Charged Lepton Flavor Violation Topical Group report

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RPF Frontier Meeting

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CLFV in a nutshell

Charged lepton flavor violating (CLFV) processes are contact interactions that do **not** conserve lepton family number(s)

- e.g. $\mu \rightarrow e$, $\tau \rightarrow \mu\mu\mu$, $K_L \rightarrow \mu e$, $H \rightarrow \tau\mu$, ...

Flavor in the Standard Model

- Quark flavor is violated in weak decays (CKM matrix)
- Neutral lepton flavor is violated (neutrino oscillations)

What about charged lepton flavor?

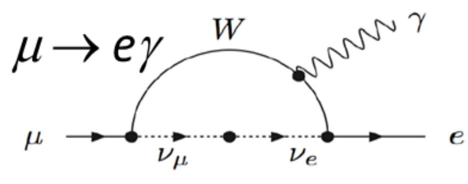
- Lepton flavor accidentally conserved in SM with massless neutrino
- Add Dirac ν masses to SM: lepton flavor violated, but incredibly tiny rates

CLFV are very sensitive and generic probes of New Physics, and an observation is an unambiguous signature of BSM physics

CLFV searches share the stage with neutrino and energy frontiers in studying the origin of neutrino mass, flavors and families.

CLFV can be generated at loop level with massive Dirac neutrinos, but rate is extremely suppressed due to GIM mechanism and tiny neutrino masses

For example:



$$\mathcal{B}^{(\mu \to e\gamma)} = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$

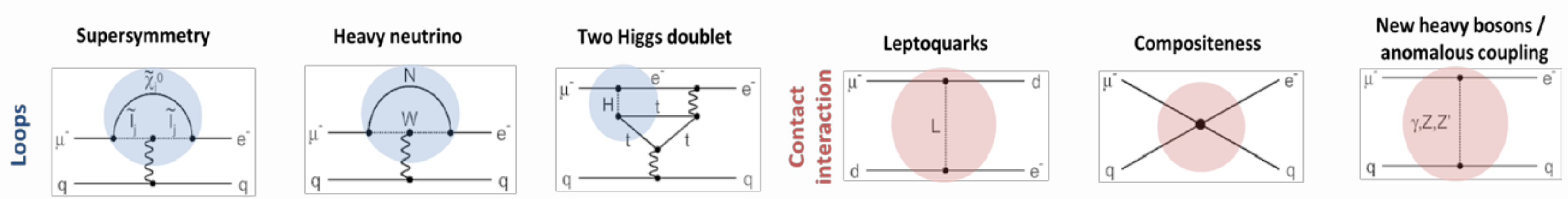
Petcov, Marciano, Shandra, Lee, Shrock, ….

PMNS unitary, $\sum U^*_{\mu i} U_{ei} = 0$

Suppression to unobservable levels is expected for other muon, tau and heavy state decays,

so an observation is clear sign of physics beyond νSM

New physics could greatly enhance these rates, e.g.



Each model generate a specific pattern of operators
→ multiple CLFV measurements to extract the underlying physics.

EFT framework

Davidson *et al*, 2204.00564

Effective field theory (EFT) calculation to analyze reach and complementarity of $\mu \to e\gamma$, $\mu \to eee$ and $\mu N \to eN$ transitions

At the experimental scale m_μ, these processes can be described by the effective Lagrangian

Dipole — Contact $\mu \to eee$ *(scalar)* — Contact $\mu \to eee$ *(vector)*

$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2}\Big[C_D(\bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re) + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re)$$
$$+ C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big]$$

Contact $\mu \to eee$ *(vector)* — Contact $\mu N \to eN$ *(light N)* — Contact $\mu N \to eN$ *(heavy N)*

$\vec{C} = \{C_D, C_S, C_{VR}, C_{VL}, C_{light}, C_{heavy}\}$

$C_D = \vec{C}\hat{e}_{DR}, \ldots.$

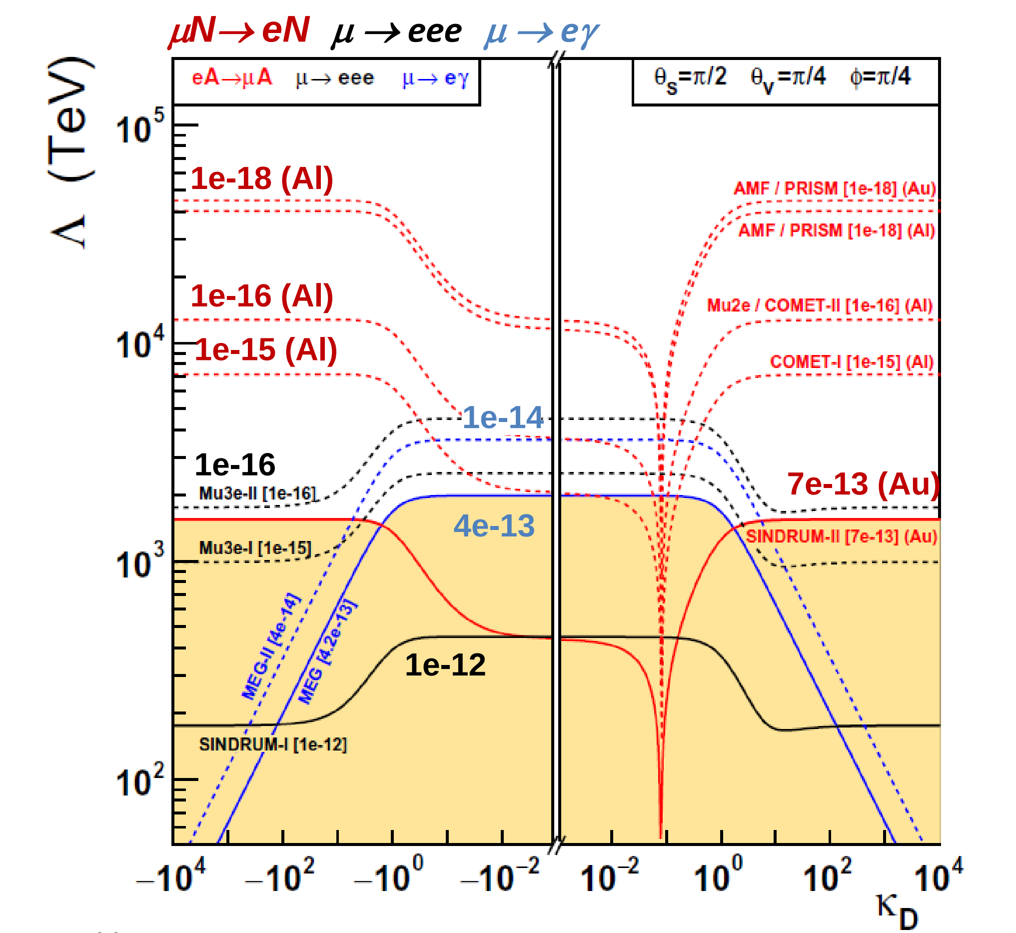
Parameterize coefficient space with spherical coordinates: $|C|^2 = 1,\ C_D = \vec{C}\hat{e}_{DR} = \cos(\theta_D)$, ...
and obtain constraints at the NP scale (Λ_{LFV}) using RGEs, e.g.

$$BR(\mu \to e_L\gamma) = 384\pi^2 \frac{v^4}{\Lambda_{LFV}^4}|\vec{C}\cdot\hat{e}_{DR}|^2 < B_{\mu\to e\gamma}^{expt} = 4.2\times 10^{-13}$$

A judicious choice of basis vectors lets you define a four-dimensional subspace corresponding in good approximation to the rates we can measure (see “extra material” for more details)

Derive robust constraints on the NP mass scale **for the three processes at the same time** with a small number of parameters (not one-at-a-time bounds), easy to visualize

Reach on NP mass scale of past and future experiments as a function of κ_D



S. Davidson, BE, 2204.00564

$$\kappa_D = cotan(\theta_D - \pi/2)$$

κ_D: relative strength of dipole vs four-fermion operators (inspired from the "κ parameterization" in 1303.0497)

$|\kappa_D|$<< 1 dipole dominant
$|\kappa_D|$ >> 1 four-fermion dominant

Upcoming experiments will probe NP mass scale above 10^4 TeV over a large fraction of the parameter space

A systematic way of deriving the reach / complementarity of the main muon reactions

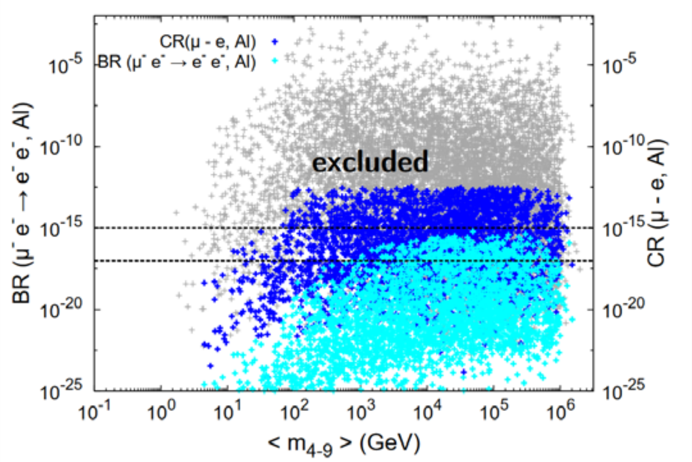
CLFV and neutrino mass generation

Many mechanisms to generate ν mass: seesaw, Zee models, RPV SUSY,…

- distinct new states realized at different scales

Low scale Seesaw: inverse seesaw

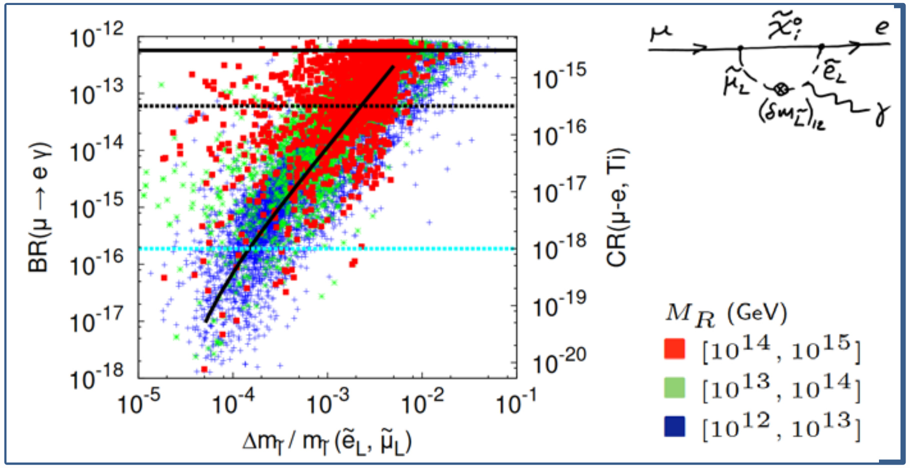
Addition of 3 “heavy” RH neutrinos and
3 extra “sterile” fermions to SM



Teixeira et al., JHEP02 (2016) 083

SUSY Seesaw

CLFV induced by exchange of SUSY particles



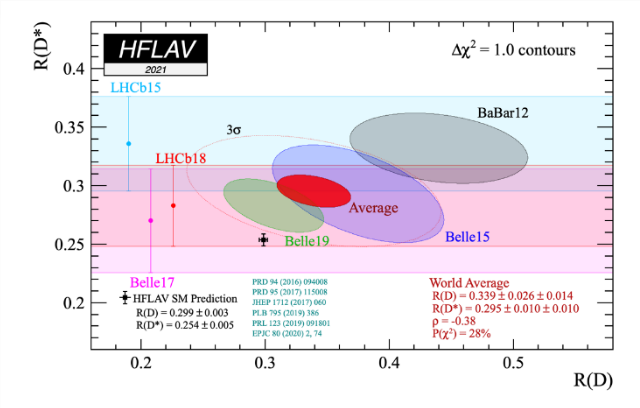
Figueiredo & Teixeira, JHEP 1041(2014) 015

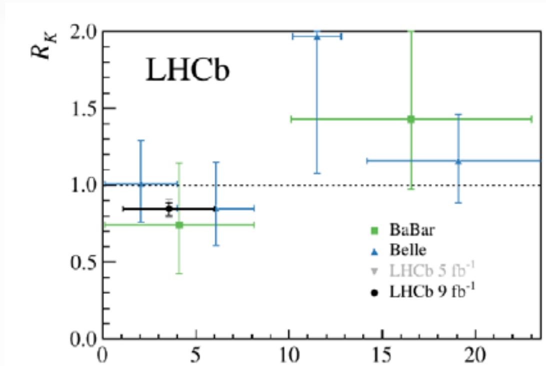
Induces sizeable CLFV rates and helps differentiate models

Non Standard Interactions might also impact neutrino oscillations

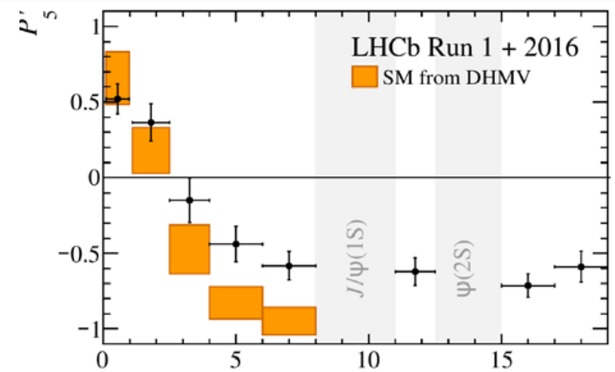
Several anomalies in B decays violating Lepton Flavor Universality: $R_D^{(*)}$, $R_K^{(*)}$, P_5'

Significant deviation from SM suggests New Physics effects at tree-level!





