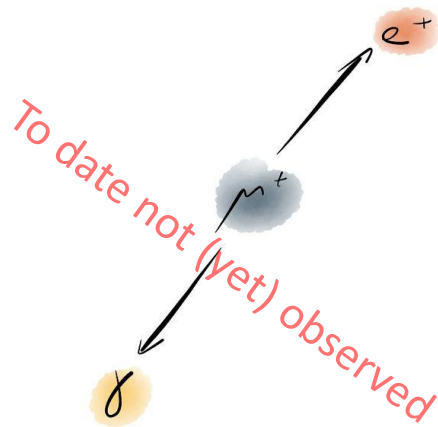
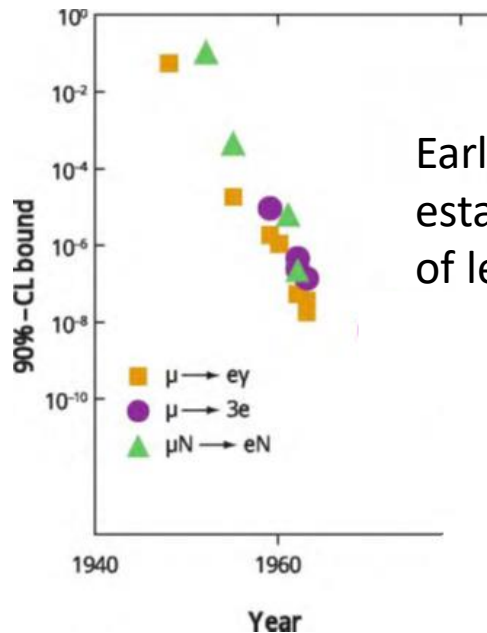


Conservation of lepton flavor number

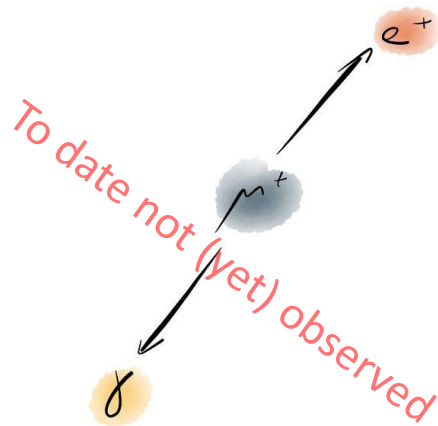


- A muon is not an excited electron
- $\nu_\mu \neq \nu_e$
- In the SM:
 - Conservation of lepton number L
 - Conservation of lepton flavor number L_e, L_μ, L_τ

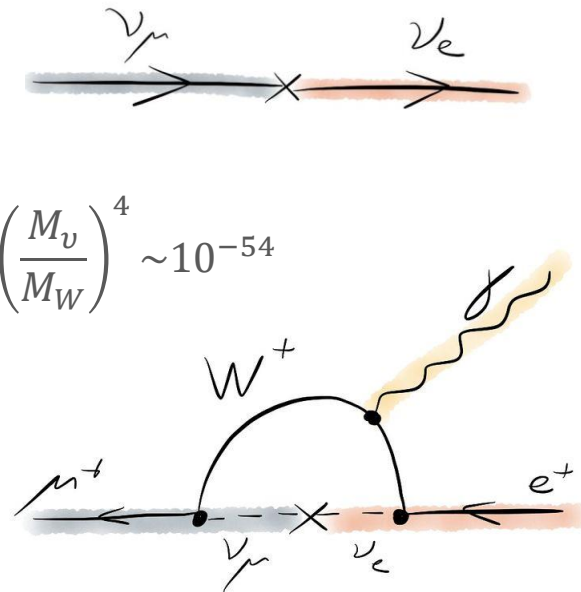


Early experiments established the existence of lepton flavor number

Conservation of lepton flavor number

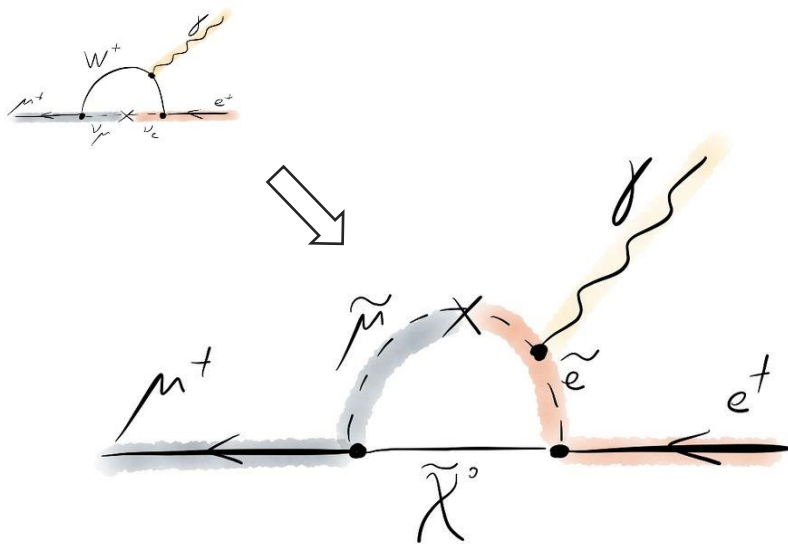


$$B.R. \sim \left(\frac{M_\nu}{M_W} \right)^4 \sim 10^{-54}$$

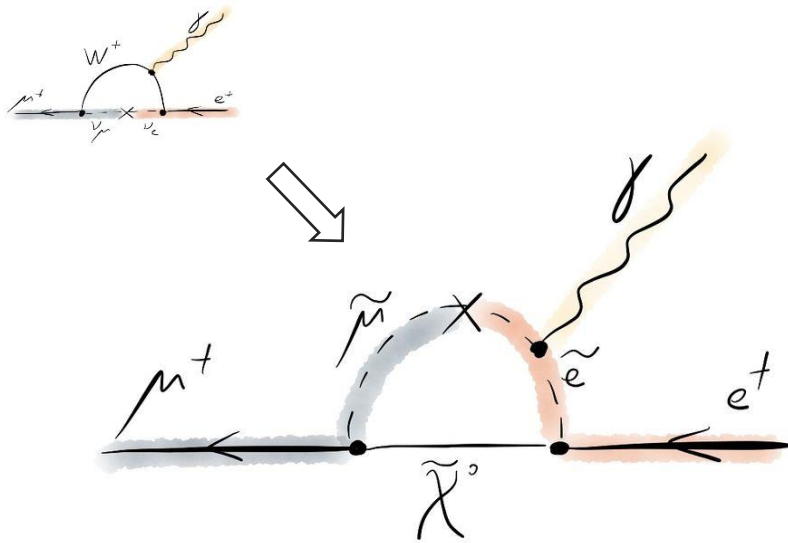


BUT:

- 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 a new physics.
- Many BSM models predict a sizeable amount of CLFV

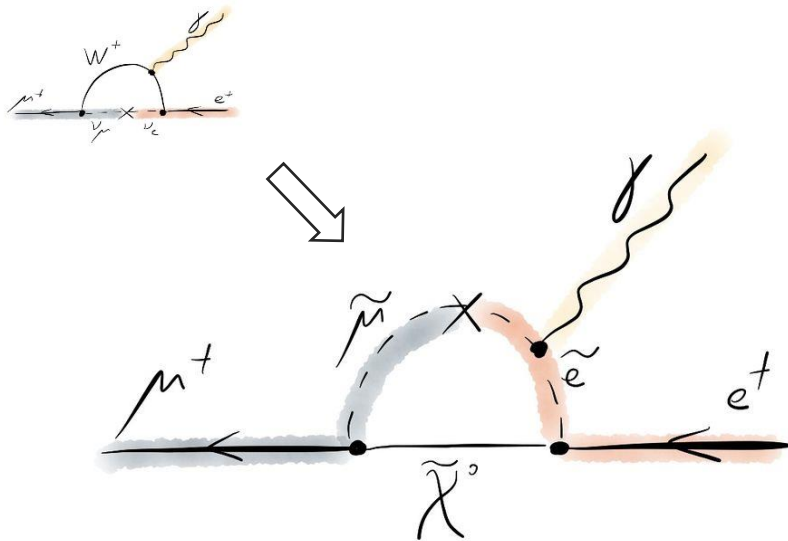


- Paradigm of the Intensity Frontier: Probe new physics at low energies through loop diagrams. Sensitivities are \geq direct searches at the LHC.



- Paradigm of the Intensity Frontier: Probe new physics at low energies through loop diagrams. Sensitivities are \geq direct searches at the LHC.
- NP scale for $\mu \rightarrow e\gamma$:
 - + $\text{BR}(10^{-12}) \leftrightarrow \Lambda \approx 1000 \text{ TeV}$
 - $\text{BR}(\mu \rightarrow e\gamma) \sim \left(\frac{1}{\Lambda}\right)^4$

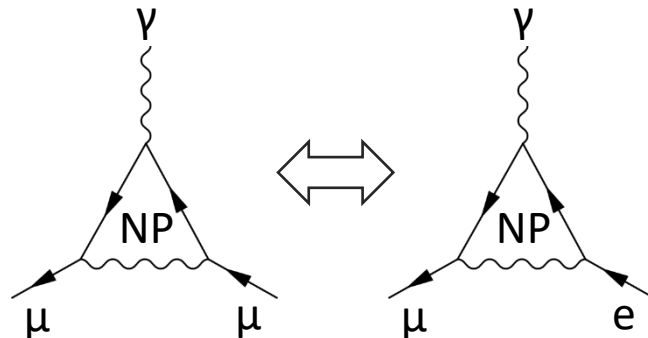
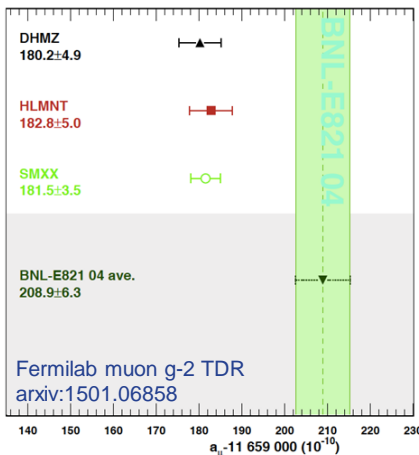
Violation of lepton flavor number



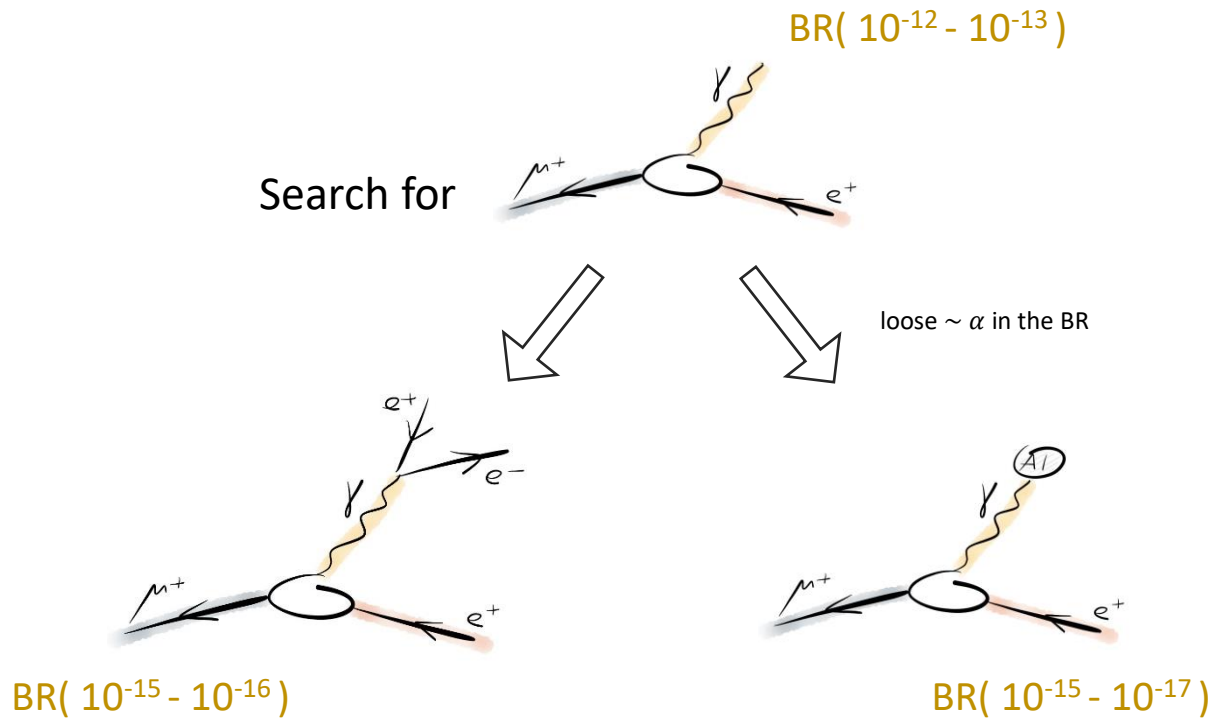
- Paradigm of the Intensity Frontier: Probe new physics at low energies through loop diagrams. Sensitivities are \geq direct searches at the LHC.
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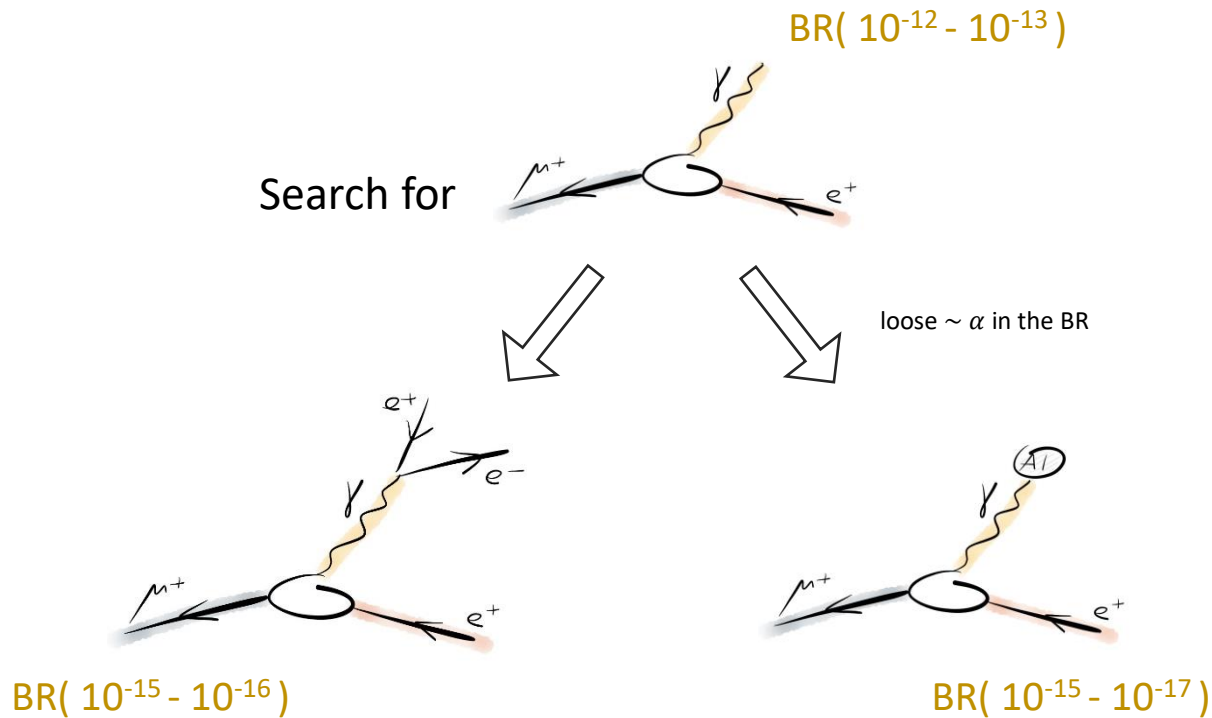
+ $BR(10^{-12}) \leftrightarrow \Lambda \approx 1000 \text{ TeV}$

