The MEG Experiment: Run I Final Results and Preparation for Run II

Terence Libeiro
University of California Irvine

On behalf of MEG Collaboration
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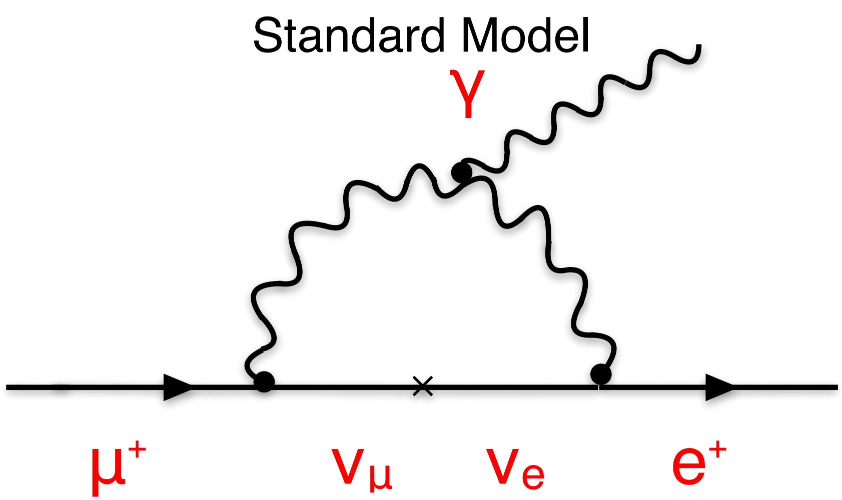
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- MEG physics
  - CLFV
  - MEG and other experiments
- MEG Setup and Results
  - Run I - Detectors and Analysis
  - Results
- MEG 2
  - Motivation
  - Upgrades in subsystems
  - Expected sensitivities and schedule

Charged Lepton Flavor Violation

- Lepton flavor violation observed in neutral sector (ν_u ν_e ν_τ). In the charged sector it is suppressed $|\Delta m^2_\nu/M^2_W|^2$.
- Small branching ratio due to light left-handed neutrinos.
- Experimentally, allows a clean, (near) background free channel to test the Standard Model, by experiments on intensity/precision frontier



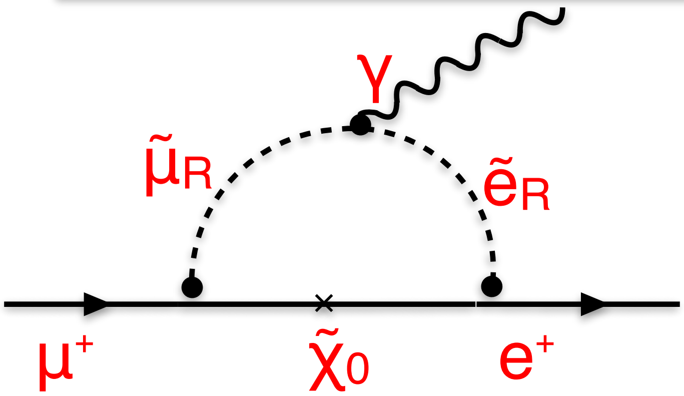
$$\mathcal{B}(\mu^+ \to e^+ + \gamma) \approx 10^{-54}$$

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2$$

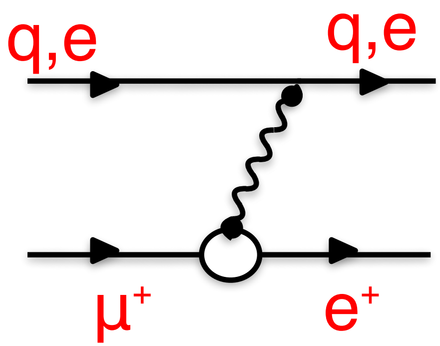
Extensions to the Standard Model

- Observation of enhancement in rate would signal new physics
- SUSY extensions predict higher rate which can be confirmed or ruled out.
- High energy probe beyond the energy reach of the LHC
- Complementary with other cLFV searches:
  - μ → eee (Mu3e, PSI),
  - μN → eN (Mu2e, FNAL) and (COMET, J-PARC)

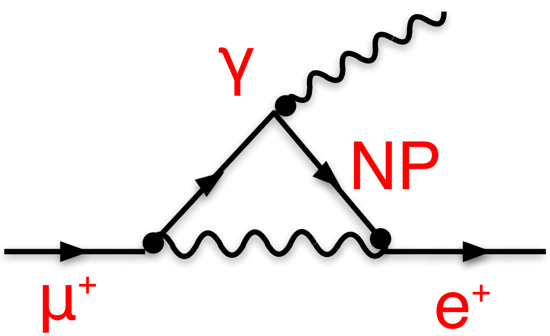
SU(5), SU(10) with SUSY-GUT



Barbieri, Masiero, Ellis, Hisano



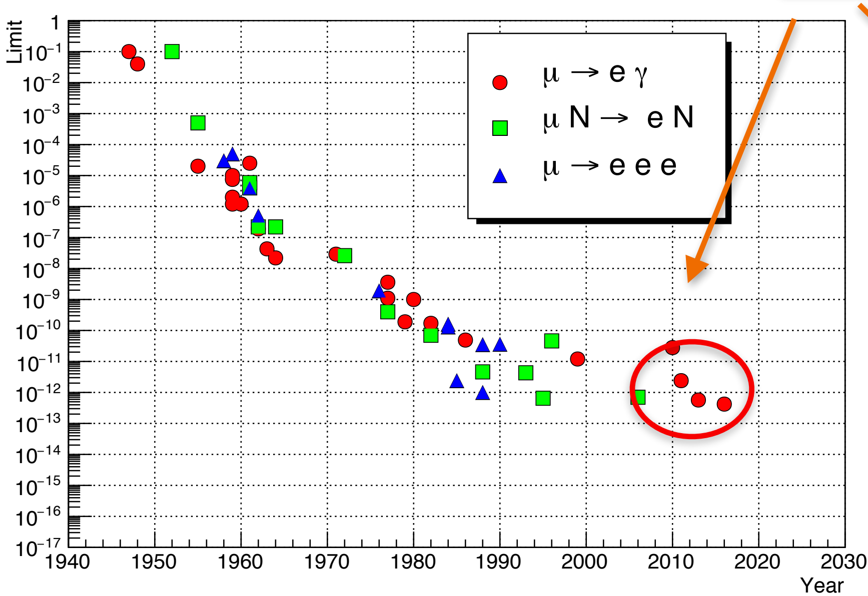
Higher order contribution to μ → 3e, μN → eN process



New Physics probe

CLFV limits so far

MEG



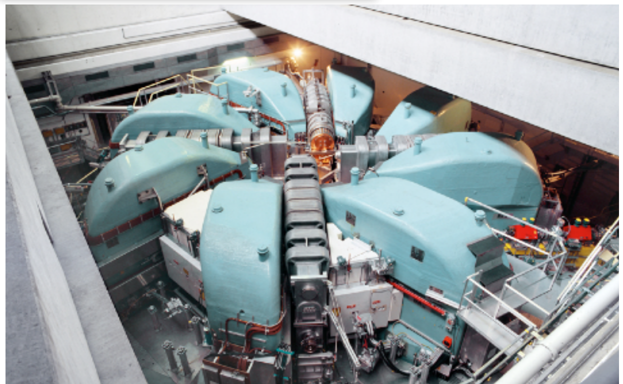
Reaction	Present limit	C.L.	Experiment	Year	Reference
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016	[49]
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988	[50]
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ †	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998	[51]
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ †	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996	[52]
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ †	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006	[54]
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ †	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998	[53]
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999	[55]
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007	[58]
$\tau \to \pi^0\mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007	[59]
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011	[60]
$\tau \to \rho^0\mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011	[60]
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008	[61]
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998	[62]
$K_L^0 \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008	[61]
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005	[63]
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013	[64]
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004	[65]
$J/\psi \to \tau\mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004	[65]
$B^0 \to \mu e$	$< 2.8 \times 10^{-9}$	90%	LHCb	2013	[68]
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008	[69]
$B^0 \to \tau\mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008	[69]
$B \to K\mu e$ ‡	$< 3.8 \times 10^{-8}$	90%	BaBar	2006	[66]
$B \to K^*\mu e$ ‡	$< 5.1 \times 10^{-7}$	90%	BaBar	2006	[66]
$B^+ \to K^+\tau\mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012	[67]
$B^+ \to K^+\tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012	[67]
$B_s^0 \to \mu e$	$< 1.1 \times 10^{-8}$	90%	LHCb	2013	[68]
$\Upsilon(1s) \to \tau\mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008	[70]
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014	[71]
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995	[72]
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997	[73]
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016	[74]
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017	[75]
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017	[75]

Calibbi and Signorelli

- Over half-century of searches, the limits have improved 10^{12}
- Limits calculated for dipole operators for comparison

