CONNECTING LOW- AND HIGH-ENERGY OBSERVABLES AT FUTURE COLLIDERS

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Work in progress with
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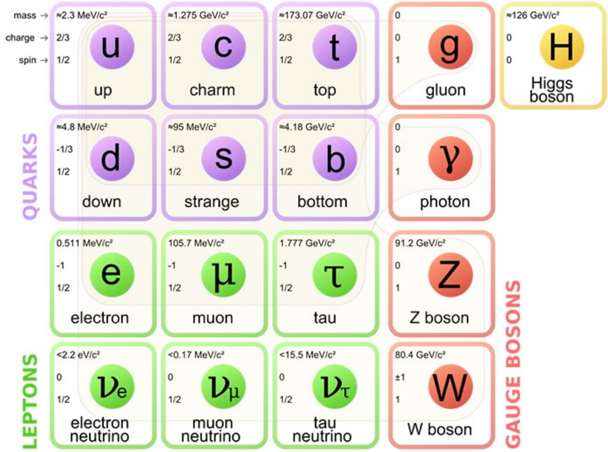
Standard Model

Standard Model (SM) of Particle Physics



Experimental reasons for NP:

- Neutrino masses
- Baryon asymmetry
- Dark matter

Theoretical reasons for NP:

- Hierarchy problem
- Strong CP problem
- Flavor puzzle
- Gravity

NP scenarios:

- 2-Higgs-Doublet
- SUSY
- Heavy Neutrinos
- Leptoquarks
- …

Future Colliders

New physics searches in collider experiments (like LHC), **absence** of signal suggests the possibility of **heavy** new physics well above the electroweak scale.

FUTURE CIRCULAR COLLIDER

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

International MUON Collider Collaboration

FCC-ee:

- e^+e^- collider, $E_{cm} \sim$ 80-400 GeV
- Higgs and EW factory
- Precision measurements

IMCC:

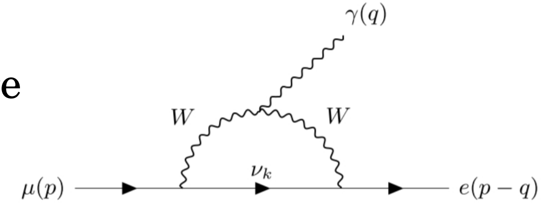
- μ collider
- Small synchrotron radiation
- $E_{cm} \sim$ 3-10 TeV

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)"

Charged Lepton Flavor Violation (CLFV)

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

If SM neutrinos are
massive



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

GIM mechanism → **much smaller** BR
than sensitivity of current experiments

Experimental observation
of CLFV **unambiguous**
sign of SM extensions

Decay/low-energy searches:

- $\mu^- \to e^-\gamma$ (MEG II), ...
- $\tau^- \to e^-e^+e^-$ (Belle II), ...
- $\mu^- N \to e^- N$ (COMET, Mu2e)

Current CLFV bounds point towards a high NP scale
$\Lambda_{LFV} \gg M_W$

Effective Field Theories & SMEFT

EFT:

Model independent way to parametrize the effects of heavy new physics

Heavy fields live at a scale Λ_{LFV} much higher than current experiments energies

In a bottom-up approach, infinite tower of higher dimensional operators:

- built from SM fields
- satisfy SM symmetries

$$\mathcal{L}_{EFT} = \mathcal{L}_{d=4} + \sum_{d>4} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

