Charged Lepton Flavor Violation Experiments

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29th WIN Conference. Sun Yat-sen University, Zhuhai. 3-8, July, 2023.

Outline

- Physics motivation
- Experimental status
  - μ sector
    - μ decays/captures
    - Transitions with μ in the final state
  - τ sector
    - τ decays
    - Transitions with τ in the final state
- Summary

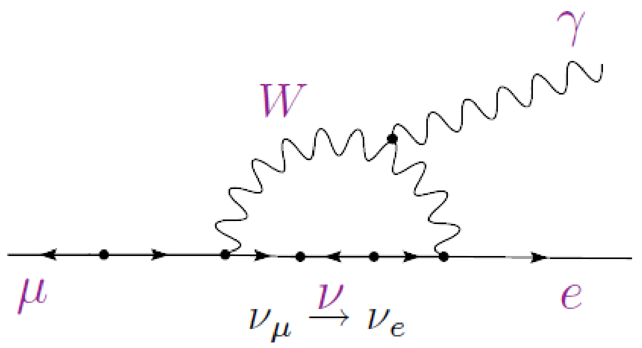
* My experience is limited to μ sector. My review on τ sector can't be very comprehensive. In case of any bias/mistake, my apologies!

Physics Motivation

Charged Lepton Flavor Violation (CLFV)

- Since 1940s, μ started to be considered as a heavy version of electron. The quest of CLFV started from searching for $\mu \rightarrow e\gamma$.
  - The null result led to the concept of flavor conservation.
- Neutrino oscillations demonstrates that neutrinos are massive, and lepton flavor conservation is violated (PMNS matrix).
- However, CLFV is still practically forbidden in SM+m_ν due to GIM
  - 40 orders of magnitude lower than current limit: Clean field to search for new physics!

Highly suppressed in SM+m_ν by GIM due to the smallness of m_ν



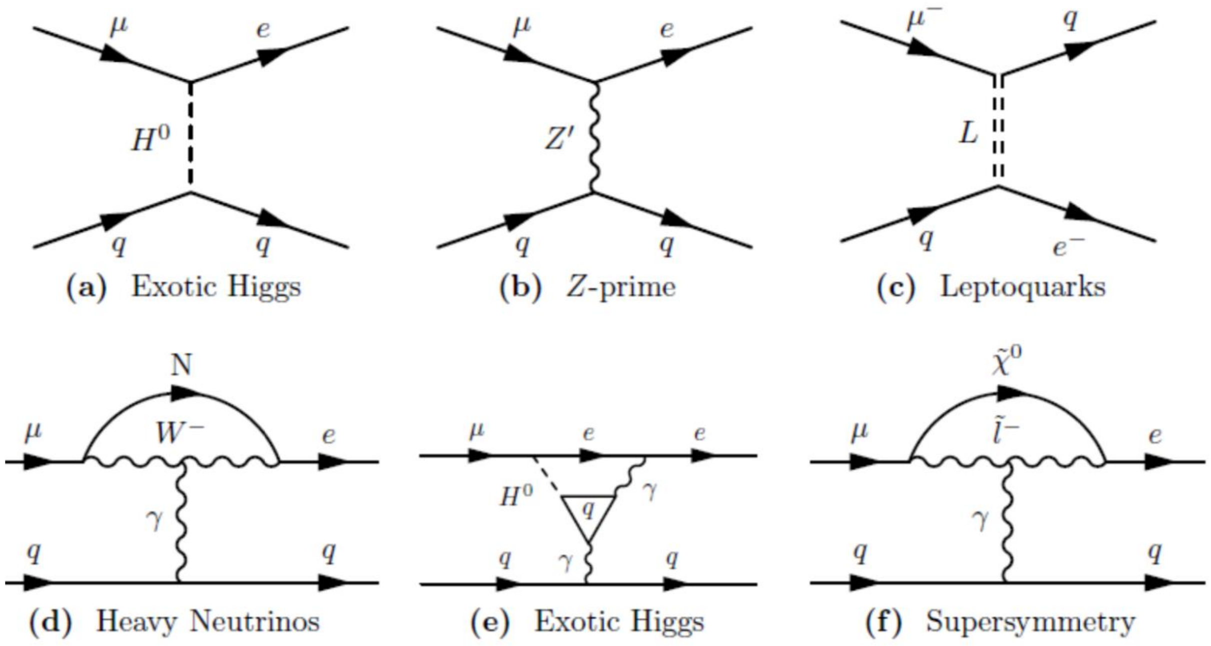
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

Charged Lepton Flavor Violation (CLFV)

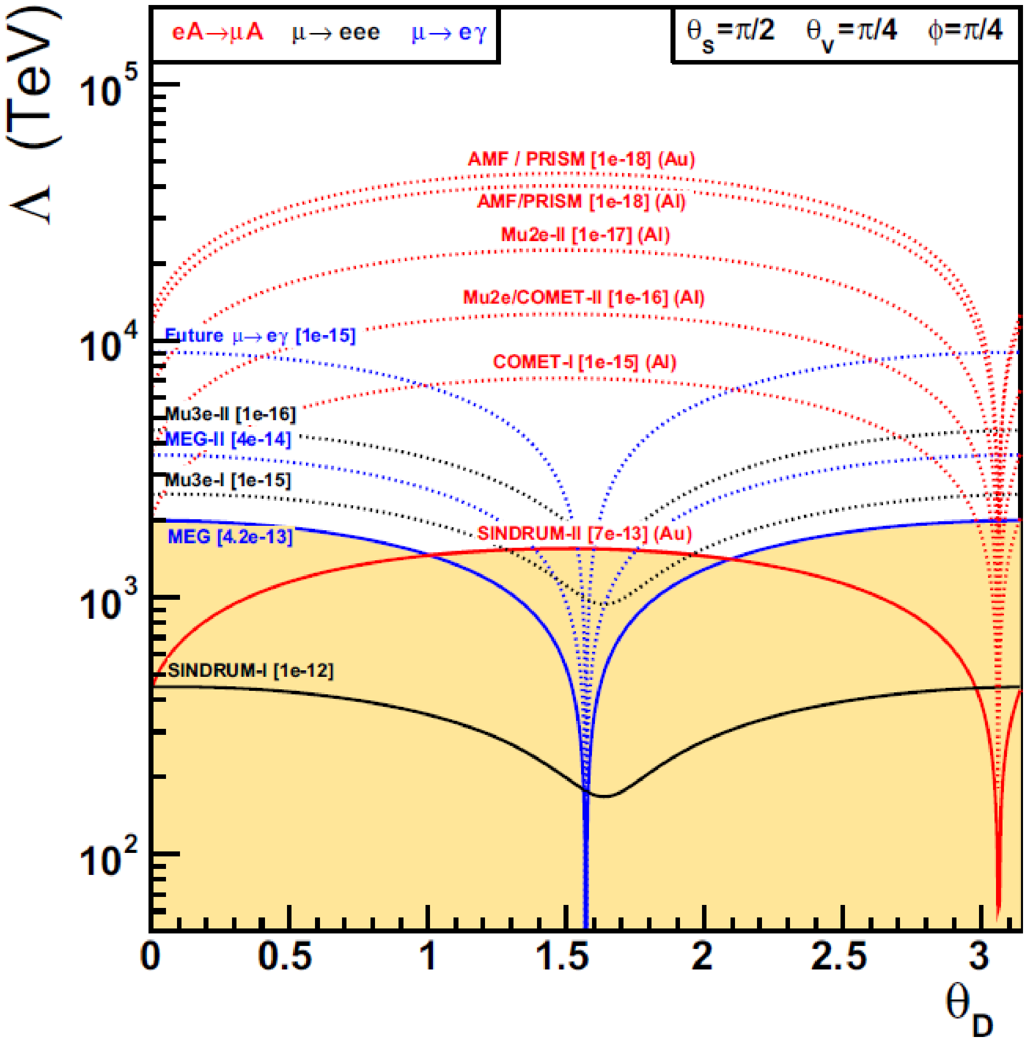
- Neutrino mass requires new physics: scale is unknown.
- There is no fundamental law to prevent CLFV.
  - Naturally exists in new physics
- CLFV is closely related to important questions:
  - neutrino mass origin, baryogenesis, flavor origin…
- Hints from anomalies: g-2, LFU

CLFV Widely predicted in NP models



Model independent approach: EFT

- Extend SM in effective field theory with higher dimension operators: $\mathcal{L} = \mathcal{L}_{SM} + \sum_{n\geq 1} \frac{{c_{ij}}^{4+n}}{\Lambda^n} \mathcal{O}^{4+n}$
- CLFV can be introduced from dim-6: $Br \sim \frac{1}{\Lambda^4}$
- Λ can reach $\mathcal{O}(10^3 \sim 10^4)$ TeV!
  - Good complementation to direct searches for new physics.



Eur. Phys. J. C (2022) 82:836

θ_D parameterizes the relative magnitude of dipole and four-fermion coefficients

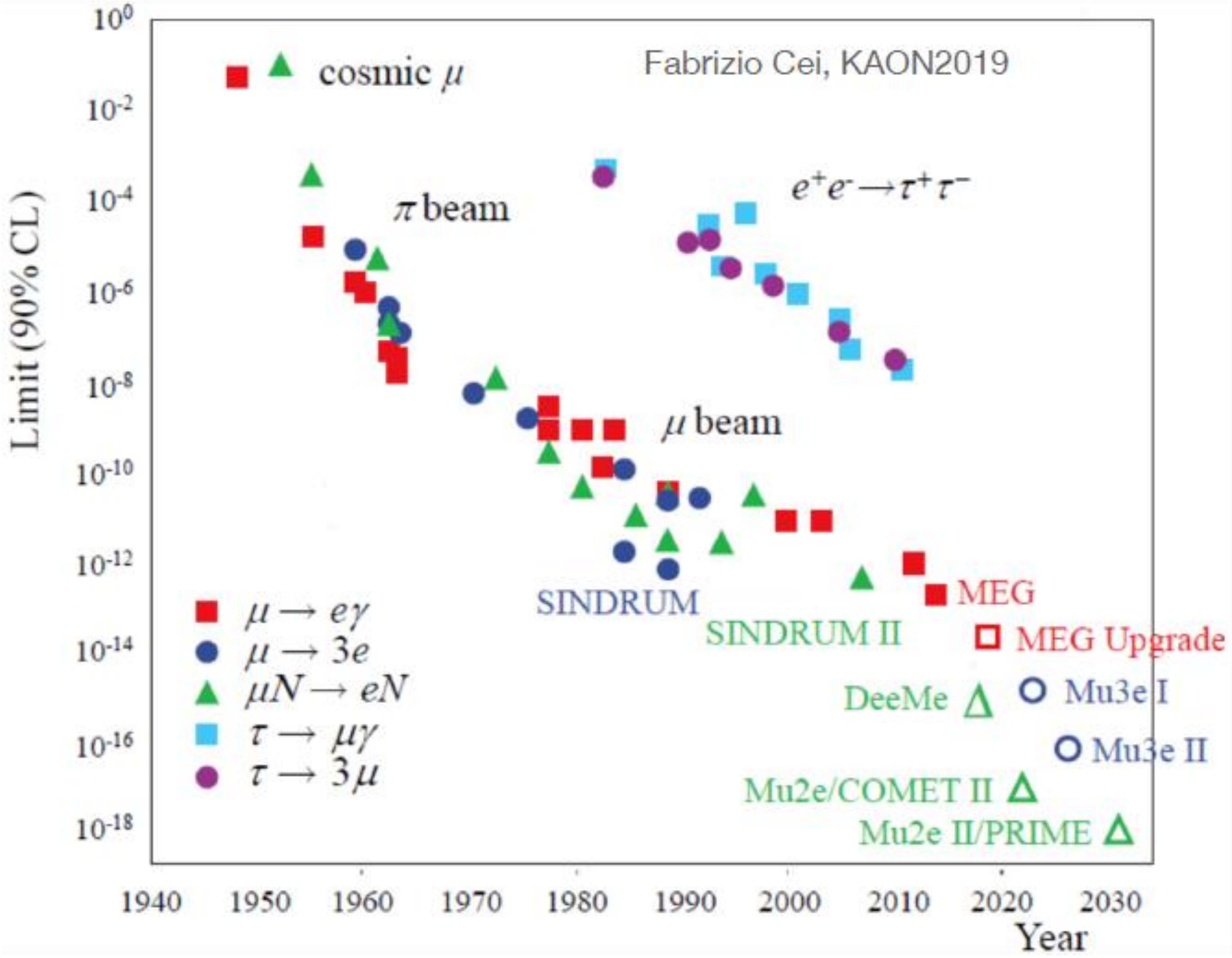
Searching for CLFV in different channels

- μ sector
  - μ decays/captures
  - Transitions with μ in the final state
- τ sector
  - τ decays
  - Transitions with τ in the final state

Complementary to each other.
We need to be thorough.

- Searching μ and τ sectors together can give us a whole picture of the flavor structure in new physics.
- Searching with different channels can give us a better understanding of the characteristics of new physics:
  - Ratios between two channels are different under different new physics.

History of CLFV: most stringent channels



Experimental status: μ sector

PSI

FermiLab

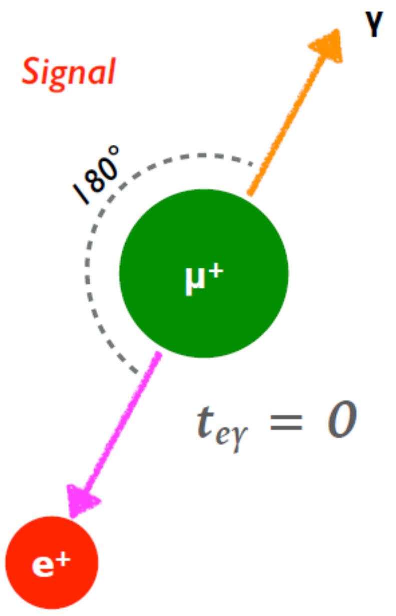
J-PARC

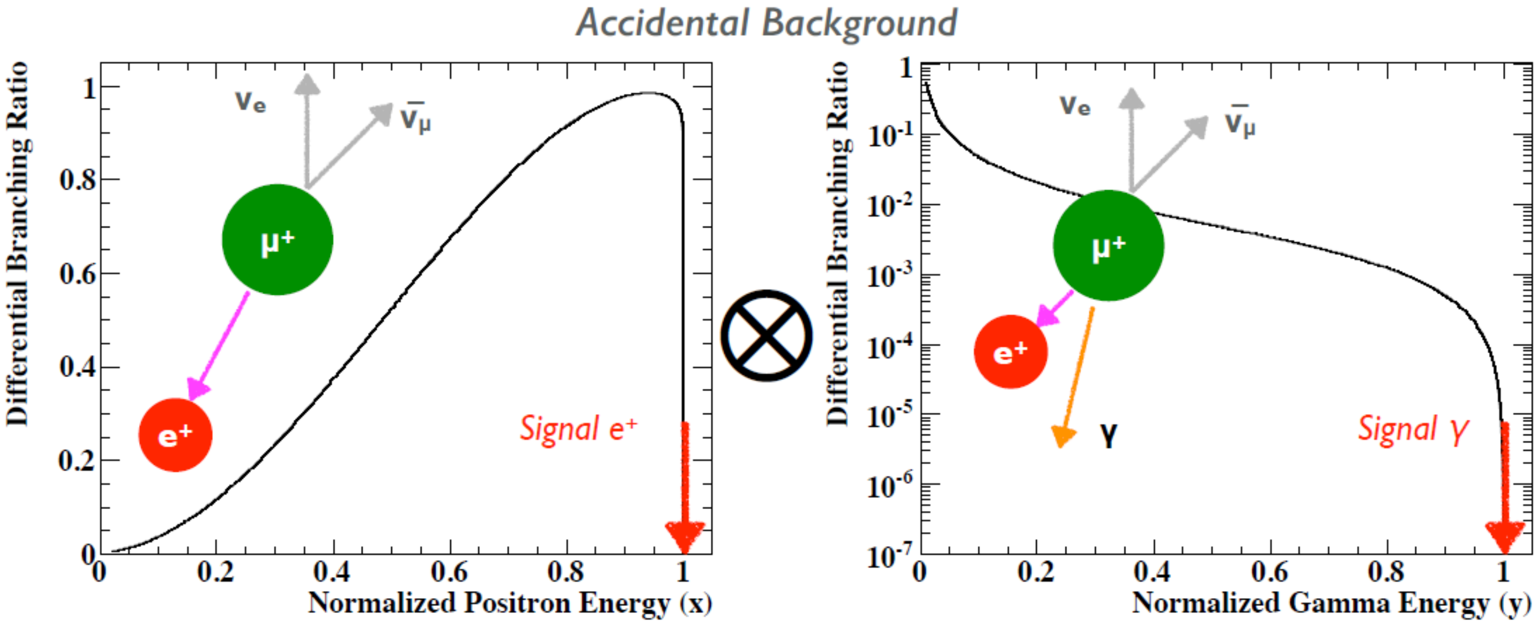
Searching CLFV in $\boldsymbol{\mu}$ sector

- μ is particularly convenient for CLFV searches
  - Relatively long lifetime: gather and deliver before decay.
  - Great accessibility: thanks to the improvement in proton accelerators, which was mostly promoted by various application and the neutrino physics quests.
- The search for CLFV in μ decay/capture processes offers the most stringent limits.
- Transitions with μ in the final state can not compete with the sensitivity achieved with μ beam.
  - But still needed for understanding the new physics: model dependency.

