

Flavor Violation in the Charged Lepton Sector

Joachim Kopp

Flavo(u)r and DM 2017 | Heidelberg, Germany | September 25–28, 2017

In this Talk

- LFV in the Standard Model
- Search Strategies
- Implications for BSM Physics
- Summary

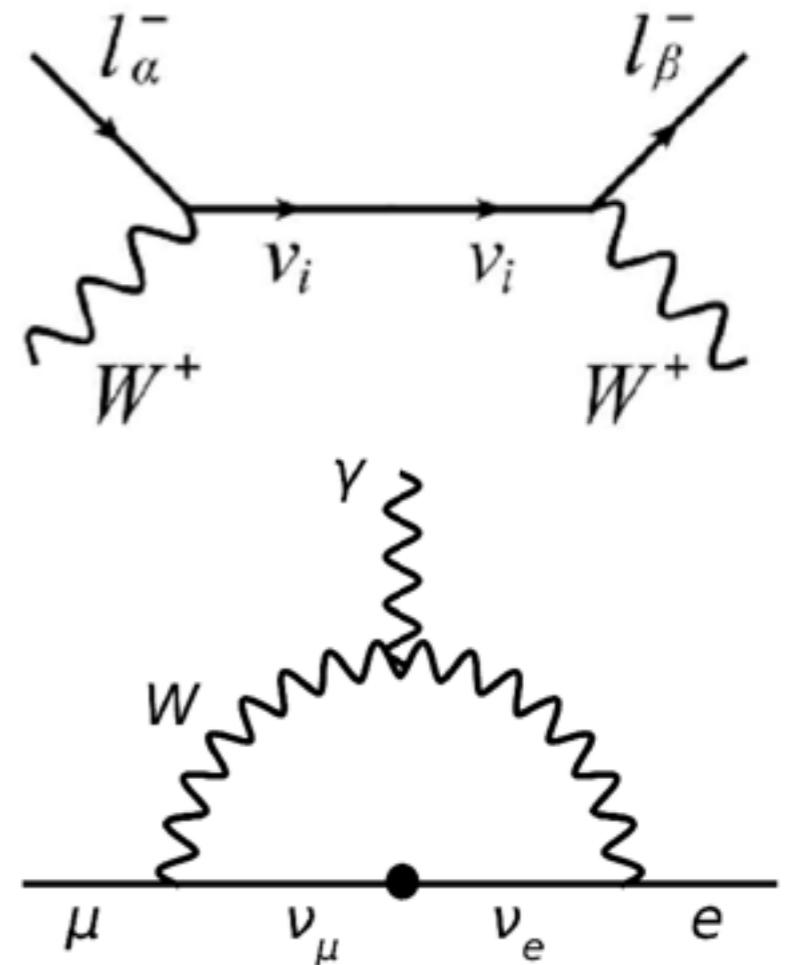
Lepton Flavor Violation in the Standard Model

Lepton Mixing in the SM

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \bar{\nu}_j U_{\alpha j}^* e_\alpha W_\mu^+ - m_j \bar{\nu}_j \nu_j + h.c.$$

Observing Flavor violation requires two flavor measurements

- Neutrino oscillations: FV at tree level



- Charged Leptons: FV at loop level

Diagrams from [1301.7654](#), [1506.01465](#)

GIM Suppression

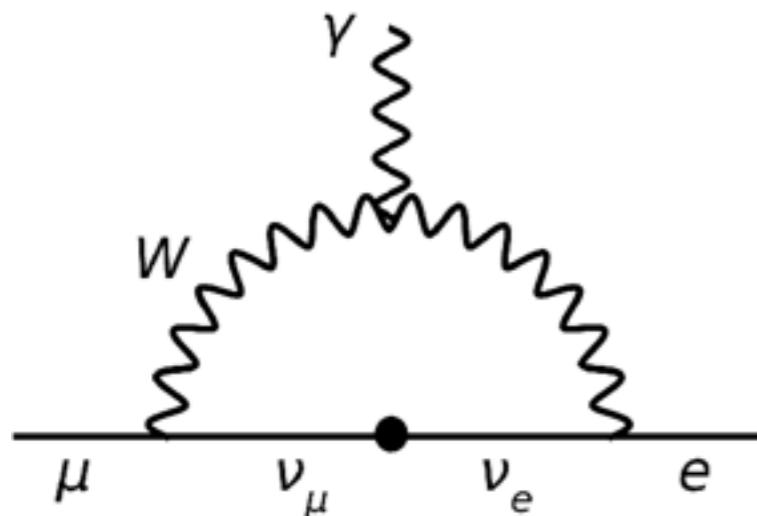


Diagram from [1506.01465](#)

$$\mathcal{M} \propto \sum_j U_{ej} U_{\mu j}^* \frac{m_j^2}{M_W^2}$$

Suppressed by

- small m_j
- Unitarity: $\sum_j U_{\alpha j} U_{\beta j}^* = \delta_{\alpha\beta}$

Branching ratio: $\text{BR}(\mu \rightarrow e\gamma) \sim \mathcal{O}(10^{-54})$

Similar conclusions for $\mu \rightarrow 3e$, $\mu \rightarrow e$ conversion, etc.

Search Strategies

Benchmark: Flavor Violating Higgs Couplings

$$\mathcal{L} \supset -m_j \bar{e}_L^j e_R^j - y_{ij} \bar{e}_L^i e_R^j h$$

Possible origins

Harnik JK Zupan [1209.1397](#)
and references therein

- Type-III Two Higgs Doublet Model:

$$\mathcal{L} \supset -y_{ij}^{(1)} \bar{L}_L^i e_R^j H^{(1)} - y_{ij}^{(2)} \bar{L}_L^i e_R^j H^{(2)}$$

- More generally: any scenario with several sources of electroweak symmetry breaking
- Higher-dimensional operators

$$\mathcal{L}_{\text{eff}} \supset \frac{\lambda_{ij}}{\Lambda^2} (\bar{f}_L^i f_R^j) H (H^\dagger H)$$

Benchmark: Flavor Violating Higgs Couplings

$$\mathcal{L} \supset -m_j \bar{e}_L^j e_R^j - y_{ij} \bar{e}_L^i e_R^j h$$

- Expectation** (to avoid tuning in the mass matrix)

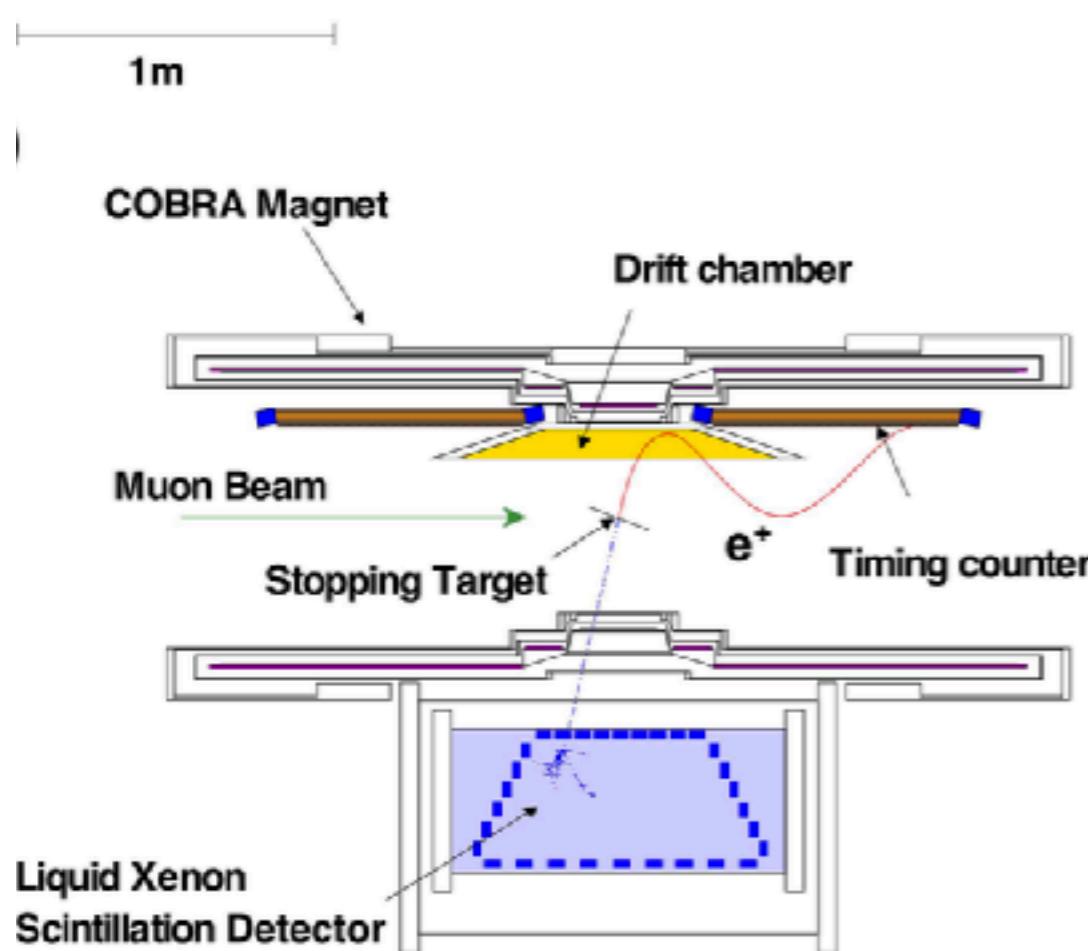
$$|Y_{ij} Y_{ji}| \lesssim \frac{m_i m_j}{v^2}$$

- Possible Consequences**

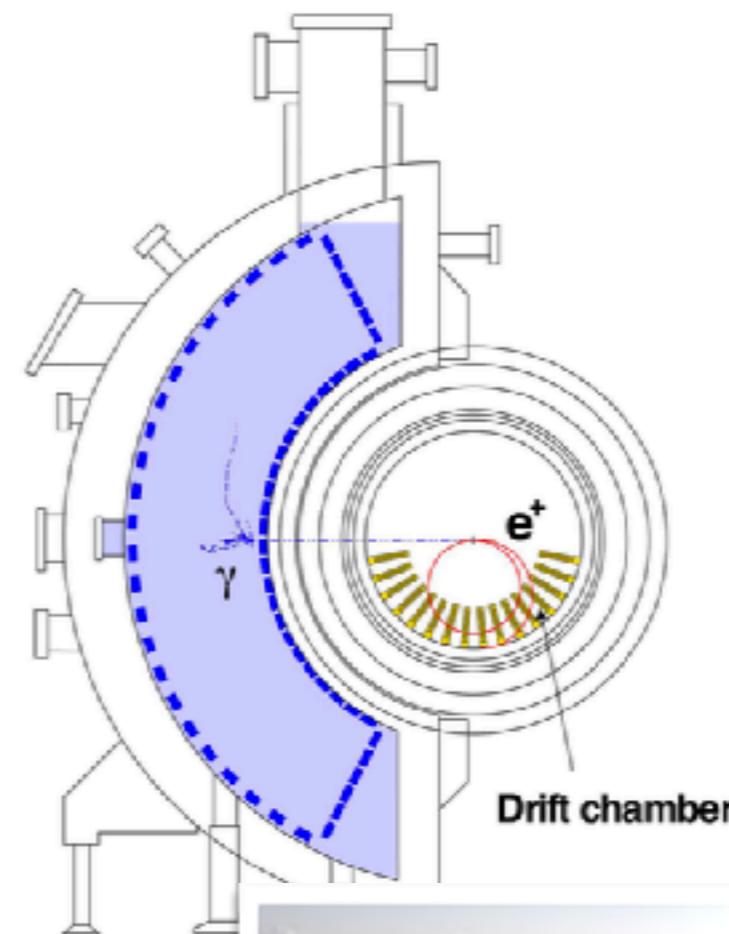
- LFV bonanza
- Flavor-violating Higgs decays @ LHC
- Similar processes in the quark sector

