Search for $\mu \to e\gamma$ in the MEG II experiment with the highest sensitivity to date

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on behalf of the MEG II collaboration

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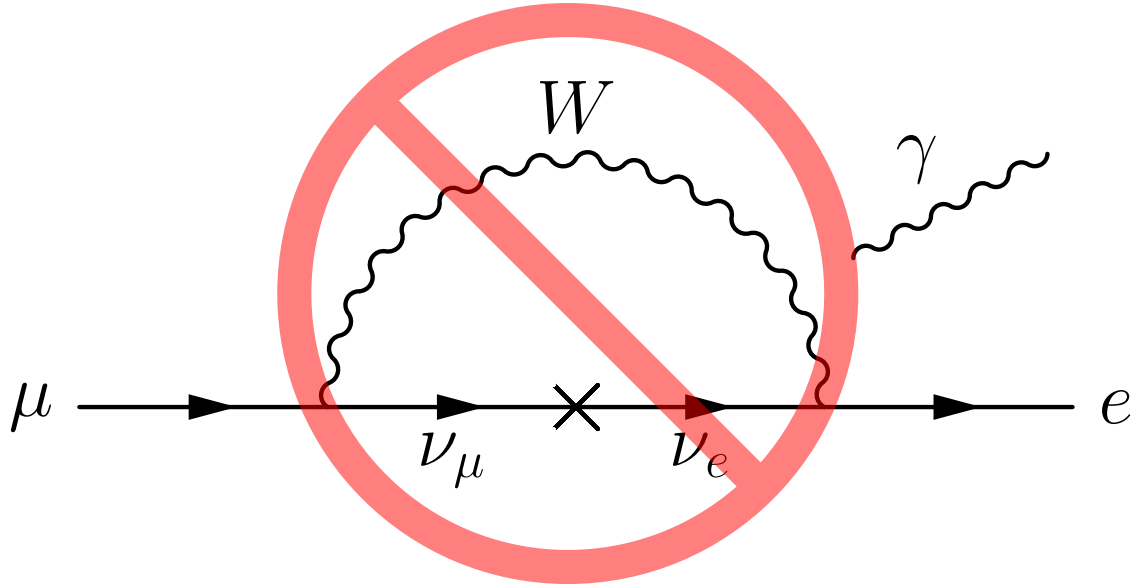
Why $\mu \to e\gamma$ search?

- No SM process for $\mu \to e\gamma$
  - Even with ν-oscillation, Br($\mu \to e\gamma$) $< 10^{-54}$

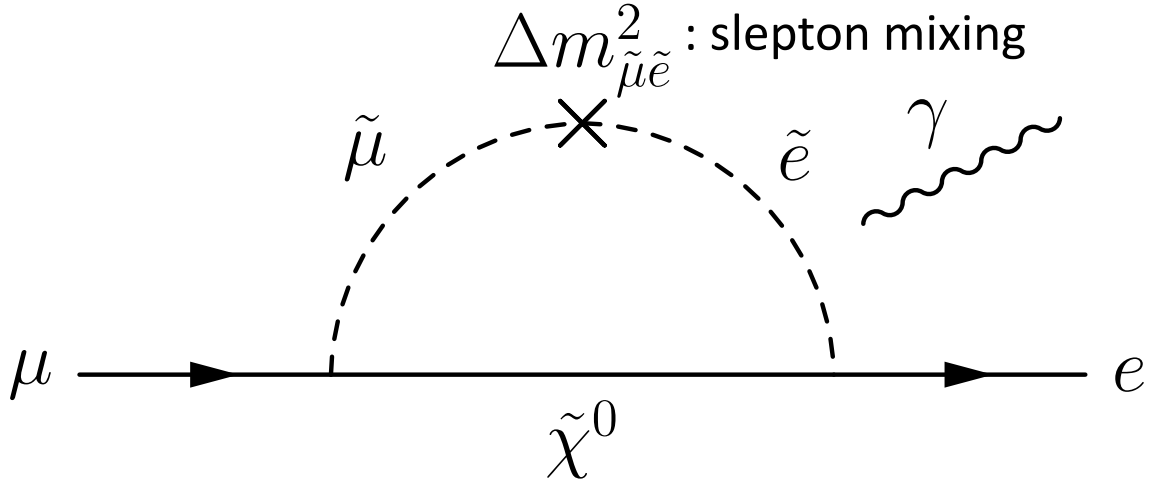
→ **Evidence of new physics if discovered**



10^{-54} : Too small for experiments

- BSM expectation for $\mu \to e\gamma$
  - E.g. SUSY in O(10 TeV): Br($\mu \to e\gamma$) $\sim 10^{-14} - 10^{-12}$

→ **Within experimental reach**

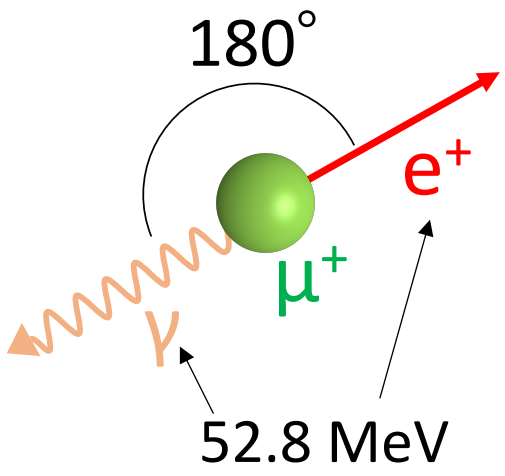


$10^{-14} - 10^{-12}$: In experimental reach

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

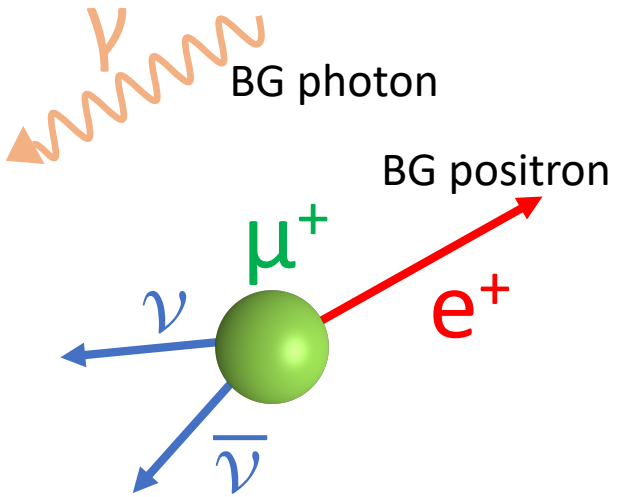
Signal

2-body kinematics



Main background

Accidental coincidence



RMD background

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

→ **Minor** (effectively 10^{-16})

Different kinematics

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

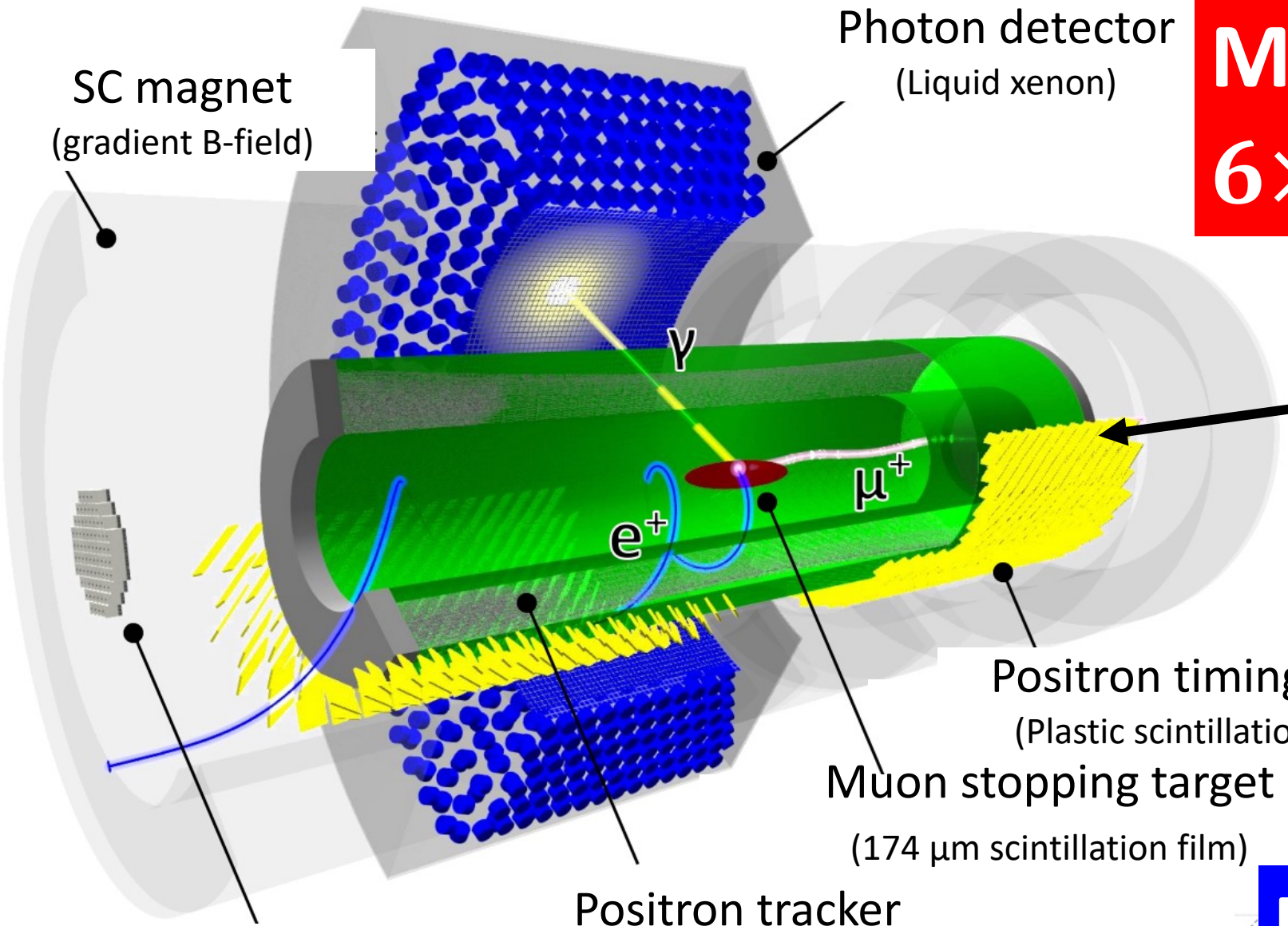
What determines sensitivity?

