TOSHINORI MORI
THE MEG II COLLABORATION

THE FIRST RESULT OF MEG II ON SEARCH FOR $\mu^+ \to e^+\gamma$

WHY ARE WE SEARCHING FOR $\mu^+ \rightarrow e^+\gamma$?

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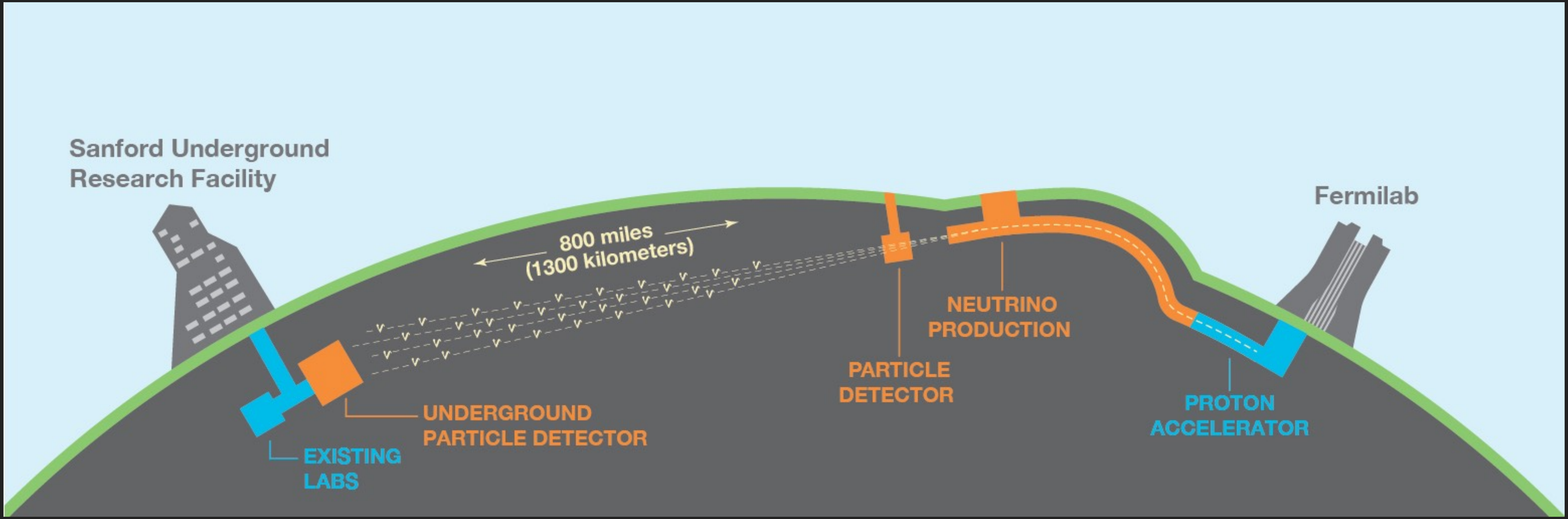
- Because it violates flavor conservation in charged leptons and is prohibited by the standard model.

WHY ARE WE SEARCHING FOR $\mu^+ \to e^+\gamma$?

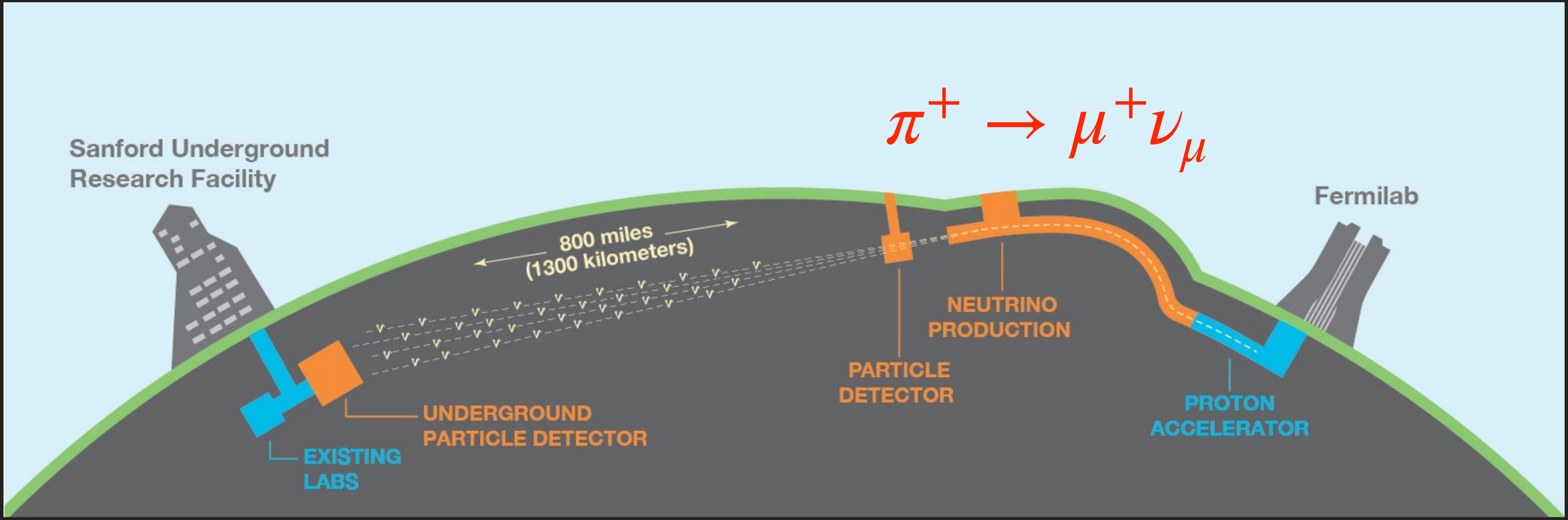
- Because it violates flavor conservation in charged leptons and is prohibited by the standard model.

Really?

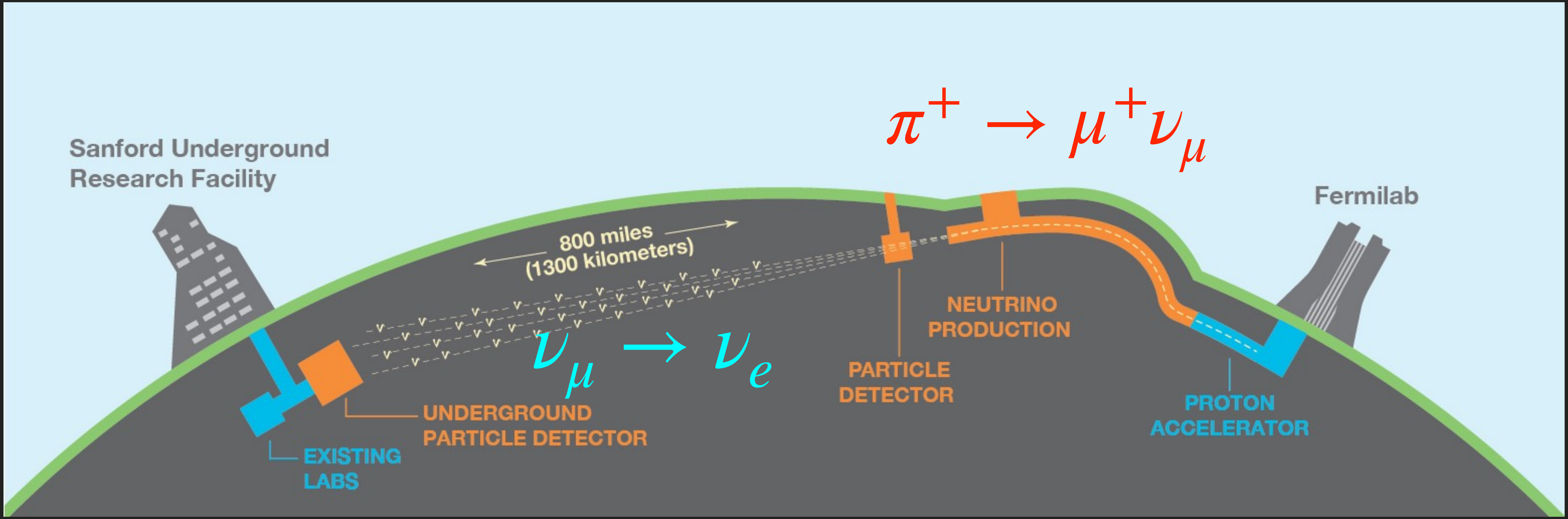
NEUTRINO OSCILLATIONS



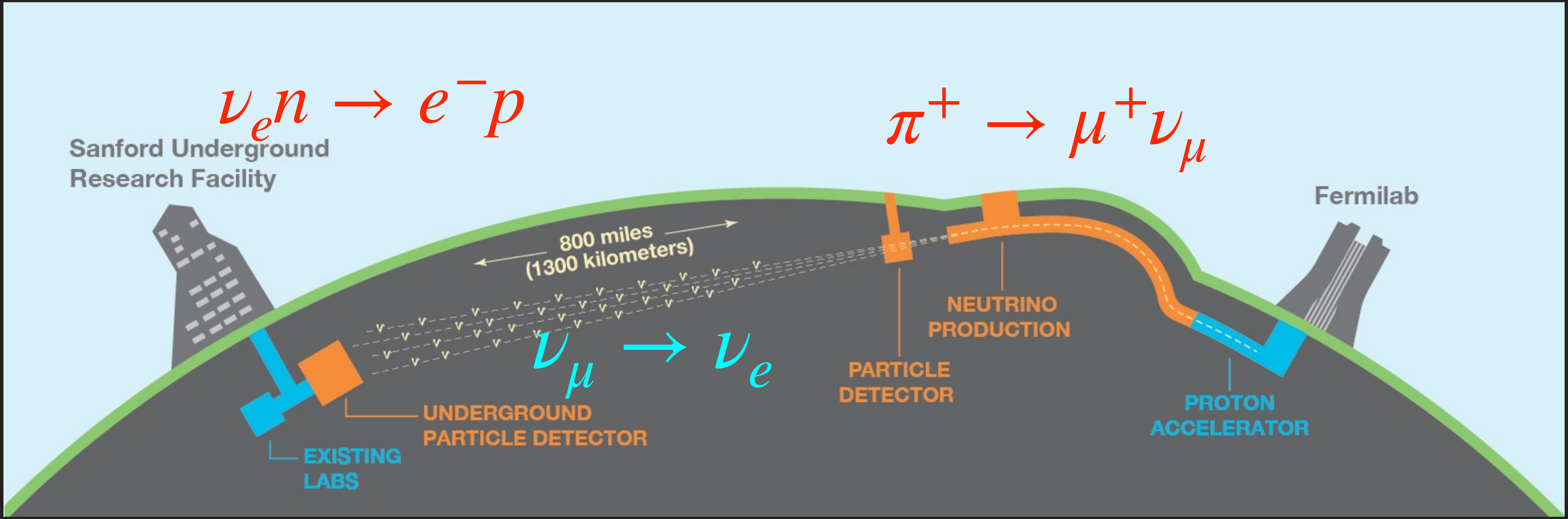
NEUTRINO OSCILLATIONS



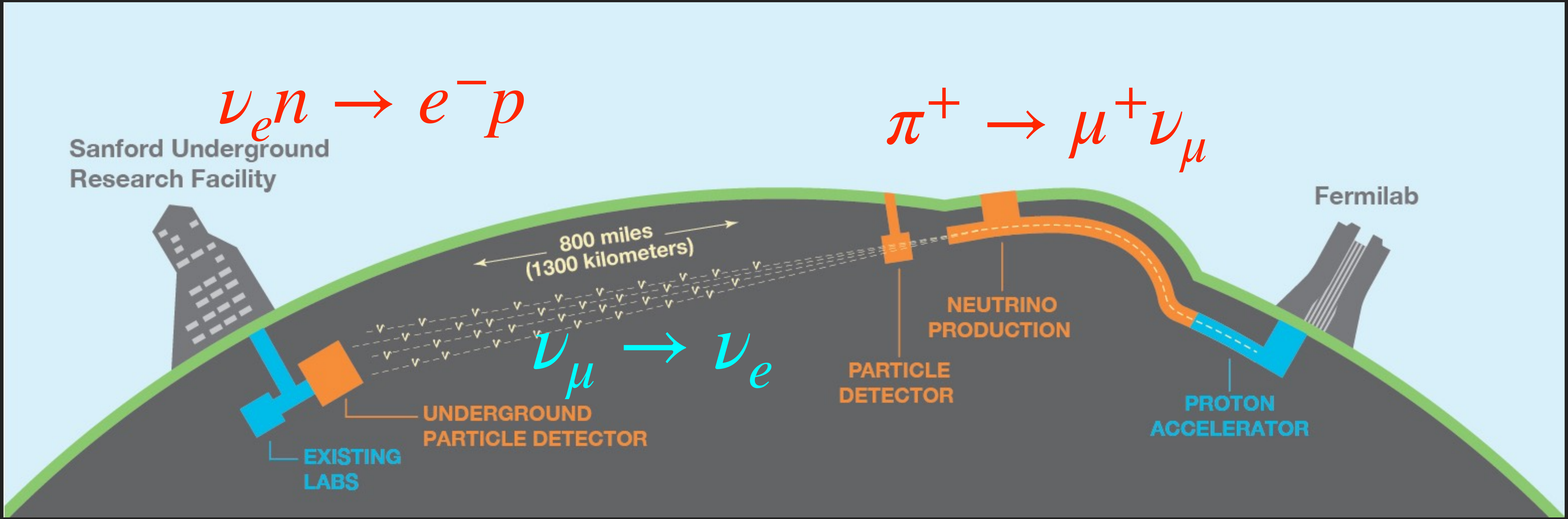
NEUTRINO OSCILLATIONS



NEUTRINO OSCILLATIONS



NEUTRINO OSCILLATIONS



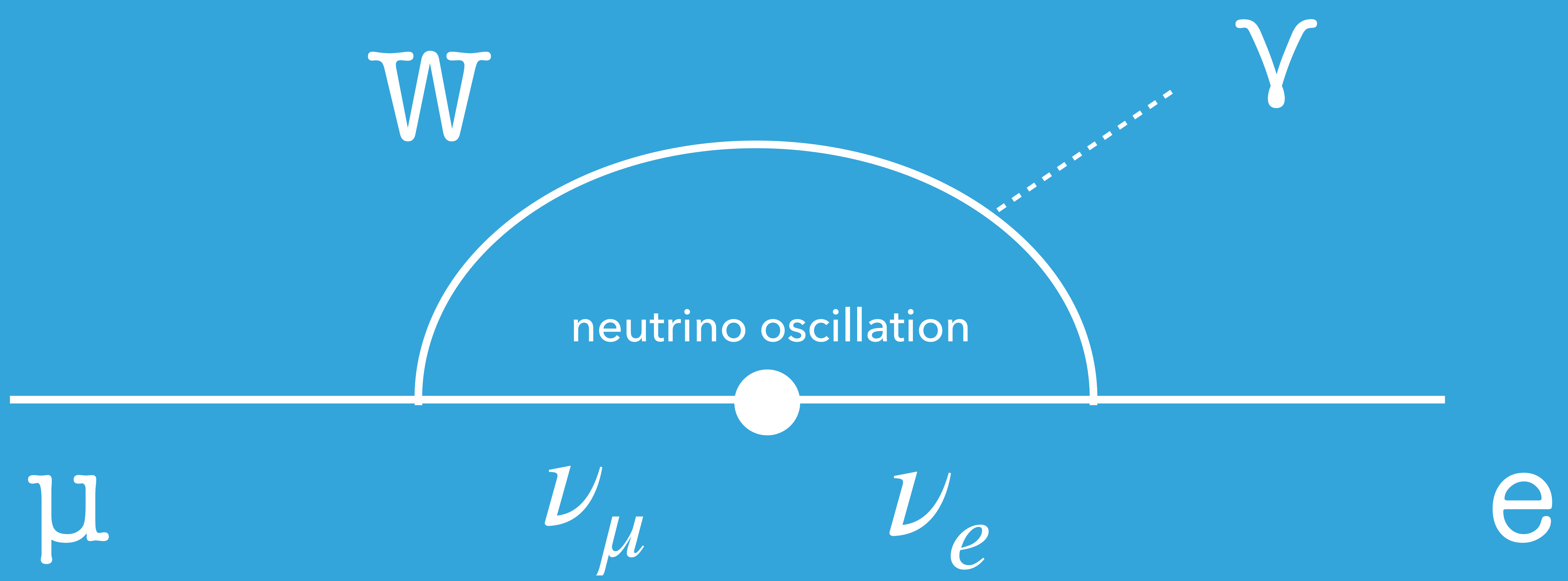
$$\pi^+ n \to \mu^+ e^- p$$

We do not really observe neutrinos in these reactions.

LEPTON FLAVORS ARE DEFINITELY VIOLATED IN CHARGED LEPTONS!

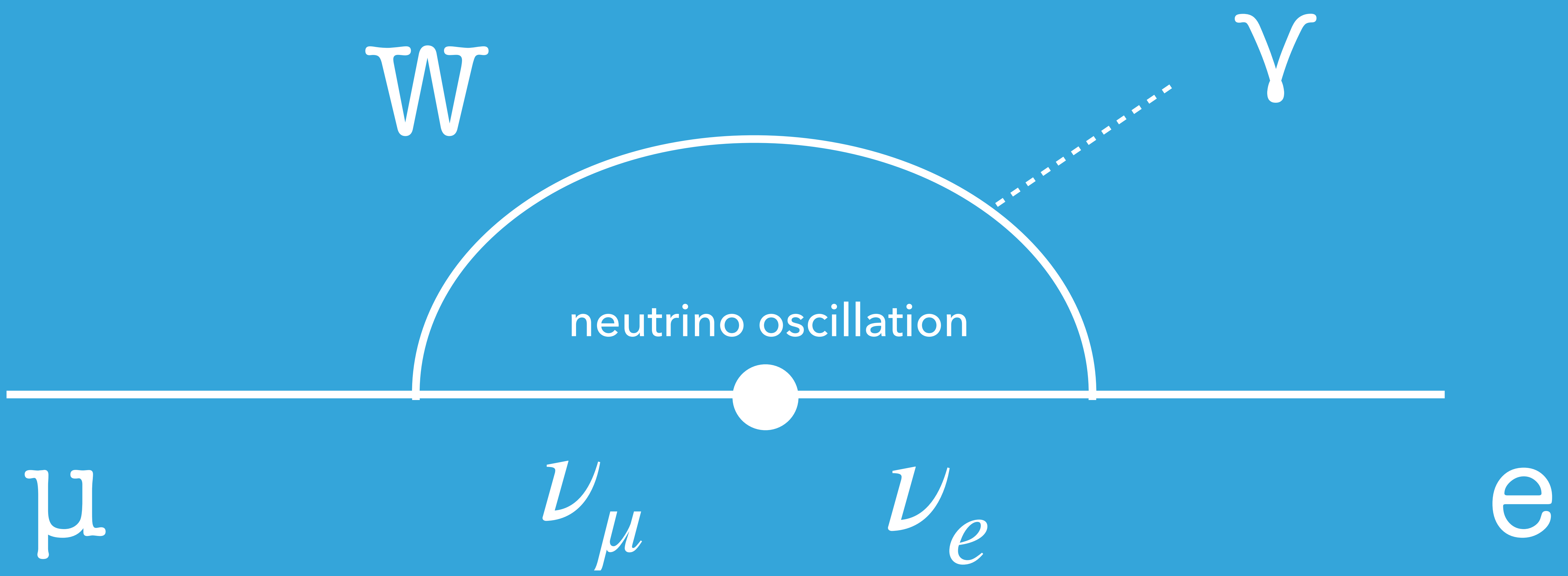
$\mu \to e\gamma$ should occur!

$\mu^+ \to e^+\gamma$ SHOULD NATURALLY OCCUR !



$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-45}$$

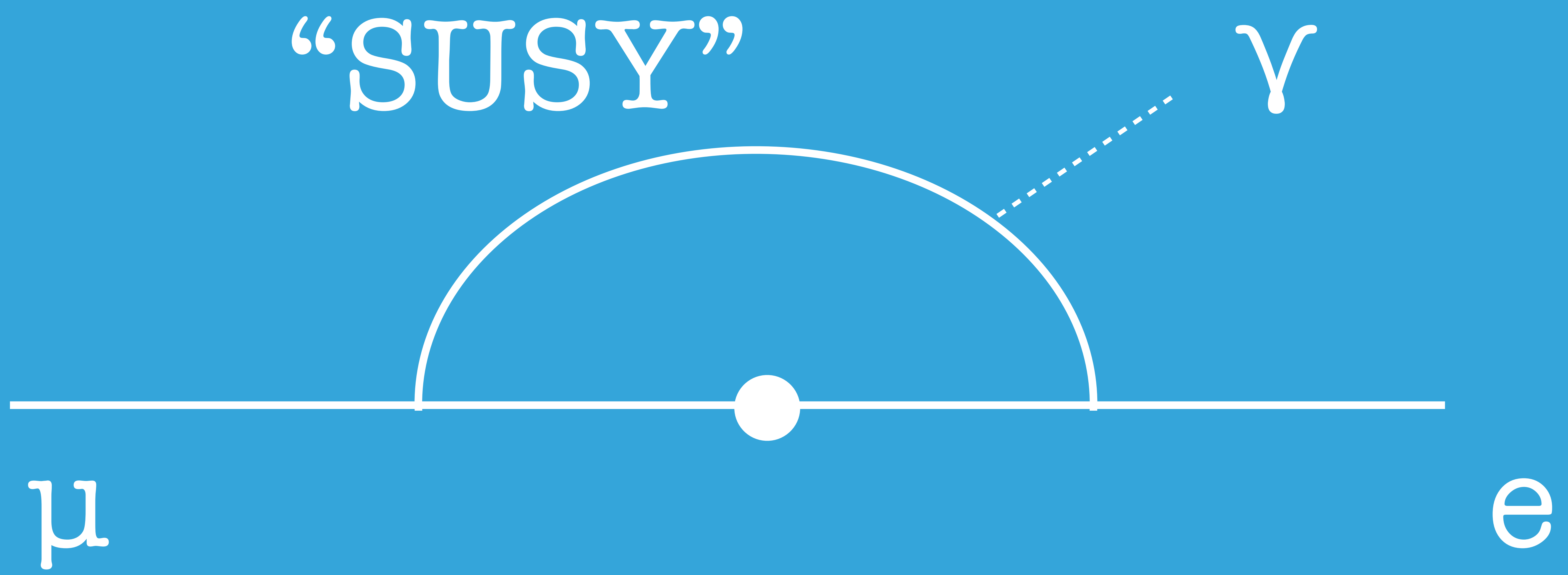
$\mu^+ \to e^+\gamma$ SHOULD NATURALLY OCCUR !



$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-45}$$

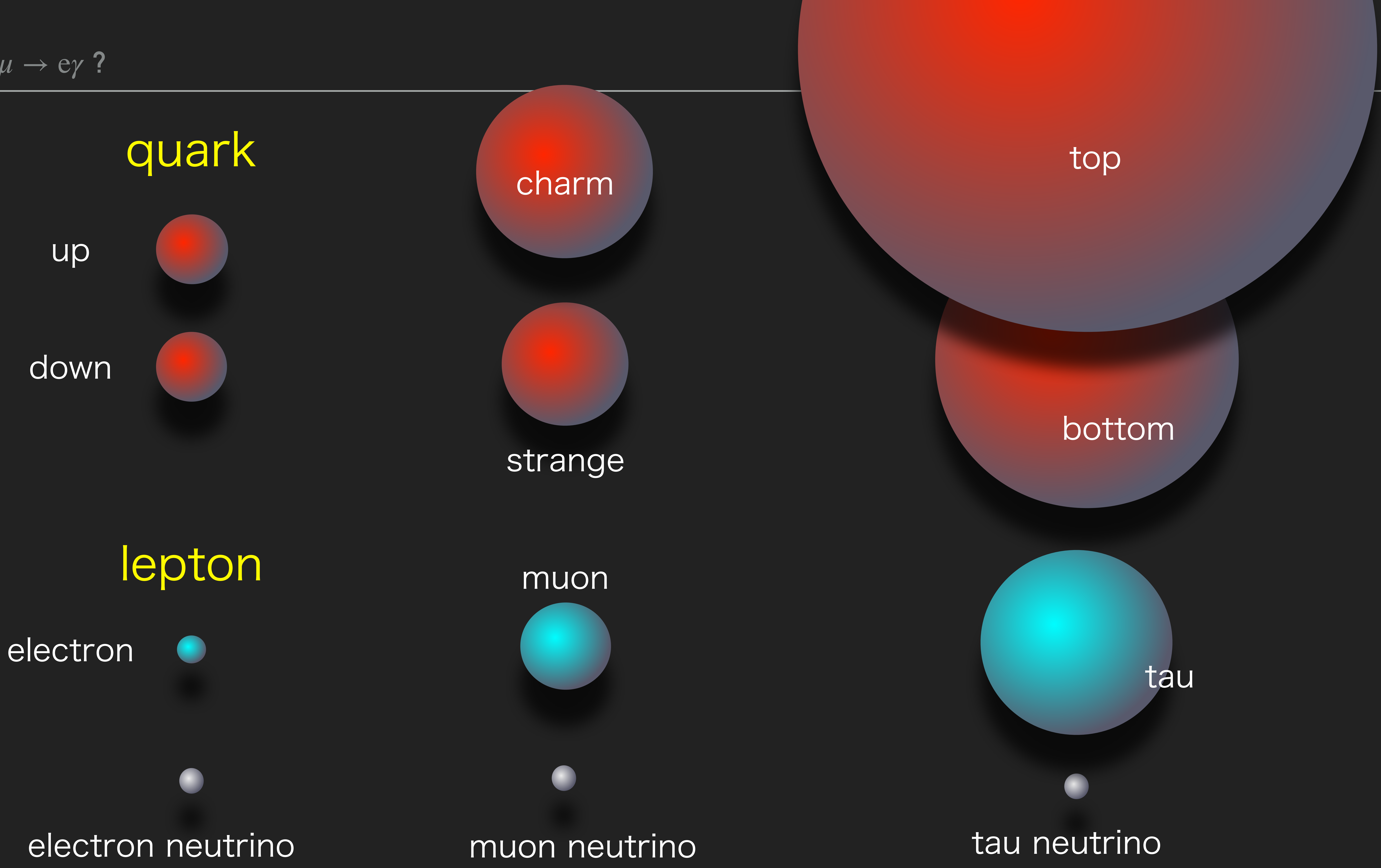
Unfortunately the neutrinos are just too light…

ANY TEV SCALE PHYSICS HELP MAKE THE BRANCHING RATIO BIGGER !



$$\left| \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{M^2_{SUSY}} \right| \simeq 10^{-12}$$

Sensitive to various new physics scenarios


quark
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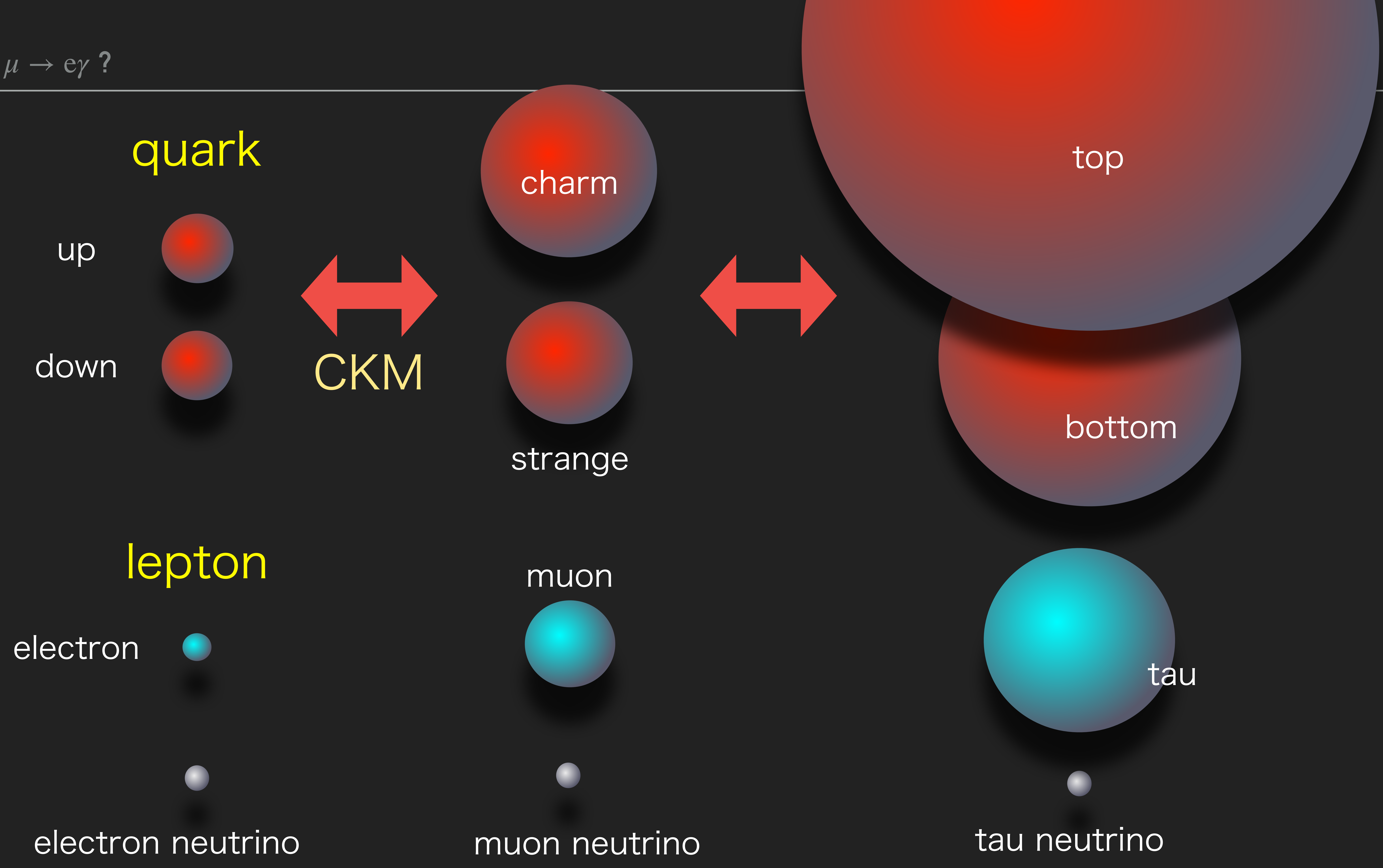
down
charm
strange
top
bottom
lepton
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino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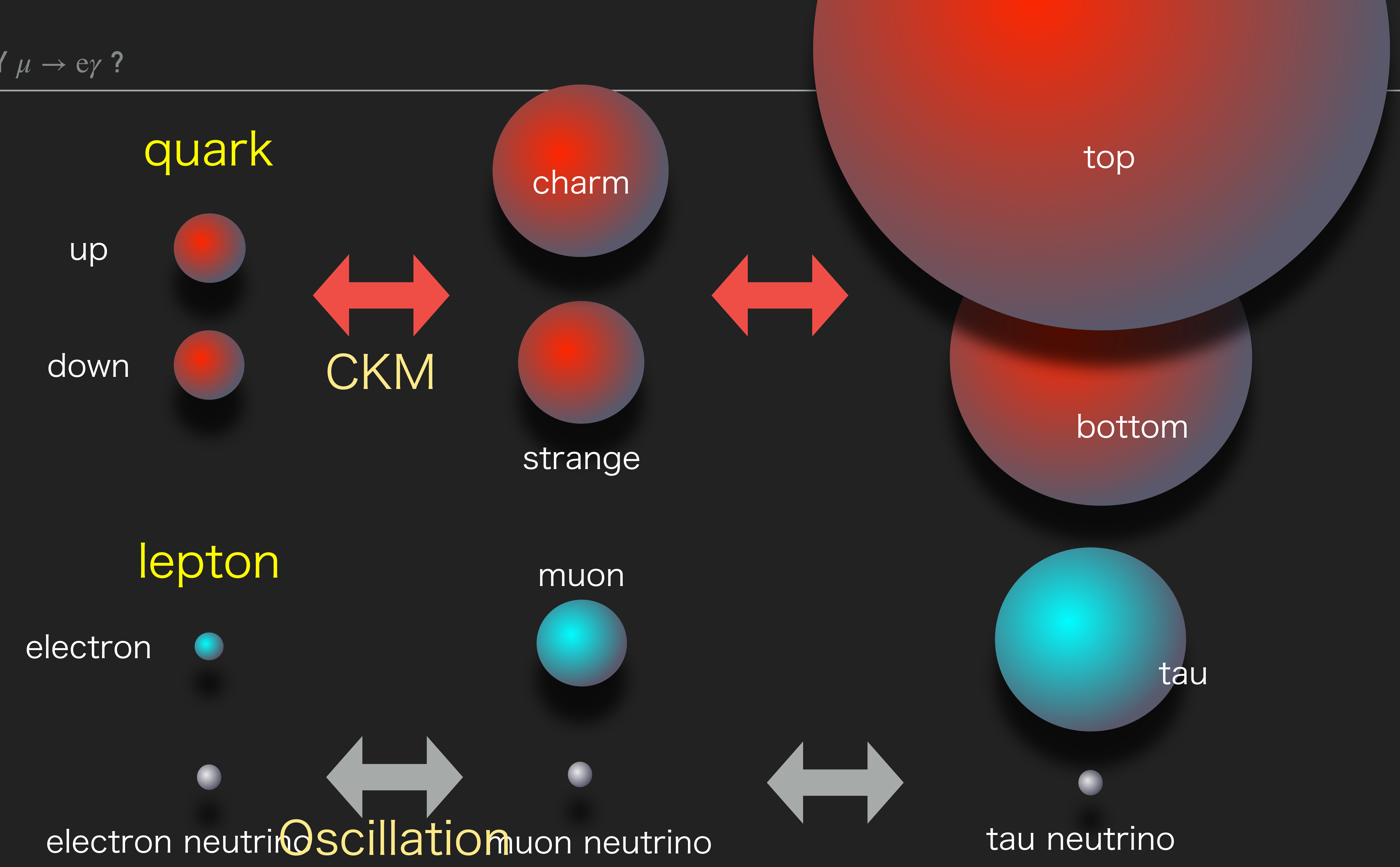
electron neutrino
muon neutrino
tau neutrino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Oscillation
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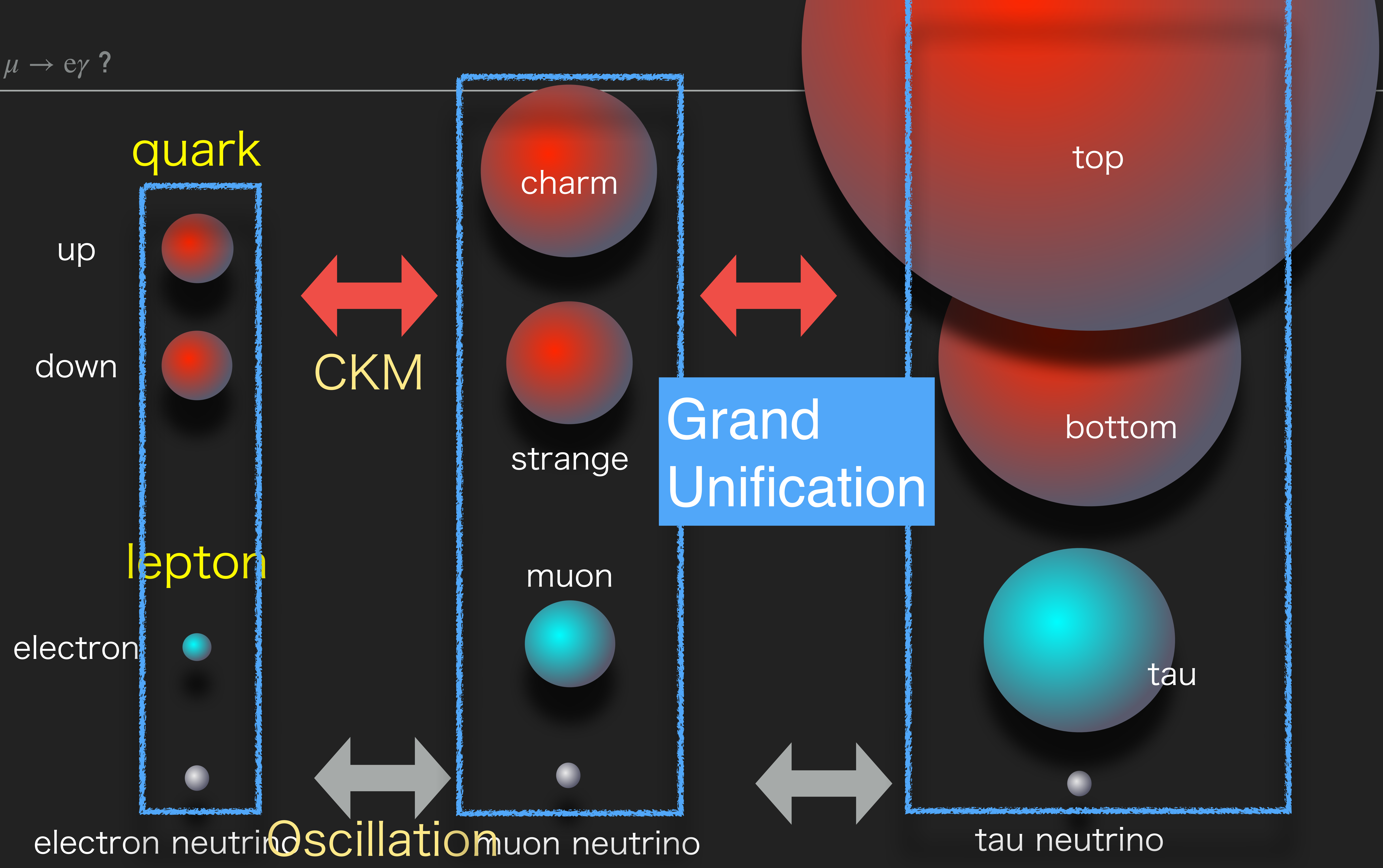
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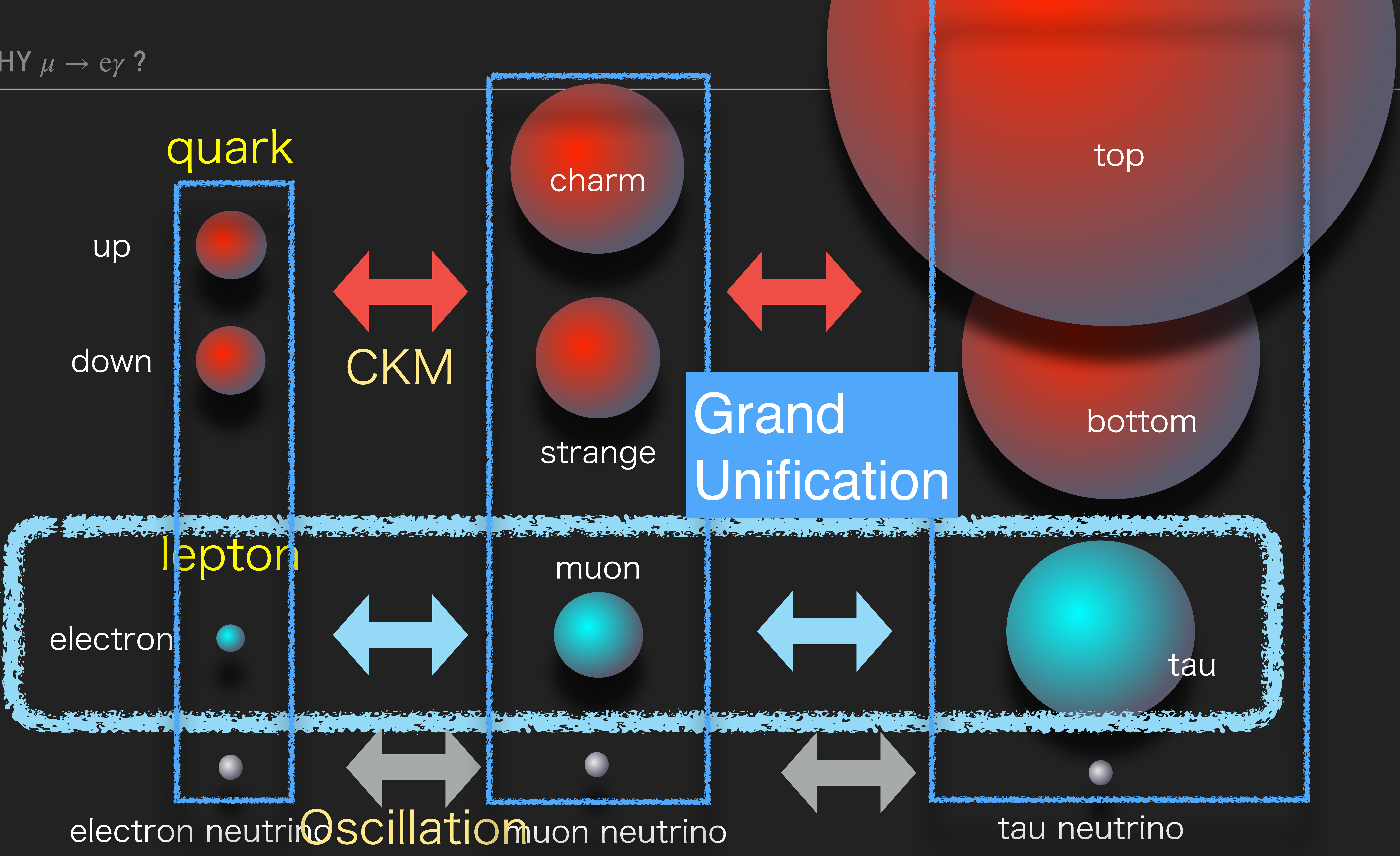
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Grand Unification
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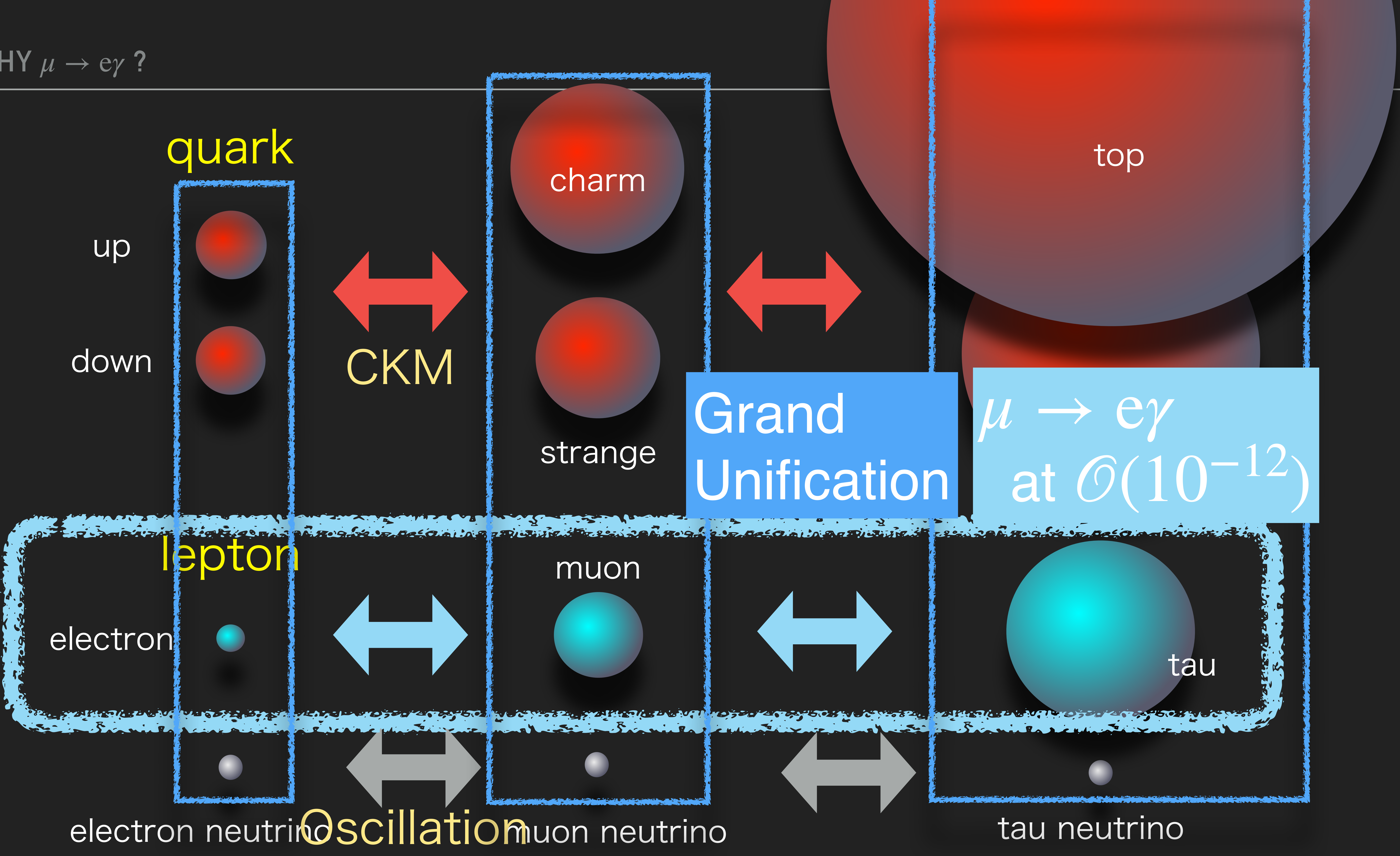
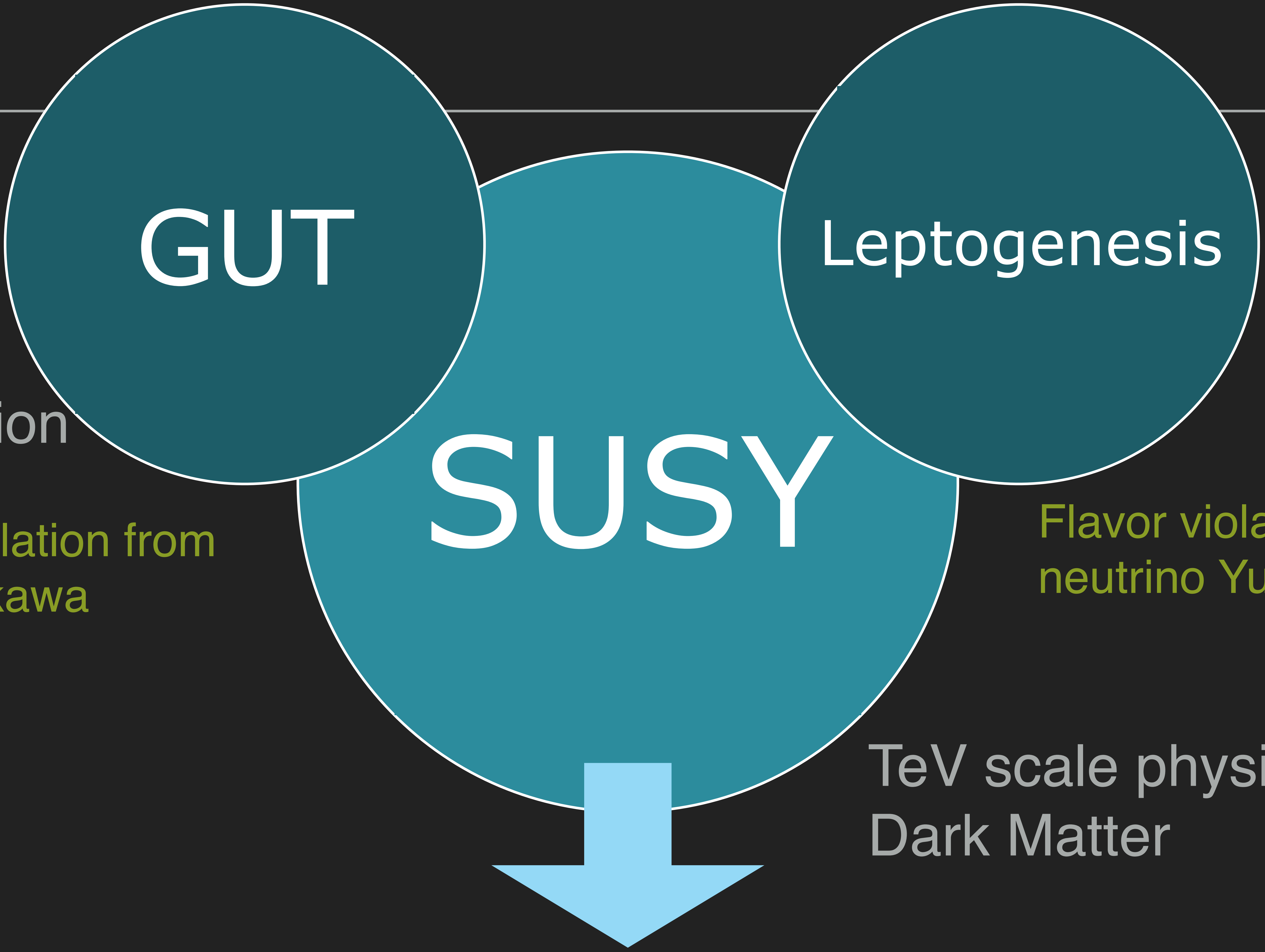
electron neutrino
Oscillation
muon neutrino
tau neutrino


