Sino-Thai International Summer School on
High Energy Physics and Astrophysics

Charged Lepton Flavour Violation (with Muons)

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SYSU, Guangzhou, July 15th 2026

Outline

The Standard Model and
the origin of fermion masses

What is (charged) Lepton Flavour Violation (CLFV)?

Experimental searches for CLFV

Effective field theories and how CLFV
constrain the new physics energy scale

The Standard Model

What is the Standard Model?

The Standard Model (SM) is the quantum field theory that currently describes properties and interactions of all the particles we know

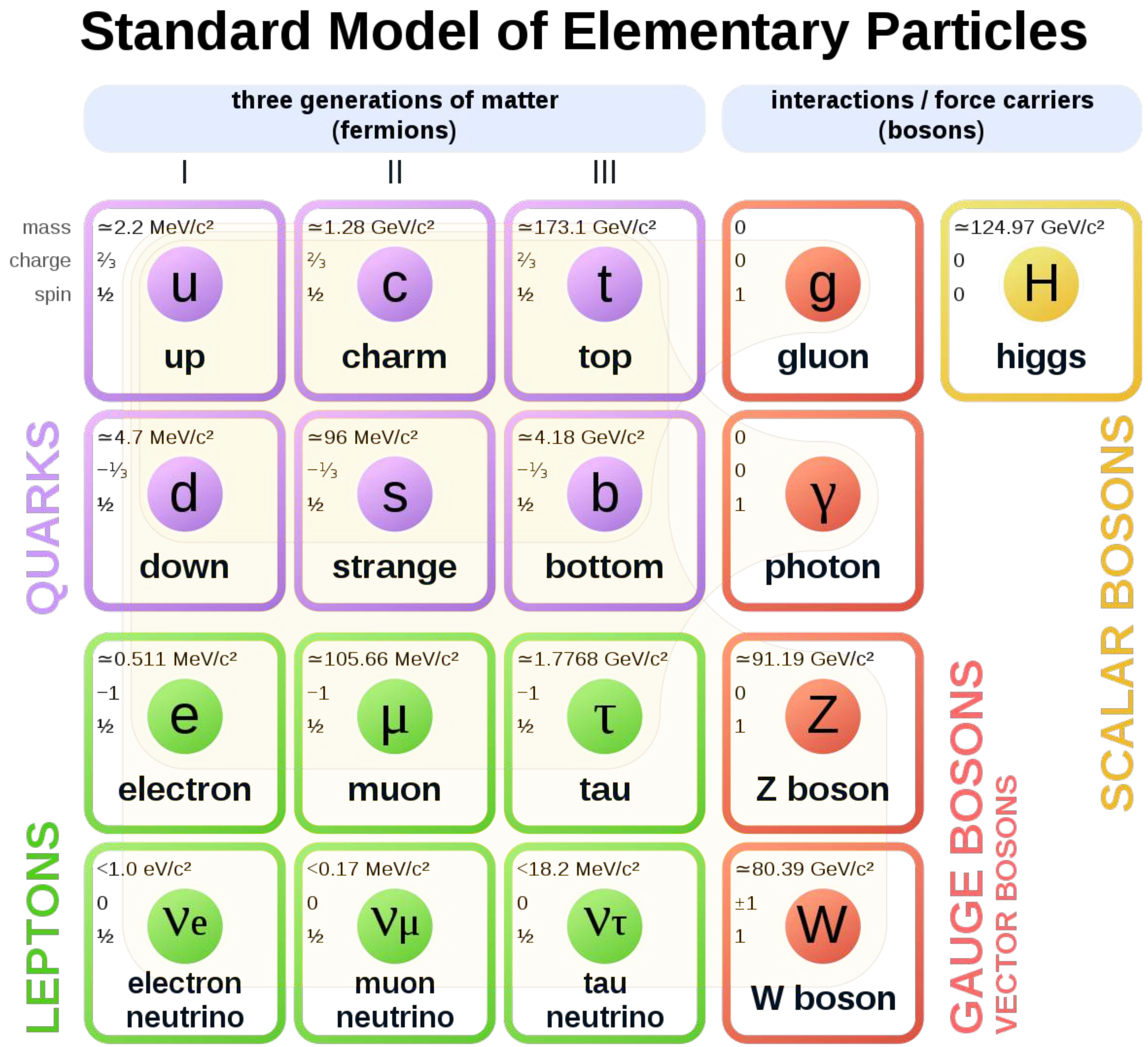
- Based on the gauge symmetries:
  (local field transformations under which the Lagrangian is invariant)

$$\underbrace{\overset{\text{colour}}{SU(3)_c}}_{\text{strong interactions}} \times \underbrace{\overset{\text{weak isospin}}{SU(2)_L} \times \overset{\text{weak hypercharge}}{U(1)_Y}}_{\text{electroweak interactions}}$$

- Its predictions have been tested by many experiments over several decades to an impressive degree of accuracy

- But we know that something is missing: neutrino masses, dark matter, matter-antimatter asymmetry…

What is the Standard Model?



Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin QUARKS	≃2.2 MeV/c^2 ⅔ ½ u up	≃1.28 GeV/c^2 ⅔ ½ c charm	≃173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c^2 0 0 H higgs
	≃4.7 MeV/c^2 −⅓ ½ d down	≃96 MeV/c^2 −⅓ ½ s strange	≃4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS	≃0.511 MeV/c^2 −1 ½ e electron	≃105.66 MeV/c^2 −1 ½ μ muon	≃1.7768 GeV/c^2 −1 ½ τ tau	≃91.19 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
	<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	≃80.39 GeV/c^2 ±1 1 W W boson	

They make up matter

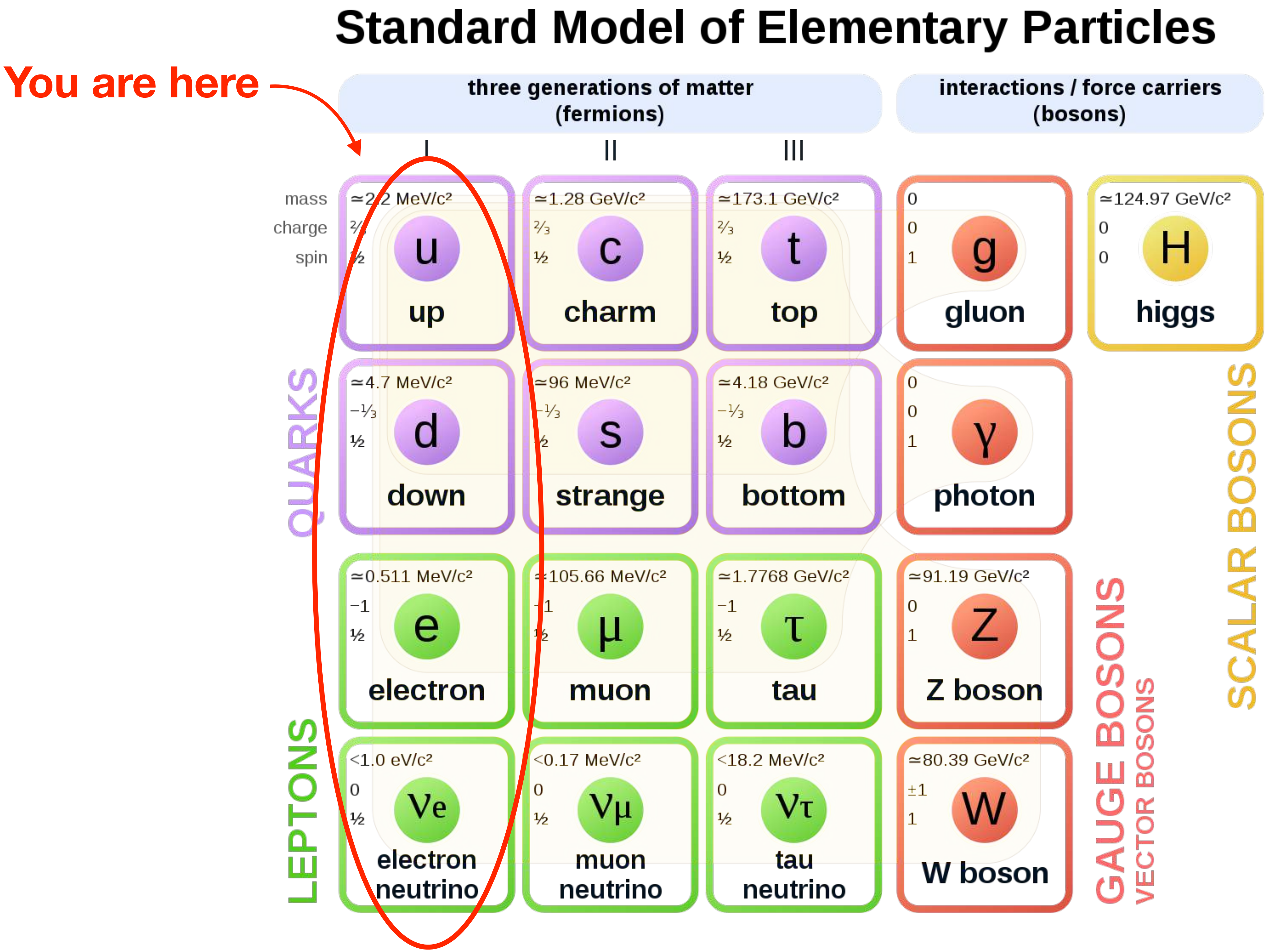
They mediate forces

Fermions (spin 1/2)

Bosons

(spin 1) **(spin 0)**

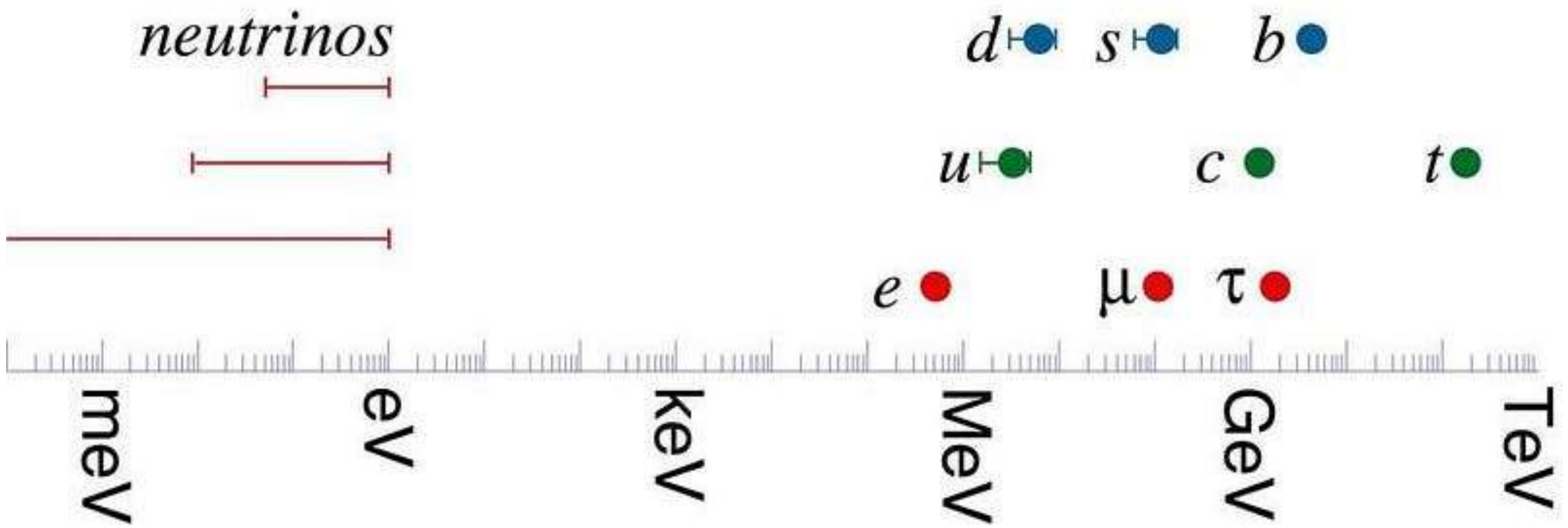
What are fermion flavours?



There are **3 families** (or **“flavours”**) of fermions with same spin and charges…

What are fermion flavours?

… but they have (very) **different masses**!



fermion mass

(for a comparison protons and neutrons ~ 1 GeV)

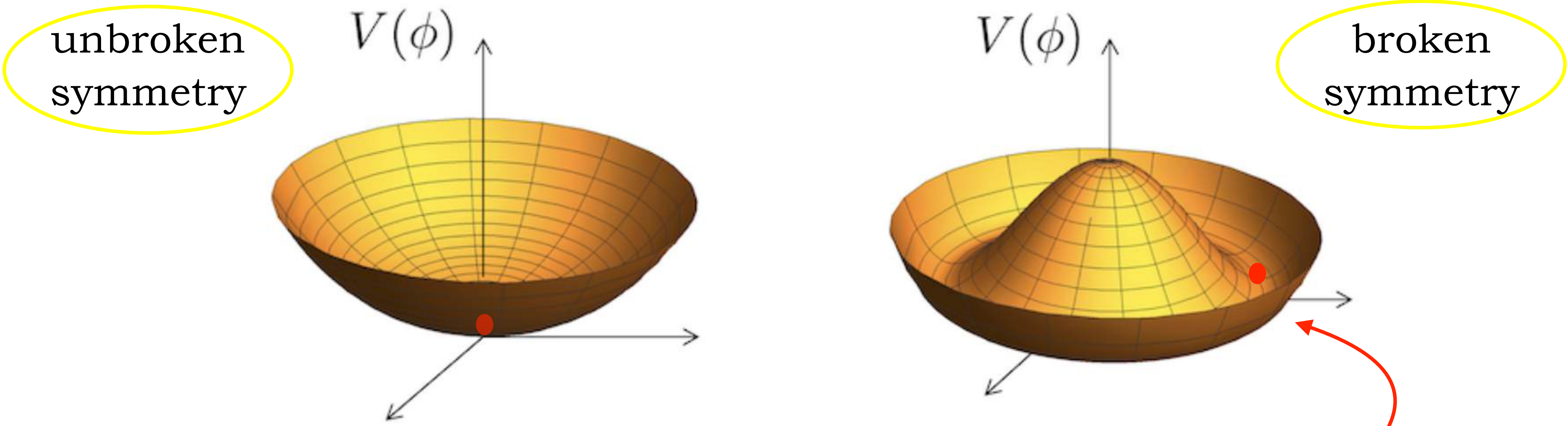
3rd generation mass ≫ 2nd generation ≫ 1st generation

Why? We don't know…

see for reviews: Zhi-zhong Xing arXiv:1909.09610, J. Zupan arXiv:1903.05062

Where do fermion masses come from?

The SM Lagrangian is invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y$ but the vacuum (ground state) of the Higgs field Φ is not:



vacuum expectation value (vev): $\langle \Phi \rangle = \frac{v}{\sqrt{2}} \simeq 174$ GeV

The vev of the Higgs field spontaneously breaks the symmetry:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_c \times U(1)_{\rm em}$$

⇨ giving mass to electroweak bosons *and fermions*

Where do fermion masses come from?

In the SM, fermion masses (hence the *flavour sector*) has origin in the Yukawa interactions among the Higgs and the fermion fields:

$$-\mathcal{L}_Y = (Y_u)_{ij}\, \overline{Q}_{L\,i}\, u_{R\,j}\, \widetilde{\Phi} + (Y_d)_{ij}\, \overline{Q}_{L\,i}\, d_{R\,j}\, \Phi + (Y_e)_{ij}\, \overline{L}_{L\,i}\, e_{R\,j}\, \Phi + h.c.$$

complex
3x3 matrix

i, j = 1,2,3 flavour indices

If $\langle\Phi\rangle = v/\sqrt{2} \neq 0$, these terms become mass matrices:

$$\Longrightarrow \qquad (m_f)_{ij} = \frac{v}{\sqrt{2}}(Y_f)_{ij}, \qquad f = u, d, e$$

We can diagonalize the fermion masses with two *unitary* matrices:

$$Y_f = V_f \hat{Y}_f W_f^\dagger, \qquad f = u, d, e \qquad \begin{array}{r} V_f^\dagger V_f = \mathbb{1} \\ W_f^\dagger W_f = \mathbb{1} \end{array}$$

flavour diagonal

This defines a rotation of the fermion fields to the physical mass basis:

$$u_R \longrightarrow W_u^\dagger u_R\,, \quad u_L \longrightarrow V_u^\dagger u_L\,, \quad \text{etc.}$$

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com
3x3 matrix

up type quarks (*u*,*c*,*t*)

down type quarks (*d*,*s*,*b*)

charged leptons (*e*,*μ*,*τ*)

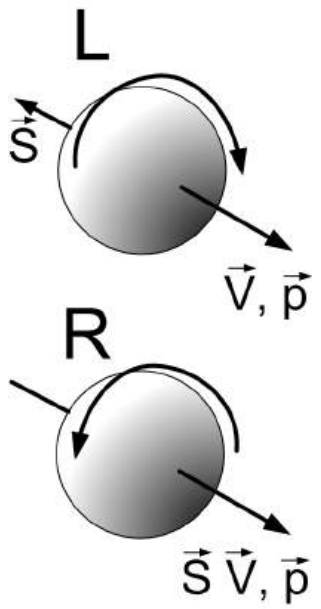
ices

If

s:

Fermion mass terms require a "left-handed" fermion to couple with a "right-handed" fermion:

$$m_f \bar{f}_L f_R$$



We can

atrices:

$$\dagger_f V_f = 1\!\!1$$

$$\dagger_f W_f = 1\!\!1$$

flavour dia

This defines a rotation of the fermion fields to the physical mass basis:

In the original formulation of the SM:
no right-handed neutrinos $\Longleftrightarrow$ neutrino have no mass!

