Charged Lepton Flavour Violation and energy frontier colliders

Spanish LHC network meeting,

CIEMAT, May 2018

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LFU, LFV and future colliders

Lepton Flavour Universality (LFU): "The coupling of the leptons to (gauge) bosons are flavour-independent".

Charged lepton flavour violation (cLFV): an interaction where a charged lepton changes flavour, without compensating neutrinos

Neutrino oscillations are a clear example of lepton flavour violation
Quarks flavours mix following the CKM matrix
Charged-lepton interactions, however, seem to conserve lepton flavour, i.e. $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

B-factories see several (related?) anomalies that seem to point to a possible violation of lepton flavour universality
Does this necessarily make lepton flavour violation more plausible?
Where should we look, how large can the effect be?

In the next slides:
explore cFLV at (future) energy frontier colliders

Intermezzo on LFU

$$BR(W \to e\nu) = BR(W \to \mu\nu) = BR(W \to \tau\nu)?$$

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.86 ± 0.09) %	
Γ_2	$e^+\nu$		(10.71 ± 0.16) %	
Γ_3	$\mu^+\nu$		(10.63 ± 0.15) %	
Γ_4	$\tau^+\nu$		(11.38 ± 0.21) %	
Γ_5	hadrons		(67.41 ± 0.27) %	
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$	95%
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	95%
Γ_8	cX		(33.3 ± 2.6) %	
Γ_9	$c\bar{s}$		$(31 {}^{+13}_{-11})$ %	
Γ_{10}	invisible	[b]	(1.4 ± 2.9) %	

[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[b] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, p< 200 MeV.

