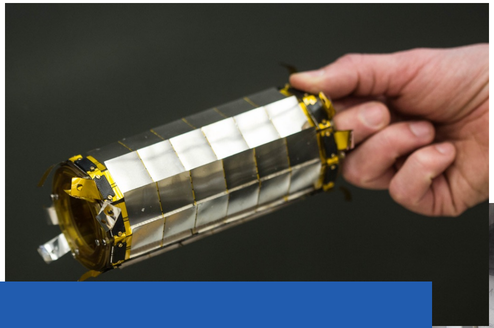
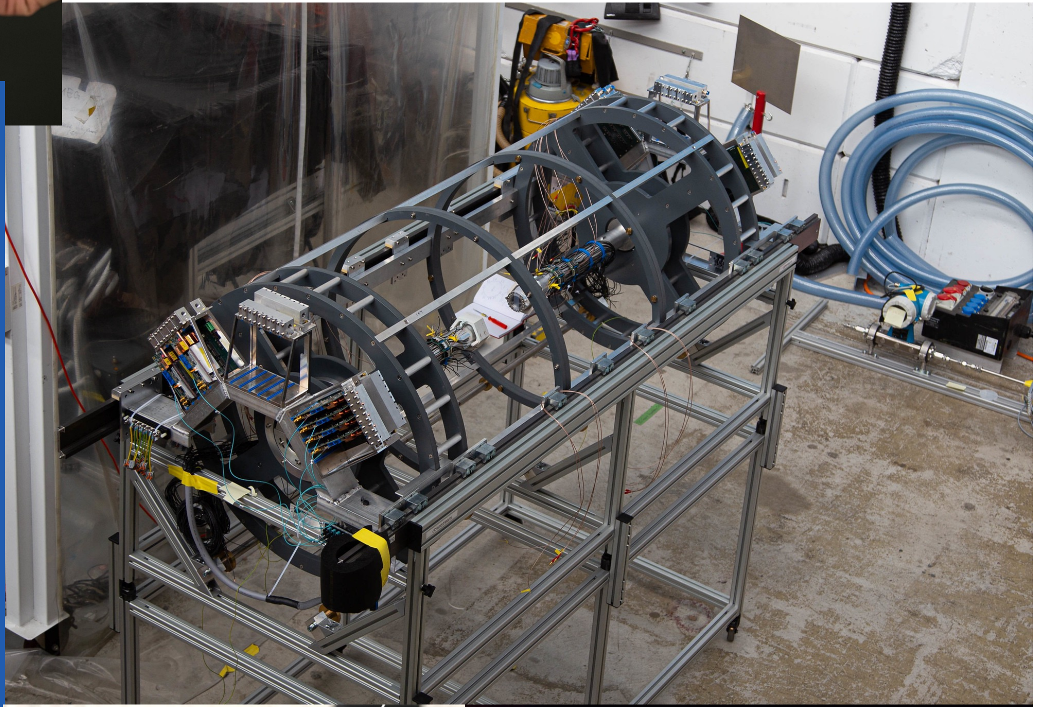
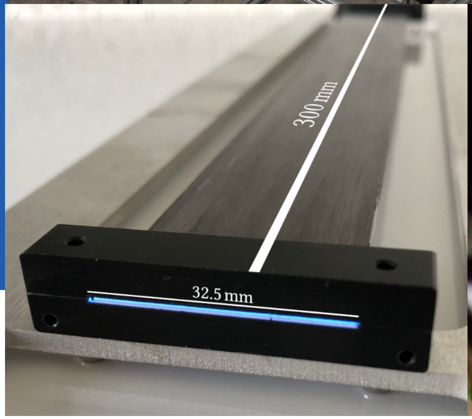


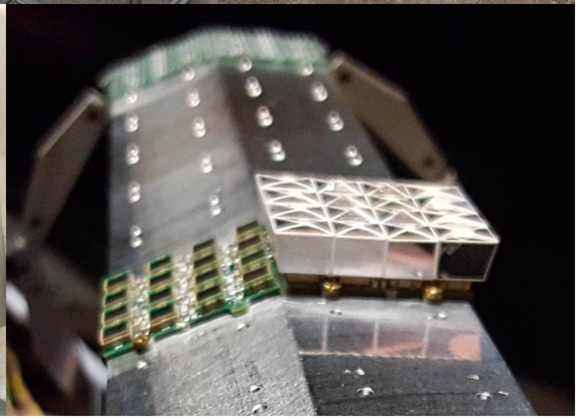


Mu3e experiment: physics and status

29th International Workshop on Weak Interactions and Neutrinos (WIN2023)

Yifeng Wang
on behalf of the Mu3e Collaboration
7.7.2023

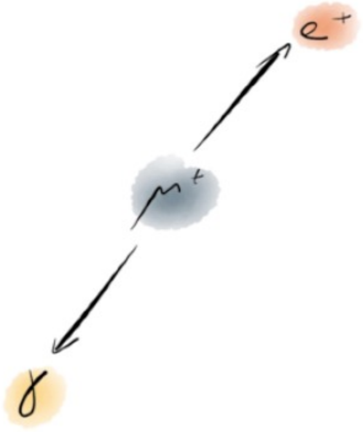




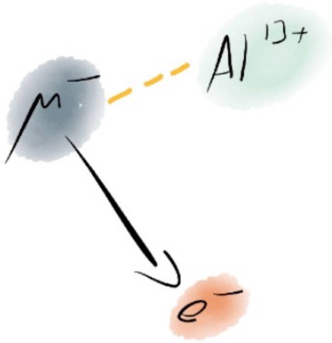
Worldwide status of muon decay search for charged LFV

See talk by Chen Wu on cLFV experiments

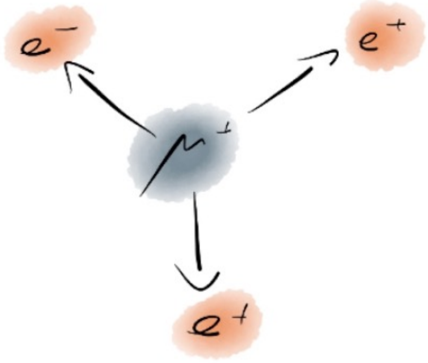
$\mu^+ \to e^+\gamma$



$\mu^- \to e^-$ (within nuclei)



$\mu^+ \to e^+e^+e^-$



Current: MEG ($< 4.2 \times 10^{-13}$)
Future: MEG II (S.E.S. 6×10^{-14})

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Current: SINDRUM II ($< 7 \times 10^{-13}$)
Future: Mu2e and COMET (S.E.S. $< 10^{-16}$)

Mu2e @ Fermilab

See talk by Shihua Huang on Mu2e

COMET @ J-PARC

See talk by Yu Xu on COMET

Current: SINDRUM ($< 10^{-12}$)
Future: **Mu3e** (S.E.S. 10^{-16})

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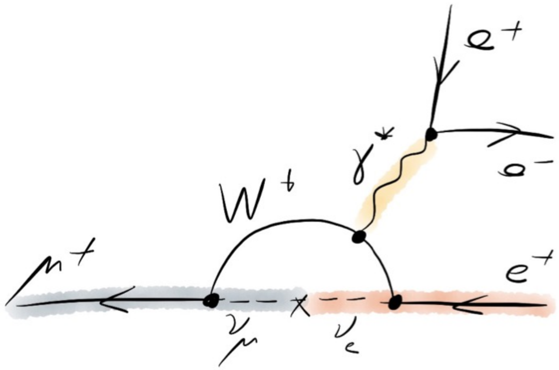
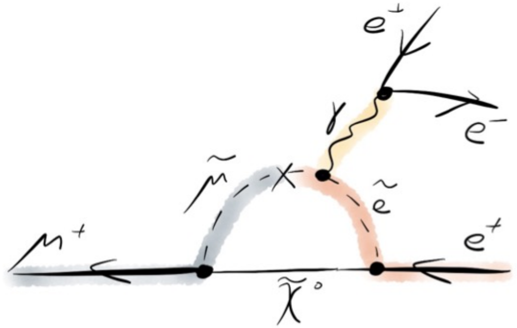
Why $\mu \to eee$ is a golden channel?

1. Strongly suppressed by SM $\Longrightarrow$ **very clean channel**



SM suggested decay

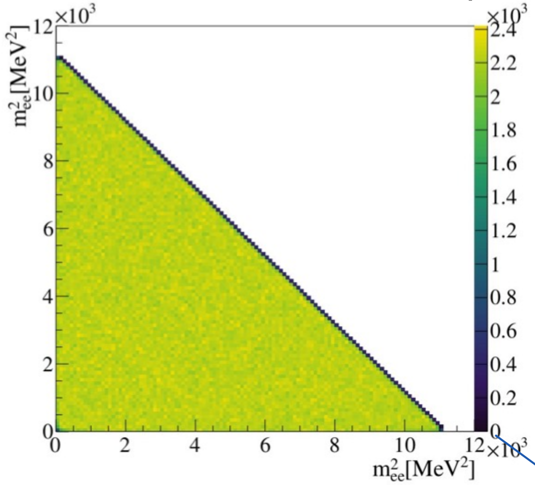


BSM suggested decay

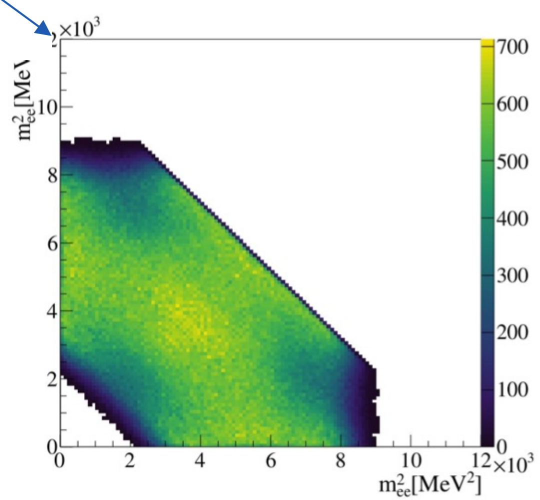
$$\mathscr{B}_{\mu\to eee} \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \quad \to \quad \mathscr{B}_{\mu\to eee} < 10^{-54}$$

2. Full 3-body decay kinematics $\Longrightarrow$ **large kinematic space coverage**

Phase space decay (Dalitz plot)



consider acceptance of detector



Self-introduction of Mu3e

- Mu3e is a future experiment in search for in search for the cLFV decay μ+ -> $e^+e^-e^+$
- **Goal:**
  - Observe μ+ -> $e^+e^-e^+$ if $\mathcal{B} > 10^{-16}$
  - Exclude $\mathcal{B} > 10^{-16}$ at 90% CL
- **Two-staged approach:**
  - $\mathcal{B} <$ a few 10^{-15} in Phase I (2025-26)
  - $\mathcal{B} < 10^{-16}$ in Phase II (2029+)
- Under construction at **Paul Scherrer Institute** (PSI) in Switzerland
- ~70 collaborators from institutes in **Switzerland**, **Germany** and **UK**.

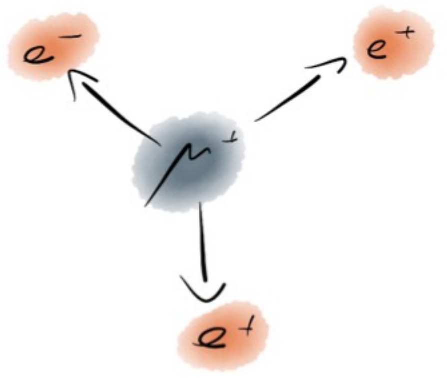
Ref:adapted from New Frontiers in Lepton Flavor by Cristina Martin Perez

Searching for cLFV at Mu3e

Phase I: >10^{15} muons = time x rate = 2.5*10^7s (290days) x $10^8 \mu^+$/s
$\Rightarrow \boldsymbol{\mathcal{B} < 2\times10^{-15}}$

Signal:

$(\mu^+ \rightarrow e^+ e^- e^+)$ signature



- Same vertex and time coincidence
- $(E, \vec{p}) = (m_\mu, 0)$

Background:

Internal conversion background

$\mathcal{B}(\mu \rightarrow eee\nu\nu) = 3\times10^{-5}$

Rejected with excellent **energy** and **momentum** resolution

- Same vertex and time coincidence
- $(E, \vec{p}) \neq (m_\mu, 0)$

Accidental background

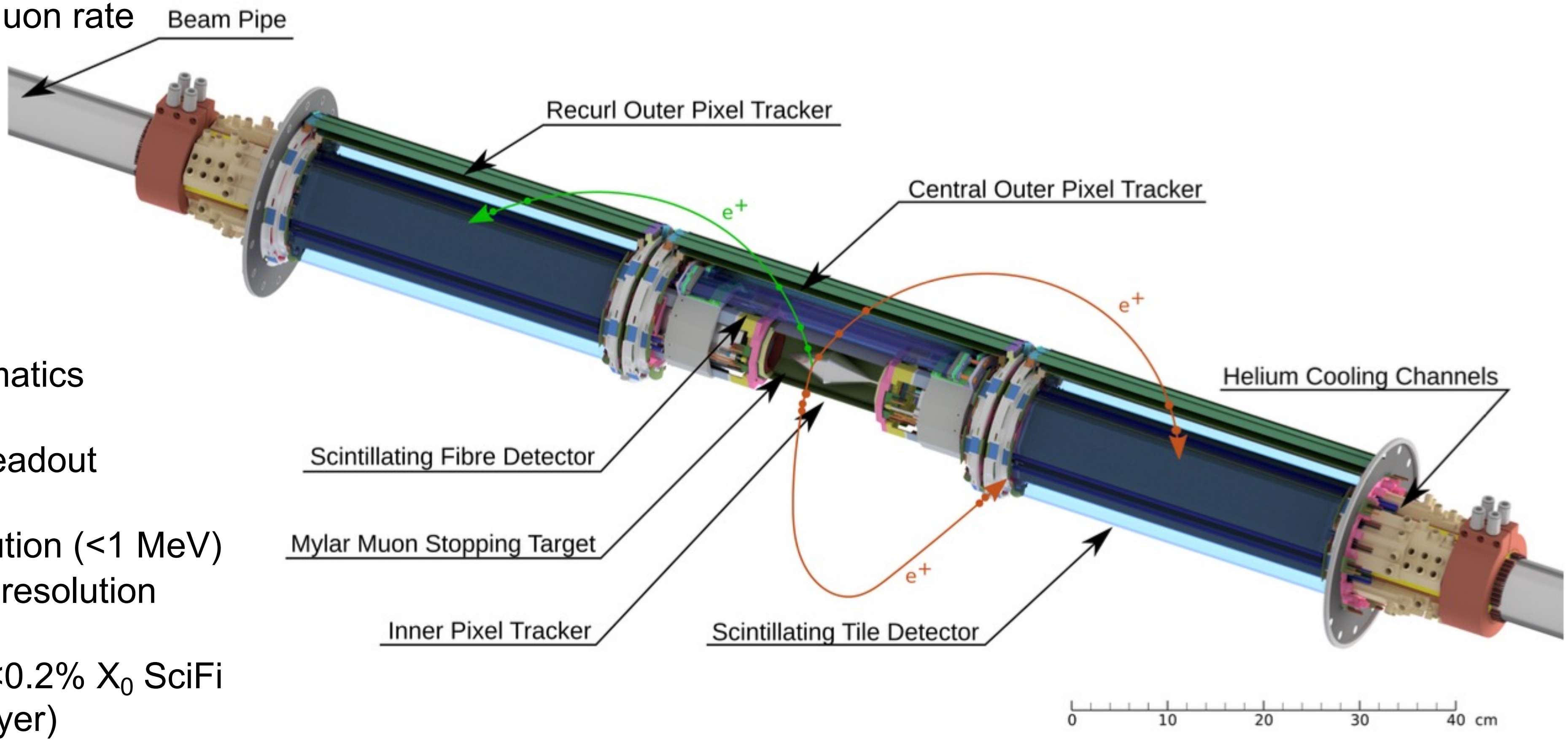
$(\mu \rightarrow e\nu\nu) + (? \rightarrow ee) \propto N$

