

Lepton flavour violation in muon decays



Istituto Nazionale di Fisica Nucleare

Luca Galli, INFN Sezione di Pisa
BLV, Madrid 23-10-2019



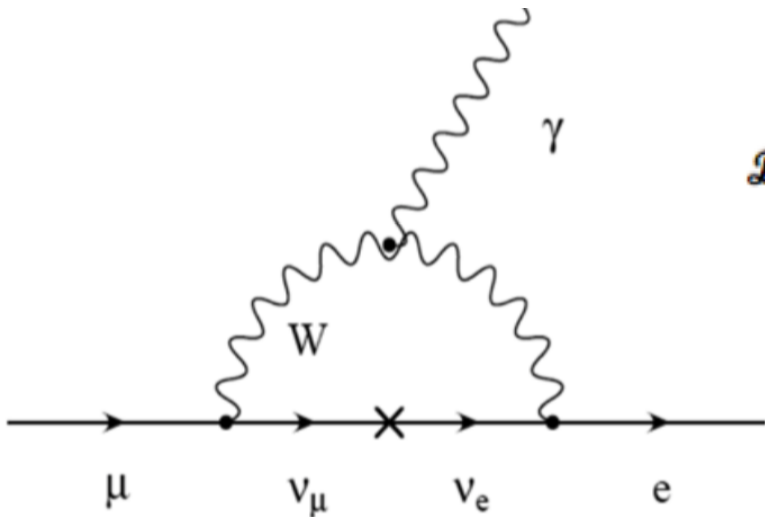
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Outlook

- Quick overview of cLFV
 - *highly sensitive to physics beyond the standard model*
 - *comparison between different channels*
- Experiments
 - *MEG II @PSI*
 - *Mu2e @FNAL*
 - *COMET @JPARC*
 - *Mu3e @PSI*
- Conclusions

cLFV = physics beyond SM

- $l \rightarrow l' + X$ ($X = \gamma, \dots, ee, \mu\mu, \text{others...}$)

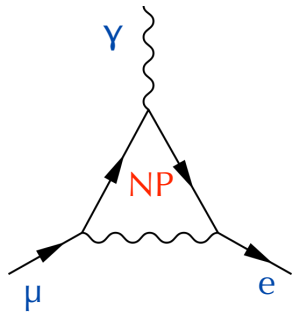


$$\mathcal{B}(\mu \rightarrow e \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 \simeq 10^{-54}$$

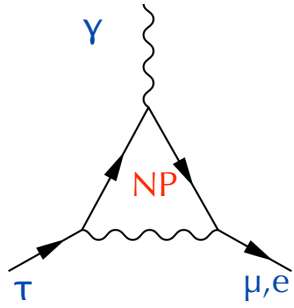
too small to be experimentally
accessible \rightarrow portal to New Physics
extensively exploited in intensity
frontier

SM background free searches!

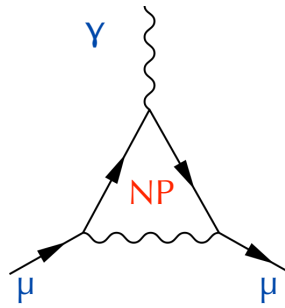
Many channels



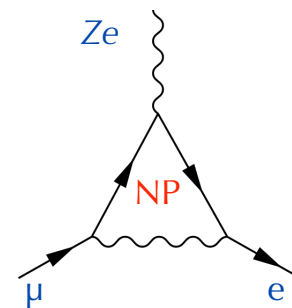
$$\mu \rightarrow e\gamma$$



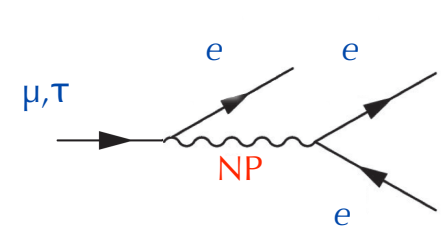
$$\begin{aligned} \tau &\rightarrow \mu\gamma \\ \tau &\rightarrow e\gamma \end{aligned}$$



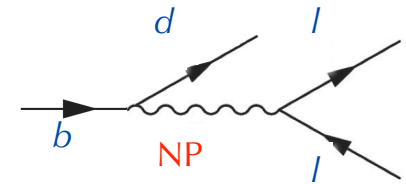
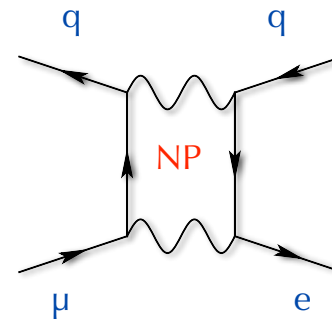
$$(g - 2)_\mu$$



$$\mu^- \mathcal{N} \rightarrow e^- \mathcal{N}$$



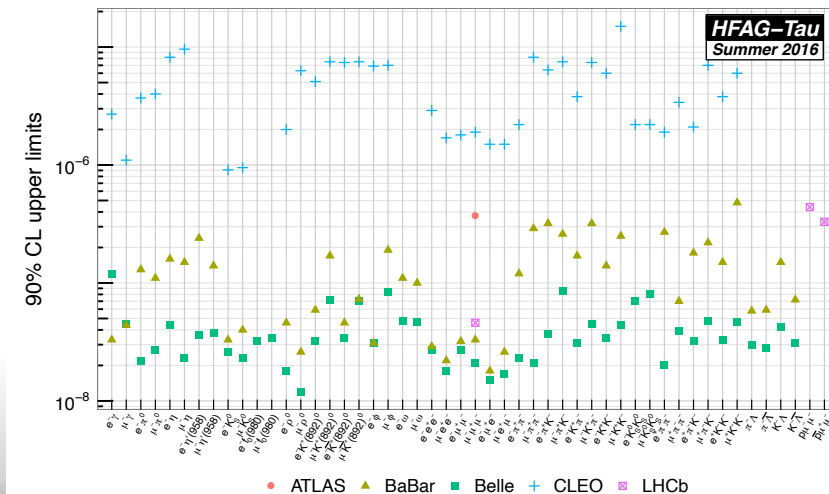
$$\mu \rightarrow eee$$



$$\begin{aligned} B &\rightarrow \ell\bar{\ell}' \\ B &\rightarrow \ell\bar{\ell}' X_s \end{aligned}$$

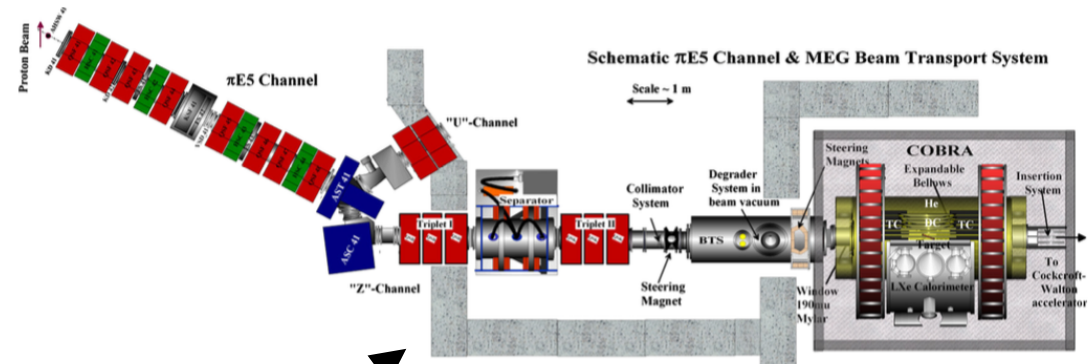
- A wide field of research

- *LFV decays of leptons*
- *Anomalous magnetic moment for the μ*
- *Muon-to-electron conversion*
- *LFV in meson decays*

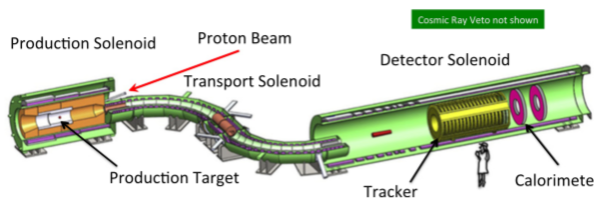


μ as a golden channel

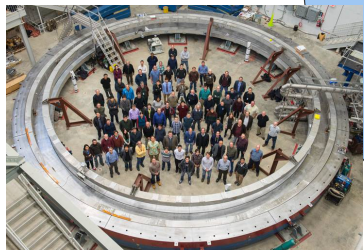
- High intensity and low energy μ beams
 - *large statistics possible*
- long decay time
 - *beam transport to a target*
- simple kinematics
 - *precise measurements in a high rate background*



