Status and prospects of new Physics searches with the MEGII experiment

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on behalf of the MEGII collaboration

Istituto Nazionale di Fisica Nucleare

XXIX International Workshop on

Deep-Inelastic Scattering and Related Subjects

DIS 2022

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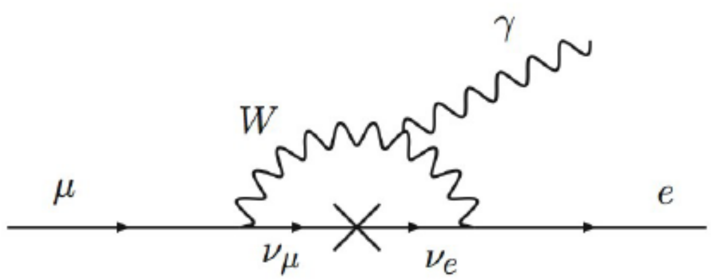
Charged Lepton Flavor Violation (cLFV)

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

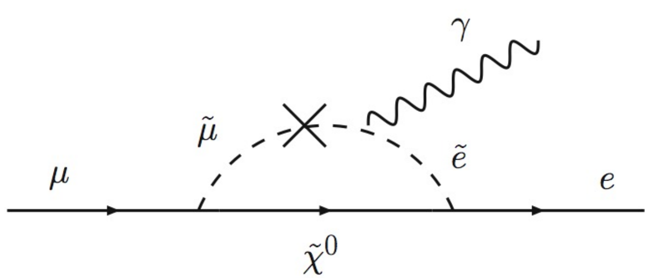
$$BR(\mu \to e\gamma)\big|_{SM} < 10^{-50}$$

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

neutrino oscillation



new particle



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

Search for NP at the Intensity Frontier

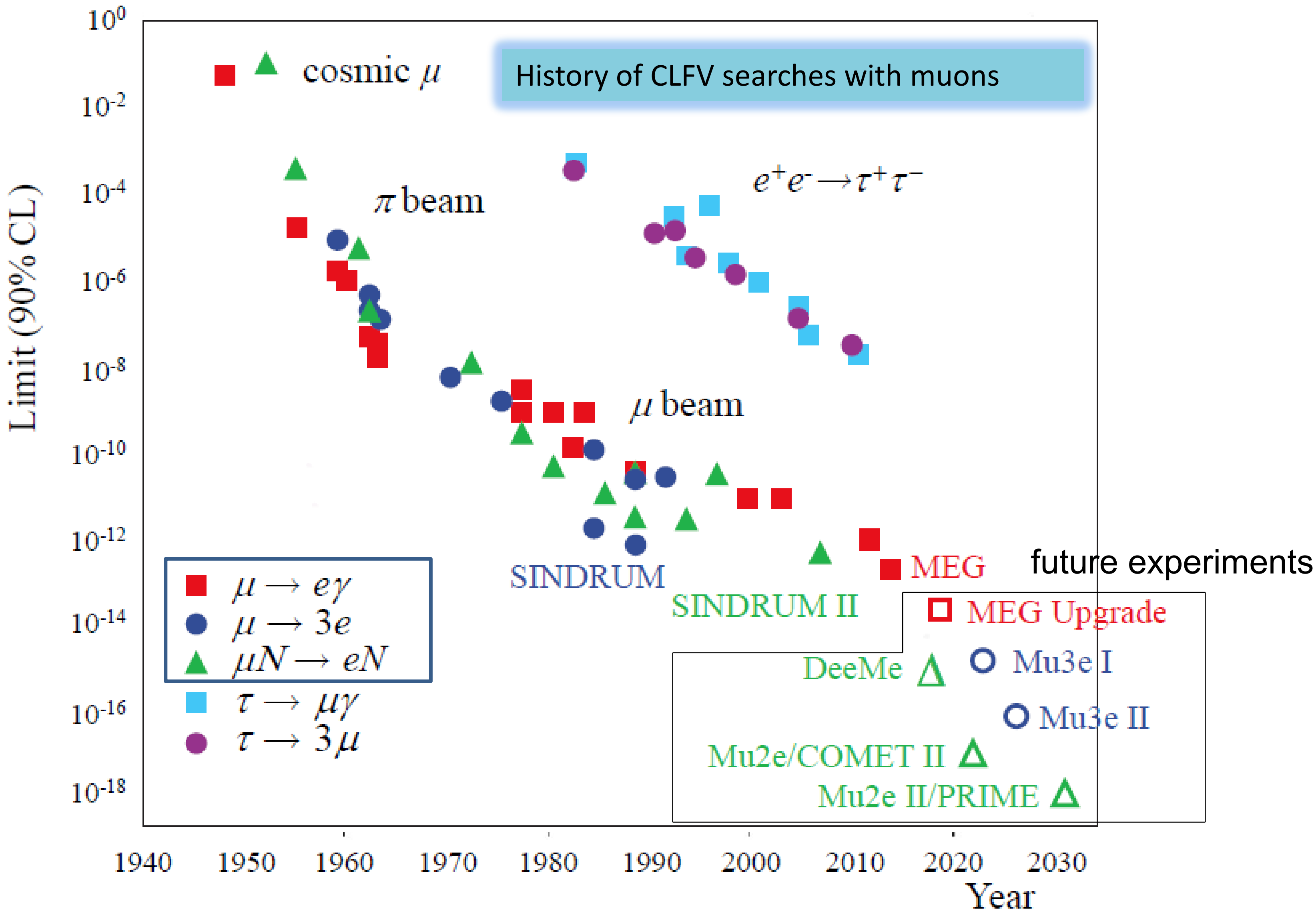
- Probe NP at very high energy scales: $\Lambda > 10^2\text{-}10^4$ TeV
- High intensity frontier: complementary to LHC
- Benchmark test for NP Models

Muons golden processes

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

- Not only muons: τ, EDM...

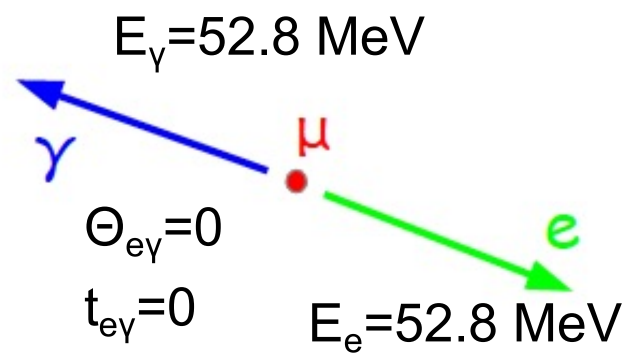
History of cLFV Searches



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

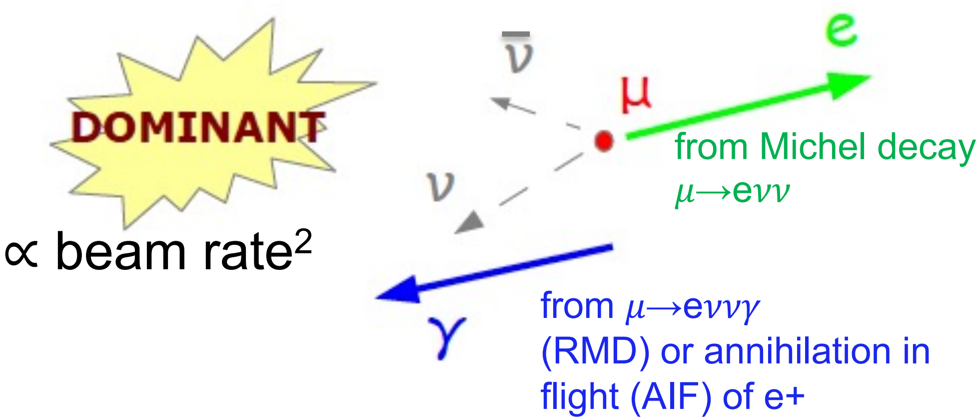
- High intensity muon beam stopped in a thin target
- Two types of **backgrounds**:
  - physical background
  - accidental background from decay products of different muons

