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The Latest Results of the MEG II Experiment

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on behalf of the MEG II Collaboration

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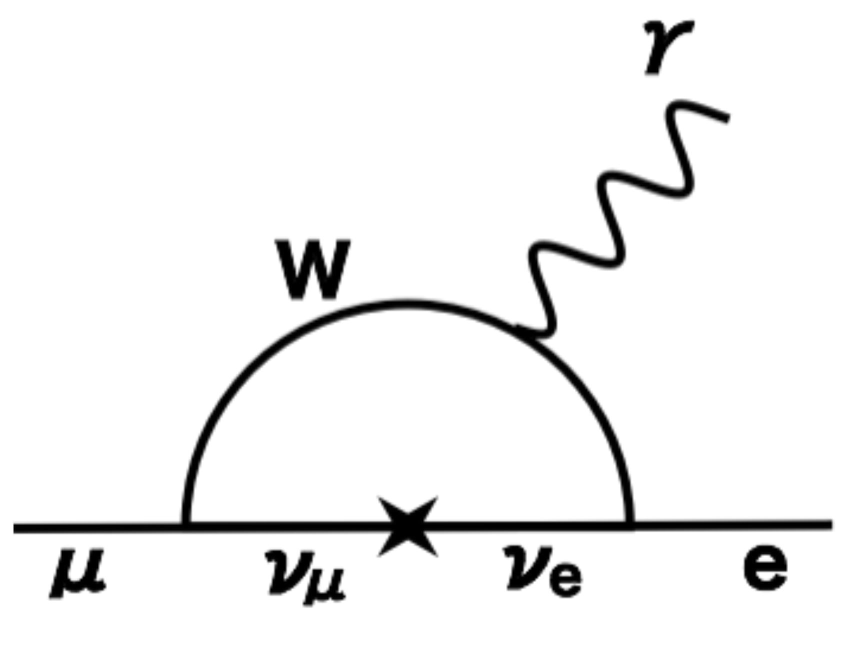
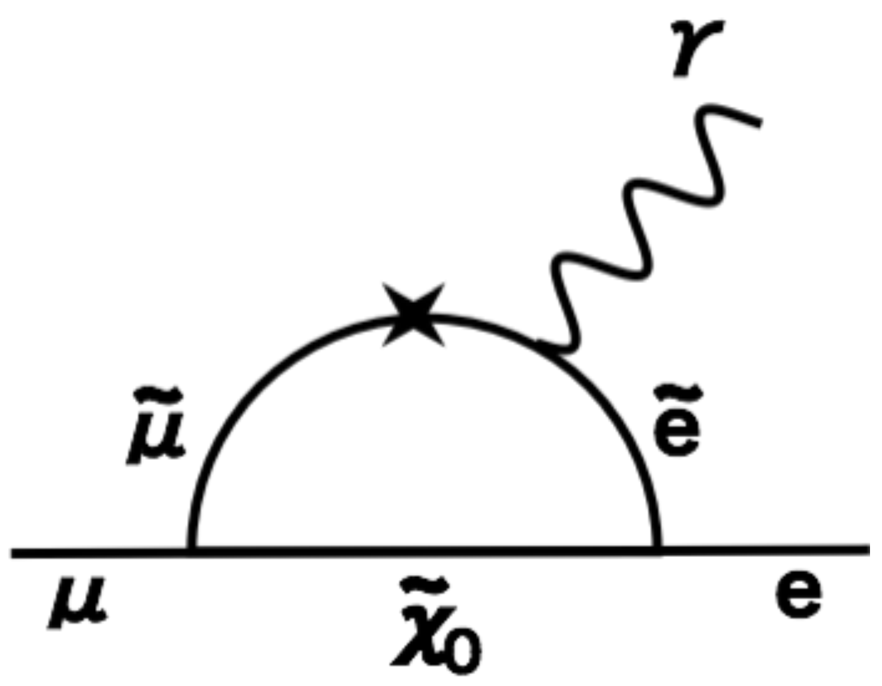
Why to Search for $\mu^+ \to e^+\gamma$

- Flavour conservation in SM is not protected by gauge symmetry
- $\mu^+ \to e^+\gamma$ should occur in SM with neutrino mass but highly suppressed with tiny neutrino mass (**No SM background)**
- Many well-motivated **new physics models predict a sizable rate of** $\mu^+ \to e^+\gamma$



SM(+neutrino osc.)

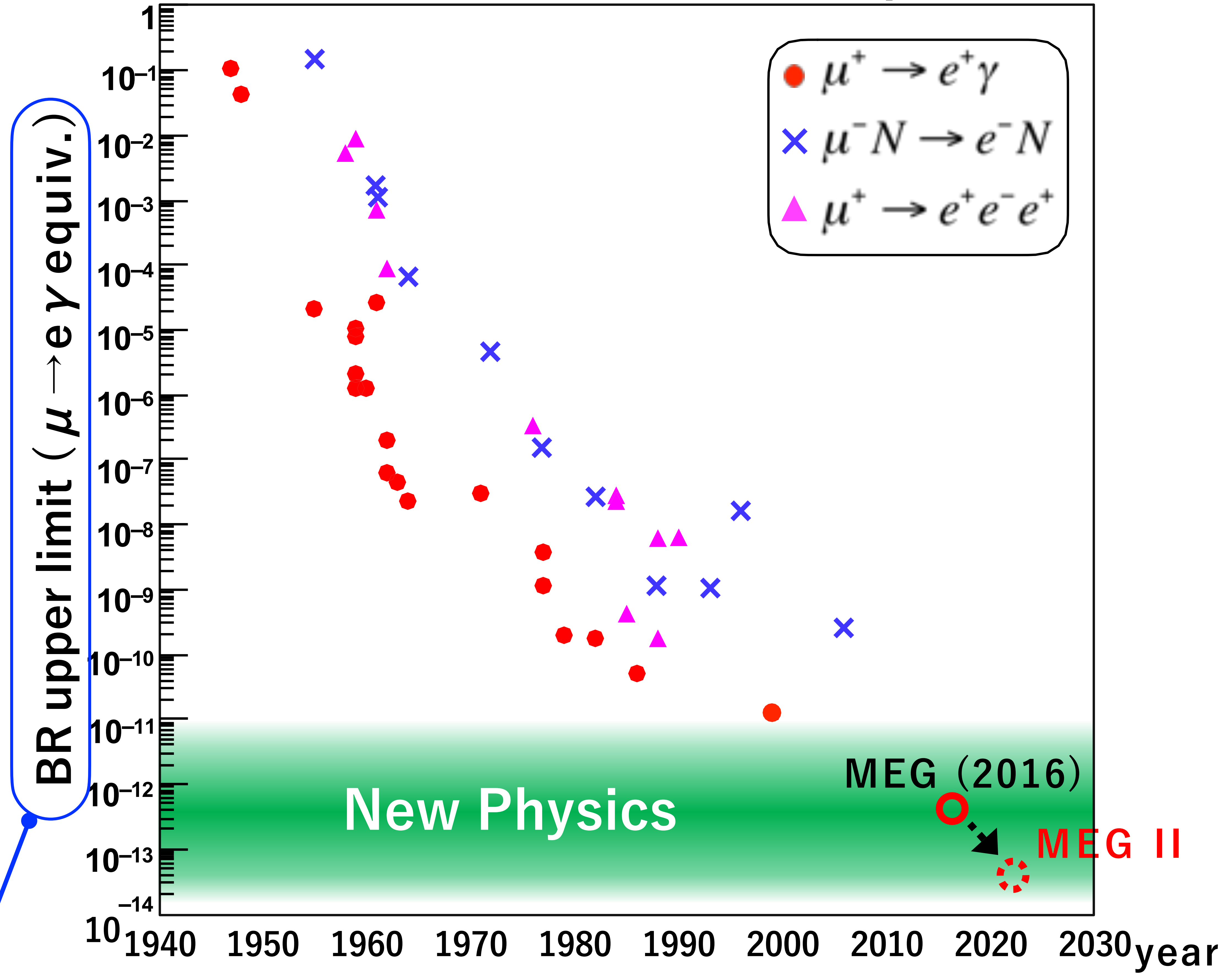
$\mathcal{B}(\mu \to \mathrm{e}\gamma) \sim 10^{-54}$



New Physics

$\mathcal{B}(\mu \to \mathrm{e}\gamma) \sim 10^{-11}\text{-}10^{-15}$

cLFV search history

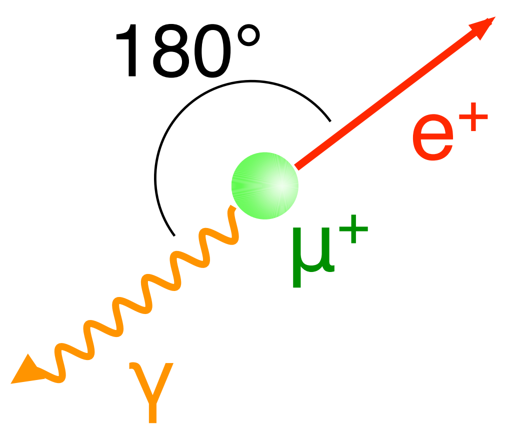


Normalised to $\mu^+ \to e^+\gamma$ rate assuming dipole interaction (à la SUSY)

$\mu^+ \to e^+\gamma$ search is already sensitive enough to strongly test new physics!