SM as a low-energy limit of an unknown UV completion

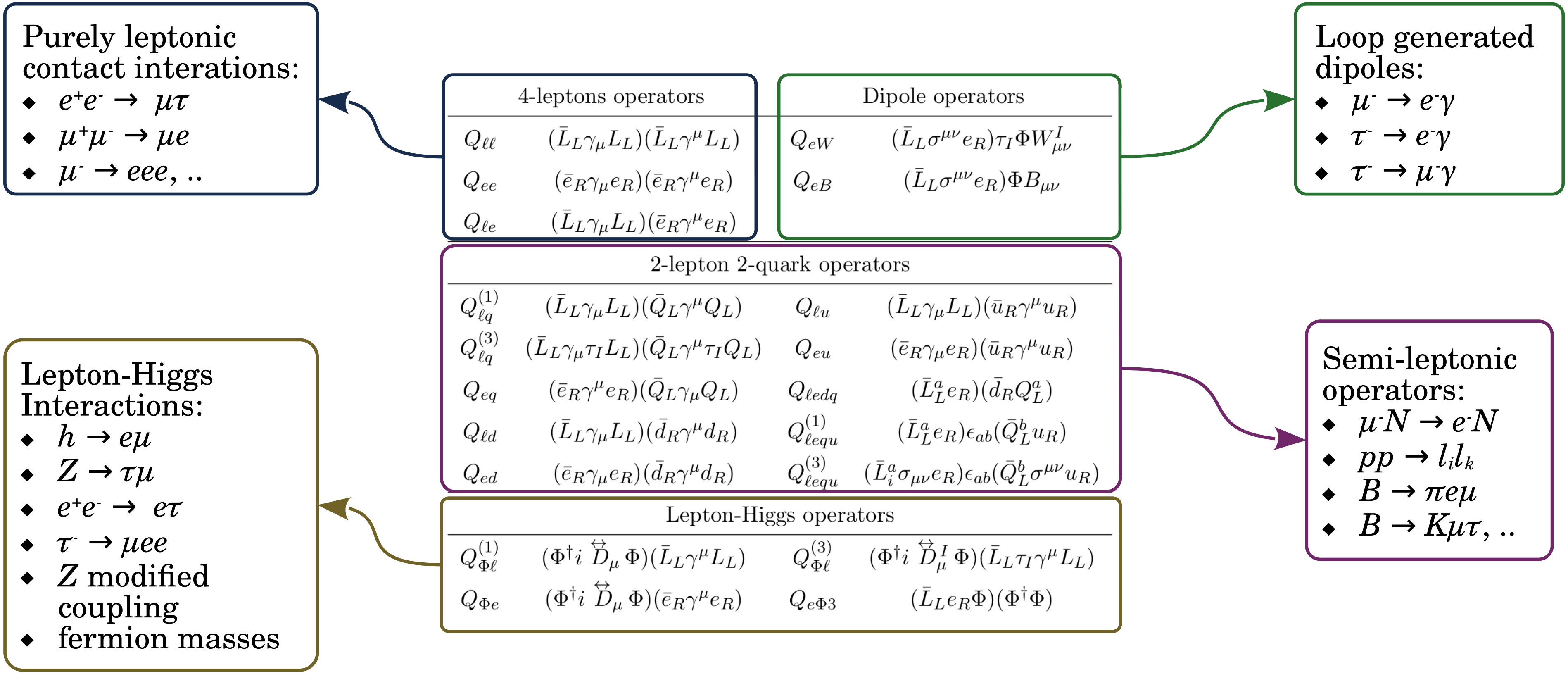
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2} \sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

A lonely dim-5 operator, Weinberg operator

A plethora of dim-6 operators (2499) giving rise to several FCNC processes

Focusing on CLFV, the analysis reduces to consider 4 operator classes

CLFV Operators in SMEFT



Purely leptonic contact interations:

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

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}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$

Loop generated dipoles:

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

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}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$

Semi-leptonic operators:

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

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

Lepton-Higgs Interactions:

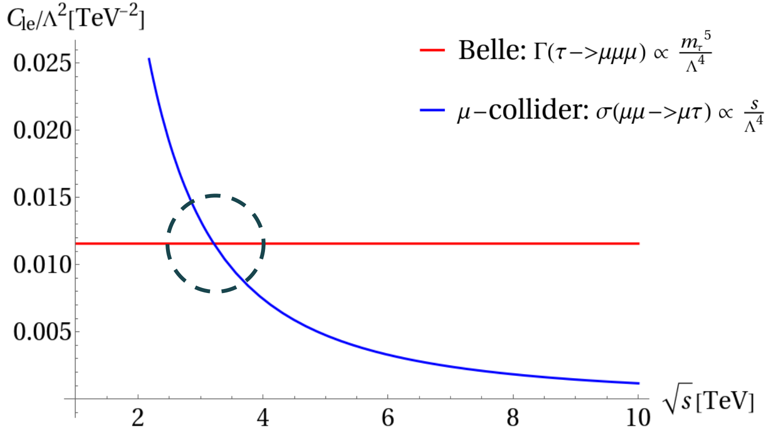
- $h \to e\mu$
- $Z \to \tau\mu$
- $e^+e^- \to e\tau$
- $\tau^- \to \mu ee$
- Z modified coupling
- fermion masses

