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Muon-Based Charged Lepton Flavor Violating Experiments

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Overview

- What is charged lepton flavor violation (CLFV) and why search for it?
- Comparison of different CLFV channels
- CLFV experimental field
- Present CLFV experiments with muons:
  - Signal/background
  - Experimental design
  - Status/results

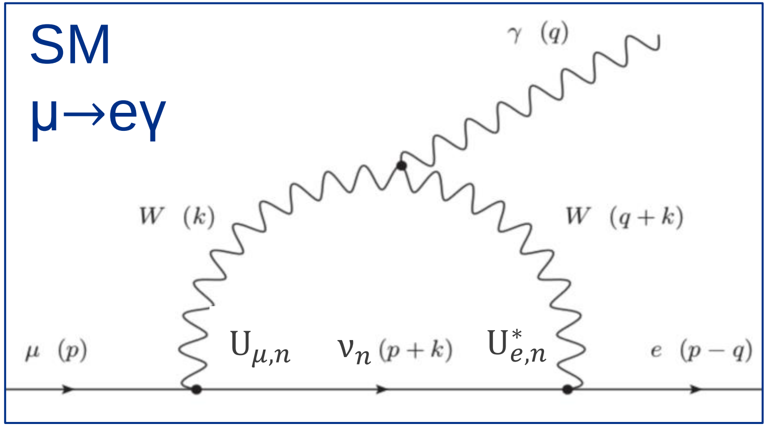
Lepton Flavor Number

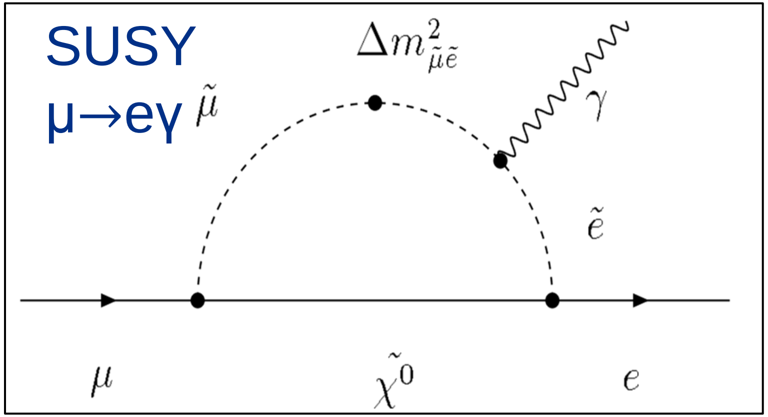
$$\begin{pmatrix} \nu_\mu \\ \mu_L \end{pmatrix} \rightarrow \exp(i\,\alpha_\mu) \begin{pmatrix} \nu_\mu \\ \mu_L \end{pmatrix}$$

- The SM with massless neutrinos contains an inherent symmetries that imply the conservation of lepton flavor number (L_e L_μ L_τ)
- **Electron, muon and tau flavor number are then conserved in all SM interactions without massive neutrinos**

What is Charged Lepton Flavor Violation and Why Search for it?

- Adding neutrino mass results in neutrino oscillation
  Observed by several experiments
  → **lepton flavor number violation for neutrinos**
- No observation charged lepton flavor violation (CLFV)
- Exists in the SM e.g. μ→eγ **BR ~10^{-54}** $\propto[\frac{(\Delta m_\nu^2)}{m_W^2}]^2$
- **Negligible SM rate →**
  CLFV discovery implies BSM physics
- Many SM extensions predict a dramatic increase in CLFV BR (e.g. μ→eγ SUSY BR ~10^{-15})
- Lack of discovery reduces parameter space of many physics models





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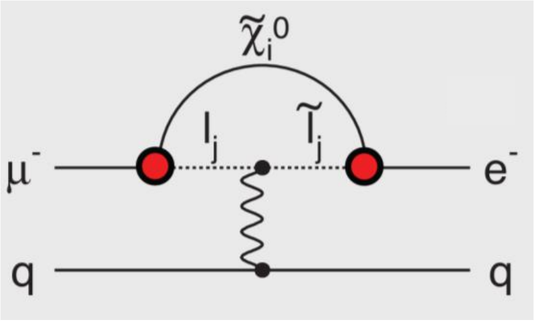
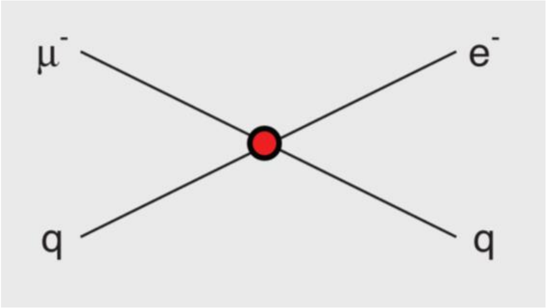
Charged Lepton Violating Theoretical Models

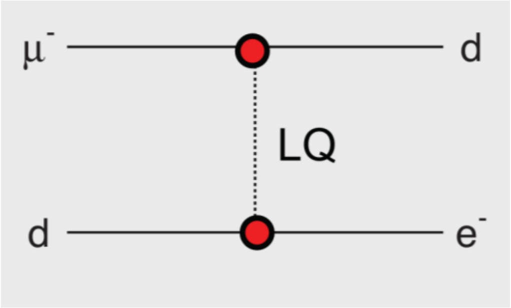
Supersymmetry



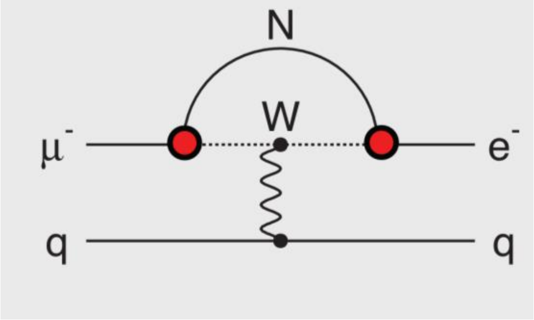
Compositeness



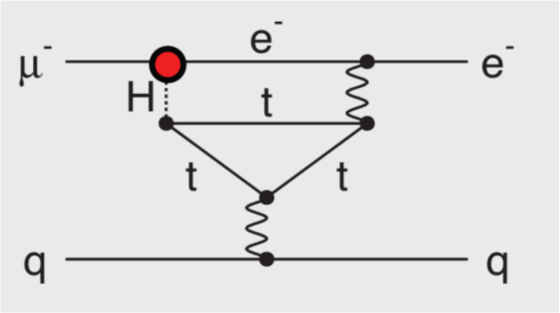
Leptoquark



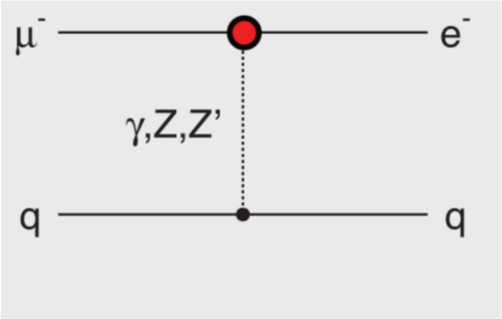
Heavy Neutrinos



Second Higgs Doublet



Heavy Z' Anomal. Z Coupling

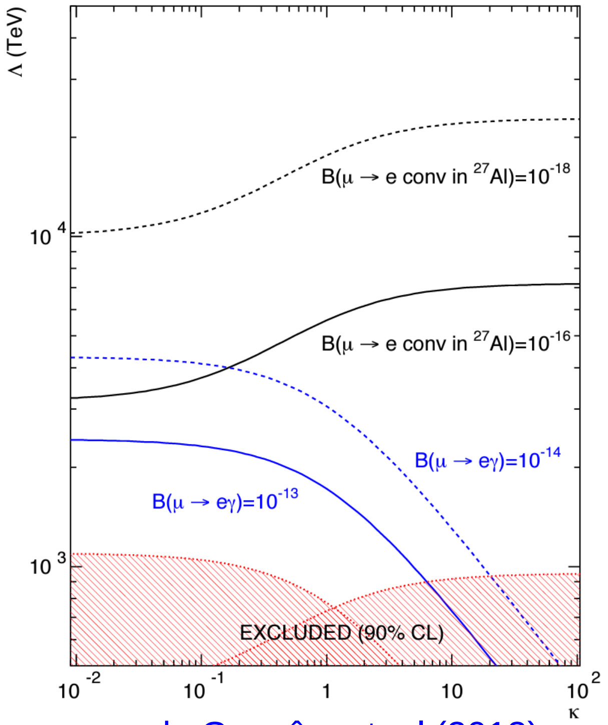


Slide originally by W. Marciano

Charged Lepton Violating Theoretical Models

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

- **By searching through many CLFV channels we can probe the underlying physics**
- Compare channels through a model-independent effective Lagrangian with two types of theoretical models
  e.g. μ → eγ / μN→eN
  - If κ<<1 (e.g. SUSY):
    BR(μ → eγ) ~ BR(μN→eN)/α
  - If κ>>1 (e.g. leptoquarks):
    μN→eN is at tree level and μ→eγ is at loop level
- Experiments are complementary! In κ<<1 models, μ → eγ result should be validated and checked by μN→eN experiment
- μN→eN far more sensitive in κ>>1 models than μ → eγ

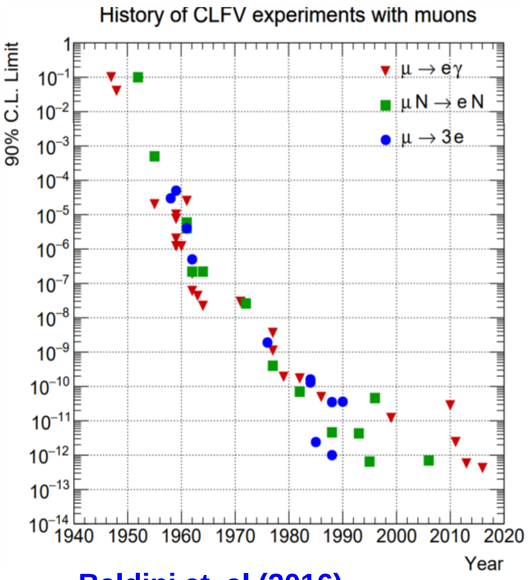


de Gouvêa, et. al (2013)

CLFV History With Muons

- Three ‘golden channels’ of CLFV through muons. All sensitive to a wide range of physics BSM
  - $\mu^+ \rightarrow e^+ \gamma$
  - $\mu^- N \rightarrow e^- N$
  - $\mu^+ \rightarrow e^+ e^- e^+$
- Searches have yet to find signal, but improved due to improved accelerators, detector technology, and experience from predecessors
- **This talk will focus on the active searches for these three processes**

Past



Baldini et. al (2016)

