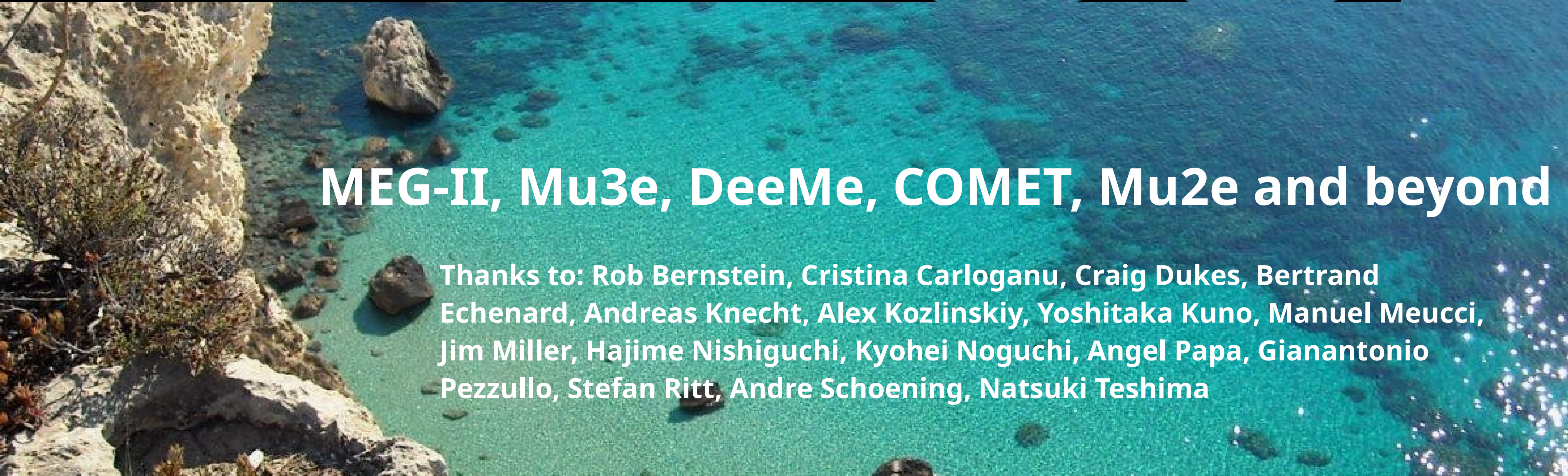
Lepton Flavour Violation:

Muon Experiments

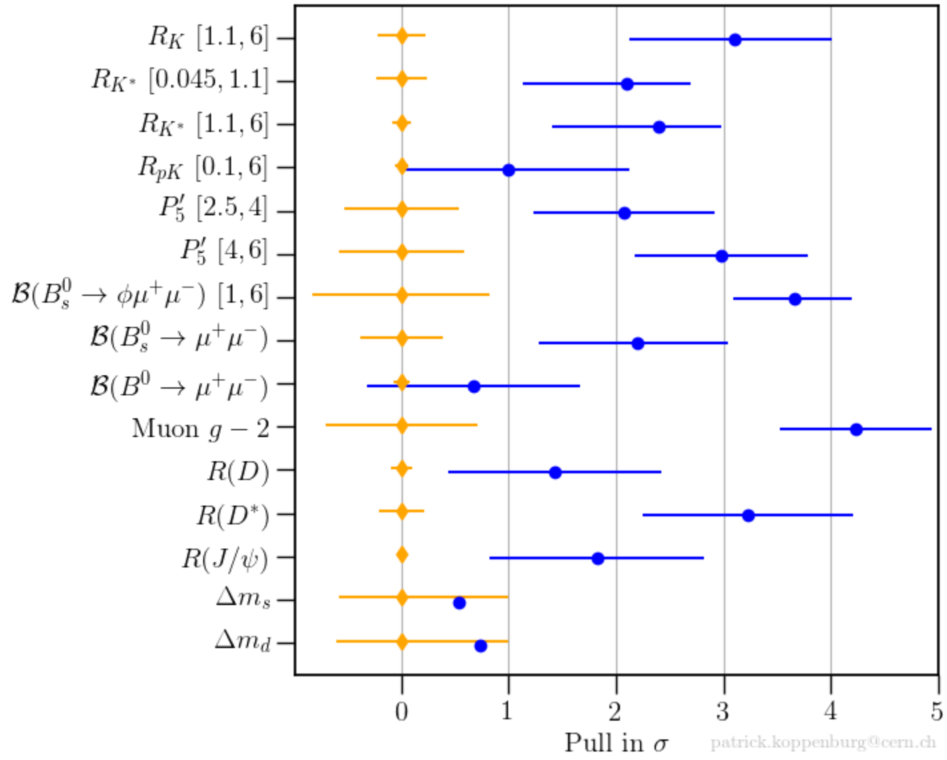
Gavin Hesketh, 10th Sept 2021
NuFACT 2021, Cagliari / online

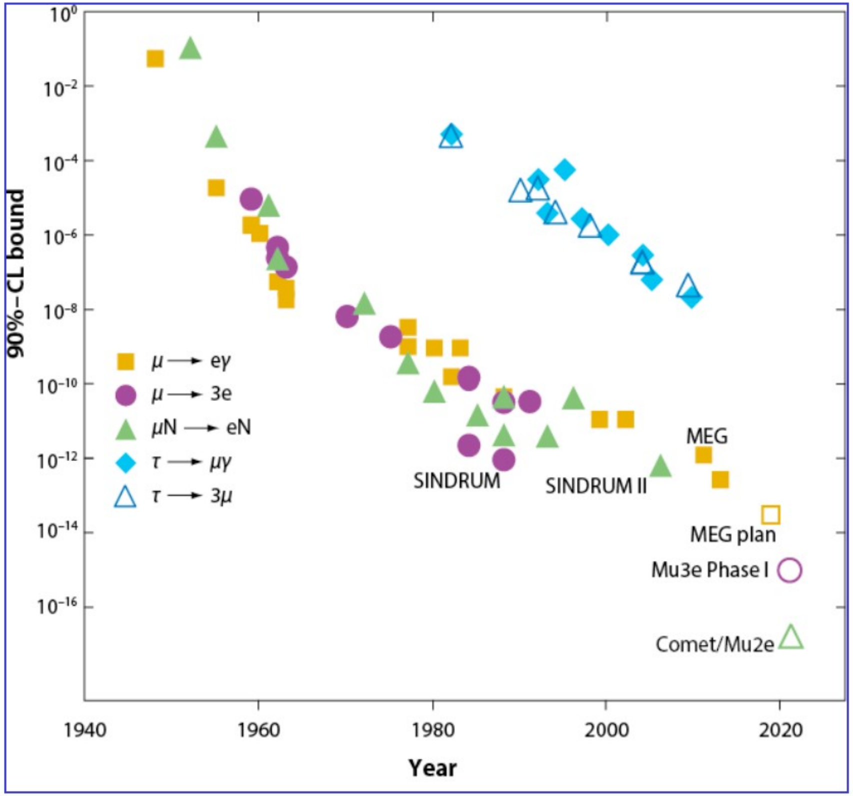


MEG-II, Mu3e, DeeMe, COMET, Mu2e and beyond

Thanks to: Rob Bernstein, Cristina Carloganu, Craig Dukes, Bertrand Echenard, Andreas Knecht, Alex Kozlinskiy, Yoshitaka Kuno, Manuel Meucci, Jim Miller, Hajime Nishiguchi, Kyohei Noguchi, Angel Papa, Gianantonio Pezzullo, Stefan Ritt, Andre Schoening, Natsuki Teshima

Motivation



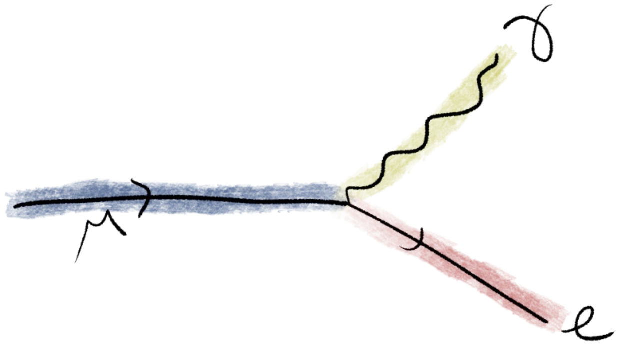


Charged lepton flavour violation is a complementary probe for BSM

→ a huge leap in sensitivity coming

History

1947: Is the muon (meson) an excited electron?



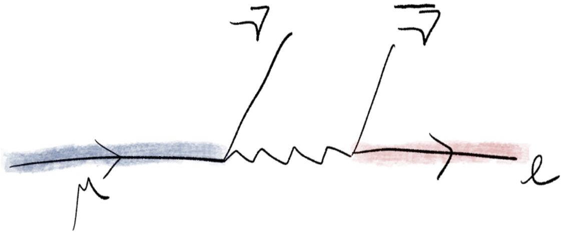
Nuclear Capture of Mesons and the Meson Decay

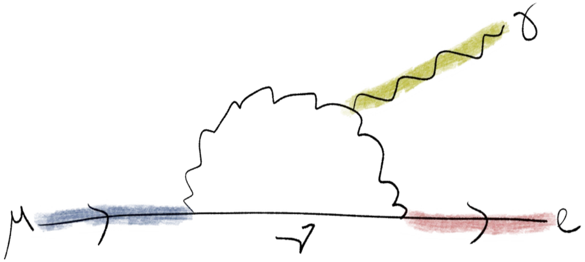
B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
June 21, 1947

...Returning to the actual decay of the meson, an experiment suggests itself which might answer the following question: Is the electron emitted by the meson with a mean life of about 2.2 microseconds accompanied by a photon of about 50 Mev? This experiment is being attempted at the present time, since it is felt that the available analysis[10] of the soft component in equilibrium with its primary meson component is probably insufficient to decide definitely whether the meson decays into either an electron plus neutral particle(s) or electron plus photon.

Yoshi Uchida

1959: Do neutrinos have flavour?





