III. Lepton Flavor Physics

Section follows lecture from S. Westhoff

1. Lepton masses and mixing in the Standard Modell

The flavor structure of the lepton sector in the Standard Model can be analyzed similarly to the quark sector (assuming massless neutrinos).

Recall that the masses of the charged leptons are generated by their interaction with Higgs VEV:

Symmetry breaking:

$$\mathcal{L}^{Lepton}_{Yukawa} = -\sum_{i,j}\left\{Y_E^{ij}\overline{L}_L^i E_R^j H + h.c.\right\} \xrightarrow{\langle H\rangle}$$

$$\mathcal{L}^{Lepton}_{Mass} = -\frac{v}{\sqrt{2}}\sum_{i,j}\left\{\overline{E}_L^i Y_E^{ij} E_R^j + h.c.\right\}$$

Y_E in general not diagonal

Leptons:	$L_L^i == \begin{pmatrix} N_L^i \\ E_L^i \end{pmatrix}$	E_R^i

Yukawa matrix $\mathbf{Y}_E$ is diagonalized by: $E_L = \mathbf{V}_{e_L} e_L$ and $E_R = \mathbf{V}_{e_R} e_R$

(Remark: different notation than in Chap. I, e_L and e_R are here linear combinations of $E_{L,R}$)

$$\hat{\mathbf{Y}}_E = \mathbf{V}_{e_L}^\dagger \mathbf{Y}_E \mathbf{V}_{e_R} = \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$$

In the mass eigenbasis of the charged leptons, the charged weak interaction (W exchange) of the leptons is given:

$$\mathcal{L}_{weak}^{cc} = \frac{g}{\sqrt{2}} \bar{N}_L \gamma^\mu V_{e_L} e_L W_\mu^+ + h.c. = \frac{g}{\sqrt{2}} \bar{\nu}_L \gamma^\mu e_L W_\mu^+ + h.c.$$

- For massless neutrinos, the transformation $N_L \to V_{\nu_L} \nu_L$ with $V_{\nu_L} = V_{e_L}$ renders the charged current flavor-diagonal $(V_{\nu_L}^\dagger V_{e_L} = V_{e_L}^\dagger V_{e_L} = 1)$.
- For massive neutrinos, the flavor mixing among left-handed leptons is physical:

$$\mathcal{L}_{weak}^{cc} = \frac{g}{\sqrt{2}} \bar{\nu}_L \gamma^\mu \underbrace{V_{\nu_L}^\dagger V_{e_L}}_{U_{PMNS}^\dagger} e_L W_\mu^+ + h.c.$$

CC does not remain diagonal in mass states

U_{PMNS} : Pontecorvo-Maki-Nakagawa-Sakata matrix

We work in a basis where Y_E is diagonal. The neutrino mass (ν_i) and flavor (N_i) eigenstates are then related by:

$$N_\alpha = U_{PMNS}^{\alpha i}\, \nu_i \qquad U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

The physical (mass) neutrino states are thus mixtures of different flavor eigenstates (see below).

Like the CKM matrix the PMNS*) matrix can be parametrized by 3 angles θ_{12}, θ_{23}, θ_{13} and 1 phase δ (if neutrinos are Majorana particles the lepton sector has two additional phases – see below). From neutrino oscillation experiments, we know that

$$\sin^2\theta_{12} \approx 0.3, \quad \sin^2\theta_{23} \approx 0.4, \quad \sin^2\theta_{13} \approx 0.02 \qquad (\text{for } m_1 < m_2 < m_3)$$

Flavor mixing in the lepton sector is thus sizeable. The PMNS matrix does not exhibit a hierarchical structure as the CKM matrix does.

*) PMNS matrix is unitary by construction

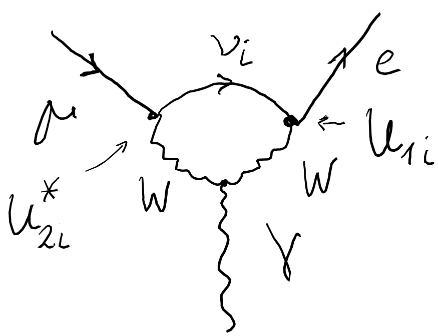
2. Very rare decays for charged leptons: flavor violation

In the Standard Model there are no FCNC with leptons at tree-level. At one-loop level, FCNC are induced by weak interactions. They can (in principle) be observed in flavor-changing processes involving charged leptons, such as

$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\mu \to 3e$ (unmeasurable small in SM, see below)

2.1 $\mu \to e\gamma$ decay:

With massive neutrinos this process can be induced at loop-level:



$$O_\gamma \sim m_\mu \bar{e}_L \sigma_{\mu\nu} F^{\mu\nu} \mu_R$$

The amplitude is given by

$$\mathcal{A} \sim \sum_{i=1}^{3} U^*_{\mu i} U_{ei} f\left(\frac{m_i^2}{M_W^2}\right) \quad \text{with} \quad f\left(\frac{m_i^2}{M_W^2}\right) \approx f(0) + f'(0)\frac{m_i^2}{M_W^2} + \ldots$$

m_i neutrino mass

Loop function (see above)

Applying the unitarity condition of the PMNS matrix $\sum_i U_{2i}^* U_{1i} = 0$ one obtains

$$\mathcal{A} \sim \sum_{i=2}^{3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \qquad \text{with} \qquad \Delta m_{i1}^2 = m_i^2 - m_1^2$$

GIM suppression.

Very small!

