Searches for Charged Lepton Flavor Violation

A (mostly) Experimental Review

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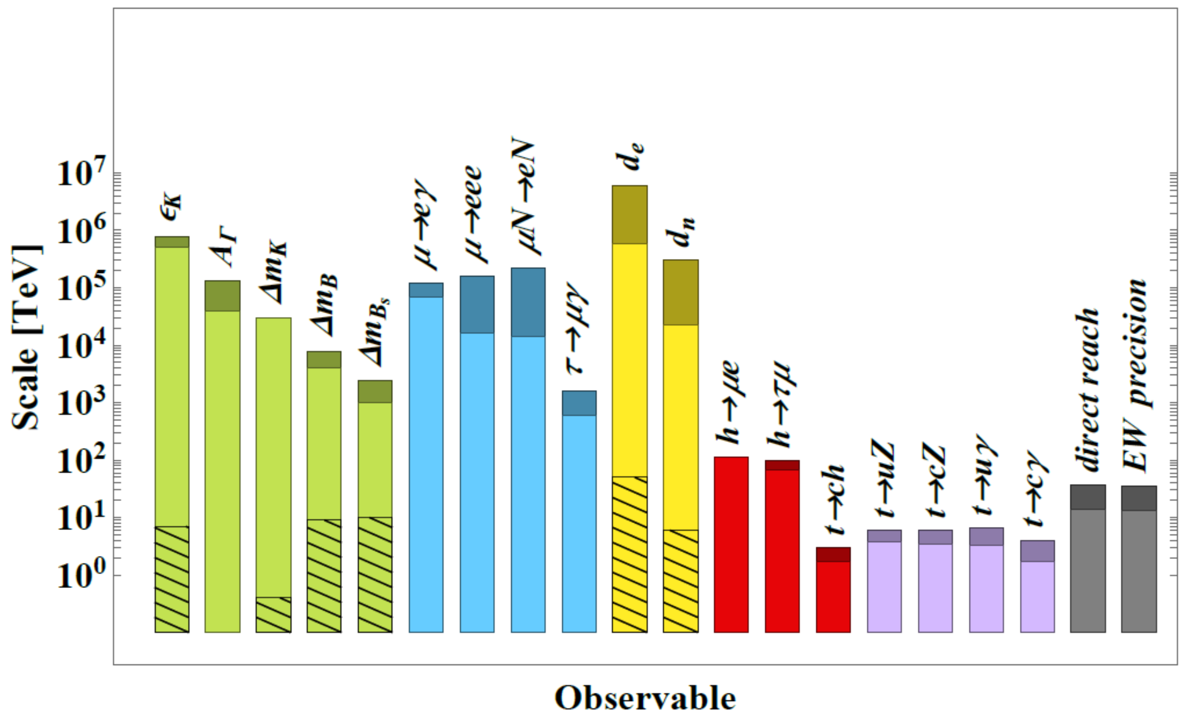
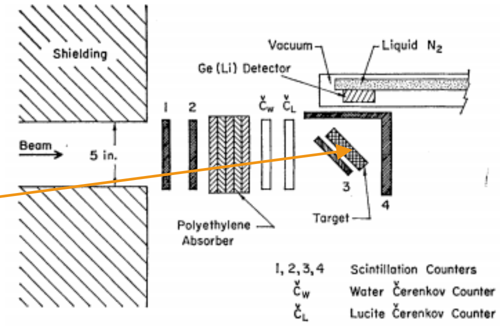
Caltech
BaBar Symposium
March 8, 2024



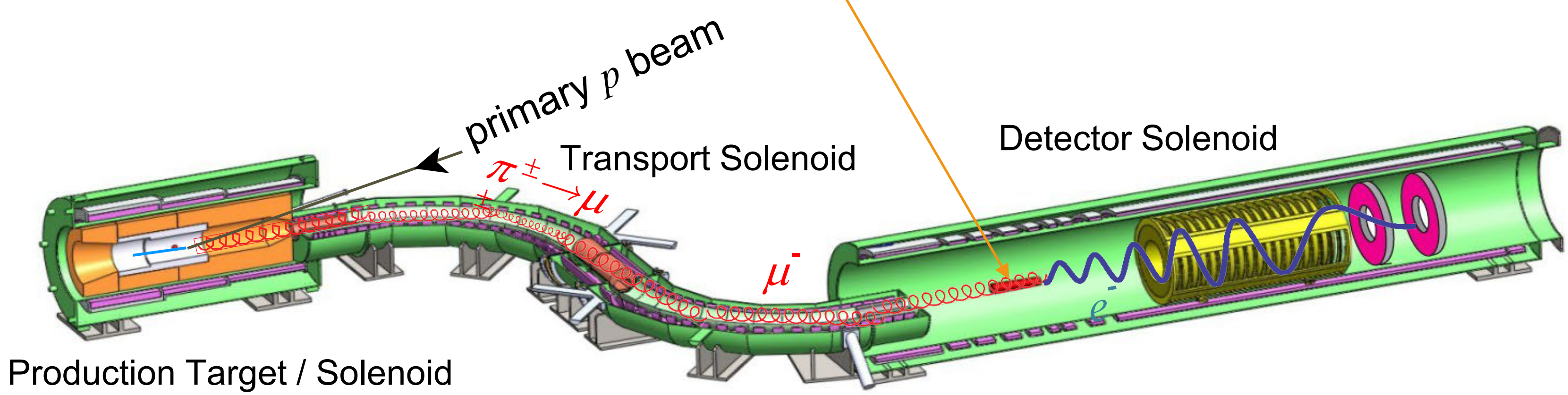
arXiv:1910.11775CERN-ESU-004

Plus ça change, plus c'est la même chose

- The first talk I gave at SLAC was in February, 1969, as part of my postdoc job interview
- The subject was my thesis topic, the measurement of the sizes and shapes of nuclei with a permanent quadrupole deformation, using detailed analysis of the hyperfine structure in muonic X-ray spectra. This involved stopping low momentum negative muons (~10^3/s) from the decay of pions produced at the 385 MeV Columbia Nevis synchrocyclotron in a variety of ~100g targets, ranging from ^{152}Sm to ^{238}U

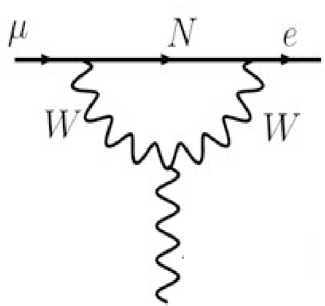


- This talk concerns searches for charged lepton flavor violation (henceforth CLFV)
  My involvement is with Mu2e at Fermilab, where we will stop large numbers (10^{10}/s) of low momentum negative muons from the decay of pions produced at the 8 GeV Fermilab booster, stopped in an ^{27}Al target (~168g) , searching for CLFV



Charged Lepton Flavor Violation (CLFV)

- CLFV denotes a transition involving μ, e or τ lepton states that doesn't conserve lepton family number, *i.e.*, there are no neutrinos involved
    - A CLF-conserving transition: $\mu^- \rightarrow e^- \nu_e \overline{\nu}_\mu$
    - A CLFV transition: $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\mu N \rightarrow e N$ ($\mu \rightarrow e$ conversion), $\tau \rightarrow l\gamma$
- Family number is not a symmetry of the Standard Model Lagrangian
    - **Quark family number** is violated in weak decays (*c.f.* the CKM matrix)
    - Neutrino oscillations are proof of the **violation of neutral lepton flavor conservation** (*c.f.* the PMNS matrix) , as well as evidence for BSM physics (*e.g.,* see-saw mechanism)
- A natural question: "Is there also **observable charged lepton flavor violation**?"



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

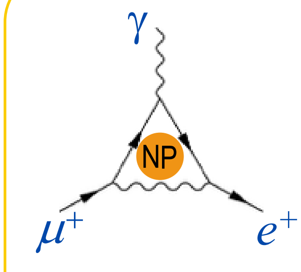
- CLFV searches are thus a clean probe of NP in the charged lepton sector

Searching for CLFV

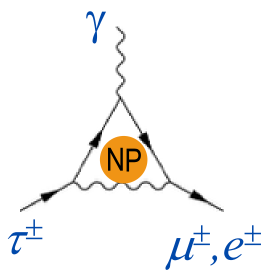
- CLFV has thus far been seen only in my garage
- Many **New Physics models** predict CLFV processes to occur at an observable level
- There are many distinct **experimental probes** and a rich phenomenology, which has led to a robust experimental scene
  - $\mu \rightarrow e\gamma$: most powerful limits: MEG-II at PSI: taking data
  - $\mu N \rightarrow e N$: muon to electron conversion: $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
    three experiments upcoming: Mu2e, COMET (Fermilab, J-PARC)
  - $\mu \rightarrow 3e$: Mu3e at PSI getting underway
  - $\mu^- N \rightarrow e^+ N(Z\text{-}2)$: (Mu2e–II, COMET Phase 2?)
  - $\mu^+ e^- \rightarrow \mu^- e^+$ (muonium→antimuonium)
  - $\tau \rightarrow (e,\mu)\gamma$ and many other τ decays (Belle II)
  - $H^0 \rightarrow \mu, e, \tau + X$ (LHC, Mu2e, COMET)
  - $K_L \rightarrow \mu e$, $B \rightarrow \mu e$, $K \rightarrow \mu e$, ... (LHC*b*, expts at J-PARC, CERN)
- The form of the CLFV Yukawa coupling matrix is model-dependent, *e.g.,* it could be PMNS-like or CKM-like
- Different theories predict **distinct correlations** between CLFV processes
- This round of experiments improves sensitivity by 1 to 4 orders of magnitude

CLFV Processes

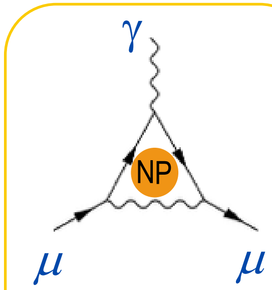
- Low energy probes: rare μ, τ and H^0 decays, $\mu \to e$ conversion, CLFV in meson decay



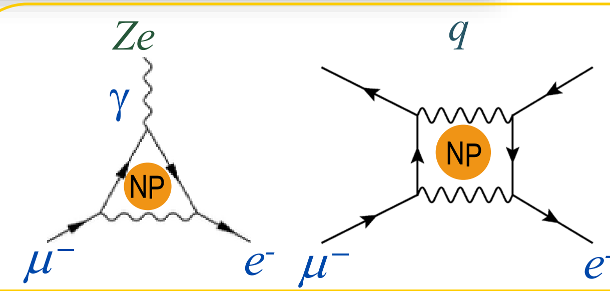
$\mu^+ \to e^+ \gamma$



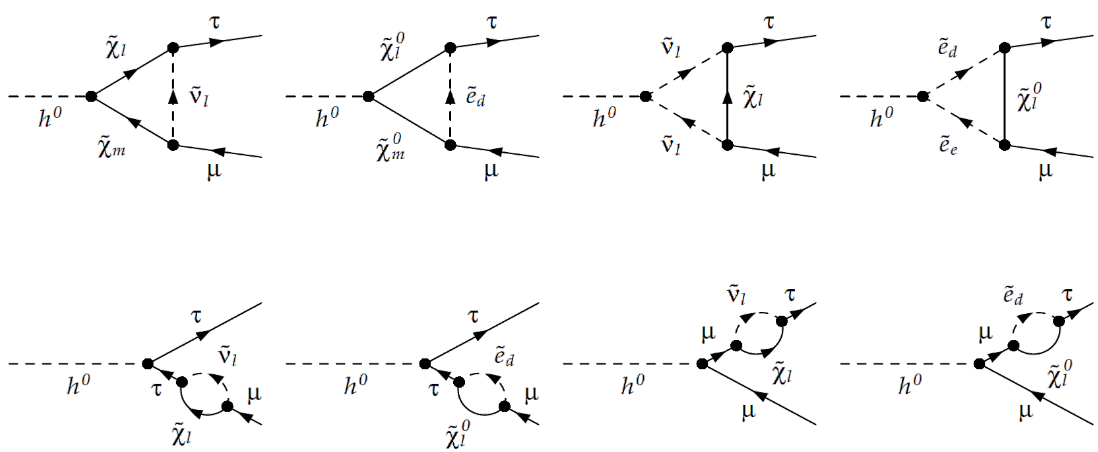
$\tau \to \mu\gamma$, $e\gamma$



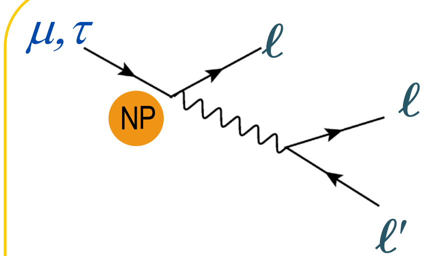
$(g\text{-}2)_\mu$



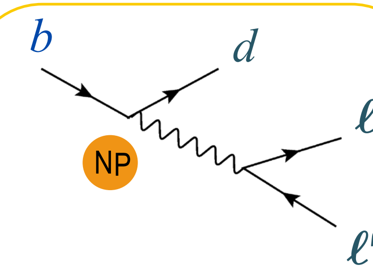
$\mu^- N \to e^- N$



Higgs decay: $H^0 \to \tau\,\mu$ (also $\tau\, e$, $\mu\, e$)



$\mu, \tau \to 3\ell$



$B \to \ell\ell'$

$B \to X_s \ell\ell'$

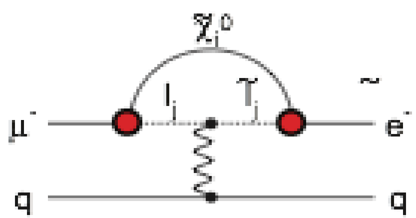
New Physics contributions to $\mu \to e$ conversion

$\mu N \to eN$ is sensitive to a wide variety of New Physics models, *e.g.*,

SUSY, 2HDM, Extra Dimensions, Leptoquarks, GUTs, LHT,…

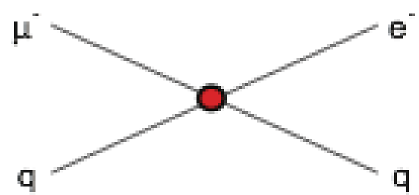
Supersymmetry

rate ~ 10^{-15}



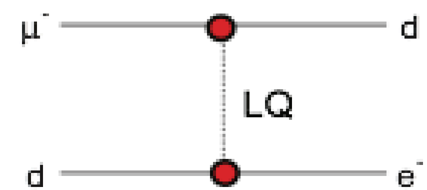
Compositeness

Λ_c ~ 3000 TeV



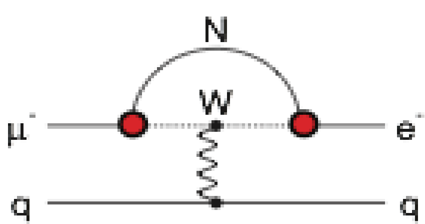
Leptoquark

M_{LQ} =
3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c²



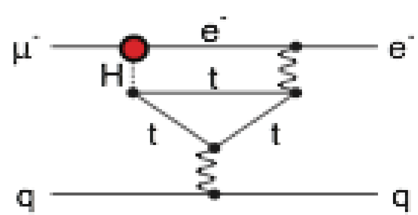
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8x10^{-13}



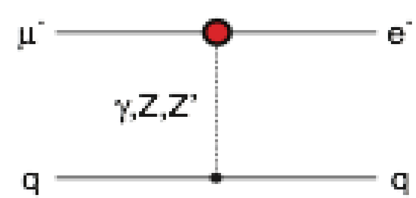
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4} g(H_{\mu\mu})$