LHCb 2103.11769, LHCb 1705.05802, 1912.08139, 2110.09501



LHCb 2003.04831

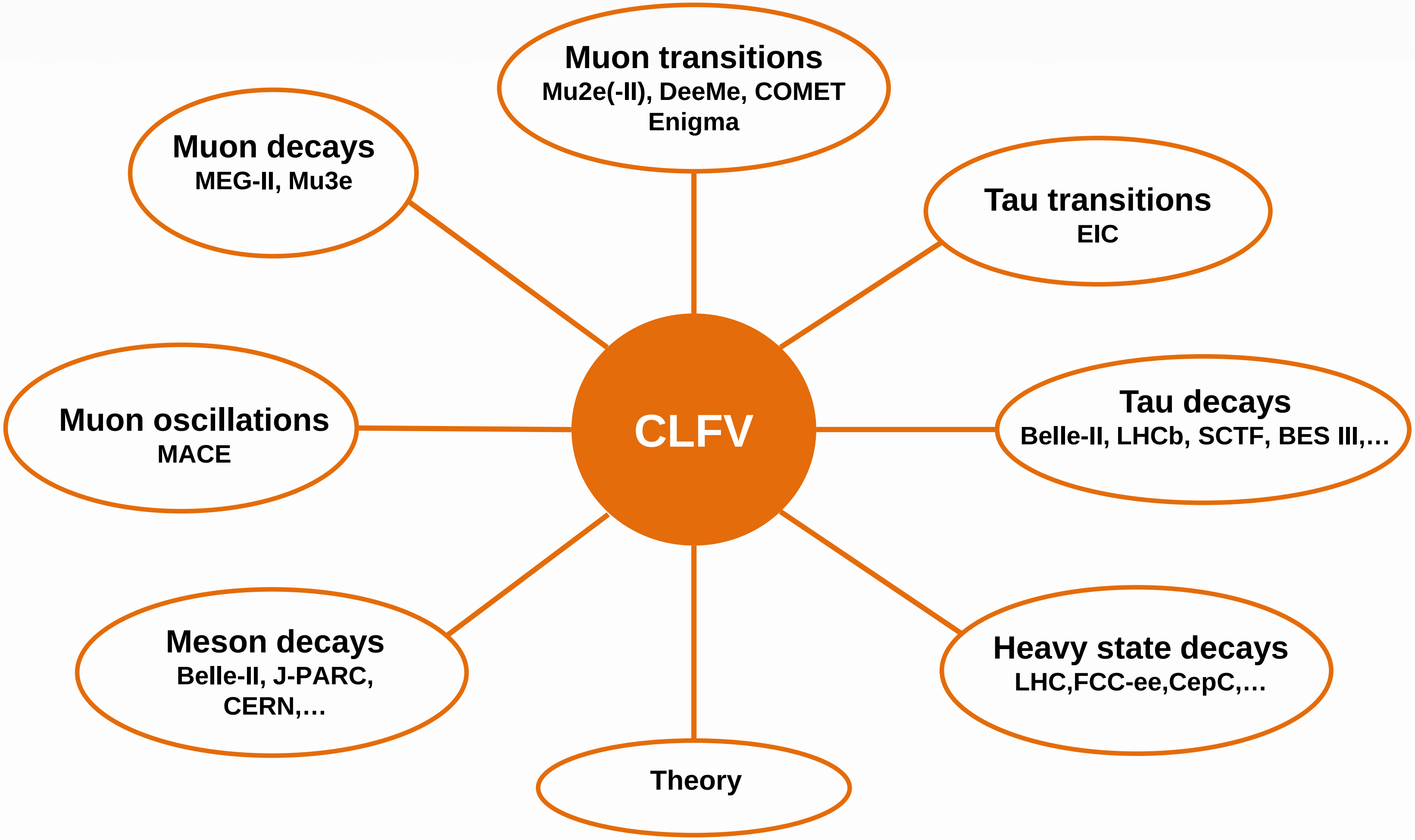
Several appealing candidates to solve these anomalies:

- Leptoquarks, Vector-like fermions, Z' ...

Many of which predict sizeable CLFV rates (e.g. $\tau \to \mu\mu\mu$) along with other observables (e.g. $B \to K\nu\nu$, $B \to \tau\mu,\dots$ + direct searches at LHC

Interplay between all aspects of flavor physics in probing BSM scenarios (see RF01 / RF02)

An overview of the topics discussed in the white papers



White papers of interest to the CLFV group

Title	Editor	Arxiv
Experimental Searches for Muon to Electron Conversionin a Nucleus: COMET, DeeMe and Mu2e	S. Middleton	2203.07089
The Mu3e Experiment	G. Hesketh	2204.00001
Muonium to antimuonium conversion	A. Petrov	2203.11406
Tau decays and transitions	S. Banerjee	2203.14919
Mu2e-II: Muon to electron conversion with PIP-II	F. Porter	2203.07569
A New Charged Lepton Flavor Violation Program at Fermilab	B. Echenard	2203.08278
The MEG experiment upgrade	A. Papa	In preparation
Charged Lepton Flavour Violations in Heavy Particle Decays	M. Dam	In preparation
Design Considerations for FNAL Multi-MW Proton Facility in the DUNE/LBNF era	J. Eldred	2203.08267

CLFV and quark flavor generally discussed in TG1/2

Charged Lepton Flavor Violation Topical Group Report

1. Executive summary
2. Introduction
3. Effective field theory
4. Muon experimental overview
    1. Muon Flavor Violation Experiments in this Decade (muon decay / conversion and muonium-antimuonium oscillations)
    2. Future initiatives and next-generation facilities (Mu2e-II and AMF)
5. Tau experimental overview
    1. Tau Flavor Violation Experiments in this Decade (Belle II, LHCb)
    2. Future initiatives and next-generation facilities (SCTF, EIC, FCC-ee)
6. Heavy state experimental overview (Z, Z', Higgs, top, BSM)

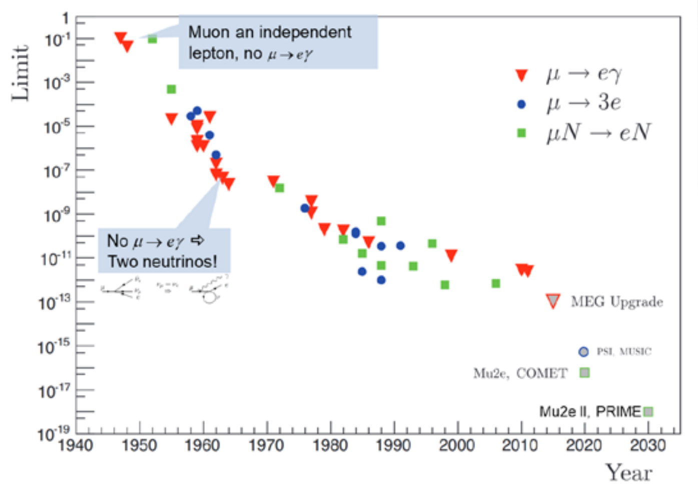
CLFV and quark flavor generally covered in TG1/2, will discuss with these groups to see if we include a short summary in the report.

Report available here: https://www.dropbox.com/s/605urz8ty9s8gei/Snowmass_TG5_report_11May.pdf?dl=0

Comments are welcome (but we are already close to the page limit so there is limited opportunity to add material)

Muon decays

The muon has consistently provided powerful constraints due to the availability of intense beams and the relatively long muon lifetime



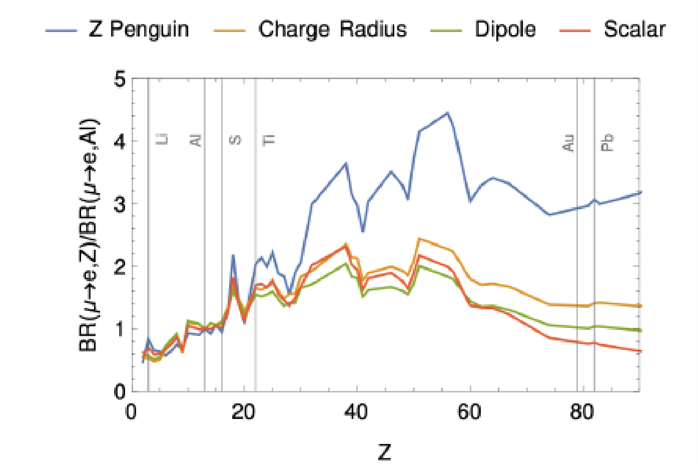
Bernstein *et al., Phys.Rept. 532 (2013) 27*

Three main modes

- $\mu^+ \to e^+\gamma$ decays
- $\mu^+ \to e^+e^-e^+$ decays
- $\mu^- N \to e^- N$ conversion

Already probe NP mass scale at the level of 10^3 TeV

Complementarity is key – each reaction probes different NP operators



https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-TF6_TF0_Heeck-043.pdf

The Z-dependence of $\mu^- N \to e^- N$ conversion provide information about the nature of NP, effect more important at high Z (see discussion later).

Two main channels

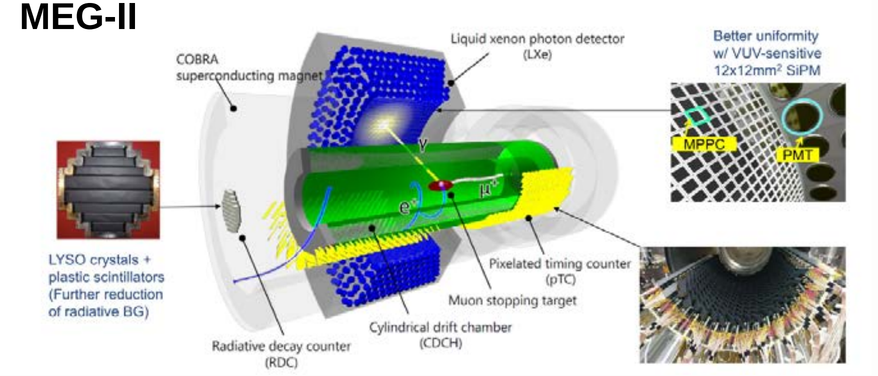
$\mu^+ \to e^+\gamma$ - **MEG II at PSI**

- Expected sensitivity at the level of 10^{-14} (3 year run)
- First engineering run in 2021

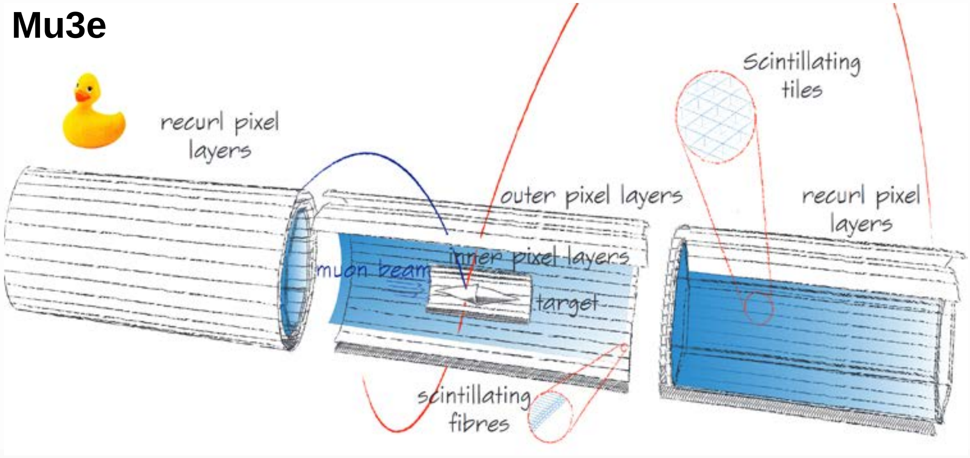
$\mu^+ \to e^+e^-e^+$ - **Mu3e at PSI**

- Expected sensitivity at the level of 10^{-15} to 10^{-16} (with HiMB)
- Expect data taking in 2022++

MEG-II



Mu3e



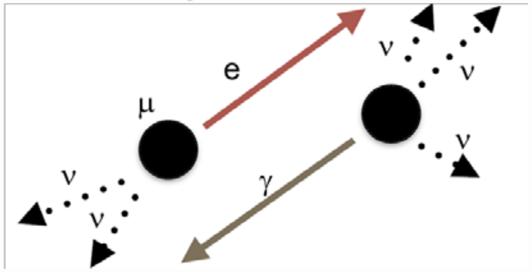
The Mu3e Experiment (G. Hesketh et al. – 2204.00001), A.M. Baldini et al., EPJC 78 (2018)

Improving the sensitivity of $\mu^+ \rightarrow e^+\gamma$ searches (and limiting factors)

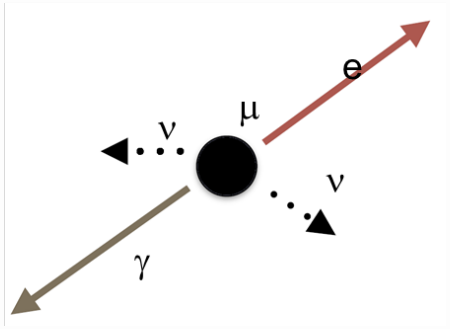
Improve detector performance to reduce backgrounds

- Accidental background scales as
  $\Gamma_{acc} \propto \Gamma^2_{\mu}\, \varepsilon_e\, \varepsilon_\gamma\, \delta E_e\, (\delta E_\gamma)^2\, (\delta\Theta_{e\gamma})^2\, \delta T_{e\gamma}$
- For high intensity beams, this background dominates over physics background (e.g. radiative muon decays)
- High-efficiency calorimeter or photon conversion to improve energy and angular resolution

