Experimental Searches for Lepton Flavor Violation (of muon)

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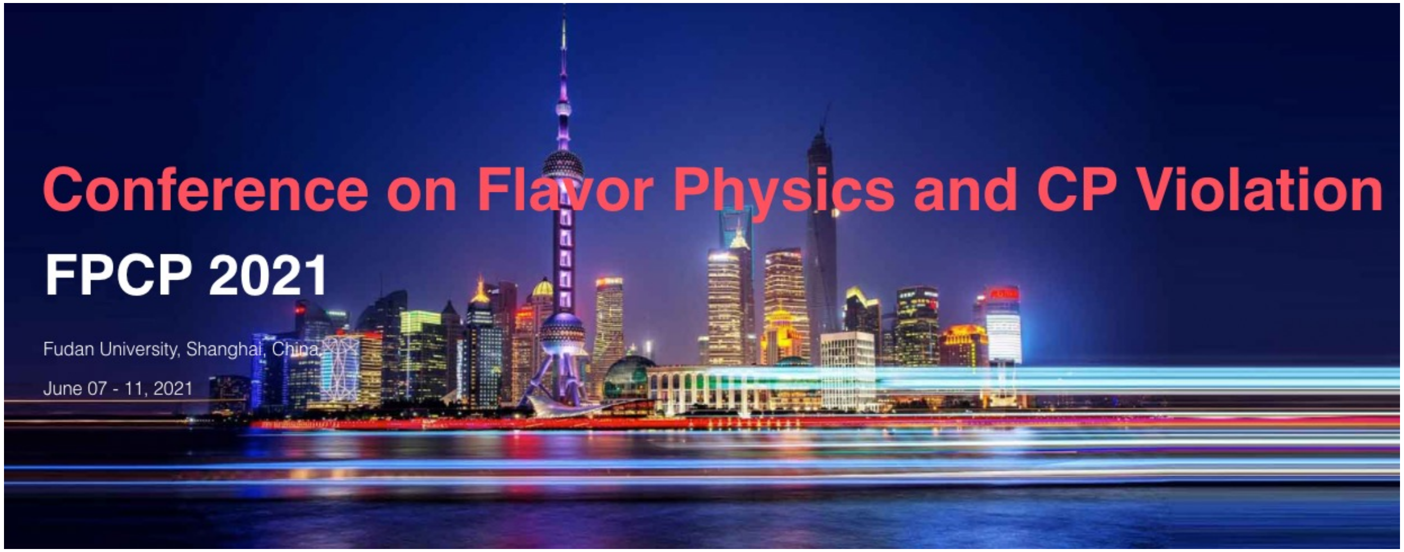
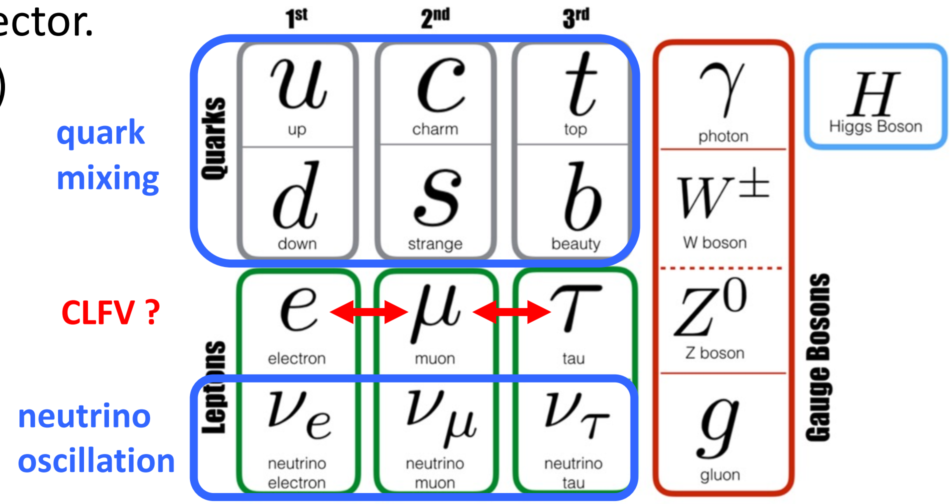
(UNIV. OF TOKYO -> KYUSHU UNIV.)
@ FPCP 2021, 2021/JUN/7



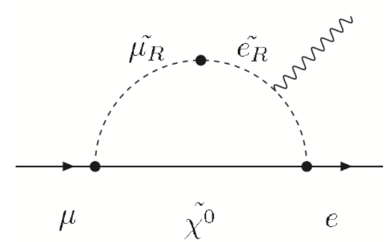
Charged lepton flavor violation

- Standard Model.
  - Flavor violation can happen in quark sector.
  - Charged Lepton Flavor Violation (CLFV) is prohibited.
- Standard model with ν oscillation.
  - CLFV can happen, but with tiny branching ratio.
    - too small to be detected
    - e.g.: Br(μ→eγ)~10^{-55}



- Beyond Standard Model.
  - CLFV is predicted at a detectable branching ratio in some BSM models (SUSY-GUT, SUSY-Seesaw, etc...)
  - e.g.: Br(μ→eγ) = 10^{-12} – 10^{-14}
  - Correlation with muon g-2 anomaly.

Theory review by A.VICENTE (on Wed).



Observation of CLFV would be a clear evidence of new physics!

Experimental searches of CLFV

- Many CLFV modes have been actively searched.
  - muon LFV
    - μ→ eγ, μ→ eee, μN→ eN
  - tau LFV
    - τ→lγ, τ→lll, etc. …
  - Others
    - LFV decays of K_L , π^0, Z, H etc.

τLFV talk by *N.TASNEEM, D.SAHOO (Wed)*
Higgs LFV talk by M.TESTA (Tue)

- Several experiments are in preparation to search for muon LFV.
  - aiming to start data-taking in the next a few years.

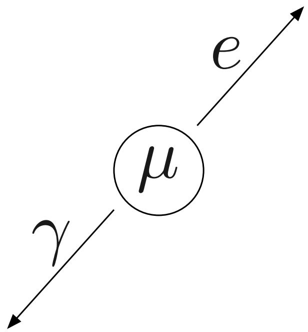
	current limit	**future prospect**
μ→ eγ	4.2×10^{-13} by MEG	~6×10^{-14} by MEG II
μ→ eee	1.0×10^{-12} by SINDRUM	$O(10^{-15})$ by Mu3e phase-I
μN→ eN	7.0×10^{-13} by SINDRUM II	down to $O(10^{-17})$ by DeeMe, COMET, Mu2e

MEG II experiment

Signal and background in μ→eγ search

- Dominant background in μ→ eγ search: accidental coincidence.
- Intense DC muon beam & good detector resolutions are the keys.

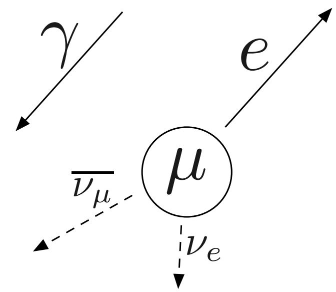
Signal



2-body decay to
nearly massless particles

- $E_e = E_\gamma = 52.8\text{MeV}(= m_\mu/2)$
- back-to-back
- coincident

Dominant background: accidental coincidence



accidental coincidence of e & γ,
originating from different muon decays.

- having nearly 52.8MeV,
- emitted nearly back-to-back
- emitted at nearly the same timing

The number of background events in signal region

$$N_{acc} \propto R_{\mu^+}^2 \times \Delta E_\gamma^{\ 2} \times \Delta p_{e^+} \times \Delta\Theta_{e^+\gamma}^2 \times \Delta t_{e^+\gamma} \times T.$$

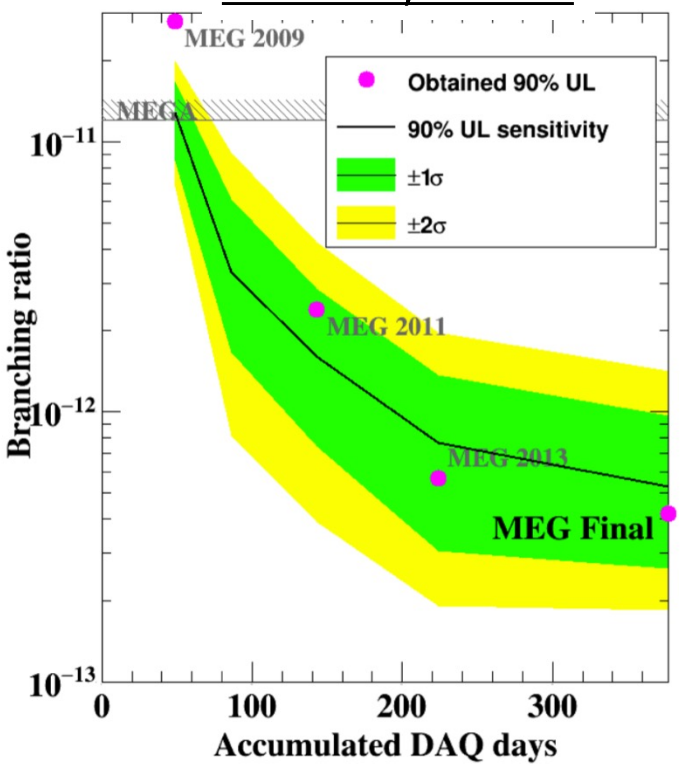
(beam rate)^2 — detector resolutions

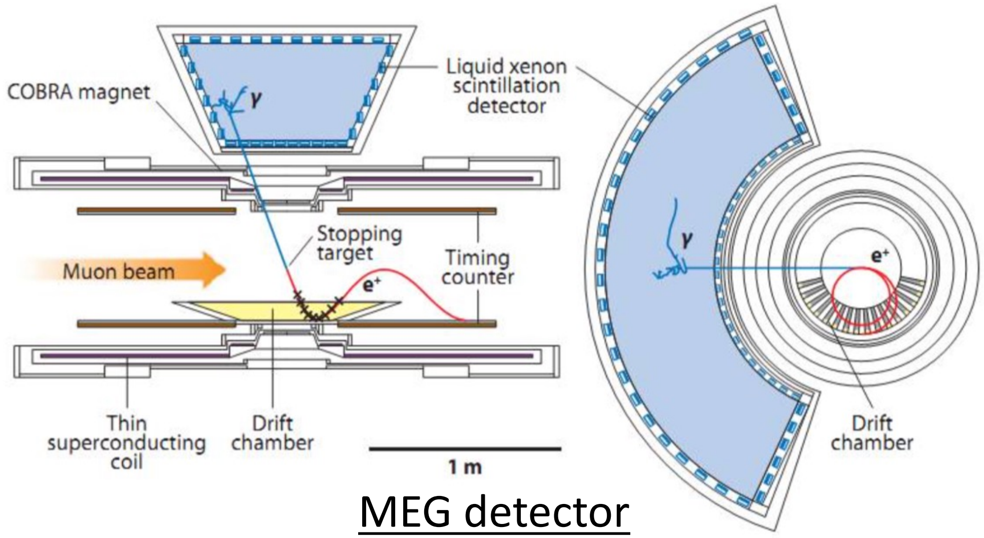
MEG experiment

- MEG experiment was carried out in 2009-2013.
  - World's most intense DC beam at PSI (Switzerland).
  - Positron spectrometer
    - Gradient magnetic field + segmented low-mass drift chamber + scintillation timing counter.
  - LXe γ-ray detector

→ MEG result with full data set:
$Br(\mu \to e\gamma) < 4.2 \times 10^{-13}$ at 90% C.L.
(Eur. Phys. J. C 76(8), 434, 2016)

Sensitivity in MEG





MEG detector

MEG II experiment

An upgraded experiment called MEG II is under commissioning to improve the sensitivity of MEG by another one order of magnitude.

Better detector resolutions.

- x2 for all detector resolutions

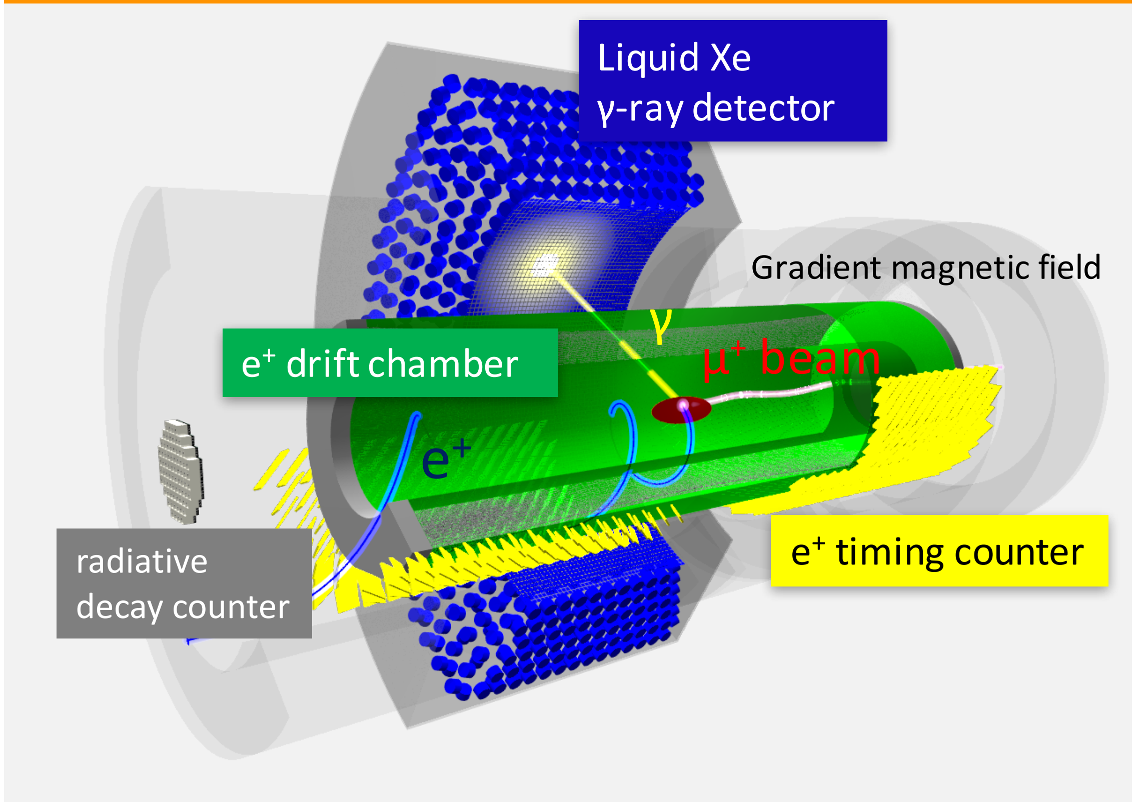
More muon statistics.