SIGNAL

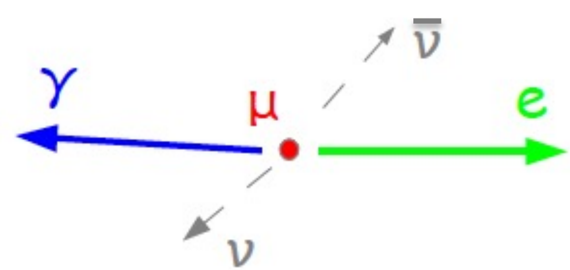


Observables: E_{e+}, E_γ, $\theta_{e\gamma}$, $\varphi_{e\gamma}$, $t_{e\gamma}$

ACCIDENTAL BACKGROUND



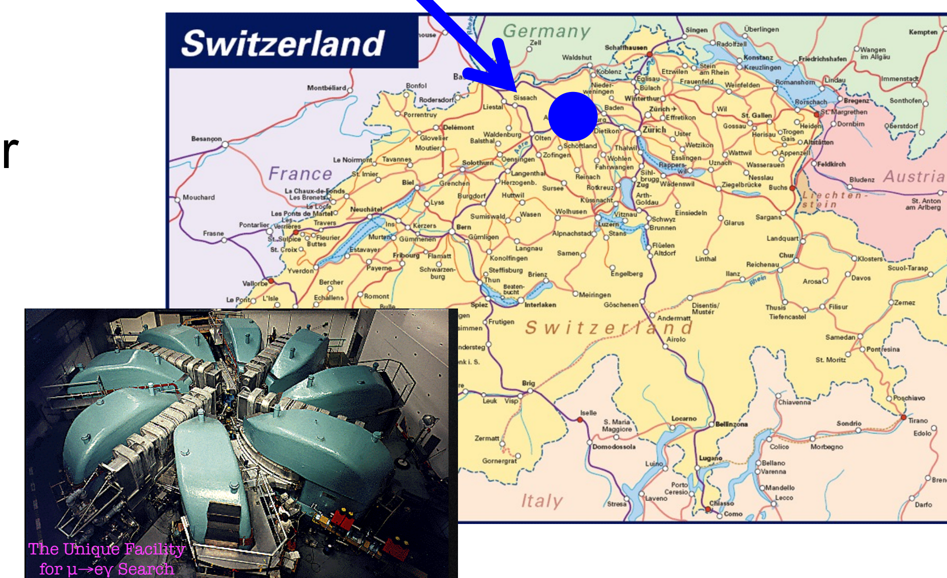
RADIATIVE MUON DECAY (RMD)