MEG experiment at PSI

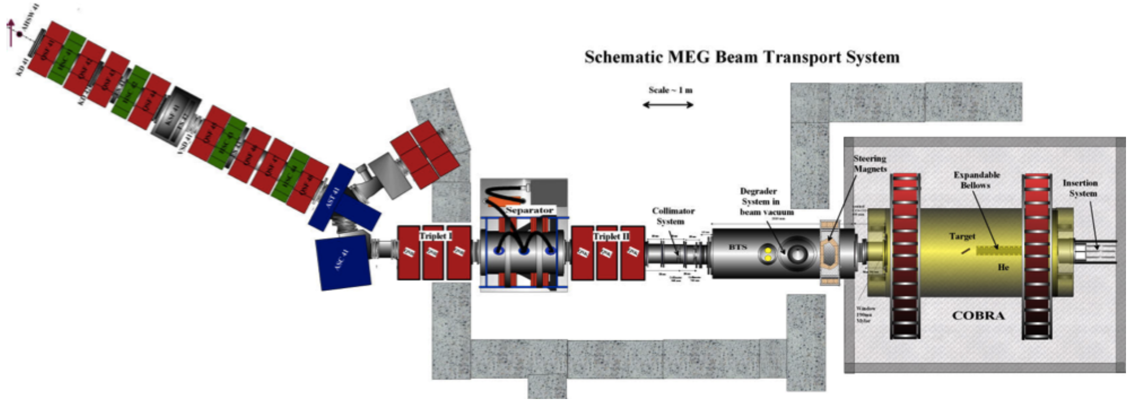
Proton cylcotron

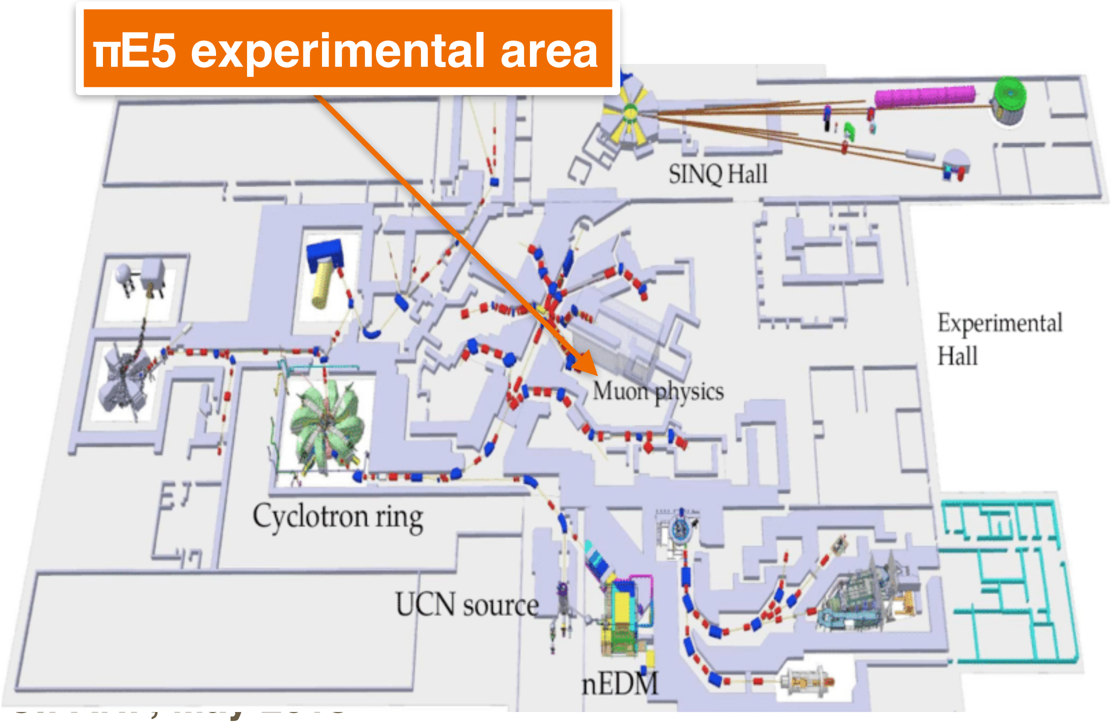


PSI Ariel view

The MEG Collaboration, ~70 researchers from 5 countries

Beam line

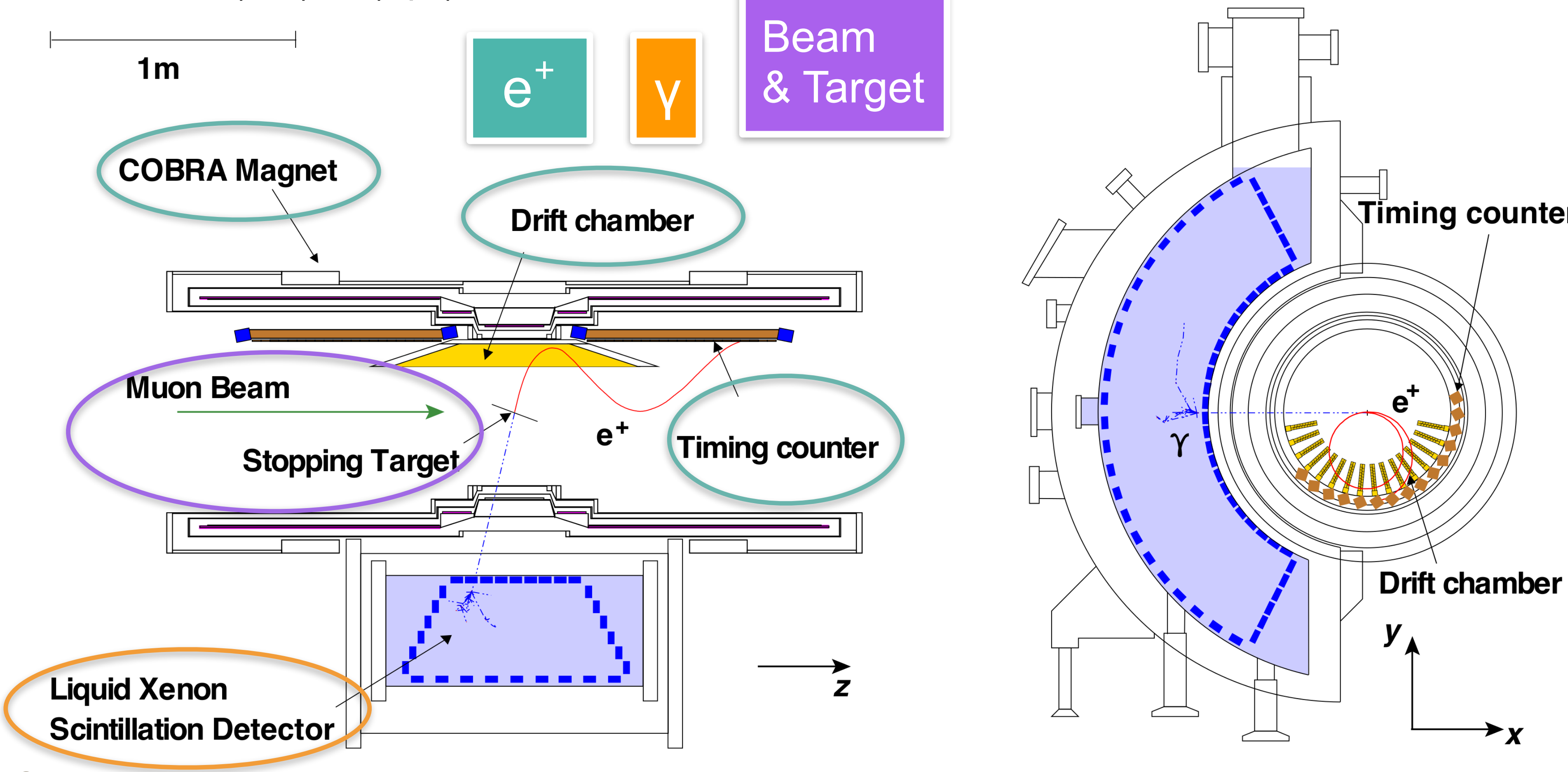




- World's most intense continuous beam: current - 2.2 mA, power - 1.4 MW , proton energy - 590 MeV
- Muons produced by π decays near target surface in secondary beam line πe5
- Monochromatic, low-momentum μ^+ source 28 MeV/c, tuned with the target to maximize μ^+ stopping rate

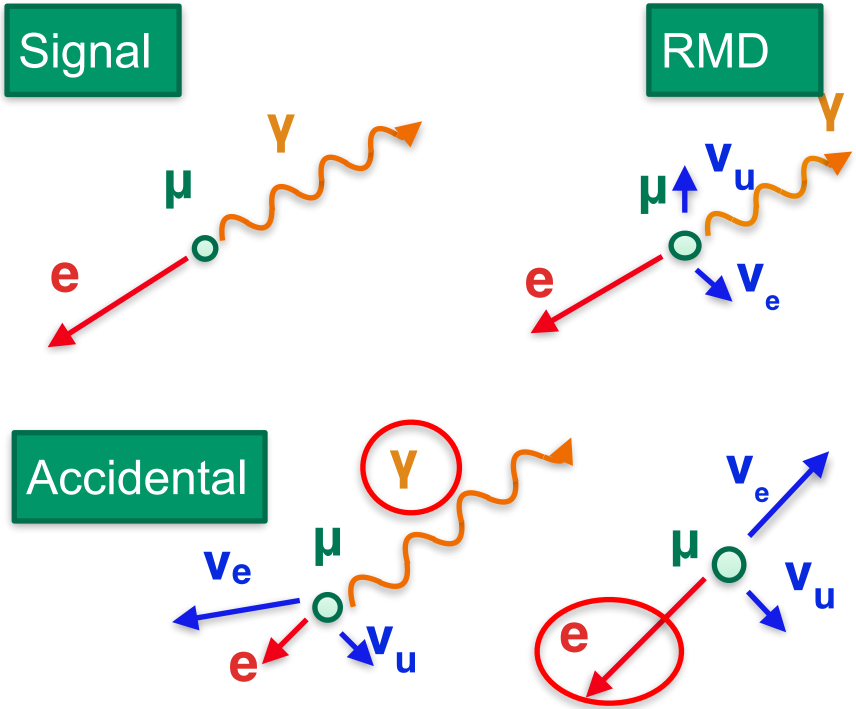
MEG detector setup

- Measurement of $\mu \rightarrow e+\gamma$ decay
- Observables for energy, position and timing of the decay products: E_e, E_γ, $t_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$



