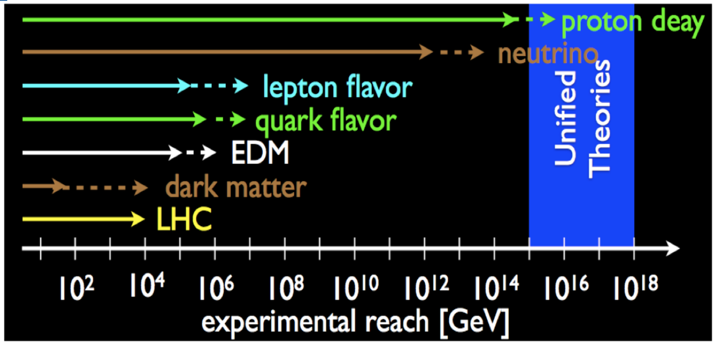
Charged Lepton Flavor Violation Experiments

Ron Ray (Fermilab – Mu2e Project Manager)

SUSY 2018

7/25/18

Charged Lepton Flavor Violation

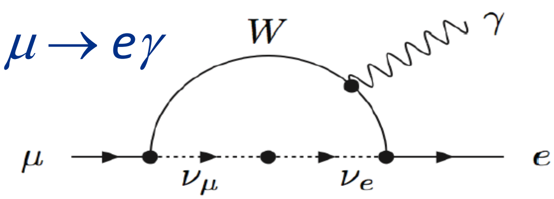


- Quarks and neutrinos both mix.
  - Those discoveries revolutionized physics
- What about charged leptons?
  - No known Global Symmetry that requires flavor conservation
  - CLFV is a probe of new physics
    - Directly addresses physics of flavor and generations
    - Many extensions to the Standard Model predict large flavor violating effects that are in reach of next generation experiments
    - Current and next generation CLFV experiments are sensitive to physics well above the TeV scale (10^3 – 10^4 TeV)
- Rates of CLFV processes are model dependent and vary widely depending on the underlying physics.
  - CLFV processes are powerful discriminators.

CLFV and the νSM

- CLFV can be generated with massive neutrinos:
- These processes are extremely suppressed in the SM, due to GIM mechanism and tiny neutrino masses. For example:

$\mu \rightarrow e\gamma$



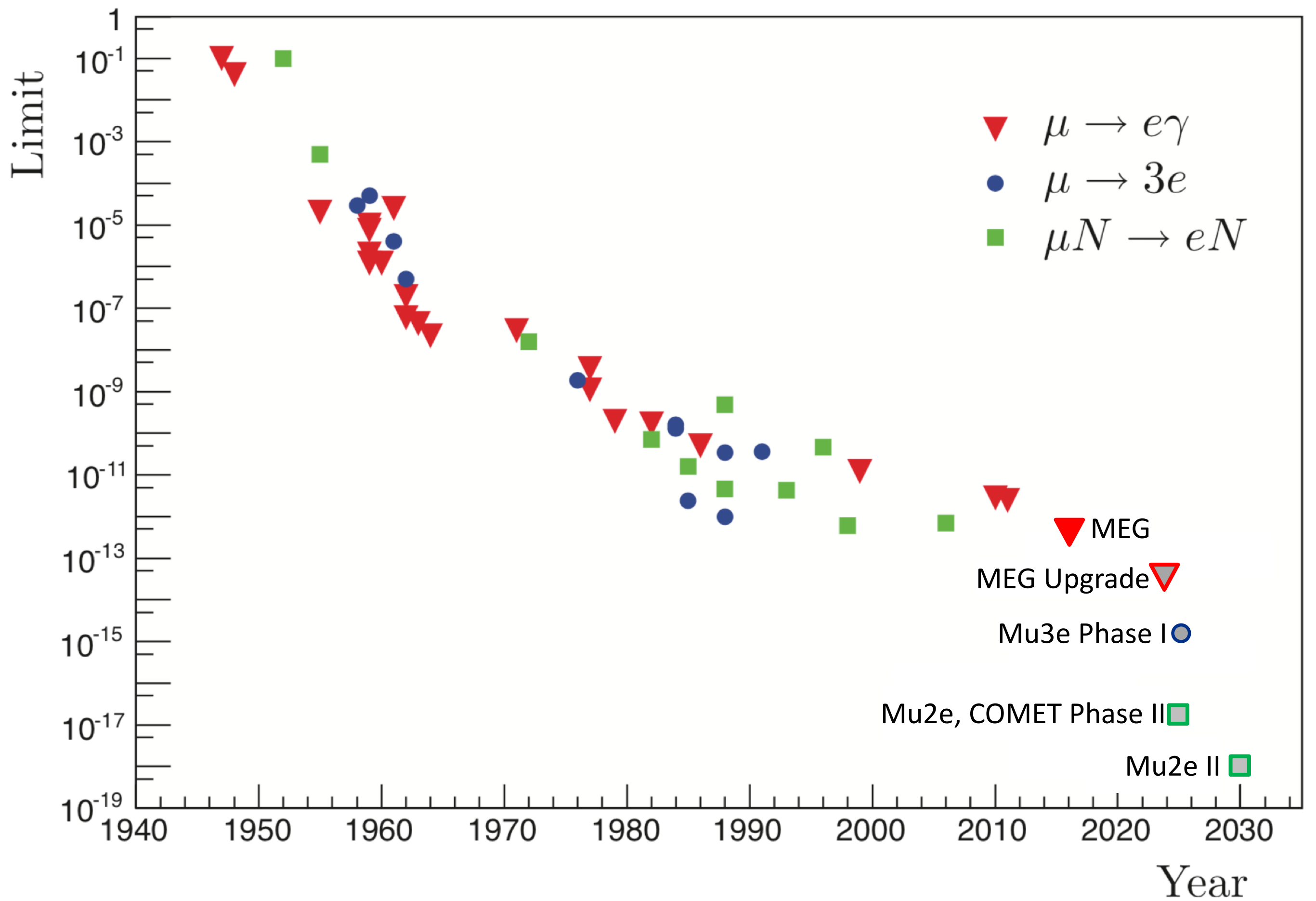
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$

PMNS unitary, $\Sigma\, U_{\mu i}^*\, U_{ei} = 0$

- Effectively zero from an experimental perspective. No SM Pollution!
- Observation of CLFV would be unambiguous evidence of physics beyond the Standard Model

History of CLFV Searches using Muons

There have been many searches for CLFV in muon decays



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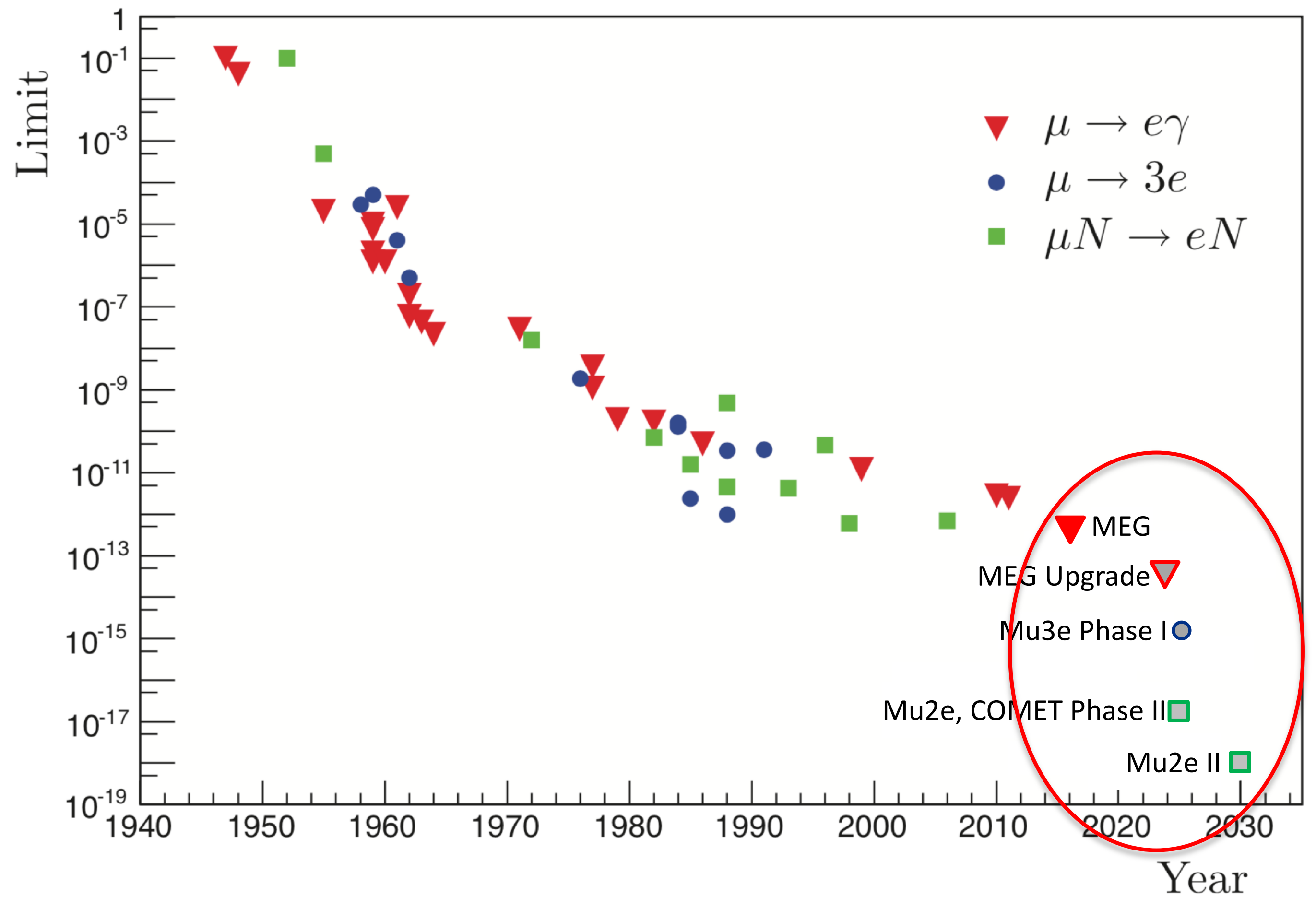

CLFV Processes

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	NA62
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	LHCb, Belle II
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu^- N \rightarrow e^- N$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

Expect significant progress in the near future

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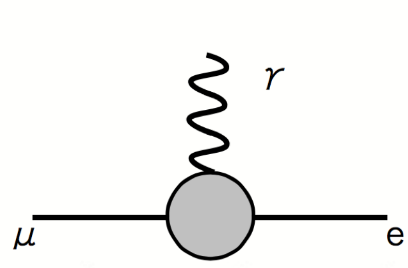
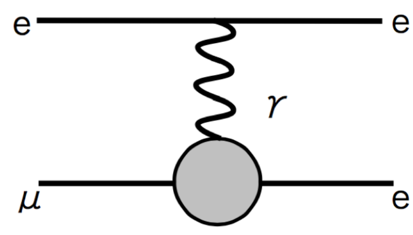
Muons provide the most sensitivity