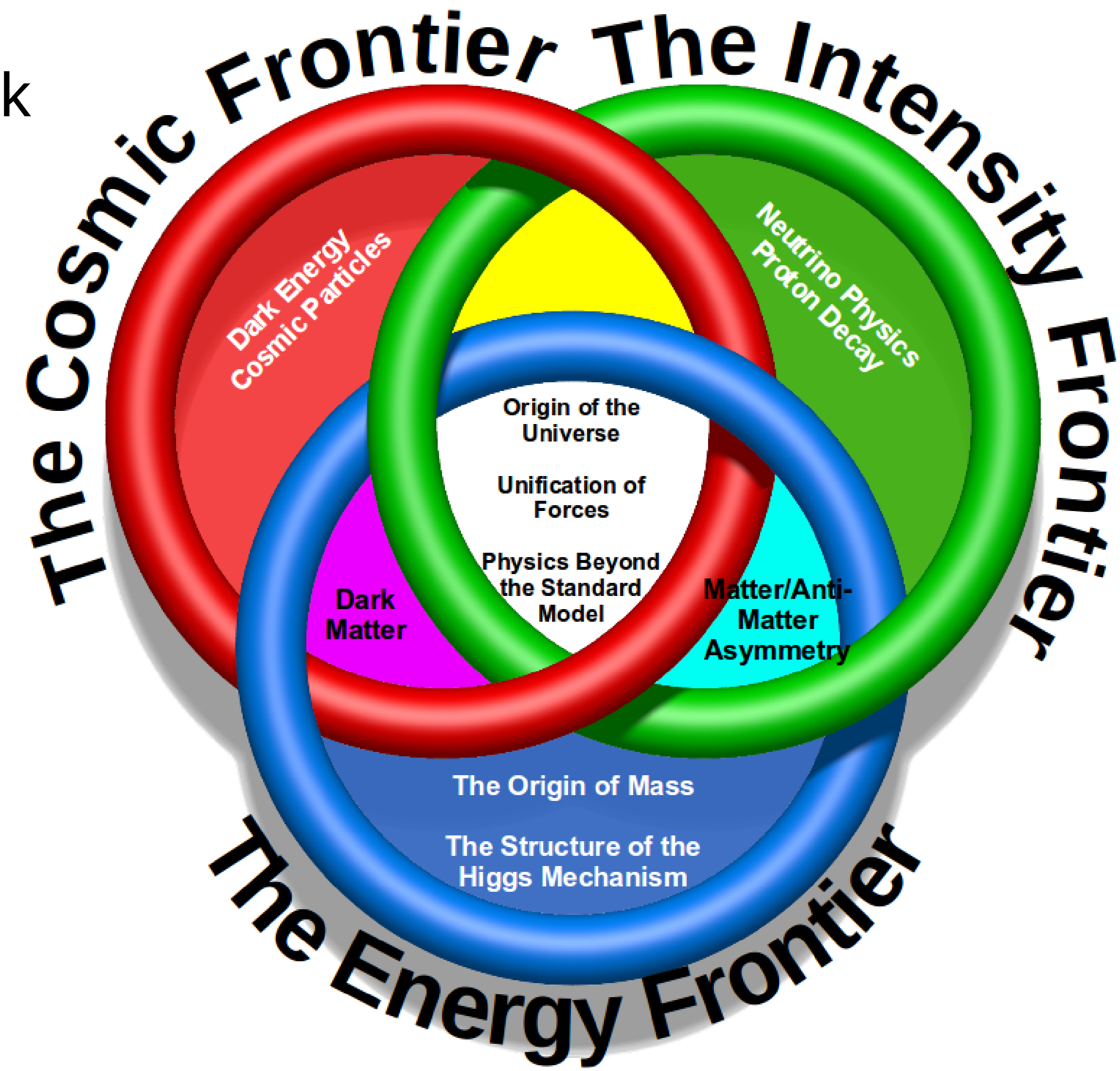
LEP, LC

PDG2017

Hints of cLFV are not new!!

The three (interlinked) frontiers

Let the cosmos do the dirty work (and hope to understand the fundamental physics)



Produce a lot of stuff, look for subtle effects

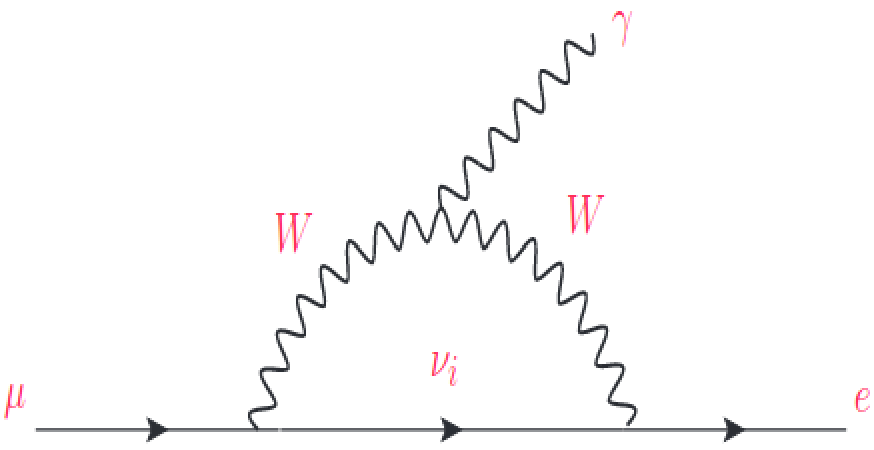
Produce energetic stuff and hope for less subtle effects

