* Examples of physics opportunities at CERN with precision measurements.

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A lot of material taken from the Intensity Frontier workshop report, Snowmass 2013, arXiv:1401.6077

Introduction

Main problem we have today in HEP is that we know there is physics beyond the SM (dark matter (energy), neutrino oscillations, matter anti-matter asymmetry) but we don't know at what energy scale(s).

Ideally, we would like to have an indication of this(these) energy scale(s) from experiment, before investing our limited resources in a mega-project. If it turns out that the energy of the LHC is not enough, the only chance is through "relevant" precision measurements.

Using the LHC data, **ATLAS** and **CMS** will measure with O(10%) or better precision the Yukawa couplings of the Higgs boson and will have a look at other interesting precision measurements like FCNC in top decays. **LHCb** will improve the measurements of FCNC in b and c decays, and will precisely measure the phase of couplings.

NA62 at the SPS will be looking at FCNC in s decays.

Are there other physics opportunities at CERN that:

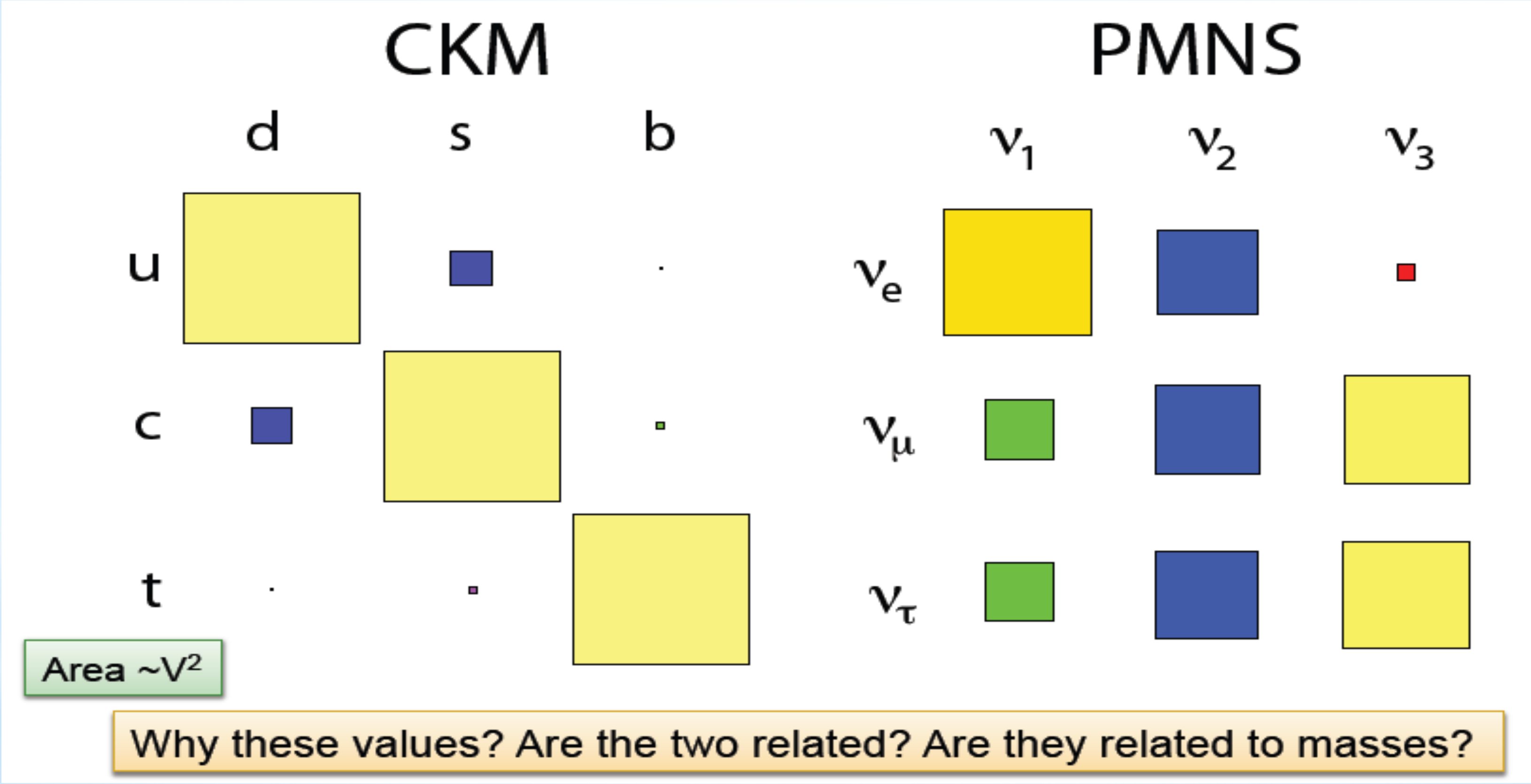
a) are sensitive probes of the scale of NP?

b) cannot be done elsewhere or can be done significantly better at CERN?

Charged Lepton Flavour Violation

Why?

We know there are FCNC in the lepton sector (analogous to the quark sector) because we have observed neutrino oscillations. Therefore the Yukawa couplings in the lepton sector do contain also a mixing matrix.



Can the seesaw mechanism explain the very different structures between quarks and leptons?