Harnik JK Zupan [1209.1397](#)
and references therein

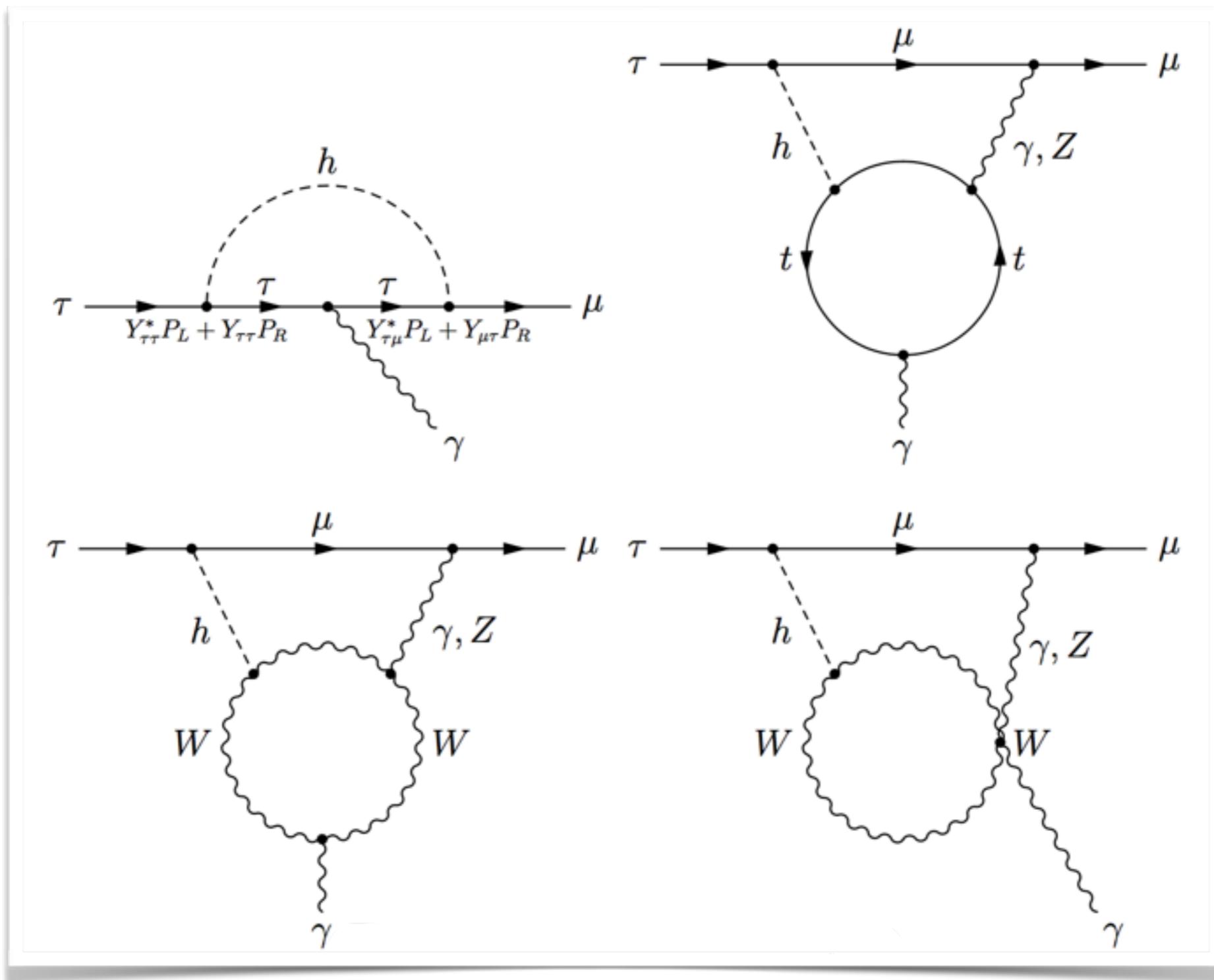
$\mu \rightarrow e\gamma$: The MEG Experiment @ PSI



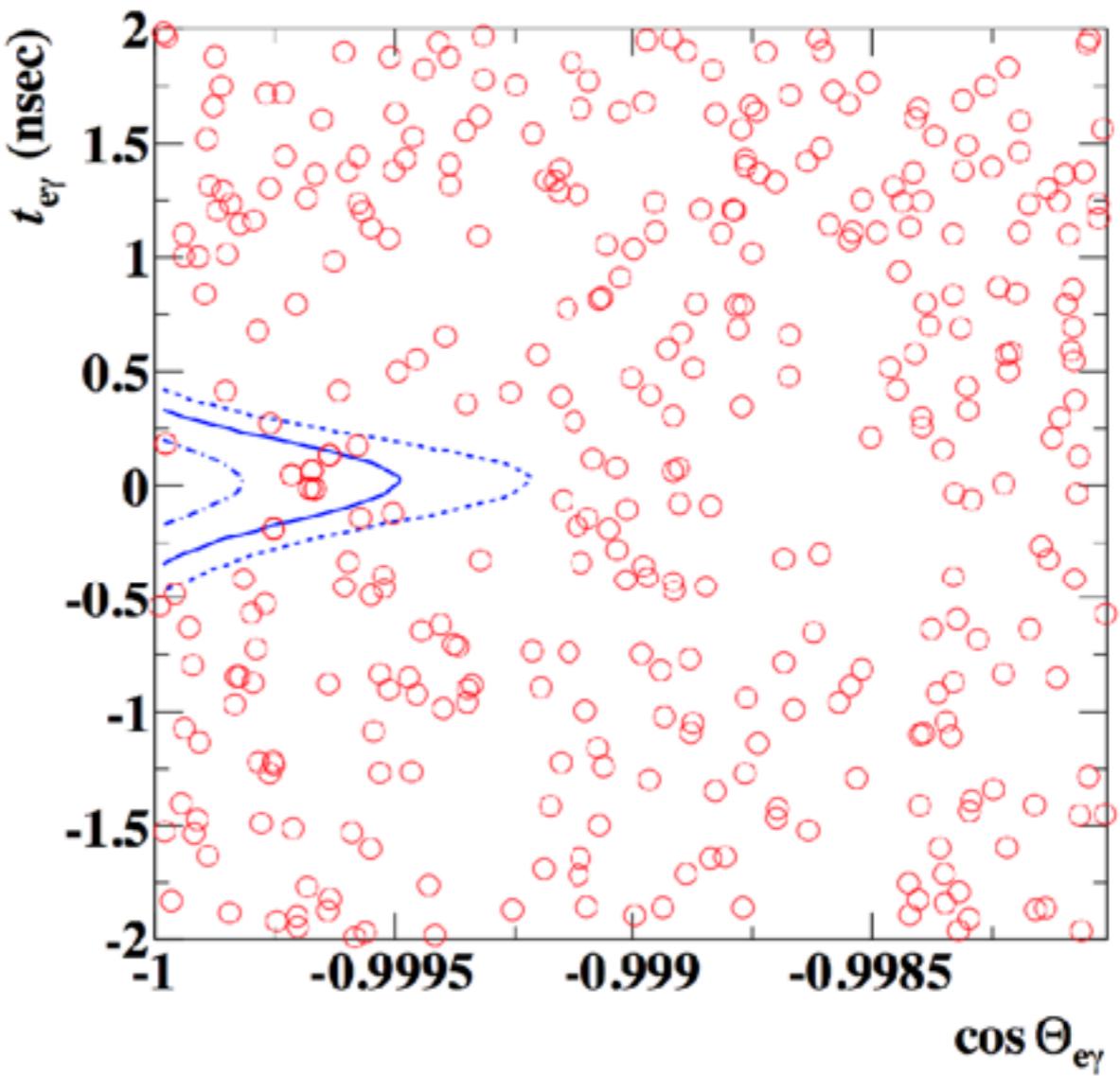
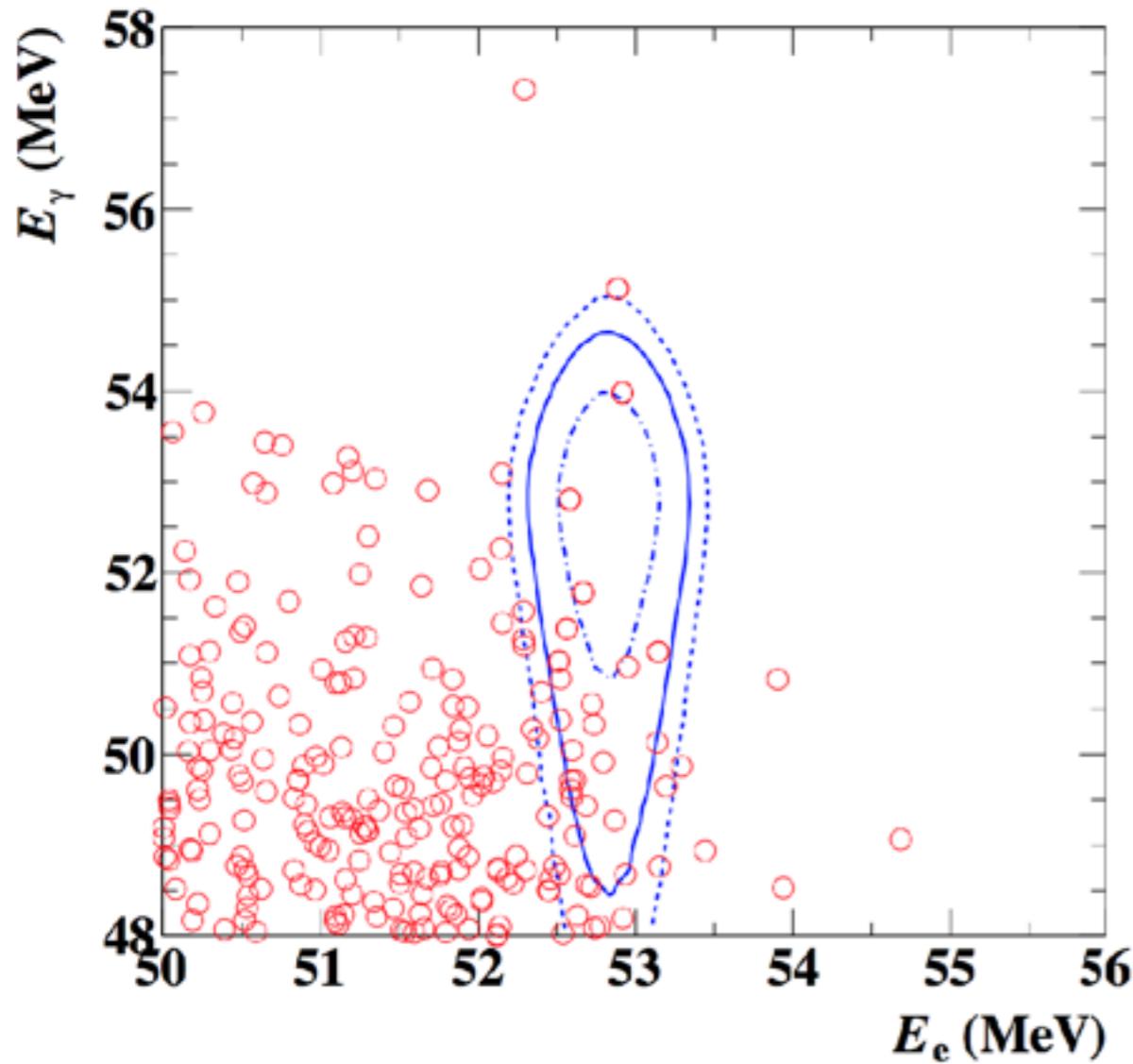
MEG Collaboration [0908.2594](#)



