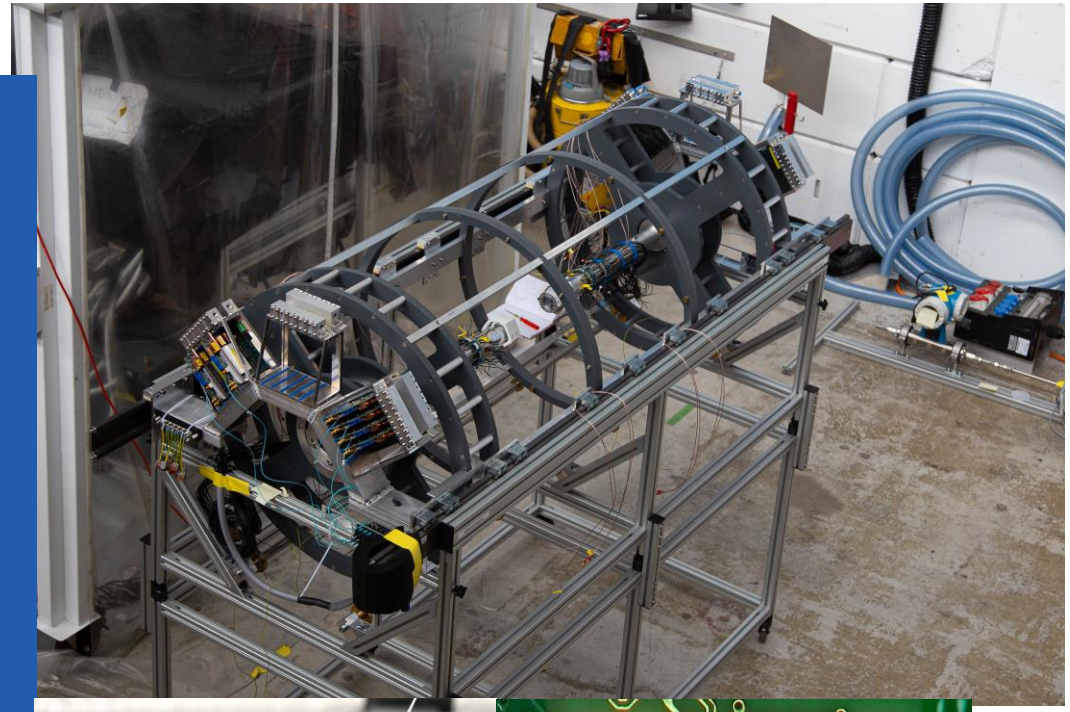
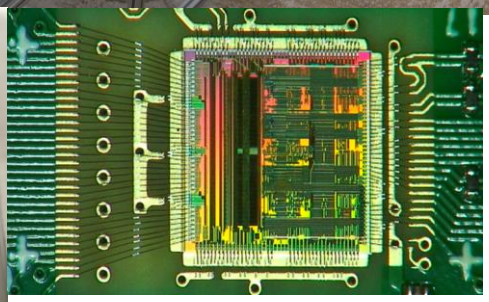
The DAQ system of the Mu3e SciFi detector

Joint Annual Meeting of the Swiss Physical Society and Austrian Physical Society

Yifeng Wang
on behalf of the Mu3e Collaboration
6.9.2023





Physics goal: Lepton flavor violation (LFV)

- Motivation: Lepton flavor violation has been observed in neutrino sector
  - SM extension for nLFV, i.e. PMNS-matrix

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

- Benefit: Free of SM background

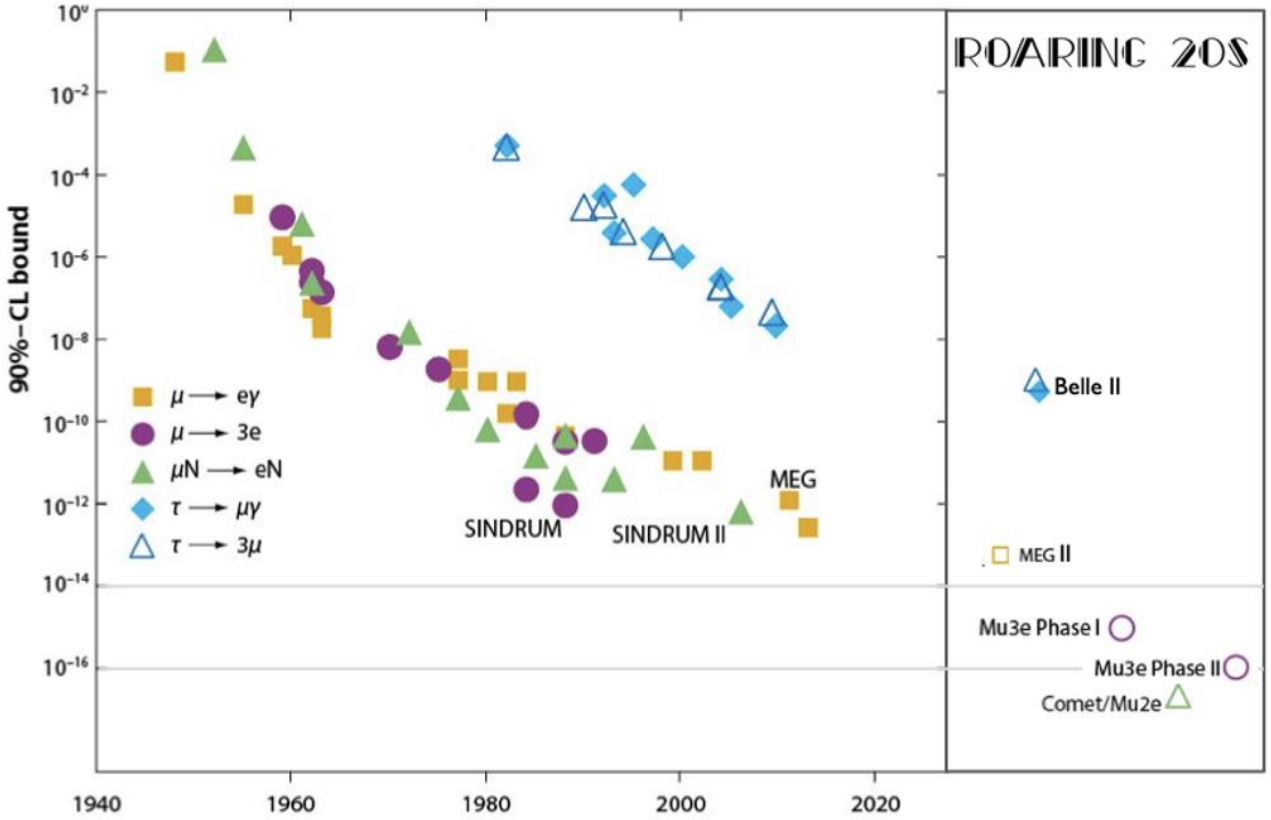
SM suggested decay

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

- Status: current limit in cLFV searches (mu->eee)

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

Worldwide status of muon decay search for charged LFV



Introduction of Mu3e Collaboration

- Constructing a future experiment 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**.

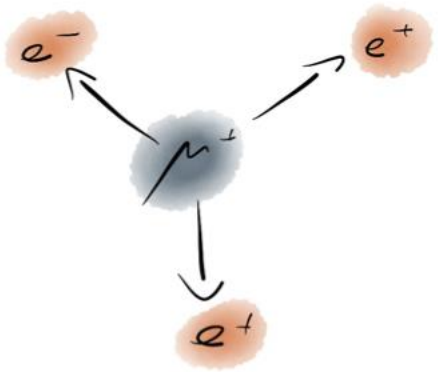
Ref:adapted from New Frontiers in Lepton Flavor by Cristina Martin Perez

Searching for cLFV at Mu3e

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

Signal:

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



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

Background:

Internal conversion background

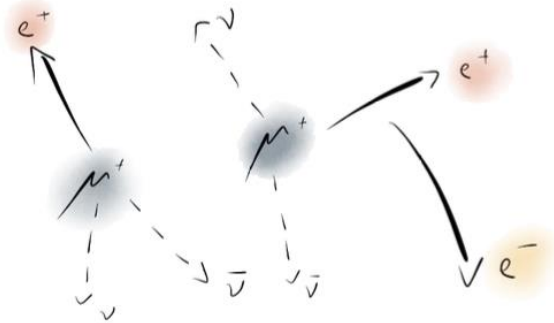
$\mathcal{B}(\mu \to eeevv) = 3 \times 10^{-5}$

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

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

Accidental background

$(\mu \to evv) + (? \to ee) \propto N$

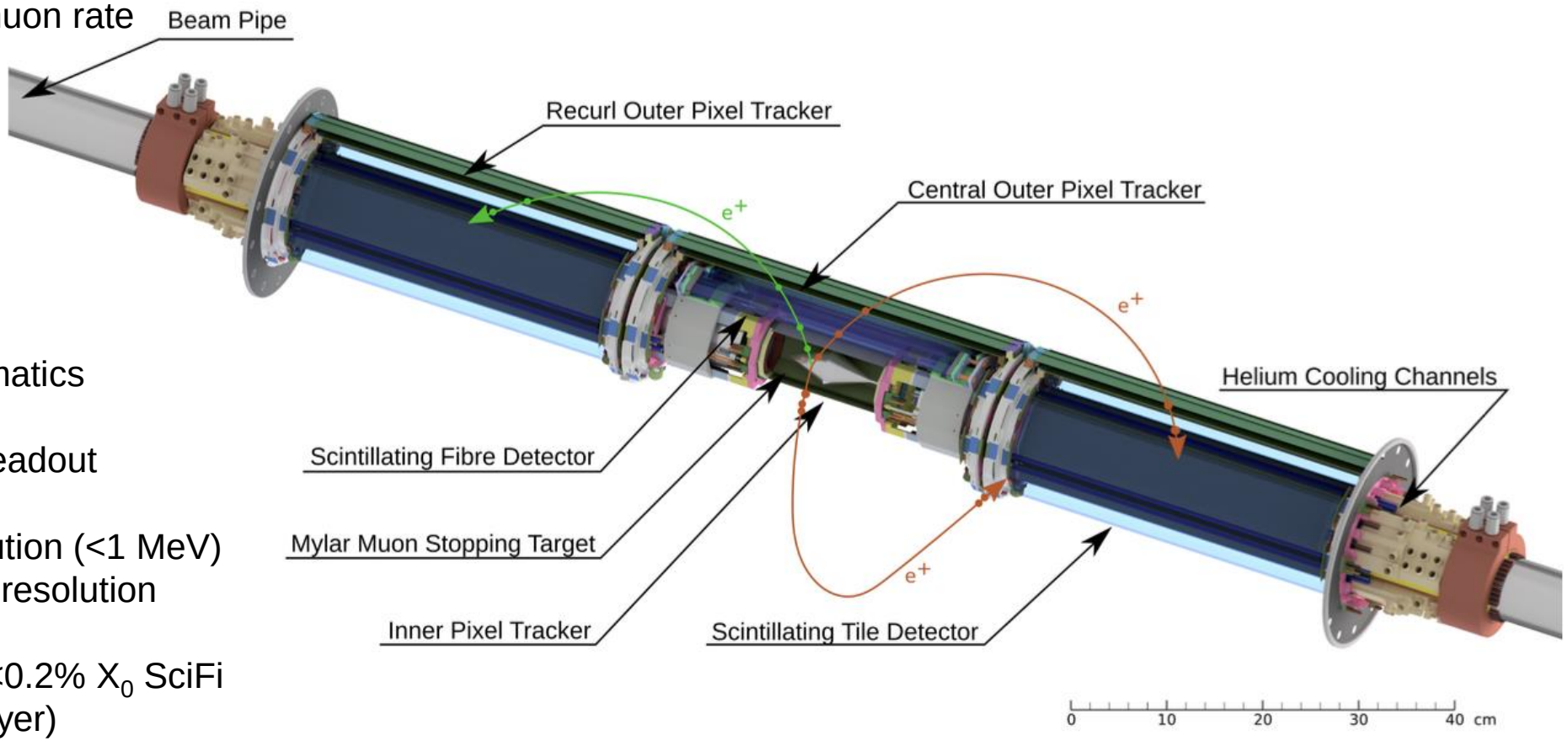


Rejected with excellent **timing** and **vertex** resolution

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

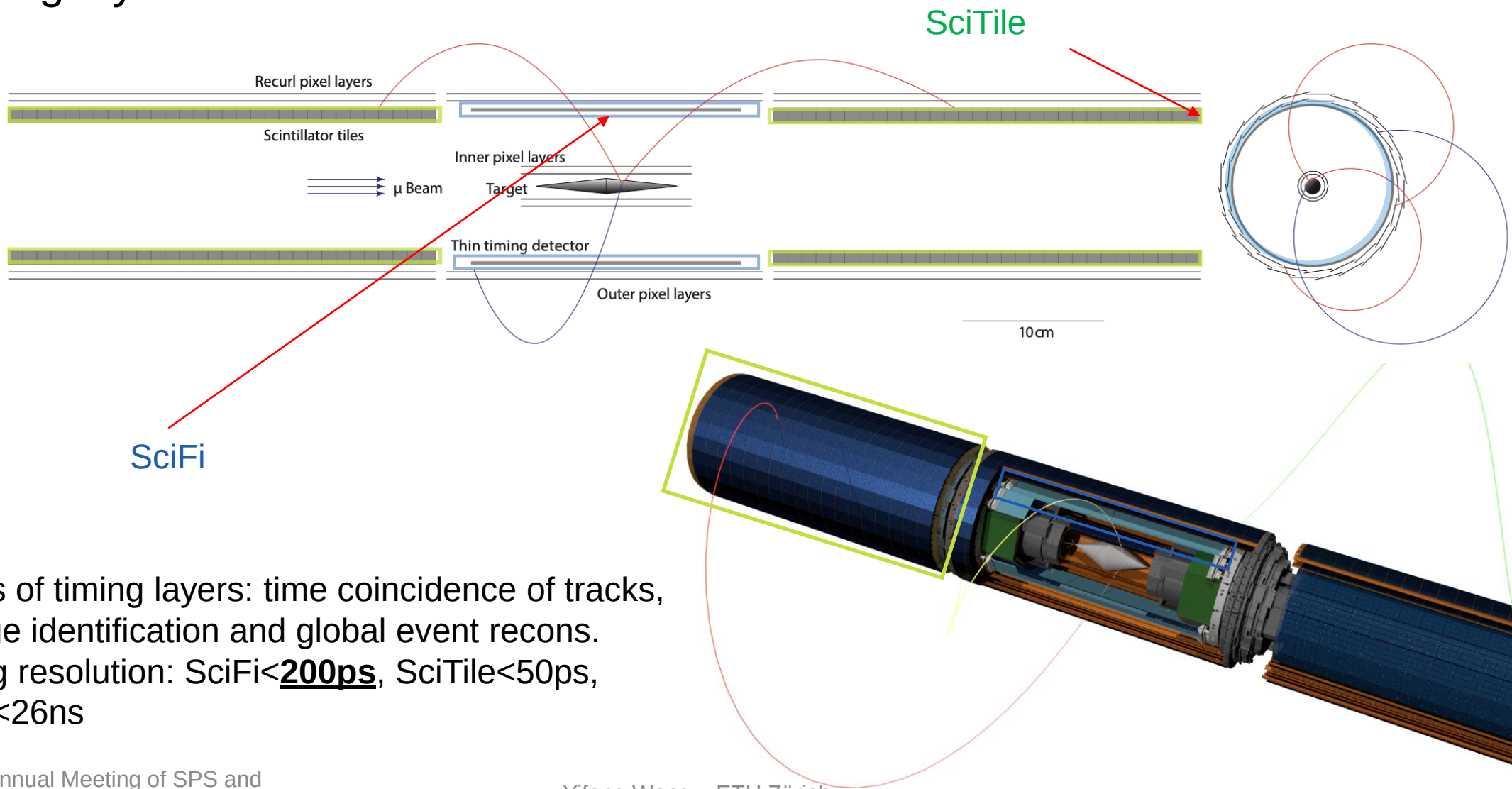
Mu3e design challenges

- 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)

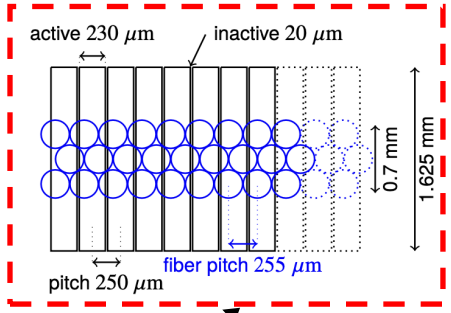
Timing layers in Mu3e



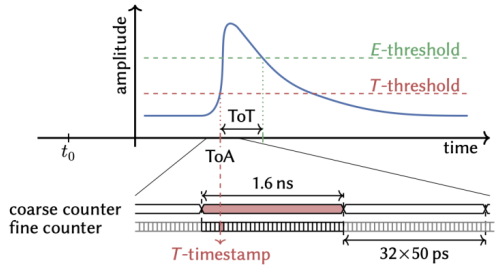
Goals of timing layers: time coincidence of tracks, charge identification and global event recons.
timing resolution: SciFi<**200ps**, SciTile<50ps, Pixel<26ns

