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

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SUSY24: The 31st International Conference on Supersymmetry and Unification of Fundamental Interactions

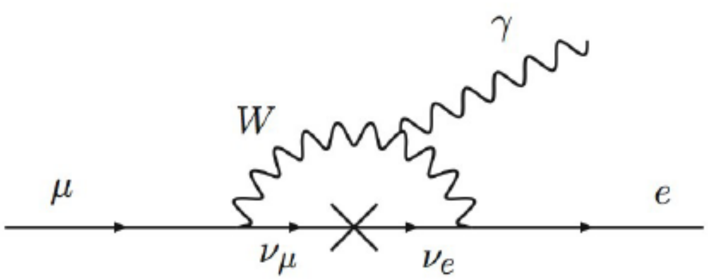
Madrid, 10-14 Jun 2024

Charged Lepton Flavor Violation (cLFV)

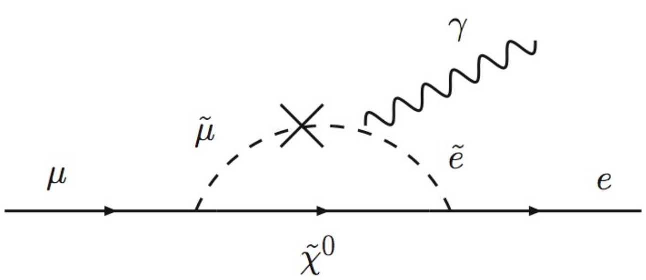
- Allowed but unobservable in the Standard Model (with neutrino mass ≠0)
- Enhanced, sometimes just below the experimental limit, in many New Physics (NP) models

$$BR(\mu \to e\gamma)\big|_{SM} < 10^{-50}$$

neutrino oscillation



new particle



Observation of cLFV is a clean signal of Physics beyond the Standard Model

cLFV in the Muon Sector (I)

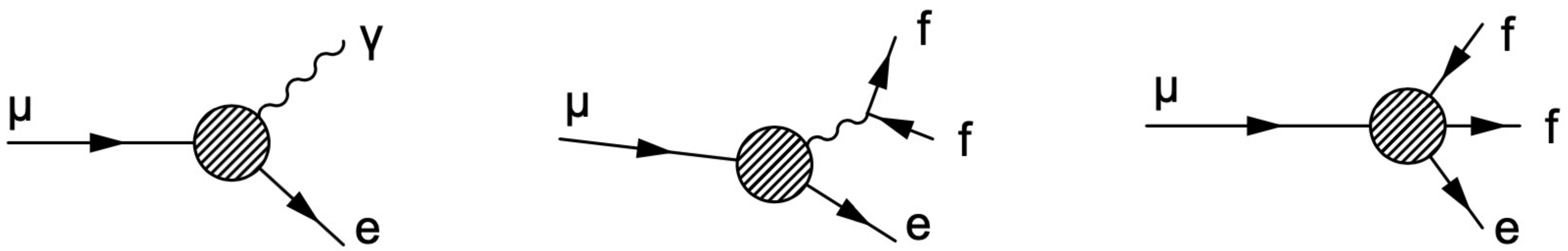
- Probe NP at very high energy scales: $\Lambda > 10^2\text{-}10^4$ TeV
- High intensity frontier: complementary to LHC
- Benchmark test for NP Models

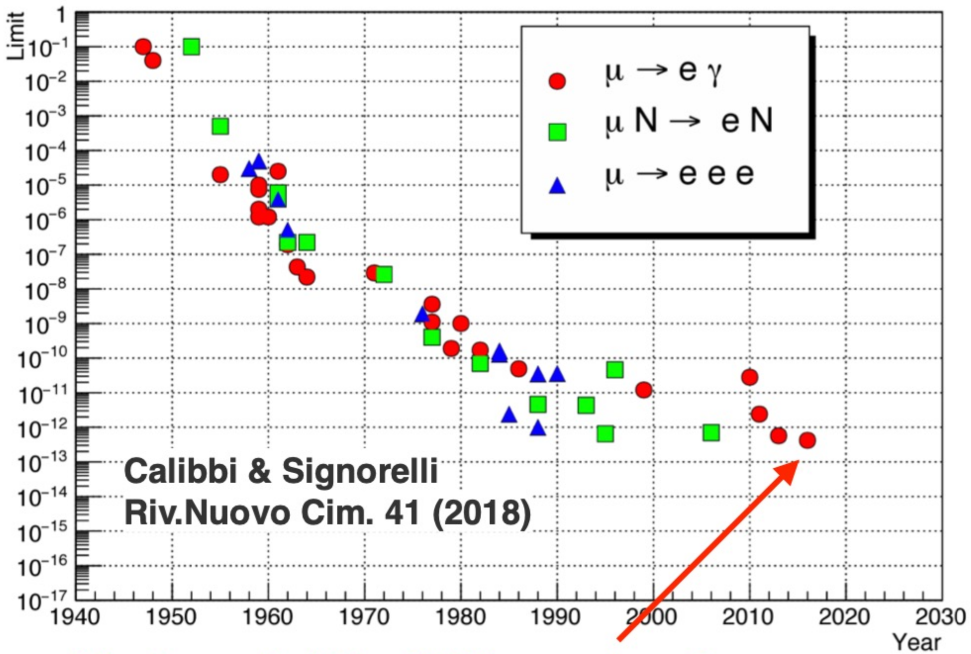
Muons golden processes

$\mu^+ \rightarrow e^+\gamma$	$\mu^+ \rightarrow e^+e^+e^-$	$\mu^- N \rightarrow e^- N$
MEG-II (PSI)	**Mu3e (PSI)**	**COMET (J-Park)**
=> this talk		**Mu2e (Fermilab)**

- Not only muons: τ, EDM...

cLFV in the Muon Sector (II)





Final result of the MEG experiment

BR < 4.2 x 10^{-13} @ 90% C.L.

Eur. Phys. J. C76 (2016)

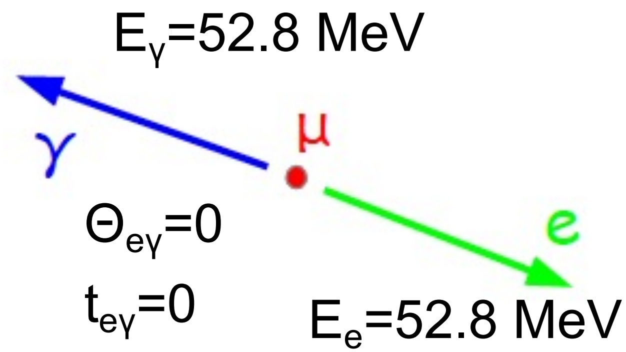
- Loops may mix dipole and 4-fermion operators creating patterns that are specific to the NP model
- Complementarity of the different muon modes