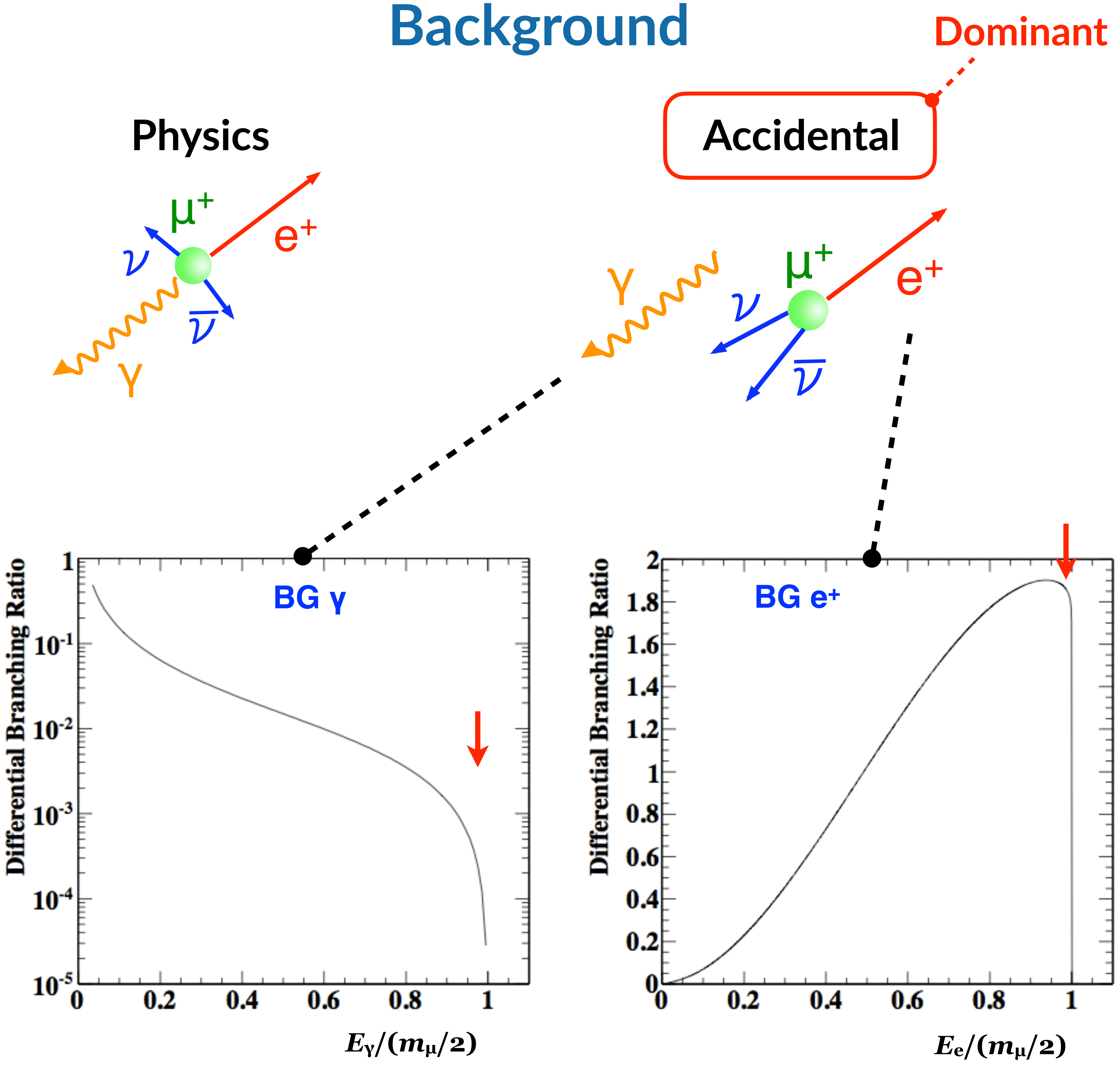
How to Search for $\mu^+ \to e^+\gamma$

Signal



- Two body decay
  - Coincident ($t_{e\gamma} = 0$)
  - Monochromatic energies ($E_e = E_\gamma = 52.8\,\mathrm{MeV}$)
  - Back-to-back ($\Theta_{e\gamma} = 180°$)

Background



Beam intensity, Acceptatnce, Branching ratio, Efficienies

Signal $N_{\mathrm{sig}} = R_\mu \times T \times \Omega \times \mathscr{B} \times \epsilon_\gamma \times \epsilon_e \times \epsilon_{\mathrm{sel}}$

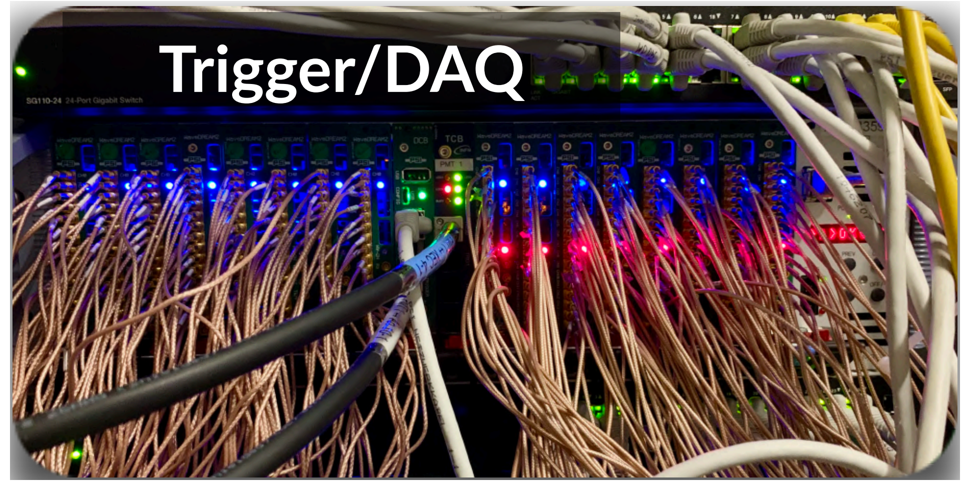
BG $N_{\mathrm{acc}} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta E_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$