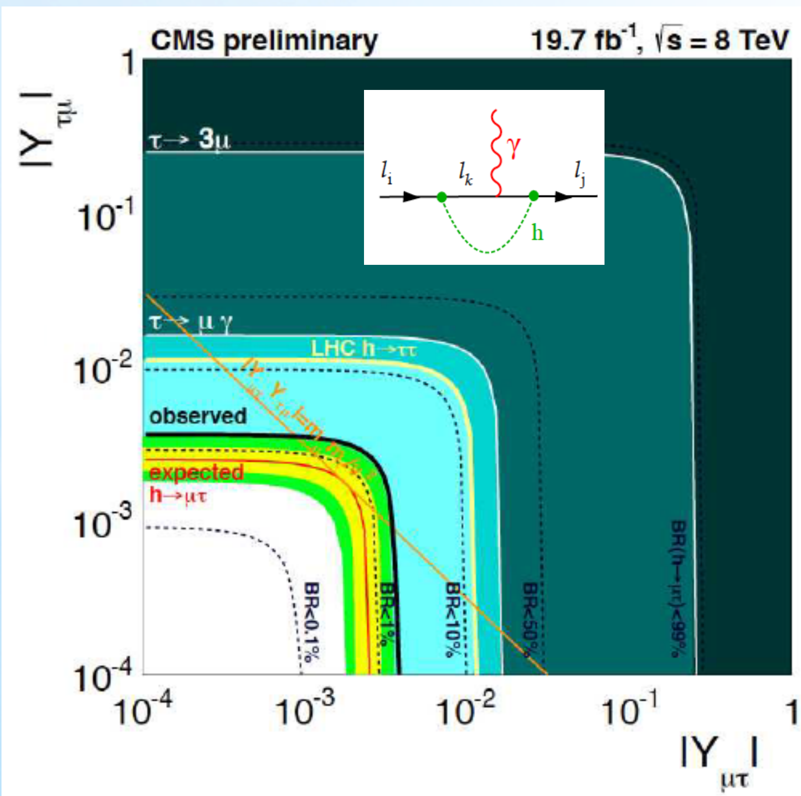
Why?

Can the seesaw mechanism explain the very different structures between quarks and leptons?

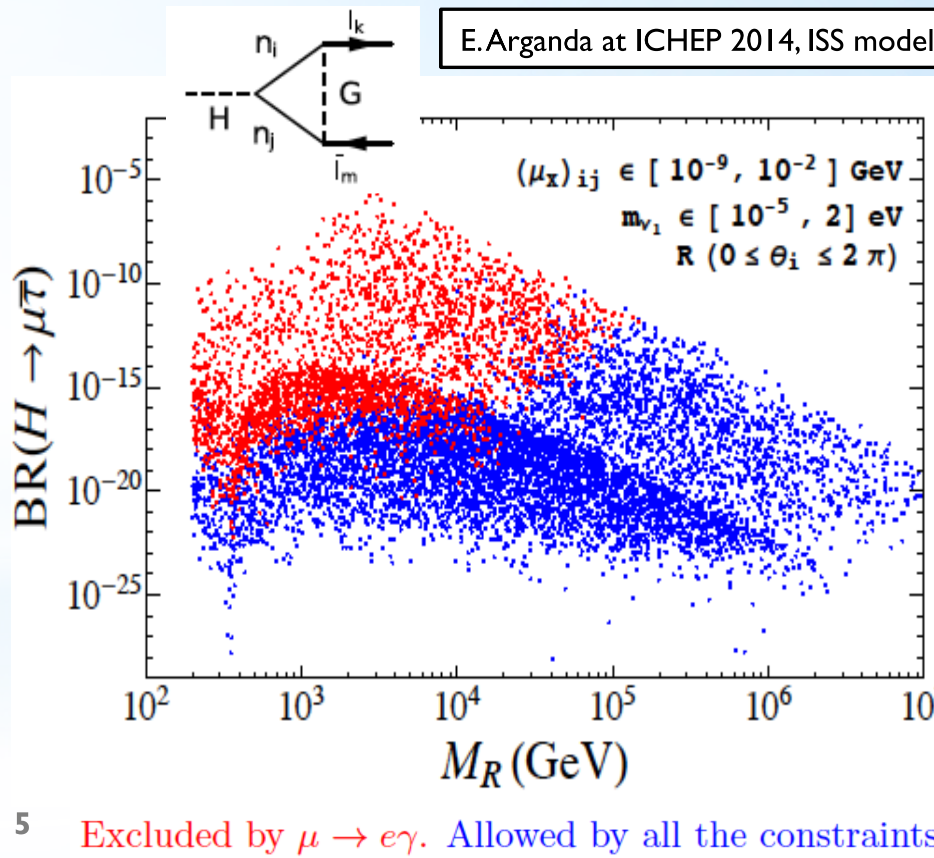
Once you start building models that predict the Yukawa couplings you have a prediction for processes like FCNC in charged lepton decays and flavour violating Higgs decays (FVHD). The interplay between neutrino measurements, FVHD and CLFV can be a very powerful constraint of the NP energy scale(s).

Examples:

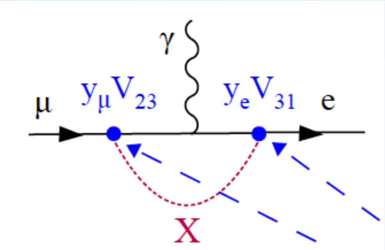
G. Isidori at ICHEP 2014

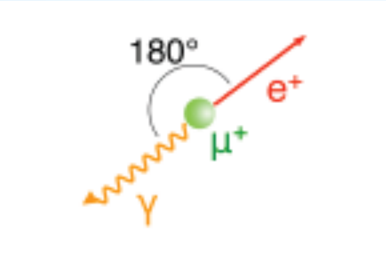


E. Arganda at ICHEP 2014, ISS model



CLFV with muon decays today and near future





MEG at PSI using 3.6x10[14] stopped muons collected in 2009-2011 has the best limit as BR($\mu \rightarrow e \gamma$)<5.7x10^{-13} @90%C.L. Expects to increase x10 sensitivity with upgraded detector (2016-2019).

