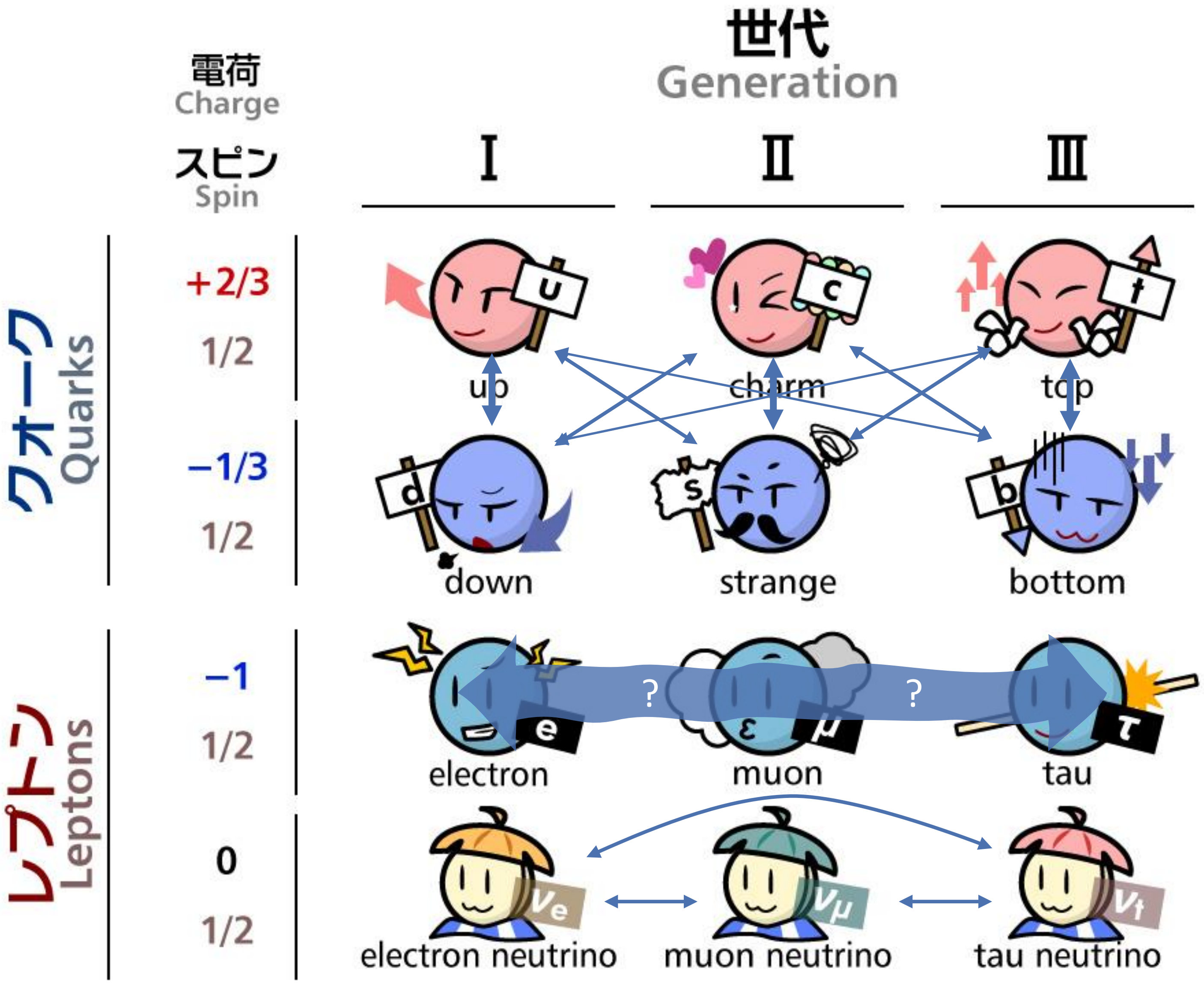
Detector technologies in searches for charged lepton flavour violation at PSI

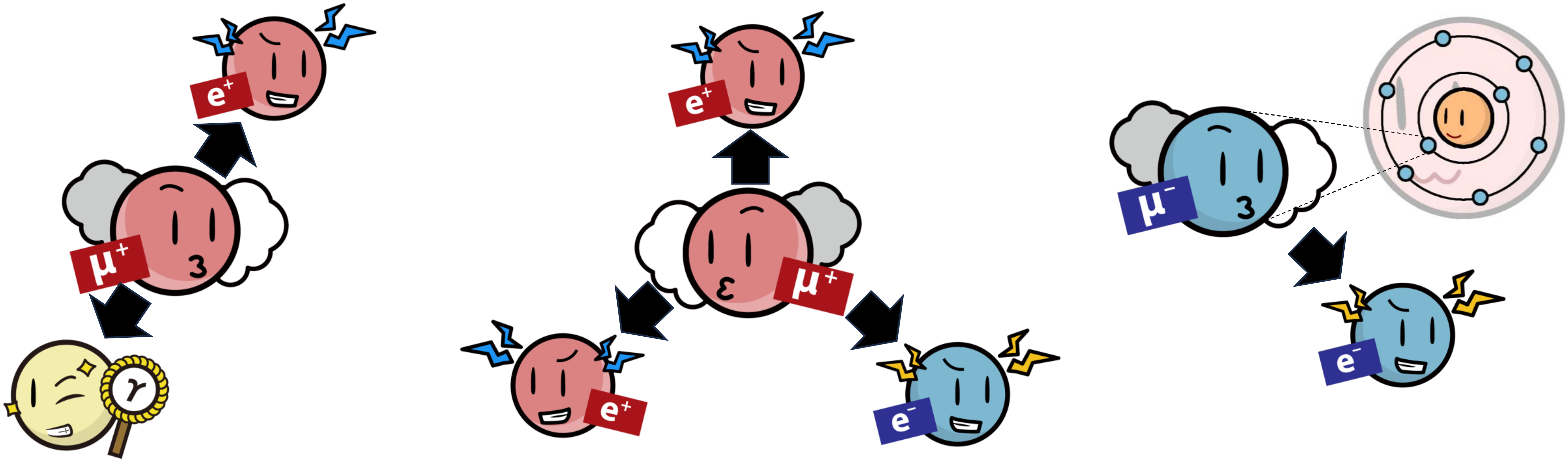
Lukas Gerritzen

BRIDGE Workshop 2023



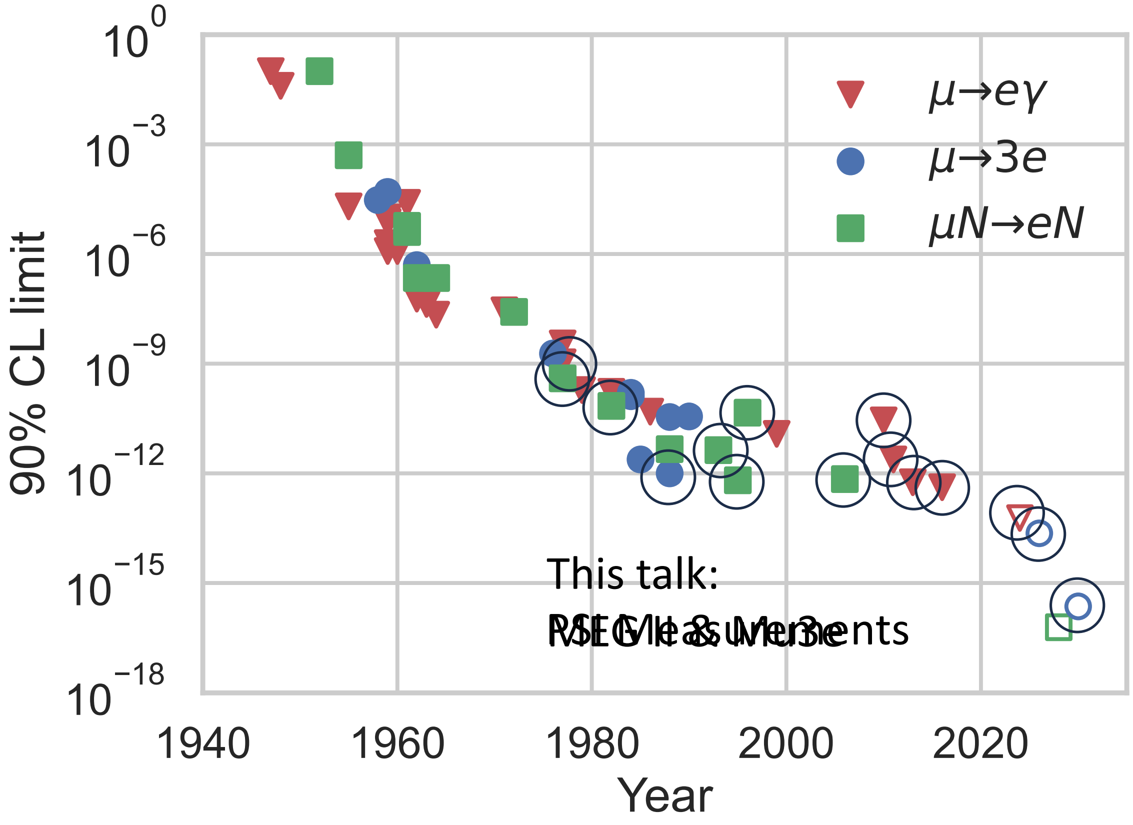
世代
Generation
電荷
Charge
スピン
Spin
I
II
III
クオーク
Quarks
+2/3
1/2
−1/3
1/2
up
charm
top
down
strange
bottom
レプトン
Leptons
−1
1/2
0
1/2
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino
?
?

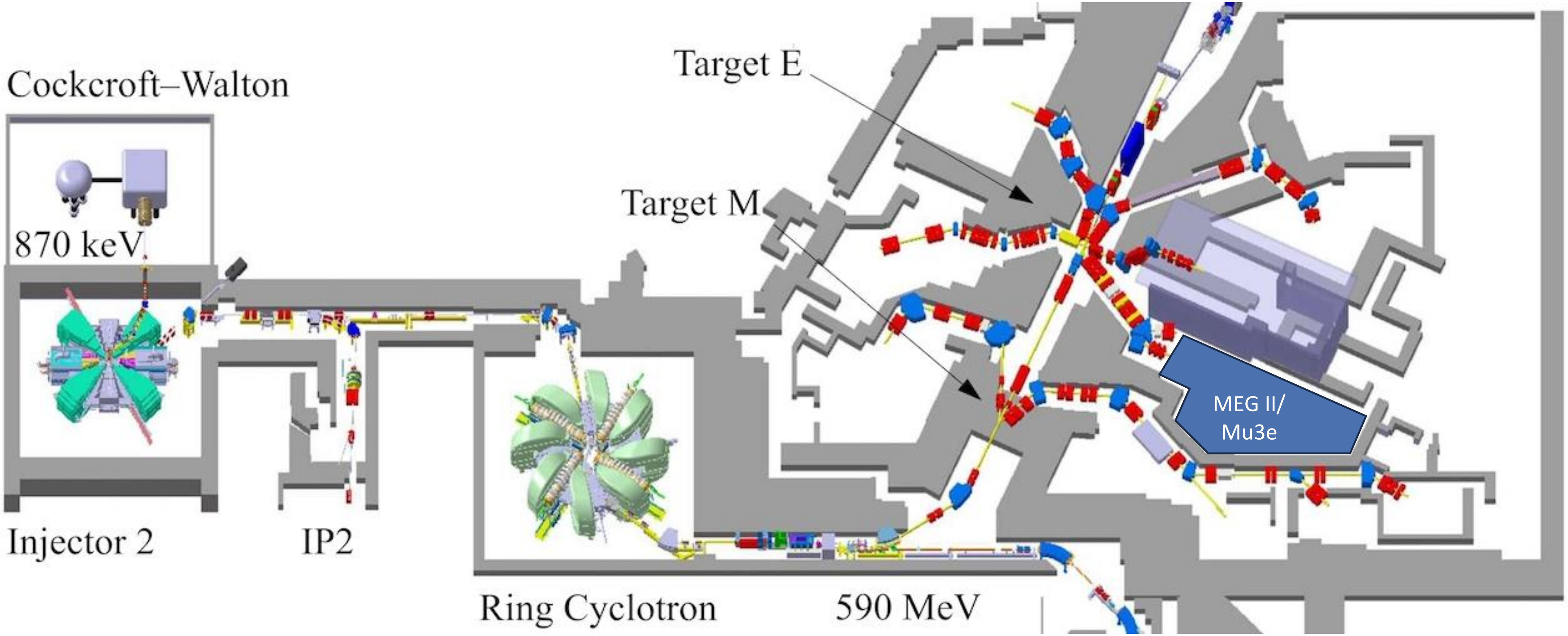
Muons: Three “Golden Channels”