Accidental background



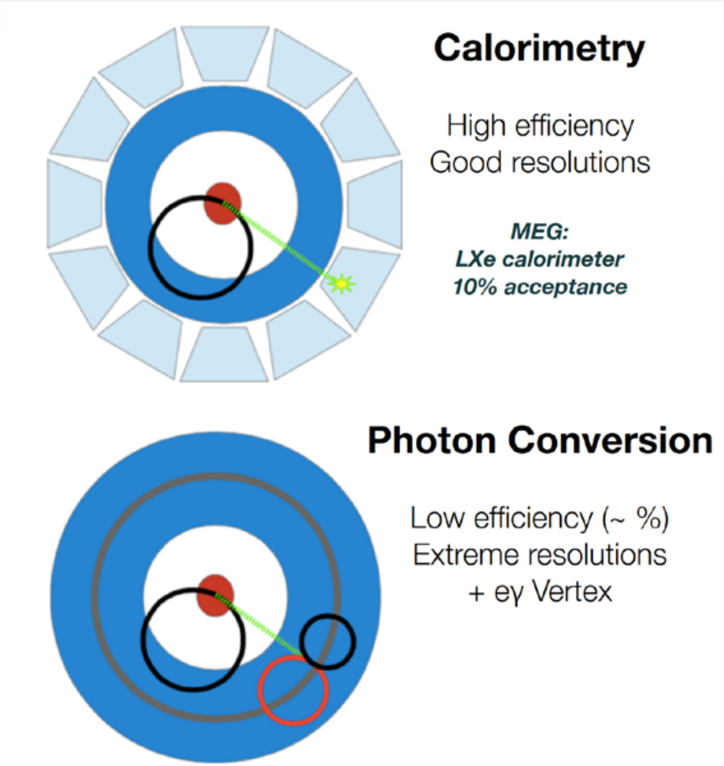
Radiative muon decay



Increase muon rate

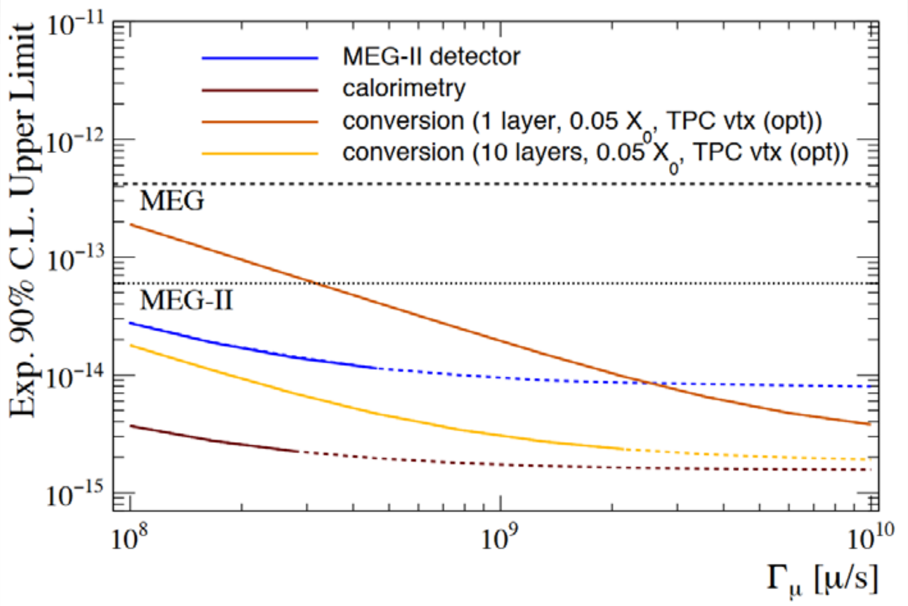
- Current PSI muon beamline 2×10^8 μ/s
- Proposed HiMB at PSI $\sim10^{10}$ μ/s
- Mu2e (+ve mode, pulsed) $\sim10^{11}$ μ/s

Muon decays – improving photon energy resolution

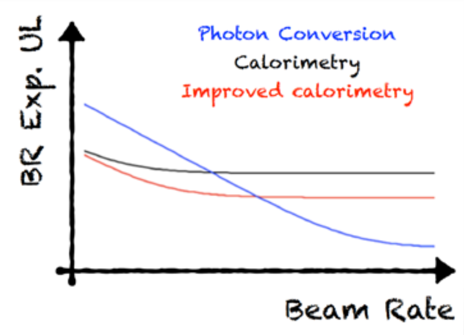


Renga *et al.*, 1811.12324

Renga *et al.*, 1811.12324



—— bkg <= 10 evts ----- bkg > 10 evts



Several possibilities to reach 10^{-15}, but taking full advantage of 10^{10} μ/s or more needs a novel experimental concept.

Interesting idea: can we build a single expt to look for $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$?

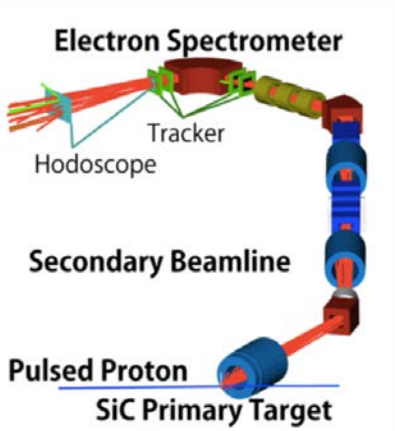
Muon conversion

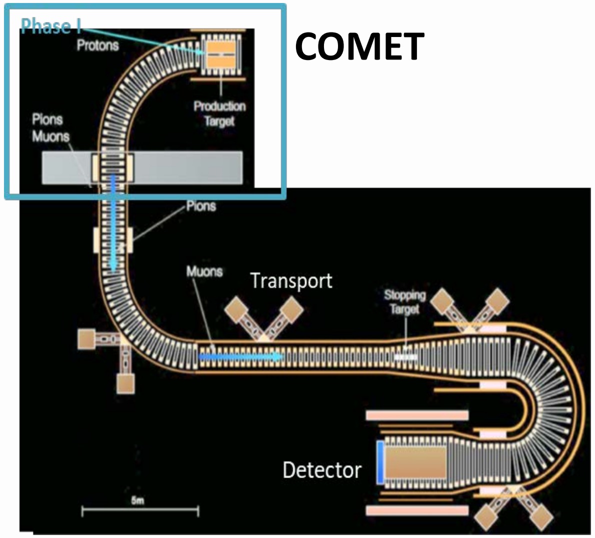
Muon conversion – current situation

Three experiments at various stage of execution, to be completed by the end of the decade with different single event sensitivity (SES)

- DeeMee at J-PARC, expected SES ~ 10^{-14}
- COMET at J-PARC, expected SES ~ 10^{-17}
- Mu2e at FNAL, expected SES ~ 10^{-17}

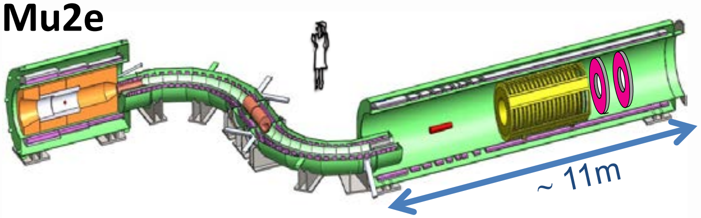
DeeMee





COMET

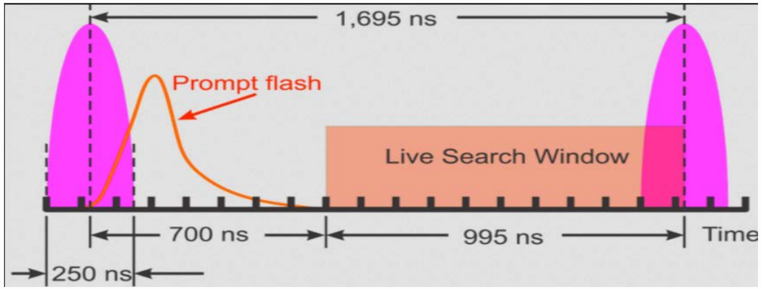
Mu2e



Experimental Searches for Muon to Electron Conversion … and Mu2e (S. Middleton et al. – 2203.07089)

Current approach (COMET / Mu2e)

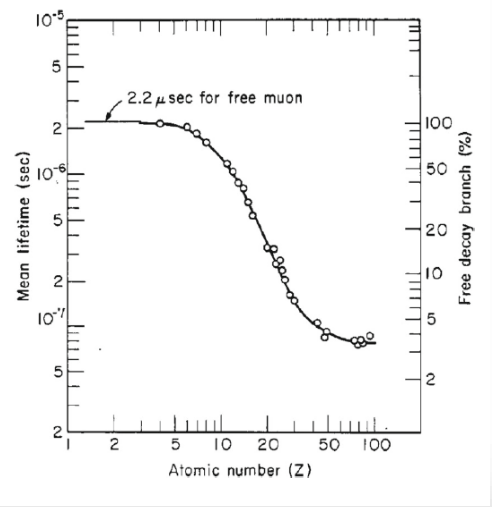
- Protons hit the production target, pions → muons captured by production solenoid (pulsed beam)
- Muons transported towards stopping target
- Muon conversion or decay products measured by detector (tracker + calorimeter)



Main limiting factors

- Dead time to wait for beam-associated backgrounds to decrease to negligible level → cannot measure conversions in atoms with short muonic lifetimes (high Z)
- Need well-defined pulse beam (extinction)
- Available beam power limits muon rate, need higher intensity

Several proposals for next generation experiments using the PIP-II accelerator complex to overcome some or all of these limitations



A. Knecht et al., EPJ. Plus (2020) 135

PIP II

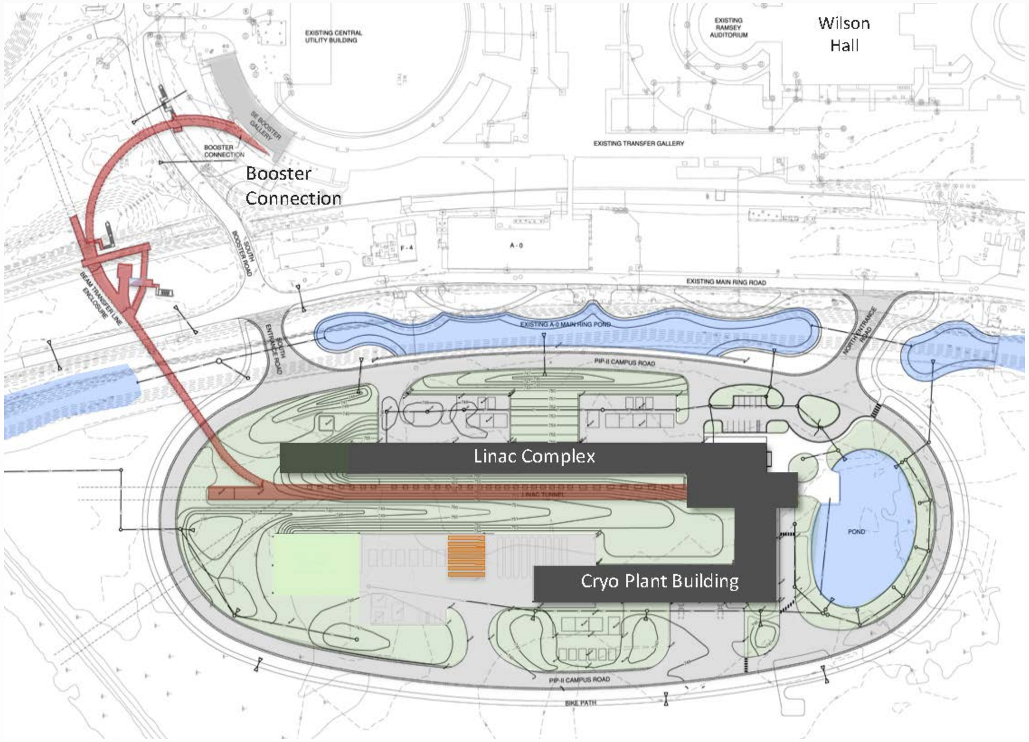
800 MeV H− linac
- Up 165 MHz bunches
- Up to 2 mA CW
- Up 1.6 MW

Upgraded Booster
- 20 Hz, 800 MeV injection
- New injection area

Upgraded Recycler & Main Injector
- RF in both rings

Groundbreaking for project
- March 2019

Protons for the High Energy Program
- ~1% of available beam!