$\mu \rightarrow e\gamma$: The MEG Experiment @ PSI

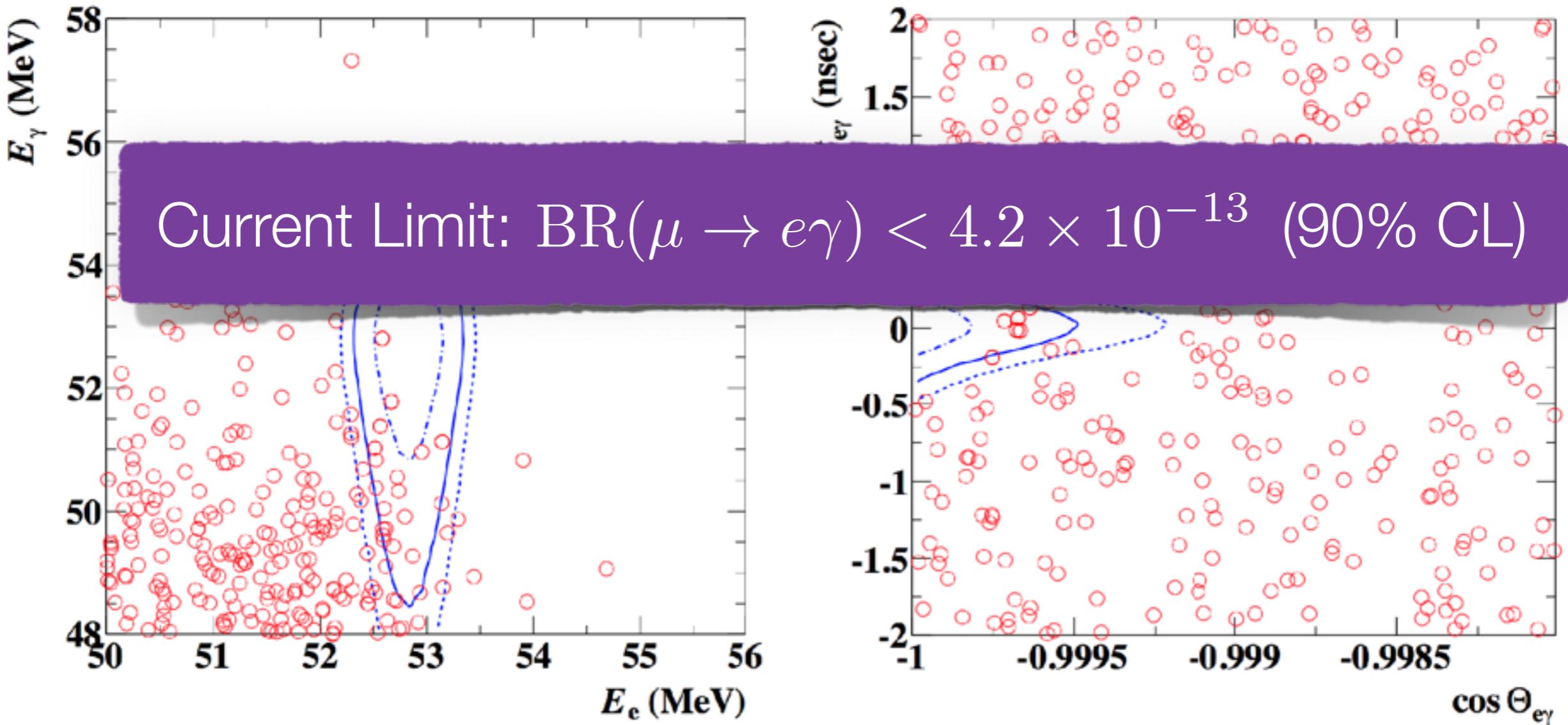


$\mu \rightarrow e\gamma$: The MEG Experiment @ PSI



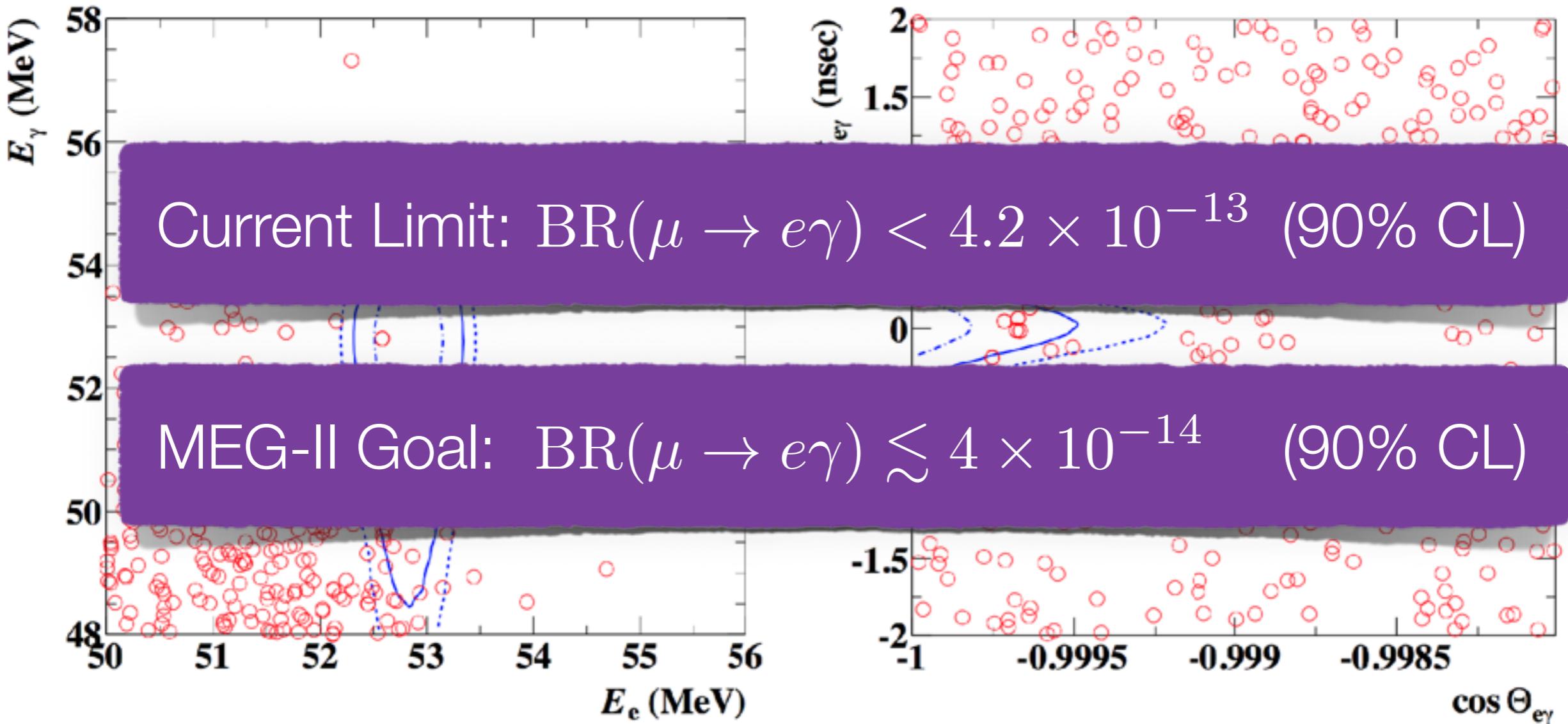
MEG Collaboration [1605.05081](#)

$\mu \rightarrow e\gamma$: The MEG Experiment @ PSI



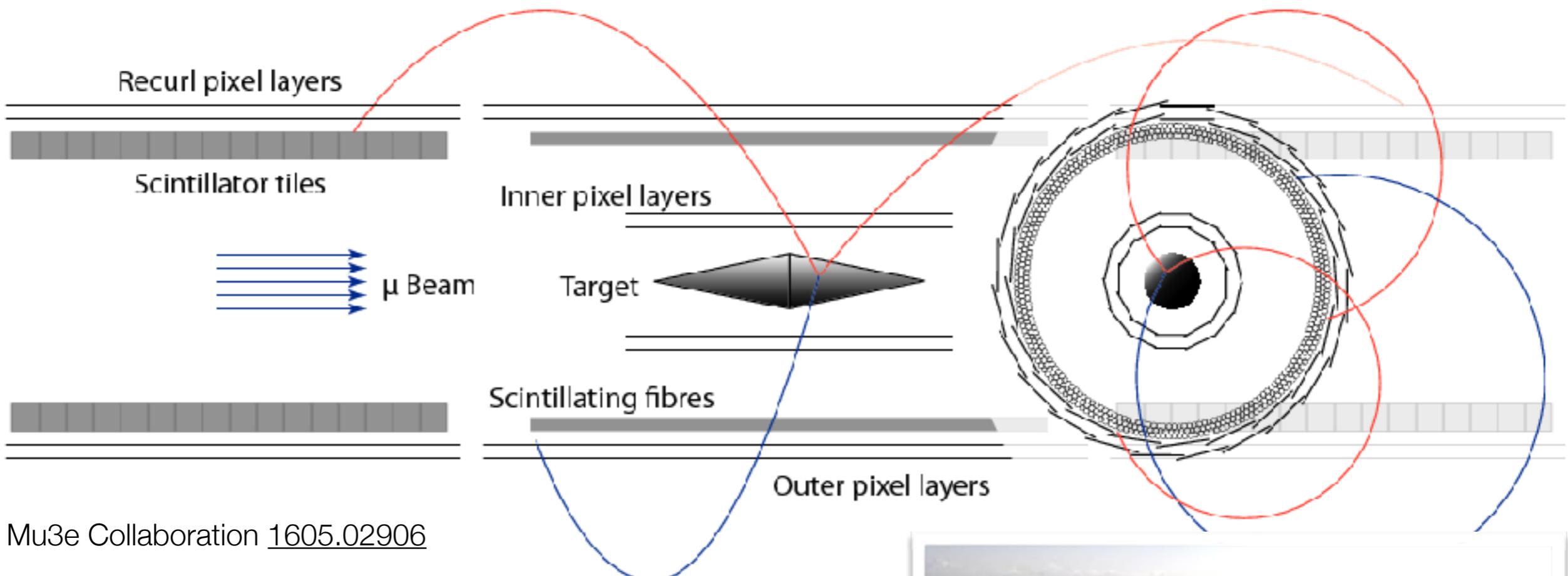
MEG Collaboration [1605.05081](#)

$\mu \rightarrow e\gamma$: The MEG Experiment @ PSI

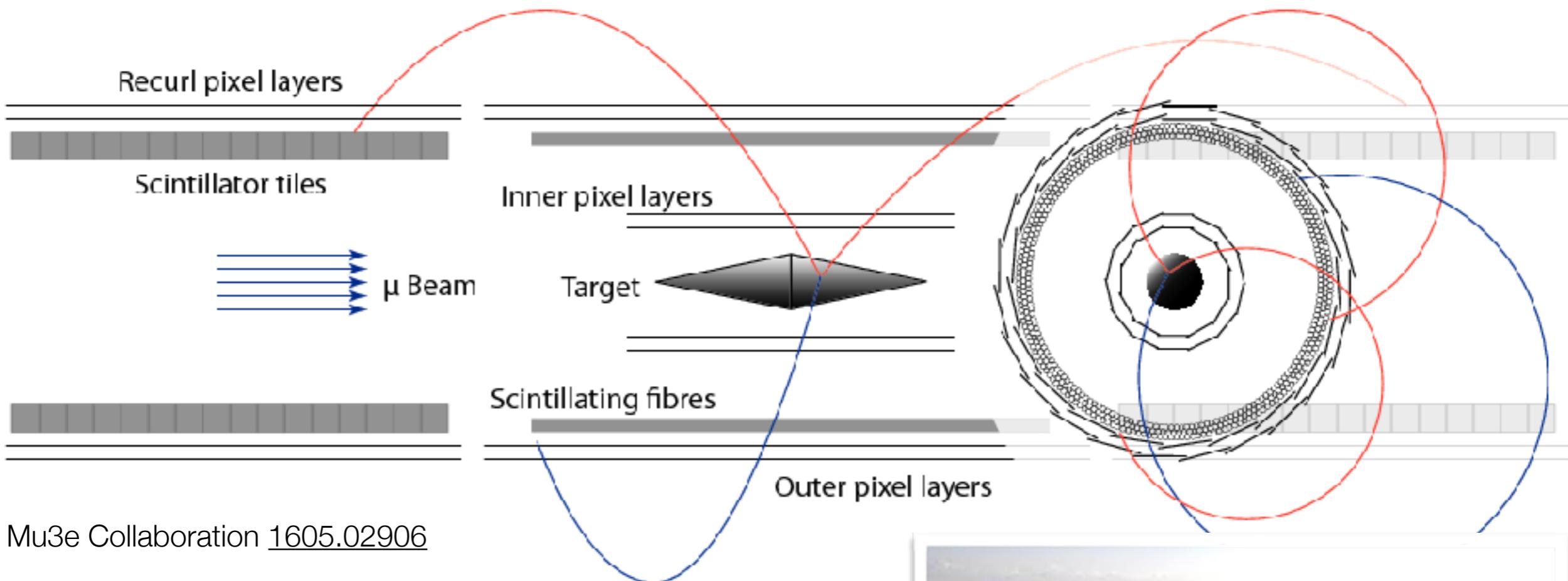


MEG Collaboration [1605.05081](#)