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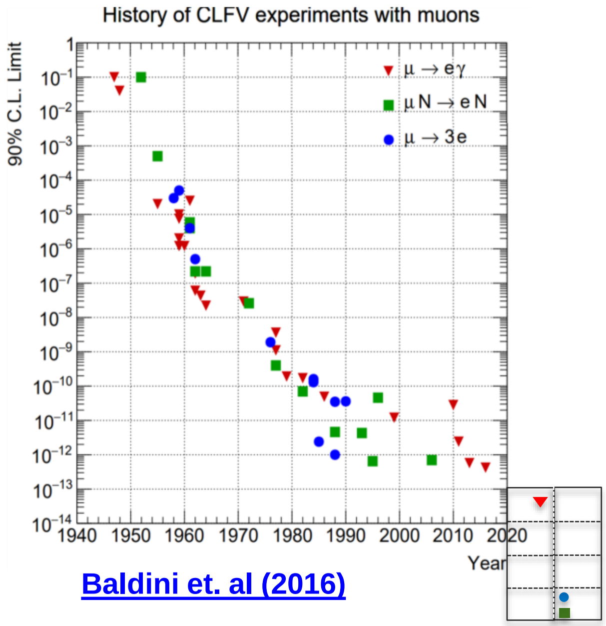
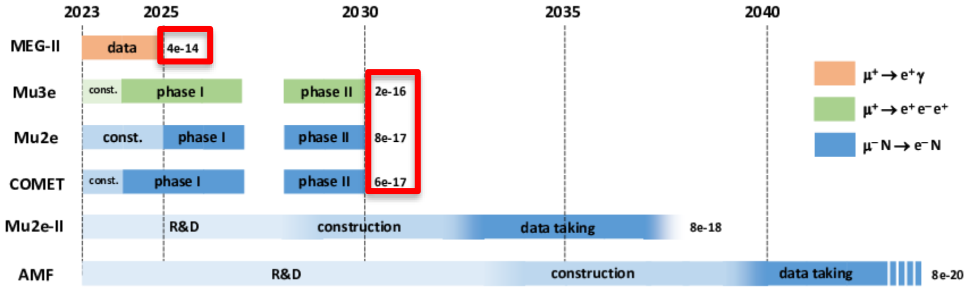


[Baldini et. al (2016)]

Future



[Snowmass 2021 Rare Processes (Artuso et. al)]

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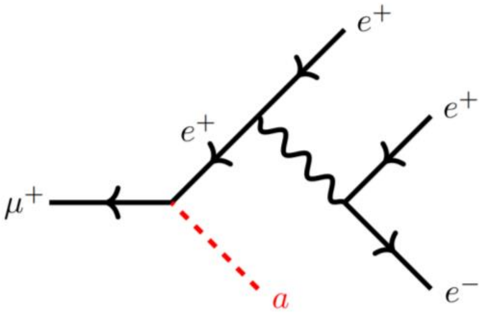
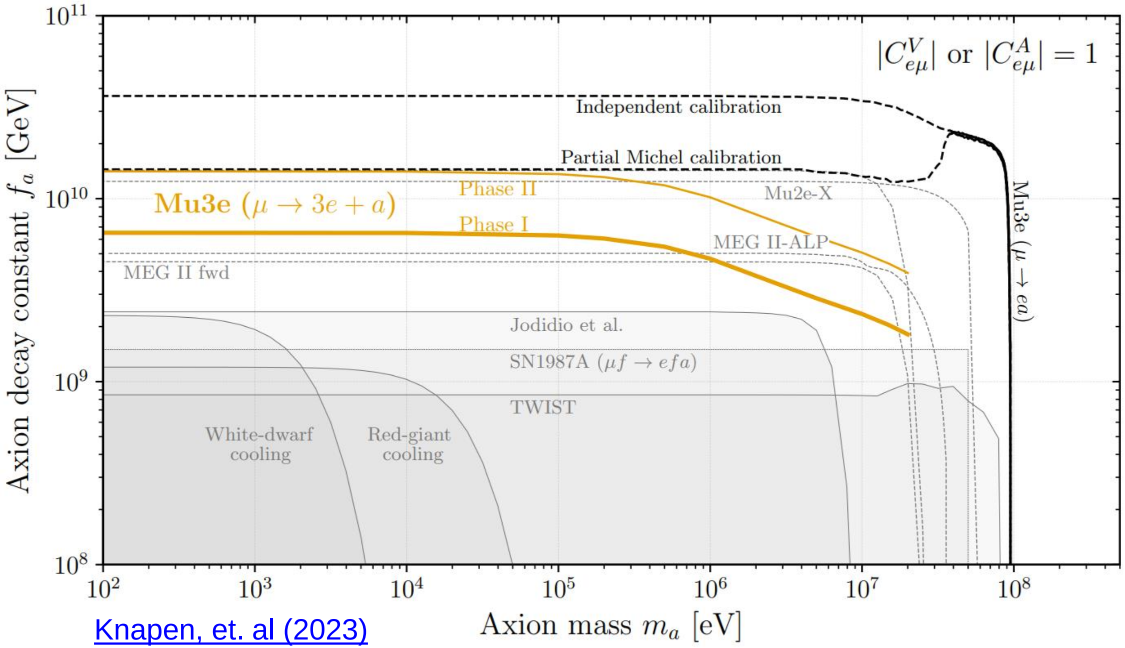
Additional CLFV Muon Searches

- These muon experiments can also probe additional channels
- Examples:
  - Recent significant interest in searching for axions:
    Mu3e $\mu^+ \rightarrow e^+ e^- e^+ \alpha$
    MEG II $\mu^+ \rightarrow e^+ \gamma \alpha$
  - Mu2e and COMET phase I will also search for $\mu^- N \rightarrow e^+ N'$
    (violation of total lepton number)



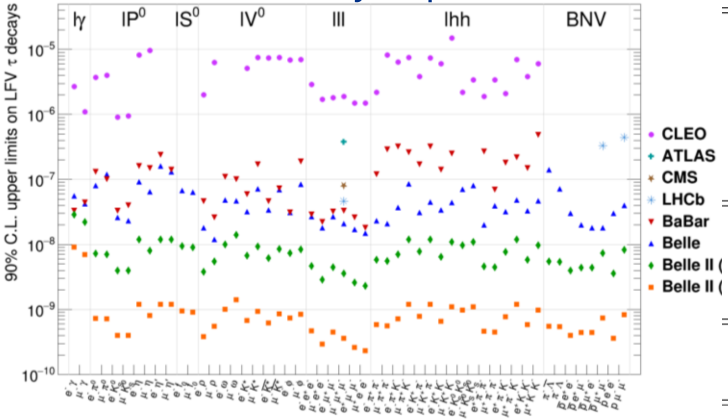


[Knapen, et. al (2023)]

Other CLFV Searches

- CLFV is actively being explored through other channels:
  - Belle II, LHCb: τ decays
    e.g. $\tau \rightarrow e\gamma$
  - NA62 (CERN): K^+decays
    e.g. $K^+ \rightarrow \pi\mu e$
  - BES III: J/ψ decays
    e.g. J/ψ→ $e\tau$
  - ATLAS+CMS: Higgs decays
    e.g. $H \rightarrow e\tau$

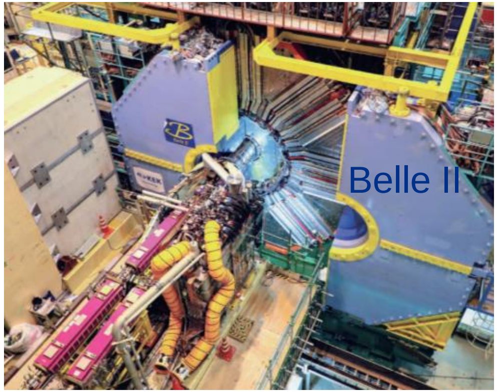
Tau Limits By Experiment



	NA62 UL (90%C.L.)
$BR(K^+ \rightarrow \pi^-\mu^+\mu^+)$	$< 4.2 \times 10^{-11}$
$BR(K^+ \rightarrow \pi^-e^+e^+)$	$< 5.3 \times 10^{-11}$
$BR(K^+ \rightarrow \pi^-\pi^0e^+e^+)$	$< 8.5 \times 10^{-10}$
$BR(K^+ \rightarrow \pi^-\pi^0\mu^+e^+)$	analysis started
$BR(K^+ \rightarrow \pi^-\mu^+e^+)$	$< 4.2 \times 10^{-11}$
$BR(K^+ \rightarrow \pi^+\mu^-e^+)$	$< 6.6 \times 10^{-11}$
$BR(\pi^0 \rightarrow \mu^-e^+)$	$< 3.2 \times 10^{-10}$
$BR(K^+ \rightarrow \pi^+\pi^0\mu^-e^+)$	analysis started
$BR(K^+ \rightarrow \mu^-\nu e^+e^+)$	$< 8.1 \times 10^{-11}$
$BR(K^+ \rightarrow e^-\nu\mu^+\mu^+)$	analysis ongoing

Snowmass Whitepaper (2022)

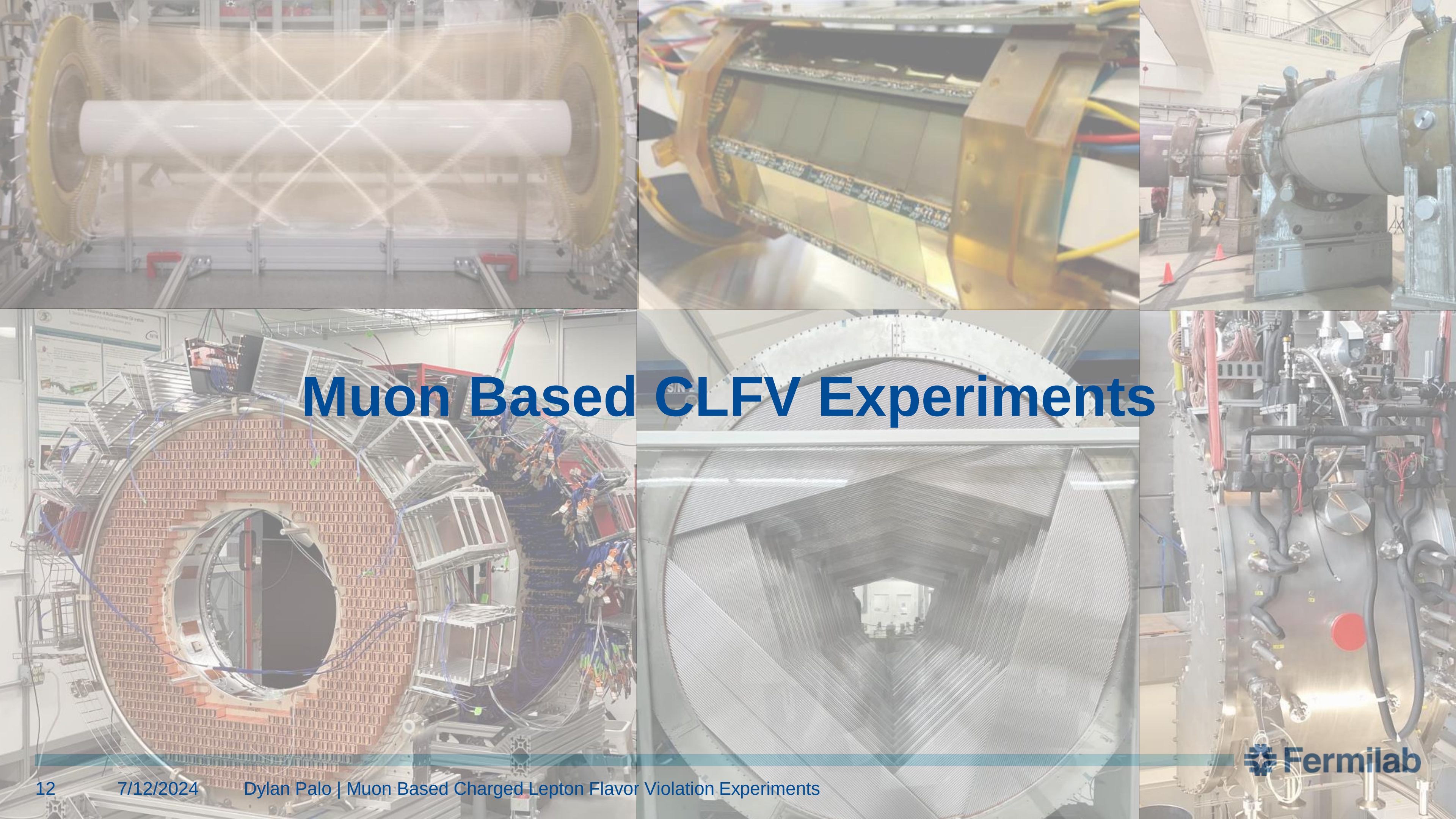
NA62 Collaboration (I. Panichi, 2023)



