Future program of muon CLFV

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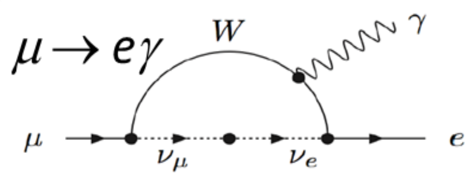
Muons in Minneapolis Workshop

December 2023

Based on
https://arxiv.org/abs/2309.05933
https://arxiv.org/abs/2210.04765
https://arxiv.org/abs/2209.00142

Charged lepton flavor violation (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:



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

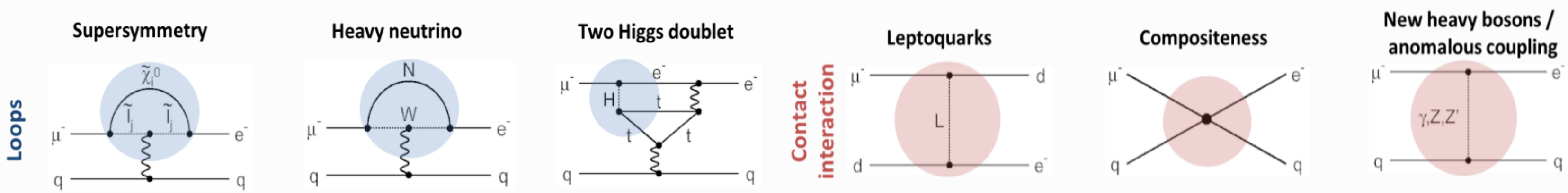
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

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.



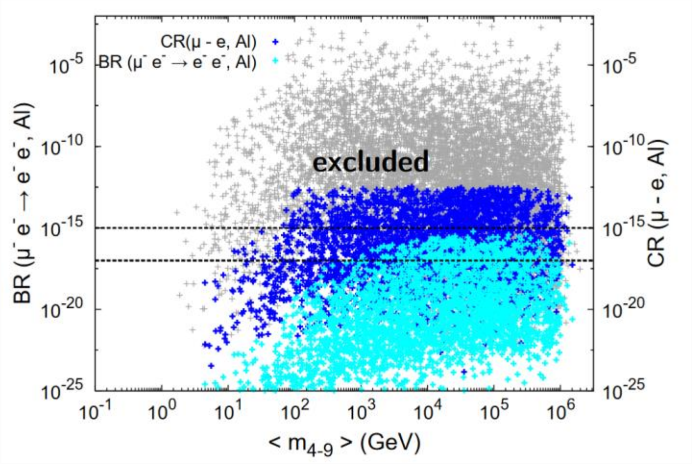
Each model generate a specific pattern of operators
→ multiple CLFV measurements to extract the underlying physics

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

- distinct new states realized at different scales

Low scale Seesaw: inverse seesaw

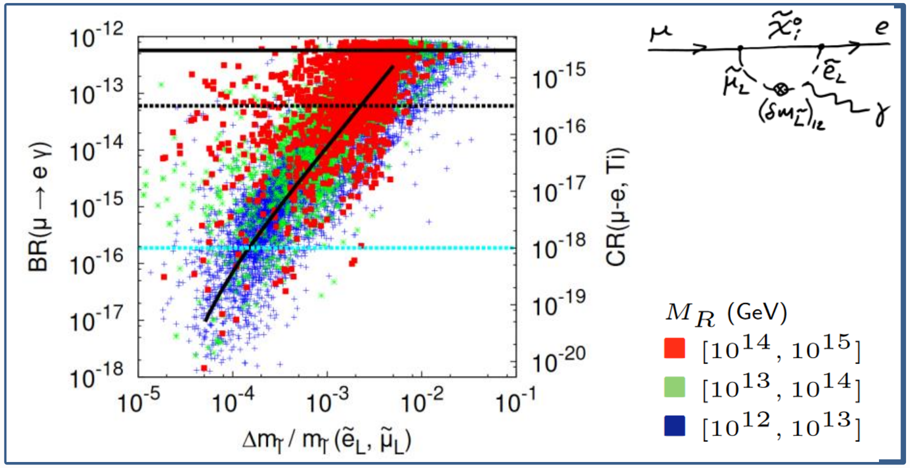
Addition of 3 "heavy" RH neutrinos and
3 extra "sterile" fermions to SM



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 between models

Strong interplay between neutrino physics and CLFV

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

Three main modes

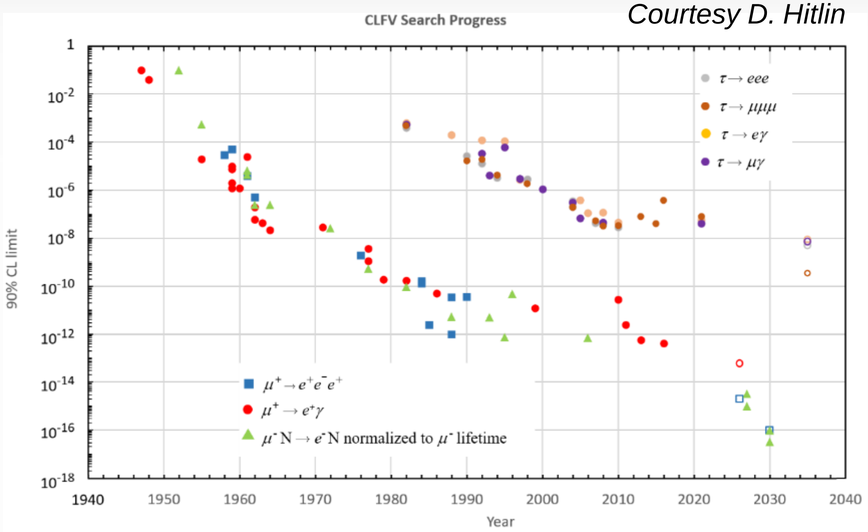
- $\mu^+ \rightarrow e^+\gamma$ decays
- $\mu^+ \rightarrow e^+e^-e^+$ decays
- $\mu^- N \rightarrow e^- N$ conversion

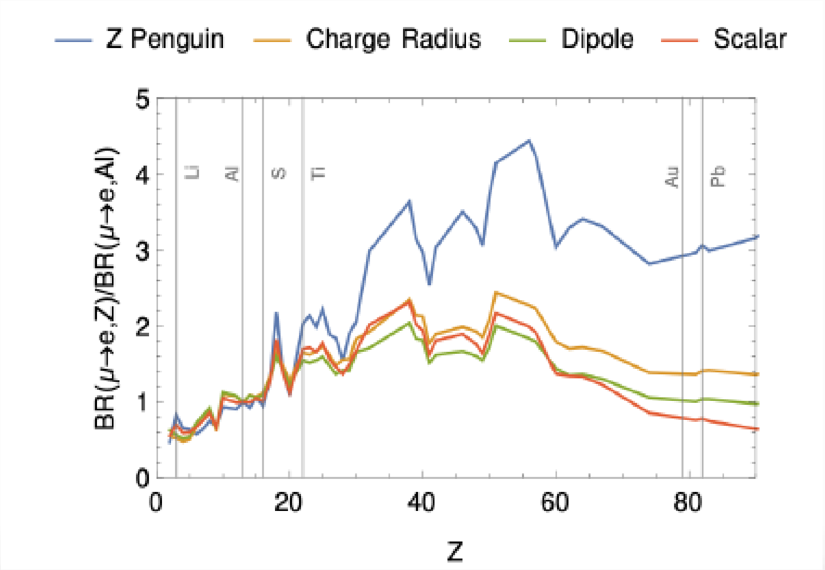
Already probe mass scale at the level of 10^3 TeV

Complementarity is key – each reaction probes different NP operators

The Z-dependence of $\mu^- N \rightarrow e^- N$ conversion provide information about the nature of NP, effect more important at high Z

Courtesy D. Hitlin





Cirigliano, *et al*, PRD **80**, 013002 (2009)

S. Davidson, BE, 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 following effective Lagrangian, assuming $\mu N \to eN$ interactions are similar for all light or all heavy targets (taken as Al and Au for concreteness)*.