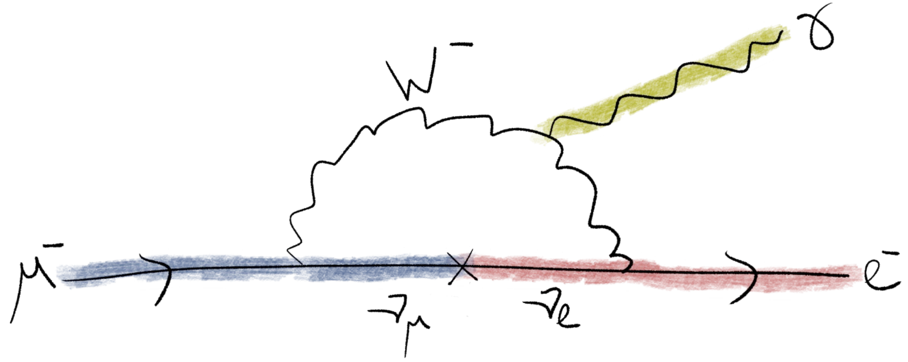
ELECTROMAGNETIC TRANSITIONS BETWEEN μ MESON AND ELECTRON*

S. Weinberg†
Columbia University, New York, New York

G. Feinberg‡
Brookhaven National Laboratory, Upton, New York
(Received June 15, 1959)

The existence of the ordinary μ decay, $\mu \to e + \nu + \bar{\nu}$, seems to prove that the muon and electron do not differ in any quantum numbers.[1] It follows that weak electromagnetic transitions between muons and electrons could occur, if there is a mechanism to produce them. For example, one such mechanism would exist if the μ decay was not caused by a direct $\bar{\mu}e\bar{\nu}\nu$ Fermi interaction but instead involved a virtual charged boson. This particular possibility seems ruled out, since the predicted[2] rate for $\mu \to e + \gamma$ would be considerably greater than the upper limit set by recent experiments.[3,4] The purpose of this note is to discuss phenomenologically (without attachment to any specific mechanism) other kinds of electromagnetic transitions between muon and electron that may be possible even if $\mu \to e + \gamma$ is somehow suppressed.

1962: discovery of the muon neutrino at BNL (Lederman, Schwartz, Steinberger)



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_k U^*_{\mu k} U_{ek} \frac{m^2_{\nu k}}{M^2_W}\right|^2 < \mathcal{O}(10^{-50})$$

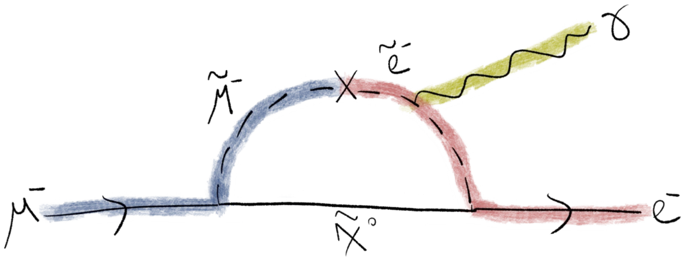
Petcov, 1977

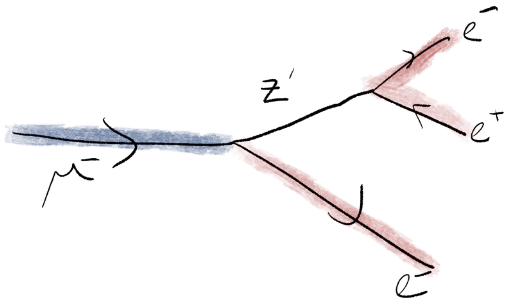
CLFV common in BSM models:

R-parity violating SUSY, SUSY-seesaw,
Little Higgs, Higgs doublets, Leptoquarks, Z’…

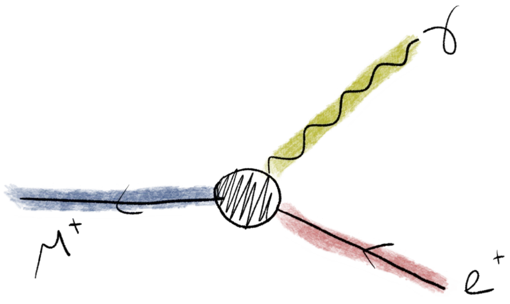
Connect to leptogenesis & neutrino mass:

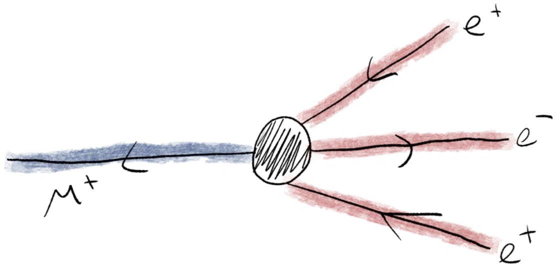
- e.g. with RH majorana neutrino see-saw

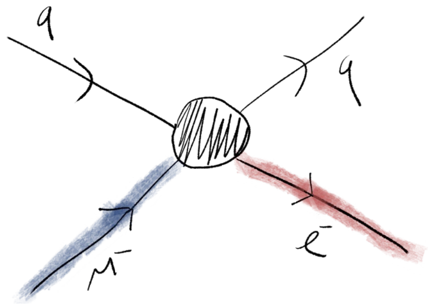




The Three Channels







μ→ e γ

Current limit:
BR < 4.2x10^{-13}
- MEG @ PSI

Future limit:
→ BR < 10^{-14}
- MEG-II @ PSI

μ→eee

Current limit:
BR < 1x10^{-12}
- SINDRUM @ PSI

Future limit:
→ BR < 10^{-16}
- Mu3e Phase 2 @ PSI

Conversion:

Current limit:
BR < 7x10^{-13}
- SINDRUM-2 @ PSI

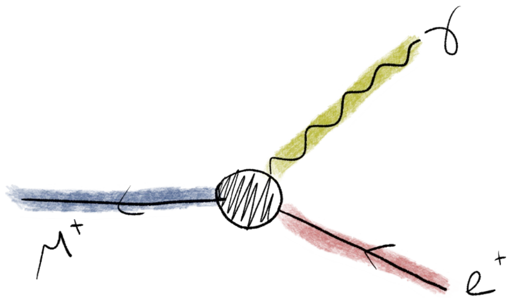
Future limit:
→ BR < 10^{-17}
- Mu2e @ FNAL
- COMET @ J-PARC
- DeeMe @ J-PARC

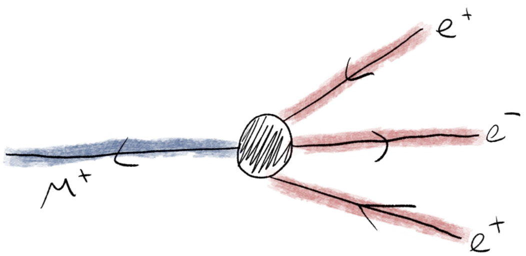
Effective Lagrangian

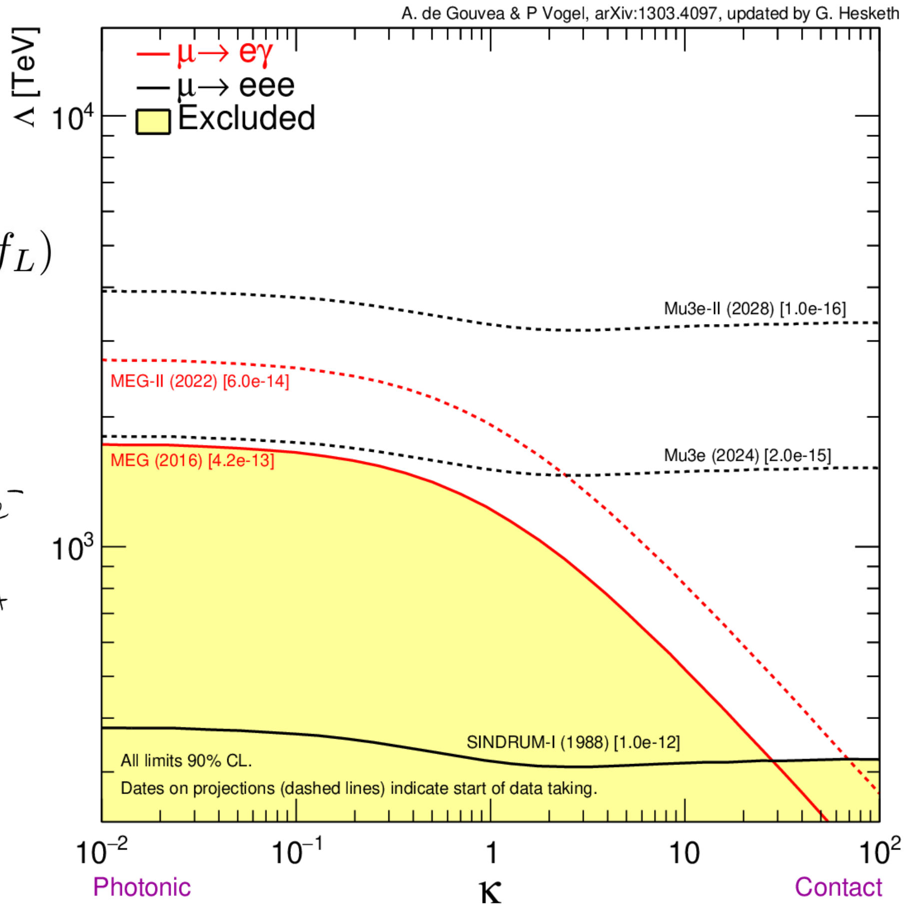
Effective Lagrangian for CLFV:

(de Gouvea & Vogel, arXiv:1203.4097)

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_R\gamma_\mu e_L(\bar{f}_L\gamma^\mu f_L)$$







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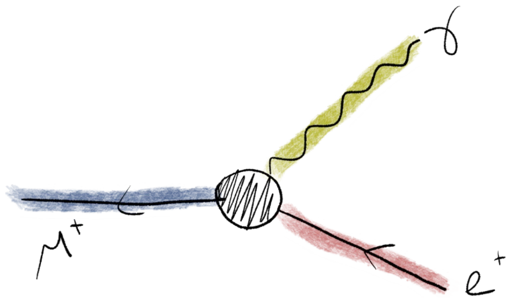

