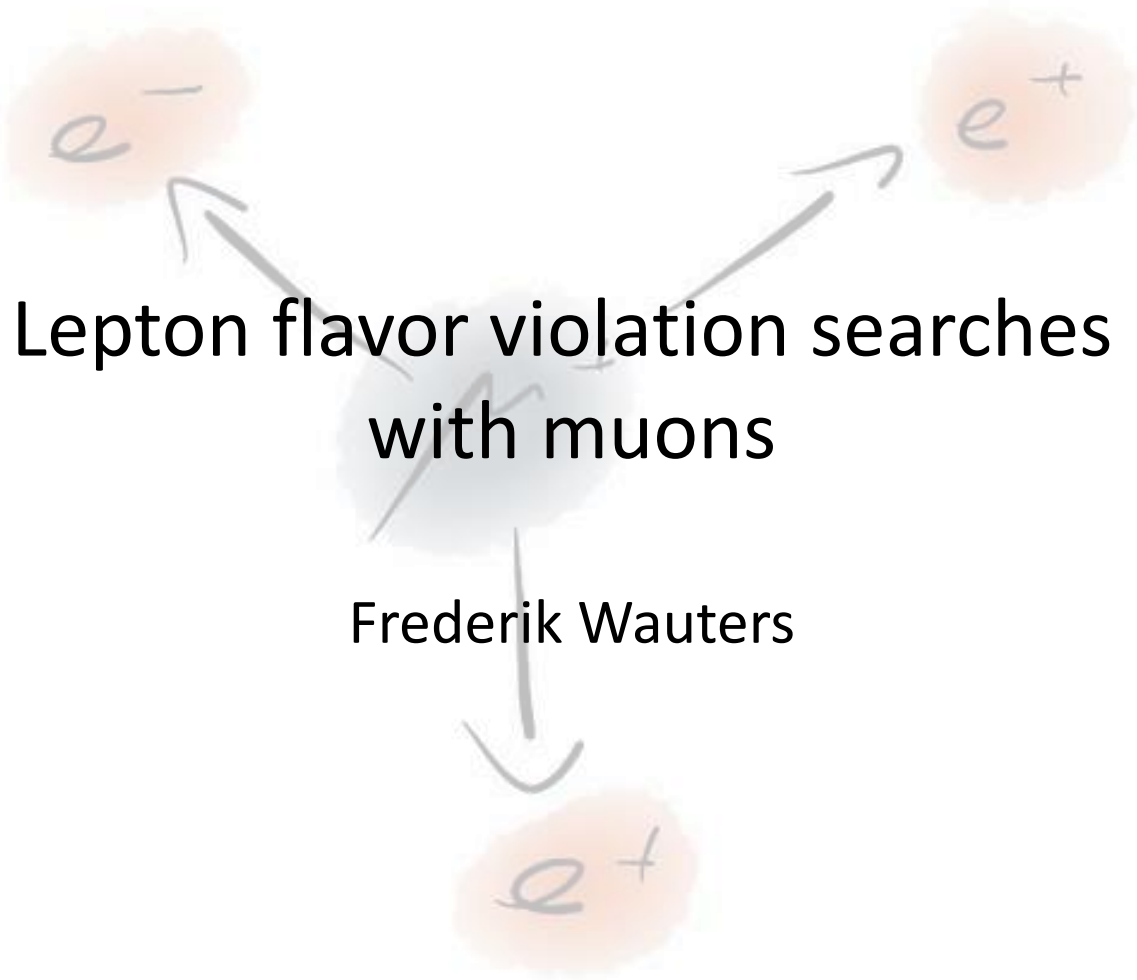
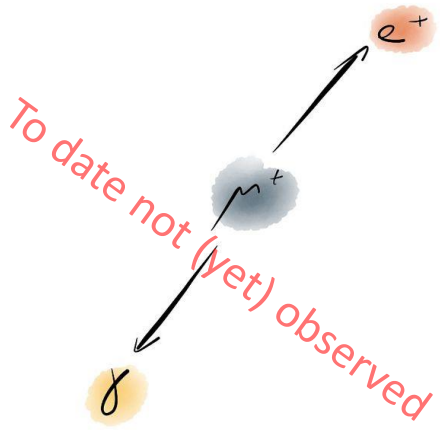
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



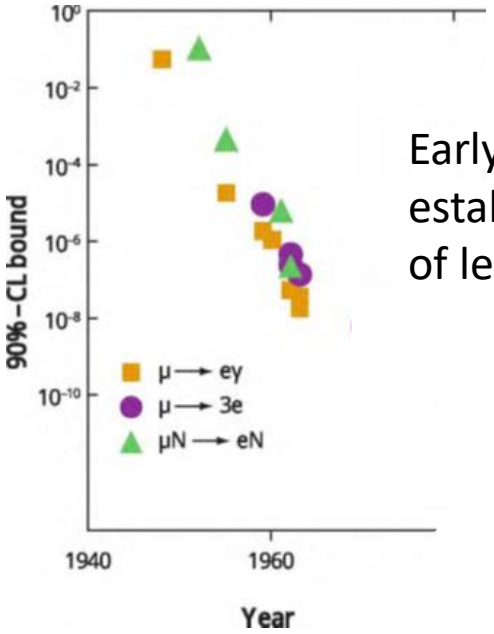
Lepton flavor violation searches with muons

Frederik Wauters

Conservation of lepton flavor number

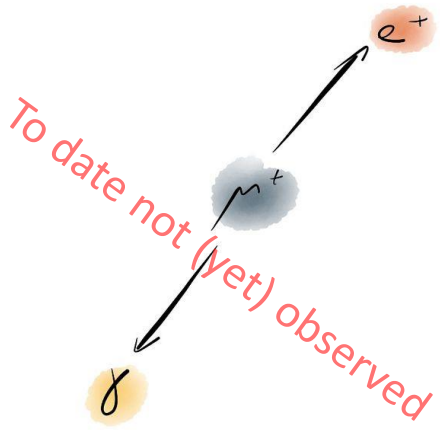


- A muon is not an excited electron
- $\nu_\mu \neq \nu_e$
- In the SM:
  - Conservation of lepton number L
  - Conservation of lepton flavor number L_e, L_μ, L_τ

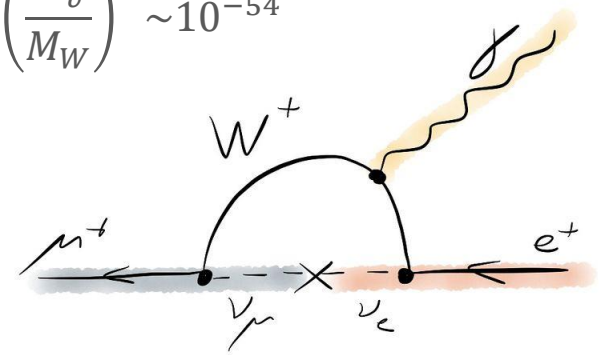


Early experiments established the existence of lepton flavor number

Conservation of lepton flavor number



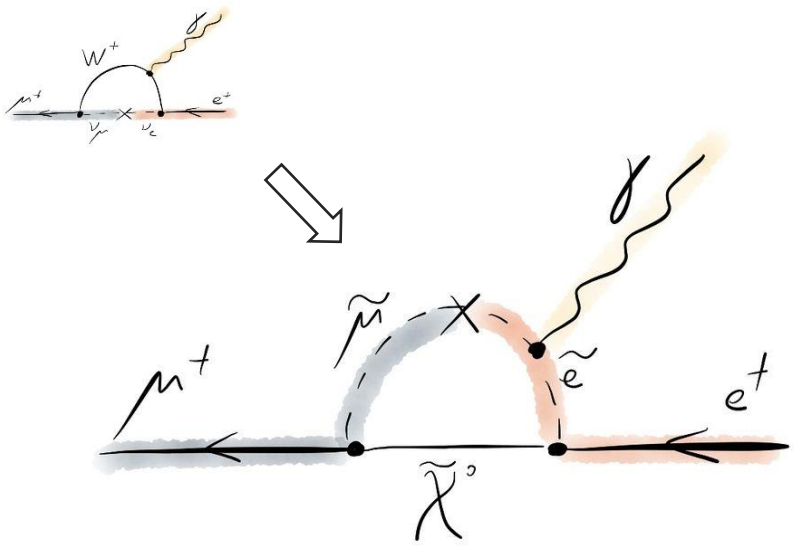
$$B.R. \sim \left(\frac{M_\upsilon}{M_W}\right)^4 \sim 10^{-54}$$



BUT:

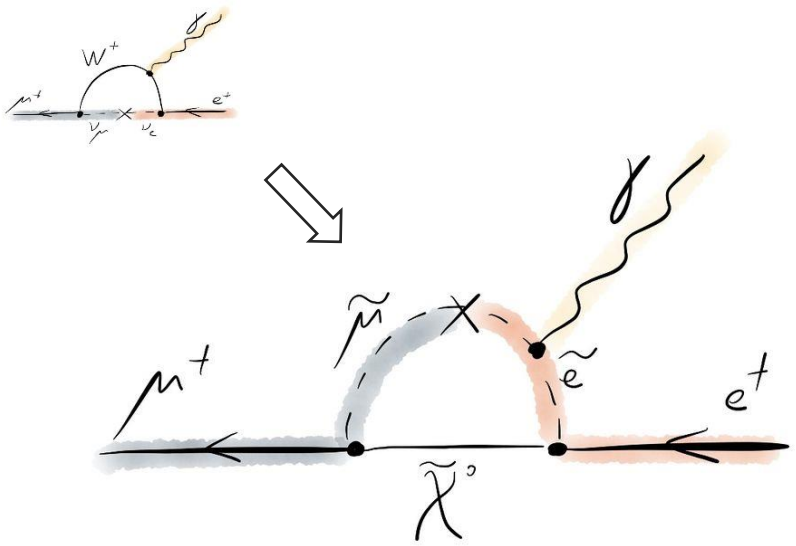
- Lepton flavor conservation is not related to a fundamental/gauge symmetry of the SM
- Neutrino oscillations → a small amount of charged lepton-flavor violation (CLFV).
  → any experimental observation of CLFV is an new physics.
- Many BSM models predict a sizeable amount of CLFV

Violation of lepton flavor number



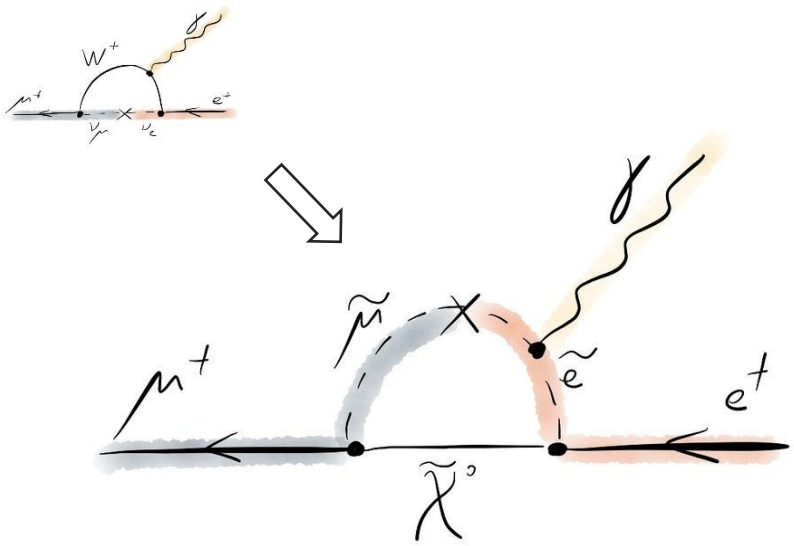
- Paradigm of the Intensity Frontier: Probe new physics at low energies through loop diagrams. Sensitivities are ≥ direct searches at the LHC.

Violation of lepton flavor number



- Paradigm of the Intensity Frontier: Probe new physics at low energies through loop diagrams. Sensitivities are ≥ direct searches at the LHC.
- NP scale for μ→eγ:
  - \+ BR(10^{-12}) ↔ Λ ≈ 1000 TeV
  - \- BR(μ→eγ) ~ $\left(\frac{1}{\Lambda}\right)^4$

Violation of lepton flavor number



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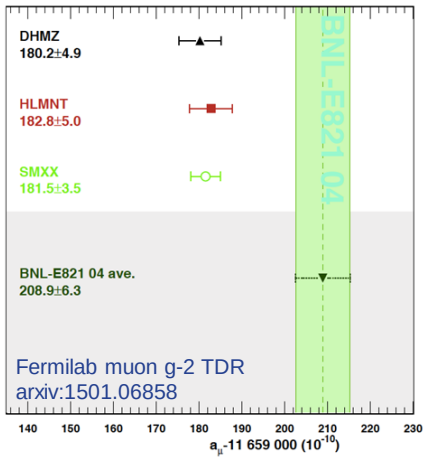
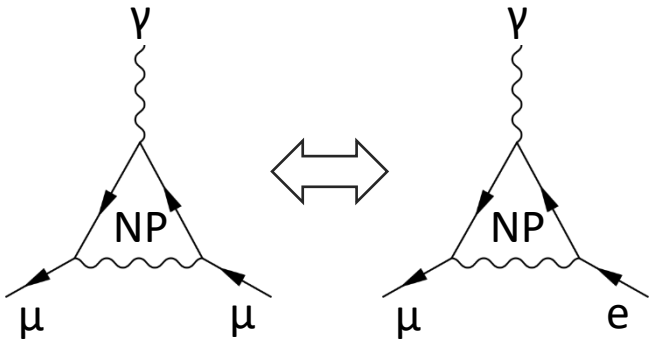


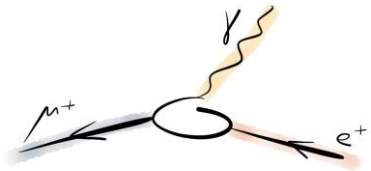


- With the current a_μ anomaly, the LFV phase of NP has to be small to be consistent with current CLFV experiments, O(10^{-4}).

