

# RF05 – Charged Lepton Flavor Violation

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Rare Processes and Precision Measurement frontier kick-off meeting– July 2020

# Outline

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**What are Charged Lepton Flavor Violating (CLFV) processes – a compelling opportunity to discover and explore New Physics**

**What are the best strategies to search for CLFV – the experimental landscape and new opportunities in the coming decades and beyond**

**What are synergies with other frontiers and rare processes topical groups - complementarity and joint studies**

**Topical group organization – activities and your input**

**RF05 – CLFV TWIKI page:** <https://snowmass21.org/rare/clfv>

**Slack channel:** rpf-05-clfv

**Mailing list:** SNOWMASS-RPF-05-CLFV@FNAL.GOV

# Charged Lepton Flavor Violation

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Charged lepton flavor violating (CLFV) processes are contact interactions that do **not** conserve lepton family number(s)

- e.g.  $\mu \rightarrow e$ ,  $\tau \rightarrow \mu\mu\mu$ ,  $K_L \rightarrow \mu e$ ,  $H \rightarrow \tau\mu$ , ...

Flavor in the Standard Model

- Quark flavor is violated in weak decays (CKM matrix)
- Neutral lepton flavor is violated (neutrino oscillations)

What about charge(d) lepton flavor?

- SM with massless neutrinos: lepton flavor accidentally conserved
- Add Dirac neutrino masses to SM : lepton flavor violated, but the rates are extremely suppressed

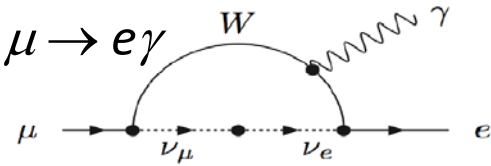
**CLFV are very sensitive and generic probes of New Physics.**

**CLFV searches share the stage with neutrino experiments in studying the origin of neutrino mass, flavors and families.**

# CLFV and BSM physics

CLFV can be generated at least at loop level with massive neutrinos:

these processes are extremely suppressed for Dirac neutrino masses, due to GIM mechanism and tiny neutrino masses. For example:



The diagram shows a muon line entering from the left, which splits into a neutrino line (labeled  $\nu_\mu$ ) and a  $W$  boson line. The neutrino line continues to the right, where it splits into an electron line (labeled  $e$ ) and another neutrino line (labeled  $\nu_e$ ). The  $W$  boson line connects the two neutrino lines, and a photon line (labeled  $\gamma$ ) is emitted from the  $W$  boson line.

$$\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

PMNS unitary,  $\sum U_{\mu i}^* U_{ei} = 0$

**Effectively zero in the SM – background free!**

By comparison, this mechanism is much less efficient in the quark sector

$$\text{Br}(b \rightarrow s\gamma) \simeq \frac{6\alpha}{\pi} \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} f(m_t/m_W, \alpha_S) \right|^2 \rightarrow_{\text{NNLO QCD}} (3.36 \pm 0.23) \times 10^{-4}$$

[Asatrian et al, 1503.01789](#)

mixing angles smaller but  $m_t \gg m_\nu \rightarrow \text{FCNC observable}$

A. Zupan

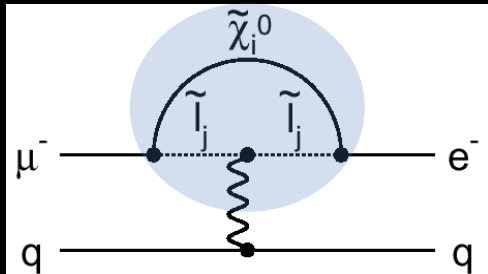
**CLFV are very clean probes - an observation is an unambiguous sign of physics beyond vSM.**

**The drawback is that rates tend to be extremely suppressed ( $1/\Lambda^4$ ), but new physics could enhance them to observable rates**

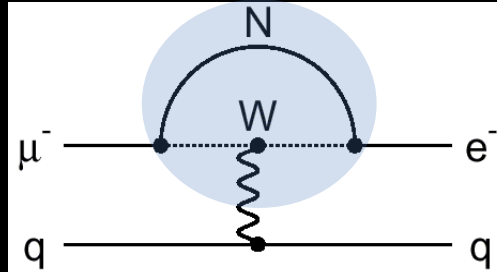
# CLFV and BSM physics

Many BSM scenarios predict observable CLFV rates, for example:

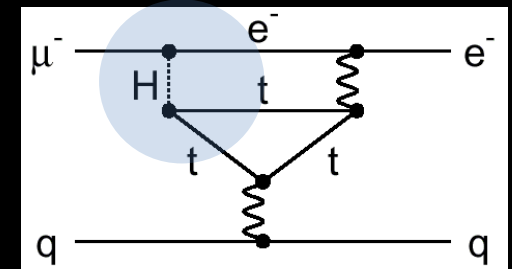
Supersymmetry



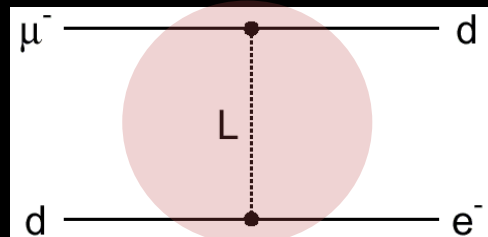
Heavy neutrino



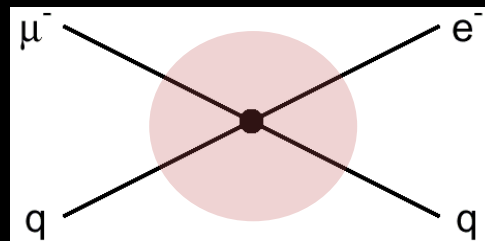
Two Higgs doublet



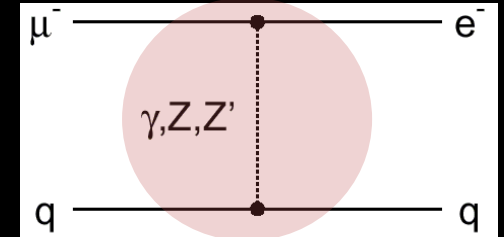
Leptoquarks



Compositeness



New heavy bosons /  
anomalous coupling



Each model generate a specific pattern of operators  $\rightarrow$  multiple CLFV measurements to extract the underlying physics.

# CLFV and SUSY (subset of models)

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



Large

Small but observable

Unobservable

## Glossary

AC	RH currents & U(1) flavor symmetry
RVV2	SU(3) flavored MSSM
AKM	RH currents & SU(3) family symmetry
$\delta$ LL	CKM like currents
FBMSSM	Flavor-blind MSSM
LHT	Little Higgs with T parity
RS	Warped extra dimensions

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi & D.M. Straub - 0909.1333

Pattern characteristic of model,  
diagnosis with multiple observables (not only CLFV)

# CLFV and BSM physics

CLFV has already set stringent limits on new operators, e.g.

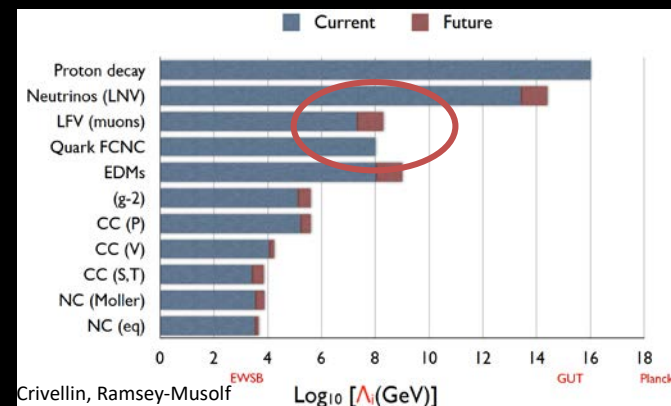
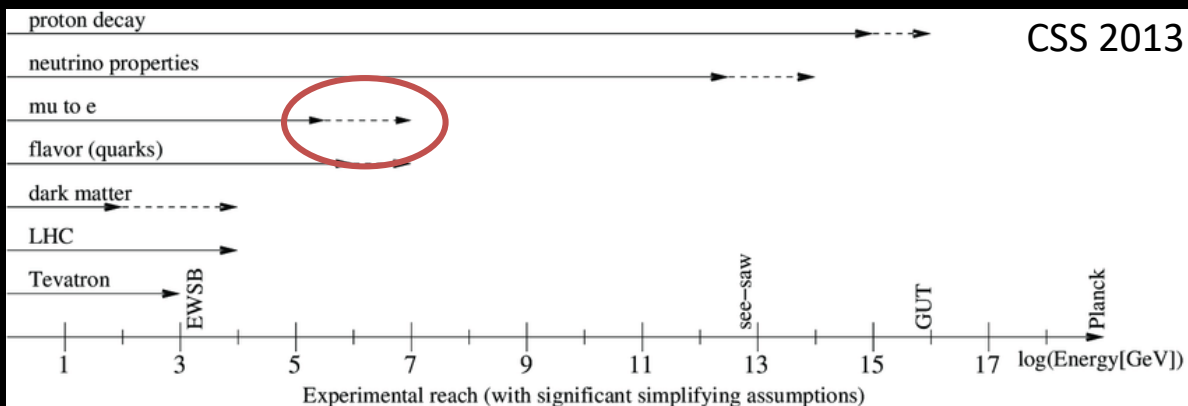
$$BR(\mu \rightarrow e\bar{e}e) \equiv \frac{\Gamma(\mu \rightarrow e\bar{e}e)}{\Gamma(\mu \rightarrow e\bar{\nu}\nu)} \simeq \frac{8G_F^2 |C_{e\mu ee}|^2}{M_{NP}^4}$$

$$B(\mu^+ \rightarrow e^+e^-e^+) < 4.2 \times 10^{-13} \quad \Rightarrow \quad M_{NP} > 250 \text{ TeV} \times |C_{e\mu ee}|^{1/2}$$

$$B(\tau^+ \rightarrow e^+e^-e^+) < 3 \times 10^{-8} \quad \Rightarrow \quad M_{NP} > 10 \text{ TeV} \times |C_{e\tau ee}|^{1/2}$$