SciFi detector - construction

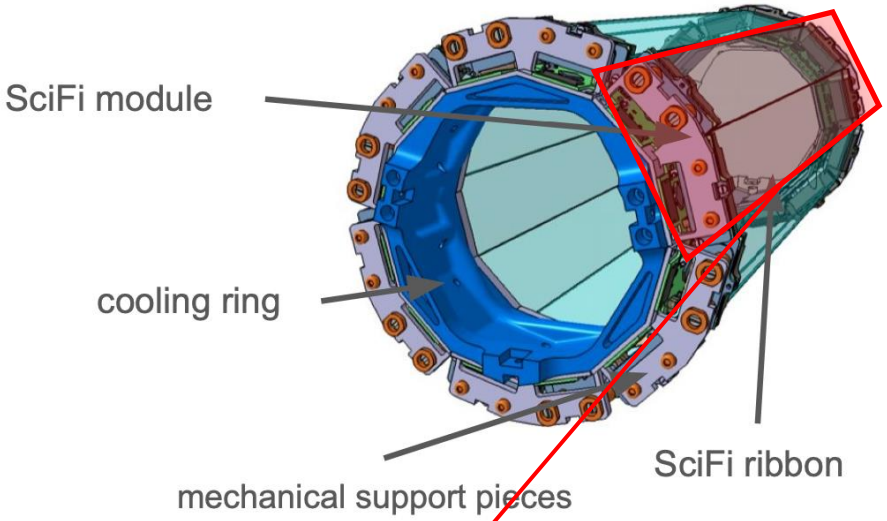
Fiber and SiPM array attached



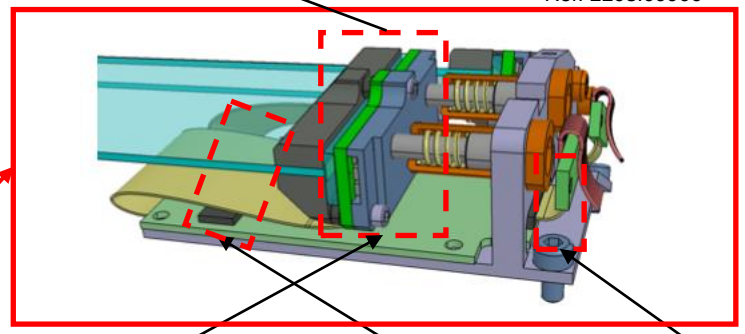
SiPM readout waveform



on one end of the fiber ribbon



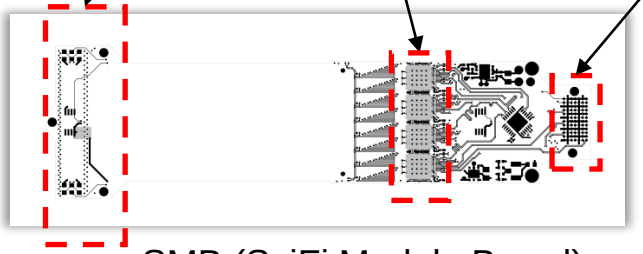
Ref: 2208.09906



Fill factor >60%

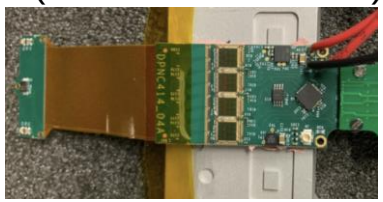
µtwsited pair (µTP) cable bundles

SiPM MuTRiG x4 interposer

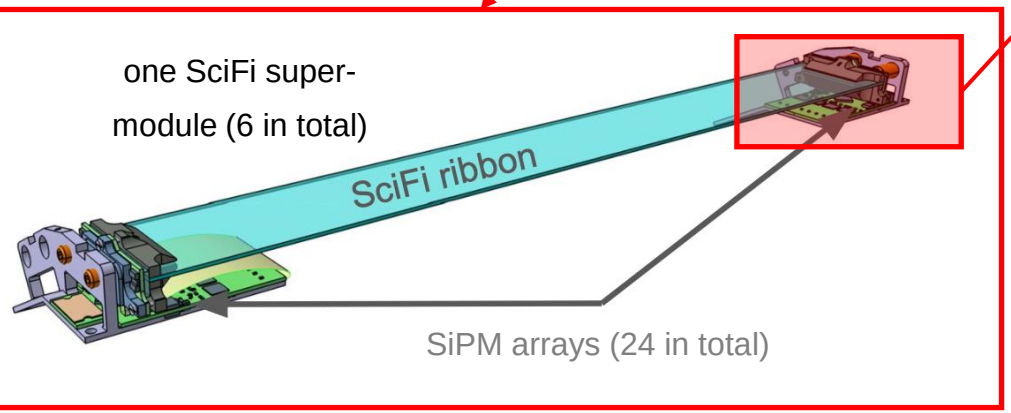


To FPGA

SMB (SciFi Module Board)



one SciFi super-module (6 in total)



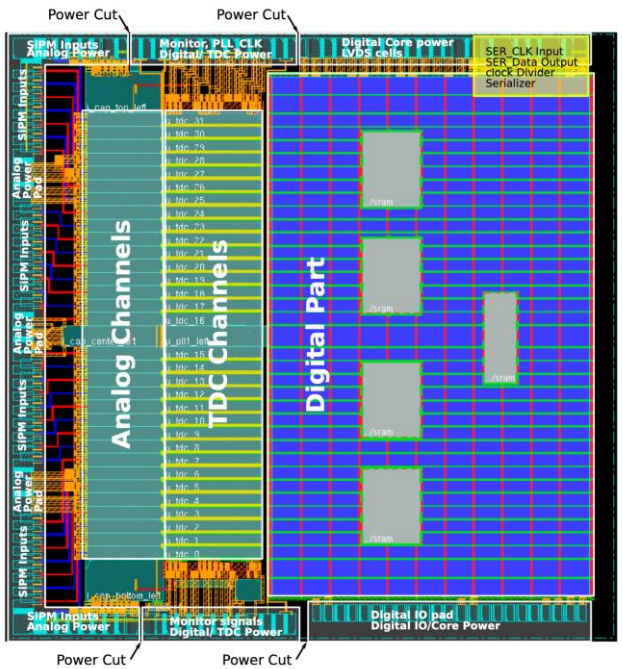
Ref: Y. Demets, BVR 2023

Specialized timing chip - MuTRiG

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

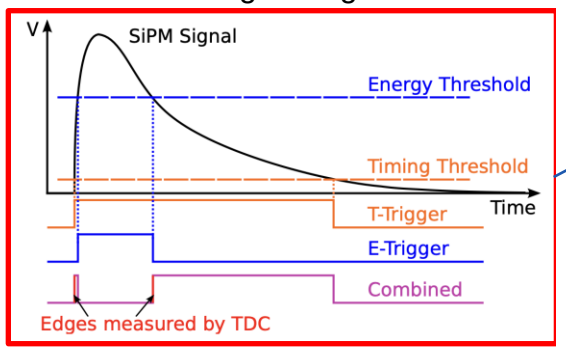
Data link	1.25 Gbps LVDS
IO ports	Fully differential
Analog channels count	**32**
Wafer	UMC 180 nm
Size	5 mm x 5 mm
Clock speed (nominal)	625MHz

MuTRiG floorplan

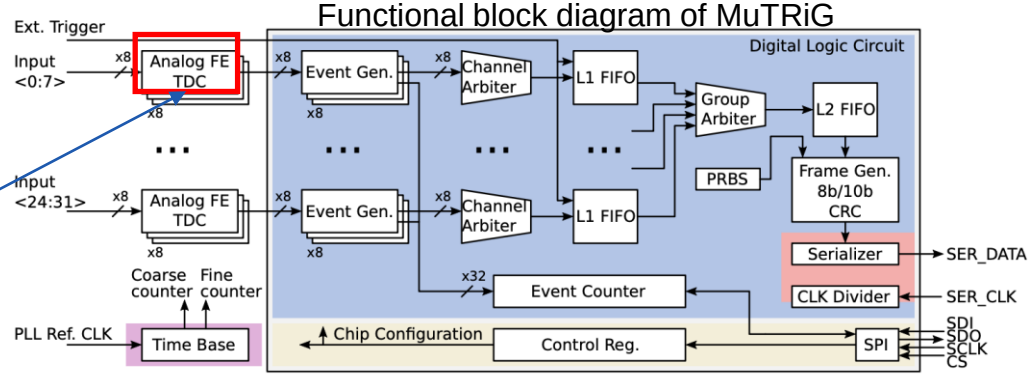


- Event rate **> 25 MHz**
- **50 ps** time resolution
- On-die **hit validation** hardware algorithm
  - Rejecting 50%+ of DCR

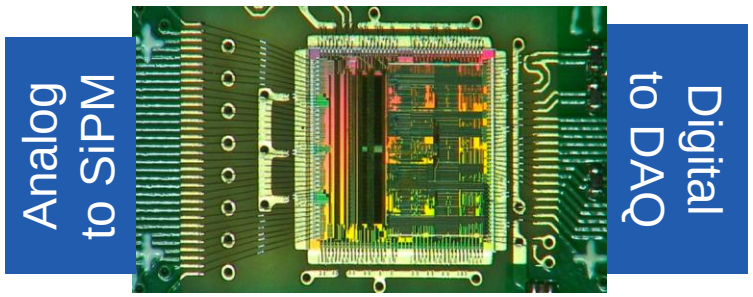
Analog FE digitization



Functional block diagram of MuTRiG

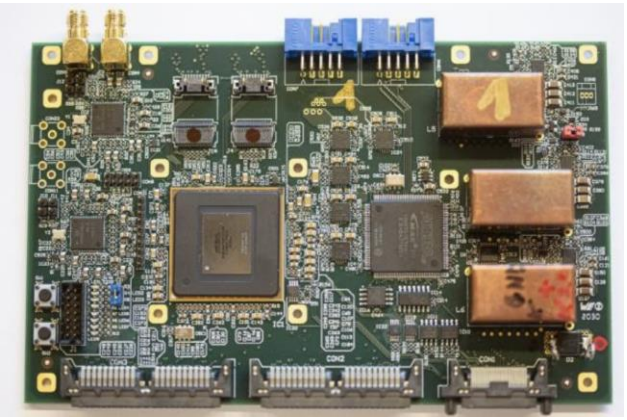


MuTRiG bonded

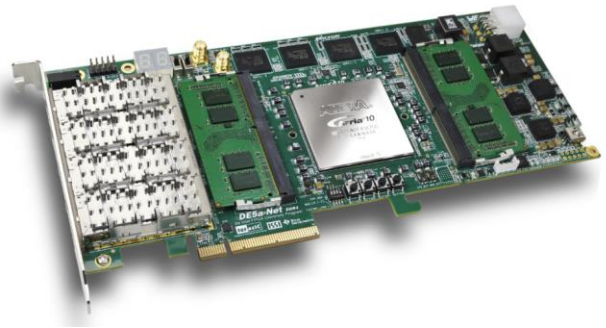


bare die version in picture for SciFi
BGA packaging used for SciTile

Triggerless Data acquisition (DAQ) system



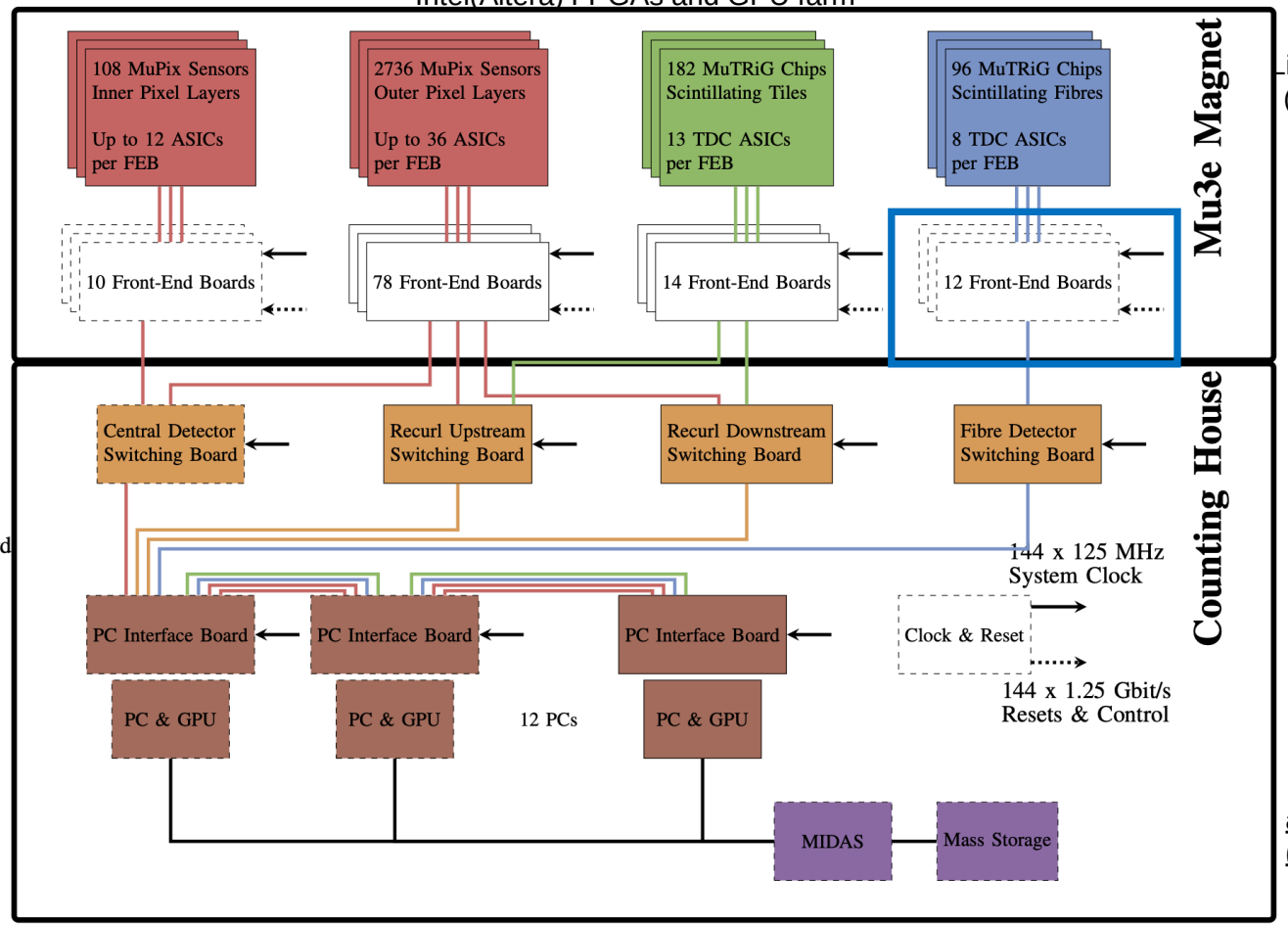
Front-end Board - **Customized Arria V board** - 8 XCVR



