Connecting Low- and High-Energy Observables at Future Colliders

Invisibles25, Sep 1 – 5, CERN

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Based on [25xx.xxxxx] with [1]R.Bartocci, [2,3]D.Pagani, [4,5]P.Paradisi

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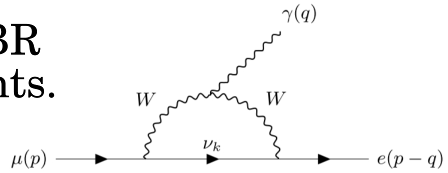
Charged Lepton Flavor Violation (CLFV)

The **minimality** of SM
with massless neutrinos
implies the **conservation**
of lepton flavor among families.

If SM neutrinos are massive:
GIM mechanism → **much smaller** BR
than sensitivity of present experiments.

$$Br(\mu \to e\gamma) \sim \frac{3\alpha}{32\pi}\frac{m_\nu^4}{M_W^4} \sim 10^{-55}$$



FUTURE CIRCULAR COLLIDER

New generation of particle accelerators
at **higher energy** and **intensities**
would improve the sensitivity
on small deviations to the SM.

International MUON Collider Collaboration

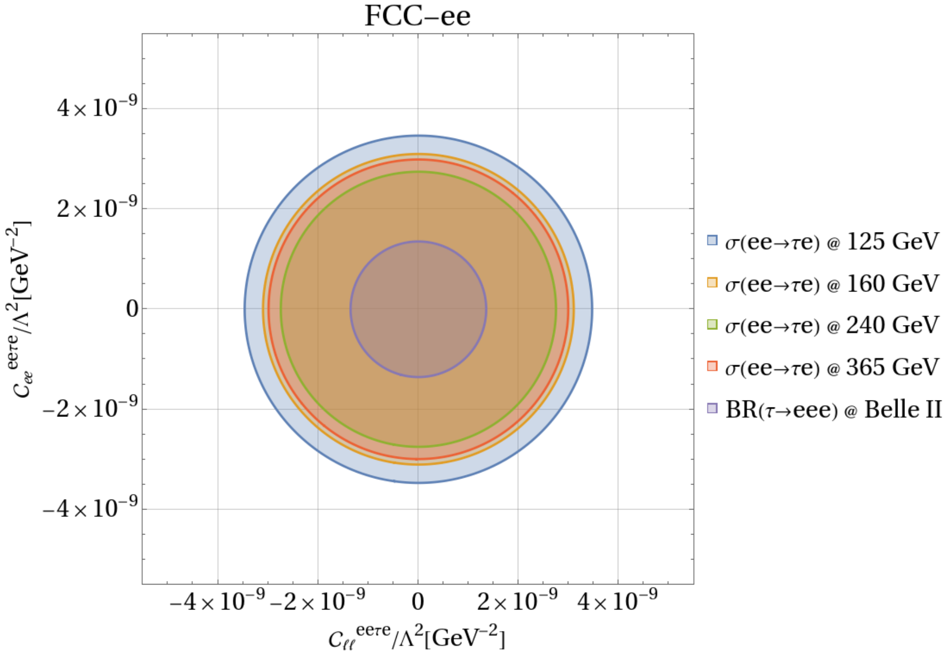
Current CLFV bounds point towards a high NP scale $\Lambda_{LFV} \gg M_W$.
→ SM effective field theory (SMEFT) as a low-energy limit of
an unknown UV completion:

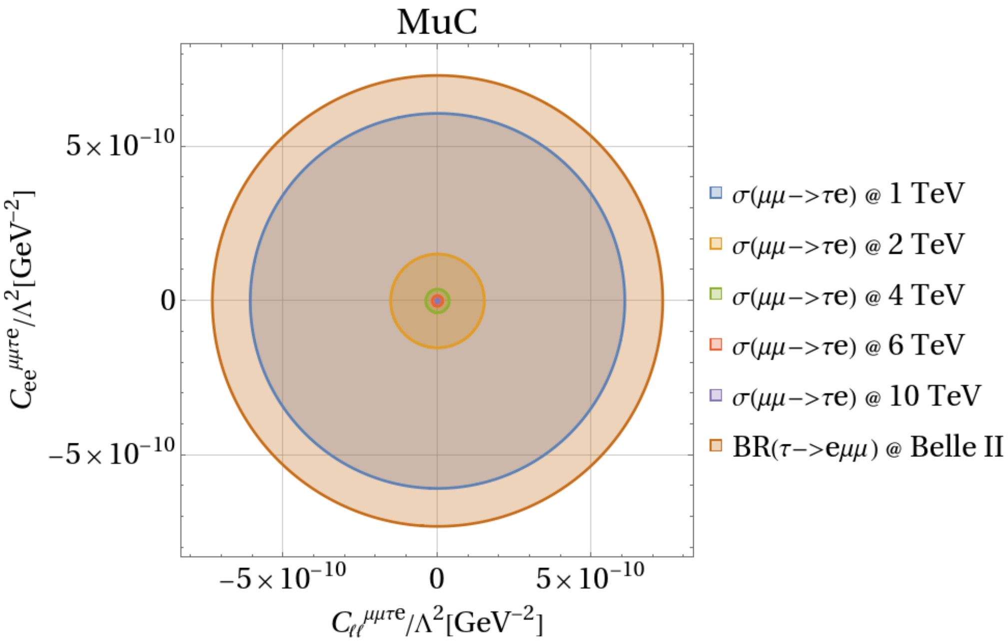
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