quark
up
down
charm
strange
top
CKM
Grand Unification
$\mu \to e\gamma$ at $\mathcal{O}(10^{-12})$
lepton
electron
muon
tau
electron neutrino
Oscillation
muon neutrino
tau neutrino

BIG PICTURE



grand unification
charge quantization

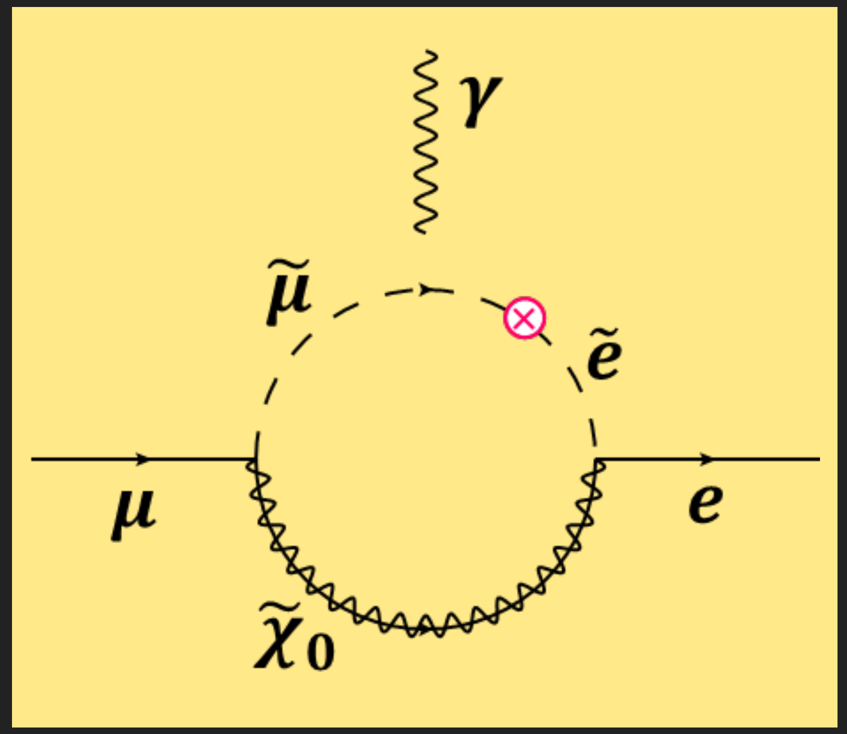
Flavor violation from
quark Yukawa

seesaw mechanism
neutrino masses

Flavor violation from
neutrino Yukawa

TeV scale physics
Dark Matter

$\mu \to e\gamma$



$\simeq 10^{-12}$

BIG PICTURE

GUT

grand unification
charge quantization

Flavor violation from
quark Yukawa

SUSY

Leptogenesis

seesaw mechanism
neutrino masses

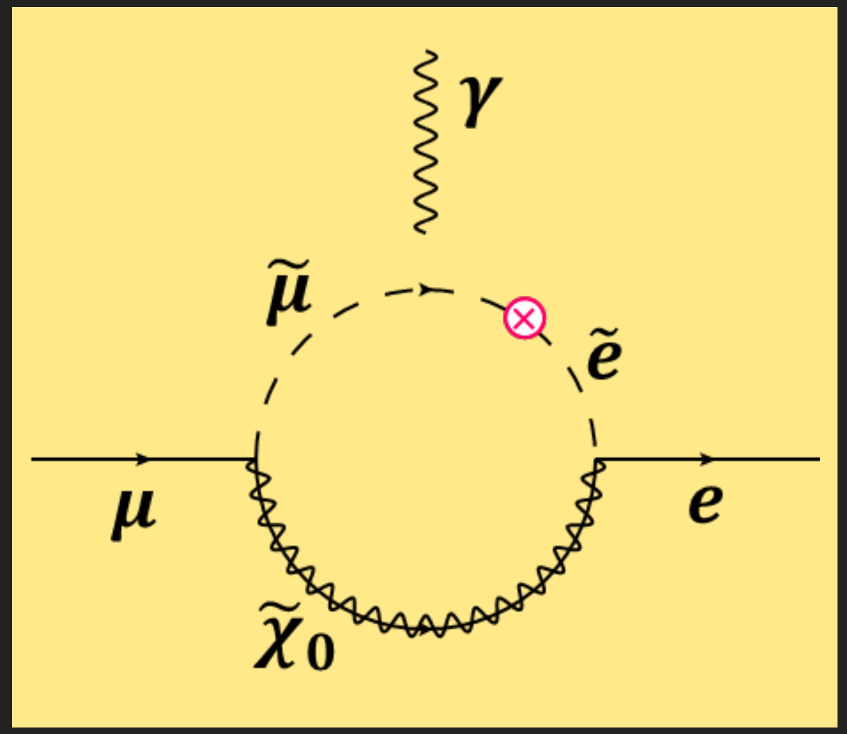
Flavor violation from
neutrino Yukawa

TeV scale physics
Dark Matter

POSSIBLE HINTS

muon g-2
lepton universality in B decays

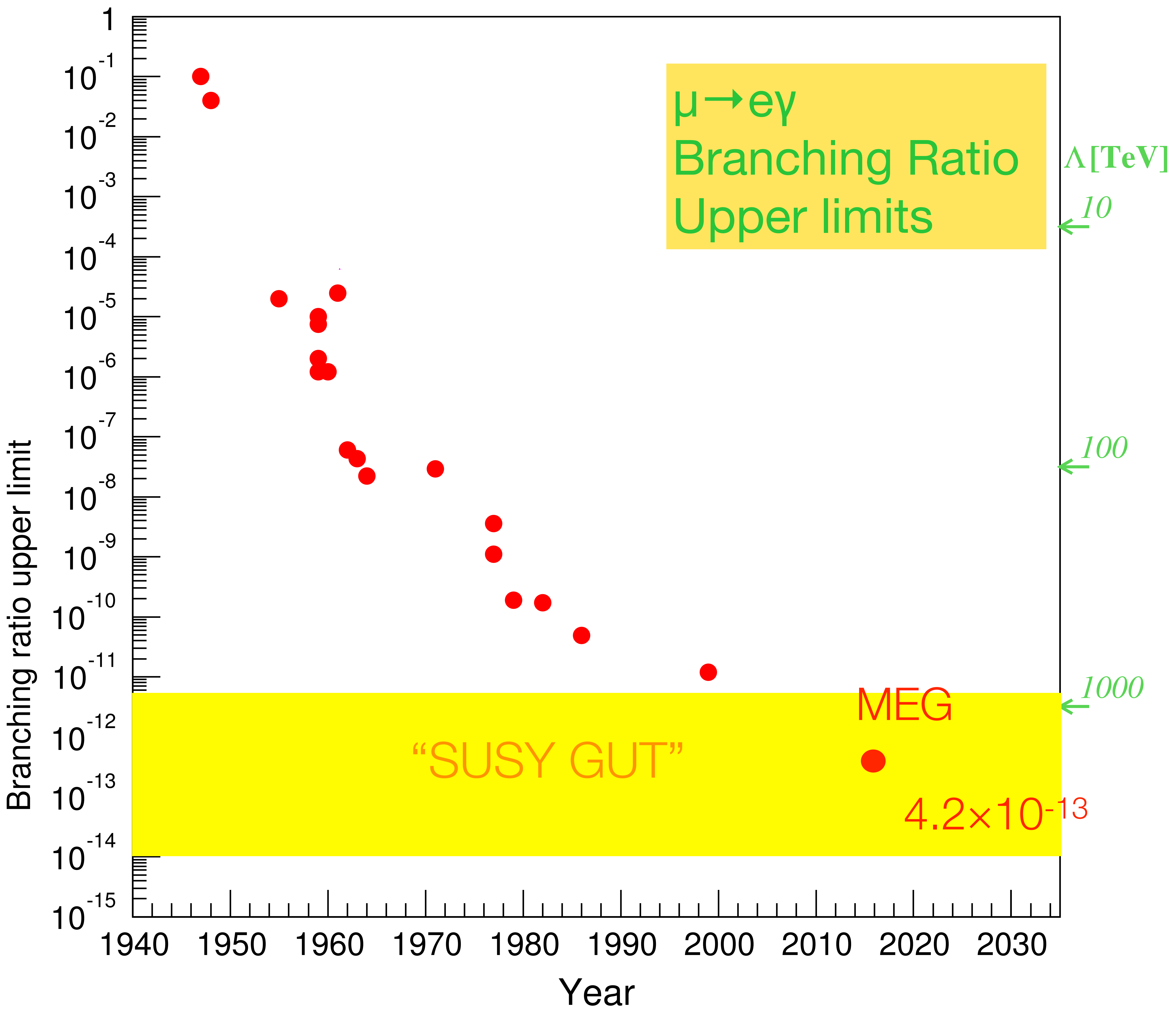
$$\mu \to e\gamma$$



$$\simeq 10^{-12}$$

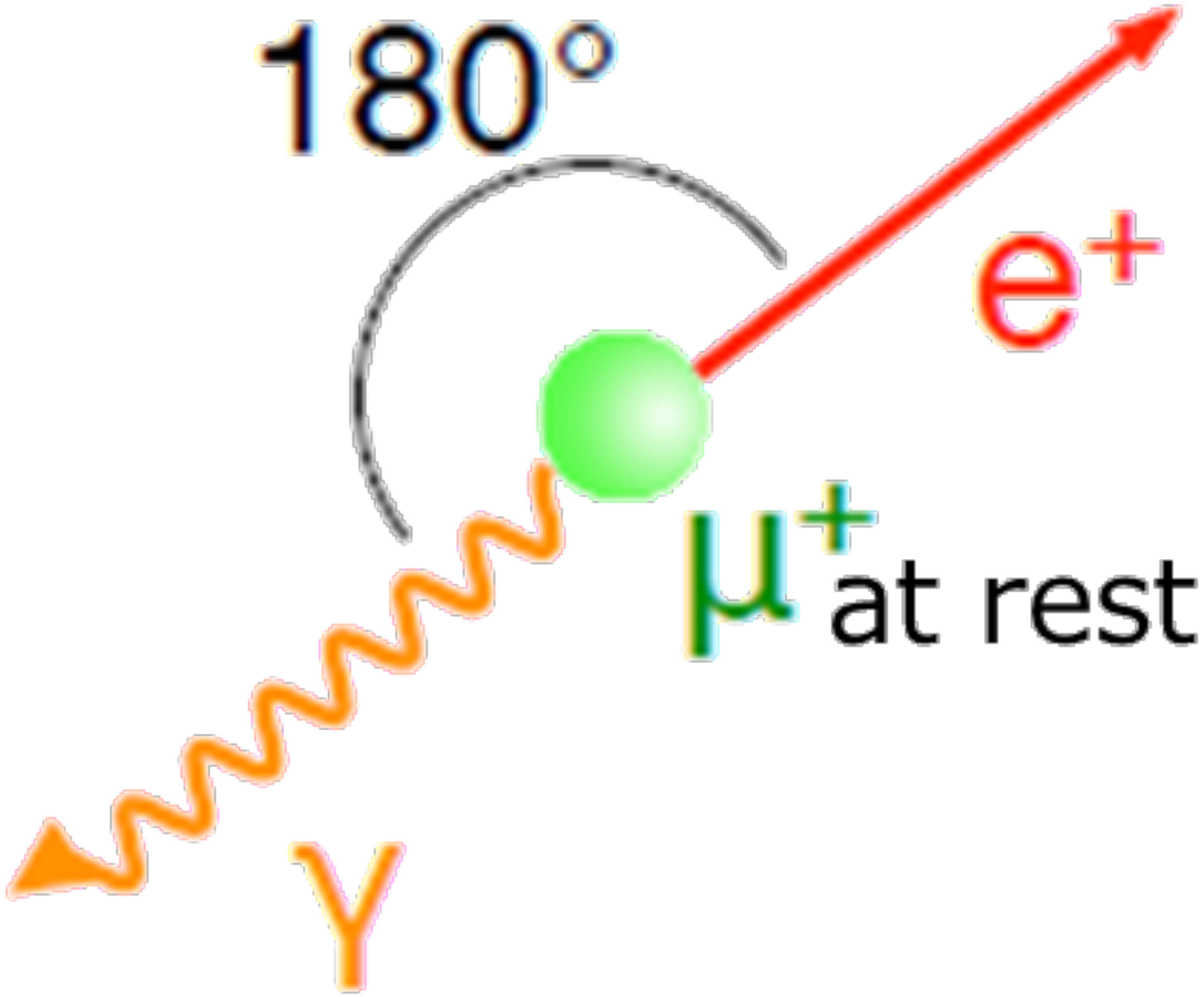
THE CURRENT STATUS:

$$\mu \to e\gamma$$



the smallest measured branching ratio for an elementary particle

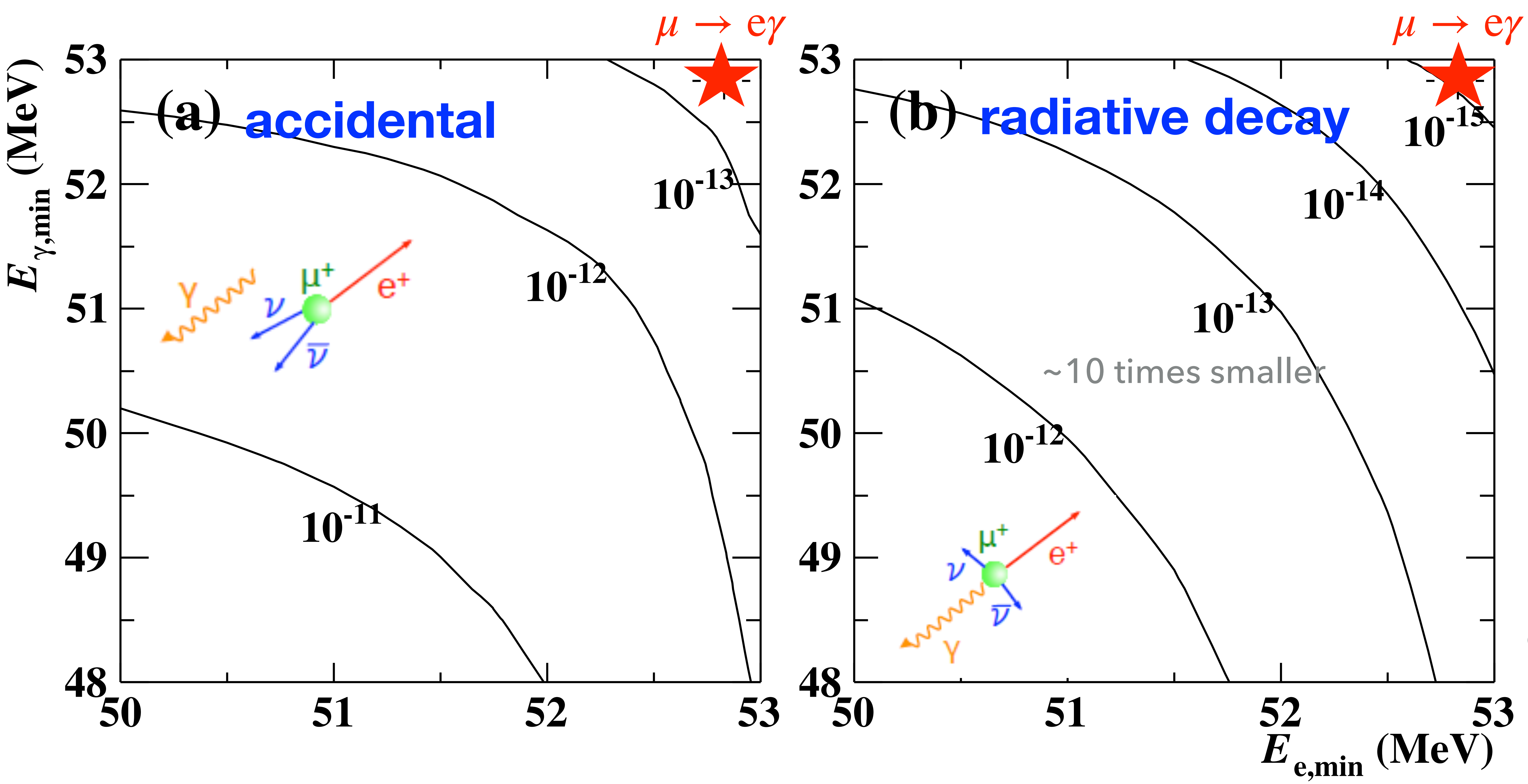
$\mu^+ \to e^+\gamma$ SEARCH REQUIRES LOTS OF MUONS



(1) If you want to find something at $<10^{-13}$, you need to observe at least $>10^{13}$ muons.

DOMINANT BACKGROUND IS ACCIDENTAL

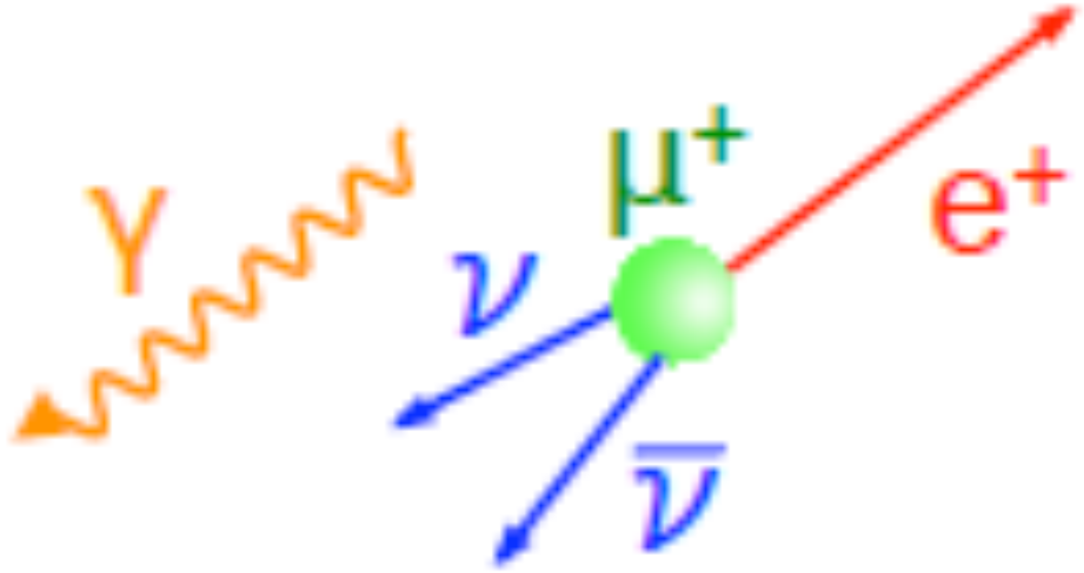
Shown are effective branching ratios for $(E_\gamma, E_e) > (E_{\gamma,min}, E_{e,min})$

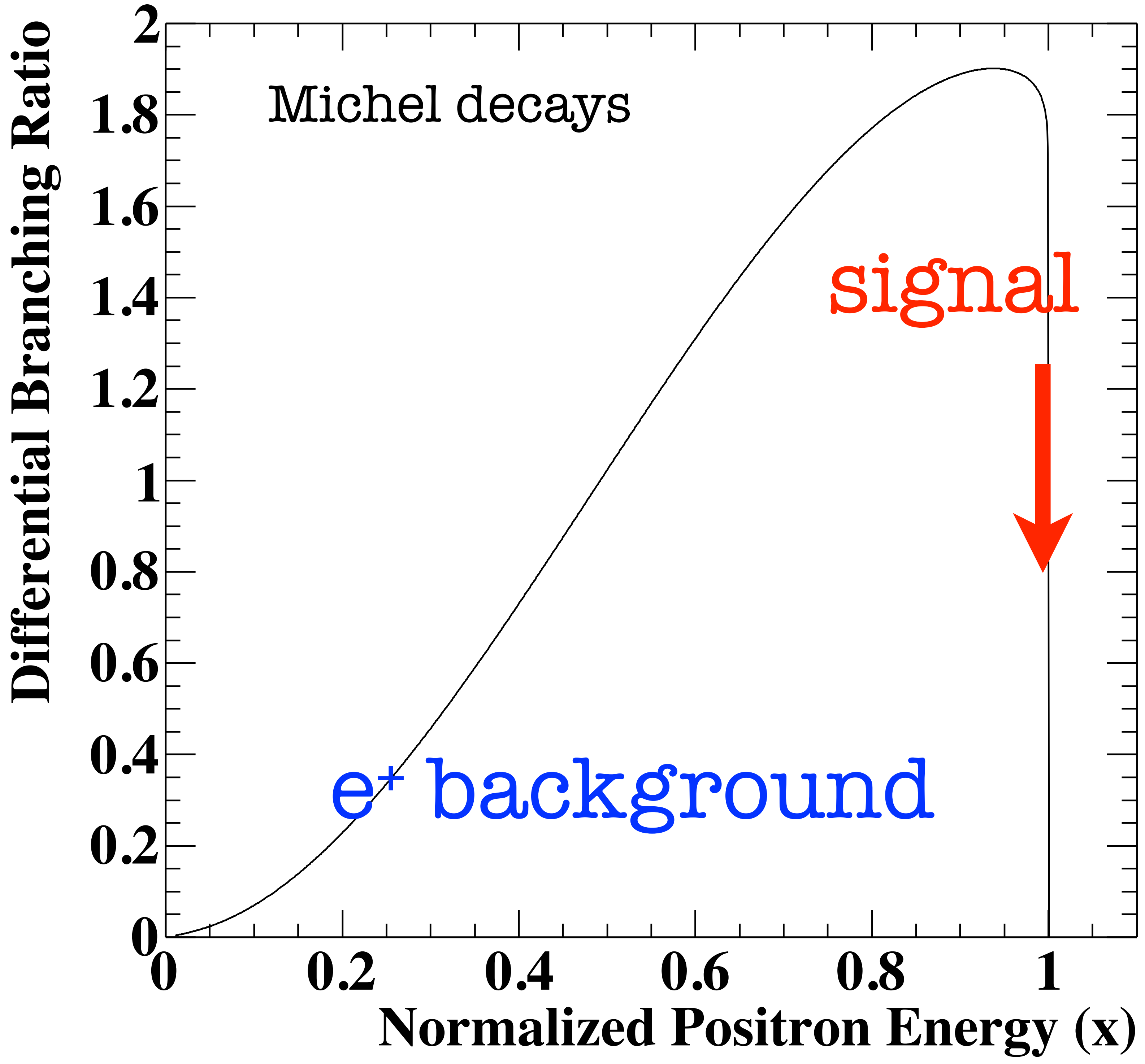


kinematic cuts:
$|t_{e\gamma}| < 0.25$ns,
$\cos\theta_{e\gamma} < -0.9996$

Accidental Background is dominant if you have good detectors

SUPPRESSING ACCIDENTAL BACKGROUND





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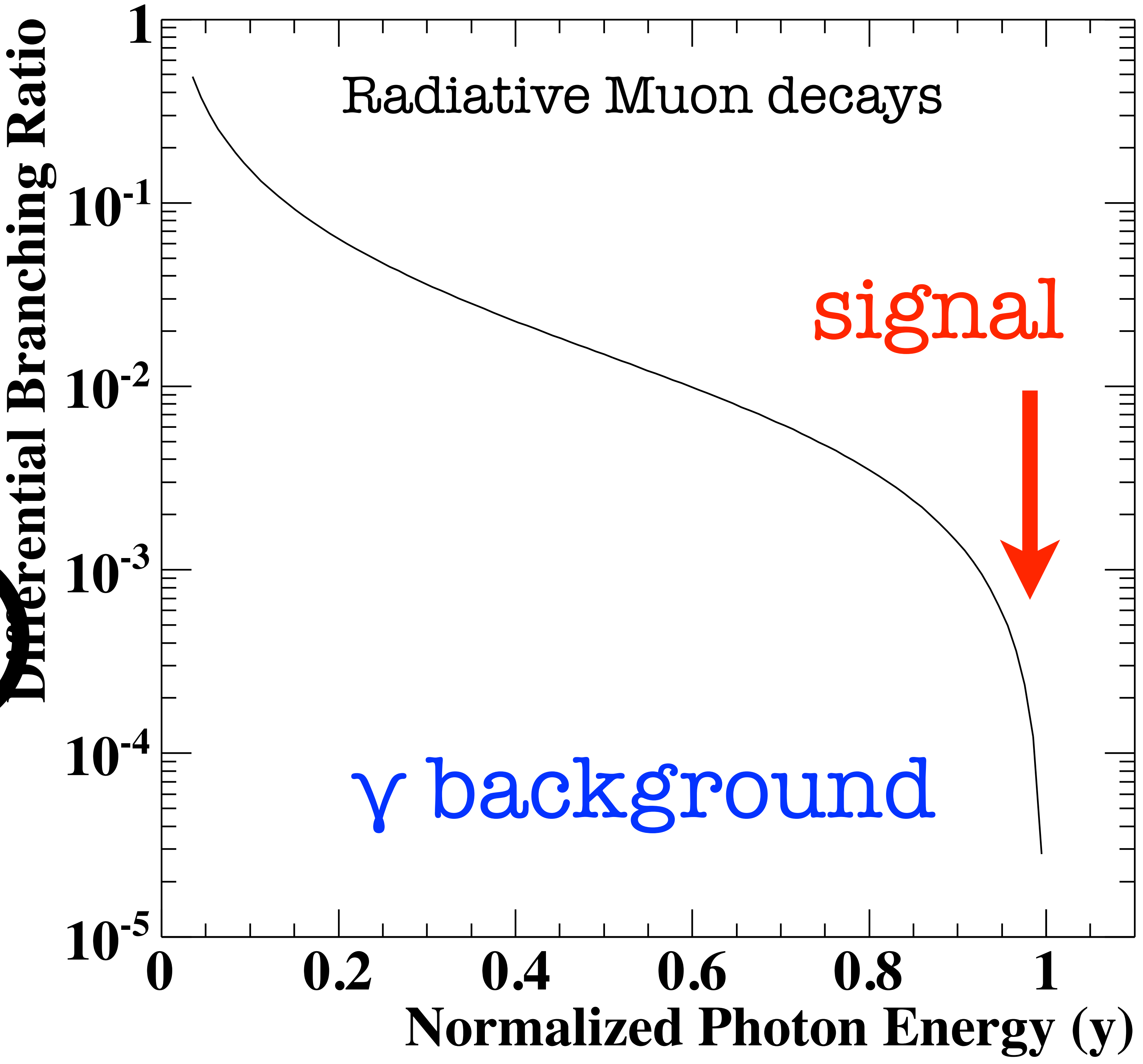


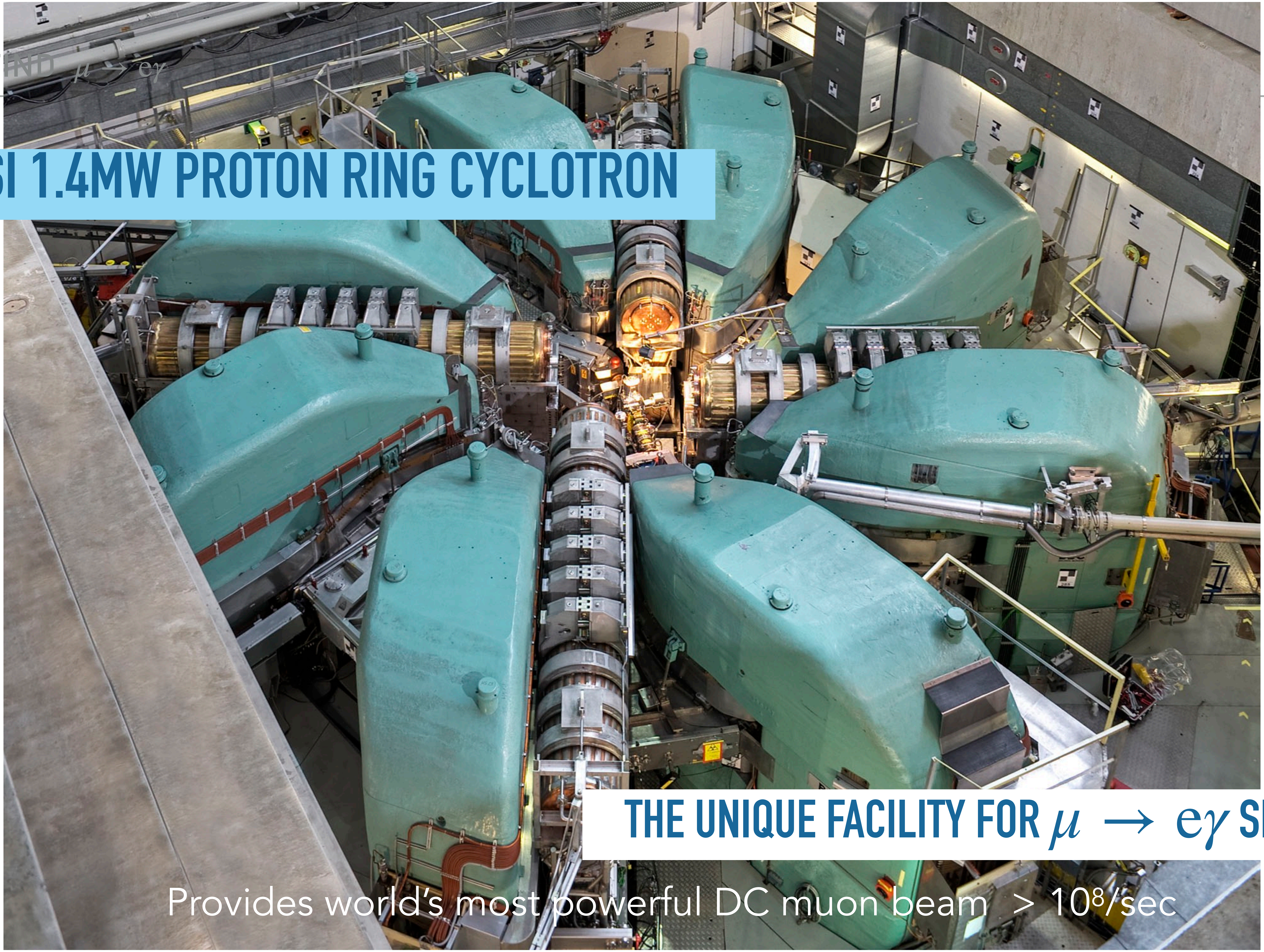
(2) must manage high rate e^+

(3) good γ resolution is most important !