- $BR(\mu \rightarrow e\gamma) \sim \left(\frac{1}{\Lambda}\right)^4$



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

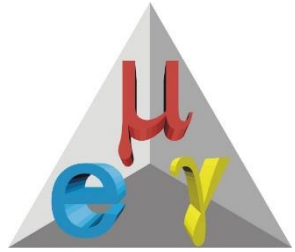




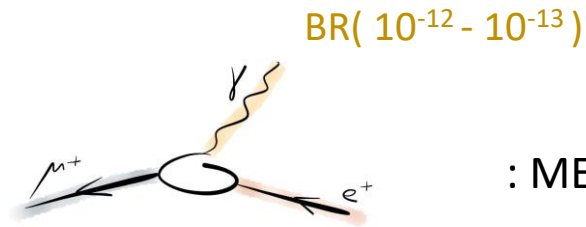
Lepton flavor violation searches
with muons

The μ as a golden channel

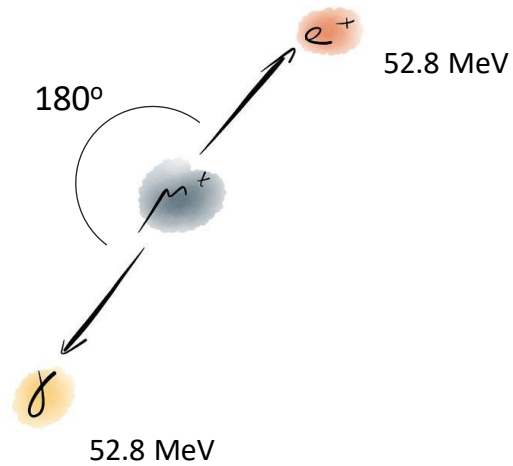
- Available in large quantities, e.g. 10^8 s^{-1} (low energy DC) at PSI
- Relatively long lived. Enables transport from production to experiment apparatus
- SM decays very well known



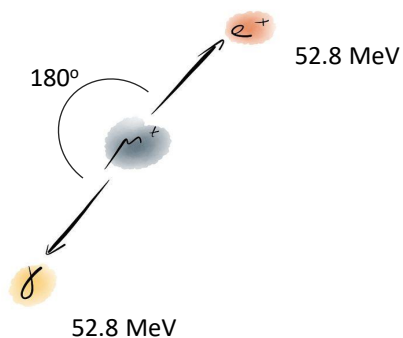
Search for

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

: MEG(II)

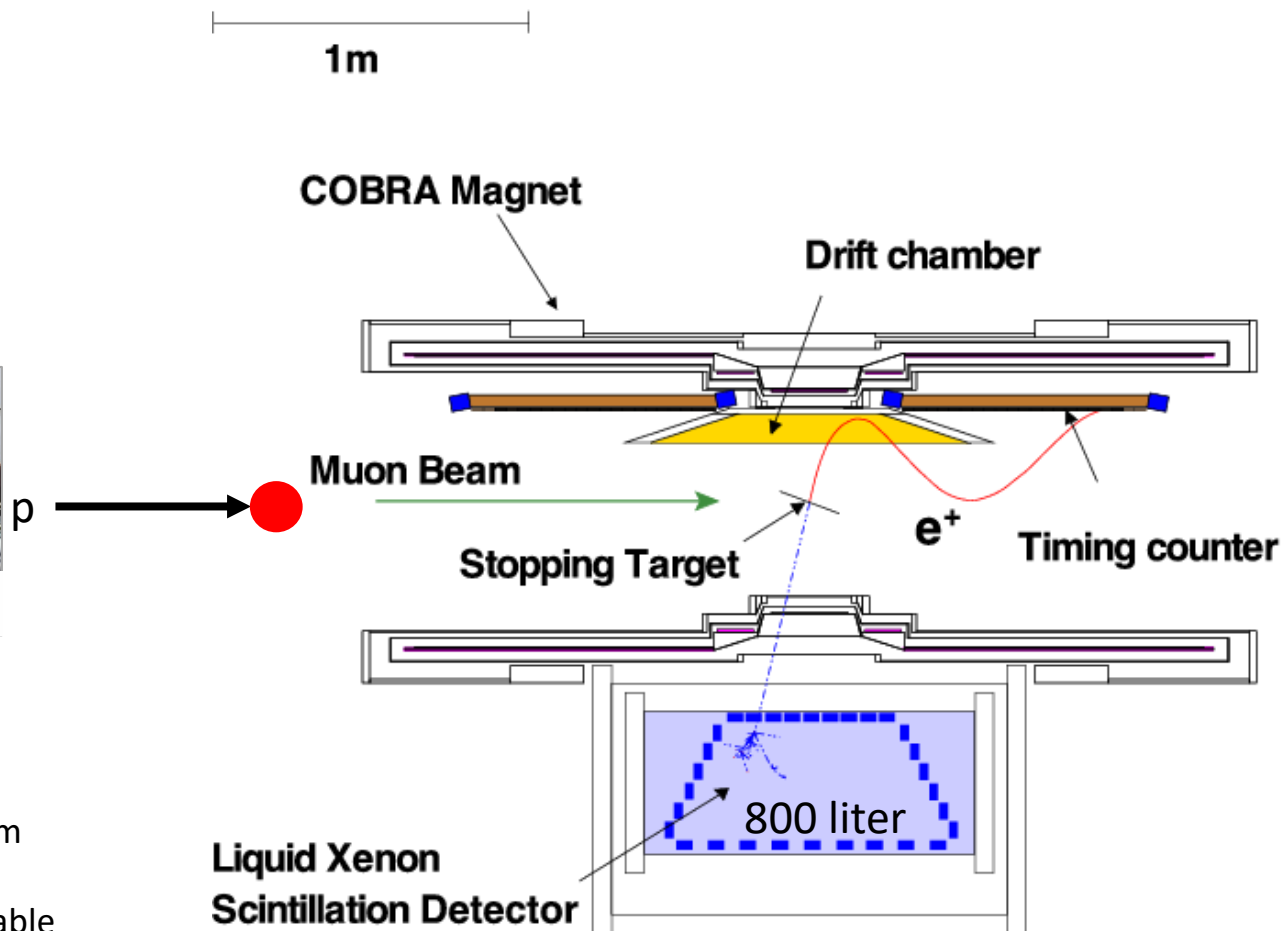


- E_γ
- E_{e^+}
- $\theta(e^+, \gamma)$
- $t(e^+, \gamma)$



HIPA @ PSI:

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

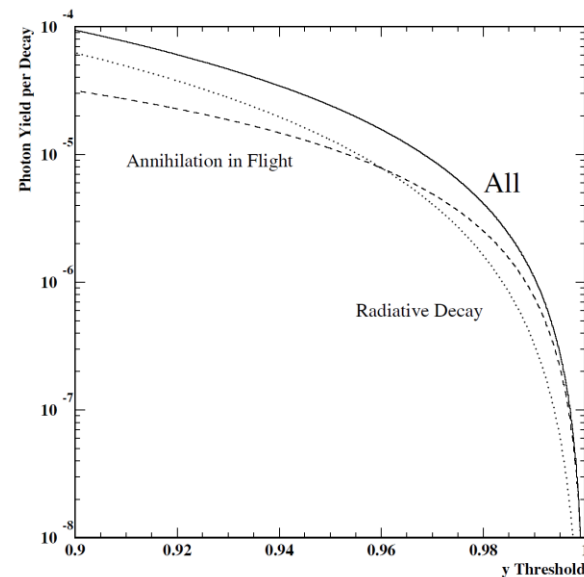
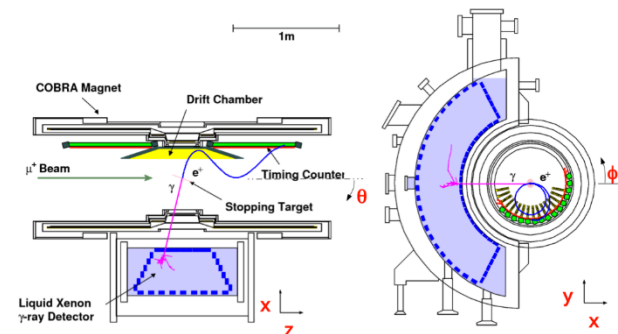


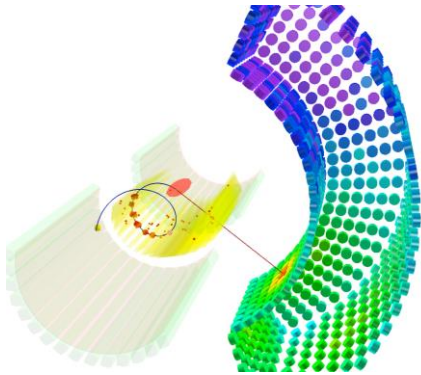
Backgrounds:

- Singles:
 - Radiative muon decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$ with
 $BR(E_\gamma > 10 \text{ MeV}) \approx \sim 1\%$, $BR(E_\gamma > 45 \text{ MeV}) \approx 6 \cdot 10^{-8}$
- Accidental (combinatorial), ordinary muon decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu + \gamma$ from
 - Annihilation in flight
 - Radiative muon decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$

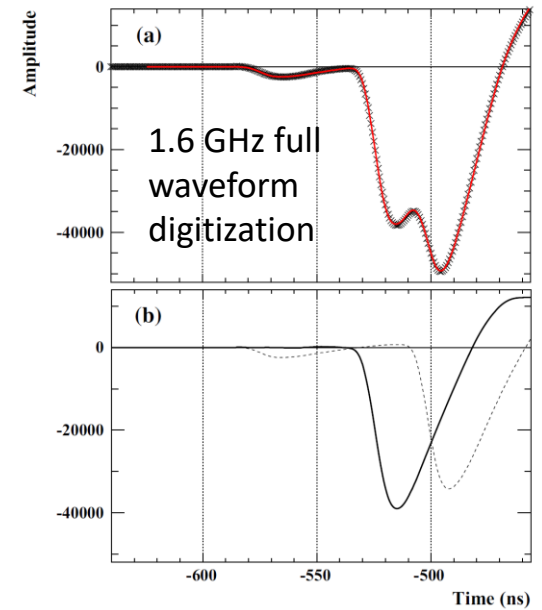
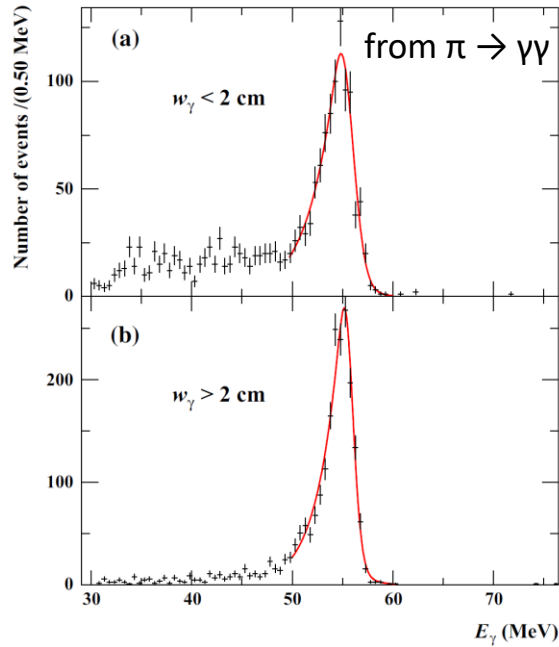
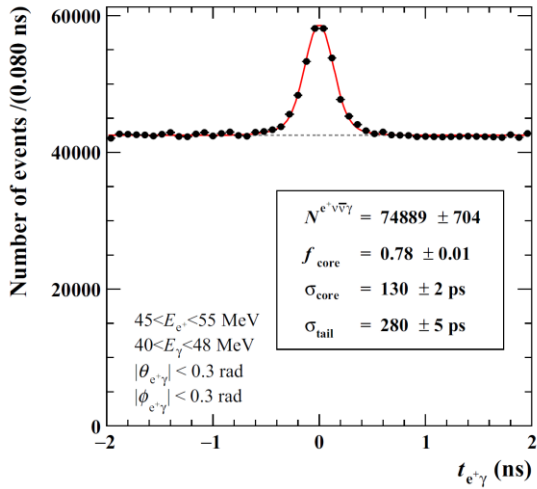
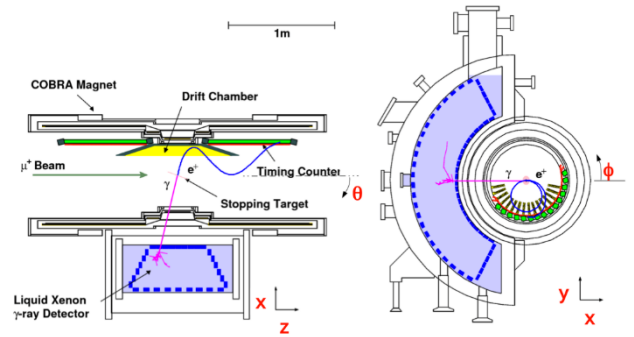
Detector specs:

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





Detector performance



+ calibration, calibration, calibration

Final MEG result

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

THE EUROPEAN
PHYSICAL JOURNAL C



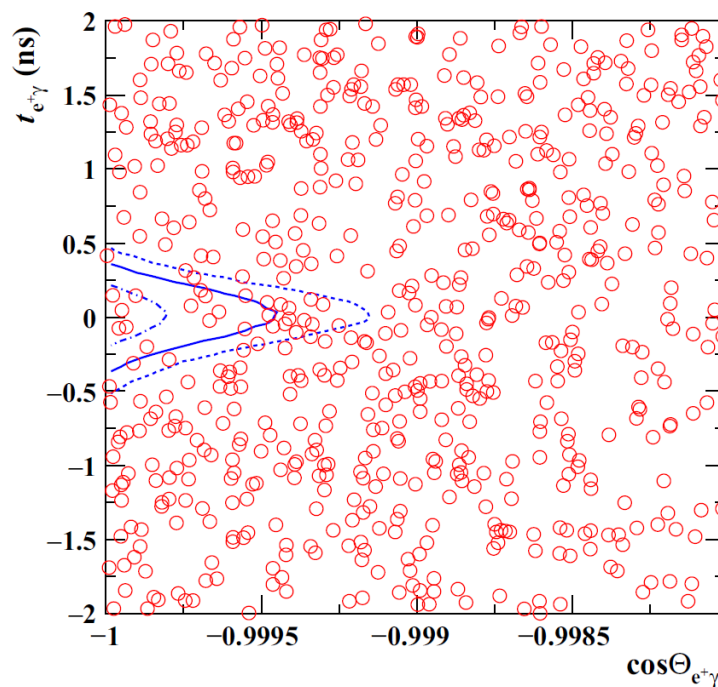
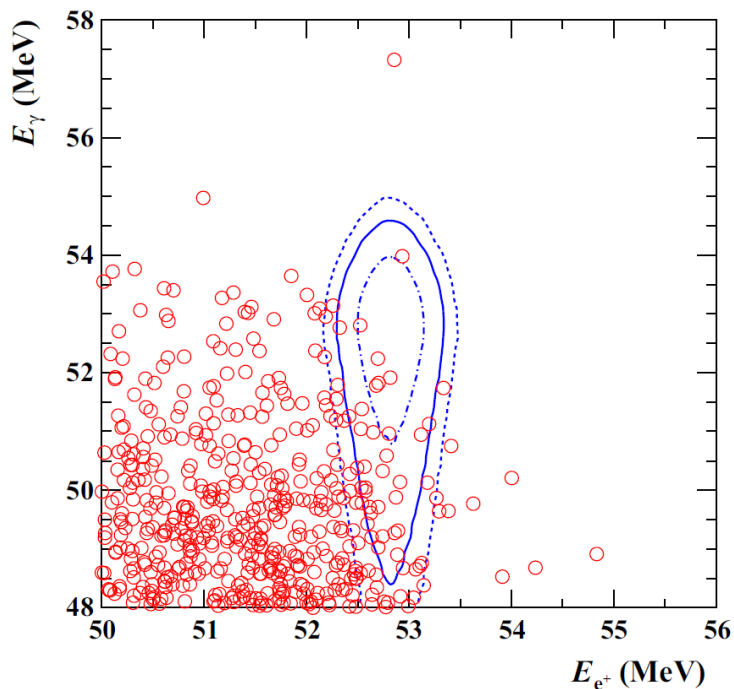
Regular Article - Experimental Physics