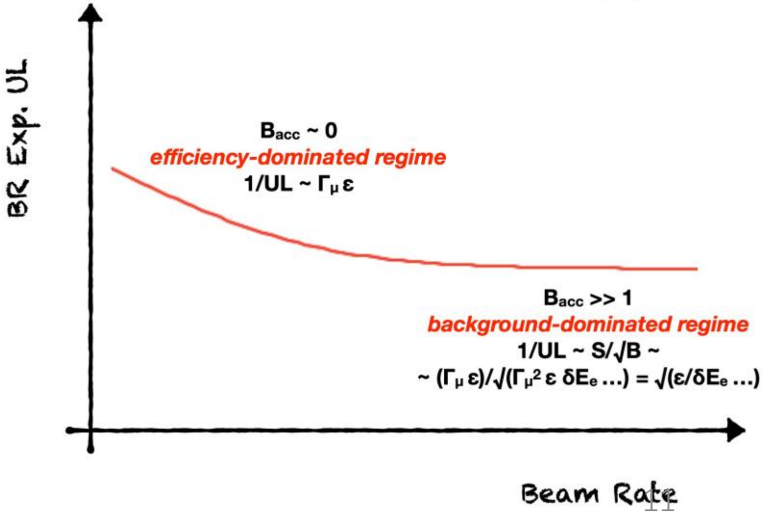
$\mu \rightarrow e\gamma$

- Starting from positive muons stopped in target.
- Signal is back-to-back electron positron pair.
- Background dominated by accidental events:
  - **DC beam** preferred. Detector resolution limit.
- Can search for $\mu \rightarrow eX(\gamma)$in the meantime





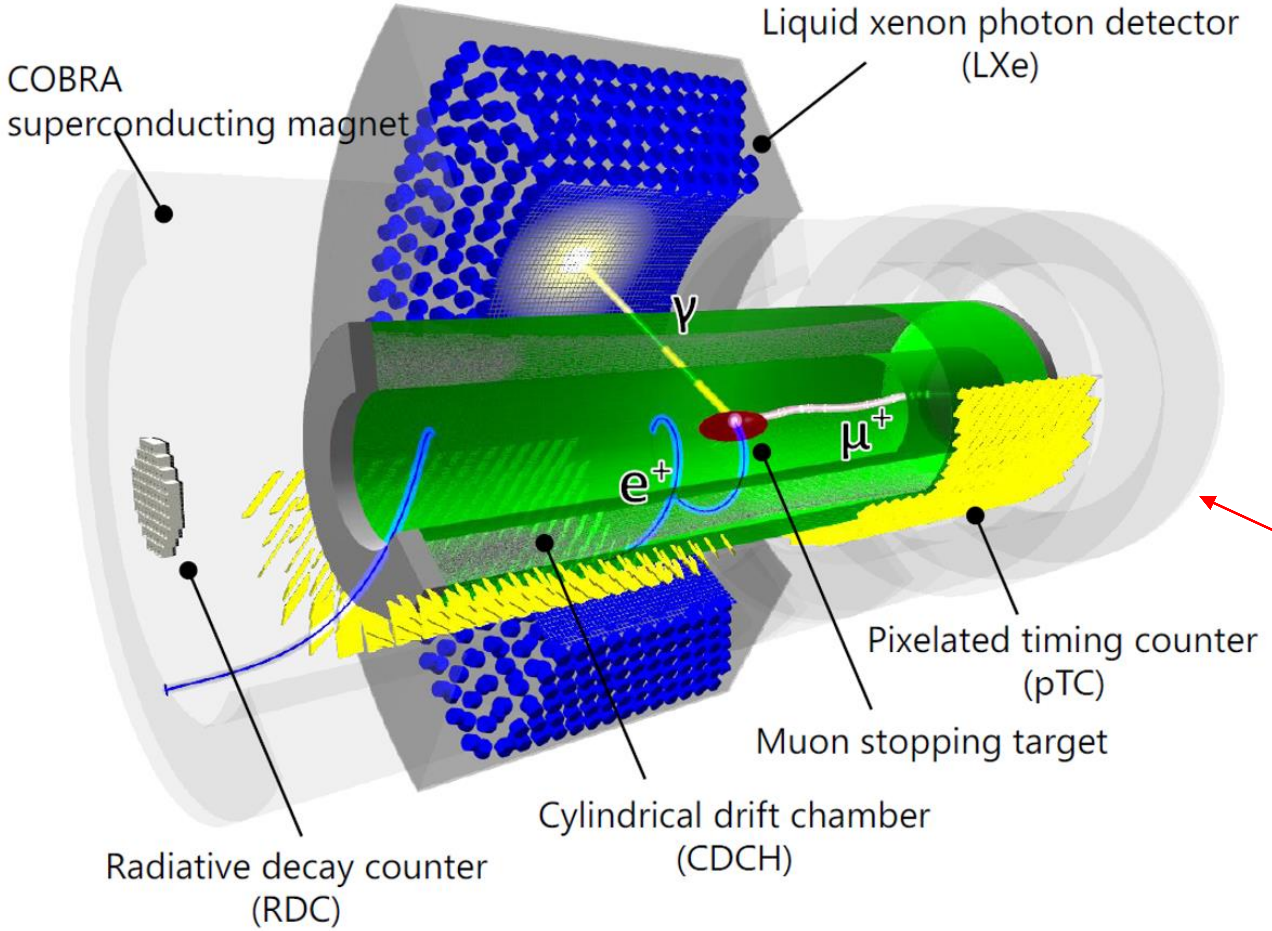
$$B_{acc} \propto \Gamma_{\mu}^{2} \cdot \delta E_{e} \cdot (\delta E_{\gamma})^{2} \cdot \delta T_{e\gamma} \cdot (\delta\Theta_{e\gamma})^{2}$$

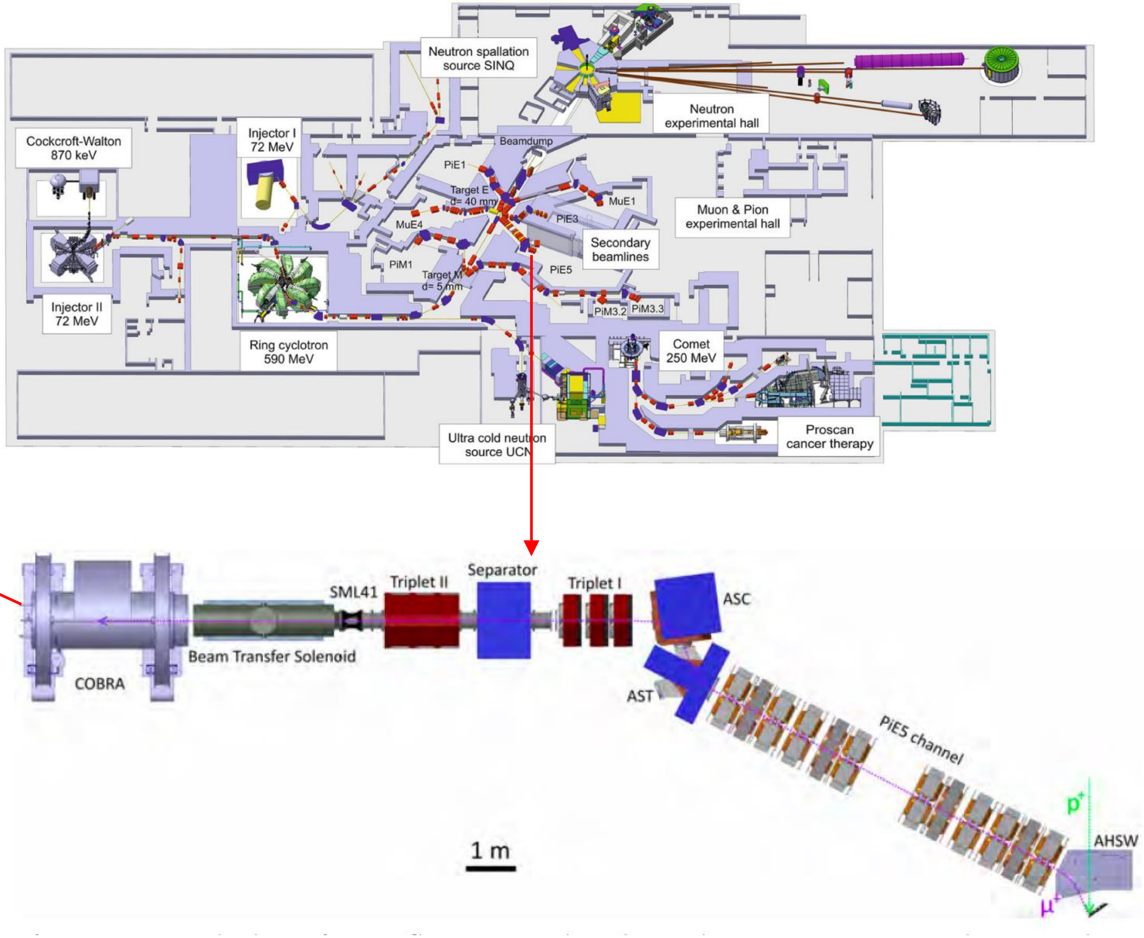


Yuki Fujii, Muon4Future workshop

Cecilia Voena, Muon4Future workshop

$\mu \rightarrow e\gamma$: MEG-II @ PSI





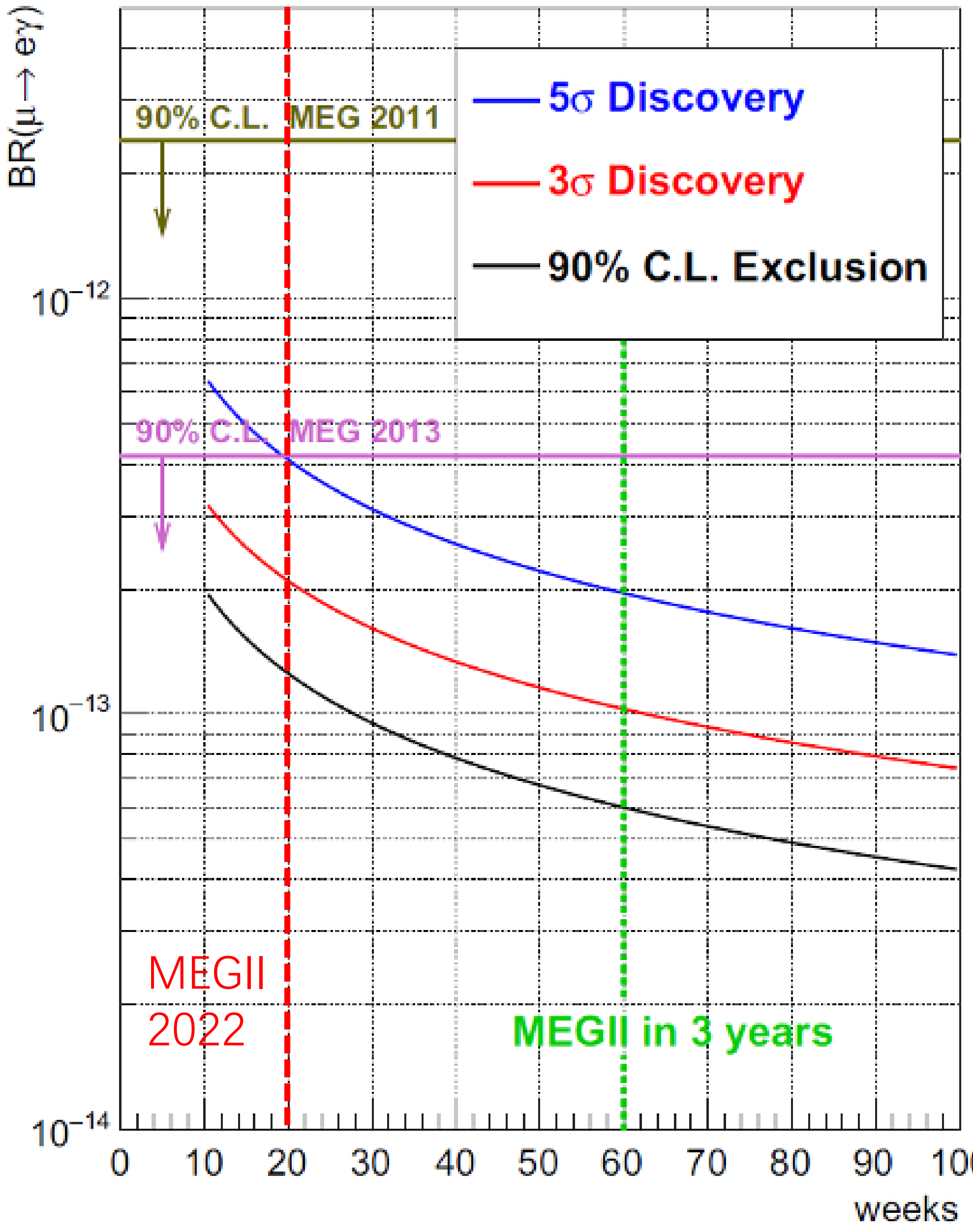
Link *to the MEG II design paper*

$\mu \rightarrow e\gamma$: MEG-II VS MEG

- MEG: operated 2008~2013, 90% CL upper limit set to 4.7×10^{-13}
- MEG II: 2021~2026, aims at 4×10^{-14}
  - detector resolution and efficiency x2
  - Beam intensity x2: $3 \times 10^{7}/s \rightarrow 5 \times 10^{7}/s$. Can achieved: $10^{8}/s$.

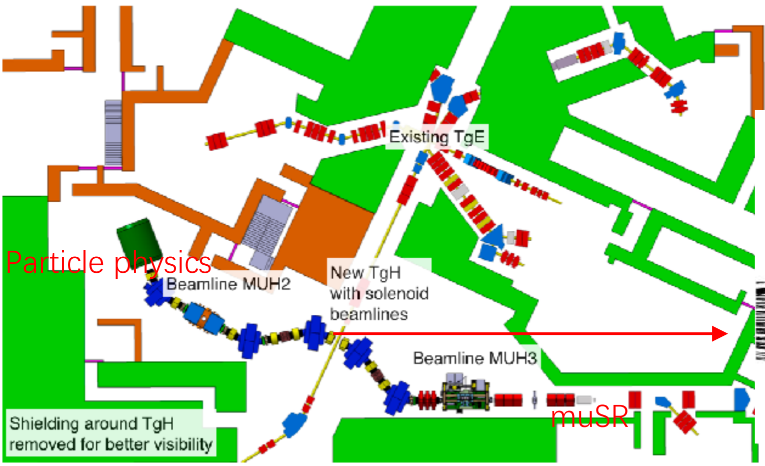
$$B_{acc} \propto \Gamma_{\mu}^{2} \cdot \delta E_{e} \cdot (\delta E_{\gamma})^{2} \cdot \delta T_{e\gamma} \cdot (\delta \Theta_{e\gamma})^{2}$$

	MEG	MEG II (design)	MEG II (Meas.)
ΔE_e [keV]	380	130	90
$\Delta\theta_e$ / $\Delta\varphi_e$ [mrad]	9/9	7.0/5.5	**8/7**
e^+ Eff. [%]	40	70	**65**
ΔE_γ [%] (deep/shallow)	1.7/2.4	1.0/1.1	**1.7/2.0**
Δpos_γ [mm]	5	2.4	**2.5**
γ Eff. [%]	60	70	**60**
$\Delta t_{e\gamma}$ [ps]	120	85	**80**

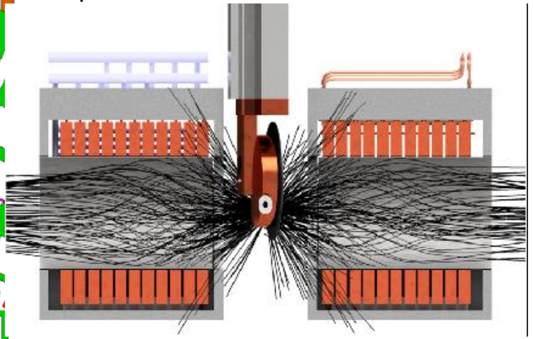


New muon beamline design in PSI: HiMB

- Aim: $10^{10}\mu/s$, surface muon, DC beam.
- Schedule: long shutdown 2027~2028
- Serves for particle physics ($\mu \to e\gamma$, $\mu \to eee$, muEDM) and muSR research.
- Optimizations on target, capture and transmission are ongoing.

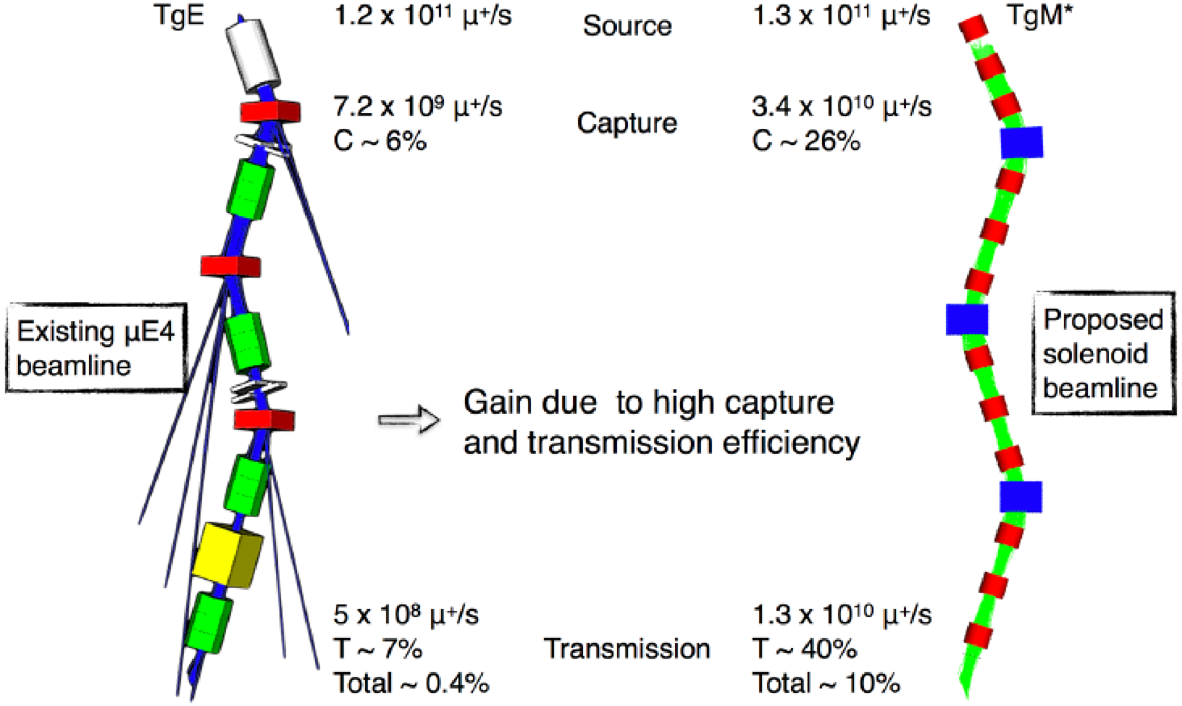


Normal-conducting, radiation-hard solenoids to capture surface muons.



0.45 T 0.1 T 0.45 T

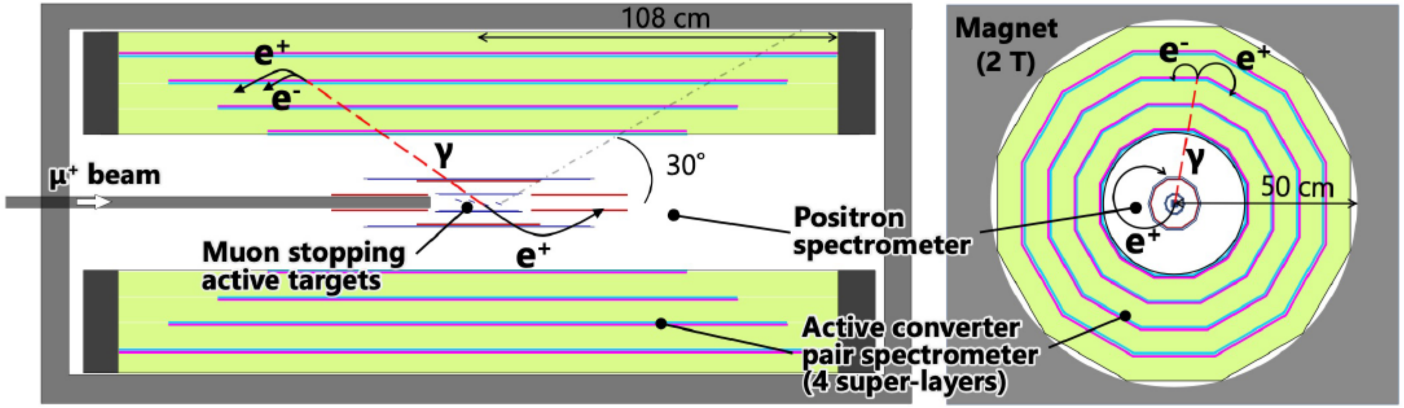
Proposed solenoidal beam line to increase the transmission efficiency



Angela Papa, Muon4Future workshop

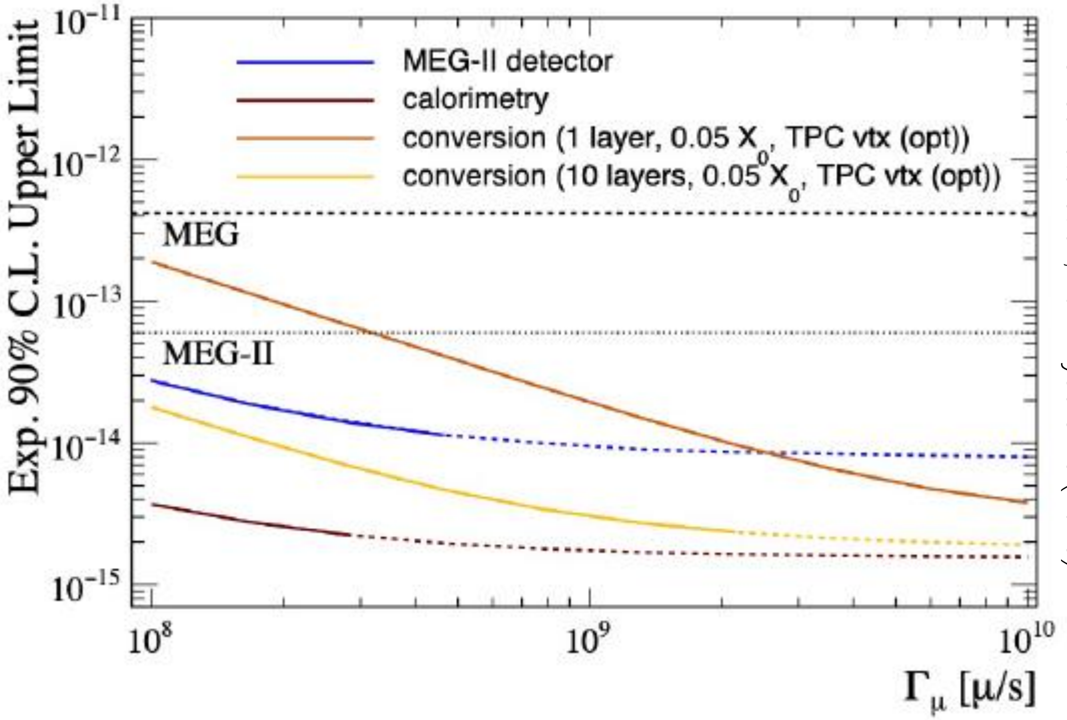
$\mu \to e\gamma$: next generation experiment

- HiMB Physics Case Workshop started from April 2021.
  - Positron detection: gaseous of silicon
  - Photon detection: calorimetry or conversion layer.