THREE STRATEGIES FOR MEG / MEG II

1. High intensity (~10^8/sec) DC muon beam
   - **Paul Scherrer Institute's 1.4MW Ring Cyclotron**
2. e^+ spectrometer that can manage high rate
   - **Gradient Magnetic Field Spectrometer (COBRA)**
3. High resolution gamma-ray detector
   - **Liquid Xenon Scintillation Detector**

(1) PSI 1.4MW PROTON RING CYCLOTRON



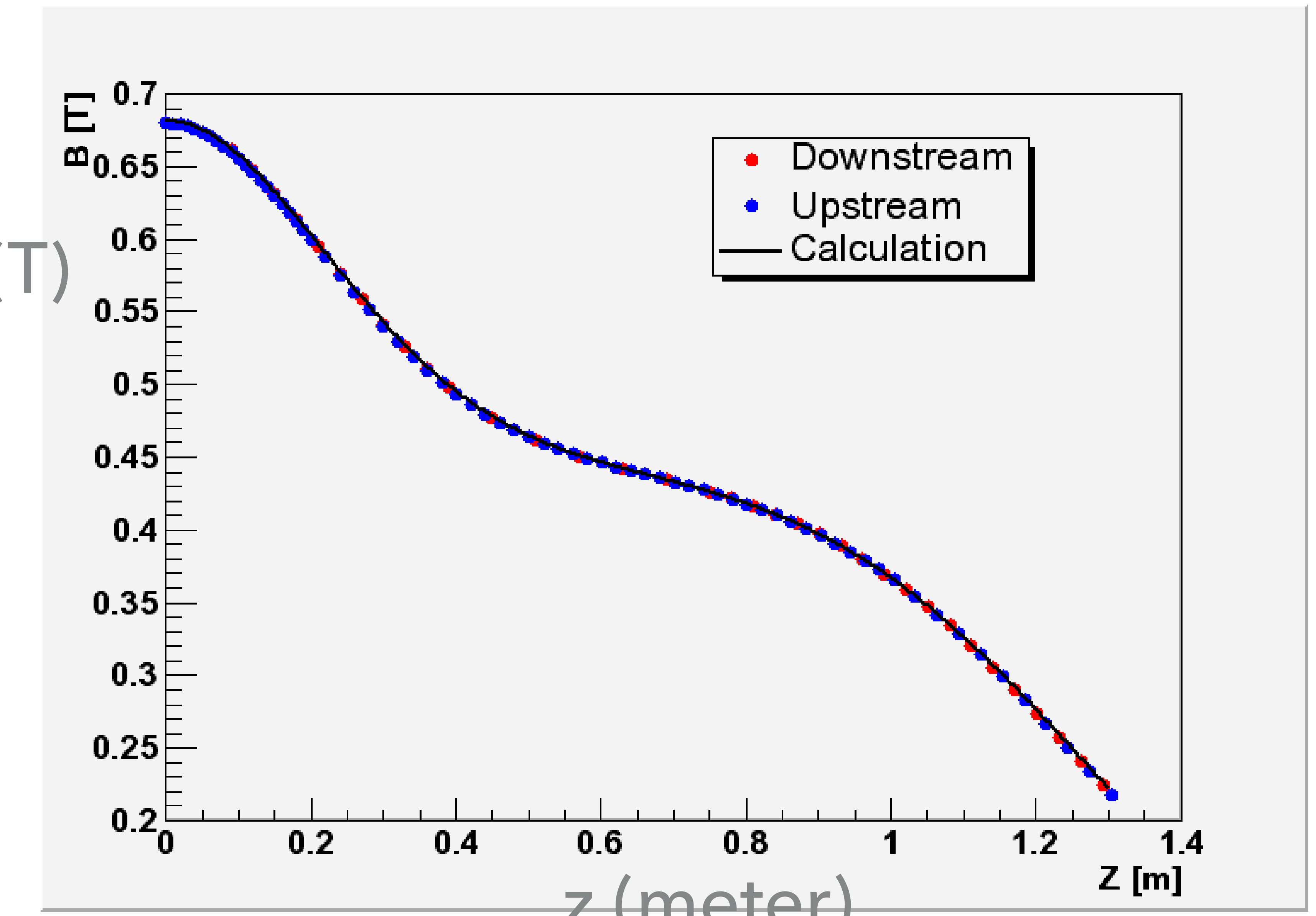
THE UNIQUE FACILITY FOR $\mu \to e\gamma$ SEARCH

Provides world's most powerful DC muon beam $> 10^8$/sec

(2) COBRA POSITRON SPECTROMETER

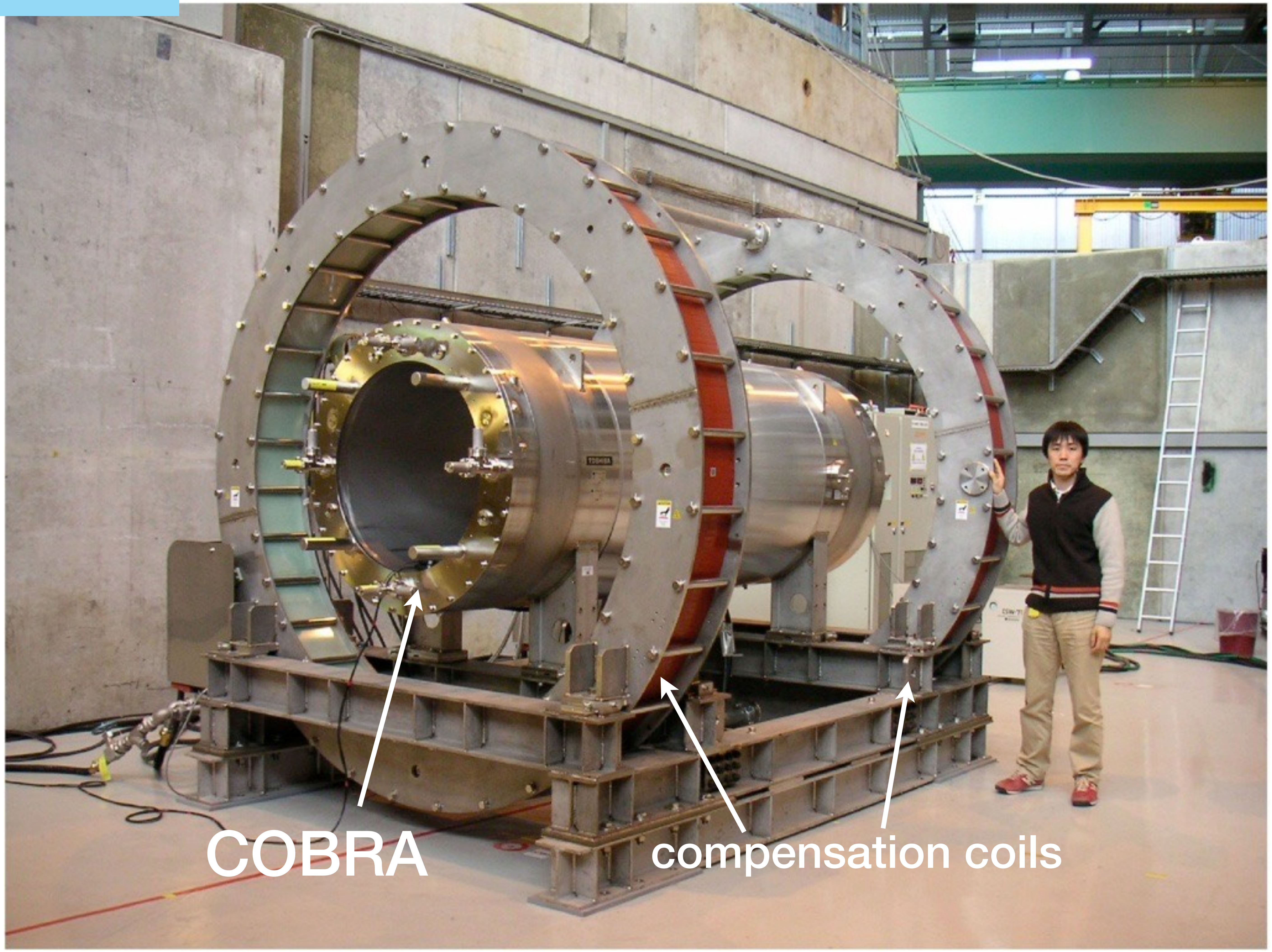
- Thin-wall SC solenoid with a gradient magnetic field: 1.27T center - 0.49T both ends

B (T)



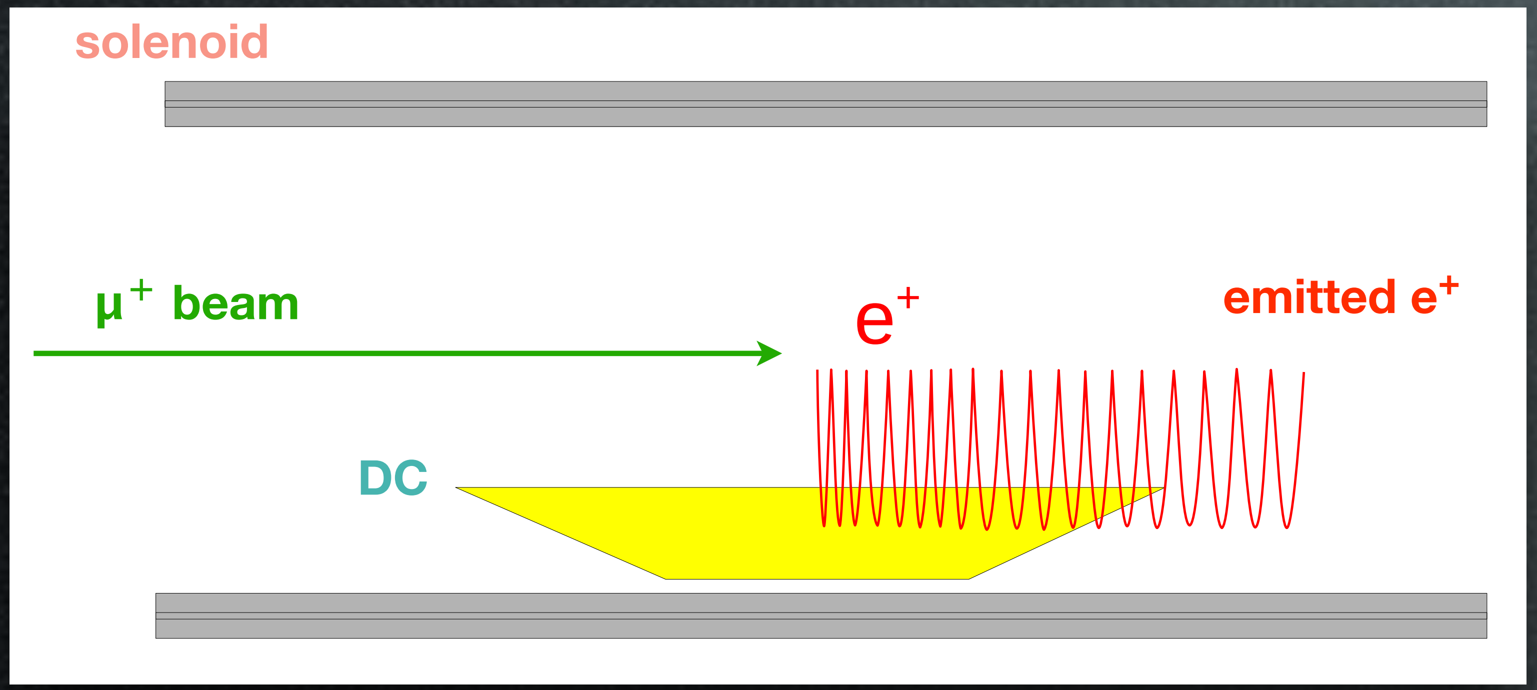
z (meter)

Gradient B field helps to manage high rate e^+

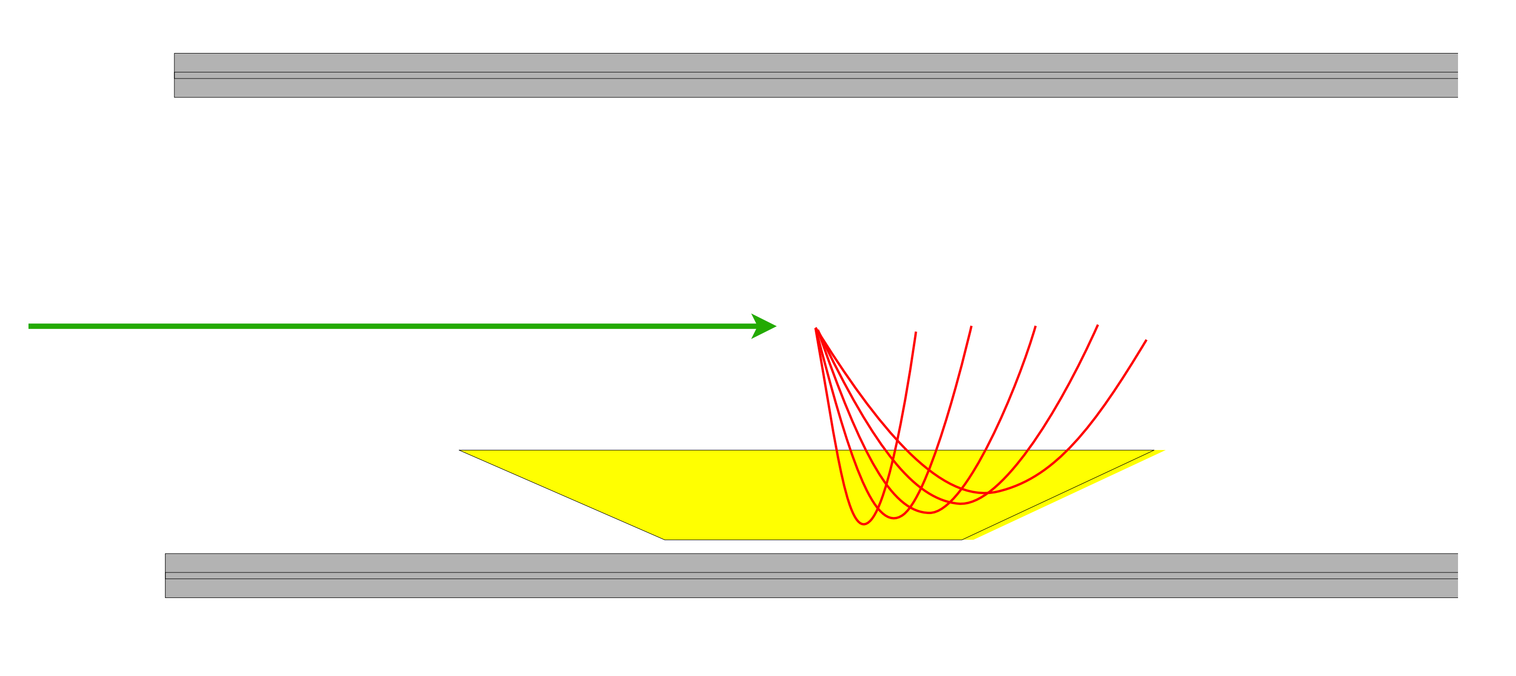


"COBRA Concept" to manage high rate positrons

COBRA = "COnstant Bending RAdius"

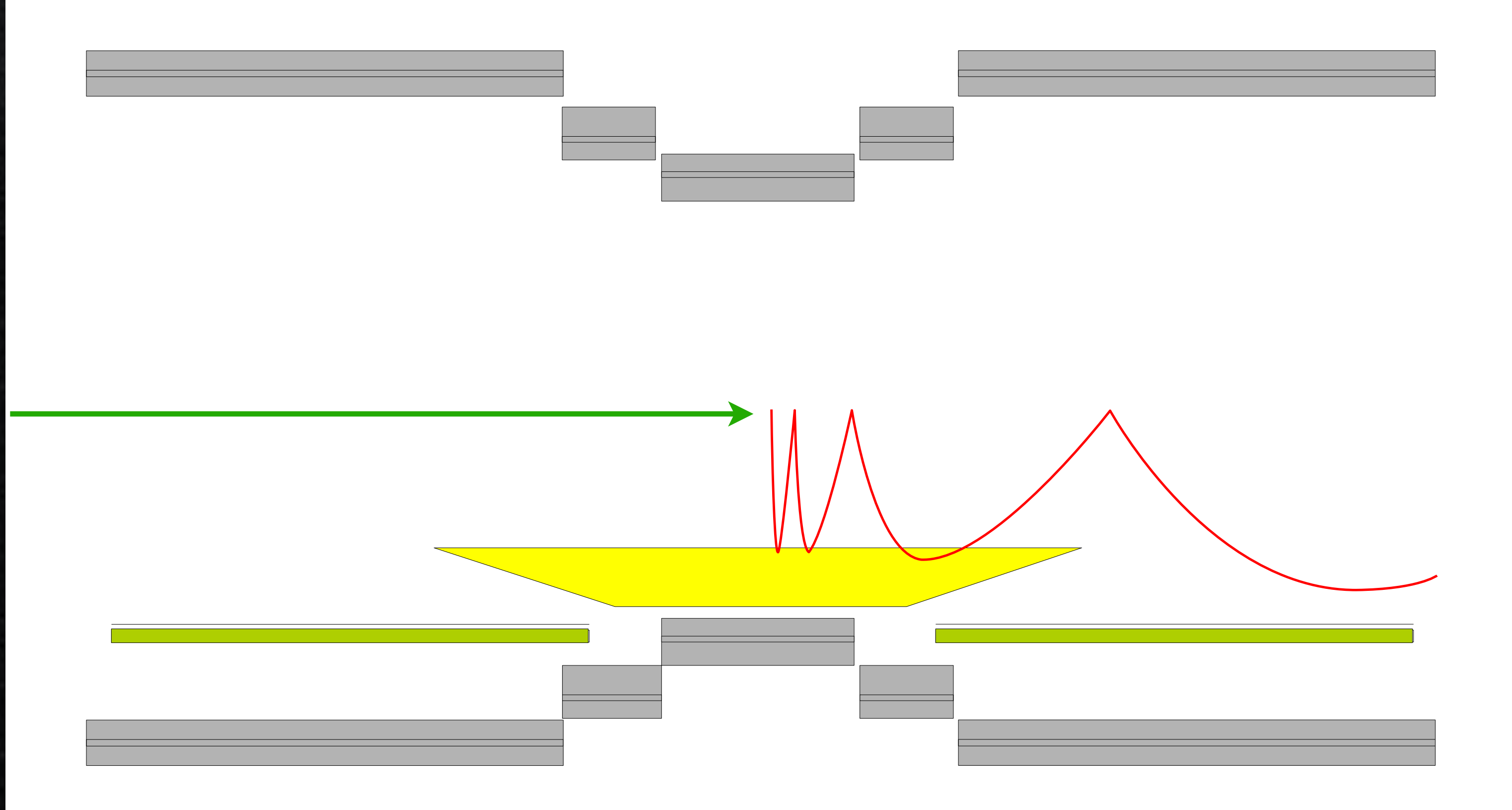


uniform B-field

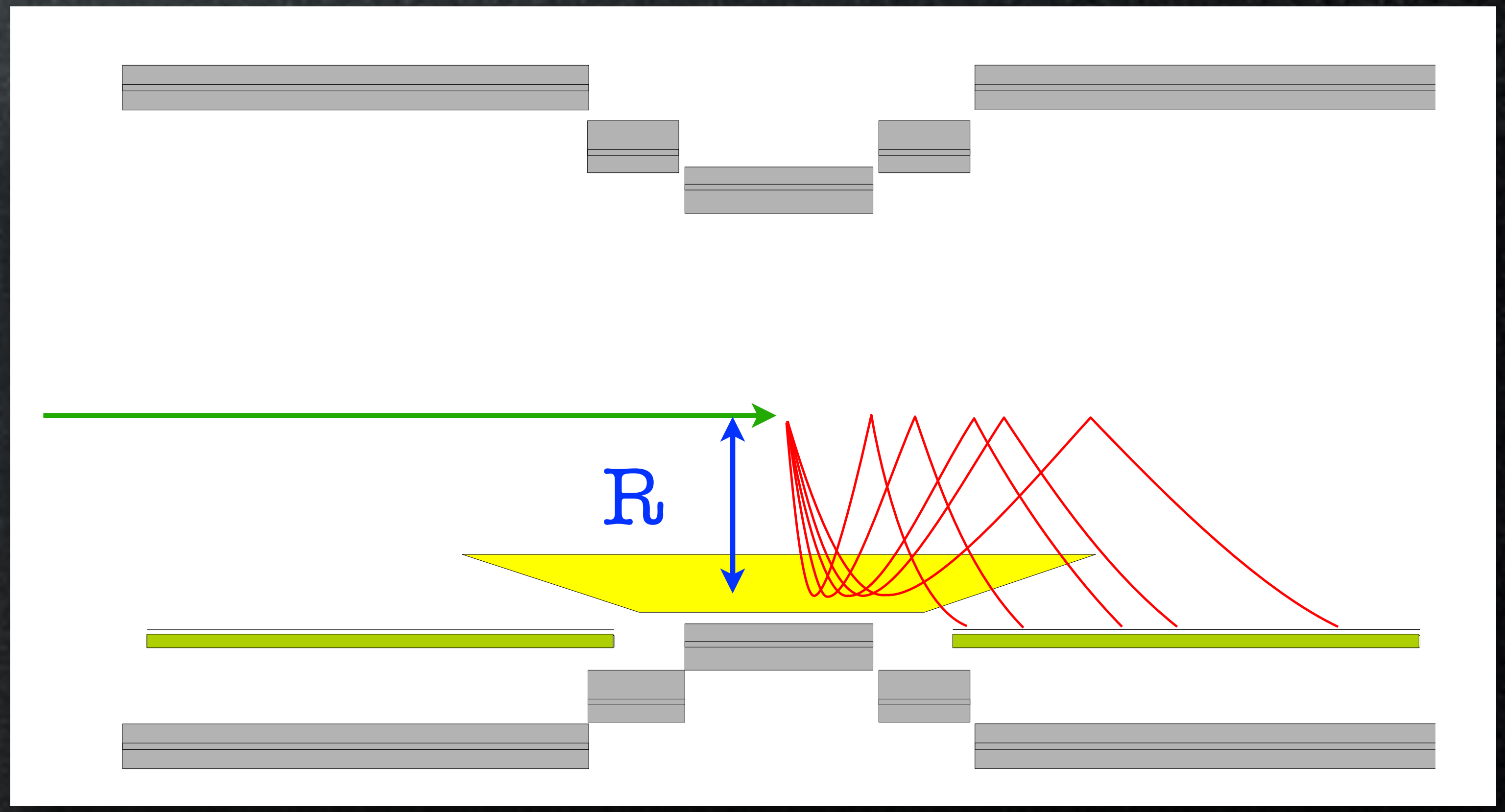


MEG I Detector

gradient B-field



Low energy positrons quickly swept out



Constant bending radius independent of emission angles

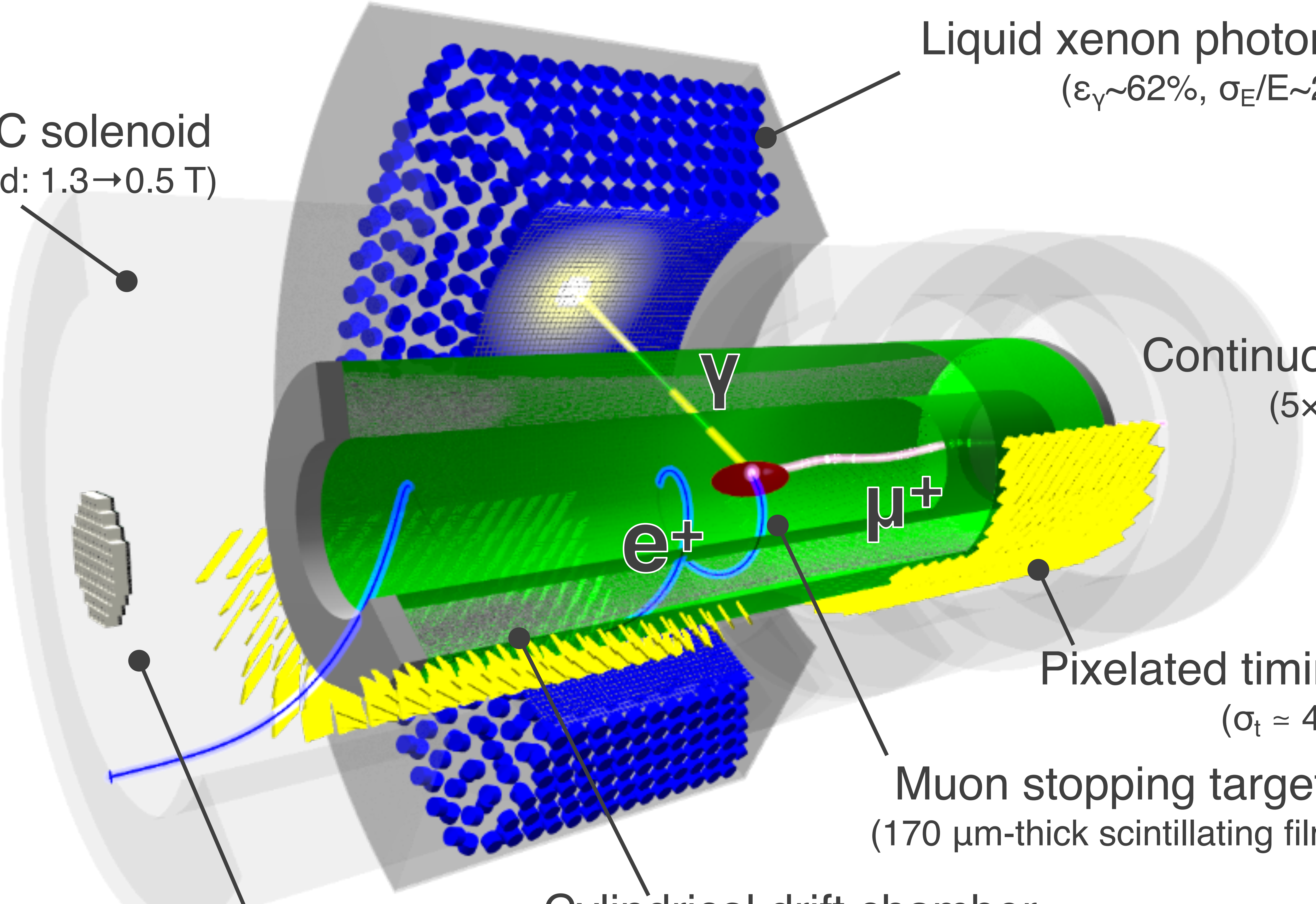
(3) 2.7TON LIQUID XENON PHOTON DETECTOR (LXE)

- Scintillation light from 900 liter LXe is detected by SiPM & PMTs mounted on all surfaces
- Fast response & high light yield provide good resolutions of energy, time, & position
- Gas/liquid circulation system to purify xenon
  - Ultimate uniformity & purity unachievable by crystal calorimeter

MEG II – UPGRADE OF MEG

higher intensity
higher resolution
higher efficiency

Search for $\mu^+ \to e^+\gamma$
down to
6×10^{-14}
(90% C.L. sensitivity)



arXiv:2310.11902
EPJ-C **78** (2018) 380

MEG II – UPGRADE OF MEG

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higher resolution
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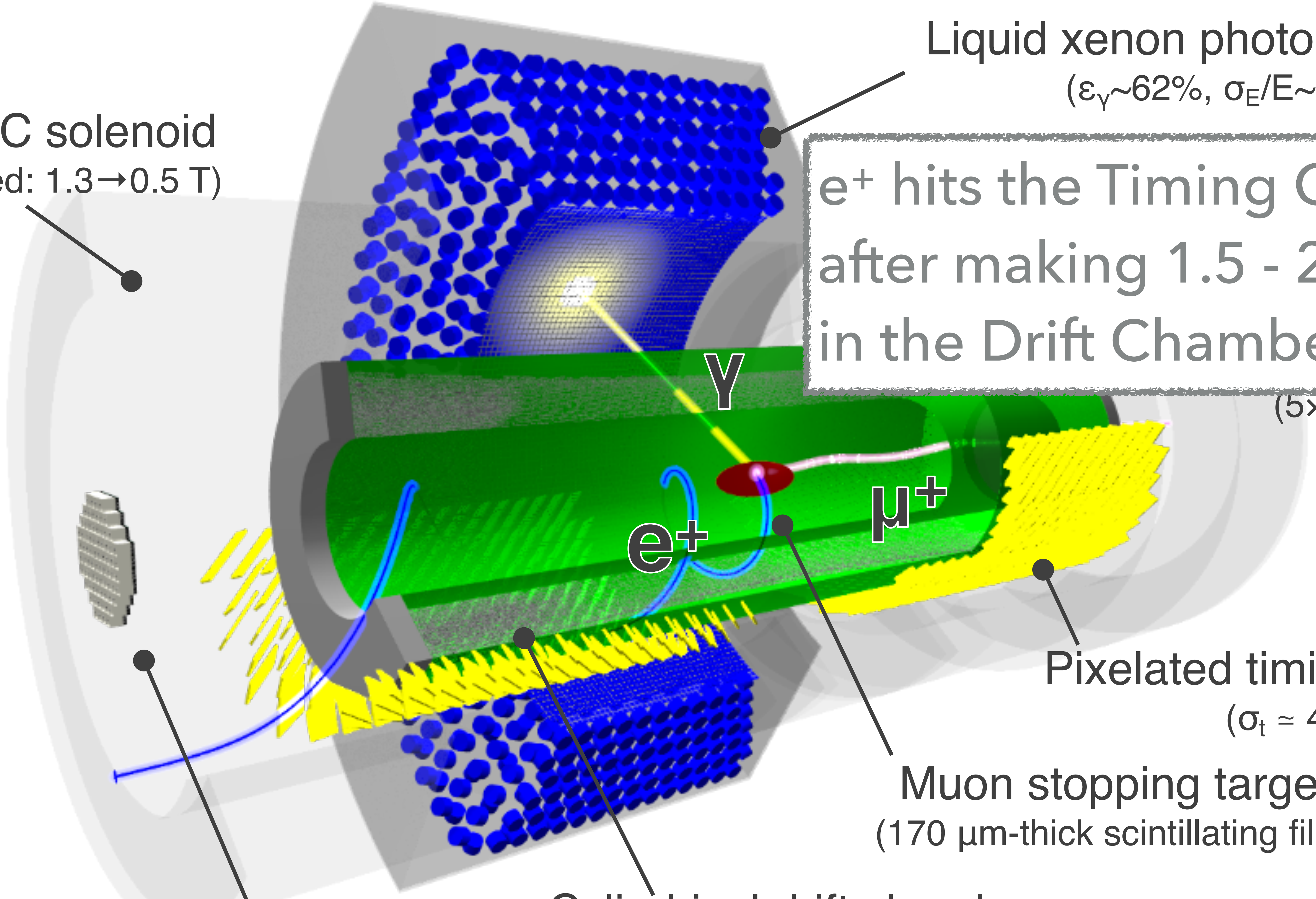

arXiv:2310.11902
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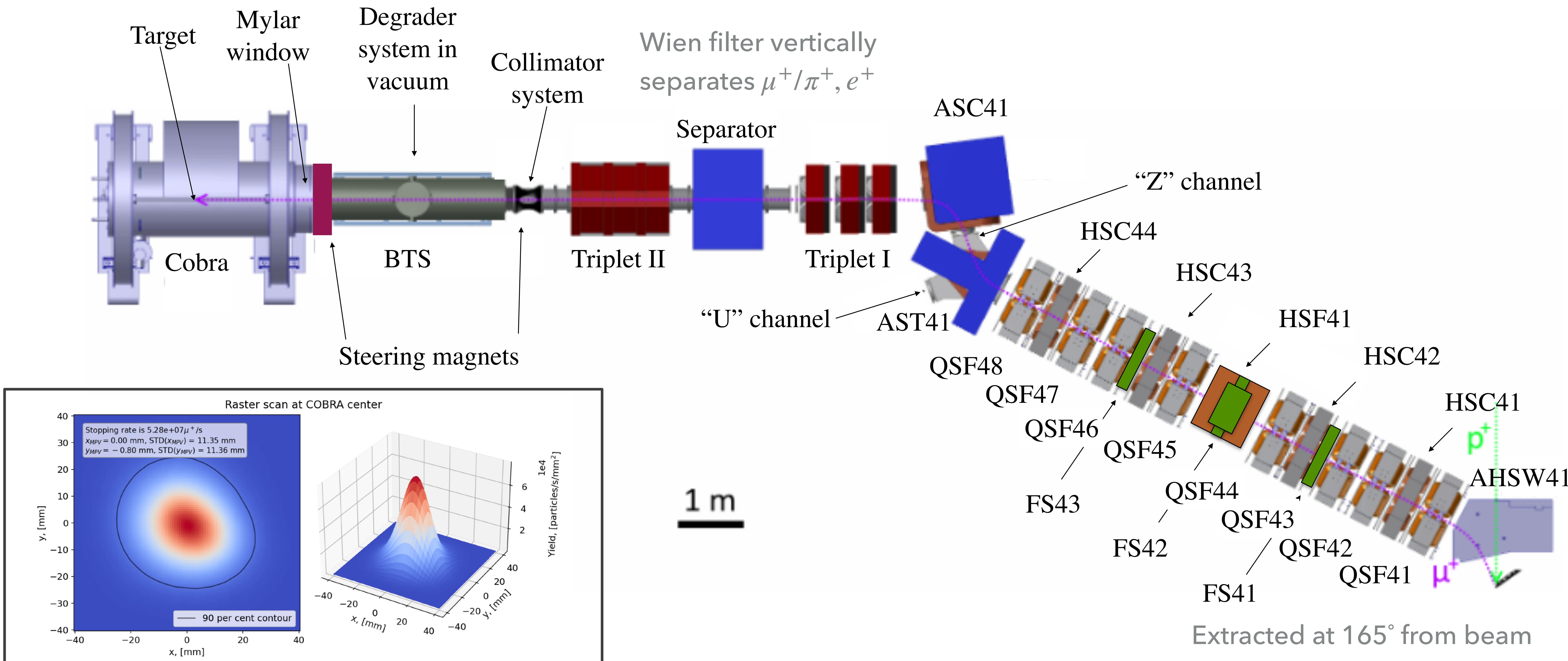
πE5 BEAMLINE



muon distribution at stopping target

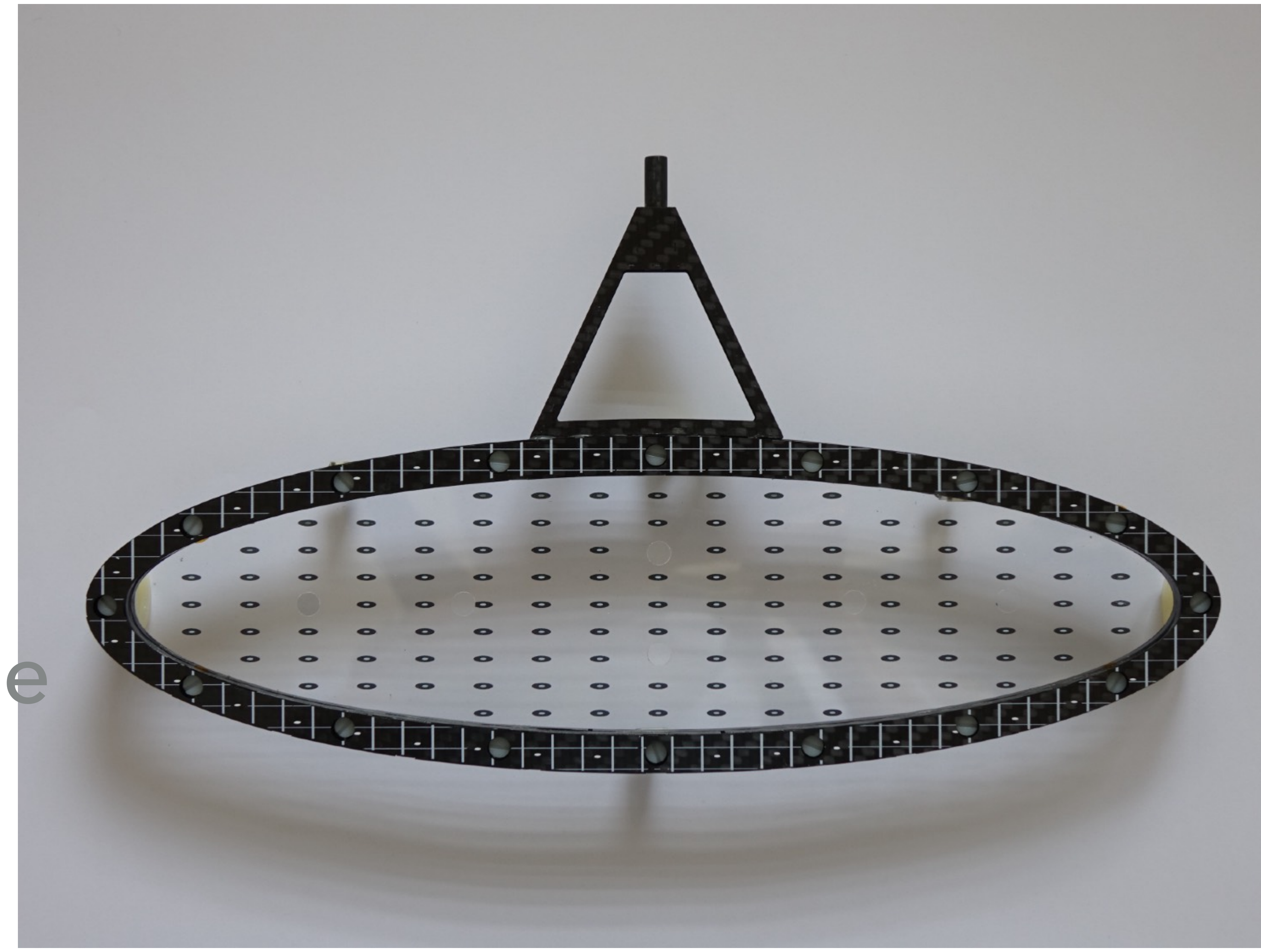
$\sigma \simeq 11$mm

Extracted at 165° from beam

Target TgE at 8° to beam

MUON STOPPING TARGET

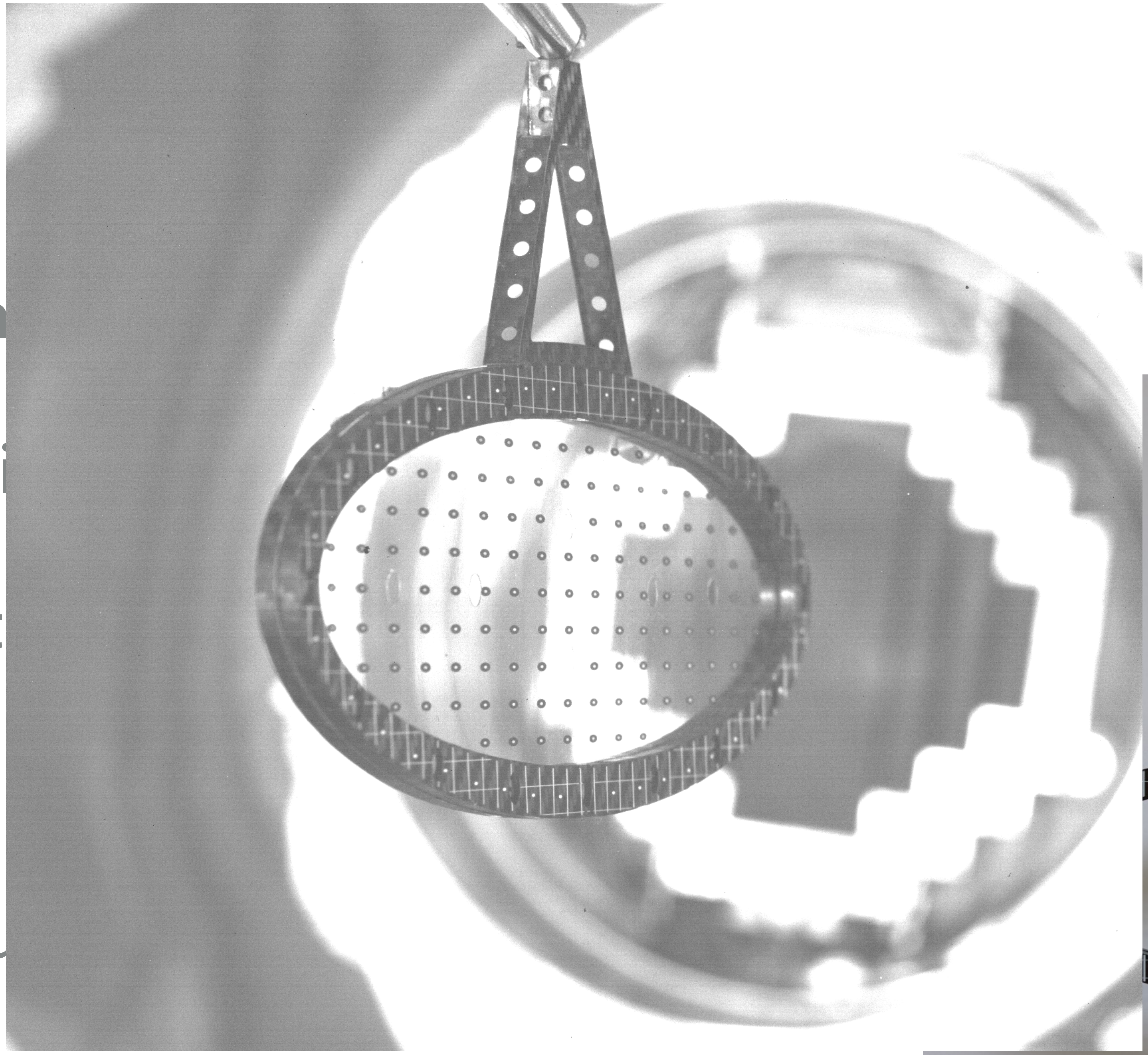
- 174μm thick (cf. MEG 205μm), 66mm height, 15° slanted, carbon fibre frame
- Displacement/deformation of target should be < 0.5mm
  - Dominant systematic error (5% in BR) of MEG
  - Six holes - systematic checks by e^+ tracking
  - NEW: photogrammetric survey by two cameras
    - good within 100μm normal to the target plane