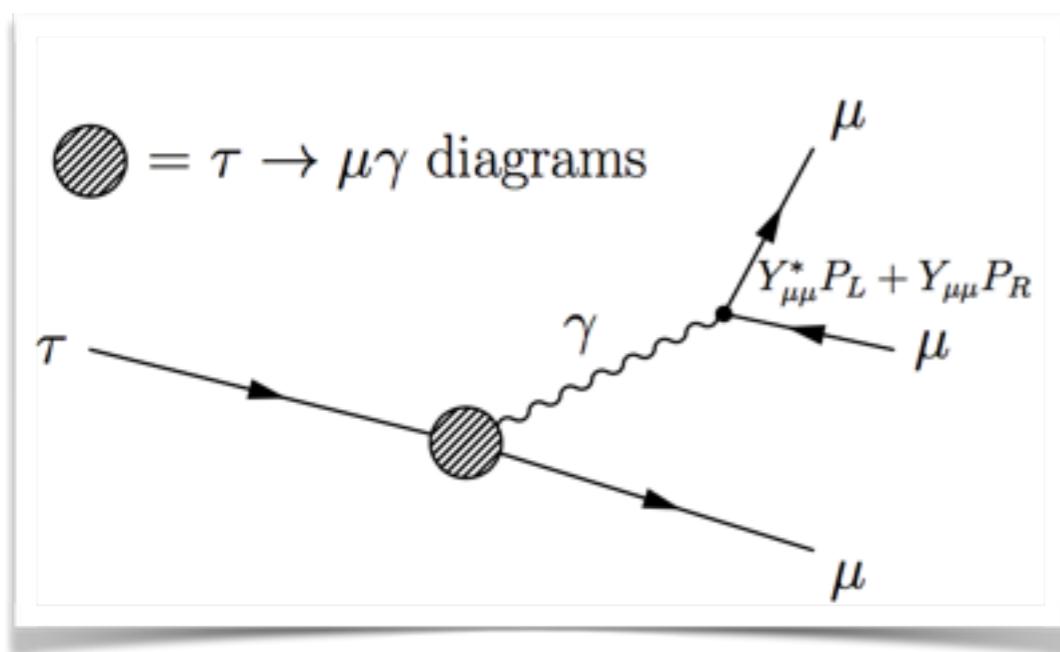
$\mu \rightarrow 3e$: The Mu3e Experiment @ PSI



$\mu \rightarrow 3e$: The Mu3e Experiment @ PSI

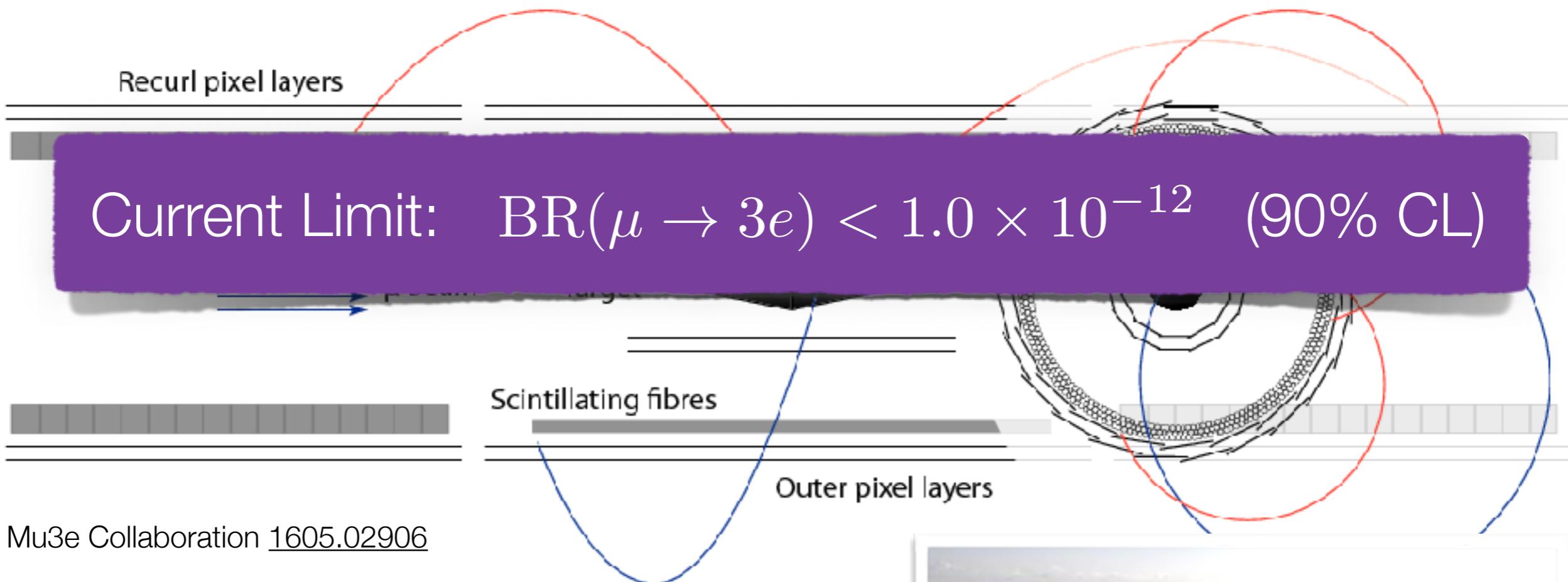


Mu3e Collaboration [1605.02906](#)

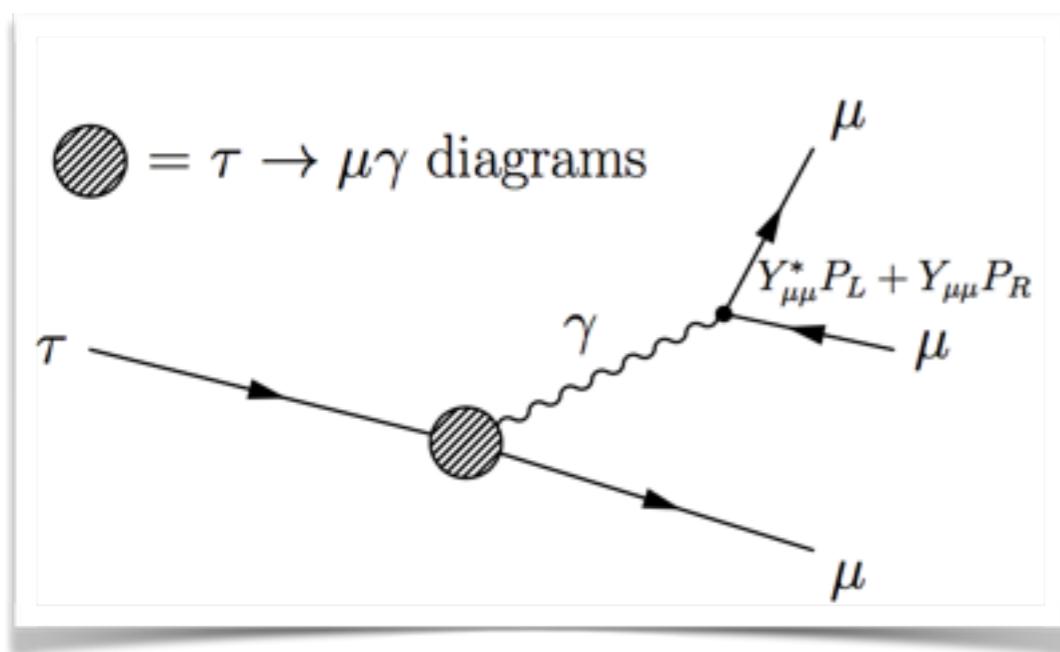


$\mu \rightarrow 3e$: The Mu3e Experiment @ PSI

Current Limit: $\text{BR}(\mu \rightarrow 3e) < 1.0 \times 10^{-12}$ (90% CL)



Mu3e Collaboration [1605.02906](#)



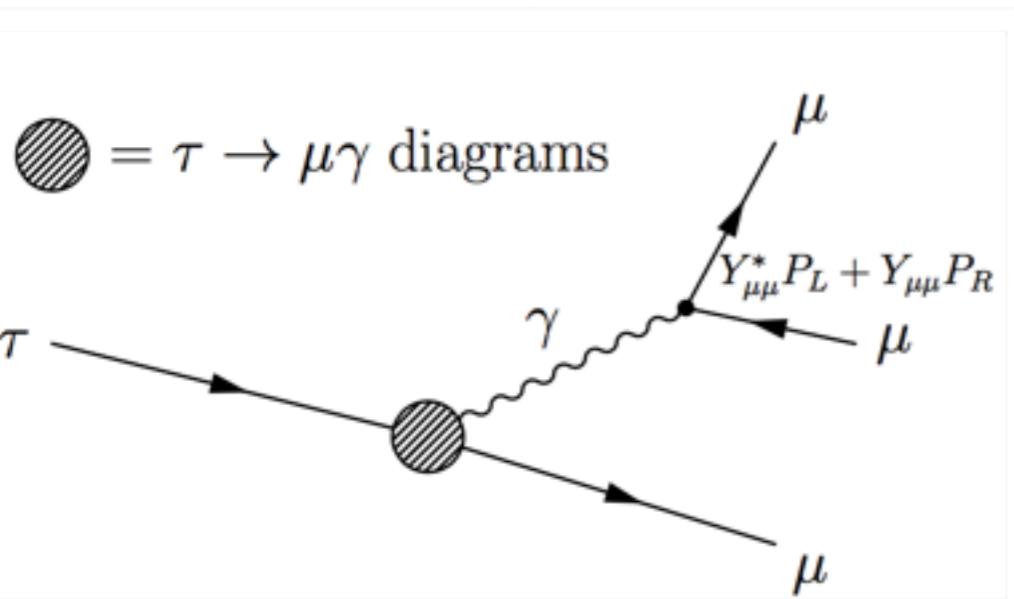
$\mu \rightarrow 3e$: The Mu3e Experiment @ PSI

Recurl pixel layers

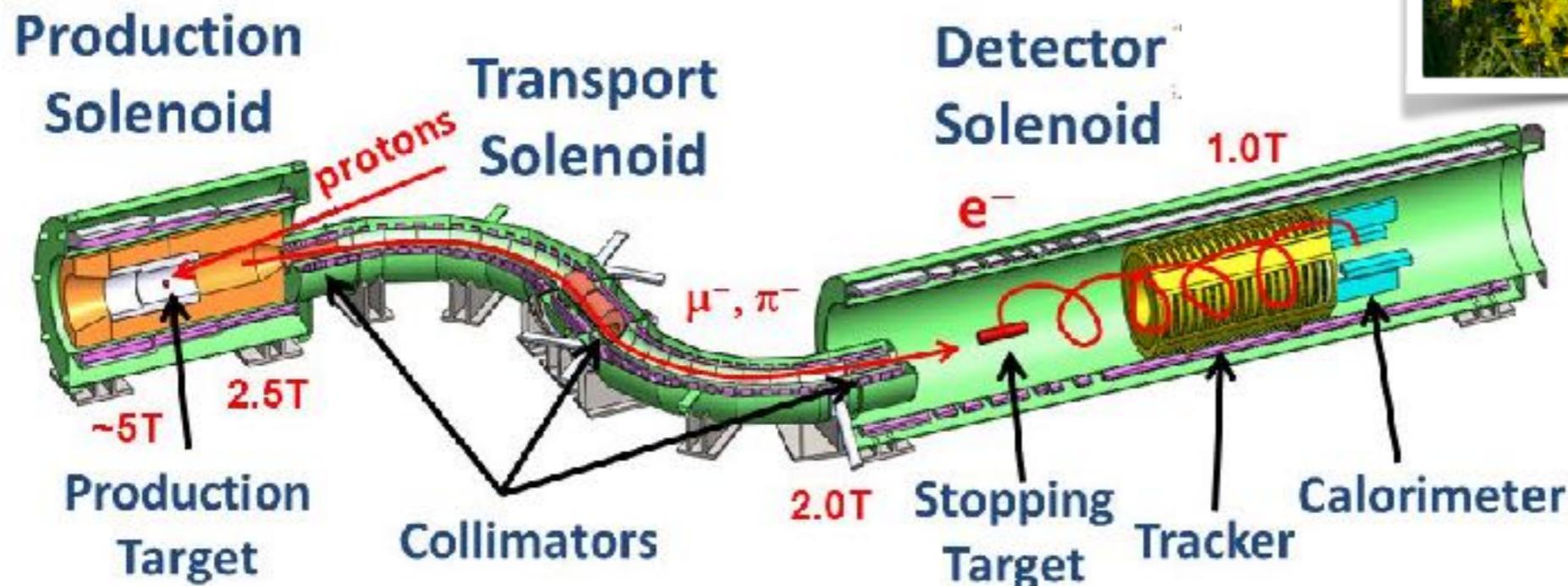
Current Limit: $\text{BR}(\mu \rightarrow 3e) < 1.0 \times 10^{-12}$ (90% CL)