Backgrounds

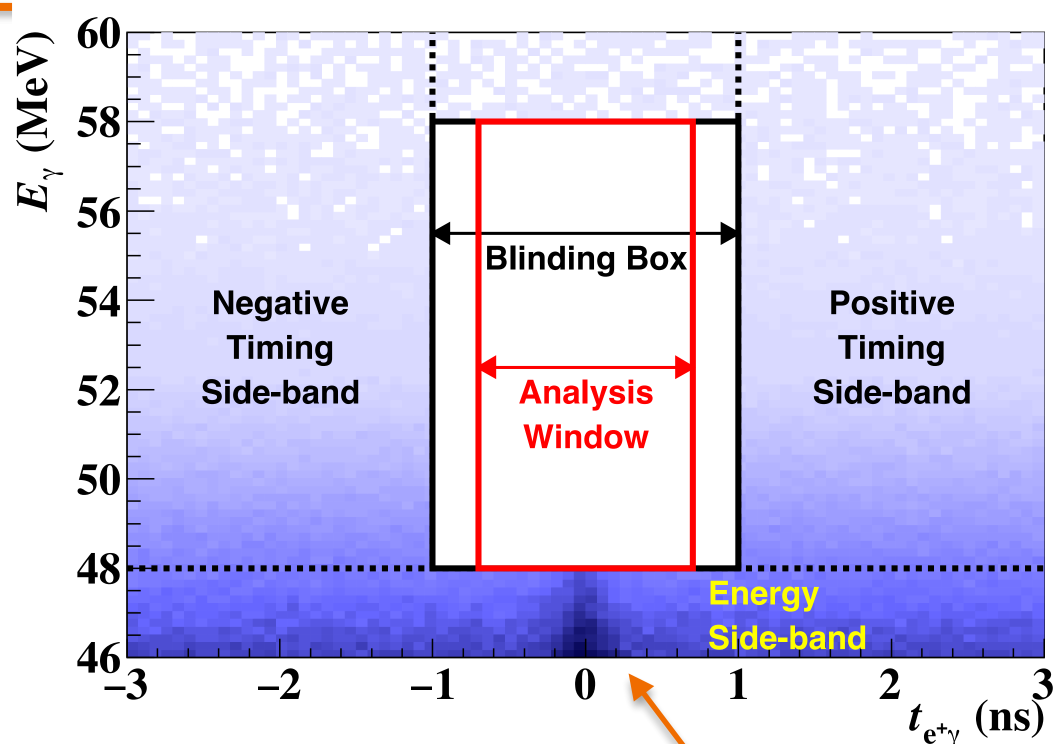
- Signal
  - $m_\mu/2$ 52.83 MeV ,
    time coincident e^+ and γ
  - Back to back topology
- Radiative Muon Decay (RMD)
  ($\mu \rightarrow e+v_u+v_e+\gamma$)
  - E < 52.83 , time coincident
- Accidental Background (ACC)
  ($\mu \rightarrow e+v_u+v_e+\gamma$ (acc))
  - E< 52.83 , flat probability dist in time
  - Michel decay + γ radiated from another decay or annihilation



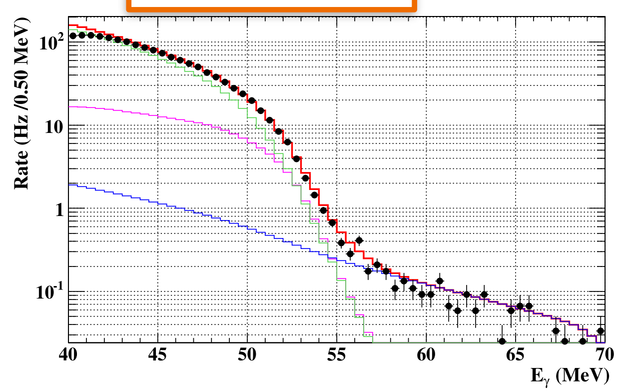
- Estimation from data/MC and analysis cuts
  - ACC pdf: estimated from data
  - RMD pdf: rates are calculated from theory, smeared with detector resolutions, also confirmed in data in sideband region

Analysis strategy

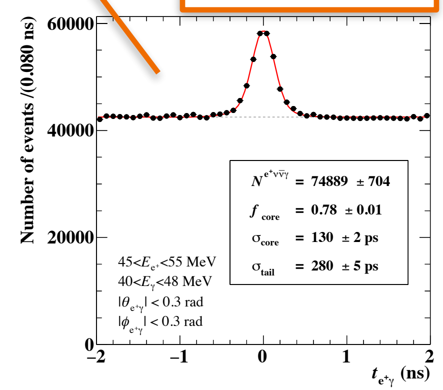
- Background pdfs event to event and constant pdfs
- Time sidebands used for background estimation
- Cuts applied to events in the analysis window:
  - $48<E_\gamma<58$,
  - $50<E_e<56$,
  - $|t_{e\gamma}|<0.7$,
  - $|\theta_{e\gamma}|<50$,
  - $|\phi_{e\gamma}|<50$.
- Events fitted in analysis window with maximum likelihood procedure, as well as in sidebands to check consistency



E_γ spectrum



RMD peak



Maximum Likelihood analysis

- Perform likelihood fits to determine Nsig, N_{Acc}, N_{RMD}
- Constraints on nuisance parameters taken into account. Time-dependent variation in target planarity(t) and position.
- Process PDFs and well-monitored up-to-date resolutions used for precise determination of background.
- Applied on event-to-event basis.

Signal **Nuisance parameters**

$$\mathcal{L}(N_{\rm Sig}, N_{\rm RMD}, N_{\rm Acc}, t) = \frac{e^{-N}}{N_{\rm obs}!} C(N_{\rm RMD}, N_{\rm Acc}, t) \times \prod_i^{N_{\rm obs}} (N_{Sig} S(x_i, t) + N_{RMD} R(x_i) + N_{Acc} A(x_i))$$

PDFs

$$where,$$

$$x_i = \{E_\gamma, E_{e^+}, t_{e^+,\gamma}, \theta_{e^+,\gamma}, \phi_{e^+,\gamma}\}$$

Vector of observables

$$N = N_{Sig} + N_{Acc} + N_{RMD}$$

Total events in the fit

Single event sensitivity (SES)

- SES: Branching ratio at which the experiment will see a single signal event
- Branching ratio is calculated as the ratio of Signal events normalized to the total muon decays observed in the experiment
- N_{total} calculated independently from RMD sidebands (μ→eγνν), and Michel events (μ→eνν) using prescaled triggers :

$$\mathcal{B}(\mu^+ \to e^+ + \gamma) = \frac{N_{Sig}(\mu^+ \to e^+ + \gamma)}{N_{total}},$$

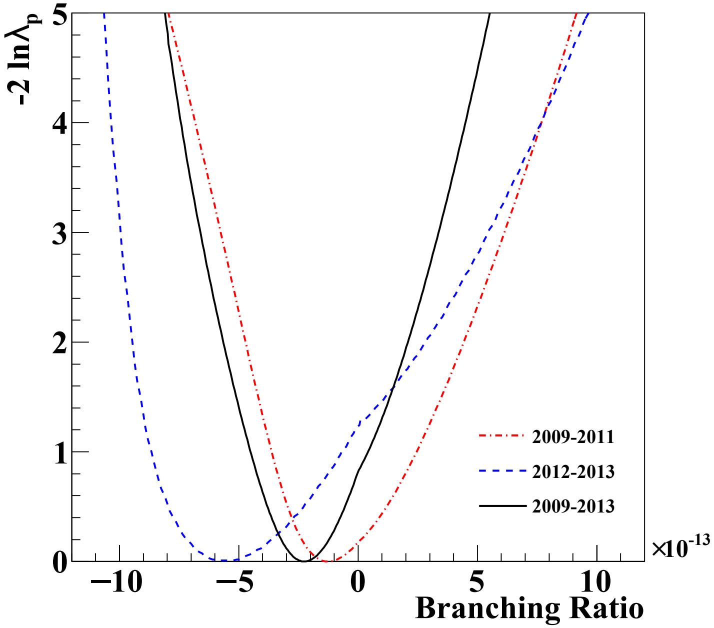
$$N_{total} = \frac{N^{RMD,Michel}}{\mathcal{B}_{RMD,Michel}} \times \frac{1}{\langle A \times \epsilon \rangle^{RMD,Michel}}$$

- N_{total} calculated from the two methods with 3.5% uncertainty

SES = 1/N_{total} = (5.84 ± 0.2) × 10^{-14}

Limit setting on the BR

- Profile likelihood ratio using events in the analysis window, shown as a function of signal branching ratio.
- The confidence interval for N_{Sig} is calculated using Feldman-Cousins method with profile-likelihood ratio ordering.
- Datasets from 2009-11,2012, 2009-13. Results consistent with null hypothesis. Systematic uncertainties dominated by target alignment-5%, other effects <1%.



