Status and prospects of charged lepton flavor violation searches with the MEG-II experiment

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on behalf of the MEGII collaboration

The 19th International

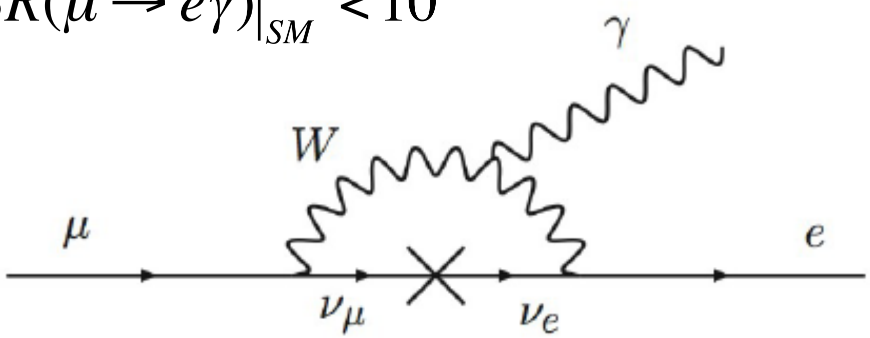
Workshop on Neutrinos from Accelerators

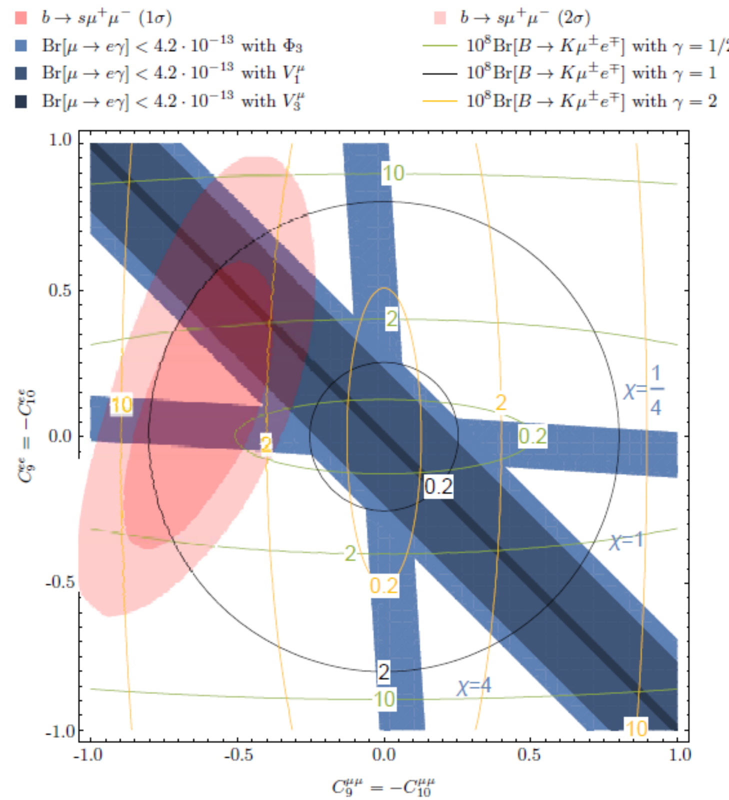
Uppsala University, 25-30 September 2017

Charged lepton flavor violation

- Allowed but unobservable in the Standard Model (with neutrino mass ≠0)

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



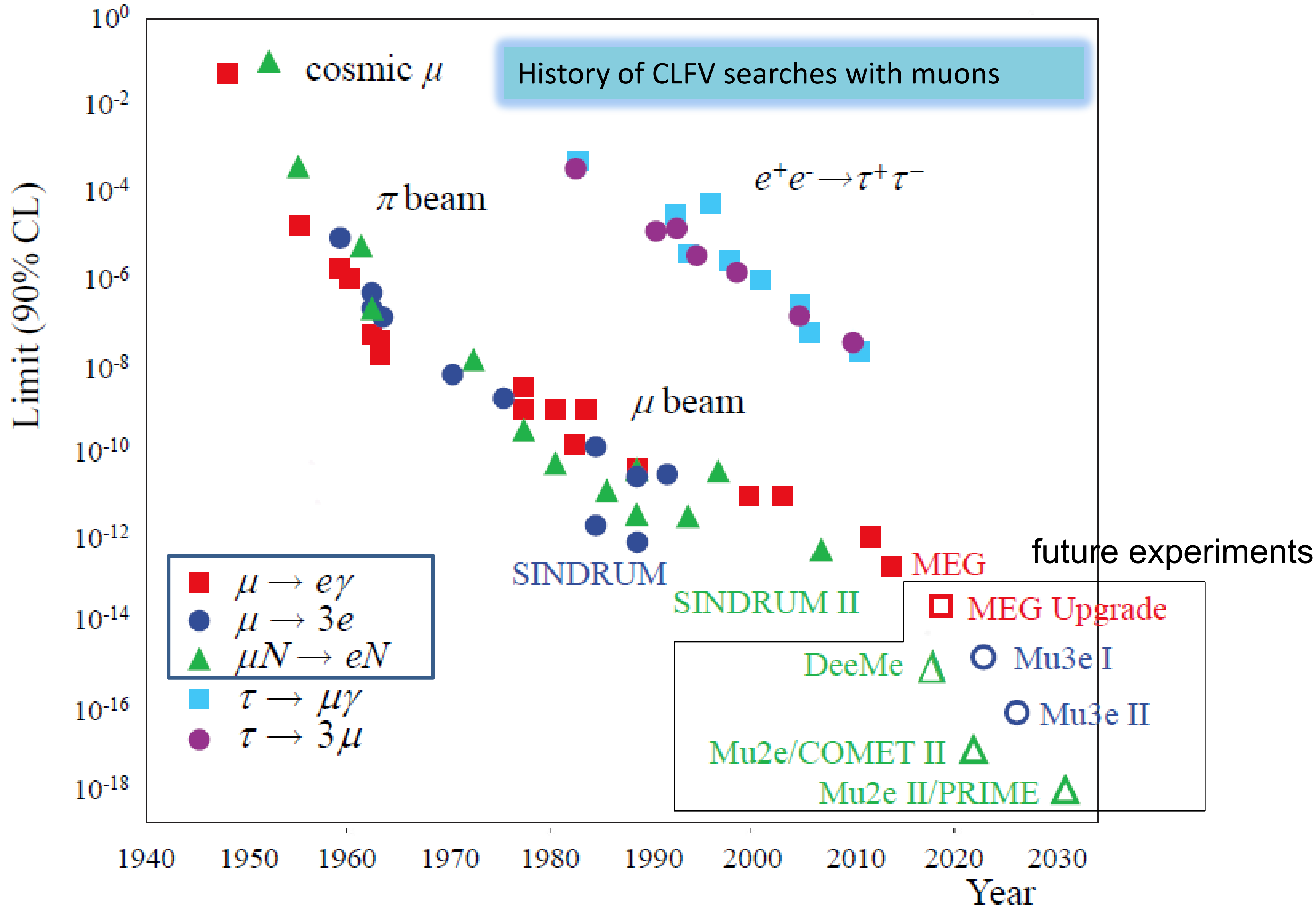


- Enanched, sometimes just below the experimental limit, in many New Physics models

Crivellin et. al.
arXiv:1706.08511

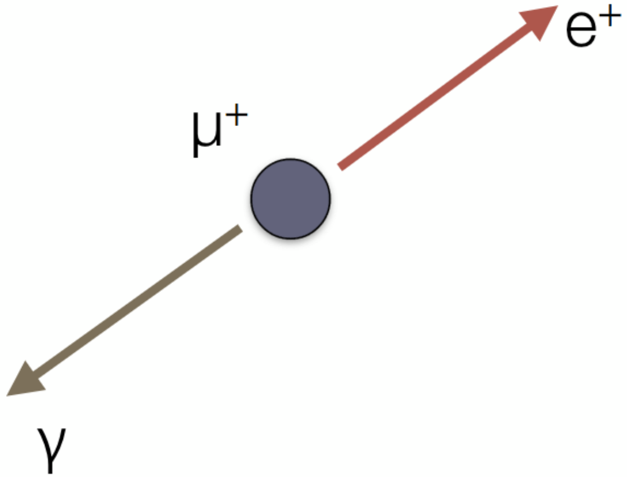
Observation of CLFV is a clean signal of Physics beyond the Standard Model

History and future experiments



Why $\mu \rightarrow e\gamma$

- Theoretically can be favored or disfavored vs other CLFV processes depending on the New Physics model
- Intense muon beams available:
  PSI presently: up to 10^8 μ/s , future perspectives: 10^9-10^{10} μ/s
- Clean experimental signature
  (positive muon decays at rest)

