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

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on behalf of the MEGII collaboration

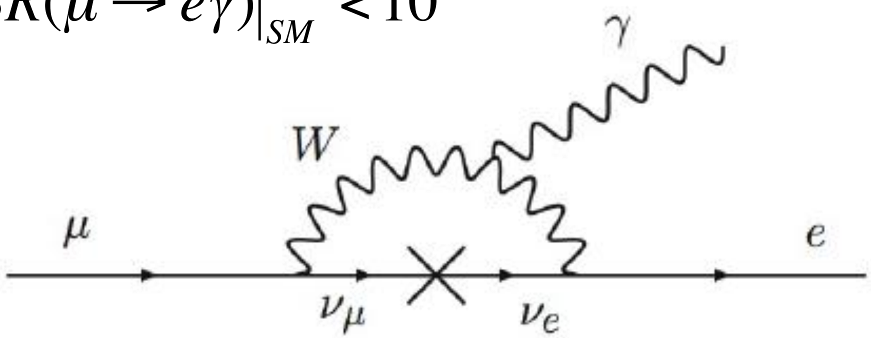
New Trends In High Energy Physics

Budva, 24-30 September 2018

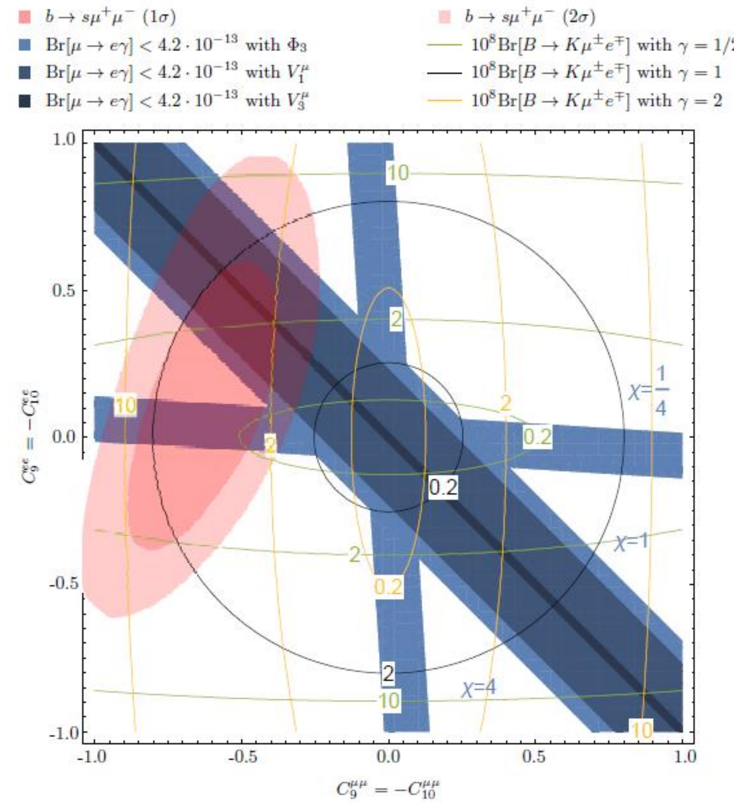
Charged lepton flavor violation

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

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



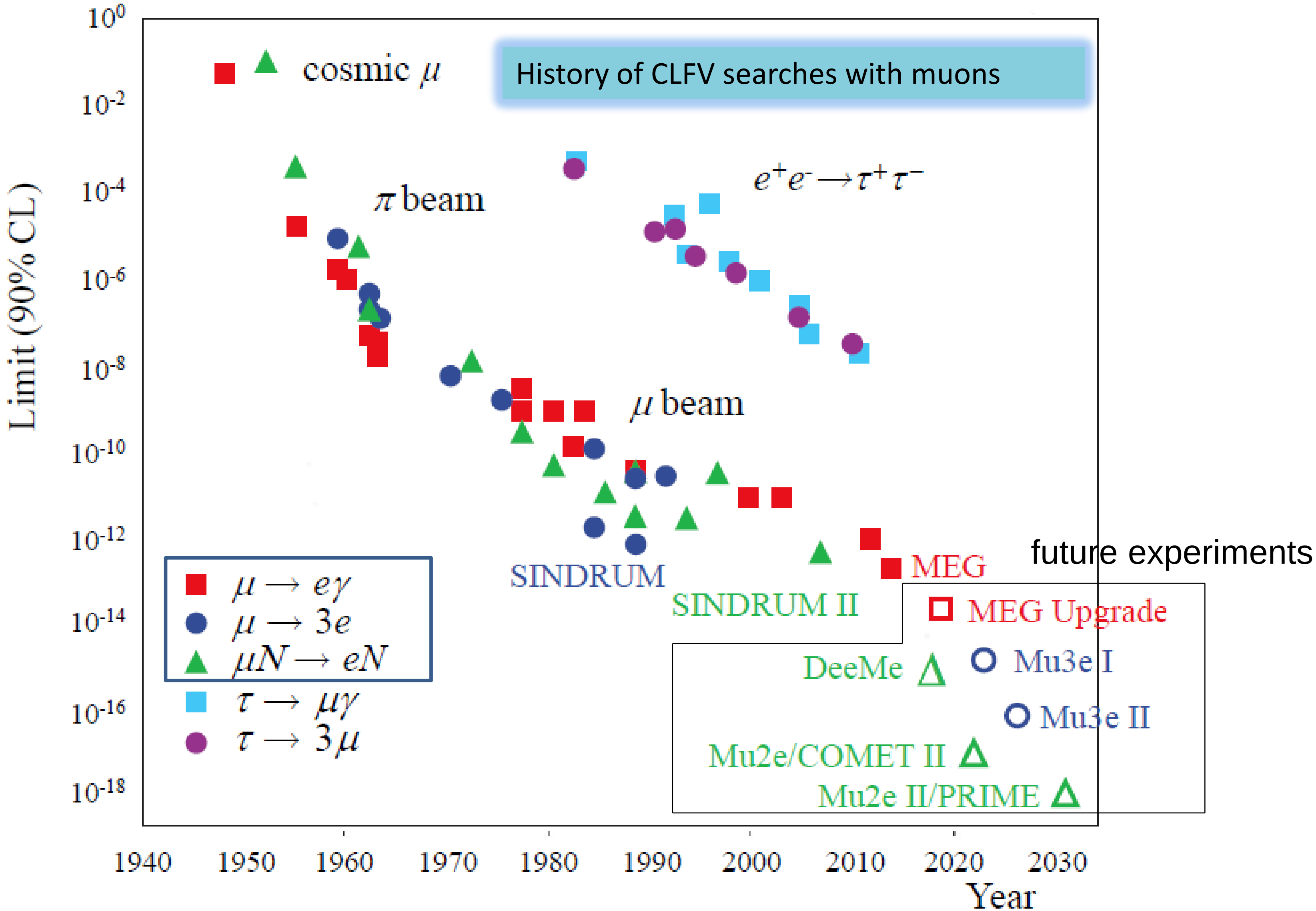
- Enanched, sometimes just below the experimental limit, in many New Physics models