Principles of $\mu \rightarrow e\gamma$ Searches

- **High intensity** muon beam stopped in a thin target

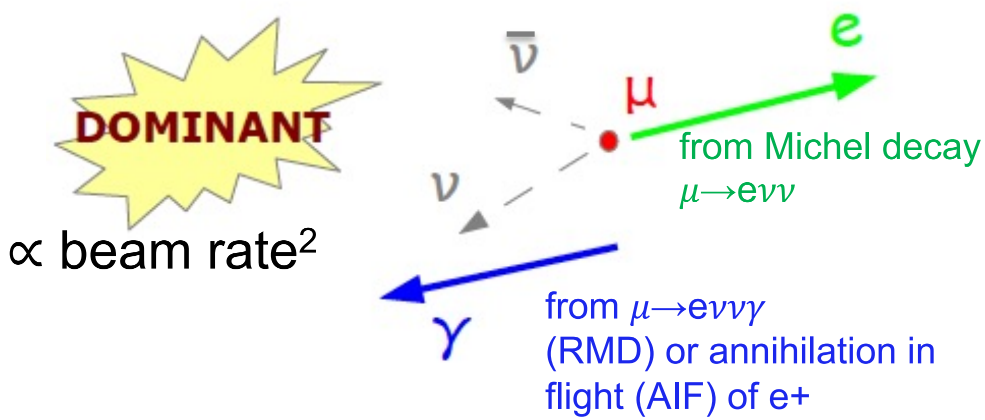
- Two types of backgrounds:
  - **physical background**
  - **accidental background** from decay products of different muons

SIGNAL

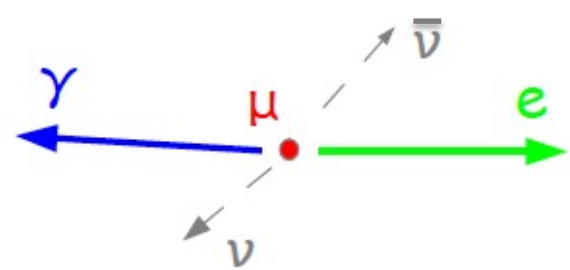


Observables: $E_{e+}, E_\gamma, \theta_{e\gamma}, \varphi_{e\gamma}, t_{e\gamma}$

ACCIDENTAL BACKGROUND



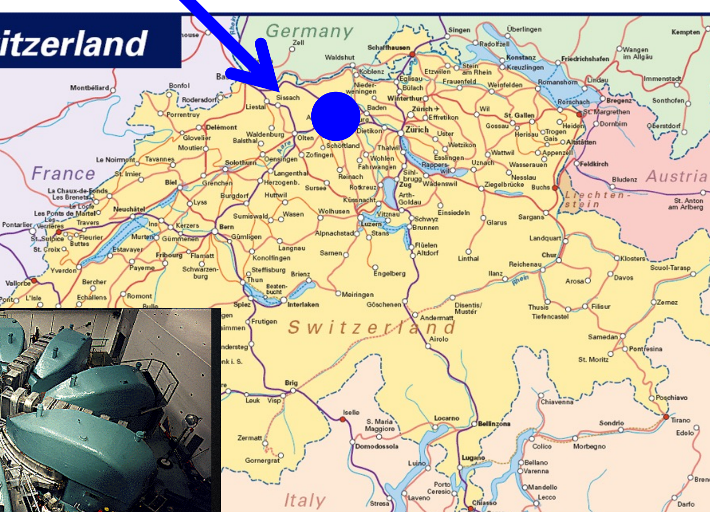
RADIATIVE MUON DECAY (RMD)

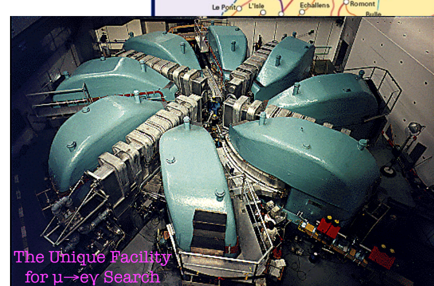


The MEG-II Location: PSI

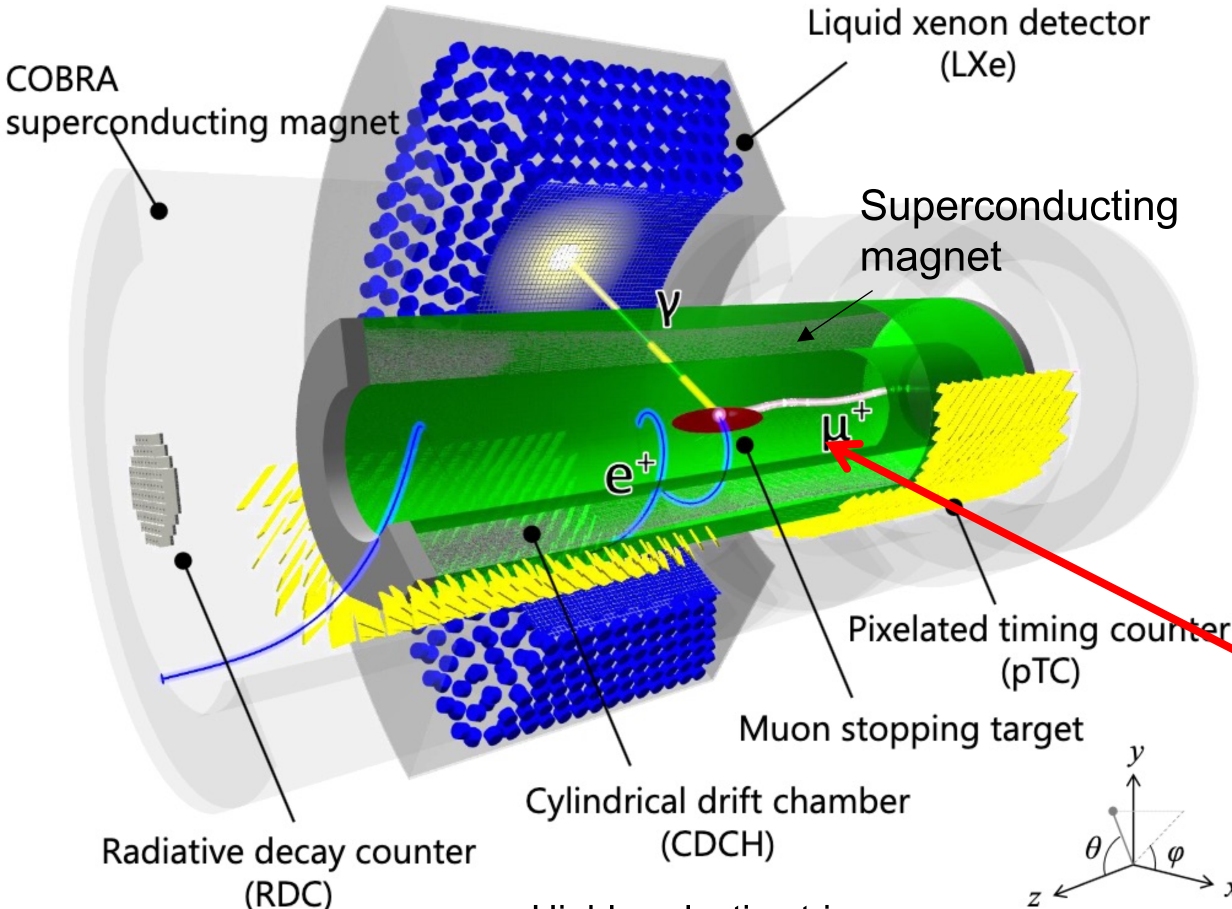
- **Paul Scherrer Institute**
  - continuous muon beam up to few 10^8 μ^+/s