Adapted from HiggsTan

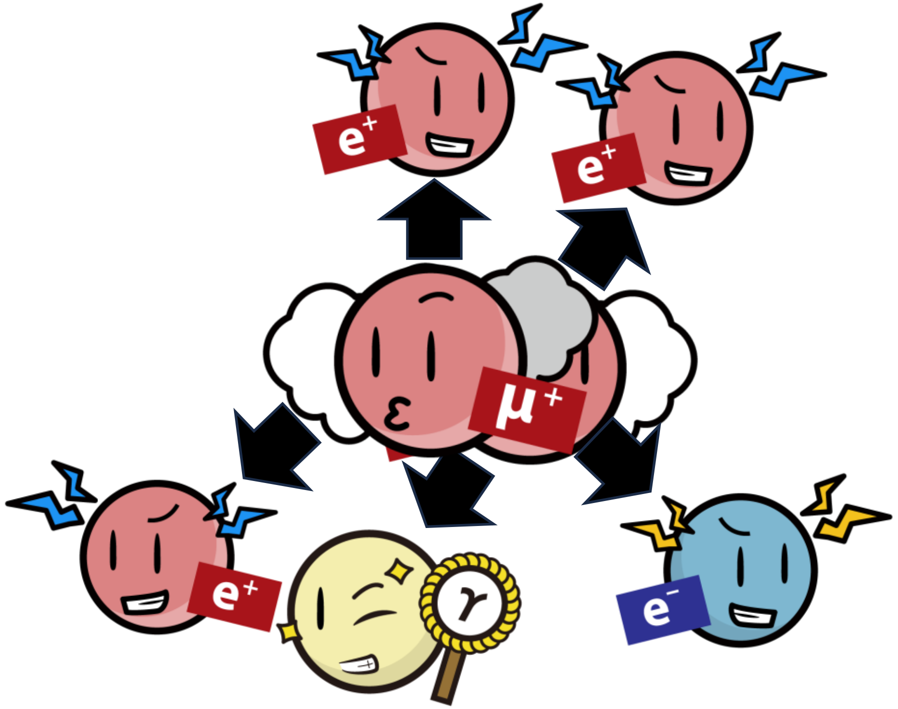
Searches for cLFV in Muons*




Cockcroft–Walton
870 keV
Target E
Target M
MEG II/
Mu3e
Injector 2
IP2
Ring Cyclotron
590 MeV

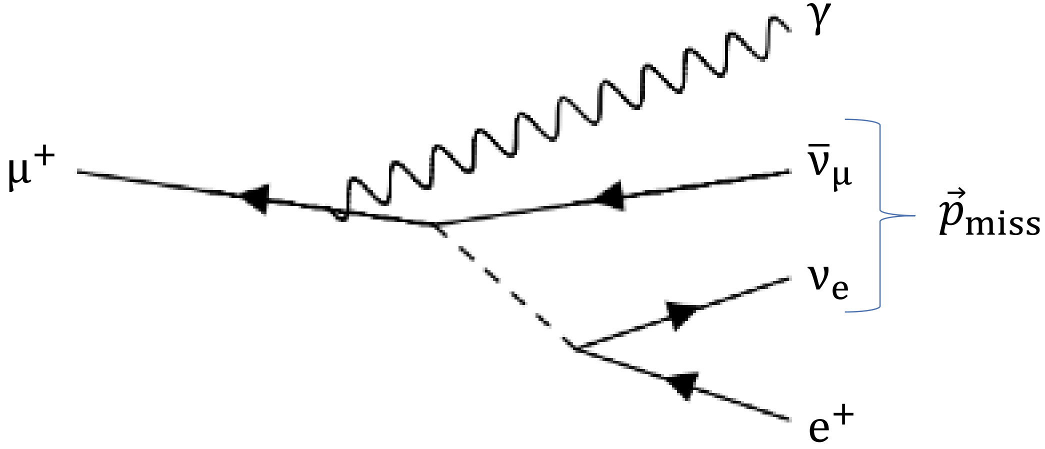
Signals

- Muon decays at rest
- Positrons (electrons) $p \leq \frac{m_\mu}{2} \approx 53\ \mathrm{MeV}$
- (Photons, $E = \frac{m_\mu}{2}$)
- $\sum E = m_\mu c^2$
- $\sum \vec{p} = 0$
- $\Delta t = 0$
- Coplanar (Mu3e) or back-to-back (MEG II)



Irreducible backgrounds

- $\mu^+ \to e^+\bar{\nu}\nu\gamma(\gamma \to e^+e^-)$
- $E < m_\mu c^2$
- $\sum\vec{p} \neq 0$
- $\Delta t = 0$
- Not coplanar/back-to-back
- Same vertex



⇒ Need excellent energy and momentum resolution

Accidental backgrounds

- Particles from unrelated processes
- $E \neq m_{\mu}c^2$
- $\sum\vec{p} \neq 0$, therefore Not coplanar/back-to-back
- $\Delta t \neq 0$
- No common vertex
- Rate dependent

$\Rightarrow$ Time and vertex resolution

Spectrometer or calorimeter?

$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_p}{p}\right)^2_{\mathrm{MS}} + \left(\frac{\sigma_p}{p}\right)^2_{\mathrm{defl}}$$

const. ~p

In muon decays: dominated by multiple scattering
Downside for photon detectors: energy loss in converter

stochastic, calibration/ nonuniformity, noise

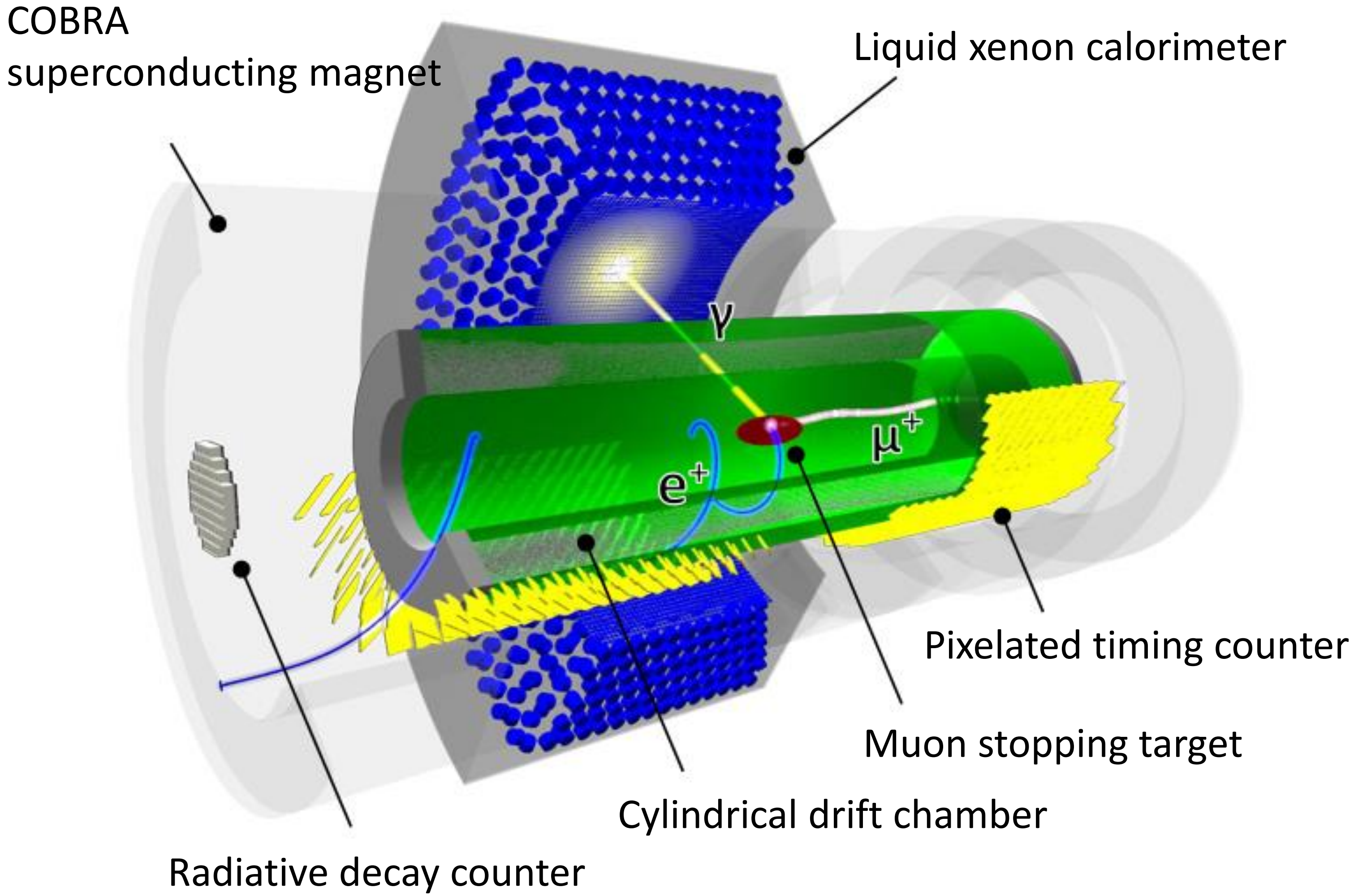
$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

Generally perform worse at μ decay energies

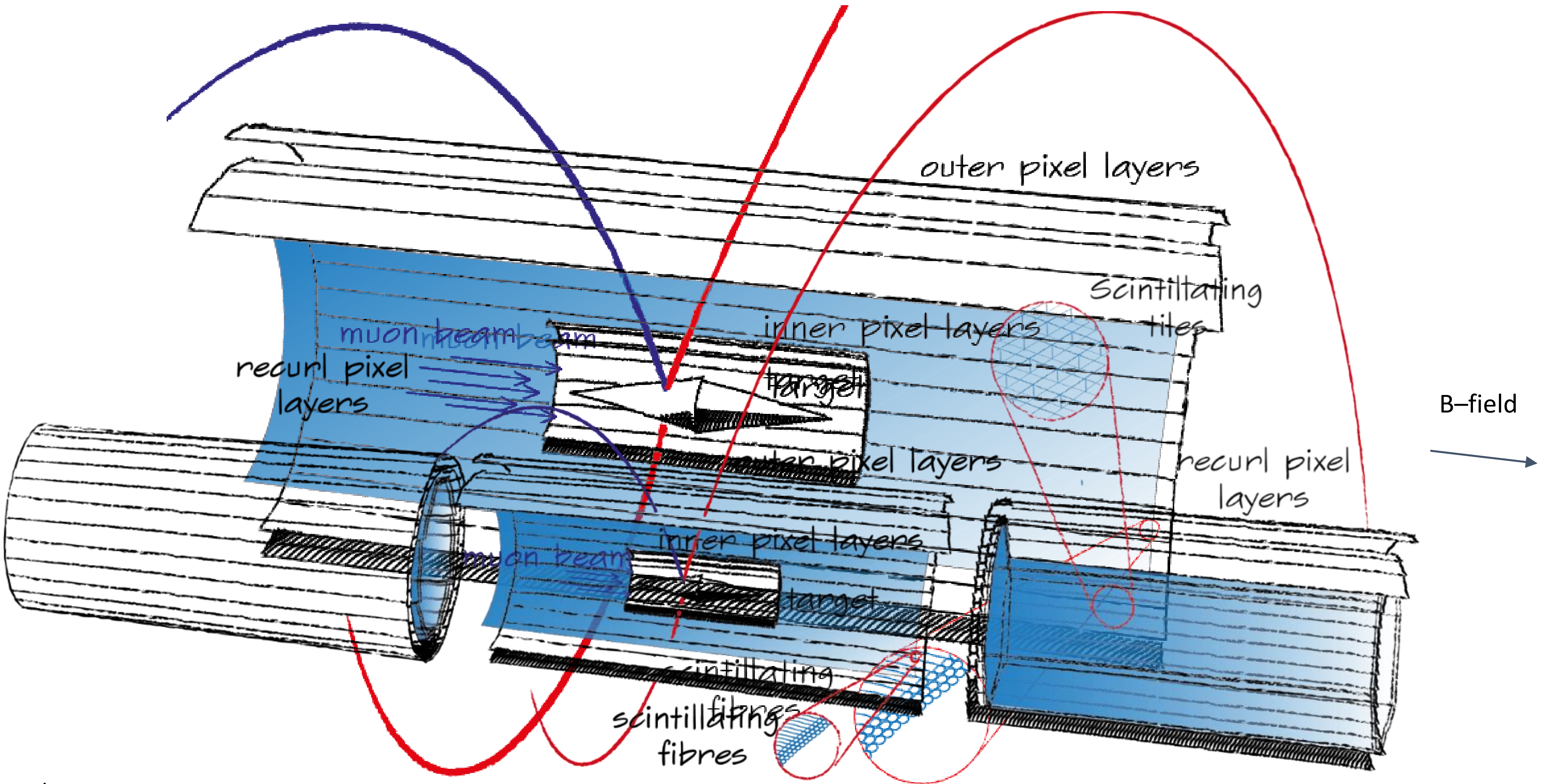
Generally not straight-forward, e.g. MEGA used photon pair spectrometer, also considered for future μ→eγ experiment, PIONEER will use positron calorimeter