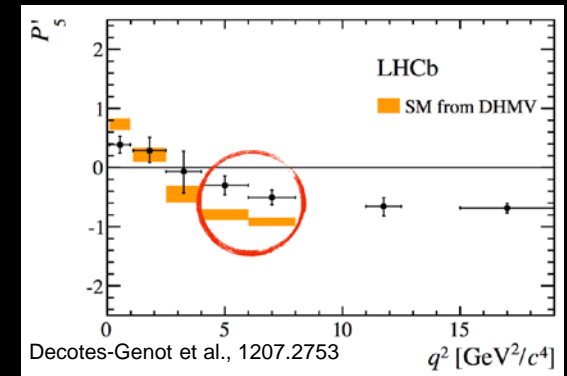
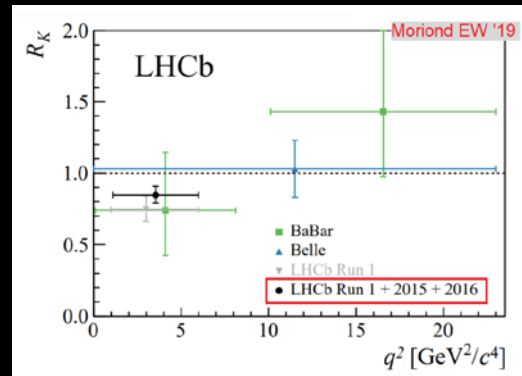
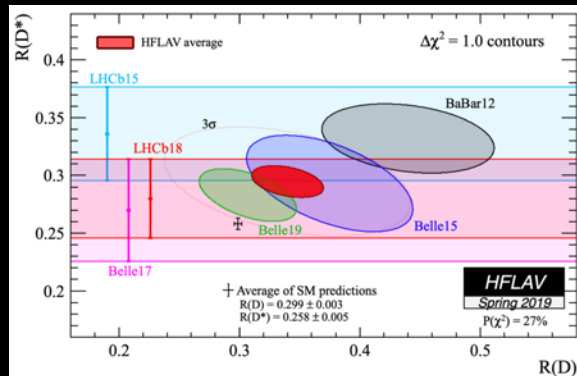
New Physics is at high mass scale or couplings are very suppressed.

**For O(1) couplings, explore New Physics scale at the level of  $\sim 10^2 - 10^3$  TeV**



# CLFV and lepton flavor universality

Several anomalies in B decays violating Lepton Flavor Universality:  $R_{D^{(*)}}$ ,  $R_{K^{(*)}}$ ,  $P_5'$   
Significant deviation from SM suggests New Physics effects at tree-level!



Several appealing candidates to solve these anomalies:

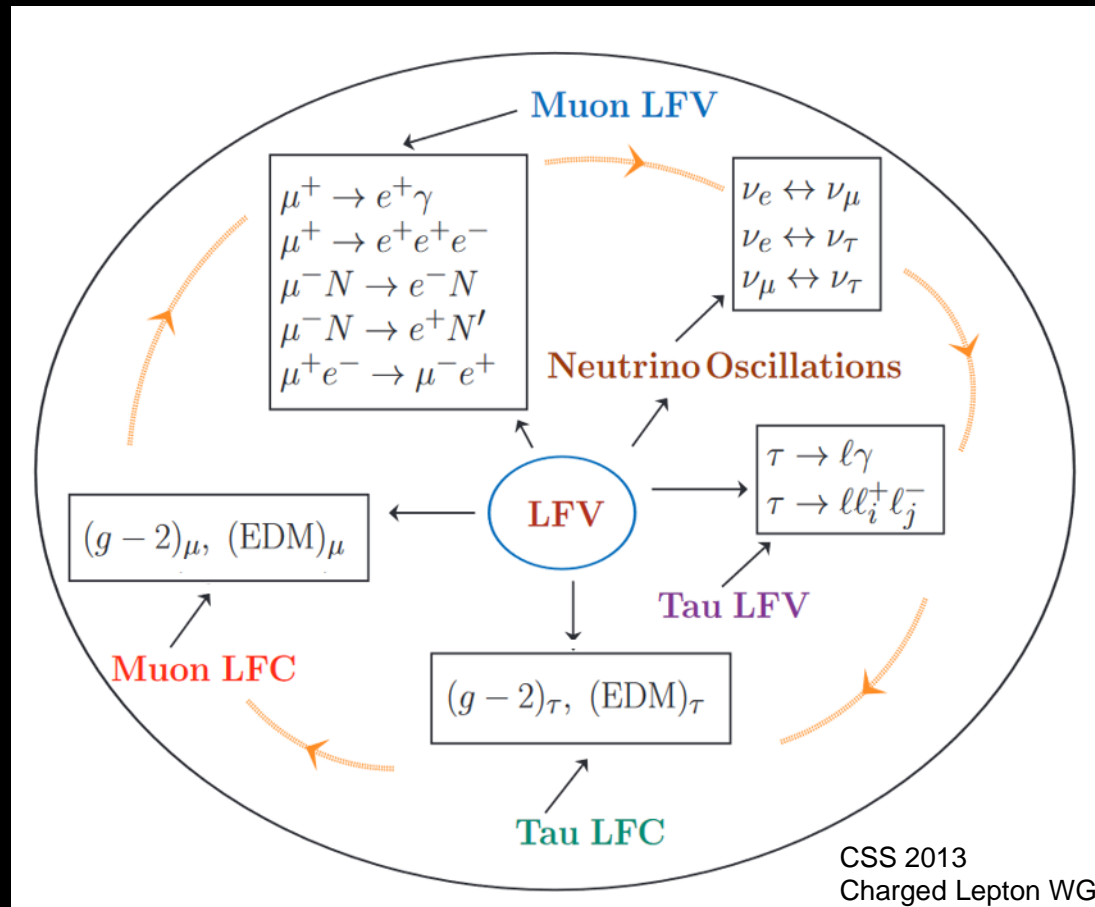
- Leptoquarks, Vector-like fermions,  $Z'$ , ...

Many of which predict sizeable CLFV rates (e.g.  $\tau \rightarrow \mu\mu\mu$ ) along with other observables (e.g.  $B \rightarrow K\nu\nu$ ,  $B \rightarrow \tau\mu, \dots$  + direct searches at LHC)

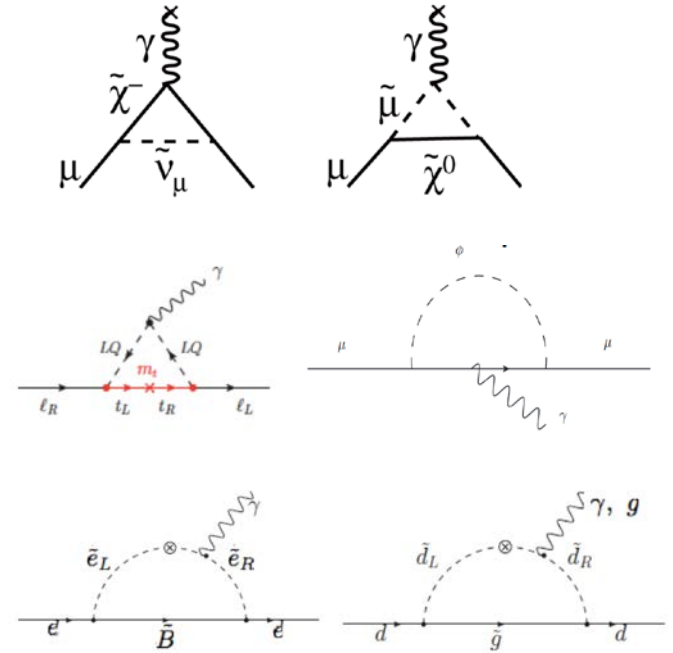
**Interplay between all aspects of flavor physics in probing BSM scenarios  
(see RF01 / RF02)**



# CLFV and lepton flavor conservation (LFC)



## Possible NP contributions



Many new physics models (strongly) correlate LFV and LFC observables

Complementarity with LFC sector (see RF03)

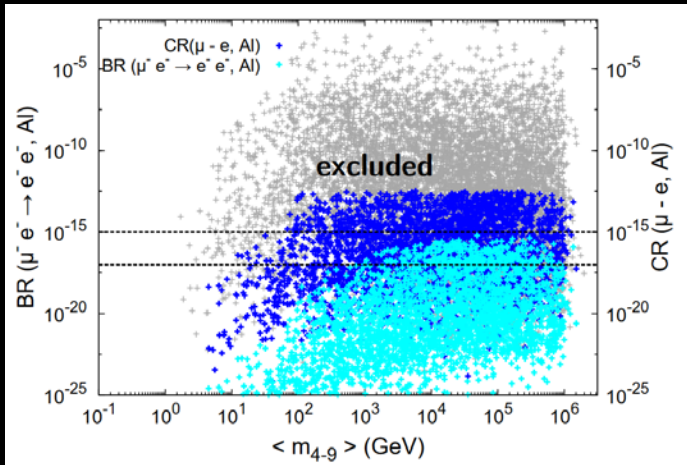
# CLFV and neutrino mass

Many mechanisms to generate  $\nu$  mass: seesaw, Zee models, RPV SUSY,...