CLFV in Muons

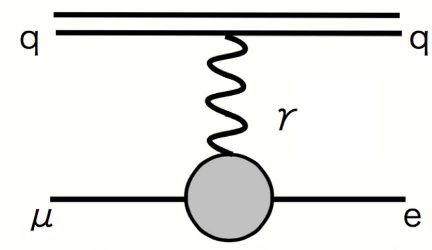
$\mu^+ \rightarrow e^+\gamma$



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

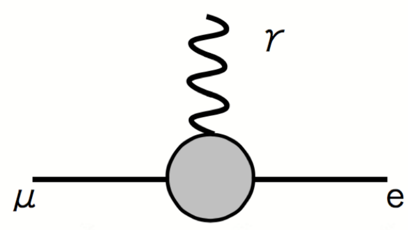


$\mu^-N \rightarrow e^-N$

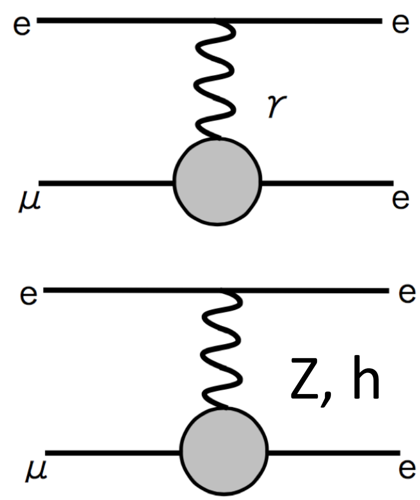


CLFV in Muons

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



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



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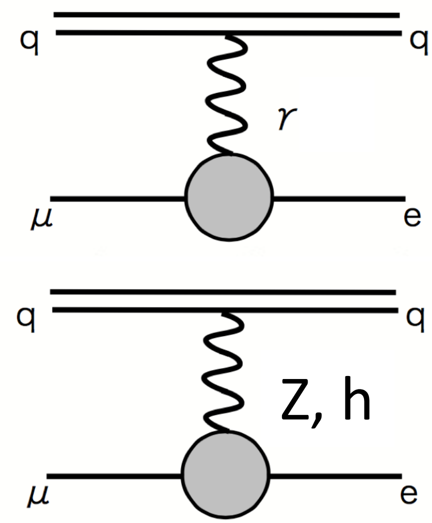
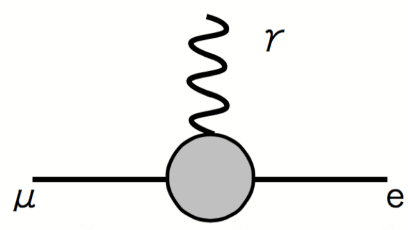


CLFV in Muons

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



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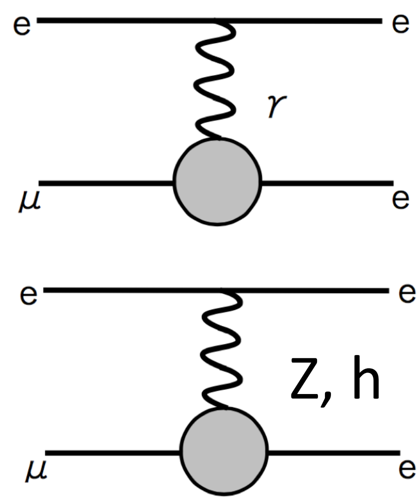

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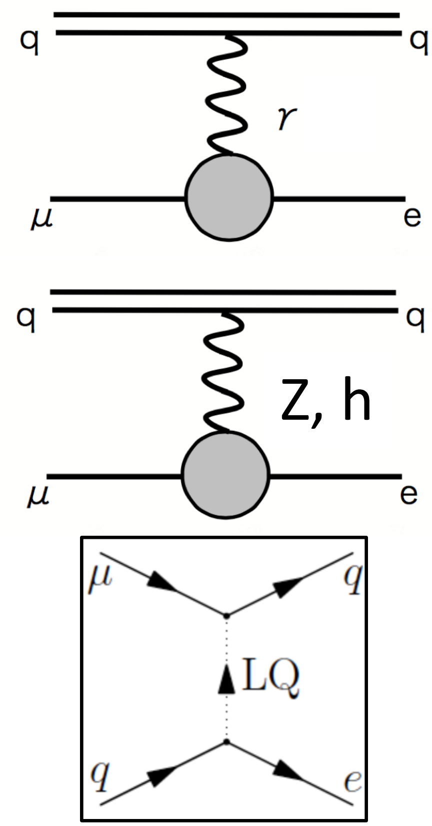


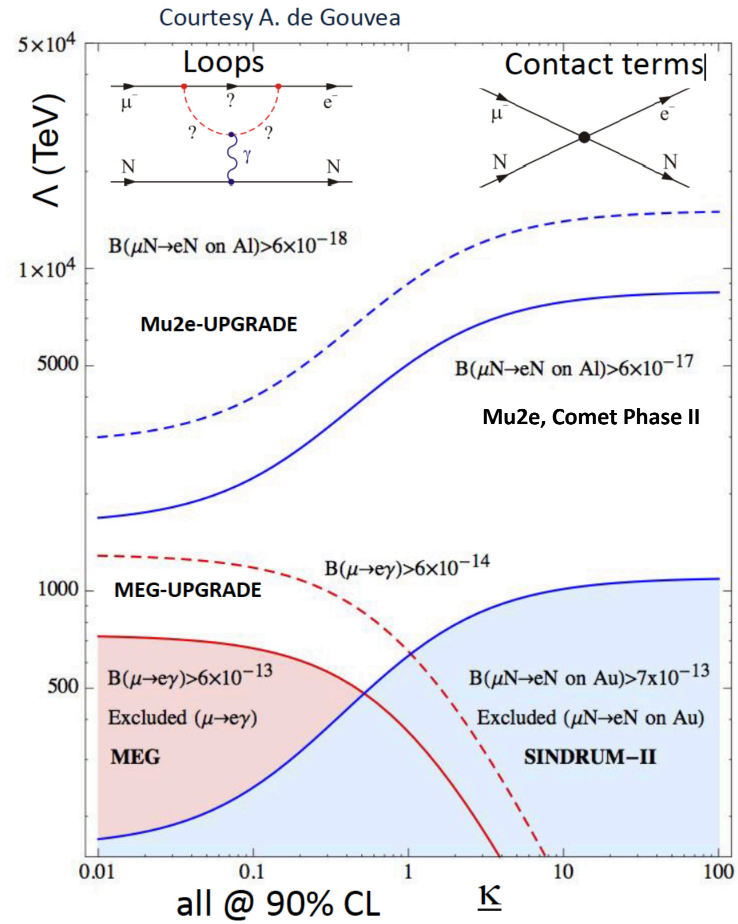
CLFV in Muons

Model Independent Evaluation

- Add CLFV operators to SM Lagrangian

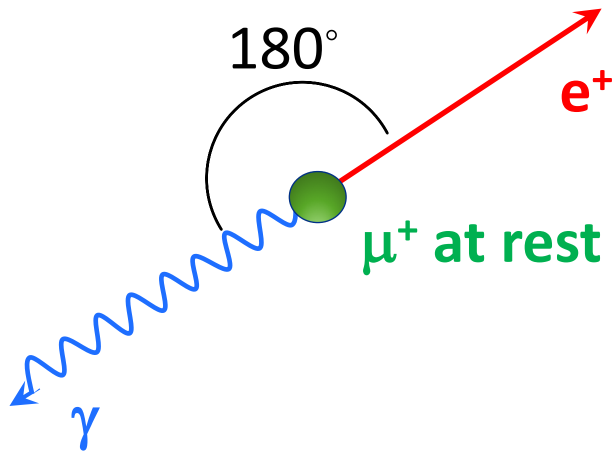
$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right)$$

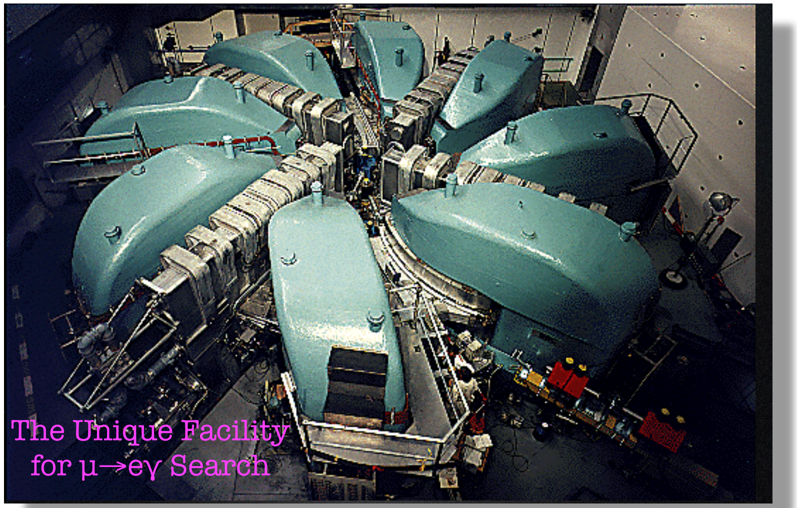
- Λ is mass scale of new physics
- κ controls relative contribution of loops and contact terms



- CLFV provides a deep probe of New Physics parameter space
  - Sensitive to $\Lambda_{eff} \sim 10^3 - 10^4$ TeV/c^2

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





MEG at PSI is the state-of-the-art for CLFV in muons

B($\mu \rightarrow e^+\gamma$) < 4.2 x 10^{-13} (90% CL)

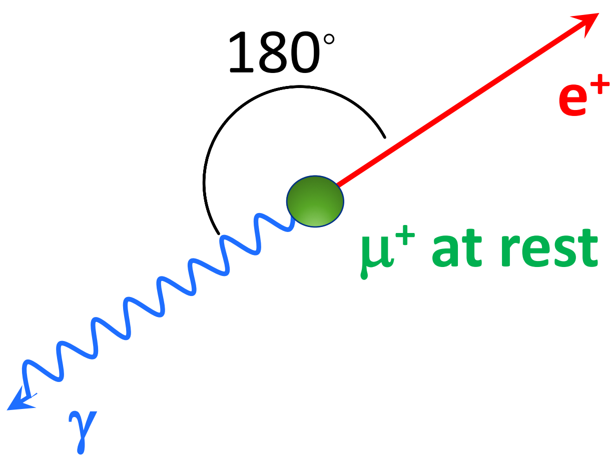
– uses full data set (2009-2013) - 7.5 x 10^{14} stopped muons