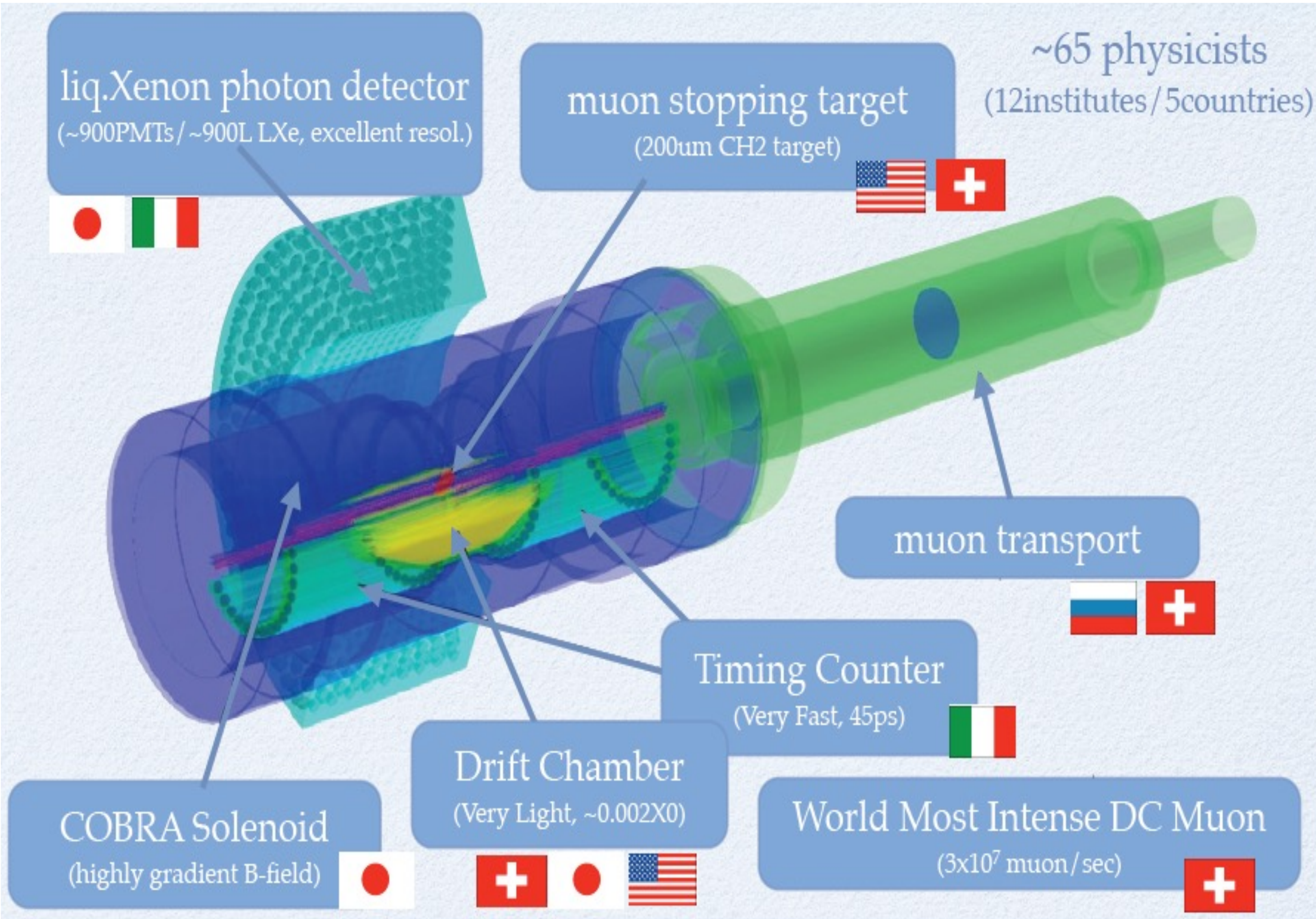
The MEG(II) Location: PSI

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

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

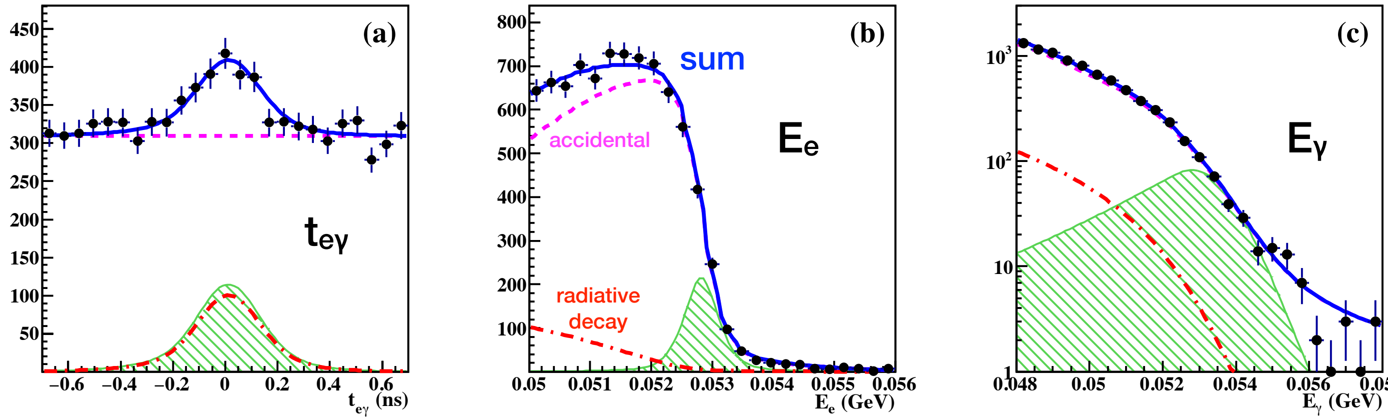


The MEG Experiment for μ→eγ Search

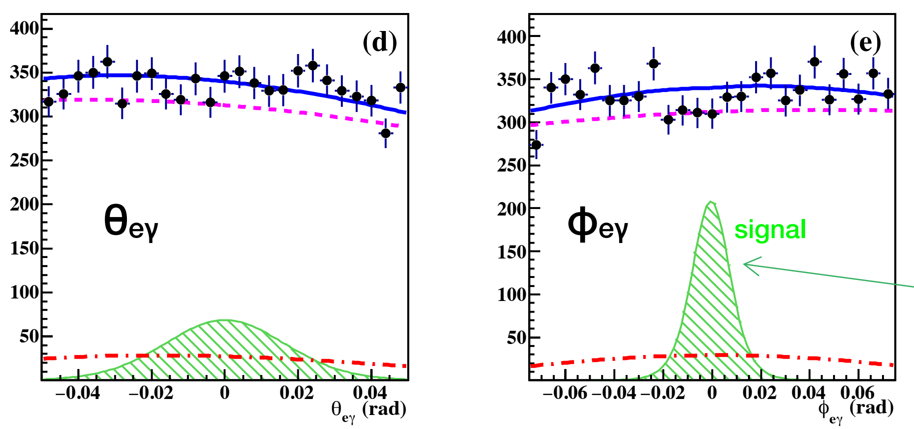


MEG BR(μ→eγ) Limit Result

- 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



Total
Accidental
Radiative
Signal



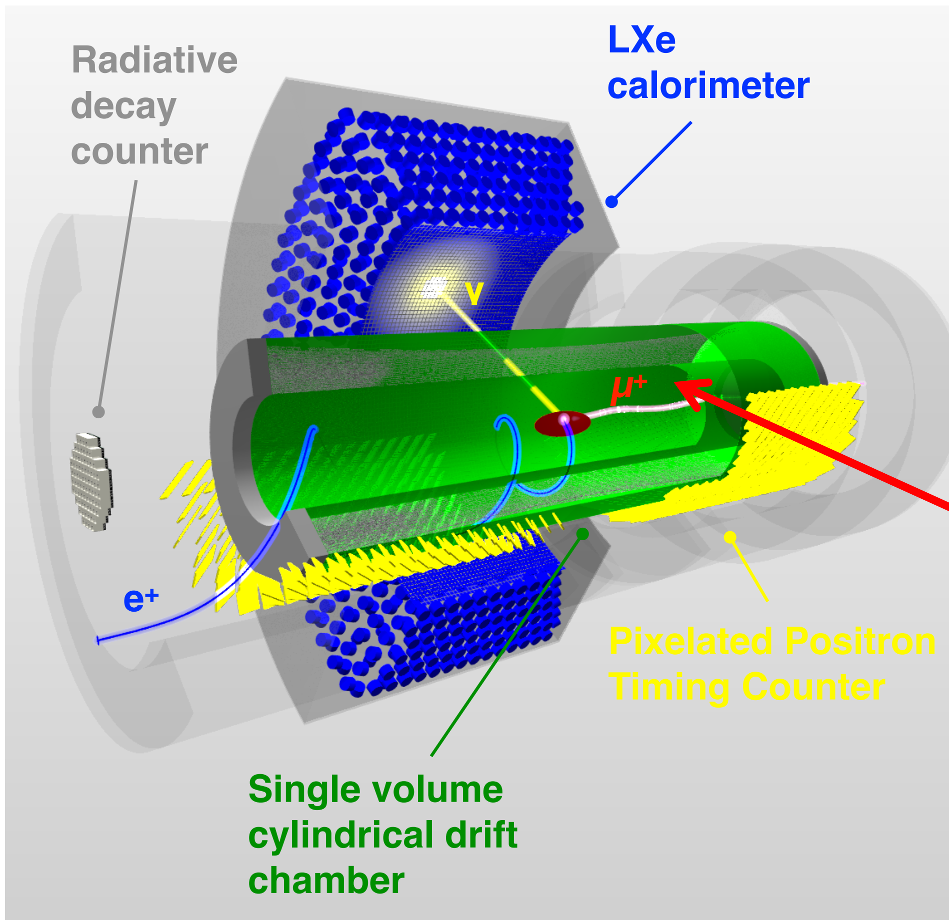
BR (μ→eγ) < 4.2×10^{-13}
at 90% C.L.

Eur.Phys.J.C76 (2016)

Magnified signal for illustrative purposes
No significant excess of the signal

The MEG Upgrade: MEGII

- Same detector concept as in MEG
- Increase beam intensity from 3 x 10^7 μ/s to 7 x 10^7 μ/s
- Improve rate capability, resolution and efficiency everywhere

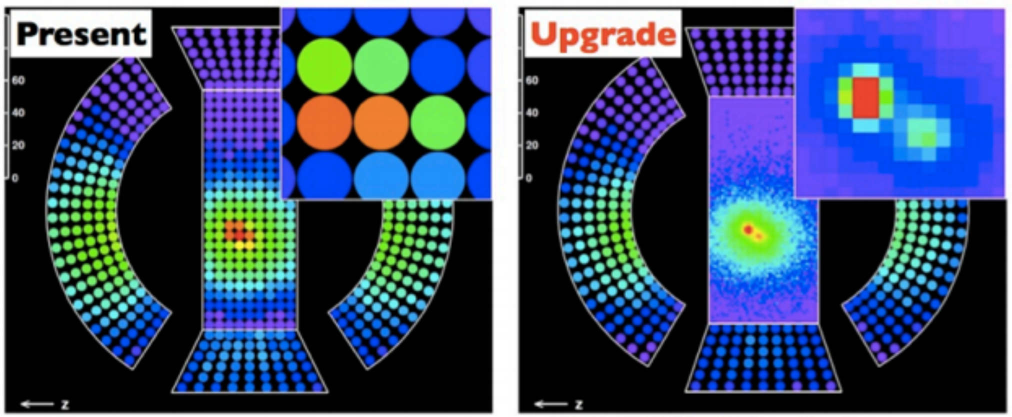


Aim to 6×10^{-14} sensitivity in 3 years data taking

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

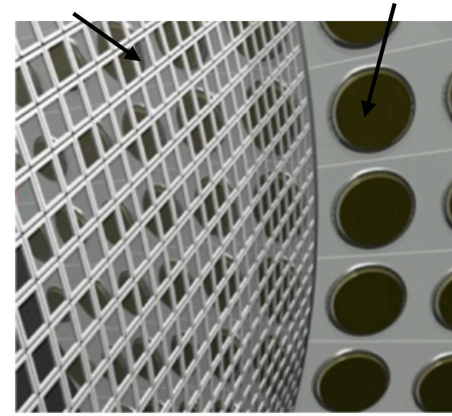
MEGII Detector Highlights: Liquid Xenon

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



MPPCs

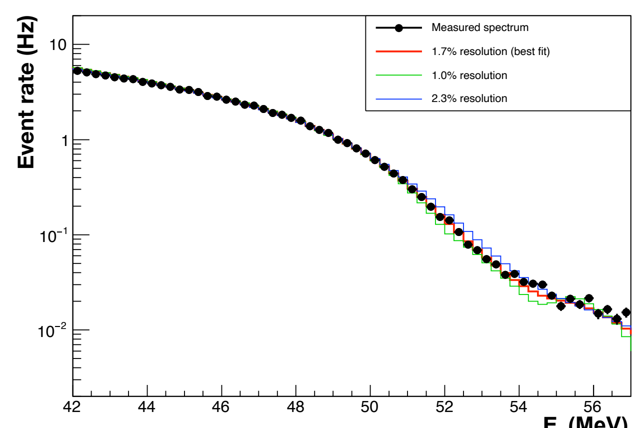
PMTs



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

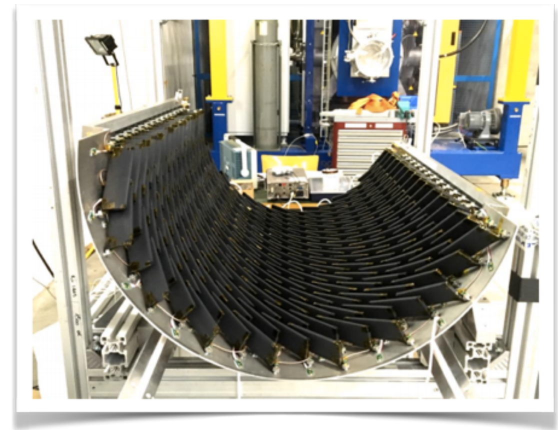
- Commissioned during engineering runs (2017-2021)

Background spectrum measured in 2019 compared to MC assuming different resolutions