Rejected with excellent **timing** and **vertex** resolution

- Different vertex and time coincidence
- $(E, \vec{p}) \neq (m_\mu, 0)$

Mu3e design challenges

- Unknown cLFV kinematics
- High and continuous muon rate
- Internal conversion
- Accidental background
- Multiple scattering



⇒ Large solid angle and kinematics acceptance
⇒ Fast and small dead-time readout electronics
⇒ Excellent momentum resolution (<1 MeV)
⇒ Excellent timing and vertex resolution (<100 ps and <0.5 mm)
⇒ Ultra-low material budget (<0.2% X_0 SciFi layer, ~0.1% X_0 per Pixel layer)

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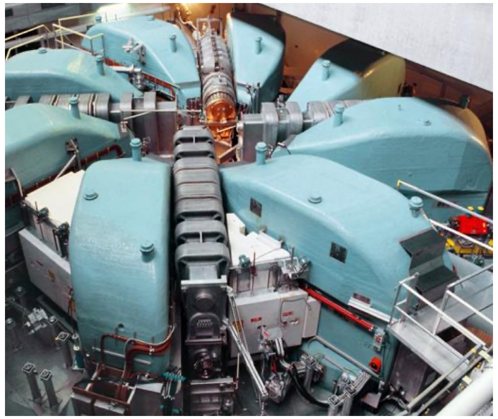
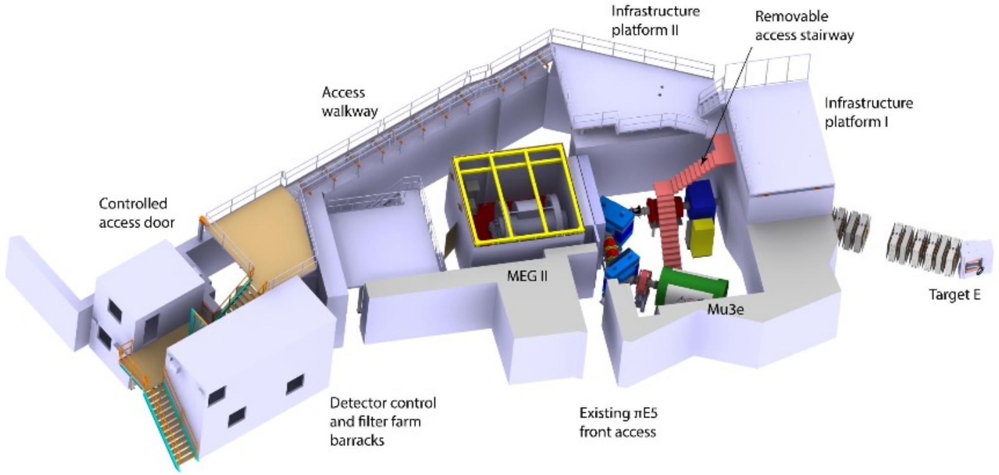
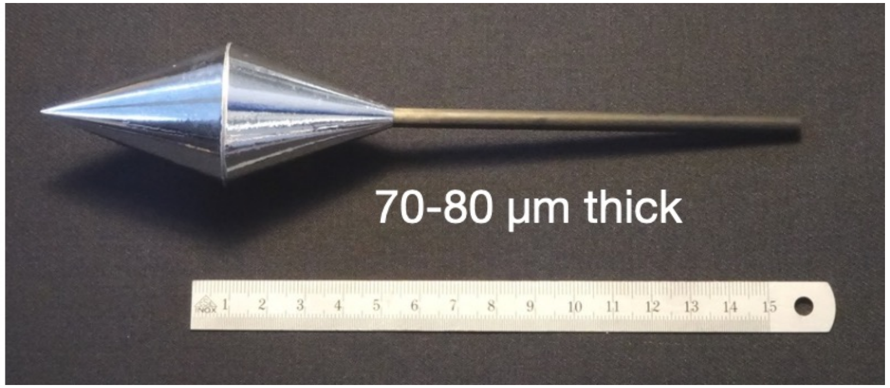
Beam and target



- Delivered by HIPA proton accelerator at PSI
- Proton -> pions -> “surface” muon
- ~28 MeV DC muon beam
- πE5 / CMBL shared by MEG II and Mu3e
- 7.5 x 10^7 muons/s on target



- Double-cone hollow target
- Distribute muon stops over large surface
- Made in Mylar
- Muon stopping ratio: 95.5%
- 100 mm long, 38 mm diameter,



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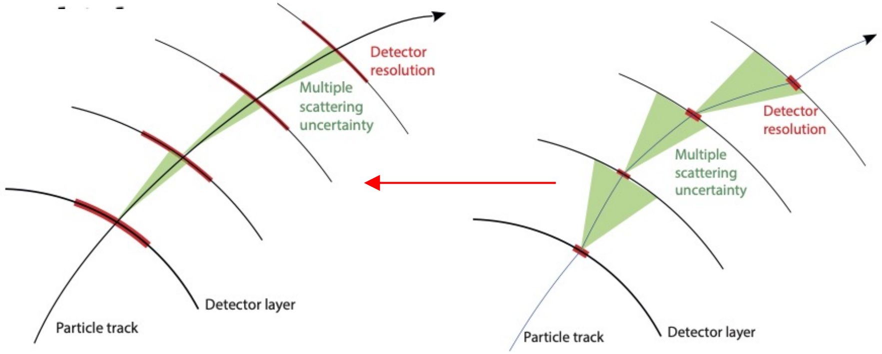
Magnet and track recurl

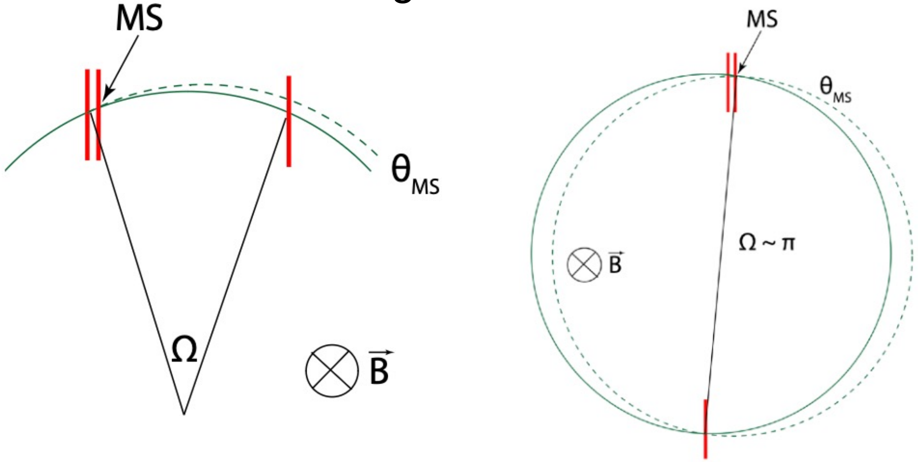
1T Magnet: Maximize the acceptance of recurler

- Solenoid magnet with 1.0 T nominal field
- Delivered at PSI, **operational**

$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$



- Momentum resolution increases as material budget decreases



- Recurl helps on reducing multiple scattering uncertainties

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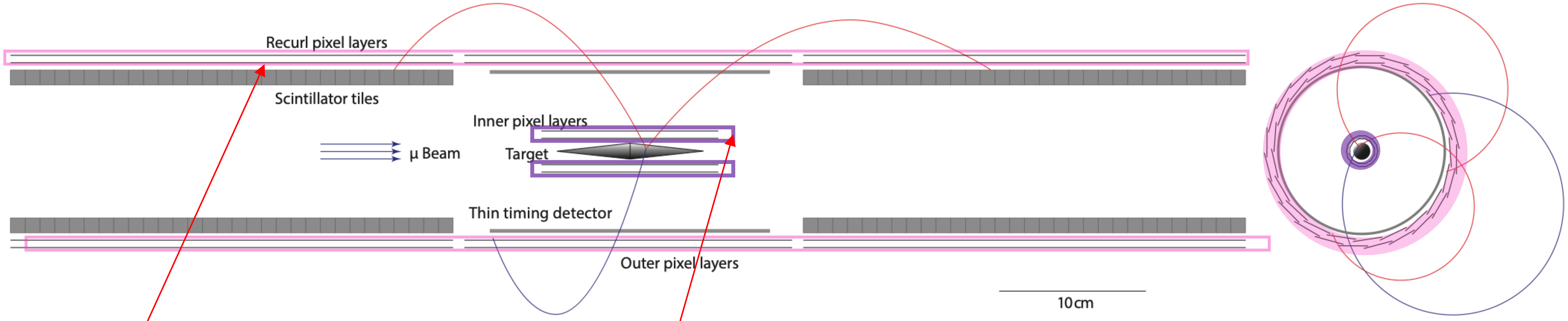
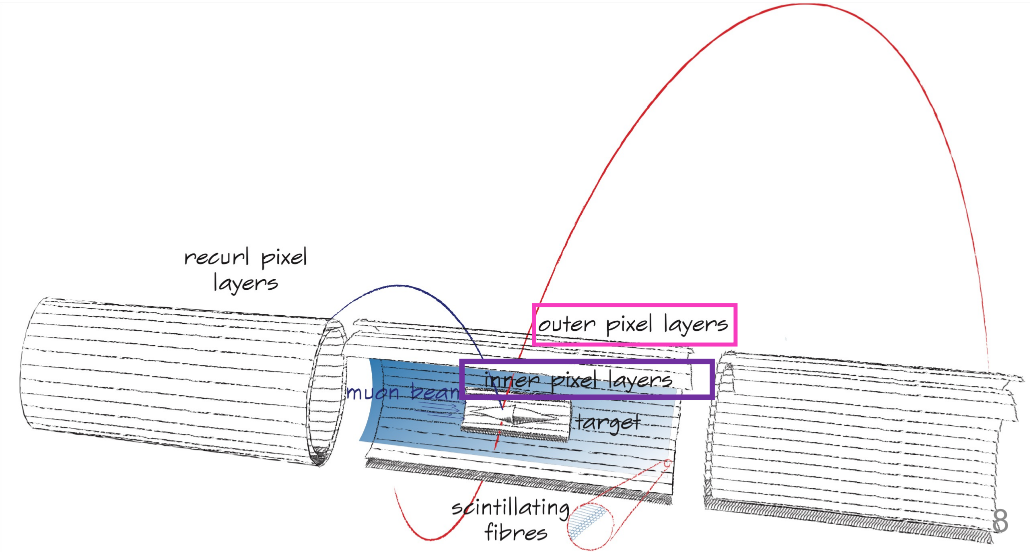
Pixel tracker in Mu3e



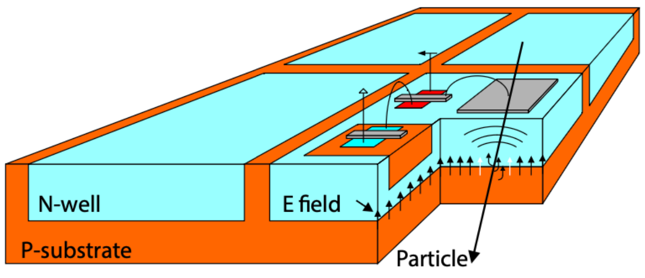
Outer pixel (recurl)

Inner pixel (vertex)

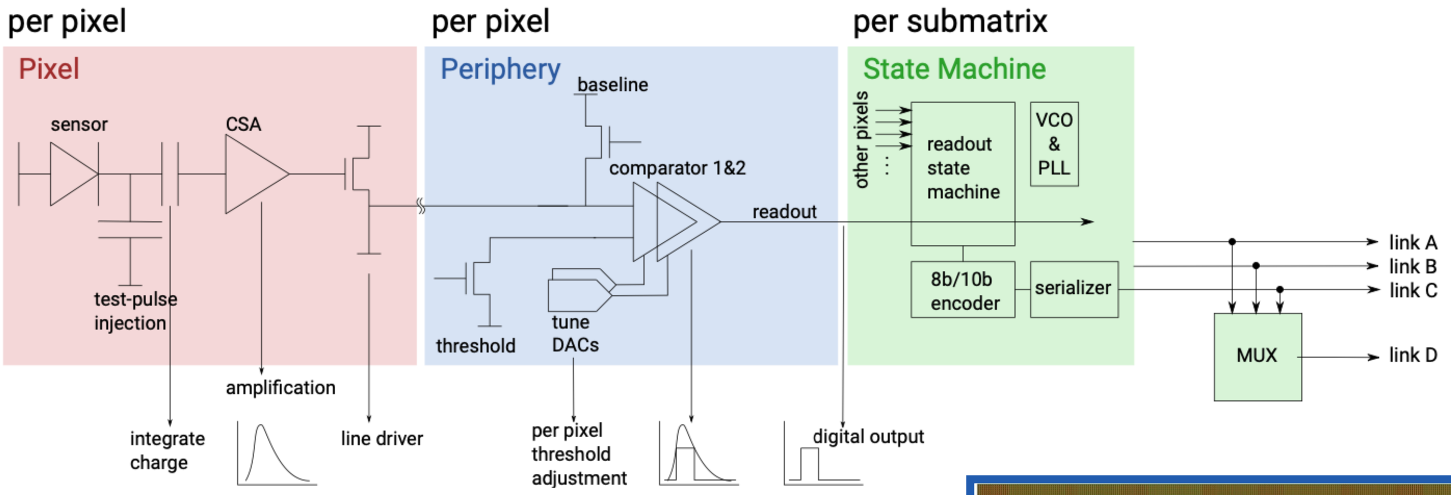


Goal of tracker: vertex and tracking
Granularity: Pixel=80μm*80μm, ScFi fiber=250μm*300mm, Tile 5mm*5mm

MuPix (HV-MAPS tech.) - high voltage, monolithic, fast charge collection, smart diode

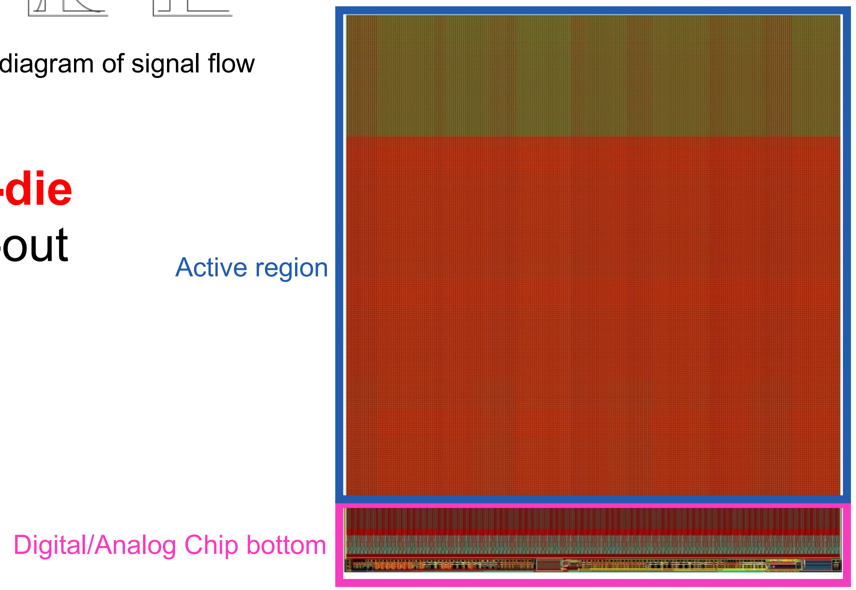


General Operating Scheme of
High-Voltage Monolithic Active Pixel Sensors



Block diagram of signal flow

- **Integration of diode sensor and detector circuit into one-die**
- World-most thin HV-MAPS, **50 μm** (~0.1% X_0) version taped-out
- Pixel size: **80 x 80 μm²**
- Pixel matrix: **256 x 250 pixels**
- Active region: **85.5%** of the whole chip
- Link type: **1.25 Gbps** LVDS