E_γ resolusion, E_e resolution, Angular reslution, Time resolution

Need high intensity beam & high performance detector

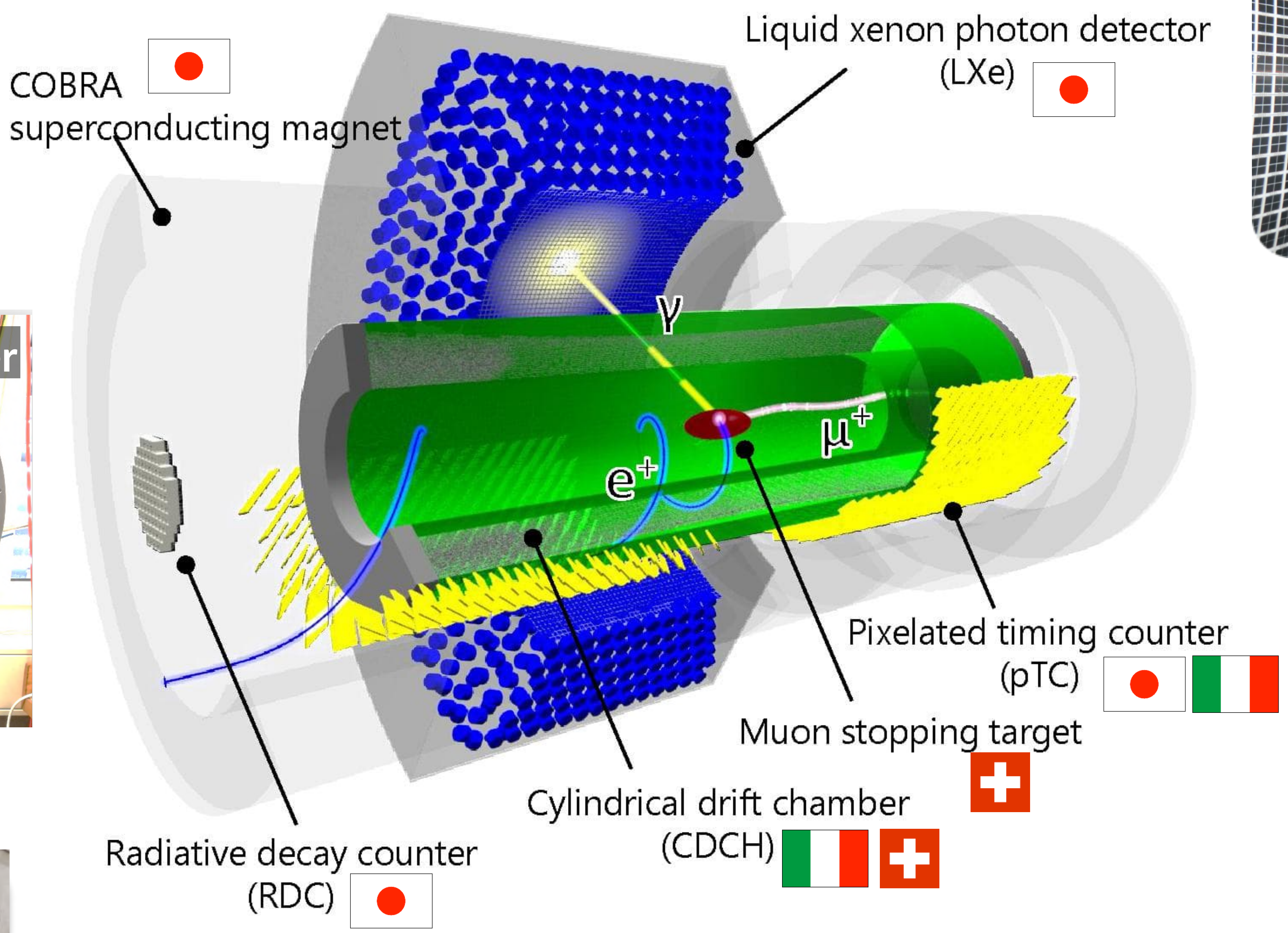
Euro. Phys. J. C(2024)84:190

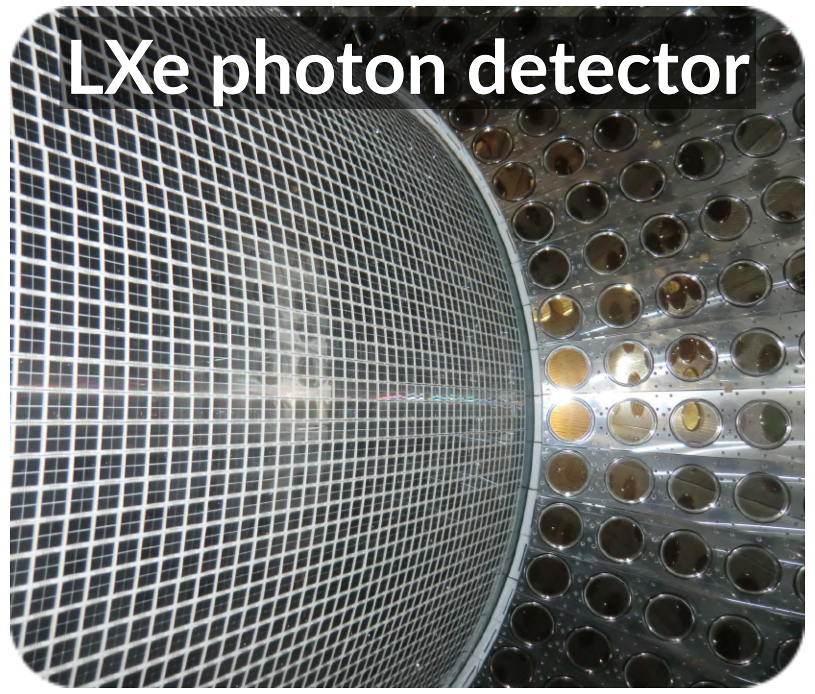
MEG II Experiment@PSI



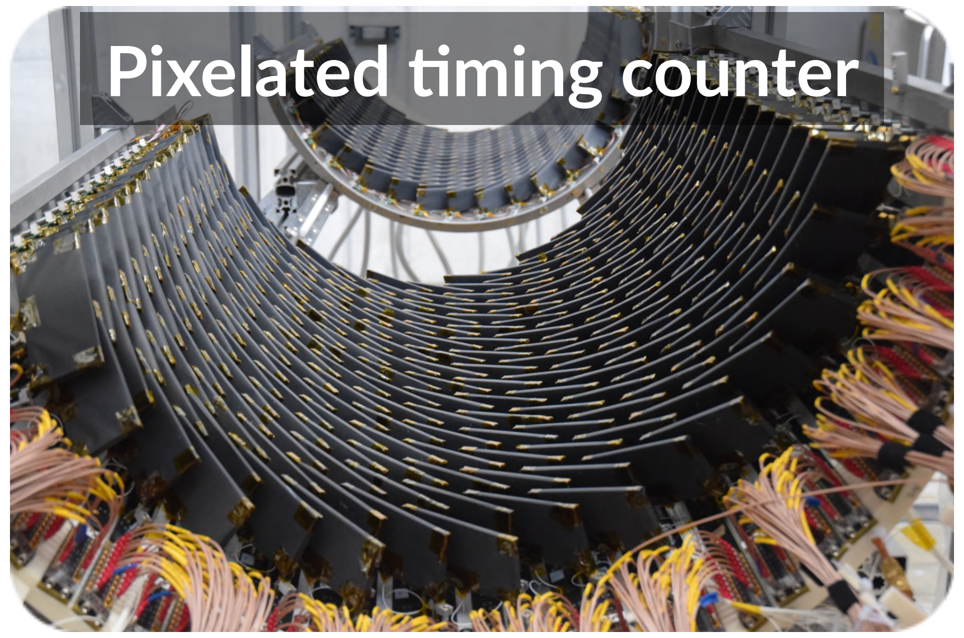
- ~9000ch waveform readout

- New in MEG II
- BG-γ suppression by identifying associated low mom. positron

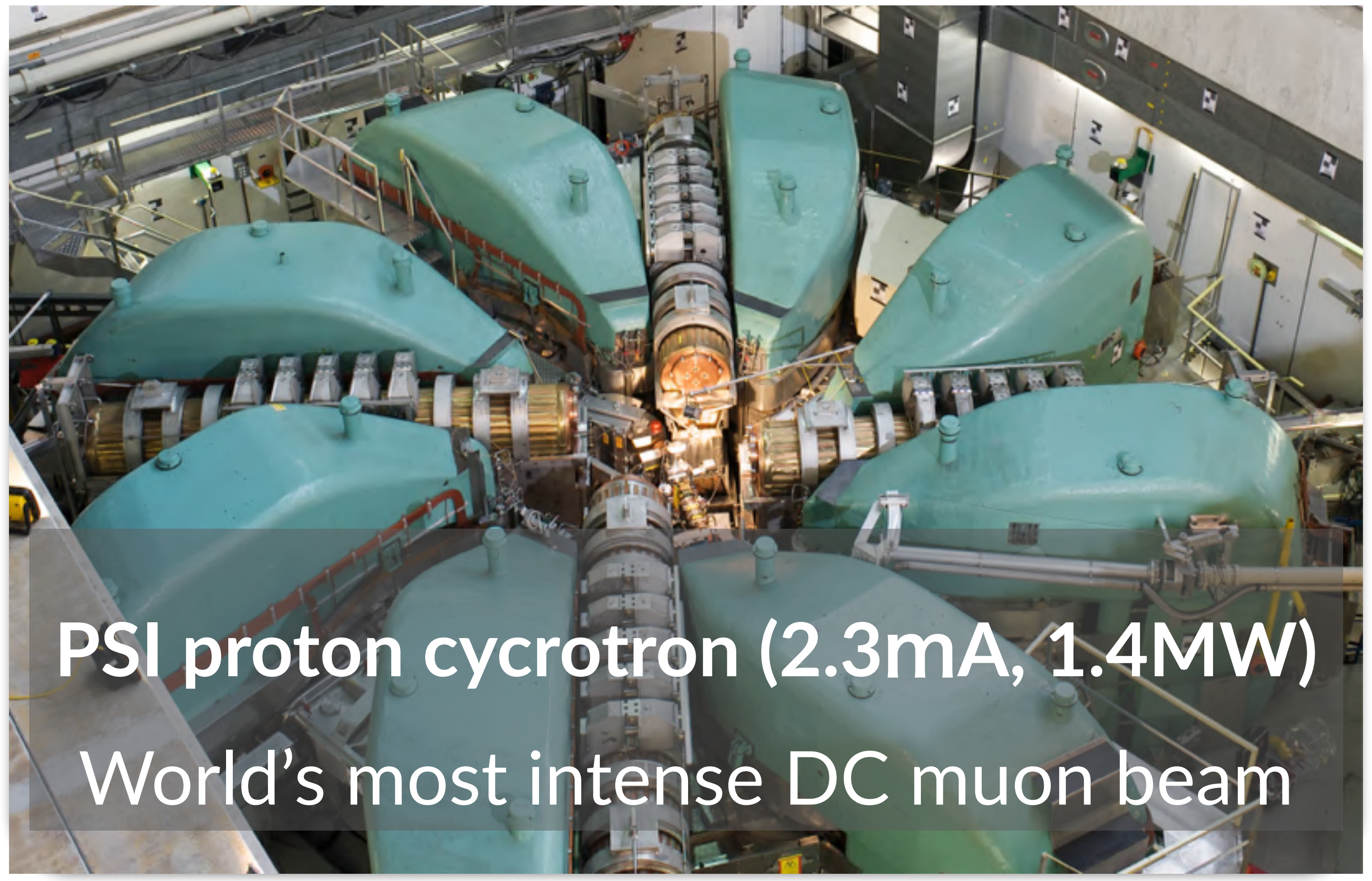




- LXe 900L (~2.7ton)
- Highly granular scintillation readout with SiPM(×4092) + PMT(×668)



- ×512 fast plastic scintillator plates
- 40ps time resolution averaged over multiple hits



Target BR sensitivity: 6×10^{-14}
($\times$ 10 better than MEG)