- **Multi-disciplinary lab:**
  - fundamental research, cancer therapy, muon and neutron sources
  - protons from cyclotron (D = 15m, E_{proton} = 590MeV P = 1.4MW)





The MEG II Experiment

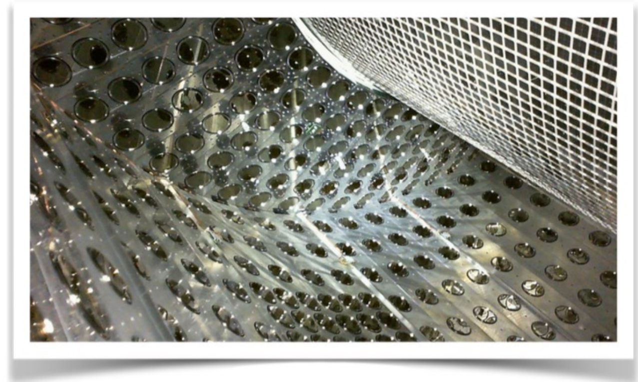


+ Highly selective trigger
& acquisition of full
waveforms for all sensors

Aim to 6×10^{-14} sensitivity

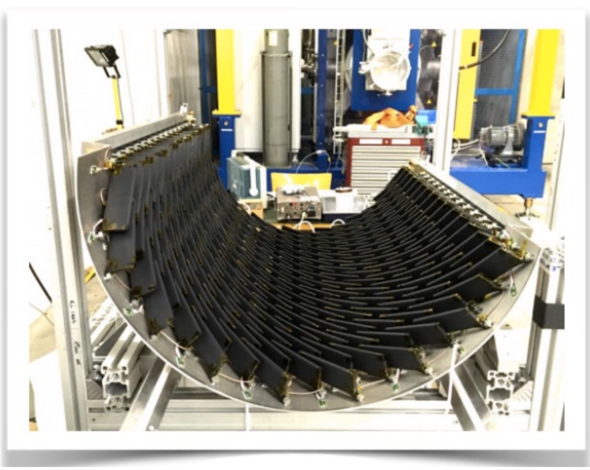
Beam intensity optimized to enhance sensitivity $3\text{-}5 \cdot 10^{7}\ \mu/s$

The MEG II Detector



- **Liquid Xenon Calorimeter** with high granularity, readout by PMTs and UV sensitive MPPC (γ detection)

- **Cylindrical Drift Chamber** in a graded magnetic field, high granularity, very thin wires (e^+ momentum and trajectory)



- **Pixelated Timing Counter** 2x256 scintillating times readout by SIPM (e^+ time)

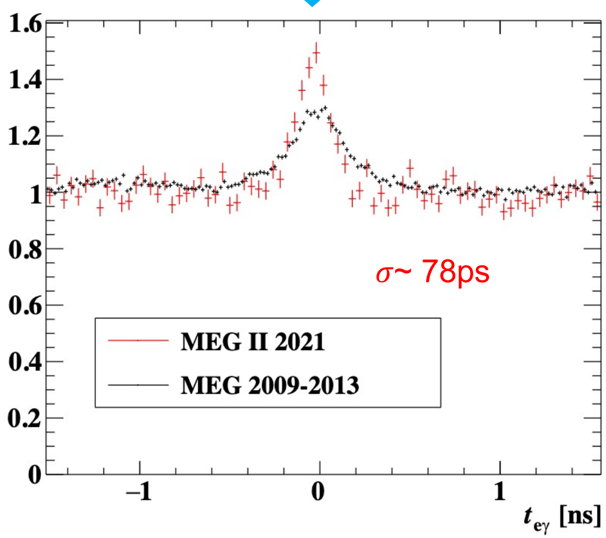
Eur. Phys. J. C78 (2018) no.5, 380

Detector Performances

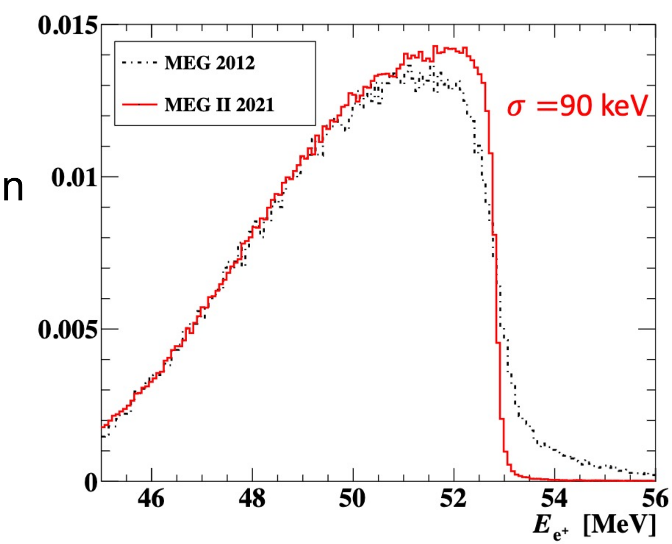
- Improvements in resolution and efficiency almost everywhere with respect to MEG

Resolutions	Foreseen	Achieved
E_{e^+} (keV)	100	89
ϕ_{e^+} [a], θ_{e^+} (mrad)	3.7/6.7	4.1/7.2
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
$u_\gamma, v_\gamma, w_\gamma$ (mm)	2.4/2.4/5.0	2.5/2.5/5.0
$t_{e^+\gamma}$ (ps)	70	78
Efficiency (%)		
ε_γ	69	62
ε_{e^+}	65	67
ε_{TRG}	≈99	80