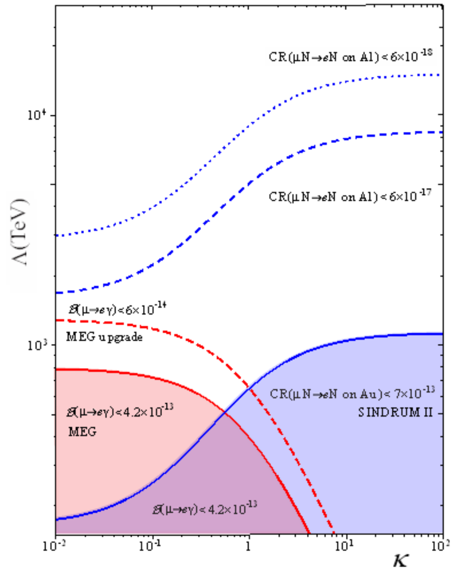
Heavy *Z′* Anomalous *Z* Coupling

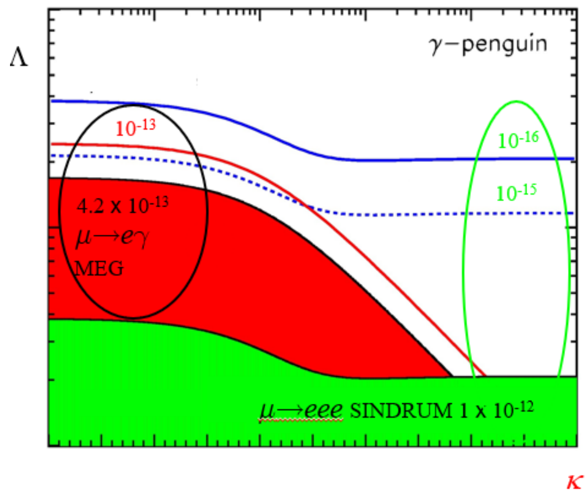
$M_{Z'}$ = 3000 TeV/c²

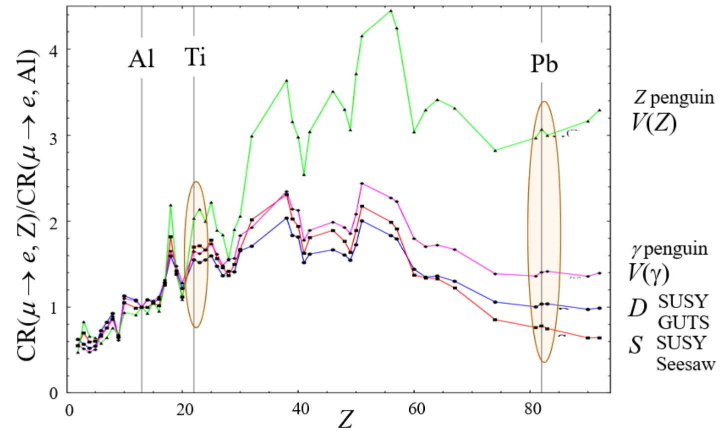


Theoretical guidance

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L) \quad + h.c.$$







- While the theory framework for interpreting CLFV results has been in place for decades, there have been several recent improvements:
  - Full Dirac equation formalism for muon wavefunctions
  - Use of EFT techniques
  - Connection of EFT formalism to specific models (seesaw, leptoquark, ALP, …)
  - Improved treatment of nuclear models, Z,A dependence

S. Davidson and B. Echenard, *Eur.Phys.J.* C 82 (2022)
M. Ardu, S. Davidson, S. Lavignac, e-Print: 2401.06214 [hep-ph]
W. Haxton, E. Rule, K. McElvain, M. Ramsey-Musolf, *Phys.Rev.*C107 (2023) 3, 03554
L. Borrel, DH, S. Middleton, e-print: 2401.15025 [hep-ph])

EFT framework

Effective field theory (EFT) is now being used to analyze reach and complementarity of $\mu \to e\gamma$, $\mu \to eee$ and $\mu N \to e N$ transitions in a systematic approach

At a given 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)

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

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

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

There are many operators, but only a few measurements. With a judicious choice of basis vectors in the coefficient space one can define a four-dimensional subspace that is a good approximation to the CLFV rates we can measure.

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

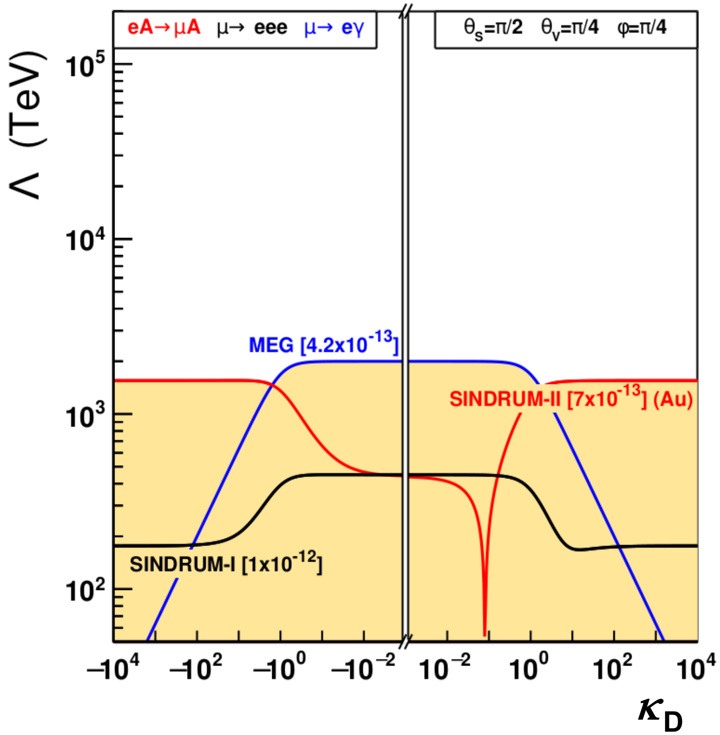
*See Haxton *et al* (2109.13503) for a discussion of the effect of nuclear structure on $\mu \to e$ conversion

Reach, complementarity – EFT framework

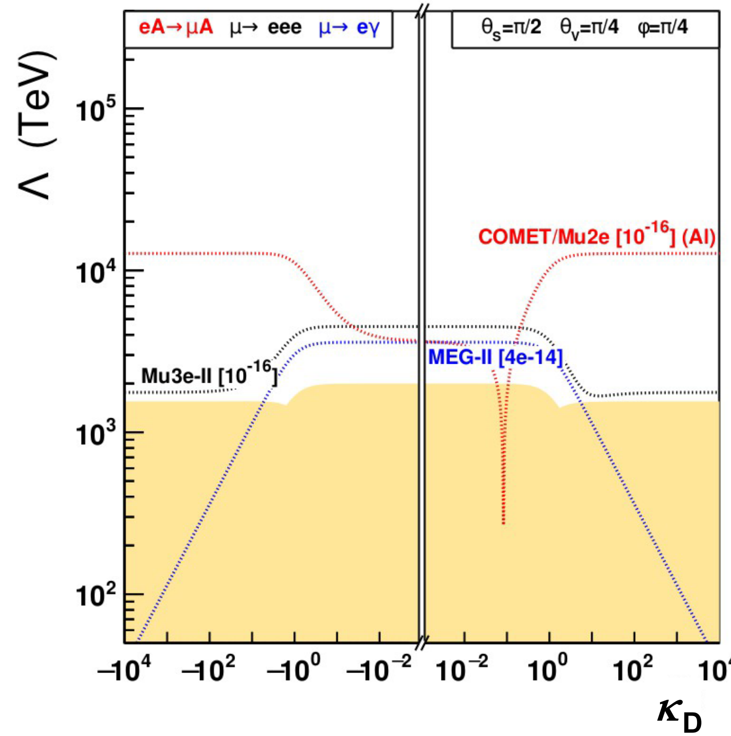
Reach and complementarity as a function of κ_D (remaining parameters representative)

S. Davidson and B. Echenard, *Eur.Phys.J.* C 82 (2022)

Current



Next round



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

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

$|\kappa_D| << 1 \Rightarrow$ dipole dominant

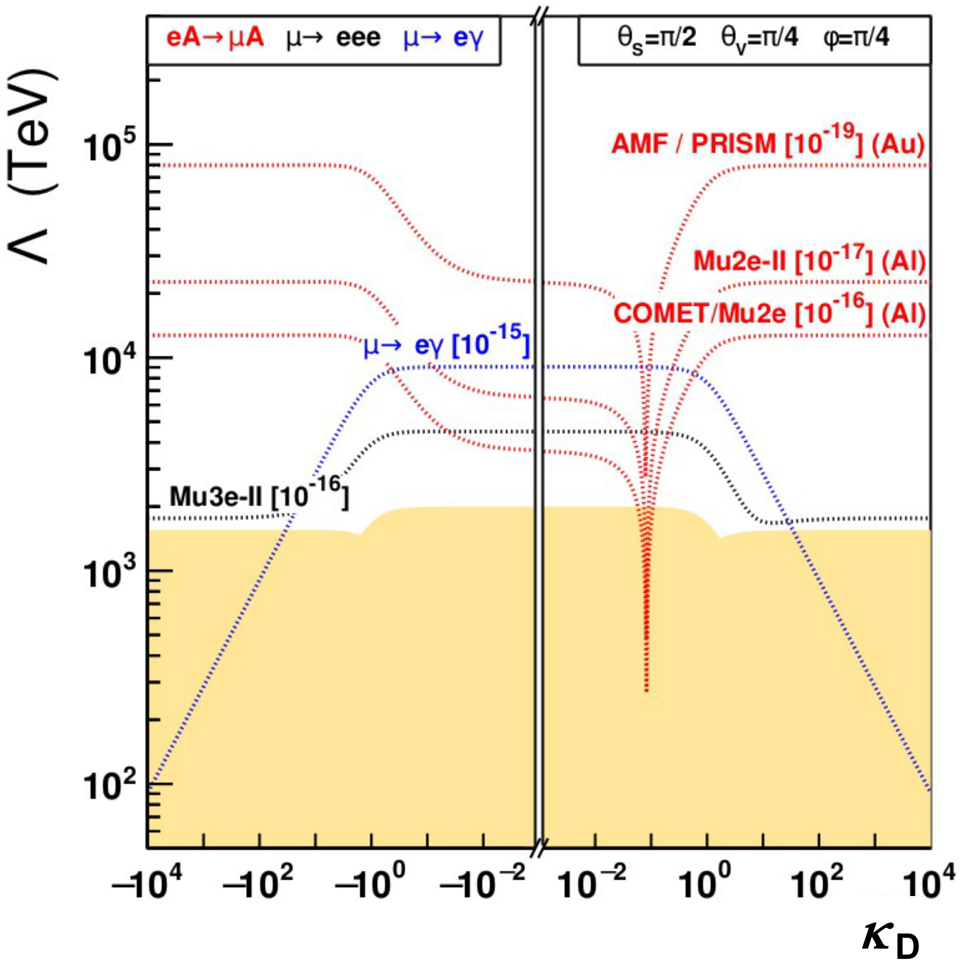
$|\kappa_D| >> 1 \Rightarrow$ four-fermion dominant

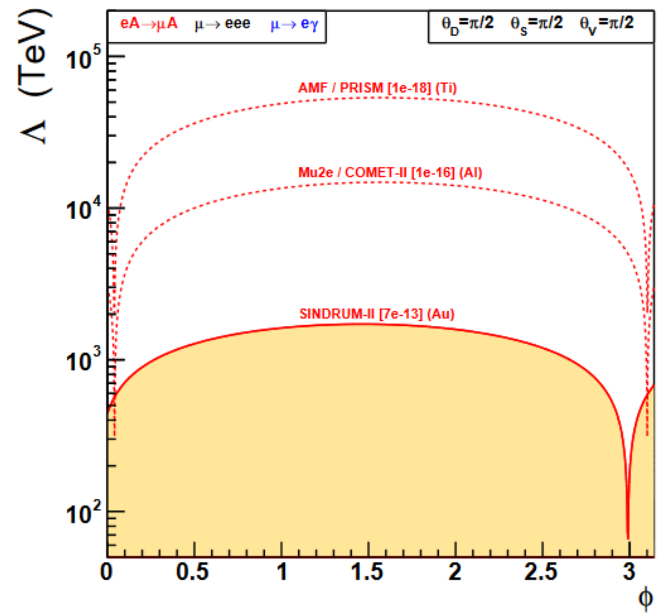
Reach, complementarity – EFT framework

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

S. Davidson and B. Echenard, *Eur.Phys.J.* C 82 (2022)

Future

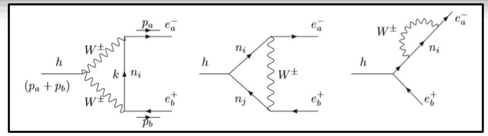


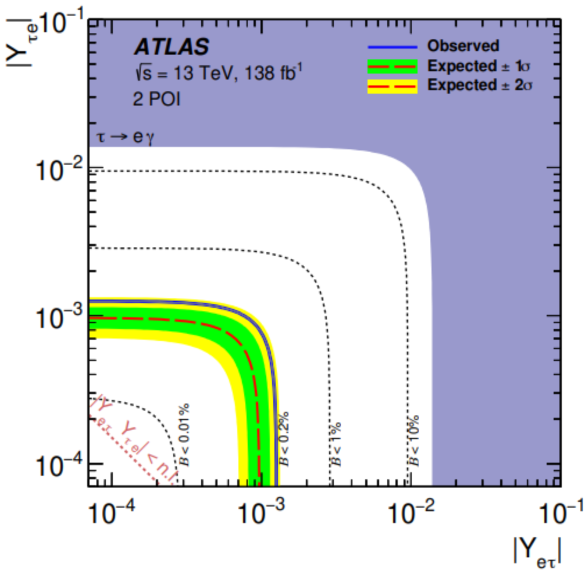


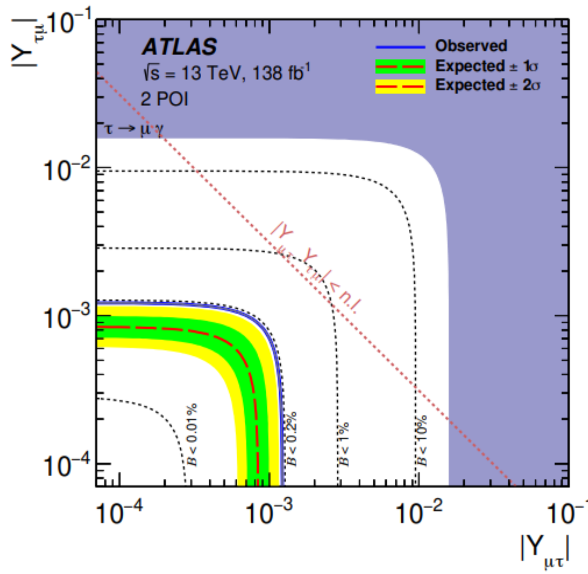
Requirements:

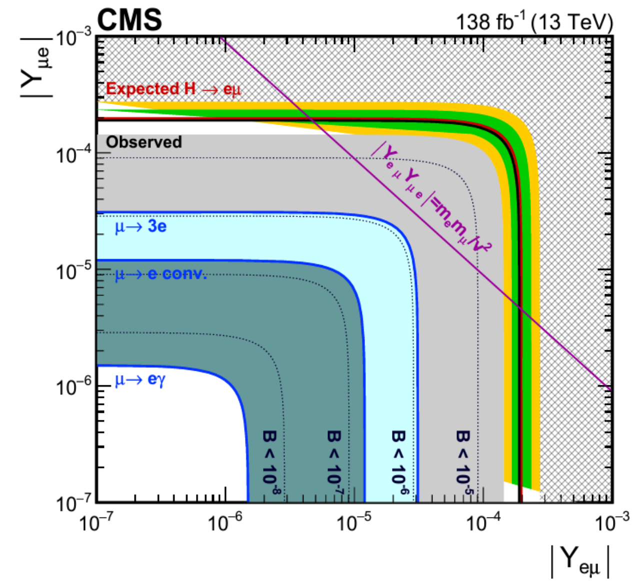
1) measure all three modes and multiple conversion targets
2) Improve sensitivity to the decay modes to keep up with the conversion mode

Higgs CLFV





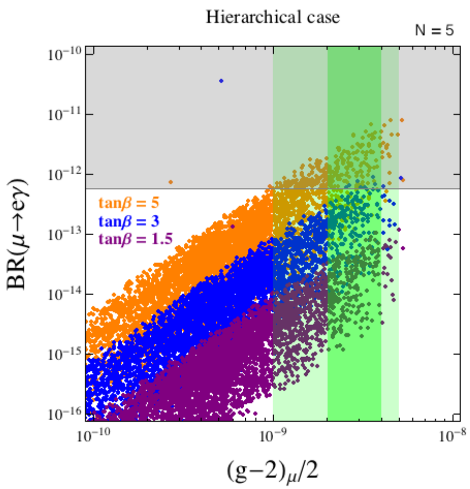




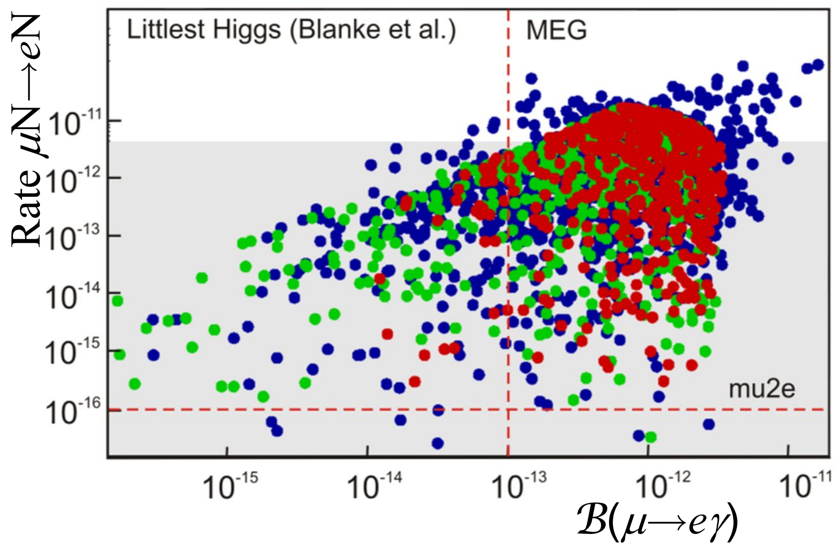
< 2.0x10^{-3} @ 95% CL ATLAS 2023 13 TeV, 138 fb^{-1}	< 1.8x10^{-3} @ 95% CL ATLAS 2023 13 TeV, 138 fb^{-1}	< 4.7x10^{-5} @ 95% CL CMS 20203 13 TeV, 138 fb^{-1}
JHEP 07,166(2023)		PHYS.REV. D108,072004(2023)

- CLFV Higgs couplings to τ (τe, $\tau\mu$) can likely be best measured at the LHC
- μe couplings are best measured in dedicated muon experiments

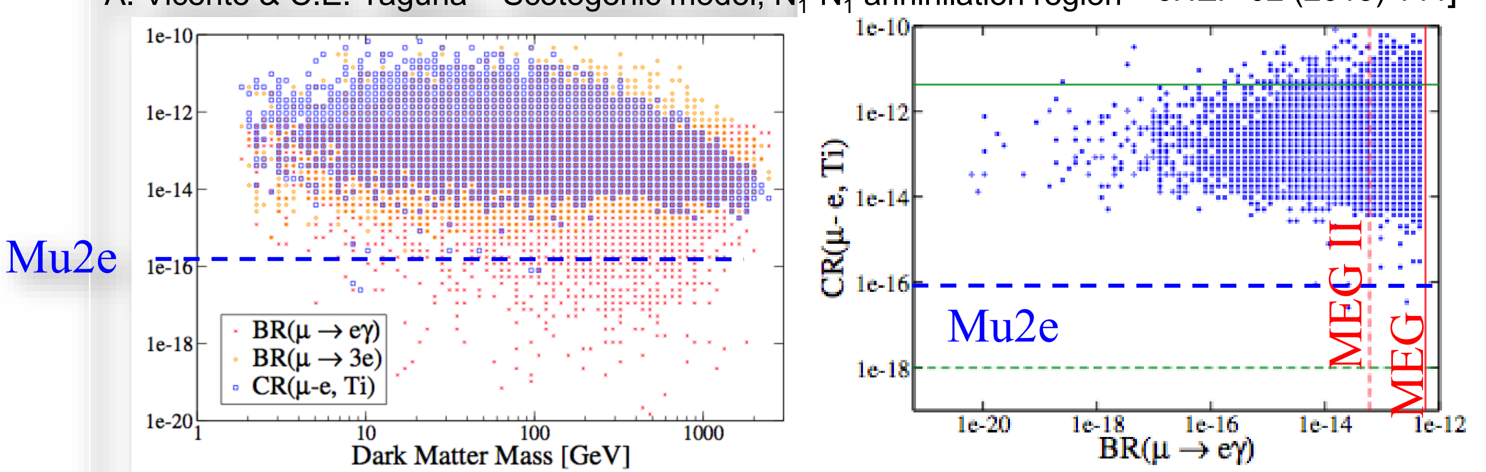
Model discrimination through correlations



M. Blanke, et al. JHEP 05 (2007) 013



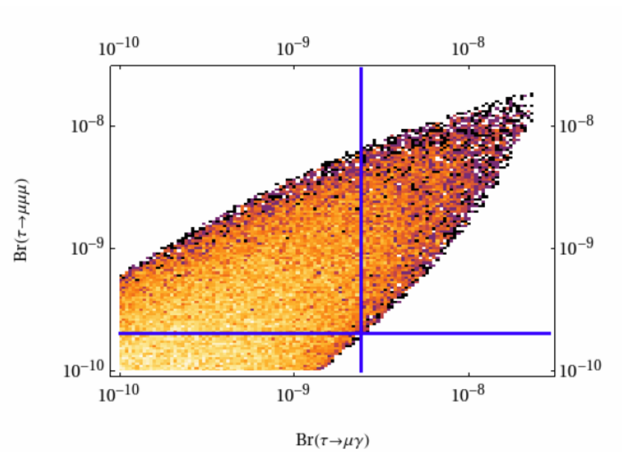
A. Vicente & C.E. Yaguna – Scotogenic model, N_1-N_1 annihilation region *JHEP* 02 (2015) 144]



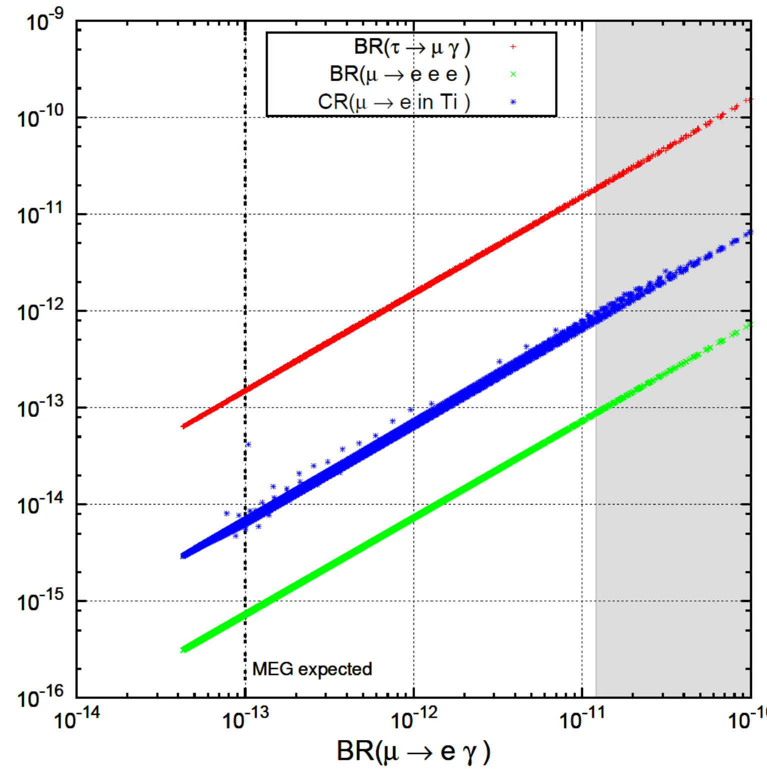
Model discrimination through correlations

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

$\tau\to\mu\gamma$ and $\ell\ell\ell$



Blanke, Buras, Duling, Recksiegel & Tarantino,
Acta Phys. Polon. B41, 657 (2010)



$\mathcal{B}(\tau\to\mu\gamma)$ *vs.* $\mathcal{B}(\mu\to eee)$ and CR($\mu\to$ e on Ti)
in an SO(10) Type II SUSY model
Calibbi, et al., JHEP 0912 057 (2009)

CLFV Physics Reach

★★★ = Discovery Sensitivity

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

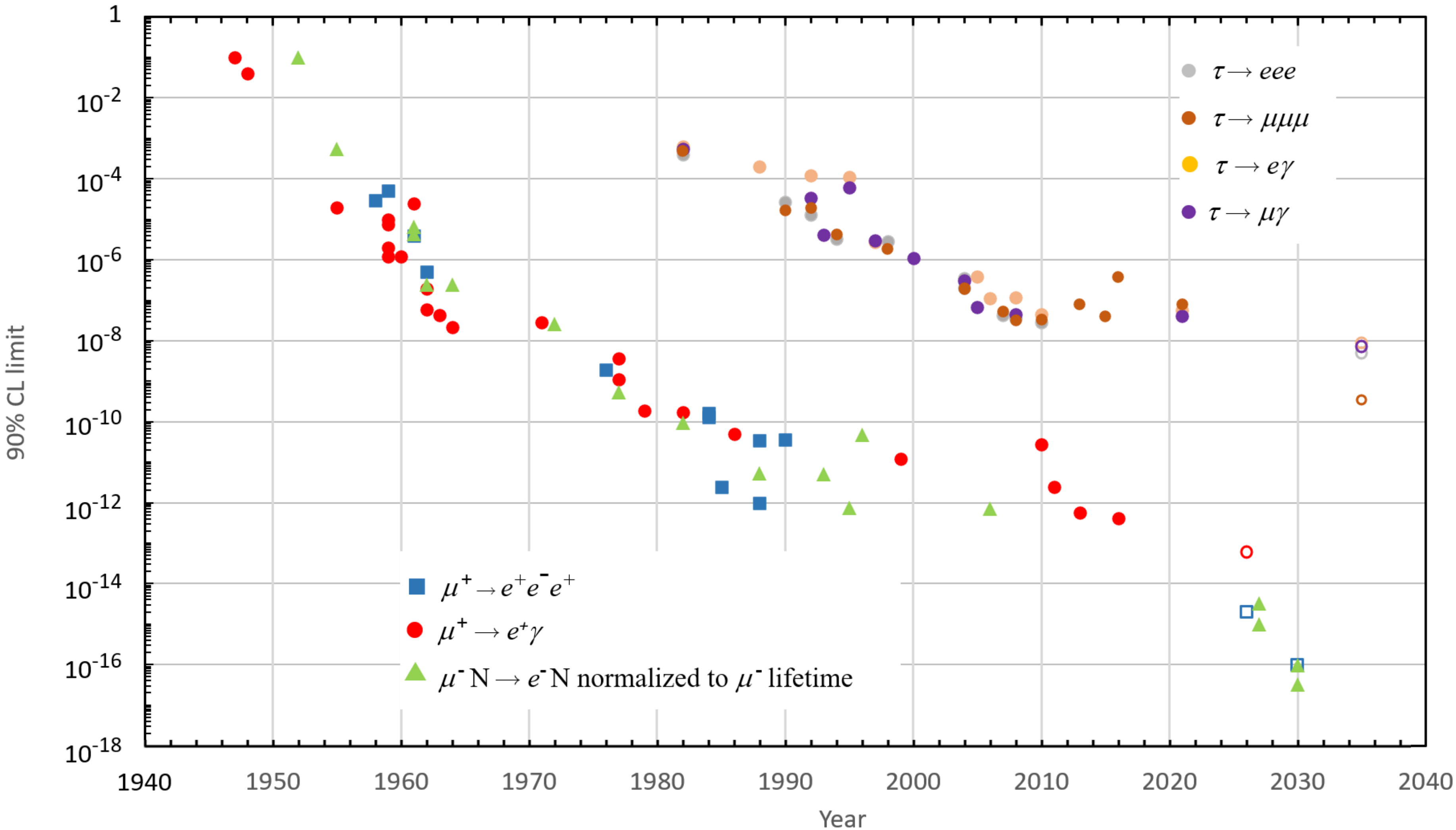
W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub
Nucl.Phys.B 830, 17 (2010)

Glossary

AC	U(1) flavor symmetry
RVV2	Non-abelian
AKM	SU(3)
δLL	Left-handed CKM-like
FBMSSM	Flavor-blind MSSM
LHT	Littlest Higgs w T-Parity
RS	Randall-Sundrum

Excellent sensitivity to many BSM models

Chronology of μ and τ CLFV searches



n.b. $\mu \to e$ conversion limits presented as conversion rates, not a quasi-“branching fractions” (L. Borrel, DH, S. Middleton arXiv 2401.15025 [hep-ph])

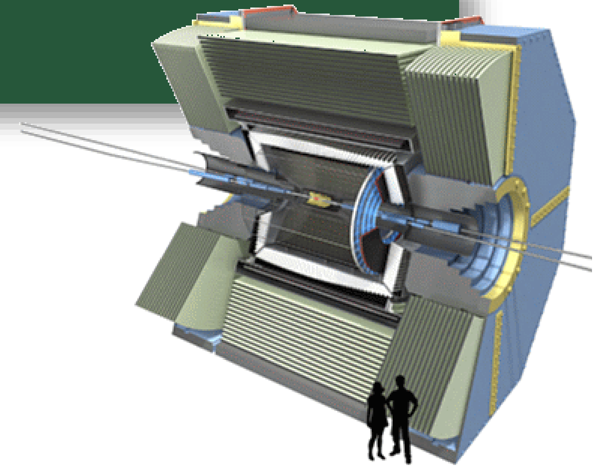
Backgrounds: the name of the game

- At the sensitivities required to advance the state of the art in both τ decays and muon experiments, the primary issue is control of backgrounds in a high rate environment
  - Irreducible backgrounds
  - Accidental backgrounds
- Problematic backgrounds are specific to the type of experiment
- Handles on background control are
  - Charged particle energy resolution
  - Neutral energy resolution
  - Time resolution
  - Particle identification
  - Prompt beam particle rejection
  - Cosmic ray rejection