Crivellin et. al. arXiv:1706.08511

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

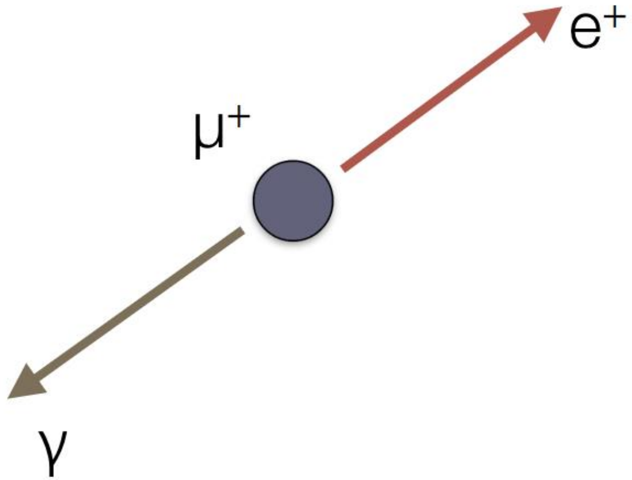
History and future experiments



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

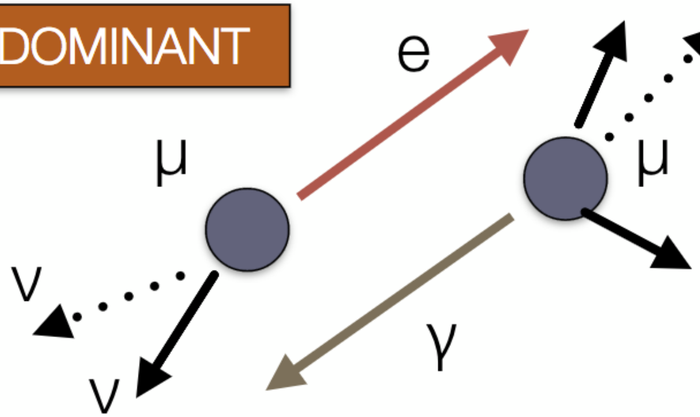
- Accidental
  - accidental coincidence of e^+ and γ
  - proportional to Γ^2_μ for given detector resolutions:
  - signal proportional to Γ_μ

  (Γ_μ= beam intensity)

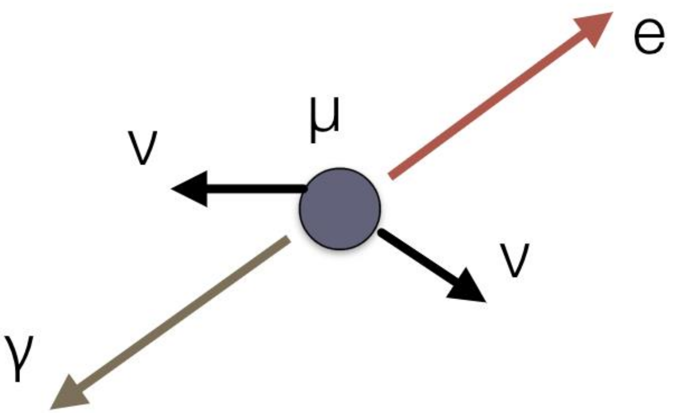
$$B_{\text{acc}} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta \Theta_{e\gamma})^2$$

Michel or radiative decay: μ->e(γ)νν

DOMINANT



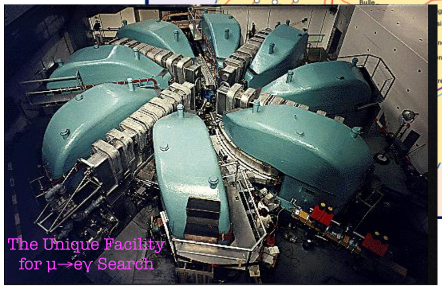
- Radiative muon decay
  - proportional to Γ_μ
  - e^+ and γ simultaneous as for signal
  - thus peaking in the $T_{e\gamma}$ variable



The MEG(II) location: PSI lab

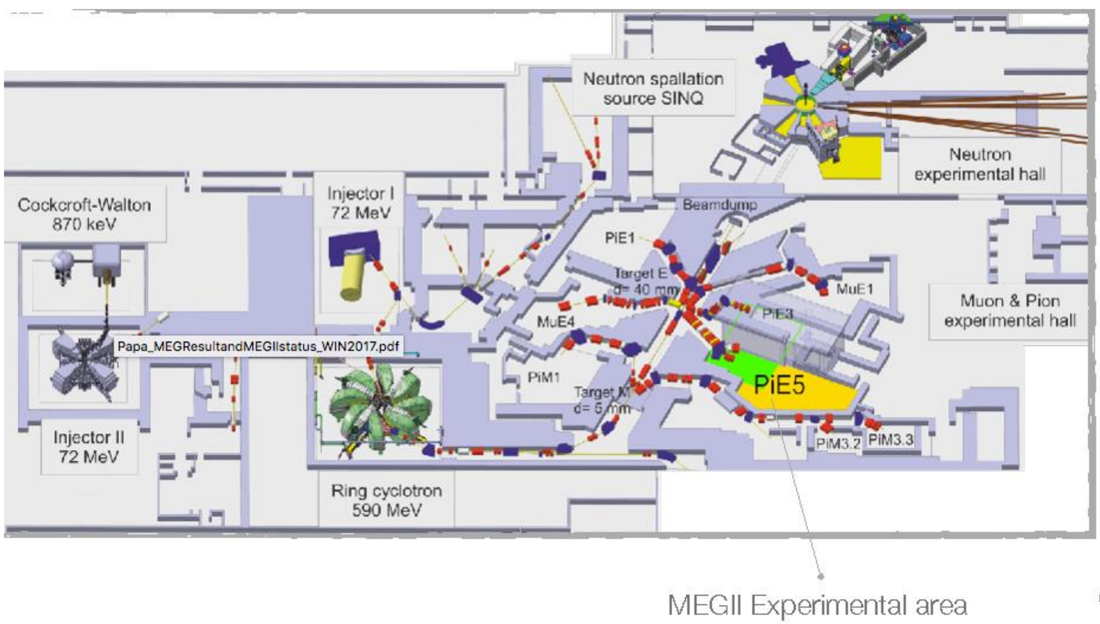
- Paul Scherrer Institute
  - continuous muon beam up to few 10^8 μ^+/s

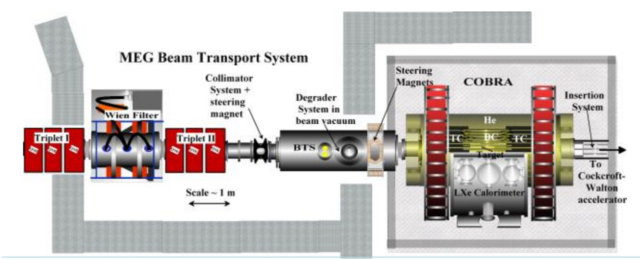
- Multi-disciplinary lab:
  - fundamental research, cancer therapy, muon and neutron sources
  - protons from cyclotron (D = 15m, E_{proton} = 590MeV P = 1.4MW)