- distinct new states realized at different scales

## Low scale Seesaw: inverse seesaw

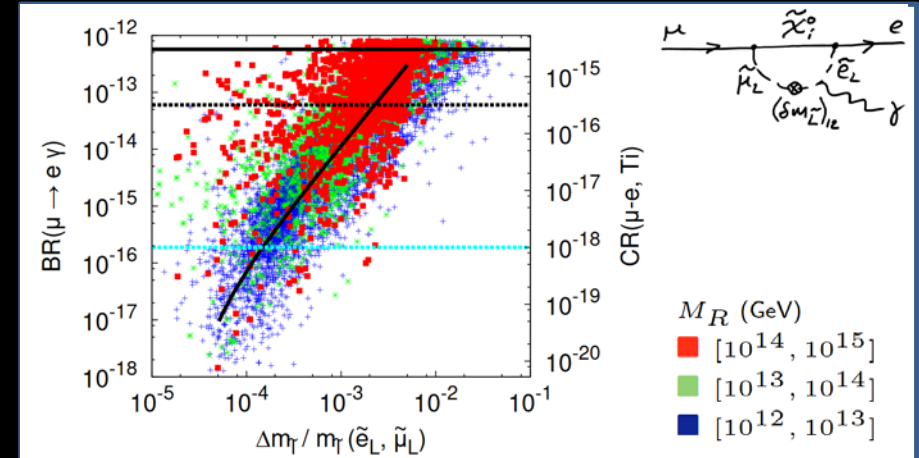
Addition of 3 “heavy” RH neutrinos and 3 extra “sterile” fermions to SM



Teixeira et al., JHEP02 (2016) 083

## SUSY Seesaw

CLFV induced by exchange of SUSY particles

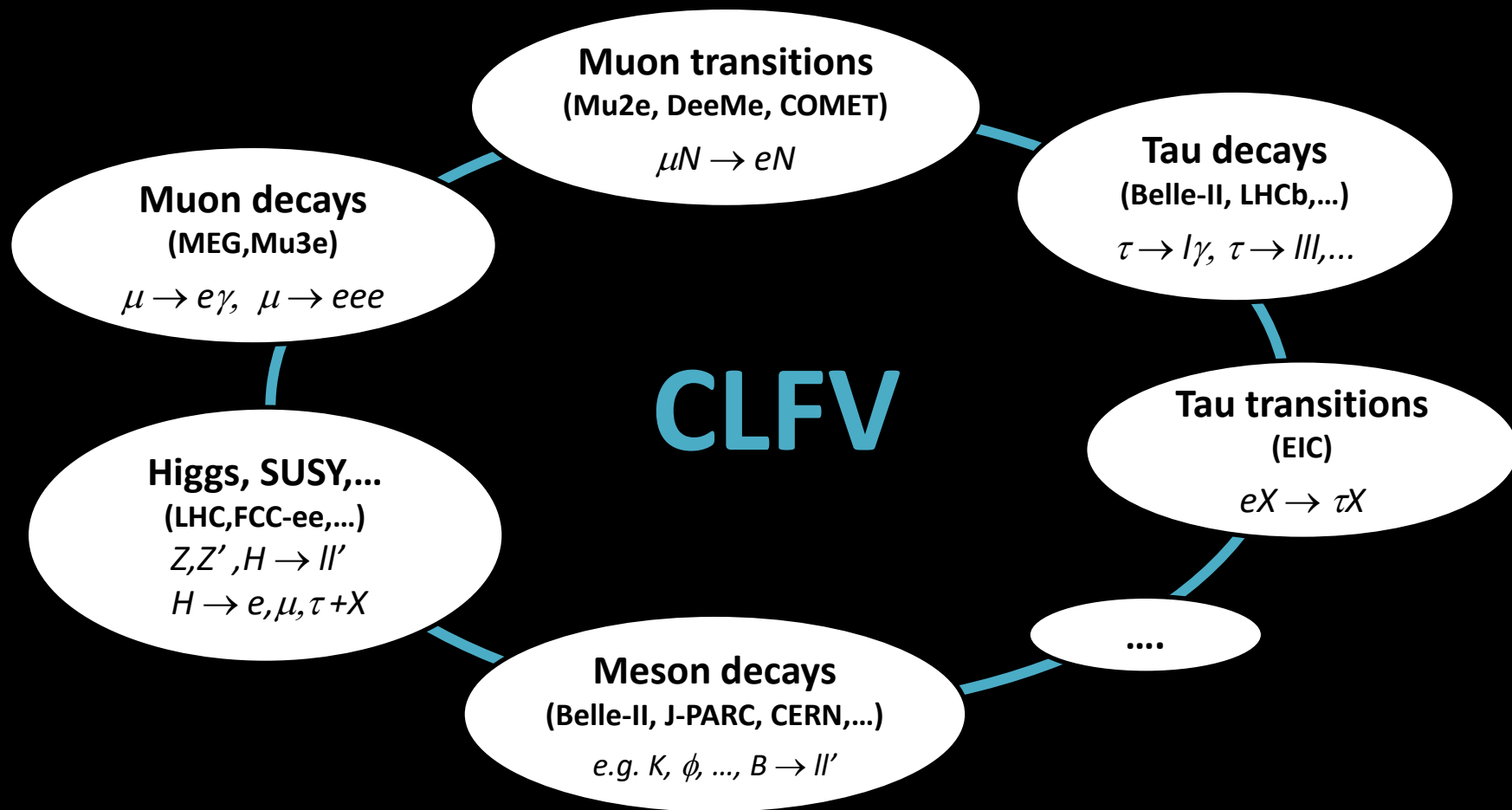


Induces sizeable CLFV rates and helps differentiate models

Non Standard Interactions might also impact neutrino oscillations

# CLFV searches – a worldwide hunt

Worldwide effort to search for experimental signatures in many different channels.