Can SM interactions change flavour?

In the SM, fermion masses (hence the *flavour sector*) has origin in the Yukawa interactions among the Higgs and the fermion fields:

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Rotations to the fermion mass basis: $Y_f = V_f \hat{Y}_f W_f^\dagger, \qquad f = u, d, e$

Unitary rotation matrices, couplings to *photon* and *Z* remain flavour-diagonal:

$$e\ \bar{f}\gamma_\mu f A^\mu \qquad\qquad (g_L\ \bar{f}_L\gamma_\mu f_L + g_R\ \bar{f}_R\gamma_\mu f_R)Z^\mu$$

Couplings to the Higgs are also flavour-conserving (aligned to the mass matrix):

$$\frac{m_f}{v}\,\bar{f}_L f_R\, h$$

NO (tree-level) flavour-changing **neutral** currents

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Rotations to the fermion mass basis: $Y_f = V_f \hat{Y}_f W_f^\dagger, \qquad f = u, d, e$

Flavour violation *only* occurs in **charged** currents:

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\overline{u}_L \gamma^\mu (V_u^\dagger V_d) d_L + \overline{\nu}_L \gamma^\mu (V_\nu^\dagger V_e) e_L \right) W_\mu^+ + h.c.$$

$$V_{\rm CKM} \equiv V_u^\dagger V_d \qquad\qquad U_{\rm PMNS} \equiv V_\nu^\dagger V_e$$

But, if neutrinos are *massless*, we can rotate them as we want and choose:

$$V_\nu = V_e$$

NO lepton flavour violation (Y_e only ‘direction’ in the leptonic flavour space)

Can SM interactions change flavour?

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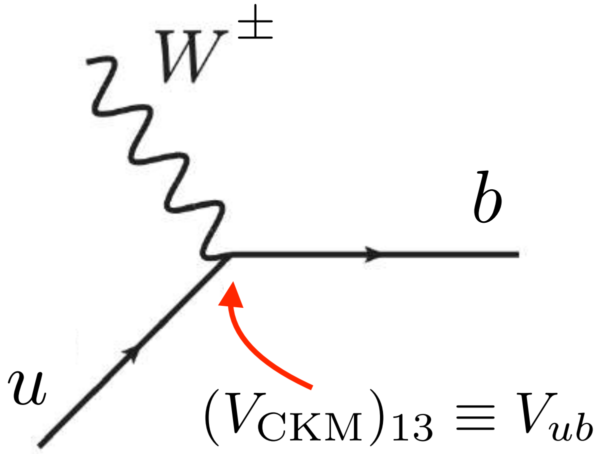
$$V_{\rm CKM} \equiv V_u^\dagger V_d$$

For example:



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$$V_\nu = V_e$$

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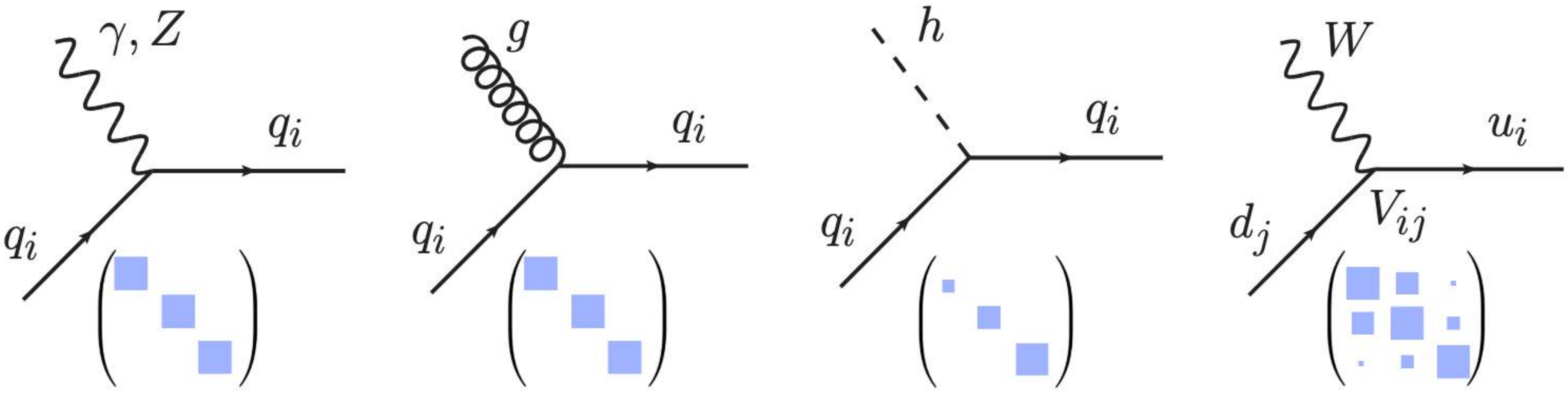
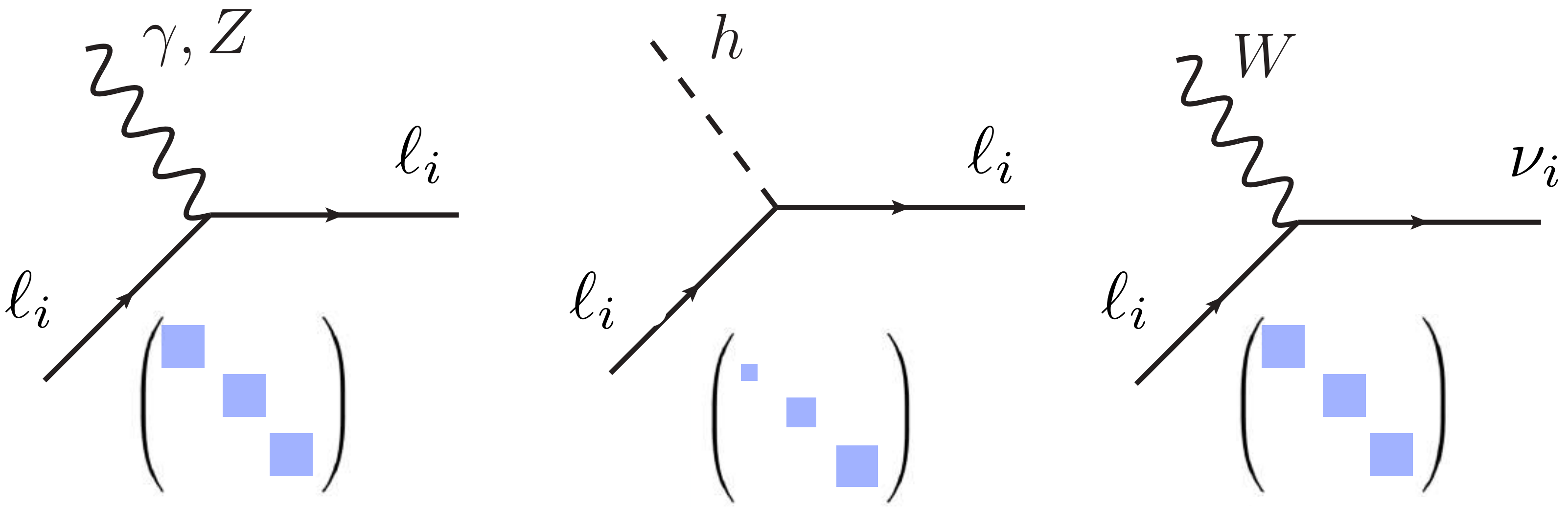
Summary: fermion interactions in the Standard Model

Quark interactions:



Lepton interactions:



courtesy of Jure Zupan

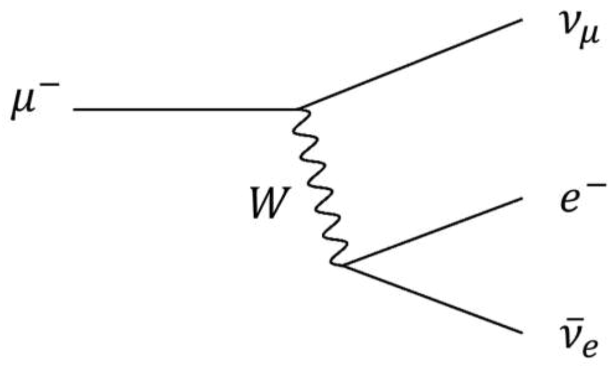
Charged Lepton Flavour Violation

Properties of the lepton sector in the Standard Model

SM interactions: lepton flavour *universal*
and (with massless neutrinos) lepton flavour *conserving*

⇨ Lepton flavour numbers are (individually) conserved in the Standard Model:

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$



✓

number of leptons minus number of antileptons

	μ^-	→	e^-	+	$\bar{\nu}_e$	+	ν_μ	
L:	1	=	1	+	-1	+	1	lepton number
L$_e$:	0	=	1	+	-1	+	0	electron number
L$_\mu$:	1	=	0	+	0	+	1	muon number

Standard muon decay
(lepton flavour conserving)

→ lifetime 10^{-6} s !

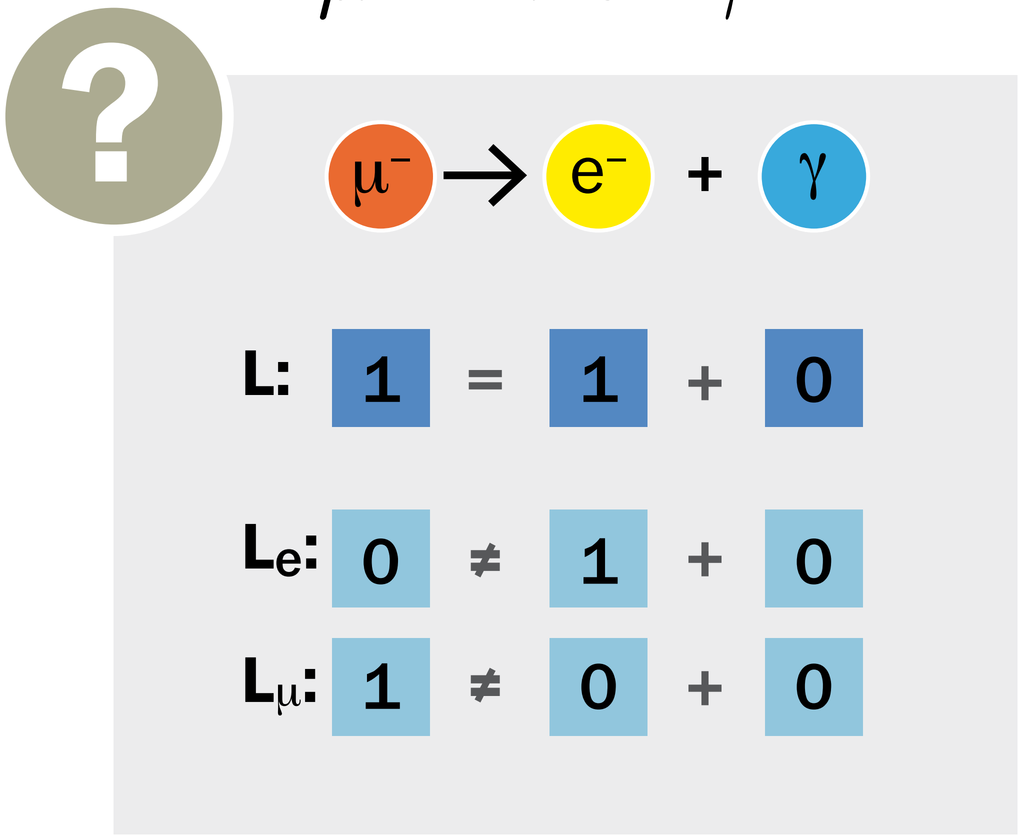
Properties of the lepton sector in the Standard Model

SM interactions: lepton flavour *universal*
and (with massless neutrinos) lepton flavour *conserving*

⇨ Lepton flavour numbers are (individually) conserved in the Standard Model:

$$\mu^- \rightarrow e^- \gamma$$

photon



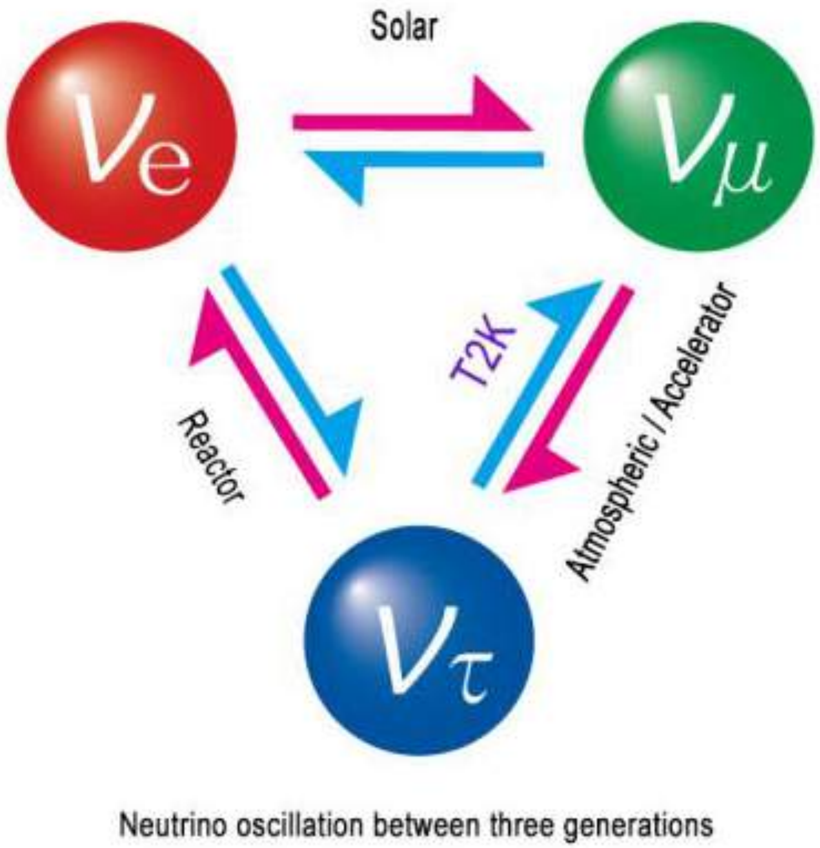
$\mu^- \rightarrow e^- + \gamma$

L:	1	=	1	+	0
L$_e$:	0	≠	1	+	0
L$_\mu$:	1	≠	0	+	0

Lepton flavour violating (LFV)
decay (never observed!)

Why searching for CLFV?

Neutrino have masses and oscillate (change flavour)!



Lepton flavour numbers are not conserved!

$$(\Longleftrightarrow U_{\rm PMNS} \equiv V_\nu^\dagger V_e \neq \mathbb{1}\,)$$

Why shouldn't we observe also *charged* LFV (CLFV) processes:

$$\mu \to e\gamma, \quad \tau \to \mu\gamma, \quad \mu \to eee, \;\text{etc.}\,?$$

Why searching for CLFV?