- x2.3 muon beam rate ($3 \times 10^7 \rightarrow 7 \times 10^7$ μ/s)
- x2.3 positron efficiency (30% -> 70%)

A new detector for background tagging.

→ **Sensitivity : ~6×10^{-14}**

MEG II detectors



Positron spectrometer

- Cylindrical wire chamber for positron momentum measurement
  - Low mass detector to avoid multiple scattering.
    - Gas: He(90%)+iC_4H_{10}(10%)
    - Wire: 20 μm W(Au) for anode, 40 or 50 μm Al(Ag) for cathode.
  - Z measurement by stereo configuration (stereo angle: 6-8.5°)

- Comparing to MEG drift chamber,
  - Better transparency to timing counter -> Better efficiency.
  - Increased number of hits per track -> Better momentum resolution.

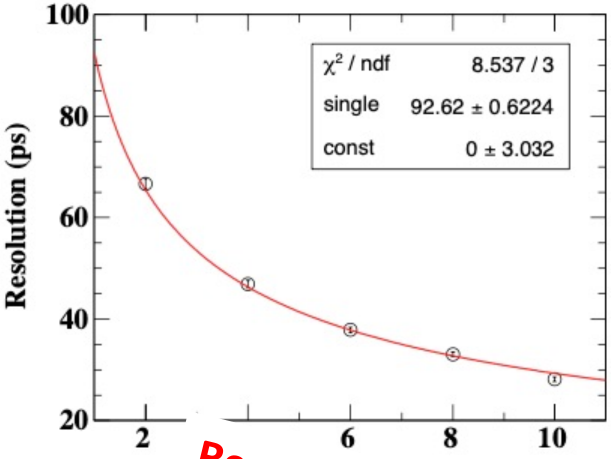
- Under commissioning.
  - Long term stability to be checked in 2021.

Positron spectrometer

- Timing measurement of the positron.
- 512 fast plastic scintillator tiles.
  - Read out by 6 SiPMs on each side connected in series.
  - 90 ps timing resolution by one tile.
- Signal positron hits ~9 counters along its track.

→ ~35 ps timing resolution is achieved.

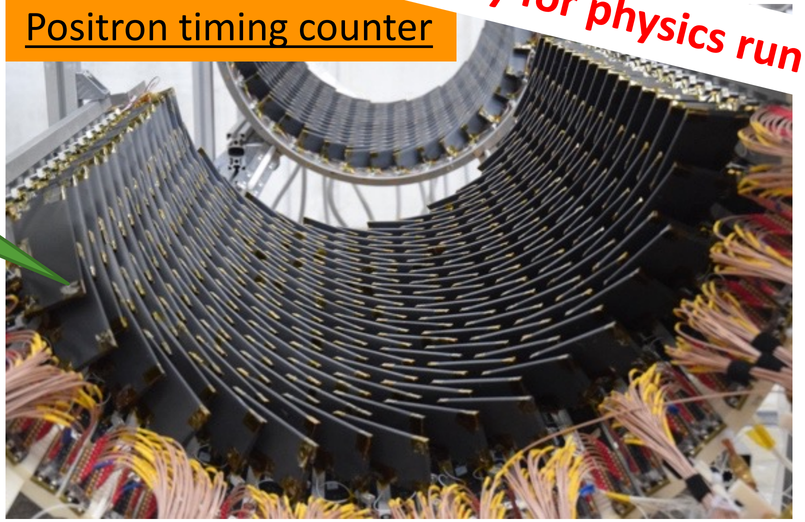
Timing resolution vs. number of hit per track



Single scintillator tile

- BC 422. 12 x 4(5) x 0.5 cm^3
- Readout by SiPM (AdvanSid)
- SiPM 6-series connected

Positron timing counter

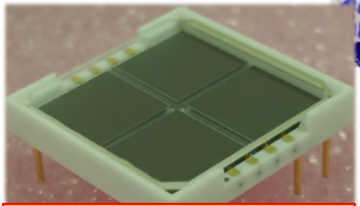


Ready for physics run

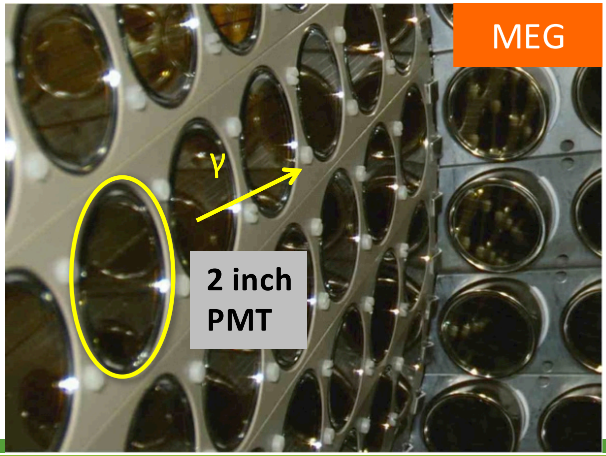
LXe γ-ray detector

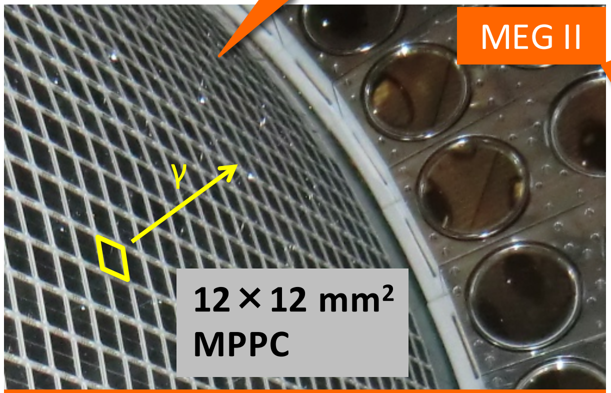
- Position, energy, and timing measurement of 53MeV γ.
- LXe scintillation light read out by photo-sensors.

- **216 PMTs** on the γ-entrance face are replaced **with 4092 MPPCs.**
  - Better granularity & uniformity
    → Better position & energy resolution.
- Utilize VUV-sensitive MPPC newly developed by HPK.
  - Unexpected radiation damage found.
    - confirmed to be recovered by annealing.

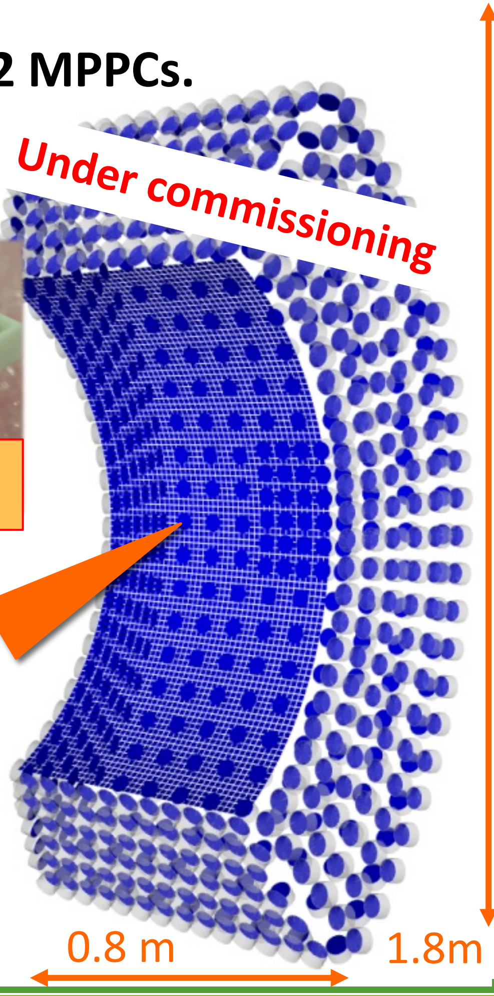


Hamamatsu S10943-4372
PDE (λ = 175nm) > 15%



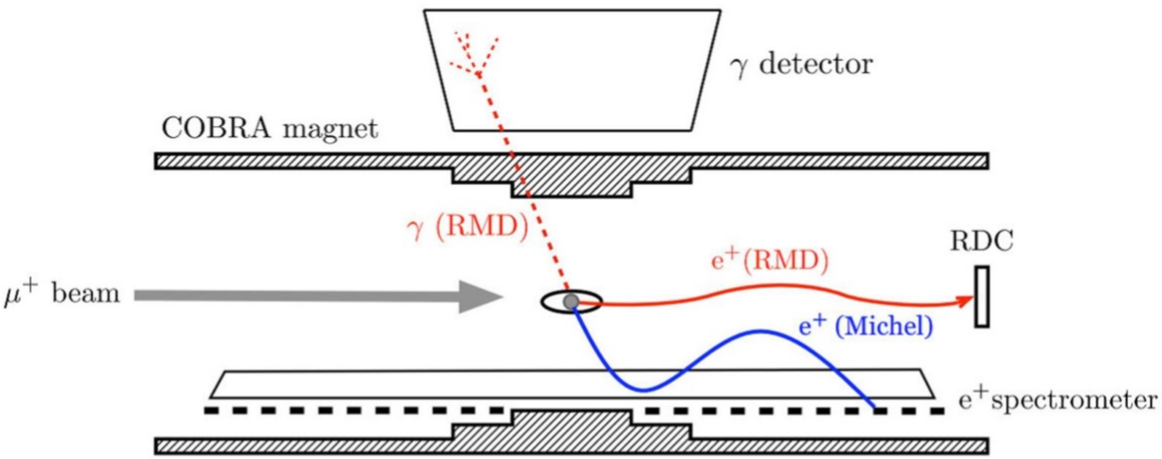


~1 m² is covered by MPPC !

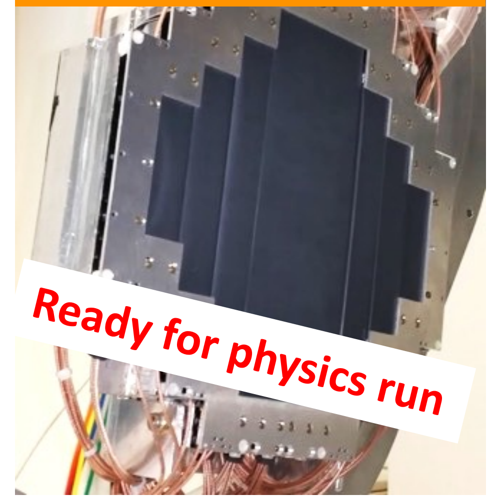


Radiative decay counter

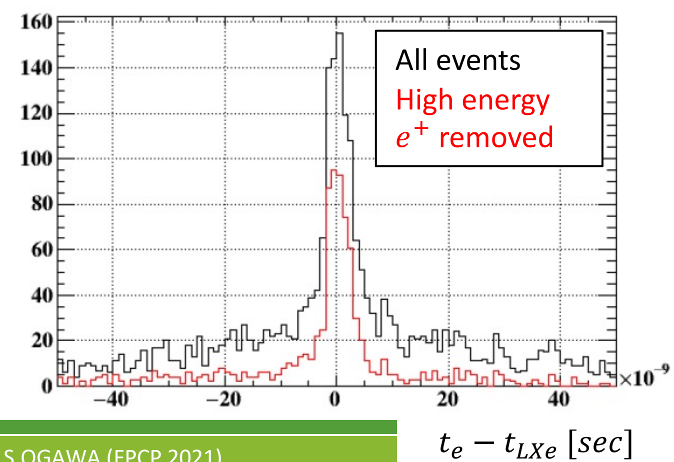
- A radiative decay counter (RDC) is newly added in MEG II.
  - To tag BG γ-rays from radiative muon decay (RMD, $\mu \rightarrow e\nu\bar{\nu}\gamma$), by detecting the low energy positron from it.



radiative decay counter



- Plastic scintillator bar for timing measurement, and LYSO crystals for energy measurement.
- RMD events (coincident e & γ in RDC & LXe) are successfully identified.