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

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

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

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

$C_D = \vec{C}\hat{e}_D, \ldots$

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

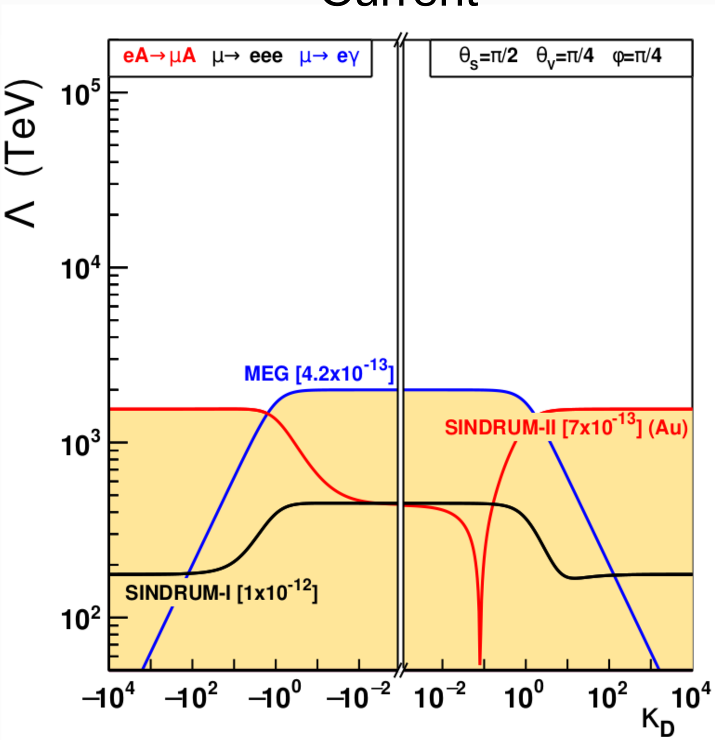
There are many operators, but only a few measurements. A judicious choice of basis vectors in the coefficient space lets you define a four-dimensional subspace corresponding in good approximation to the rates we can measure.

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

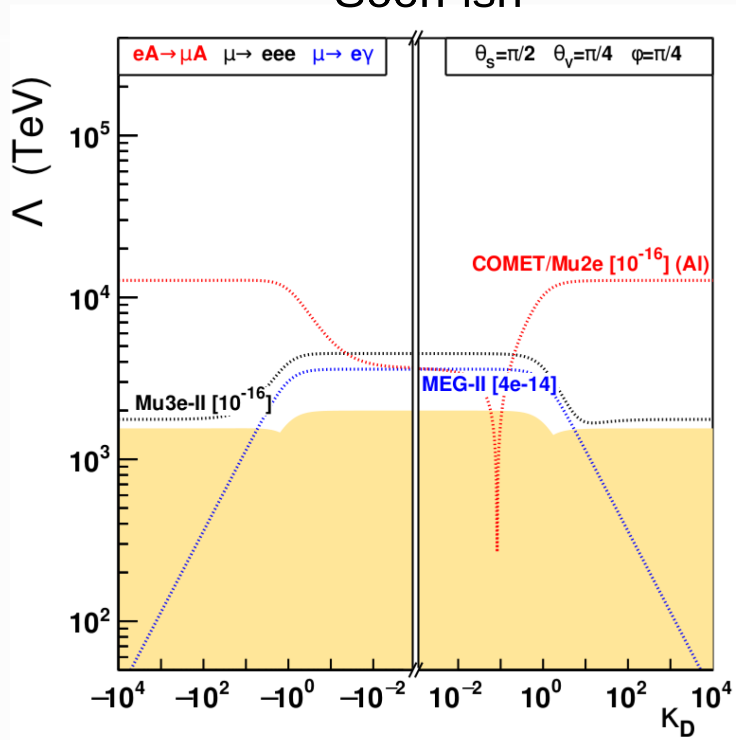
*See Haxton et al (2109.13503) for a detailed discussion about the effect of nuclear structure on $\mu \to e$ conversion

Reach and complementarity as a function of κ_D (remaining parameters representative)