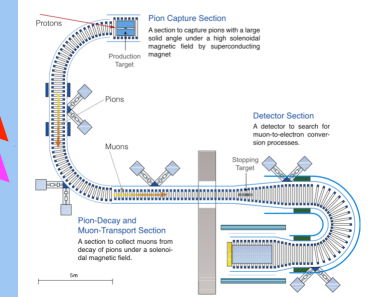
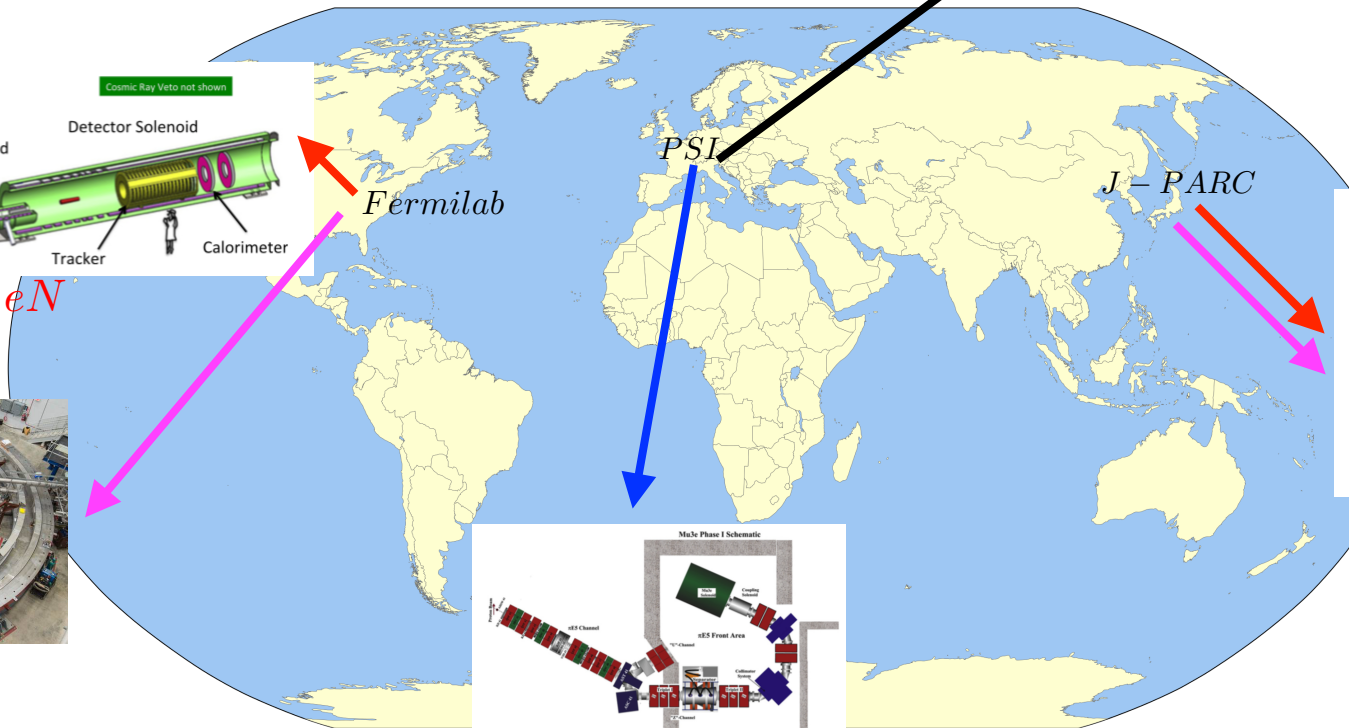
MEG : $\mu \rightarrow e\gamma$



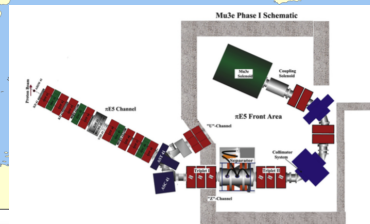
Mu2e : $\mu N \rightarrow eN$



Muon $g-2$



COMET : $\mu N \rightarrow eN$
 DeeMe : $\mu N \rightarrow eN$
 J-PARC $g-2$



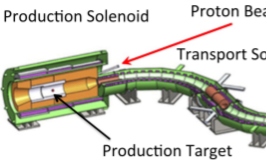
Mu3e : $\mu \rightarrow eee$

μ as a golden channel

Table 8

“DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models
 ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

- High intensity
- large size
- long decay length
- beam time
- simple kinematics
- precise



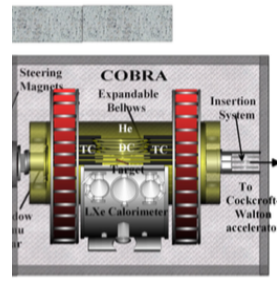
$Mu2e : \mu N \rightarrow e \gamma$



$Muon g - 2$

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \rightarrow X_S \gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \rightarrow K^* \mu^+ \mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \rightarrow K^* \mu^+ \mu^-)$	★	★	★	★	★	★	?
$B \rightarrow K^{(*)} \nu \bar{\nu}$	★	★	★	★	★	★	★
$B_S \rightarrow \mu^+ \mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \rightarrow e \gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \rightarrow \mu \gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \rightarrow e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g - 2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