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

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

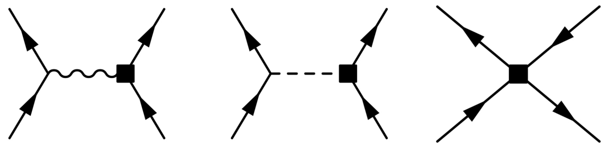


Example of interplay between Belle measurements and the predictions for a muon collider in the case of 4-fermion operators

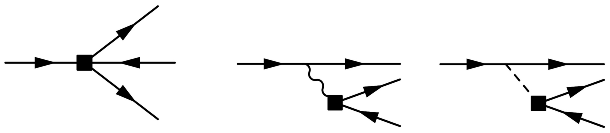
The greater the energy, the stronger is the upper bound derived from scattering events

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

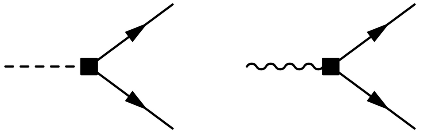
$ee \to e\tau$:
(Z/γ/h/contact)



$\tau \to eee$:
(Z/γ/h/contact)



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



CLFV Signal & Background

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

Signal

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

Background

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

Future colliders sensitivity at 95% C.L. by

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

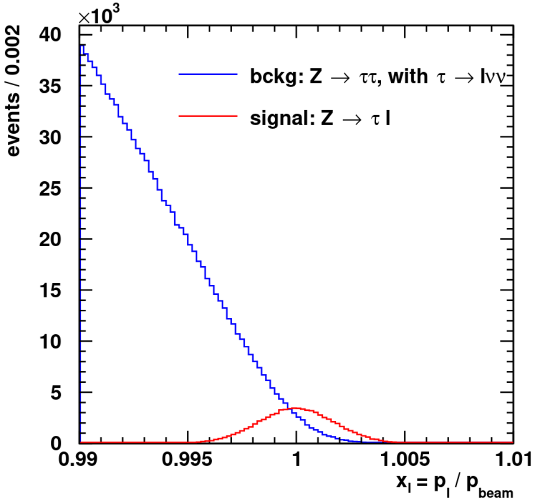
Dominant background from the Z decays nearby the Z resonance

Cut on the electron momentum to select the correct signal

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

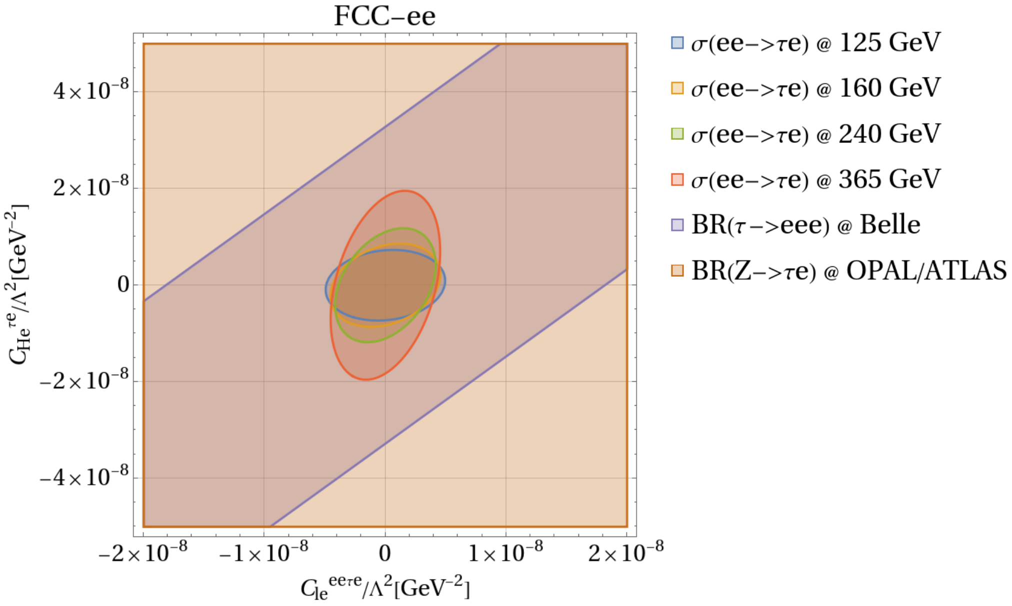
Decay channels like $\tau \to 3e$ are background free

