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

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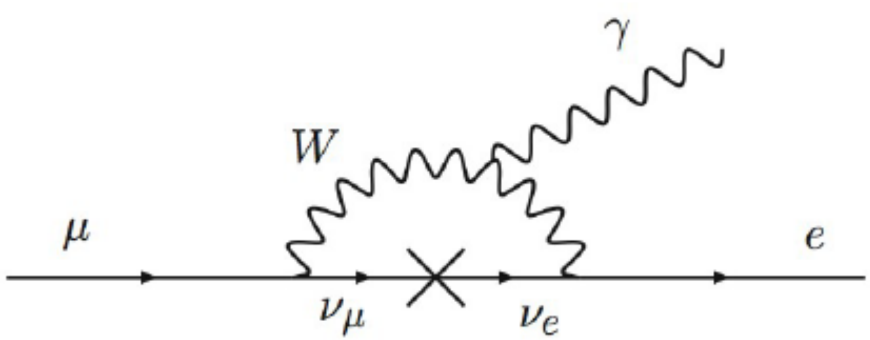
XXV International Symposium
PASCOS 2019
Manchester, 1-5 July 2019

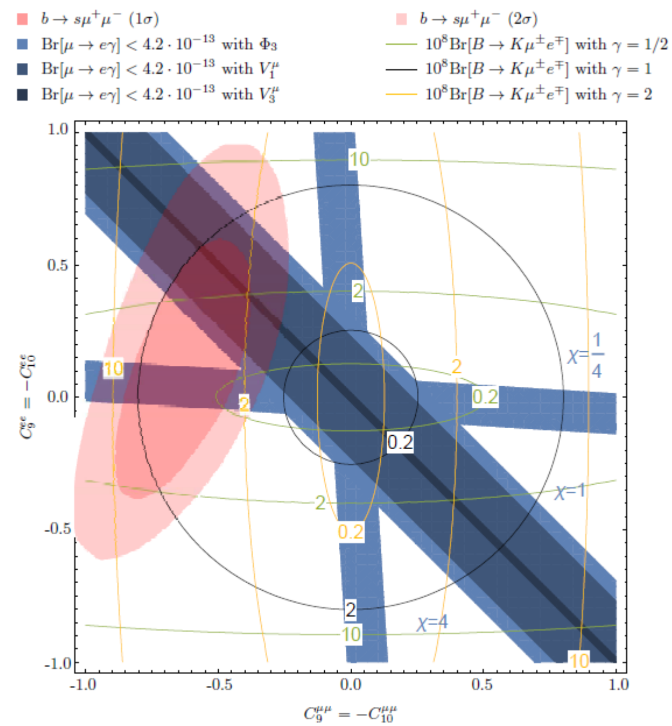
Charged Lepton Flavor Violation (cLFV)

Crivellin et. al.
arXiv:1706.08511

- Allowed but unobservable in the Standard Model (with neutrino mass ≠0), e.g. $\mu \rightarrow e\gamma$

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





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

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

Search for New Physics at the Intensity Frontier

- Probe New Physics at very high energy scales: $\Lambda > 10^2$-10^4 TeV
- Very intense beams are needed
- High intensity frontier: complementarity with high energy frontier (LHC)
- *Flavor is the usual graveyard of BSM EW theory* (European strategy @Granada)
- Muons golden processes

$\mu^+ \to e^+\gamma$ — **MEG-II (PSI)** **=> this talk**

$\mu^+ \to e^+e^+e^-$ — **Mu3e (PSI)**

$\mu^- N \to e^- N$ — **COMET (J-Park)** **Mu2e (Fermilab)**

- Not only muons: τ, EDM...

New Physics Reach

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

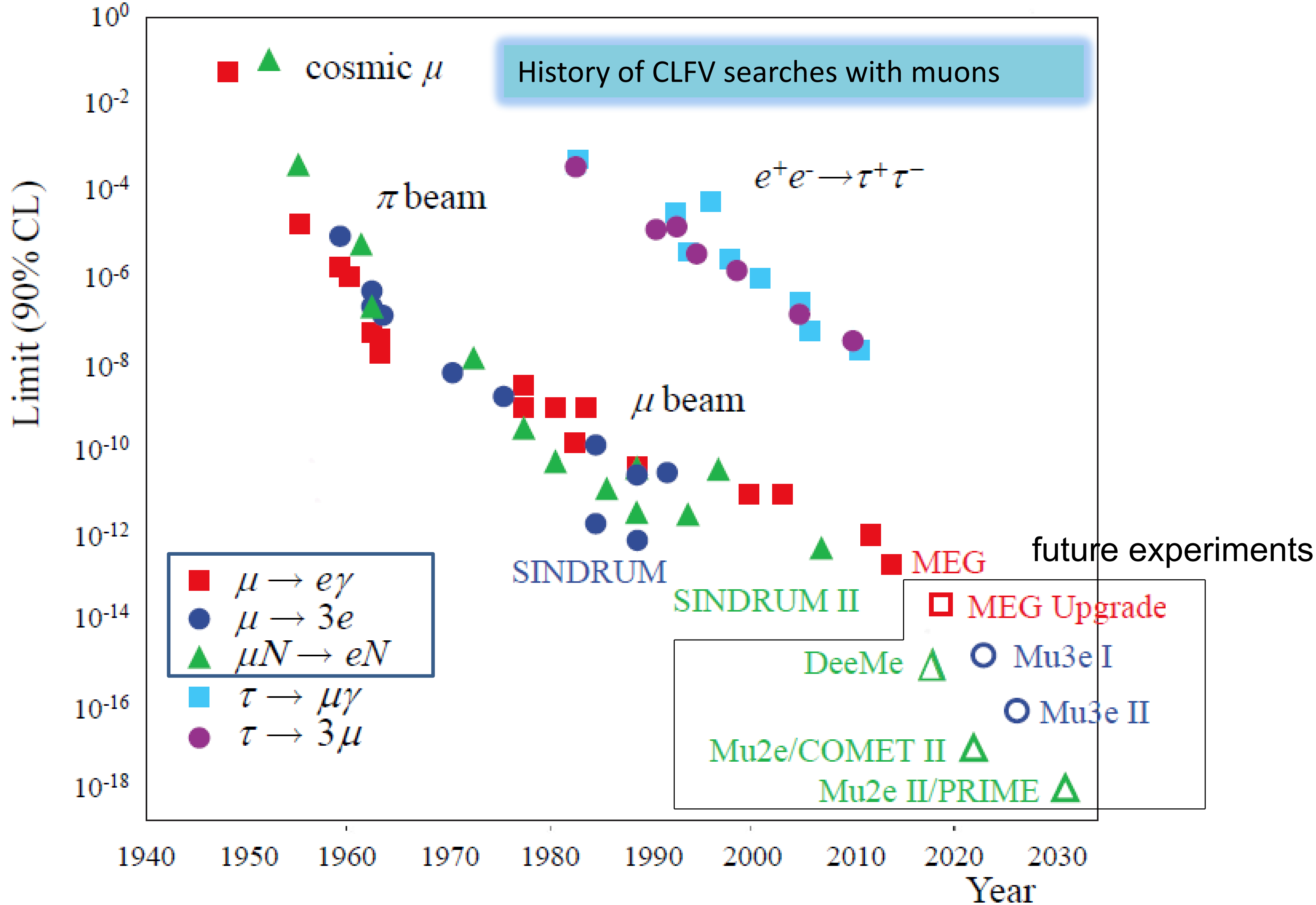
	$\mathrm{Br}(\mu^+ \to e^+\gamma)$		$\mathrm{Br}(\mu^+ \to e^+e^-e^+)$		$\mathrm{Br}^{\mathrm{Au/Al}}_{\mu\to e}$	
	$4.2 \cdot 10^{-13}$	$4.0 \cdot 10^{-14}$	$1.0 \cdot 10^{-12}$	$5.0 \cdot 10^{-15}$	$7.0 \cdot 10^{-13}$	$1.0 \cdot 10^{-16}$
C_L^D	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$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

arXiv:170203020
A. Crivellin et al.