best CLFV limit by a factor of 30

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

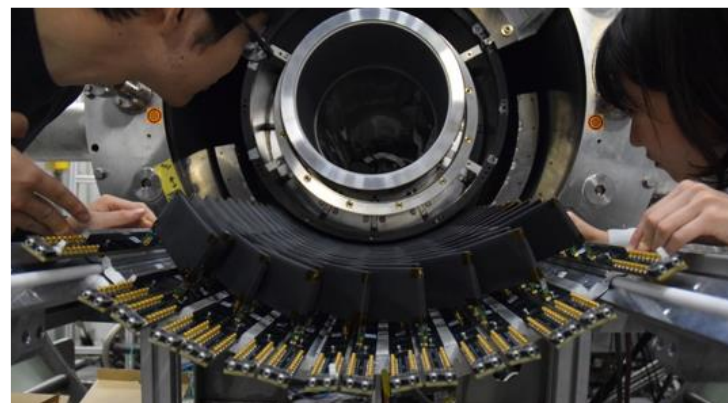
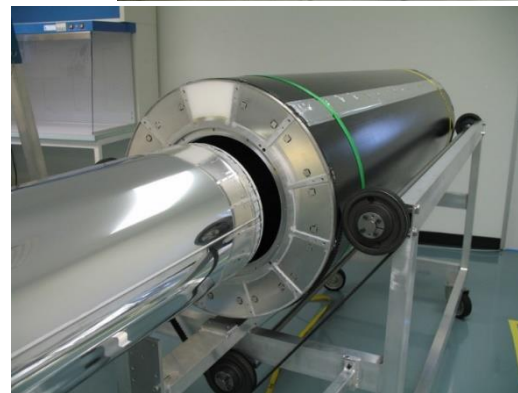
$$BR(\mu^+ \rightarrow e^+\gamma) < 4.2 \cdot 10^{-13}$$

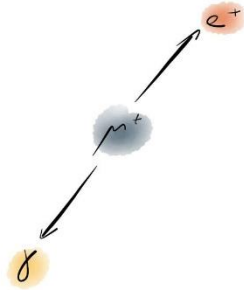
MEG Collaboration



MEGII is under construction:

- go from $4 \cdot 10^{-13} \rightarrow 4 \cdot 10^{-14}$ B.R. sensitivity
- Improve all detector systems:
 - PMT \rightarrow 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
- $\mu \rightarrow e\gamma$ sensitivity is limited by accidental background, going beyond 10^{-14} is unlikely





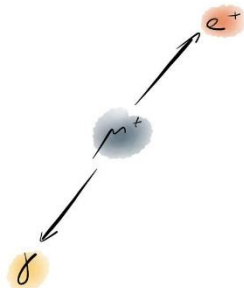
- 2-body decay
- back to back γ - e
- mono energetic γ - e

Background

- Accidental background
→ DC Beam (PSI)

CLFV sensitivity

- $\div 1$



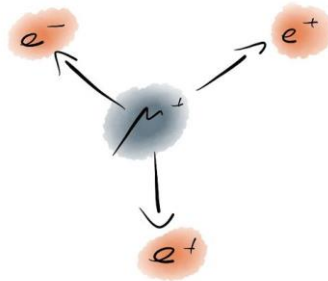
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Background

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CLFV sensitivity

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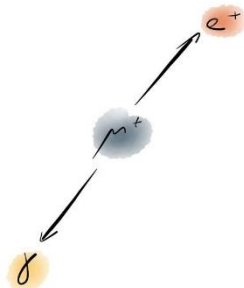
- 3-body decay
- $\sum \vec{p}_e = 0$
- $\sum E_e = m_\mu$

Background

- Accidental background
→ DC Beam (PSI)
- Radiative muon decay

CLFV sensitivity

- $\div 170$



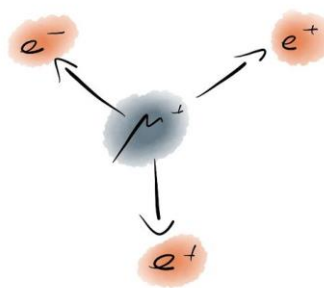
- 2-body decay
- back to back $\gamma - e$
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Background

- Accidental background
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CLFV sensitivity

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Background

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→ DC Beam (PSI)
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CLFV sensitivity

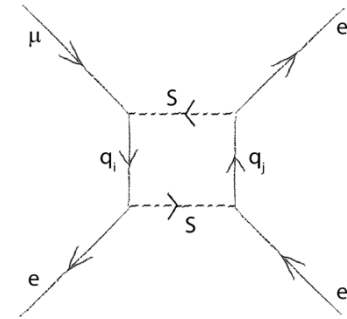
- $\div 170$

Angular correlations/Dalitz plot
extra window in NP

But: only true for
loop diagrams

$$\frac{m_\mu}{(1 + \kappa)\Lambda^2} \left(\text{(SUSY) loop} \right) + \frac{\kappa}{(1 + \kappa)\Lambda^2} \left(\text{tree level / eff. Fermi interaction} \right)$$

+ box diagrams like

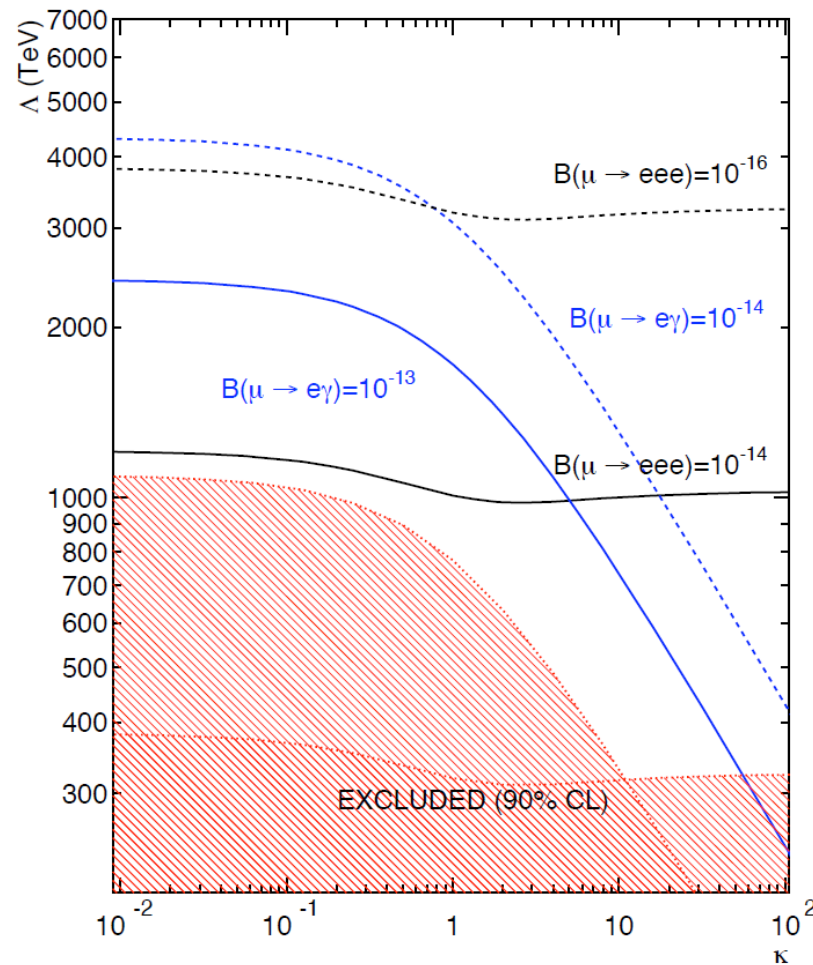


+ ...

Search for $\mu \rightarrow e^+e^-e^- : \mu 3e$

$$\frac{m_\mu}{(1+\kappa)\Lambda^2} \left(\begin{array}{c} \text{wavy line} \\ \bullet \\ \text{two lines} \end{array} \right) + \frac{\kappa}{(1+\kappa)\Lambda^2} \left(\begin{array}{c} \text{two lines} \\ \bullet \\ \text{two lines} \end{array} \right)$$

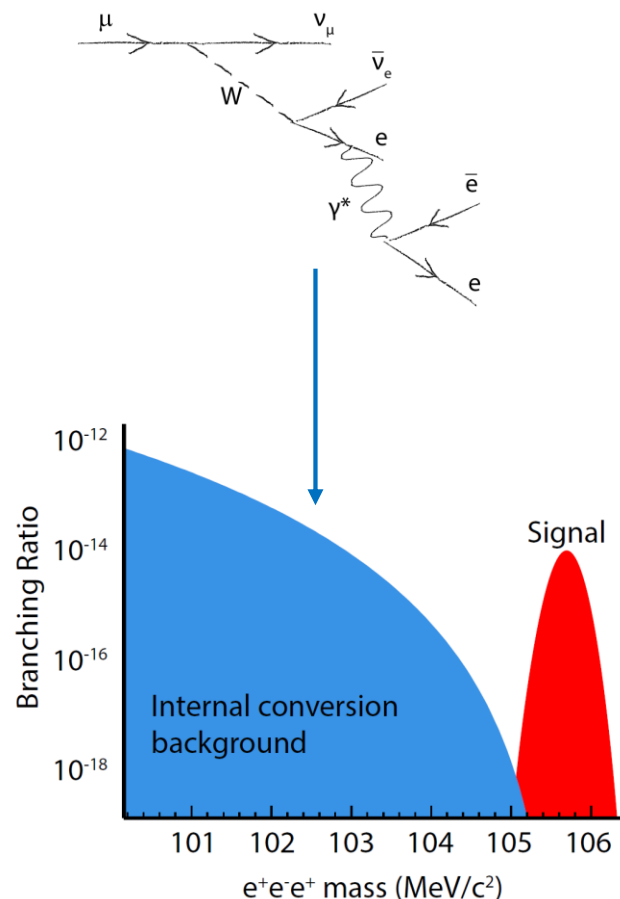
de Gouvea and Vogel, 2013





The mu3e experiment

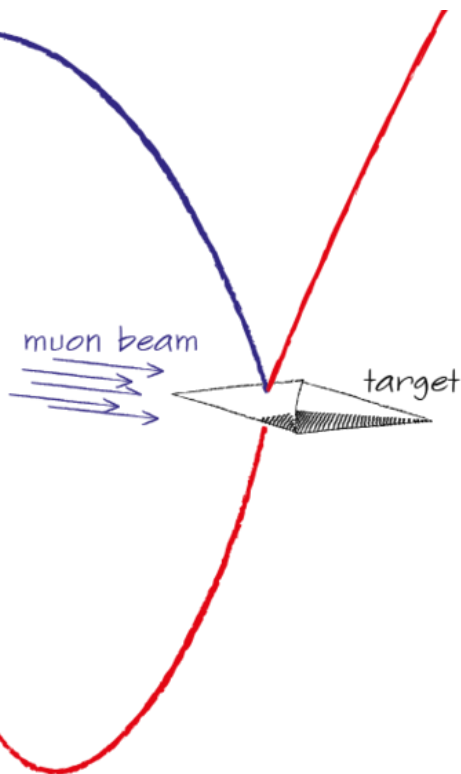
- Coincidence of $e^+e^+e^-$ with $\sum \vec{p} = 0$ and $\sum E = m_\mu$
Need to see electrons of all energies !
- Background from
 - internal conversion
 - Accidental background from Michel decay +
 - Bhabha scattering
 - Photon conversion
 - misreconstructed tracks
- Continuous streaming readout ($E_e > 15$ 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)