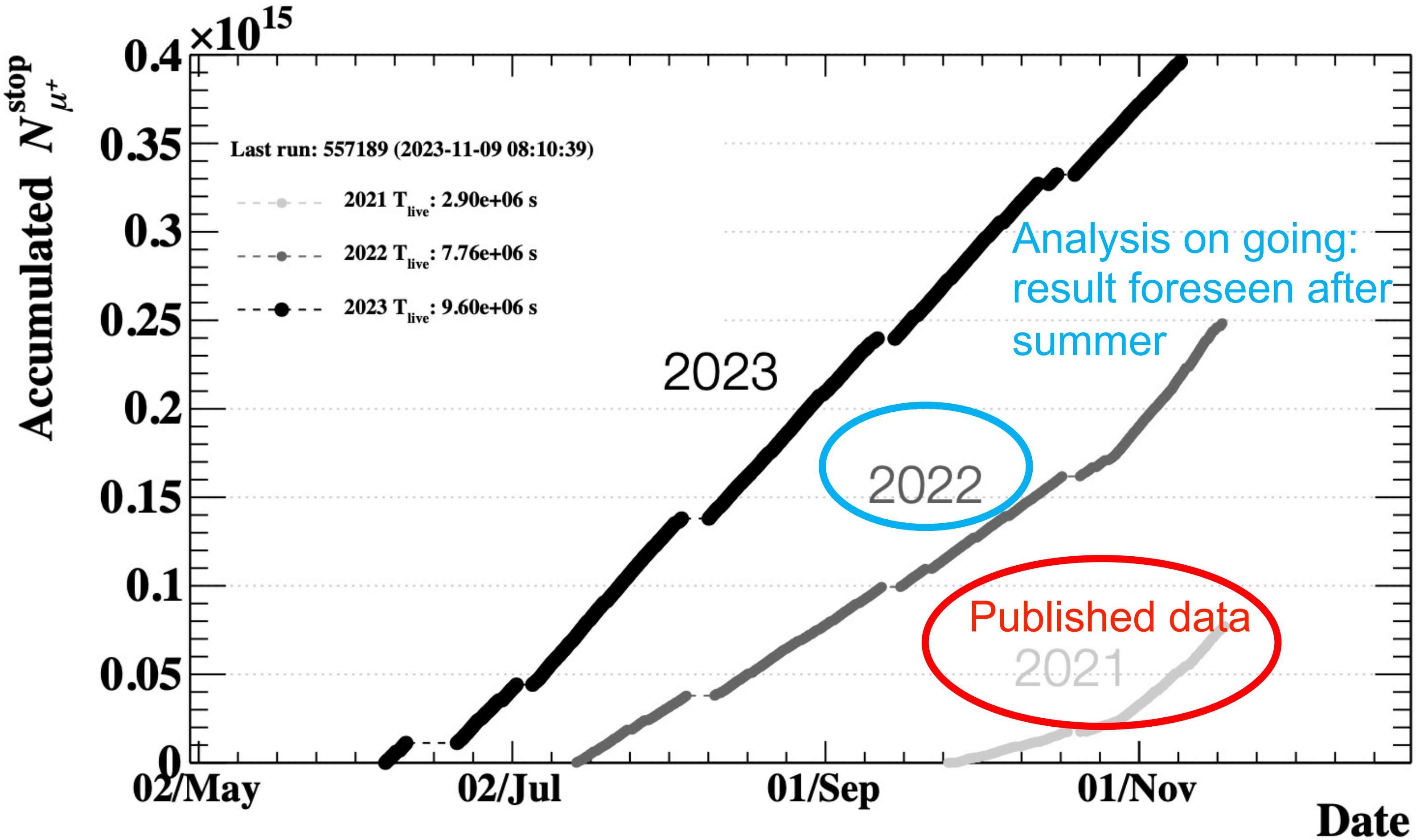
relative time resolution from muon radiative decay



positron momentum resolution from muon Michel decay



The MEG II Dataset (so far)



Likelihood (Blind) Analysis

- Extended unbinned maximum likelihood fit to estimate the number of signal events
- Region where the signal is expected is kept hidden until the analysis is defined

$$L(N_{sig}, N_{Acc}, N_{RMD}, x_{syst}) = C(N_{Acc}, N_{RMD}, x_{syst})$$

← Constraints on nuisance parameters

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

- Fully frequentistic confidence intervals using the **Feldman-Cousins prescription** with **profile likelihood ordering** for the treatment of nuisance parameters

$$\lambda_p(N_{\mathrm{sig}}) = \begin{cases} \dfrac{\mathcal{L}(N_{\mathrm{sig}}, \hat{\hat{\boldsymbol{\theta}}}(N_{\mathrm{sig}}))}{\mathcal{L}(0, \hat{\hat{\boldsymbol{\theta}}}(0))} & \text{if } \hat{N}_{\mathrm{sig}} < 0 \\ \dfrac{\mathcal{L}(N_{\mathrm{sig}}, \hat{\hat{\boldsymbol{\theta}}}(N_{\mathrm{sig}}))}{\mathcal{L}(\hat{N}_{\mathrm{sig}}, \hat{\boldsymbol{\theta}})} & \text{if } \hat{N}_{\mathrm{sig}} \geq 0 \end{cases}$$

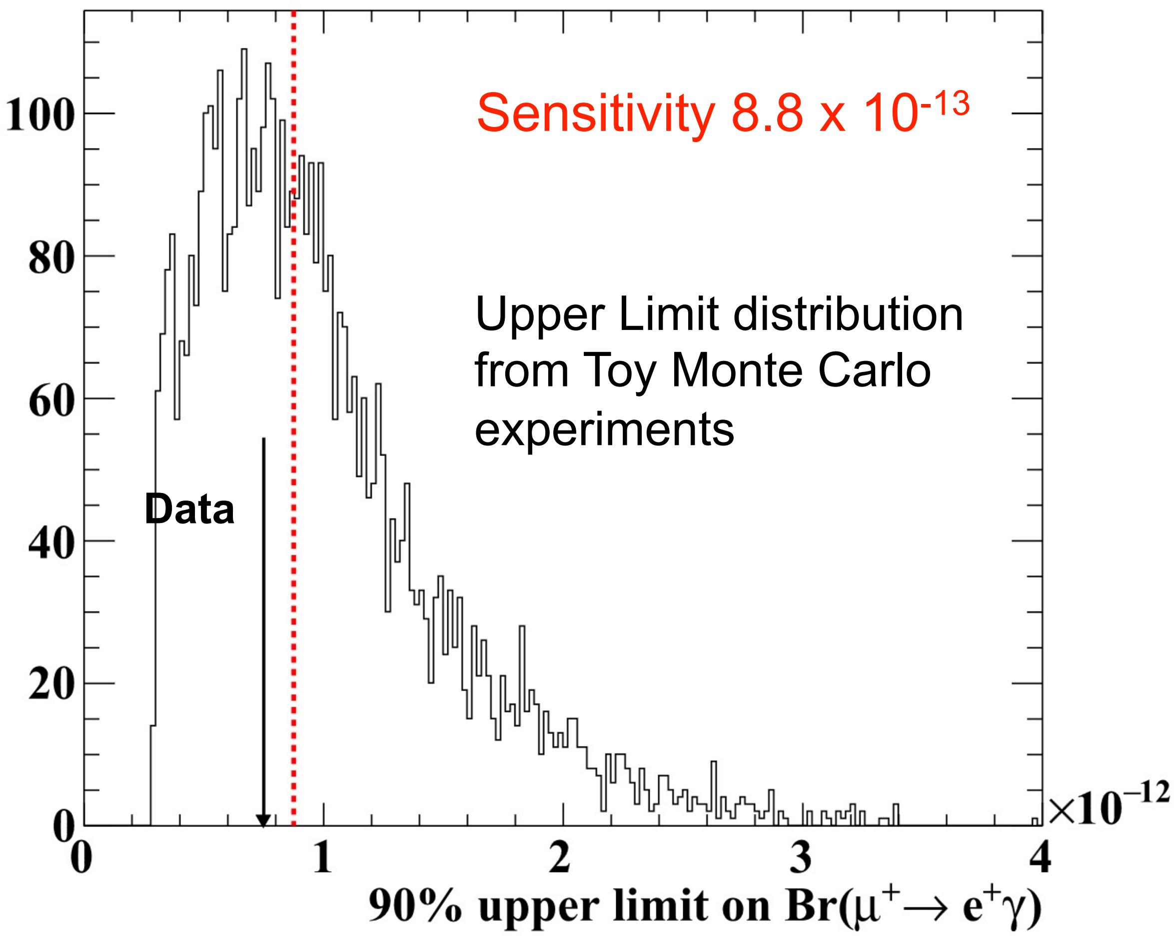
Nuisance parameters

$$\boldsymbol{\theta} = (N_{\mathrm{RMD}}, N_{\mathrm{ACC}}, x_{\mathrm{T}})$$

- N_{RMD}: number of radiative decay events
- N_{ACC}: number of accidental events
- x_{T}: target alignment parameter