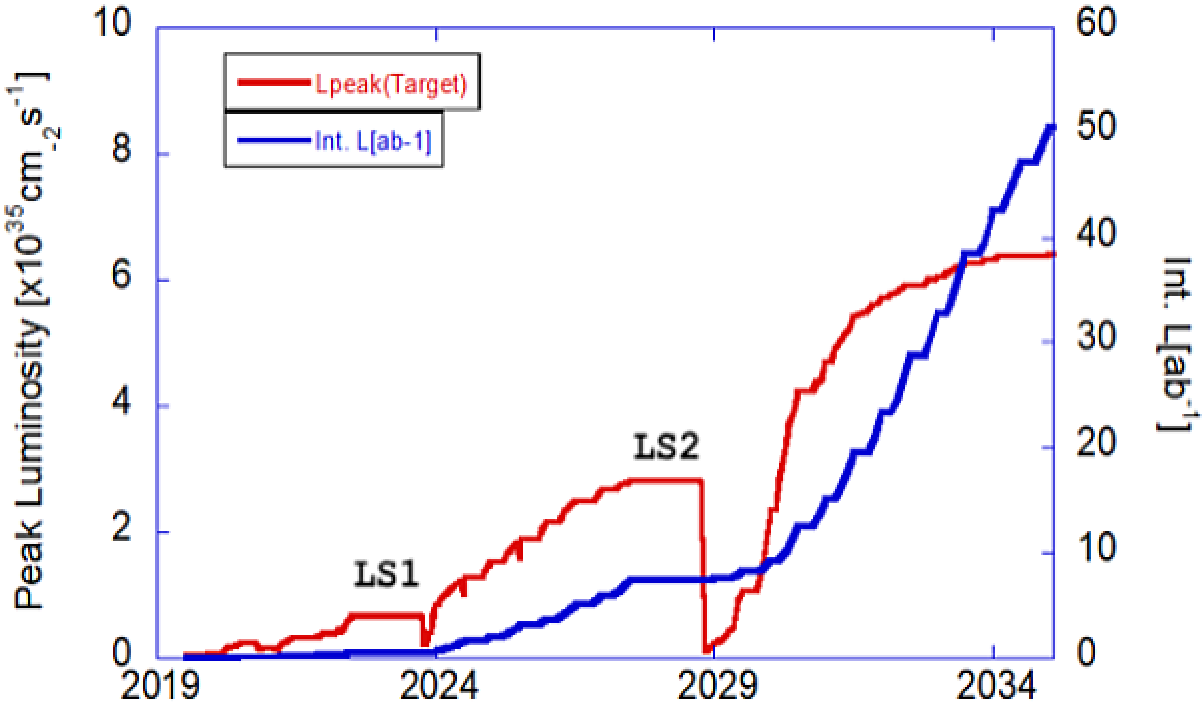
New muon experiments

- MEG II
- Mu3e
- Mu2e, COMET

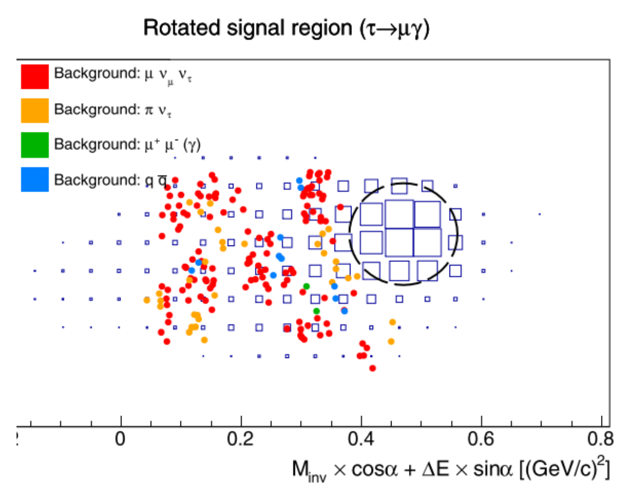
Belle II τ CLFV limits



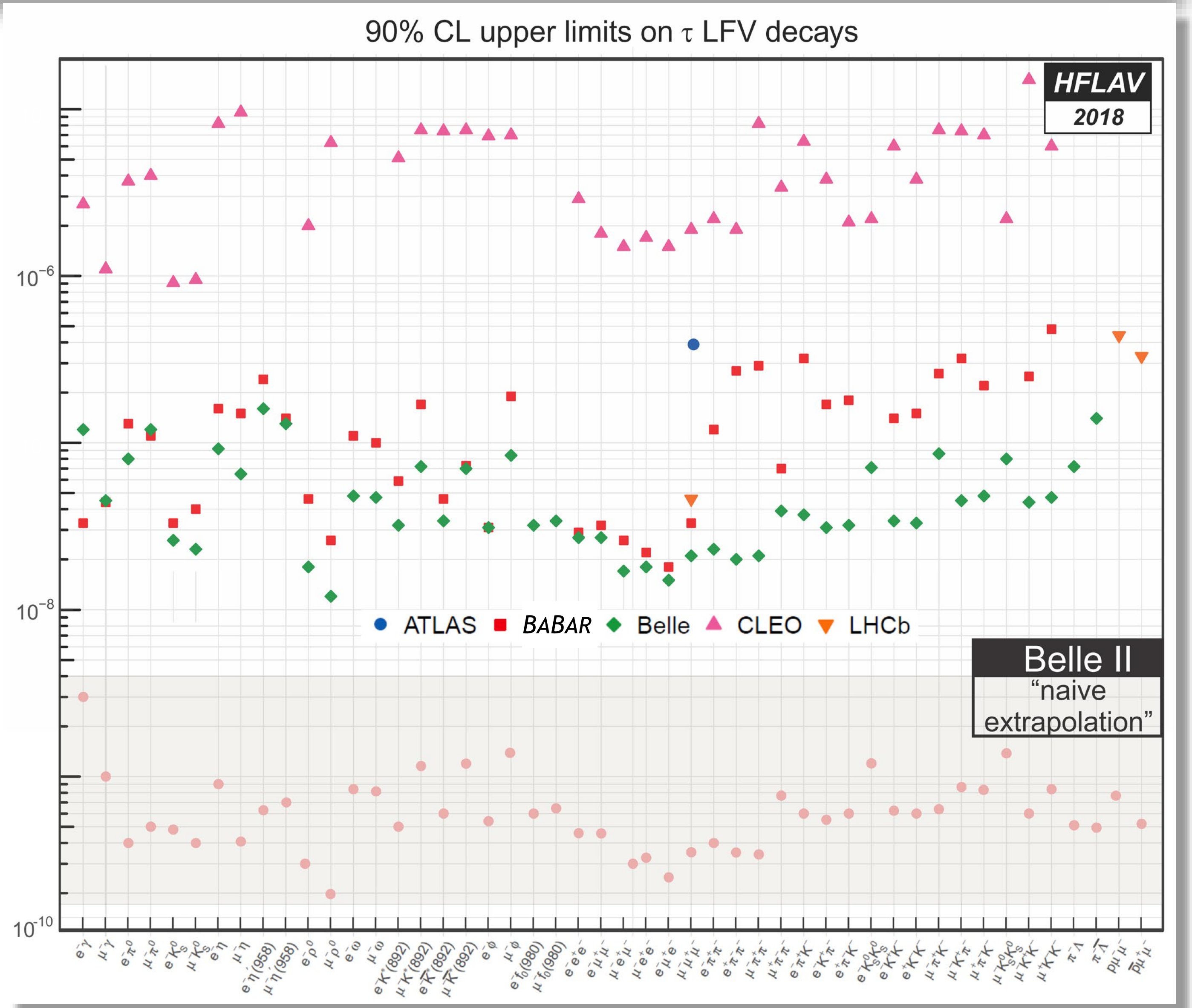
- The target integrated luminosity of 50 ab^{-1} (~5×10^{10} $\tau\tau$) will be reached in ~2035
- The improvement in sensitivity to CLFV τ decays depends on whether or not a particular mode has backgrounds
  - *e.g.*, limits on $\mathcal{B}(\tau \to \ell\ell\ell)$ improve as $1/\int \mathcal{L} dt$ if there is no background, but more slowly, as ~ $1/\int \mathcal{L} dt^{1/2}$, if there is background



ab^{-1} Belle II detector

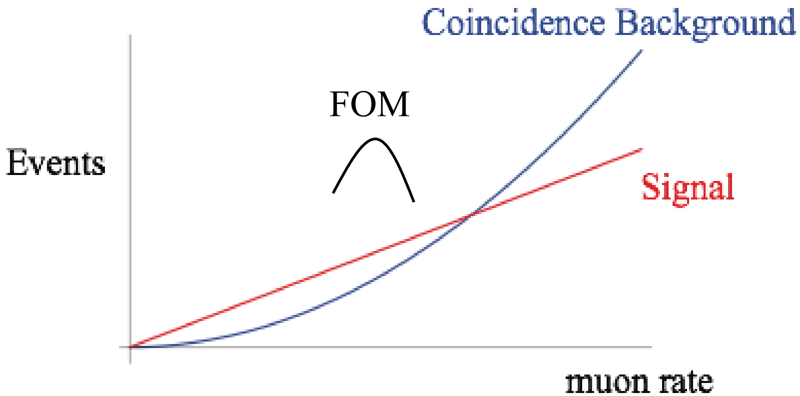


Limits on CLFV τ decays

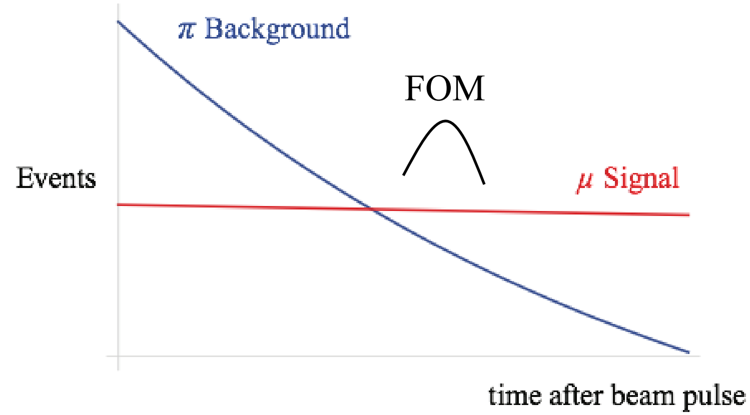


Muon experiments: CW *vs* pulsed beams

- **Muon decay** experiments $\mu\rightarrow e\gamma$, $\mu\rightarrow eee$ use a continuous μ^+ beam, such as the PSI synchrocyclotron surface muon beam
- The dominant backgrounds come from accidental coincidences of two decays
  - background $\propto$ (rate)^2
  - signal $\propto$ rate



- $\mu\rightarrow e$ **conversion** experiments use a pulsed μ^- beam, such as FNAL or J-PARC
  - There are many prompt pion-induced backgrounds immediately after the proton pulse
  - Use the muon/pion lifetime difference to reduce background



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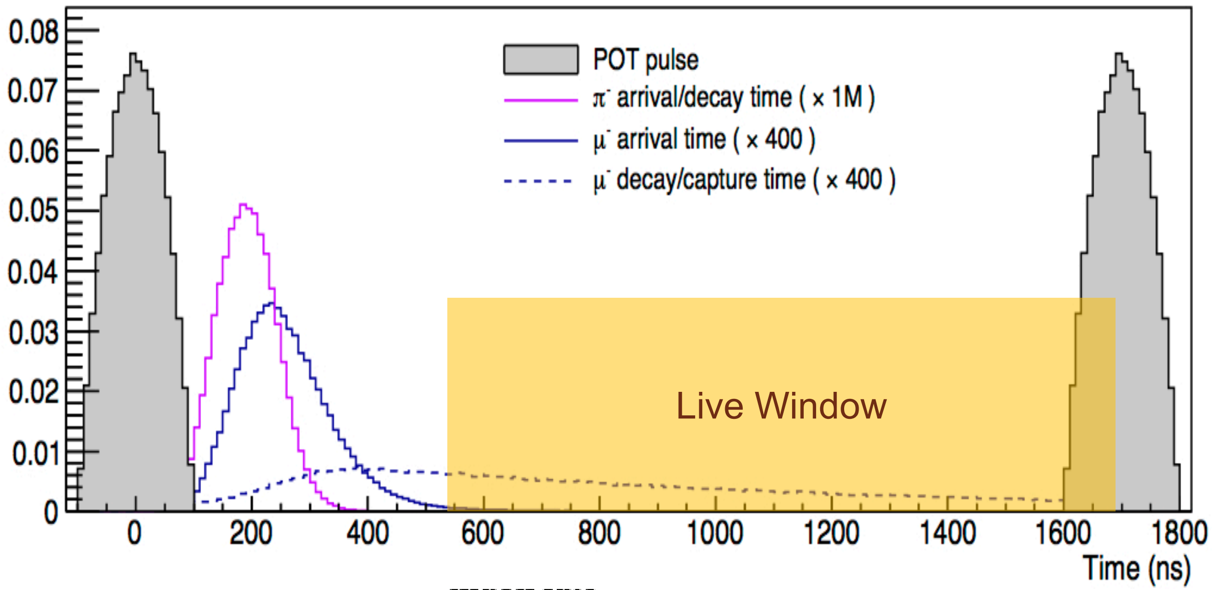
ıce



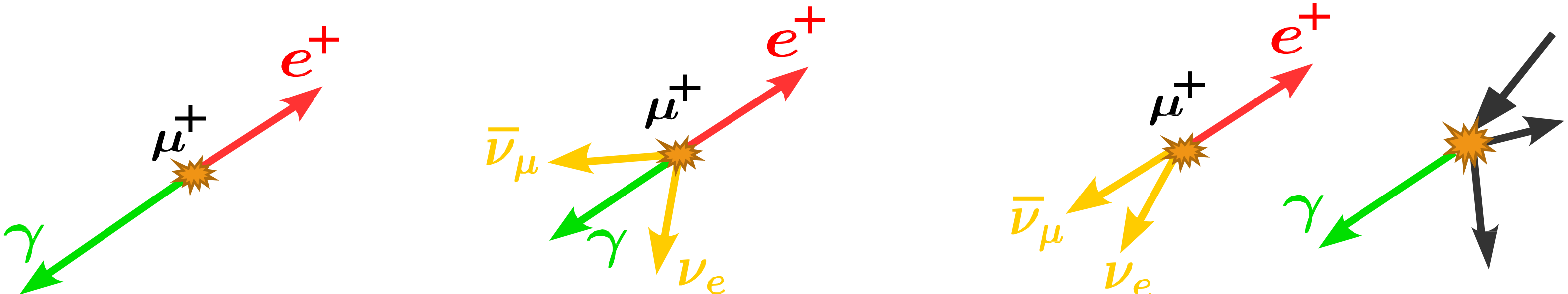
μ Signal

ume after beam pulse

DC optimizes the S/N

Pulsed operation optimizes the S/N

$\mu \rightarrow e\gamma$ signal and backgrounds



$\mu^+ \rightarrow e^+\gamma$

$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e\gamma$

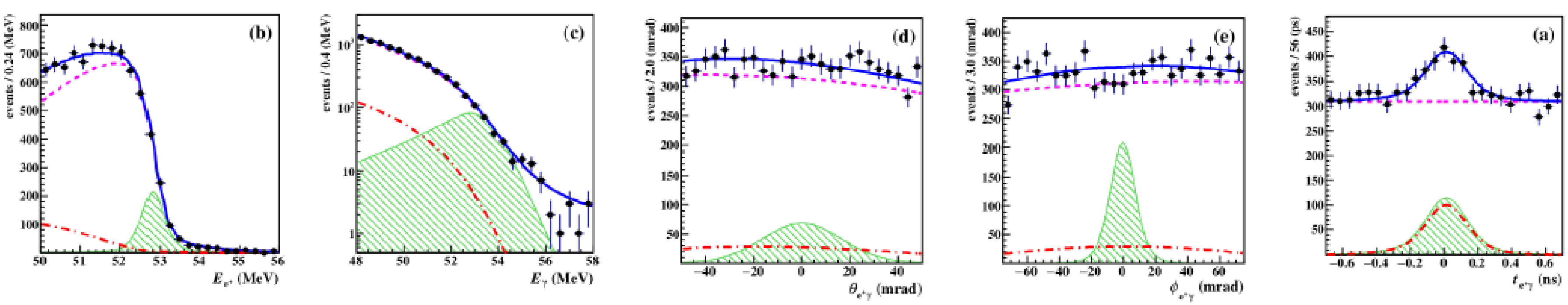
$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e$