G. Bernardi et al., "The Future Circular Collider: a Summary for the US 2021 Snowmass Process"
C. Accettura et al. "Interim report for the International Muon Collider Collaboration (IMCC)"

Bounds on SMEFT: Scattering

$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$ vs $(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$





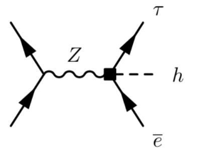
Non unitarity energy scaling of the 4-fermion cross section:

- not enough energy at FCC-ee to reach the Belle-II projections,
- MuC constrain better than Belle-II slightly above 1 TeV.

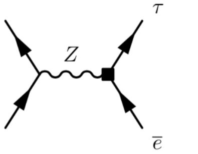
Lorenzo Calibbi, Xabier Marcano, and Joydeep Roy., "Z lepton flavour violation as a probe for new physics at future e+e− colliders."

Multi-Leg Final States: Higgs Emission

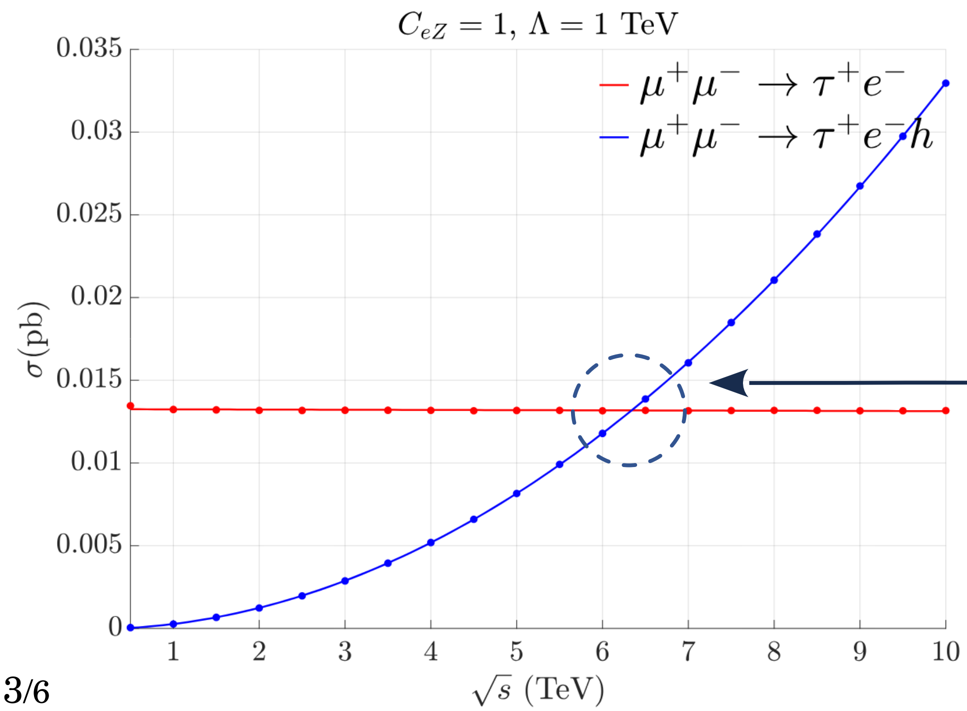
Insertion of the Higgs as **VEV** or **dynamical field** modifies the **energy scaling** of the cross sections.
A new window on NP may open at **extreme high-energies** provided by the clean environment of muonic collisions (MuC).



$$\Rightarrow \quad \sigma \sim \frac{|C_{eZ}^{\tau e}|^2}{\Lambda^4}\frac{g^2}{c_w^2}\boldsymbol{s}$$



$$\Rightarrow \quad \sigma \sim \frac{|C_{eZ}^{\tau e}|^2}{\Lambda^4}\frac{g^2 v^2}{c_w^2}$$