Motivation and Search Summary

- Active work on many different channels of CLFV!
- **CLFV discovery is unambiguous evidence of physics beyond the standard model**
- **Require the work from many different experiments to get a better picture to the underlying physics**

Muon Based CLFV Experiments

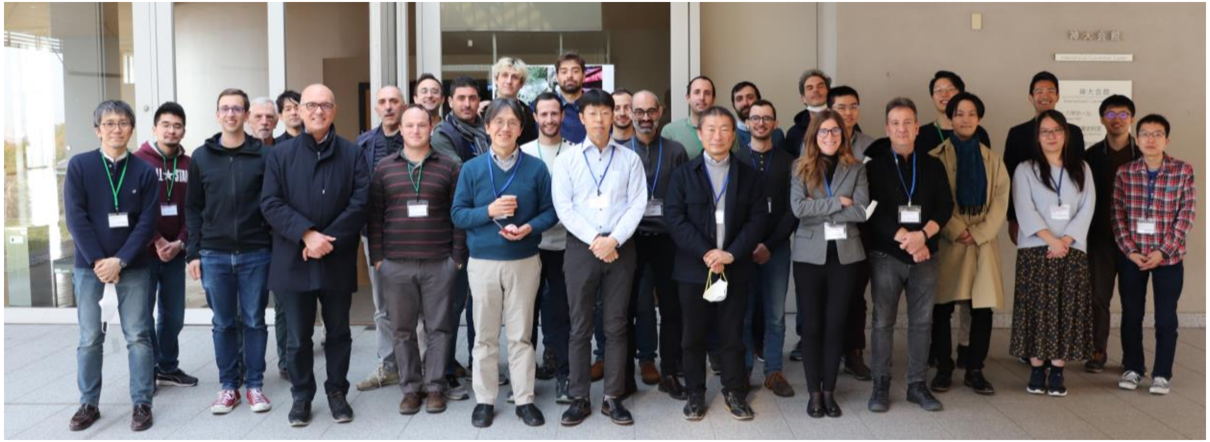


Focus of Muon CLFV Searches

- **Background suppression:**
  - Rare decay searches conveniently have no SM background
  - Instead, the background consists of:
    - Time coincidences of 2+ SM interactions
      - **Suppressed by precise timing and vertex resolution**
    - SM interaction resulting in small momentum neutrinos; process almost mimics the signal
      - **Suppressed by momentum/energy resolution**
      - **Includes detector requirements of low material budgets to suppress MS**
    - Additional background via cosmics, pions, etc.
- **High beam rates:**
  - Used to achieve strong limits, but requires detectors (gain loss), trigger, electronics, computational power to handle the high beam rate ($\sim 10^{10} \mu/s$)
  - Must suppress time coincidences to handle the high beam rate
- **Calibration:**
  - Requires precise calibration and alignment to achieve optimal resolutions mentioned above
  - Requires measurements of resolutions and expected background for the final analysis

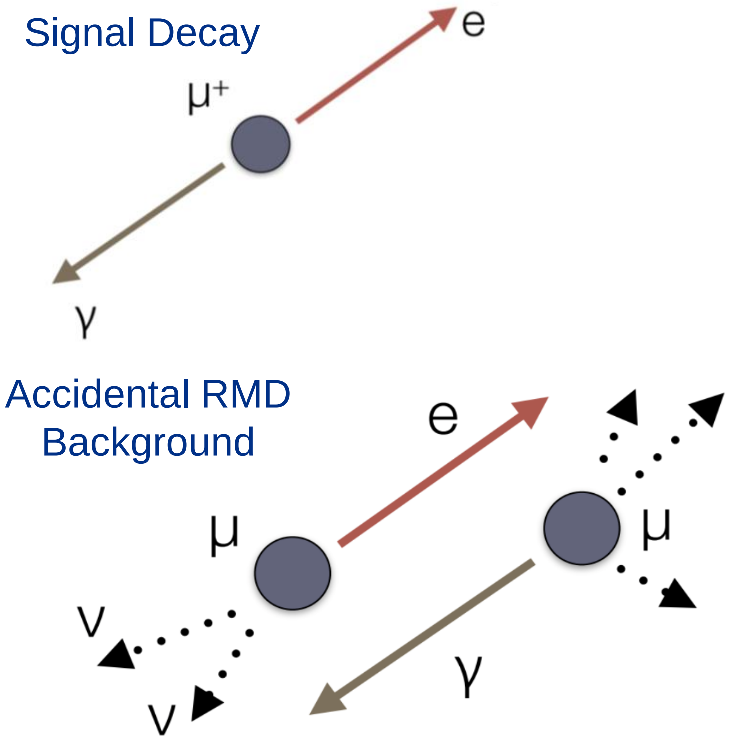
MEG II Experiment

- Search for $\mu^+ \rightarrow e^+ \gamma$ at Paul Scherrer Institut (PSI)
- Upgrade of MEG experiment.. Aims for x10 sensitivity improvement ($6 \ * 10^{-14}$ 90% CL)
- Uses the PSI proton ring cyclotron
  - 590 MeV protons
  - Unbunched surface muon beam produced: Stop rate ~ 4×10^7 Hz, 28 MeV muons



MEG II Experiment: Signal/Background

- $\mu^+ \rightarrow e^+ \gamma$ signal: 2-body decay at rest, e/γ have equal and opposite momentum (m_μ/2)
- Background:
  - RMD (radiative muon decay) **:** $\mu^+ \rightarrow \gamma\, e^+ \nu_\mu \overline{\nu_e}$ (small E $\nu_\mu \overline{\nu_e}$)
  - **Accidental background**: high p_{e_+} coincident with γ from RMD, AIF ($e^+ e^- \rightarrow \gamma\gamma$)
- The experiment uses kinematic measurements of the decay products to distinguish between signal/background

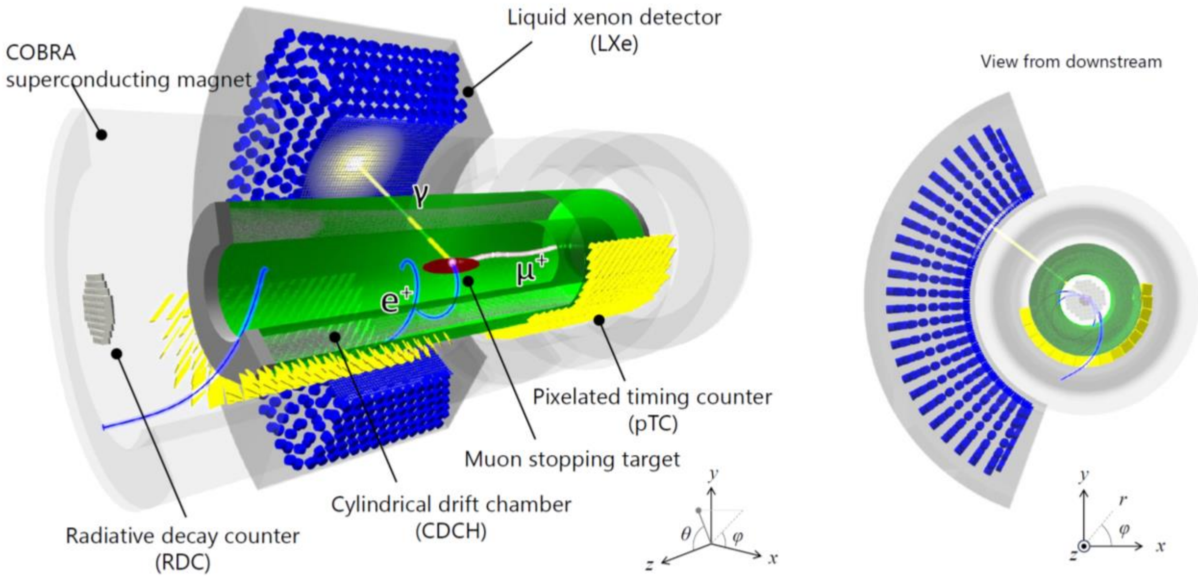


MEG II Experiment: Apparatus

$N_{acc} \propto \boldsymbol{R}^{\boldsymbol{2}}_{\boldsymbol{\mu}^+} \bullet \Delta E_\gamma^2 \bullet \Delta p_{e^+} \bullet \Delta\varphi_{e^+\gamma} \bullet \Delta\theta_{e^+\gamma} \bullet \Delta t_{e^+\gamma} \bullet \mathrm{T}$

Max B~1.3 T

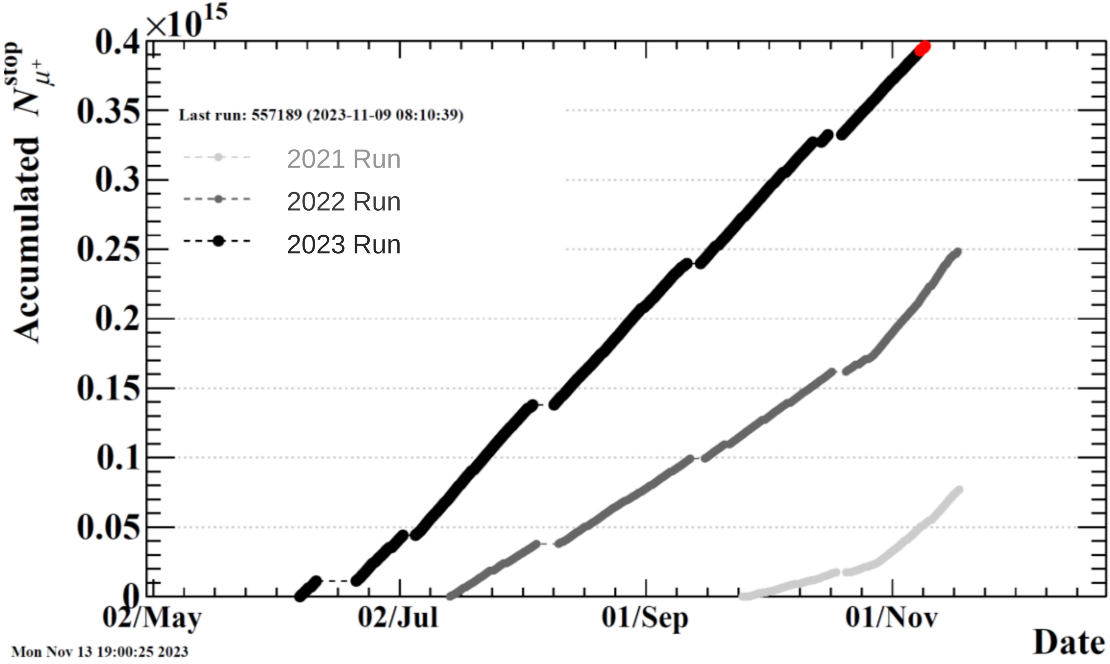
- Stopped μ^+ decay in target; decay products (e, γ) are measured in various detectors
- Similar design to MEG I, but all detectors have been upgraded
- Kinematic estimates at target by propagating e^+ to the target, then projecting γ to e^+ target vertex ($\Delta\theta_{e^+\gamma}, \Delta\varphi_{e^+\gamma}, \Delta t_{e^+\gamma}, E_\gamma, p_{e^+}$)