The plan with active multiple layer conversion layers.
Silicon detector for positron.

A few 10^{-15} level seems to be within reach for 3 years running at 10^9 μ/s
(further improvements possible with R&D)

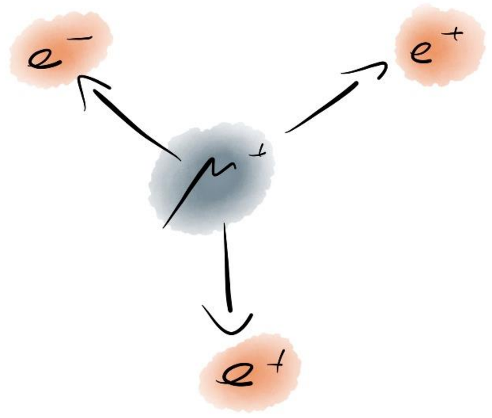


G. Cavoto et al., Eur.Phys.J.C 78 (2018)

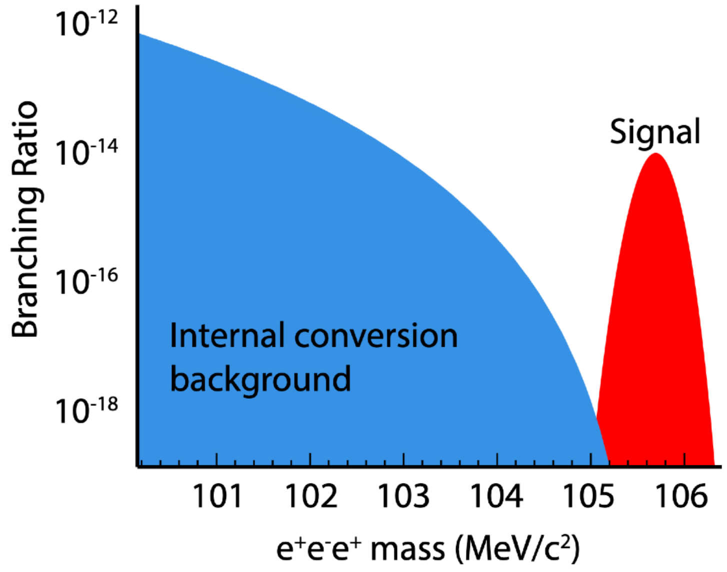
$\mu \rightarrow eee$

- Starting from positive muons stopped in the target.
- Signal: 3 electrons from the same vertex.
- Background: internal and combinatorial events:
  - **DC beam** preferred. Detector resolution limit.
- Can search for $\mu \rightarrow eX(\gamma)$in the meantime

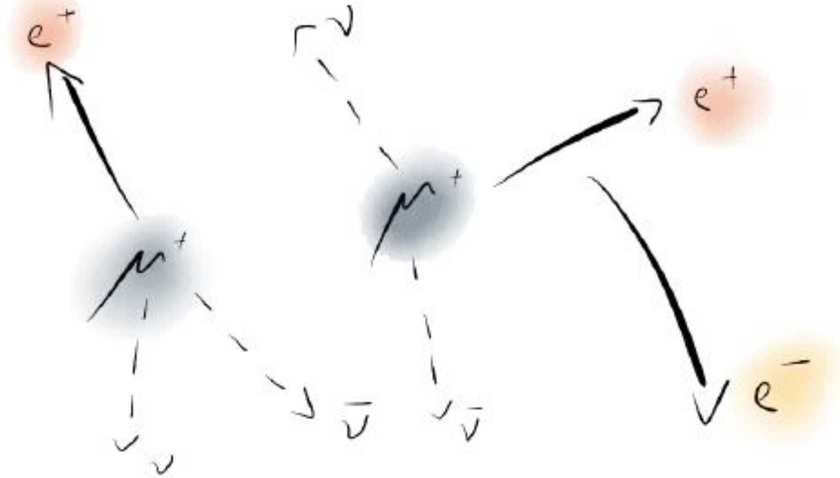
Signal



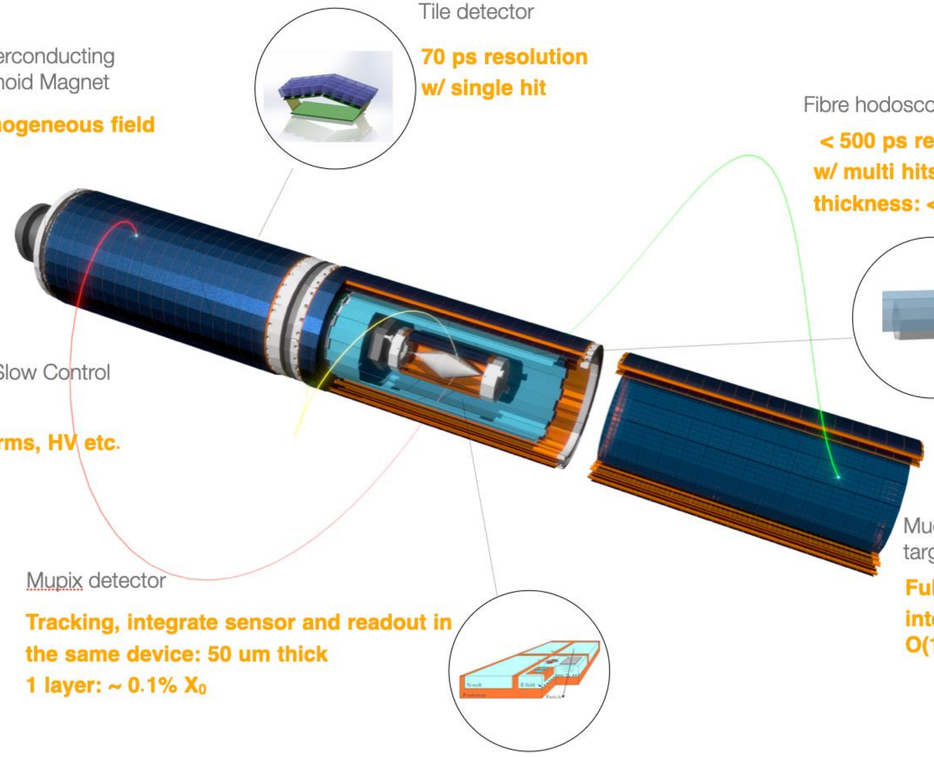
Internal background

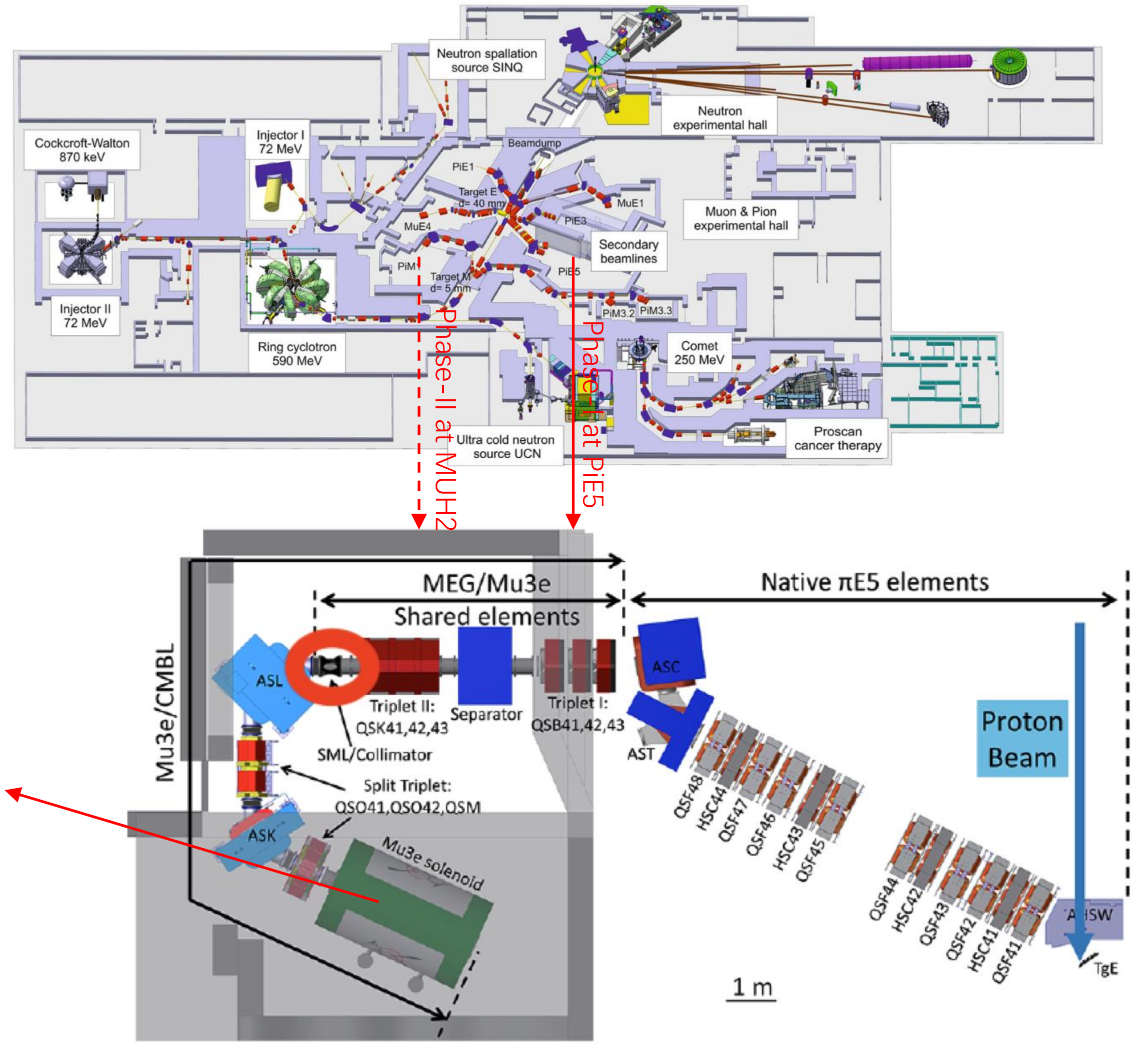


Combinatory background



$\mu \rightarrow eee$: Mu3e @ PSI

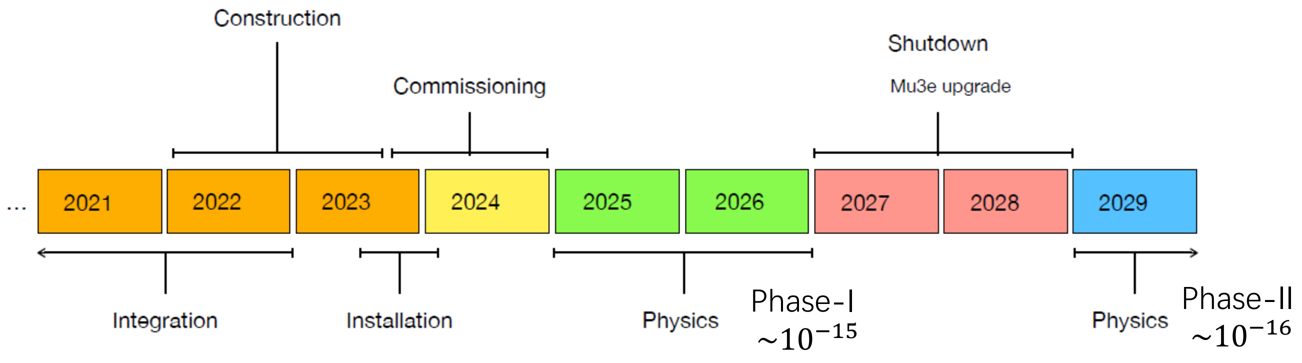


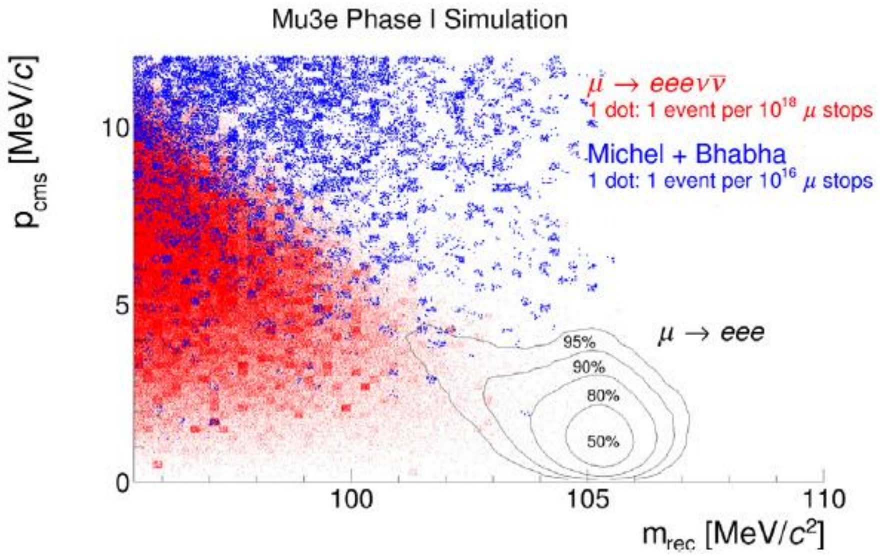


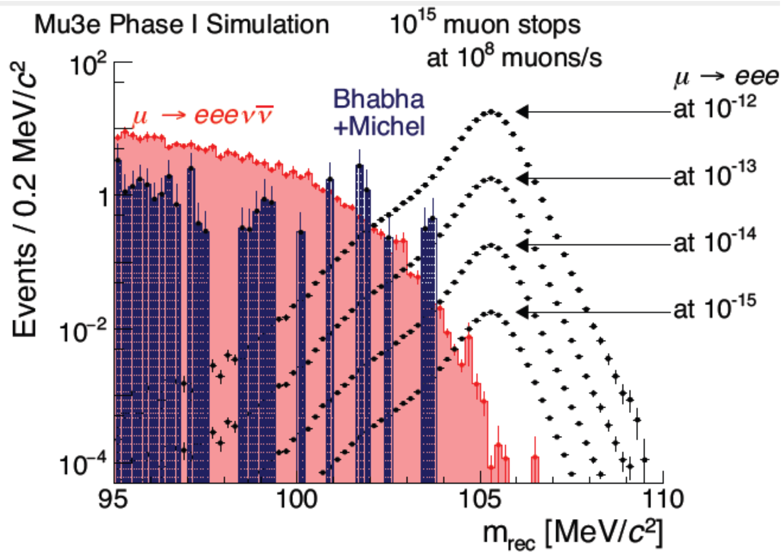
[Link](#) to the Mu3e design paper

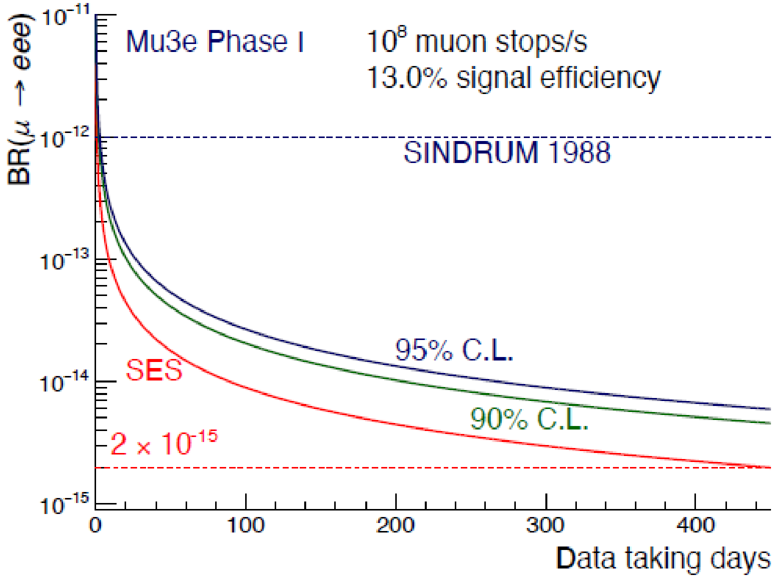
$\mu \to eee$: Mu3e @ PSI

- Phase-I aims at $\sim 10^{-15}$ sensitivity.
- Phase-II aims at $\sim 10^{-16}$ sensitivity.
  - Will use muons from HiMB: $10^9 \mu/s$
  - Detector needs upgrade.





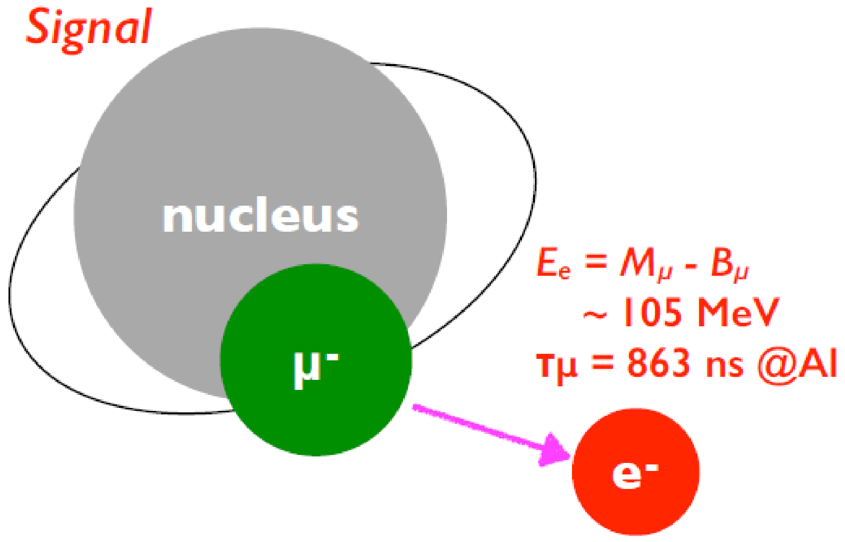




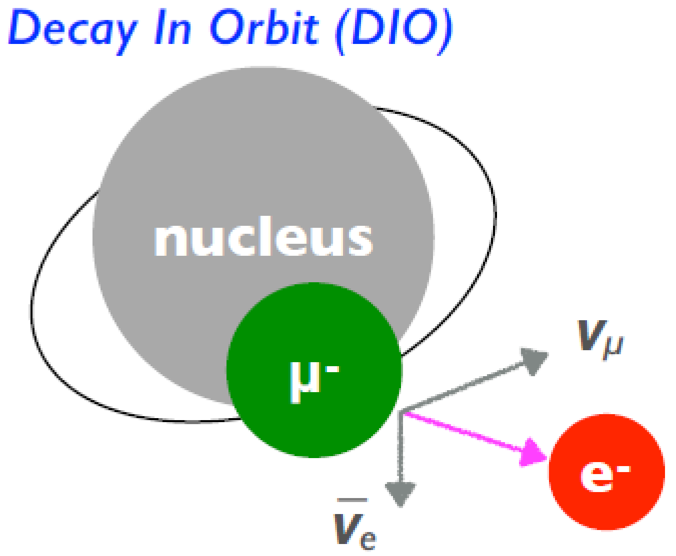
Technical design of the Phase I Mu3e Experiment

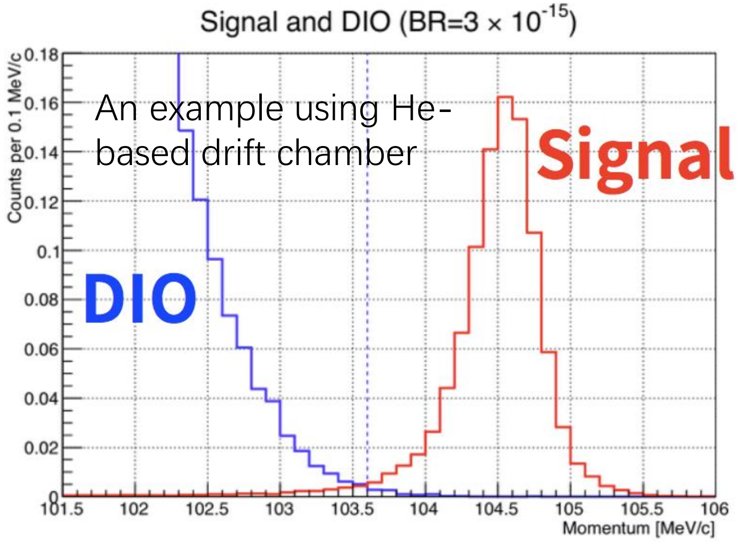
$\mu N \to eN$

- Starting from negative muons stopped in the target.
- Signal: 1 mono-energetic electron.
- Background: intrinsic, beam related, cosmic ray
  - **Pulsed beam** preferred. Excellent extinction factor required.
  - Cosmic ray veto needed.
- Can search for $\mu^- N \to e^+ N$, $\mu \to eX$ in the meantime.