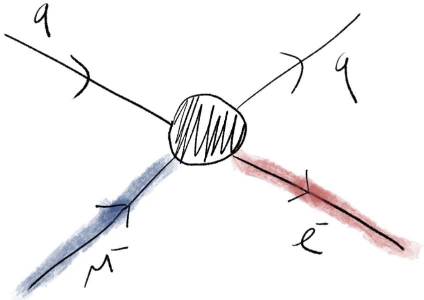

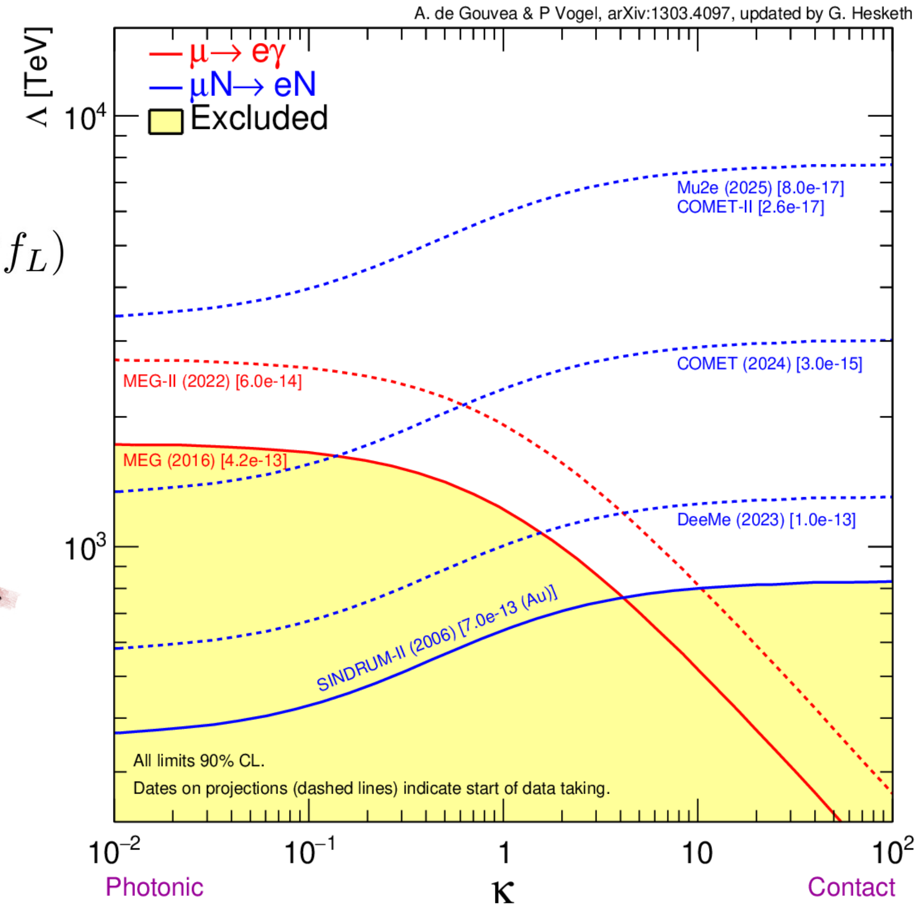

Current limits

Effective Lagrangian for CLFV:

(de Gouvea & Vogel, arXiv:1203.4097)

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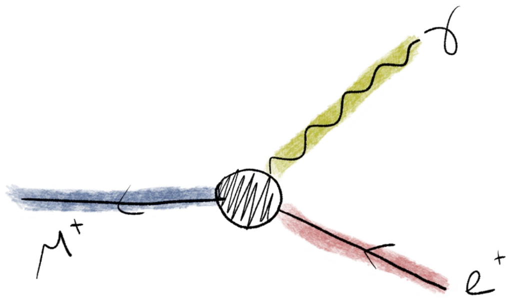
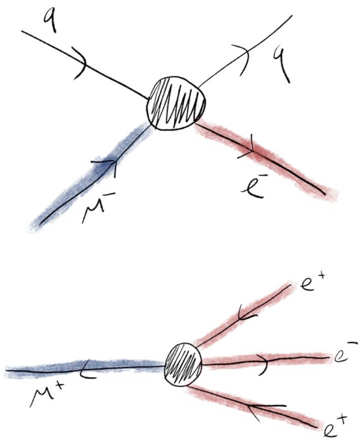
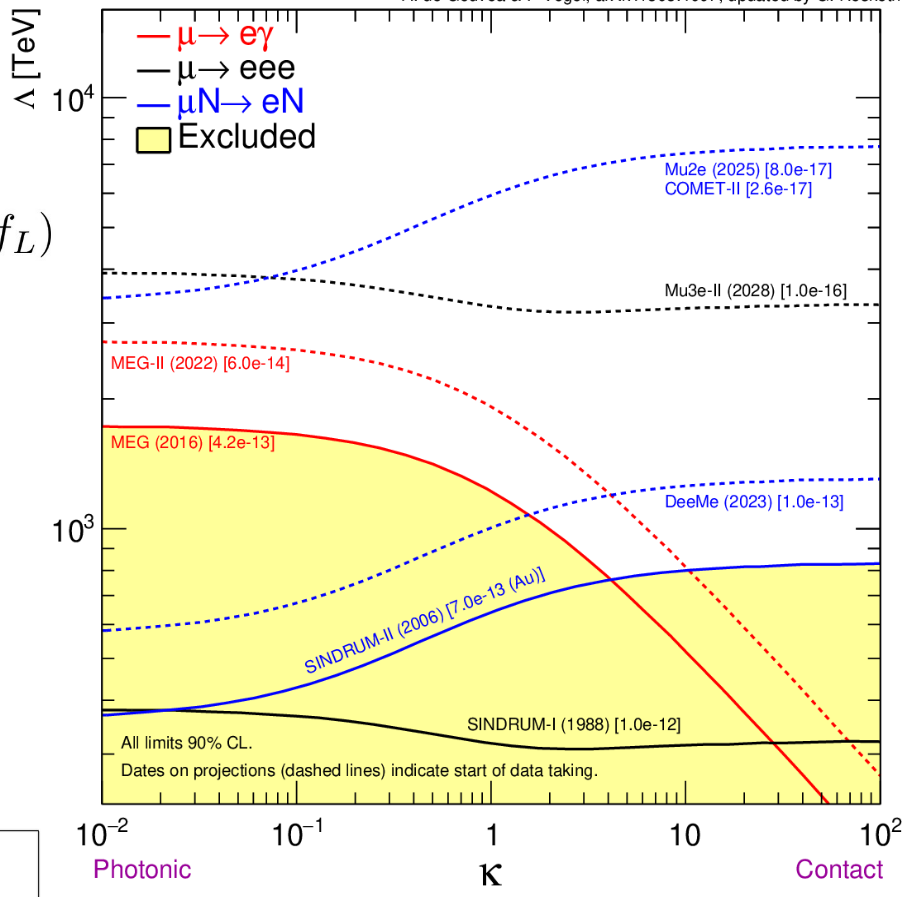




ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{R(\mu Ti\to eTi)}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

Buras et al, JHEP 1009:104,2010

A. de Gouvea & P Vogel, arXiv:1303.4097, updated by G. Hesketh

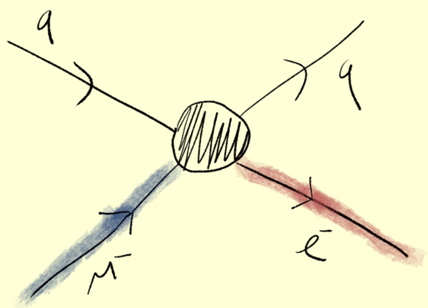


Experimental Challenges

Muon decay:

- coincidence search, combinatorics important

→ D.C. muon beam



Muon conversion:

- prompt backgrounds,
  delayed signal

→ pulsed muon beam,
  high extinction factor

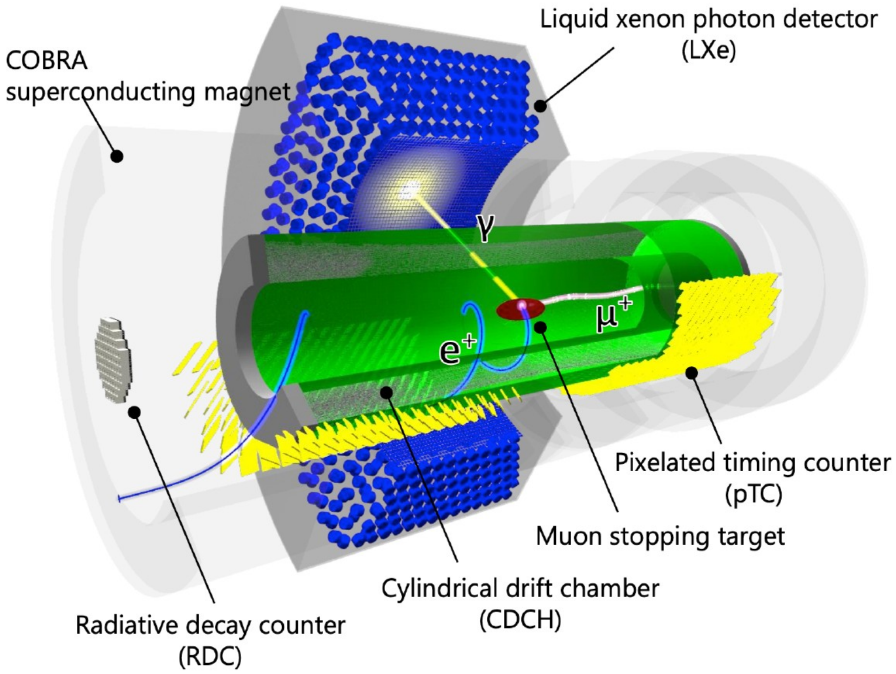
- Experiments are “end point” searches → resolution critical
- Require tracking of low energy (~100 MeV or less) electrons
- Deal with high rates (10^7 - 10^{11} muons per second)

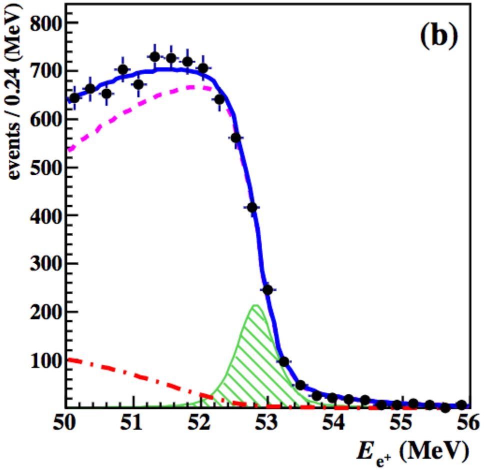
MEG ran 2009 – 2013
- πE5 beam, 3×10^{7} muons/s @ 28 MeV
- 7.5×10^{14} muon stops

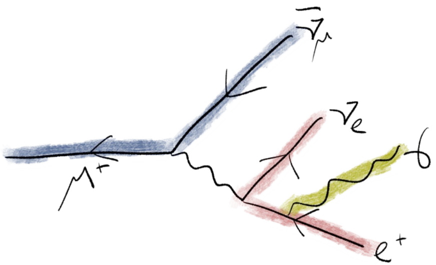
BR($\mu \rightarrow e\gamma$) < 4.3×10^{-13} (90% C.L.)