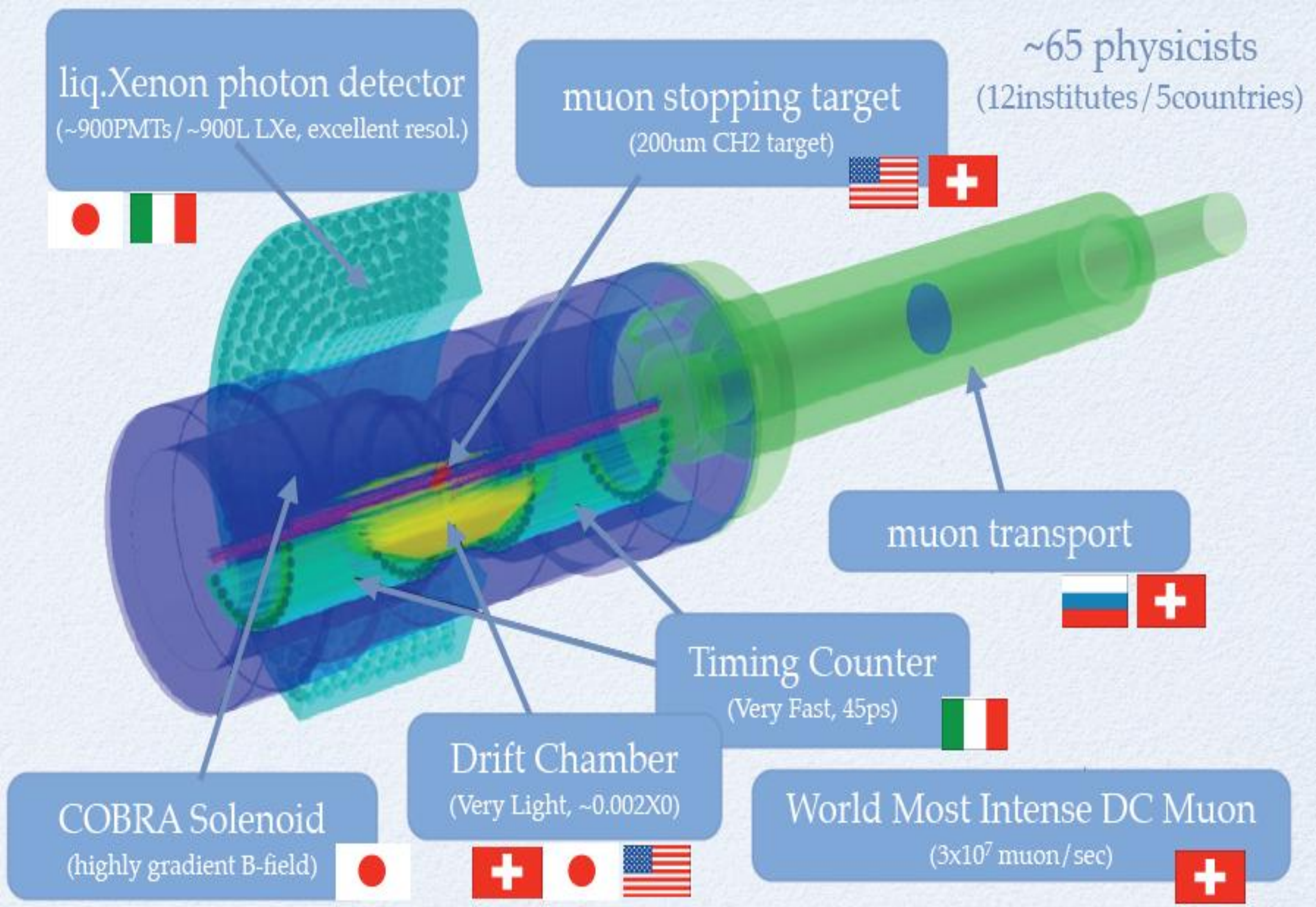
The PSI surface muon beam

- 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^+



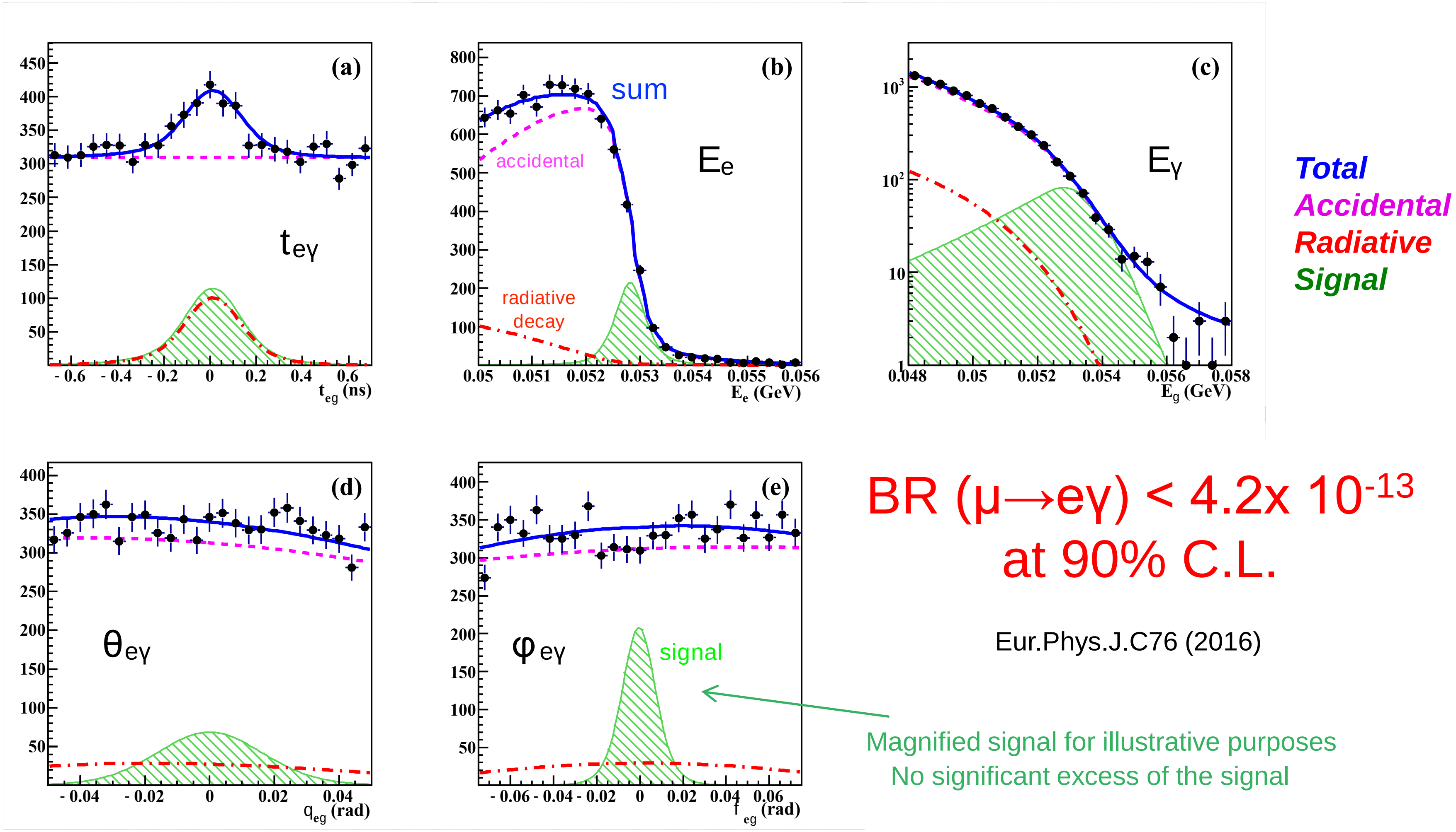


The MEG experiment for μ→eγ search



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



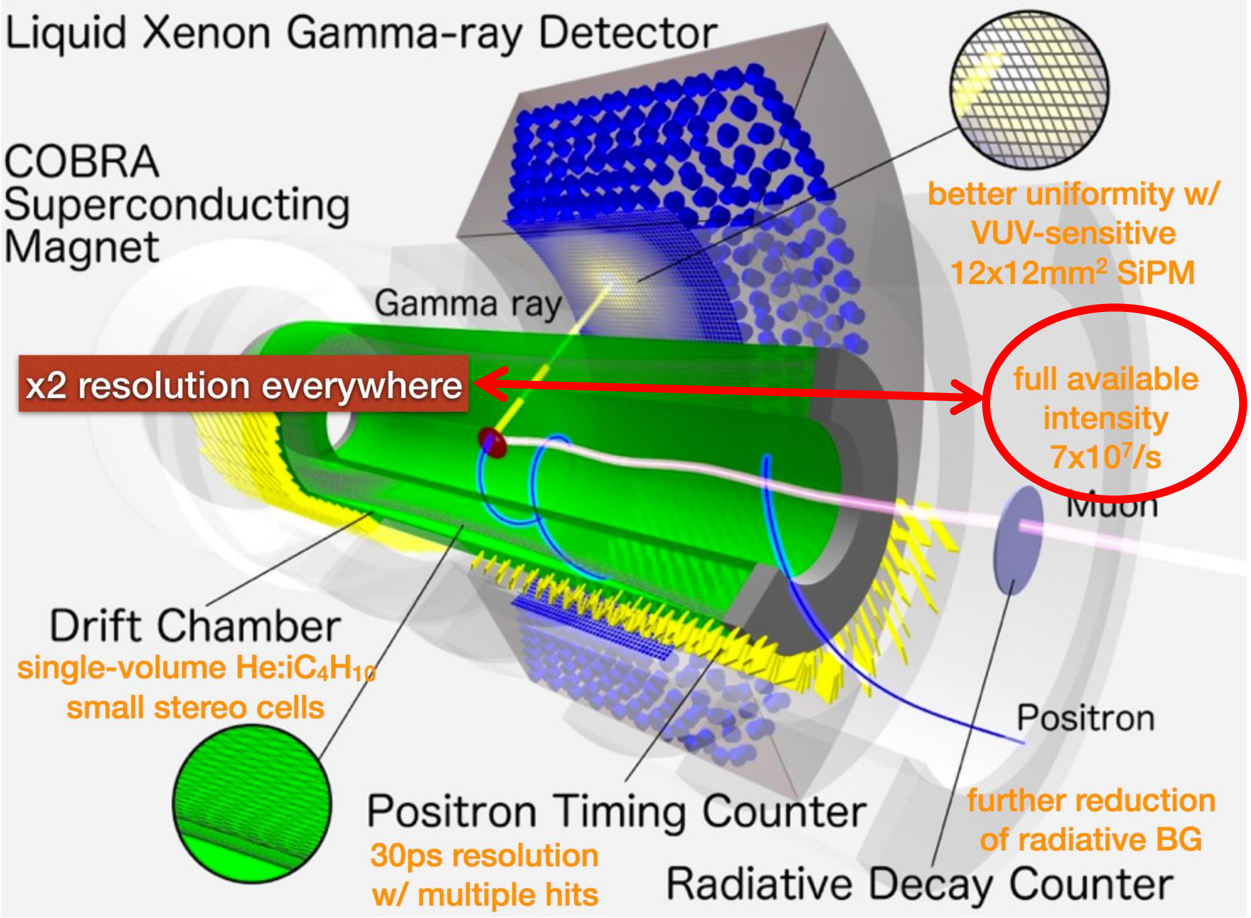
BR (μ→eγ) < 4.2×10^{-13}
at 90% C.L.

Eur.Phys.J.C76 (2016)

Magnified signal for illustrative purposes
No significant excess of the signal

Next: MEG upgrade: MEG-II

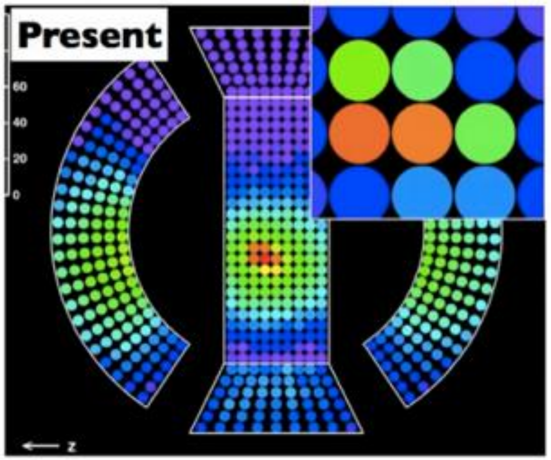
- Same detector concept as in MEG
- Increase beam intensity from 3 x 10^7 μ/s to 7 x 10^7 μ/s