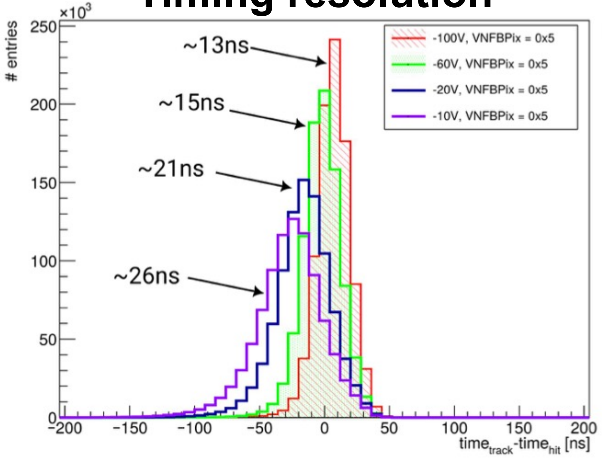


Floorplan of MuPix

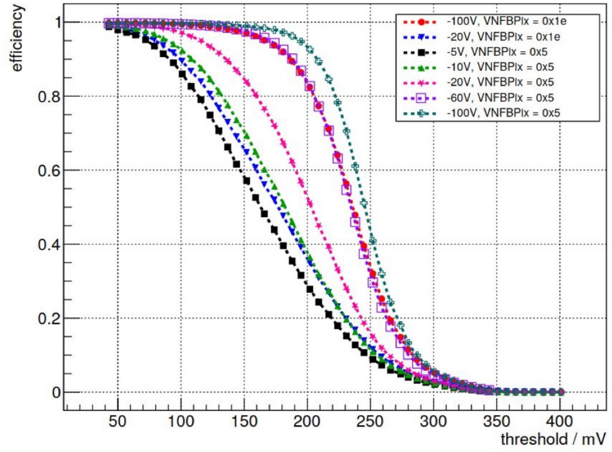
MuPix performance

Timing resolution

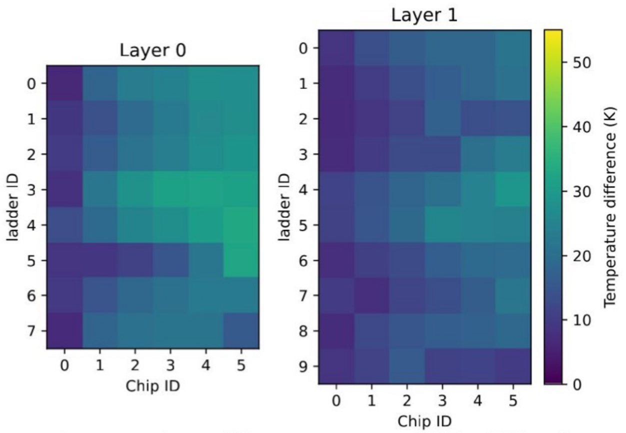
Raw timing resolution (w/o time-walk and delay correction)



MIP detection efficiency MuPix11 (100µm)



Innovative **gaseous helium cooling** solution with 2g/s, sensor < 70˚C

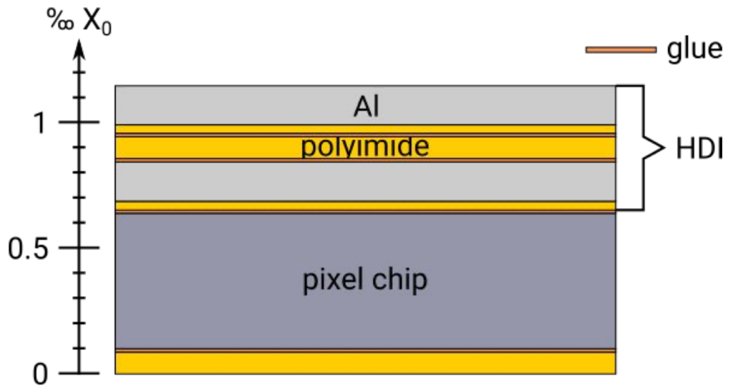


temperature difference maps 215 mW/cm²
(expected scenario)

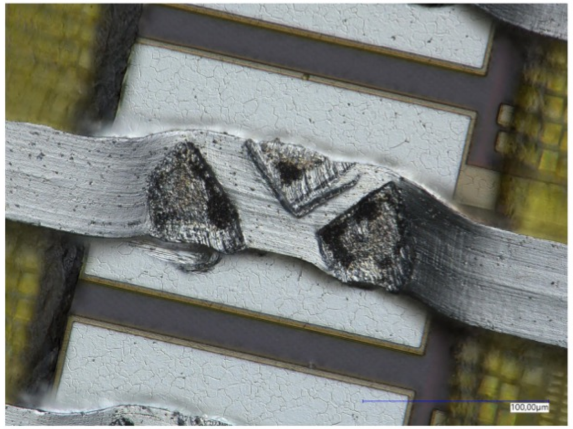
Measured temperature difference of dummy load (at ~ 215 mW/cm2)

- Max. temperature difference < 35 K (215 mW/cm2)
- Max. temperature difference < 54 K (350 mW/cm2)

spTAB bonding for High-Density Interconnects



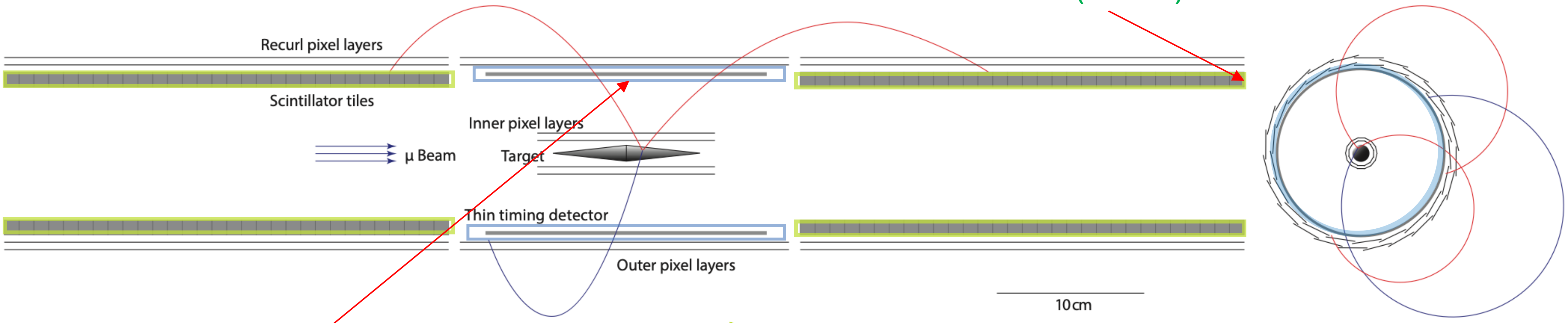
Resulting material budget



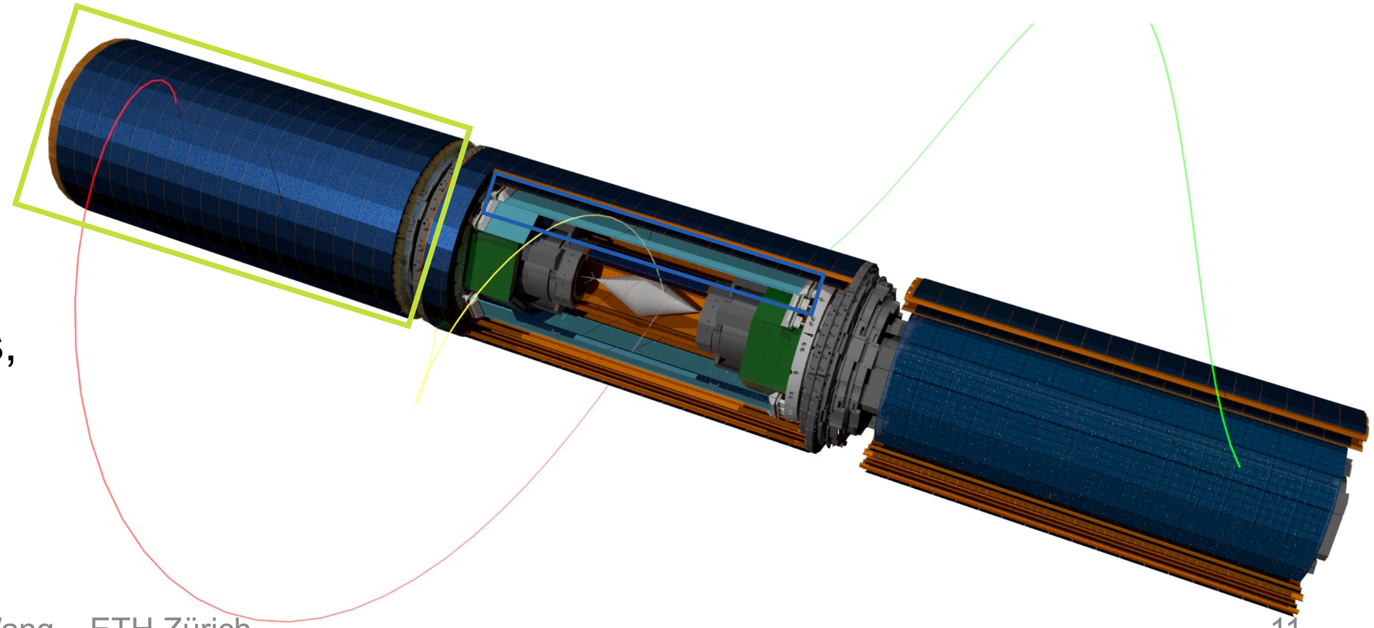
spTAB connection

Timing layers in Mu3e

SciTile (recurl)



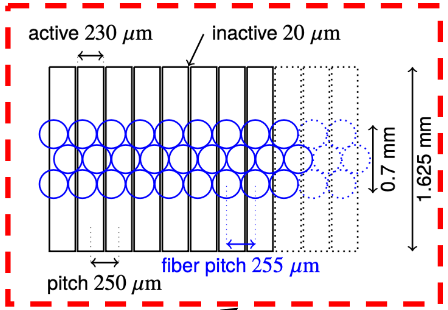
SciFi (timing)



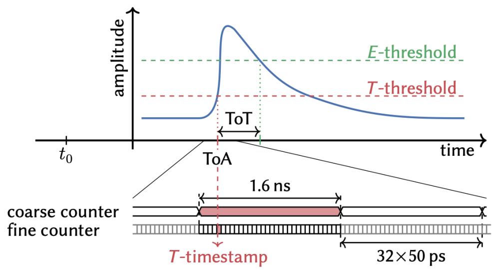
Goals of timing layers: time coincidence of tracks, charge identification and global event recons.
timing resolution: SciFi<200ps, SciTile<50ps, Pixel<26ns

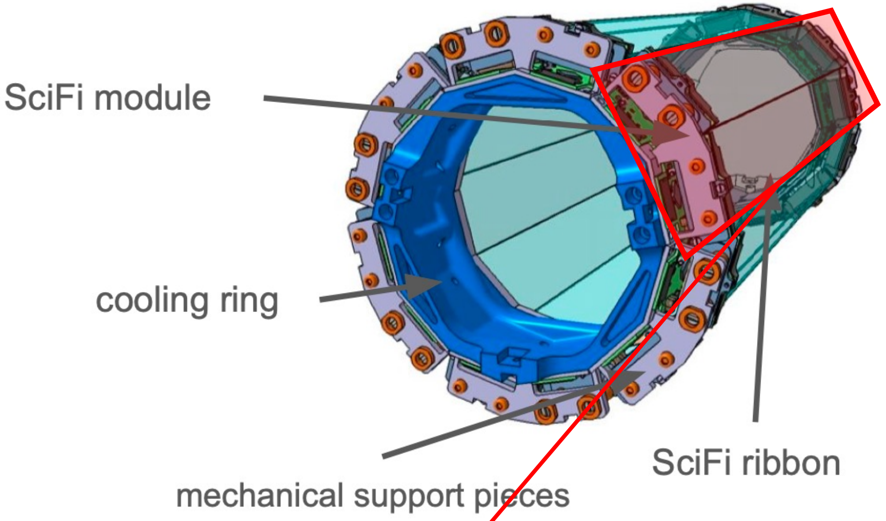
SciFi detector - construction

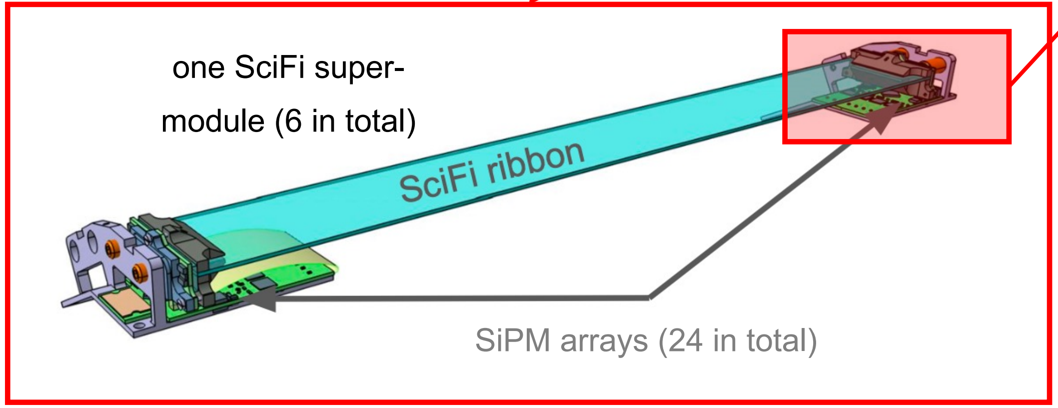
Fiber and SiPM array attached



SiPM readout waveform

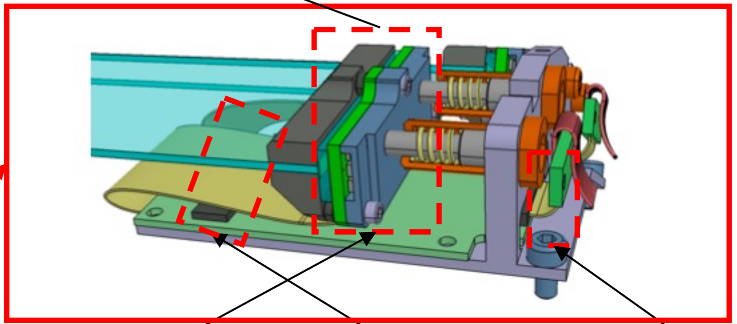






on one end of the fiber ribbon

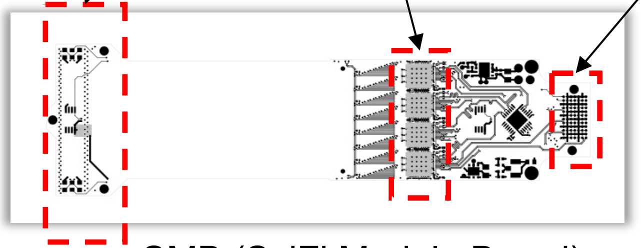
Ref: 2208.09906



SiPM

MuTRiG x4

interposer



SMB (SciFi Module Board)

