

Experimental Searches Lepton Flavor Violation

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SLAC Summer Institute

2025

Caltech

Outline

Flavor Physics and the Lepton Sector

Charged Lepton Flavor Violation (CLFV)

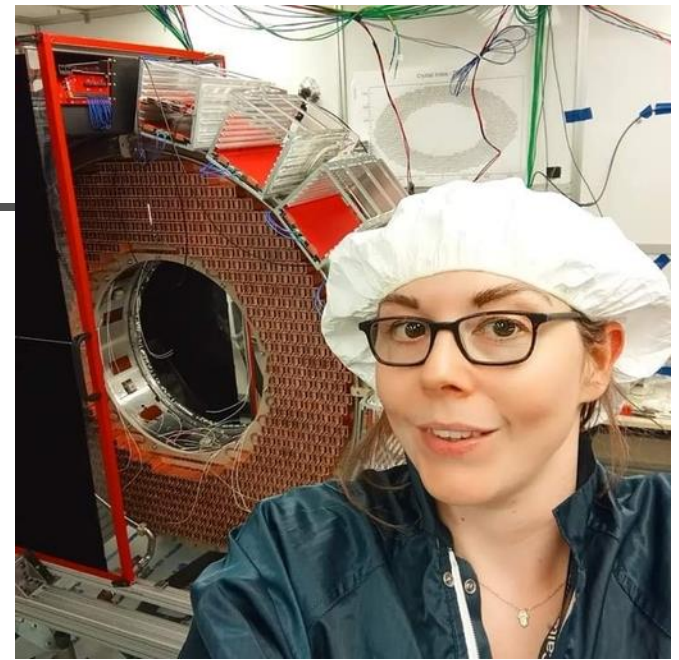
Muon CLFV Searches

Tau CLFV Searches

Summary

About me

- Originally from the UK
- BSc, MSci and PhD from Imperial College London (2018)
 - PhD thesis on the Muon Ionization Cooling Experiment
 - First demonstration of ionization cooling of a muon beam
→ a step on the road to a muon collider.....
- Post-Doc on Mu2e at the University of Manchester (2018 - 2019)
- Now a Senior Post-Doc at Caltech (2019 – present)
 - Work on Mu2e, BaBar and LDMX
 - On Mu2e:
 - Developing offline software, analysis & simulation infrastructure
 - Constructing and calibrating our calorimeter system
 - On BaBar:
 - Tau decay studies, looking for new physics in tau decays
 - Dark sector searches using B mesons



Goals

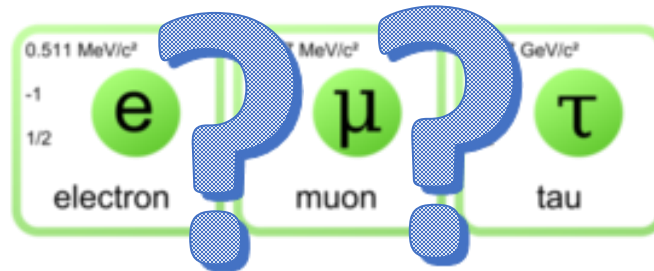
- In this lecture we will answer the following:



What examples of Lepton Flavor Violation have been experimentally verified?

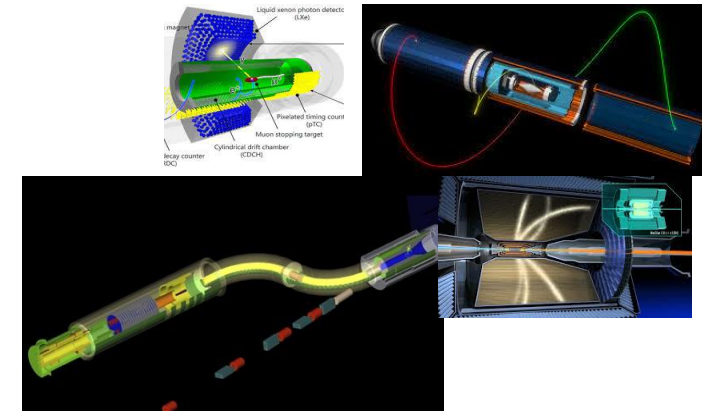
What have we learned so far?

What does this imply about the Charged Leptons?



How can searches for Charged Lepton Flavor Violations be pathways to new physics?

How are experimentalists trying to find evidence of Charged Lepton Flavor Violation?



Flavor Physics in the Lepton Sector

Flavor Physics and the Lepton Sector

Charged Lepton Flavor Violation (CLFV)

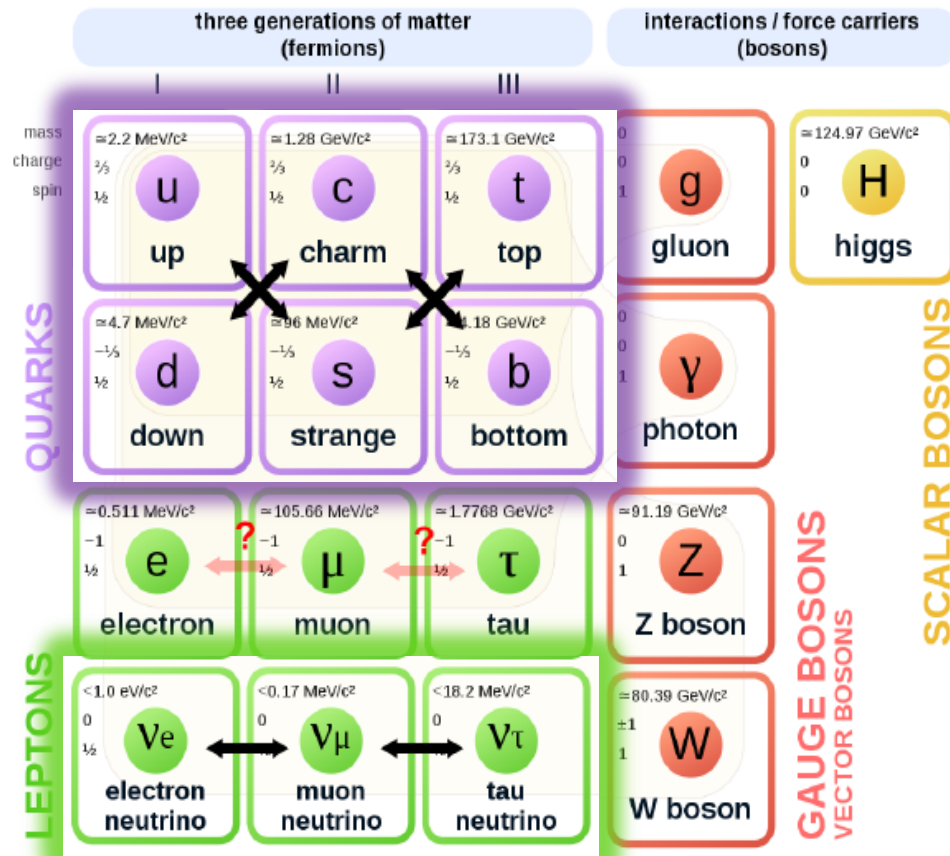
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Summary

Neutrino Mixing Matrix

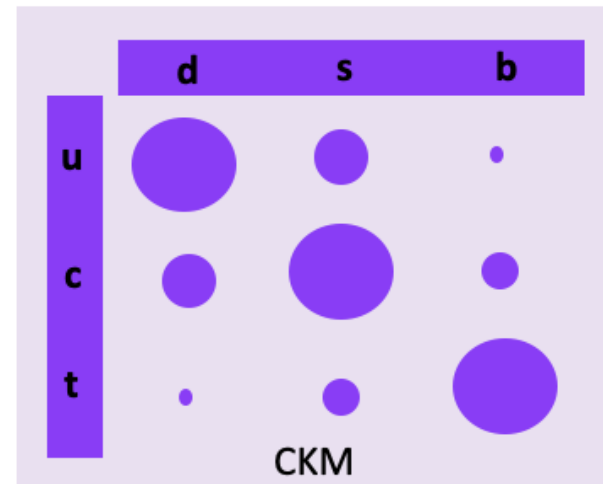
Standard Model of Elementary Particles



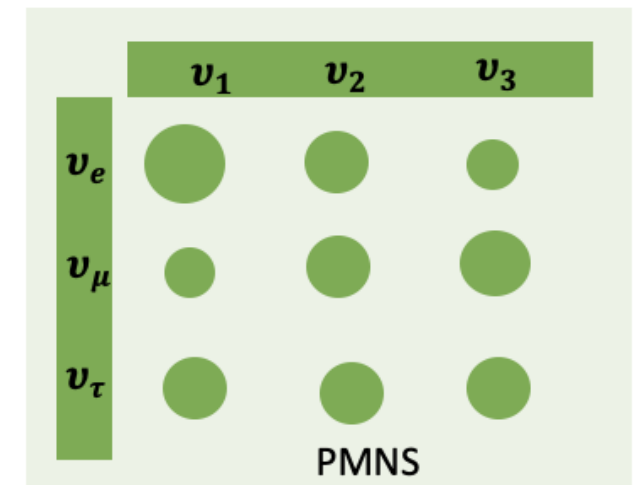
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Quarks – see Phoebe’s talk

Neutral Leptons – Elizabeth’s talk



Cabibbo-Kobayashi-Maskawa matrix



Pontecorvo-Maki-Nakagawa-Sakata matrix

Neutrino Oscillations

See lecture by Elizabeth Worcester

- Neutrino oscillations are only experimentally verified physics beyond the SM → neutrinos have mass!
- Mixing parameterized using **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matrix.

$$|\nu_\ell\rangle = \sum_i U_{\ell i} |\nu_i\rangle .$$

Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)

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Flavor States

Mass States

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$$|\nu_\ell\rangle = \sum_i U_{\ell i} |\nu_i\rangle .$$

Experimental data favors "3 lepton flavors"
Additional neutrinos must be "sterile"

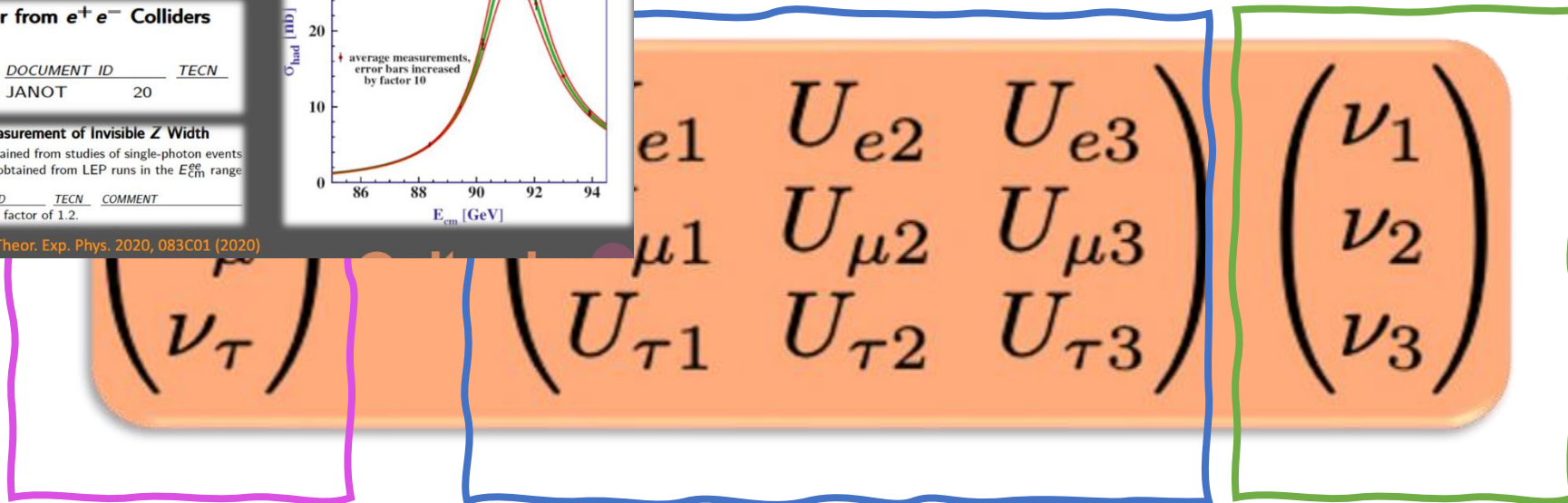
Number from $e^+ e^-$ Colliders			
Number of Light ν Types	VALUE	DOCUMENT ID	TECN
	2.9963 ± 0.0074	1 JANOT	20

Number of Light ν Types from Direct Measurement of Invisible Z Width
In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$. All are obtained from LEP runs in the $E_{\text{cm}}^{\text{ee}}$ range 88–209 GeV.

VALUE	DOCUMENT ID	TECN	COMMENT
2.92 ± 0.05 OUR AVERAGE			Error includes scale factor of 1.2.

Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

awa-Sakata matrix (PMNS)



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Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P$$

where $s_{ij} = \sin(\theta_{ij})$, $c_{ij} = \cos(\theta_{ij})$ with $\theta_{ij} = [0, \pi/2]$, $\delta = [0, 2\pi]$ is the Dirac CP violation phase.

$\mathcal{P} = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$ for Majorana neutrinos

Describes probability of one flavor of neutrino oscillating to another

Neutrino Oscillations

See lecture by Elizabeth Worcester

Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)

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$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4 \sum_{j>k} \mathcal{R}_e \left\{ U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \right\} \sin^2 \left(\frac{\Delta_{jk} m^2 L}{4E} \right) + 2 \sum_{j>k} \mathcal{I}_m \left\{ U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \right\} \sin \left(\frac{\Delta_{jk} m^2 L}{2E} \right),$$

Probability to oscillate from ν_α to ν_β and depends on:

- U mixing matrix elements
- L "baseline"
- E neutrino energy
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$ neutrino mass splitting

Latest Results

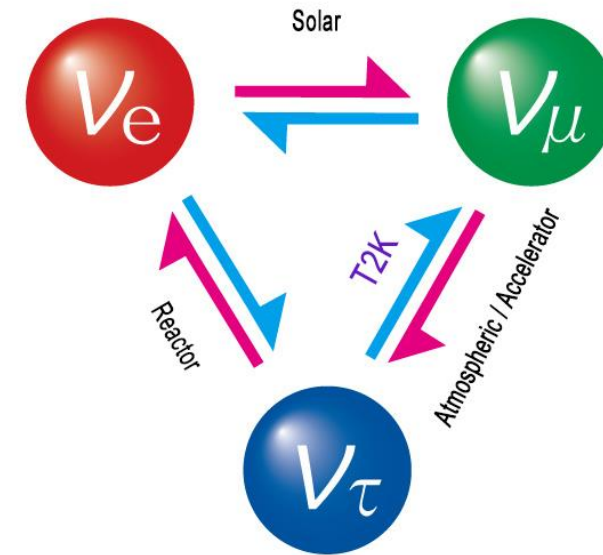
See lecture by Elizabeth Worcester

- Different types of neutrino experiment e.g. solar, reactor, accelerator measure different parts of the mixing matrix:
 - **Solar e.g. Super-K** → sensitive to mixing angle θ_{12} , also known as the solar mixing angle.
 - **Reactor e.g. Daya Bay** → sensitive to mixing angle θ_{13} and, to a lesser extent, θ_{12} .
 - **Accelerator e.g. T2K** → sensitive to atmospheric mixing angle θ_{23} and CP-violating phase δ_{CP} , provide constraints on θ_{13} and the mass hierarchy.

From NuFIT Global Analysis (2024): <https://arxiv.org/pdf/2410.05380>

IC24 with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	$0.308^{+0.012}_{-0.011}$	0.275 → 0.345	$0.308^{+0.012}_{-0.011}$	0.275 → 0.345
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	31.63 → 35.95	$33.68^{+0.73}_{-0.70}$	31.63 → 35.95
$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.013}$	0.435 → 0.585	$0.550^{+0.012}_{-0.015}$	0.440 → 0.584
$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	41.3 → 49.9	$47.9^{+0.7}_{-0.9}$	41.5 → 49.8
$\sin^2 \theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	0.02030 → 0.02388	$0.02231^{+0.00056}_{-0.00056}$	0.02060 → 0.02409
$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	8.19 → 8.89	$8.59^{+0.11}_{-0.11}$	8.25 → 8.93
$\delta_{CP}/^\circ$	212^{+26}_{-41}	124 → 364	274^{+22}_{-25}	201 → 335
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.49^{+0.19}_{-0.19}$	6.92 → 8.05	$7.49^{+0.19}_{-0.19}$	6.92 → 8.05
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.513^{+0.021}_{-0.019}$	+2.451 → +2.578	$-2.484^{+0.020}_{-0.020}$	-2.547 → -2.421

Normal Ordering (NO) ==> $m_1 < m_2 < m_3$,
 Inverted Ordering (IO) ==> $m_3 < m_1 < m_2$



Neutrino oscillation between three generations

Graphic: J-PARC

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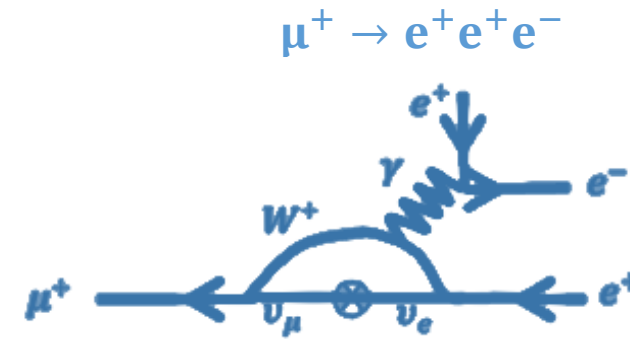
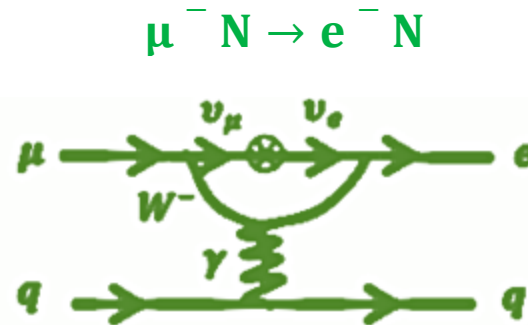
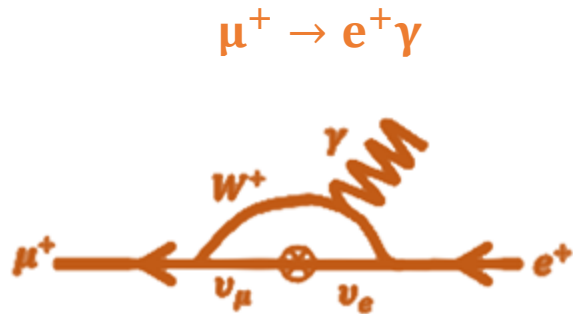
Charged Lepton Flavor Violation

- We know that neutral leptons (neutrinos) exhibit flavor violation → **what about charged leptons?**
 - **Charged Lepton Flavor Violation (CLFV) has never been seen.**
- In the coming years many experiments will search for CLFV in several different channels:
 - **Muons:** $\mu \rightarrow e\gamma, \mu \rightarrow eee, N\mu \rightarrow Ne \rightarrow$ **MEG-II, Mu3e, Mu2e, COMET**
 - **Taus:** $\tau \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \tau \rightarrow \mu ee$ etc. → **Belle-II**
 - **Muonium:** $\mu^+e^- \rightarrow e^-\mu^+ \rightarrow$ **MACE**
 - **Higgs LFV:** $H \rightarrow \mu e, \tau e$ etc. → **LHC**
 - **Z LFV:** $Z \rightarrow \mu e, \tau e$ etc. → **LHC**
 - **Meson LFV:** $K^0, (B^0, D^0) \rightarrow \mu e, \tau e$ etc. → **several experiments.**
- There are also complementary searches for LFV + Lepton Number Violation:
 - Neutrinoless double beta decay: $(A, Z) \rightarrow 2e^- + (A, Z + 2) \rightarrow$ **vast experimental program globally.**
 - $(A, Z) + \mu^- \rightarrow e^+ + (A, Z - 2) \rightarrow$ **Mu2e**
- **Here there is also a change in the total number of particles belonging to each lepton “family”**

Charged Lepton Flavor Violation (CLFV)

- Adding neutral lepton flavor violation to the Standard Model, introduces CLFV at loop level, mediated by W bosons:

Muon Examples



No outgoing neutrinos!