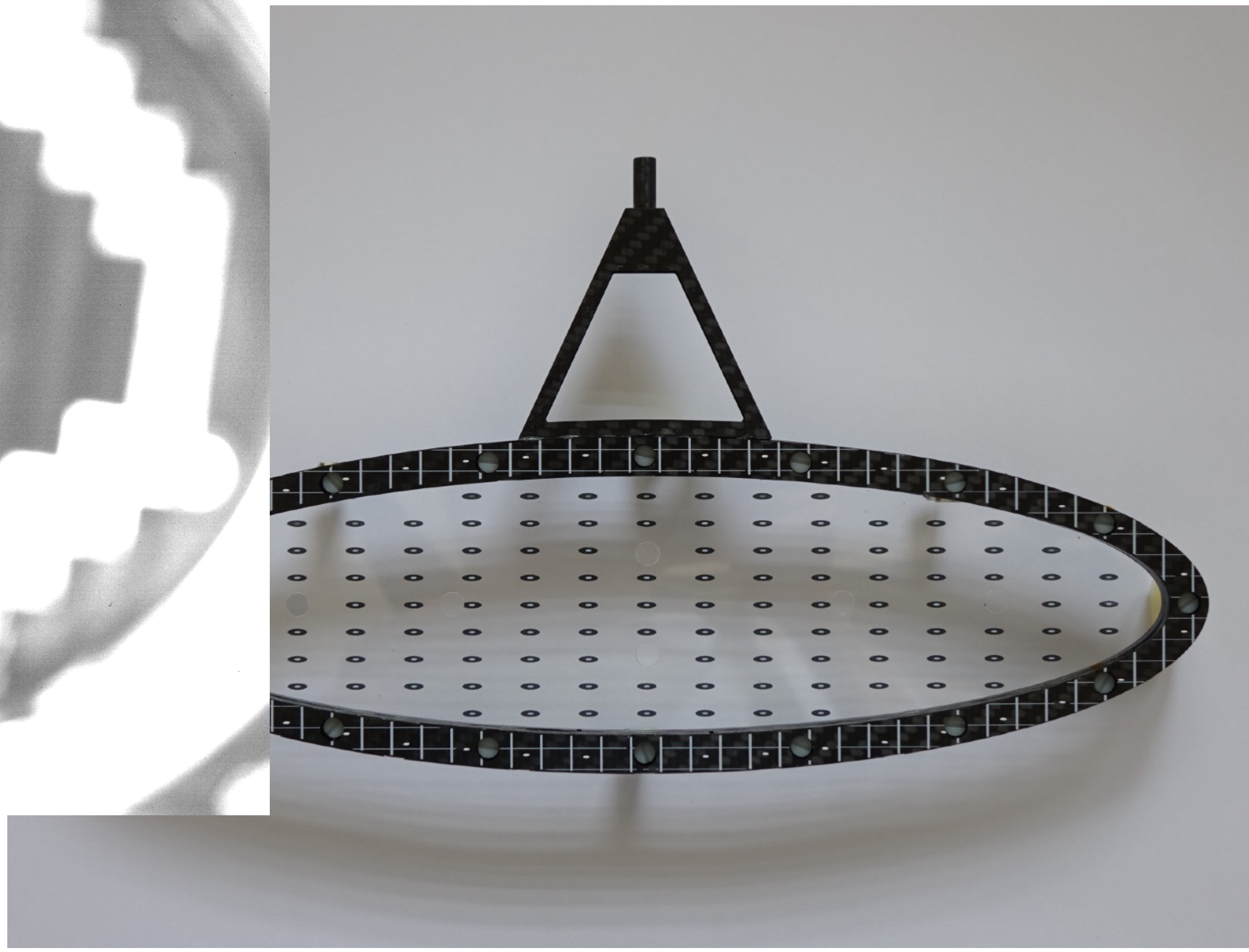


Nucl. Instrum. Methods A 944, 162511 (2019); Rev. Sci. Instrum. 92(4), 043707 (2021)

MUON STOPPING TARGET

- 174μm thick (cf. MEG carbon fibre frame
- Displacement/deform
  - Dominant systemati
  - Six holes - systemat
  - NEW: photogramm
    - good within 100μ





Nucl. Instrum. Methods A 944, 162511 (2019); Rev. Sci. Instrum. 92(4), 043707 (2021)

CYLINDRICAL DRIFT CHAMBER (CDCH)

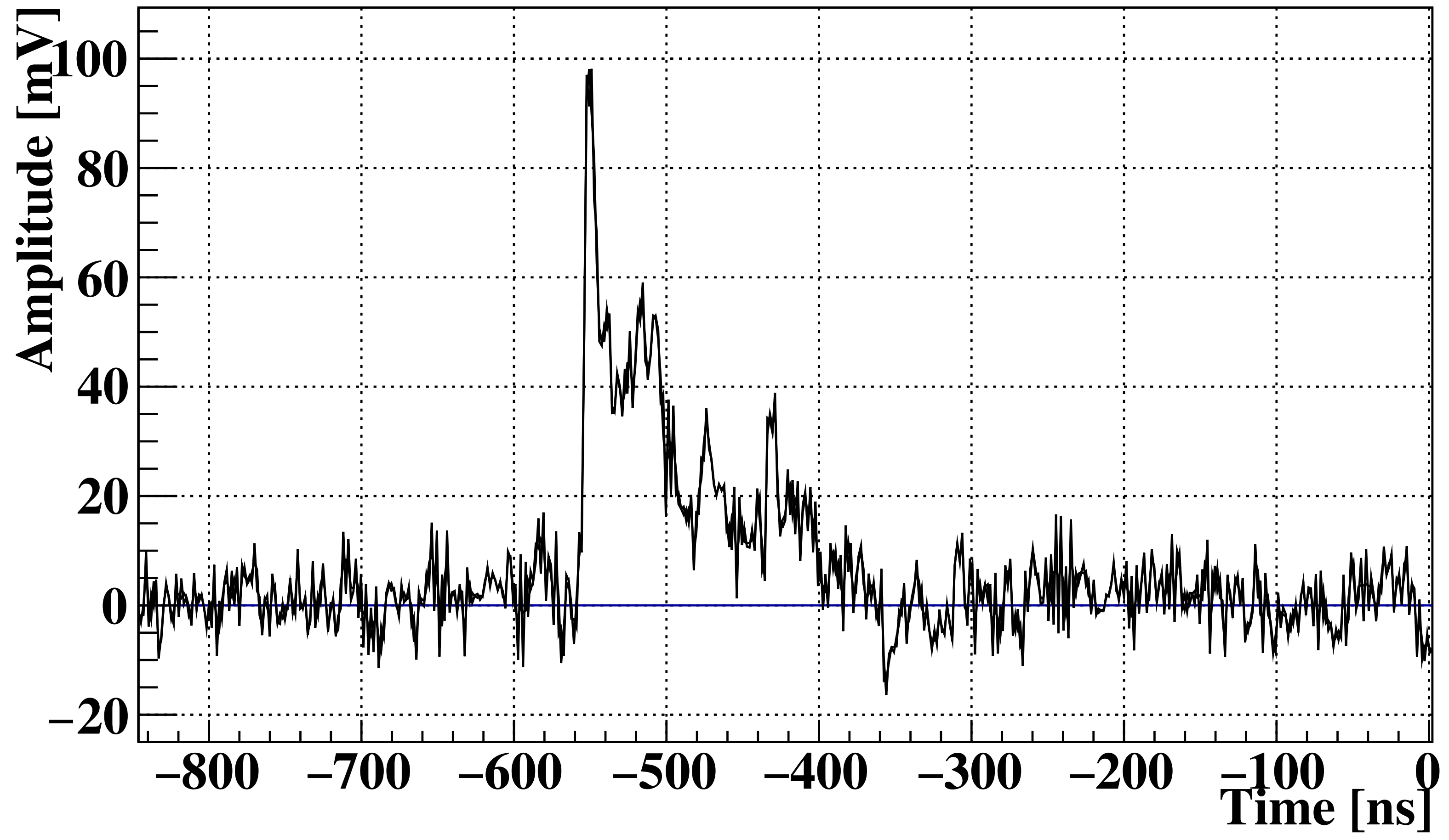
arXiv:2310.12865

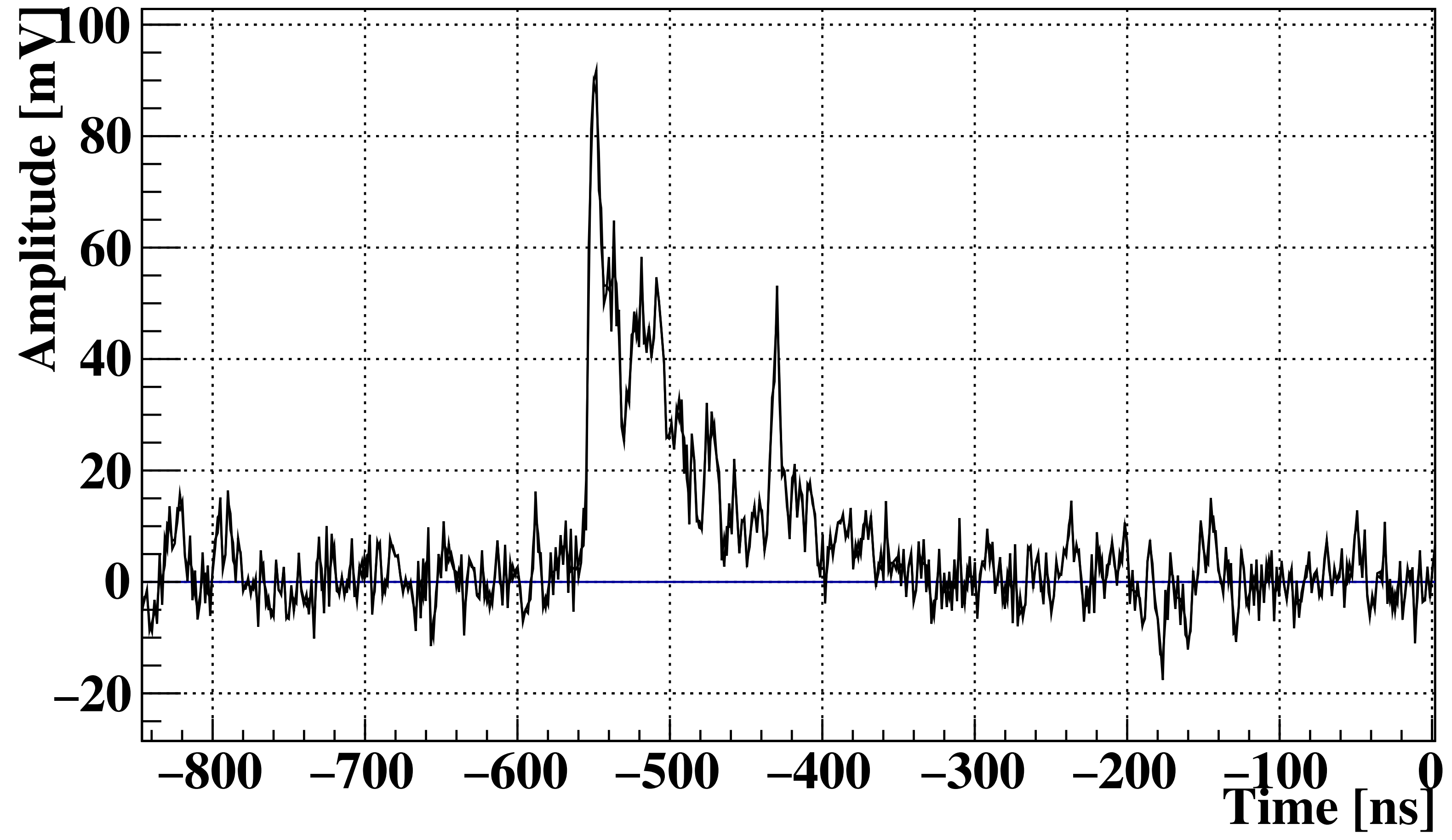
CYLINDRICAL DRIFT CHAMBER (CDCH)

- Low material: $1.58 \times 10^{-3} X_0$ /e+-turn (cf. $2.0 \times 10^{-3} X_0$ for MEG)
  - He-Isobutane (90:10) with oxygen 0.5% + isopropyl alcohol 1.5%
    to avoid corona discharge & current spikes
  - Radius of 17 - 29cm, 1.93m long
  - 9 layers of drift cells of 6 - 9mmø with stereo angles of 6.0 - 8.5°
  - 1,728 Au-plated W anode wires (20μm), of which 1,200 within acceptance are readout
  - Ag-plated Al cathode/guard wires (40μm)
    Earlier corrosions problems solved by maintaining dry atmosphere
  - innermost cells at > 1MHz for $5 \times 10^{7} \mu$/sec, max occupancy ~25%
  - ~110μm position resolution

CDCH – HIT DETECTION

- Convolutional Neural Network to help identify
  - Remove coherent noise
  - Obtain first cluster arrival time
    - Tracking efficiency improved by 26%

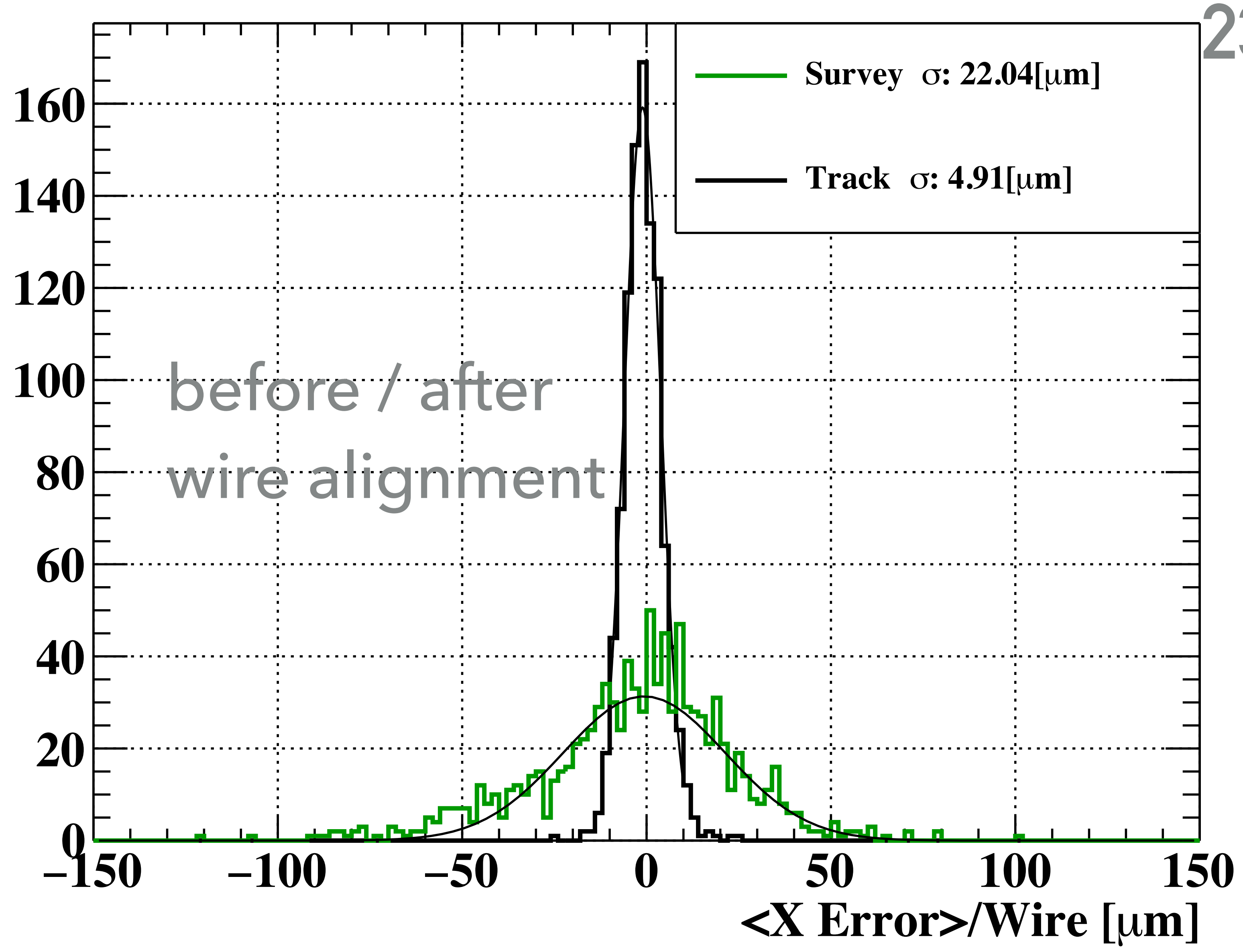


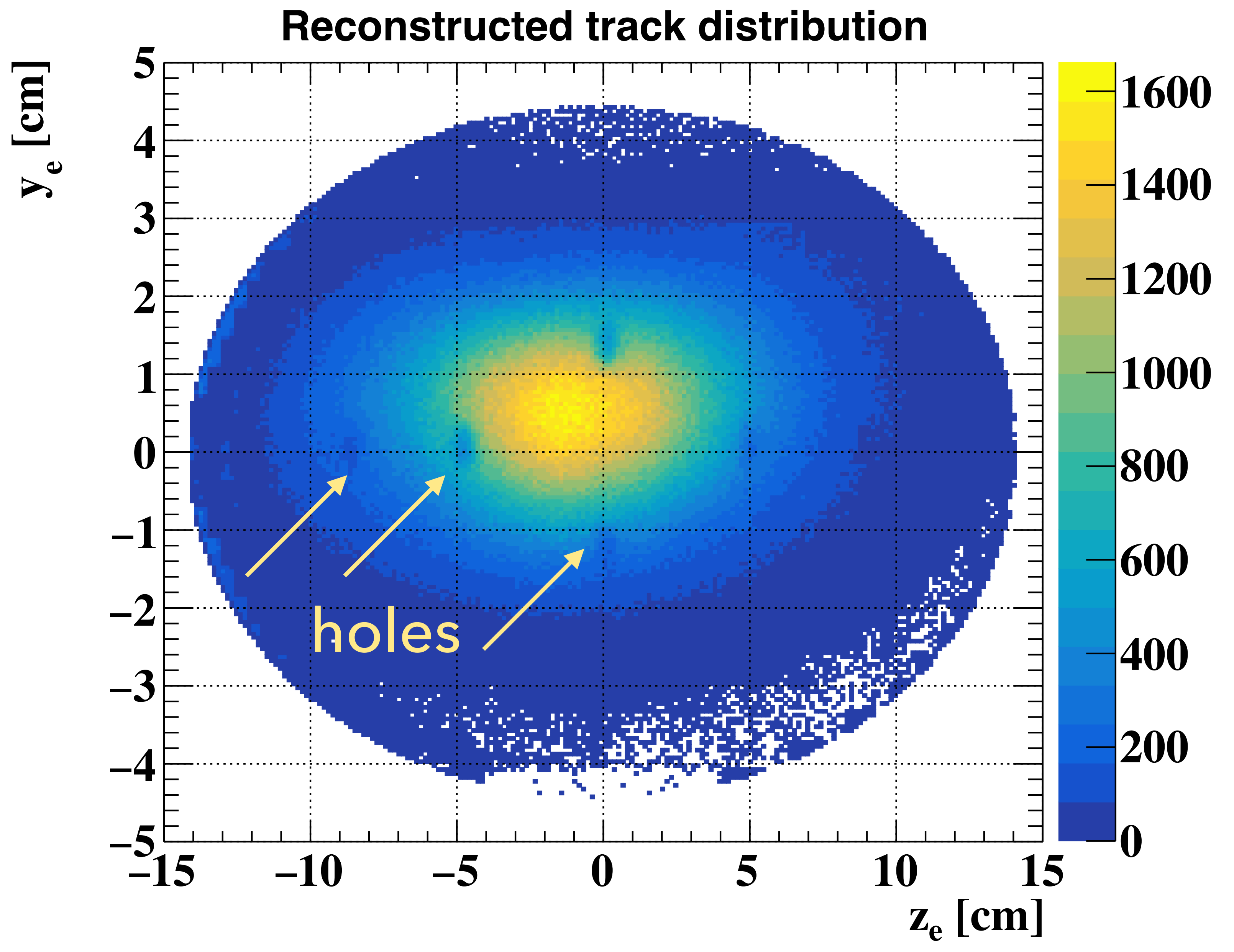


(distance of closest approach)

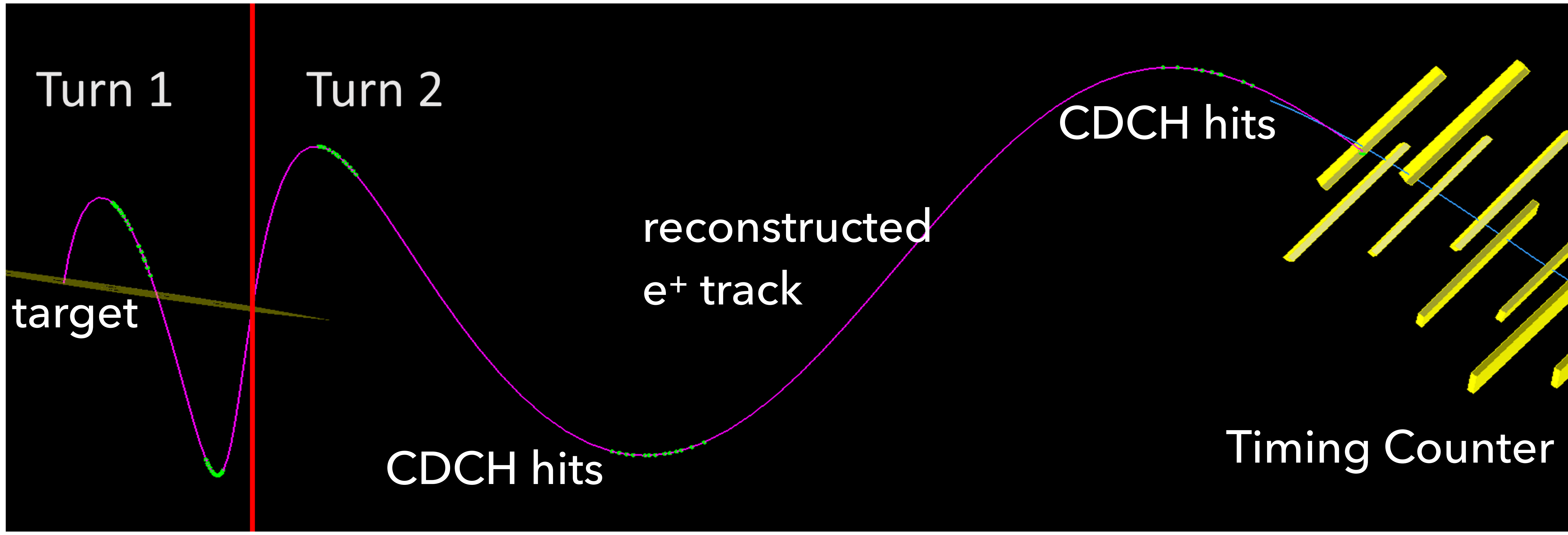
ALIGNMENTS

- CDCH wire alignment by Michel positrons
  - 22 - 25µm survey errors → < 5µm
- CDCH - Magnetic Field Map
  - Non-uniform field could affect E_{e^+} measurement
    $\delta_{E_e} < 10$ keV
- CDCH - Target
  - Target hole reconstruction - 100µm uncertainty
    Rotation < a few mrad
- CDCH - LXe photon detector ≤ 1mm
  - Cosmic-rays penetrating both CDCH & LXe

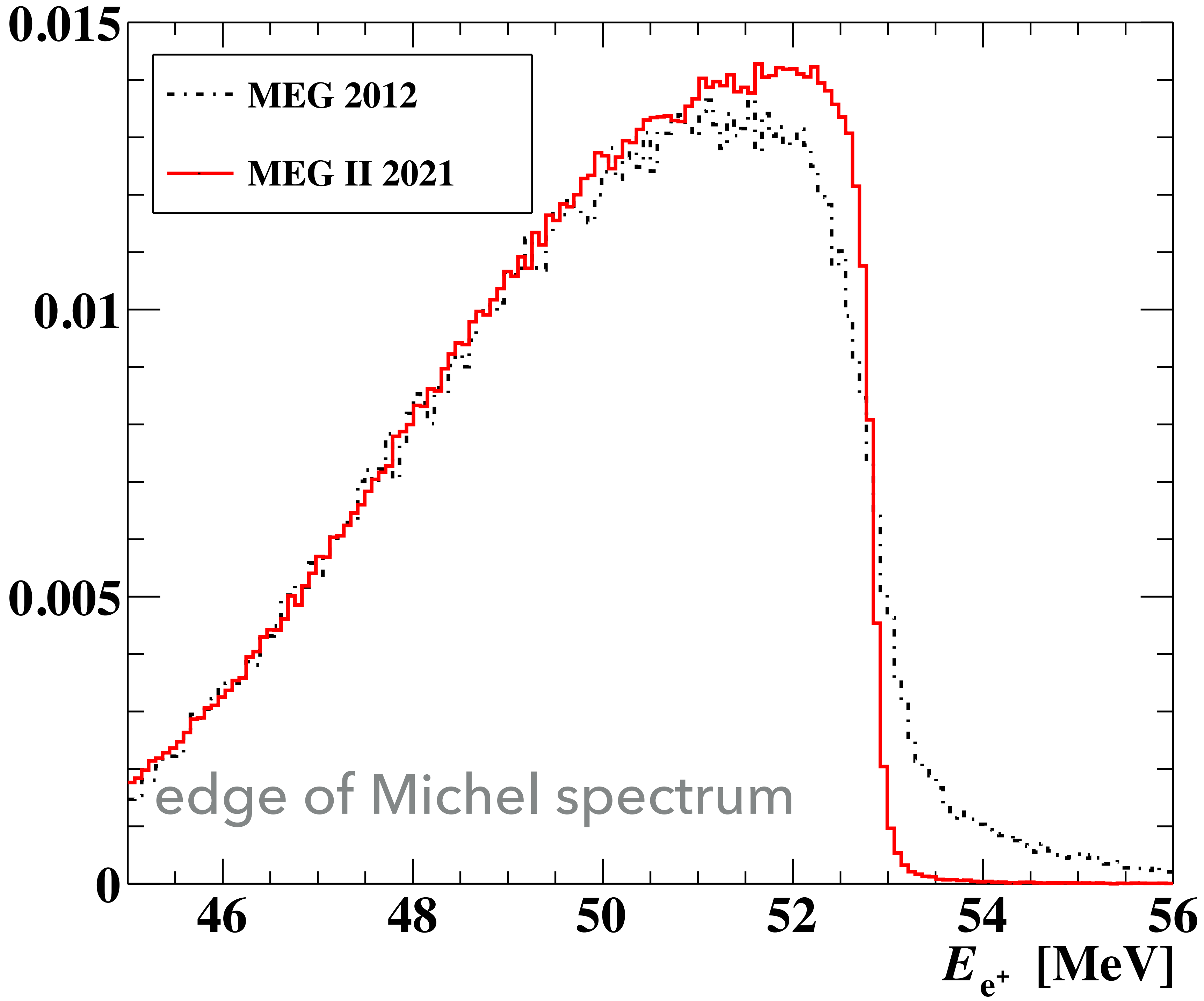




CDCH - PERFORMANCE



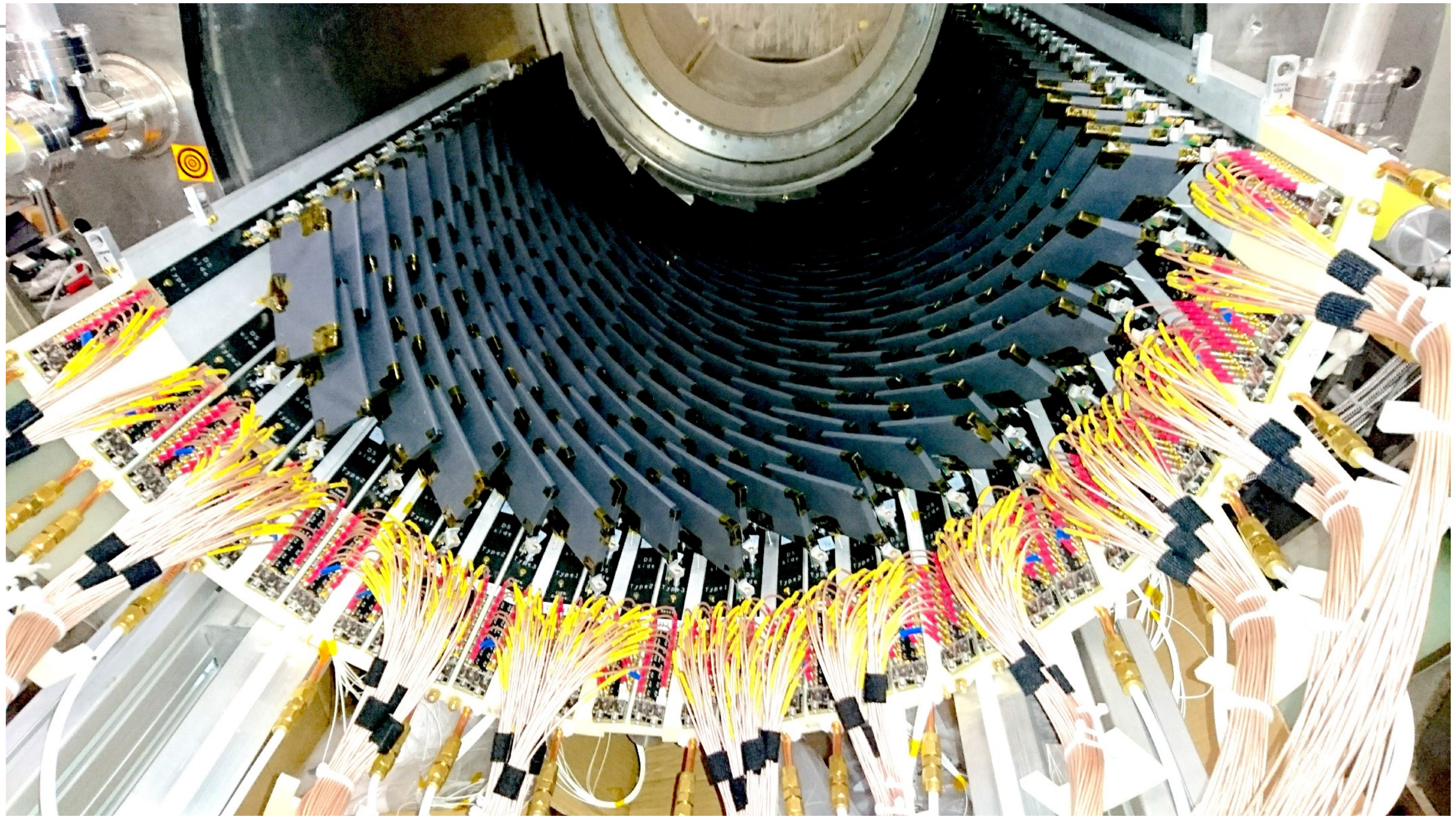
- Double-turn method for evaluation
- Michel edge evaluation
  - Improved by CNN DOCA reconstruction
  - $\sigma_{E_e^+} \approx 90$ keV (cf. MEG 320 keV)
  - Efficiency CDCH-pTC = 67% @$3 \times 10^7 \mu$/sec
    - Less material & better tracking than MEG (30%)



