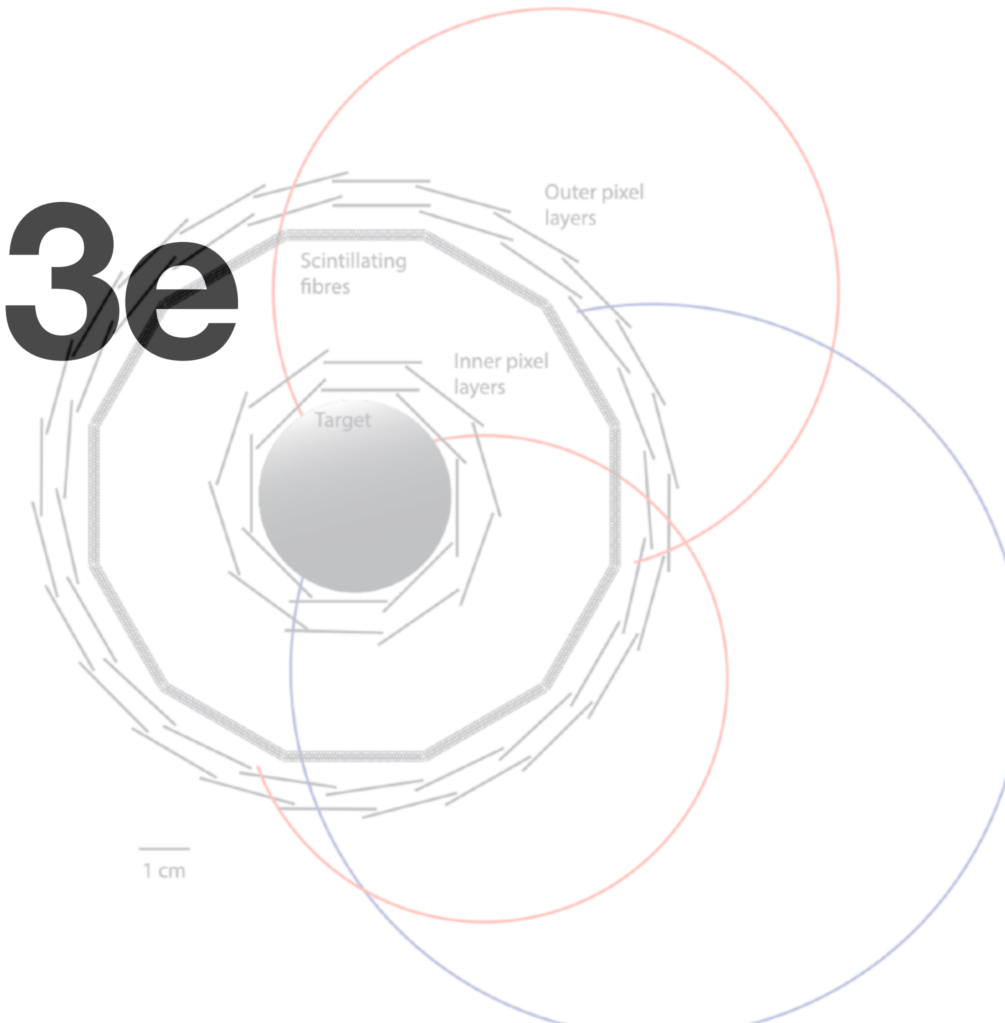
Physics at Mu3e

The search for $\mu^+ \rightarrow e^+ e^- e^+$



May 16, 2023 | New Frontiers in Lepton Flavor | Pisa (IT)

Cristina Martin Perez on behalf of the Mu3e Collaboration | ETH Zurich

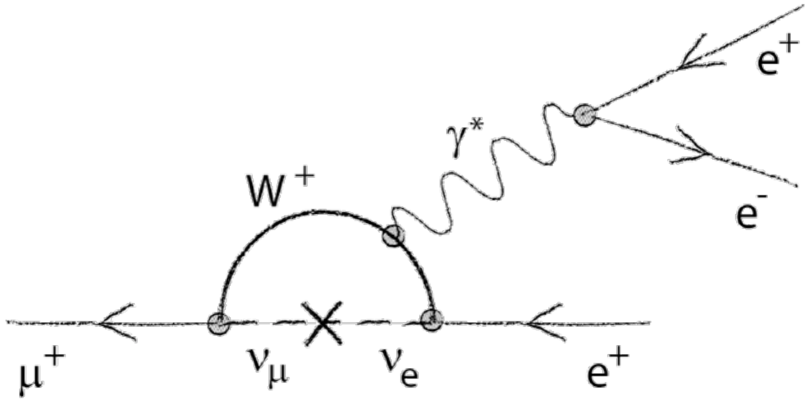
Lepton flavor violation

as a sign of physics beyond the SM

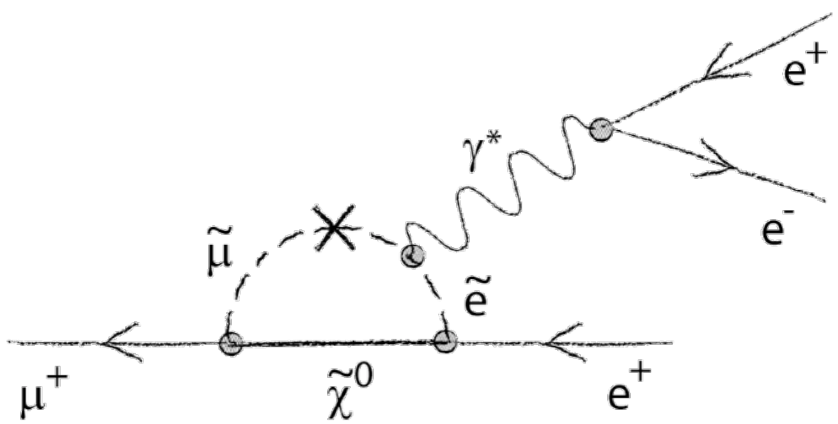
- **Lepton flavor** is strictly conserved in the Standard Model (m_ν=0)
  - … but there are **neutrino oscillations** ($m_\nu \neq 0$)

- **Charged lepton flavor violation** (cLFV) has not been observed
  - it is heavily suppressed (via neutrino mixing)

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



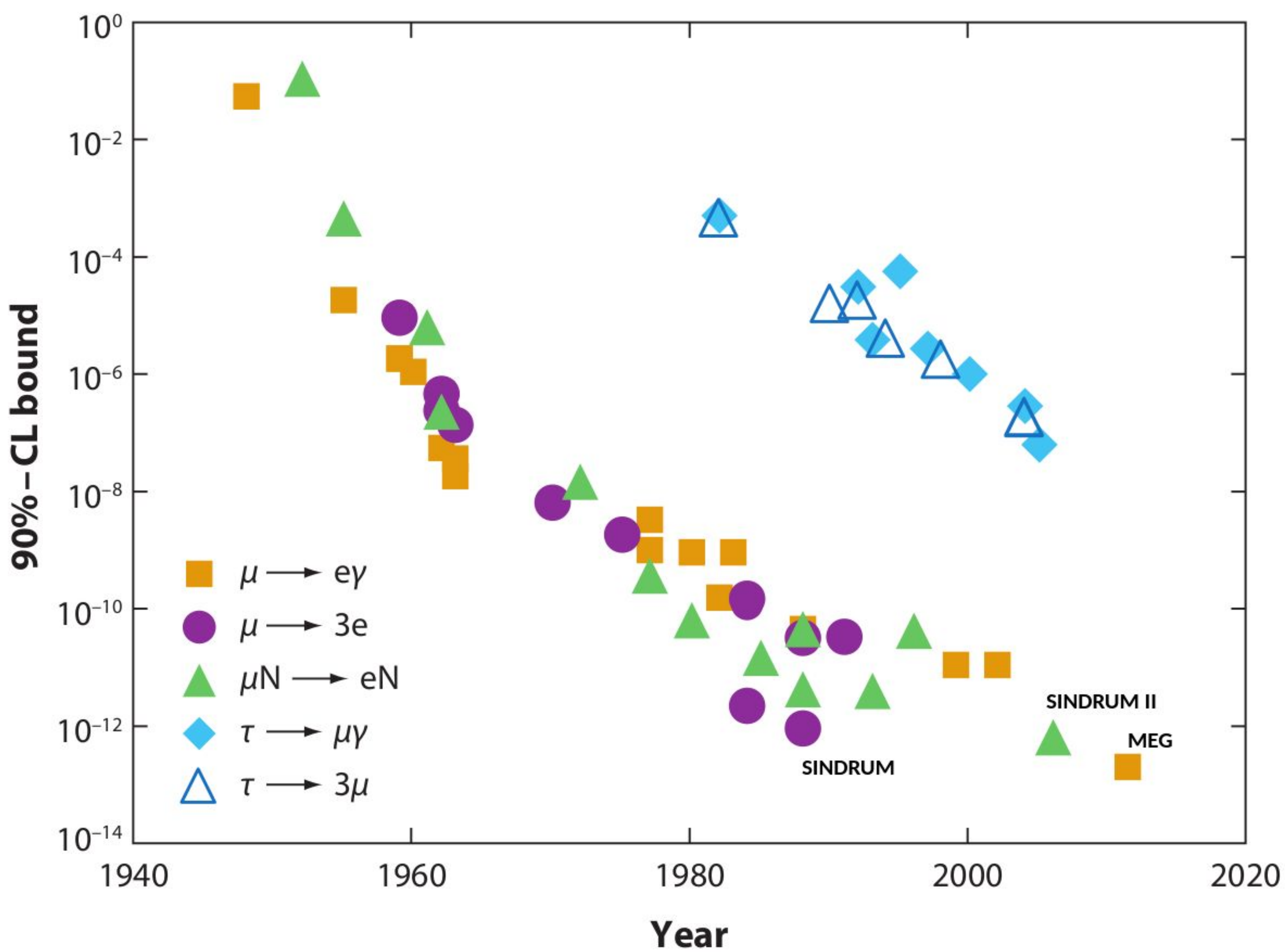
- Observation of cLFV would be an unambiguous sign of **new physics** beyond the SM
  - SUSY, GUT, extended Higgs sector, …



Muons

as probes of cLFV

- Muons are a versatile probe of charged lepton flavor violation:
  - **clean**: long lifetime, few and simple SM decay modes
  - **available** at high-intensity muon beams (PSI, J-PARC, Fermilab)
  - **sensitive**: high mass scales, model-independent effective Lagrangian

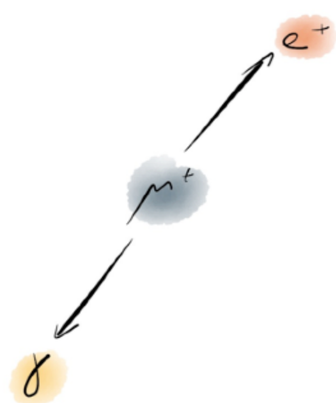


Golden muon channels

looking for cLFV

- Three **golden channels** in muon decays:

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



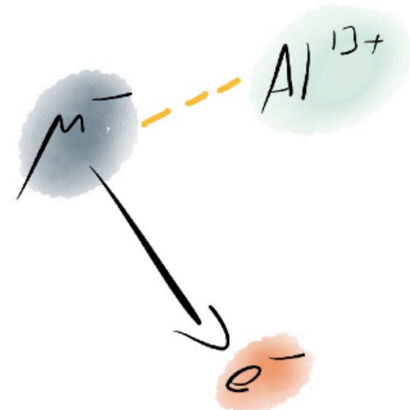
Current limit: MEG

$\mathcal{B} < 4.2 \times 10^{-13}$

Future: MEG II

$\mathcal{B} < 5 \times 10^{-14}$

$\mu^- N \to e^- N$



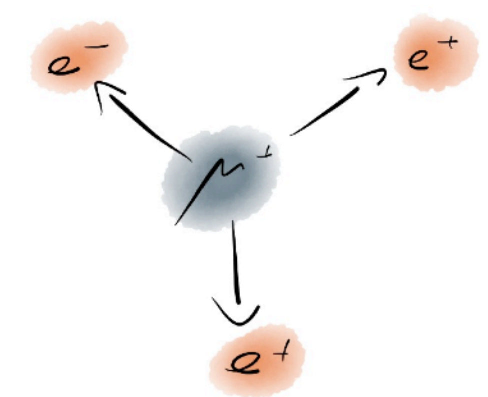
Current limit: SINDRUM II

$\mathcal{B}$ (Au) $< 7 \times 10^{-13}$

Future: Mu2e, COMET

$\mathcal{B} < 10^{-16}$

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



Current limit: SINDRUM II

$\mathcal{B} < 1.0 \times 10^{-12}$

Future: **Mu3e** (PSI)

$\mathcal{B} < 10^{-16}$

- **Complementarity** in sensitivity to scalar, vector and tensor interactions
  - comparison gives insight into the **nature** of the new physics

The Mu3e experiment

in the search for $\mu^+ \to e^+ e^- e^+$

- **Mu3e** is a future experiment in the search of the cLFV decay $\boldsymbol{\mu^+ \to e^+ e^- e^+}$

- Goal:
  - Observe $\mu^+ \to e^+ e^- e^+$ if $\mathcal{B} > 10^{-16}$
  - Exclude $\mathcal{B} > 10^{-16}$ at 90% CL

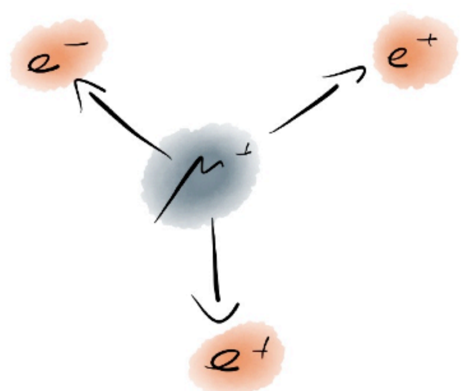
- Two-stage approach:
  - $\mathcal{B} <$ few $\mathbf{10^{-15}}$ in phase I (2025-26)
  - $\mathcal{B} < \mathbf{10^{-16}}$ in phase II (2029+)

- Under construction at the **Paul Scherrer Institute** (PSI) in Switzerland
- ~70 collaborators from institutes in **Switzerland**, **Germany** and **UK**

Signal

and related kinematics

Signal



- Common vertex
- Time coincidence
- $|\Sigma\,\vec{p}\,| = 0$
- $\Sigma\,E = m_\mu$

- **Unknown** underlying cLFV mechanism

1 Large **phase** space coverage

- Phase I: Need > 10^{15} muons
- 2.5 x 10^{7} s (290 days) at 20% efficiency
  - Rate **> 1 x 10^{8} muons/s**

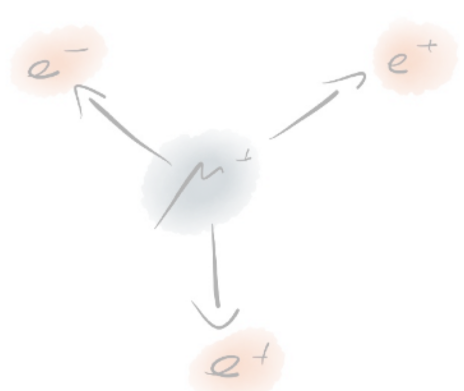
2 High **rate** capability

Backgrounds

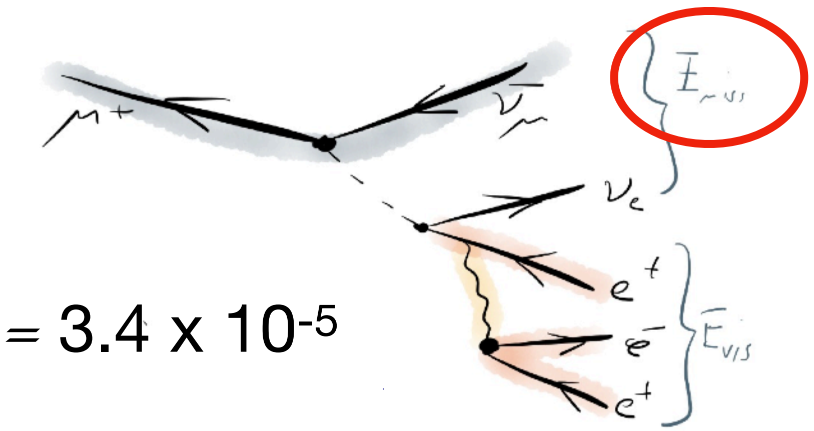
and related kinematics

Signal vs. **Internal conversion**

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



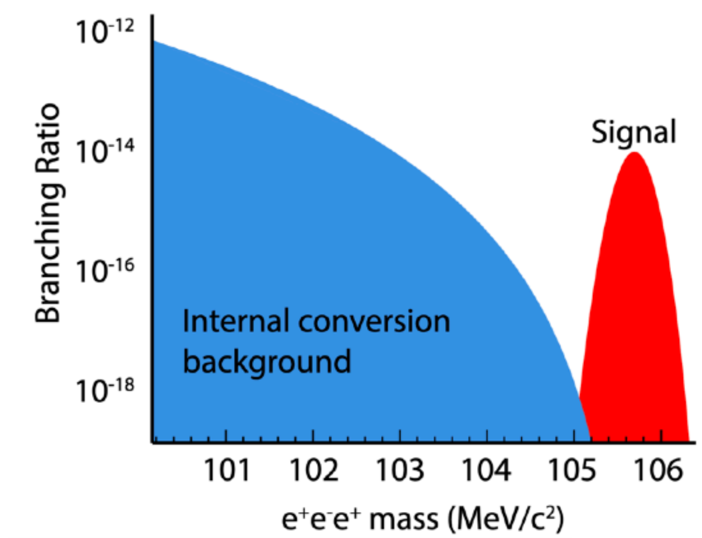
- Common vertex
- Time coincidence
- $|\Sigma\,\vec{p}\,| = 0$
- $\Sigma\,E = m_\mu$