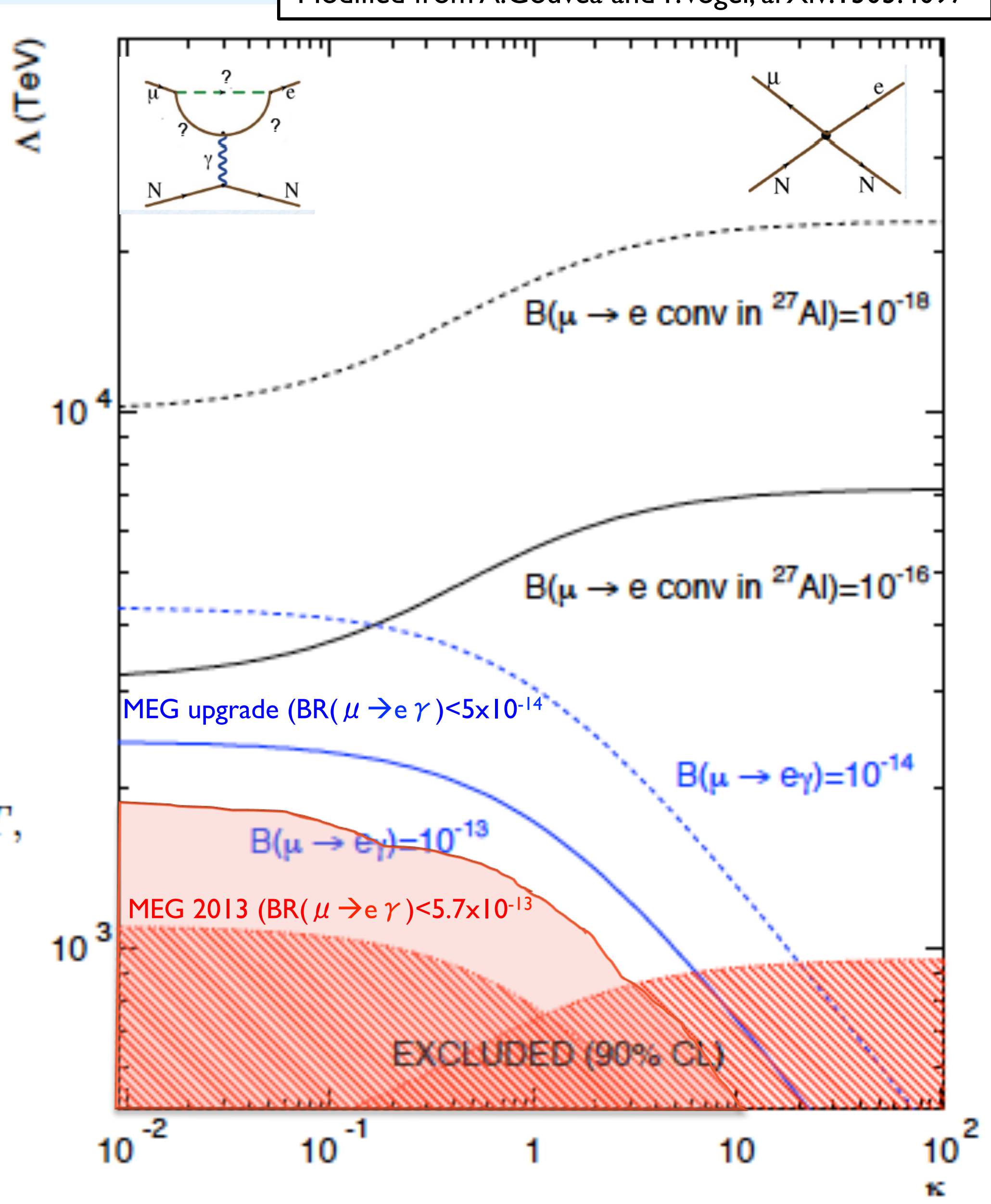
Difficult to improve with this technique due to accidental backgrounds, which should increase with beam intensity.

$$N_{\rm acc} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T,$$

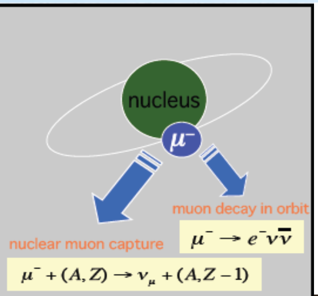
Preliminary studies within ProjectX show that the improvement in Δe_γ using converted photons, could overcome the lost in efficiency, and reach to 10^{-15}.

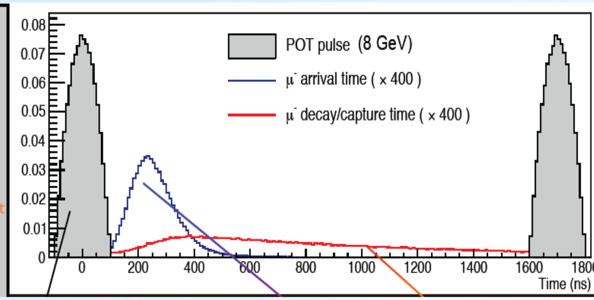
Maybe other ideas can be tested?