A. M. Baldini, et al. (MEG) Eur. Phys. J. C76, 8 (2016) 434.

MEG II upgrade designing for a factor of 10 improvement over current state-of-the-art

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

Signal



Electron and gamma are back-to-back
$E_e = E_\gamma = m_\mu/2$

Backgrounds

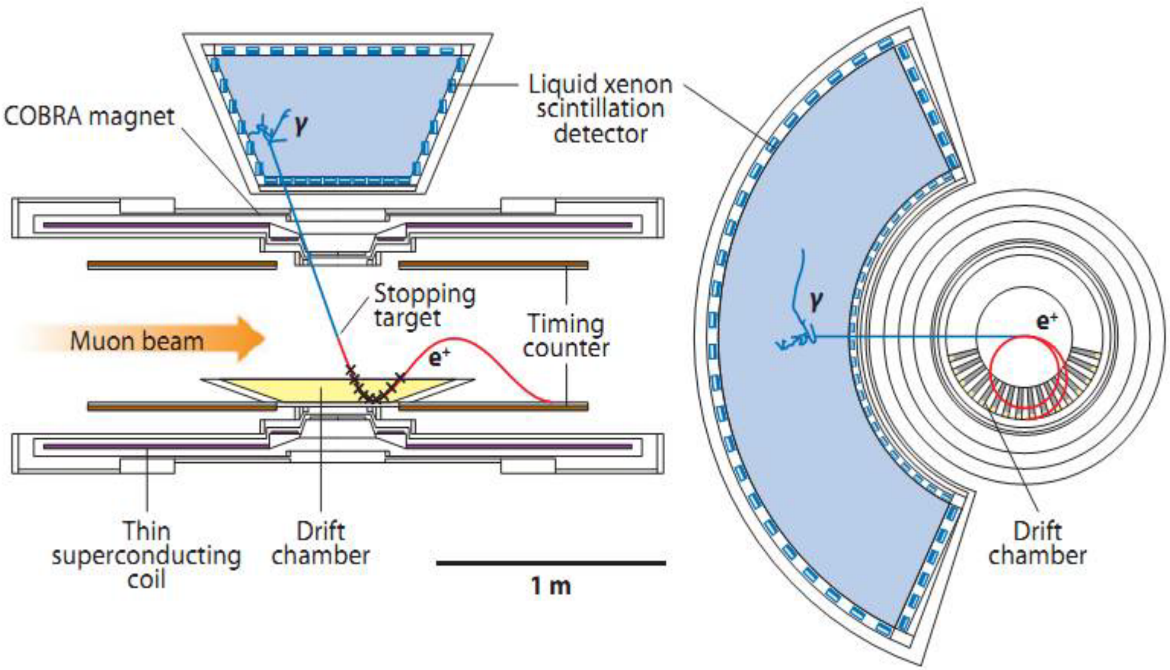
$\mu^+ \rightarrow e^+\nu\nu\gamma$ (*Radiative Muon Decay*)

Accidentals

$$B_{ACC} \propto \left(\frac{R_\mu}{D}\right)(\Delta t_{e\gamma})\left(\frac{\Delta E_e}{m_\mu/2}\right)\left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

Keys to success: Excellent energy, timing and angular resolutions

MEG Detector



- Liquid Xe calorimeter
  - PMT readout
  - 11% of solid angle
- Drift Chamber (DC)
  - Radius : 19 - 28 cm
- Scintillator timing counters (TC)
- DC and TC inside graded solenoid field
- 205 μm polyethelene target

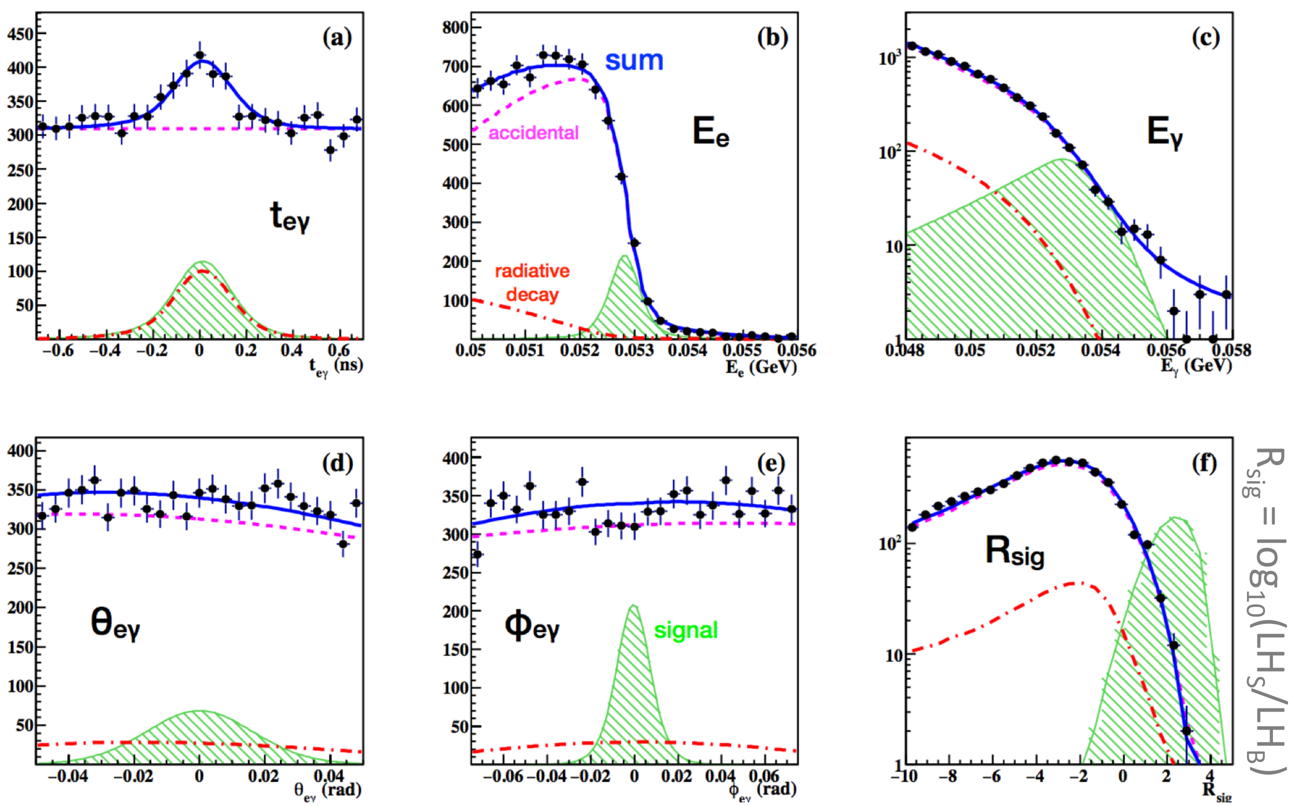
MEG Calibrations

Table 1 The calibration tools of the MEG experiment.

Process		Energy	Main Purpose	Frequency
Cosmic rays	$\mu^{\pm}$ from atmospheric showers	Wide spectrum O(GeV)	LXe-DCH relative position	annually
			DCH alignment	
			TC energy and time offset calibration	
			LXe purity	on demand
Charge exchange	$\pi^- p \to \pi^0 n$ $\pi^0 \to \gamma\gamma$	55, 83, 129 MeV photons	LXe energy scale/resolution	annually
Radiative μ–decay	$\mu^+ \to e^+ \gamma\nu\bar{\nu}$	photons > 40 MeV,	LXe-TC relative timing	continuously
		positrons > 45 MeV	Normalisation	
Normal μ–decay	$\mu^+ \to e^+ \nu\bar{\nu}$	52.83 MeV end-point positrons	DCH energy scale/resolution	continuously
			DCH and target alignment	
			Normalisation	
Mott positrons	e^+ target $\to e^+$ target	$\approx$ 50 MeV positrons	DCH energy scale/resolution	annually
			DCH alignment	
Proton accelerator	$^{7}Li(p, \gamma)^{8}Be$	14.8, 17.6 MeV photons	LXe uniformity/purity	weekly
	$^{11}B(p, \gamma)^{12}C$	4.4, 11.6, 16.1 MeV photons	TC interbar/ LXe–TC timing	weekly
Neutron generator	$^{58}Ni(n, \gamma)^{59}Ni$	9 MeV photons	LXe energy scale	weekly
Radioactive source	$^{241}Am(\alpha, \gamma)^{237}Np$	5.5 MeV α's, 56 keV photons	LXe PMT calibration/purity	weekly
Radioactive source	$^{9}Be(\alpha_{^{241}Am}, n)^{12}C^{\star}$ $^{12}C^{\star}(\gamma)^{12}C$	4.4 MeV photons	LXe energy scale	on demand
LED			LXe PMT calibration	continuously

Scale and resolutions determined with high degree of confidence

MEG Final Result

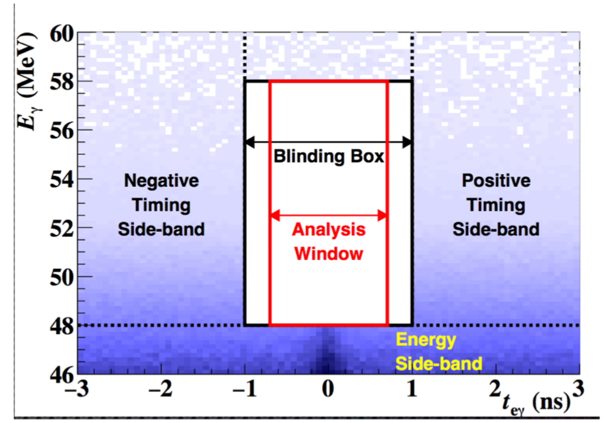


Utilizes 5 variables

- E_e, E_γ
- $t_{e\gamma} = t_e - t_\gamma$
- $\theta_{e\gamma}$
- $\phi_{e\gamma}$