- Neutrinos oscillate → we have to introduce neutrino mass terms:

Dirac: $$\mathcal{L}_D = -(Y_\nu)_{ij}\,\overline{\nu}_{R\,i}\,\widetilde{\Phi}^\dagger\,L_{L\,j} + \text{h.c.} \quad\Longrightarrow\quad (m^D_\nu)_{ij} = \frac{v}{\sqrt{2}}(Y_\nu)_{ij}.$$

or Majorana: $$\mathcal{L} \supset \frac{C_{ij}}{\Lambda}\left(\overline{L^c_{L\,i}}\,\tau_2\Phi\right)\left(\Phi^T\tau_2 L_{L\,j}\right) + \text{h.c.} \quad\Longrightarrow\quad (m^M_\nu)_{ij} = \frac{C_{ij}v^2}{\Lambda}$$

- PMNS becomes ‘physical’: neutrino mass eigenstates couple to charged leptons of different flavours

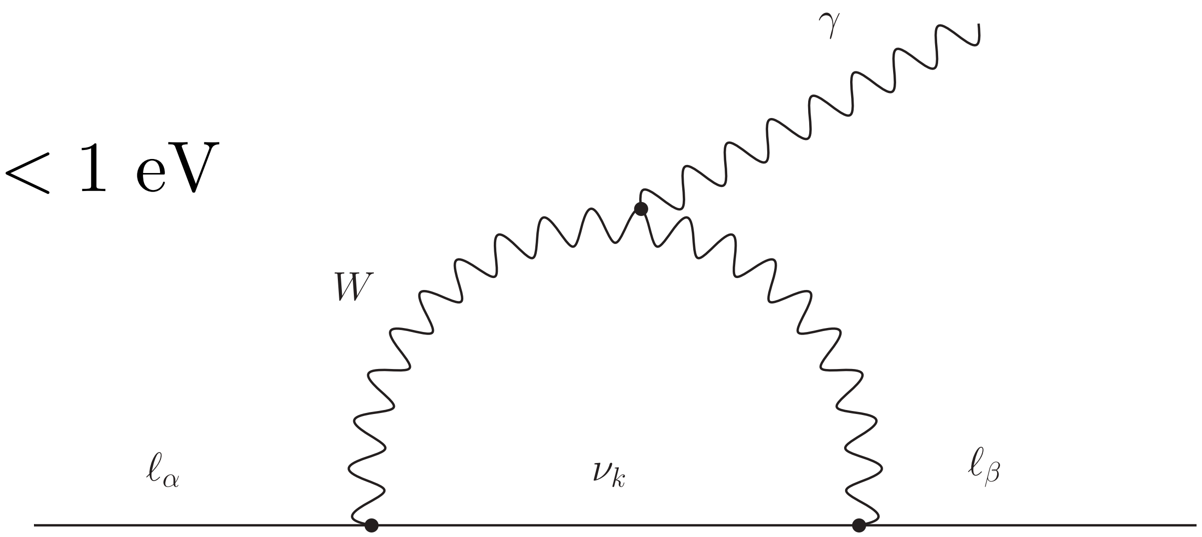
- In the SM + massive neutrinos:

$m_\nu < 1$ eV

$$\frac{\Gamma(\ell_\alpha\to\ell_\beta\gamma)}{\Gamma(\ell_\alpha\to\ell_\beta\nu\bar{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{k=1,3}U_{\alpha k}U^*_{\beta k}\frac{m^2_{\nu_k}}{M^2_W}\right|^2$$

$M_W \approx 80$ GeV

Petcov ’77; Cheng Li ’77, ’80



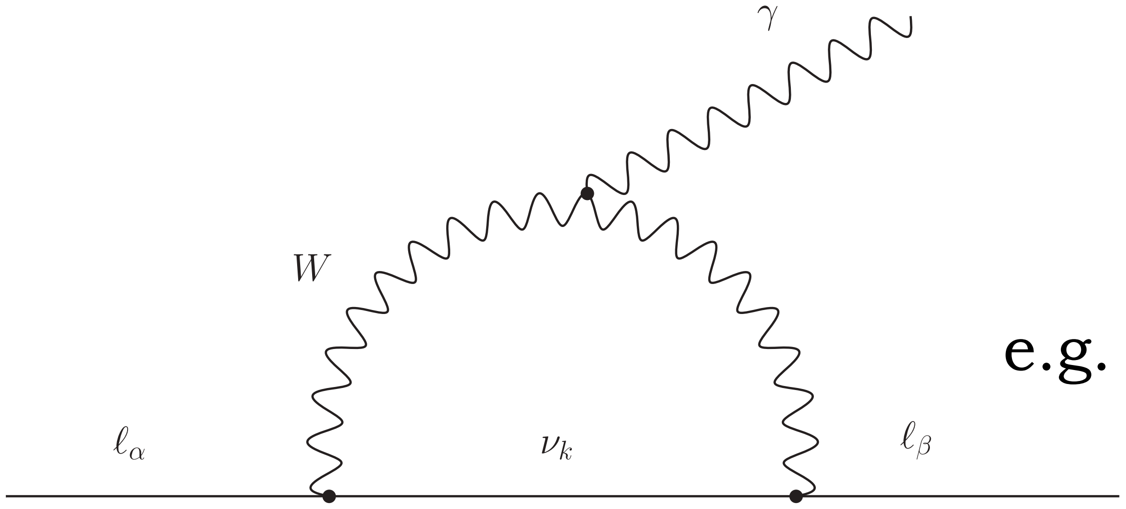
$$\Longrightarrow \quad \text{BR}(\mu\to e\gamma)\approx\text{BR}(\tau\to e\gamma)\approx\text{BR}(\tau\to\mu\gamma) = 10^{-55}\div 10^{-54}$$

unobservable!

Huge suppression because neutrinos much lighter than the W boson

⟹ but in presence of **new physics** particles, we can have larger effects

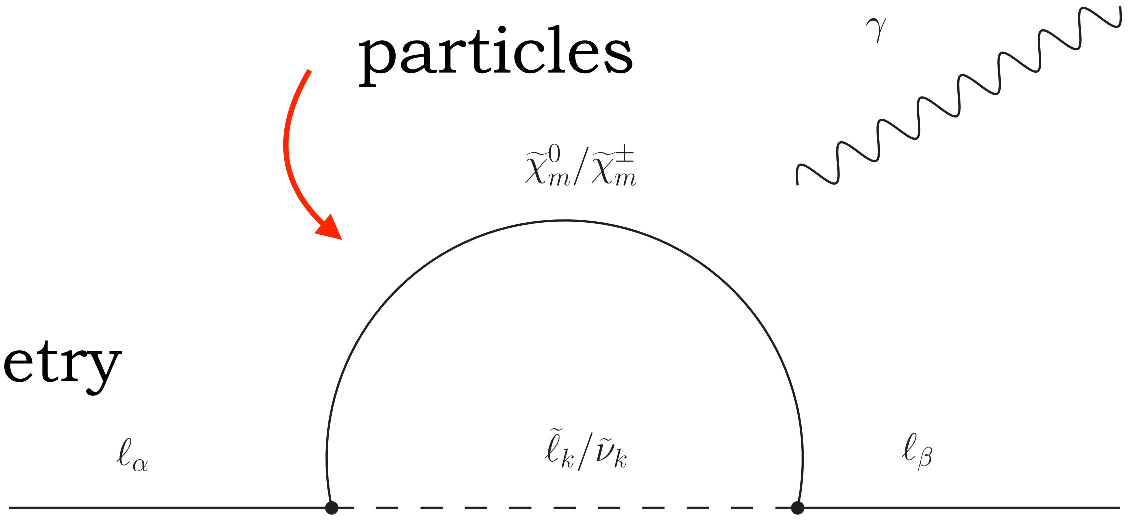
Why searching for CLFV?



e.g. supersymmetry

Borzumati Masiero ‘86;
Hisano et al. ‘95

new physics
particles



$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$

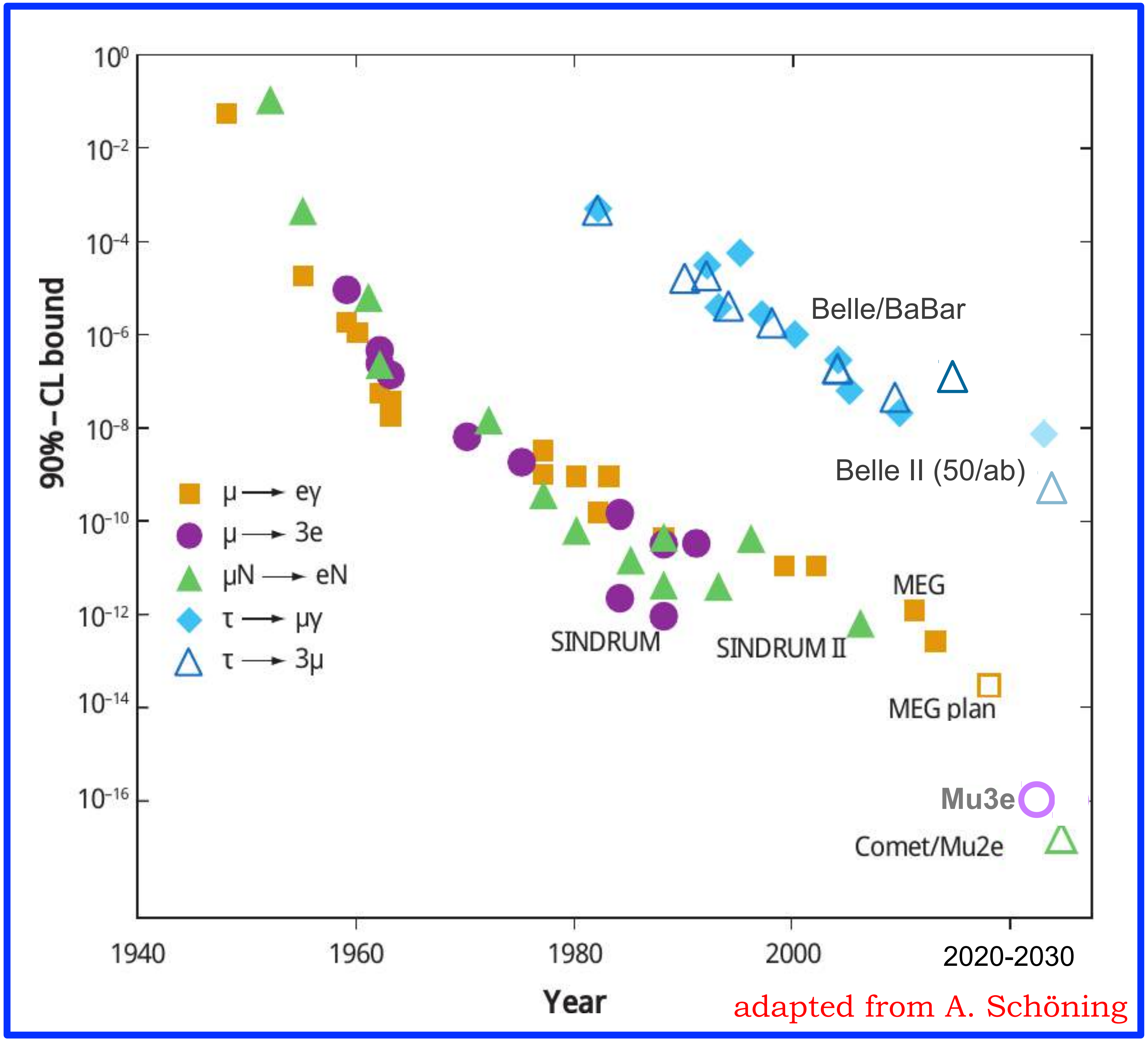
$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} \sim \frac{|\delta_{\alpha\beta}|^2}{G_F^2\, m^4_{\mathrm{SUSY}}}$$

SUSY flavour
mixing param.

- Unambiguous signal of New Physics
- Stringent test of NP coupling to leptons
- It probes scales far beyond collider exps.

⇒ For a pedagogical introduction (exp + th) cf. LC and Signorelli ‘17

CLFV has not been found for more than 70 years...



adapted from A. Schöning

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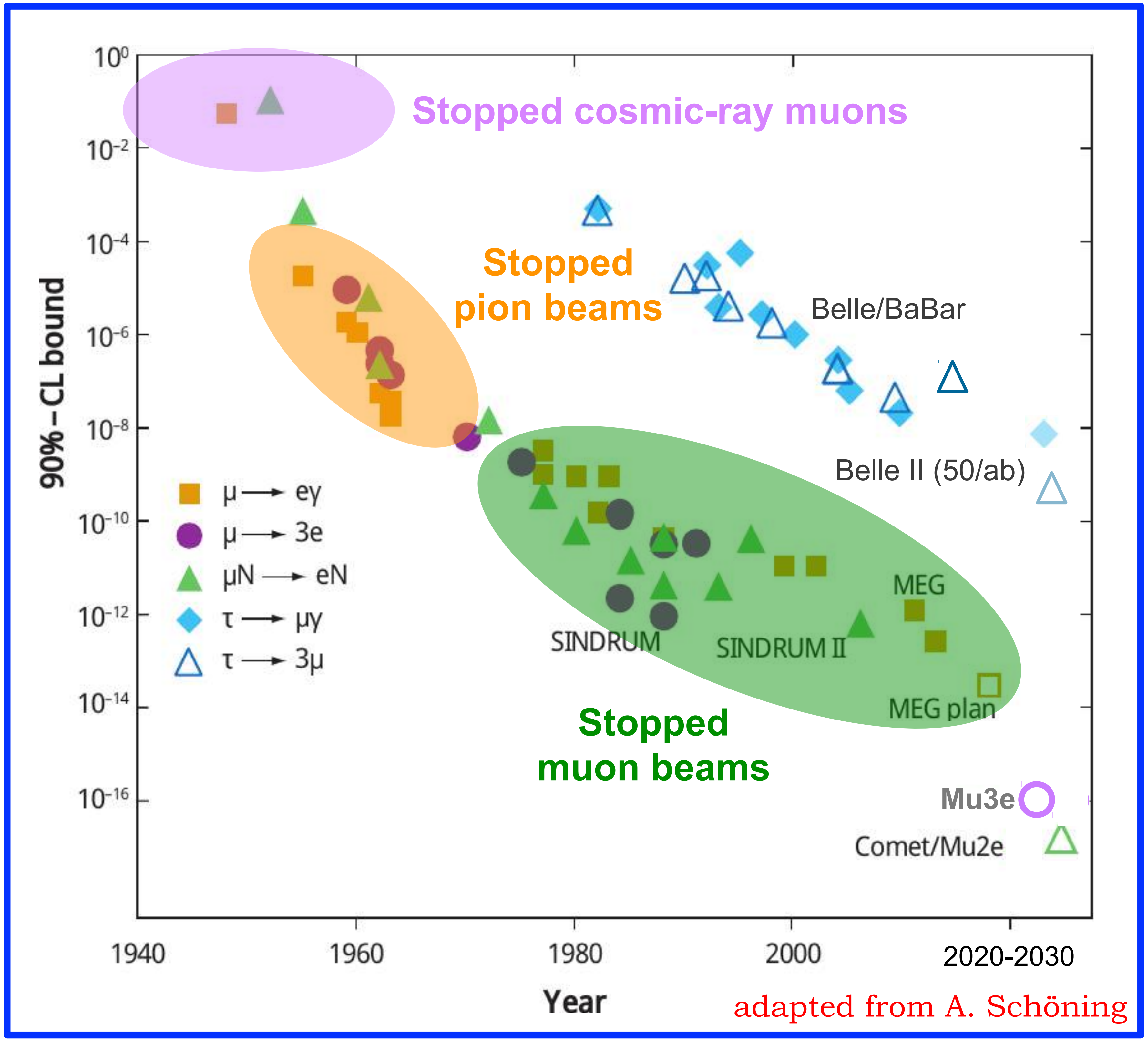
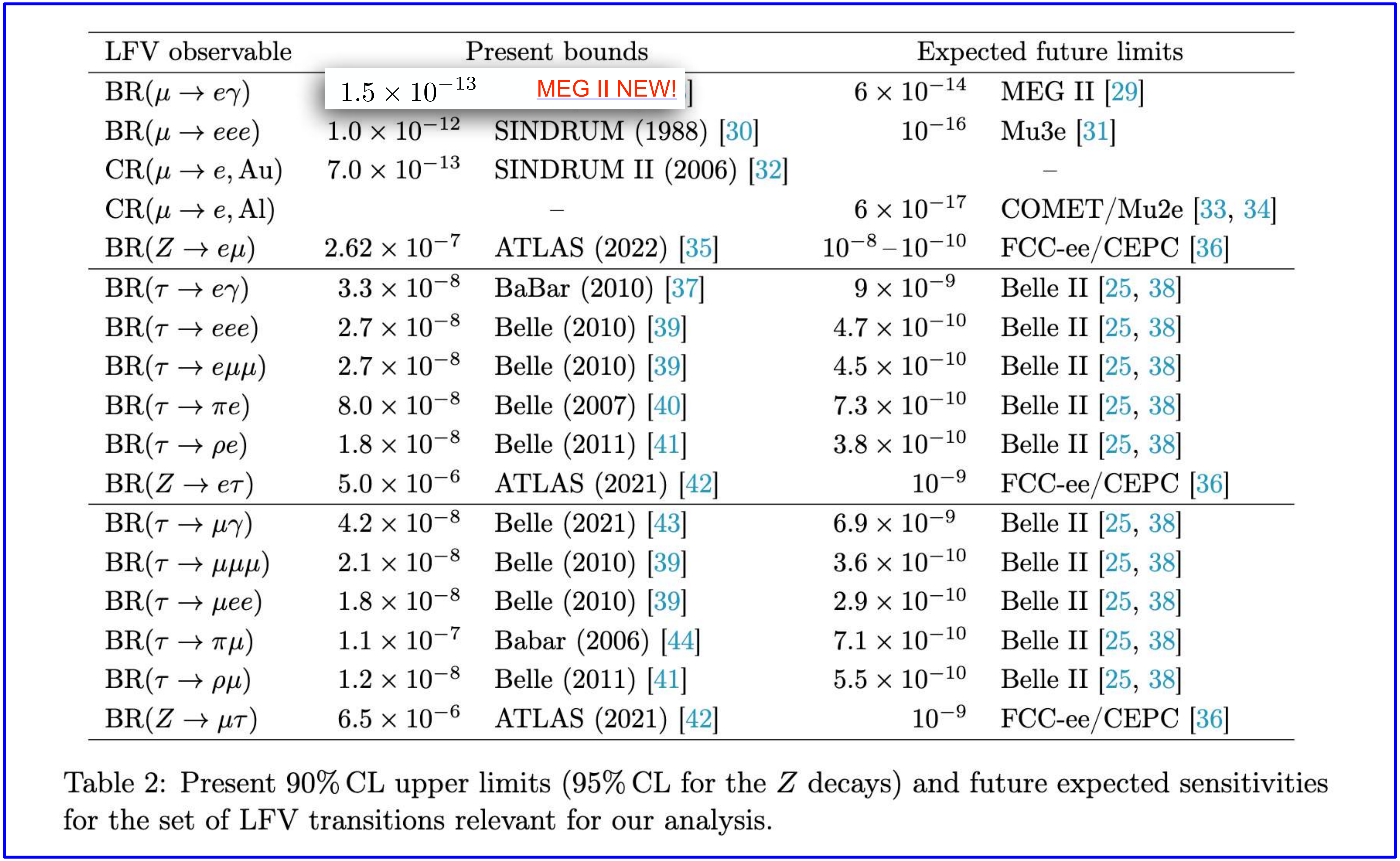


adapted from A. Schöning

… and we have new experiments!

