ICEPP
The University of Tokyo

$\mu \rightarrow e\gamma$ @MEG II
- First result and plans -

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on behalf of the MEG II collaboration

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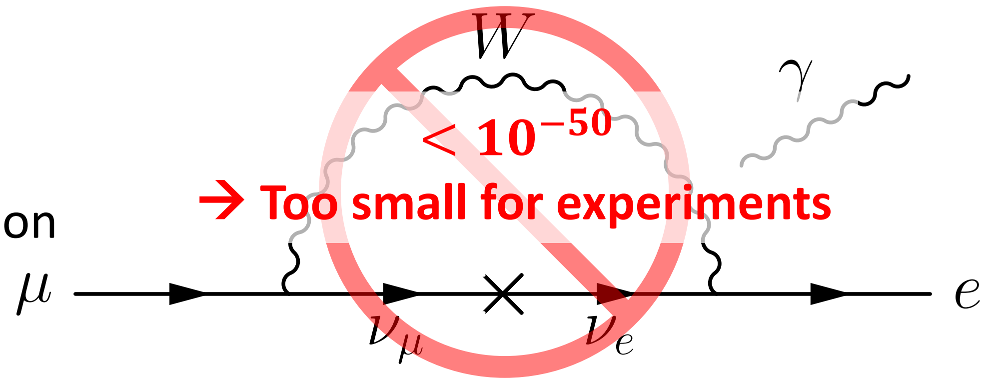
Outline

1. Introduction to $\mu \rightarrow e\gamma$

Motivation of MEG II

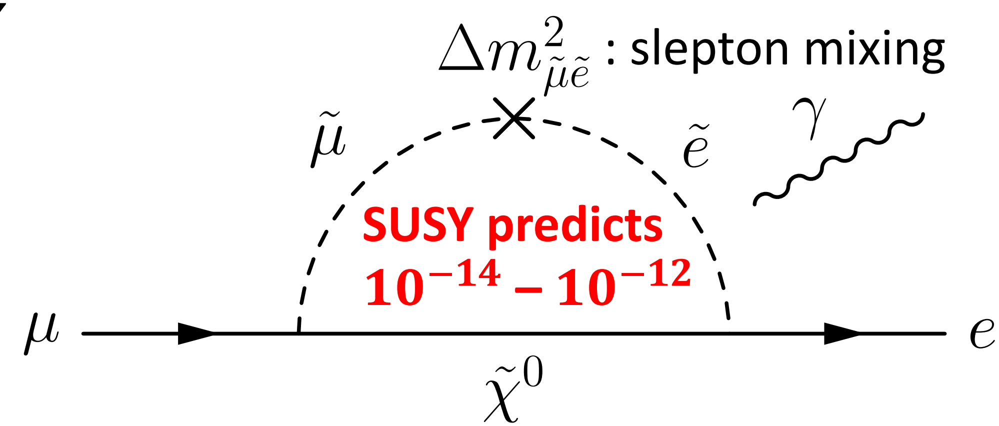
- $\mu \to e\gamma$ is prohibited in SM
  - No SM background is expected
  - Unexpected even with ν-oscillation

  → Clear evidence of new physics if discovered



- Theory expectation for $\mu \to e\gamma$
  - SUSY particles of O(10 TeV): 10^{-14} – 10^{-12} branching ratio

  →Experimentally reachable

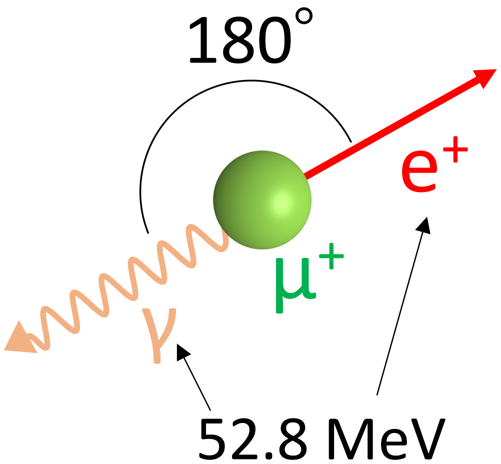


- MEG II: Search for $\mu \to e\gamma$
  - Target sensitivity: 6×10^{-14}
  - MEG sensitivity (2016): 5.3×10^{-13}
  - Aim first discovery of charged lepton flavor violation

How to detect $\mu \to e\gamma$?

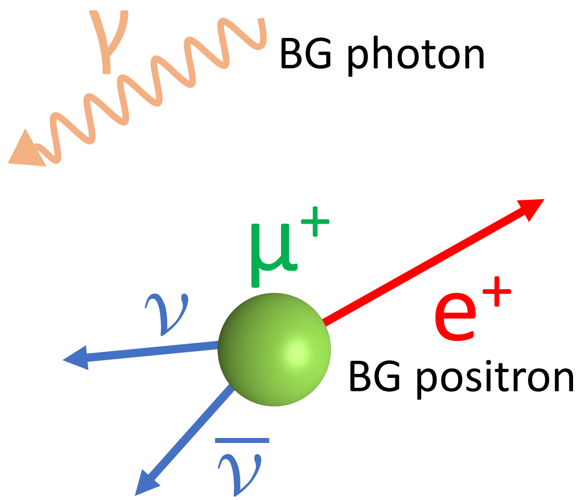
Signal

2-body kinematics



Main background

Accidental coincidence



RMD background

Radiative muon decay ($\mu \to e\nu\nu\gamma$)

→ **Negligible** (effectively 10^{-16})

Different kinematics

	Signal	Main background
E_e	52.8	< 52.8
E_γ	52.8	< 52.8
$t_{e\gamma}$	0	Flat distribution
$\Theta_{e\gamma}$	180°	No correlation

Strategy:

- **High rate**
- **High efficiency**
- **High resolution**

Outline

1. Introduction to $\mu \rightarrow e\gamma$
2. MEG II experiment
3. First result
4. Plan & Sensitivity

Operation and performance of the MEG II detector

The MEG II collaboration

K. Afanaciev [1], A. M. Baldini [2a], S. Ban [3], V. Baranov [1†], H. Benmansour [2ab], M. Biasotti [4a], G. Boca [5ab], P. W. Cattaneo [5a*], G. Cavoto [6ab], F. Cei [2ab], M. Chiappini [2ab], G. Chiarello [7a], A. Corvaglia [7a], F. Cuna [7ab***], G. Dal Maso[8,9], A. De Bari [5a], M. De Gerone [4a], L. Ferrari Barusso [4ab], M. Francesconi [10], L. Galli [2a], G. Gallucci [4a], F. Gatti [4ab], L. Gerritzen [3], F. Grancagnolo [7a], E. G. Grandoni [2ab], M. Grassi [2a], D. N. Grigoriev [11,12,13], M. Hildebrandt [8], K. Ieki [3], F. Ignatov [14], F. Ikeda [3], T. Iwamoto [3], S. Karpov [11,13], P.-R. Kettle [8], N. Khomutov [1], S. Kobayashi [3], A. Kolesnikov [1], N. Kravchu ... ev [1], A. Matsush ... F. Morsani ... [3], R. Onda [3], ... nacci [6a], A. Popov [11,13], F. Raffaelli [2a], F. Renga [6a], S. Ritt [8], M. Rossella [5a], A. Rozhdestvensky [1], P. Schwendimann [8], K. Shimada [3], G. Signorelli [2a], A. Stoykov [8], M. Takahashi [17], G.F. Tassielli [7ab****], K. Toyoda [3], Y. Uchiyama [3,17], M. Usami [3], A. Venturini [2ab], B. Vitali [2a,6b], C. Voena [6ab], K. Yamamoto [3], K. Yanai [3], T. Yonemoto [3], K. Yoshida [3], Yu.V. Yudin [11,13]**

https://arxiv.org/abs/2310.11902

(Accepted by EPJ-C)

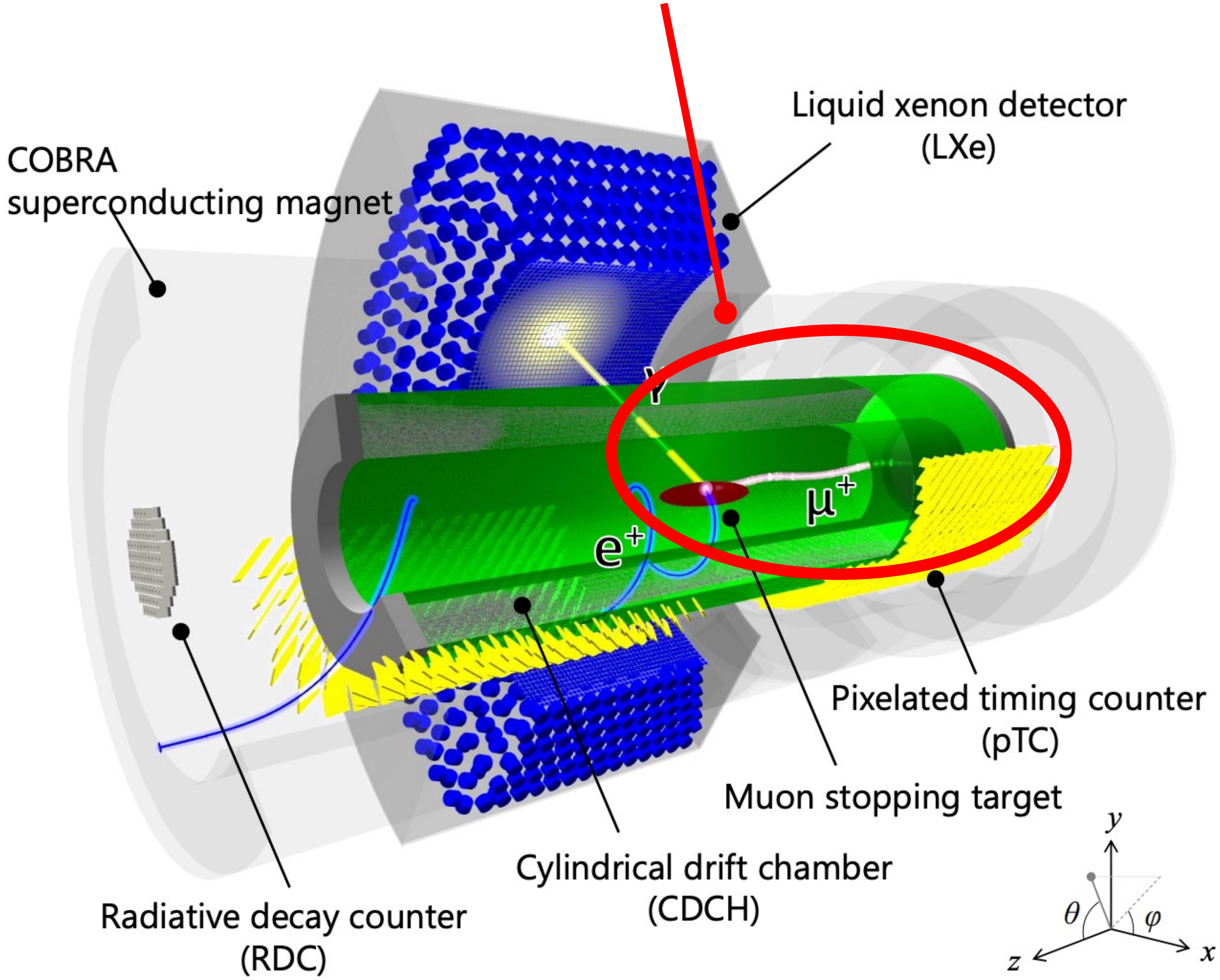
2. MEG II experiment

MEG II overview

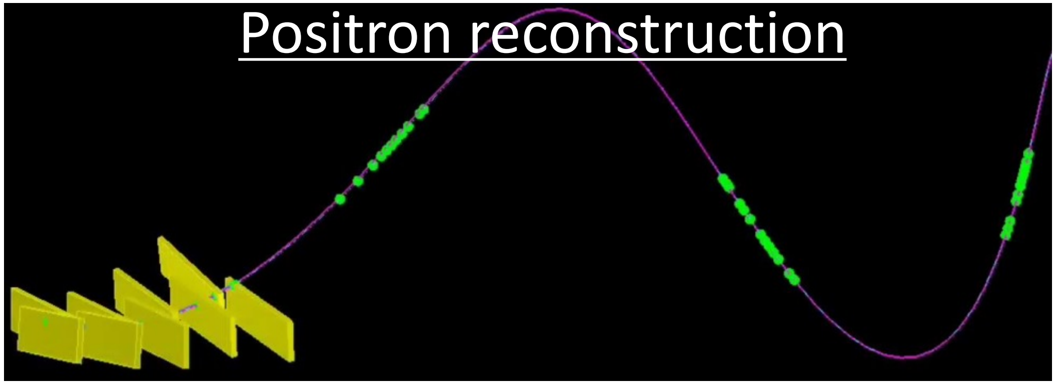
- **High rate**
  → **μ beam @PSI ($3-5\times 10^{7}$ μ/s) stopped on target**

Detectors with

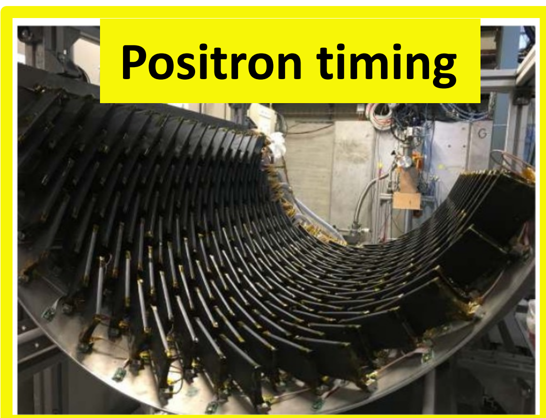
- **High efficiency**
- **High resolution**



Positron detector



Positron spectrometer
- **Gradient B-field**
- **Drift chamber for tracking**
- **Scintillation timing counter**

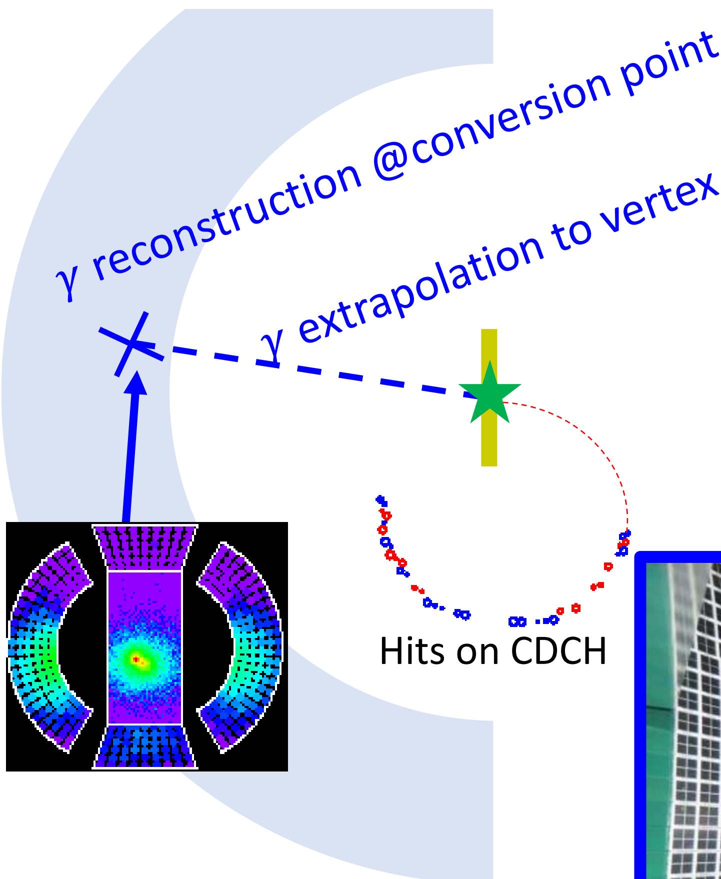


- 512 plastic counters in total
- 110 ps resolution / hit
- 9 hits (average) / 52.8 MeV track