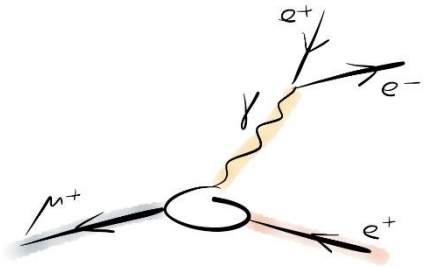
Search for μ→eγ

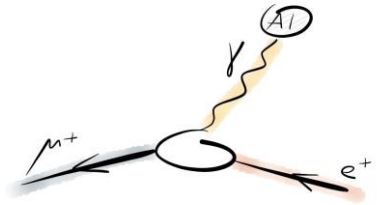
BR(10^{-12} - 10^{-13})

Search for



loose ~ α in the BR

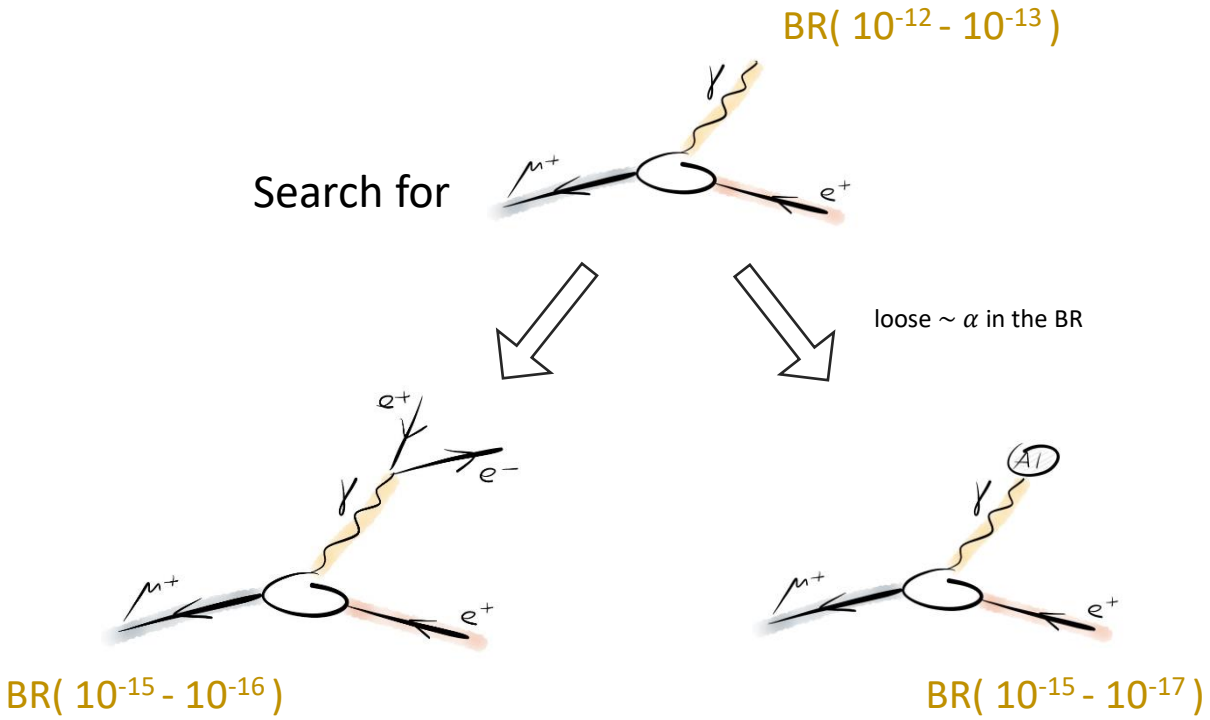




BR(10^{-15} - 10^{-16})

BR(10^{-15} - 10^{-17})

Search for μ→eγ

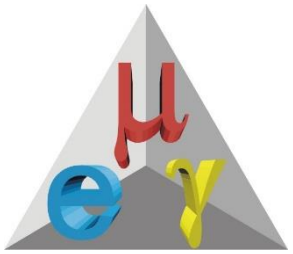


Lepton flavor violation searches **with muons**

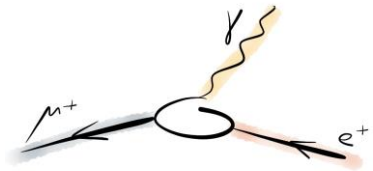
The μ as a golden channel

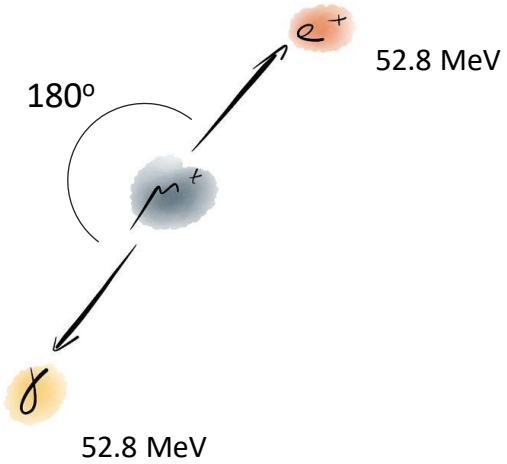
- Available in large quantities, e.g. 10^8 s^{-1} (low energy DC) at PSI
- Relatively long lived. Enables transport from production to experiment apparatus
- SM decays very well know

Search for μ→eγ : MEG



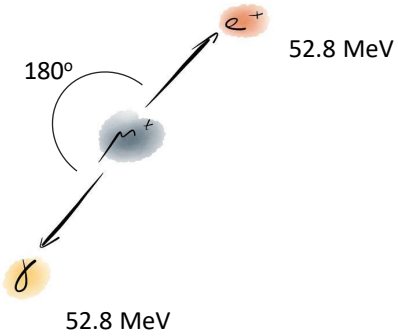
BR(10^{-12} - 10^{-13})

Search for  : MEG(II)

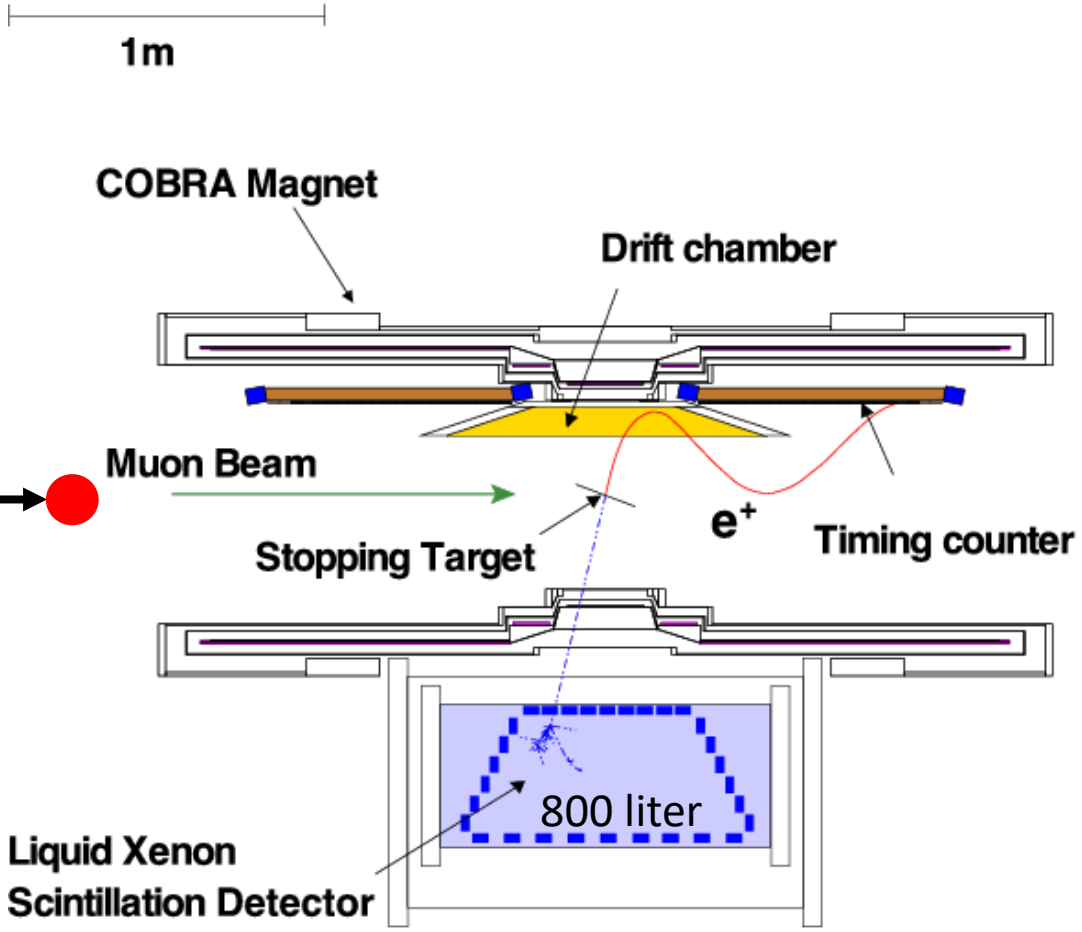


- E_γ
- E_{e+}
- $\theta(e^+,\gamma)$
- $t(e^+,\gamma)$

Search for μ→eγ : MEG



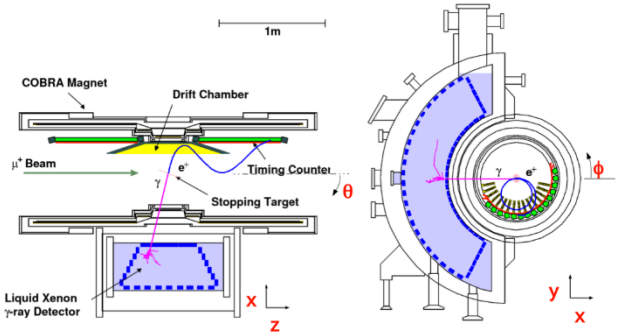
p



HIPA @ PSI:

- Most powerful p beam (2.3 mA @ 600 MeV)
- Most intense μ DC beam
- Also π and neutron secondary beams available

Search for μ→eγ : MEG



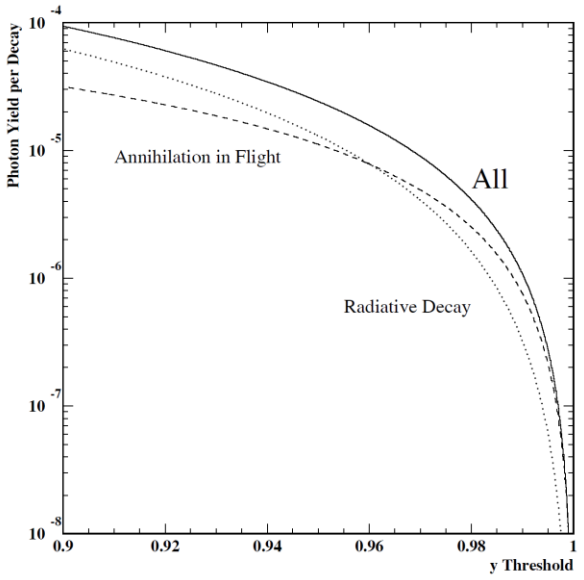
Backgrounds:

- Singles:
  - Radiative muon decay $\mu^+ \rightarrow e^+ \upsilon_e \bar{\upsilon}_\mu \gamma$ with
    BR($E_\gamma > 10\ MeV$) ≈ ~1%, BR($E_\gamma > 45\ MeV$) ≈ 6 10^{-8}

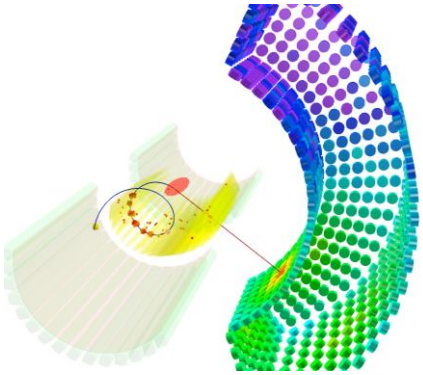
- Accidental (combinatorial), ordinary muon decay $\mu^+ \rightarrow e^+ \upsilon_e \bar{\upsilon}_\mu + \gamma$ from
  - Annihilation in flight
  - Radiative muon decay $\mu^+ \rightarrow e^+ \upsilon_e \bar{\upsilon}_\mu \gamma$

Detector specs:

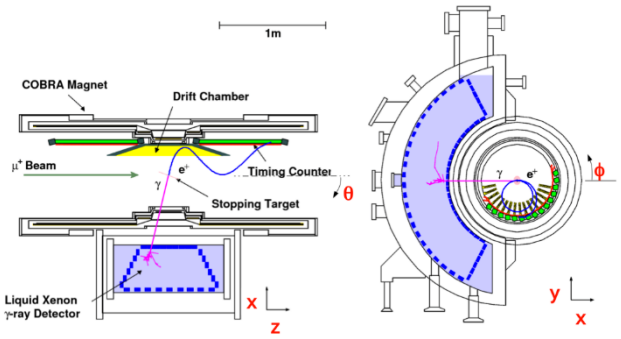
- t_e and t_γ < 100 ps
- $\sigma(E_\gamma)$ < 2 %
- $\sigma(E_e)$ < 1 %
- $\sigma(\theta_{e\gamma})$ < 20 mrad

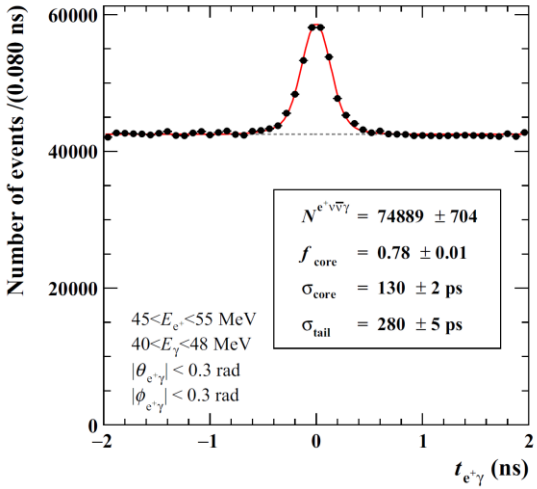


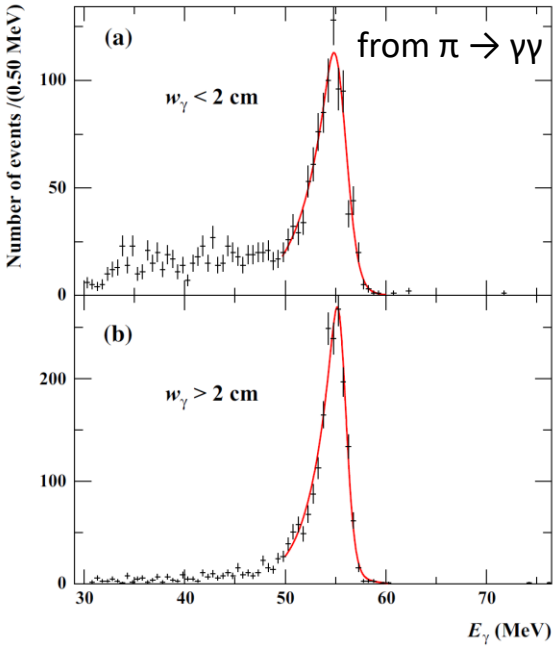
Search for μ→eγ : MEG

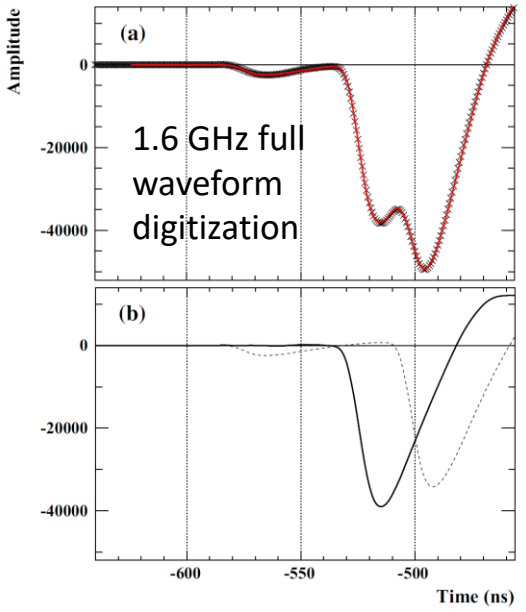


Detector performance









\+ calibration, calibration, calibration

Search for μ→eγ : MEG

Final MEG result

best CLFV limit by a factor of 30

Eur. Phys. J. C (2016) 76:434
DOI 10.1140/epjc/s10052-016-4271-x

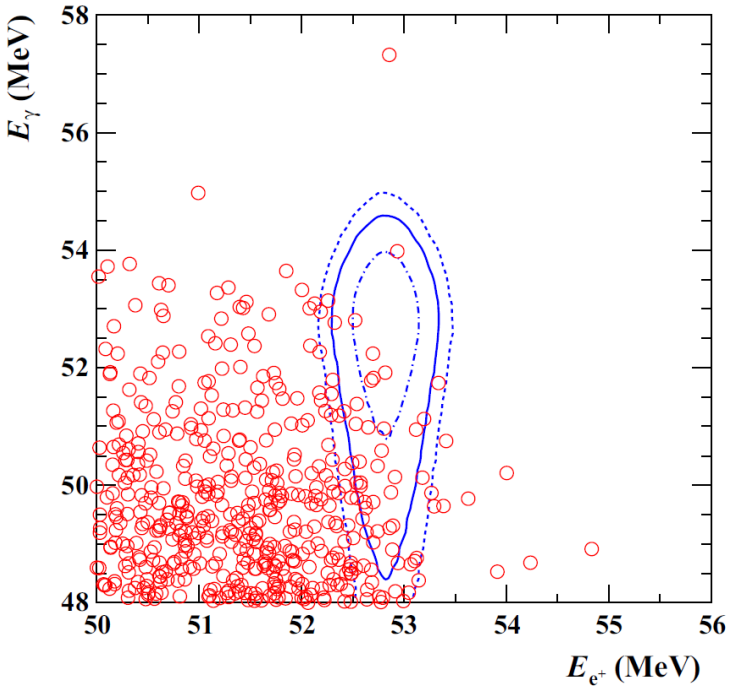
THE EUROPEAN PHYSICAL JOURNAL C

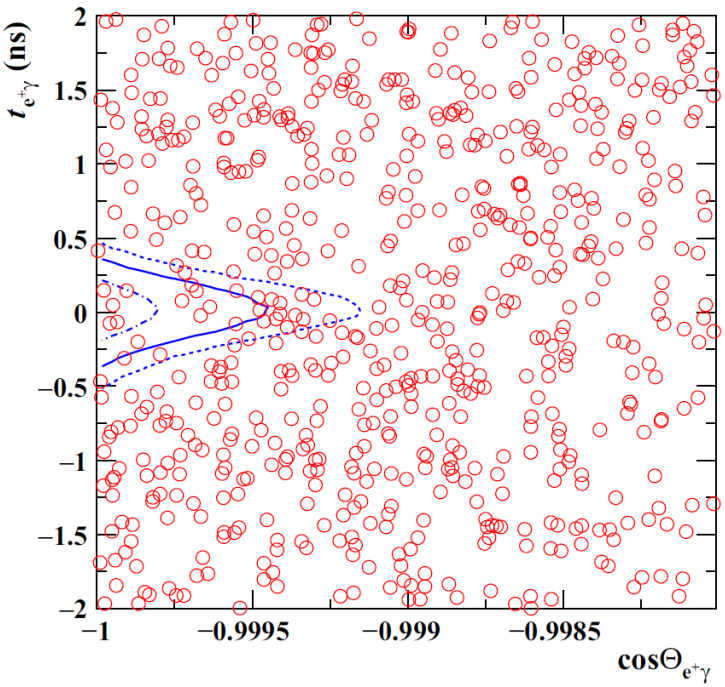
Regular Article - Experimental Physics

Search for the lepton flavour violating decay $\mu^+ \to e^+\gamma$ with the full dataset of the MEG experiment