See for example

Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58

M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008

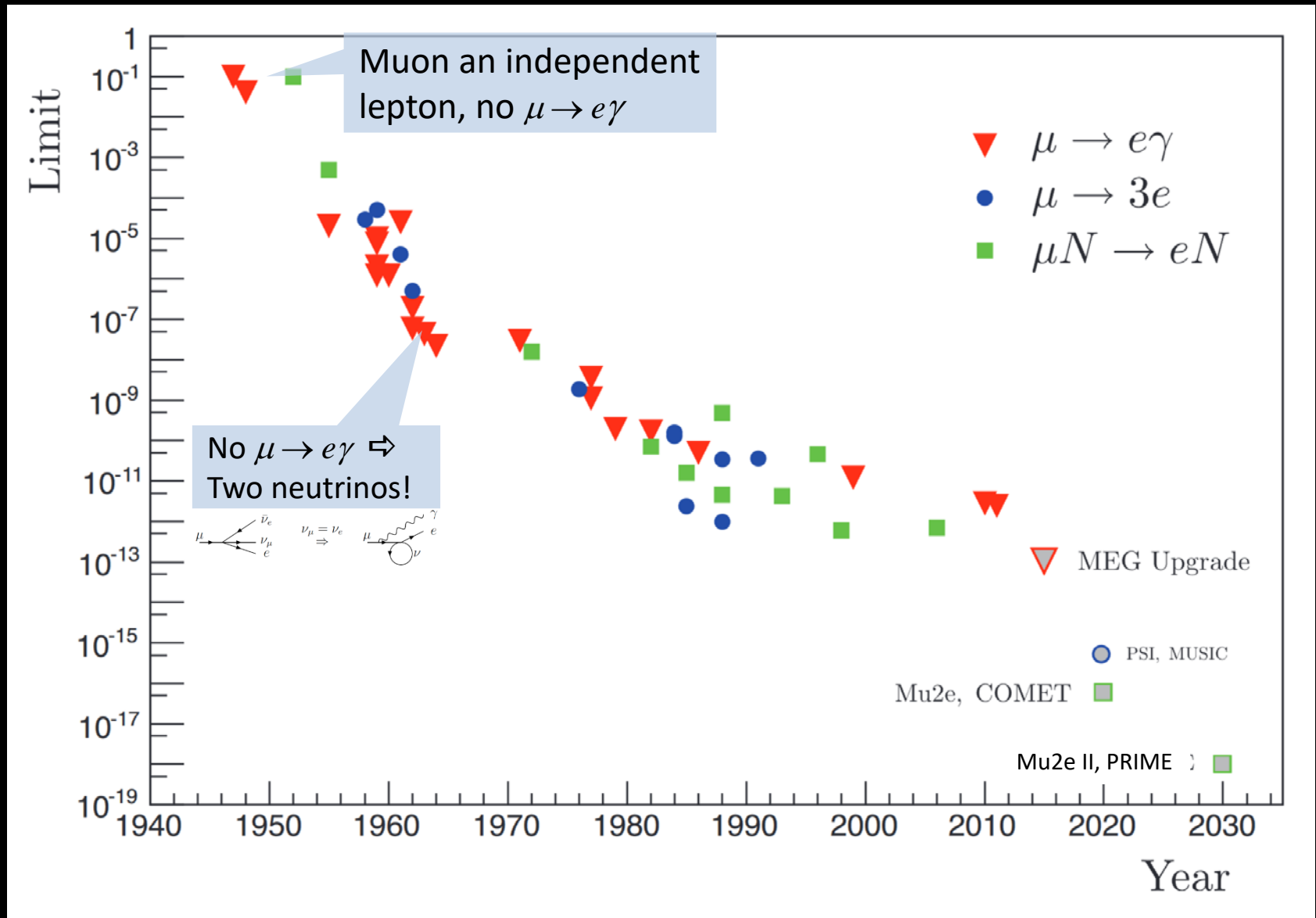
A. de Gouvêa, P. Vogel, arXiv:1303.4097

Signorelli and Calibbi, arxiv:1709.00294

# Muons

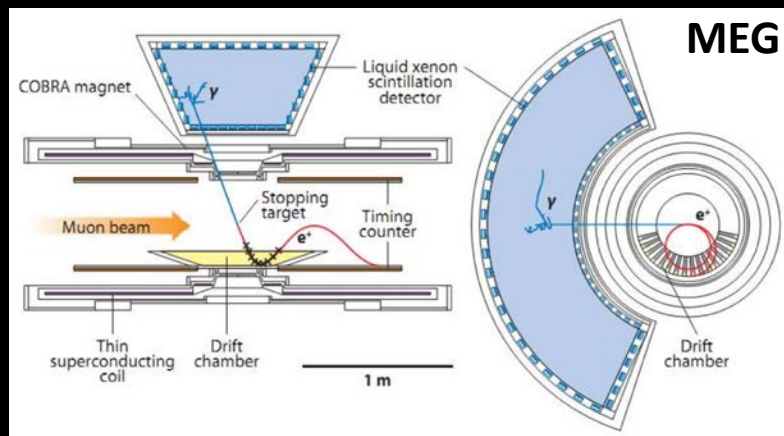
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# Chronology of LFV muon processes



# Muon decays

## MEG / MEG II at PSI Search for $\mu^+ \rightarrow e^+ \gamma$

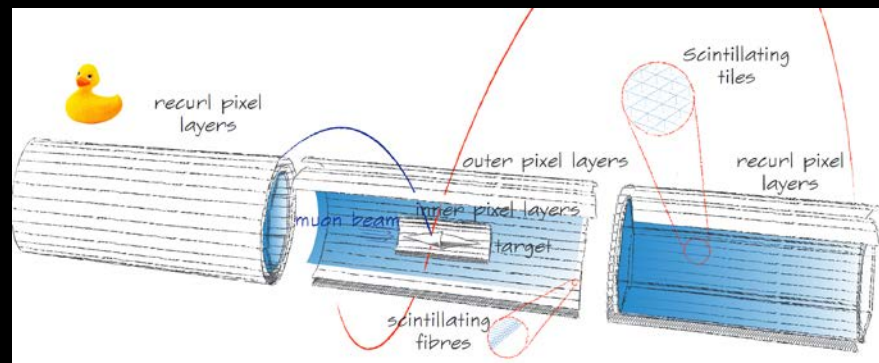


- Most sensitive measurement of  $\mu^+ \rightarrow e^+ \gamma$
- $7.5 \times 10^{14}$   $\mu$  on target
  - $\text{BR}(\mu^+ \rightarrow e^+ \gamma) < 4.2 \times 10^{-13}$  @90% C.L.

Detector upgrade (MEG II) to improve the limit by one order of magnitude with a 3 year run

Expect first physics run in 2021

## Mu3e at PSI Search for $\mu^+ \rightarrow e^+ e^- e^+$



- Best limit from SINDRUM experiment
- $$\text{BR}(\mu^+ \rightarrow e^+ e^- e^+) < 10^{-12} \text{ @ 90\% C.L.}$$

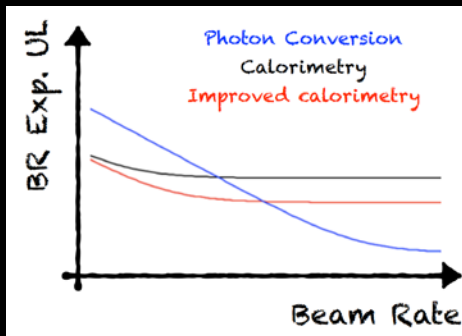
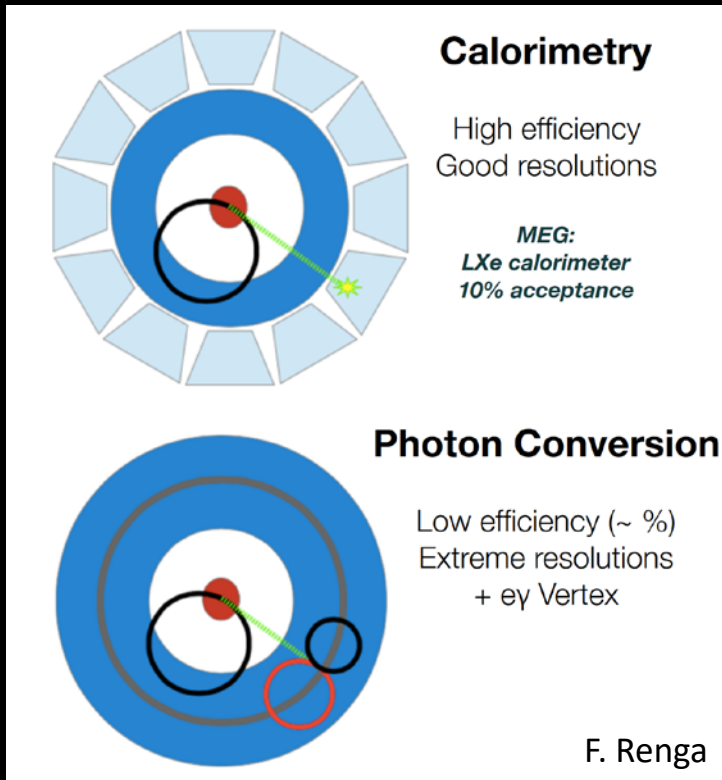
Phase I (existing PiE5 beamline)  
sensitivity at the level of  $10^{-15}$

Phase II (need new HiMB beamline)  
improve by one order of magnitude

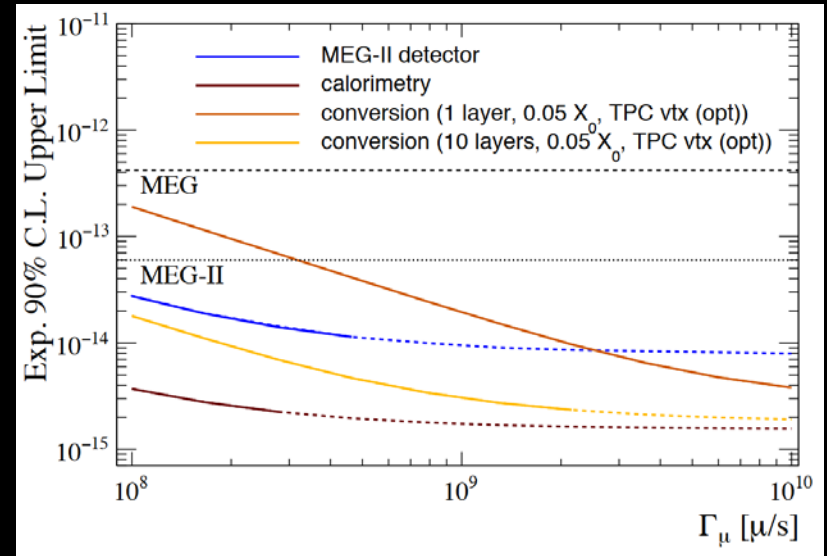
Expect data taking 2022++

# Muon decays – going beyond

## Improving photon energy resolution



Renga *et al.*, 1811.12324



—— Bkg  $\leq 10$  evts    - - - - - bkg  $> 10$  evts

Several possibilities to reach  $10^{-15}$ , but taking full advantage of  $10^{10} \mu/s$  and improving sensitivity need a novel experimental concept.

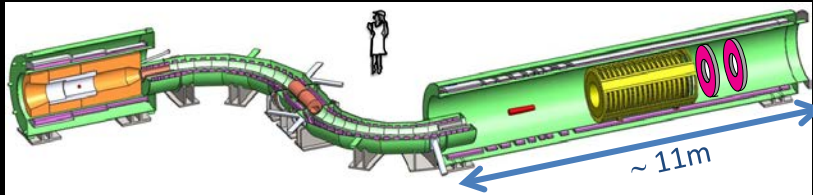
Can we build a single experiment to look for  $\mu^+ \rightarrow e^+ \gamma$  and  $\mu^+ \rightarrow e^+ e^- e^+$ ?