- Wire chamber with stereo geometry
- High-density readout (2 – 3 cells / cm^2)
- Reduced material ($1.6\times10^{-3}\ X_0$)

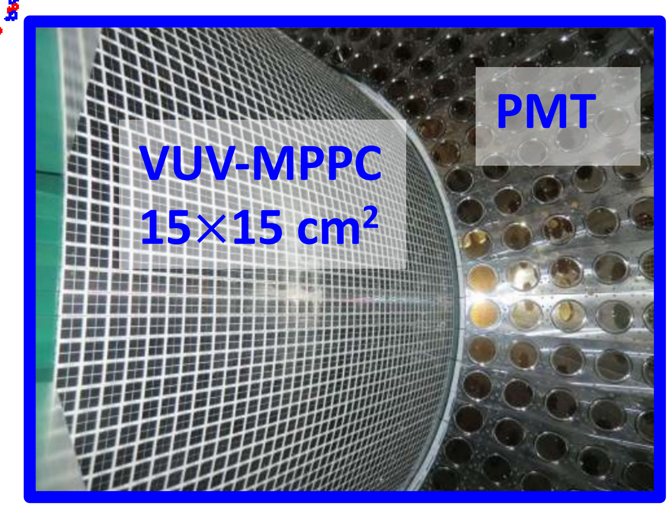
Photon detector

Photon reconstruction



Photon detector
- **LXe scintillator (900 L)**
- **VUV-sensitive sensors**

LXe properties
- High stopping power (X_0 =2.8 cm)
- High light yield (46000 photon/MeV)
- Fast response (45 ns decay time)
- Emission of VUV scintillation light (175 nm)



- 4092 MPPC (inner face)
  → Granular & uniform
- 668 PMT (other face)

Performance (vs MEG)

- Resolution improved from that in MEG experiment

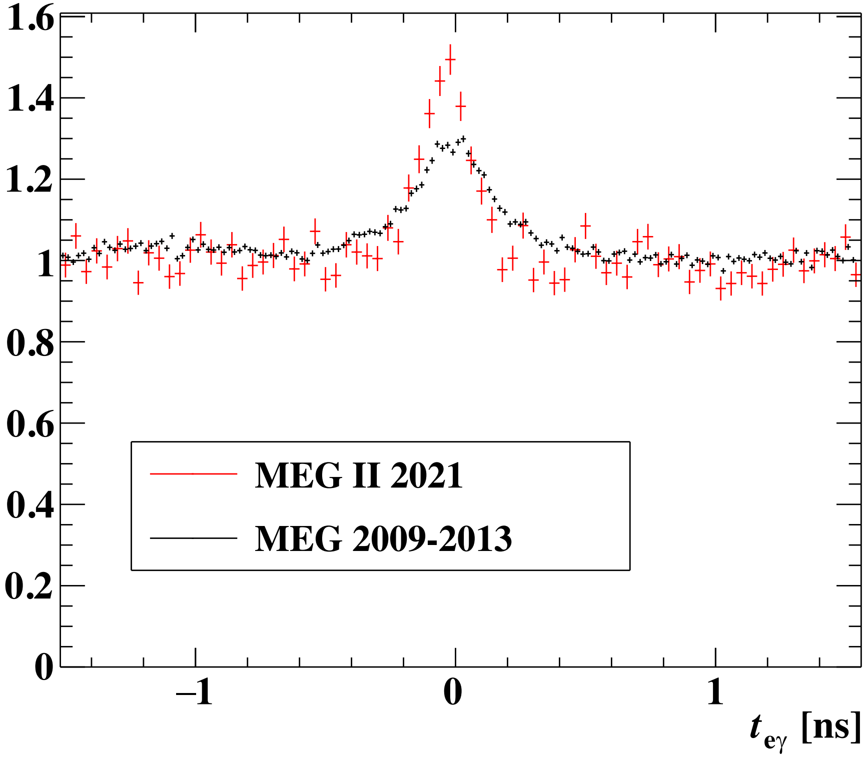
Resoluition	MEG performance	MEG II achieved value
E_e (keV)	320	90
θ_e (mrad)	9.4	7.2
ϕ_e (mrad)	8.7	4.1
z_e/y_e (mm) core	2.4/1.2	2.0/0.7
E_γ(%) (w<2 cm)/(w>2 cm)	2.4/1.7	2.0/1.8
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.5/2.5/5
$t_{e\gamma}$ (ps)	122	84

Efficiency (%)		
Trigger	≈ 99	~ 80
Gamma-ray	63	62
Positron	30	67

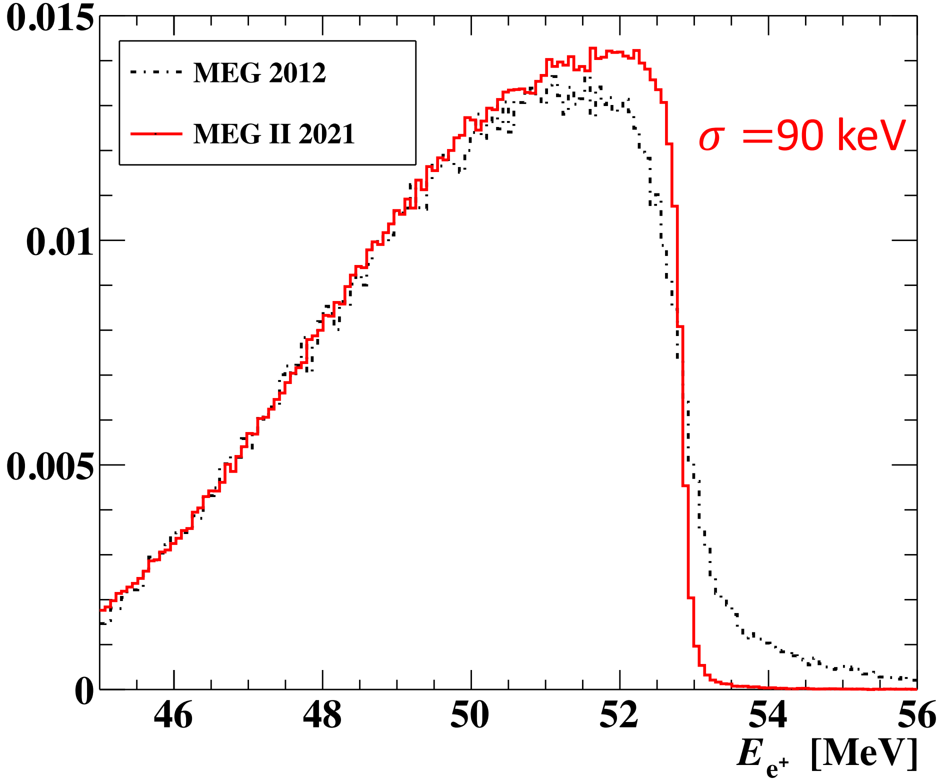
Performance (highlight)

- Resolution improved from that in MEG experiment

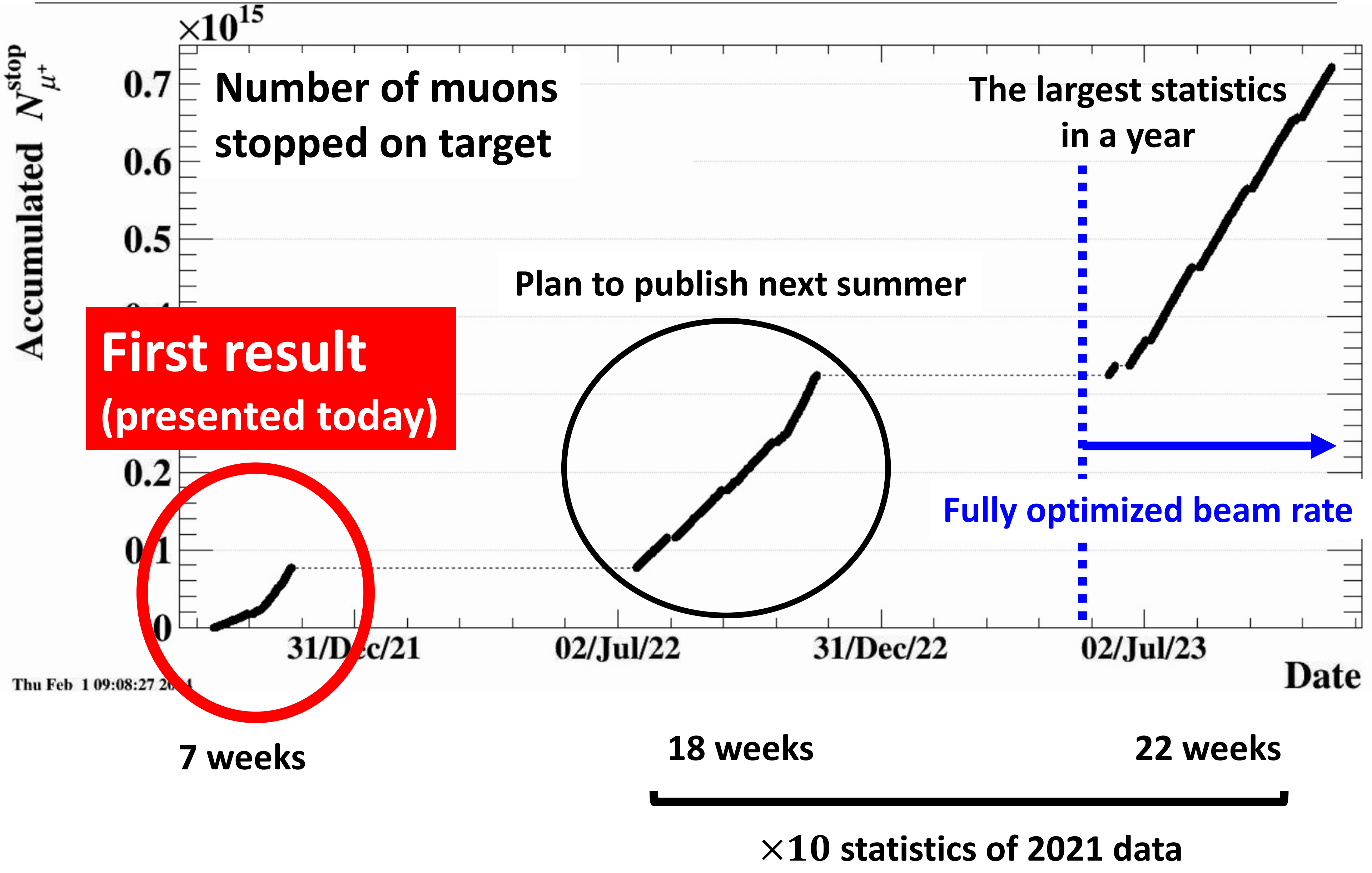
Time resolution improved by ×1.5
($\mu \rightarrow e\nu\nu\gamma$ samples in the peak)



Positron momentum improved by ×3.5
(Data samples: $\mu \rightarrow e\nu\nu$)



Data taking so far



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1. Introduction to $\mu \rightarrow e\gamma$
2. MEG II experiment
3. First result
4. Plan & Sensitivity

A search for $\mu^+ \rightarrow e^+\gamma$ with the first dataset of the MEG II experiment

The MEG II collaboration

K. Afanaciev [1], A. M. Baldini[2a], S. Ban [3], V. Baranov [1†], H. Benmansour[2ab],
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W. Ootani [3], A. Oya [3], D. Palo [15], M. Panareo [7ab], A. Papa [2ab8], V. Pettinacci [6a],
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https://arxiv.org/abs/2310.12614

(Accepted by EPJ-C)

3. First result (With 2021 data)

How many muons were measured?

- Normalization factor: k
  - Number of effectively measured muons

$$Br(\mu \to e\gamma) = \frac{N_{sig}}{k}$$

- $k_{2021} = (2.64 \pm 0.12) \times 10^{12}$
  1. Evaluation by background positron counting in dedicated dataset
  2. Evaluation by counting $\mu \to e\nu\nu\gamma$ events

  → Can automatically include efficiency factors

Breakdown of k-factor

	Value	Inclusion in counted number
Stopped muons	7.7×10^{13}	Included in both count
Geometrical acceptance	11%	Included in both count
$\epsilon_{positron}$ (average)	67%	Included in both count
ϵ_{photon}	62%	Included in $\mu \to e\nu\nu\gamma$ count
$\epsilon_{trigger}$	80%	Partly included in $\mu \to e\nu\nu\gamma$ count
ϵ_{DAQ}	85%	Included in both count

Improved in 2022 DAQ. ($\epsilon_{trigger}$, ϵ_{DAQ})

Analysis framework

- Extended un-binned likelihood to estimate N_{sig}

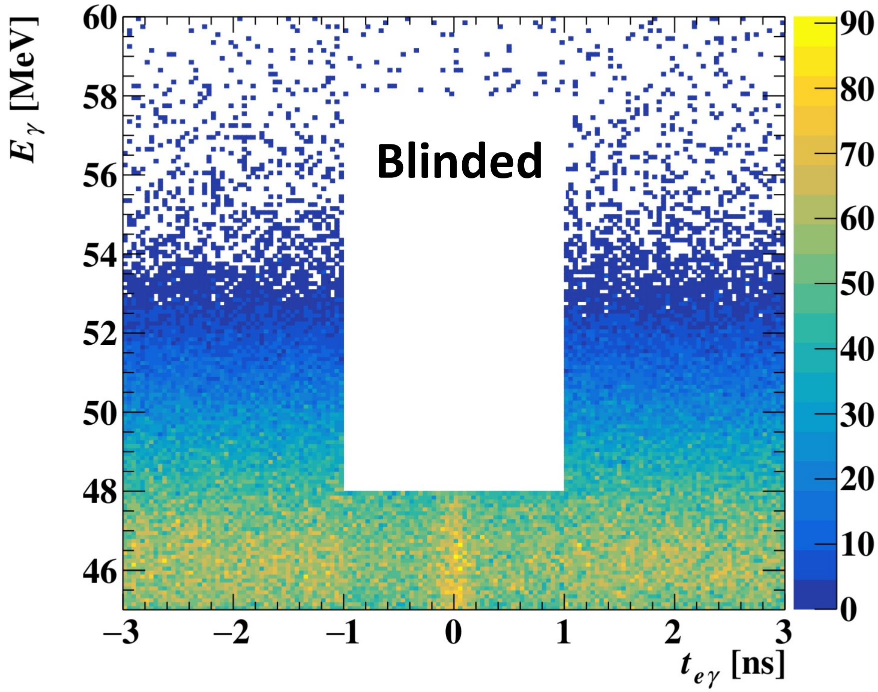
$$L(N_{sig}, N_{Acc}, N_{RMD}, x_{syst}) = C(N_{Acc}, N_{RMD}, x_{syst})$$ ← Constraints on nuisance parameters

$$\times \frac{e^{-(N_{sig}+N_{Acc}+N_{RMD})}}{N_{obs}!} \times \prod_{dataset}\left(N_{sig}\cdot S(x) + N_{acc}\cdot A(x) + N_{RMD}\cdot R(x)\right)$$