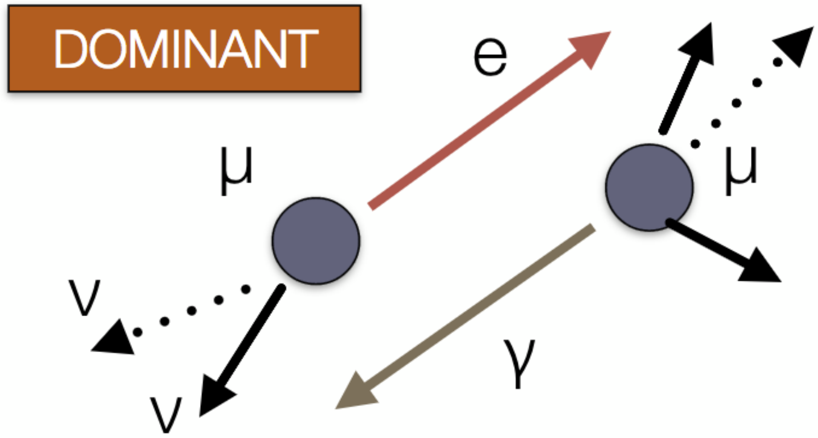


Simultaneous back-to-back e^+ and γ with $E_\gamma = E_{e+} = 52.8$MeV

Discriminating variables:
$E_{e+}, E_\gamma, T_{e\gamma}, \Theta_{e\gamma}$

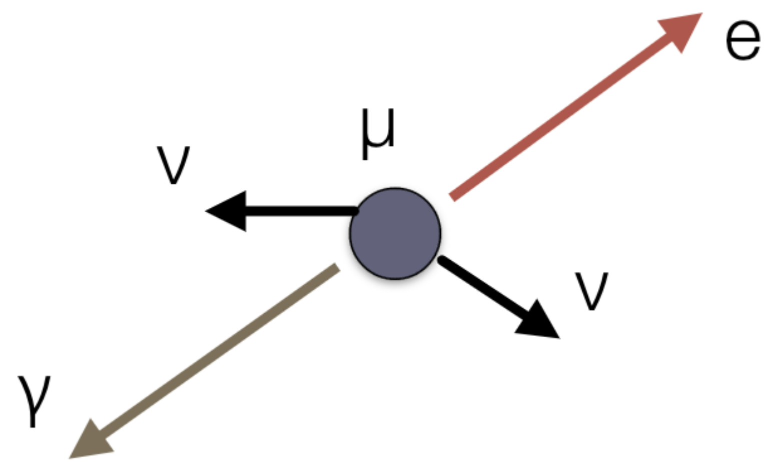
μ→eγ backgrounds

- Accidental background
  - Accidental coincidence of e^+ and γ:
  - Proportional to Γ^2_μ while signal proportional to Γ_μ (Γ_μ= beam intensity)
  - Compromise between high signal and low background



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

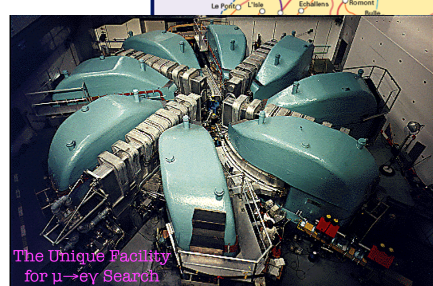
- Radiative muon decay background
  - Proportional to Γ_μ
  - Note: e^+ and γ simultaneous as for signal



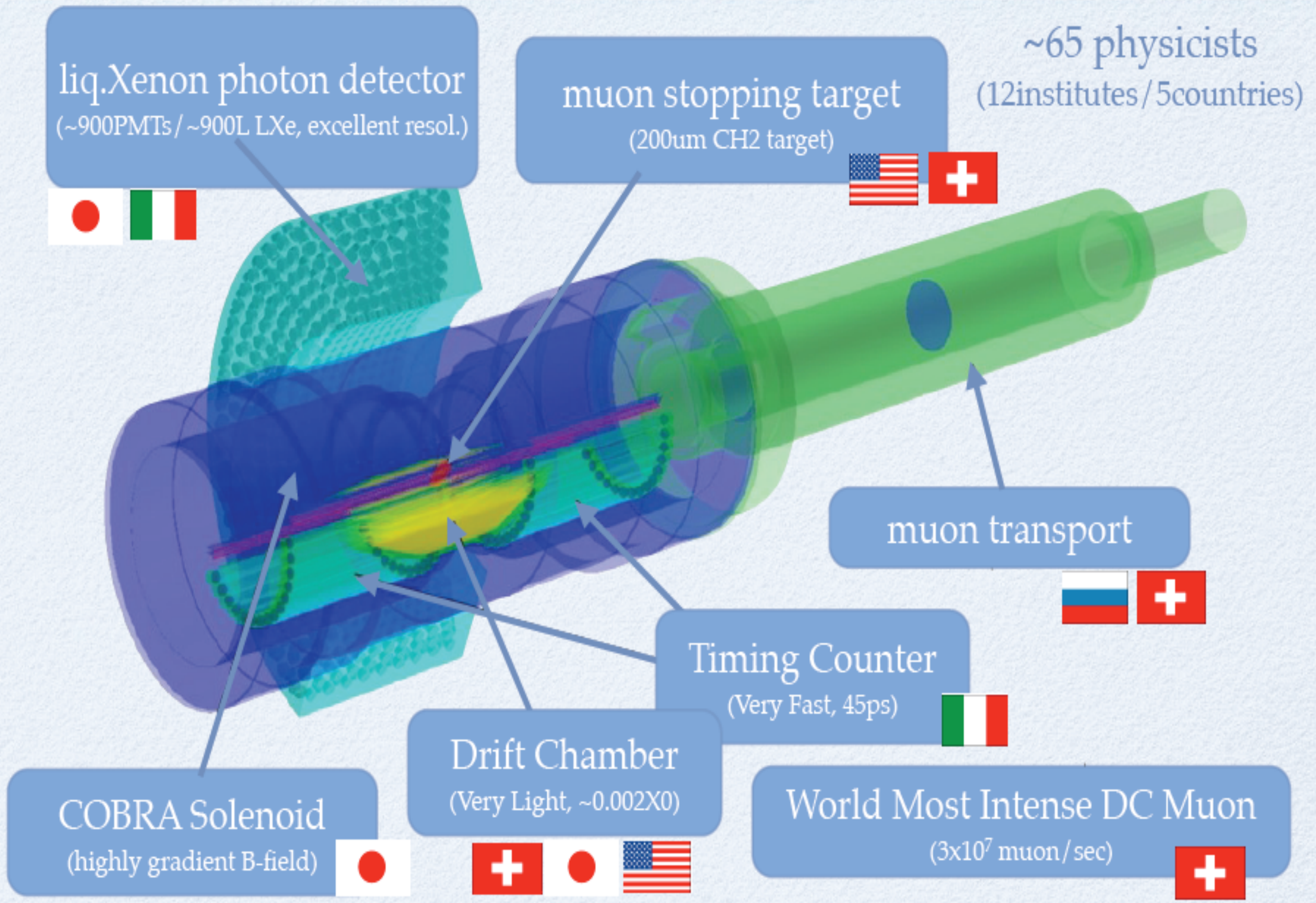
The MEG(II) location: PSI lab

The 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 ($D=15m$, $E_{proton}=590MeV$ $I=2.2mA$)