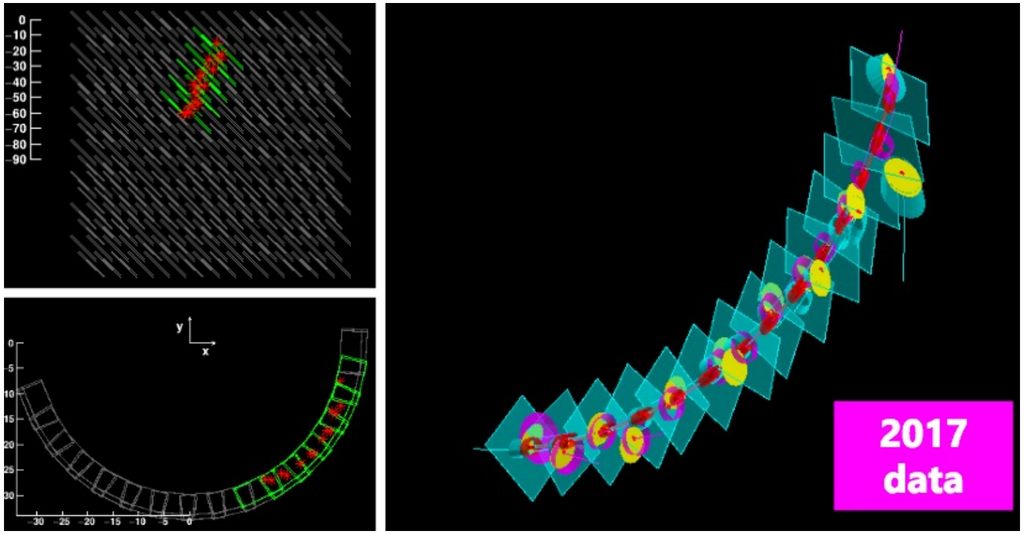
MEGII Detector Highlights: Timing Counters

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

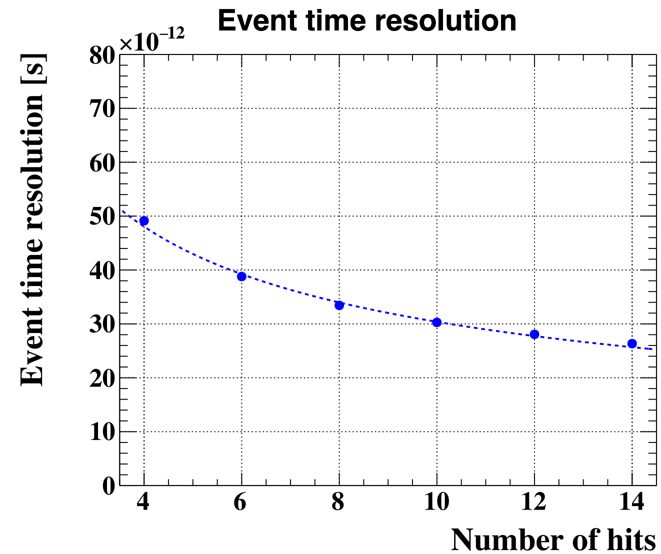


- Commissioned during 2017-2021 engineering runs

- **Reached design resolution σ_T=~35ps**

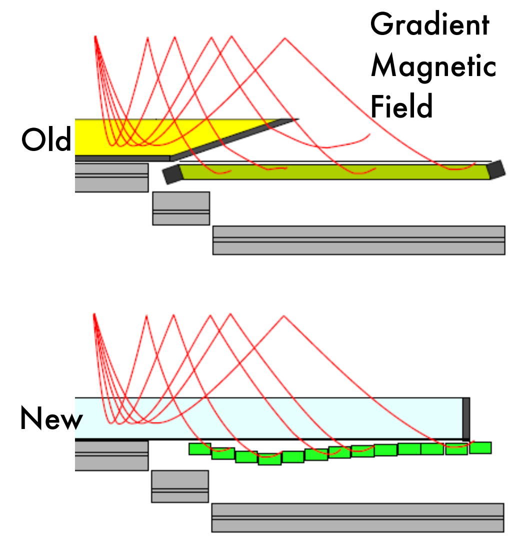


Time resolution (2017 data) as a function of the e^+ hits



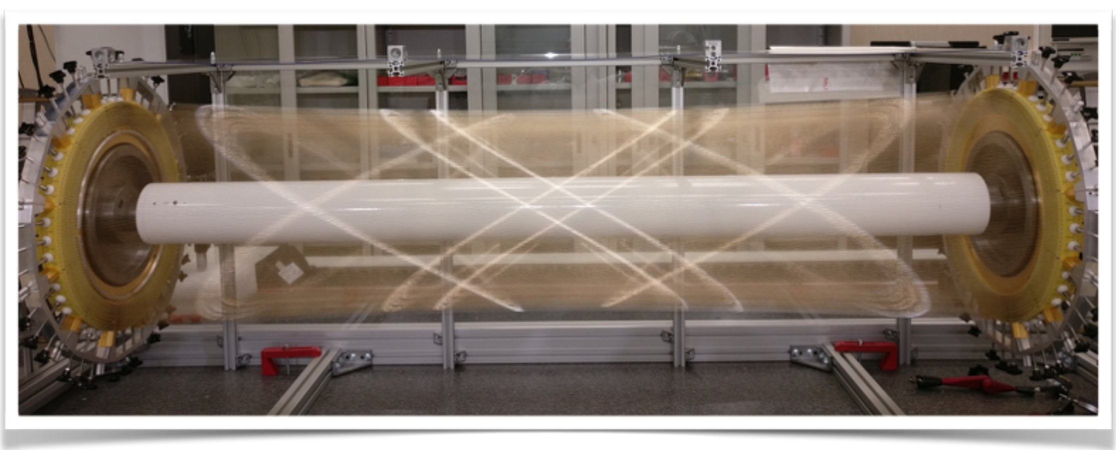
MEGII Detector Highlights: Drift Chamber

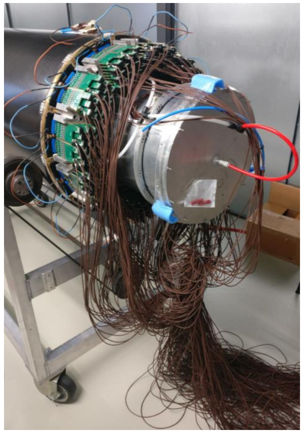
- **Single volume drift chamber** with 2π coverage
  - low mass single volume
  - 2m long ,1300 sense wires
  - stereo angle
  - high trasparency to TC



- Problems of wire fragility in presence of contaminants+humidity

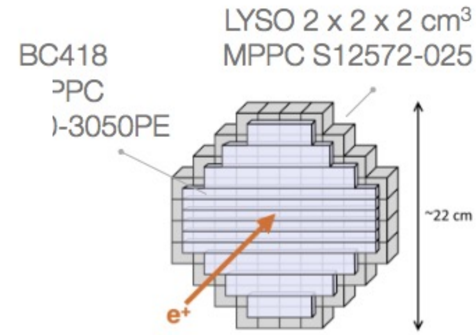
- **Detector successfully operated since 2020 with a gas mixture He:C_4H_{10} + isopropylic alcool + O_2**

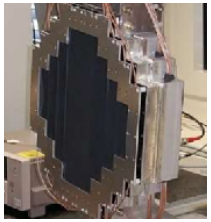




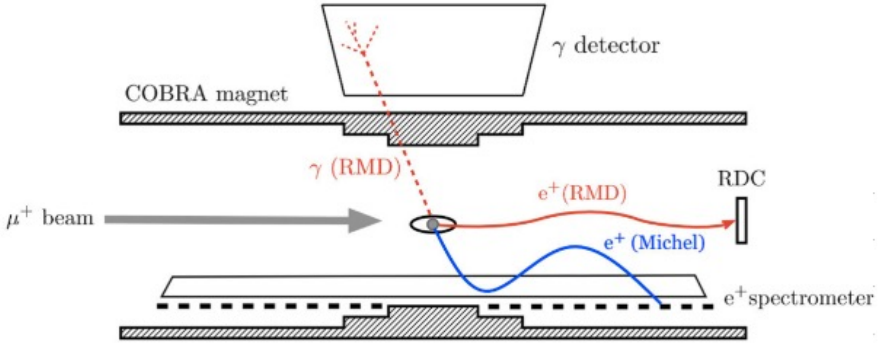
MEGII Detector Highlights: RDC

- **Radiative Decay Counter** (RDC):
  new auxiliary detector for background rejection
  - ~50% of accidental background has a photon that comes from a radiative decay
  - detects positron in coincidence with a photon in calorimeter
  - improve sensitivity by ~15%