PIP-II will deliver 1.2 MW proton beam for LBNF, but that program uses a very small fraction of the available beam → opportunity for new muon experiments

Mu2e-II is a proposed Mu2e upgrade to take full advantage of PIP-II and improve the SES by an order of magnitude over Mu2e (i.e. SES $\sim 10^{-18}$)

Either explore higher mass scale if no observation has been made by Mu2e, or perform precision measurements with several targets in case of discovery $\rightarrow$ **no lose scenario**

Re-use as much of Mu2e infrastructure as possible, and upgrade components required to handle higher beam intensity. In particular:

- Beam delivery: higher beam intensity, lower beam energy, extinction
- Tracker: higher occupancy and limited resolution
- Calorimeter: high rate and radiation damage
- Cosmic ray veto: higher occupancy and background from neutrals
- DAQ system: higher rate and throughput

Dedicated R&D efforts in all these domains (and others) to meet the requirements

Mu2e-II: Muon to electron conversion with PIP-II (F. Porter et al. – 2203.07569)

Tracking system

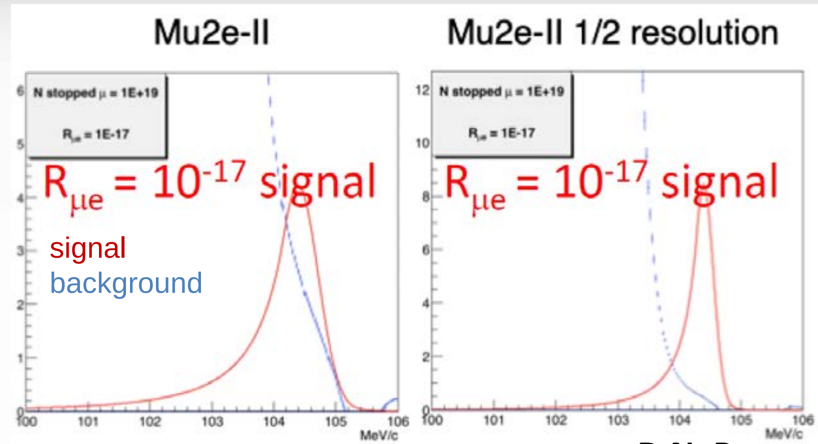
The DIO contribution would increase by a factor x10 with higher beam intensity

Need to improve momentum resolution to mitigate this background. Potential solutions:

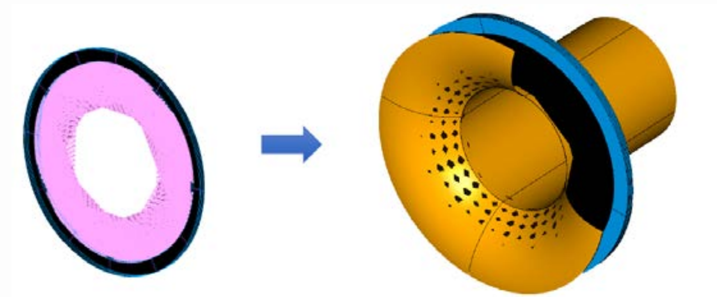
Reduce tracker mass
- Thinner straws (15 μm $\rightarrow$ 8μm)
- Remove gold layer inside straw

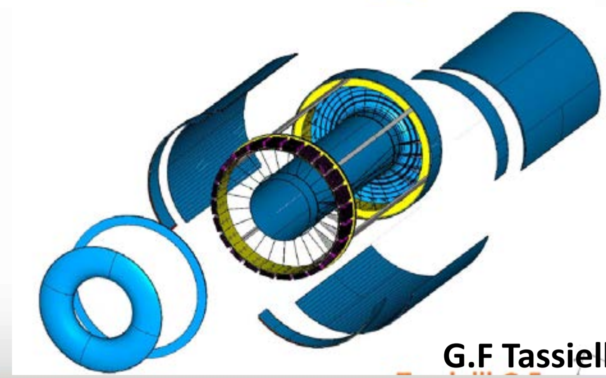
Investigate alternative tracker geometries
- Use ultra-light pressure vessel to ease requirements on straw leakage while keeping Mu2e straw layout (i.e panel geometry)
- Construct a high granularity and high transparency drift chamber à la MEG II.

Also investigate potential of silicon sensors (e.g. HVMaps for Mu3e) or MPGD (e.g. μ-RWell)



D.N. Brown





G.F Tassielli

The Advanced Muon Facility (AMF) is a new facility for the next generation of muon experiments at FNAL with the PIP-II accelerator.

This complex would provide **the world's most intense positive and negative muon beam**, and enable a suite of experiments, including

- CLFV in muon decay and transitions
- Muonium-antimuonium oscillations
- Muon EDM
- Muon spin rotation

and potential synergies with the development of a muon collider and a dark matter program

A beam for a next generation muon conversion experiment

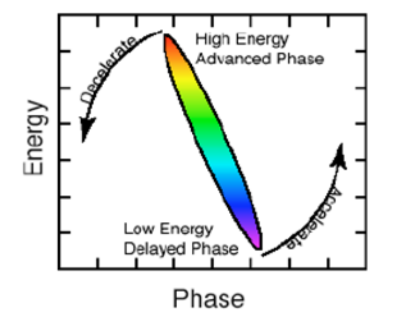
- **Probe R_{me} sensitivity down to 10^{-19}**, with the ultimate objective to reach 10^{-20} and probe $O(10^4 - 10^5)$ TeV effective mass scale
- **Probe high-Z target** (e.g. Au) to explore underlying new physics if CLFV is observed
- Based on the PRISM concept to provide a low momentum, quasi-mono-energetic muons beam with extremely low pion contamination

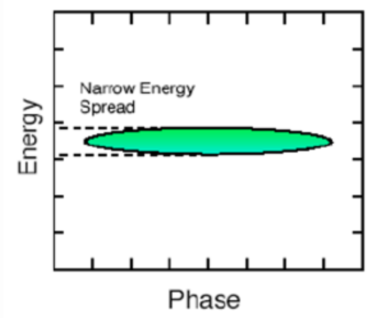
A New Charged Lepton Flavor Violation Program at Fermilab (B. Echenard et al. – 2203.08278)
Design Considerations for FNAL Multi-MW Proton Facility in the DUNE/LBNF era (J. Eldred at al – 2203.08267)

New beam for conversion experiment, based on the PRISM (Phase Rotated Intense Slow Muon beam) concept proposed by Y. Kuno and Y. Mori

PRISM concept:

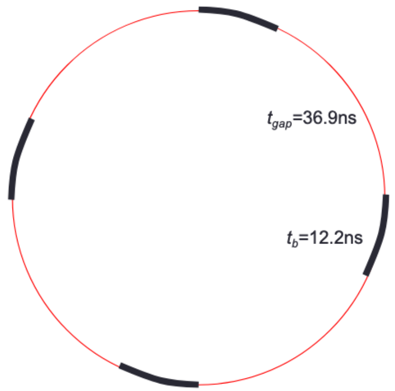
- High intensity (MW) proton beam with very short pulse duration hit target in a capture solenoid, producing $\pi \rightarrow \mu$
- Inject muons into a fixed-field alternating gradient (FFA) ring
- Phase rotates to reduce the beam energy spread (slow down leading edge, accelerate trailing edge)
- Pion contamination is drastically reduced during phase rotation (O(μs))
- Extract purified muon beam to detector





Requires a compressed proton bunch and high power beam to achieve high μ rate
$\rightarrow$ PIP II with a compressor ring (bunch size limit is much too small for the FFA)

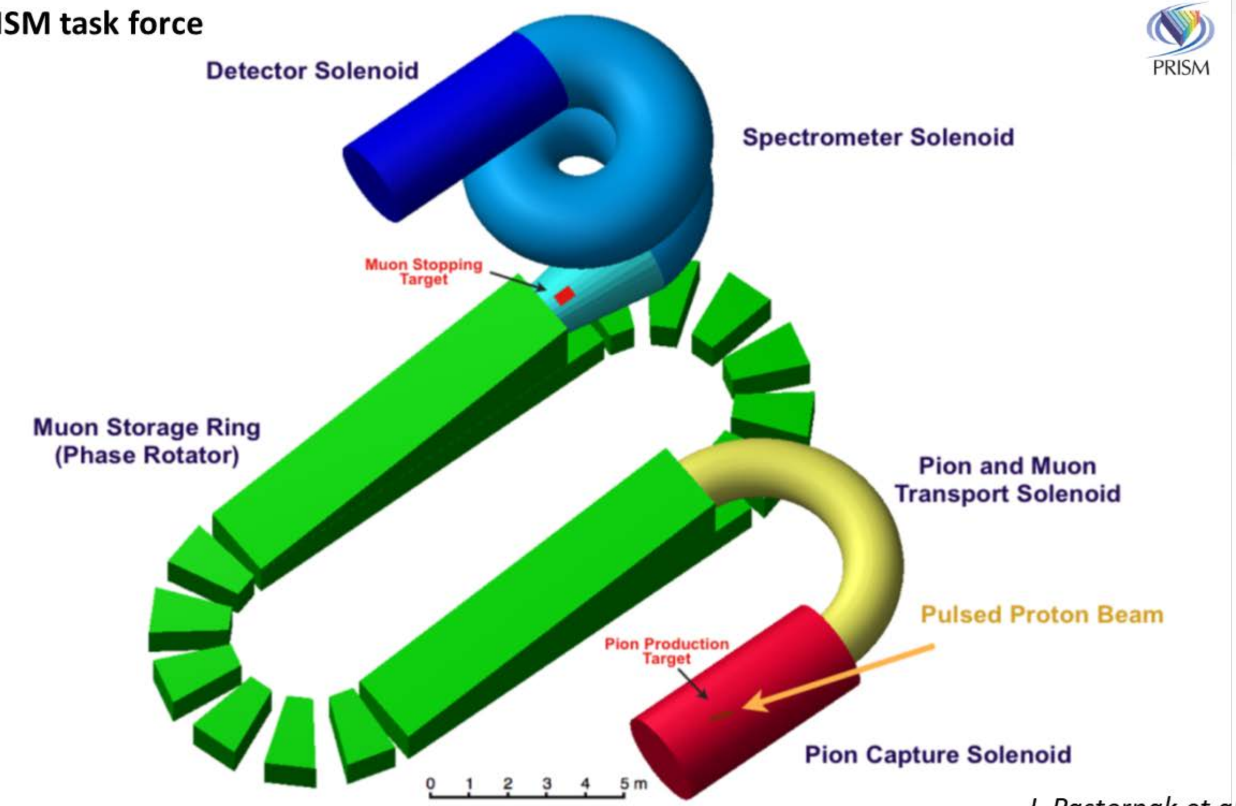
Compressor ring



E. Prebys

Circumference:	$C = 49.7$ m
RF Frequency:	$f_{RF} = 40.62$ or 20.31 MHz
harmonic:	$h = 8$ or 4
Protons/bunch:	$n_b = 1\times10^{12}$
Bunch length:	$t_b = 12.2$ ns
Fill time:	$t_{fill} = 1.3$ ms

PRISM task force



J. Pasternak et al.

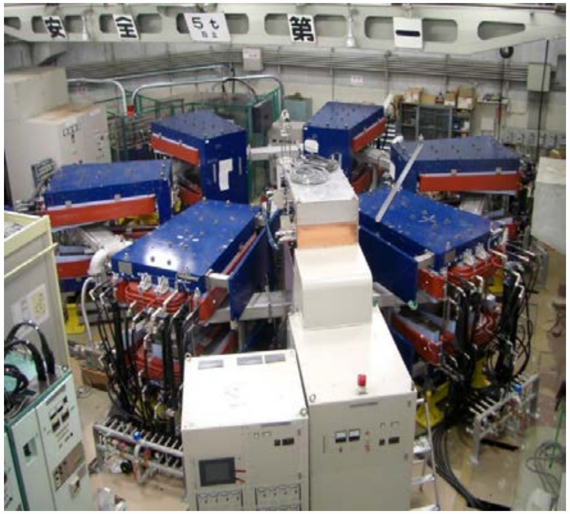
https://indico.phys.vt.edu/event/34/contributions/685/attachments/529/625/PRISM_nufact18.pdf

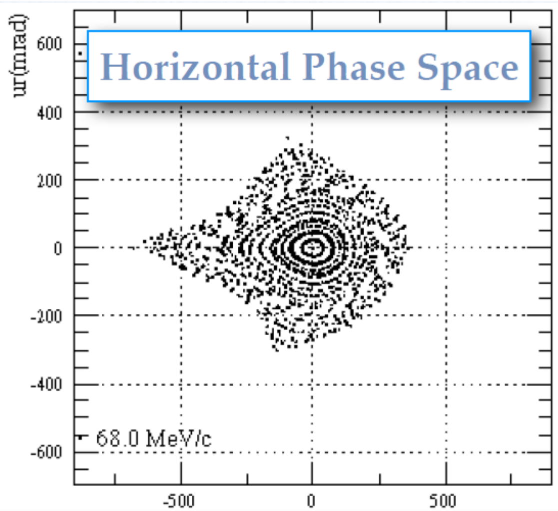
https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys-071.pdf

PRISM is in a position to be one of the incremental steps of a comprehensive muon program at FNAL

PRISM FFA - proof of concept

- 10 cell DFD ring has been designed
- FFA magnet-cell has been constructed and verified
- RF system has been tested and assembled
- 6 cell ring was assembled and its optics was verified with α particles
- Phase rotation was demonstrated for α particles





Pasternak et al., https://indico.phys.vt.edu/event/34/contributions/685/attachments/529/625/PRISM_nufact18.pdf
A. Alekou et al., arxiv: 1310.0804

Muonium-antimuonium

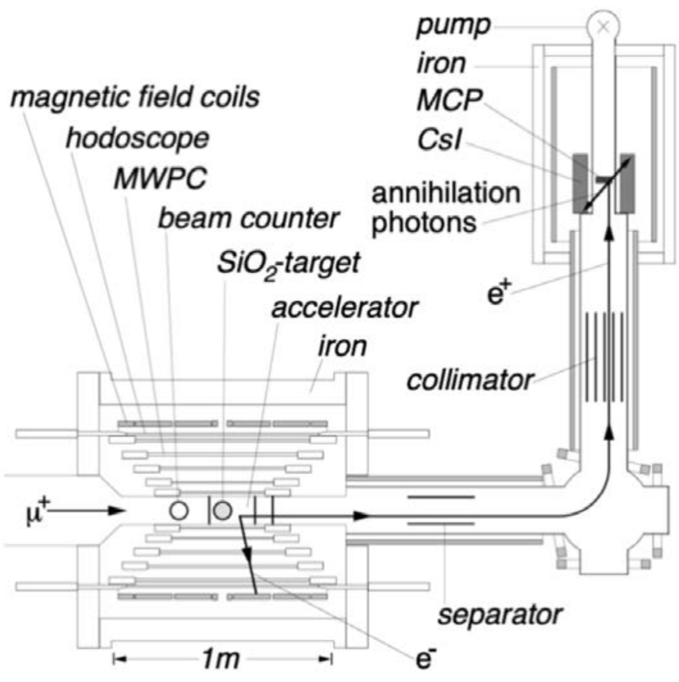
Muonium: bound state of μ^+ and e^-. Purely QED, no hadronic uncertainties

Muonium – antimuonium transitions ($\Delta L=2$) are extremely suppressed in the SM, but rates can be enhanced by NP. Could be linked to Majorana neutrino masses.