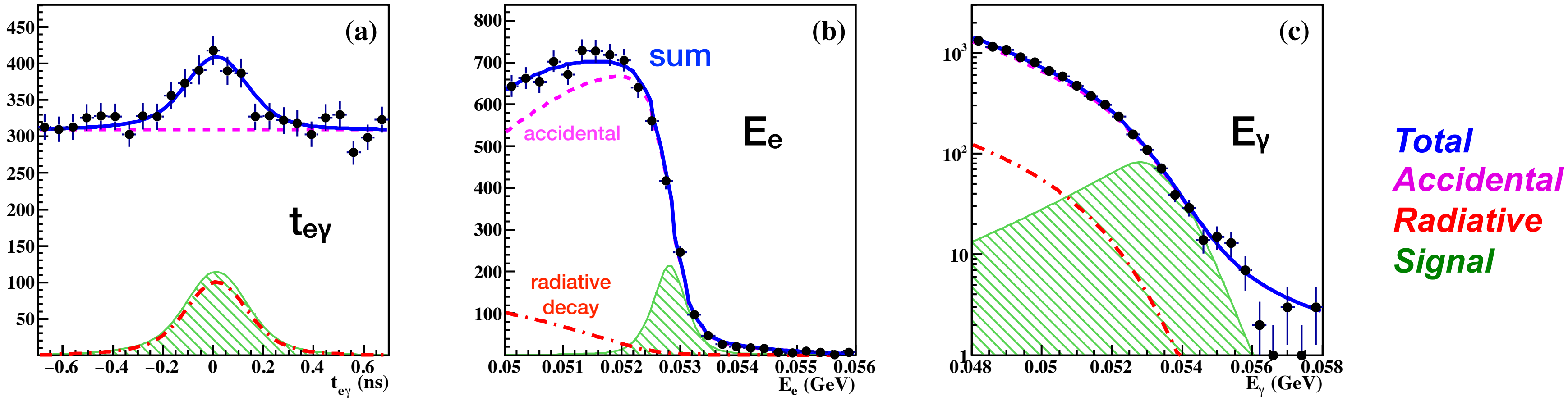


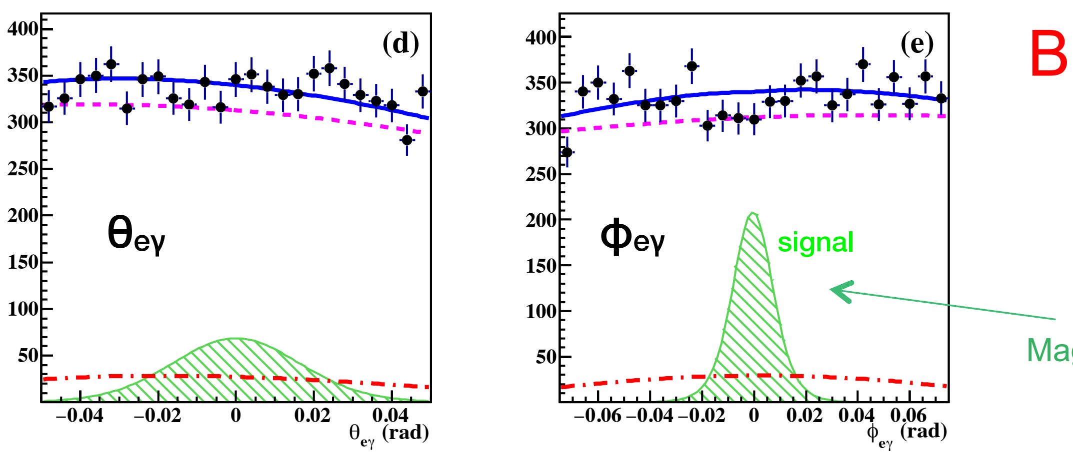
The MEG experiment for μ→eγ search



MEG BR(μ→eγ) limit result

- 7.5×10^{14} stopped muons in 2009-2013
- 5 discriminating variables: E_e, E_γ, $T_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$
- likelihood analysis





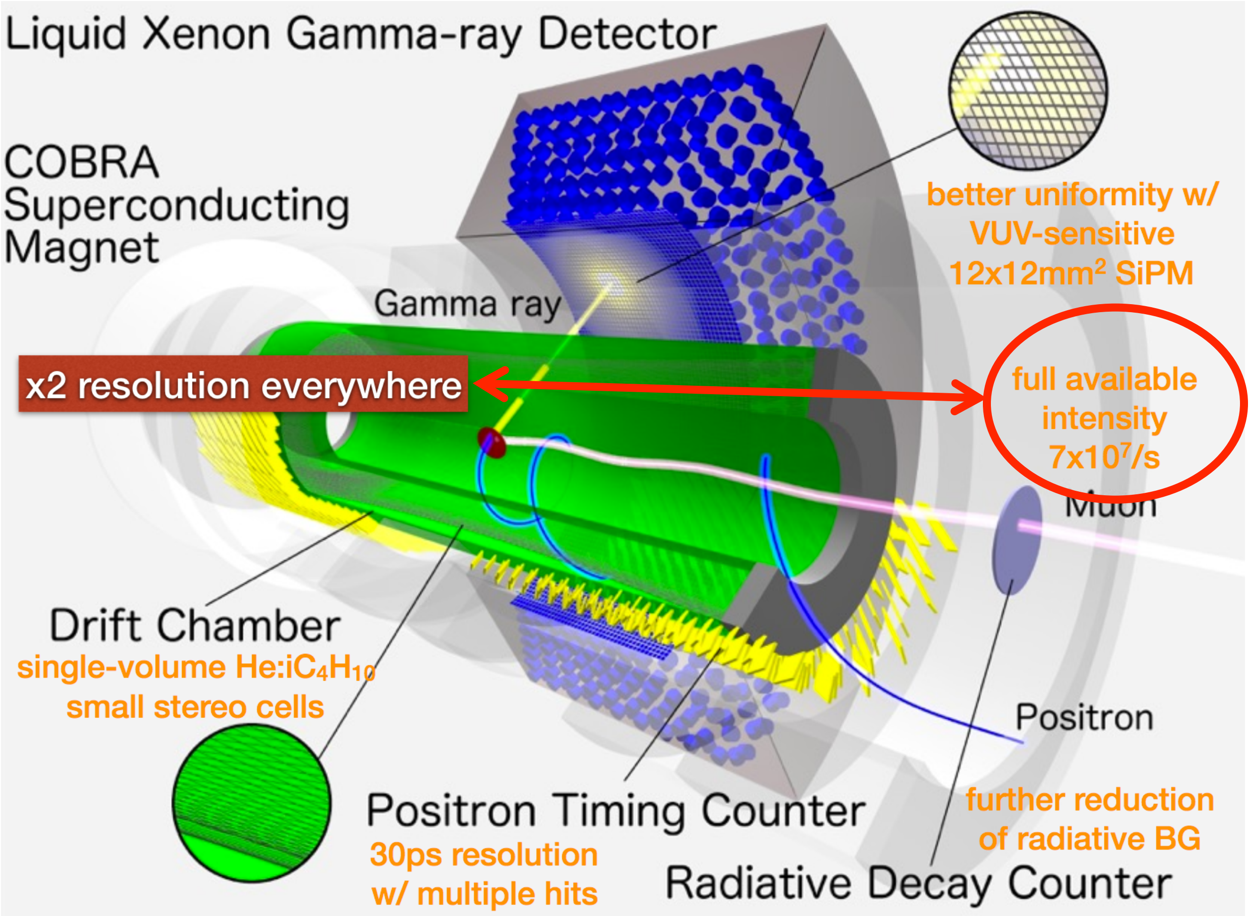
Magnified signal for illustrative purposes

BR (μ→eγ) < 4.2x 10^{-13} at 90% C.L.

Eur.Phys.J.C76 (2016)

Next: MEG upgrade: MEG-II

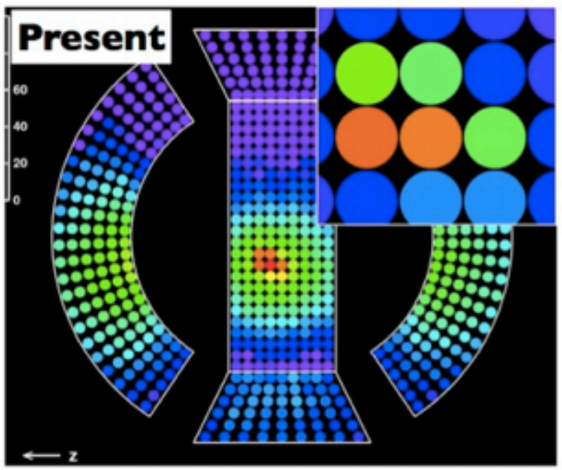
- Extending the search of $\mu \rightarrow e\gamma$ is complementary to New Physics searches at the high energy frontier
- Same detector concept as in MEG