Due to the small neutrino mass differences, the GIM mechanism is extremely effective and strongly suppresses the decay rate. Normalized to the dominant decay process $\mu \to e \nu_\mu \bar{\nu}_e$ one obtains the branching fraction:

$$BR(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e \nu_\mu \bar{\nu}_e)} = \frac{3\alpha}{32\pi} \left| \sum_{i=2}^{3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 < 10^{-54}$$

The currently strongest experimental limit is provided by the MEG experiment:

$$BR(\mu \to e\gamma) < 4.2 \cdot 10^{-13} \text{ (90\%CL)}$$

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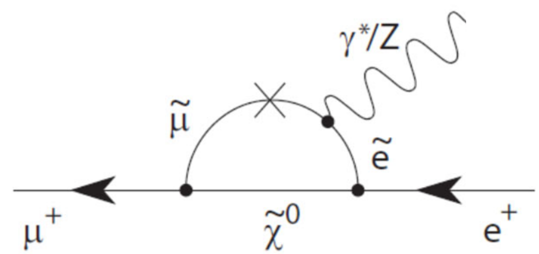
(many orders above the SM prediction)

Due to the strong suppression of the Standard Model contribution an experimental observation of the decay $\mu \rightarrow e\gamma$ would be a clear sign of New Physics, e.g. from additional SUSY contributions:



Also other Lepton Flavor Violating (LFV) decays are excellent probes for NP.

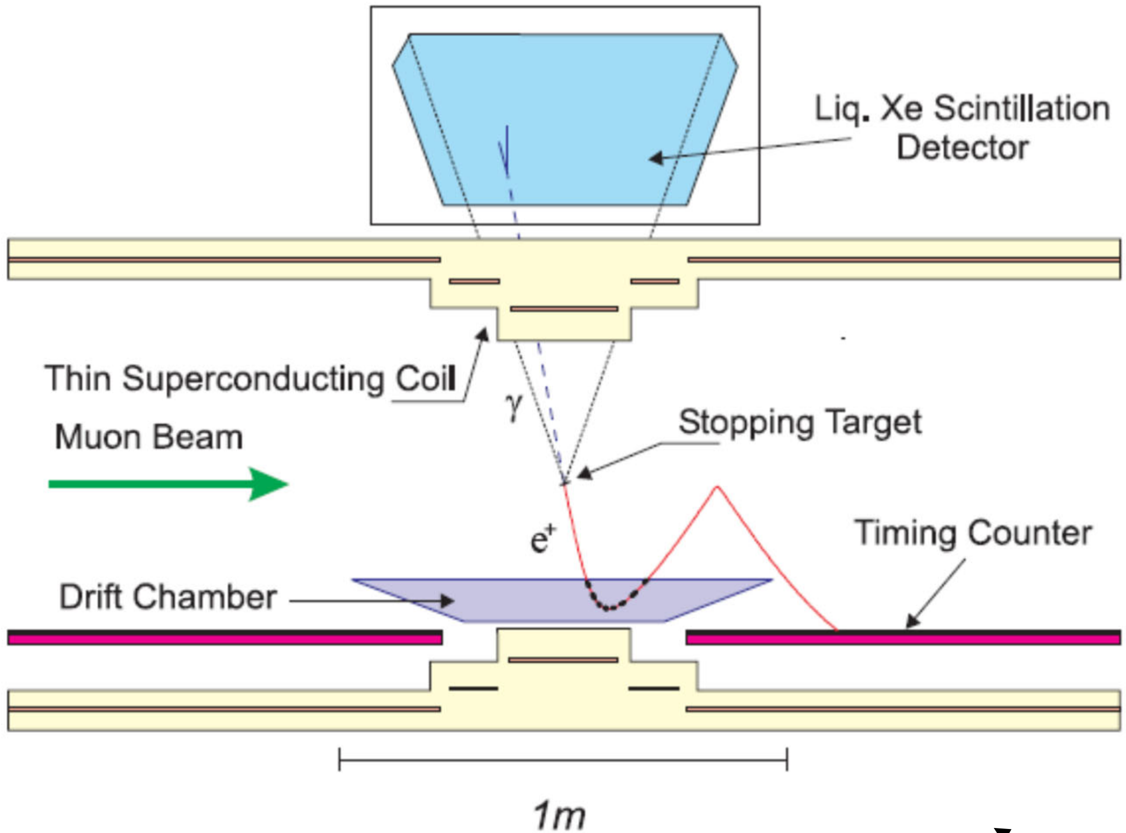
<u>MEG/MEG-II experiment:</u>

Search for $\mu \rightarrow e\gamma$ requires a high-intensity μ-beam, stopped inside a detector.

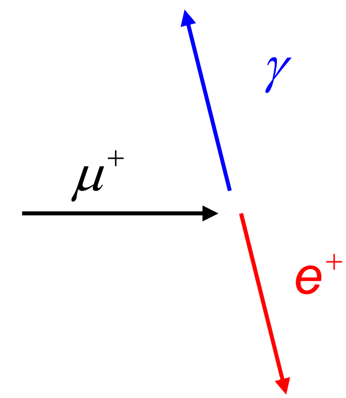
PSI (Paul Scherrer Institute, Villingen, Schweiz): μ^+-beam w/ intensities of up to 10^8 μ/sec (produced by a 1.2 MW proton cyclotron). Future plan to build a new beam-line w/ ~10^9 μ/sec.

Principle:
Muon beam is stopped on target in the detector: back-to-back topology of the $e\gamma$.

MEG Detector:



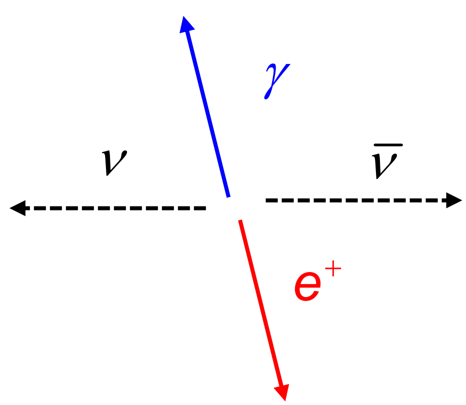
Signature:

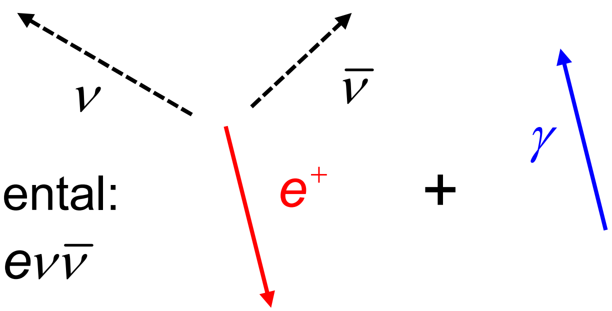


Backgrounds:

Radiative μ decay
(correlated)

$\mu \to e(\gamma)\nu\bar{\nu}$





Accidental:

$\mu \to e\nu\bar{\nu}$

$+\gamma$

(from different source: e.g. e^+ annihilation)

MEG Results: sample of 1.8×10^{14} μ^+ decays   Eur. Phys. J. C (2016) 76:434

Signal:
100times
upper limit

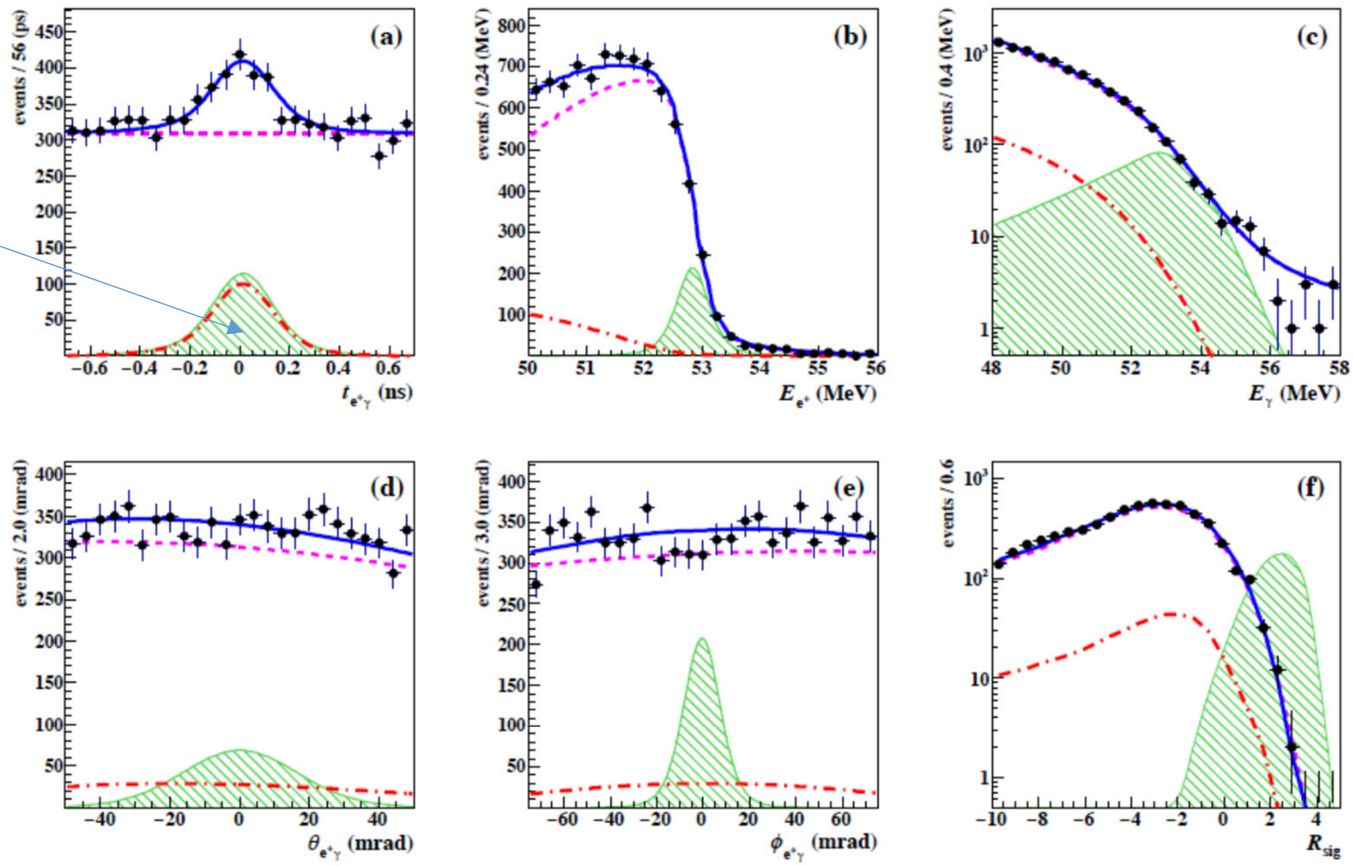
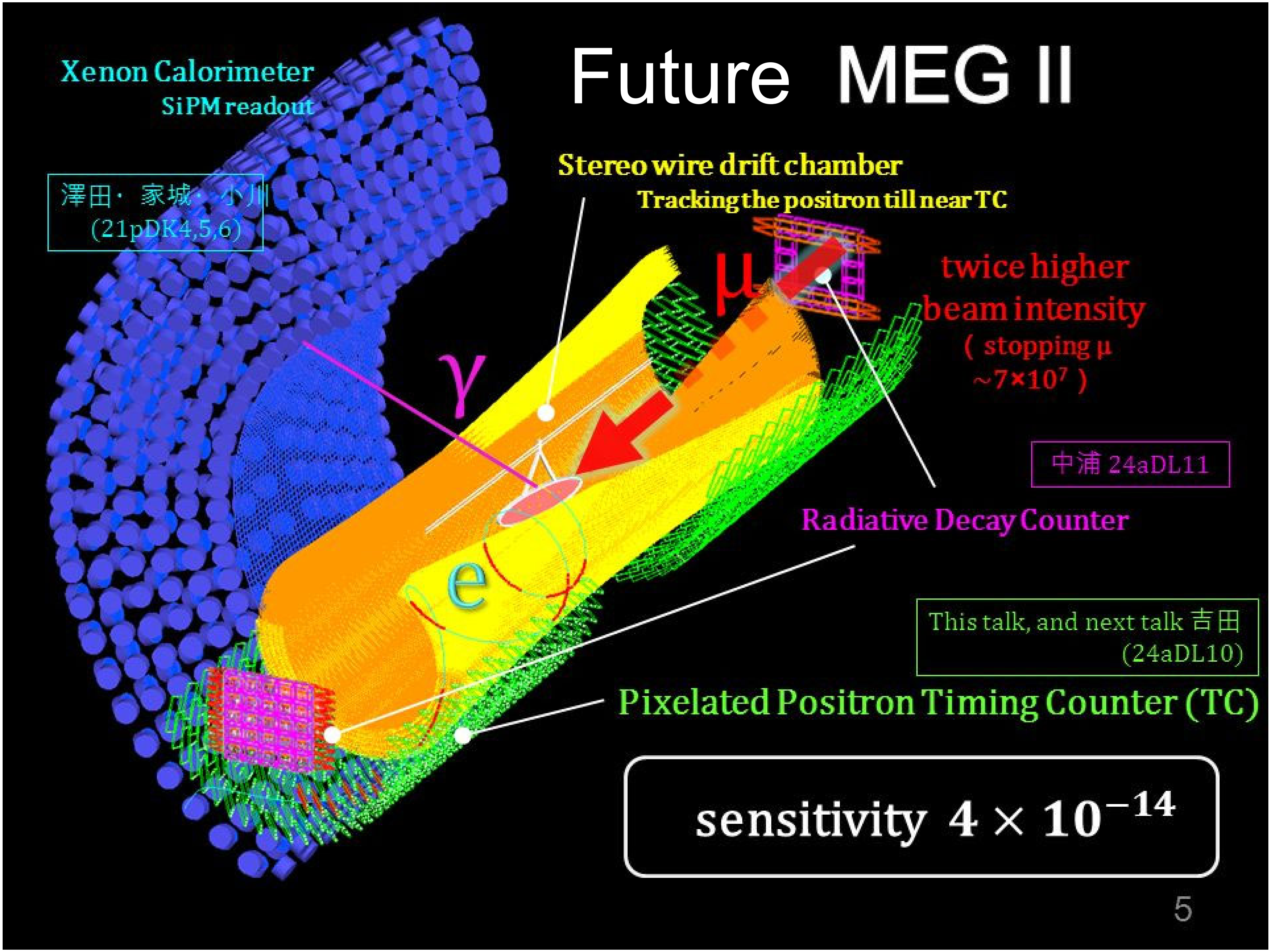