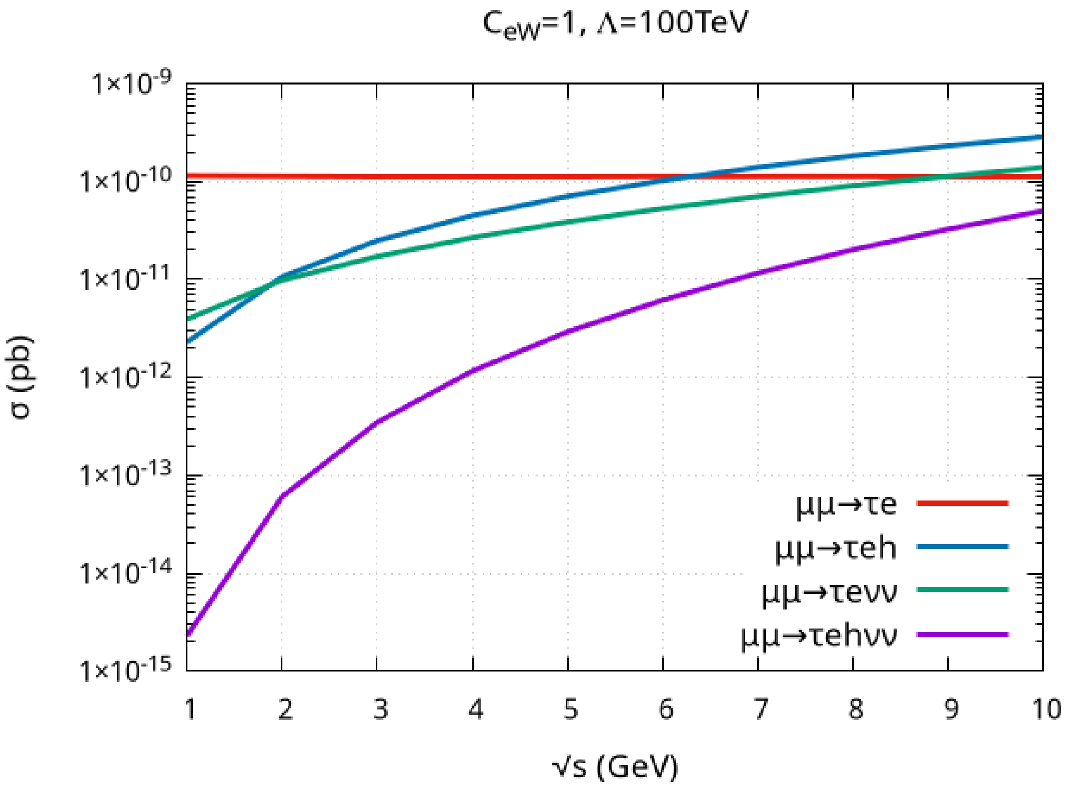
C_{eZ}: the modified scaling from Higgs emission generate a greater cross section above **6 TeV**.

The sensitivity is comparable to that resulting from the Z decays in a MuC.

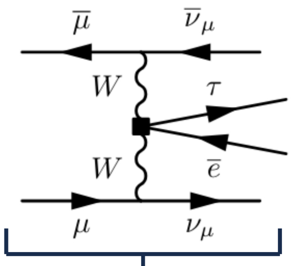
$$N_{\tau e h} = 132942\frac{|C_{eZ}|^2}{\Lambda^4}\,\mathrm{TeV}^4 \qquad N_{Z\text{-decay}} = 500993\frac{|C_{eZ}|^2}{\Lambda^4}\,\mathrm{TeV}^4$$

Multi-Leg Final States: VBF

Z dipole operator, O_{eZ}, written in the SM broken phase where Z_μ and A_μ are linear combination of $W_\mu^{(3)}$ and B_μ.
The **same** happens for the **Wilson** coefficients C_{eZ} and $C_{e\gamma}$.



O_{eW}:



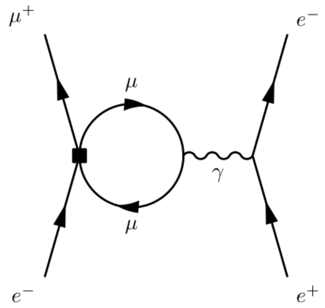
$$m_{\tau e} \sim v \frac{|C_{eW}^{\tau e}|}{\Lambda^2} \hat{s}$$

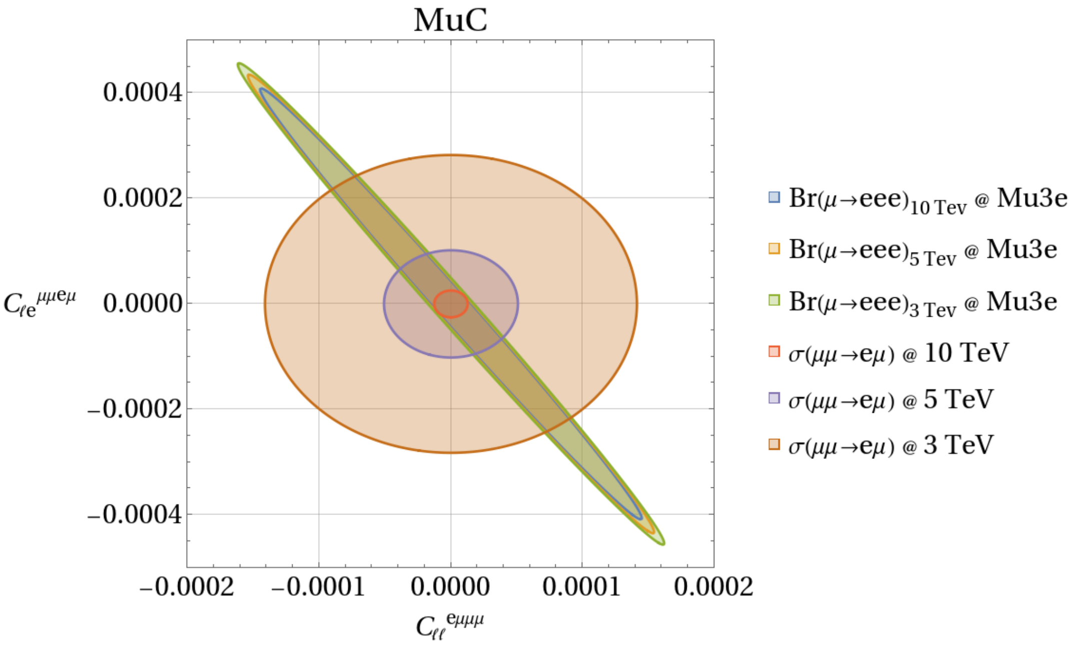
Non-abelianity of SU(2): effective contact interaction in the **subprocess** between two W bosons and charged leptons.