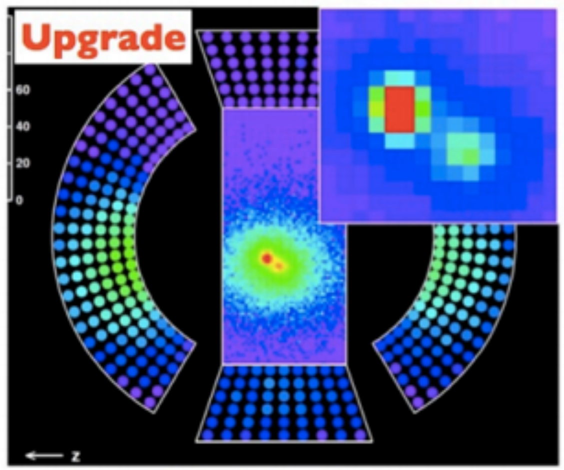


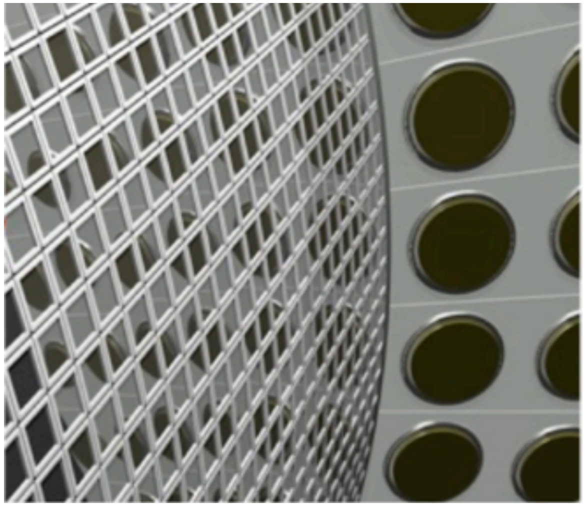
optimized to enhance sensitivity (accidental background prop. to I^2_{μ})

MEG-II detector highlights: Liquid Xenon

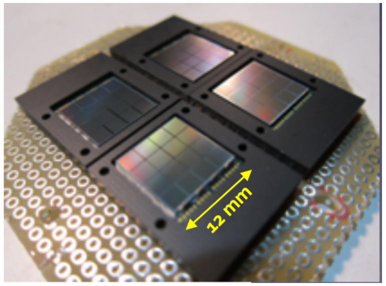
Liquid Xenon Calorimeter with higher granularity in inner face:
=> better resolution, better pile-up rejection







Large UV-ext SiPM

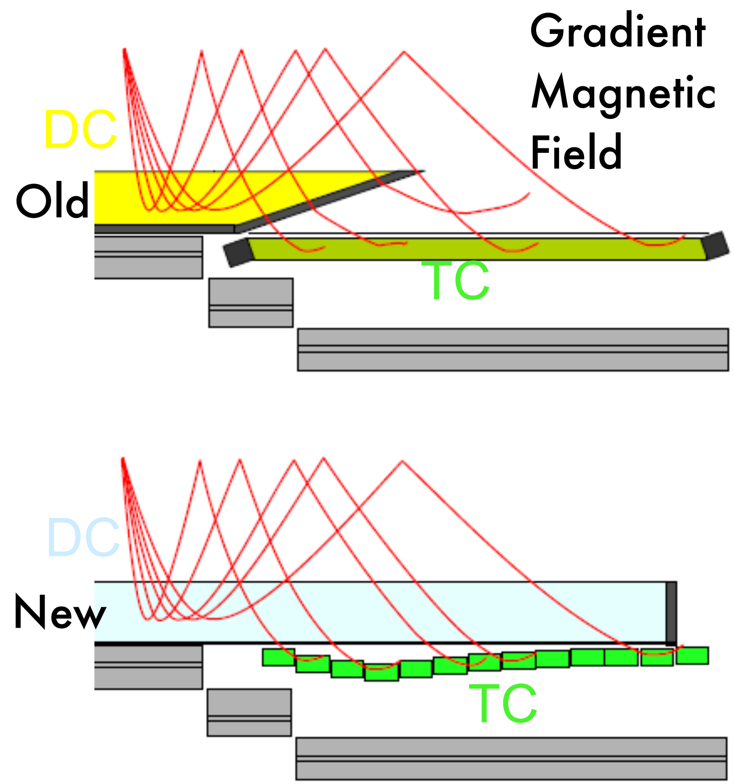


- Developed UV sensitive MPPC
(vacuum UV 12x12mm^2 SiPM)

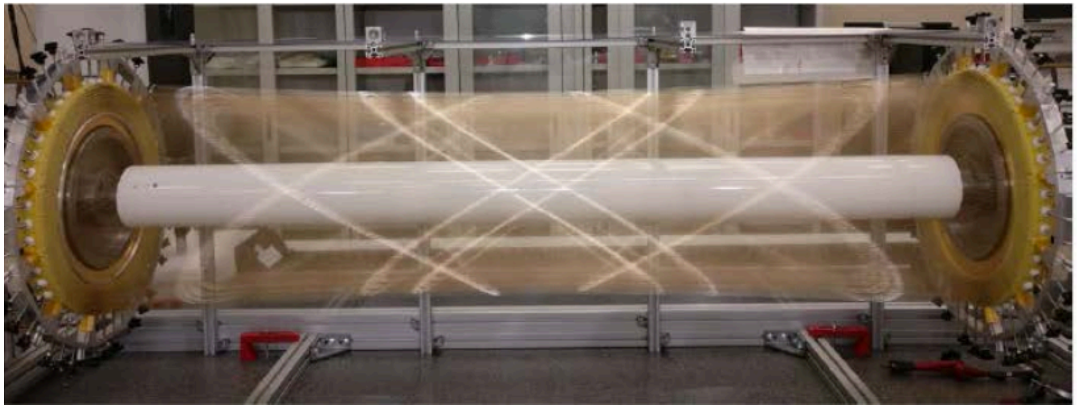
- Detector assembled, filled with LXe
(commissioning on-going, tests during 2017 pre-engineering run)

MEG-II detector highlights: Drift Chamber

- Single volume drift chamber with 2π coverage
  - 2m long
  - 1300 sense wires
  - stereo angle (6°-8°)
  - low mass
  - high trasparency to TC
    (double signal efficiency)



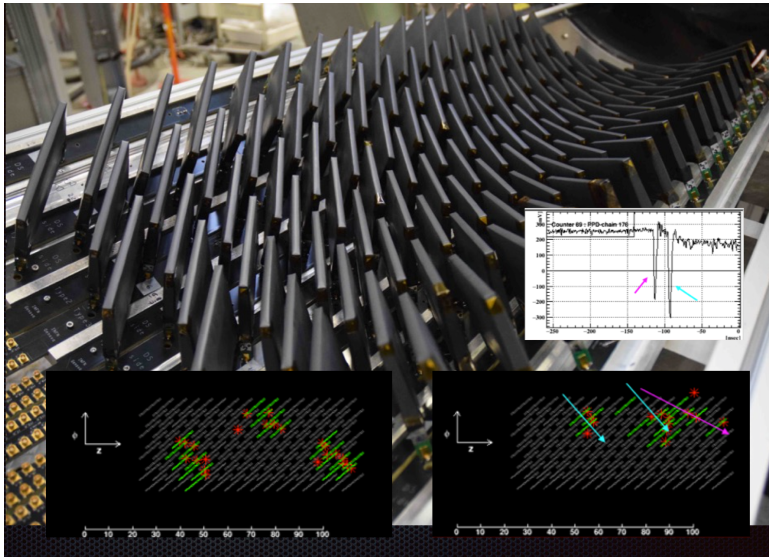
- Assembly: 78% (wiring~70%)
- Will be transported at PSI: Jan 2018

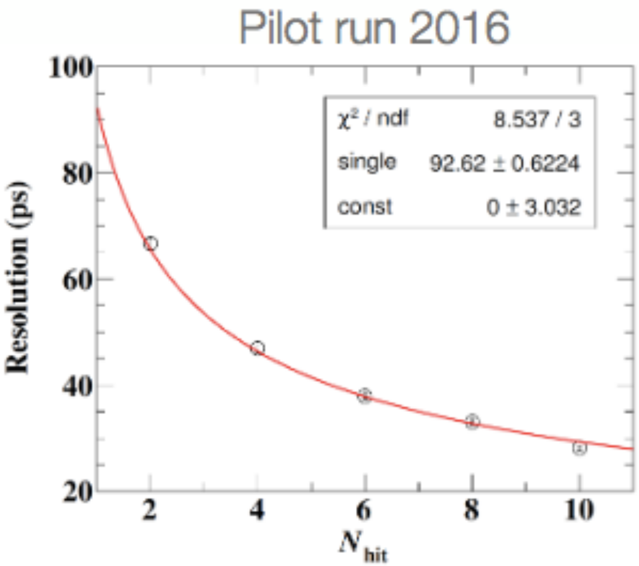


MEG-II detector highlights: Timing Counter

- High granularity: 2 x 256 BC422 scintillator plates read by SiPM

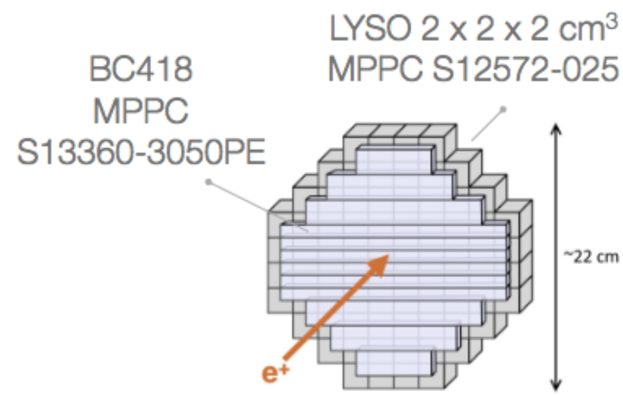
  - improved timing resolution: 35ps (70ps in MEG)
  - Assembly: completed
  - Installation in COBRA in progress
  - Full test during 2017 pre-engineering run
    (expected detector performances already confirmed in data)