Figure 2: Data and PDFs from the analysis of the 2009-2013 data. Black dots: data. Blue: Total PDF. Magenta: accidental background. Red: RMD background. Green: Expected signal for a BR equal to 100 times the upper limit. See the text for the definition of R_{sig} the bottom-right plot.

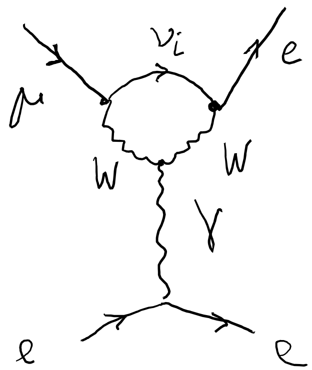
$$BR\left(\mu \rightarrow e\gamma\right) < 4.2\cdot 10^{-13} \text{ (90\%CL)}$$

SM: $B(\mu\rightarrow e\nu\bar{\nu}\gamma)=(6.03\pm0.14(\text{stat.})\pm0.53(\text{sys.}))\times10^{-8}$, $E_e>45$ MeV and $E_\gamma>40$ MeV,



Future MEG II
Xenon Calorimeter
SiPM readout
澤田・家城・小川
(21pDK4,5,6)
Stereo wire drift chamber
Tracking the positron till near TC
μ
γ
e
twice higher
beam intensity
(stopping μ
~7×10^7)
中浦 24aDL11
Radiative Decay Counter
This talk, and next talk 吉田
(24aDL10)
Pixelated Positron Timing Counter (TC)
sensitivity 4 × 10^−14

2.2 μ→eee decay:



$$O_\gamma \sim m_\mu \bar{e}_L \sigma_{\mu\nu} F^{\mu\nu} \mu_R$$

$$O_{4\ell} \sim \left(\bar{e}_L \gamma_\mu \mu_L\right)\left(\bar{e}\gamma^\mu e\right)$$

Additional suppression from γ conversion.

Currently strongest experimental limit from SINDRUM experiment:

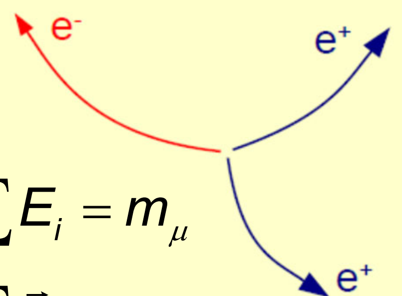
$$BR\left(\mu \to eee\right) < 1.0 \cdot 10^{-12} \text{ (90\%CL)}$$

Future experiment:
Mu3e at PSI – strong Heidelberg contribution (AG Prof. A. Schöning).
Very promising experiment – will be discussed in the following.