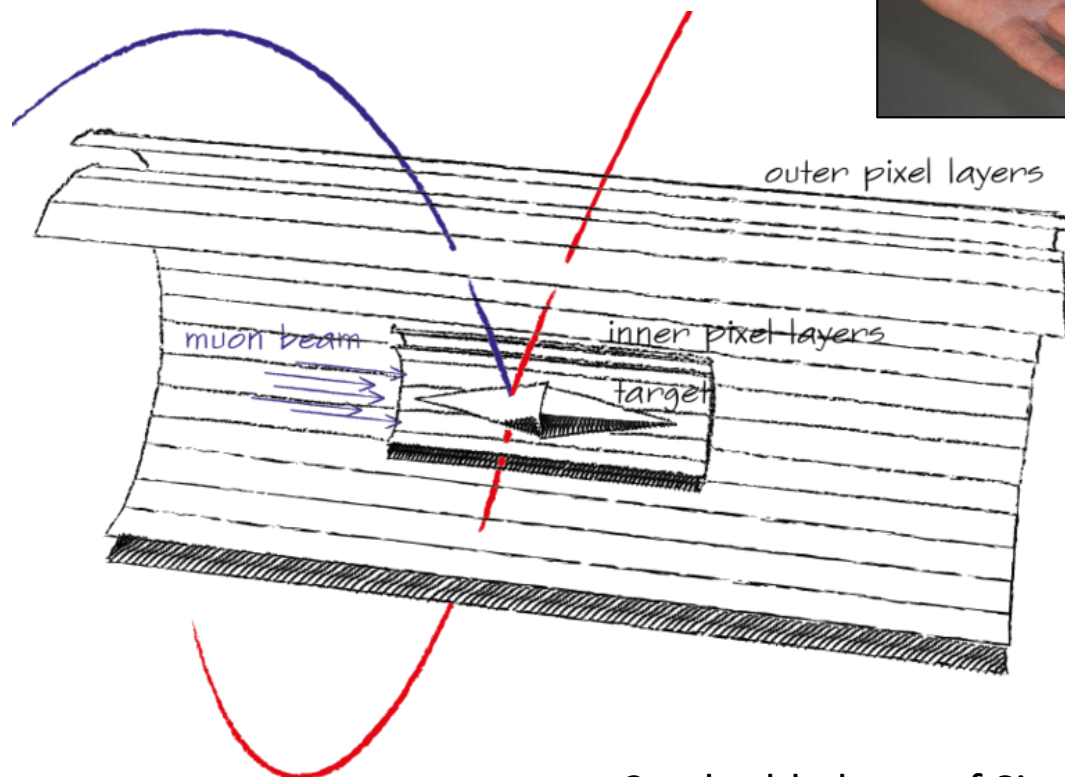
The detector

10^8 μ /s from the
 π E5 beamline at PSI



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

The detector

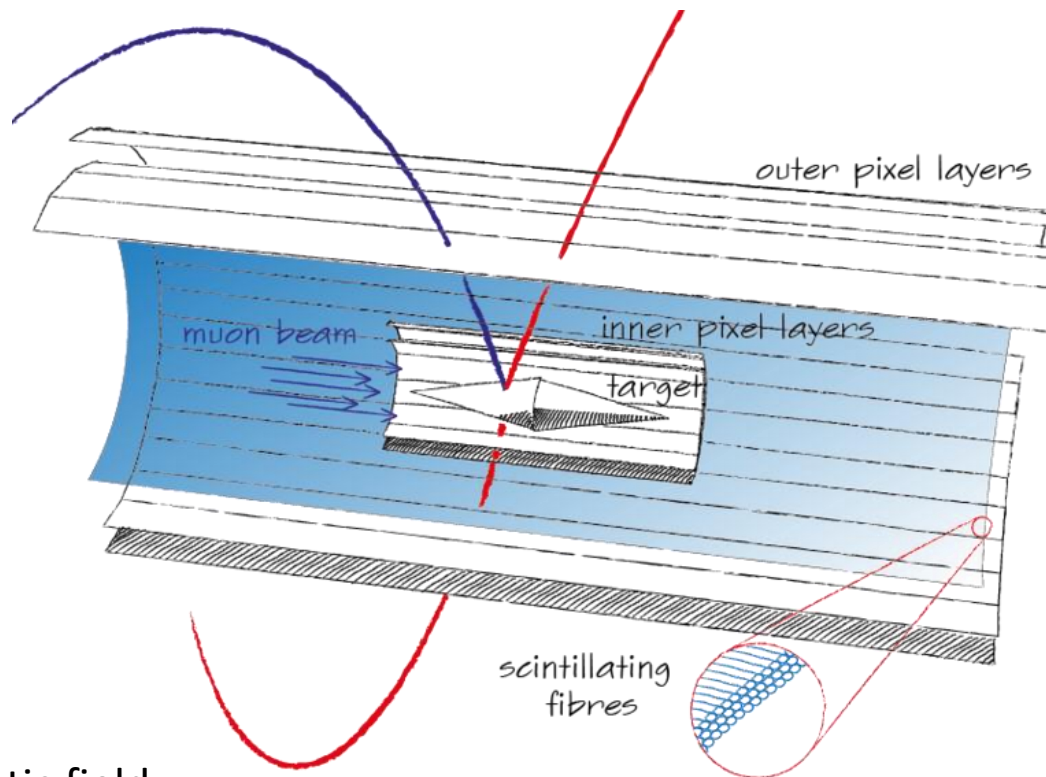


1 T magnetic field

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

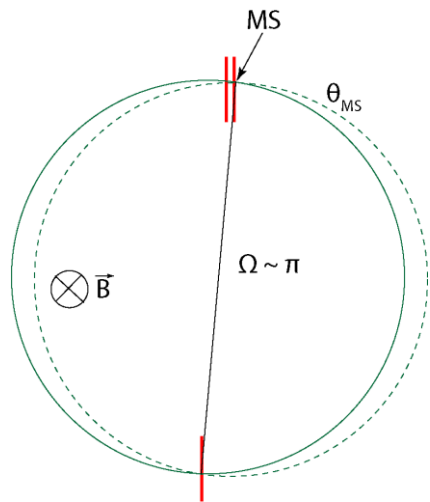


The detector



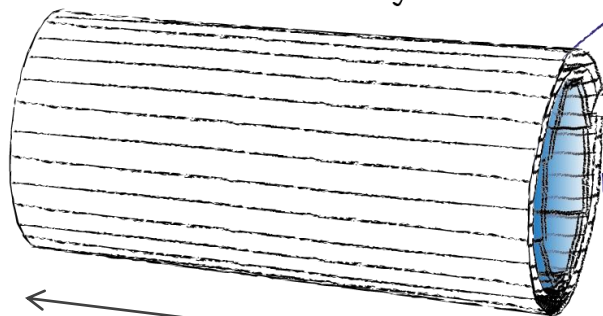
1 T magnetic field

Scintillating fibers as a thin, fast timing detector

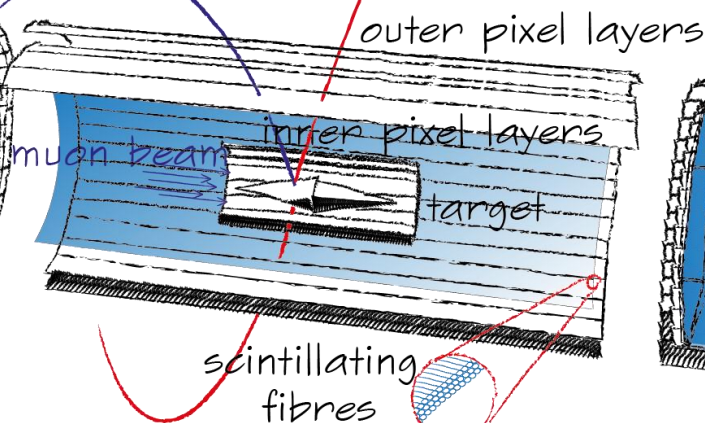


Recurl stations optimize momentum resolution, minimizing sensitivity to multiple scattering

recurl pixel layers



40 cm



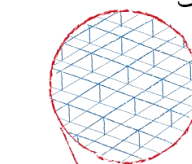
scintillating fibres

outer pixel layers

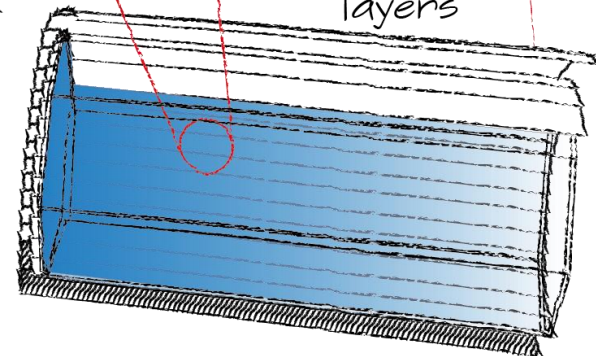
inner pixel layers

target

Scintillating tiles



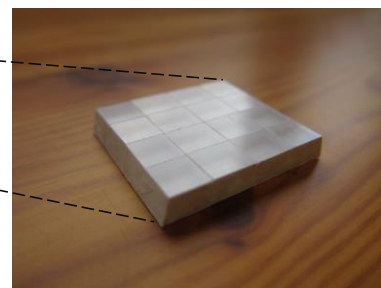
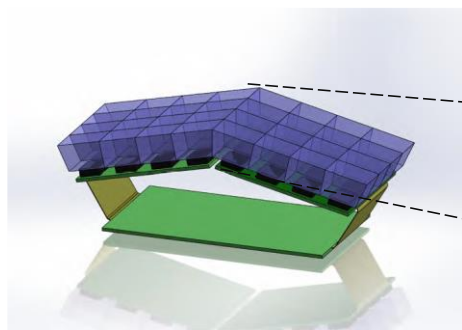
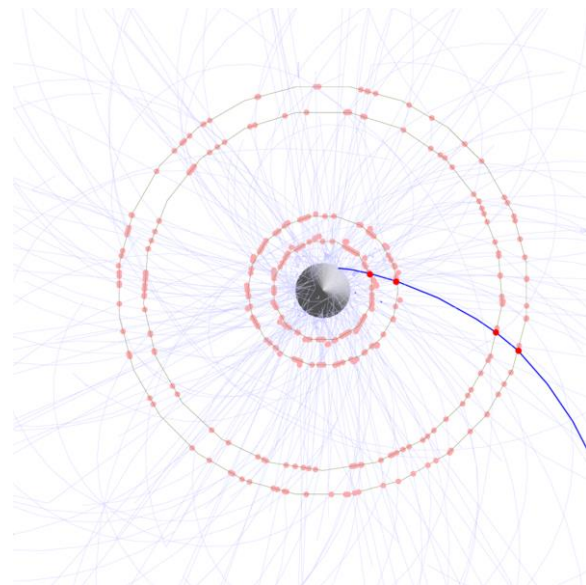
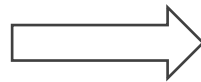
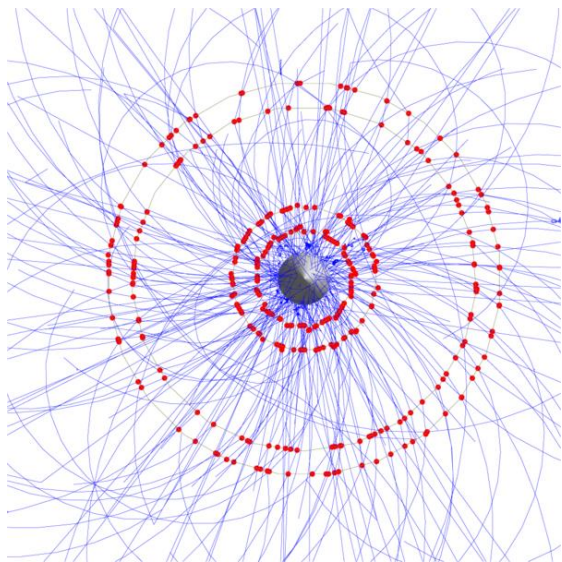
recurl pixel layers



Scintillating tiles yield optimal timing resolution



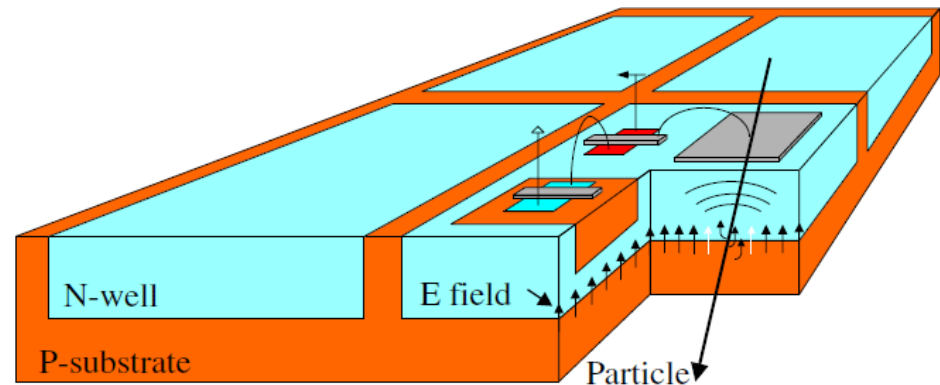
Why timing is important: up to 100 tracks in the Si tracker per 50 ns readout frame





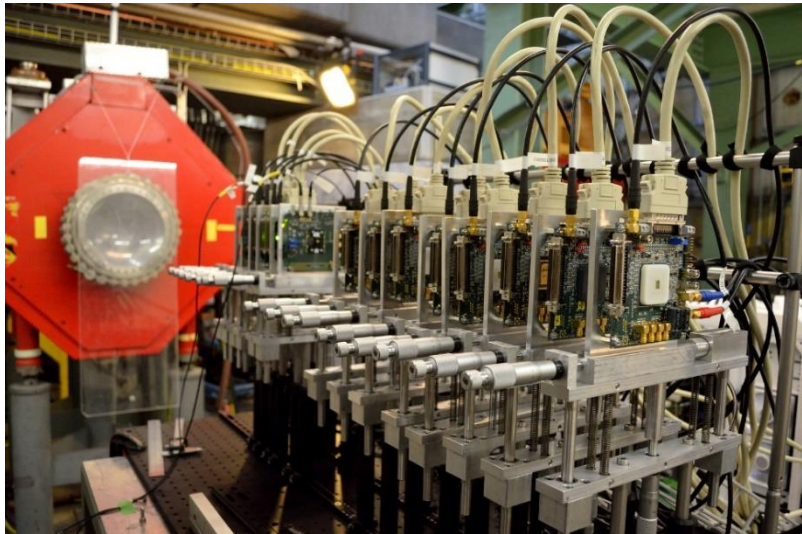
Mu3e Pixel detector:

- 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

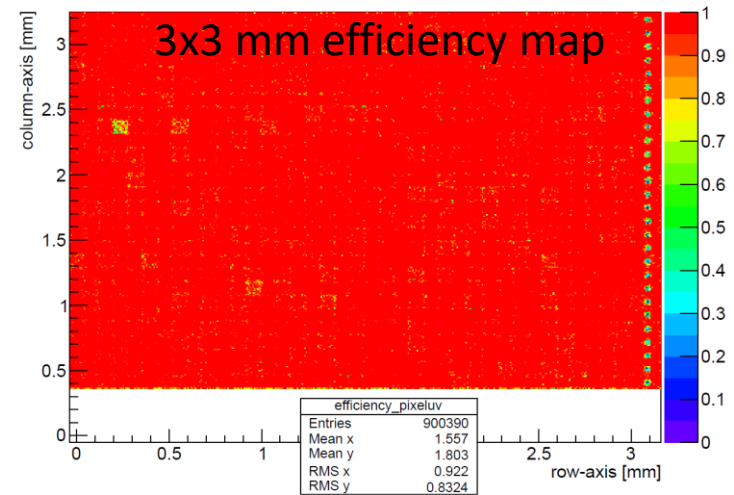


I. Peric et al., NIMA **731**, 131 (2008)

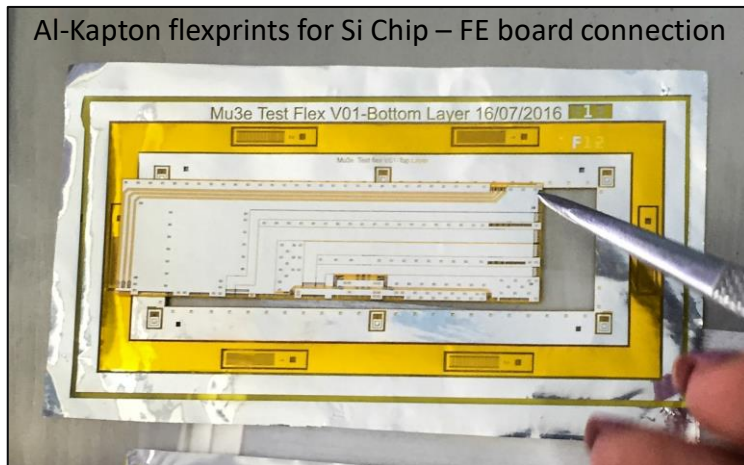
Beam telescope as a test bench for the Si pixel detectors:



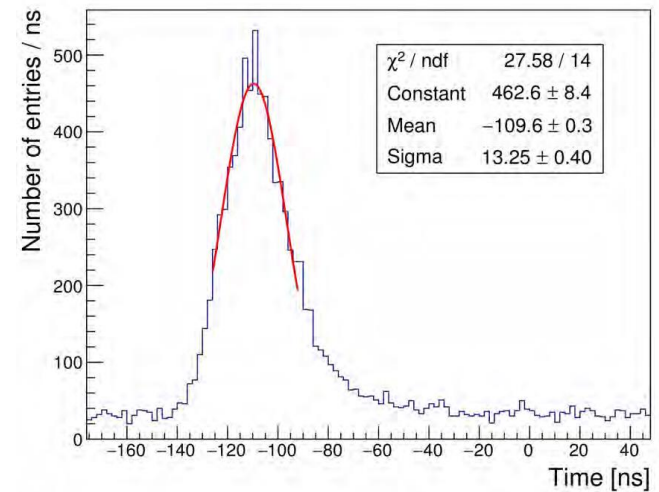
Mupix7, 735 mV threshold, HV = -85 V



Al-Kapton flexprints for Si Chip – FE board connection



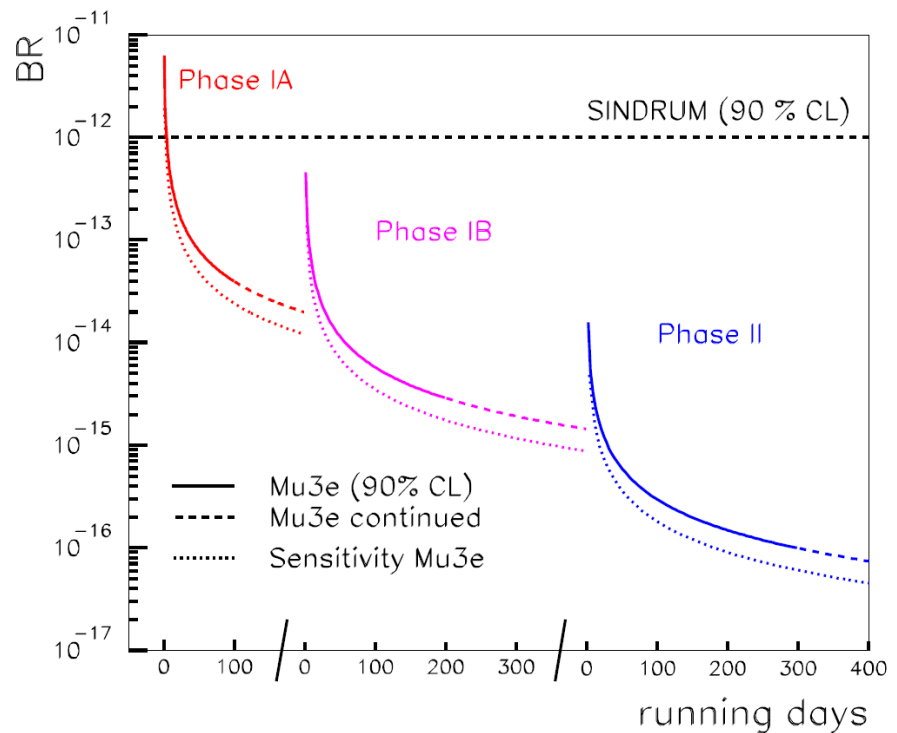
14 ns time resolution

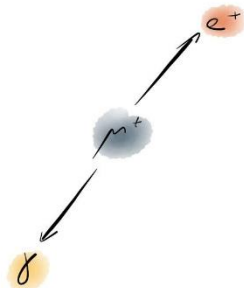




Mu3e Outlook:

- 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: $10^8 \mu/s$ for a B.R. of 10^{-15}
- Phase II: $10^9 \mu/s$ for a B.R. of 10^{-16}





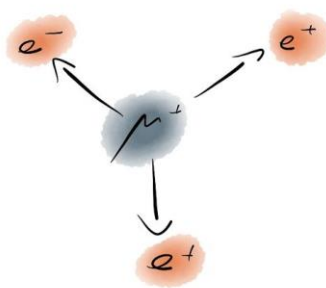
- 2-body decay
- back to back $\gamma - e$
- mono energetic $\gamma - e$

Background

- Accidental background
→ DC Beam (PSI)

CLFV sensitivity

- $\div 1$



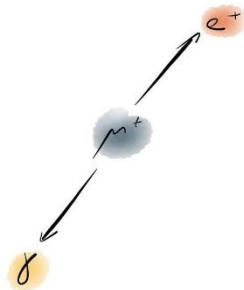
- 3-body decay
- $\sum \vec{p}_e = 0$
- $\sum E_e = m_\mu$

Background

- Accidental background
→ DC Beam (PSI)
- Radiative muon decay

CLFV sensitivity

- $\div 170$



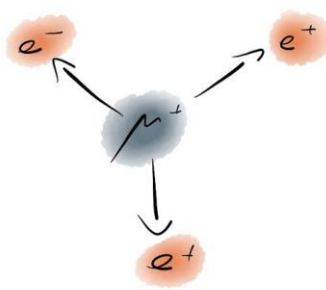
- 2-body decay
- back to back $\gamma - e$
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Background

- Accidental background
→ DC Beam (PSI)

CLFV sensitivity

- $\div 1$



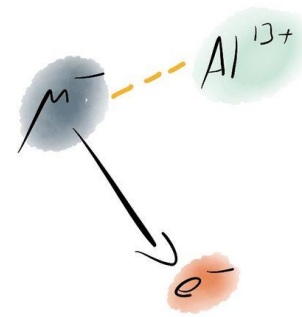
- 3-body decay
- $\sum \vec{p}_e = 0$
- $\sum E_e = m_\mu$

Background

- Accidental background
→ DC Beam (PSI)
- Radiative muon decay

CLFV sensitivity

- $\div 170$



- quasi 2-body decay
- Mono energetic electron

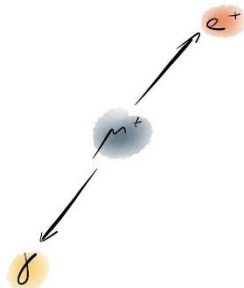
Background

- Beam-related background
→ Pulsed beam Fermilab
- Decay in orbit

CLFV sensitivity

- $\div 389$ (for Al)

Search for $\mu N \rightarrow e^- N$: mu2e & COMET



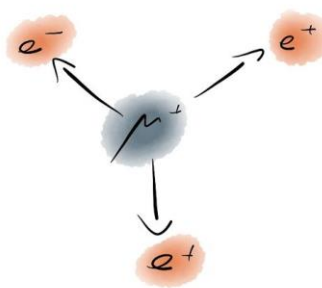
- 2-body decay
- back to back $\gamma - e$
- mono energetic $\gamma - e$

Background

- Accidental background
→ DC Beam (PSI)

CLFV sensitivity

- $\div 1$



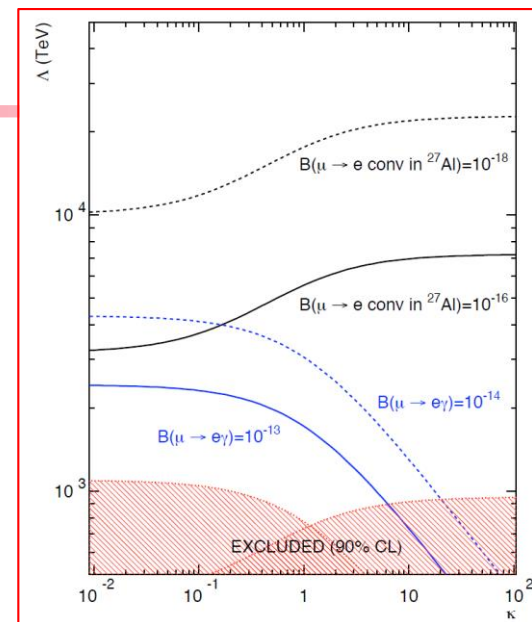
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Background

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→ DC Beam (PSI)
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CLFV sensitivity

- $\div 170$



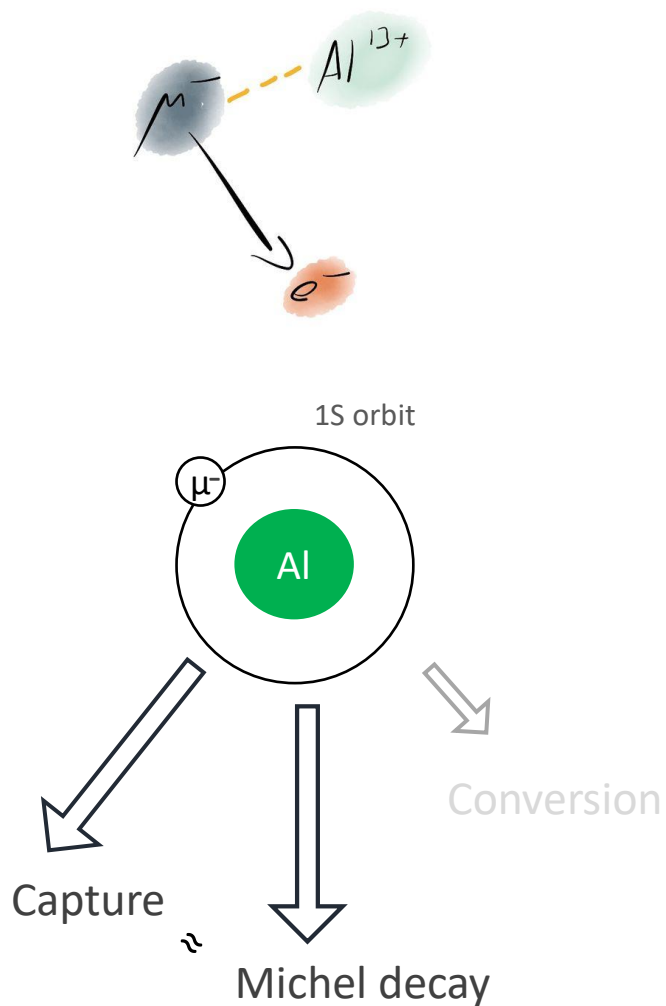
- quasi 2-body decay
- Mono energetic electron

Background

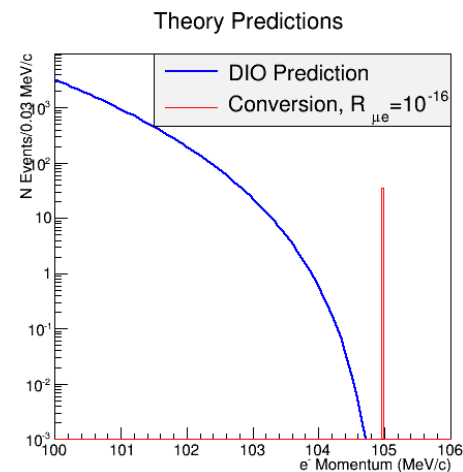
- Beam-related background
→ Pulsed beam Fermilab
- Decay in orbit

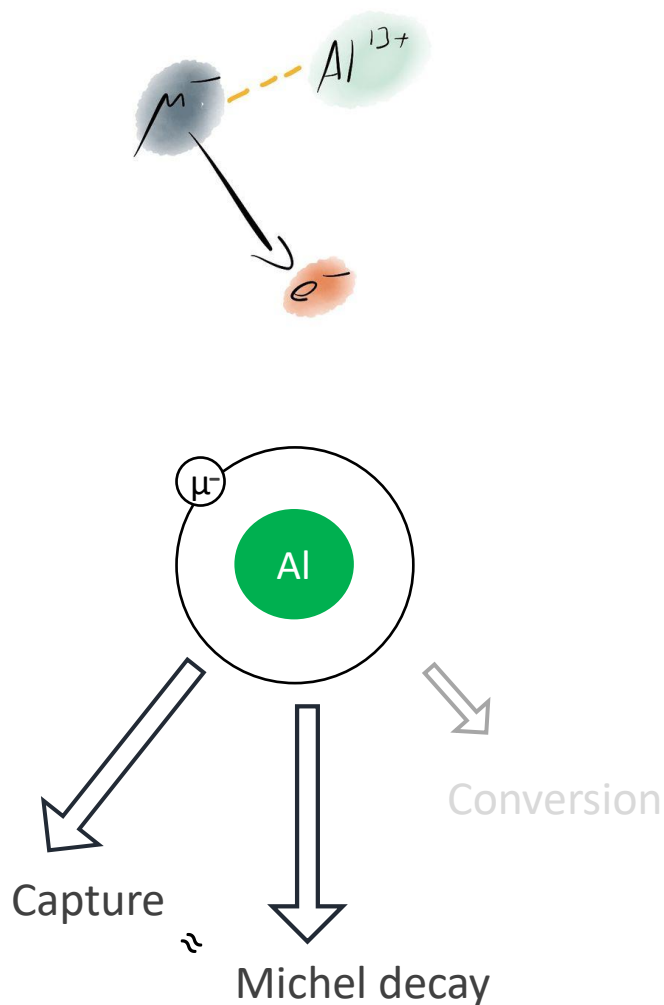
CLFV sensitivity

- $\div 389$ (for Al)



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





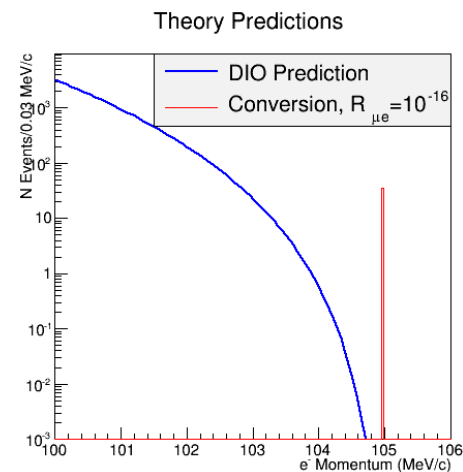
- Mono-energetic electron of 105 MeV

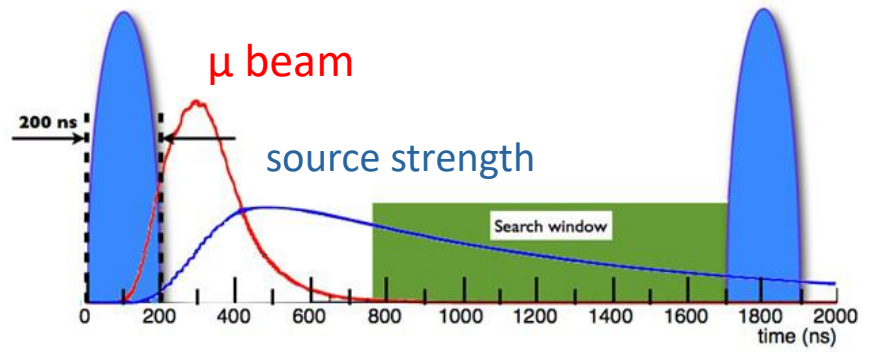
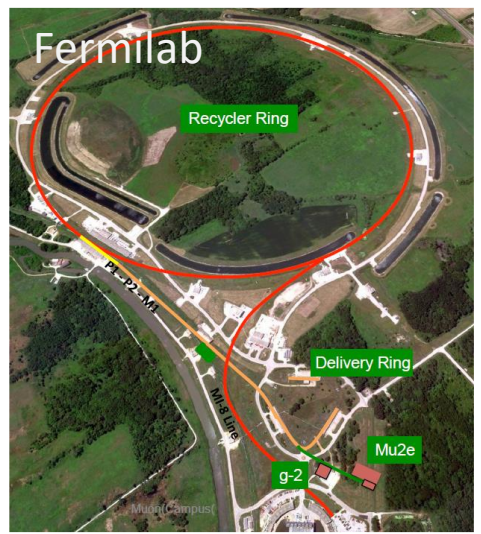
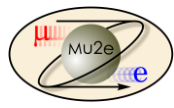
- Background from:

- Decay in orbit
- Beam background: $\pi^- N \rightarrow \gamma N^* + \text{pair production}$
- δ electrons from cosmic μ 's

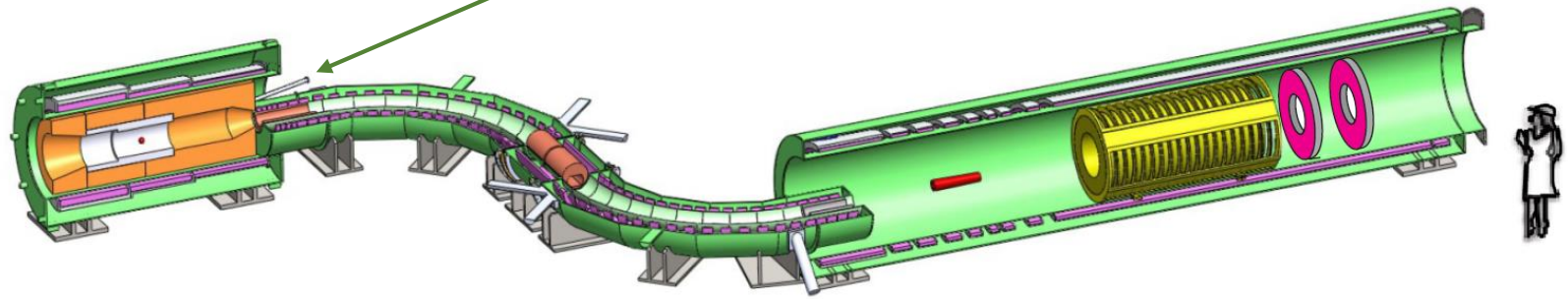
- Aims for a sensitivity of $3 \cdot 10^{-17}$ but also $10^{18} \mu$'s on target