Mu3e Phase I: $\text{BR}(\mu \rightarrow 3e) \lesssim 1.0 \times 10^{-15}$ (90% CL)

Mu3e Collaboration [1605.02906](#)



$\mu \rightarrow e$ Conversion in Nuclei

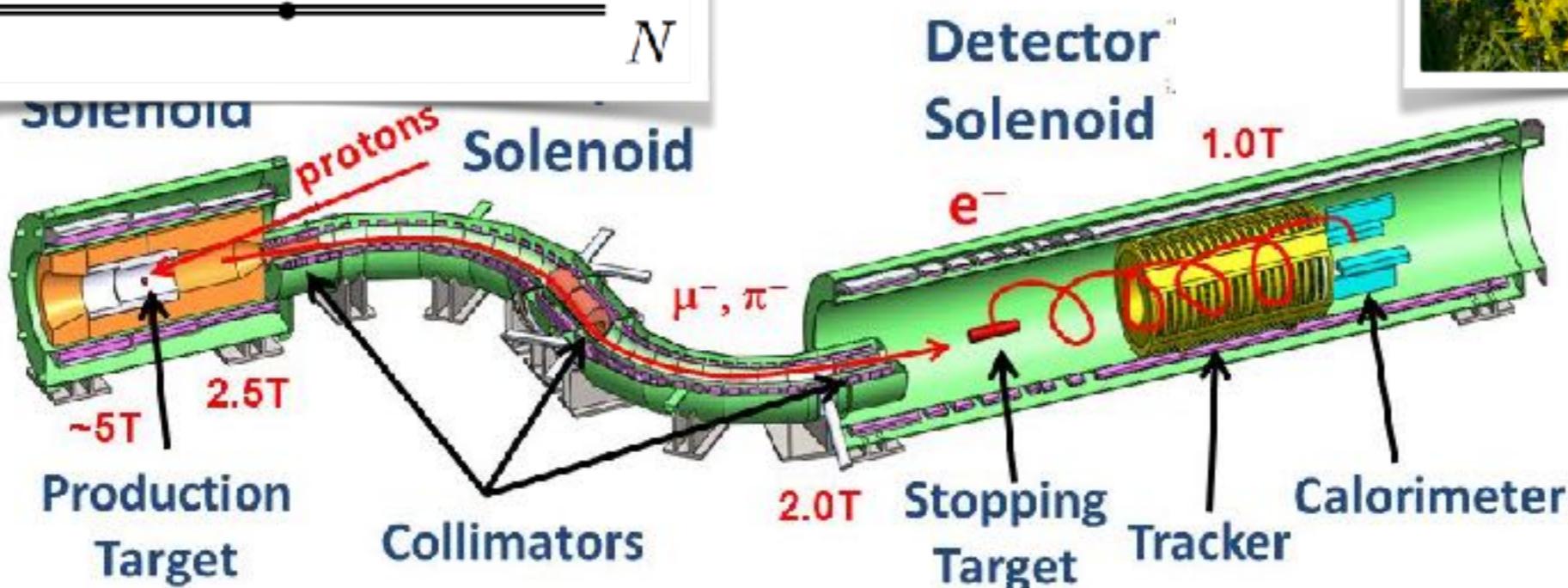
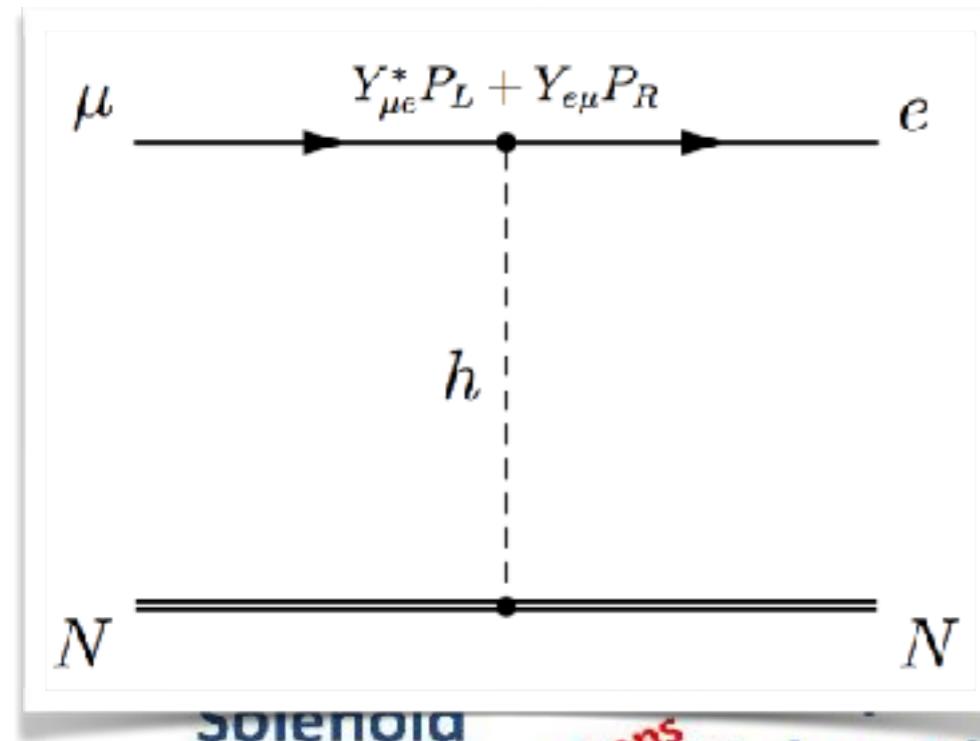


(not shown: Cosmic Ray Veto, Proton Dump, Muon Dump, Proton/Neutron absorbers, Extinction Monitor, Stopping Monitor)

Mu2e Experiment @ Fermilab



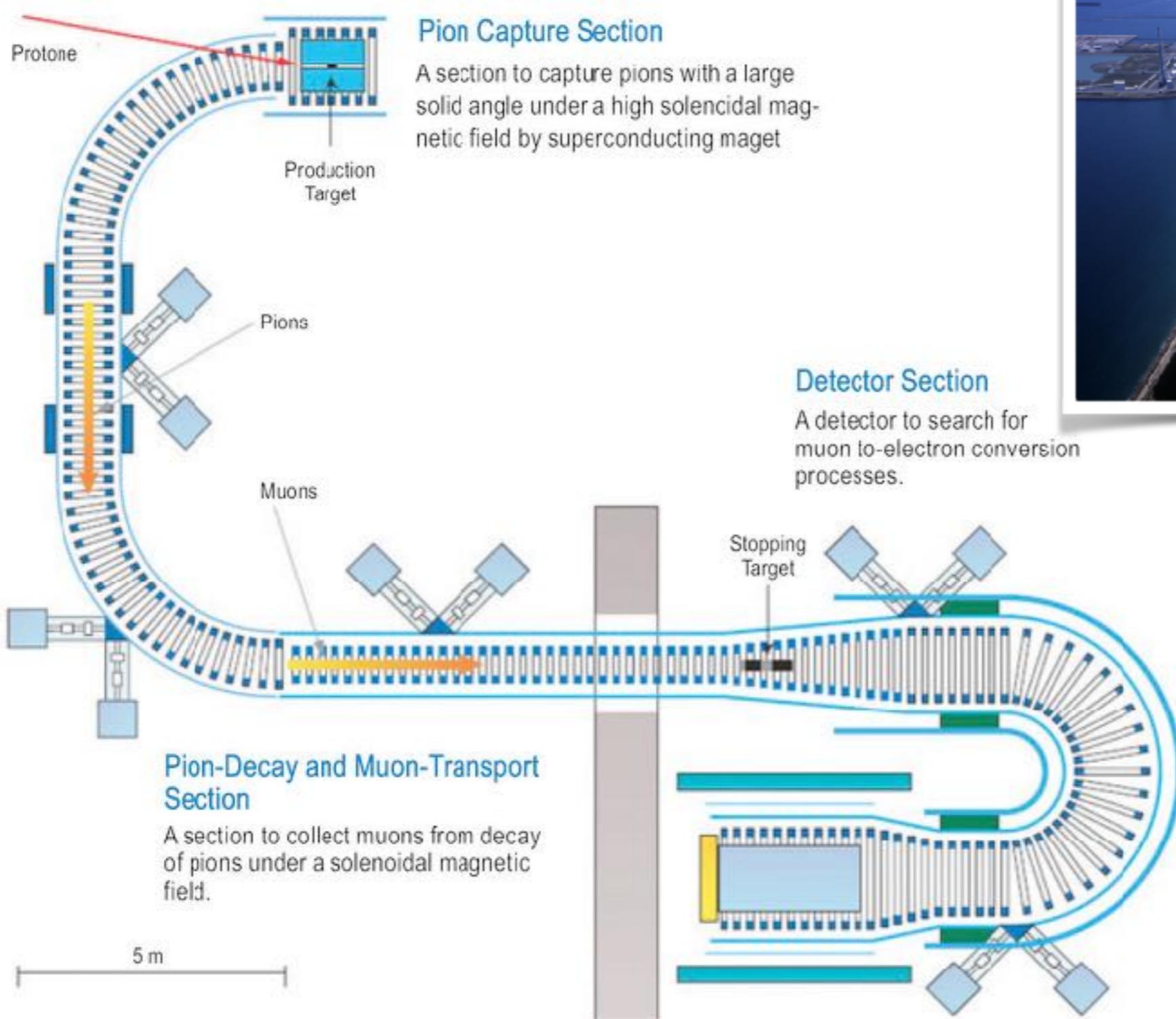
$\mu \rightarrow e$ Conversion in Nuclei



(not shown: Cosmic Ray Veto, Proton Dump, Muon Dump, Proton/Neutron absorbers, Extinction Monitor, Stopping Monitor)