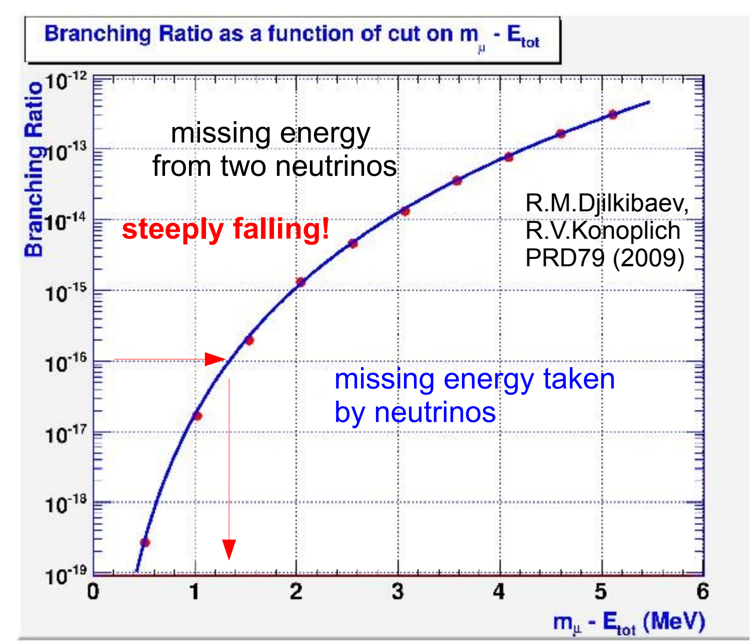


$\mathcal{B}$ = 3.4 x 10^{-5}

- Common vertex
- Time coincidence
- $|\Sigma\,\vec{p}\,| \neq 0$
- $\Sigma\,E \neq m_\mu$

3 Excellent **momentum** and **total energy** resolution (<1 MeV)





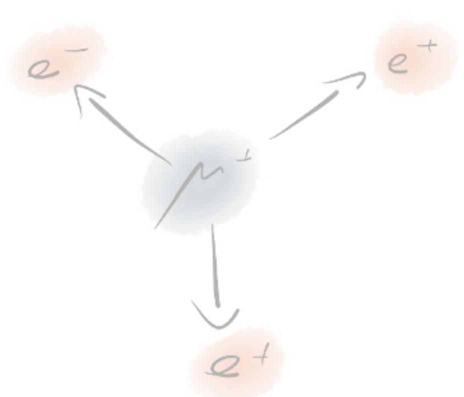
Backgrounds

and related kinematics

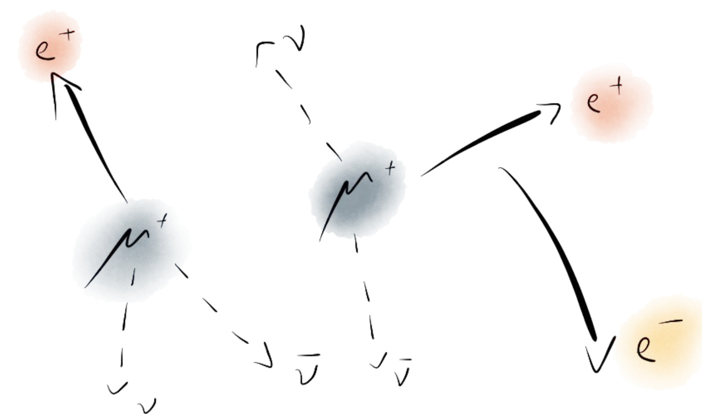
Signal

vs.

Accidental / Combinatorial



- Common vertex
- Time coincidence
- $|\Sigma\,\vec{p}\,| = 0$
- $\Sigma\, E = m_\mu$



- No common vertex
- No time coincidence
- $|\Sigma\,\vec{p}\,| \neq 0$
- $\Sigma\, E \neq m_\mu$

Overlays of two ordinary Michel e^+ with an e^- from:

* Bhabha scattering

* Photon conversion

* Mis-reconstruction

N ~ rate

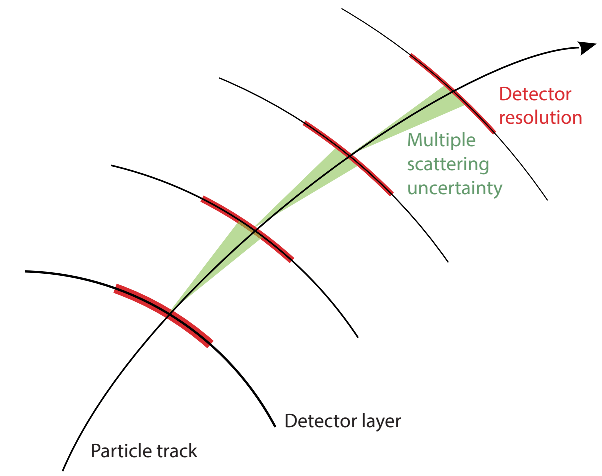
4

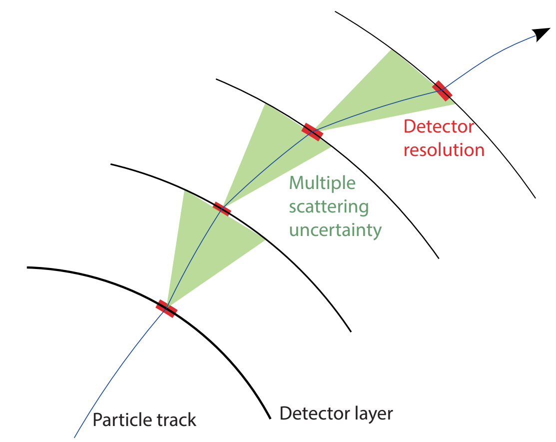
Excellent **timing** (<100ps) and **vertexing** (<0.5 mm), kinematic reconstruction

Momentum measurement

and multiple scattering

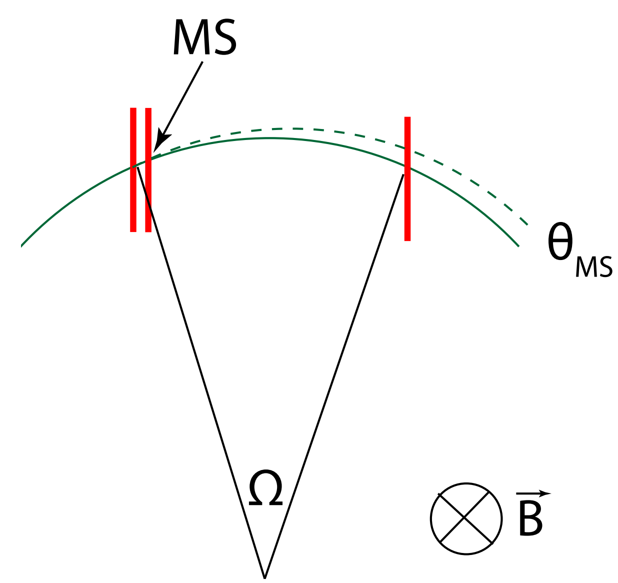
- Apply strong magnetic field (**1T**) and measure the curvature of the particles
- Muon decays at rest into **low energy** electrons and positrons (<53 MeV):
  - Momentum resolution dominated by **multiple scattering**, not position resolution

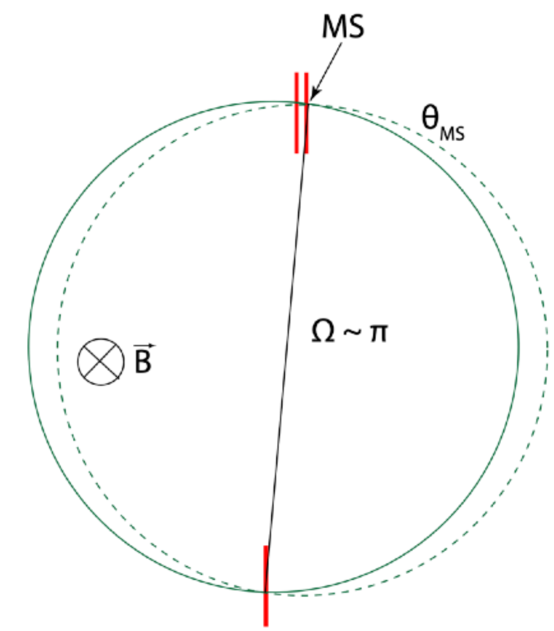




- At first order:

$$\frac{\sigma_p}{p} \sim \frac{\theta_{MS}}{\Omega}$$





5 Low **material** budget

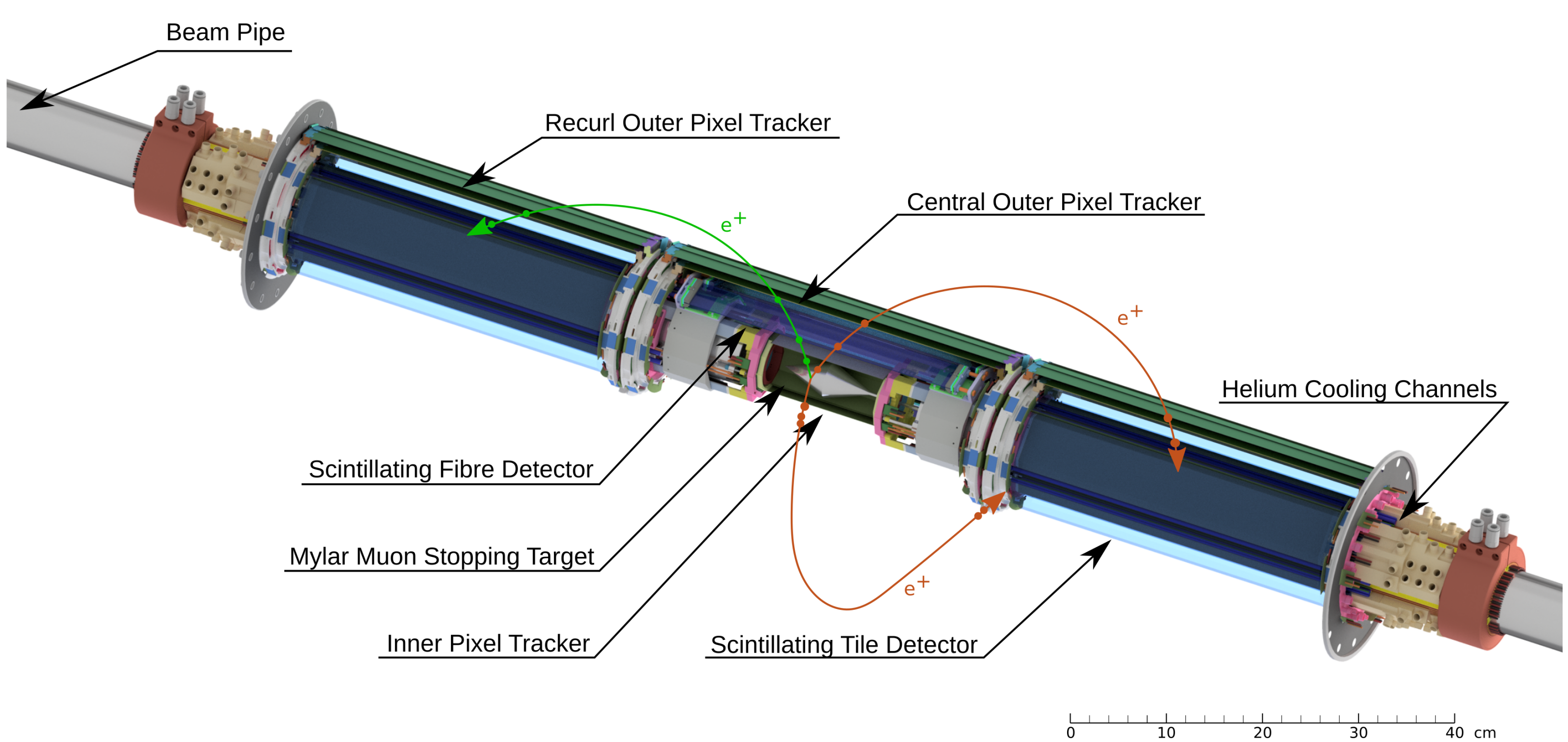
6 Large bending **angle**

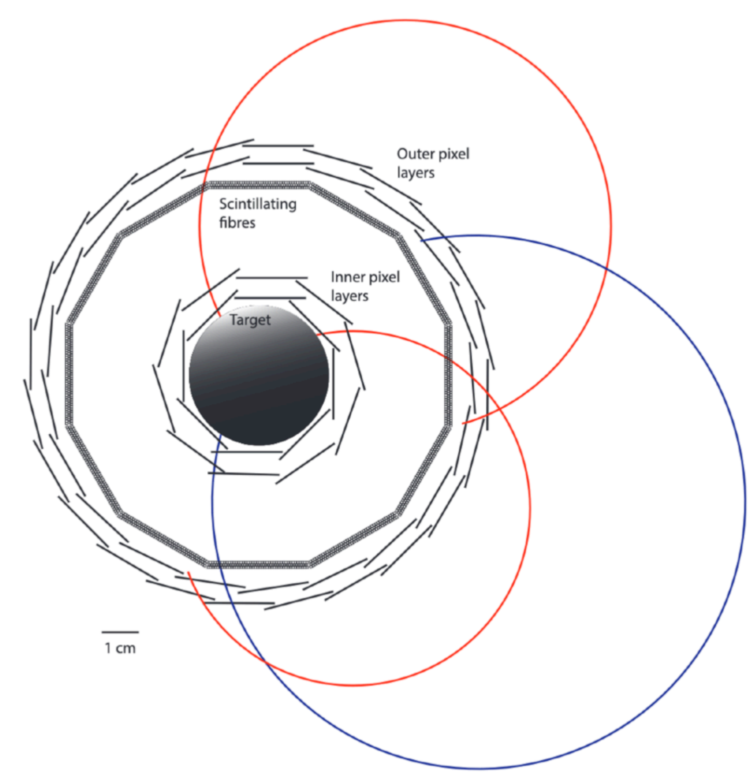
- MS uncertainties cancel out after half turn
- Allow particles to **recurl** in the detector

Mu3e design

based on experimental requirements

- Very challenging (compact) experimental design:
  - Unknown cLFV kinematics → large solid angle and kinematic **acceptance**
  - High muon rates → high **granularity** and **fast** processing
  - Internal conversion → excellent **momentum** resolution
  - Accidental background → good **timing** / **vertex** resolution
  - Multiple scattering → low **material** budget, optimized **recurling**