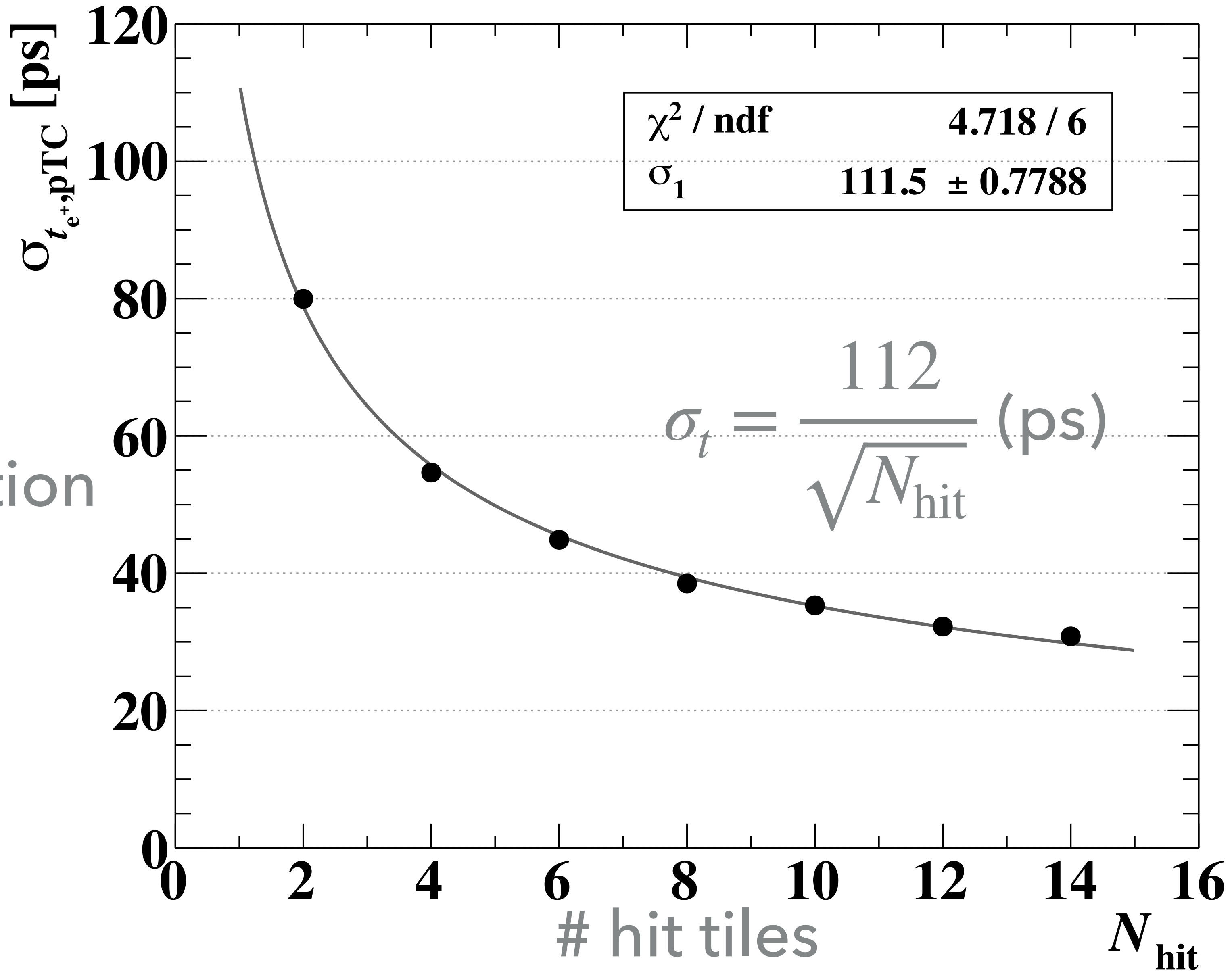
PIXELATED TIMING COUNTER (PTC)

- 256 tile scintillators on each side
- each tile ~100ps resolution
  - e⁺ hits 9 tiles on average → ~**37ps**

cf. ~65ps MEG

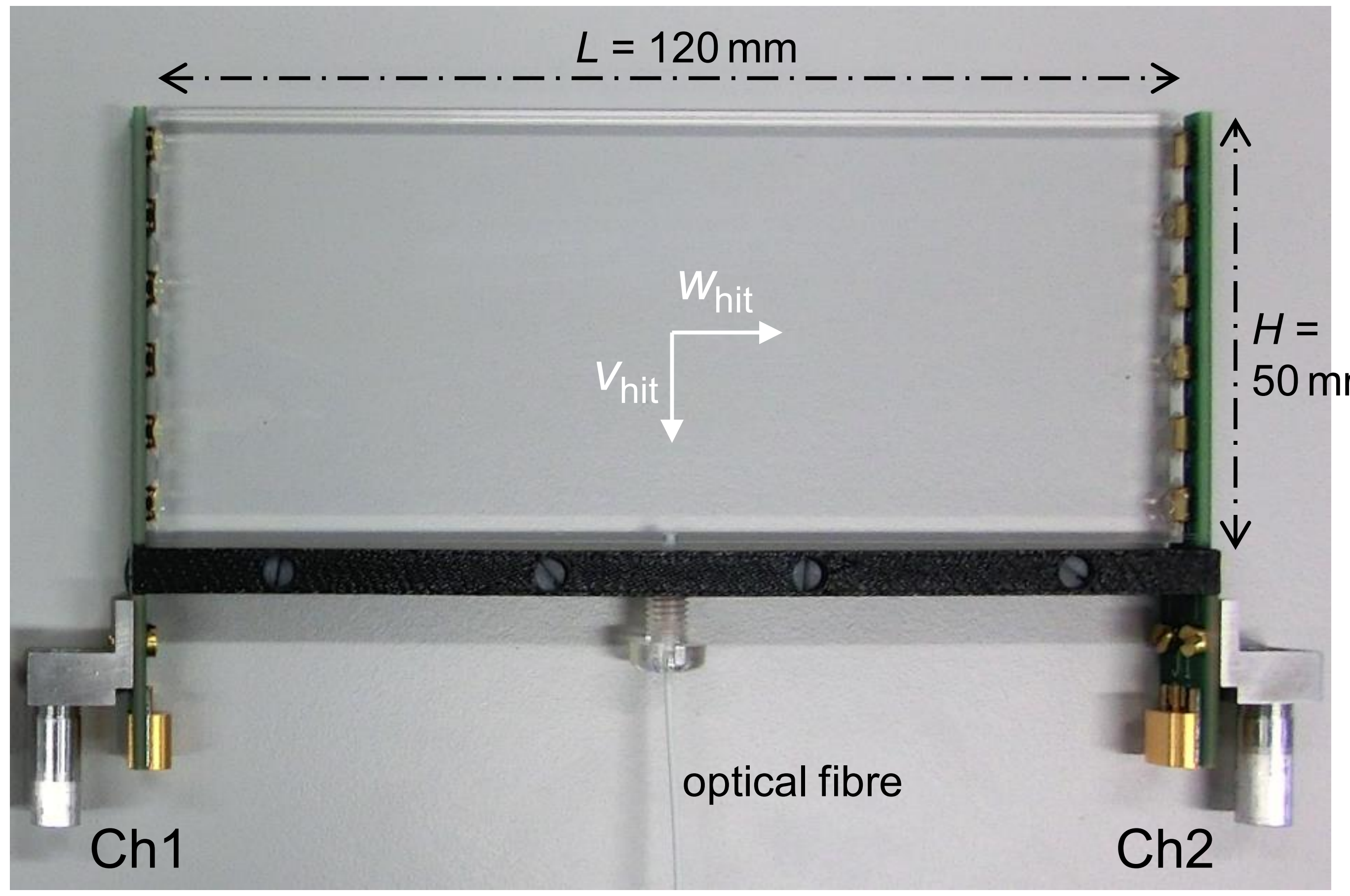


timing resolution (psec)



\# hit tiles

optical fibre for laser calibration



a tile scintillator

120x50/40x5mm³

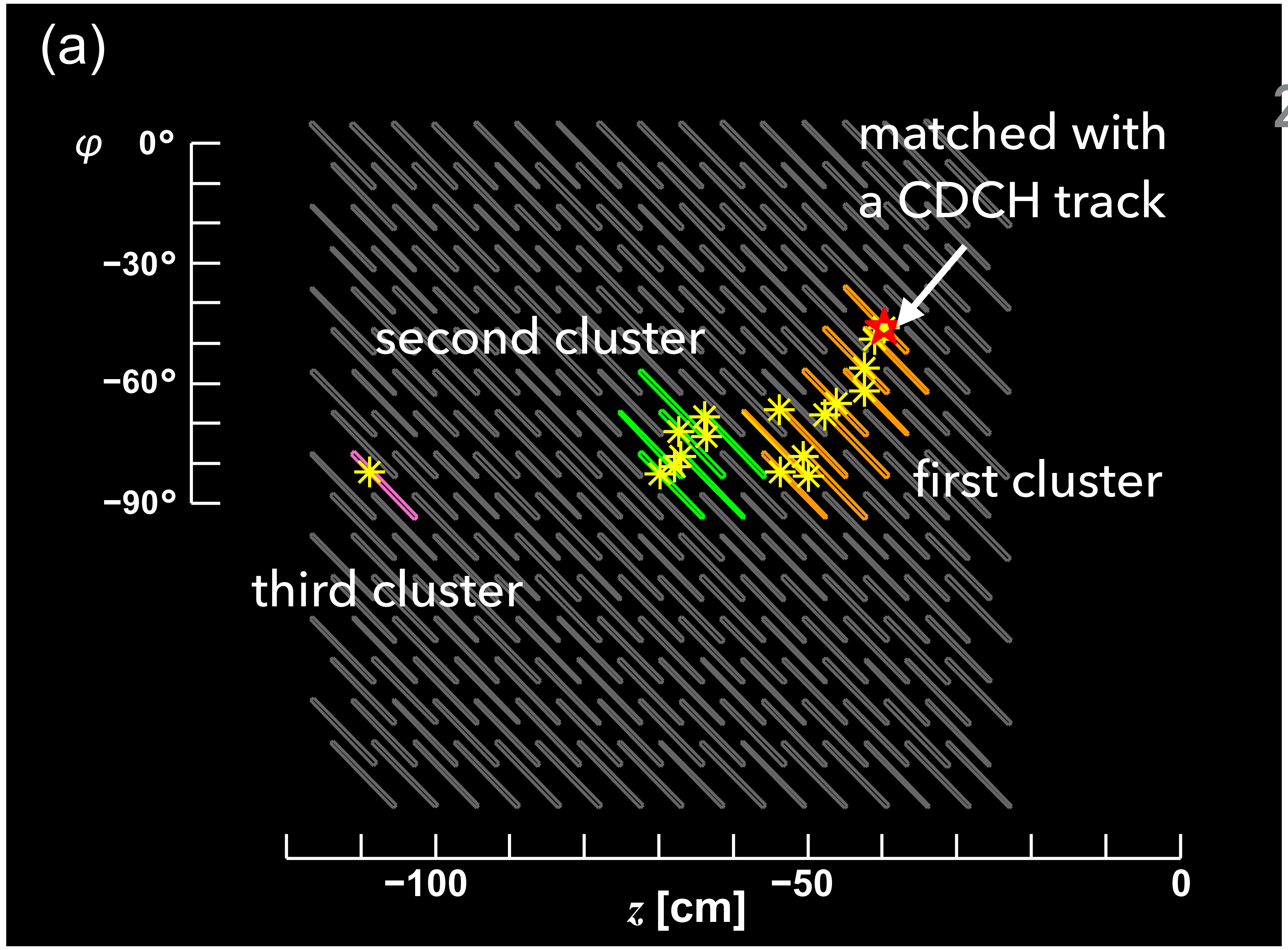
array of six SiPMs (AdvanSiD 3x3mm²) connected in series on each side

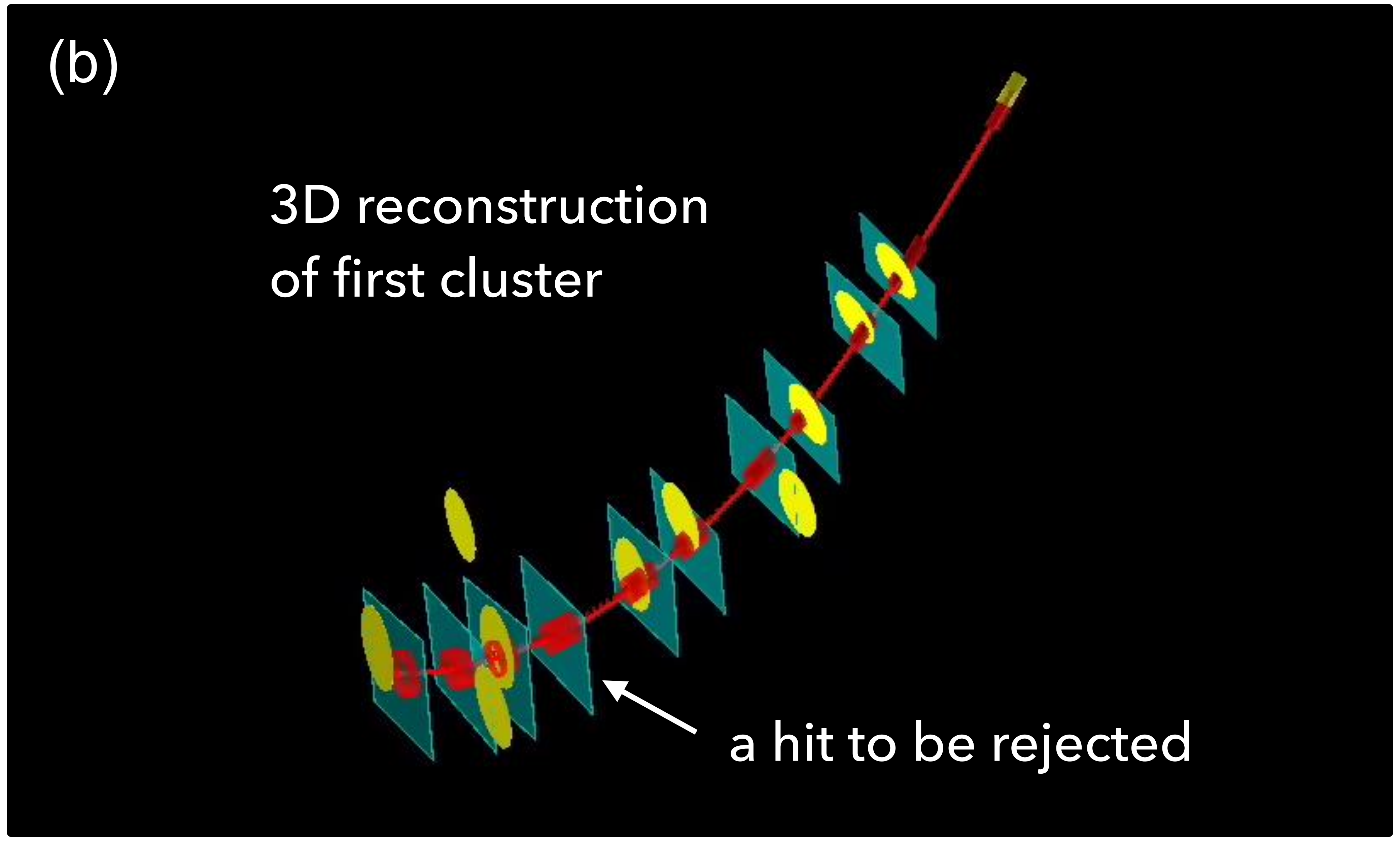
PIXELATED TIMING COUNTER (PTC)

- Clusters of hit tiles are reconstructed
  - Then matched with CDCH tracks
- Calibration among the tiles ~15ps
  - Track-based calibration
  - Laser calibration via optical fibres
- Temperature maintained within ±1˚C

  Support structure water-cooled at 11-15˚C
  - To slow down radiation damage

    <13% degradation by end of experiment
  - < 75kHz / tile at 5 x 10^7 muons/sec

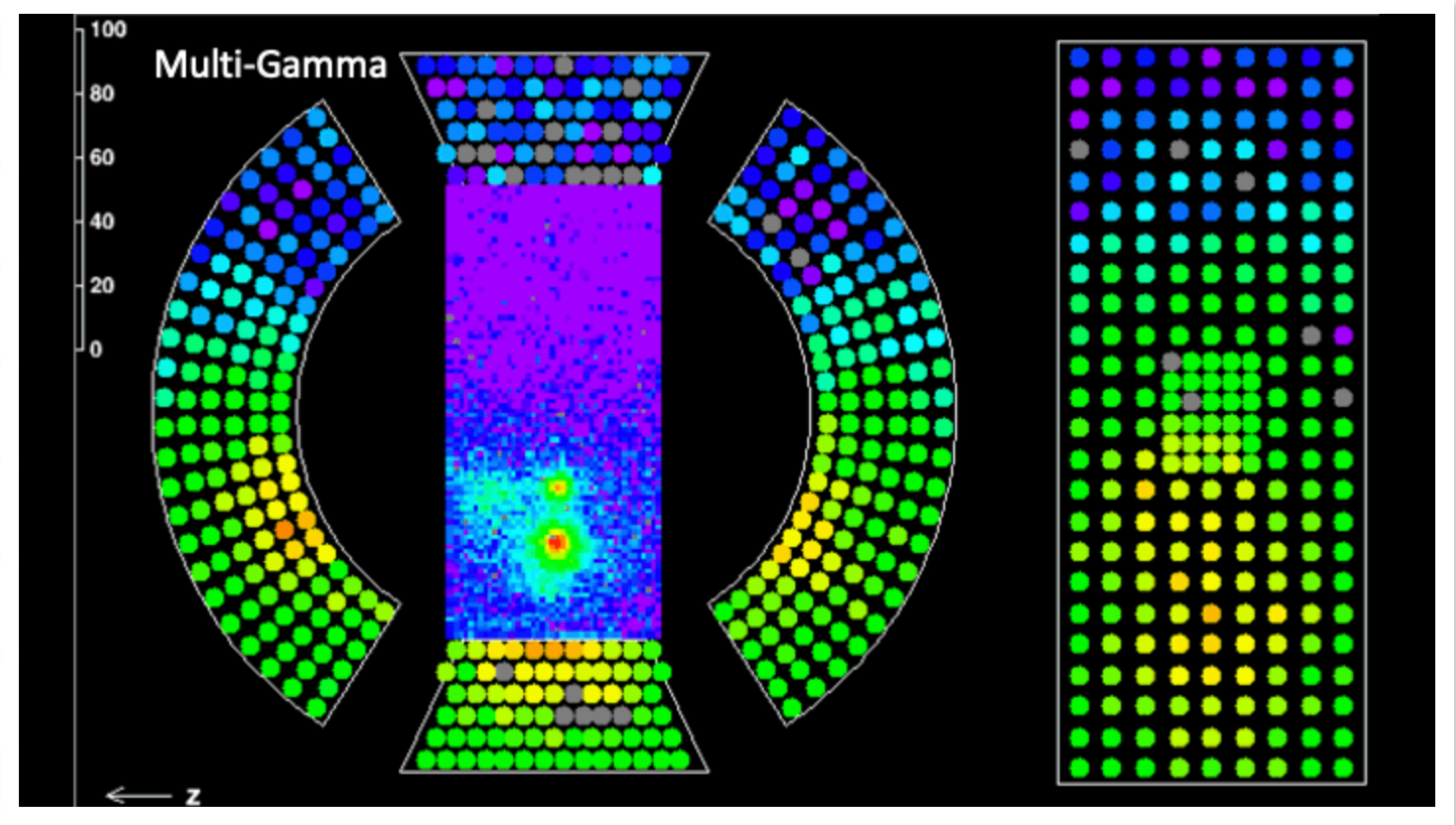




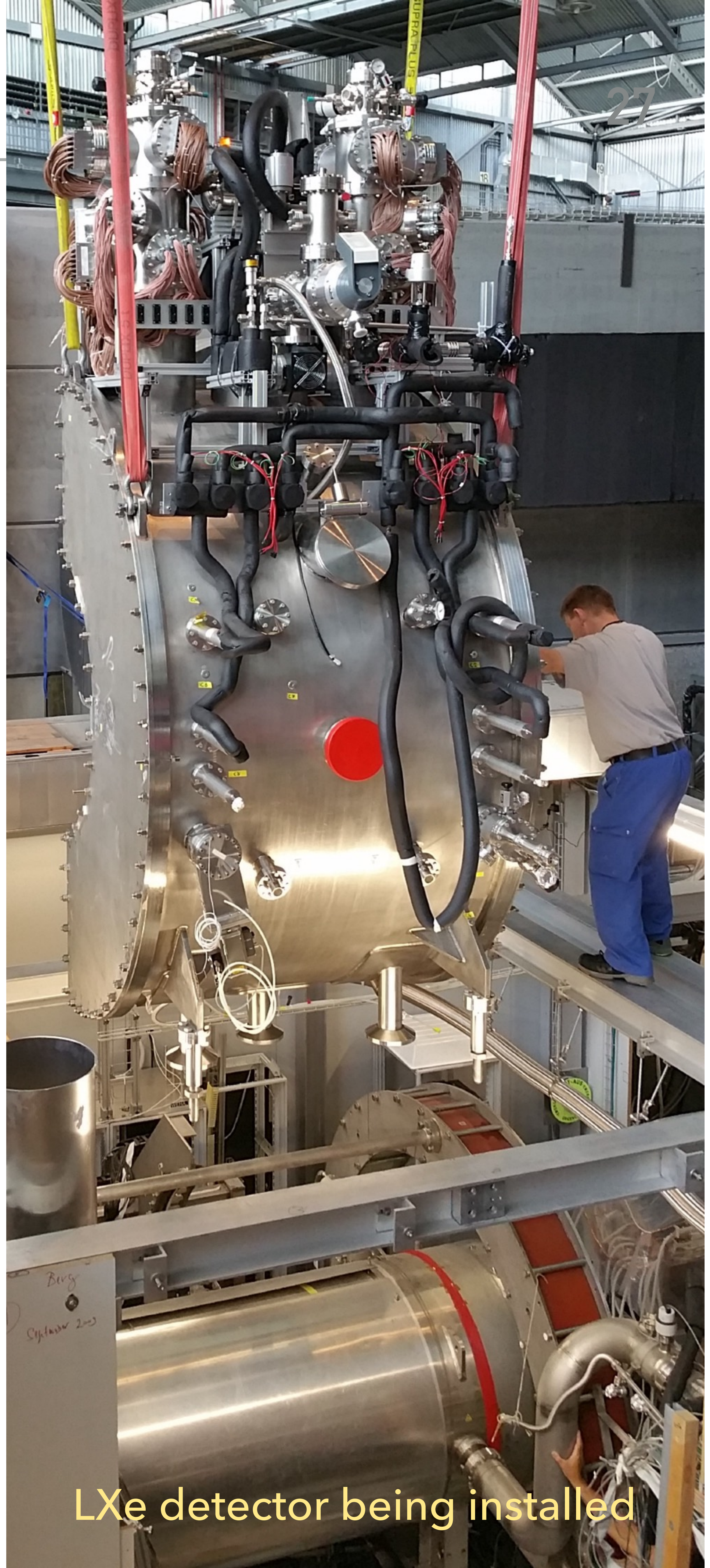
LIQUID XENON PHOTON DETECTOR (LXE)

- All photosensors operational @165K & sensitive to VUV light
  - 4,092 MPPCs (15x15mm^2) on front face cf. MEG uses 2″ PMTs

    Better uniformity enables more precise reconstruction of position & energy
  - 668 2″ PMTs on other faces



Multiple photons are separated by position & timing and simultaneously measured

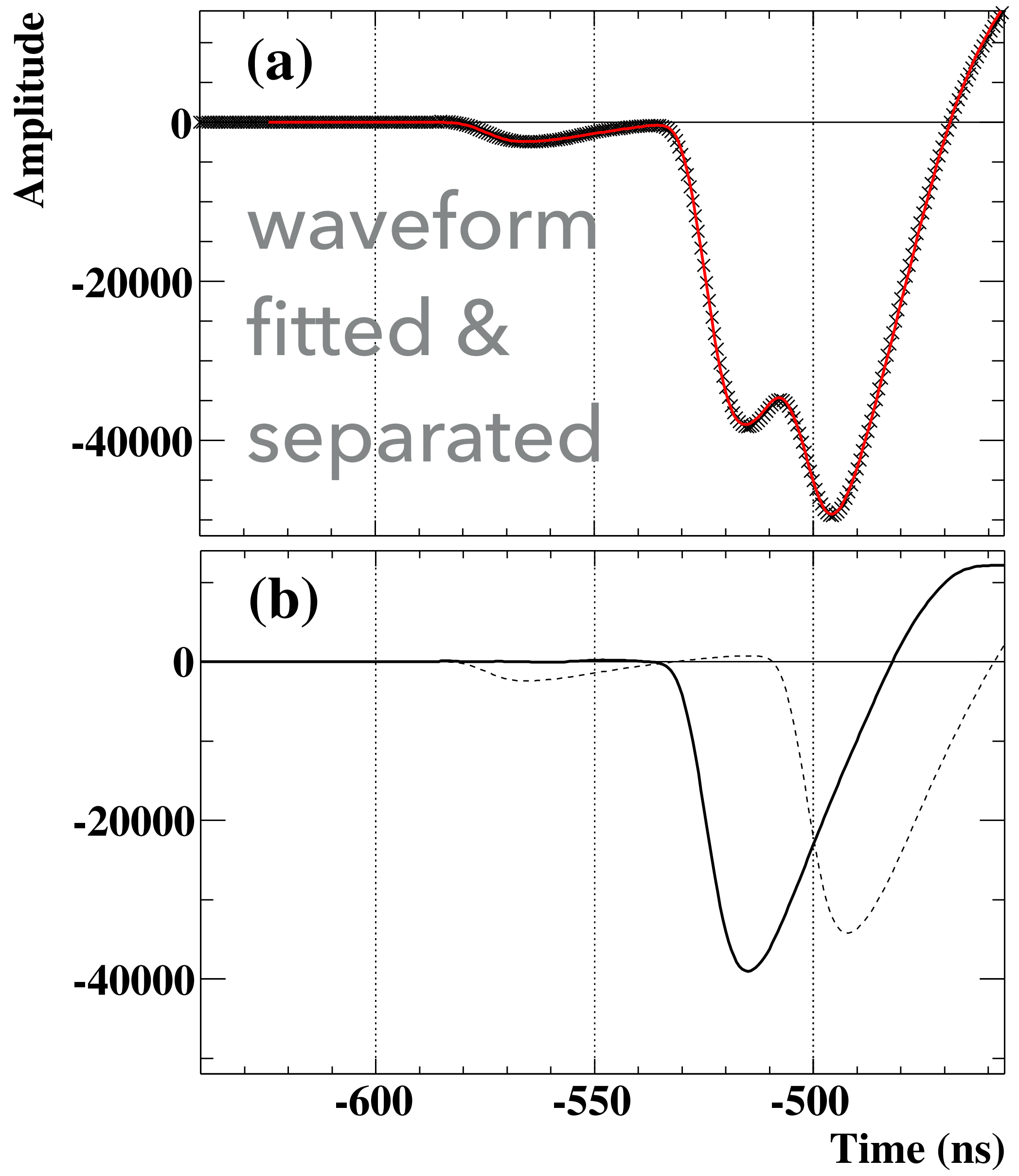


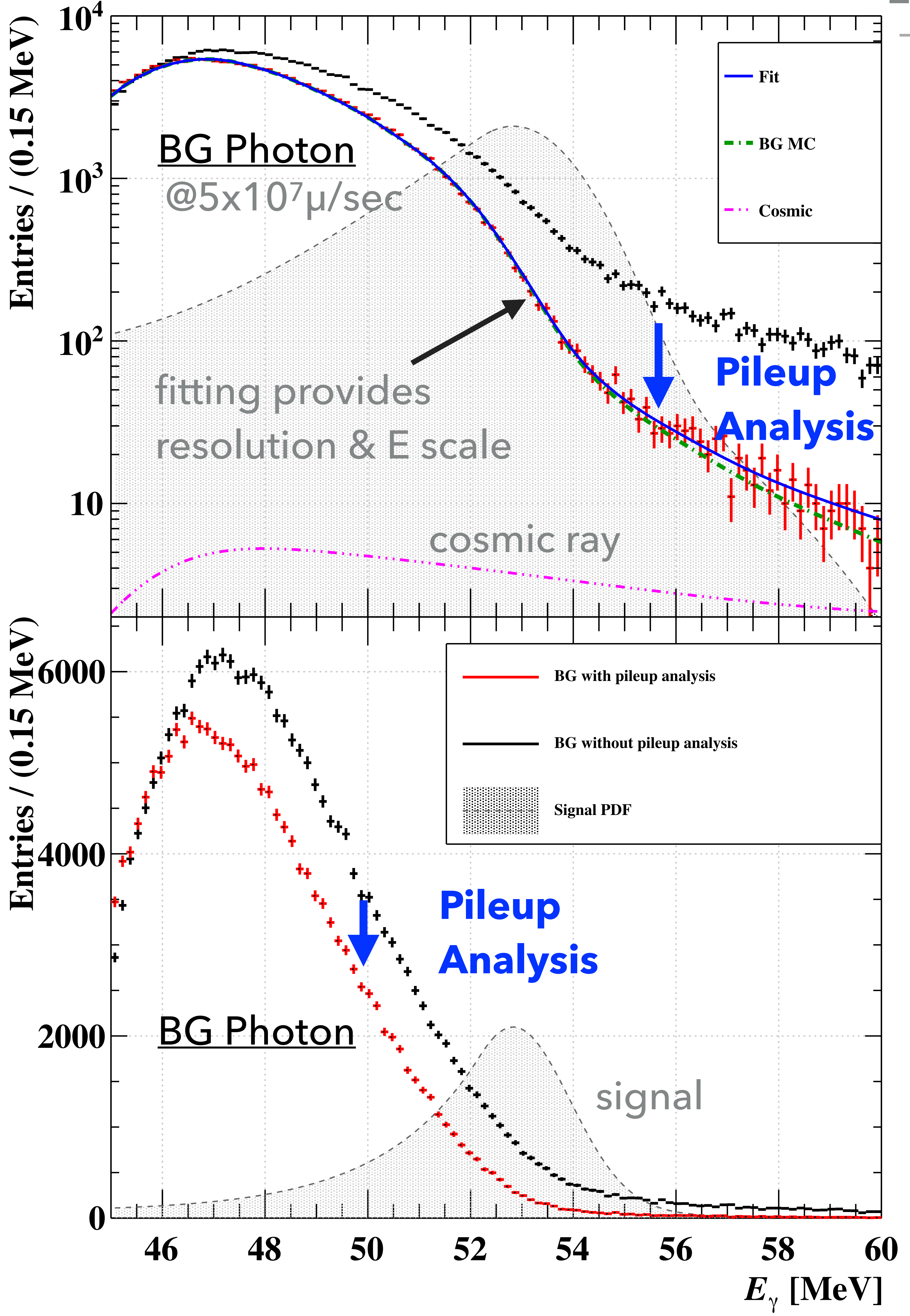
LXe detector being installed

LXE DETECTOR – PILEUP ANALYSIS

- Pileup photons are separated by fitting:
  - light distribution in the MPPCs, and
  - summed waveforms of MPPCs & PMTs
- Works up to 1x10^8 μ/sec
- Efficiency = 92±2%

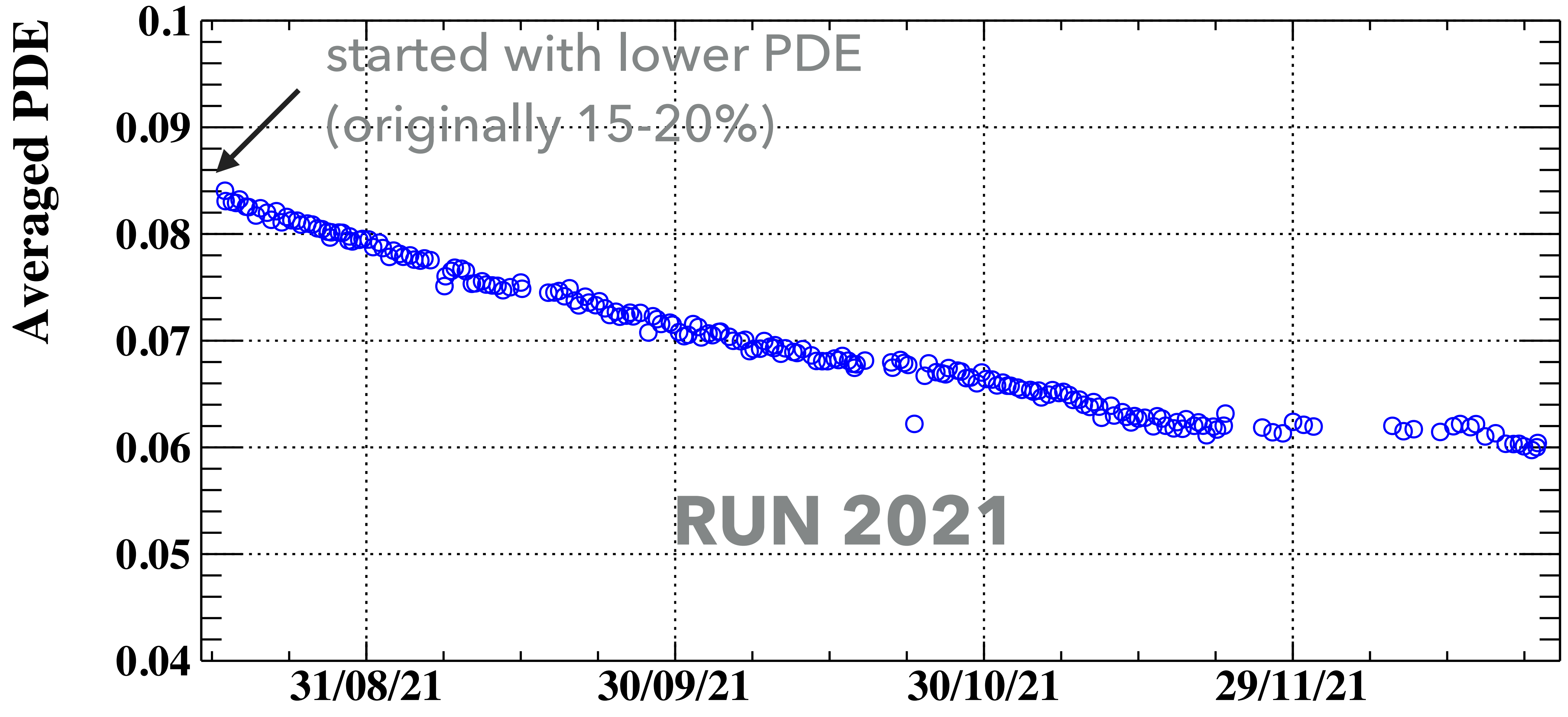
@3x10^{7}μ/sec

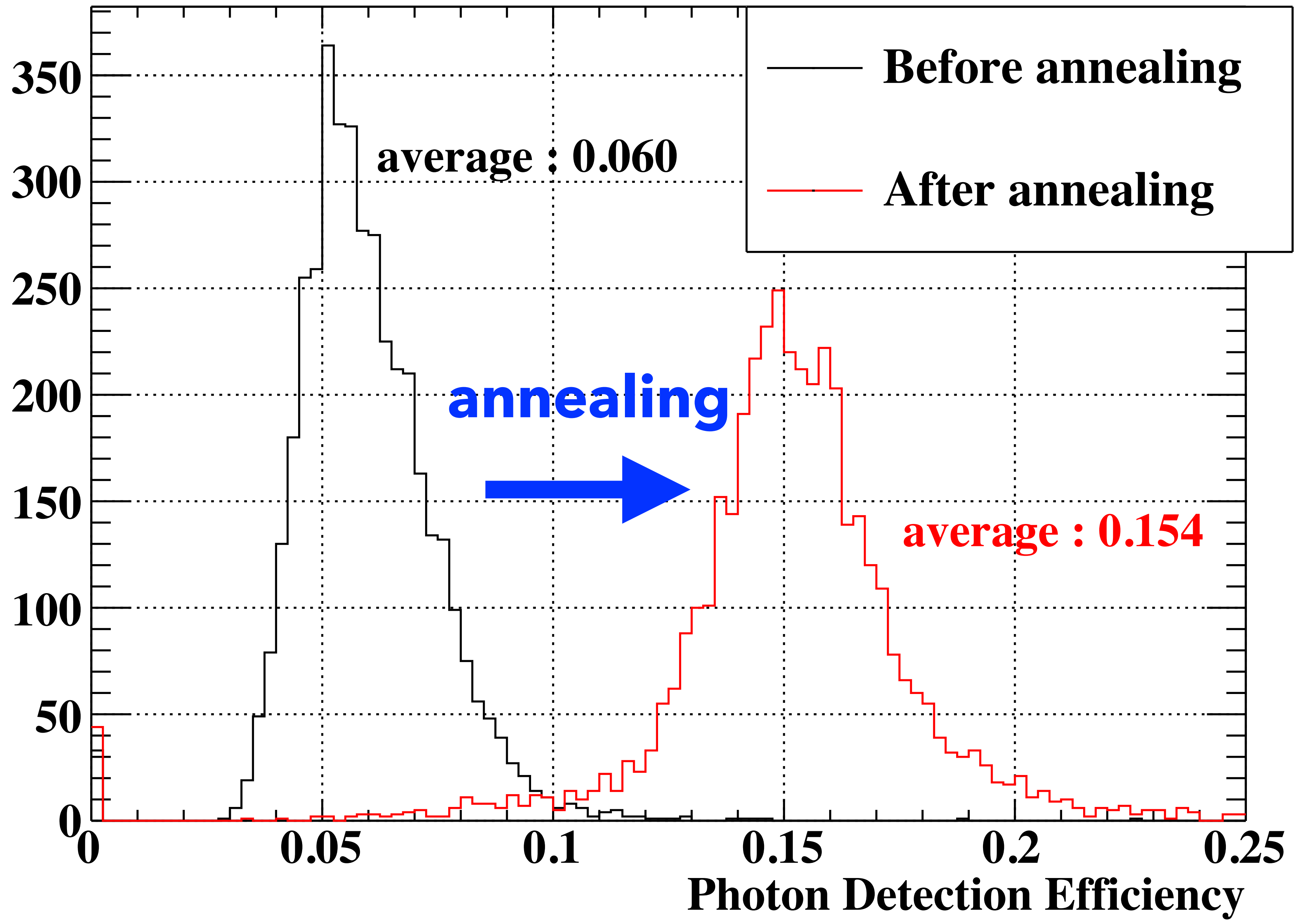




LXE DETECTOR – RADIATION DAMAGE ON MPPC PDE

- The photon detection efficiency (PDE) of MPPCs for VUV light decreased significantly during the run due to surface damage by radiation. (The real cause of the damage is still unknown and under investigation.)
  - PDE > 2% should not significantly degrade the detector performance.
- **Annealing (Joule heating of MPPCs up to 75˚C) restored the reduced PDE**.
  - ~28h annealing for each MPPC during the winter shutdown is sufficient to recover PDE for the next year's run.