MEG Collaboration

$$BR(\mu^+ \to e^+\gamma) < 4.2\ 10^{-13}$$





Search for μ→eγ : MEGII

MEGII is under construction:

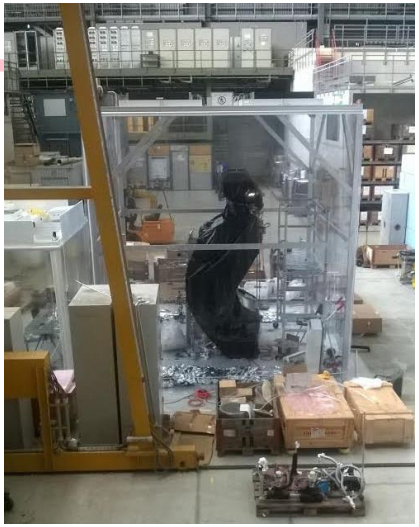
- go from 4 10^{-13} → 4 10^{-14} B.R. sensitivity

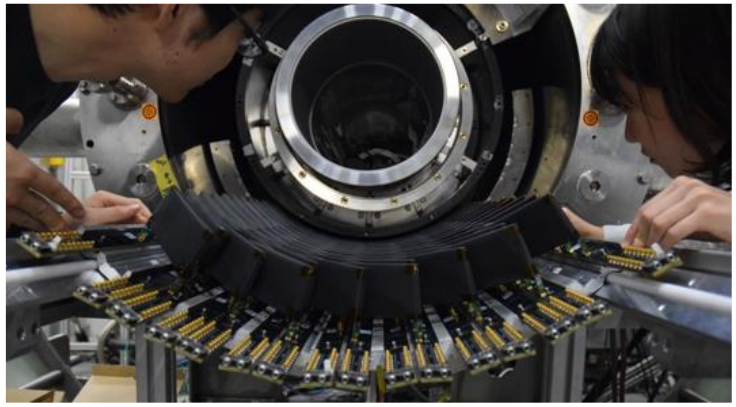
- Improve all detector systems:
  - PMT → SiPM for the LXe detector
  - New e^+ tracker (He drift chamber)
  - New e^+ timing detector
  - Go to 5 GHz Waveform sampling

  ….

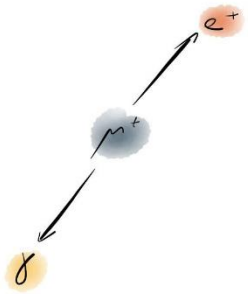
- Engineering runs start this year
- First physics run 2017

- μ→eγ sensitivity is limited by accidental background, going beyond 10^{-14} is unlikely





Search for $\mu \rightarrow e^+e^+e^-$: mu3e



- 2-body decay
- back to back γ - e
- mono energetic γ – e

Background

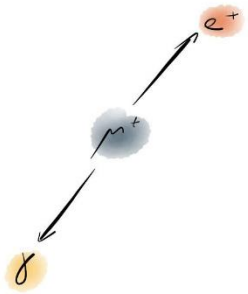
- Accidental background

→ DC Beam (PSI)

CLFV sensitivity

- ÷ 1

Search for $\mu \rightarrow e^+e^+e^-$: mu3e



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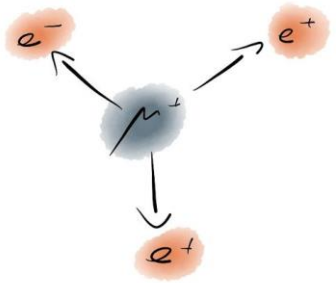
→ DC Beam (PSI)

CLFV sensitivity
- $\div 1$



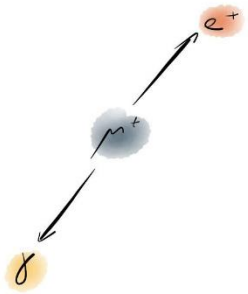
- 3-body decay
- $\sum \bar{p}_e = 0$
- $\sum E_e = m_\mu$

Background
- Accidental background

→ DC Beam (PSI)
- Radiative muon decay

CLFV sensitivity
- $\div 170$

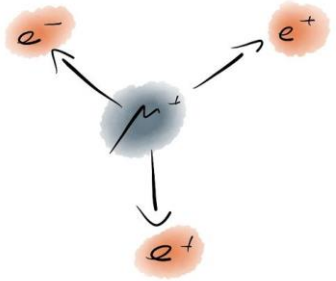
Search for μ→e⁺e⁺e⁻ : mu3e



- 2-body decay
- back to back γ - e
- mono energetic γ – e

Background
- Accidental background

→ DC Beam (PSI)



- 3-body decay
- $\sum \bar{p}_e = 0$
- $\sum E_e = m_\mu$

Background
- Accidental background

→ DC Beam (PSI)
- Radiative muon decay

Angular correlations/Dalitz plot
extra window in NP

CLFV sensitivity
- $\div 1$

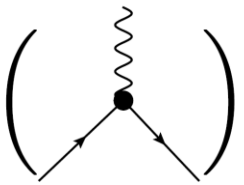
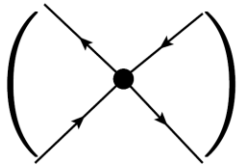
CLFV sensitivity
- $\div 170$

But: only true for loop diagrams

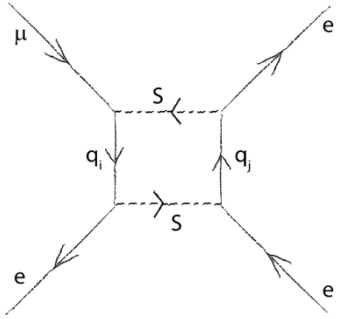
Search for μ→e⁺e⁺e⁻ : mu3e

(SUSY) loop

tree level / eff. Fermi interaction

$$\frac{m_\mu}{(1+\kappa)\Lambda^2}$$  $$+\frac{\kappa}{(1+\kappa)\Lambda^2}$$ 

+ box diagrams like

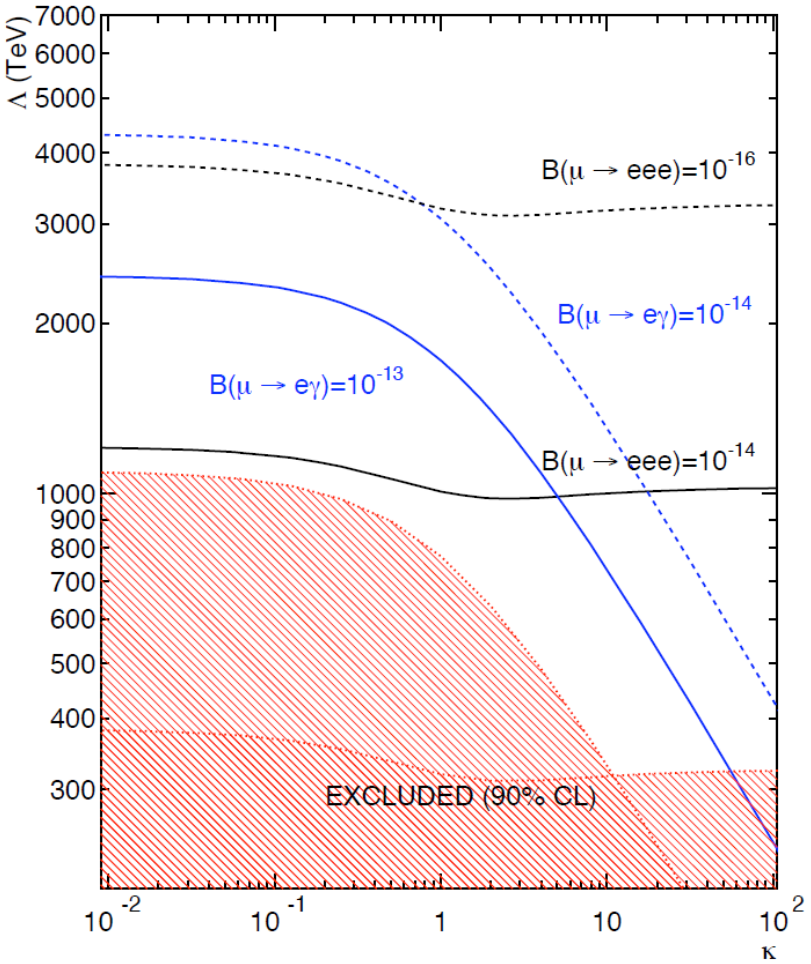


+ …

Search for μ→e⁺e⁺e⁻ : mu3e

$$\frac{m_\mu}{(1+\kappa)\Lambda^2}\left(\quad\right)+\frac{\kappa}{(1+\kappa)\Lambda^2}\left(\quad\right)$$

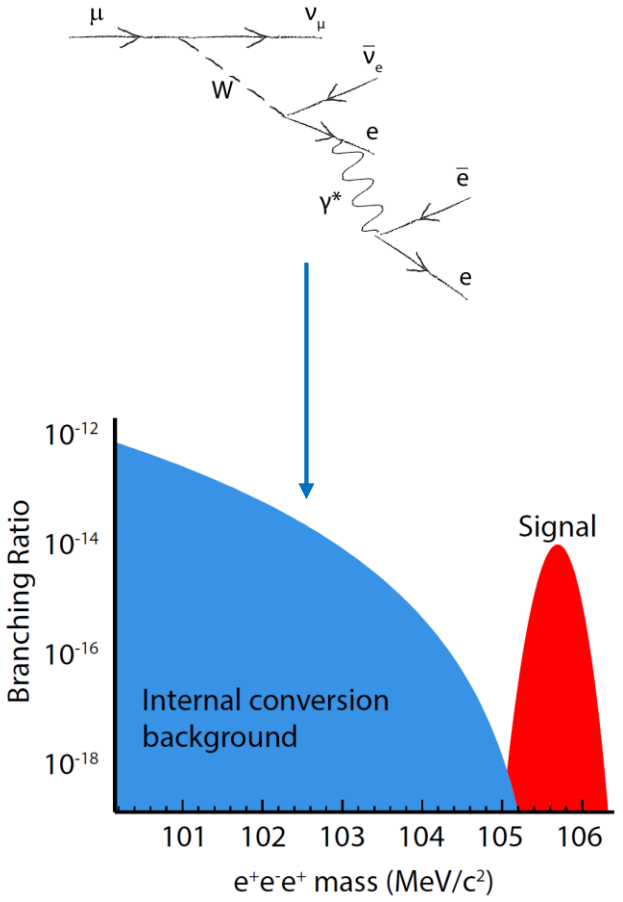
de Gouvea and Vogel, 2013



Search for $\mu \rightarrow e^+e^+e^-$: mu3e

The mu3e experiment

- Coincidence of $e^+e^+e^-$ with $\sum \bar{p} = 0$ and $\sum E = m_\mu$
  Need to see electrons of all energies !
- Background from
  - internal conversion
  - Accidental background from Michel decay +
    - Bhabha scattering
    - Photon conversion
    - misreconstructed tracks



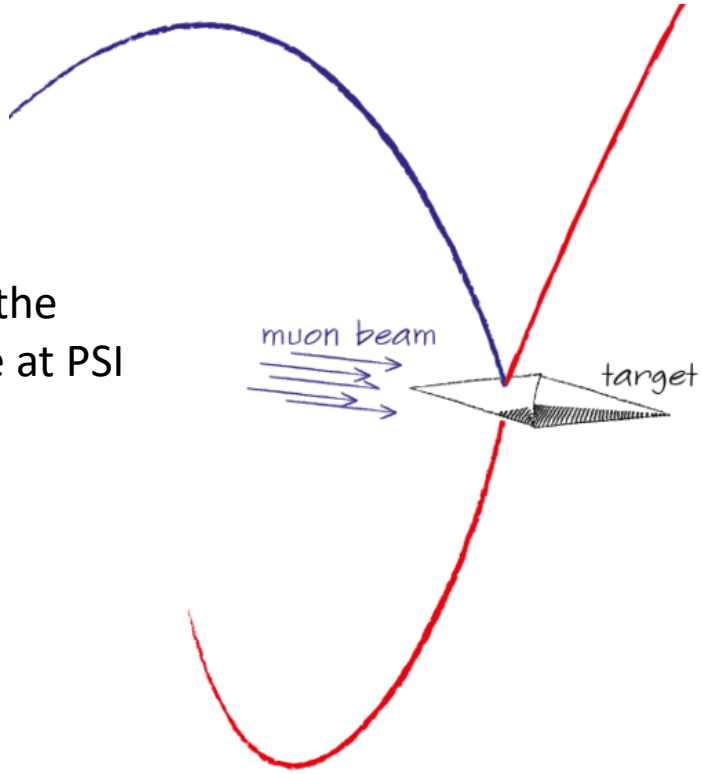
- Continuoius streaming readout ($E_e > 15$ MeV) with 10^8 - 10^9 μ/s, DAQ handles up to 100 GB/s
- Excellent energy (< 0.5 MeV) and time resolution (< 100 ps)

- Goal: Sensitivity to the B.R. of **10^{-15} (Phase I)** and 10^{-16} (Phase II), increase current limits on $\mu \rightarrow e^+e^+e^-$ by 4 orders of magnitude (SINDRUM, 1988)