MEG II Collaboration

MEG II Experiment: Status

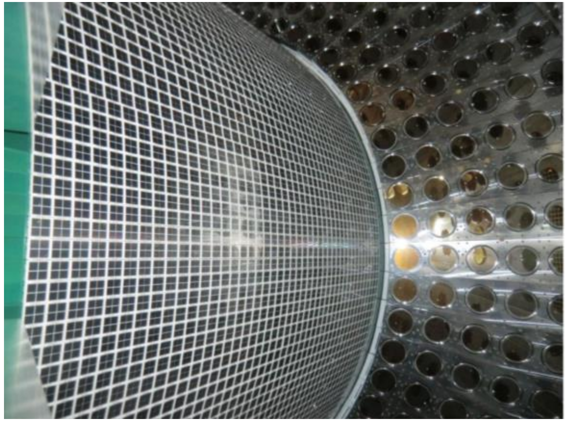
- Experiment has successfully taken 3 physics runs
- Physics result published based on 2021 data. **The 2021 run showed the detectors can handle the beam rates and achieve resolutions required for improved sensitivity**

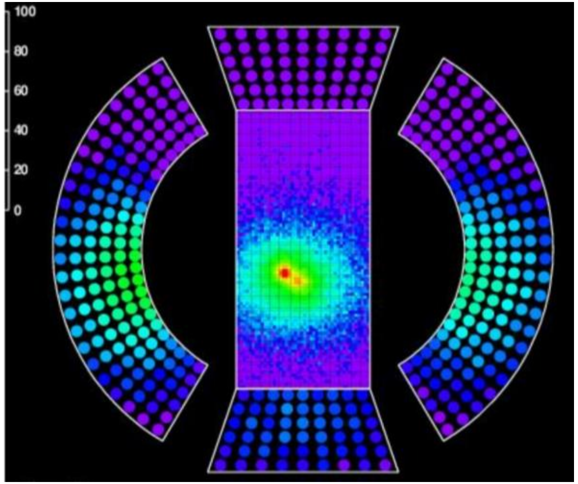


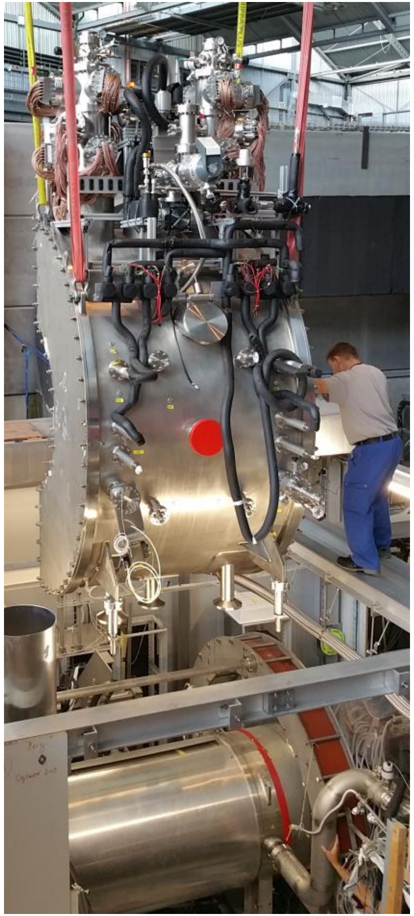
MEG II γ: LXe Detector

- One of world's largest liquid Xe detector (800 L)
- Upgrade: inner face PMTs replaced by 4092 15x15 mm^2 MPPCs (Multi-Pixel Photon Counters)
- Other sides remain covered by PMT photon counters

Kinematic Resolution	MEG I	MEG II 2021 Measured
E_γ (%)	2.4	**1.9**
t_γ (ps)	60	70
u_γ /v_γ/w_γ (mm)	5/5/6	2.4/2.4/5







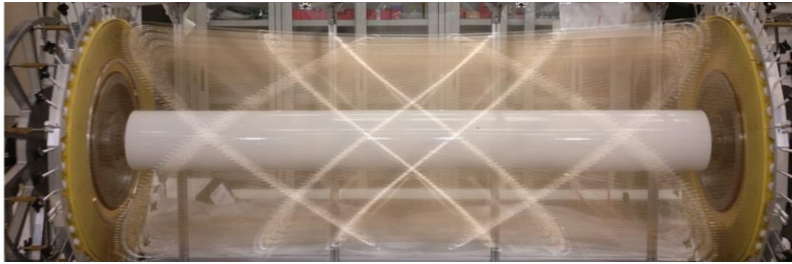
Images from MEG II Collaboration

MEG II e^+: CDCH + SPX

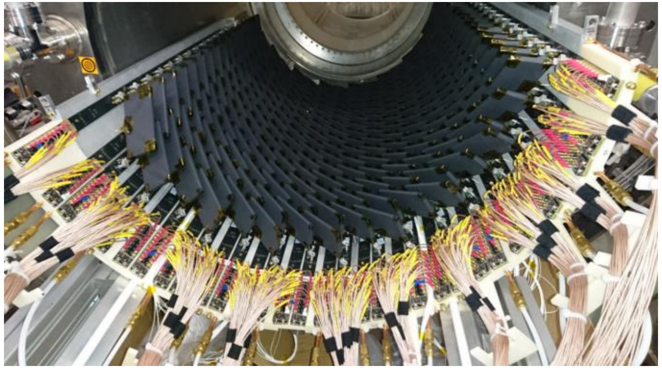
- Cylindrical Drift Chamber (CDCH):
  - Ultra-light open cell stereo drift chamber with 1150 readout drift cells
- Pixelated Timing Counter (SPX):
  - Scintillation tile detector (500 tiles) equipped with SiPM readout
  - High hit multiplicity to improve resolution

Kinematic Core σ	MEG I	MEG II Measured
p_{e_+} (keV)	380	89
θ_{e+} / φ_{e+} (mrad)	9.4 / 8.7	7.2/4.1
t_{e+} (ps)	70	~40
z_{e+} / y_{e+} (mm)	2.4/1.2	2.0/0.74
e+ Efficiency	30	78

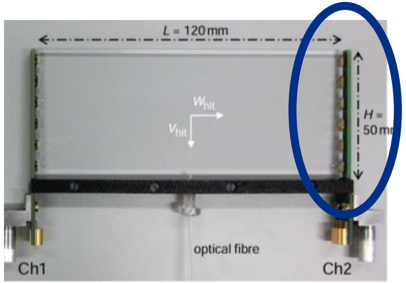
CDCH



Downstream SPX



Single Scintillator Tile

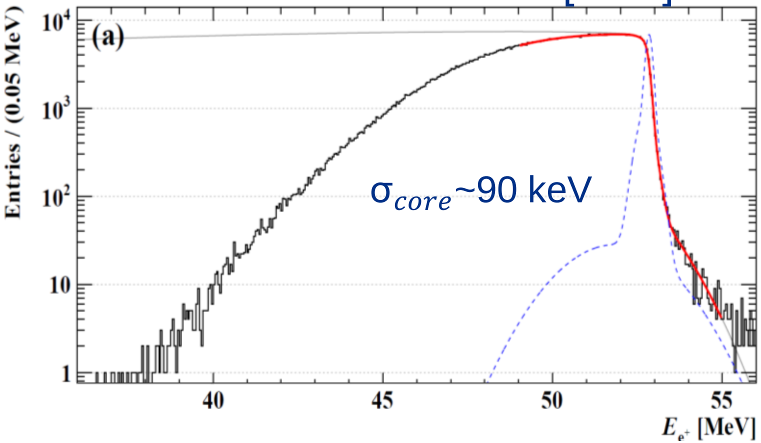


Images from MEG II Collaboration

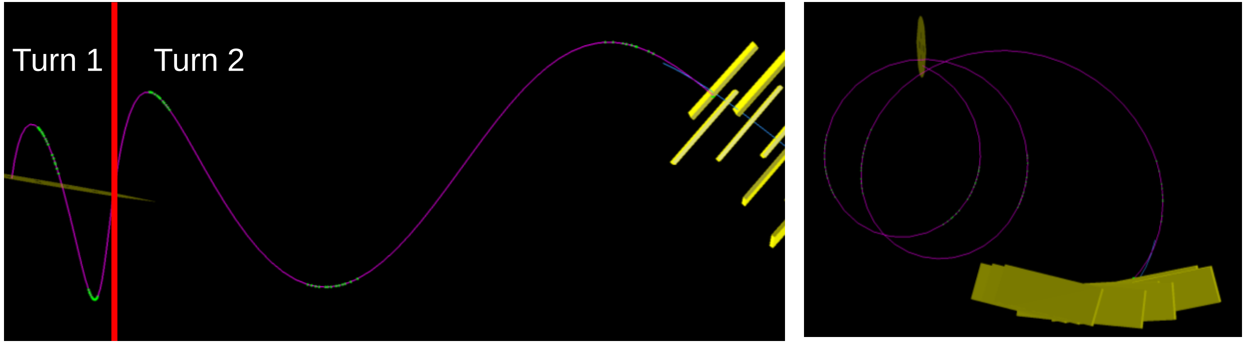
MEG II e^+ Kinematic Resolution Estimates

- Data-driven e^+ kinematic resolution estimate compares two independently measured/fit turns on a single e^+ track: double turn analysis
- Compare kinematics at a common plane between the turns
- Michel edge used for momentum scale, resolution, and expected background

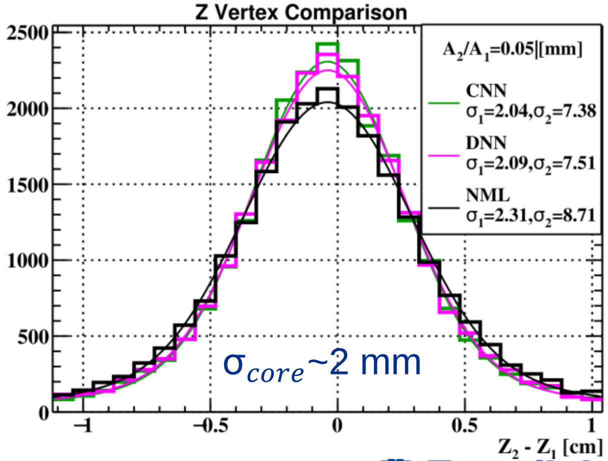
Michel e^+ Momentum [MeV]



Double Turn Event



Double Turn Vertex Z2-Z1 [cm]