Eur. Phys. J. C (2016) 76:434

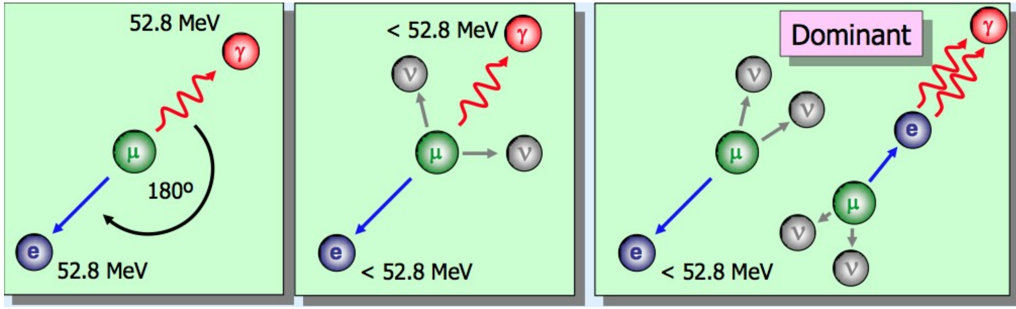
MEG-II
- optimised detector
- higher beam intensity (7×10^{7} muons/s)







BR($\mu \rightarrow e\nu\nu\gamma$)~$10^{-8}$

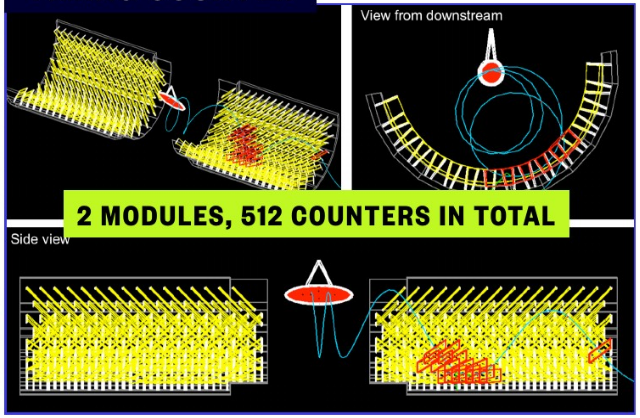


MEG-II @ PSI

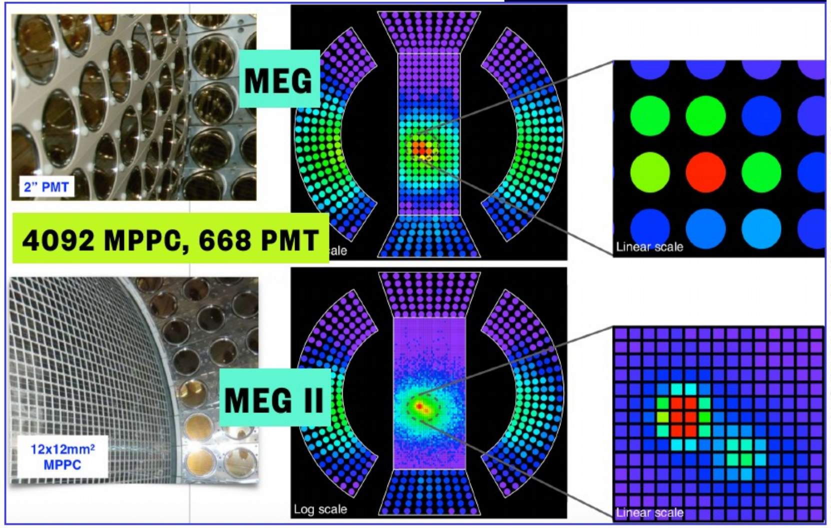
Detector performance

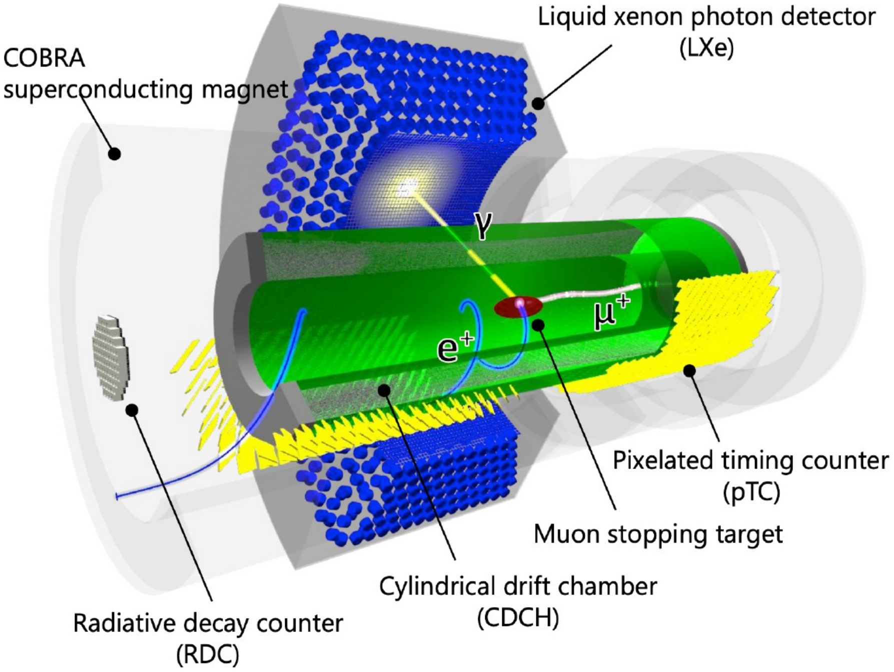
PDF parameters	MEG	MEG II
E_{e^+} (keV)	380	130
θ_{e^+} (mrad)	9.4	5.3
ϕ_{e^+} (mrad)	8.7	3.7
z_{e^+}/y_{e^+} (mm) core	2.4/1.2	1.6/0.7
$E_\gamma(\%)$ (w>2 cm)/(w<2 cm)	2.4/1.7	1.1/1.0
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.6/2.2/5
$t_{e^+\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	≈ 99	≈ 99
Photon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

TIMING COUNTER



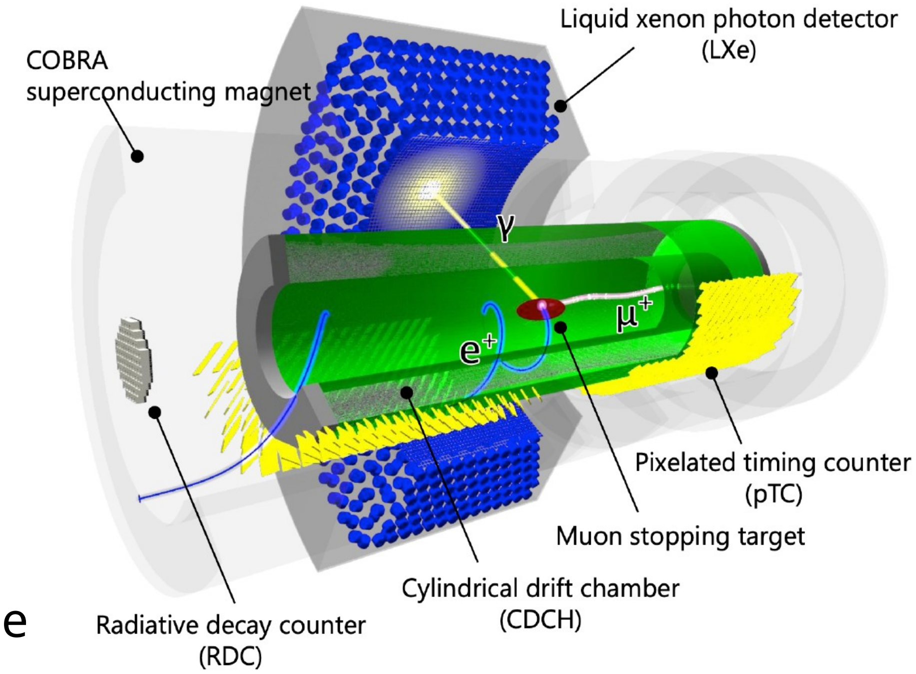
LXE CALORIMETER





CYLINDRICAL DRIFT CHAMBER

MEG-II @ PSI



Pre-engineering run Oct-Dec 2020
- with all detectors, limited readout
- stability & performance studied
- MPPC & CDC issues resolved

Engineering run Aug-Dec 2021
- complete detector and TDAQ
- final studies of detector stability and performance
- first physics data at end of run
- tests for X(17) measurement using proton beam from LXe calibration

Expect sensitivity of 6×10^{-14} based on 3 years running (x10 improvement in BR limit)

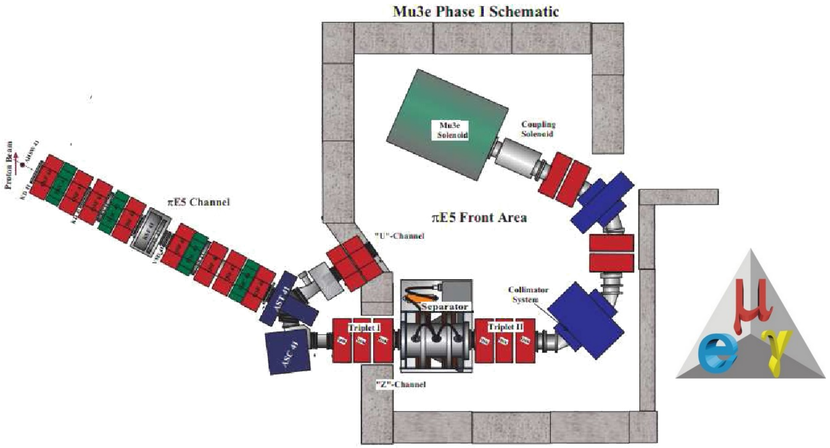
See talk by Manuel Meucci on Tuesday

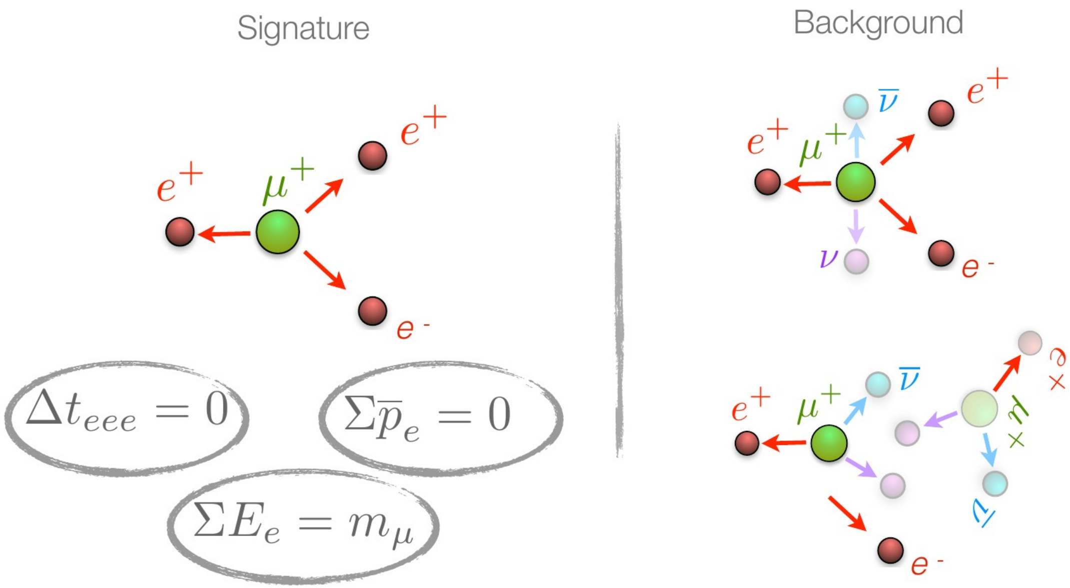
Mu3e @ PSI:

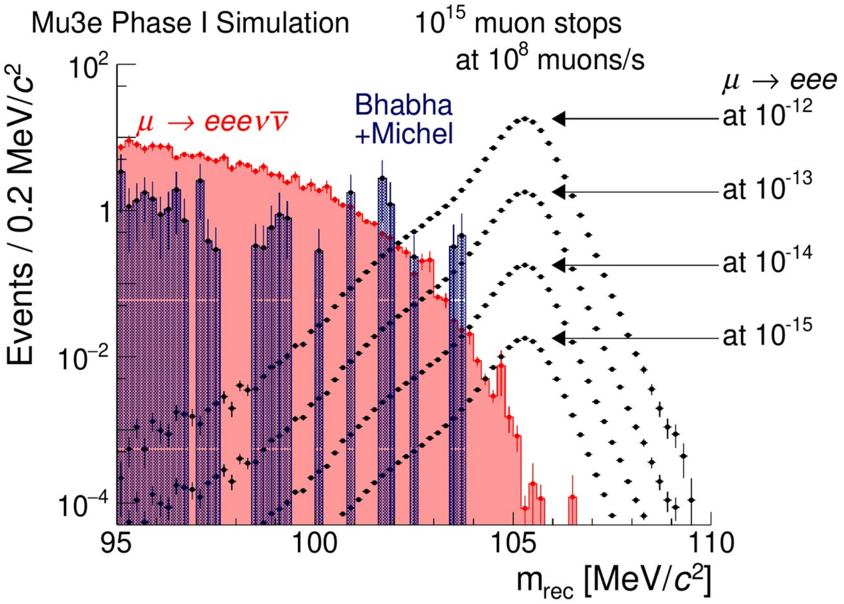
- search for $\mu \rightarrow eee$
- share πE5 beamline with MEG-II (10^8 muons / s)
- Phase-I target BR < 2×10^{-15} (~10^3 improvement)

Require timing, momentum & vertex resolution

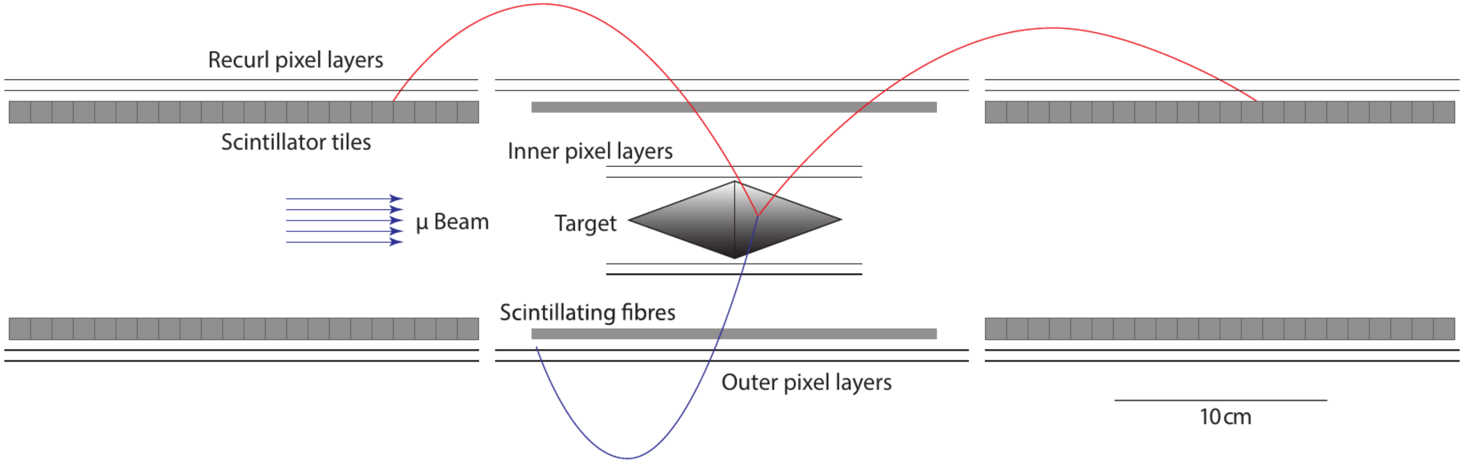
on low-energy ($E<m_\mu/2$) electrons

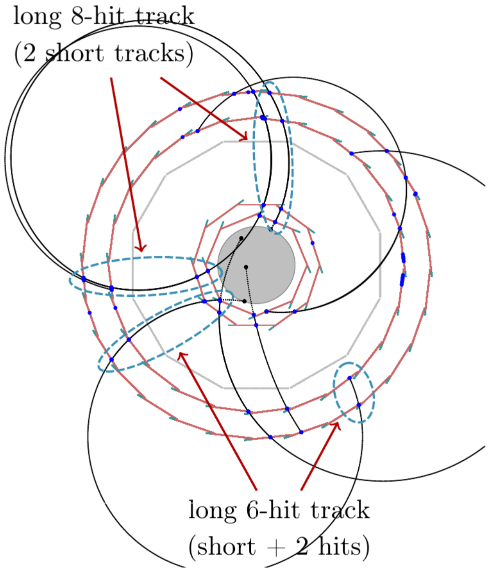






Mu3e @ PSI





Four layer HV-MAPS tracker: (talk by Andre Schoening)

- MuPix11: 80x80um, 256x250 pix, thinned to 50um ($0.01X_0$ per layer)

→ vertex resolution 200um, momentum resolution 0.5 MeV.

Timing detectors:

- Scintillating fibres (<1ns) and tiles (<100ps)

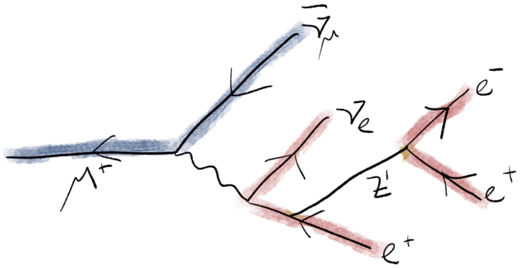
Online tracking on GPU farm

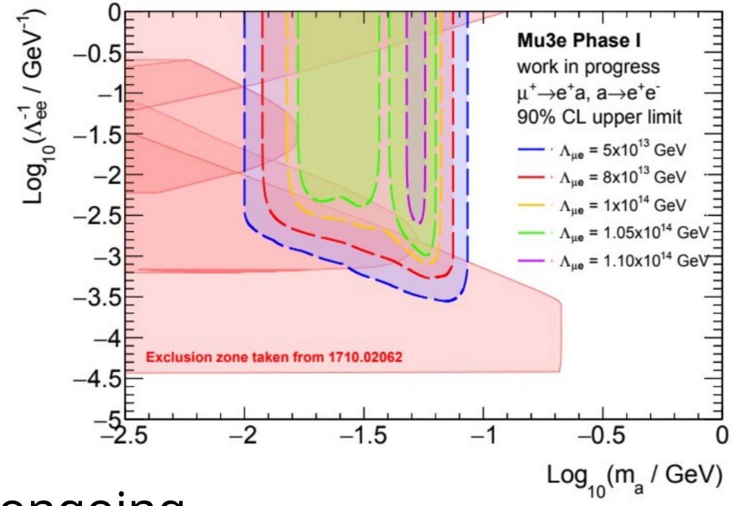
TDR: NIM A: Vol. 1014 (2021) 165679

See talk by Alex Kozlinskiy on Tuesday

Dielectron resonance search:

dark photons, ALPs, LLPs,…





Integration run May/June 2021 (poster by Marius Köppel)

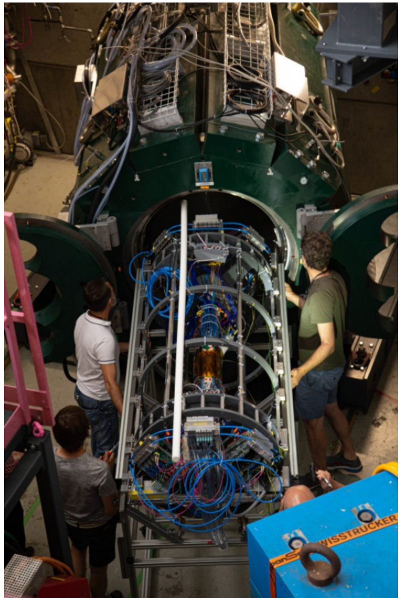
- magnet & beam-line commissioned
- two layers of pixels + scintillating fibres, data analysis ongoing

Engineering run 2023, physics 2024

- target BR< 2×10^{-15} (x1000 on SINDRUM limit)

Mu3e Phase-II:

- HiMB @ PSI: 2028, $>2 \times 10^{9}$ μ / s (talk by Andreas Knecht)
- detector upgrade: increase acceptance & deal with occupancy
- BR(μ→eee) < 10^{-16} (x10 improvement, $\times 10^{4}$ on SINDRUM)