Cooling to -20˚C with silicon oil

Fill factor >60%

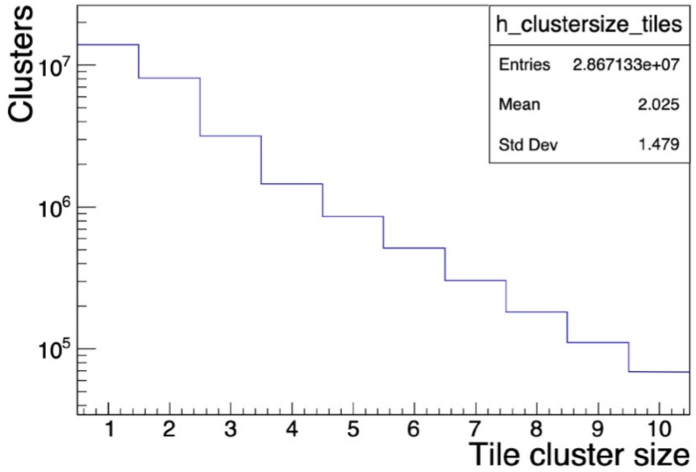
µtwsited pair (µTP) cable bundles

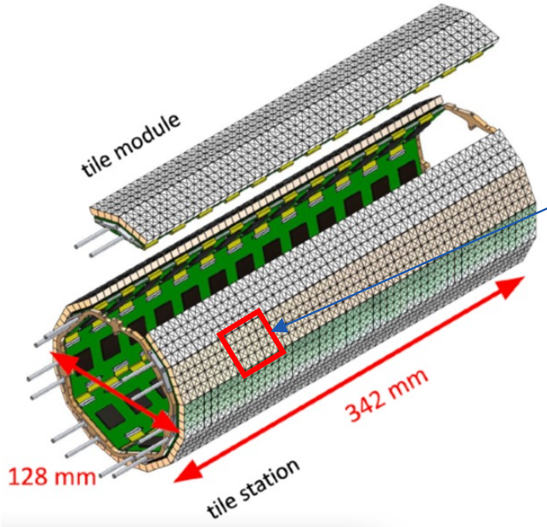
To FPGA

Ref: Y. Demets, BVR 2023

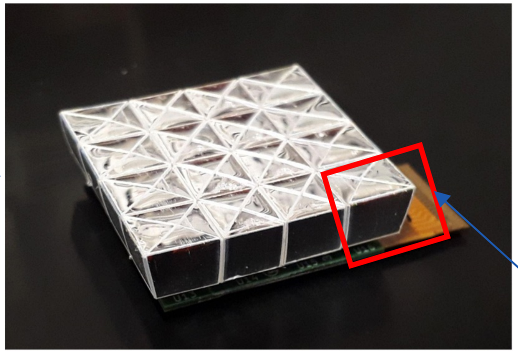
Scintillating Tiles detector

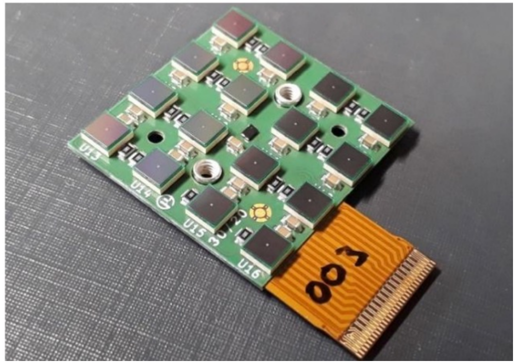
- Consists of size of 6 x 6 x 5 mm^3 scintillating tiles
- Readout with 3 x 3 mm^2 SiPM (MPPC S13360-3050VE)
- Digitized by MuTRiG (TDC)
- Efficiency > 99%, time resolution ~40ps



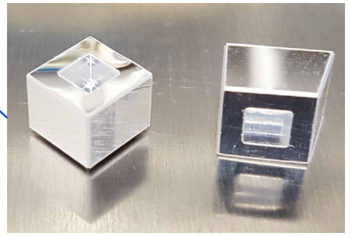


Tile Subdetector



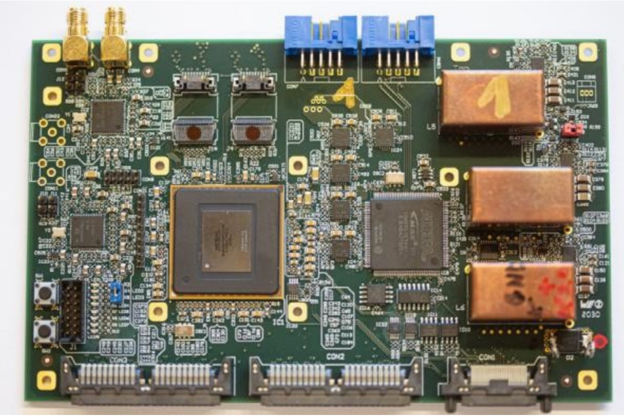


Tile Matrix
(top) w/ scintillator
(bottom) w/o scintillator

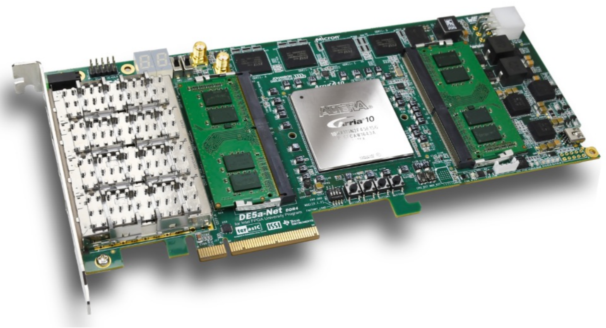

Tile-shape scintillator

Triggerless Data acquisition (DAQ) system

Intel(Altera) FPGAs and GPU farm



Front-end Board - **Customized Arria V board** - 8 XCVR



Farm Board – Dev kit Arria 10 – **Customized PCIe DMA controller**

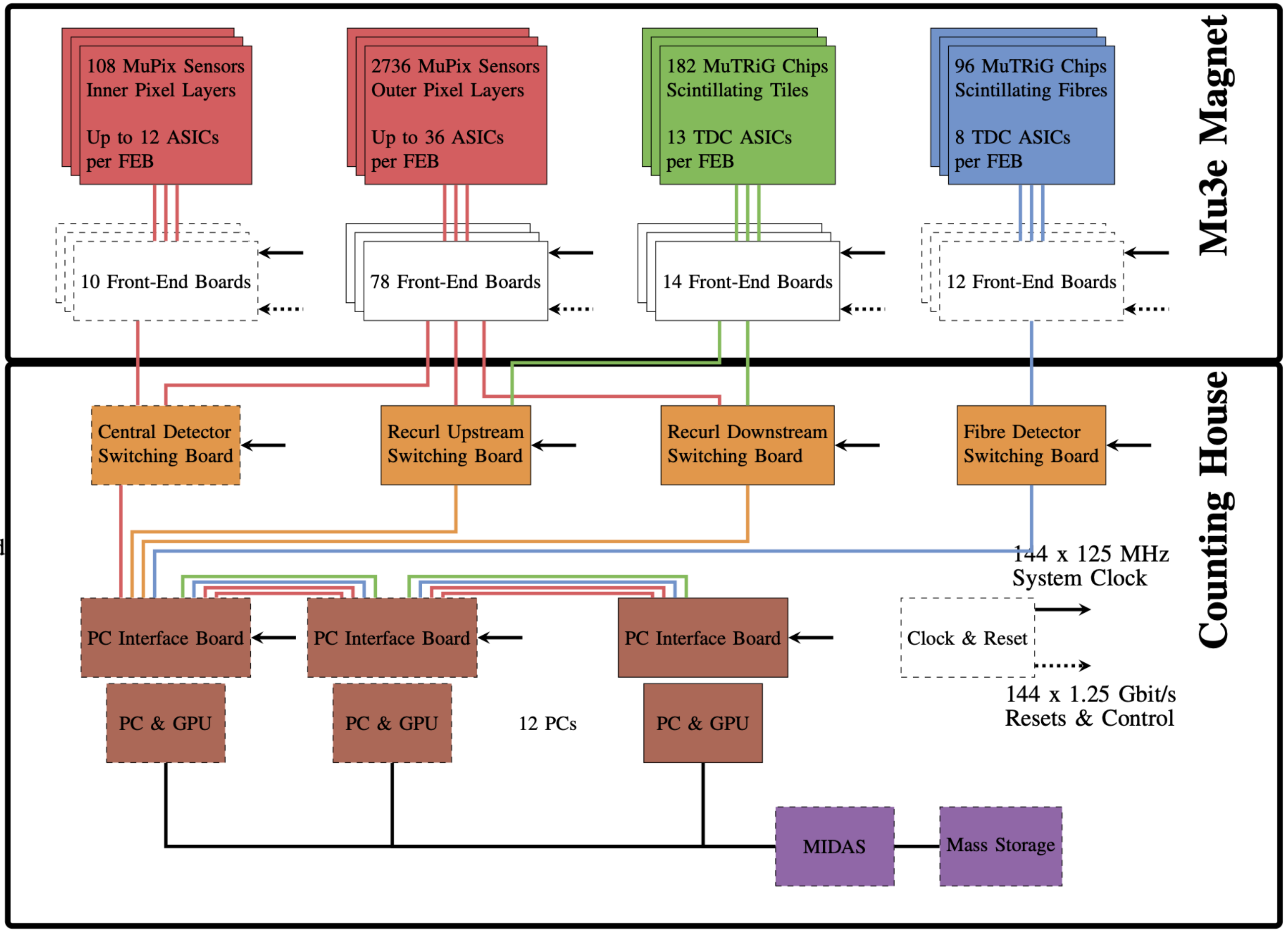
up to 3 x 1.25 Gbit/s LVDS links per ASIC

1-2 x 6.25 Gbit/s optical link per FEB

2-8 x 10 Gbit/s optical links per Switching Board

16 inputs per Farm FPGA

Gbit Ethernet



Link bottleneck bandwidth (maximum allowed data rate)

9 Tbps

0.7-1.4 Tbps

80-320 Gbps

a few Gbps

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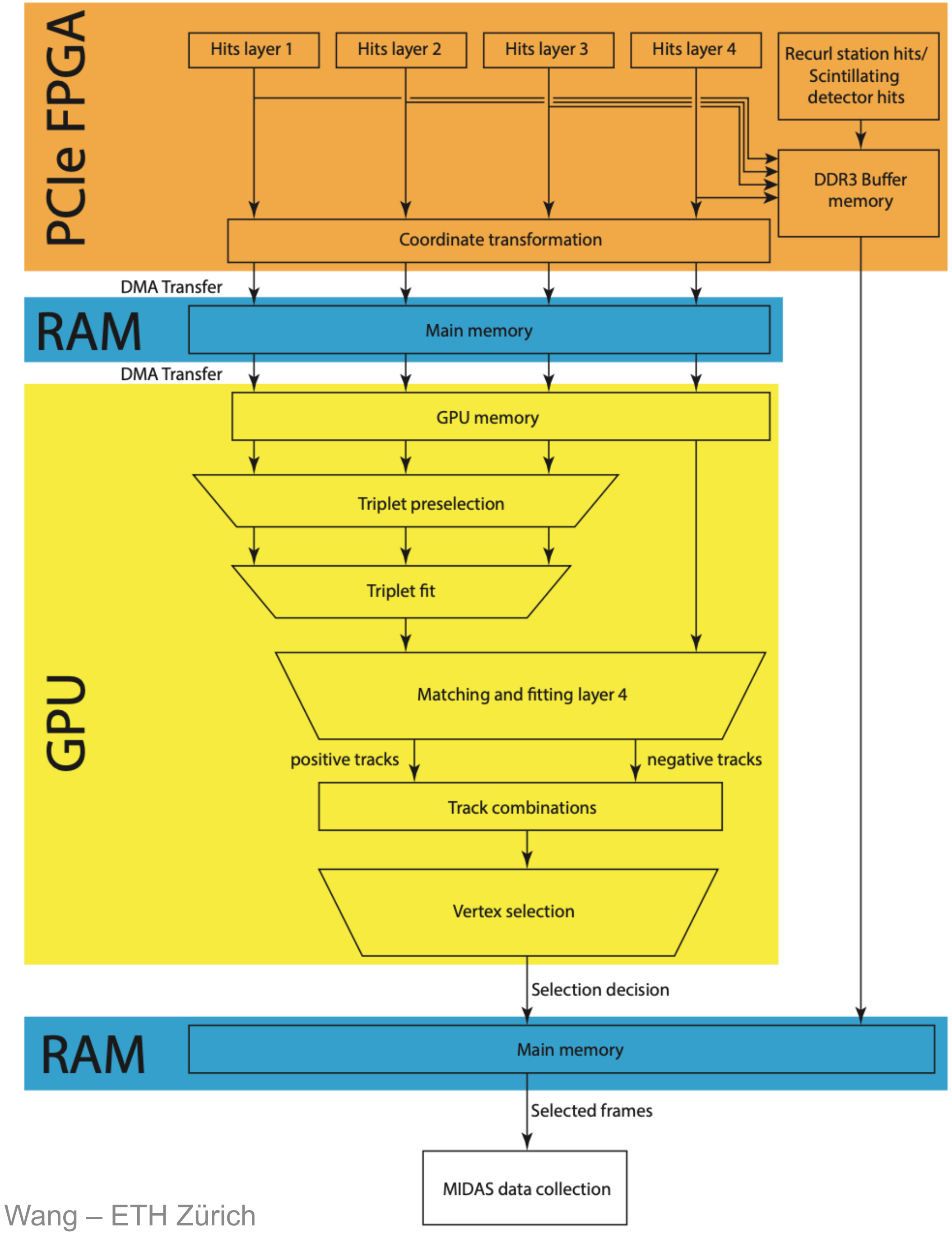
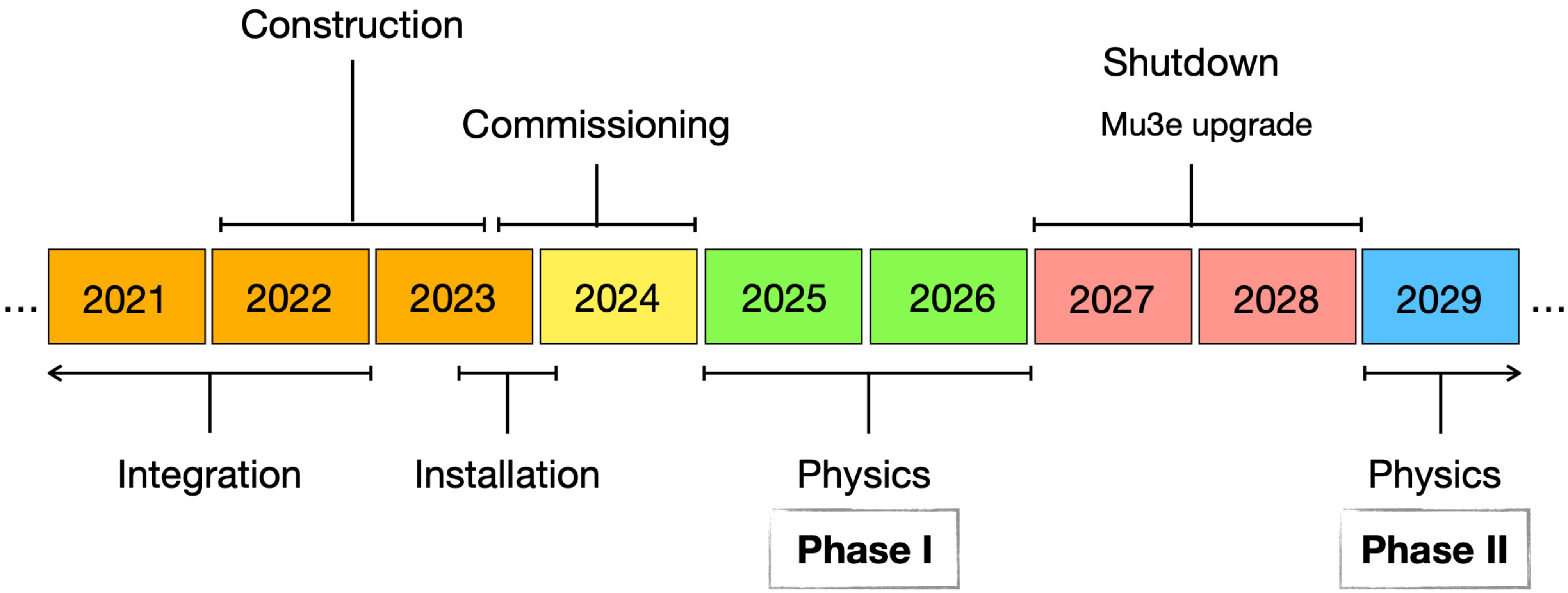
Filter farm