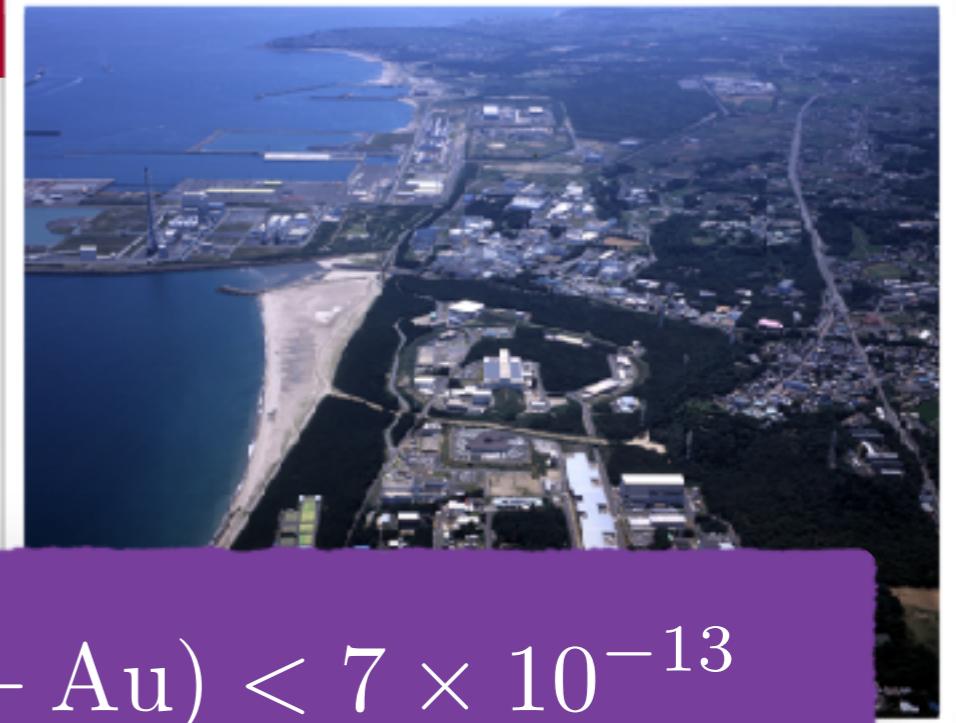
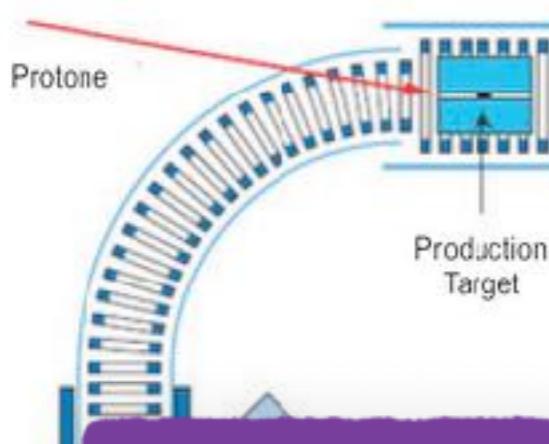
Mu2e Experiment @ Fermilab

$\mu \rightarrow e$ Conversion in Nuclei

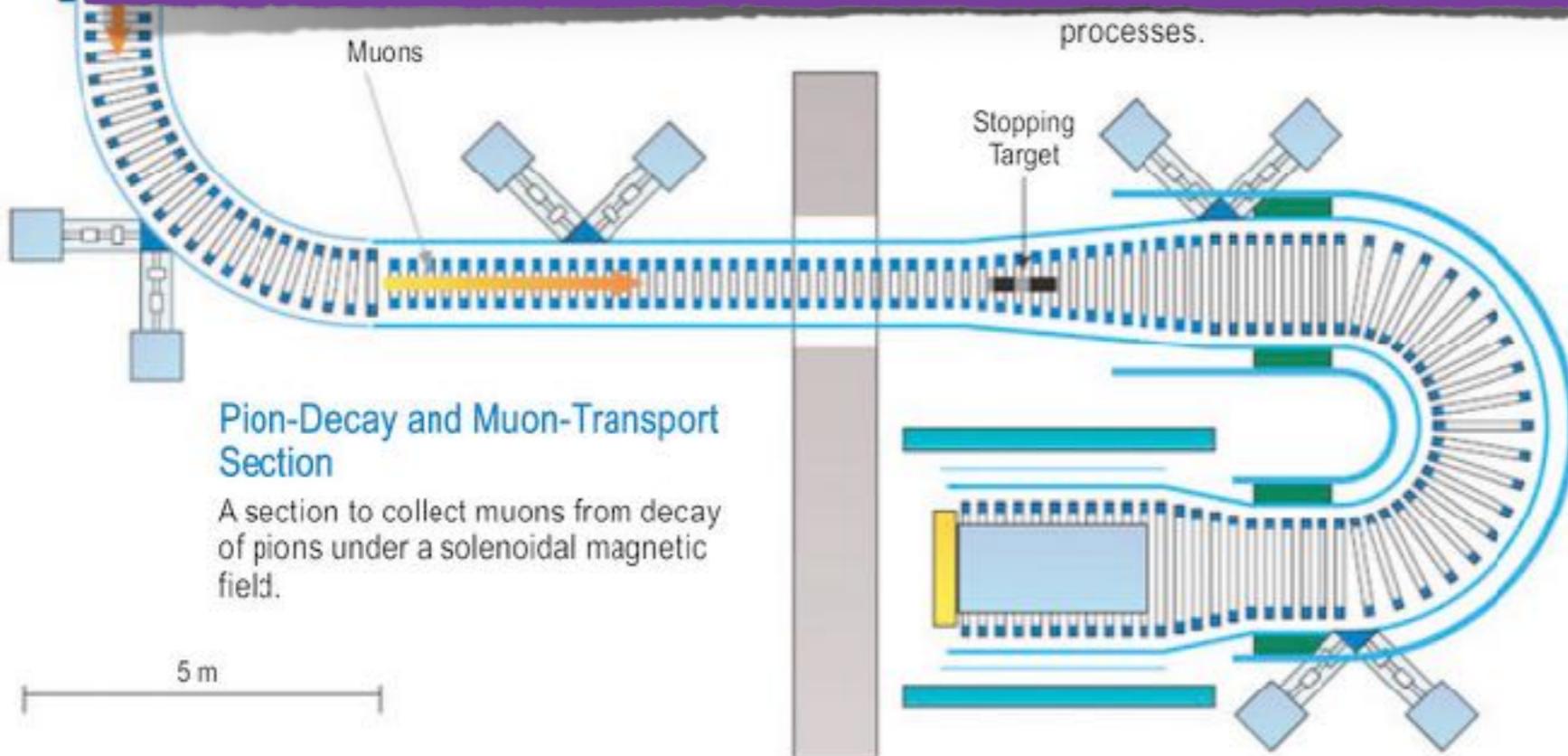


COMET Experiment @ JPARC

$\mu \rightarrow e$ Conversion in Nuclei

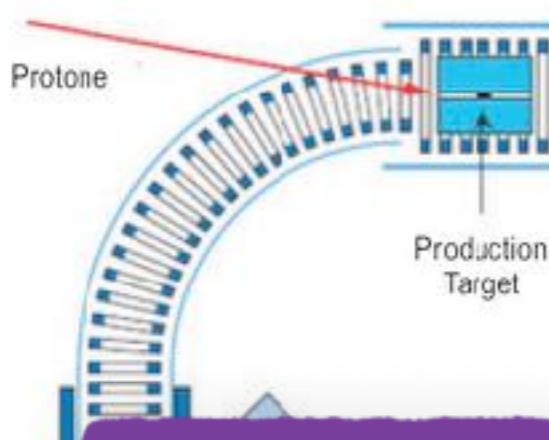


Current Limit: $\text{BR}(\mu + \text{Au} \rightarrow e + \text{Au}) < 7 \times 10^{-13}$



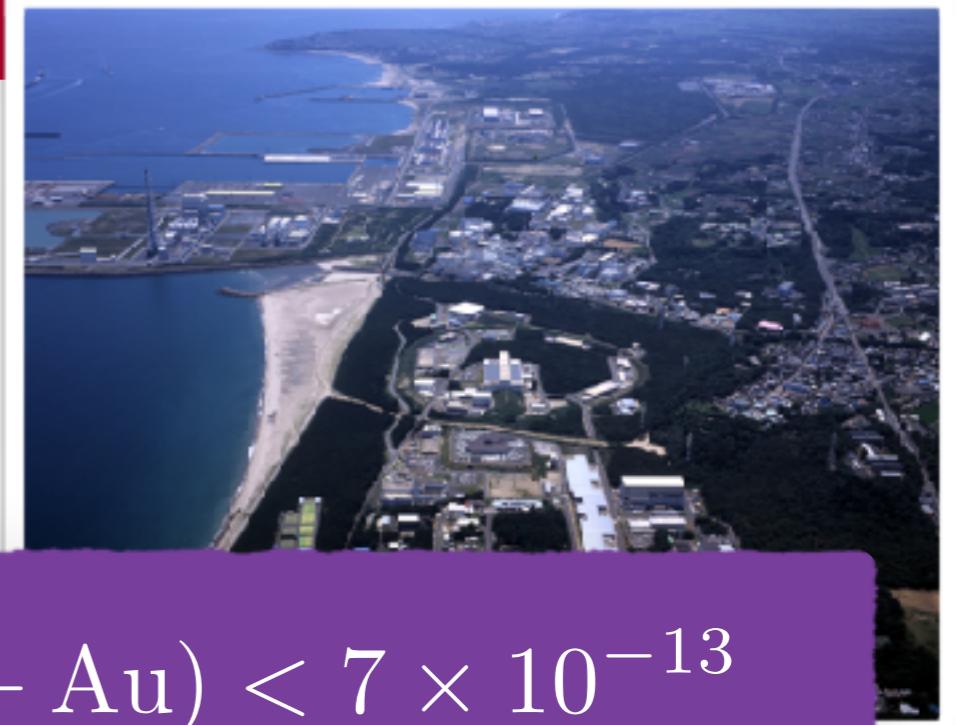
COMET Experiment @ JPARC

$\mu \rightarrow e$ Conversion in Nuclei

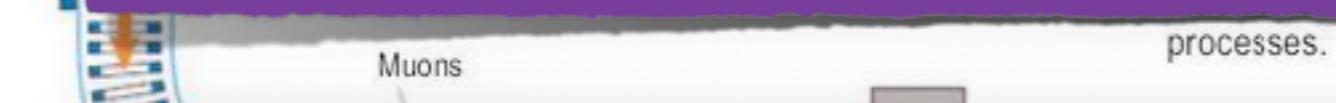


Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet



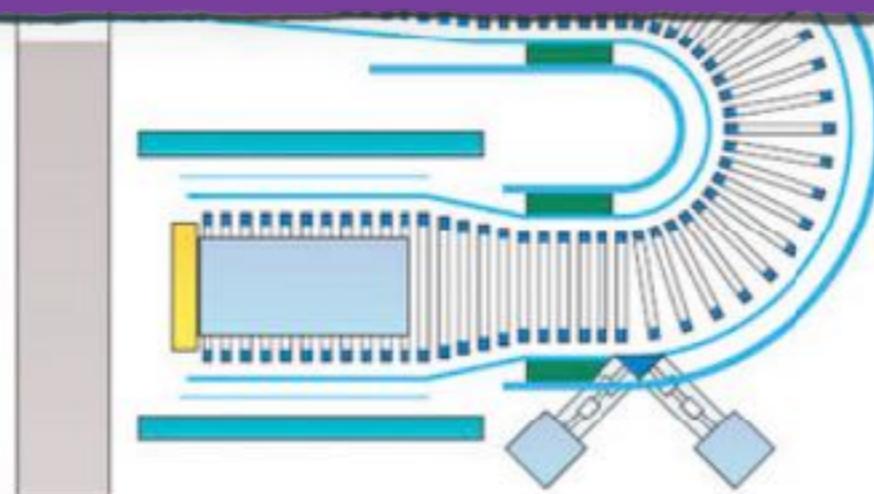
Current Limit: $\text{BR}(\mu + \text{Au} \rightarrow e + \text{Au}) < 7 \times 10^{-13}$



Mu2e/COMET: $\text{BR}(\mu + \text{Al} \rightarrow e + \text{Al}) < \text{few} \times 10^{-17}$

Pion-Decay and Muon-Transport Section

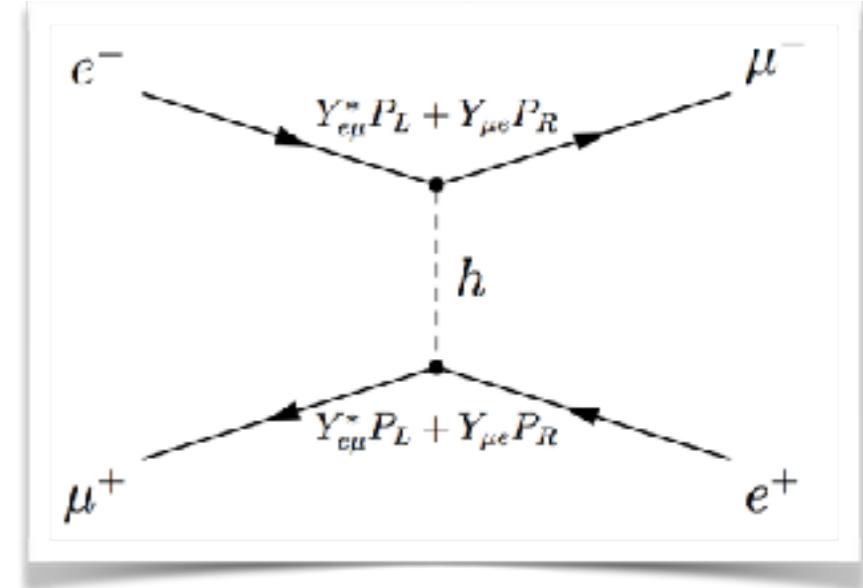
A section to collect muons from decay of pions under a solenoidal magnetic field.