Positive muon beam on SiO_2 target, detect electron from negative muon and atomic positron

Best limits from MACS experiment (1999) based on 5.7×10^{10} muonium atoms

$$P(M_\mu \rightarrow M_\mu) < 8.3 \times 10^{-11} / S_B(B_0)$$
$$G_{MMbar} < 3 \times 10^{-3}\, G_F \text{ (90\% CL)}$$

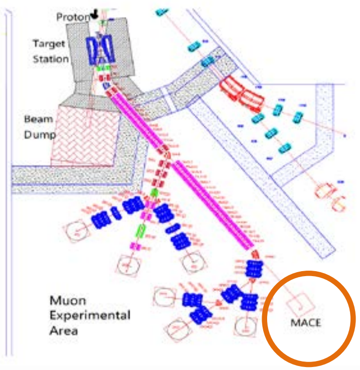


Muonium-Antimuonium Conversion Spectrometer (MACS)

L. Willmann, et al. PRL 82 (1999) 49

MACE: proposal for a new muonium-antimuonium experiment based on the same principle with the goal to improve sensitivity x100

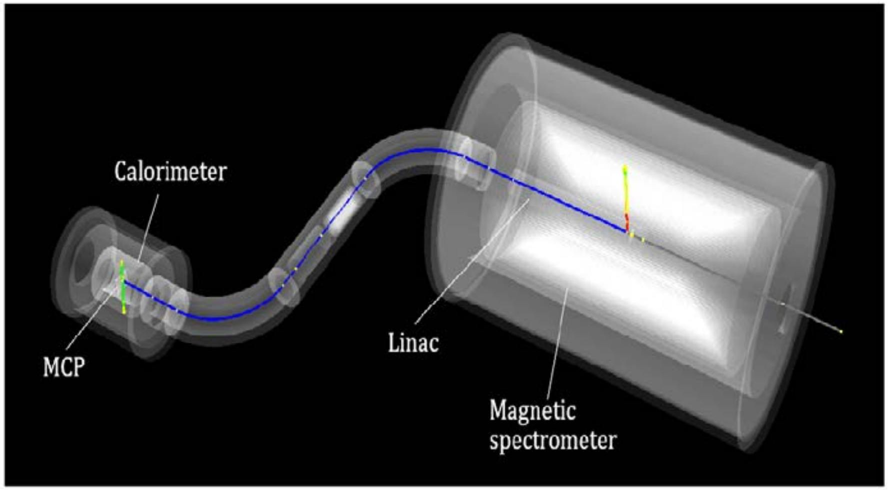
Exprimental Muon Source (EMuS) at CSNS – new facility in China



	Proton driver [MW]	Intensity [$\times 10^6$/s]	Polarization[%]	Spread [%]
PSI	1.30	420	90	10
ISIS	0.16	1.5	95	≤ 15
RIKEN/RAL	0.16	0.8	95	≤ 15
JPARC	1.00	100	95	15
TRIUMF	0.075	1.4	90	7
EMuS	0.025	83	50	10

EMuS: expect muon beam up to 10^8 μ^+/s

MACE concept



In a nutshell

- Form muonium in ablated aerogel target
- Wait for transition to antimuonium
- Reconstruct Michel electron from muon decay with spectrometer
- Accelerate shell positron to MCP
- Detect annihilation photon with calorimeter
- Triple coincidence to suppress bkgs

On-going physics studies and detector R&D

Muonium to antimuonium conversion (A. Petrov et al. – 2203.11406)

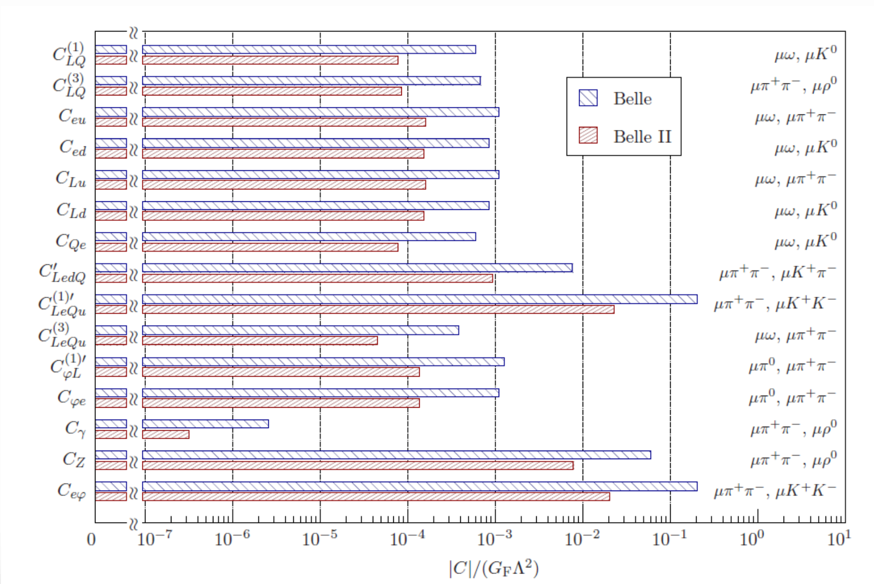
Tau sector

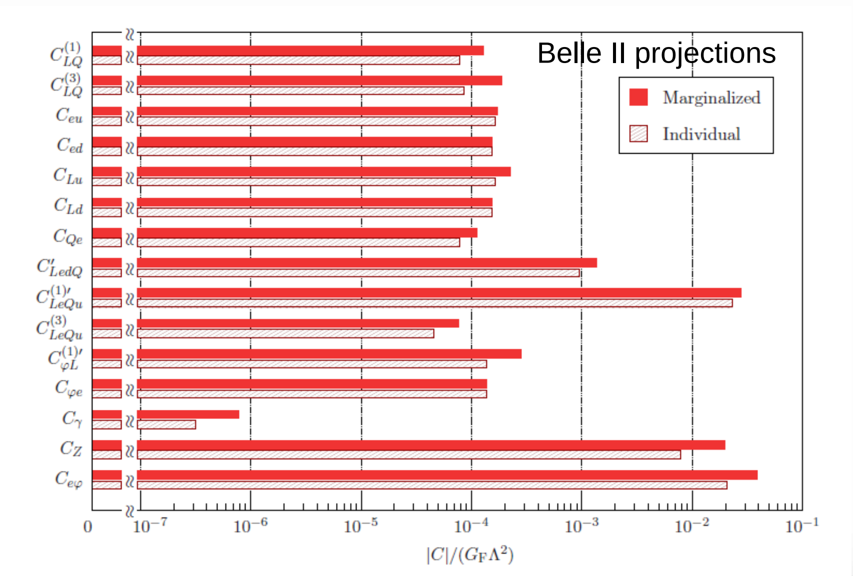
Tau CLFV searches can be conducted over many final states → promising to identify the underlying New Physics

In the third generation, the signal rate is enhanced w.r.t muon decays in some scenarios. However, the typical sample size collected at colliders is much smaller than the muon production rate at dedicated facilities.

Current bounds on $\tau \to \mu\gamma$ probe NP mass scale $\Lambda \sim 720$ TeV ($C_\gamma \approx 1$), and will further improve by the end of the decade by factor ~1.5.

Bounds on Wilson coefficients in EFT analysis



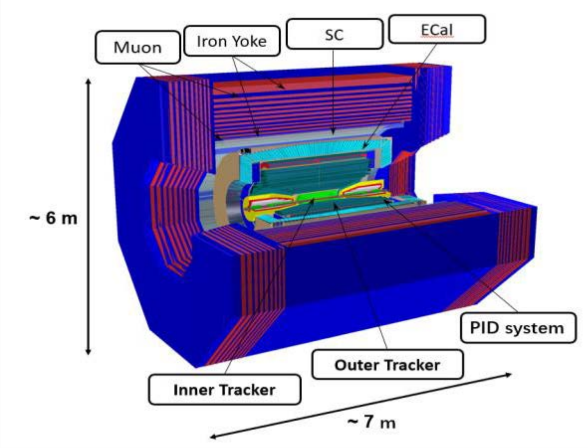


S. Banerjee *et al.*, arxiv:2203.14919

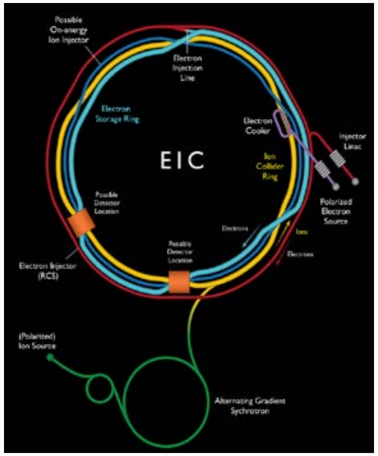
Belle-II at Super KEKB

LHCb, ATLAS, CMS at LHC

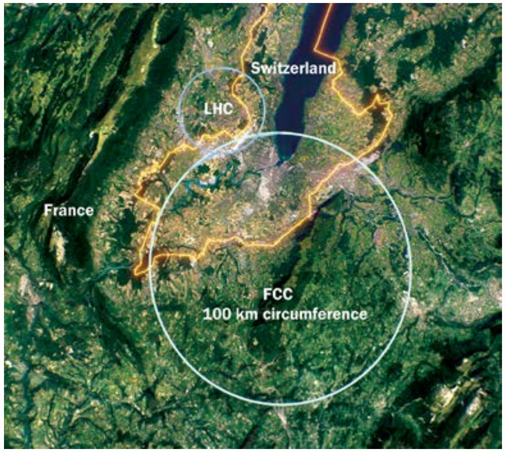
SCTF proposal – Novosibirsk or China



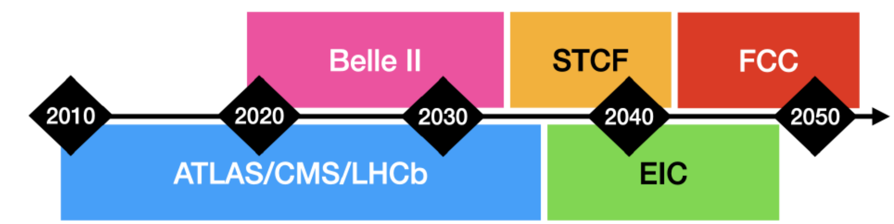
EIC at Brookhaven



FCC-ee proposal – CERN

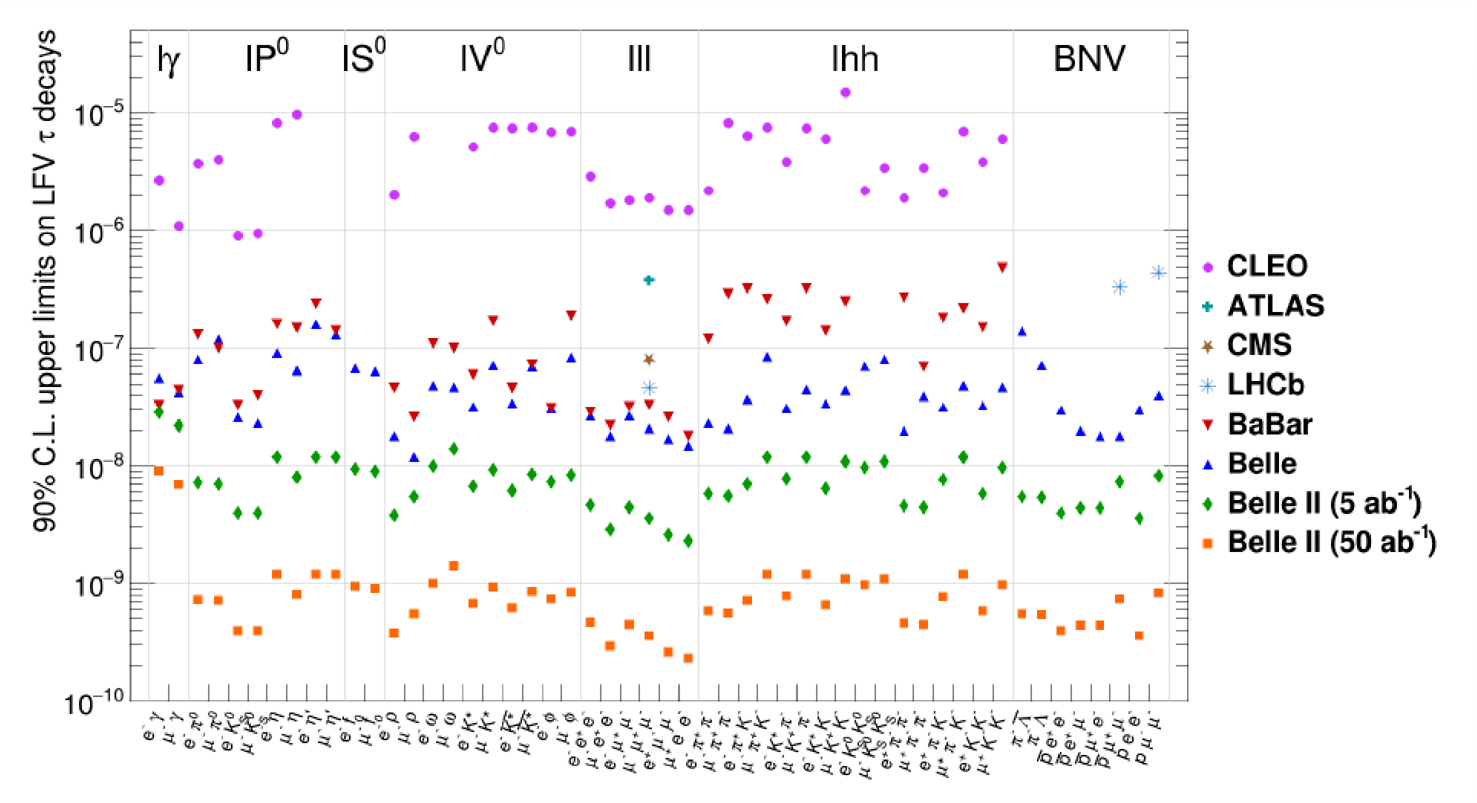


Tentative timeline



Tau decays and transitions (S. Banerjee et al. 2203.14919)