Current



Soon-ish



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

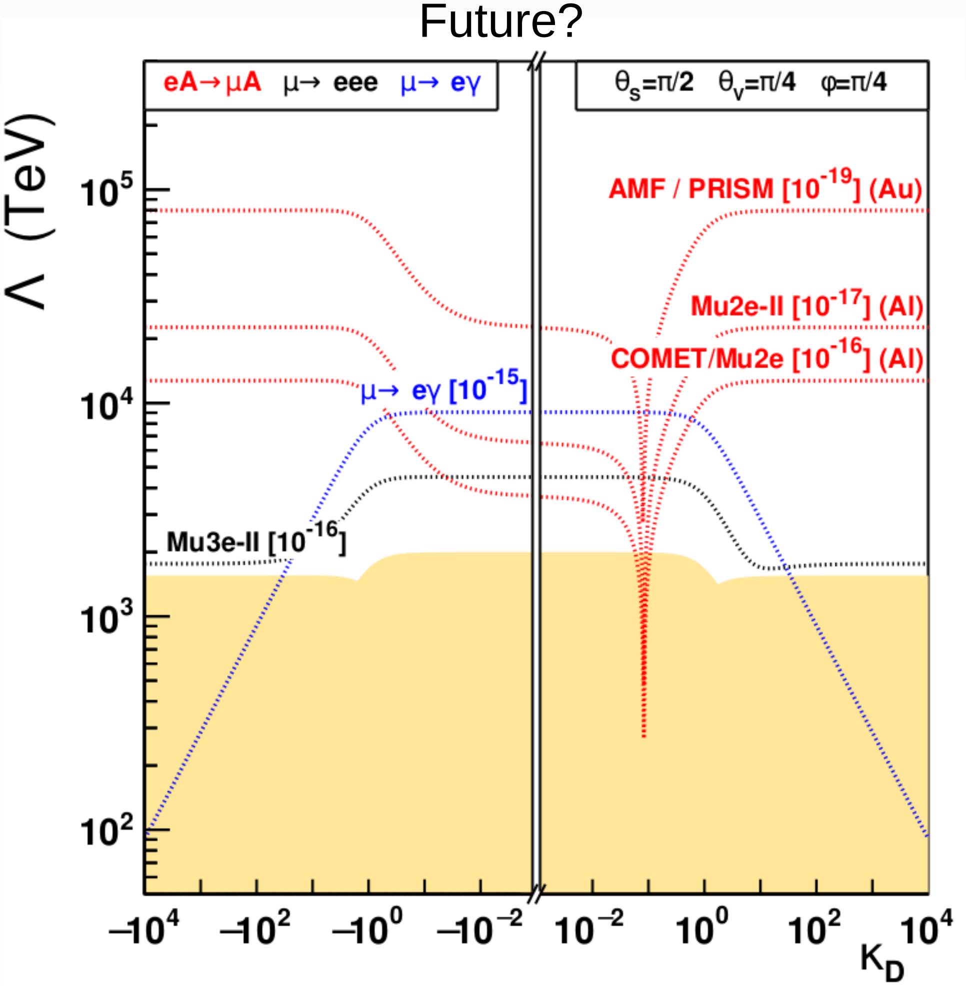
$$\kappa_D = cotan(\theta_D - \pi/2)$$

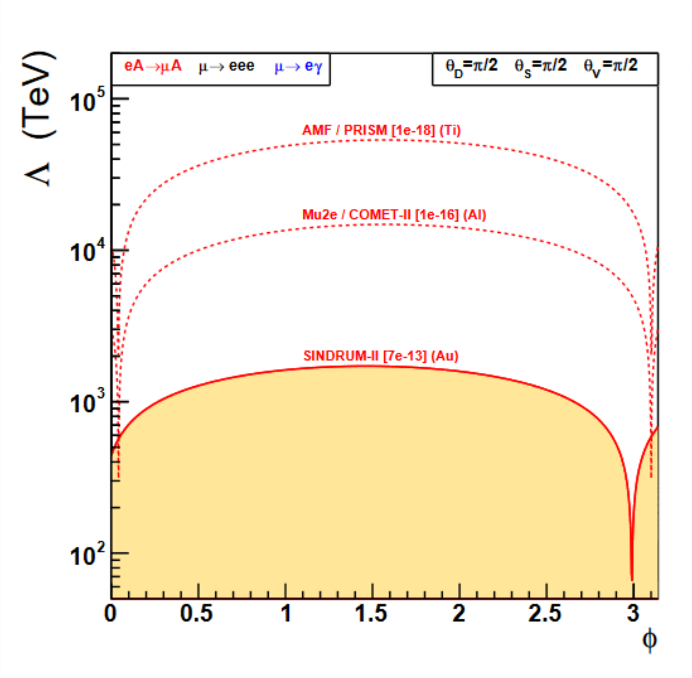
$|\kappa_D| << 1$ dipole dominant

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

Reach and complementarity as a function of κ_D or ϕ (remaining parameters representative)

Future?





Need to measure all three modes and multiple targets for conversion

Need to push the sensitivity of the decay modes to keep up with the conversion mode

Current and next-generation initiatives

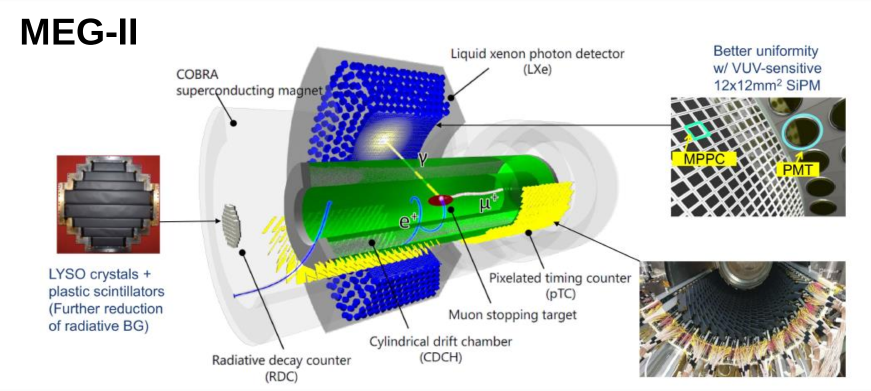
Two main channels

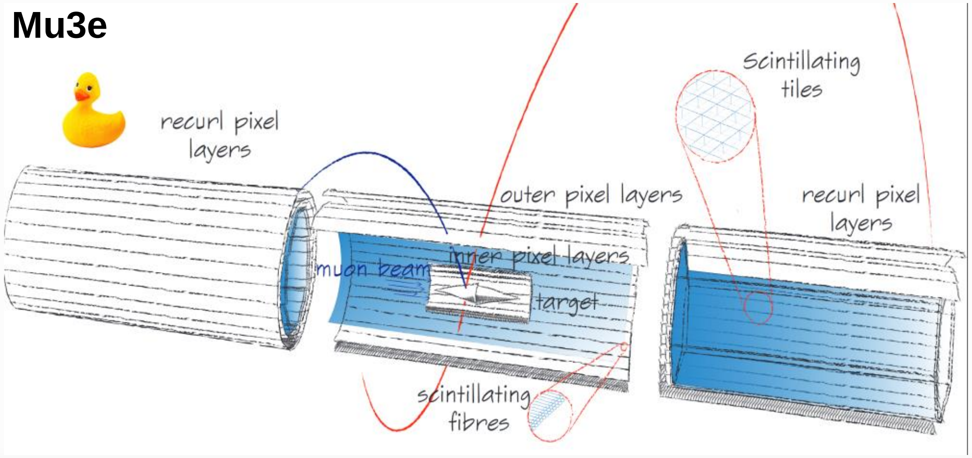
$\mu^+ \rightarrow e^+\gamma$ - MEG II at PSI

- Expected sensitivity at the level of 10^{-14}
- **Taking data !!!**

$\mu^+ \rightarrow e^+e^-e^+$ - Mu3e at PSI

- Expected sensitivity at the level of 10^{-15} to 10^{-16} (with HiMB)
- Expect taking first data in 2024-2025 (see Ann-Katrin's talk)





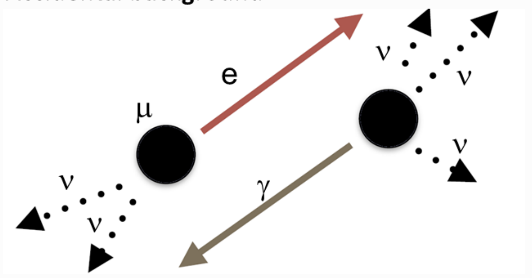
The Mu3e Experiment (G. Hesketh et al. – 2204.00001), A.M. Baldini et al., EPJC 78 (2018)

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

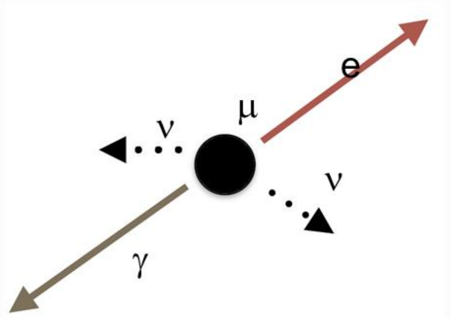
Improve detector performance to reduce backgrounds