  - Observables of multidimensional probability density function
    - $\phi_{e\gamma} \coloneqq \pi + \phi_e - \phi_\gamma$, $\theta_{e\gamma} \coloneqq \pi - \theta_e - \theta_\gamma$, E_γ , E_e, $t_{e\gamma} \coloneqq t_\gamma - t_e$, RDC hit

- Confidence interval calculation
  - Feldman-Cousins method
  - With likelihood ratio ordering

$$\lambda_p(N_{sig}) = \begin{cases} -\log\dfrac{L\left(N_{sig}, \hat{\hat{\nu}}(N_{sig})\right)}{L(\widehat{N}_{sig}, \hat{\nu})} & (\widehat{N}_{sig} > 0) \\ -\log\dfrac{L\left(N_{sig}, \hat{\hat{\nu}}(N_{sig})\right)}{L\left(0, \hat{\hat{\nu}}(N_{sig}=0)\right)} & (\widehat{N}_{sig} < 0) \end{cases}$$

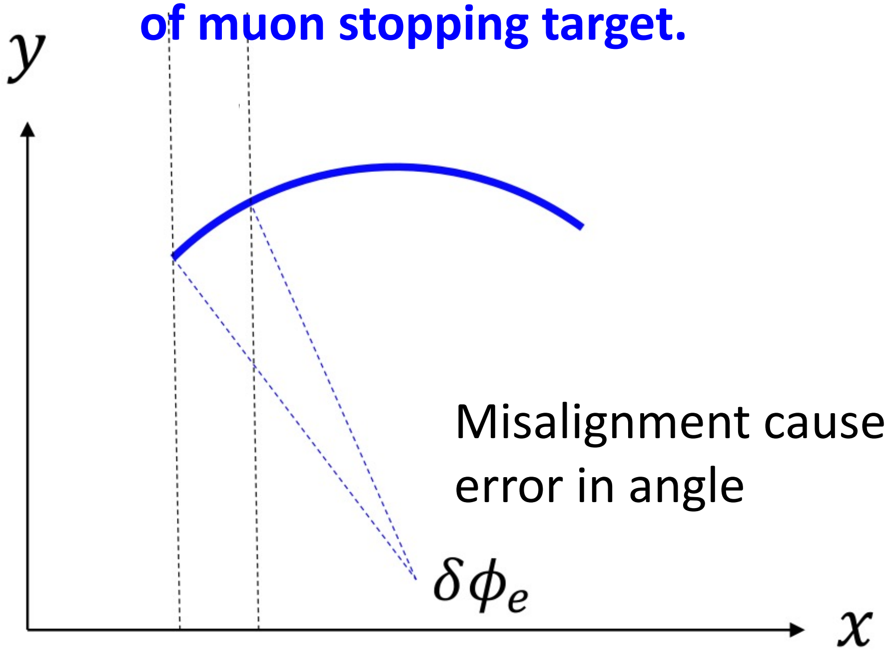


Systematic uncertainties

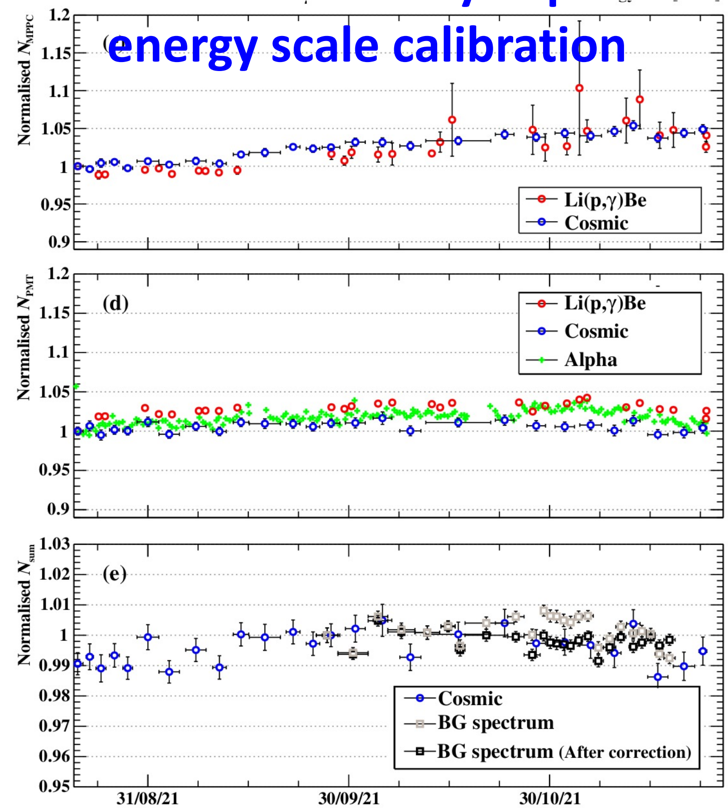
- Overall impact
  - 4% on sensitivity → Uncertainty dominated by statistics
  - c.f. 13% in MEG 2016 → Successful suppression of systematics

Dominant sources of systematics

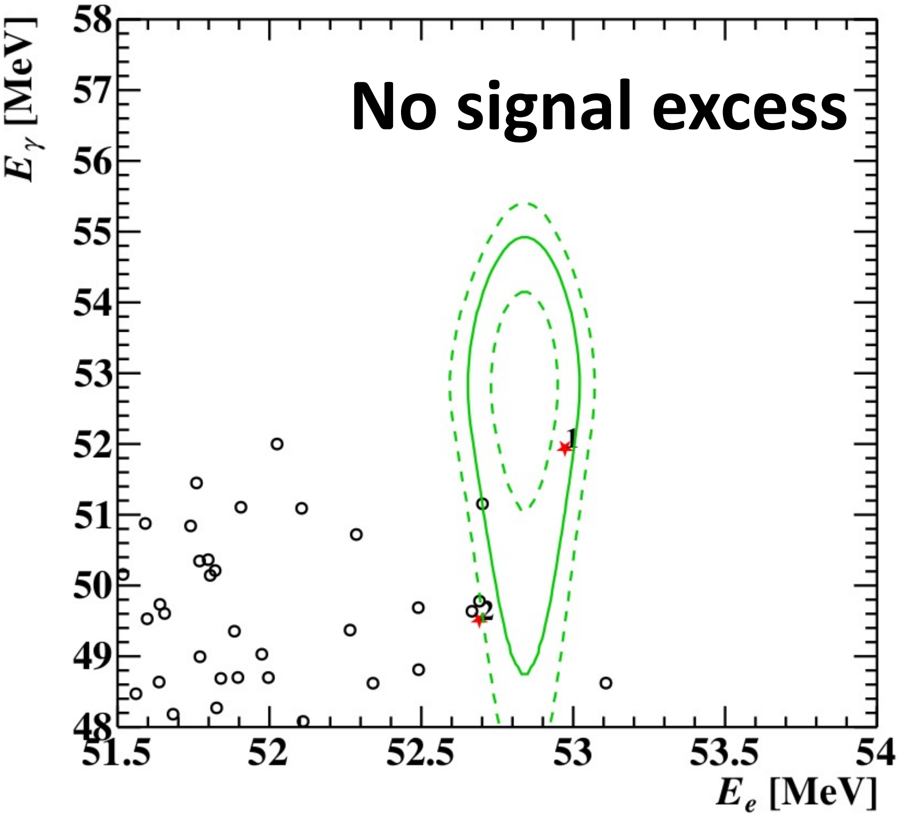
100 µm alignment uncertainty of muon stopping target.



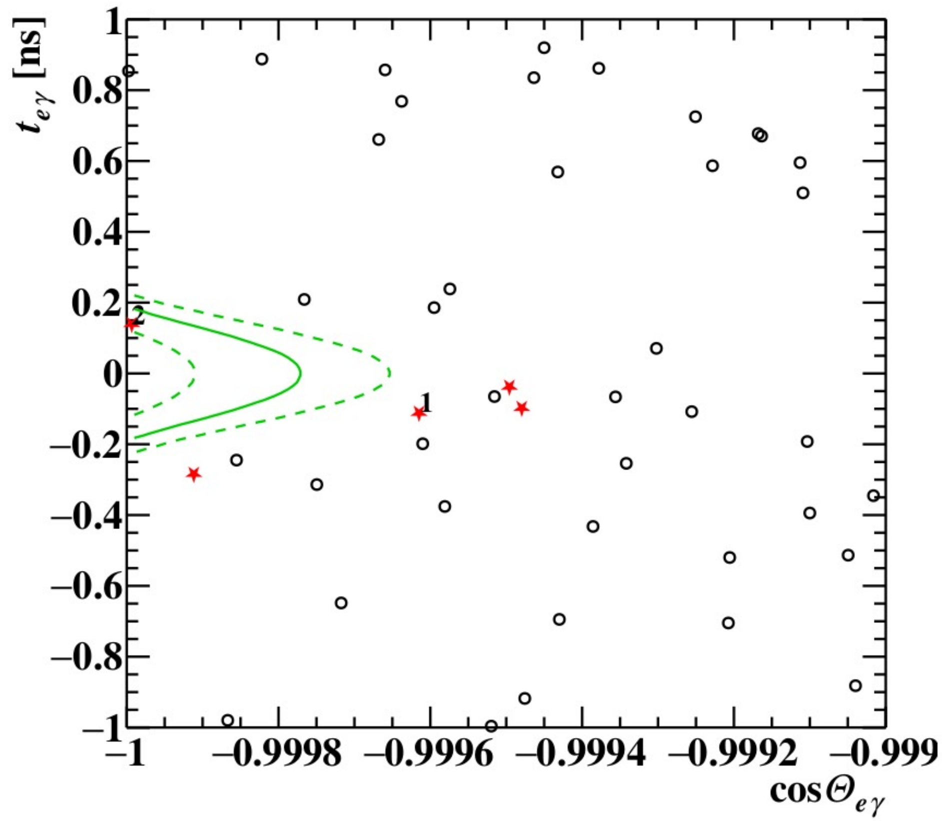
0.4% uncertainty in photon energy scale calibration



Event distribution

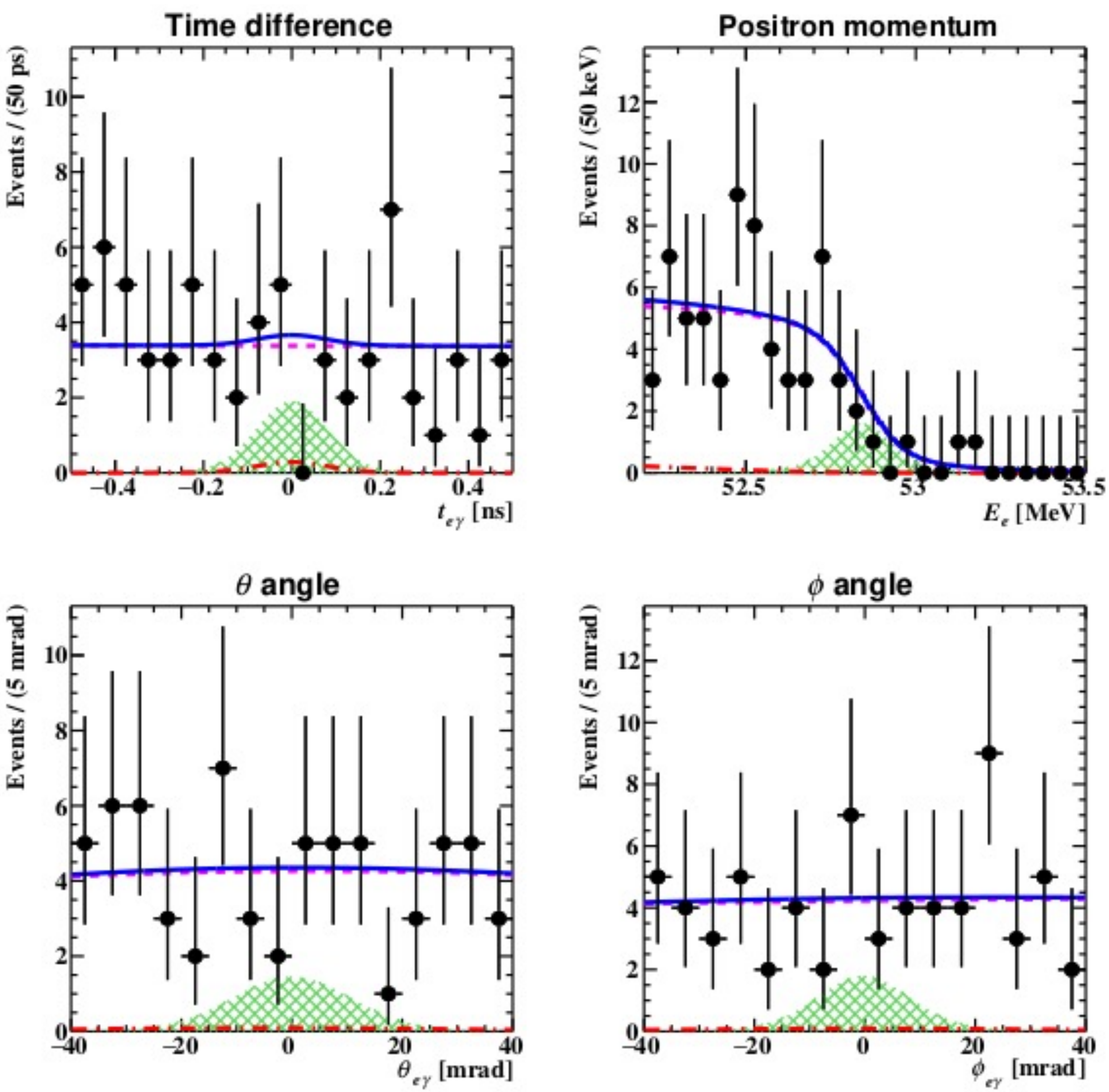


$\cos\Theta_{e\gamma} < -0.9995$
$|t_{e\gamma}| < 200$ ps



$52.5 < E_e < 53.2$ MeV
$49 < E_\gamma < 55$ MeV

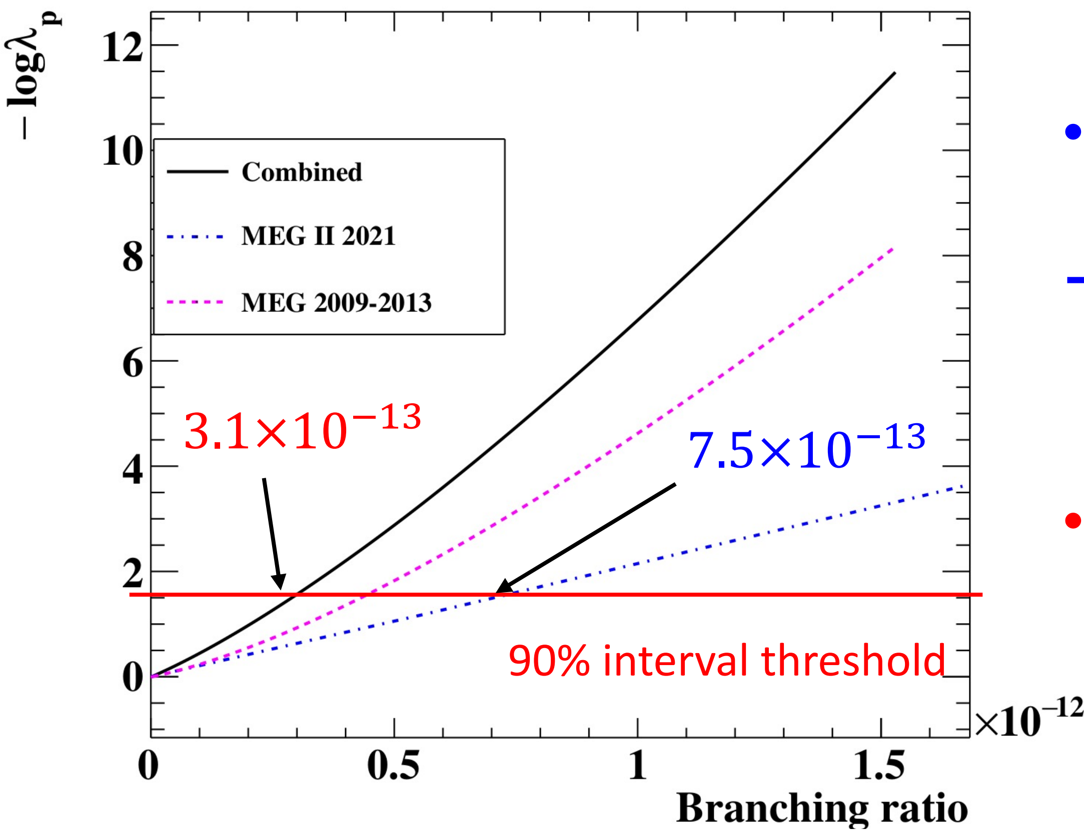
Event distribution



Signal (magnified to $4\times\mathrm{UL}$)
RMD BG
Accidental BG
Best-fit

Result

	Sensitivity	Limit from data
MEG final (2016)	5.3×10^{-13}	$Br(\mu \to e\gamma) < 4.2\times10^{-13}$
MEG II 2021	8.8×10^{-13}	$Br(\mu \to e\gamma) < 7.5\times10^{-13}$
Combined	4.3×10^{-13}	$Br(\mu \to e\gamma) < 3.1\times10^{-13}$