IEG Beam Transport System

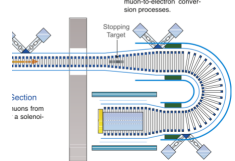


$\mu \rightarrow e \gamma$

Pion Capture Section

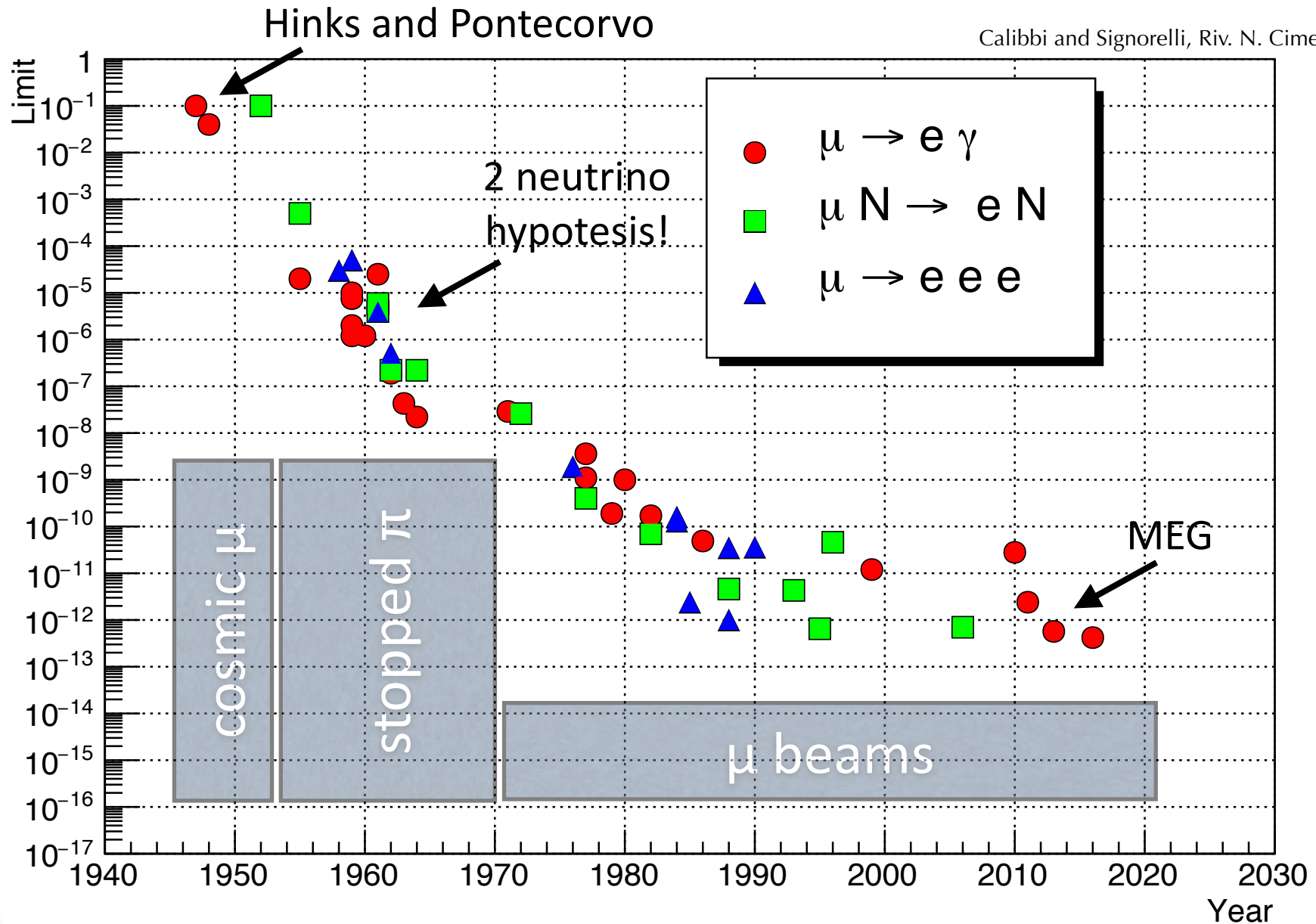


Detector Section

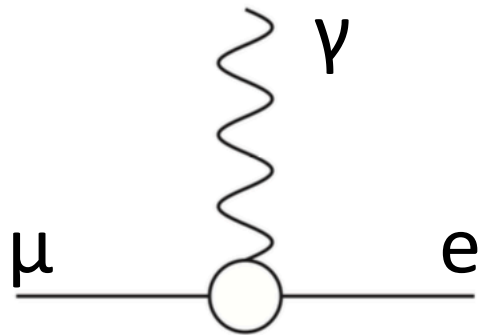


$[ET : \mu N \rightarrow e N$
 $Te : \mu N \rightarrow e N$
 'ARC $g - 2$

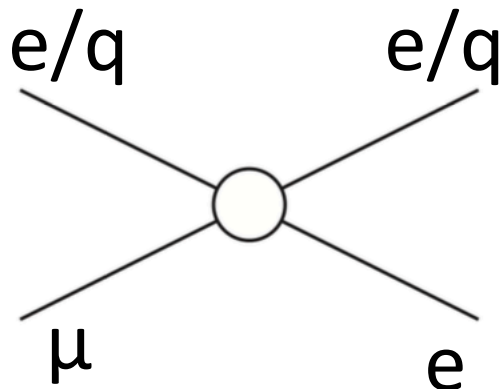
70 years of searches



New physics* couplings



dipole transition
 $\mu \rightarrow e\gamma$ favoured

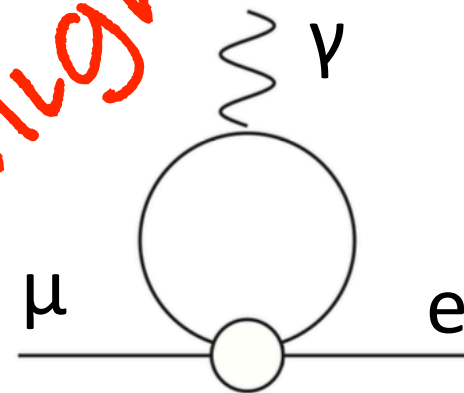
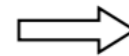
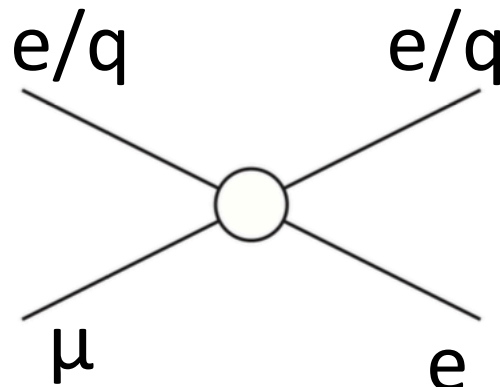
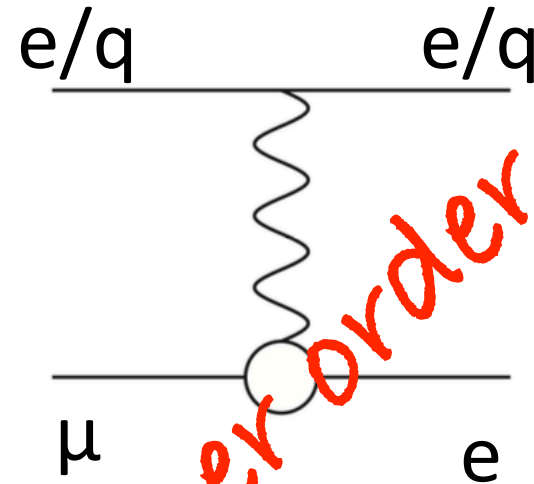
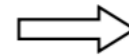
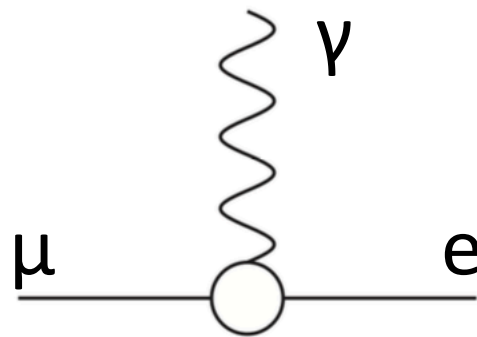


four particle interaction
 $\mu N \rightarrow eN, \mu \rightarrow eee$ favoured

*Model independent approach

Calibbi and Signorelli, Riv. N. Cimento, 2017

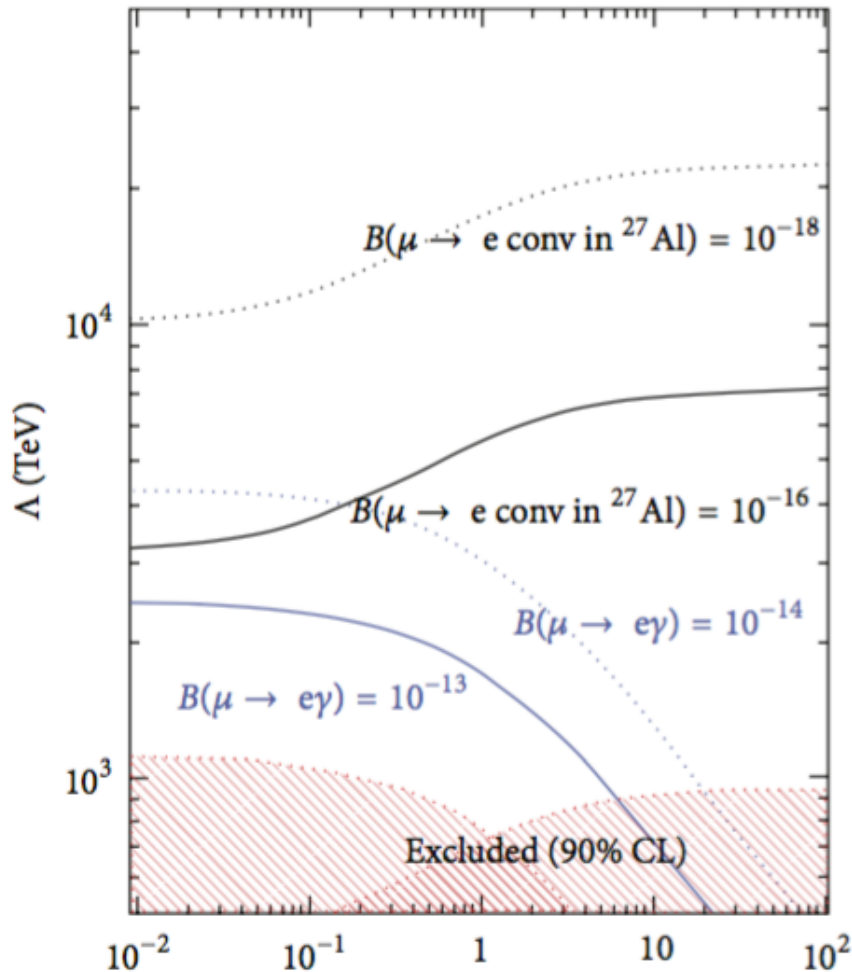
New physics* couplings



*Model independent approach

Calibbi and Signorelli, Riv. N. Cimento, 2017

Effective parametrisation



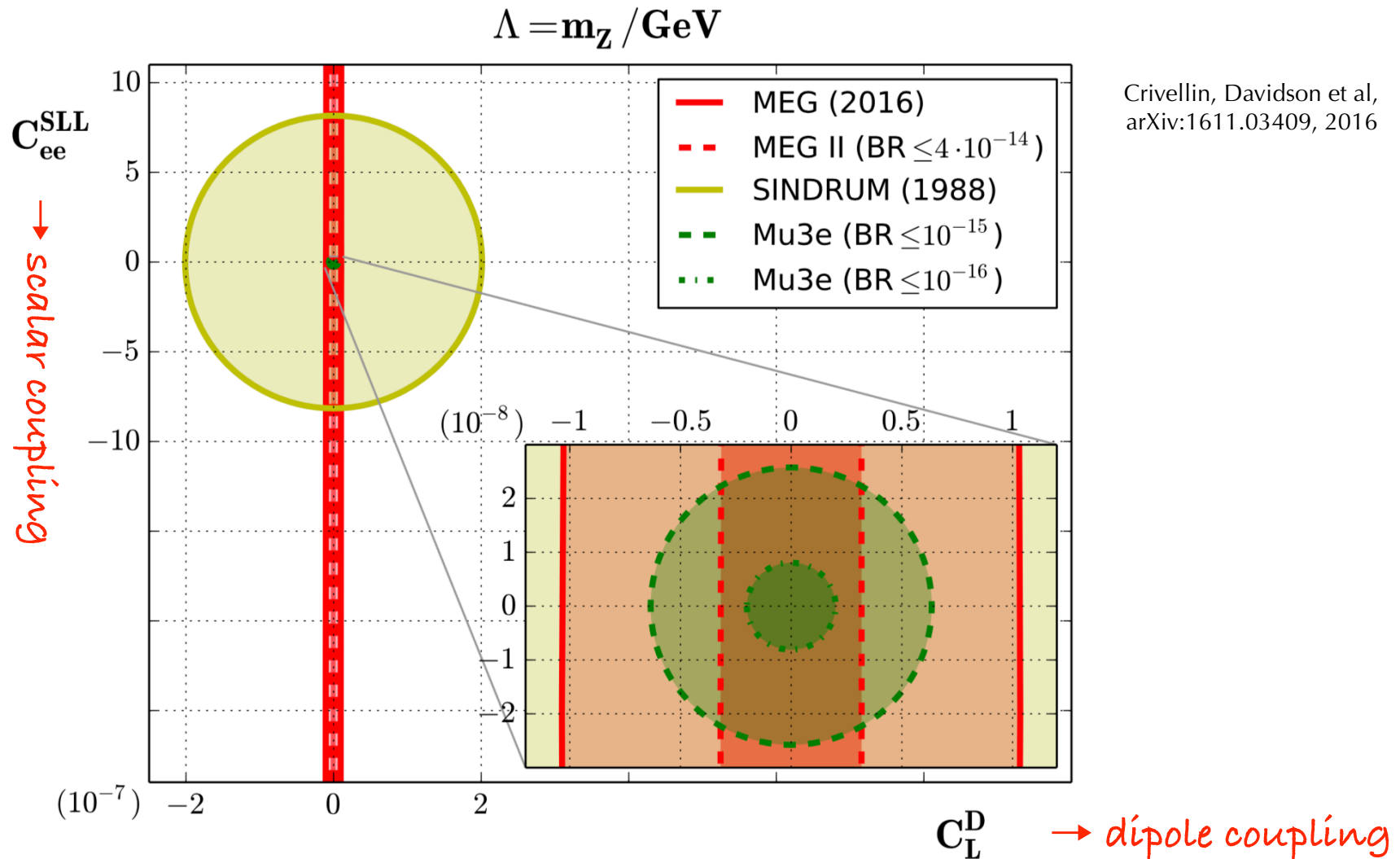
$$\frac{m_\mu}{(1+\kappa)\Lambda^2} \left(\text{diagram with wavy line} \right) + \frac{\kappa}{(1+\kappa)\Lambda^2} \left(\text{diagram with crossed lines} \right)$$