MEG II Collaboration

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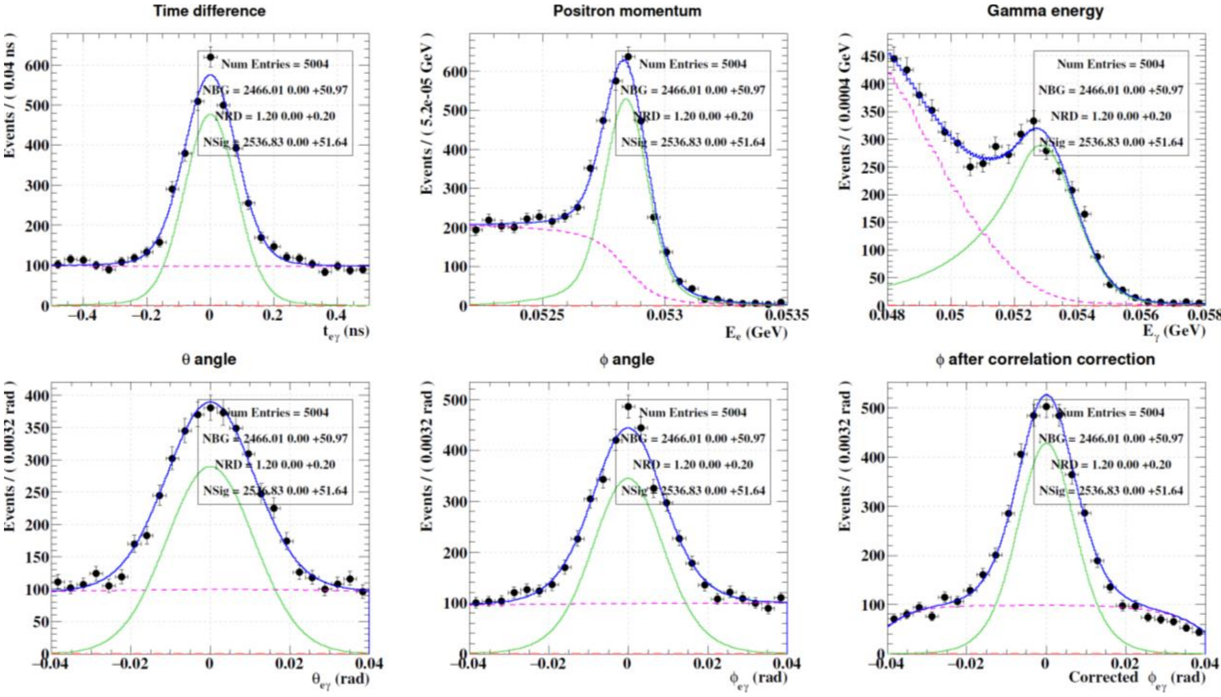
MEG II Signal and Background PDFs

- Using resolutions and background studies, build the probability density functions for the signal and the background
- Input to likelihood physics analysis



[MEG II Collaboration (2023)]

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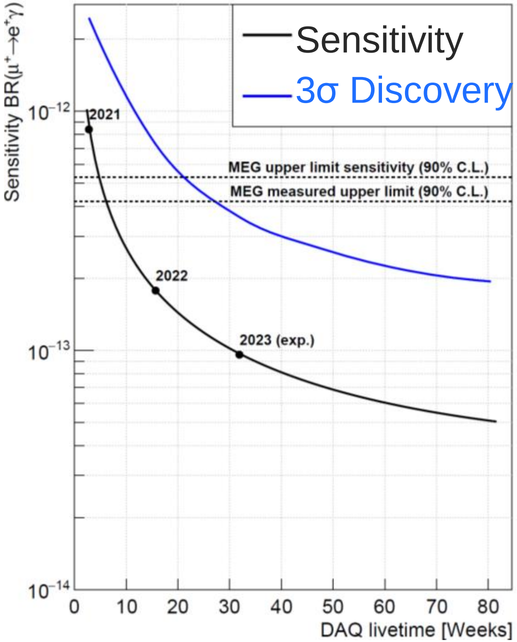
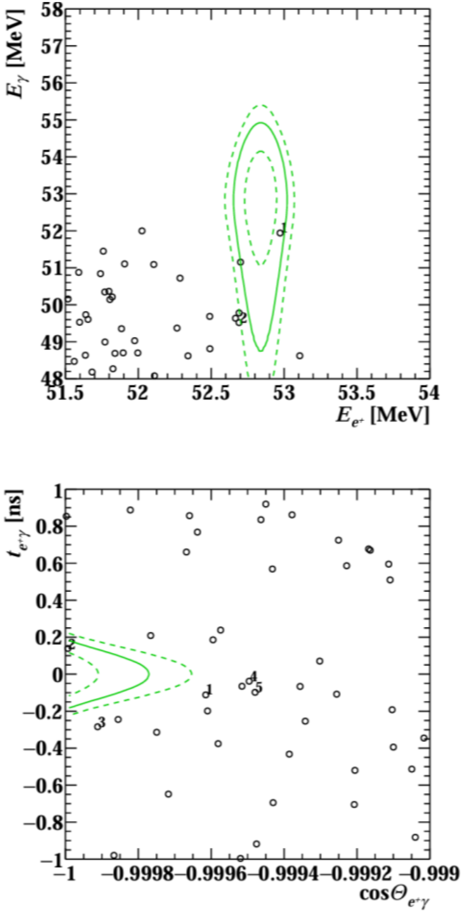
MEG II 2021 Physics Result

- Unblinding resulted in a limit consistent with the median toy MC experiment with a null signal (sensitivity)
- No events centered inside the 5D signal region
- Based on resolutions and expected total data, we expect to reach the goal of x10 sensitivity improvement on MEG
- Analysis of 2022 data expected to be published this fall; aim to remain taking data until PSI shutdown in 2027



MEG II Collaboration (2023)

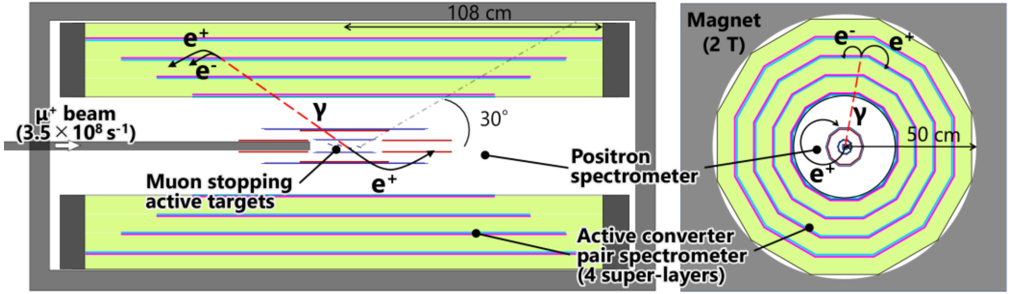
Signal Region 2D Slices

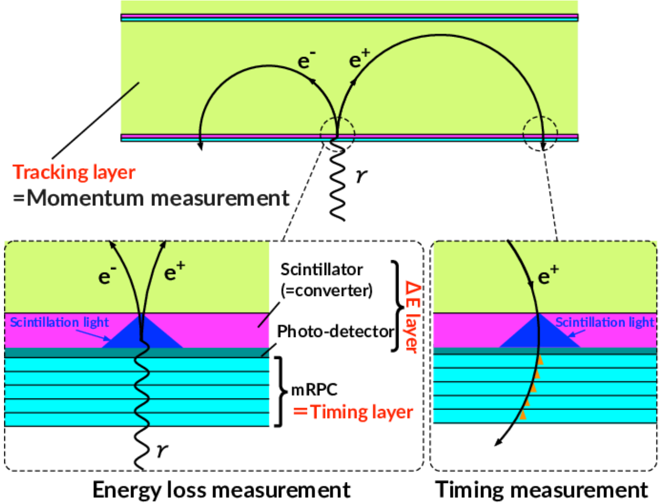


Dataset	Sensitivity (10^{-13})	Single Event Sensitivity (10^{-13})	Limit (10^{-13})
MEG II 2021	8.8	3.8	7.5

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

- Future experiments will likely need to cope with higher beam rate; suppress time coincidences, pileup effects, gain loss, etc.
- Consider positron spectrometer using pixel detector (Mu3e)
- Convert photon to achieve improved photon resolution, but at the cost of efficiency
- Can gain in sensitivity by having a vertex constraint via photon angle estimate





F. Renga, C. Voena (2023-2024)

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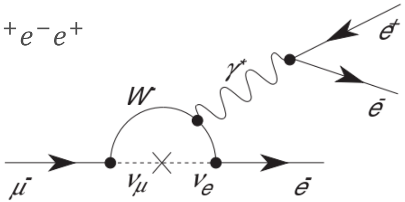
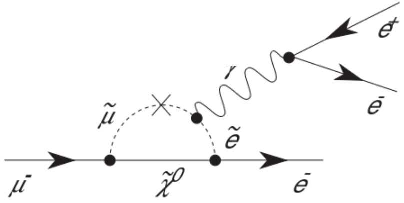
Mu3e Experiment

- Also located at PSI
- Search for $\mu^+ \rightarrow e^+e^-e^+$
- Planning to improve the sensitivity of the search by four orders of magnitude! $(10^{-12} \rightarrow 10^{-16})$
- Slides focus on phase one $(10^{-15}$ level sensitivity)

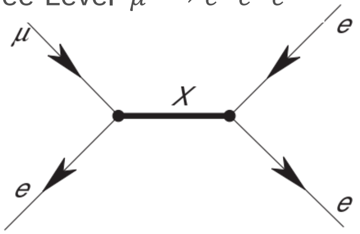
SM $\mu^+ \rightarrow e^+e^-e^+$



SUSY $\mu^+ \rightarrow e^+e^-e^+$



Tree-Level $\mu^+ \rightarrow e^+e^-e^+$



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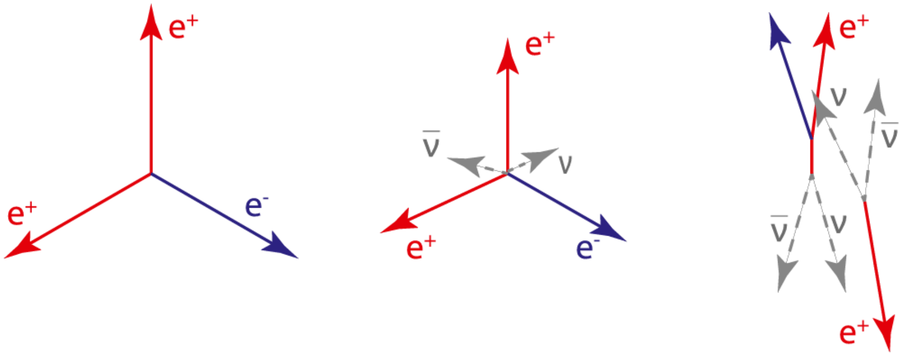
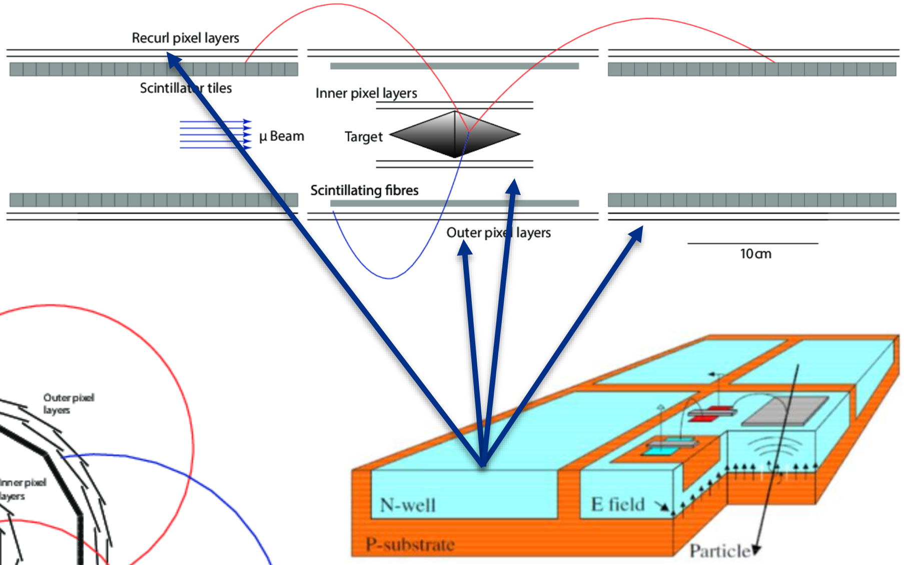
Mu3e Experiment Signal/Background

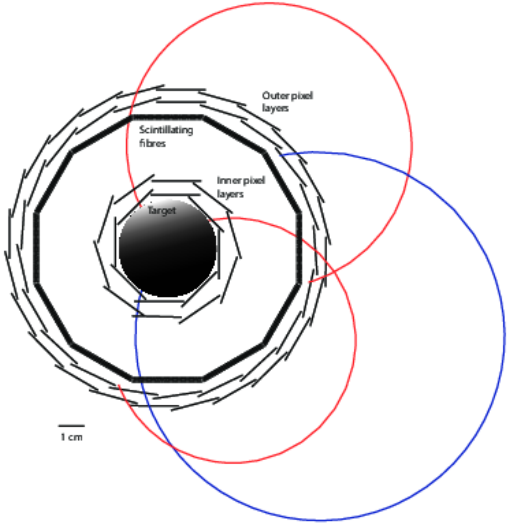
- Signal is a 3-body decay containing $2\ e^{+}, 1\ e^{-}$ consistent with a muon decay stopped in the target
- Background is analogous to MEG
  - Time+vertex coincidence: Michel e^{+} coincidence with another process(es)
  - SM process with negligible neutrino momentum $(\mu^{+} \rightarrow e^{+}e^{-}e^{+}\ \overline{\nu^{\mu}}\nu^{e})$
- Like MEG, Mu3e relies on kinematic measurements to distinguish!