The MEG II Experiment

- Search for $\mu^+ \to e^+\gamma$
- Kinematic variables: $(E_e, E_\gamma, \Delta t_{e\gamma}, \theta_{e\gamma})$
- $\mathcal{O}(10^8)$ μ^+ per second
- Detectors optimized for $E_{\gamma,\mathrm{e}} = \frac{m_\mu}{2} \approx 53$ MeV



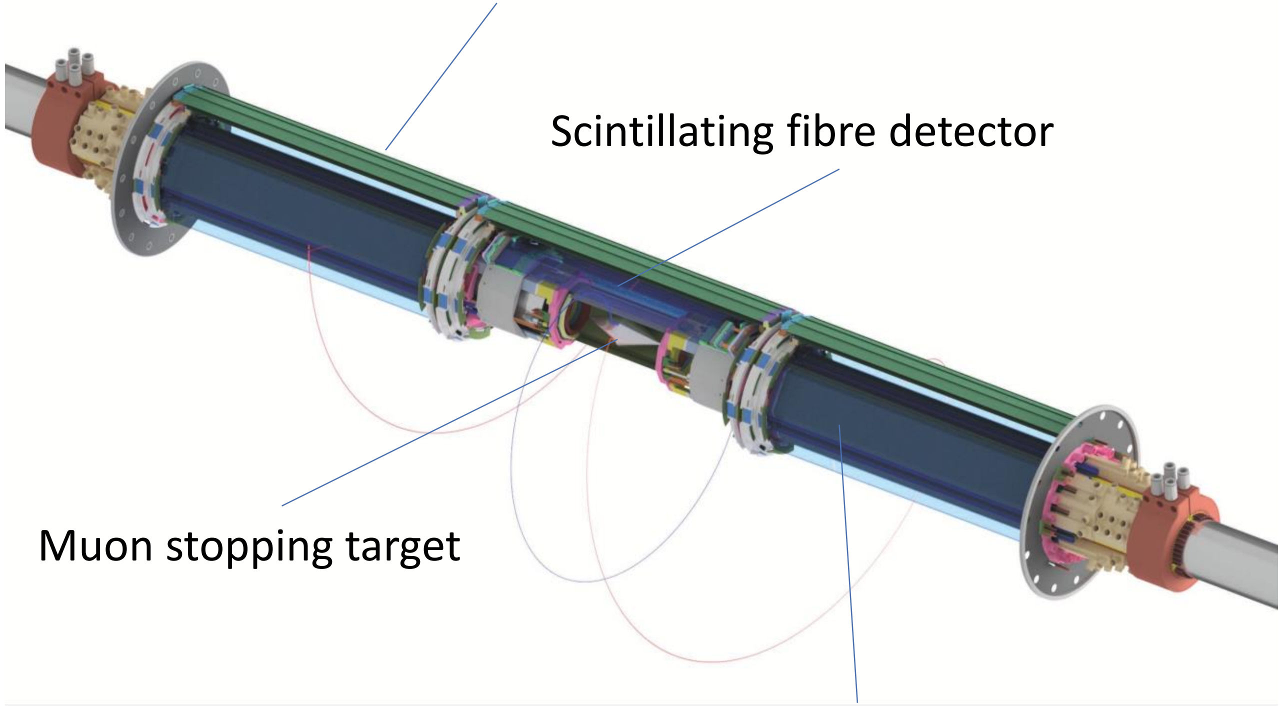
The Mu3e experiment



Illustrations: Mu3e collaboration

The Mu3e Experiment

- Search for $\mu^+ \rightarrow e^+e^+e^-$
- $\mathcal{O}(10^8)$ μ^+ per second
- Detectors optimized for $E_e < \frac{m_\mu}{2}$
- Aimed to be background free



LU

Give me a brief list of detector technologies of current and planned experiments searching for charged lepton flavour violation at PSI.

As of my last training data in January 2022, the Paul Scherrer Institut (PSI) has been involved in experiments searching for charged lepton flavor violation (cLFV). The primary experiments in this realm are the Mu3e and MEG II. Here's a brief list of the detector technologies for these experiments:

Mu3e (searching for the decay $\mu^+ \to e^+ e^- e^+$):

- **Silicon pixel detectors**: For precise vertex reconstruction and momentum measurement.
- **Scintillating fiber detectors**: Used for ~~triggering~~ and timing purposes.
- **Thin scintillator tiles**: For additional precise timing measurements.

MEG II (an upgrade of the MEG experiment, searching for $\mu^+ \to e^+ \gamma$):

- **Liquid xenon photon calorimeter**: To detect the high-energy photons from the decay.
- **Cylindrical drift chamber**: Used for tracking the charged particles.
- **Timing counters**: To measure the timing of the detected particles.