In the near future, Belle II and LHCb will be major contributors

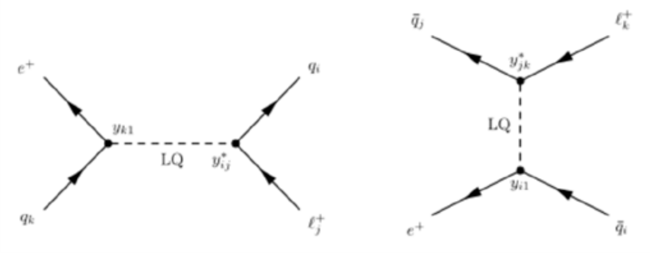


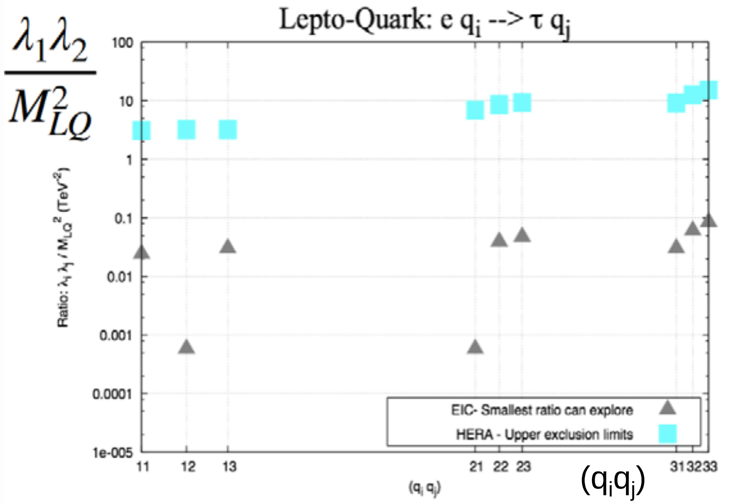
One to two order of magnitude increase in sensitivity w.r.t BABAR / Belle, probing branching ratios down to 10^{-10} – 10^{-9} over a wide range of final states

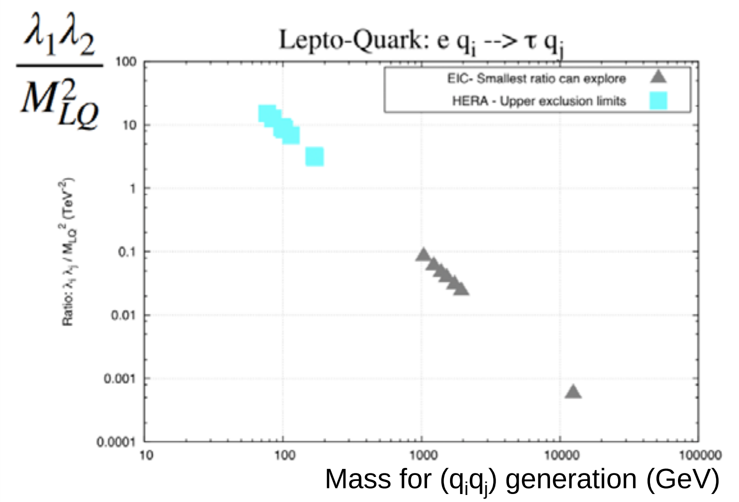
Further improvements possible with polarized beams at e^+e^- colliders

Possibility to study $e \rightarrow \tau$ transitions at the EIC

- Some models predict better sensitivity with heavier leptons
- Benchmark study at EIC with leptoquark model (Cirigliano et al., 2102.06176)
- Current limits on leptoquarks set by HERA





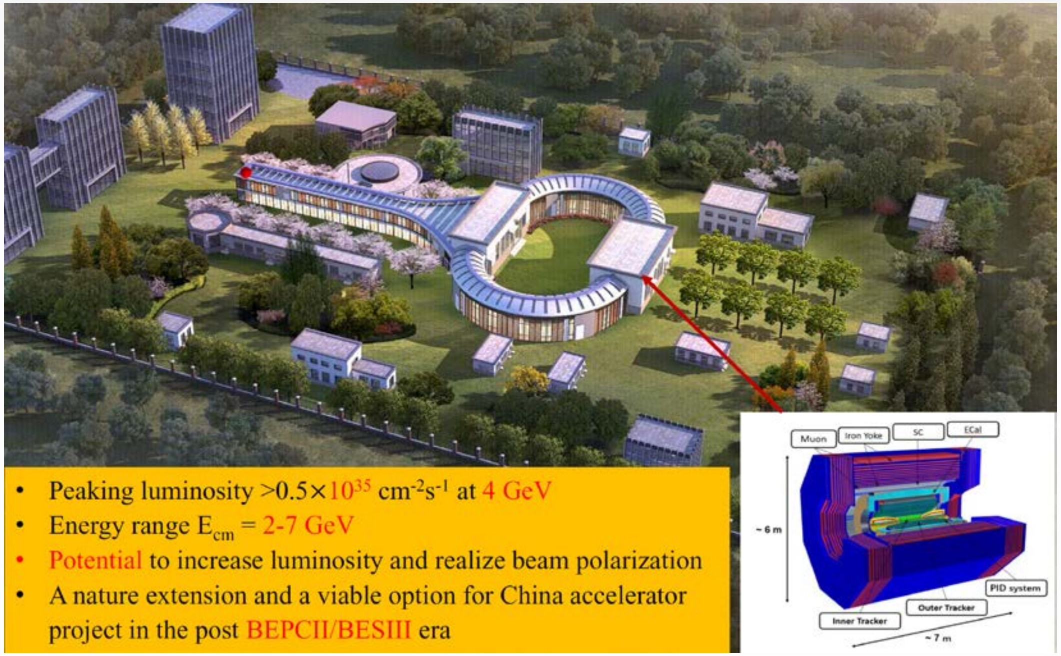


Deshpande, Huang, Kumar Zhang, Zhao

Potential to improve current sensitivity by two orders of magnitude

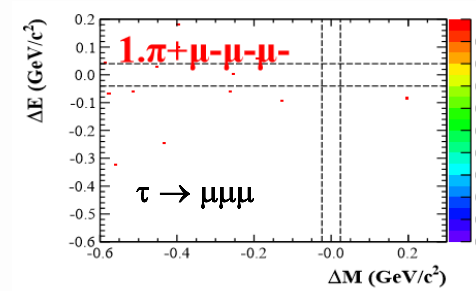
SCTF in China

X. Zhou



Several CLFV τ decay accessible, representation performance with 1 ab^{-1} of data

BR($\tau \rightarrow \mu\mu\mu$) < 1.5 x 10^{-9}
BR($\tau \rightarrow \mu\gamma$) < 1.2 x 10^{-8}

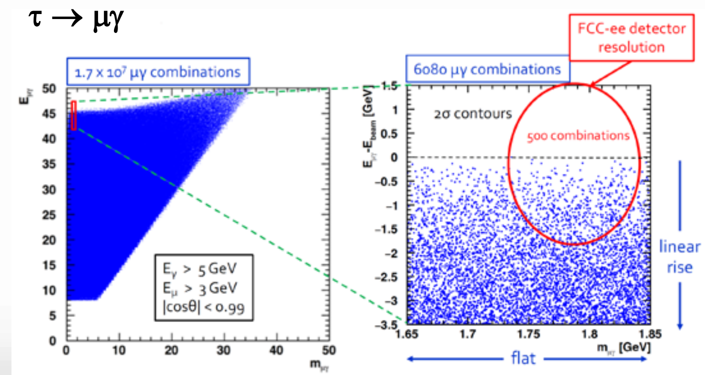


FCC-ee at CERN

Large τ sample from 1.7 x 10^{11} Z $\rightarrow \tau^+\tau^-$ decays:

BR($\tau \rightarrow \mu\mu\mu$) < ~10^{-10}
BR($\tau \rightarrow \mu\gamma$, e$\gamma$) < 2 x 10^{-9}

$\tau \rightarrow \mu\gamma$



M. Dam

Heavy state decays

Collider experiments directly probe CLFV interactions of heavy particles that only contribute indirectly to low-energy processes

In general, constraints involving the μe final state are weaker than those derived from low-energy probes (same dependence on NP, but more muons than Z/h), while final state with taus offer comparable sensitivity – there are of course exceptions…

Lepton flavor violating *Z* decays

Current limits (ATLAS 2010.02566, 2105.12491)

BR ($Z \to \mu e$) < 3×10^{-7}

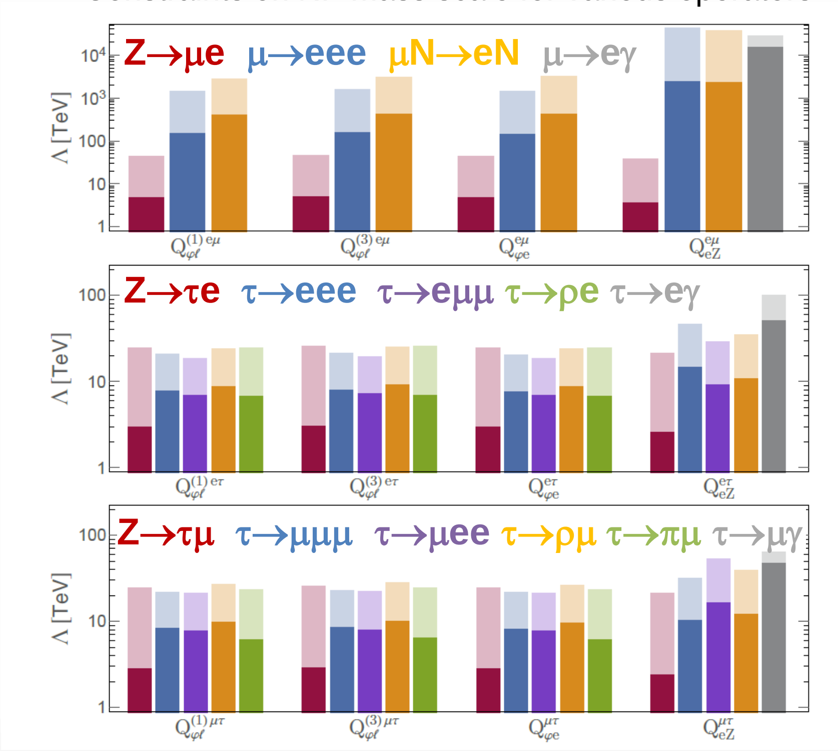
BR ($Z \to \tau e$) < 5×10^{-6}

BR ($Z \to \tau\mu$) < 7×10^{-6}

Expect improvement by factor ~10 at HL-LHC, and possibly 2 to 3 orders of magnitude at FCC-ee

Competitive constraints for final states with tau lepton

Constraints on NP mass scale for various operators



Calibbi, Marcano and Roy, 2107.1027

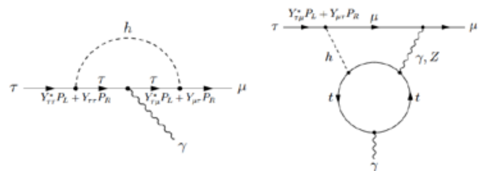
Charged Lepton Flavour Violations in Heavy Particle Decays (M. Dam et al. – in preparation)

LFV Higgs couplings

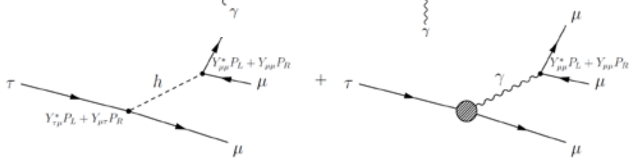
$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c.\,.$$

CLFV Higgs decay $\sqrt{|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2} = \frac{8\pi\Gamma_H(SM)}{m_H}\frac{BR(H\to\ell\tau)}{1-BR(H\to\ell\tau)}$