.....

1 column = present best limit
2 column = future limit

History of cLFV Searches



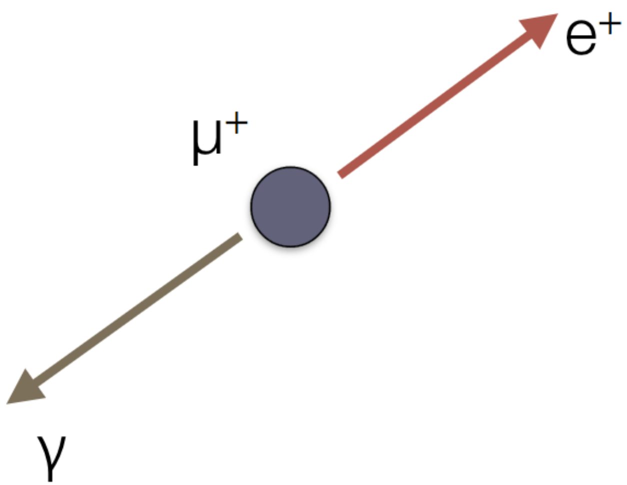
Why $\mu \rightarrow e\gamma$?

- 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, monochromatic
e^+ and γ with $E_\gamma = E_{e+} = 52.8$ MeV

Discriminating variables:

energies: E_{e+}, E_γ
relative time: $T_{e\gamma}$
relative angle: $\Theta_{e\gamma}$

μ→eγ Backgrounds

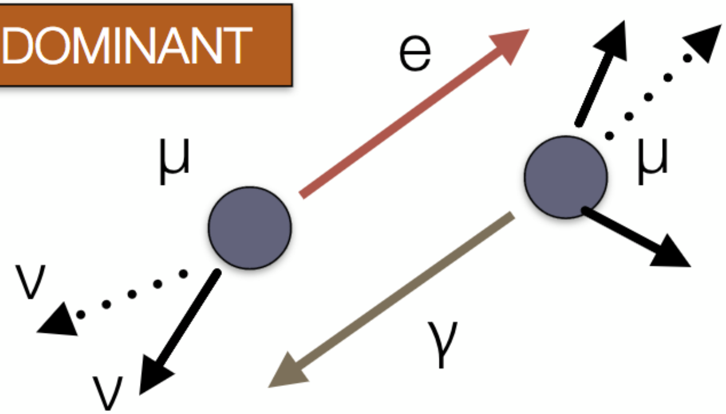
- **Accidental**
  - accidental coincidence of e^+ and γ
  - proportional to Γ^2_μ for given detector resolutions
  - signal proportional to Γ_μ

    (Γ_μ= beam intensity)

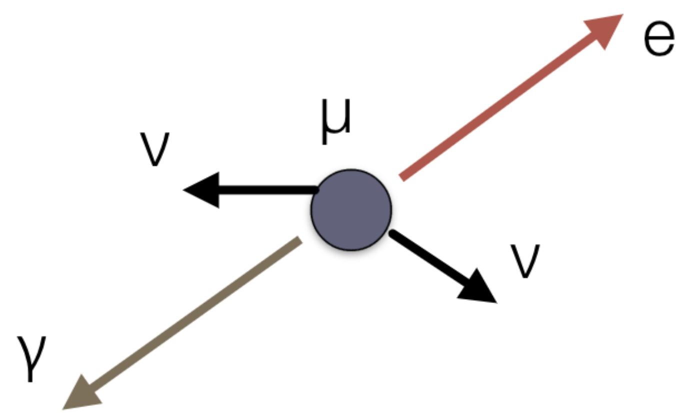
$$B_{\text{acc}} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta \Theta_{e\gamma})^2$$

Michel or radiative decay: μ→e(γ)νν

DOMINANT



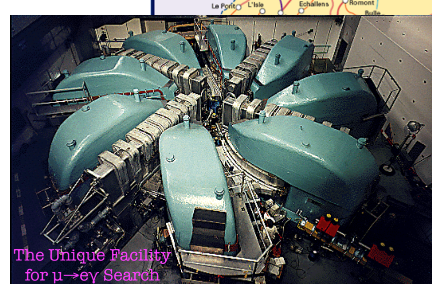
- **Radiative muon decay**
  - proportional to Γ_μ
  - e^+ and γ simultaneous as for signal
  - thus peaking in the $T_{e\gamma}$ variable



The MEG(II) Location: PSI

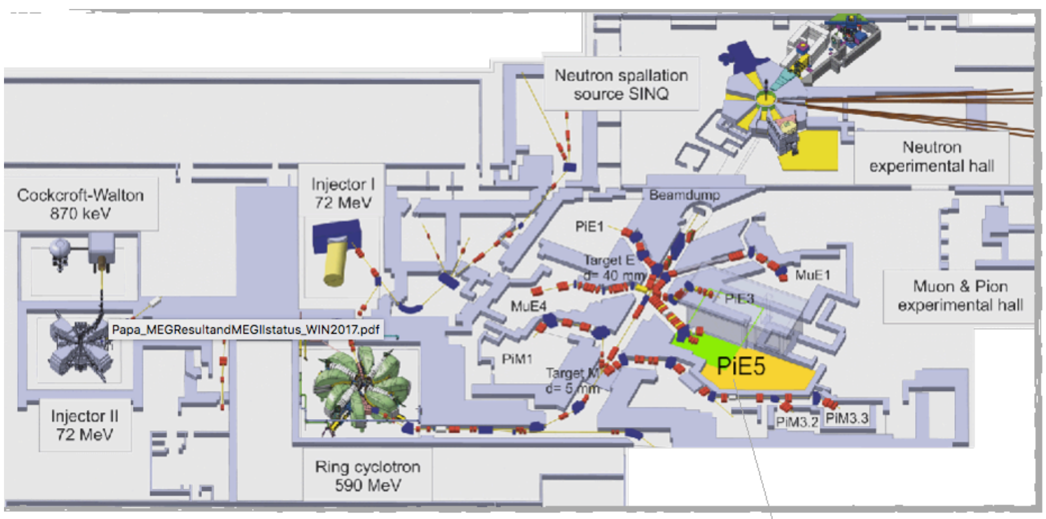
- Paul Scherrer Institute
  - continuous muon beam up to few 10^8 μ^+/s

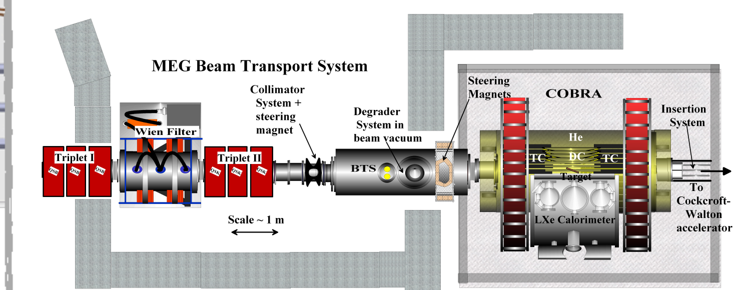
- Multi-disciplinary lab:
  - fundamental research, cancer therapy, muon and neutron sources
  - protons from cyclotron ($D = 15m$, $E_{proton} = 590MeV$ $P = 1.4MW$)