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- cLFV branching ratio upper limit is set at :

$$\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}\ (90\%\ C.L.)$$

Sensitivity limit, Motivation for MEG2

$$N_{Sig} = R_\mu \times t \times \Omega \times \mathcal{B} \times \epsilon_\gamma \times \epsilon_{\mathrm{e}+} \times \epsilon_{\mathrm{s}}$$

Number of Signal events

Muon stopping rate

Measurement time

Geometric acceptance

Detector and selection efficiencies

$$Bkg \sim R_\mu^2 \times \Delta E_\gamma^2 \times \Delta p_{e+} \times \Delta\Theta_{e+\gamma}^2 \times \Delta t_{e+\gamma} \times t$$

Number of Background events

Muon stopping rate

detector resolutions γ, e^+

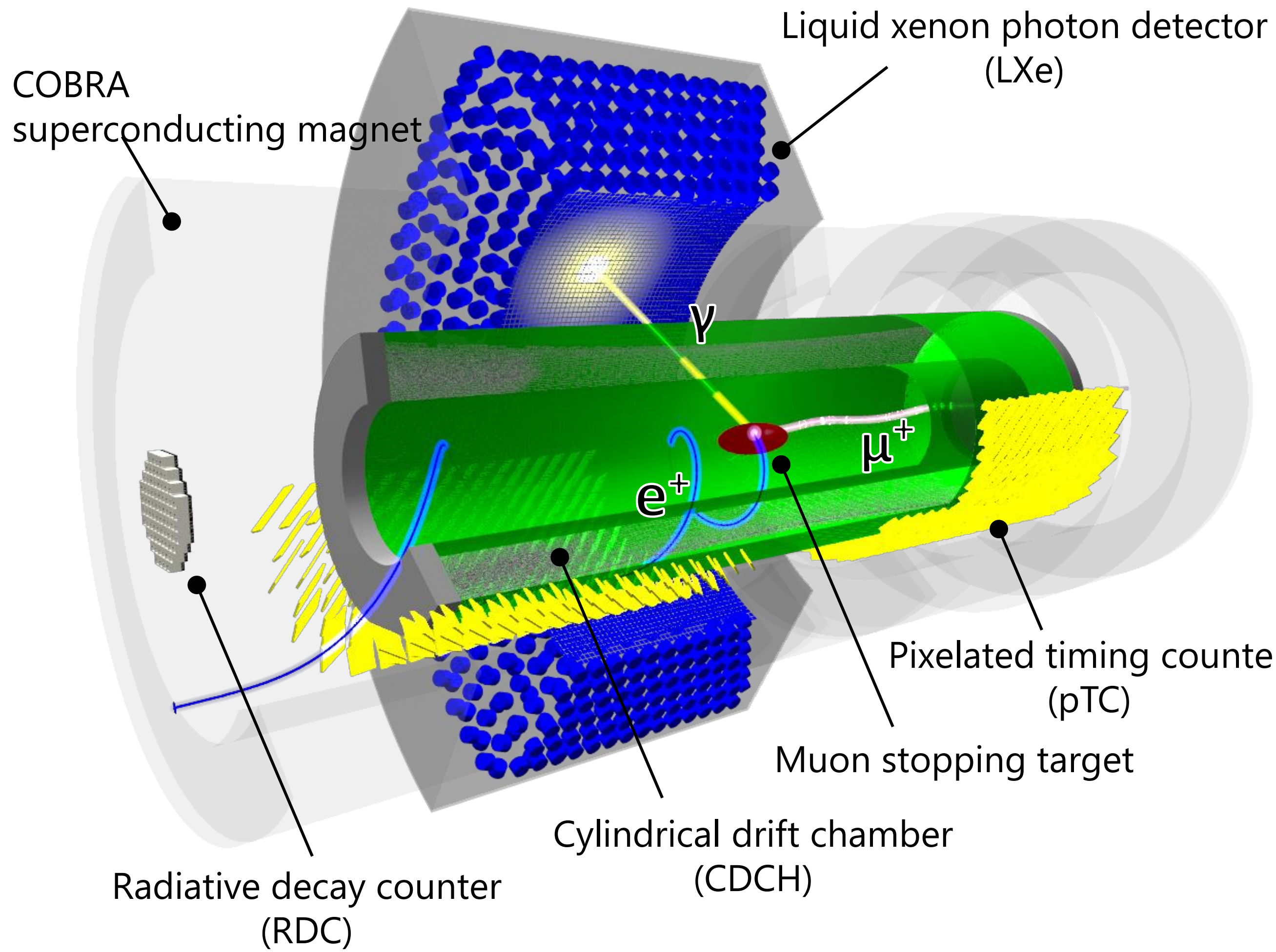
Measurement time

To get best sensitivity:

- higher statistics, better acceptance and efficiency
- better background rejection, better resolutions

MEG 2

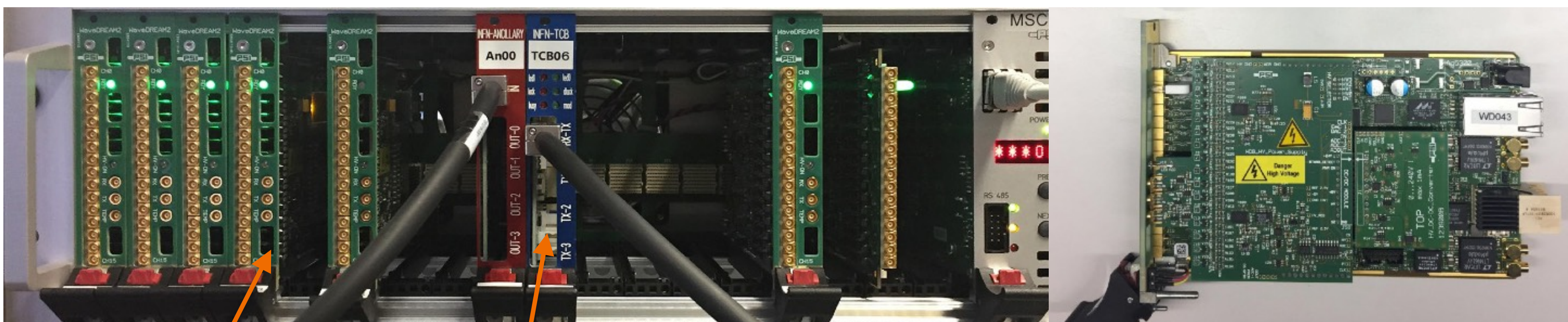
- **Best possible limits of allowed by the detector technology**
- **Upgraded detector components**
- **High statistics**
- **Improved resolutions, acceptance and background rejection**



Upgrade proposal : arXiv:1301.7225

DAQ

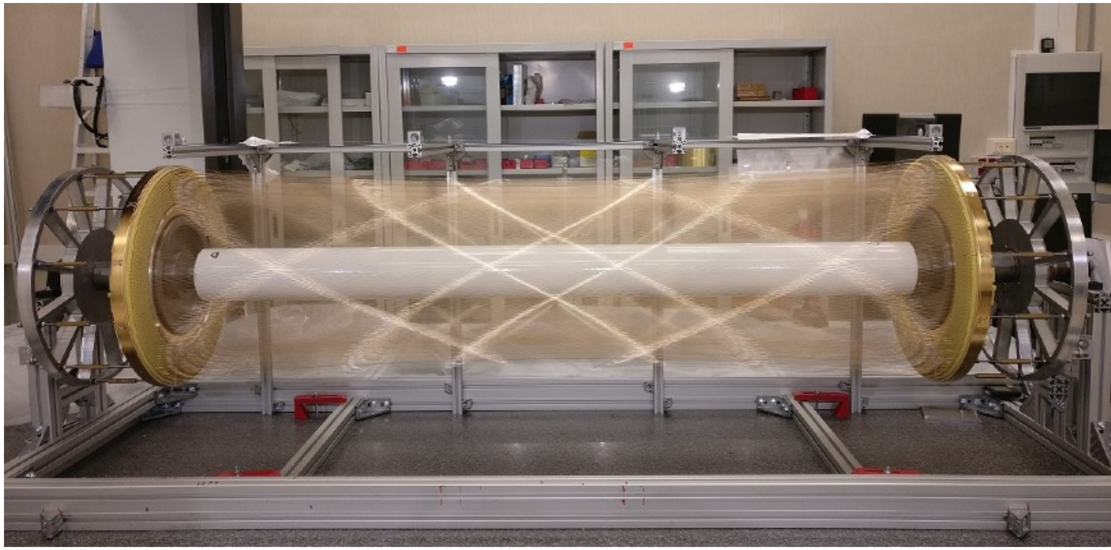
- Front-End requirements:
  - fast and high quality signal sampling,
  - large number of readout channels (~9K),
  - pre-amplification,
  - Triggering
- WaveDream board designed for MEG II
  - 16 channels (DRS4) with gain amplification and pole-zero cancelation
  - read with 12 bit resolution
  - Integrated FPGA for triggering
  - 5 GSPS analog sampling
- Status: Tested successfully with LXe, pTC and RDC in 2017