**Good ideas are welcome**

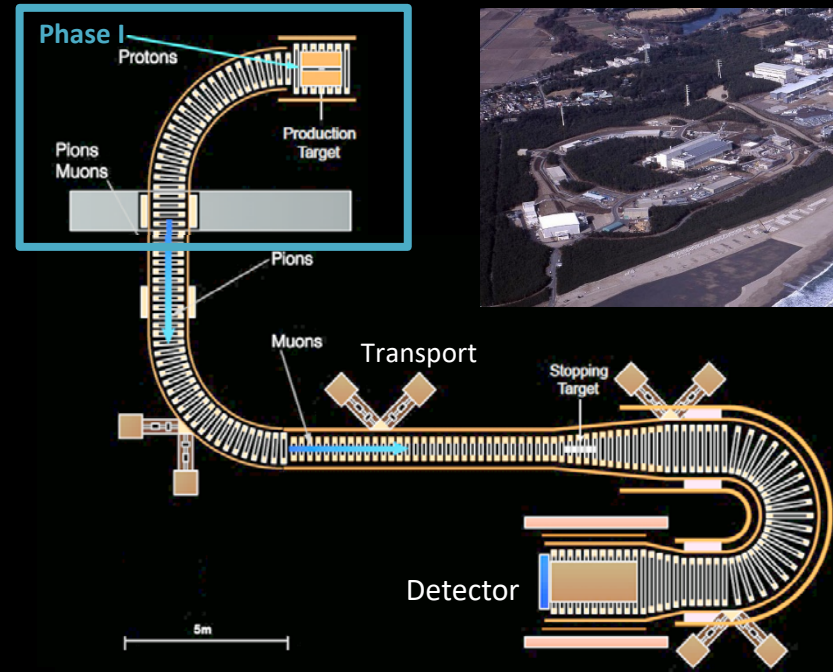


# Muon-to-electron conversion

## Mu2e at FNAL



## COMET at JPARC



Currently four experiment in various stages of execution:

DeeMee at J-PARC

COMET at J-PARC

Mu2e at FNAL

PRISM/Prime

} Aim to achieve single event sensitivity  $R_{\mu e} \sim 10^{-17}$  by the end of the decade

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A, Z) \rightarrow e^- + N(A, Z))}{\Gamma(\mu^- + N(A, Z) \rightarrow \text{all muon captures})}$$



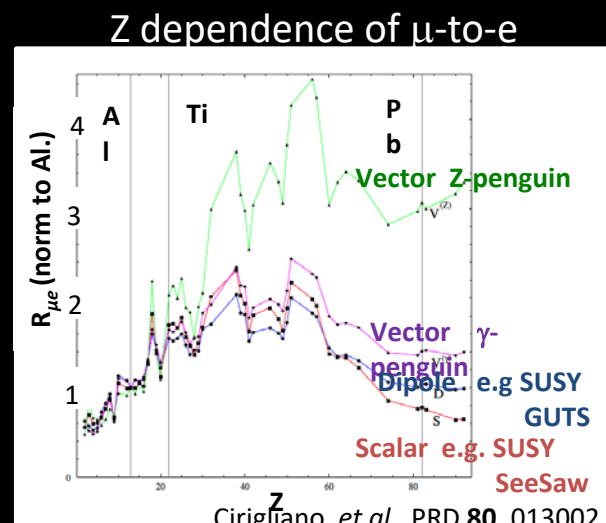
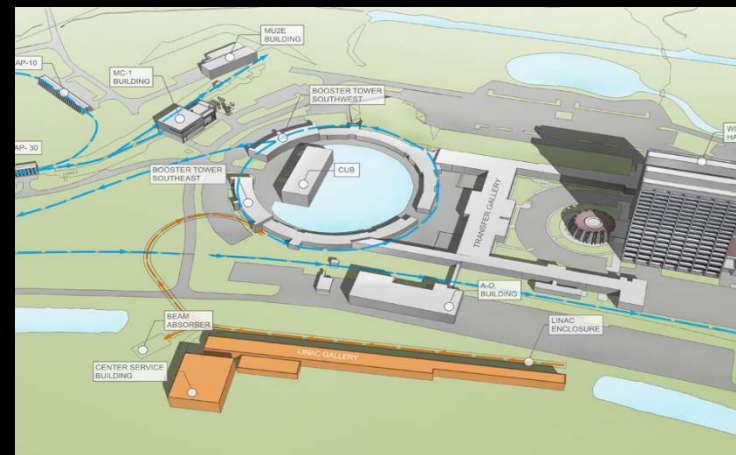
# Mu2e II @ PIP II

**PIP II** is a superconducting linac for LBNF and intensity frontier at FNAL

- 800 MeV, ~1MW available for intensity frontier physics, including muon campus
- Groundbreaking for project in March 2019

**Mu2e II**, proposed Mu2e upgrade taking advantage of PIP II linac

- Order of magnitude increase in muon stops
- If  $\mu \rightarrow e$  conversion has been found, use heavier targets to ascertain the (A,Z)-dependence
- If conversion is not seen, then improve sensitivity by order of magnitude



**More opportunities with PIP II for muon decays / conversion experiments**  
**international groups starting to explore these possibilities for Snowmass**

# PRISM / PRIME

Phase Rotated Intense Slow Muon source

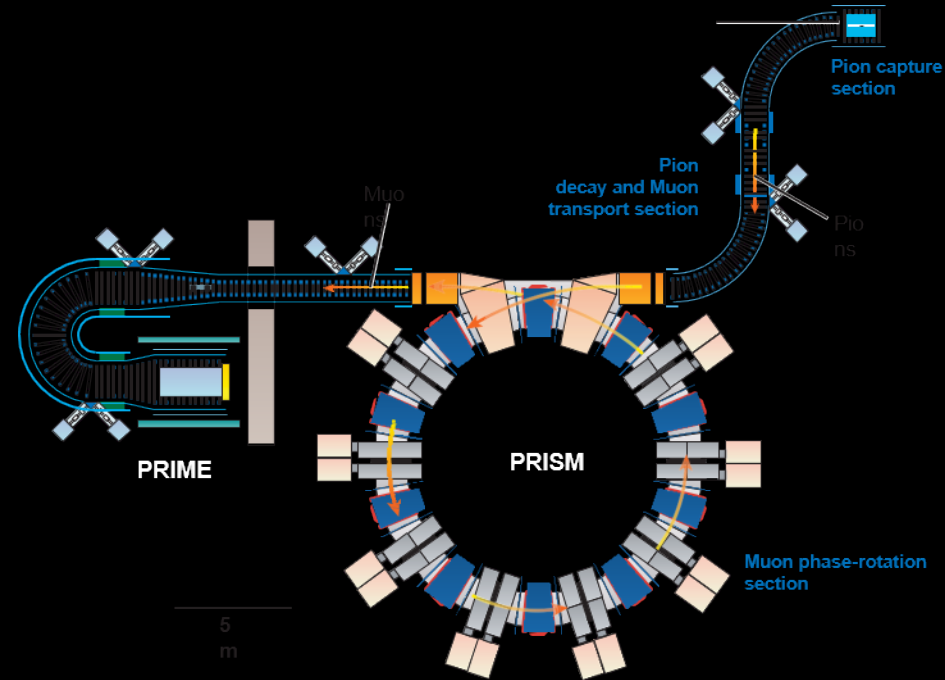
PRISM Muon Electron conversion

A muon storage ring (FFA),  
feeding a COMET-like detector

Very high muon intensity  $10^{11} - 10^{12} \mu^-/s$

Low momentum, quasi-mono-energetic muons

Very low pion contamination  $< 10^{-18}$ . Opens up  
possibility to observe conversion in heavier nuclei.



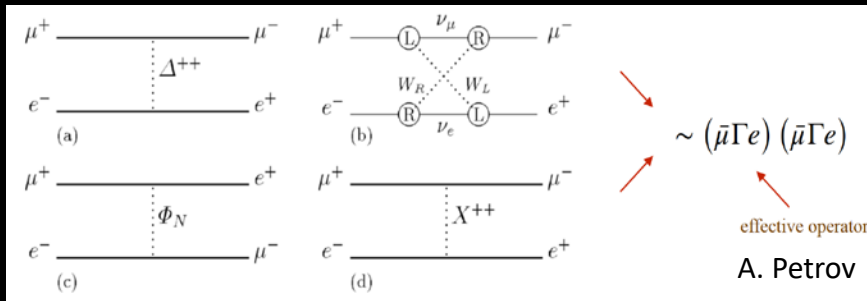
Timescale > 2030

**Aims for a single event sensitivity at the level of  $10^{-19}$ .**

# Muonium – antimuonium transitions

Muonium: bound state of  $\mu^+$  and  $e^-$ . Purely QED, no hadronic uncertainties

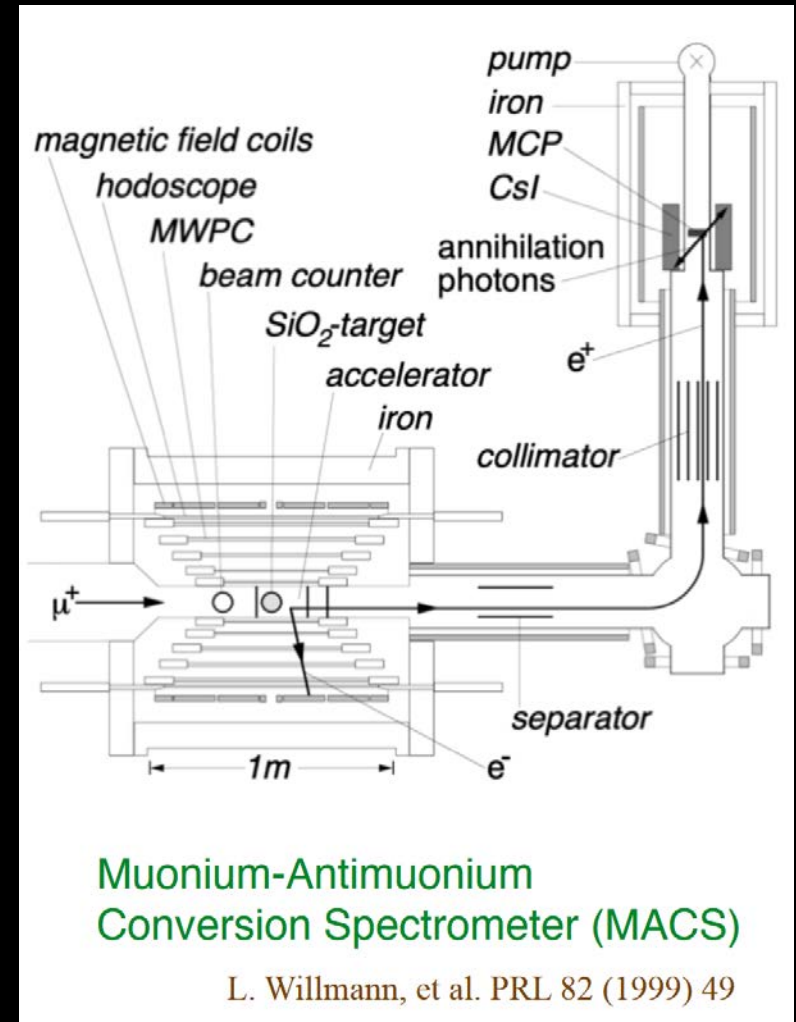
Muonium – antimuonium transitions ( $\Delta L=2$ ) are extremely suppressed in the SM, but rates can be enhanced by NP