- Cannot exploit full available beam intensity due to accidental background

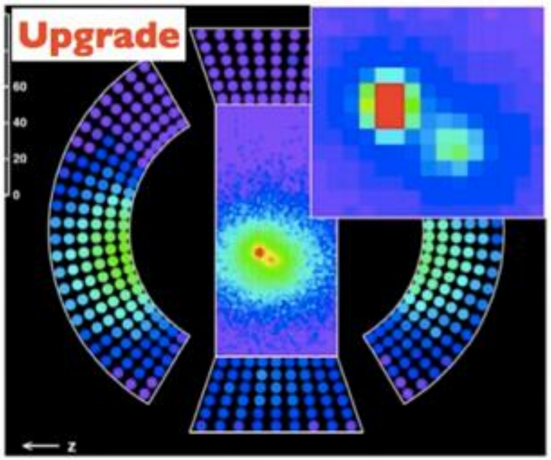


optimized to enhance sensitivity (accidental background prop. to I^2_μ)

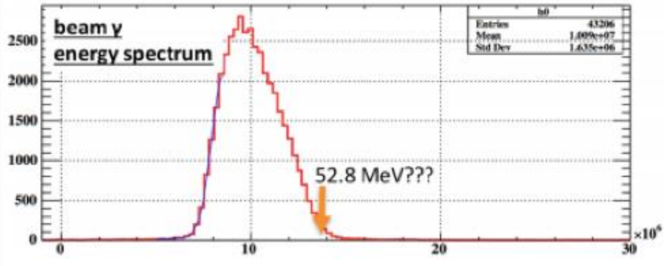
MEG-II detector highlights: Liquid Xenon

- 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

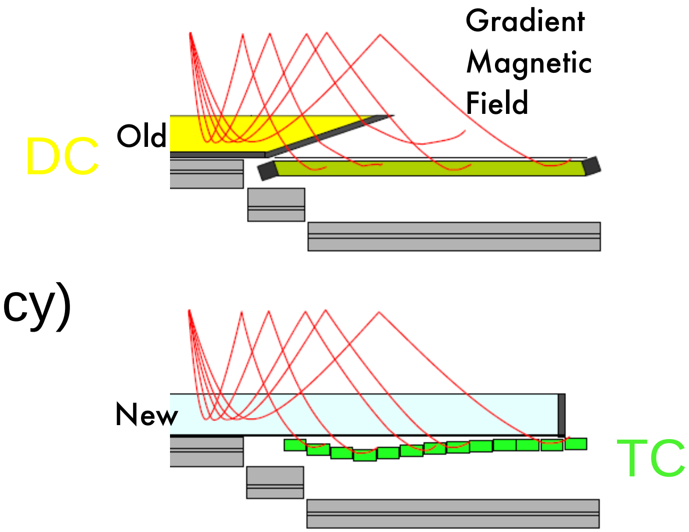
- Detector assembled, filled with LXe
  - commissioning on-going, tests already during 2017 pre-engineering run

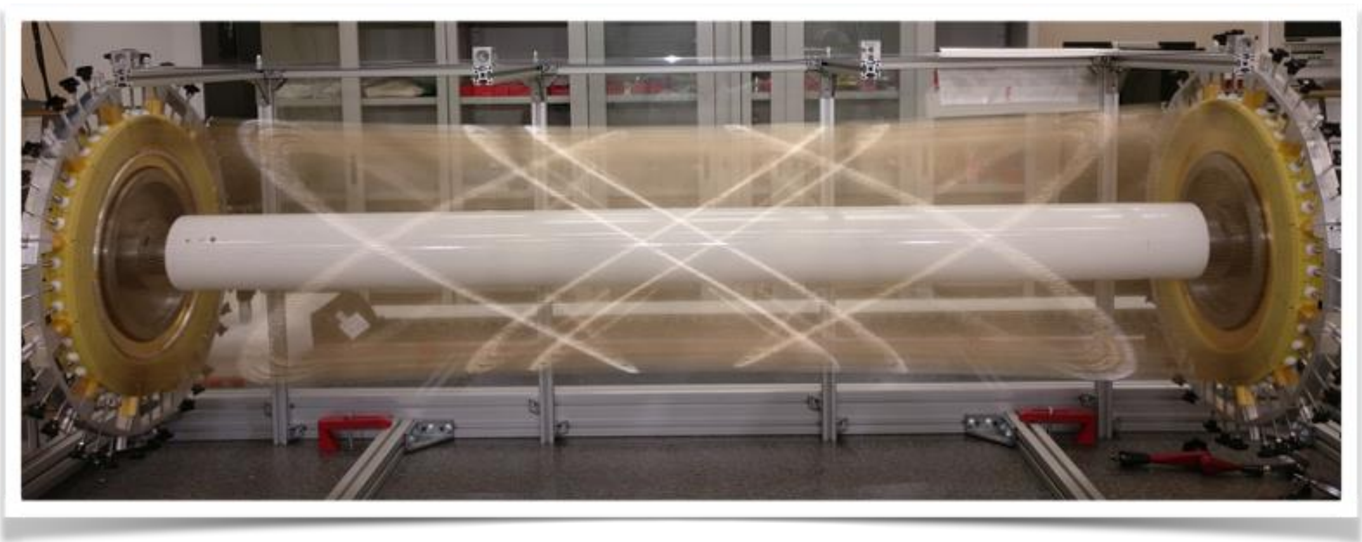
MEG-II detector highlights: Drift Chamber