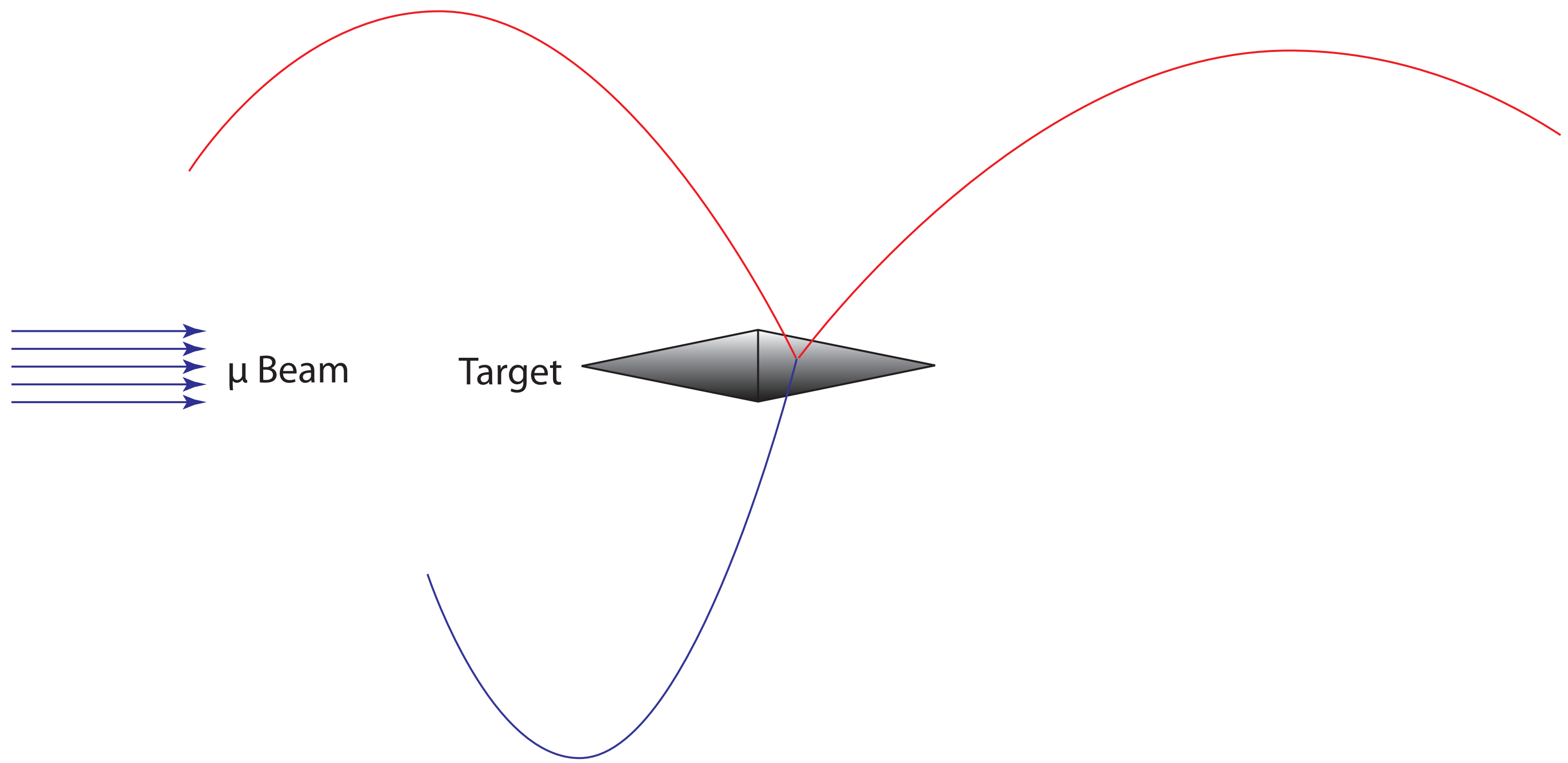
Mu3e experiment

Beam and target

- **10^8 muons/s** stopped on a thin hollow stopping target

Mu3e experiment

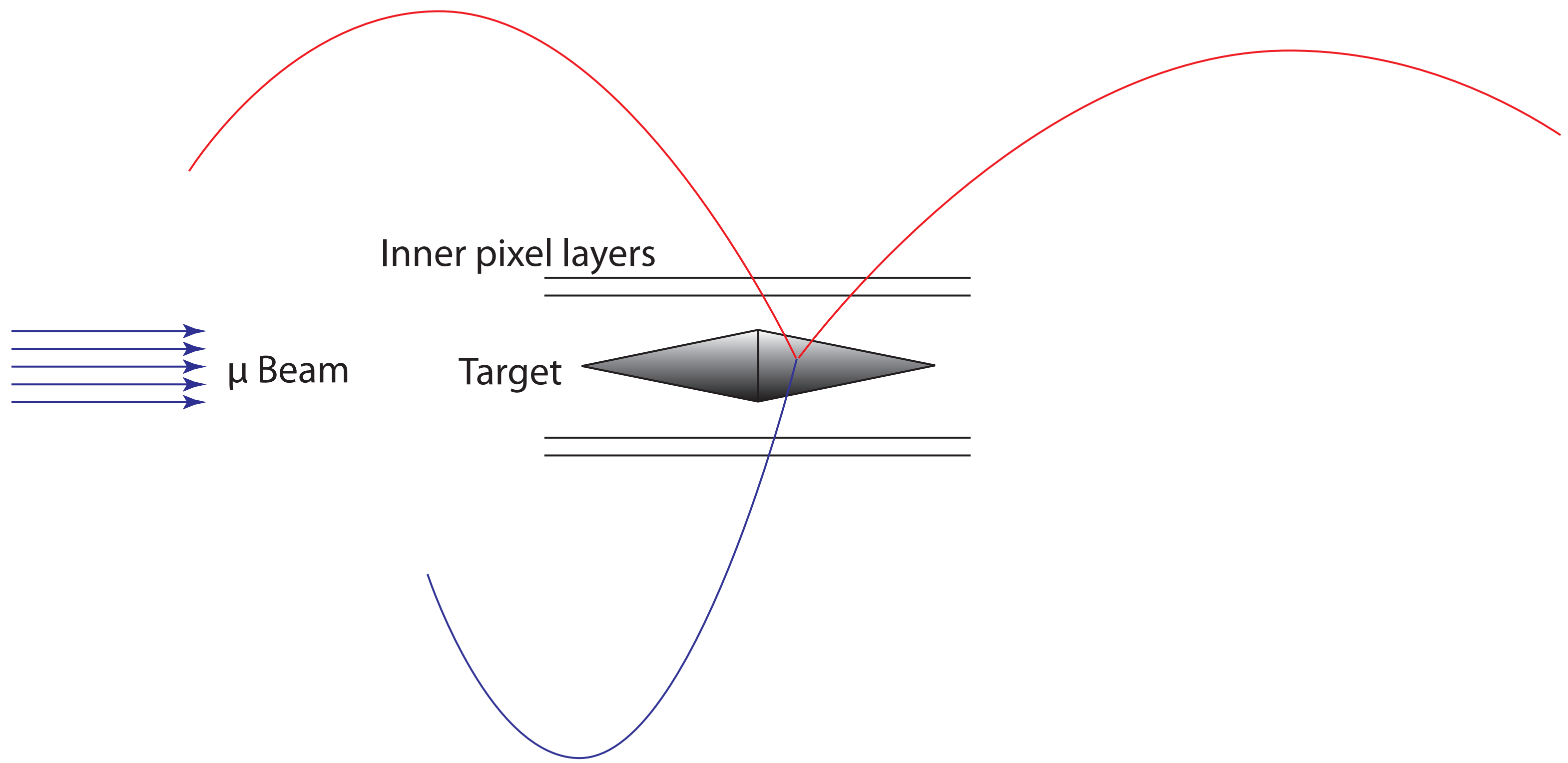
Magnetic field



- 10^8 muons/s stopped on a thin hollow stopping target
- Helical tracks in strong uniform 1 T **magnetic** field

Mu3e experiment

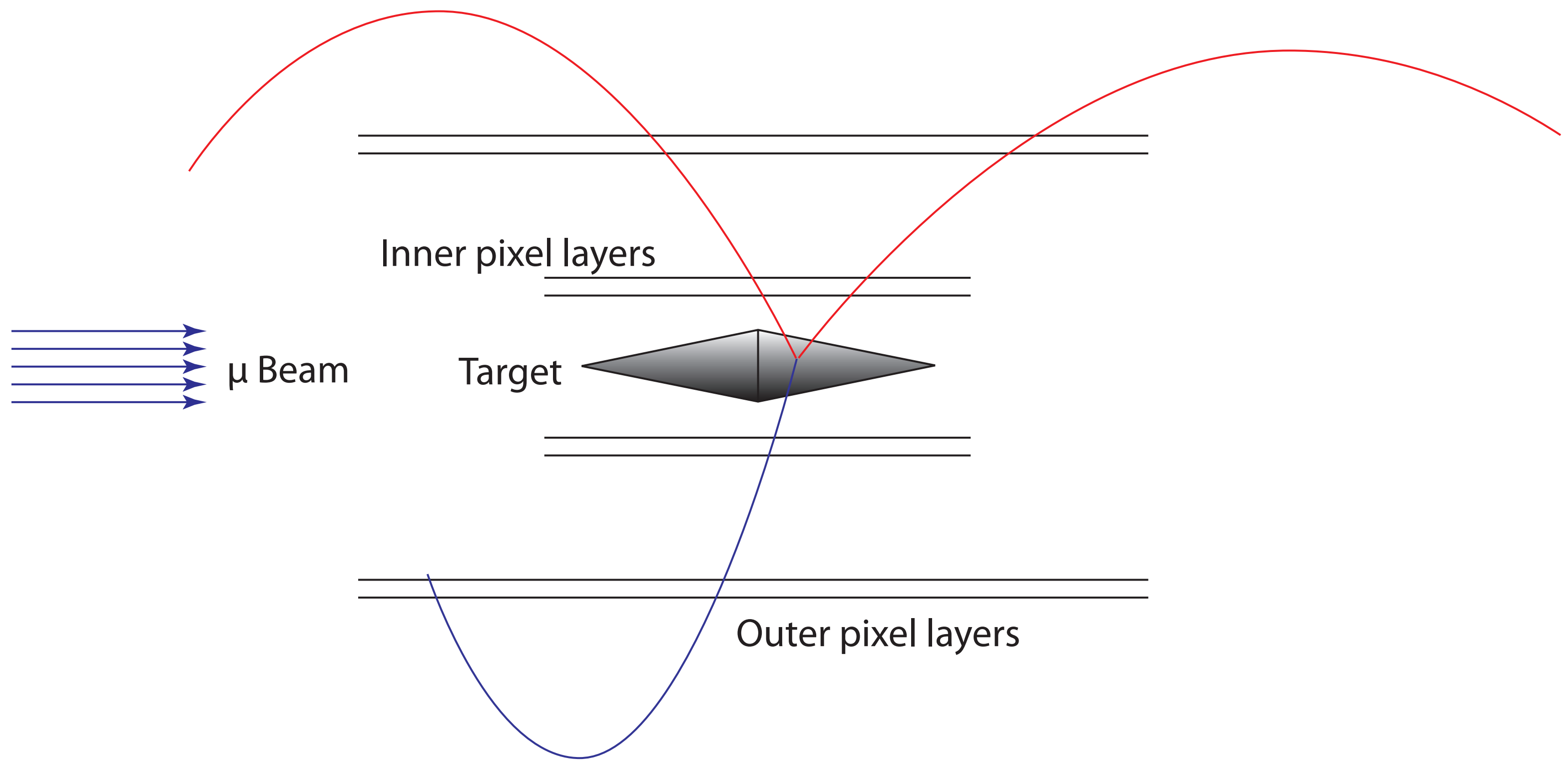
Inner pixel detector



- 10^8 muons/s stopped on a thin hollow stopping target
- Helical tracks in strong uniform 1 T magnetic field
- Two layers of ultra thin silicon pixels for **vertexing**

Mu3e experiment

Outer pixel detector

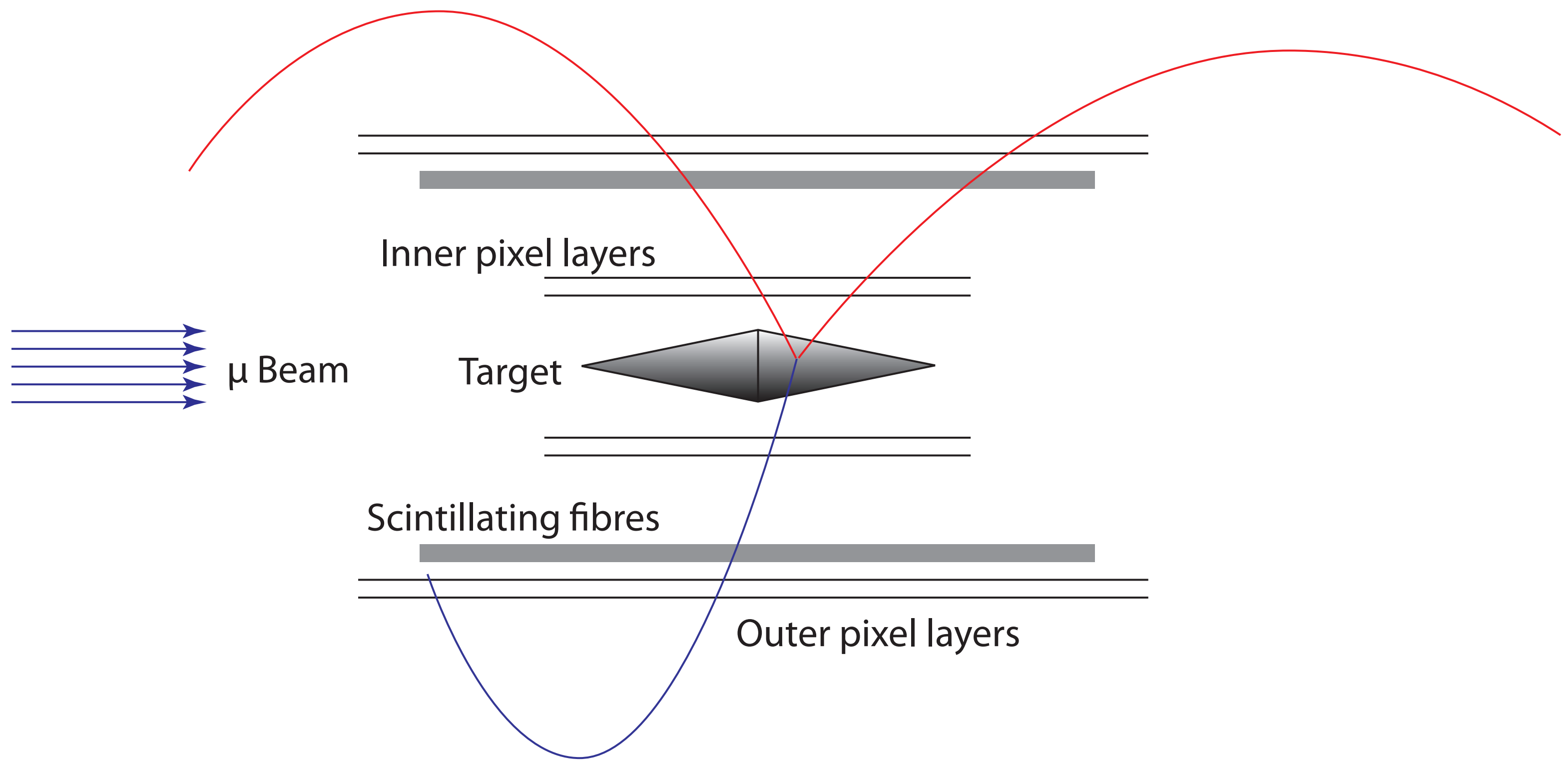


- 10^8 muons/s stopped on a thin hollow stopping target
- Helical tracks in strong uniform 1 T magnetic field
- Two layers of ultra thin silicon pixels for vertexing

- Two outer pixel layers for 4-hit **track** reconstruction

Mu3e experiment

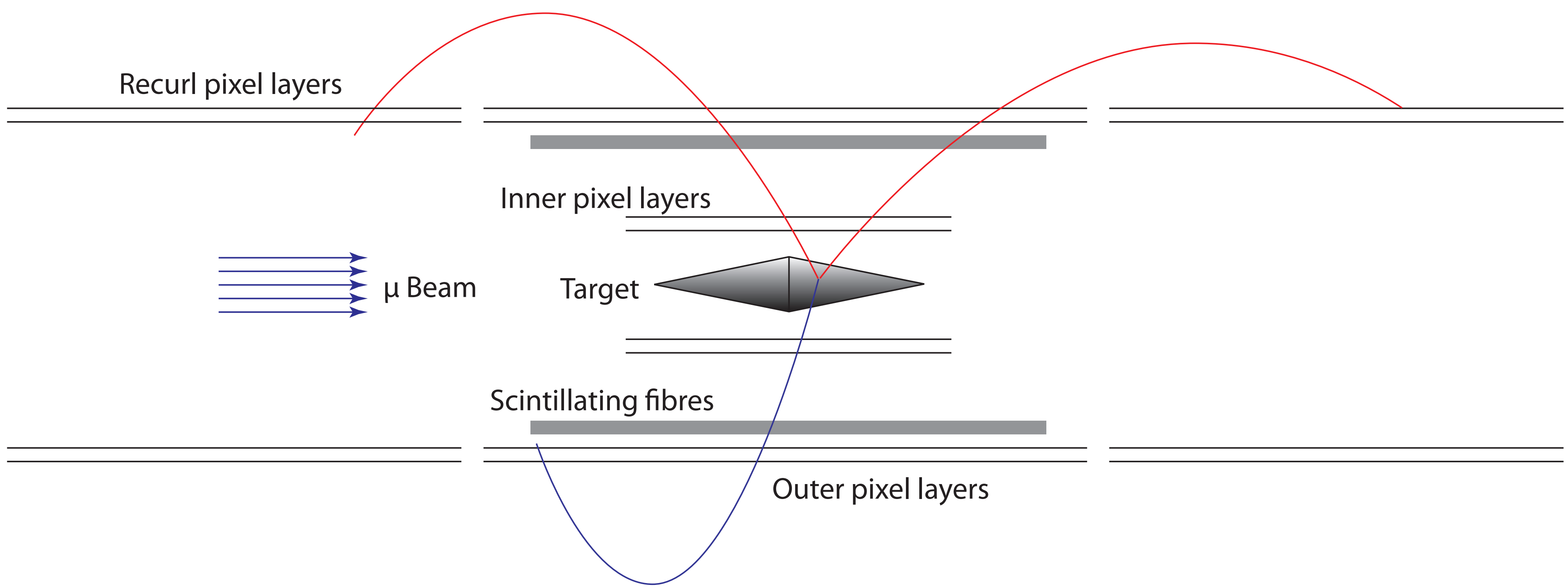
Scintillating fibres detector



- 10^8 muons/s stopped on a thin hollow stopping target
- Helical tracks in strong uniform 1 T magnetic field
- Two layers of ultra thin silicon pixels for vertexing
- Two outer pixel layers for 4-hit track reconstruction
- Scintillating fibres for precise **timing** and **charge** measurement