de Gouvea and Vogel, Prog. Part. Nucl. Phys. 2013

- effective Lagrangian
 - function of the **NP scale Λ** and **NP nature through κ**
 - dipole transition
 - $BR(\mu \rightarrow e\gamma)/BR(\mu N \rightarrow eN) \approx 10^{-2}$
 - four fermion interaction
 - $\mu N \rightarrow eN$ favoured
 - From **current and future experiments 10^3 TeV** new physics scale **sensitivity**

	current limit	future limit
$\mu \rightarrow e\gamma$	4.2×10^{-13}	6×10^{-14}
$\mu N \rightarrow eN$	$10^{-12} - 10^{-13}$	3×10^{-17}
$\mu \rightarrow eee$	10^{-12}	$10^{-15} - 10^{-16}$

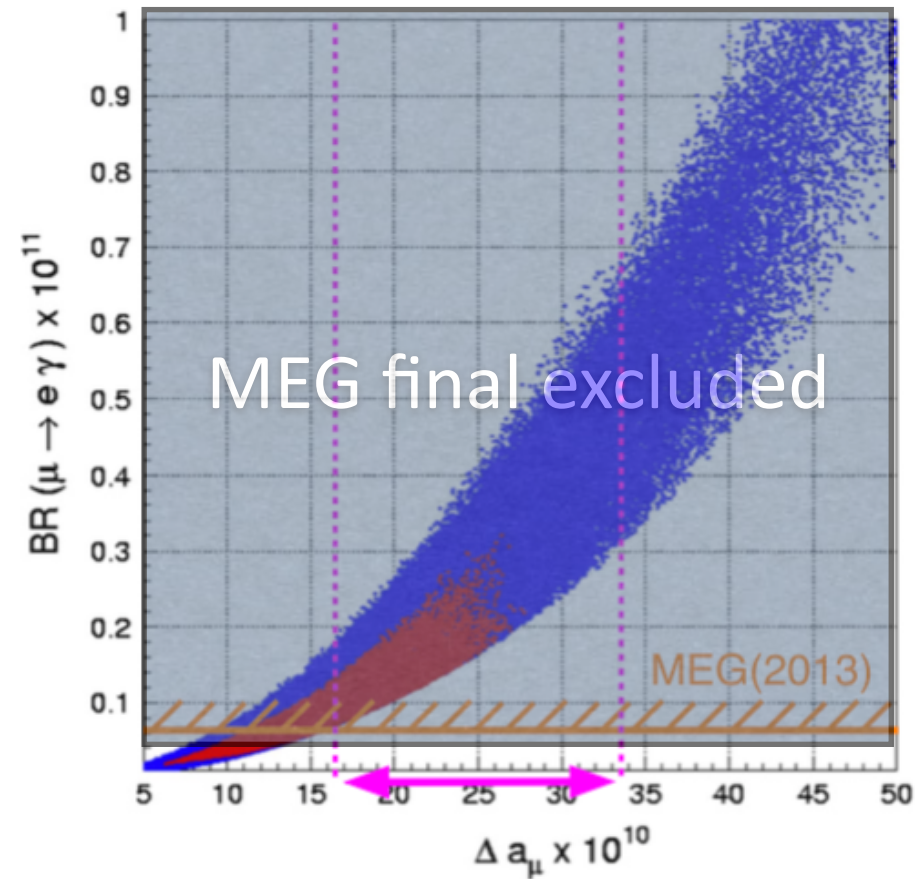
Complementarity $\mu \rightarrow e\gamma \Leftrightarrow eee$



Crivellin, Davidson et al,
arXiv:1611.03409, 2016

Comparison* with g-2 experiment

- **3.4 σ discrepancy** w.r.t. Standard Model prediction
 - *possible hint of new physics*
 - *this would enhance to $\mu \rightarrow e\gamma$ for example in a supersymmetric model*
 - **cLFV coupling** $|\delta_{LL}^{12}|^2 \approx 10^{-4}$ almost excluded
- resolution **improvements** by a **factor 4** from future experiments at **Fermilab** and **J-PARC**
 - *together with new generation cLFV experiments will be sensitive to $|\delta_{LL}^{12}|^2 \approx 10^{-5}$*

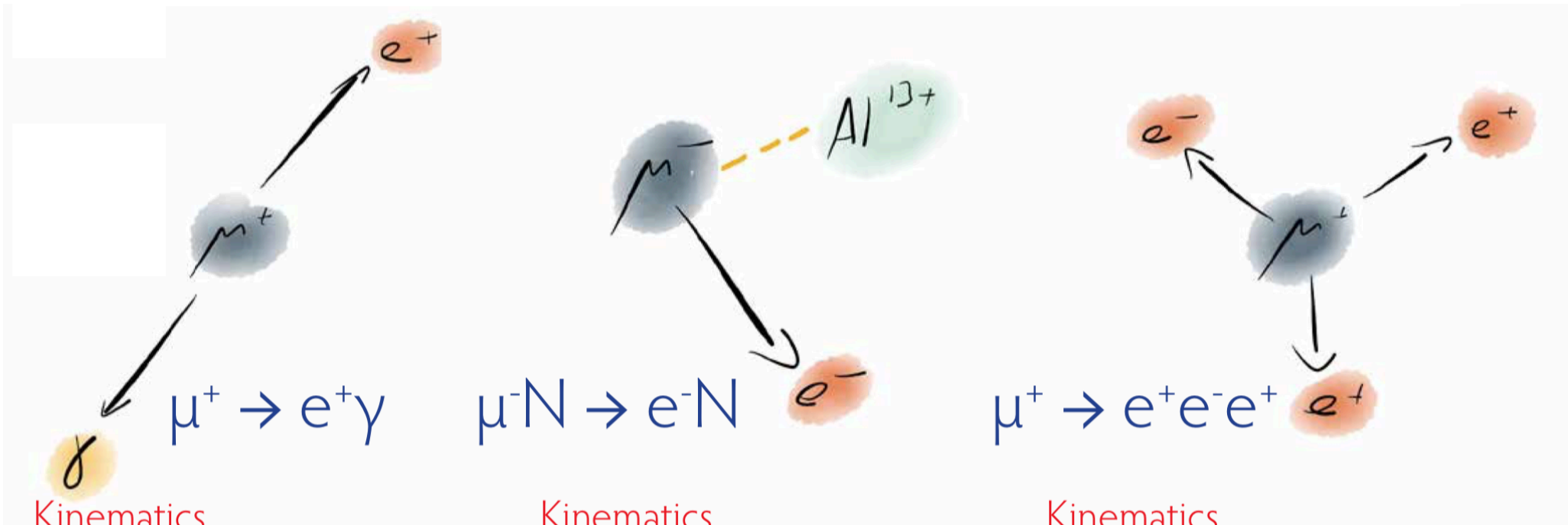


$$\mathcal{B}(\mu \rightarrow e\gamma) \approx 10^{-4} \left(\frac{\Delta a_\mu}{200 \times 10^{-11}} \right)^2 |\delta_{LL}^{12}|^2$$

