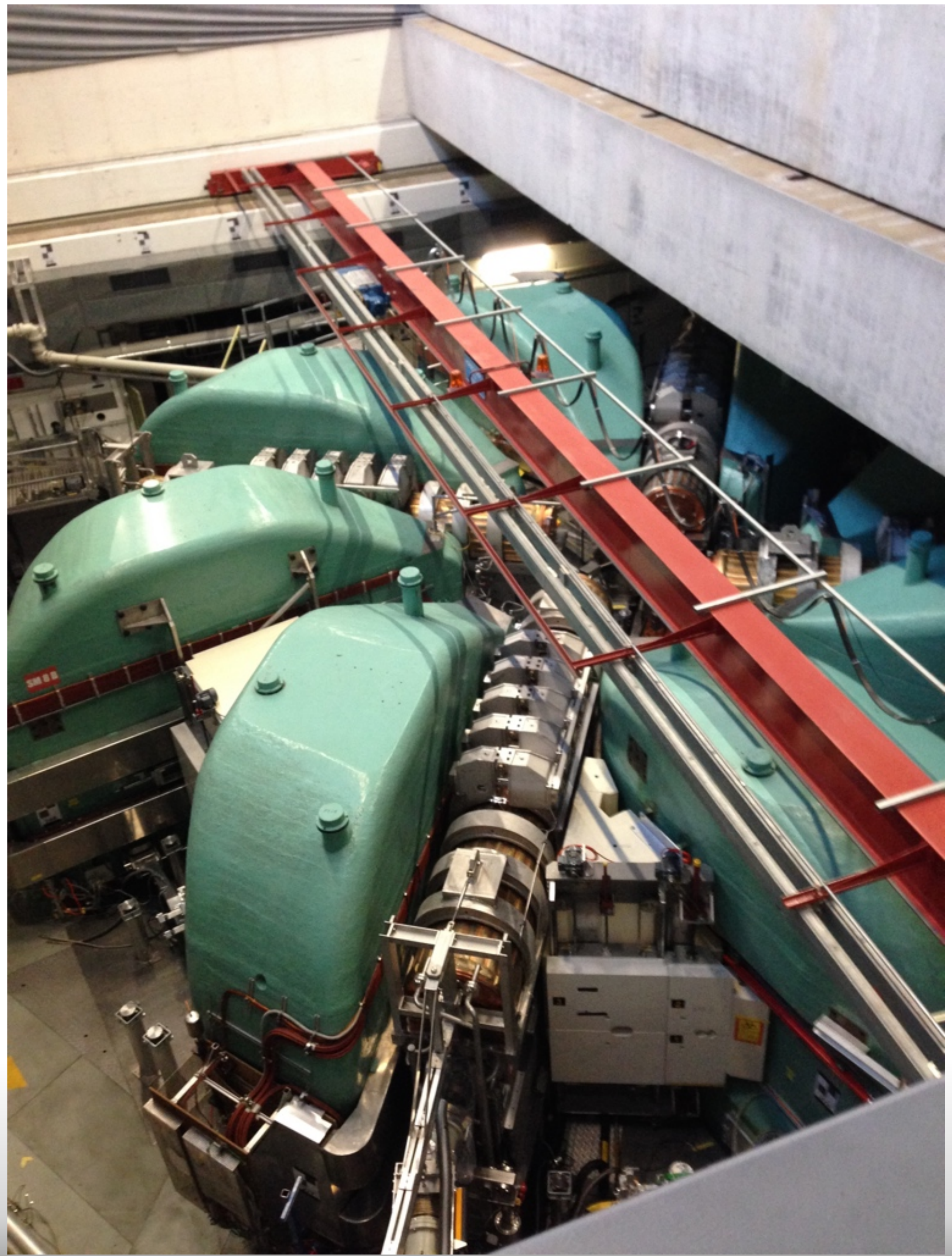
extensively exploited in intensity frontier searches

SM background free searches!

The MEG II experiment @PSI





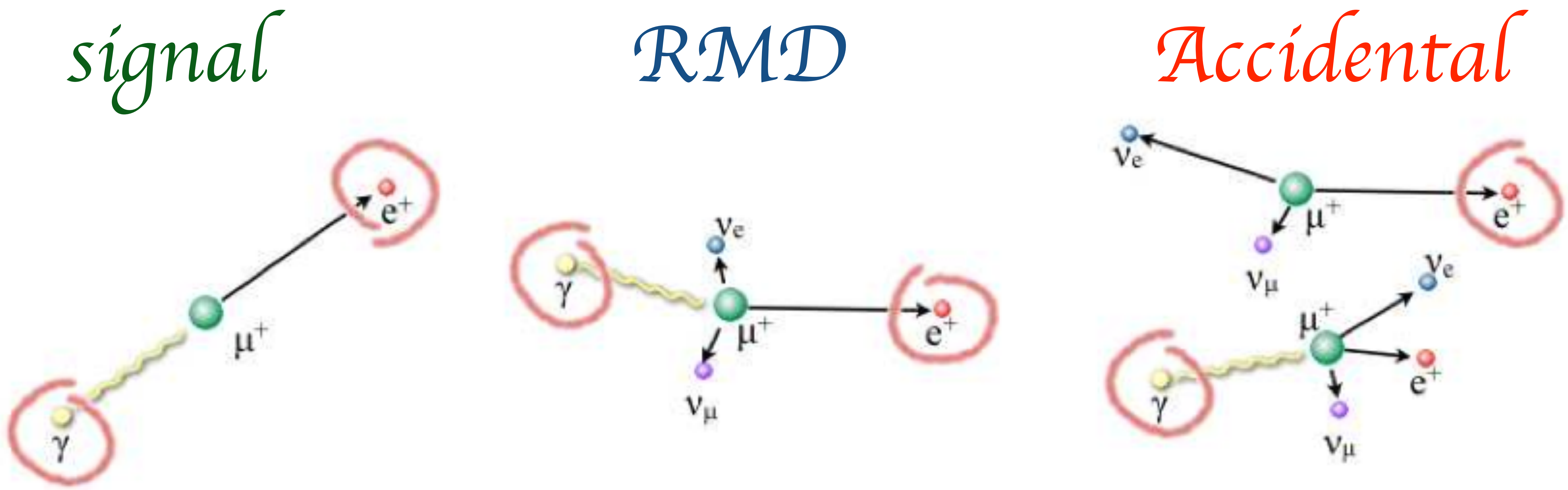


PSI Ring
Cyclotron

MEG collaboration

~60 physicists from 12 institutes from 5 countries

μ→eγ search: signal and background



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

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

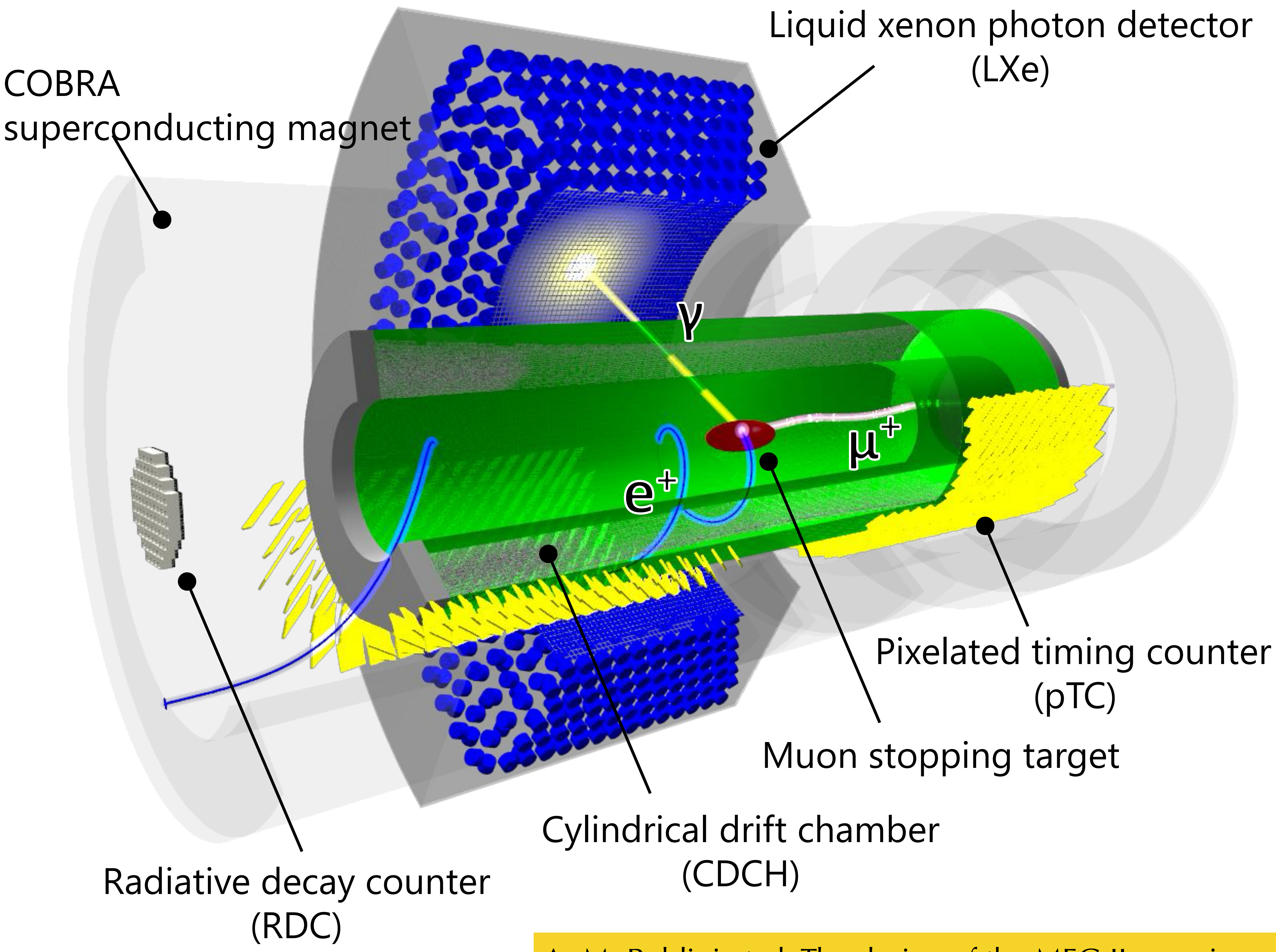
(2) **fast**: high rate $\Longleftrightarrow$ high intensity frontier

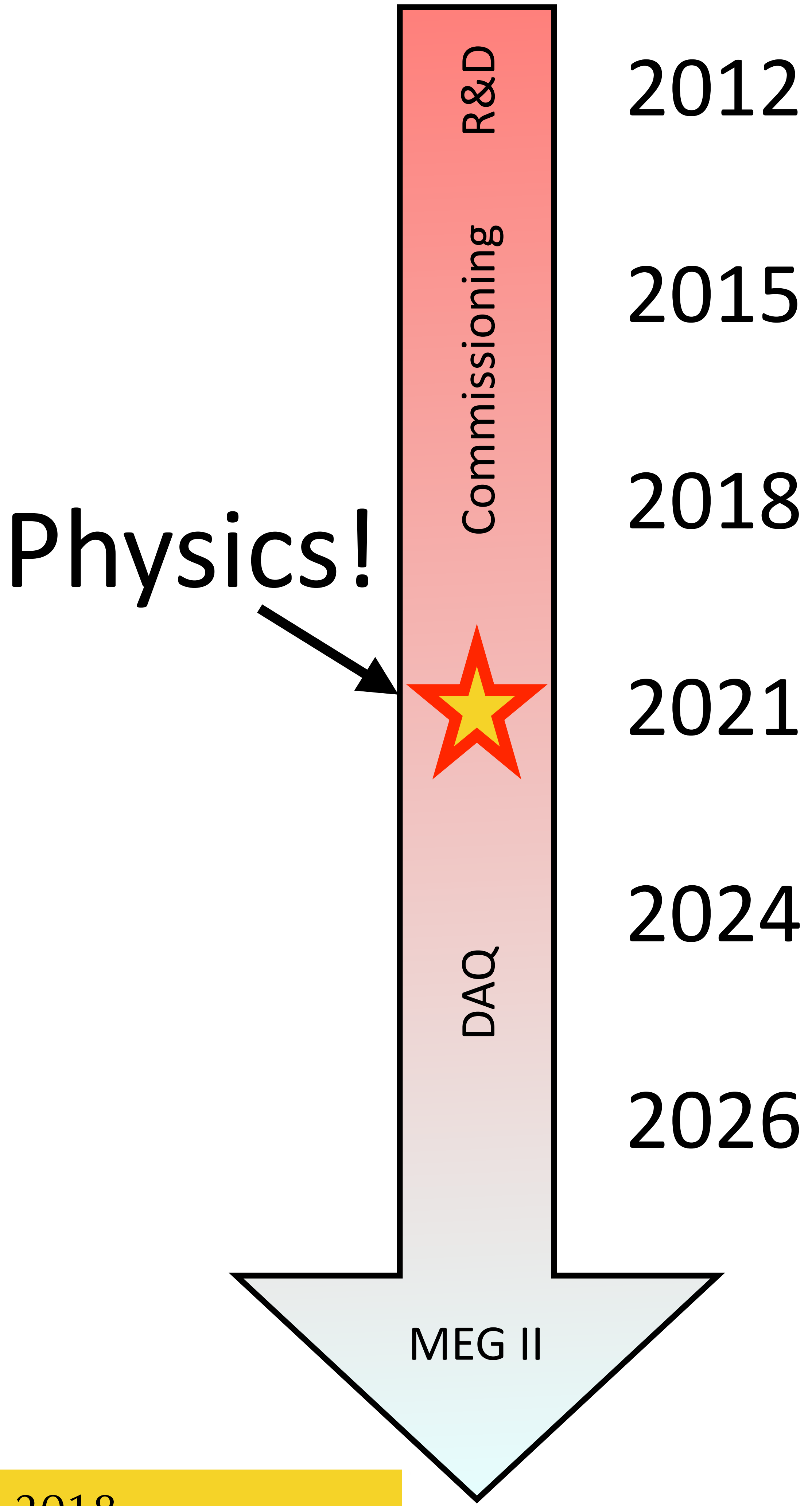
(3) **stable**: precision measurement $\Longleftrightarrow$ background rejection

MEG II solutions

. **μ beam stopped** on a 174μm 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)

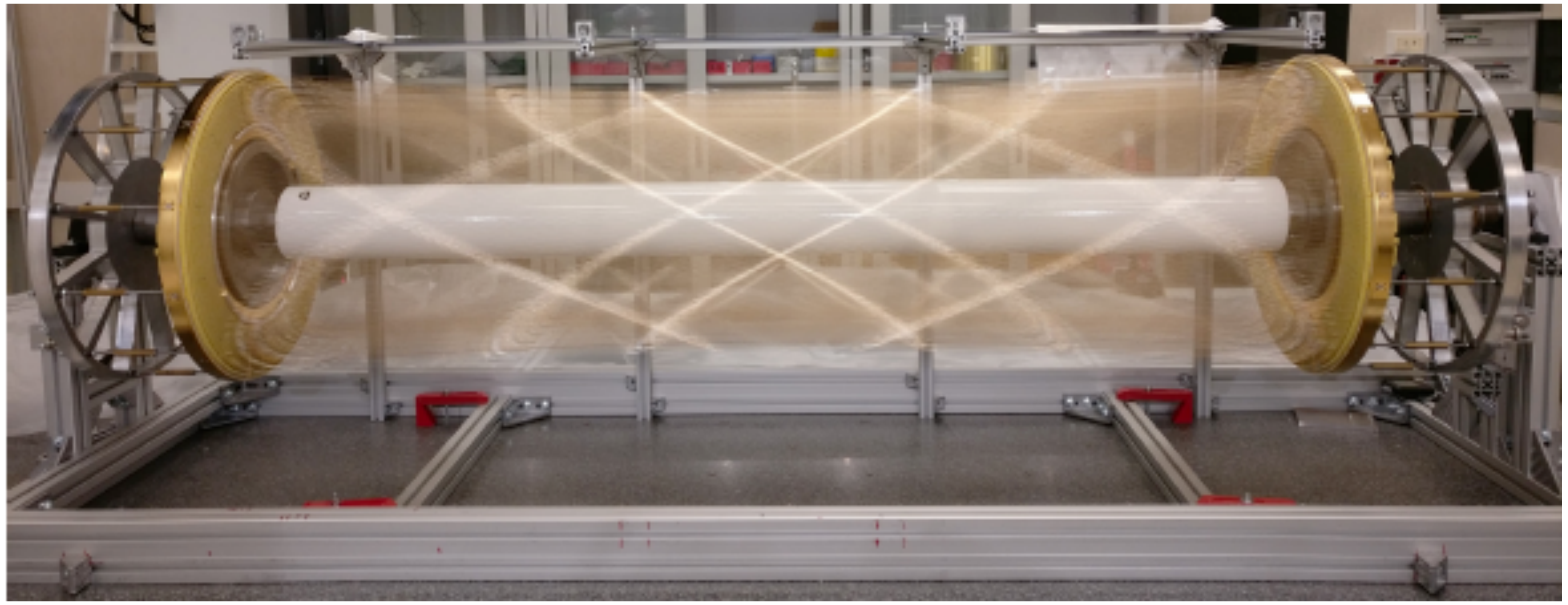
Experimental approach

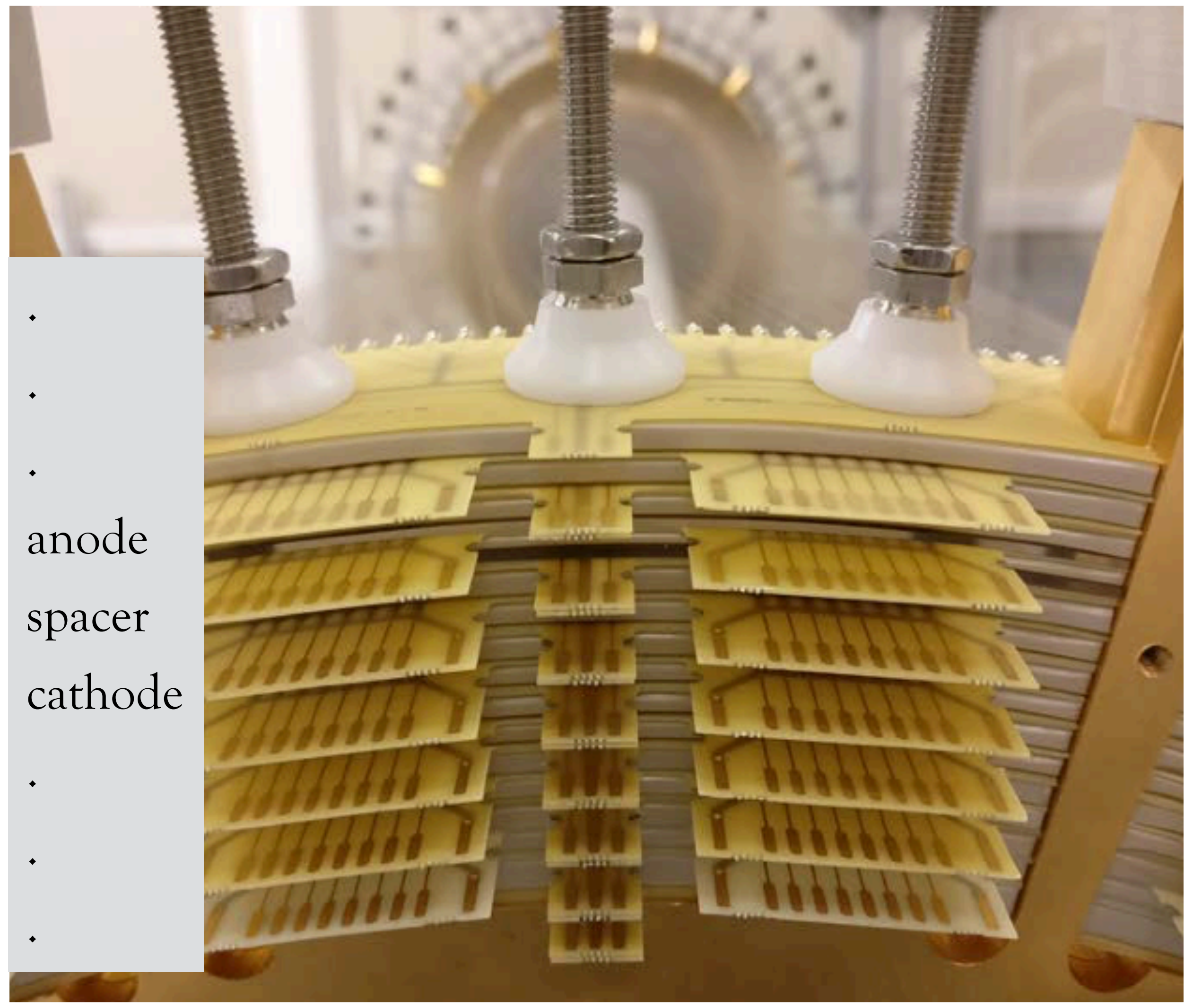




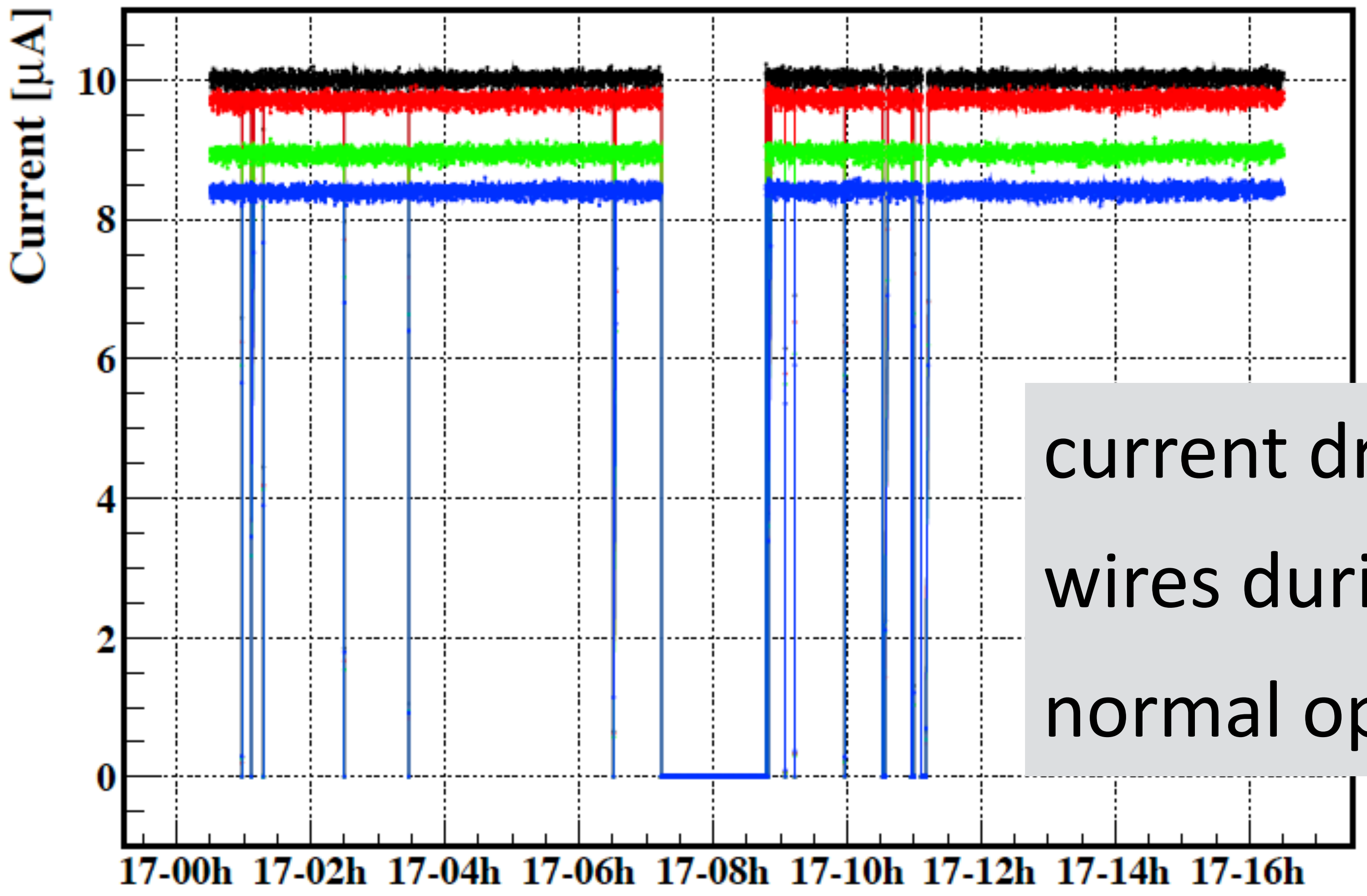
A. M. Baldini et al, The design of the MEG II experiment EPJC, 2018
K. Afanaciev et al, Operation and performance of the MEG II detector EPJC, 2023

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 x 10^{-3} radiation length** per **track***
- **1728 anode** wires + **~10000 cathodes**
  - ***anode**: **20μm** W/Au, **cathode**: **40/50 μm** Al/Ag*
  - ***7 degree stereo** angle*
- In **operation** since **late 2020** after 2 years of commissioning