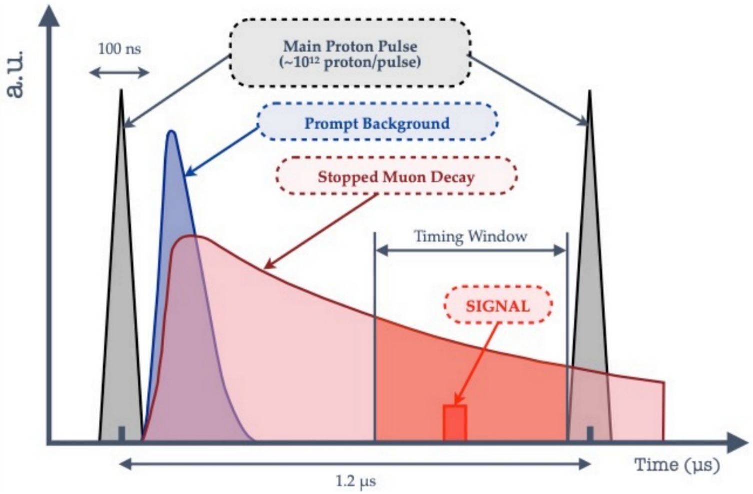


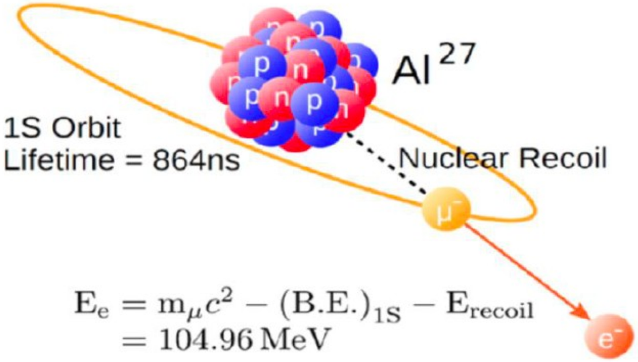
Conversion experiments:

- signal: mono-energetic electron

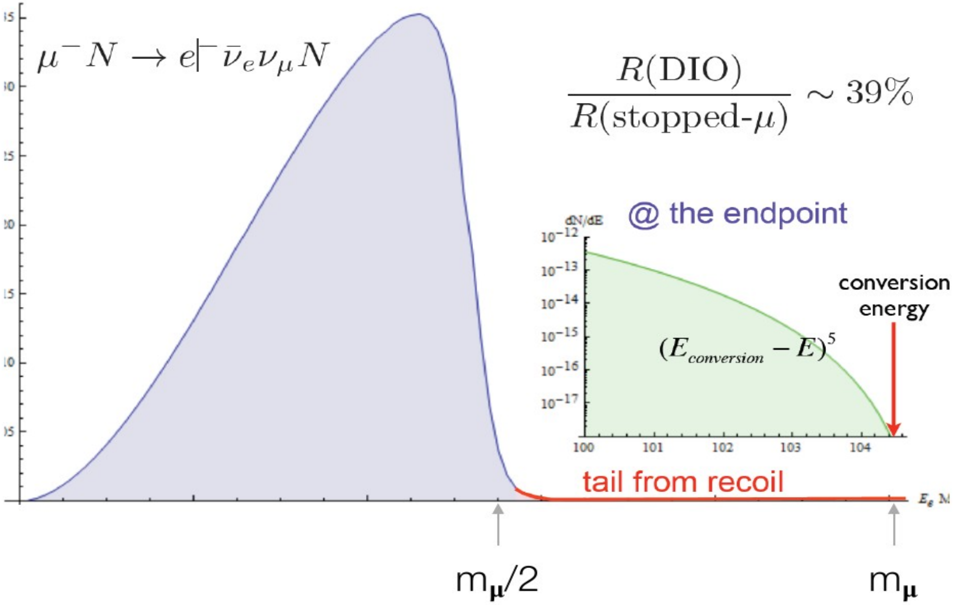
Backgrounds:

- pions, d.i.f., radiative nuclear capture
- cosmics (veto system)
- decay in orbit is primary background



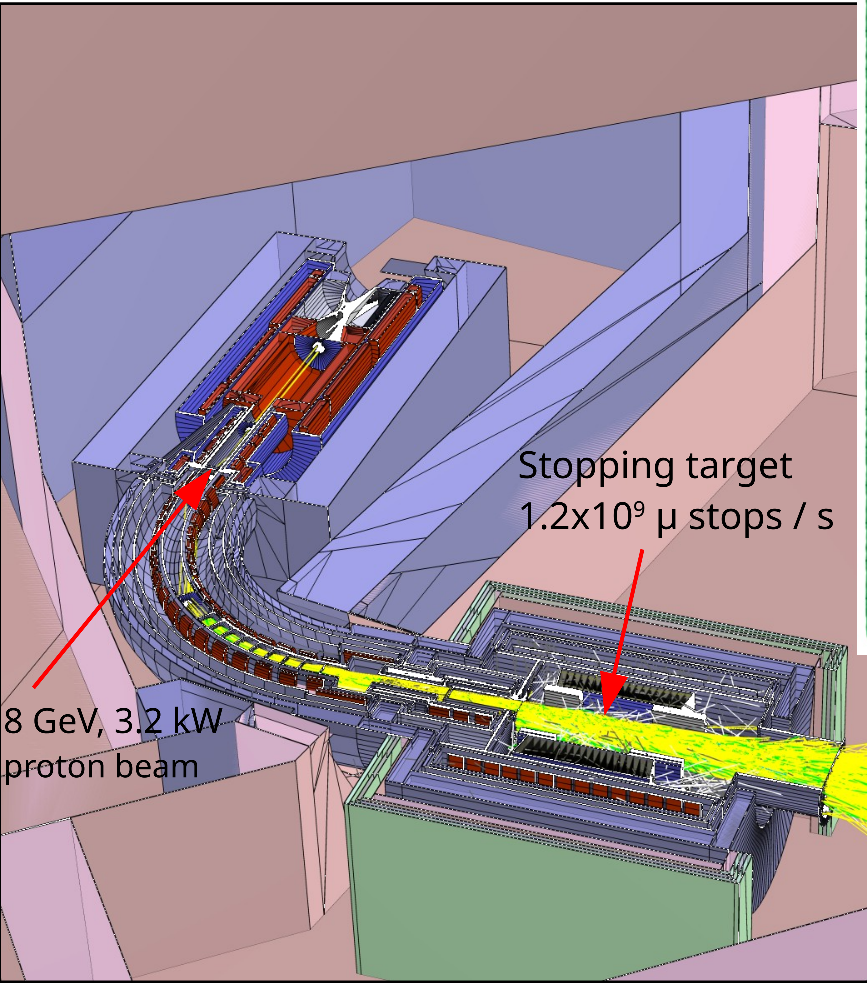


$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\,\mathrm{MeV}$$

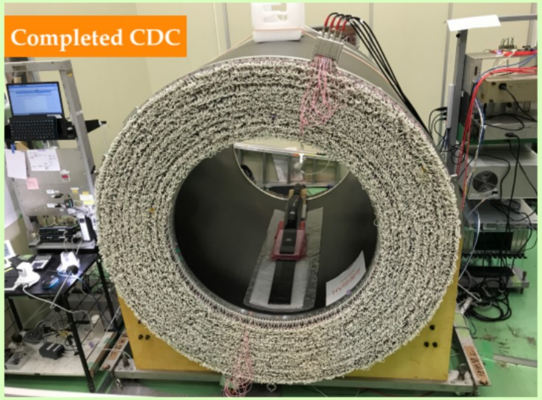


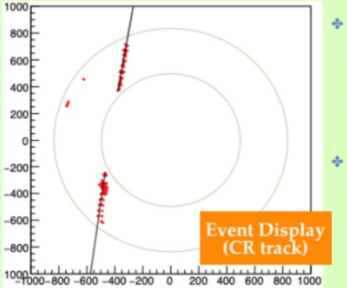
COMET @ J-PARC

Talk by Cristina Carloganu



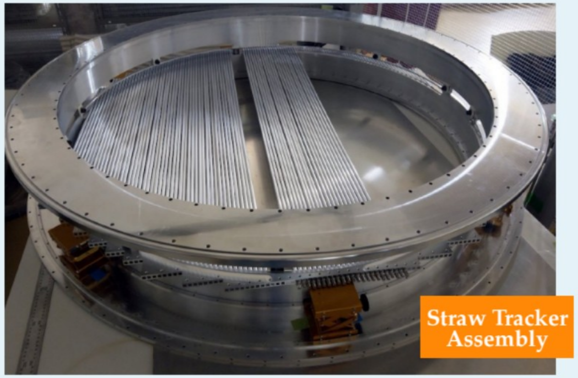
CyDet (for μ-e conv. search)



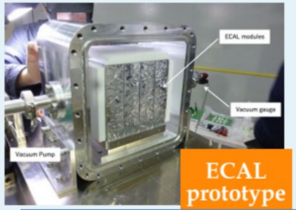


- CDC, completed and under commissioning with cosmic-ray.
- Trigger hodoscope is under development.

StrECAL (for beam measurement)



- First station complete
- Five stations in total.



- ECAL prototype successfully completed.
- Detector assembly will start soon.