+ Radiative Decay Counter

HV-MAPS Spectrometer

Plastic scintillators

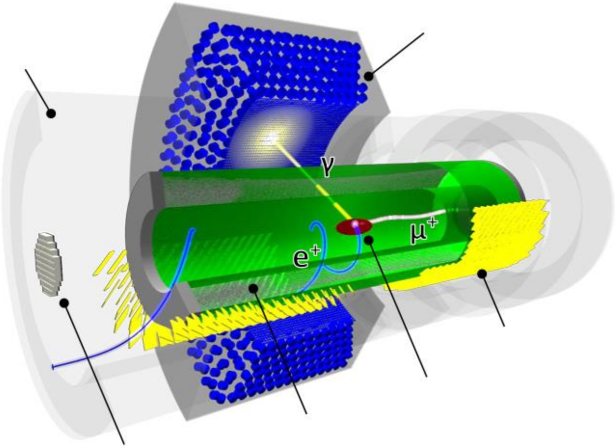
Liquid noble gas Calorimeter

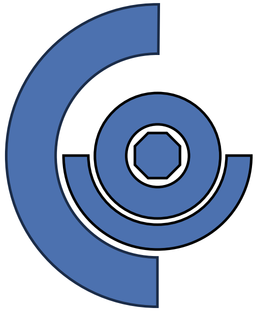
Gas detector Spectrometer

Cristal scintillators

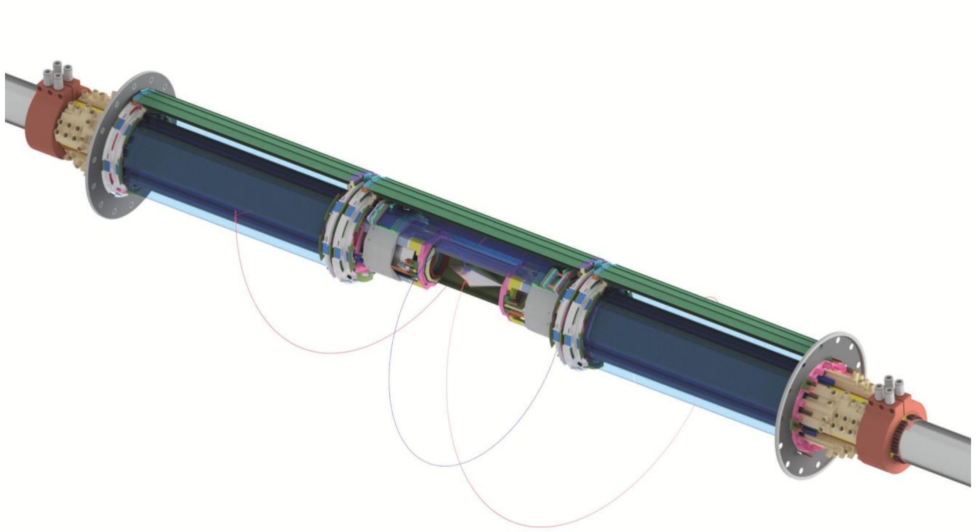
Orientation

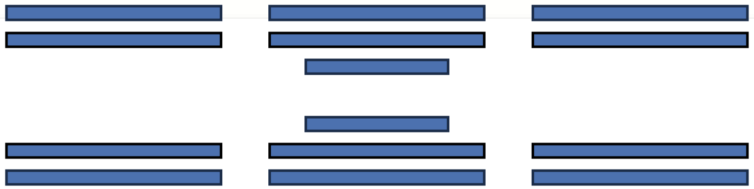
MEG II



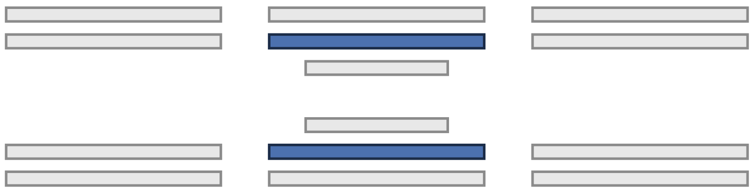


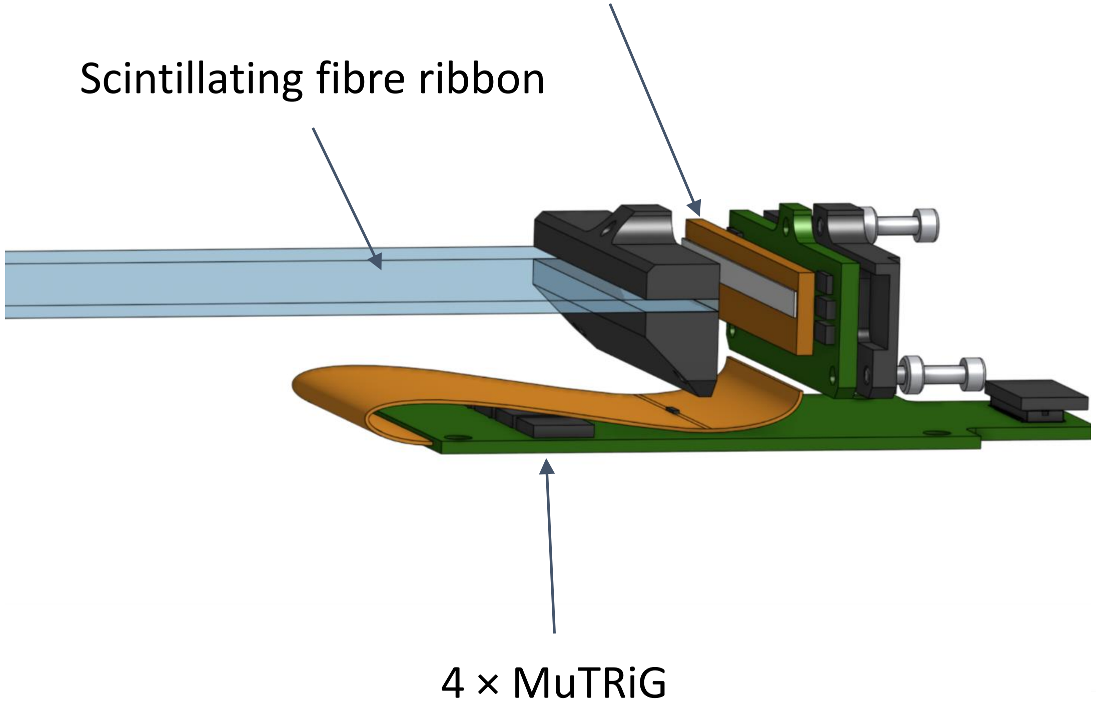
Mu3e



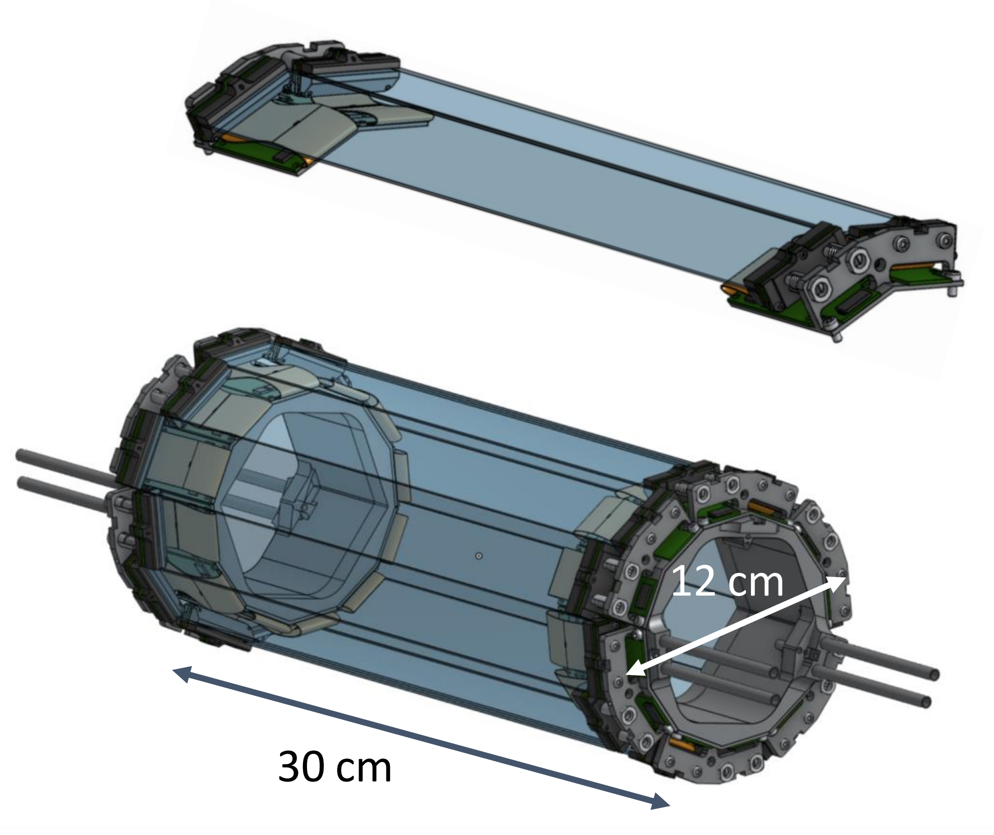


Scintillating Fibre Detector



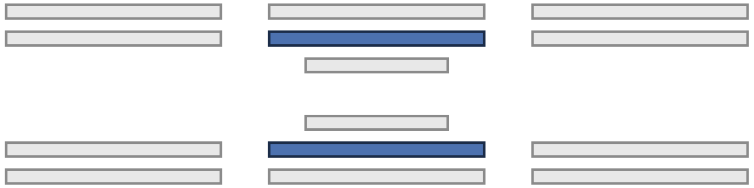


Silicon photomultiplier array

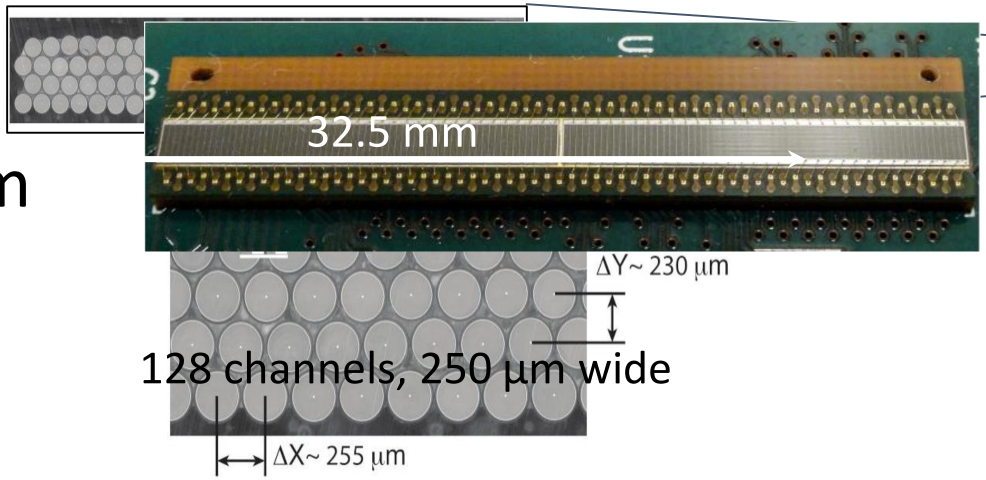


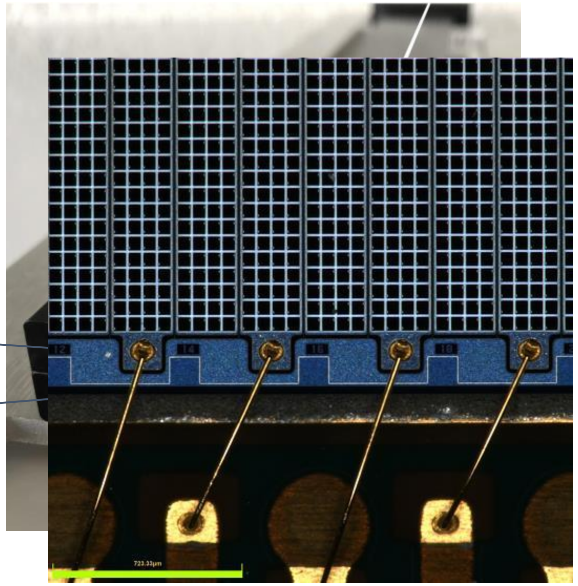
12 ribbons

Scintillating Fibre Detector



- Minimal multiple scattering ($X/X_0 < 0.2\ \%$)
- Hamamatsu S13552 SiPM array (128 channels)
- 3 layers of Kuraray SCSF-78MJ
- $\sigma_t \approx 250\ \mathrm{ps}$
- Readout with custom ASIC (MuTRiG)

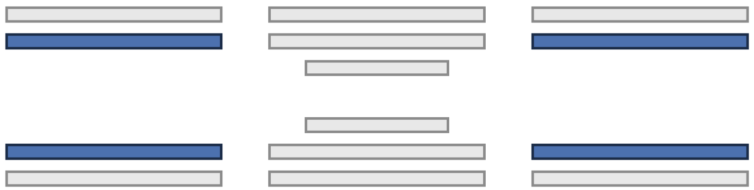




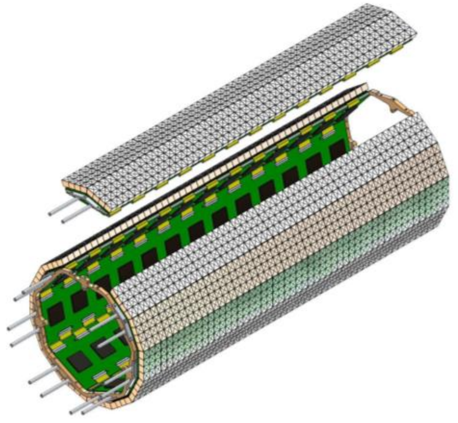
Per channel:
4 × 26 pixels of
(57.5 × 62.5) µm²

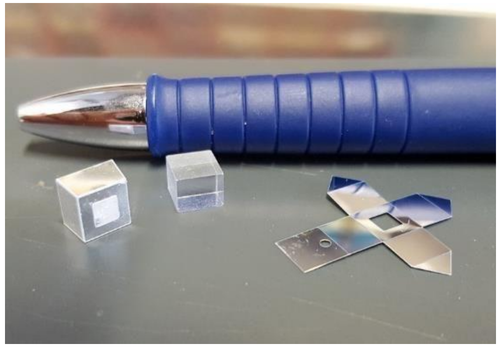
[arXiv:2208.09906v1]

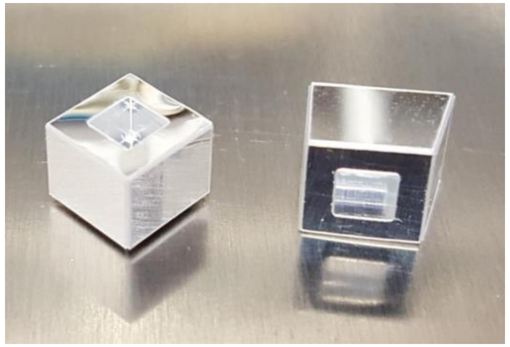
Scintillating Tile Detector

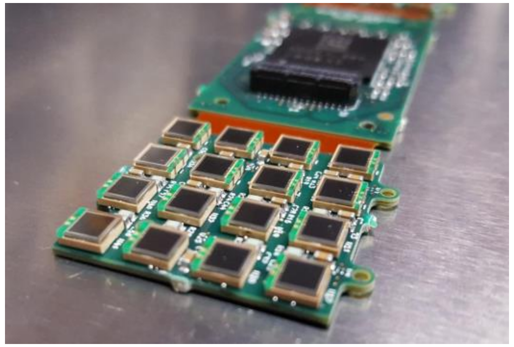


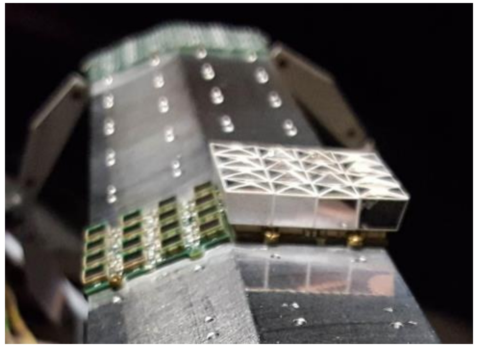
- 6272 ~(5mm)^3 tiles
- Eljen Technology EJ-228
- Hamamatsu S13360-3050VE
- $\sigma_t \approx 70$ ps (down to 45 ps in beam tests)
- Read out with MuTRiG