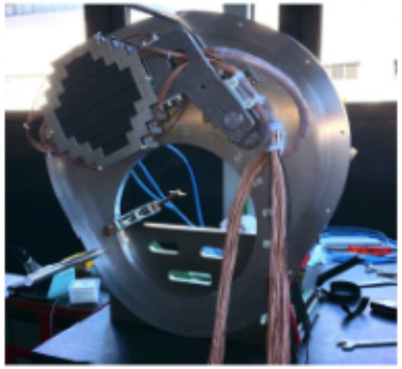


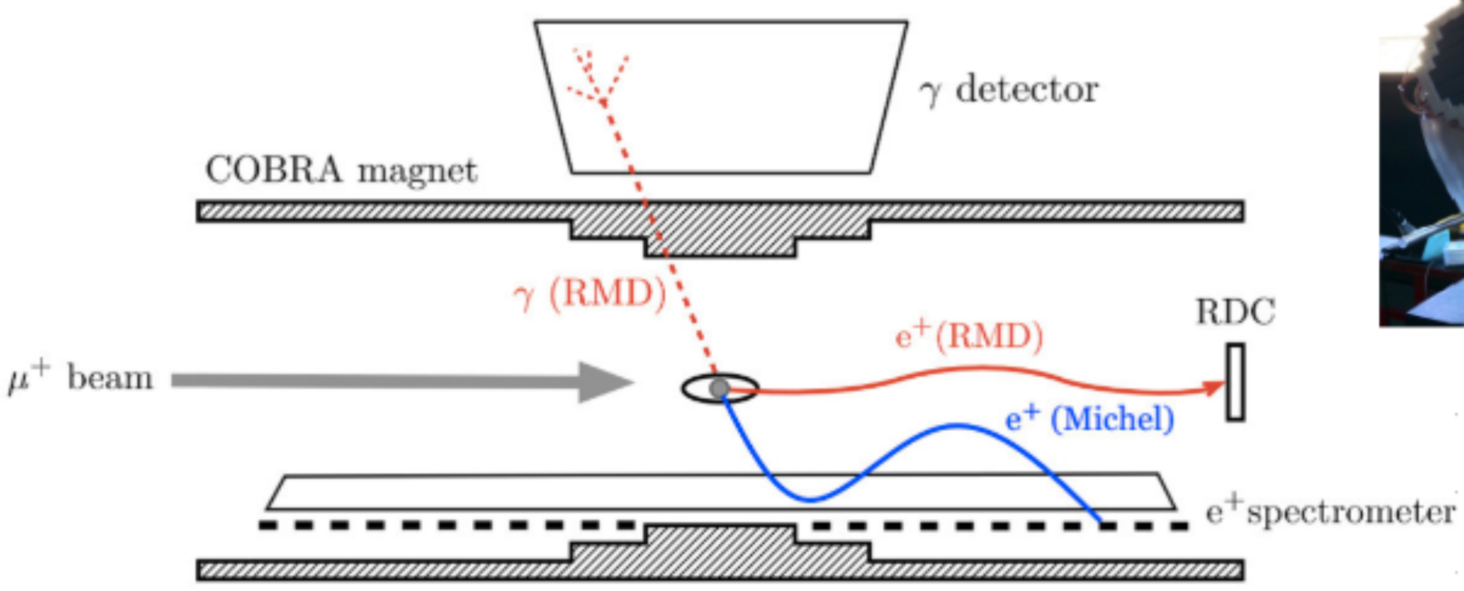


MEG-II detector highlights: Radiative Decay Counter

- New auxiliary detector for background rejection purpose
  => improve sensitivity by 15%
- Commissioned during 2016 run
- Ready for 2017 pre-engineering run





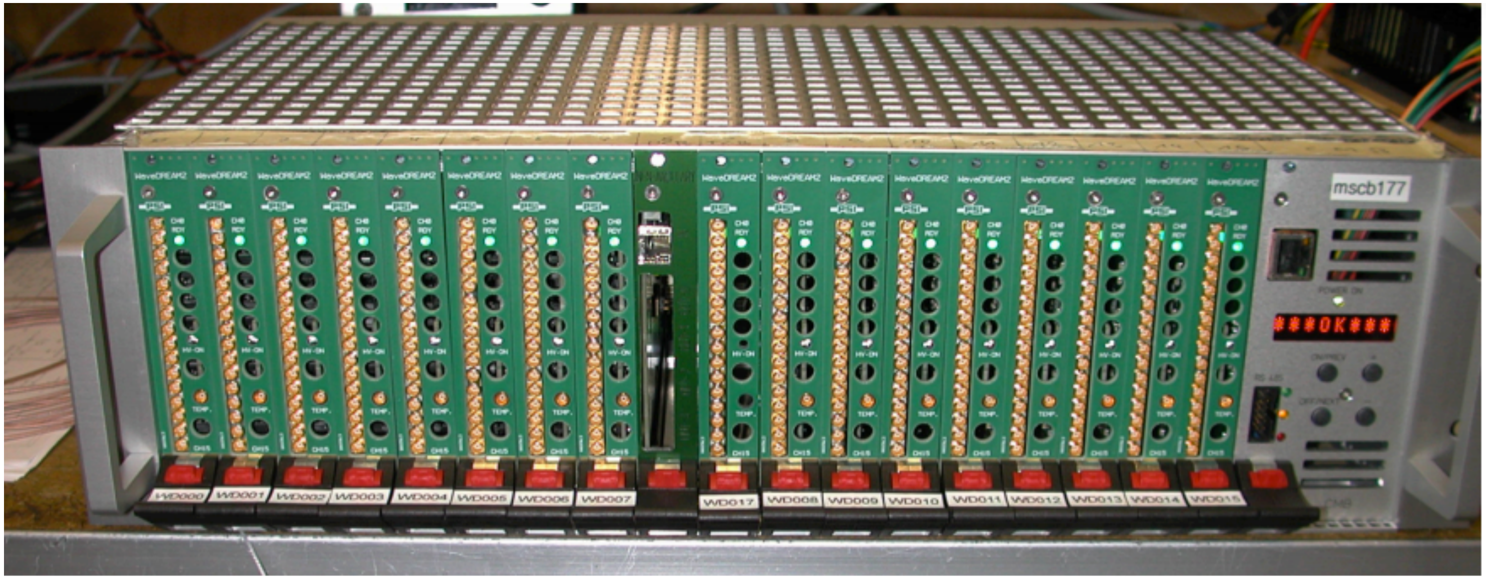


MEG-II new trigger and DAQ system

- New version of DRS (Wavedream) custom digitization board integrating both digitization, triggering and some HV

  - ~9000 channels (5GSPS)
  - 256 channels (1crate) tested during 2016 pre-engineering run
  - > 1000 channels available for the upcoming 2017 pre-engineering run

- Final production expected in winter 2018

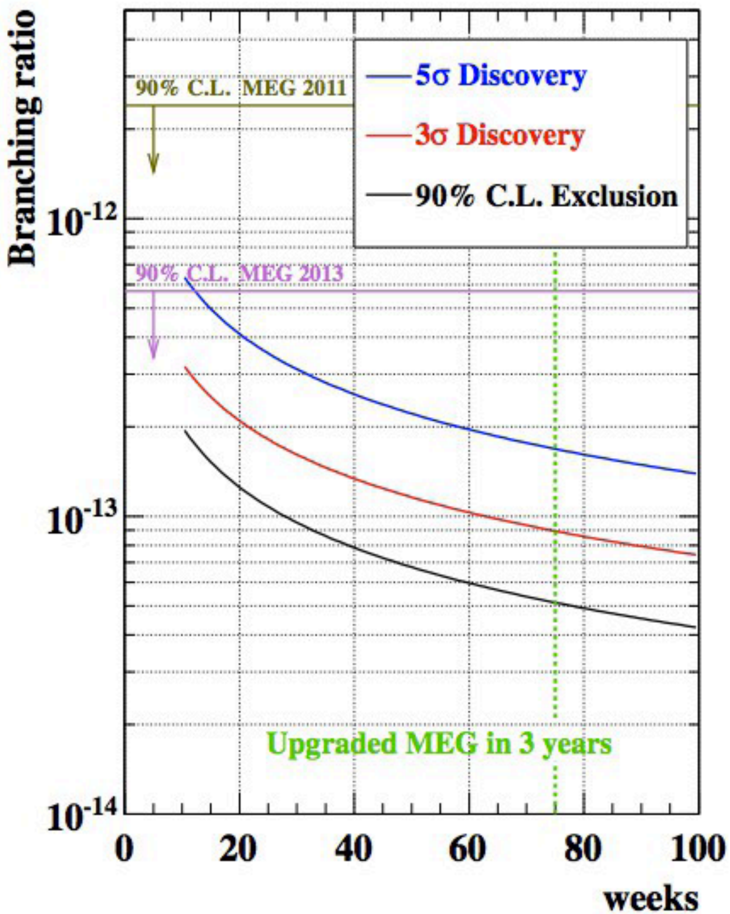


MEG-II goals and schedule

- MEG-II is expected to start taking data with the full detector next year (full engineering run)
- Final sensitivity: 4×10^{-14}