LFU, LFV and colliders

Decays such as $\mu \to e\,\gamma$

are extremely suppressed

in the SM: BR ~ 10^{-54}

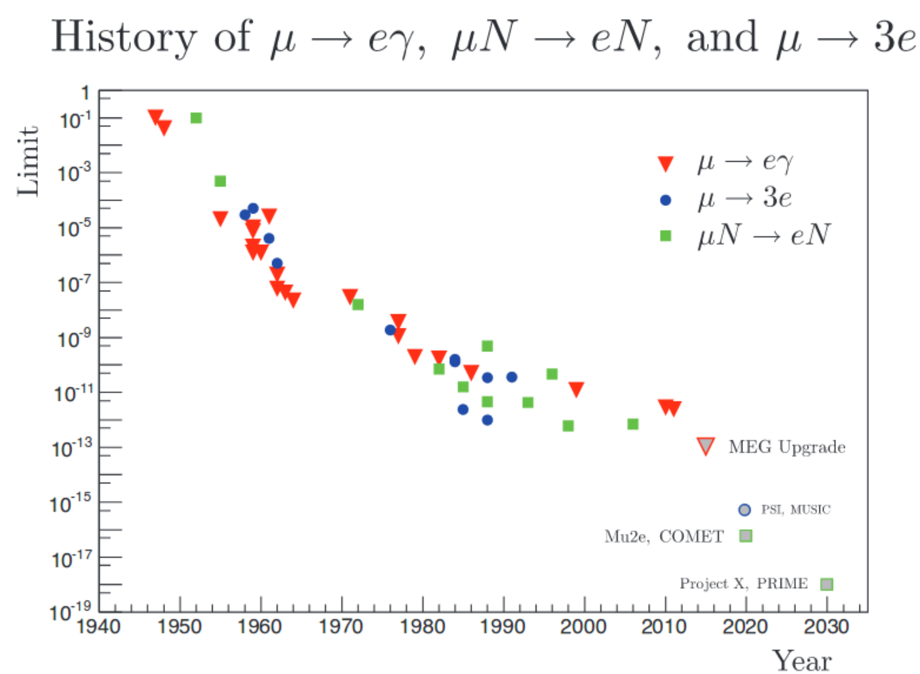


Dedicated experiments look for cLFV

MEG (PSI): BR < 10^{-13},

Mu2e (FNAL): BR < 10^{-17}

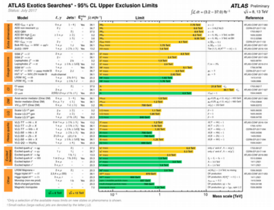
Mu3e (PSI): BR ($\mu \to$ eee) < 10^{-16}

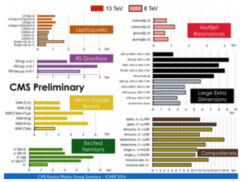


History and future of the intensity frontier, from Ref. 1307.5787

cLFV and energy-frontier colliders

- Existing and new energy frontier machines hope to produce the massive new particles that are responsible for cLFV (i.e. Z', W', massive neutrinos, leptoquarks, …)
- Current limits from LHC… 0.7-4 TeV





- New pp colliders: HE-LHC @ 30 TeV, FCChh/SPPC @ 100 TeV

  → mass limit scales as LHC * sqrt(s)/13

- New e^+e^- colliders: ILC 0.25-1 TeV, CLIC 0.38-3 TeV, FCCee/CEPC 0.09 – 0.36 TeV

  → mass limit typically sqrt(s)/2

- Exotic projects: ep collider (i.e. LHeC), or muon collider can be very interesting for specific models

CFLV and energy frontier colliders

New, improved precision measurements

- cLFV: Z-pole running: $Z \rightarrow e\mu/\mu\tau/e\tau$
- cLFV: Higgs factory: $H \rightarrow \mu e/\mu\tau/e\tau$
- cLFV: Top production: $t \rightarrow e\mu q$

S. Davidson, M. Mangano et al.
Eur. Phys. J. C (2015) 75: 450

Think of the new colliders as an intense source of massive objects (W, Z, H, t) and perform precision searches for rare decays

Typically, hadron colliders are more intense, but lepton colliders achieve higher precision. Especially for “not-so-obvious” final states.