Sensitivity

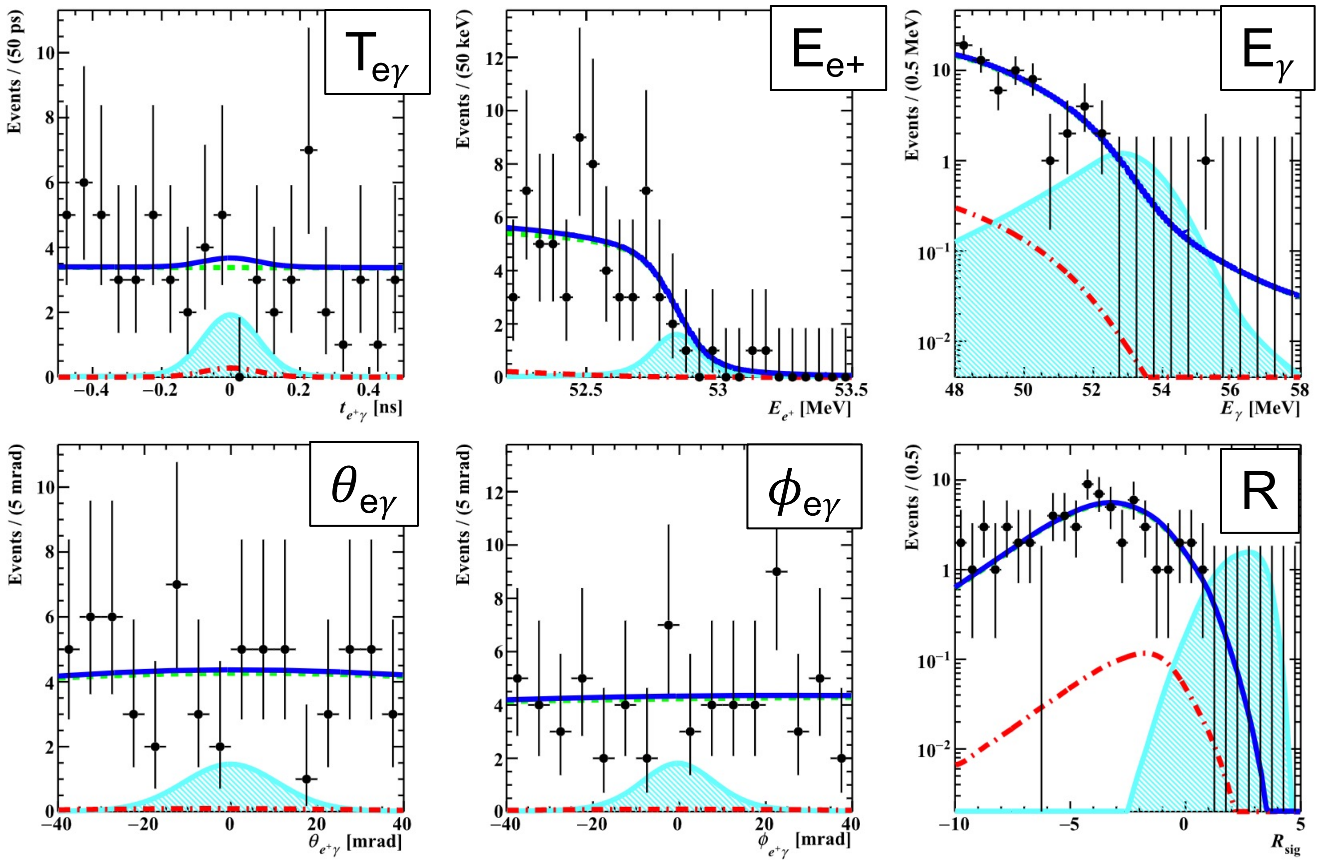
- Sensitivity: 90% upper limit in case no signal is observed