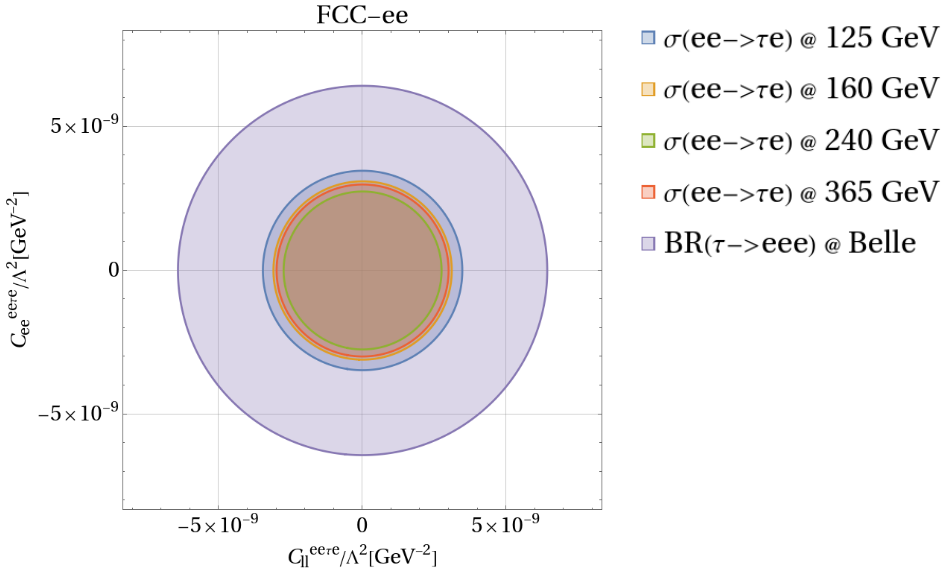
Mogens Dam,"Tau-lepton Physics at the FCC-ee circular e+e- Collider"



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

Parameter Space Constraints





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

vs

$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_R\gamma^\mu e_R)$

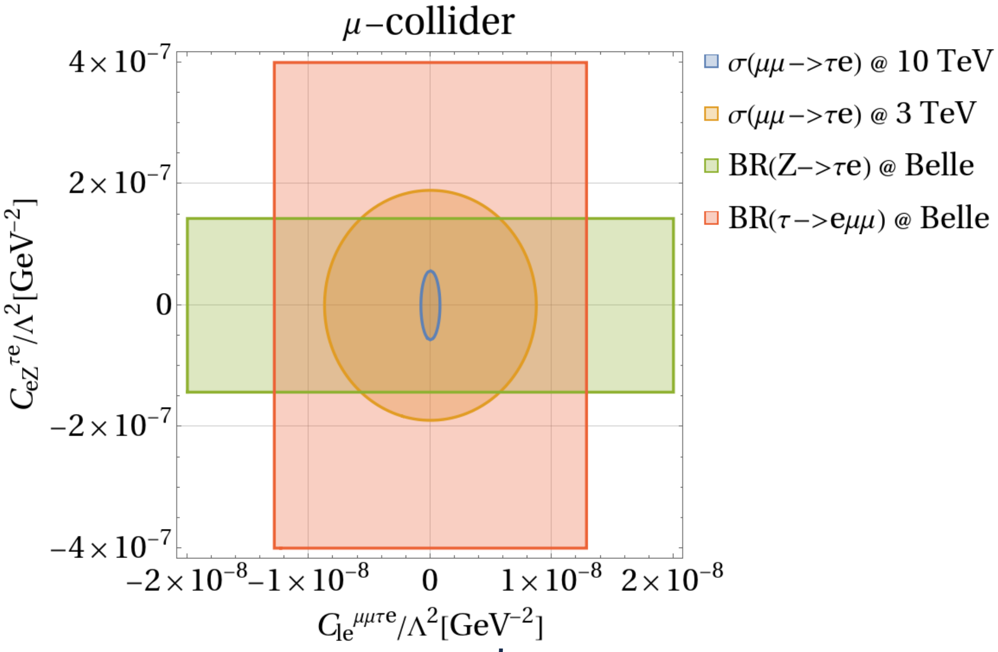
FCC-ee constraints in the parameter space with two operators switched on showing the **competitiveness** of future colliders with respect to low energy measurements of Belle, OPAL and ATLAS.