Loop Effects

$\mu\mu \to \mu e$ generated at high-energy by 4-fermion operators.
The corresponding decay $\mu \to \mu\mu e$ however is **forbidden** by kinematics.

Wilson coefficients entering the cross section may contribute to a **different decay**, such as $\mu \to eee$.





$$\sigma(\mu\mu \to e\mu) = \frac{s}{12\pi\Lambda^4}\left(4|C_{\ell\ell}^{e\mu\mu\mu}|^2 + 4|C_{ee}^{e\mu\mu\mu}|^2 + |C_{\ell e}^{e\mu\mu\mu}|^2 + |C_{\ell e}^{\mu\mu e\mu}|^2\right)$$

$$Br(\mu \to eee) = \frac{1}{16G_F^2\Lambda^4}\left(4|C_{\ell\ell}^{eee\mu}|^2 + 4|C_{ee}^{eee\mu}|^2 + |C_{\ell e}^{eee\mu}|^2 + |C_{\ell e}^{e\mu ee}|^2\right)$$

If only one coefficient (C_{ll}) is active, probing TeV scales is **equivalent** to reach a sensitivity of:

$$Br(\mu \to 3e) \sim 10^{-14} \ \text{at} \ \sqrt{s} \sim \text{TeV}\,,$$

$$Br(\mu \to 3e) \sim 10^{-18} \ \text{at} \ \sqrt{s} \sim 10\,\text{TeV}\,.$$

Conclusions & Outlooks

- CLFV in the SM is extremely suppressed → any experimental signal would be an anambiguos sign of new physics.
- Heavy new physics effects are conveniently described by the SMEFT.
- Future colliders would improve the limits on the SMEFT coefficients w.r.t. low energy experiments.

- RGE effects may improve constraints from other tree-level processes,
- Detailed analysis for SM-VBF background in progress.