Search for $\mu \rightarrow e^+e^+e^-$: mu3e

The detector

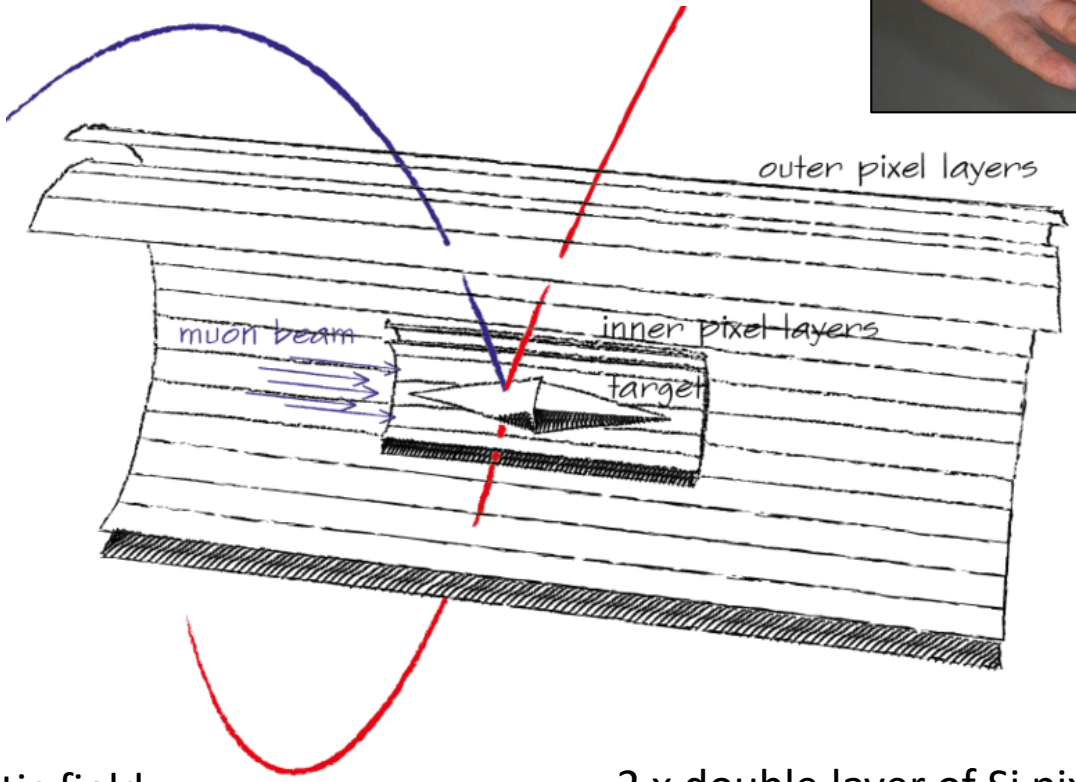
10^8 μ/s from the
πE5 beamline at PSI



Cone shaped thin target
→ well defined vertices,
spread out in z

Search for $\mu \rightarrow e^+e^+e^-$: mu3e

The detector

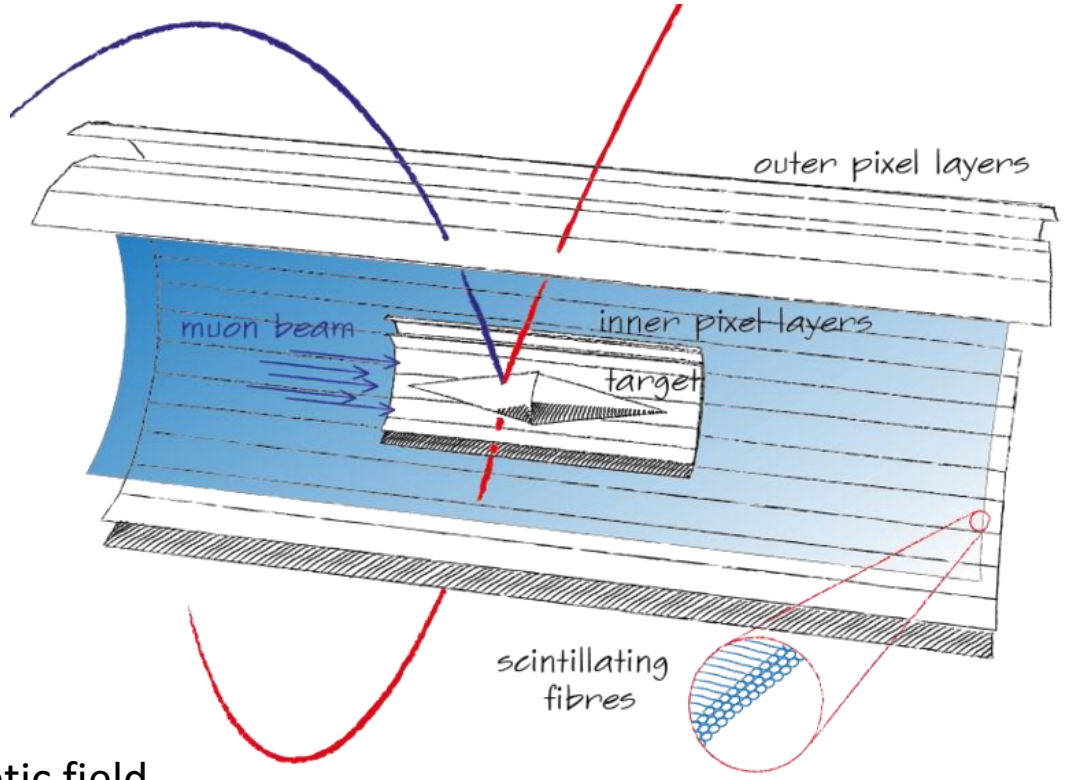


1 T magnetic field

2 x double layer of Si pixel detectors
Each layer is < 0.1 % of a radiation length

Search for μ→e⁺e⁺e⁻ : mu3e

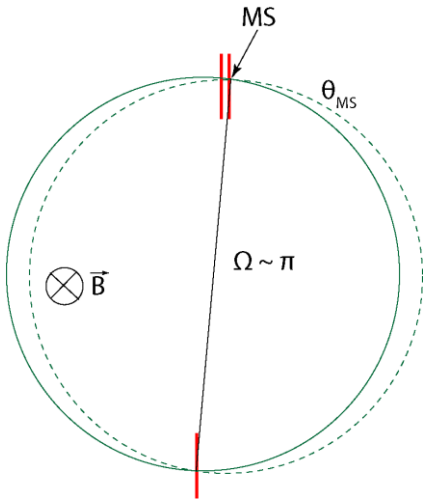
The detector



1 T magnetic field

Scintillating fibers as a thin, fast timing detector

Search for μ→e⁺e⁺e⁻ : mu3e

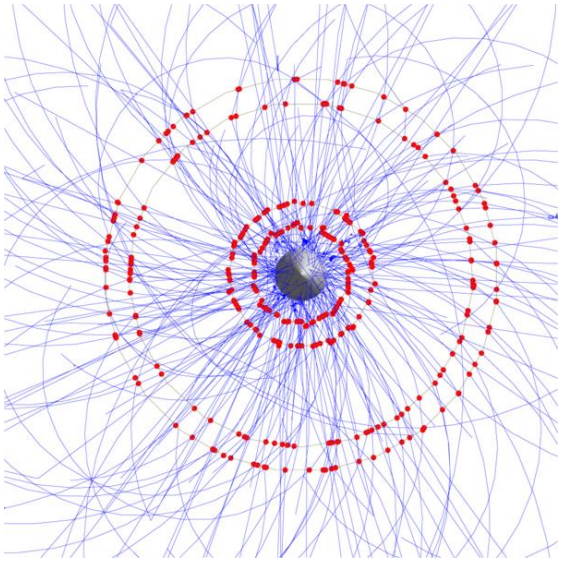


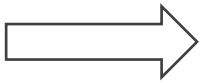
Recurl stations optimize momentum resolution, minimizing sensitivity to multiple scattering

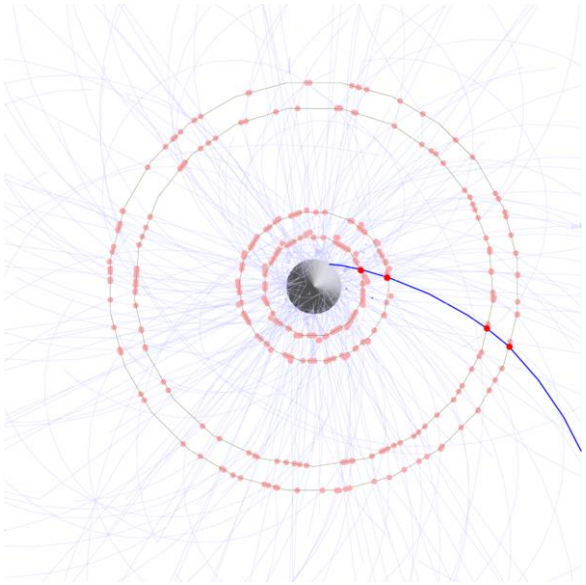
Scintillating tiles yield optimal timing resolution

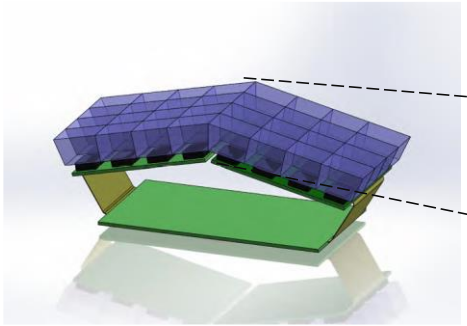
Search for $\mu \rightarrow e^+e^+e^-$: mu3e

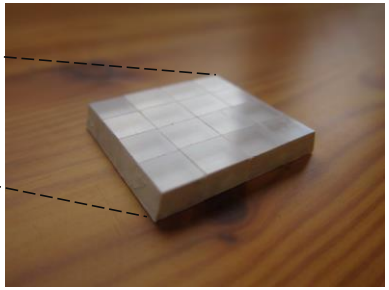
Why timing is important: up to 100 tracks in the Si tracker per 50 ns readout frame







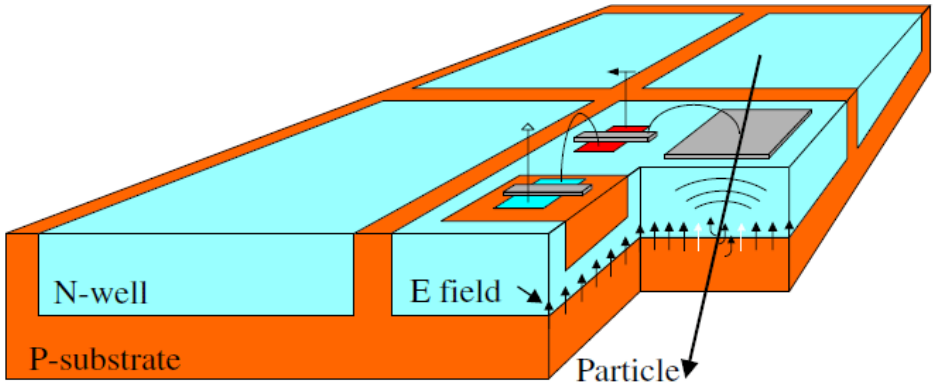




Search for $\mu \rightarrow e^+e^+e^-$: mu3e

Mu3e Pixel detector:

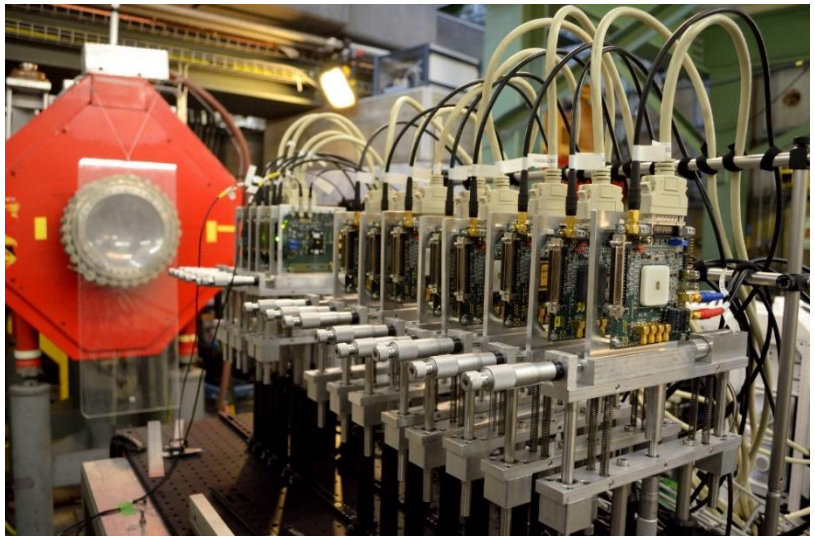
- High Voltage Monolithic Active Pixel Sensors (HV-MAPS)
- Fast charge collection with HV=-85V
- Readout and logic on chip: zero-suppressed hit addresses and timestamps
- Thinned to 50 µm
- Pixel size: 80 x 80 µm
- 2 x 2 cm chip
- 1.25 Gb/s LVDS readout

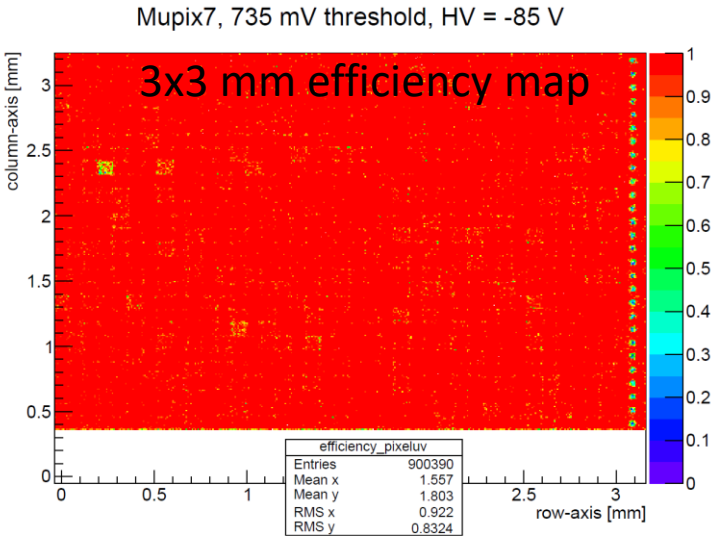


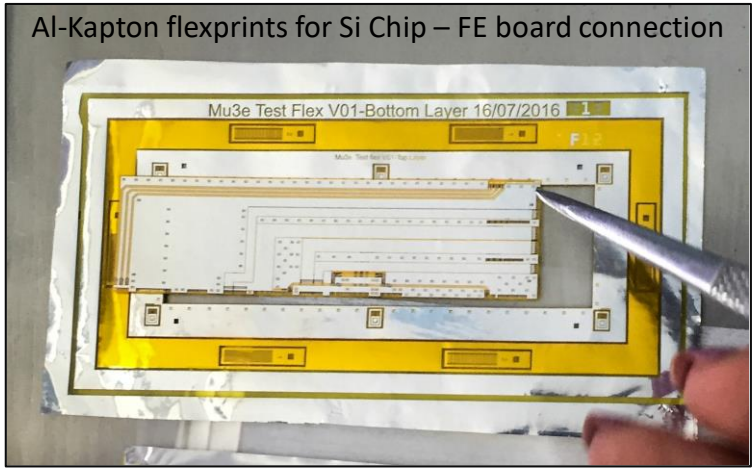
I. Peric et al., NIMA **731**, 131 (2008)

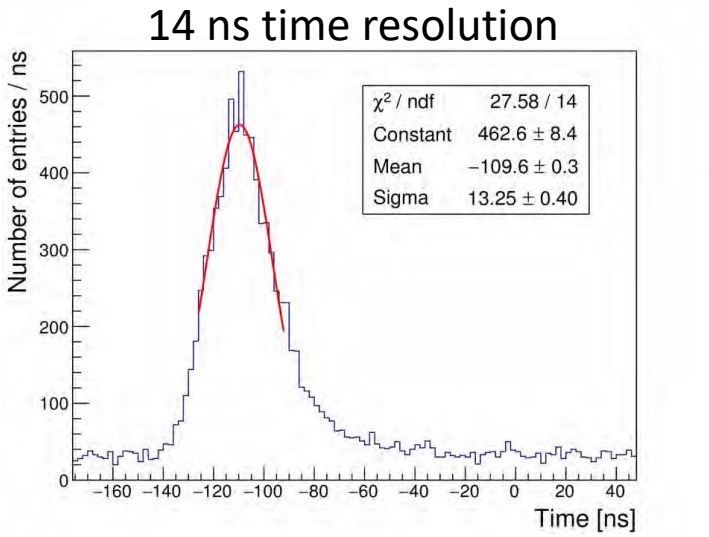
Search for $\mu \rightarrow e^+e^+e^-$: mu3e

Beam telescope as a test bench for the Si pixel detectors:





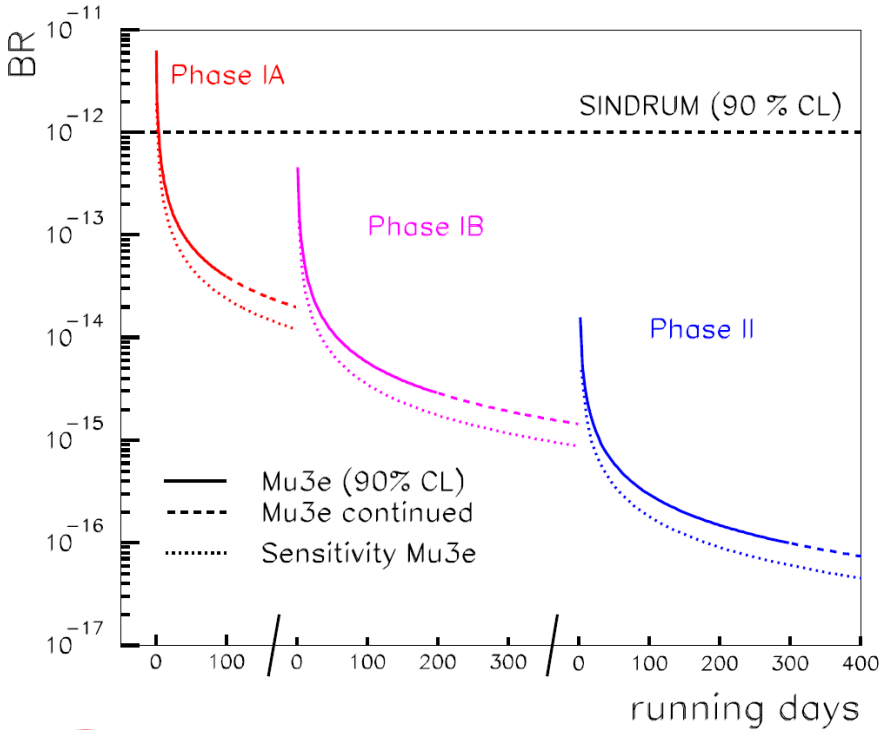




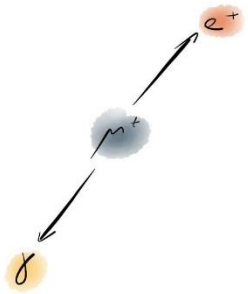
Search for $\mu \rightarrow e^+e^+e^-$: mu3e

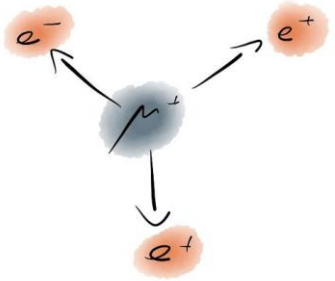
Mu3e Outlook:

- 2016:
  - Full size Si pixel chip
  - All detector and readout prototypes up to specs
  - FPGA/GPU based DAQ for 100 GB/s in development
- 2017: Magnet delivery
- 2018: First Phase I data taking
- Phase I: 10^8 μ/s for a B.R. of 10^{-15}
- Phase II: 10^9 μ/s for a B.R. of 10^{-16}



Search for μN→e⁻N : mu2e & COMET





- 2-body decay
- back to back γ - e
- mono energetic γ – e

<u>Background</u>

- Accidental background

→ DC Beam (PSI)

<u>CLFV sensitivity</u>

- $\div 1$

- 3-body decay
- $\sum \bar{p}_e = 0$
- $\sum E_e = m_\mu$

<u>Background</u>

- Accidental background

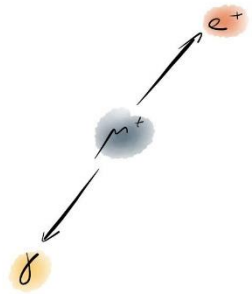
→ DC Beam (PSI)

- Radiative muon decay

<u>CLFV sensitivity</u>

- $\div 170$

Search for μN→e⁻N : mu2e & COMET

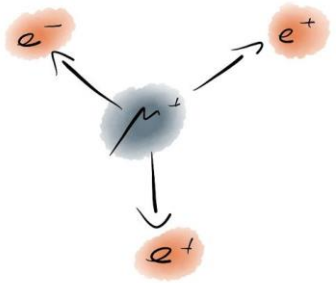


- 2-body decay
- back to back γ - e
- mono energetic γ – e

Background
- Accidental background

→ DC Beam (PSI)

CLFV sensitivity
- $\div 1$



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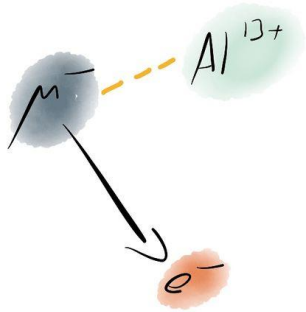
- Radiative muon decay

CLFV sensitivity
- $\div 170$



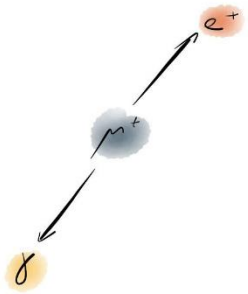
- quasi 2-body decay
- Mono energetic electron

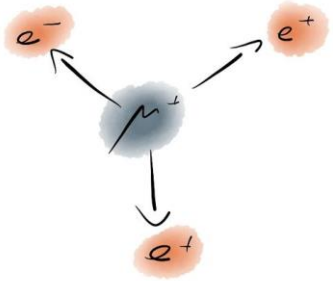
Background
- Beam-related background

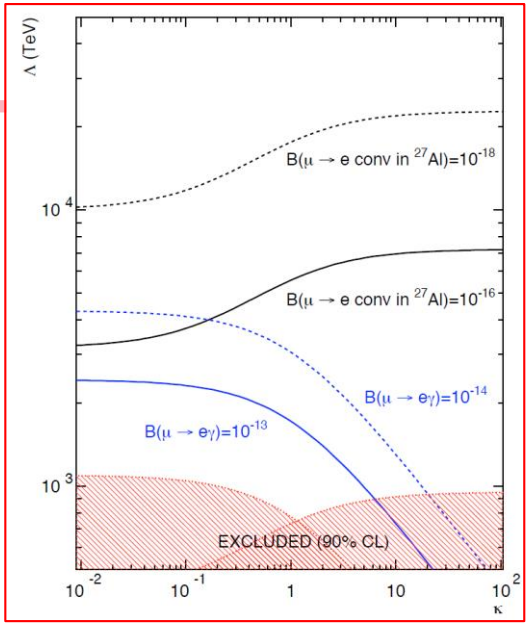
→ Pulsed beam Fermilab
- Decay in orbit

CLFV sensitivity
- $\div 389$ (for Al)

Search for μN→e⁻N : mu2e & COMET







- 2-body decay
- back to back γ - e
- mono energetic γ – e

Background
- Accidental background

→ DC Beam (PSI)

CLFV sensitivity
- $\div 1$

- 3-body decay
- $\sum \bar{p}_e = 0$
- $\sum E_e = m_\mu$

Background
- Accidental background

→ DC Beam (PSI)
- Radiative muon decay

CLFV sensitivity
- $\div 170$

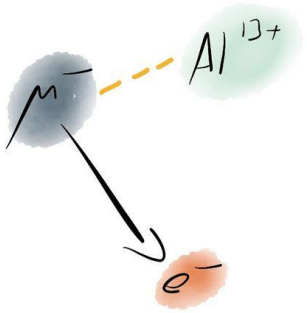
- quasi 2-body decay
- Mono energetic electron

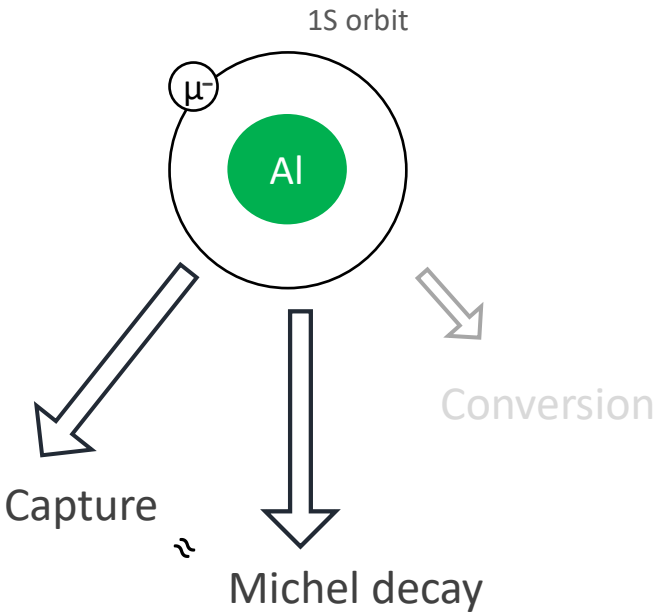
Background
- Beam-related background

→ Pulsed beam Fermilab
- Decay in orbit

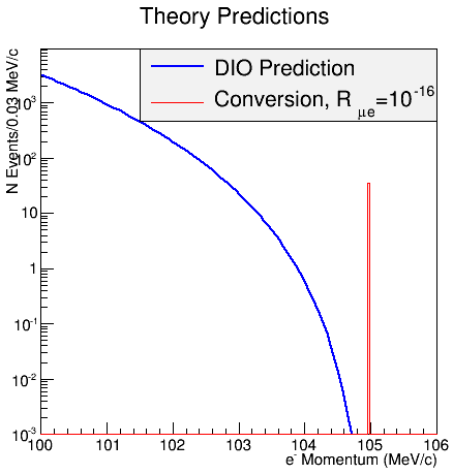
CLFV sensitivity
- $\div 389$ (for Al)

Search for μN→e⁻N : mu2e & COMET

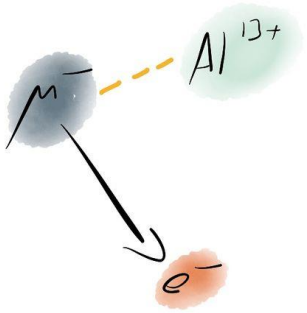


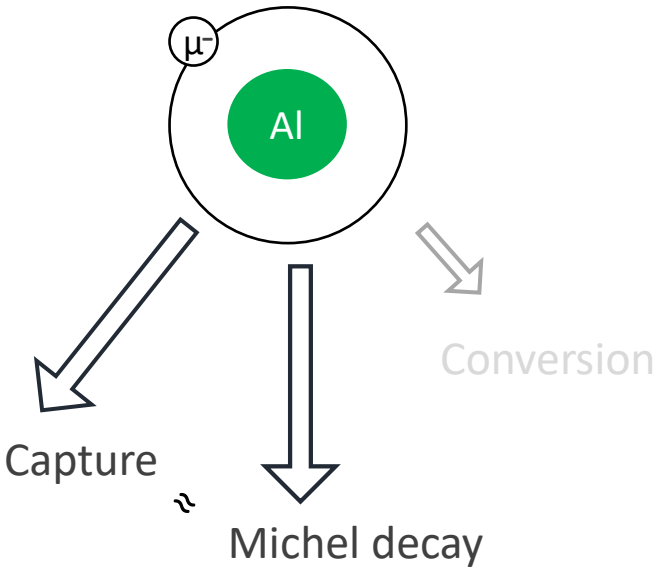


- Mono-energetic electron of 105 MeV
- Background from:
  - Decay in orbit
  - Beam background: $\pi^- N \rightarrow \gamma N^*$ + pair production
  - δ electrons from cosmic μ's

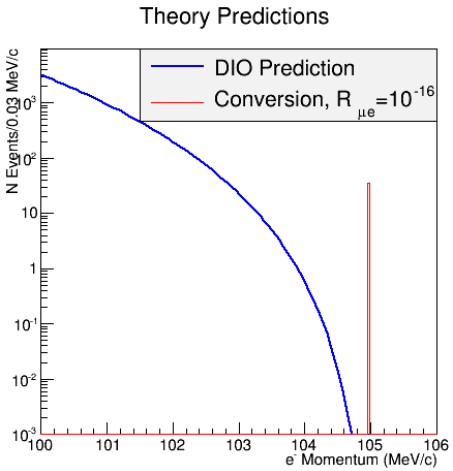


Search for μN→e⁻N : mu2e & COMET



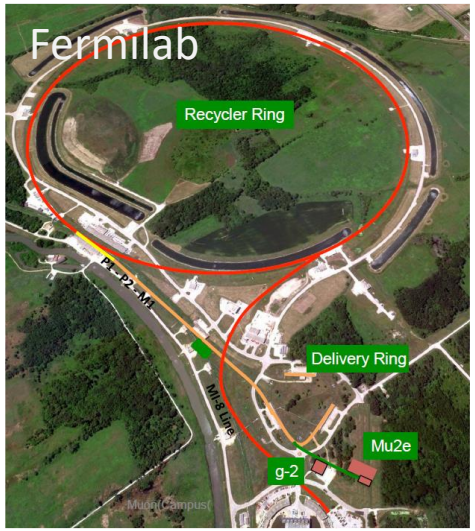


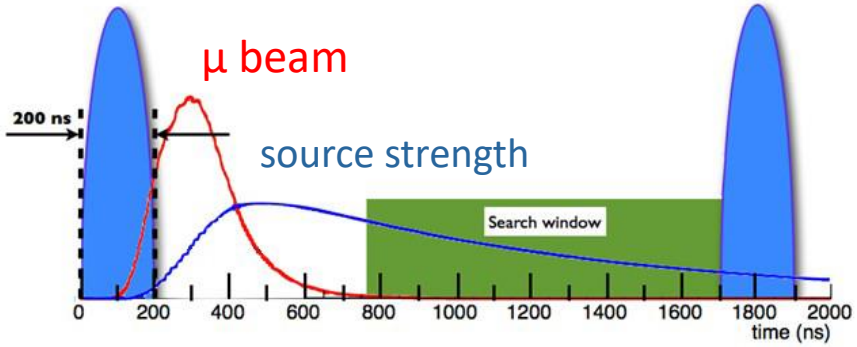
- Mono-energetic electron of 105 MeV
- Background from:
  - Decay in orbit
  - Beam background:
    $\pi^- N \rightarrow \gamma N^*$ + pair production
  - δ electrons from cosmic μ's
- Aims for a sensitivity
  of 3 10^{-17}
  but also 10^{18} μ's on target



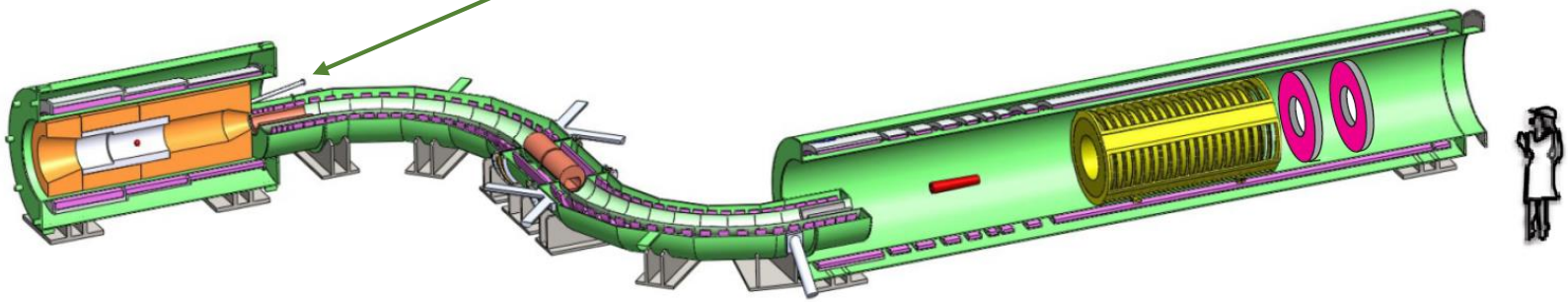
- ➢ 10^{10} μ/s pulsed beam
- ➢ excellent momentum resolution and particle identification
- ➢ shielding
- ➢ Big, large, and expensive

Search for μN→e⁻N : mu2e





2 10^7 8 GeV protons

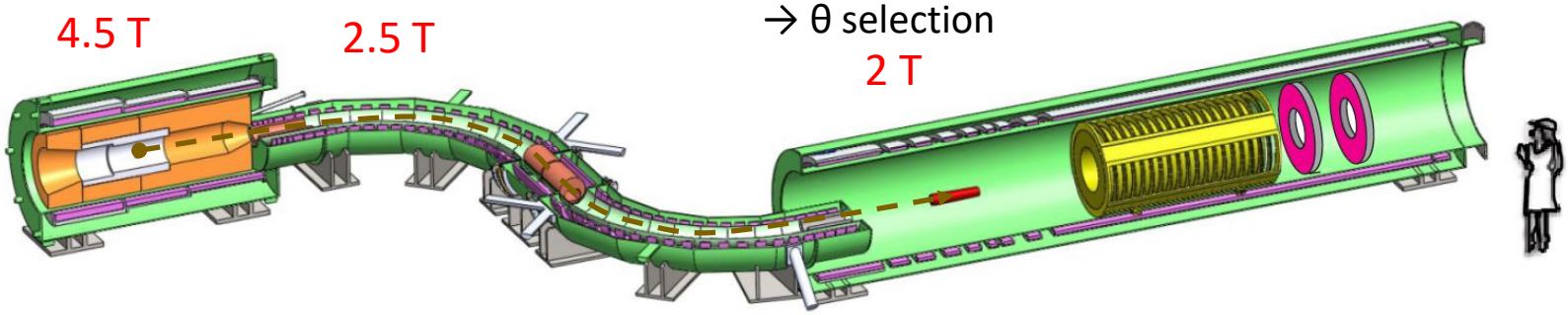


Search for μN→e⁻N : mu2e

Production
- $p^T \rightarrow p^=$
- efficient collection
- magnetic mirror

Transport
- πμ separation
- no line of sight to the target

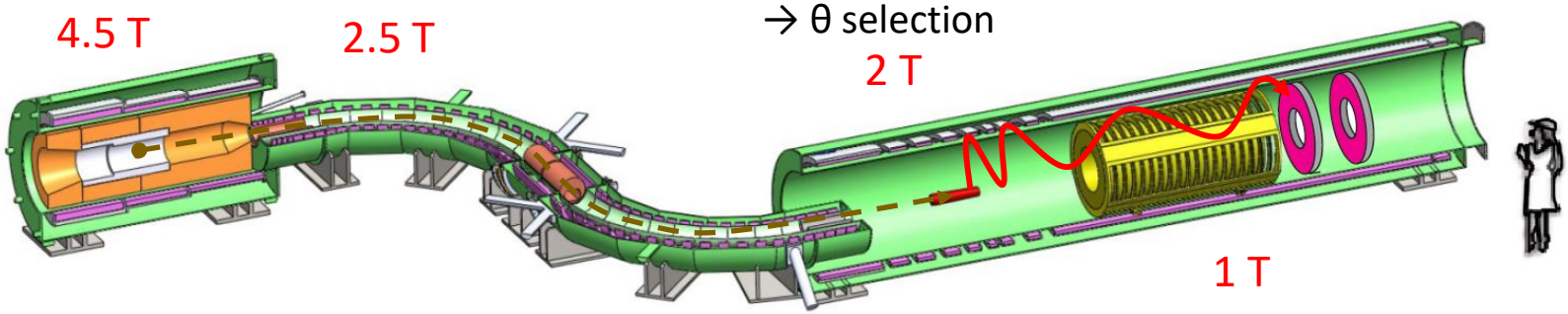
Stopping target
- Stack of Alu foils
- also in gradient field
  → θ selection



! 0.002 μ's on target / proton !