- Ultra-low-mass with single gas-volume
- Drift cells with stereo wires

Physics Data Acquired So Far

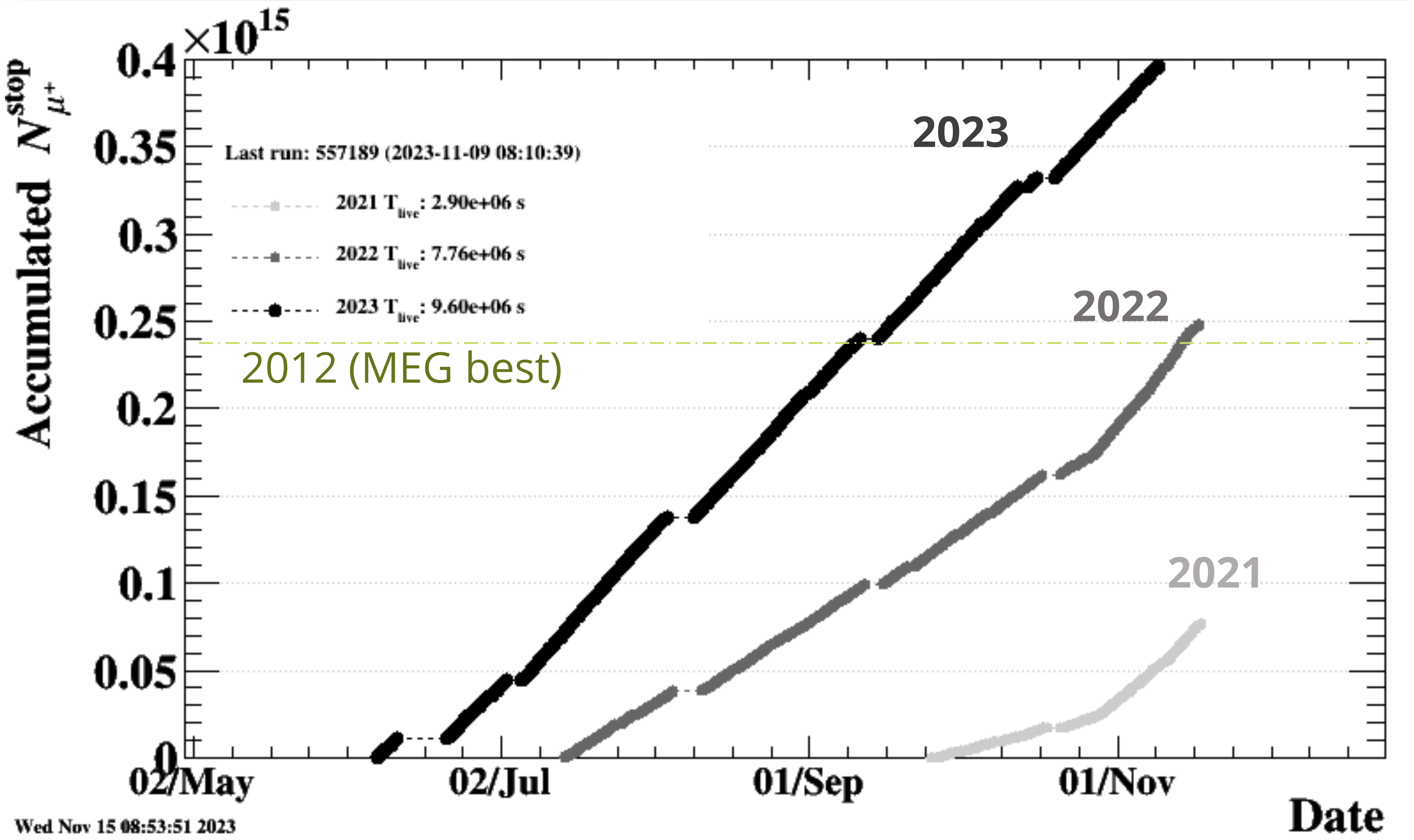
Physics runs for three years

2021: First physics run where the detector operating conditions were optimised

→ **Recently published (**Euro. Phys. J. C(2024)84:216**)** ← This talk

2022: Stable DAQ with optimal detector conditions

2023: Longest physics run

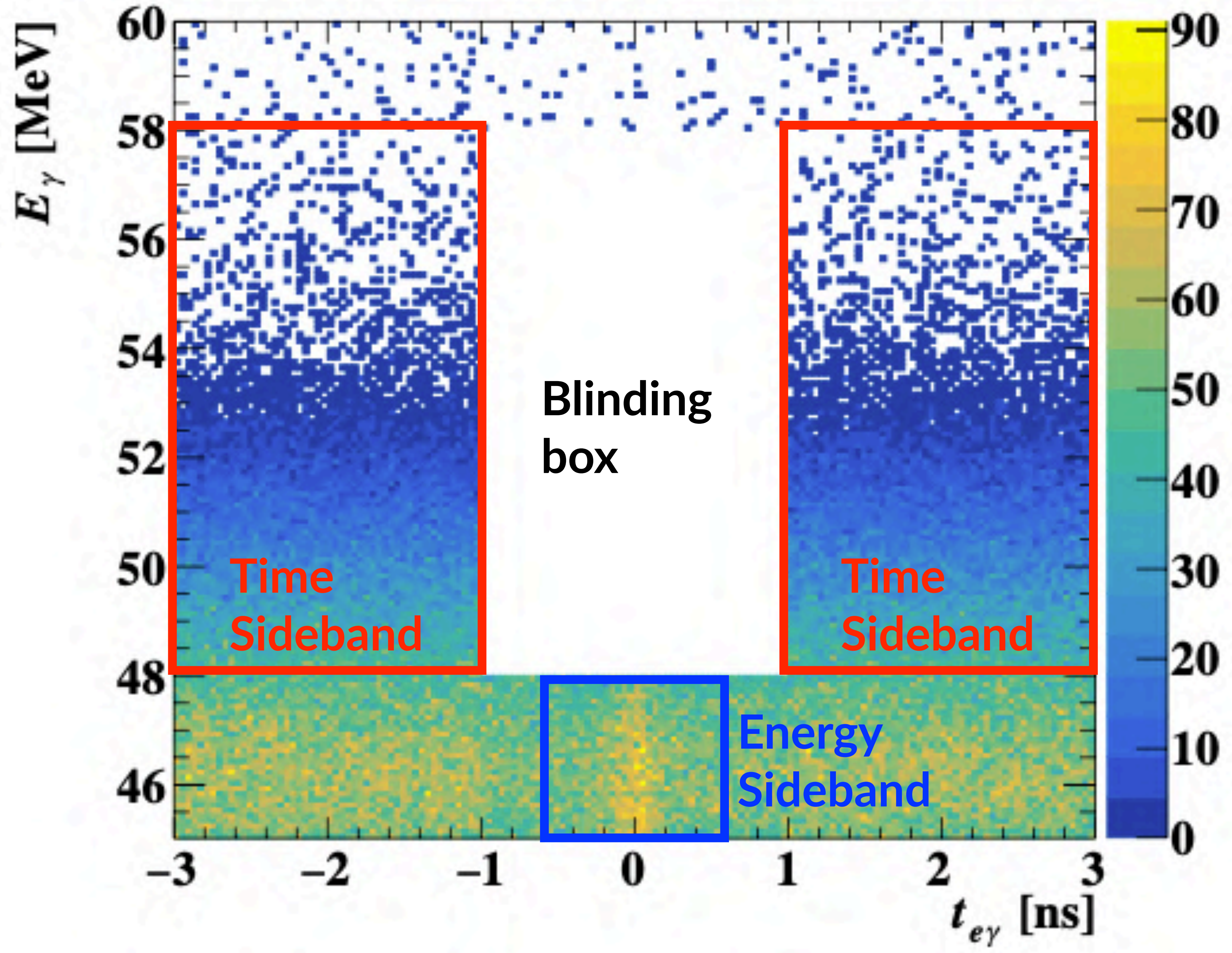


$\mu^+ \to e^+\gamma$ Analysis Strategy

- **Observables to characterise $\mu^+ \to e^+\gamma$ signal**

  $t_{e\gamma}$, E_γ, E_e, $\theta_{e\gamma}$, $\phi_{e\gamma}$

- **Blinding signal region**
  - Blind box: $48 < E_\gamma < 58\,\mathrm{MeV},\ |t_{e\gamma}| < 1\,\mathrm{ns}$
  - BG study at sidebands
    - Accidental BG at time sidebands
    - RMD at energy sidebands



- **Maximum likelihood analysis to estimate N_{sig}**
  - Likelihood fit to analysis window:

    $48 < E_\gamma < 58\,\mathrm{MeV}, 52.2 < E_e < 53.5\,\mathrm{MeV}$

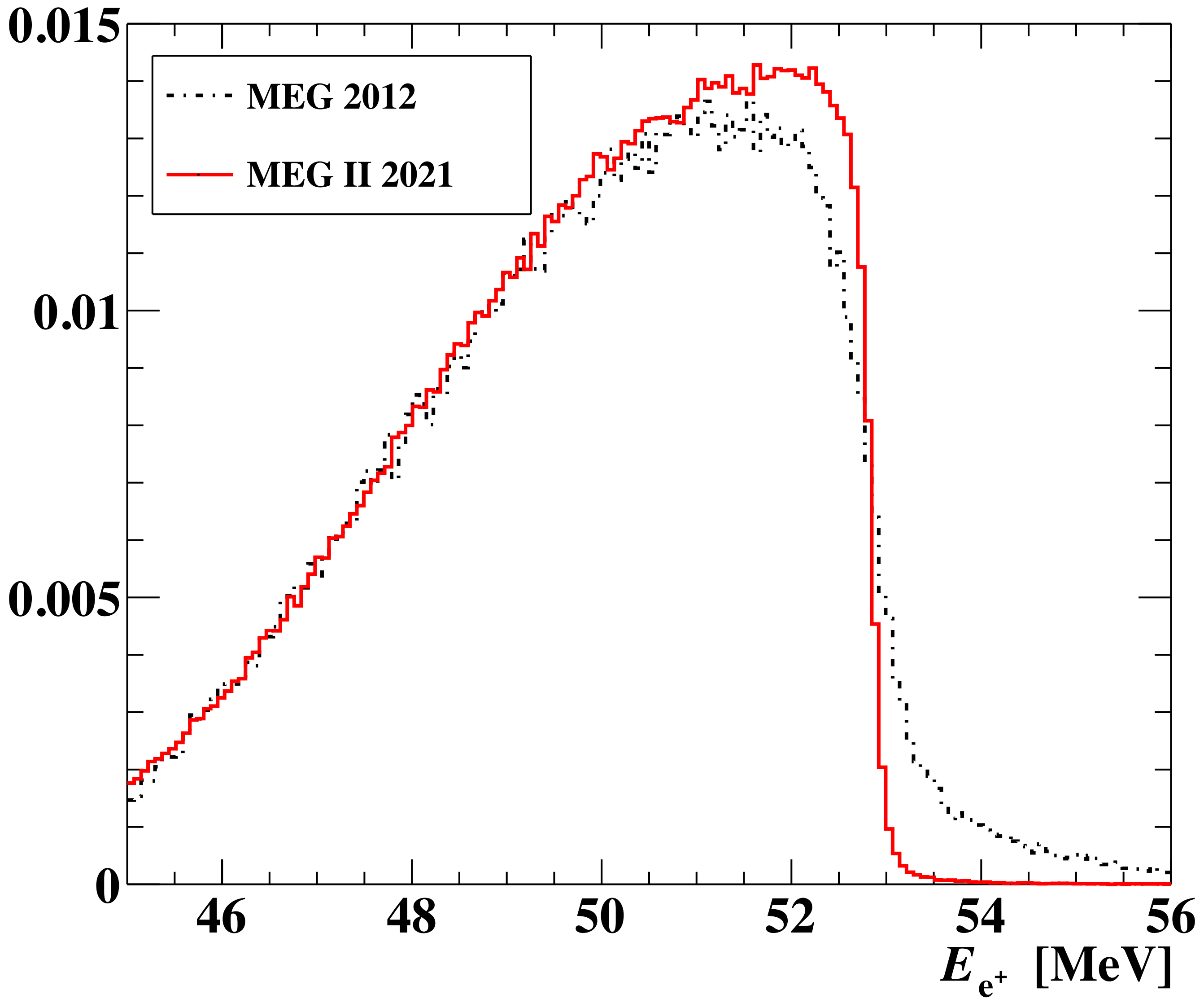
    $|t_{e\gamma}| < 0.5\,\mathrm{ns}, |\phi_{e\gamma}| < 40\,\mathrm{mrad}, |\theta_{e\gamma}| < 40\,\mathrm{mrad}$

$$\mathcal{L}(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{ACC}}, x_{\mathrm{T}}) = \frac{e^{-(N_{\mathrm{sig}}+N_{\mathrm{RMD}}+N_{\mathrm{ACC}})}}{N_{\mathrm{obs}}!} C(N_{\mathrm{RMD}}, N_{\mathrm{ACC}}, x_{\mathrm{T}}) \times \prod_{i=1}^{N_{\mathrm{obs}}} (N_{\mathrm{sig}} S(\vec{x}_i) + N_{\mathrm{RMD}} R(\vec{x}_i) + N_{\mathrm{ACC}} A(\vec{x}_i)),$$

- **Two independent analyses**
  - **Per-event PDFs with two angular observables $\theta_{e\gamma}$, $\phi_{e\gamma}$** (← reference)
  - **Constant PDFs with single angular observable $\Theta_{e\gamma}$** (← crosschecking)