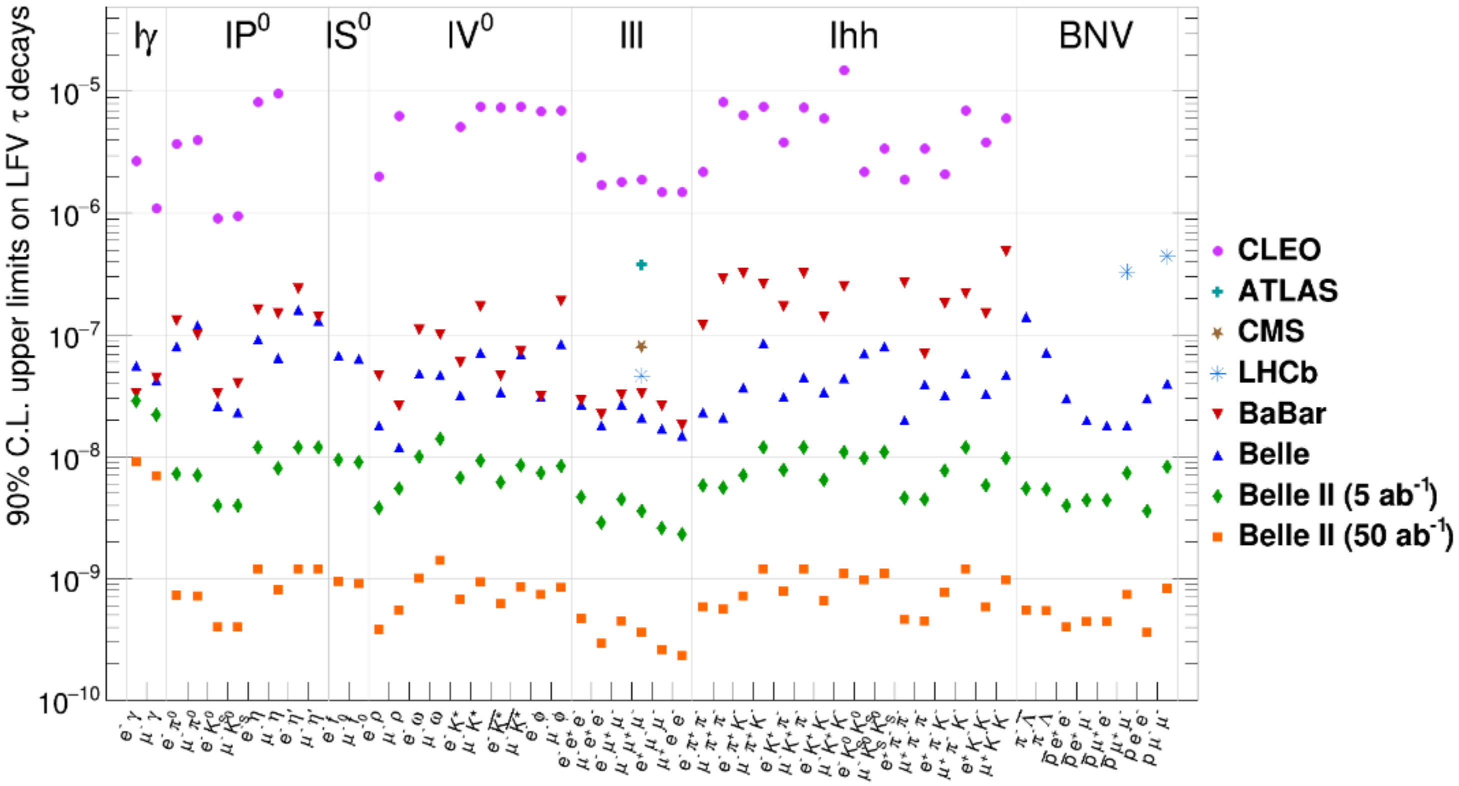
Back-up Slides

Current Bounds From Experiments

cLFV obs.	Present upper bounds (90% CL)	
$\mathrm{BR}(\mu \to e\gamma)$	3.1×10^{-13}	MEG II (2023)
$\mathrm{BR}(\mu \to eee)$	1.0×10^{-12}	SINDRUM (1988)
$\mathrm{CR}(\mu \to e, \mathrm{S})$	7.0×10^{-11}	Badertscher *et al.* (1982)
$\mathrm{CR}(\mu \to e, \mathrm{Ti})$	4.3×10^{-12}	SINDRUM II (1993)
$\mathrm{CR}(\mu \to e, \mathrm{Pb})$	4.6×10^{-11}	SINDRUM II (1996)
$\mathrm{CR}(\mu \to e, \mathrm{Au})$	7.0×10^{-13}	SINDRUM II (2006)
$\mathrm{BR}(\pi^0 \to \mu^- e^+)$	3.2×10^{-10}	NA62 (2021)
$\mathrm{BR}(\pi^0 \to \mu^+ e^-)$	3.8×10^{-10}	E865 (2000)
$\mathrm{BR}(\pi^0 \to \mu e)$	3.6×10^{-10}	KTeV (2007)
$\mathrm{BR}(\eta \to \mu e)$	6.0×10^{-6}	Saturne SPES2 (1996)
$\mathrm{BR}(\eta' \to \mu e)$	4.7×10^{-4}	CLEO (2000)
$\mathrm{BR}(\phi \to \mu e)$	2.0×10^{-6}	SND (2009)
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8}	BaBar (2010)
$\mathrm{BR}(\tau \to ee\bar{e})$	2.7×10^{-8}	Belle (2010)
$\mathrm{BR}(\tau \to e\mu\bar{\mu})$	2.7×10^{-8}	Belle (2010)
$\mathrm{BR}(\tau \to e\pi)$	8.0×10^{-8}	Belle (2007)
$\mathrm{BR}(\tau \to e\eta)$	9.2×10^{-8}	Belle (2007)
$\mathrm{BR}(\tau \to e\eta')$	1.6×10^{-7}	Belle (2007)
$\mathrm{BR}(\tau \to e\pi\pi)$	2.3×10^{-8}	Belle (2012)
$\mathrm{BR}(\tau \to e\omega)$	2.4×10^{-8}	Belle (2023)
$\mathrm{BR}(\tau \to e\phi)$	2.0×10^{-8}	Belle (2023)
$\mathrm{BR}(\tau \to \mu\gamma)$	4.2×10^{-8}	Belle (2021)
$\mathrm{BR}(\tau \to \mu\mu\bar{\mu})$	2.1×10^{-8}	Belle (2010)
$\mathrm{BR}(\tau \to \mu e\bar{e})$	1.8×10^{-8}	Belle (2010)
$\mathrm{BR}(\tau \to \mu\pi)$	1.1×10^{-7}	BaBar (2006)
$\mathrm{BR}(\tau \to \mu\eta)$	6.5×10^{-8}	Belle (2007)
$\mathrm{BR}(\tau \to \mu\eta')$	1.3×10^{-7}	Belle (2007)
$\mathrm{BR}(\tau \to \mu\pi\pi)$	2.1×10^{-8}	Belle (2012)
$\mathrm{BR}(\tau \to \mu\omega)$	3.9×10^{-8}	Belle (2023)
$\mathrm{BR}(\tau \to \mu\phi)$	2.3×10^{-8}	Belle (2023)
$\mathrm{BR}(\tau \to ee\bar{\mu})$	1.5×10^{-8}	Belle (2010)
$\mathrm{BR}(\tau \to \mu\mu\bar{e})$	1.7×10^{-8}	Belle (2010)