The PSI Surface Muon Beam

- Decay at rest of π^+ on the target surface
- Select positive muons to avoid caputre (P_μ~29 MeV)
- It is possible to focalize and stop the muons in a thin target to reduce multiple scattering of the e^+

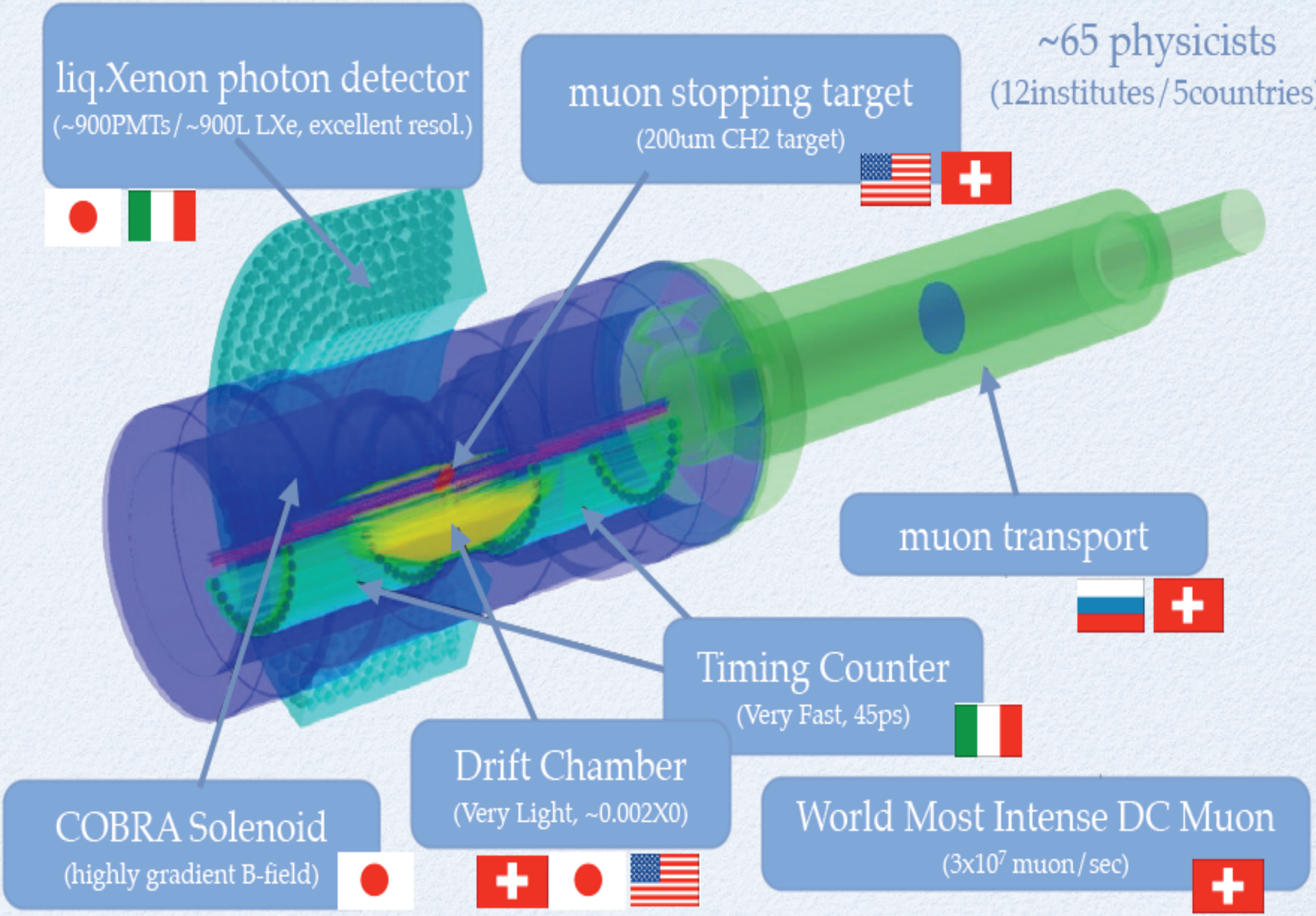




MEGII Experimental area

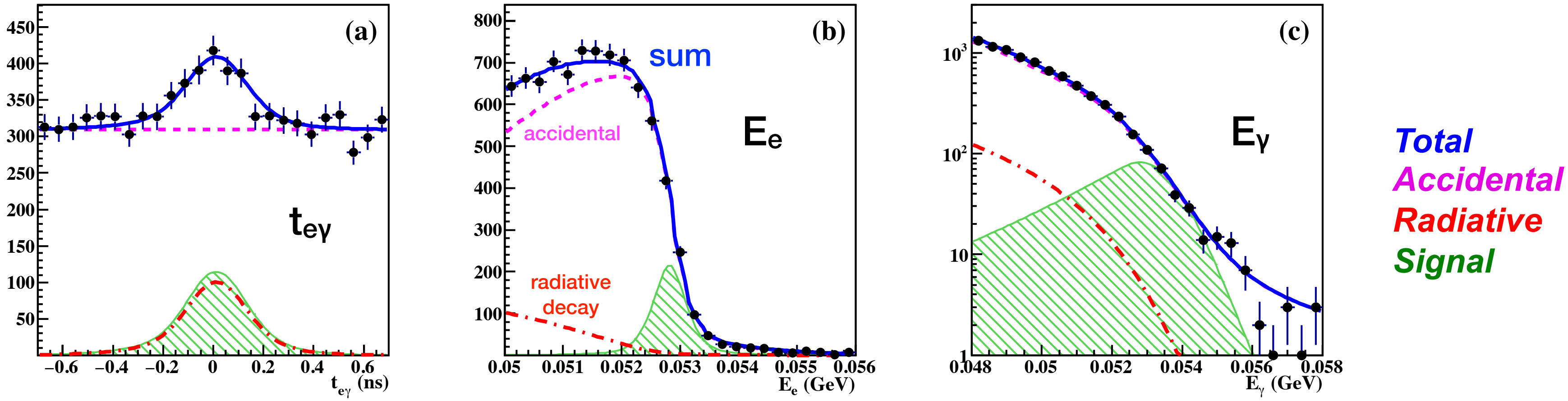
6

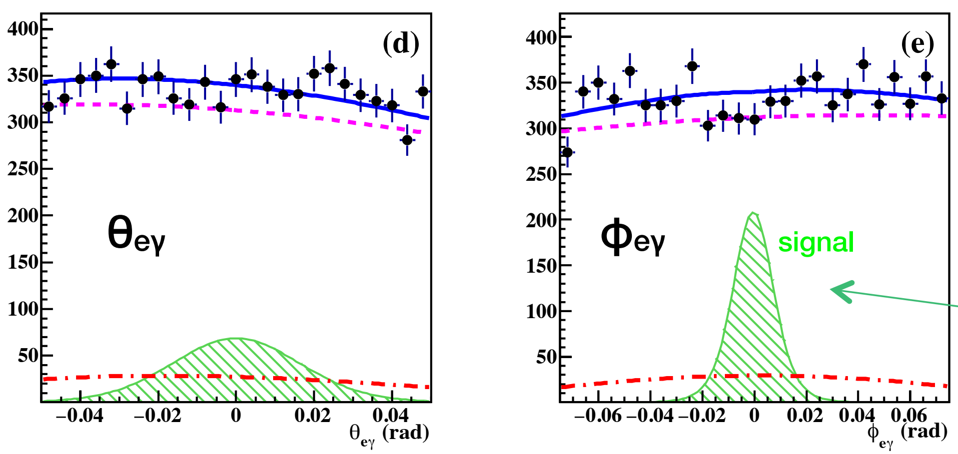
The MEG Experiment for μ→eγ Search



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 + frequentistic approach





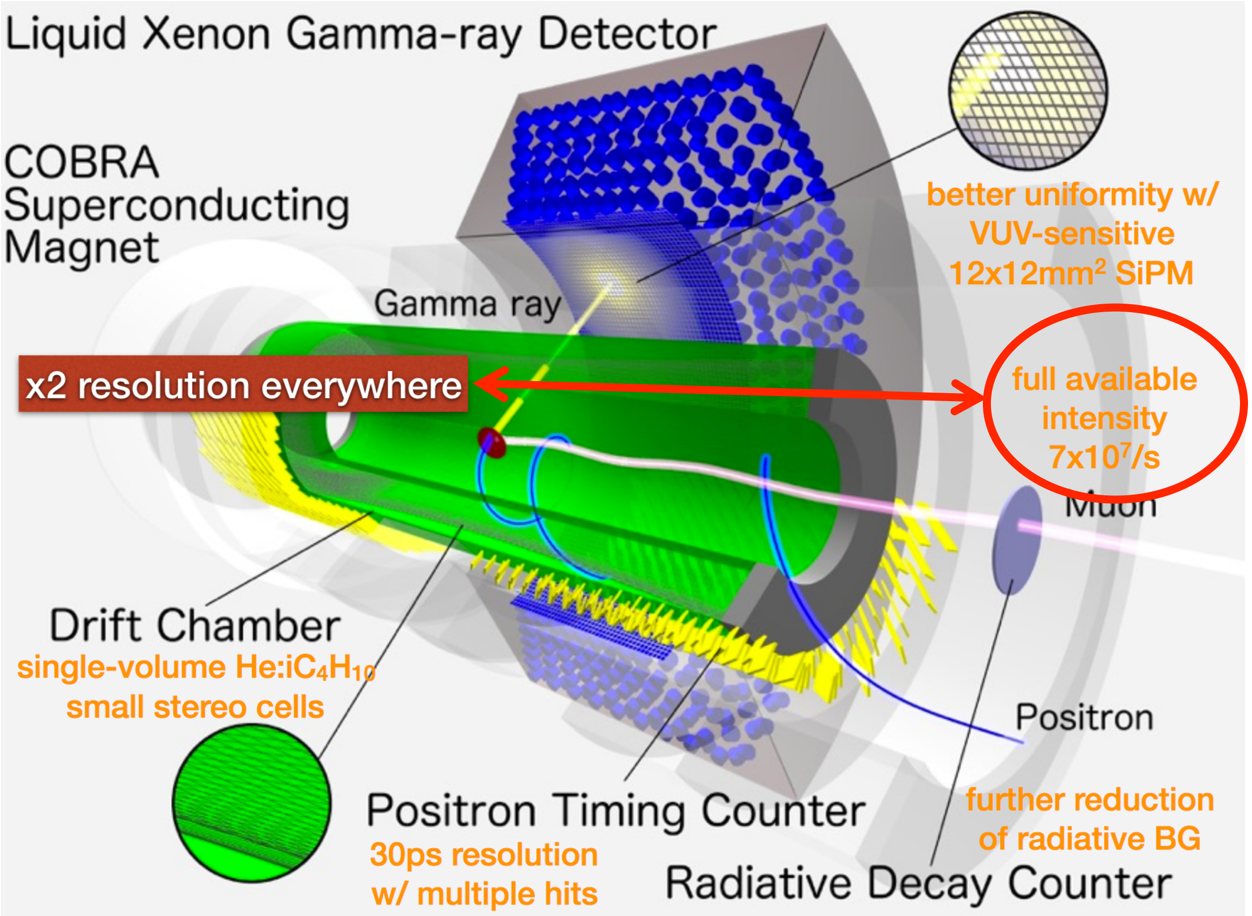
BR (μ→eγ) < 4.2x 10^{-13}
at 90% C.L.

Eur.Phys.J.C76 (2016)

Magnified signal for illustrative purposes