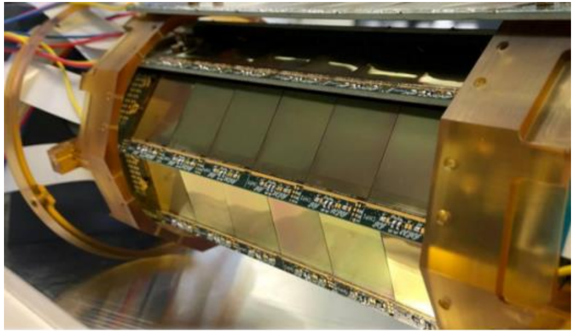
Mu3e Experiment Experimental Design

- Mu3e plans to make use of the upgraded muon beam at PSI (reaching $2 * 10^9\ \mu/s$)
- Implement a pixel detector to deal with the high-rate environment
- Pixel detector employs 2844 Monolithic active pixel sensors (HV-MAPS) designed for Mu3e (MUPIX)
- To optimize resolution, pixels are made as thin and small as possible (~100/80 μm)
- Expected to achieve ~<1 MeV resolution (RMS of 440/250 keV for phase I/II respectively)



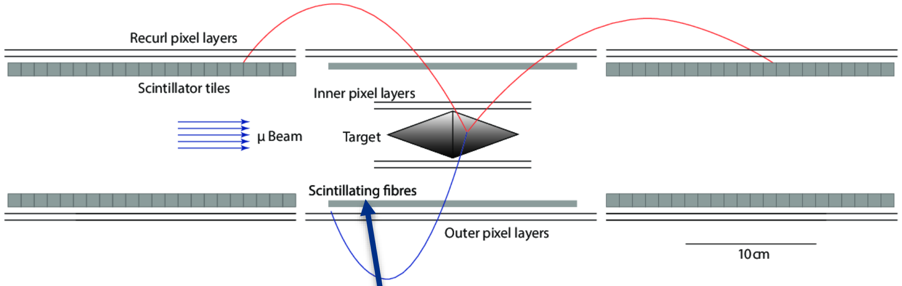


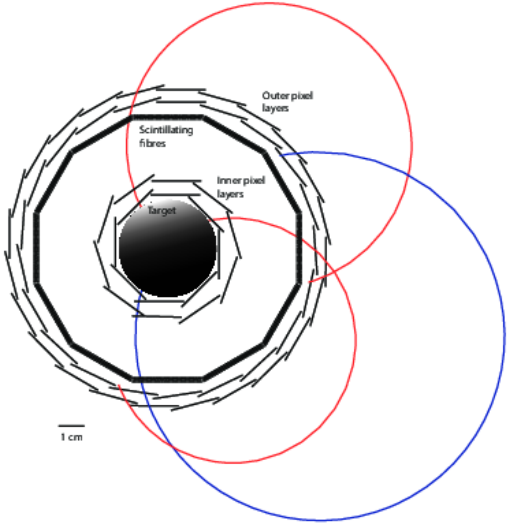
Prototype Pixel Tracker



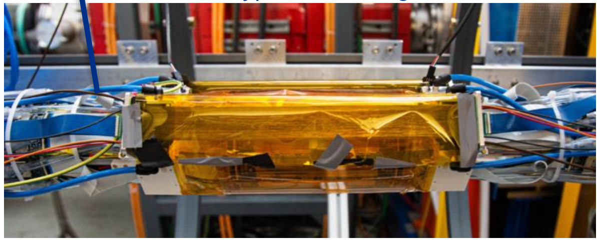
Mu3e Experiment Experimental Design

- In addition, a series of scintillating fibers/tiles precisely measure the timing
- Immediately after the inner-pixels, the e^+e^- intersect scintillating fibers for initial time estimate at pixel
- Finally, the e^+e^- intersect an array of scintillating tiles for the precise timing measurement
- $\sigma_t < 250/100$ ps in the scintillating fibers/tiles respectively



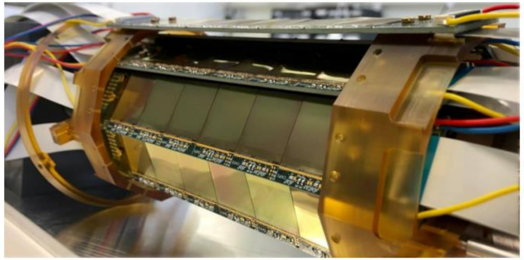


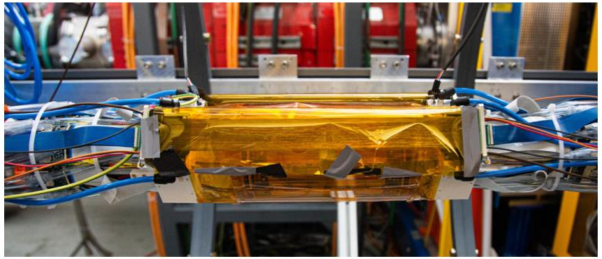
Prototype Scintillating Fiber

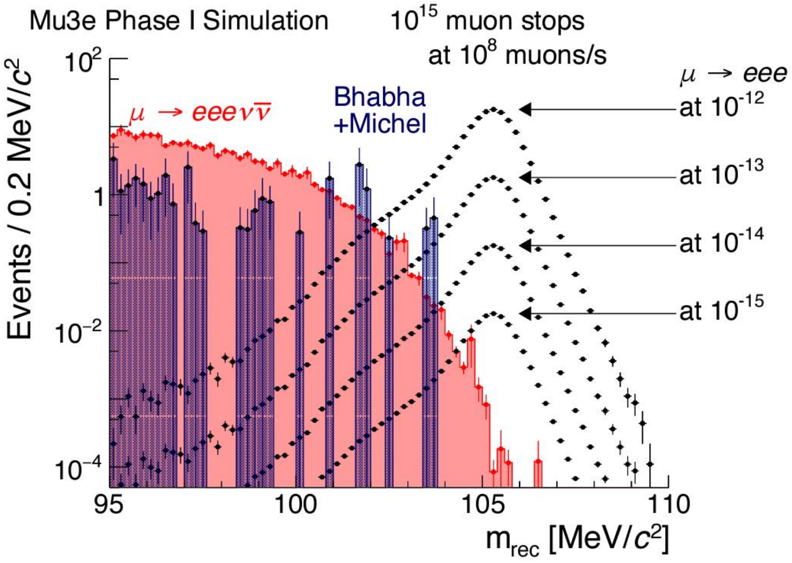


Mu3e Experiment Status

- Prototype detectors have operated in the Mu3e magnet, in helium with beam on
- Plan is to commission the inner detector system in 2024
- **Aiming for a full engineering run in 2025 with physics in 2025/2026**

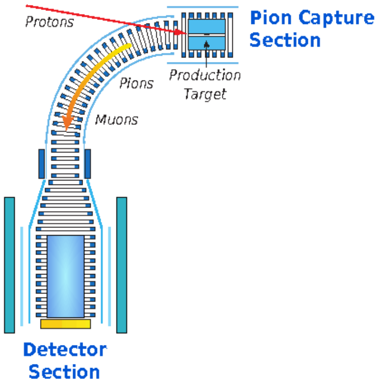




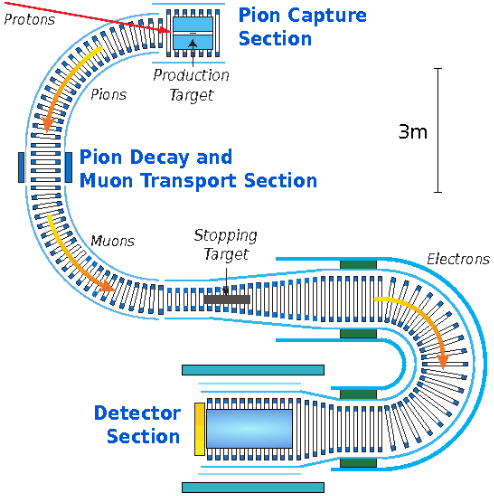


$\mu^- N \rightarrow e^- \ N$ Mu2e + COMET + DeeMe

- Three upcoming experiments searching for $\mu^- N \rightarrow e^- \ N$: Mu2e, COMET, and DeeMe
- DeeMe has commissioned their detector and expect to take data in upcoming years (x10 sensitivity improvement over current UL of $7 * 10^{-13}$, SINDRUM II)
- Mu2e and COMET phase 2 aim for **x10000** sensitivity improvement
- **COMET is currently constructing phase I (x100 sensitivity improvement) with the intent of being physics ready by 2026**
- Will focus on Mu2e, but considerations for COMET detector performance are very similar



COMET Phase-I

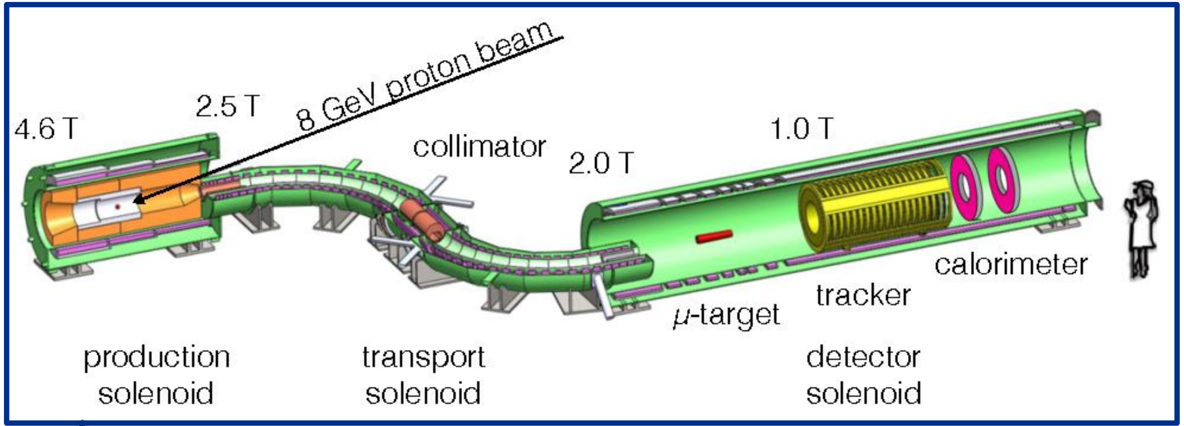


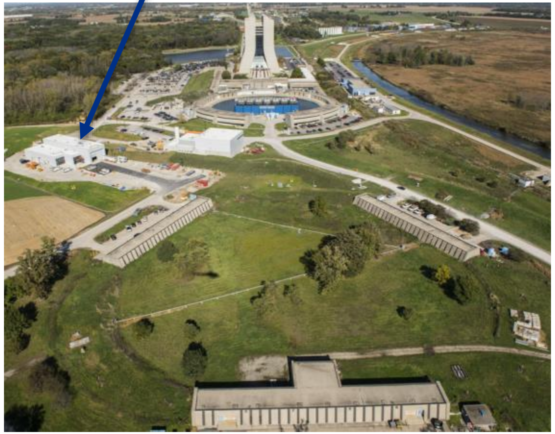
COMET Phase-II

Fermilab

Mu2e Status

- The Mu2e experiment at Fermilab is presently in the construction phase, with **magnets and detectors expected in the Mu2e hall for cosmic runs starting in 2025**
- Mu2e will have beam for the full 2027 calendar year for commissioning and physics data-taking
- Will detail the beamline, magnet system, and detector system used to optimize the signal/background