(1 order of magnitude improvement vs MEG)

PDF parameters	MEG	MEG II
E_{e^+} (keV)	380	130
θ_{e^+} (mrad)	9.4	5.3
ϕ_{e^+} (mrad)	8.7	3.7
z_{e^+}/y_{e^+} (mm) core	2.4/1.2	1.6/0.7
E_γ(%) (w >2 cm)/(w <2 cm))	2.4/1.7	1.1/1.0
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.6/2.2/5
$t_{e^+\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	≈ 99	≈ 99
Photon	63	69
e^+ (tracking × matching)	30	70



Next generation of μ→eγ 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

Cavoto et. al.
arXiv:1707.01805
submitted to Eur.Phys J.C.

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

- For a given detector, there is no advantage in the increase of Γ_μ over a certain limit since at some point the sensitivity becomes constant (background dominated regime)

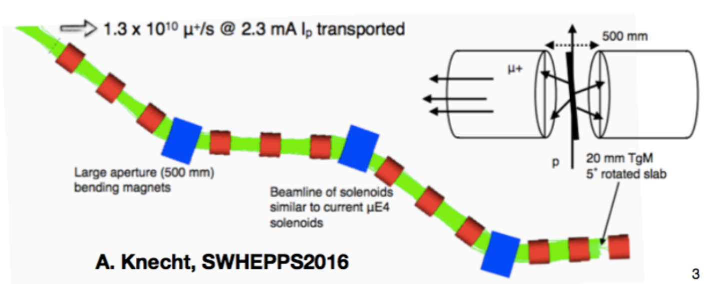
- MEGII, for example exploits 7×10^7 muon/s (available 10^8 muon/s)

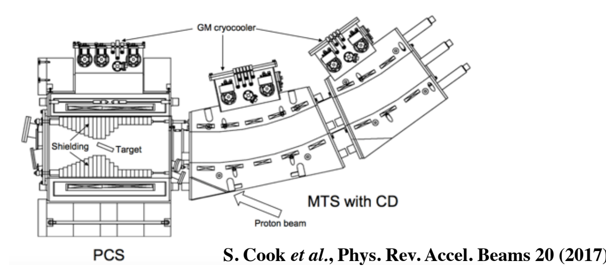
HiMB Project @ PSI

x4 μ capture eff.

x6 μ transport eff.

1.3×10^{10} μ/s





MuSIC Project @ RCNP

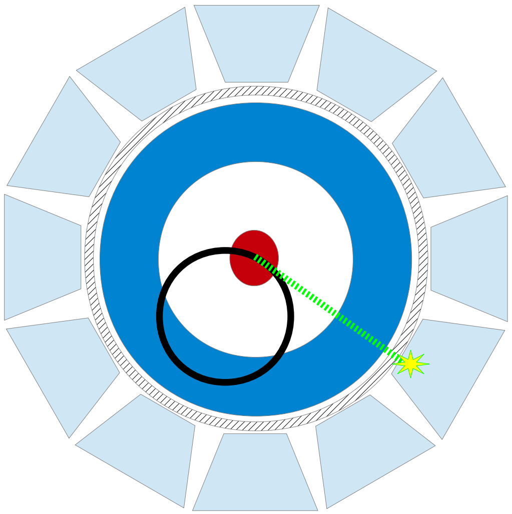
Thick production target

π capture solenoid

4×10^8 μ/s

Next generation of μ→eγ searches: photon

Calorimeter



- high efficiency
- good resolution

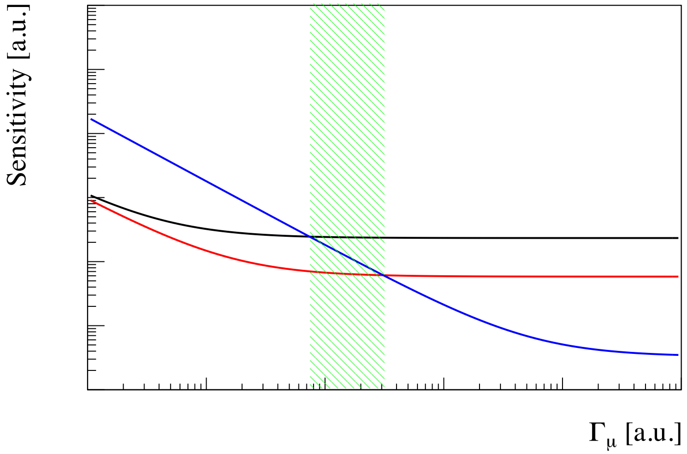
Requirements:
- high light yield
- fast response

Sensitivity trend vs beam intensity

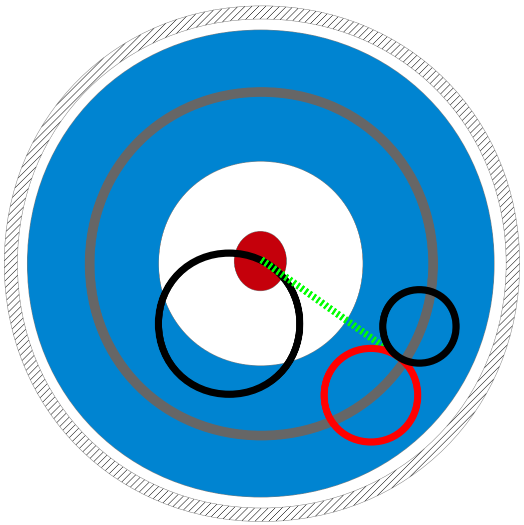
blue = pair conversion design

black = calorimeter design

red = calorimeter design with x2 resolution



Photon conversion



- low efficiency (%)
- extreme resolution
- photon direction

Requirements:
- optimization of converter thickness
(efficiency vs pair energy and angle resolution)

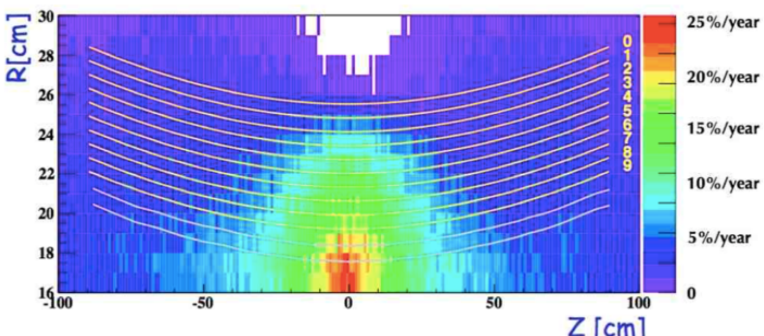
Next generation of μ→eγ searches: positron

- Tracking detectors in a magnetic field are the gold candidates: high efficiency, good resolution

- Need very light detector (MEGII~$10^{-3}X_0$) : positron reconstruction is ultimately limited by MS:

  - in the target & tracker-> angular resolution
  - in the tracker -> momentum resolution

- Silicon trackers are not competitive with gaseous detector in terms of resolution but could be the solution at very high rate