88 M USD in solenoids

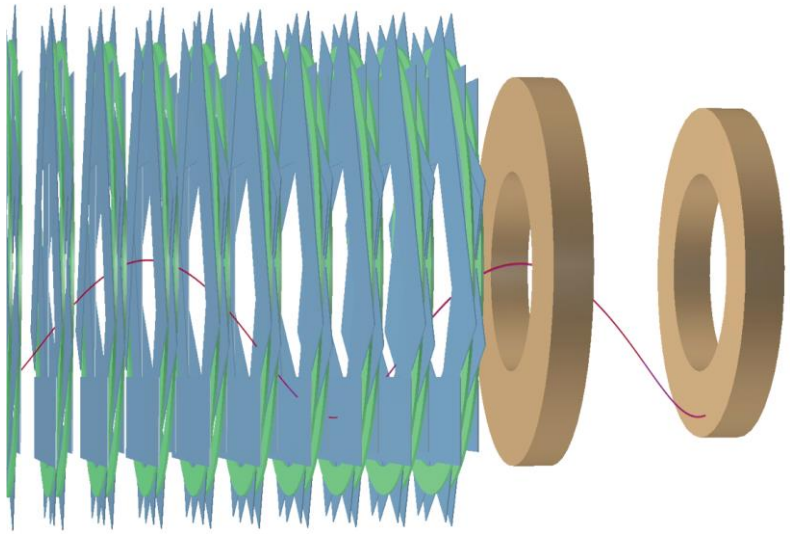
Search for μN→e⁻N : mu2e



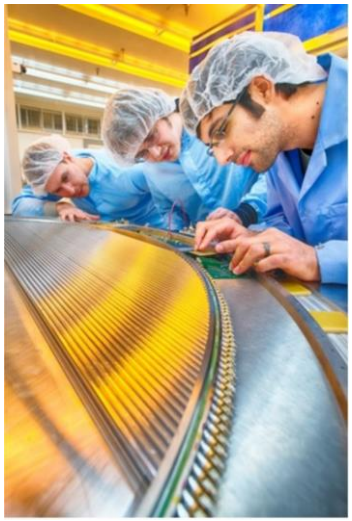
Stopping target
- Stack of Alu foils
- also in gradient field
  → θ selection

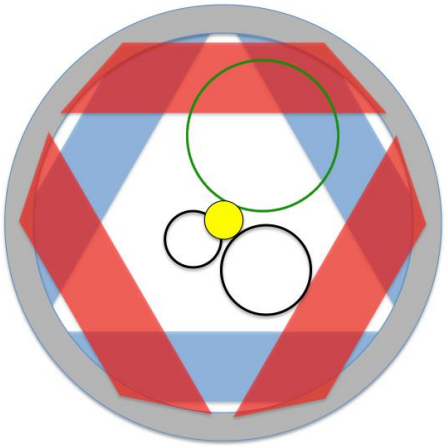
Spectrometer
- Uniform field
- Straw tracker
- Calorimeter

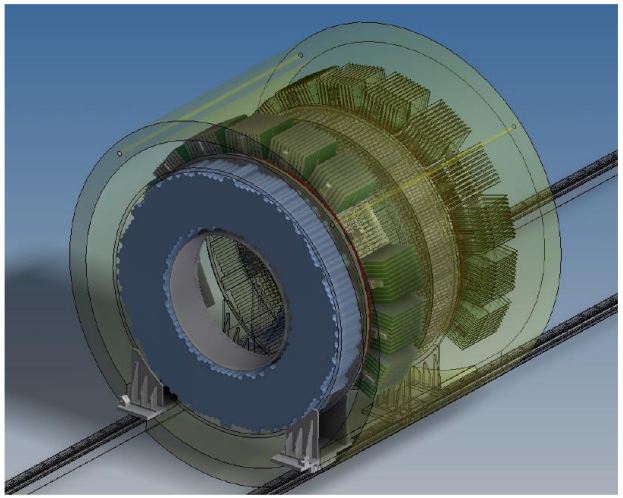
Search for μN→e⁻N : mu2e & COMET



- Electrons with energy > 53 MeV are accepted
- Calorimetry with 2 BaF_2 discs
- Timing and trigger with BaF_2

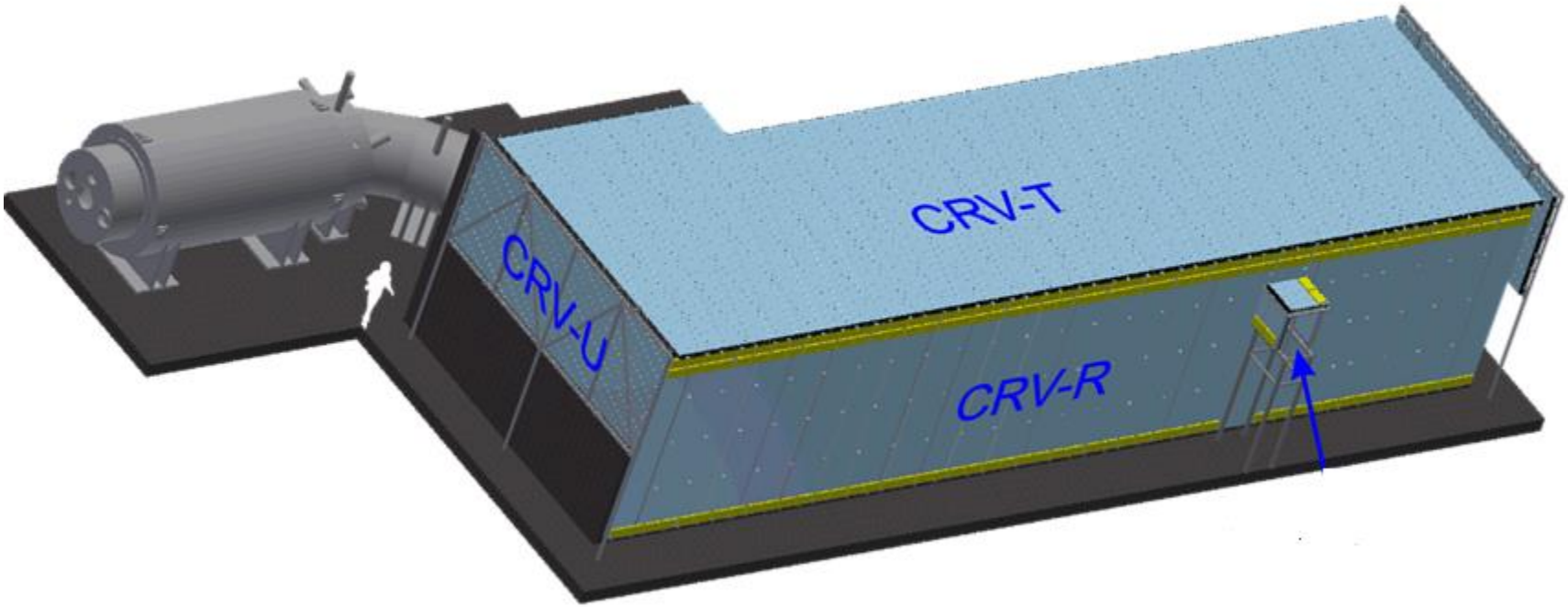






Search for μN→e⁻N : mu2e

Cosmic ray veto

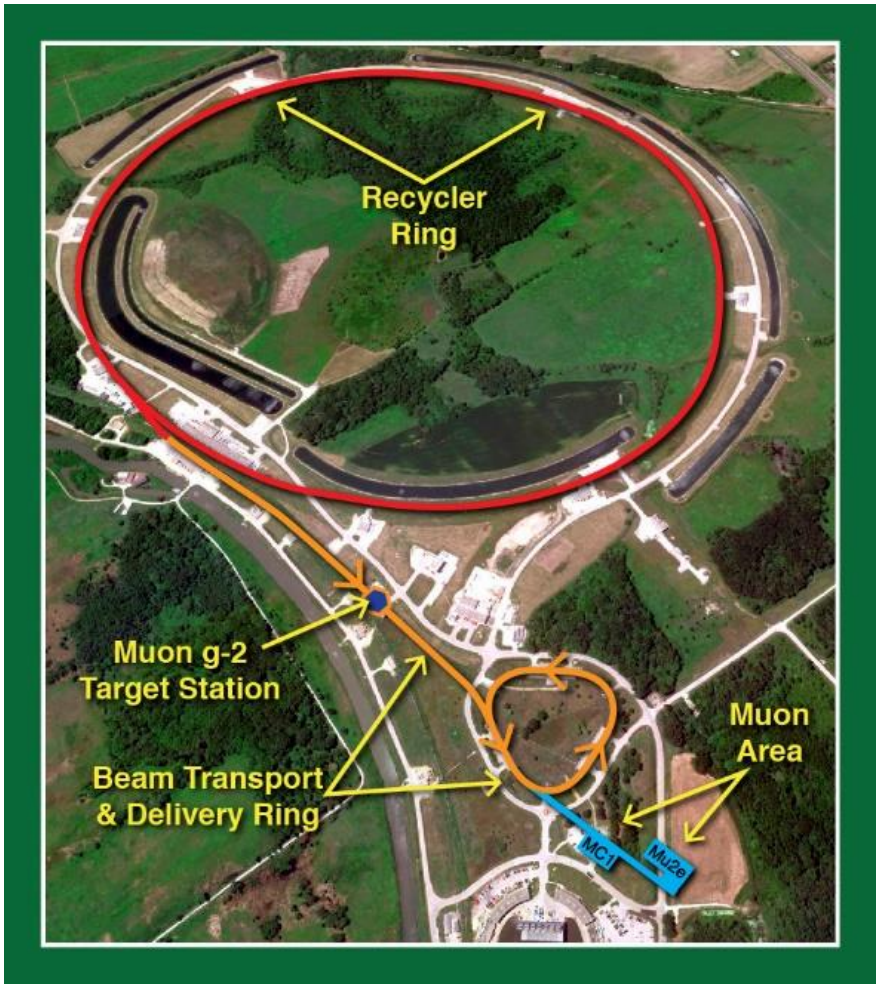


Search for μN→e⁻N : mu2e

- Full TDR in 2014
- CD-3 approved in July 2016
- Construction 2017-2020(1)
- Data taking starts in 2020-2021
  3 years for full statistics

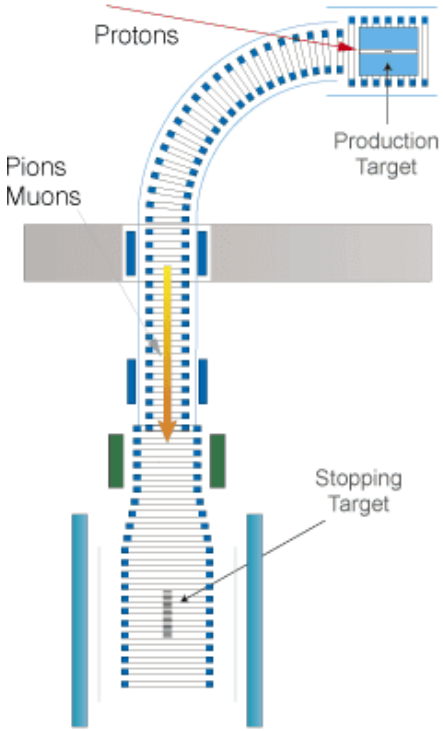
Construction of the mu2e exp hall started at Fermilab