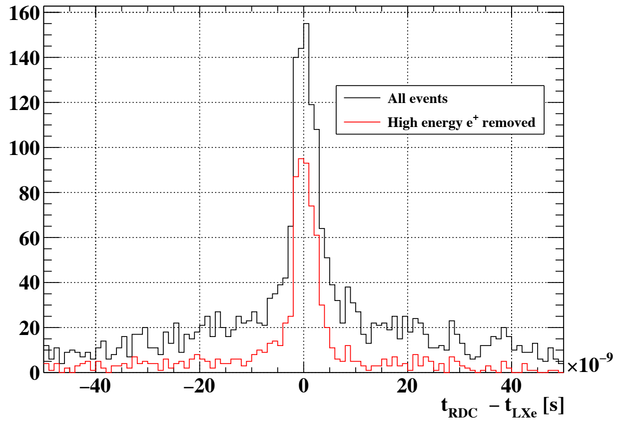




- **Performances demonstrated already in 2017 run**

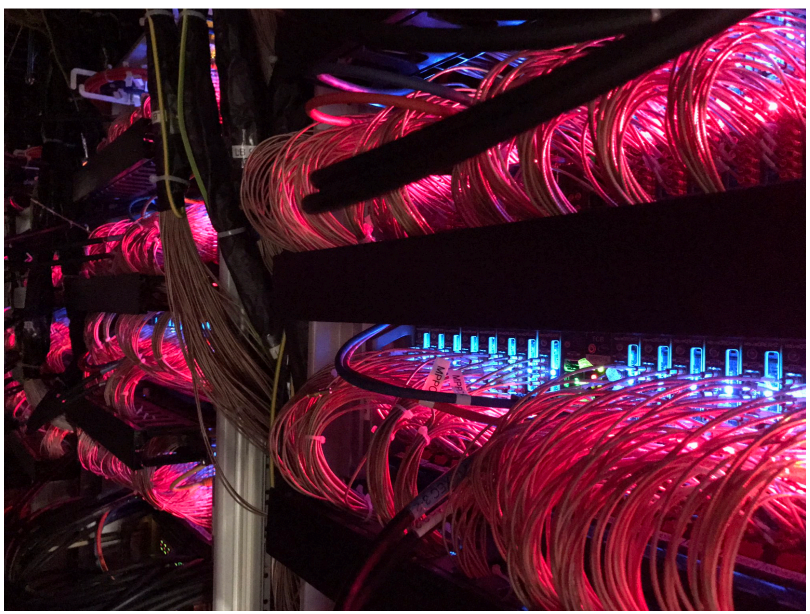


Time difference between an e^+ measured in RDC and a γ in the calorimeter



MEGII Detector Highlights: DAQ, Trigger

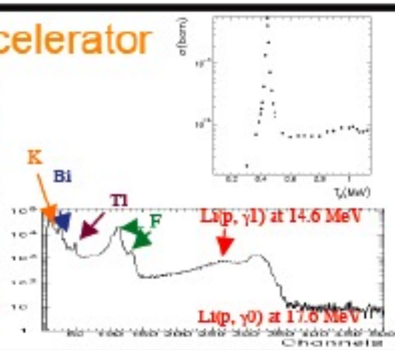
- **Trigger and DAQ** are now integrated in a custom designed compact board (WaveDAQ)
- Based on DRS4 chip
- Also provides power and amplification for SiPM and MPPC
- **The full system was successfully operated** during 2021 run



MEGII Calibrations

Xenon Calibration

Proton Accelerator



Li(p,γ)Be

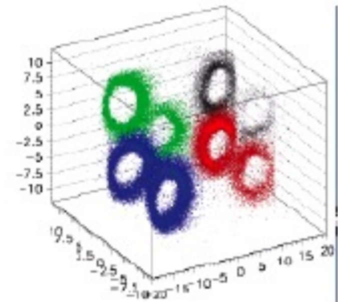
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

Alpha on wires

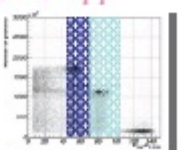


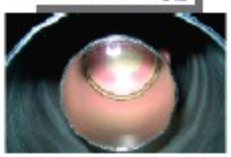
PMT QE & Att. L

Cold GXe

LXe

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





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

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

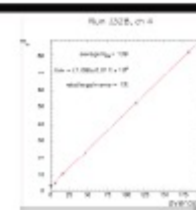
$\pi^- + p \rightarrow \gamma + n$ (129MeV)

LH_2 target

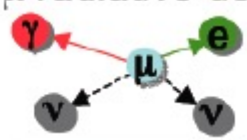
LED

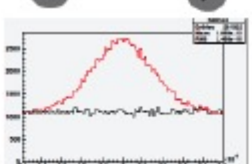
PMT Gain

Higher V with light att.



μ radiative decay





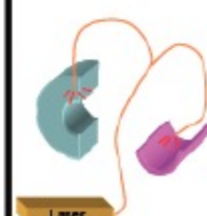
Lower beam intensity < 10^7

Is necessary to reduce pile-ups

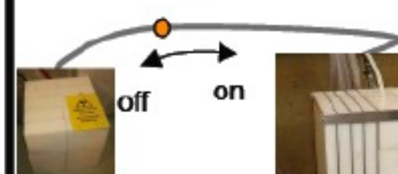
A few days ~ 1 week to get enough statistics

Laser

relative timing calib.

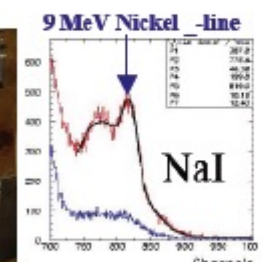


Nickel γ Generator



Illuminate Xe from the back

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



MEGII Status and Prospects

- Detector commissioned during engineering runs 2017-2021
- All detectors ran with complete readout in MEGII experimental conditions
- Run 2021 has already physics potential
- Everything is ready for the incoming physics data taking time (Summer 2022)
- We plan to reach 6×10^{-14} sensitivity in 3 years of data taking (MEG sensitivity = 5.3×10^{-13})

Symmetry 13 (2021) 9, 1591

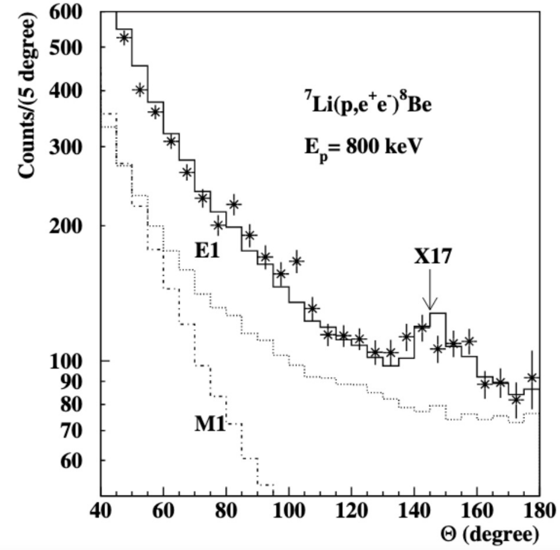
	R_{μ^+}	$\sigma_{p_{e^+}}$	$\sigma_{\theta_{e^+}}$	σ_{E_γ}	σ_{x_γ}	$\sigma_{t_{e^+\gamma}}$	ϵ_{e^+}	ϵ_γ	S_{90}
MEG	$3 \times 10^7\ s^{-1}$	380 keV/c	9.4 mrad	2.4%/1.7%	5 mm	122 ps	30%	63%	5.3×10^{-13}
MEG II design	$7 \times 10^7\ s^{-1}$	130 keV/c	5.3 mrad	1.1%/1.0%	2.4 mm	84 ps	70%	69%	6×10^{-14}
MEG II updated	$7 \times 10^7\ s^{-1}$	100 keV/c	6.7 mrad	1.7%/1.7%	2.4 mm	70 ps	65%	69%	6×10^{-14}