K. Ieki et al., Nucl. Instrum. Methods A 1053, 168365 (2023)

LXE DETECTOR – MONITORING E_γ DURING THE RUN

- Various methods to monitor E_γ stability during the run:

  (a) 17.6MeV γ-ray from $^7Li(p,\gamma)^8Be$ using Cockcroft-Walton accelerator three times a week

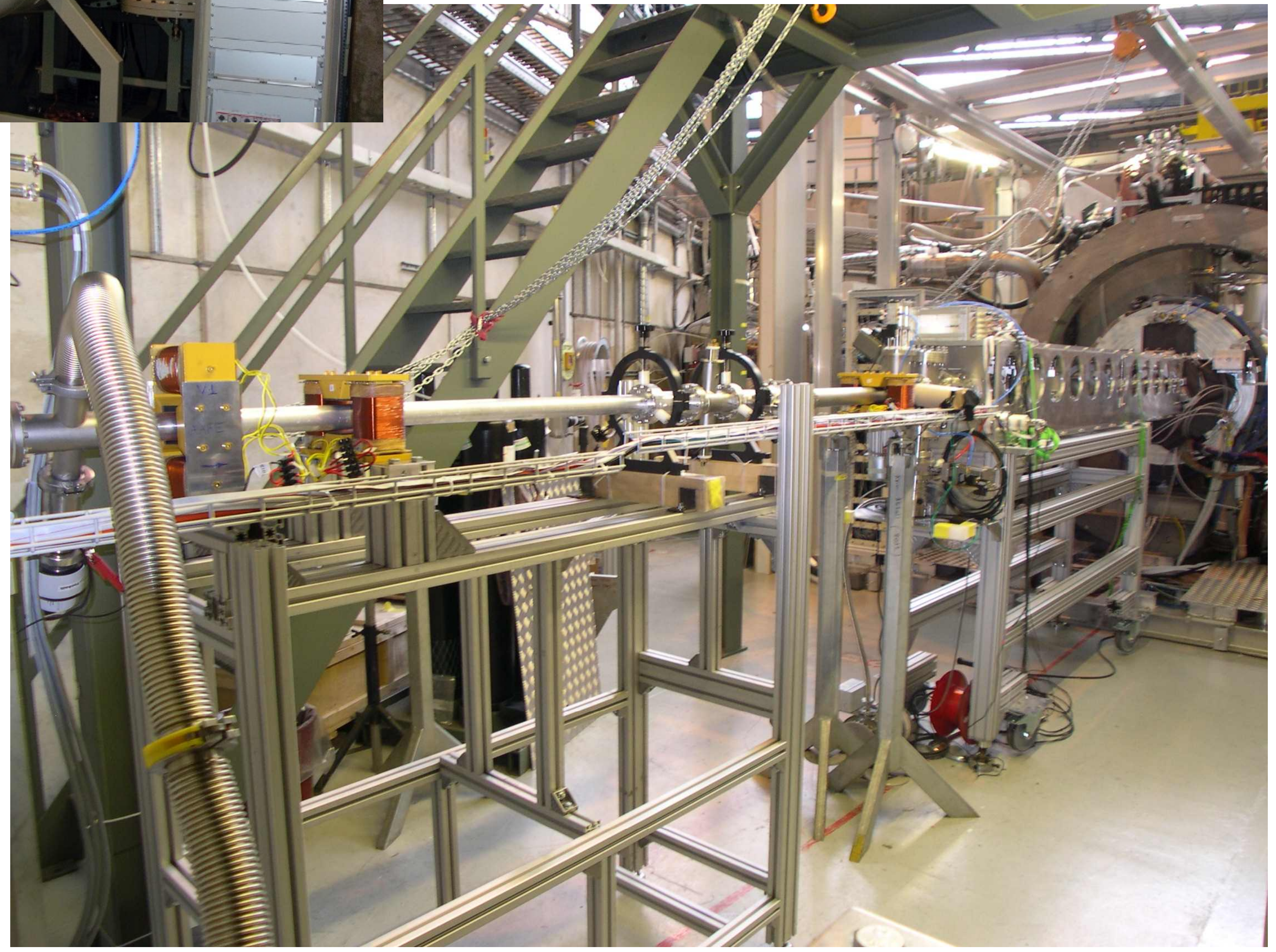
  (b) Cosmic rays selected to have penetrated the detector

  (c) Background photon spectrum (radiative decays, annihilations in flight)

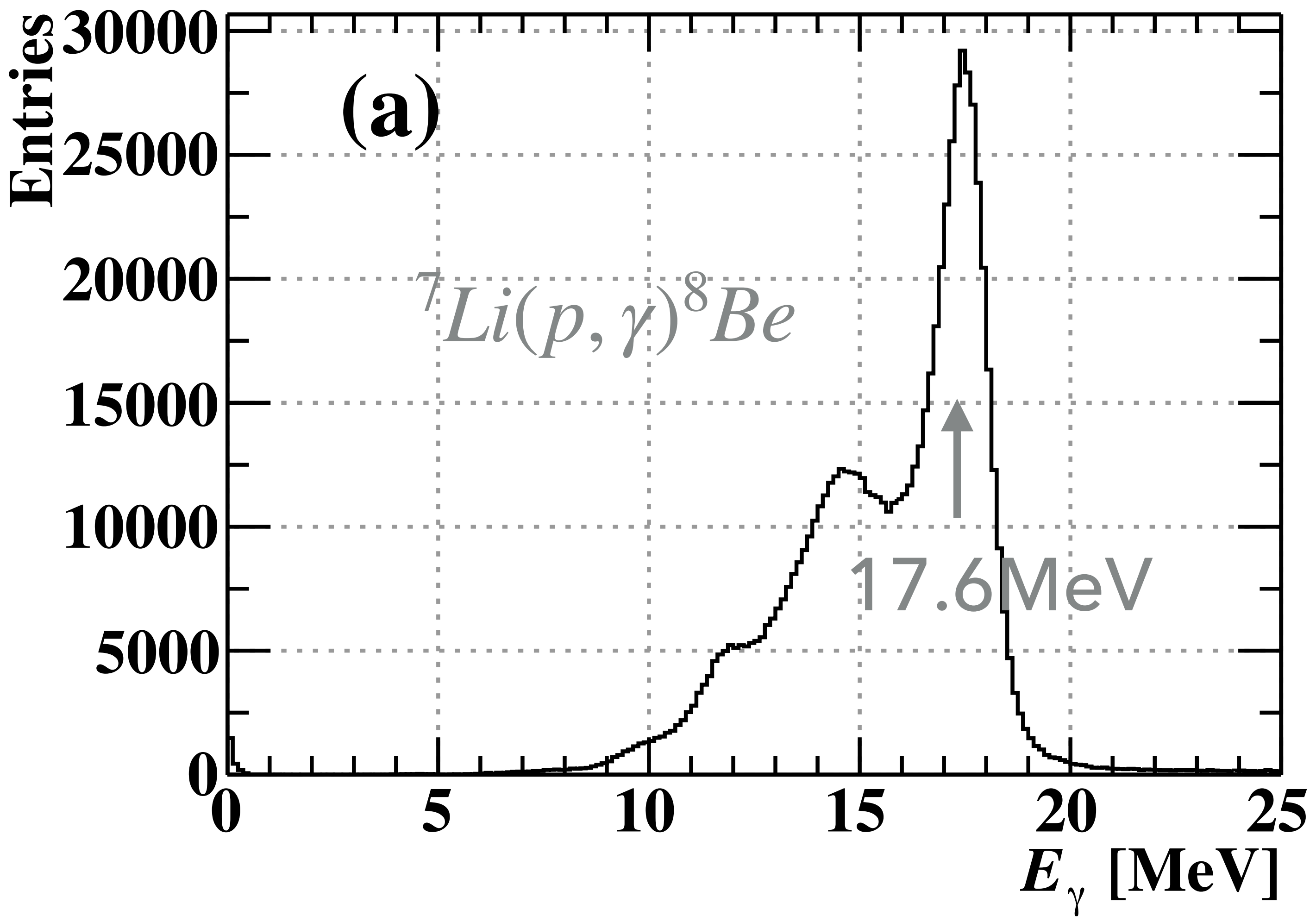
  (d) alpha-rays from ^{241}Am sources embedded in the detector

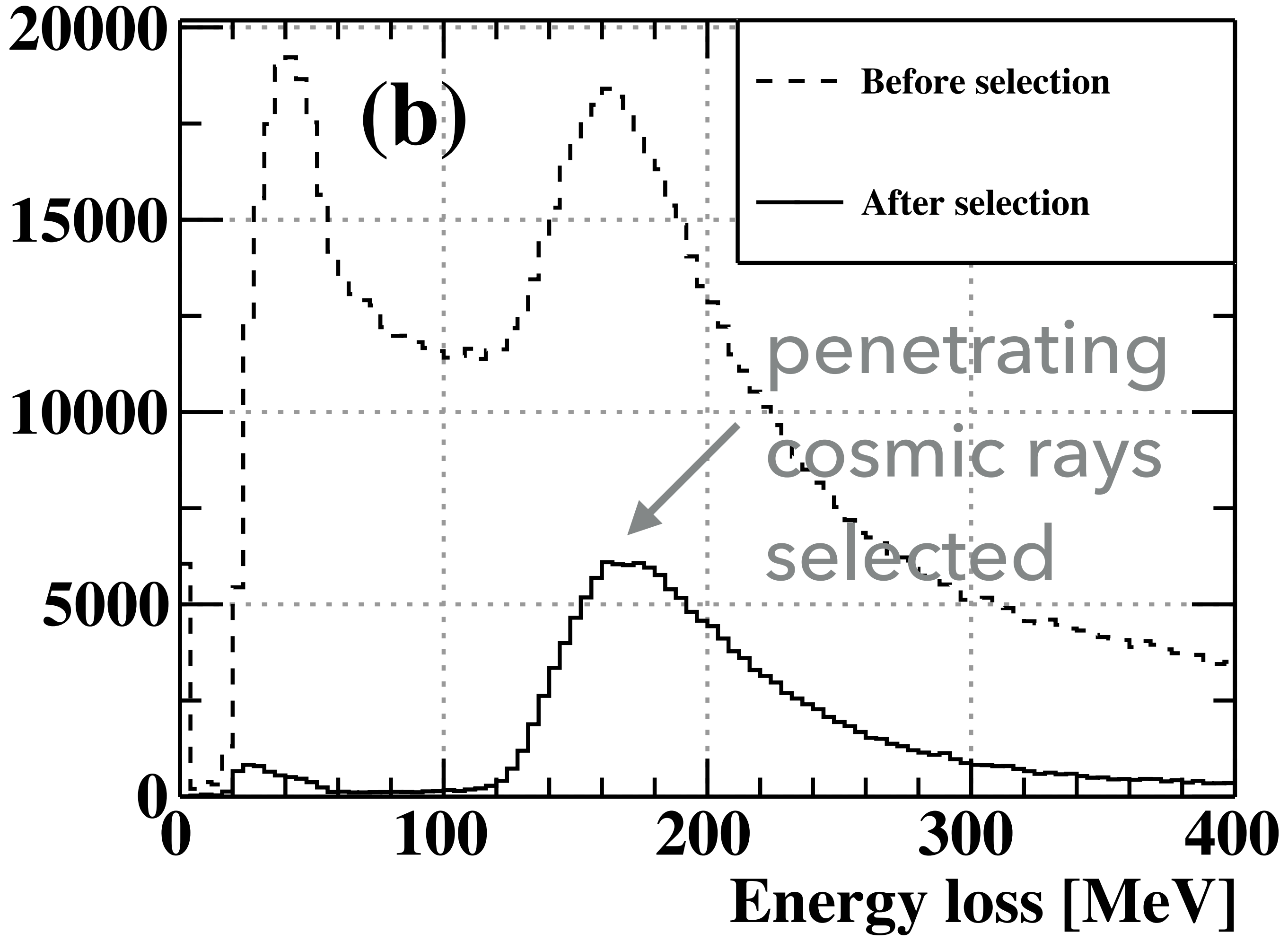
  (e) 9MeV γ-rays from $^{58}Ni(n,\gamma_9)^{59}Ni$ by using neutron generator

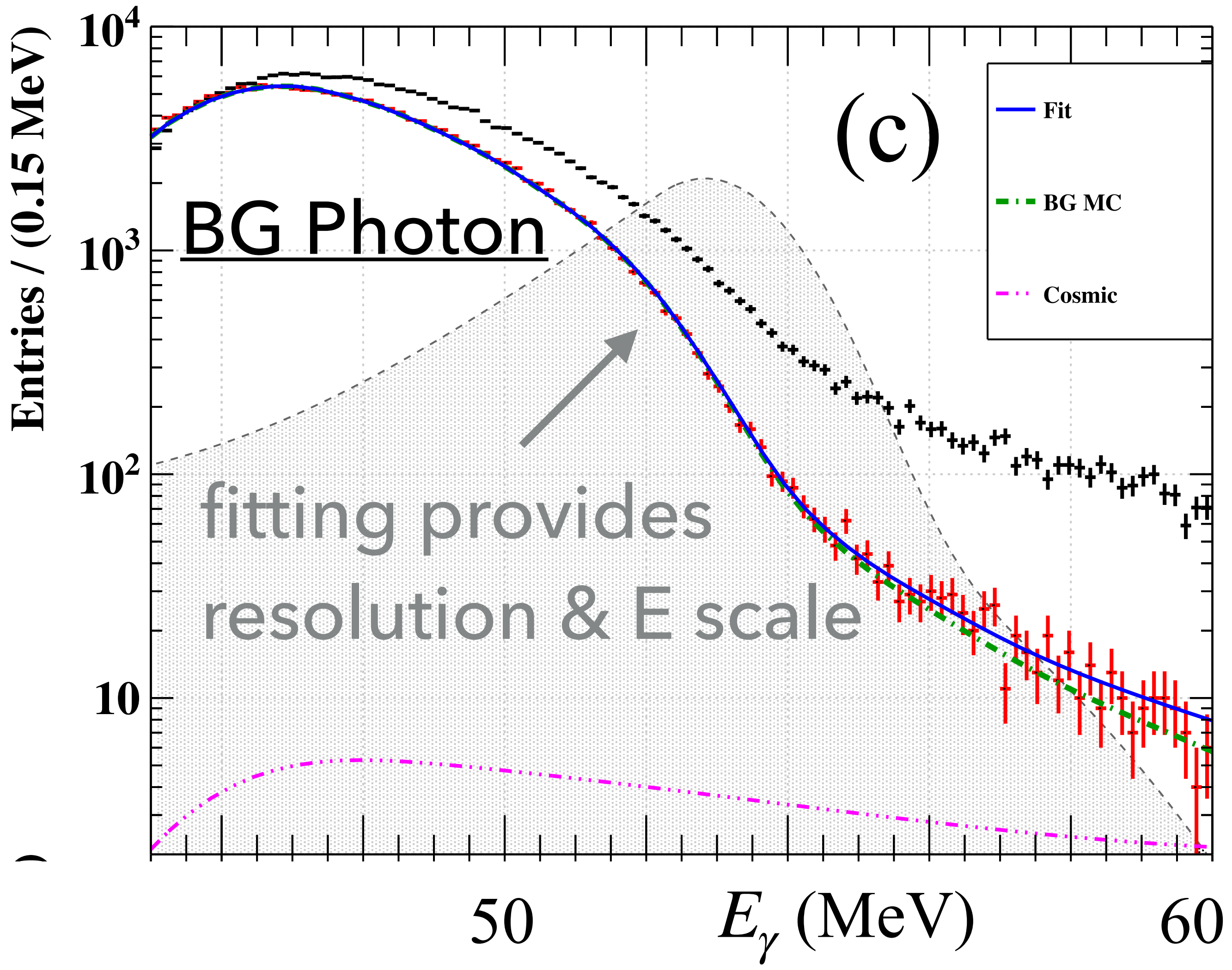
- Estimated uncertainty of temporal evolution = **0.3%**

dedicated Cockcroft-Walton accelerator & beam line

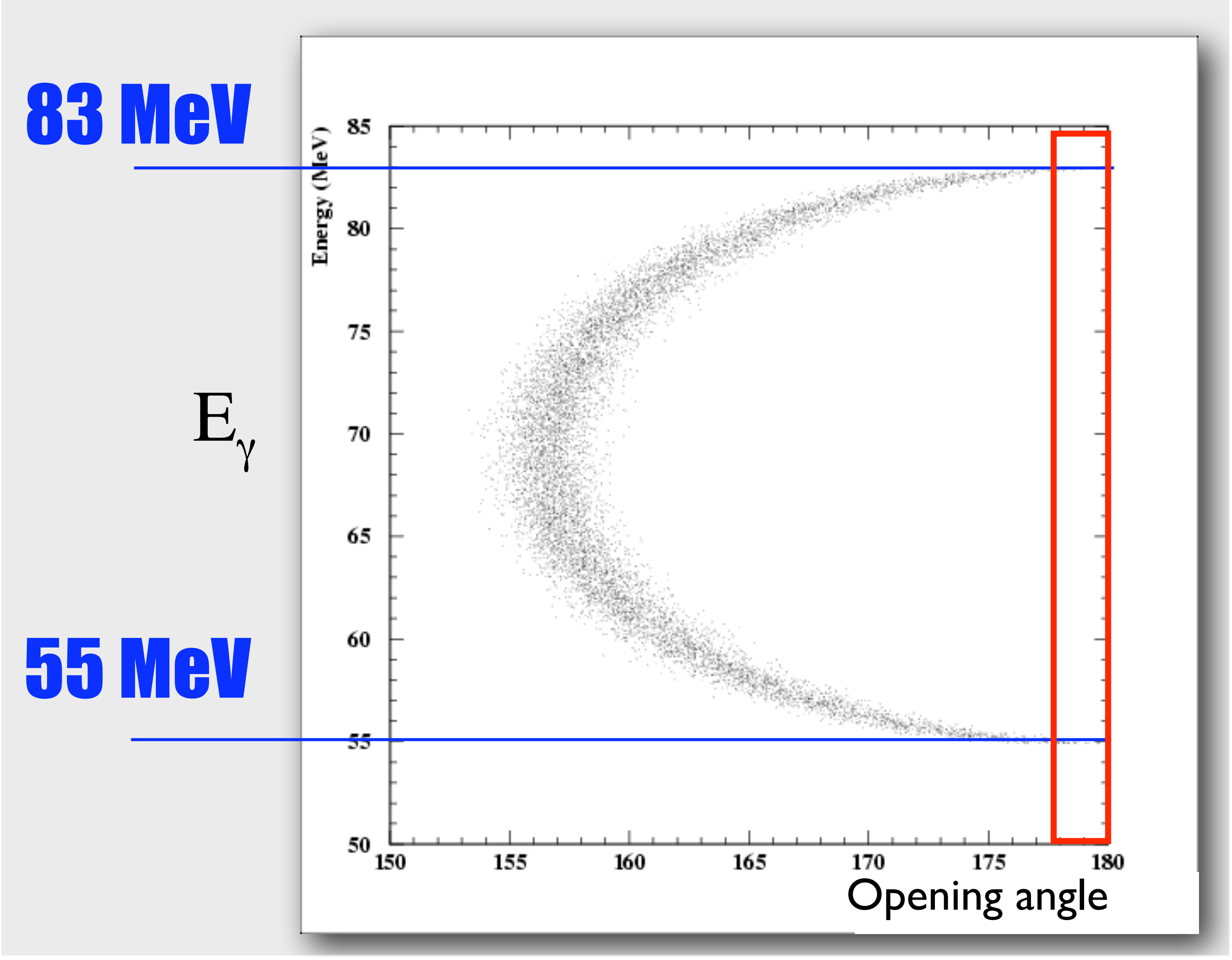




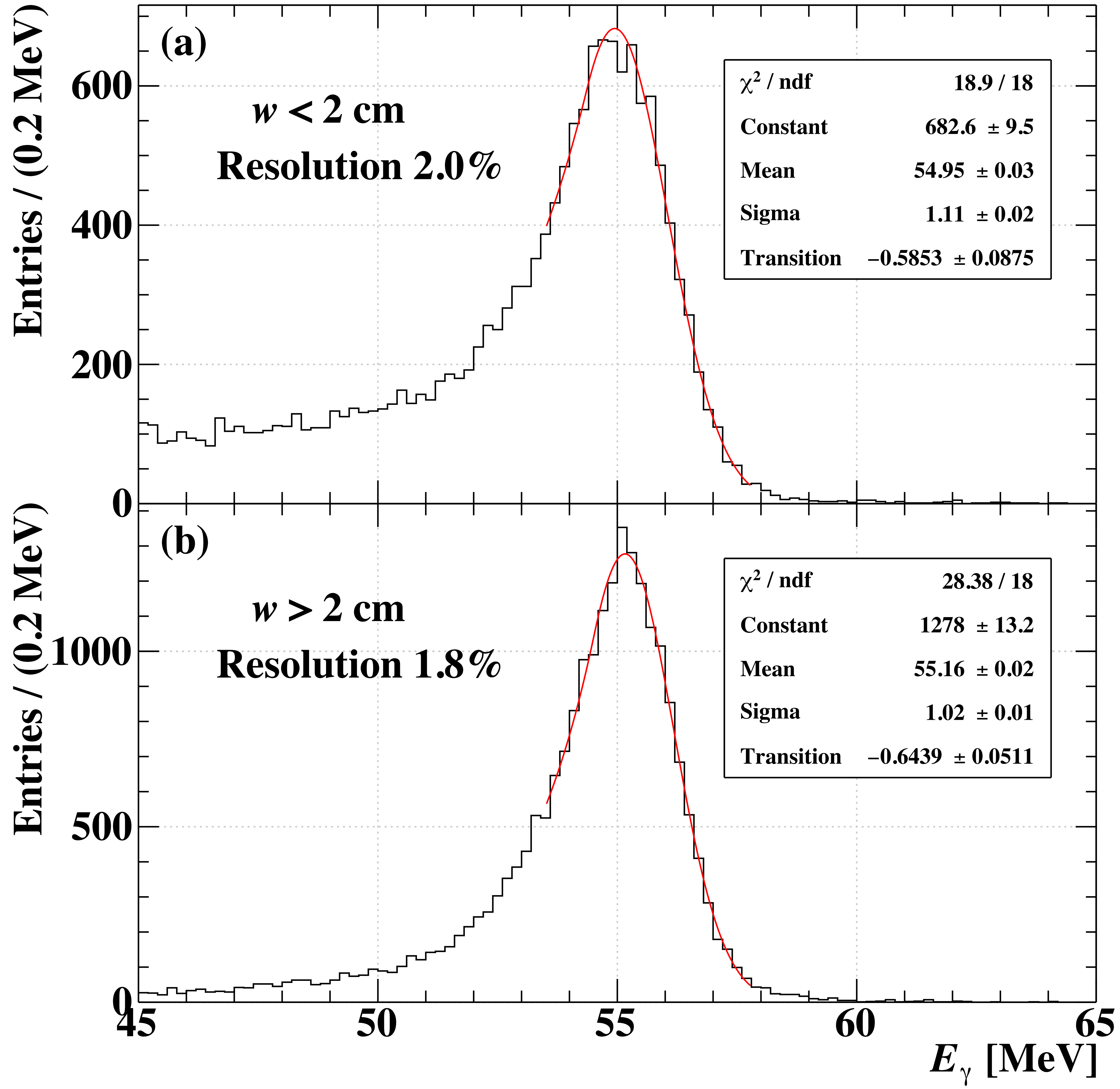


LXE DETECTOR – ABSOLUTE E_γ SCALE

- Charge-exchange reaction $\pi^- p \to \pi^0 n \to \gamma\gamma n$ provides a **55MeV monochromatic γ-ray** by tagging the other γ-ray on the opposite side
- A dedicated calibration run using π^- beam on liquid hydrogen target for each year
- Energy resolution depends on depth (**w**) of photon conversion point

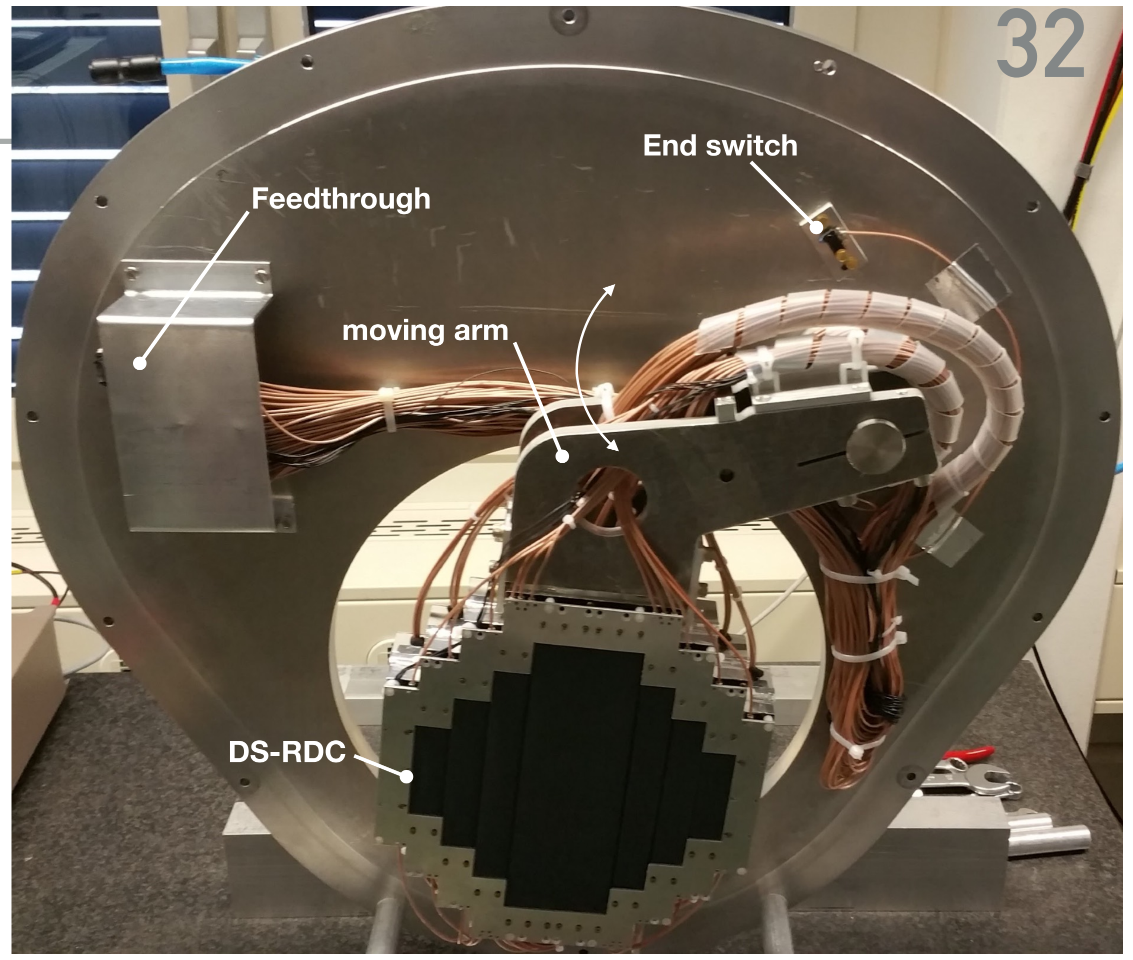


BGO crystal array on a movable stand to tag photon

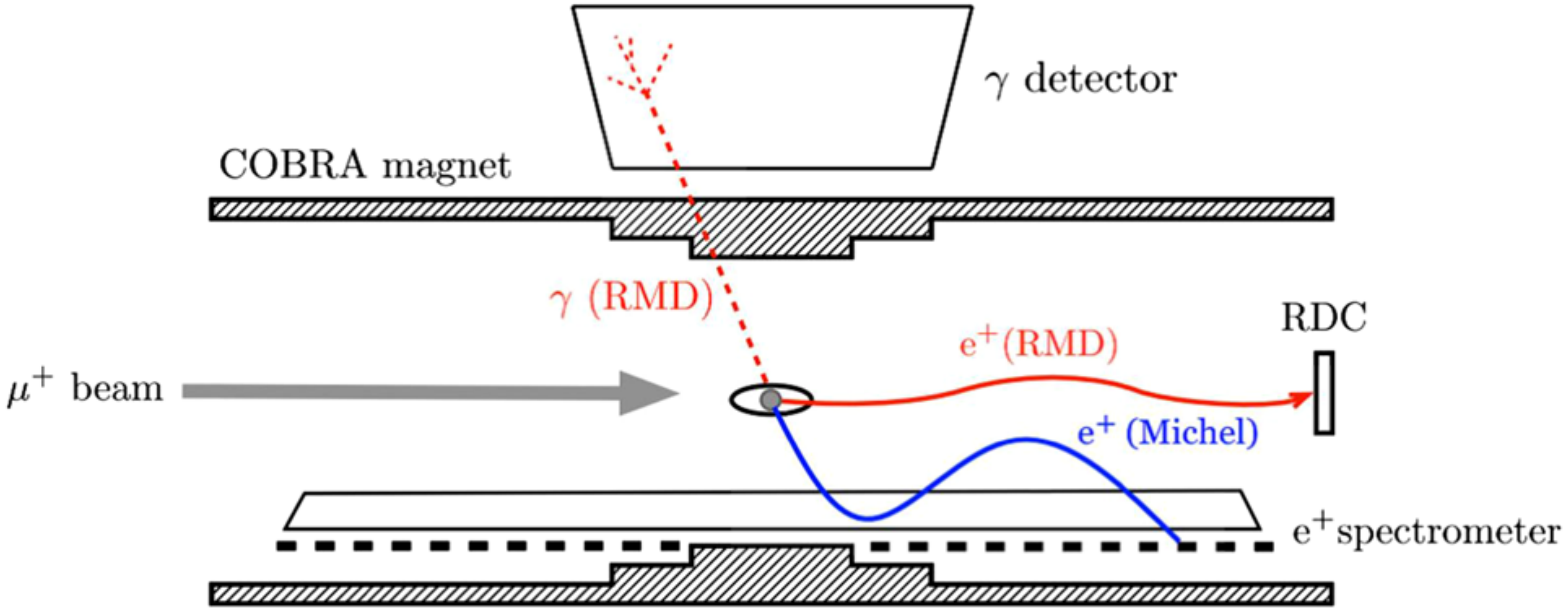


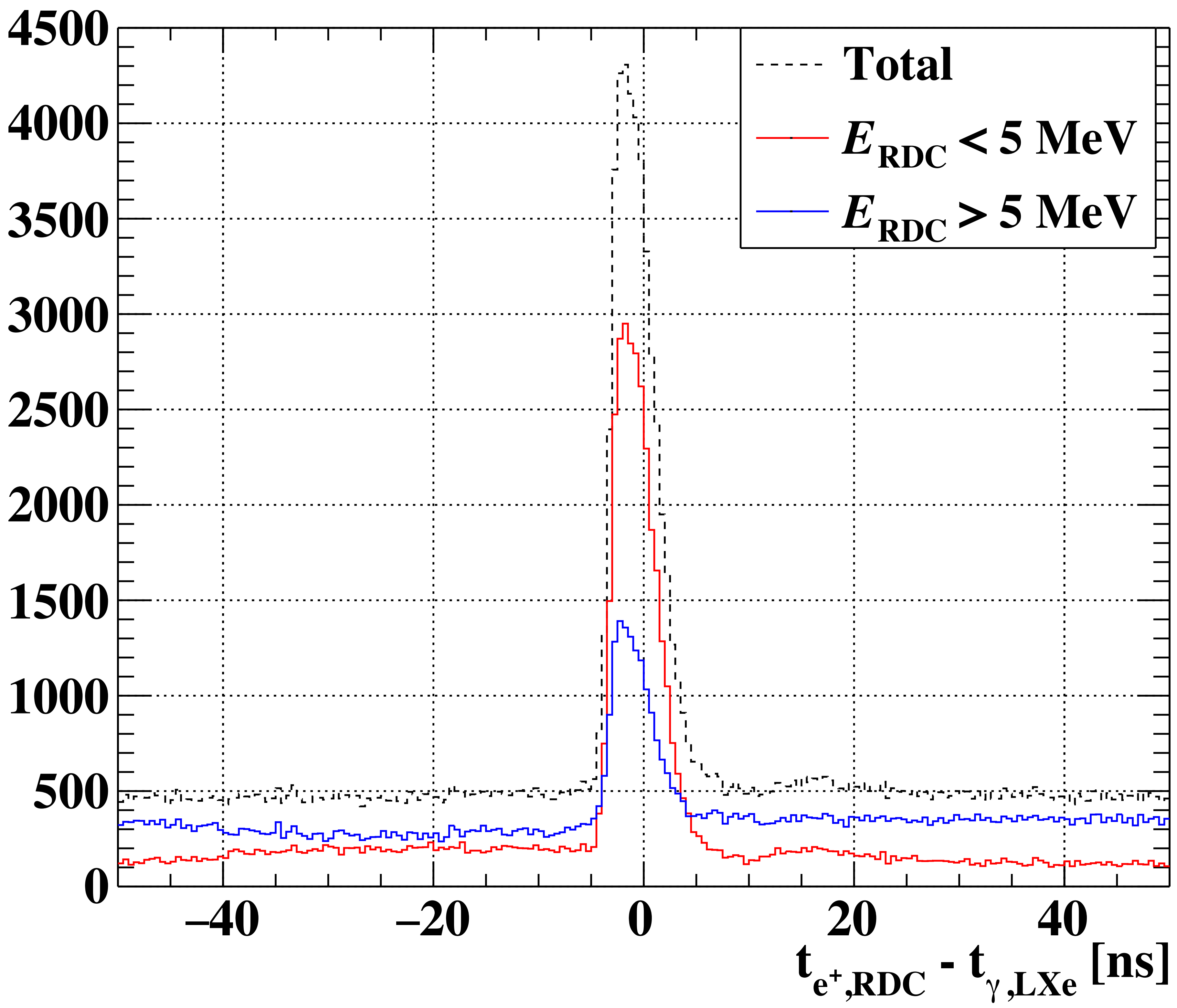
Overall energy scale uncertainty = 0.4%

RADIATIVE DECAY COUNTER (RDC)

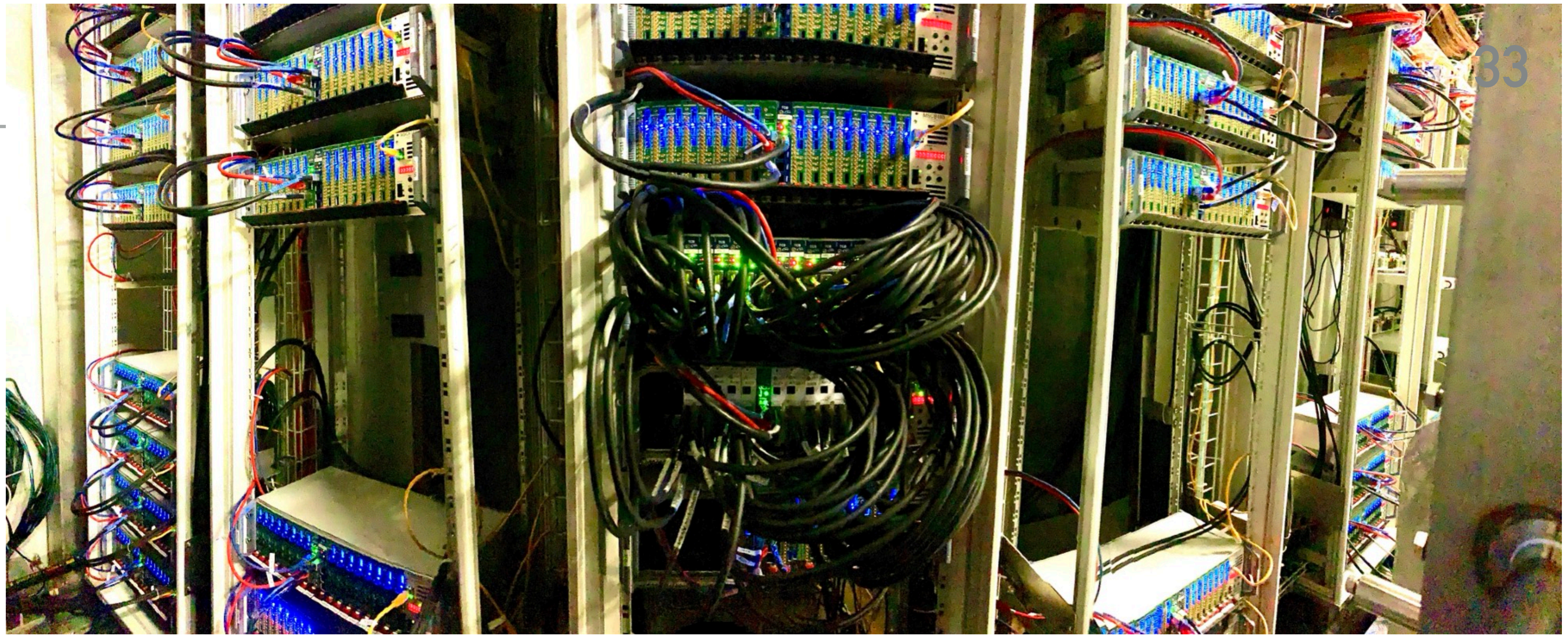


- Tag a high energy γ-ray as coming from a radiative decay by detecting a low energy e^+ in the forward direction.
- Provide discriminating variables in Likelihood Analysis.
- Successfully tagged radiative γ-rays with $\varepsilon \sim 14\%$.
- Search sensitivity improved by 7%.