Key points of this result

- Approached MEG2016 sensitivity only in 7 weeks

→Demonstrated MEG II capability of $\mu \to e\gamma$ search

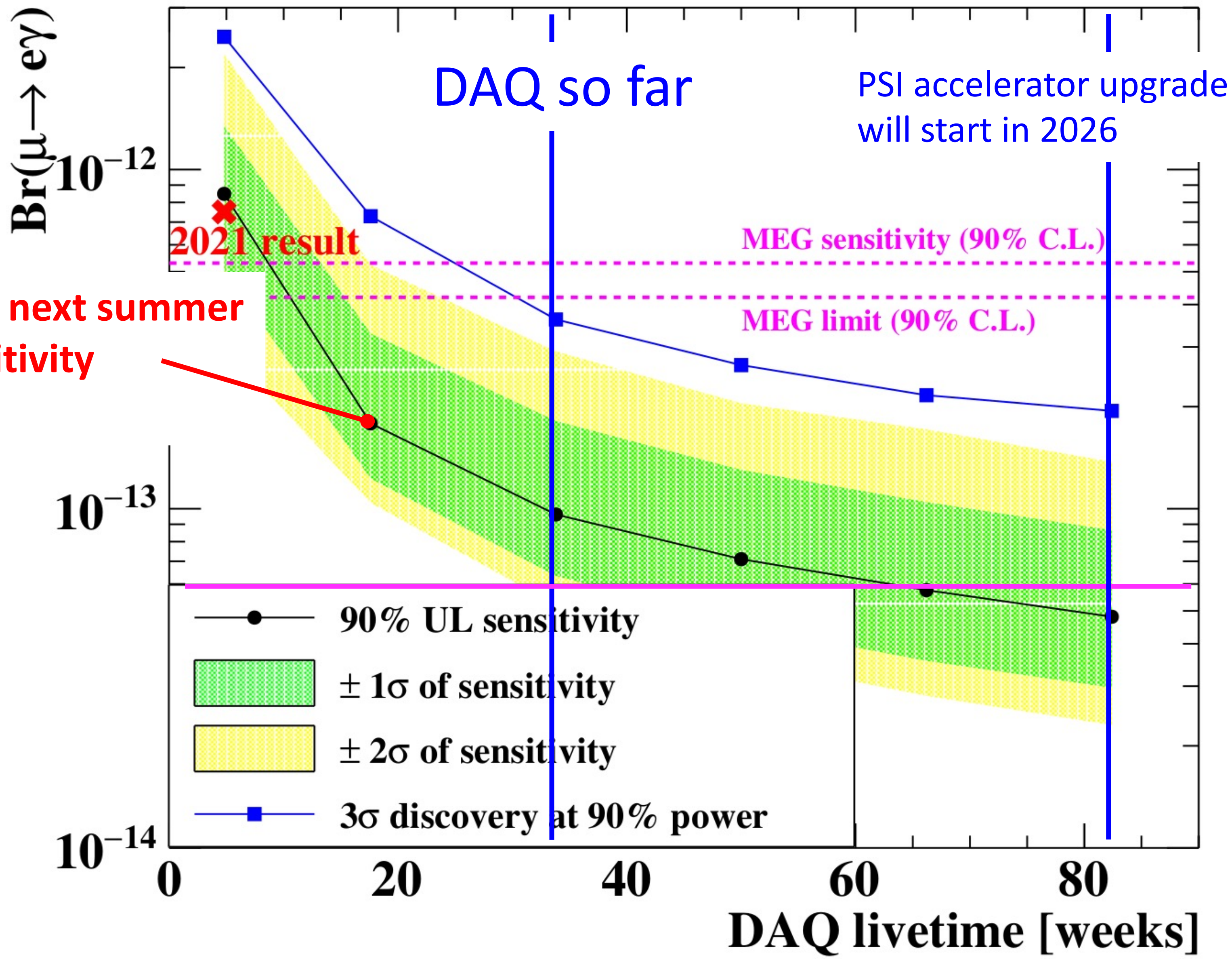
- 3.1×10^{-13}
  → Most stringent ever

Outline

4. Plan & Sensitivity

Prospect: Sensitivity

Plan to publish next summer
2×10^{-13} sensitivity
(preliminary)



Summary

- MEG II aims to search $\mu \to e\gamma$ at 6×10^{-14} sensitivity
  - $\times\mathbf{10}$ **improvement** from MEG final (2016)

- First result of MEG II by measuring 2.64×10^{12} muons
  - No signal excess →$B(\mu \to e\gamma) < 7.5\times10^{-13}$
  - Combined limit with MEG 2016→ $\boldsymbol{B(\mu \to e\gamma) < 3.1\times10^{-13}}$
  - They are from **only 7 weeks** of data statistics

→**Demonstrated capability of** 6×10^{-14} **in a few years**

- Plan of MEG II
  - 2023 DAQ successfully finished → Analysis ongoing
  - Continue till 2026 to reach 6×10^{-14} sensitivity

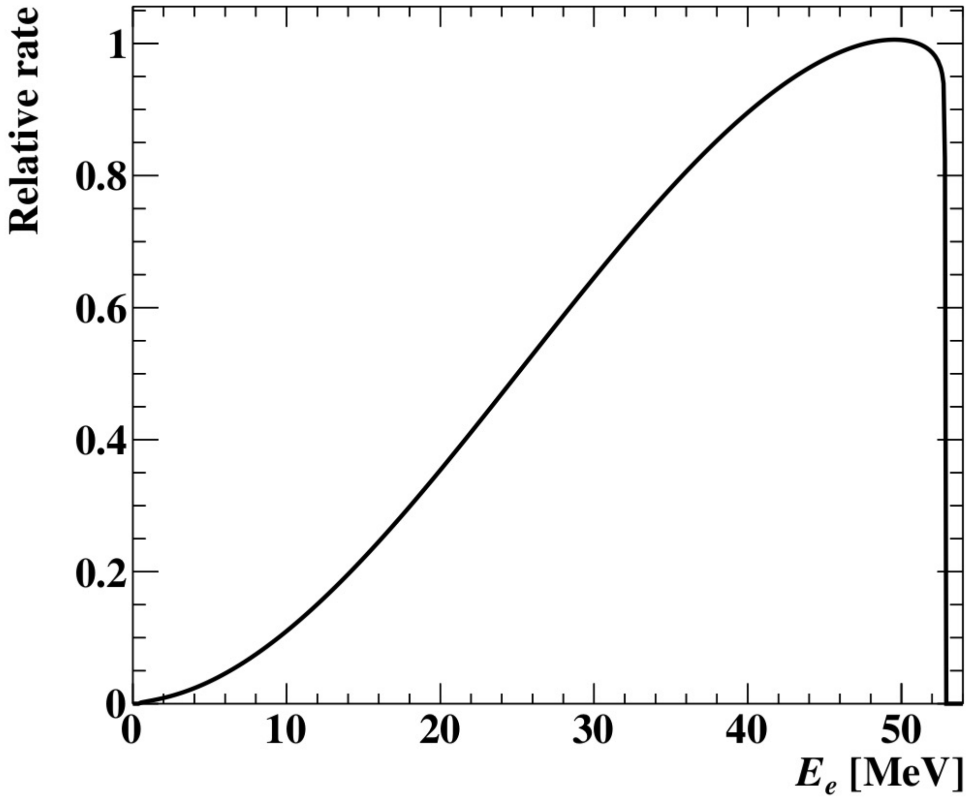
→ **Chance of discovery. Stay tuned!!**

Backup

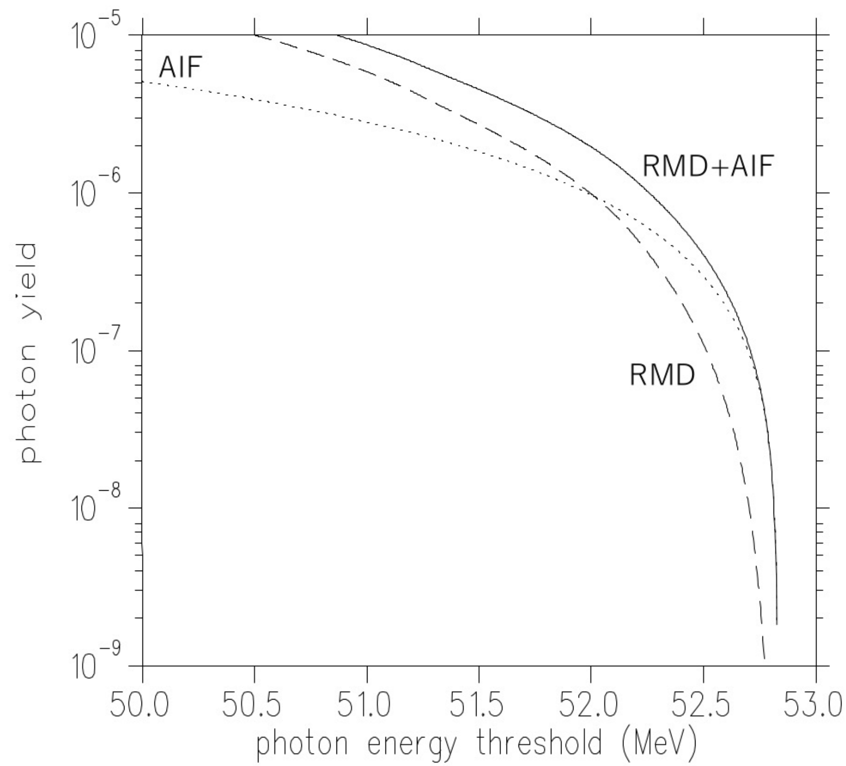
Energy spectrum

https://arxiv.org/abs/hep-ph/9909265

BG positron spectrum

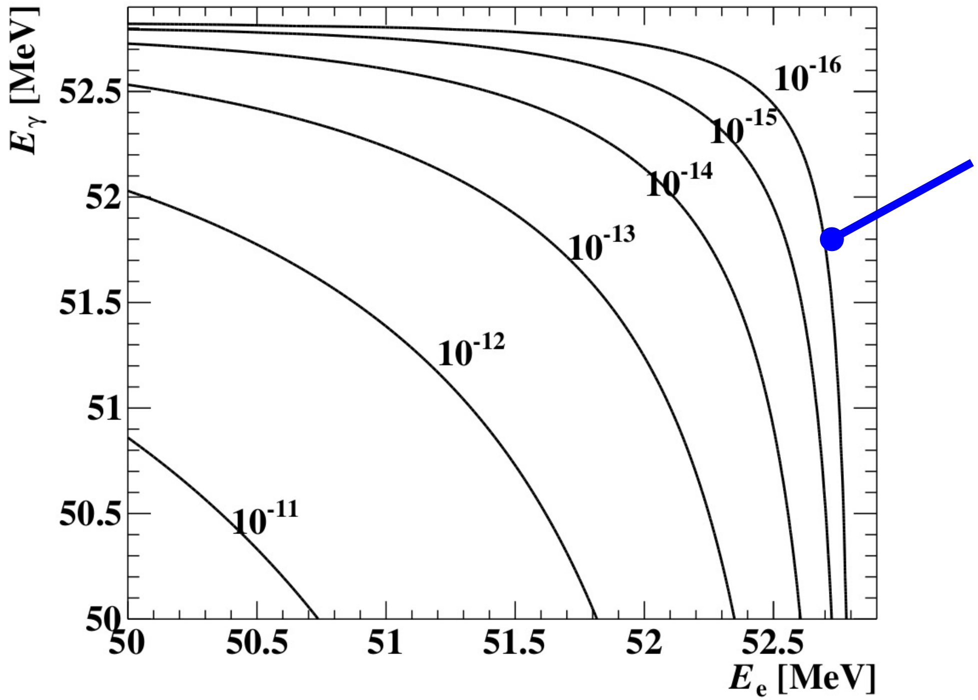


BG gamma-ray spectrum



Background from radiative decay

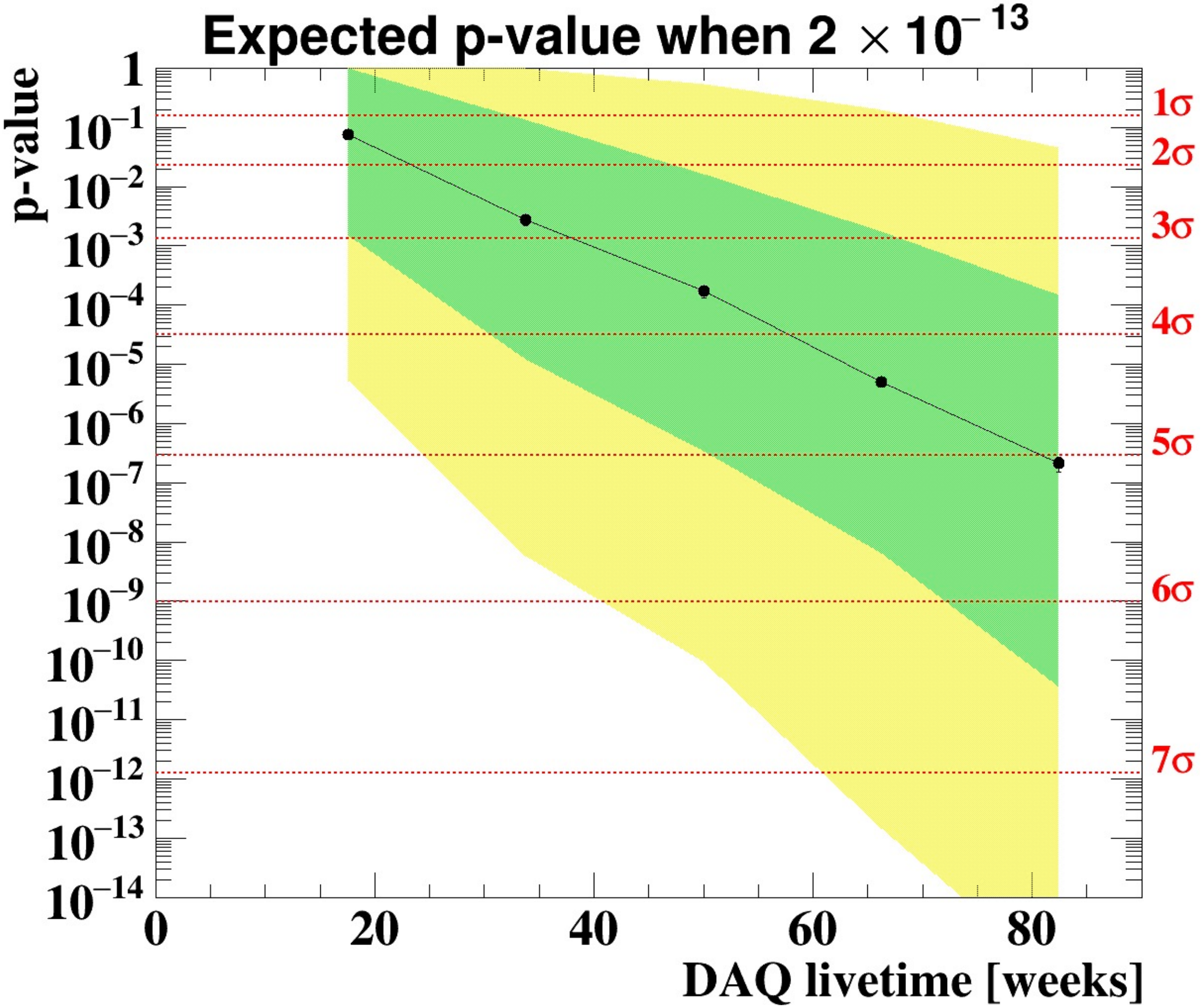
- RMD background
  - Radiative decay ($\mu \to e\nu\nu\gamma$) with small energy carried by neutrinos
- Gives minor contribution
  - $B(\mu \to e\nu\nu\gamma)$ is vanishing at high E_e and E_γ