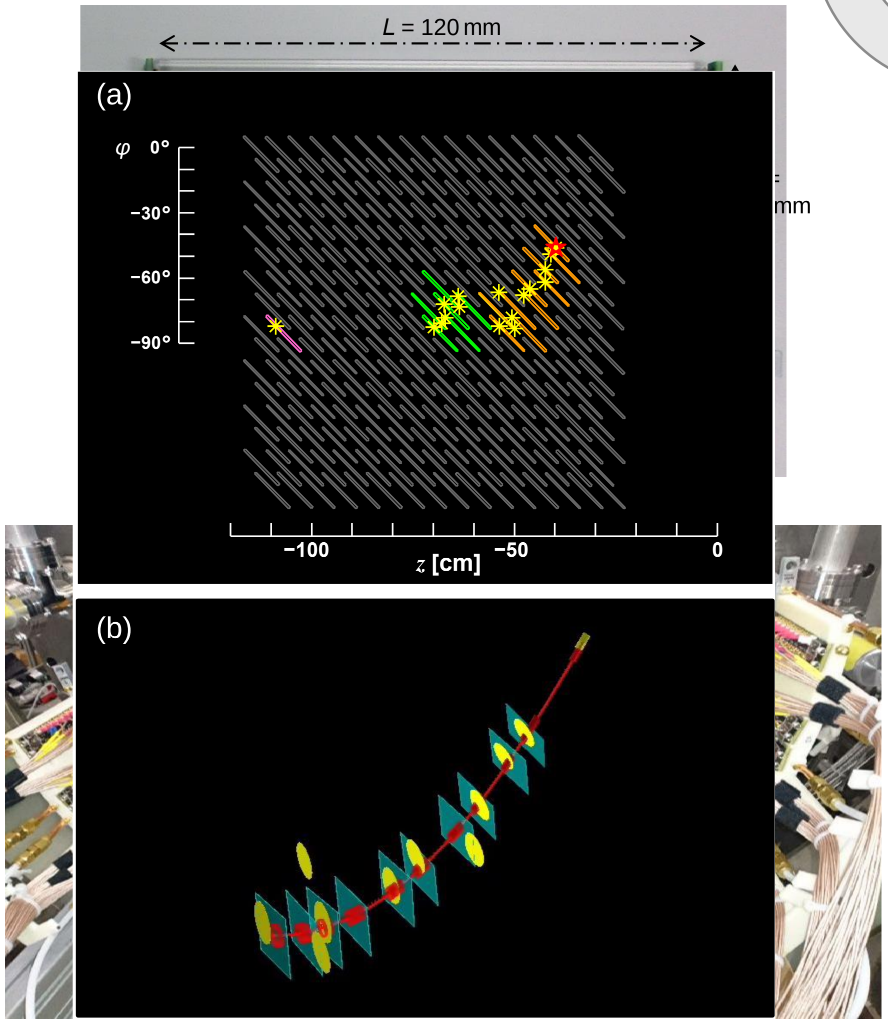




Pixelated Timing Counter

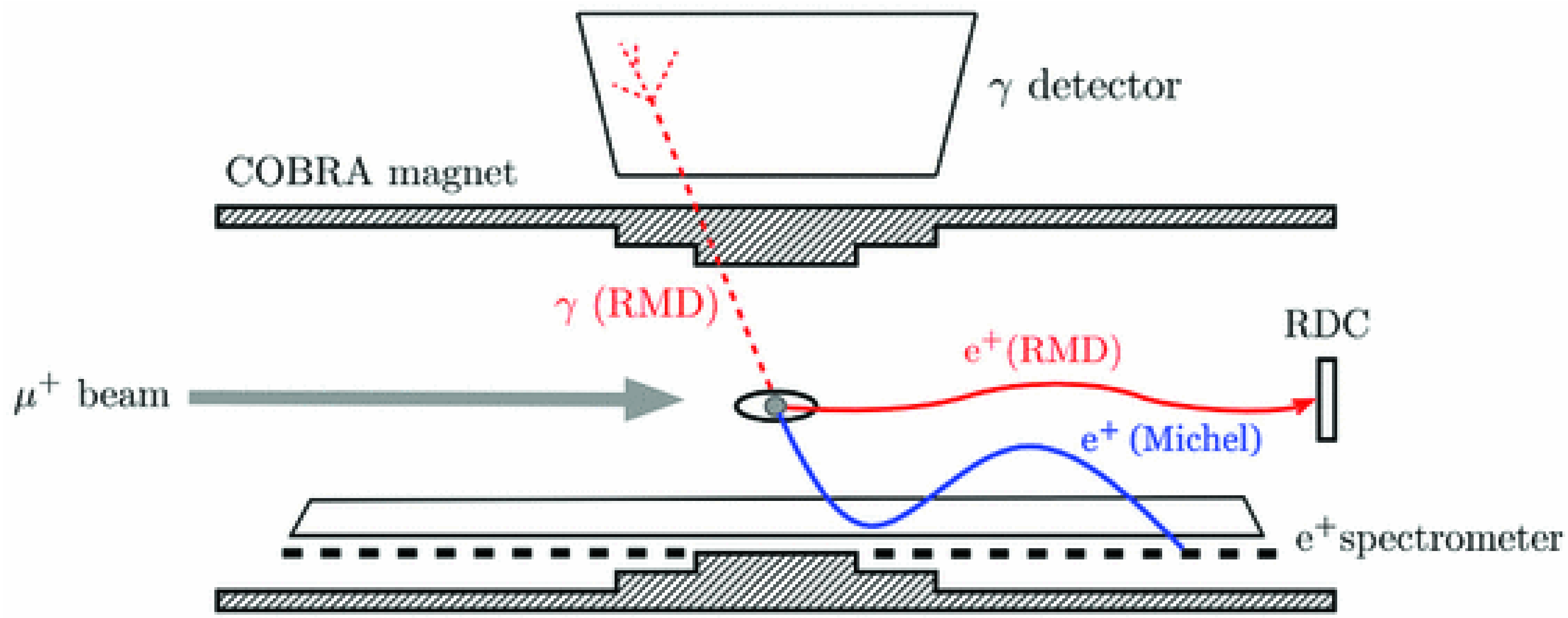
- 512 Saint-Gobain BC-422 tiles
- 2×6 SiPMs in each tile (ASD-NUV3S-P-High-Gain)
  - Upgrade planned: $(3\times3)\text{mm}^2 \rightarrow (4\times4)\text{mm}^2$
- $\mathcal{O}(40\text{ ps})$ time resolution

- See also poster by T. Yonemoto



https://doi.org/10.1016/j.nima.2022.167751

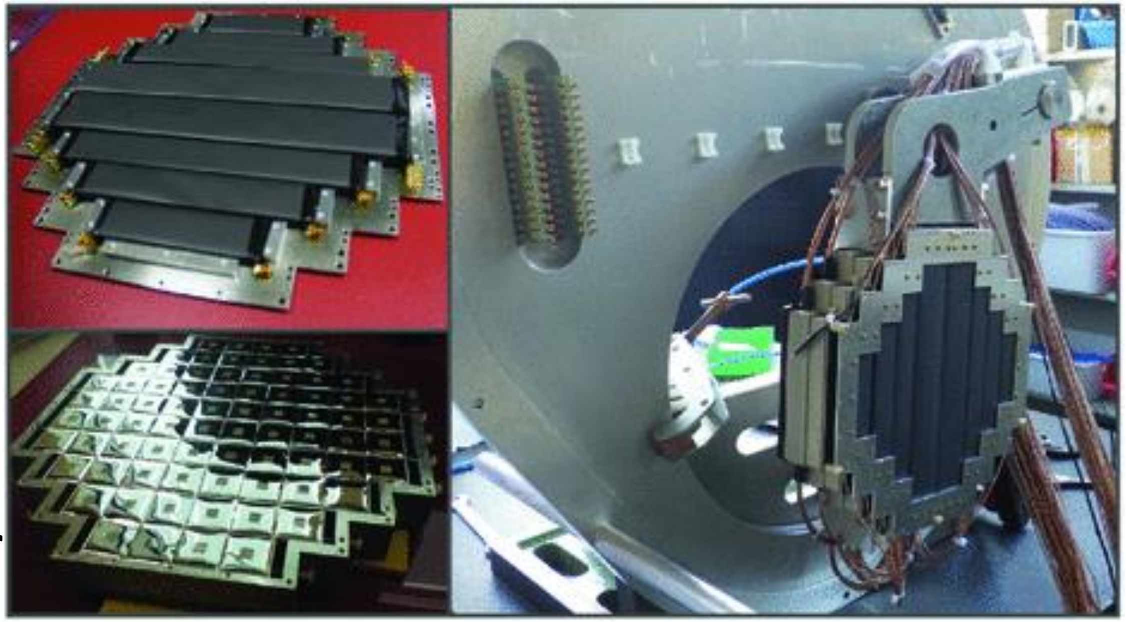
Radiative Decay Counter



Time & energy measurement

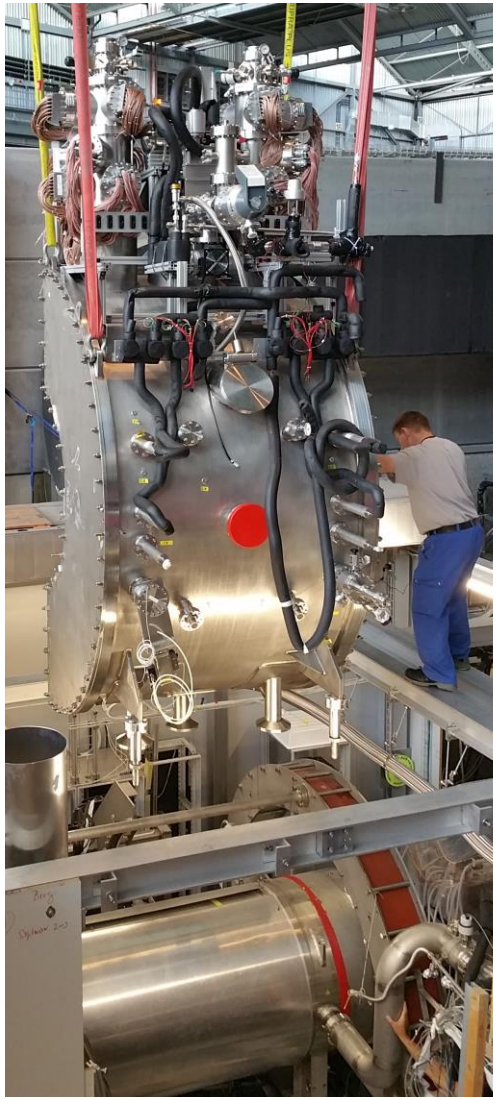
Radiative Decay Counter

- Plastic Scintillator + LYSO
- BC-418 + S13360-3050PE
- LYSO + S12572-025P
- $\sigma_t < 90$ ps
- $\sigma_E/E = (7.5 \pm 0.3)$ %
- Used in analysis, not as veto counter



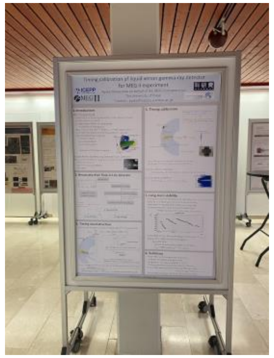
Liquid Xenon Calorimeter

- 900l of LXe (VUV-emitting scintillator)
- 668 PMTs, 4092 MPPCs
- Several great posters outside
- $\sigma_E/E \approx 2\%$
- First large-scale liquid xenon detector, now very popular for dark matter searches



Calorimeter calibration methods

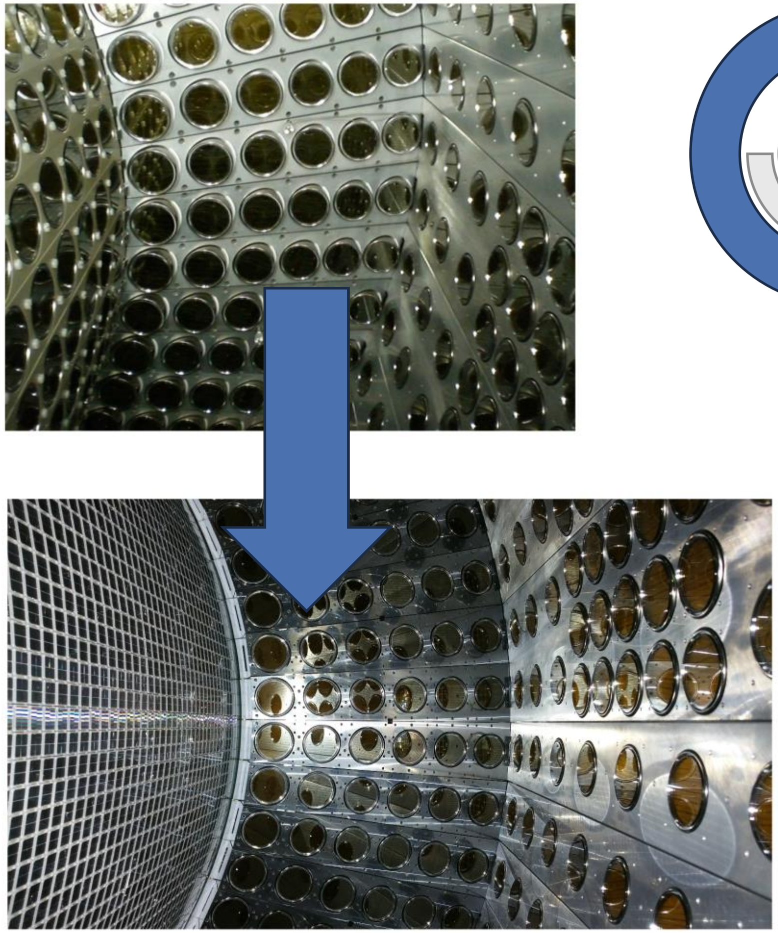
- Radiative muon decays (background)
- 9 MeV photons from neutron capture in nickel
- Upstream proton accelerator for Li(p, γ)Be: 17.6 MeV photons
- Liquid hydrogen target + π^- beam for charge exchange
  - 55/83 MeV photons from $\pi^0 \rightarrow \gamma\gamma$ back-to-back
  - Timing (see poster by A. Matsushita outside)
- LEDs
- Alpha-emitters inside the xenon
- Cosmics