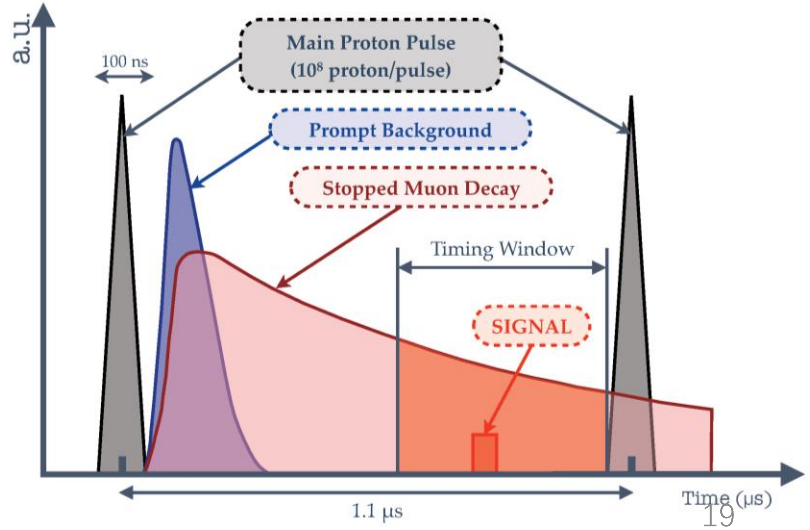


Intrinsic background: DIO. Can be well separated with current detector.



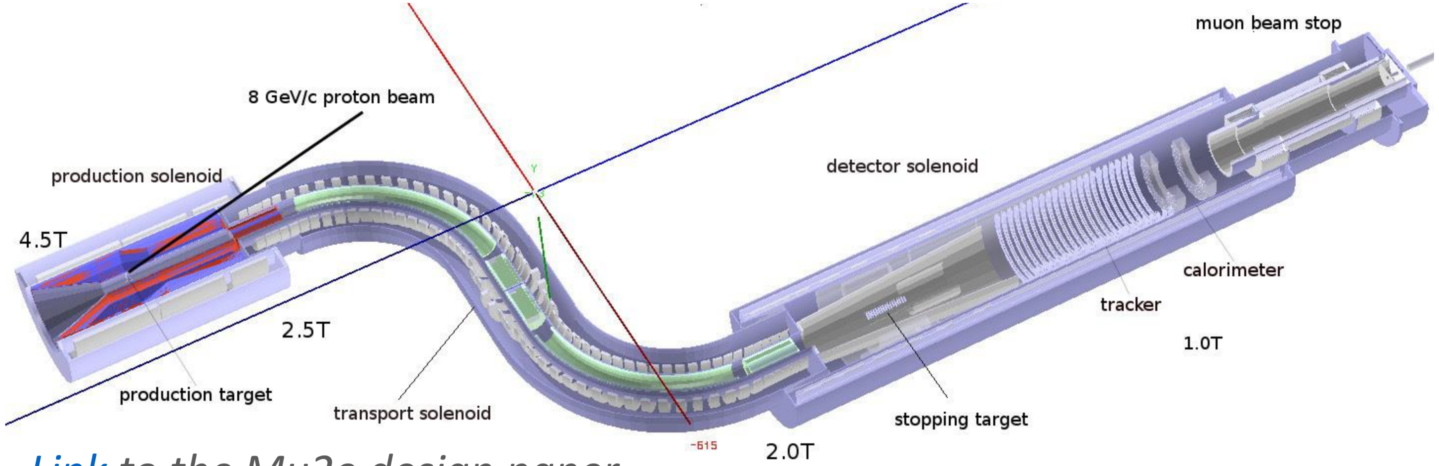


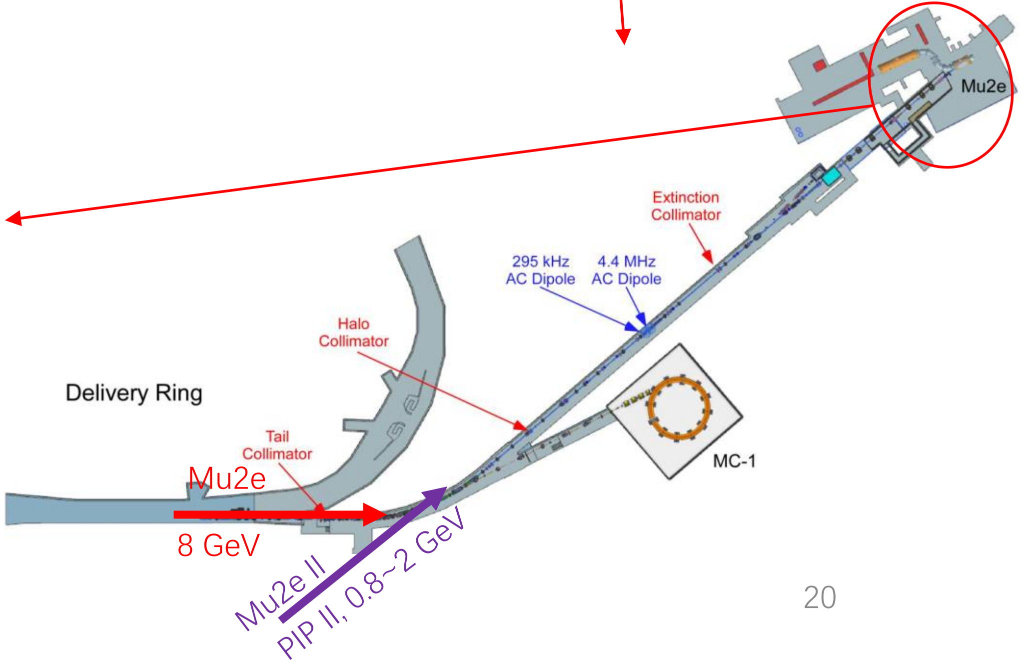
Using pulsed beam and delayed window to avoid beam related background.



$\mu N \to eN$: Mu2e @ FermiLab

- Mu2e aims at 90% CL upper limit 8×10^{-17} with 8 kW proton beam.
    - Under construction. Data taking from 2025~2026.
    - 1/2y before shutdown (run 1), 4y after (run 2).
- Mu2e II aims at 8×10^{-18} with 100 kW proton beam.
    - planed after PIP-II upgrade. Somewhere after 2030.
    - Needs 5 years data taking.
    - Infrastructure will be reused. Target/Detectors need upgrade.

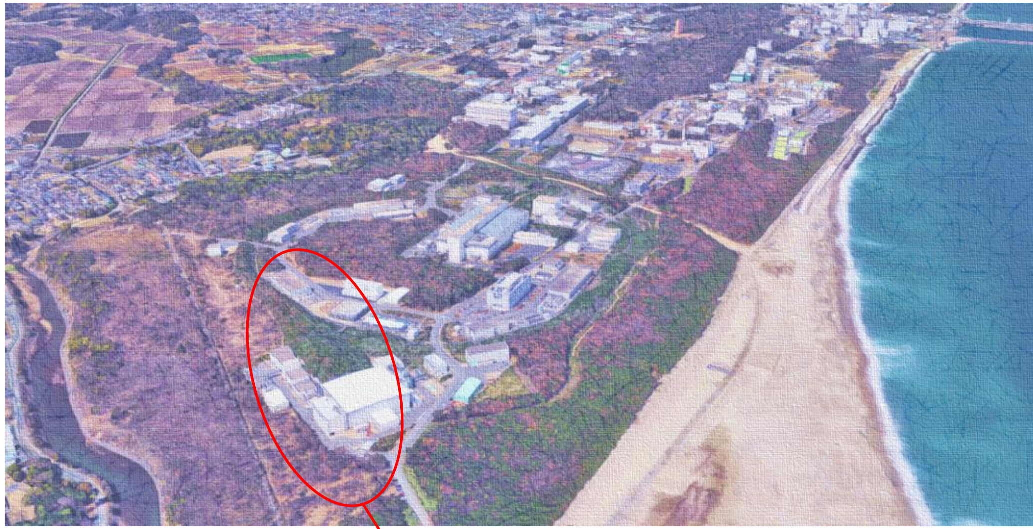


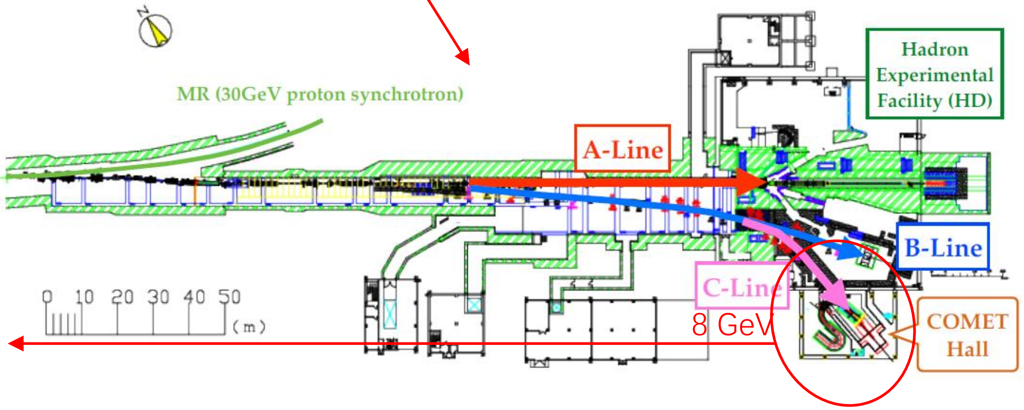


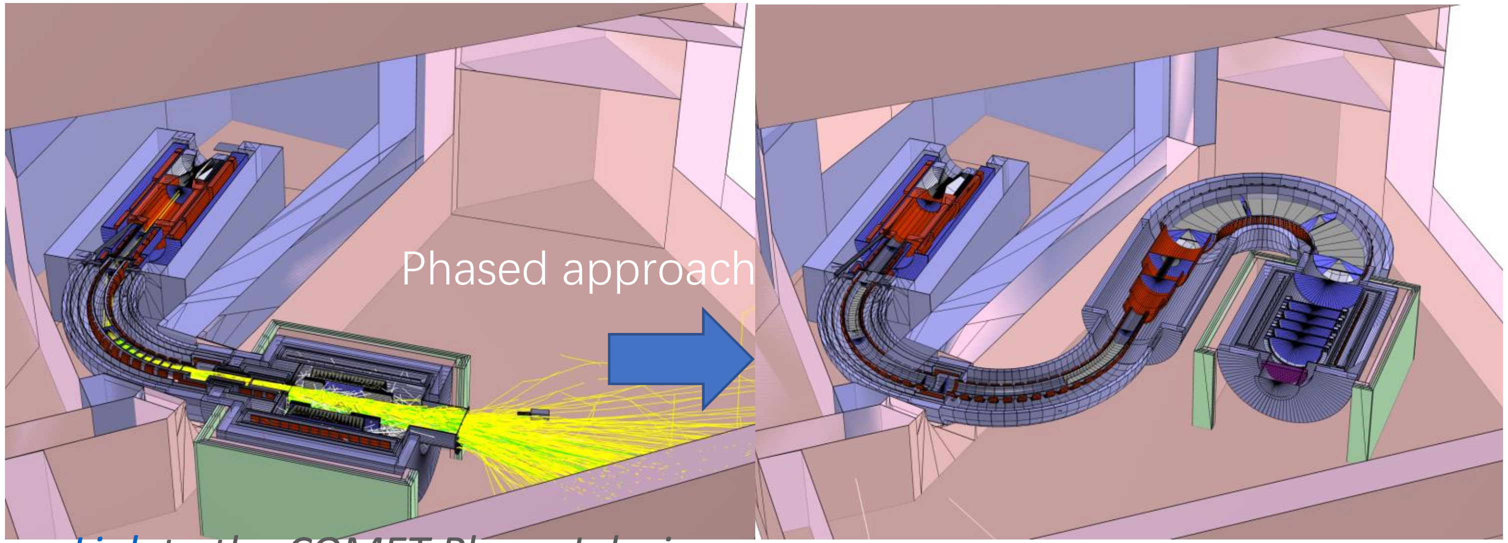
Link to the Mu2e design paper

$\mu N \rightarrow eN$: COMET @ J-PARC

- Phase-I aims at 90% CL upper limit 7×10^{-15} with 3.2 kW proton beam
  - Under construction. Data taking from 2024~2025.
  - 150 days data taking.
- Phase-II aims at 4.6×10^{-17} with 56 kW proton beam
  - Planned 3 years after Phase-I. Needs 1 year data taking.
  - May aim at 7×10^{-18} in case of schedule delay.
  - Infrastructure will be reused. Target/Detectors need upgrade. SC beamline needs extension.



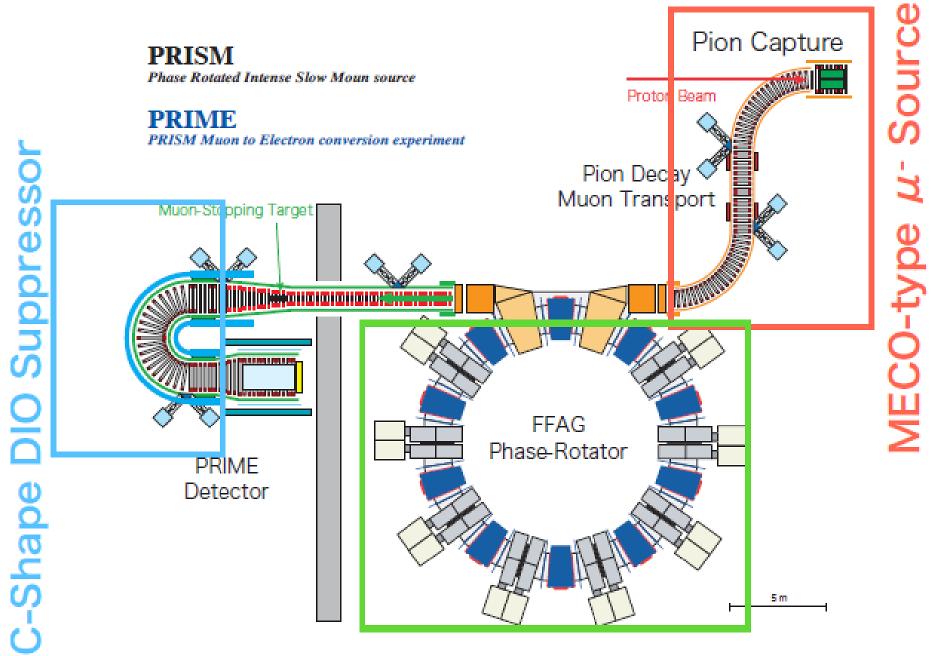




Link to the COMET Phase-I design paper

$\mu N \to eN$: Next generation

The original design before COMET
Started from 2005.



μ- Beam Manipulator(PRISM)

Aiming to achieve an ultimate sensitivity: BR<10^{-18}

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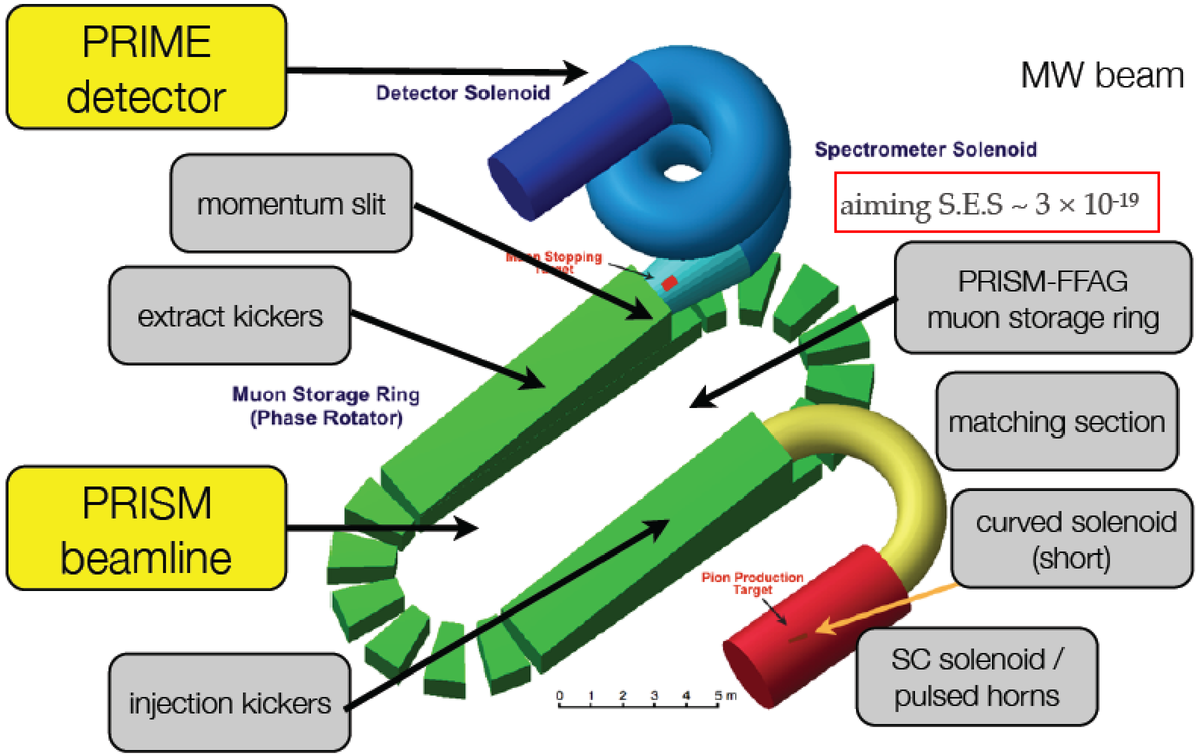
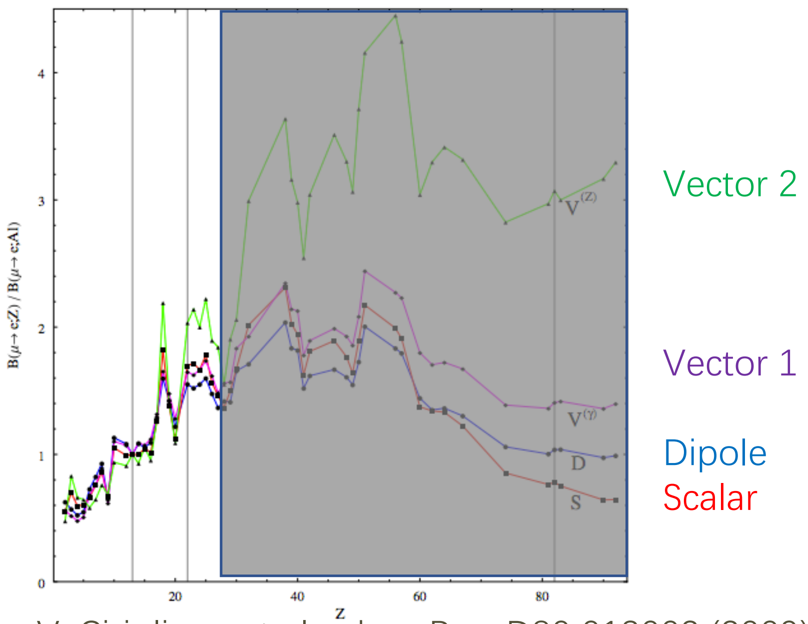
The PRISM group is still updating the design to achieve an ultimate search for $\mu N \to eN$