Not Only $\mu \rightarrow e\gamma$: X17 Search

- An experiment at the Atomki lab (Hungary), observed a 7σ significant excess in the distribution of the e^+e^- relative angle in the nuclear reaction:

  $^{7}Li(p,e^+e^-)^{8}Be$

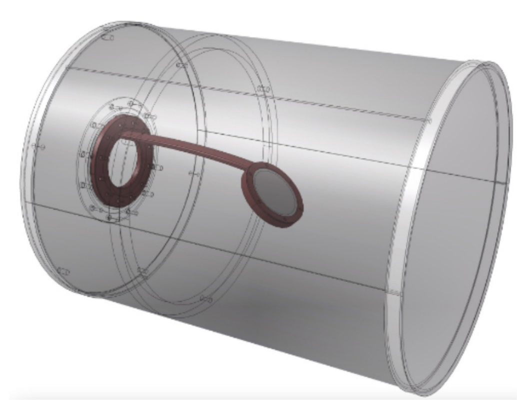
- This anomaly can be interpreted as **a new particle called X17**



- MEGII has the opportunity to search for the X17 with:

  - the C-W accelerator used for calibrating the calorimeter to produce nuclear reaction
  - the drift chamber to detect e^+e^- pair (reduced magnetic field)

Redesign of the target region



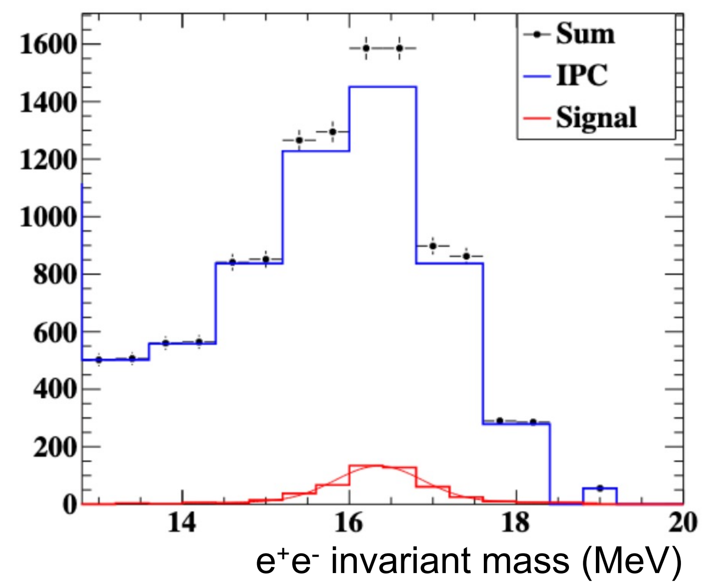
Not Only μ→eγ: X17 search

- Preliminary feasibility studies show that ~5σ sensitivity could be reached in few days data taking

  - First tests done during 2021 and 2022 shutdowns (stability of the setup, trigger...)

  - Measurement foreseen in late 2022

Signal and background (Internal Pair Creation) from MC simulations for 40 hours DAQ (preliminary)

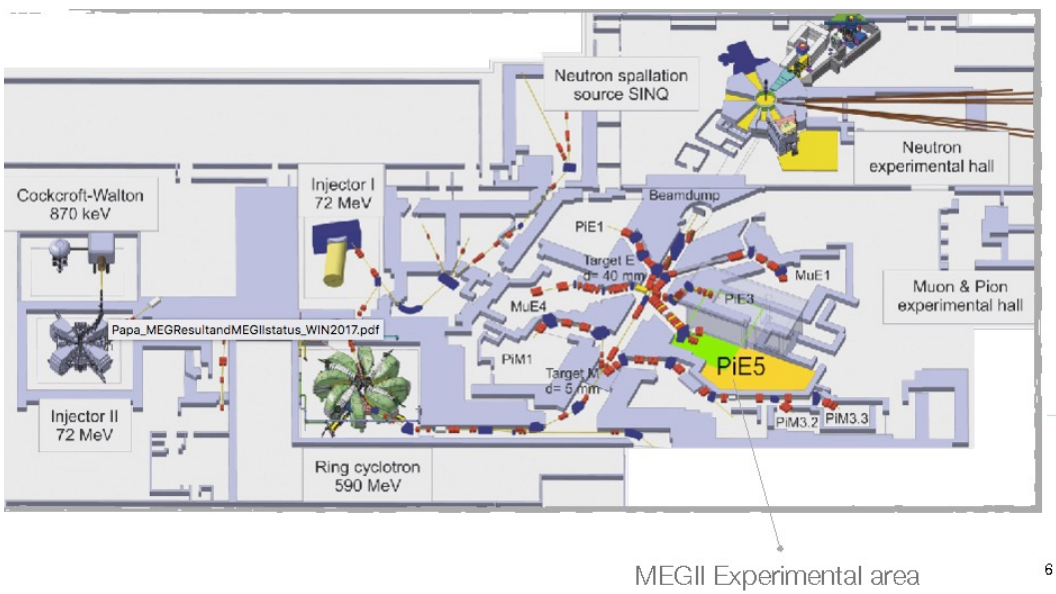


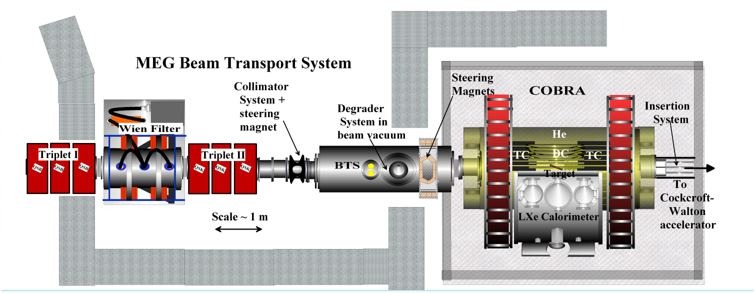
Thank you for the attention

Backup

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^+





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

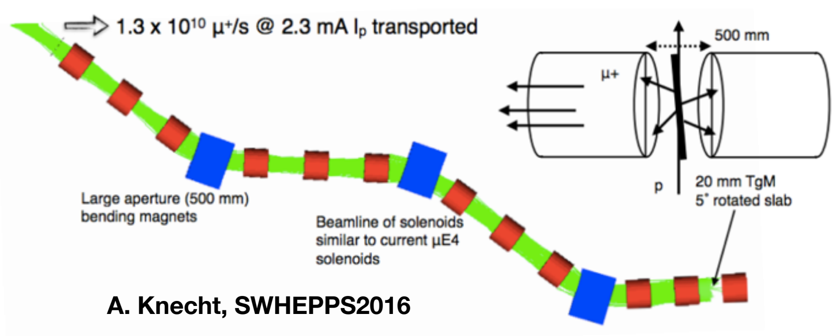
$$B_{sig} \propto \Gamma_\mu \qquad B_{acc} \propto \Gamma_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta T_{e\gamma} \cdot (\delta\Theta_{e\gamma})^2$$

HiMB Project @ PSI

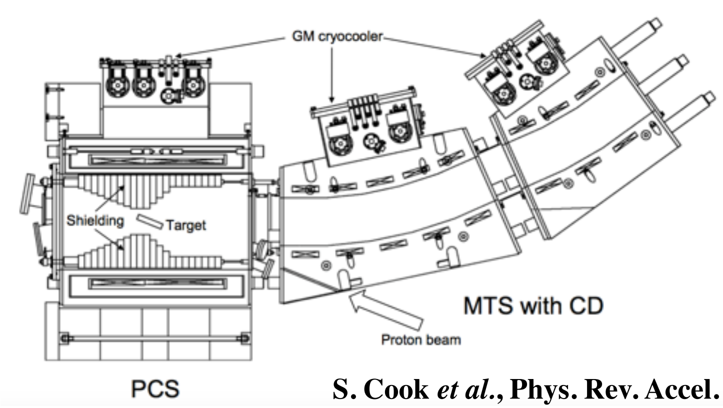
x4 μ capture eff.