Results: Likelihood Projection

N_{obs} = 66
$N_{exp,ACC}$ = 68.0 ± 3.5
$N_{exp,RMD}$ = 1.2 ± 0.2
N_{sig}<2

K. Afanaciev et al., Eur. Phys. J. C 84 (2024) 3, 216

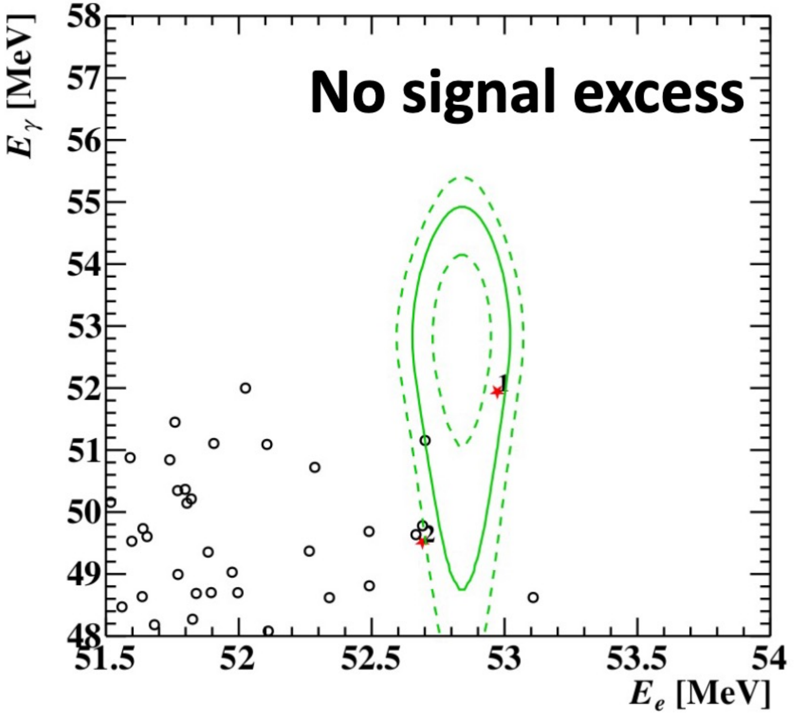


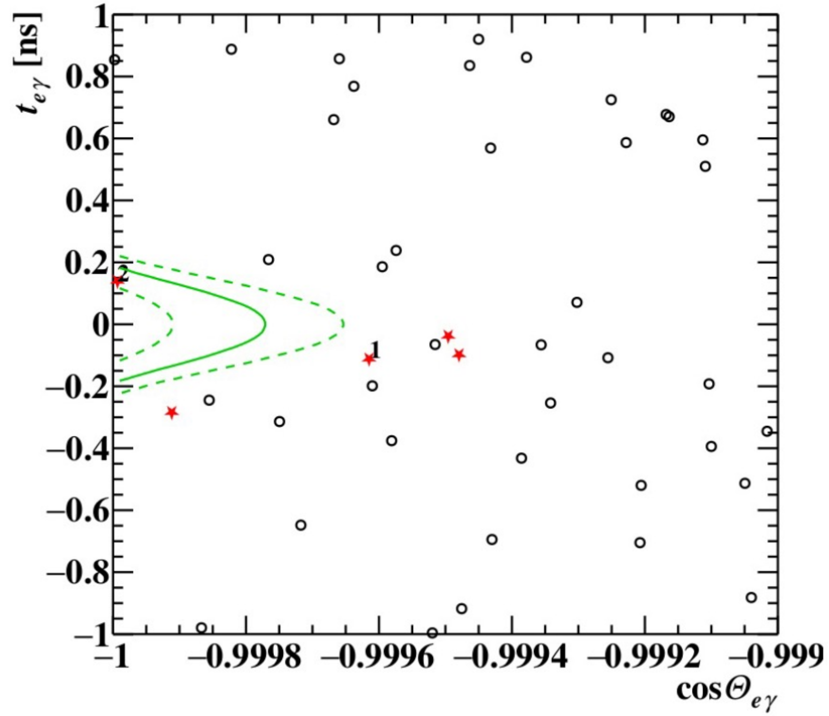
Signal (magnified)
Radiative decay bkg
Accidental decay bkg
Best fit
dots: data

Relative signal likelihood

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

Results: the Signal Box



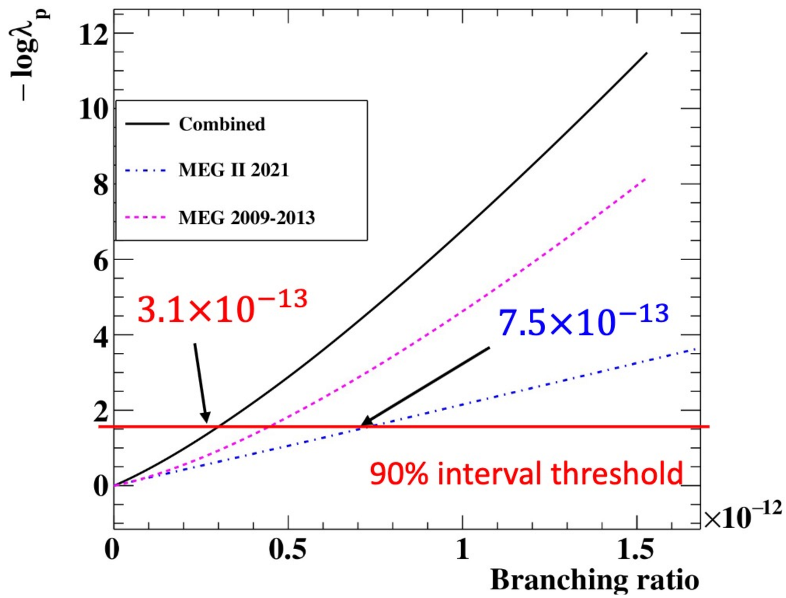


$\cos\Theta_{e\gamma} < -0.9995$
$|t_{e\gamma}| < 200$ ps

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

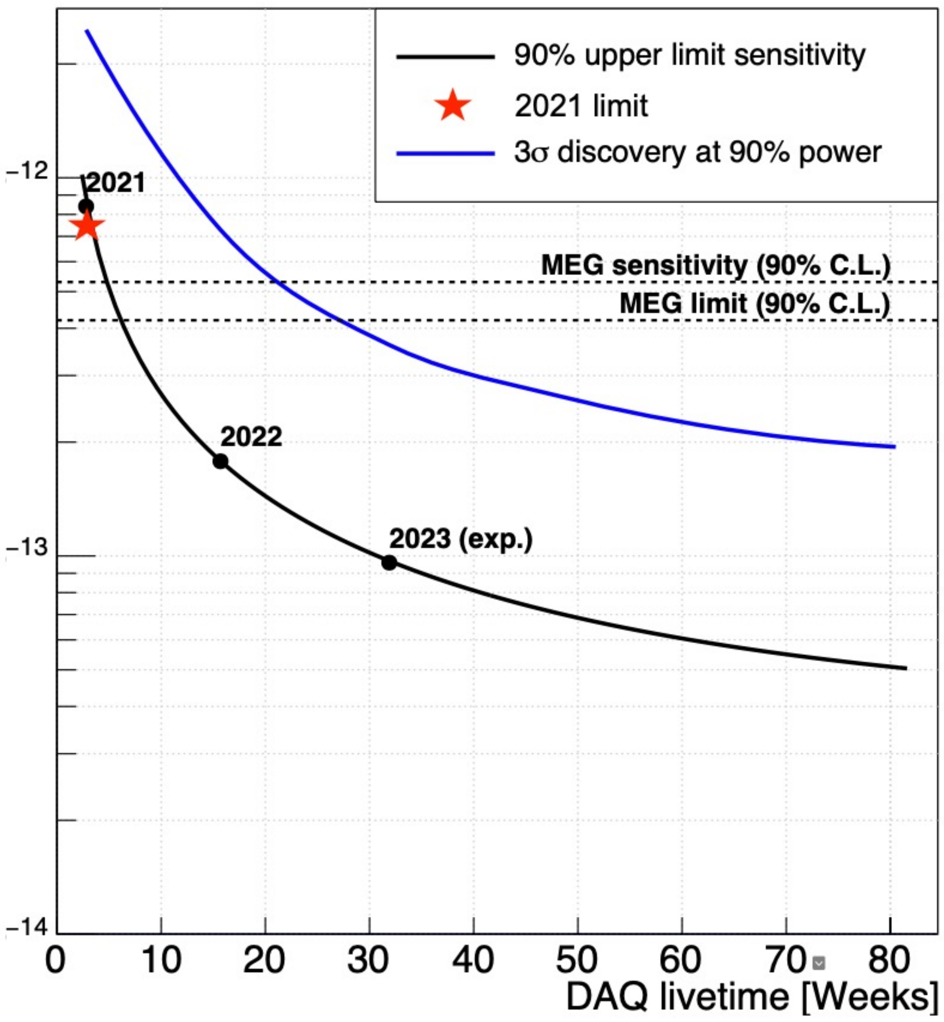
Results: Upper Limit on $\mu \rightarrow e\gamma$

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



- New best limit in the world
- Already reached ~MEG (2016) sensitivity

MEG II Perspectives



Plan: run until 2026, aim at $6x10^{-14}$ sensitivity

Summary and Conclusions

- **MEG II goal**: search $\mu \rightarrow e\gamma$ with **6×10^{-14} sensitivity**
  => $\times 10$ improvement vs MEG final result (2016)