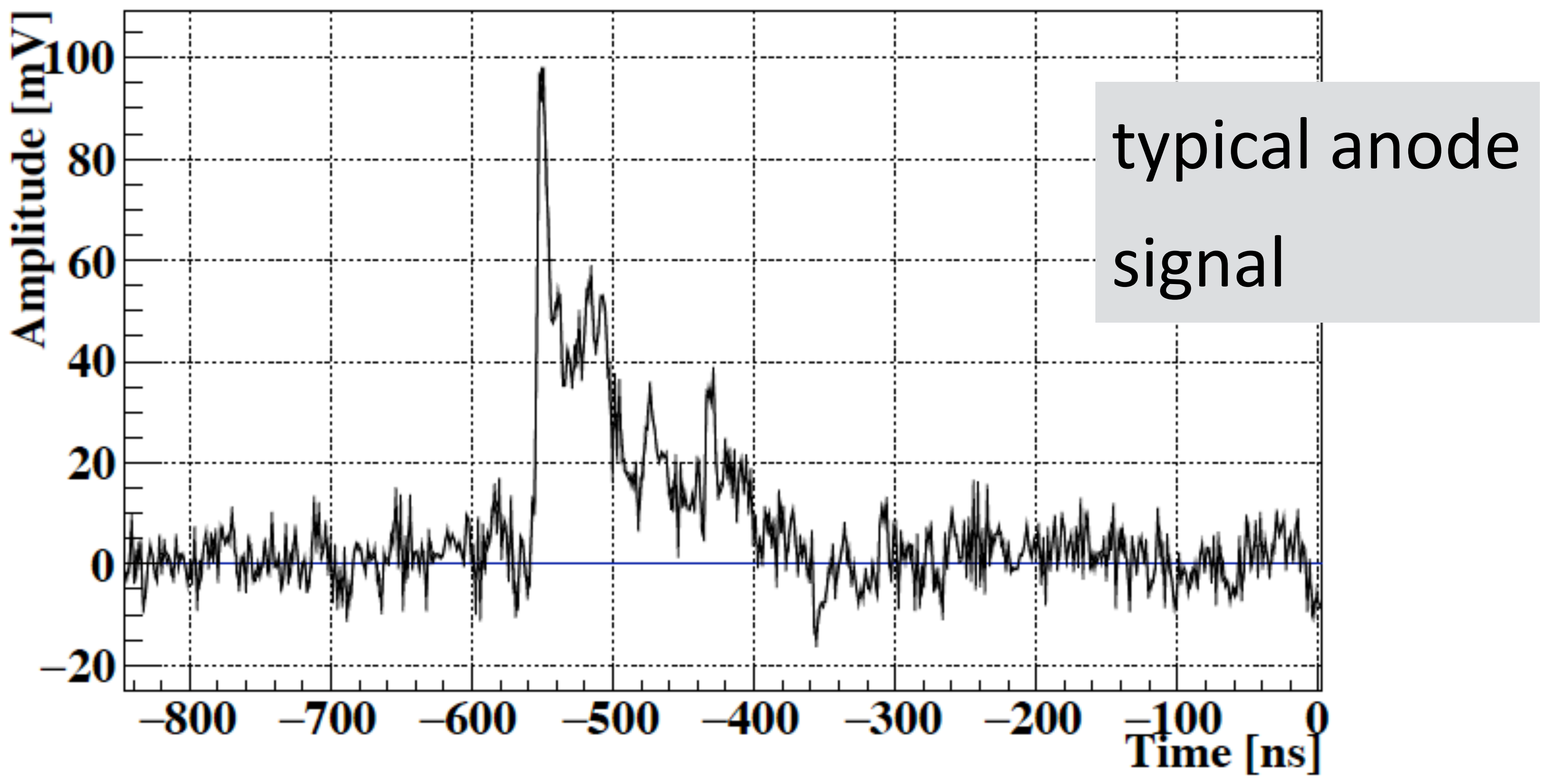


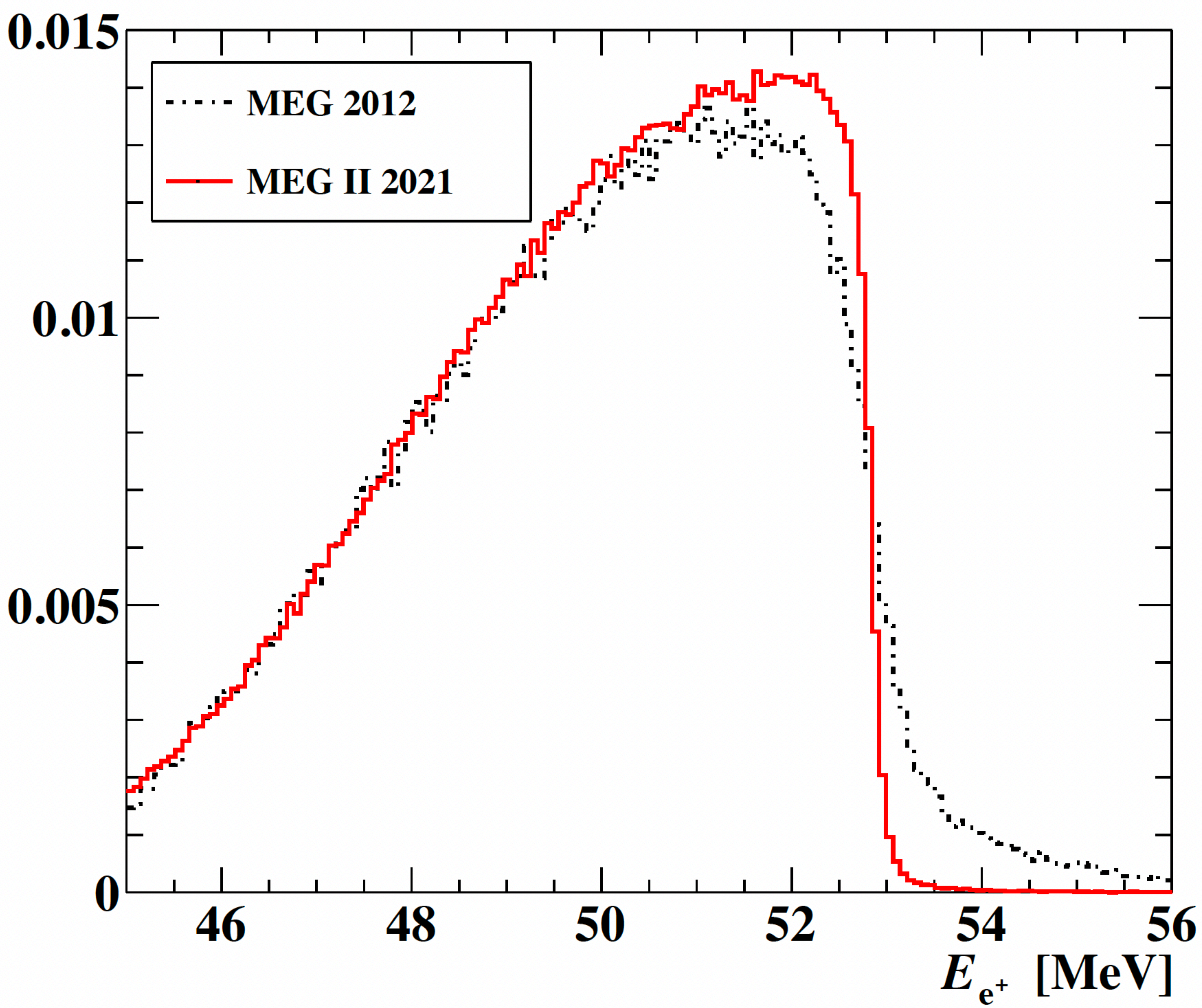
current drawn by wires during normal operation

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 **~150μm***
  - ***momentum** resolution **~90keV/c (core)***

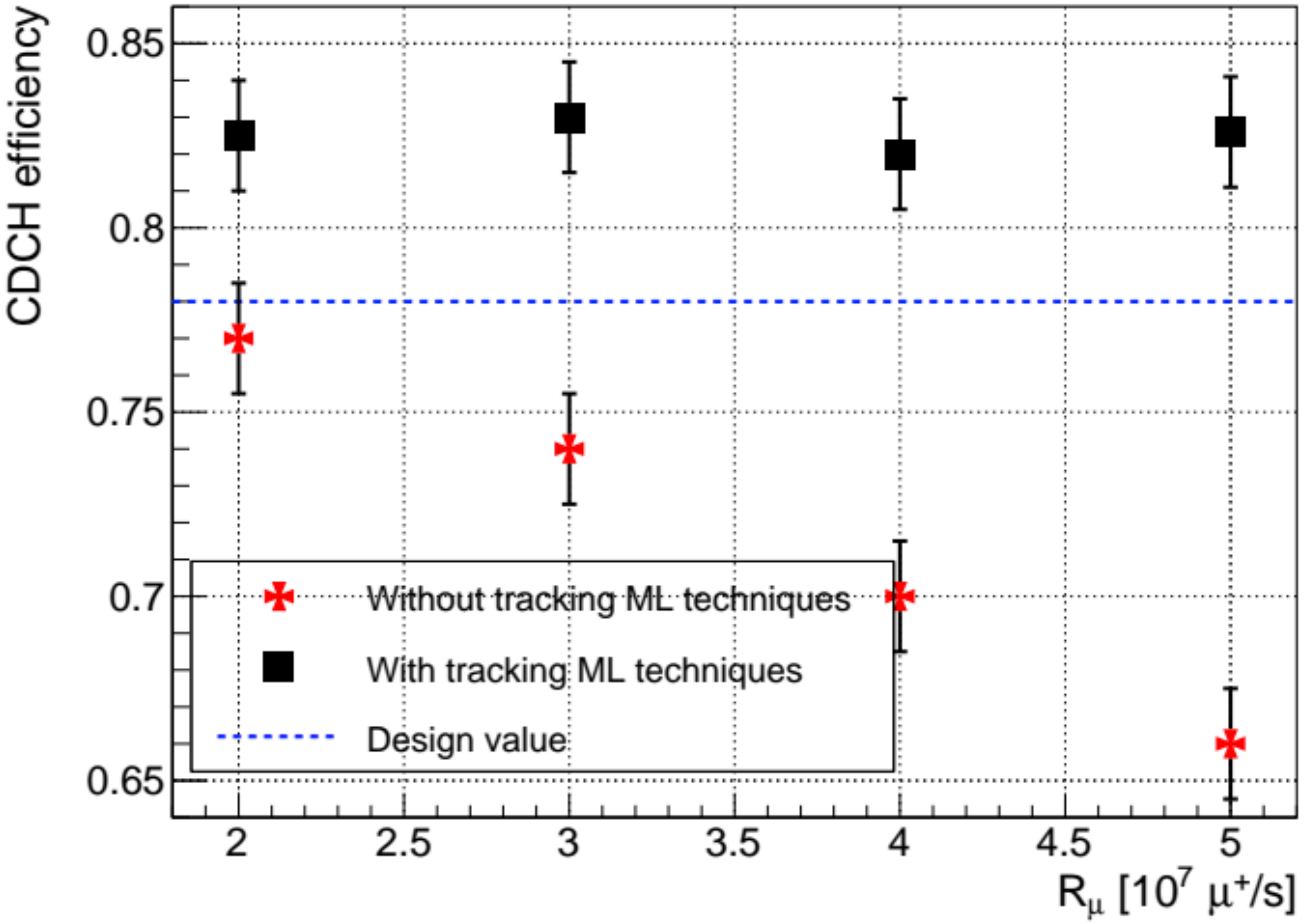




A. M. Baldini et al, Performances of a new generation tracking detector: the MEG II cylindrical drift chamber, EPJC 2024

Tracking efficiency improvements

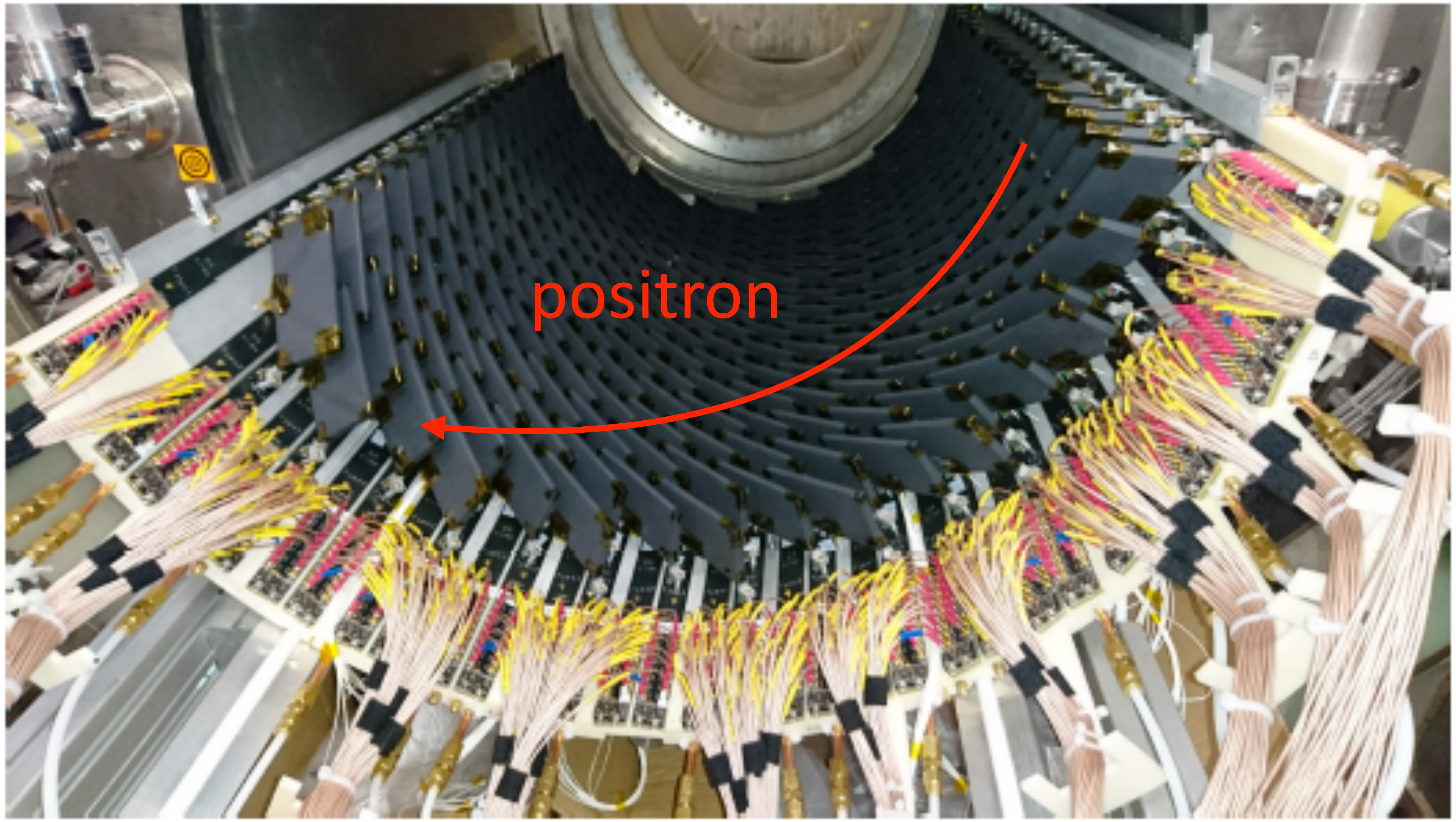
- Conventional **pattern recognition** for track finding limited at higher intensity due to pileup hits
- **New algorithms** based on **machine learning** resulted in **large tracking improvement** at higher rates
  - *Using a mixed approach with **Transformer** (arXiv: 2512.19482) and **GNN** (recently presented at RT2026 conference)*
    - —> **Higher beam intensity** can be used (refer to slide 17)



- **25% efficiency improvement** at **@5 10^7 μ/s** beam rate
- **~10% improvement** in overall **experiment sensitivity**

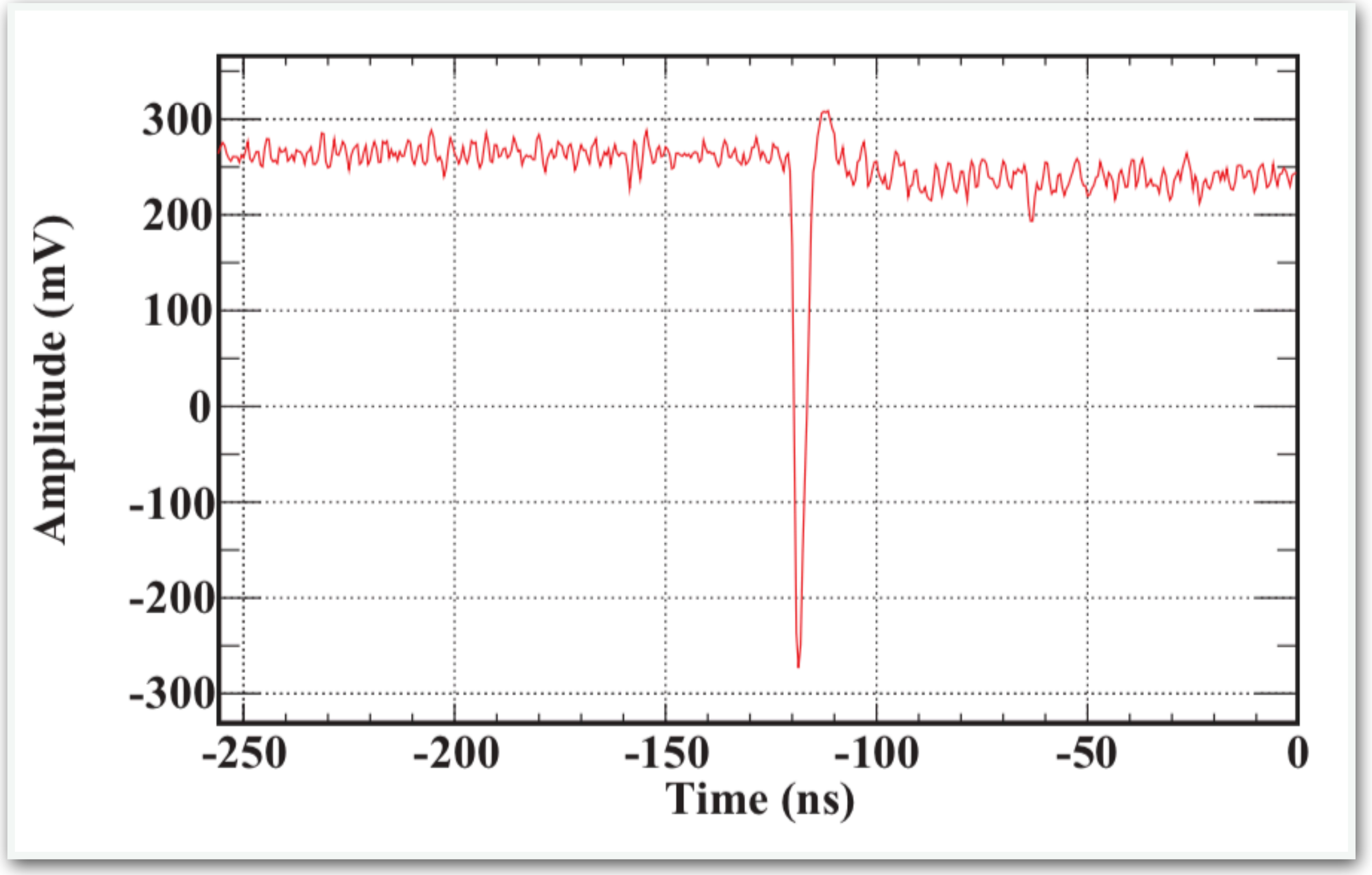
Pixelated Timing Counter detector

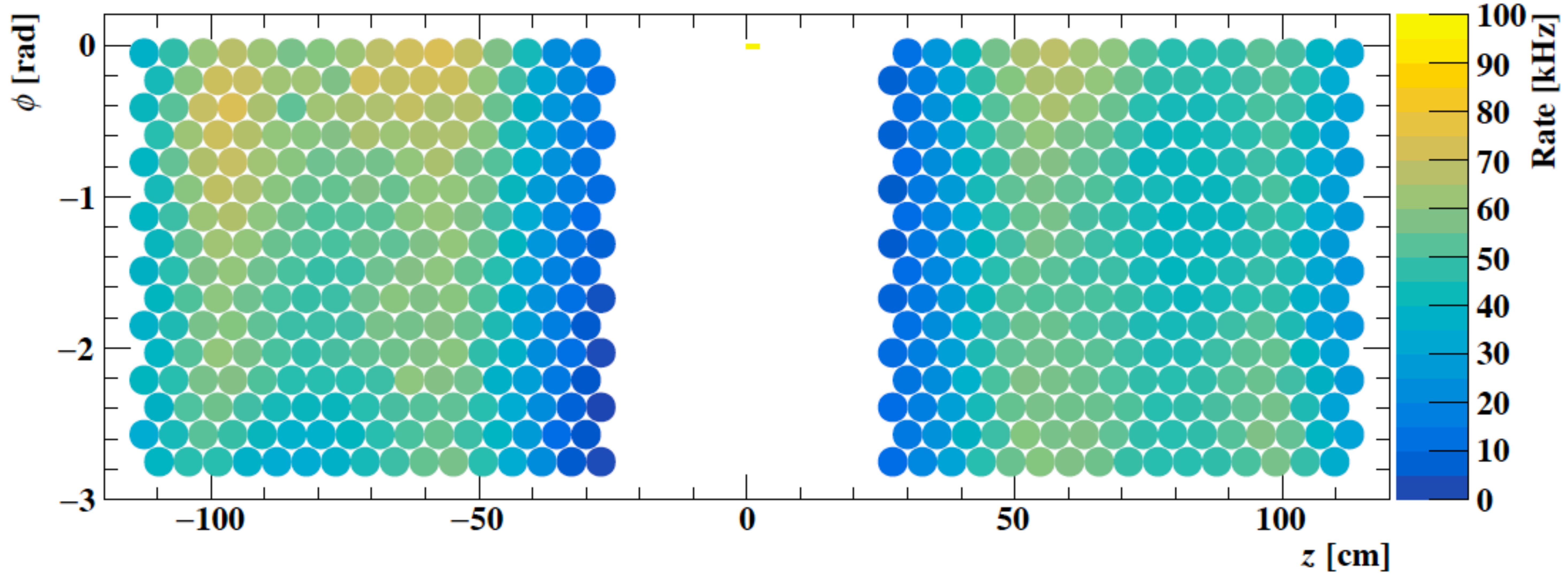
- **Highly segmented** detector
  - ***Two sectors*** *made of* ***256 scintillation tiles*** *each*
    - **Bicron BC422** read by **Advansid SiPM**
  - ***Time*** *by* ***averaging*** *the* ***tiles*** *hit by a positron*
    - **8 tiles** on **average** for **signal** positrons
  - ***Laser*** *can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