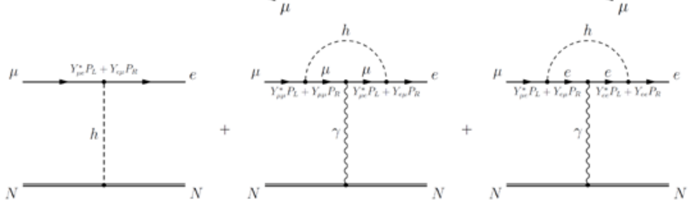
$\tau\to\mu\gamma\ (\mu\to e\gamma)$



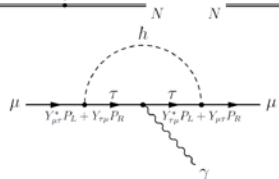
$\tau\to l'll\ (\mu\to eee)$



$\mu N\to eN$

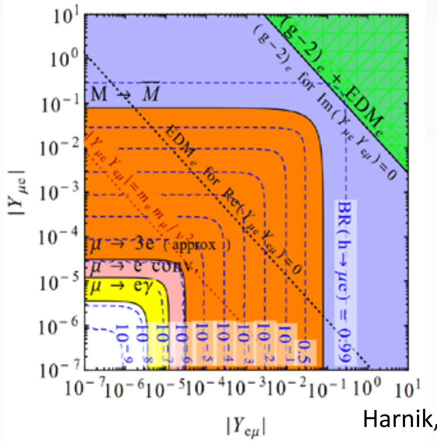


g-2



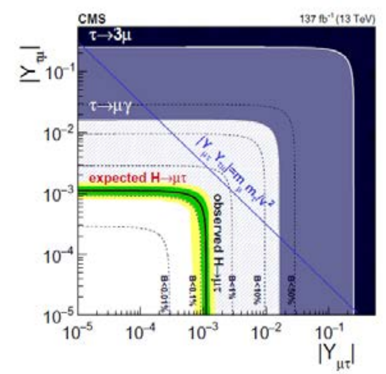
Harnik, Kopp, Zupan 1209.1397

μe coupling

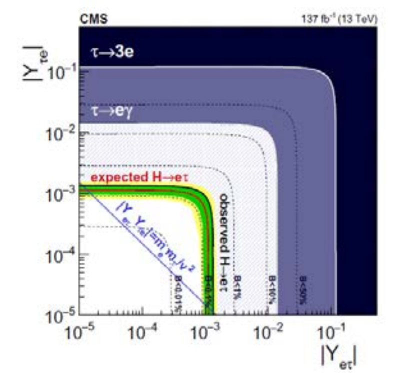


Harnik, Kopp, Zupan 1209.1397

τμ coupling



τe coupling

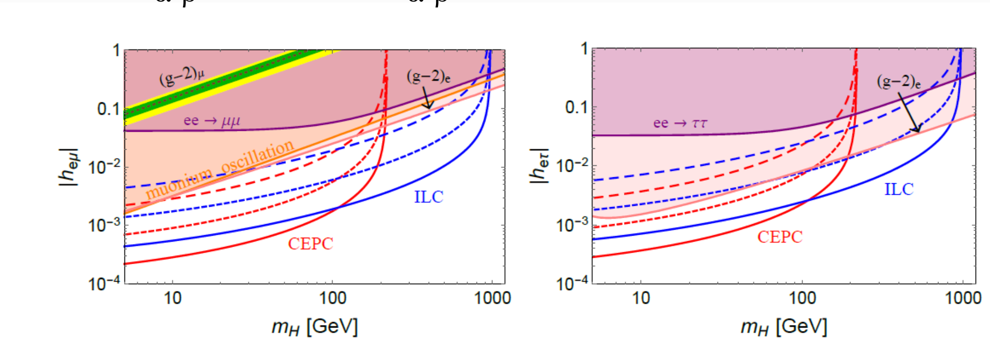


CMS, 2105.03007

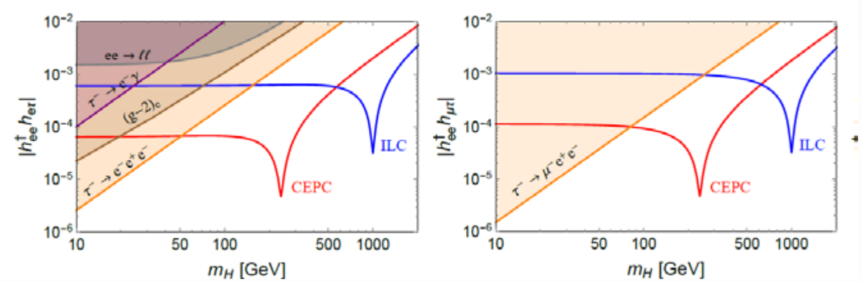
Still room for discovery, expect significant improvement in sensitivity with HL-LHC and future e⁺e⁻ colliders

Heavy neutral scalar H with LFV coupling $h_{\alpha\beta}$

$e^+e^- \to l_\alpha l_\beta$ + H, H $\to l_\alpha l_\beta$

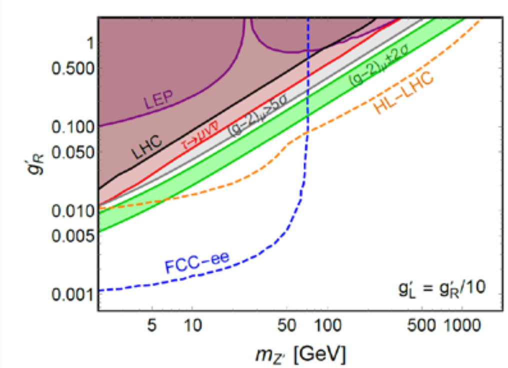


$e^+e^- \to l_\alpha l_\beta$



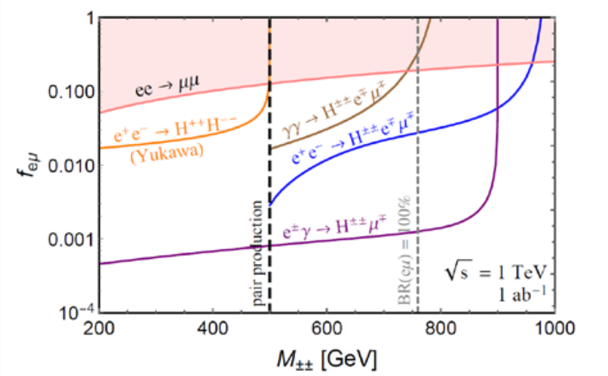
Dev, Mohapatra, Zhang 1711.08430

Z' boson with LFV coupling g'_R / g'_L



Altmanshofer et al., 1607.06832

Double charged Higgs $H^{\pm\pm}$



Dev, Mohapatra, Zhang 1711.08430

Very rich phenomenology, future colliders will substantially increase coverage

Concluding remarks

What comes next

TG5 – Tuesday parallel session (morning)

Physics talks – theory and current muon experiments

TG5 – Tuesday parallel session (afternoon)

Physics talks – next generation muon experiments, taus and heavy state decays

TG5 – Wednesday parallel session (morning and afternoon)

Presentation / discussion of the report

See slack channel for connection information

Summary

CLFV processes are very clean probes of new physics, and an observation would be transformative. Together with the neutrino and energy frontiers, CLFV share the stage in studying the origin of neutrino mass, flavors and families.

Several experiments are underway to improve current sensitivity in the muon and tau sectors by one-to-several orders of magnitude.

New experimental concepts and ideas have been proposed to further improve the physics reach by another few orders of magnitude

Strong and continued support of the US community towards current experimental efforts and the development of next-generation facilities is critical to the realization of the long term physics goals of this program

People interested in exploring synergies or contributing to this program are welcomed to join the effort

Thank you for your attention

Extra material

More references

Next generation MW muon facility at FNAL

A New Charged Lepton Flavor Violation Program at Fermilab
https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf

A Phase Rotated Intense Source of Muons (PRISM) for a $\mu \rightarrow$ e Conversion Experiment
https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf

Bunch Compressor for the PIP-II Linac
https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys2-203.pdf

Muon decays

The MEG II experiment and its future development
https://www.snowmass21.org/docs/files/summaries/ RF/SNOWMASS21-RF5_RF0_MEGII-062.pdf

A new experiment for the $\mu \rightarrow e\gamma$ search
https://www.snowmass21.org/docs/files/summaries/ RF/SNOWMASS21-RF5_RF0_Tassielli-067.pdf

Mu2e-II

Mu2e-II
https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_Frank_Porter-106.pdf

Low-E facility at FNAL

Upgraded Low-Energy Muon Facility at Fermilab
https://www.snowmass21.org/docs/files/summaries/ RF/SNOWMASS21-RF0-AF0-007.pdf

High intensity muon beam (HiMB) at PSI

Towards an High intensity Muon Beam (HiMB) at PSI
https://indico.cern.ch/event/577856/contributions/3420391/attachments/1879682/3097488/Papa_HiMB_EPS2019.pdf

HIMB Physics Case Workshop
https://indico.psi.ch/event/10547/timetable/?view=standard

Parameterize coefficient space with spherical coordinates: $|C|^2 = 1,\ C_D = \vec{C}\hat{e}_{DR} = \cos(\theta_D)$, ...
and obtain constraints at the NP scale (Λ_{LFV}) using RGEs.

$$\mathrm{BR}(\mu \to e_L\gamma) = 384\pi^2 \frac{v^4}{\Lambda_{LFV}^4}\left[|\vec{e}_D|\cos\theta_D\right]^2$$

$$\mathrm{BR}(\mu \to e\bar{e}e) = \frac{v^4}{\Lambda_{LFV}^4}\Big[\frac{|\vec{e}_S|^2\sin^2\theta_D\cos^2\theta_S}{8} + (|\vec{e}'_{VR}|\sin\theta_D\sin\theta_S\cos\theta_V + 4e|\vec{e}_D|\cos\theta_D)^2$$
$$+2(|\vec{e}'_{VL}|\sin\theta_D\sin\theta_S\cos\theta_V + 4e|\vec{e}_D|\cos\theta_D)^2 + 18.76(|\vec{e}_D|\cos\theta_D)^2\Big]$$

$$\mathrm{BR}(\mu Al \to eAl) = \frac{6144\pi^3 v^4}{2.197 g_{Al}^{cap}\Lambda_{LFV}^4}\left[|\vec{u}_{Al}||\vec{e}_{Al}|\sin\theta_D\sin\theta_S\sin\theta_V\sin\phi + \frac{D_{Al}}{4}|\vec{e}_D|\cos\theta_D\right]^2$$

$$\mathrm{BR}(\mu Au \to eAu) = \frac{6144\pi^3 v^4}{2.197 g_{Au}^{cap}\Lambda_{LFV}^4}\Big[|\vec{u}_{Au}|(\cos\theta_{AuAl}|\vec{e}_{Al}|\sin\theta_D\sin\theta_S\sin\theta_V\sin\phi$$
$$+\sin\theta_{AuAl}|\vec{e}_{\perp}|\sin\theta_D\sin\theta_S\sin\theta_V\cos\phi) + \frac{D_{Au}}{4}|\vec{e}_D|\cos\theta_D\Big]^2$$

Spherical coordinate parameterization

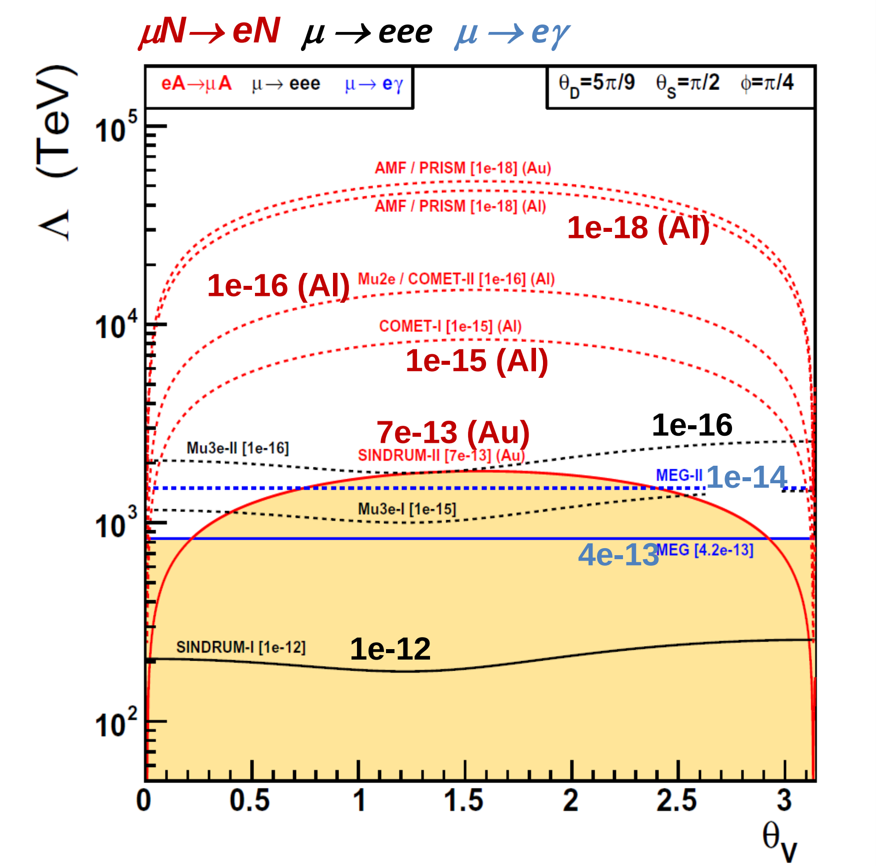
$\vec{C}\cdot\vec{e}_D$	$\lvert\vec{e}_D\rvert\cos\theta_D$
$\vec{C}\cdot\vec{e}_S$	$\lvert\vec{e}_S\rvert\sin\theta_D\cos\theta_S$
$\vec{C}\cdot\vec{e}_{VL}$	$\lvert\vec{e}'_{VL}\rvert\sin\theta_D\sin\theta_S\cos\theta_V$
$\vec{C}\cdot\vec{e}_{VR}$	$\lvert\vec{e}'_{VR}\rvert\sin\theta_D\sin\theta_S\cos\theta_V$
$\vec{C}\cdot\vec{e}_{Alight}$	$\lvert\vec{e}_{Alight}\rvert\sin\theta_D\sin\theta_S\sin\theta_V\sin\phi$
$\vec{C}\cdot\vec{e}_{Aheavy\perp}$	$\lvert\vec{e}_{Aheavy\perp}\rvert\sin\theta_D\sin\theta_S\sin\theta_V\cos\phi$