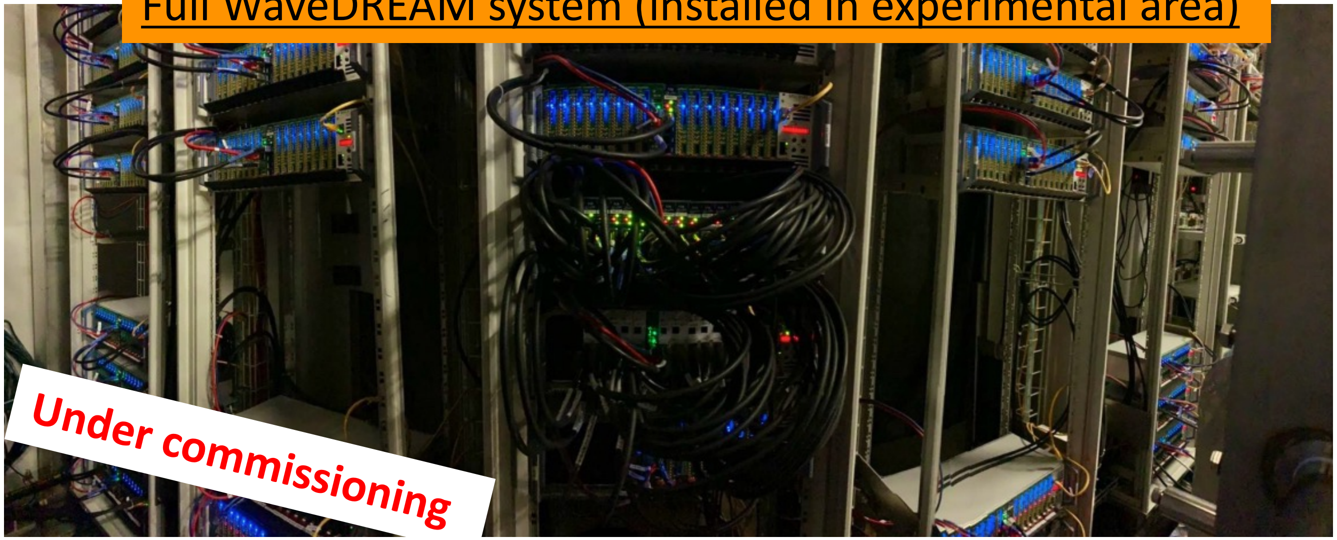


Readout electronics

- A dedicated readout electronics (called WaveDAQ) is developed.
- An integrated DAQ system for MEG II.
  - TRG generation based on online reconstruction of e & γ.
  - Waveform digitization by DRS4 chips.
  - Amplifier & HV supply for SiPM.
  - Total number of channel: ~9000.

- Full system installed this March. Under commissioning.

Full WaveDREAM system (installed in experimental area)



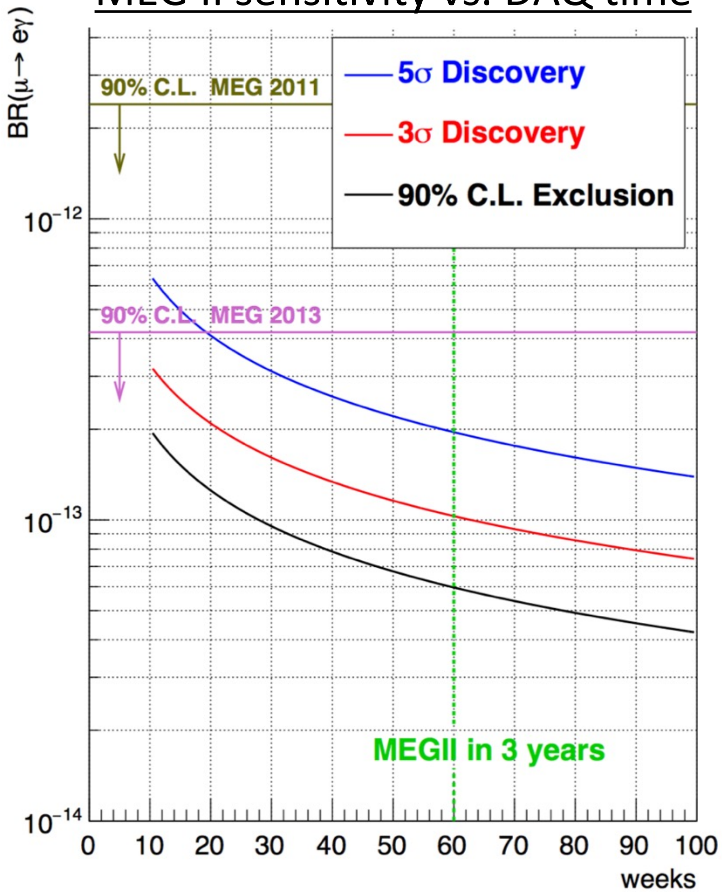
MEG II Prospect

- MEG II experiment: Under commissioning.
- Engineering run from this summer followed by the physics run.
- Expected sensitivity of MEG II : ~6×10^{-14} (3 years DAQ)
  - Sensitivity based on the measured detector resolutions under estimation.

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_γ(%) (w>2 cm)/(w<2 cm)	2.4/1.7	1.1/1.0
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.6/2.2/5
$t_{e^+\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	≈ 99	≈ 99
Photon	63	69
e^+(tracking × matching)	30	70

MEG II sensitivity vs. DAQ time

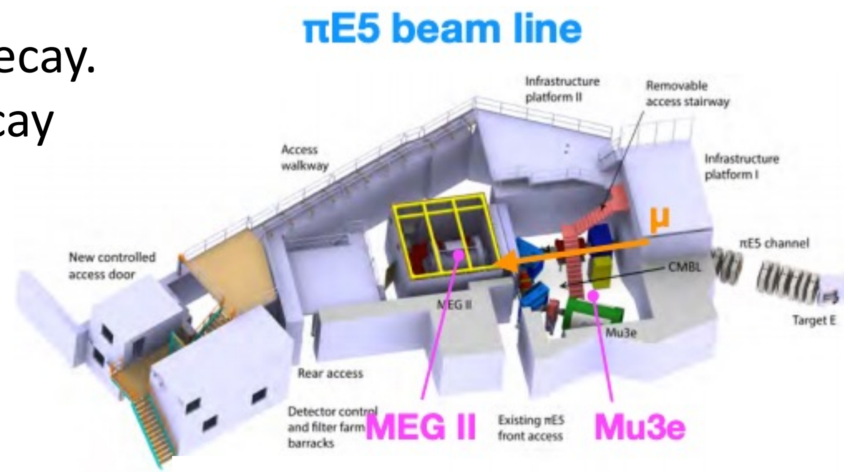


Mu3e experiment

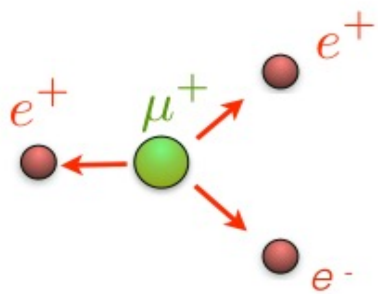
Figures, plots from
A.Papa(TIPP 2021)
N.Berger (Snowmass CLFV 2020)
TDR of Mu3e Phase-I (arXiv: 2009.11690)

Signal and background in μ→eee search

- Mu3e experiment searches for μ→eee decay.
- Background from internal conversion decay (μ→eeeνν) & combinatorial background.
  → Precise positron momentum
  & timing measurement needed.
- Performed at PSI (same as MEG II).



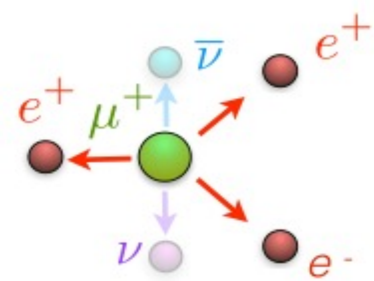
Signal



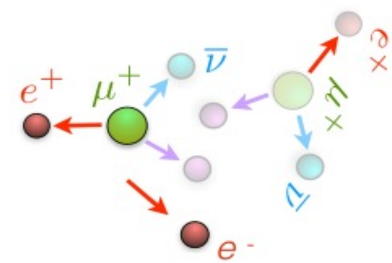
Signature of signal event
- timing coincident
- $\sum E_e = m_\mu$
- $\sum P_e = 0$

Background

internal conversion decay

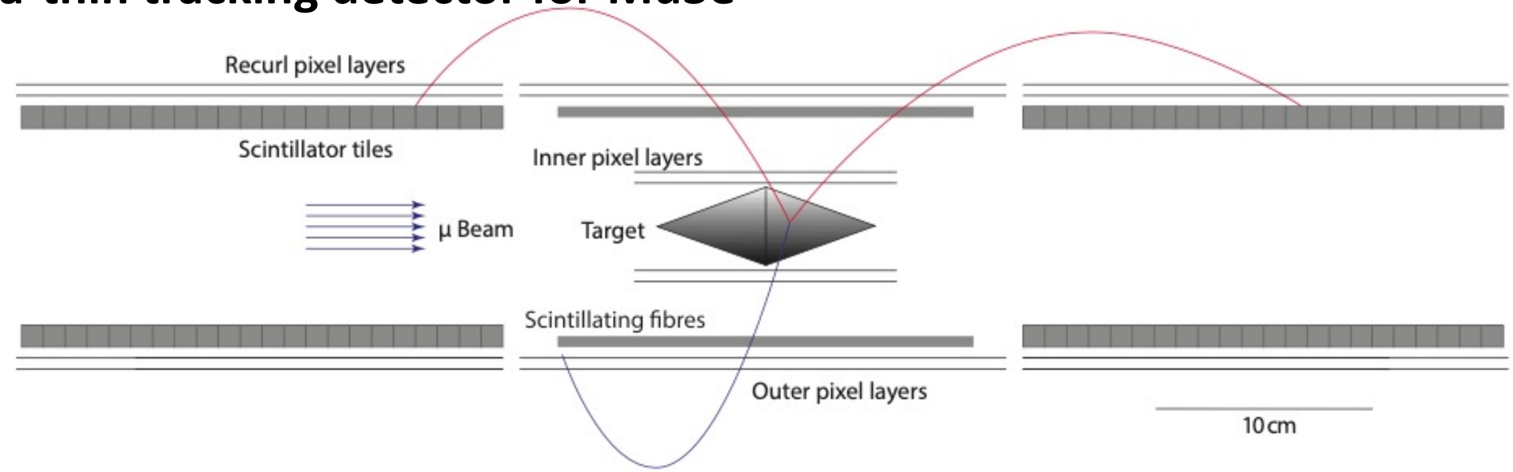


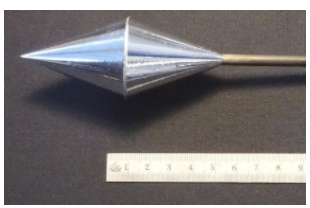
combinatorial

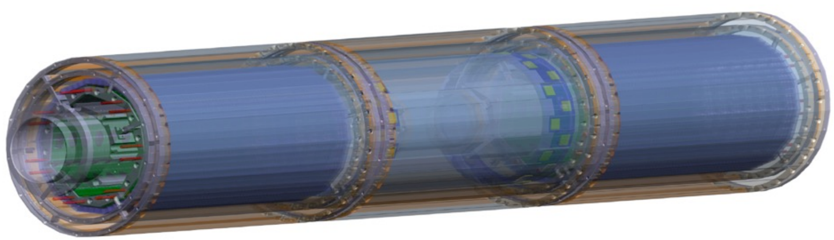


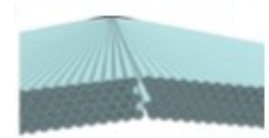
Mu3e detector (for phase-I)

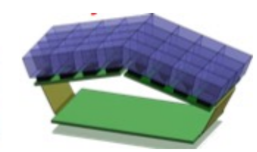
Ultra-thin tracking detector for Mu3e











<u>Target</u>
- Hollow double-cone structure
- Aluminized Mylar foil.

<u>Pixel tracker</u>
- Based on HV- MAP
- Pixel dimension: 80 x 80 μm^2
- 70% geometrical acceptance
- < 0.5MeV/c resolution for large phase space
- X/X_0 ~ 0.1% per layer

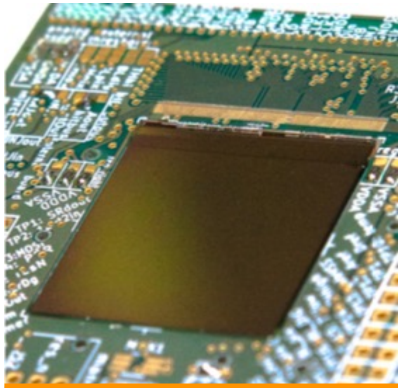
<u>Scintillating Fibers</u>
- 250um diameter scintillating fiber ribbon readout by SiPM array
- ~1ns timing resolution
- X/X_0 < 0.2%

<u>Scintillating tiles</u>
- 6x6x5mm^3 tile readout by SiPM
- < 100 ps timing resolution
- > 95% efficiency

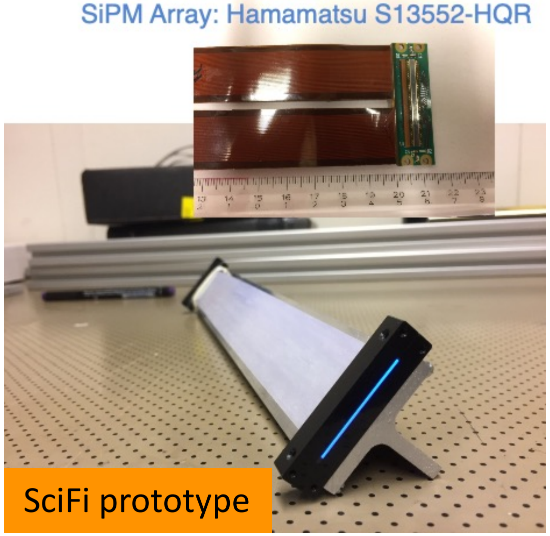
Status of Mu3e experiment

- Detector R&D finished.
  Under prototyping.
- Mu3e magnet installed.