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

Mu3e DAQ architecture

Intel(Altera) FPGAs and GPU farm



Link bottleneck bandwidth (maximum allowed data rate) of SciFi

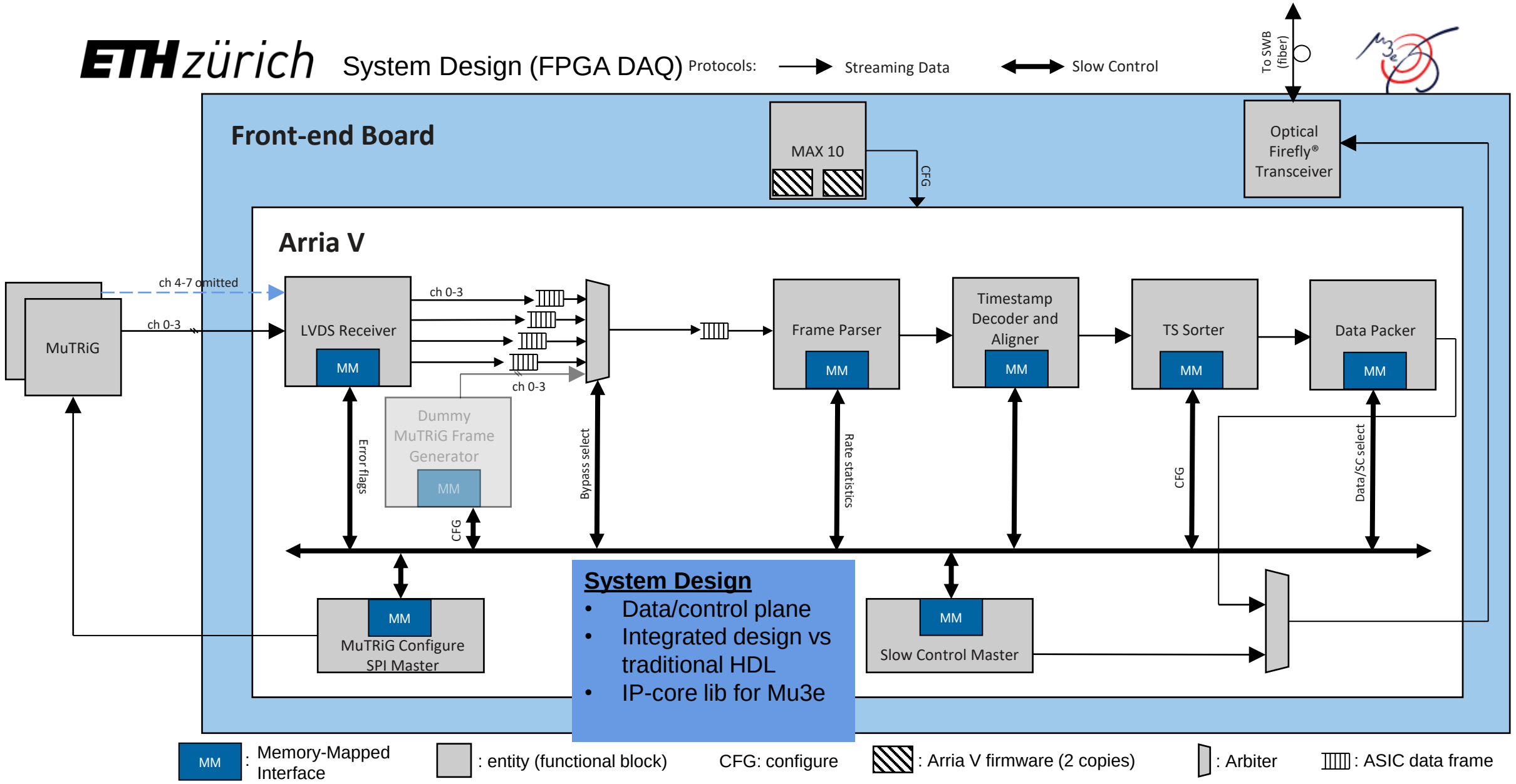
120 Gbps

144 Gbps

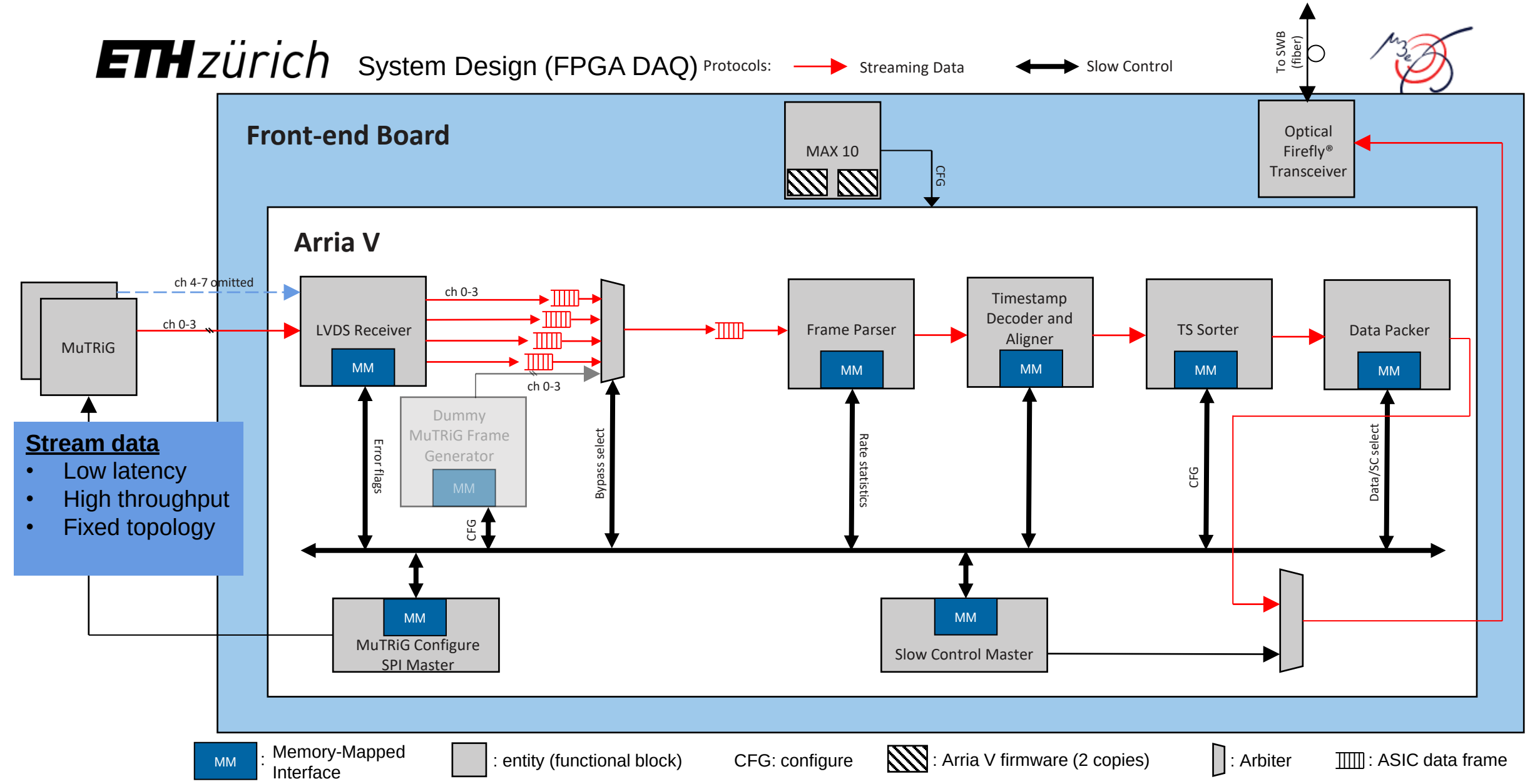
38 Gbps

a few Gbps (whole mu3e)

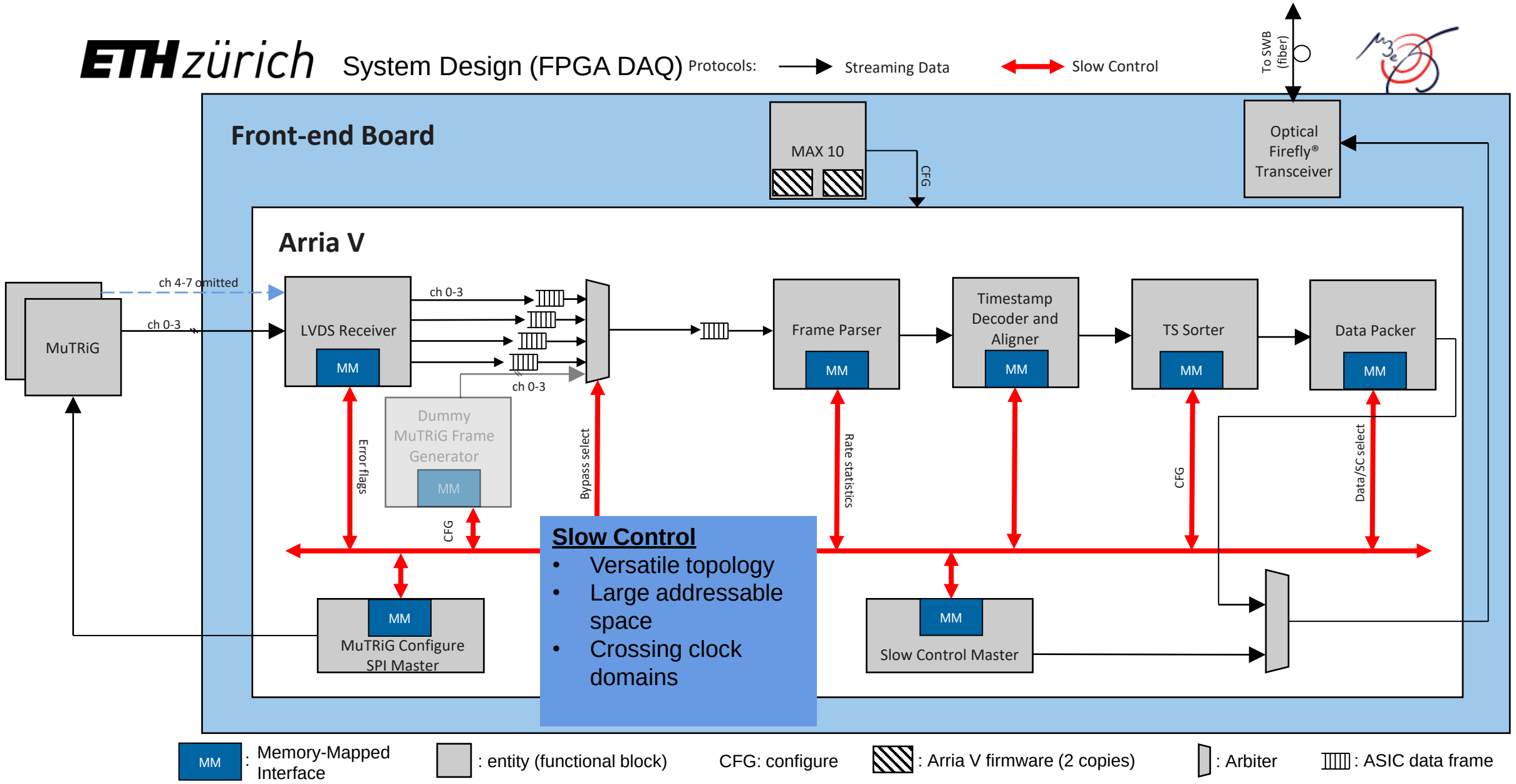
System Design (FPGA DAQ)



System Design (FPGA DAQ)

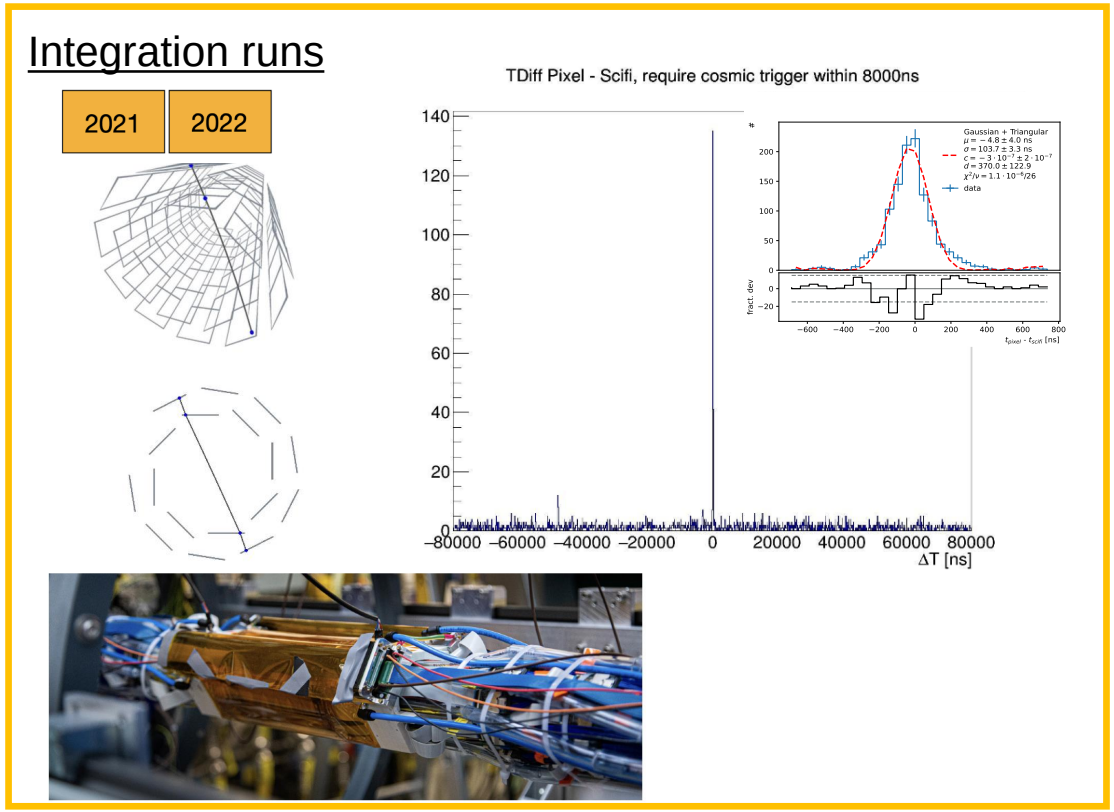


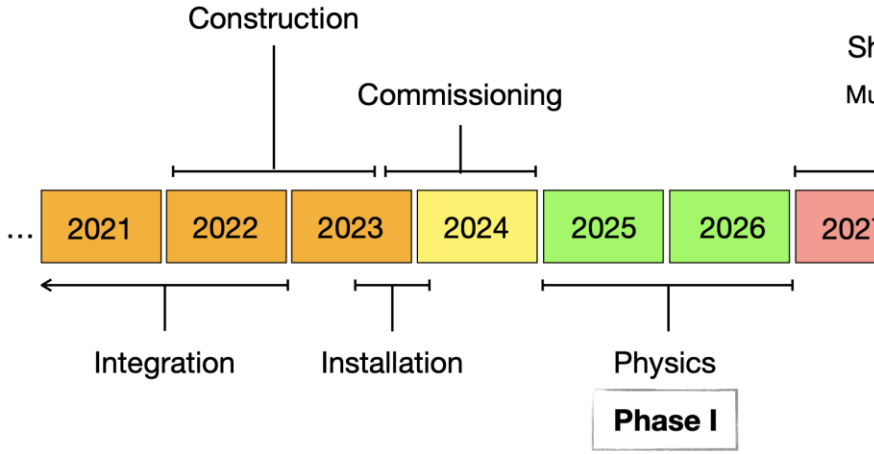
System Design (FPGA DAQ)



Conclusion

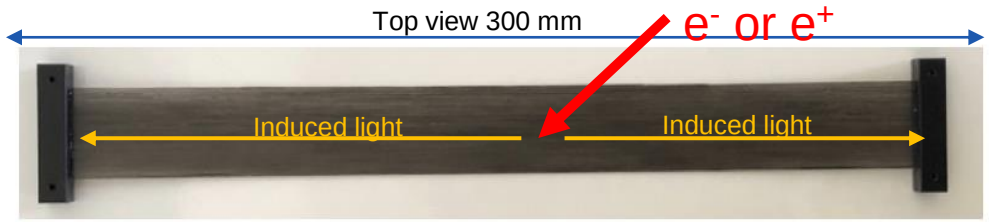
- Two-phase physics plan
  - $\mathcal{B} <$ a few 10^{-15} in Phase I (2025-26)
  - $\mathcal{B} < 10^{-16}$ in Phase II (2029+)
- Mu3e searching for cLFV violation decay mu->eee
- Technical challenges in SciFi (timing, high data-rate, …)
- FPGA-based DAQ system (low latency, high throughput, IP-packaging, …)

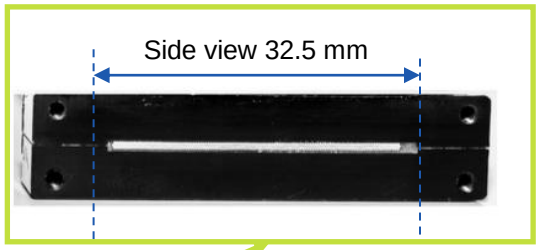




Backup slides

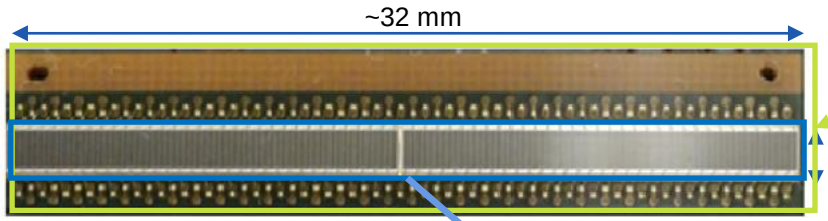
SciFi detector – light detection



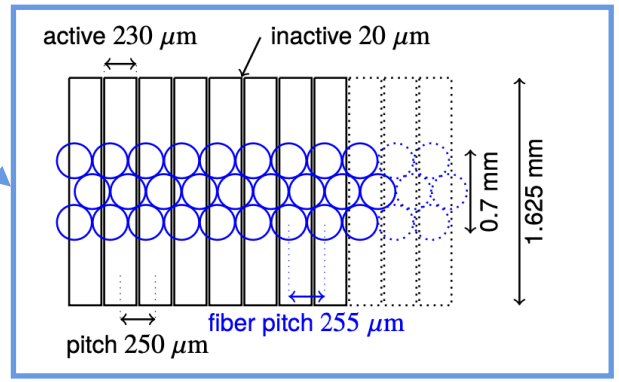


fiber ribbon (3 layer 250 µm round black epoxy coated rods)
(Kuraray SCSF-78MJ)