- Triggerless, continuous reconstruction
- Track reconstruction in central pixel detector and vertex finding on GPUs
- Events with μ → eee candidates are send off to mass storage
- Data reduction by a factor of 80

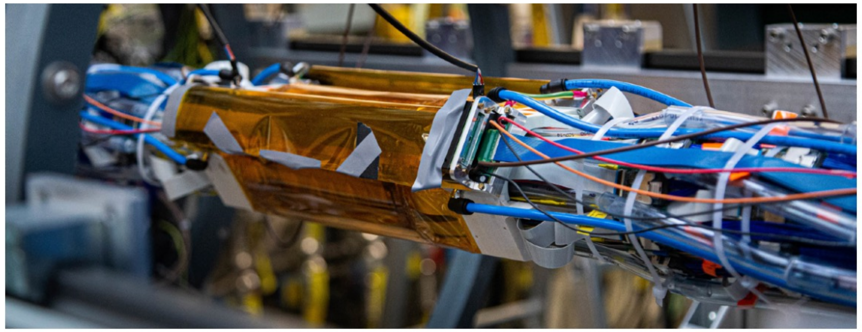


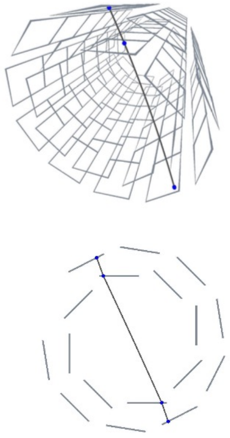
Mu3e timescale

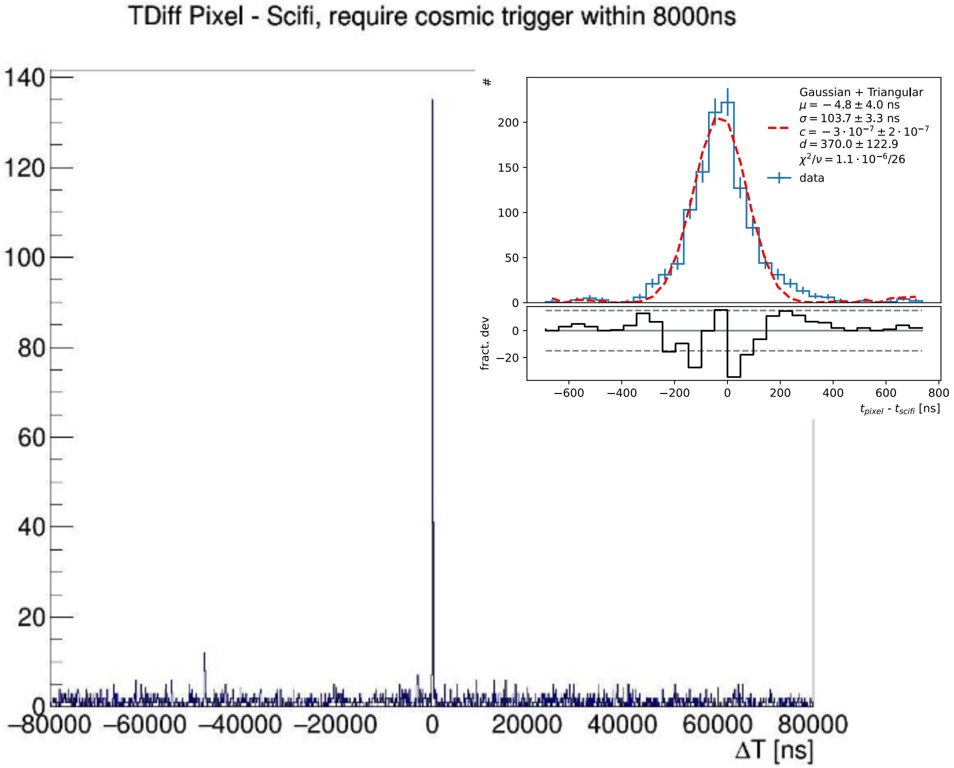


Past integration runs

2021 | 2022



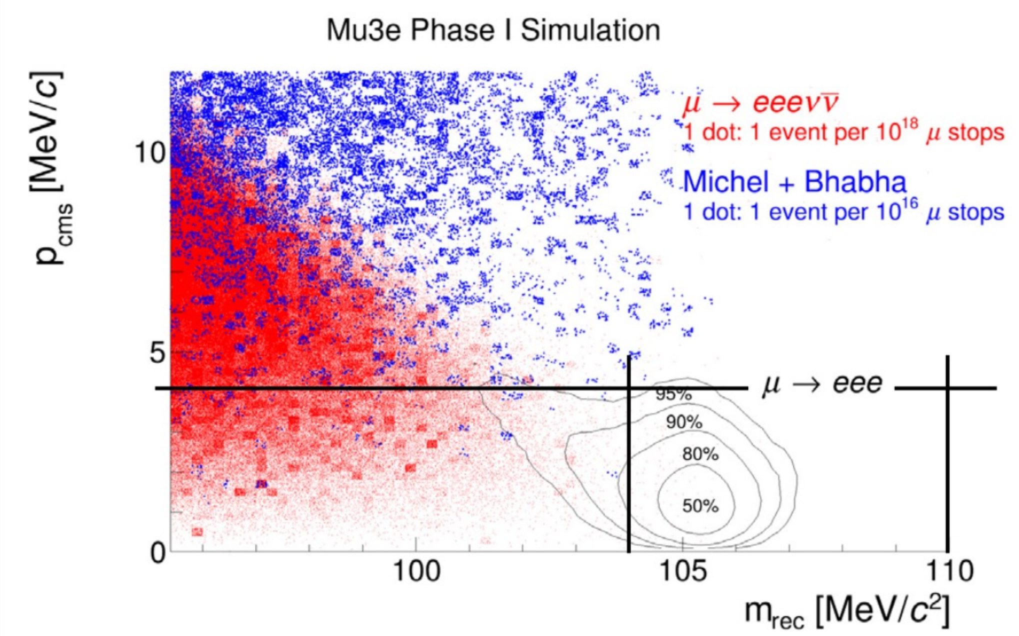




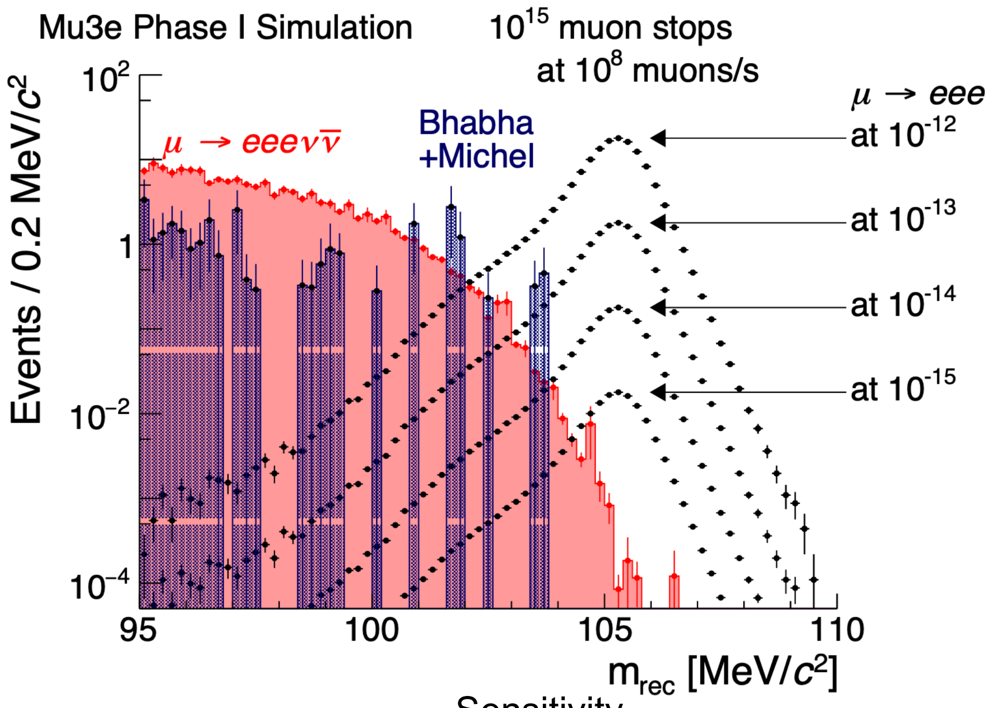
- Integrated runs and testbeam of DAQ, helium/water cooling, magnet
- Reconstructed cosmic muons and recurl electrons
- Track reconstruction and coincidence found to validate the prototype
- Pixel-SciFi and Pixel SciTile combined coincidence search

Simulation for Phase I physics

2021 2022 2023 2024 **2025** **2026** 2027 2028 2029



Phase space



Sensitivity

- Vertex resolution ~0.3 mm (<0.5 mm)
- Momentum resolution ~0.9 MeV (<1 MeV)

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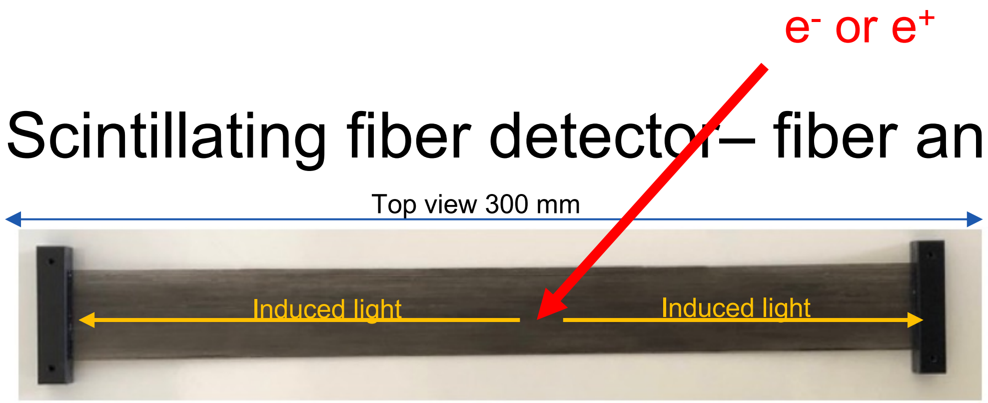
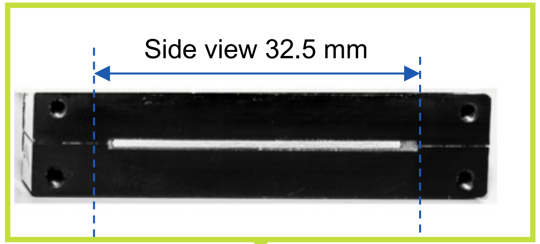
Conclusion

- Mu3e searching for cLFV violation decay mu->eee
- Technical challenges (momentum, vertex and timing…)
- Innovative technologies (HV-MAPS, MuTRiG, Helium cooling, GPU farm…)
- Two-phase physics plan
  - $\mathcal{B} <$ a few 10^{-15} in Phase I (2025-26)
  - $\mathcal{B} < 10^{-16}$ in Phase II (2029+)

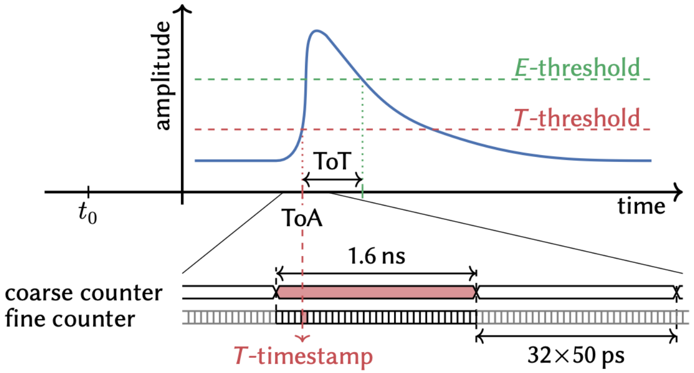
Backup slides

Scintillating fiber detector – fiber and SiPM



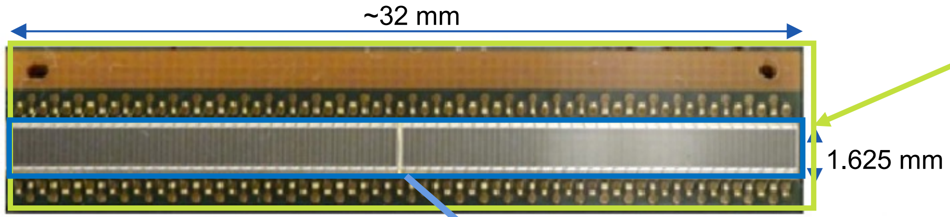


3 layer 250 µm round black epoxy coated fiber
(Kuraray SCSF-78MJ)

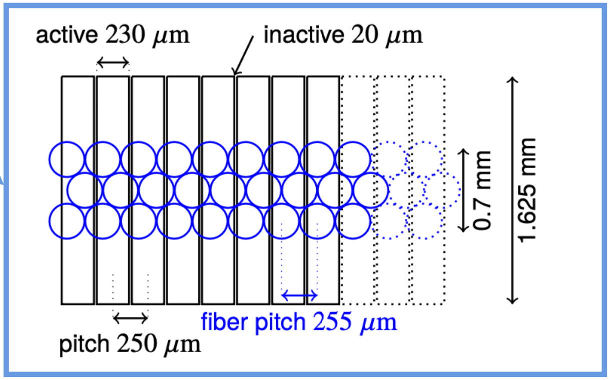


SiPM readout waveform

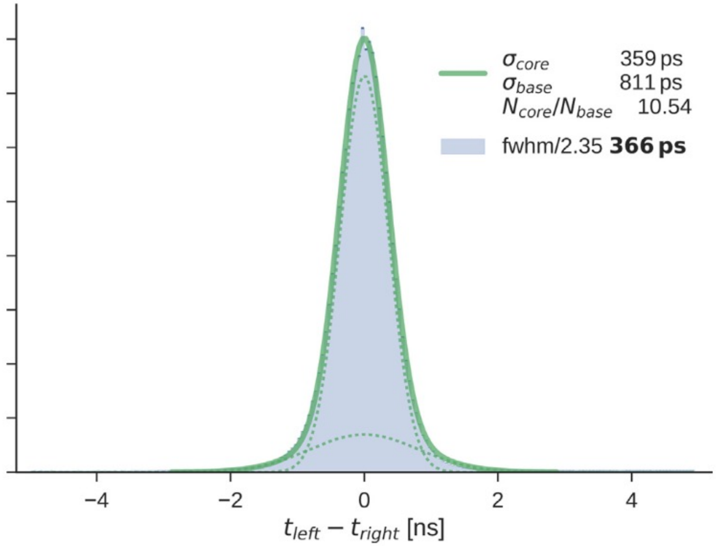
Attaching



SiPM Array
(Hamamatsu S13552-HRQ)