Detector Performance Highlight

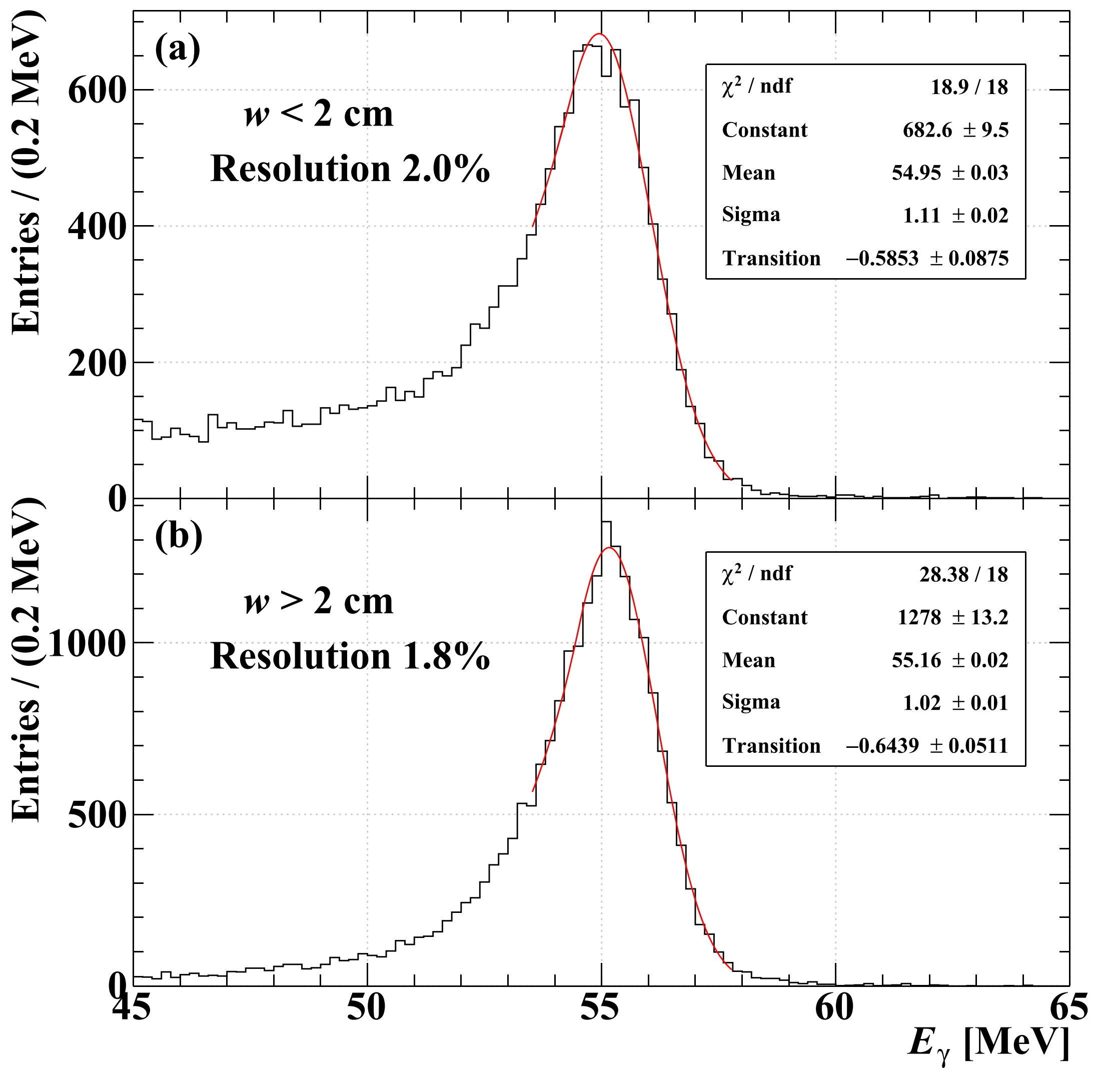
Positron tracking



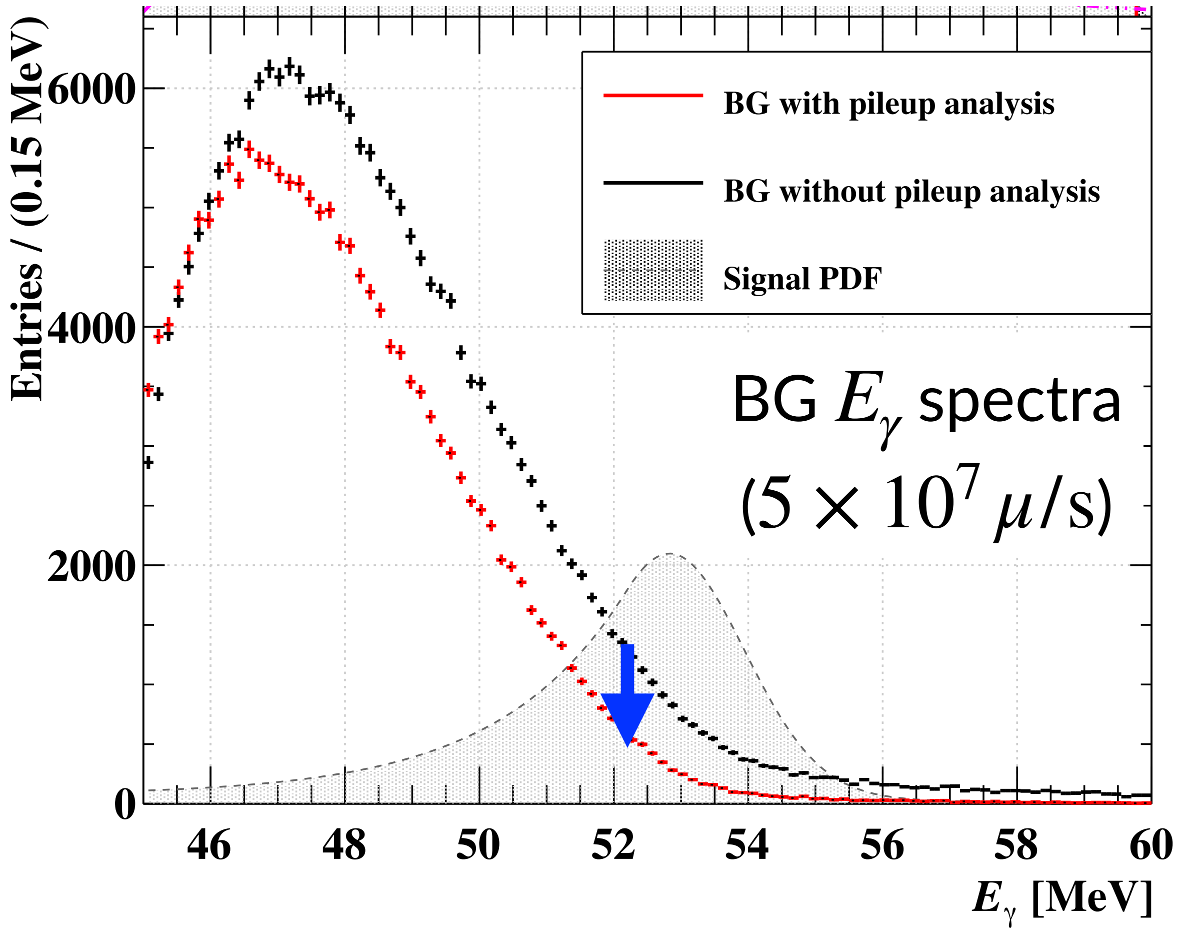
- Energy resolution: **90** keV
  (↔ 320 keV@MEG)
- Efficiency: **67 %** @ $3 \times 10^7 \mu/s$
  (↔ 30 % @MEG)

Photon energy

Energy resolution

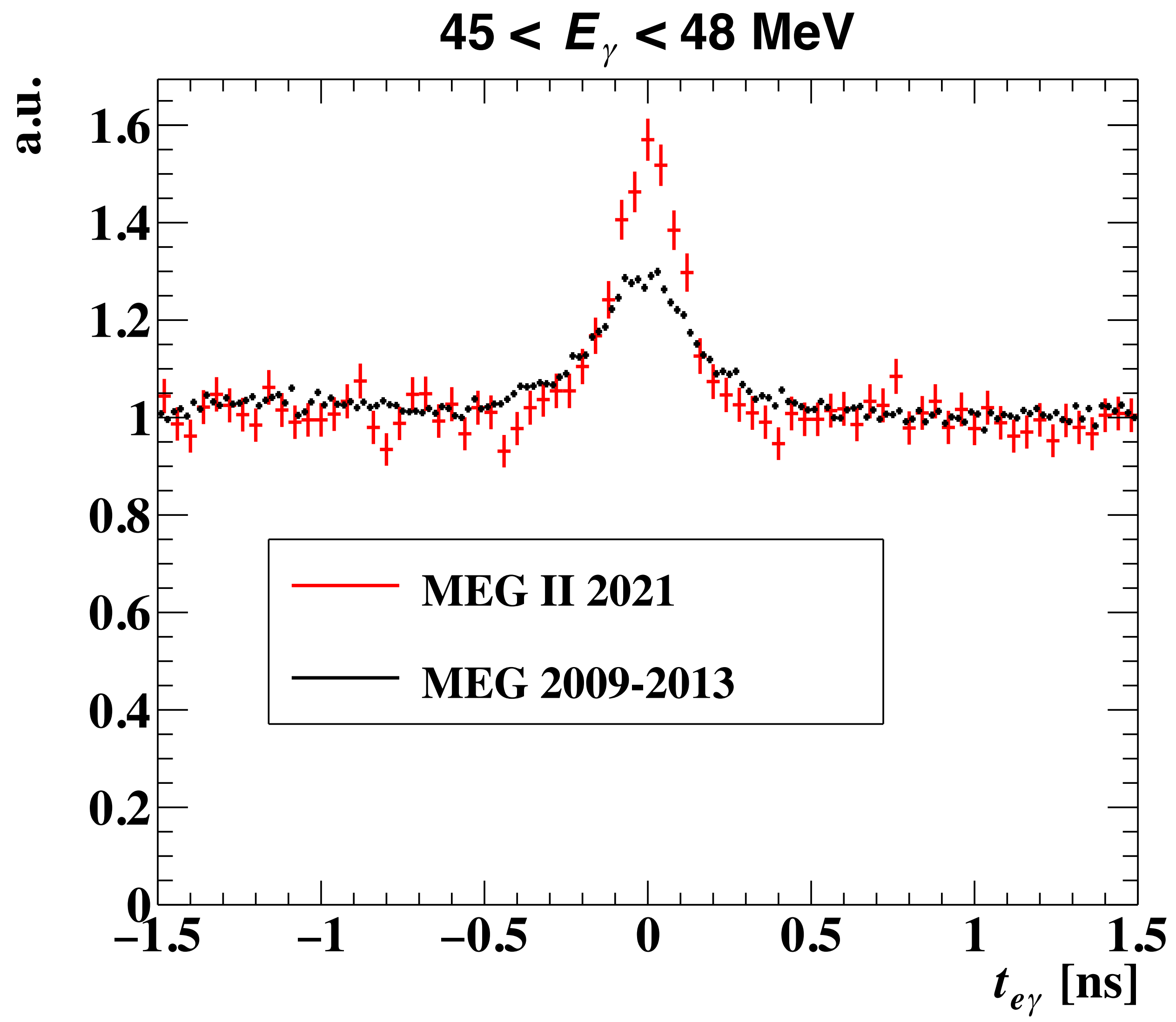


Pileup analysis



- High-granularity and uniform readout by MPPCs
- Energy resolution: **2.0%/1.8% for (conv. depth: <2cm/>2cm)**
- **Pielup BG reduction by 35%** at 48-58MeV ($5 \times 10^7 \mu/s$)