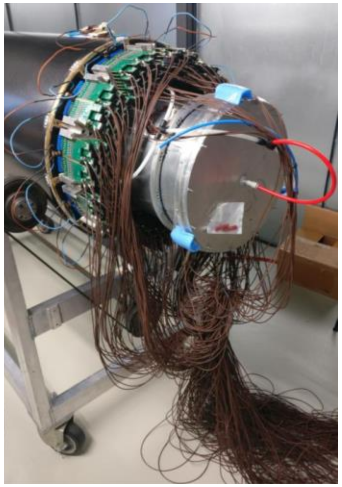
- Single volume drift chamber with 2π coverage

  - 2m long ,1300 sense wires
  - stereo angle (6° -8°)
  - low mass
  - high trasparency to TC (double signal efficiency)

- On beam in fall 2018

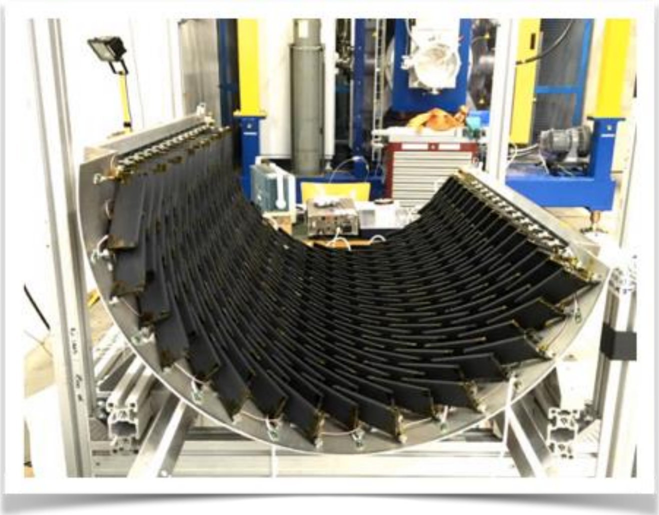


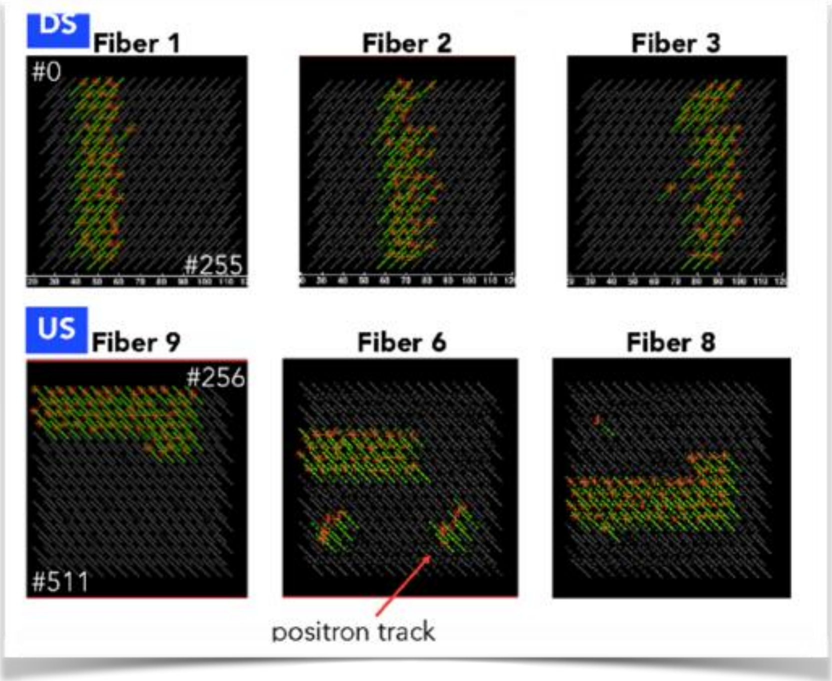


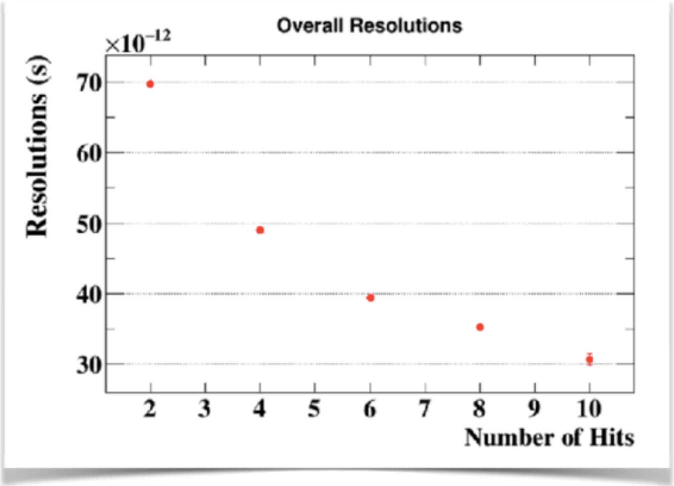


MEG-II detector highlights: Timing Counter

- High granularity:
  - 2 sections of 256 plastic scintillator tiles
  - tiles read by 3x3 mm^2 SiPM
- Complete detector took data in 2017
  - already reached design resolution
  - σ_T=35ps



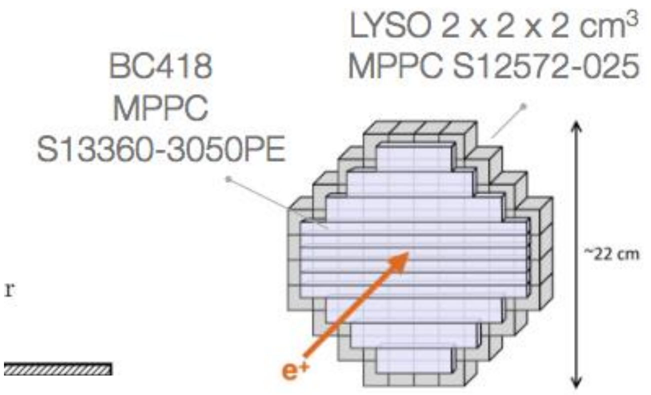


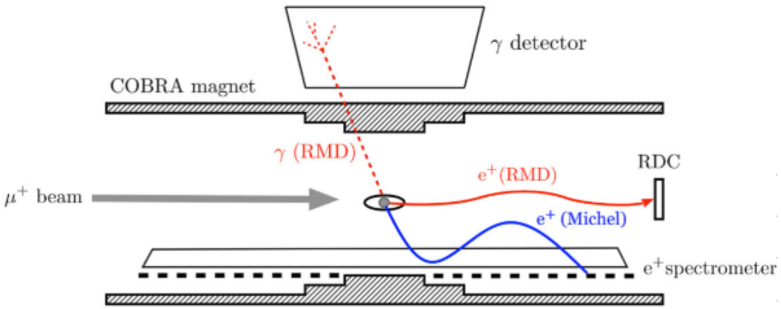


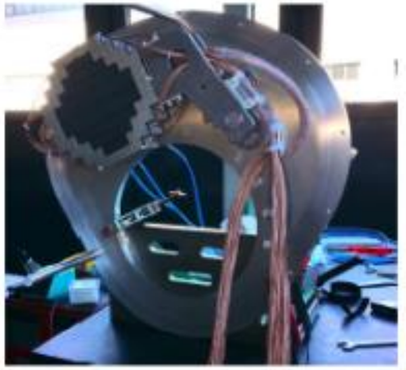
MEG-II detector highlights: RDC, DAQ, Trigger