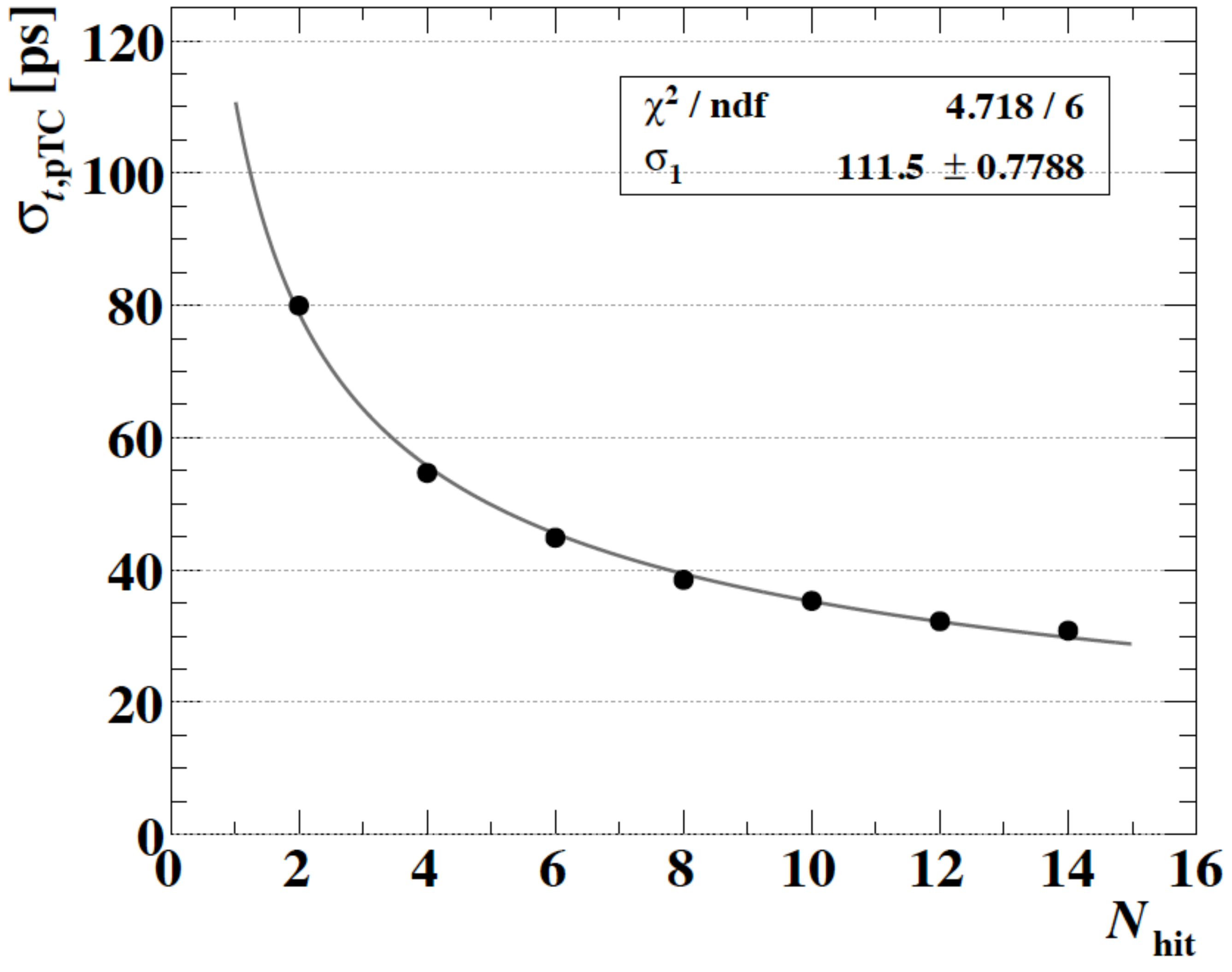
pTC performance

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

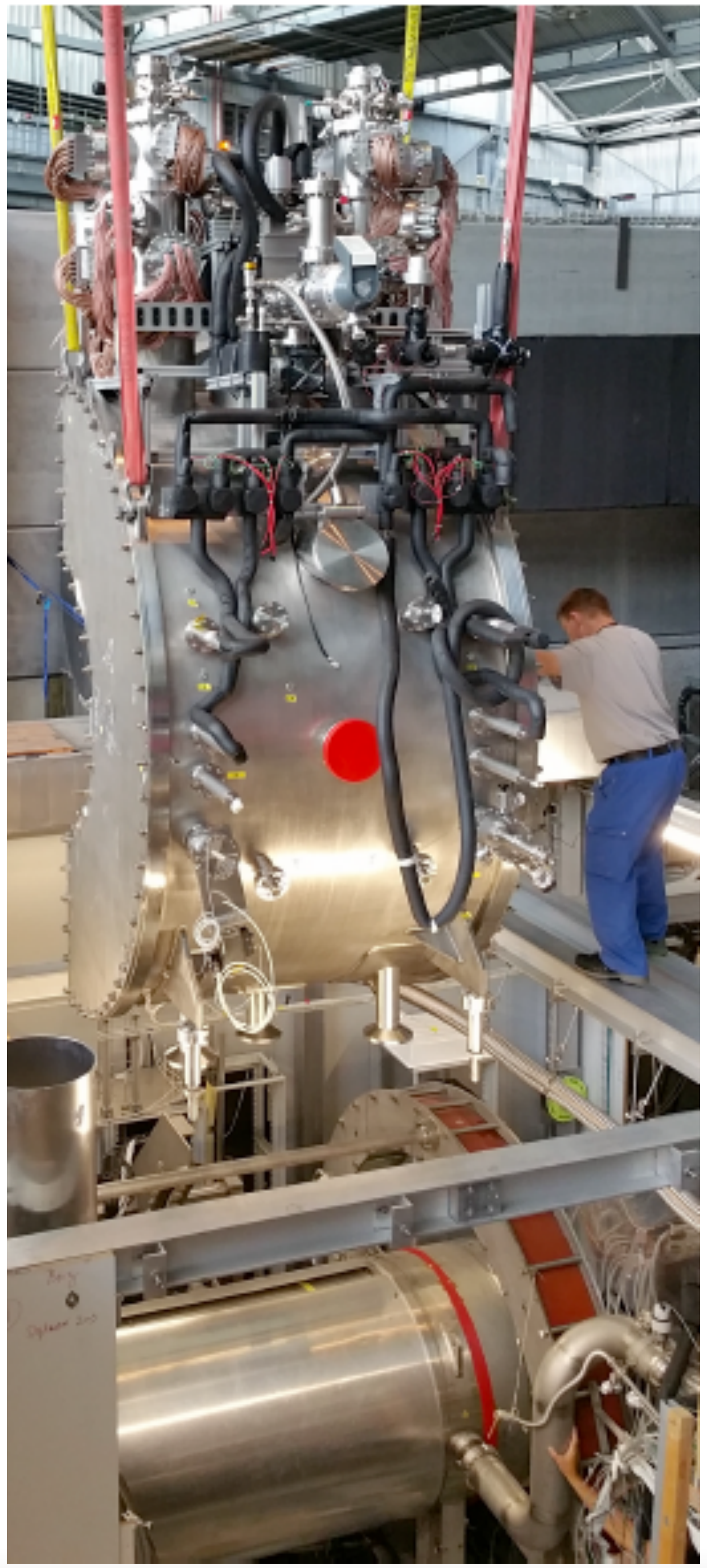




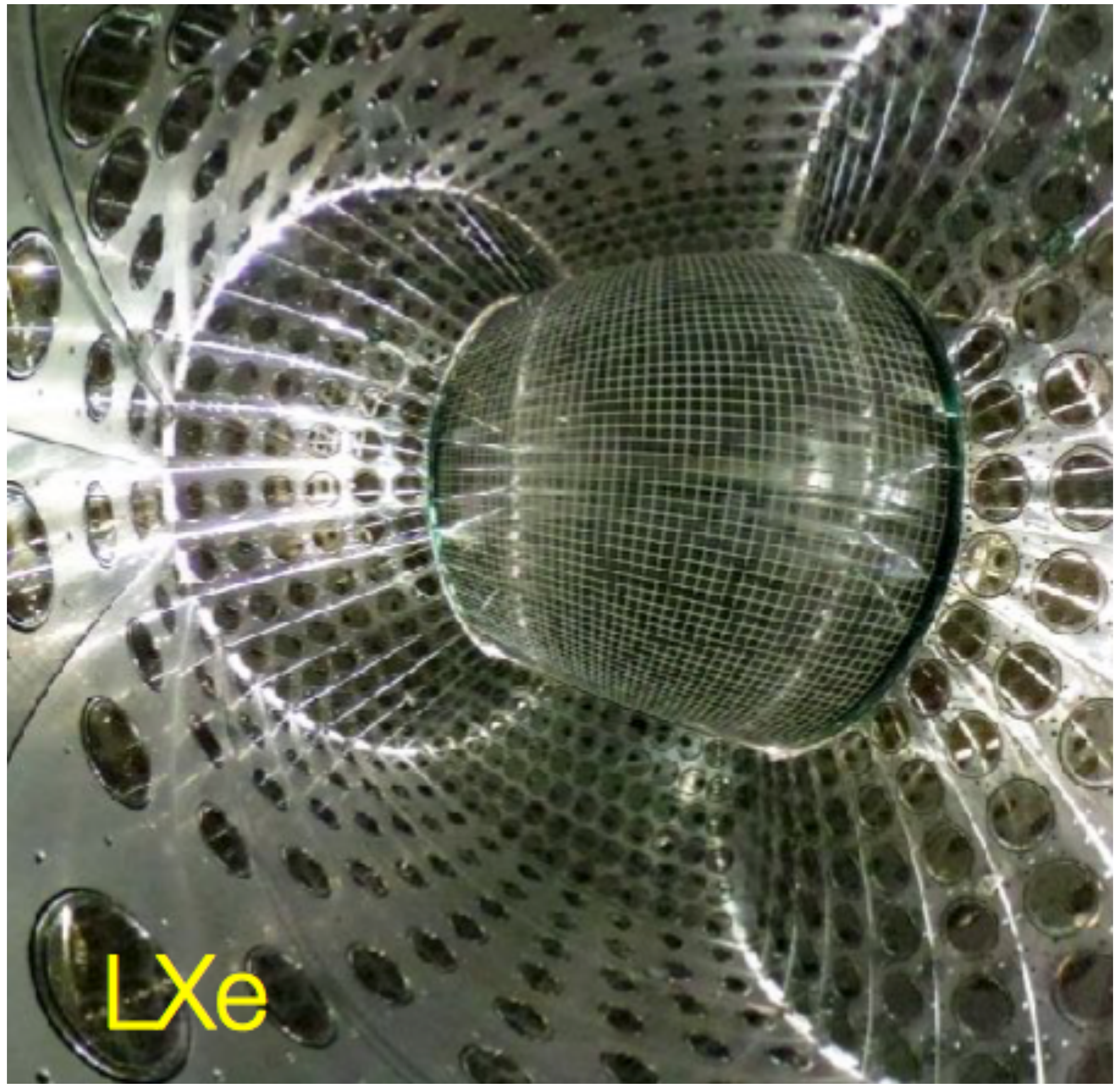
- **Stable** detector **operation**
- **Tile rates** in **agreement** with **expectation**
- **Time resolution** of about **30ps** for signal positrons

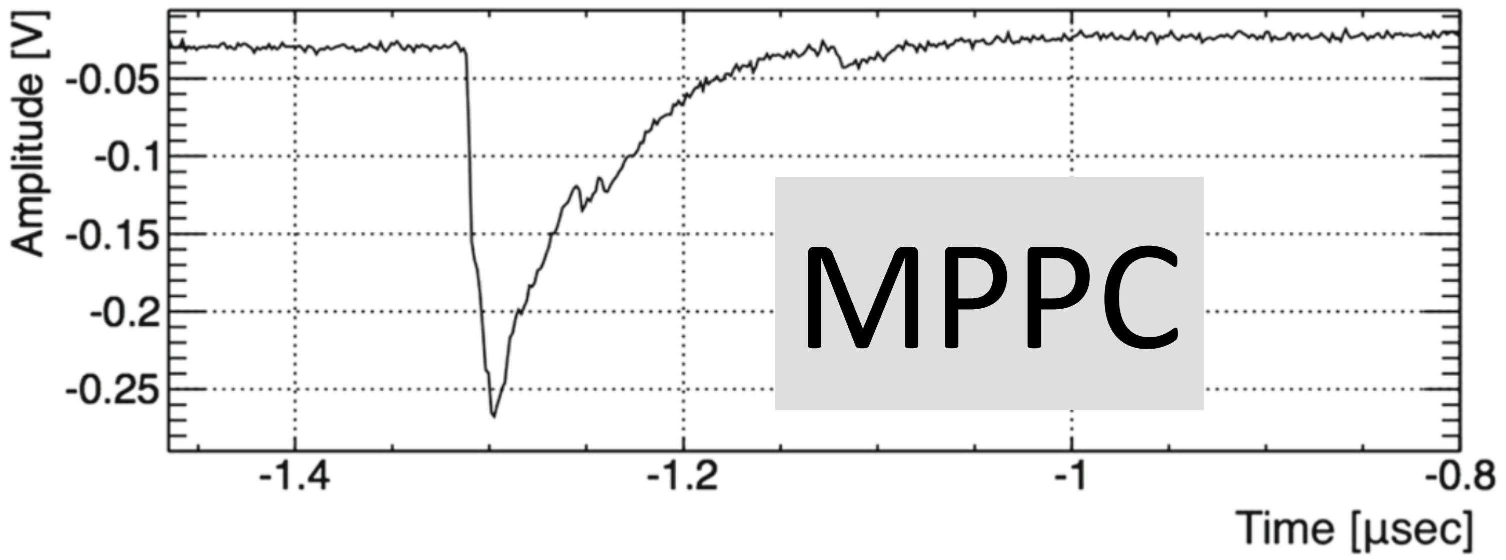


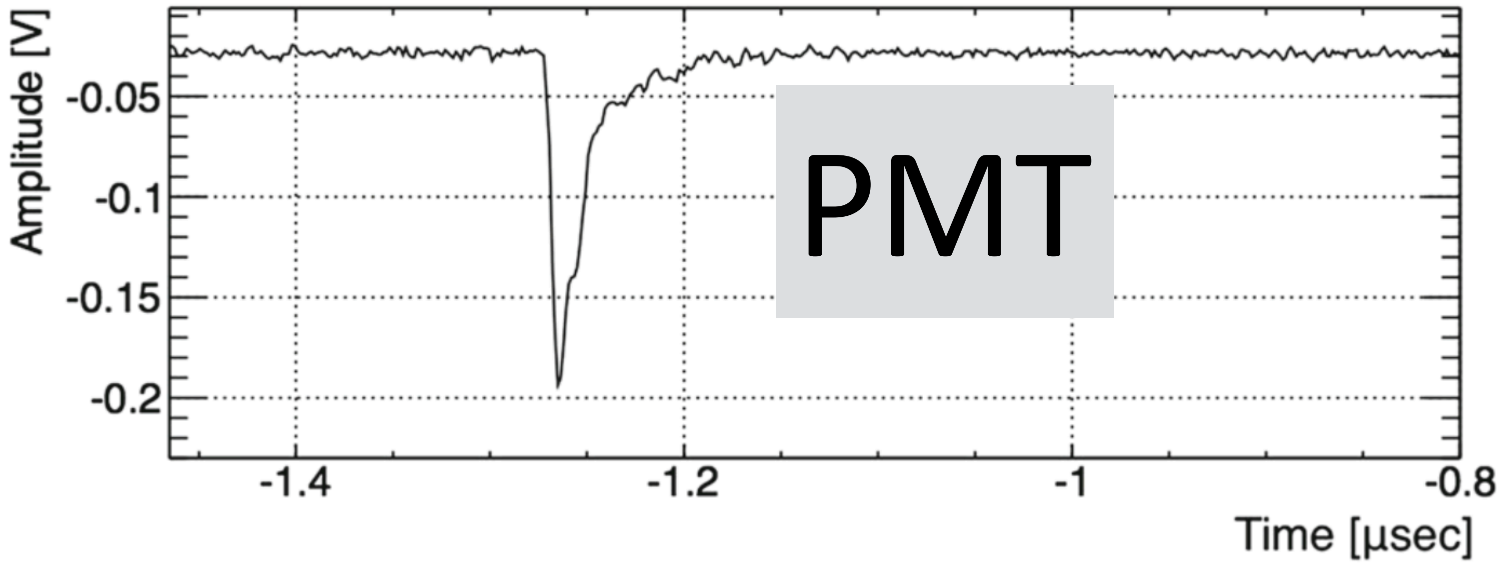
LXe detector



- **homogenous** volume of LXe
  - ***LXe** as **scintillator***
    - **bright**: 40 photons/keV
    - **fast**: 4/22/45 ns
  - ***VUV MPPC** replacing **PMTs** in the **inner face***
    - **4092** channels **instead** of **216**!!
    - **uniform response** in particular for **shallow events**





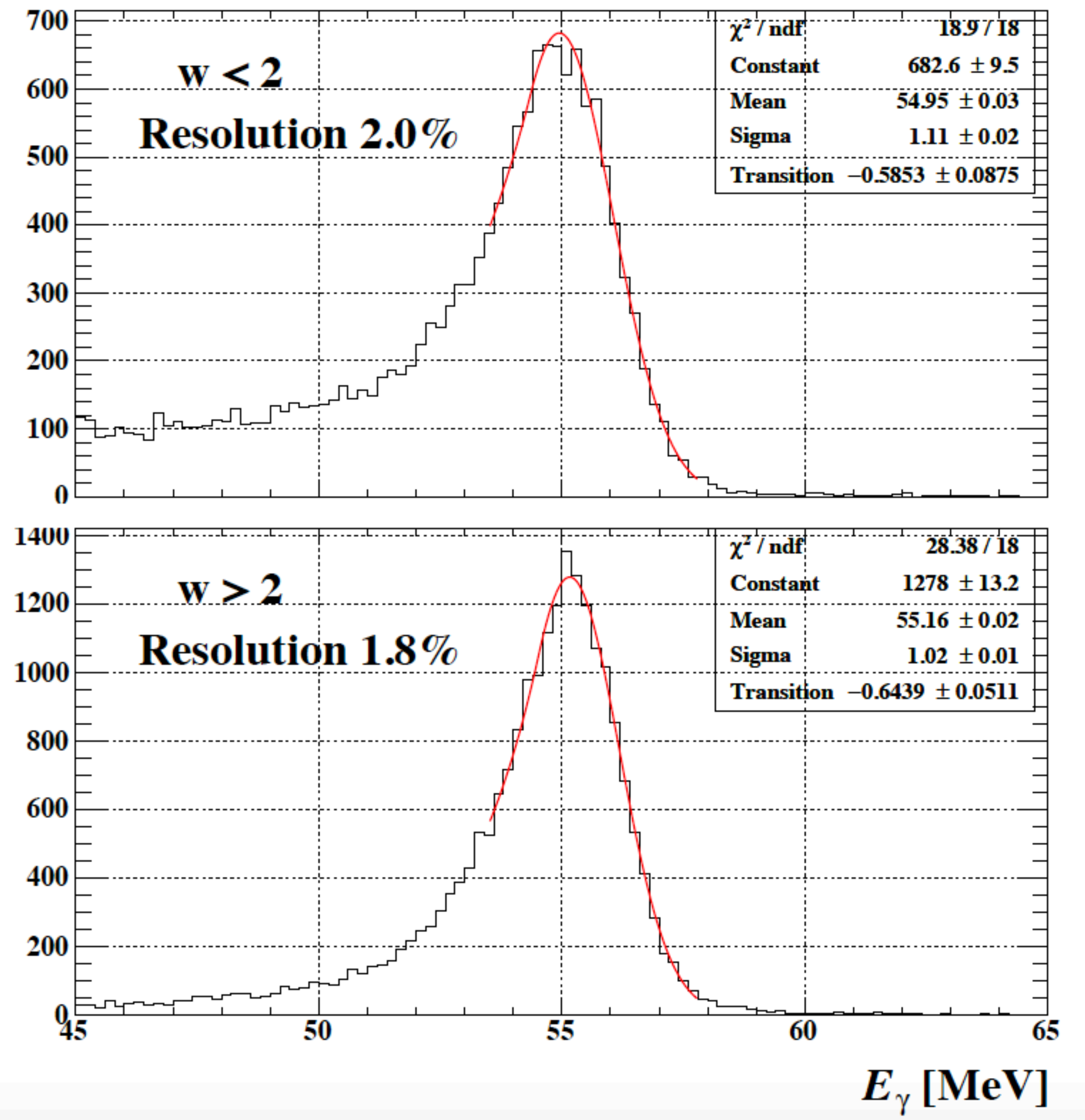


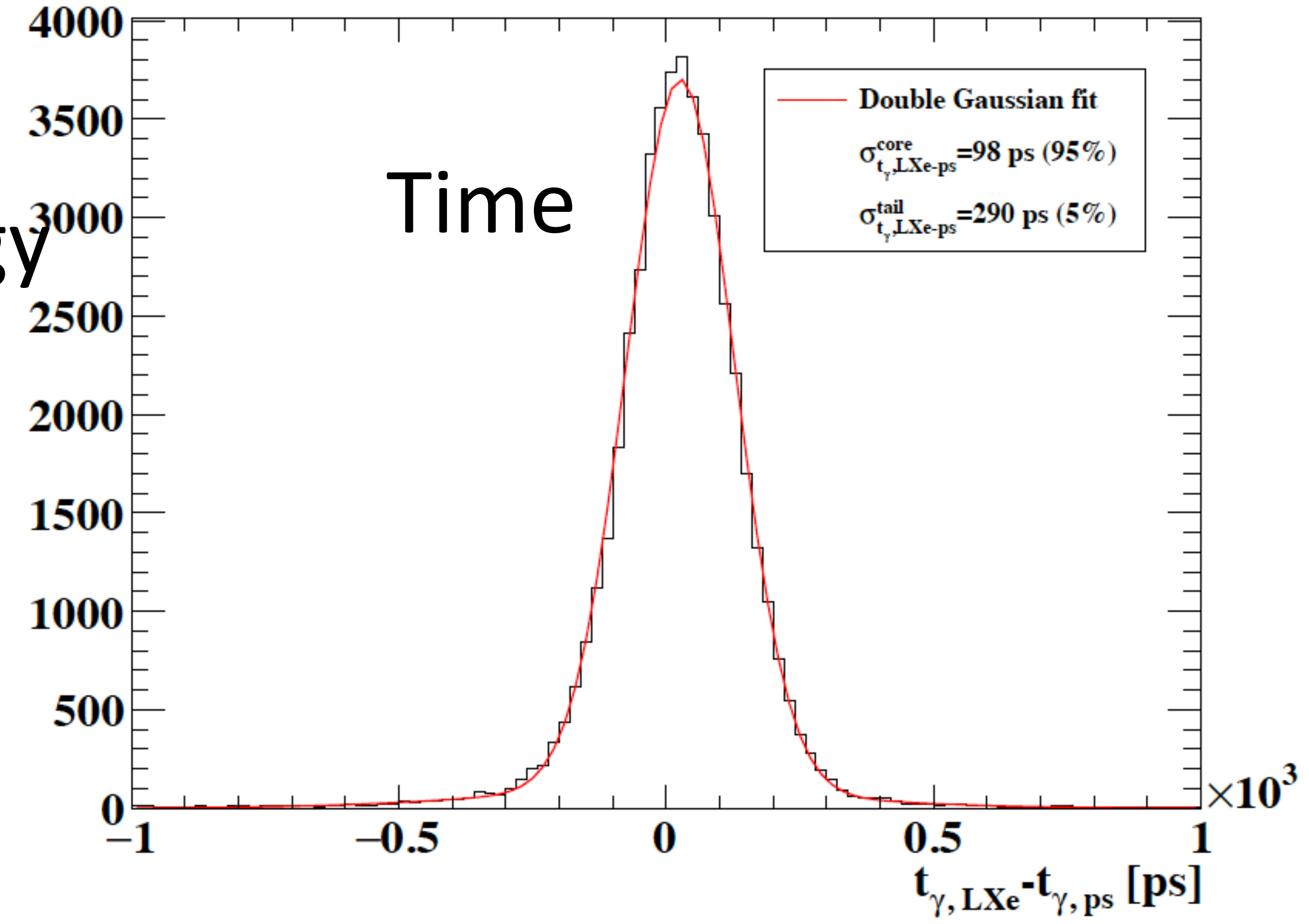
Performance

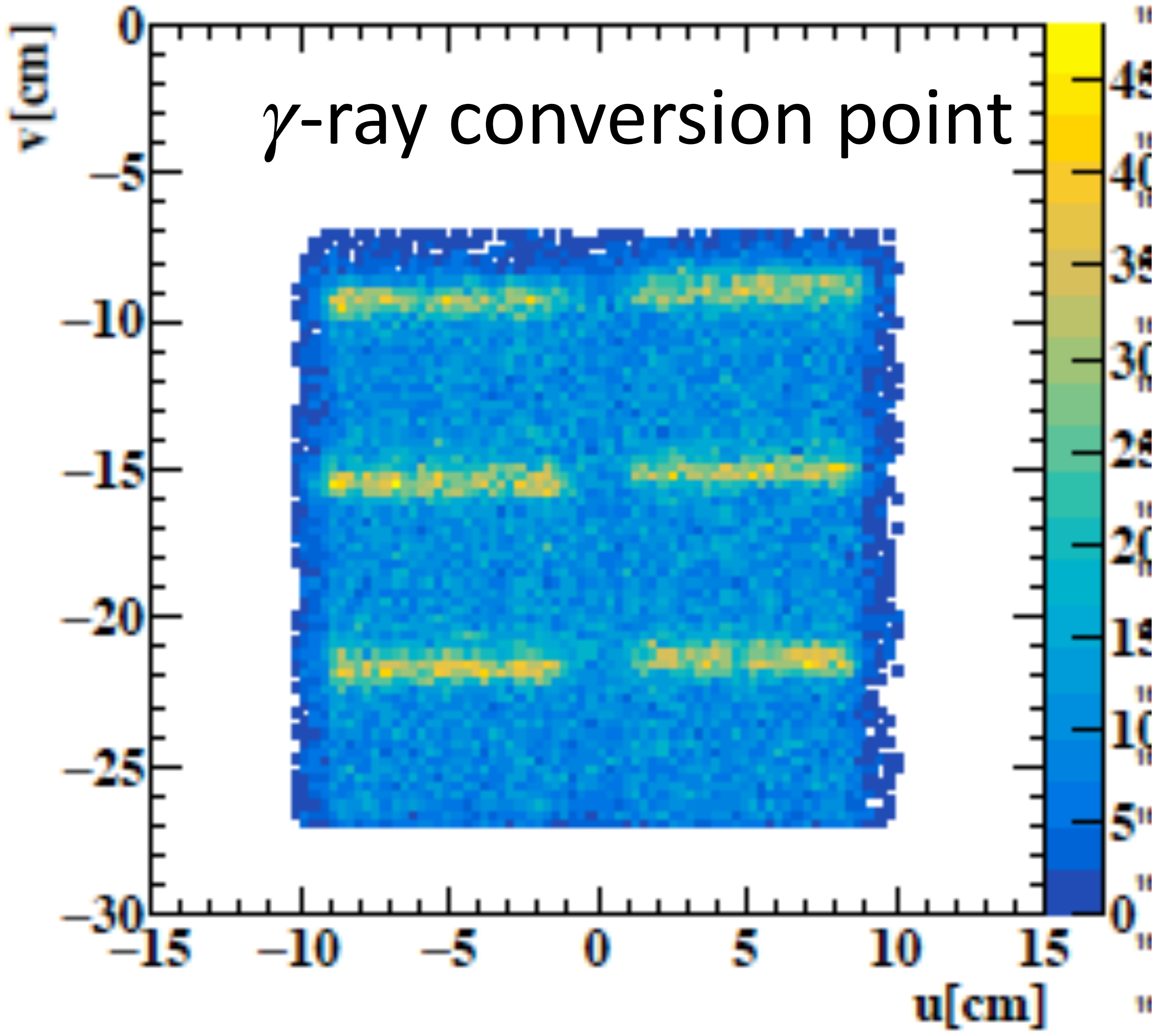
$$B_{acc} \propto R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\Theta_{e\gamma}^2 \Delta t_{e\gamma}$$

- **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 systems

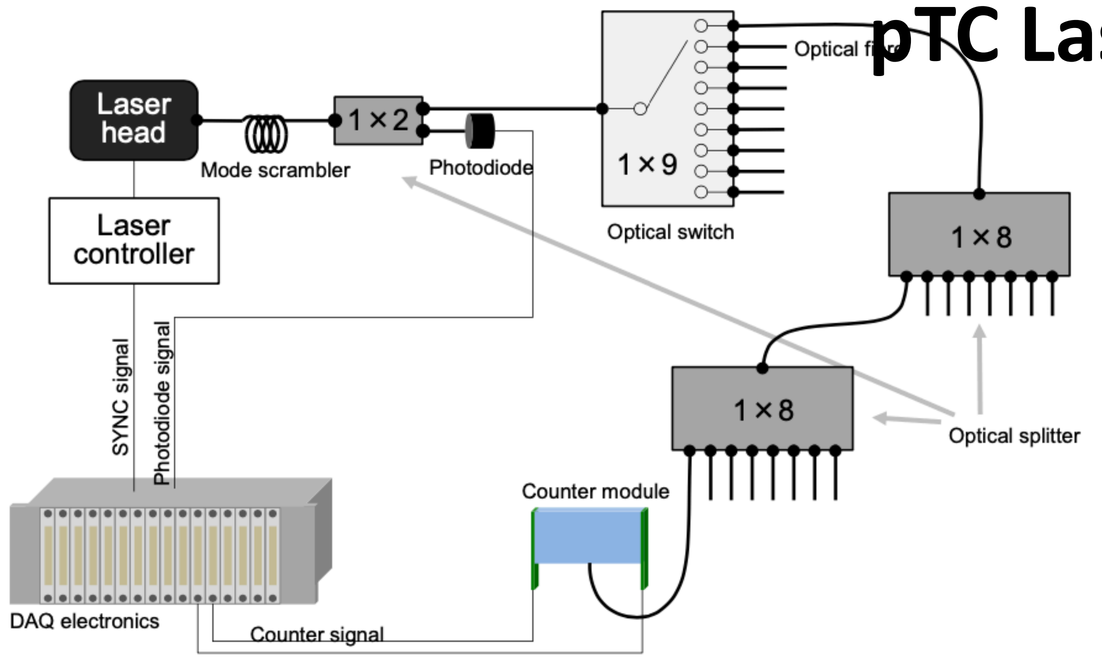
C-W proton accelerator

Up to 1 MeV proton on $LiBO_4$ target

Energy calibration line :

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

pTC Laser system

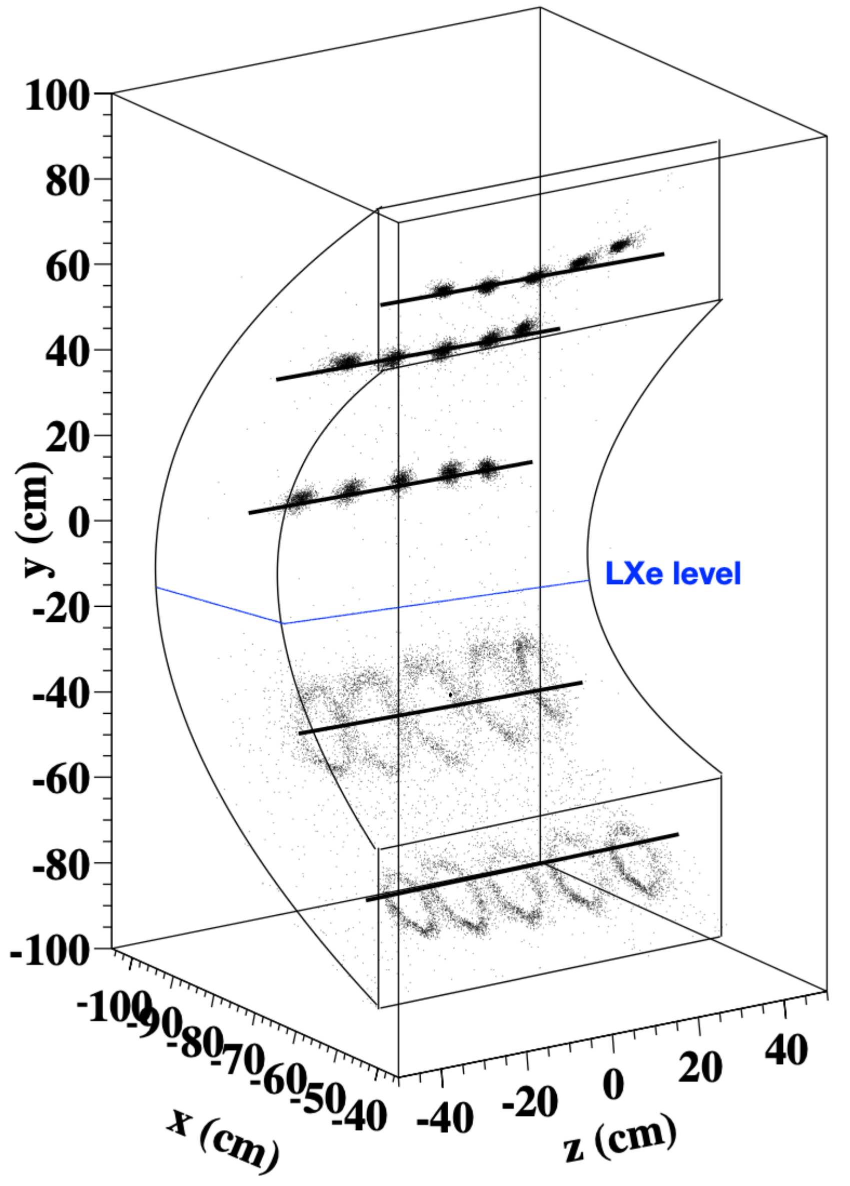


401 nm laser

Distribution to a big part of pTC Tiles

Time offset monitoring

α particle sources in Liquid Xenon



25 point-like sources on wires

Localised energy deposit (40 μm range in LXe)