- First result of MEG II on 2021 data

- No signal excess => BR($\mu \rightarrow e\gamma$) < $7.5 \cdot 10^{-13}$ @90%CL

- Combined limit with MEG 2016
  => BR($\mu \rightarrow e\gamma$) < $3.1 \cdot 10^{-13}$ @90%CL

- **Plan of MEG II**
  - 2023 DAQ successfully finished
  - run 2024 about to start
  - continue till 2026 to reach **6×10^{-14} sensitivity**

Backup

Other Opportunities at MEG II

- **Search for $\mu \to ea\gamma$** (axion-like particle)

  - dedicated run at very low intensity
  - search for a peak in missing mass distribution

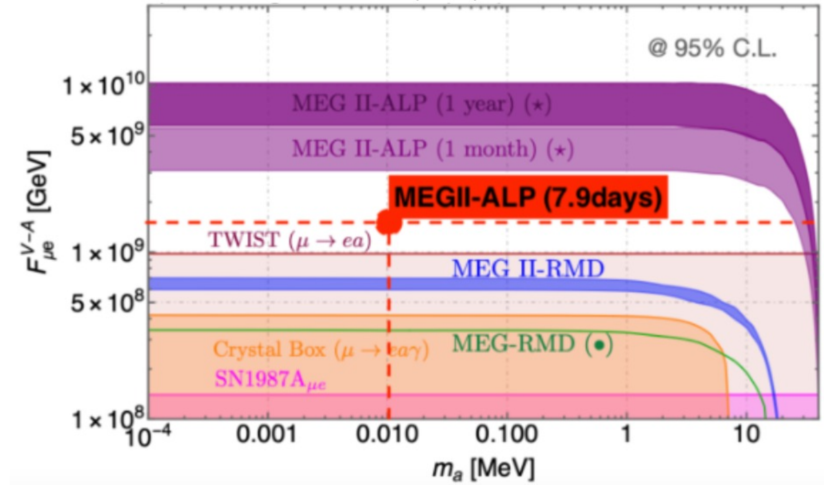
- **Search for the X17 boson**

  - attempt to confirm/exclude the excess observed at ATOMKI (Hungary) in the angular spectrum of e^+e^- pairs from Internal Pair Conversion (IPC) in 8Be* (and other nuclei) transitions

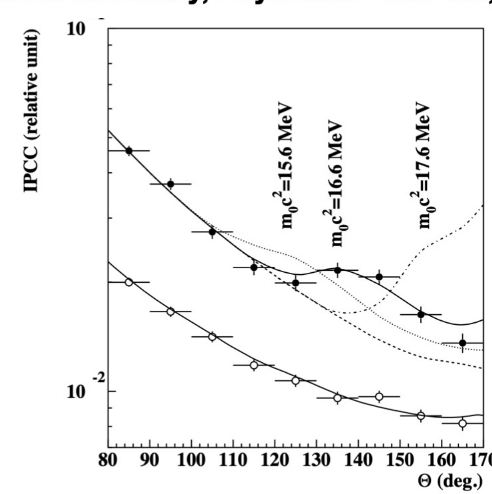
  - 4 weeks of DAQ at the beginning of 2024 (3-5σ expected)

  - options for additional data taking to be evaluated

E. G. Grandoni, Master's thesis,
Modified from *JHEP* 10 (2022) 029



A.J. Krasznahorkay, Phys. Rev. Lett. 116, 042501 (2016)



Normalization

- How many muons: normalization factor k

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

$$k_{2021} = (2.64 \pm 0.12) \times 10^{12}$$

- Evaluation by background positron counting in dedicated dataset
- Can automatically include efficiency factors

Systematics

Parameter	Impact on limit
$\phi_{e\gamma}$ 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 %

Table 4: Sumamry of uncertain parameters

Parameter	Uncertainty
Target alignment	100 μm
LXe global shift	1 mm
Normalization	5 %
E_γ energy scale	0.3 %
E_e energy scale	6 keV
$t_{e\gamma}$ center	4 ps
Positron correlation	5 – 10 %

Future $\mu \rightarrow e\gamma$ Searches

- Activities around the world to increase the muon beam rate to 10^9-10^{10} muons/s
- Crucial to understand which factors will limit the sensitivity

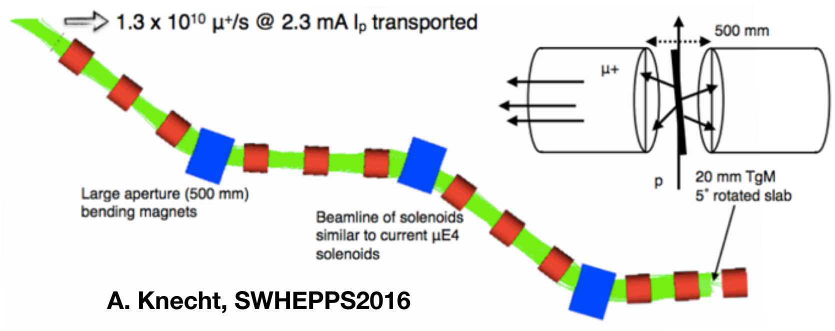
$$B_{sig} \propto \Gamma_\mu \qquad B_{acc} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta \Theta_{e\gamma})^2$$

HiMB Project @ PSI

x4 μ capture eff.

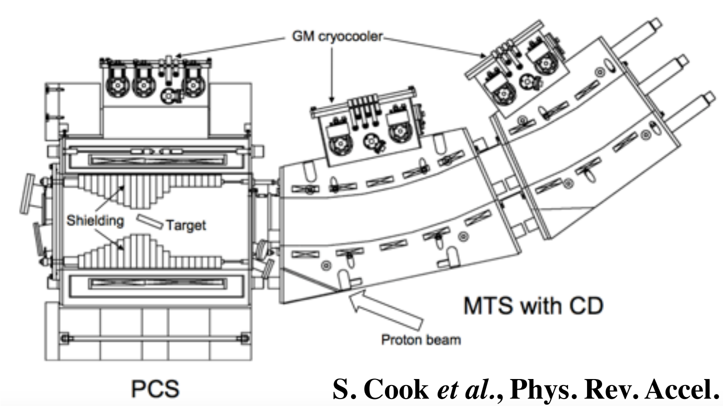
x6 μ transport eff.