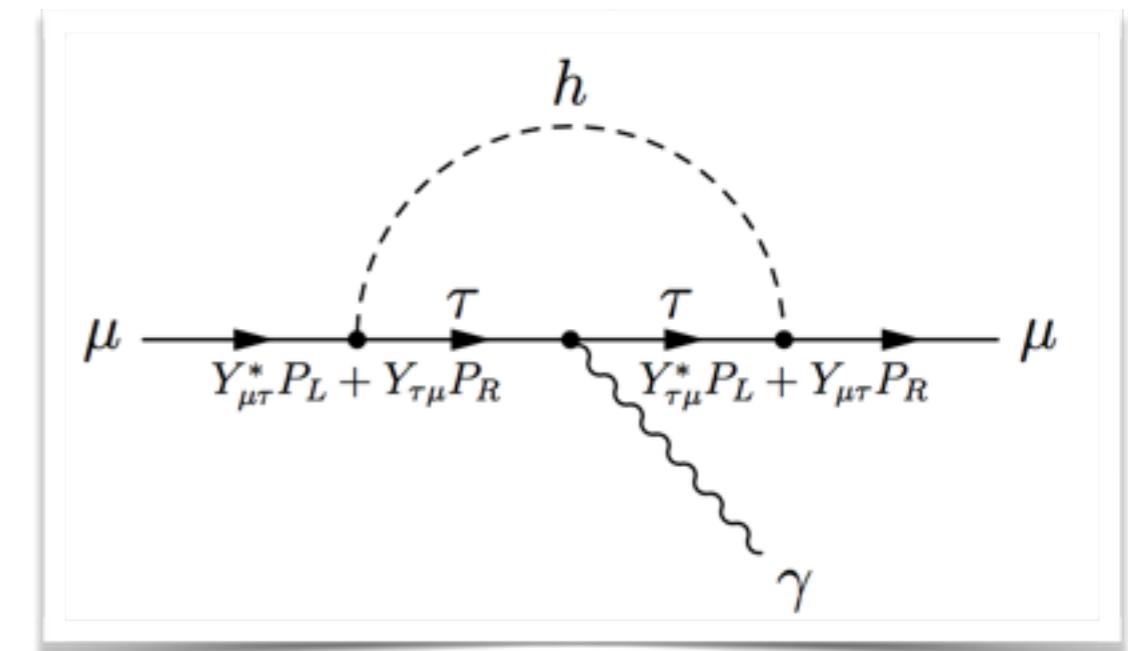
COMET Experiment @ JPARC

Other Processes

Muonium—Antimuonium Oscillations



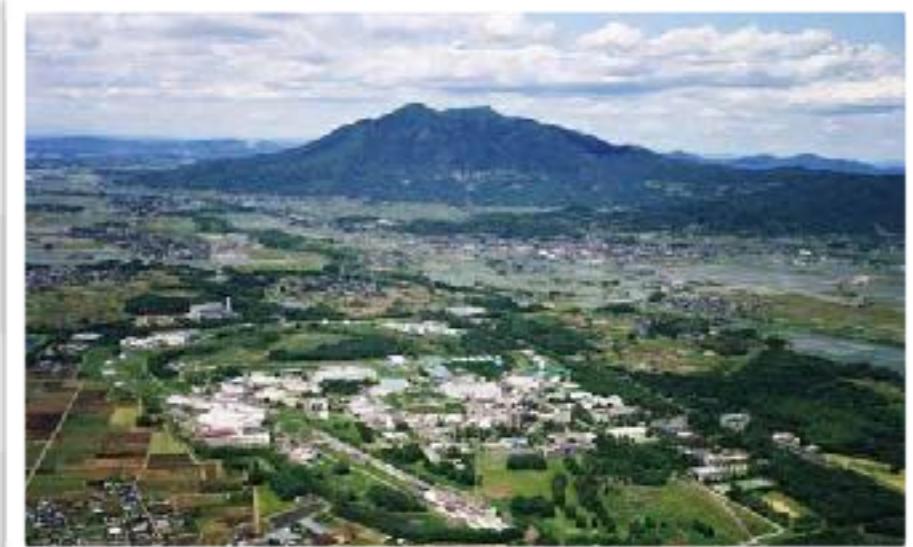
g-2, EDMs



Rare τ Decays

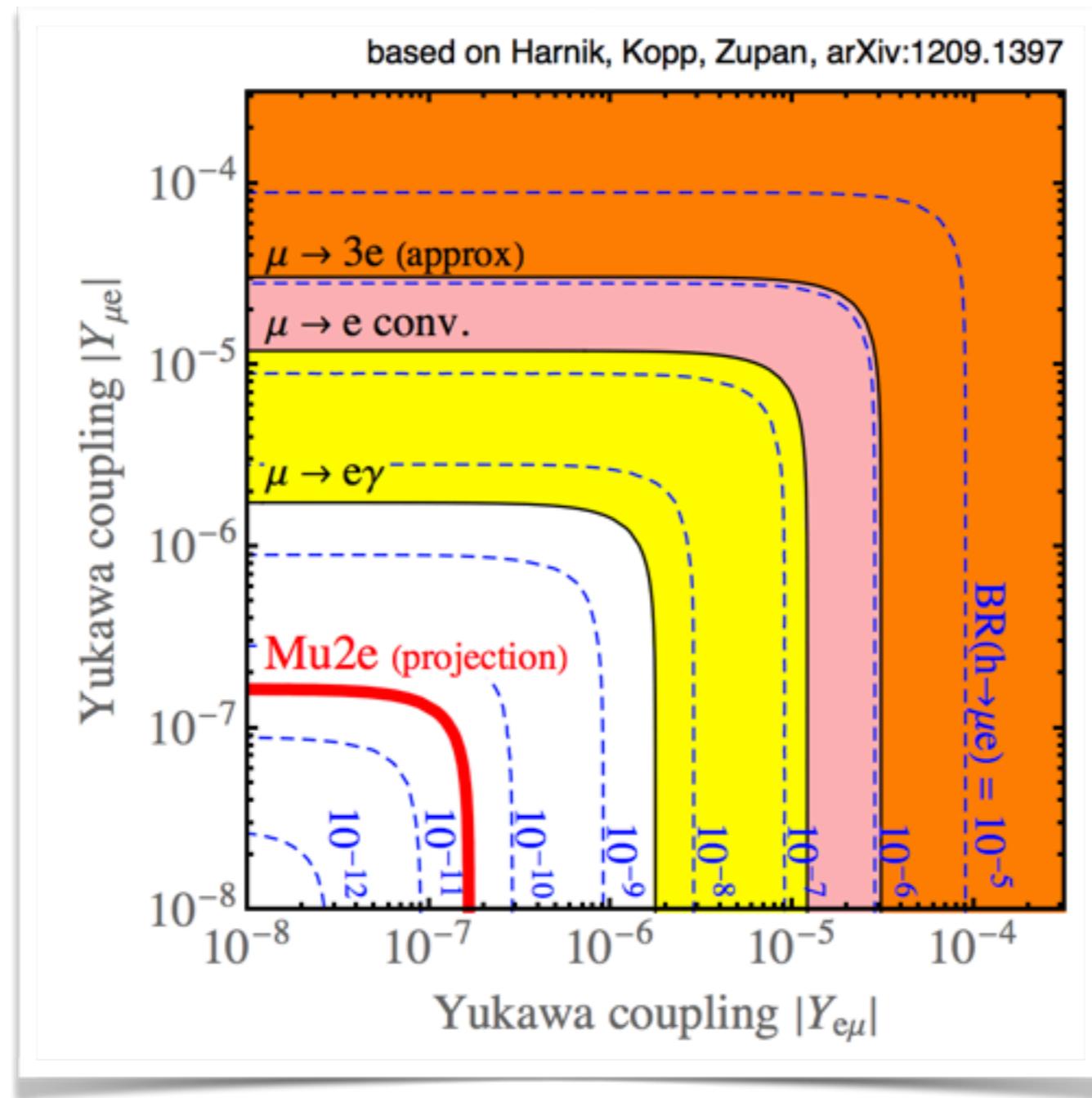
▼ Lepton Family number (LF), Lepton number (L), or Baryon number (B) violating modes

Γ_{184}	$e^- \gamma$	$< 3.3 \times 10^{-8}$
Γ_{185}	$\mu^- \gamma$	$< 4.4 \times 10^{-8}$
Γ_{186}	$e^- \pi^0$	$< 8.0 \times 10^{-8}$
Γ_{187}	$\mu^- \pi^0$	$< 1.1 \times 10^{-7}$
Γ_{188}	$e^- K_S^0$	$< 2.6 \times 10^{-8}$
Γ_{189}	$\mu^- K_S^0$	$< 2.3 \times 10^{-8}$
Γ_{190}	$e^- \eta$	$< 9.2 \times 10^{-8}$
Γ_{191}	$\mu^- \eta$	$< 6.5 \times 10^{-8}$
Γ_{192}	$e^- \rho^0$	$< 1.8 \times 10^{-8}$
Γ_{193}	$\mu^- \rho^0$	$< 1.2 \times 10^{-8}$