$$N_{sig} \propto R_\mu \times \mathrm{Br}(\mu \to e\gamma) \times \mathrm{efficiency}$$

$$N_{BG} \propto R_\mu^2 \underbrace{\sigma_t\, \sigma_\Theta^2\, \sigma_{E_e}\, \sigma_{E_\gamma}^2}_{\text{Resolution}}$$

- **High efficiency & high rate**
- **Continuous muon beam**
- **High resolution**

MEG II overview



SC magnet
(gradient B-field)

Photon detector
(Liquid xenon)

MEG II goal:
6×10^{-14} sensitivity

Continuous muon beam@PSI
($3-5\times10^{7}$ μ/s)

Positron timing counter
(Plastic scintillation counter)

Muon stopping target
(174 μm scintillation film)

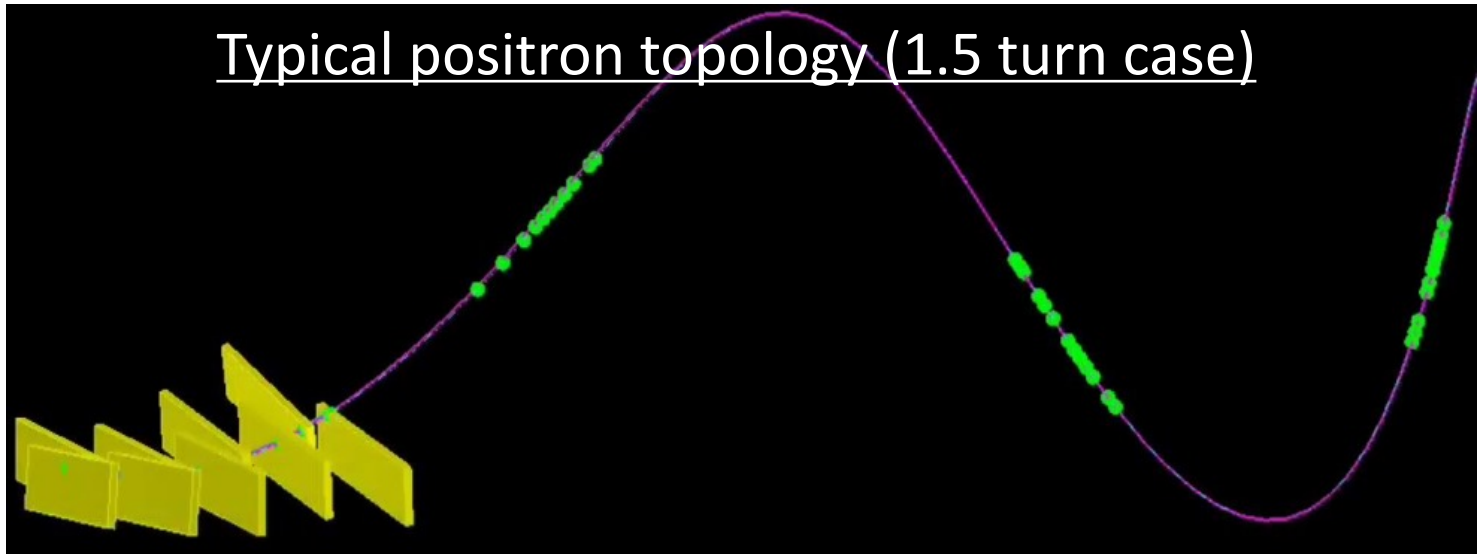
Positron tracker
(Cylindrical drift chamber)

BG-γ tagging counter

DAQ plan: 2021 – 2026

Positron detector

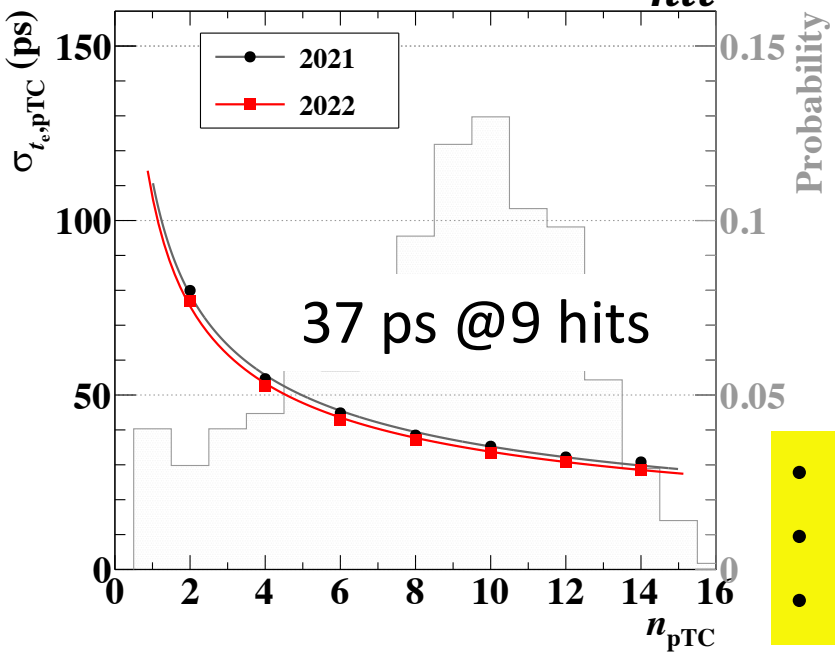
Typical positron topology (1.5 turn case)



Tracking resolution

E_{e+} (keV)	89
ϕ_{e+}, θ_{e+} (mrad)	5.2/6.2
y_{e+}, z_{e+} (mm)	0.61/1.76

Time resolution vs N_{hit}



Positron timing

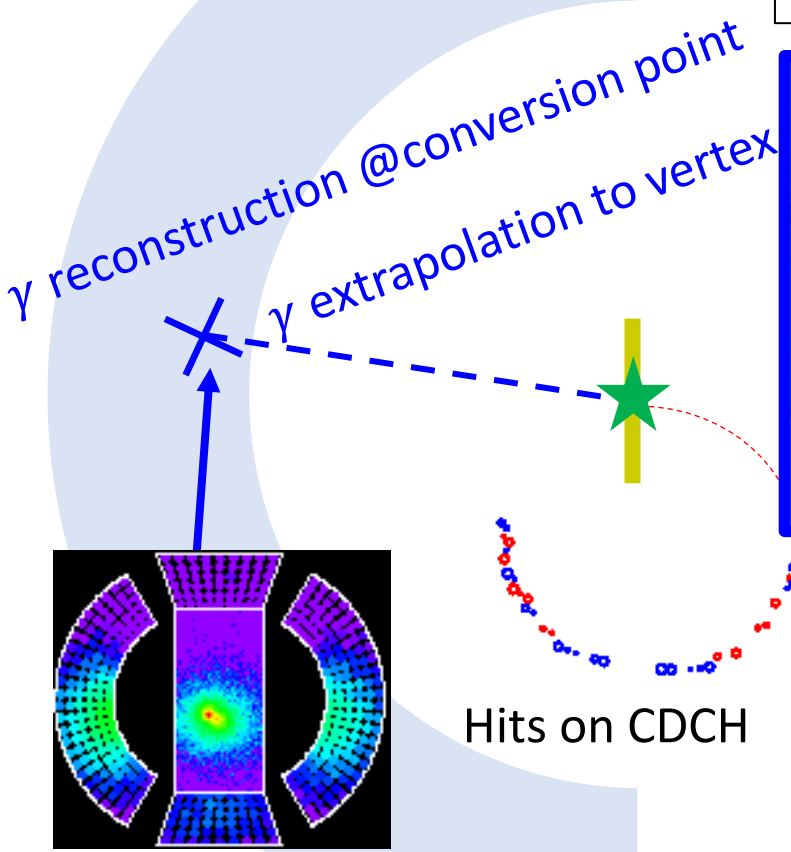
- 512 plastic counters in total
- 110 ps resolution / hit
- 9 hits (average) / signal track

Positron tracking: Drift chamber

- Wire chamber with stereo geometry
- High-density readout (2 – 3 cells / cm²)
- Reduced material ($1.6\times10^{-3}\ X_0$)