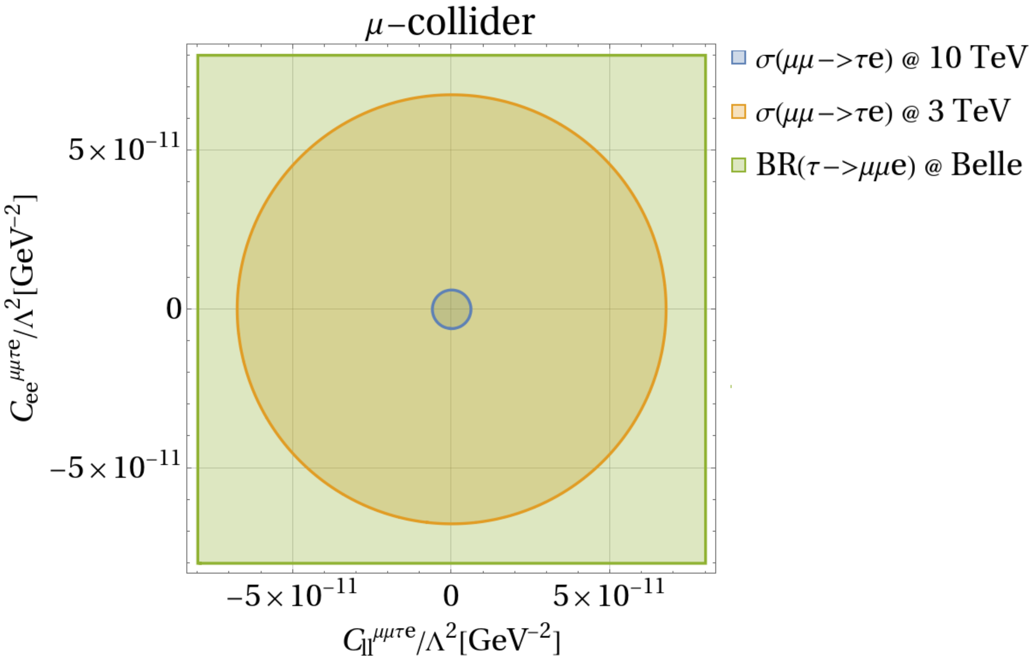
$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$

vs

$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$

Parameter Space Constraints





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

vs

$(\bar{L}_L\sigma_{\mu\nu}e_R)Z^{\mu\nu}$

Signal: $\mu^+\mu^- \to \tau e$

μ-collider predictions in the parameter space, essentially background free, showing the competitiveness with low-energy experiments.