Relative timing



- Overall resolution: **84** ps
  (↔122 ps@MEG)

Significant improvements over MEG

Detector Performance Summary

Resoluition	MEG performance	➡ MEG II achieved value with this work
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 → to be improved from 2022 onward (>90%)
Gamma-ray	63	62
Positron	30	67

Significant improvements over MEG

Normalisation

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

- **Normalisation factor k**

  = # effectively measured muons (=1/SES)

- **Two independent methods**
  - Counting Michel positrons
    - Pre-scaled Michel positron trigger
    - Include positron efficiency and beam rate instability
  - Counting RMD events
    - RMD events in energy sideband
- **Combined normalisation factor**

  $(2.64 \pm 0.12) \times 10^{12}$

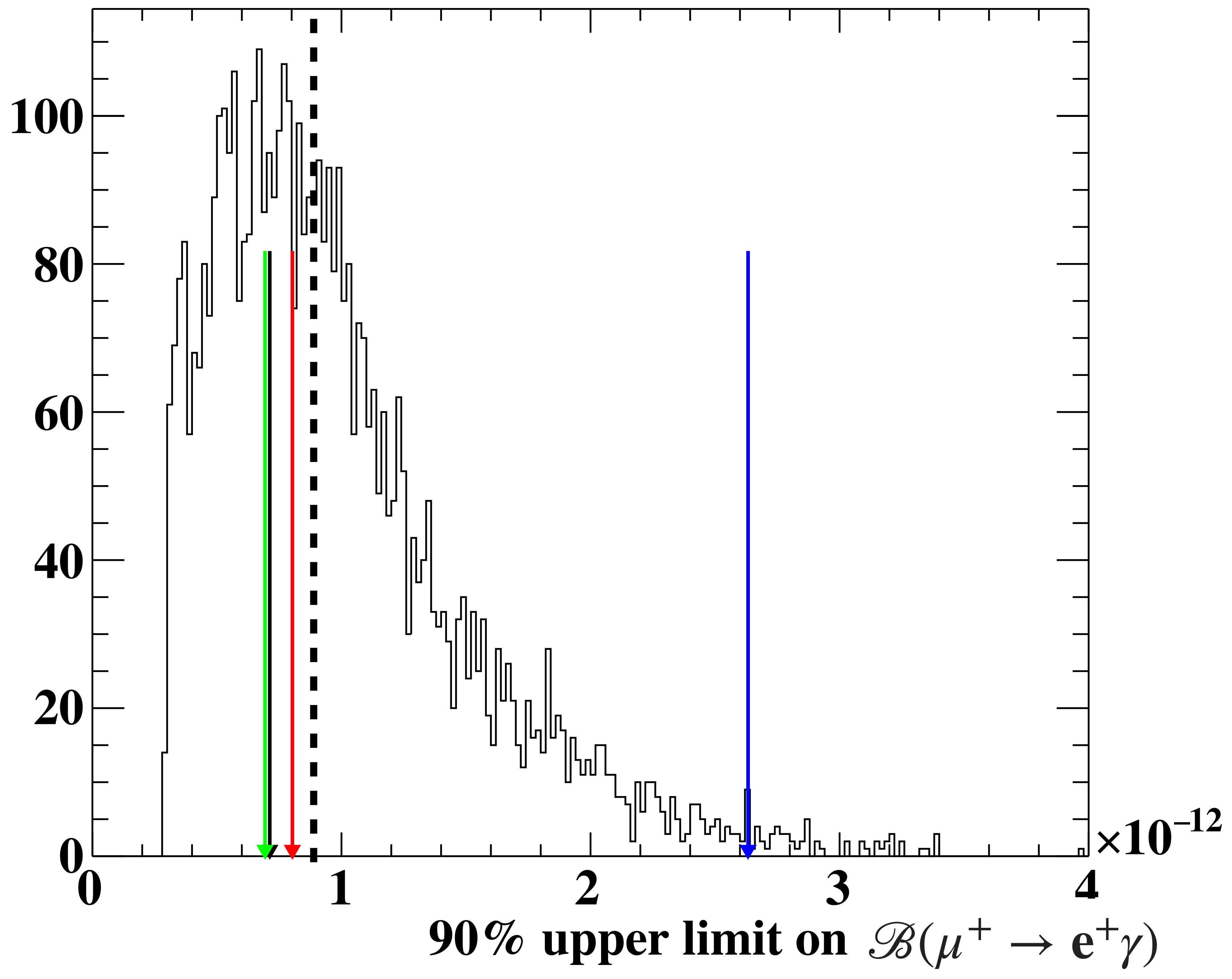
Systematics

- **Major sources for systematics**
  - Detector alignment
  - E_γ scale
  - Normalisation
- **Effect on sensitivity ~4%**
  - Better controlled than MEG (~13%)