Background reduction

Signal topology:

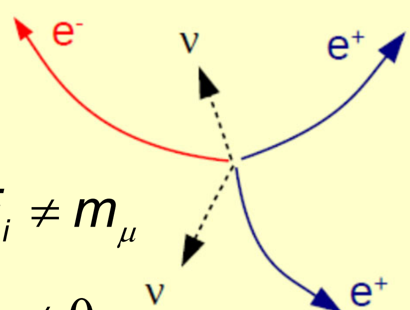
decay
at rest



$$\sum_i E_i = m_\mu$$

$$\sum_i \vec{p}_i = 0$$

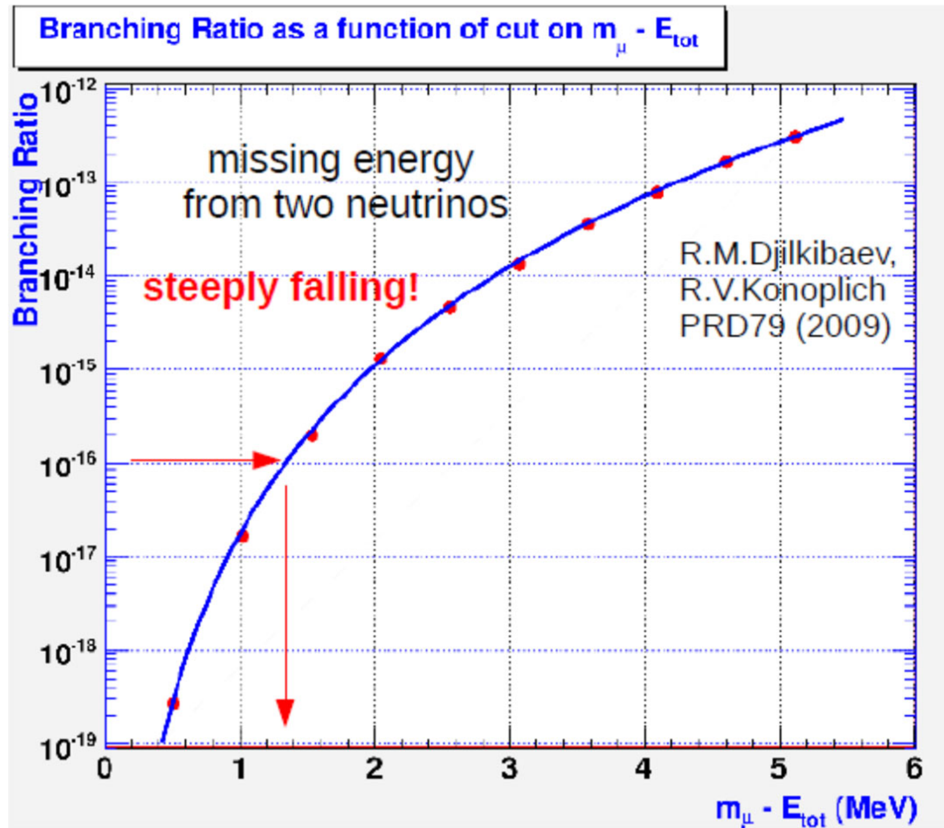
Radiative decays:



$$\sum_i E_i \neq m_\mu$$

$$\sum_i \vec{p}_i \neq 0$$

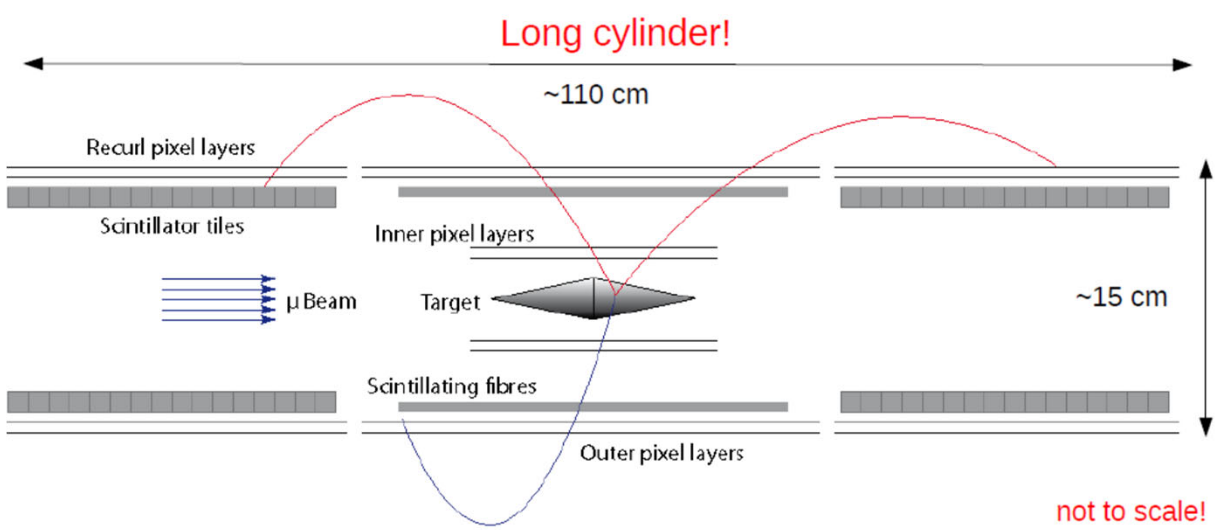
Accidentals:
Overlay of 2 ordinary
decays with another e.

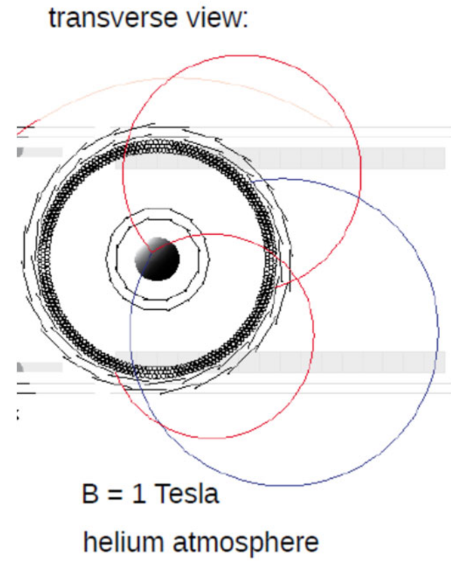


Experimental
energy resolution

Sensitivity to BR of 10^{-14} requires experim.tal energy resolution better than 1 MeV!
In addition excellent vertex resolution.