Talk by Hajime Nishiguchi

Beamline completed in 2023, expect physics in 2024

BR< 7×10^{-15} (0.4 years running)

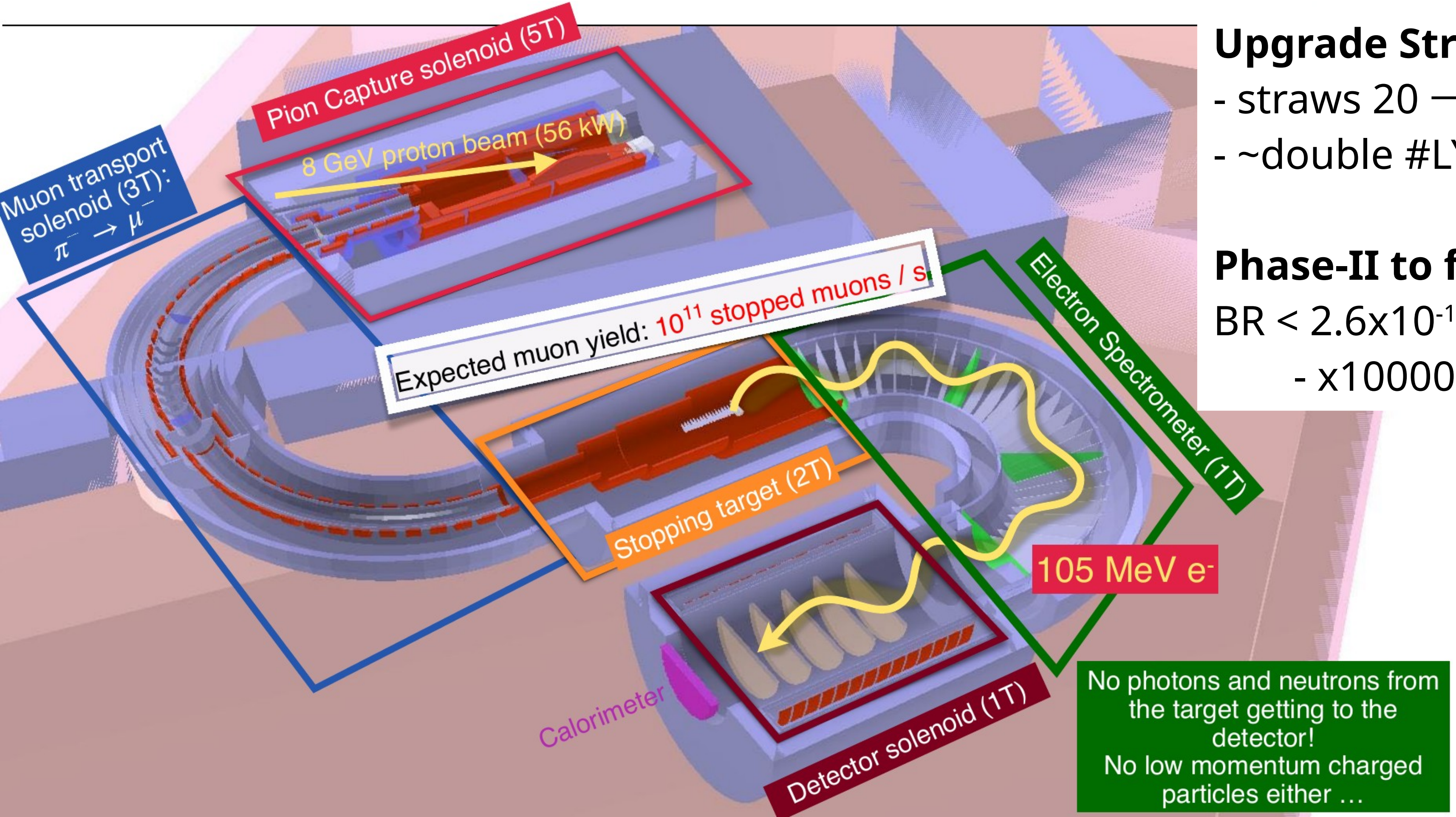
- x100 on SINDRUM-II

COMET Phase-II @ J-PARC

Talk by Cristina Carloganu

Higher beam power, x100 stops / s

Additional transport solenoid: reduced beam backgrounds



Upgrade StrECAL:

- straws 20 → 12 um thick
- ~double #LYSO crystals

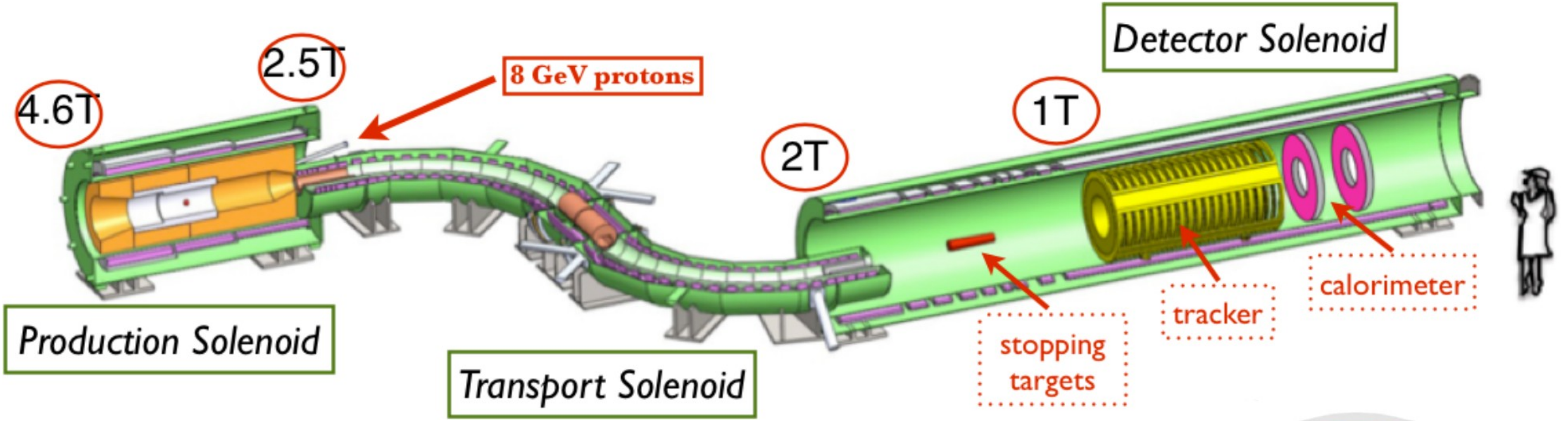
Phase-II to follow Phase-I

BR < 2.6×10^{-17} (1 year running)

- x10000 on SINDRUM-II

Mu2e @ FNAL

Talk by Gianantonio Pezzullo



Cylindrical straw tracker:

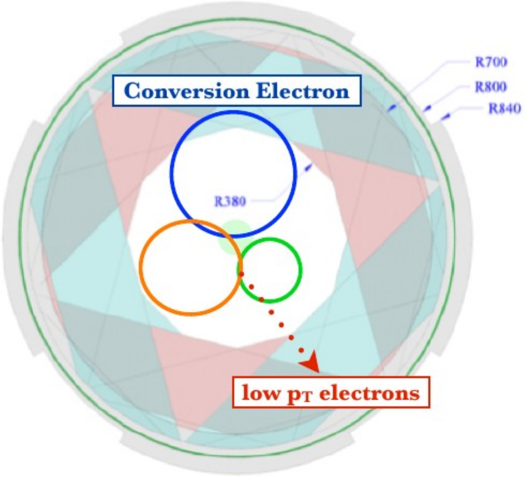
- 20k straw tubes in 36 planes (5 complete)

Calorimeter:

- 2 disks, 630 undoped CsI crystals

STM:

- downstream, gamma-rays from muon capture



Status:

Beam-line complete (shared with Muon g-2)

Beam on target late 2024 (800 MeV, 8kW)

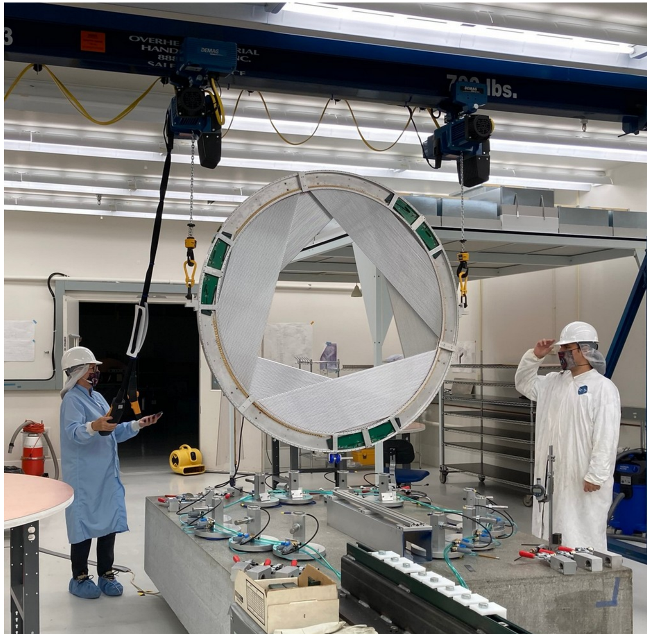
- talk by Diktys Stratakis

Data in 2025

→ limit BR < 5×10^{-16} (~1000x SINDRUM-II)

Shutdown 2026 (PIP-II installation), resume 2029

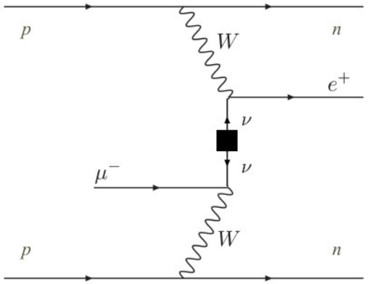
→ limit BR < 8×10^{-17}



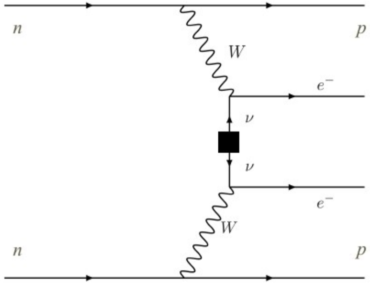
Search for $\mu^- \rightarrow e^+$:

→ Run-I sensitivity 4×10^{-16}

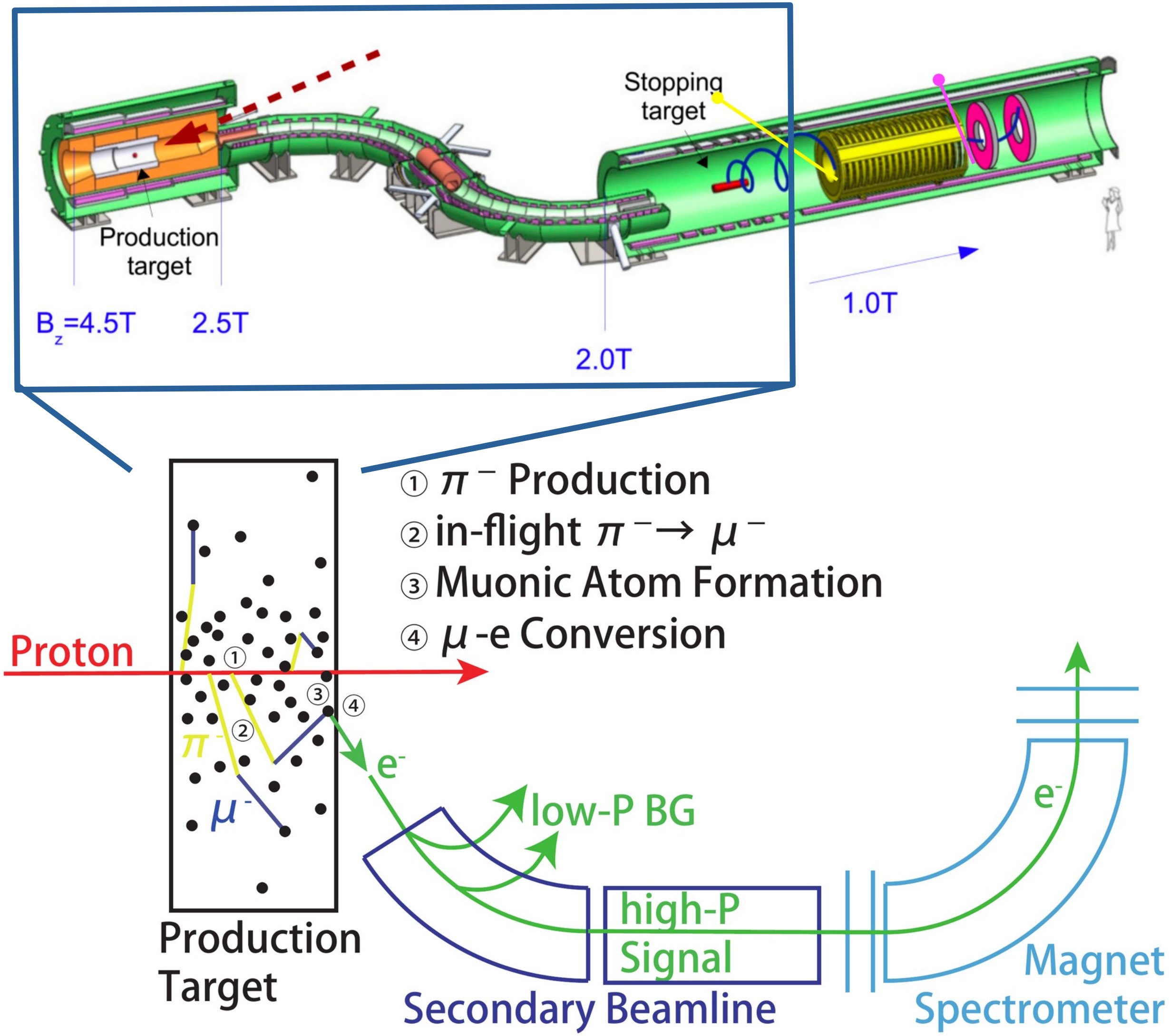
$\mu^- N \rightarrow e^+ N^*$



0νββ decay



DeeMe @ J-PARC



DeeMe @ J-PARC:

- simpler experiment,
  different systematics
- integration run in 2019,
  DIO measurement
- H-line ready 2022, data to follow

Limits (based on 1 year running):

- C target, BR < 1×10^{-13}
- SiC target, BR < 2×10^{-14}

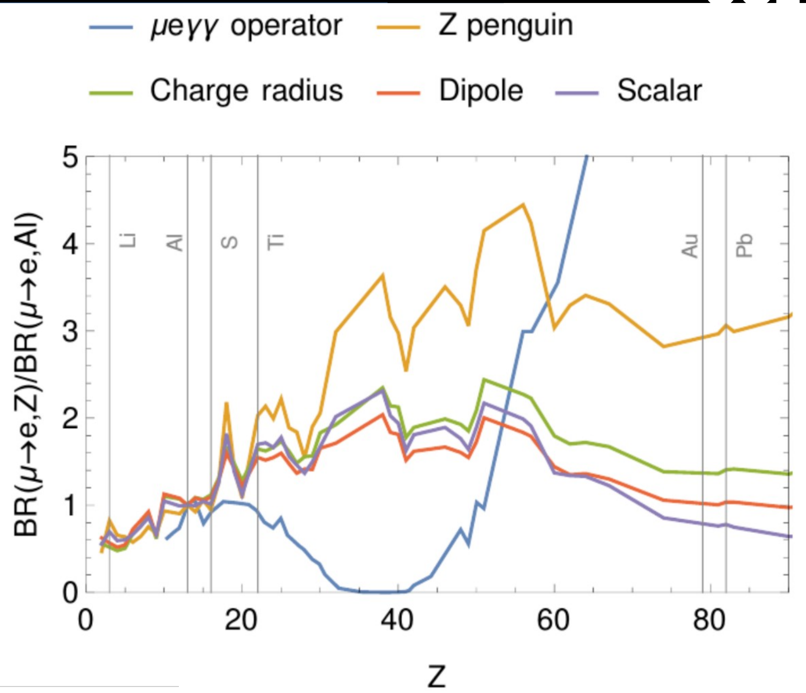
See talk by Natsuki Teshima, Weds

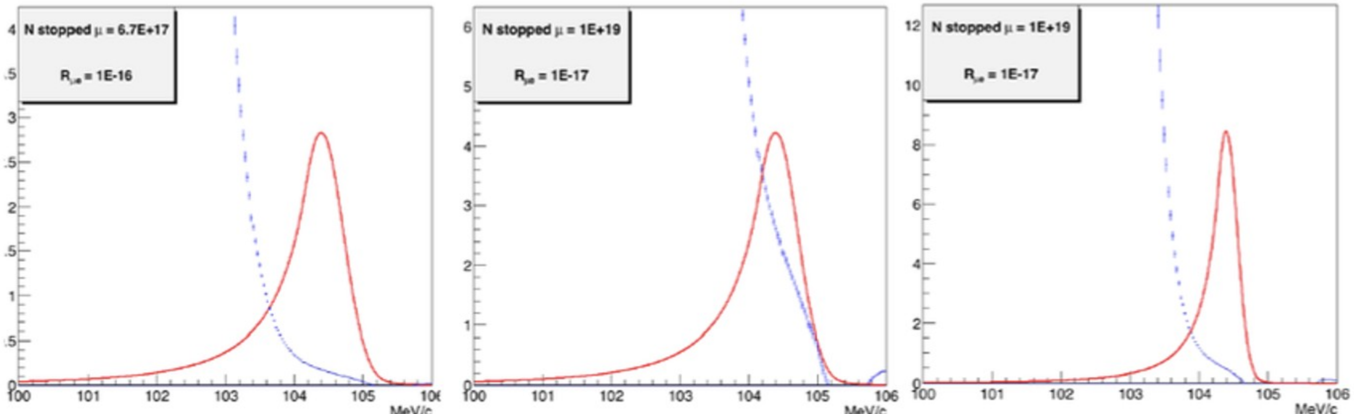
Mu2e-II @ FNAL

Conversion sensitivity BR<10^{-18} (x10 over Mu2e)
- full use of PIP-II beam:
    - ~3X increase in muon beam intensity
    - ~3X increase in live time

Requires new production target
- opportunity to study different *Z* stopping targets

New solenoids and new detectors



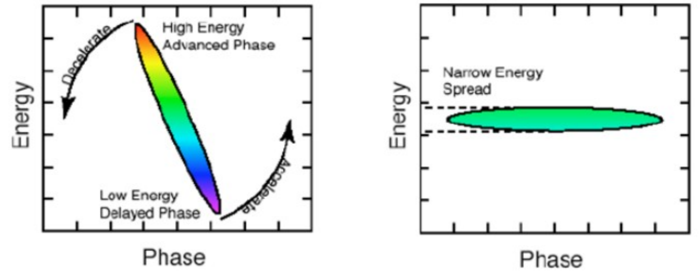


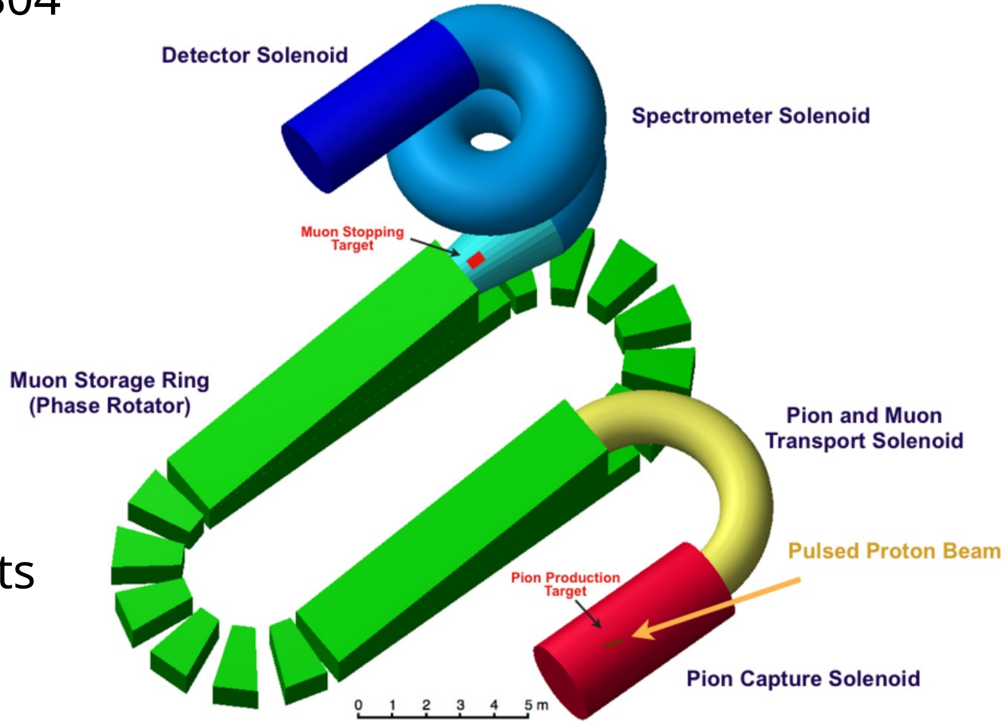
Talk by Craig Dukes

Further ahead

PRISM (Phase Rotated Intense Source of Muons)
- FFA ring, intense pulsed beam
- synergy with muon collider/nu factory R&D
- Proof-of-concept MUSIC (Osaka), arXiv:1310.0804
- PRISM+PRIME detector @ J-PARC
    → x100 on conversion limit

SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf





ENIGMA @ FNAL:
- surface muons with PIP-II: 10^{12} μ / s
    - x100 on the MEG-II limit
- PRISM-based pulsed muon beam
    - conversion down to 10^{-20}, different Z targets

SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf

See talk by Bertrand Echenard, Weds

Conclusion

Complementary search for BSM physics

Three "golden channels":

- μ→eγ: MEG-II
- μ→eee: Mu3e
- conversion: DeeMe, COMET, Mu2e

Huge increase in sensitivity coming: BR < ~10^{-17}

Future beam facilities offer further significant gains

A. de Gouvea & P Vogel, arXiv:1303.4097, updated by G. Hesketh