G. Isidori et al., PRD, 2007

*Model dependent

Muon cLFV: kinematics



Kinematics

- 2-body decay
- Monoenergetic e^+ , γ
- Back-to-back

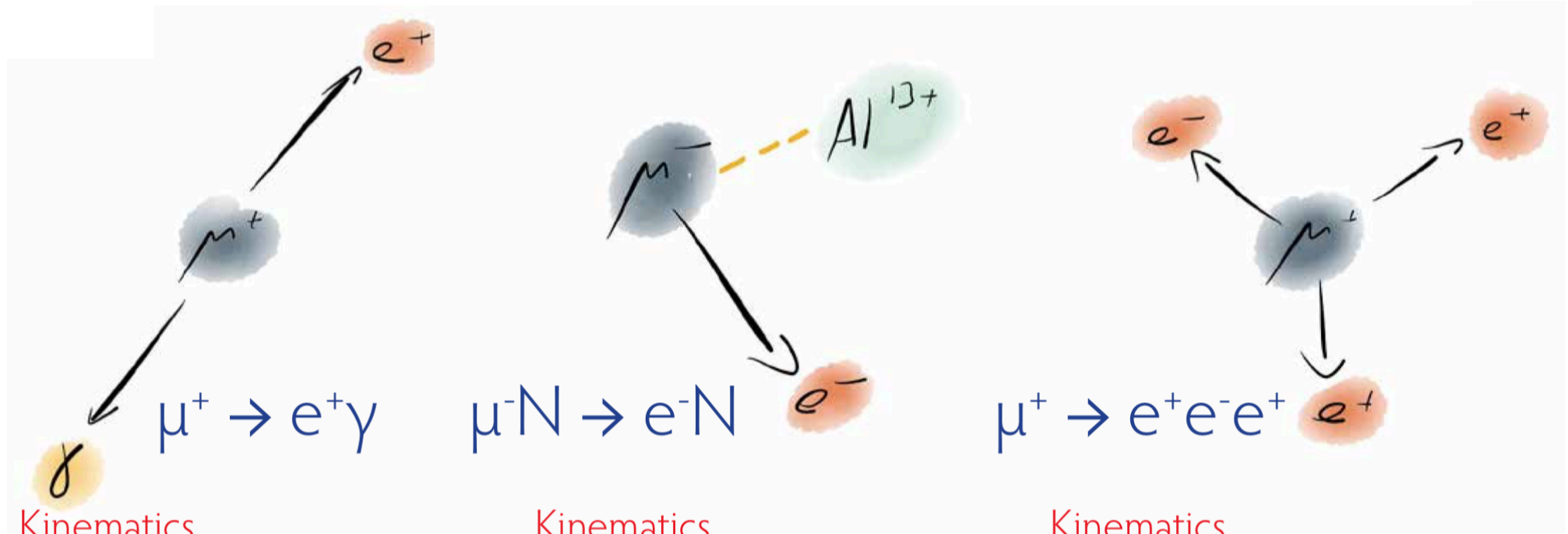
Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Kinematics

- 3-body decay
- Invariant mass constraint
- $\sum p_i = 0$

Muon cLFV: background



Kinematics

- 2-body decay
- Monoenergetic e^+ , γ
- Back-to-back

Background

- Accidental background

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions

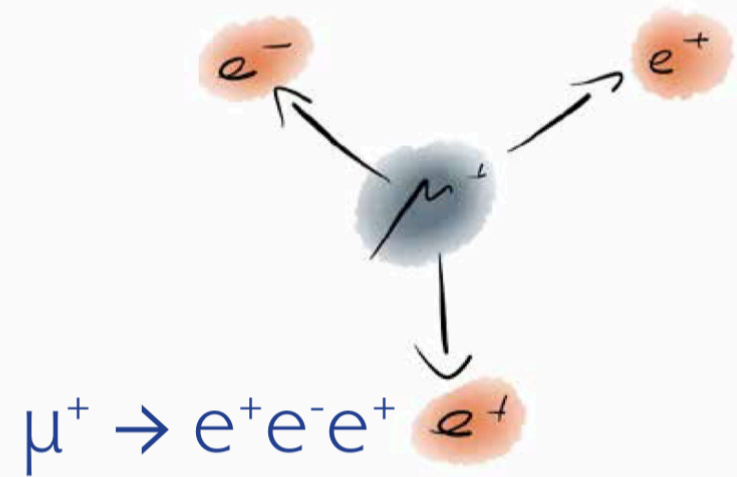
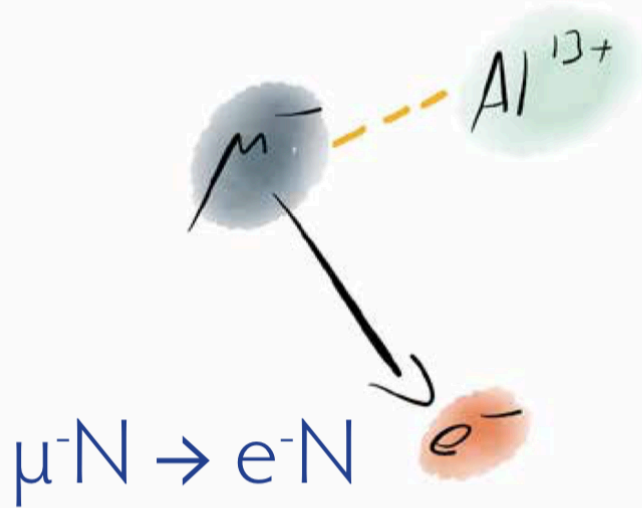
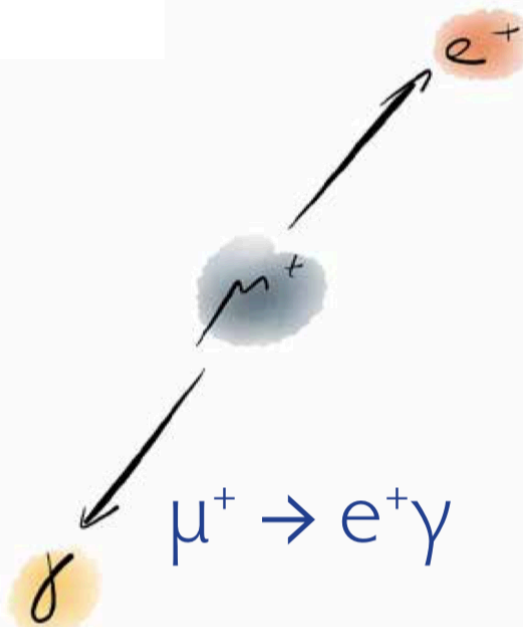
Kinematics