θ_D angle between the dipole and four-fermion type of operators
θ_V angle between four-fermion operators on leptons or quarks
θ_S angle between scalar and vector operators for $\mu \to eee$
ϕ angle between “light: and “heavy” operators in $\mu N \to eN$ conversion

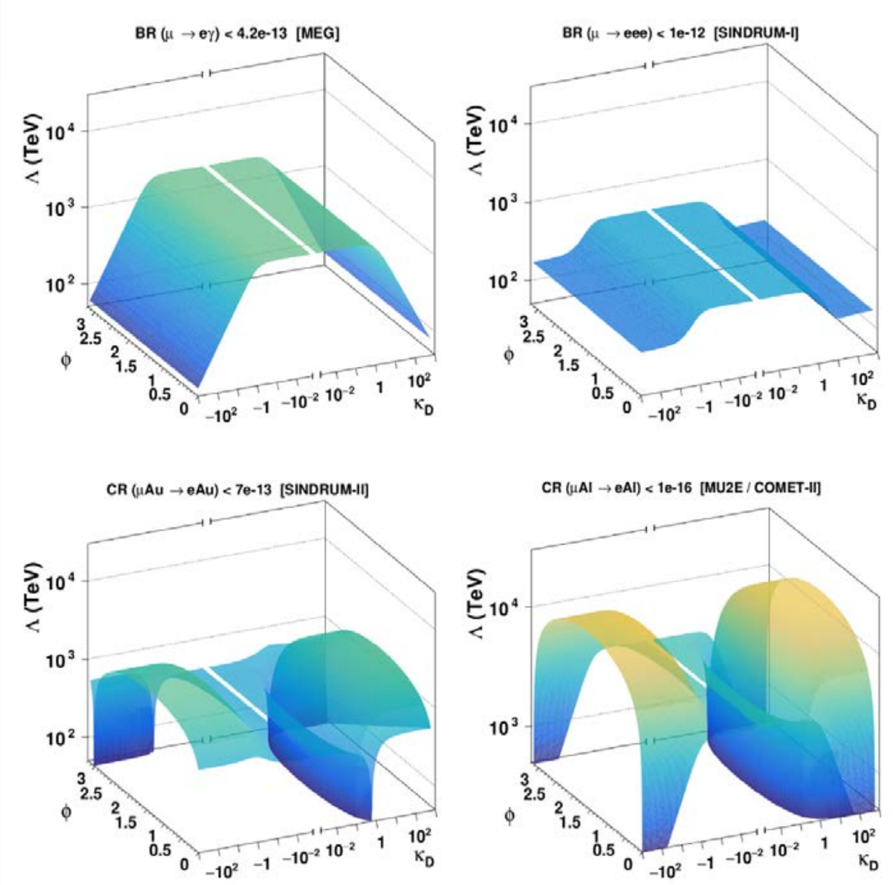
$\boldsymbol{\kappa_D}$ = cotan(θ_D- π/2): parameterization inspired from De Gouvea *et al* (1003.0497) to enlarge the regions near $\theta_D = 0, \pm\pi/2$ where the dipole operators ($|\kappa_D| \ll 1$) or the four-fermion ($|\kappa_D| \gg 1$) operators dominate

Davidson *et al*, 2204.00564

Reach on NP mass scale of past and future experiments



S. Davidson, BE, 2204.00564



θ_D angle between the dipole and four-fermion type of operators

θ_V angle between four-fermion operators on leptons or quarks

θ_S angle between scalar and vector operators for $\mu \to eee$

ϕ angle between "light: and "heavy" operators in $\mu N \to eN$ conversion

Straw R&D (FNAL LDRD program)

Develop 8 μm Mylar straws using 3.5 μm Mylar + 1 μm adhesive + 3.5 μm Mylar double helical wrap

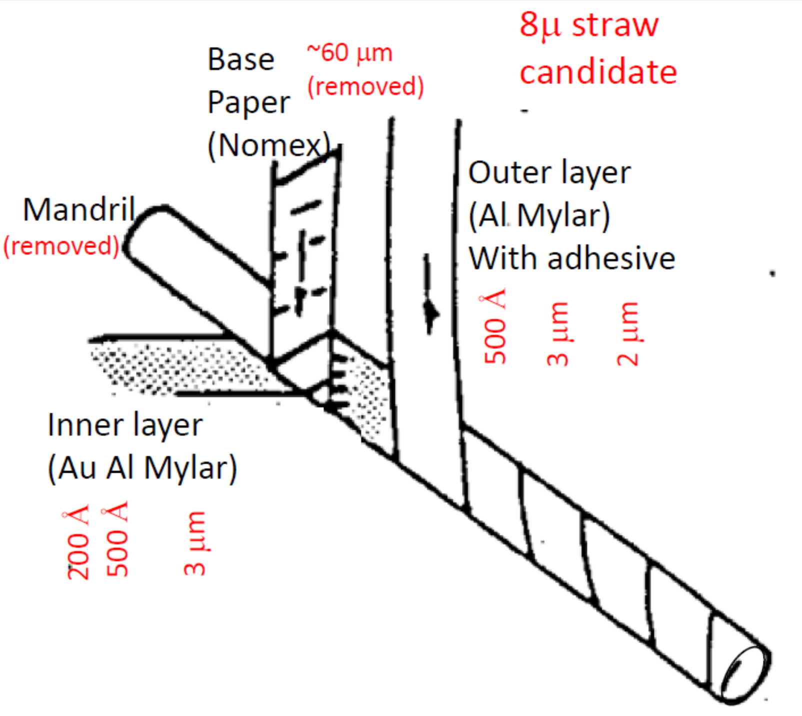
Held 15 PSI for multiple days and 400 g tension without visible distortion

Handling straws with internal outward force without causing obvious damage

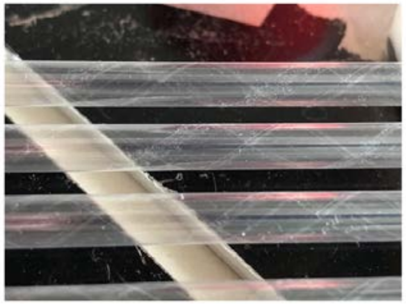
- Paper is inside
- Inflated straws

Almost no compression force can be applied, making the installation of straw termination challenging

Integrated readout electronics must be able to handle large radiation dose



8 μm Mylar Straw



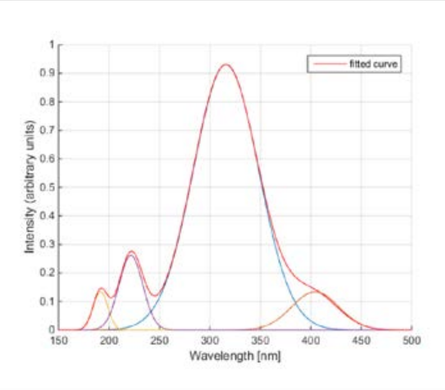
Pressurized 8 μm Mylar Straws

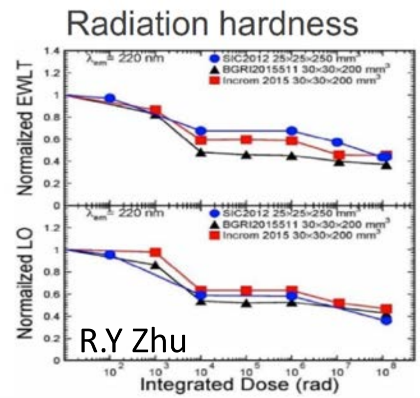
Barium fluoride crystal calorimeter

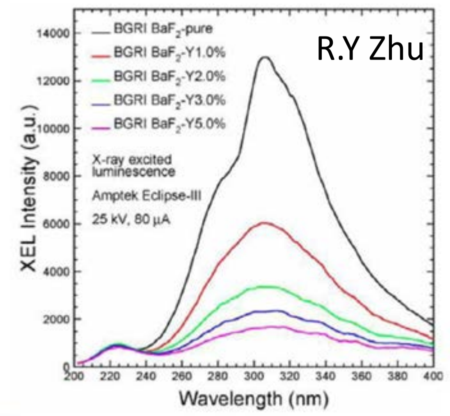
Rate and radiation dose are too high for pure CsI
- Up to ~ 1Mrad and 1E13 n [1MeVeq/cm2]

BaF_2 is an excellent candidate for ultra fast, high rate, radiation hard crystal calorimeter
- Fast components (<1 ns) at 195 and 200 nm
- Can support > 1 Mrad radiation dose

Must use fast component at 200 nm without undue interference from slow 320 nm component. Two complementary approaches:
- Yttrium doping can suppress slow component by factor x5 without reducing fast signal
- Develop photo-sensor only sensitive to fast component: solar blind UV-sensitive SiPM /APD, UV-sensitive MCP or LAPPD, nano-particle wavelength shifting filter,…







Solar-blind UV-sensitive SiPM

Add anti-reflection filter to SiPM surface

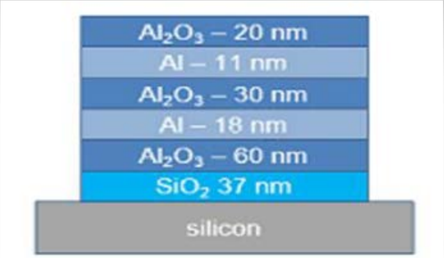
- Select fast component, further suppress slow component
- Improve overall efficiency (light bounces back)

Add superlattice by implementing boron layer just below the Si surface with molecular beam epoxy

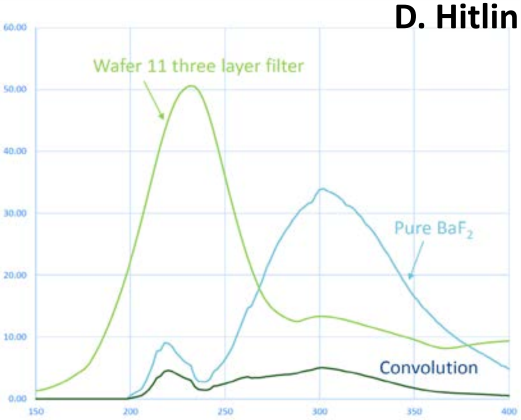
- Improve quantum efficiency and timing performance by reducing undepleted region near surface
- Provide stability under intense UV illumination

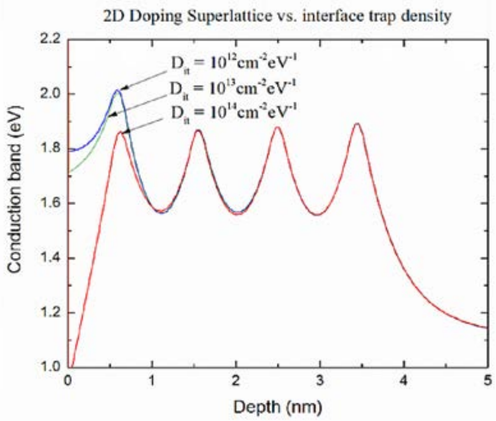
Currently under R&D from Caltech, JPL and FBK

- First tests with 3 layer filter (no superlattice) show good sensitivity to fast component.
- Further R&D to include 5 layer filter and superlattice



D. Hitlin





Other possibilities

- MCP not yet suitable for reading crystal in high-rate environment, as charge collected by anode is orders of magnitude too large for device capabilities (max few C/cm^2). Would need further R&D.
- Nano-particle WLS filter require more R&D to understand QE and timing performance

https://indico.fnal.gov/event/46746/contributions/210202/attachments/141121/177609/Hitlin_CPAD__210318-.pdf

Production target

Investigate design of pion production target inside solenoid to handle increase beam power

Explore rotation target, fixed granular target or conveyor belt with small target elements

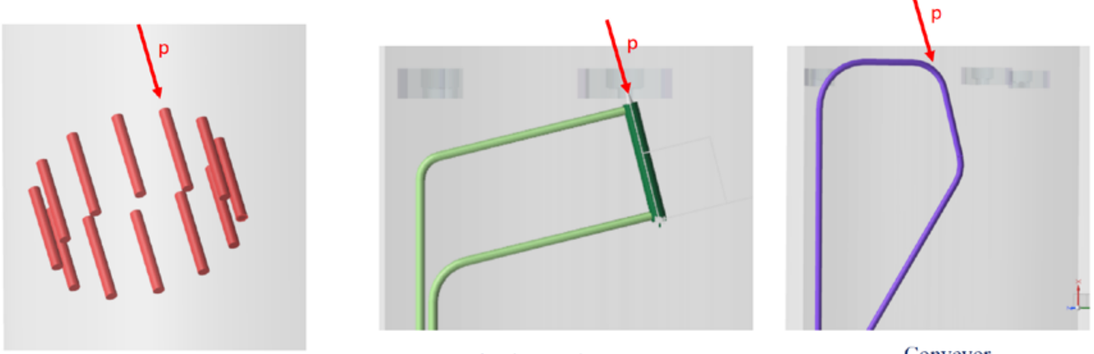
Understand solenoid shielding requirements

Current LDRD program at FNAL, conveyor belt seem the favored solution so far

Designs under consideration

V. Pronskikh

To simulate the overall target pion production performance and durability at beam induced pulsed energy deposition spikes, thermal stress, radiation damage, muon stopping rates, residual activation and radiation loads



Rotating Elements   Fixed Granular Target   Conveyor

Pion-production target for Mu2e-II | V.Pronskikh   4

	Tungsten/WC	Lower-density bent (Carbon)
Rotated	Requires a large hardware in HRS	Too large to fit HRS
Fixed granular	DPA is too high	DPA is high; lower pion production
Conveyor	Thermal analysis is ongoing	Lower pion production; thermal analysis is ongoing