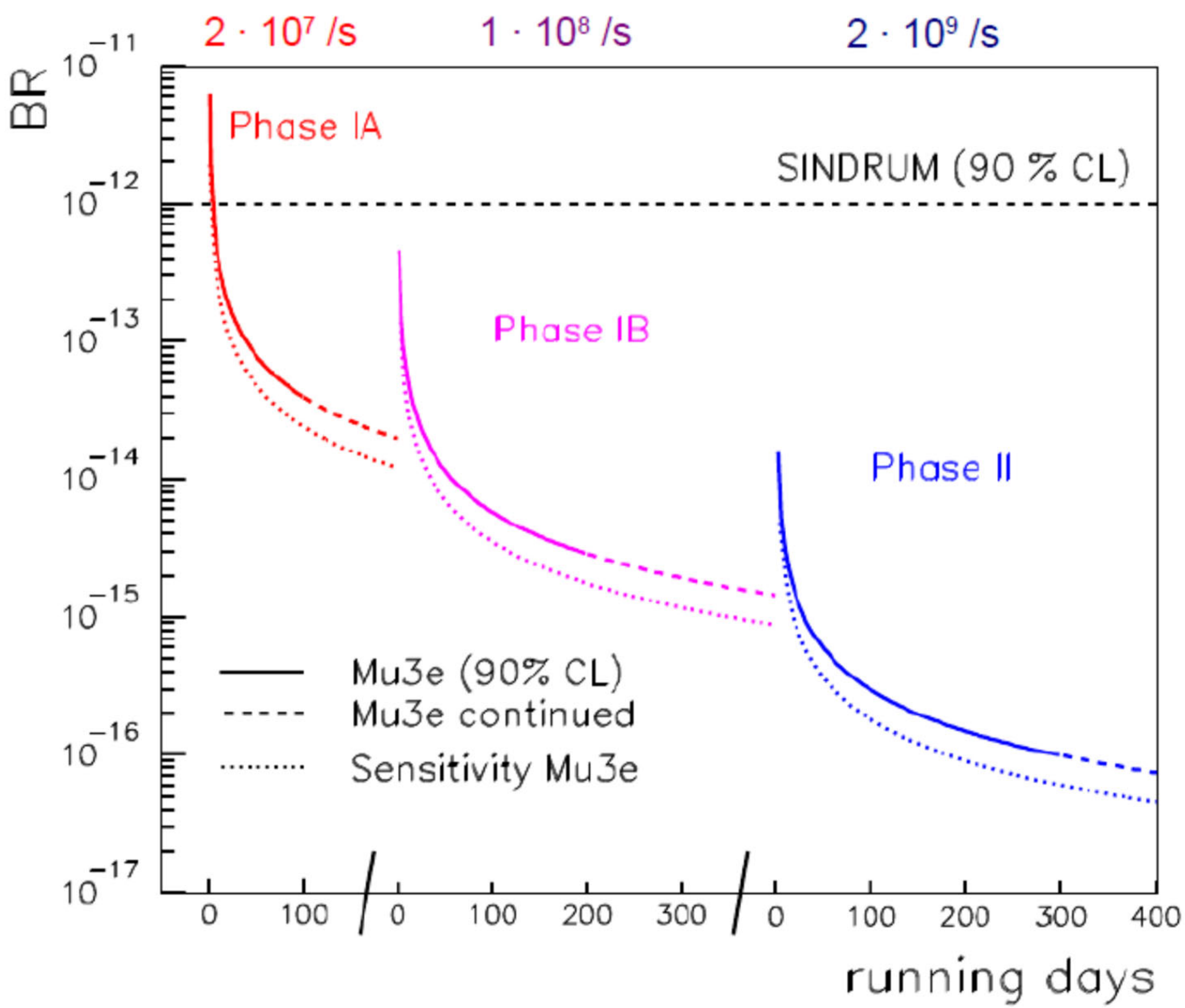
Mu3e detector



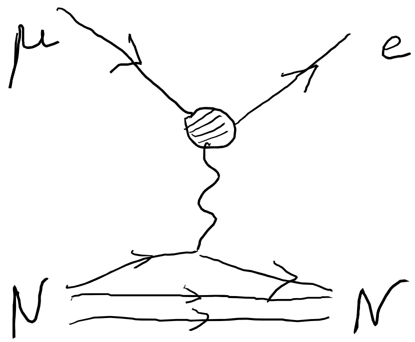


Tracking detector will consist of very thin CMOS pixel sensors to minimize multiple scattering and to optimize energy / vertex resolution.

Mu3e Prospects



2.3 $\mu \to e$ conversion: $\mu^- N \to e^- N$



$$O_\gamma \sim m_\mu \bar{e}_L \sigma_{\mu\nu} F^{\mu\nu} \mu_R$$

$$O_{2\ell 2q} \sim \left(\bar{e}_L \gamma_\mu \mu_L\right)\left(\bar{q}\gamma^\mu q\right)$$

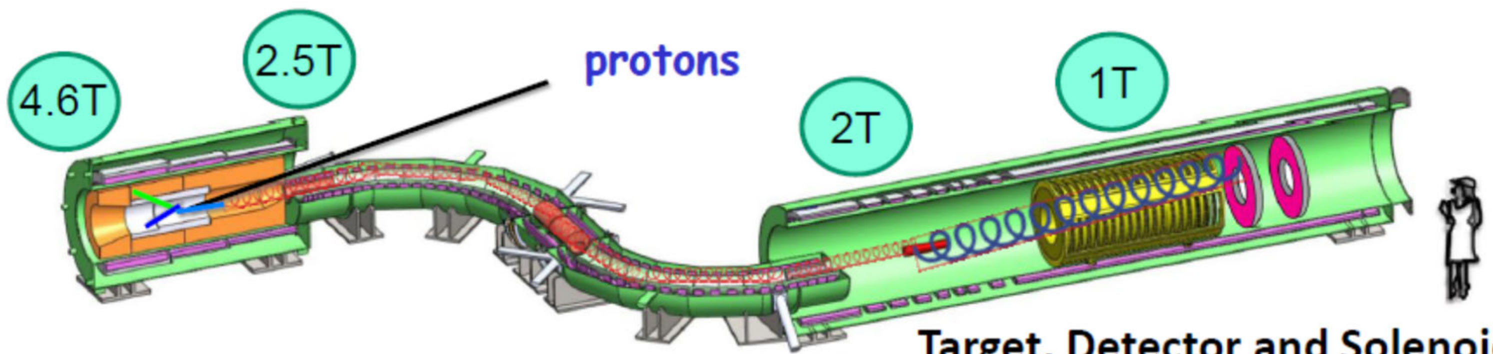
Similar operator can be tested in $\tau \to \phi\mu$