For detection efficiency monitoring calibration

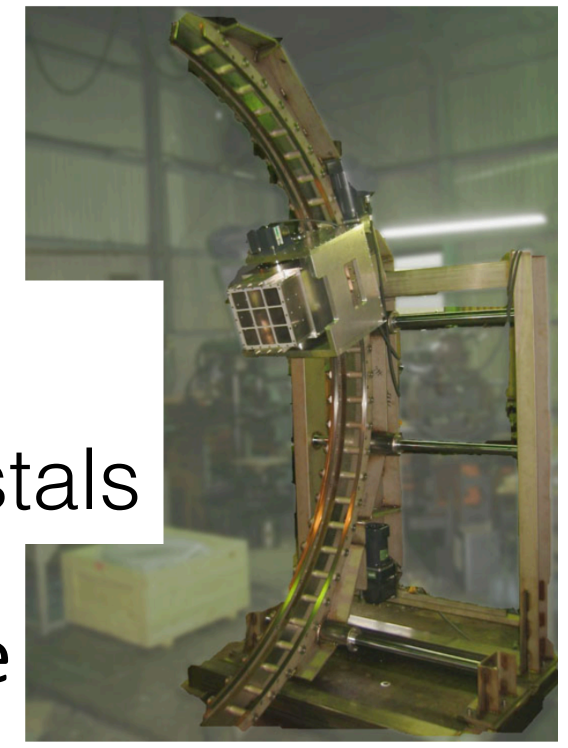
Charge Exchange reaction

Energy & time calibration at signal energy

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

Movable array of BGO Crystals

Energy in 55-83 MeV range



Other calibrations

Drift chamber:

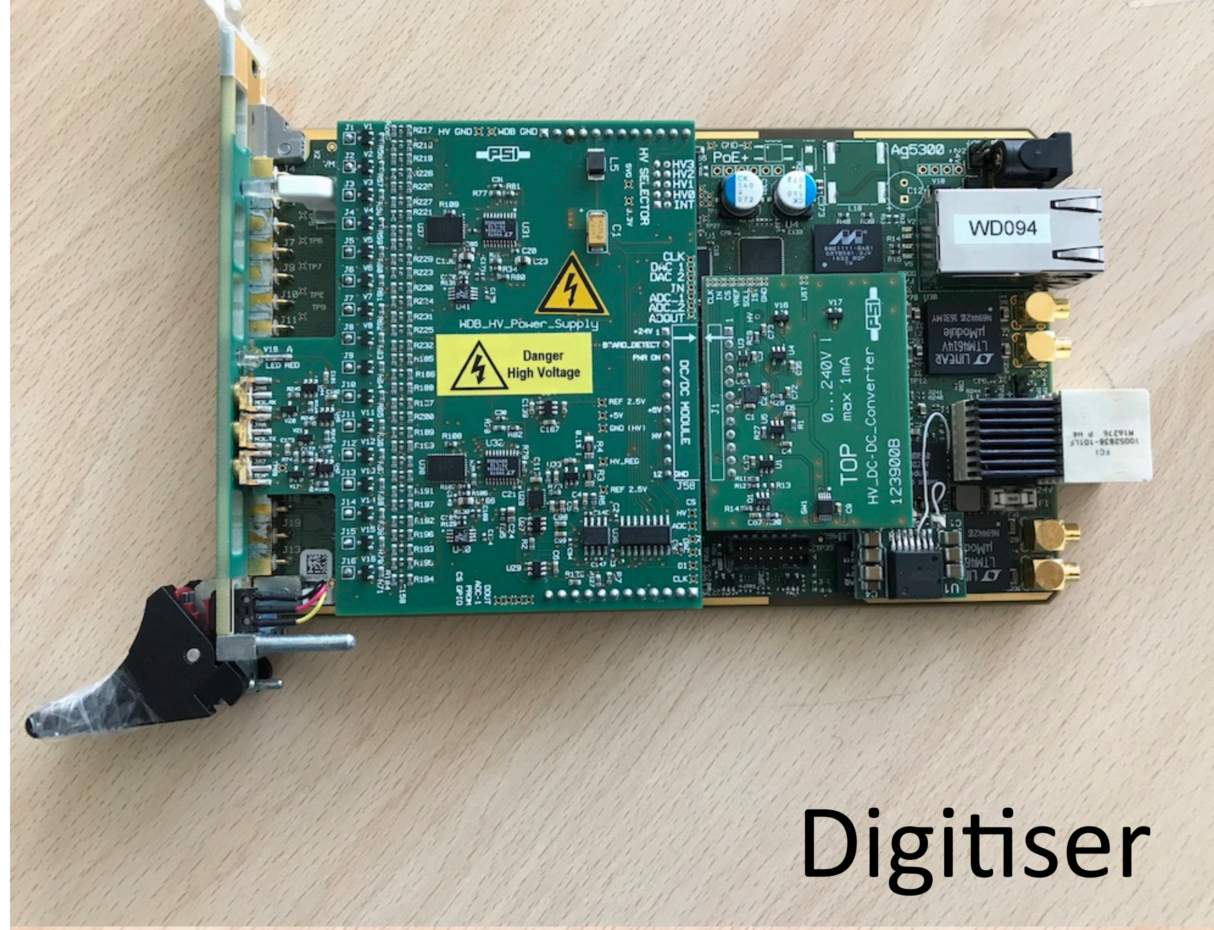
- Cosmic rays
- B-field mapping

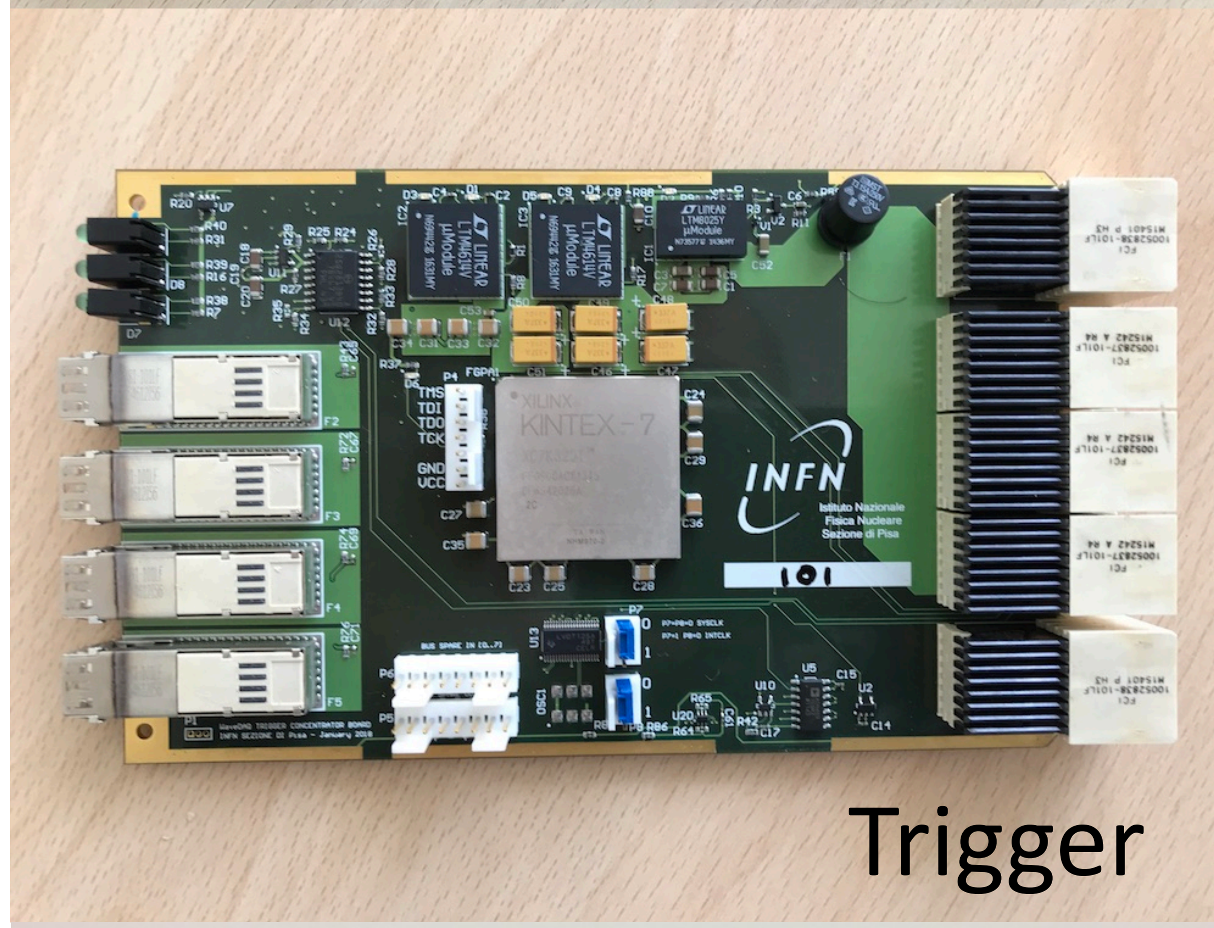
Liquid Xenon detector:

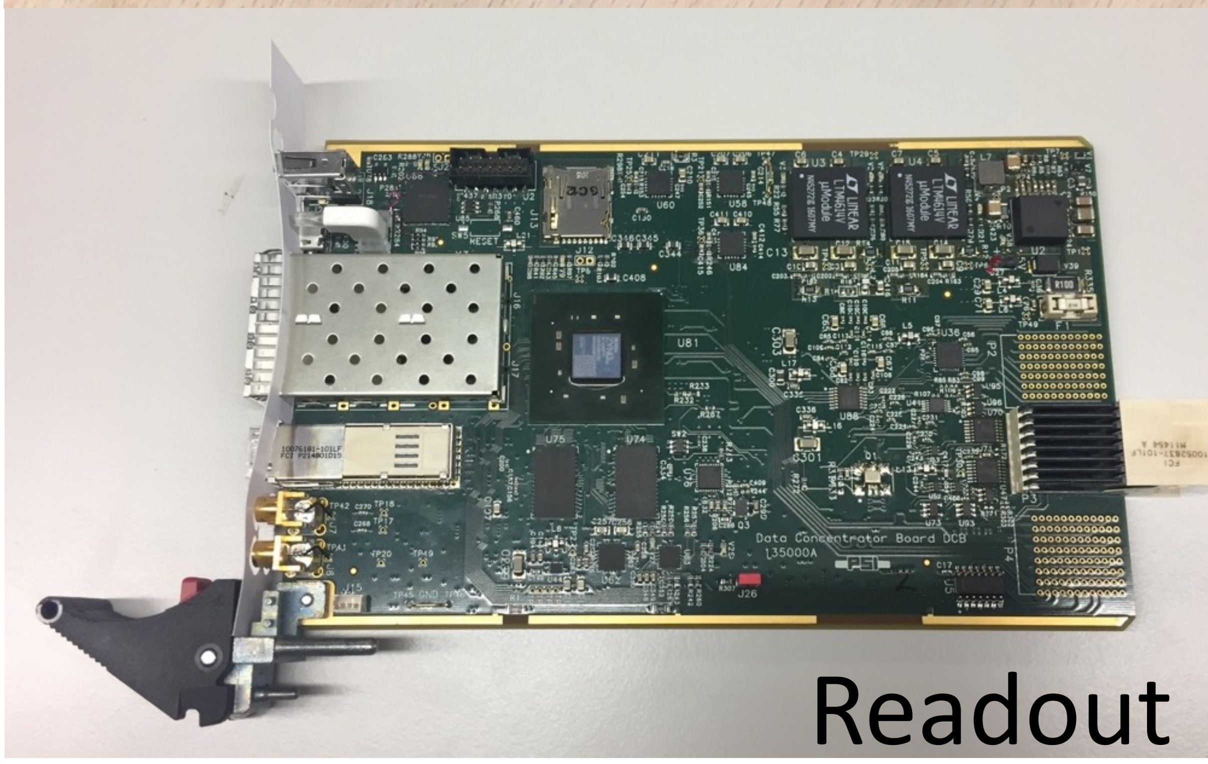
- LED
- Neutron-Nicke γ(9 MeV)
- ^{57}Co X-Ray position survey

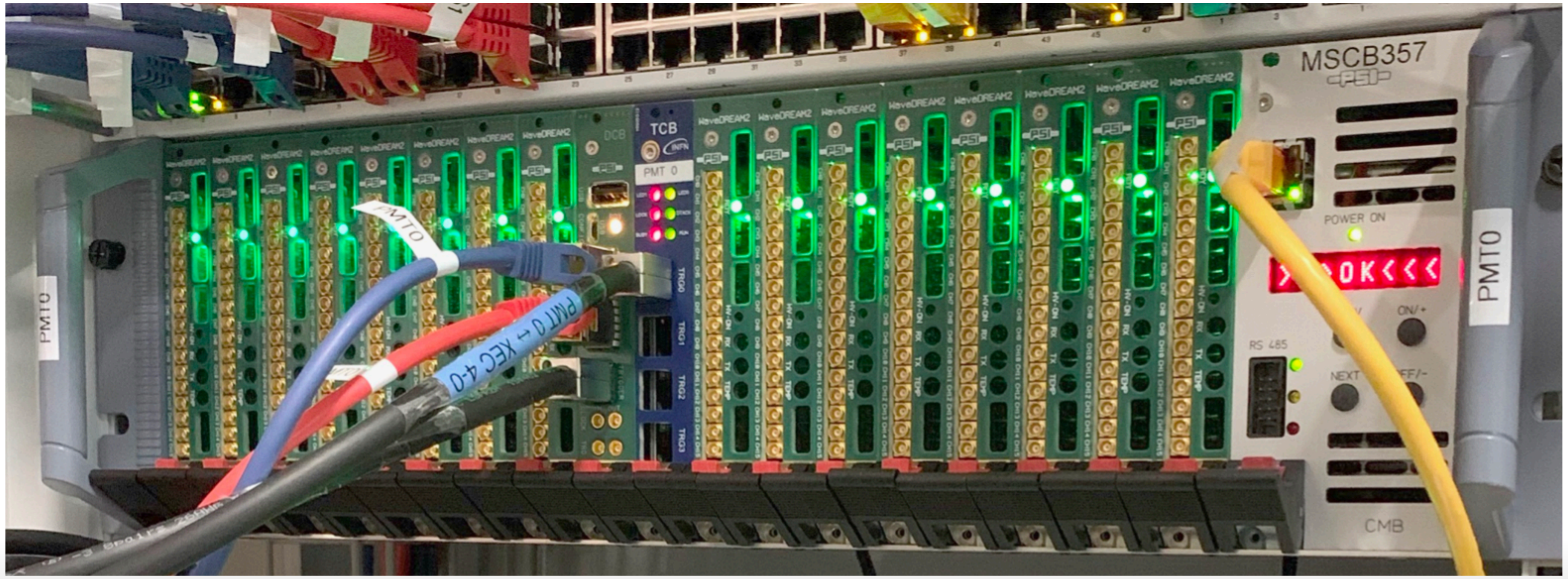
TDAQ electronics: WaveDAQ

- **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 <450ns***
  - ***up to 10 Gb/s DAQ throughput (50 Hz)***

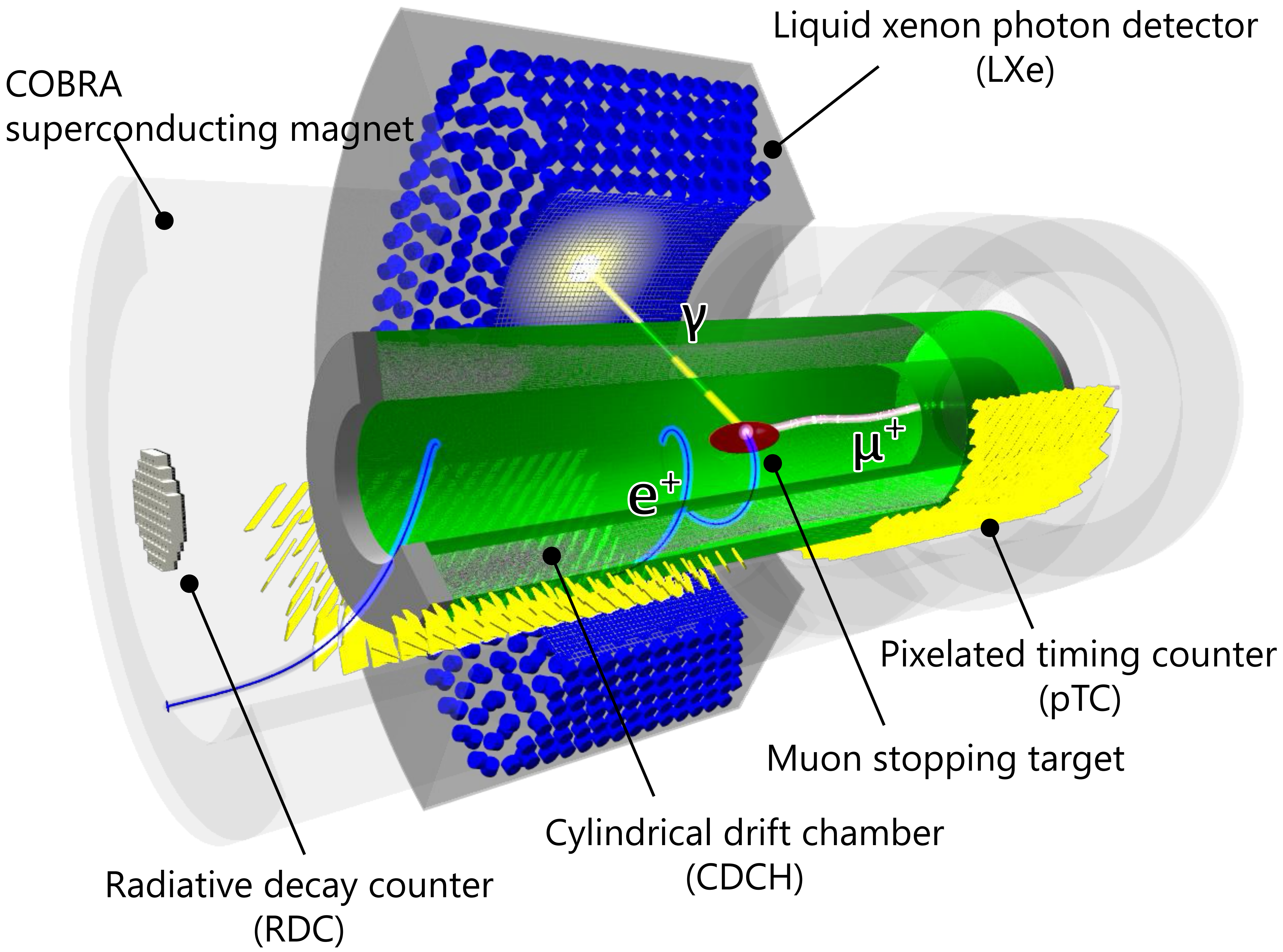




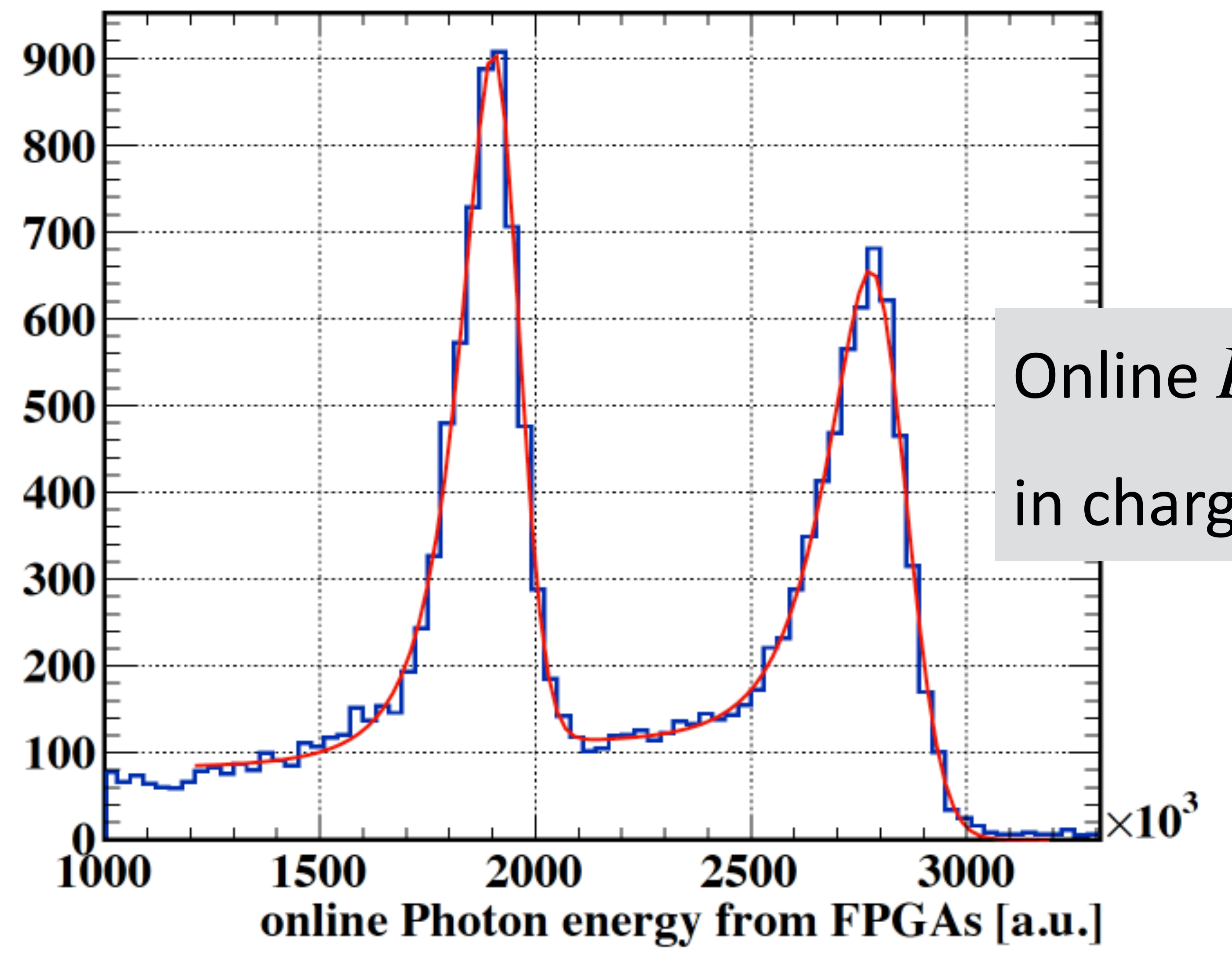




MEG trigger logic



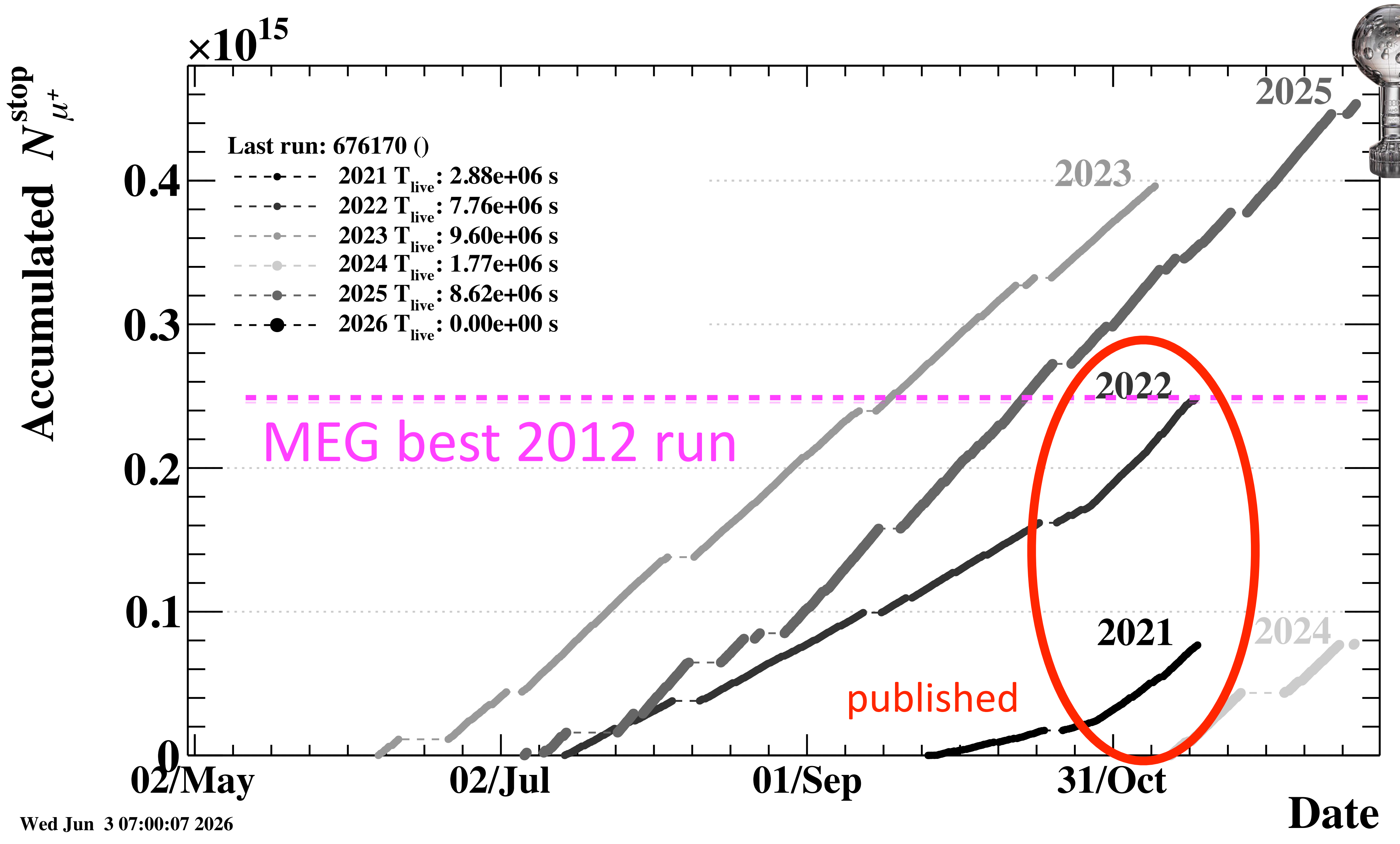
- E_γ > threshold (~40-44 MeV)
- $|T_{e\gamma}|$ < time window (~10-12.5ns)
- Direction match condition: $e\gamma$ hit positions correlation
  - *From O(10^7) μ decays/s → O(**10) Hz trg rate***