Modified from A.Gouvea and P.Vogel, arXiv:1303.4097



CLFV with muon decays today and near future





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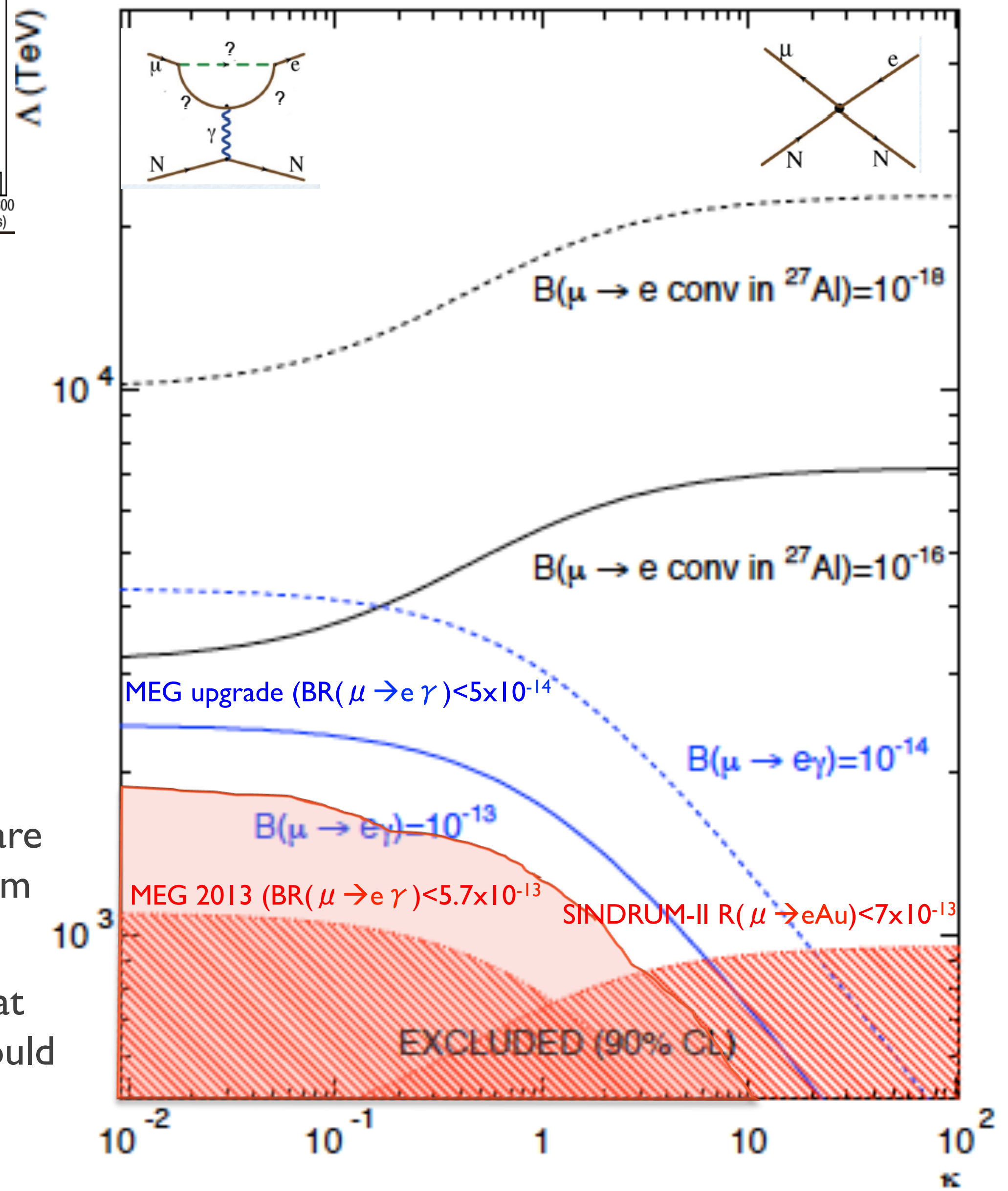


Less of a challenge is to improve on $\mu \to eN$ conversions.

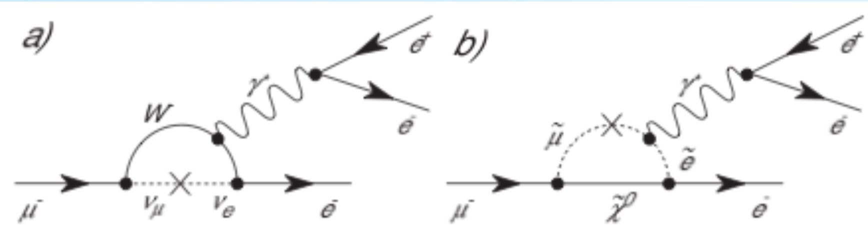
Best existing limits from **SINDRUM-II at PSI**: $R(\mu \to eAu)$ $<7\times10^{-13}$ @90% C.L. with $O(10^8)$ μ^-/sec and time between pulses <20ns.

Mu2e at the **booster** will use $O(10^{10})$ μ^-/sec and time between pulses ~1700ns, to reach $R(\mu \to eAl)$ $<7\times10^{-17}$ @90% C.L. In a similar time scale, and with similar beam parameters, **COMET-II** at **JPARC's main ring** will reach similar sensitivities.

About 50% bkg are intrinsic $\mu \to e \nu \nu$, but 25% are anti-p capture, that will be nil at lower proton beam energies (3 GeV), as in ProjectX.

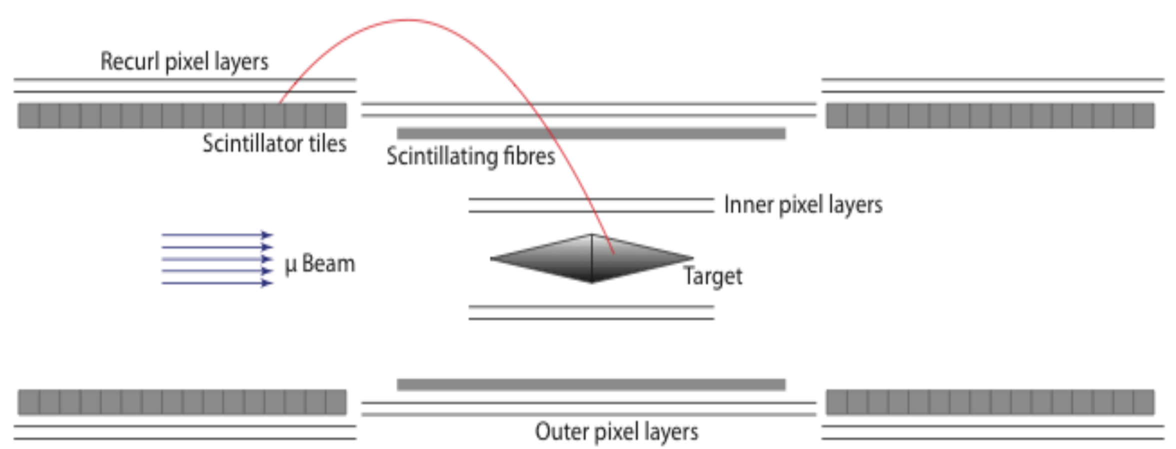
Preliminary studies show that an upgraded Mu2e at ProjectX and PRIME/PRISM (using Ti) at JPARC could increase x10 sensitivity of Mu2e.