- 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

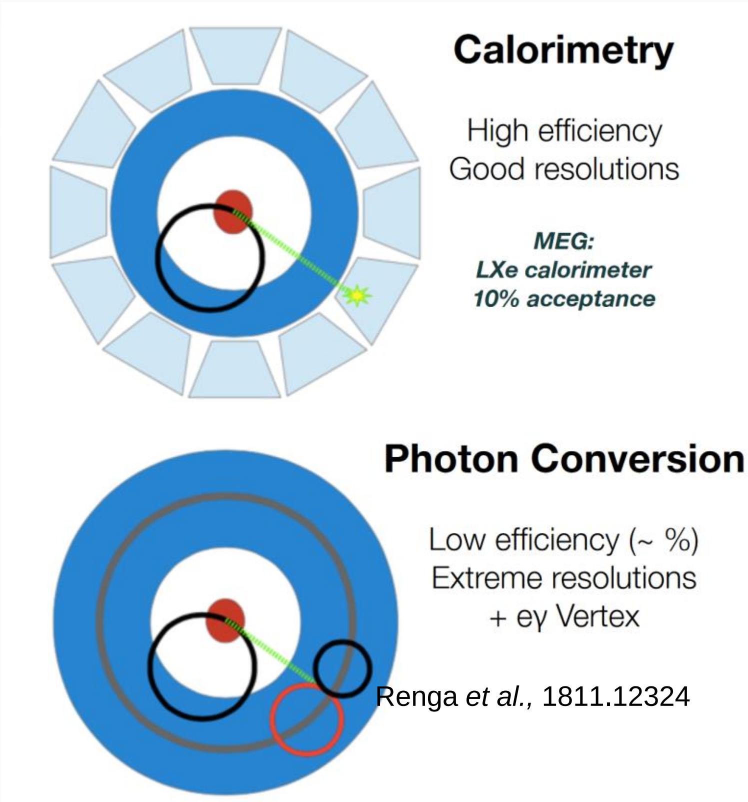


Increase muon rate

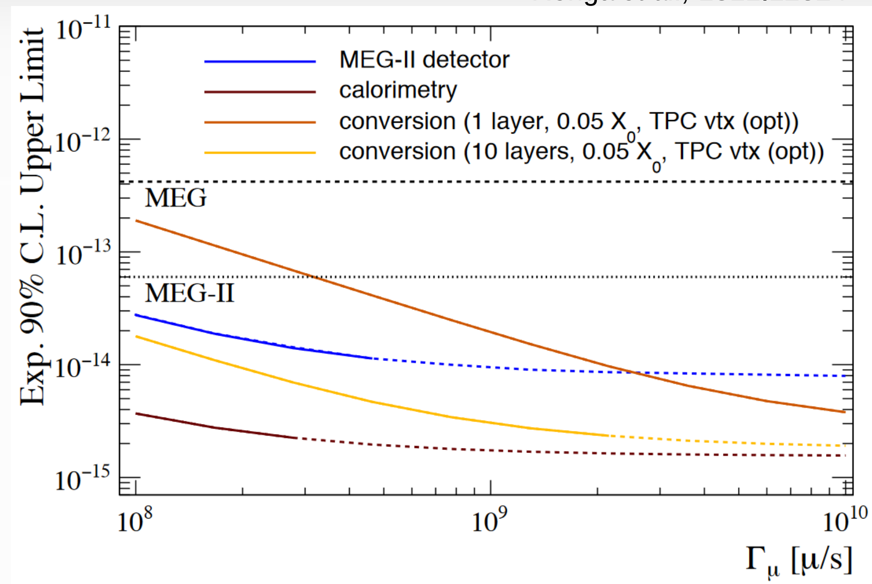
Current PSI muon beamline	2×10^8 μ/s
Proposed HiMB at PSI	$\sim10^{10}$ μ/s
Mu2e (+ve mode, pulsed)	$\sim10^{11}$ μ/s

Muon decays – going beyond

Two possible options



Renga *et al.*, 1811.12324



—— bkg <= 10 evts ----- bkg > 10 evts

New effort to design an experiment to reach 10^{-15} (MEG III?)

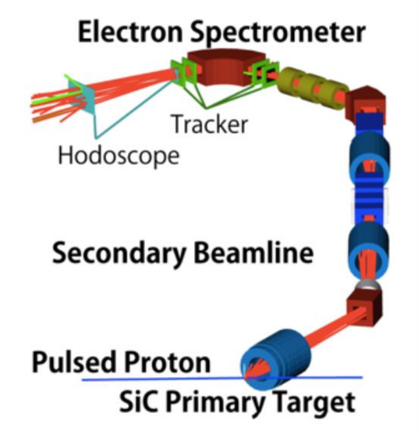
Taking full advantage of 10^{10} μ/s or more will need a novel experimental concept

Challenge: can we build an expt to search simultaneously for $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$?

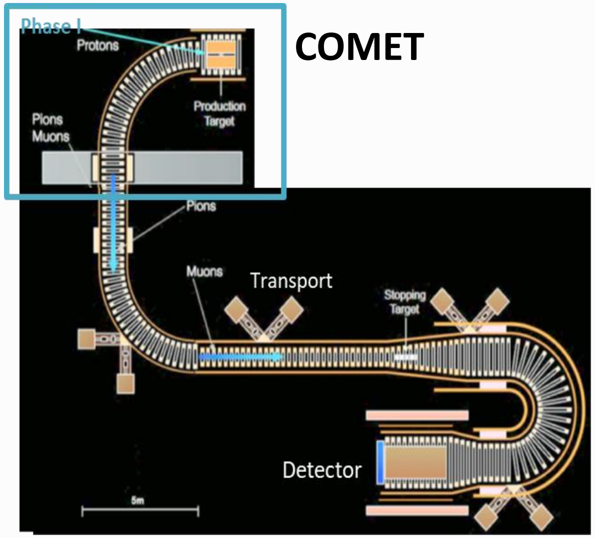
Three experiments at various stage of execution, to be completed by the end of the decade with different single event sensitivity (SES)

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

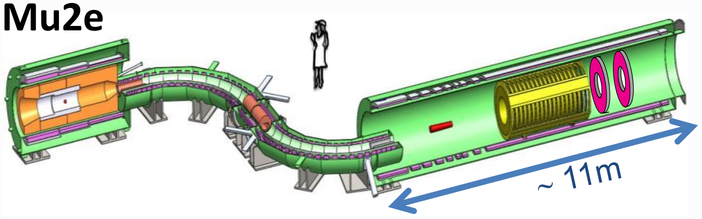
DeeMee



COMET



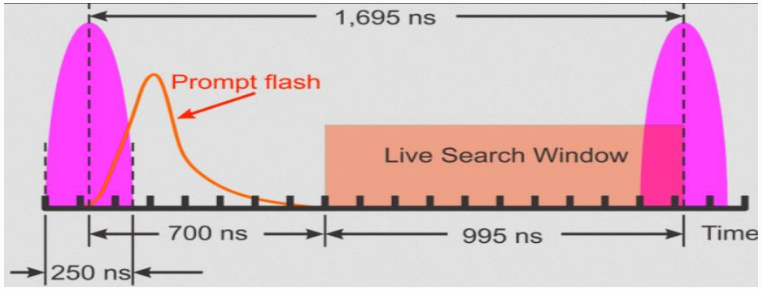
Mu2e



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

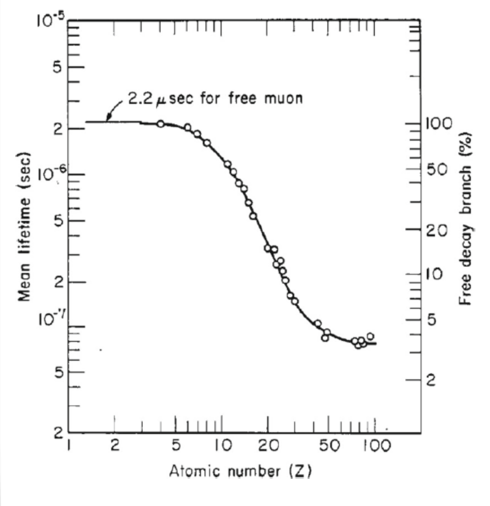
Current approach (COMET / Mu2e)

- 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
- Detector performance: track momentum resolution (tracker, target), cosmic ray veto, radiation dose, trigger bandwidth…