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 %

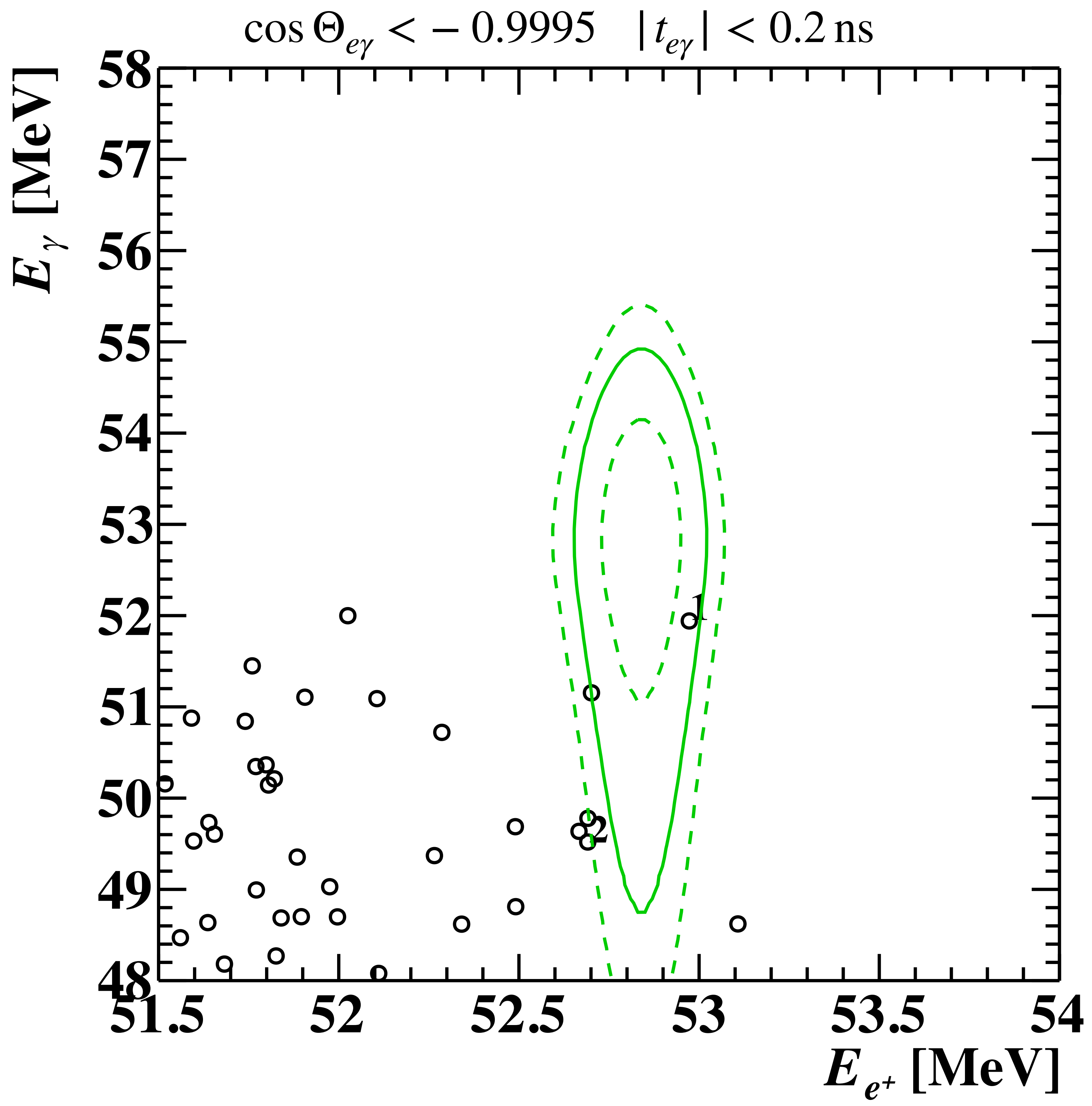
Sensitivity

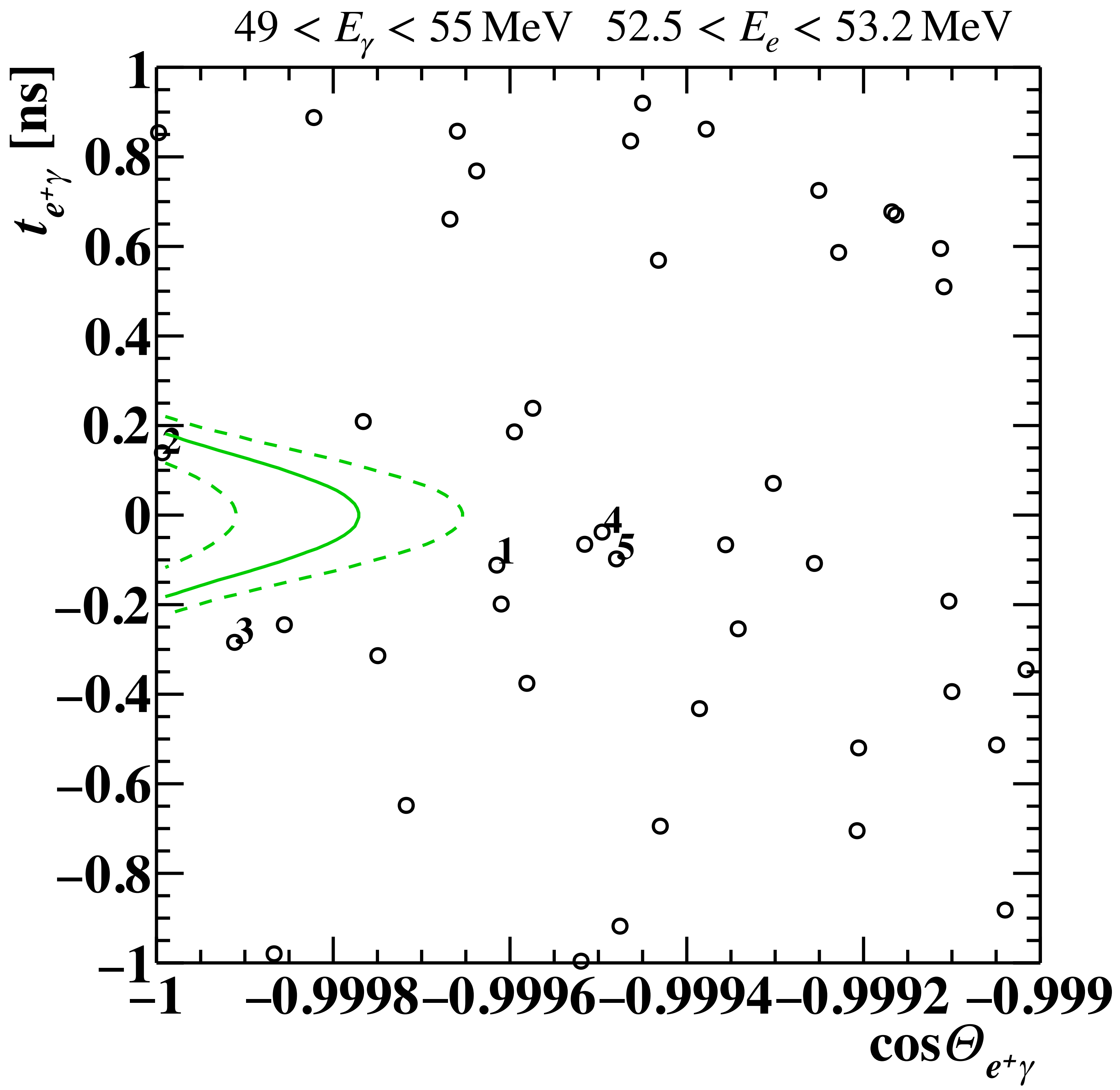
- Sensitivity $\mathcal{S}_{90} = 8.8 \times 10^{-13}$
  - Median of the 90% UL distribution for pseudo experiments with null-signal hypothesis
  - ULs observed in the four fictitious analysis windows in the timing sidebands are consistent with the sensitivity



Comparable sensitivity w.r.t. MEG (5.3×10^{-13}) only with the first several weeks data

Event Distribution after Unblinding



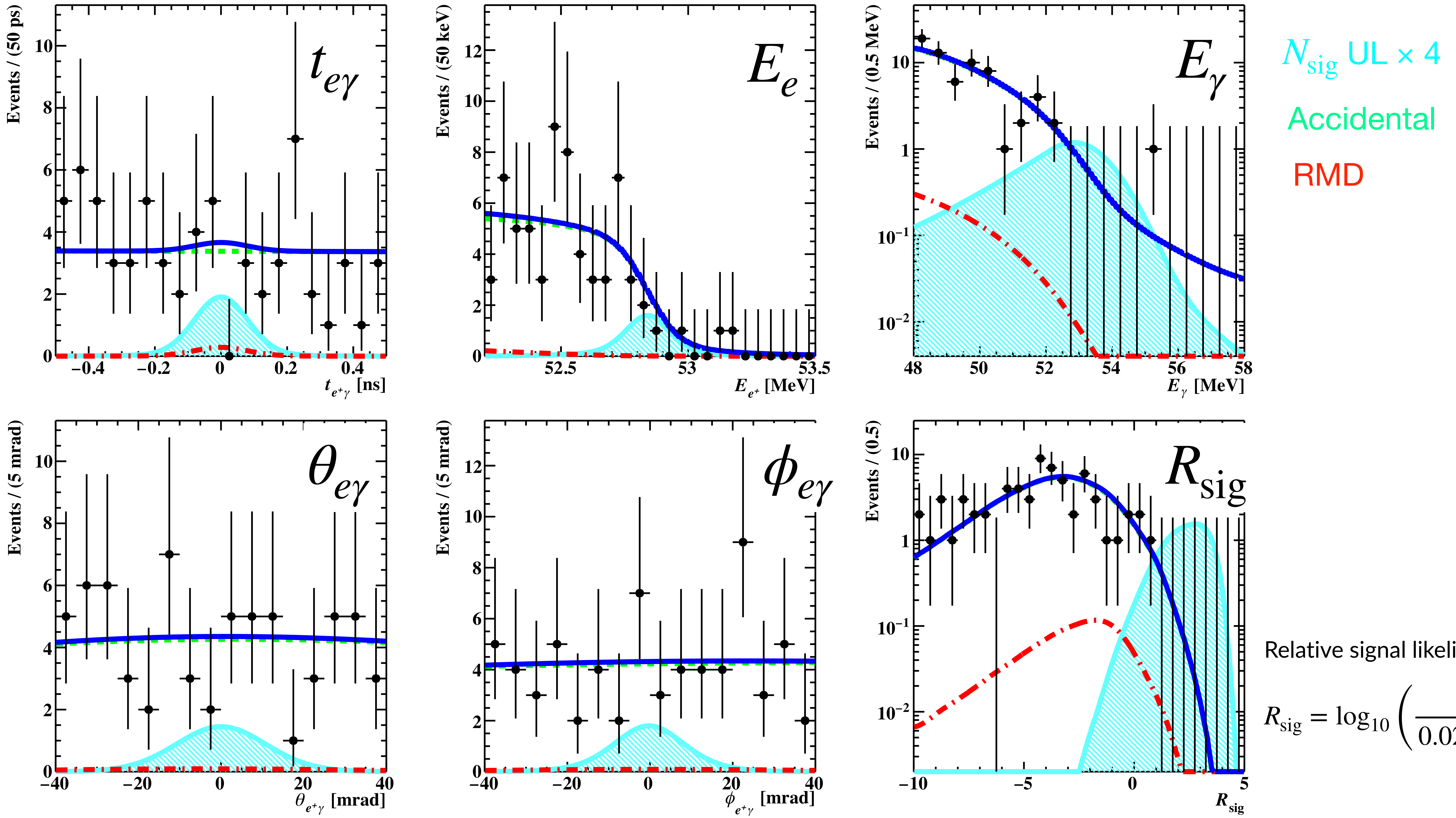


PDF contours (1, 1.64, 2 σ)

No excess of events over expected BG around signal region

Likelihood Fit

Projection of fit results



Relative signal likelihood

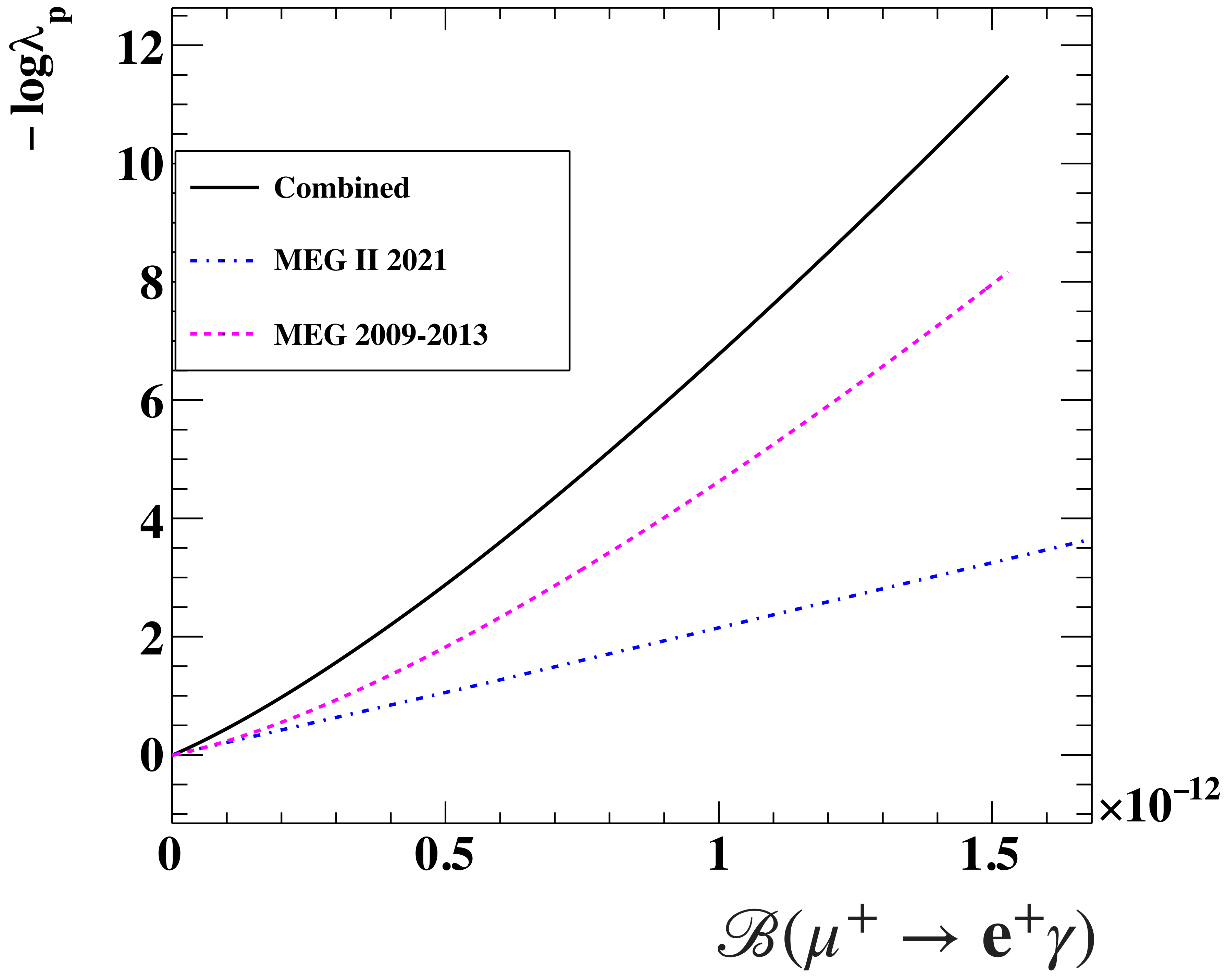
$$R_{\rm sig} = \log_{10}\left(\frac{S}{0.02R + 0.98A}\right)$$