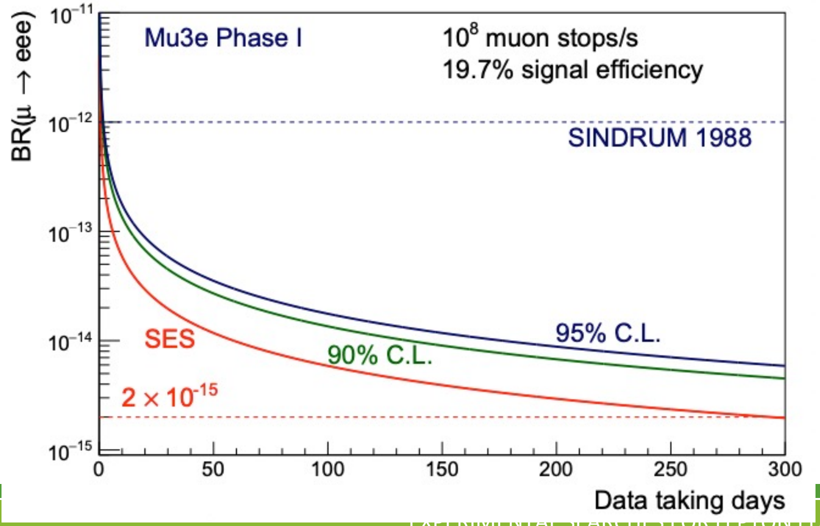
- Phase-I:
  aiming for O(10^{-15}) sensitivity
  at existing πE5 beamline (10^8 μ/s).
- Phase-II:
  aiming for O(10^{-16}) sensitivity
  at a new high-intensity muon beamline (HiMB).



Mupix10:
O(400) mm² prototype
of HV-MAP



SciFi prototype



Mu3e magnet

COMET/Mu2e experiment

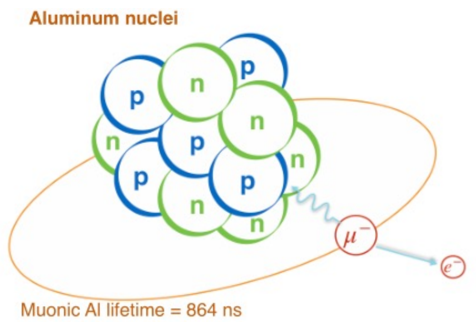
Figures, plots from
H.Nishiguchi (ICHEP 2020)
M.Yucel (ICEHP2020)
L.Morescalchi (ICHEP2020)
Fermilab news (20/Nov/11)
TDR of COMET phase-I (arXiv: 1812.09018)
TDR of Mu2e (arXiv: 1501.05241)

Signal and background in μN→eN search

- Searches for coherent neutrino less conversion of muons.
  - $R_{\mu e} := \dfrac{\Gamma(\mu N \to eN)}{\Gamma(\mu N \to \text{all captures})}$
- Signal: emission of a mono-energetic single electron
- One background from decay in orbit (DIO) of muons.

-> Precise momentum measurement of the emitted positrons.

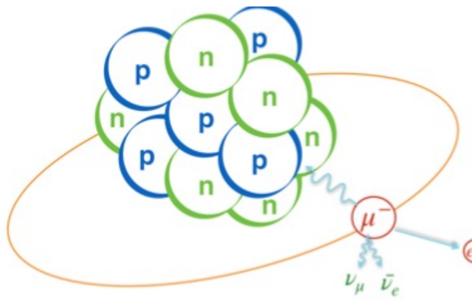
Signal

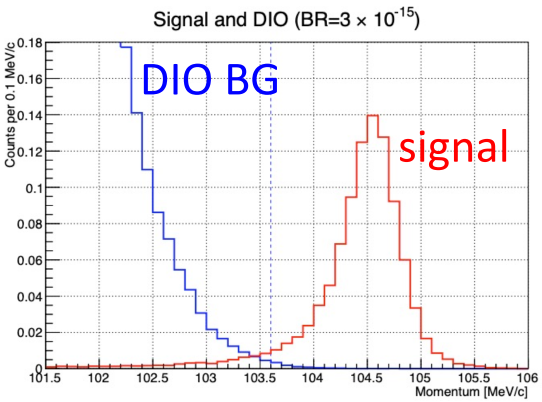


Monoenergetic electron

$$E_e = m_\mu - E_{\text{bind}} - E_{\text{recoil}}$$
$$= 104.97\ \text{MeV}$$

DIO Background

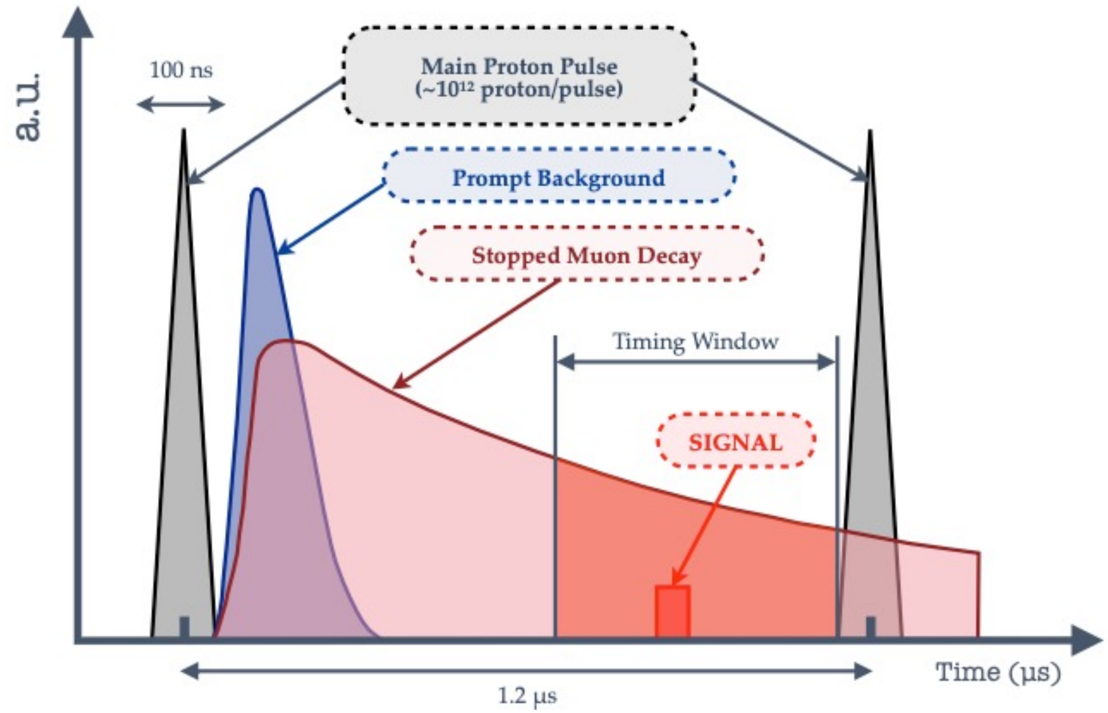




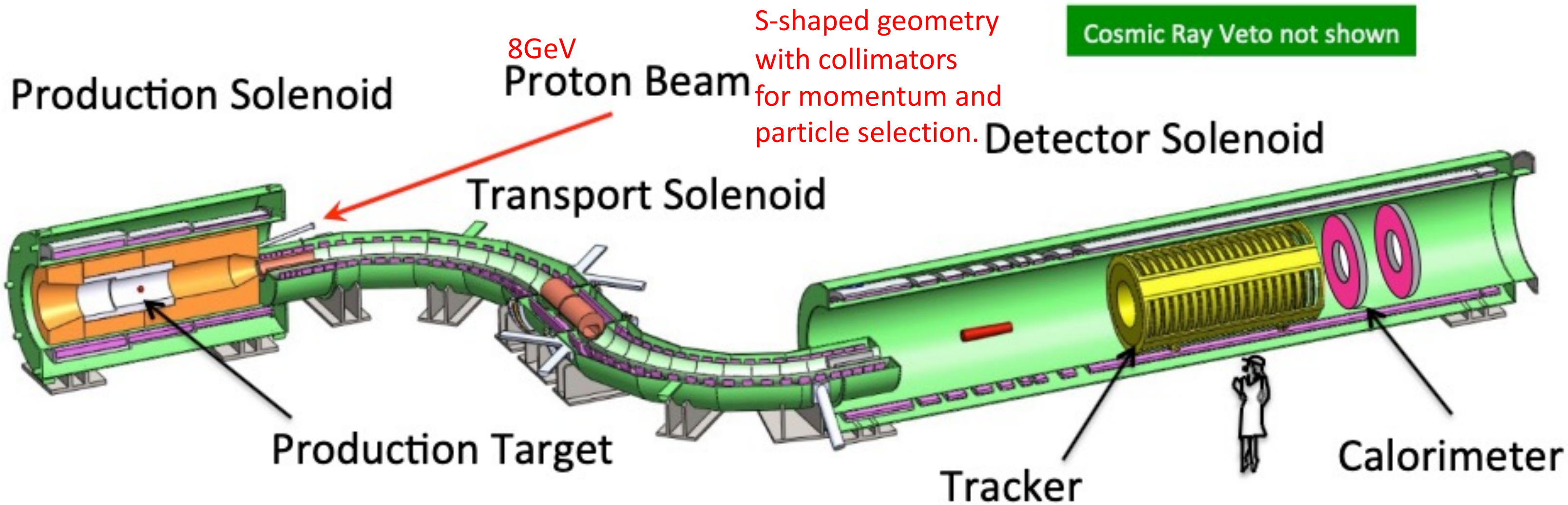
E_e < "signal energy"

Signal and background in μN→eN search

- Another background from beam related prompt background.
- Delayed DAQ window allows us a BG free measurement.
  - Pulsed muon beam. → performed at FNAL/J-PARC.
  - Lifetime of muonic atom of Al : ~0.9ns.
- Extinction (:= out of time proton/proton in main bunch) has to be ~10^{-10} to reach O(10^{-17}) sensitivity.

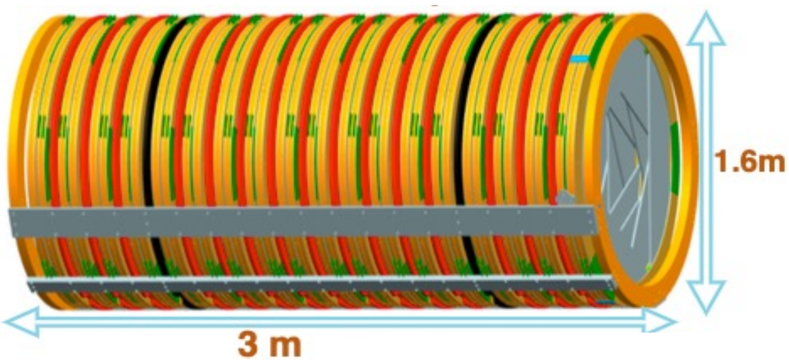


Mu2e experiment



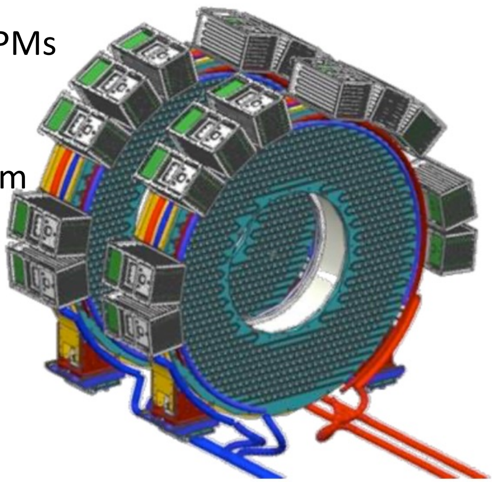
Low mass tracker by straw drift tubes.

- $ArCo_2$ gas.
- double 6 μm Mylar walls
- 36 tracker planes
- Momentum resolution < 180KeV/c



EM calorimeter

- Undoped CsI crystals
- Readout by UV-extended SiPMs
- σ(E)/E : ~10%
- σ(t) < 500ps
- σ(position) < 1cm

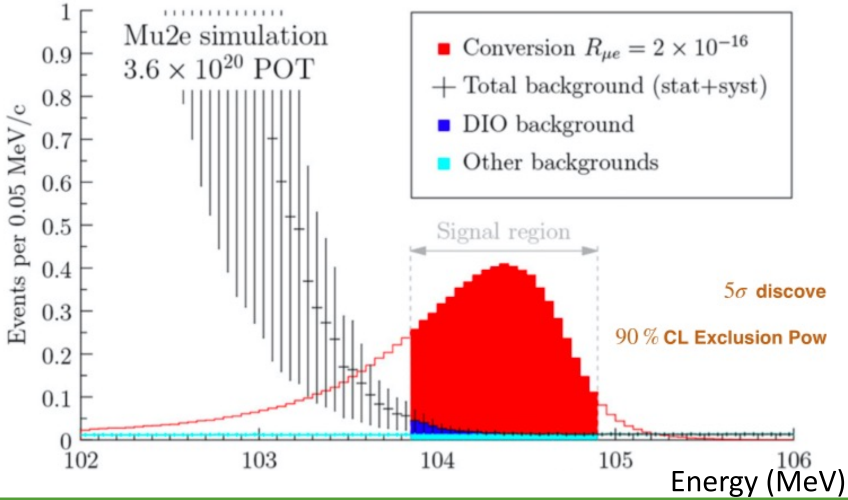


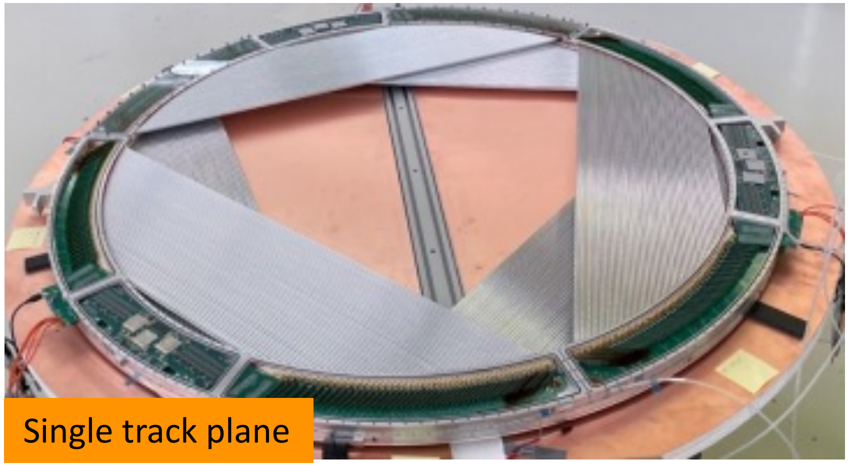
Status of Mu2e experiment

- Transport solenoid delivered.
- Detectors in construction.