No significant excess of the signal

Next: MEG Upgrade: MEG-II

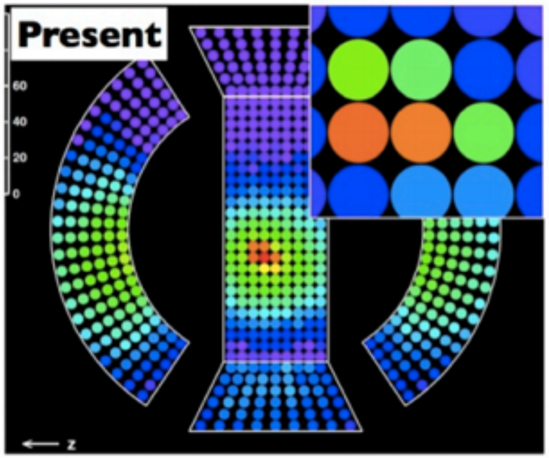
- Same detector concept as in MEG
- Increase beam intensity from 3 x 10^7 μ/s to 7 x 10^7 μ/s
- Cannot exploit full available beam intensity due to accidental background

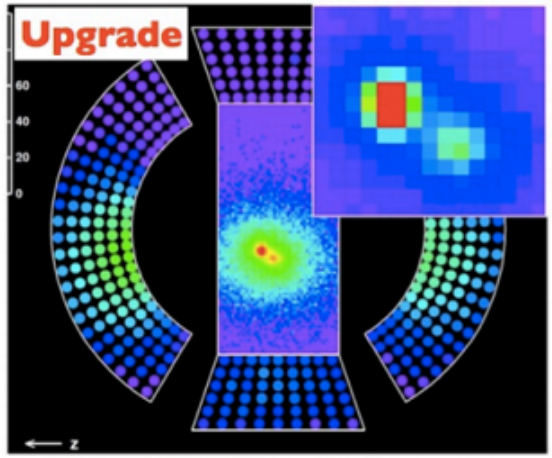


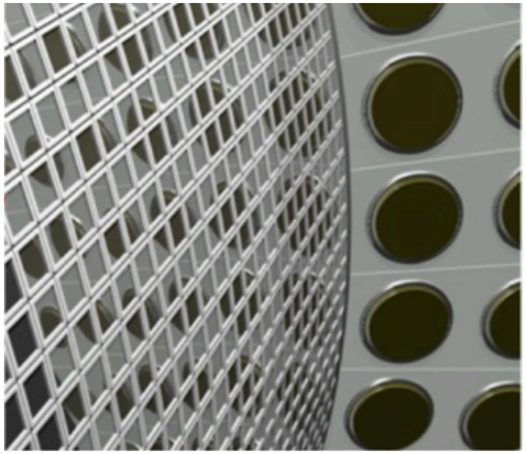
optimized to enhance sensitivity (accidental background prop. to I^2_{μ})

MEG-II Detector Highlights: Liquid Xenon

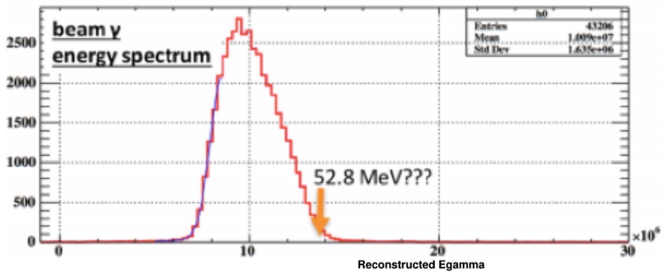
- Liquid Xenon Calorimeter with higher granularity in inner face:
  - better resolution, better pile-up rejection