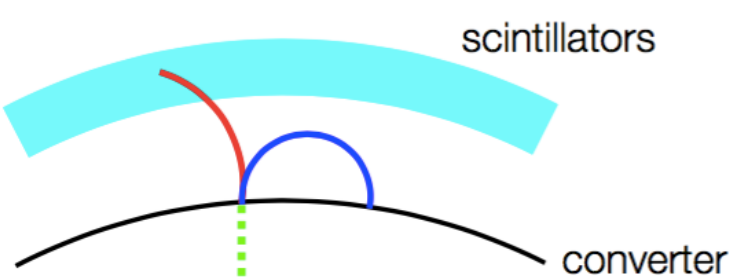


expected aging in MEG-II DCH

A. Baldini et al., MEG Upgrade Proposal, arXiv:1301:7225

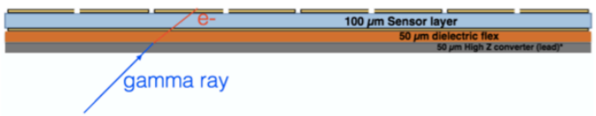
Next generation of μ→eγ searches: relative time

- Timing plays a crucial role to avoid accidental coincidences
- Calorimetric approach: calorimeters+positron scintillating counters (MEG-II: $T_{e\gamma}$~80ps)
- Photon conversion approach: need to measure e^+ or e^- time with a fast detector for photon timing
- Several conversion layers imply to have active material behind the converter



FAST SILICON DETECTORS

- R&D on going for PET application (**TT-PET**)



M. Benoit et al., JINST 11 (2016) no. 03, P03011

Next generation of $\mu \rightarrow e\gamma$ searches: possible scenarios

CALORIMETRY (R&D with $LaBr_3(Ce)$)

Variable	Resolution				
	w/o vtx detector	*w/ TPC vtx detector*		*w/ silicon vtx detector*	
		conservative	optimistic	conservative	optimistic
$\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad]	7.3 / 6.2	6.1 / 4.8	3.5 / 3.8	8.0 / 7.4	6.3 / 6.9
$T_{e\gamma}$ [ps]			30		
E_e [keV]			100		
E_γ [keV]			850		
Efficiency [%]			42%		

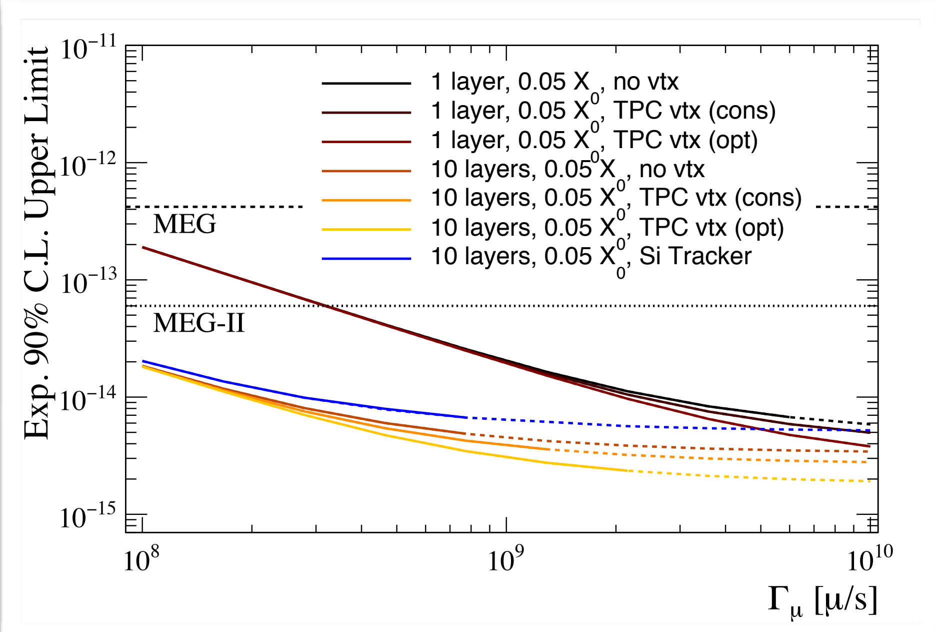
gaseous
detector

PHOTON CONVERSION

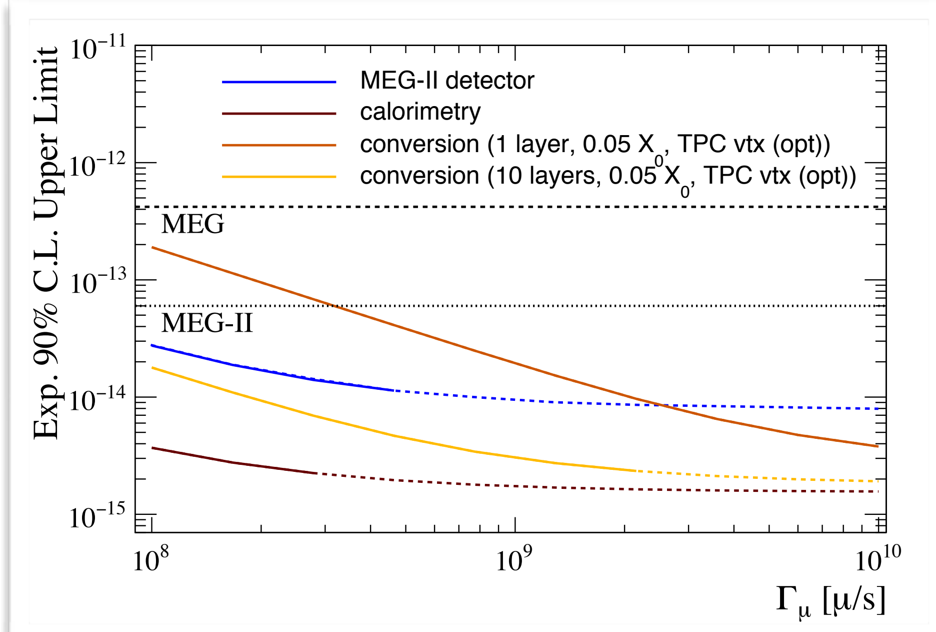
Variable	Resolution				
	w/o vtx detector	*w/ TPC vtx detector*		*w/ silicon vtx detector*	
		conservative	optimistic	conservative	optimistic
$\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad]	7.3 / 6.2	6.1 / 4.8	3.5 / 3.8	8.0 / 7.4	6.3 / 6.9
$T_{e\gamma}$ [ps]			50		
E_e [keV]			100		
E_γ [keV]			320		
Efficiency [%]			1.2 **(1 LAYER, 0.05 X_0)**		

Expected sensitivity

Photon conversion approach



Photon conversion vs calorimetric approach



A few 10^{-15} level seems to be within reach for 3 years running at 10^{8} muon/s with calorimetry or 10^{9} muons/s with photon conversion

Conclusion

- Best constraint on the $\mu \to e\gamma$ decay set by the MEG experiment with its final dataset: 7.5×10^{14} stopped μ^+

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

submitted to EPJC

- MEG-II detector is in the construction phase
  - same design of MEG but better resolution and higher beam rate

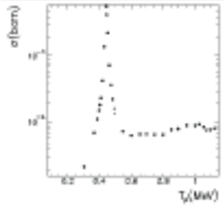
- Engineering run in 2018, sensitivity pushed to $\sim 4 \times 10^{-14}$ in 3 years

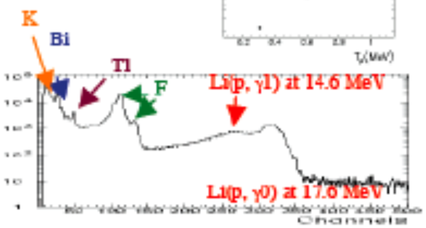
- Ultimate $\mu^+ \to e^+\gamma$?
  - 10^9-10^{10} μ/s seems possible (HiMB,MUSIC..)
  - A few 10^{-15} level seems to be within reach for 3 years running at 10^8 muon/s with calorimetry or 10^9 muons/s with photon conversion approach
  - Further improvements require new detector concepts

Backup

Calibrations

Proton Accelerator





Li(p,γ)Be

LiF target at COBRA center

17.6MeV γ

~daily calib.

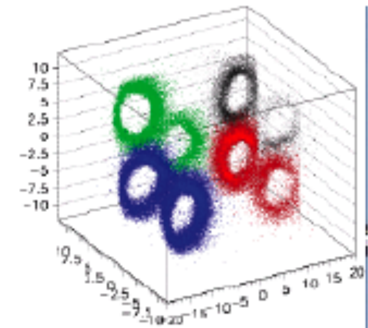
also for initial setup

Alpha on wires

PMT QE & Att. L

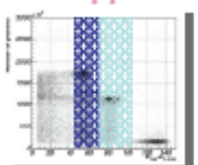
Cold GXe

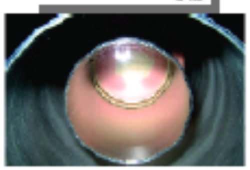
LXe



Xenon Calibration

$\pi^0 \rightarrow \gamma\gamma$



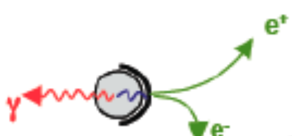


$\pi^- + p \rightarrow \pi^0 + n$

$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

$\pi^- + p \rightarrow \gamma + n$ (129MeV)

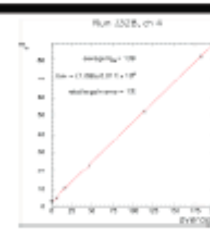
LH_2 target



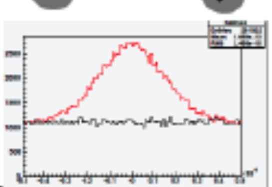
LED

PMT Gain

Higher V with light att.