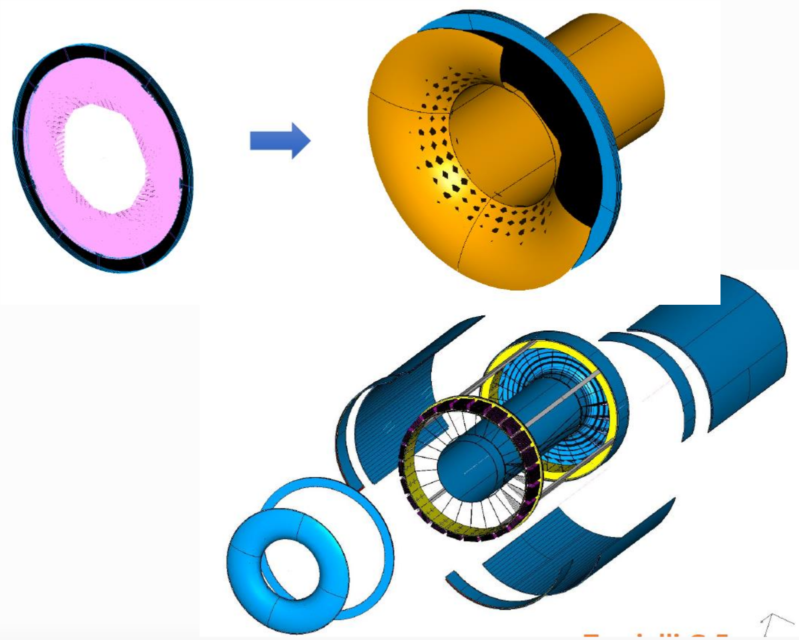
A. Knecht et al., EPJ. Plus (2020) 135

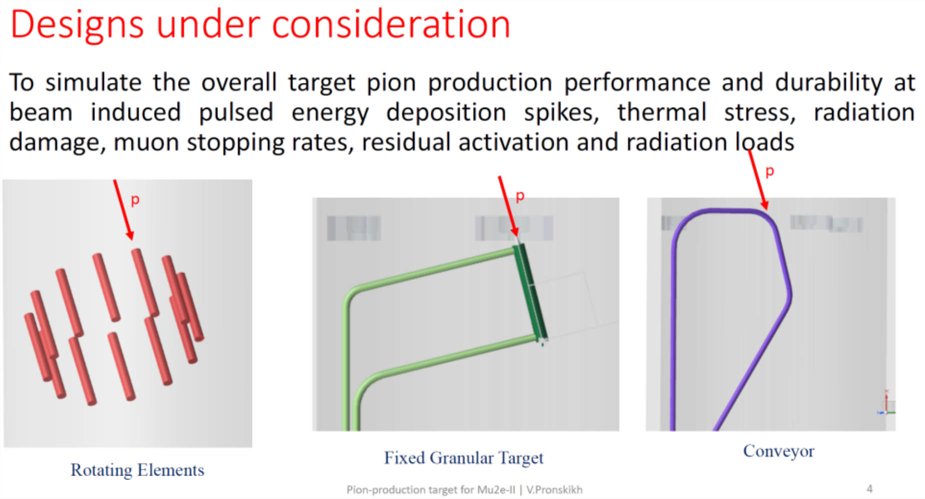
Several proposals for next generation experiments to overcome some or all of these limitations

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 → **no lose scenario**

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



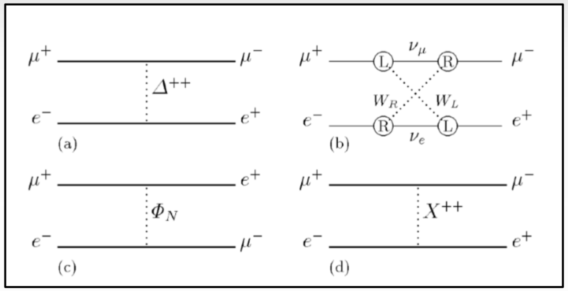


Mu2e-II: Muon to electron conversion with PIP-II (F. Porter et al. – 2203.07569)

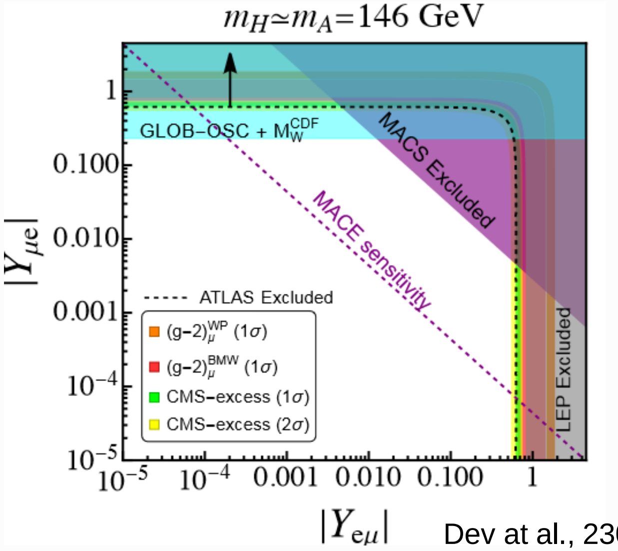
Muonium: bound state of μ^+ and e^-. Purely QED, no hadronic uncertainties

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

Connection to $0\beta\nu\nu$ if neutrinos are Majorana particles (black box theorem - hep-ph/0608207)



Leptophilic 2HDM model



Dev at al., 2305.19314

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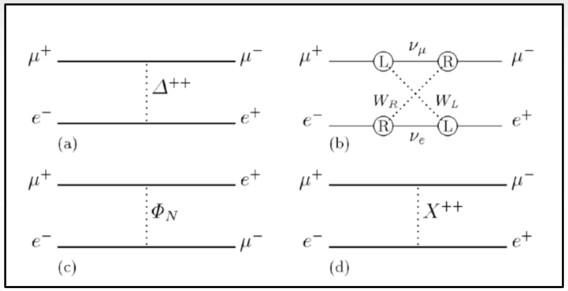
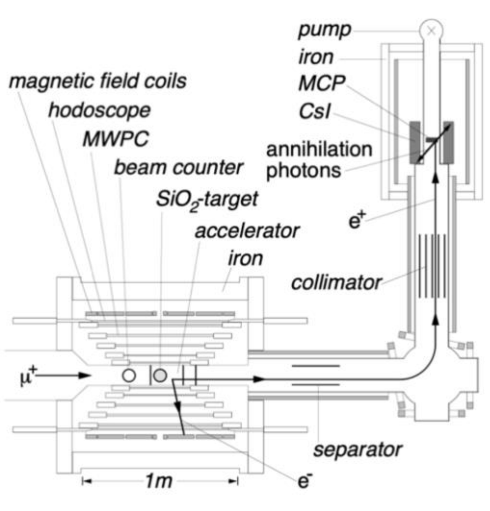
Muonium – antimuonium transitions ($\Delta L=2$) are extremely suppressed in the SM, but rates can be enhanced by NP.

Connection to $0\beta\nu\nu$ if neutrinos are Majorana particles (black box theorem - hep-ph/0608207)

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

$$P(M_\mu \rightarrow M_\mu) < 8.3\times10^{-11} / S_B(B_0)$$
$$G_{MMbar} < 3\times10^{-3}\, G_F \text{ (90\% CL)}$$

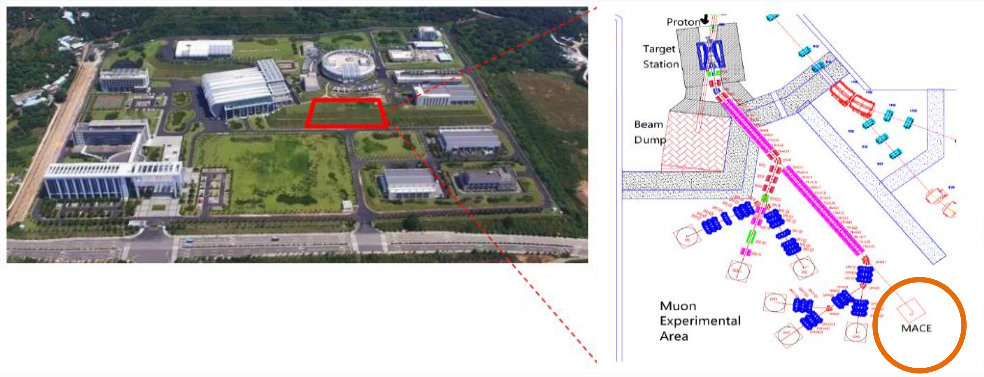




Muonium-Antimuonium Conversion Spectrometer (MACS)
L. Willmann, et al. PRL 82 (1999) 49

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

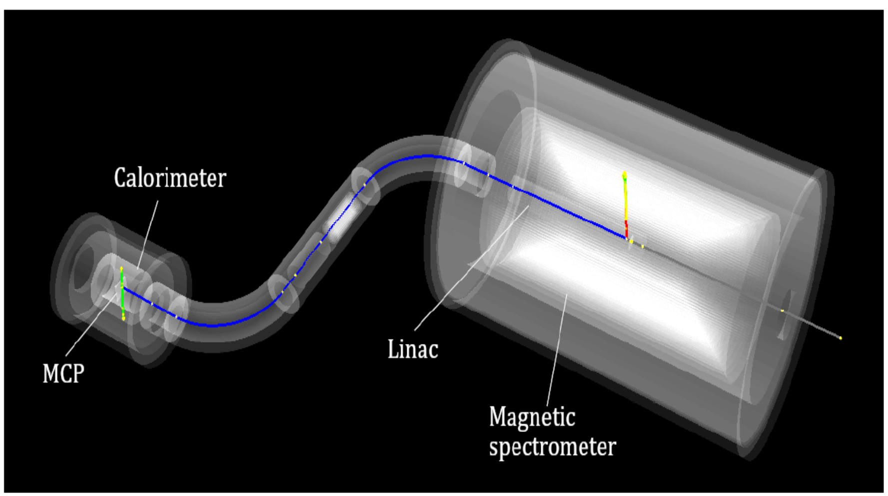
Exprimental Muon Source (EMuS) at CSNS – new facility in China



	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)

Next-to-next generation

The Advanced Muon Facility (AMF) is a proposal for a new muon complex for the next generation of experiments at FNAL or J-PARC

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 spin rotation
- …..