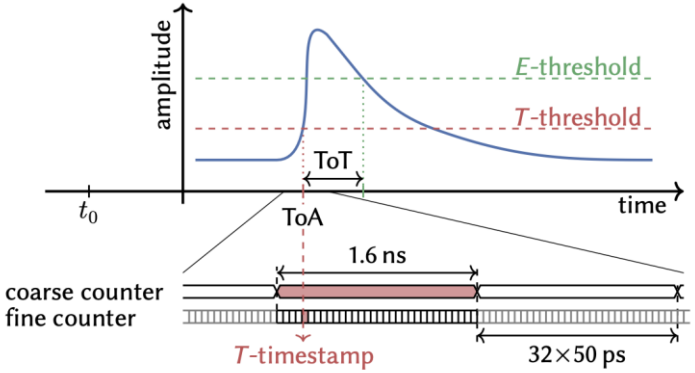
Attaching



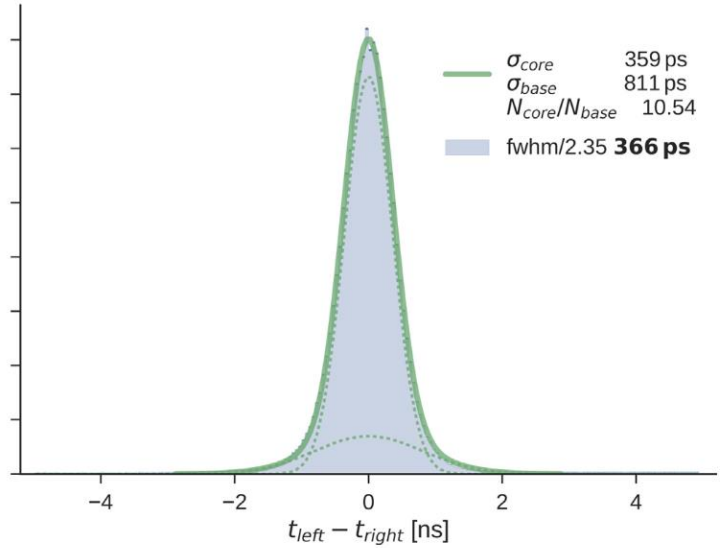
SiPM Array
(Hamamatsu S13552-HRQ)



Fiber and SiPM array attached



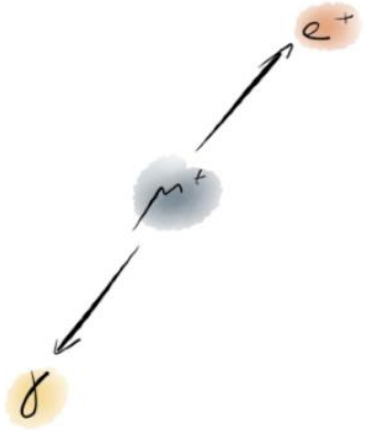
SiPM readout waveform



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

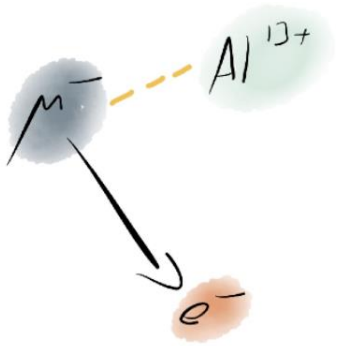
Worldwide status of muon decay search for charged LFV

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



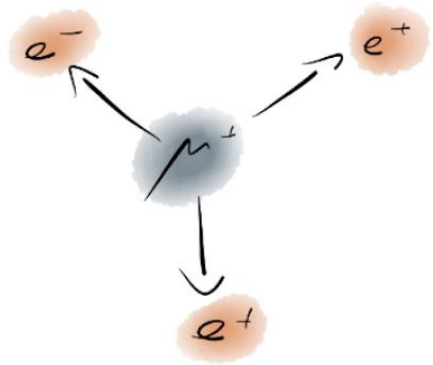
Current: MEG ($< 4.2 \times 10^{-13}$)
Future: MEG II (S.E.S. 6×10^{-14})

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



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

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



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

PAUL SCHERRER INSTITUT PSI

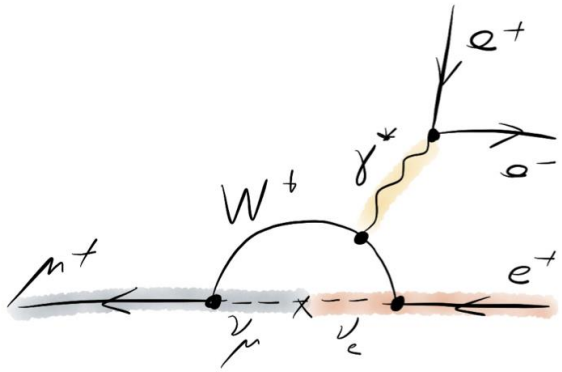
Mu2e @ Fermilab

COMET @ J-PARC

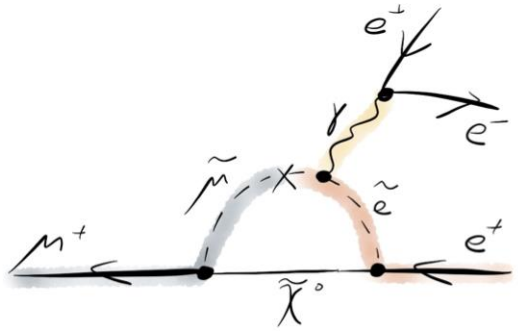
PAUL SCHERRER INSTITUT PSI

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

1. Strongly suppressed by SM ⟹ **very clean channel**



SM suggested decay

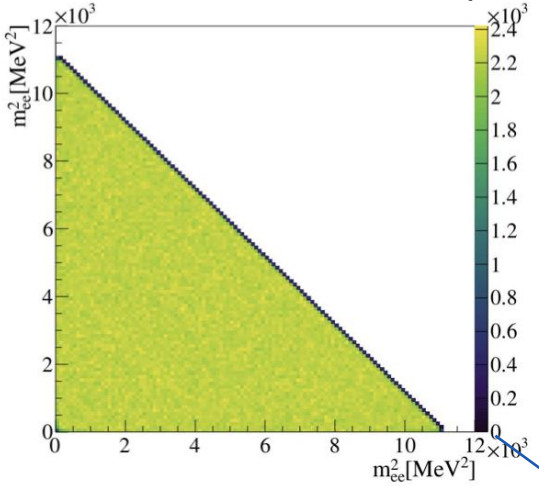


BSM suggested decay

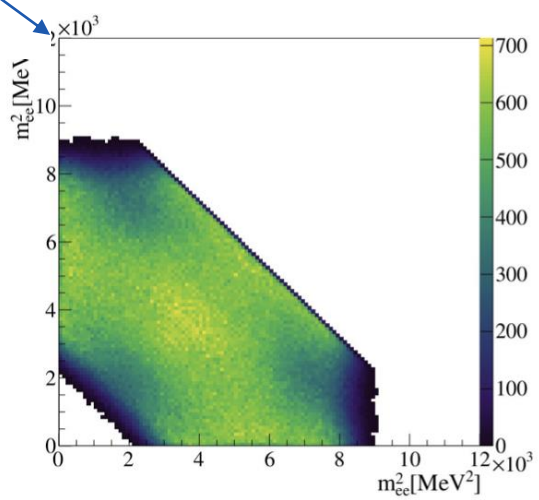
$$\mathcal{B}_{\mu\to eee} \propto \left(\frac{\Delta m^2_\nu}{m^2_W}\right)^2 \quad \to \quad \mathcal{B}_{\mu\to eee} < 10^{-54}$$

2. Full 3-body decay kinematics ⟹ **large kinematic space coverage**

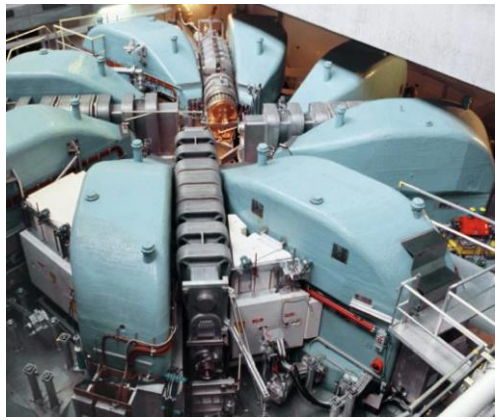
Phase space decay (Dalitz plot)



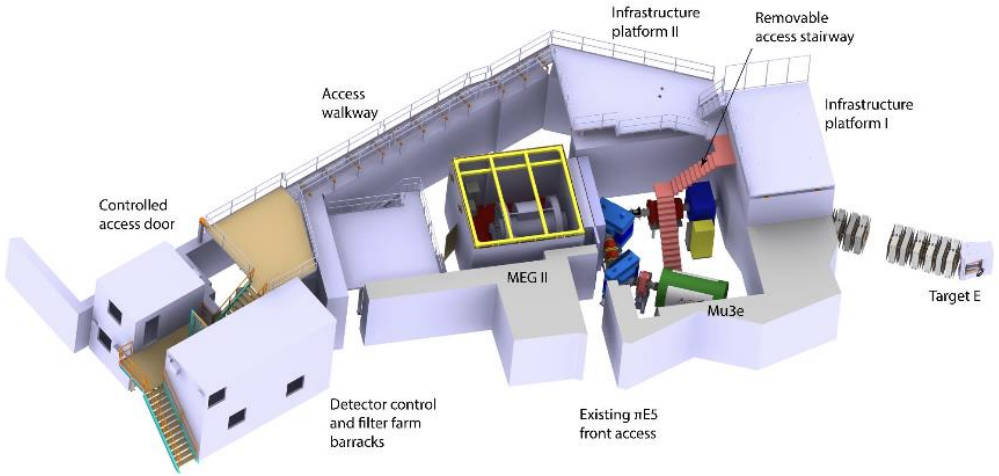
consider acceptance of detector



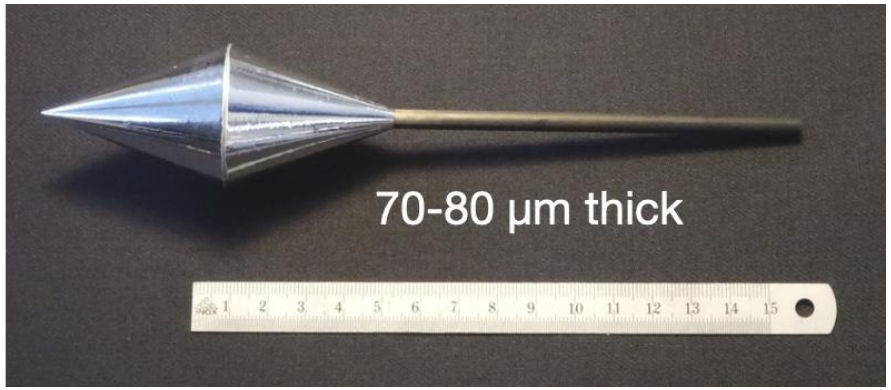
Beam and target



- 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,

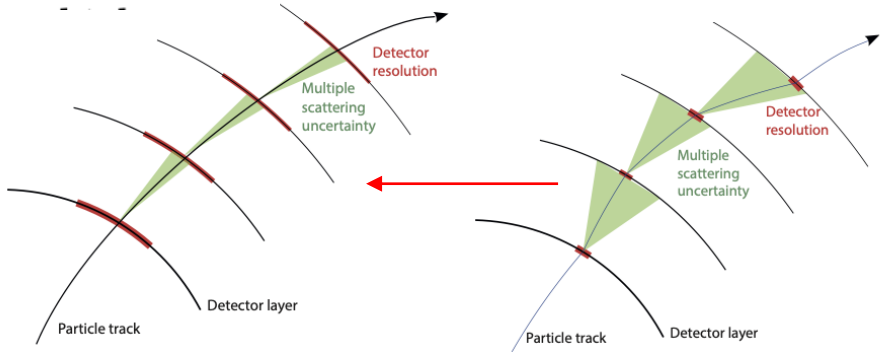


Magnet and track recurl

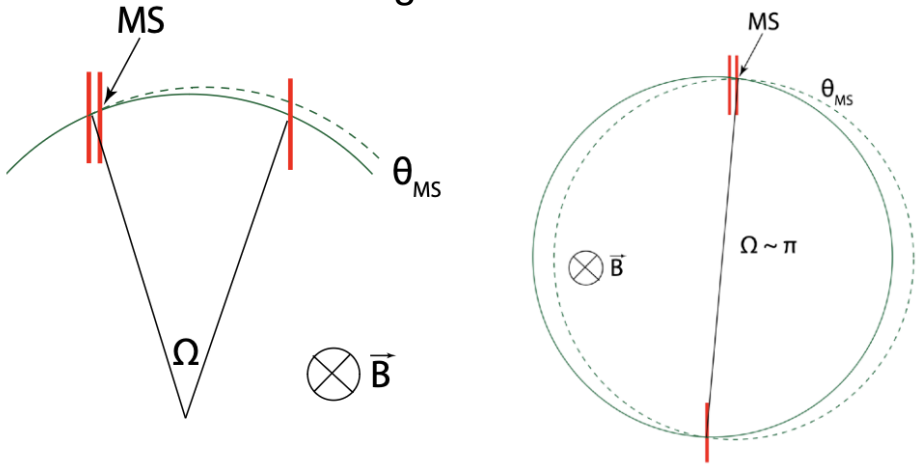
1T Magnet: Maximize the acceptance of recurler

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

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

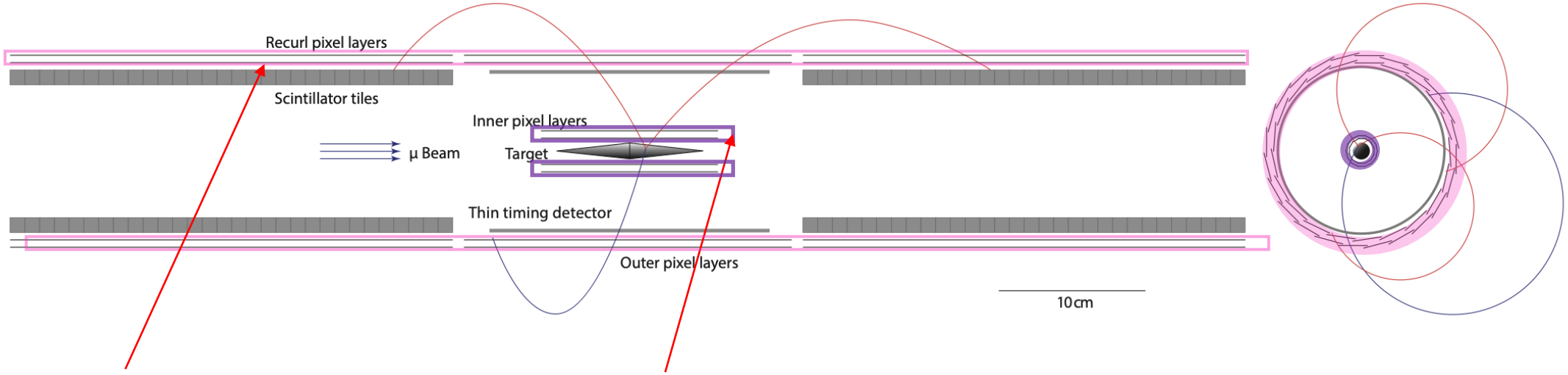


- Momentum resolution increases as material budget decreases



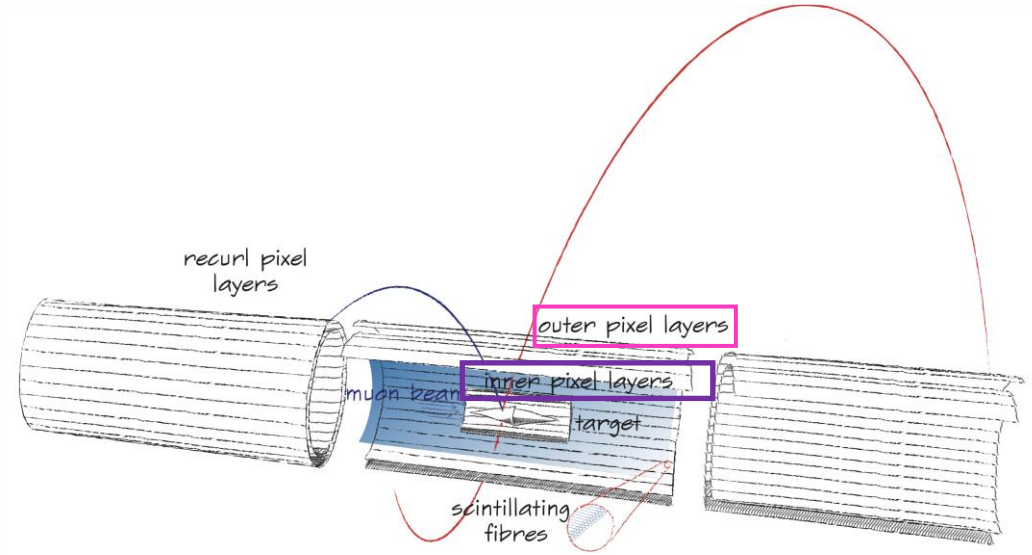
- Recurl helps on reducing multiple scattering uncertainties