- Rates heavily suppressed by GIM suppression and are far below any conceivable experiment could measure:

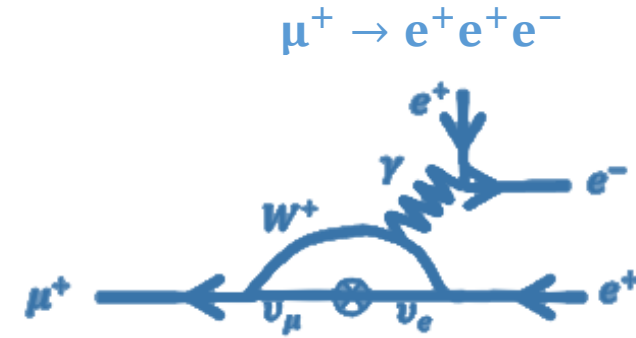
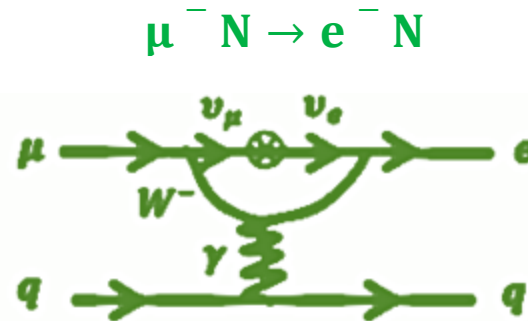
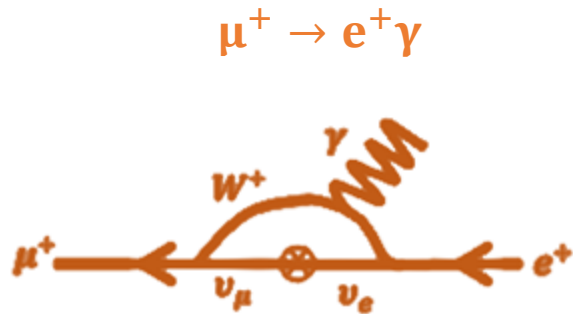
$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left(\frac{1}{4}\right) \sin^2 2\theta_{13} \sin^2 \theta_{23} \left| \frac{\Delta m_{13}^2}{M_W^2} \right|^2$$

$$B(\mu \rightarrow e\gamma) \sim \mathcal{O}(10^{-54})$$

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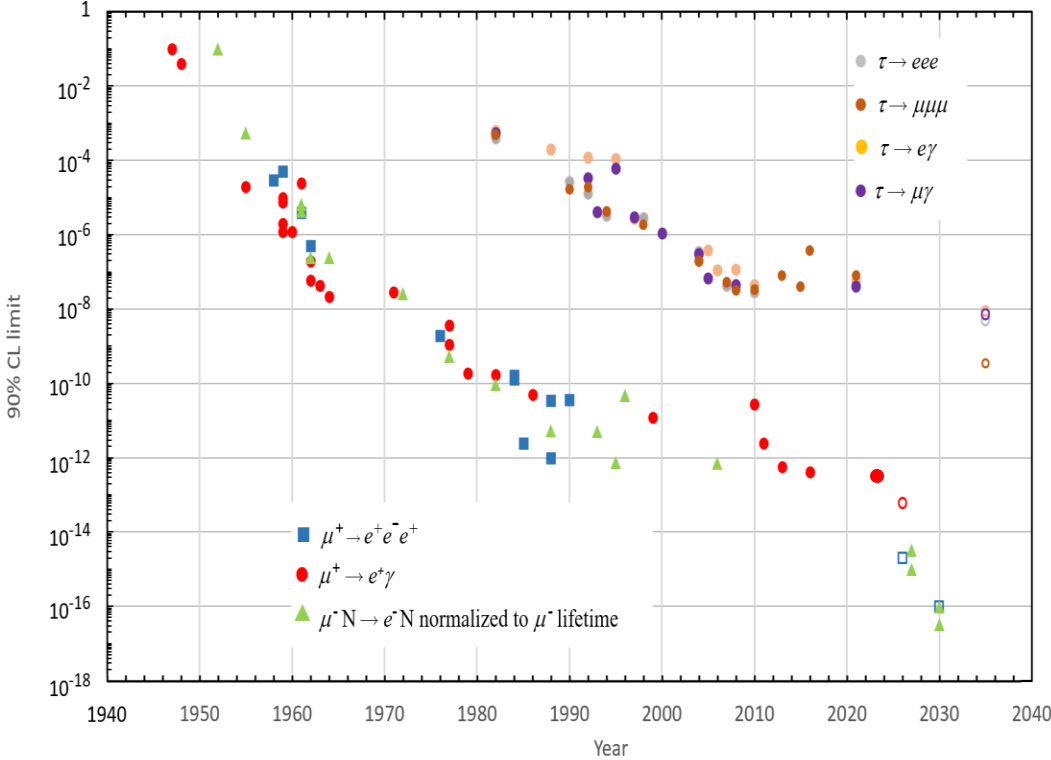
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$$B(\mu \rightarrow e\gamma) \sim \mathcal{O}(10^{-54})$$

- ...but many Beyond Standard Model (BSM) theories (e.g. SO(10) SUSY, scalar leptoquarks, seesaw models) predict enhanced rates of CLFV such that the next generation of experiments could detect it.

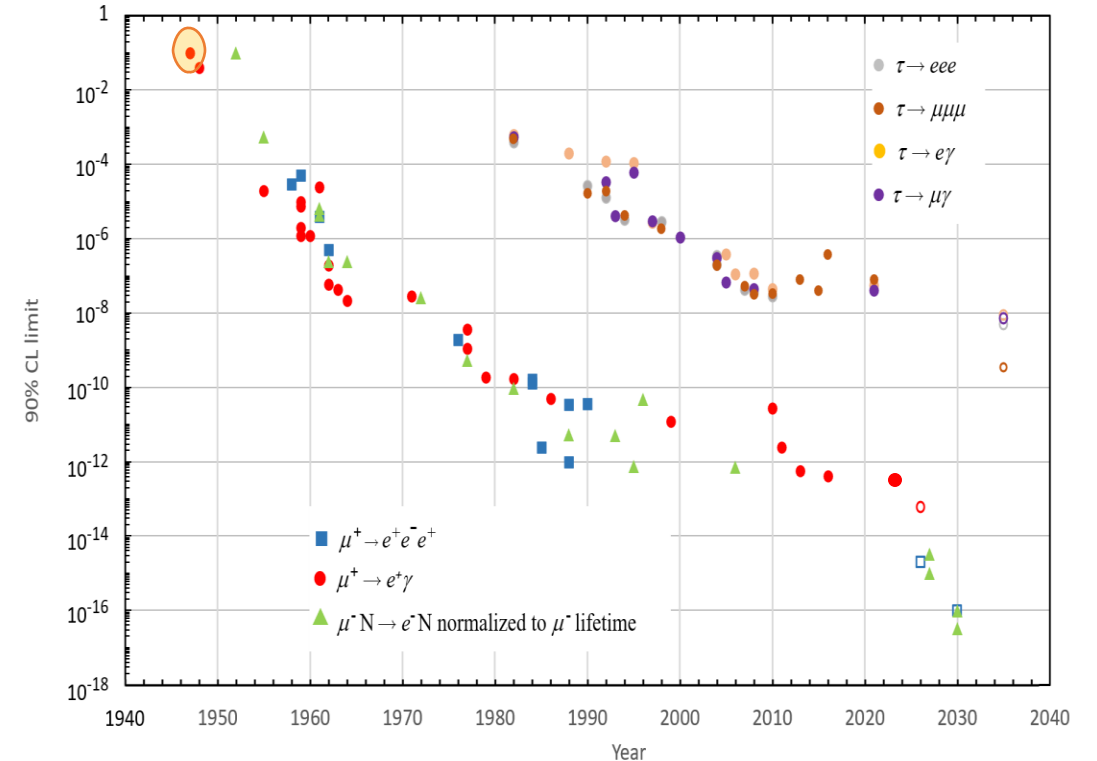
CLFV is an indirect search for New Physics and offers a deep probe of well-motivated BSM theories.

A Brief History of CLFV



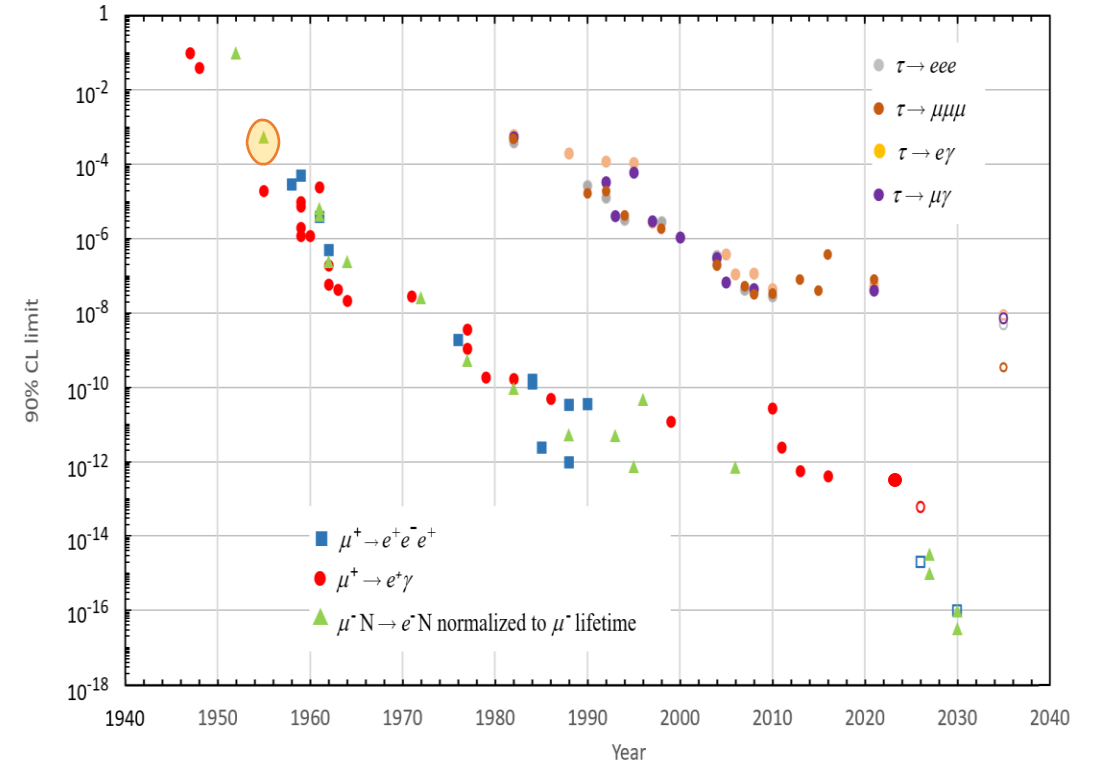
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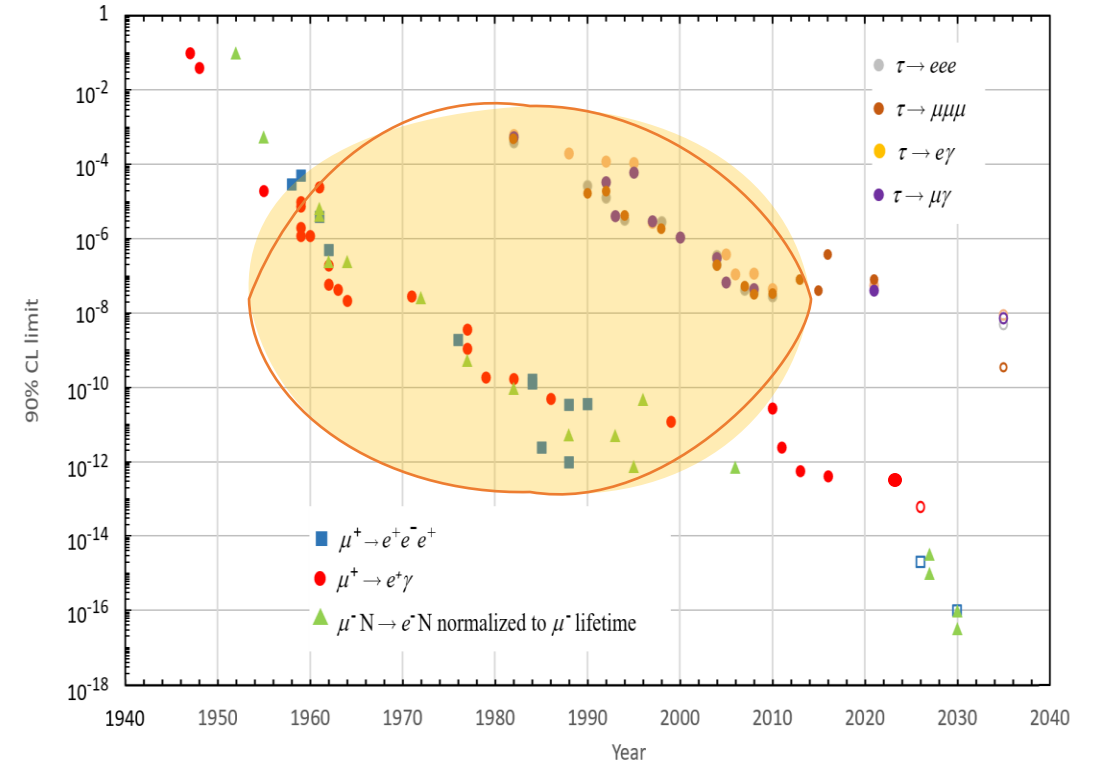
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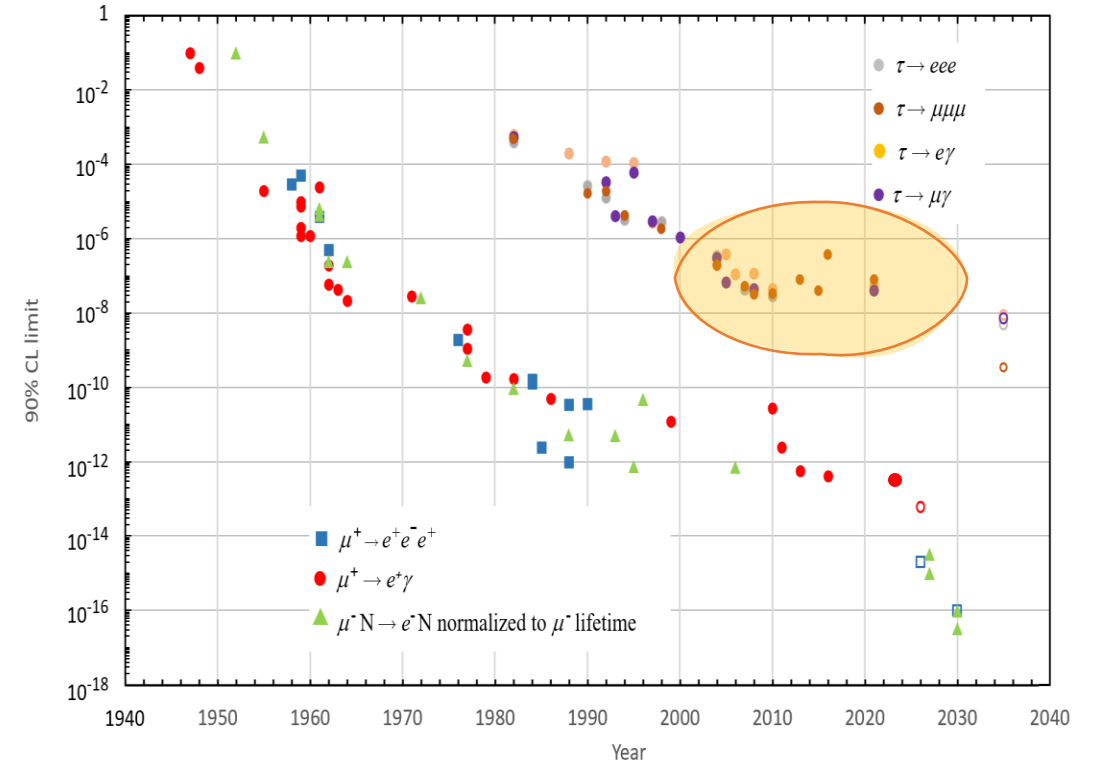
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- Many subsequent attempts to measure, limits improve by upto x10000