Best fit $N_{\rm sig} = -2.9 \times 10^{-4}$ ($\mathscr{B} = -1.1 \times 10^{-16}$)

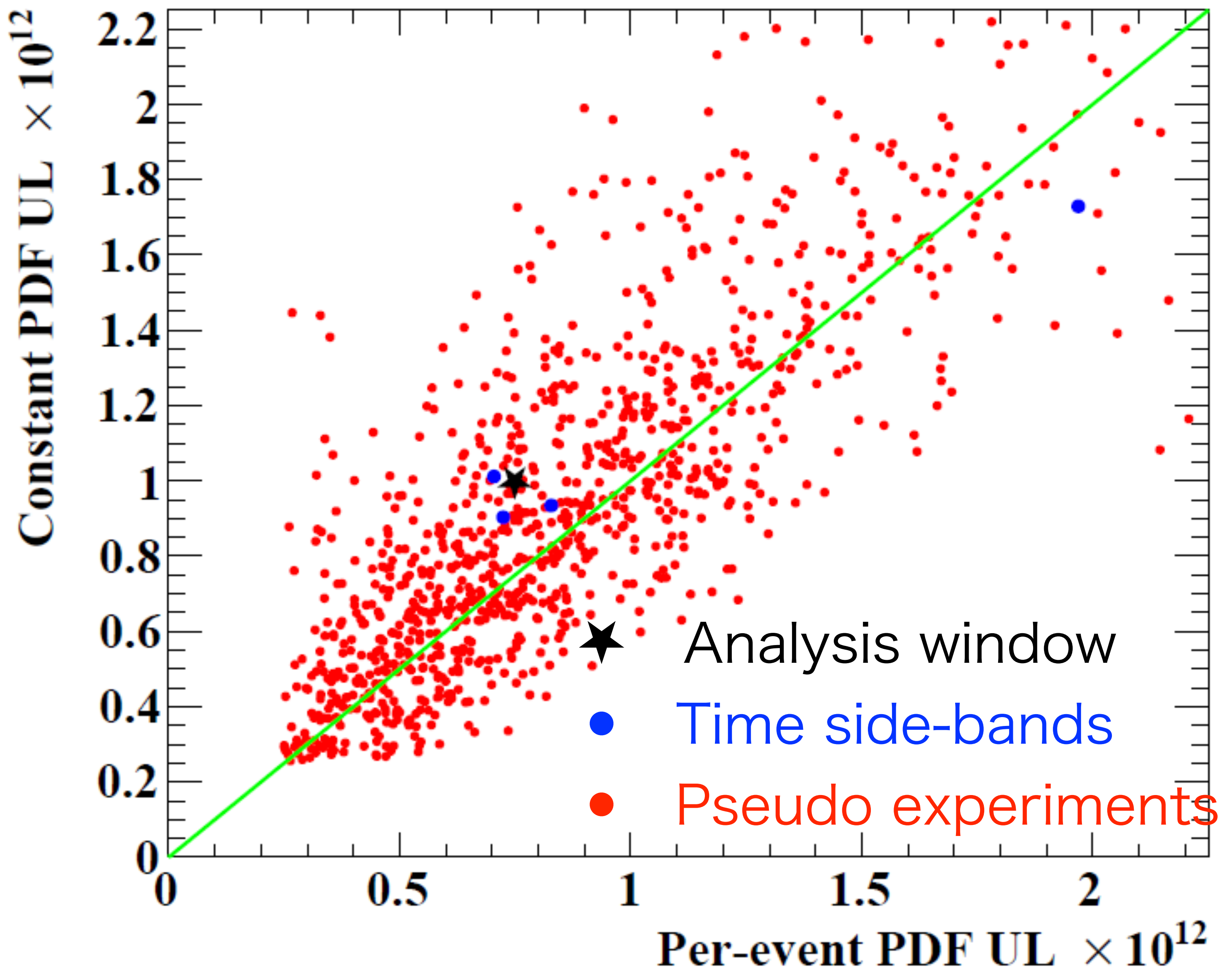
Confidence Interval

- Feldman-Cousins prescription with profile likelihood ratio ordering

Profile likelihood ratio



Constant PDF vs. Per-event PDF

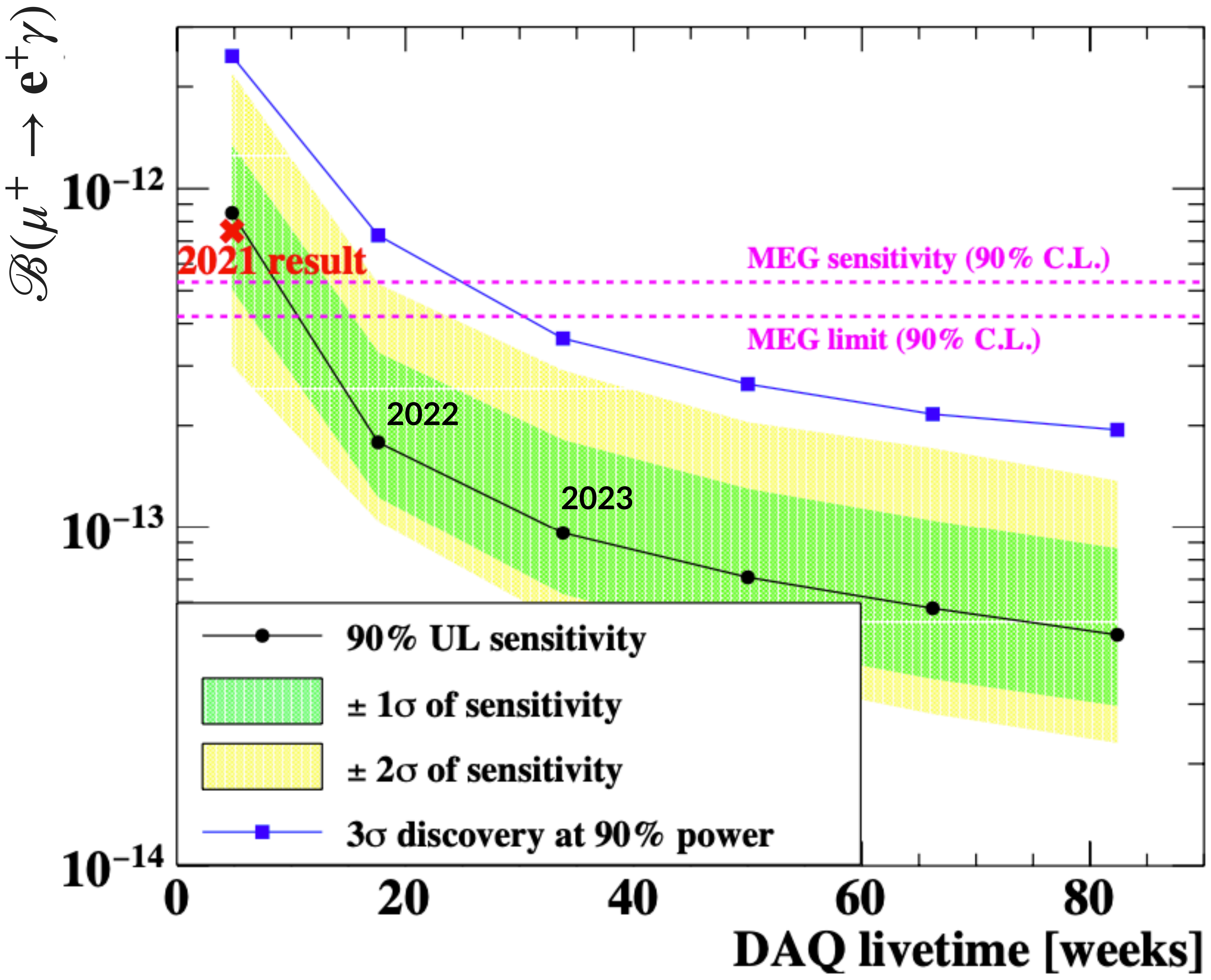


Branching ratio upper limit (MEG II): $\mathscr{B}(\mu^+ \to e^+\gamma) < 7.5 \times 10^{-13}$ (90% C.L.) (sensitivity: 8.8×10^{-13})

MEG+MEG II combined: $\mathscr{B}(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13}$ (90% C.L.) (sensitivity: 4.3×10^{-13})

Summary and Prospects

- **MEG II in search for $\mu^+ \to e^+\gamma$ has been producing physics data since 2021**
- **Results from the first physics run in 2021**
  - No excess over BG-only hypothesis
    - Upper limit: $\mathscr{B}(\mu^+ \to \mathrm{e}^+\gamma) < 7.5 \times 10^{-13}$: (90% C.L.)
    - Combined with MEG: $\mathscr{B}(\mu^+ \to \mathrm{e}^+\gamma) < 3.1 \times 10^{-13}$: (90% C.L.)
  - Comparable sensitivity w.r.t. MEG only with the data for the first several weeks, **well demonstrating MEG II capability**
- **$\times 10$ more data already acquired until run 2023**
  - **Results with data 2022 well beyond MEG sensitivity are coming**
- **Physics run will continue until PSI accelerator shutdown from 2027 to reach the sensitivity goal of 6×10^{-14} ($\times 10$ MEG), hopefully with discovery**



See also talk by A. Papa "The X17 search with the MEG II apparatus"

Thank you for your attention!