$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e\gamma$
$e^+e^- \rightarrow \gamma\gamma$
$e^+N \rightarrow e^+N\gamma$

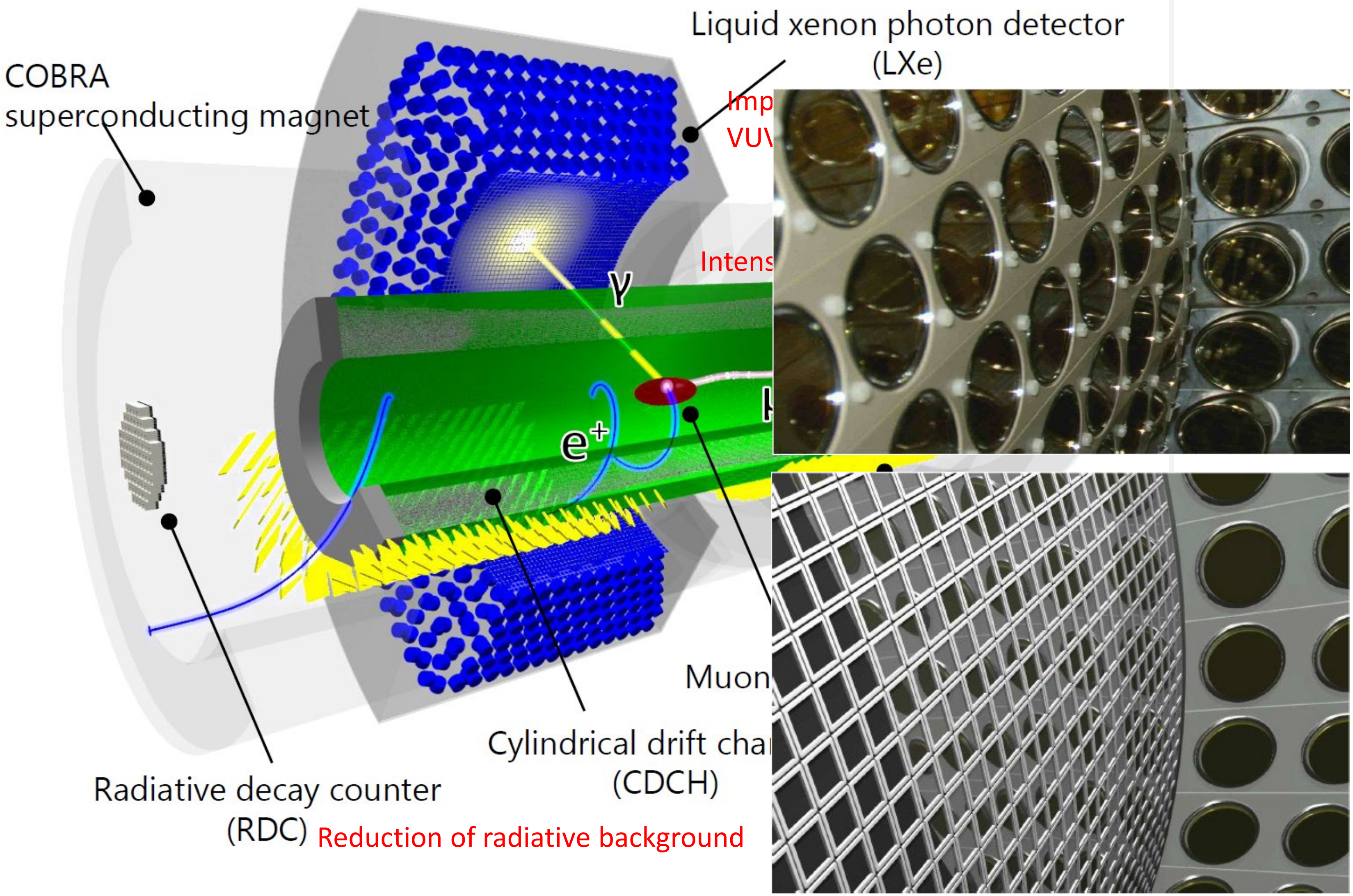
CLFV signal | Radiative muon decay $\propto R_\mu$ | Accidental background $\propto R_\mu^2$

Events are described by five variables: $E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}$

MEG at PSI



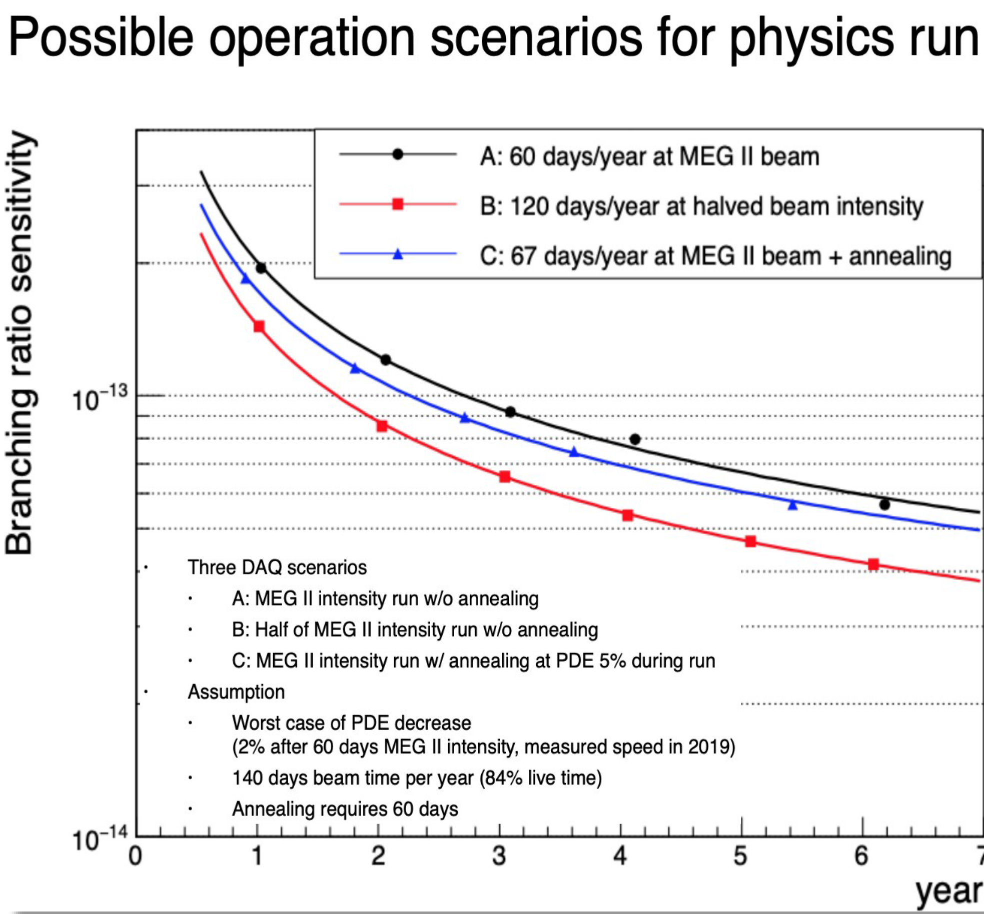
MEG II – 2x resolution improvement



MEG II status

- The MEG II Upgrade improves the detector (2x improvements in resolution and efficiency) to aim for a 90% CL limit of $\mathcal{O}$ 6 x 10^{-14} in a three year run

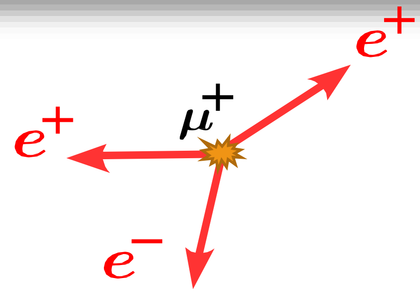
- Schedule
  - Commissioning runs in 2017-2020
  - Engineering run in Aug 2021
    - Install full DAQ, electronics
    - Full LXe electronics
    - Degradation of MPPC PDE ($\Rightarrow$limit on μ stops/run),
    - Drift chamber conditioning to reduce corona discharge
      - New chamber to be built by March 2023



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

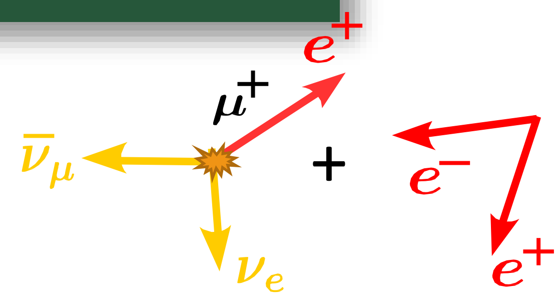
Signal

$E = m_\mu$
$\Sigma p_i = 0$
Vertex

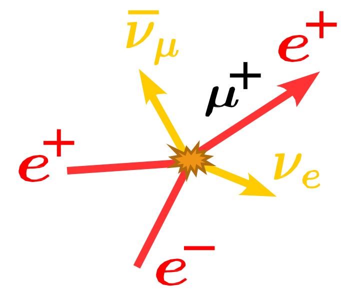


Background

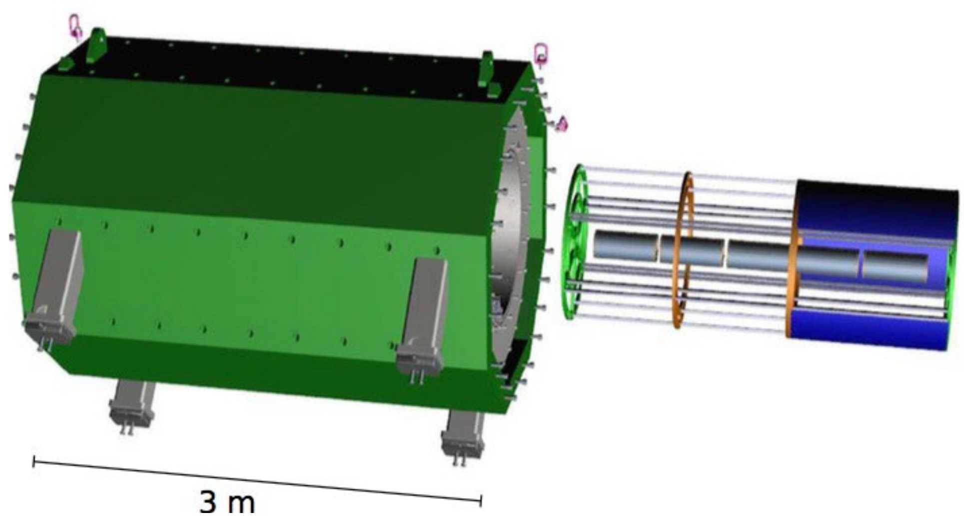
Accidentals



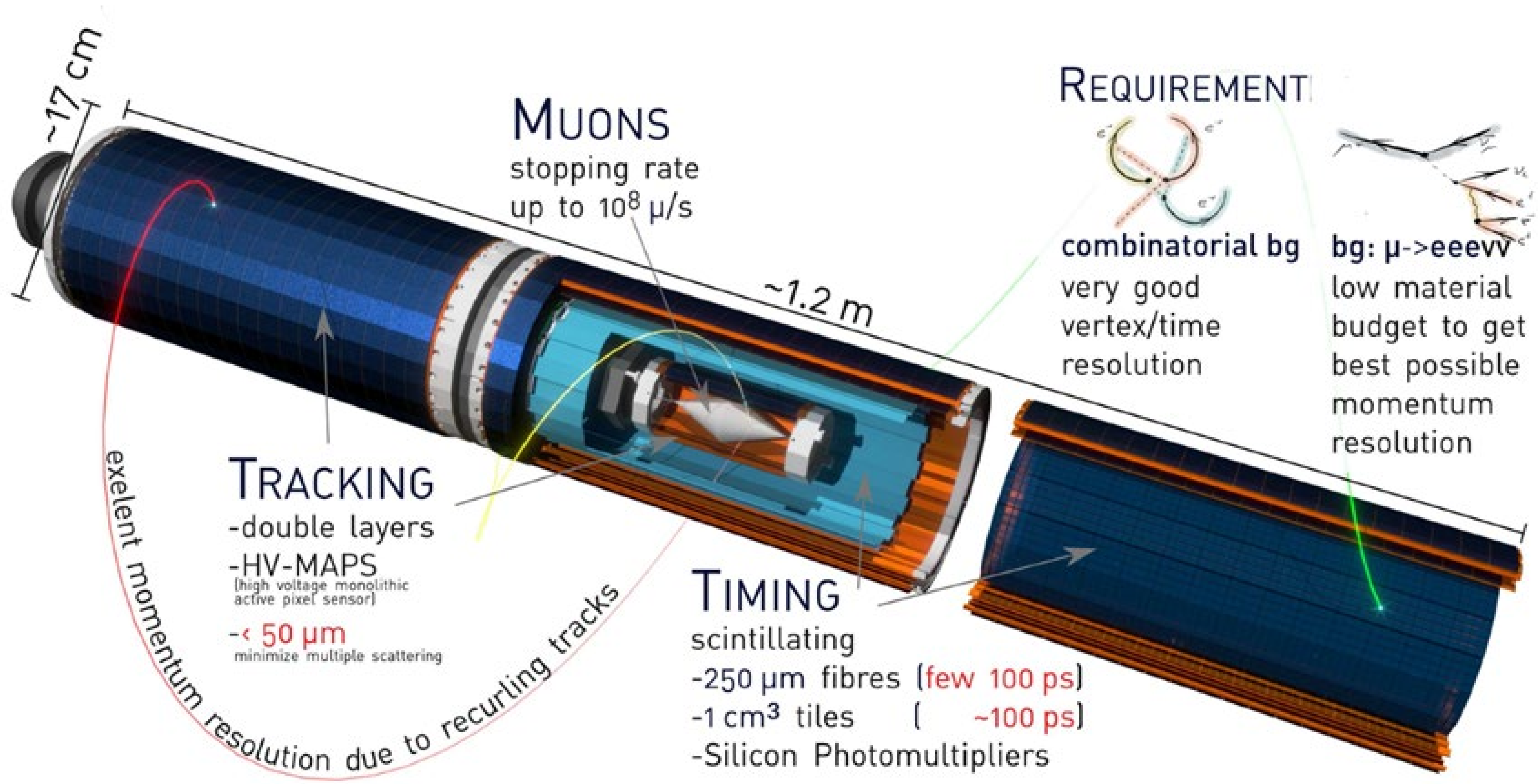
Radiative decay
w internal conversion



- **Current limit:** 1.0×10^{-12} (SINDRUM at PSI, 1988)
- Mu3e at will provide substantial improvement
  - Uses a surface muon beam - πE5 beamline
  - Phase I
    - ~~2018~~ - 10^8 μ^+/s
    - Sensitivity 10^{-15}
  - Phase II HIMB 10^9 μ^+/s
    - Sensitivity 10^{-16}