Pixel tracker in Mu3e



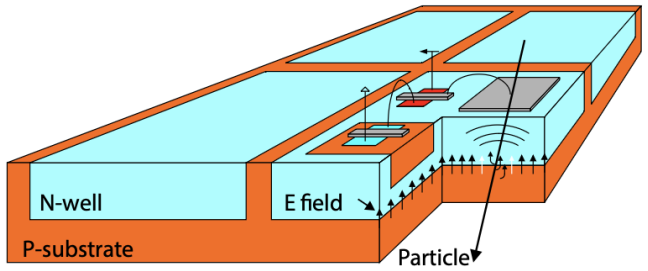
Outer pixel (recurl)

Inner pixel (vertex)

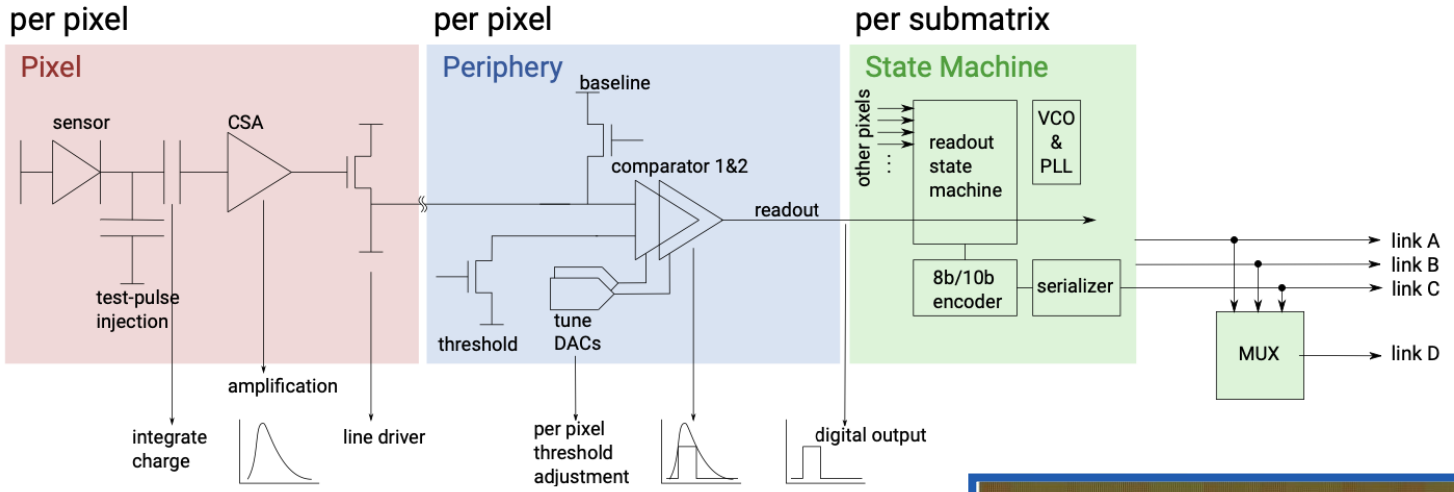


Goal of tracker: vertex and tracking
Granularity: Pixel=80μm*80μm, ScFi fiber=250μm*300mm,
Tile 5mm*5mm

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

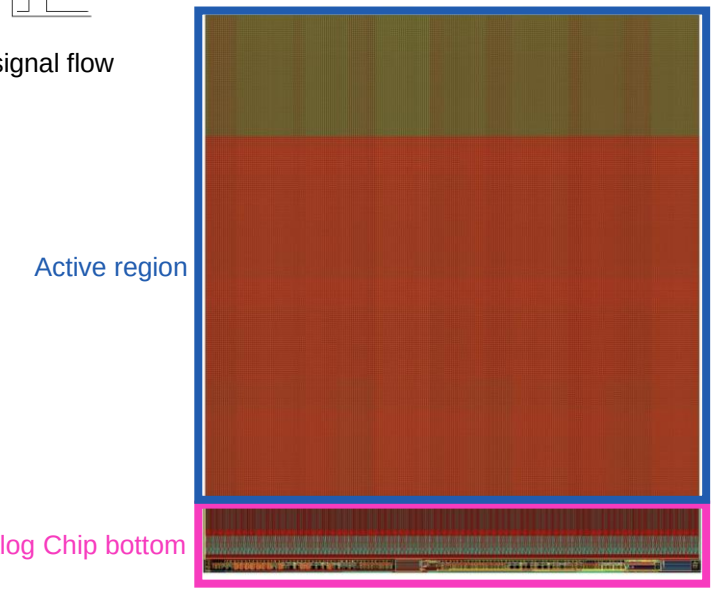


General Operating Scheme of
High-Voltage Monolithic Active Pixel Sensors



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

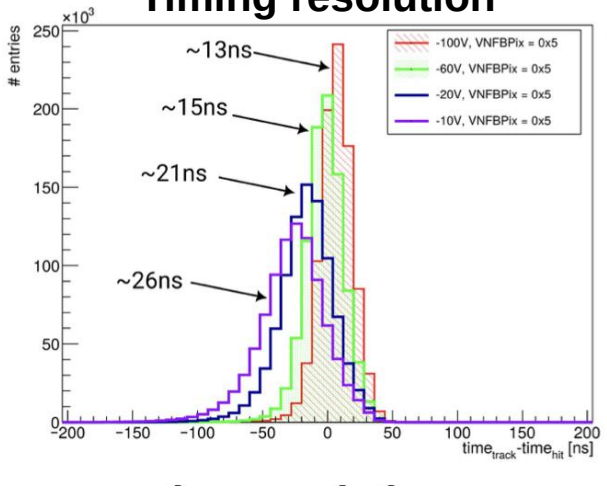


Floorplan of MuPix

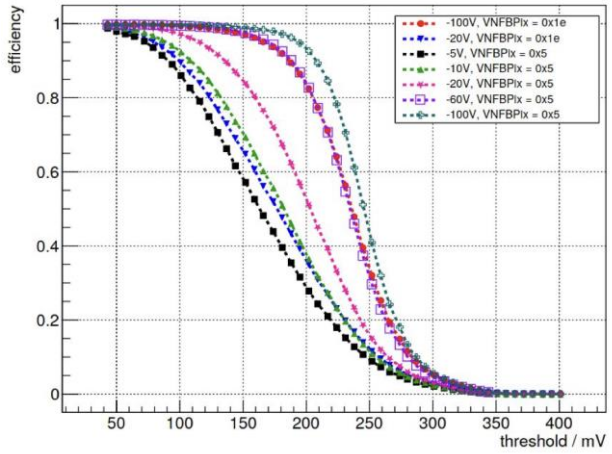
MuPix performance

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

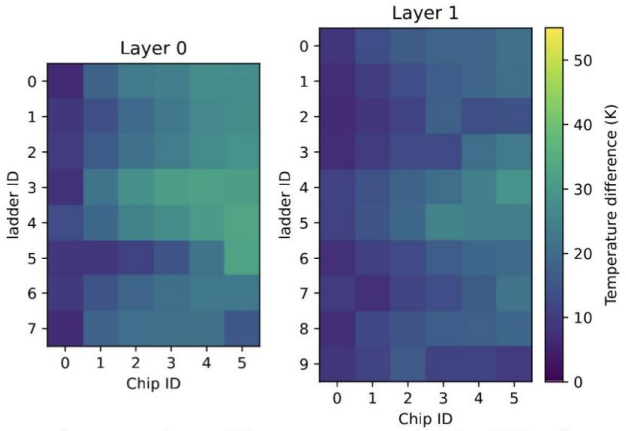
Timing resolution



MIP detection efficiency MuPix11 (100µm)



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

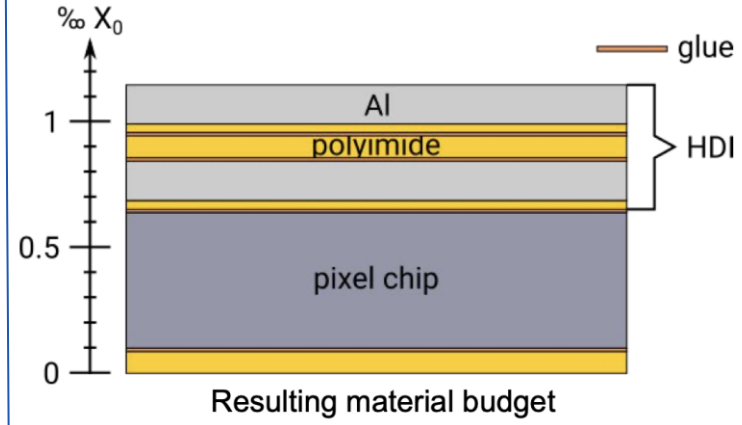


temperature difference maps 215 mW/cm²
(expected scenario)

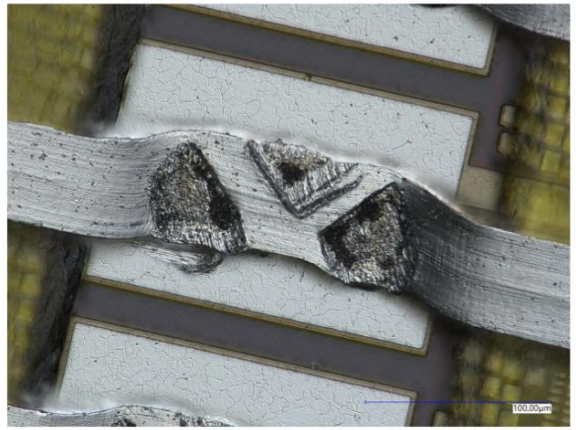
Measured temperature difference of dummy load (at ~ 215 mW/cm2)

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

spTAB bonding for High-Density Interconnects



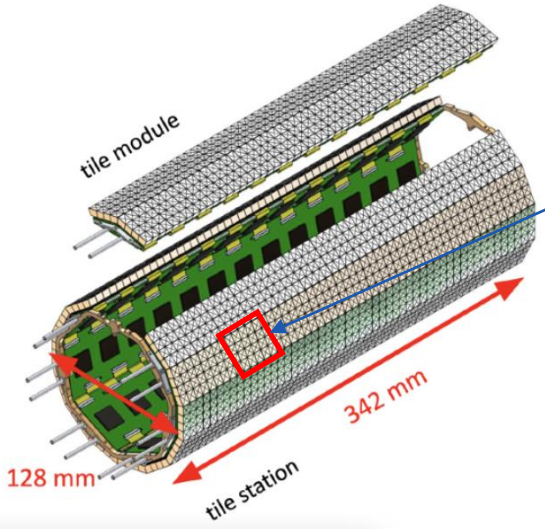
Resulting material budget



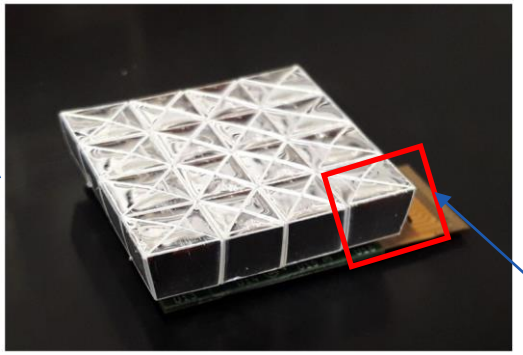
spTAB connection

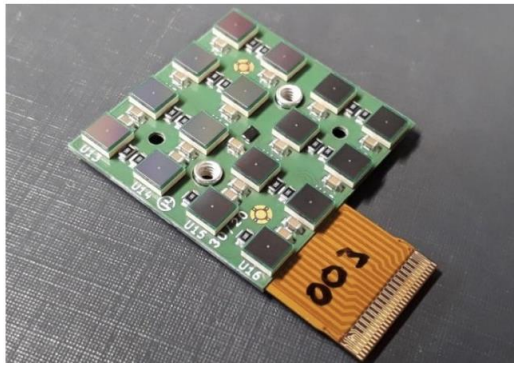
Scintillating Tiles detector

- 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

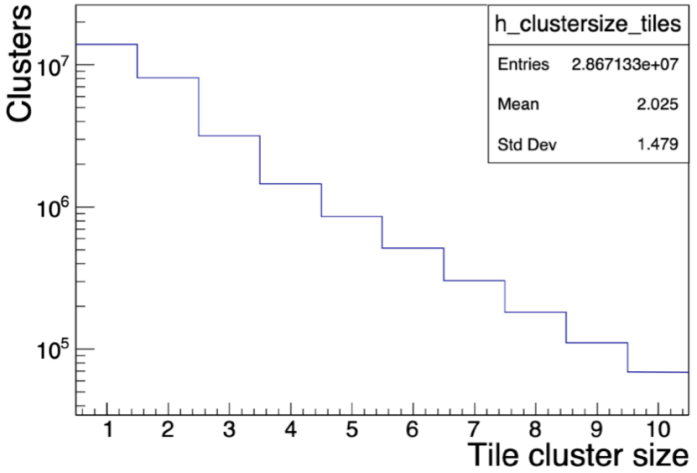


Tile Subdetector





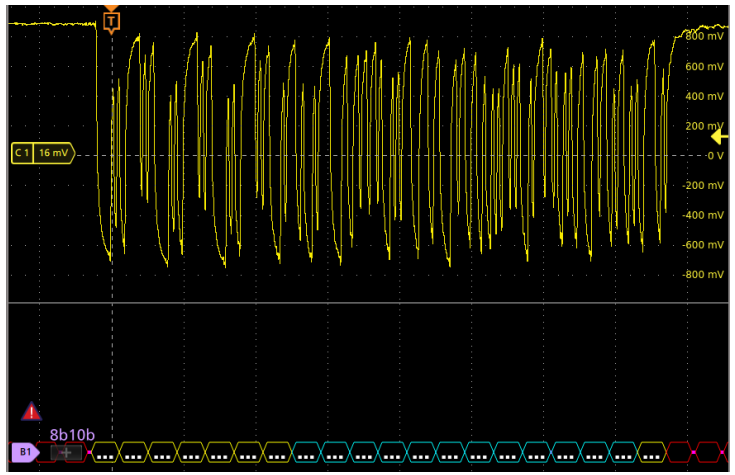
Tile Matrix
(top) w/ scintillator
(bottom) w/o scintillator



Tile-shape scintillator

MuTRiG

Raw waveform



LVDS Receiver

MM

8b/10b symbols

1250	-5.588047ns	1100000101	--	K28.5+	
1251	2.326239ns	0011111010	--	K28.5-	
1252	10.22008ns	1100000101	--	K28.5+	Idle
1253	18.31773ns	0011111010	--	K28.5-	
1254	26.26451ns	1100000101	--	K28.5+	
1255	34.30483ns	0011111010	--	K28.5-	
1256	42.25649ns	1100001011	--	K28.0+	header
1257	50.25629ns	1001000101	D16.2+	--	
1258	58.29413ns	1110000110	D7.6-	--	Frame ID
1259	66.45631ns	0110110110	D16.6-	--	
1260	74.20299ns	1000101011	D1.0+	--	Frame flag and length
1261	82.28915ns	1000111001	D17.1	--	
1262	90.3338ns	1000011011	D30.0+	--	
1263	98.36967ns	0011001001	D24.1+	--	
1264	106.3007ns	0101101010	D26.5	--	Hit events
1265	114.4557ns	0010111011	D20.0-	--	
1266	122.3902ns	0100101001	D2.1+	--	
1267	130.3448ns	1000110110	D17.6	--	
1268	138.48ns	0101100101	D26.2	--	CRC checksum
1269	146.3457ns	0011110010	--	K28.4-	