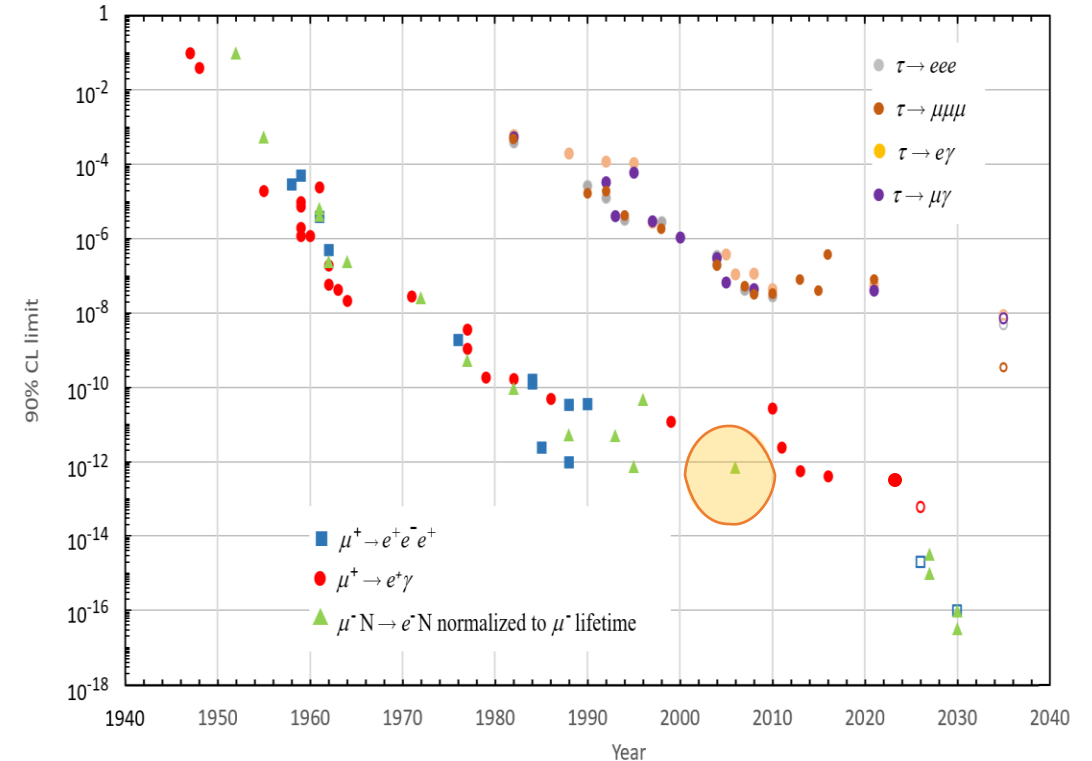
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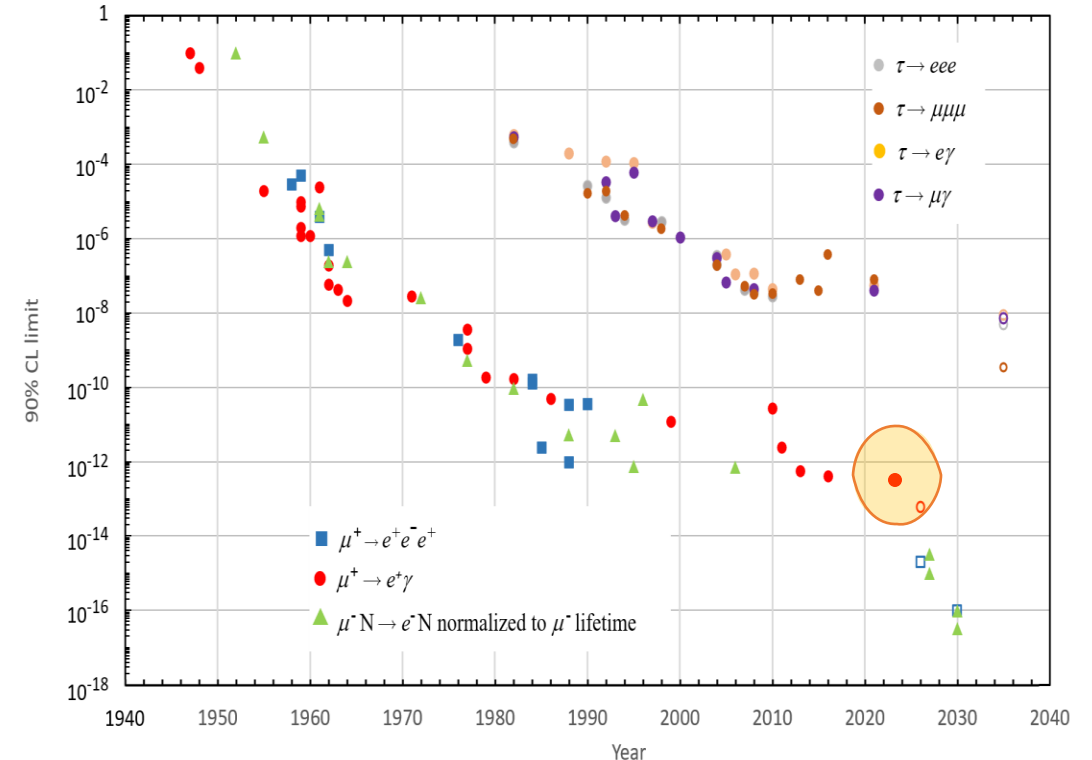
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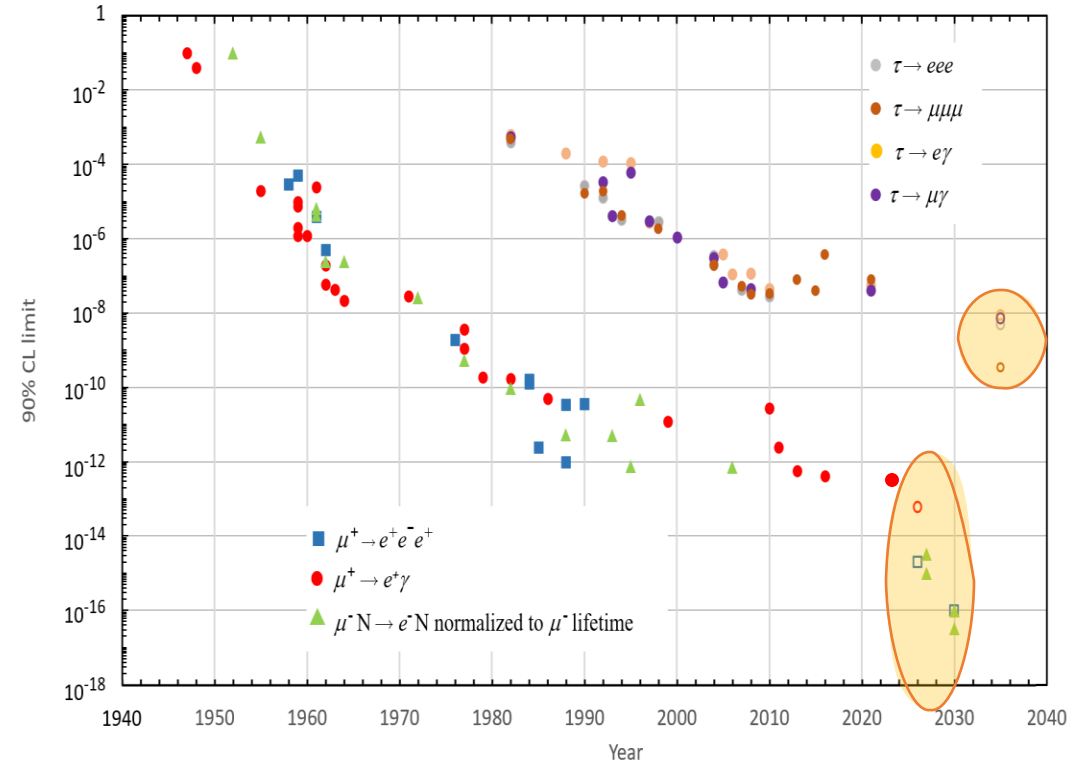
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- **2024**– MEG-II (looking for $\mu \rightarrow e\gamma$) publishes strictest limit so far. *Eur.Phys.J.C 84 (2024) 3, 216*



A Brief History of CLFV

- **2025 – 2030s** Over the next decade many experiments will seek to measure CLFV in several forms. Unprecedented limits or discovery will be achieved!



Muons as powerful probes of CLFV

- There is a global program of experiments currently coming online and which seek to observe 3 types of muon CLFV:

Mode	Current Upper Limit (at 90% CL)	Projected Limit (at 90% CL)	Upcoming Experiment/s
$\mu^+ \rightarrow e^+ \gamma$	3.1×10^{-13}	4×10^{-14}	MEG II
$\mu^+ \rightarrow e^+ e^+ e^-$	1.0×10^{-12}	5×10^{-15} 10^{-16}	Mu3e Phase-I Mu3e Phase-II
$\mu^- N \rightarrow e^- N$	7×10^{-13} (SINDRUM-II, 2006)	8×10^{-15} 6×10^{-16} 8×10^{-17}	COMET Mu2e Run-I Mu2e Run-II

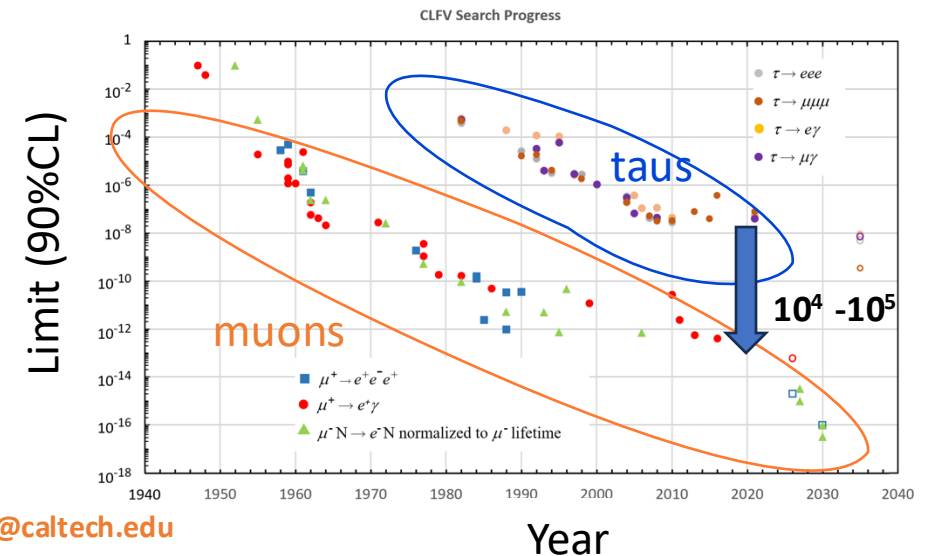
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Muon has experimental advantages:

- can create intense muon beams in existing facilities;
 - e.g. $10^7 - 10^{10} \mu/s$
- long (microsecond) lifetime;
 - $2.2 \mu s$
- reducible, well understood SM backgrounds.



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Where we'll be in the next decade

Over the next few years these experiments will push by up to 10000x below the current limits

- There is potential for discovery of new physics from all these experiments

Effective Field Theory

Note: This is not a “theory” talk, but I think this helps explain the complementarity in a nice way.

- Standard Model Effective Field Theory (SMEFT) captures new potential sources of CLFV above the electroweak scale ($v=246$ GeV) in a model-independent way.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n, D \geq 5} \frac{C_n^{(D)}}{\Lambda^{D-4}} O_n^{(D)} .$$

- The scale Λ represents generically the mass of the lowest-lying new particles appearing in the underlying new theory. The Wilson Coefficients $C_n^{(D)}$ encode information about the underlying model.
- The leading CLFV operators appear at dimension $D = 6$ and therefore are suppressed by $1/\Lambda^2$.

Effective Physics Reach (a focus on muons)

- Can think of physics possibilities in terms of Effective Field Theories;
- 90+ operators describe these processes;
- *Eur.Phys.J.C 82 (2022) 9, 836* reduced to 6 terms for $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, and spin-independent $\mu N \rightarrow eN$;
- Effective Lagrangian shows the complementarity between these three channels:

$$\begin{aligned} \delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2} & \left[C_D(m_\mu \bar{e}\sigma^{\alpha\beta} P_R\mu) F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_R e) \right. \\ & + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_R e) \\ & + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_L e) + C_{A\text{light}}\mathcal{O}_{A\text{light}} \\ & \left. + C_{A\text{heavy}\perp}\mathcal{O}_{A\text{heavy}\perp} \right] \end{aligned} \quad (2.1)$$

Λ = Effective Mass Reach, \mathbf{D} = dipole, \mathbf{V} = vector, \mathbf{S} = scalar

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- *Eur.Phys.J.C 82 (2022) 9, 836* reduced to 6 terms for $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, and spin-independent $\mu N \rightarrow eN$;
- Effective Lagrangian shows the complementarity between these three channels:

$$\begin{aligned} \delta\mathcal{L} = & \frac{1}{\Lambda_{LFV}^2} \left[C_D(m_\mu \bar{e}\sigma^{\alpha\beta} P_R\mu) F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_R e) \right. \\ & + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_R e) \\ & + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_L e) + C_{A\text{light}}\mathcal{O}_{A\text{light}} \\ & \left. + C_{A\text{heavy}\perp}\mathcal{O}_{A\text{heavy}\perp} \right] \end{aligned} \quad (2.1)$$

Λ = Effective Mass Reach, **D** = dipole, **V** = vector, **S** = scalar

Effective Physics Reach

Dipole Term:

Mediating $\mu \rightarrow e\gamma$

Contributing to $\mu \rightarrow eee$ and $\mu N \rightarrow eN$ at loop level

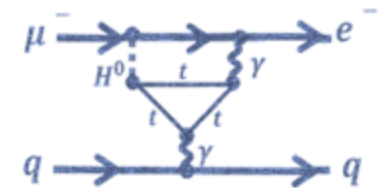


SO(10) SUSY

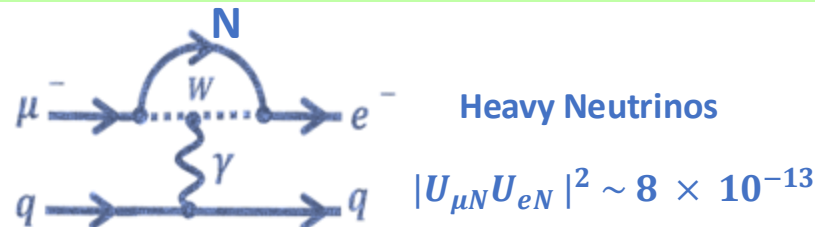
Rate $\sim 10^{-15}$

$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2} \left[C_D(m_\mu \bar{e} \sigma^{\alpha\beta} P_R \mu) F_{\alpha\beta} + C_S(\bar{e} P_R \mu)(\bar{e} P_R e) \right. \\ \left. + C_{VR}(\bar{e} \gamma^\alpha P_L \mu)(\bar{e} \gamma_\alpha P_R e) \right. \\ \left. + C_{VL}(\bar{e} \gamma^\alpha P_L \mu)(\bar{e} \gamma_\alpha P_L e) + C_{A\text{light}} \mathcal{O}_{A\text{light}} \right. \\ \left. + C_{A\text{heavy}\perp} \mathcal{O}_{A\text{heavy}\perp} \right] \quad (2.1)$$

2 Higgs Doublets



$$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$$



Heavy Neutrinos

$$|U_{\mu N} U_{eN}|^2 \sim 8 \times 10^{-13}$$

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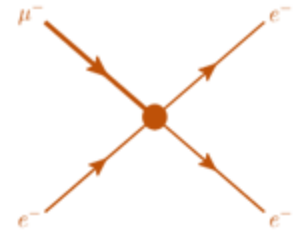
Effective Physics Reach

Also accessible at Mu2e/COMET through $\mu e \rightarrow ee$



“Contact”
Scalar
 $\mu \rightarrow eee$

Leptonic “Contact” term
i.e. 4 Fermion Term
 $\mu \rightarrow eee$ at leading order.
Heavily suppressed in $\mu \rightarrow e\gamma$



$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2} \left[C_D(m_\mu \bar{e} \sigma^{\alpha\beta} P_R \mu) F_{\alpha\beta} + C_S(\bar{e} P_R \mu)(\bar{e} P_R e) \right. \\ \left. + C_{VR}(\bar{e} \gamma^\alpha P_L \mu)(\bar{e} \gamma_\alpha P_R e) \right. \\ \left. + C_{VL}(\bar{e} \gamma^\alpha P_L \mu)(\bar{e} \gamma_\alpha P_L e) + C_{A\text{light}} \mathcal{O}_{A\text{light}} \right. \\ \left. + C_{A\text{heavy}\perp} \mathcal{O}_{A\text{heavy}\perp} \right] \quad (2.1)$$

“Contact”
Vector
 $\mu \rightarrow eee$

Effective Physics Reach

quark “Contact” term

i.e. 4 Fermion Term

$\mu N \rightarrow e N$ at leading order.

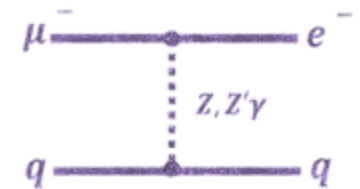
Heavily suppressed in $\mu \rightarrow e \gamma$

$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2} \left[C_D (m_\mu \bar{e} \sigma^{\alpha\beta} P_R \mu) F_{\alpha\beta} + C_S (\bar{e} P_R \mu) (\bar{e} P_R e) \right. \\ \left. + C_{VR} (\bar{e} \gamma^\alpha P_L \mu) (\bar{e} \gamma_\alpha P_R e) \right. \\ \left. + C_{VL} (\bar{e} \gamma^\alpha P_L \mu) (\bar{e} \gamma_\alpha P_L e) + C_{A\text{light}} \mathcal{O}_{A\text{light}} \right. \\ \left. + C_{A\text{heavy}\perp} \mathcal{O}_{A\text{heavy}\perp} \right] \quad (2.1)$$

Au and Al are prototypical “heavy” and “light” targets

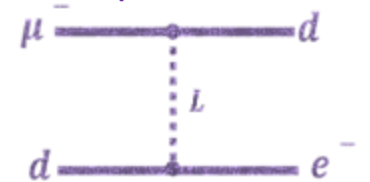
New Bosons

$$M_{Z'} = 3000 \text{ TeV}/c^2$$



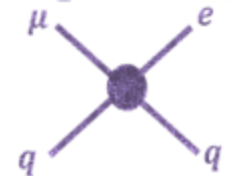
Leptoquarks

$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{e d})^{\frac{1}{2}} \text{ TeV}/c^2$$



Compositeness

$$\Lambda_c \sim 3000 \text{ TeV}$$

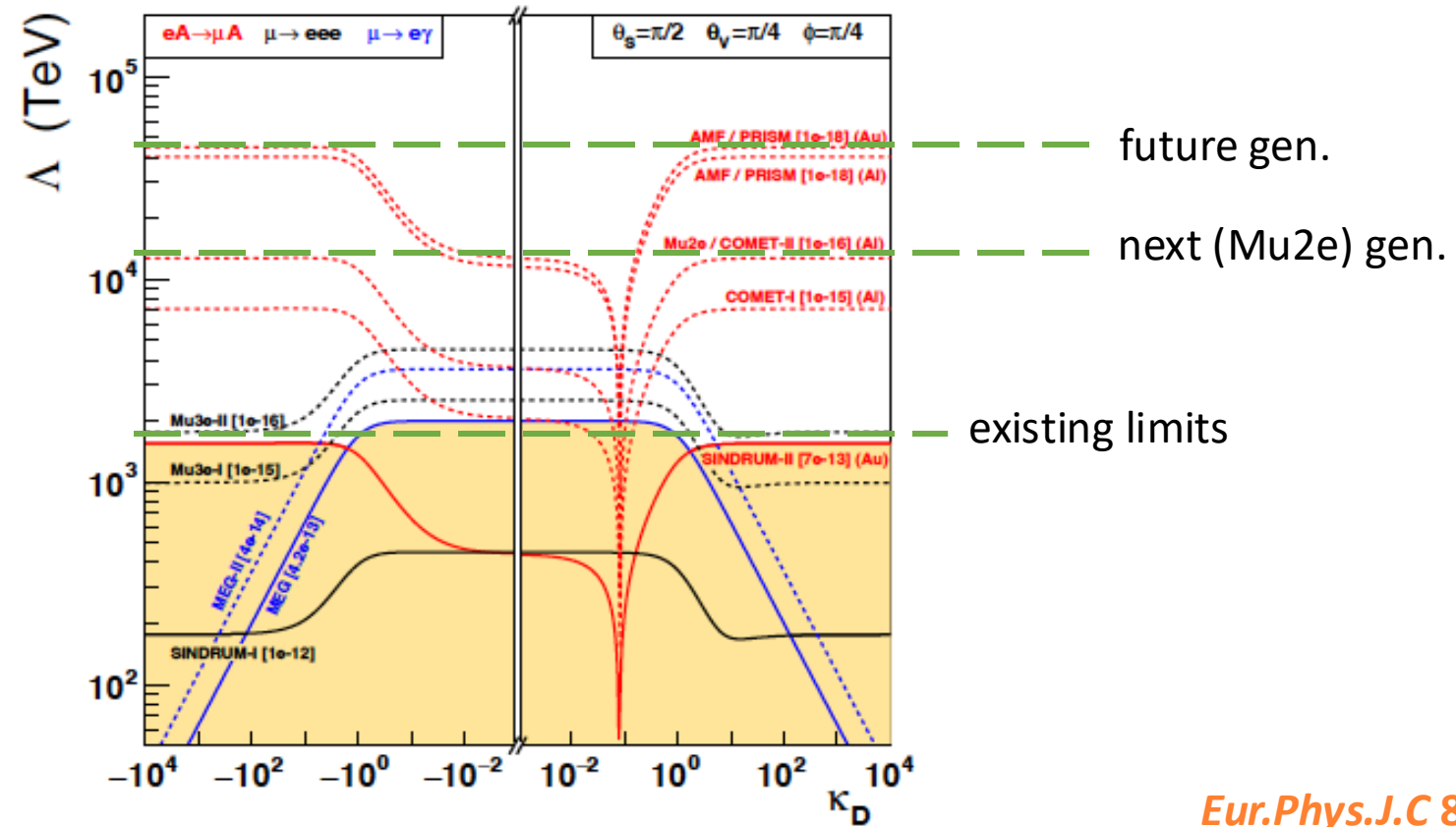


Effective Physics Reach

High magnitude κ_D = contact-like, closer to zero is dipole-like

Λ = effective mass reach

Current physics reach at $O(10^3)$ TeV, Projections of upto $O(10^4)$ TeV in next generation.