CLFV collider synergy

Group	Process	Current	Future	
$\Delta(L_e - L_\mu) = 2$	$\mu \to e\gamma$	4.2×10^{-13} [15]	4×10^{-14} [16]	MeG, Mu2e, SINDRUM, COMET
	$\mu \to e\bar{e}e$	1.0×10^{-12} [17]	10^{-16} [18]	
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$ [19]	10^{-17} [20, 21]	
	$h \to e\bar{\mu}$	3.5×10^{-4} [22]	2×10^{-4} [23]	ATLAS, CMS, LC
	$Z \to e\bar{\mu}$	7.5×10^{-7} [24]	–	
	had$\to e\bar{\mu}$(had)	4.7×10^{-12} [25]	10^{-12} [26]	BNL, NA62
$\Delta(L_e - L_\tau) = 2$	$\tau \to e\gamma$	3.3×10^{-8} [27]	10^{-9} [28]	Babar, Belle, Belle II [28]=SuperB report
	$\tau \to e\bar{e}e$	2.7×10^{-8} [29]	10^{-9} [28]	
	$\tau \to e\bar{\mu}\mu$	2.7×10^{-8} [29]	10^{-9} [28]	
	$\tau \to e\,$had	$\mathcal{O}(10^{-8})$ [30]	10^{-9} [28]	
	$h \to e\bar{\tau}$	6.9×10^{-3} [22]	5×10^{-3} [23]	ATLAS, CMS, LC
	$Z \to e\bar{\tau}$	9.8×10^{-6} [31]	–	LEP, LC
	had$\to e\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$ [32, 33]	–	BES, BABAR, BELLE, BELLE II
$\Delta(L_\mu - L_\tau) = 2$	$\tau \to \mu\gamma$	4.4×10^{-8} [27]	10^{-9} [28]	Babar, Belle, Belle II [28]=SuperB report
	$\tau \to \mu\bar{e}e$	1.8×10^{-8} [29]	10^{-9} [28]	
	$\tau \to \mu\bar{\mu}\mu$	2.1×10^{-8} [29]	10^{-9} [28]	
	$\tau \to \mu\,$had	$\mathcal{O}(10^{-8})$ [30]	10^{-9} [28]	
	$h \to \mu\bar{\tau}$	1.2×10^{-2} [7]	5×10^{-3} [23]	ATLAS, CMS, LC
	$Z \to \mu\bar{\tau}$	1.2×10^{-5} [34]	–	LEP, LC
	had$\to \mu\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$ [32, 33]	–	BES, BABAR, BELLE, BELLE II

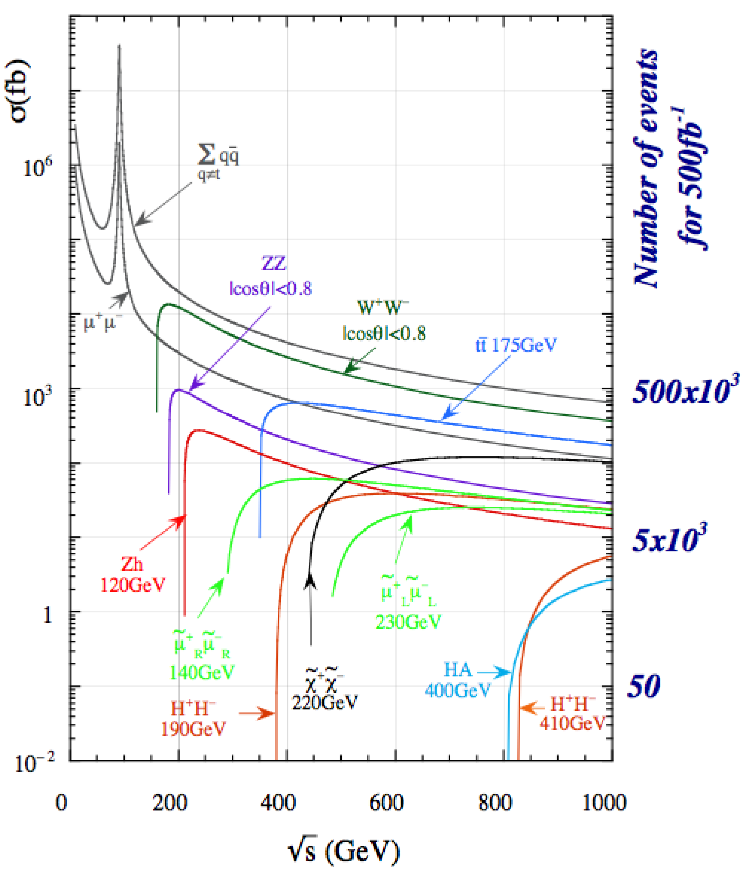
TABLE I: CLFV with conserved L and B, omitting CP conjugate processes. Current limits on the branching ratios are at 90% C.L. (h/Z decays at 95% C.L.). A full list of CLFV involving hadrons (had) can be found in the PDG [30].