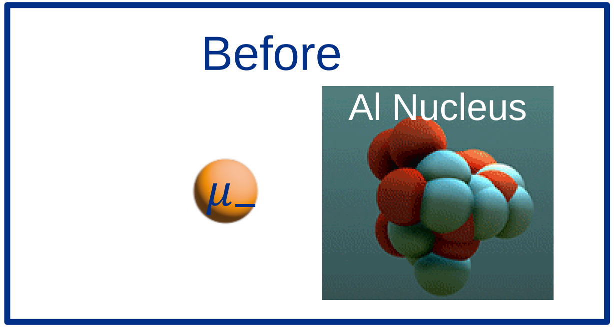


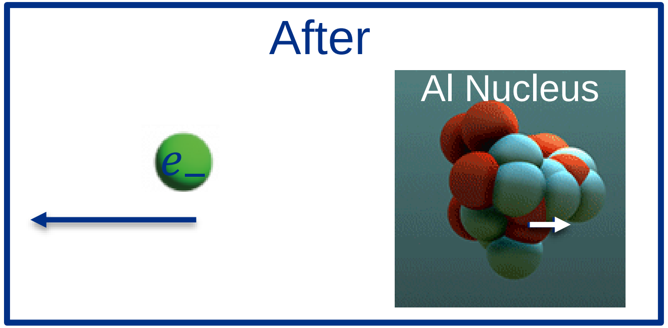


Fermilab

$\mu^- N \rightarrow e^- N$

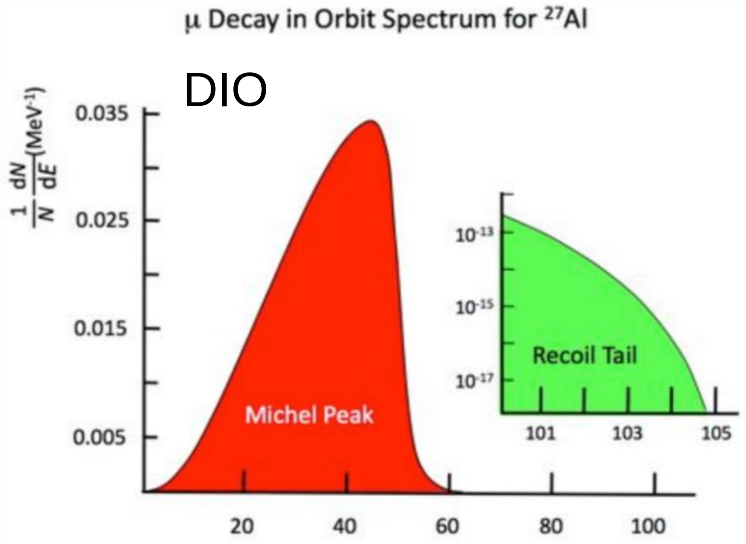
- $$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$
- Signal:
  - Conversion of a muon in the field of the target nucleus (1S state)
  - Coherent recoil of the muon off the target nucleus
  - Results in monochromatic electron: $E_e = m_\mu c^2 - B_\mu(Z) - C(A)$ = **104.97 MeV** ~ m_μ - 0.6 MeV
- **No time coincidence like other mentioned searches, any signal energy electron can mimic the signal!**



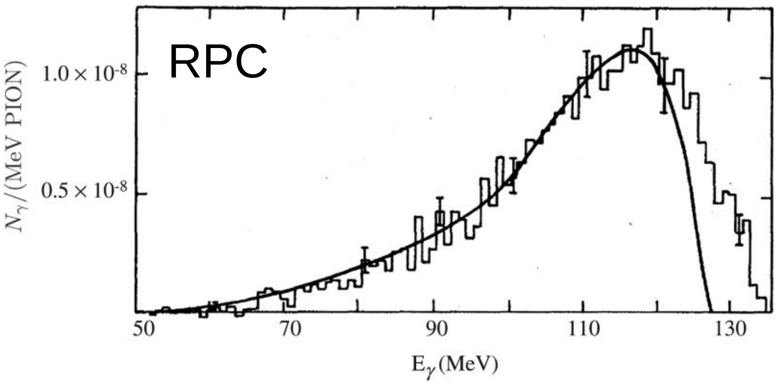


$\mu^- N \rightarrow e^- N$ Main Backgrounds

- Decay in orbit (DIO):
  - Decay in the presence of the nucleus: small “recoil tail” when muon exchanges momentum with the nucleus
  - Analogous to RMD MEG background (negligible momentum neutrinos)
  - **Requires precise momentum resolution**
- Radiative pion capture (RPC)
  - $\pi^- N \rightarrow \gamma N^*$
  - If π hits μ target, can make high energy photon that can produce signal energy electron (e.g. pair produce)
  - **Suppressed by pulsed beam**
- Cosmic rays:
  - Cosmic rays (e.g. muon) can intersect material (stopping target) and can break free an electron at the signal energy
  - Indistinguishable from the signal
  - **Surround entire detector with cosmic ray “veto”**

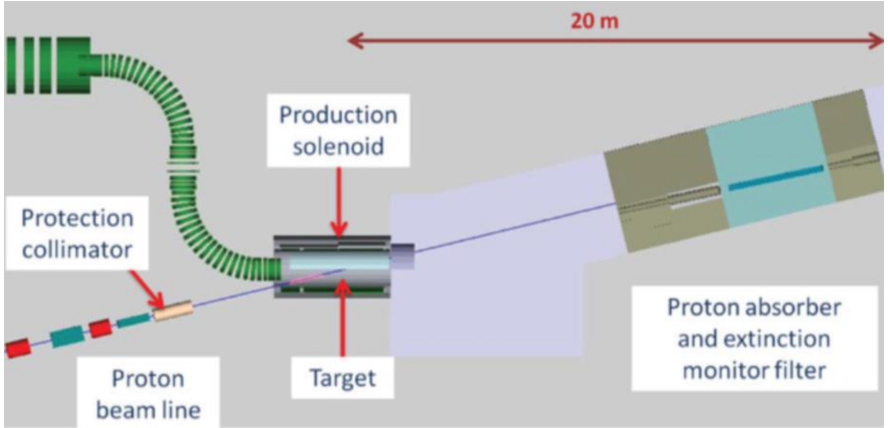


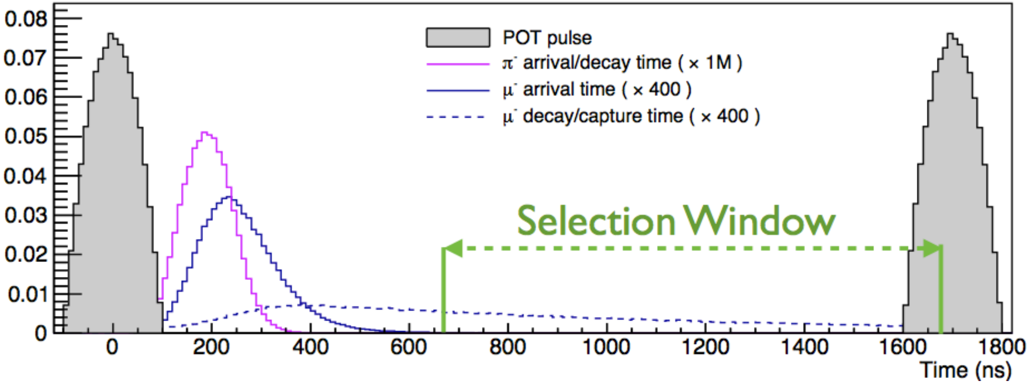
Mu2e Technical Design



Mu2e Beamline

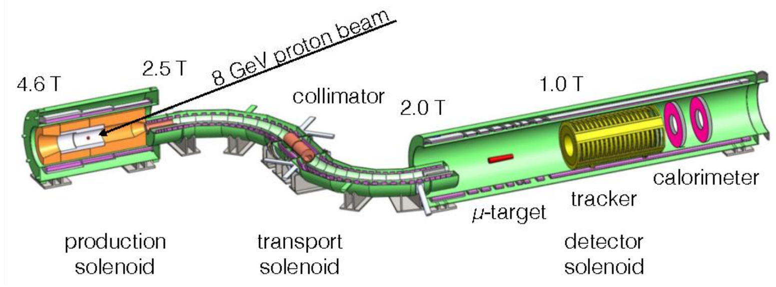
- Proton beam intersects a tungsten target, results in π that decay to μ in flight
- Unlike MEG II or Mu3e, Mu2e implements a "pulsed" proton beam at ~6 MHz (1700 ns)
- Pulses "wait out" the π RPC background: $\tau_{\pi} \ll \tau_{\mu \text{ in Al}}$ (864 ns)
- Start data-collection once π have decayed
- Require extinction of 10^{-10}; measured by extinction monitor





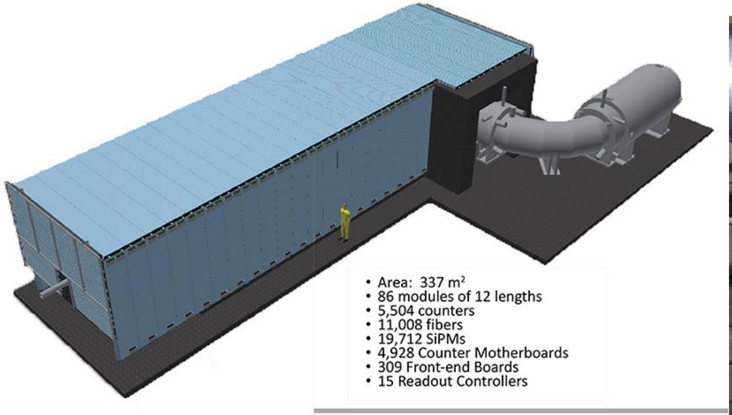
Mu2e Magnets

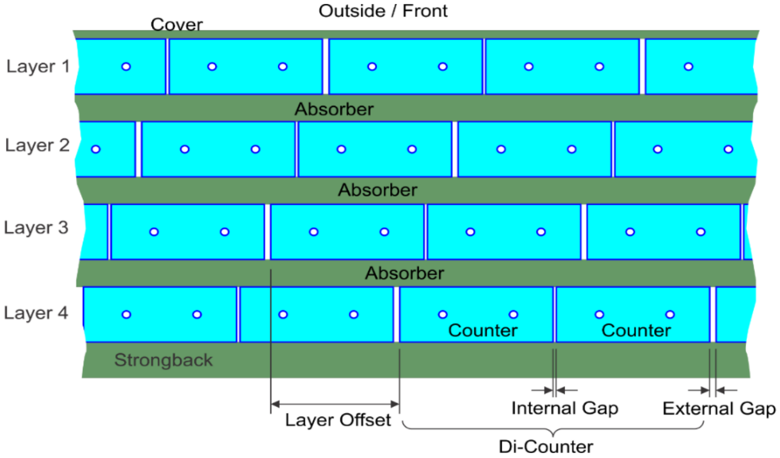
- Production solenoid removes vast majority of unwanted particles from proton target interactions and remaining protons; backwards π then decay to muons
- Transport solenoid ‘S’ shape selects negative charge and desired muon momentum
- Detector solenoid is grated; curves signal electrons towards from the μ-target to the tracker+calorimeter