TRIGGER & DATA ACQUISITION

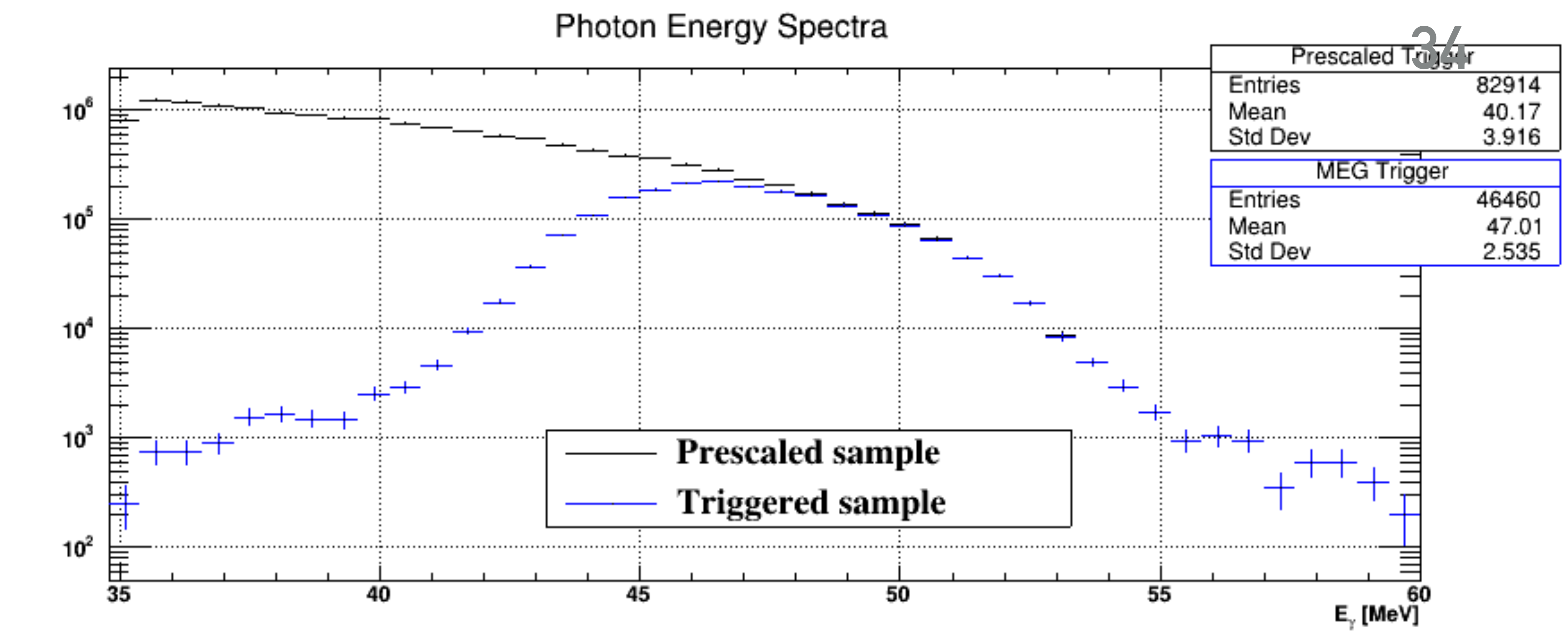


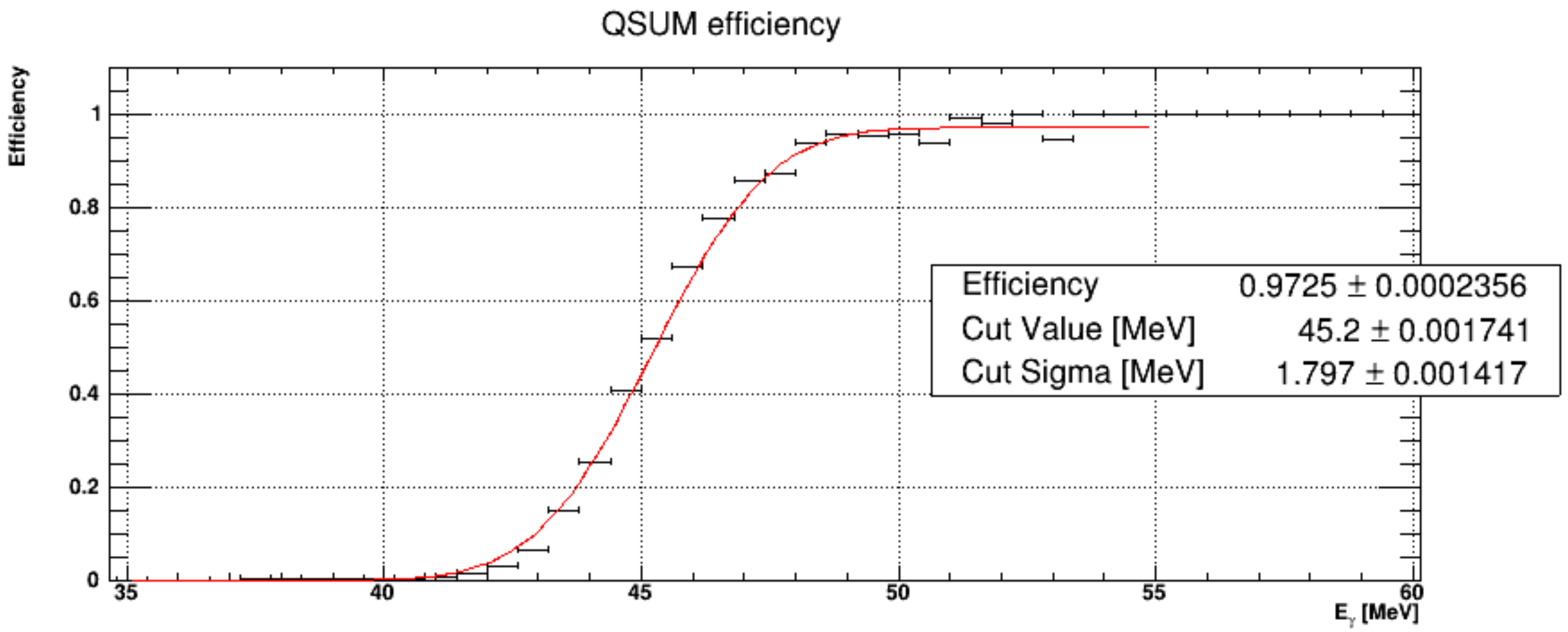
- **WaveDAQ system**
  - Trigger and DAQ are integrated in a single, compact system to accommodate 4 times more channels of waveform readouts (8,591) than MEG.
    - All detector signals are **waveforms**, making the event size as big as ~16MB.
  - 35 crates, each holding up to 16 WaveDREAM modules.
    - **WaveDREAM**: 16-ch DAQ platform with 2 DRS4 chips up to 5.0GSPS sampling speed.
  - **Installed & commissioned in March 2021**
  - Efficiency >99% for trigger rate up to 35Hz, corresponding to traffic rate of ~8Gbit/s.

M. Francesconi et al., Nucl. Instrum. Methods A 1045, 167542 (2023)

TRIGGER & DATA ACQUISITION

- Trigger for $\mu \to e\gamma$
  1) **γ-ray energy**
     - LXe weighted sum, $\varepsilon_{E_\gamma} = 96\,\%$
  2) **Time coincidence**
     - LXe & pTC, $\varepsilon_T = 94\,\%$
       - inefficiency for deeper conversion events
  3) **Direction match**
     - LXe & pTC positions, $\varepsilon_{DM} = 88.5\,\%$
       - inefficiency due to a small offset of beam position
- Trigger Efficiency for the 2021 Run: $\varepsilon_{TRG} = 80 \pm 1\,\%$ @ $3 \times 10^7 \mu^+$/s
  - Largely improved since the 2022 Run





E_γ (MeV)

PERFORMANCE SUMMARY

Table 6 Resolutions (Gaussian σ) and efficiencies measured at $R_\mu = 4 \times 10^7\ \mathrm{s}^{-1}$, compared with the predictions from [3, 57].

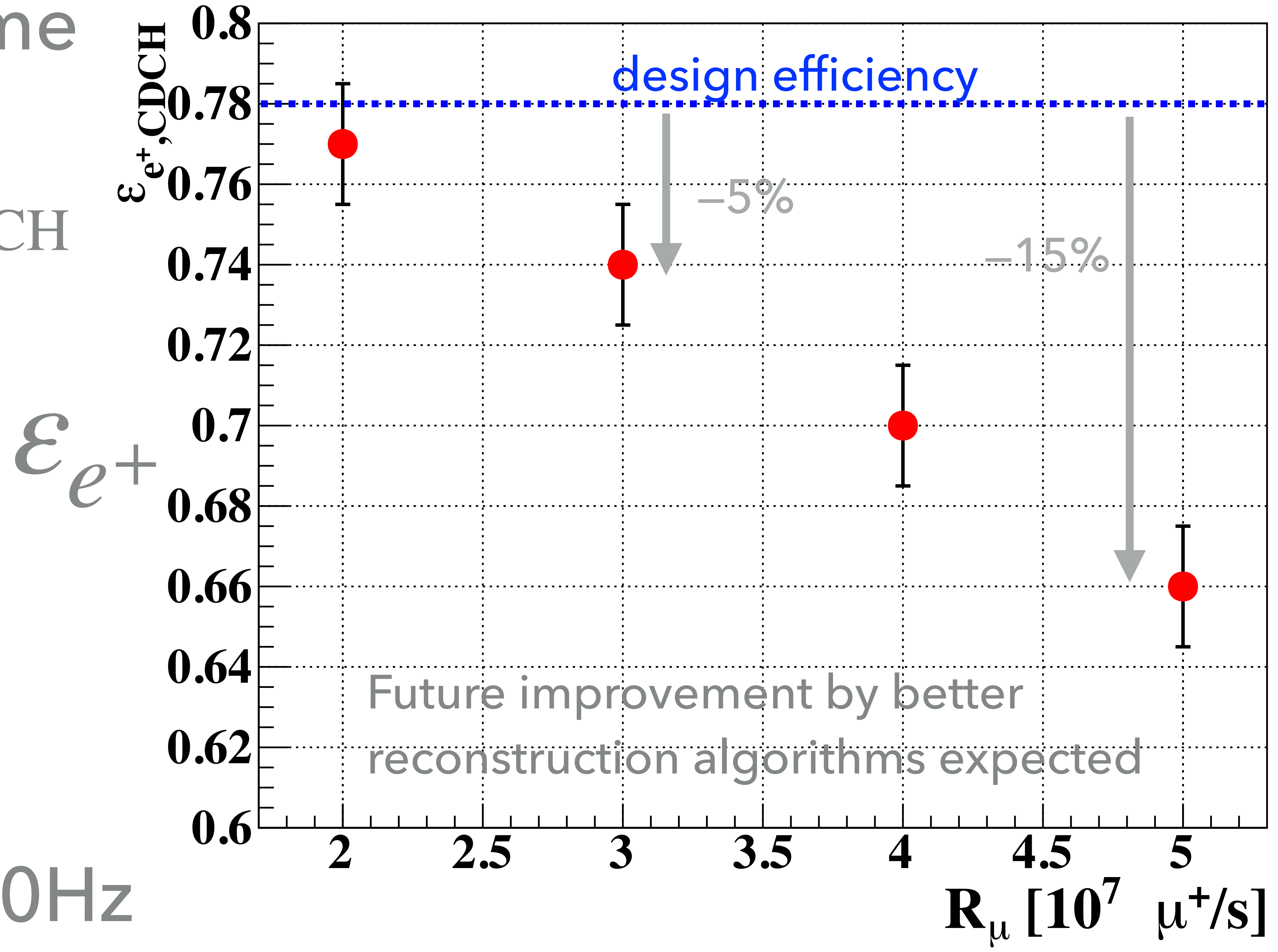
Resolutions	Foreseen	Achieved	**MEG**
E_{e^+} (keV)	100	89	320
ϕ_{e^+} [a], θ_{e^+} (mrad)	3.7/6.7	4.1/7.2	9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.74/2.0	
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.0/1.8	2.4 / 1.7
$u_\gamma, v_\gamma, w_\gamma$ (mm)	2.4/2.4/5.0	2.5/2.5/5.0	5 / 5 / 6
$t_{e^+\gamma}$ (ps)	70	78	122
Efficiency (%)			
ε_γ	69	62	63
ε_{e^+}	65	67	30
$\varepsilon_{\mathrm{TRG}}$	≈99	80	99

a) At $\phi_{e^+} = 0$ with correlation taken into account. See text for the details.

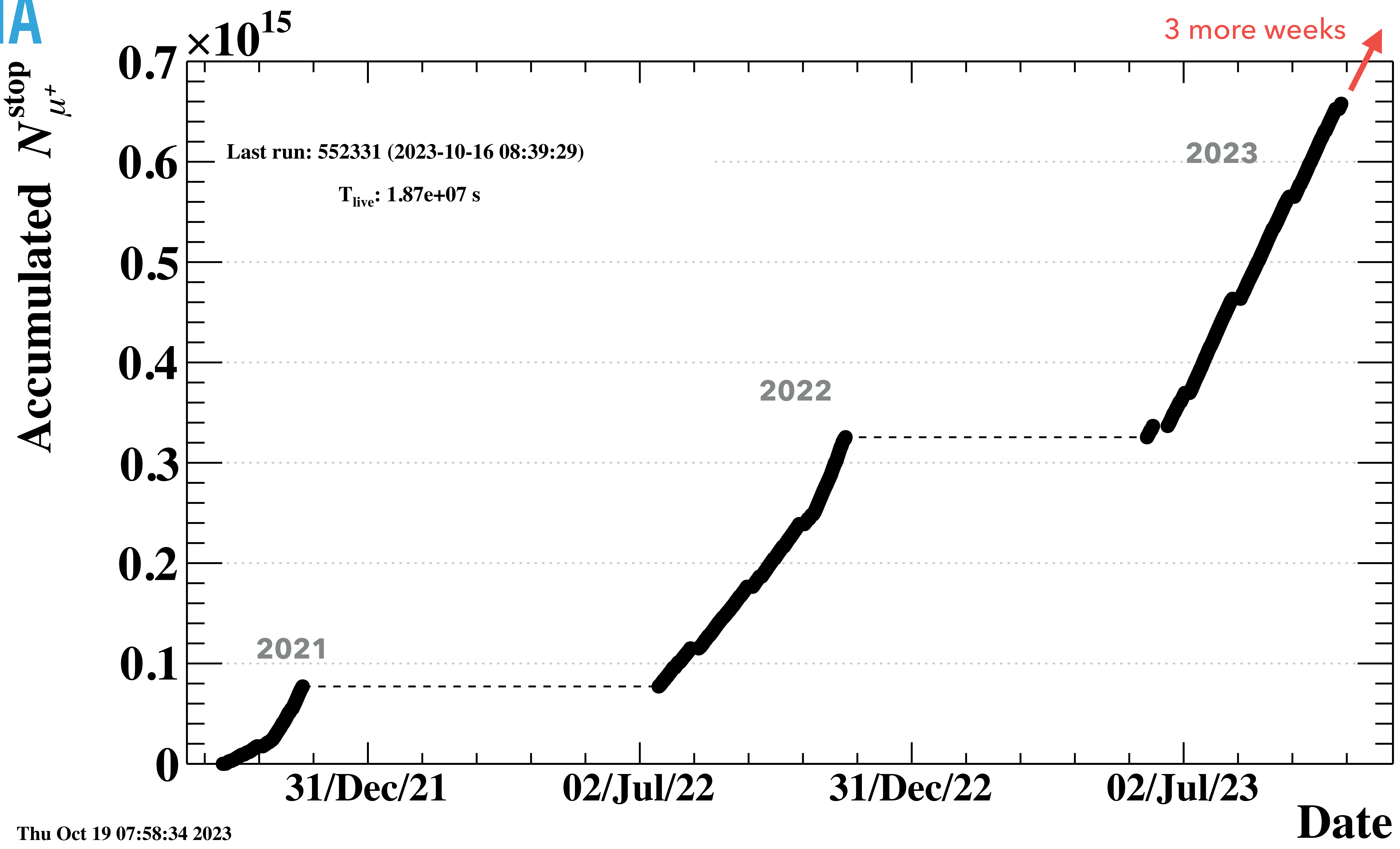
OPTIMIZING BEAM RATE R_μ

- Several beam rates $R_\mu = (2 - 5) \times 10^7$/s were tried to optimize sensitivity.
  - Higher R_μ for more statistics in a fixed Run time
  - Higher R_μ increases pileup & degrades $\varepsilon_{\mathrm{e^+CDCH}}$
  - Background increases as $(R_\mu)^2$
  - Rate capability of detectors & DAQ

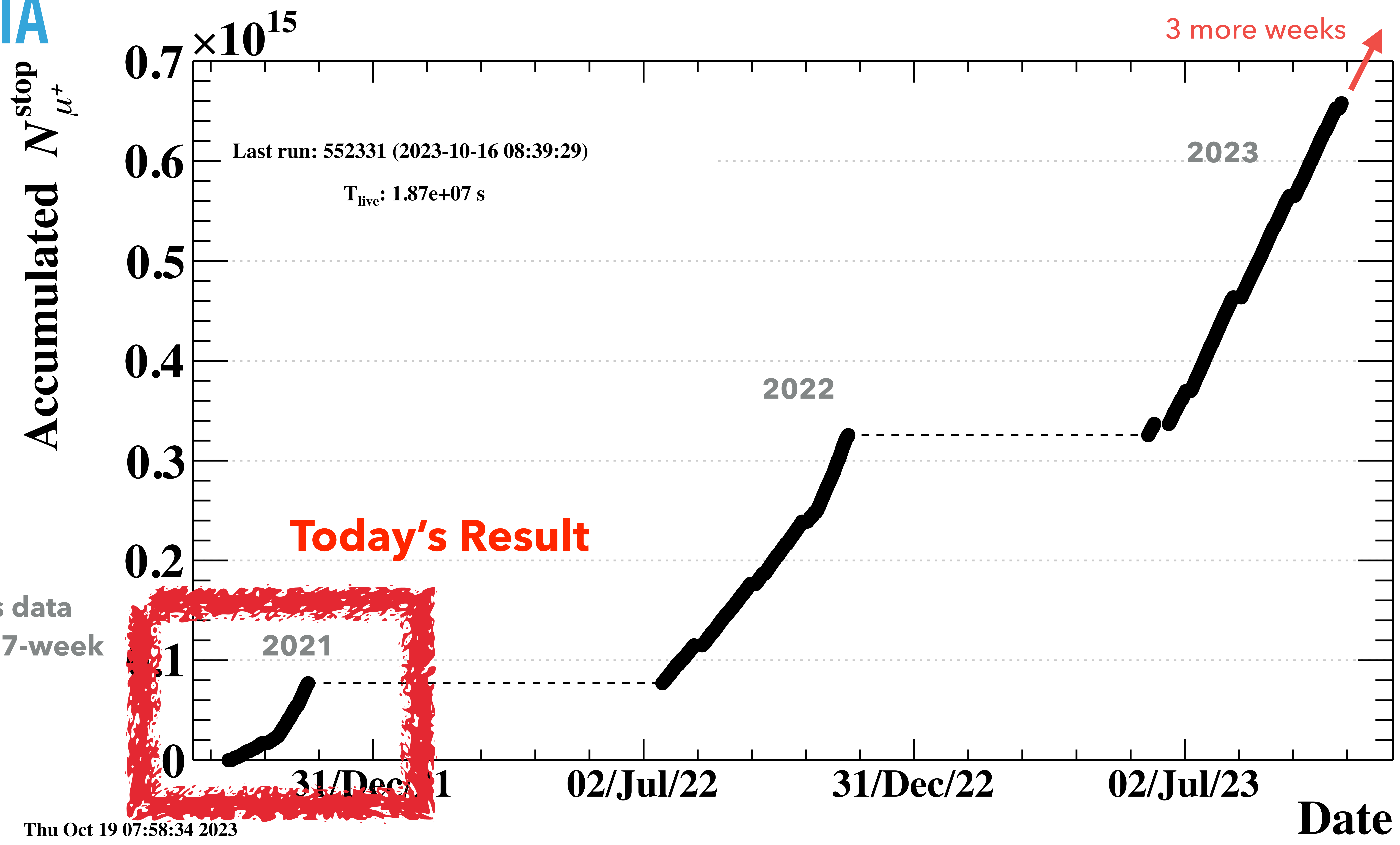
    MPPC PDE degradation turned out to be OK
- Running fractions (13%, 41%, 20%, 26%)
  - for (2, 3, 4, 5) $\times 10^7$/s with trigger rates 4-20Hz



MEG II DATA

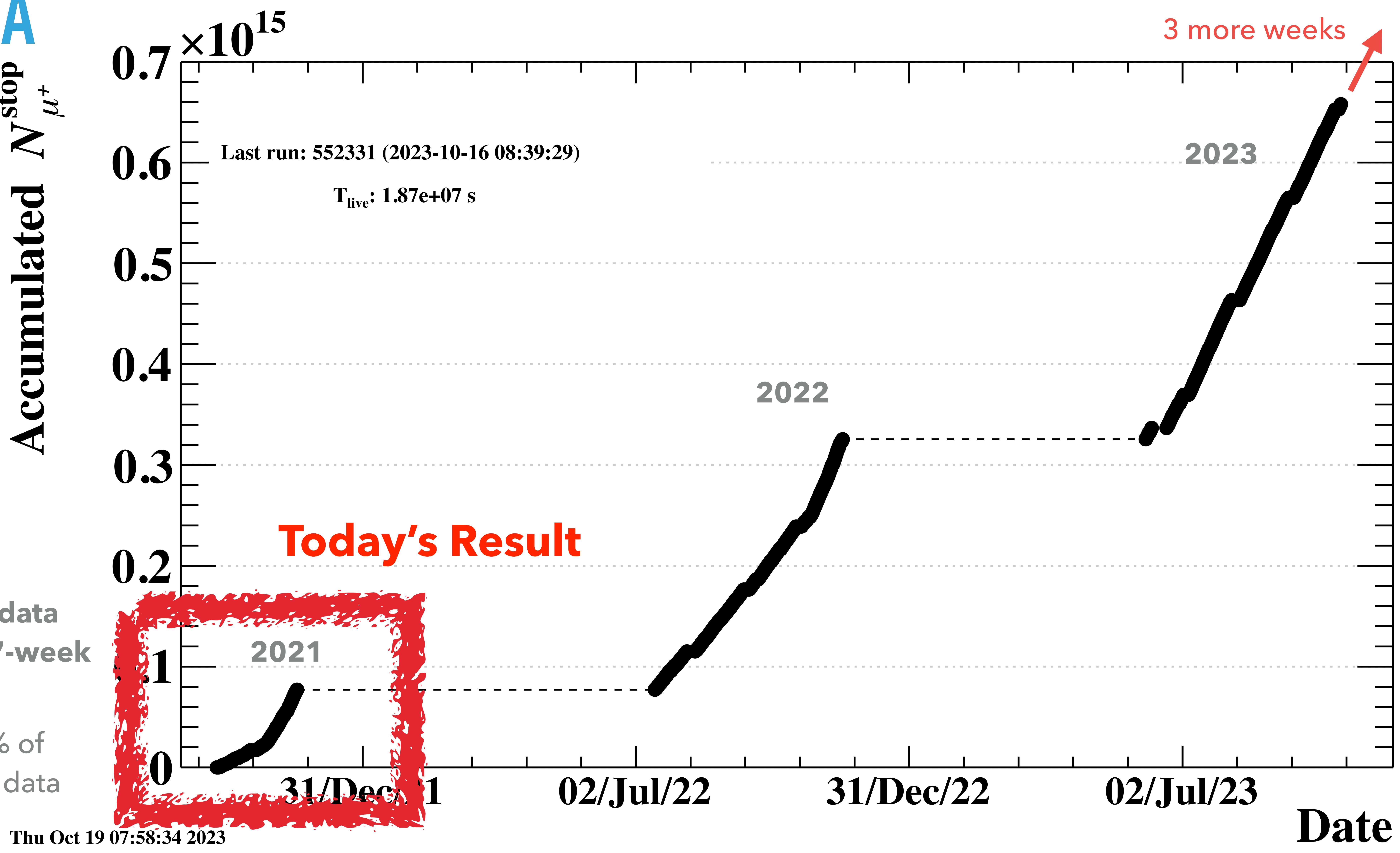

$\times 10^{15}$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Accumulated $N_{\mu^+}^{stop}$
Last run: 552331 (2023-10-16 08:39:29)
T_{live}: 1.87e+07 s
2021
2022
2023
3 more weeks
31/Dec/21
02/Jul/22
31/Dec/22
02/Jul/23
Date
Thu Oct 19 07:58:34 2023

MEG II DATA



The first physics data obtained in the 7-week Run in 2021

MEG II DATA



The first physics data obtained in the 7-week Run in 2021

Sensitivity ~60% of the whole MEG data (2009-2013)

BLIND & LIKELIHOOD ANALYSIS

- Blinded: $48 < E_\gamma < 58\text{MeV}, |t_{e\gamma}| < 1\text{ns}$
- Unbinned maximum likelihood

nuisance parameters

$$\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{ACC}}, x_{\text{T}}) =$$

$$\frac{e^{-(N_{\text{sig}}+N_{\text{RMD}}+N_{\text{ACC}})}}{N_{\text{obs}}!} C(N_{\text{RMD}}, N_{\text{ACC}}, x_{\text{T}}) \times$$

constrained

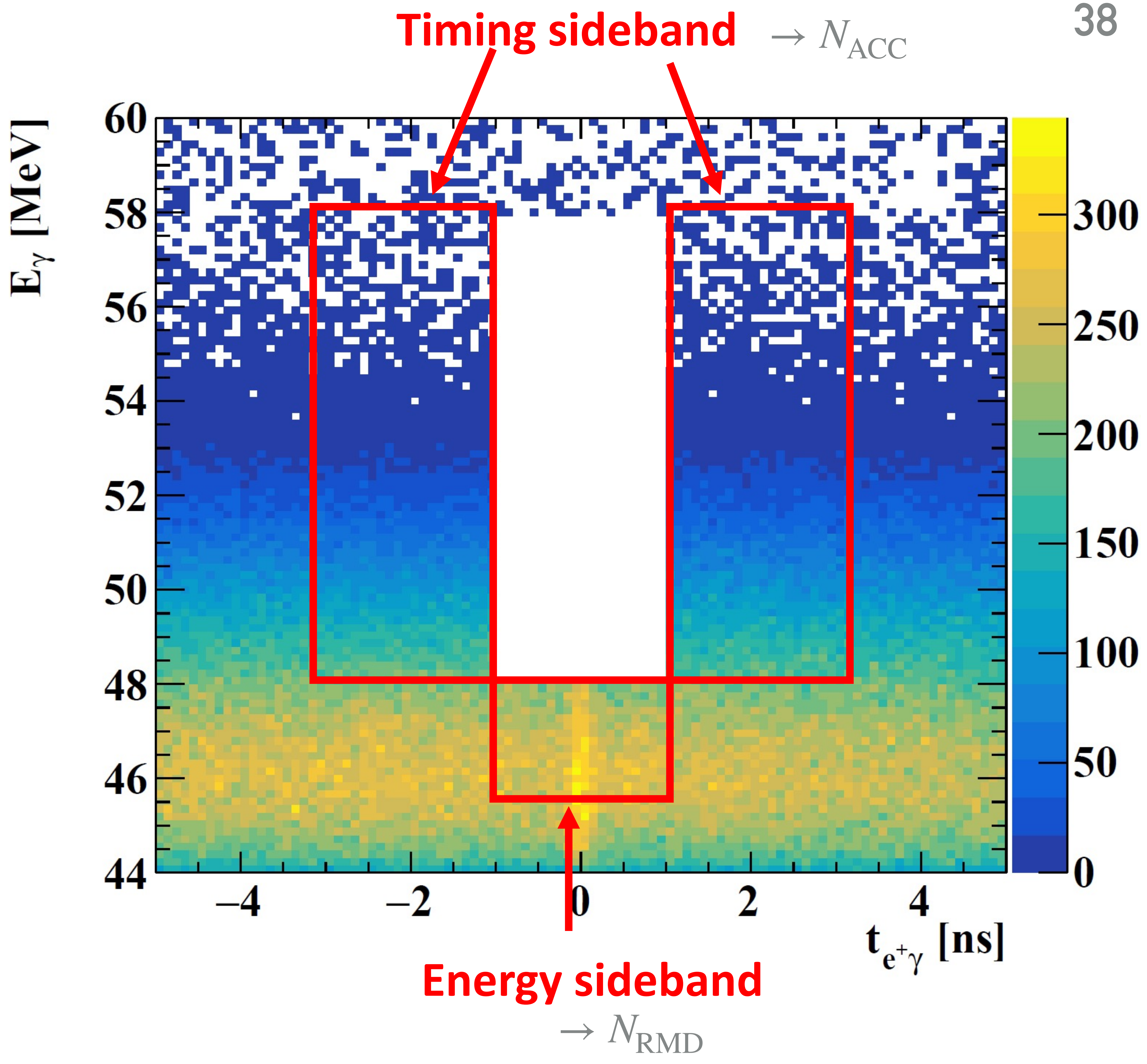
constrained by sideband

$$\prod_{i=1}^{N_{\text{obs}}} (N_{\text{sig}} S(\vec{x}_i) + N_{\text{RMD}} R(\vec{x}_i) + N_{\text{ACC}} A(\vec{x}_i))$$

per-event PDFs

$\vec{x}_i = (E_{\text{e}}, E_\gamma, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}, \Delta t_{\text{RDC}}, E_{\text{RDC}}, n_{\text{pTC}})$

x_{T} represents the target misalignment uncertainty



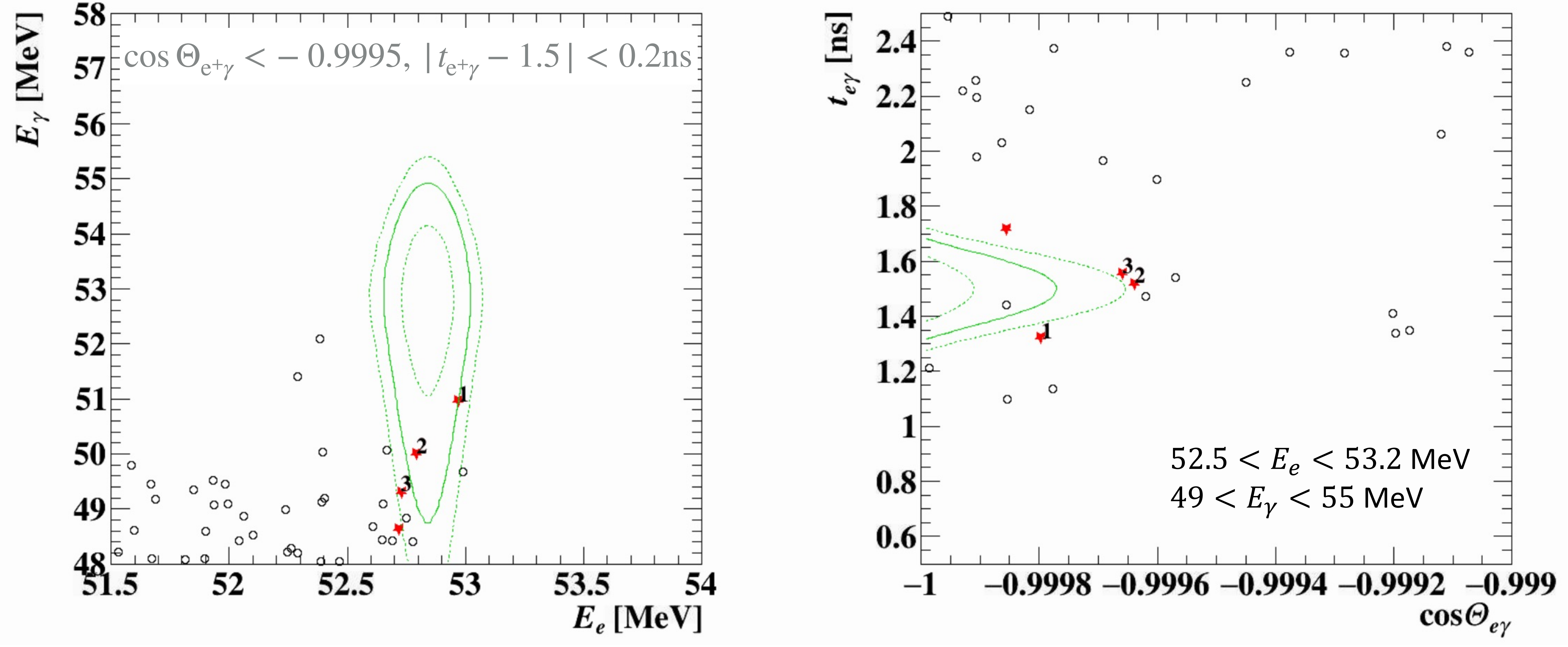
Analysis Region

$48 < E_\gamma < 58\text{MeV}$ $\quad 52.2 < E_{e^+} < 53.5\text{MeV}$

$|t_{e^+\gamma}| < 0.5\text{ns}$ $\quad |\theta_{e^+\gamma}| < 40\text{mrad}$ $\quad |\phi_{e^+\gamma}| < 40\text{mrad}$

TIMING SIDEBAND

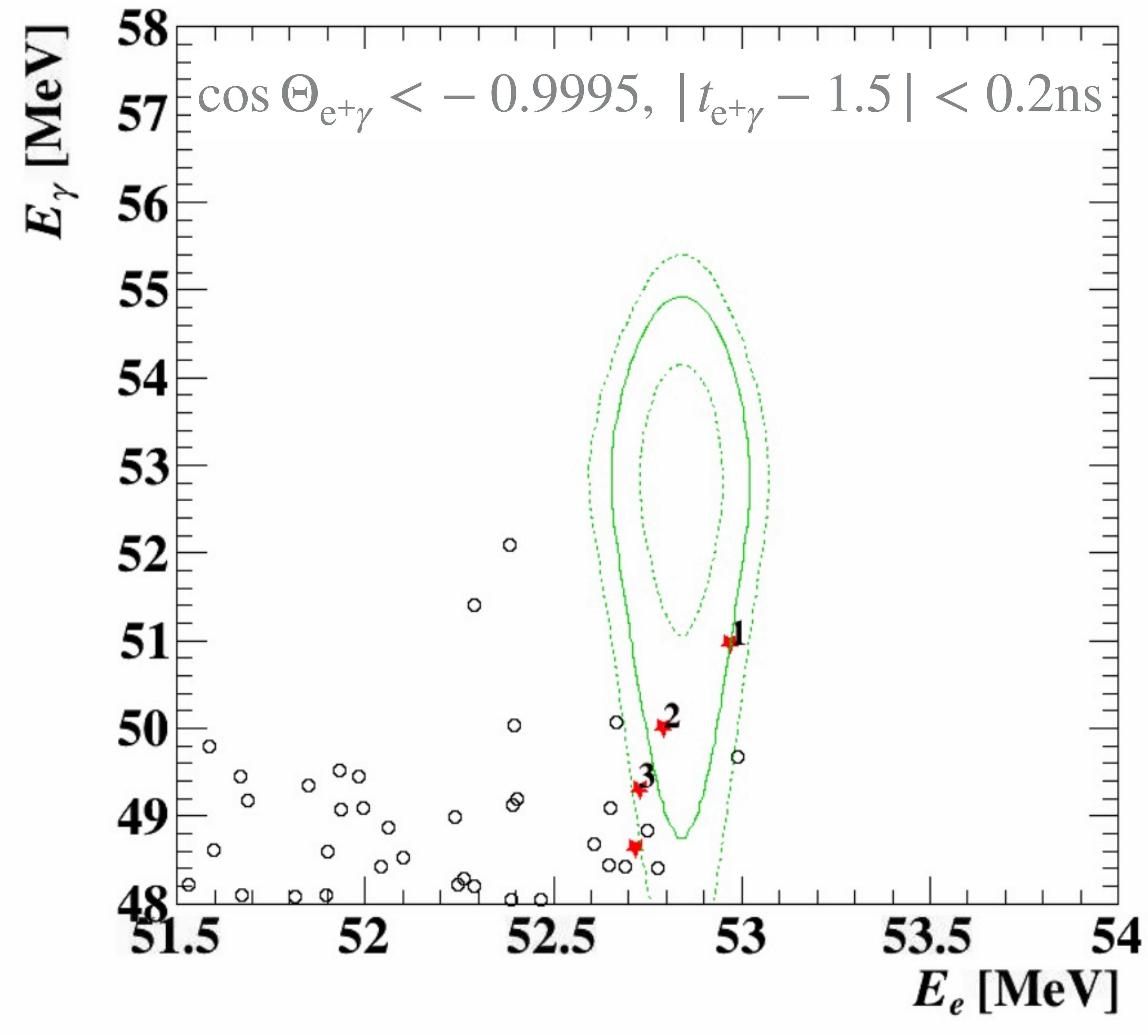
4D distribution

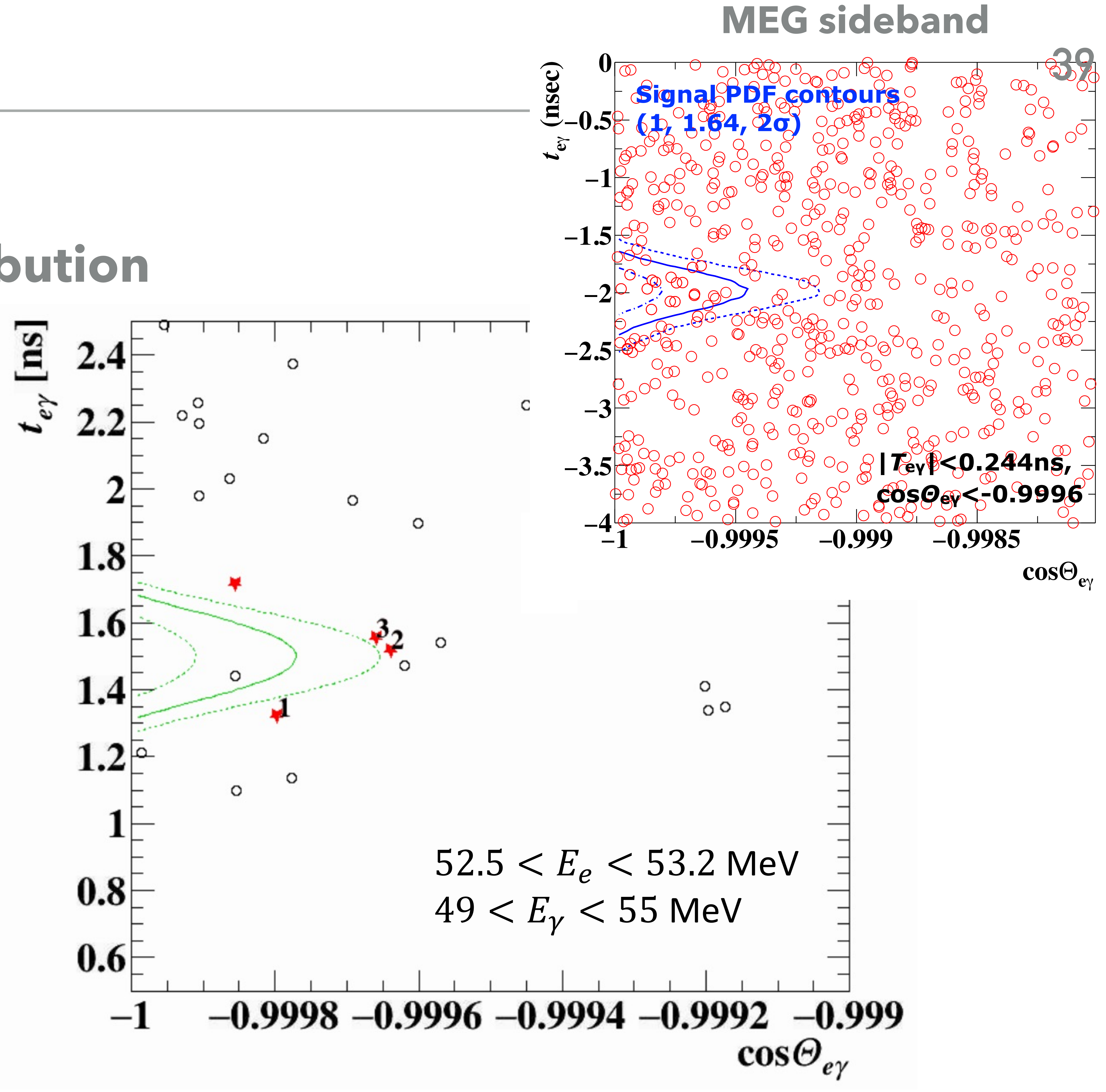


- **Sensitivity** $\mathcal{S}_{90}$, defined as median of distributions of 90% C.L. upper limits for an ensemble of pseudo-experiments with null-signal, is $\underline{8.8 \times 10^{-13}}$. cf. MEG 5.3×10^{-13}