This facility should provide

- Lowest possible momentum and small Δp to reduce the thickness of a stopping target
- Pure muon beam to reduce backgrounds
- Pulsed or continuous muon beams

This could be achieved with a small muon storage ring based on a fixed field alternating gradient (FFA) synchrotron with phase rotation (PRISM concept).

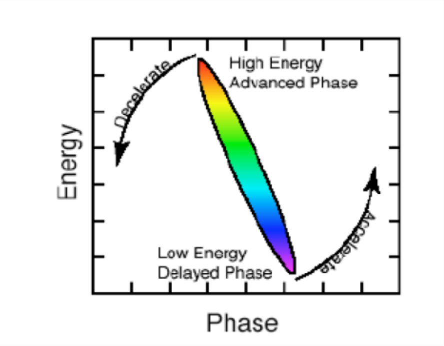
A surface muon beam could also provide a low-momentum, monochromatic beam for positive muons (e.g. HIMB at PSI), but the FFA option might work for both charges

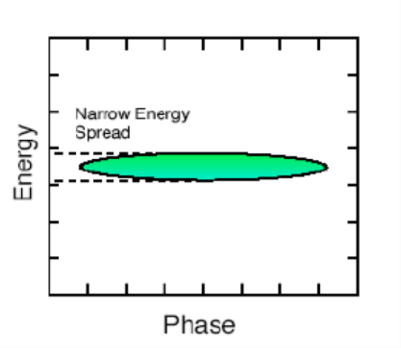
A New Charged Lepton Flavor Violation Program at Fermilab (B. Echenard et al. – 2203.08278)
Design Considerations for FNAL Multi-MW Proton Facility in the DUNE/LBNF era (J. Eldred at al – 2203.08267)

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

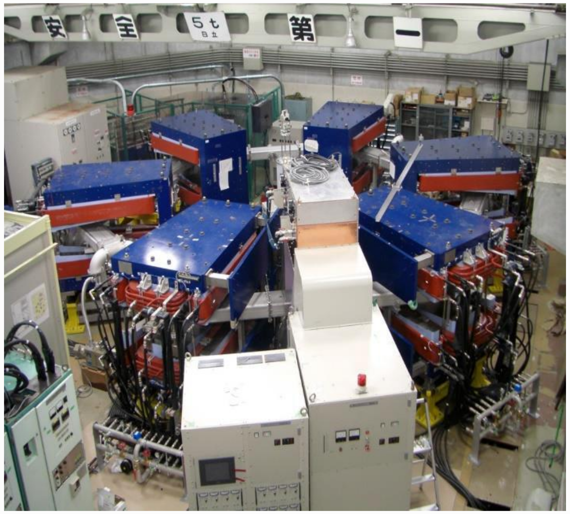


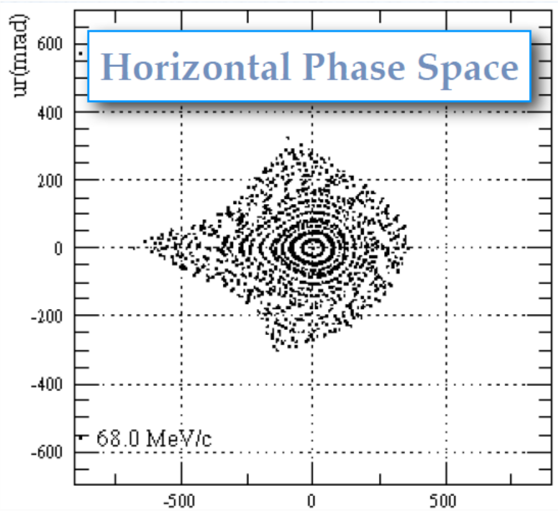


Requires a compressed proton bunch and high power beam to achieve high μ rate

PRISM FFA - proof of concept

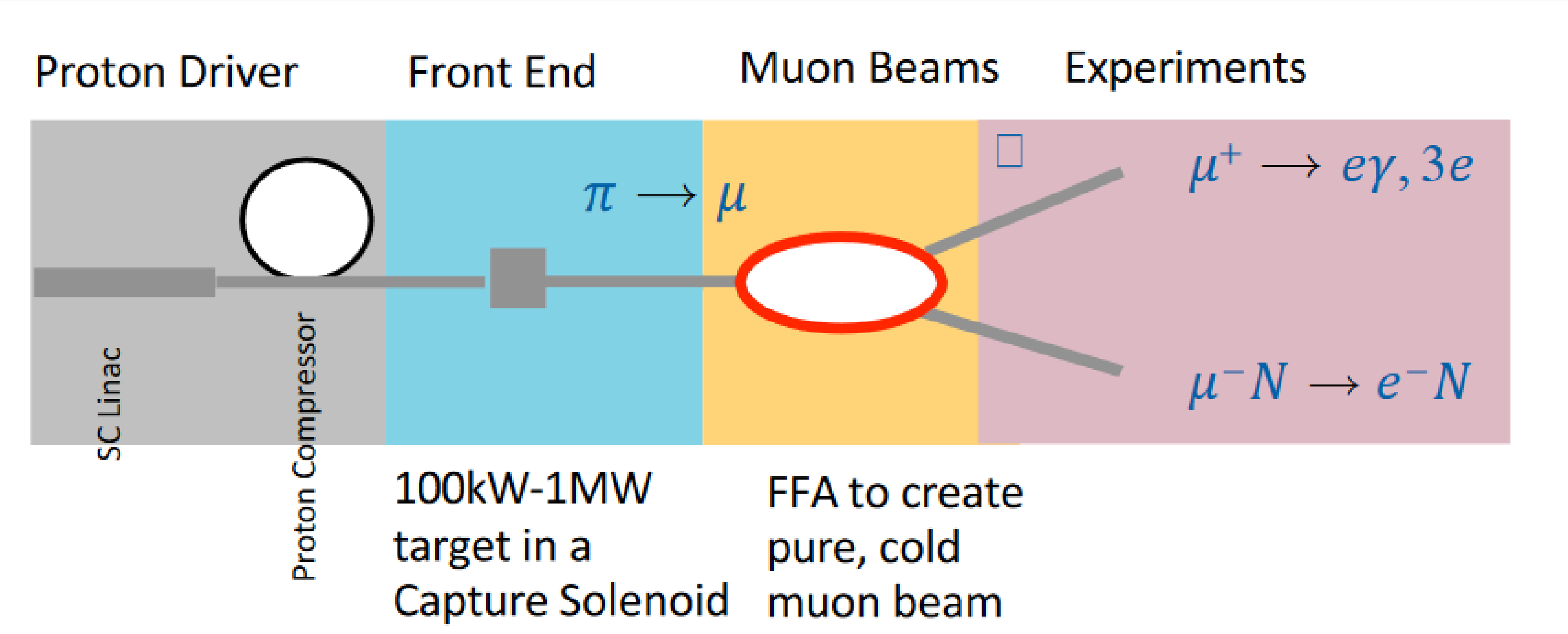
- 10 cell DFD ring has been designed
- FFA magnet-cell has been constructed and verified
- RF system has been tested and assembled
- 6 cell ring was assembled and its optics was verified with α particles
- Phase rotation was demonstrated for α particles