CLFV with muon decays today and near future



The best limit BR($\mu\rightarrow$eee)<10^{-12} is from **SINDRUM**, with essentially zero bkg.

Mu3e proposal improves sensitivity to 10^{-16}, by using the proposed **HiMB line at PSI**, with rates of 2×10^{19} μ/sec DC beams. Accidental bkg are under control with excellent detector resolution. Limitation may come from $\mu\rightarrow e\nu\nu\gamma$(ee).



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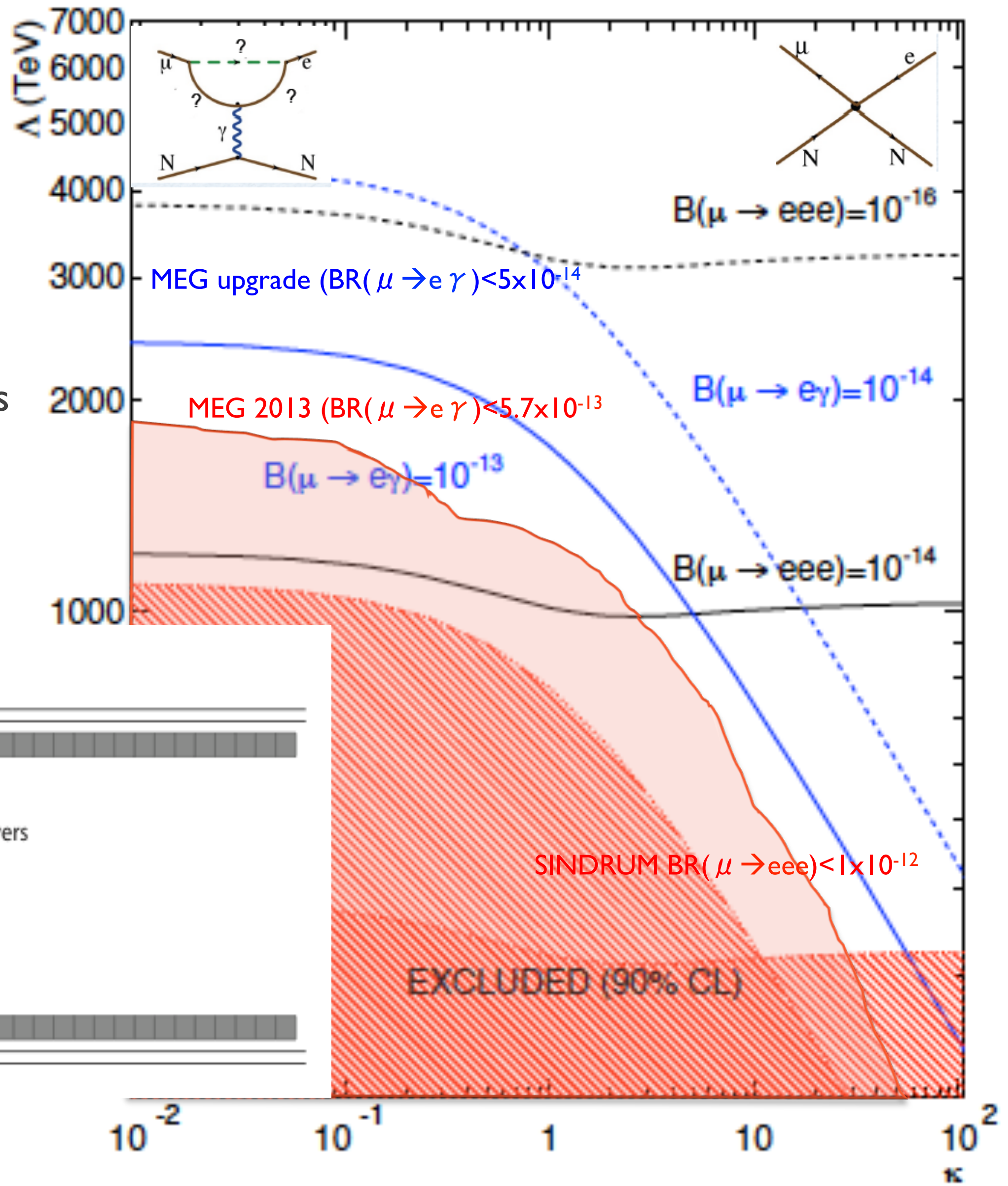


Existing facilities for CLFV with muon decays

Experiment	Beam	Momentum [MeV/c]	Rates [s^{-1}]	BBeamline
MEG ($\mu \to e\gamma$) [25]	μ^+	29.8	$3 \cdot 10^7$	πE5 at PSI
MuLan [24]	μ^+	29.8	$8 \cdot 10^6$	πE3 at PSI
TWIST [26]	μ^+	29.8	$< 5 \cdot 10^3$	TRIUMF
MEG upgrade* ($\mu \to e\gamma$) [27]	μ^+	29.8	$7 \cdot 10^7$	πE5 at PSI
Mu2e* ($\mu^- \to e^-$) [9]	μ^-	~ 40	10^{10}	FNAL
$\mu^+ \to e^+e^-e^+$ (Phase 1)* [29]	μ^+	29.8	$< 1 \cdot 10^8$	πE5 at PSI
$\mu^+ \to e^+e^-e^+$ (Phase 2)* [29]	μ^+	29.8	$2 \cdot 10^9$	HIMB at PSI