Mu3e experiment

Recurl pixel detector



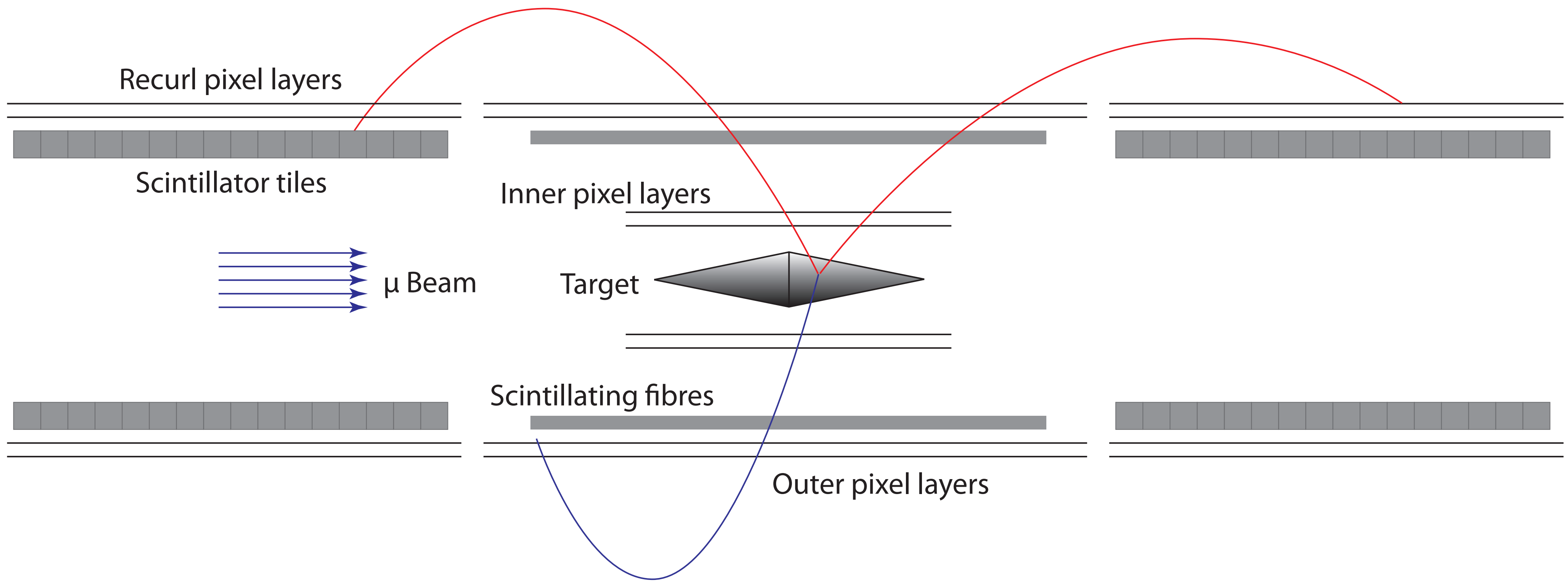
- 10^8 muons/s stopped on a thin hollow stopping target
- Helical tracks in strong uniform 1 T magnetic field
- Two layers of ultra thin silicon pixels for vertexing

- Two outer pixel layers for 4-hit track reconstruction
- Scintillating fibres for precise timing and charge measurement

- Pixel recurl stations for optimal **momentum** resolution and acceptance

Mu3e experiment

Scintillating tiles detector



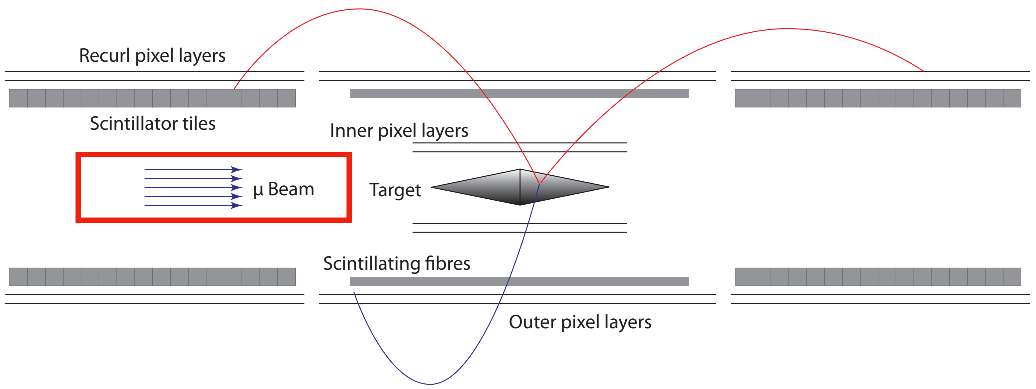
- 10^8 muons/s stopped on a thin hollow stopping target
- Helical tracks in strong uniform 1 T magnetic field
- Two layers of ultra thin silicon pixels for vertexing

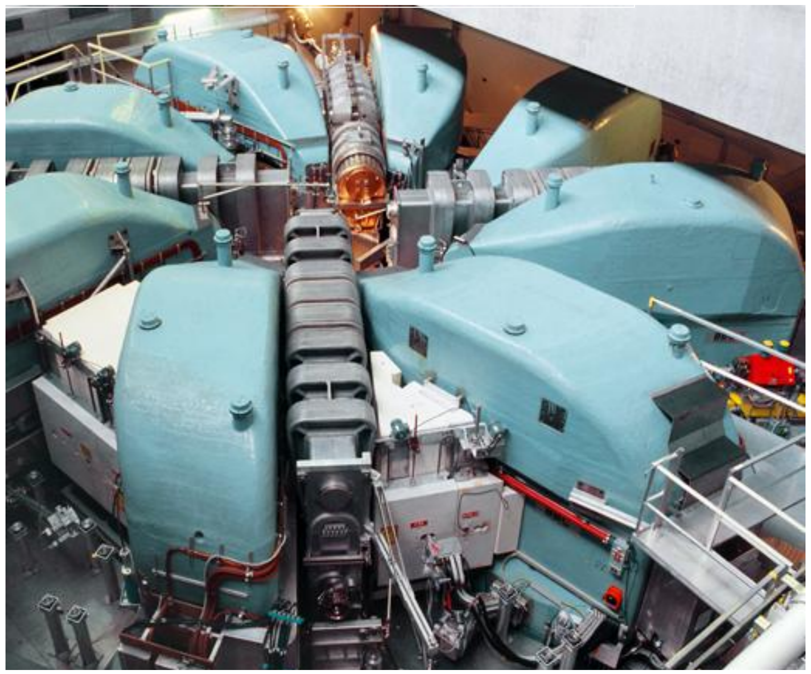
- Two outer pixel layers for 4-hit track reconstruction
- Scintillating fibres for precise timing and charge measurement

- Pixel recurl stations for optimal momentum resolution and acceptance
- Extra scintillating tiles for optimal **timing**

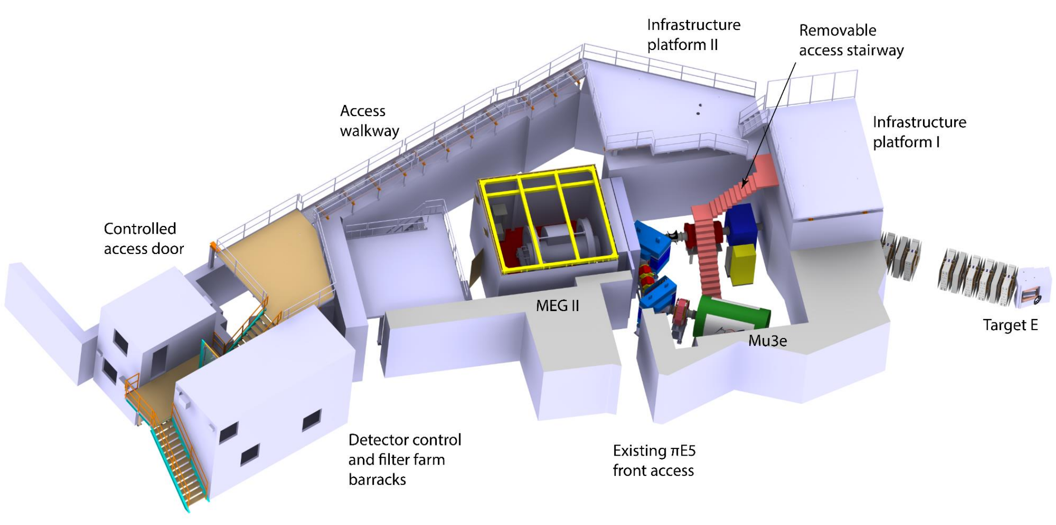
Muon beam

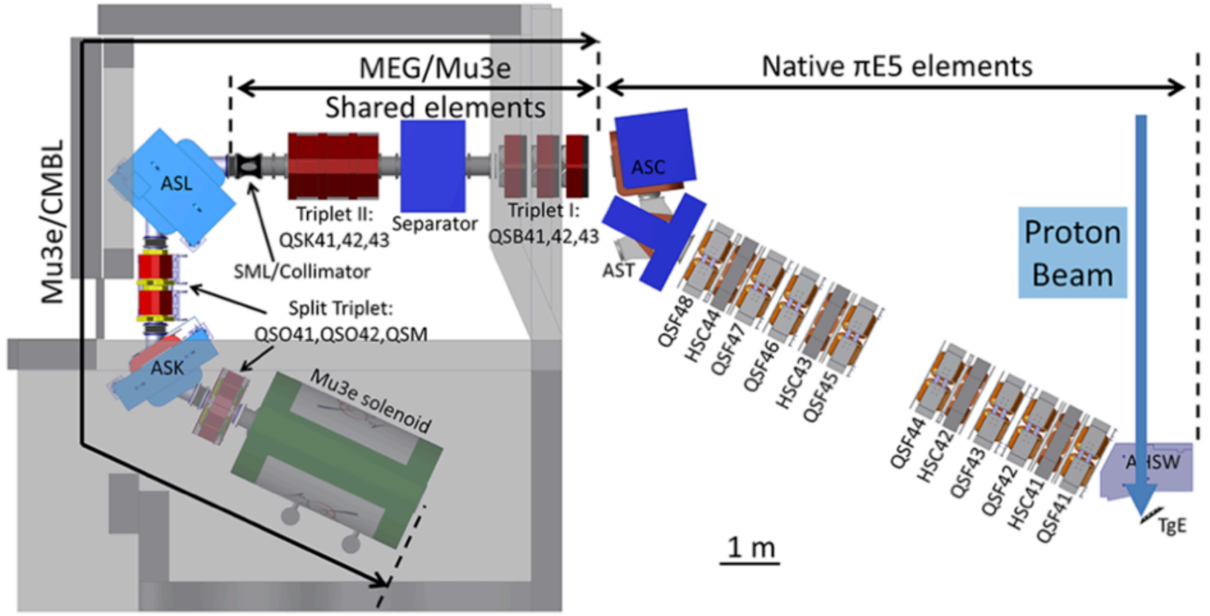
HIPA proton accelerator





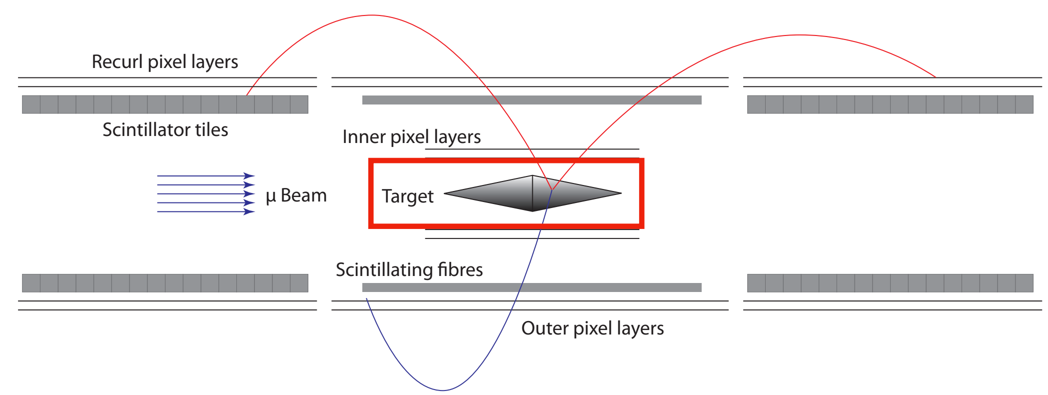
- **Phase I:** high-intensity continuous muon beam
- **HIPA** proton accelerator at PSI in Switzerland:
  - 2.2 mA protons at 590 MeV (1.5 MW)
  - protons → pions → "surface" muons
- World's most intense **DC muon beam**:
  - Low momentum ~28 MeV
  - **πE5 / CMBL** shared MEG II and Mu3e
  - 1.4 x **10^8 muons/s** delivered



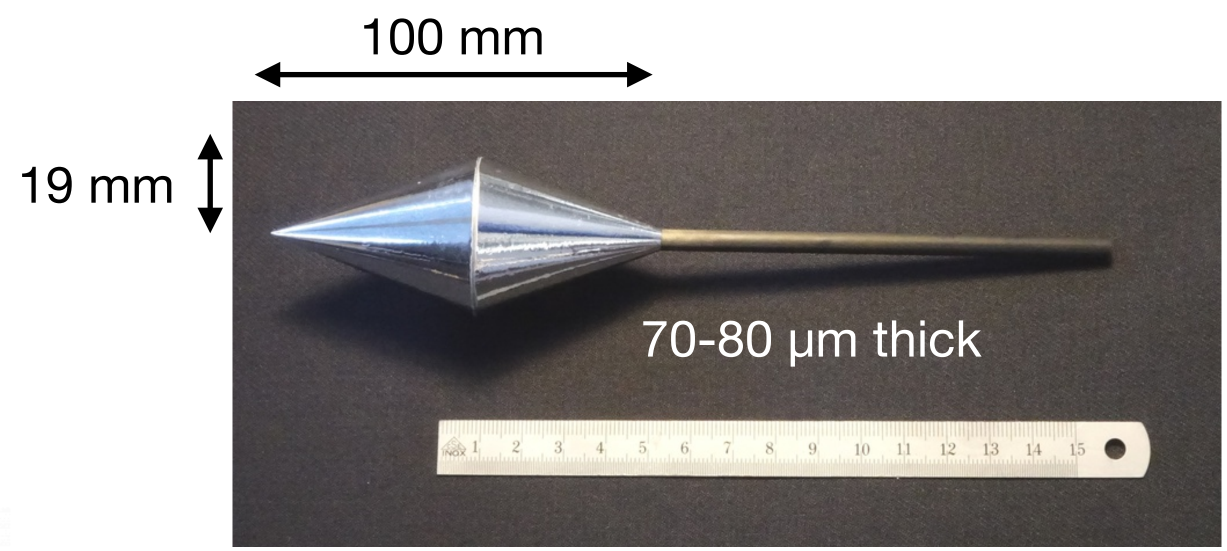


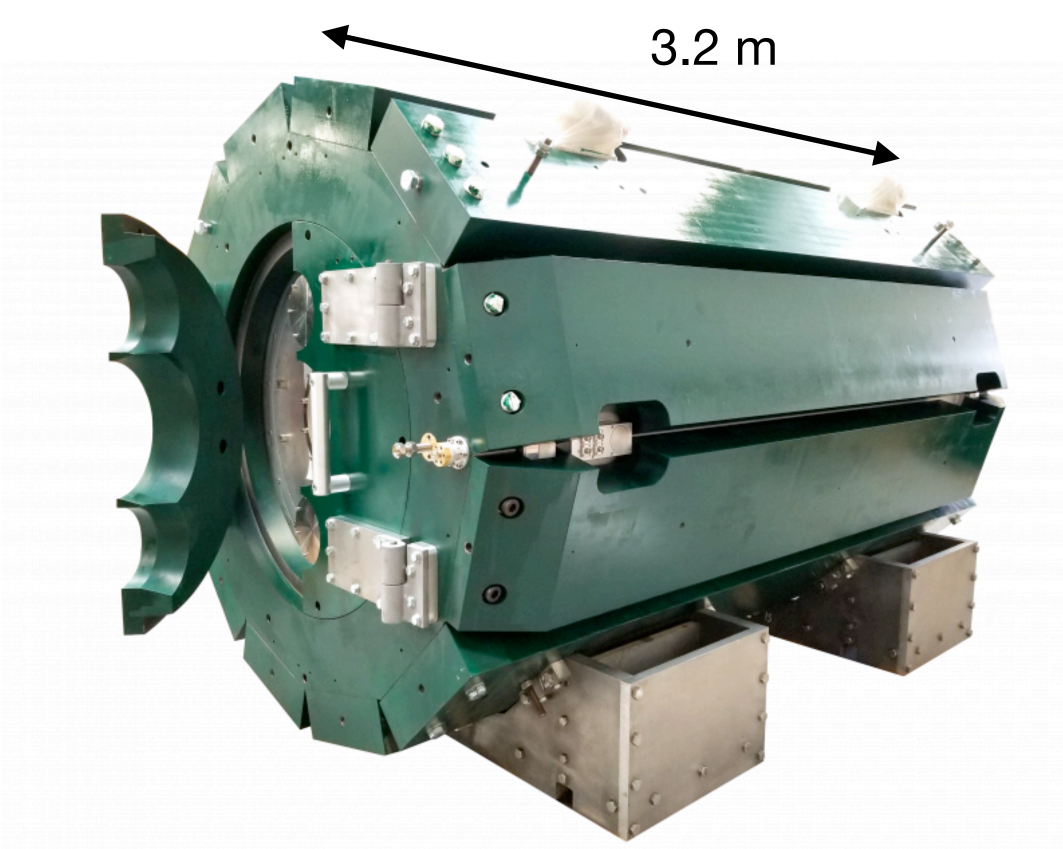
Stopping target

and magnet



- Stopping **target**:
  - **Hollow** and **double-cone**
  - Made in **Mylar**
  - Stops ~96% of muons