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Note: plots are a slice in multi-dimensional space, several other plots shown in paper for different slices

Searches for Lepton Flavor Violation - Sophie Middleton -
smidd@caltech.edu

Global Search: muons

- The multiplicity of probes is essential to infer information on:
 - the underlying mediation mechanism**
 - different CLFV processes within the same two families (e.g. $\mu \rightarrow e\gamma$ vs $\mu \rightarrow e$ conversion or $\mu \rightarrow 3e$ or $\tau \rightarrow e\gamma$ vs $\tau \rightarrow e\pi\pi$, etc.).

Mode	$\mu^+ \rightarrow e^+ e^+ e^-$	$\mu^- N \rightarrow e^- N$	$\frac{BR(\mu^+ \rightarrow e^+ e^+ e^-)}{BR(\mu^+ \rightarrow e^+ \gamma)}$	$\frac{BR(\mu^- N \rightarrow e^- N)}{BR(\mu^+ \rightarrow e^+ \gamma)}$
MSSM	Loop	Loop	$\sim 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type I Seesaw	Loop	Loop	$3 \times 10^{-3} - 0.3$	0.1-10
Type II Seesaw	Tree	Loop	$(0.1 - 3) \times 10^3$	10^{-2}
Type III Seesaw	Tree	Tree	$\sim 10^3$	10^3
LFV Higgs	Loop	Loop	10^{-2}	0.1
Composite Higgs	Loop	Loop	0.05-0.5	2-20

See-saw models can help explain the neutrino mass origins, they can also producing signatures in our CLFV experiments

Global Search: taus

- The multiplicity of probes is essential to infer information on:
 1. **the underlying mediation mechanism**
 - different CLFV processes within the same two families (e.g. $\mu \rightarrow e\gamma$ vs $\mu \rightarrow e$ conversion or $\mu \rightarrow 3e$ or $\tau \rightarrow e\gamma$ vs $\tau \rightarrow e\pi\pi$, etc.).
 2. **the underlying sources of lepton family violation**
 - CLFV transitions among different families ($\mu \leftrightarrow e$, $\tau \leftrightarrow \mu$, and $\tau \leftrightarrow e$),
- **Therefore, tau and muon CLFV probes are highly complementary.**
- Taus also decay hadronically, there are several possible modes in which taus can exhibit LFV, all indicate new physics:
 - $\tau^\pm \rightarrow l^\pm \gamma$ with $l = e, \mu$ (2 modes)
 - $\tau^\pm \rightarrow l^\pm l^\pm l^\mp$ with $l = e, \mu$ (6 modes)
 - $\tau^\pm \rightarrow l^\pm P^0$ where pseudoscalar meson $P^0 = \pi^0, K^0, \eta, \eta'$ (8 modes)
 - $\tau^\pm \rightarrow l^\pm S^0$ where scalar meson $S^0 = f_0(980)$ (2 modes)
 - $\tau^\pm \rightarrow l^\pm V^0$ where vector meson $V^0 = \rho, \omega, K^{*0}, \overline{K}^{*0}, \phi$ (10 modes)
 - Tau decays to lepton + two mesons (16 modes)
 - $\tau^- \rightarrow \pi^- \Lambda$ and $\tau^- \rightarrow \pi^- \overline{\Lambda}$ (2 modes)
 - Tau decays into proton/antiproton plus two leptons (6 modes)
- To create taus in large numbers we need collider-based experiments.
- B-factories can also provide large numbers of taus. Belle-II has a vast tau program which will be discussed later.

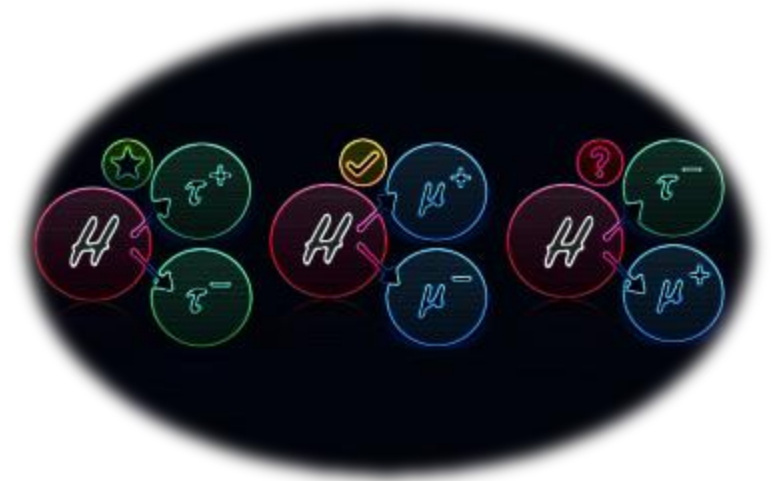
Global Search: Higgs & Z boson LFV decays

- The LHC is also looking for evidence of LFV in the form of boson decays to leptons.
- Higgs LFV decays arise in many frameworks of New Physics at the electroweak scale such as **two Higgs doublet models, extra dimensions, or models of compositeness.**

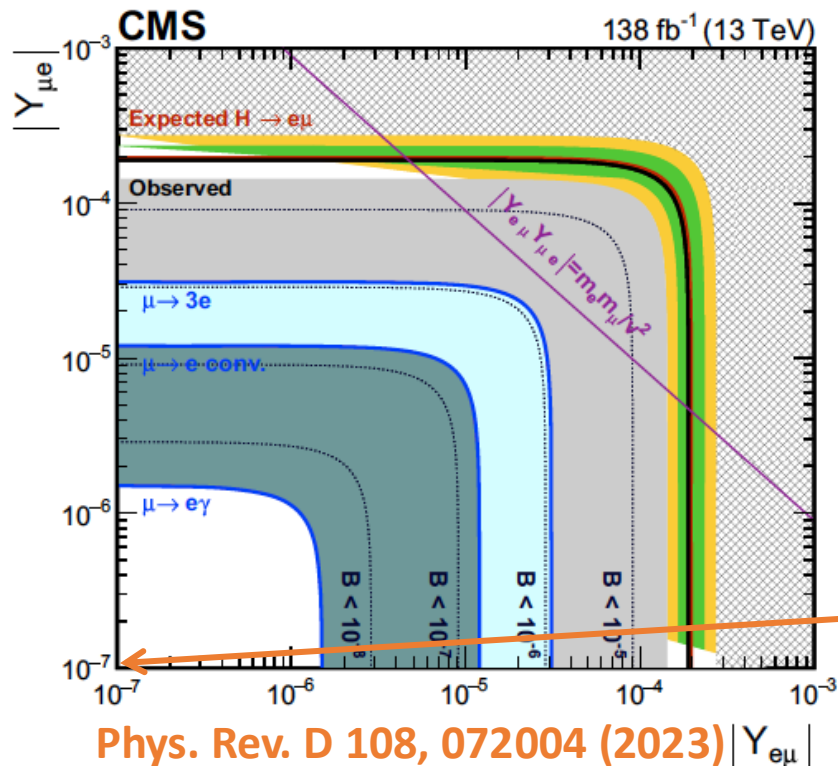
e.g

$$\Gamma(H \rightarrow e\mu) = \frac{m_H}{8\pi} (|Y_{e\mu}|^2 + |Y_{\mu e}|^2).$$

	current	future		current	future
$\text{Br}(Z \rightarrow e\mu)$	$< 2.62 \times 10^{-7}$ ATLAS [50]	$\lesssim 10^{-8}$ FCC-ee-Z [51]	$\text{Br}(H \rightarrow e\mu)$	$< 4.4 \times 10^{-5}$ CMS [52]	$< \mathcal{O}(0.02)\%$ HL-LHC [53] e^+e^- collider [54]
$\text{Br}(Z \rightarrow e\tau)$	$< 5.0 \times 10^{-6}$ ATLAS [55]	$\lesssim 10^{-9}$ FCC-ee-Z [51]	$\text{Br}(H \rightarrow e\tau)$	$< 2.0 \times 10^{-3}$ ATLAS [56]	$< \mathcal{O}(0.5)\%$ HL-LHC [53] e^+e^- collider [54]
$\text{Br}(Z \rightarrow \mu\tau)$	$< 6.5 \times 10^{-6}$ ATLAS [55]	$\lesssim 10^{-9}$ FCC-ee-Z [51]	$\text{Br}(H \rightarrow \mu\tau)$	$< 1.5 \times 10^{-3}$ CMS [57]	$< 1.0 \times 10^{-3}$ HL-LHC [58] e^+e^- collider [54]



Global Search: Higgs LFV



- The $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ channels provide constraints but conversion searches such as Mu2e provide tightest projected constraints
- Current $\mu \rightarrow e$ conversion implies:

$$\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} < 4.6 \times 10^{-5}$$

- Mu2e is expected to be sensitive to:

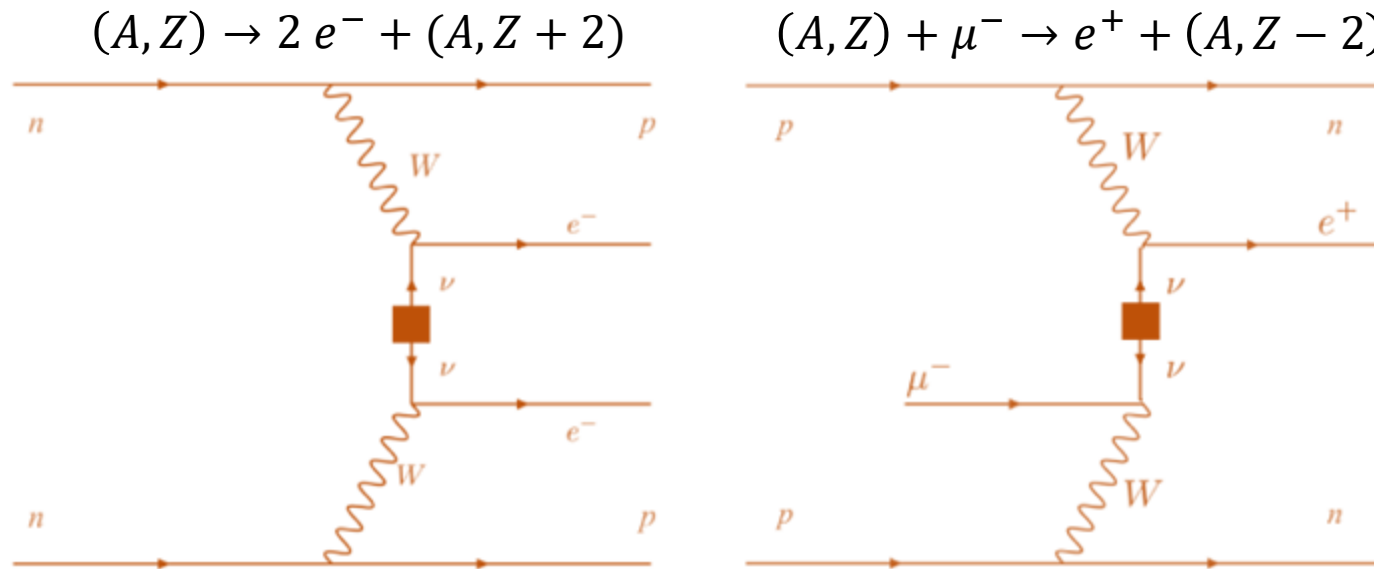
$$\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} \sim \mathcal{O}(10^{-7})$$

where $|Y_{\mu e}|$ and $|Y_{e\mu}|$ are flavor-violating Yukawa couplings for a 125 GeV Higgs boson i.e. $h \rightarrow \mu e$.

Lepton Number Violation + LFV

See Lecture by Vincenzo

- Experiments searching for LFV could also be sensitive to lepton number violation (LNV).
- An example is $(A, Z) + \mu^- \rightarrow e^+ + (A, Z - 2) \rightarrow \text{Mu}2e \rightarrow$ probes μe
- Complementary to the neutrino-less double beta decay searches: $(A, Z) \rightarrow 2 e^- + (A, Z + 2) \rightarrow$ probes ee
- **Could indicate the existence of Majorana neutrinos**



Muon CLFV Experiments

Flavor Physics and the Lepton Sector

Charged Lepton Flavor Violation

Muon CLFV Searches

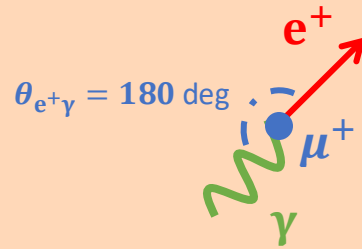
Tau CLFV Searches

Summary

$\mu^+ \rightarrow e^+ \gamma$: Physics

Signal:

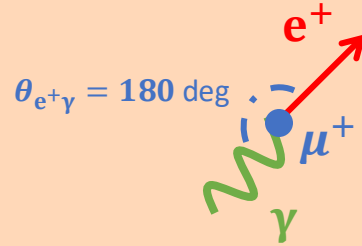
- Two body decay:
 - $e^+ \gamma$ coincidence in time;
 - $E_{e^+} = E_\gamma$ 52.8 MeV;
 - $\theta_{e^+ \gamma} = 180$ deg. i.e. back-to-back.



$\mu^+ \rightarrow e^+ \gamma$: Physics

Signal:

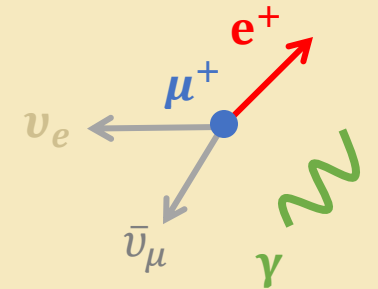
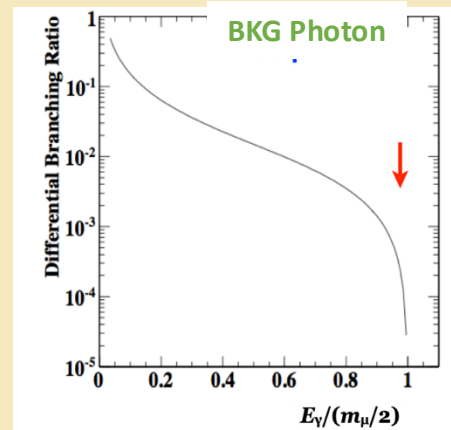
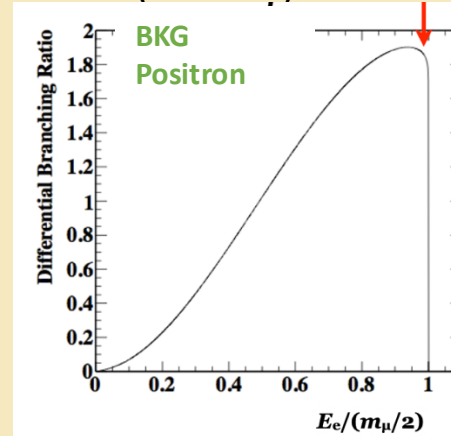
- Two body decay:
 - $e^+ \gamma$ coincidence in time;
 - $E_{e^+} = E_\gamma = 52.8 \text{ MeV}$;
 - $\theta_{e^+ \gamma} = 180 \text{ deg.}$ i.e. back-to-back.



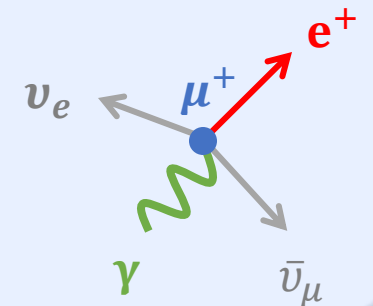
Backgrounds:

- Dominant background from **accidentals**:

W. Otani (ICHEP 2024)



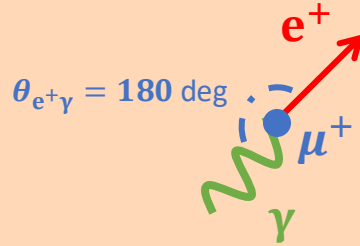
Also, **rare physics background**:



$\mu^+ \rightarrow e^+ \gamma$: Physics

Signal:

- Two body decay:
 - $e^+ \gamma$ coincidence in time;
 - $E_{e^+} = E_\gamma$ 52.8 MeV;
 - $\theta_{e^+ \gamma} = 180$ deg. i.e. back-to-back.



Strategy:

- Measure $E_\gamma, p_{e^+}, \theta_{\gamma e^+}, t_{e^+}$ with the best possible resolutions.