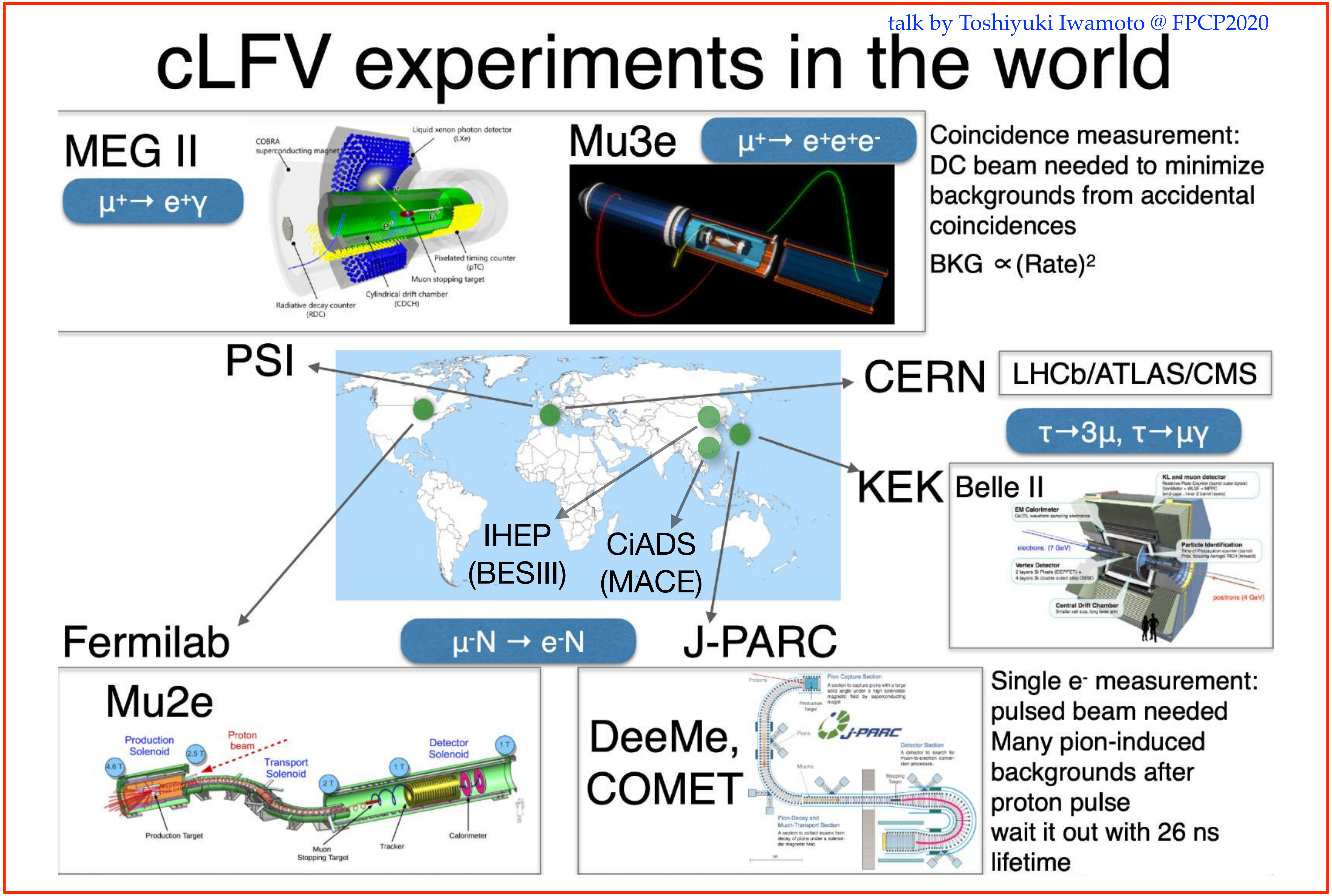


LFV observable	Present bounds		Expected future limits	
$\mathrm{BR}(\mu \to e\gamma)$	1.5×10^{-13}	MEG II NEW!]	6×10^{-14}	MEG II [29]
$\mathrm{BR}(\mu \to eee)$	1.0×10^{-12}	SINDRUM (1988) [30]	10^{-16}	Mu3e [31]
$\mathrm{CR}(\mu \to e, \mathrm{Au})$	7.0×10^{-13}	SINDRUM II (2006) [32]	–	
$\mathrm{CR}(\mu \to e, \mathrm{Al})$	–		6×10^{-17}	COMET/Mu2e [33, 34]
$\mathrm{BR}(Z \to e\mu)$	2.62×10^{-7}	ATLAS (2022) [35]	$10^{-8} - 10^{-10}$	FCC-ee/CEPC [36]
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8}	BaBar (2010) [37]	9×10^{-9}	Belle II [25, 38]
$\mathrm{BR}(\tau \to eee)$	2.7×10^{-8}	Belle (2010) [39]	4.7×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to e\mu\mu)$	2.7×10^{-8}	Belle (2010) [39]	4.5×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \pi e)$	8.0×10^{-8}	Belle (2007) [40]	7.3×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \rho e)$	1.8×10^{-8}	Belle (2011) [41]	3.8×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(Z \to e\tau)$	5.0×10^{-6}	ATLAS (2021) [42]	10^{-9}	FCC-ee/CEPC [36]
$\mathrm{BR}(\tau \to \mu\gamma)$	4.2×10^{-8}	Belle (2021) [43]	6.9×10^{-9}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \mu\mu\mu)$	2.1×10^{-8}	Belle (2010) [39]	3.6×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \mu ee)$	1.8×10^{-8}	Belle (2010) [39]	2.9×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \pi\mu)$	1.1×10^{-7}	Babar (2006) [44]	7.1×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(\tau \to \rho\mu)$	1.2×10^{-8}	Belle (2011) [41]	5.5×10^{-10}	Belle II [25, 38]
$\mathrm{BR}(Z \to \mu\tau)$	6.5×10^{-6}	ATLAS (2021) [42]	10^{-9}	FCC-ee/CEPC [36]

Table 2: Present 90% CL upper limits (95% CL for the Z decays) and future expected sensitivities for the set of LFV transitions relevant for our analysis.

Experimental searches for CLFV

Current/upcoming experiments



talk by Toshiyuki Iwamoto @ FPCP2020

cLFV experiments in the world

MEG II

$\mu^+ \to e^+\gamma$

Mu3e

$\mu^+ \to e^+e^+e^-$

Coincidence measurement:
DC beam needed to minimize backgrounds from accidental coincidences

BKG $\propto$ (Rate)^2

PSI

CERN

LHCb/ATLAS/CMS

$\tau \to 3\mu$, $\tau \to \mu\gamma$

KEK

Belle II

IHEP (BESIII)

CiADS (MACE)

Fermilab

$\mu^- N \to e^- N$

J-PARC

Mu2e

DeeMe, COMET

Single e$^-$ measurement:
pulsed beam needed
Many pion-induced backgrounds after proton pulse
wait it out with 26 ns lifetime

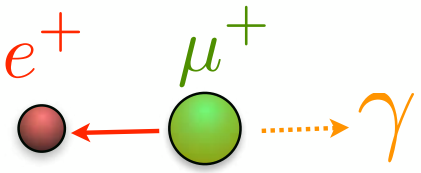
Current/upcoming experiments: MEG II

slide borrowed from A. Papa

The MEGII experiment at PSI: Signal and backgrounds

- Searching for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~ **$6\ 10^{-14}$**
- Best upper limit on the BR ($\mu^+ \rightarrow e^+ \gamma$) set by the MEG experiment (**$4.2\ 10^{-13}$** @90% C.L.)
- **Positive** muons from a **continuous** beam are usually stopped in a (thin) target to fully exploit the clear signature of a decay at rest
- **Five** observables (E_γ, E_e, $\Delta t_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$) to identify a $\mu \rightarrow e\gamma$ event and reject background events
  - Precise expectation for a signal event, poor correlated for RMD events, not correlated for Accidental events

Signal

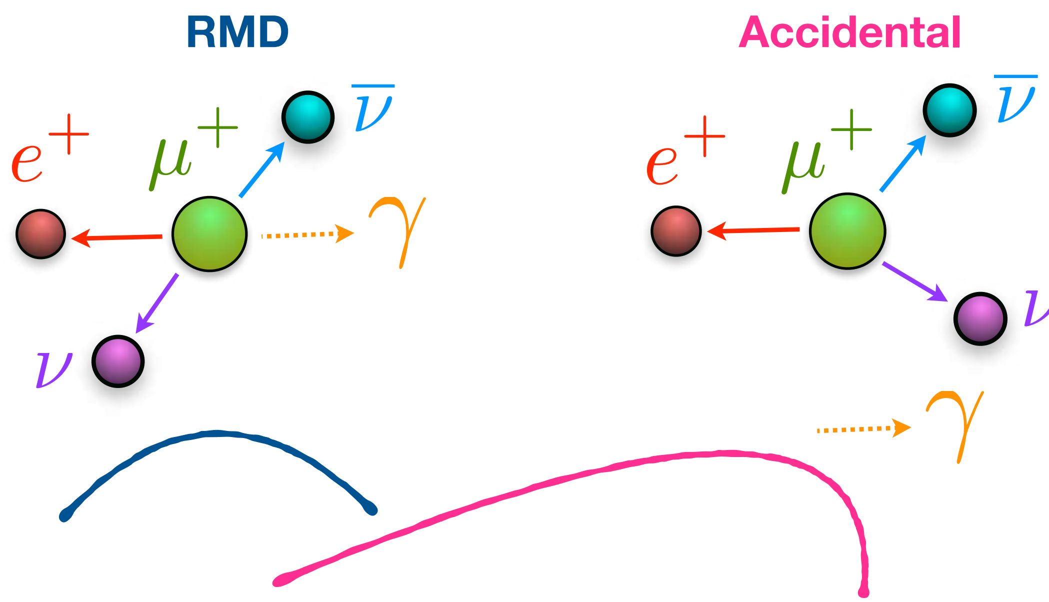


$E_\gamma \sim E_e \sim m_\mu/2$

$\Delta t_{e\gamma} \sim 0$

$\Delta\Theta_{e\gamma} \sim \pi$

Backgrounds



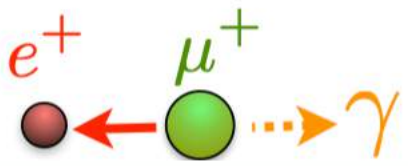
(RMD, AIF and Breamstrahlung)

E_γ, E_e, $\theta_{e\gamma}$, $\varphi_{e\gamma}$,

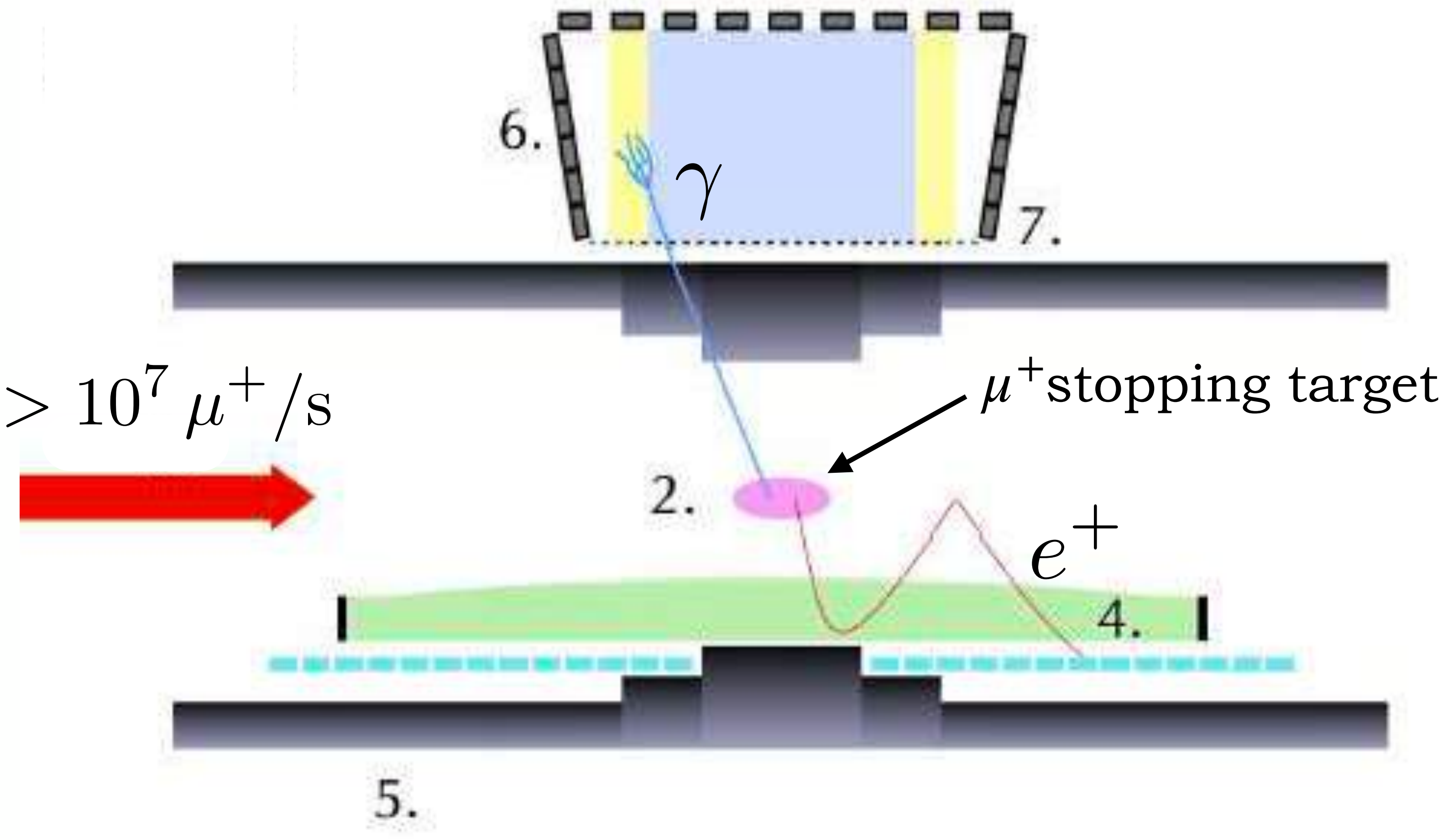
$\Delta t_{e\gamma}$

Current/upcoming experiments: MEG II

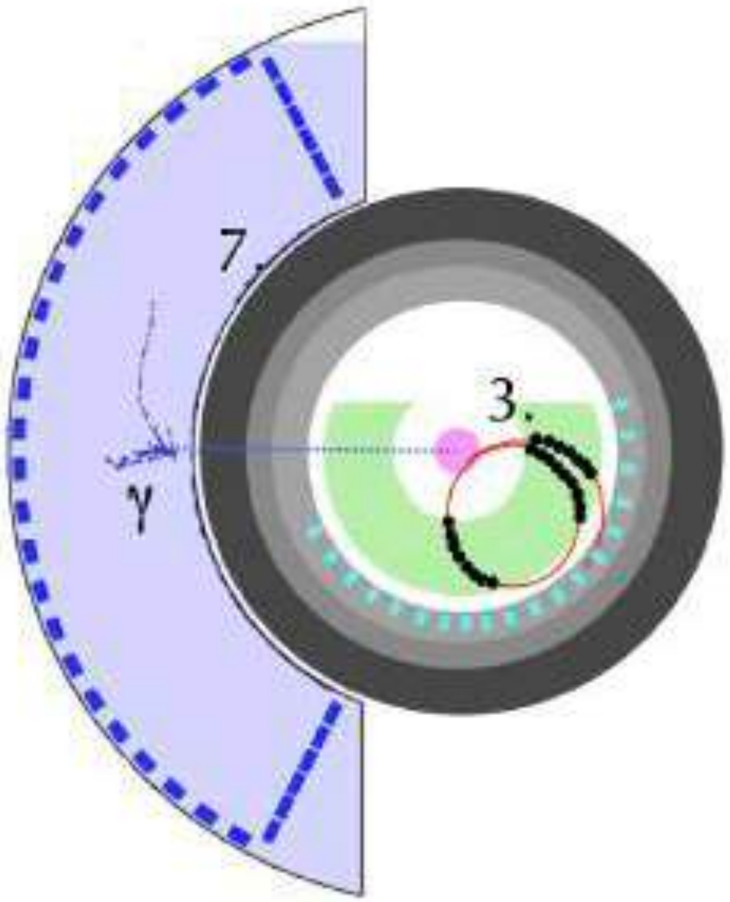
Signature



Longitudinal view



Transverse view



No events observed beyond expected background, they set the limit :

$$\mathrm{BR}(\mu^+ \to e^+\gamma) < 1.5 \times 10^{13}$$ (MEG II 2025)

(and they keep taking data)

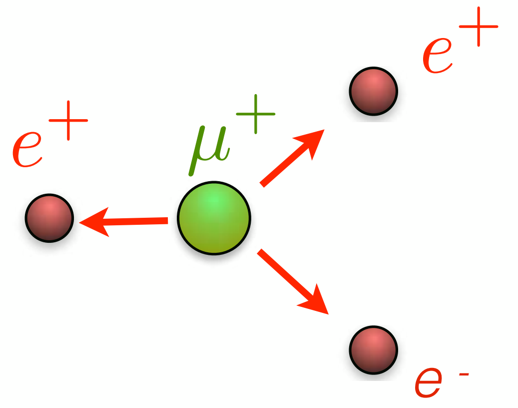
Current/upcoming experiments: Mu3e

slide borrowed from A. Papa

Mu3e: The $\mu^+ \to e^+ e^+ e^-$ search

- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-15}$ (Phase I) up to down $\sim 10^{-16}$ (Phase II). Previous upper limit $BR(\mu^+ \to e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to eee$ events