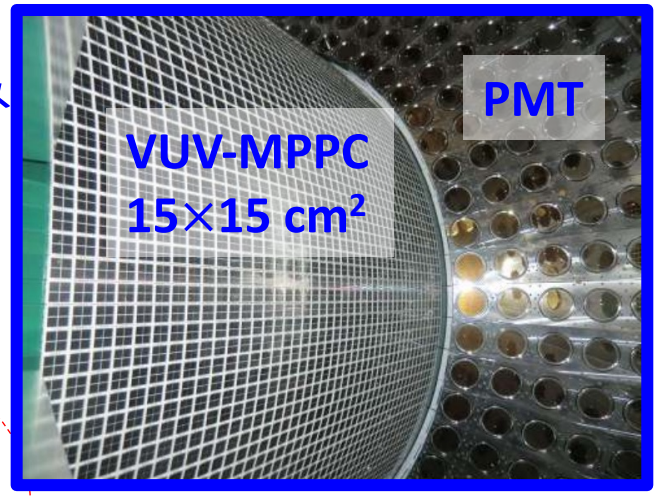
Photon detector

Photon reconstruction



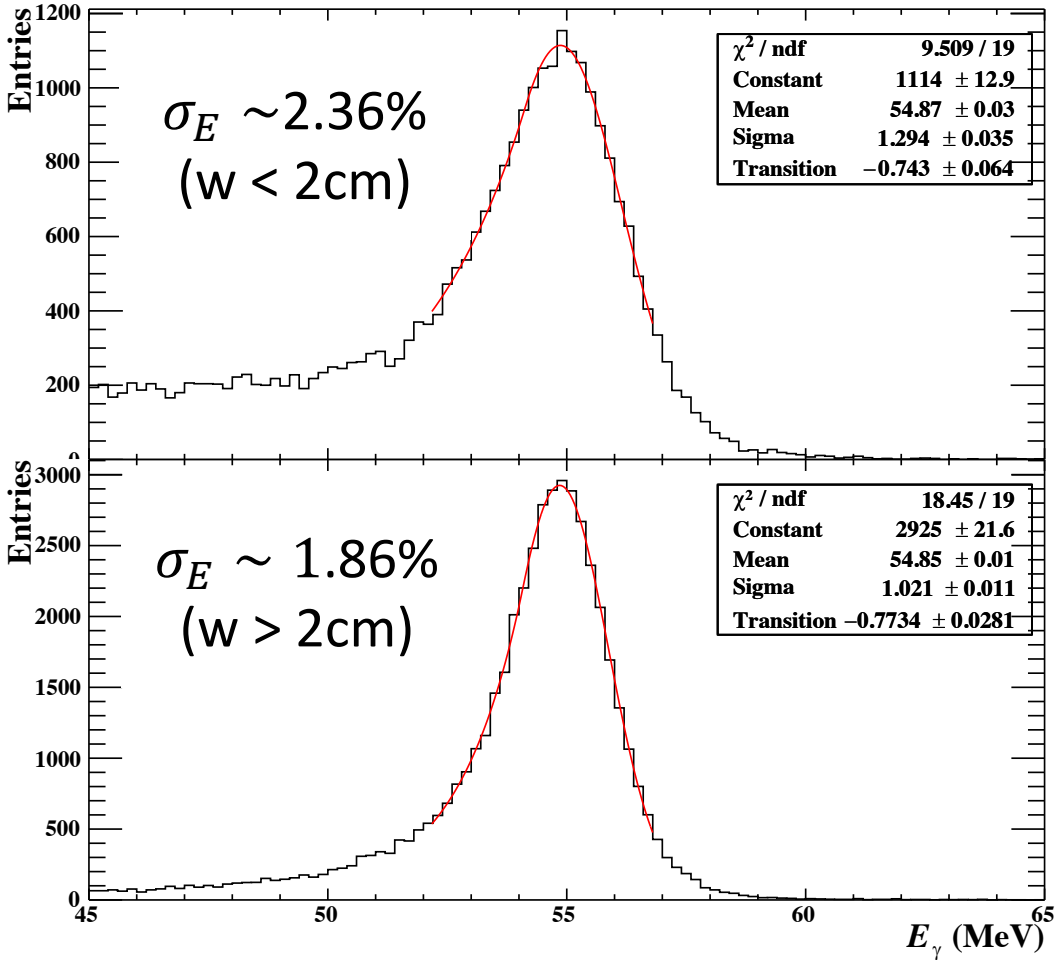
Photon detector

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



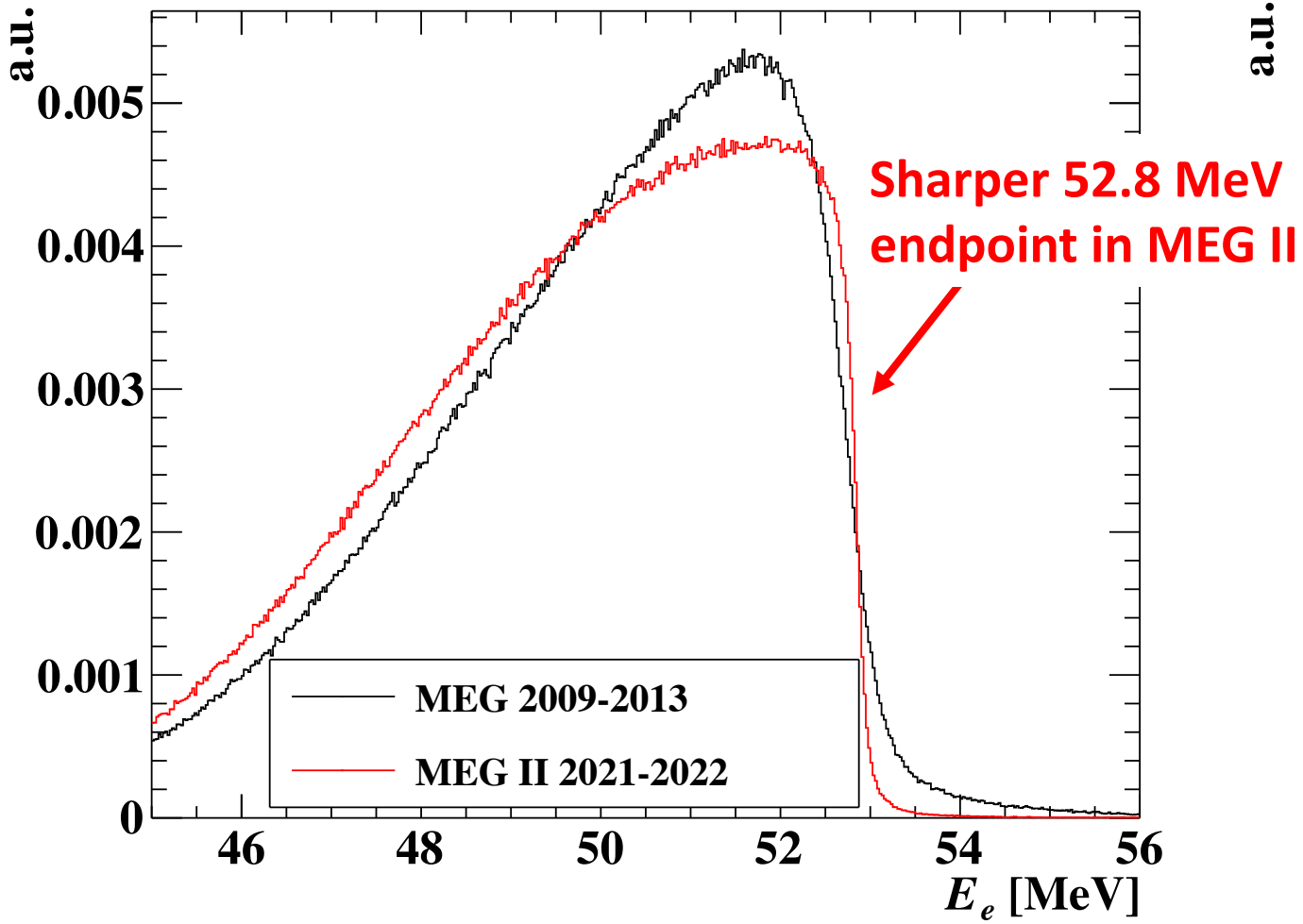
- 4092 MPPC (inner face)
  → Granular & uniform
- 668 PMT (other face)

Response to 55 MeV photon
(From boosted $\pi^0 \to \gamma\gamma$)