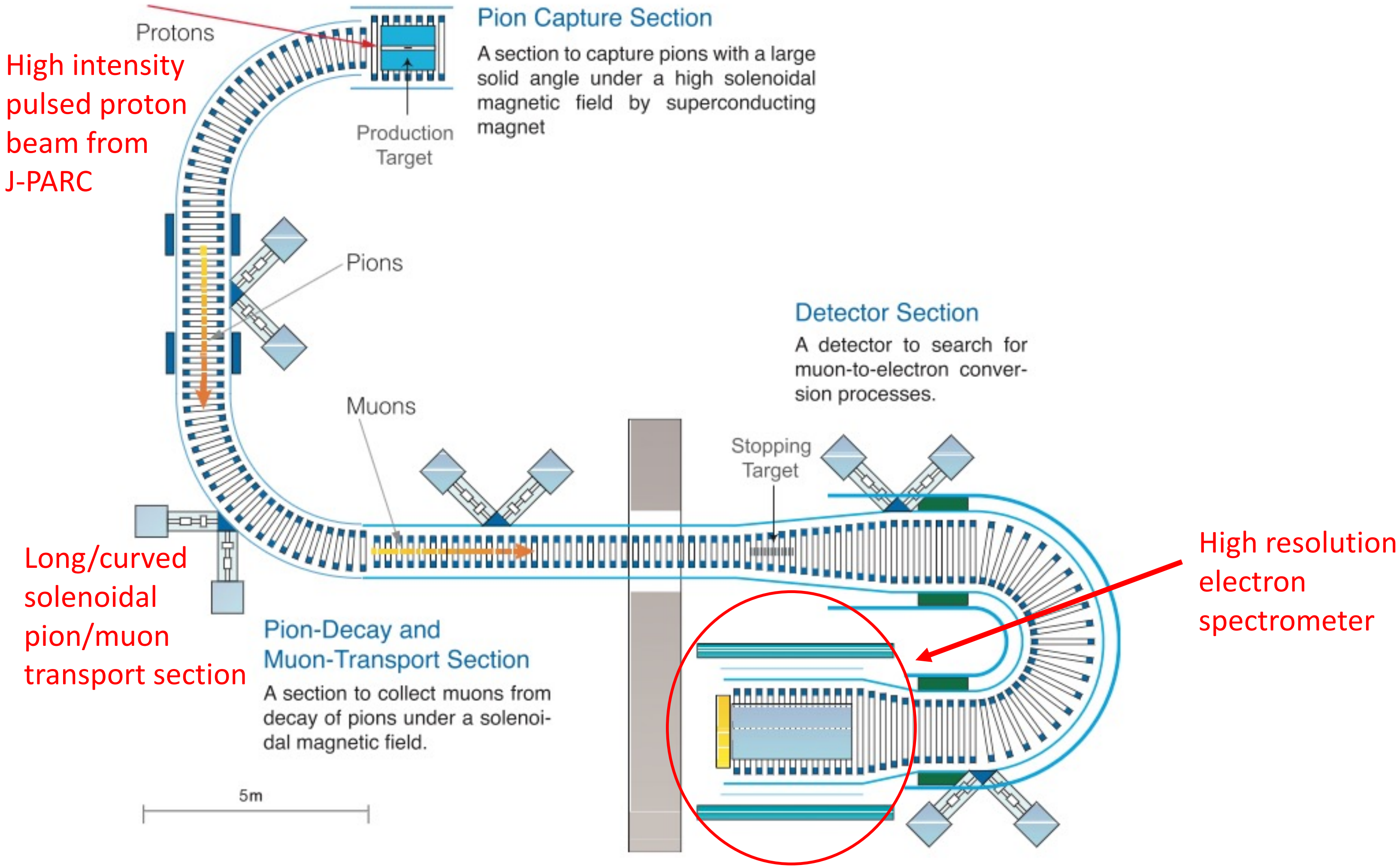
- Construction is expected to finish in 2023.
- Physics data-taking from 2024.

- Aiming to improve the current limit on conversion rate by 10^4 @ $R_{\mu e} = 3 \times 10^{-17}$.



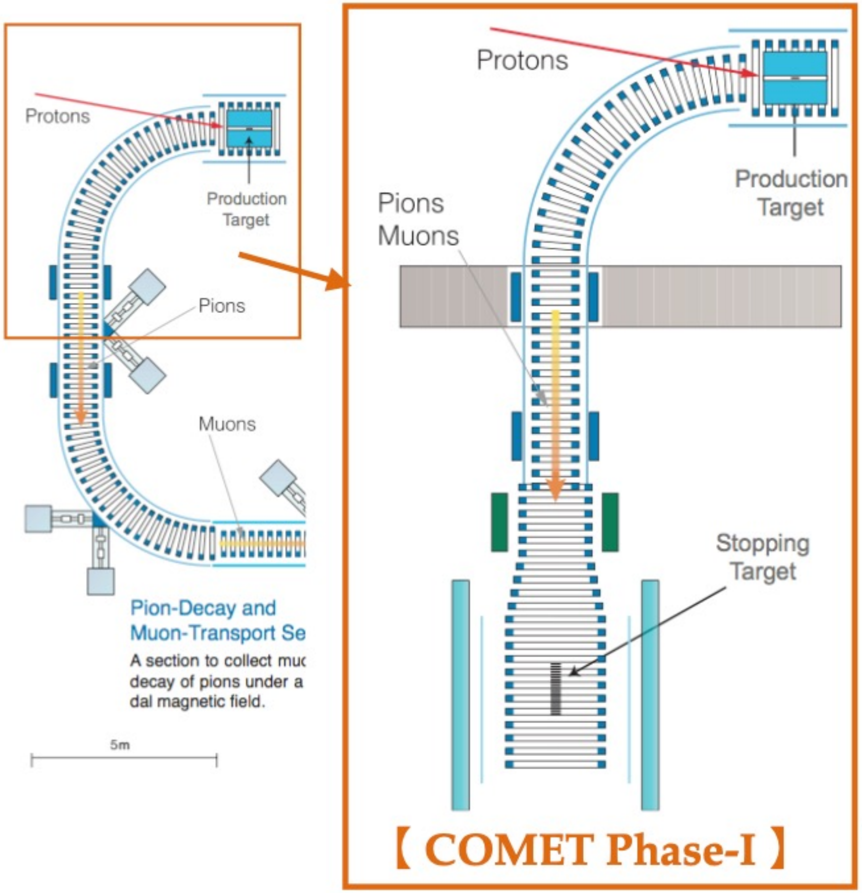


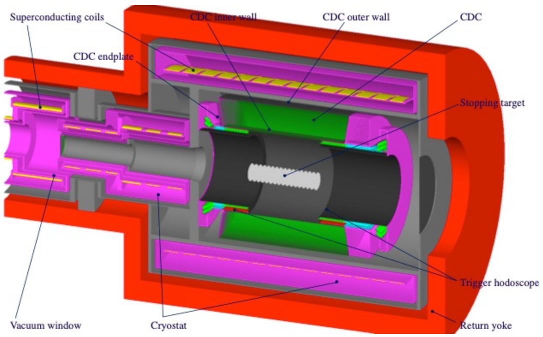
COMET experiment



COMET experiment (phase-I)

A staged approach is adopted.

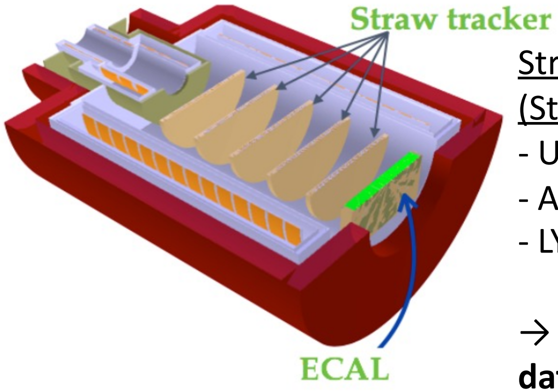




Cylindrical Detector System (CyDet) for physics search
- wire chamber with stereo configuration
- gas He:iC_4H_{10}=90:10
- with trigger hodoscope

→

μ-e conversion study with O(10^{-15}) sensitivity



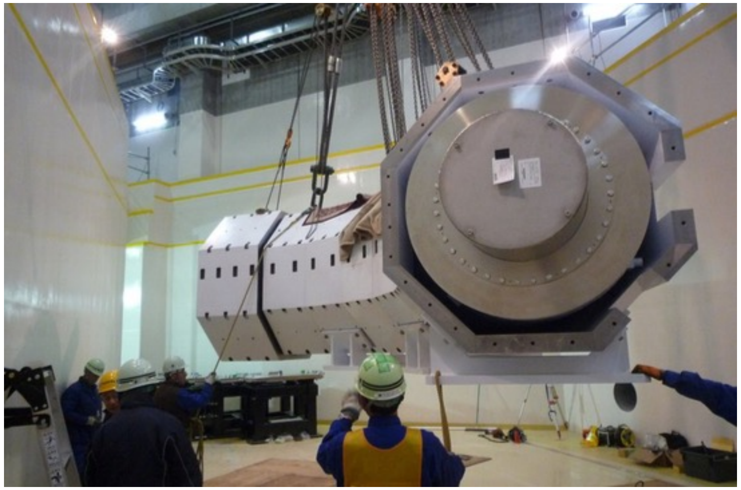
Straw tracker and ECAL (StrECAL) for beam study
- Ultra thin straw tube chamber
- Ar:C_2H_6=50:50
- LYSO crystal for ECAL

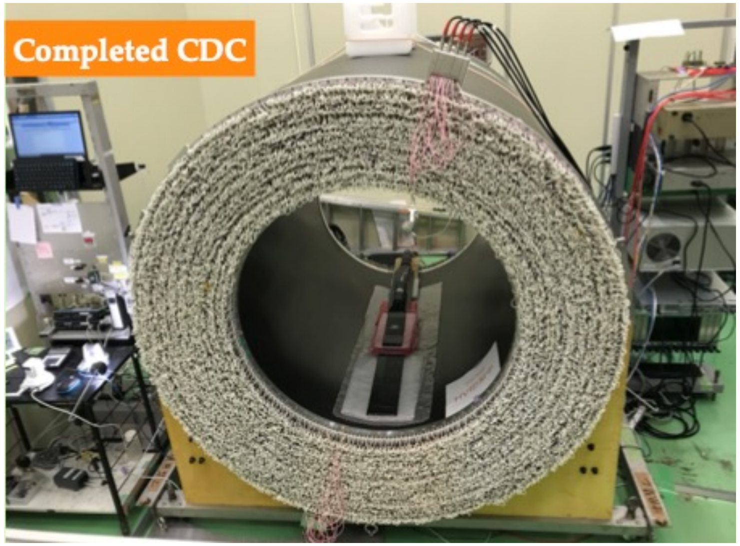
→

data-driven estimate of BG
Prototype of phase-II detector

Status of COMET experiment

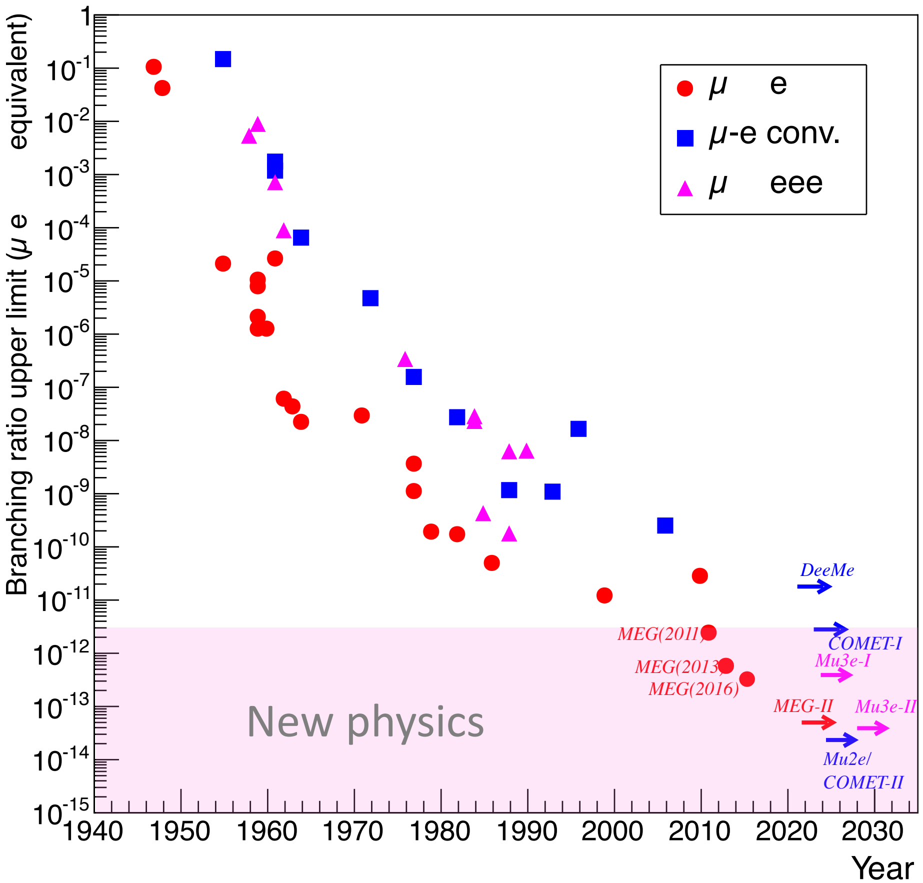
- Beam line under construction.
  - expected to be ready in 2023.
- Detector for phase-I:
  - CyDet:
    under commissioning. σ_x ~165μm confirmed.
  - StrECAL:
    under construction. Completed in 2022.
- Beam commissioning will be followed by the engineering and physics run of Phase-I.
- The sensitivity will be
  - 7×10^{-15} (90% C.L.) for phase-I
  - $O(10^{-17})$ for phase-II





Summary

- CLFV is an interesting probe for the new physics.
- Several experiments which searches for μLFV are in preparation or under commissioning.
- They aims to start physics data-taking in the next a few years.