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





$2 \cdot 10^7$ 8 GeV protons



Production

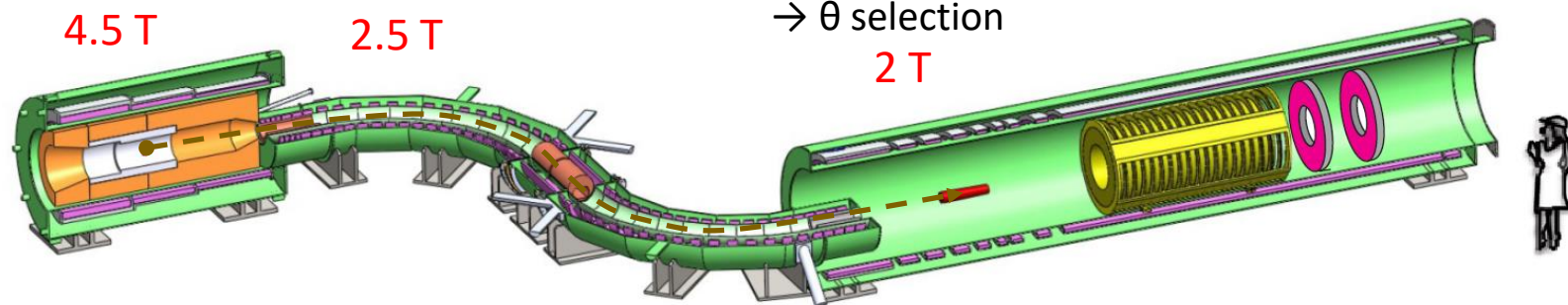
- $p^+ \rightarrow p^-$
- efficient collection
- magnetic mirror

Transport

- $\pi\mu$ separation
- no line of sight to the target

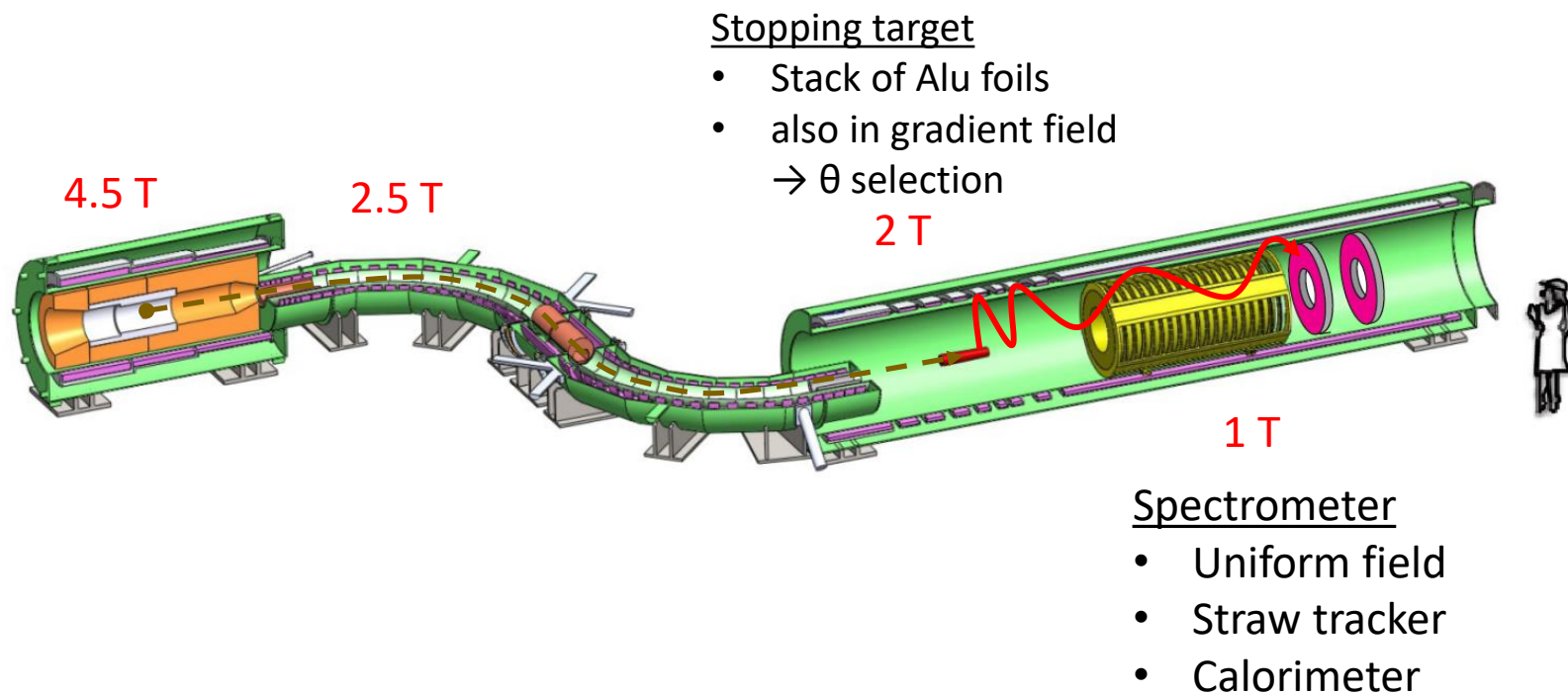
Stopping target

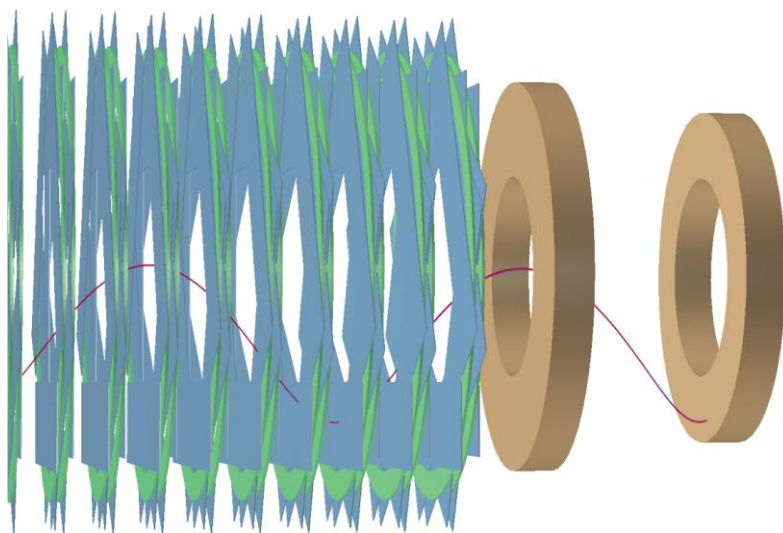
- Stack of Alu foils
- also in gradient field
→ θ selection



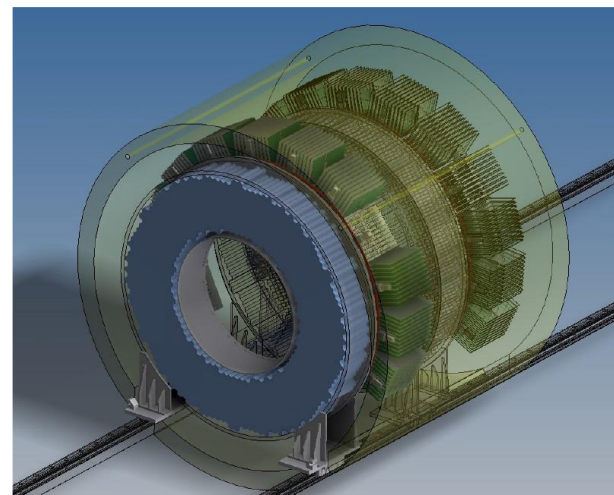
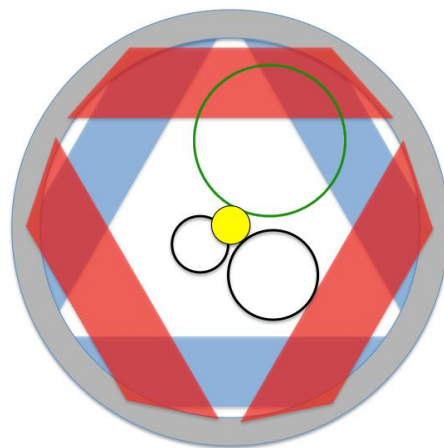
! 0.002 μ 's on target / proton !

88 M USD in solenoids

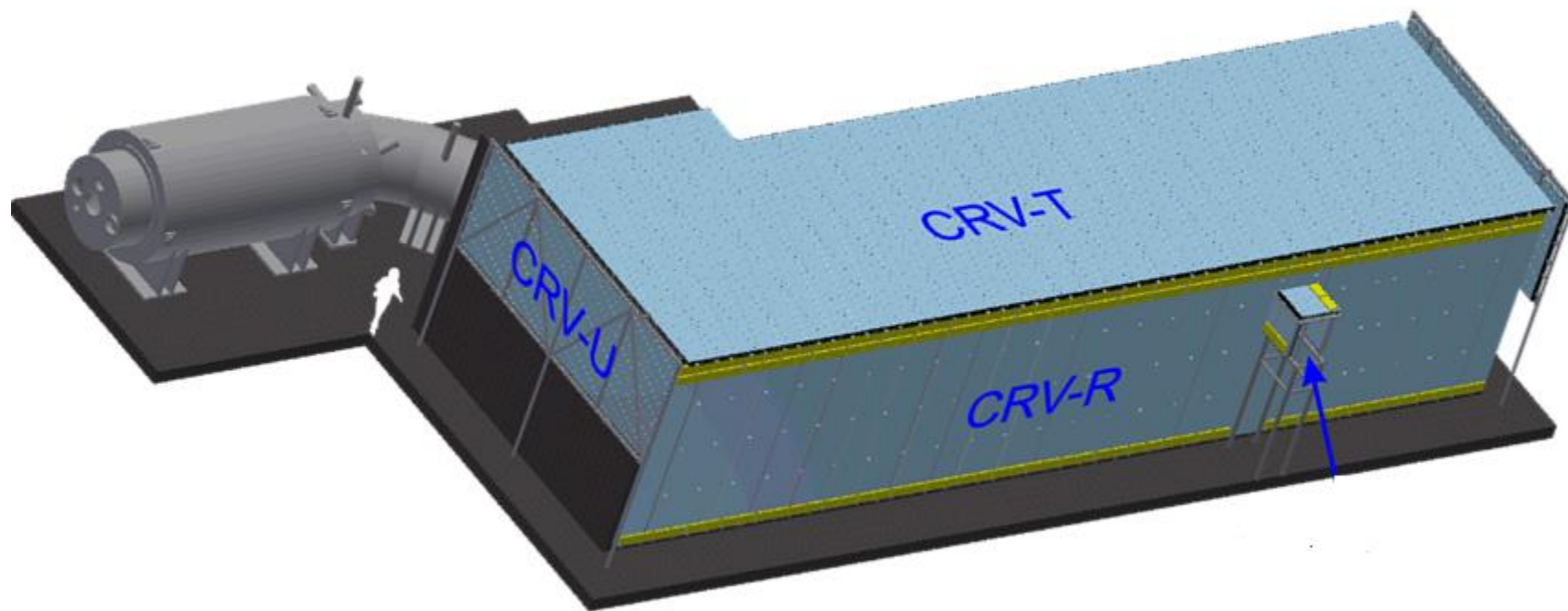




- Electrons with energy > 53 MeV are accepted
- Calorimetry with 2 BaF₂ discs
- Timing and trigger with BaF₂