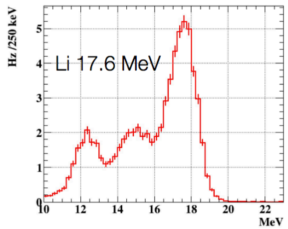
First events/spectra from 2017 data



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

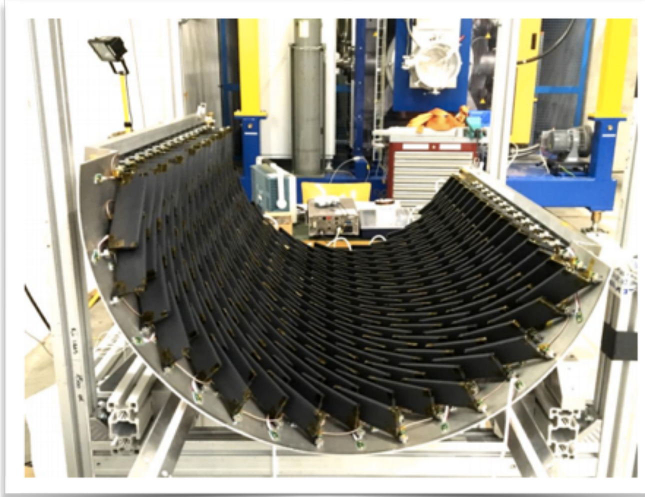
- Commissioned during 2017 and 2018 pre-engineering runs

2018 calibration with CW

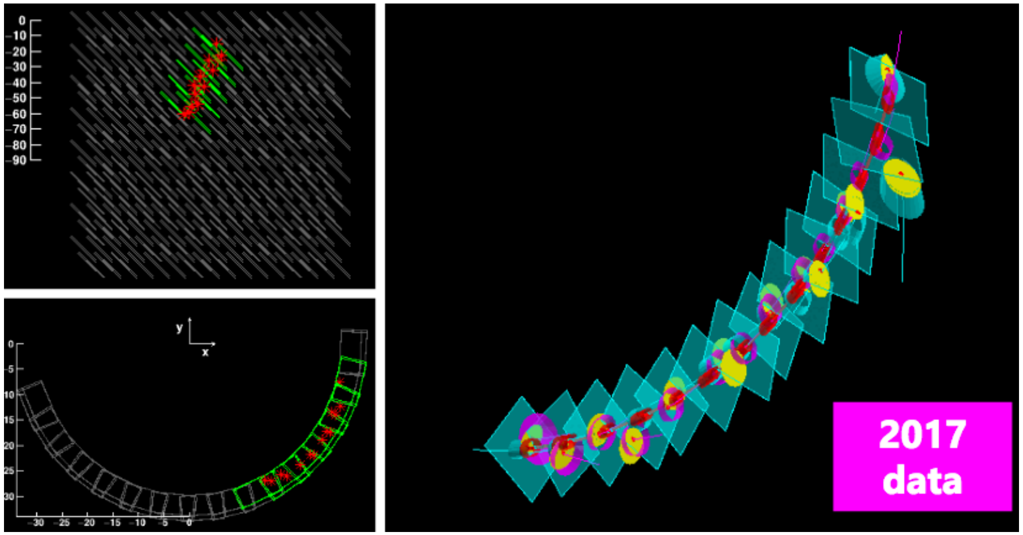


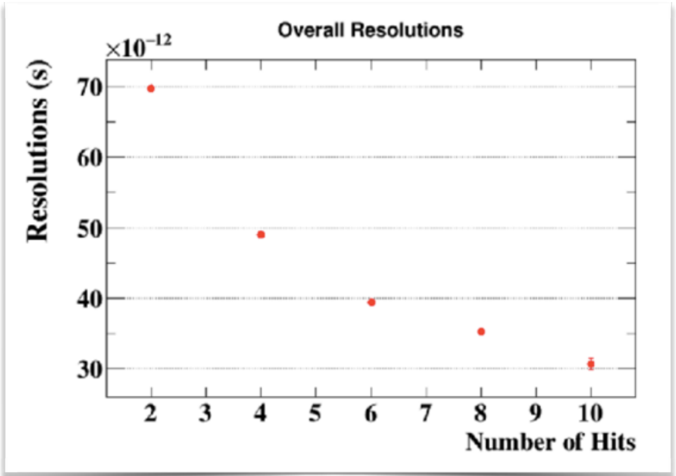
MEG-II Detector Highlights: Timing Counters

- High granularity:
  - 2 sections of 256 plastic scintillator tiles
  - tiles read by 3x3 mm^2 SiPM



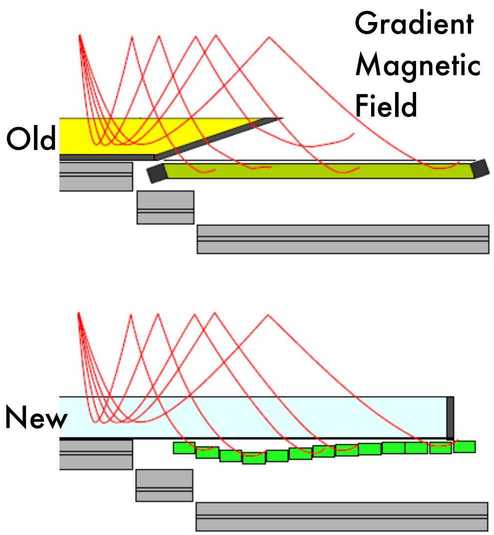
- Complete detector took data in 2017 & 2018
  - already reached design resolution
  - σ_T=~35ps





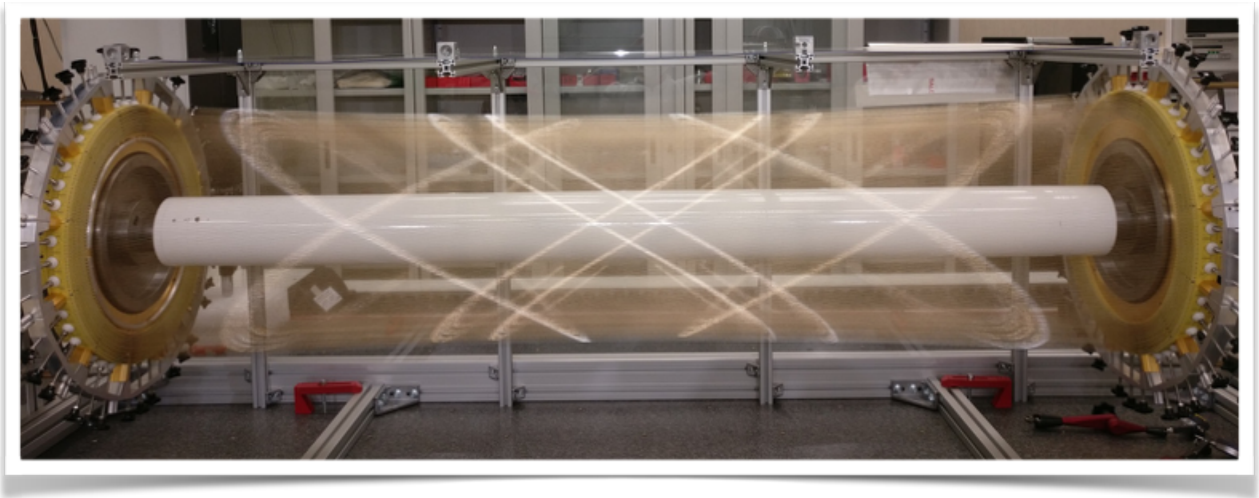
MEG-II Detector Highlights: Drift Chamber