Signal

$$N_{\text{sig}} = R_\mu \times T \times \Omega \times \mathcal{B} \times \epsilon_\gamma \times \epsilon_e \times \epsilon_{\text{sel}}$$

Beam intensity Acceptance Branching ratio Efficiencies

Background

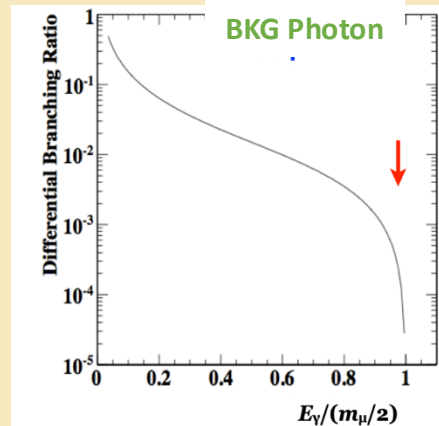
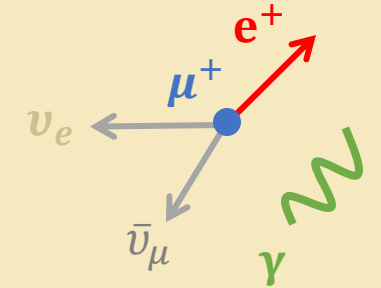
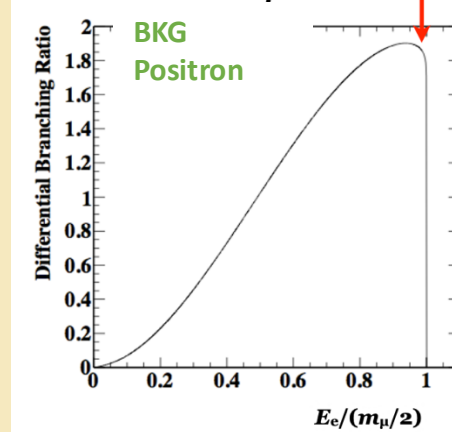
$$N_{\text{acc}} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta E_e \times \Delta \Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$$

E_γ resolution E_e resolution Angular resolution Time resolution

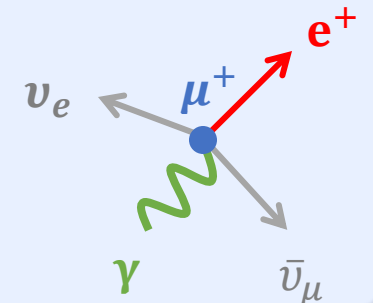
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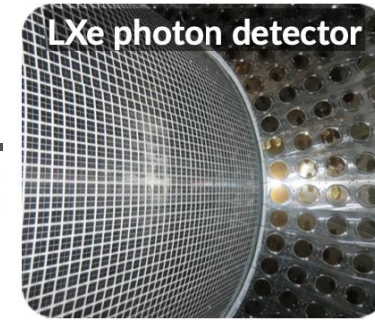
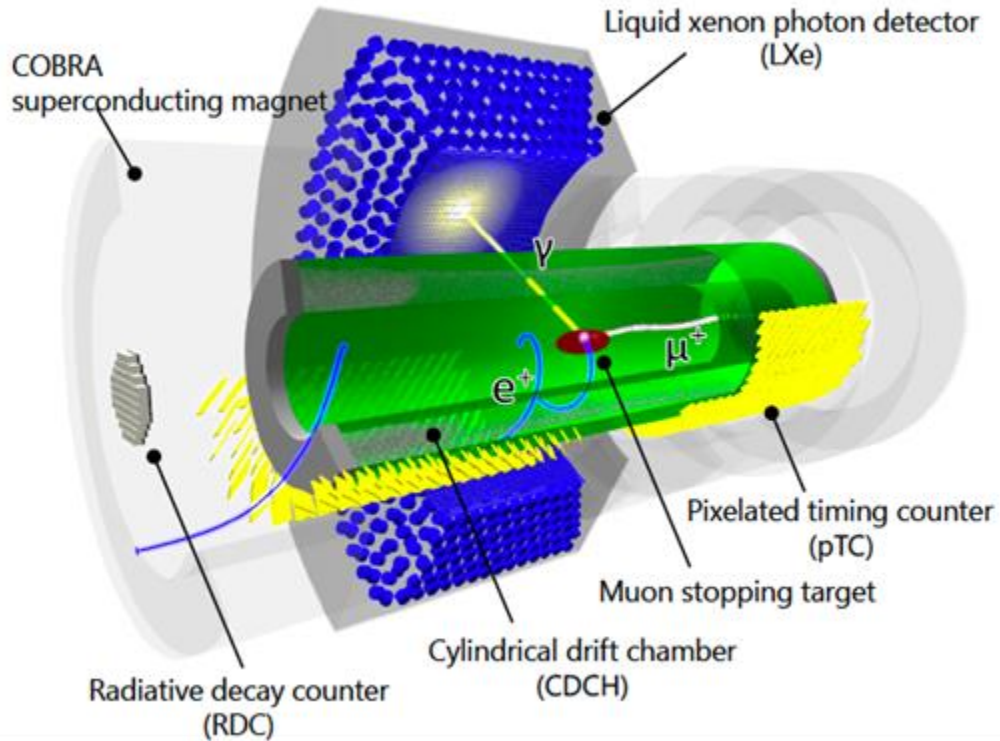
Also, **rare physics background**:



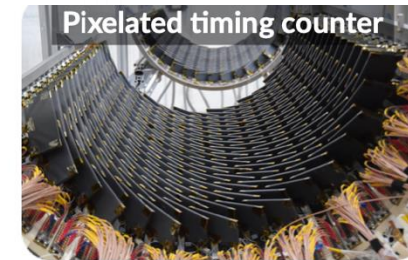
$\mu^+ \rightarrow e^+ \gamma$: MEG-II Design



- BKG photon suppression by identifying associated low mom. positron.



- 900L of LXe
- Highly granular scintillation readout with 4092 SiPM and 668 PMT



- 512 plastic scintillator plates
- 40 ps time resolution average



- Low mass design with single gas volume
- Drift cells with stereo wires

Design:

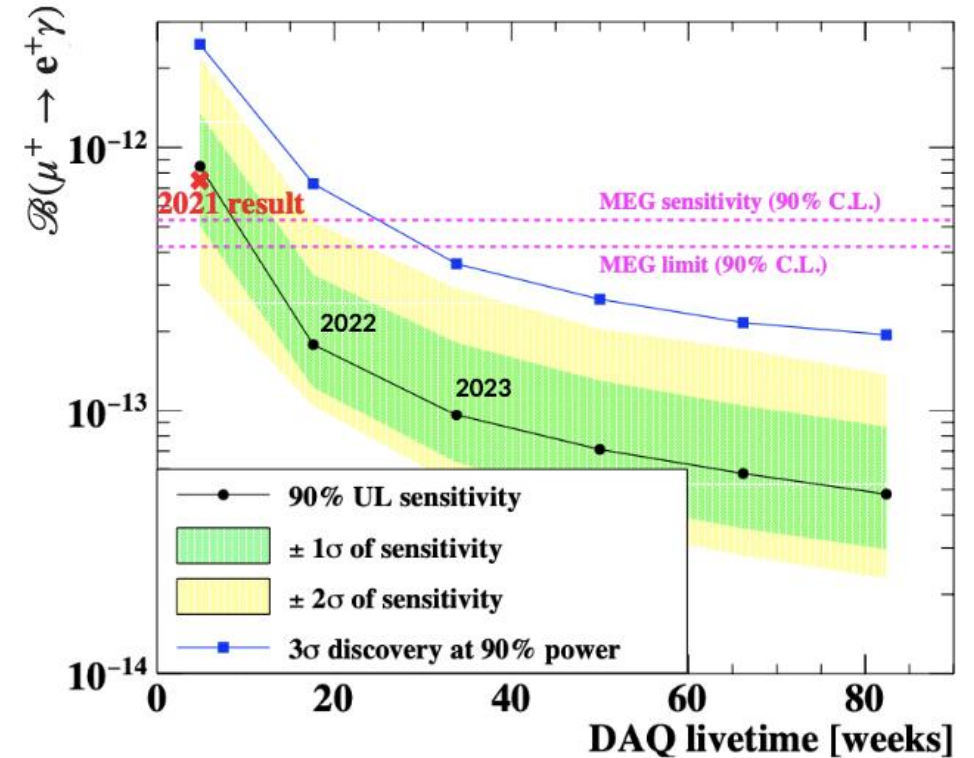
- Based at PSI, muon stopping rate of $10^7 \mu^+/s$, $p = 28 \text{ MeV}/c$.
- μ^+ stopped on thin plastic target - decay at rest to exploit the two-body kinematics.
- Accurate reconstruction of photon and positron energy and time:
 - **Magnetic spectrometer and low mass drift chamber** to track the candidate positron.
 - **LXe photon detector** measures the timing, energy and position of the photon.

$\mu^+ \rightarrow e^+ \gamma$: Status

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Status:

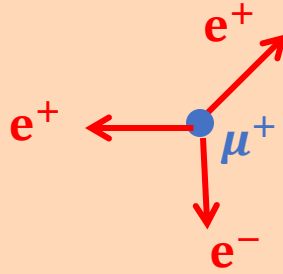
- MEG-II has been taking physics data since 2021.
- Results from the first physics run show:
 - No excess over background-only hypothesis:
 - Upper limit $\mathbf{B(\mu^+ \rightarrow e^+ \gamma) < 7.5 \times 10^{-13}}$ (90% C.L.)
 - Combined with MEG: $\mathbf{B(\mu^+ \rightarrow e^+ \gamma) < 3.1 \times 10^{-13}}$ (90% C.L.)
- x10 more data already taken: new results coming soon!
- Physics run will continue until PSI shutdown in 2027.
 - Goal to reach 6×10^{-14} (x10 on MEG) and potential discovery.



$\mu^+ \rightarrow e^+ e^+ e^-$: Physics

Signal:

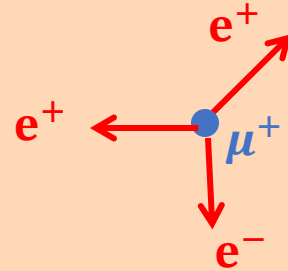
- **Three body decay:**
 - Common vertex
 - Coplanar
 - $\sum p_i = 0, \sum E_i = m_\mu, \Delta t_{eee} = 0$



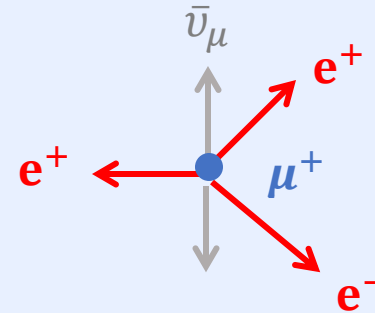
$\mu^+ \rightarrow e^+ e^+ e^-$: Physics

Signal:

- **Three body decay:**
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 - Coplanar
 - $\sum p_i = 0, \sum E_i = m_\mu, \Delta t_{eee} = 0$



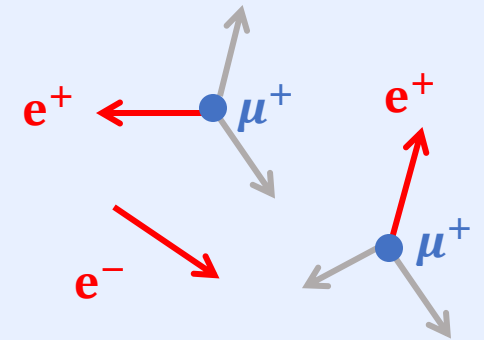
Backgrounds:



Internal conversions:

- Common vertex
- $\sum p_i \neq 0,$
- $\sum E_i < m_\mu,$
- $\Delta t_{eee} = 0$

Combinational:

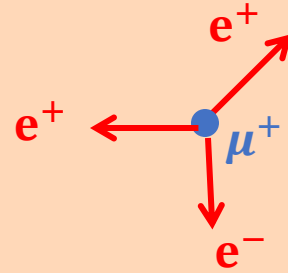


- No common vertex
- $\sum p_i \neq 0,$
- $\sum E_i \neq m_\mu,$
- $\Delta t_{eee} \neq 0$

$\mu^+ \rightarrow e^+ e^+ e^-$: Physics

Signal:

- **Three body decay:**
 - Common vertex
 - Coplanar
 - $\sum p_i = 0, \sum E_i = m_\mu, \Delta t_{eee} = 0$

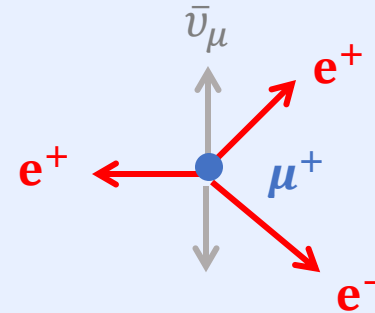


Strategy:

Need to establish that three charged tracks (total +) emanate from the same location and coincide in time, this requires:

- Precise time resolution;
- Excellent position and momentum resolution.

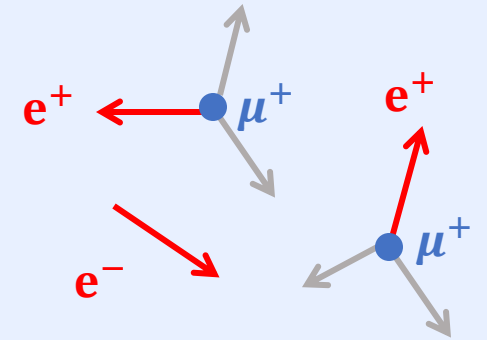
Backgrounds:



Internal conversions:

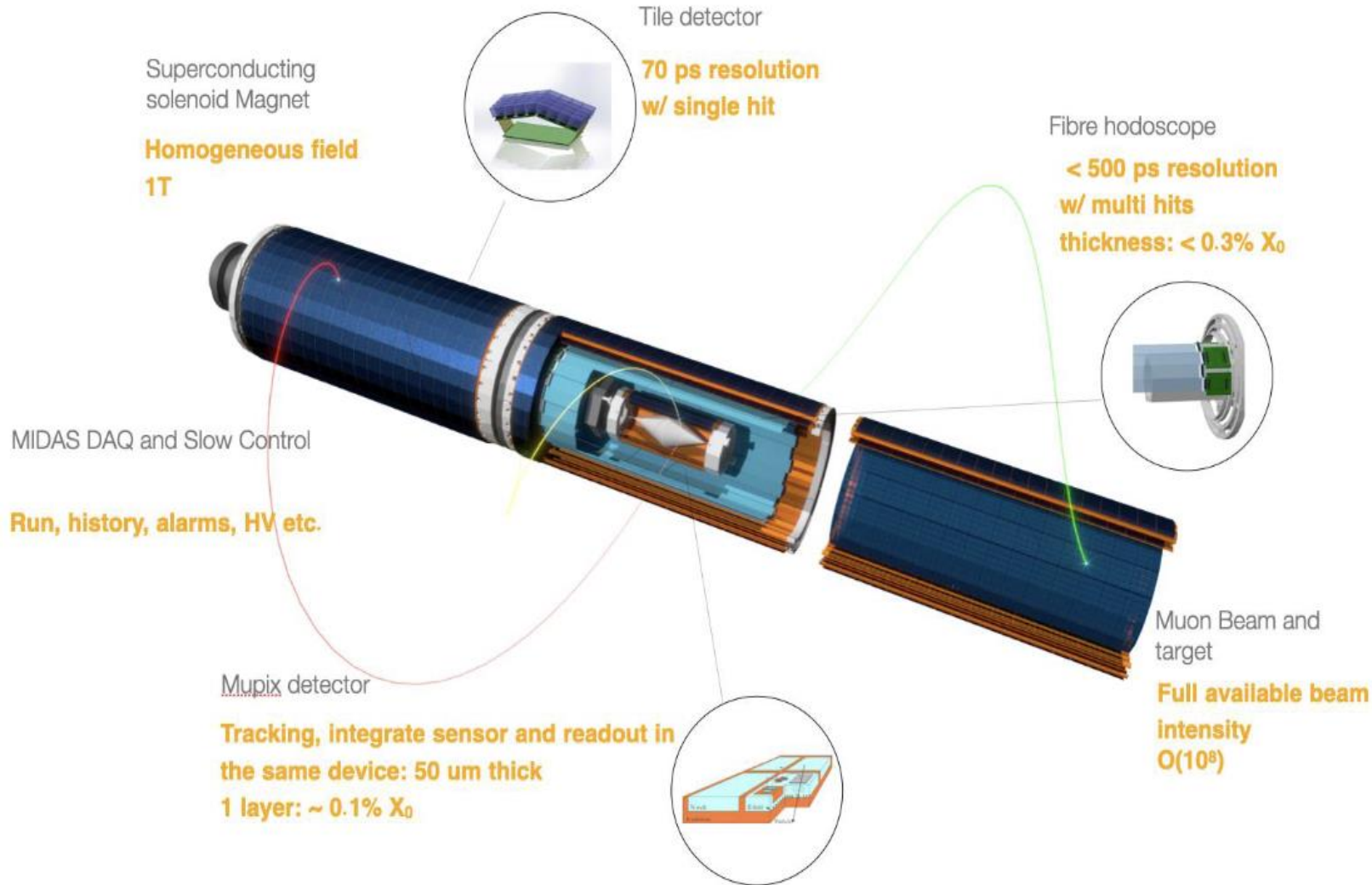
- Common vertex
- $\sum p_i \neq 0,$
- $\sum E_i < m_\mu,$
- $\Delta t_{eee} = 0$

Combinational:



- No common vertex
- $\sum p_i \neq 0,$
- $\sum E_i \neq m_\mu,$
- $\Delta t_{eee} \neq 0$

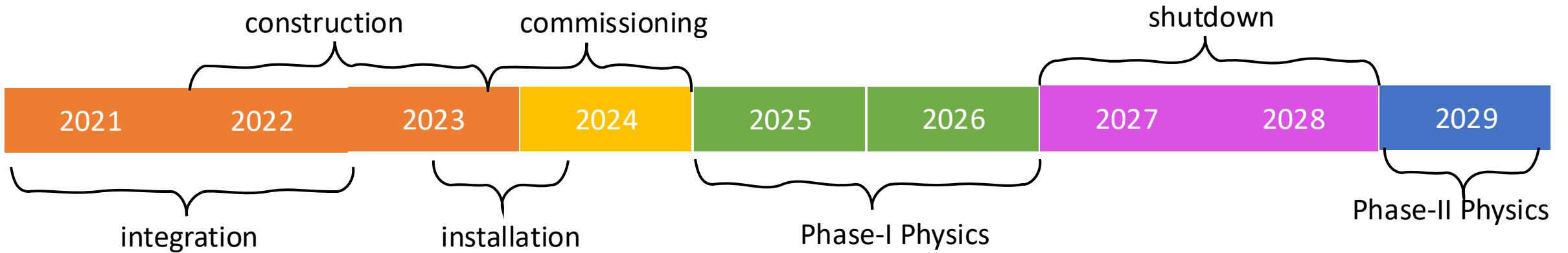
$\mu^+ \rightarrow e^+ e^+ e^-$: Mu3e Design



Design:

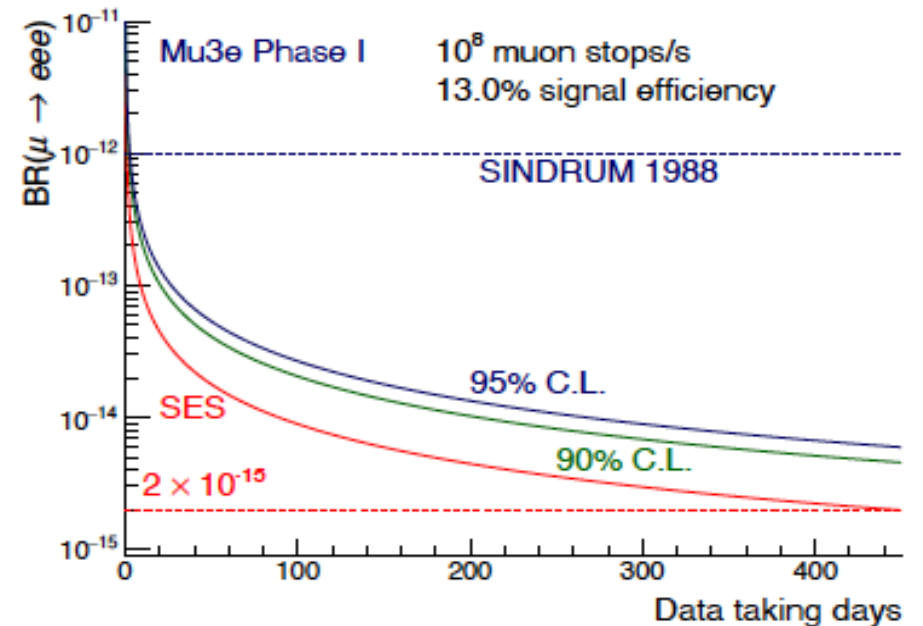
- High tracker occupancy requires excellent timing and position resolution to select hits belonging to the same track: thin, fast, high-resolution detectors:
 - 175 HV-MAPS channels
 - ~ 3000 SciFi and $\sim 7K$ Tile TOF channels.
- Method of recurling tracks allows good momentum resolution.
- Superconducting magnet (not shown).