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

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	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$	$1.4 \cdot 10^{-8}$	$2.0 \cdot 10^{-7}$	$2.9 \cdot 10^{-9}$
$C_{ee}^{S\,LL}$	$4.8 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	$8.1 \cdot 10^{-7}$	$5.8 \cdot 10^{-8}$	$1.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-5}$
$C_{\mu\mu}^{S\,LL}$	$2.3 \cdot 10^{-7}$	$7.2 \cdot 10^{-8}$	$4.6 \cdot 10^{-6}$	$3.3 \cdot 10^{-7}$	$7.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
$C_{\tau\tau}^{S\,LL}$	$1.2 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$2.4 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$2.4 \cdot 10^{-5}$	$3.5 \cdot 10^{-7}$
$C_{\tau\tau}^{T\,LL}$	$2.9 \cdot 10^{-9}$	$9.0 \cdot 10^{-10}$	$5.7 \cdot 10^{-8}$	$4.1 \cdot 10^{-9}$	$5.9 \cdot 10^{-8}$	$8.5 \cdot 10^{-10}$
$C_{\tau\tau}^{S\,LR}$	$9.4 \cdot 10^{-6}$	$2.9 \cdot 10^{-6}$	$1.8 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$2.7 \cdot 10^{-6}$
$C_{bb}^{S\,LL}$	$2.8 \cdot 10^{-6}$	$8.6 \cdot 10^{-7}$	$5.4 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$9.0 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$

.....

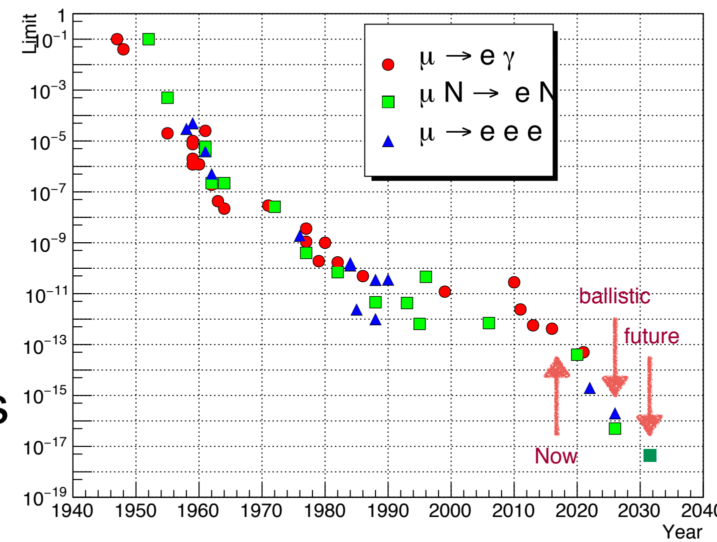
arXiv:170203020
A. Crivellin et al.

1 column = present best limit
2 column = future limit

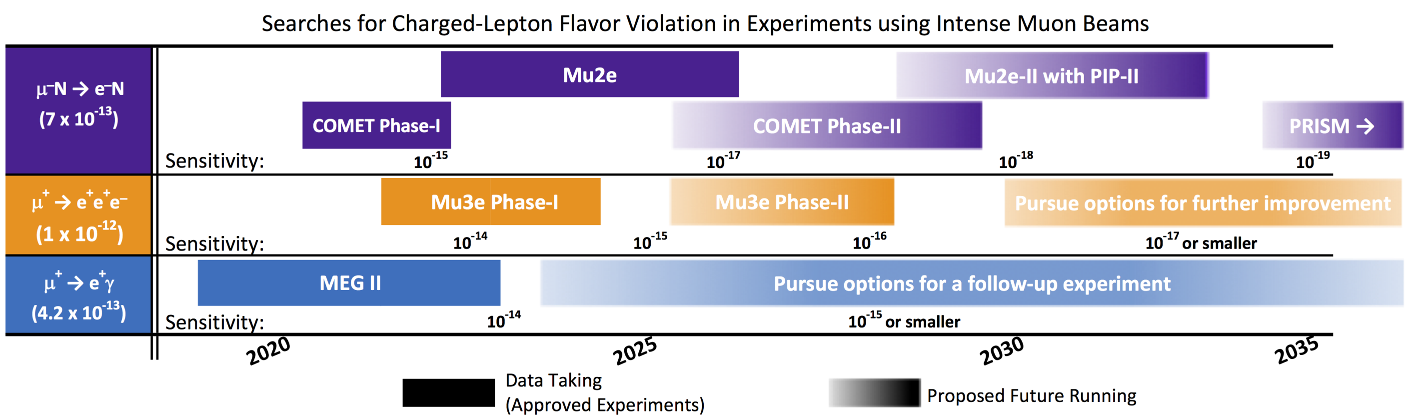
Future μ→e experiment

- 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

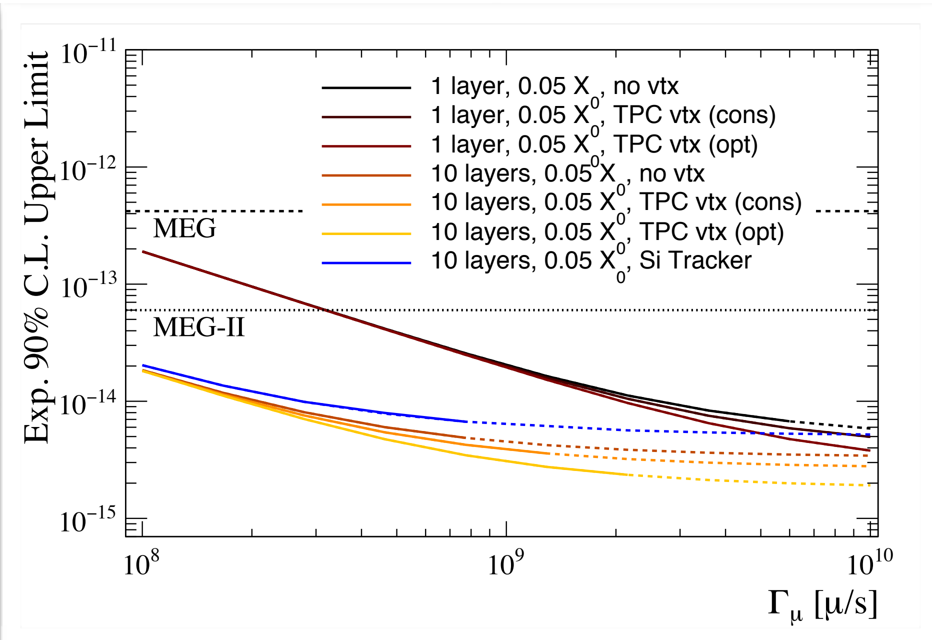


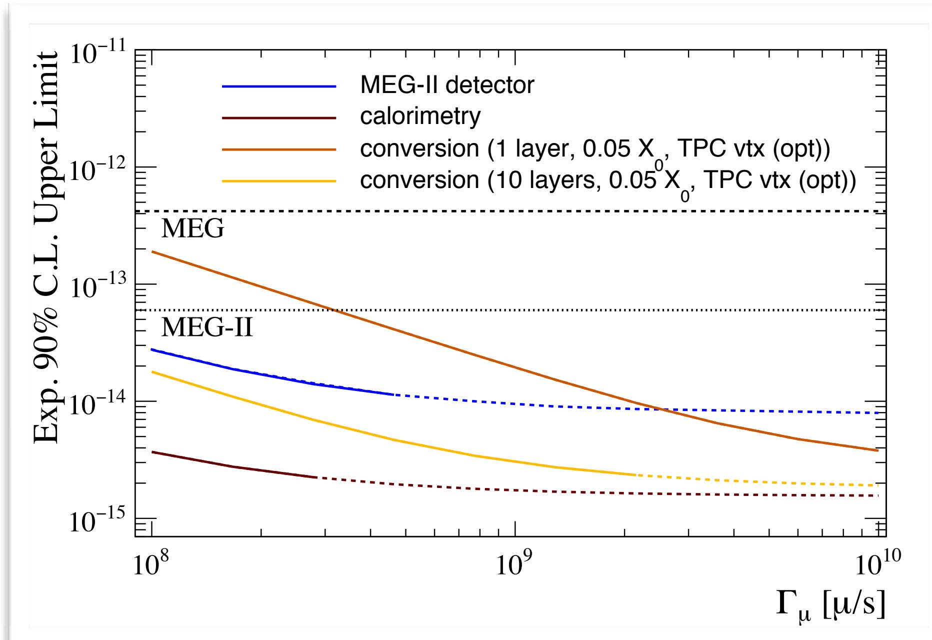
Future μ→eγ experiment

Photon conversion approach

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

Photon conversion vs calorimetric approach





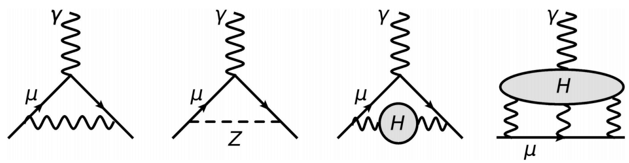
- A few 10^{-15} level seems to be within reach for 3 years running with 10^9 muons/s with