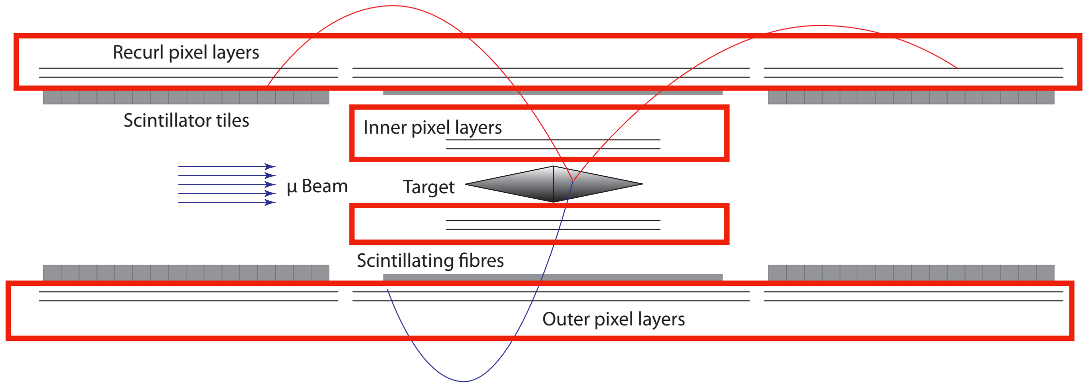




- **Solenoidal** superconducting magnet:
  - Precise **momentum** reconstruction with recurlers
  - Strong magnetic field **1 Tesla**
  - Stable and homogeneous
  - Delivered at PSI, **operational**

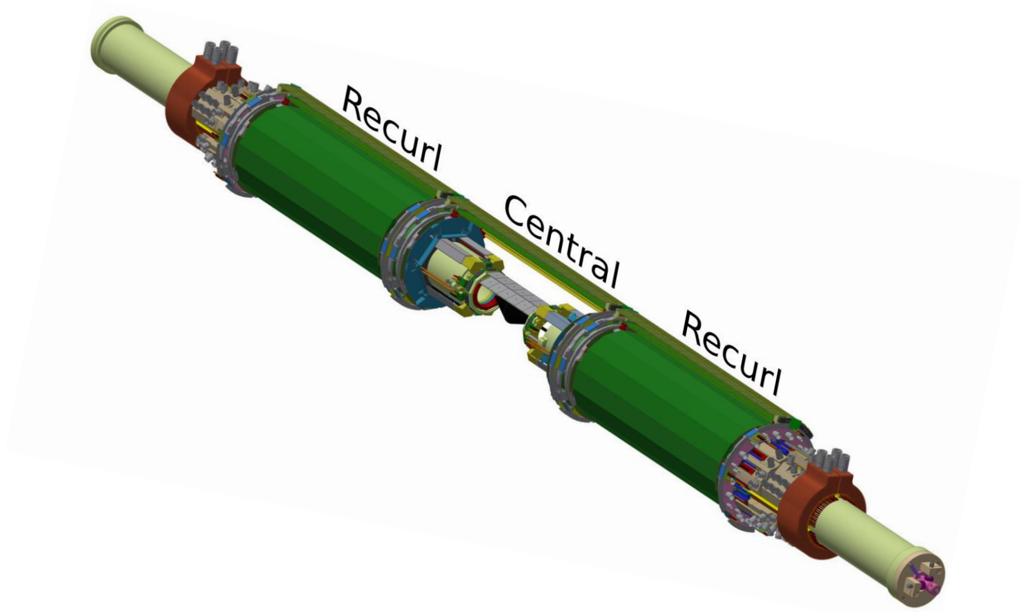
Pixel detectors

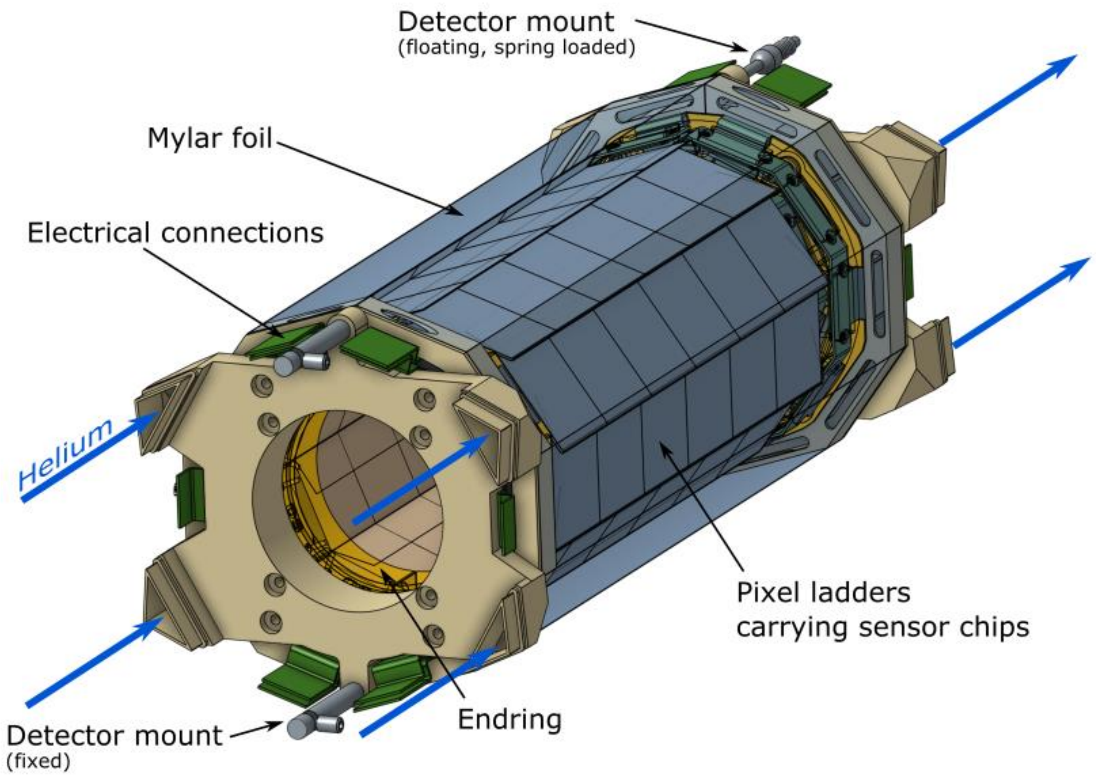
Mechanics



- **Vertex** identification and **momenta** measurement:
  - Very thin, fast, precise hit information
- Cylindrical, 4 **layers** (2 inner + 2 outer)
  - **Central** station for precise track reconstruction
  - **Recurl** stations for high purity and acceptance
- Cooled by innovative gaseous **helium system**

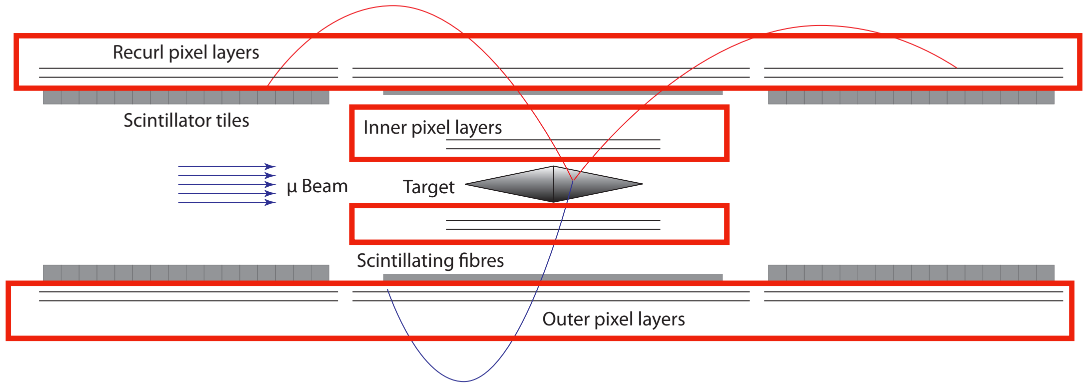
See talk by T. Rudzki this afternoon





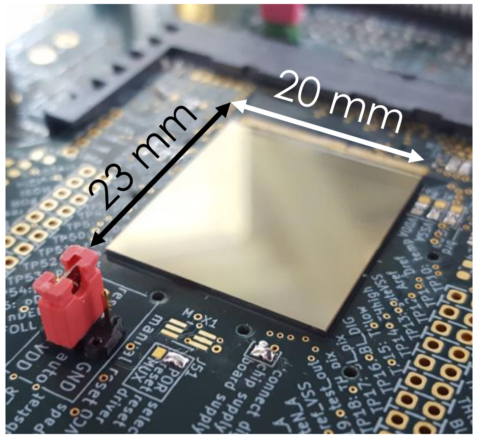
Pixel detectors

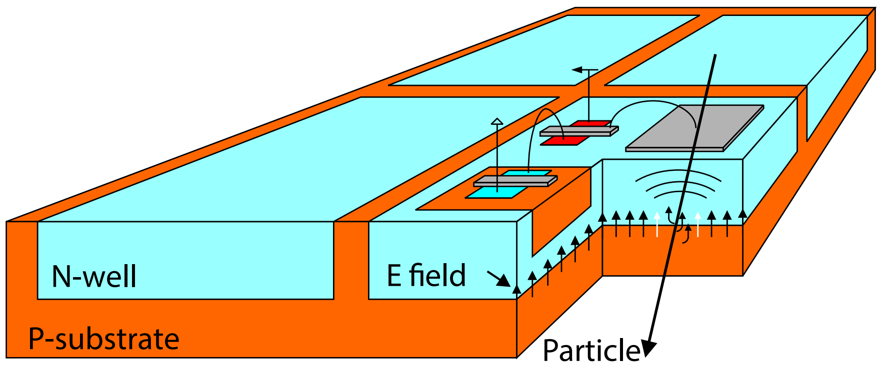
Sensors

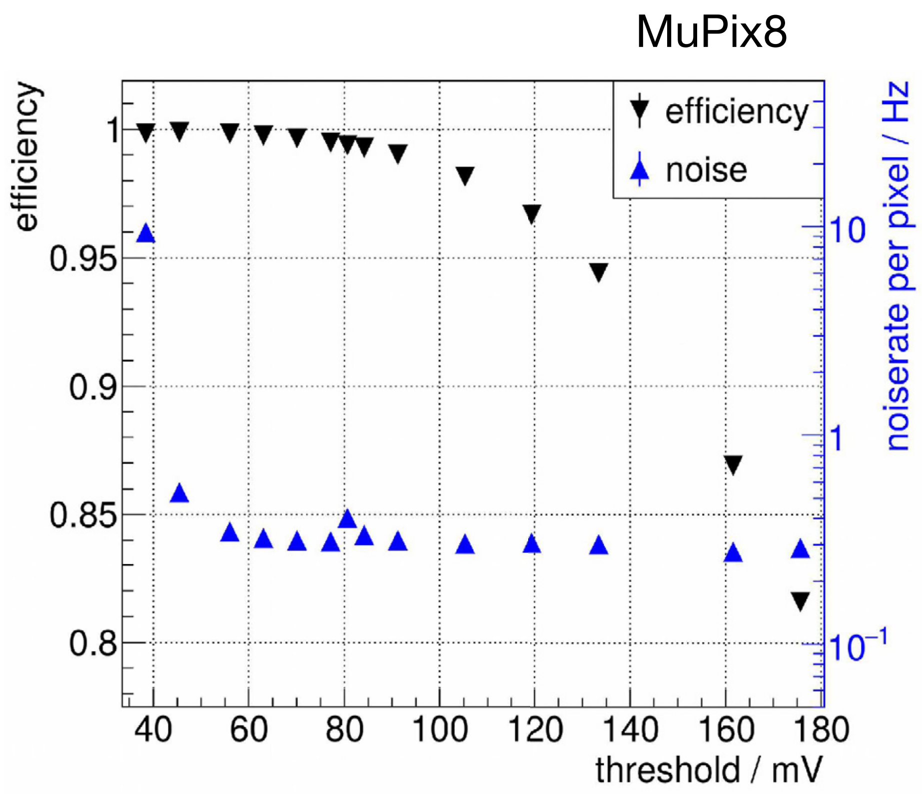


- **MuPix** - high voltage monolithic active pixel sensors (**HV-MAPS**):
  - HV-CMOS, 180 nm technology, fully **monolithic**
  - 20 x 23 mm² sensors with 80 x 80 μm² pixels
  - Large depletion region, **fast** charge collection via **drift** (~ns)
  - **Digital electronics** embedded in N-well ("*smart diode*")
  - Can be thinned down to **50 μm** (~**1‰** X_0)
- Efficiency **> 99%**, time resolution < 20 ns
- Final version (**MuPix11**) operational