Blind Analysis

Full Likelihood fit



Best fit BF($\mu^+ \rightarrow e^+\gamma$) = -2.2 x 10^{-13}

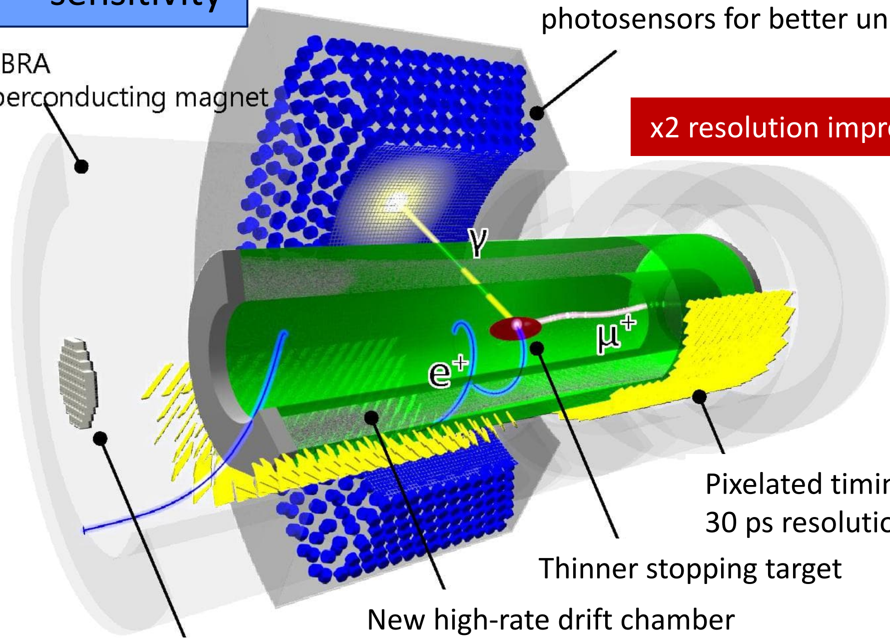
BF($\mu^+ \rightarrow e^+\gamma$) < 4.2 x 10^{-13} @ 90% CL

~7.5 x 10^{14} stopped μ^+ from full data set (2009-2013)

Eur. Phys. J. C76, 8 (2016) 434 [arXiv:1605.05081]

MEG II Upgrade – Another Factor of 10

~4x10^{-14} sensitivity

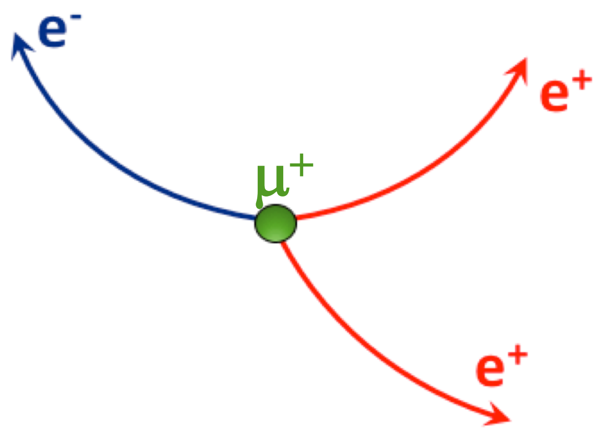


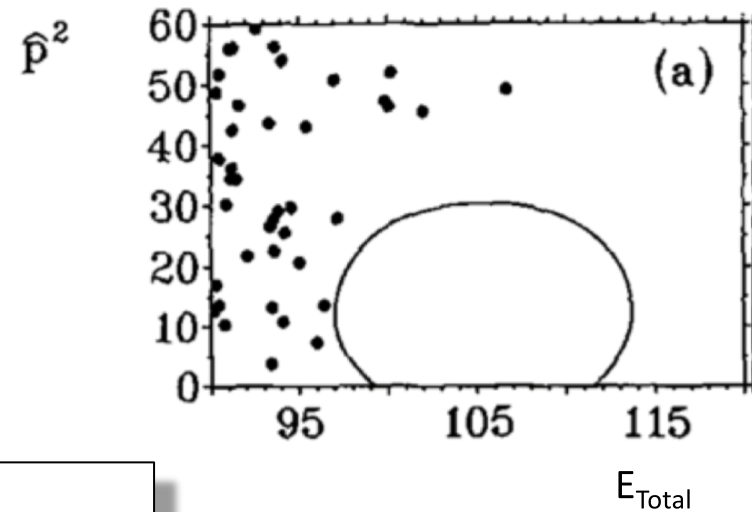
x2 resolution improvement everywhere

PDF parameters	MEG	MEG II
E_{e^+} (keV)	380	130
θ_{e^+} (mrad)	9.4	5.3
ϕ_{e^+} (mrad)	8.7	3.7
z_{e^+}/y_{e^+} (mm) core	2.4/1.2	1.6/0.7
E_γ(%) (w>2 cm)/(w<2 cm)	2.4/1.7	1.1/1.0
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.6/2.2/5
$t_{e^+\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	≈ 99	≈ 99
Photon	63	69
e^+(tracking × matching)	30	70

- Commissioning with beam has begun!
- Physics data taking will begin 2019 – 3 year run
- See talk by Cecilia Voena in Flavor Physics session for more details

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





Current state-of-the-art

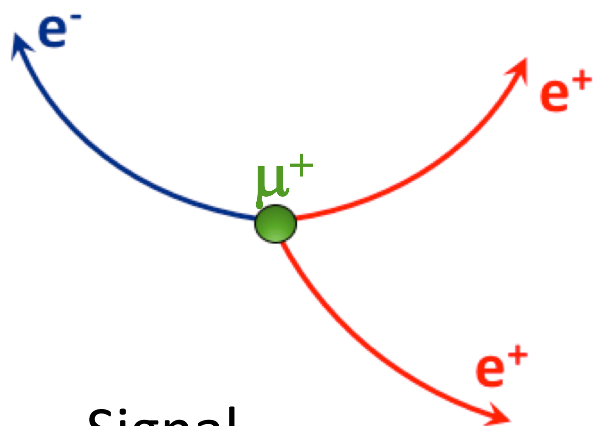
$B(\mu^+ \rightarrow e^+e^+e^-)$ < 1 x 10^{-12} (90% CL)

U. Bellgardt, et al. (SINDRUM) Nucl.Phys. B299 (1988) 1.

<u>Next generation at PSI</u>

Mu3e	Phase I	x400 (early 2020s)
	Phase II	x10,000

$\mu^+ \to e^+e^+e^-$



Signal

$$\Sigma p = 0$$

$$E_e < \frac{m_\mu}{2}$$

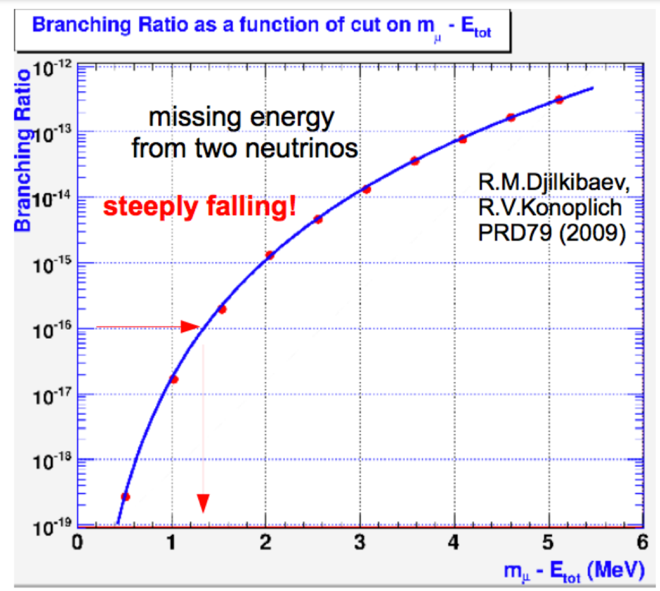
$$\Sigma E_e = m_\mu$$

Backgrounds

Accidentals

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

(Radiative Muon Decay)

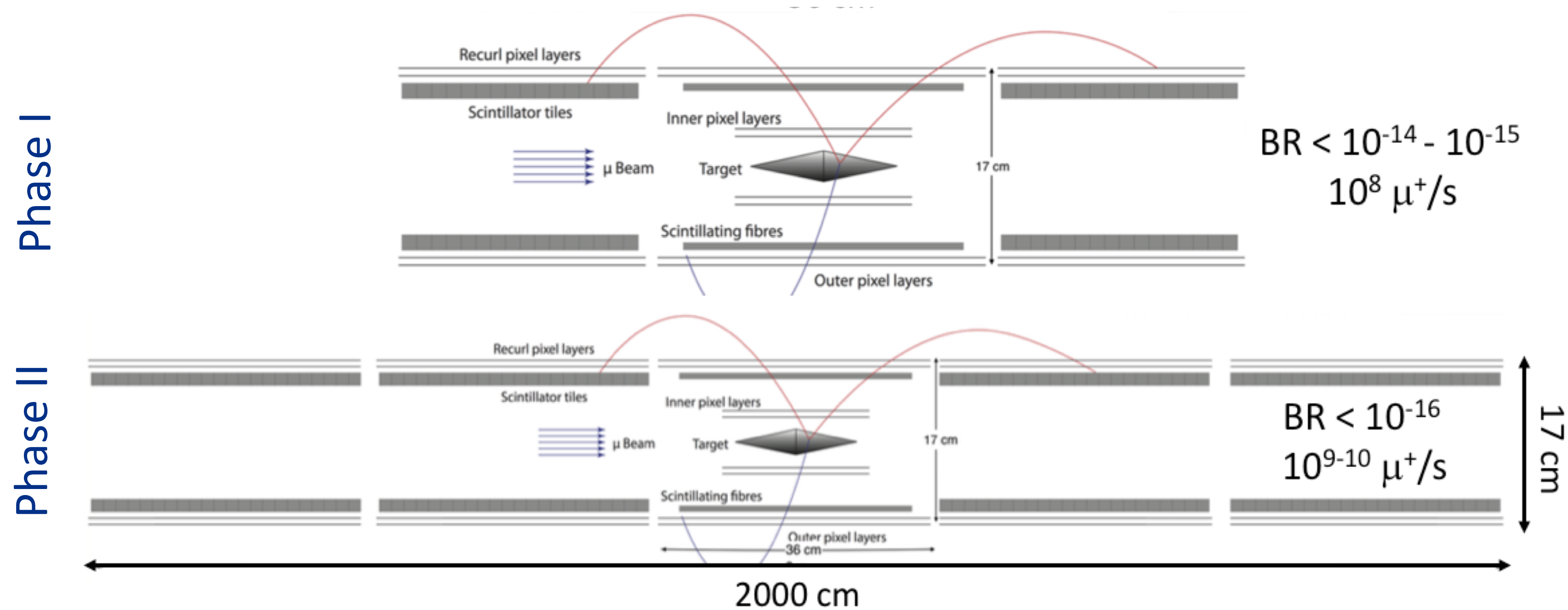


Keys to success: excellent momentum, timing, and vertex resolutions

Mu3e Experiment

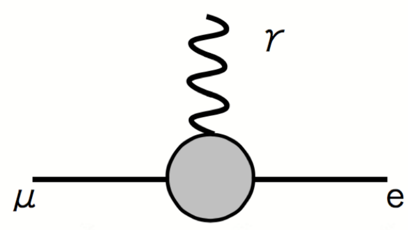
- Relies on development of fast, very thin pixel sensors
  - HV Maps technology
  - Prototyping underway
- Phased Experiment
  - Phase I - PiE5 beamline shared with MEG – Early 2020s
  - Phase II - New High Intensity Muon Beamline