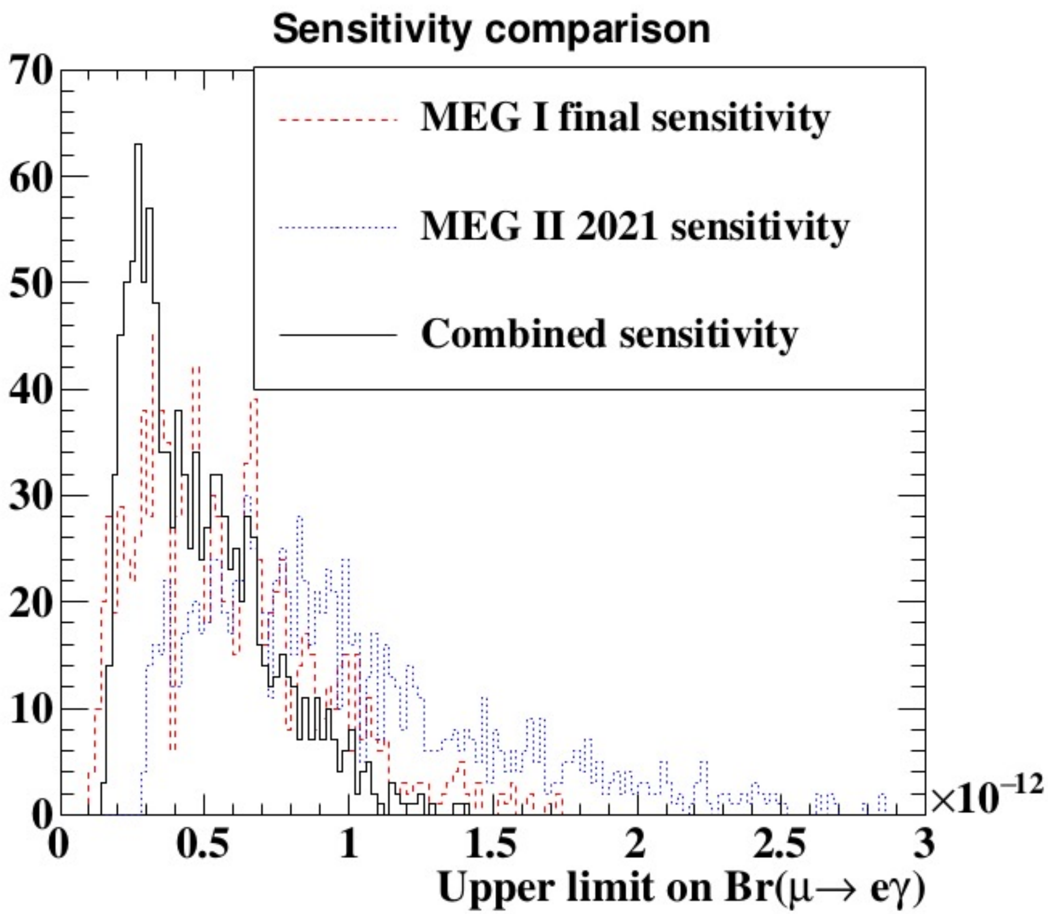
$\sim 10^{-16}$ within detector resolution
- E_e resolution: $\sim$ 0.1 MeV
- E_γ resolution: $\sim$ 1 MeV

Discovery case

- Simulation with $2{\times}10^{-13}$



Sensitivity when combined



Qualitative behavior when combined

- If BG populate for two datasets, combined sensitivity behaves
  - $s_{comb} \sim \sqrt{\frac{1}{(1/s_A^2+1/s_B^2)}}$
  - Sensitivity reflects the uncertainty from BG fluctuation
    → Behaves more alike the usual error propagation
  - When 8.8 & 5.3 are combined in this way, 4.5

- If two datasets are BG-free, combined sensitivity behaves
  - $s_{comb} \sim \frac{1}{(1/s_A+1/s_B)}$
  - Sensitivity reflects only the number of measured muon decays
  - When 8.8 & 5.3 are combined in this way, 3.3

- In reality
  - BG-free in 8.8
  - BG populates in 5.3

→ Combined sensitivity: 4.3

Systematic uncertainty

- Breakdown of impact on sensitivity

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	$< 0.1\,\%$

Normalization

- Michel positron counting method
  - Count number of reconstructed positrons in positron-only trigger

$$k_{Michel} = \frac{N_{\mathrm{Michel}}}{Br(\mu\to e\nu\nu)} \cdot \frac{P_{\mathrm{MEG}}}{P_{\mathrm{Michel}}} \cdot \frac{\epsilon_{\mathrm{MEGTRG}}}{\epsilon_{\mathrm{MicTRG}}} \cdot \frac{\epsilon_{53\ \mathrm{MeV}}}{\epsilon_{\mathrm{Michel}}} \cdot \epsilon_{\gamma} \cdot \epsilon_{\mathrm{sel}}$$

  - Automatically include beam rate & positron efficiency

$\mathcal{B}^{e\nu\bar{\nu}}$	0.101	
$\epsilon_{\mathrm{trg}}^{e\gamma}$	0.77 – 0.79	
$\epsilon_{\mathrm{trg}}^{e\nu\bar{\nu}}$	$\sim$ 0.9 depending on beam rate (Eq.(6.7))	
$\epsilon_{e}^{e\gamma}/\epsilon_{e}^{e\nu\bar{\nu}}$	1.09	
$P^{e\nu\bar{\nu}}$	$2 \times 10^6 - 7 \times 10^6$ depending on periods	
ϵ_{γ}	0.67 (detection efficiency) $\times$ 0.93 (analysis efficiency)	← 3% uncertainty
$A_{\gamma}^{e\gamma}$	0.97	
$\epsilon_{\mathrm{sel}}^{e\gamma}$	0.93	← 3% uncertainty

- Result: $(2.55 \pm 0.13)\times 10^{12}$

Normalization

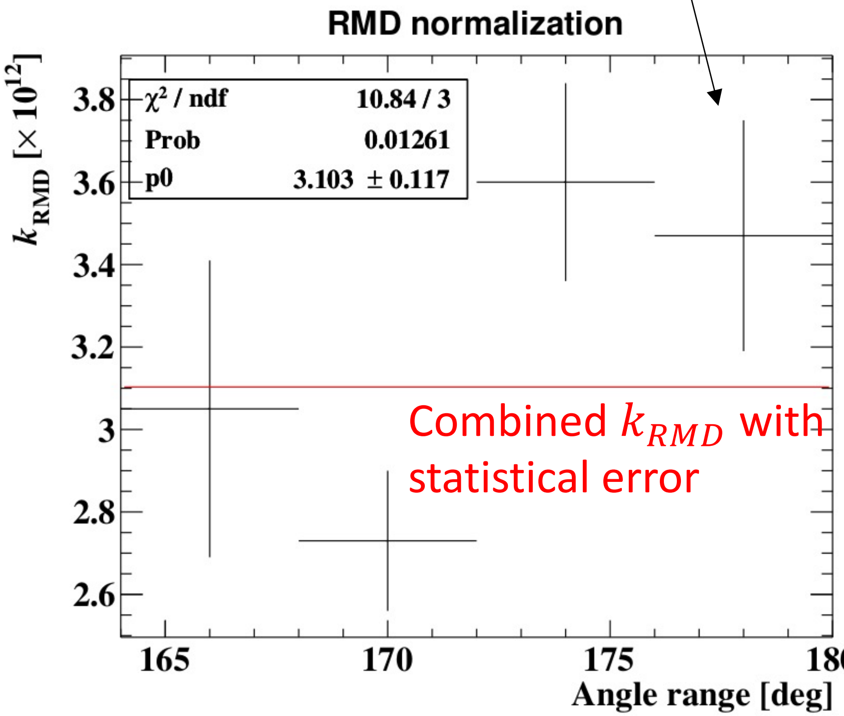
- RMD event counting method

$$k_{RMD} = \frac{N_{RMD}}{Br(RMD)} \cdot \frac{\epsilon_e^{SIG}}{\epsilon_e^{RMD}} \cdot \frac{\epsilon_\gamma^{SIG}}{\epsilon_\gamma^{RMD}} \cdot \frac{\epsilon_{TRG}^{SIG}}{\epsilon_{TRG}^{RMD}} \cdot \frac{\epsilon_{sel}^{sig}}{\epsilon_{sel}^{RMD}}$$

  - Also includes gamma-ray efficiency
  - But larger systematics in correction factors

- Result: $(3.1 \pm 0.3) \times 10^{12}$
  - Dominated by $\frac{\epsilon_\gamma^{SIG}}{\epsilon_\gamma^{RMD}}$ uncertainty
    - Highly sensitive to E_γ calibration
  - 3 – 5% uncertainty in $\frac{\epsilon_e^{SIG}}{\epsilon_e^{RMD}}$ and $\frac{\epsilon_{sel}^{sig}}{\epsilon_{sel}^{RMD}}$
  - Also considered angle inconsistencies

Only statistical error in this plot



Normalization

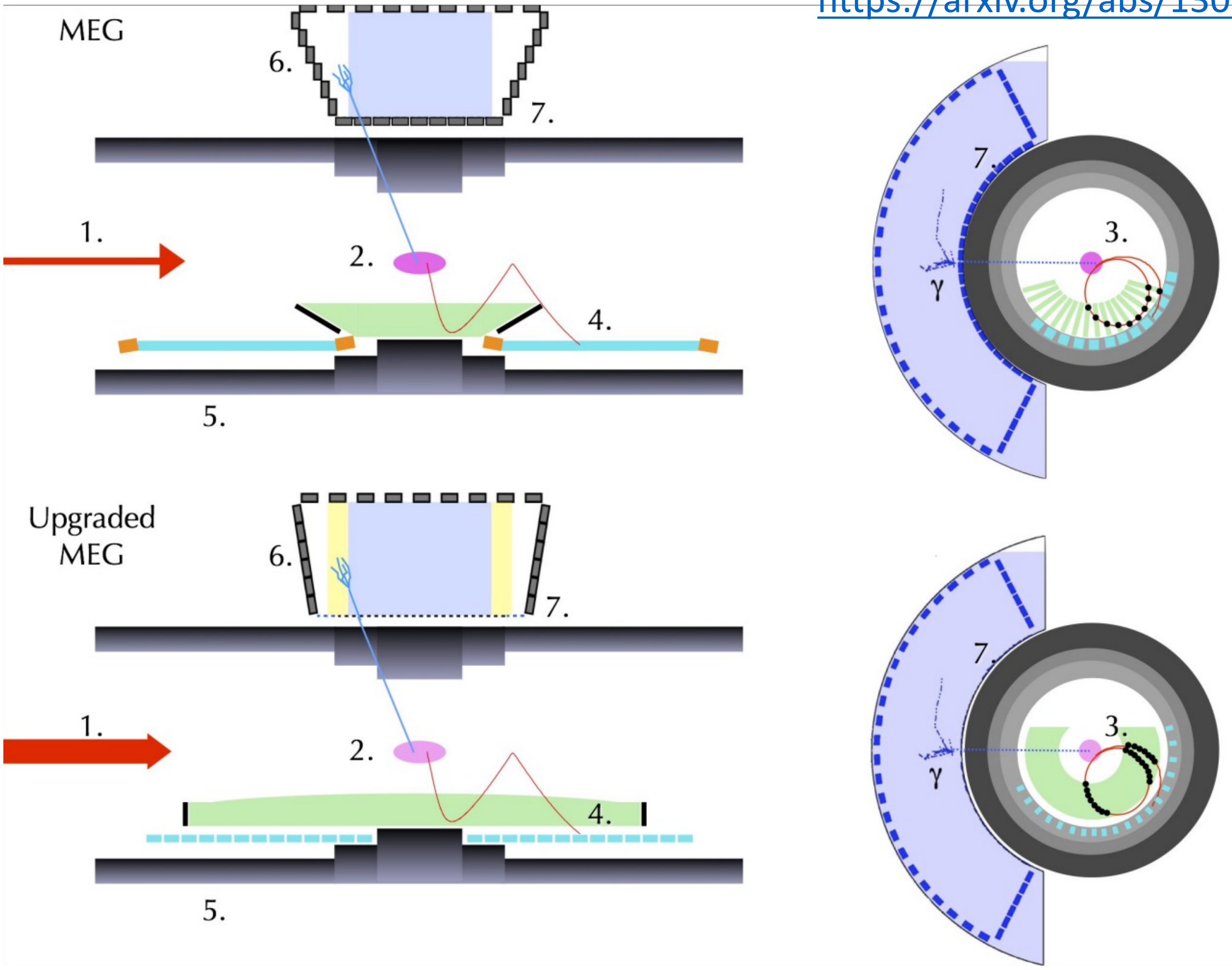
- Result
  - $(2.55 \pm 0.13) \times 10^{12}$ in Positron counting method
  - $(3.1 \pm 0.3) \times 10^{12}$ in RMD event counting in energy sideband
  - $(2.64 \pm 0.12) \times 10^{12}$ when combined

- Discrepancy between two methods: 1.7σ
  - Not concluded whether it is really from systematics
  - If it is real, k_{RMD} is more suspicious than k_{Michel}