Ardu, Marco and Pezzullo, Gianantonio, "Introduction to Charged Lepton Flavor Violation"

Belle II Projections: τ Decays



CLFV Operators in SMEFT

- $e^+e^- \to \mu\tau$,
- $\mu^+\mu^- \to \mu e$,
- $\mu^- \to eee$, … .

4-leptons operators	
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$

Dipole operators	
Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$

- $\mu^- \to e^-\gamma$,
- $\tau^- \to e^-\gamma$,
- $\tau^- \to \mu^-\gamma$.

2-lepton 2-quark operators			
$Q^{(1)}_{\ell q}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$

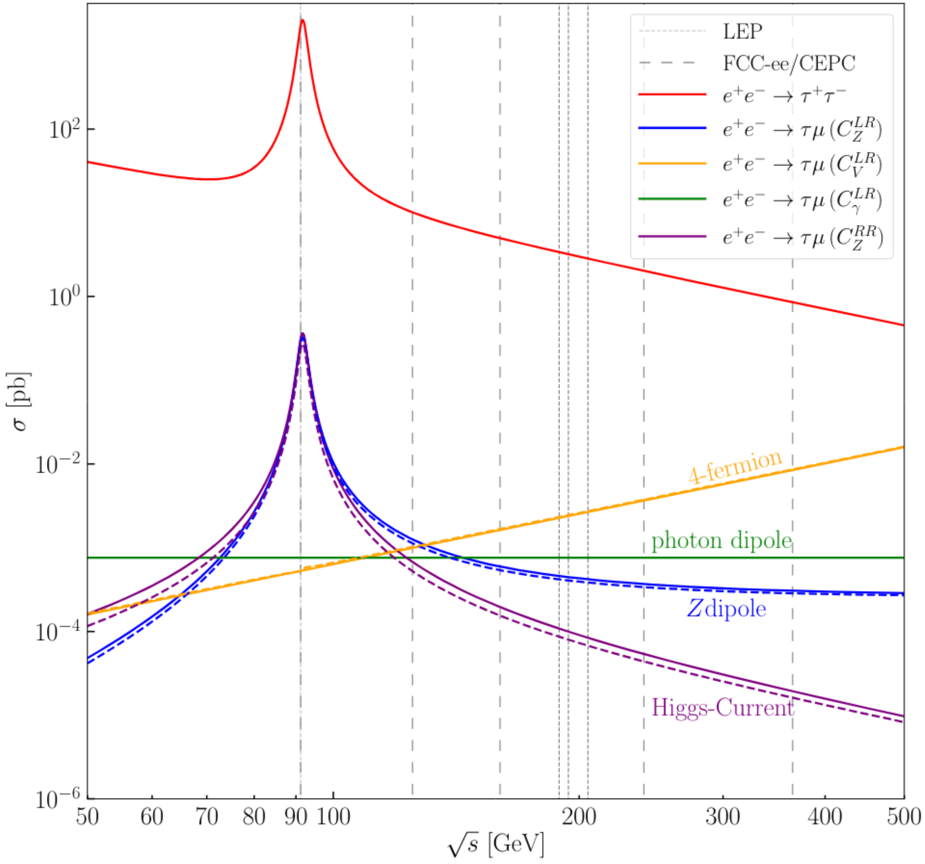
- $\mu^-N \to e^-N$,
- $pp \to l_i l_k$,
- $B \to \pi e\mu$,
- $B \to K\mu\tau$, … .

Lepton-Higgs operators			
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

- $h \to \tau\mu$,
- $Z \to \tau\mu$,
- $e^+e^- \to e\tau$,
- $\tau^- \to \mu ee$, … .