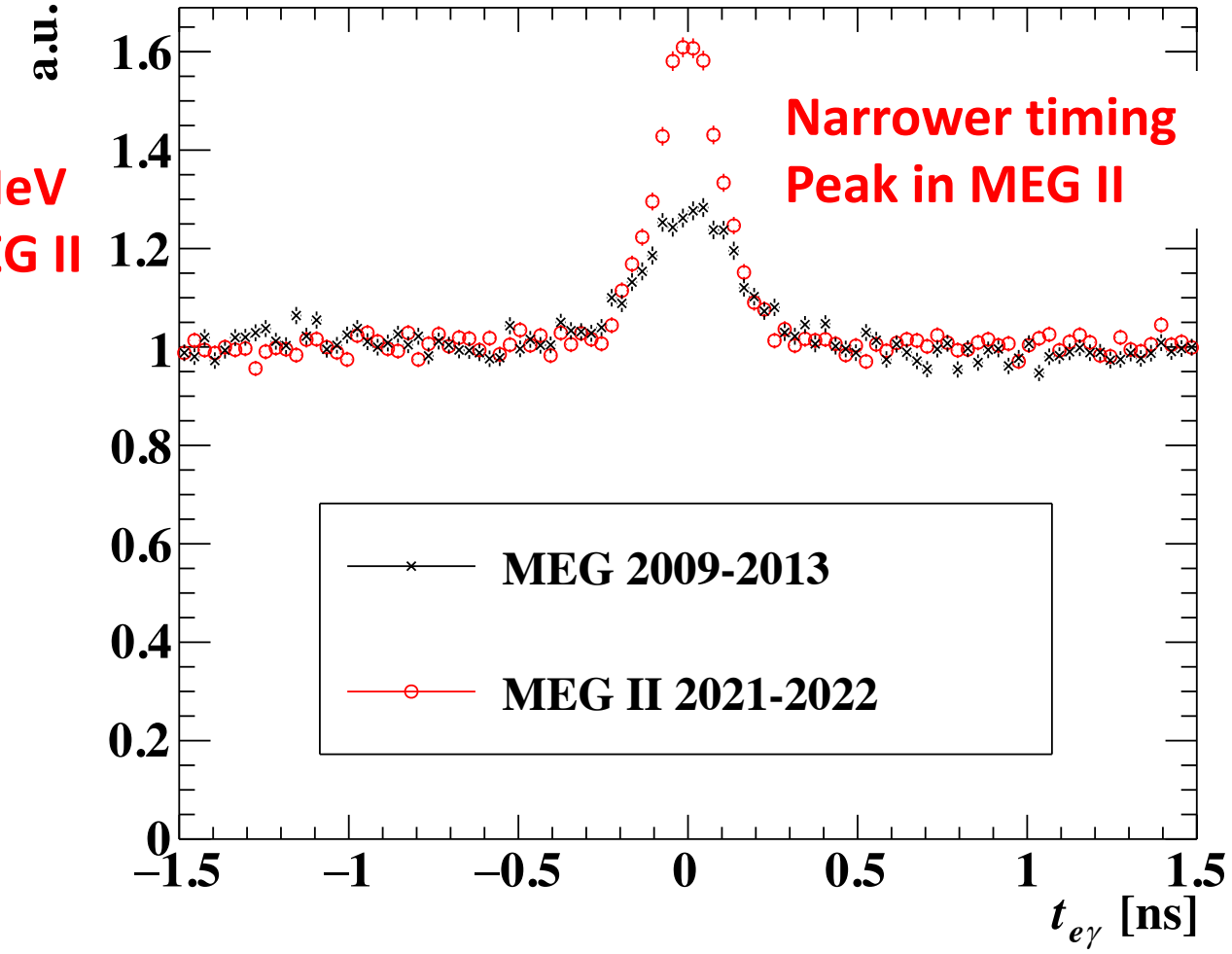


Highlight: Performance vs MEG

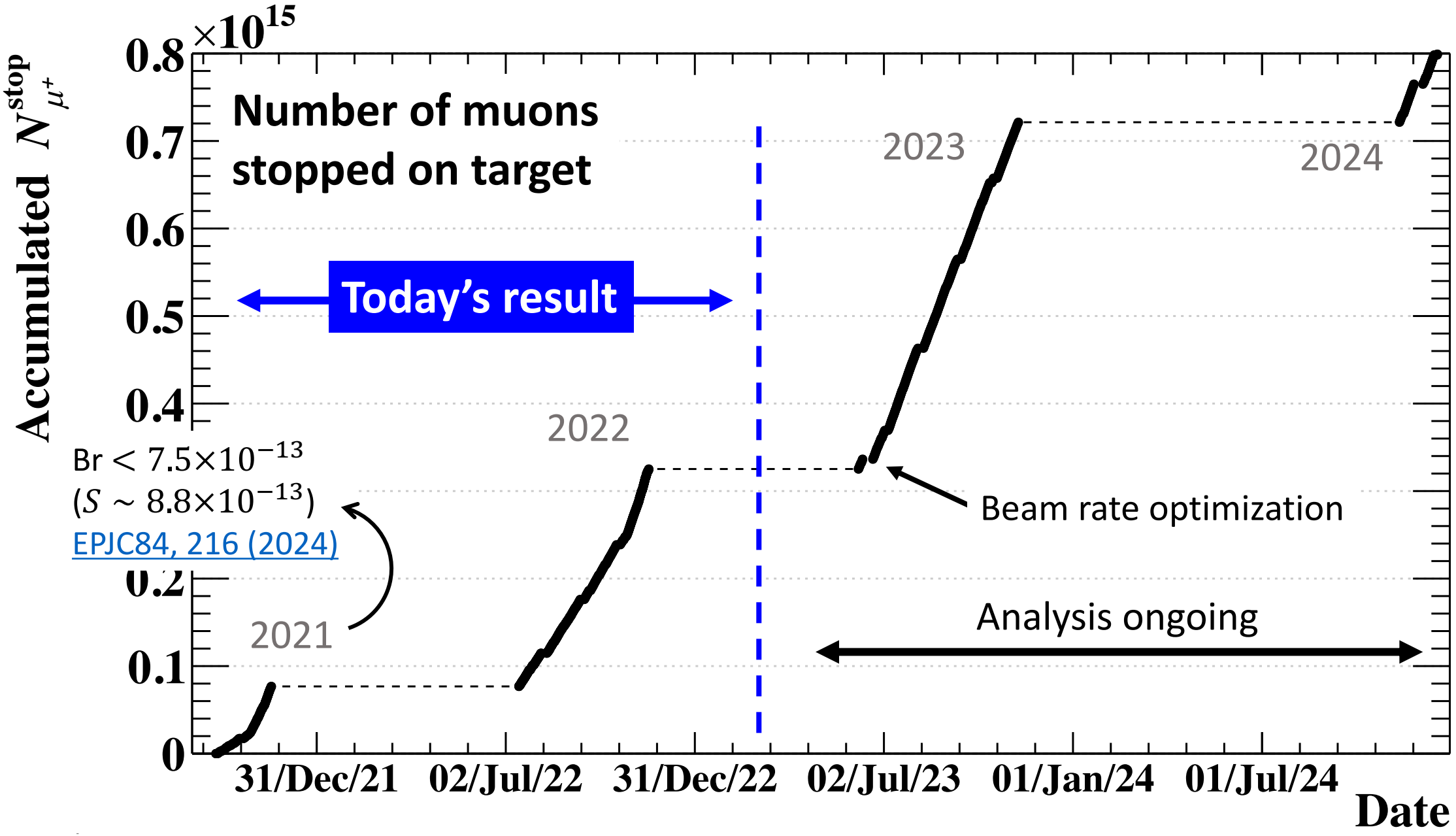
52.8 MeV endpoint spectrum of $\mu \to e\nu\bar{\nu}$:
$\times 3.6$ improvement in momentum resolution



Timing peak from $\mu \to e\nu\bar{\nu}\gamma$ samples:
$\times 1.5$ improvement in time resolution



Timeline (since DAQ start)



Analysis strategy

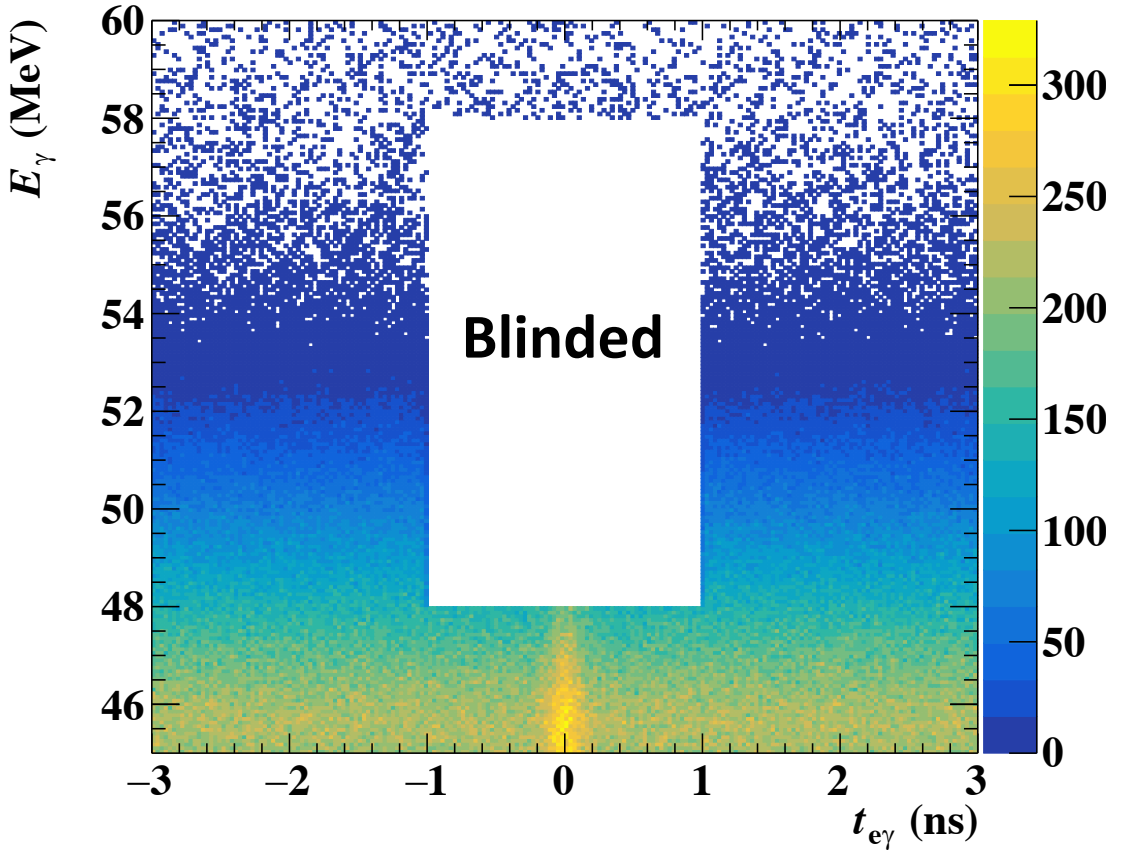
- Extended un-binned likelihood fit to estimate N_{sig}