$\mu^+ \rightarrow e^+ e^+ e^-$: Mu3e Status



Status:

- Based at PSI, expect data-taking by 2025-26.
- Two Phased implementation:
 - **Phase-I** – Sensitivity 10^{-15} ;
 - **Phase-II** – Sensitivity 10^{-16} (requires beam upgrade).



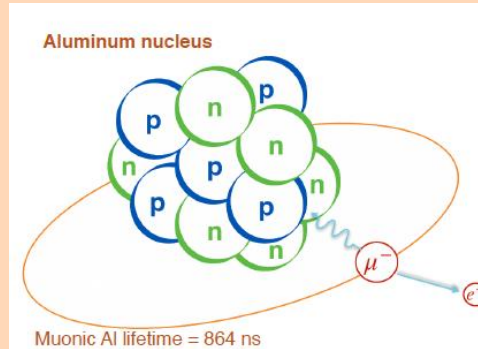
$N\mu^- \rightarrow Ne^-$: Physics

Signal:

- Monoenergetic electron (1st order)

$$E_e = m_\mu - E_{recoil} - E_{1SB.E}, \text{ e.g For Al: } E_e = 104.97 \text{ MeV}$$

- Coherent = nucleus stays intact.
- Will be smeared by scattering and energy losses



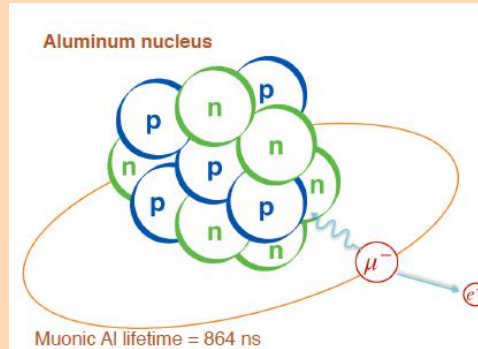
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- Coherent = nucleus stays intact.
- Will be smeared by scattering and energy losses



Backgrounds:

Decay in Orbit:

- 39 % of stopped muons decay :



Radiative Pion Capture:

- Pions captured into Al nucleus, undergo a radiative process (internal or external), results in: $\gamma \rightarrow e^+e^-$
- Electrons have energy up to \sim pion mass.

Cosmic Induced:

- Cosmic muons or secondary particles can be confused for signal if appear to emanate from target.

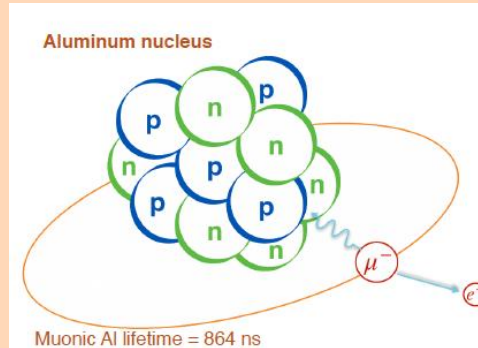
$N\mu^- \rightarrow Ne^-$: Physics

Signal:

- Monoenergetic electron (1st order)

$$E_e = m_\mu - E_{recoil} - E_{1SB.E}, \text{ e.g For Al: } E_e = 104.97 \text{ MeV}$$

- Coherent = nucleus stays intact.
- Will be smeared by scattering and energy losses



Strategy:

Stop 10^{18} muons with $\ll 1$ background in signal region:

- Intense muon beam;
- Efficient transportation and collection of muons;
- Pulsed beam to eliminate pions;
- Precise momentum resolution to remove decay backgrounds.

Backgrounds:

Decay in Orbit:

- 39 % of stopped muons decay :



Radiative Pion Capture:

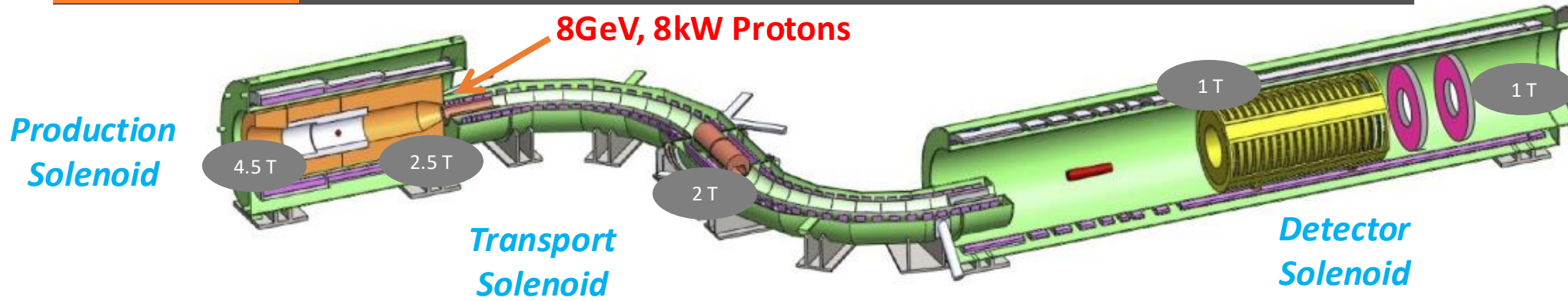
- Pions captured into Al nucleus, undergo a radiative process (internal or external), results in: $\gamma \rightarrow e^+e^-$
- Electrons have energy up to \sim pion mass.

Cosmic Induced:

- Cosmic muons or secondary particles can be confused for signal if appear to emanate from target.

$N\mu^- \rightarrow Ne^-$: Mu2e Design

*Intense muon beam;
Efficient transportation and collection;*



Production Solenoid:

- Pulsed 8 GeV Protons enter, hit Production Target. π produced, decay to μ .
- Graded magnetic field reflects muons to transport solenoid.

Transport Solenoid:

- “S” shape removes line of sight backgrounds.
- Collimators select low momentum, negative muons.

Detector Solenoid:

- Thin aluminum foil target captures the muons.
- Possible signal electrons are detected by a tracker and a calorimeter.
- Cosmic ray veto covers the whole detector solenoid and half the transport solenoid.

$N\mu^- \rightarrow Ne^-$: Mu2e Projections

2027 Run-I:

- 1×10^{-15} 5σ discovery,
- Single-Event-Sensitivity = 2×10^{-16}
- U.L : 6×10^{-16} (90% C.L.)
 - **1000 x current limit.**
 - **Universe 2023, 9, 54** shows simulated analysis for Run-I.

Total (Run-I + Run-II) end-goal:

- 2×10^{-16} 5σ discovery,
- Single-Event-Sensitivity = 3×10^{-17}
- U.L : 8×10^{-17} (90% C.L.)
 - **10000 x current limit.**

Need to stop $O(10^{18})$ muons and have $\ll 1$ background event over entire lifetime of the experiment to achieve these numbers!

$N\mu^- \rightarrow Ne^-$: (Mu2e) Backgrounds

Beam delivery and detector systems optimized for high intensity, pure muon beam – must be “background free”:

Type	Source	Mitigation	Yield (for Run-I only)*
Intrinsic	Decay in Orbit (DIO)	Tracker Design/Resolution	0.038 ± 0.002 (stat) $^{+0.025}_{-0.015}$ (sys)
Beam Backgrounds	Pion Capture	Beam Structure/Extinction	(in time) 0.010 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (sys) (out time) $(1.2 \pm 0.001$ (stat) $^{+0.1}_{-0.3}$ (sys)) $\times 10^{-3}$
Cosmic Induced	Cosmic Rays	Active Veto System	0.046 ± 0.010 (stat) ± 0.009 (sys)

* assumes signal region of $103.6 < p < 104.9$ MeV/c and $640 < t < 1650$ ns

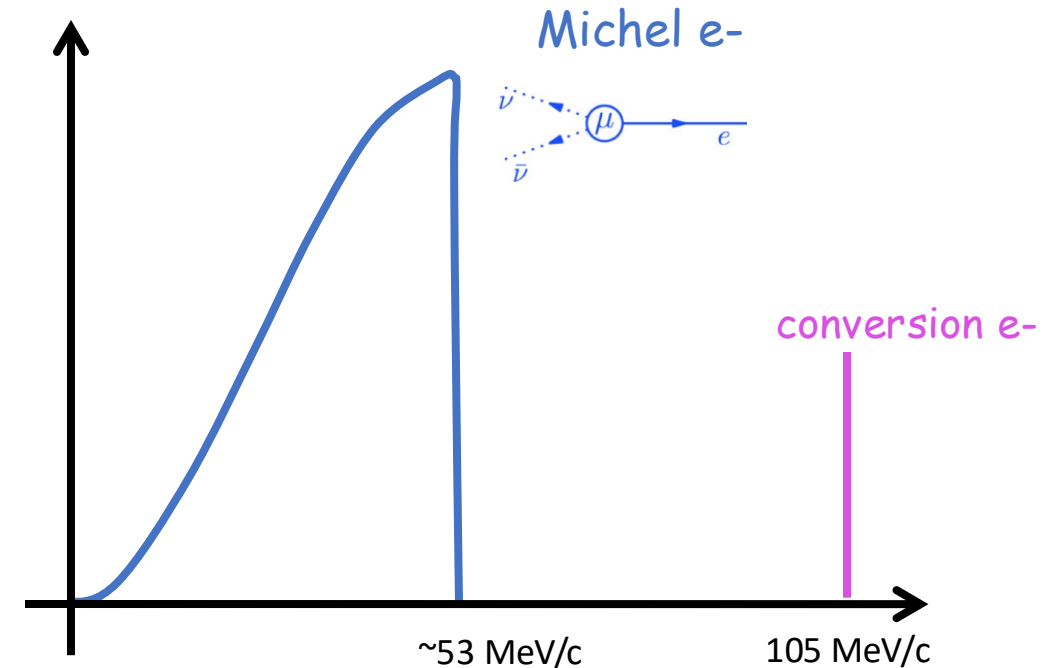
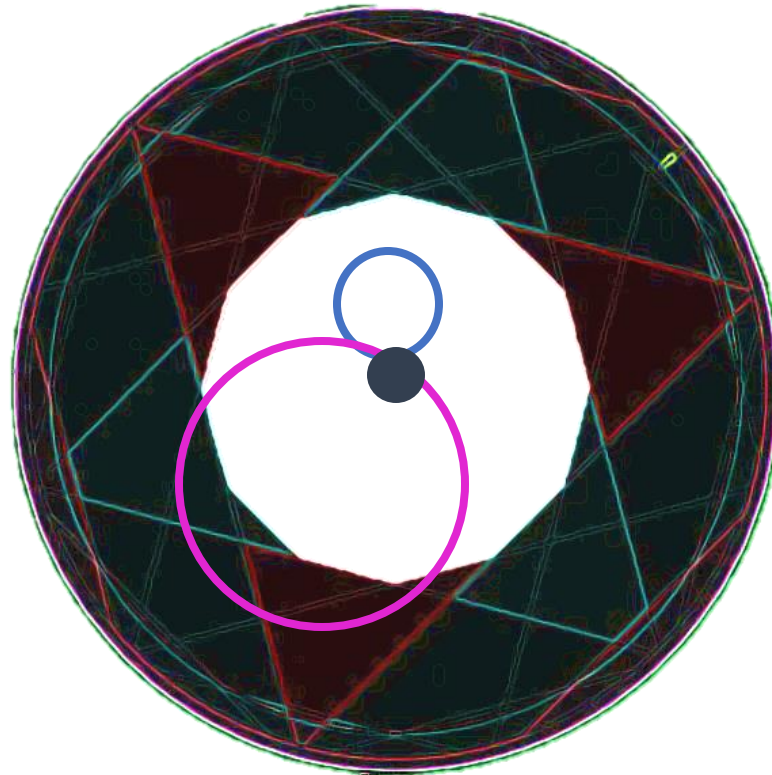
Run-I Sensitivity of Mu2e:
Universe 2023, 9, 54.

(Mu2e) Decay in Orbit (DIO) Backgrounds

- Annular tracker: Removes most of DIO (all Michel peak electrons), analyze 10^5 instead of 10^{18} muons.

$$R = \frac{p_{\perp}}{qB} = 35\text{cm}$$

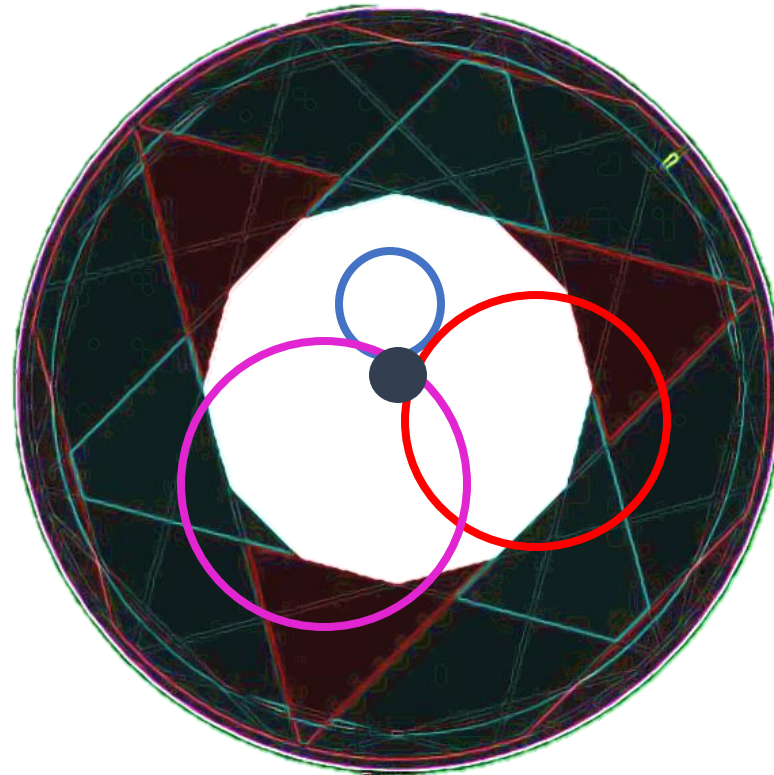
- Michel Electron ($< 52\text{MeV}/c$)
- Signal ($105\text{MeV}/c$)



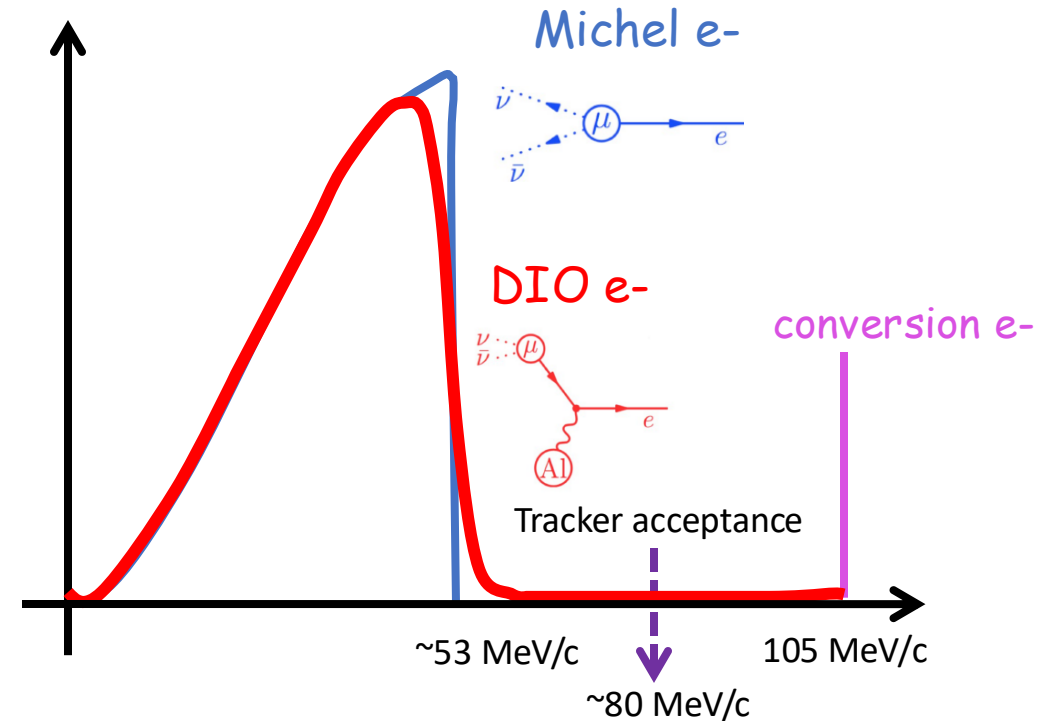
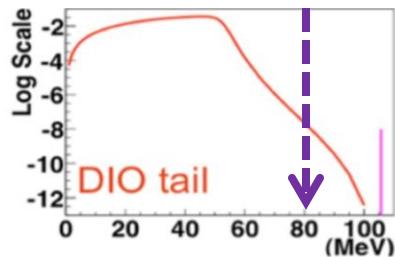
(Mu2e) Decay in Orbit (DIO) Backgrounds

- Annular tracker: Removes most of DIO (all Michel peak electrons), analyze 10^5 instead of 10^{18} muons.
- However, when decay happens in orbit, exchange of momentum produces recoil tail close to signal region (105 MeV/c).
- To remove remaining backgrounds necessitates < 200 keV/c momentum resolution.

$$R = \frac{p_{\perp}}{qB} = 35\text{cm}$$



- Michel Electron ($< 52\text{MeV}/c$)
- Signal ($105\text{MeV}/c$)
- Problematic Tail ($>100\text{MeV}/c$)



(Mu2e) Straw Tracker: achieving resolution

- Need a high-resolution (< 200 keV/c) momentum measurement to distinguish tail DIO from signal:
 - Minimize energy loss by operating in vacuum and using low mass straws of $15\ \mu\text{m}$ thickness filled with 80:20 Ar:CO₂ ;
 - Include extra hit position information with high-angle stereo overlaps and readout on both ends of straw.