WDB Board Trigger

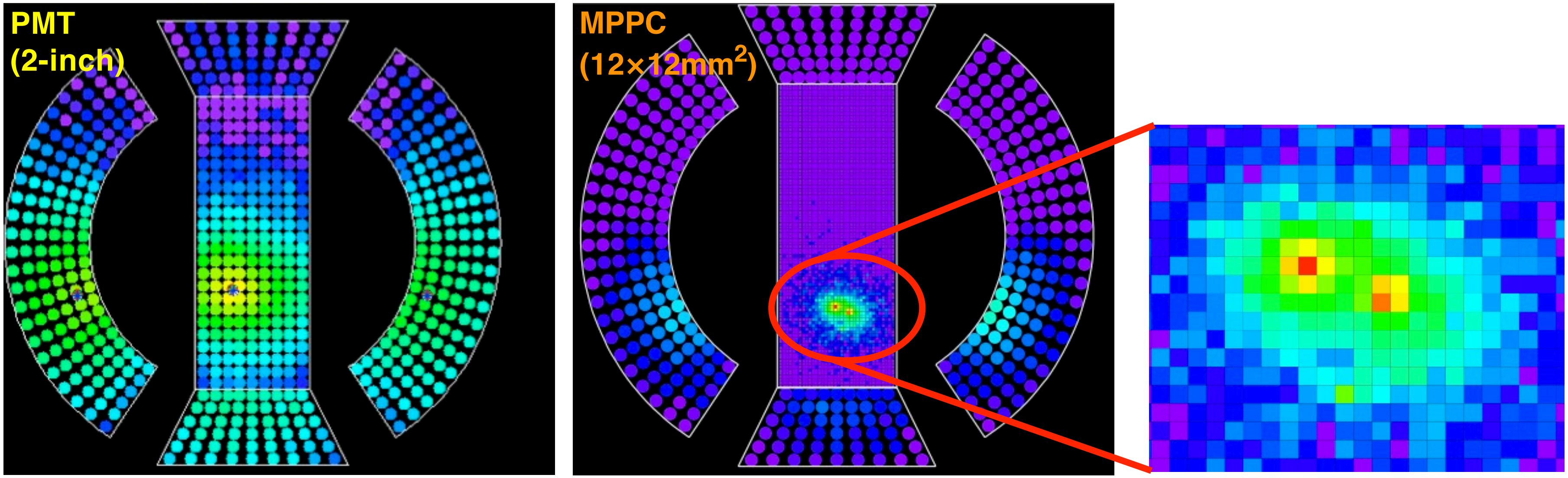
DCH

- Single volume drift chamber
- 40-50 µm Ag/Al cathode,
  20 µm Au/W anode
- He-Isobutane (90:10)
- Increased transparency,
  reduced multiple scattering
- Increased reconstruction efficiency, & transparency to pTC for matching
- High acceptance 2π
- Operate under high pile-up environment (7×10^7 µ/s)
- Fast electronics and improved reconstruction algorithm



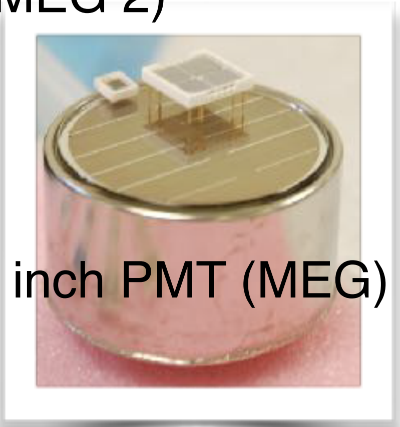
Core gaussian resolutions (σ)	MEG	MEG II (MC)
p_e(keV)	306	130
θ_e (mrad)	9.4	5.3
φ_e (mrad)	8.7	3.7
e Efficiency	40	78
pTC match Efficiency	45	90

LXe Calorimeter



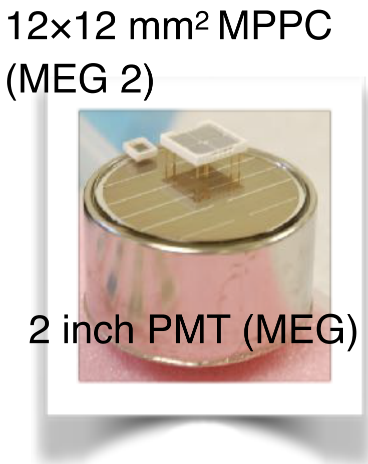
- Increase granularity, greater active area
- Higher light collection efficiency, γ detection
- Increase pile-up rejection
- Uniform response for shallow events

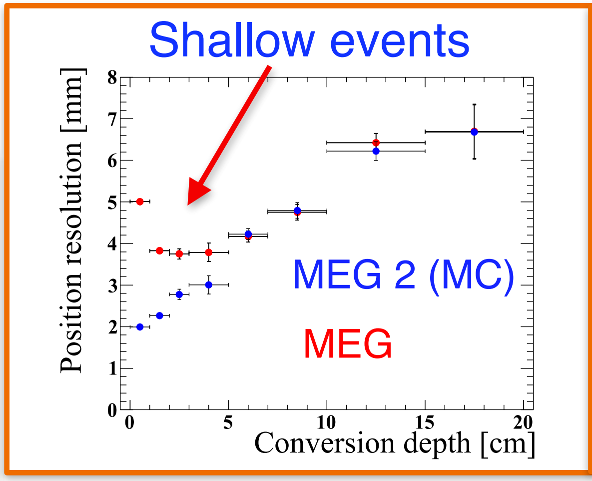
12×12 mm² MPPC (MEG 2)

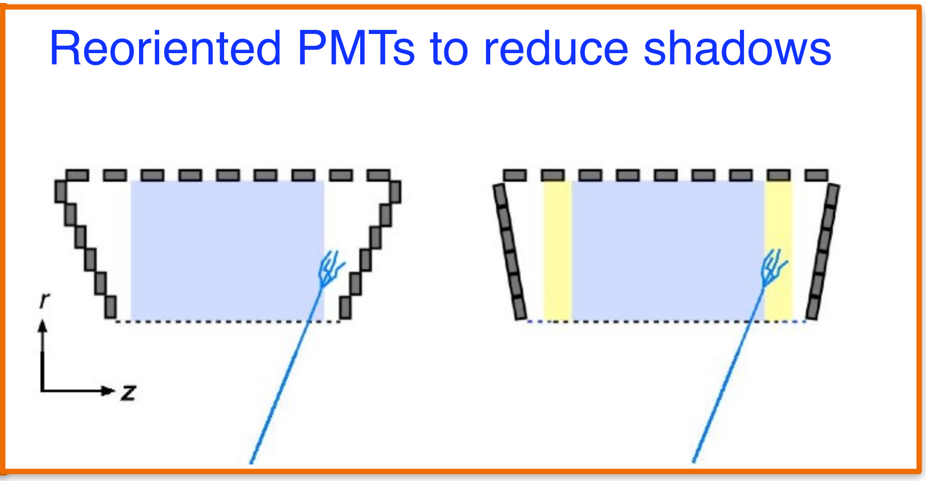


2 inch PMT (MEG)

LXe Calorimeter







- Increase granularity, greater active area
- Higher light collection efficiency, γ detection
- Increase pile-up rejection
- Uniform response for shallow events
- Increased acceptance
- Improved position and energy resolution

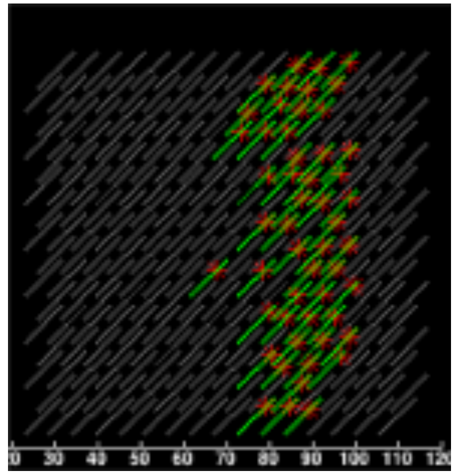
Core gaussian resolutions (σ)	MEG	MEG 2 (MC)
Photon E (%)	2.4 (w>2cm) 1.7 (w<2cm)	1.1(w>2cm) 1.0(w<2cm)
Photon Position (u,v,w) (mm)	5,5,6	2.6,2.2,5
γ-e^+ timing (ps)	122	84

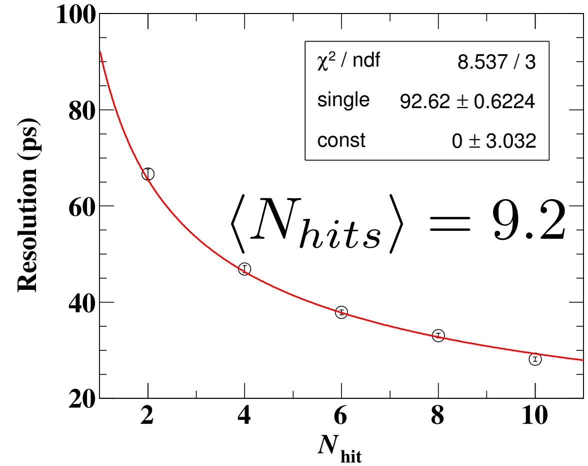
pixelated Timing Counter (pTC)

- 2 Large pixelated arrays (US, DS) 16× 16 small scintillating tiles (BC-422)
- Readout by AdvanSiD SiPMs
- Provide fast response, good pileup rejection (10^8 μ/s), uniform photon propagation path
- Calculated resolutions with μ^+ beam running conditions meet expectations:

  σ_{te^+} (N_{hits} = 9) ≈ 31 ps,

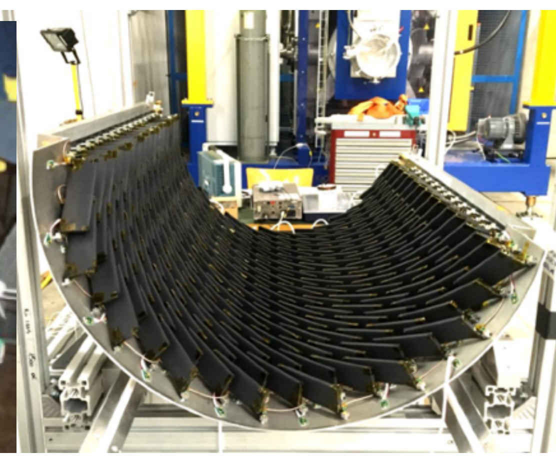
  σ_{te^+} (N_{hits} = 1) ≈ 93 ps





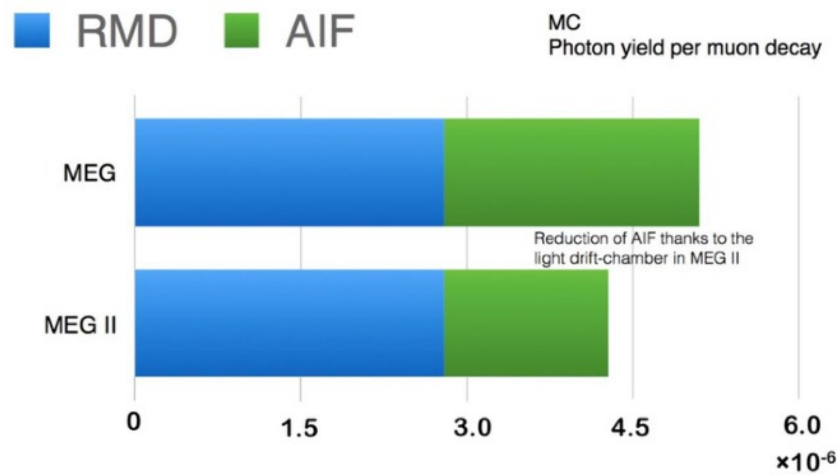
MEG

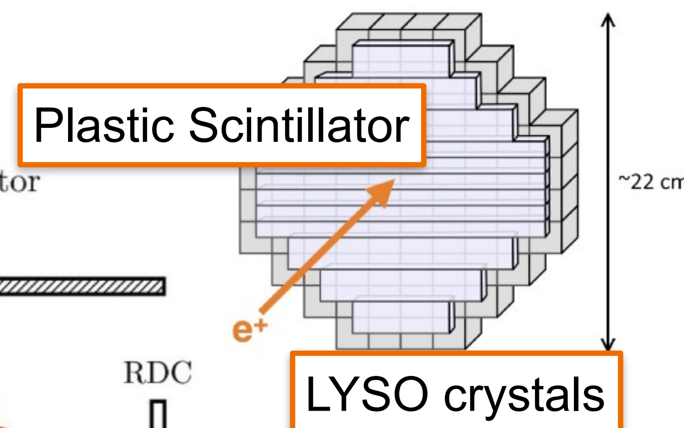
MEG 2

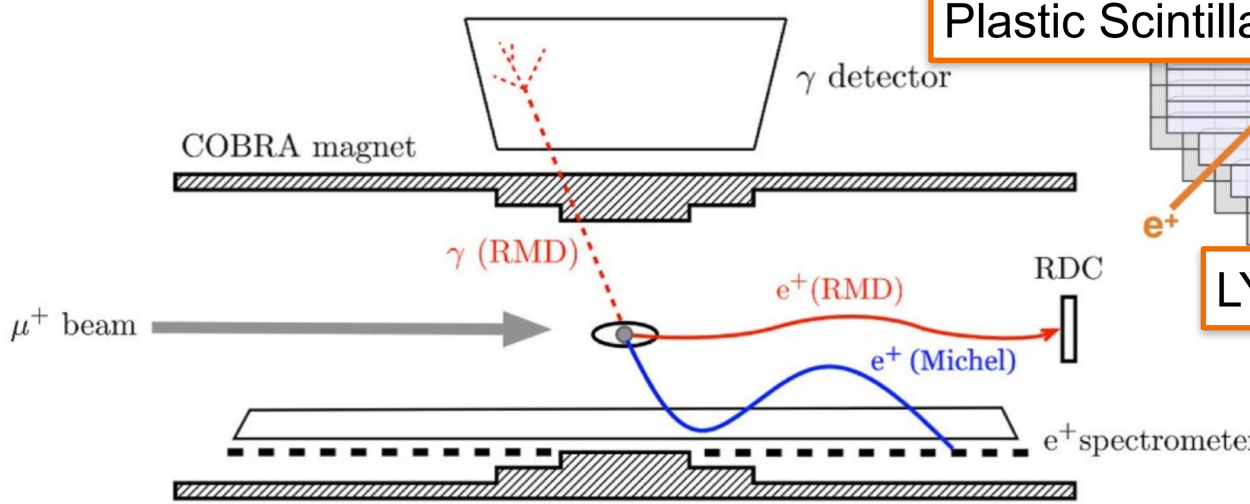


Radiative Decay Counter (RDC)

- Relatively large fraction of Accidental RMD background will contribute in MEG 2
- RDC designed to tag radiative muon decays coincident with γ close to the kinematic limit, i.e. low-momentum e^+.
- 2 Layers: Plastic scintillator for timing, LYSO for energy measurement
- Expected 15% improvement in sensitivity

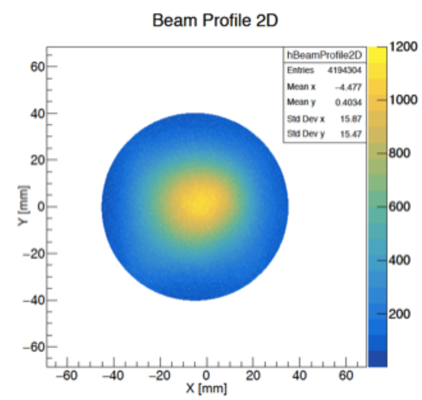




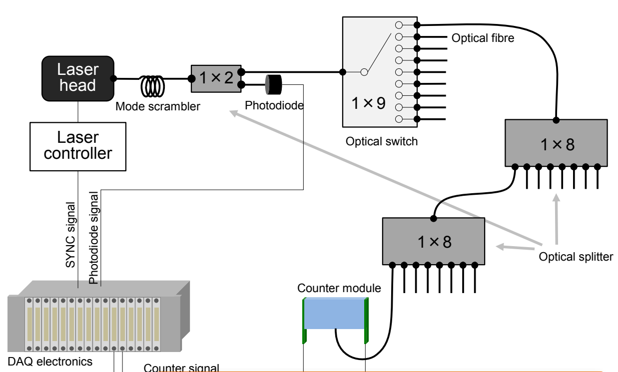


New Calibration methods

- Laser: pTC timing calibration individual channels using synchronous laser
- Target Alignment: Continuously monitor target foil for deformation, and change in position using high resolution photography
- X-ray: Position Survey of MPPC photodetectors inside LXe using X-ray
- Scintillation foil (Luminophore): In-situ, non-destructive system for beam profile monitoring based in CsI(Tl)/ Lavsan(Mylar)

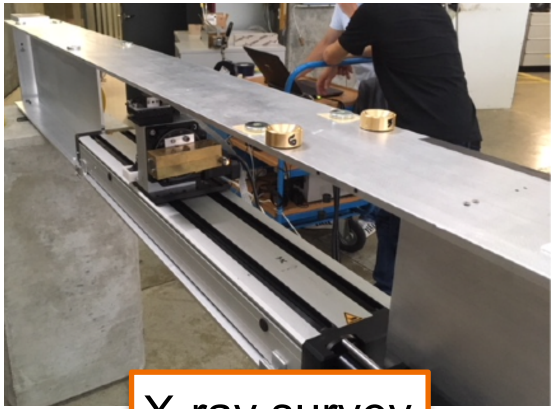


Scintillation foil



pTC Laser system

Target Alignment

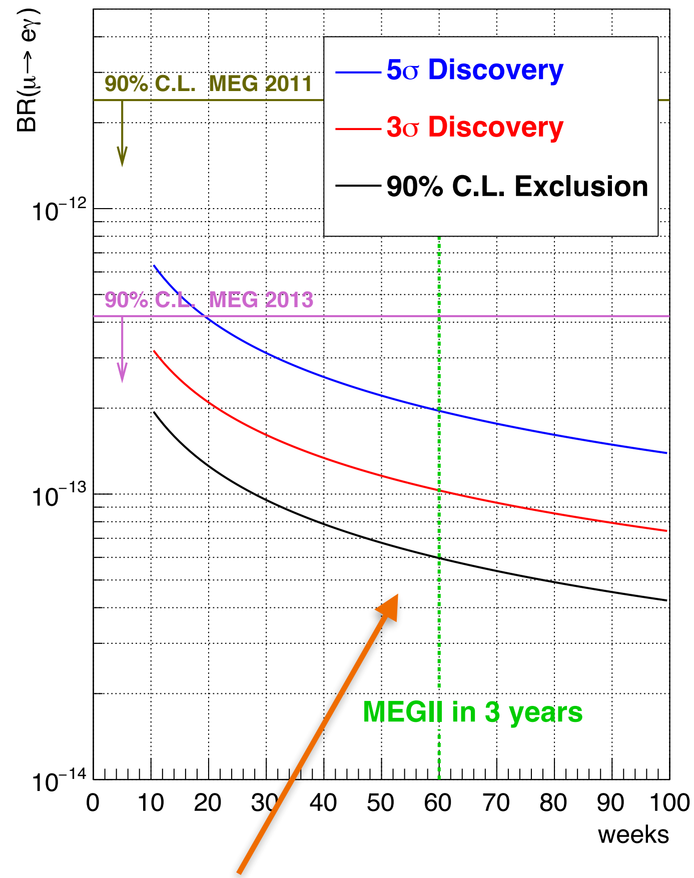


X-ray survey

Resolutions expected in MEGII

Core gaussian resolutions (σ)	MEG	MEG 2 (MC)
Positron E (keV)	380	130
Positron θ (mrad)	9.4	5.3
Positron φ (mrad)	8.7	3.7
Photon E (%)	2.4 (w>2cm) 1.7 (w<2cm)	1.1(w>2cm) 1.0(w<2cm)
Photon Position (u,v,w) (mm)	5,5,6	2.6,2.2,5
Positron-Photon timing (ps)	122	84