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

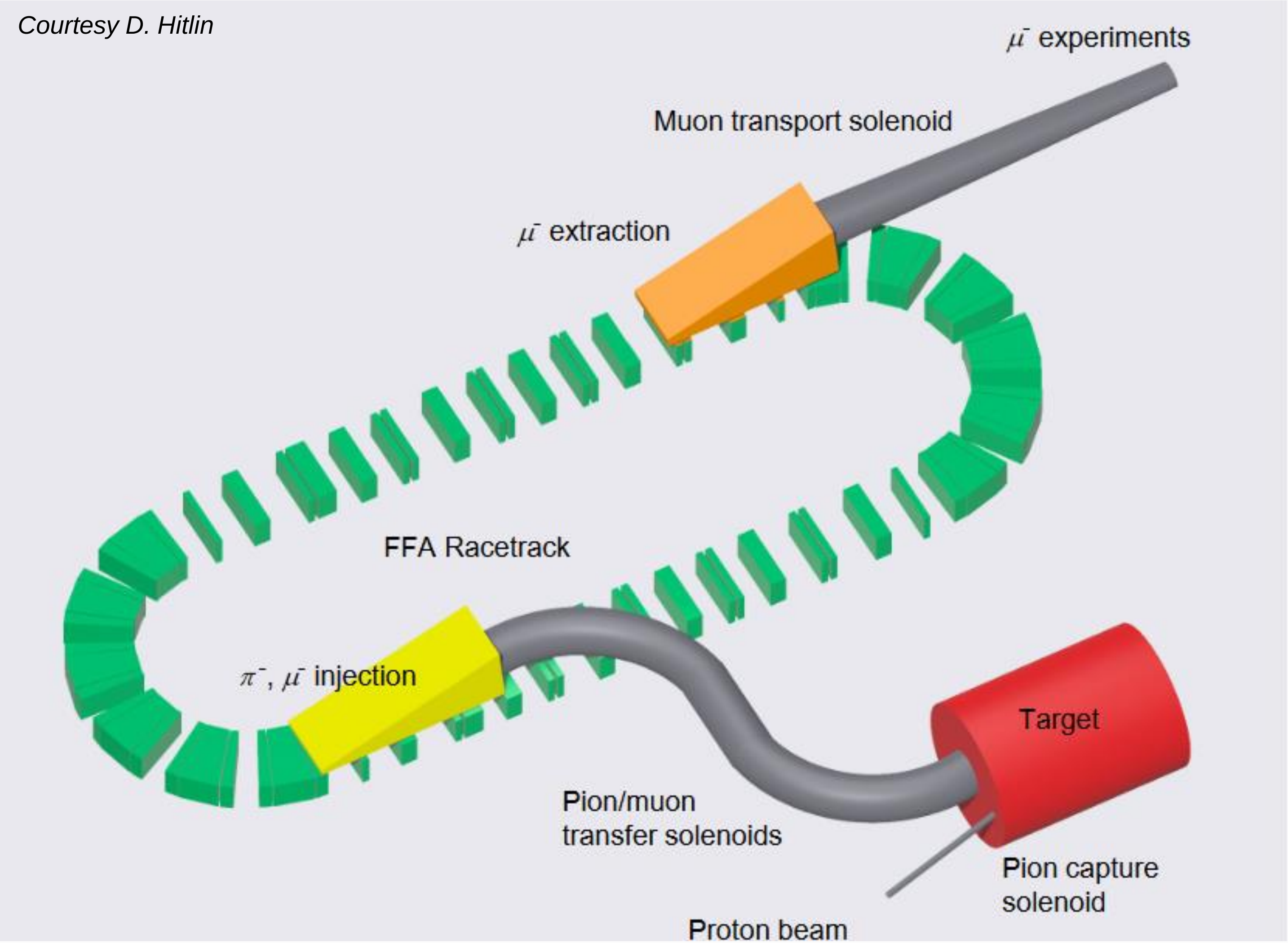
AMF concept



Several concepts have been proposed for the FFA, including circular or racetrack geometries, scaling or non-scaling options, μ+ and μ- simultaneously,…

Strong synergies with the muon collider for the development of a target station

AMF – a conceptual design



Take advantage of cold, monochromatic, pure muon beam at the exit of the FFA for conversion experiments

No beam-induced background

Pions decay in the FFA – corresponding background is extremely suppressed

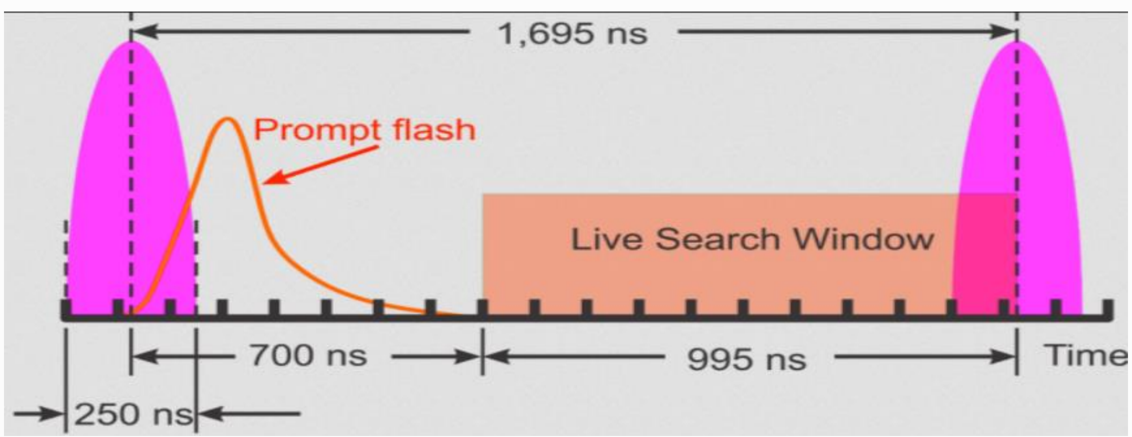
No beam flash, antiprotons, delayed electrons, muon decay in flight,…

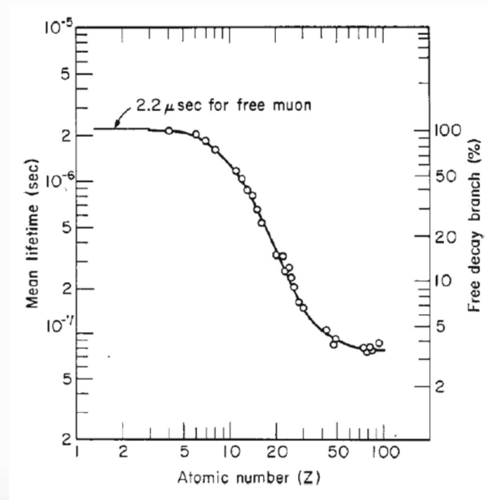
→

Can measure short muonic atom lifetime → high Z material

No stringent requirements on out-of-time protons

Less radiation in the detector





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➡

Can measure short muonic atom lifetime → high Z material

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Less radiation in the detector

Cold beam

Use thinner stopping target to stop muons, ideally a single thin foil → reduce energy loss fluctuations in target material

➡

Improved momentum resolution, better muon DIO rejection

Low duty cycle

100 - 1000 Hz instead of MHz

➡

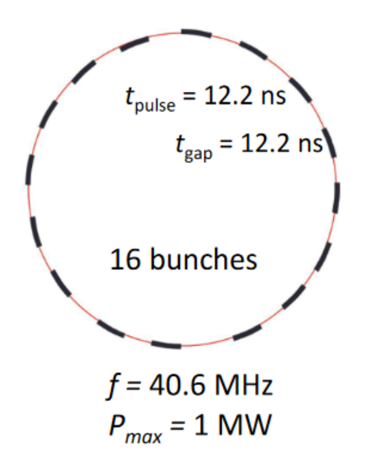
Reduce cosmic induced backgrounds

PIP-II at FNAL is an ideal accelerator to provide the MW proton beam for AMF, but the continuous beam structure is not optimal