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
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ †	$< 6.1 \times 10^{-13}$	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

Connection with g_μ-2

- Deviation of the anomalous magnetic moment of the muon (a_μ = g_μ-2) from SM prediction recently confirmed by FNAL

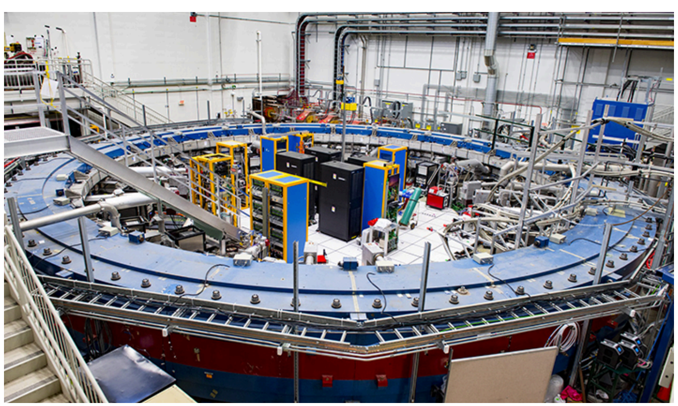


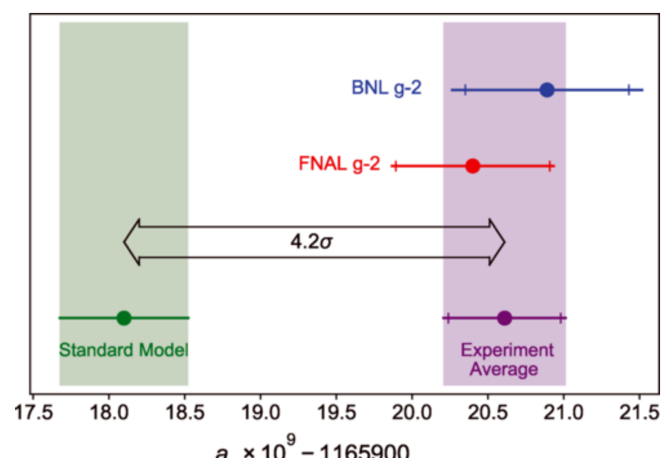
- $\mu \to e\gamma$ and g_μ-2 are intrinsically connected
- Dipole operator in effective field theory

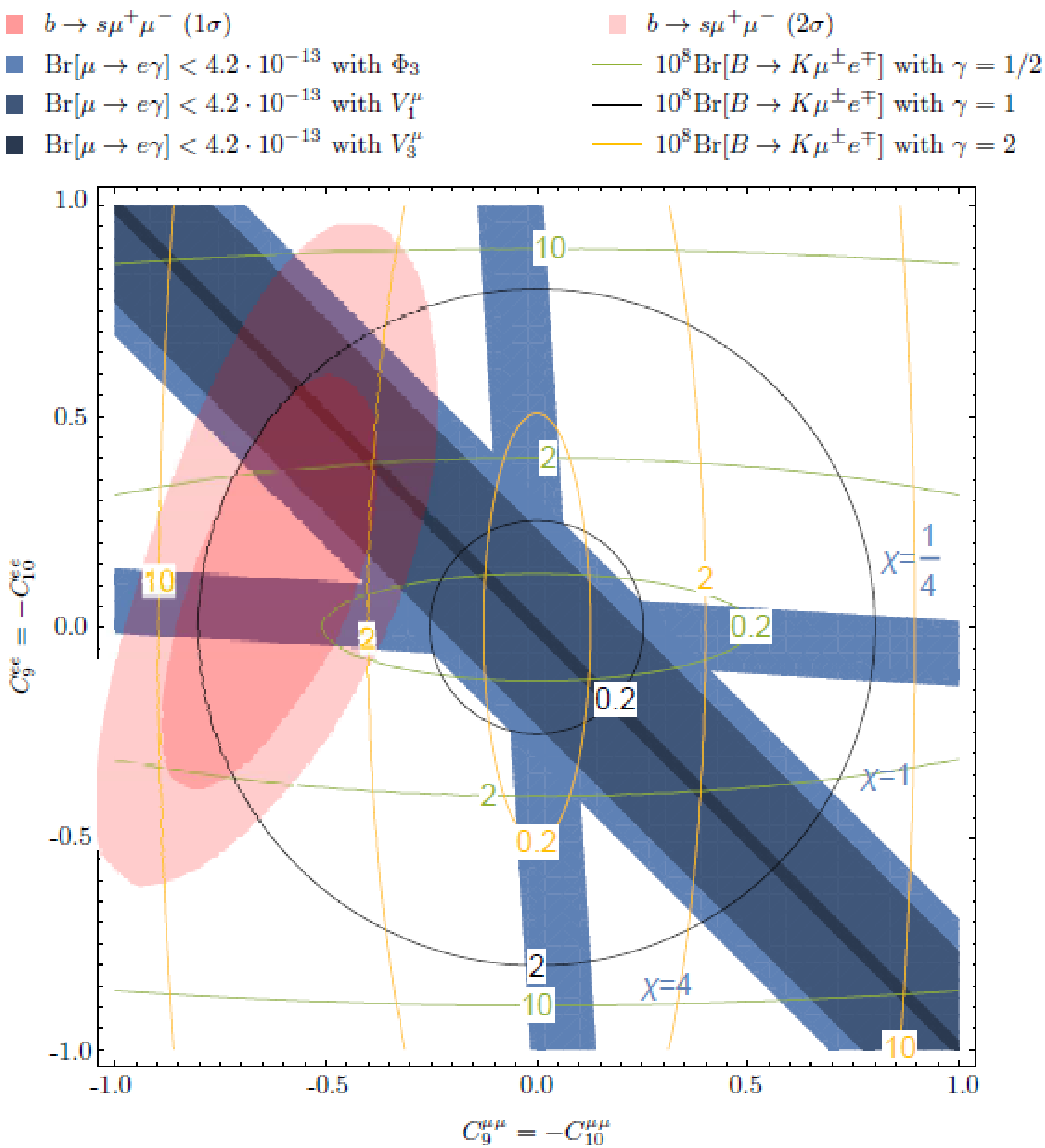
$$\mathcal{H}_{\rm eff} = c_R^{\ell_f \ell_i}\, \bar{\ell}_f \sigma_{\mu\nu} P_R \ell_i F^{\mu\nu}$$

$$a_{\ell_i} = -\frac{4 m_{\ell_i}}{e}\, \mathrm{Re}\, c_R^{\ell_i \ell_i}$$

$$\mathrm{Br}[\mu \to e\gamma] = \frac{m_\mu^3}{4\pi\, \Gamma_\mu}\left(|c_R^{e\mu}|^2 + |c_R^{\mu e}|^2\right)$$






$b \to s\mu^+\mu^-$ (1σ)
$b \to s\mu^+\mu^-$ (2σ)
$\mathrm{Br}[\mu \to e\gamma] < 4.2 \cdot 10^{-13}$ with Φ_3
$10^8 \mathrm{Br}[B \to K\mu^\pm e^\mp]$ with $\gamma = 1/2$
$\mathrm{Br}[\mu \to e\gamma] < 4.2 \cdot 10^{-13}$ with V_1^μ
$10^8 \mathrm{Br}[B \to K\mu^\pm e^\mp]$ with $\gamma = 1$
$\mathrm{Br}[\mu \to e\gamma] < 4.2 \cdot 10^{-13}$ with V_3^μ
$10^8 \mathrm{Br}[B \to K\mu^\pm e^\mp]$ with $\gamma = 2$
$\chi=\frac{1}{4}$
$\chi=1$
$\chi=4$
$C_9^{ee} = -C_{10}^{ee}$
$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$

MEG II Target Monitoring System

- Dominant systematic in MEG due to target position and deformation (5% change in upper limit)

- Photogrammetric method to monitor the target during the run has been developed

- Need precision < 100μm not to affect positron angle resolution

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