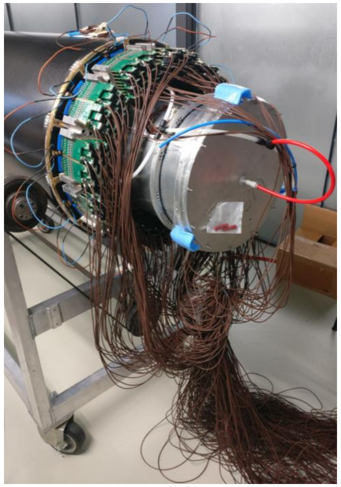
- Single volume drift chamber with 2π coverage
  - low mass single volume
  - 2m long ,1300 sense wires
  - stereo angle (6°-8°)
  - high trasparency to TC



- Delay due to problems of wire fragility in presence of contaminants+humidity

- Succesfully installed and took data in pre-engineering run 2018 (only few electronic channels)





MEG-II Detector Highlights: Drift Chamber

- Electrostatic stability problems in 2018 run => inner layers could not reach the working point

- Wire elongation in Spring 2019

- New HV tests show that all the chamber can be operated at the working point with 100V safety margin

Working point
1400-1500V
@ 5 x 10^5 gain,
He-Iso 90-10

Layer	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
9 (1500 V)	1500	1500	1500	1500	1500	1430	1500	1500	1500	1500	1500	1500
8 (1510 V)	1510	1510	1510	1500	1510	1510	1510	1510	1510	1510	1510	1510
7 (1520 V)	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520
6 (1530 V)	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530
5 (1540 V)	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540
4 (1550 V)	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550
3 (1560 V)	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560
2 (1570 V)	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570
1 (1580 V)	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580

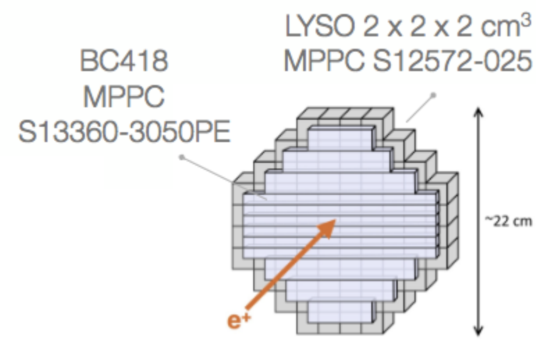
↑ Working point + 100V

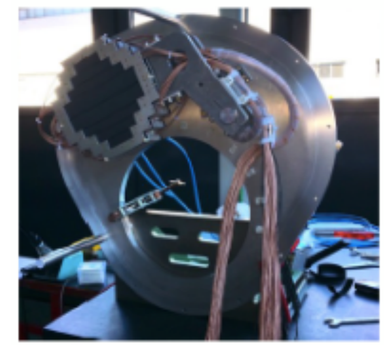
green = goal reached

MEG-II Detector Highlights: RDC

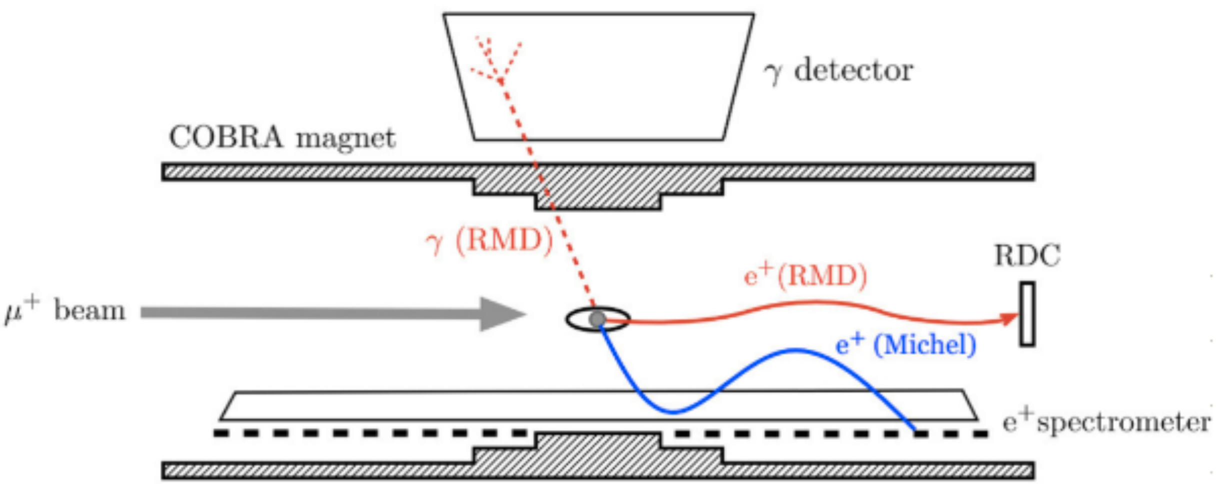
- **Radiative Decay Counter** (RDC):
  new auxiliary detector for background rejection

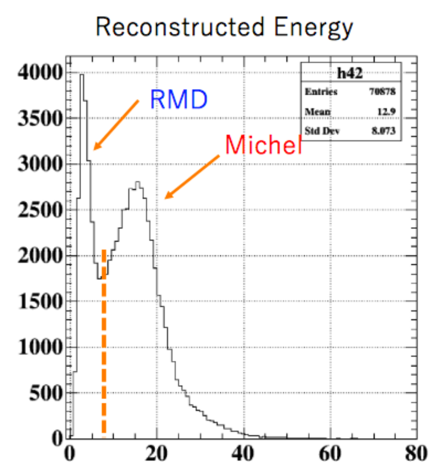
  - ~50% of accidental background has a photon that comes from a radiative decay
  - detect positron in coincidence with a photon in calorimeter
  - improve sensitivity by ~15%





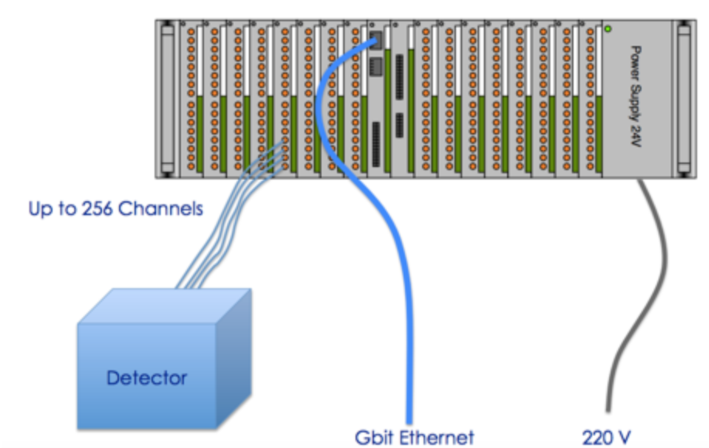
- Performances demonstrated already in 2017 run





MEG-II Detector Highlights: DAQ, Trigger

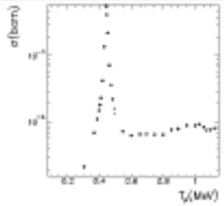
- Trigger and DAQ will be integrated in a single custom system (**WaveDAQ**) which also provides power and amplification for SiPM and MPPC
- Preliminary versions of the boards were tested during 2017 and 2018 pre-engineering run
- Common noise problems found and fixed
- Final design and test is going to be finalized in the next few months, mass production will start immediately after

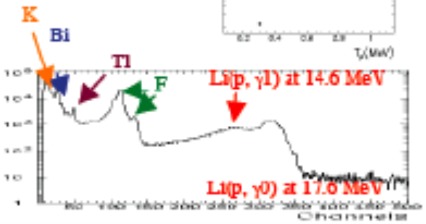


MEG-II Calibrations

Xenon Calibration

Proton Accelerator





Li(p,γ)Be

LiF target at COBRA center

17.6MeV γ

~daily calib.