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

← Constraints on nuisance parameters

  - $S(x), A(x), B(x)$: Multi-dimensional function of energy, time & BG-γ counter
  - Confidence interval calculation with Feldman-Cousins method

- Blinding according to
  - Time difference
  - Photon energy

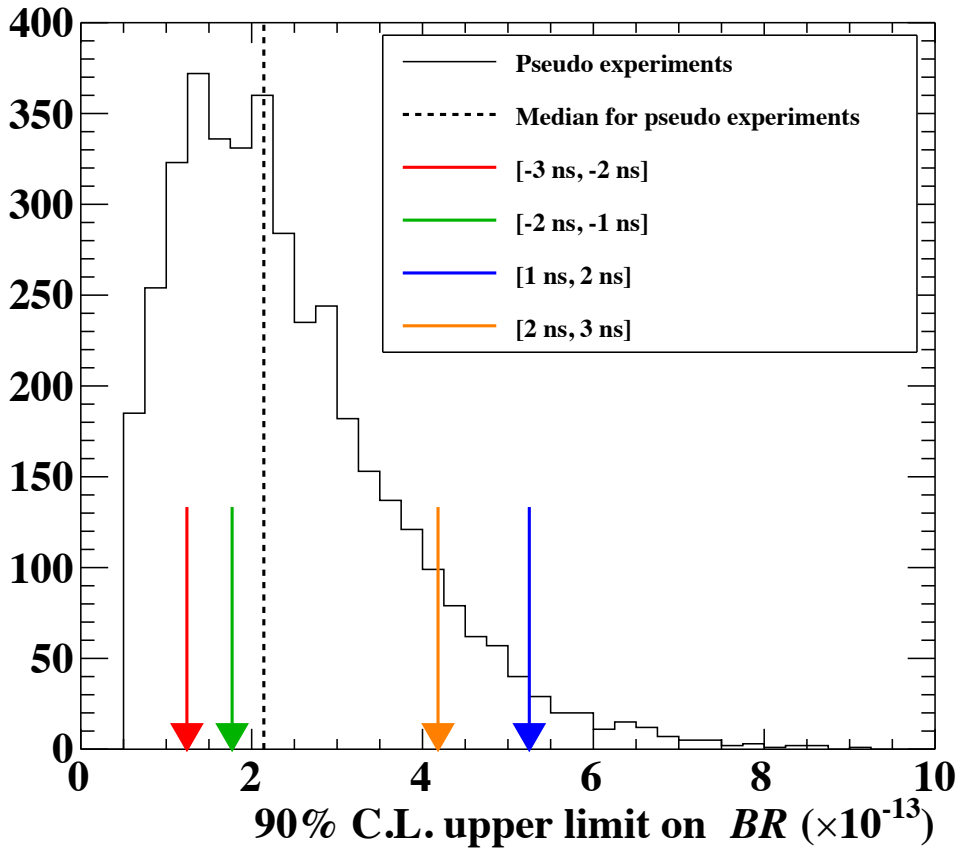


Sensitivity of this search

- Measured # of muons: $\boldsymbol{k = (1.34 \pm 0.07)\times 10^{13}}$
  - Number of effectively measured muons
  - Evaluation by background positron counting in dedicated dataset
    → Automatic incorporation of positron efficiency & beam rate fluctuation

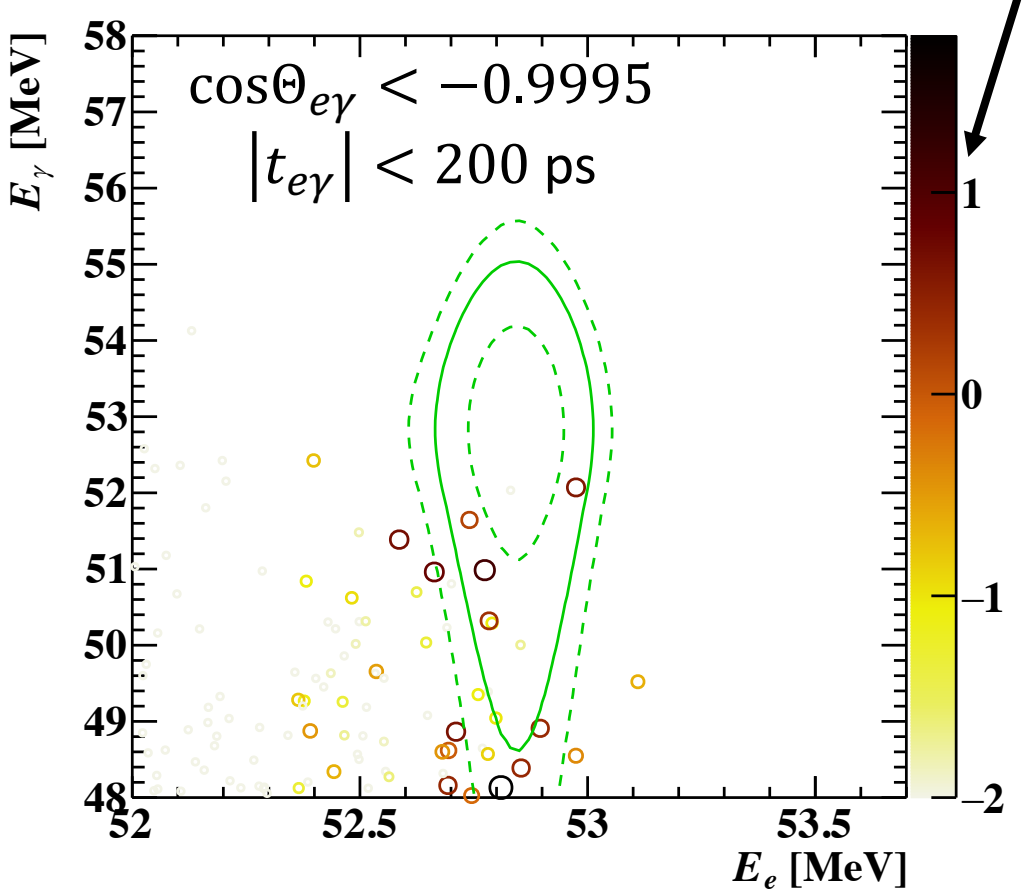
$$\boldsymbol{Br(\mu \to e\gamma) = \frac{N_{sig}}{k}}$$

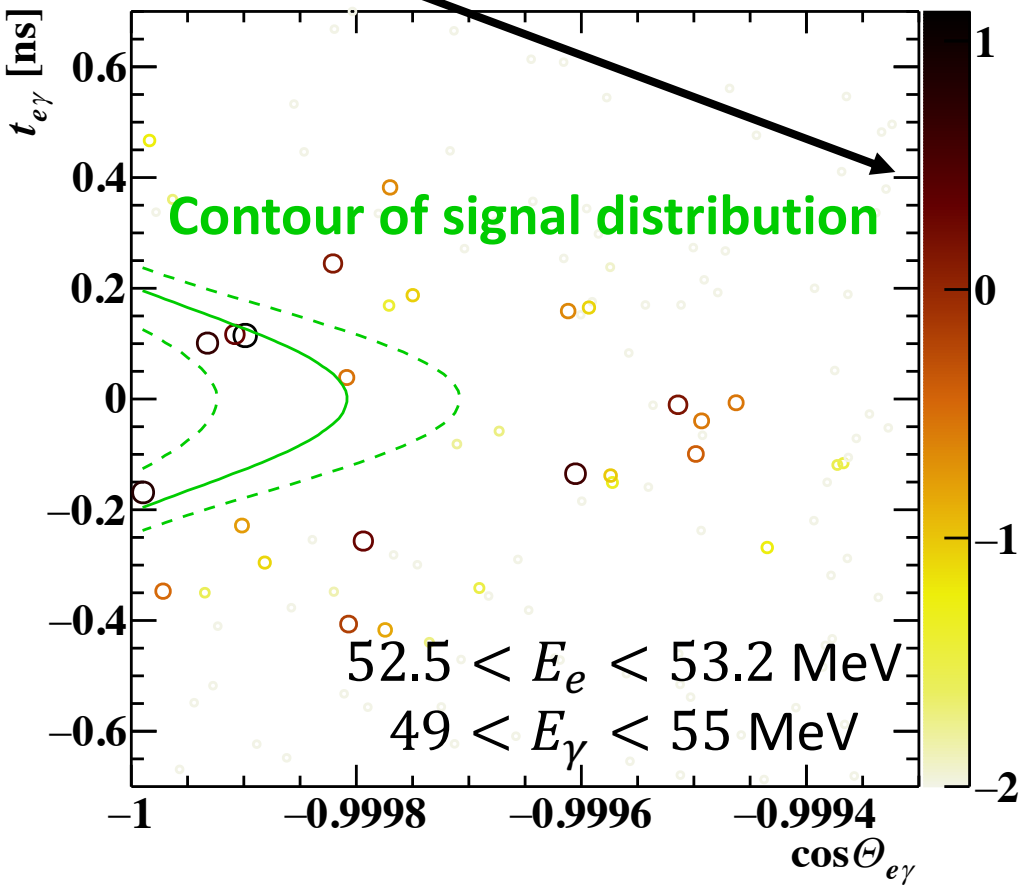
- Sensitivity to Br($\mu \to e\gamma$): $\boldsymbol{2.2\times 10^{-13}}$
  - Defined as median UL of simulations with BG-only hypothesis