Current best limit: $BR\left(\mu^- + Au \to e^- + Au\right) < 7 \times 10^{-13}$ (SINDRUM II)

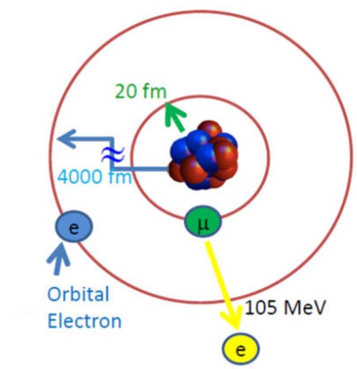
Future experiments:

Mu2e and COMET, both aiming at $BR\left(\mu^- + Al \to e^- + Al\right) < 10^{-16}$

Mu2e at Fermilab



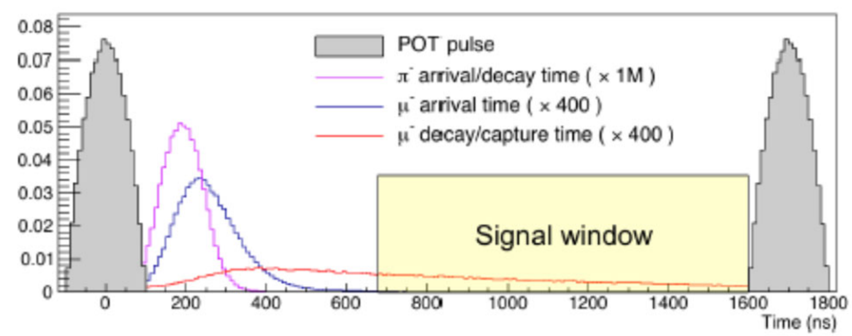
Target, Detector and Solenoid (DS)-
11m long x 2m dia



Mu2e in a nutshell:

- Generate *pulsed* beam of low energy negative muons
- Stop the muons in material: 0.002 stopped muons per 8 GeV proton. muons settle in 1S state.
- Wait for prompt backgrounds to disappear
- Measure the electron spectrum
- Look for the *monoenergetic* conversion electron (for Al E_e ~105 MeV)

Expected limits: 10^{-16}



2.4 LFV in τ-decays

τ-pairs are abundantly produced at the e^+e^- B factories:

$$e^+e^- \to \tau^+\tau^- \quad \text{with} \quad \sigma(\sqrt{s}=10.56) \approx 1 \text{ nb} \approx \sigma_{bb}$$

$\tau \to 3\mu$

$\tau \to 3\mu$ signature is an easy to trigger and to reconstruct topology: $\left(\sum_i p_{\mu_i}\right) = m_\tau^2$

Current limits: $BR < 2\,(4) \times 10^{-8}$ by Belle (BABAR) limited by available statistics.

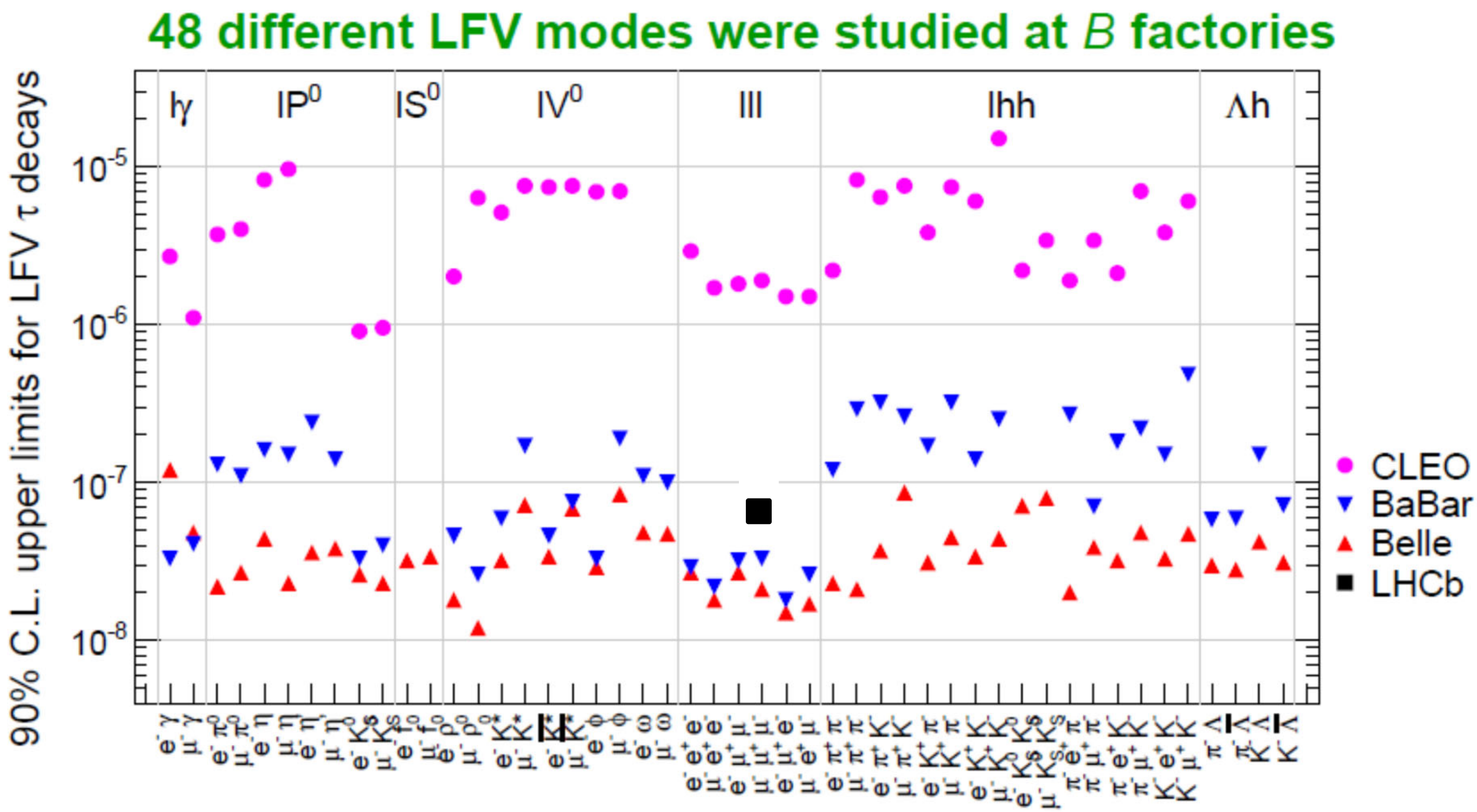
Prospects for SuperKEKB (Belle-2) $BR < 10^{-9}$