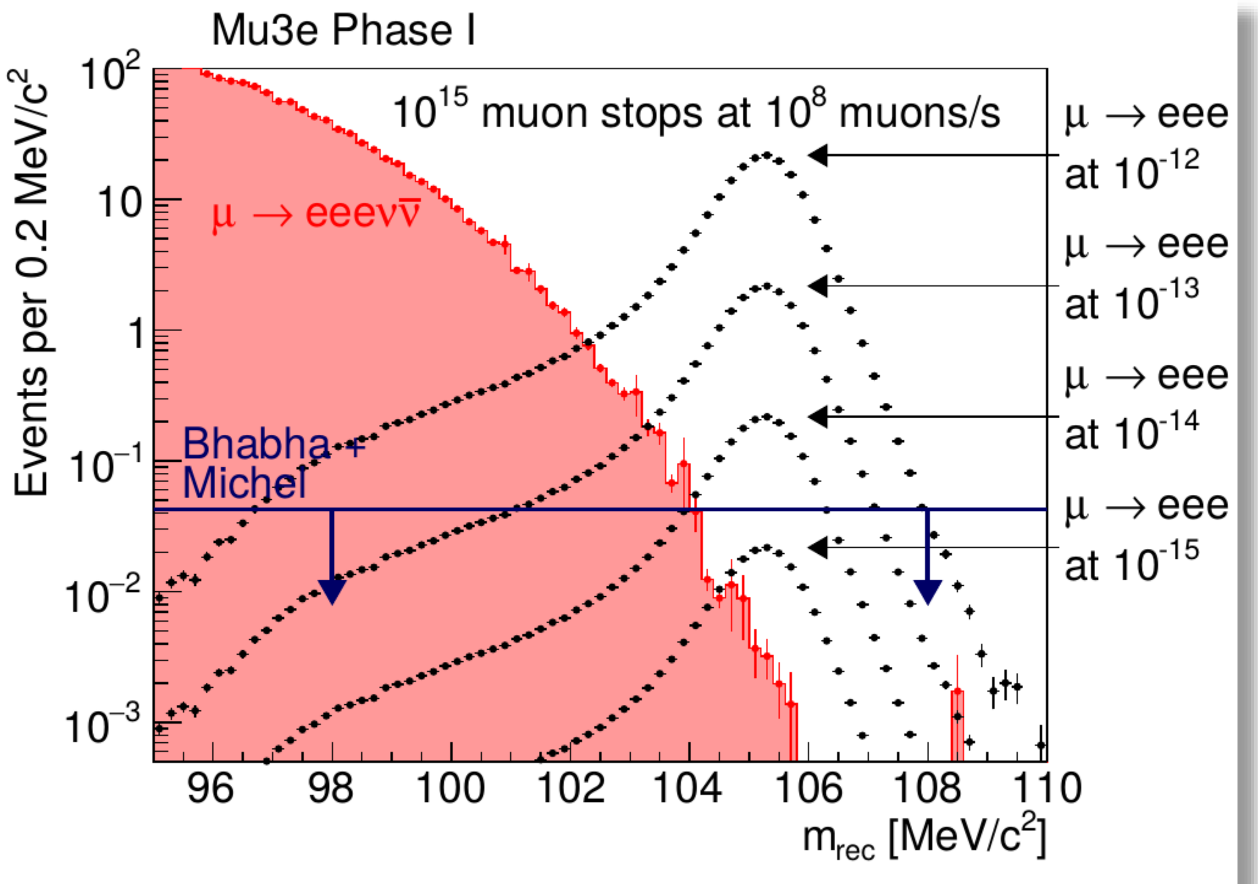


Mu3e detail

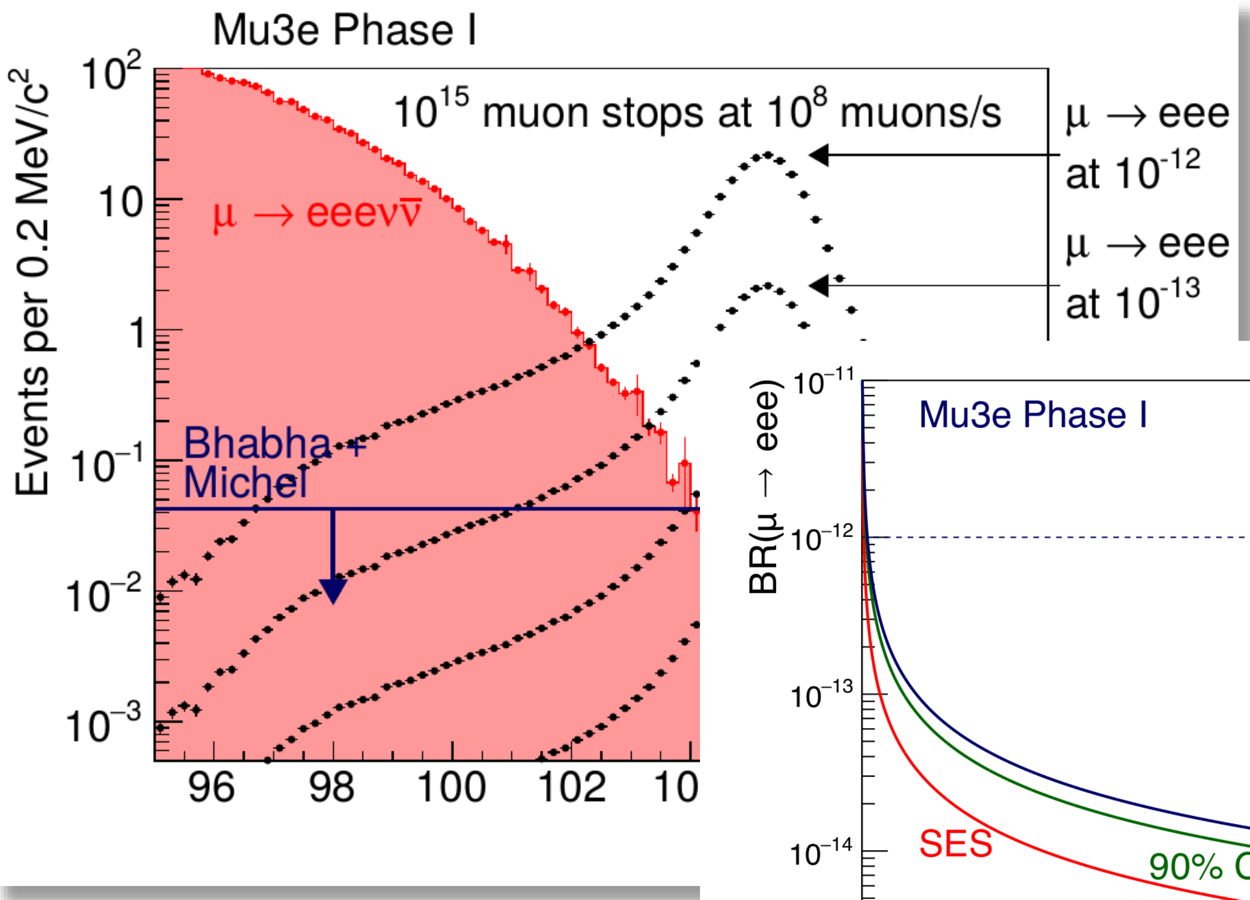


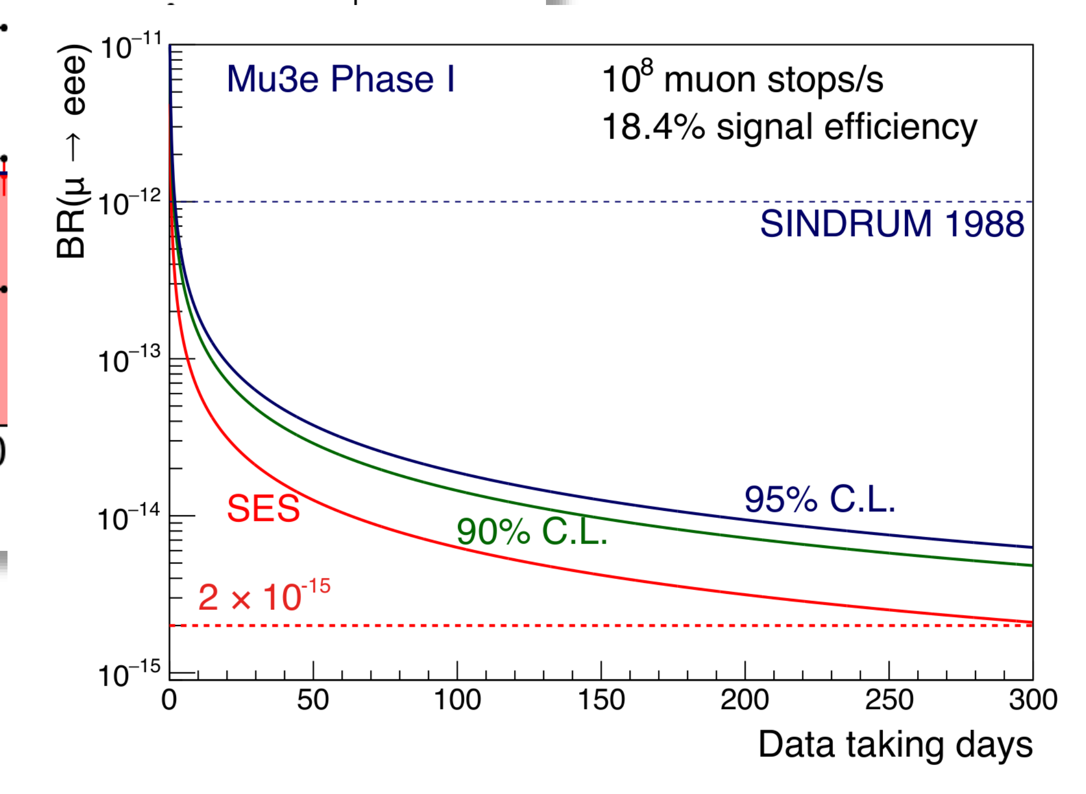
~17 cm
~1.2 m
MUONS
stopping rate
up to 10^8 μ/s
REQUIREMENT
combinatorial bg
very good
vertex/time
resolution
bg: μ->eeevv
low material
budget to get
best possible
momentum
resolution
TRACKING
-double layers
-HV-MAPS
(high voltage monolithic active pixel sensor)
-< 50 μm
minimize multiple scattering
TIMING
scintillating
-250 μm fibres (few 100 ps)
-1 cm³ tiles (~100 ps)
-Silicon Photomultipliers
exelent momentum resolution due to recurling tracks

Mu3e sensitivity



Mu3e sensitivity

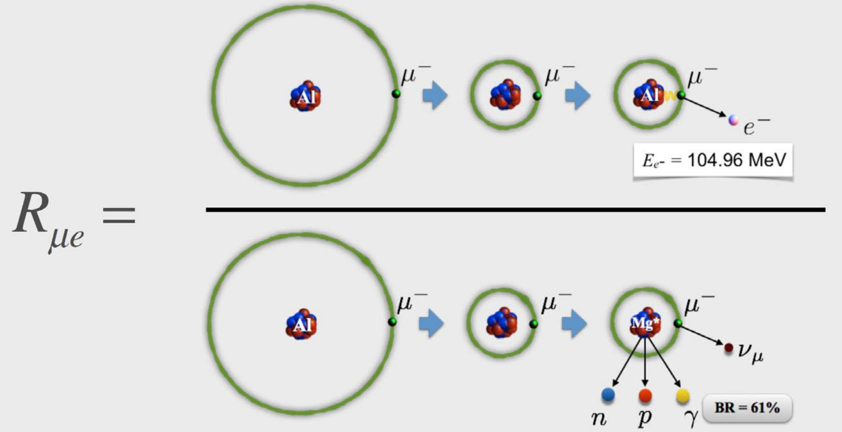




μ to e conversion experiments

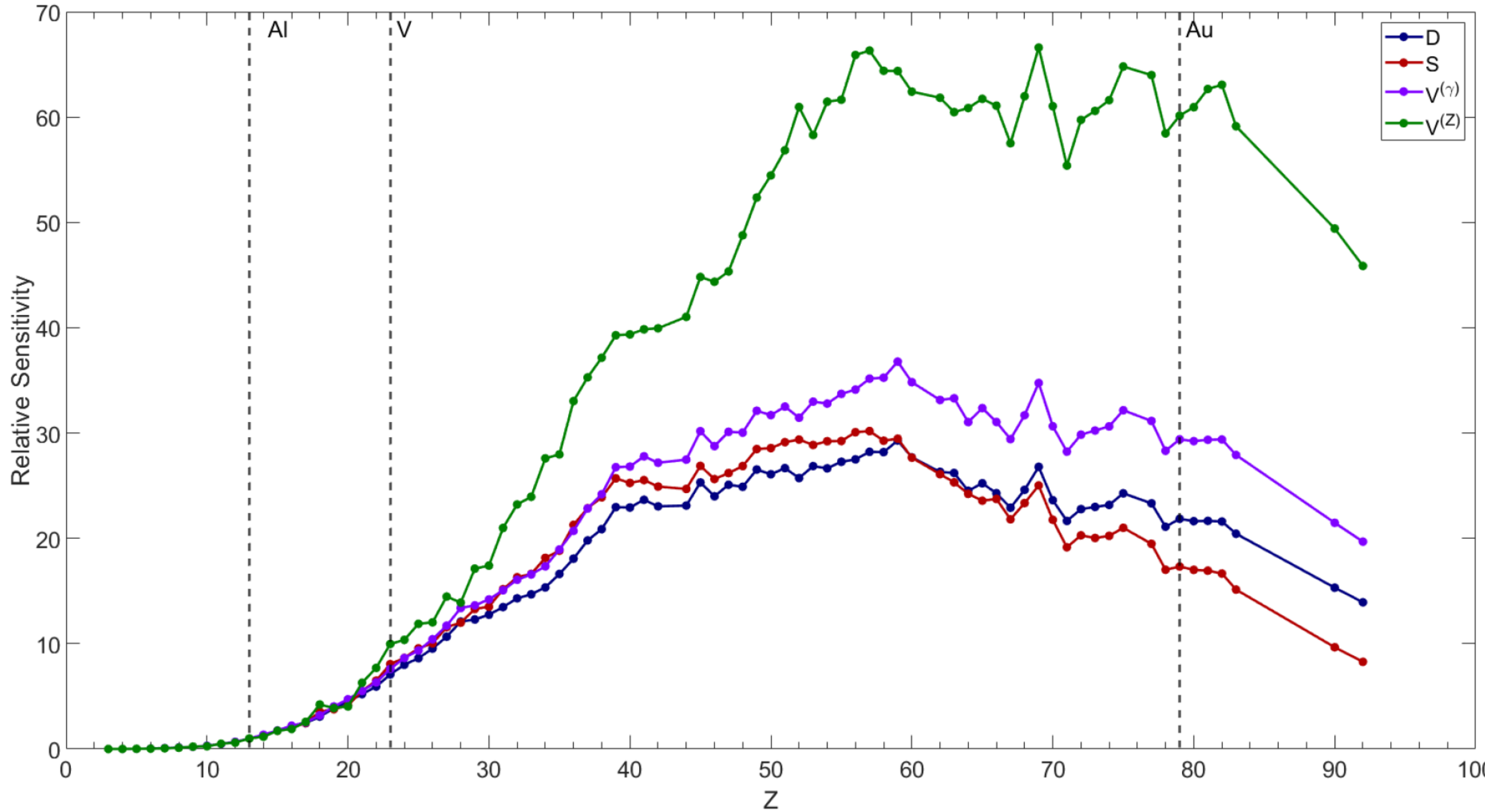
- The signal is a single mono-energetic electron
- If N = Al, E_e ~105 MeV
  - Conversion electron energy depends on Z, due to atomic binding energy
- Coherent nuclear recoil
- There are two experiments in various stages of preparation
  - COMET Phase I and Phase II
  - Mu2e
    - Both face similar challenges, addressed in specific ways
      - High rates to achieve required sensitivity
      - Prompt and delayed beam-related backgrounds
      - Cosmic ray backgrounds