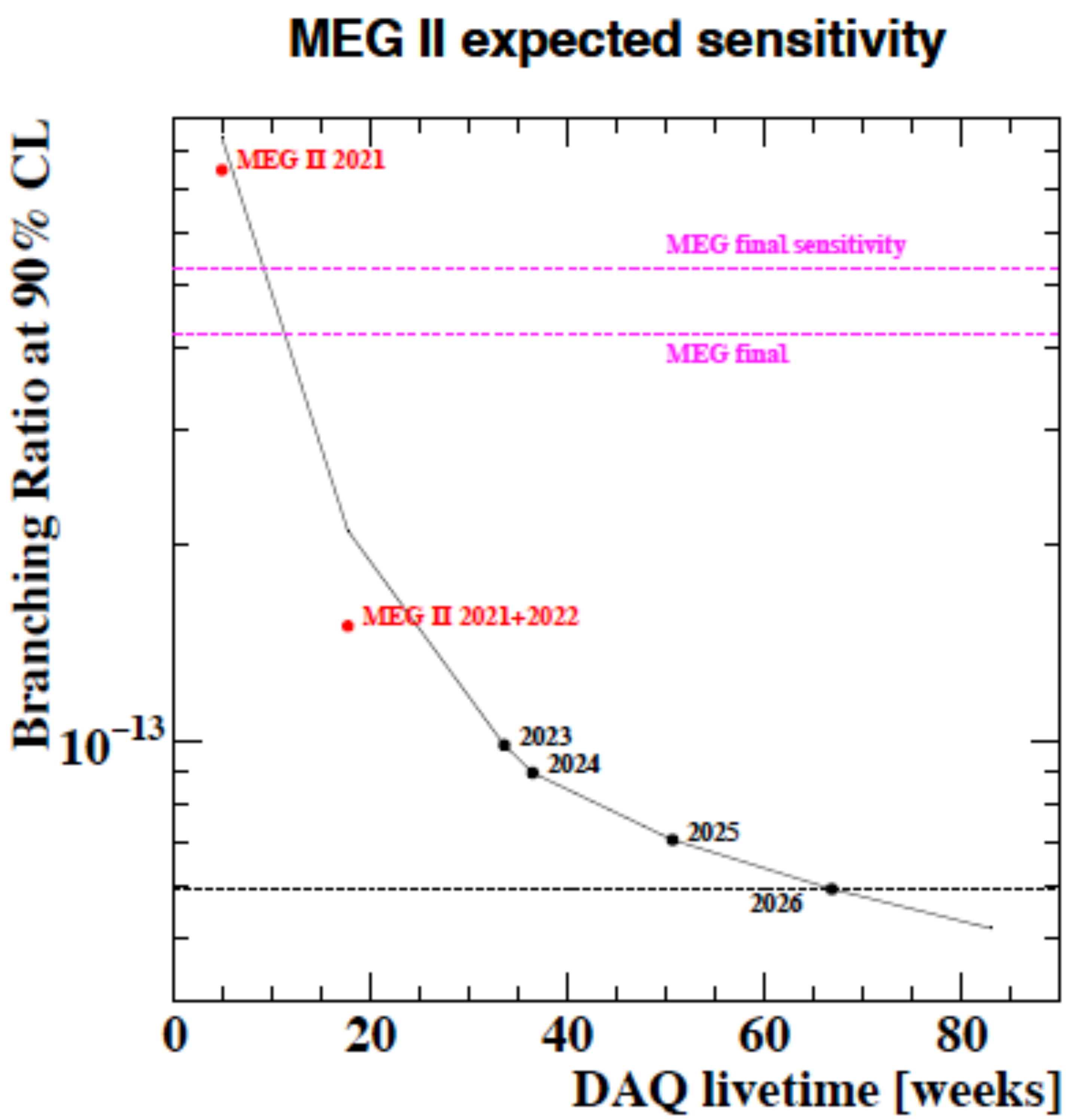


Online E_γ reconstruction in charge exchange run

MEG II logbook

- **2021**: **First physics** run, mostly **@3e7 μ/s**
- **2022: First long data** collection, mostly **@3e7 μ/s**
  - *~4 times 2021 statistics*
  - ***2021 + 2022 data analysis published***
- **2023: Long and stable run** un MEG history
  - *beam intensity **@4 10⁷ μ/s***
- **2024:** statistics **similar to 2021** due to external conditions
  - *beam **@4 10⁷ μ/s***
- **2025:** largest statistics collected in one calendar year so far
  - *Thanks to ML-based tracking we should use **5 10⁷ μ/s***
- We plan in **2026 last 4 months of DAQ, statics ~2023 run**
  - *this will **guarantee** to **reach goal sensitivity***

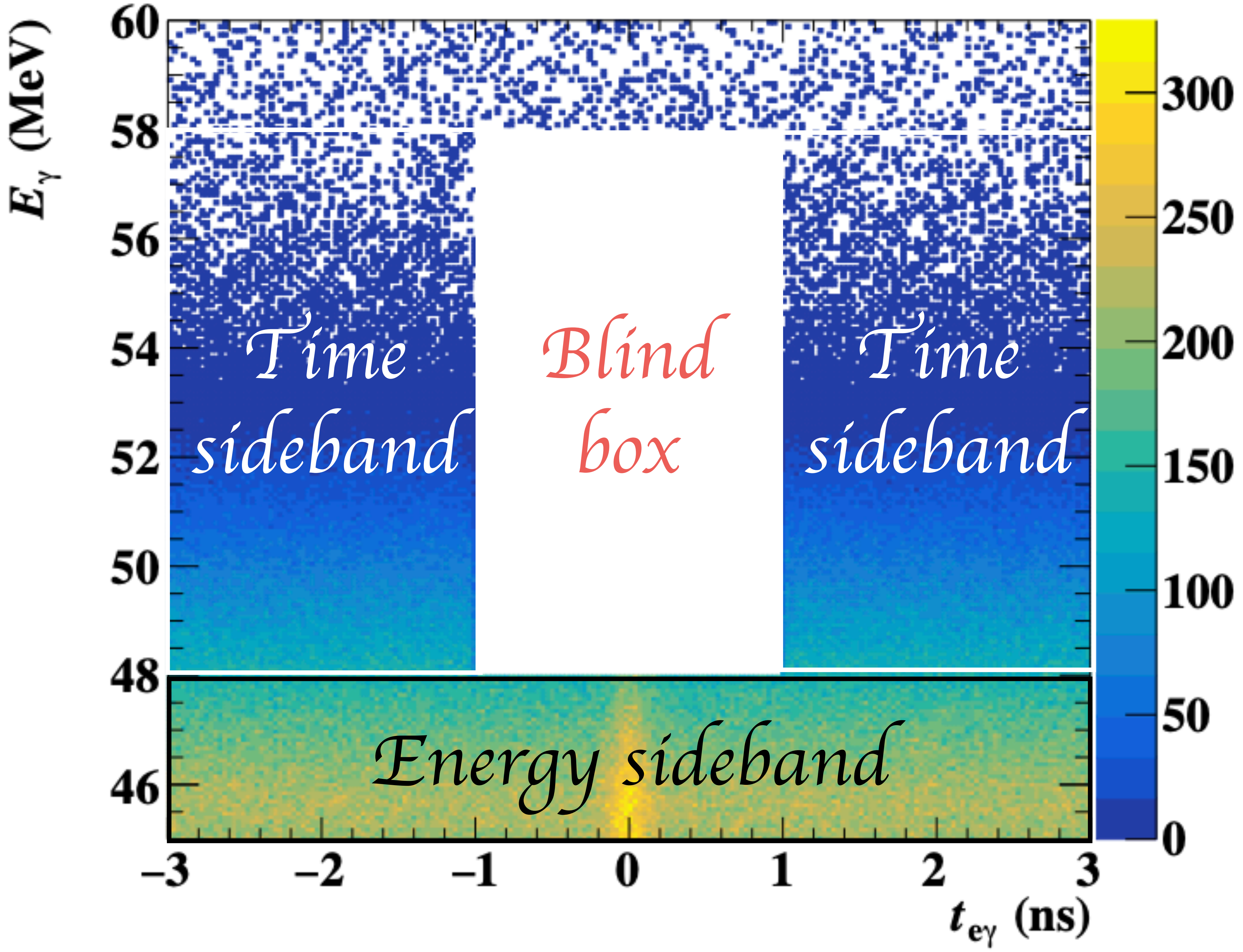




Data analysis

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

- Decided to extract **CL to B(μ→eγ)** 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***

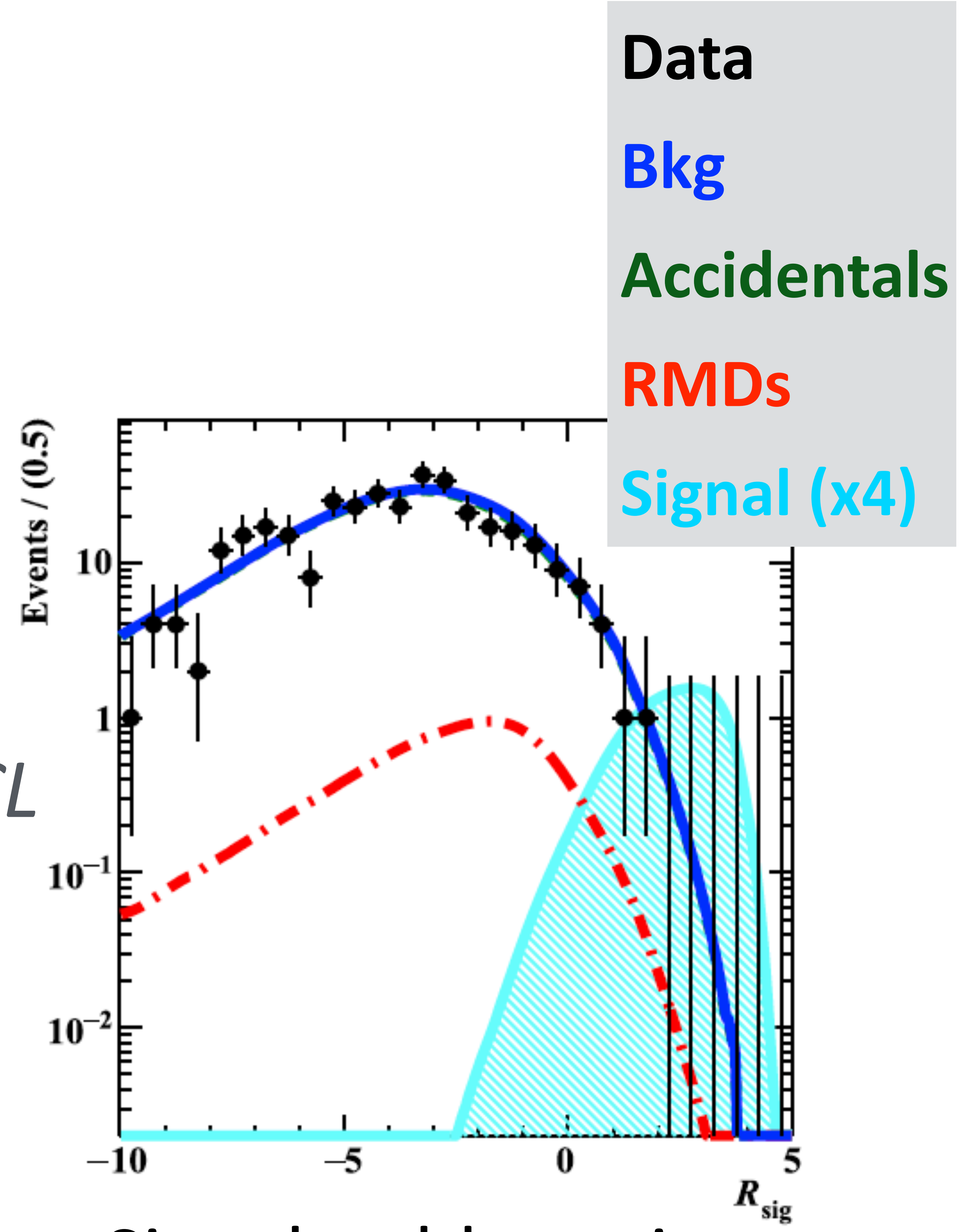


Normalisation by counting positrons

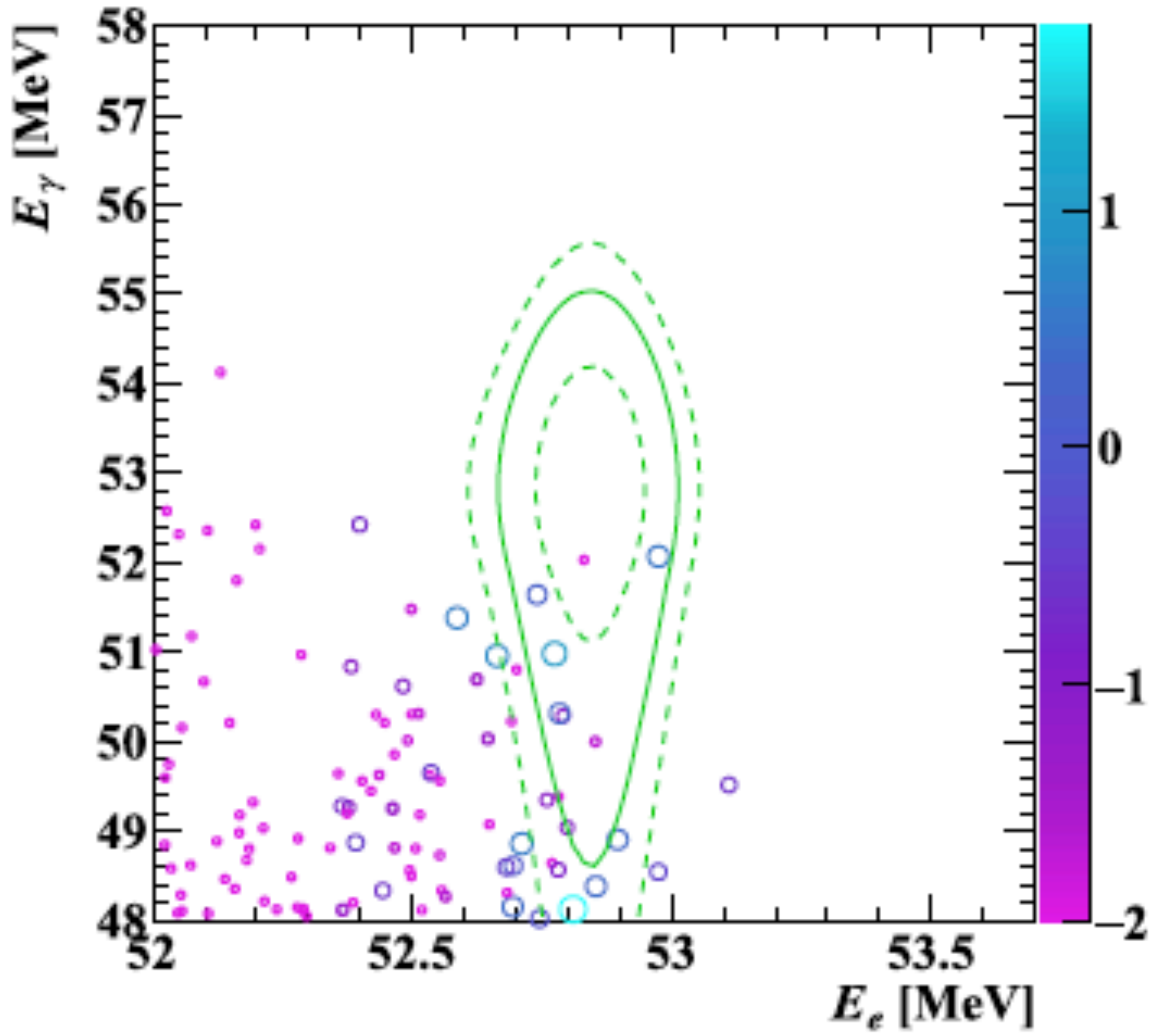
$$k_{michel} = \frac{N_{Michel}}{BR(\mu \to e\nu\nu)} \cdot \frac{\varepsilon_{trg0}}{Presacling_{trg0}} \cdot \frac{Prescaling_{trg21}}{\varepsilon_{trg21}} \cdot \frac{\varepsilon_{signal}}{\varepsilon_{michel}} \cdot \varepsilon_\gamma \cdot \varepsilon_{sel}$$

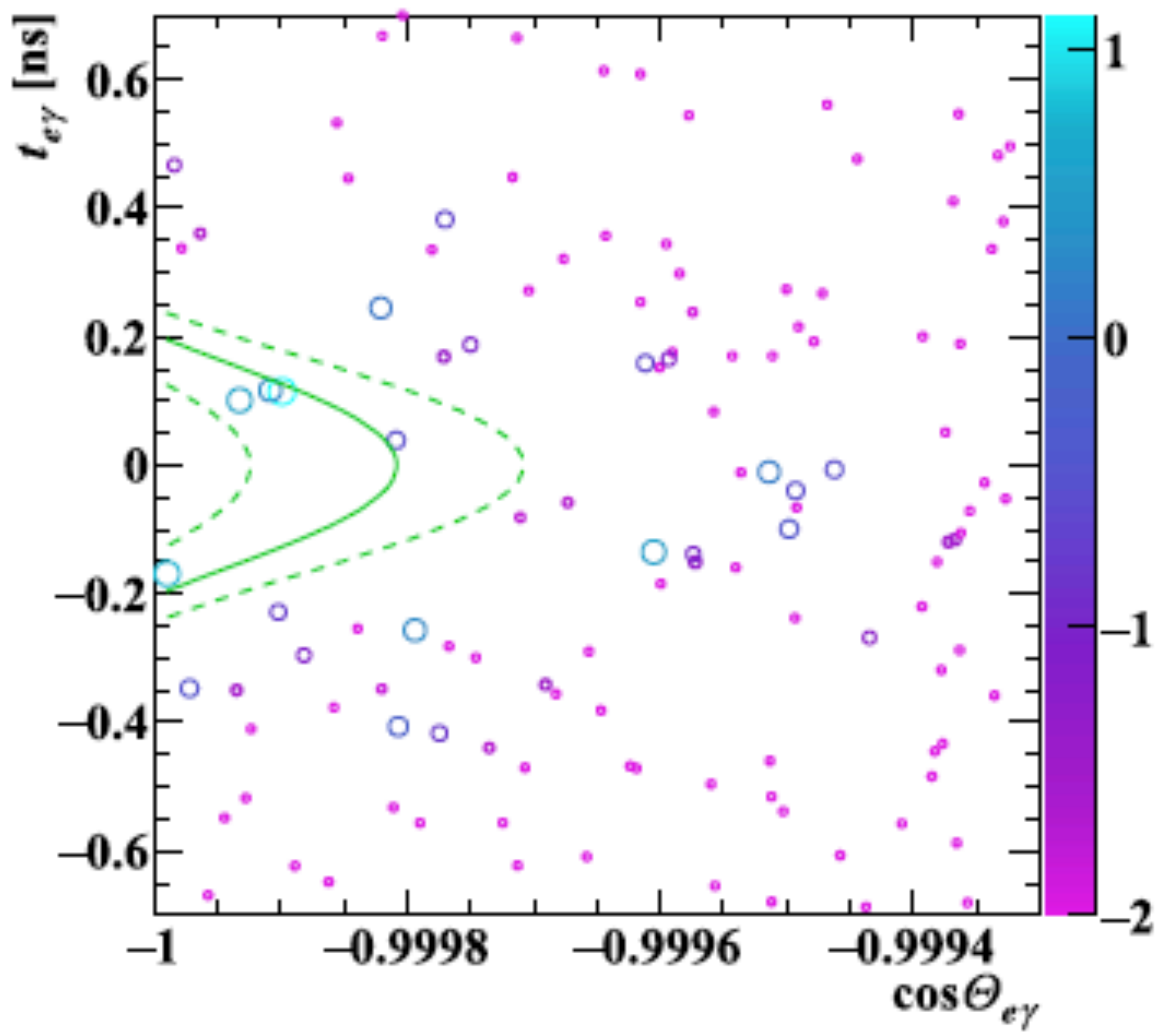
MEG II 2021+2022 result

- **No signal evidence**
- Run 2021+2022 result
  - ***sensitivity***: *BR(μ->eγ)<2.2 10^{-13} @90%CL*
  - ***result***: *BR(μ->eγ)<1.5 10^{-13} @90%CL*



Signal to bkg ratio



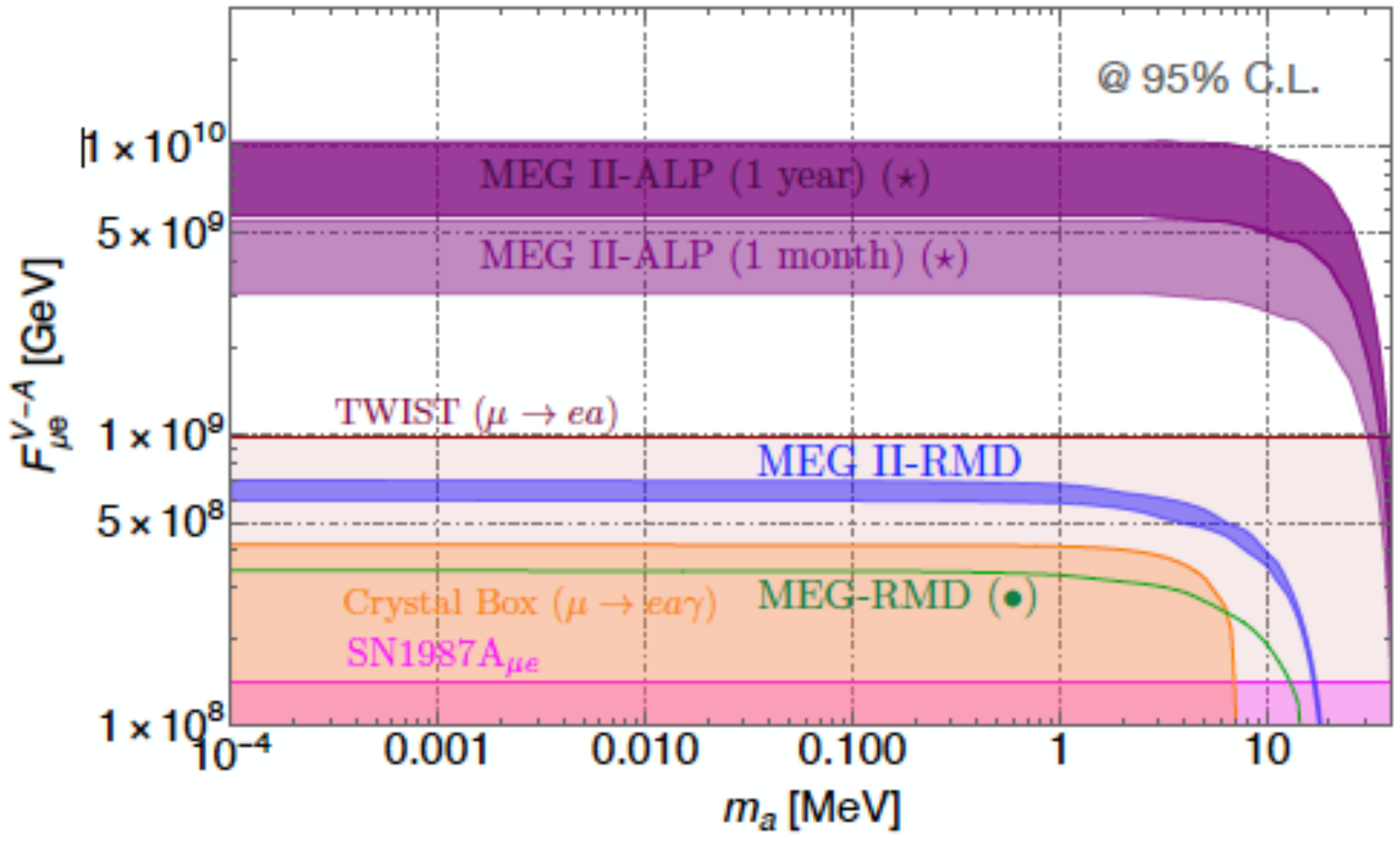


K. Afanaciev et al, New limit in the μ→eγ with the MEG II experiment, EPJC, 2025

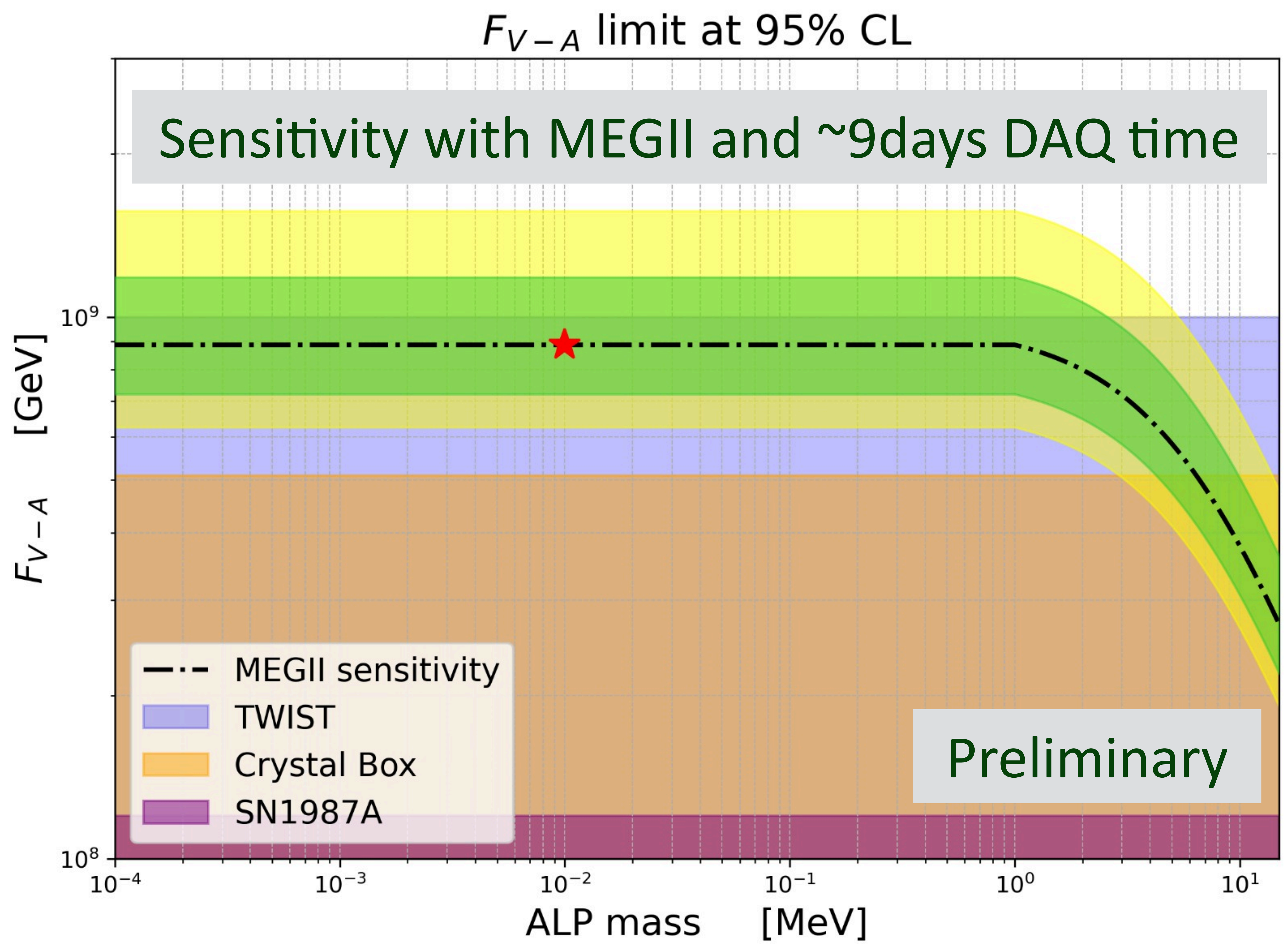
What about $\mu \to ea\gamma$?