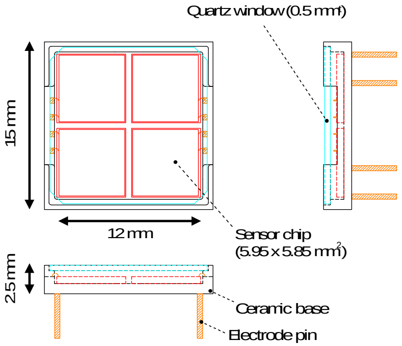


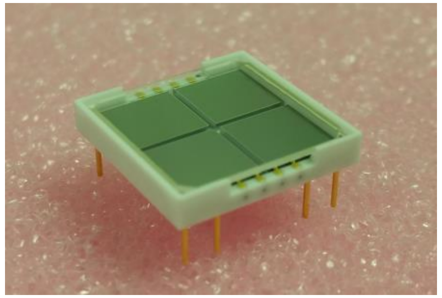
VUV-sensitive MPPCs

- MEG → MEG II upgrade
- Hamamatsu S10943-4372
- PDE up to 21%
- Improved position and time resolution, pileup rejection
  - Posters by A. Matsushita and K. Yamamoto

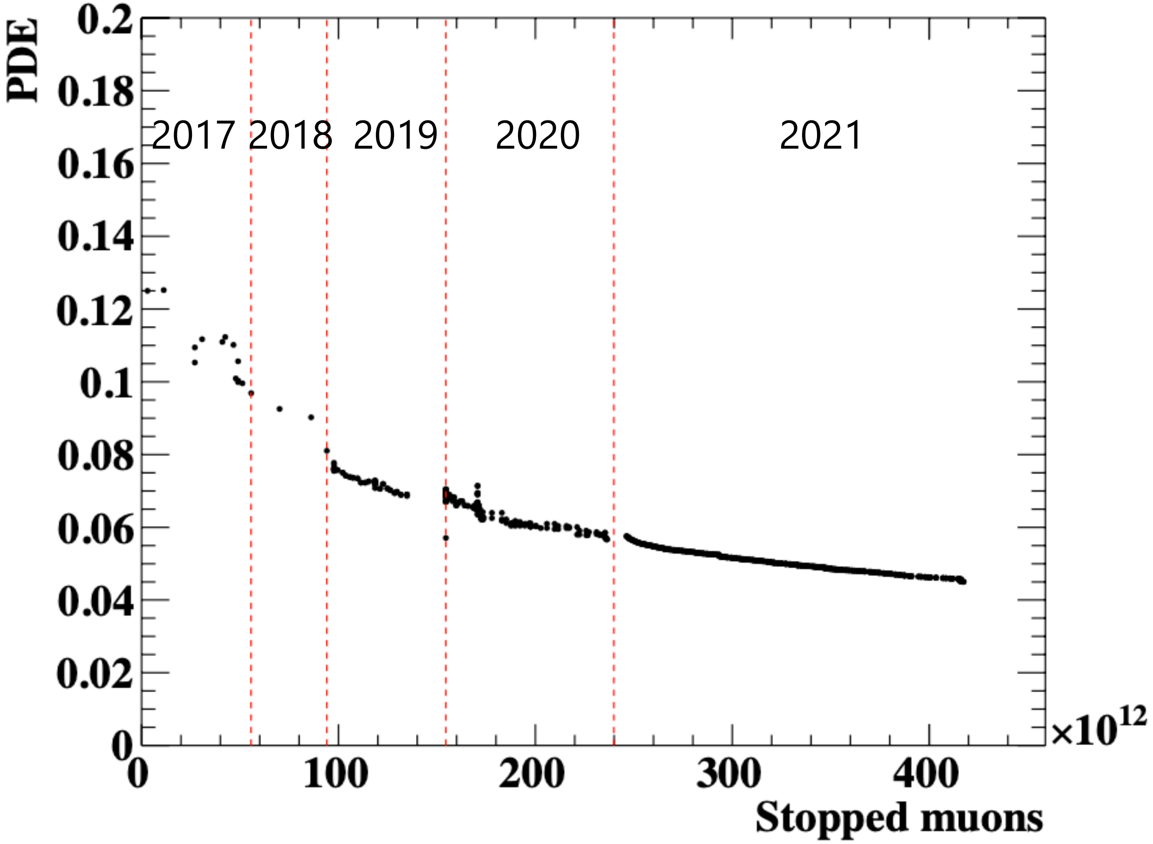
[arXiv:1809.08701]



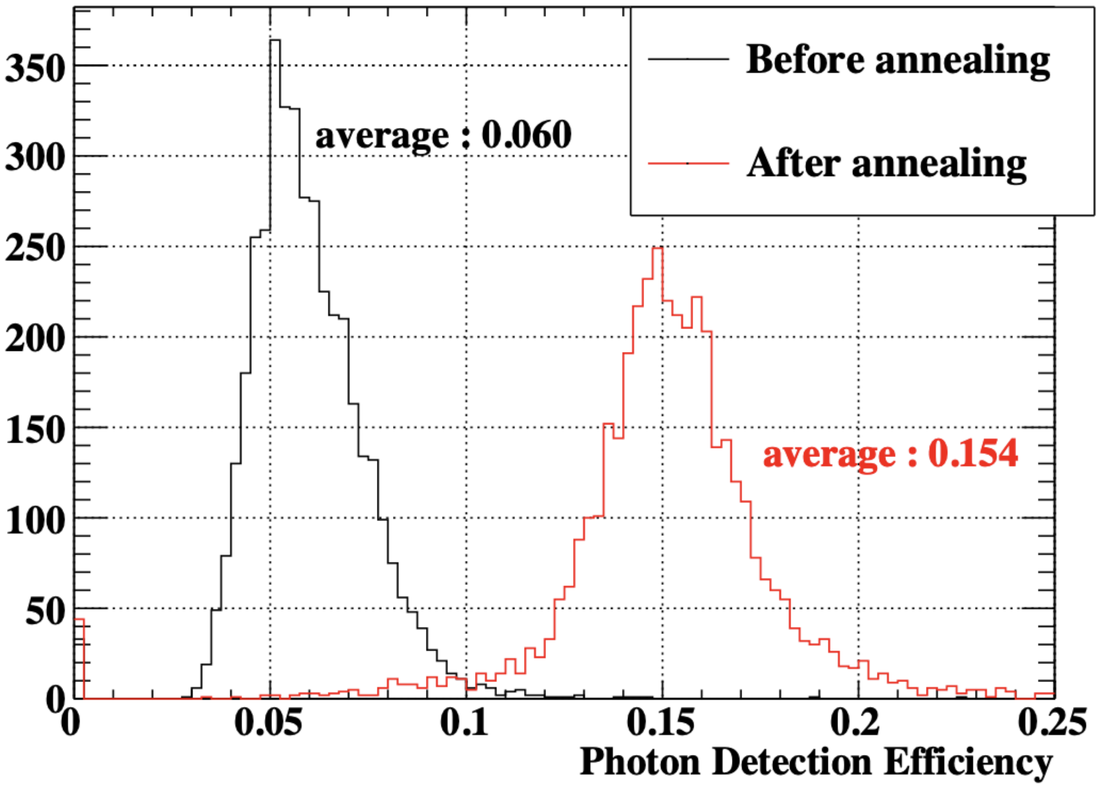




MPPC degradation



PDE degradation during operation
Cause being investigated, see poster by R. Umakoshi

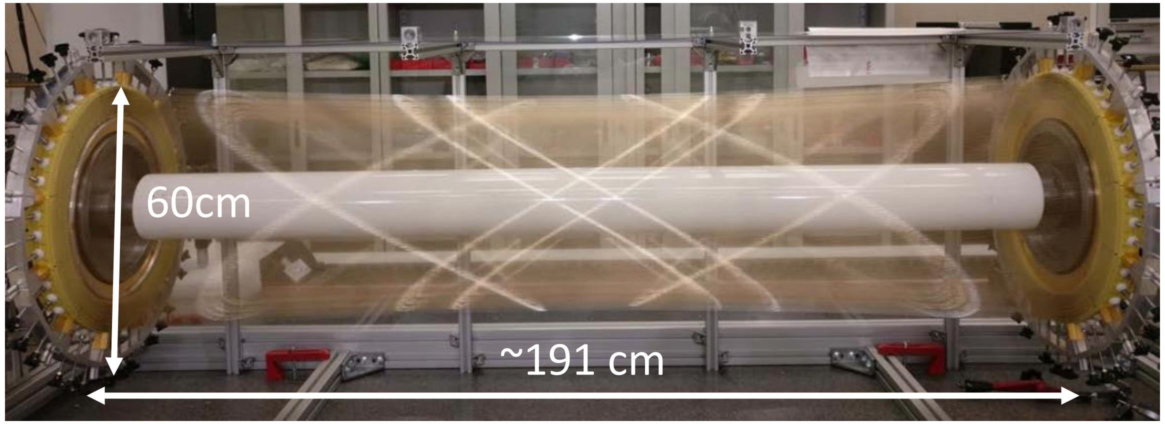


2022 annealing result, [arXiv:2310.11902]

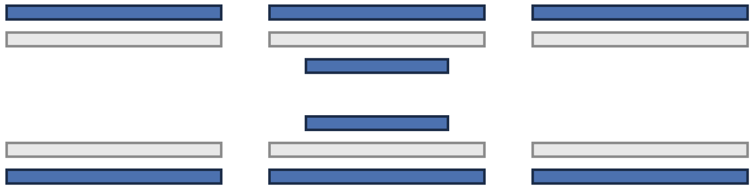
Cylindrical Drift Chamber

- $X/X_0 \approx 1.6 \cdot 10^{-3}$
- $\mathcal{O}(100\ \mathrm{keV})$ momentum resolution
- Details:

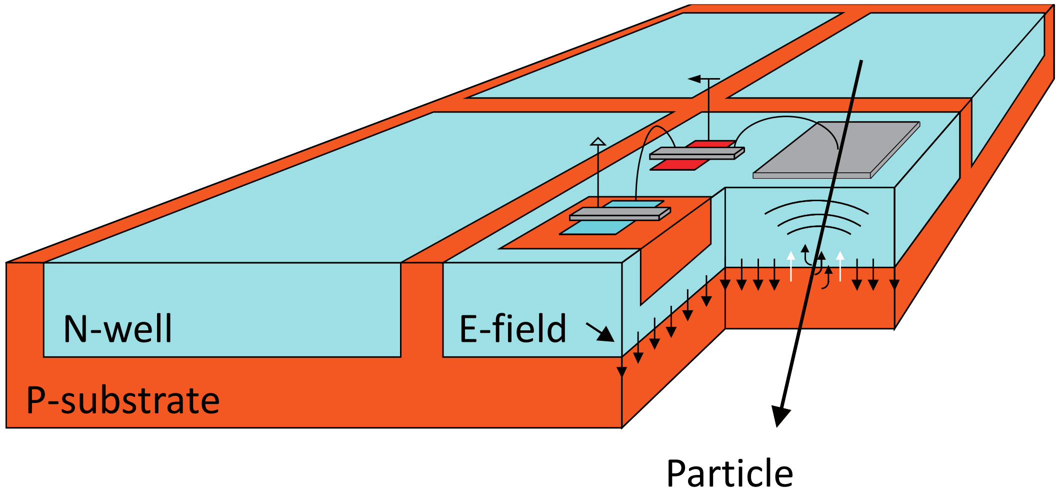
Detectors used at CHRISP and SINQ - insights into different technologies	*Malte Hildebrandt*
Auditorium, WHGA/001	17:00 - 17:30