μ→eγ equivalent BR calculted by
Br(μN→eN)/Br(μ→eγ) $=2.6\times10^{-3}$
Br(μ→3e) /Br(μ→eγ) $=6\times10^{-3}$

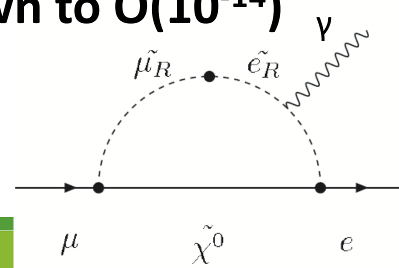
Thank you for your Attention!

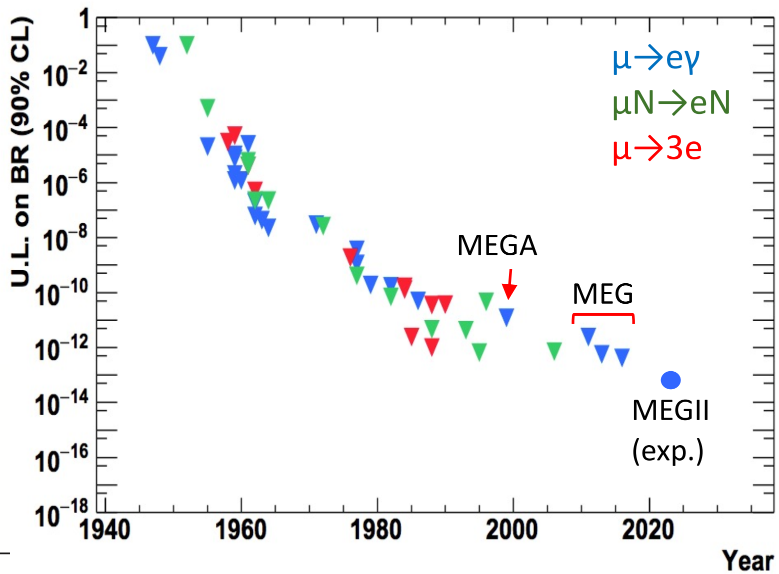
backup

Charged lepton flavor violation

- Standard Model.
  - Flavor violation can happen in quark & neutrino sector.
  - Charged Lepton Flavor Violation (CLFV) prohibited.
- Beyond Standard Model.
  - CLFV is predicted at a detectable branching ratio in some BSM models (SUSY-GUT, SUSY-Seesaw, etc...)
- Experimental search of μ→eγ
  - Expected to be Br(μ→eγ) = 10^{-12} – 10^{-14} in BSM.
  - Best limit before MEG: 1.2 x 10^{-11} @90%C.L. give by MEGA (1999)

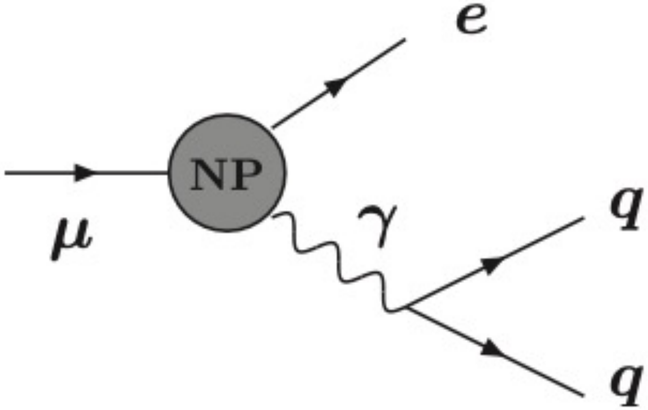
MEG searches for μ→eγ down to O(10^{-14})



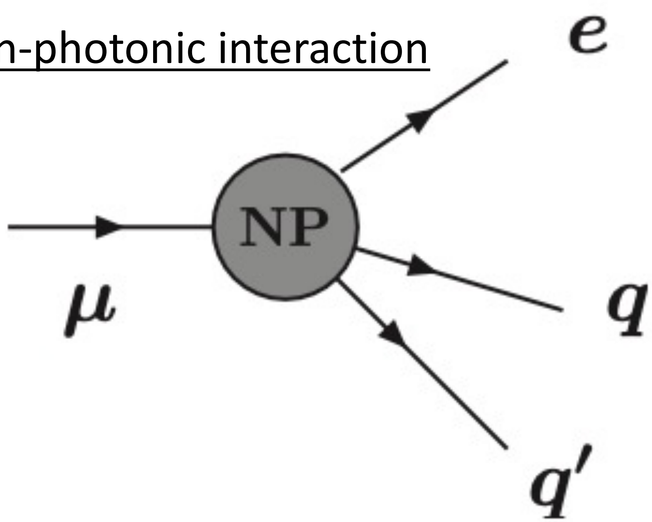


CLFV

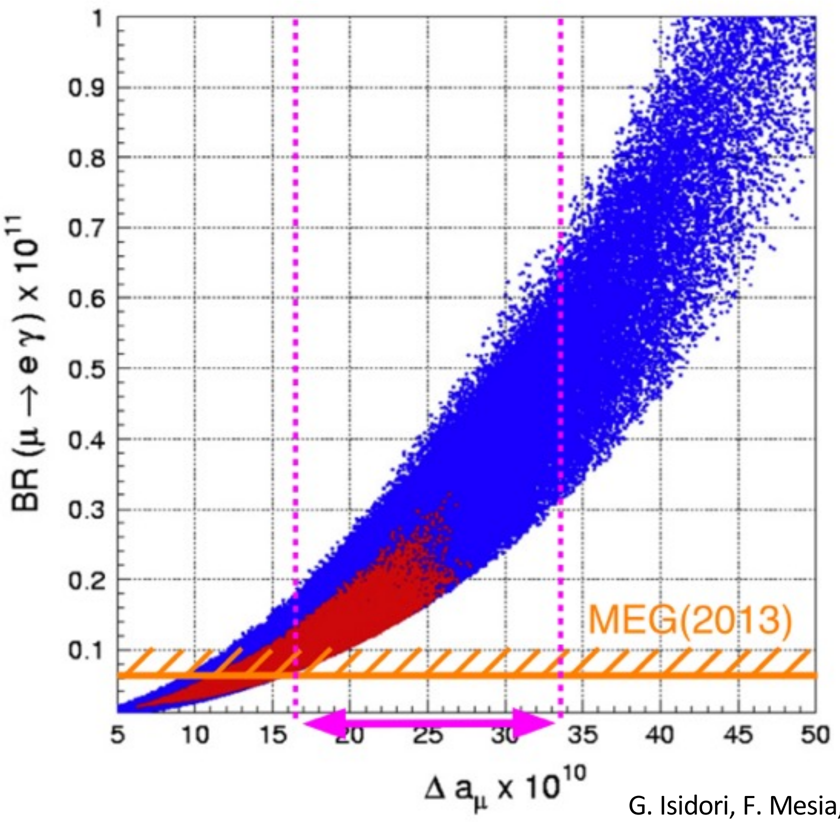
photonic interaction



non-photonic interaction

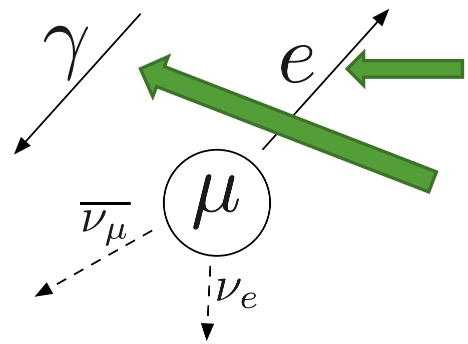


Correlation with g-2.



G. Isidori, F. Mesia, P. Paradisi,
D. Temes, Phys. Rev. D 75 (2007) 115019.

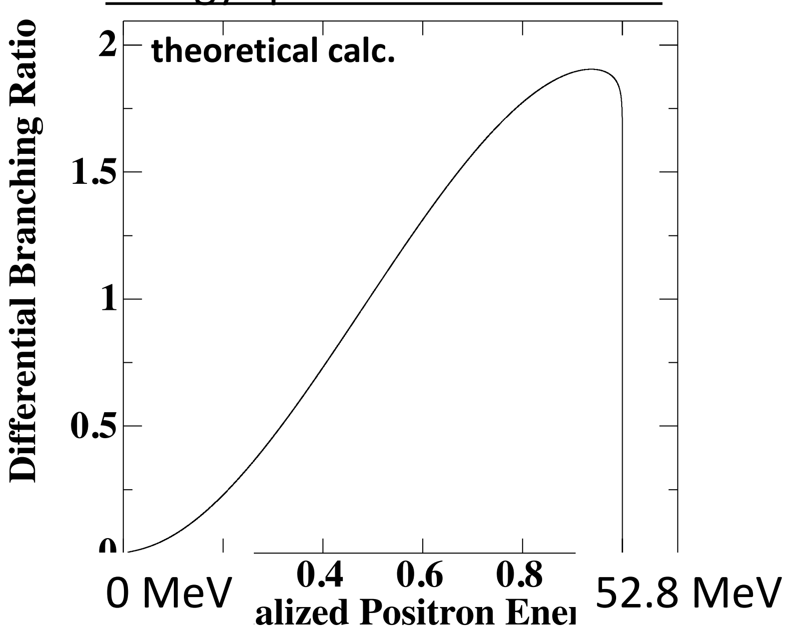
Source of accidental background in μ→eγ



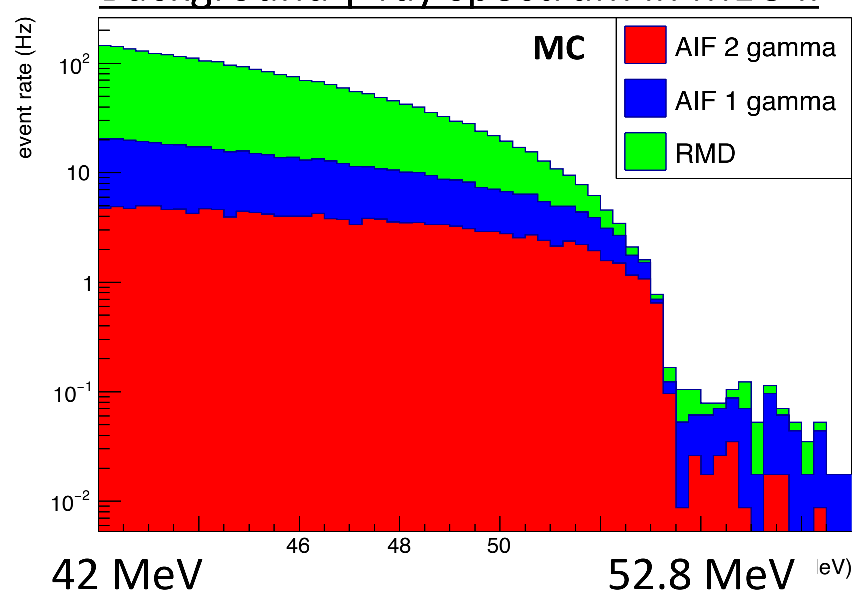
positron from Michel decay ($\mu \rightarrow e\nu\bar{\nu}$)

γ-ray from
radiative muon decay (RMD, $\mu \rightarrow e\nu\bar{\nu}\gamma$),
and
annihilation of Michel positron in flight