MuTRiG Event Table

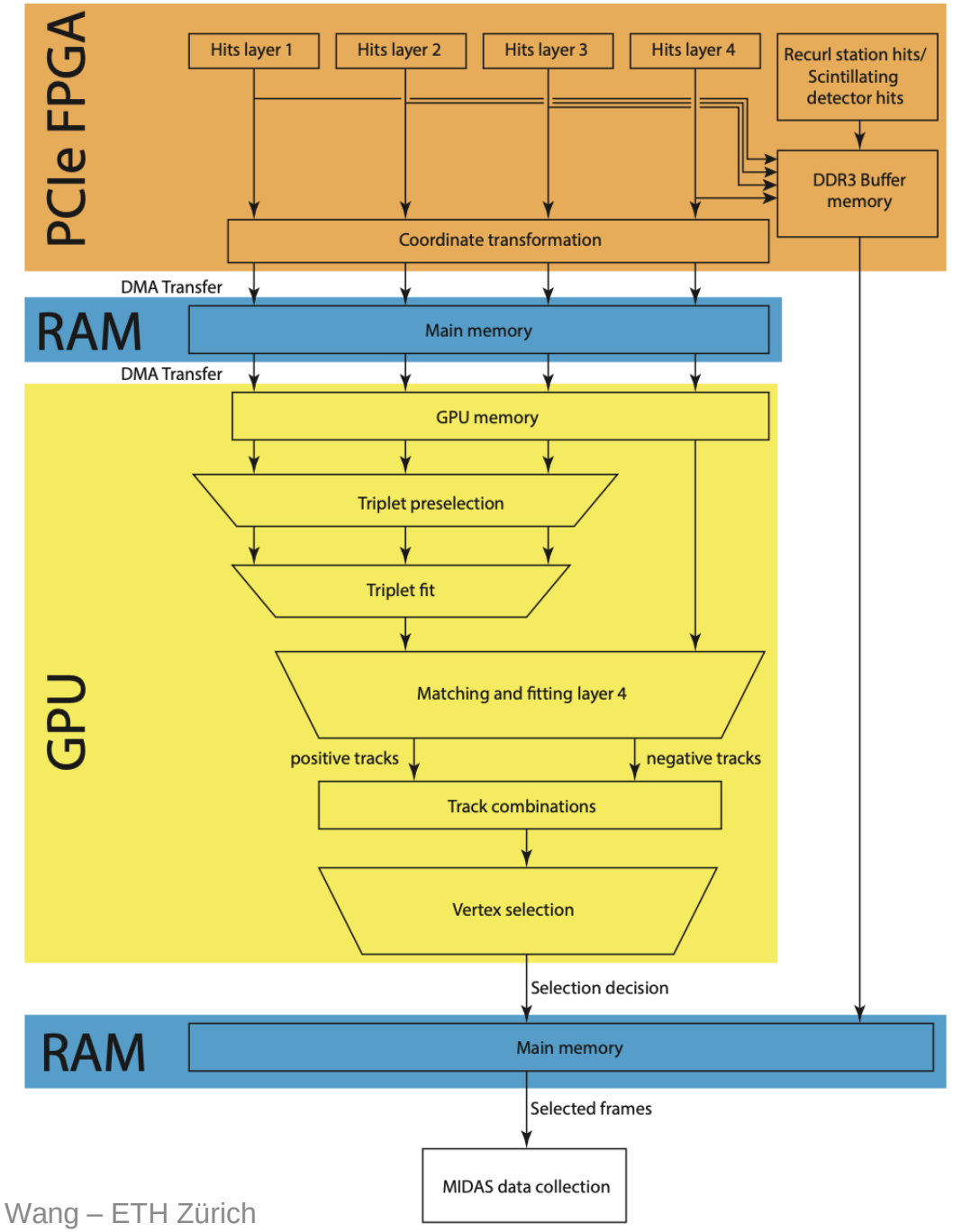
Bit Field	Definition
[47:43]	Channel Number
[42]	T - BadHit
[41:27]	T - Coarse Counter
[26:22]	T - Fine Counter
[21]	E - BadHit
[20:6]	E - Coarse Counter
[5:1]	E - Fine Counter
[0]	E - Flag

Frame Parser

MM

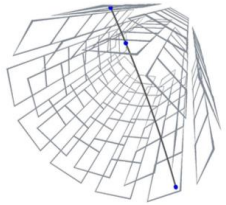
Filter farm

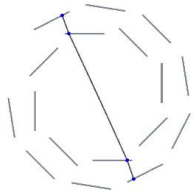
- Triggerless, continuous reconstruction
- Track reconstruction in central pixel detector and vertex finding on GPUs
- Events with μ → eee candidates are send off to mass storage
- Data reduction by a factor of 80

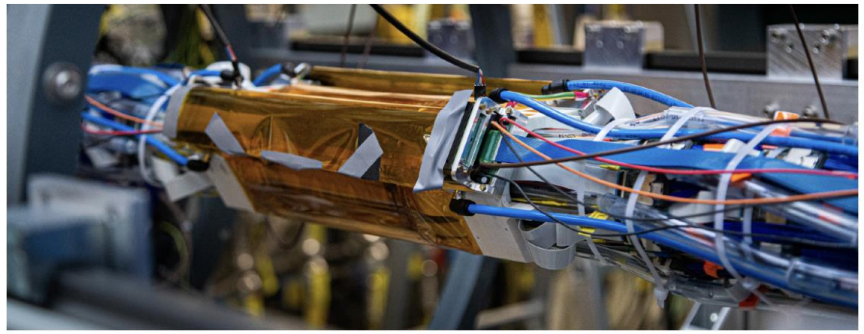


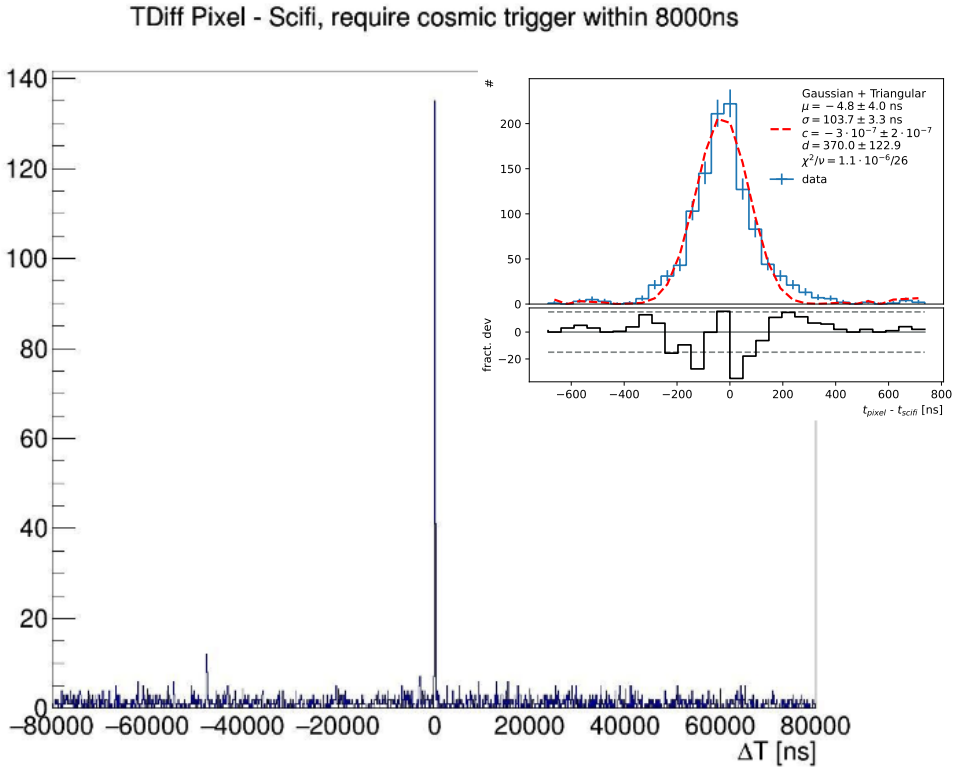
Past integration runs

2021	2022





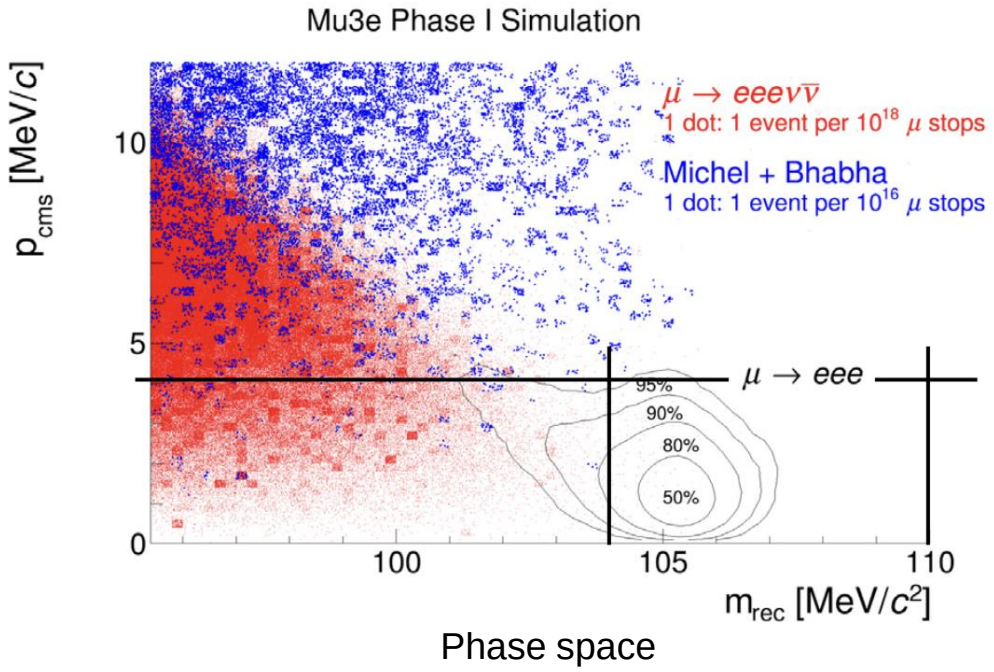




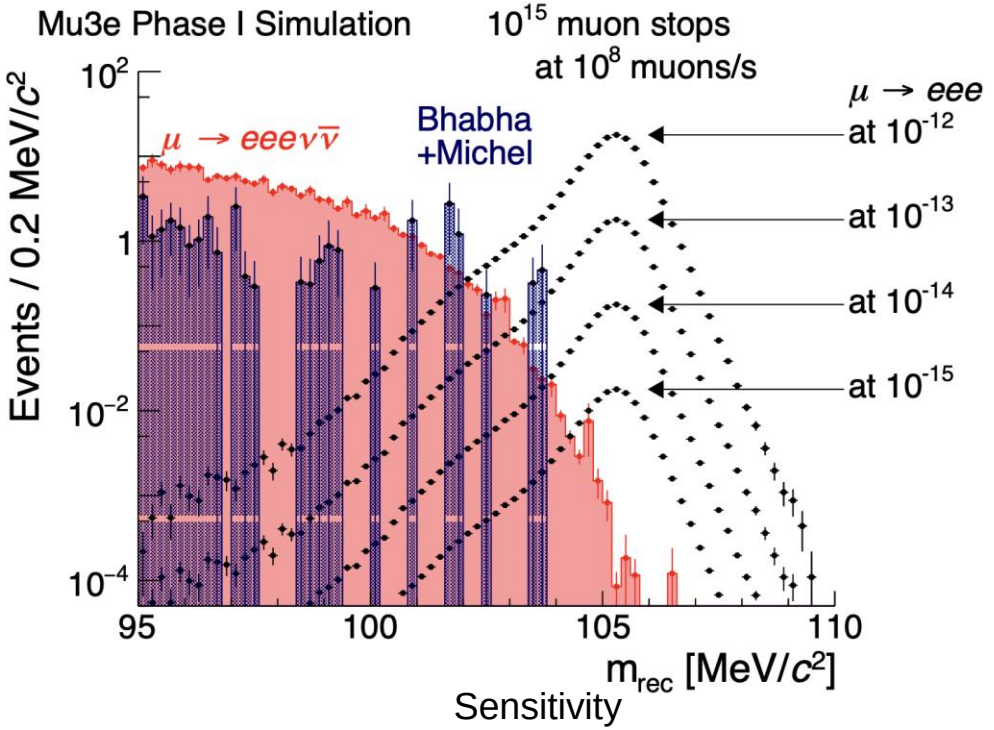
- Integrated runs and testbeam of DAQ, helium/water cooling, magnet
- Reconstructed cosmic muons and recurl electrons
- Track reconstruction and coincidence found to validate the prototype
- Pixel-SciFi and Pixel SciTile combined coincidence search

Simulation for Phase I physics

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



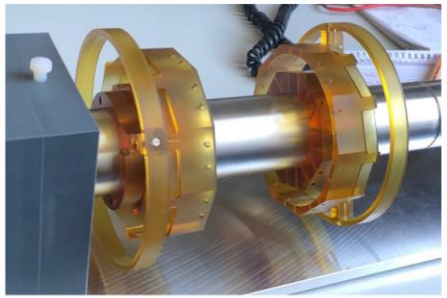
Phase space



Sensitivity

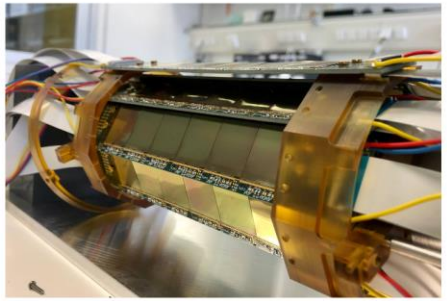
- Vertex resolution ~0.3 mm (<0.5 mm)
- Momentum resolution ~0.9 MeV (<1 MeV)

MuPix assemble to pixel ladder

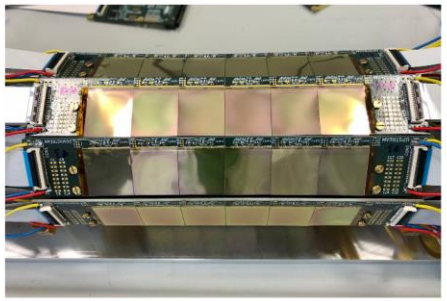


(a) PEI end pieces and double-rings.

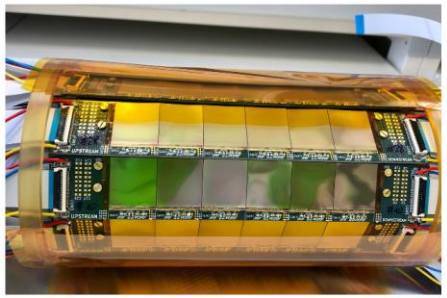
(b) Space for cable feedthrough.



(c) Full L0 assembled.



(d) Full L1 assembled.

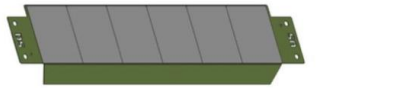


(e) Mounting of the helium confinement.

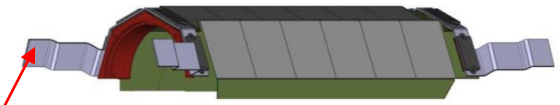
(f) Fully assembled prototype.