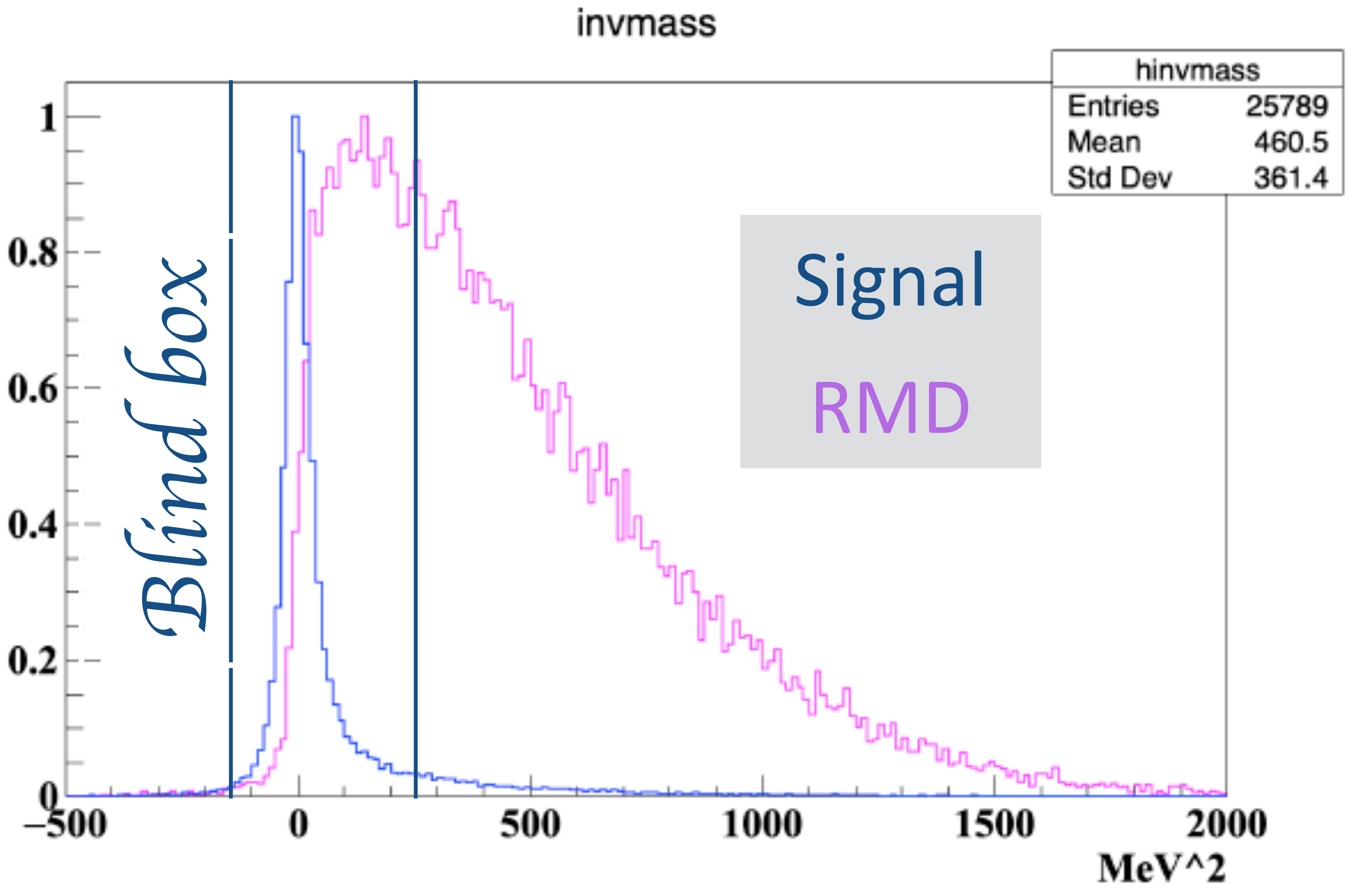
arXiv:2203.11222v1

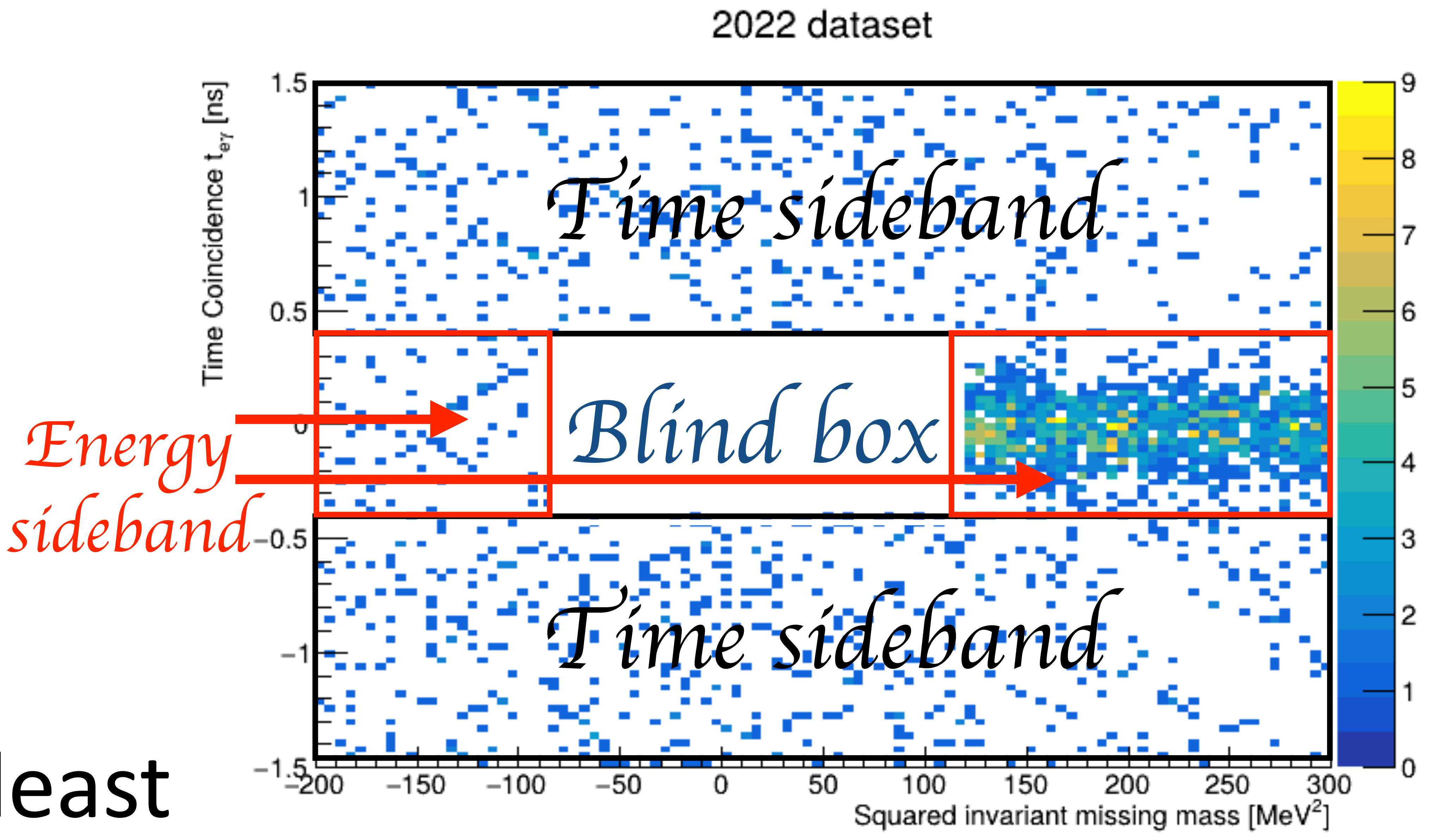
- **Boost** from discussions among **MEG II group** and **D. Redigolo**
  - *Can **MEG-II** be **competitive** w.r.t. **TWIST**?*
  - ***how** can we **increase sensitivity**?*
    - **dedicated trigged**
      - Gamma energy **threshold** close to **15 MeV**
    - **beam intensity** and **DAQ time needed**
      - ***~10^6 μ/s** as in case of initial **detector calibration***



ALP search in MEG II



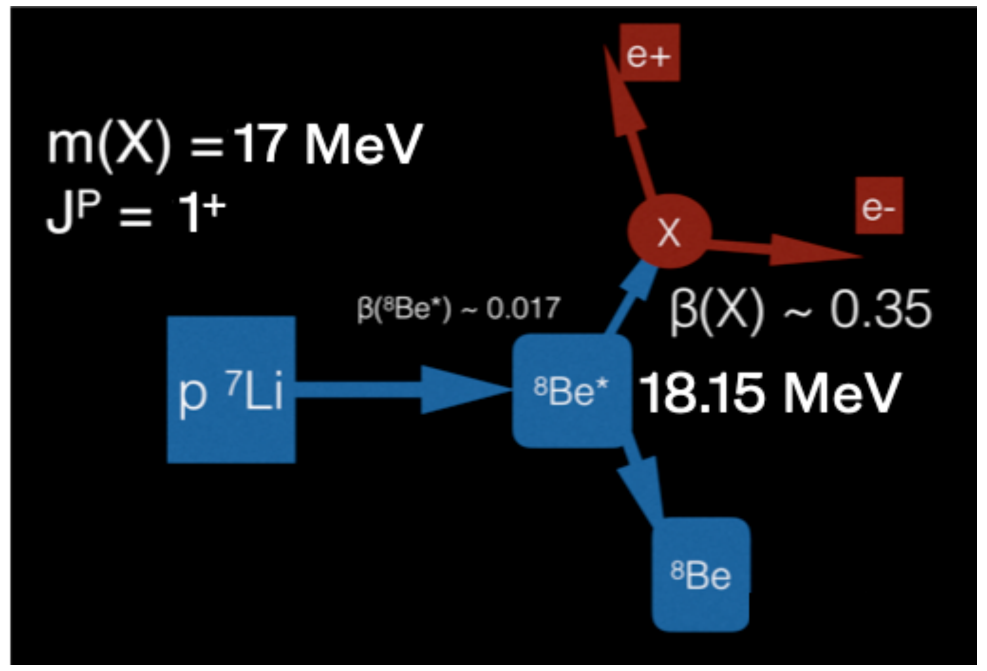


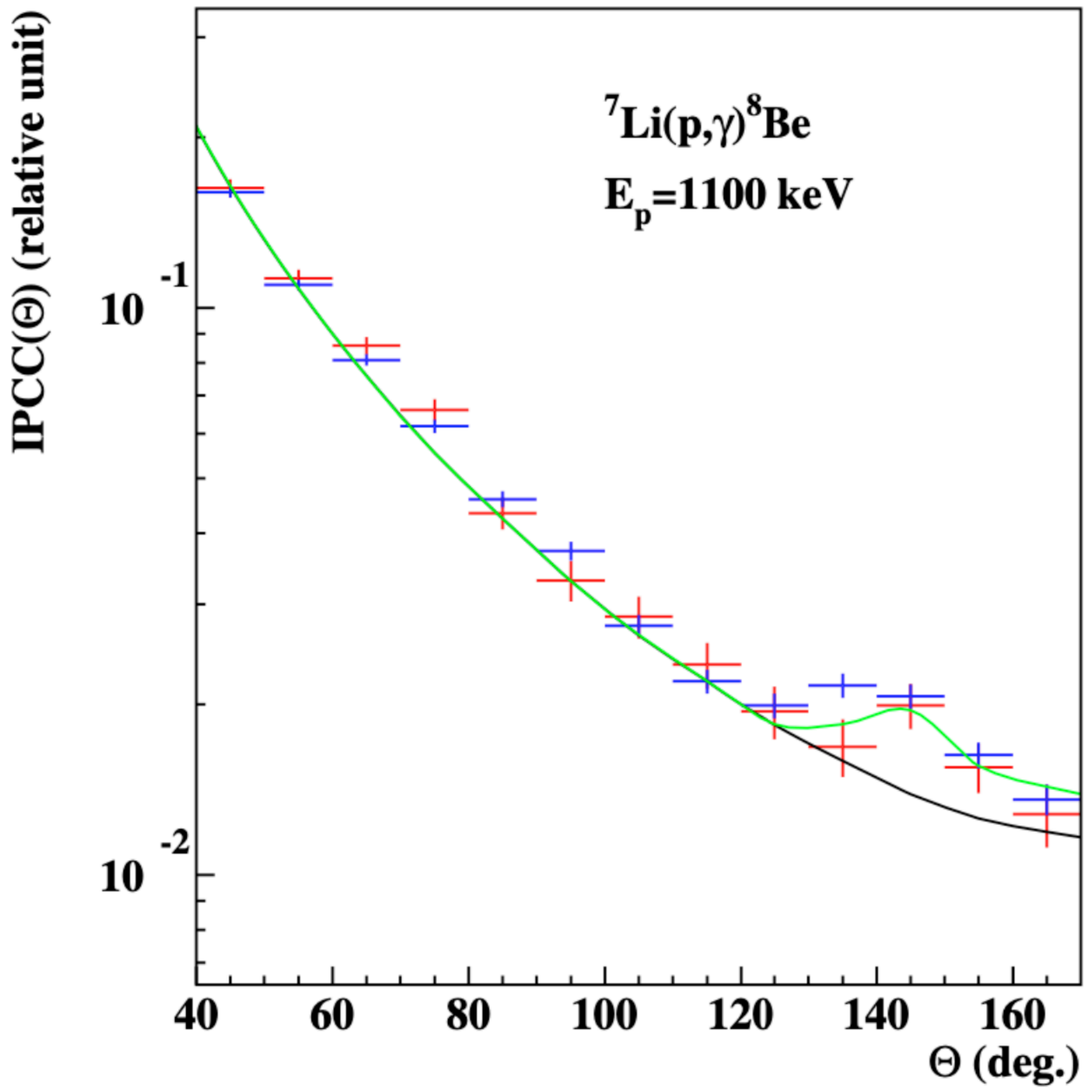


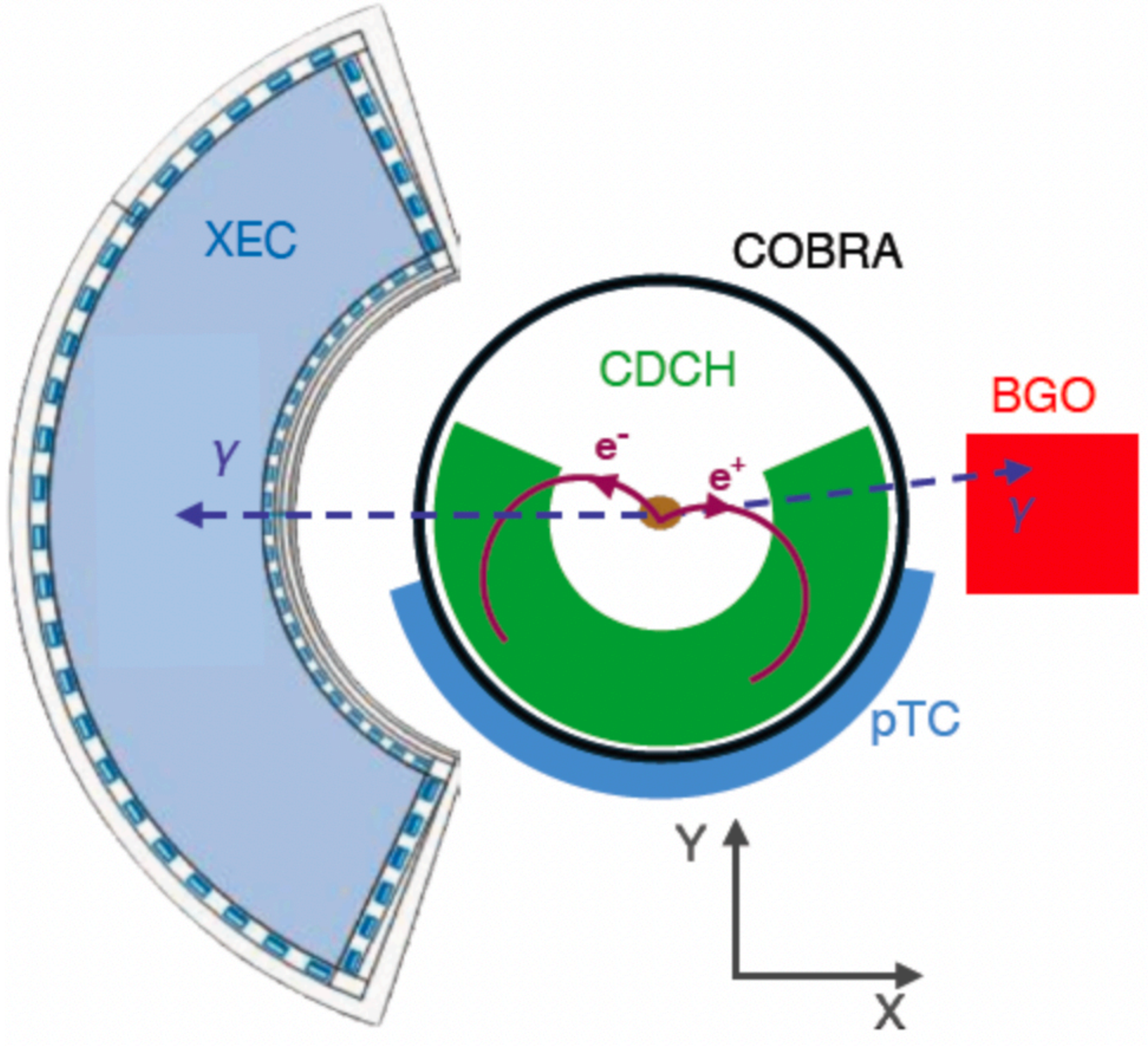
- MEG II plans accumulate O(15 days) of DAQ at least

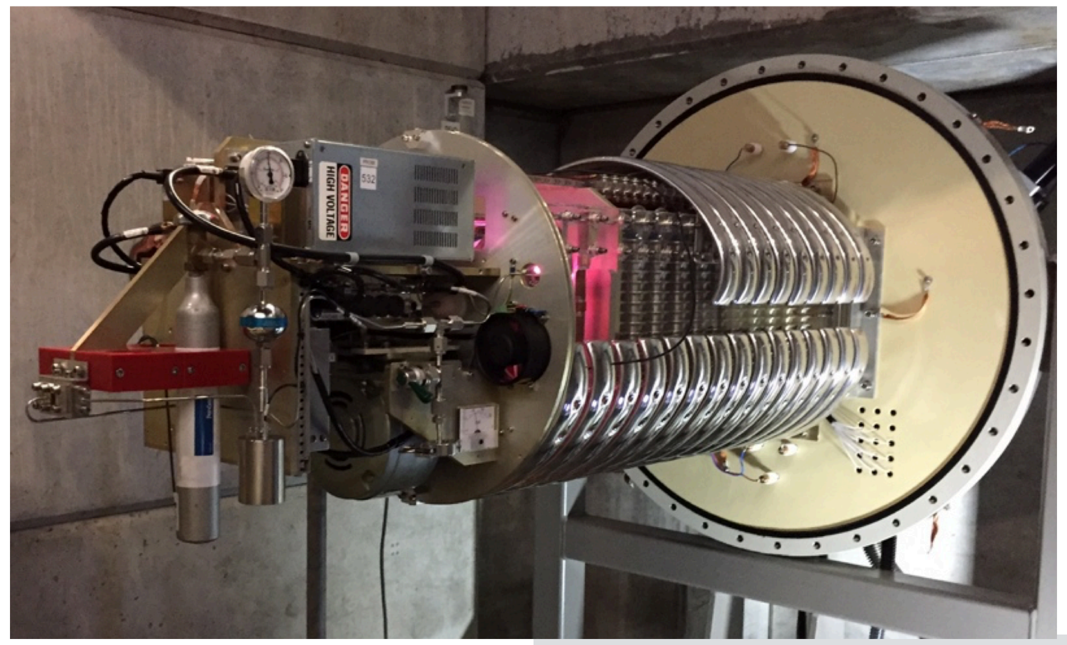
Other physics: X(17 MeV) Boson

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





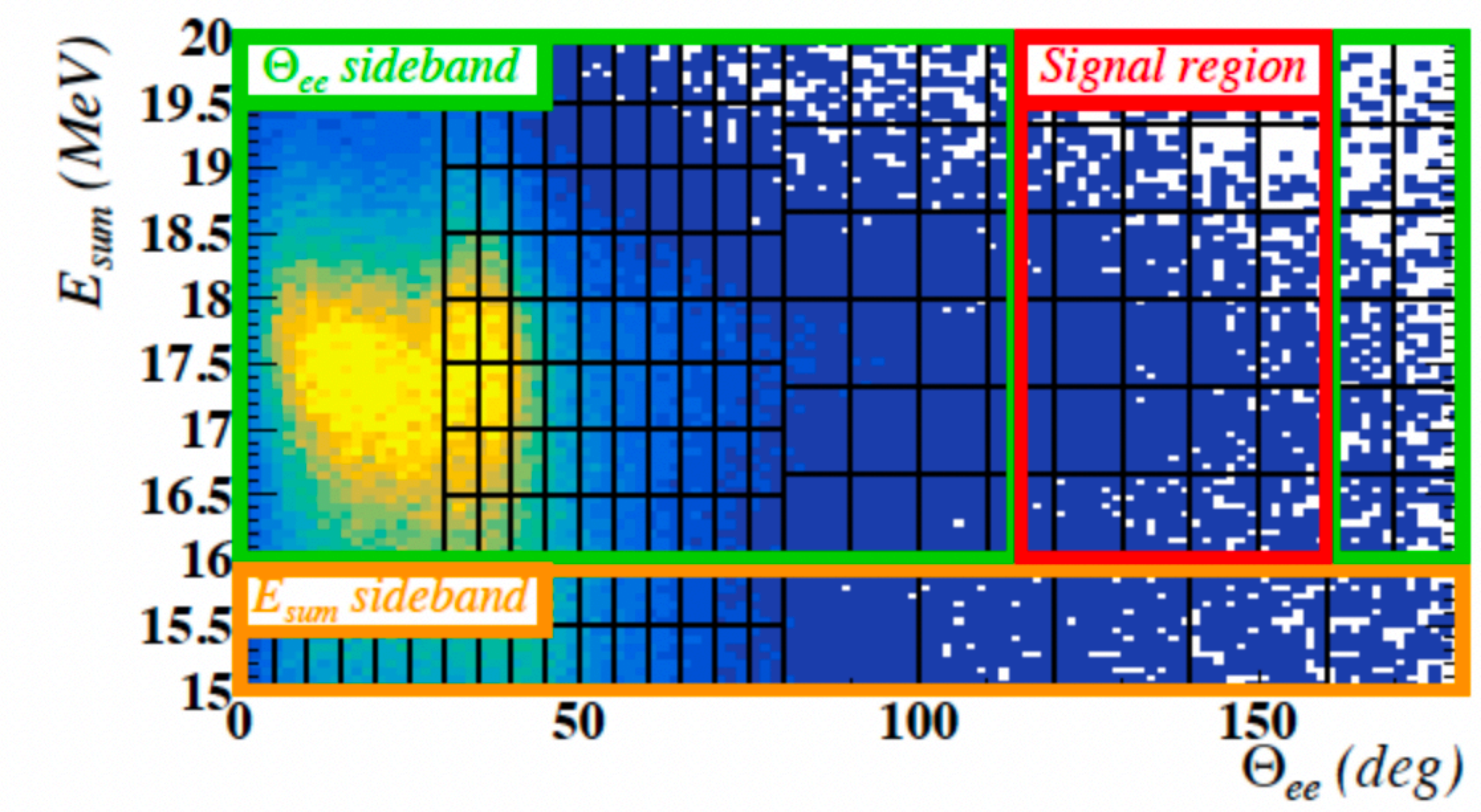


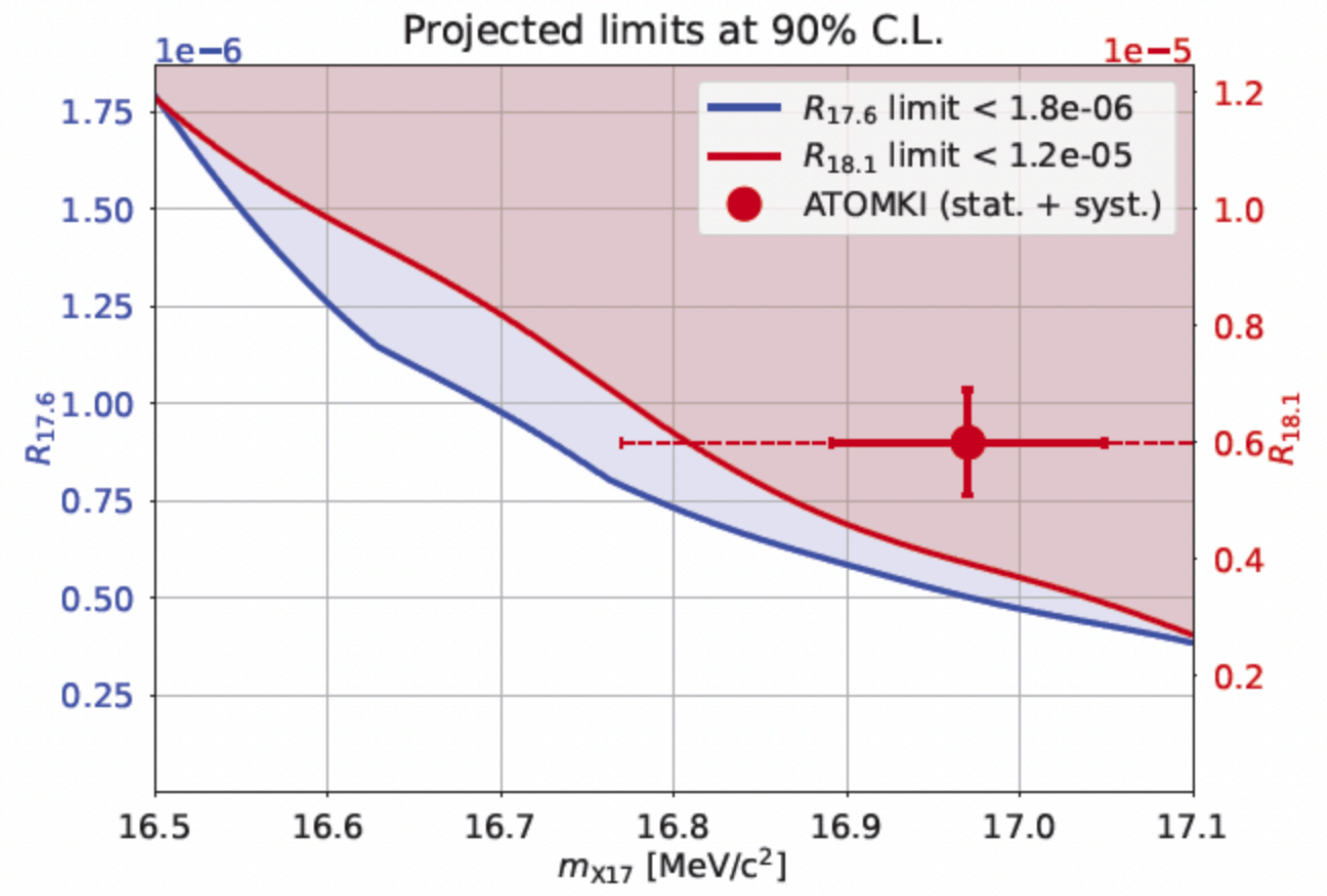


from slide 14…

“Our” result on X17

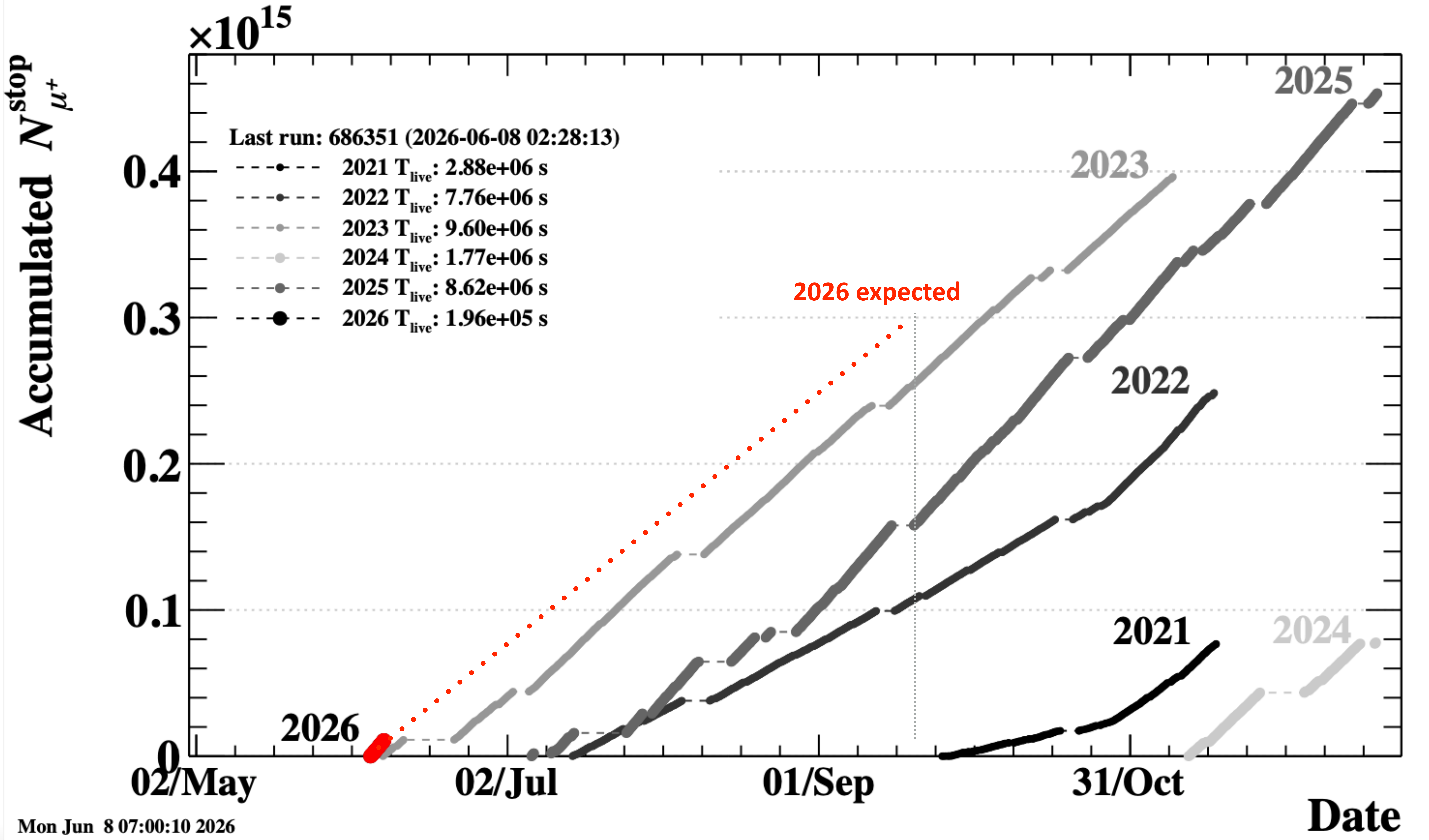
- **Combined fit** on the **energy sum** of the electron and position and their **relative angle**
- **Best fit** on X17 signal is **0 events** with an **expectation of 100 events**
  - *our result is* ***incompatible*** *with* ***ATOMKI*** *result* ***at 94%***
- We are **preparing** for a **new DAQ**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