- RDC: New auxiliary detector for radiative decay background rejection
  - detect positron in coincidence with photon
  - improve sensitivity by 15%

- Commissioned during 2017 run

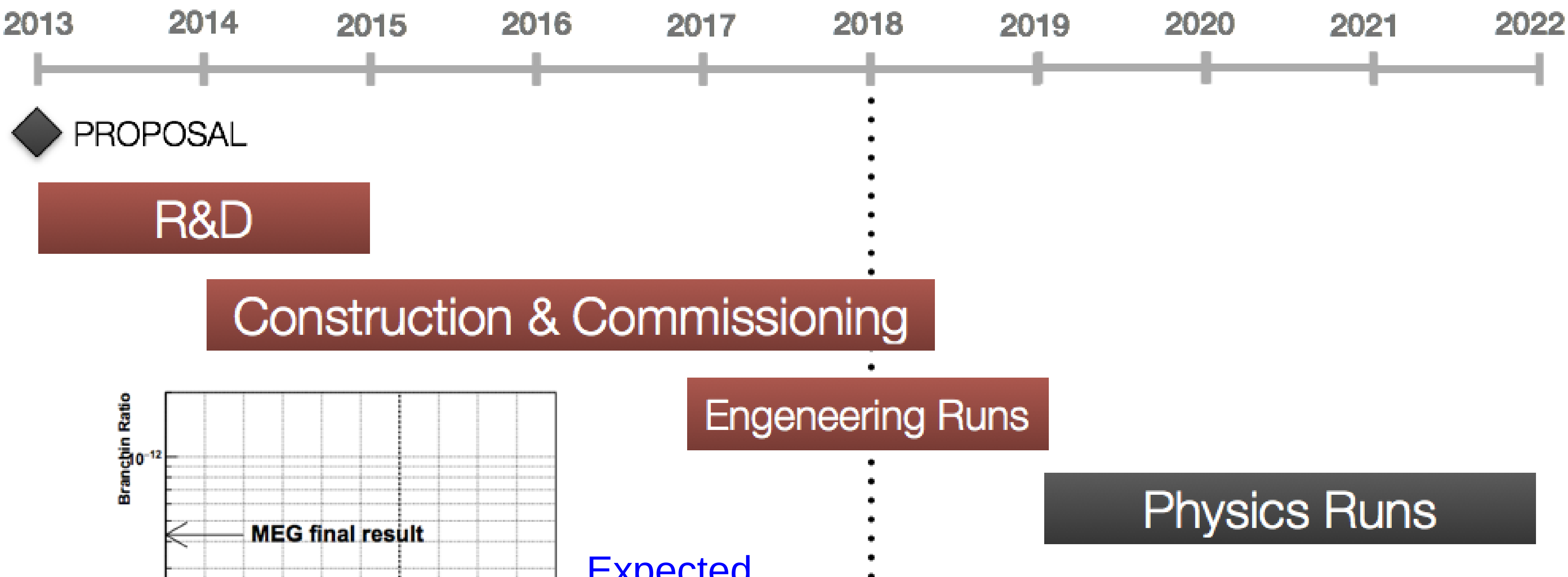


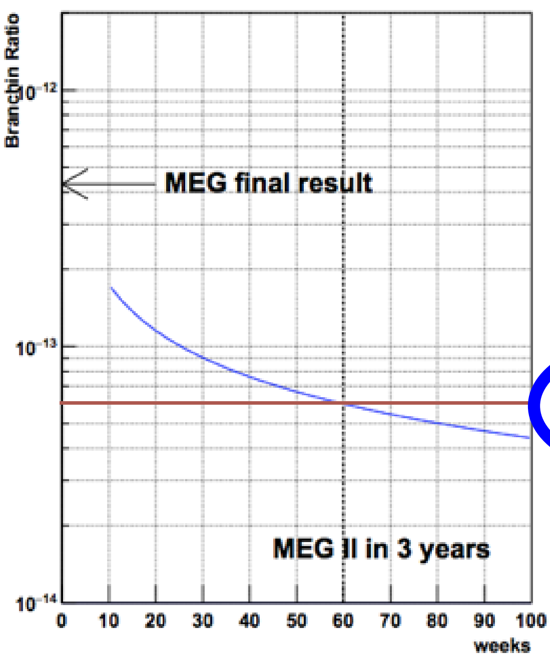




- New version of DRS (Wavedream) custom digitization board integrating both digitization, triggering and some HV
  - successfully tested in 2017 with XEC, TC, RDC

MEG-II goals and schedule





Expected sensitivity

6×10^{-14}

PDF parameters	Present MEG	Upgrade scenario
$\sigma_{E_{e^+}}$ (keV)	380	110
e^+ σ_θ (mrad)	9	5
e^+ σ_ϕ (mrad)	11	5
e^+ σ_Z / σ_Y(core) (mm)	2.0/1.0	1.2/0.7
$\frac{\sigma_{E_\gamma}}{E_\gamma}$ (%) w>2 cm	1.6	1.0
γ position at LXe $\sigma_{(u,v)}$-σ_w (mm)	4	2
γ-e^+ timing (ps)	120	80
Efficiency (%)		
trigger	≈ 99	≈ 99
γ reconstruction	60	60
e^+ reconstruction	40	95
event selection	80	85

Next generation of μ→eγ searches

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

- 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

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

- 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)

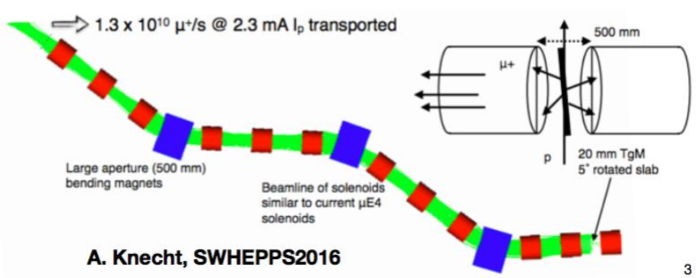
- MEGII, for example exploits 7×10^7 muon/s (available 10^8 muon/s)

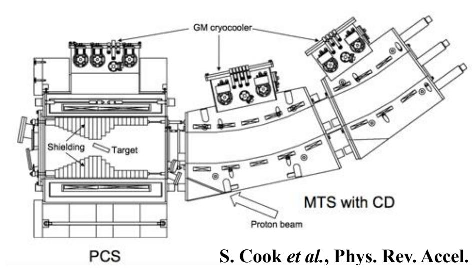
HiMB Project @ PSI

x4 μ capture eff.

x6 μ transport eff.