LHCb has also performed a search for $\tau \to 3\mu$: $BR < 4.6 \times 10^{-8}$
(sensitivity is limited by irreducible backgrounds)

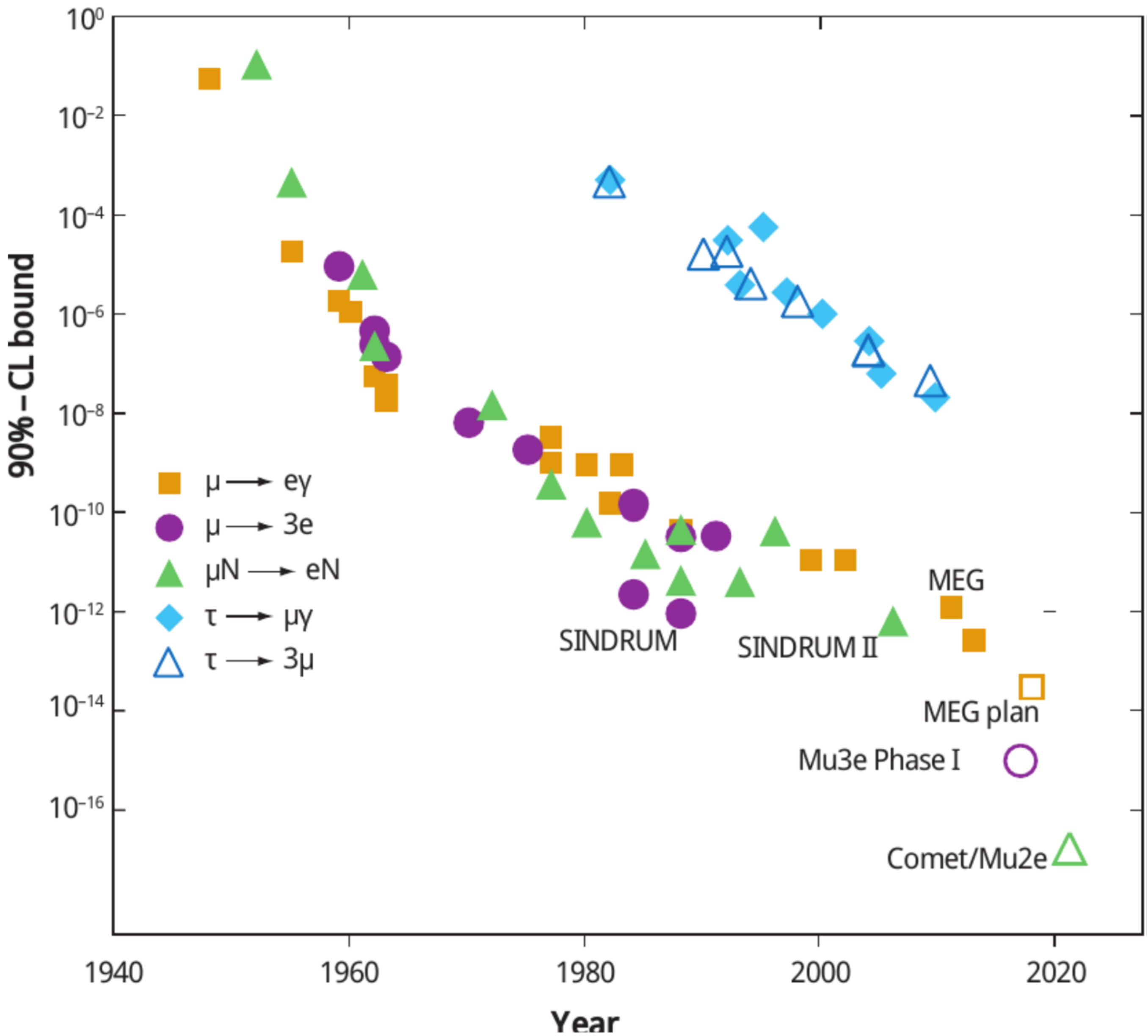
$\tau \to \mu\gamma$: $BR < 4 \times 10^{-8}$ (Belle)

Prospects for SuperKEKB (Belle-2) $BR < 10^{-9}$

Prospect for LFV measurements in τ decays at Belle-2:



2.5 Summary Limits on LFV



Final remark:

For the search for New Physics (see arguments for $b \to sll$ decays) the complementarity of $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion and τ-decays is interesting: Depending on the effective new interaction, the sensitivity of the respective observables can change significantly.