- 3-body decay
- Invariant mass constraint
- $\sum p_i = 0$

Background

- Radiative decay
- Accidental background

Muon cLFV: beam line



Kinematics

- 2-body decay
- Monoenergetic
- Back-to-back

Background

- Atomic background

Kinematics

- Quasi 2-body decay
- Monoenergetic
- Single particle detected

Background

- Γ orbit
- Atomic protons, pions

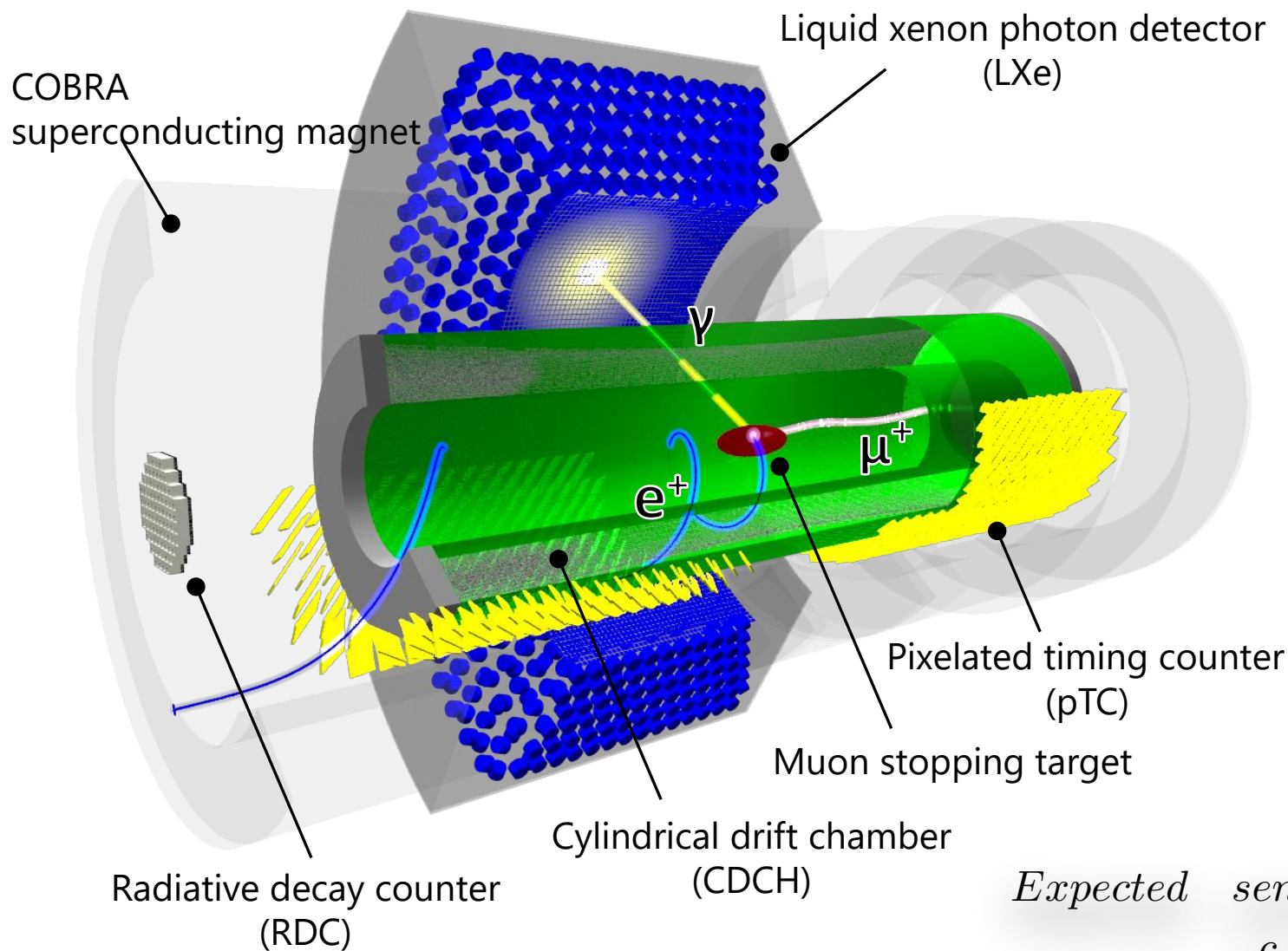
Kinematics

- 3-body decay
- Invariant mass constraint
- $\sum p_i = 0$

Background

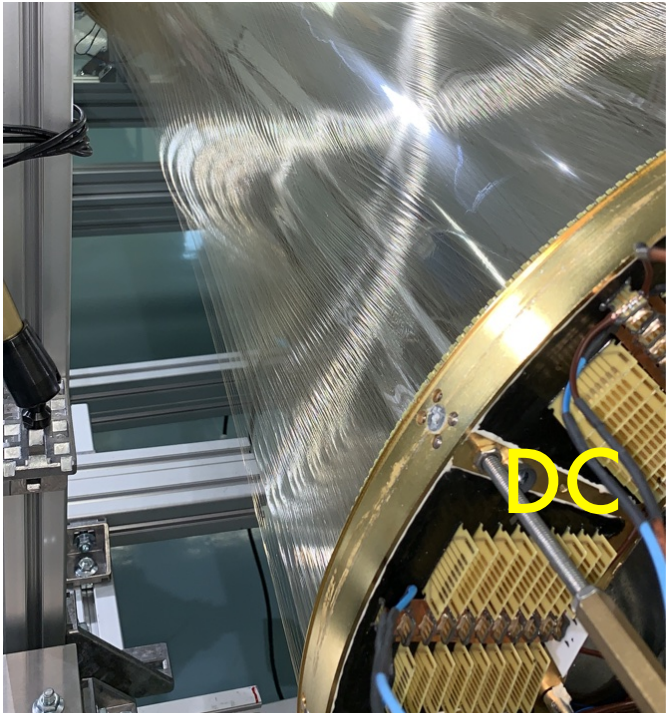
- Radiative decay
- Atomic background

MEG II@PSI



Expected sensitivity
 6×10^{-14}

Construction status



2012

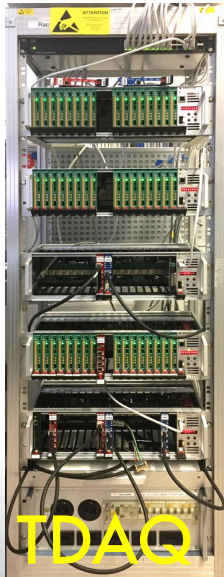
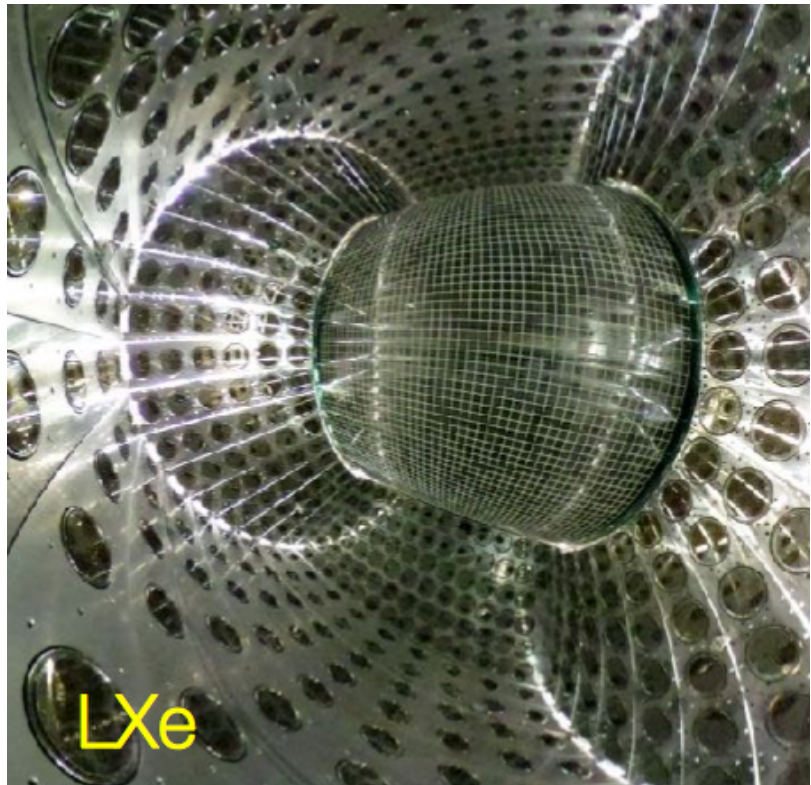
R&D

2017

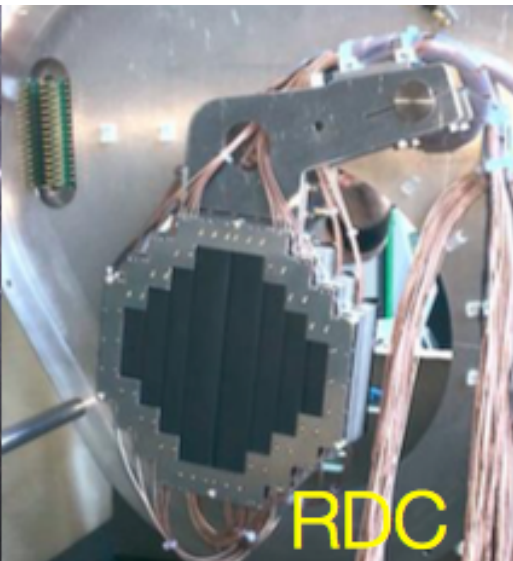
Commissioning

2022

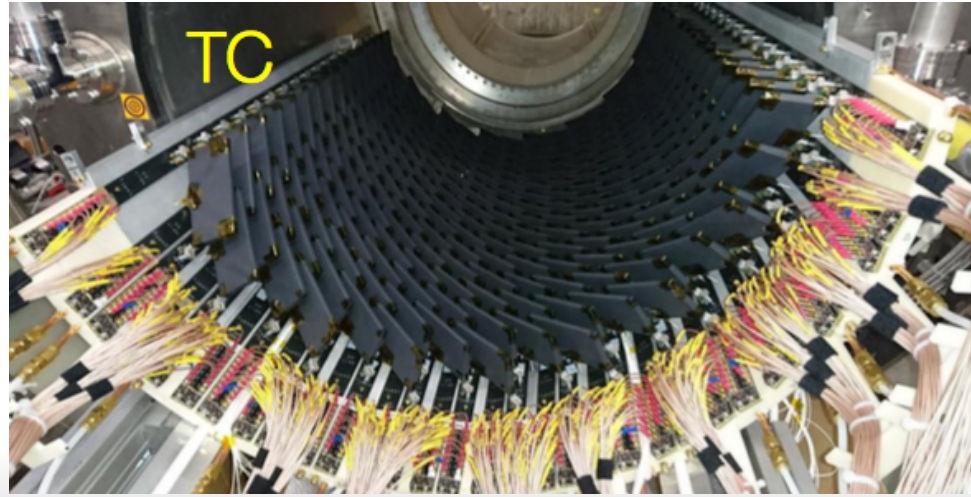
DAQ



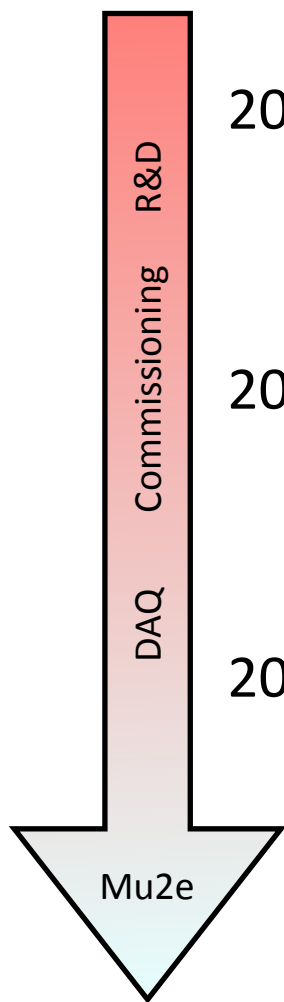
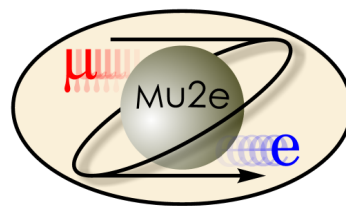
23-10-2019