$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$

vs

$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$

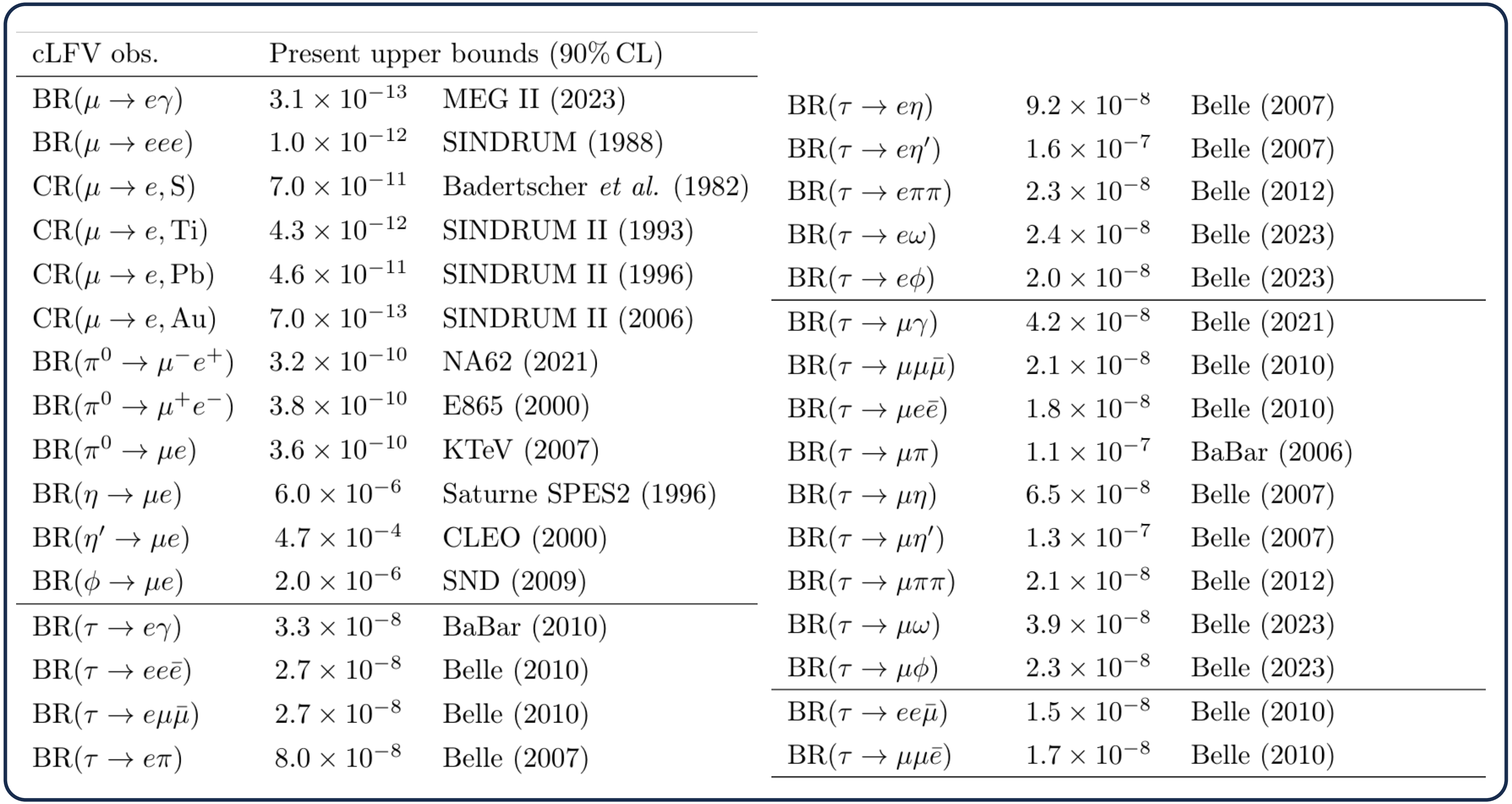
Conclusions & Outlooks

- 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.

- Improve the theoretical accuracy including **running effects**.
- Improve the studies for a **muon collider**, LHC-HL and other colliders.

Thank you for the attention!

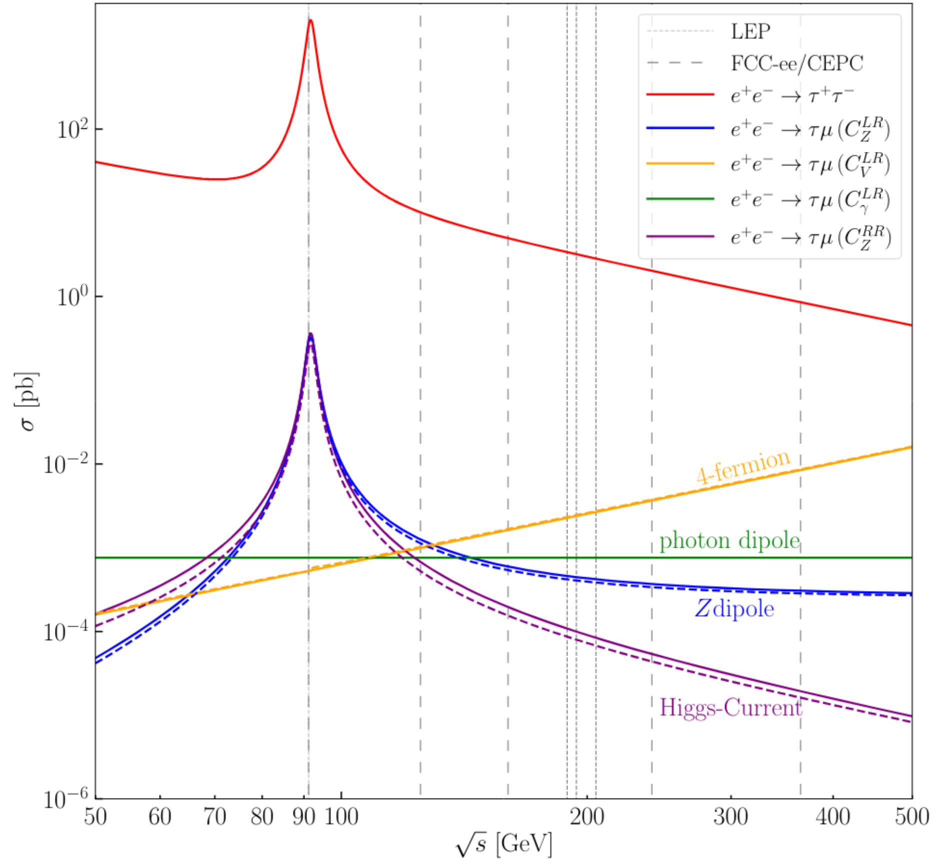
Current Bounds From Experiments



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

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

Dependence On The C.o.M. 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.