See talk by T. Rudzki this afternoon

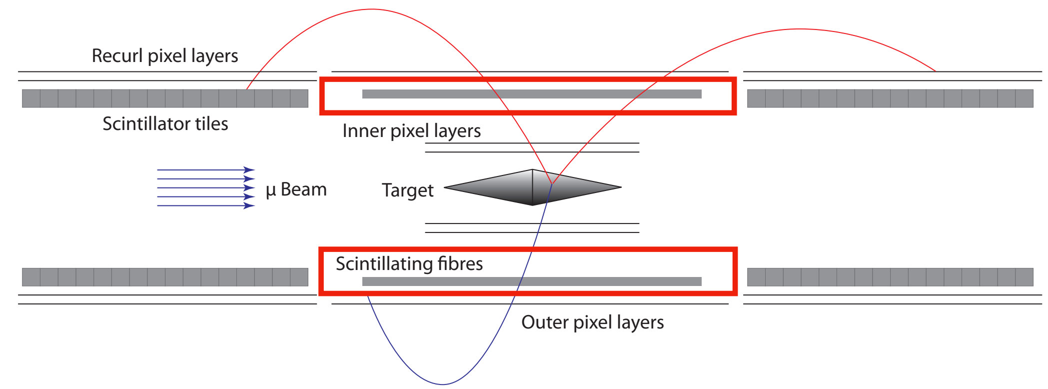




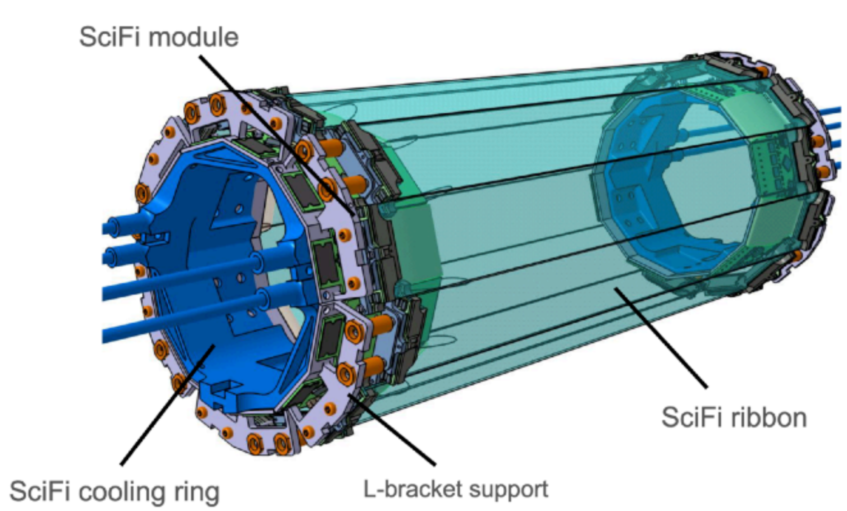


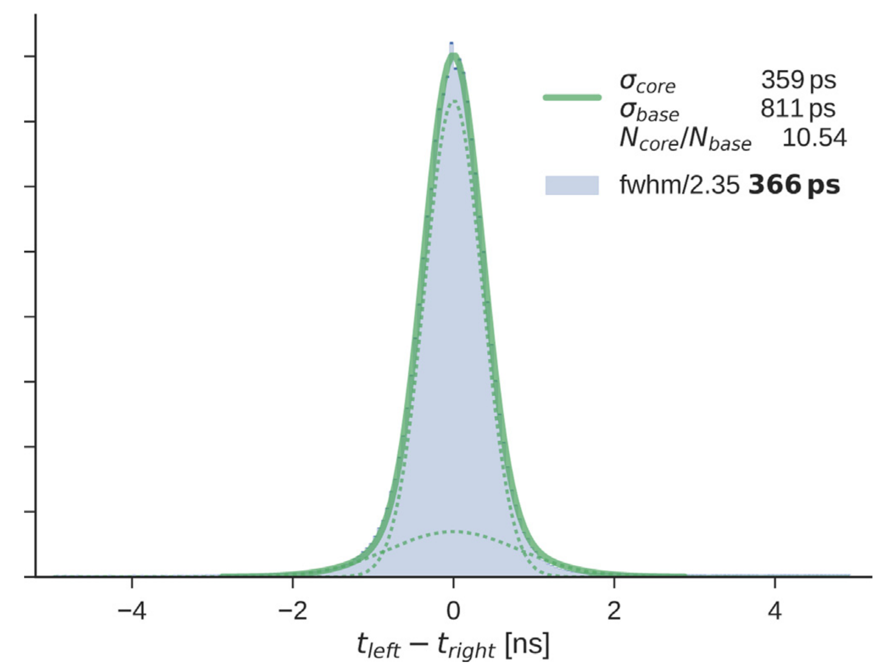
Timing detectors

Scintillating fibres detector



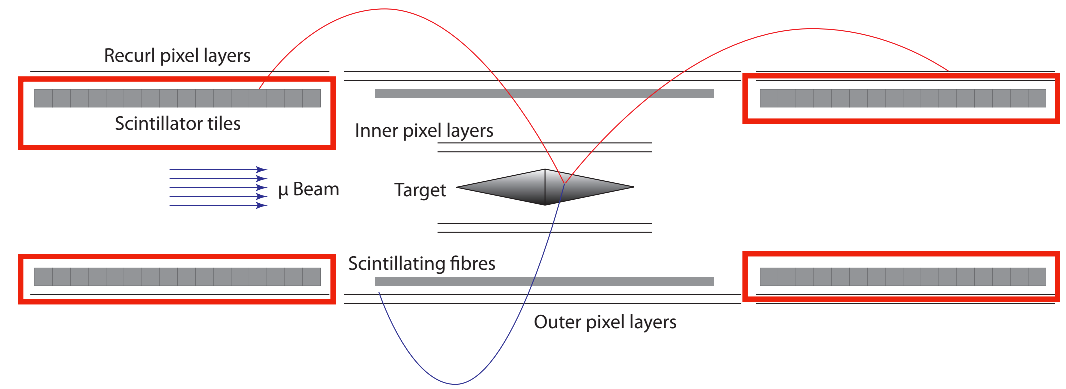
- Suppress **combinatorial background** and enable **charge** identification:
    - High rates, low material, good timing
- Cylindrical, central station:
    - 12 **ribbons** with 3 layers of 250 μm **thin** fibers (< 2‰ X_0)
- Readout with **SiPM** arrays and dedicated **MuTRiG** ASIC
- Cooled down to -10ºC with silicon oil
- Efficiency > 95%, time resolution ~ **250 ps**



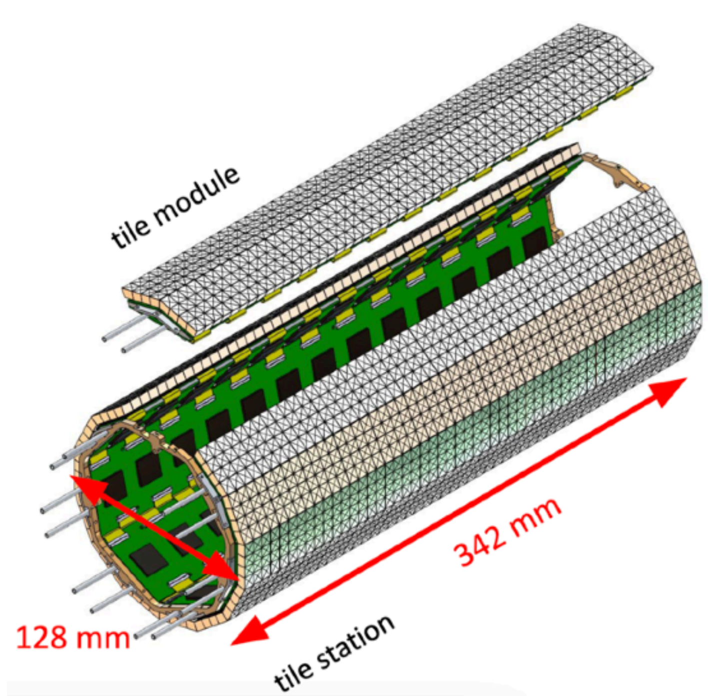


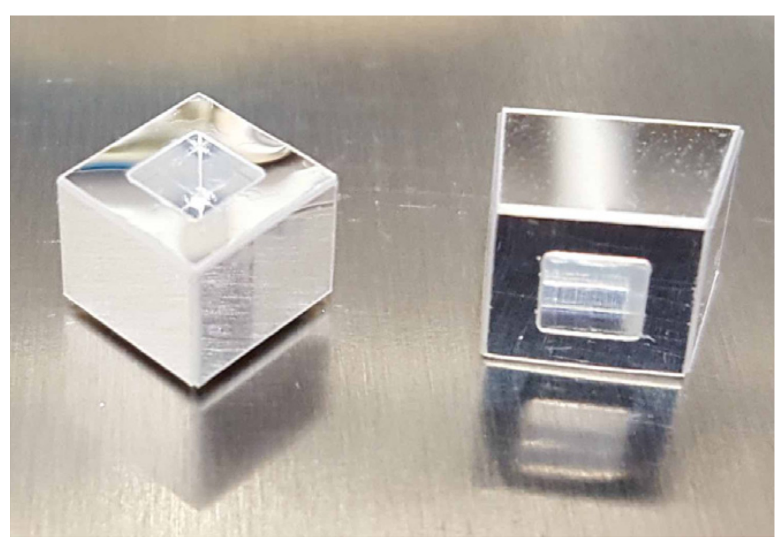
Timing detectors

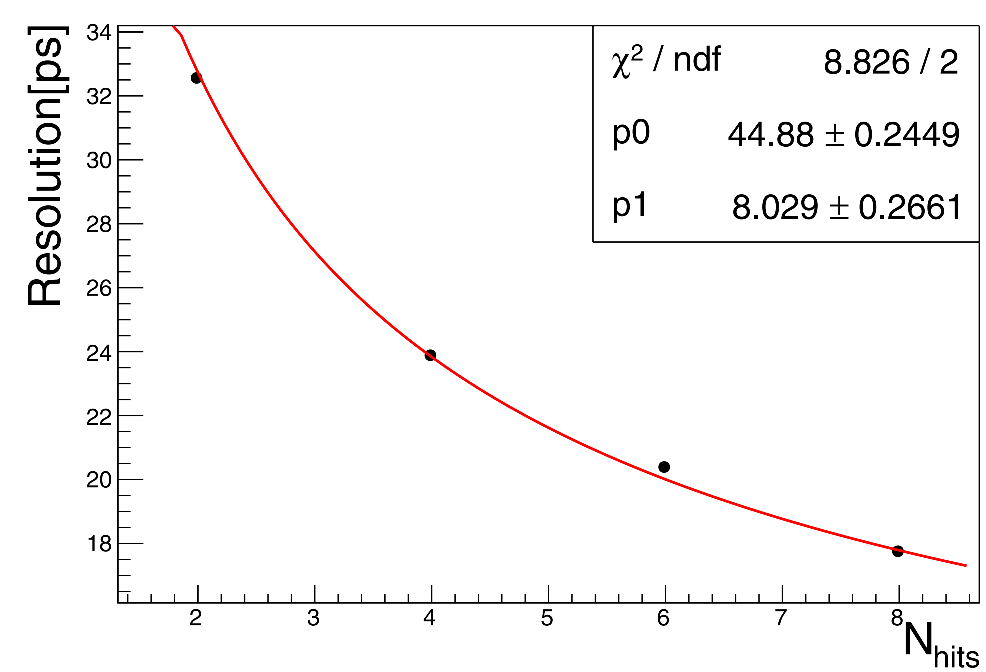
Scintillating tiles detector



- Lower occupancy, more space, very good timing
- Cylindric geometry, two recurl stations
  - Segmented in **granular** tiles (6 x 6 x 5 mm^3) with reflective foil
- Readout with **SiPM** and dedicated **MuTRiG** ASIC (common to ScFi)
- Cooled down to 0°C with silicon oil (common to ScFi)
- Efficiency > 99%, time resolution ~**40 ps**

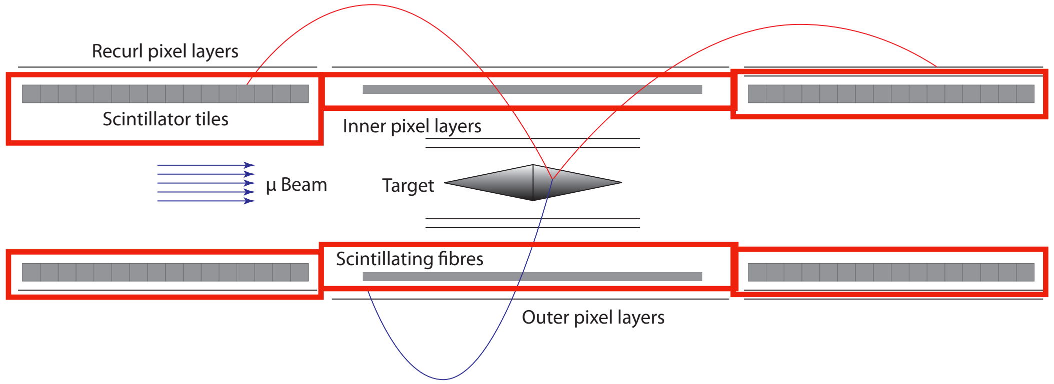




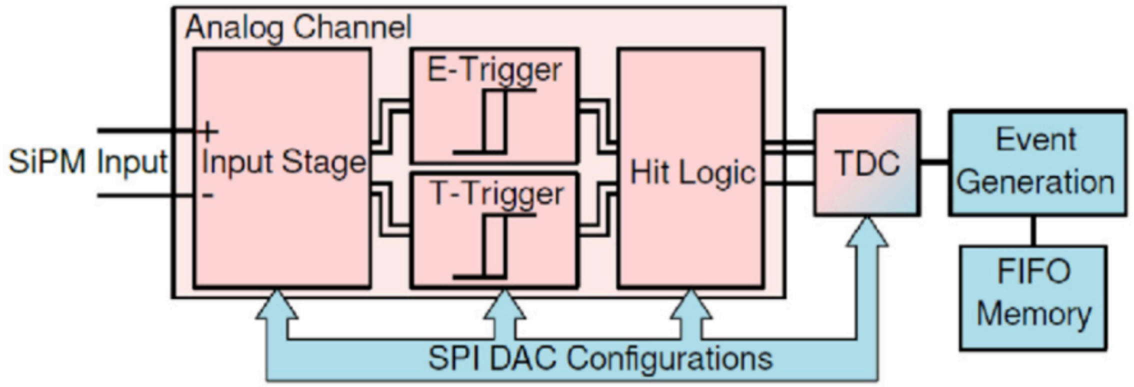


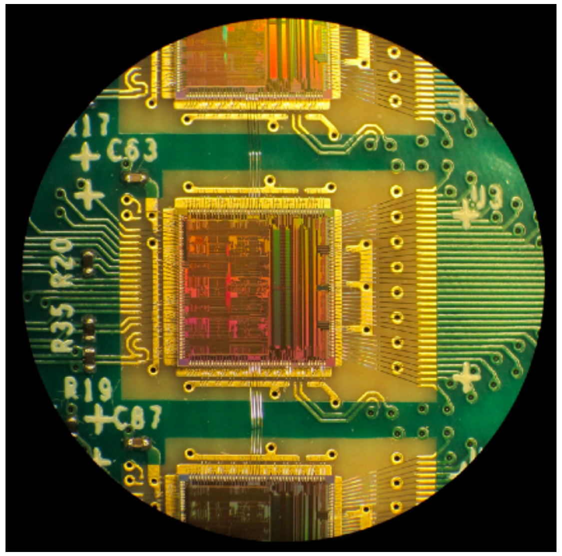
Timing detectors

Readout ASIC



- **MuTRiG -** Custom readout ASIC for SciFi and SciTiles:
  - **Fast SiPM** readout at **high rates**, based on UMC 180nm CMOS
    - High resolution TDC (**50 ps**)
    - High rate acceptance (~1 MHz/channel)
  - Tunable output event structure (separate time and energy thresholds)
  - **Clustering** logic on-chip (coincidence)
- Final version (**MuTRiG3**) under validation

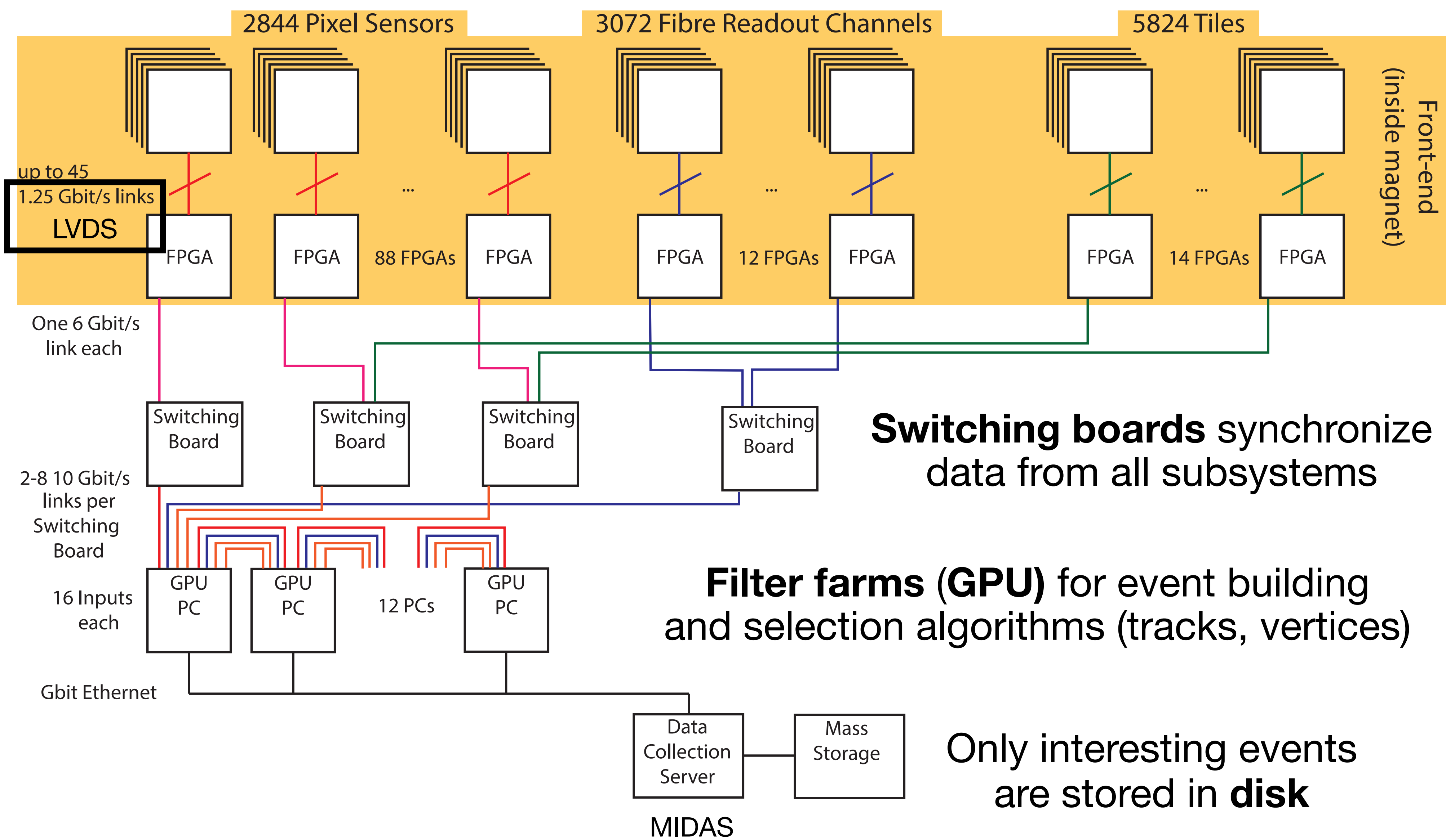


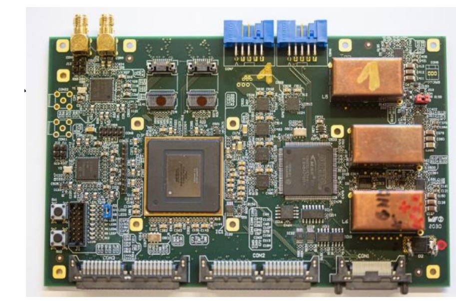


Data acquisition system

and online reconstruction

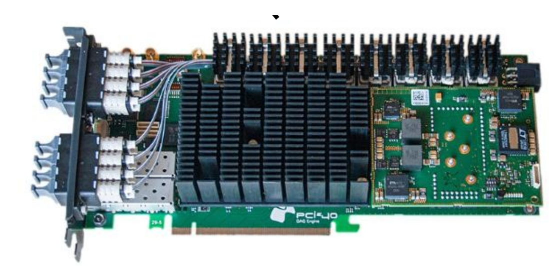
- **Triggerless** continuous (zero-suppression) readout of all sub-detectors:





Front-end boards collect and sort data

Switching boards synchronize data from all subsystems

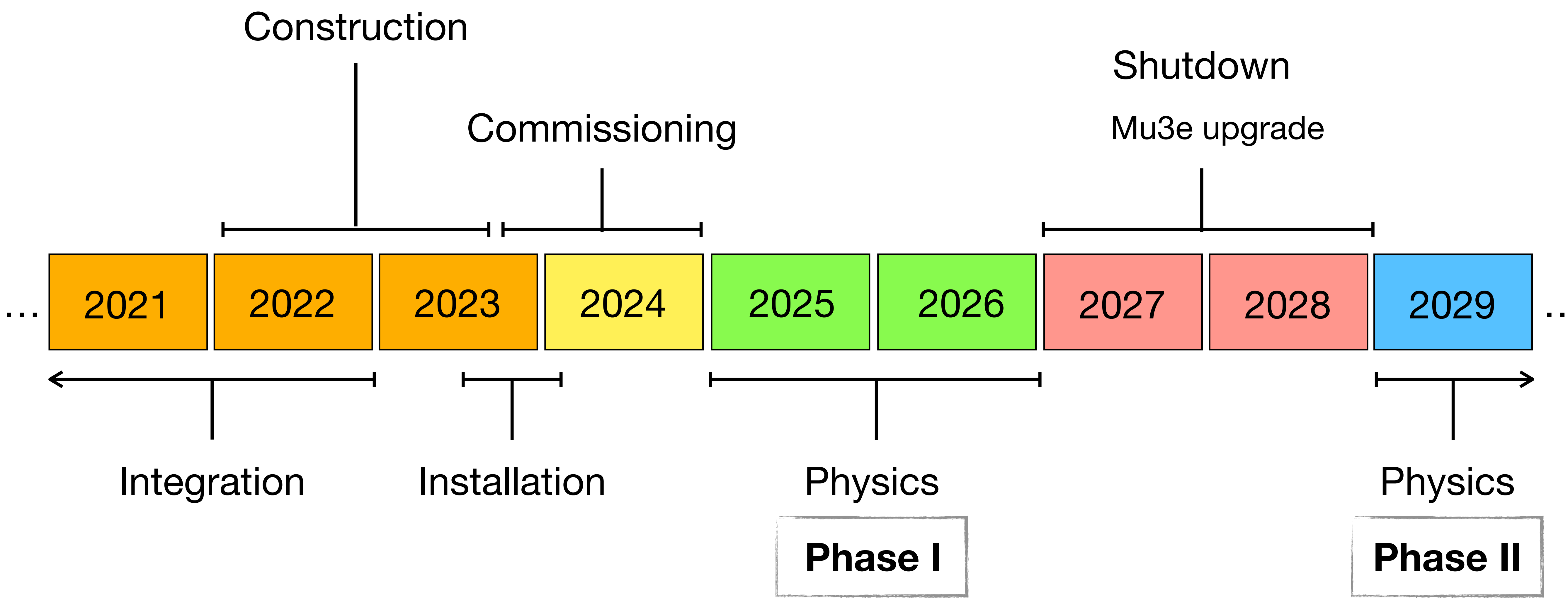


Filter farms (GPU) for event building and selection algorithms (tracks, vertices)

Only interesting events are stored in **disk**

Mu3e timeline

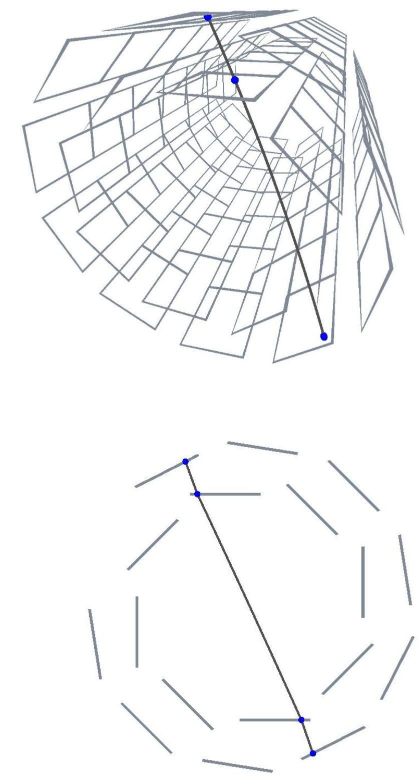
from construction to physics

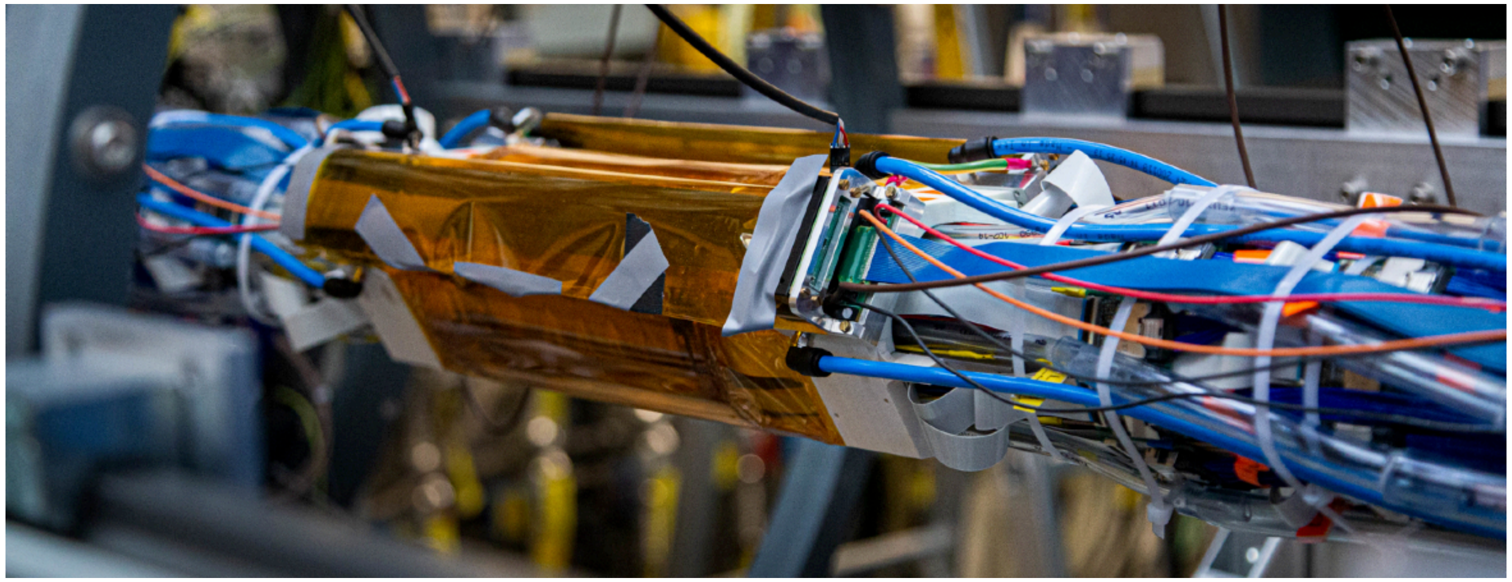


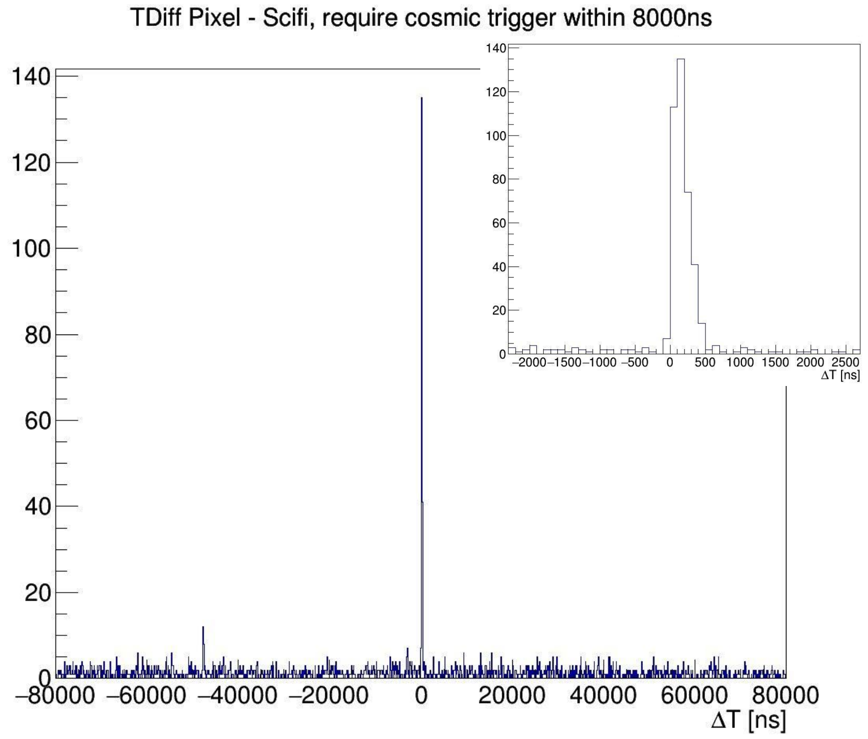
Integration

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

- "**Integration**" and "cosmic" runs (PSI, 2021/22), test beam campaigns, thermo-mechanical **mock-ups**…
- Integration of **services**, **cooling** and **DAQ**
- Hardware validation in **magnet** and **beam**
- Combined vertex-SciFi and vertex-SciTiles **operation**
- **Reconstruction** of cosmic tracks and recurl electrons, sub-detector correlations,…



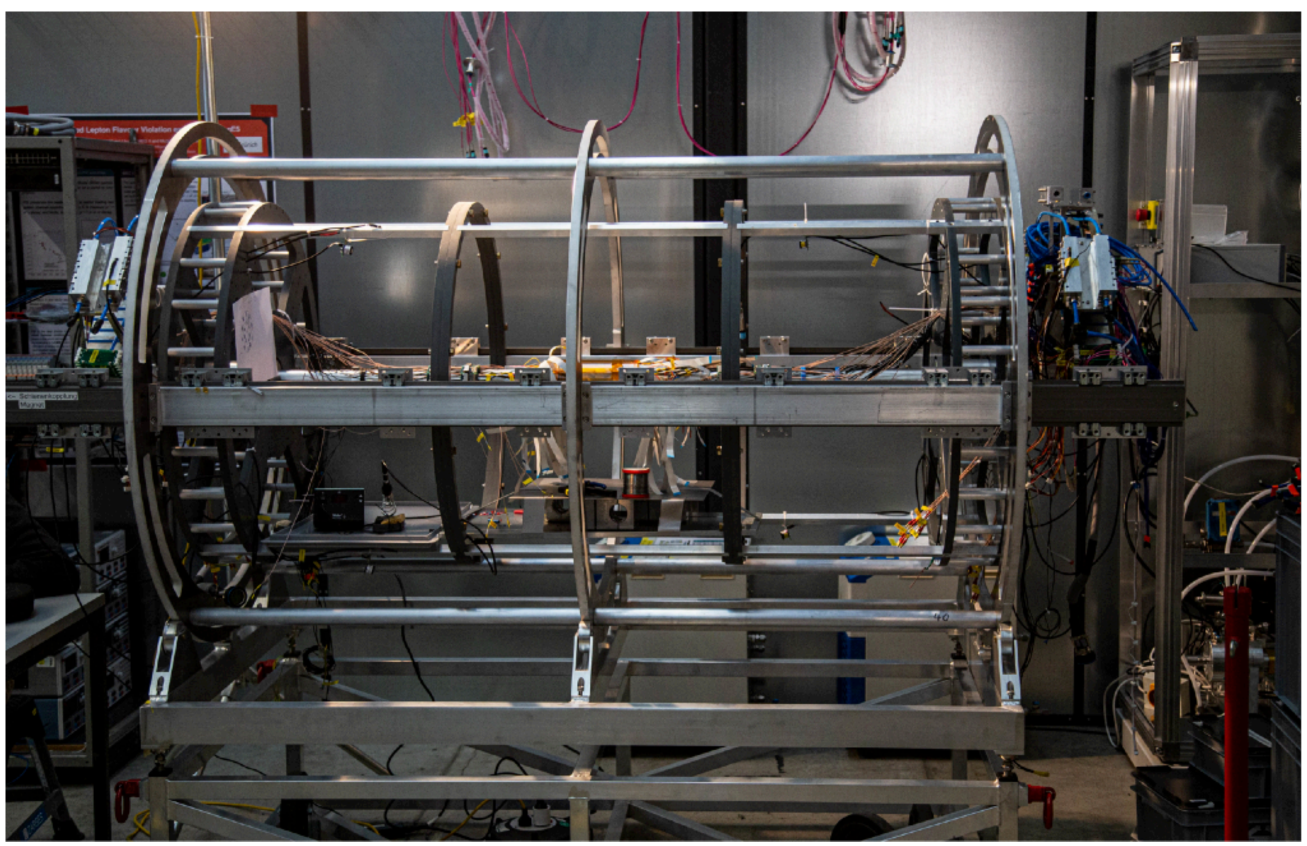


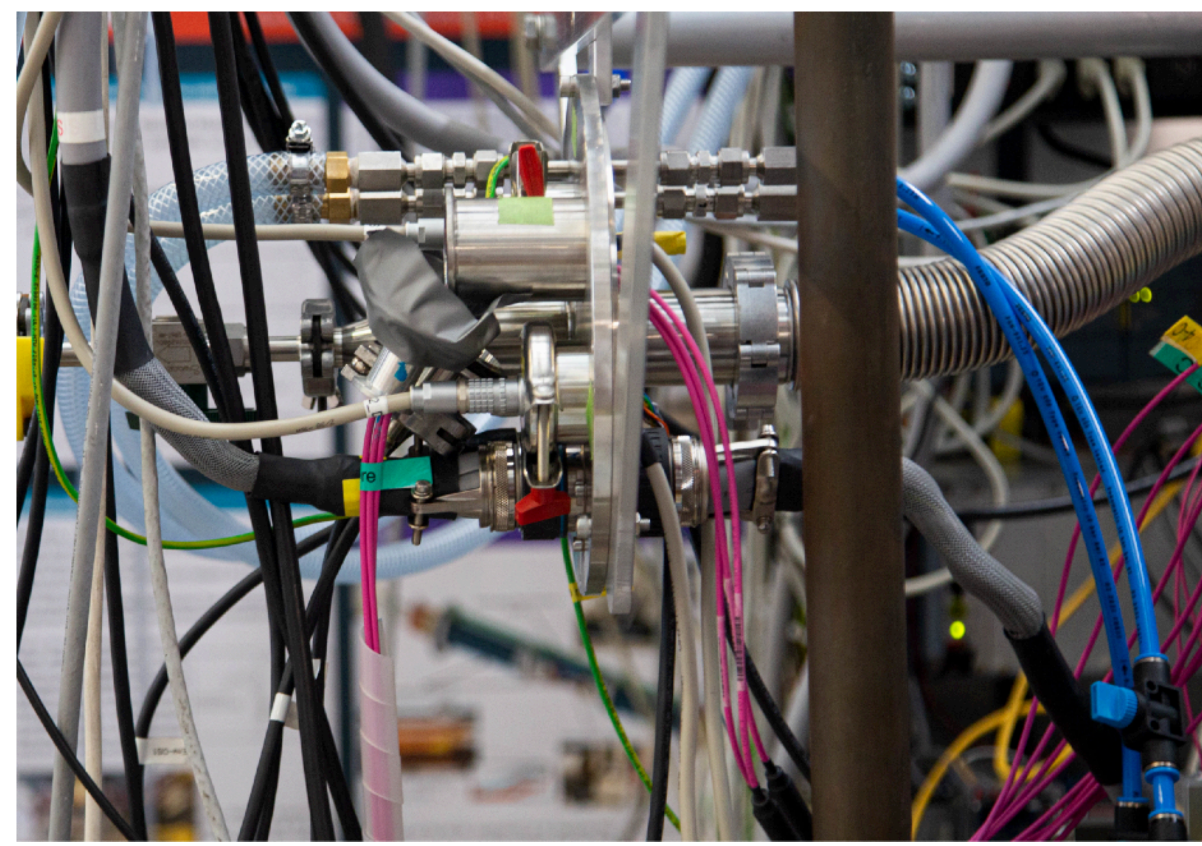


Construction and commissioning

2021	2022	2023	2024	2025	2026	2027	2028	2029

- Integration of sub-detectors and DAQ with **final hardware**
- Phase I detector **construction** has started
    - consolidating production and QC pipelines
- Permanent **staging/construction** area at PSI
    - detector installation, QC and commissioning