Best limits from MACS experiment based on  $5.7 \times 10^{10}$  muonium atoms

$$P(M_\mu \rightarrow \overline{M}_\mu) < 8.3 \times 10^{-11} / S_B(B_0)$$

$$G_{MMbar} < 3 \times 10^{-3} G_F \text{ (90\% CL)}$$

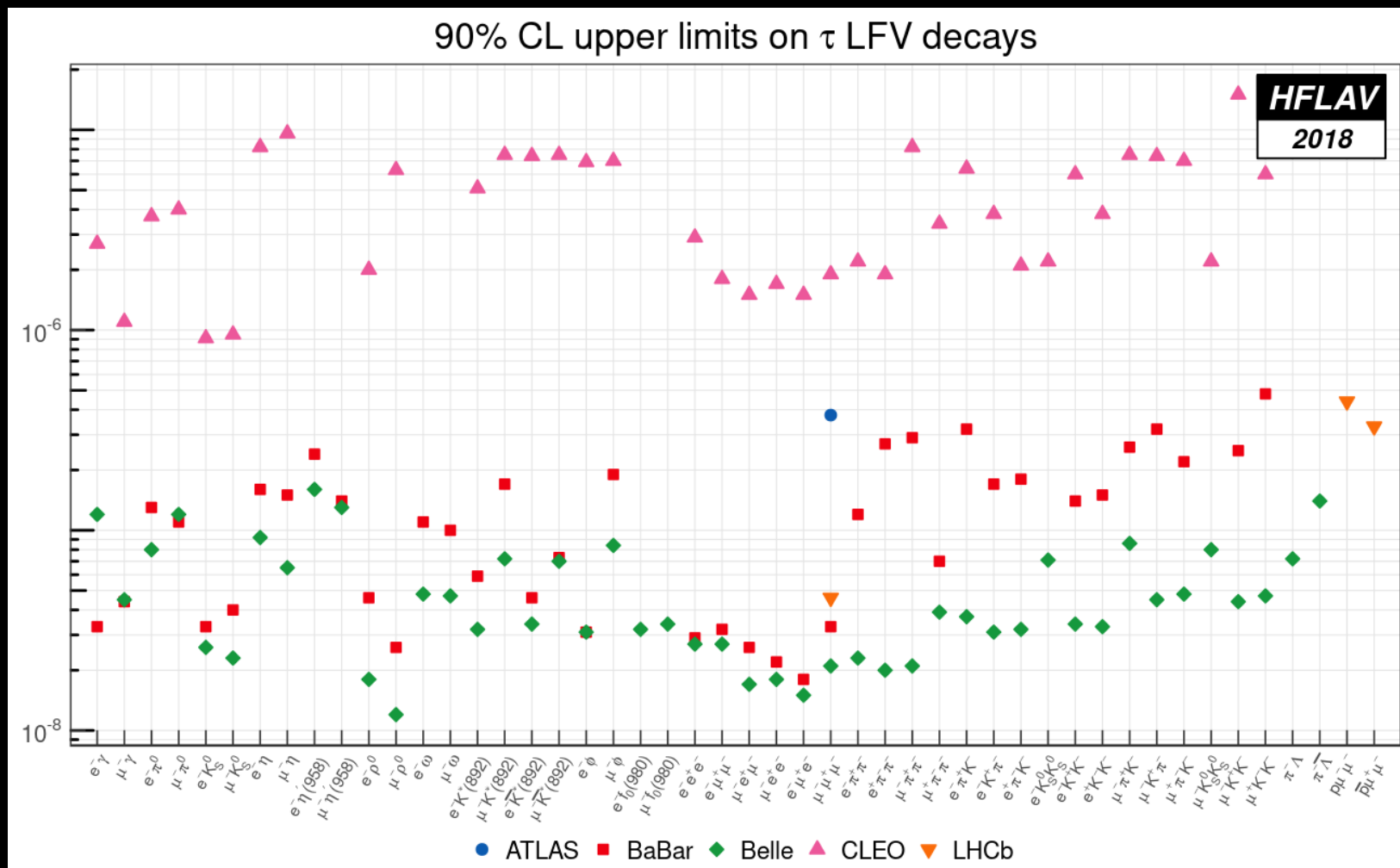


**Latest experimental data from 1999. Time for a new experiment?**

Taus

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# Tau LFV decays



**Wide variety of final states, limits at the level of  $10^{-8} - 10^{-7}$**

# Tau LFV decays

## Belle II at Super KEKB



## LHCb, CMS, ATLAS @ LHC



### Future prospects (representative set):

- $\tau \rightarrow l \gamma$  at level of  $10^{-10}$  -  $10^{-9}$  by Belle II
- $\tau \rightarrow \mu \mu \mu$  at level of  $10^{-10}$  -  $10^{-9}$  by LHCb with  $50 \text{ fb}^{-1}$ .

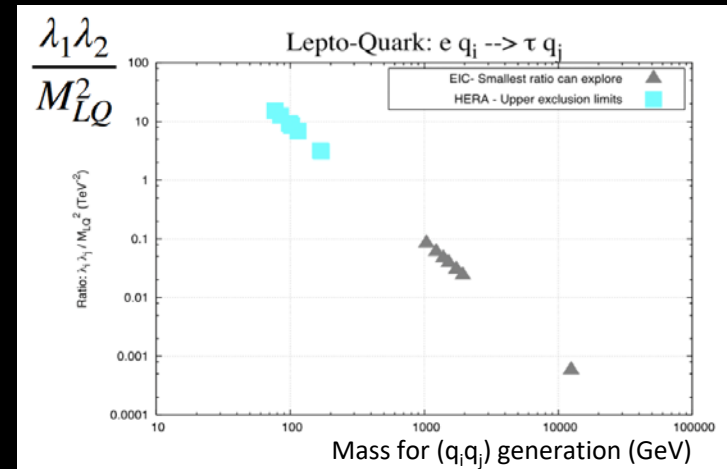
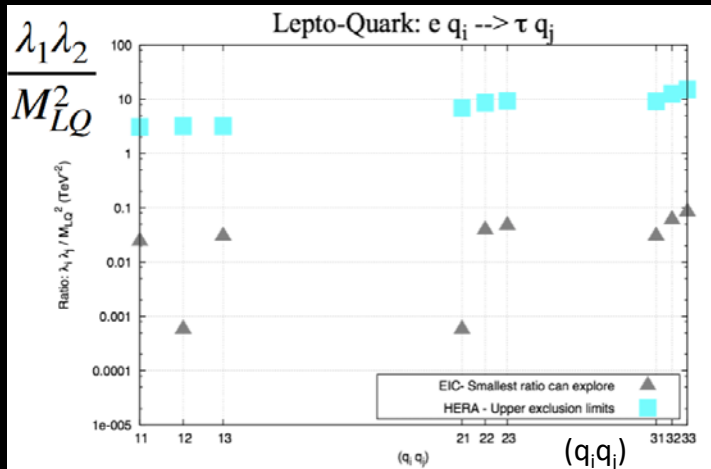
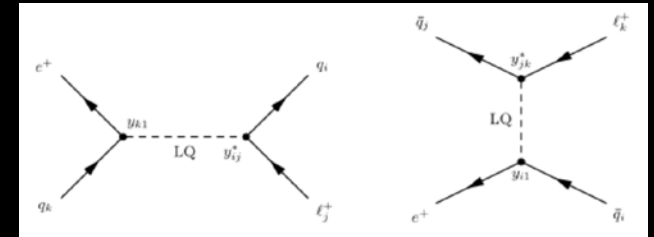
**Possible improvements with polarized beams at  $e^+e^-$  colliders, or with new experimental concepts (e.g. STCF, TauFV,...).**



# Tau transitions

Possibility to study  $e \rightarrow \tau$  transitions at EIC

- Some models predict better sensitivity with heavier leptons
- Benchmark study at EIC with leptoquark model (Gonderinger et al, JHEP (2010) 2010: 45)
- Current limits on leptoquarks set by HERA



Deshpande, Huang, Kumar Zhang, Zhao

Potential to improve sensitivity by two orders of magnitude at EIC

# High-energy probes

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# High-energy probes

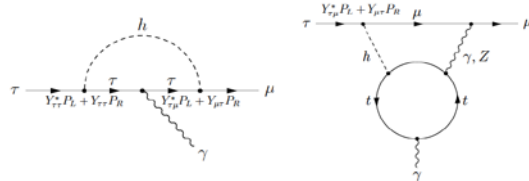
High energy colliders offer complementary way to search for CLFV