K. Afanaciev et al, Search for the X17 particle in $^7Li(p, e+e-)^8Be$ processes with the MEG II detector, EPJC, 2025

2026 DAQ campaign just started

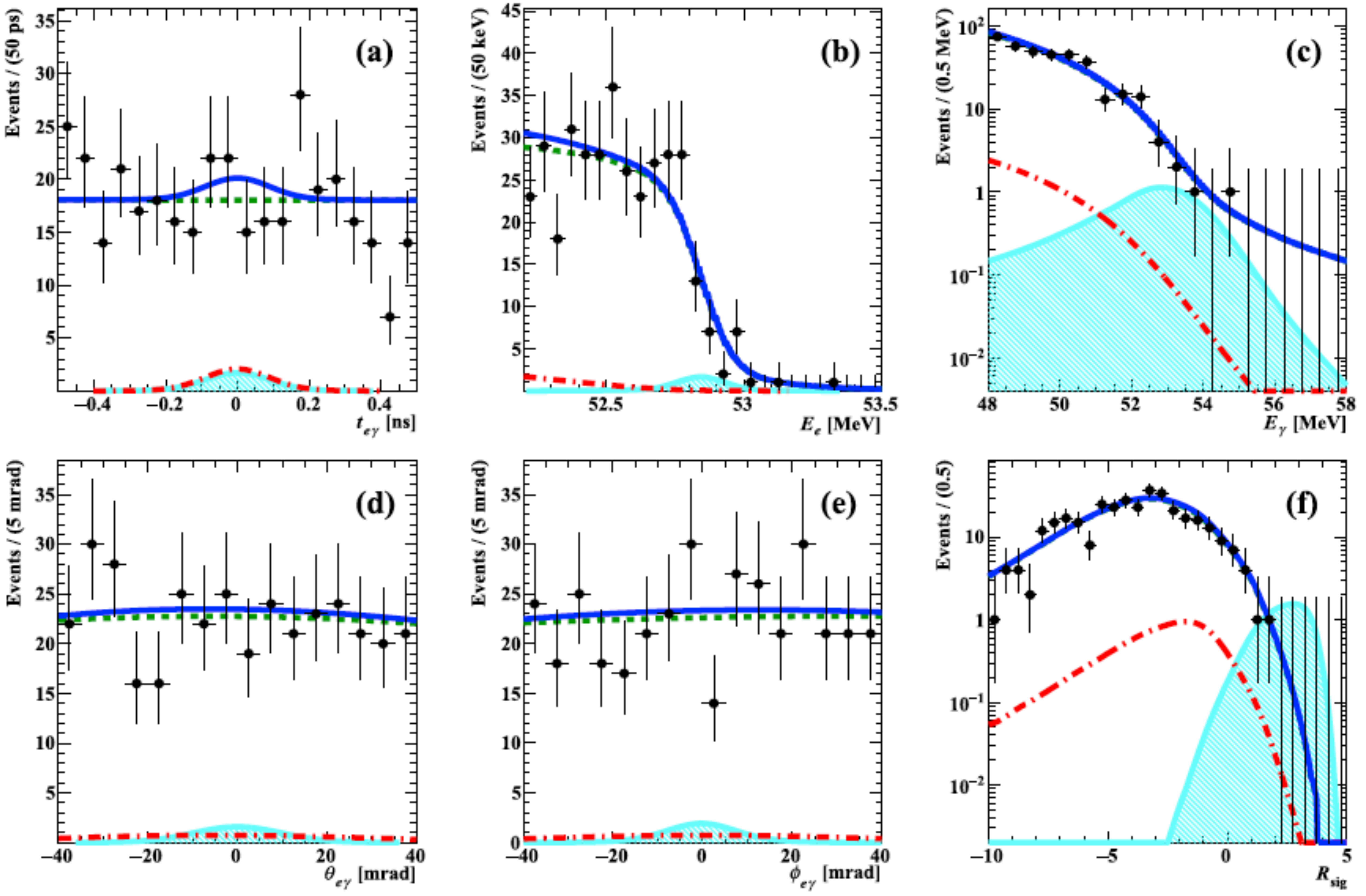


Conclusions

- **cLFV** with **muons** features a **unique opportunity** to discover **physics beyond the standard model**
- **MEG II** collecting **physics** data **from 2021**
  - ***goal*** *sensitivity:* ***6 x 10^{-14}*** *by taking data* ***until 2026***
  - ***first result*** *with* ***2021+2022 data*** *combined with MEG data: BR(μ->eγ)<1.5 10^{-13} @90%CL*
  - *We are analysing the data and still improving our algorithms aiming at BR(μ->eγ)<6 10^{-14} @90%CL sensitivity: <u>plan to publish 2021-2024 data before the end of 2027</u>*
- a **full physics** program, with also **exotic channels**, looks just behind the corner!

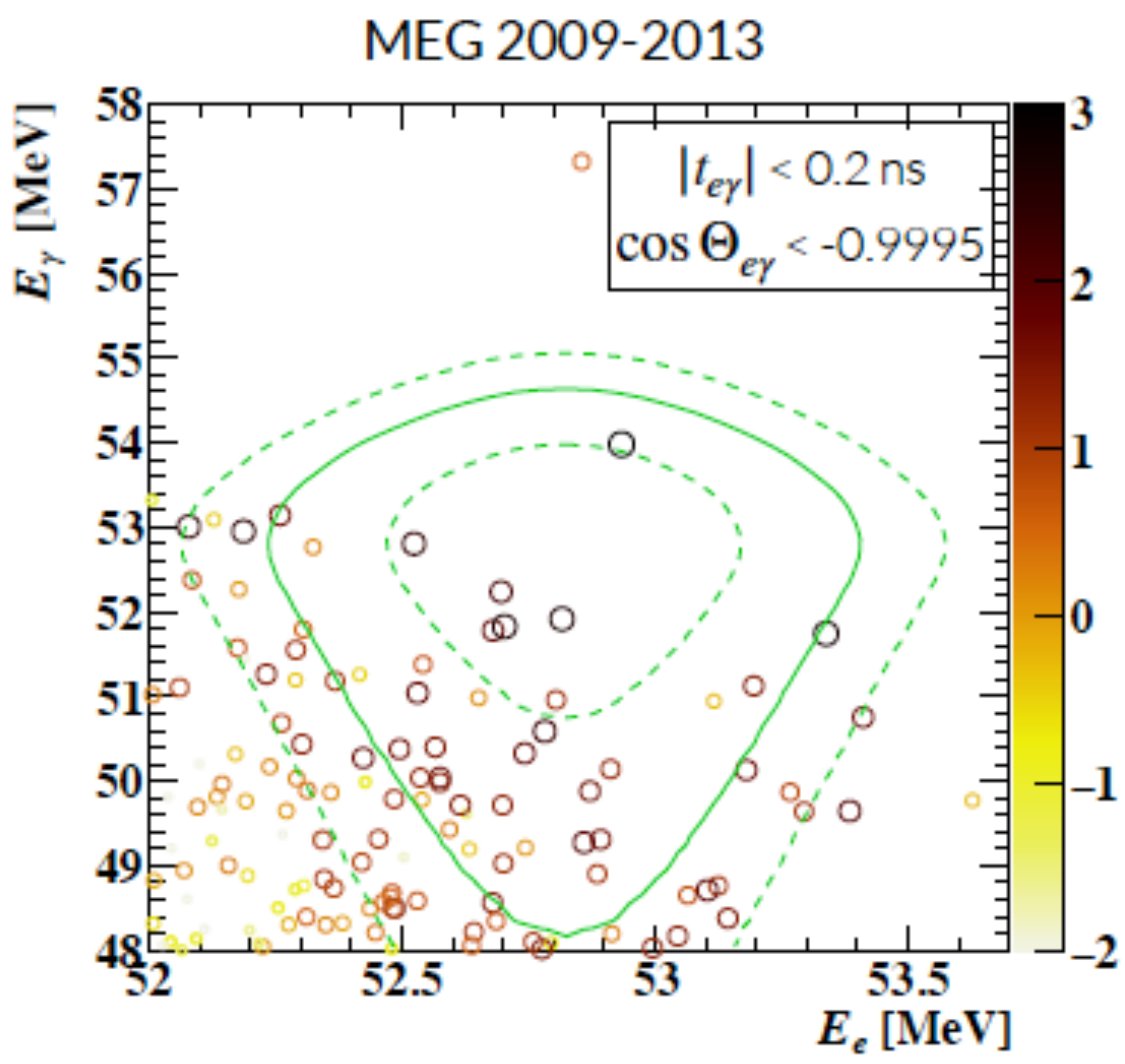
Thanks for your attention!

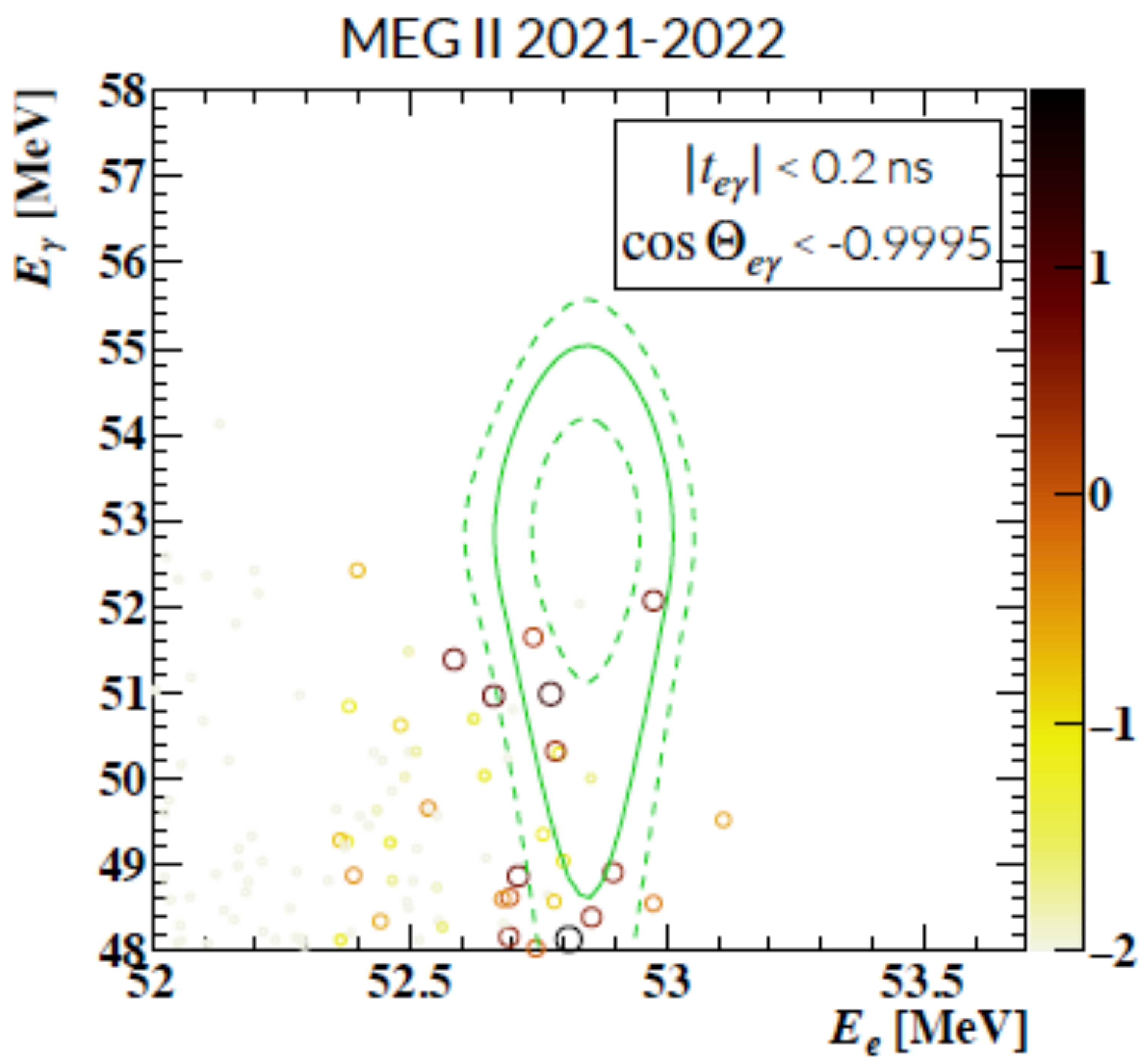
Fit on 2021+2022 data



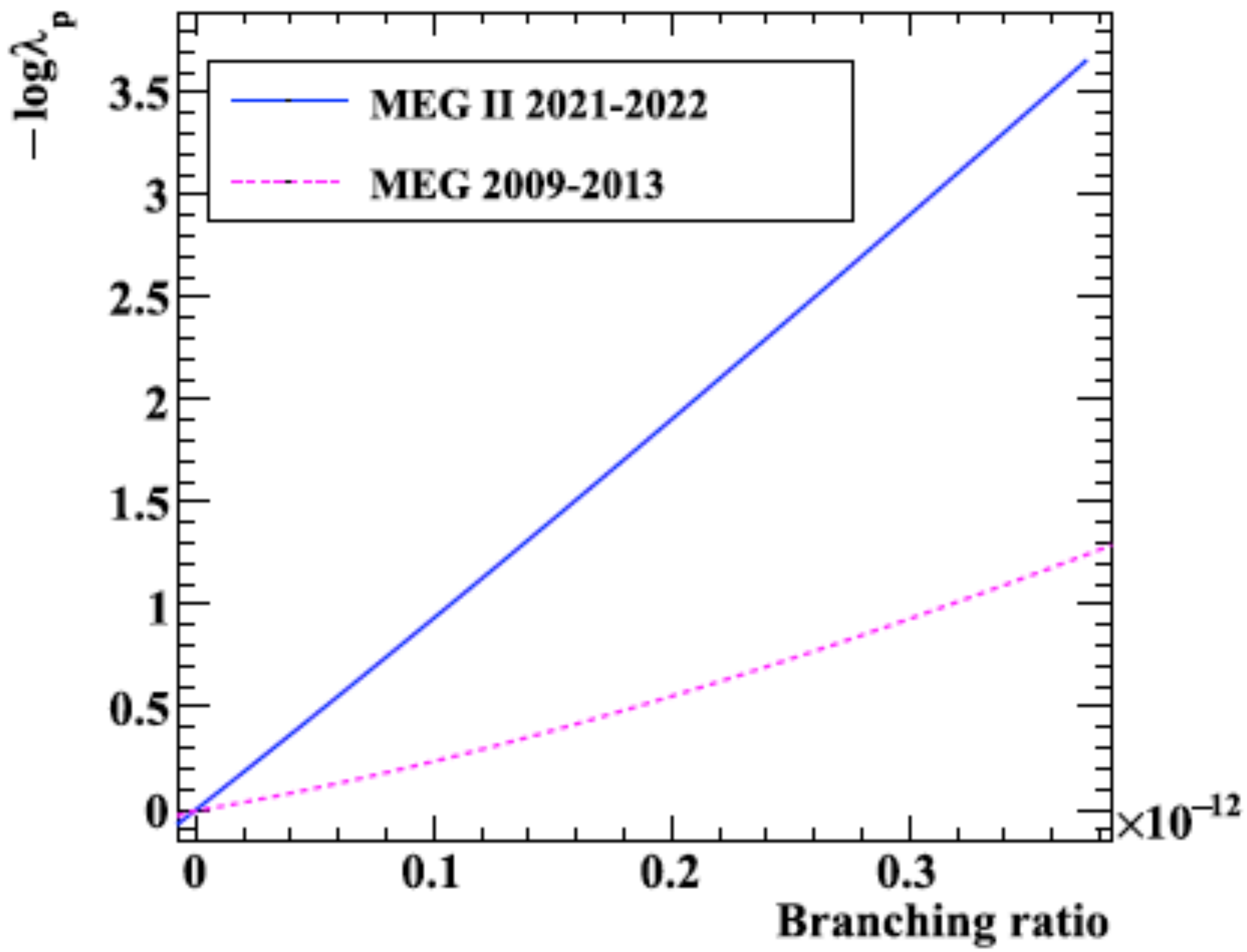
Data
Bkg
Accidentals
RMDs
Signal (x4)

Comparison with MEG



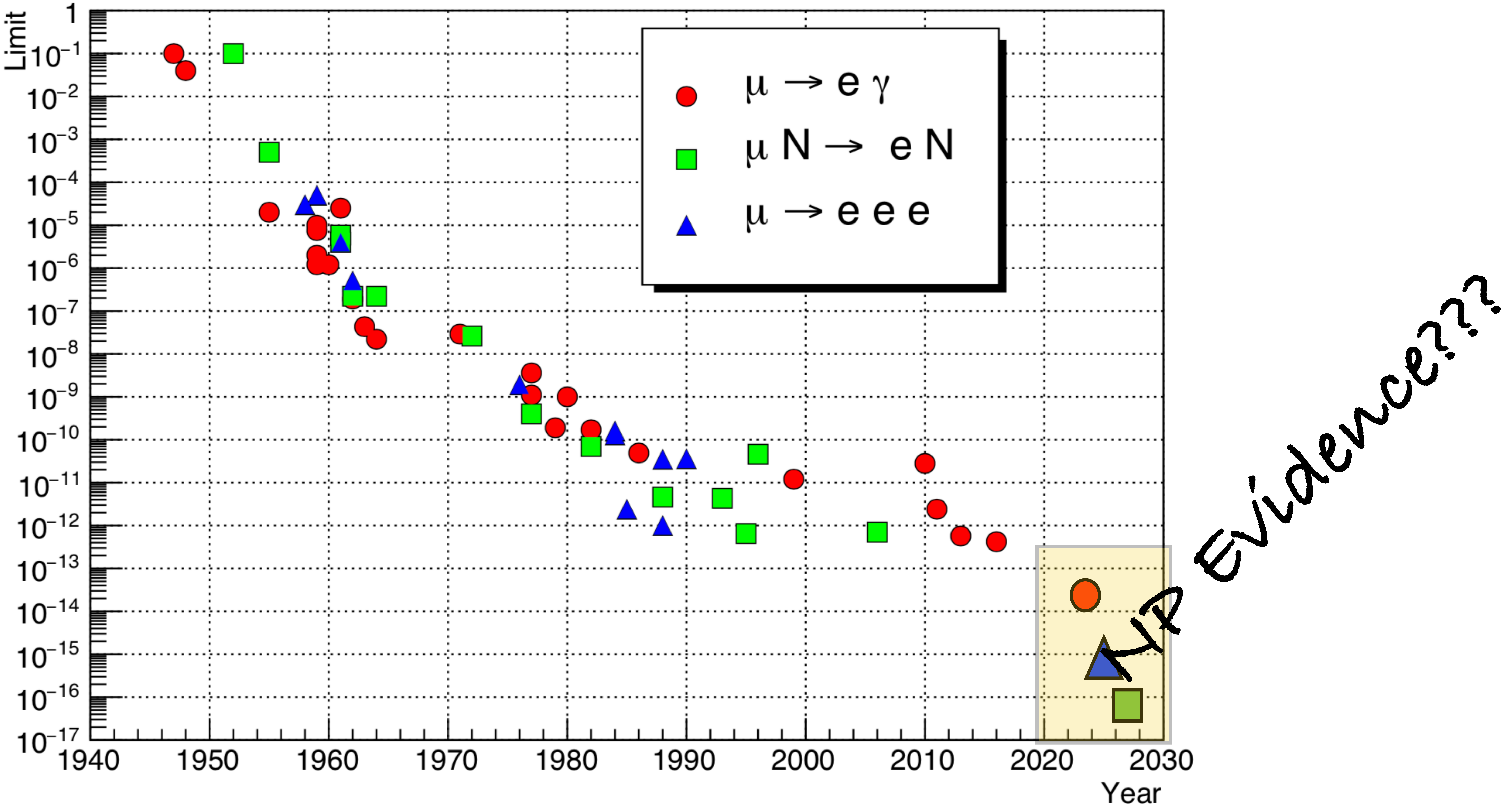


Comparison with MEG (2)

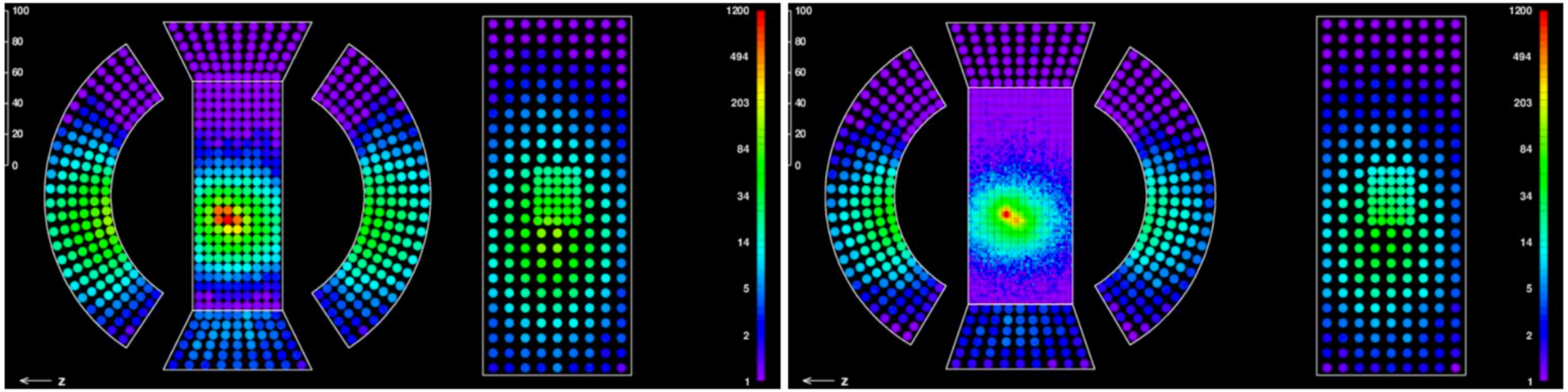


cLFV in 10 years

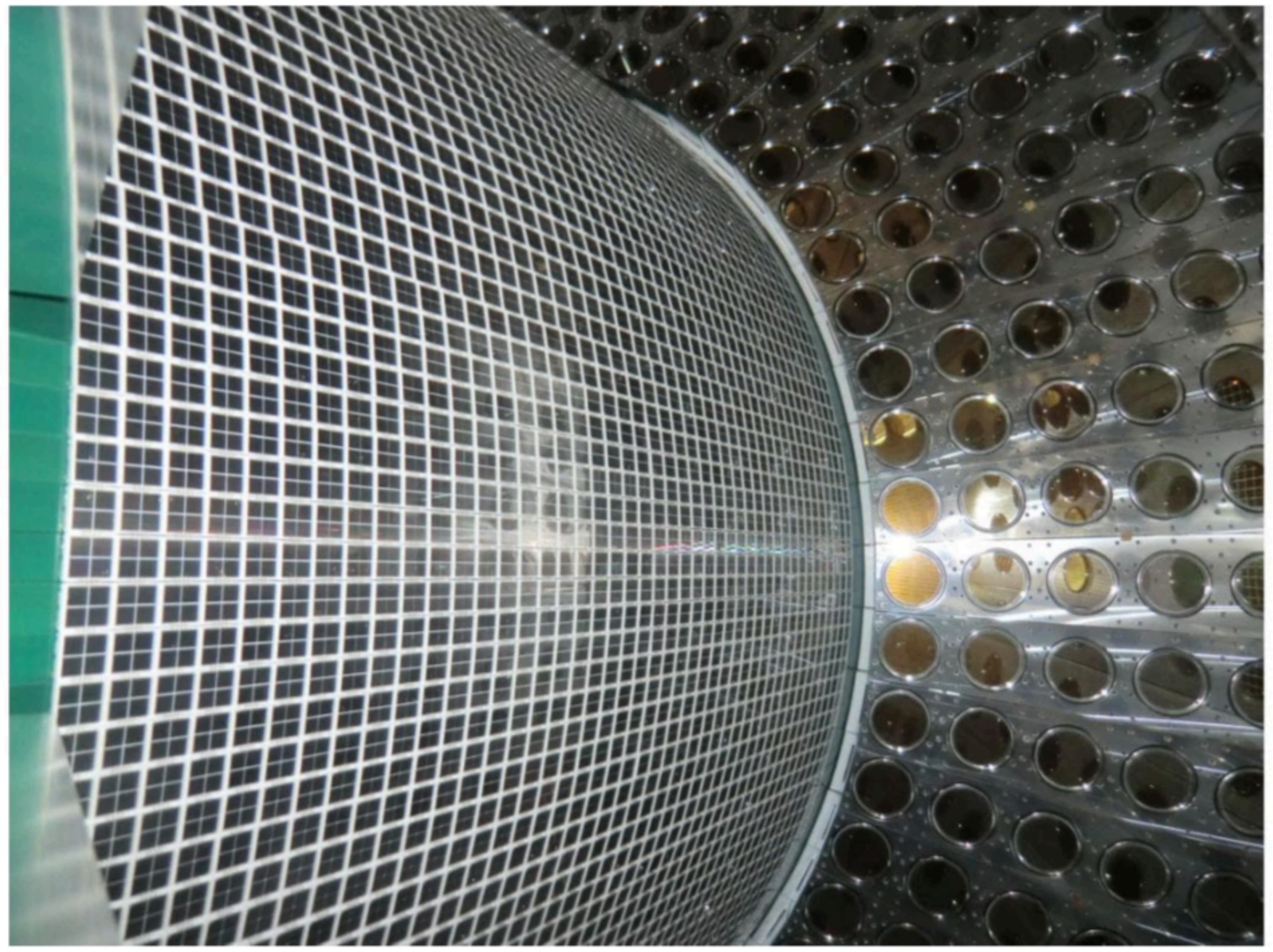
Calibbi and Signorelli, Riv. N. Cimento, 2017