- Need a compressor ring to provide short (~10 ns), intense pulses

A few possibilities have been proposed, including in the context of the FNAL accelerator complex evolution (ACE) proposal

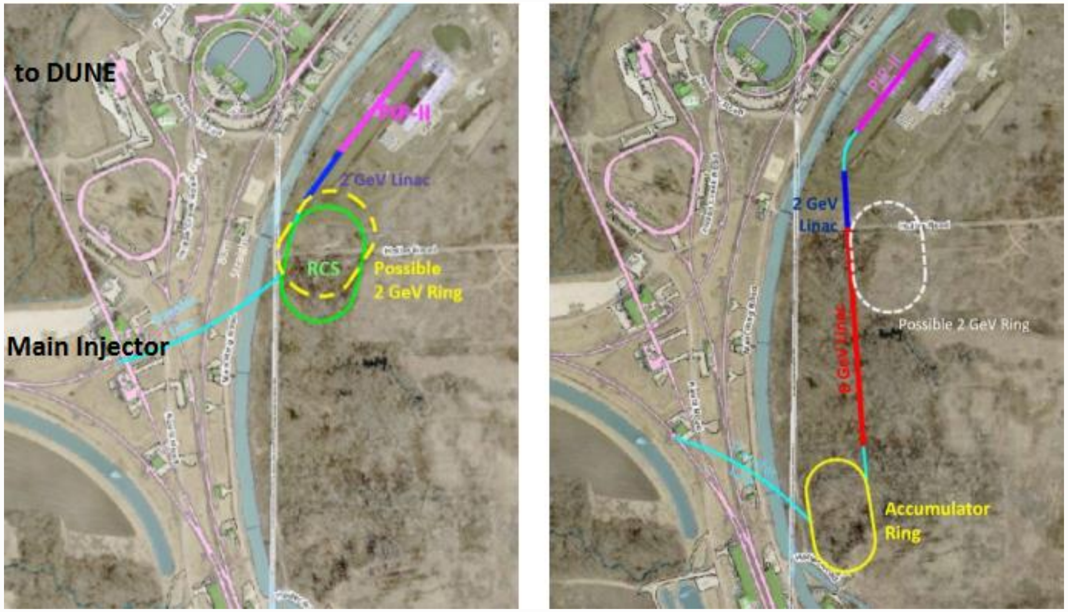
Compressor ring for PIP-II
(E. Prebys)



$$|\Delta\nu_{sc}| = \frac{B n_b N_b r_0}{2\pi\beta\gamma^2\epsilon_N} < \sim 0.2$$

Number of bunches; Particles per bunch; Maximum space charge tune shift; Relativistic βγ factors; Transverse emittance (prop to beam-size squared)

Potential 2 GeV ring for different upgrade scenarios



https://indico.fnal.gov/event/59663/attachments/167657/224734/Report_from_the_Fermilab_Proton_Intensity_Upgrade_Central_Design_Group-FN-1229.pdf

Challenges

Many challenges remain to be solved…

FFA ring design

- large aperture and acceptance elements
- vertical plane muon beam injection / extraction

Target and capture system

- MW class target in a solenoid – very challenging conditions
- in full synergy with the Neutrino Factory and a Muon Collider

Design of the muon beam transport from the solenoidal capture to the FFA ring

- very different beam dynamics conditions
- very large beam emittances and the momentum spread

Muon beam injection/extraction into/from the FFA ring

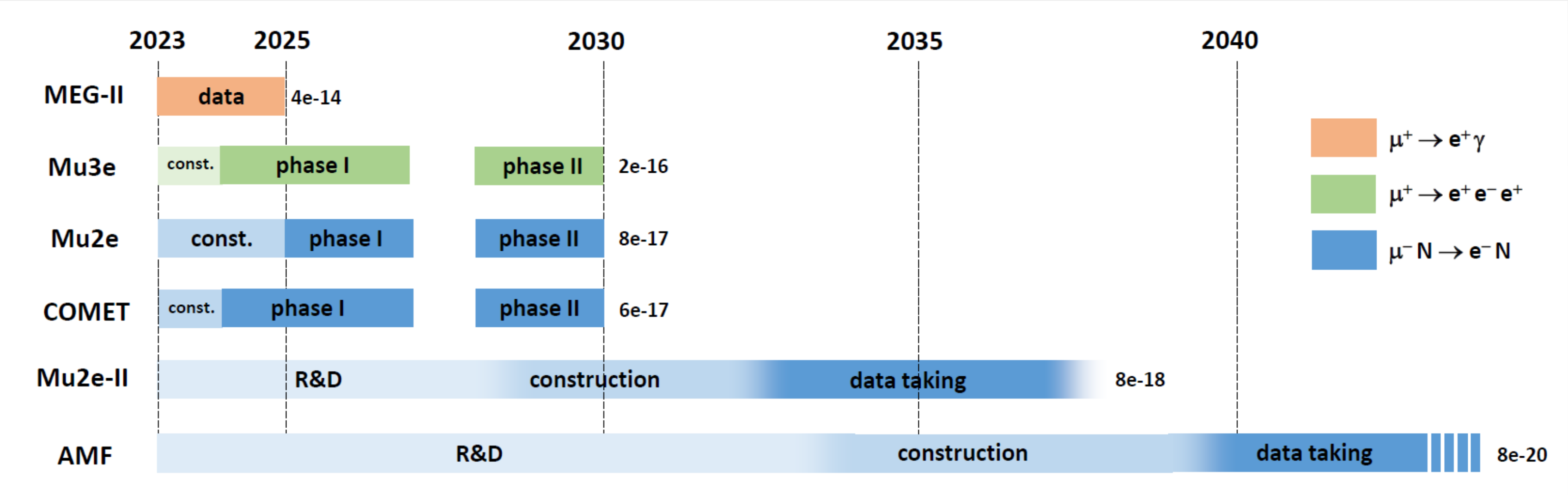
- very large beam emittances and the momentum spread

Compressor ring

- Fast kicker to transfer beam from compressor ring at 1kHz

Synergies with the development of a muon collider and/or neutrino factory

Potential timeline



We plan to form a team to address these challenges and develop a concept for AMF as part the Fermilab complex and program

This includes the development on experimental concepts as the design of the accelerator system matures

New ideas for exploiting the physics potential of this facility are welcome – don't be shy!

https://arxiv.org/abs/2309.05933
https://arxiv.org/abs/2210.04765

The future of muon CLFV searches is bright

The Advanced Muon Facility rocks!

Get in touch if you are interested or have new ideas for this facility!

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

S. Davidson, BE, 2204.00564

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.

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

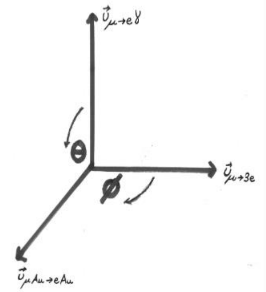
$$\mathrm{BR}(\mu \to e\bar{e}e) = \frac{v^4}{\Lambda_{LFV}^4} \left[\frac{|\vec{e}_S|^2 \sin^2\theta_D \cos^2\theta_S}{8} + (|\vec{e}\,'_{VR}| \sin\theta_D \sin\theta_S \cos\theta_V + 4e|\vec{e}_D| \cos\theta_D)^2 \right.$$
$$\left. + 2(|\vec{e}\,'_{VL}| \sin\theta_D \sin\theta_S \cos\theta_V + 4e|\vec{e}_D|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

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

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

Spherical coordinate parameterization

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



- 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