1.3×10^{10} μ/s



A. Knecht, SWHEPPS2016

Preliminary study at FNAL (PIP-II)



S. Cook *et al.*, Phys. Rev. Accel. Beams 20 (2017)

MuSIC Project @ RCNP

Thick production target

π capture solenoid

4×10^8 μ/s

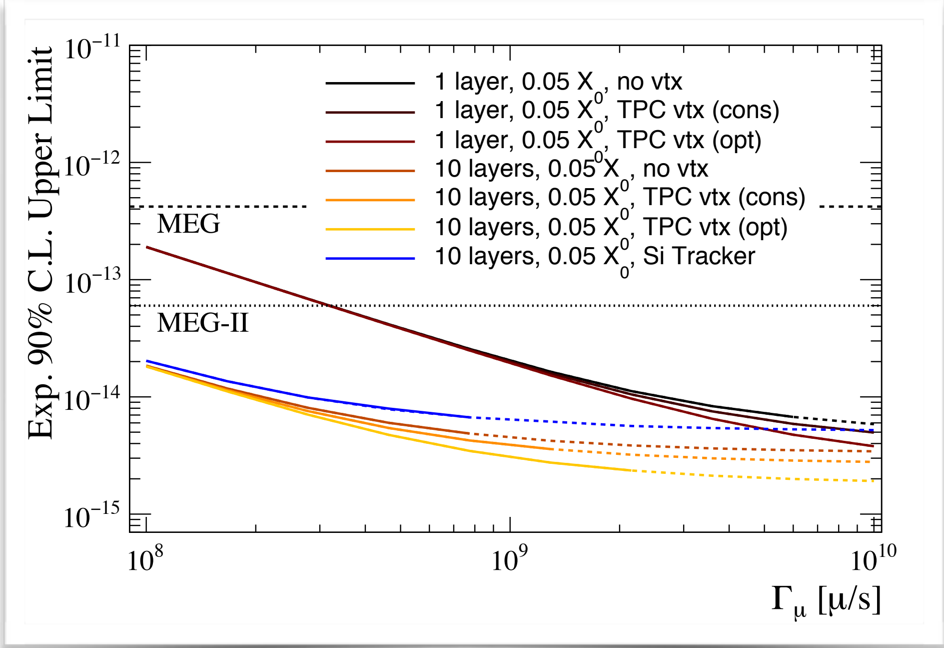
at the production target

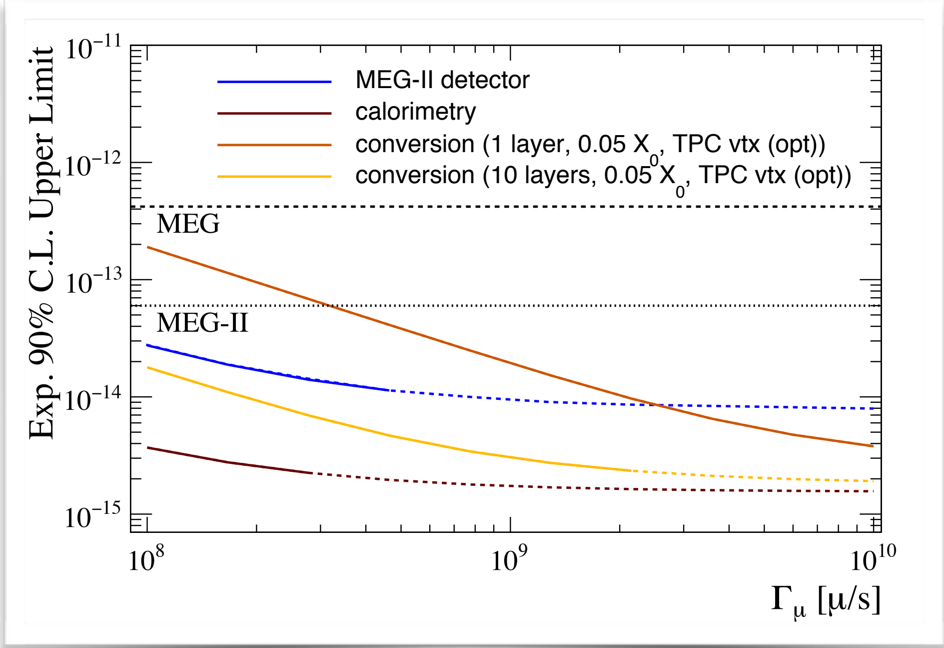
Future $\mu \to e\gamma$ Experiment

Photon conversion approach

Cavoto et. al. Eur.Phys J.C78 (2018) 1-37

Photon conversion vs calorimetric approach





- A few 10^{-15} level seems to be within reach for 3 years running with 10^{9} muons/s with

Wilson Coefficient

- Limits on the Wilson coefficients of LFV effective operators from present and future cLFV muon processes

	$\mathrm{Br}(\mu^+ \to e^+\gamma)$		$\mathrm{Br}(\mu^+ \to e^+e^-e^+)$		$\mathrm{Br}^{\mathrm{Au/Al}}_{\mu\to e}$	
	$4.2 \cdot 10^{-13}$	$4.0 \cdot 10^{-14}$	$1.0 \cdot 10^{-12}$	$5.0 \cdot 10^{-15}$	$7.0 \cdot 10^{-13}$	$1.0 \cdot 10^{-16}$
C_L^D	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$	$1.4 \cdot 10^{-8}$	$2.0 \cdot 10^{-7}$	$2.9 \cdot 10^{-9}$
$C_{ee}^{S\,LL}$	$4.8 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	$8.1 \cdot 10^{-7}$	$5.8 \cdot 10^{-8}$	$1.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-5}$
$C_{\mu\mu}^{S\,LL}$	$2.3 \cdot 10^{-7}$	$7.2 \cdot 10^{-8}$	$4.6 \cdot 10^{-6}$	$3.3 \cdot 10^{-7}$	$7.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
$C_{\tau\tau}^{S\,LL}$	$1.2 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$2.4 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$2.4 \cdot 10^{-5}$	$3.5 \cdot 10^{-7}$
$C_{\tau\tau}^{T\,LL}$	$2.9 \cdot 10^{-9}$	$9.0 \cdot 10^{-10}$	$5.7 \cdot 10^{-8}$	$4.1 \cdot 10^{-9}$	$5.9 \cdot 10^{-8}$	$8.5 \cdot 10^{-10}$
$C_{\tau\tau}^{S\,LR}$	$9.4 \cdot 10^{-6}$	$2.9 \cdot 10^{-6}$	$1.8 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$2.7 \cdot 10^{-6}$
$C_{bb}^{S\,LL}$	$2.8 \cdot 10^{-6}$	$8.6 \cdot 10^{-7}$	$5.4 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$9.0 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$

arXiv:170203020
A. Crivellin et al.

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1 column = present best limit
2 column = future limit

Present cLFV Limit

Reaction	Present limit	C.L.	Experiment	Year
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ †	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ †	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ †	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ †	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998
$K_L^0 \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004
$J/\psi \to \tau\mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004
$B^0 \to \mu e$	$< 2.8 \times 10^{-9}$	90%	LHCb	2013
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008
$B^0 \to \tau\mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008
$B \to K\mu e$ ‡	$< 3.8 \times 10^{-8}$	90%	BaBar	2006
$B \to K^*\mu e$ ‡	$< 5.1 \times 10^{-7}$	90%	BaBar	2006
$B^+ \to K^+\tau\mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012
$B^+ \to K^+\tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012
$B_s^0 \to \mu e$	$< 1.1 \times 10^{-8}$	90%	LHCb	2013
$\Upsilon(1s) \to \tau\mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017