- Higher statistics (x10) due to higher beam intensity ($7\times10^7 \mu/s$) and higher efficiency and slightly higher acceptance
- MEG 2 sensitivity calculated using simulated events and up-to-date detector resolutions

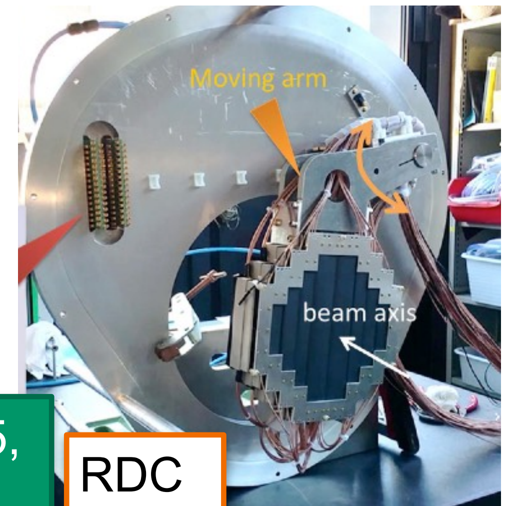


6×10^{-14} (90% C.L.)

Upgrades summary

1. DAQ:Tested. Full production in 2018
2. DCH: Assembly finished. Shipped to PSI
3. LXe: Upgrades finished. Tested with 30% channels. Electronics tests and calibrations ongoing.
4. Target: Ready. Testing alignment and monitoring systems
5. pTC: Fully tested. Ready for Data.
6. RDC: Tested. Ready for Data.
7. Calibrations: Hardware ready. Analysis algorithms development in progress.

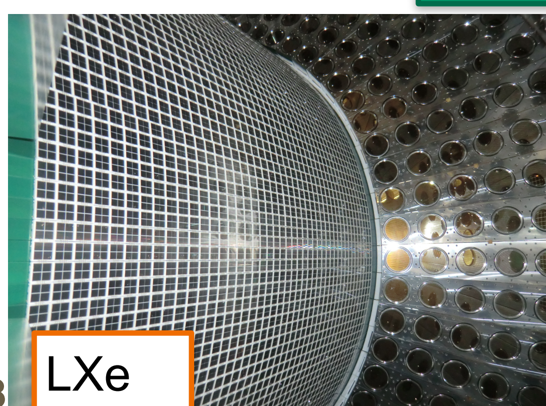
Target



RDC

Eur.Phys.J. C78 (2018) 5, 380

DCH



LXe

pTC

Conclusions

- Results from MEG I using complete dataset set the limit on cLFV at 4.2×10^{-13} (90% C.L.). Best cLFV result to date. An improvement of x30 over MEGA experiment. [EPJC (2016) 76:434, PRL **83**(8),1521–1524 (1999)]

- An upgrade of MEG is underway, with hardware and assembly phase finished. Sub-detectors are either in testing phase, or ready for physics. The small scale test with all detectors is scheduled for end of this year (2018), first engineering run in 2019. Analysis strategy is the same as MEG, algorithms need to be tuned to the new detectors and running conditions. [EPJC(2018) 78:380]

- The upgrades have focussed on improving all detectors, target and beam intensity to get the highest possible sensitivity for $\mu\to e\gamma$ using current detector technology. Overall, resolutions are improved by x2, statistics will improve x10, permits the final sensitivity 6×10^{-14} (90% C.L.) in running period of 3 years.

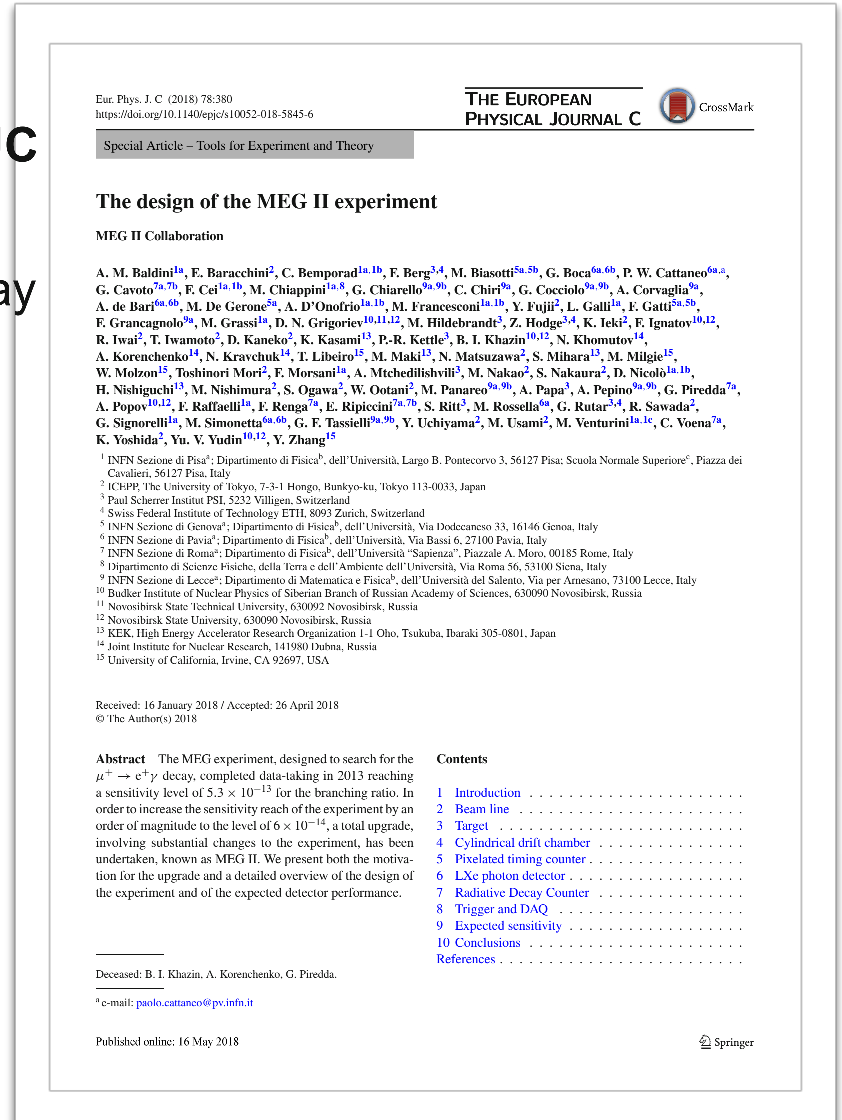
Backup

Efficiencies

	MEG I (%)	MEG II (%)
μ^+ stops	80	83
Trigger	99	99
γ	63	69
e^+	30	70

Publications

1. The design of the MEG II experiment, **EPJC (2018) 78:380**
2. Search for the lepton flavour violating decay $\mu^+ \to e^+\gamma$ with the full dataset of the MEG experiment, **EPJC (2016) 76:434**
3. Muon polarization in the MEG experiment: predictions and measurements, **EPJC (2016) 76:223**
4. Measurement of the radiative decay of polarized muons in the MEG experiment, **EPJC (2016) 76:108**



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Special Article – Tools for Experiment and Theory

The design of the MEG II experiment

MEG II Collaboration

A. M. Baldini[1a], E. Baracchini[2], C. Bemporad[1a,1b], F. Berg[3,4], M. Biasotti[5a,5b], G. Boca[6a,6b], P. W. Cattaneo[6a,a], G. Cavoto[7a,7b], F. Cei[1a,1b], M. Chiappini[1a,8], G. Chiarello[9a,9b], C. Chiri[9a], G. Cocciolo[9a,9b], A. Corvaglia[9a], A. de Bari[6a,6b], M. De Gerone[5a], A. D'Onofrio[1a,1b], M. Francesconi[1a,1b], Y. Fujii[2], L. Galli[1a], F. Gatti[5a,5b], F. Grancagnolo[9a], M. Grassi[1a], D. N. Grigoriev[10,11,12], M. Hildebrandt[3], Z. Hodge[3,4], K. Ieki[2], F. Ignatov[10,12], R. Iwai[2], T. Iwamoto[2], D. Kaneko[2], K. Kasami[13], P.-R. Kettle[3], B. I. Khazin[10,12], N. Khomutov[14], A. Korenchenko[14], N. Kravchuk[14], T. Libeiro[15], M. Maki[13], N. Matsuzawa[2], S. Mihara[13], M. Milgie[15], W. Molzon[15], Toshinori Mori[2], F. Morsani[1a], A. Mtchedilishvili[3], M. Nakao[2], S. Nakaura[2], D. Nicolò[1a,1b], H. Nishiguchi[13], M. Nishimura[2], S. Ogawa[2], W. Ootani[2], M. Panareo[9a,9b], A. Papa[3], A. Pepino[9a,9b], G. Piredda[7a], A. Popov[10,12], F. Raffaelli[1a], F. Renga[7a], E. Ripiccini[7a,7b], S. Ritt[3], M. Rossella[6a], G. Rutar[3,4], R. Sawada[2], G. Signorelli[1a], M. Simonetta[6a,6b], G. F. Tassielli[9a,9b], Y. Uchiyama[2], M. Usami[2], M. Venturini[1a,1c], C. Voena[7a], K. Yoshida[2], Yu. V. Yudin[10,12], Y. Zhang[15]