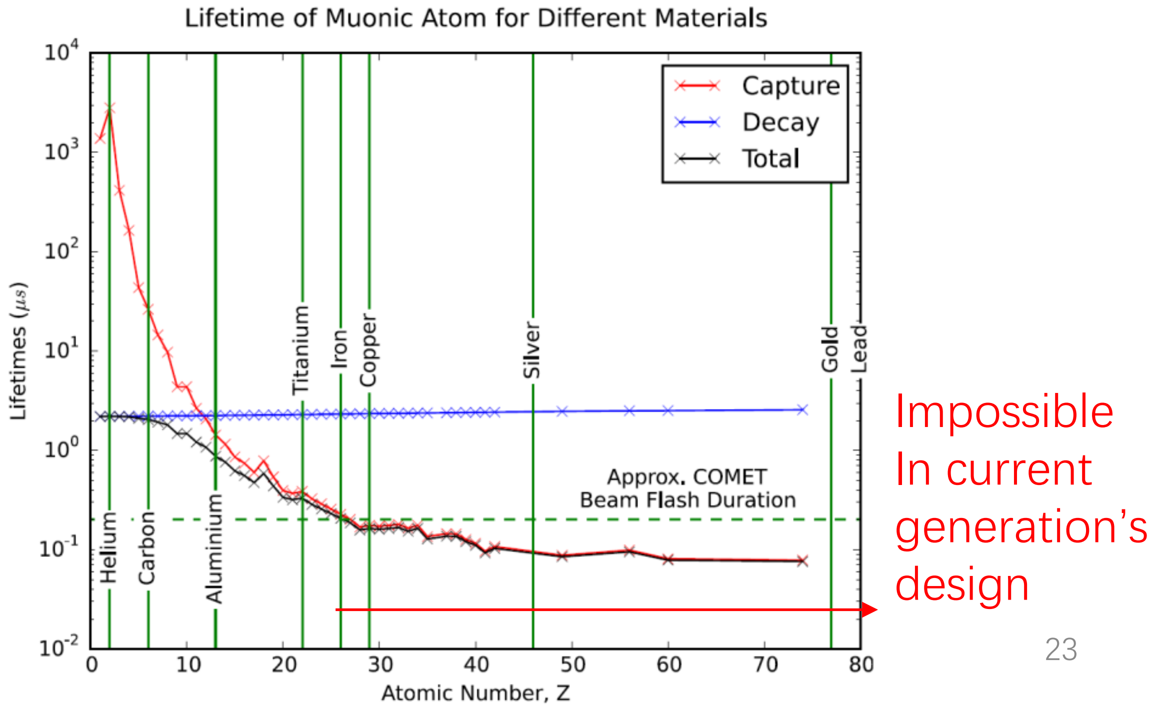
In synergy with muon collider: target, capture, and storage ring. Might be the most intense muon beam before muon collider.

$\mu N \to eN$: Next generation

- Issues
  - FFA needs special muon beam input: narrow bunch, low rate.
  - 1 MW brings challenge to target station and detector/electronics.
- Benefits
  - Pure low energy muon beam: no longer relies on delay window. We can finally probe high-Z material: possible to tell apart different NP models.

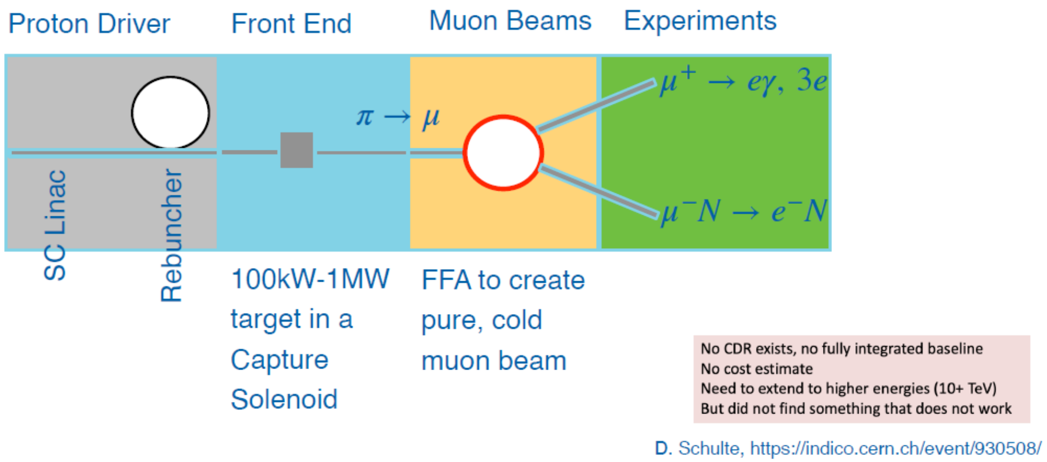


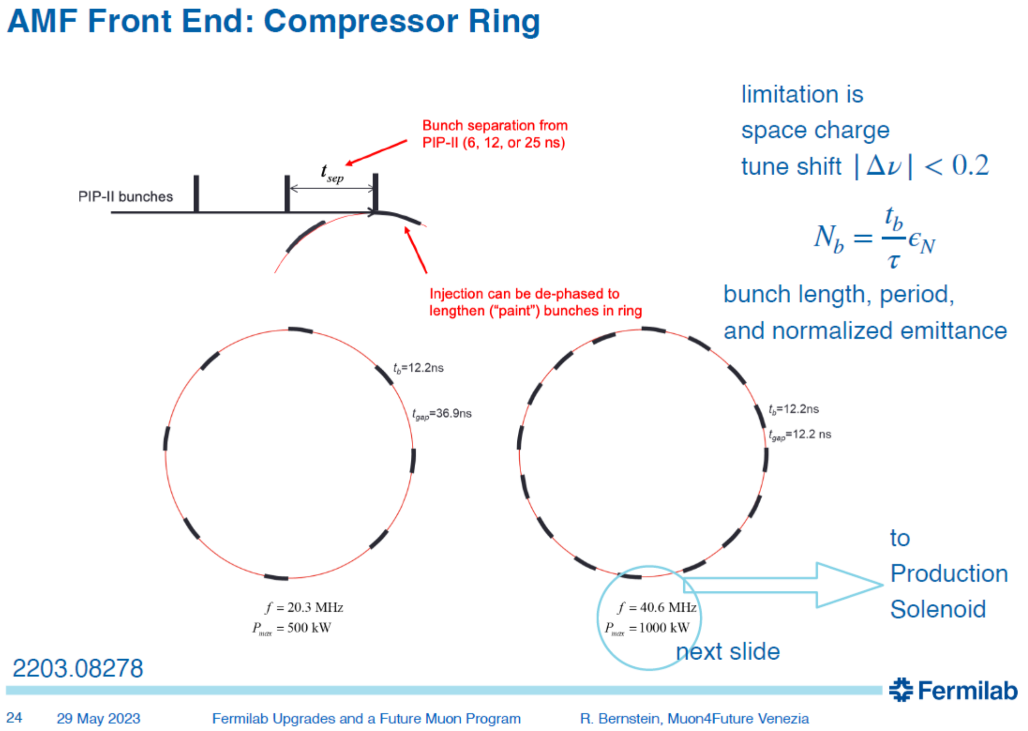
V. Cirigliano et al., phys. Rev. D80 013002 (2009)



$\mu N \to eN$: Next generation

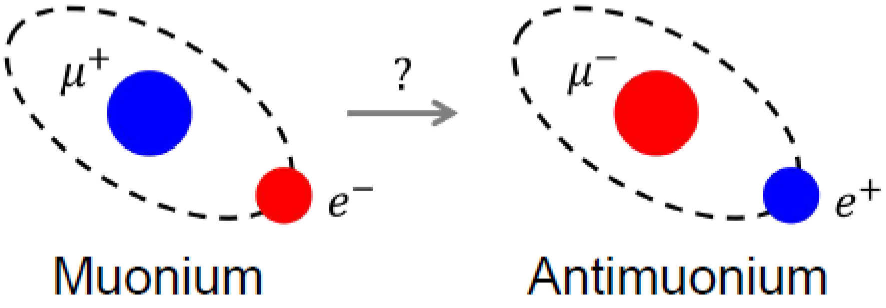
- FermiLab will have its accelerator upgraded: PIP-II, 8kW -> 100 kW
- Advanced Muon Facility (AMF) was proposed to make use of PIP-II for next generation muon physics
- $\mu N \to eN$ plan in AMF took the idea from PRISM: in cooperation.
- AMF proposed to use compressor ring to make beam structure for FFA
  - 10 ns bunches at 100-1000 Hz
- Pile-up effect will be too much
  - Need PRISM type detector: select electrons.
  - $\mu^- N \to e^+ N$ needs separate run in this case.

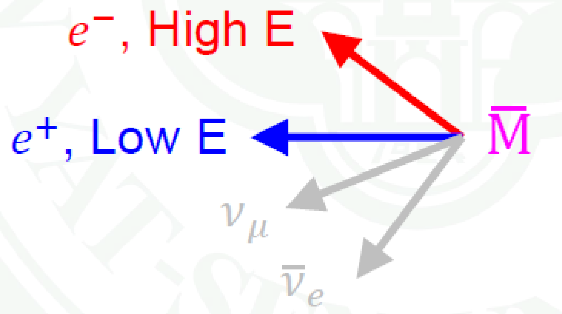




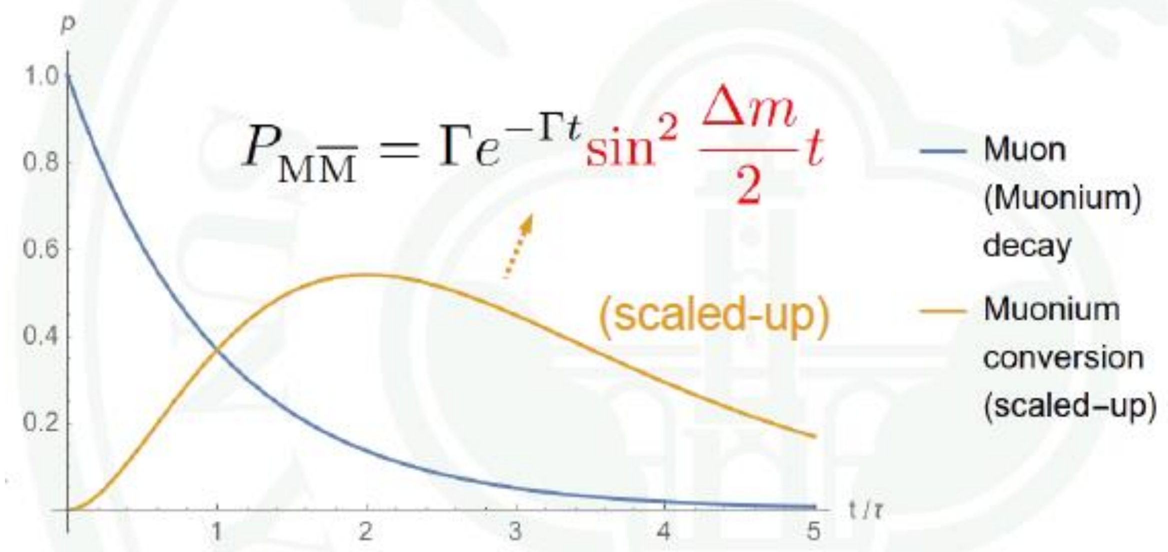
AMF: hep-ex 2203.08278

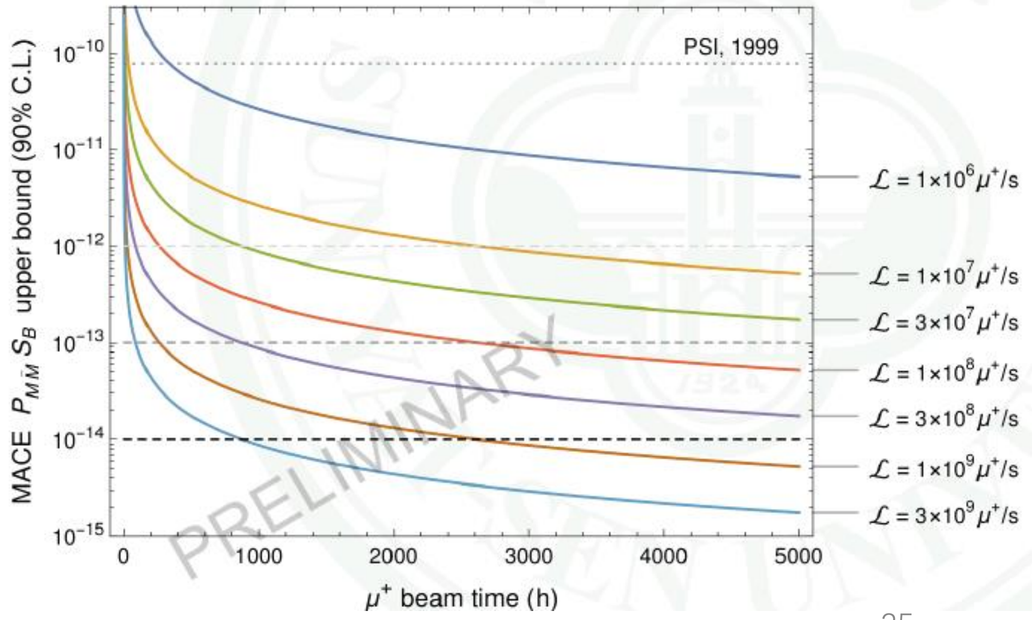
$$M \rightarrow \bar{M}$$





- Starting from muonium formed in special target (Aerogel/SF-He/⋯)
- Search for the the high-E electron and low-E positron.
- Background: internal ($\mu \rightarrow ee e\nu\nu$) and combinatorial events





Transitions with μ in the final state

Giulia Frau, CLFV 2023

Results from LHCb

- **Improved upper limits** at 90%(95%) CL

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7(6.9)\times10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8(7.9)\times10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1(11.7)\times10^{-9}$$

wrt Belle's result ($\mathcal{O}(10^{-7})$) [PRD 98, 071101(R) (2018)]

- **World's first limit** at 90%(95%) CL

$$\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 16.0(19.8)\times10^{-9}$$

Results from NA62, based on Run1 (2016-2018). Run2 on going (2021-CERN LS3)

Channel	BR UL (PDG 2019)	BR UL : NA62	Expected Background	Observed	Publication
$K^+ \to \pi^-\mu^+e^+$	50×10^{-11}	4.2×10^{-11}	1.07 ± 0.20	0	PRL 127 (2021) 131802
$K^+ \to \pi^+\mu^-e^+$	52×10^{-11}	6.6×10^{-11}	0.92 ± 0.34	2	PRL 127 (2021) 131802
$\pi^0 \to \mu^-e^+$	34×10^{-10}	3.2×10^{-10}	0.23 ± 0.15	0	PRL 127 (2021) 131802
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	4.2×10^{-11} *	0.92 ± 0.34	1	PLB 797 (2019) 134794
$K^+ \to \pi^-e^+e^+$	64×10^{-11}	5.3×10^{-11}	0.43 ± 0.09	0	PLB 830 (2022) 137172
$K^+ \to \pi^-\pi^0e^+e^+$	N/A	8.5×10^{-10}	0.044 ± 0.020	0	PLB 830 (2022) 137172
$K^+ \to \mu^-\nu e^+e^+$	N/A	8.1×10^{-11}	0.26 ± 0.04	0	PLB 838 (2023) 137679

Joel Swallow, CLFV 2023

Results from BES III

Teng XIANG, CLFV 2023

	J^P	Generate	$e\mu$
η'	0^-	$J/\psi\to\gamma\eta'$, $(5.25\pm0.07)\times10^{-3}$	4.7×10^{-4}
$\eta_c(1S)$	0^-	$J/\psi\to\gamma\eta_c(1S)$, (1.7 ± 0.4) %	no result
J/ψ	1^-	$e^+e^-\to J/\psi$, 1×10^{10}	4.5×10^{-9}
$\psi(3686)$	1^-	$e^+e^-\to\psi(3686)$, 2.7×10^{9}	no result
χ_{cJ}	J^+	$\psi(2S)\to\gamma\chi_{cJ}$, ~10 %	no result
$h_c(1P)$	1^+	$\psi(2S)\to\pi^0h_c(1P)$, $(7\pm5)\times10^{-4}$	no result

Results from Belle/Belle II

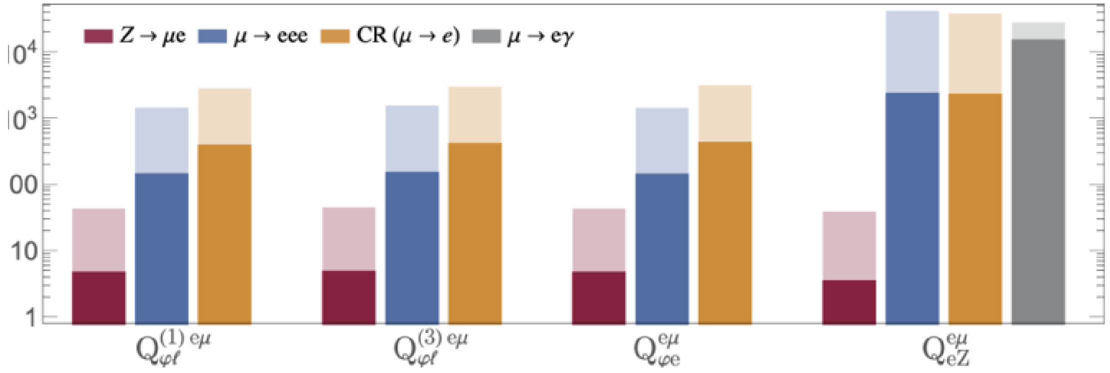
Belle opened world best constraints of the LFV $\boldsymbol{K^*l^+l^-}$ modes

$$\mathcal{B}(B^0\to K^{*0}\mu^+e^-) < 1.2\times10^{-7}$$
$$\mathcal{B}(B^0\to K^{*0}\mu^-e^+) < 1.6\times10^{-7}$$
$$\mathcal{B}(B^0\to K^{*0}\mu^\pm e^\mp) < 1.8\times10^{-7}$$

Belle II can reach 90% of UL at O(10^{-8}) with 50 ab^{-1}

Tomoyuki Konno, CLFV 2019

Expectation from FCC-ee/CEPC, and a comparison in EFT.