MuPix8 prototype



Muon to Electron Conversion

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



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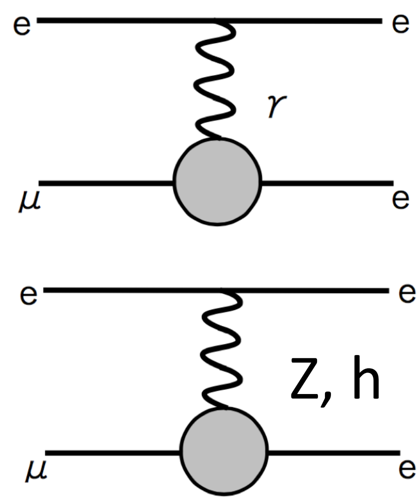
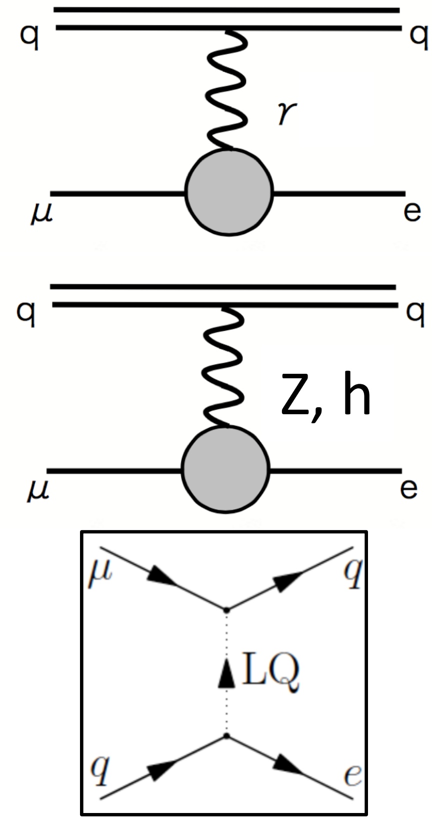


$\mu^- N \rightarrow e^- N$

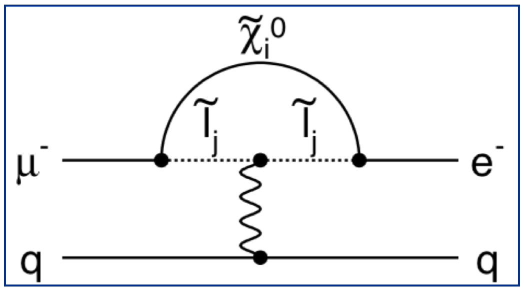


- Different channels offer complementary sensitivity.
- Their comparison is a powerful model discriminant.

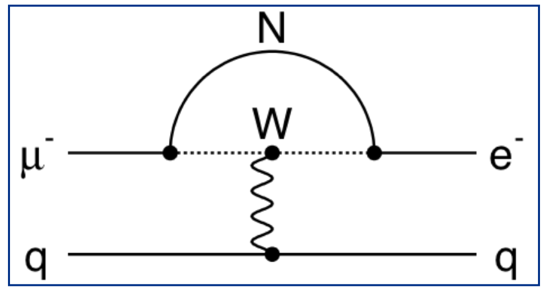
Muon to Electron Conversion

A wide array of BSM physics allow for $\mu N \rightarrow eN$ conversion, either through loops or exchange of heavy intermediate particles

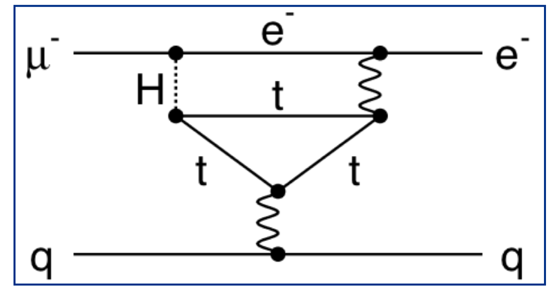
Loops



Supersymmetry

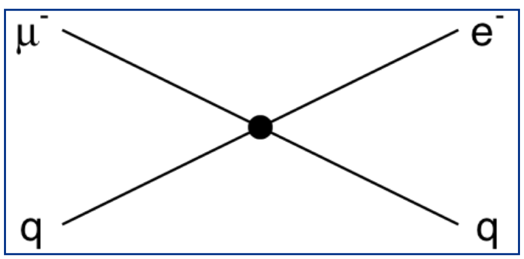


Heavy Neutrinos

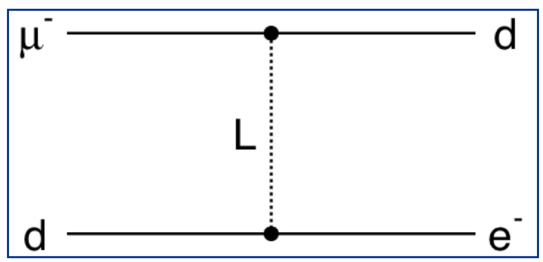


Two Higgs Doublets

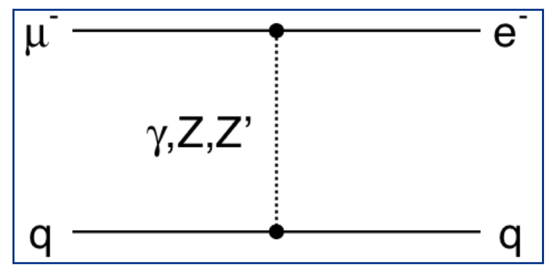
Contact Interactions



Compositeness

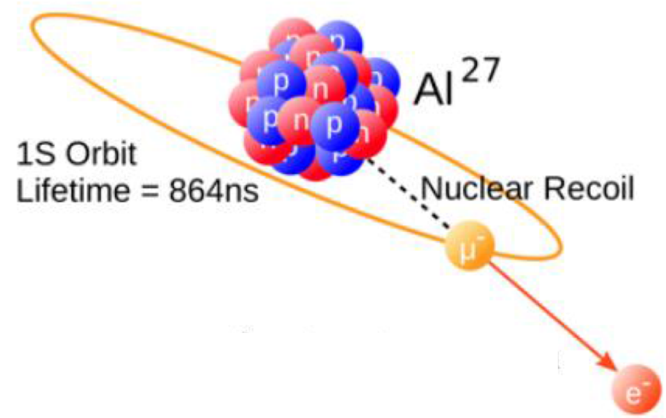


Leptoquarks



New Heavy Bosons / Anomalous Couplings

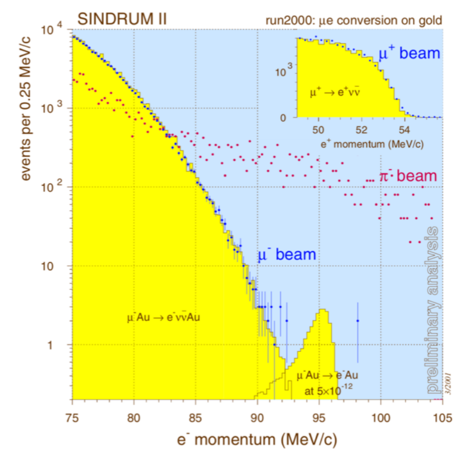
Muon to Electron Conversion



Current state-of-the-art

$$R_{\mu e} = \frac{\Gamma(\mu^- Au \rightarrow e^- Au)}{\Gamma(\mu^- Au\ Capture)} < 7 \times 10^{-13}\ (90\%\ CL)$$

W. Bertl, et al. (SINDRUM-II) Eur. Phys. J. C47 (2006) 337.

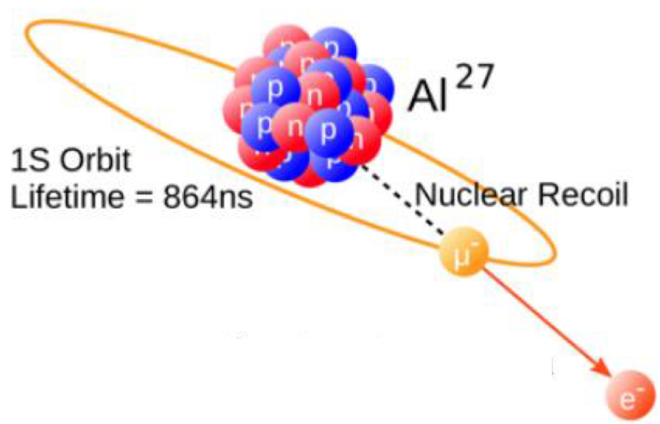


<u>Next generation</u>

DeeMee (J-PARC)	x10 (currently operating at low power)
Mu2e (Fermilab)	x10,000 (2021)
Comet (J-PARC) Phase-I	x10 – 100 (2020)
Phase-II	x10,000 (?)

Muon to Electron Conversion

Signal



Mono-energetic electron
$E_{\mu e} = m_{\mu} - B(A,Z) - R(A,Z) \sim 105$ MeV

Coherent interaction with nucleus

Backgrounds

Decay in Orbit (DIO)
$(\mu^- N \rightarrow e^- \nu \nu N)$

Radiative Pion Capture (RPC)
$(\pi^- N \rightarrow \gamma N' \rightarrow e^+ e^- N')$

Cosmic Rays

Keys to success: Large flux of stopped muons, excellent spectrometer resolution, pulsed proton beam, high efficiency cosmic veto

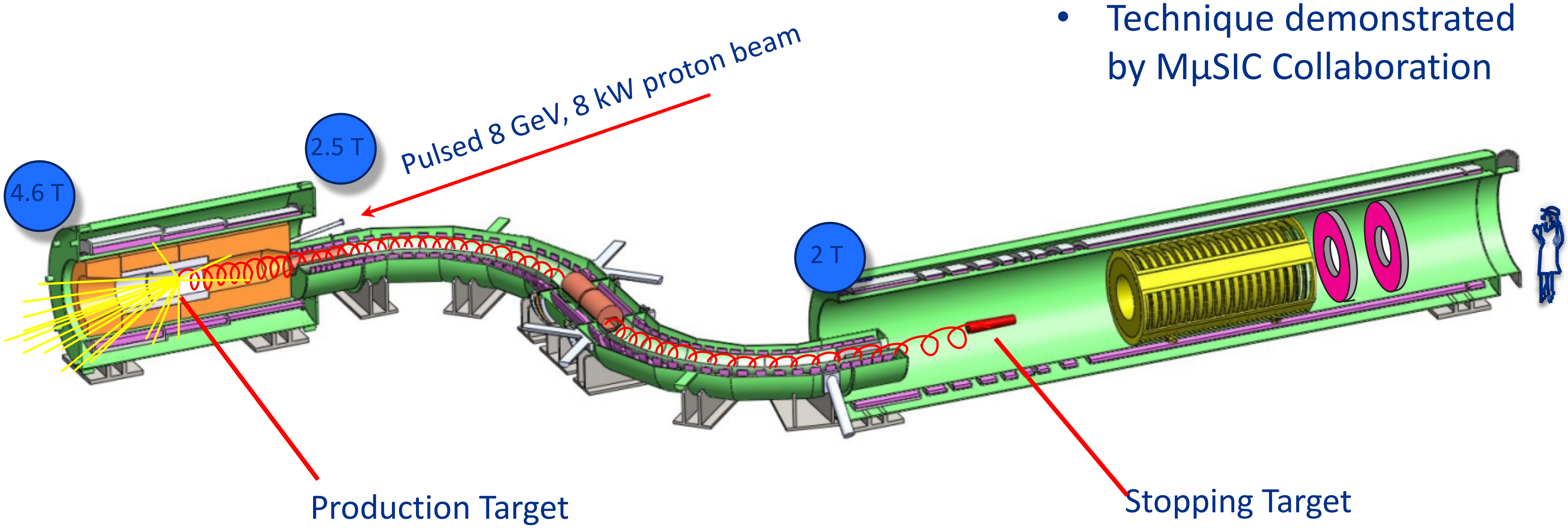
Mu2e Detector

Mu2e Project scope includes

- The Mu2e apparatus
  - Superconducting Solenoids
    - Production Solenoid
    - Transport Solenoid
    - Detector Solenoid