Detector: MEG vs MEG II

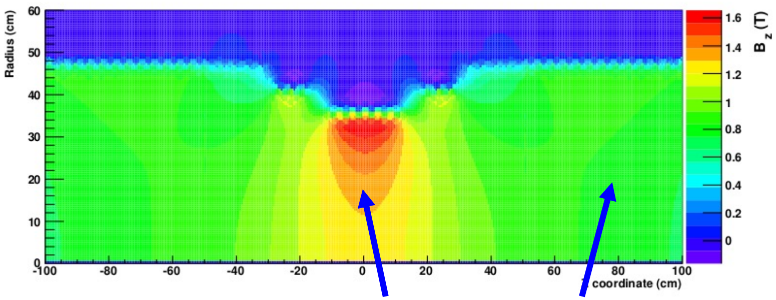
- a

https://arxiv.org/abs/1301.7225



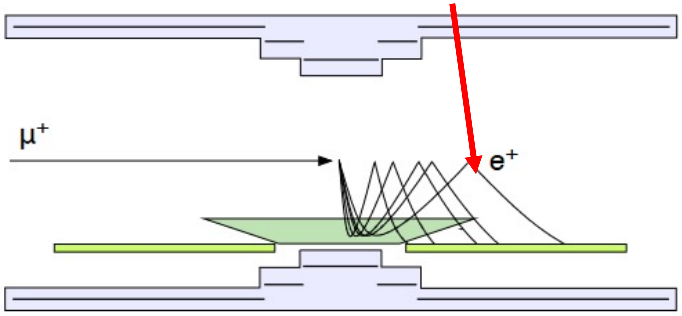
Magnetic field

- Dedicated gradient field



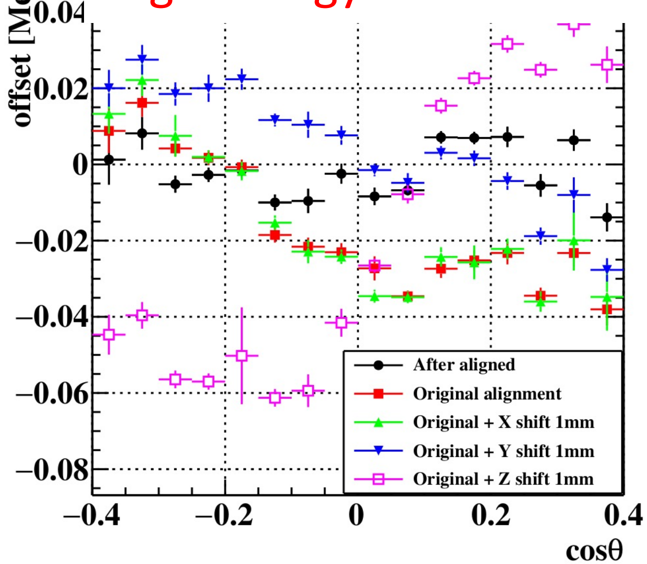
Strong field at center, weak field at ends

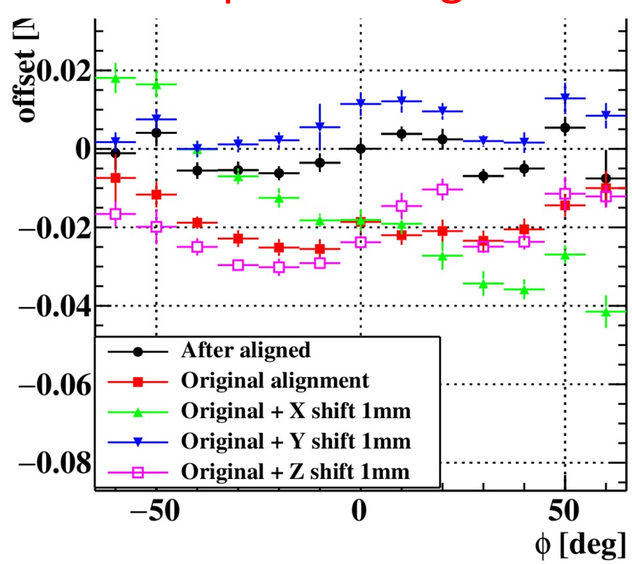
Small emission angle dependence



- Calibration: Alignment with 100 μm precision

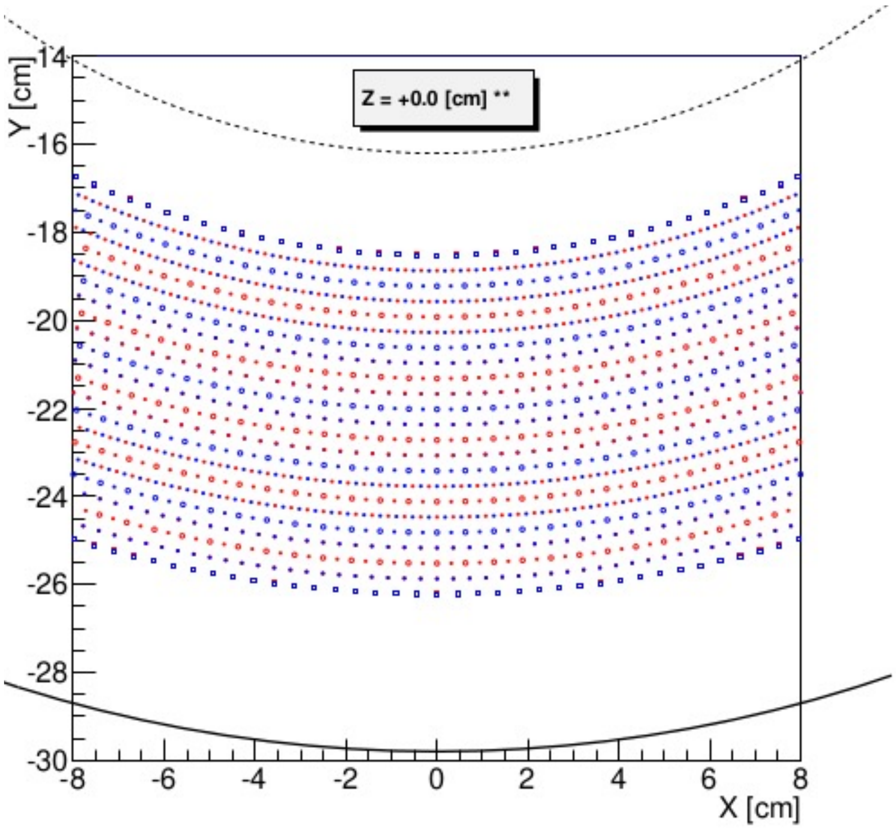
High energy scale uniformity thanks to precise alignment

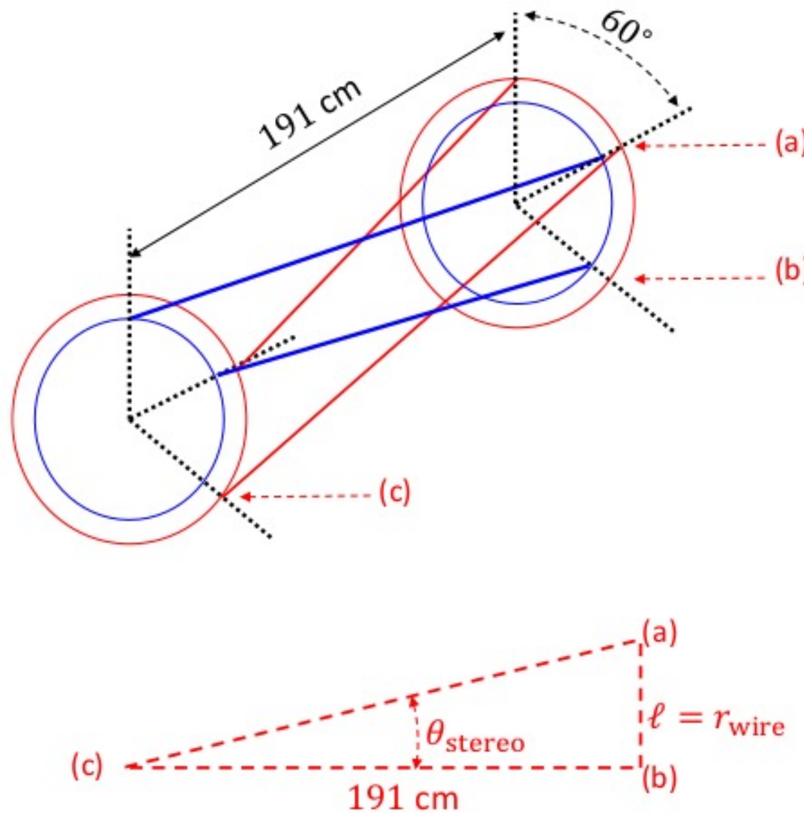




CDCH geometry

- CDCH: Chamber with stereo wiring

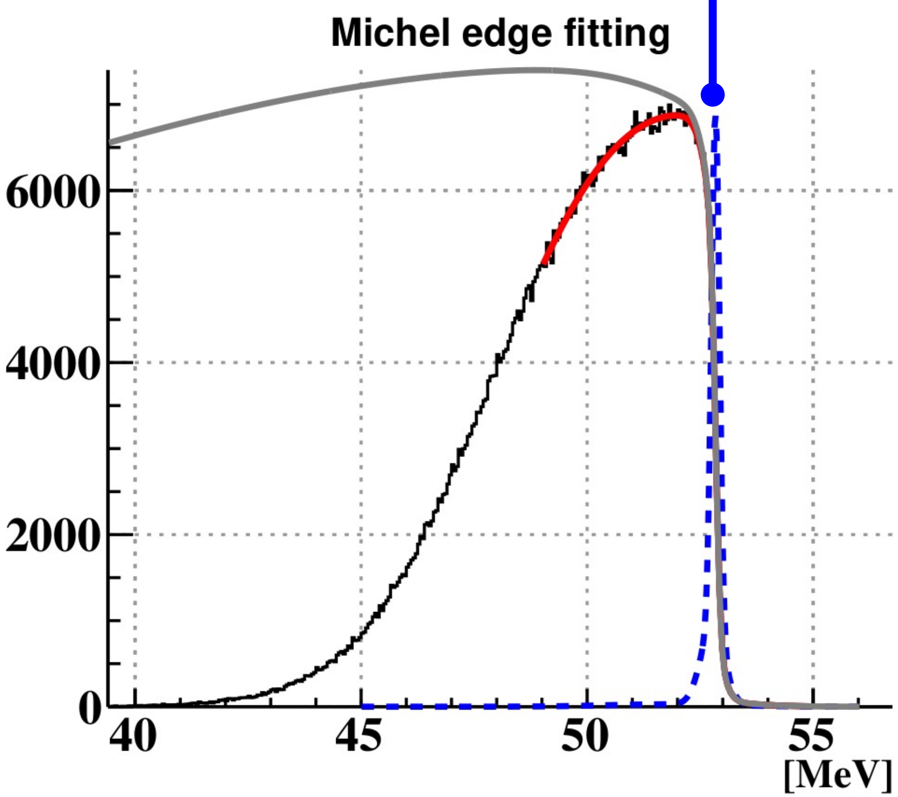




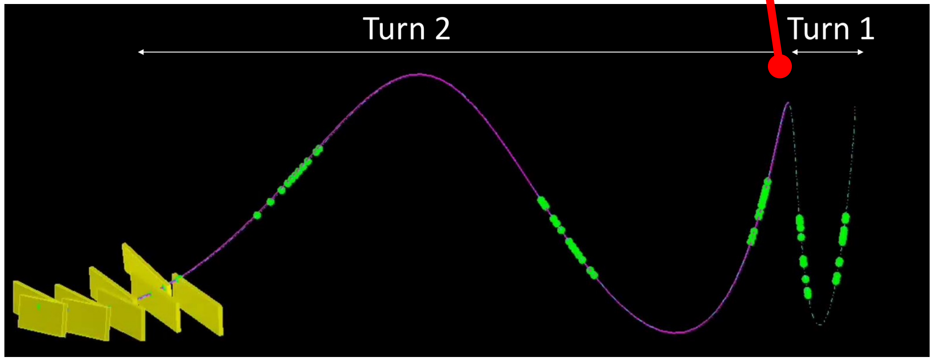
Evaluation of tracking resolution

- Momentum resolution: Fit to 52.8 MeV end-point
- Position & angle resolution: Double-turn analysis

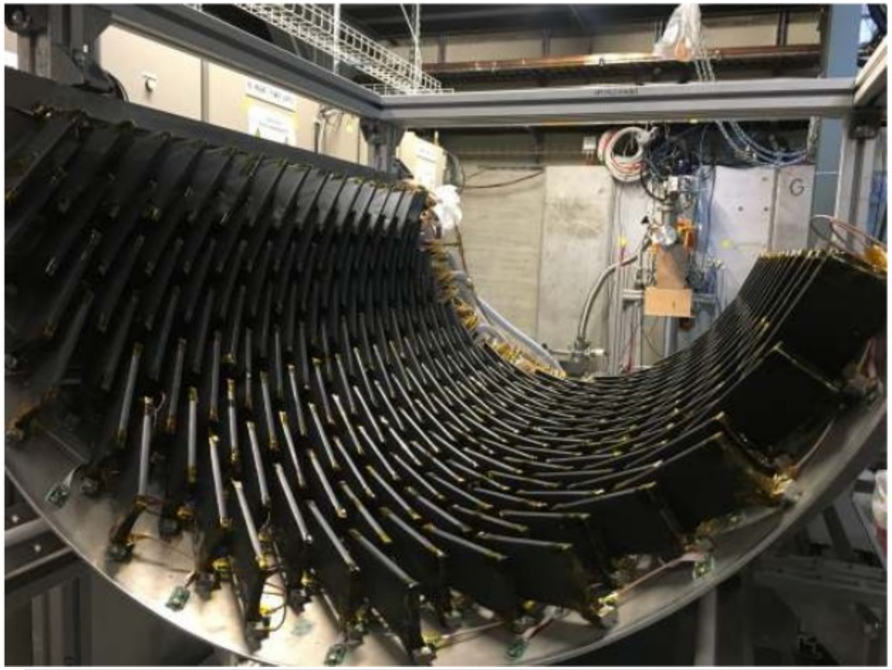
90 keV momentum resolution
(380 keV in previous experiment)