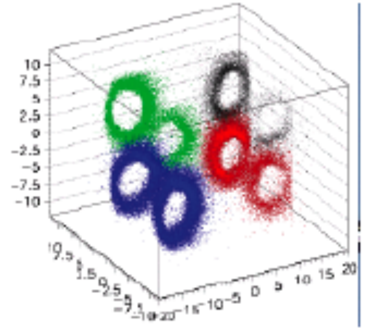
also for initial setup

Alpha on wires

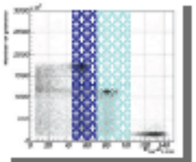
PMT QE & Att. L

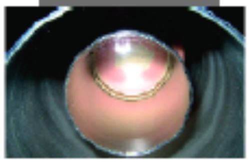
Cold GXe

LXe



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



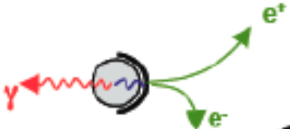


$\pi^- + p \rightarrow \pi^0 + n$

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

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

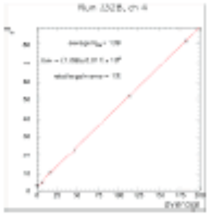
LH_2 target



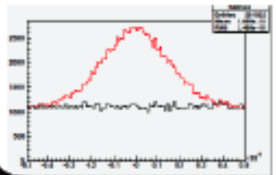
LED

PMT Gain

Higher V with light att.



μ radiative decay



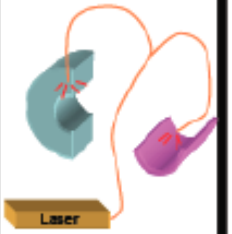
Lower beam intensity < 10^7

Is necessary to reduce pile-ups

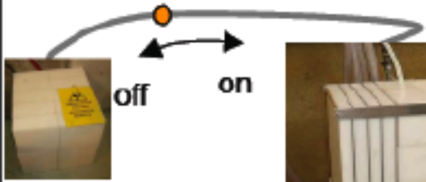
A few days ~ 1 week to get enough statistics

Laser

relative timing calib.

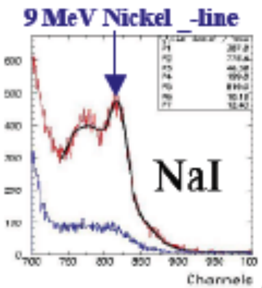


Nickel γ Generator



Illuminate Xe from the back

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



MEG-II Goals and Schedule

2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

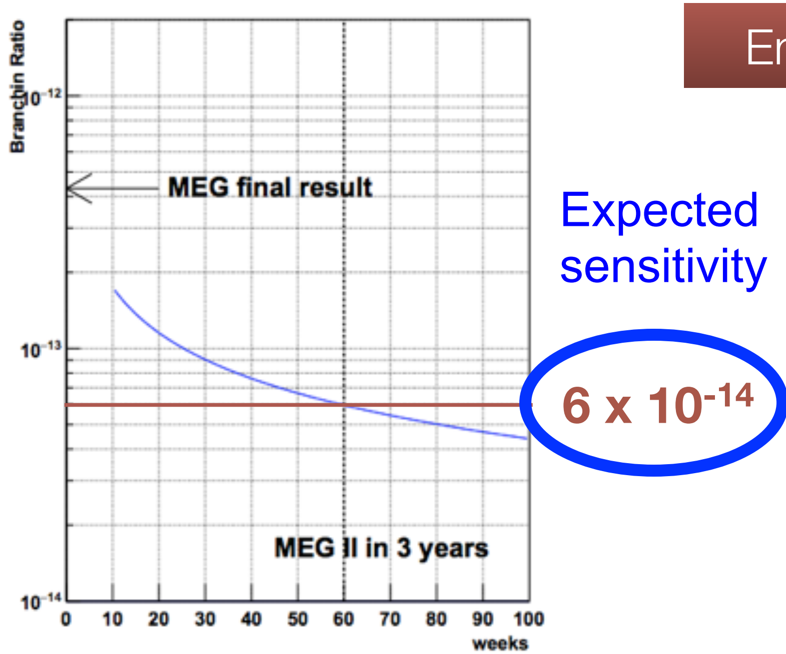
PROPOSAL

R&D

Construction & Commissioning

Engineering Runs

Physics Runs



Resolutions (σ)	MEG	MEG II	Status
θ/ϕ (e^+) mrad	9.4 / 8.7	5.9 / 5.7	9-layer DC simulation
E(e^+) keV	380	85	9-layer DC simulation
y/z(e^+) mm	1.2 / 2.4	0.7 / 1.3	9-layer DC simulation
u/v/w(γ) mm	5 / 5 / 6	2.6 / 2.2 / 5	under study
E(γ) %	2.4 / 1.7	1.1 / 1.0	waiting for electronics
t(e^+γ) ps	126	64 - 80	38 (TC) / 44 (LXe intrinsic)
Efficiency (%)		Goal	
trigger	~99	~99	
γ	63	69	
e^+	30	62	
90% Sensitivity (10^{-14})	53	6	3 full years of DAQ

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

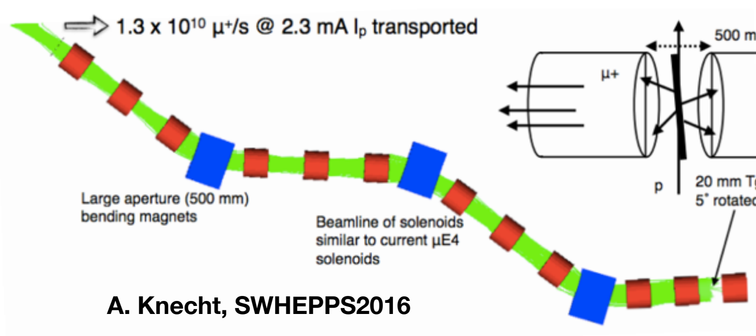
$$B_{sig} \propto \Gamma_\mu \qquad B_{acc} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta\Theta_{e\gamma})^2$$

HiMB Project @ PSI

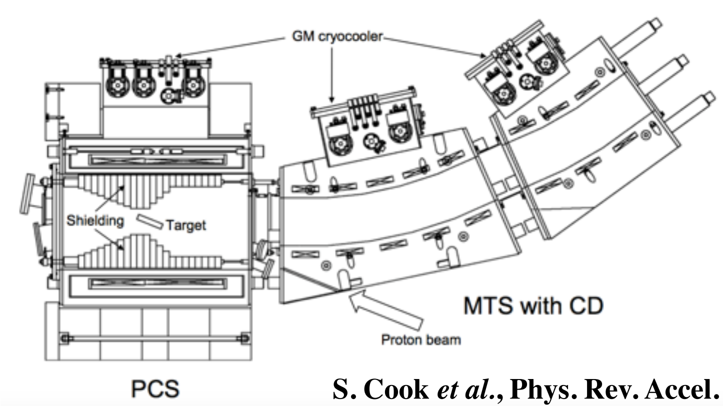
x4 μ capture eff.

x6 μ transport eff.