Signature

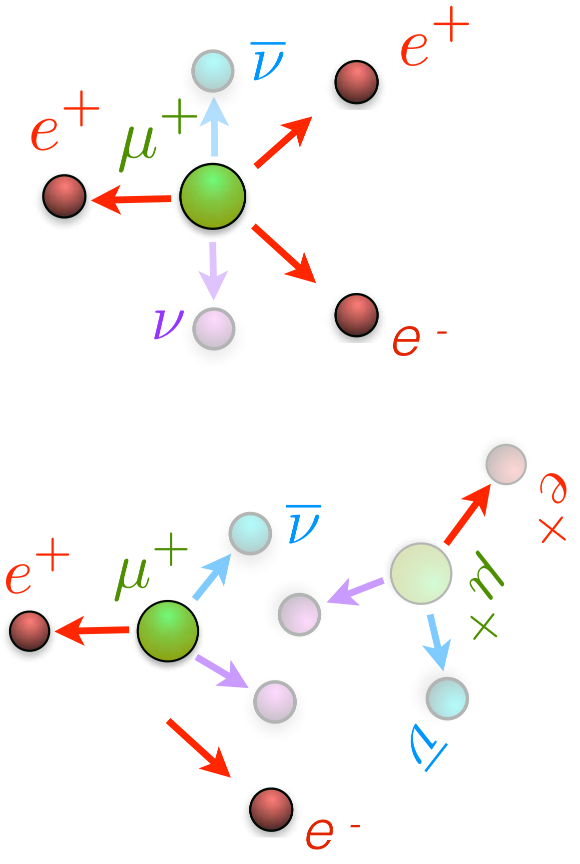


$$\Delta t_{eee} = 0$$

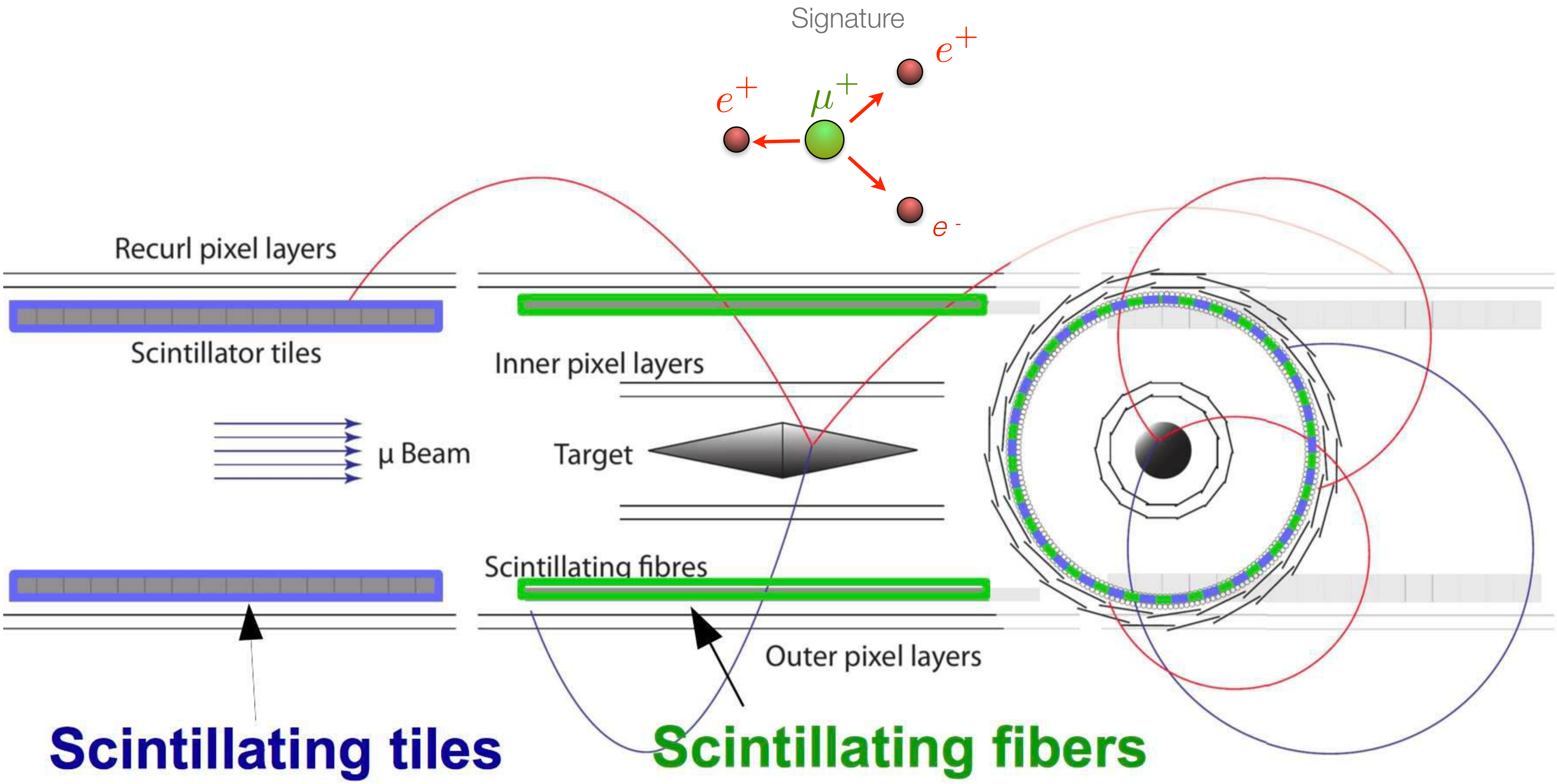
$$\Sigma \overline{p}_e = 0$$

$$\Sigma E_e = m_\mu$$

Background

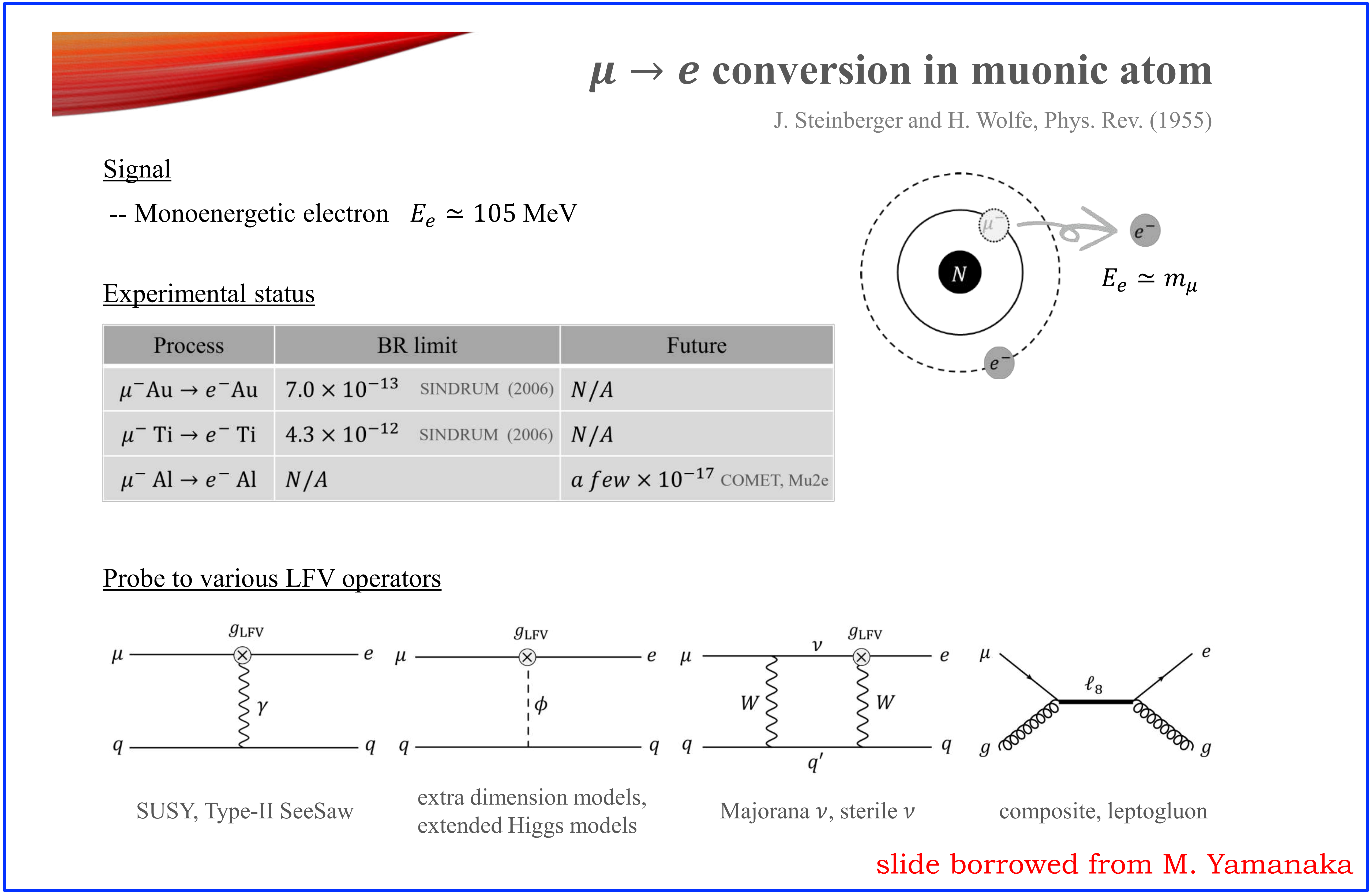


Current/upcoming experiments: Mu3e



Mu3e recently started running, first results are expected within a few years!

…. and more searches for muon LFV are under construction



$\mu \to e$ conversion in muonic atom

J. Steinberger and H. Wolfe, Phys. Rev. (1955)

Signal

-- Monoenergetic electron $E_e \simeq 105$ MeV

Experimental status

Process	BR limit	Future
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	7.0×10^{-13} SINDRUM (2006)	N/A
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	4.3×10^{-12} SINDRUM (2006)	N/A
$\mu^-\mathrm{Al} \to e^-\mathrm{Al}$	N/A	$a\ few \times 10^{-17}$ COMET, Mu2e

Probe to various LFV operators

SUSY, Type-II SeeSaw

extra dimension models,
extended Higgs models

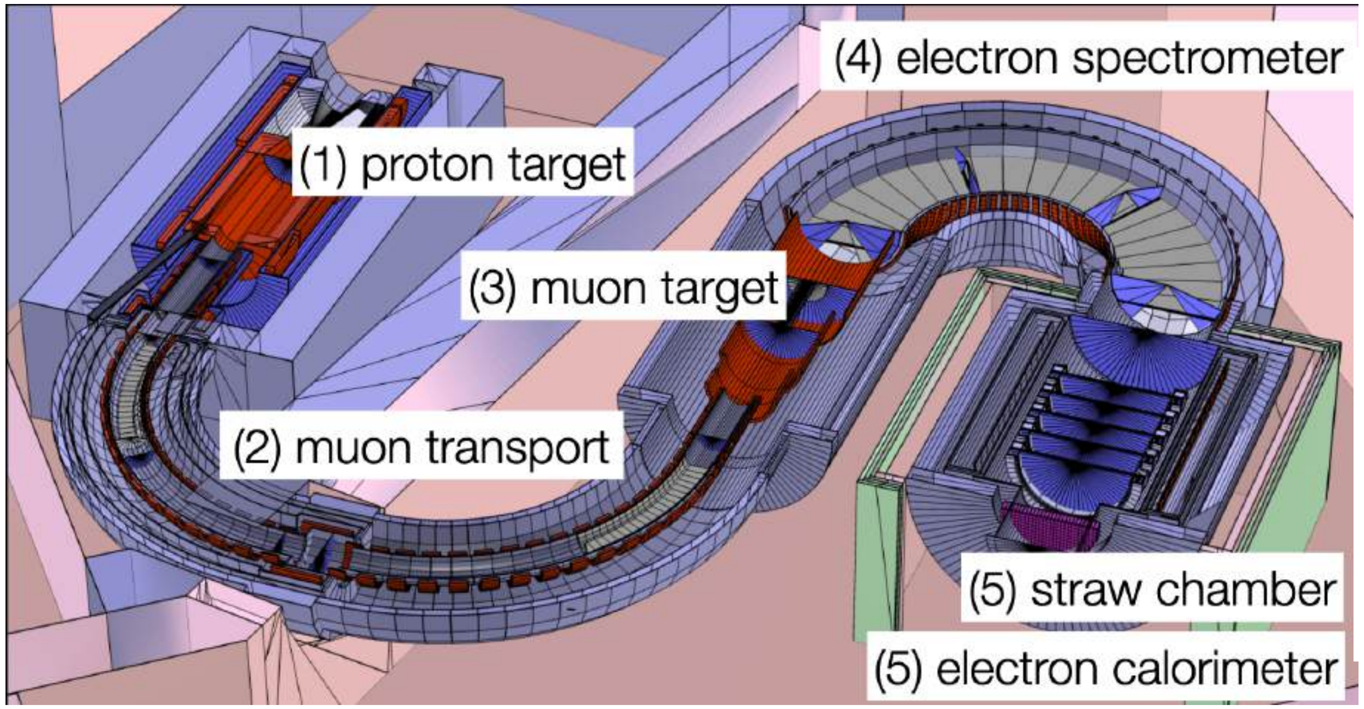
Majorana ν, sterile ν

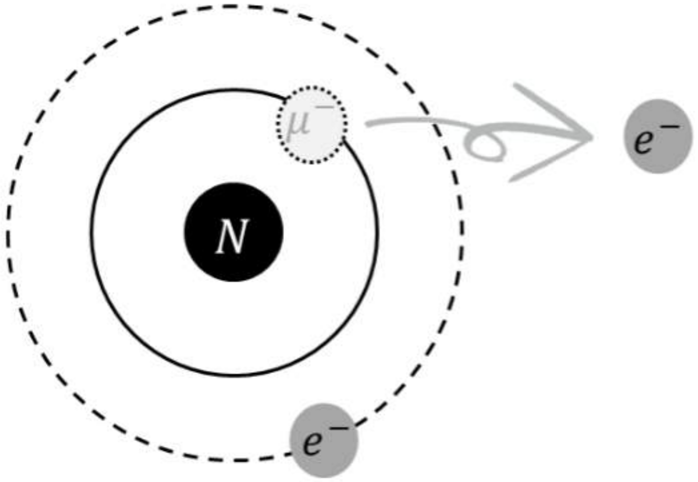
composite, leptogluon

slide borrowed from M. Yamanaka

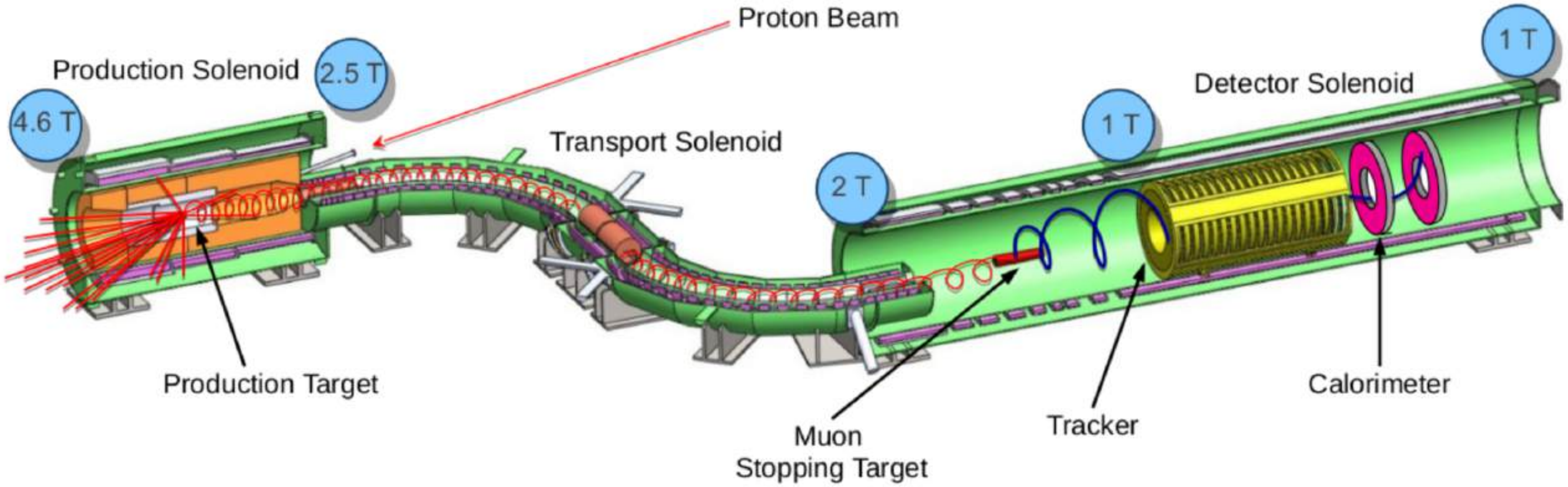
…. and more searches for muon LFV are under construction

$\mu \to e$ conversion in nuclei experiments





$\mu^- \to e^-$ conversion



What about tau CLFV?