CLFV Cross Section @ High Energy

$$
\begin{aligned}
\sigma(\ell_i\ell_i \to \ell_j\ell_i) = \frac{s}{12\pi\Lambda^4}\Bigg\{ & |C_{\ell e}^{iiji}|^2 + |C_{\ell e}^{jiii}|^2 + |C_{\ell\ell}^{jiii} + C_{\ell\ell}^{iiji}|^2 + |C_{ee}^{jiii} + C_{ee}^{iiji}|^2 + \mathcal{O}\left(\frac{m_{i,j}^2}{s}\right) + \\
& + \frac{9v^2m_i^2}{16s^2}\left[|\hat{C}_{eH}^{ij}|^2 + |\hat{C}_{eH}^{ji}|^2 + \mathcal{O}\left(\frac{m_h^2}{s}\right)\right] + \\
& - \frac{3vm_i}{8\sqrt{2}s}\left[\Re\{C_{\ell e}^{jiii*}\hat{C}_{eH}^{ji} + C_{\ell e}^{iiji}\hat{C}_{eH}^{ij}\}\right] + \\
& + \frac{v^2e^2}{s}\left(|C_{e\gamma}^{ij}|^2 + |C_{e\gamma}^{ji}|^2\right)\left(3\log\frac{s^3}{m_i^2(m_j^2 - m_i^2)^2} - 4\right) + \\
& + \frac{v^2g^2}{4s\,c_W}\Bigg[|C_{eZ}^{ji}|^2\left(6(g_R^2 + g_L^2)\log\frac{s}{M_Z^2} - 5g_L^2 - 11g_R^2\right) + \\
& + |C_{eZ}^{ij}|^2\left(6(g_L^2 + g_R^2)\log\frac{s}{M_Z^2} - 11g_L^2 - 5g_R^2\right) + \mathcal{O}\left(\frac{M_Z^2}{s}\right)\Bigg] + \\
& + \frac{egv^2}{2s\,c_W}\Bigg[\Re\{C_{eZ}^{ij}C_{e\gamma}^{ij*}\}\left(6(g_L + g_R)\log\frac{s}{M_Z^2} + g_L - 5g_R\right) + \\
& + \Re\{C_{eZ}^{ji}C_{e\gamma}^{ji*}\}\left(6(g_L + g_R)\log\frac{s}{M_Z^2} + g_R - 5g_L\right) + \mathcal{O}\left(\frac{M_Z^2}{s}\right)\Bigg]\Bigg\} + \\
& + \frac{g^4v^4}{64\pi M_Z^2 c_W^4\Lambda^4}\left(g_R^2 + g_L^2\right)\left[|C_{H\ell}^{(1)ji} + C_{H\ell}^{(3)ji}|^2 + |C_{He}^{ji}|^2\right] + \\
& + \frac{g^2v^2}{48\pi c_W^2\Lambda^4}\Re\{C_{\ell e}^{jiii*}g_R(C_{H\ell}^{(1)ji} + C_{H\ell}^{(3)ji}) + C_{\ell e}^{iiji*}g_L C_{He}^{ji}\} + \\
& - \frac{g^2v^2}{16\pi c_W^2\Lambda^4}\Re\{C_{\ell e}^{iiji*}g_R(C_{H\ell}^{(1)ji} + C_{H\ell}^{(3)ji}) + C_{\ell e}^{jiii*}g_L C_{He}^{ji}\}\log\frac{s}{M_Z^2} + \mathcal{O}\left(\frac{M_Z^2}{s}\right)
\end{aligned}
$$