Cosmic ray veto

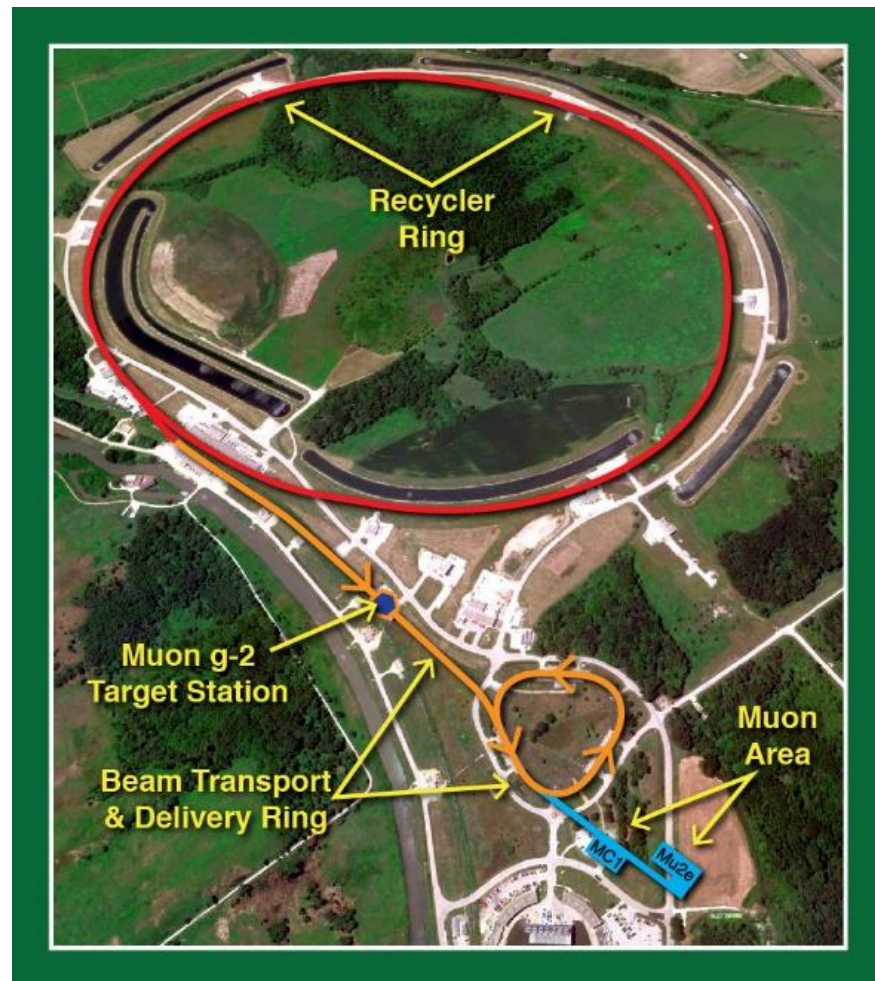


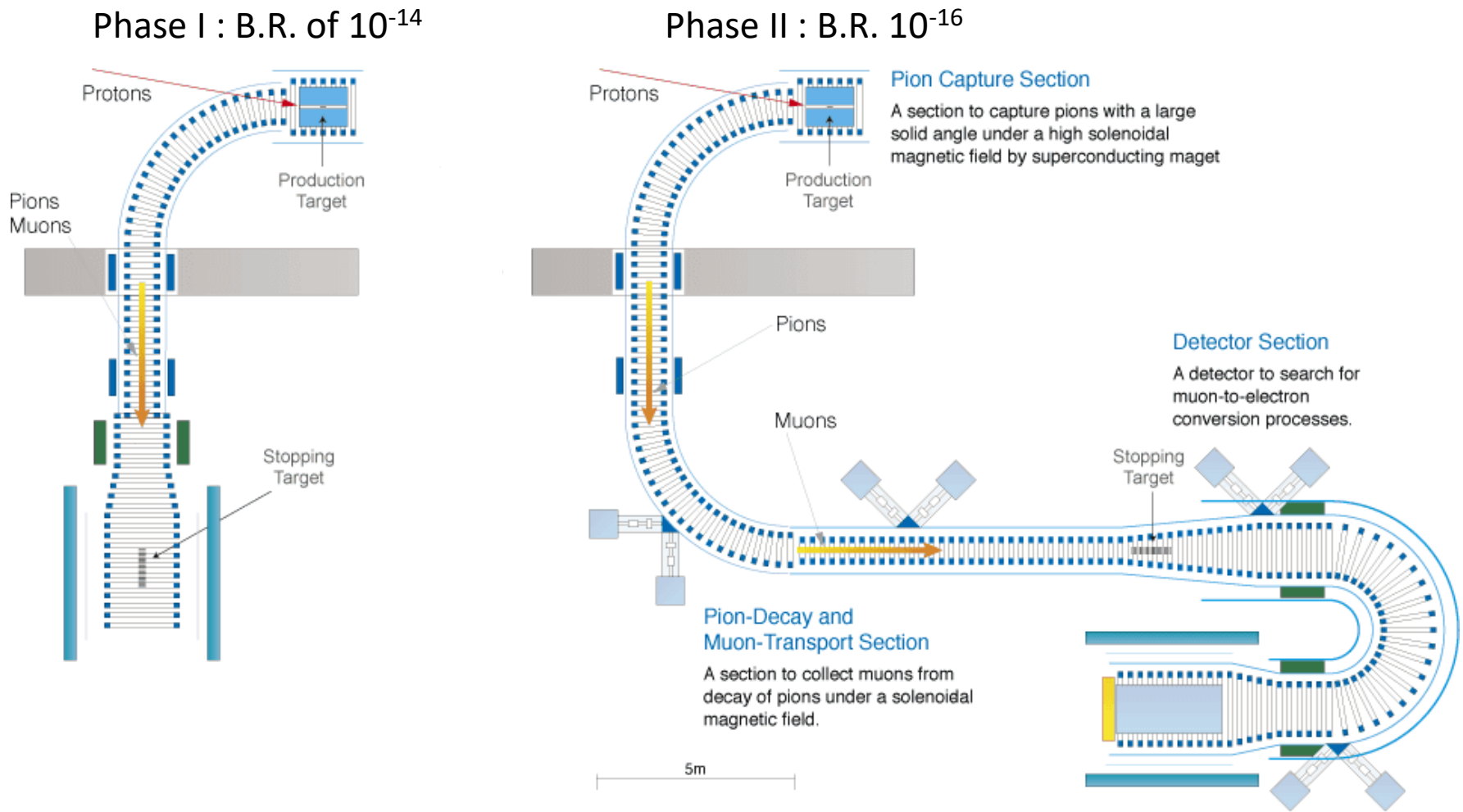
- Full TDR in 2014
- CD-3 approved in July 2016
- Construction 2017-2020(1)
- Data taking starts in 2020-2021
3 years for full statistics

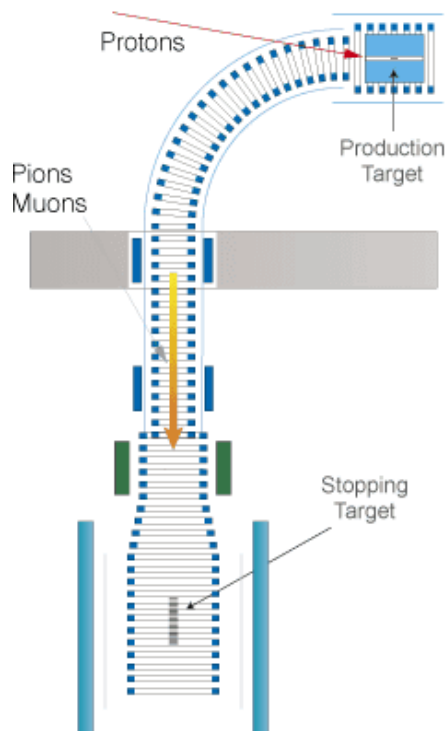
Construction of the mu2e exp hall started at Fermilab



Muon campus at Fermilab



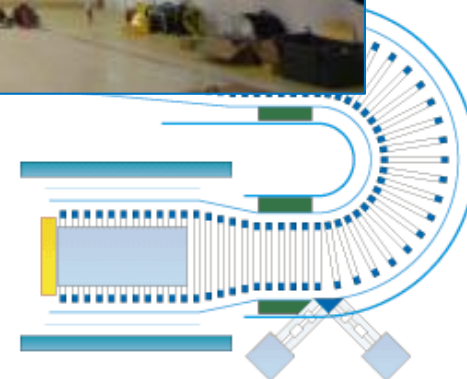


Phase I : B.R. of 10^{-14} 

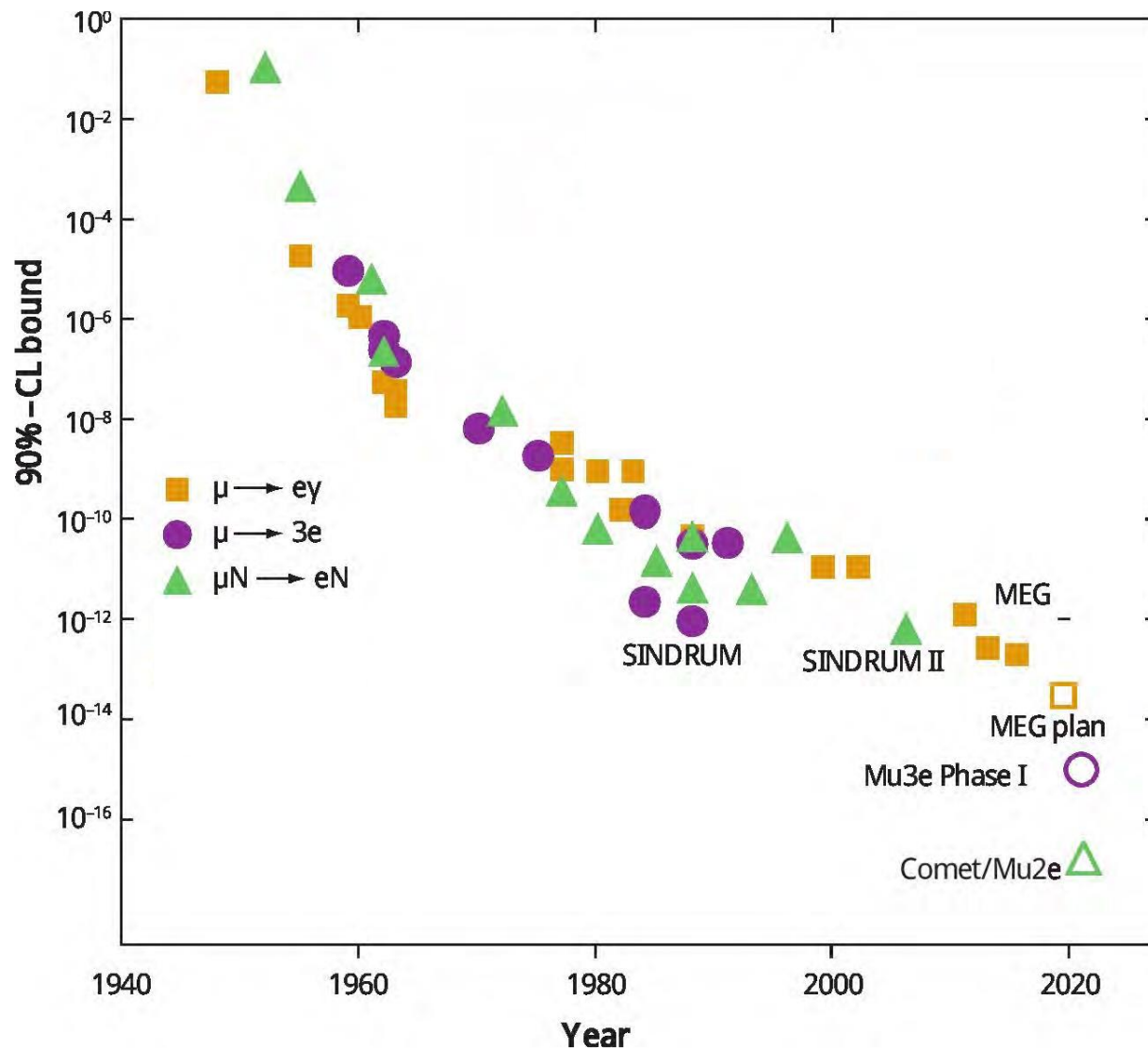
Pion-Decay and Muon-Transport Section

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

5m

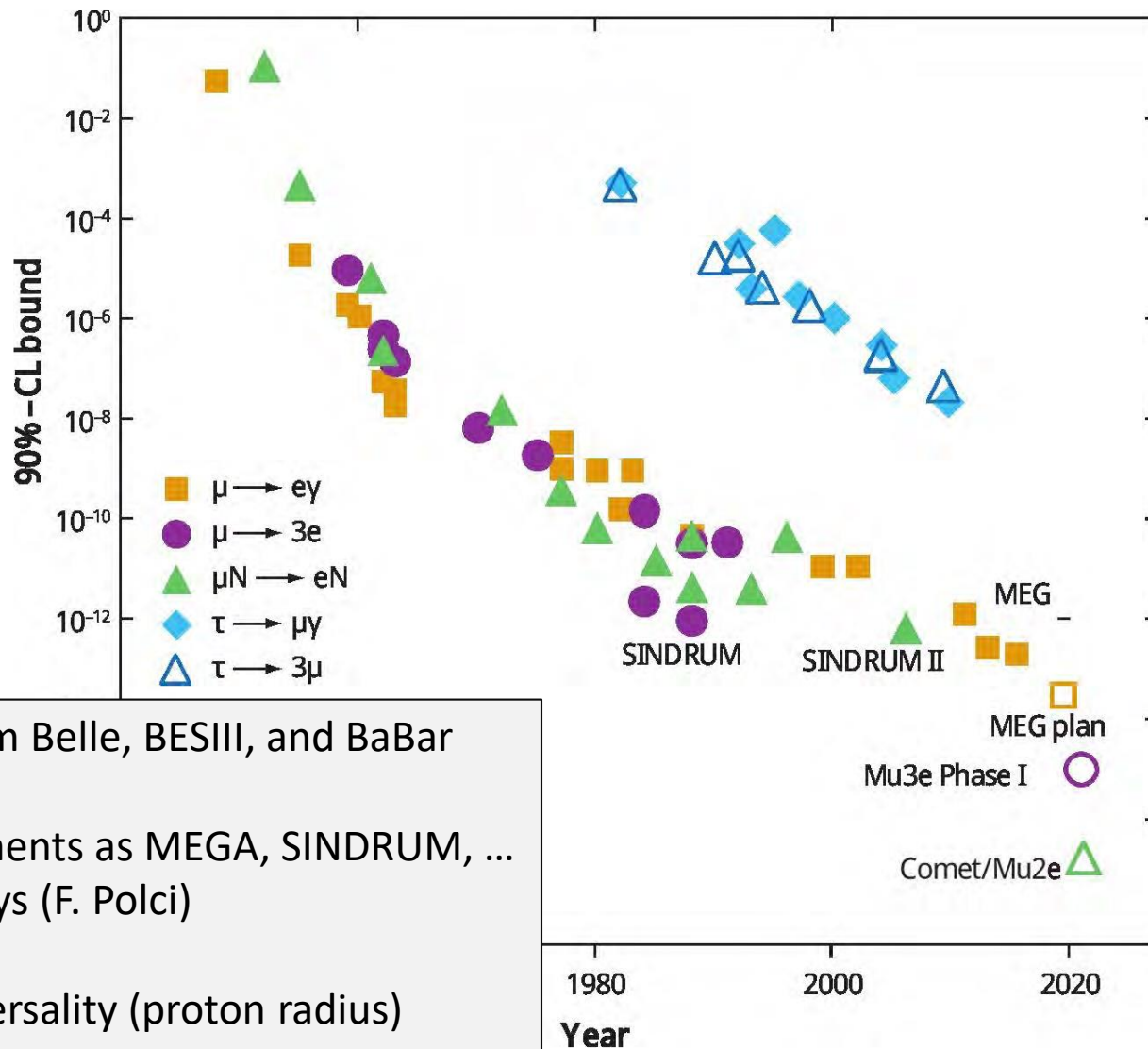


During the next decade, a new window in physics beyond the Standard Model is opening up:

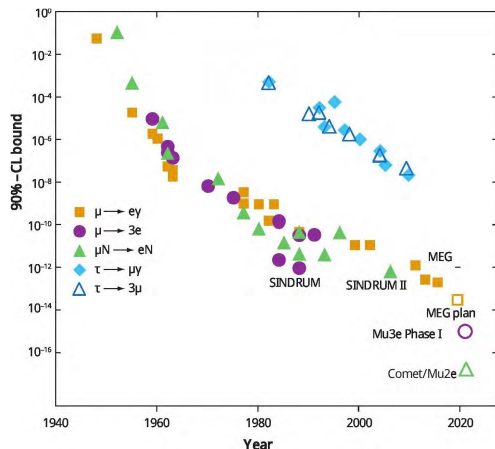


One can **not** cover everything:

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)
- + ...



- 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)
- A. de Gouvêa and P. Vogel **71**, 75 (2013)
- W. J. Marciano et al., Annu. Rev. Nucl. Part. Sci. **58**, 315 (2008)
- 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
- A. Perrevoort et al., arXiv:1605.02906 **Mu3e**

theory

review

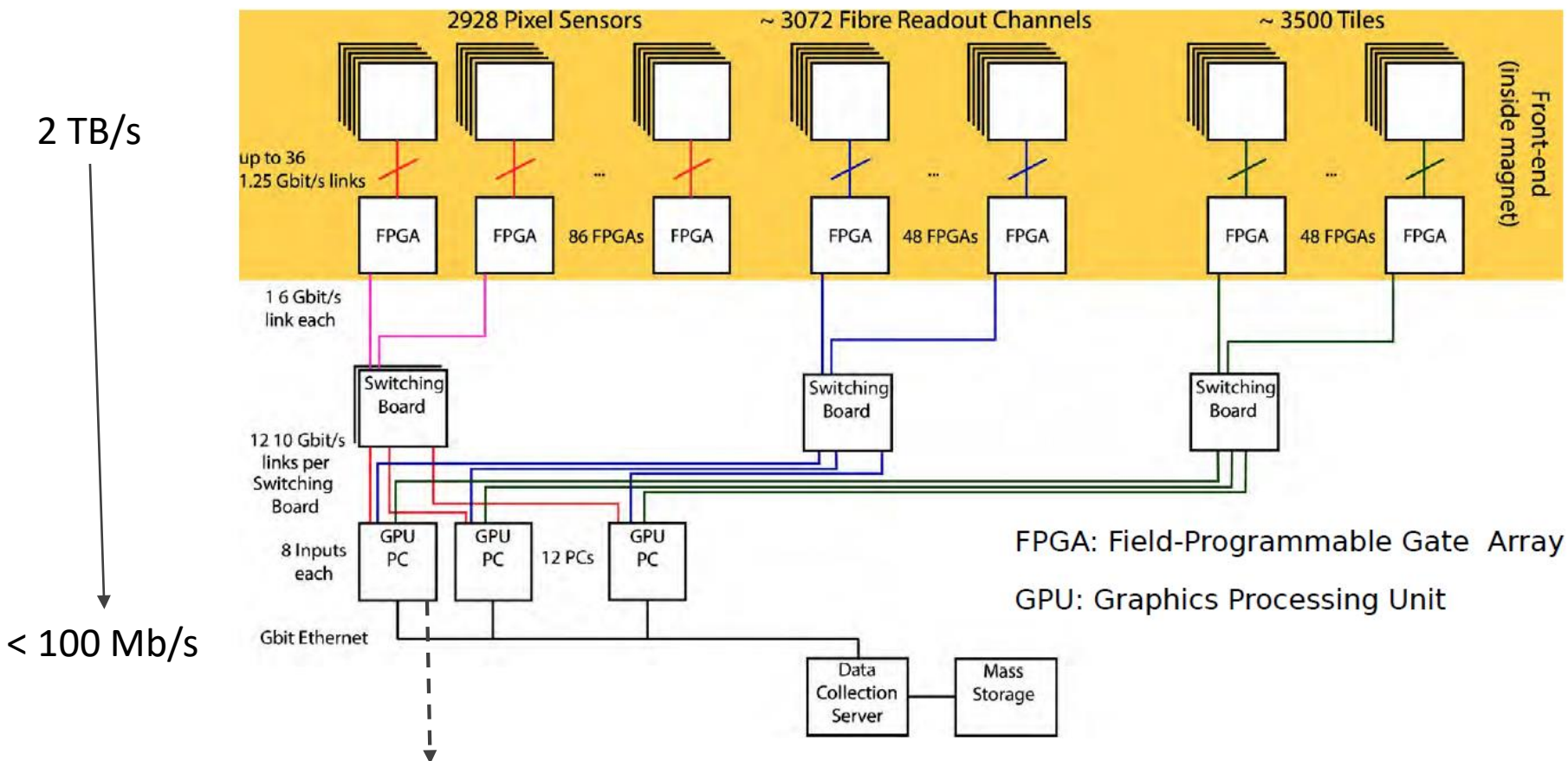
Mu3e

EXTRA

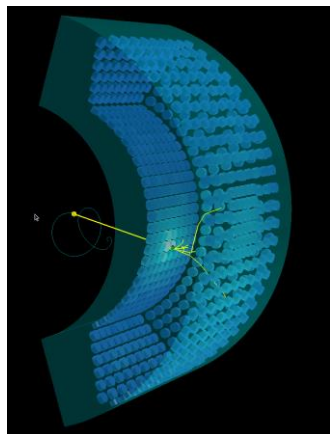


Readout: All muon decays are detected + beam background

Need full detector info for event selection (no local trigger)