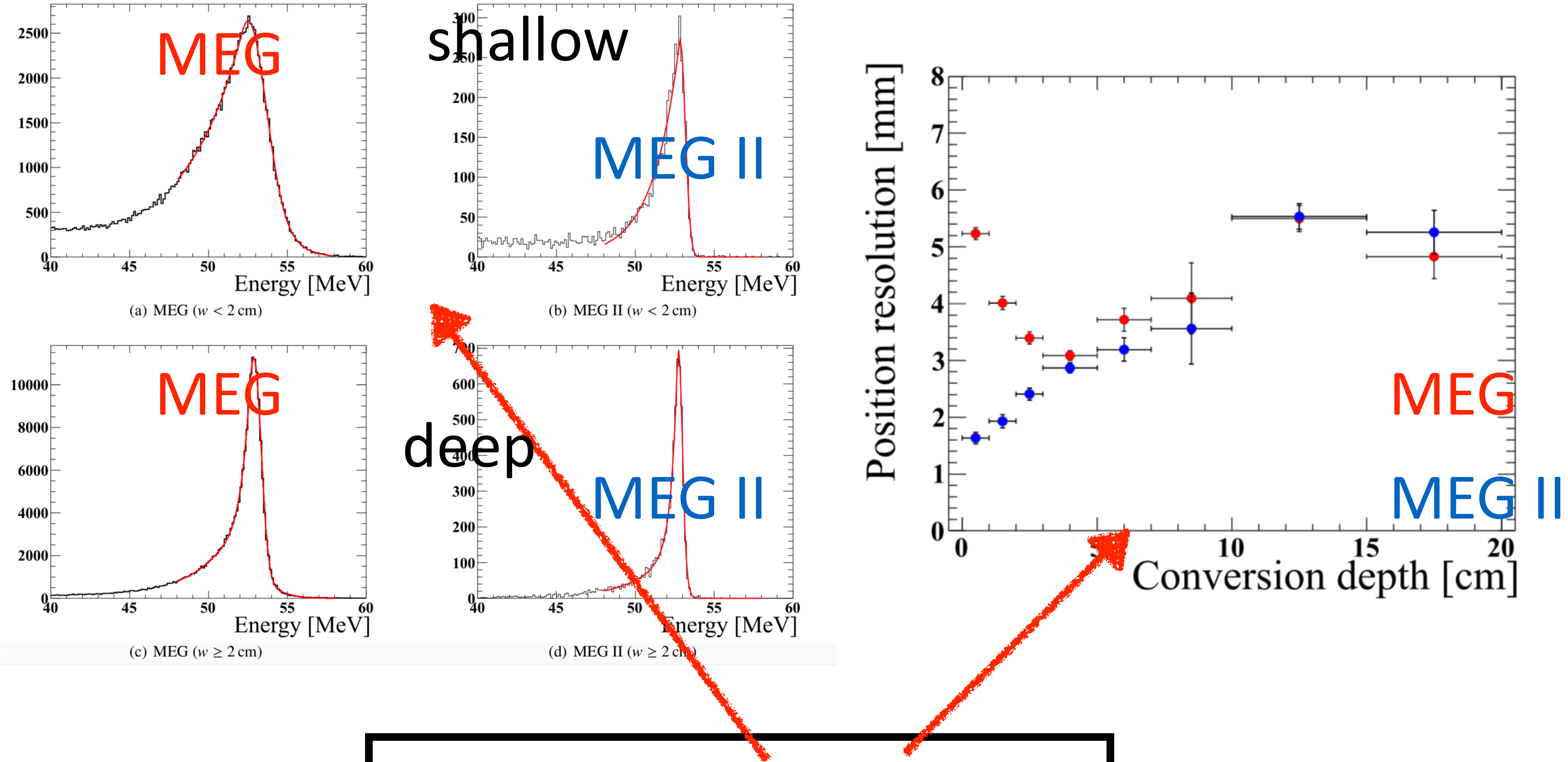
LXe detector



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

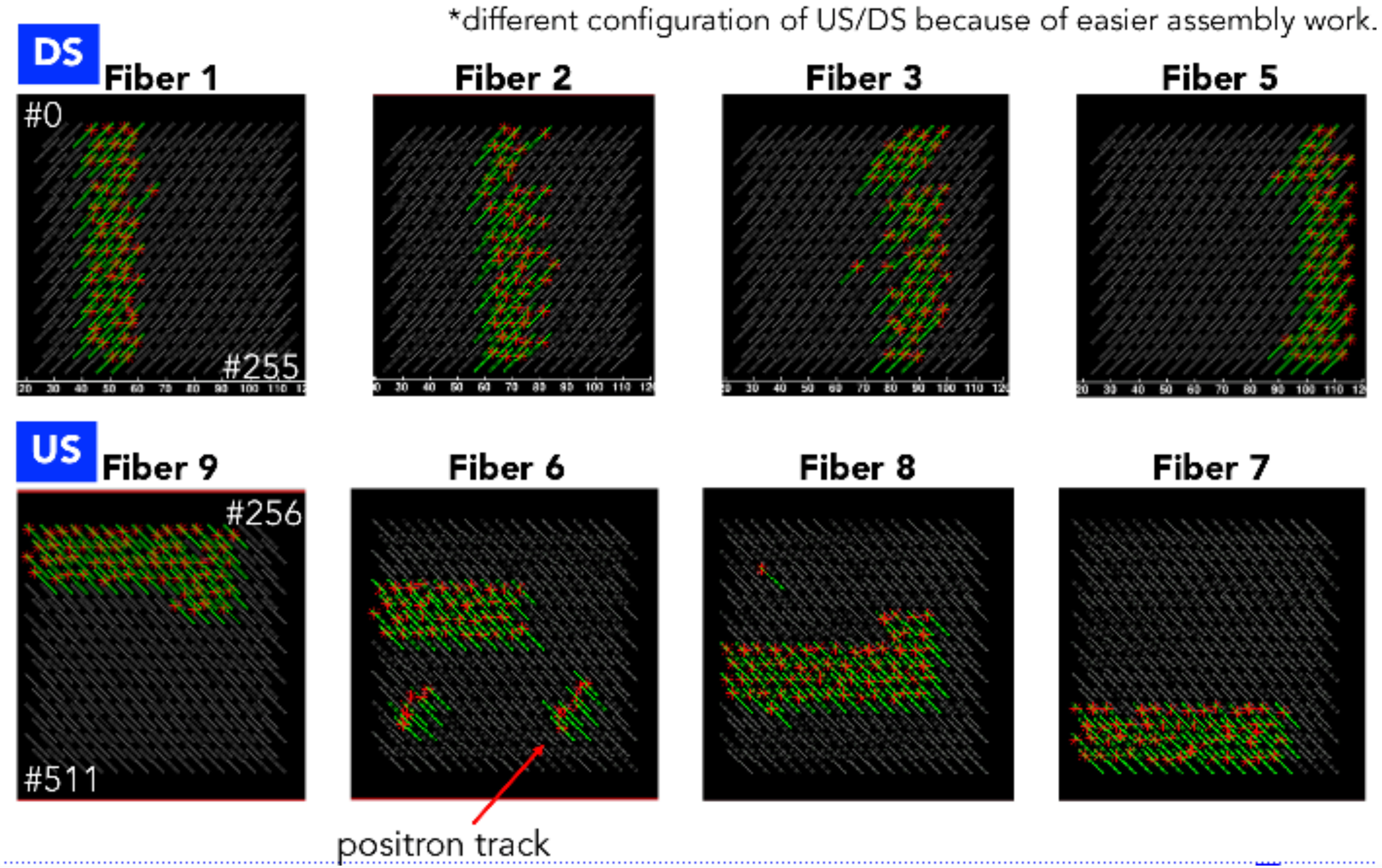


Performance improvement



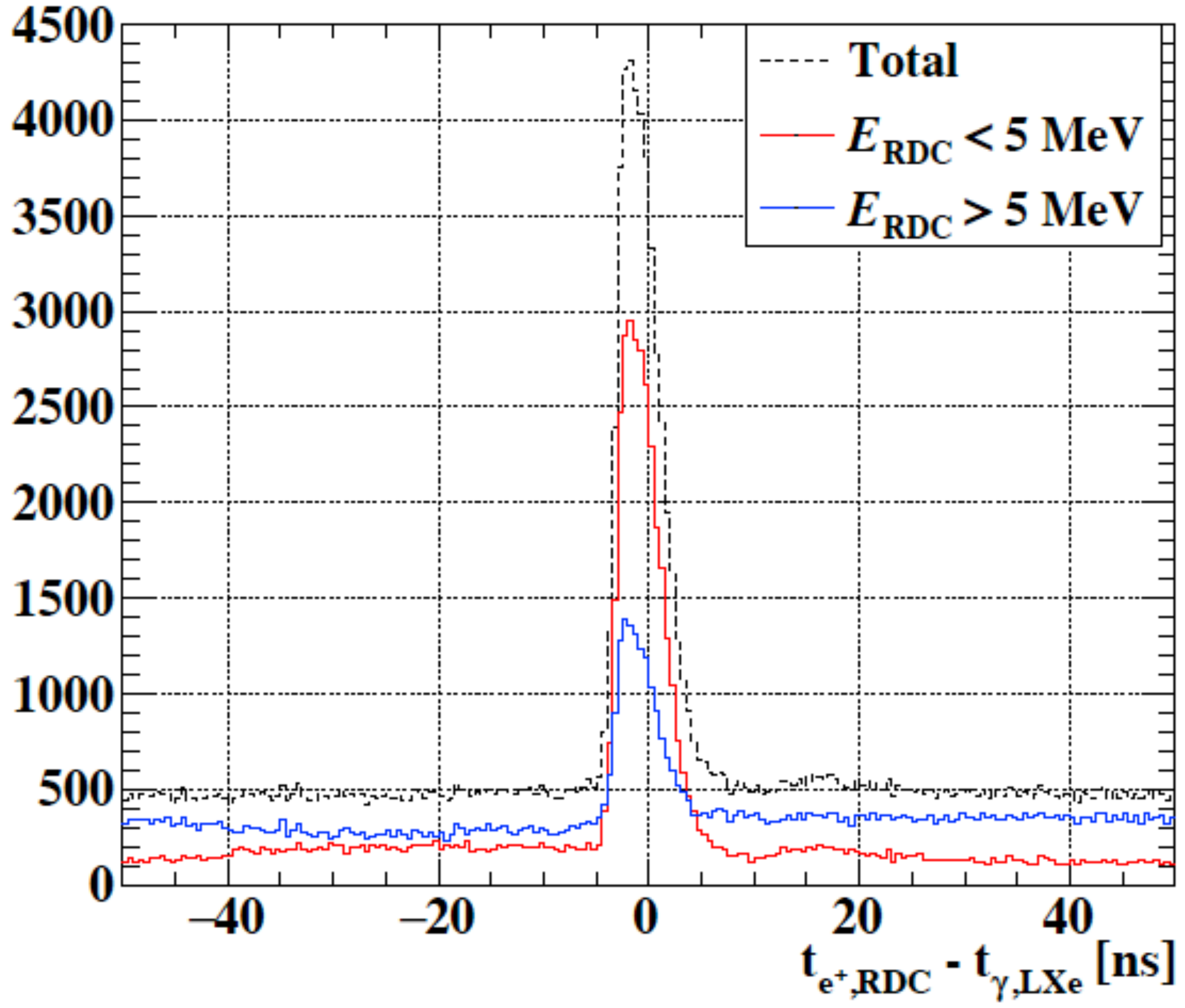
$$B_{acc} \propto R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\Theta_{e\gamma}^2 \Delta t_{e\gamma}$$

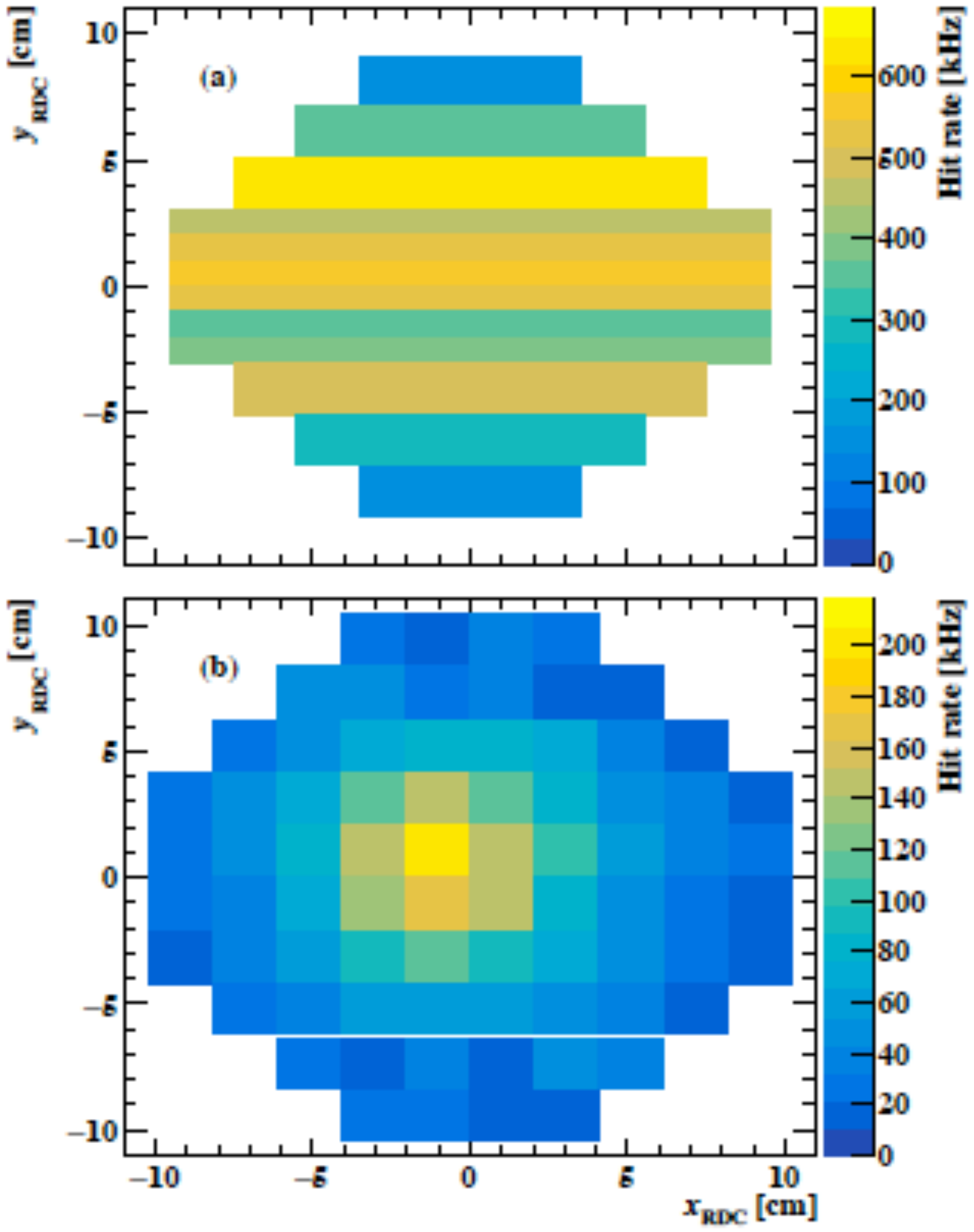
Calibration with laser

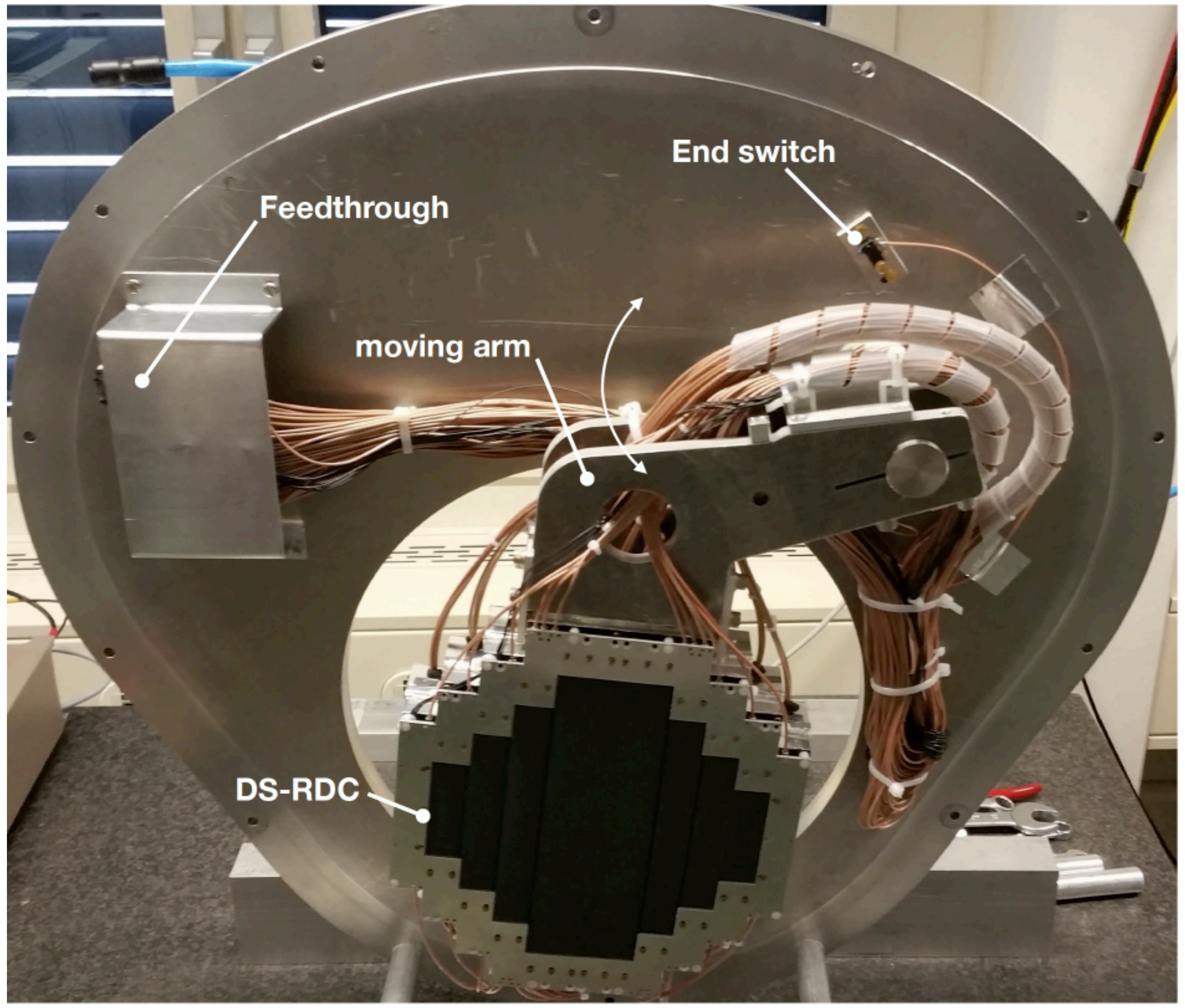


Radiative Decay Counter

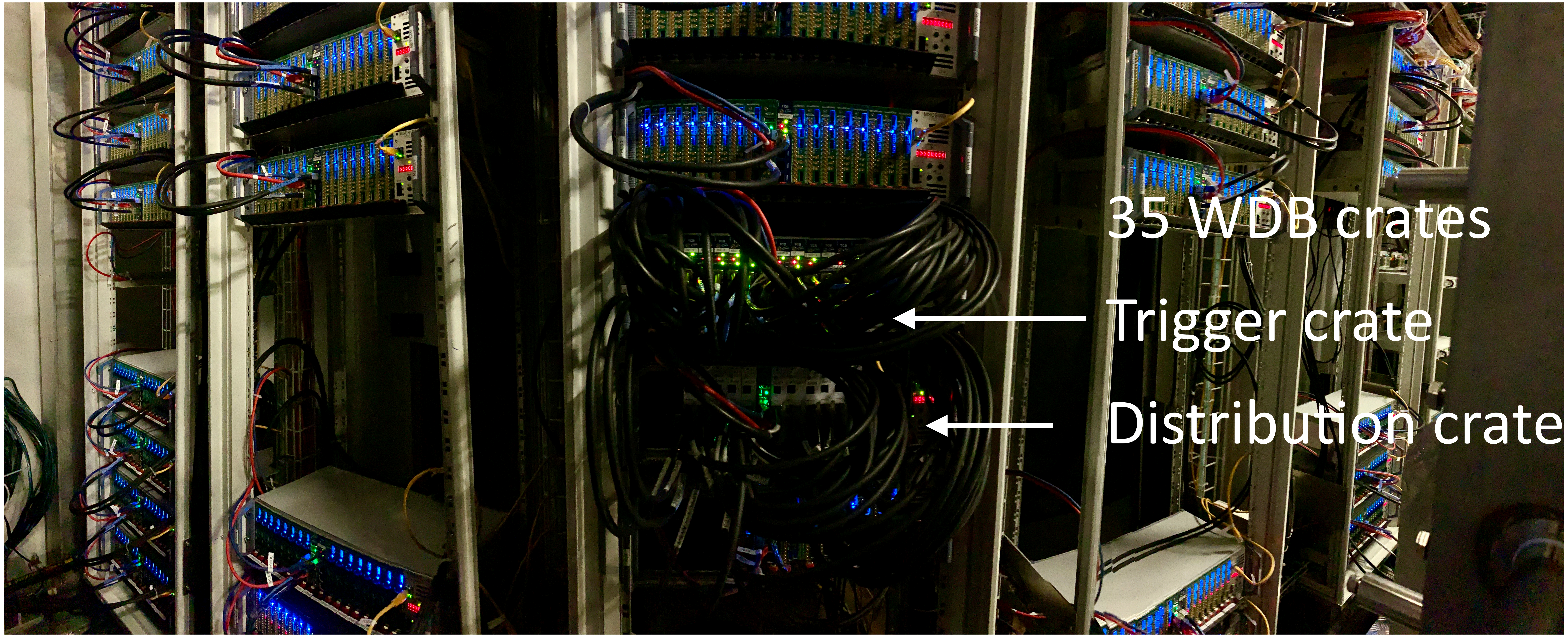
- **Tags** BG γ-rays from muon **radiative decays** by detecting **low energy positrons**
  - **(a) scintillation tile** in the front for **timing**
  - **(b) LYSO** cube for **energy** measurement
- **Sensitivity improved** by **15%**



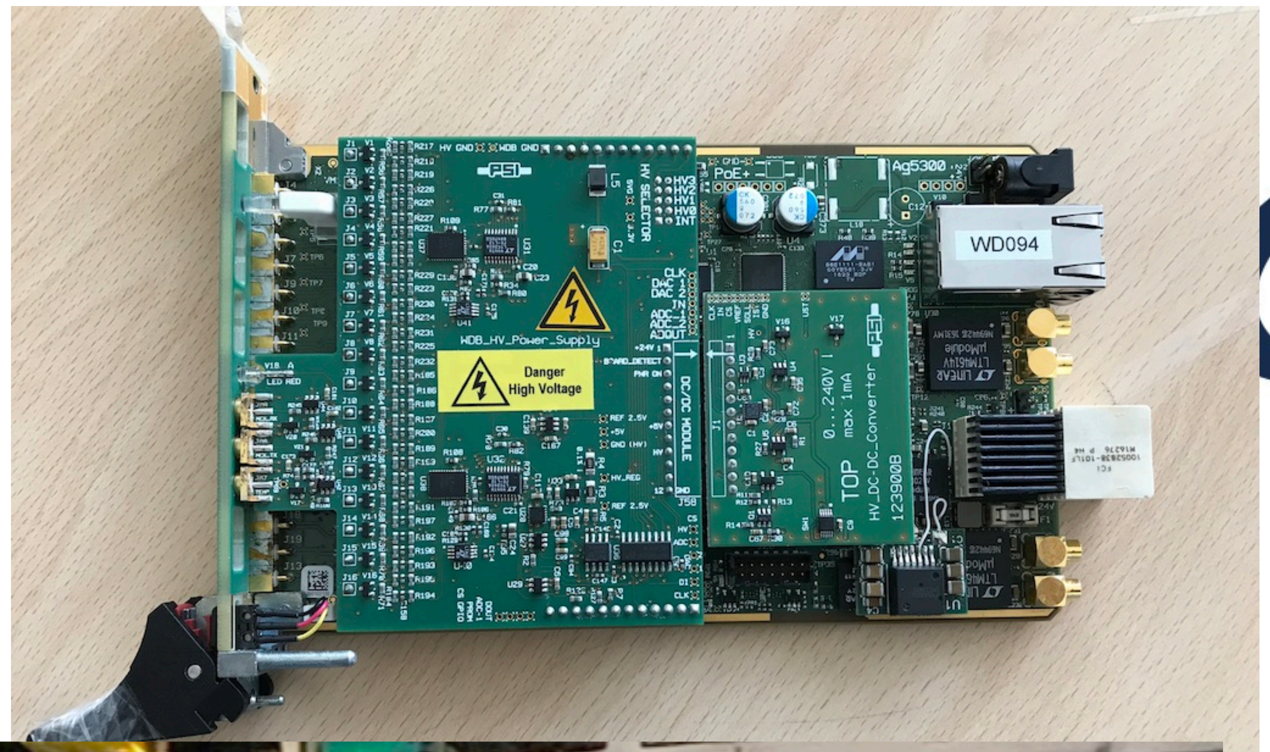




TDAQ system



TDAQ electronics



- **Full cus**
- **Trigger**
  - *wavef*
    - **SiPM**
  - *Compl*
  - *up to 10 Gb/s DAQ throughput (50 Hz)*