Crivellin, A. and Najjari, S. and Rosiek, J., "Lepton flavor violation in the Standard Model with general dimension-six operators"

Dependence On The CoM Energy

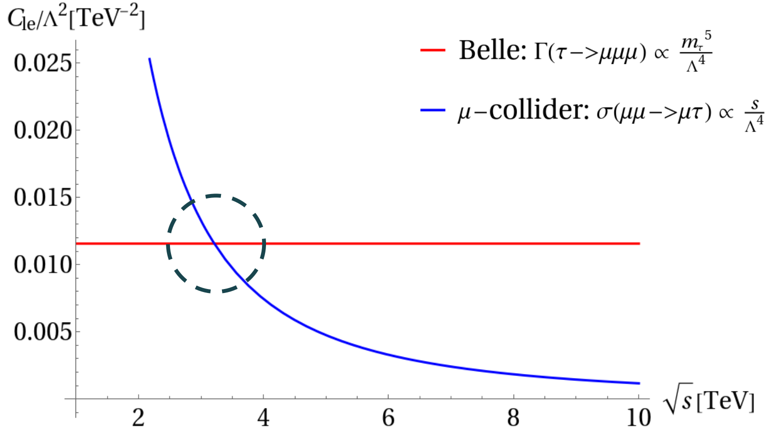


[2305.03869] Wolfgang Altmannshofer et al. :
cross section of the process $e^+e^- \to \tau\mu$ as function of the center of mass energy with NP scale set at $\Lambda = 3$ TeV and the Wilson coefficients set to 1.

Low/High Energy Interplay

Combination of limits from different processes
in the SMEFT framework.

There is a crossing point where observables dominate in one energy range over the other:

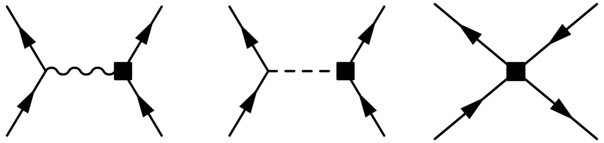


Example of interplay between Belle measurements and the predictions for a muon collider in the case of 4-fermion operators.

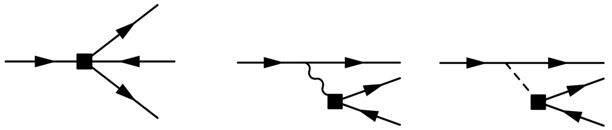
The greater the energy, the stronger is the upper bound derived from scattering events.

CLFV effects in τ decays are much **less constrained** than in μ decays.

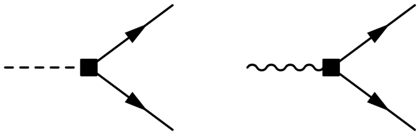
$ee \to e\tau$:
($Z/\gamma/h$/4f)



$\tau \to eee$:
($Z/\gamma/h$/4f)



$h \to \tau e$, $Z \to \tau e$:



CLFV Signal & Background

Signal

- $e^+e^- \to \tau^+e^-$
- $e^+e^- \to Z^* \to \tau^+e^-$

Background

- $e^+e^- \to Z^*\gamma^* \to \tau\tau \to \tau_{had.}e\nu\nu$
- $e^+e^- \to W^*W^* / Z^*Z^* \to \tau_{had.}e\nu\nu$

Analysis inspired by Wolfgang Altmannshofer et al., "Probing Lepton Flavor Violation at Circular Electron-Positron Colliders"

Mogens Dam,"Tau-lepton Physics at the FCC-ee circular e+e- Collider"

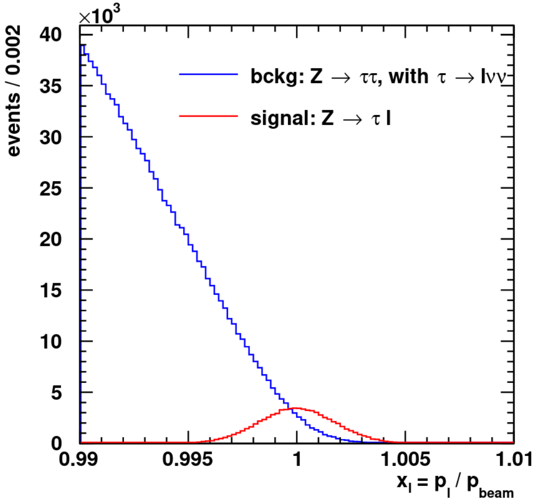
Achieve sensitivity at the 95% C.L. in future colliders:

$$N_{\rm sig} \geq 2\sqrt{N_{\rm bkg} + N_{\rm sig}}$$

Dominant background from the Z decays nearby the Z resonance.

Cut on the electron momentum to select the correct signal:

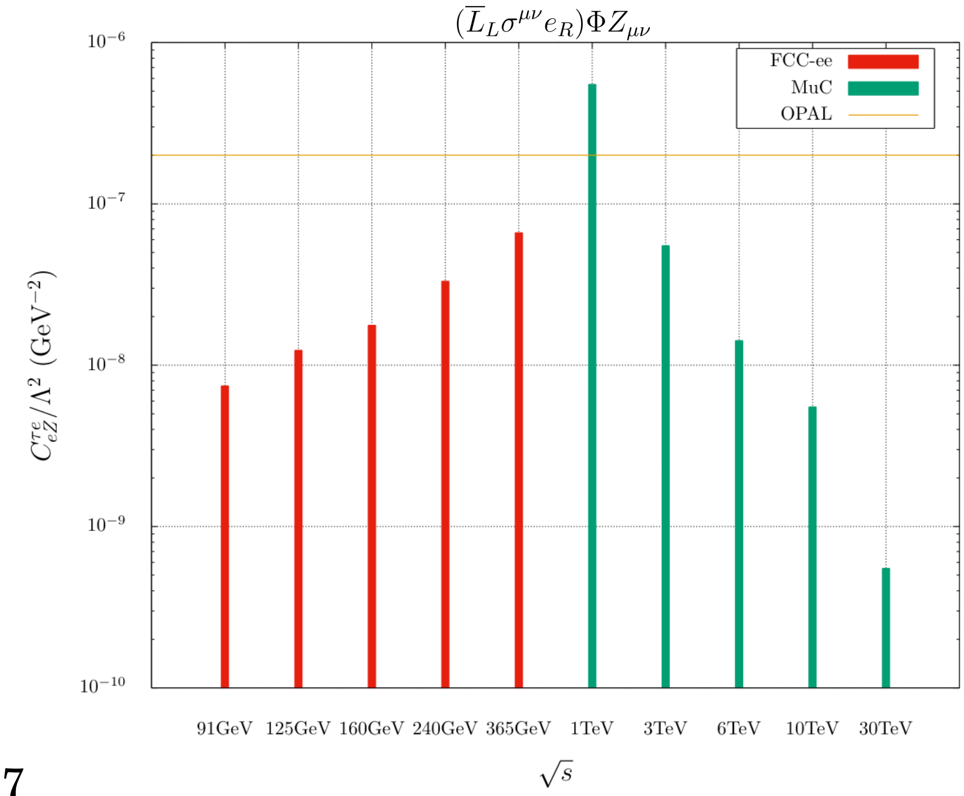
$$\frac{p_e}{p_{beam}} \gtrsim 1$$

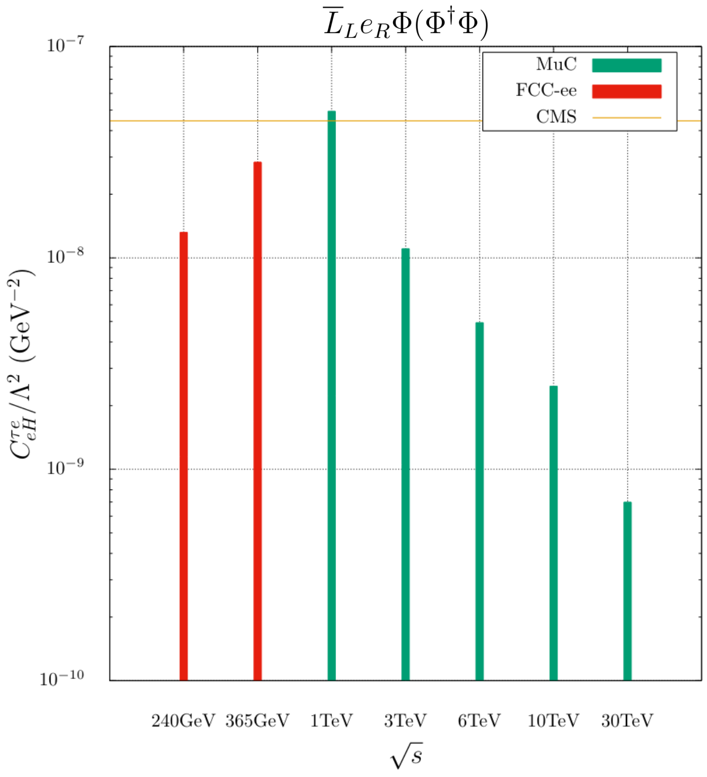


Momentum distribution of the final state lepton l for the signal and for the background from $Z \to \tau\tau$

Bounds on SMEFT: Decays

Strong bounds on CLFV from low-energy **radiative** decays: BR($\mu \to e\gamma$), BR($\tau \to e\gamma$), BR($\tau \to \mu\gamma$).
Loose bounds on Z and h **decays** in τ, l → improvement at future colliders.

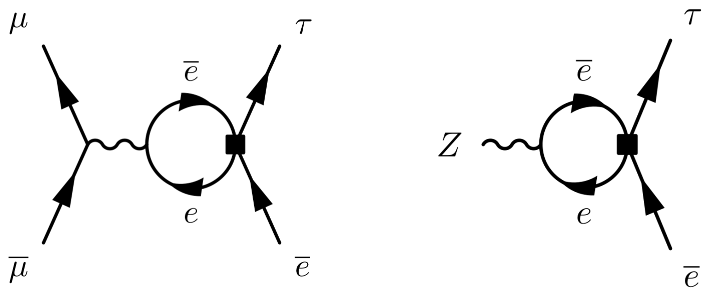




RGE effects

Complementarity between colliders.

A better probe for 4-fermion coefficients of FCC-ee?



Tree-level in one collider, loop-induced on the other.

MuC able to probe better C_{ll} and C_{ee} than FCC-ee and the future projections of Belle II.