each GPU processes a 50 ns time slice

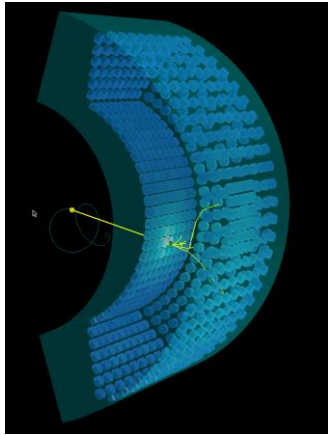


Operating a 2.7 T LXe photon detector

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

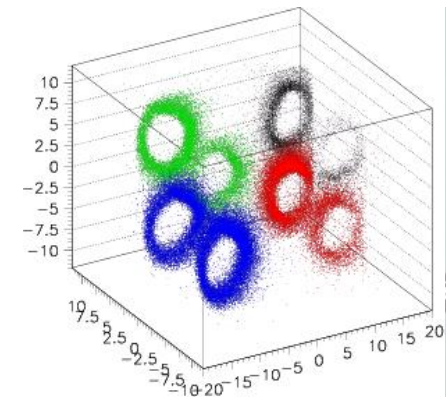


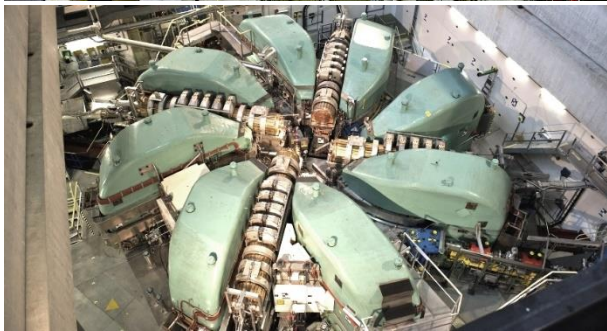
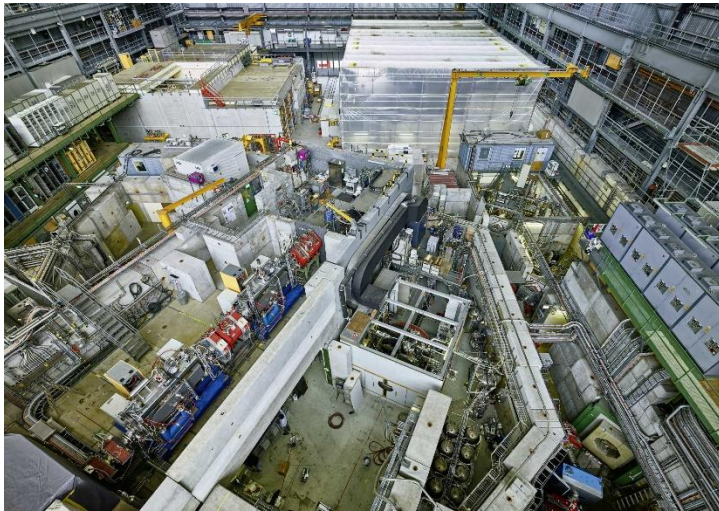
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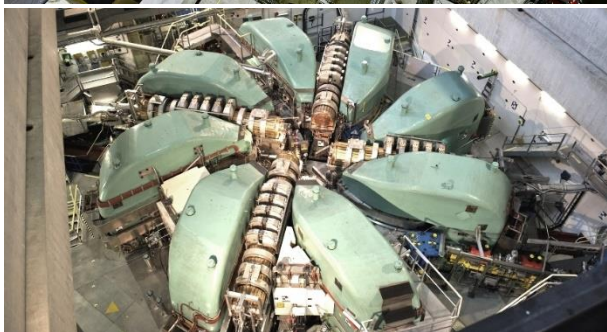
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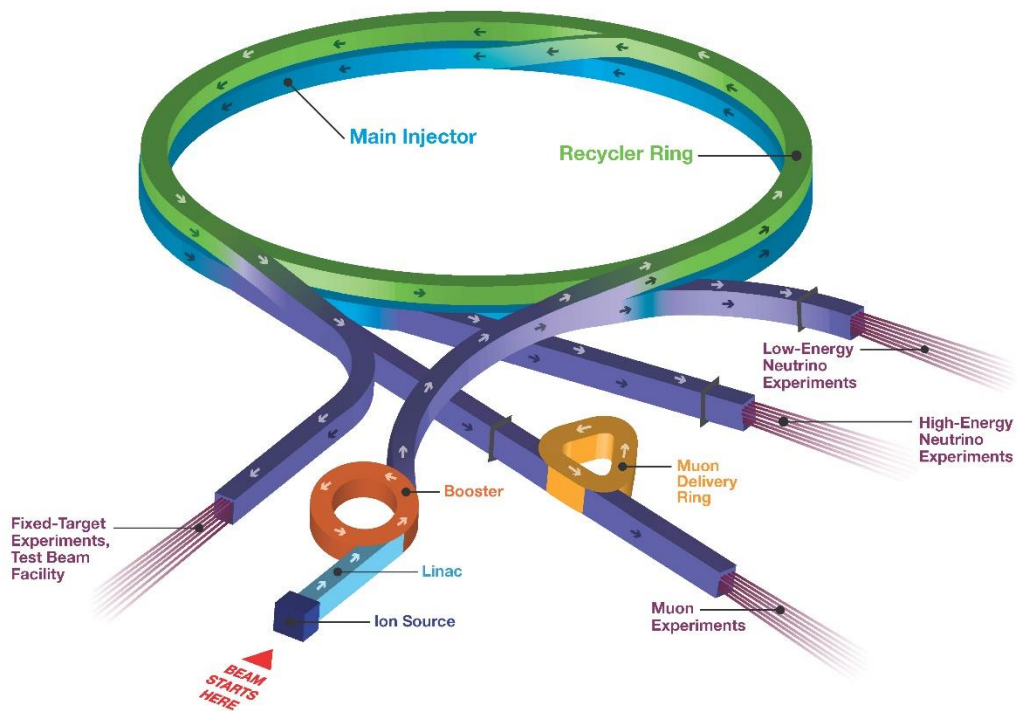
- 2.2 mA 600 MeV proton beam
- $10^8 \mu^+$ DC beam
- 10^9 in R&D phase
- Several particle physics experiments in parallel
+ solid state physics
+ applied physics
+ ...

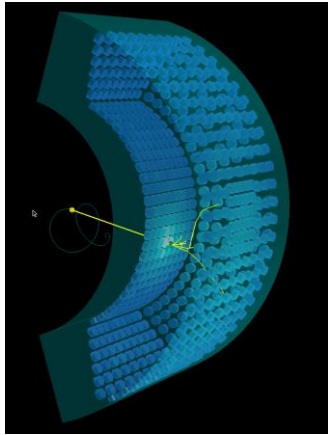
Facilities at the center of the Intensity Frontier



- 2.2 mA 600 MeV proton beam
- $10^8 \mu^+$ DC beam

Fermilab Accelerator Complex





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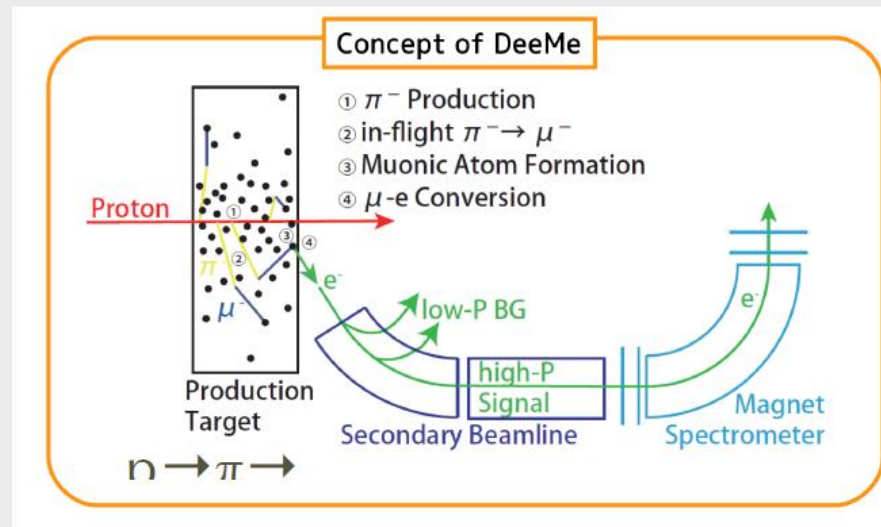
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LED			LXe PMT calibration	Continuously

0.3-1 MeV p Cockcroft-Walton accelerator



DeeMe

- **DeeMe** at J-PARC $\mu N \rightarrow e N$ with a 2×10^{-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**



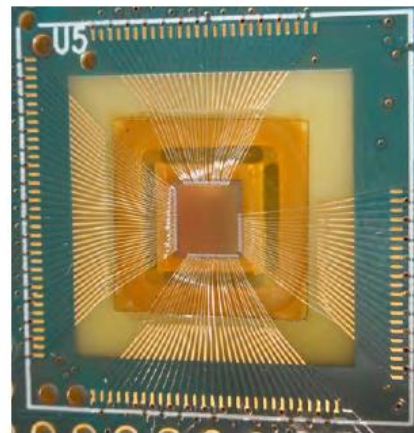
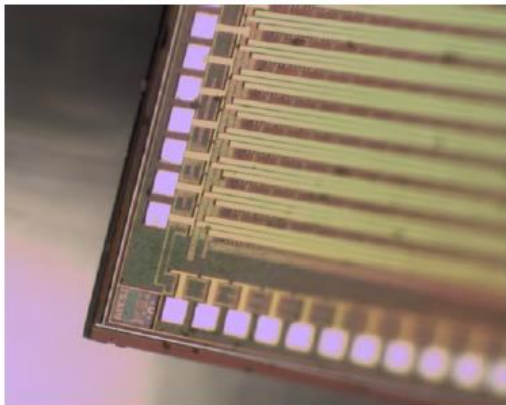
Nakatsugawa, CLFV 2016; Natori, this conf.



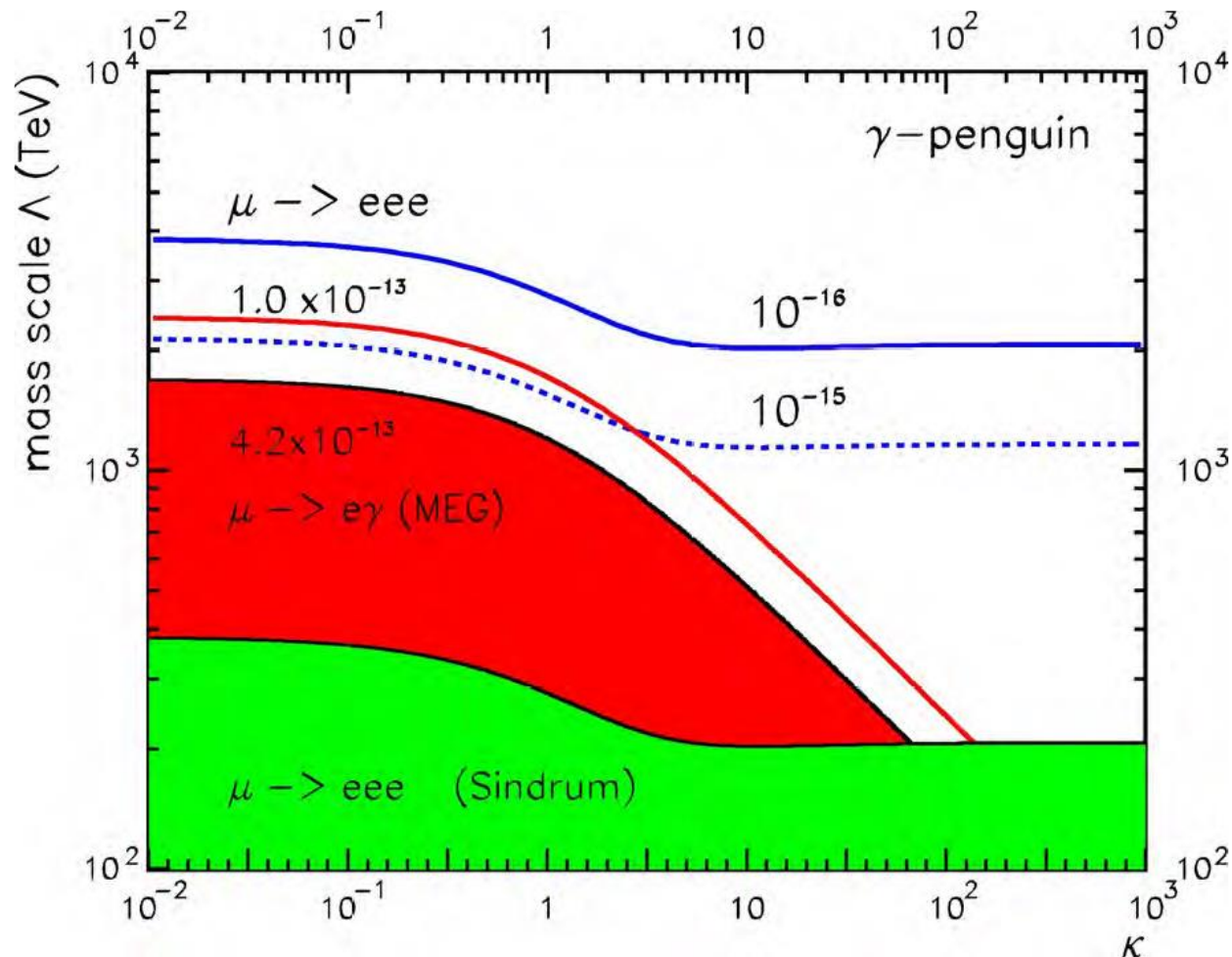
Mupix Prototype



- 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



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