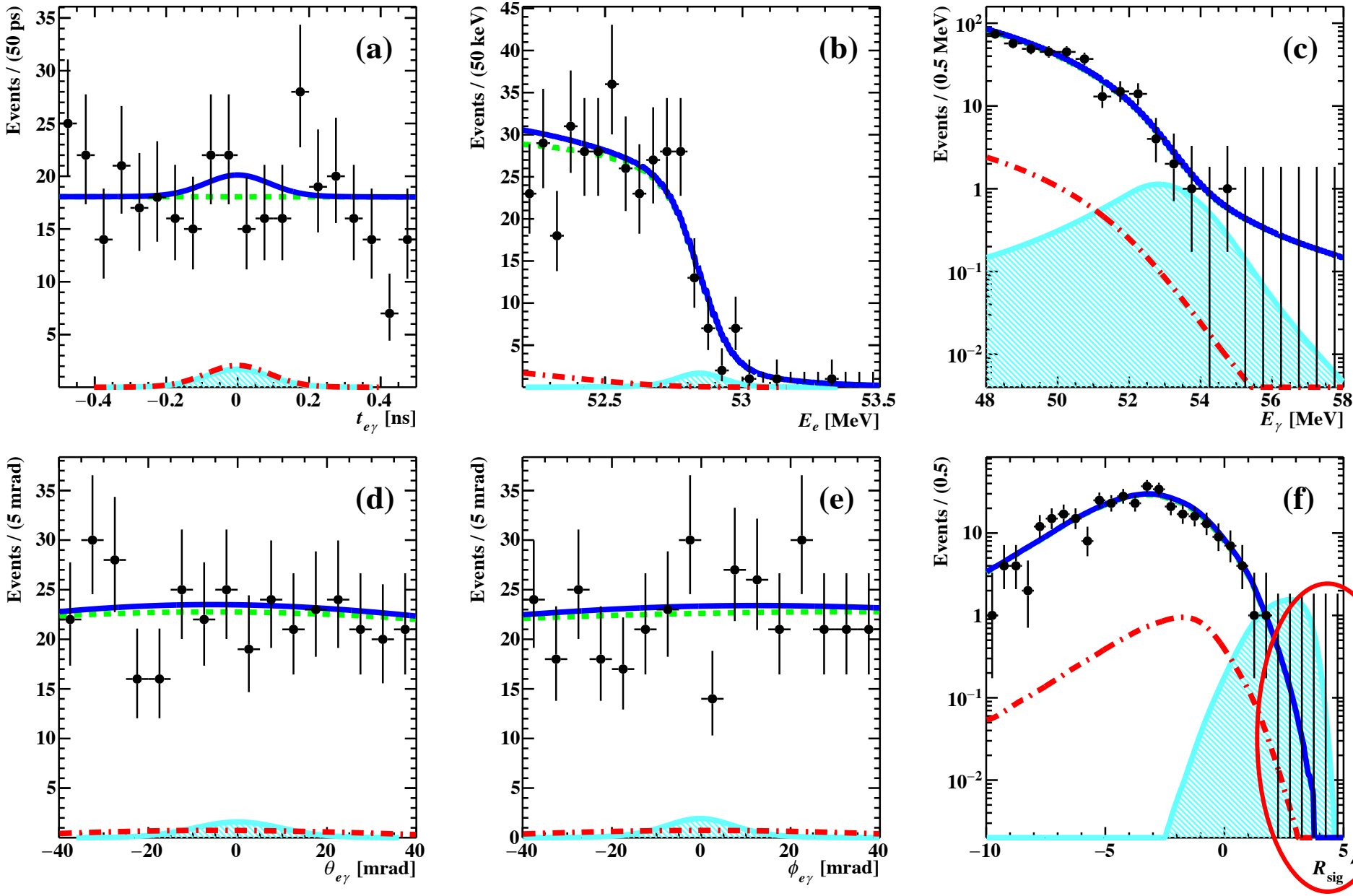
Event distribution

- No signal excess observed
  - Marker color and size according to $R_{sig} := \log_{10}\left(\frac{S(x)}{B(x)}\right)$ (Defined by Neyman-Pearson lemma)