From: arXiv:1610.07623v2 [hep-ph]

Linear collider Z, Higgs, top

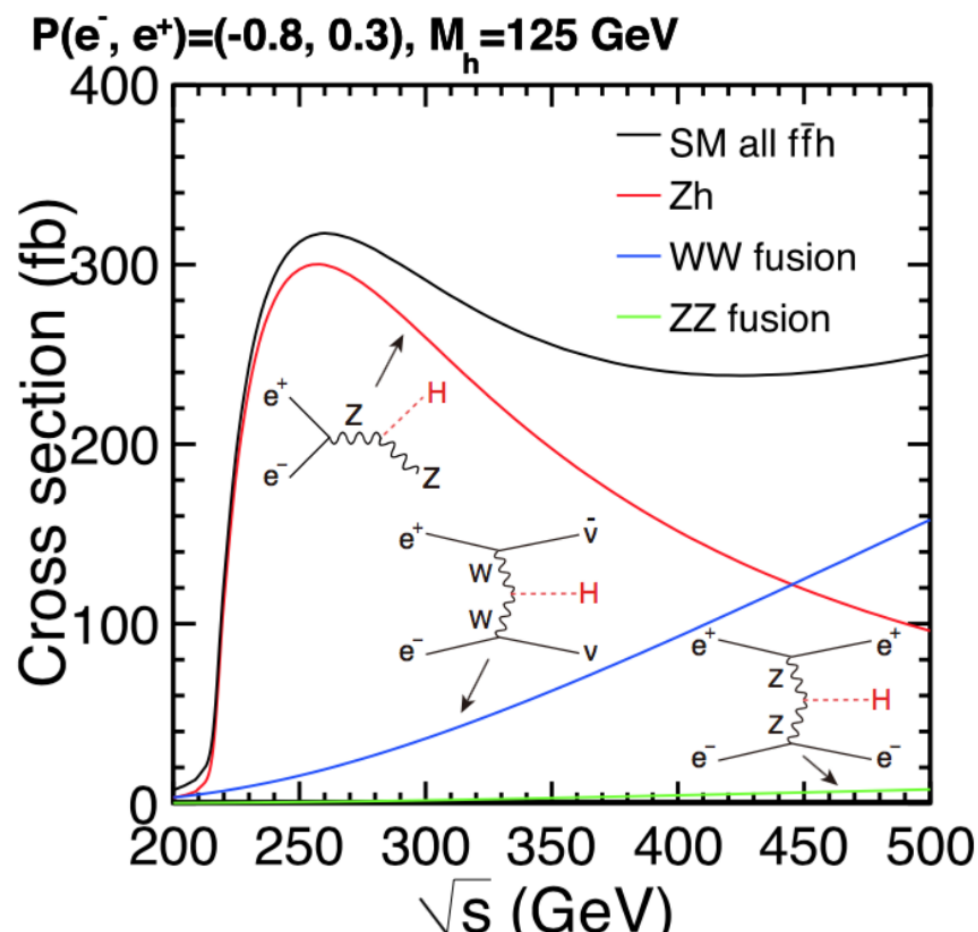
ILC / Higgs factory at 250 GeV:

- half a million Higgs bosons
- 1 million Z-boson pairs
- 10 million W-boson pairs