17



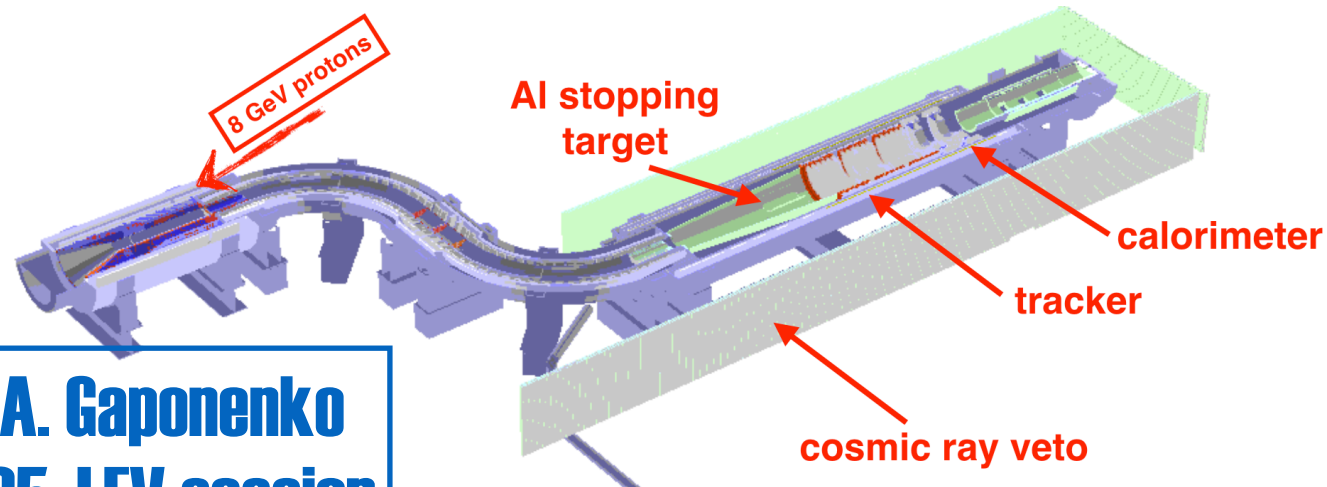
Mu2e @FNAL



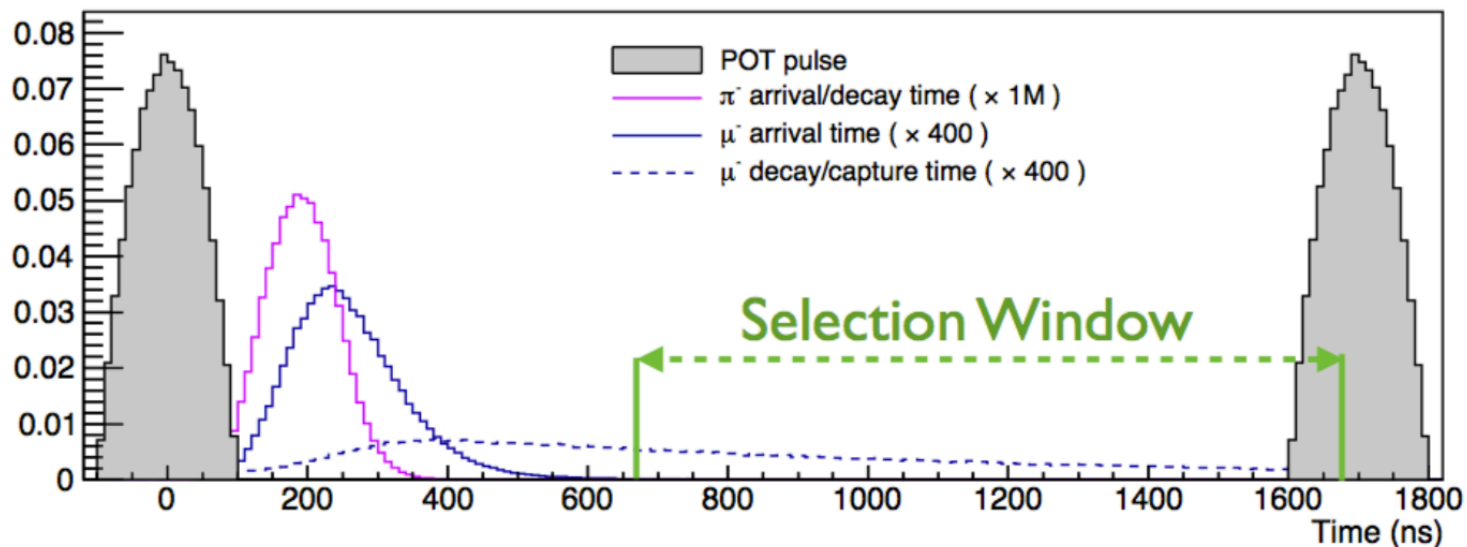
2017

2020

2023

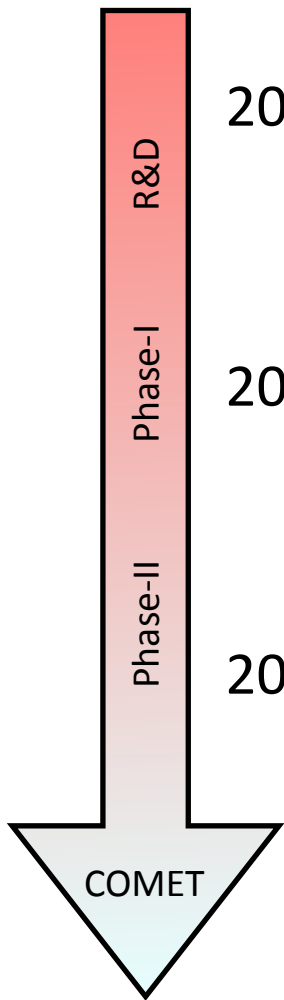
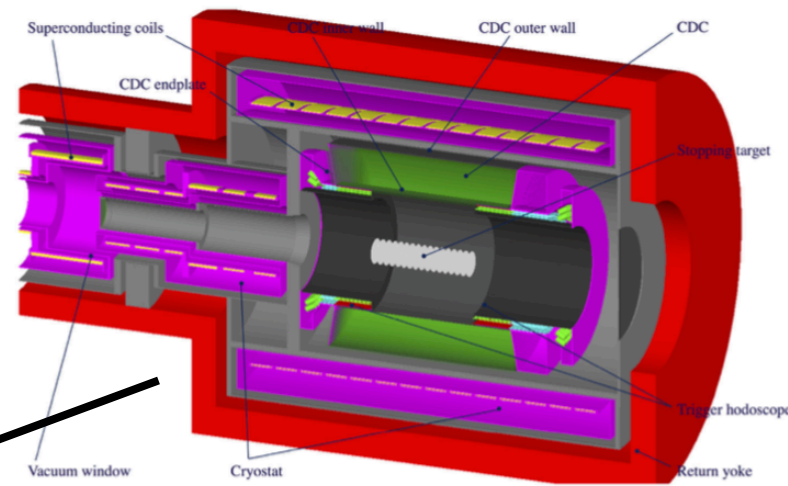