Tau vs muons:

Tau lifetime much shorter:

$$\tau_\mu \simeq 2 \times 10^{-6}\mathrm{s} \quad \gg \quad \tau_\tau \simeq 3 \times 10^{-13}\mathrm{s}$$

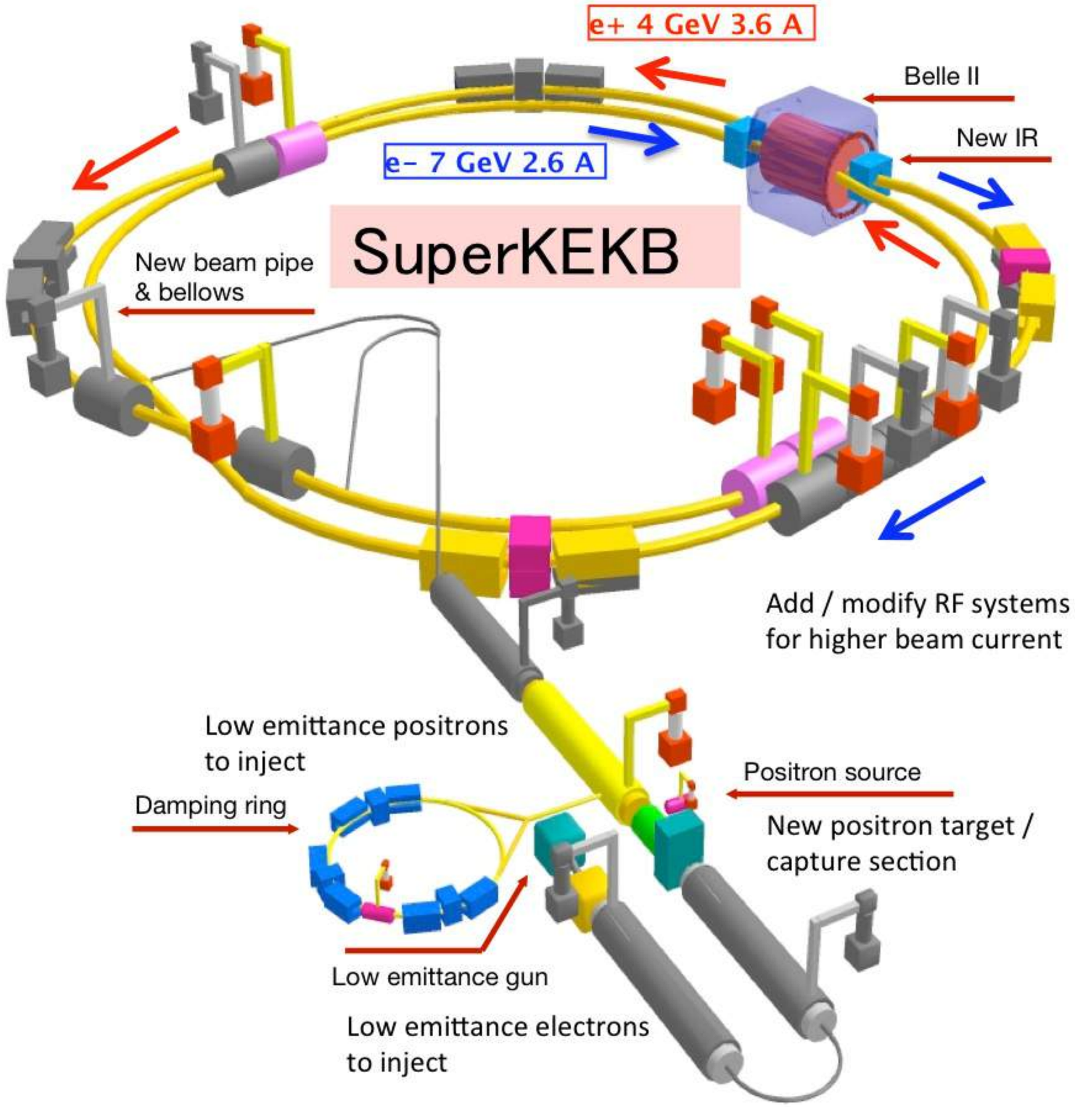
- We can not produce “tau beams”, stop them and observe the decays
- Taus only produced at colliders, e.g. $e^+e^- \to \tau^+\tau^-$ (Belle II), $pp \to \tau^+\tau^-$ (LHC)

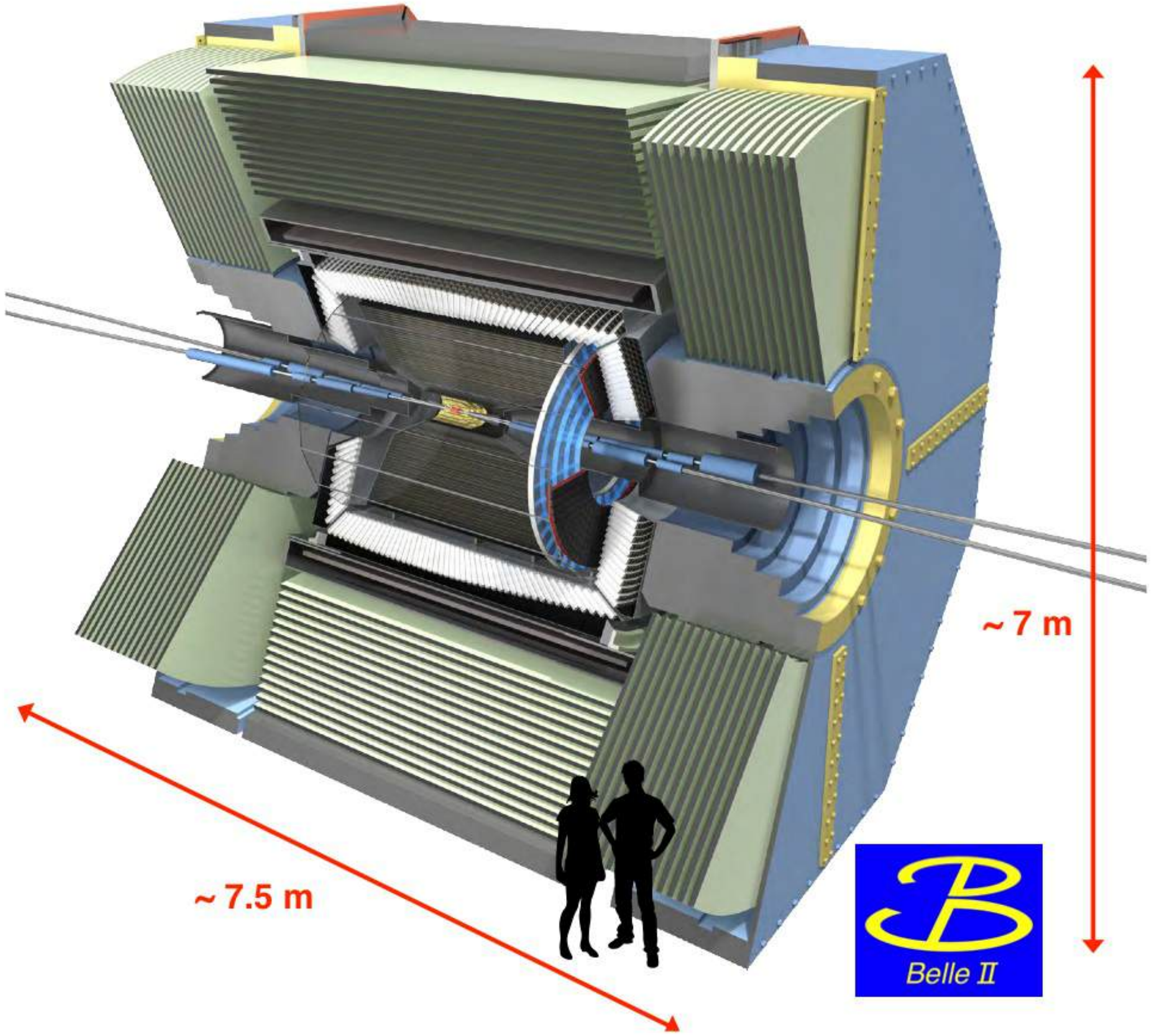
Tau much heavier:

$$m_\mu \simeq 0.106 \text{ GeV} \quad \ll \quad m_\tau \simeq 1.77 \text{ GeV}$$

- $m_\tau > m_\pi$: only lepton that can decay into hadrons
- In principle, many LFV decay modes one can search for

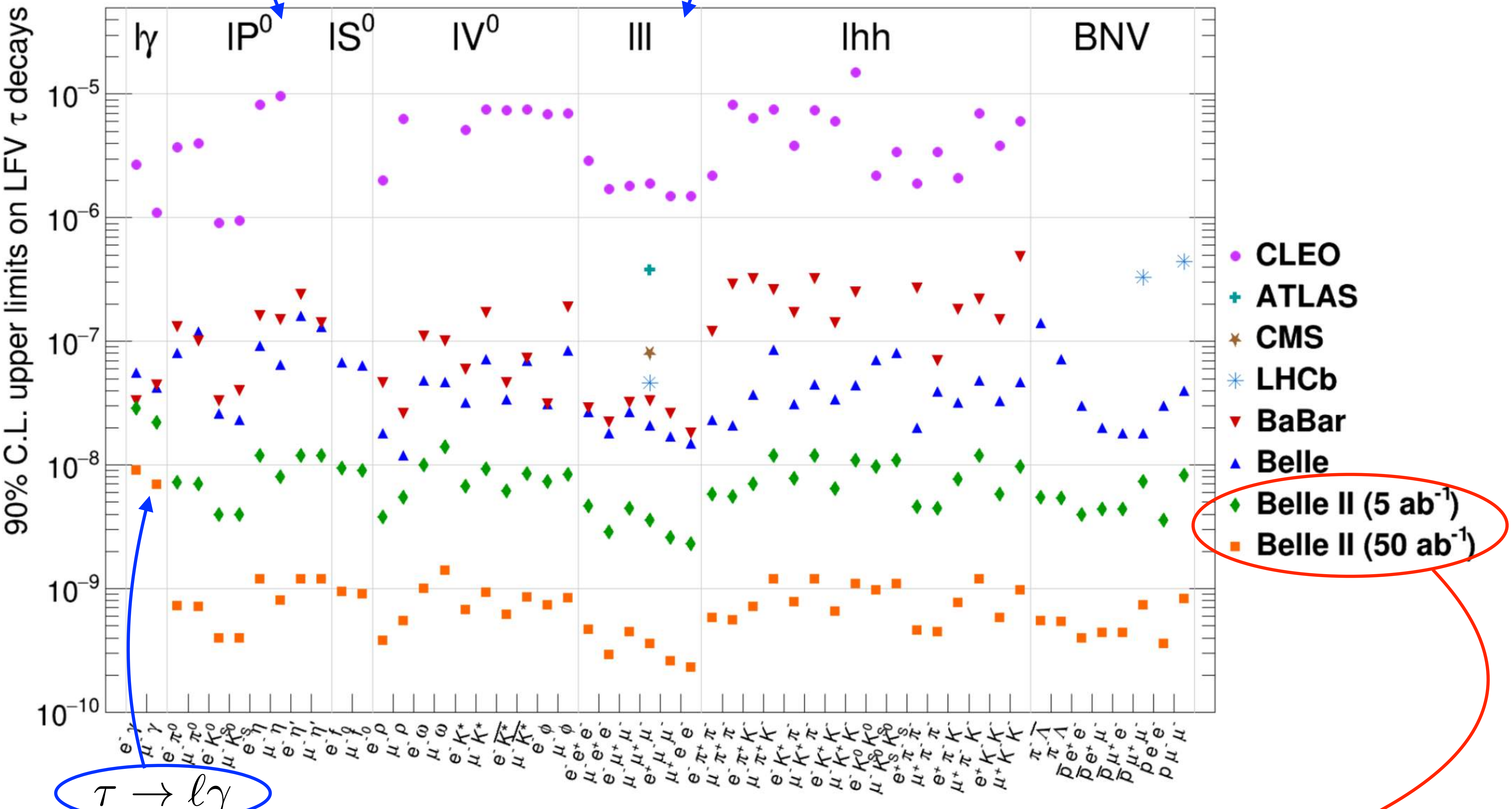
Current/upcoming experiments: Belle II





Currently running: within ~10 years, Belle II will collect more than 10^{10} $e^+e^- \to \tau^+\tau^-$ events

Belle II prospects for tau CLFV



$\tau \to \ell\, P$

$\tau \to \ell\, V$

$\tau \to \ell\ell'\ell'$

Belle II Snowmass, arXiv:2207.06307

$\tau \to \ell\gamma$

(limited by ISR bg)

Expected sensitivities

Lepton Flavour Violation

Lorenzo Calibbi (Nankai)

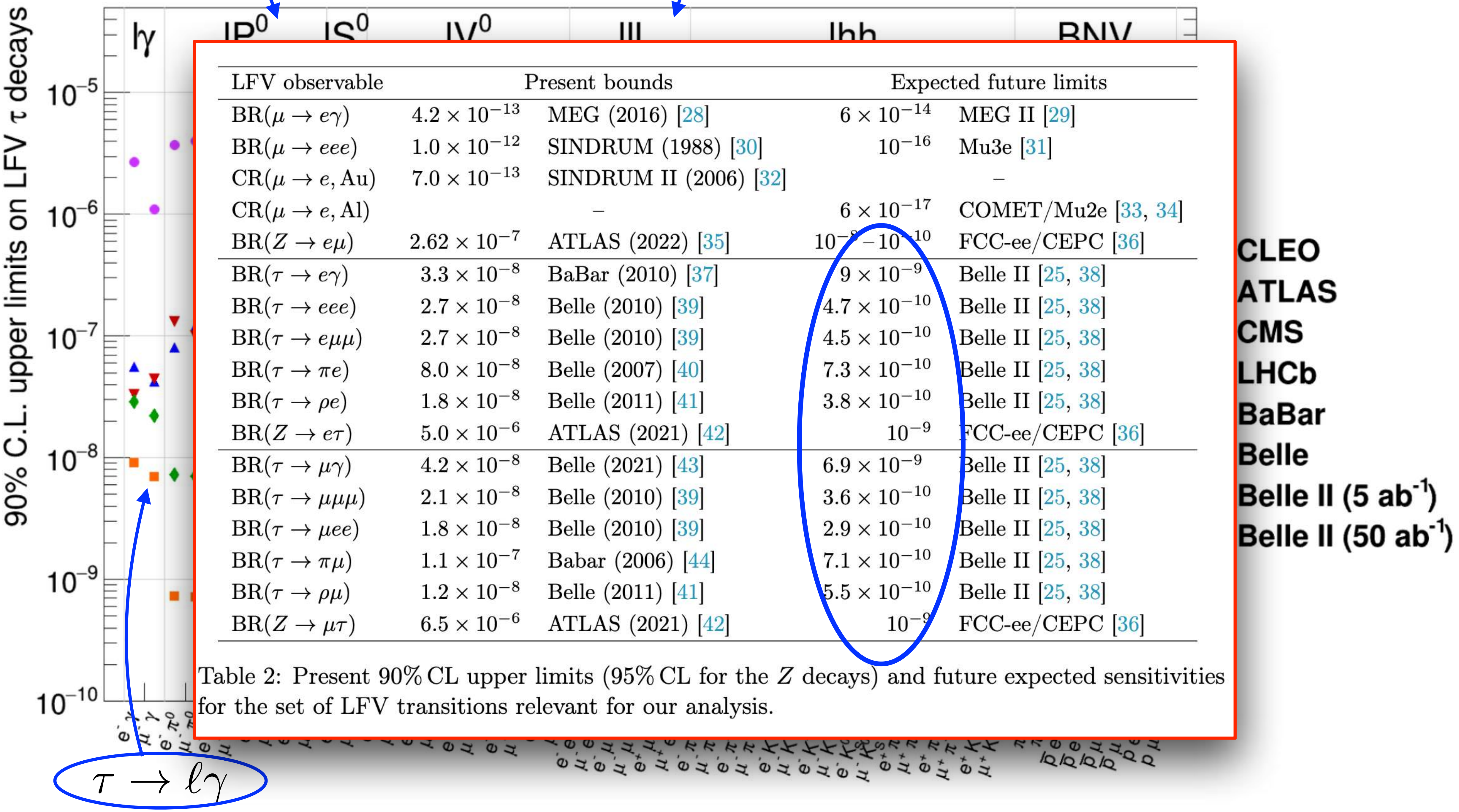
Belle II prospects for tau CLFV

$\tau \to \ell P$

$\tau \to \ell V$

$\tau \to \ell \ell' \ell'$

Belle II Snowmass, arXiv:2207.06307



LFV observable	Present bounds		Expected future limits	
BR($\mu \to e\gamma$)	4.2×10^{-13}	MEG (2016) [28]	6×10^{-14}	MEG II [29]
BR($\mu \to eee$)	1.0×10^{-12}	SINDRUM (1988) [30]	10^{-16}	Mu3e [31]
CR($\mu \to e$, Au)	7.0×10^{-13}	SINDRUM II (2006) [32]		–
CR($\mu \to e$, Al)		–	6×10^{-17}	COMET/Mu2e [33, 34]
BR($Z \to e\mu$)	2.62×10^{-7}	ATLAS (2022) [35]	$10^{-8} - 10^{-10}$	FCC-ee/CEPC [36]
BR($\tau \to e\gamma$)	3.3×10^{-8}	BaBar (2010) [37]	9×10^{-9}	Belle II [25, 38]
BR($\tau \to eee$)	2.7×10^{-8}	Belle (2010) [39]	4.7×10^{-10}	Belle II [25, 38]
BR($\tau \to e\mu\mu$)	2.7×10^{-8}	Belle (2010) [39]	4.5×10^{-10}	Belle II [25, 38]
BR($\tau \to \pi e$)	8.0×10^{-8}	Belle (2007) [40]	7.3×10^{-10}	Belle II [25, 38]
BR($\tau \to \rho e$)	1.8×10^{-8}	Belle (2011) [41]	3.8×10^{-10}	Belle II [25, 38]
BR($Z \to e\tau$)	5.0×10^{-6}	ATLAS (2021) [42]	10^{-9}	FCC-ee/CEPC [36]
BR($\tau \to \mu\gamma$)	4.2×10^{-8}	Belle (2021) [43]	6.9×10^{-9}	Belle II [25, 38]
BR($\tau \to \mu\mu\mu$)	2.1×10^{-8}	Belle (2010) [39]	3.6×10^{-10}	Belle II [25, 38]
BR($\tau \to \mu ee$)	1.8×10^{-8}	Belle (2010) [39]	2.9×10^{-10}	Belle II [25, 38]
BR($\tau \to \pi\mu$)	1.1×10^{-7}	Babar (2006) [44]	7.1×10^{-10}	Belle II [25, 38]
BR($\tau \to \rho\mu$)	1.2×10^{-8}	Belle (2011) [41]	5.5×10^{-10}	Belle II [25, 38]
BR($Z \to \mu\tau$)	6.5×10^{-6}	ATLAS (2021) [42]	10^{-9}	FCC-ee/CEPC [36]

Table 2: Present 90% CL upper limits (95% CL for the Z decays) and future expected sensitivities for the set of LFV transitions relevant for our analysis.