Laboratory / Beam Line	Energy / Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	"	$4 \cdot 10^8$	
πE5	"	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10} (\mu^+)$
J-PARC (JP)	(3 GeV, 1MW, Pulsed) currently 210 KW		
MUSE D-line	"	$3 \cdot 10^7$	
MUSE U-line	"		$2 \cdot 10^8 (\mu^+)(2012)$
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11} (\mu^-)(2019/20)$
PRIME/PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12} (\mu^-)(> 2020)$
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10} (\mu^-)(2019/20)$
Project X Mu2e	(3 GeV, 750 kW, DC to pulsed)		$2 \cdot 10^{12} (\mu^-)(> 2022)$

What about CERN and CLFV muon decays?

In my opinion it would be difficult to do much better than the proposed experiments at JPARC and Fermilab in $\mu \rightarrow eN$ at CERN.

There is, however, an opportunity to improve significantly on the proposed PSI experiment for $\mu \rightarrow eee$ (maybe also $\mu \rightarrow e\gamma$), if we could sort out the experimental challenges and a very intense low energy proton beam is available.

Is it conceivable to have a continuous proton beam that produces $>10^{11}\ \mu$/sec at HP-SPL?

	Option 1	Option 2
Energy (GeV)	2.5 or 5	2.5 and 5
Beam power (MW)	2.25 MW (2.5 GeV) <u>or</u> 4.5 MW (5 GeV)	5 MW (2.5 GeV) <u>and</u> 4 MW (5 GeV)
Protons/pulse ($\times 10^{14}$)	1.1	2 (2.5 GeV) + 1 (5 GeV)
Av. Pulse current (mA)	20	40
Pulse duration (ms)	0.9	1 (2.5 GeV) + 0.4 (5 GeV)

CLFV tau decays today and near future.

In principle τ are more sensitive than μ since mass typically decreases GIM suppression, (>500). However, rates at e^+e^- B-factories are ~2×10^9 τ/ab or $O(10^2)$ τ/sec .

So the best limits using ~1.4×10^9 τ events at the B-factories are:

$BR(\tau \to \mu\gamma) < 4.4\times10^{-8}$ @90%C.L.

$BR(\tau \to \mu\mu\mu) < 2.1\times10^{-8}$ @90%C.L.

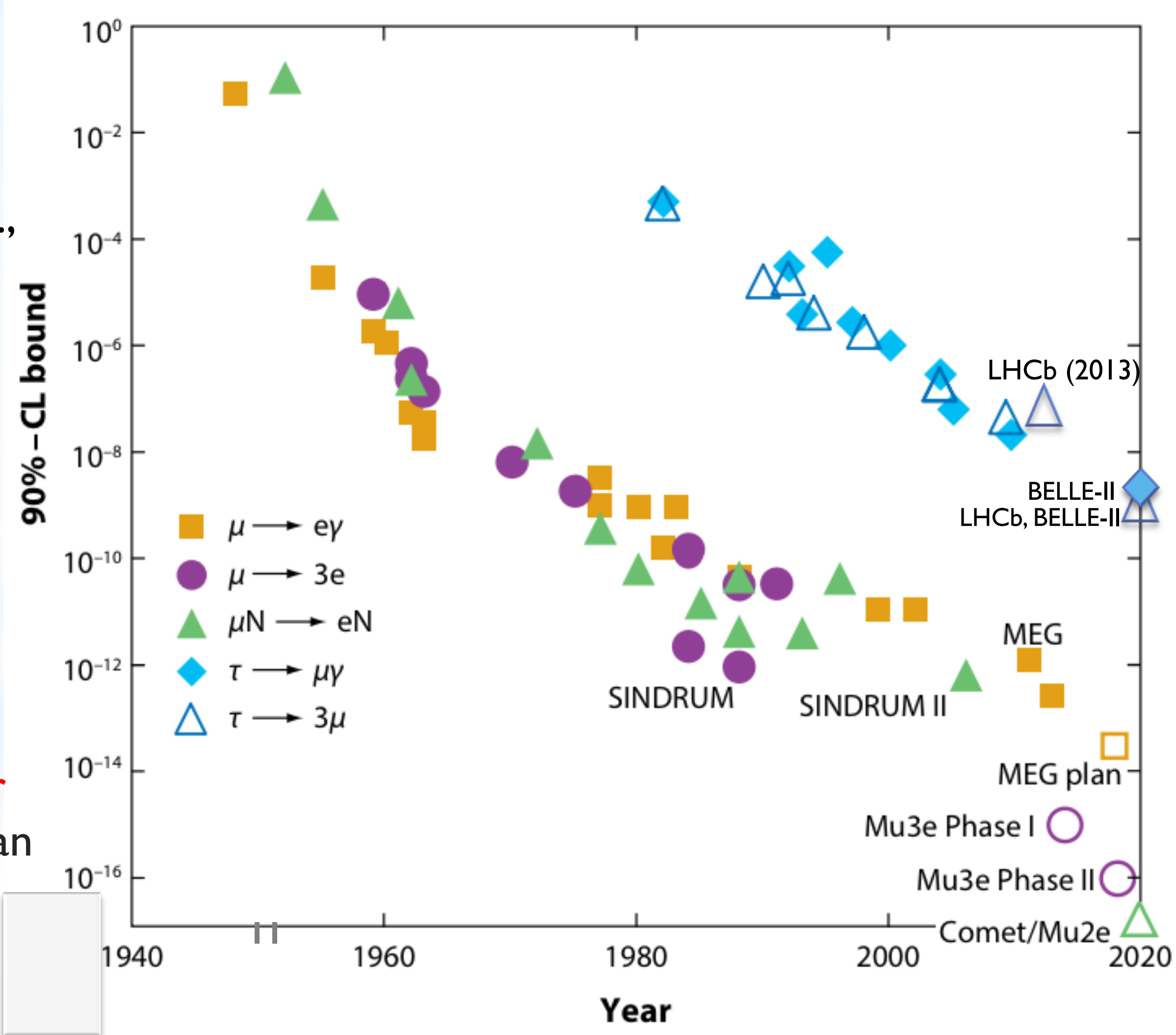
Belle-II expects to collect $50ab^{-1}$, i.e., $O(10^{11})$ events, and reach:

$BR(\tau \to \mu\gamma) < 3\times10^{-9}$ @90%C.L.