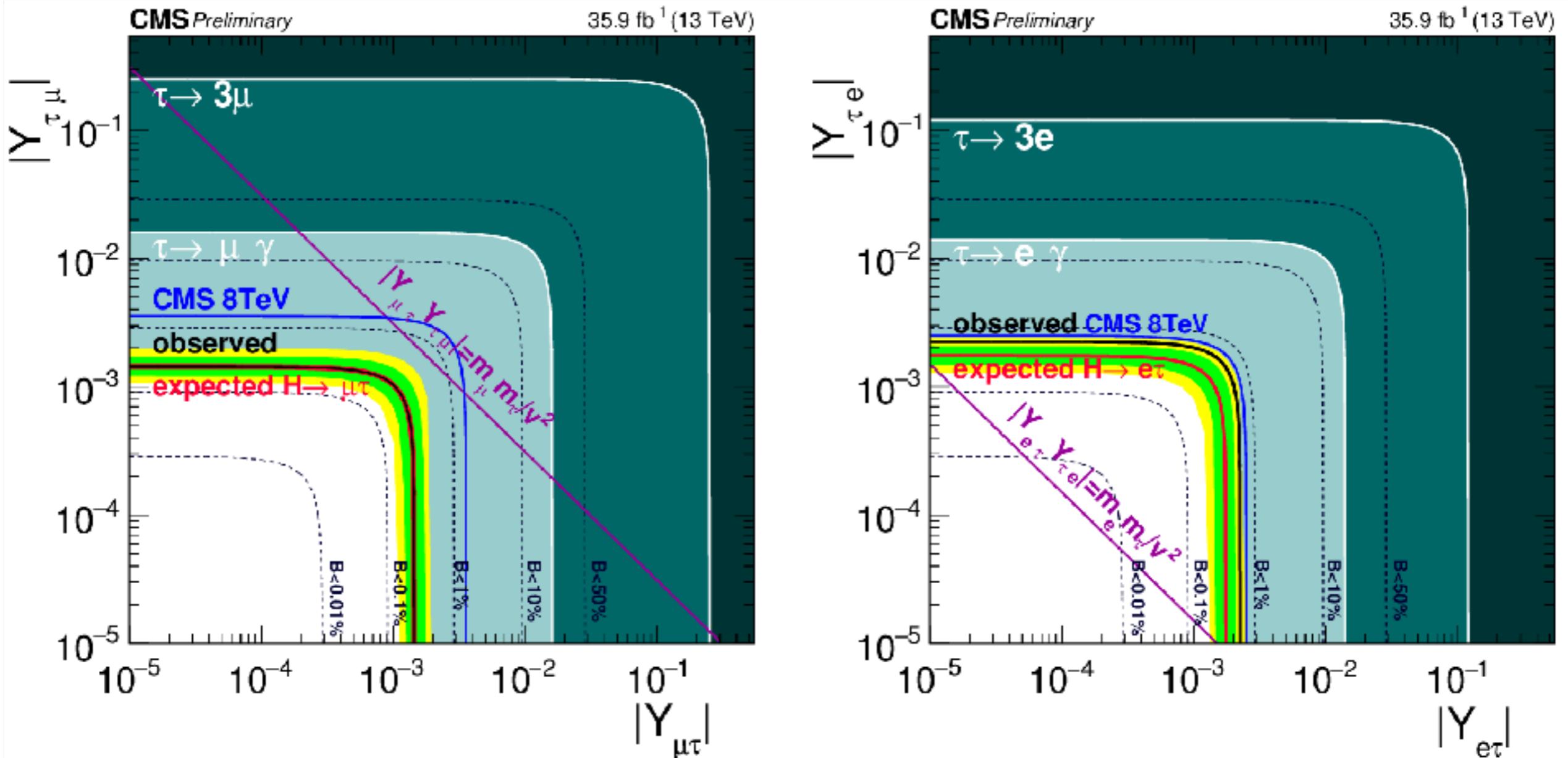


Implications for BSM Physics

Results for FV Higgs Benchmark



Results for FV Higgs Benchmark



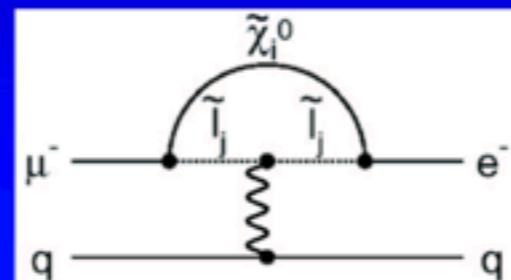
CMS-PAS-HIG-17-001

LFV in BSM Scenarios

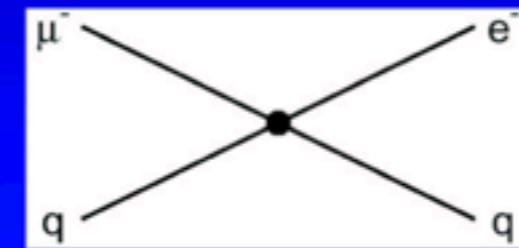
Sensitivity to Different Muon Conversion Mechanisms



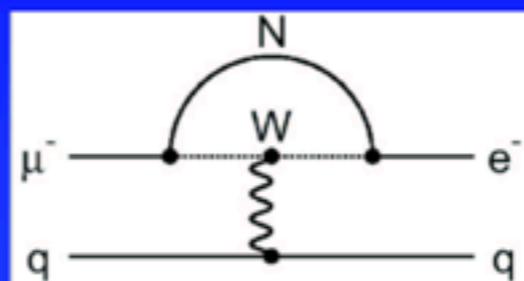
Supersymmetry
Predictions at 10^{-15}



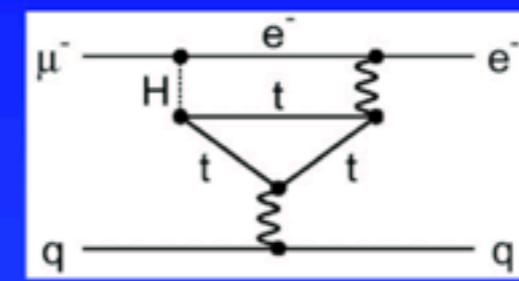
Compositeness
 $\Lambda_c = 3000 \text{ TeV}$



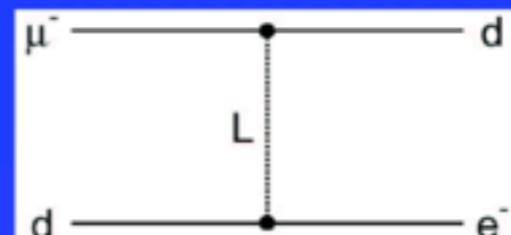
Heavy Neutrinos
 $|U_{\mu N}^* U_{e N}|^2 = 8 \times 10^{-13}$



Second Higgs doublet
 $g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$



Leptoquarks
 $M_L = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2} \text{ TeV}/c^2$



After W. Marciano

Heavy Z' ,
Anomalous Z
coupling
 $M_{Z'} = 3000 \text{ TeV}/c^2$
 $B(Z \rightarrow \mu e) < 10^{-17}$

Complementarity Between Searches

$$\begin{aligned}\mathcal{L} \supset & c_L \frac{e}{8\pi^2} m_\mu (\bar{e} \sigma^{\alpha\beta} P_L \mu) F_{\alpha\beta} \\ & - \frac{1}{2} \sum_q \left[g_{LS}^q (\bar{e} P_R \mu) (\bar{q} q) + g_{LP}^q (\bar{e} P_R \mu) (\bar{q} \gamma_5 q) \right. \\ & + g_{LV}^q (\bar{e} \gamma^\mu P_L \mu) (\bar{q} \gamma_\mu q) + g_{LA}^q (\bar{e} \gamma^\mu P_L \mu) (\bar{q} \gamma_\mu \gamma_5 q) \\ & \left. + \frac{1}{2} g_{LT}^q (\bar{e} \sigma^{\alpha\beta} P_R \mu) (\bar{q} \sigma_{\alpha\beta} q) \right] + L \leftrightarrow R.\end{aligned}$$

Complementarity Between Searches

accessible to $\mu \rightarrow e\gamma$

$$\mathcal{L} \supset c_L \frac{e}{8\pi^2} m_\mu (\bar{e} \sigma^{\alpha\beta} P_L \mu) F_{\alpha\beta}$$

$$- \frac{1}{2} \sum_q \left[g_{LS}^q (\bar{e} P_R \mu) (\bar{q} q) + g_{LP}^q (\bar{e} P_R \mu) (\bar{q} \gamma_5 q) \right.$$

$$+ g_{LV}^q (\bar{e} \gamma^\mu P_L \mu) (\bar{q} \gamma_\mu q) + g_{LA}^q (\bar{e} \gamma^\mu P_L \mu) (\bar{q} \gamma_\mu \gamma_5 q)$$

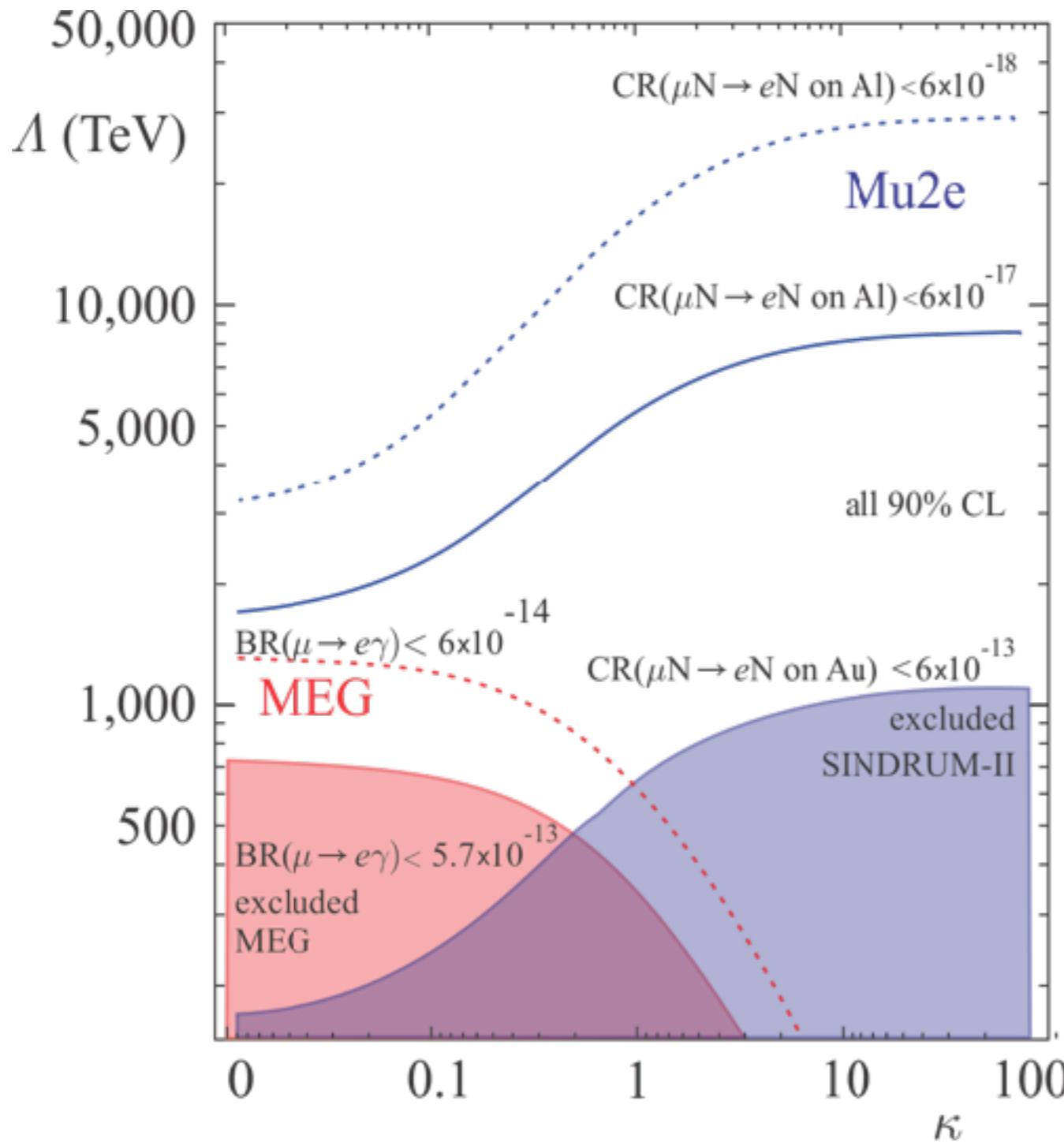
$$\left. + \frac{1}{2} g_{LT}^q (\bar{e} \sigma^{\alpha\beta} P_R \mu) (\bar{q} \sigma_{\alpha\beta} q) \right] + L \leftrightarrow R.$$

Complementarity Between Searches

$$\begin{aligned}\mathcal{L} \supset & e_L \frac{e}{8\pi^2} m_\mu (\bar{e} \sigma^{\alpha\beta} P_L \mu) F_{\alpha\beta} \\ & - \frac{1}{2} \sum_q \left[g_{LS}^q (\bar{e} P_R \mu) (\bar{q} q) + g_{LP}^q (\bar{e} P_R \mu) (\bar{q} \gamma_5 q) \right. \\ & + g_{LV}^q (\bar{e} \gamma^\mu P_L \mu) (\bar{q} \gamma_\mu q) + g_{LA}^q (\bar{e} \gamma^\mu P_L \mu) (\bar{q} \gamma_\mu \gamma_5 q) \\ & \left. + \frac{1}{2} g_{LT}^q (\bar{e} \sigma^{\alpha\beta} P_R \mu) (\bar{q} \sigma_{\alpha\beta} q) \right] + L \leftrightarrow R.\end{aligned}$$

accessible to $\mu \rightarrow e$ conversion

Complementarity Between Searches



$$\begin{aligned} \mathcal{L} \supset & \frac{m_\mu}{(1 + \kappa)\Lambda^2} \bar{\mu}_R \sigma^{\alpha\beta} e_L F_{\alpha\beta} \\ & + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \sum_q \bar{q}_L \gamma^\mu q_L \end{aligned}$$

Summary

Summary

SM rates for cLFV negligible → clean search for new physics

Search Strategies:

- $\mu \rightarrow e\gamma$
- $\mu \rightarrow 3e$
- $\mu \rightarrow e$ conversion in nuclei
- Muonium– antimuonium oscillations
- $g - 2$, EDMs
- $\tau \rightarrow e/\mu + X$

Implications for BSM Physics

- cLFV rather generic in BSM scenarios
- Complementarity between searches

Summary

Summary