Fiber and SiPM array attached



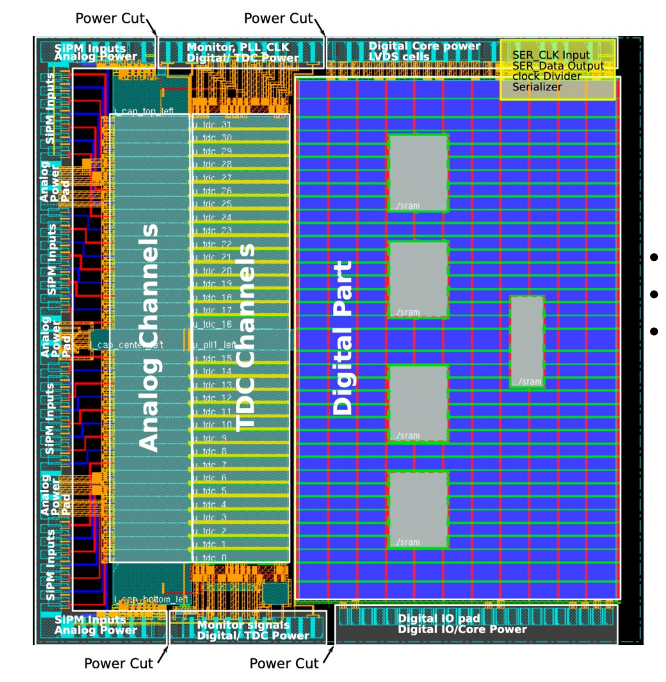
SiPM pulse time resolution
measured with DRS4 (ADC, timing resolution **200 ps**)
To be measured with MuTRiG (TDC, timing resolution **50 ps***)*

MuTRiG - chip design

- MuTRiG (**M**uon **T**iming **R**esolver **i**ncluding **G**igabit-link)

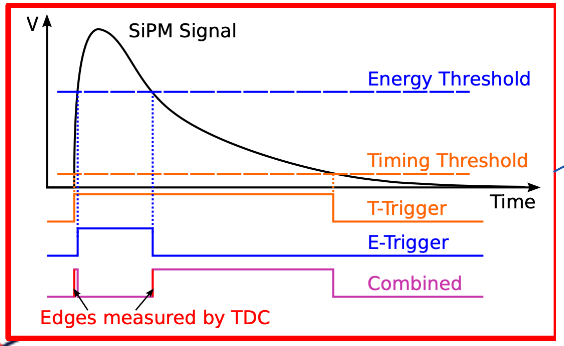
Data link	1.25 Gbps LVDS
IO ports	Fully differential
Analog channels count	32
Wafer	UMC 180 nm
Size	5 mm x 5 mm
Clock speed (nominal)	625MHz

MuTRiG floorplan

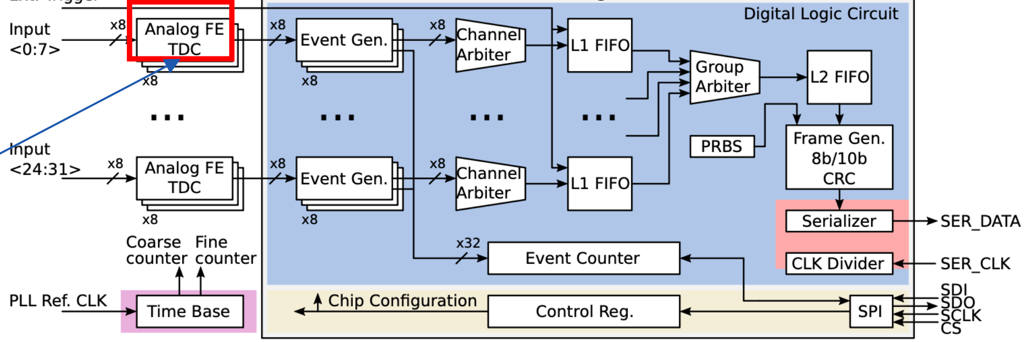


- Event rate > 25 MHz
- 50 ps time resolution
- On-die hit validation by cluster
  - Rejecting > 1MHz of DCR per ASIC

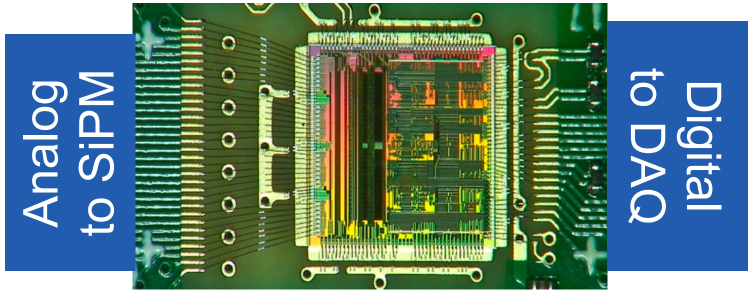
Analog FE digitization



Functional block diagram of MuTRiG



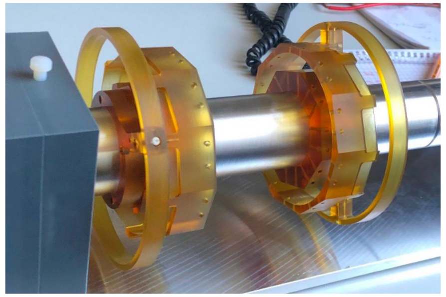
MuTRiG bonded



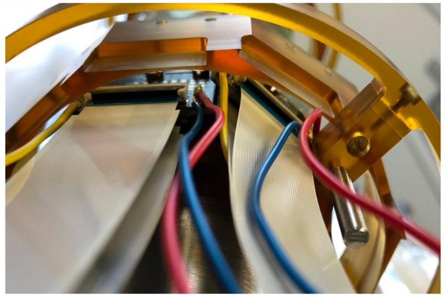
bare die version in picture for SciFi

BGA packaging used for SciTile

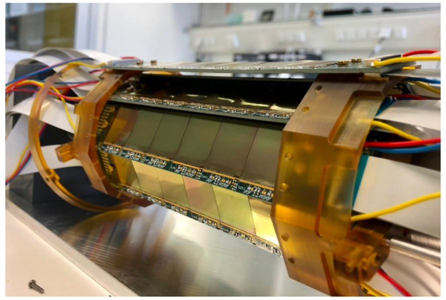
MuPix assemble to pixel ladder



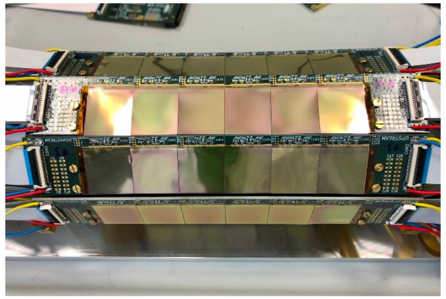
(a) PEI end pieces and double-rings.



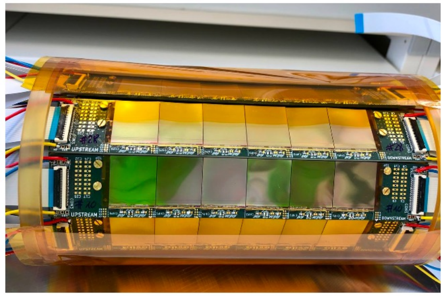
(b) Space for cable feedthrough.



(c) Full L0 assembled.



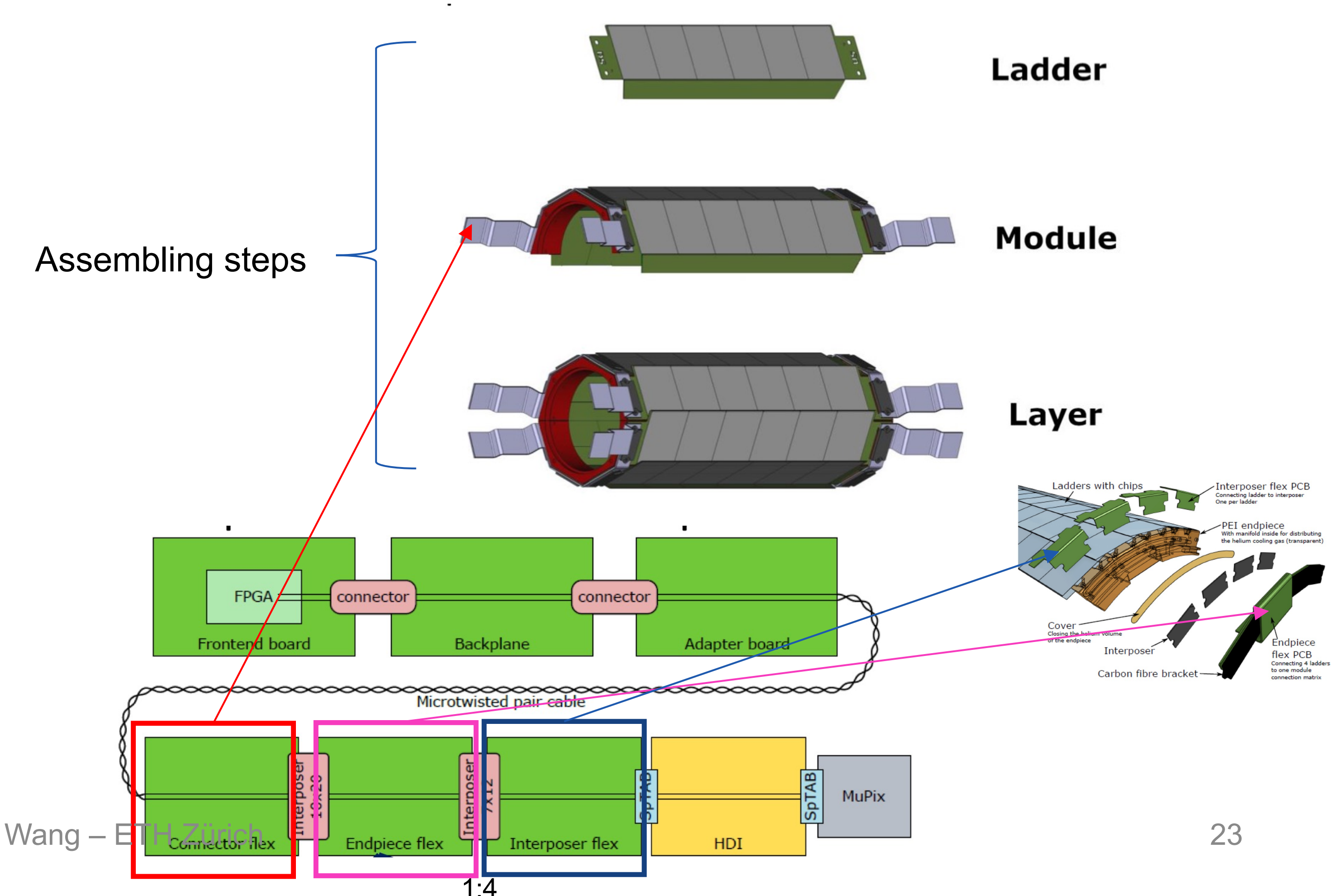
(d) Full L1 assembled.



(e) Mounting of the helium confinement.

(f) Fully assembled prototype.

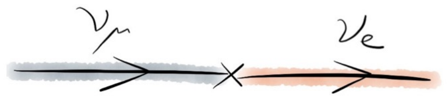
- Mock-ups of cabling and assembly performed for innermost pixel layers
- Extreme space constrains for cabling, flex and uTP cable used



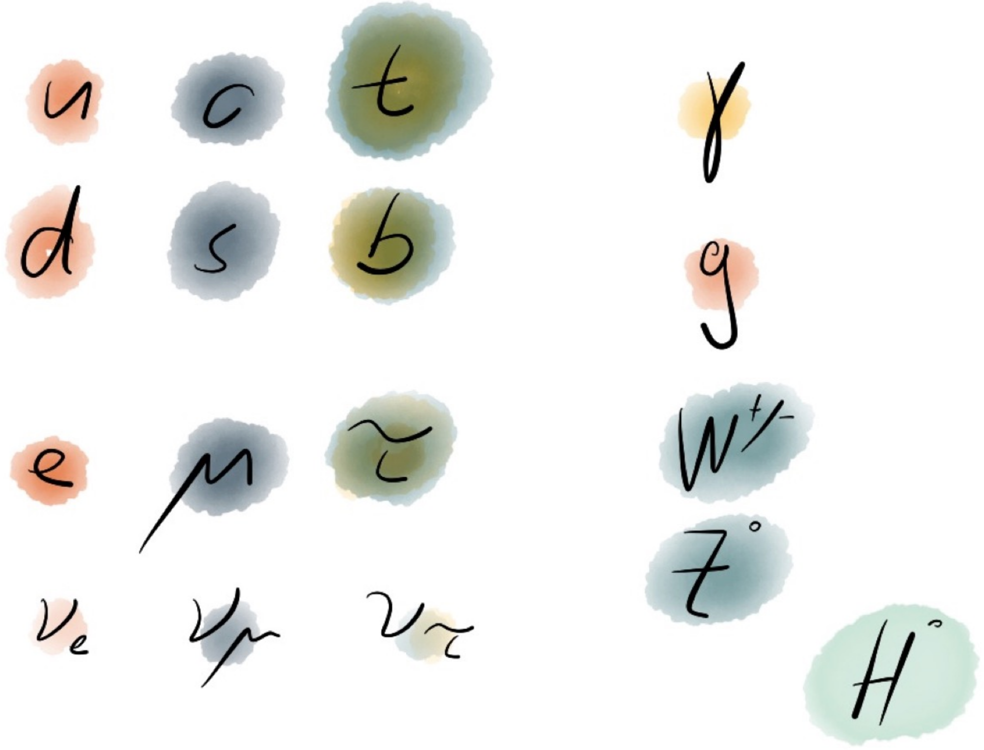
Lepton flavor violation (LFV)

Lepton flavor violation has been observed in neutrino sector (nLFV)

=> SM extension for nLFV, i.e. PMNS-matrix



Lepton flavor violation has never been observed in charge lepton sector (cLFV)



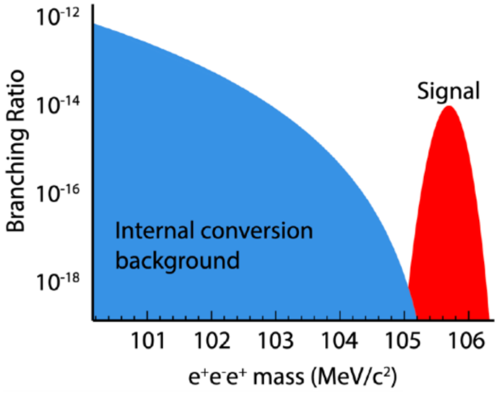
Standard Model particles

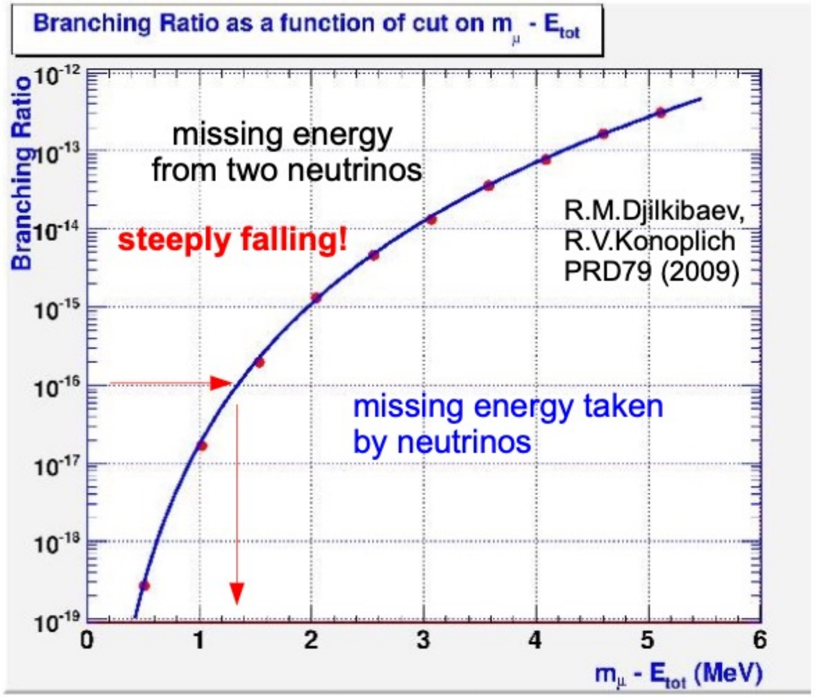
Mu3e physics with kinematics

- All decayed tracks have momemtum <53MeV

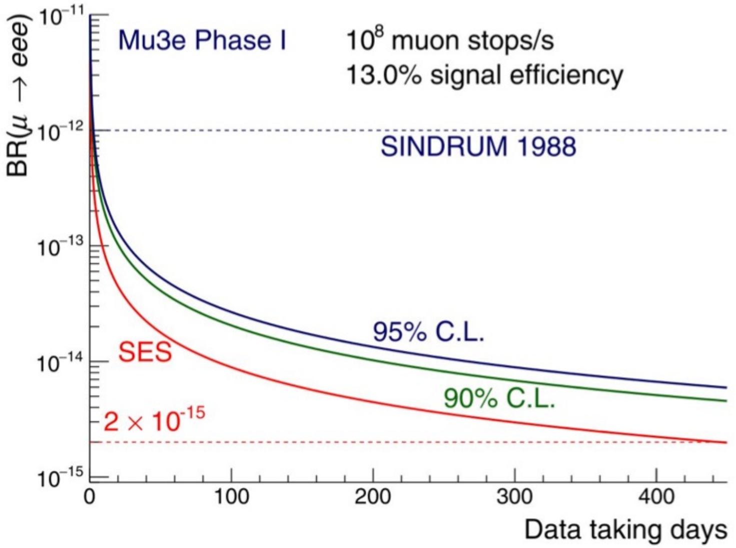
$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$