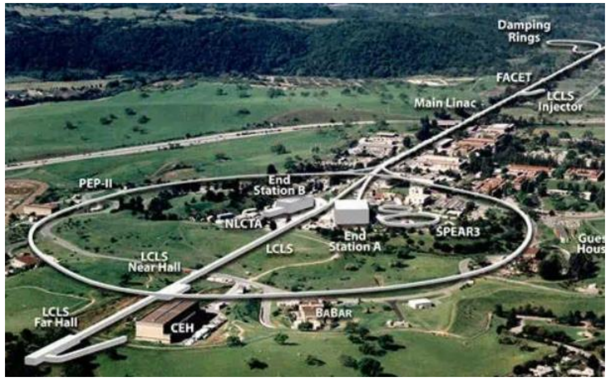


L. Calibbi, X. Marcano and J. Roy, Eur. Phys. J. C 81 (2021) 1054

Experimental status: τ sector

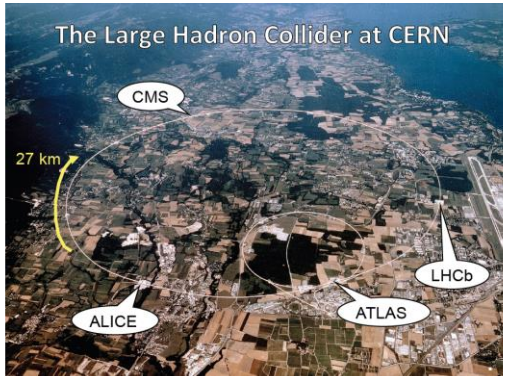
Existing:

BABAR at SLAC



BELLE-II at SuperKEKB

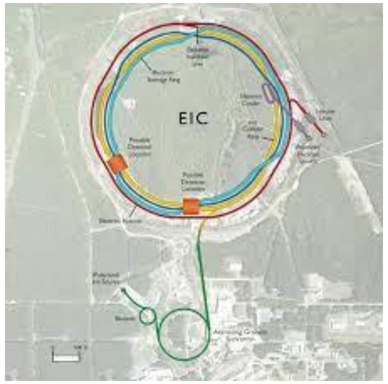
ATLAS, CMS, LHCb at LHC



Proposed:

FCC at CERN

EIC at BNL



STCF at China

Searching CLFV in τ sector

- Complementary to μ sector.
- Availability: B-Factory experiments BaBar, Belle and Belle II, and future prospects at Super Tau Charm Factory, LHC, EIC and FCC-ee experiments.
- Low energy processes
  - τ decay: more than 50 channels.
  - B decay, J/ψ decay.
- High energy processes
  - Heavy decay: Higgs, Z, top quark.

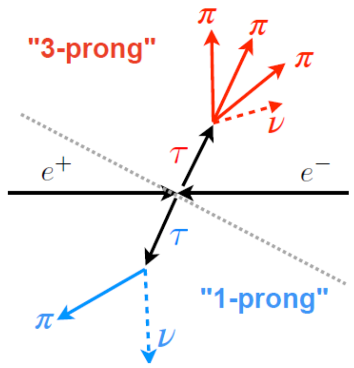
Complementary to each other: sensitive to different models/operators.

τ decay: ~50 benchmark decay channels

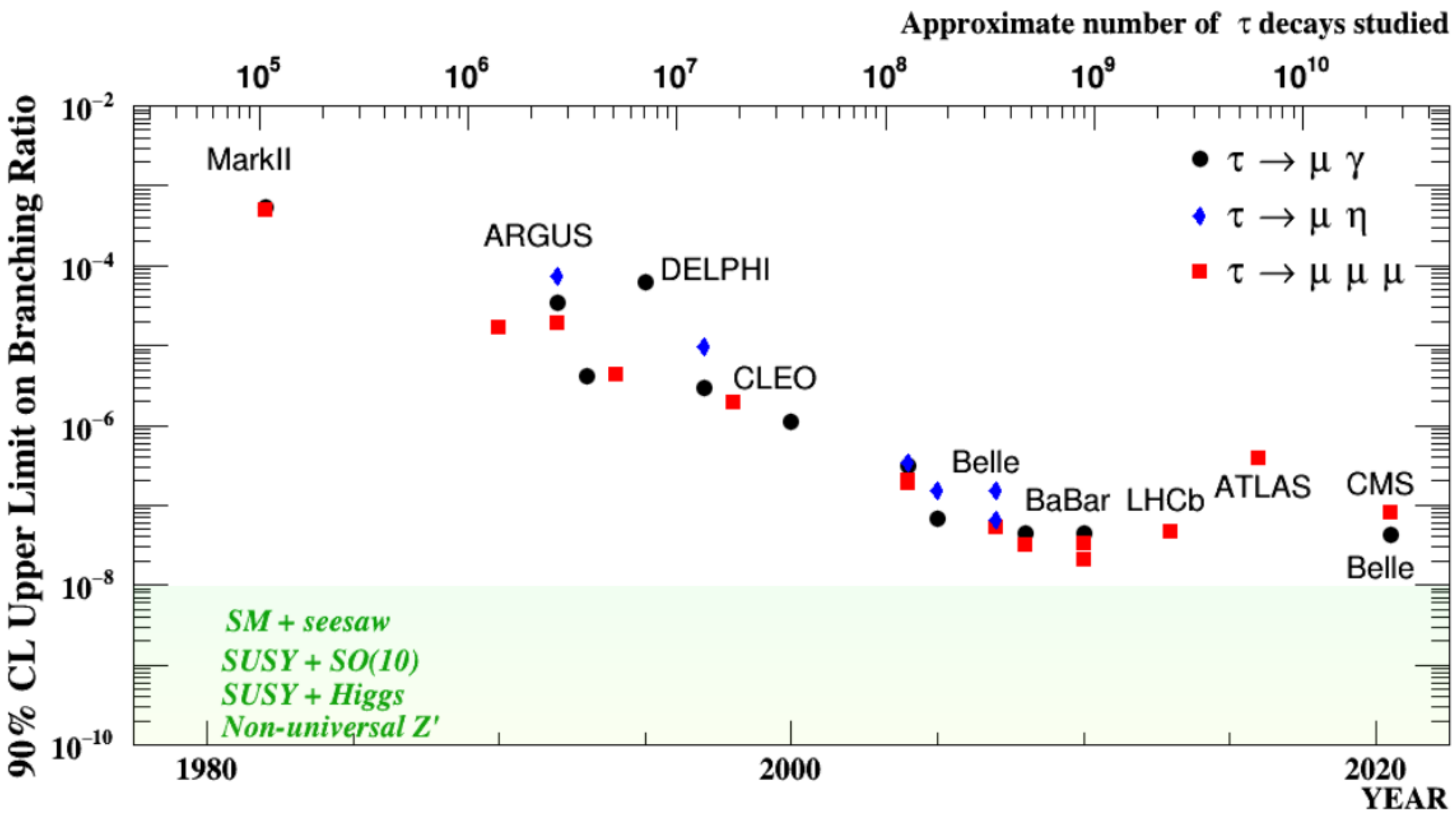
Swagato Banerjee, CIPANP2022

- **Lepton flavor violation (charge conjugate modes implied)**
  - $\tau \to e/\mu\ \gamma$ (Belle II, STCF, FCC-ee)
  - $\tau \to e/\mu$ (scalar/pseudoscalar/vector mesons) (Belle II)
  - $\tau \to e\ e\ e$ (Belle II)
  - $\tau \to \mu\ \mu\ \mu$ (Belle II, ATLAS, CMS, LHCb, STCF, FCC-ee)
  - $\tau \to e\ \mu\ \mu$, $\mu\ e\ e$ (Belle II)
  - $\tau \to e/\mu\ h\ h$ (non-resonant final states with $h=\pi/K$) (Belle II, STCF)
  - $\tau \to e/\mu$ invisible (α) (Belle II)
  - $H \to e\ \tau$, $\mu\ \tau$ (ATLAS, CMS)
  - $Z(Z') \to e\ \tau$, $\mu\ \tau$ (ATLAS, CMS)
  - $e \to \tau$ transitions (EIC)
- **Lepton number violation**
  - $\tau^- \to e^+\ h^-\ h^-$ (non-resonant final states with $h=\pi/K$) (Belle II)
  - $\tau^- \to \mu^+\ h^-\ h^-$ (non-resonant final states with $h=\pi/K$) (Belle II)
- **Baryon number violation**
  - $\tau^- \to \Lambda\ \pi^-$, $\bar{\Lambda}\ \pi^-$ (Belle II)
  - $\tau^- \to \bar{p}\ \mu^+\ \mu^-$, $p\ \mu^-\ \mu^-$ (Belle II, LHCb)

- Best place to search for τ decay is the B factory from e^+e^- collider.
  - Large production cross-section.
  - Well-defined initial state
  - A large
  - Formerly: CLEO, BaBar, Belle
  - Now: Belle II
- pp collider can still compete on some channels.

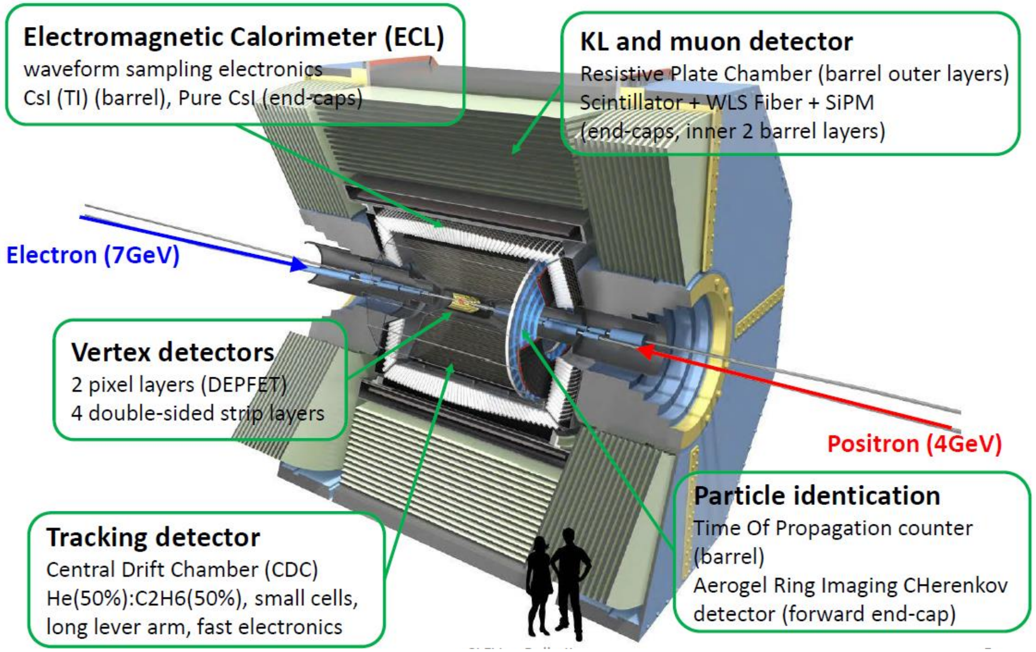


History of golden channels



Swagato Banerjee, CIPANP2022

Recent updates on Belle II



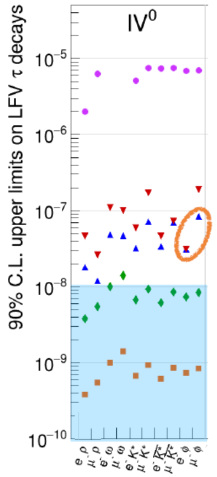
arXiv:2203.14919

	Observed Limits			Expected Limits		
$\tau^- \to$	Experiment	Luminosity	UL (obs)	Experiment	Luminosity	UL (exp)
$\mu^-\phi$	Belle [99]	854 fb^{-1}	8.4×10^{-8}	Belle II [54]	50 ab^{-1}	8.4×10^{-10}
	BaBar [100]	451 fb^{-1}	1.9×10^{-7}			

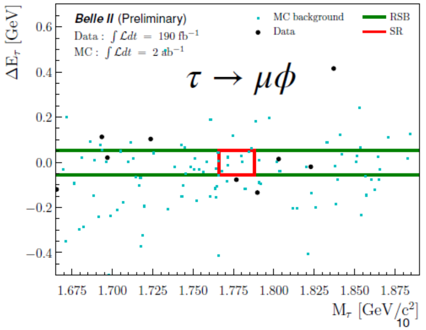
Using 2019-2021 data: 190 fb^{-1}

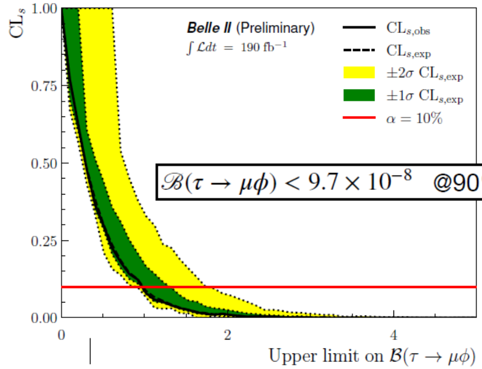
arXiv:2305.04759

Enhancing statistics: $\tau \to \ell\phi$



- Channel favored by models with e.g. vector leptoquarks.
- **Improve Belle efficiency x2** by not reconstructing the other τ: **ε=6.5%(μ)/6.1%(e)**
- Reconstruct $\tau \to \ell\phi(\to K^+K^-)$, suppress background with BDT instead.
- Poisson counting in **signal region (SR)**, expected background from **reduced sidebands (RSB)** in data, scaled with simulations.



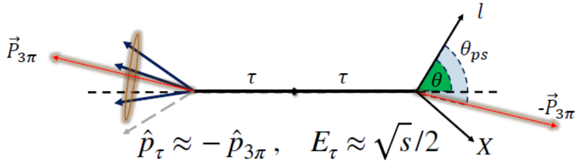


$\mathcal{B}(\tau \to \mu\phi) < 9.7\times10^{-8}$ @90% C.L.

PRL 130, 181803 (2023) | 63 fb^{-1}

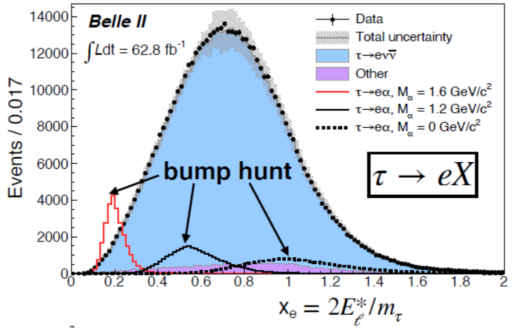
New searches: $\tau \to \ell X$

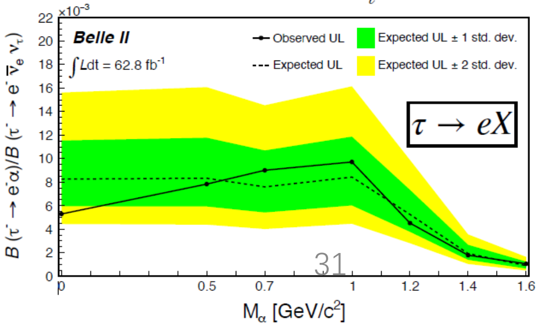
- Invisible LFV particles ("X" or "α") can emerge from NP models e.g. light ALP: JHEP 09 (2021) 173
- Approximate the τ rest frame using $\tau \to 3\pi\nu$:



$\hat{p}_\tau \approx -\hat{p}_{3\pi}\,,\quad E_\tau \approx \sqrt{s}/2$

- Bump search over the $\tau \to \ell\bar{\nu}\nu$ spectrum.
- Ratio $\mathcal{B}(\tau \to \ell X)/\mathcal{B}(\tau \to \ell\bar{\nu}\nu)$ allows partial cancellation of systematics (mainly lepton ID).
- **Most stringent** limit, **2.2-14 better** than previous.

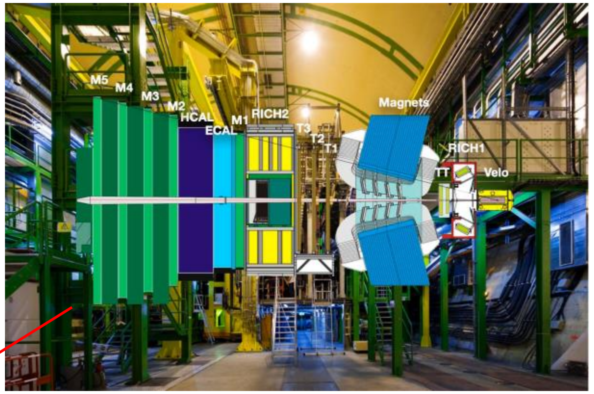


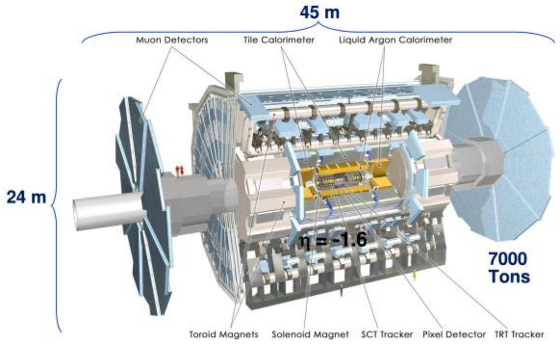


Recent updates on LHCb & CMS

arXiv:2203.14919

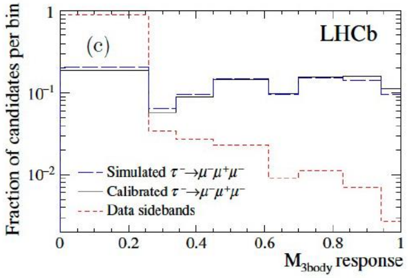
$\tau^- \to$	Observed Limits			Expected Limits		
	Experiment	Luminosity	UL (obs)	Experiment	Luminosity	UL (exp)
$\mu^-\mu^+\mu^-$	Belle [102]	782 fb^{-1}	2.1×10^{-8}	Belle II [54]	50 ab^{-1}	3.6×10^{-10}
	BaBar [103]	468 fb^{-1}	3.3×10^{-8}			
	LHCb [61]	3 fb^{-1}	4.6×10^{-8}	LHCb [76]	300 fb^{-1}	$\mathcal{O}(10^{-9})$
	CMS [67]	33 fb^{-1}	8.0×10^{-8}	CMS [77]	3 ab^{-1}	3.7×10^{-9}
	ATLAS [68]	20 fb^{-1}	3.8×10^{-7}	ATLAS [78]	3 ab^{-1}	1.0×10^{-9}
				STCF [74]	1 ab^{-1}	1.4×10^{-9}
				FCC-ee [87, 91]	150 ab^{-1}	$\mathcal{O}(10^{-10})$

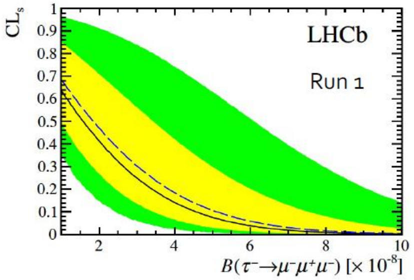




The $\tau^+ \to \mu^+\mu^-\mu^+$ decay

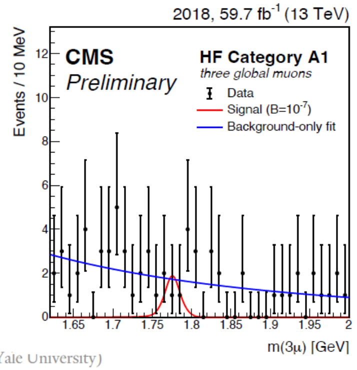
- Current **best experimental limit** from **Belle** [arXiv:1001.3221]
  - 2.1×10^{-8} at 90% CL
- **LHCb** analysis on **Run 1** data [JHEP02(2015)121]
  - $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$ used as a normalisation channel
  - Challenges: identify and reject background sources
    - Combinatorial and mis-ID background ($D_{(s)}^+ \to 3\pi$, $D^+ \to K^-\pi^+\pi^+$)
  - Background suppression achieved by means of multivariate classifiers
  - Upper limit: $4.6(5.6)\times10^{-8}$ at 90%(95%) CL
- **Ongoing analysis with Run 2 data (coming out soon!)**
- **Extrapolated limit** from Run 1 to Run 1 + Run 2 (higher luminosity and cross section)
  - $2.5(3.1)\times10^{-8}$ at 90%(95%) CL
- Development of a more efficient selection