Muon campus at Fermilab

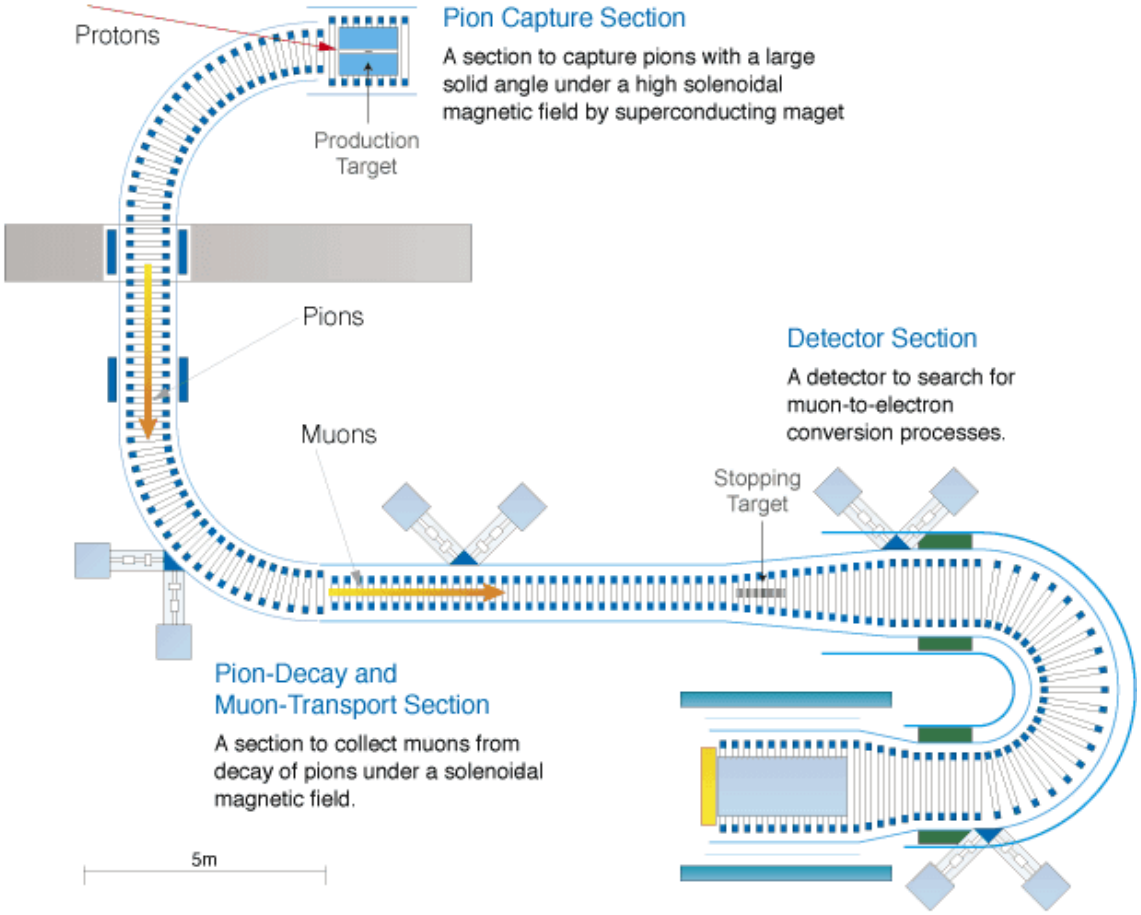


Search for μN→e⁻N : COMET

Phase I : B.R. of 10^{-14}

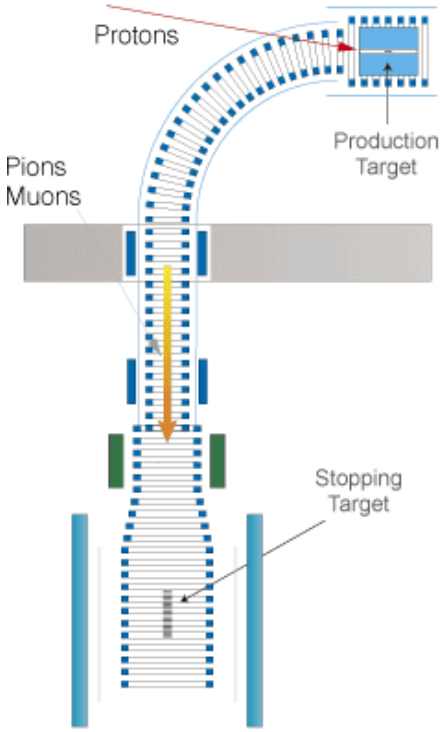


Phase II : B.R. 10^{-16}



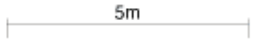
Search for μN→e⁻N : COMET

Phase I : B.R. of 10^{-14}



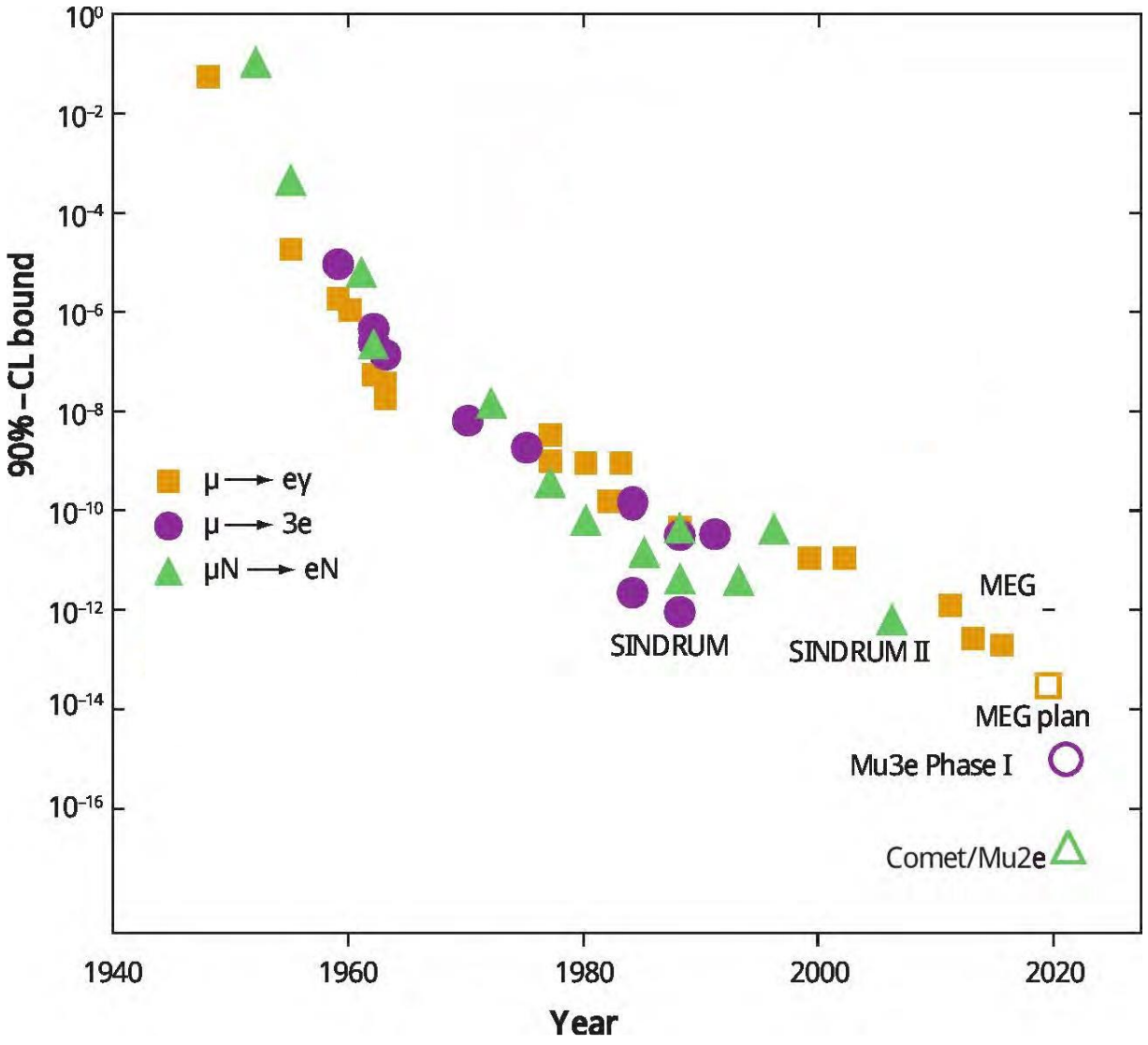
Pion-Decay and Muon-Transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.



CLFV, a new window in BSM physics

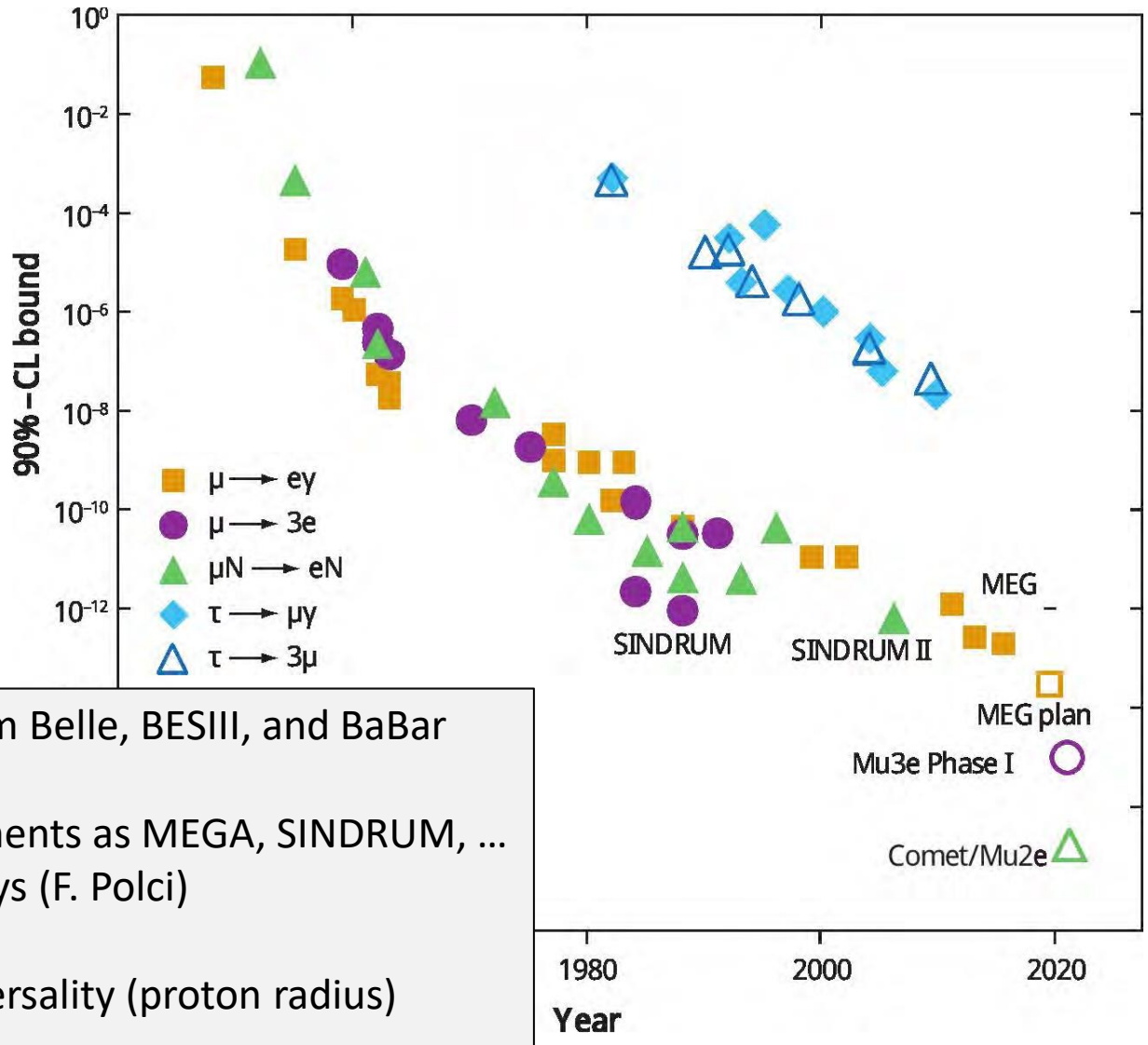
During the next decade, a new window in physics beyond the Standard Model is opening up:



CLFV, a new window in BSM physics

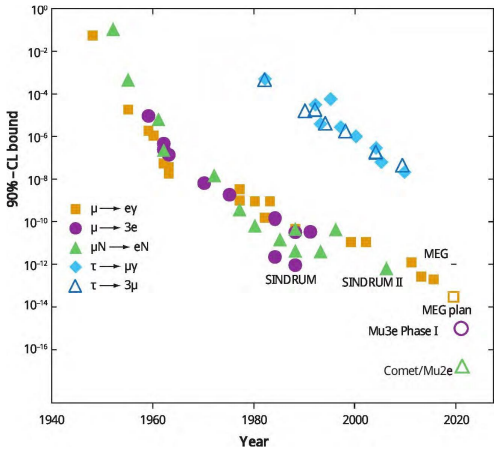
One can **not** cover everything:

Picture adapted from W. J. Marciano et al., Annu. Rev. Nucl. Part. Sci. **58**, 315 (2008)



+ τ decays from Belle, BESIII, and BaBar
+ DeeMe
+ Past experiments as MEGA, SINDRUM, …
+ Meson decays (F. Polci)
+ Z decays
+ Lepton universality (proton radius)
+ …

Conclusions



- A big push in experimental sensitivity for CLFV is coming up
- Intense beams at PSI, Fermilab, J-PARC
- 1000-10000 TeV physics
- μ decay is the golden channel
- If CLFV is seen, the 3 main channels combined yield a complimentary view on new physics

Good reads:

- Y. Kuno and Y. Okada, Rev. Mod. Phys. **73**, 151 (2001) theory
- A. de Gouvêa and P. Vogel **71**, 75 (2013)
- W. J. Marciano et al., Annu. Rev. Nucl. Part. Sci. **58**, 315 (2008) review
- S. Mihara et al., Annu. Rev. Nucl. Part. Sci. **63**, 531 (2013)
- A. M. Baldini et al., Eur. Phys. J. C **76**, 434 (2016) MEG
- W. Bertl et al. Eur. Phys. J. C. **47**, 337 (2006) SINDRUMII
- J. R. Abrams et al., arXiv:1211.7019 Mu2e
- A. Blondel et al., arXiv:1301.6113 Mu3e
- A. Perrevoort et al., arXiv:1605.02906

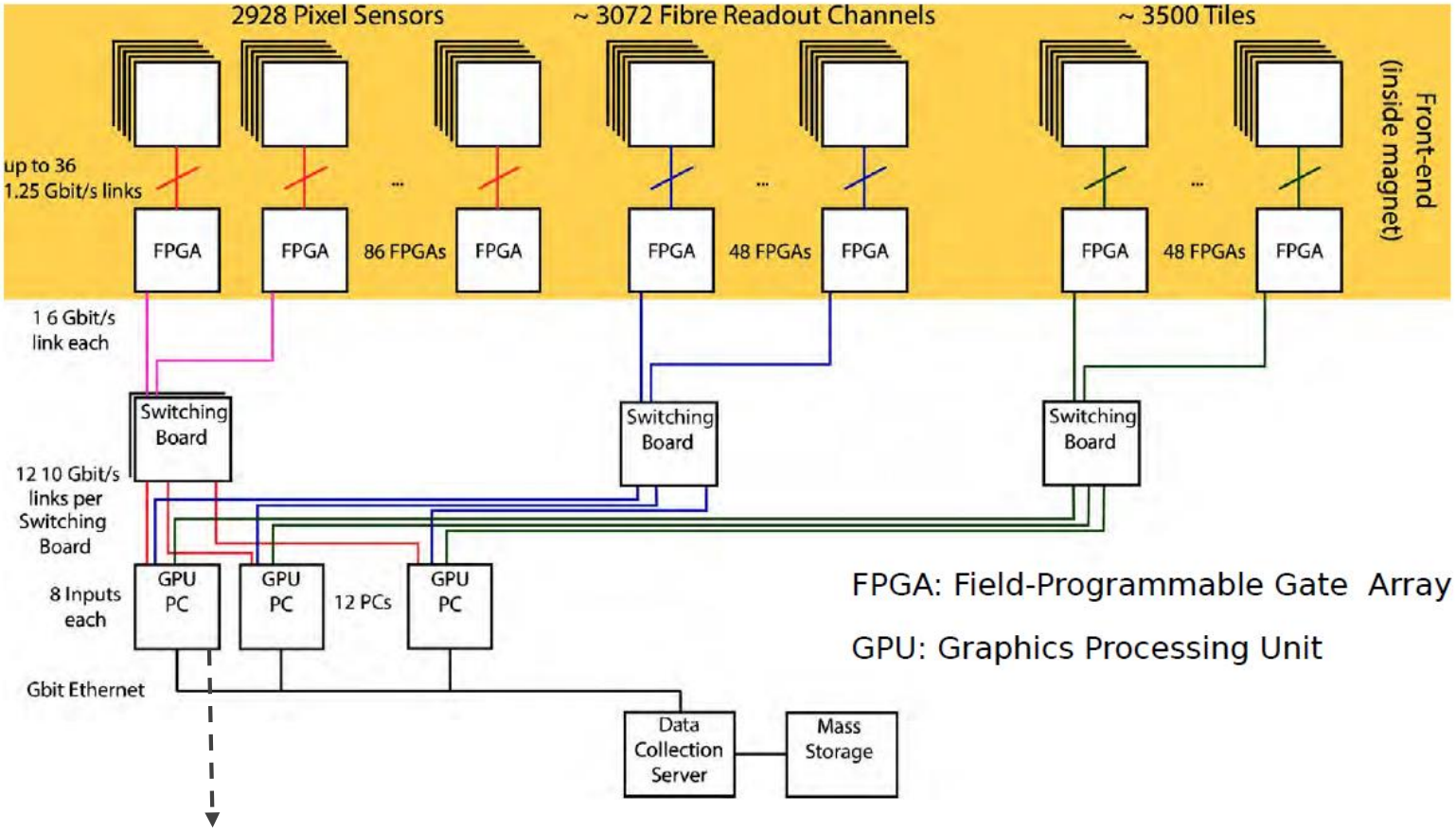
EXTRA

Search for $\mu \rightarrow e^+e^+e^-$: mu3e

Readout: All muon decays are detected + beam background
Need full detector info for event selection (no local trigger)