Muon radiative decays
with internal conversion
$\mu^+ \to e^+e^-e^+\nu\nu$





physics sensitivity, simulations



More about beam

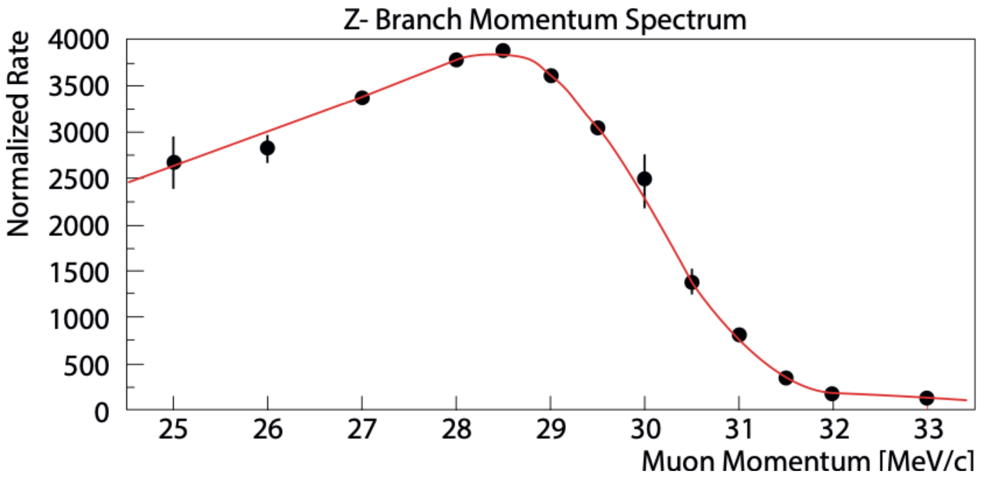


Figure 3.1: Measured muon momentum spectrum in πE5, with full momentum acceptance. Each point is obtained by optimising the whole beam line for the corresponding central momentum and measuring the full beam-spot intensity. The red line is a fit to the data, based on a theoretical $p^{3.5}$ behaviour, folded with a Gaussian resolution function corresponding to the momentum-byte plus a constant cloud-muon background.

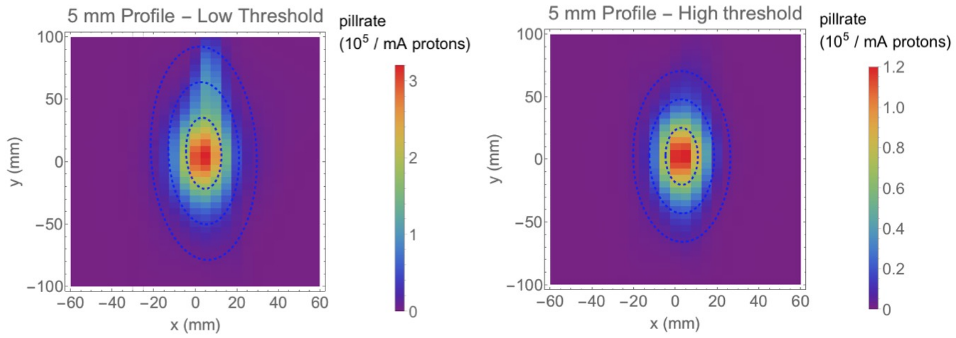
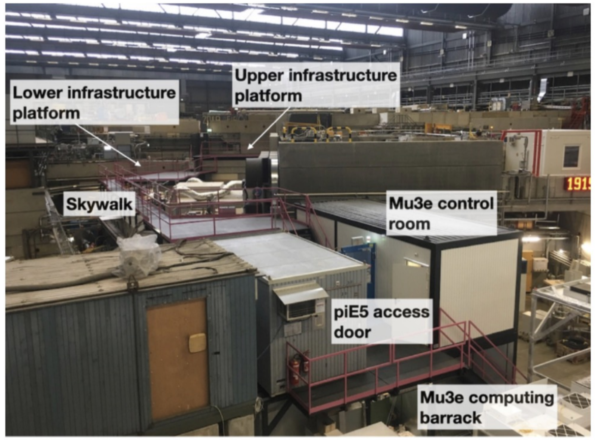
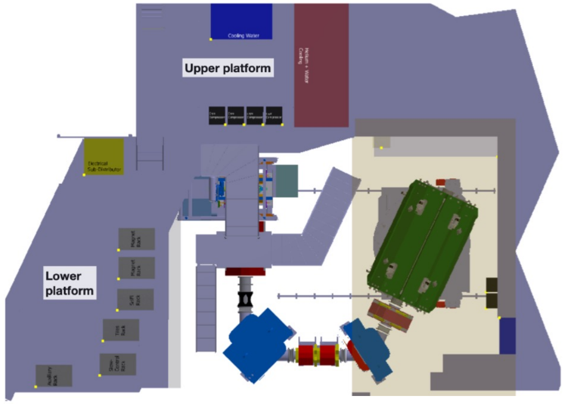


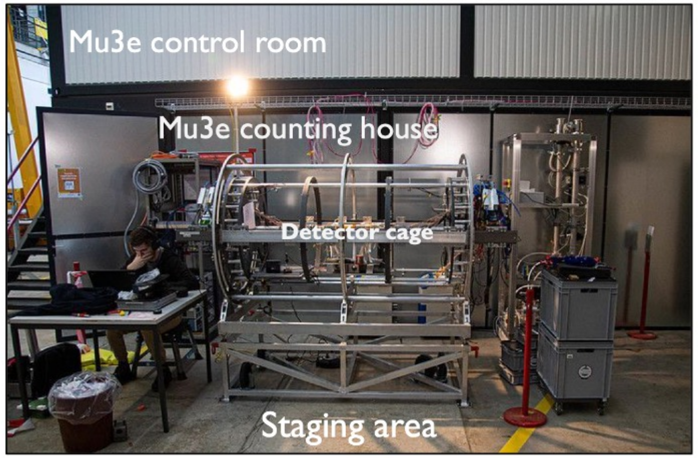
Figure 3.7: Measured beam spot at the injection point to the Mu3e solenoid triggering on either a low (left: muons + Michels + beam positrons) or high (right: muons only) threshold. A 2D Gaussian fit to the muon data yields $\sigma_x = 8$ mm and $\sigma_y = 23$ mm with a total rate of 1.1×10^8 μ^+/s at a proton current of 2.4 mA for a 40 mm long Target E. The vertical beam positron tail in the low threshold profile (top-part) is without the e^+-stopper in triplet II and will be totally removed with the upgraded Wien-filter.

construction and commissioning status, staging-setup, etc

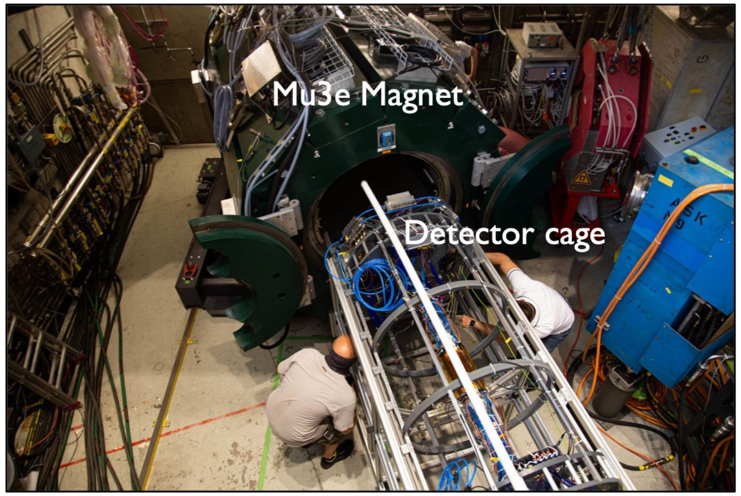




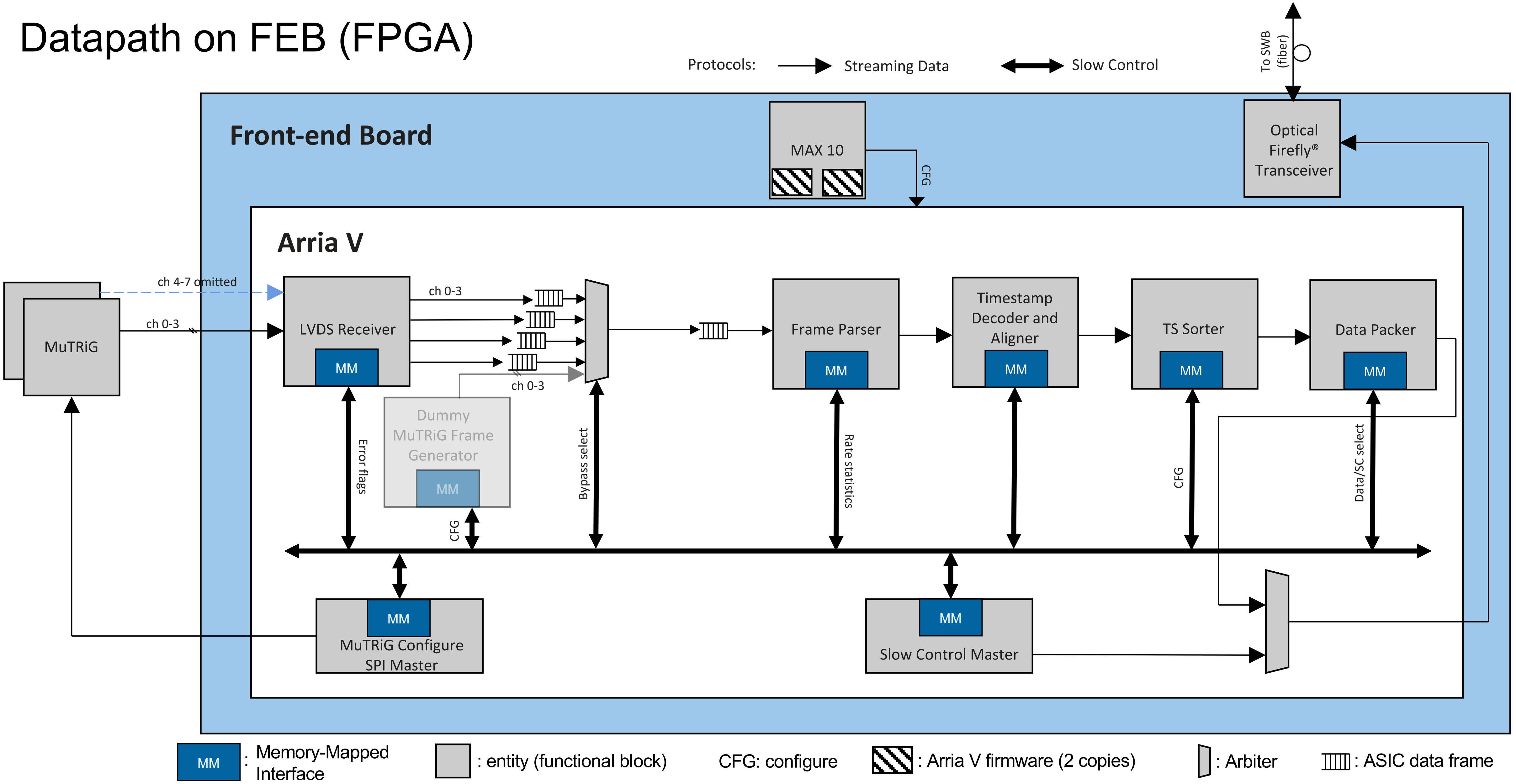
Cosmics in 2022



Beam in 2021

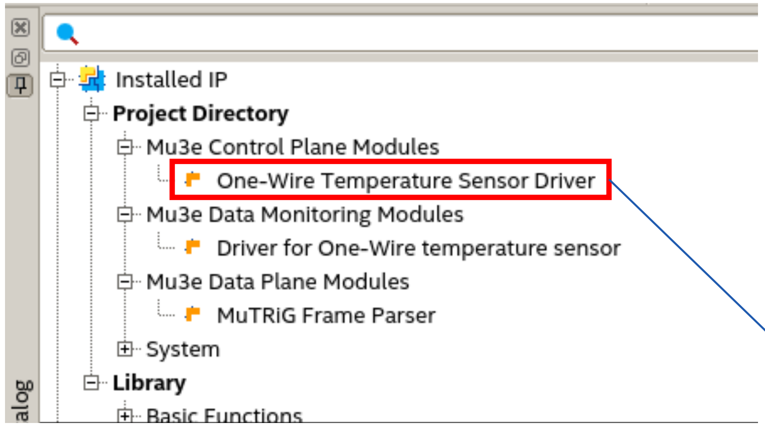


Datapath on FEB (FPGA)