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$



Using calculated conversion rate

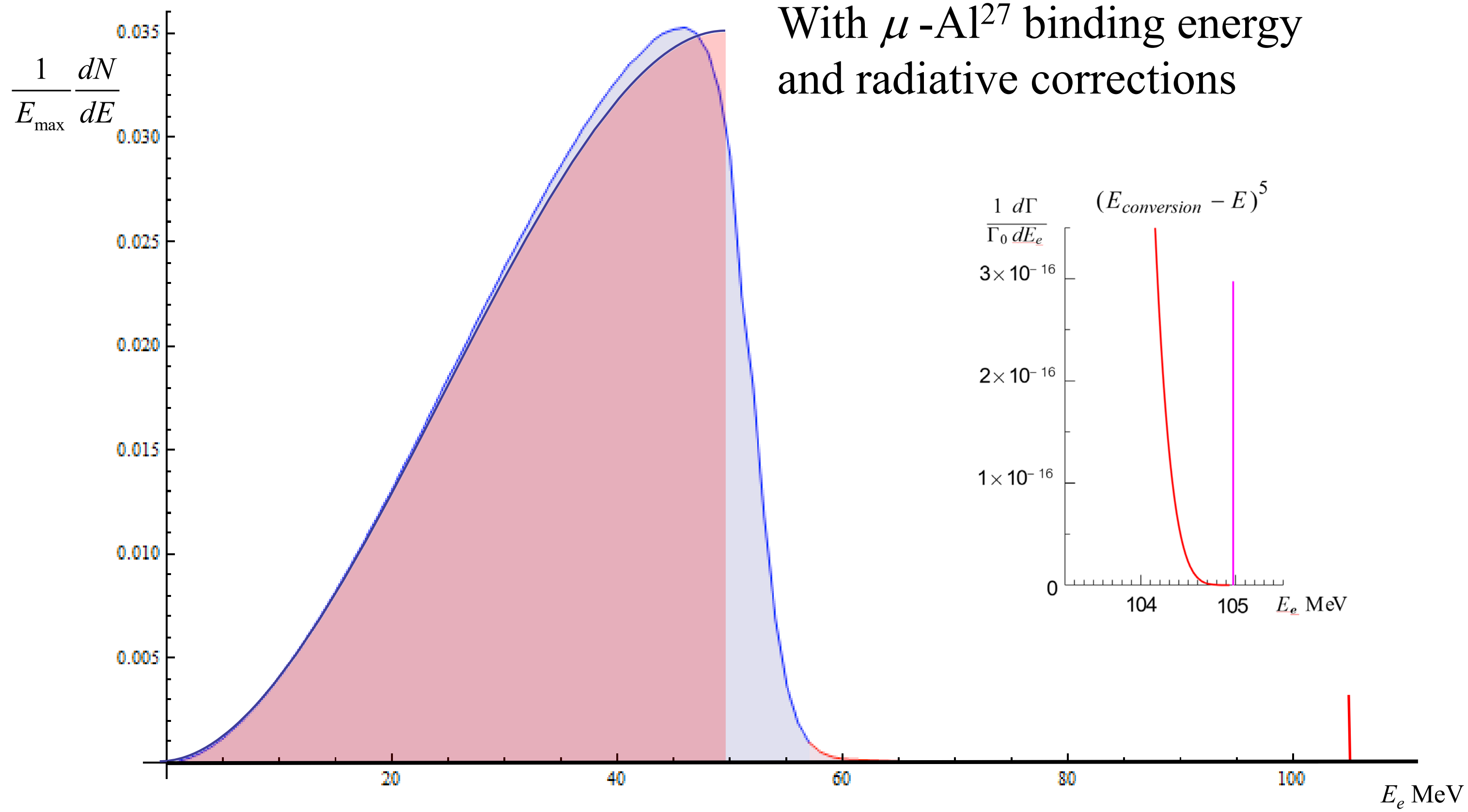
- Historical approach of normalizing the calculated and measured conversion rate (a coherent process) to mu capture (an incoherent process) introduces extraneous structure into Z dependence



- Solution: theorists publish the rate they calculate, experiments publish the rate they measure

Decay-in-Orbit Shape

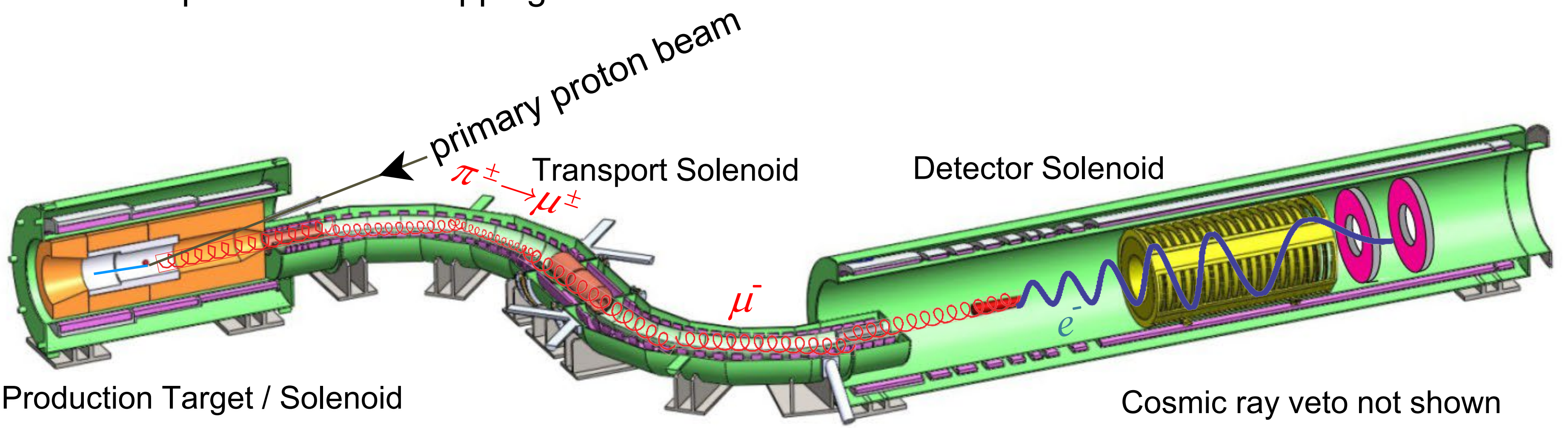
With μ-Al^{27} binding energy and radiative corrections



Czarnecki, Szafron

Mu2e

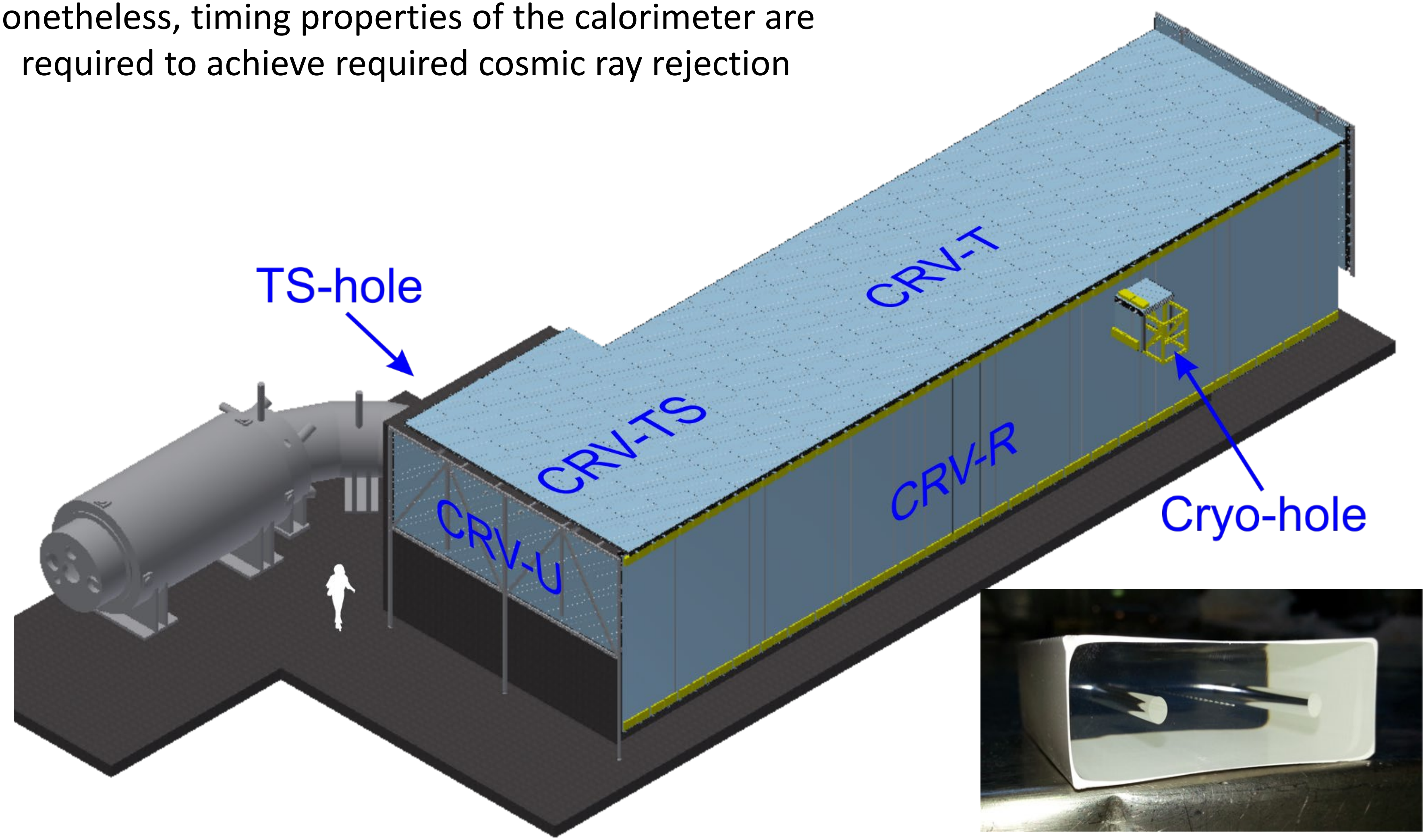
- The Mu2e sensitivity goal 2.6 x 10^{-17} demands a total of ~ $6x10^{17}$ stopped muons in a 3 year run of ~ $6x10^{7}$ seconds total
- This requires a muon stopping rate of 10^{10}/sec



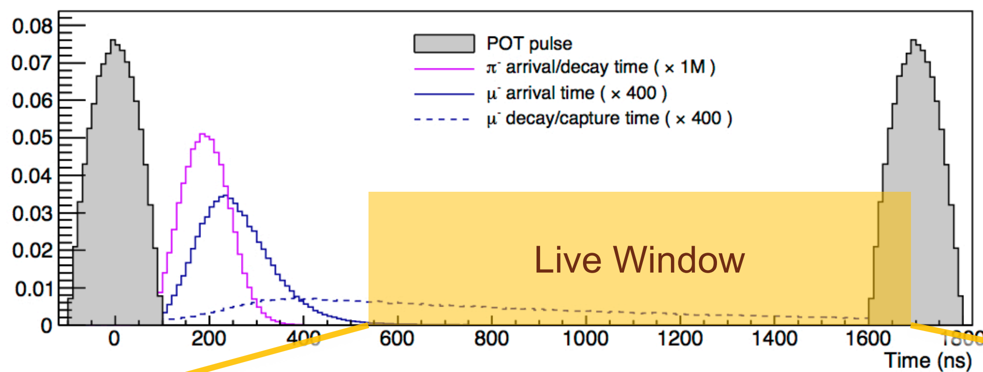
- Experimental design
  - Pulsed proton beam produce pions, which are captured in the backward direction
  - Transport muons from pion decay, with momentum and sign selection
  - Since electron backgrounds are at lower momentum than the sought conversion electrons, confine lower momentum particles to smaller helical radii in a solenoid and a provide hole in tracker and calorimeter for them to pass through
  - Reject cosmic ray events

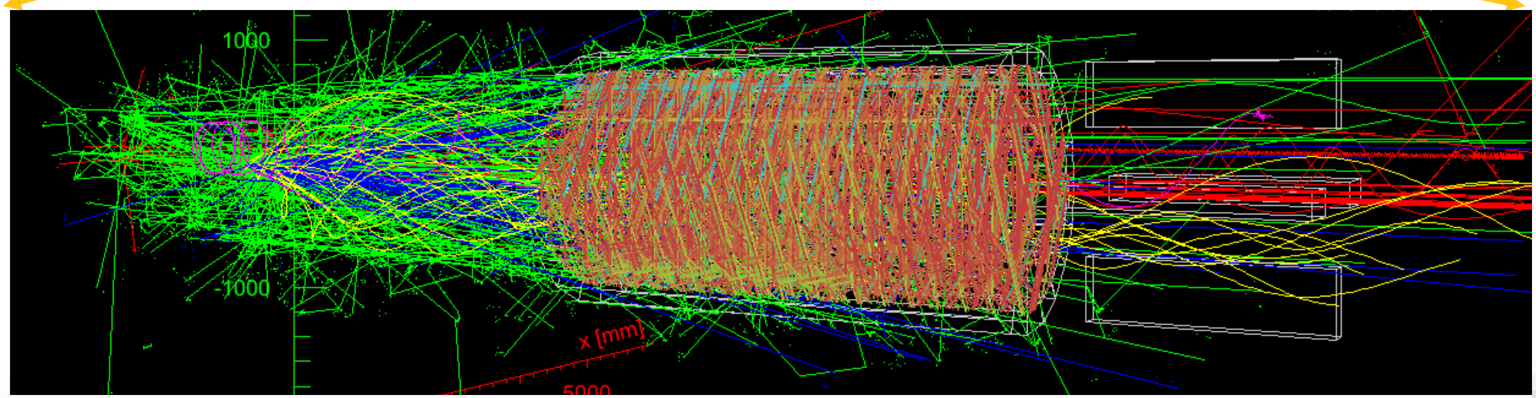
Cosmic ray veto (four layers)

Covers as much of the transport and detector solenoids as possible
Nonetheless, timing properties of the calorimeter are
required to achieve required cosmic ray rejection



What happens during a microbunch ?