96 Straws



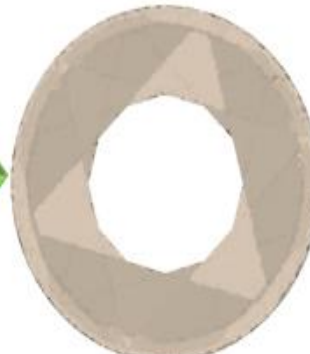
6 Panels



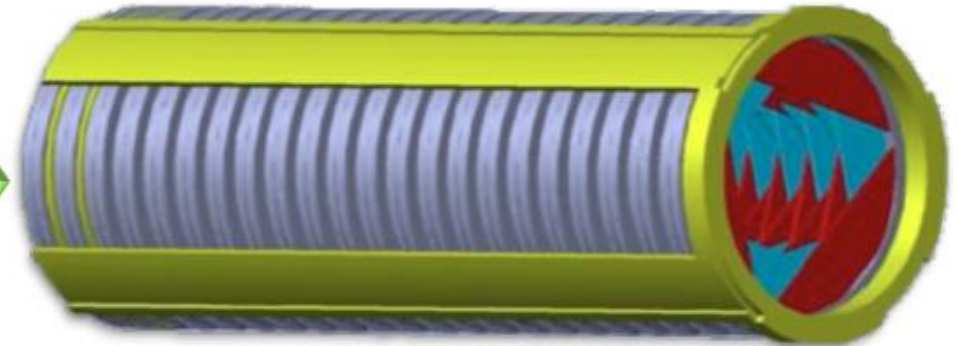
2 Plane



1 Station



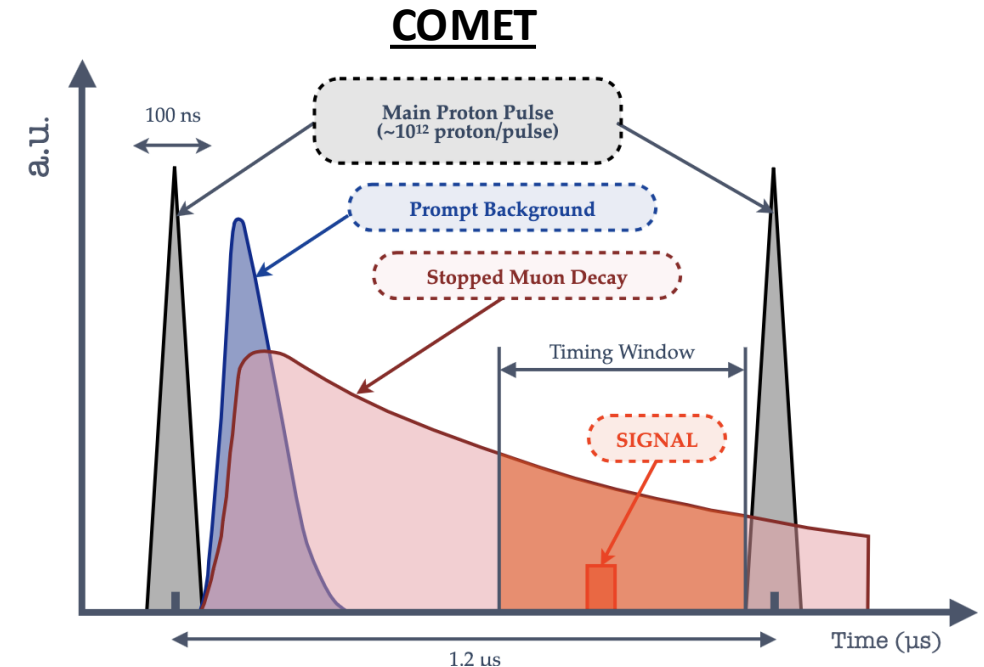
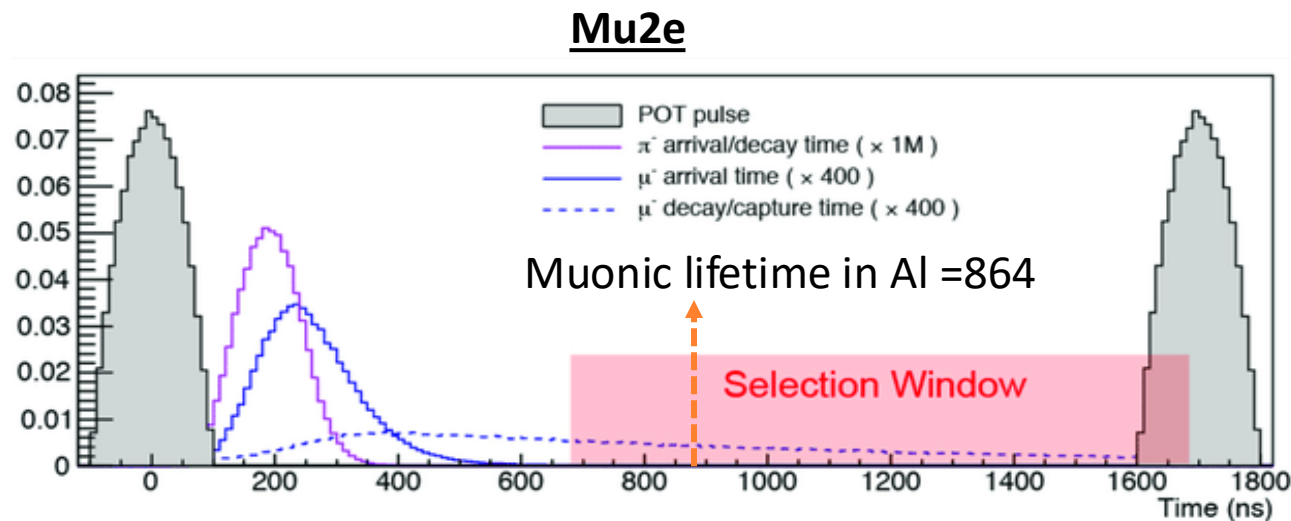
18 Station = 1 Tracker



Radiative Pion Capture Backgrounds

- Use timing information!
- Pion lifetime 26 ns at rest. Pulsed proton beam (250 ns wide, pulses 1695 ns apart) → wait out pion decay.
- In addition, upstream extinction removes out-of-time protons.

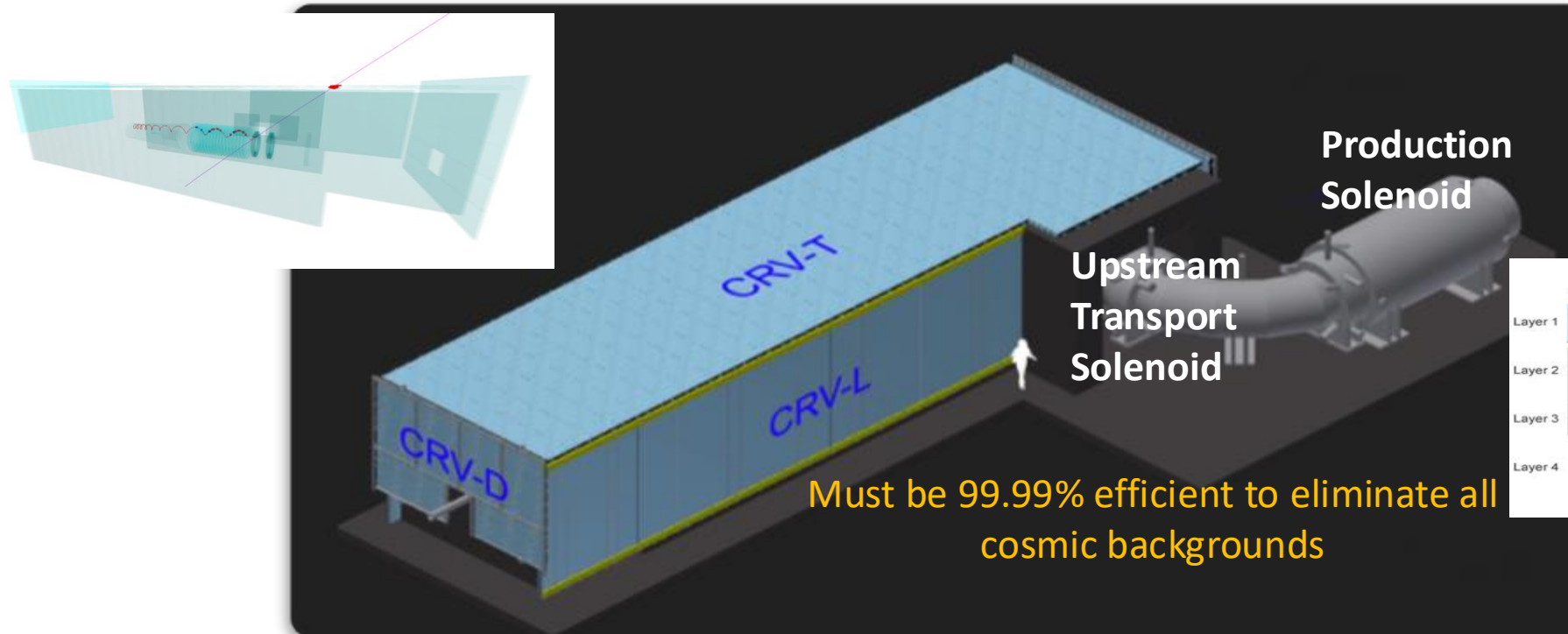
Delayed live-gate helps remove pion and beam backgrounds.



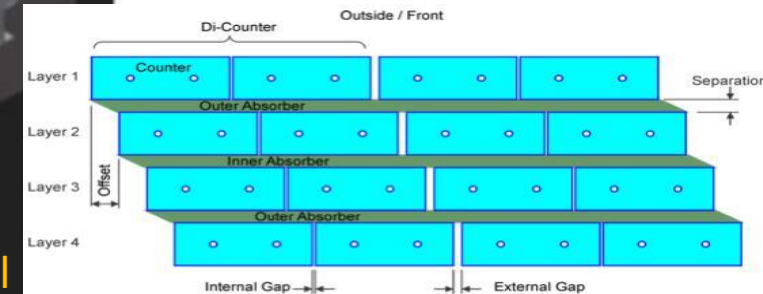
Cosmic Induced Backgrounds

- Cosmic-ray muons can initiate 105 MeV particles that appear to emanate from the stopping target.
- Remove using active veto (CRV) + overburden and shielding concrete surrounding the Detector Solenoid.

Active Cosmic Ray Veto system is key to eliminating cosmic induced backgrounds.



Mu2e (COMET has similar)

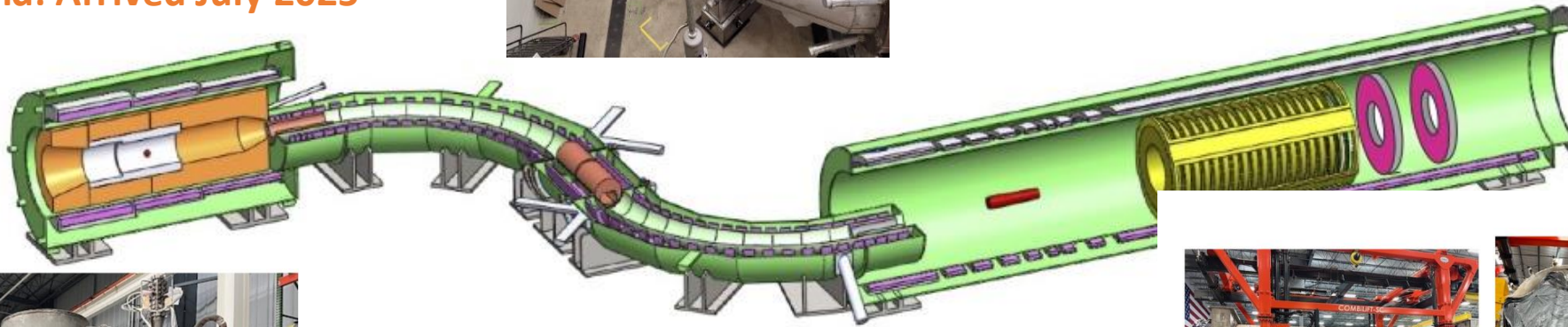


$N\mu^- \rightarrow Ne^-$: Mu2e Status (solenoids)



Transport Solenoid: Installed in Mu2e Hall in 2024

Production Solenoid: Arrived July 2025

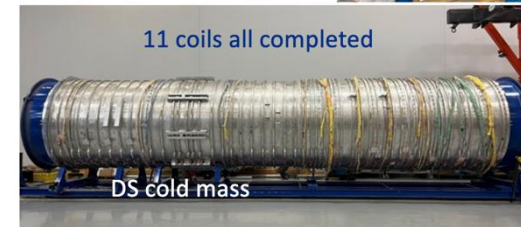


PS in cold test area

Detector Solenoid:
Expected early 2026



Outer vacuum vessel

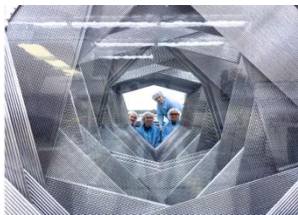


11 coils all completed

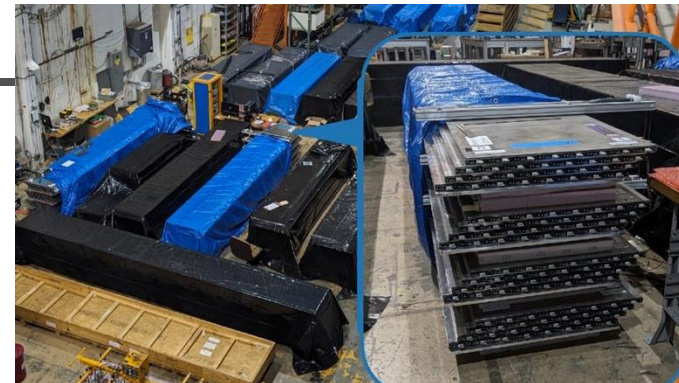
DS cold mass

$N\mu^- \rightarrow Ne^-$: Mu2e Status

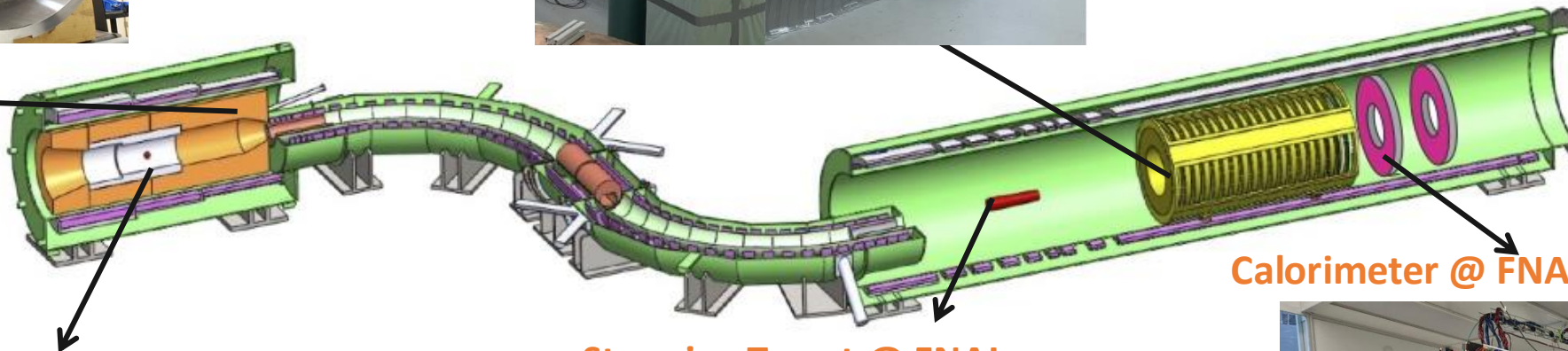
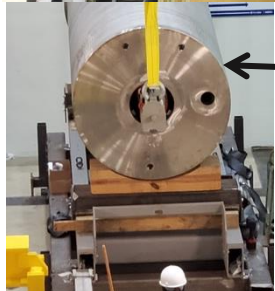
Heat Shield @ FNAL



Tracker @ FNAL

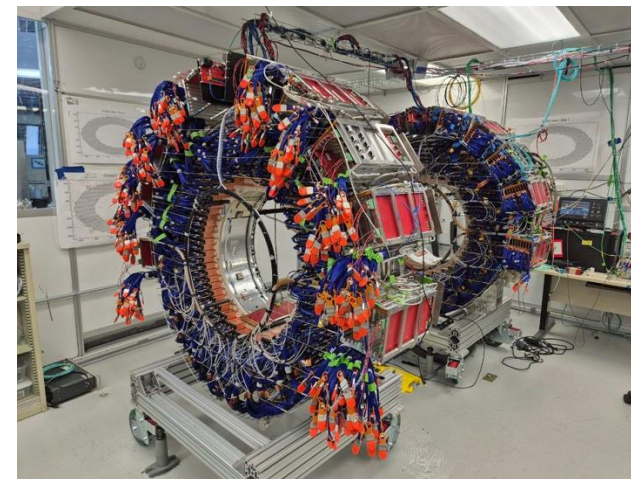
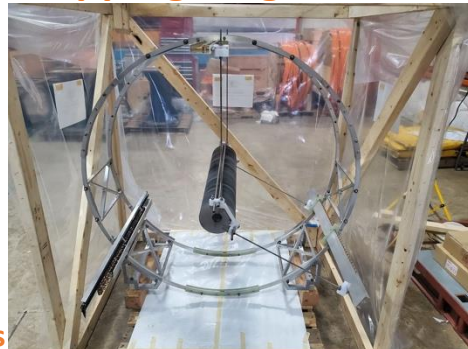