1.3×10^{10} μ/s





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

MuSIC Project @ RCNP

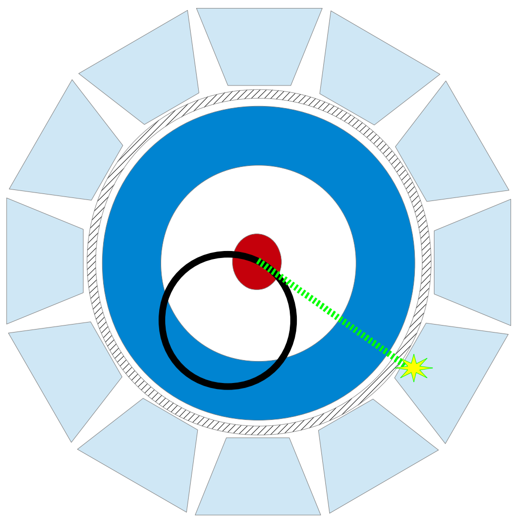
Thick production target

π capture solenoid

4×10^8 μ/s

Next generation of μ→eγ searches: photon

Calorimeter



- high efficiency
- good resolution

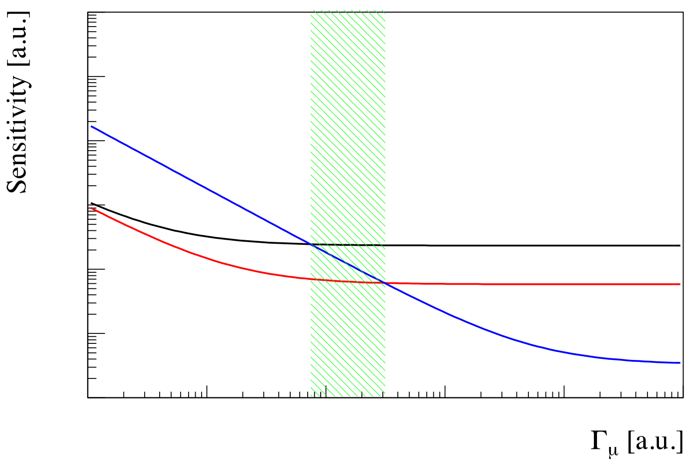
Requirements:
- high light yield
- fast response

Sensitivity trend vs beam intensity

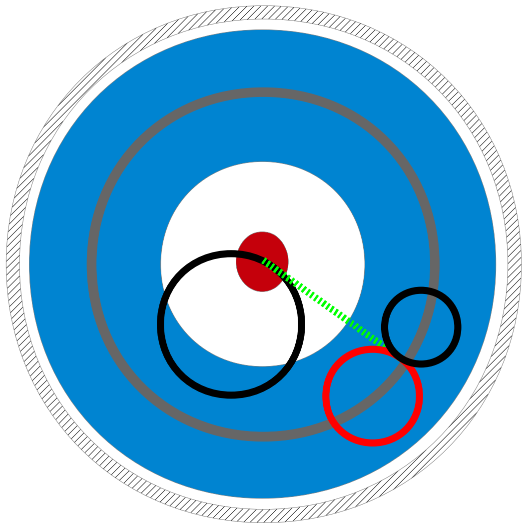
blue = pair conversion design

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)

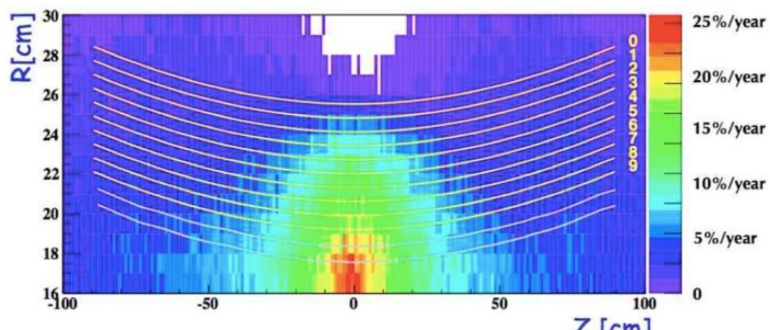
Next generation of μ→eγ searches: positron

- 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

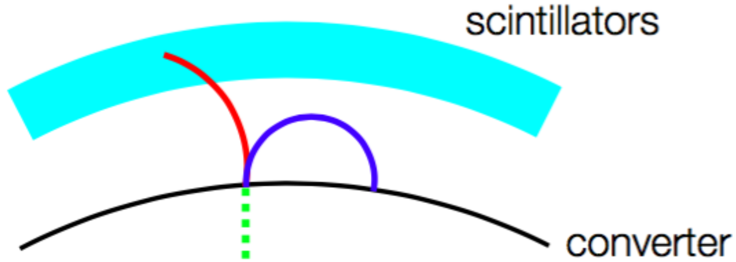
Next generation of μ→eγ searches: relative time

- Timing plays a crucial role to avoid accidental coincidences

- Calorimetric approach: calorimeters+positron scintillating counters (MEG-II: $T_{e\gamma}$~80ps)

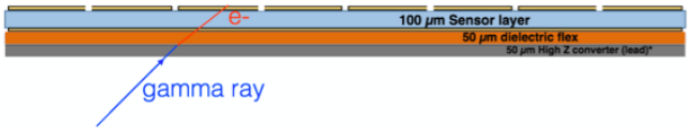
- Photon conversion approach: need to measure e^+ or e^- time with a fast detector for photon timing

- 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 μ→eγ searches: possible scenarios

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

Variable	Resolution w/o vtx detector	w/ TPC vtx detector conservative	w/ TPC vtx detector optimistic	w/ silicon vtx detector conservative	w/ silicon vtx detector 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%		

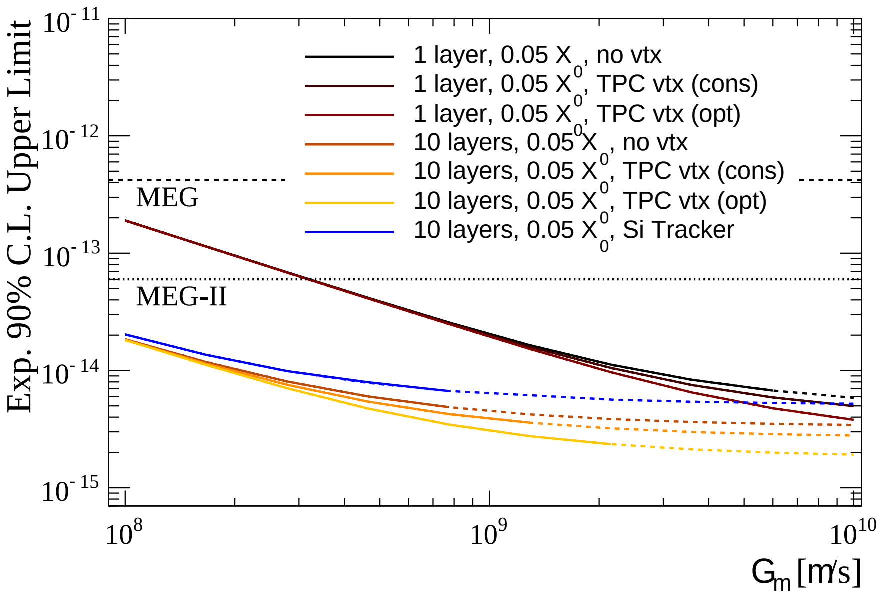
gaseous
detector

PHOTON CONVERSION

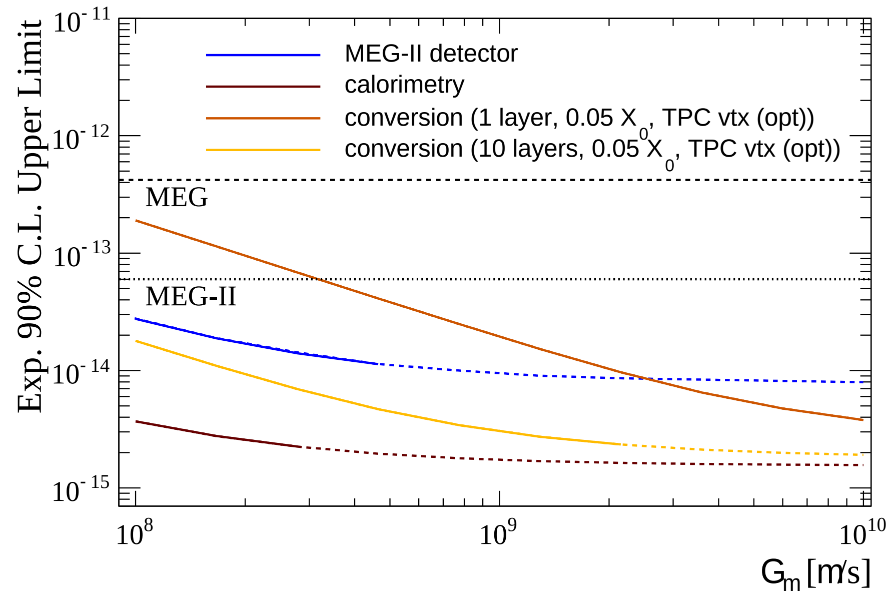
Variable	Resolution w/o vtx detector	w/ TPC vtx detector conservative	w/ TPC vtx detector optimistic	w/ silicon vtx detector conservative	w/ silicon vtx detector optimistic
$\theta_{e\gamma}$ / $\phi_{e\gamma}$ [mrad]	7.3 / 6.2	6.1 / 4.8	3.5 / 3.8	8.0 / 7.4	6.3 / 6.9
$T_{e\gamma}$ [ps]			50		
E_e [keV]			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 with 10^9 muons/s