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

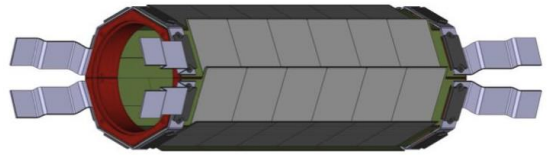
Assembling steps



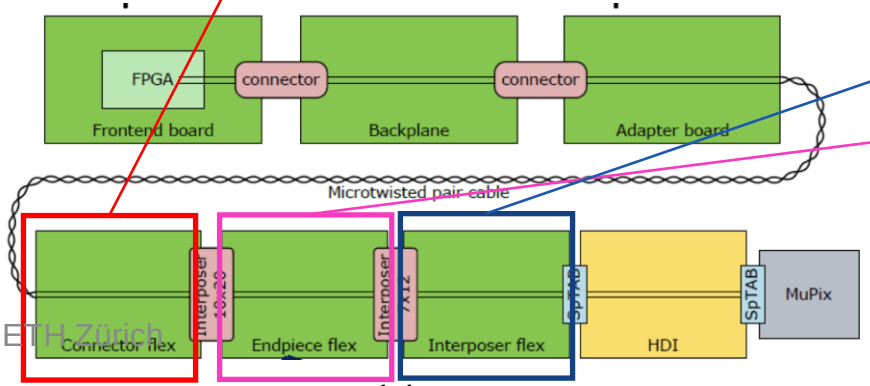
Ladder

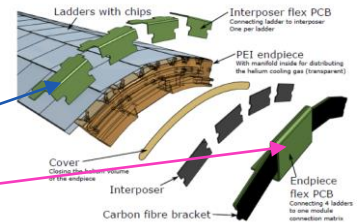


Module



Layer



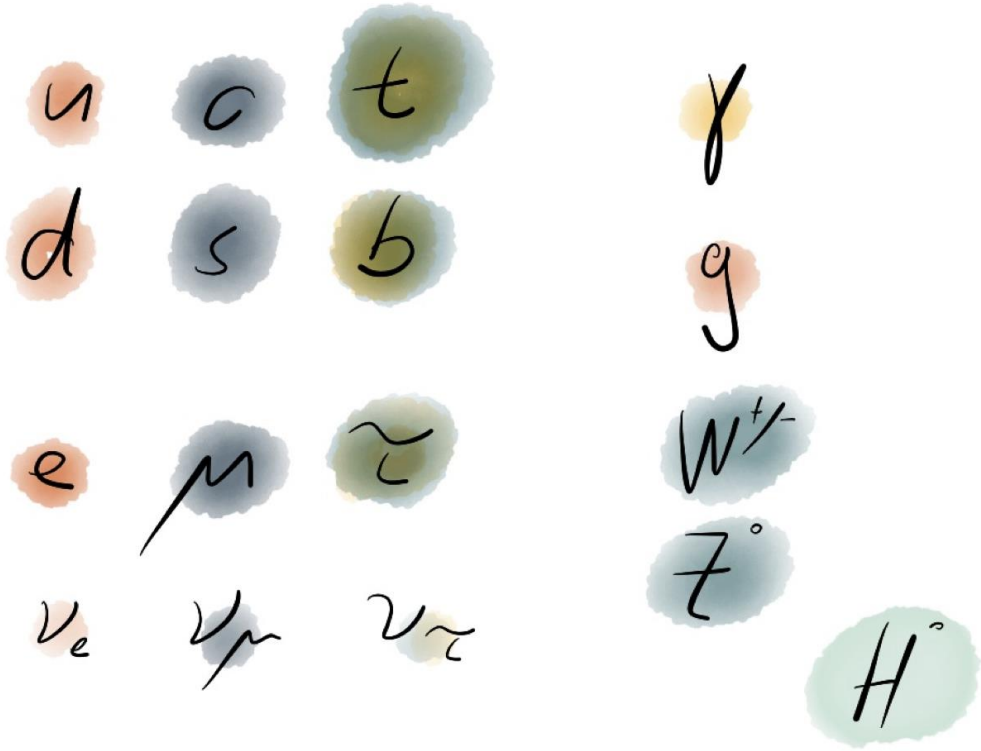


Lepton flavor violation (LFV)

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

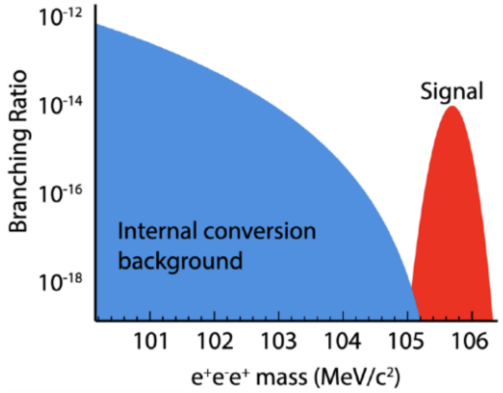
Mu3e physics with kinematics

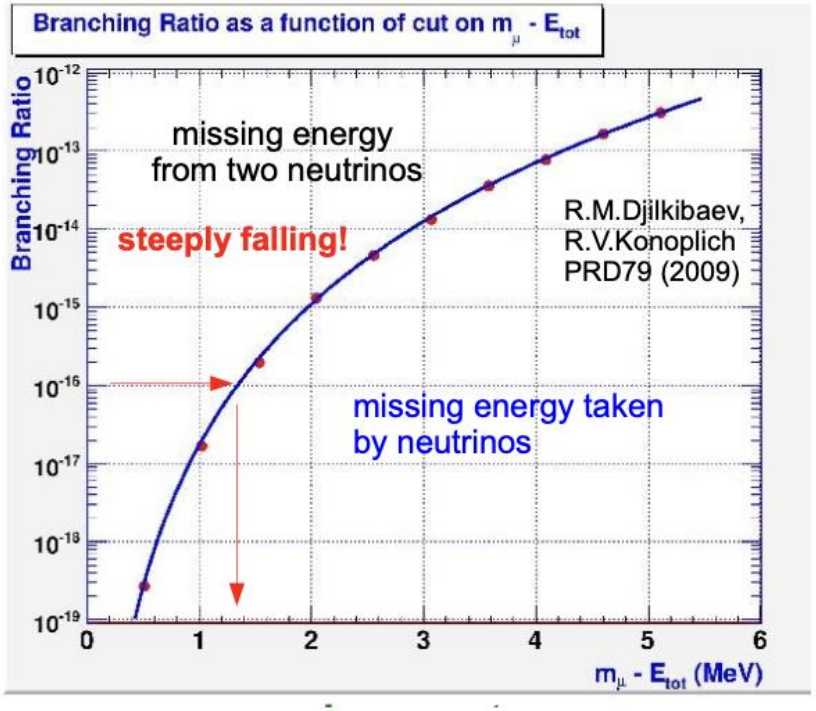
- All decayed tracks have momemtum <53MeV

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

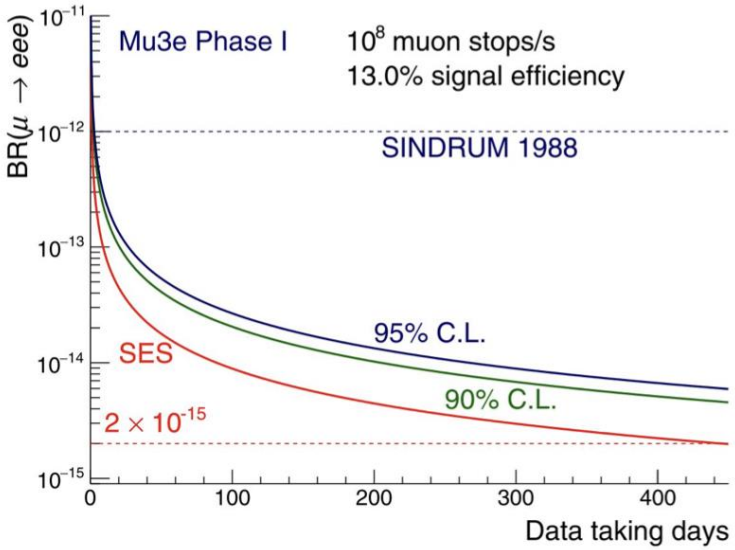
Muon radiative decays with internal conversion

$\mu^+ \rightarrow e^+e^-e^+\nu\nu$





physics sensitivity, simulations



More about beam

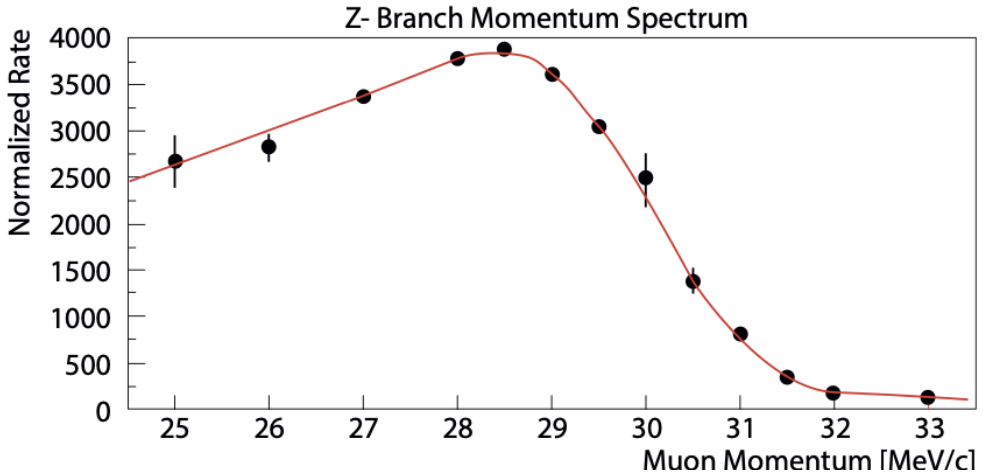


Figure 3.1: Measured muon momentum spectrum in πE5, with full momentum acceptance. Each point is obtained by optimising the whole beam line for the corresponding central momentum and measuring the full beam-spot intensity. The red line is a fit to the data, based on a theoretical $p^{3.5}$ behaviour,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

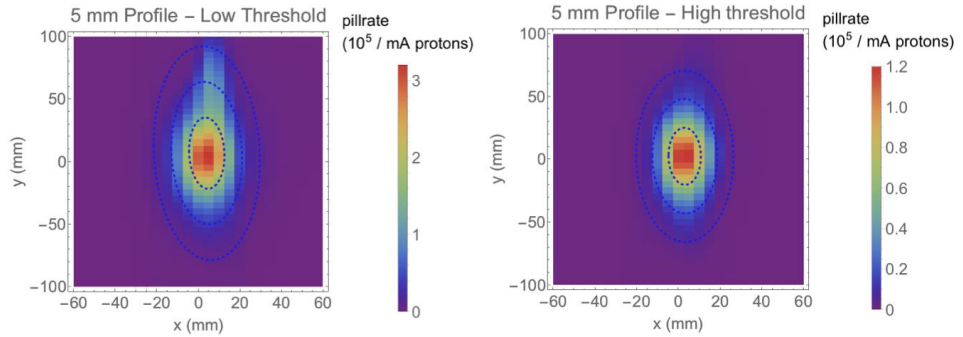
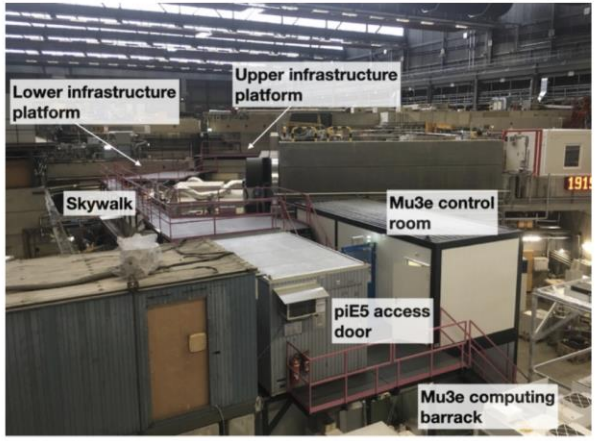
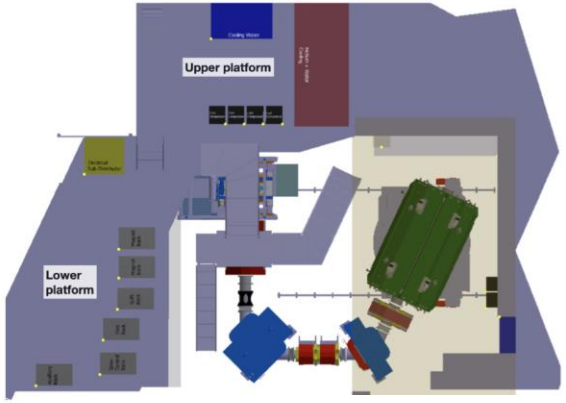


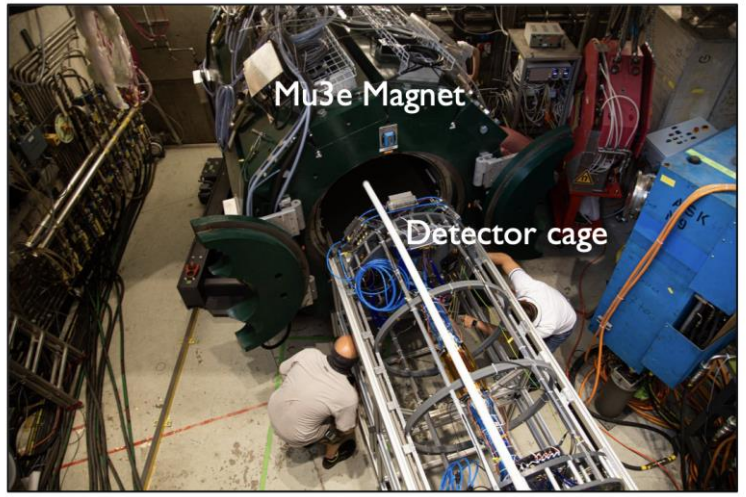
Figure 3.7: Measured beam spot at the injection point to the Mu3e solenoid triggering on either a low (left: muons + Michels + beam positrons) or high (right: muons only) threshold. A 2D Gaussian fit to the muon data yields $\sigma_x = 8\,\text{mm}$ and $\sigma_y = 23\,\text{mm}$ with a total rate of $1.1 \times 10^8\ \mu^+/\text{s}$ 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