CLFV Decay Rates @ Low Energy

$$\Gamma\left(h \to \ell_i \ell_j\right) = \frac{m_h v^4}{32\pi\Lambda^4}\left(|[L_e^\dagger C_{e\Phi 3}^\dagger R_e]_{ij}|^2 + |[L_e^\dagger C_{e\Phi 3}^\dagger R_e]_{ji}|^2\right).$$

$$\Gamma(Z \to \ell_i \ell_j) = \frac{1}{24\pi} M_Z \left[\frac{M_Z^2 v^2}{\Lambda^4}(|C_{eZ}^{ji}|^2 + |C_{eZ}^{ij}|^2) + |a_{ji}^Z|^2 + |b_{ji}^Z|^2\right].$$

$$\begin{aligned}\Gamma\left(\ell_j^\pm \to \ell_i^\mp \ell_l^\pm \ell_l^\pm\right) =& \frac{m_j^5}{16\cdot 192\pi^3\Lambda^4}\left[4|c_{\ell\ell}^{V,ijll}|^2 + 4|c_{ee}^{V,ijll}|^2 + |c_{\ell e}^{V,ijll}|^2 + |c_{\ell e}^{V,llij}|^2\right] + \\ &+ \frac{m_j^5}{64\cdot 192\pi^3\Lambda^4}\left[4|c_{\ell\ell}^{S,ijll}|^2 + 4|c_{ee}^{S,ijll}|^2 + |c_{\ell e}^{S,ijll}|^2 + |c_{\ell e}^{S,llij}|^2\right].\end{aligned}$$

$$\begin{aligned}\Gamma\left(\ell_j^\pm \to \ell_i^\pm \ell_i^\pm \ell_i^\mp\right) =& \frac{m_j^5}{16\cdot 192\pi^3\Lambda^4}\left[4|c_{\ell\ell}^{V,ijii}|^2 + 4|c_{ee}^{V,ijii}|^2 + |c_{\ell e}^{V,ijii}|^2 + |c_{\ell e}^{V,iiij}|^2\right] + \\ &+ \frac{m_j^5}{64\cdot 192\pi^3\Lambda^4}\left[4|c_{\ell\ell}^{S,ijii}|^2 + 4|c_{ee}^{S,ijii}|^2 + |c_{\ell e}^{S,ijii}|^2 + |c_{\ell e}^{S,iiij}|^2\right] + \\ &+ \frac{m_j^3 e^2 v^2}{192\pi^3\Lambda^4}\left(\log\frac{m_j^2}{m_i^2} - \frac{11}{4}\right)(|C_{e\gamma}^{ij}|^2 + |C_{e\gamma}^{ji}|^2) + \\ &- \frac{\sqrt{2} m_j^4 e v}{768\pi^3}\Re\left[\left(2c_{\ell\ell}^{V,ijii} + c_{\ell e}^{V,ijii} - \frac{1}{2}c_{\ell e}^{S,ijii}\right)C_{e\gamma}^{ij*} + \right. \\ &\left. - \left(2c_{ee}^{V,ijii} + c_{\ell e}^{V,iiij} - \frac{1}{2}c_{\ell e}^{S,iiij}\right)C_{e\gamma}^{ji}\right].\end{aligned}$$

$$\begin{aligned}\Gamma\left(\ell_j^\pm \to \ell_i^\pm \ell_l^\pm \ell_l^\mp\right) =& \frac{m_j^5}{8\cdot 192\pi^3\Lambda^4}\left[|c_{\ell\ell}^{V,ijii}|^2 + |c_{ee}^{V,ijii}|^2 + |c_{\ell e}^{V,ijii}|^2 + |c_{\ell e}^{V,iiij}|^2\right] + \\ &+ \frac{m_j^5}{32\cdot 192\pi^3\Lambda^4}\left[|c_{\ell\ell}^{S,ijii}|^2 + |c_{ee}^{S,ijii}|^2 + |c_{\ell e}^{S,ijii}|^2 + |c_{\ell e}^{S,iiij}|^2\right] + \\ &+ \frac{m_j^3 e^2 v^2}{96\pi^3\Lambda^4}\left(\log\frac{m_j^2}{m_i^2} - 3\right)(|C_{e\gamma}^{ij}|^2 + |C_{e\gamma}^{ji}|^2) + \\ &- \frac{\sqrt{2} m_j^4 e v}{384\pi^3}\Re\left[\left(c_{\ell\ell}^{V,ijii} + c_{\ell e}^{V,ijii}\right)C_{e\gamma}^{ij*} + \right. \\ &\left. - \left(c_{ee}^{V,ijii} + c_{\ell e}^{V,iiij}\right)C_{e\gamma}^{ji}\right].\end{aligned}$$