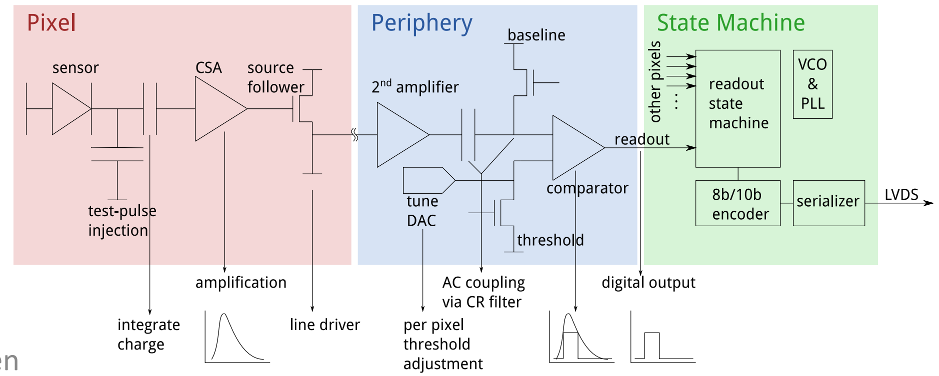


HV-MAPS



- High Voltage Monolithic Active Pixel Sensor
  - Fast charge collection via drift
  - Combined sensor and readout
- High particle rates
- Thinner than hybrid sensors
- Radiation hard



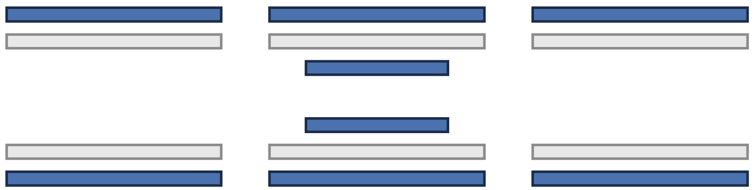


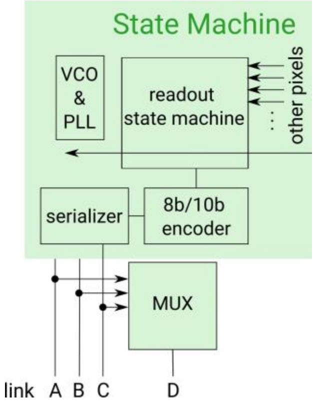
https://doi.org/10.1016/j.nima.2007.07.115

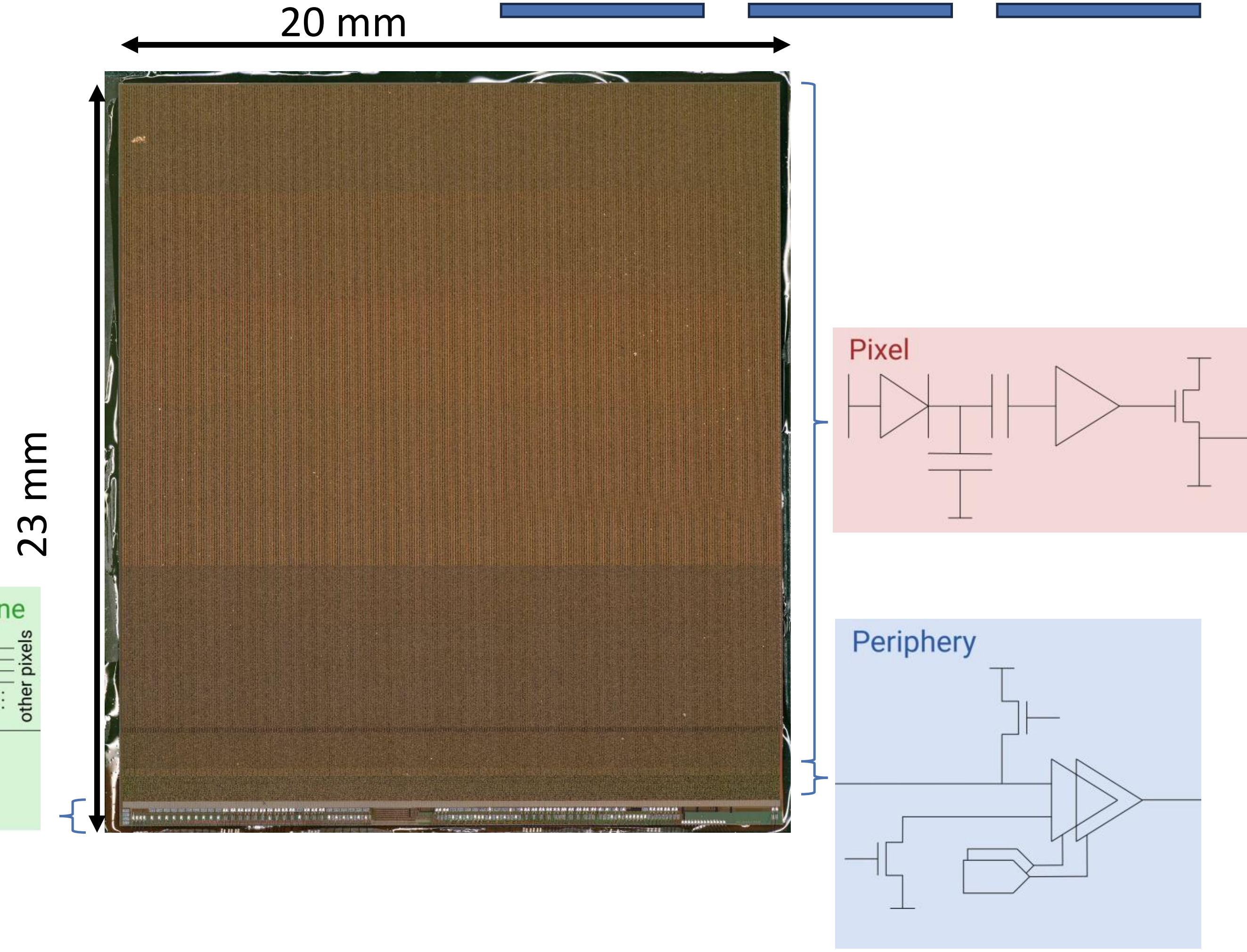
MuPix 11

- HV-MAPS chip developed for Mu3e
- 180 nm HV-CMOS process (TSI Semiconductors)

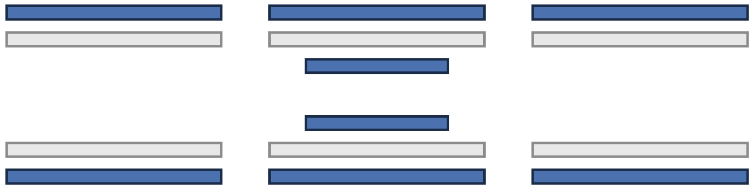
Pixel size [μm²]	80 x 80
Pixel matrix	256 x 250
Active area [mm²]	20.48 x 20.0
Sensor size [mm²]	20.66 x 23.18
Thickness [μm]	50, 70
Radiation length [x/X_0]	~ 0.5‰, ~ 0.7‰
Resistivity [Ωcm]	80, 370
ToA + ToT [bits]	11 + 5
TS binning [ns]	8 (option for 1.6)
Data links	3 + 1 (mux)
Link speed [Gbit/s]	1.25