$BR(\tau \to \mu\mu\mu) < 1\times10^{-9}$ @90%C.L.

However, **at HE pp collisions (LHC) taus are copiously produced** (mainly from charm decays, $D_s \to \tau\nu$).

Recently, **LHCb** has reached similar sensitivities for $BR(\tau \to \mu\mu\mu)$ than B-factories using $1fb^{-1}$, 8×10^{10} τ produced.



CLFV tau decays using proton beams.

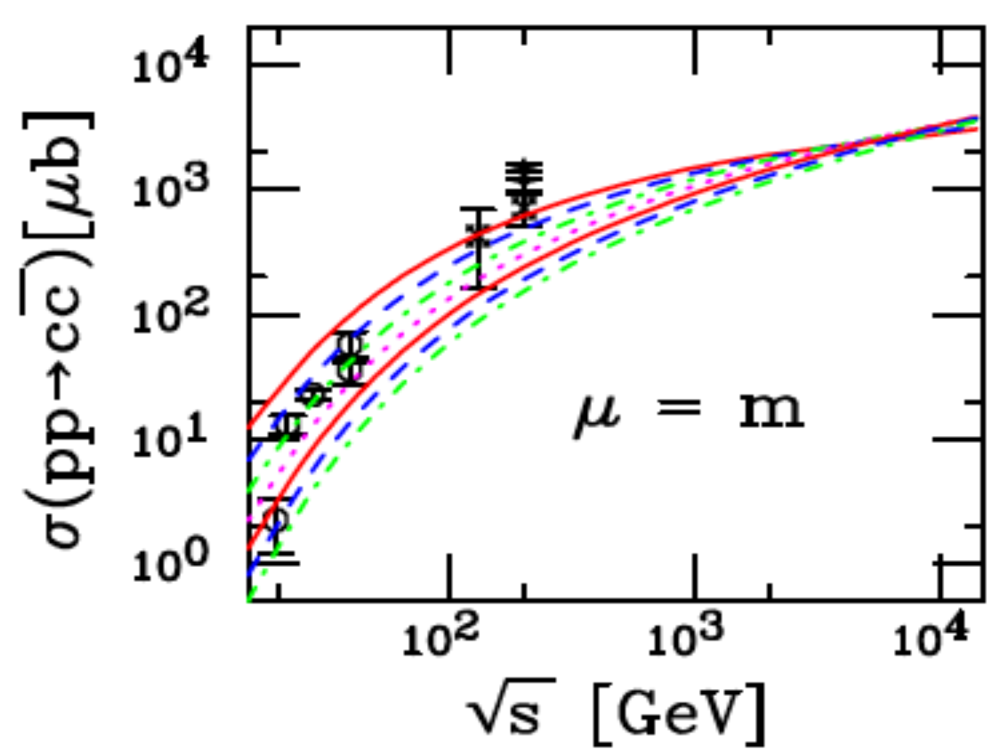
LHCb plans to collect 50fb^{-1} at 14 TeV which should provide similar sensitivities than Belle-II, ~8x10^{12} τ produced.

However, in the HL-LHC regime, at 14 TeV pp collisions expect ~1.6x10^{14} τ /ab^{-1} produced or **~10^{6} τ /sec**. Notice that even a e^+e^- τ /charm factory has only x3 larger Xsection than a B-factory.

If an experiment can have similar (or better) acceptance than LHCb and profit from such rates, expect BR($\tau \rightarrow \mu\ \mu\ \mu$)<10^{-10}, or even 10^{-11} depending on how the bkg scales.

Energy of the collisions helps. Going down to 0.03 TeV pp collisions (SPS fixed target), is ~50 lower cc Xsection.

However invariant mass resolution is crucial in hadronic environtment.



What about CERN and CLFV tau decays?

One possibility is to use a 400 GeV SPS beam to hit a target with equivalent luminosities to ~50 larger than HL-LHC. Or use an extracted 7 TeV LHC beam with equivalent luminosities to ~2. But I'm not sure on achieving the necessary experimental resolution → needs active targets and/or clever target design.

Ideally, you want to do this experiment in pp collisions **at $\sqrt{s}>O(100GeV)$** and equivalent **pp instantaneous luminosities > 10^{35}**.

Can we imagine to have a specialized experiment taking pp collisions at these energies and luminosities (SPS, LHC)?

What would be the maximum luminosities one could imagine to achieve at upgraded (SPS,LHC)?

Notice pileup is probably less of an issue for such experiments → no need of leveling.

Nucleon/lepton EDMs

Nucleon/lepton electric dipole moment status

Why the SM does not include CP violation in the strong sector? One idea is the spontaneously broken **Peccei-Quinn** symmetry, but where's the axion?