1 INFN Sezione di Pisa[a]; Dipartimento di Fisica[b], dell'Università, Largo B. Pontecorvo 3, 56127 Pisa; Scuola Normale Superiore[c], Piazza dei Cavalieri, 56127 Pisa, Italy
2 ICEPP, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
3 Paul Scherrer Institut PSI, 5232 Villigen, Switzerland
4 Swiss Federal Institute of Technology ETH, 8093 Zurich, Switzerland
5 INFN Sezione di Genova[a]; Dipartimento di Fisica[b], dell'Università, Via Dodecaneso 33, 16146 Genoa, Italy
6 INFN Sezione di Pavia[a]; Dipartimento di Fisica[b], dell'Università, Via Bassi 6, 27100 Pavia, Italy
7 INFN Sezione di Roma[a]; Dipartimento di Fisica[b], dell'Università "Sapienza", Piazzale A. Moro, 00185 Rome, Italy
8 Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente dell'Università, Via Roma 56, 53100 Siena, Italy
9 INFN Sezione di Lecce[a]; Dipartimento di Matematica e Fisica[b], dell'Università del Salento, Via per Arnesano, 73100 Lecce, Italy
10 Budker Institute of Nuclear Physics of Siberian Branch of Russian Academy of Sciences, 630090 Novosibirsk, Russia
11 Novosibirsk State Technical University, 630092 Novosibirsk, Russia
12 Novosibirsk State University, 630090 Novosibirsk, Russia
13 KEK, High Energy Accelerator Research Organization 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
14 Joint Institute for Nuclear Research, 141980 Dubna, Russia
15 University of California, Irvine, CA 92697, USA

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Abstract The MEG experiment, designed to search for the $\mu^+ \to e^+\gamma$ decay, completed data-taking in 2013 reaching a sensitivity level of 5.3×10^{-13} for the branching ratio. In order to increase the sensitivity reach of the experiment by an order of magnitude to the level of 6×10^{-14}, a total upgrade, involving substantial changes to the experiment, has been undertaken, known as MEG II. We present both the motivation for the upgrade and a detailed overview of the design of the experiment and of the expected detector performance.

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2 Beam line
3 Target
4 Cylindrical drift chamber
5 Pixelated timing counter
6 LXe photon detector
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8 Trigger and DAQ
9 Expected sensitivity
10 Conclusions
References

Deceased: B. I. Khazin, A. Korenchenko, G. Piredda.

[a] e-mail: paolo.cattaneo@pv.infn.it

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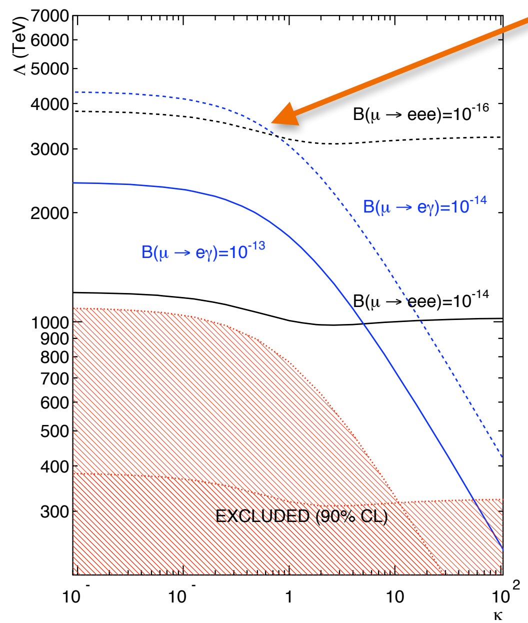
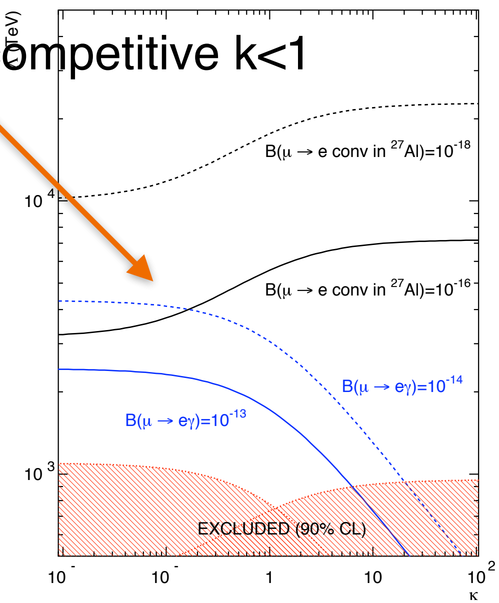
Comparison to Mu2e, Mu3e

Gouvea, Vogel (2013): arXiv:1303.4097

μ → eγ vs μ → 3e



μ → eγ vs μN → eN



MEG 2 competitive k<1

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_R\gamma_\mu e_L \bar{f}\gamma^\mu f$$

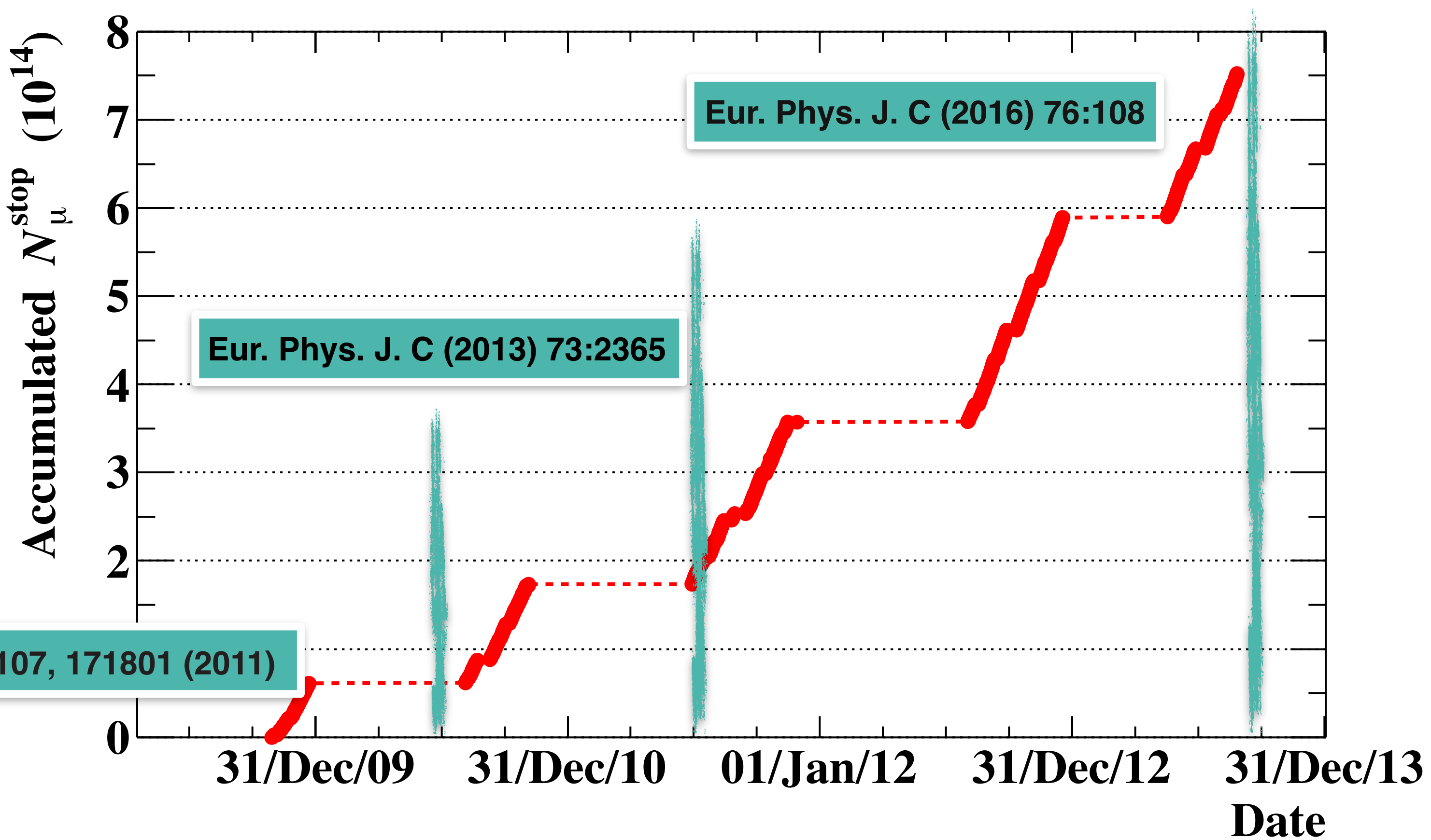
$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_R\gamma_\mu e_L (\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

dipole interaction

μe,μq interaction

Data taking periods MEG

- Data taking during 2009-2013



Calibration methods MEG

	Calibration of	Frequency
μ decays	CDCH	Continuously
Mott positrons	CDCH	Annually
Cosmic rays	LXe, LXe-CDCH	Annually
Charge Exchange $p \to n$	LXe	Annually
Radiative μ decay	LXe-pTC	Continuously
Proton accelerator	LXe, LXe-pTC	Weekly
Neutron generator	LXe	Weekly
Radioactive source	LXe	Annually
LED	LXe	Continuously
Laser	pTC	Continuously