Energy spectrum of Michel e



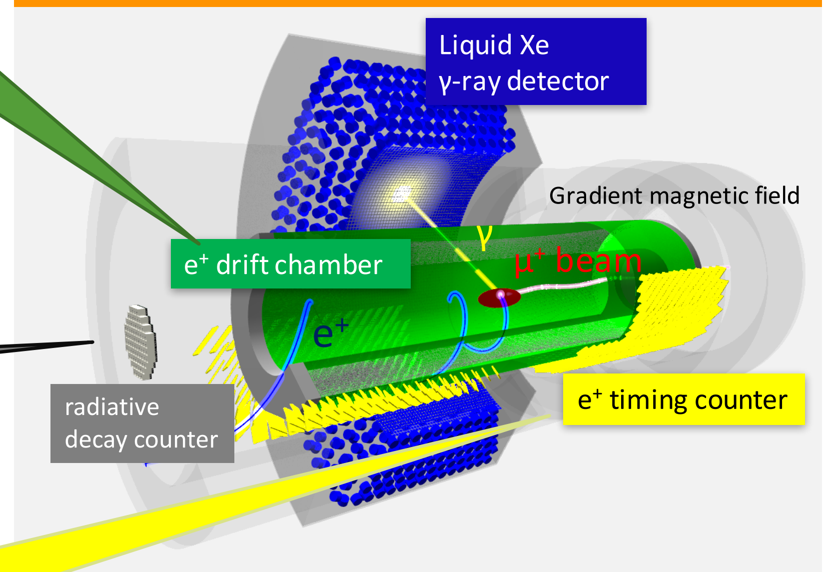
Background γ-ray spectrum in MEG II



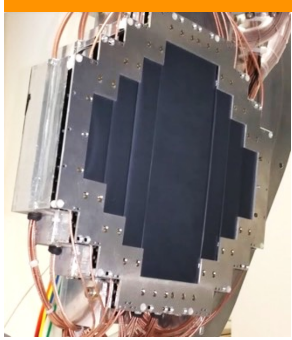
MEG II status

Drift chamber

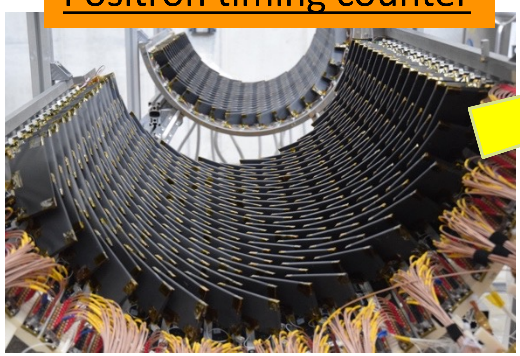
MEG II detectors



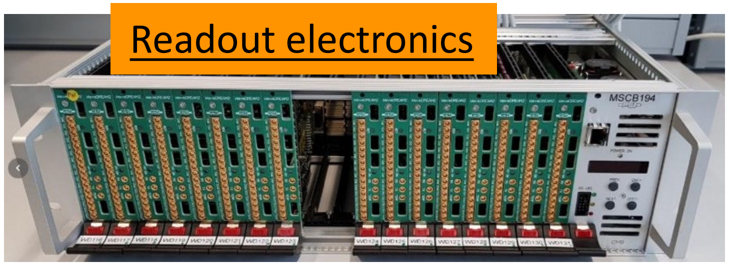
Radiative decay counter



Positron timing counter



Readout electronics

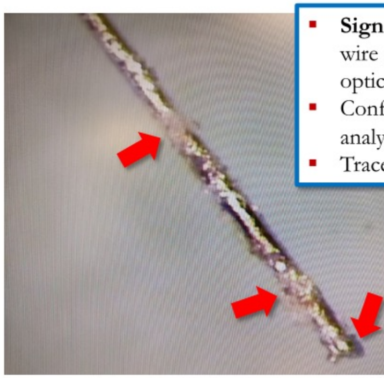


MEG II experiment: under commissioning.

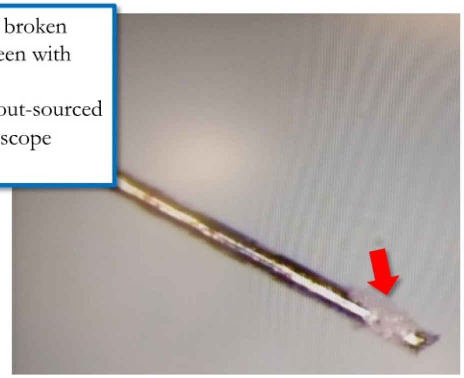
In 2021:
Engineering run from this summer.
followed by the physics run.

MEG II CDCH

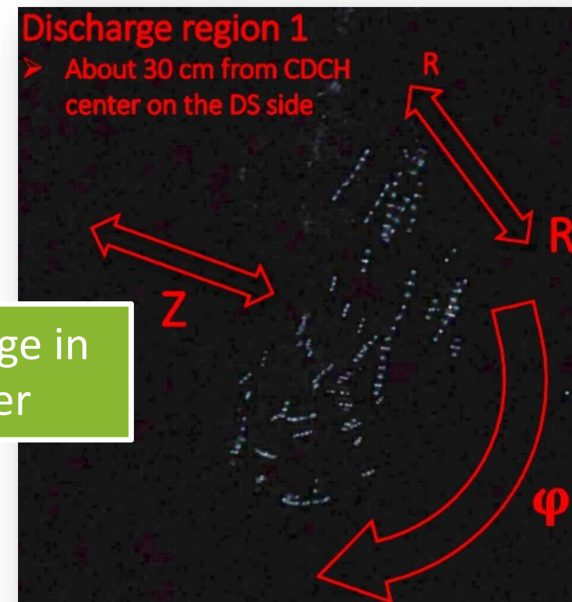
Broken wires



- **Sign of corrosion** on each broken wire at the breaking point seen with optical microscope
- Confirmed by internal and out-sourced analysis with electron microscope
- Traces of Cl seen



- The chamber has been extra-stretched by 0.4 mm to induce the breaking of weak cathodes (6.0 mm, 75% of the elastic limit)
- Then it will be shortened again to the final length (5.6 mm , 70% of the elastic limit)
- In total 56 cathode wires have been removed:
  - 53 40 um inter-layer cathodes and
  - 3 50 um inter-anode cathodes



Corona discharge in drift chamber

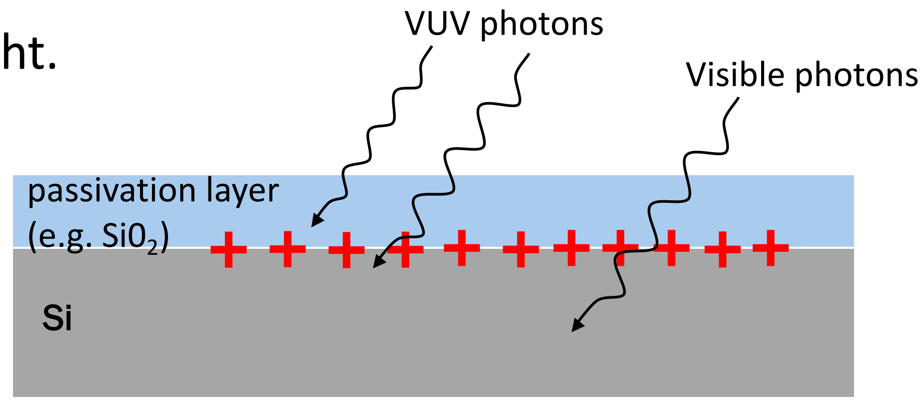
Cause of PDE degradation

Observed degradation may be related to a special detection mechanism of VUV photon in our MPPC.

- Visible photon directly reaches the sensitive region.
- Attenuation length of VUV light in silicon is only 5 nm, and VUV photons cannot directly reach the sensitive region.
  → Convert in shallow region, and drift to the sensitive region.

One hypothesis: Surface damage by VUV irradiation.

VUV irradiation
→ Accumulation of stationary charges near the sensor surface
→ Distortion of the electric field
→ Degradation of PDE only for VUV light.



Recovery of damage by annealing

Annealing is known to be useful for radiation damage of MPPCs.

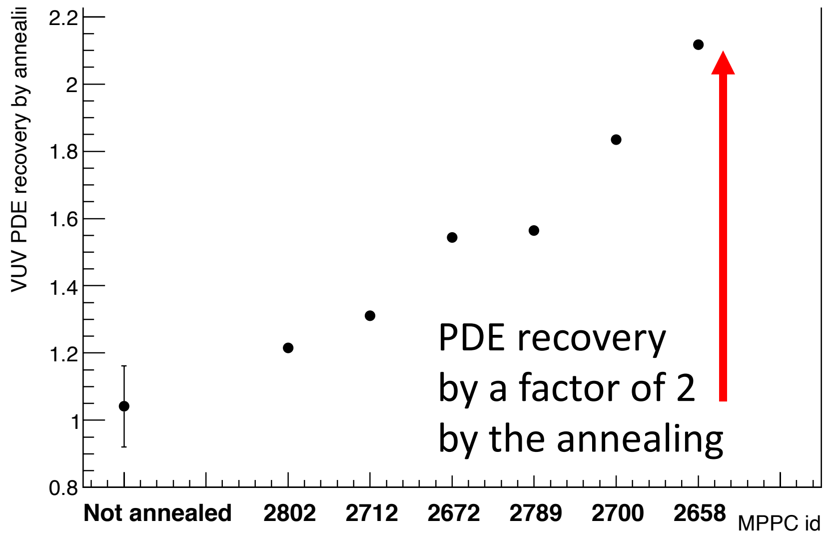
- By keeping MPPC at higher temperature, accumulated charges can be de-trapped by thermal excitation.

→ Tested also for our MPPC.
(for small number of MPPCs in the detector)

Recovery of the damage by the annealing is confirmed.

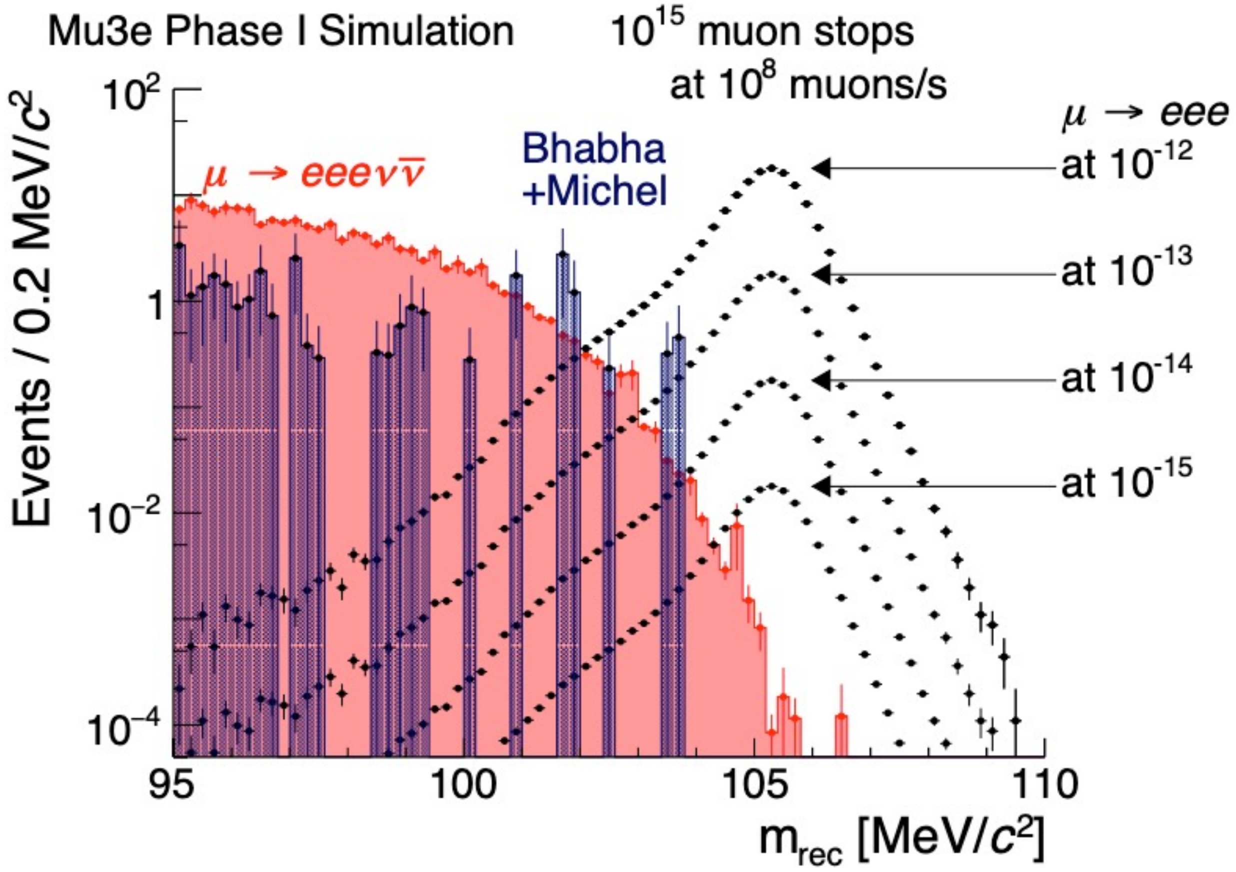
- MPPCs are heated to ~ 70℃ by a Joule heat for 1-2 days.