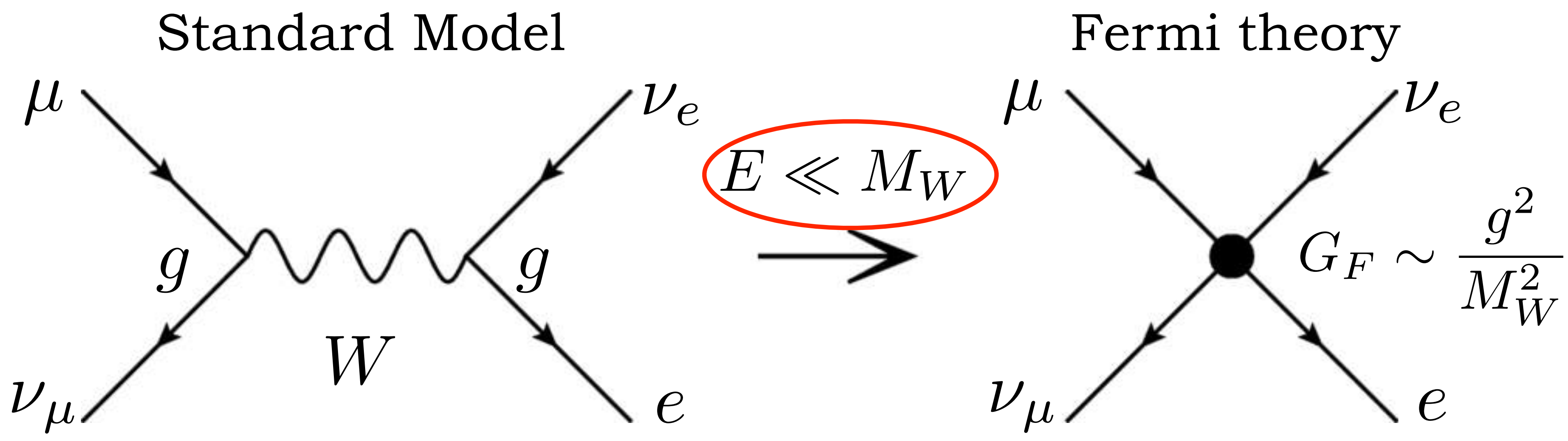
$\tau \to \ell\gamma$

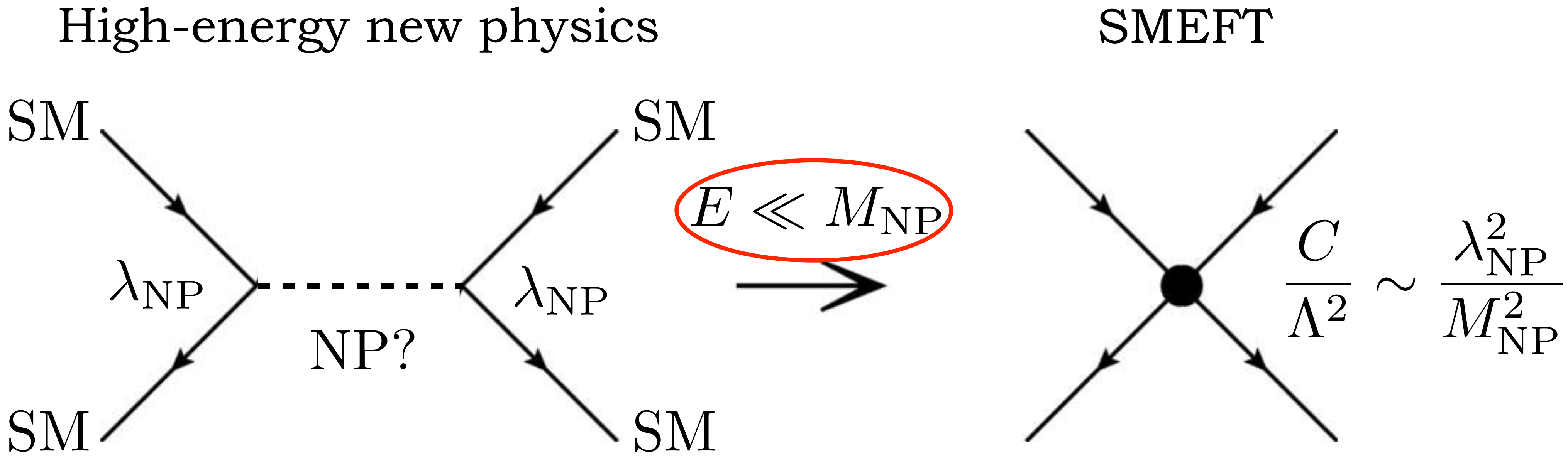
(limited by ISR bg)

Testing high-energy new physics

Heavy New Physics: Effective Field Theory approach

classic example:





SM effective field theory (SMEFT): we parametrize heavy NP introducing $D > 4$ operators purely made of SM fields, respecting SM symmetries

CLFV from heavy new physics (SMEFT)

If NP scale **Λ**≫m_{W} : $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \ldots$

Dimension-6 effective operators that can induce CLFV

4-leptons operators		Dipole operators	
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W_{\mu\nu}^I$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
2-lepton 2-quark operators			
$Q_{\ell q}^{(1)}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q_{\ell q}^{(3)}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}_L^a e_R)(\bar{d}_R Q_L^a)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q_{\ell equ}^{(1)}$	$(\bar{L}_L^a e_R)\epsilon_{ab}(\bar{Q}_L^b u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q_{\ell equ}^{(3)}$	$(\bar{L}_i^a\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}_L^b\sigma^{\mu\nu}u_R)$
Lepton-Higgs operators			
$Q_{\Phi\ell}^{(1)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q_{\Phi\ell}^{(3)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

Grzadkowski et al. ’10; Crivellin Najjari Rosiek ‘13

CLFV from heavy new physics (SMEFT)

If NP scale **Λ**≫m_W : $$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \ldots$$

Example: LFV 4-lepton operator

$$\frac{C_{\ell\ell}}{\Lambda^2}(\bar e_L \gamma_\mu \mu_L)(\bar e_L \gamma^\mu e_L)$$

$$\Longrightarrow \qquad {\rm BR}(\mu \to e e \bar e) = \frac{m_\mu^5}{768\,\pi^3\,\Gamma_\mu}\,\frac{|C_{\ell\ell}|^2}{\Lambda^4}$$

to be confronted with:

$$ {\rm BR}(\mu \to e e \bar e)^{\rm exp} < 1.0 \times 10^{-12}$$

⇨ constraint on C/Λ^2 !

$Q_{\Phi e}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar e_R \gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar L_L e_R \Phi)(\Phi^\dagger \Phi)$

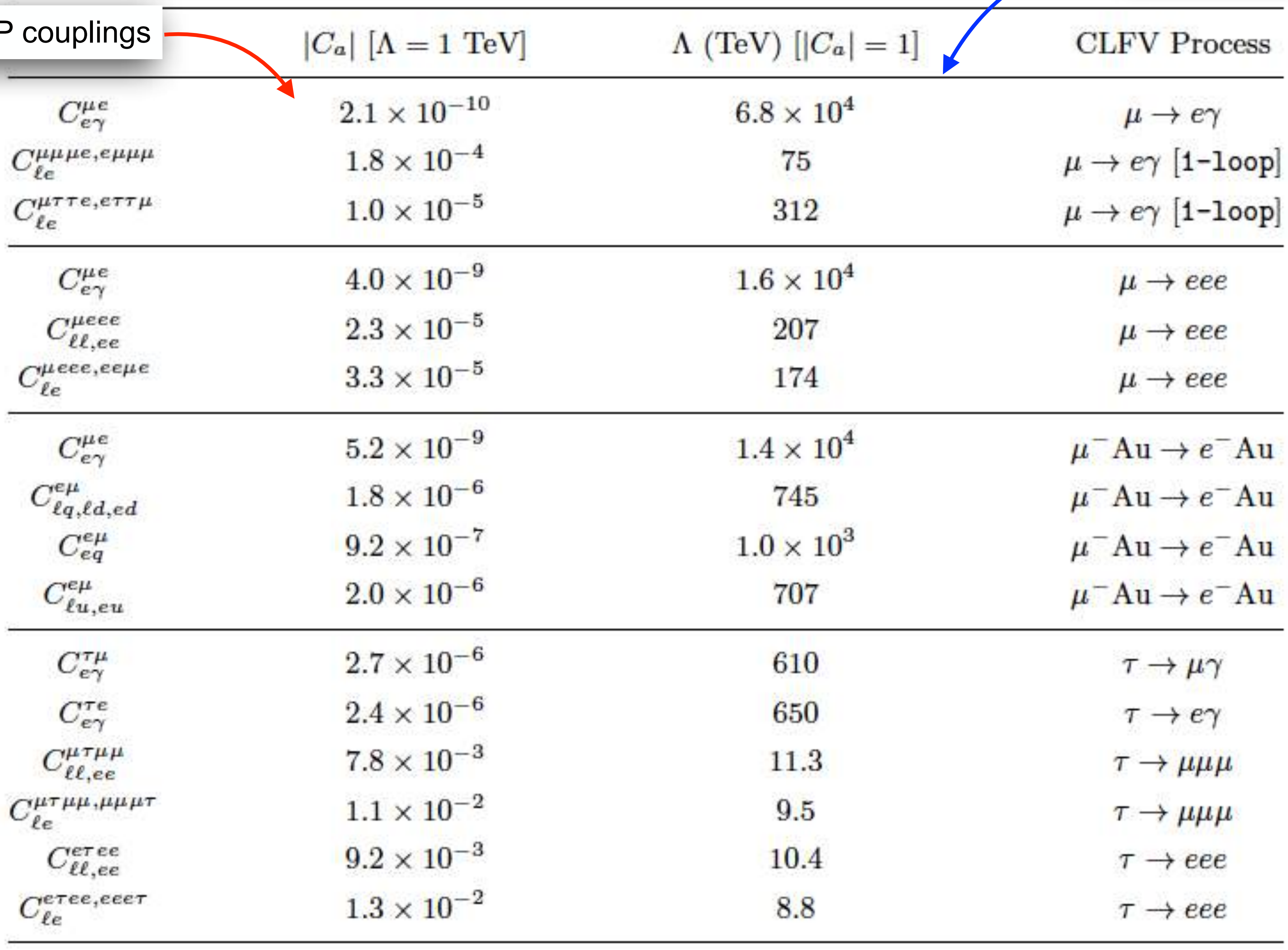
Grzadkowski et al. '10; Crivellin Najjari Rosiek '13

CLFV probes very high-energy scales

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

lower limits on the NP masses

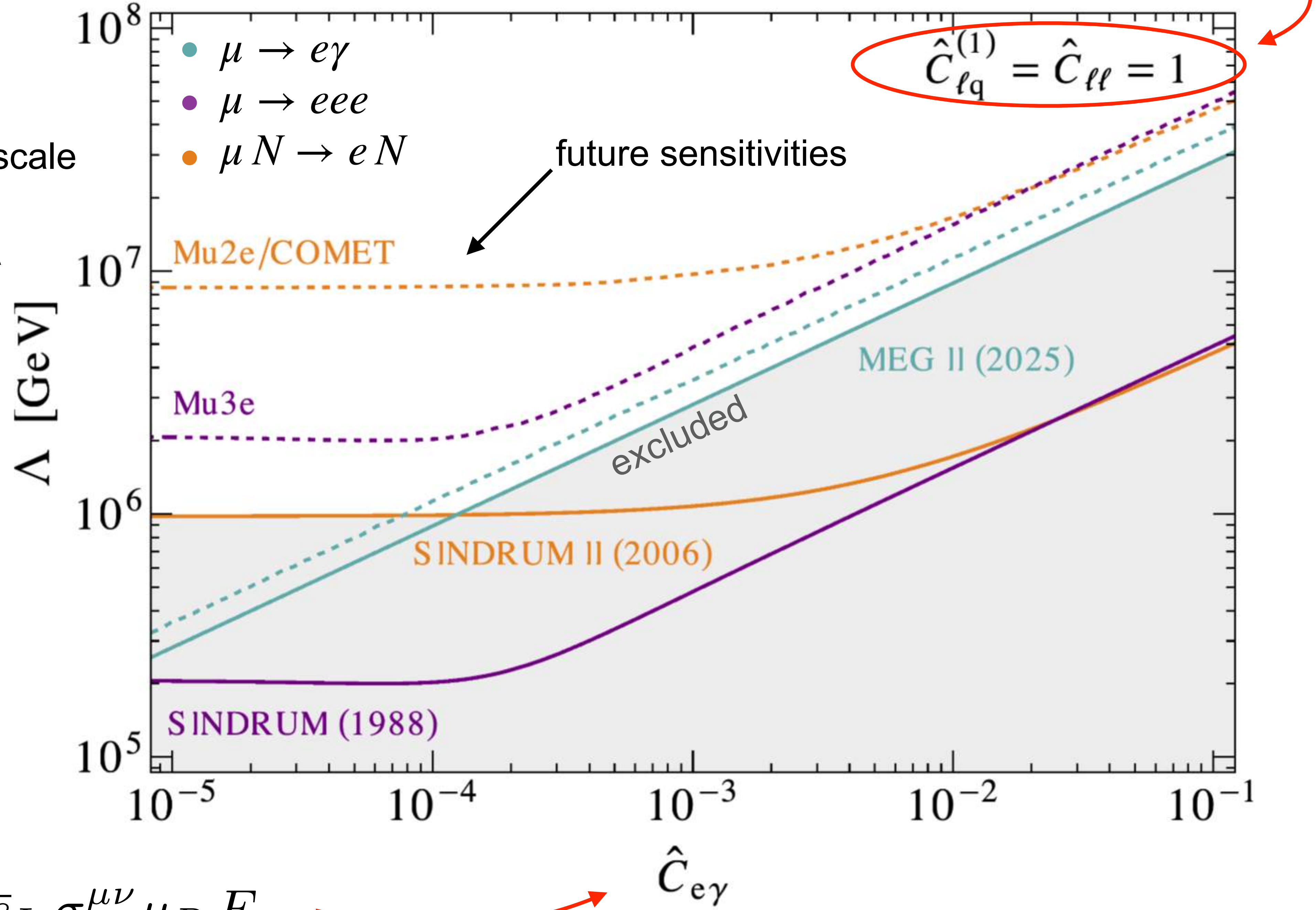
upper limits on the NP couplings



	$\lvert C_a \rvert$ $[\Lambda = 1$ TeV$]$	Λ (TeV) $[\lvert C_a \rvert = 1]$	CLFV Process
$C_{e\gamma}^{\mu e}$	2.1×10^{-10}	6.8×10^{4}	$\mu \to e\gamma$
$C_{\ell e}^{\mu\mu\mu e, e\mu\mu\mu}$	1.8×10^{-4}	75	$\mu \to e\gamma$ [1-loop]
$C_{\ell e}^{\mu\tau\tau e, e\tau\tau\mu}$	1.0×10^{-5}	312	$\mu \to e\gamma$ [1-loop]
$C_{e\gamma}^{\mu e}$	4.0×10^{-9}	1.6×10^{4}	$\mu \to eee$
$C_{\ell\ell, ee}^{\mu eee}$	2.3×10^{-5}	207	$\mu \to eee$
$C_{\ell e}^{\mu eee, ee\mu e}$	3.3×10^{-5}	174	$\mu \to eee$
$C_{e\gamma}^{\mu e}$	5.2×10^{-9}	1.4×10^{4}	$\mu^-{\rm Au} \to e^-{\rm Au}$
$C_{\ell q, \ell d, ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^-{\rm Au} \to e^-{\rm Au}$
$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^{3}	$\mu^-{\rm Au} \to e^-{\rm Au}$
$C_{\ell u, eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^-{\rm Au} \to e^-{\rm Au}$
$C_{e\gamma}^{\tau\mu}$	2.7×10^{-6}	610	$\tau \to \mu\gamma$
$C_{e\gamma}^{\tau e}$	2.4×10^{-6}	650	$\tau \to e\gamma$
$C_{\ell\ell, ee}^{\mu\tau\mu\mu}$	7.8×10^{-3}	11.3	$\tau \to \mu\mu\mu$
$C_{\ell e}^{\mu\tau\mu\mu, \mu\mu\mu\tau}$	1.1×10^{-2}	9.5	$\tau \to \mu\mu\mu$
$C_{\ell\ell, ee}^{e\tau ee}$	9.2×10^{-3}	10.4	$\tau \to eee$
$C_{\ell e}^{e\tau ee, eee\tau}$	1.3×10^{-2}	8.8	$\tau \to eee$