Stopping Target Straw Tracker Crystal Calorimeter

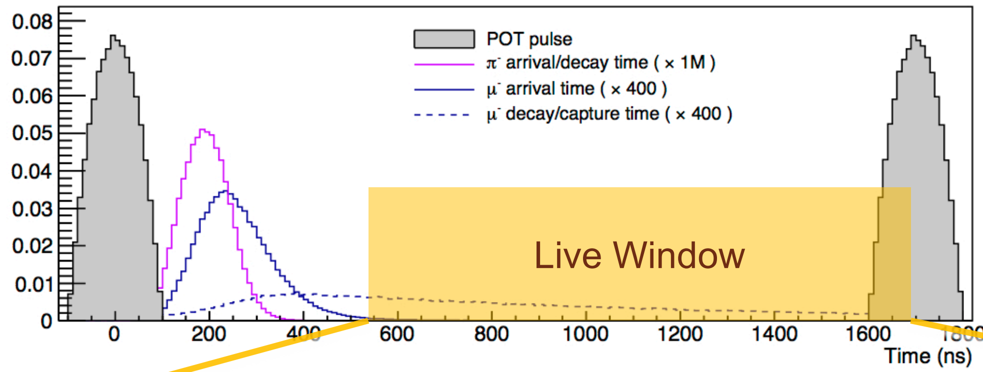
Use of pulsed proton beam and a delayed live gate allows suppression of prompt backgrounds by many orders of magnitude

Proton pulses must be narrow

Out-of-time protons must be suppressed by $\mathcal{O}(10^{10})$

- Simulations encompass a full ~1μs, including all the background overlays from the beam flash, μ capture products, neutrons, *etc*. and properly account for contributions from previous bunches.

What happens during a microbunch ?



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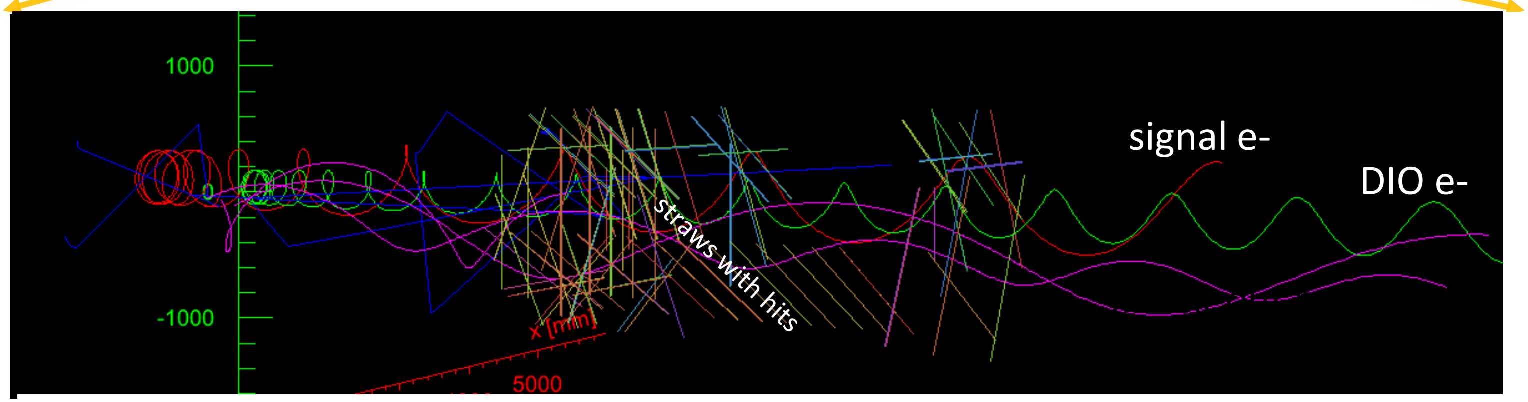

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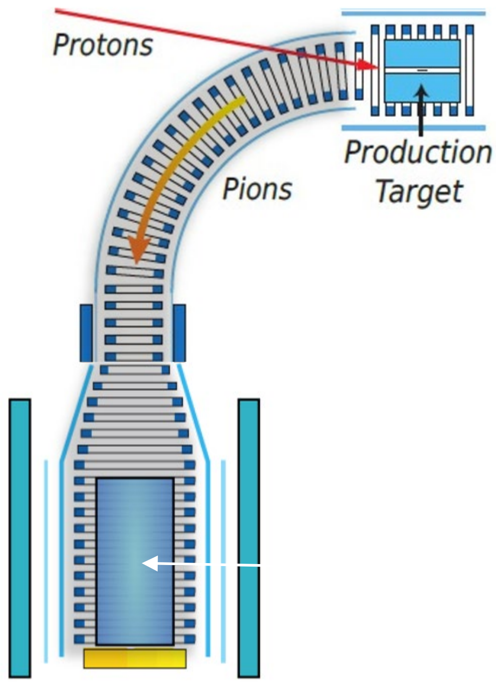
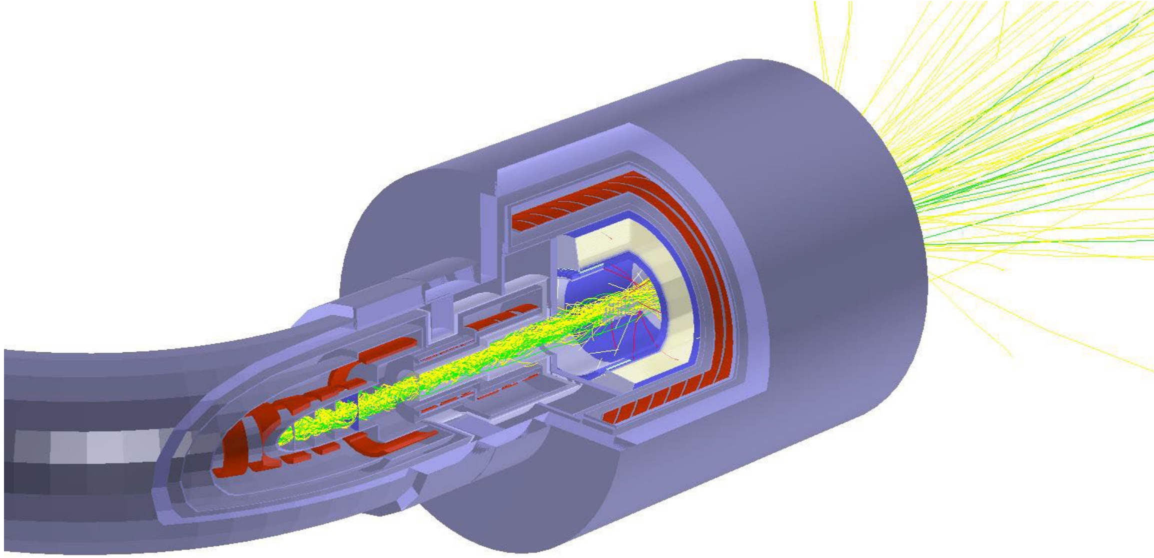
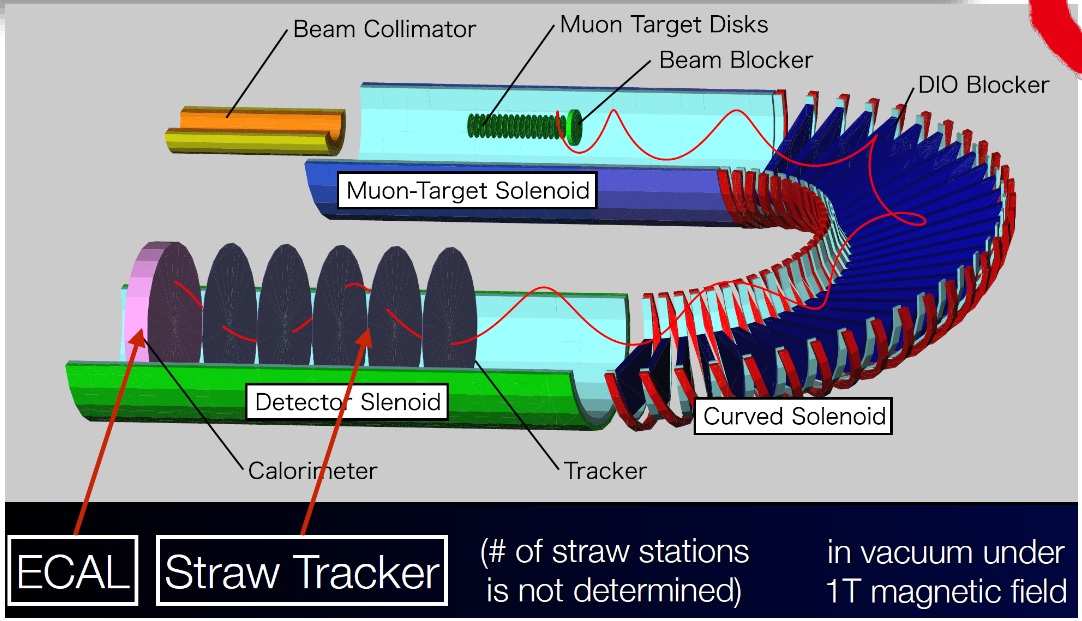
COMET Phase I

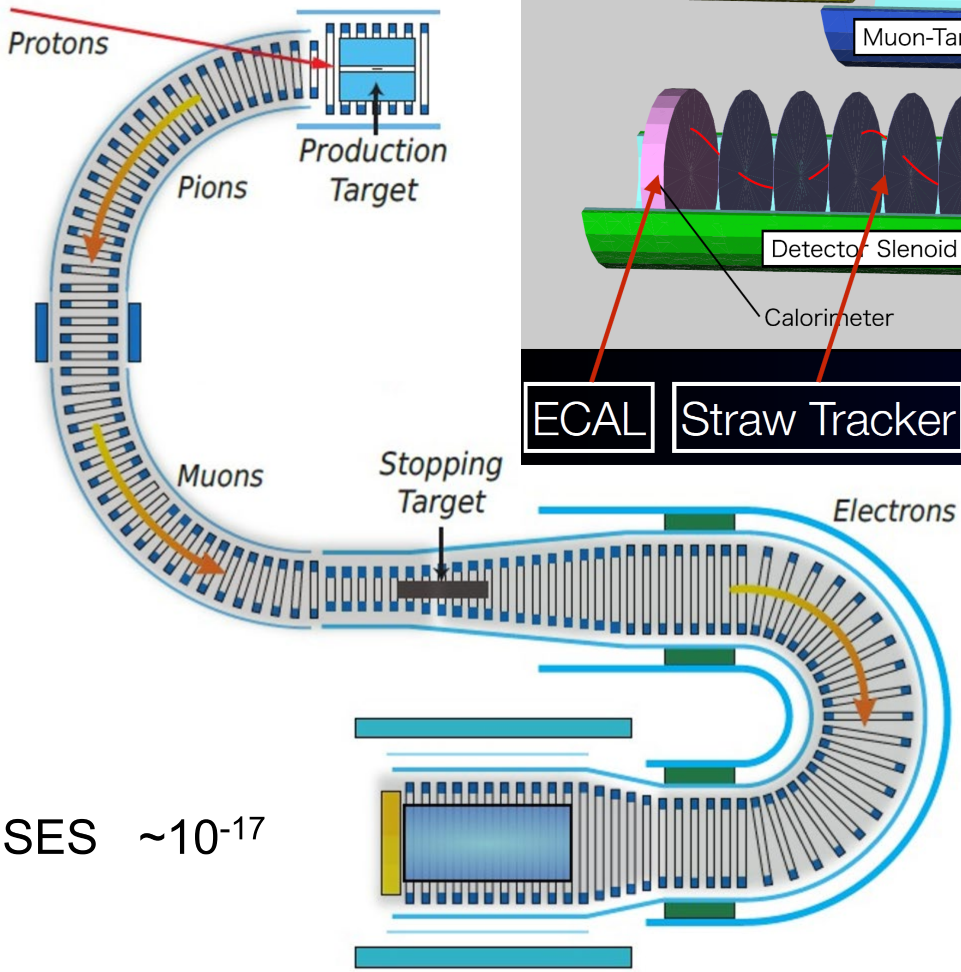




SES 3×10^{-15}
or $< 6 \times 10^{-15}$ @ 90% CL
for 150 days at 3.2 kW

COMET Phase-II (not approved)

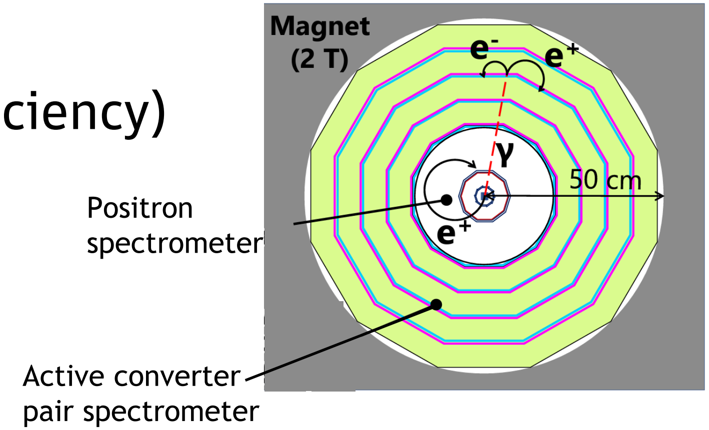


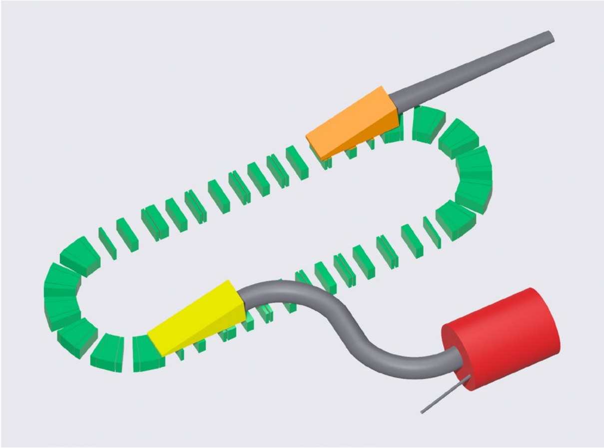


SES ~10^{-17}

The experiments after the next experiments

- $\mu^+ \rightarrow e^+ \gamma$
  - Improve time and spatial resolution – convert the γ (costs factor of 100 in efficiency)
- $\mu^+ \rightarrow e^+ e^- e^+$
  - Improve time resolution
- $\mu^- N \rightarrow e^+ N$
  - PIP-II: 10x μ^- stops: SES 3x10^{-18}
    - New production target
    - Thinner tracker, faster calorimeter
    - If CLFV found in Al, use higher Z target (Ti, V, Au) to study coupling
    - If not found, improve sensitivity on Al
  - PRISM (J-PARC), AMF (Fermilab)
    - FFAG storage ring to produce an even more intense, monochromatic, muon beam (+ or -) with no pion contamination
- $\mu^- N \rightarrow e^+ N^*$ ΔL=2
- Muonium-antimuonium $\mu^- e^+ \rightarrow \mu^+ e^-$





Conclusions

- Searches for charged lepton flavor violation provide the basis for a robust program of BSM investigations that have probe a wide variety of models
- Near-term experiments are running or coming online and upgrades and/or new facilities promise meaningful improvements in sensitivity

- The highest sensitivity is in general achievable with muons:
  - $\mu^+ \to e^+\gamma$
  - $\mu^+ \to e^+e^-e^+$
  - $\mu^- N \to e^+ N$
  - $\mu^- N \to e^+ N^*$ ΔL=2
  - $\mu^- e^+ \to \mu^+ e^-$
- However, τ CLFV decays access unique otherwise inaccessible BSM couplings