PDF(after annealing) / PDE(before annealing) vs. annealing strength (duration & temperature)



Mu3e background

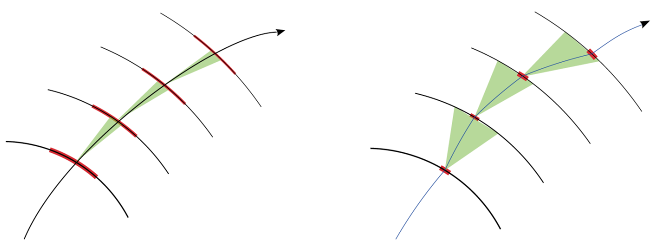
a



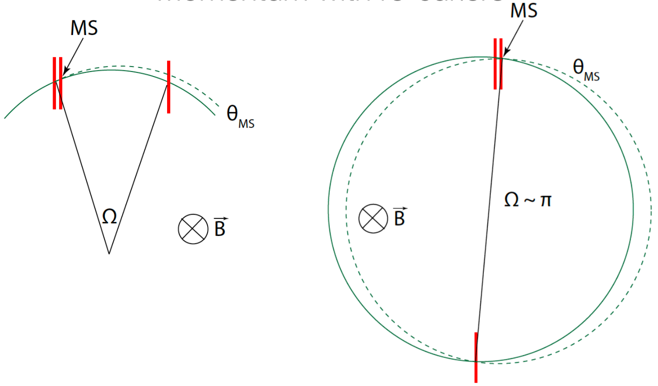
The pixel tracker: The principle

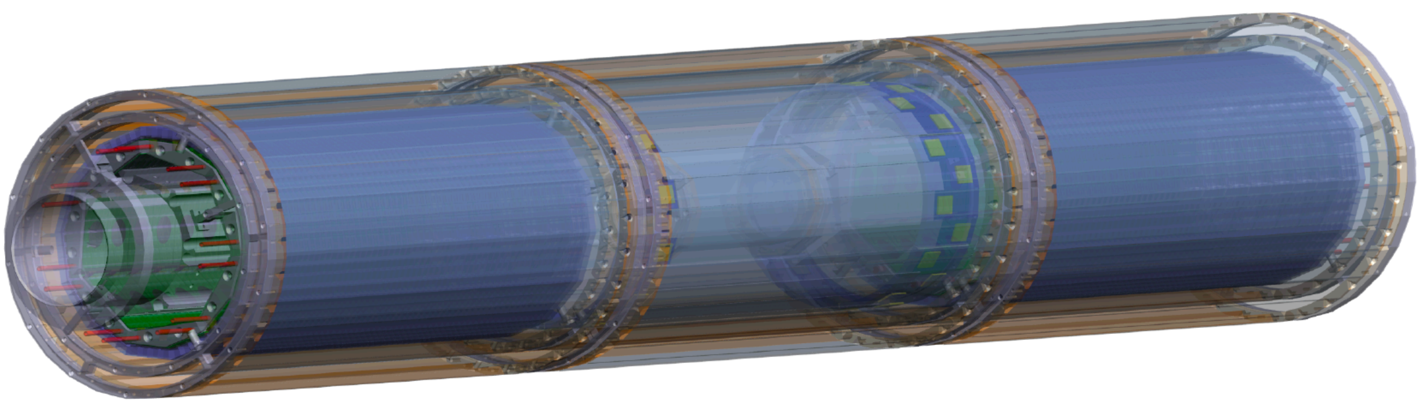
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime

Tracking in the spacial and scattering dominated regime



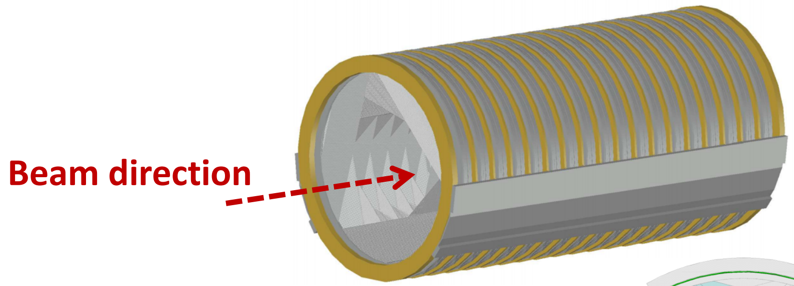
Momentum with re-curlers





Tracker Requirements

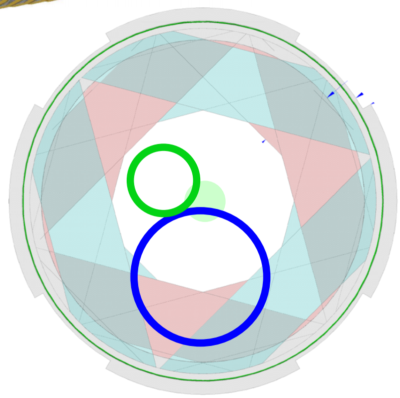
- Electron momentum resolution: < 180 keV/c at 105 MeV/c
- Efficiency for acceptance and reconstruction of 105 MeV/c electron tracks: >20%
- Outgassing rate :< 6 sccm (standard cubic cm per minute)
- Hit rate: > 5MHz/channel, 500 ns after proton bunch hits production target
- Access : < once per year
- Operation time: > 10 yrs



Solution

Straw drift tubes measure track curvature through a 1 T magnetic field.

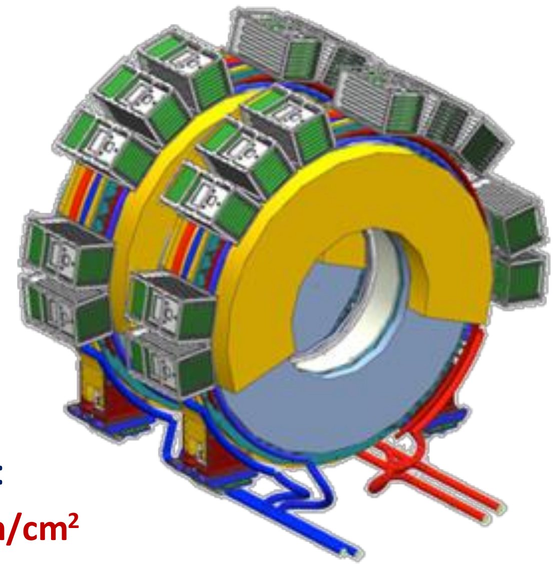
- High segmentation to minimize occupancy
- Very thin wall to minimize multiple scattering
- No support structure in tracking region
- High radiation survival (structure & electronics)



Beam's-eye view of Tracker

Technical Specifications

- Fast signal for Pileup and Timing:
  - **τ of emission < 40 ns**
  - Fast Digitization (WD) to disentangle signals in pileup
- Crystals with high Light Yield for timing/energy:
  - resolution → **LY(photosensors) > 20 pe/MeV**
- 2 photo-sensors/preamps/crystal for redundancy:
  - reduce MTTF requirement → **1 million hours/SIPM**
- Radiation Hardness (5 years of running with a safety factor 3):
  - Crystals should survive a TID of **90 krad** and a fluence of **$3x10^{12}$ n/cm^2**
  - Photo-sensors should survive **45 krad** and a fluence of **$1.2x10^{12}$ n_1MeV/cm^2**
- The 1 T magnetic field + the very small available space suggests the use of SiPMs

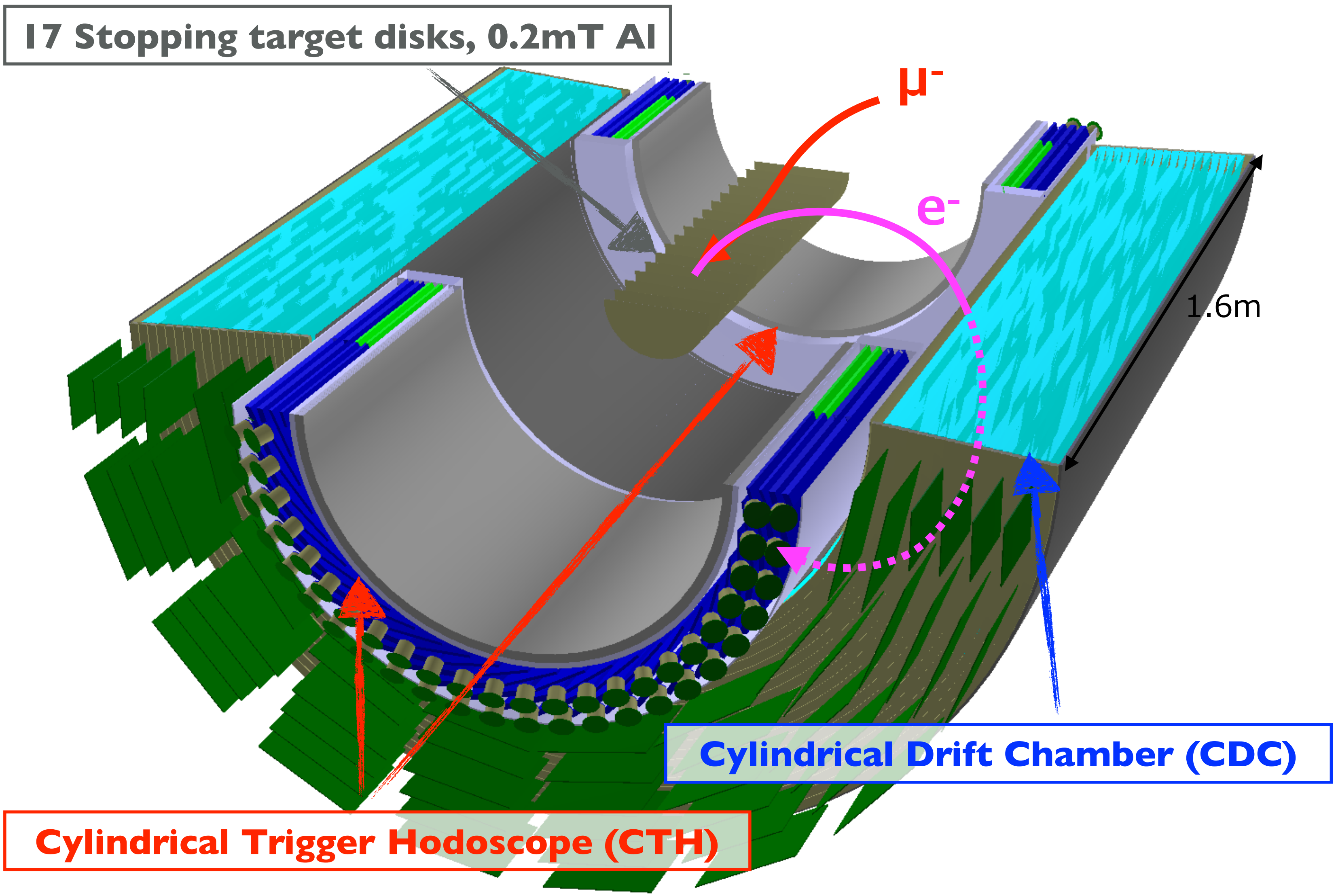


Viable solution

Undoped CsI + UV-extended SiPMs

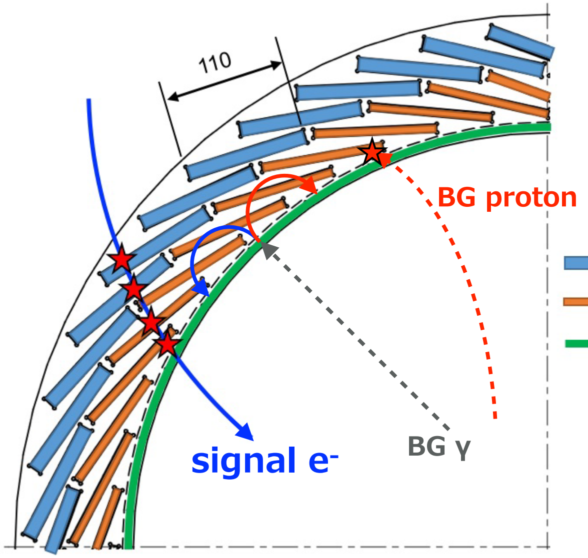
Undoped CsI	UV-extended SiPMs
→ It is radiation hard	→ 30 % PDE @ 310 nm
→ It has a fast emission time	→ New silicon resin window
→ Emits at 310 nm	→ TSV readout, Gain = 10^6

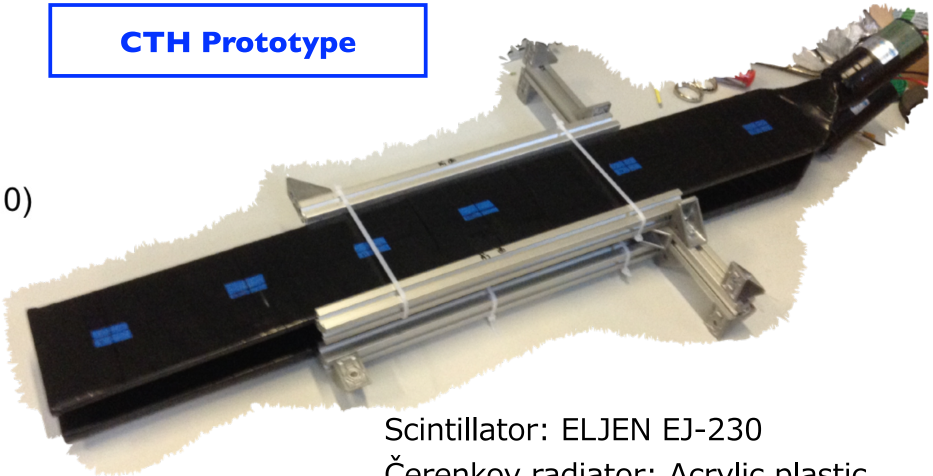
CyDet



17 Stopping target disks, 0.2mT Al
μ-
e-
1.6m
Cylindrical Drift Chamber (CDC)
Cylindrical Trigger Hodoscope (CTH)

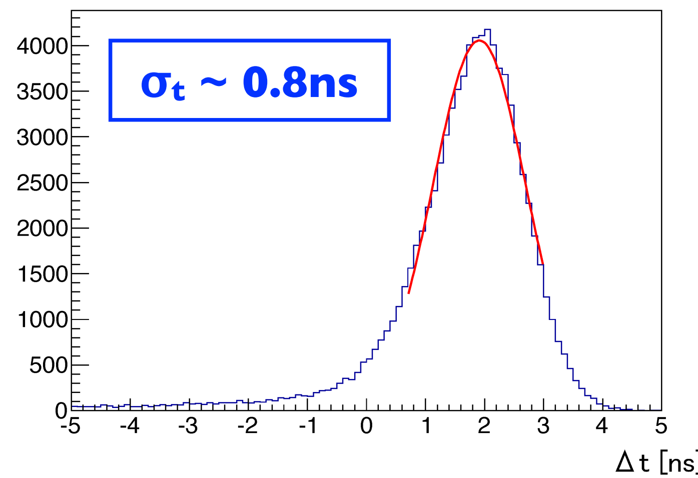
CTH





Scintillator: ELJEN EJ-230
Čerenkov radiator: Acrylic plastic
PMT: Hamamatsu H8403-70

- Determine the primary trigger and precise T0 value within the 1ns precision
- 64 or 48 plastic scintillators/acrylic Čerenkov radiators cylindrically aligned both upstream/downstream
- A Čerenkov layer reject all low-β particles (<0.65)
- Use the magnetic field tolerable fine-mesh PMTs
- 4-fold coincidence strongly suppresses the accidental pileups
- Final detector design is almost fixed



DeeMe experiment