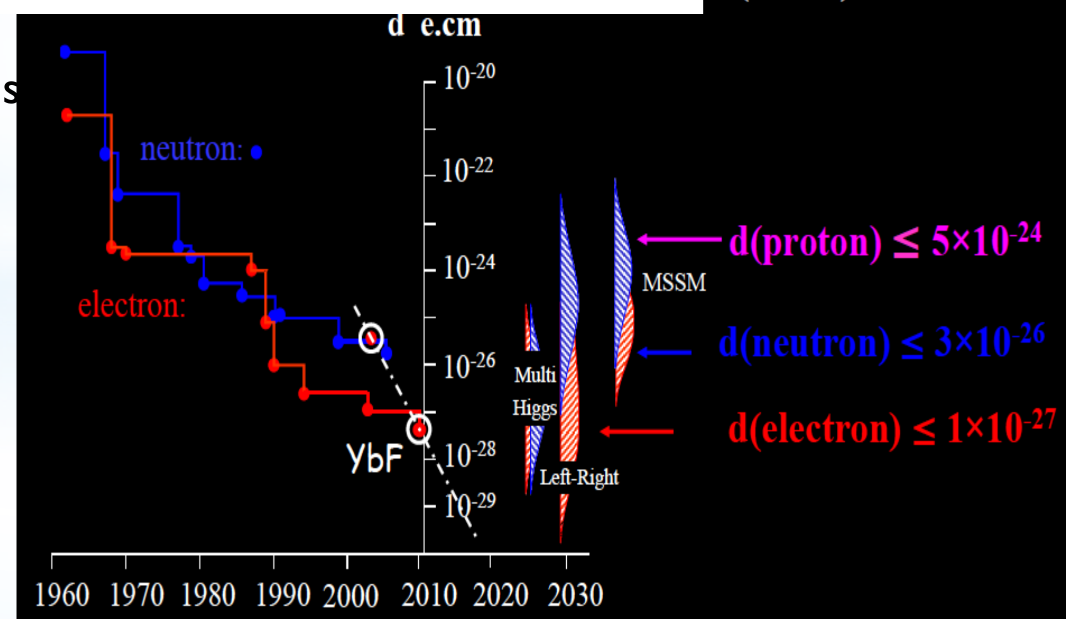
Within the SM $\mathbf{d_{nucl}^{SM} \sim < 10^{-31}}$ **e cm.** Present experimental status: $\mathbf{d_{neutron} < 2.9 \times 10^{-26}}$ **e cm @90%CL**. An observation of a non-zero **EDM** in the foreseeable future will be a clear indication of NP (**in the case of nucleons, possibly CP violation in the strong interactions**)

Category	Limit (e cm)	Experiment	Standard Model Value (e cm)
Electron	1.0×10^{-27} (90% C.L.)	YbF molecules in a beam [10]	10^{-38}
Muon	1.9×10^{-19} (95% C.L.)	Muon storage ring [11]	10^{-35}
Neutron	2.9×10^{-26} (90% C.L.)	Ultracold neutrons in a bottle [12]	10^{-31}
Proton	$[7.9 \times 10^{-25}]$	Inferred from ^{199}Hg [13]	10^{-31}
Nucleus	3.1×10^{-29} (95% C.L.)	^{199}Hg atoms in a vapor cell [13]	10^{-33}

Many proposal in the world to improve these limits, and in particular for neutrons in Europe: **ILL,PNPI,PSI and FRM-2**.

Essentially all projects aim at neutron-EDMs $\mathbf{10^{-28}}$ within the next decade. The nEDM experiment at PSI is already taking data.

Interesting to know what **ESS** can do.



Proton/muon EDMs in storage rings.

The sensitivities reached with charged particles (p, μ) are much lower. Muon EDMs can be measured as byproducts of the g-2 storage rings at **JPARC** and **Fermilab.**

Two groups, **Brookhaven** and **FZ Julich** (Germany), are developing plans for storage rings with 10^{10} p/sec and **>80% polarization** with a reach of **proton-EDM 10^{-29} e cm.**

Recent study in the context of **Project-X** (including stochastic cooling) claims:

Table V-4: The required beam parameter values and the projected sensitivities

Particle	Beam intensity, polarization, NP^2	Horizontal, vertical emittance 95%, normalized [mm-mrad], dp/p	Momentum [GeV/c]	Projected Sensitivity [$e$cm]
Protons	4×10^{10}, $> 80\%$	2, 6, 2×10^{-4} rms	0.7	10^{-29}, 10^{-30}
Deuterons	2×10^{11}, $> 80\%$	3, 10, 10^{-3}	1	10^{-29}
^{3}He	TBD, $> 80\%$	TBD	TBD	$< 10^{-28}$
Muons	$NP^2 = 5 \times 10^{16}$ total	800, 800 , 2% max	3,1	10^{-24}

Storage rings at CERN?

The existing proposals at **Brookhaven, FZJ**, **JPARC** and **Fermilab** are certainly interesting, and may not be easier to do much better, in particular with neutrons. Probably best sensitivity for neutrons at **ESS**.

Building such storages rings (R~40m, 10MV/m) and provide high intensity low energy polarized proton and muon beams is certainly a challenge to the Accelerator and Beam departments ➔ building expertise on many accelerator challenges which CERN used to have.

Can we imagine to have polarized 0.7 GeV proton beams with >10^{11} p/sec?

Can we foresee an storage ring that could be upgraded later on to also measure the Deuteron EDMs?

What about 3.1 GeV muon beams with >10^{11} μ/sec.?

Other possibilities.

As we have discussed, if we have high intensity proton beams at energies ~>100 GeV, we have an enormous source of **charm** (hence of **taus**). But also and enormous production of **beauty** and **strange** mesons.

For some time there have been discussions to use beams from the LHC extracted by bent a crystal, see for instance, contribution from Lansberg et al. submitted to the European Strategy Open Symposium (2012). This could provide protons on target collisions of ~115GeV and $>10^{??}$ protons on target, while still delivering enough luminosity to the LHC experiments.

Are there clean measurements with strange, charm and beauty decays that could give information on the scale of NP, and be performed on such facility?

Are there specific NP searches that could benefit from these beam lines? Dark Matter, Dark Photons/HNL, …