Production and Transport System

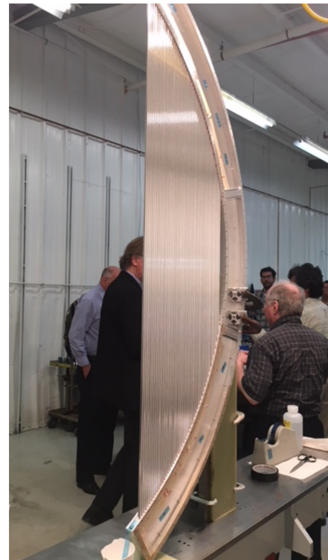
- Production target inside superconducting solenoid significantly enhances stopped muon yield
- Collimation system selects muon charge and momentum range
- 10^{10} Hz of stopped muons!
  - Technique demonstrated by MμSIC Collaboration

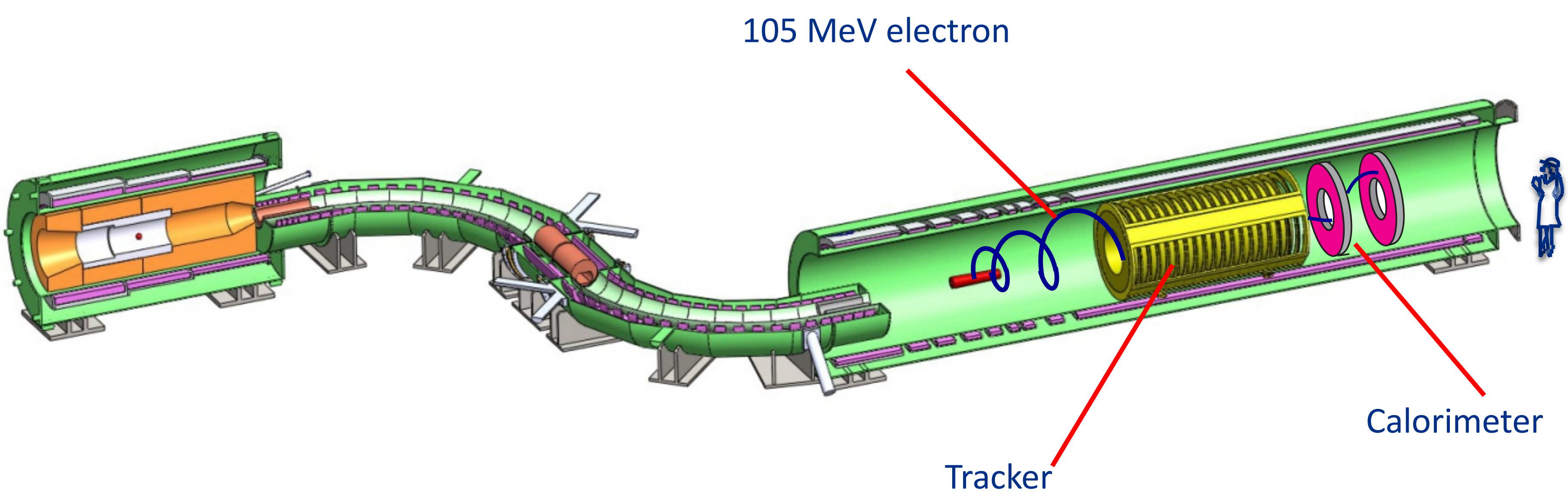


Mu2e Detector

Mu2e Project scope includes

- The Mu2e apparatus
  - Superconducting Solenoids
  - Tracker – Straw drift tubes
  - Calorimeter – Pure CsI crystals

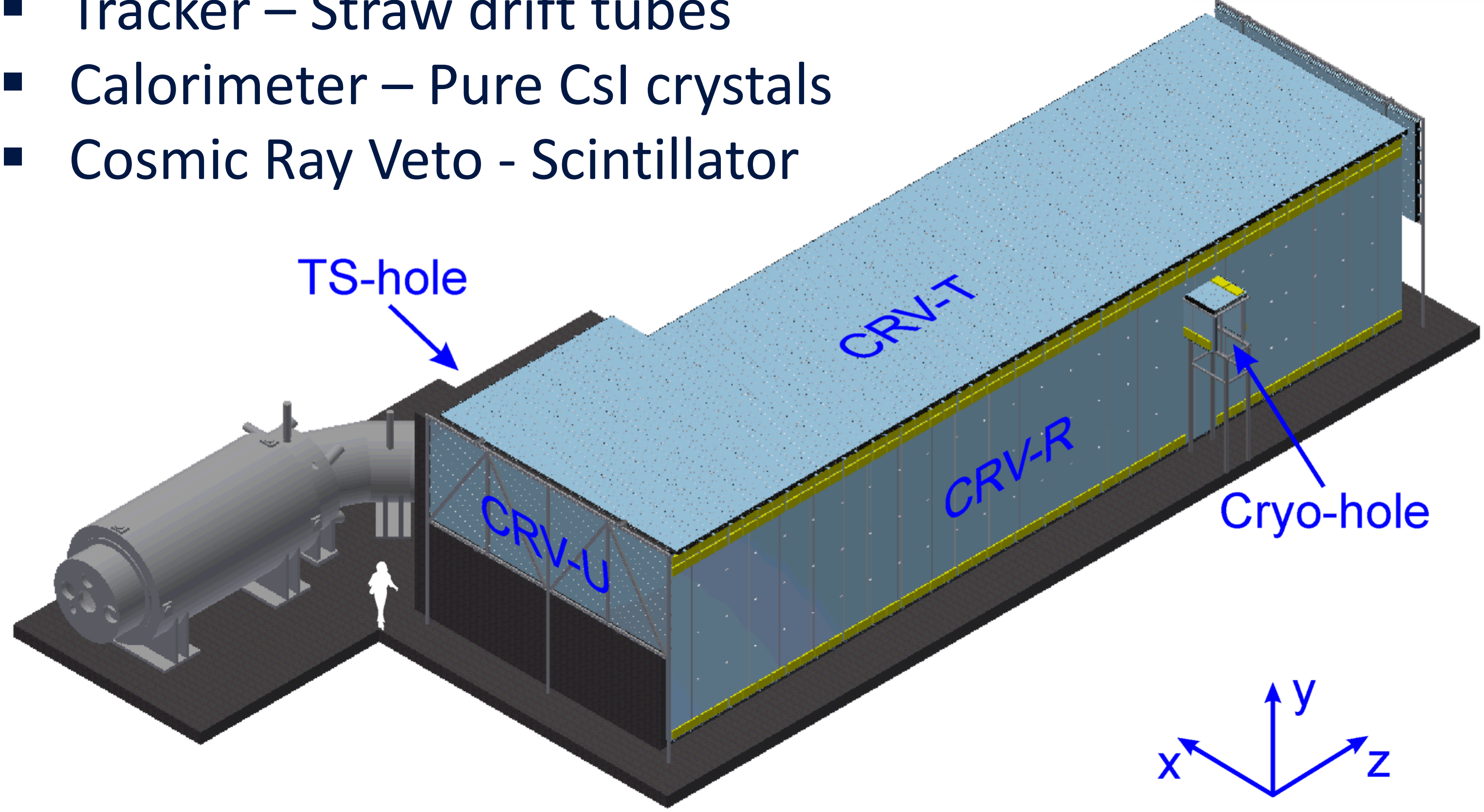




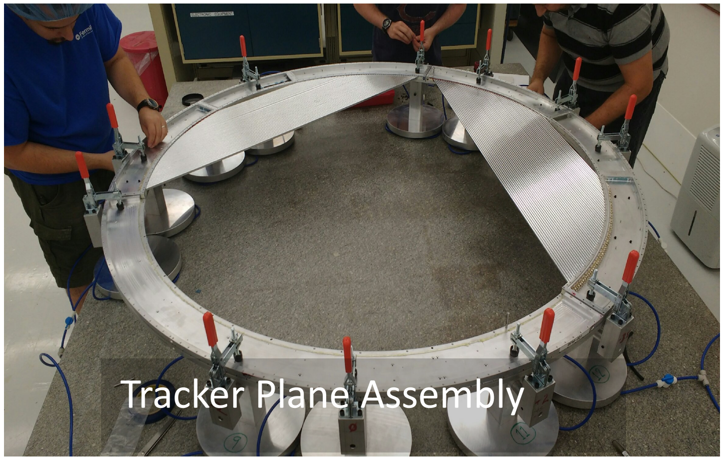
Mu2e Detector

Mu2e Project scope includes

- The Mu2e apparatus
  - Superconducting Solenoids
  - Tracker – Straw drift tubes
  - Calorimeter – Pure CsI crystals
  - Cosmic Ray Veto - Scintillator