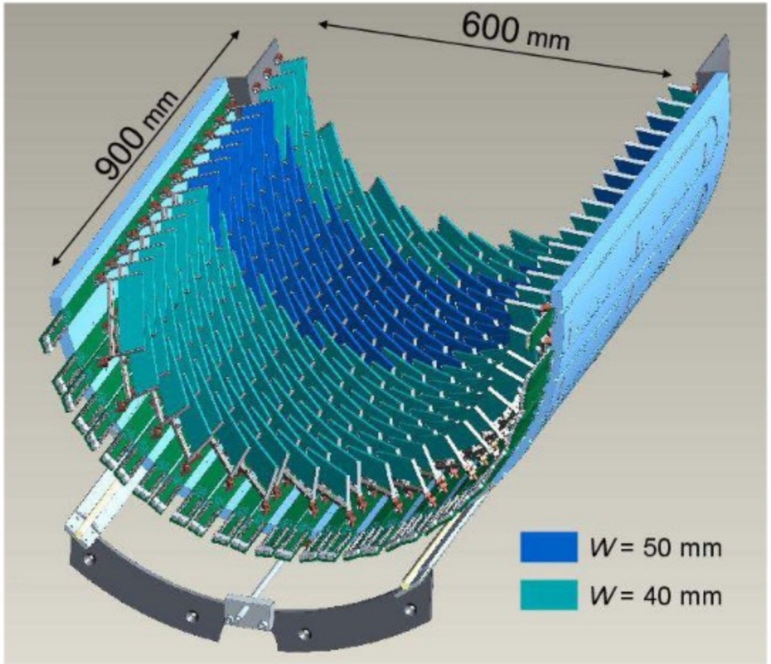


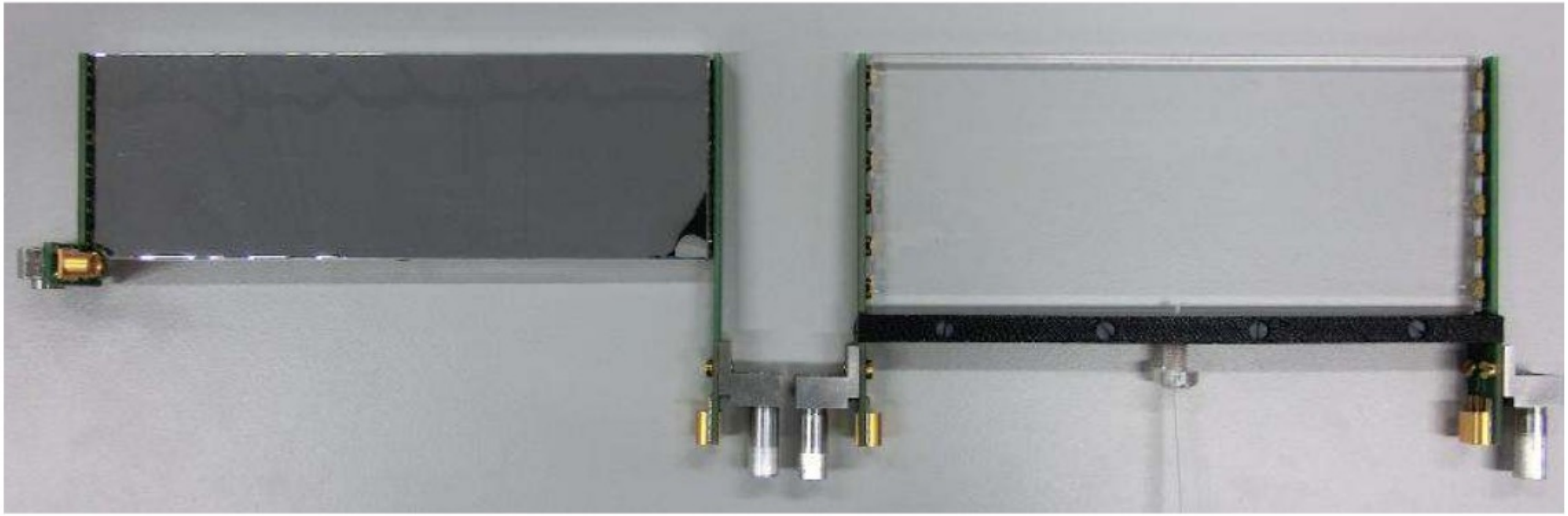
7 mrad & 1 mm resolution
(9 mrad & 1.5mm in previous experiment)



Timing counter

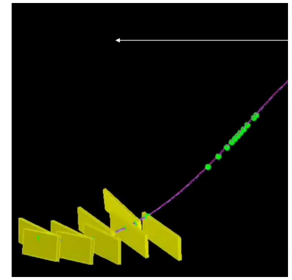


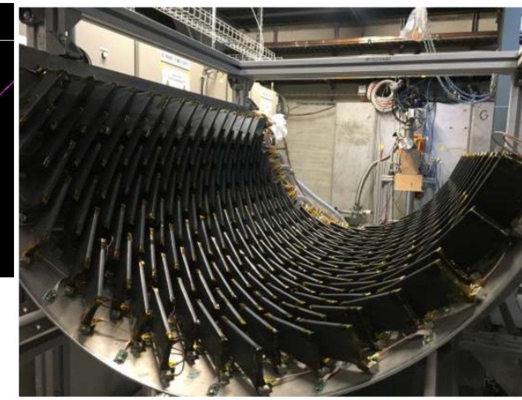




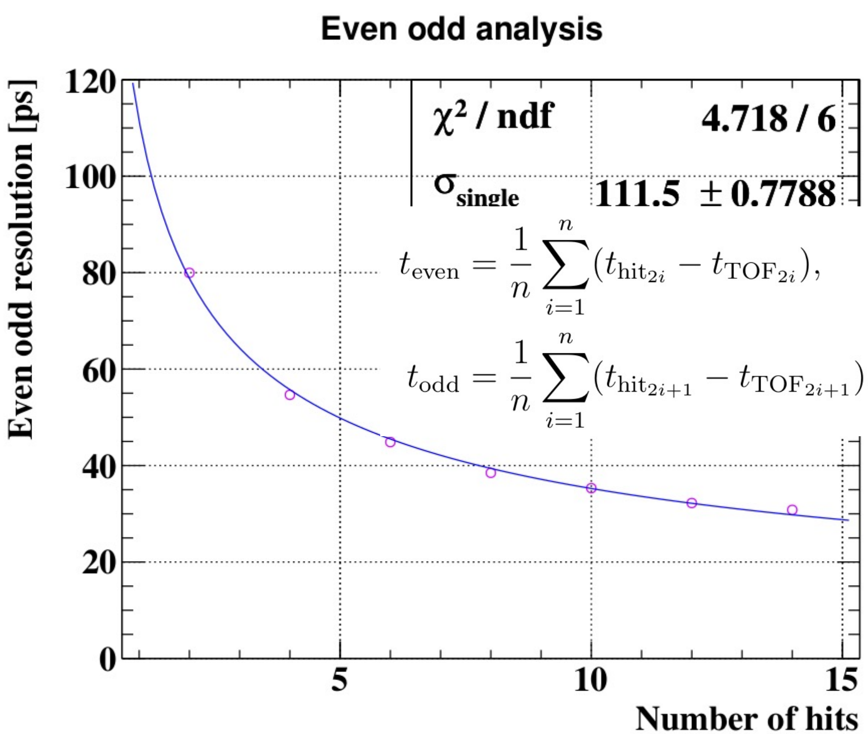
Resolution & Calibration

- Positron timing counter
  - High precision by combining n_{TC} hits
  - Each scintillation counter: 112 ps
  - Calibration reported in arXiv:2310.11902





Timing resolution at different n_{TC}

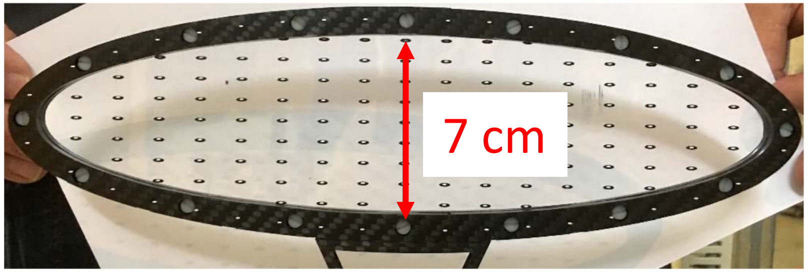


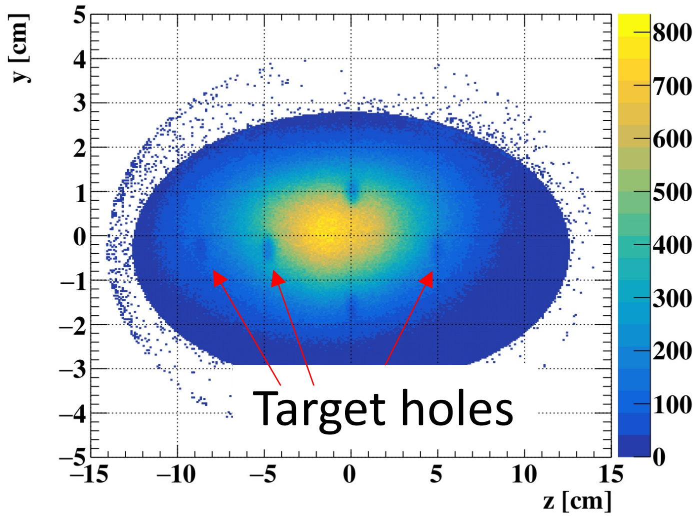
$$t_{\text{even}} = \frac{1}{n}\sum_{i=1}^{n}(t_{\text{hit}_{2i}} - t_{\text{TOF}_{2i}}),$$

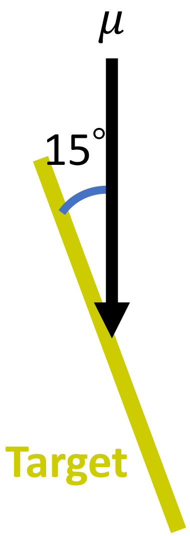
$$t_{\text{odd}} = \frac{1}{n}\sum_{i=1}^{n}(t_{\text{hit}_{2i+1}} - t_{\text{TOF}_{2i+1}}).$$

Muon stopping target

- Stops μ in 174 µm thick plastic

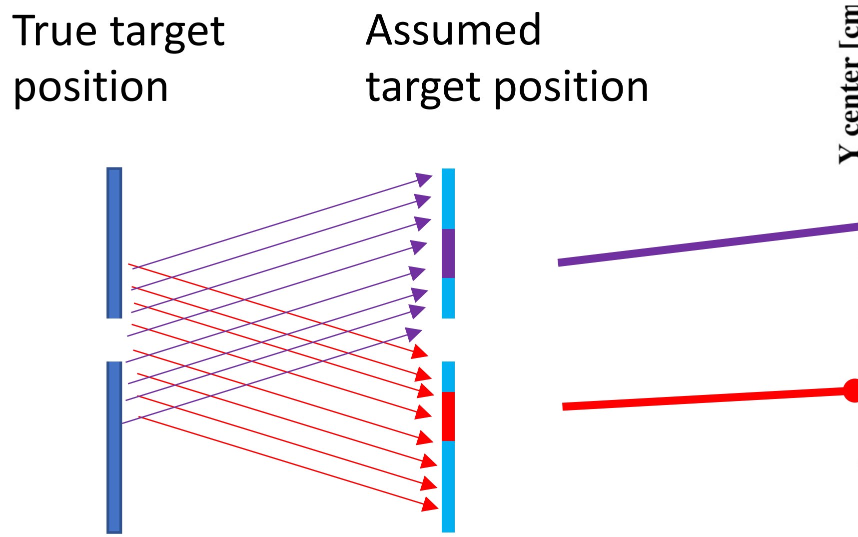


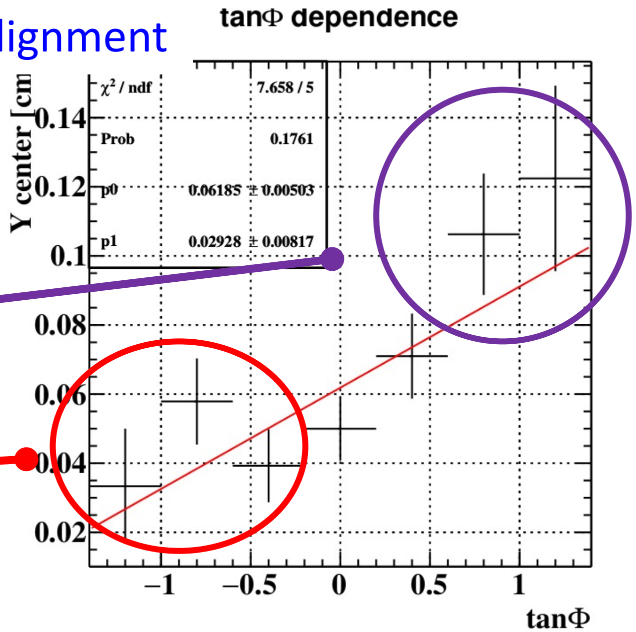




- Alignment with 100 µm precision
  - By hole analysis

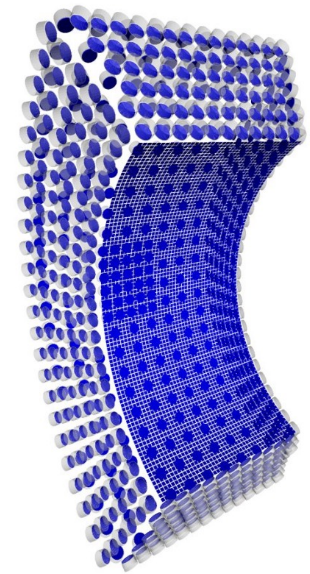
Principle of target alignment





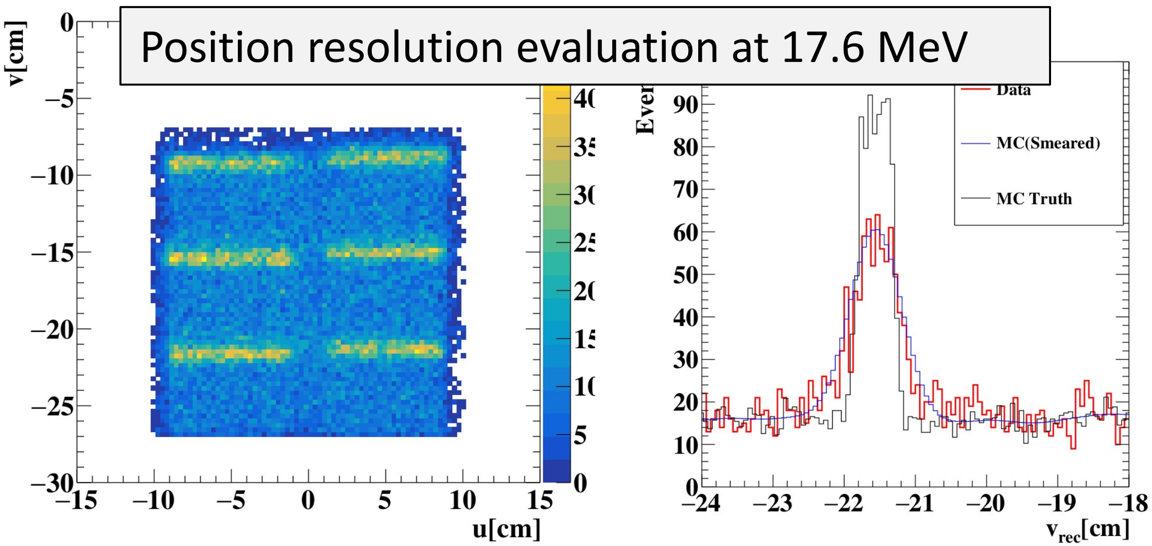
Gamma-ray detector

- 900L LXe surrounded by VUV-sensitive SiPMs & PMTs
  - LXe emits 175 nm VUV light
  - Hosted in C-shaped cryostat

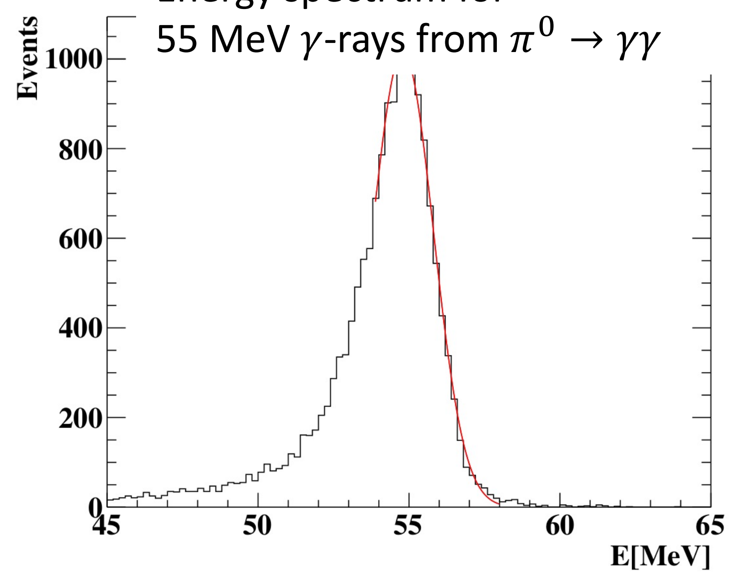


- Position & energy measurement
  - Position resolution : ~ 2 mm
    - ×2 improvement from previous experiment
  - Energy resolution: 2%
  - Timing resolution: 70 ps