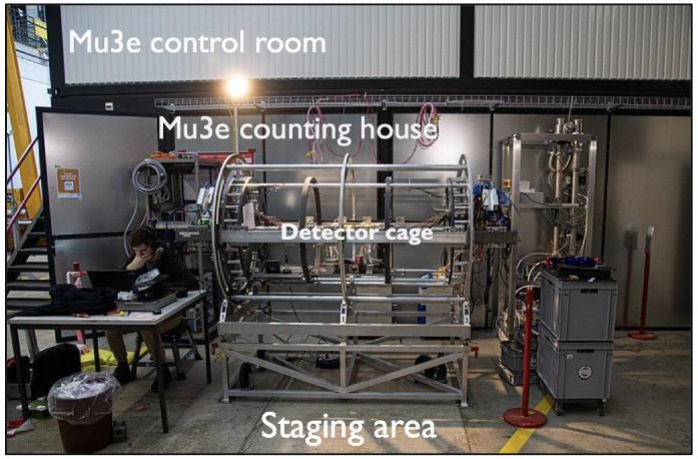




Beam in 2021

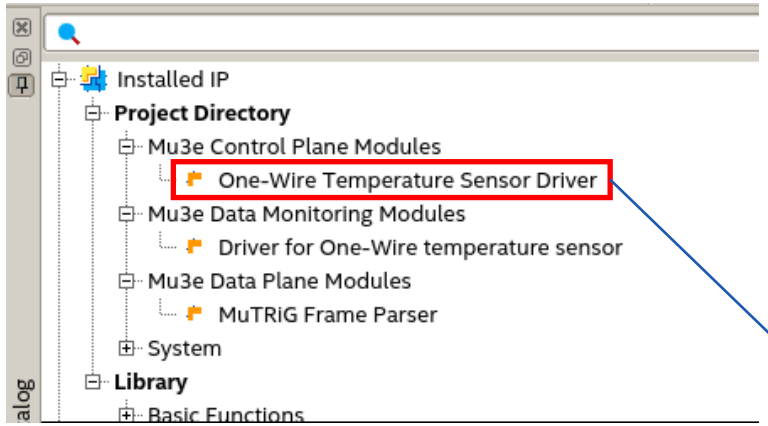


Cosmics in 2022

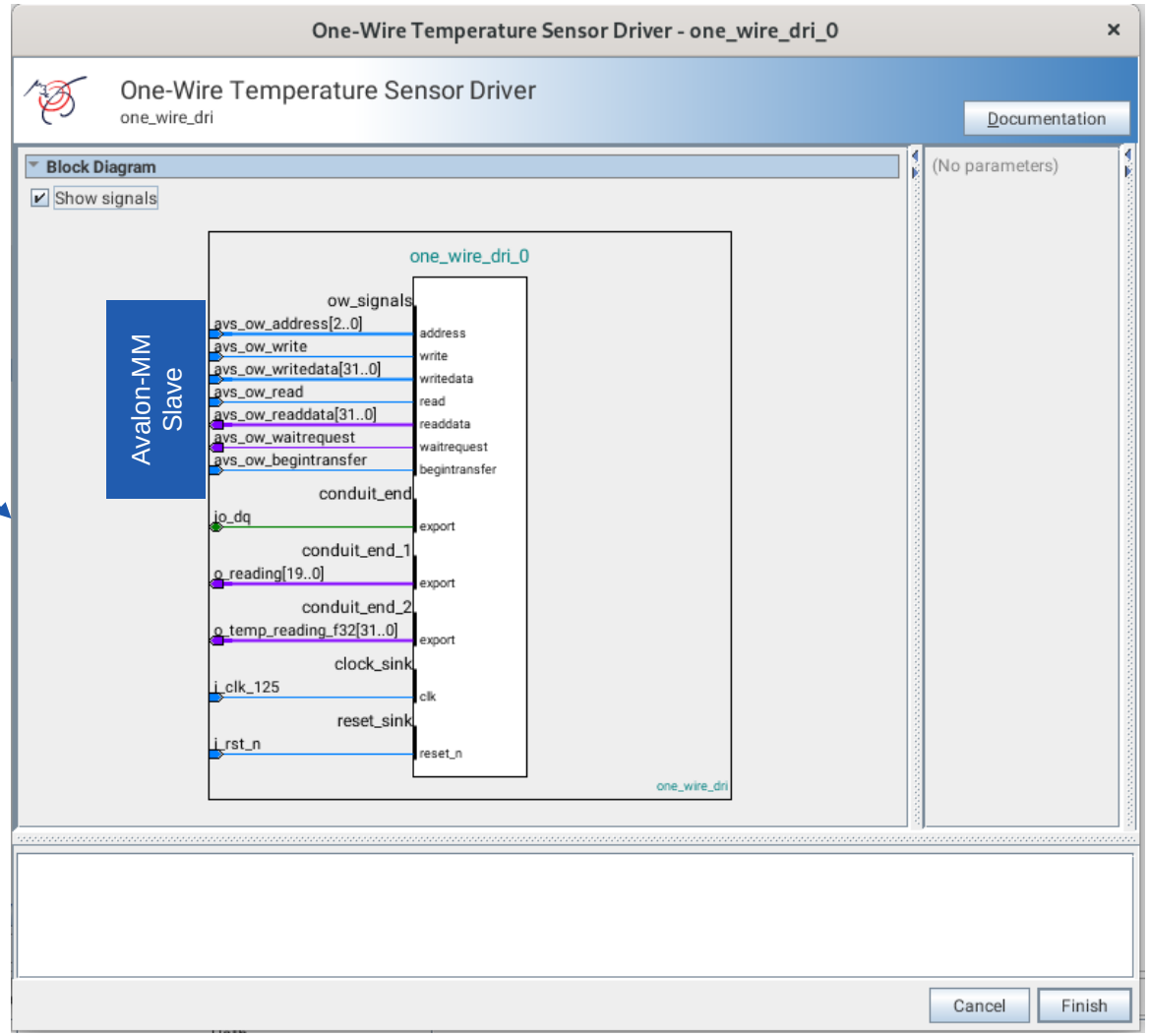


IP-core library of Mu3e experiment

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

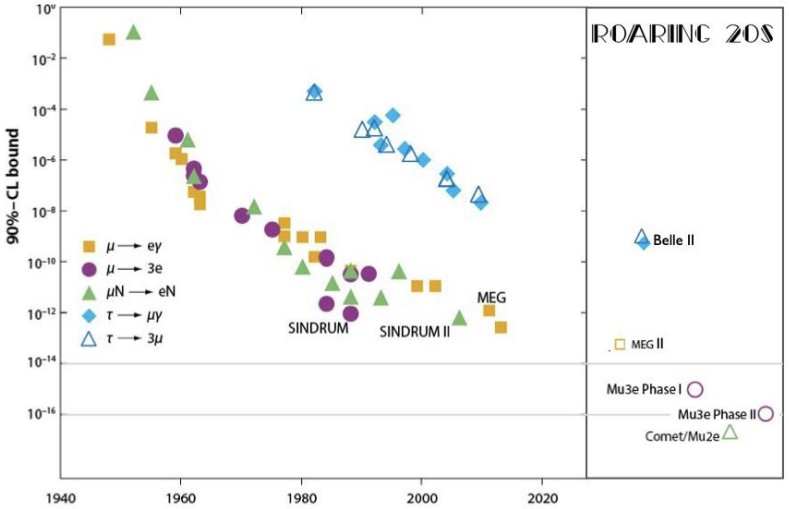
Mu3e phase II

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



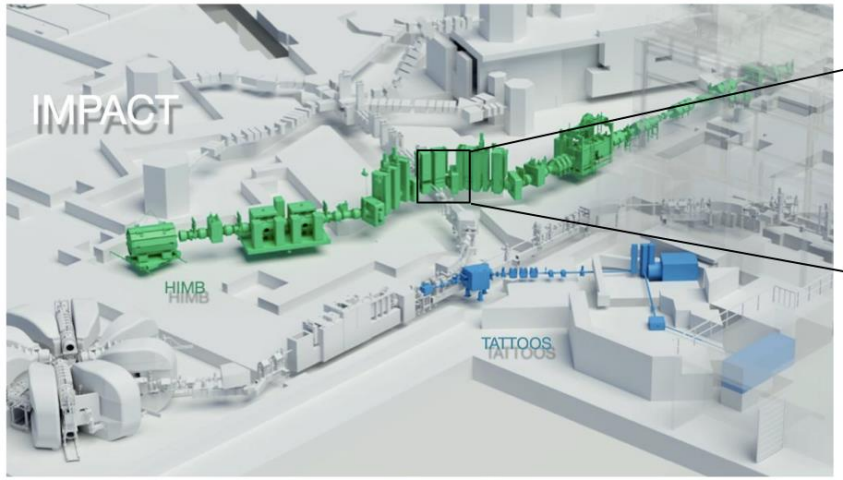
Slides from Frederik Wauters in CLFV2023

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

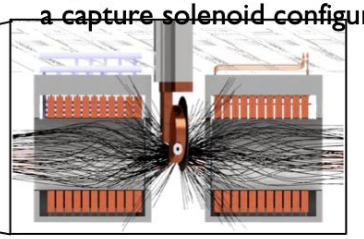
Science Case for the new High-Intensity Muon Beams HIMB at PSI
Edited by A. Knecht, F. Meier Aeschbacher, T. Prokscha, S. Ritt, A. Signer

arXiv:2111.05788

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



Repace target M with a capture solenoid configuration



Mu3e phase II

Mu3e Phase I experiment:

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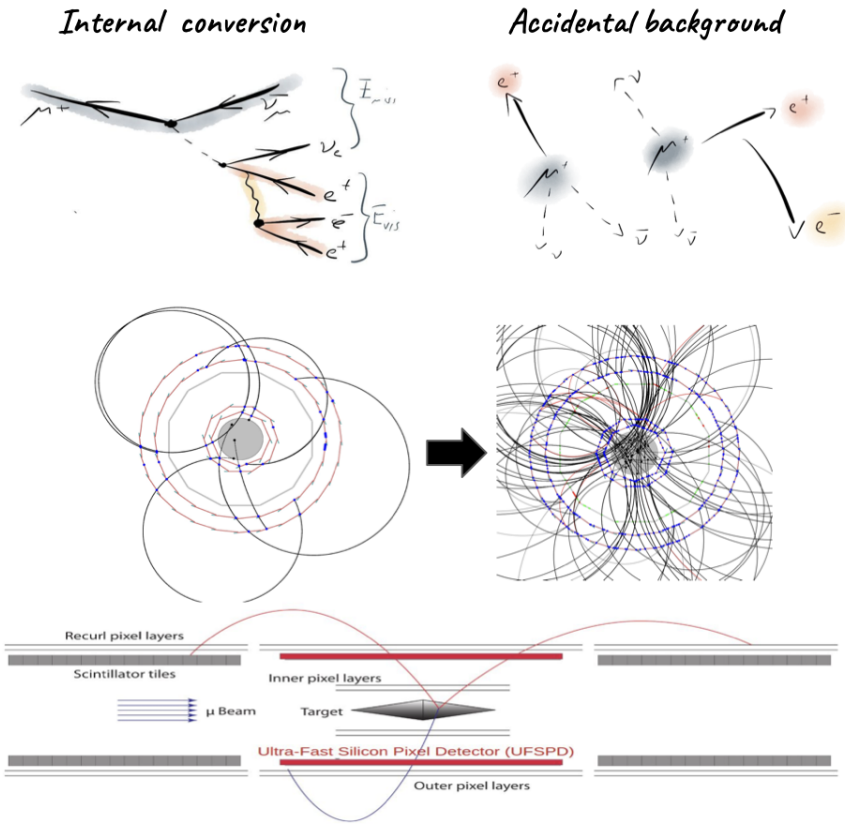
- ❑ Reach 10^{-16} S.E.S. on $\mu^+ \rightarrow e^+e^+e^-$
- ❑ Can not run at the existing beamline, Need 10^9 μ^+/s on target
  - □ HIMB

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



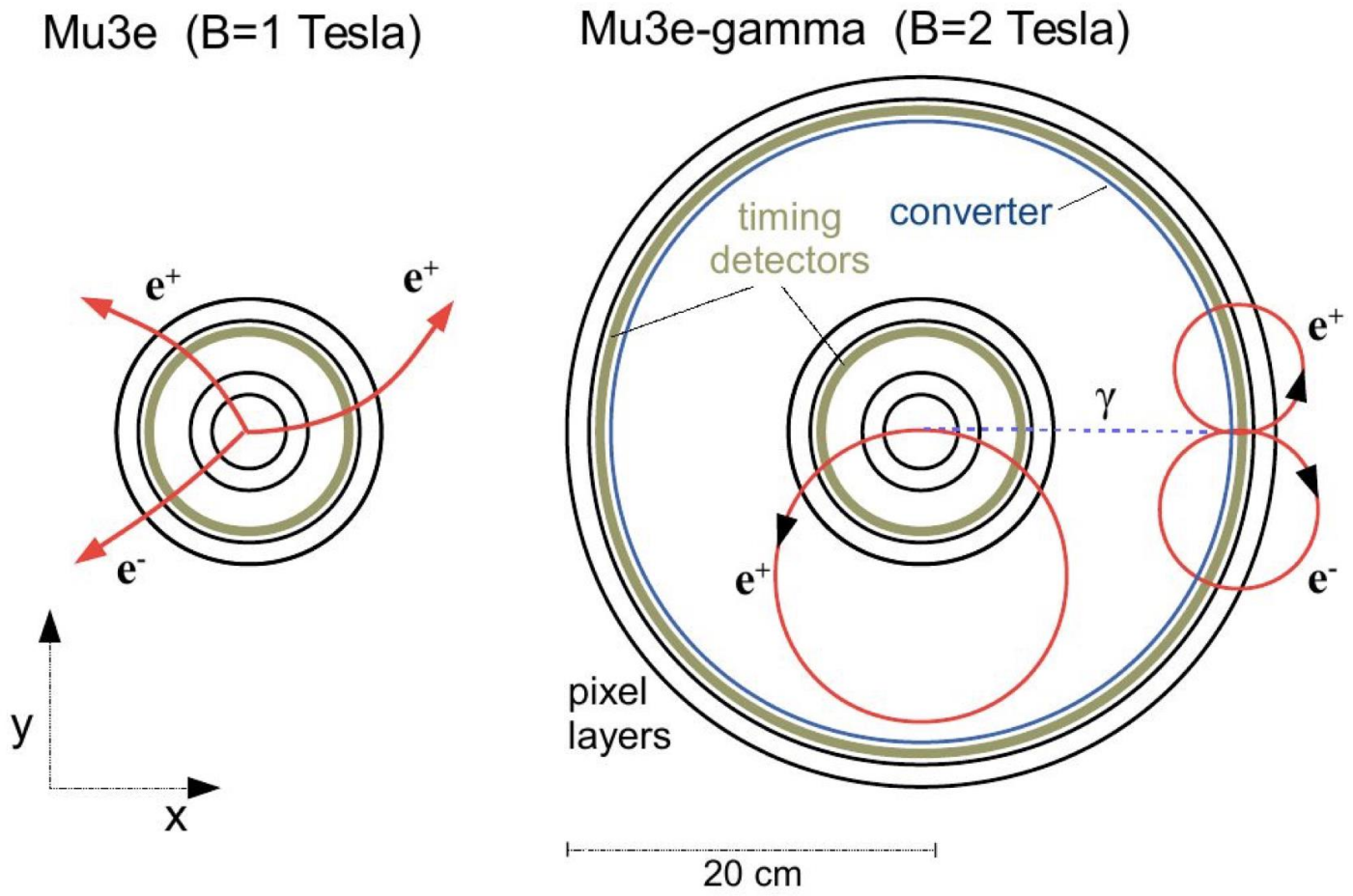
➡ Most of the Phase I detector needs a redesign

➡ We need new, fast the active pixel detector

- SiGe CMOS?

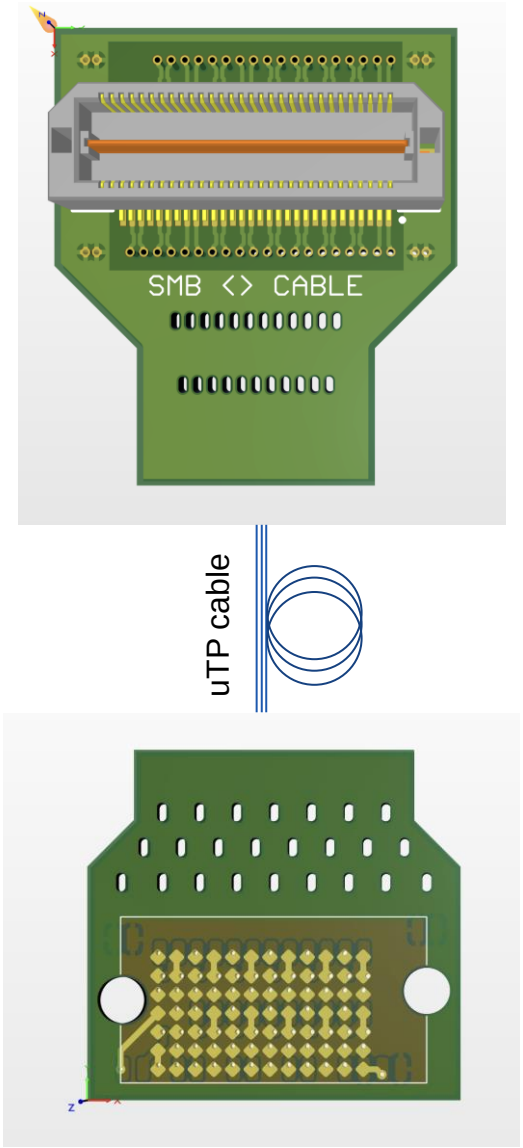
Slides from Frederik Wauters in CLFV2023

Conceptual design for gamma conversion at Mu3e



Slides from Frederik Wauters in CLFV2023

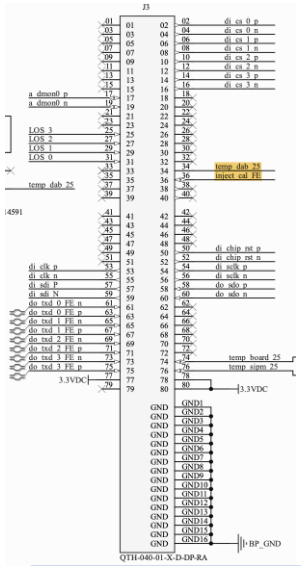
Connector boards

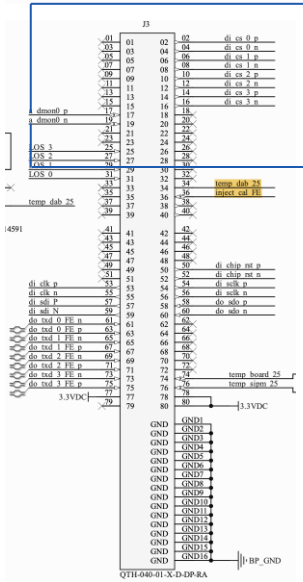


How do we test charge injection without final DAB

FEB

Backplane





CMOS 2.5V

CMOS 2.5V

DAB 2.1

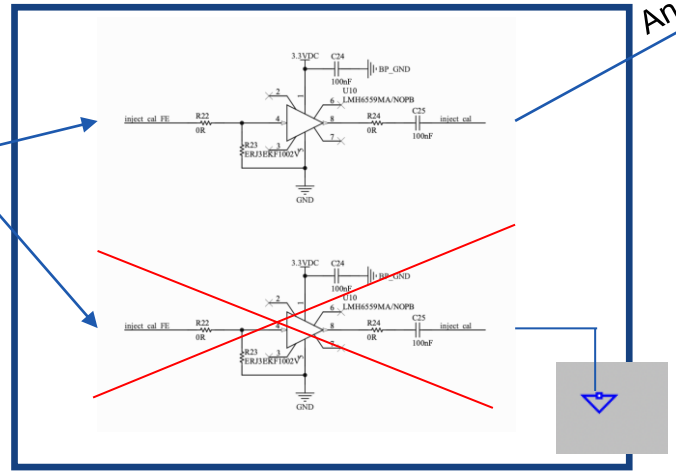
Normal data reading

SMB

Charge injection port

+ -

Analog pulse



Charge Injection Evaluation Board

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