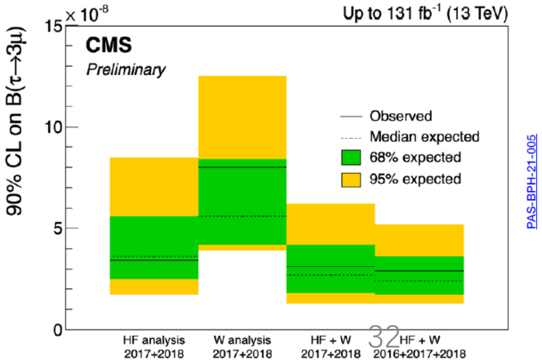




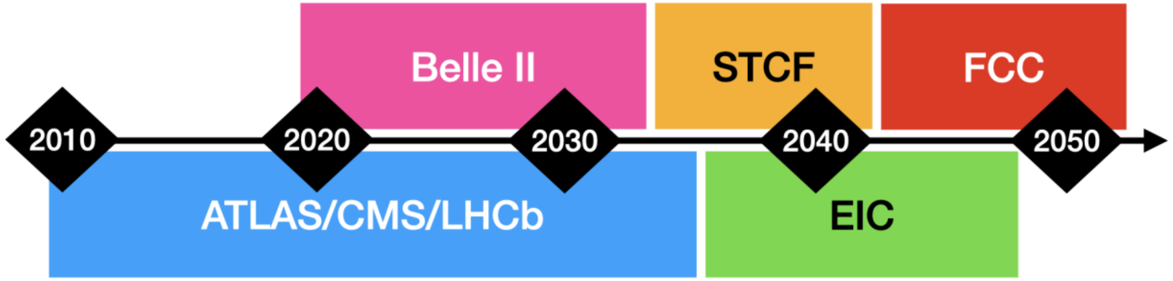
$\tau \to \mu\mu\mu$ decay

- Final result extracted from simultaneous parametrized fit to all the signal regions including the results from 2016 data
- Br($\tau \to \mu\mu\mu$) < 2.9 x10^{-8} at 90% CL
  - Getting very close to the world limit from Belle (2.1x10^{-8} at 90% CL)

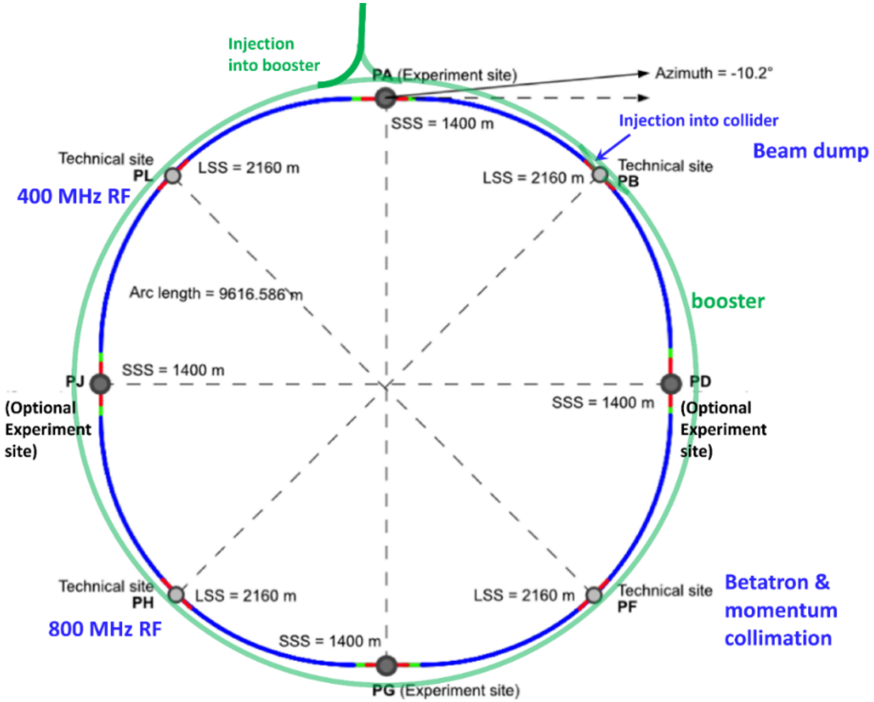


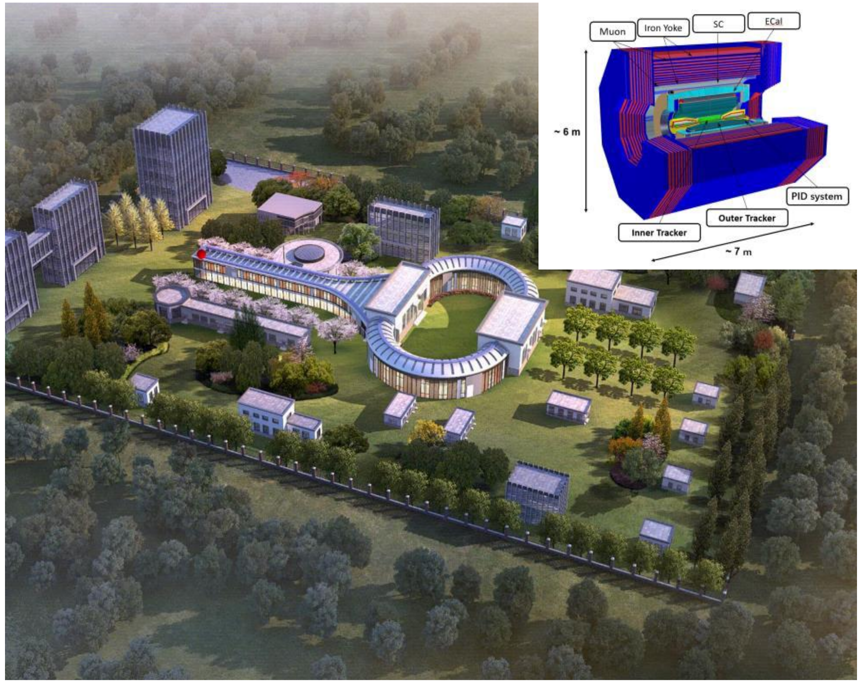


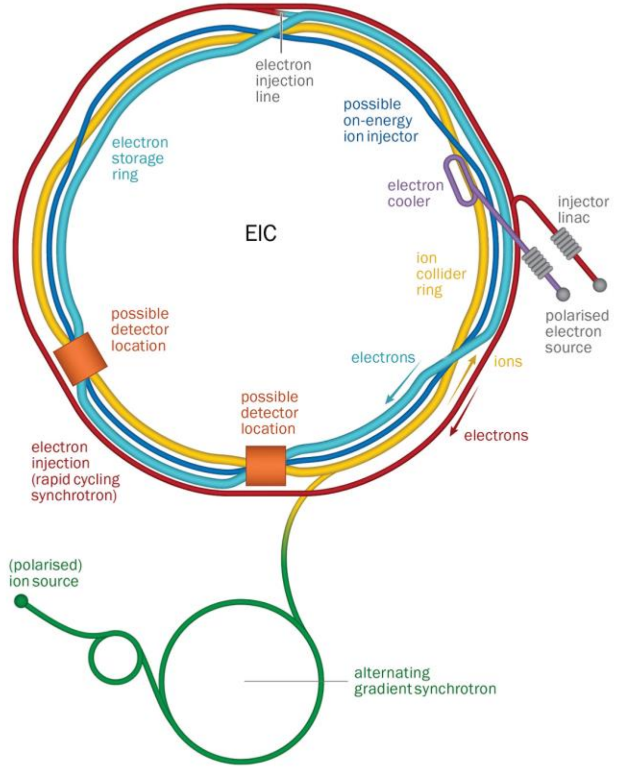
Future projects



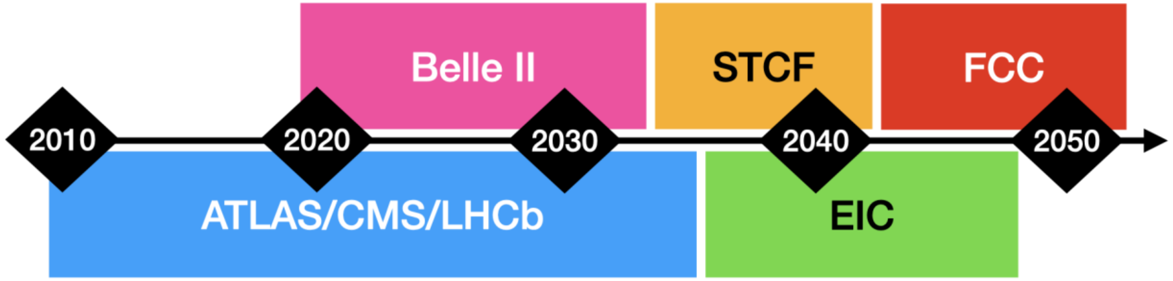
Tentative timeline for data-taking arXiv:2203.14919





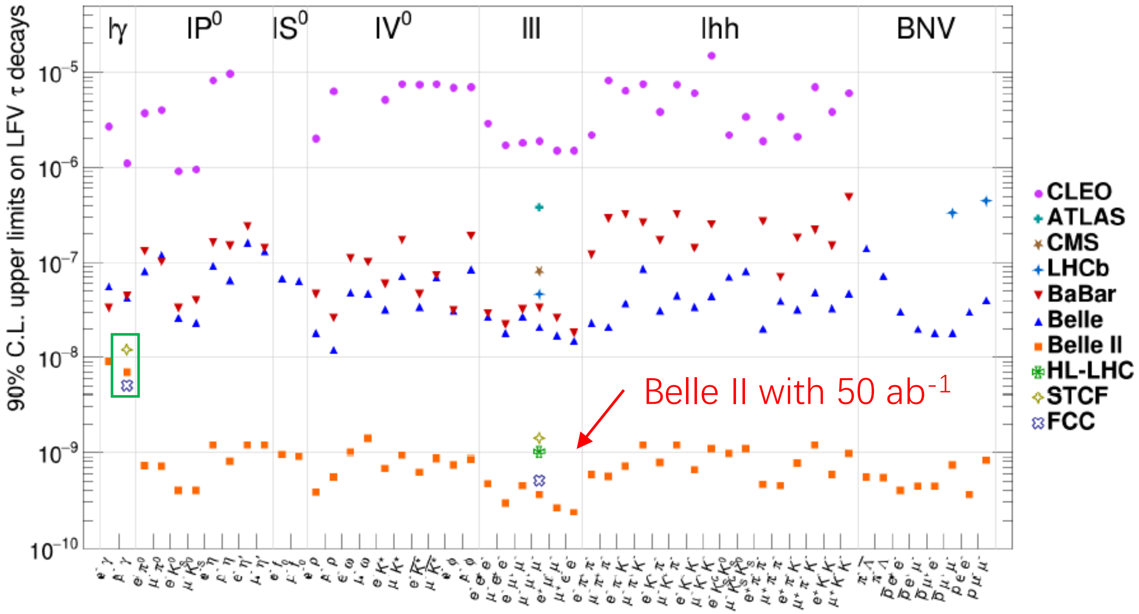


Prospect in the future



Tentative timeline for data-taking arXiv:2203.14919

Estimation as of Snowmass 2021 arXiv:2203.14919



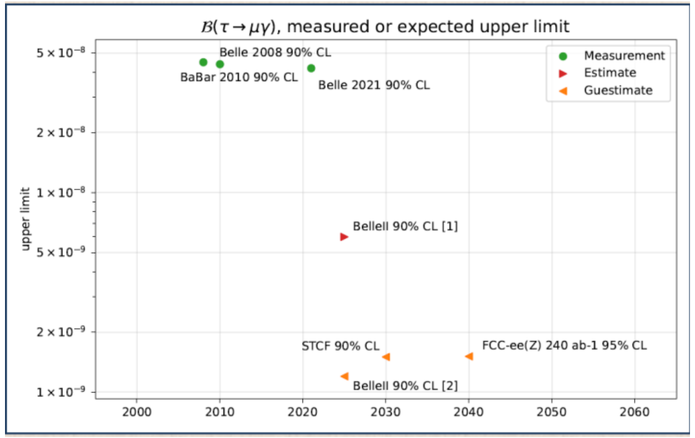
Estimation as of CLFV 2023

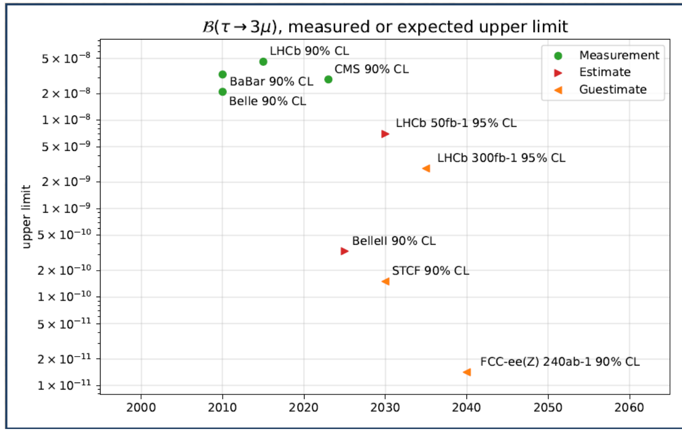
present → future

	CLEO, CLEOIII	LEP 100	Belle, BABAR	Belle II	SCT	STCF	CEPC(Z)	FCC-ee(Z)
E_{CM} [GeV]	~10.6	92	~10.6	~10.6	2 – 6	2 – 7	92	
$\int \mathcal{L}dt$ [ab^{-1}]	0.01		1.5	50	10			240
tau pairs	$1{\cdot}10^7$	$0.8{\cdot}10^6$	$1.4{\cdot}10^9$	$46{\cdot}10^9$	$30{\cdot}10^9$		$30{\cdot}10^9$	$270{\cdot}10^9$

note: SCT & SCFT tau pairs estimate assuming 10 years of tau-pairs-optimized CM energies running

Alberto Lusiani, CLFV 2023





Details about $\tau \to \mu\mu\mu$:

$\tau^- \to$	Observed Limits			Expected Limits		
	Experiment	Luminosity	UL (obs)	Experiment	Luminosity	UL (exp)
$\mu^-\mu^+\mu^-$	Belle [102]	782 fb^{-1}	$2.1{\times}10^{-8}$	Belle II [54]	50 ab^{-1}	$3.6{\times}10^{-10}$
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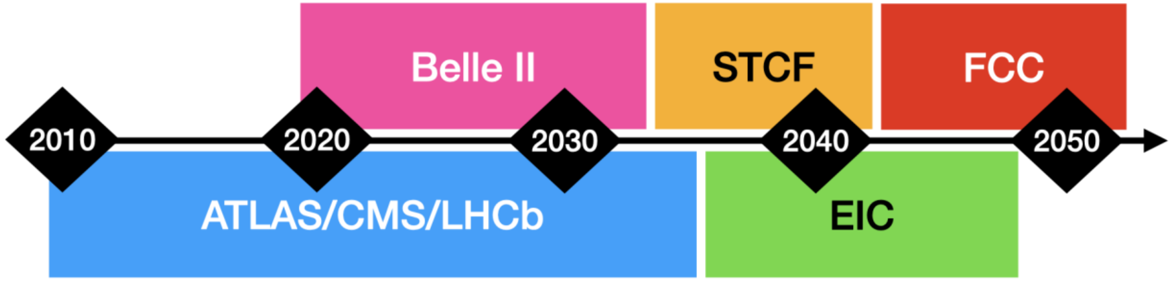
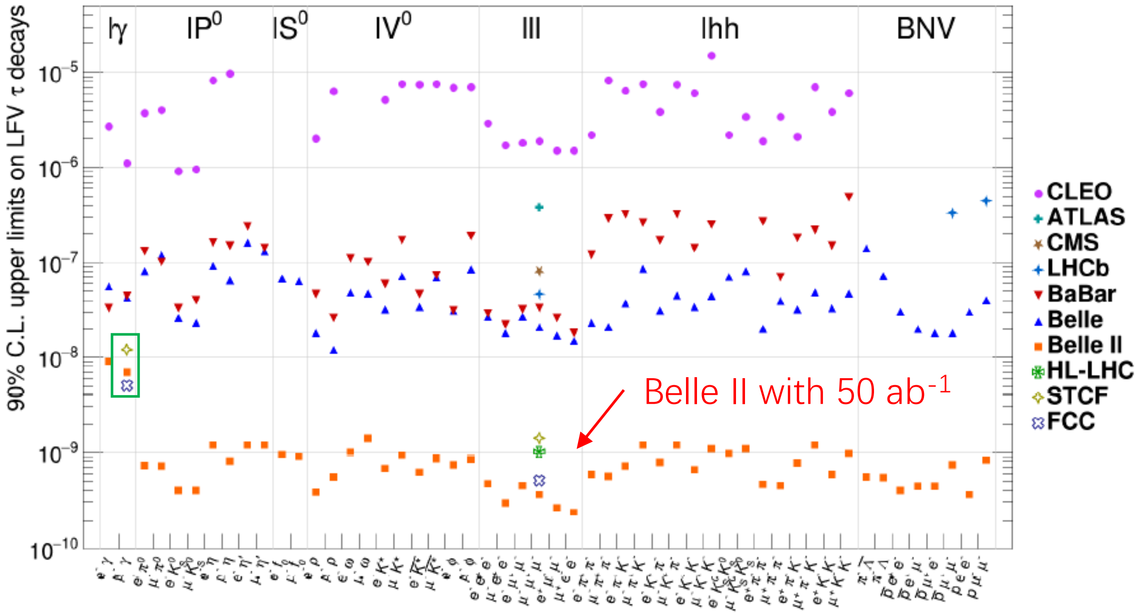
arXiv:2203.14919

Prospect in the future



Tentative timeline for data-taking arXiv:2203.14919

Estimation as of Snowmass 2021 arXiv:2203.14919



Estimation as of CLFV 2023

present → future

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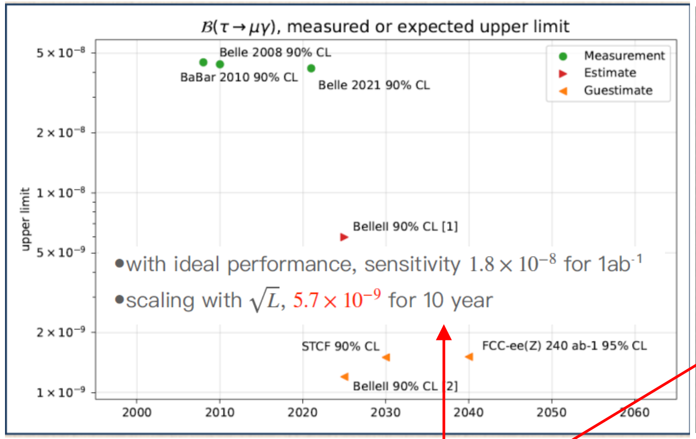
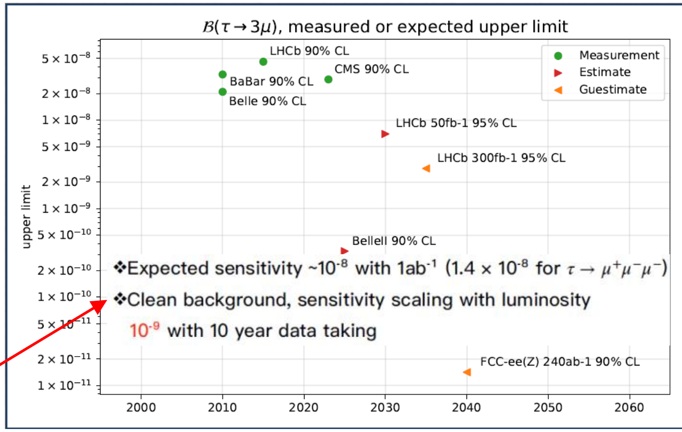
note: SCT & SCFT tau pairs estimate assuming 10 years of tau-pairs-optimized CM energies running

Alberto Lusiani, CLFV 2023





STCF estimated UL according to Teng XIANG, CLFV 2023

Details about $\tau\to\mu\mu\mu$:

$\tau^-\to$	Observed Limits			Expected Limits		
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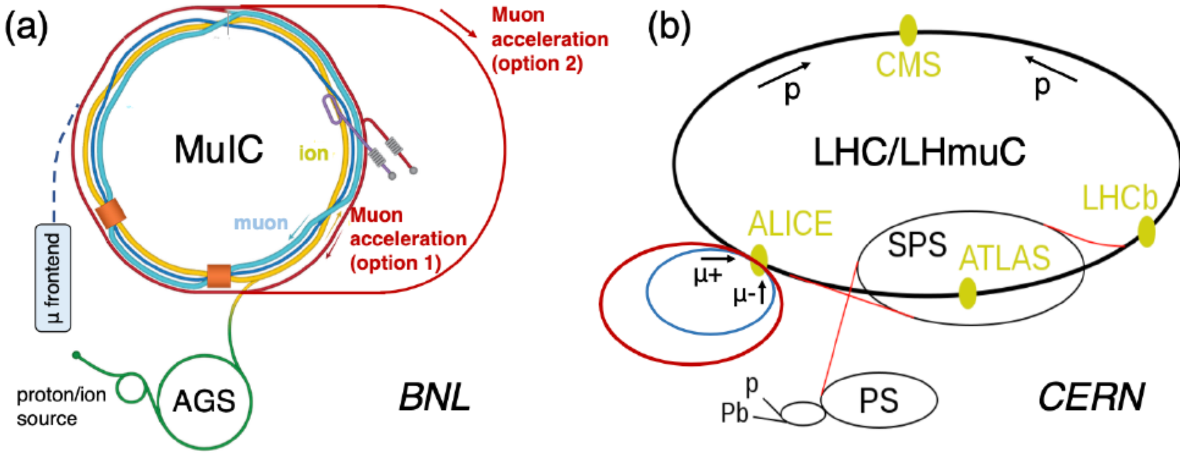
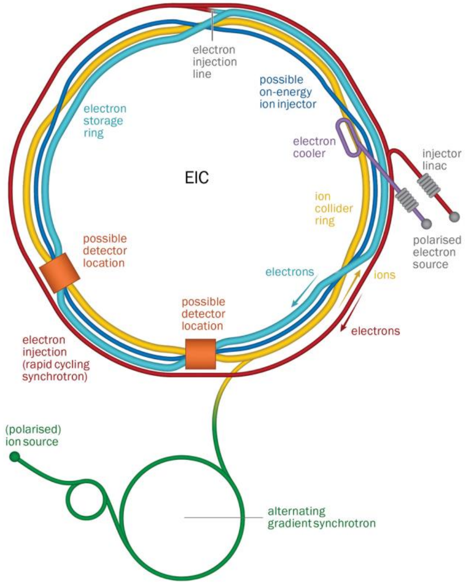
				STCF [74]	1 ab^{-1}	1.4×10^{-9}
				FCC-ee [87, 91]	150 ab^{-1}	$\mathcal{O}(10^{-10})$

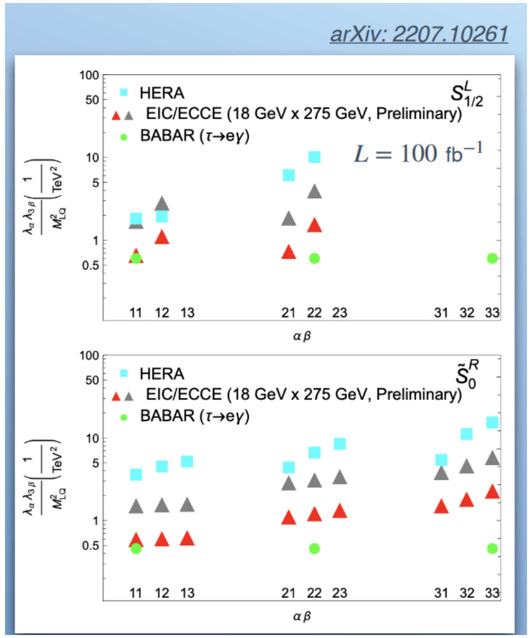
arXiv:2203.14919

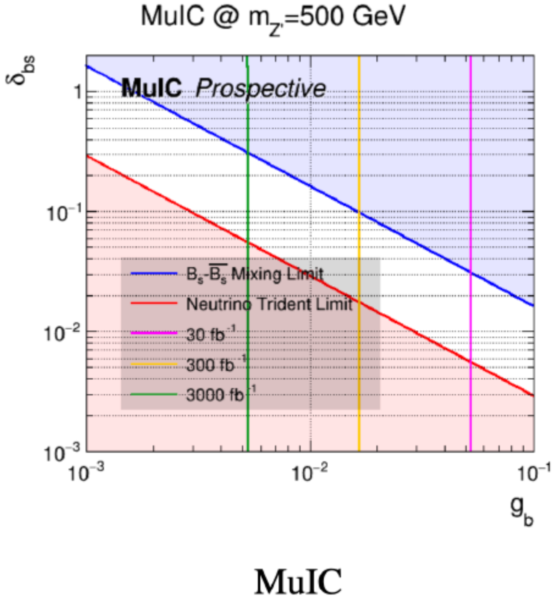
Prospect in the future: EIC, MuIC, LHC/LHmuC

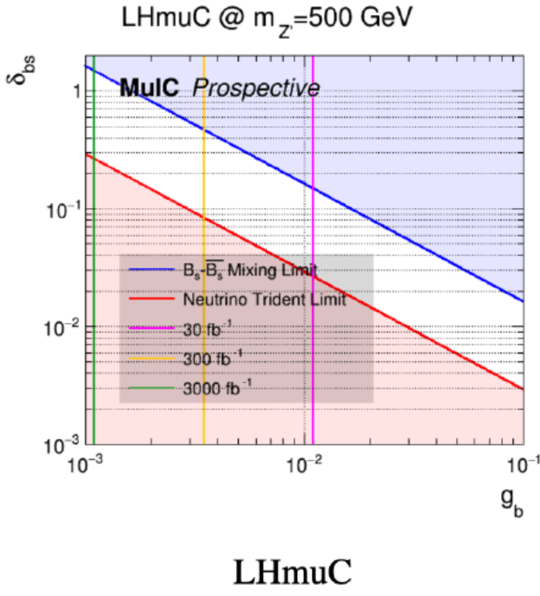
- EIC and MuIC, LHmuC provide sensitivities on unique channels.
  - Two examples shown here.











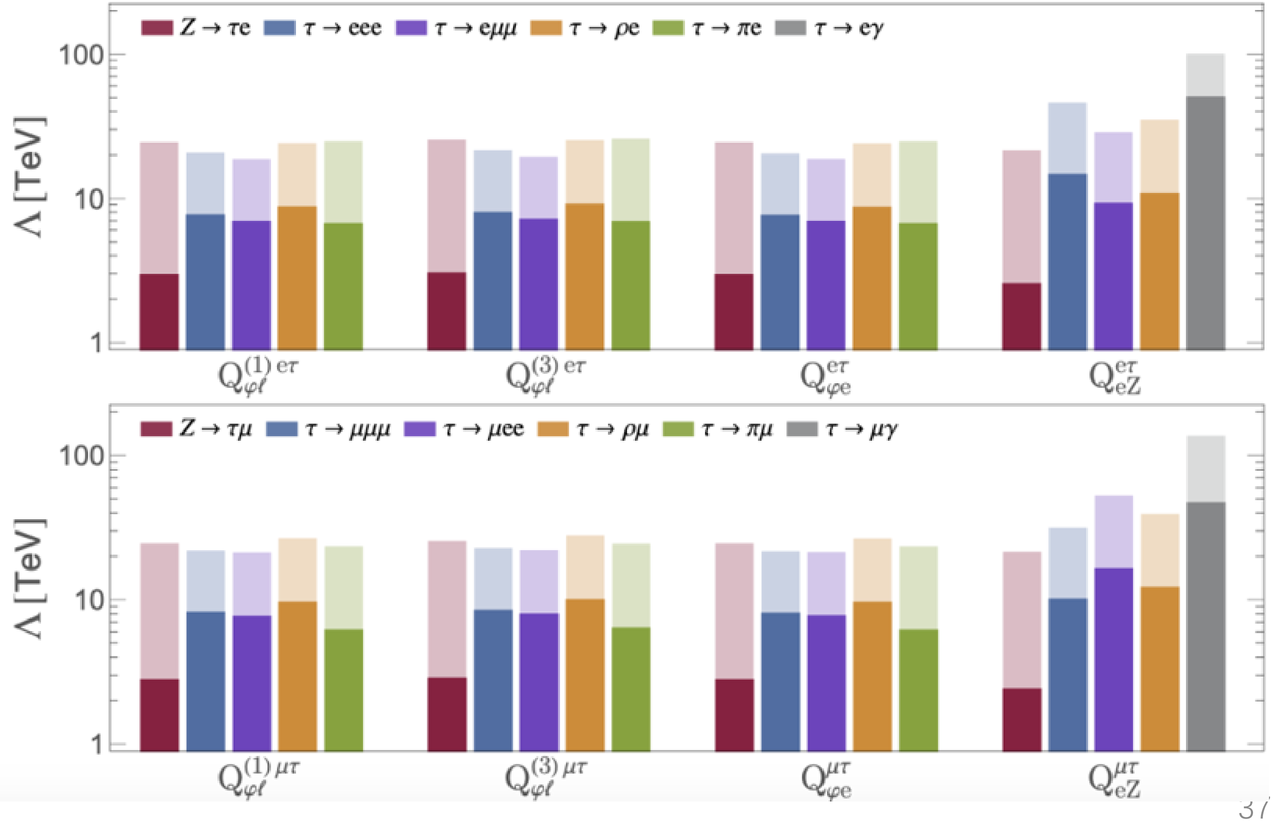
Transitions with τ in the final state

Current limits: arXiv:2203.14919

Channel	Upper limit	Experiment [Ref.]
$J/\psi \to e^\pm\tau^\mp$	7.5×10^{-8}	BES III [108]
$J/\psi \to \mu^\pm\tau^\mp$	2.0×10^{-6}	BES [109]
$B^0 \to e^\pm\tau^\mp$	2.8×10^{-5}	BaBar [110]
$B^0 \to \mu^\pm\tau^\mp$	2.2×10^{-5}	BaBar [110]
	1.2×10^{-5}	LHCb [62]
$B^+ \to \pi^+e^\pm\tau^\mp$	7.5×10^{-5}	BaBar [111]
$B^+ \to \pi^+\mu^\pm\tau^\mp$	7.2×10^{-5}	BaBar [111]
$B^+ \to K^+e^\pm\tau^\mp$	3.0×10^{-5}	BaBar [111]
$B^+ \to K^+\mu^\pm\tau^\mp$	4.8×10^{-5}	BaBar [111]
$B^+ \to K^+\mu^-\tau^+$	3.9×10^{-5}	LHCb [63]
$B^0_s \to \mu^\pm\tau^\mp$	3.4×10^{-5}	LHCb [62]
$\Upsilon(1S) \to e^\pm\tau^\mp$	2.7×10^{-6}	Belle [112]
$\Upsilon(1S) \to \mu^\pm\tau^\mp$	2.7×10^{-6}	Belle [112]
$\Upsilon(2S) \to e^\pm\tau^\mp$	3.2×10^{-6}	BaBar [113]
$\Upsilon(2S) \to \mu^\pm\tau^\mp$	3.3×10^{-6}	BaBar [113]
$\Upsilon(3S) \to e^\pm\tau^\mp$	4.2×10^{-6}	BaBar [113]
$\Upsilon(3S) \to \mu^\pm\tau^\mp$	3.1×10^{-6}	BaBar [113]
$Z \to e^\pm\tau^\mp$	5.0×10^{-6} (*)	ATLAS [69]
$Z \to \mu^\pm\tau^\mp$	6.5×10^{-6} (*)	ATLAS [69]
$H \to e^\pm\tau^\mp$	0.47% (*)	ATLAS [65]
	0.22% (*)	CMS [66]
$H \to \mu^\pm\tau^\mp$	0.28% (*)	ATLAS [65]
	0.15% (*)	CMS [66]
	26% (*)	LHCb [64]

Expectation from FCC-ee/CEPC, and a comparison in EFT.

- High energy processes keep competitive with low energy ones!



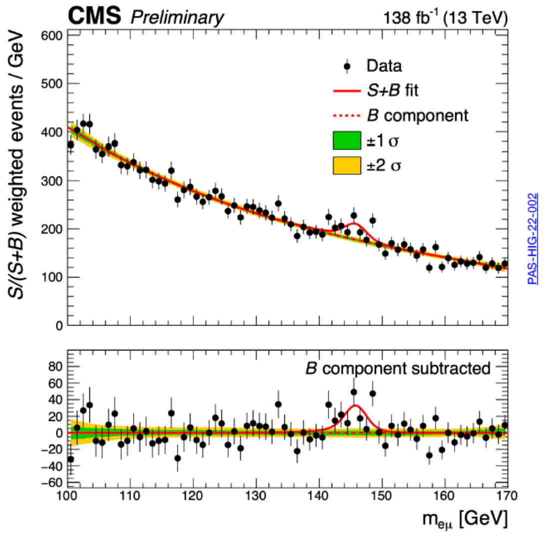
L. Calibbi, X. Marcano and J. Roy, Eur. Phys. J. C 81 (2021) 1054

Hint about CLFV on CMS?

- Not found on ATLAS.
- Needs further scrutinization…

Near Higgs eμ search in CMS

- CMS searched also for $X \rightarrow e^{\pm}\mu^{\mp}$ near the Higgs mass
- Two categories to split VBF from non-VBF production modes
- Background modeled using a Bernstein polynomial function



Near Higgs eμ search in ATLAS

- ATLAS search for $H(125) \rightarrow e\mu$ not directly comparable with CMS analysis, but back-of-the-envelope calculation from sideband data disfavors a narrow-width excess, as observed by CMS

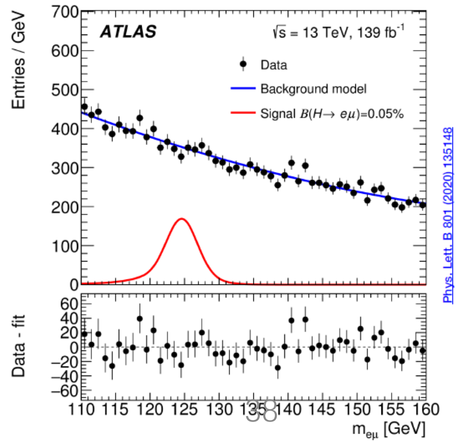
Back-of-the-envelope calculation courtesy of N. Berger and T. Masubuchi

Limit for 125 GeV Higgs:
BR(H→eμ) < 6.2x10^{-5} (observed)
< 5.9x10^{-5} (expected)

Fold in total Higgs cross-section of 55.6 fb at 13 TeV:
σ x BR < 3.4 fb (observed)
< 3.3 fb (expected)

Rough scaling of backgrounds (slightly lower at 146 GeV than 125 GeV:
σ x BR < ~3 fb (expected and observed, since no excess seen)

Not entirely conclusive (ballpark estimates + no directly comparable analysis), but CMS excess is disfavoured by ATLAS.



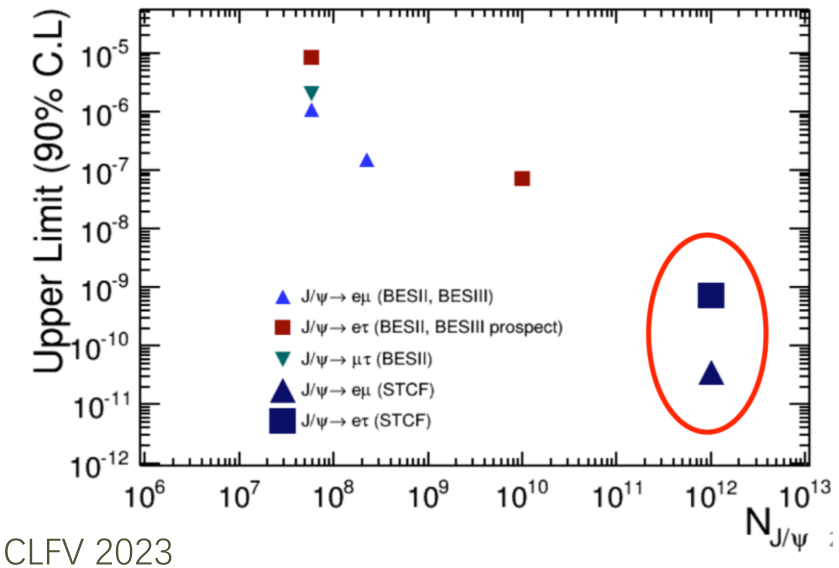
BES IIII & STCF

Results from BES III

PRD 94, 074023 (2016)

	J^P	Generate	$e\mu$	$e\tau$	$\mu\tau$	$\gamma\ell_1\bar{\ell}_2$
η'	0^-	$J/\psi \to \gamma\eta'$, $(5.25 \pm 0.07) \times 10^{-3}$	4.7×10^{-4}	–	–	
$\eta_c(1S)$	0^-	$J/\psi \to \gamma\eta_c(1S)$, $(1.7 \pm 0.4)\,\%$	no result	no result	no result	
J/ψ	1^-	$e^+e^- \to J/\psi$, 1×10^{10}	4.5×10^{-9}	7.5×10^{-8}	2.0×10^{-6}	
$\psi(3686)$	1^-	$e^+e^- \to \psi(3686)$, 2.7×10^{9}	no result	no result	no result	no result
χ_{cJ}	J^+	$\psi(2S) \to \gamma\chi_{cJ}$, $\sim 10\,\%$	no result	no result	no result	
$h_c(1P)$	1^+	$\psi(2S) \to \pi^0 h_c(1P)$, $(7 \pm 5) \times 10^{-4}$	no result	no result	no result	

Prospect on STCF

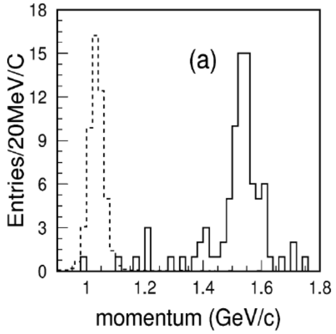


Teng XIANG, CLFV 2023

$J/\psi \to \mu\tau$

Phys. Lett. B 598 (2004) 172–177

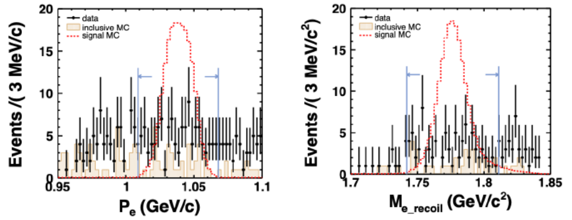
- ❖ $J/\psi \to \mu\tau$, $\tau \to e\nu\nu$, BESII 58M
  - Two opposite charged tracks, identified as e and mu
  - No photons
  - Electron momentum < 1.4GeV to suppress Bhabha bkg
  - Signal region: mono-energetic muon, momentum in [1.0, 1.08]GeV
- ❖ No events observed.
- ❖ Upper limit: $Br(J/\psi \to \mu\tau) < 2.0 \times 10^{-6}$ @ 90% C.L.
- ❖ Update with 10B J/ψ in progress

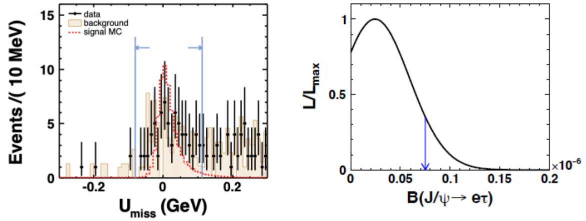


$J/\psi \to e\tau$

Phys. Rev. D 103, 112007 (2021)

- ❖ $J/\psi \to e\tau$, $\tau \to \pi\pi^0\nu$, 10B J/ψ
  - blind analysis to avoid bias
  - select one electron and one charged pion.
  - at least two photon showers and one π^0.
  - two-body decay: mono-energetic e and recoiling
  - one undetected neutrino with missing energy
  - signal region on Umiss
- ❖ No excess of events observed over the expected background (J/ψ + continuum)
  - 82 v.s. 70.5 ± 13.3
- ❖ UL with Bayesian approach
  - $Br(J/\psi \to e\tau) < 7.5 \times 10^{-8}$ @ 90% C.L.
  - improves the previous result by two orders of magnitudes
  - comparable with the theoretical predictions





Summary

- CLFV processes provide a clean test field for new physics models.
  - The search for CLFV can strengthen our understanding to the essence of flavors.
- CLFV shall be searched in both μ sector and τ sector. And the search shall explore all possible channels.
  - To understand the new physics better.
- 2020's will be a fruitful decade for CLFV experiments:
  - μ sector: MEGII, Mu3e (phase I & Phase II), Mu2e (run 1 & run 2), COMET (Phase I & Phase II), MACE,⋯
  - τ sector: Belle II, HL-LHC
- 2030's and onward will be more exciting with the planned experiments:
  - μ sector: Next stage $\mu \to e\gamma$ and $\mu \to eee$? Mu2e II, AMF, PRISM, ⋯
  - τ sector: EIC, FCC-ee, STCF