## LFV Higgs couplings

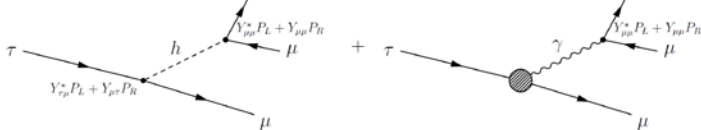
$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

CLFV Higgs decay  $\sqrt{|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2} = \frac{8\pi\Gamma_H(SM)}{m_H} \frac{BR(H \rightarrow \ell\tau)}{1 - BR(H \rightarrow \ell\tau)}$

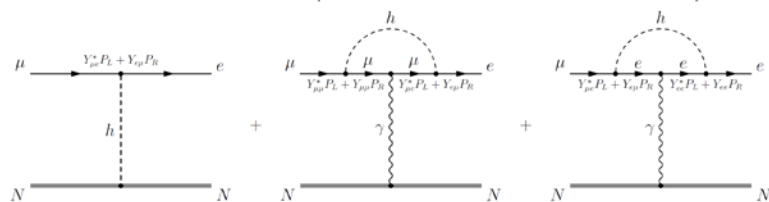
$\tau \rightarrow \mu\gamma$  ( $\mu \rightarrow e\gamma$ )



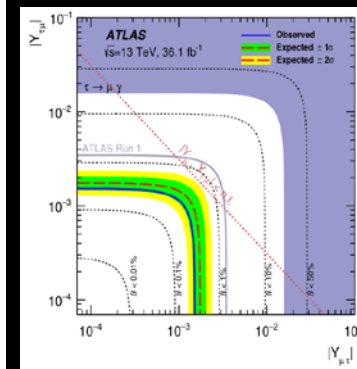
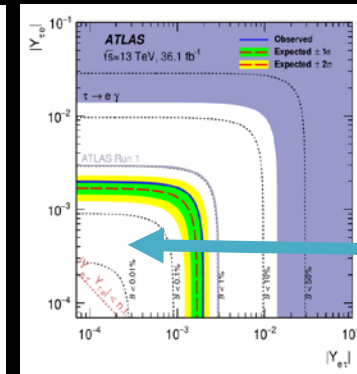
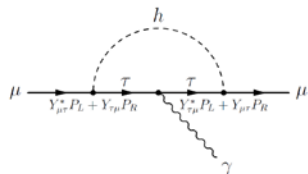
$\tau \rightarrow l'l'l$  ( $\mu \rightarrow eee$ )



$\mu N \rightarrow e N$

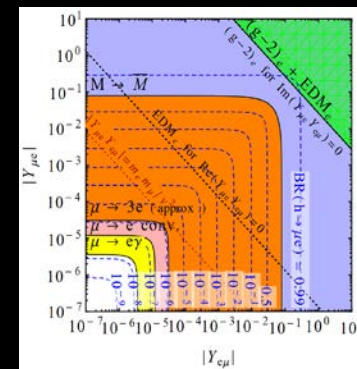


$g-2$



Phys. Lett. B 800 (2020) 135069

Room for discovery



Harnik, Kopp, Zupan 1209.1397

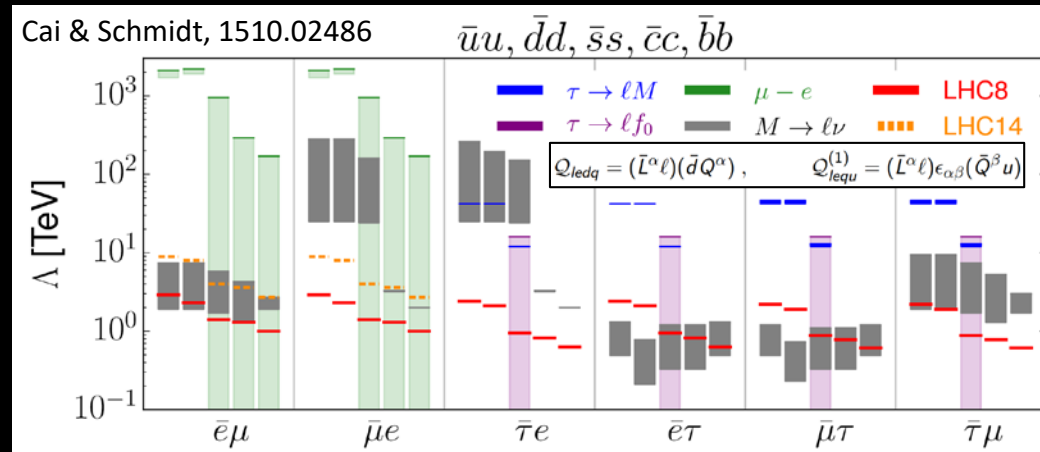
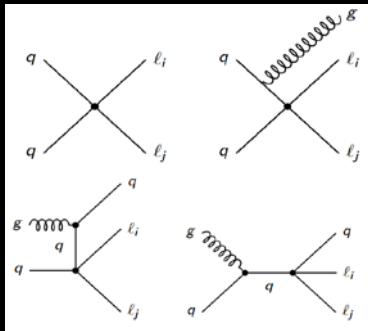
## Competitive bounds for $\tau$ leptons

# High-energy probes

High energy colliders offer complementary way to search for CLFV

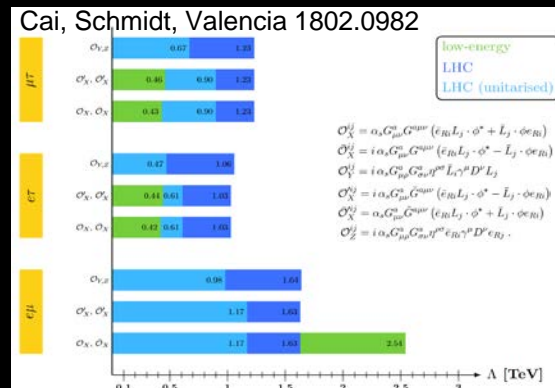
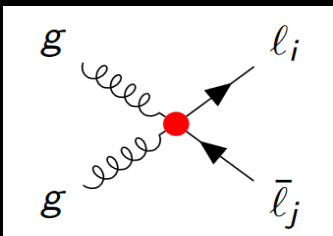
## Quark D6 operators

$$pp \rightarrow l_i l_j + \text{jets}$$



## Gluonic D8 operators

$$pp \rightarrow l_i l_j$$



+ many other possibilities

Better sensitivity to some operators (often heavy leptons)!

Interplay between low- and high-energy probes

Coordinate efforts between CLFV group and high energy frontier

# A few more questions

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A non-exhaustive list of questions and comments to further explore:

- Improve  $\mu \rightarrow e$  conversion calculations: spin-dep rates/precise nuclear models
- Perturbative loop effects are important above 2 GeV for all mu decays. What are strong interactions doing below 2 GeV ?
- Strong interactions in (LFV) tau decay: do we understand them?
- Approaches to measure  $\mu \rightarrow e$  conversion with heavy nuclei ?
- New ideas for  $\mu \rightarrow eee$  and  $\mu \rightarrow e\gamma$  experiments. Can we build a single experiment to look for both final states?
- What about  $e \rightarrow \mu$  or  $\mu \rightarrow \tau$ ? Can they be competitive ?
- What about tau in final state at LHC: heavy decays, collisions,...?
- .....

**Feel free to contribute and tackle some of these questions**

# RF05 organization

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## RF05 topical group structure

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Our topical group will address experimental and theoretical aspects of charged lepton flavor violation:

- Muon and tau LFV reactions ( $\mu \rightarrow e \gamma$ ,  $\mu \rightarrow 3e$ ,  $\mu$ -e conversion, tau decays)
- Muonium-antimuonium oscillations and LFV leptonium decays
- Meson and baryon LFV decays ( $K \rightarrow \pi e \mu$ ,  $B \rightarrow K \tau e$ , ...)
- Decays of heavy states ( $h, t, Z, Z' \dots$ ) and other LFV processes at high-energy colliders
- Light to heavy lepton LFV transitions (EIC, muon beam,...)

Aim to collect and coherently organize studies on these broad set of topics to develop a global picture and a future roadmap.

# Connection with other frontiers / topical groups

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Some topics will overlap with other groups / frontiers (non-exhaustive list)

## RP frontier:

RF1: Weak decays of b and c quarks

RF2: Weak decays of strange and light quarks

RF3: Fundamental physics in small experiments

## Other frontiers:

AF5: Accelerators for PBC and Rare Processes

EF02: EW Physics: Higgs Boson as a portal to new physics (and top,Z)

EF09: BSM physics – more generic explorations

NF03: Neutrino BSM

TF06: Theory for precision

TF08: BSM model building

.....

Unsure where your idea belongs? Don't hesitate to contact us and we'll gladly help you

We have started discussion to understand how to organize cross-group / cross-frontier topics with some of these groups. For all synergistic activities, we plan to follow the relevant developments and organize joint discussions when beneficial.

# CLFV activities

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The CLFV group is organizing a series of  $\sim\frac{1}{2}$  day mini-workshops during the summer to discuss various CLFV processes and explore synergies with other frontiers.