CRV @ FNAL



Calorimeter @ FNAL

Stopping Target @ FNAL



Production Target @ FNAL

Tau CLFV Experiments

Flavor Physics and the Lepton Sector

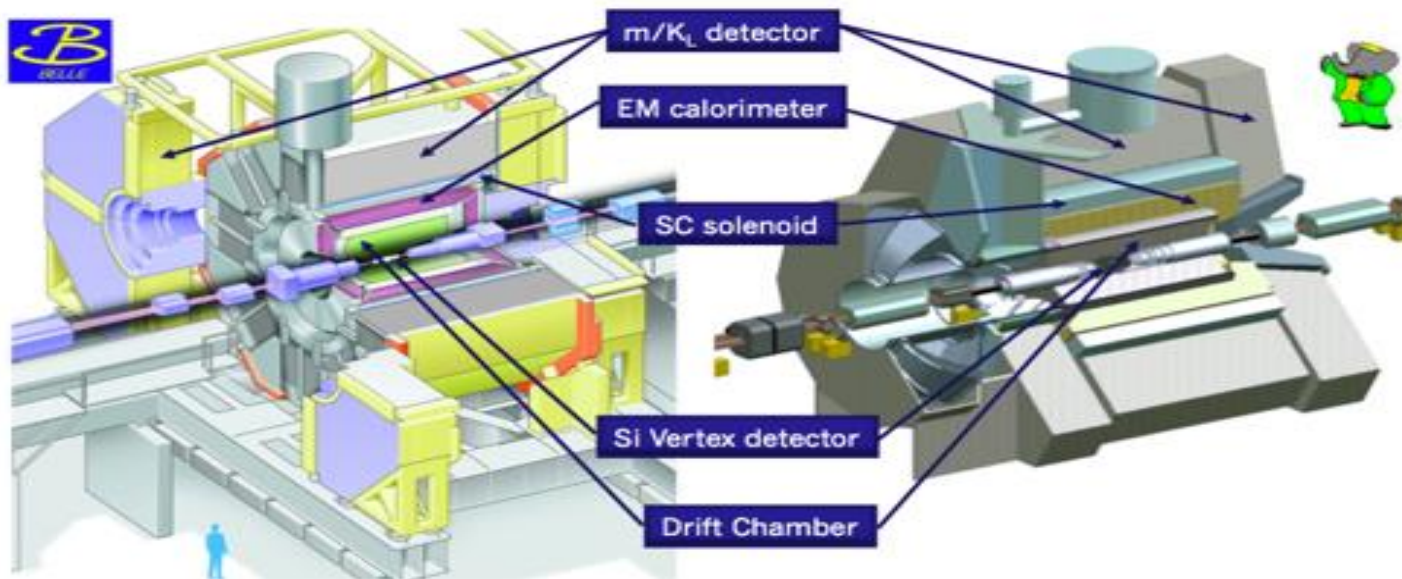
Charged Lepton Flavor Violation

Muon CLFV Searches

Tau CLFV Searches

Summary

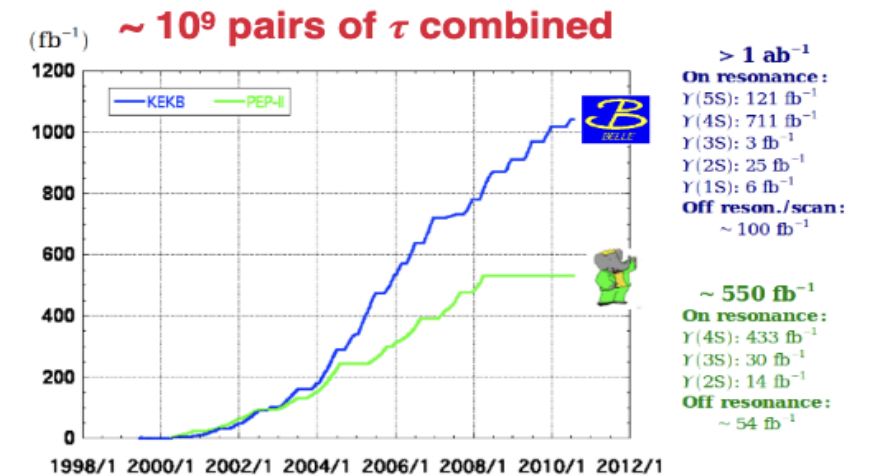
CLFV at B-Factories



- At the $\Upsilon(4S)$ resonance:
 - $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92 \text{ nb}$
 - Belle (711 fb^{-1}) and BaBar (433 fb^{-1})
- B-Factories are also tau-factories!
 - E.g. = BaBar had 470 million $\tau^+\tau^-$ pairs and more at Belle.
- Provide excellent environment for exploring new physics in tau-decays.

Features of a B-Factory:

- High luminosity.
- Well-defined initial state.
- High vertex resolution.
- Excellent calorimetry.
- Sophisticated particle ID.

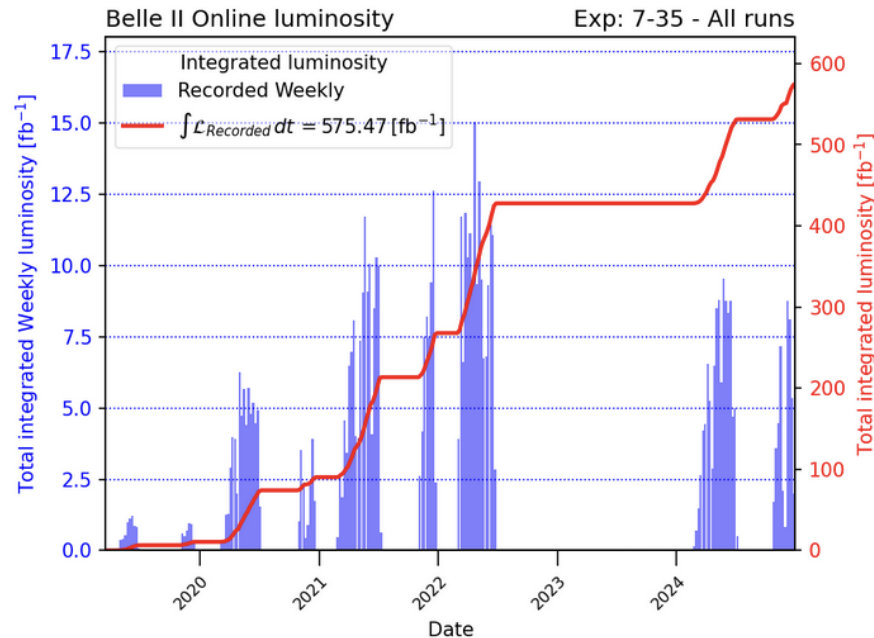


Belle-II Tau CLFV Program

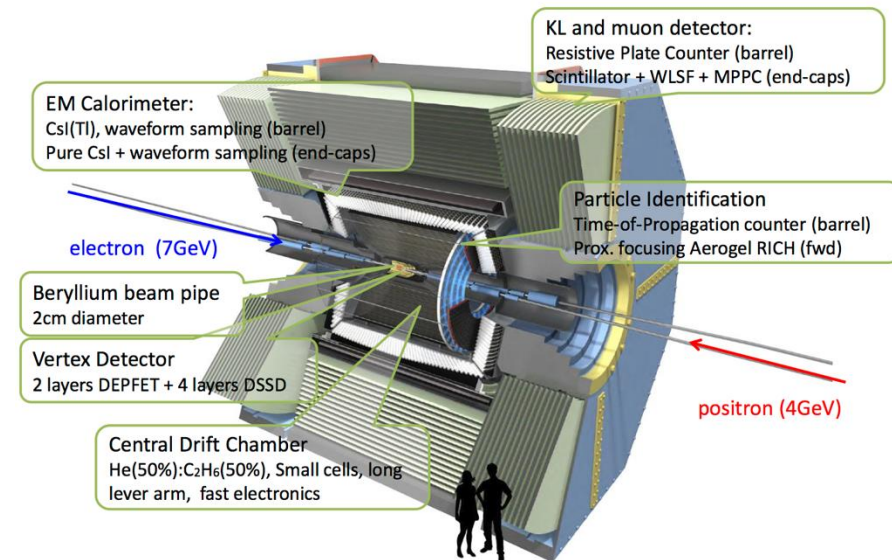
- Belle-II aims to reach $50 \text{ ab}^{-1} \rightarrow$ x50 more than Belle using upgraded SuperKEKB facility.
- Belle/BaBar signal efficiencies lied between 3% and 12% depending on the decay channel.
 - Belle-II to improve on this.
- Many models predict LFV in τ decays at $10^{-10} - 10^{-8}$ levels,
 - probed by $e^-e^+ \rightarrow \tau\tau^+$ events at Belle-II.

● **Advantages of Belle and Belle II in τ LFV searches:**

- the increase of the luminosity;
- the increase of the signal detection efficiency and background suppression:
 - ✓ on clean environment,
 - ✓ high trigger efficiency,
 - ✓ zero background searches

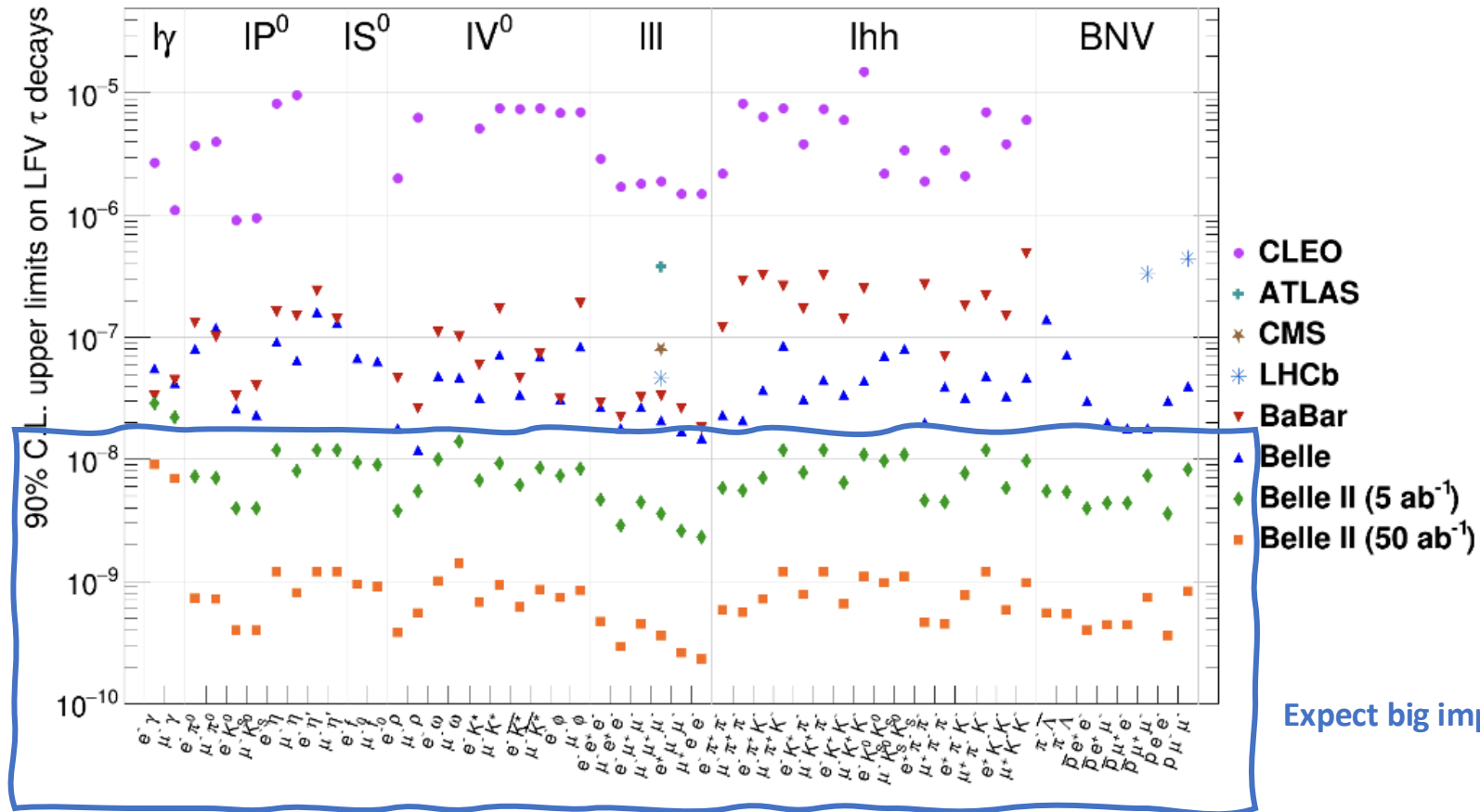


Belle II Detector



Tau CLFV at B-Factories

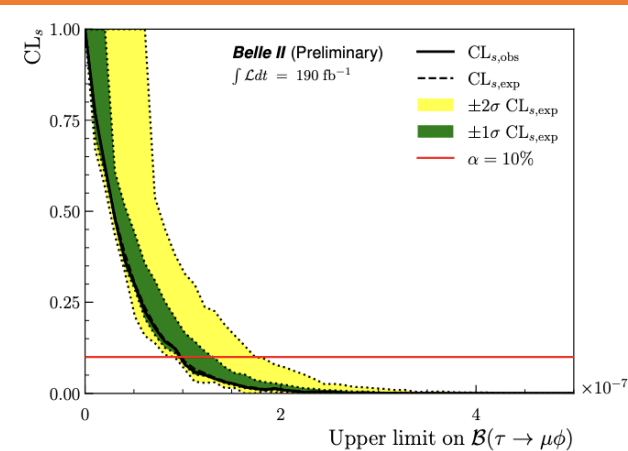
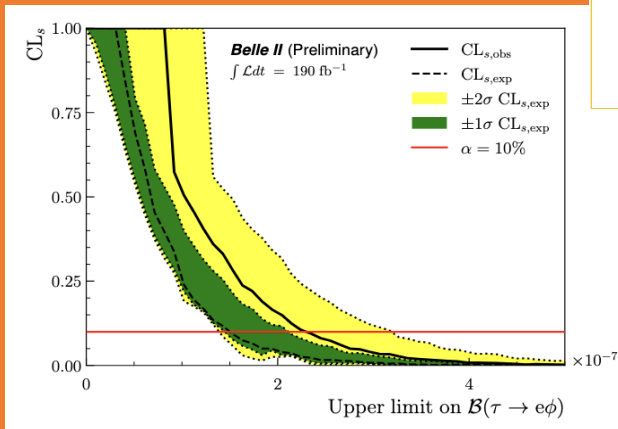
- In total, 52 LFV τ decay modes have been searched in B-Factory experiments:



Results so far Belle-II Tau CLFV Program

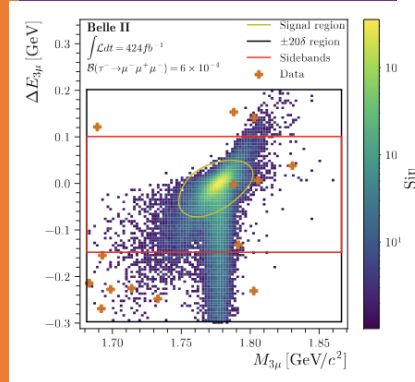
- Initial results from Belle-II

<https://arxiv.org/abs/2305.04759>



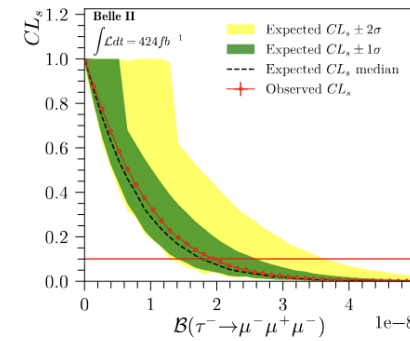
Results not competitive yet (Small data set);
 First, successfully untagged strategy approach for tau physics at Belle II;
 exploited for other measurements;

<https://arxiv.org/pdf/2405.07386>



The obtained result is from 2.2 to 14 times more stringent compared to the previous bounds provided by the ARGUS Collaboration

<https://arxiv.org/pdf/2212.03634>



Most stringent limit to date

	UL at 90% C.L. on $\mathcal{B}(\tau \rightarrow 3\mu)$
ATLAS	3.8×10^{-7} ($\mathcal{L} = 20.3 \text{ fb}^{-1}$)
LHCb	4.6×10^{-8} ($\mathcal{L} = 3.0 \text{ fb}^{-1}$)
CMS	2.9×10^{-8} ($\mathcal{L} = 131 \text{ fb}^{-1}$)
Belle	2.1×10^{-8} ($\mathcal{L} = 782 \text{ fb}^{-1}$)
BaBar	3.3×10^{-8} ($\mathcal{L} = 486 \text{ fb}^{-1}$)
Belle II	1.9×10^{-8} ($\mathcal{L} = 424 \text{ fb}^{-1}$)

α is an invisible spin-0 boson predicted in models with axionlike particles

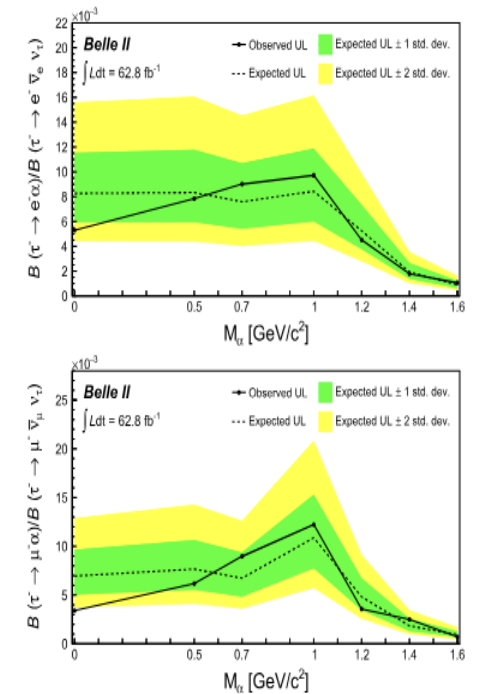


FIG. 2. Upper limits at 95% C.L. on the branching-fraction ratios $\mathcal{B}(\tau^- \rightarrow e^- \alpha)/\mathcal{B}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_e)$ (top) and $\mathcal{B}(\tau^- \rightarrow \mu^- \alpha)/\mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\mu)$ (bottom) as a function of the α mass, as well as their expectations from background-only hypothesis. All values are linearly interpolated between mass points.

Summary

Flavor Physics and the Lepton Sector

Charged Lepton Flavor Violation

Muon CLFV Searches

Tau CLFV Searches

Summary

Summary

- Neutral leptons i.e. neutrino exhibit flavor violation, known as “neutrino oscillations”.
- A large experimental program is underway to fully understand these oscillations and the neutrinos themselves.
- The existence of flavor violation in the neutral lepton sector has implications for the charged lepton sector i.e. CLFV.
- Neutrino oscillations can induce CLFV, but at very low rates. This is not something we could conceivably measure.
- However, many new physics scenarios can enhance the rates of CLFV. Therefore, CLFV searches are interesting ways to indirectly probe well-motivated beyond SM physics models.
- Searches are underway to look for CLFV in lepton decays, Higgs and Z boson decays, meson decays and other places.
- The next decade will see many experiments explore CLFV, projected sensitivities are many orders of magnitude better than current limits.
 - **This is a very exciting era for CLFV.**
 - **CLFV searches are an important part of our pathway to new physics!**

*Thank you for listening,
Any questions?*