Mu2e CRV

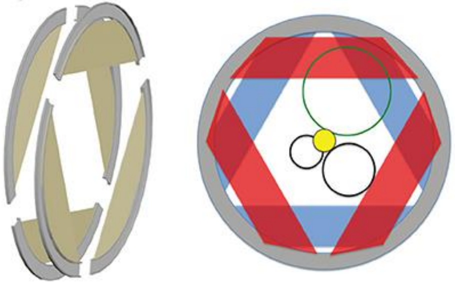
- Cosmic ray veto module surrounds the detector solenoid aiming to eliminate background from cosmics
- 4 layers, O(10k) fibers+SiPMs
- **All modules constructed!**

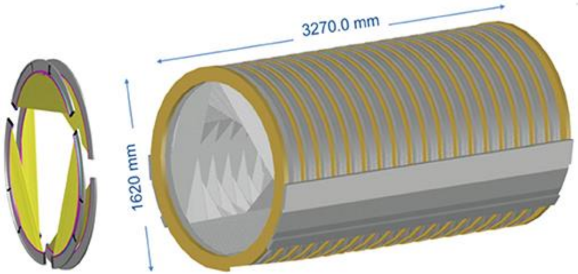




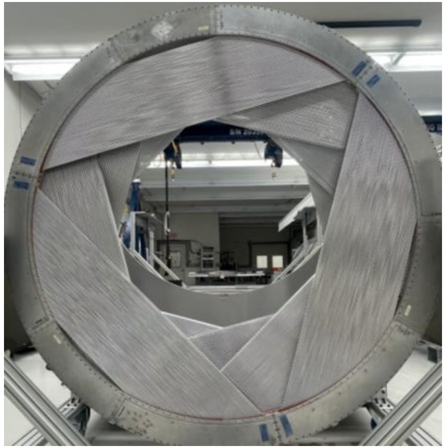
Mu2e Tracker

- Mu2e e^-drift chamber
- DIO spectrum at end-point motivates precise momentum resolution requirement (**goal ~150 keV**)
- Vast majority of e^- to escape through inner hole without interaction
- Total of ~20k 5 mm diameter straws
- 120 degree 'panels' with 96 straws
- Oriented and positioned to optimize acceptance, resolution, etc. (216 panels, 36 planes, 18 stations)
- ~1.6 m diameter/3.2 m length
- 33/36 planes completed!
- **Expected completion in Early 2025**

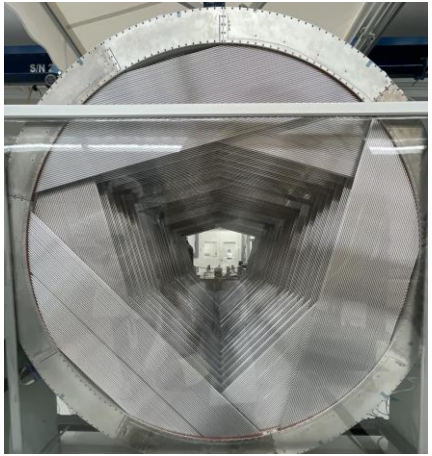




Assembled Station

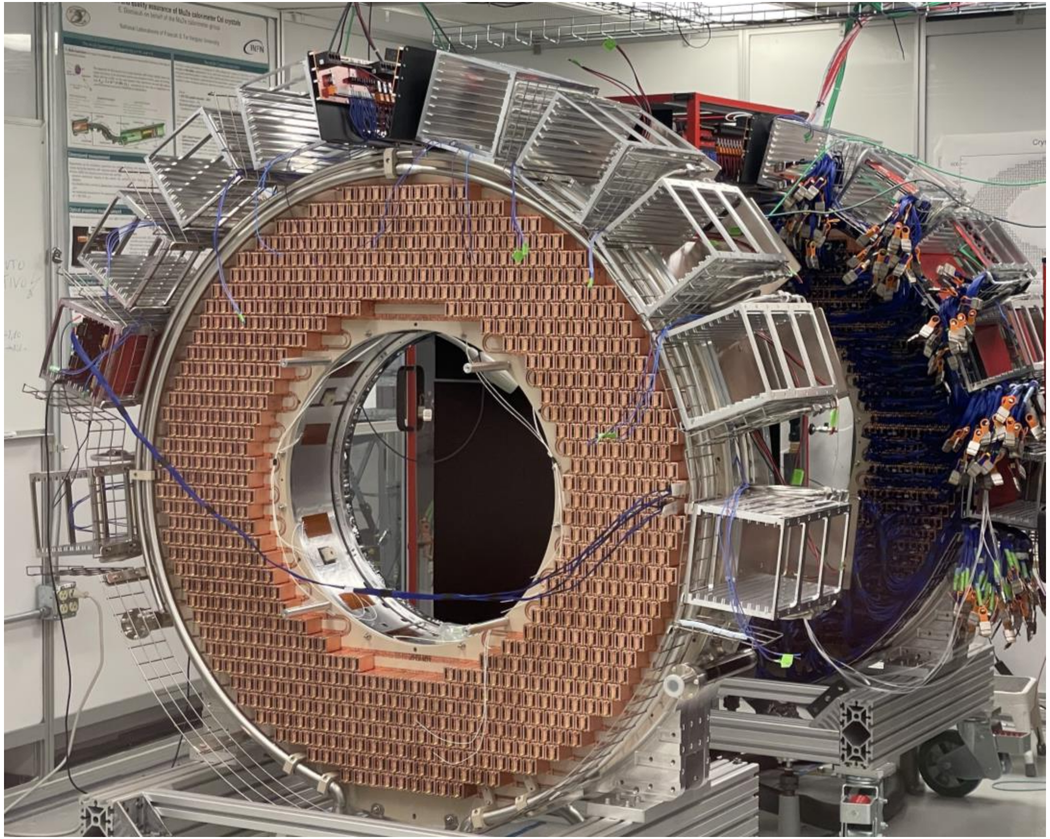


Assembled Planes



Mu2e Calorimeter

- 2 circular disks with a total of 674 undoped CsI crystals
- Objectives:
  - Particle identification (μ at signal momentum)
  - Track seeding (T0)
  - Stand alone trigger
- **Disks are complete; currently cabling and preparing for deliver to hall**

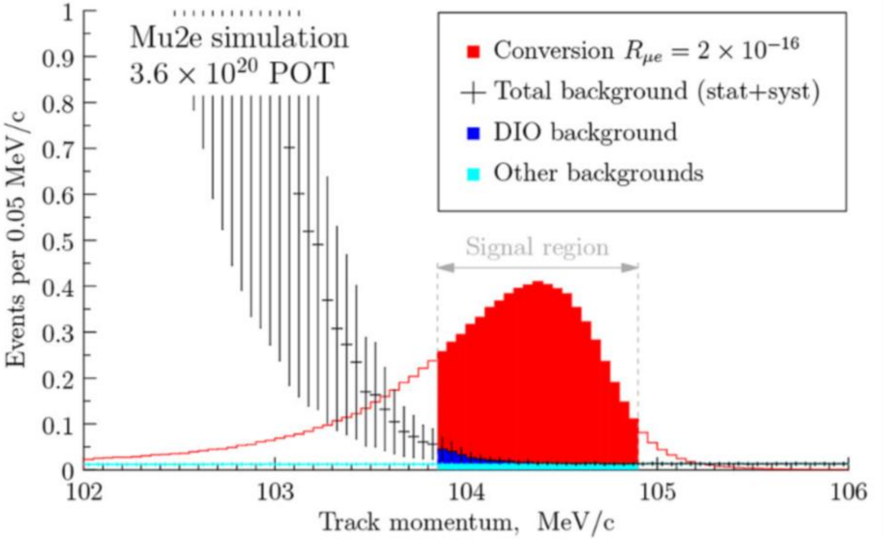


Mu2e Expected Physics Background Rates

- Dominant sources of background are expected from cosmics and DIO (0.35/0.41)

Expected Background for Full Runtime

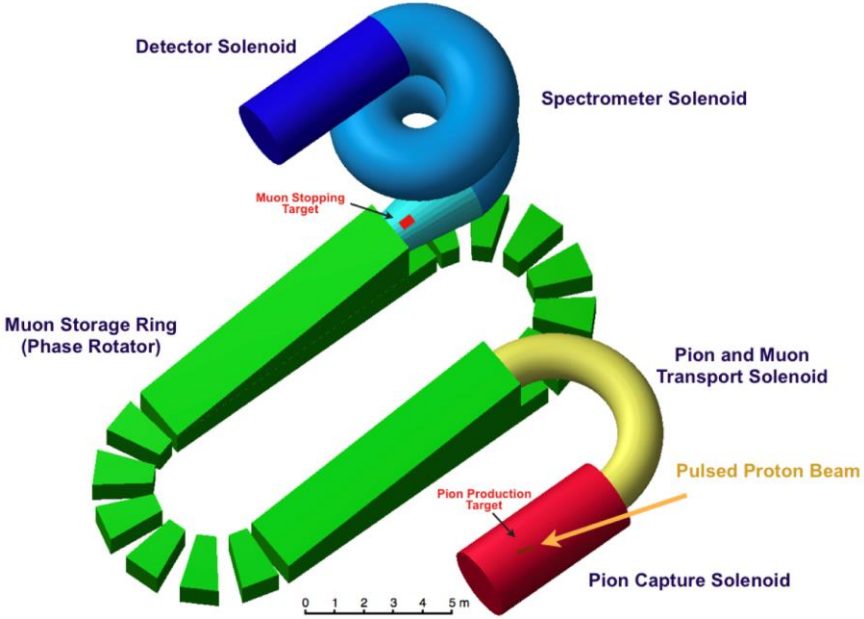
Process	Expected number
Cosmic ray Muons	$0.209 \pm 0.02 \pm 0.06$
DIO	$0.144 \pm 0.03 \pm 0.11$
Antiprotons	$0.040 \pm 0.001 \pm 0.020$
RPC	$0.021 \pm 0.001 \pm 0.002$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$2.1 \pm 1.0 \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	0.41 ± 0.03



Mu2e Collaboration

Mu2e II - AMF - PRISM

- Future $\mu^- N \rightarrow e^- N$ experimental designs being discussed at both US and Japanese facilities are motivated by further background suppression (e.g. Fermilab: B. Echenard et al. 2203.08278)
- Example Improvements:
  - Likely requires alternate beam structure e.g. muon storage ring to suppress background
  - Low momentum muon beam (30 MeV)
  - Different target materials



J. Pasternak et al., 2018; Adapted from Y. Kuno 2005

Summary

- CLFV discovery implies physics BSM
- MEG II is taking its 4th year of physics data at PSI; first physics result is published and expects to reach goal of x10 improvement beyond MEG
- Mu3e experiment is in the commissioning phase with data-taking starting as soon as 2025 and plans to improve beyond current limit by x10000
- Mu2e and COMET $\mu^- N \to e^- N$ experiments plan for x10000 sensitivity improvement and physics data-taking in a few years