μ radiative decay



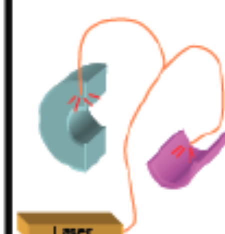
Lower beam intensity < 10^7

Is necessary to reduce pile-ups

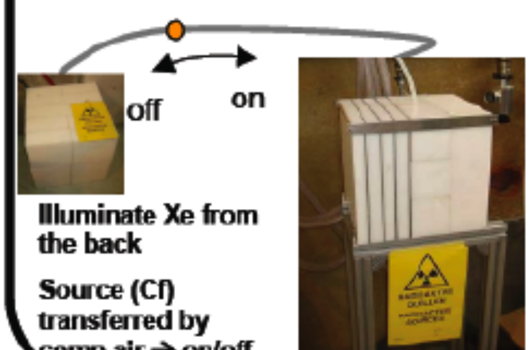
A few days ~ 1 week to get enough statistics

Laser

relative timing calib.

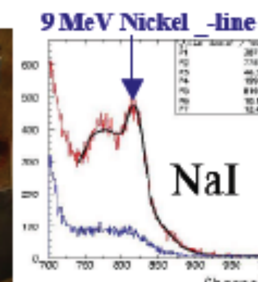


Nickel γ Generator



Illuminate Xe from the back

Source (Cf) transferred by comp air → on/off

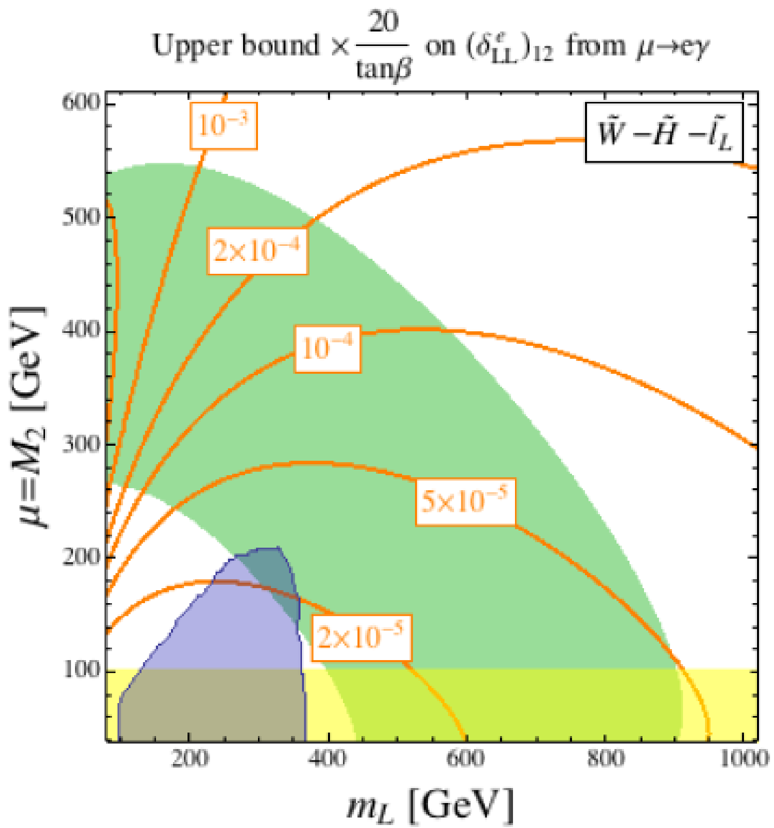


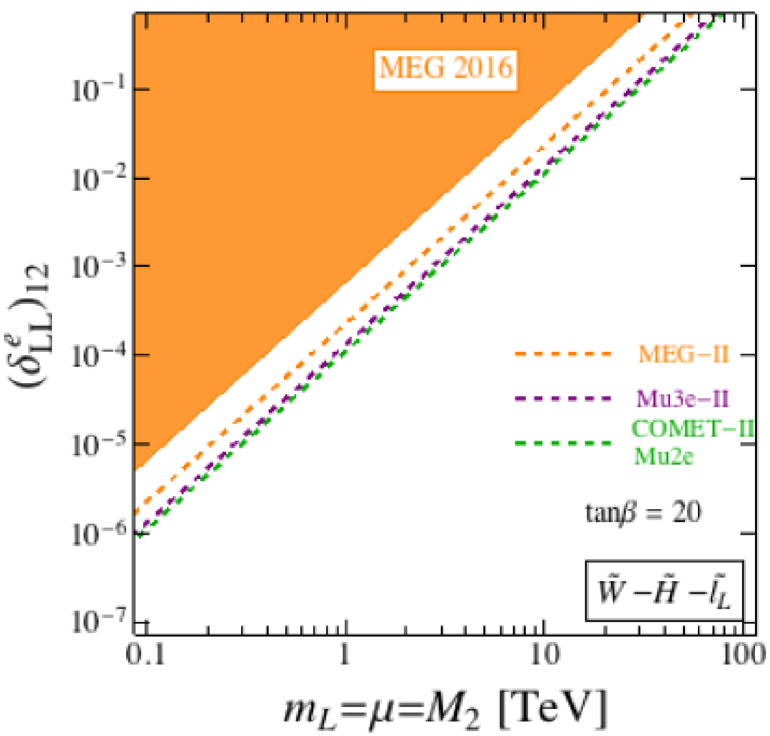
Present CLFV limits

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

Comparison with SUSY searches at LHC

$$(\delta_{\rm LL})_{ij} = \frac{(\Delta_{\rm LL})_{ij}}{\sqrt{(\tilde{m}^2_L)_{ii}(\tilde{m}^2_L)_{jj}}},$$





Calibbi, Signorelli, NC 2017

MEG-II calibrations

Process		Energy	Main Purpose	Frequency
Cosmic rays	$\mu^{\pm}$ from atmospheric showers	Wide spectrum $\mathcal{O}$(GeV)	LXe–CDCH relative position	Annually
			CDCH alignment	
			LXe purity	On demand
Charge exchange	$\pi^- p \rightarrow \pi^0 n$	55, 83, 129 MeV photons	LXe energy scale/resolution	Annually
	$\pi^0 \rightarrow \gamma\gamma$			
Radiative μ–decay	$\mu^+ \rightarrow e^+ \nu\bar{\nu}\gamma$	Photons > 40 MeV,	LXe–pTC relative timing	Continuously
		Positrons > 45 MeV	Normalisation	
Normal μ–decay	$\mu^+ \rightarrow e^+ \nu\bar{\nu}$	52.83 MeV end-point positrons	CDCH energy scale/resolution	Continuously
			CDCH and target alignment	
			pTC time/energy calibration	
			Normalisation	
Mott positrons	e^+ target $\rightarrow e^+$ target	$\approx$ 50 MeV positrons	CDCH energy scale/resolution	Annually
			CDCH alignment	
Proton accelerator	^{7}Li(p, γ)^{8}Be	14.8, 17.6 MeV photons	LXe uniformity/purity	Weekly
	^{11}B(p, γ)^{12}C	4.4, 11.6, 16.1 MeV photons	LXe–pTC timing	Weekly
Neutron generator	^{58}Ni(n, γ)^{59}Ni	9 MeV photons	LXe energy scale	Weekly
Radioactive source	^{241}Am(α, γ)^{237}Np	5.5 MeV α's	LXe PMT/SiPM calibration	Weekly
			LXe purity	
Radioactive source	^{9}Be($\alpha_{^{241}\mathrm{Am}}$, n)^{12}C*	4.4 MeV photons	LXe energy scale	On demand
	^{12}C*(γ)^{12}C			
Radioactive source	^{57}Co(EC, γ)^{57}Fe	136 (11 %), 122 keV (86 %) X-rays	LXe–spectrometer alignment	Annually
LED		UV region	LXe PMT/SiPM calibration	Continuously
Laser		401 nm	pTC inter-counter timing	Continuously