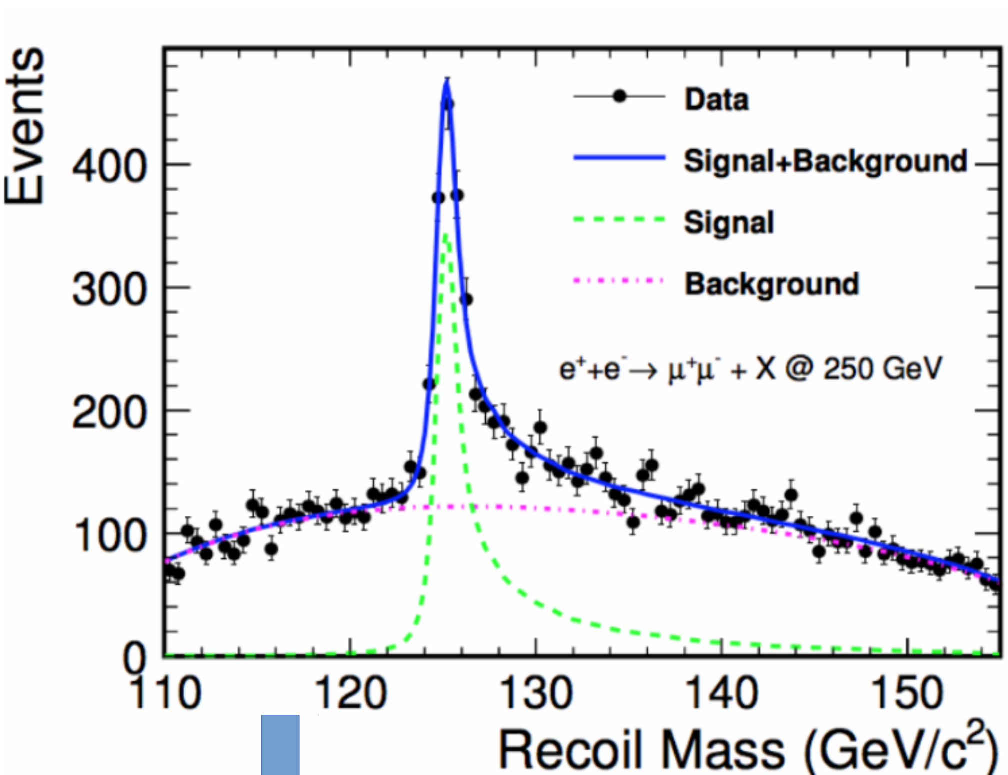
Higher energy → low s-channel rates, but high lumi & high sensitivity & t-channel

tt, tth, hh production require high energy

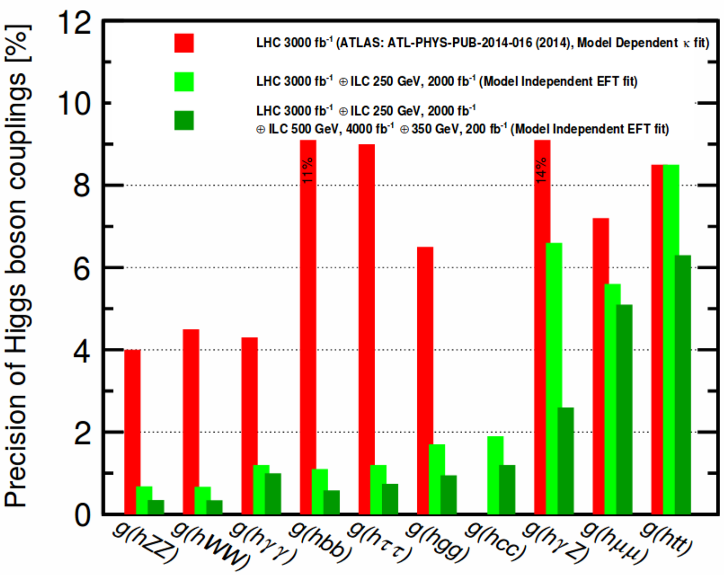


Prospects & Eur. strategy

- Detailed prospect studies missing for Z, H $\rightarrow$ ll’
- Higgs recoil-mass analysis is likely a goldmine



Standard couplings



Exotic decays
limit on invisible decays
is upper limit (0.3%)
Dedicated analysis ???

Invisible decays

The 250 GeV ILC is expected to be sensitive to invisible Higgs decays with branching ratios as small as 0.3% [20], a factor of 20 below the expected HL-LHC sensitivity, arXiv:1710.07621