TIMING SIDEBAND

4D distribution





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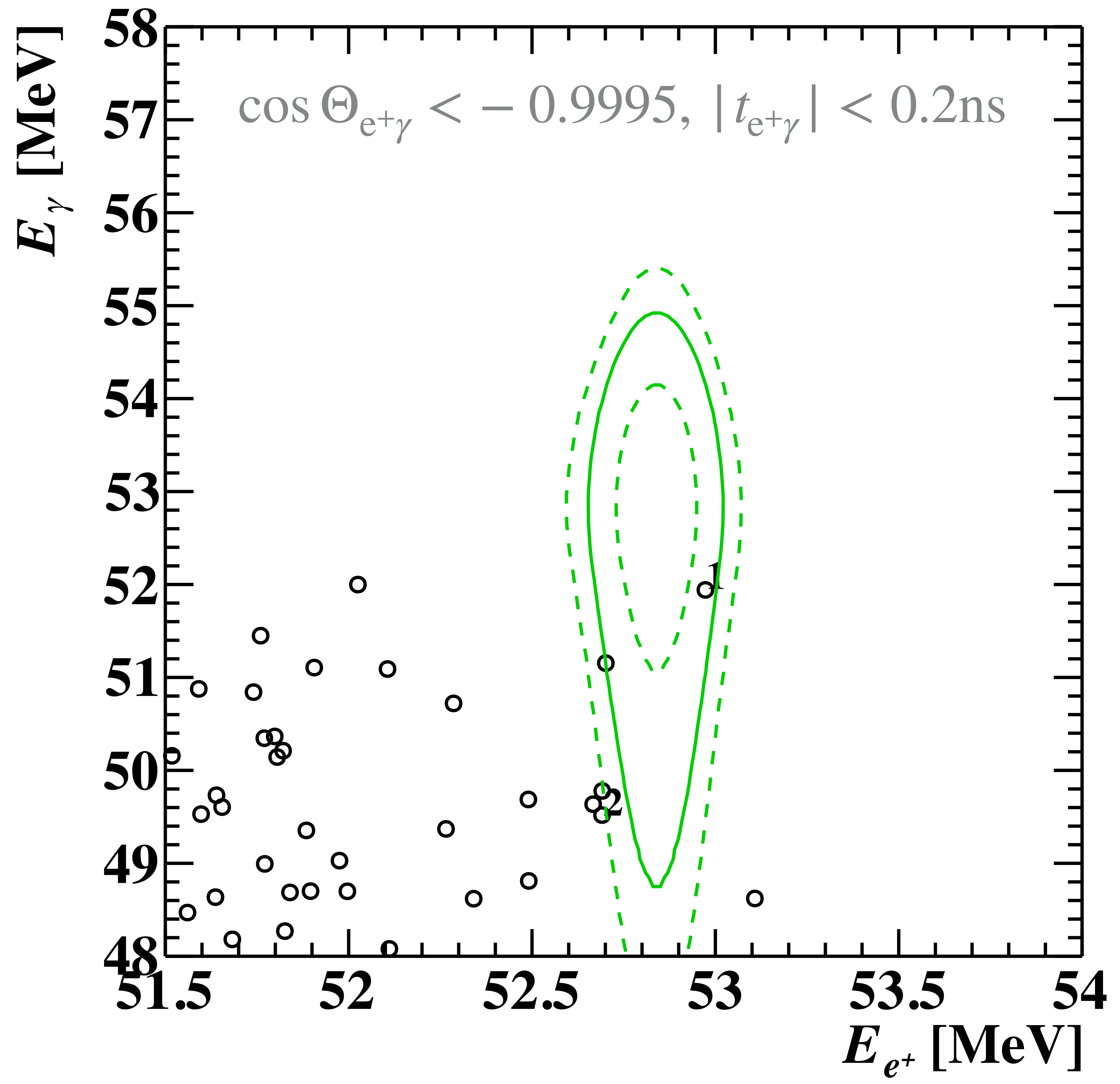
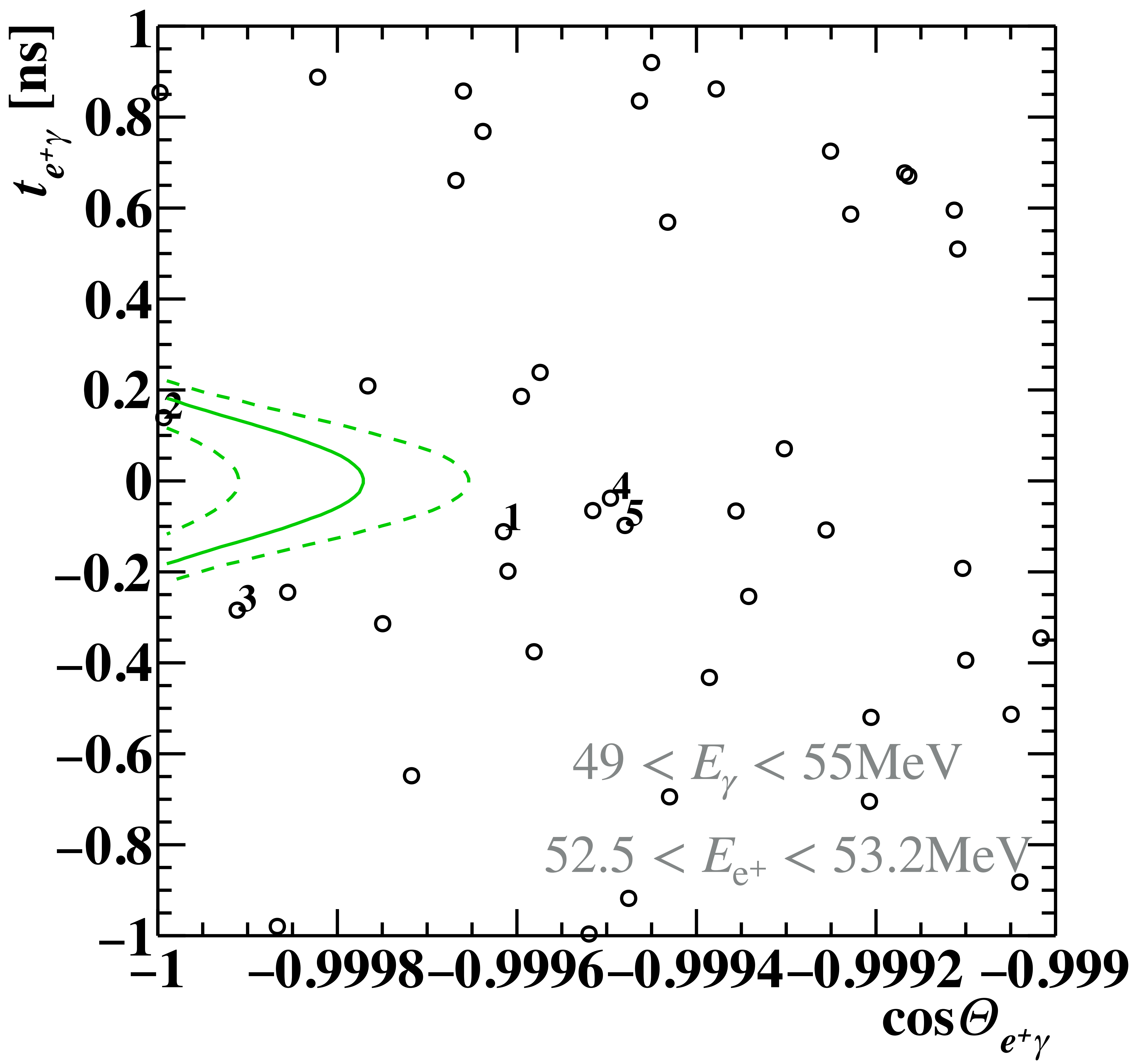
UNBLINDED 2021 DATA

UNBLINDED 2021 DATA

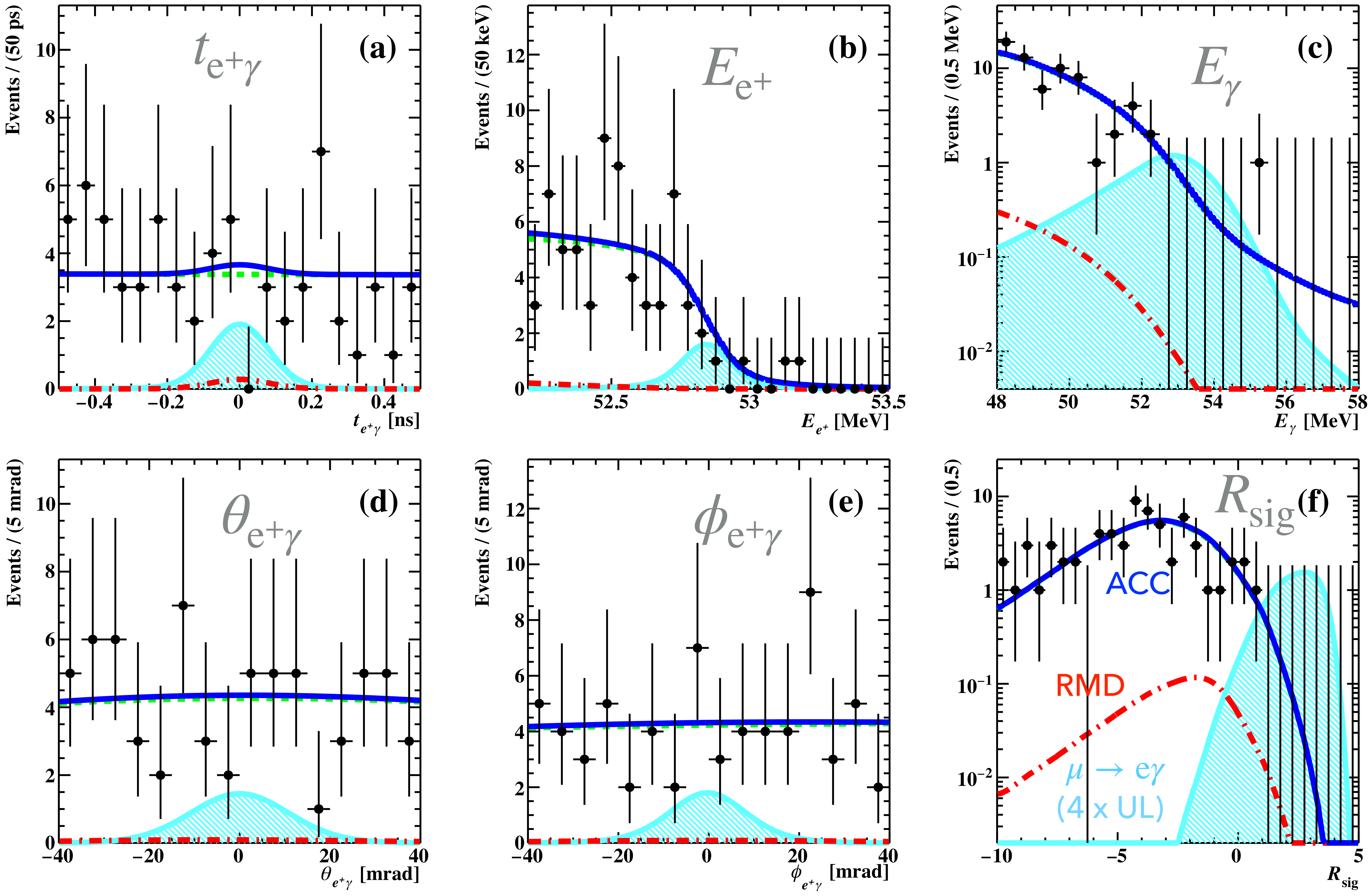
66 events in Analysis Region
(Sideband estimate 68.0 ± 3.5)

4D distribution





DATA & BEST-FITTED PDF DISTRIBUTIONS



(f) Relative signal likelihood

$$R_{\rm sig} = \log_{10}\left(\frac{S(x_i)}{f_{\rm RMD}R(x_i) + f_{\rm ACC}A(x_i)}\right)$$

$f_{\rm RMD} = 0.02,\ f_{\rm ACC} = 0.98$

OBSERVED PROFILE LIKELIHOOD RATIO

- Confidence interval for $N_{\mathrm{sig}} > 0$
  - à la Feldman-Cousins
  - Best fit branching ratio $\mathscr{B}_{\mathrm{fit}}$

$$\mathscr{B}_{\mathrm{fit}} = -1.1 \times 10^{-16}$$

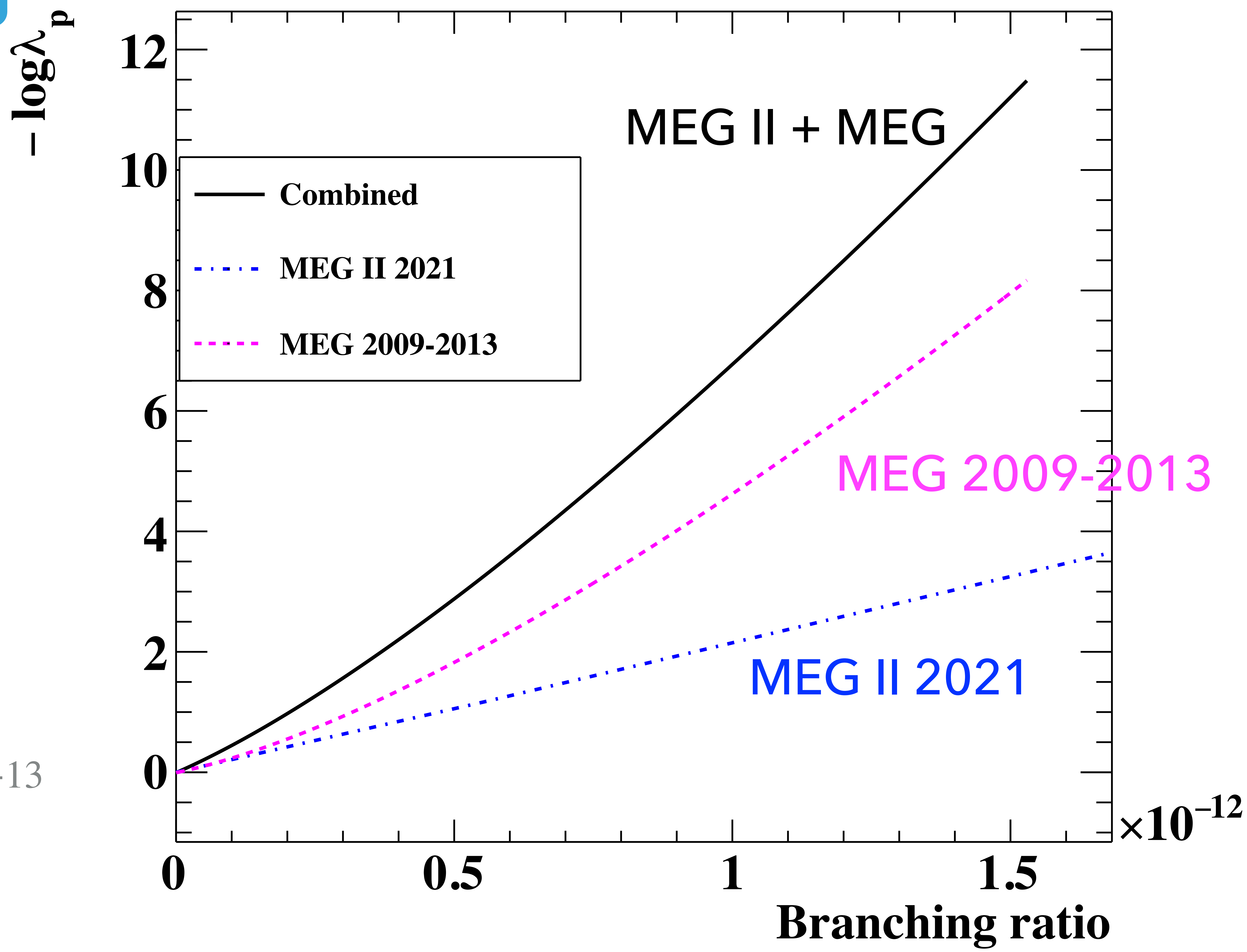
- 90% C.L. upper limit of branching ratio:

$$\mathscr{B}_{90} = 7.5 \times 10^{-13}$$

MEG: $\mathscr{B}_{90} = 4.2 \times 10^{-13}$

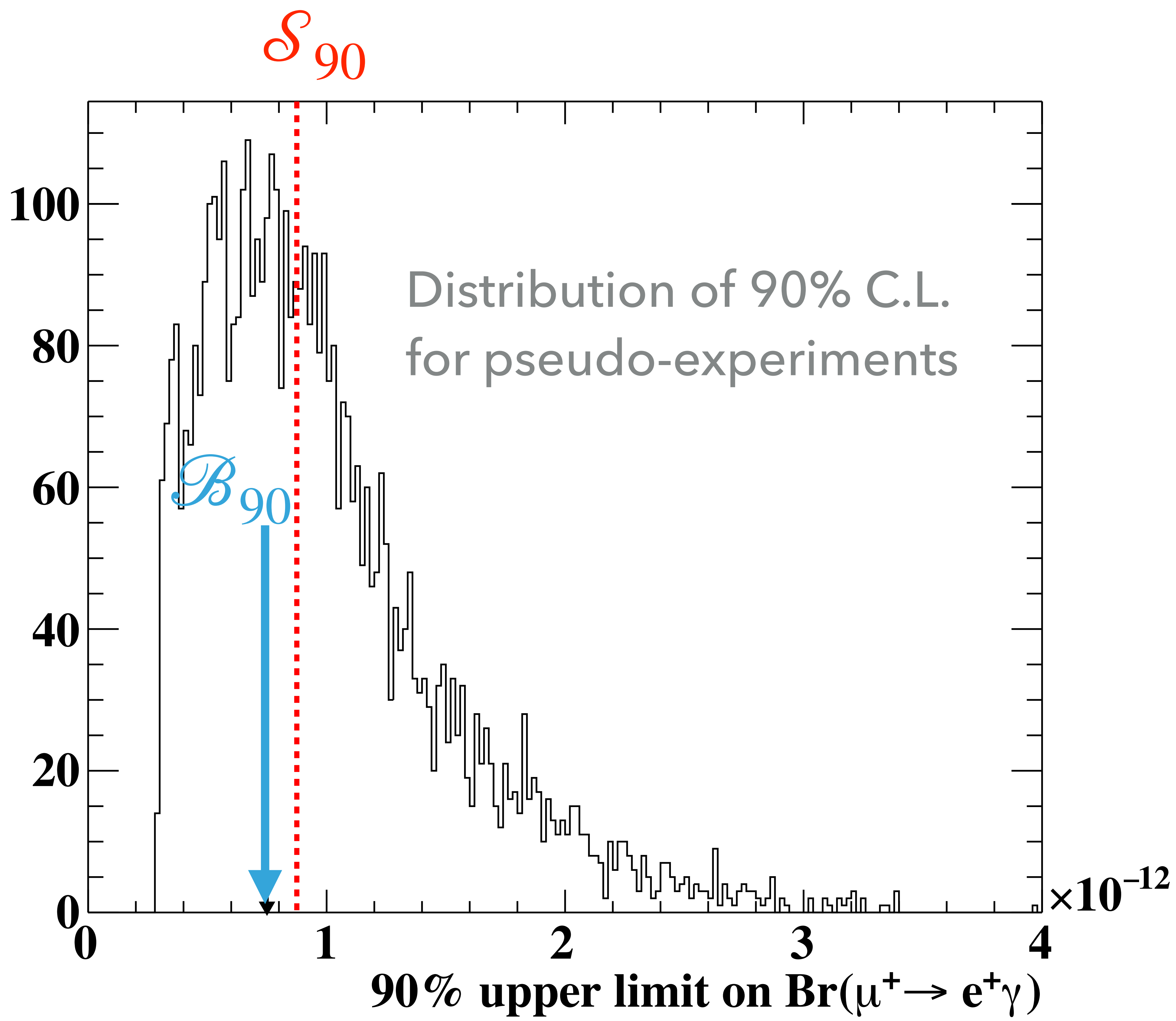
- MEG II + MEG combined:

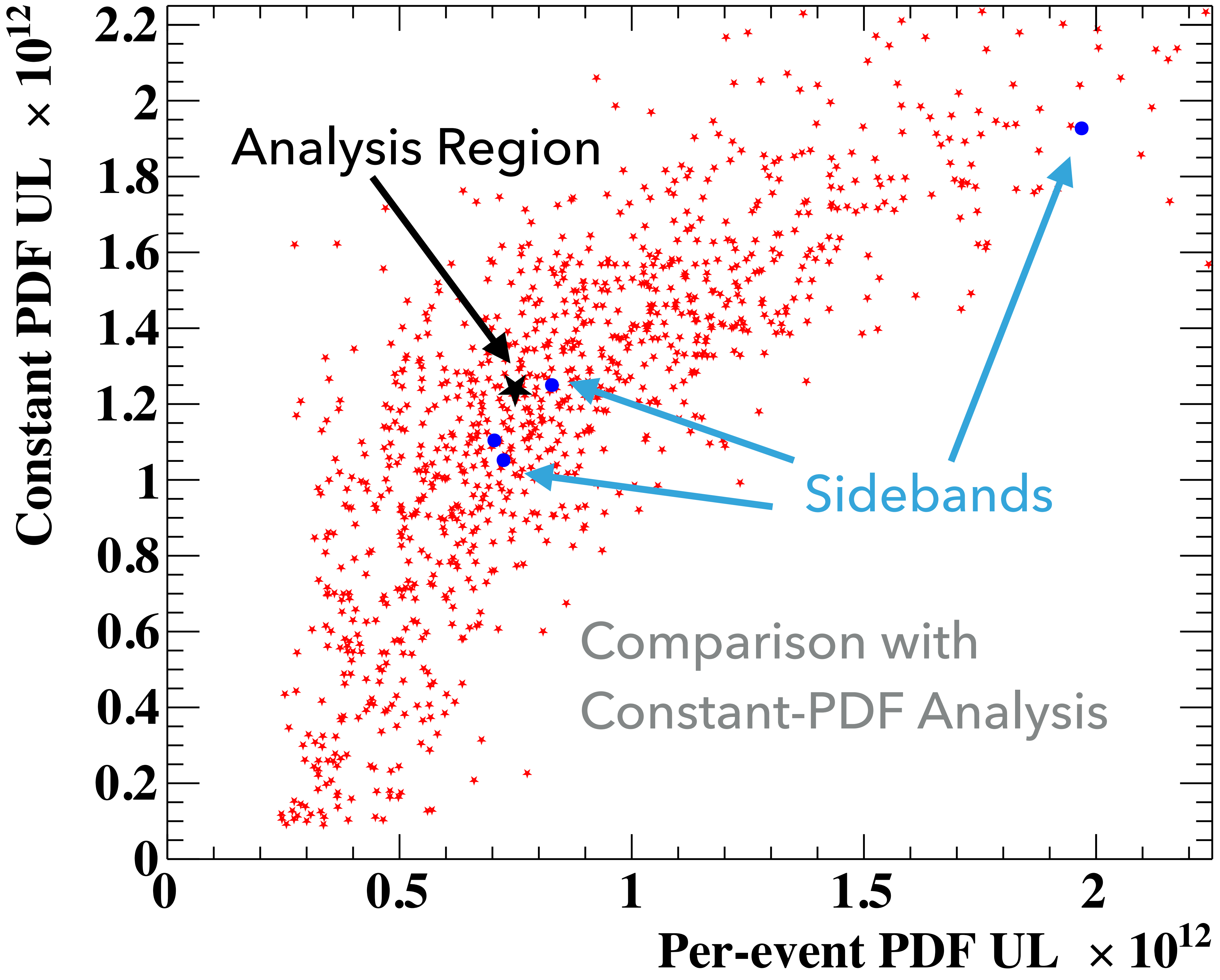
$$\mathscr{B}_{90} = 3.1 \times 10^{-13}$$



combined sensitivity: $\mathscr{S}_{90} = 4.3 \times 10^{-13}$

CONSISTENCY CHECK





Also: Likelihood fit with no constraints on N_{RMD} and N_{ACC} lead to a consistent result

SUMMARY AND PROSPECTS

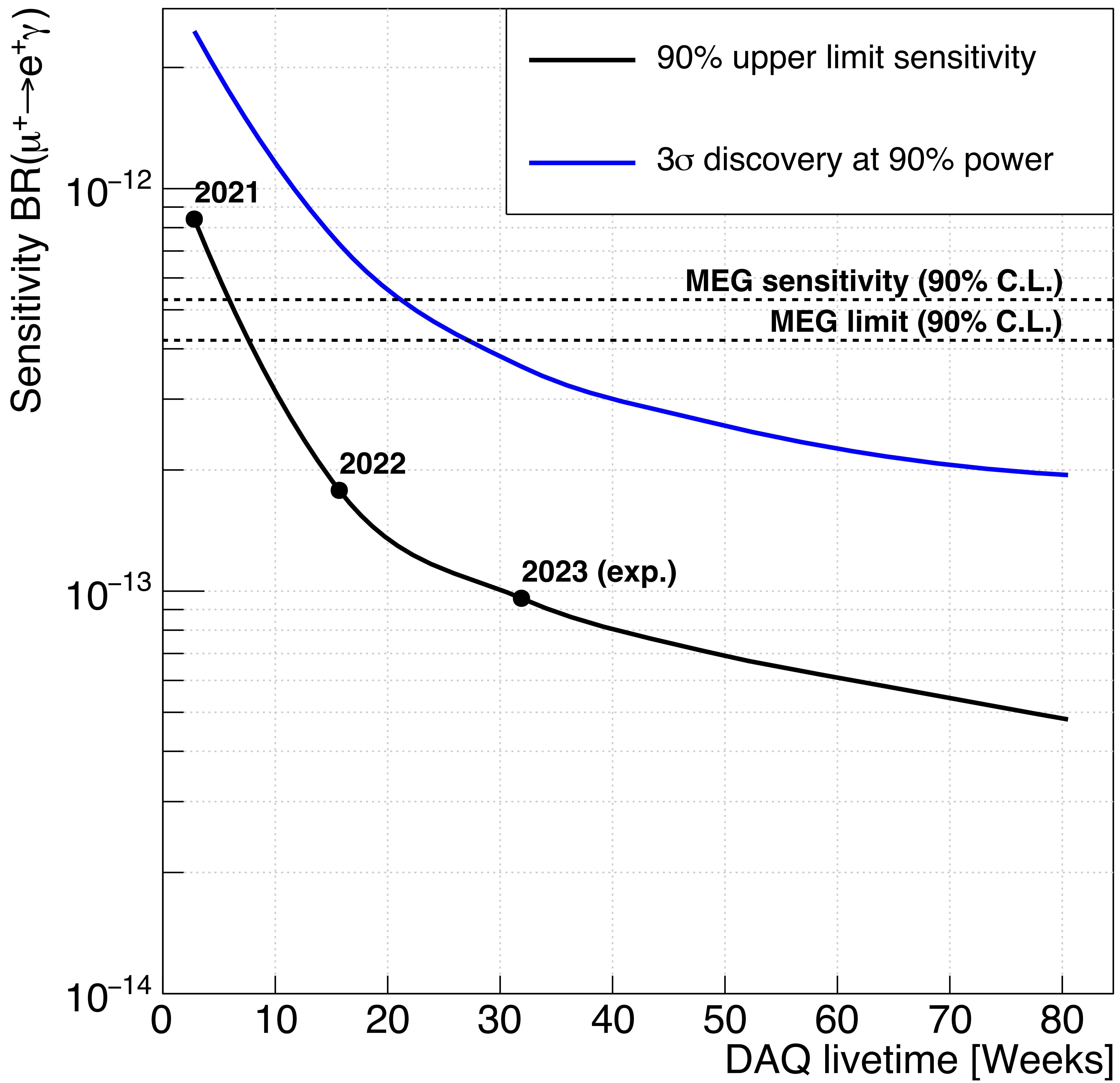
- The first 7-week data in 2021 achieved a Sensitivity ~60% of MEG 2009-2013.

$$\mathscr{B}_{90} = 7.5 \times 10^{-13}$$

- A combination MEG + MEG II provides the most stringent limit on the branching ratio of $\mu^+ \to e^+\gamma$

$$\mathscr{B}_{90} = 3.1 \times 10^{-13}$$

- Expected to finalize the 2022 data analysis in ~a half year.



arXiv:2310.12614, Submitted to EPJ C

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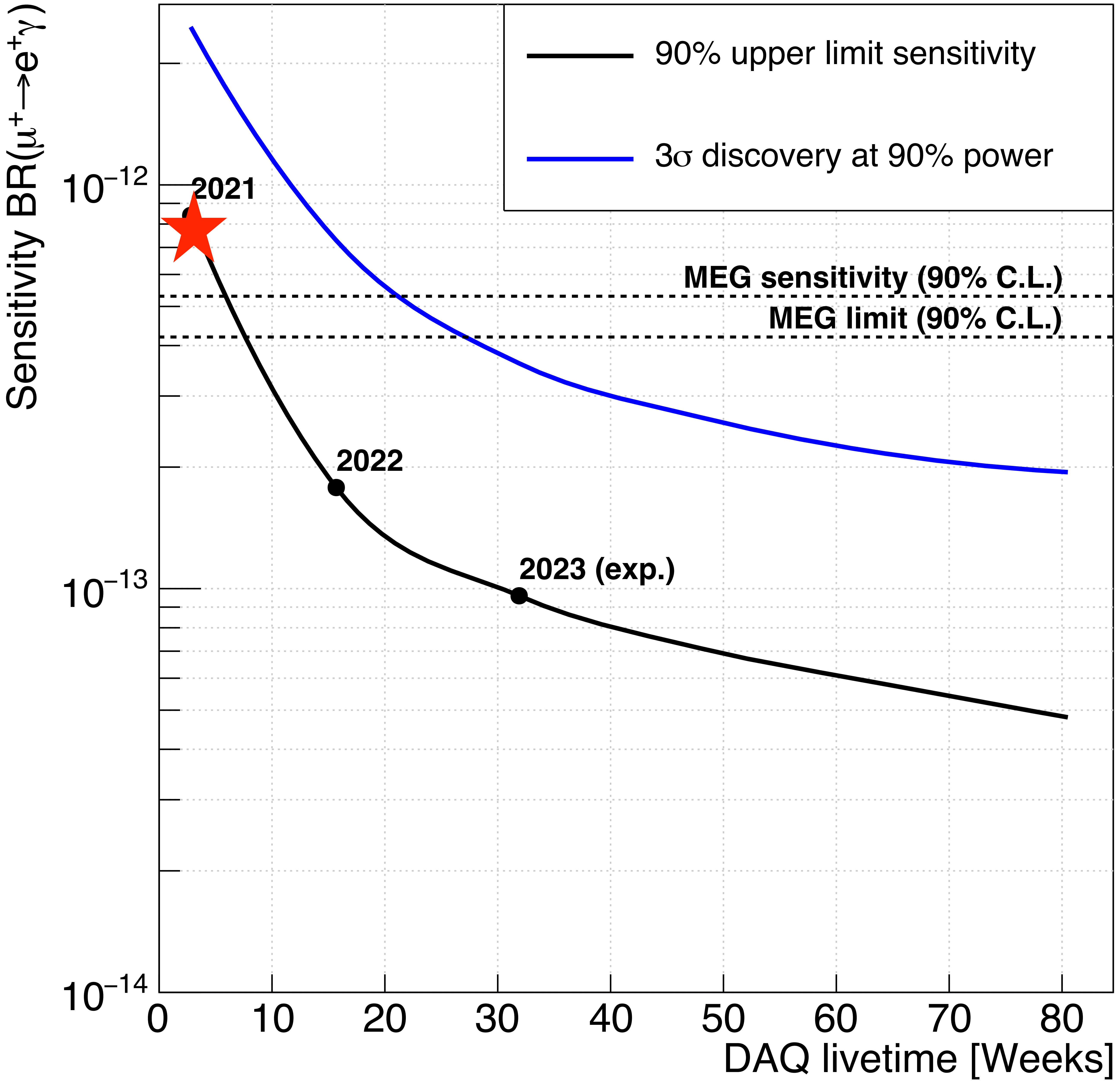

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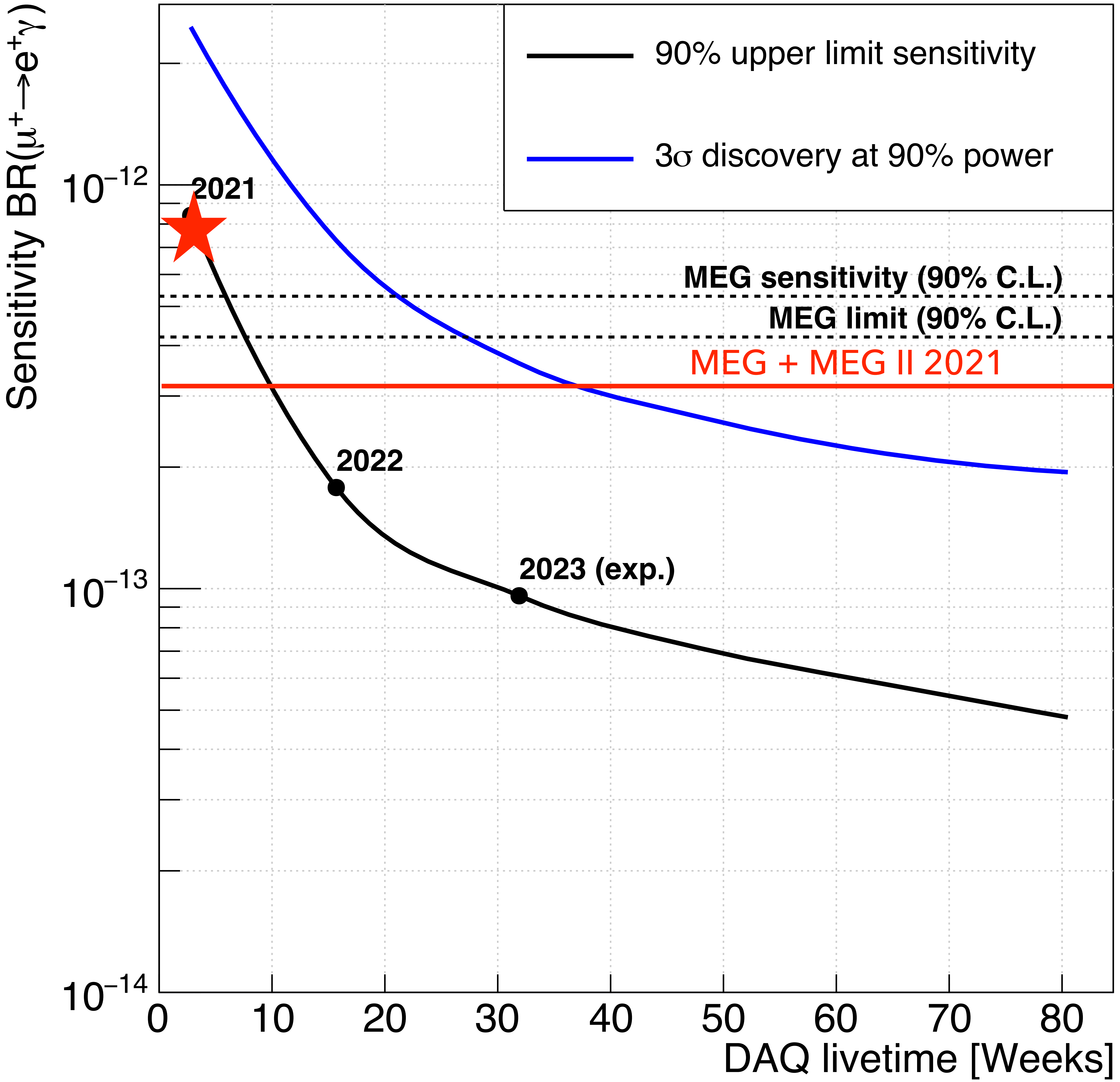

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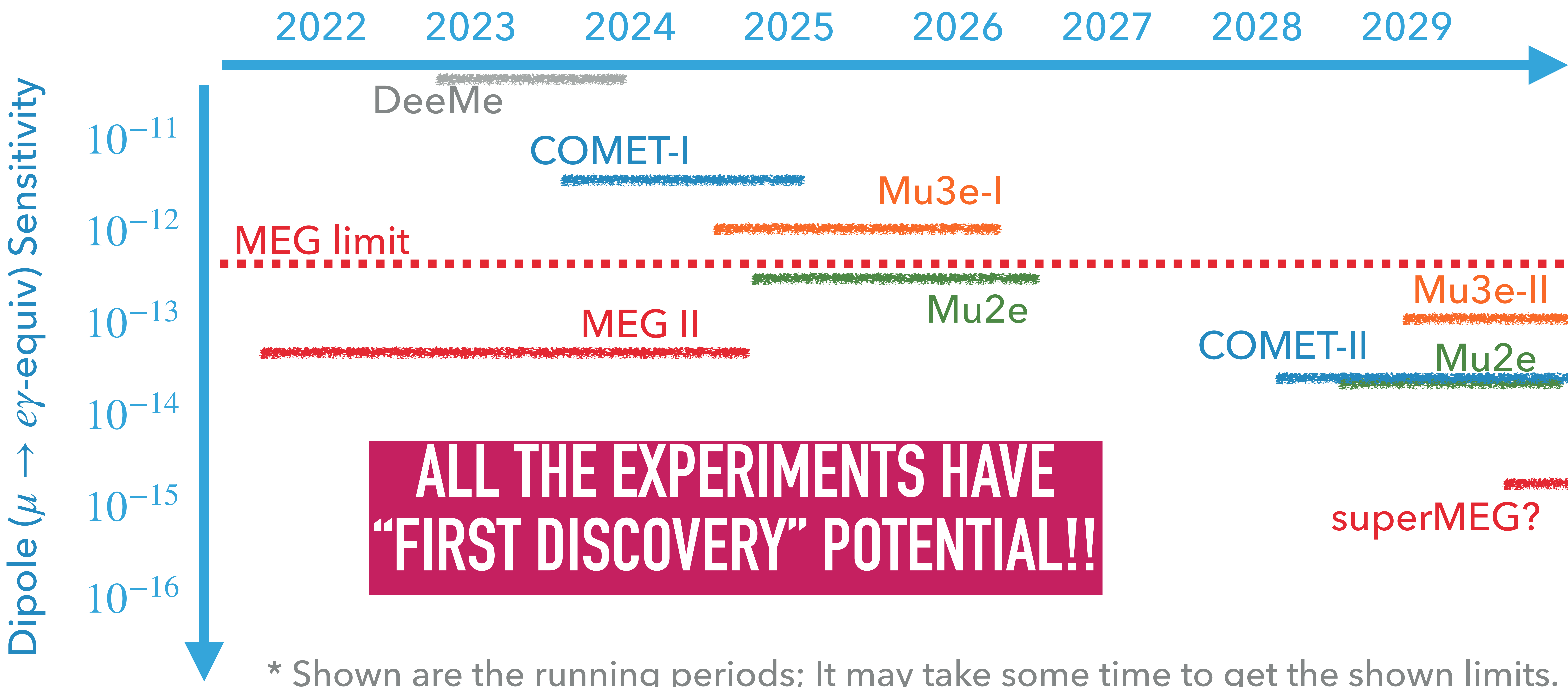
BACKUP SLIDES

TIMELINE OF MUON CLFV EXPERIMENTS

As presented at ICHEP2022, July 2022, by TM

PROSPECTS OF SENSITIVITY IMPROVEMENTS

As presented at ICHEP2022, July 2022, by TM



* Shown are the running periods; It may take some time to get the shown limits.