Mu2e Construction Well Underway


Tracker Plane Assembly


Transport Solenoid Module


Production target testing


Transport Solenoid Warm Bore


Coils for transport solenoid

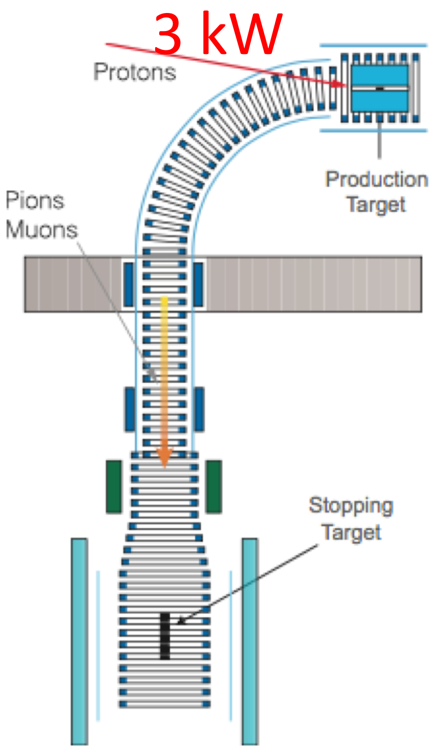

Production and Detector Solenoid Warm Bores

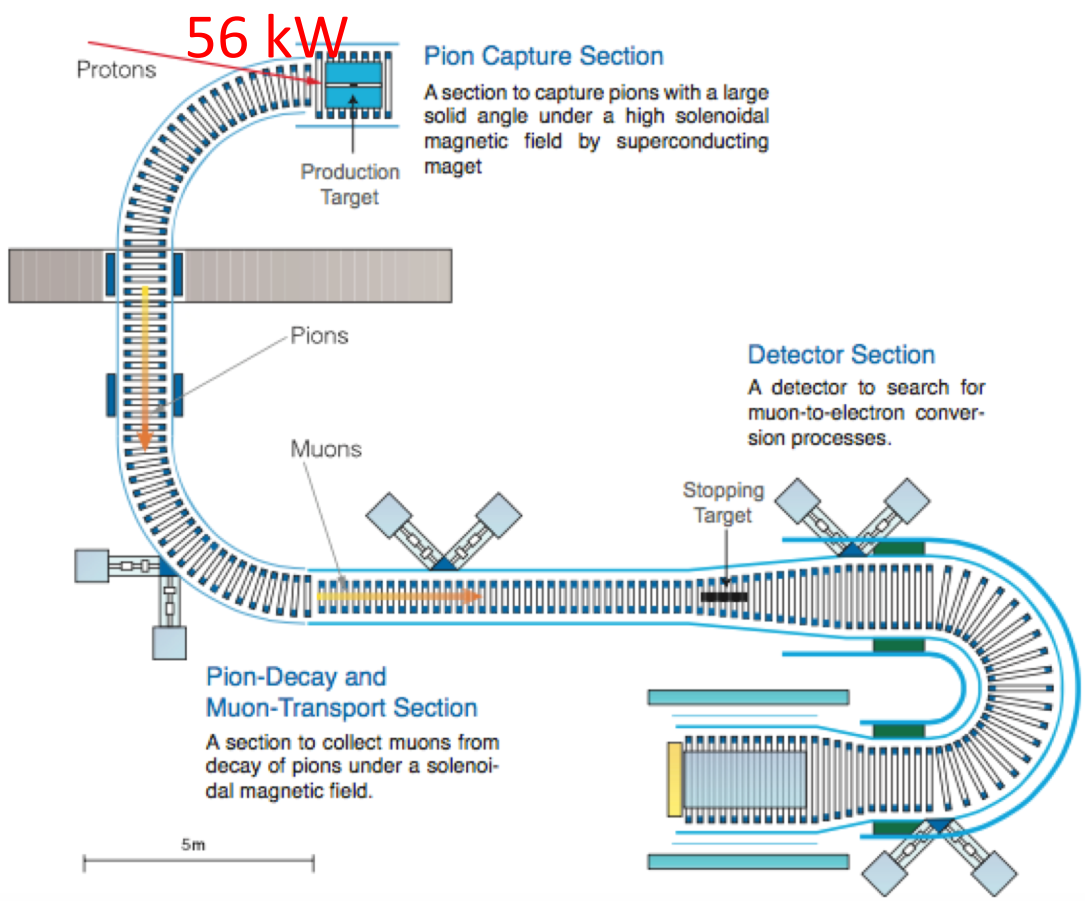
Commissioning begins in 2021

Comet Detector

Phase I

Phase –II





Starts ~2020

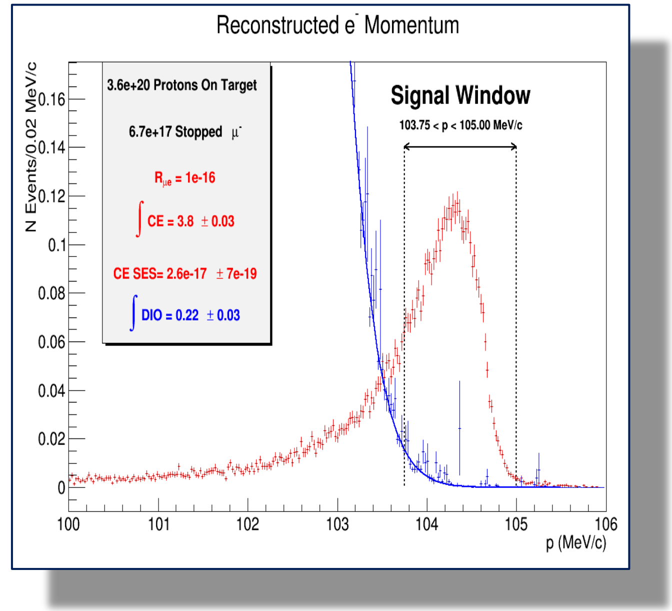
$R_{\mu e} < 10^{-14}$

Background Estimates

Mu2e Background estimates (COMET Phase-II very similar)

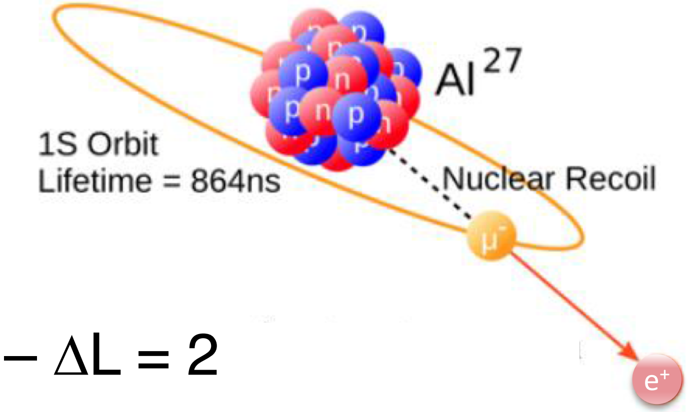
Category	Source	Events
Intrinsic	μ Decay in Orbit	0.14
	Radiative μ Capture	<0.01
Late Arriving Beam	Radiative π Capture	0.02
	Beam electrons	<0.01
	μ Decay in Flight	<0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton induced	0.04
	Cosmic Ray induced	0.21
Total Background		0.41

(assuming 6.7E17 stopped muons in 6E7 s of beam time)



Designed to be nearly background free

$\mu^- \rightarrow e^+$



Related to neutrinoless double beta decay – ΔL = 2

- Process not coherent.
- Nucleus can be in ground or excited state, so e^+ is not mono-energetic

Current state-of-the-art

$$R_{\mu e^+} = \frac{\Gamma(\mu^- \, {}^{48}Ti \rightarrow e^+ \, {}^{48}Ca)}{\Gamma(\mu^- \, {}^{48}Ti \rightarrow \nu_\mu \, {}^{48}Sc)} < 1.7 \times 10^{-12} \text{ (90\% CL)}$$

J. Kaulard, et al. (SINDRUM-II) Phys. Lett. B422 (1998) 334.

- Accessible to Mu2e during normal running.
- Comet Phase II requires a special run.

CLFV in tau Decays

- Relative theoretical parameter reach of μ and τ decays is model-dependent. Comparisons distinguish between models.
- Taus more powerful event-by-event – less GIM suppression
  - Can stop $\sim 10^{10}$ μ/s.
  - BABAR and Belle τ samples over a decade totaled $\sim 10^{10}$
- Significant effort from BABAR, Belle and LHCb, CMS, ATLAS
- Super flavor factories could significantly extend sensitivity
  - Polarized beams could provide additional advantages
    - Background reduction
    - CP violation in τ decays
    - g-2 of the τ
    - τ EDM
- Rich physics program with enough τ decays

Summary

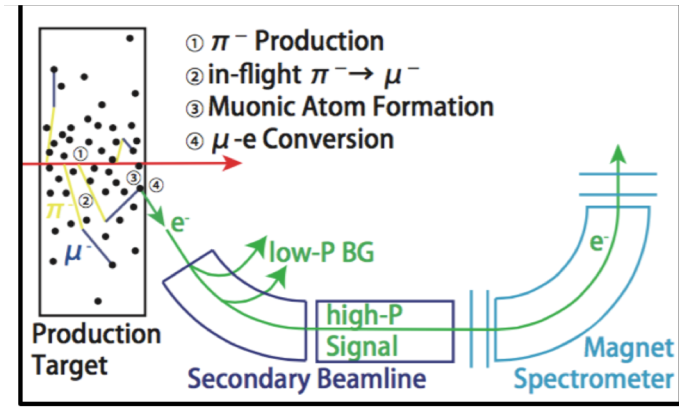
- The future is now for CLFV physics!
- Upcoming next generation muon experiments will make substantial leap in sensitivity
  - Broad, deep probes of new physics parameter space
    - $\Lambda_{NP} \sim O(10^3 - 10^4)$ TeV >> LHC
  - Compelling discovery sensitivity over a broad range of New Physics models (SUSY, GUT, Littlest Higgs, Multiple Higgs,...)
- Combining information from multiple processes is a powerful discriminator to understand underlying physics