Conclusion

- Search of $\mu \rightarrow e\gamma$ decay continues
- Best word limit from MEG experiment

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

- **MEG-II**

  => expect a sensitivity of **4x10^{-14}** in 3 years

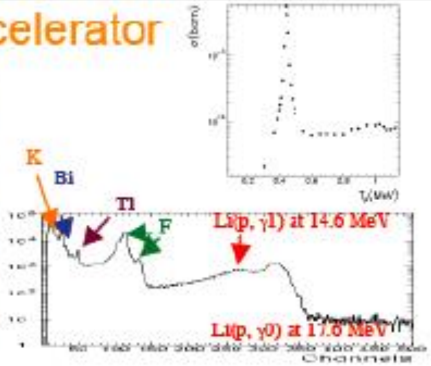
- What's next?

  - 10^{9}-10^{10} μ/s seems possible (HiMB,MUSIC..)
  - A sensitivity of few 10^{-15} level seems to be within reach for 3 years running at 10^{9} muon/s
  - Further improvements require new detector concepts

Backup

Calibrations

Proton Accelerator



Li(p,γ)Be

LiF target at COBRA center

17.6MeV γ

~daily calib.

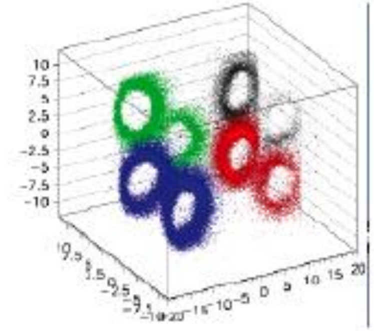
also for initial setup

Alpha on wires

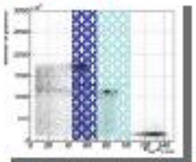
PMT QE & Att. L

Cold GXe

LXe



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



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

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

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

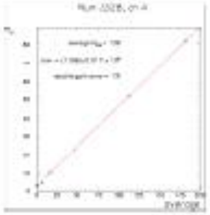
LH_2 target

Xenon Calibration

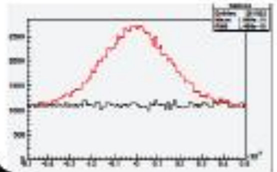
LED

PMT Gain

Higher V with light att.



μ radiative decay



Lower beam intensity < 10^7

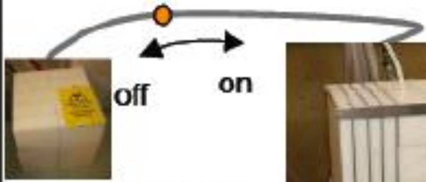
Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics

Laser

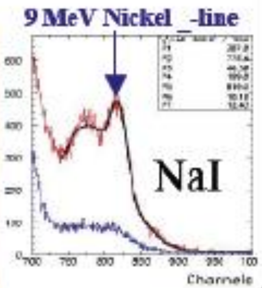
relative timing calib.

Nickel γ Generator



Illuminate Xe from the back

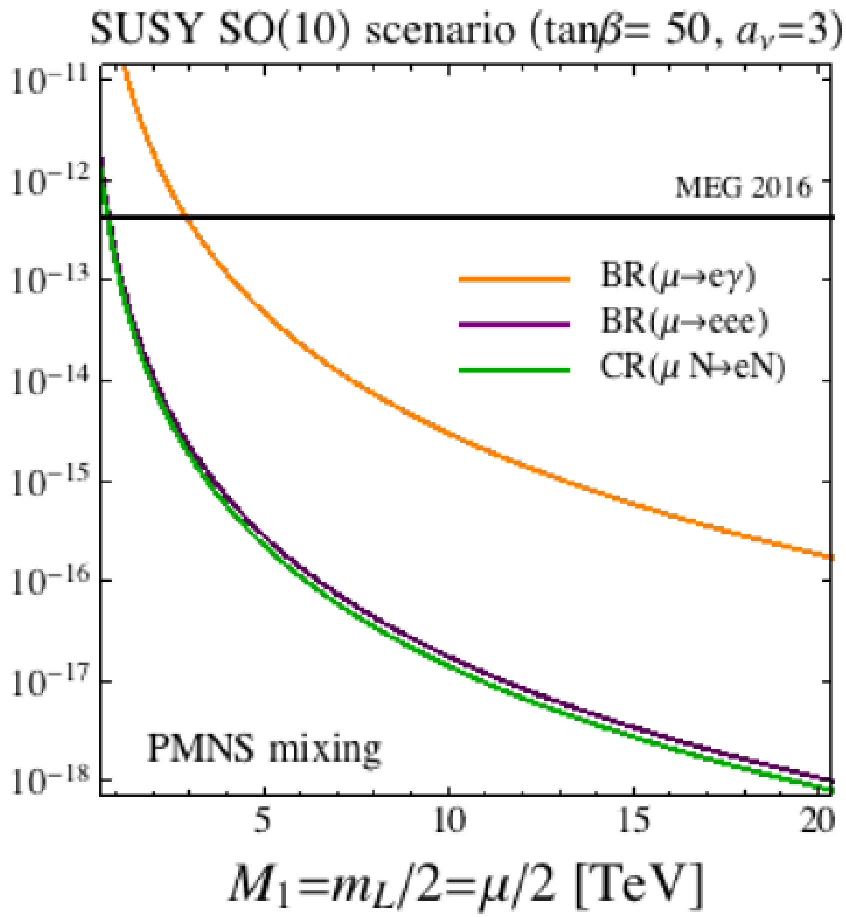
Source (Cf) transferred by comp air → on/off



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
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}^{\dagger}$	$< 6.1 \times 10^{-13}$	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
$K^0_L \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998
$K^0_L \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$	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
$B^0_s \to \mu e$	$< 1.1 \times 10^{-8}$	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

Interplay with SUSY searches at LHC



SUSY seesaw SO(10) with PMNS slepton mixing; Calibbi, Signorelli 2017 and references therein.

MEG-II calibrations

Process	Current Limit	Next Generation exp
□ → ∝□	BR < 6.5 E-8 BaBar	
□ → ∝□	BR < 6.8 E-8 BaBar	10^{-9} - 10^{-10} (Belle II)
□ → ∝∝∝	BR < 3.2 E-8 Belle	
□ → eee	BR < 3.6 E-8 Belle	
K_L → e∝	BR < 4.7 E-12 BNL	
K^+ → $□^+e^□∝^+$	BR < 1.3 E-11 BNL	NA62 might improve by O(10)
B^0 → e∝	BR < 7.8 E-8 LHCb	Belle II - LHCb
B^+ → K^+e∝	BR < 9.1 E-8 BaBar	
$∝^+$ → e^+□	BR < 4.2 E-13 MEG@PSI	10^{-14} (MEG@PSI)
$∝^+$ → $e^+e^+e^-$	BR < 1.0 E-12 SINDRUM@PSI	10^{-16} (PSI)
∝N → eN	$R_{∝e}$ < 7.0 E-13 SINDRUM@PSI	10^{-17} (Mu2e, COMET)