1.3×10^{10} μ/s



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

Conclusions

- Search of $\mu \to e\gamma$ decay continues
- LHC searches still leave lot of space for cLFV
- Best world limit from MEG experiment

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

- **MEG-II**

  => expect a sensitivity of **6×10^{-14}** in 3 years starting from 2020

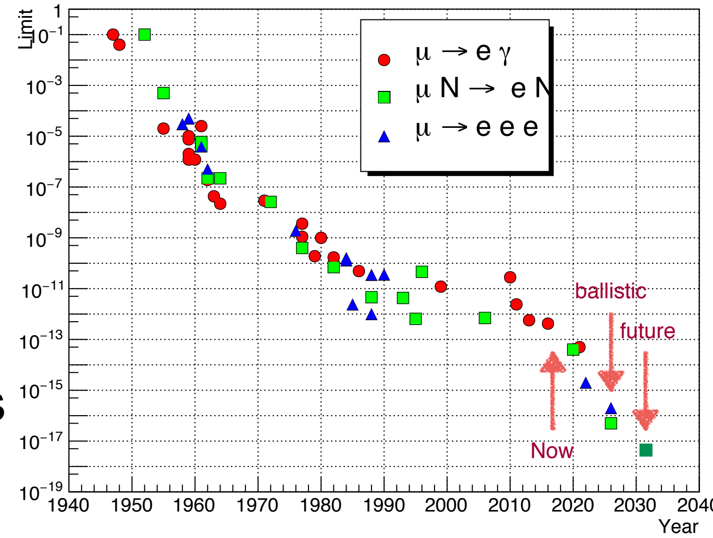
- What's next?

  - 10^9-10^{10} μ/s seems possible (HiMB,MuSIC..)
  - Need to think carefully a detector for a future $\mu \to e\gamma$ experiment in order not to be overwhelmed by accidental background
  - Interplay with other μ cLFV modes

Backup

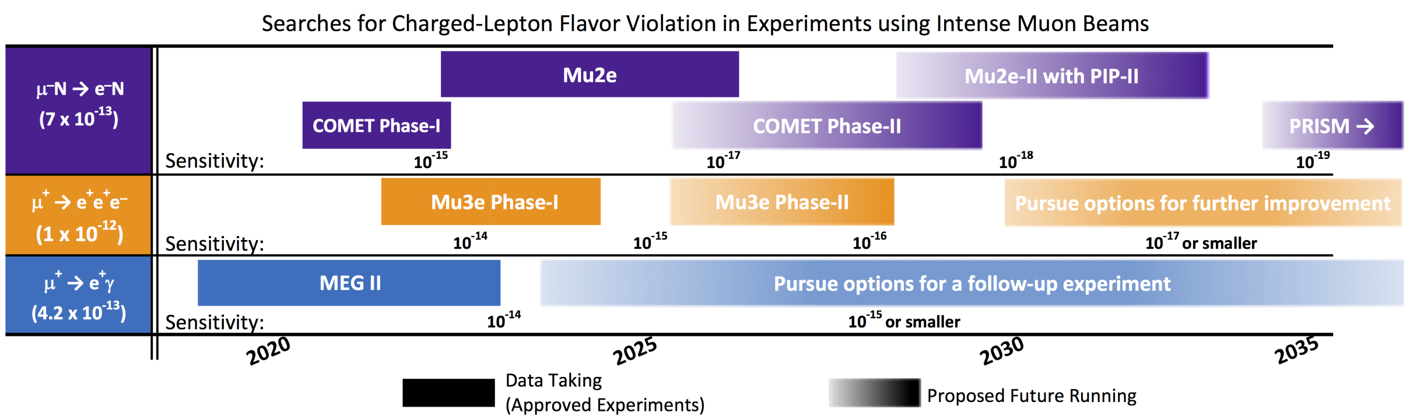
Future μ→e experiment

- Mu2e and Mu3e are structured in different phases and upgrades have been proposed



- For μ->eγ, preliminary (simulation) studies have been performed for future experiment (after MEG-II)

European strategy update @ Granada

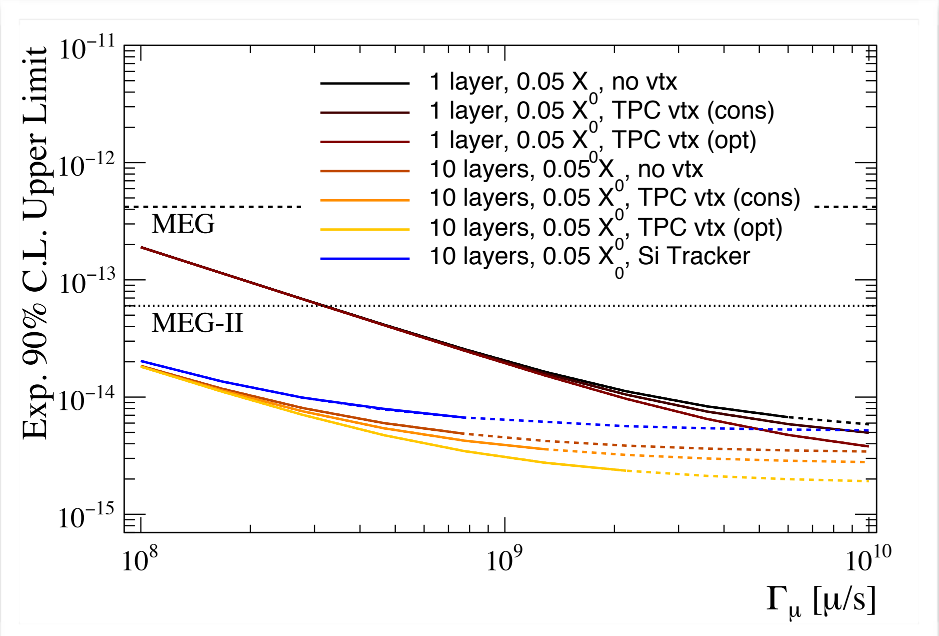


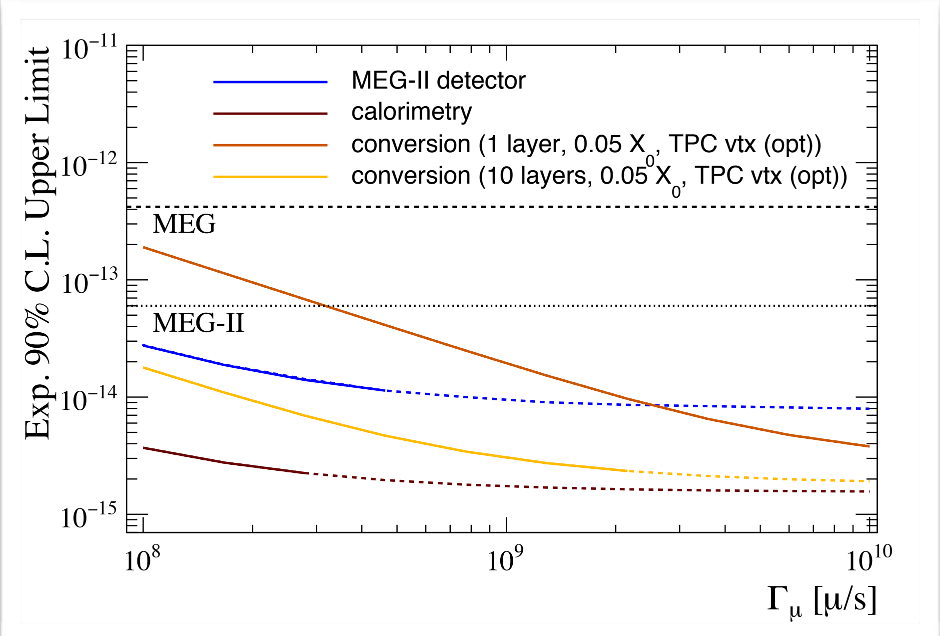
Future μ→eγ experiment

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

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
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}^{\dagger}$	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}^{\dagger}$	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}^{\dagger}$	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^{*\,\dagger}$	$< 3.6 \times 10^{-11}$	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
$B \to K\mu e^{\ddagger}$	$< 3.8 \times 10^{-8}$	90%	BaBar	2006
$B \to K^*\mu e^{\ddagger}$	$< 5.1 \times 10^{-7}$	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