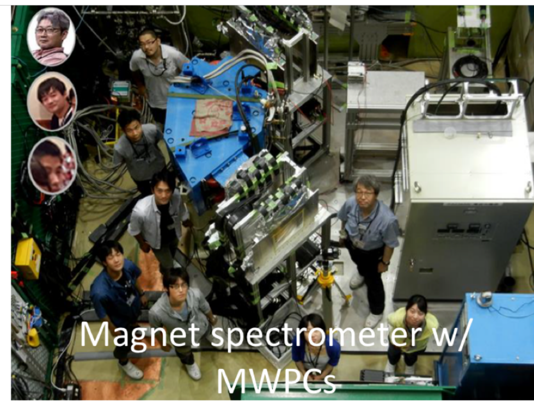
For More Information

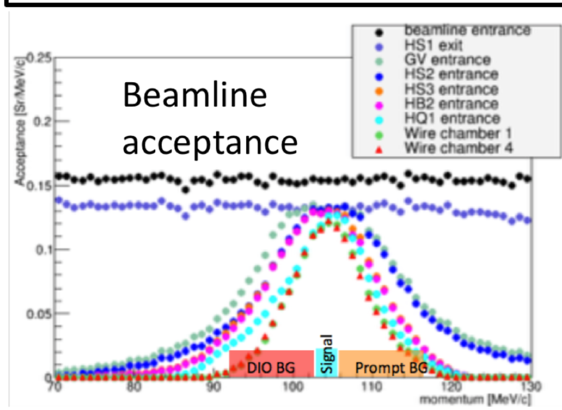
- Useful reviews
  - L. Calibbi and G. Signorelli, Riv. Nuovo Cimento, 41 (2018) 71
  - T. Gorringe & D. Hertzog, Prog.Part.Nucl. Phys. 84 (2015) 73.
  - S. Mihara, J.P. Miller, P. Paradisi, G. Piredda, Annu.Rev.Nucl.Part.Sci. 63 (2013) 552.
  - R.H. Bernstein & P.S. Cooper, Phys. Rept. 532 (2013) 27.
  - Y. Kuno & Y. Okada, Rev.Mod.Phys. 73 (2001) 151.
- About the experiments
  - MEG: http://meg.icepp.s.u-tokyo.ac.jp (MEG-II TDR: arXiv:1801.04688)
  - Mu2e: http://mu2e.fnal.gov (TDR: arXiv:1501.05241)
  - COMET: http://comet.kek.jp/Introduction.html (Proposal: http://comet.kek.jp/Documents_files/Phase-I-Proposal-v1.2.pdf)
  - DeeMee: http://deeme.hep.sci.osaka-u.ac.jp (Proposal: http://deeme.hep.sci.osaka-u.ac.jp/documents/deeme-proposal-r28.pdf/view)
  - Mu3e: https://www.psi.ch/mu3e/mu3e (Proposal: https://www.psi.ch/mu3e/documents)

Backup Slides

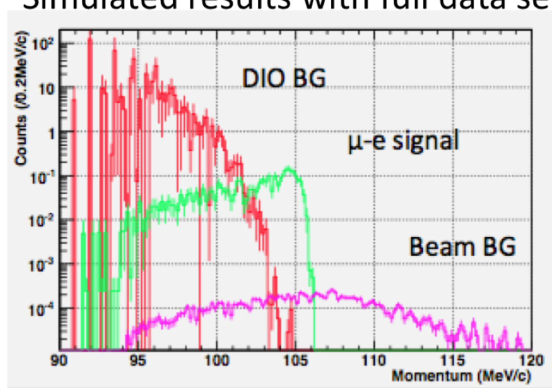
DeeMee - $\mu^- N \rightarrow e^- N$







Simulated results with full data set

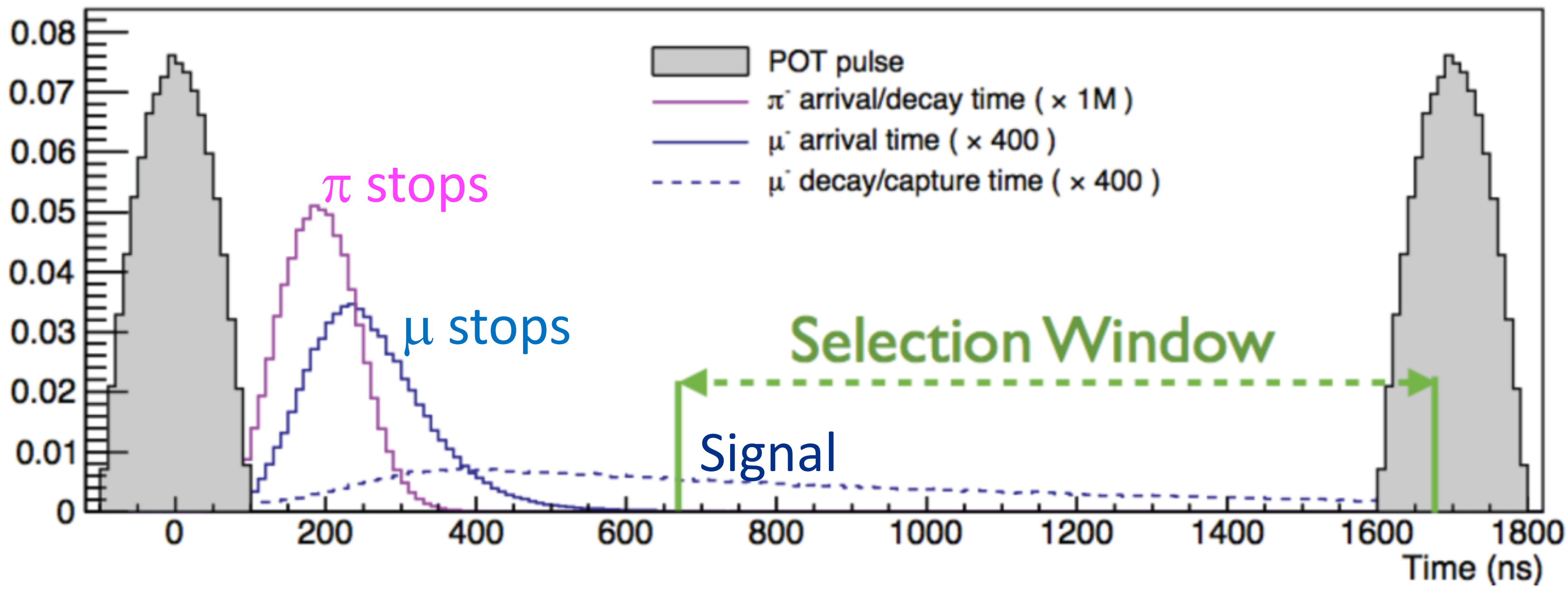


Signal Region: 102.0 -- 105.6 MeV/c

- New concept at JPARC
  - 3 GeV from RCS H-Line
- Use thick target as production, decay, and stopping volumes (graphite, SiC)
- Customize beam line to select momentum bite near $E_{\mu e} \sim m_\mu$ so that you're sensitive to μN→eN that occurs near the target surface
- Goal: $R_{\mu e} < 2 \times 10^{-14}$ @ 90%CL
  - 2-3y of running at 1 MW
  - Currently operating at ~400 kW

Pulsed Beam for Muon Conversion Experiments

Pulsed beam significantly suppresses prompt backgrounds



Pions that survive to the stopping target are promptly captured on the nucleus

- Few % of the time, radiate γ with $E_\gamma \sim m_\mu$
- Suppressed by 10^9-10^{10} with pulsed proton beam and utilizing a delayed search window while maintaining a high efficiency for signal (~50%)

Muonium – Antimuonium Oscillations

- Muonium – Coulombic bound state of $e^{-}\mu^{+}$
- Antimuonium – Coulombic bound state of $e^{+}\mu^{-}$
- Time dependent oscillation between distinct levels of particle species common quantum mechanical phenomenon
  - $K^0\overline{K}^0$, $B^0\overline{B}^0$ ...
- Muonium – Antimuonium Oscillation would be a clear signal of new physics. ΔL=2 transition.
- Numerous models predict oscillations

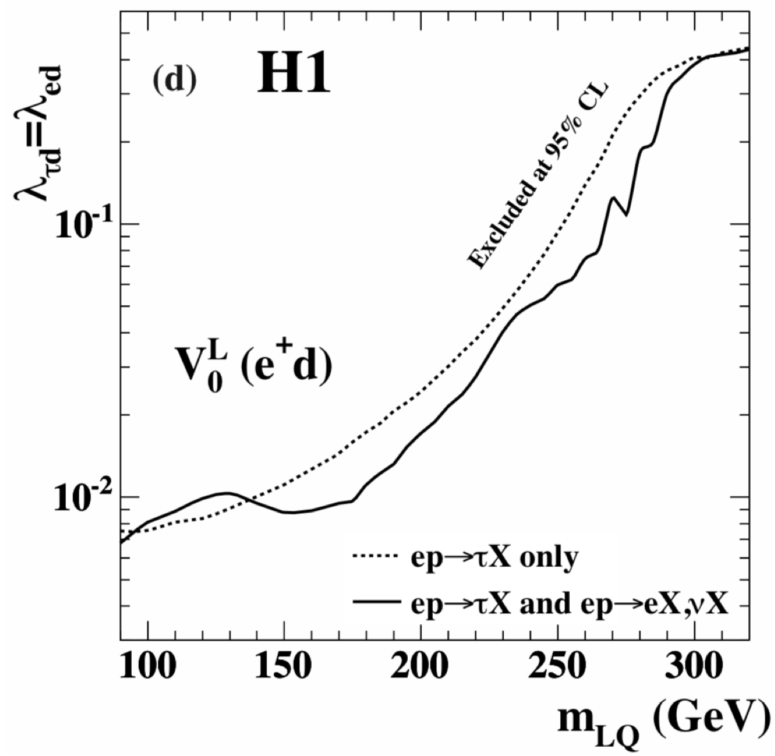
Current state of the art

$P_{M\bar{M}} < 8.3\times10^{-11}$

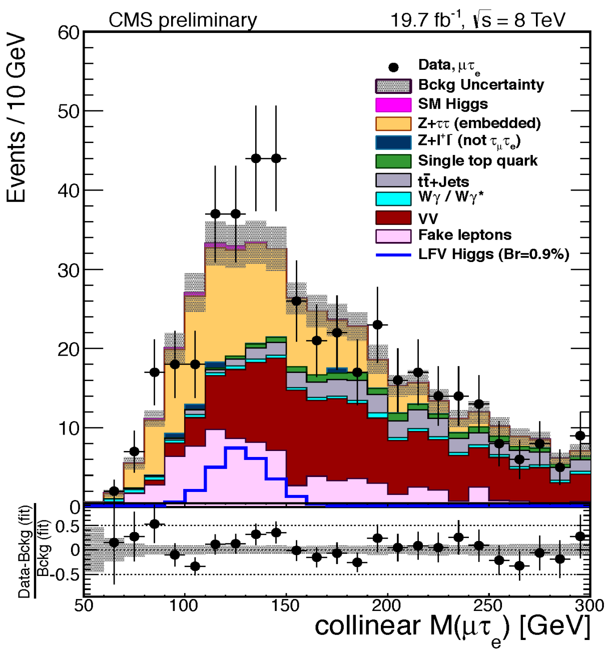
L. Willmann et al., Phys. Rev. Lett. 82, 49 (1999)

Electron – Tau Conversion

- Electron to tau conversion in e⁻p deep inelastic scattering has been studies at HERA and could be extended at an electron – ion collider.
- Predicted in Leptoquark models. Null searches used to set limits on leptoquark parameters.



Direct Searches for CLFV Higgs decays



$\underline{\text{CMS}}$ - $B(h \rightarrow \tau\mu) < 1.51\times10^{-2}$

$\underline{\text{ATLAS}}$ - $B(h \rightarrow \tau\mu) < 1.43\times10^{-2}$

Rare Higgs decays are extremely sensitive to new physics if additional Higgs couplings exist.

- Large physics program at LHC to search for CLFV
  - Direct searches
  - Higgs LFV searches
  - Z decays
  - tau decays
- No signals observed, but much more data to come!