Data vs Fit



Best fit

UL on $N_{sig}\times 4$

Accidental

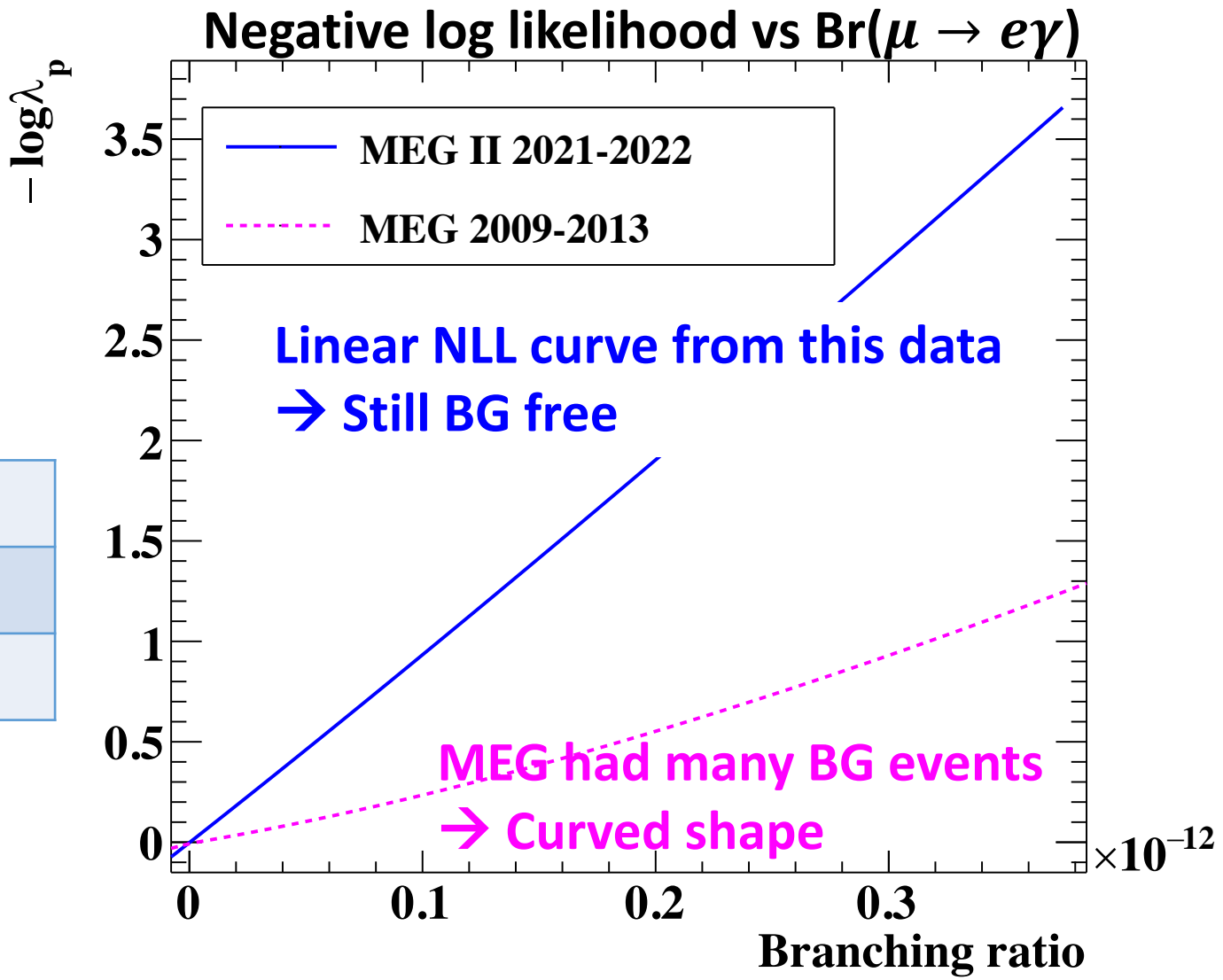
RMD

No signal excess

$$R_{sig} := \log_{10}\left(\frac{S(x)}{B(x)}\right)$$

Result

New limit:
$\mathrm{Br}(\mu \to e\gamma) < 1.5\times10^{-13}$



Summary of numbers in this analysis

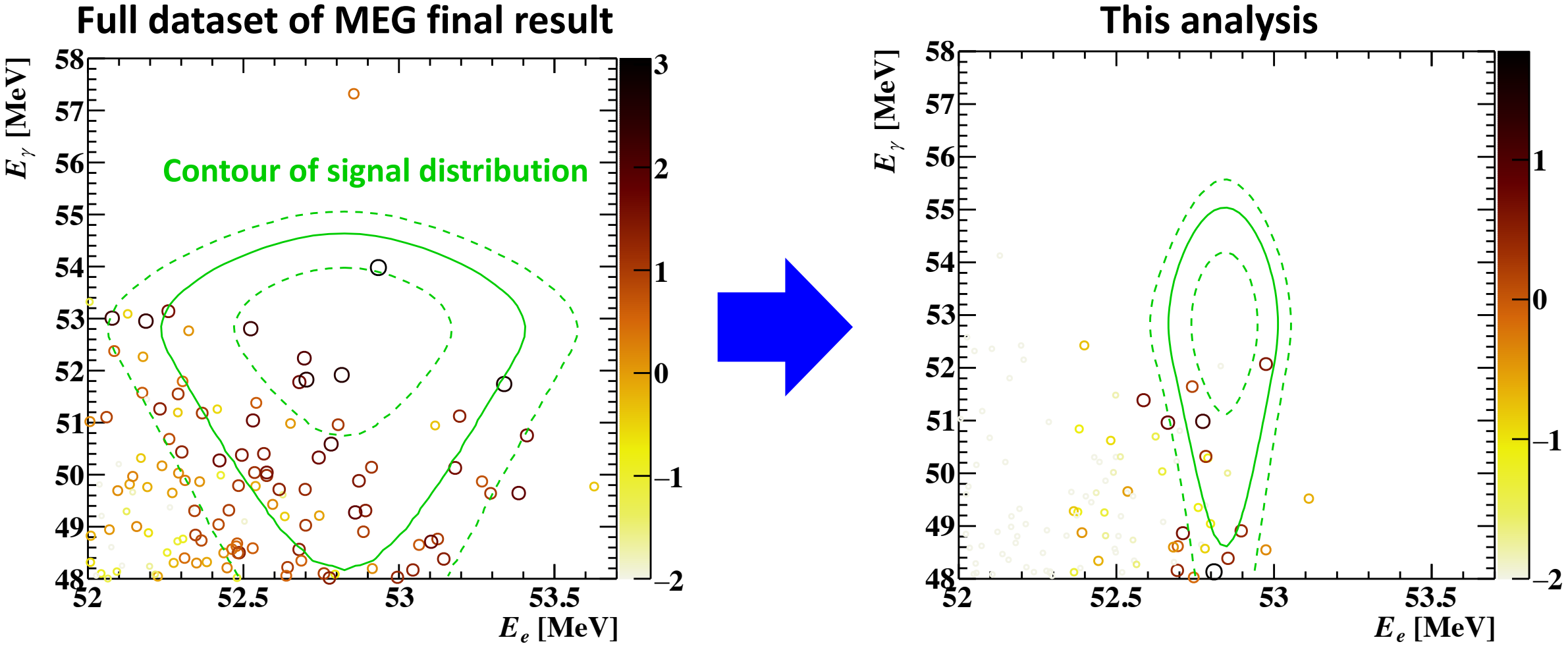
# of muons	1.34×10^{13}
Sensitivity	2.2×10^{-13}
Limit	$\mathrm{Br}(\mu \to e\gamma) < 1.5\times10^{-13}$

Comparison with MEG

- Number of observed muon decays
  - MEG: 1.71×10^{13} (in 5 years)
  - This result: 1.34×10^{13} (in 1 year+7 weeks)
  - **i.e. Overall efficiency improved by $\times 4$**
- Sensitivity on N_{sig}
  - MEG: $N_{sig}^{sens} \sim 9$
    → Limited by BG
  - This analysis: $N_{sig}^{sens} \sim 2.9$
    → Still BG-free

$\times 2.4$ higher sensitivity achieved in a year!!

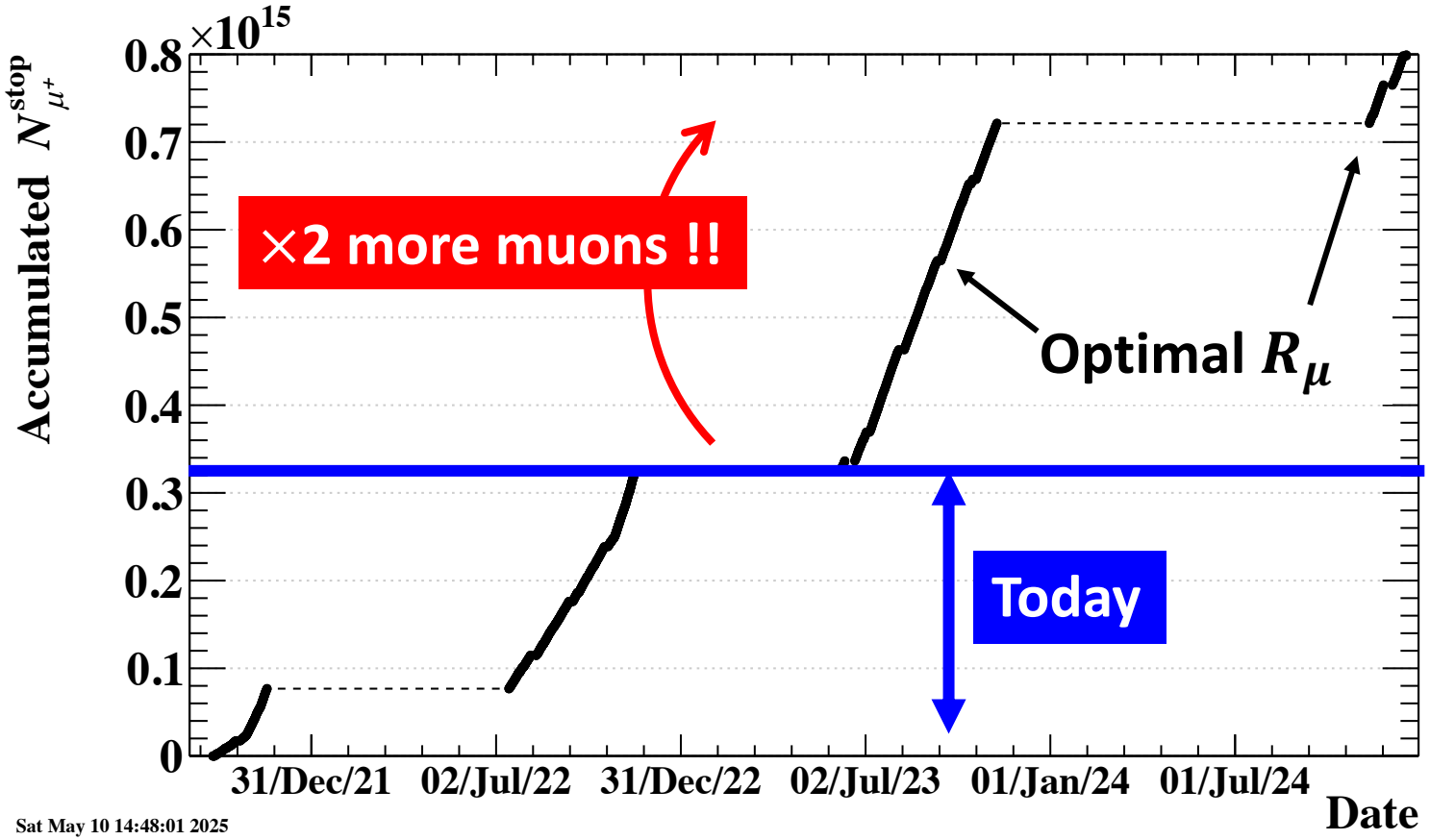
How N_{BG} reduced?



Prospects: Additional data samples

- Analysis of 2023 + 2024
  - Optimized $R_\mu = 4\times10^7$ μ/s
  - Observed ×2 more muon decays
    → O(10^{-14}) in reach
  - Analysis ongoing
- DAQ planned until 2026
  - 20 weeks assigned in 2025
- Reconstruction improvement

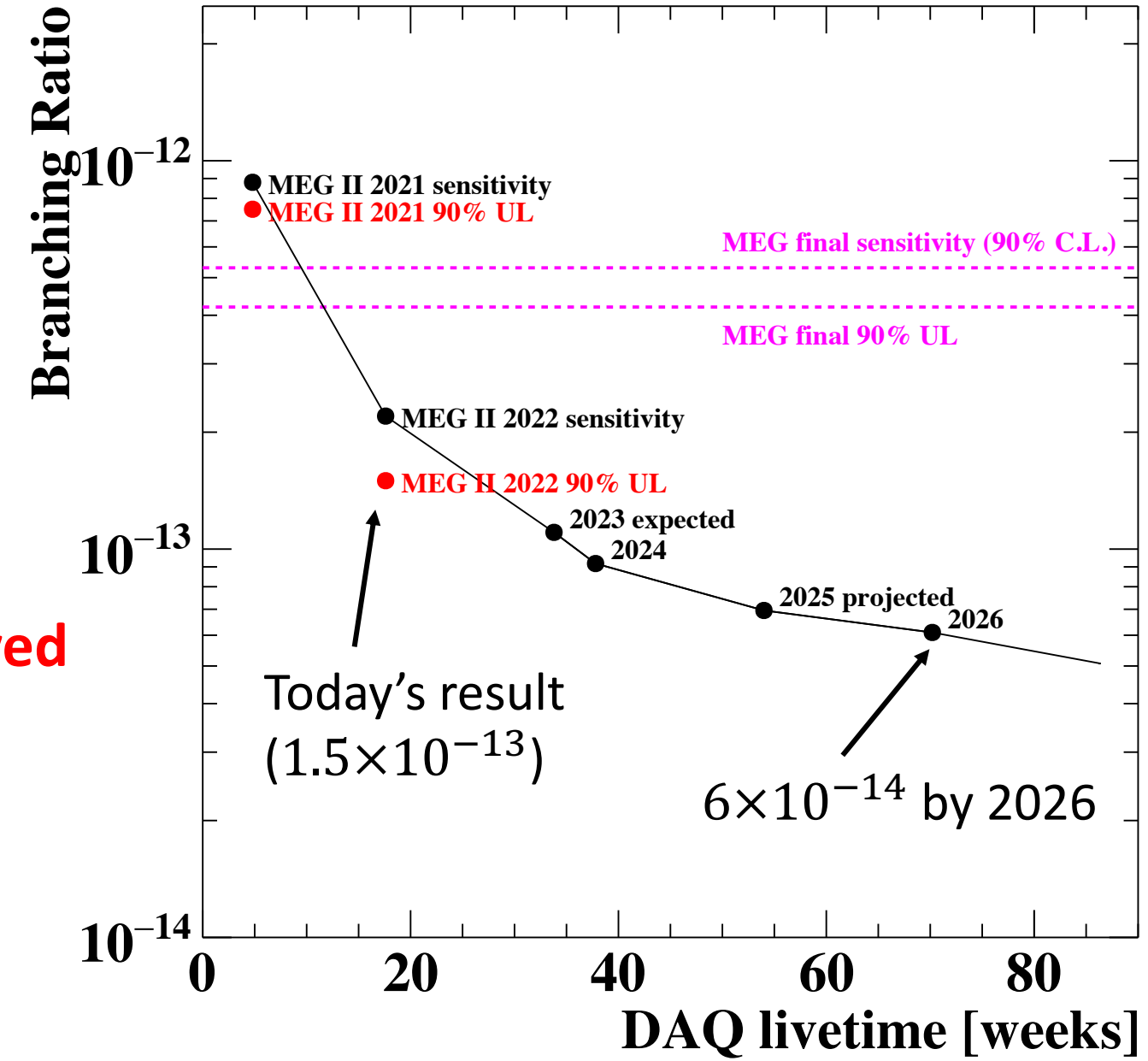
1. Increase in BG: $N_{BG} \propto R_\mu^2$
2. Declining performance of detector
   (In particular, positron tracking efficiency)