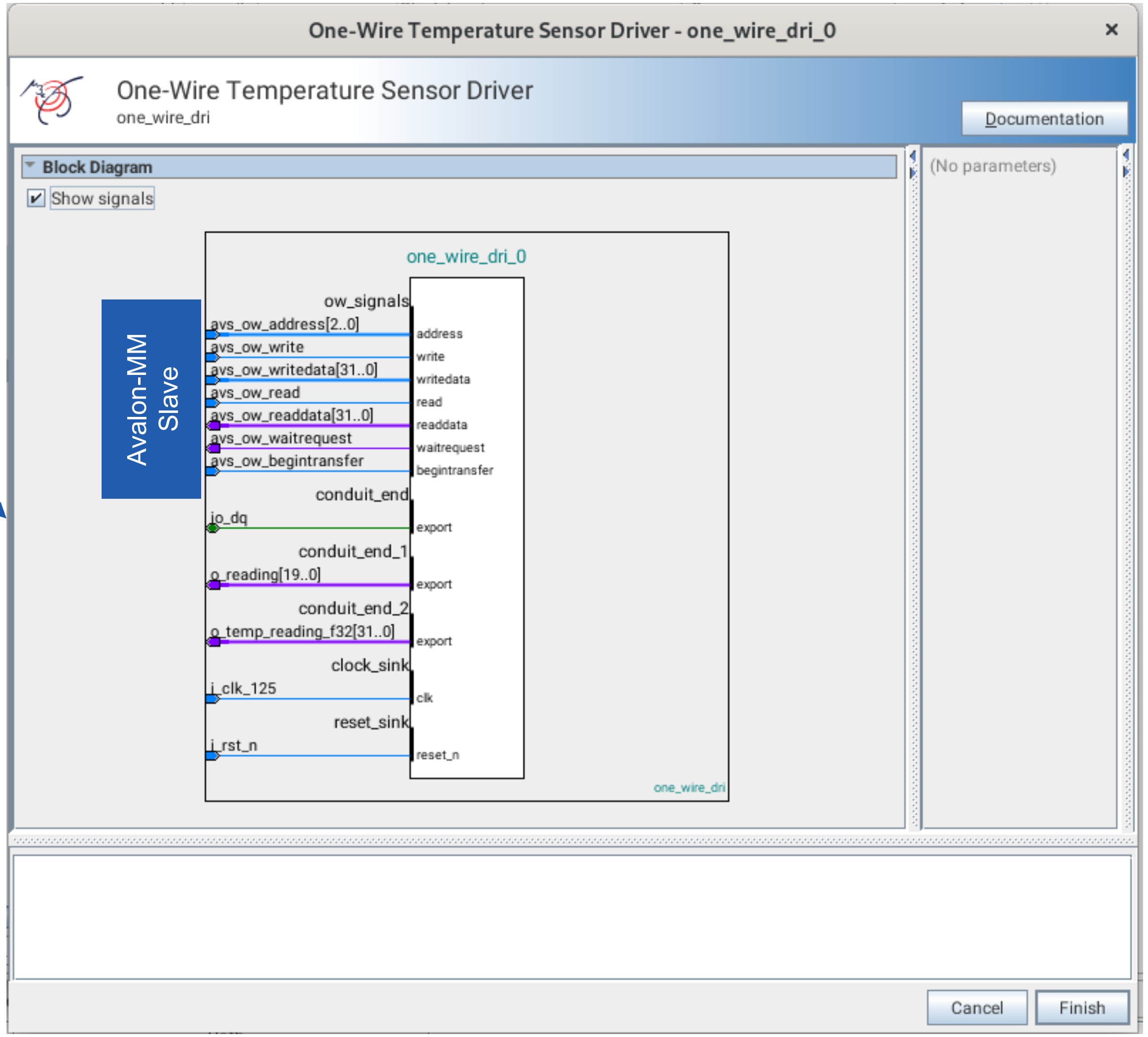


IP-core library of Mu3e experiment

Created Mu3e-specific IP category



Instantiation tab



- Exportable across system (FEB or SWB)
- Integration with NIOS or System Console
- One-click instantiation
- Zero-debugging effort from user side
- User Friendly GUI
- Auto-interconnection with Avalon-Memory Mapped interface

- Display floating-point 32 reading
- Support parasitic powering (with 500 Ohm pull-up resistor)
- Support rolling or one-time readout

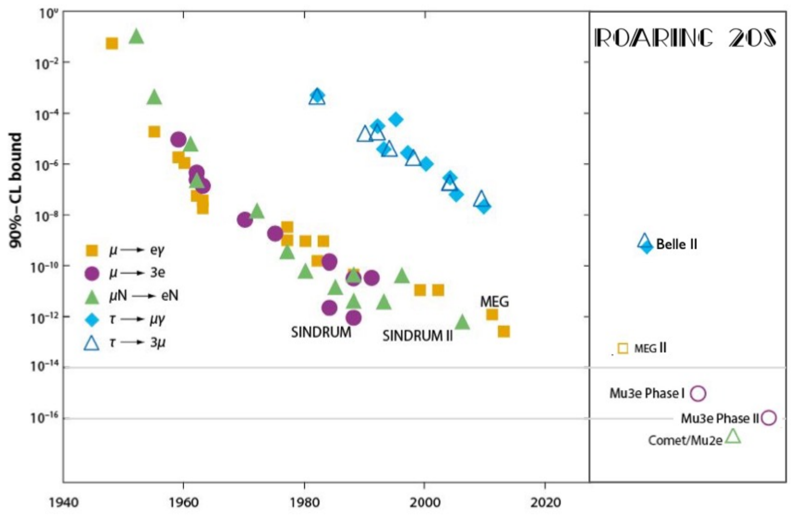
Mu3e phase II

Mu3e Phase I experiment:

- ❑ Run at the πE5 CMBL
- ❑ Reach 2 x 10^{-15} S.E.S in 400 days

Phase I, so there is a phase II?

- ❑ Reach 10^{-16} S.E.S. on $\mu^+ \to e^+e^+e^-$
- ❑ Can not run at the existing beamline,
  Need 10^9 μ^+/s on target
  - HIMB



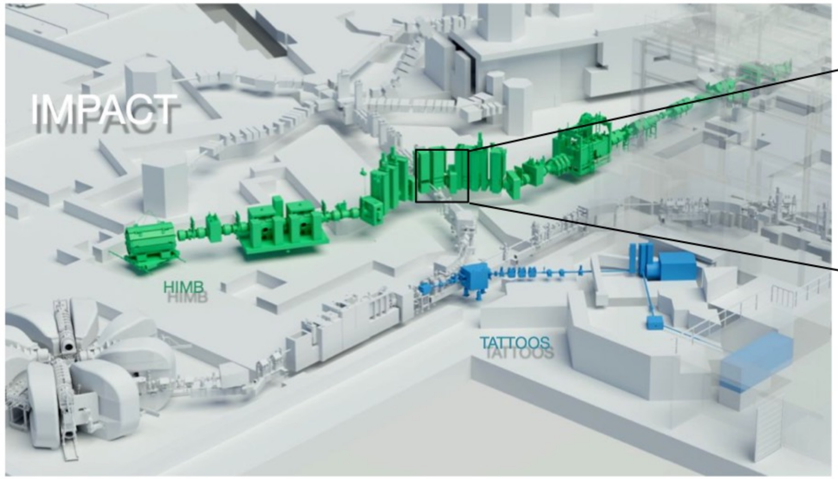
Slides from Frederik Wauters in CLFV2023

Mu3e one of the main physics cases for this next generation facility.

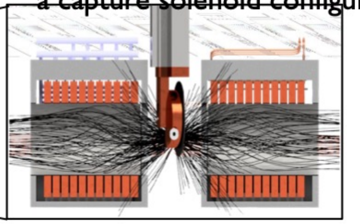
Science Case for the new High-Intensity Muon Beams HIMB at PSI
Edited by A. Knecht, F. Meier Aeschbacher, T. Prokscha, S. Ritt, A. Signer

arXiv:2111.05788

+ https://www.psi.ch/en/impact
+ Thursday afternoon at this conference



Repace target M with
a capture solenoid configuration



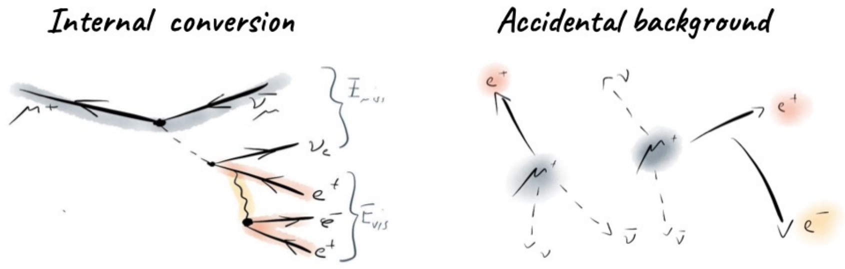
50

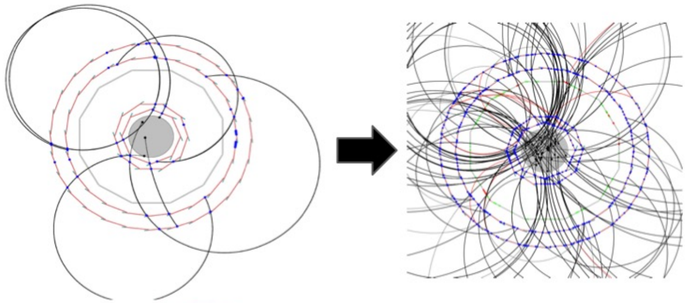
Mu3e phase II

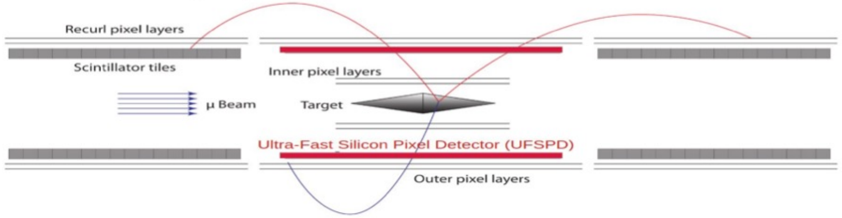
Mu3e Phase I experiment:
- ❑ Run at the πE5 CMBL
- ❑ Reach 2 x 10^{-15} S.E.S in 400 days

Phase I, so there is a phase II?
- ❑ Reach 10^{-16} S.E.S. on $\mu^+ \to e^+e^+e^-$
- ❑ Can not run at the existing beamline,
  Need 10^9 μ^+/s on target
  - HIMB

Mu3e Phase II Challenges:
- ❑ Internal conversion goes with #muons
  → Thinner (total material budget) ~~Fibre Detector~~
- ❑ Accidental goes with #muons^2
  → Faster (silicon sensors)
  → Smaller (silicon pixels)
  → Larger (target)
- ❑ As does the combinatorics of track finding
  → Smarter (online filtering)
- ❑ Large phase space of the beam



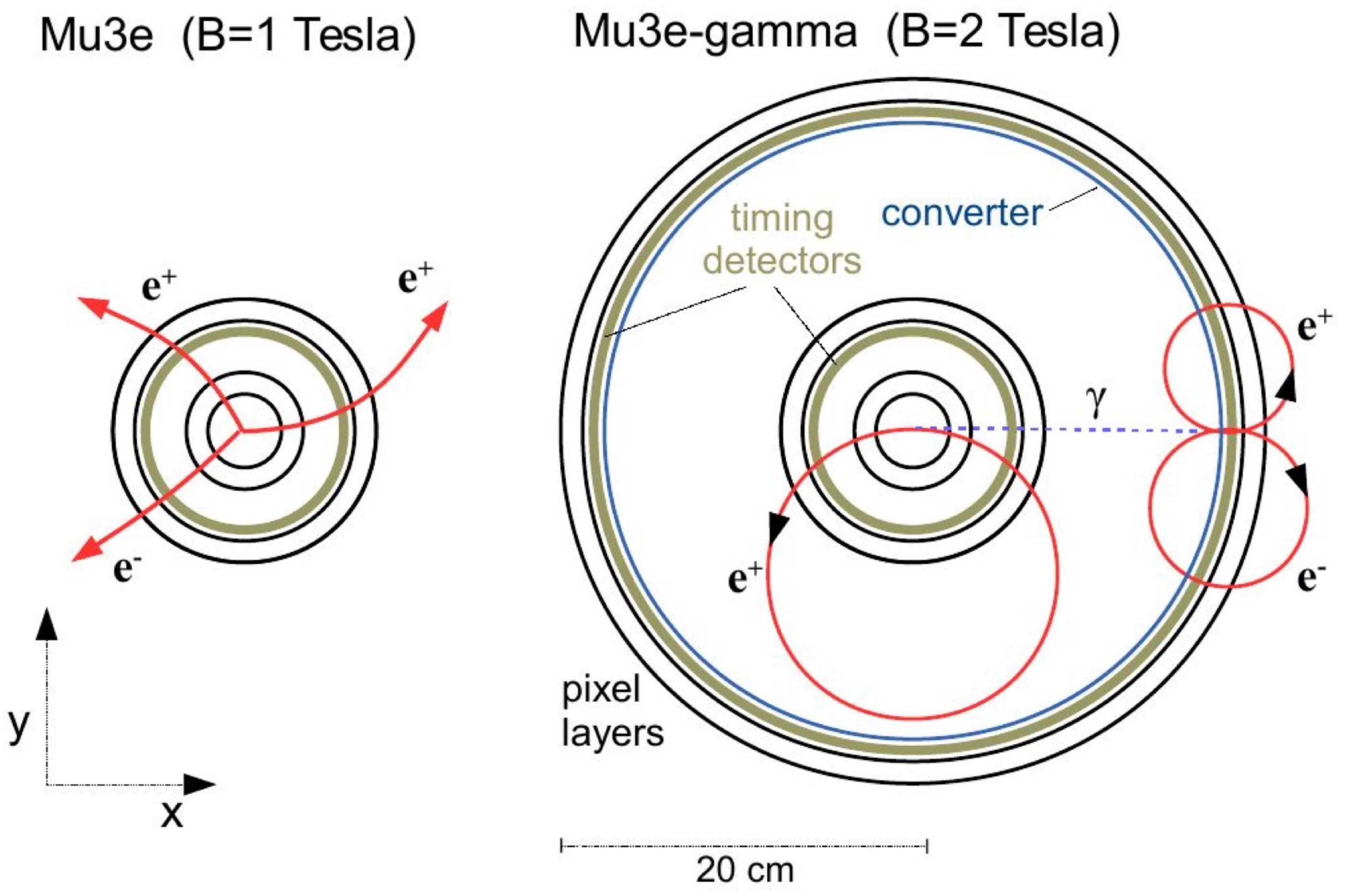




➡ Most of the Phase I detector needs a redesign
➡ We need new, fast the active pixel detector
- SiGe CMOS?

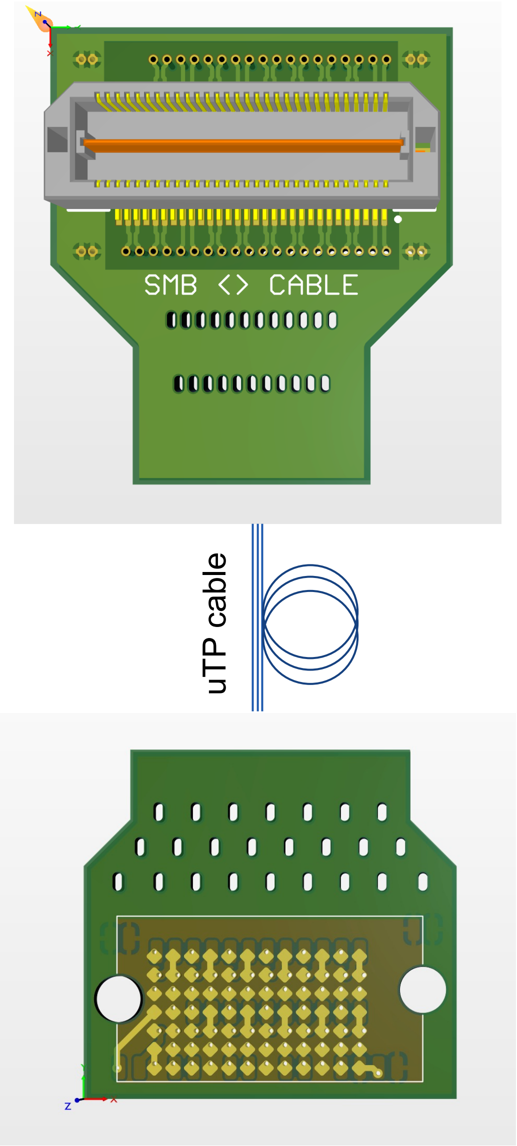
Slides from Frederik Wauters in CLFV2023

Conceptual design for gamma conversion at Mu3e



Slides from Frederik Wauters in CLFV2023

Connector boards



ETH zürich

Yifeng Wang
D-PHYS
yifenwan@phys.ethz.ch

ETH Zürich
Inst. f. Teilchen- und Astrophysik
HPK E 25
Otto-Stern-Weg 5
8093 Zürich Switzerland