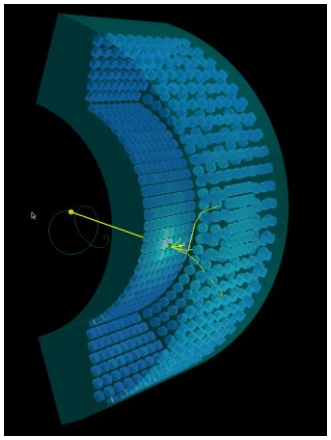
2 TB/s

< 100 Mb/s



each GPU processes a 50 ns time slice

Search for μ→eγ : MEG



Operating a 2.7 T LXe photon detector

- full coverage by 846 PMT's
- full waveform digitization
- Photon vertex reconstruction
- calibrating, and calibrating, and more calibration

Process		Energy	Main purpose	Frequency
Cosmic rays	$\mu^{\pm}$ from atmospheric showers	Wide spectrum $\mathcal{O}$(GeV)	LXe-DCH relative position DCH alignment TC energy and time offset calibration	Annually
			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, Positrons > 45 MeV	LXe-TC relative timing Normalisation	Continuously
Normal μ−decay	$\mu^+ \to e^+ \nu \bar{\nu}$	52.83 MeV end-point positrons	DCH energy scale/resolution DCH and target alignment Normalisation	Continuously
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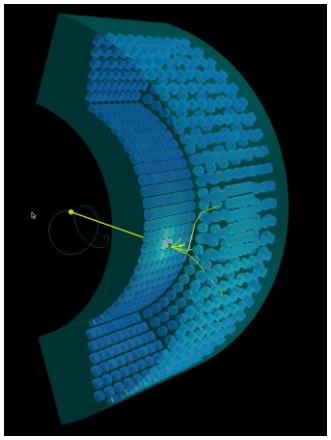
Radioactive source	^{241}Am(α, γ)^{237}Np	5.5 MeV α's, 56 keV photons	LXe PMT calibration/purity	Weekly
Radioactive source	^{9}Be($\alpha_{^{241}\mathrm{Am}}$, n)^{12}C* ^{12}C$^\star(\gamma)^{12}$C	4.4 MeV photons	LXe energy scale	On demand
LED			LXe PMT calibration	Continuously

Search for μ→eγ : MEG



Operating a 2.7 T LXe photon detector

- full coverage by 846 PMT's
- full waveform digitization
- Photon vertex reconstruction
- calibrating, and calibrating, and more calibration

Process		Energy	Main purpose	Frequency
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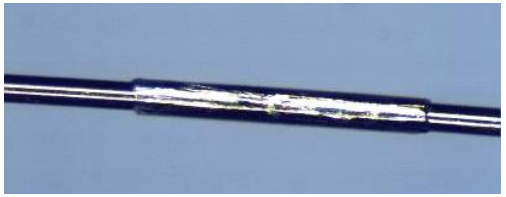
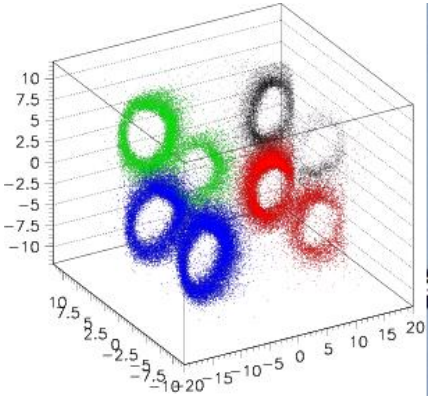
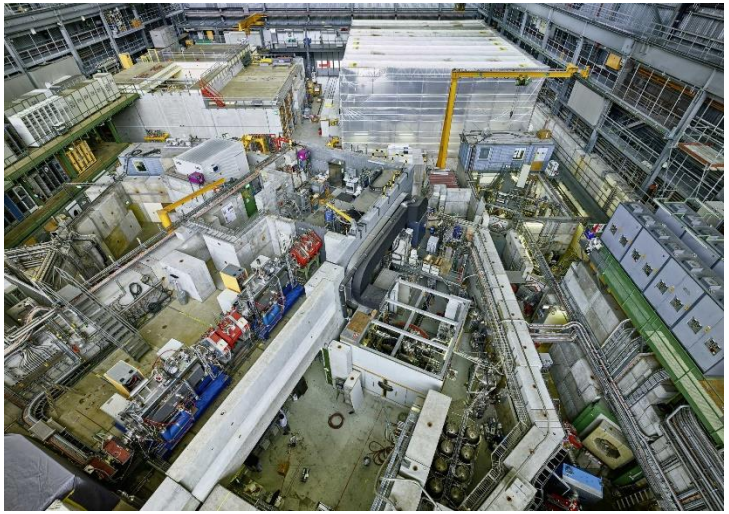




Facilities at the center of the Intensity Frontier

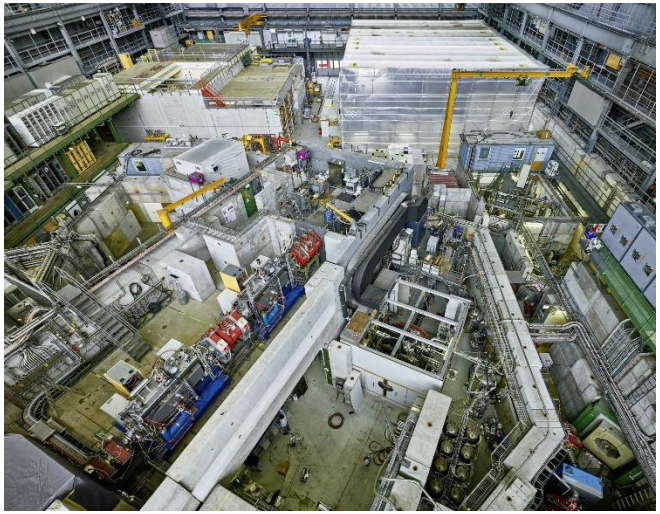
PAUL SCHERRER INSTITUT

PSI



- 2.2 mA 600 MeV proton beam
- 10^8 μ^+ DC beam
- 10^9 in R&D phase
- Several particle physics experiments in parallel
  + solid state physics
  + applied physics
  + …

Facilities at the center of the Intensity Frontier



PAUL SCHERRER INSTITUT

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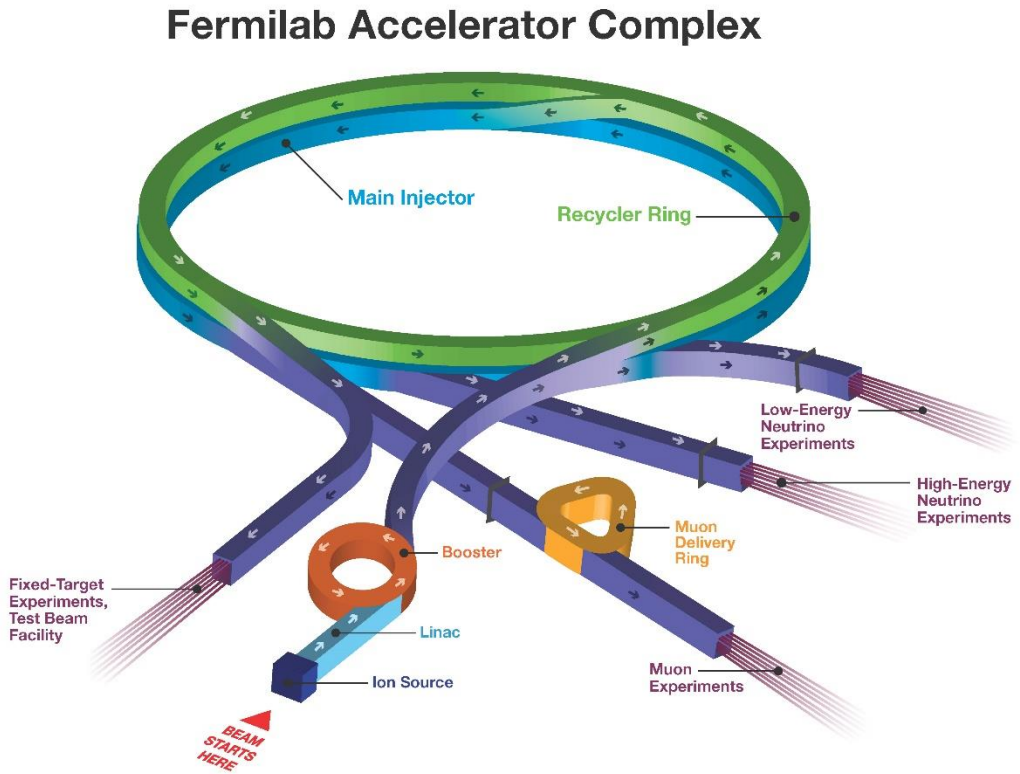
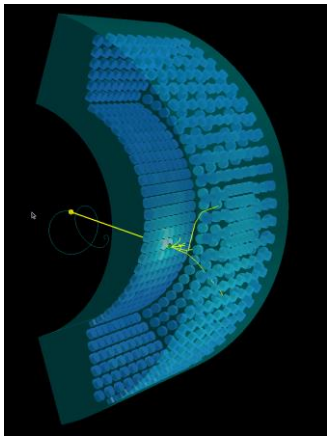


Search for μ→eγ : MEG



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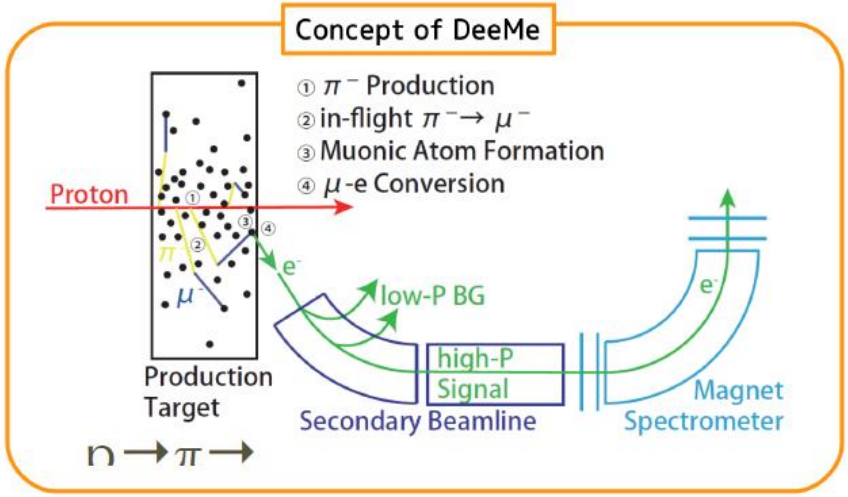
LED			LXe PMT calibration	Continuously

0.3-1 MeV p Cockcroft-Walton accelerator

DeeMe

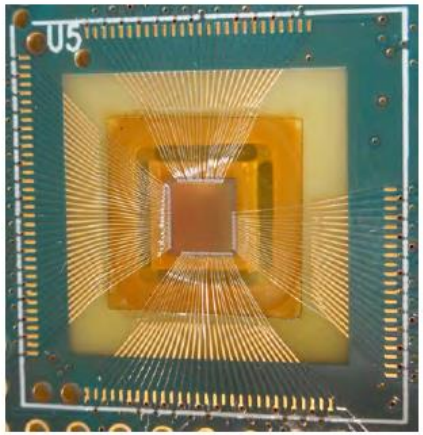
- DeeMe at J-PARC $\mu N \rightarrow eN$ with a 2 x 10^{-14} SES, x10 better than existing
- production target and conversion target are the same
- rotating Silicon Carbide target
- physics data taking planned to start in 2017

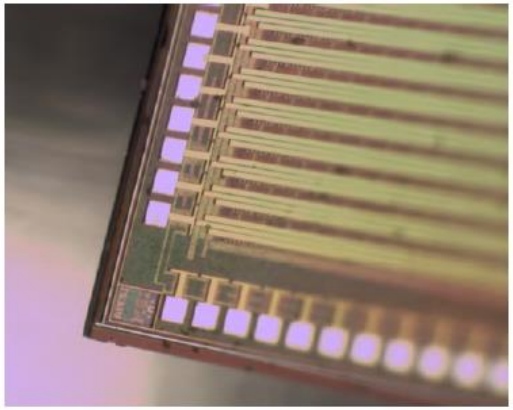


Nakatsugawa, CLFV 2016; Natori, this conf.

Mupix Protoype

- Mupix7: latest prototype
- Thinned to 50 μm
- 32 x 40 pixel matrix
- Pixel size: 103 μm x 80 μm
- 3.2 x 3.2 mm^2

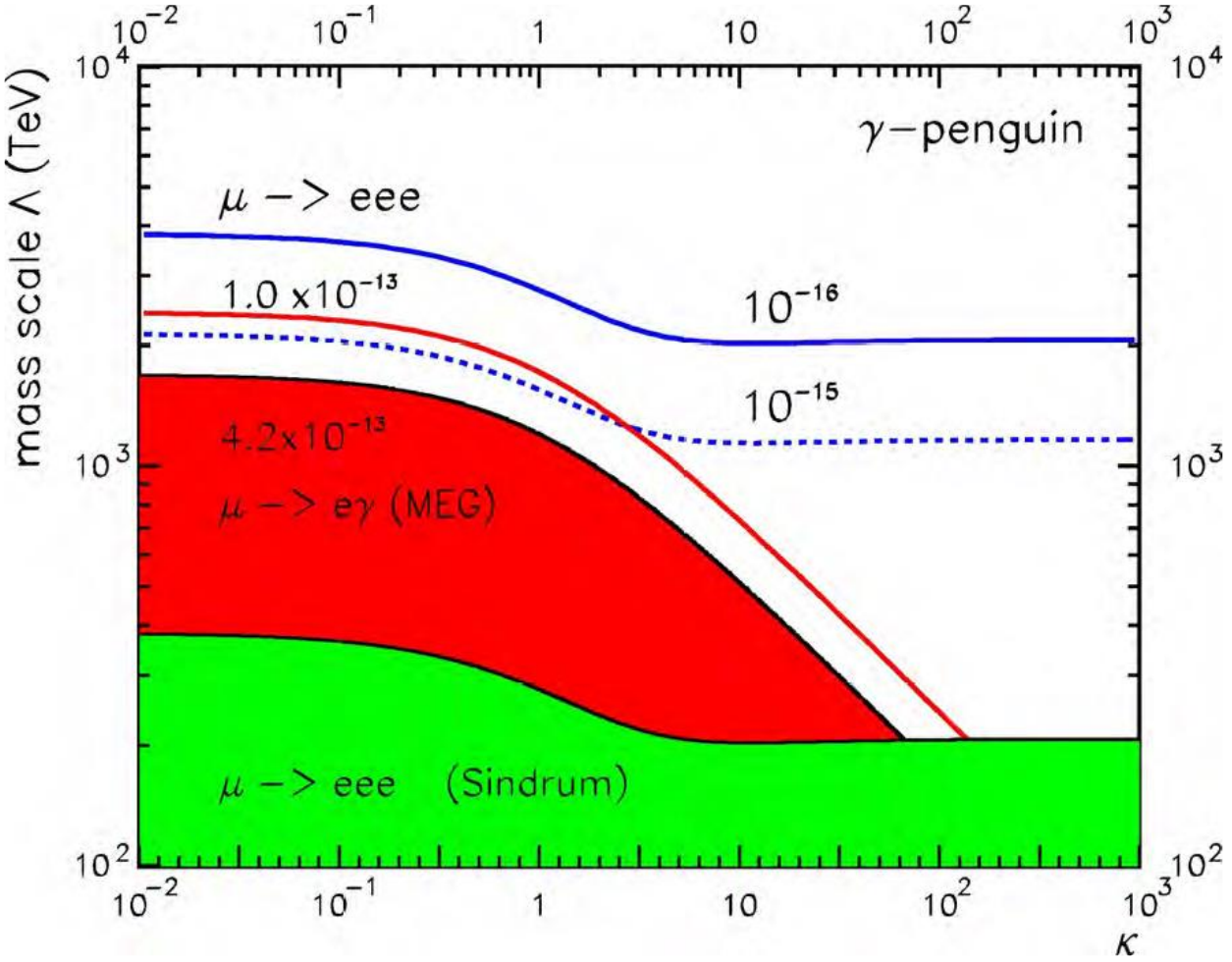




- Readout electronics on chip
- Fast LVDS link: 1.25 Gbit/s,

  ~ 30 million hits/s

Search for μ→e⁺e⁺e⁻ : mu3e



Based on A. de Gouvêa, P. Vogel,
Prog.Part.Nucl.Phys 71,
75-92 (2013)