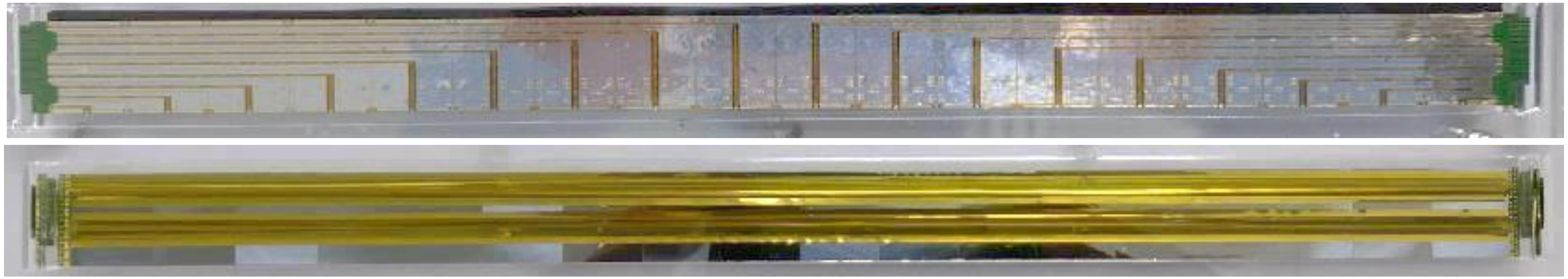




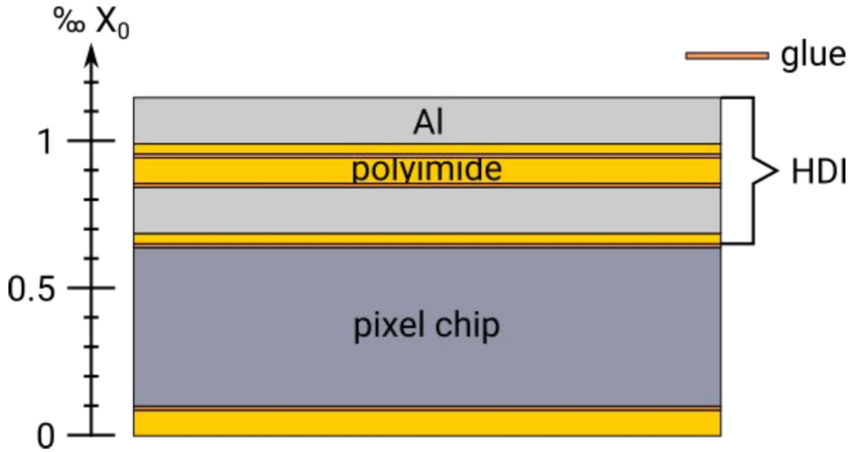


Support and HDI

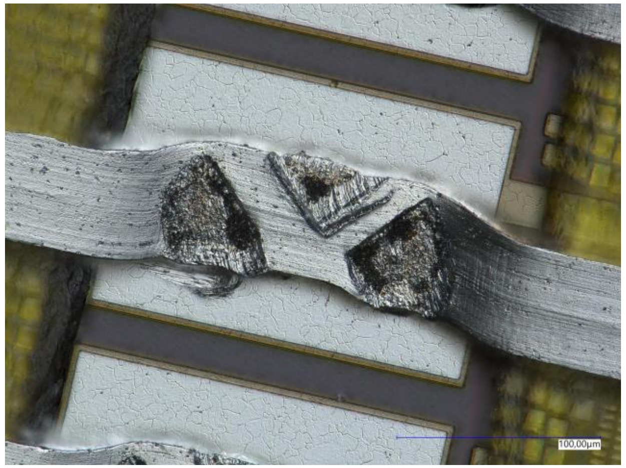




V-folds for stability

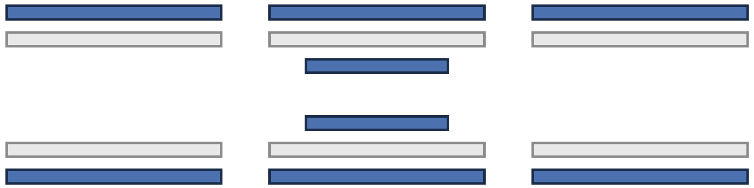


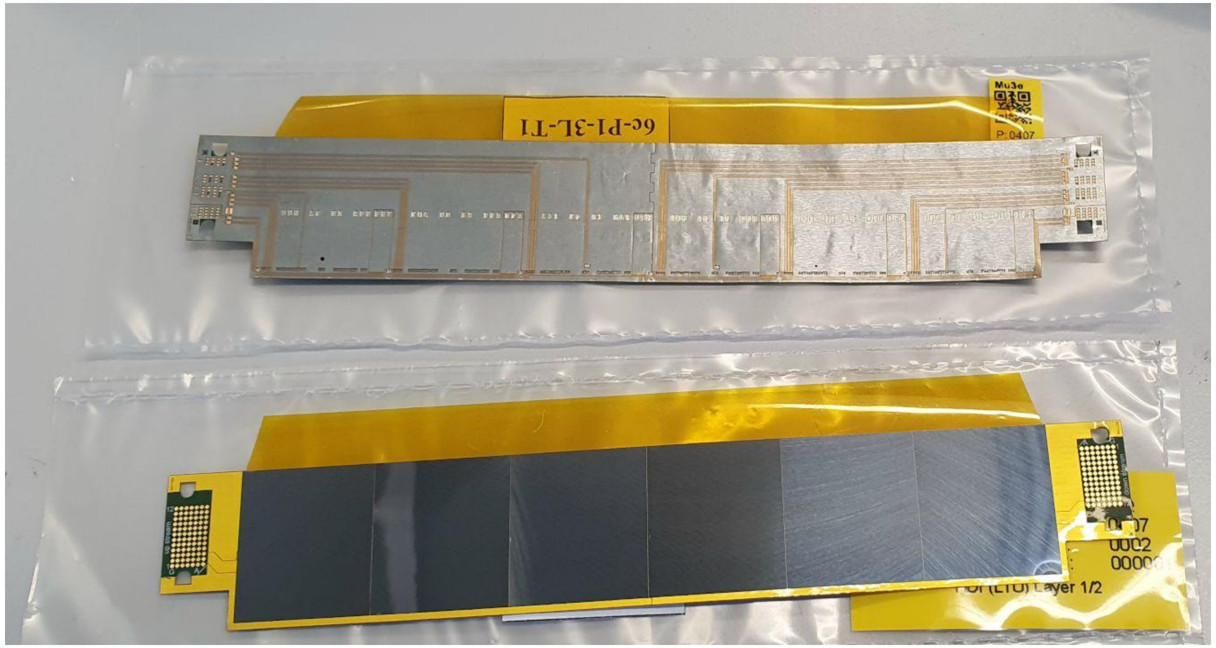
Resulting material budget

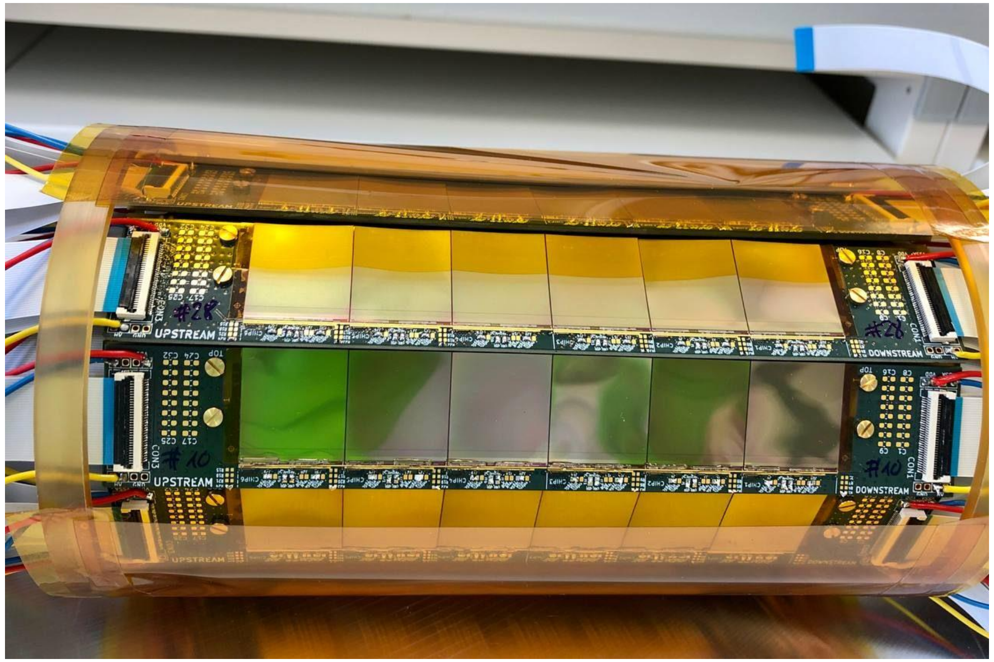


SP-TAB bonding: No additional material

Ladder Assembly

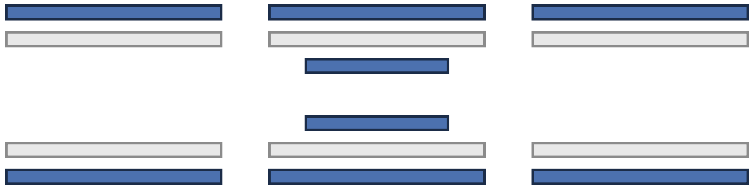


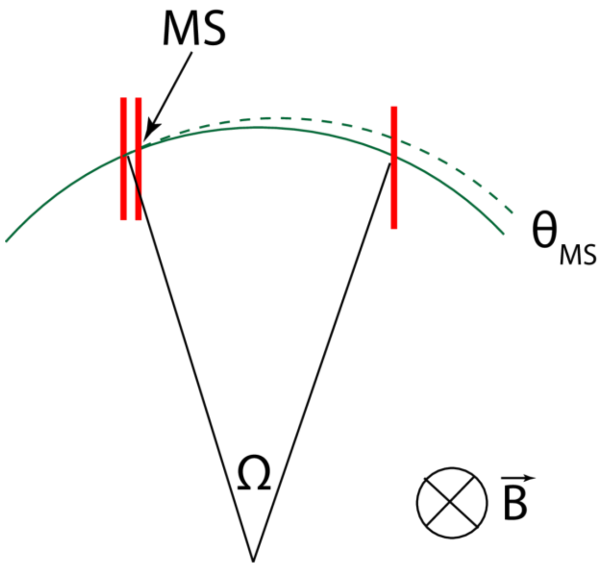




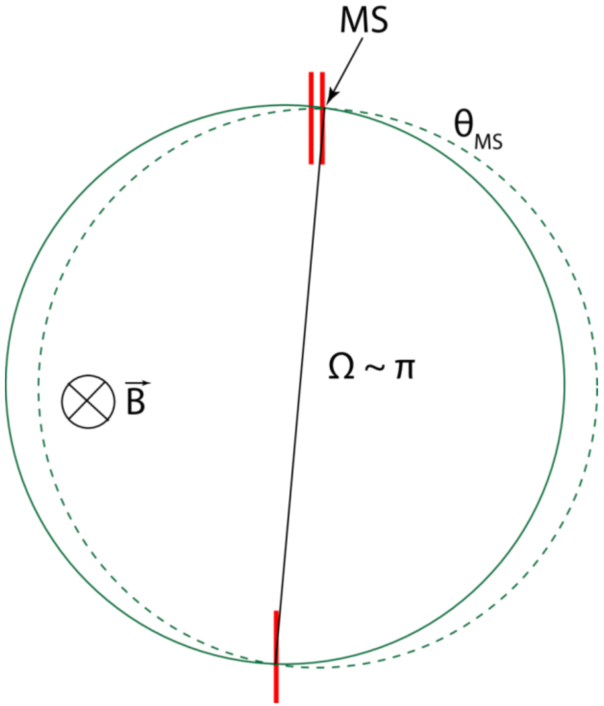
Cooling with gaseous helium: [arXiv:2301.13813], [arXiv:2307.14803]

Multiple Coulomb Scattering

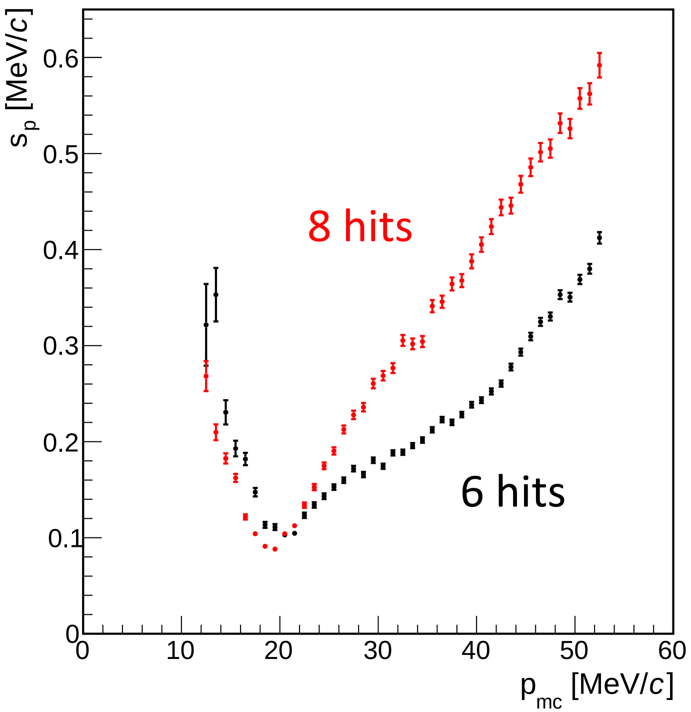




$$\frac{\sigma_p}{p} \propto \frac{\theta_{\mathrm{MS}}}{\Omega}$$



$$\frac{\sigma_p}{p} \propto \mathcal{O}\left(\theta_{\mathrm{MS}}^2\right)$$



B field and detector size are tuned to minimize multiple scattering

Summary

- Multiple scattering is dominant at low energies
- Timing is crucial for high rates
- MEG II:
  - Stable operation
  - Performance preprint submitted yesterday [arXiv:2310.11902]
  - First results tomorrow:

The First Result of MEG II on Search for mu -> e + gamma *Prof. Toshinori Mori*

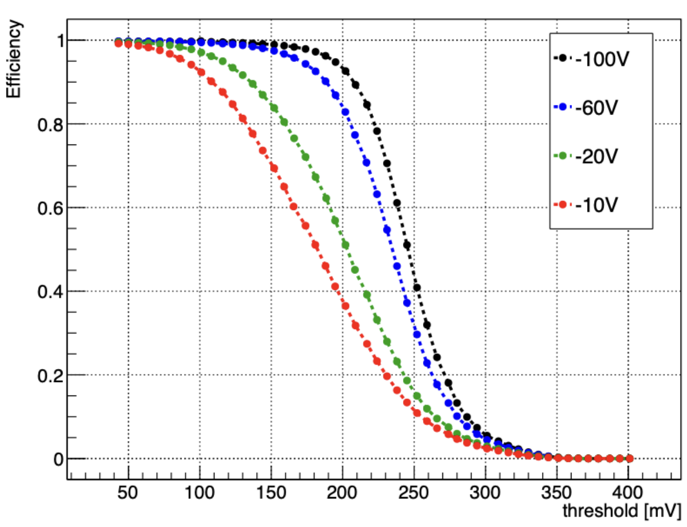
Auditorium, WHGA/001 09:00 - 10:00

- Mu3e:
  - Construction phase
  - Comissioning and physics run from 2024

Thank you for your attention

Backup

MuPix 11 performance



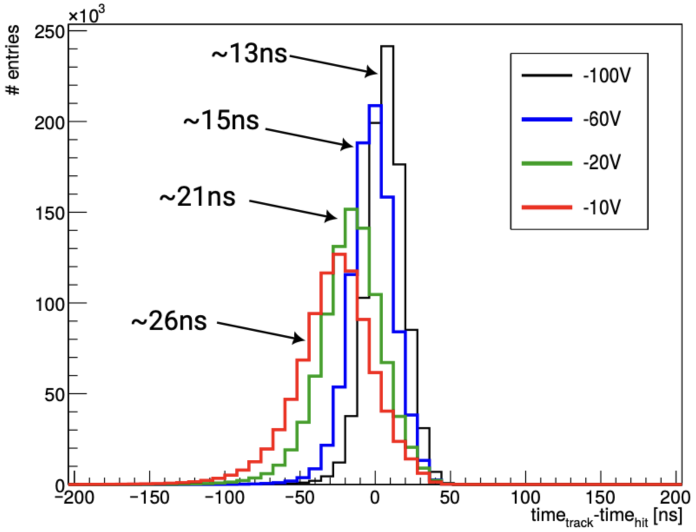


Figure 3. First performance results of a 100 μm thick MuPix11 with a substrate resistivity of 370 Ω cm at different bias voltages and a beam particle momentum of 350 MeV/c. Left: Hit detection efficiency as a function of the comparator threshold. Right: Uncorrected time difference between the track timestamp and its associated hit cluster timestamps for the lowest threshold data point. Indicated is the standard deviation of each corresponding distribution, respectively.