Prospects: Expected sensitivity

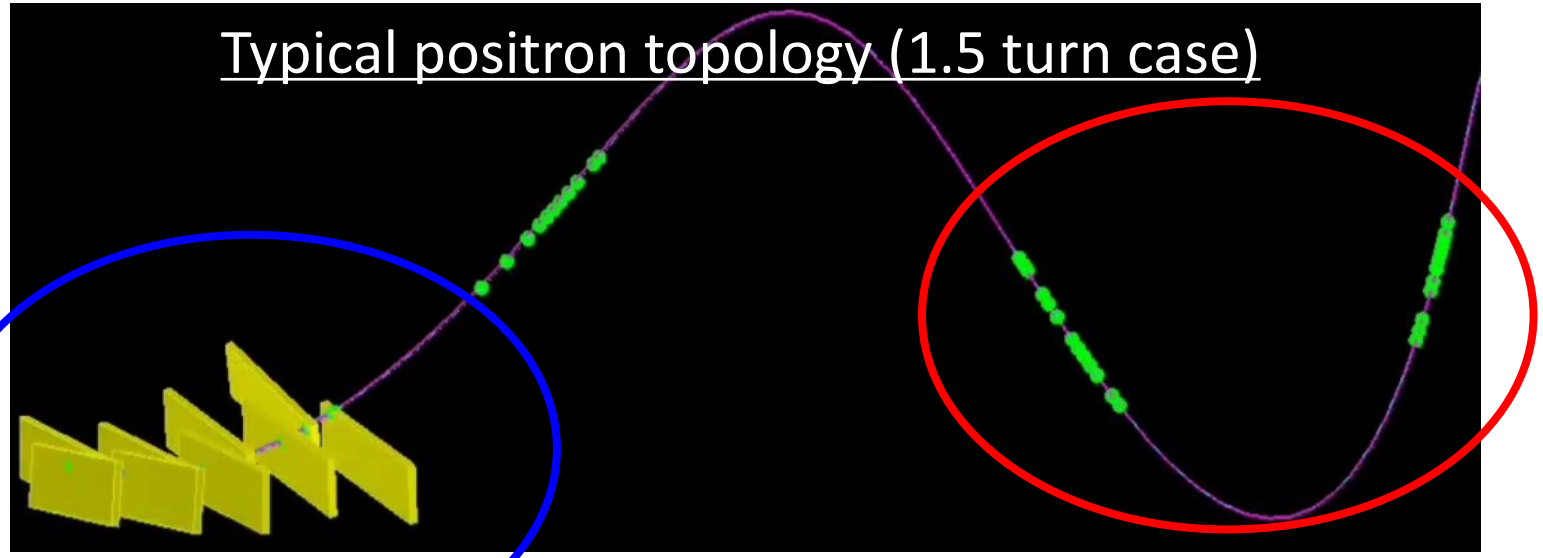
- Assumptions:
  - 20 weeks of DAQ in 2025 & 2026
  - Analysis with achieved performance
- Expected to finally reach 6×10^{-14}

… In addition, analysis getting improved



Foreseen analysis improvement

- (Disclaimer: Here, I selected my own work)
- Developing Transformer-based ML algorithm for positron tracking
  - Transformer: Good at associating queries through *attention mechanism*
  - Input query: Tracker hits & timing counter hits
  - Outputs: Classification of each tracker hits, “Track hits” or “Pileup hits”



Attention mechanism tries to connect different CDCH hits belonging to the same track

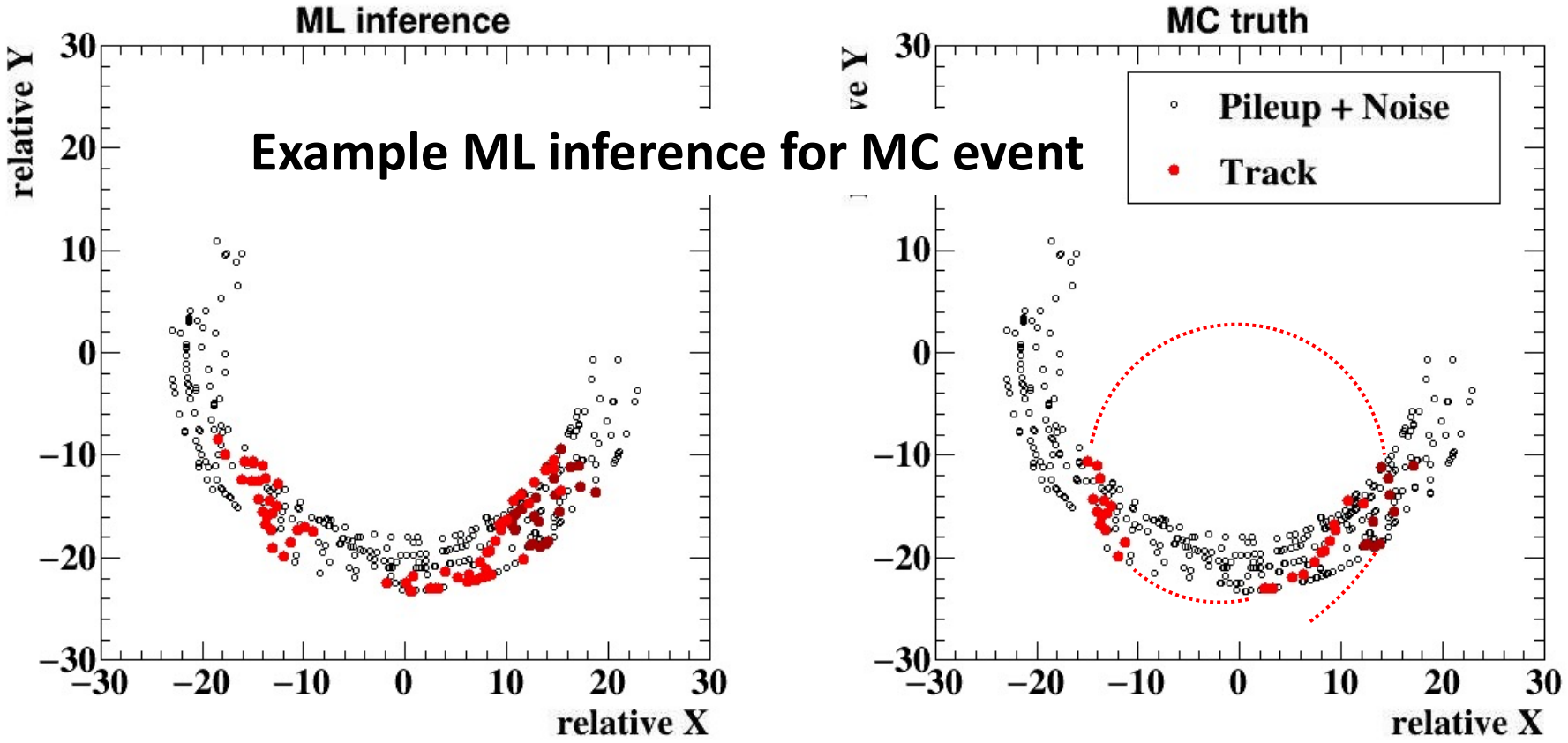
Classification: Do CDCH hits belong to the same track as timing counter hits?

ML-tracking

- ML-output used to filter out pileup hits
  - Demonstrating application to data
  - Expecting O(10%) efficiency improvement
  - And ~5% resolution improvement

MEG II is not just adding new data samples!!

Example ML inference for MC event



Summary

- MEG II aiming at 6×10^{-14} sensitivity
  - Started in 2021 & planned until 2026

- Latest result from 2021 + 2022
  - Search with $\times2.4$ better sensitivity than MEG final result only in 1 year+7 weeks data
  - Updated limit: $\mathrm{Br}(\mu \to e\gamma) < 1.5\times10^{-13}$ at 90% CL

- Prospects
  - Planned analysis improvement & Some are already demonstrated for coming analysis

- Talks for other MEG II works
  - Sensitivity study of $\mu^+ \to e^+a\gamma$ cLFV decay with the MEG II apparatus
  - The X17 search at the MEG II experiment