## Upcoming workshops – Thursdays at 10h00am Central Time (each 3 weeks)

- July 2: *Muon transitions and decays, muonium-antimuonium*
- July 23: *Tau decays, electron-tau transitions*
- August 13: *Meson and baryon decays (with RF01)*
- September 3\*: *Heavy states decays (with EF02/09)*
- September 24\*: *CLFV with high intensity muon factory*

These workshops will be followed by shorter meetings during the fall / winter to discuss specific topics.

\*Still tentative, final dates to be confirmed on CLFV TWIKI page / slack channel

# Contacting us

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## **RF05 – CLFV TWIKI page:**

<https://snowmass21.org/rare/clfv>

## **Slack channel:**

rpf-05-clfv

## **Mailing list:**

SNOWMASS-RPF-05-CLFV@FNAL.GOV

## **Convener:**

S. Davidson (s.davidson@lupm.in2p3.fr),  
B. Echenard (echenard@caltech.edu)



# Your input to the process

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## Letters of Interest (submission : April 1, 2020 – August 31, 2020)

- Help conveners to organize activities and encourage the community to study these ideas
- Should contain a brief description and cite the relevant papers to study
- Submission at <https://snowmass21.org/loi>

## Contributed Papers (submission : April 1, 2020 – July 31, 2021)

- Part of the Snowmass proceedings and permanent record of Snowmass 2021
- May include white papers on specific scientific areas, technical articles presenting new results on relevant physics topics, and reasoned expressions of physics priorities, including those related to community involvement.
- Submission instructions: <https://snowmass21.org/submissions/>

## Expression of Interest

- Informal message to conveners to aid us in probing the interest of the community at large, organize future meetings and facilitate connections between people interested in similar studies. Please fill this [google form](#). **Let us know if you plan to do something!**
- Feel free to contact us with ideas or for volunteering to show your work or your ideas

**Please help us to reach out to the community and encourage participation!**

## To conclude

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CLFV provides very sensitive and generic probes of New Physics, and an observation is an unambiguous sign of physics beyond  $\nu$ SM.

The drawback is that CLFV rates tend to be very suppressed, but many models predict rates accessible to the next generation(s) of experiment.

Complementarity is key! CLFV is an important piece of the puzzle, but we need a combination of flavor, low-energy and high-energy measurements to pinpoint the nature of New Physics.

A vigorous experimental program is underway to search for CLFV in many observables, and new ideas have been proposed to further push the boundaries.

## To conclude

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CLFV are very sensitive and generic probes of New Physics, and an observation is an unambiguous sign of physics beyond  $\nu$ SM.

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Complementarity is key! CLFV is an important piece of the puzzle, but we need a combination of flavor, low-energy and high-energy measurements to pinpoint the nature of New Physics.

A vigorous experimental program is underway to search for CLFV in many observables, and new ideas have been proposed to further push the boundaries.

**So join us to define a strong and exciting vision for the future of CLFV.**

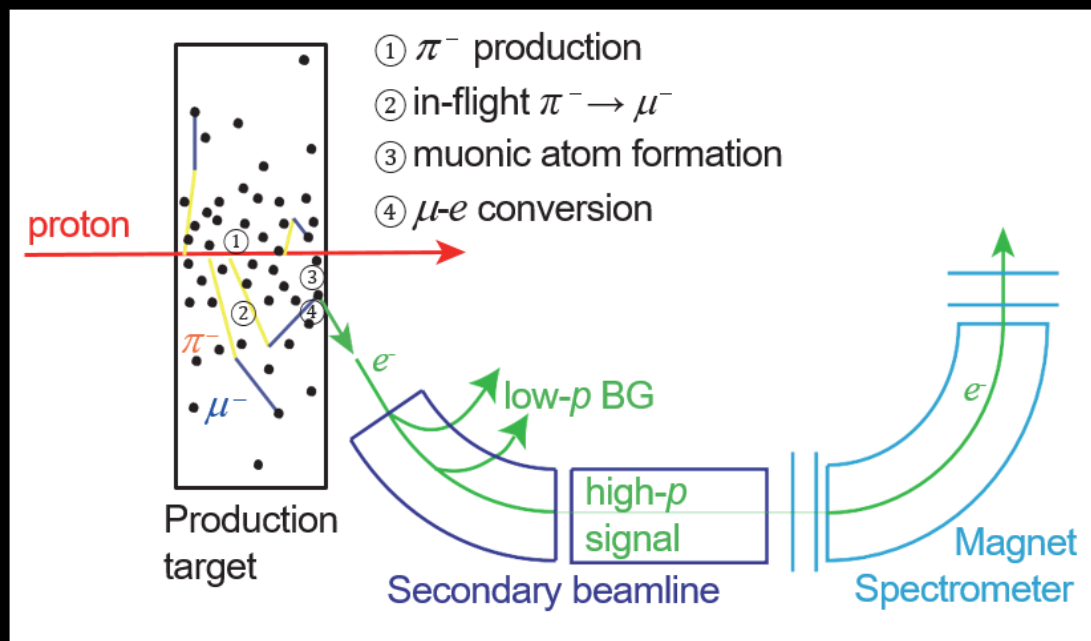
**Additional material**

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# DeeMe experiment

Search for  $\mu \rightarrow e$  conversion with a high power, high purity proton beam at J-PARC

Conversion happens in production target. Initially graphite target, upgrade to SiC



Single event sensitivity with 1 MW beam :

1 year:  $1.2 \times 10^{-13} \rightarrow 2.1 \times 10^{-14}$  upgrade

4 years:  $2.5 \times 10^{-14} \rightarrow 5 \times 10^{-15}$  upgrade

# EFT approach

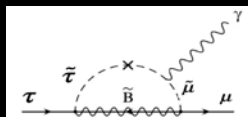
Write all Dim>5 LFV operators

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

- Dipole
- Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector)
- Lepton-gluon (Scalar, Pseudo-scalar)
- 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector)

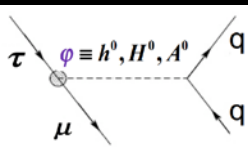
Dipole

$$\mathcal{L}_{eff}^D \supset -\frac{C_D}{\Lambda^2} m_\tau \bar{\mu} \sigma^{\mu\nu} P_{L,R} \tau F_{\mu\nu}$$



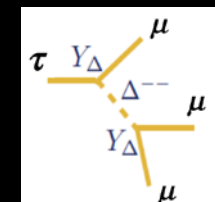
(pseudo)  
Scalar

$$\mathcal{L}_{eff}^S \supset -\frac{C_S}{\Lambda^2} m_\tau m_q G_F \bar{\mu} P_{L,R} \tau \bar{q} q$$



4 leptons

$$\mathcal{L}_{eff}^{4\ell} \supset -\frac{C_{S,V}^{4\ell}}{\Lambda^2} \bar{\mu} \Gamma P_{L,R} \tau \bar{\mu} \Gamma P_{L,R} \mu$$



Tree-level contributions from low-scale operators

	$\tau \rightarrow 3\mu$	$\tau \rightarrow \mu\gamma$	$\tau \rightarrow \mu\pi^+\pi^-$	$\tau \rightarrow \mu K\bar{K}$	$\tau \rightarrow \mu\pi$	$\tau \rightarrow \mu\eta^{(\prime)}$
$O_{S,V}^{4\ell}$	✓	—	—	—	—	—
$O_D$	✓	✓	✓	✓	—	—
$O_V^q$	—	—	✓	✓	—	—
$O_S^q$	—	—	✓	✓	—	—
$O_{GG}$	—	—	✓	✓	—	—
$O_A^q$	—	—	—	—	✓	✓
$O_P^q$	—	—	—	—	✓	✓
$O_{G\tilde{G}}$	—	—	—	—	—	✓

Celis, Cirigliano, Passemar, 1403.5781

Each model generates a specific pattern

Different final states sensitive to  
different operators, no “best probe”

# Selection of current and future sensitivities

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu \gamma$	$\text{BR} < 4.4 \times 10^{-8}$	Belle II, LHC
$\tau \rightarrow \mu \mu \mu$	$\text{BR} < 2.1 \times 10^{-8}$	Belle II, LHC
$\tau \rightarrow e e e$	$\text{BR} < 2.7 \times 10^{-8}$	Belle II, LHC
$K_L \rightarrow e \mu$	$\text{BR} < 4.7 \times 10^{-12}$	NA62
$K \rightarrow \pi e \mu$	$\text{BR} < 5.2 \times 10^{-10}$	NA62
$B^0 \rightarrow e \mu$	$\text{BR} < 2.8 \times 10^{-9}$	LHCb / Belle II
$B^+ \rightarrow K^+ e \mu$	$\text{BR} < 3.8 \times 10^{-8}$	LHCb / Belle II
$H \rightarrow e \mu$	$\text{BR} < 6.1 \times 10^{-5}$	LHC
$H \rightarrow \tau \mu$	$\text{BR} < 2.5 \times 10^{-3}$	LHC
$\mu^+ \rightarrow e^+ \gamma$	$\text{BR} < 4.2 \times 10^{-13}$	MEG II
$\mu^+ \rightarrow e^+ e^+ e^-$	$\text{BR} < 1.0 \times 10^{-12}$	Mu3e
$\mu N \rightarrow e N$	$R_{\mu e} < 7.0 \times 10^{-13}$	Mu2e, COMET

New physics effects could be larger for taus than muons, but colliders produce  $O(10^{10})$   $\tau$ /year, while dedicated muon experiments can produce  $O(10^{10})$   $\mu$ /s.

High energy collider can test more Lorentz structure and are better at probing some operators