CLFV probes very high-energy scales

E.g., dipole *and* 4-fermion operators: $\frac{C_{\ell q}}{\Lambda^2}(\bar{e}_L\gamma_\mu\mu_L)(\bar{Q}\gamma^\mu Q)$ $\frac{C_{\ell\ell}}{\Lambda^2}(\bar{e}_L\gamma_\mu\mu_L)(\bar{e}_L\gamma^\mu e_L)$



new physics scale

future sensitivities

$\frac{C_{e\gamma}}{\Lambda^2}\langle H\rangle\,\bar{e}_L\,\sigma^{\mu\nu}\mu_R\,F_{\mu\nu}$

dipole coefficient

LFV selection rules from residual symmetries

Very high energies ($\gg$ LHC's c.o.m. E) can be tested

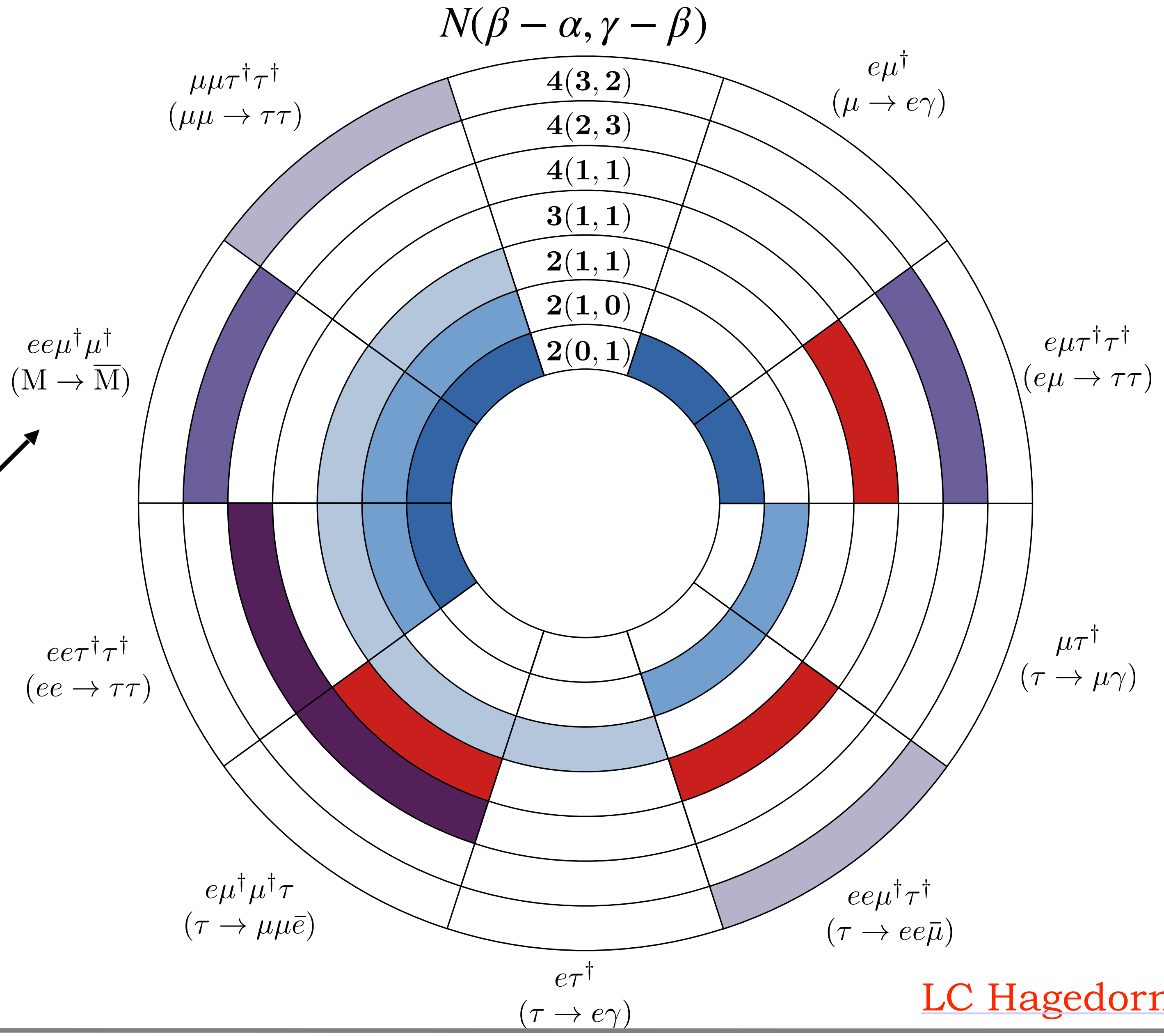
$\mu \to e$ conversion in nuclei seems to be the most powerful probe

BUT...

it is important to look for any channels:
non-trivial symmetries might forbid certain processes allowing others

$$G_\ell = \mathbb{Z}_N(\alpha,\beta,\gamma)$$

residual symmetry
for charged leptons
and charges



muonium to
anti-muonim
conversion

LC Hagedorn Schmidt Vandeleur '25

LFV selection rules from residual symmetries

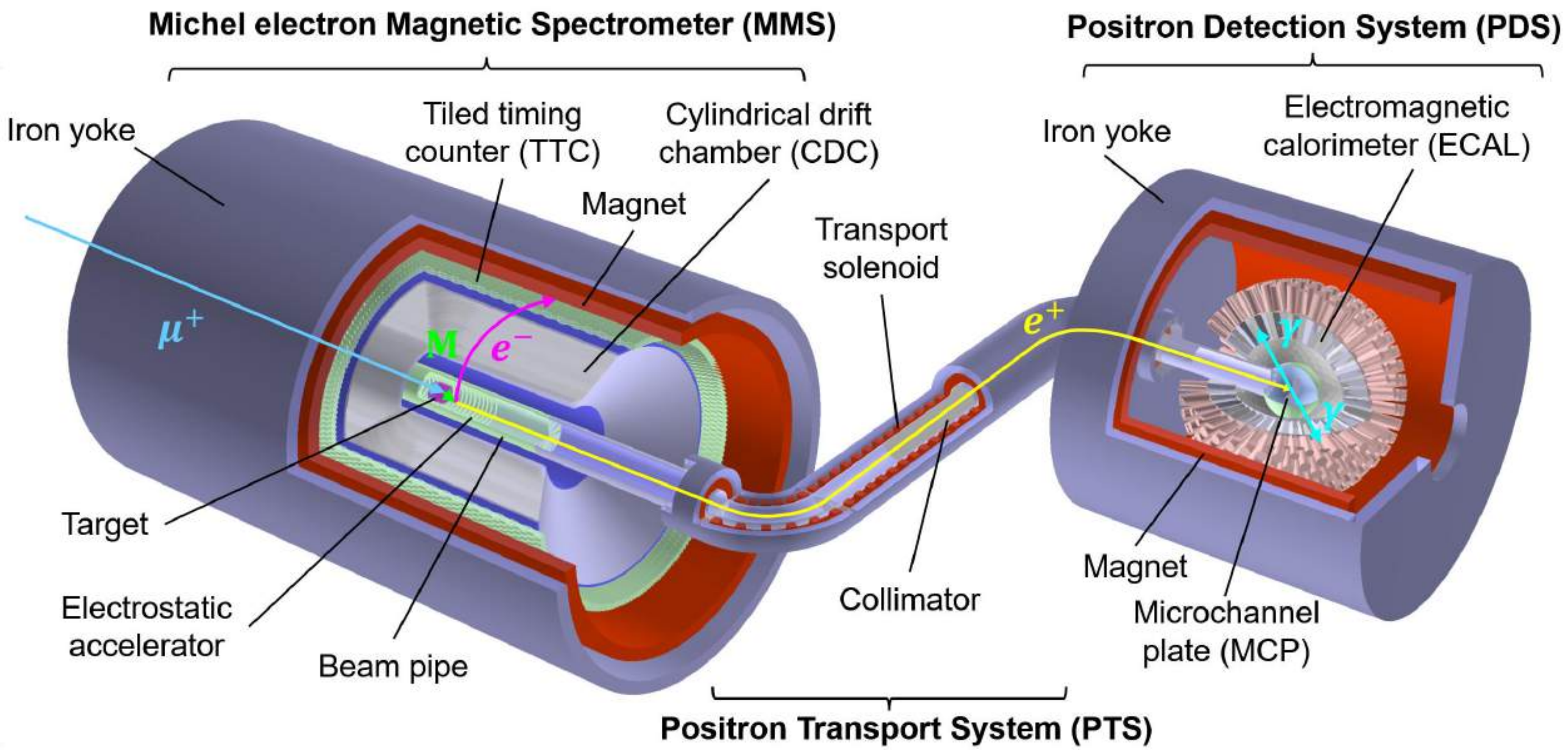
Very high energies ($\gg$ LHC's c.o.m. E) can be tested

MACE will increase the sensitivity on the

$|\Delta L_\mu| = |\Delta L_e| = 2$ process

$\mathrm{Mu}\,(\mu^+e^-) \to \overline{\mathrm{Mu}}\,(\mu^-e^+)$

by about three order of magnitude



➡ $P_{\mathrm{Mu}\,\overline{\mathrm{Mu}}} < 7 \times 10^{-14}$ MACE '24

no

ers

$G_\ell = \mathbb{Z}$

residual s

for charge

and ch

muoni

anti-m

conve

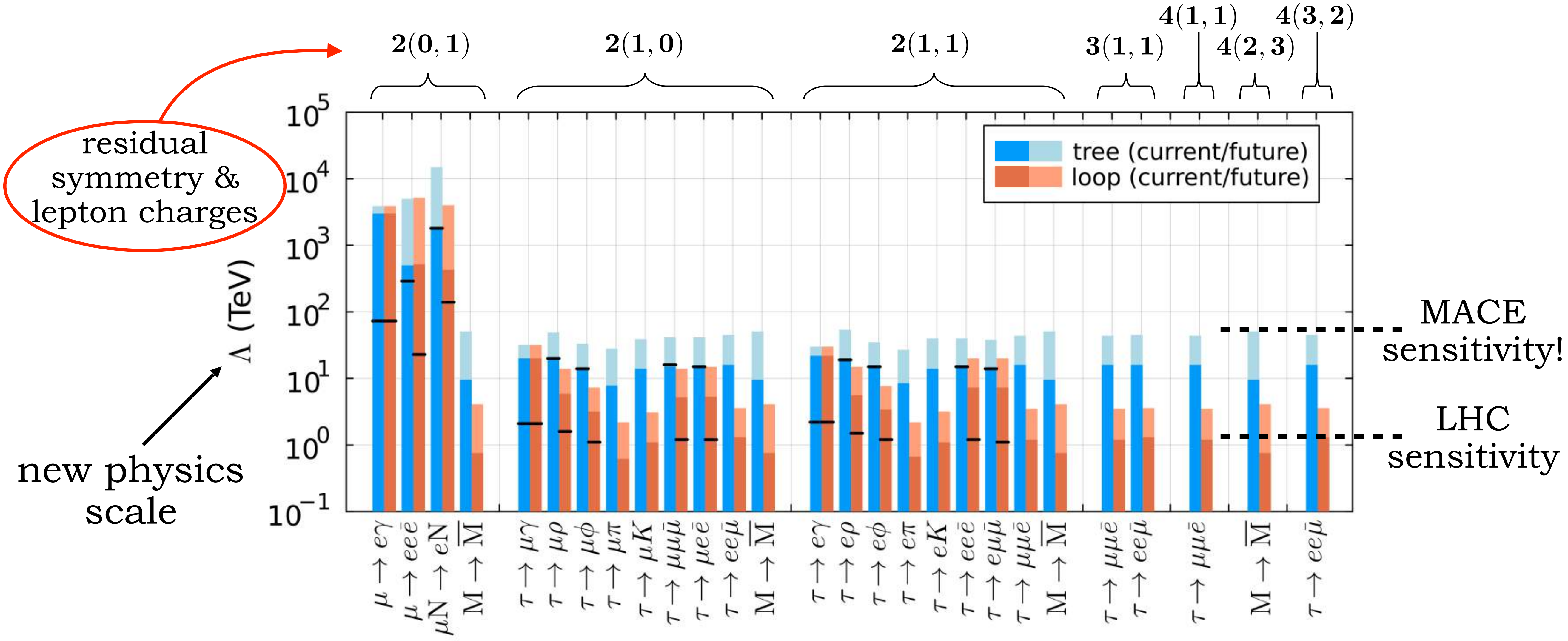
$e\tau^\dagger$

$(\tau \to e\gamma)$

LC Hagedorn Schmidt Vandeleur '25

LFV selection rules from residual symmetries

- Many models of neutrino masses and mixing introduce discrete flavour symmetries (e.g. A_4)
- After symmetry breaking, a residual Abelian symmetry (Z_N) in the charged lepton sector is often preserved (at least approximately)
- A residual symmetry imply selection rules on the possible LFV operators
- $\mu \to e$ decays may be forbidden such that τ and muonium CLFV is stronger



residual symmetry & lepton charges

new physics scale

MACE sensitivity!

LHC sensitivity

LC Hagedorn Schmidt Vandeleur '25

Summary

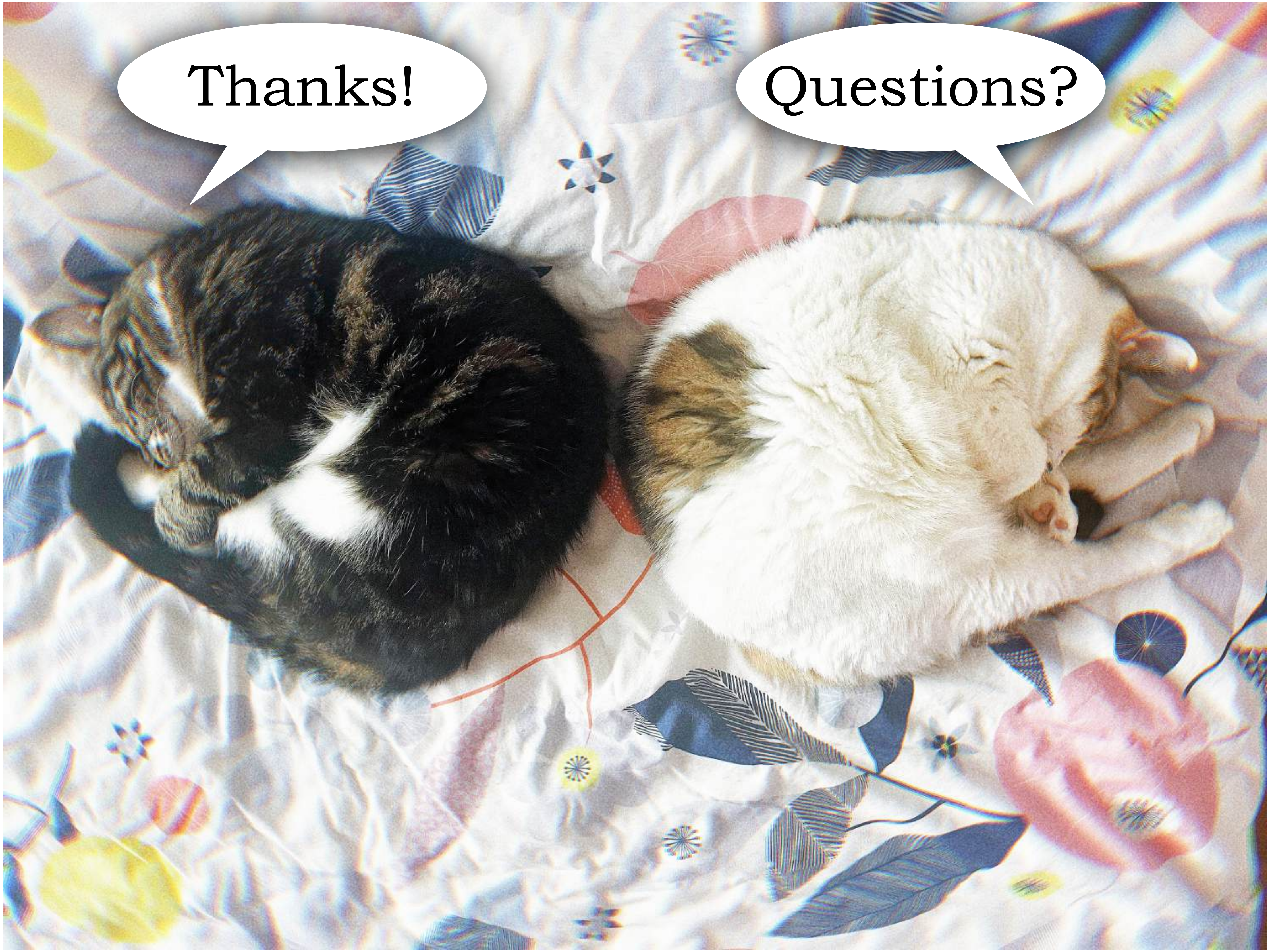
CLFV does not occur within the Standard Model

Hence, CLFV processes are among the cleanest
and most stringent tests of new physics

Present/future CLFV experiments can test new physics
up to very large energies: of the order of $10^7 - 10^8$ GeV

We might have indirect evidence of new particles or
interactions in the upcoming years!

For a pedagogical introduction to CLFV, check out:
LC and Signorelli arXiv:1709.00294


Thanks!
Questions?