Position resolution evaluation at 17.6 MeV



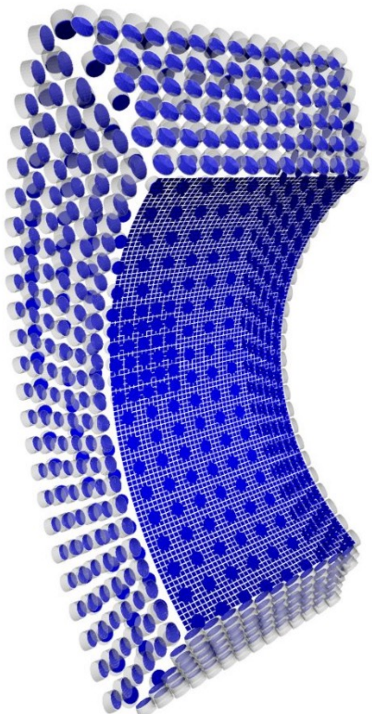
Energy spectrum for 55 MeV γ-rays from $\pi^0 \rightarrow \gamma\gamma$

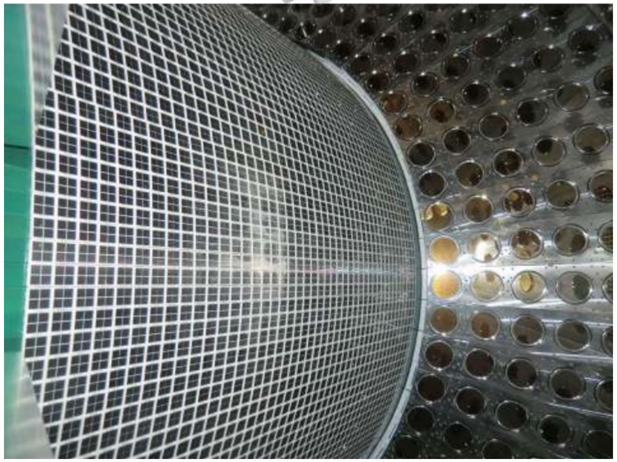


Gamma-ray detector

- Use of liquid Xenon as scintillator
  - Efficient gamma-ray detection (small X_0)
  - Good energy resolution (high light yield)
  - Good time resolution (fast scintillation process)
  - Scintillation light in VUV regime (175 nm)

- Sensors for scintillation photons
  - Lxe surrounded by VUV-sensitive SiPMs & PMTs
  - Position resolution is determined by entrance face
  - SiPMs enables high granularity
    → Used for entrance face





Combined timing

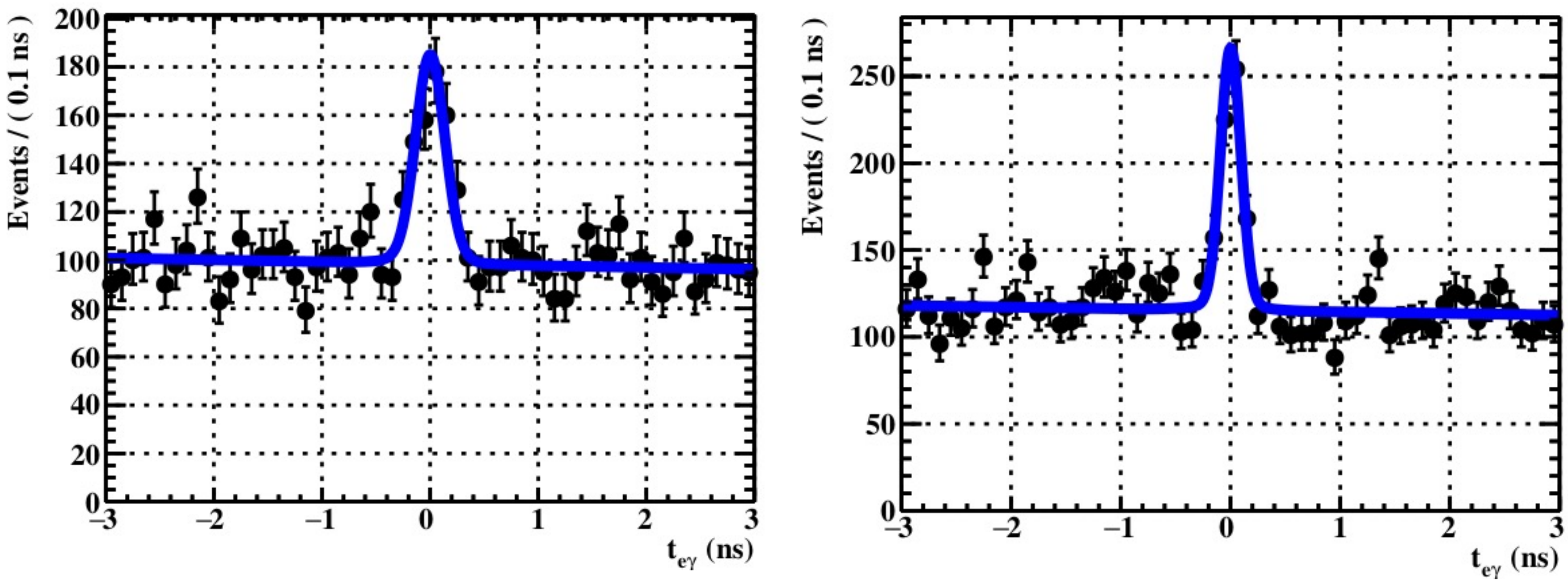
- Combined resolution: $\frac{112}{\sqrt{n_{TC}}} \oplus 70$ ps
  - 70 ps dominated by photon resolution
  - $\frac{112}{\sqrt{n_{TC}}}$ from positron timing counter

  → 84 ps on average for signal

Evaluation with $\mu \rightarrow e\nu\nu\gamma$ samples

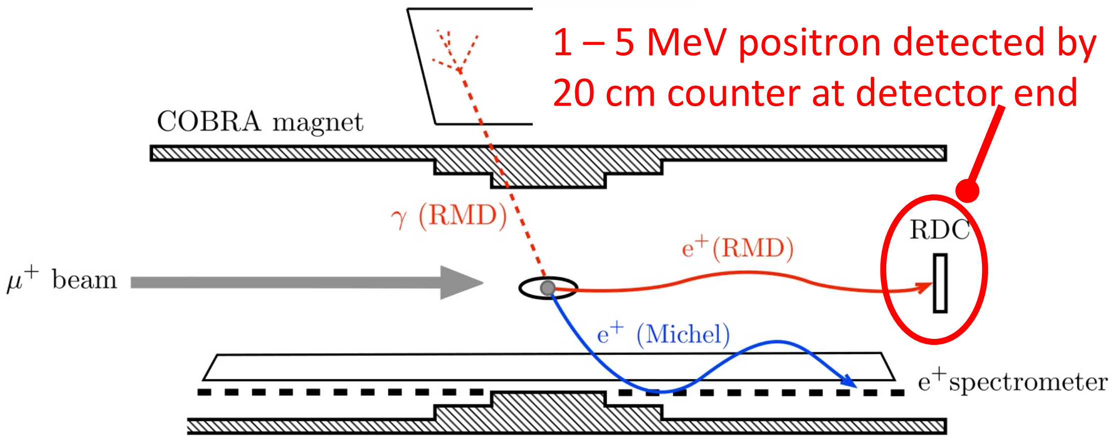
Samples with 1 pTC hits

Samples with 4 pTC hits

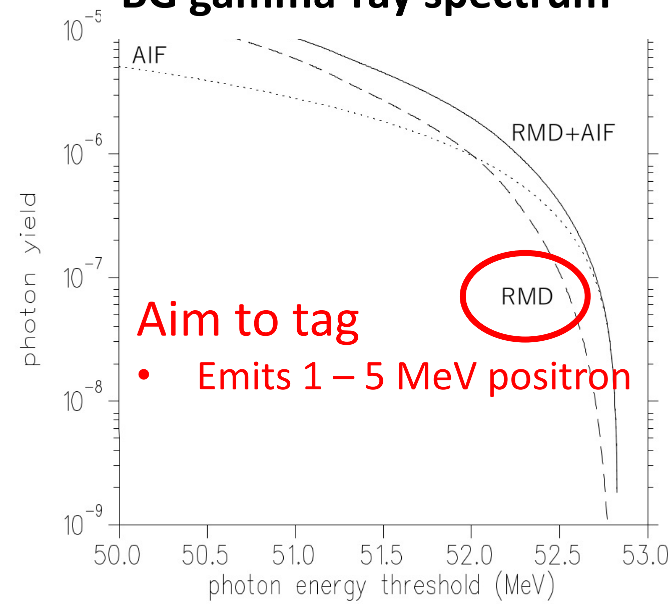


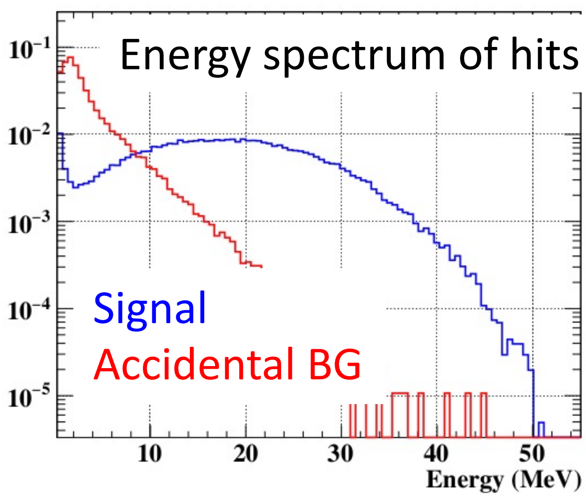
BG-γ tagging detector

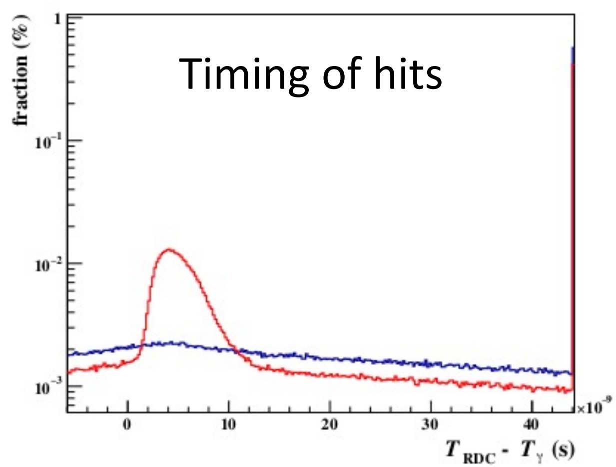
- Aim to detect γ-rays in **accidental BG**
  - BG γ-rays from radiative decay
  - Measurement of positron timing and energy

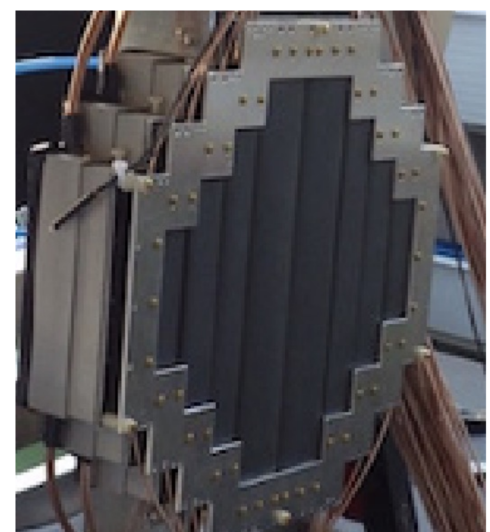


BG gamma-ray spectrum









Electronics and Triggering

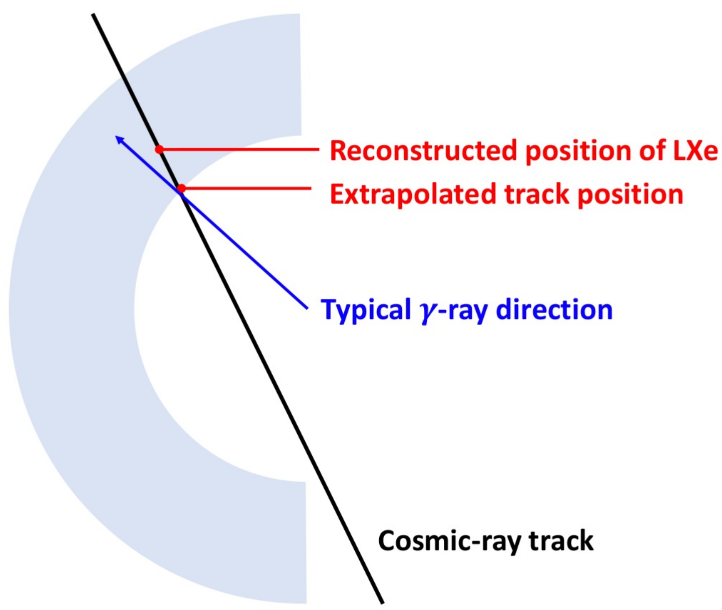
- Raw detector waveform collected with waveform digitizer
  - WaveDream: Integrated machine for waveform digitization & triggering

- Trigger logic
  - γ-ray energy
  - Time difference between LXe and TC
    - No TOF correction in trigger logic
  - Direction matching
    - Use of LXe and TC-hit position
    - Not based on tracking

- Trigger rate: ~10 Hz
- Latency: ~ 600 ns
- CDCH not used to reduce latency

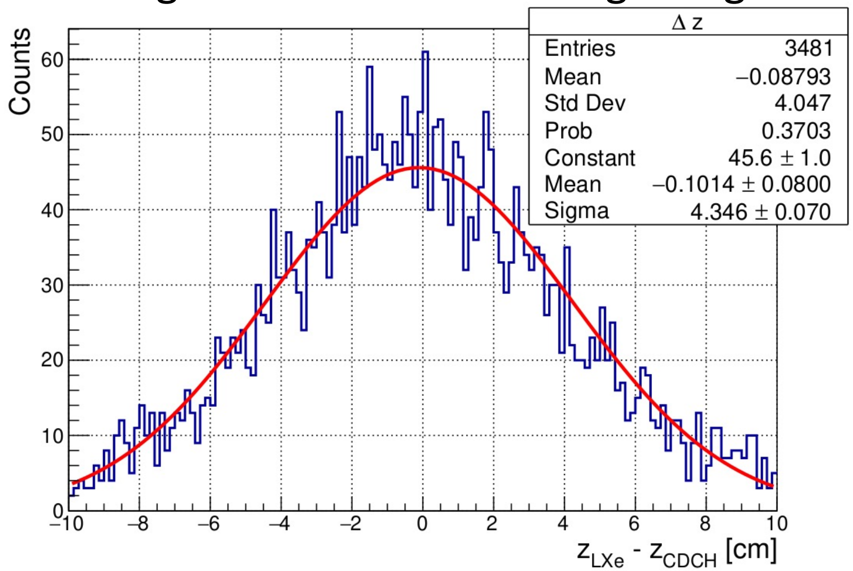
CDCH – LXe alignment

- Cosmic-ray tracks: Used in z-alignment
  - Not useful in x, y alignment due to bias in direction
  - Available for z-alignment thanks to symmetry (bias cancels)
- Optical alignment: Used in x, y-alignment
  - LXe position estimated by X-ray injection
  - CDCH alignment based on optical scan



1 mm z-shift was observed

→ Agrees with B-field & target alignment



→ Concluded that LXe – CDCH Alignment uncertainty is 1 mm