details in A. Gaponenko talk at 14:35, LFV session



Expected sensitivity $\approx 3 \times 10^{-17}$

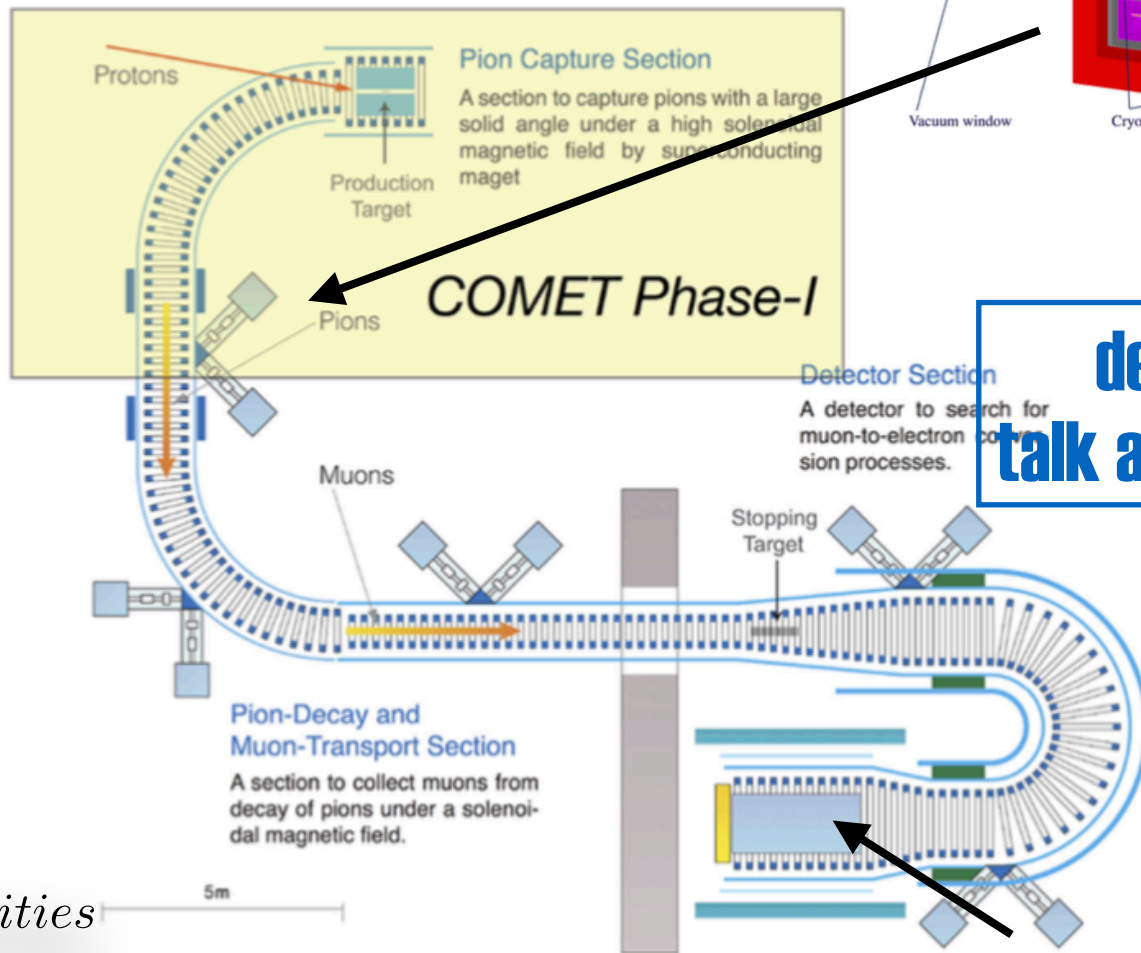
COMET @J-PARC



2016

2019

2022



details in Y. Kuno talk at 14:15, LFV session

Straw tube tracker

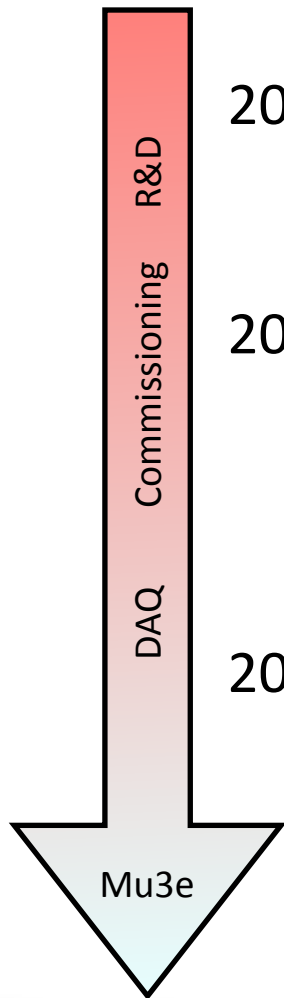
*studies ongoing to improve 1 more order of magnitude

Expected sensitivities

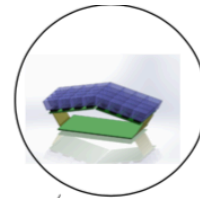
Phase - I 7×10^{-15}

Phase - II 3×10^{-17}

Mu3e @PSI

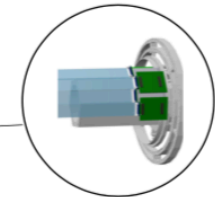


Superconducting solenoid Magnet
Homogeneous field 1T



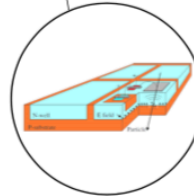
Tile detector
70 ps resolution w/ single hit

Fibre hodoscope
< 500 ps resolution w/ multi hits
thickness: < 0.3% X₀



MIDAS DAQ and Slow Control
Run, history, alarms, HV etc.

Mupix detector
Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X₀



Muon Beam and target
Full available beam intensity O(10⁸)

Target prototype



$$\Delta t_{eee} = 0$$

$$\Sigma \bar{p}_e = 0$$

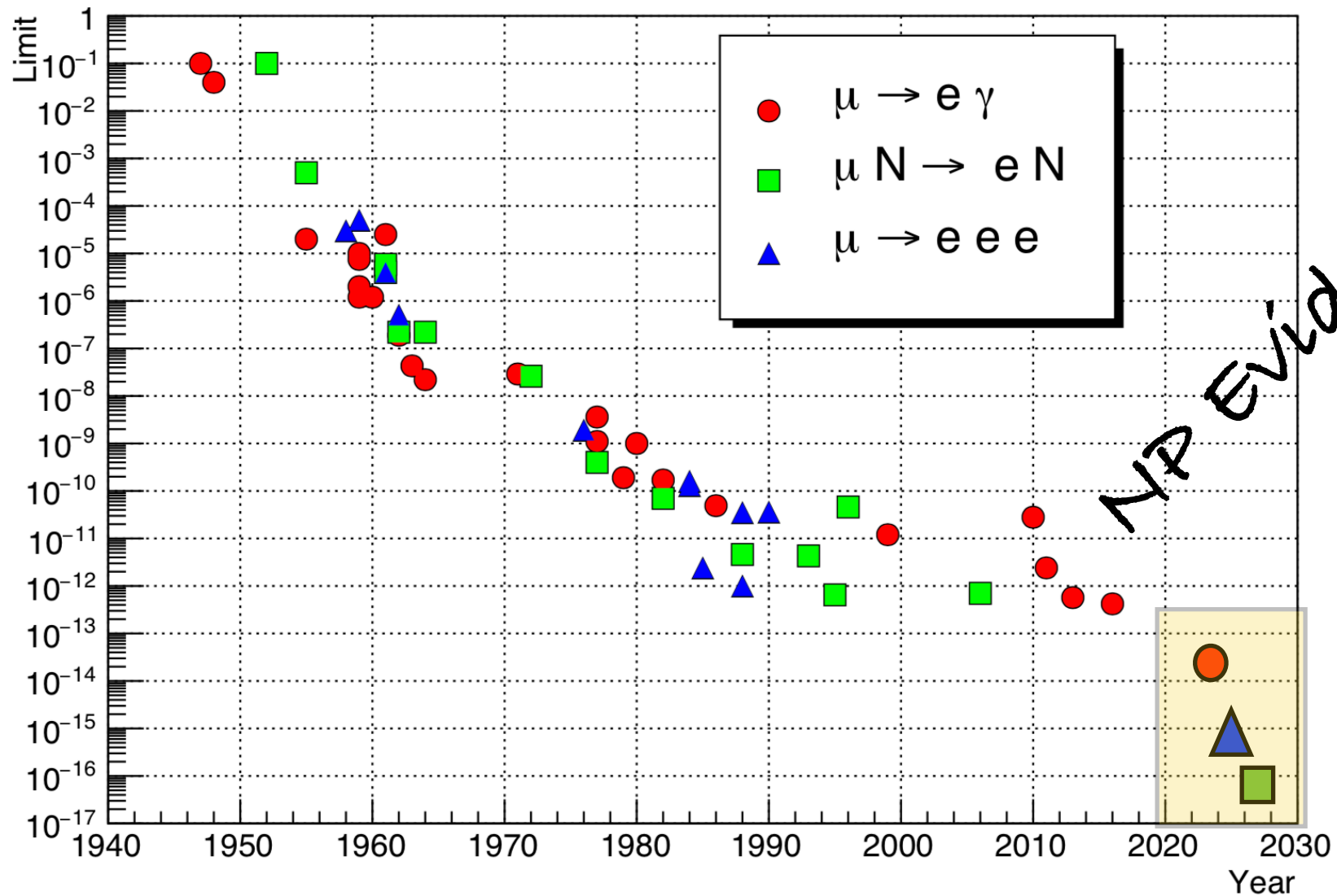
$$\Sigma E_e = m_\mu$$

Expected sensitivities

Phase - I $\approx 10^{-15}$

Phase - II $\approx 10^{-16}$

cLFV in 10 years



Conclusions

- cLFV with muons features a unique opportunity to discover physics beyond the standard model
- *muon sector is the most promising from:*
 - $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$ and $\mu \rightarrow eee$
 - *complementary searches: sensitive to different new physics dynamics*
- A full complementary experimental search ongoing
 - *R&D in very advanced phase*
 - *results in five years from now*