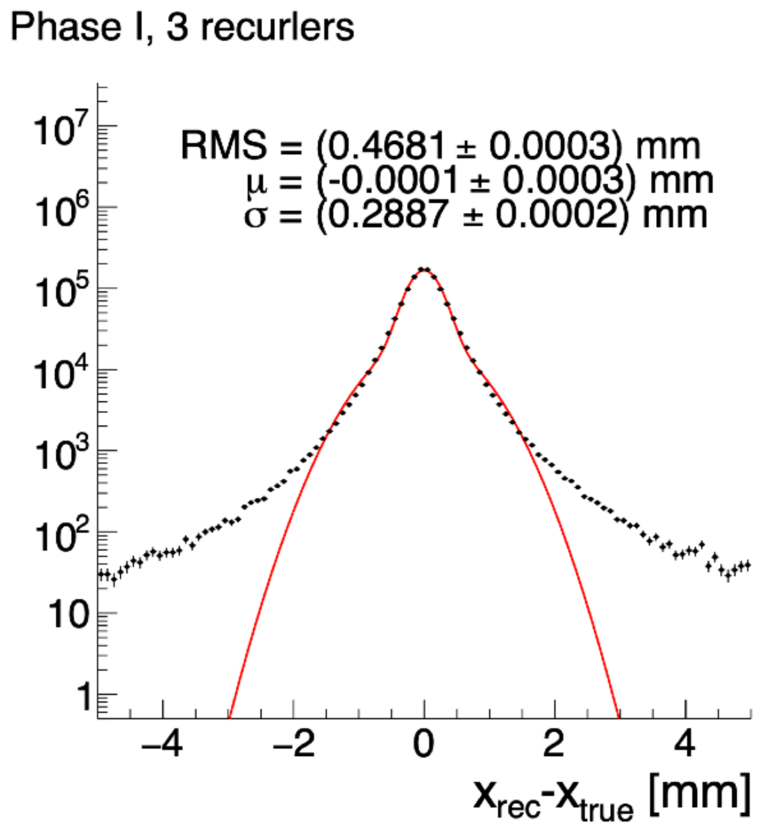


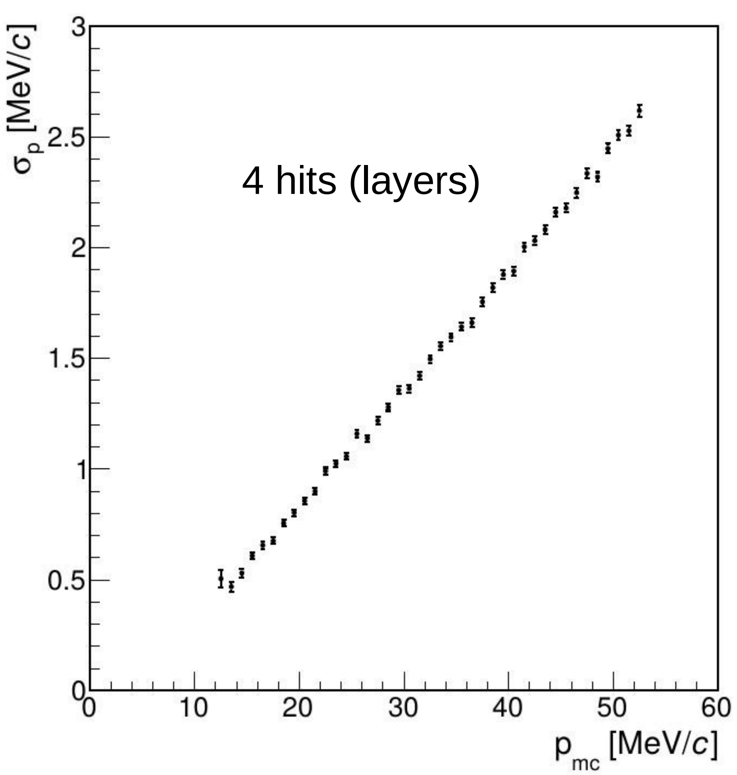


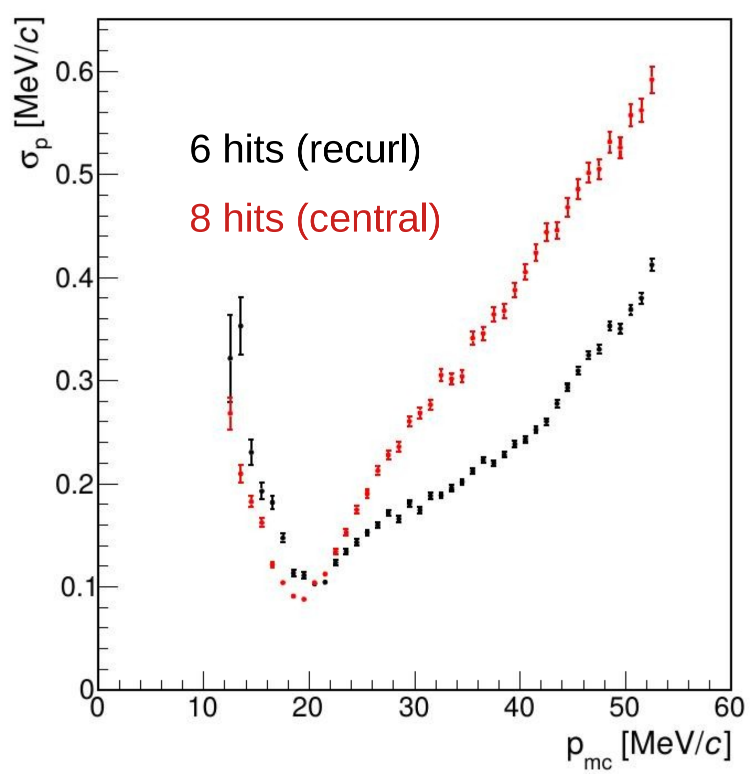
Physics in phase I

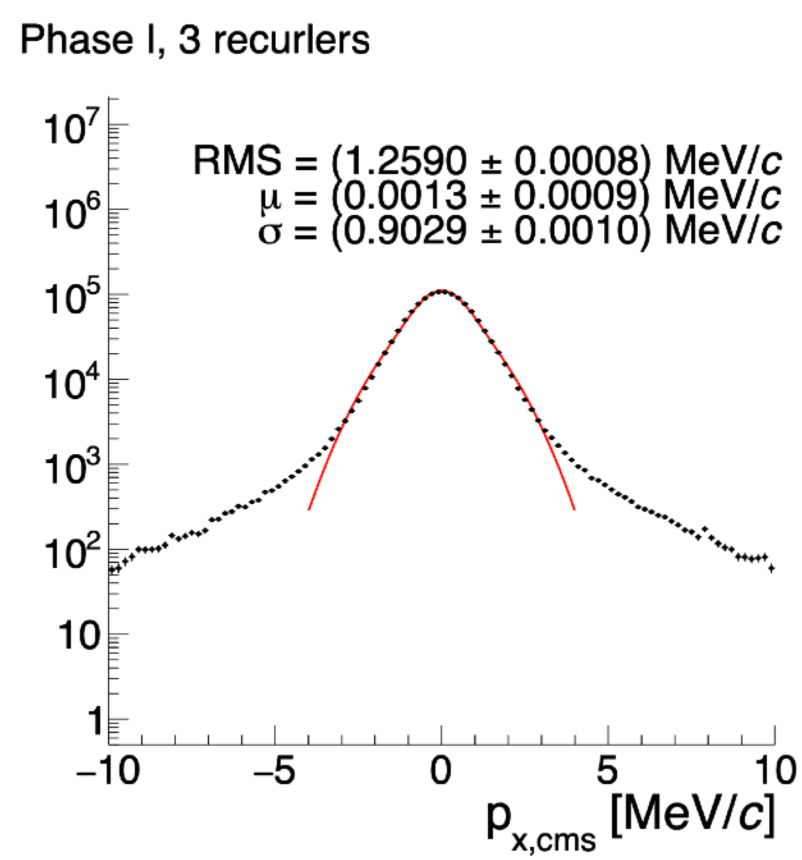
2021 | 2022 | 2023 | 2024 | **2025** | **2026** | 2027 | 2028 | 2029

- Track reconstruction via simulation:
  - **Vertex** resolution ~0.3 mm
  - **Momentum** resolution ~0.9 MeV
  - Reconstruction of recurlers improves momentum resolution up to a **factor 10**





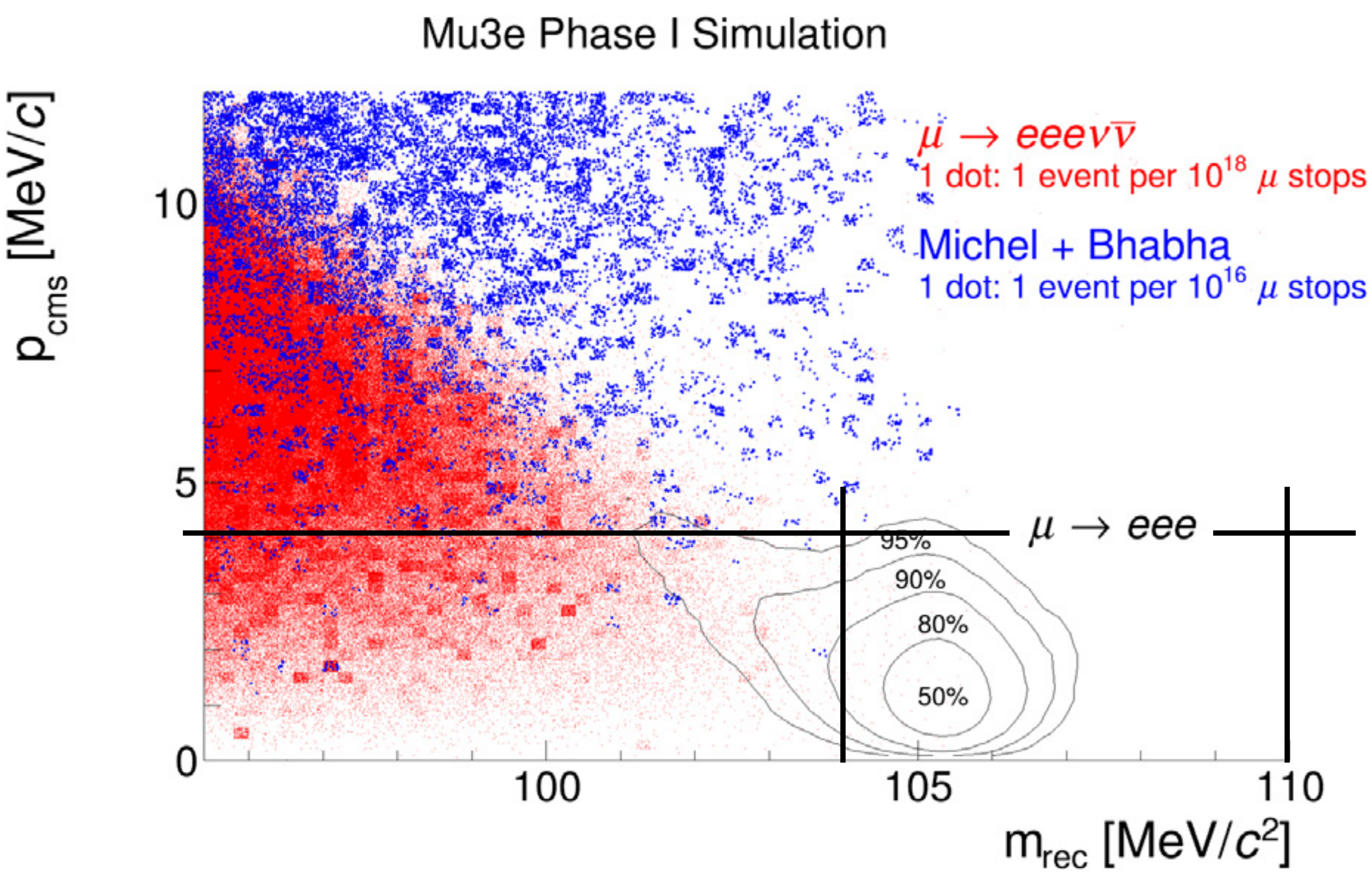


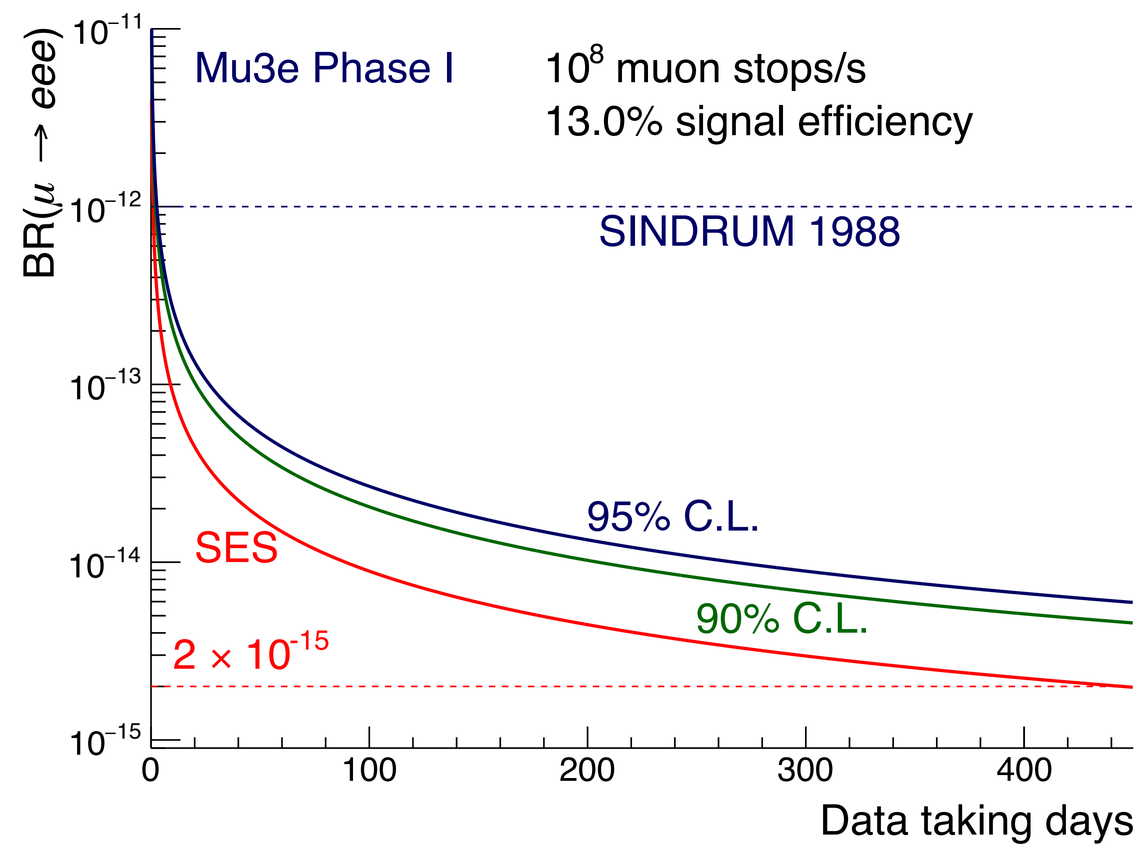


Physics in phase I

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

- Expected physics sensitivity in phase I:
  - **Background-free** measurement (<1 event) for > 2.5 x 10^{15} muon stops
  - ~**300 days** of continuous running at 1 x 10^{8} muon stops / s

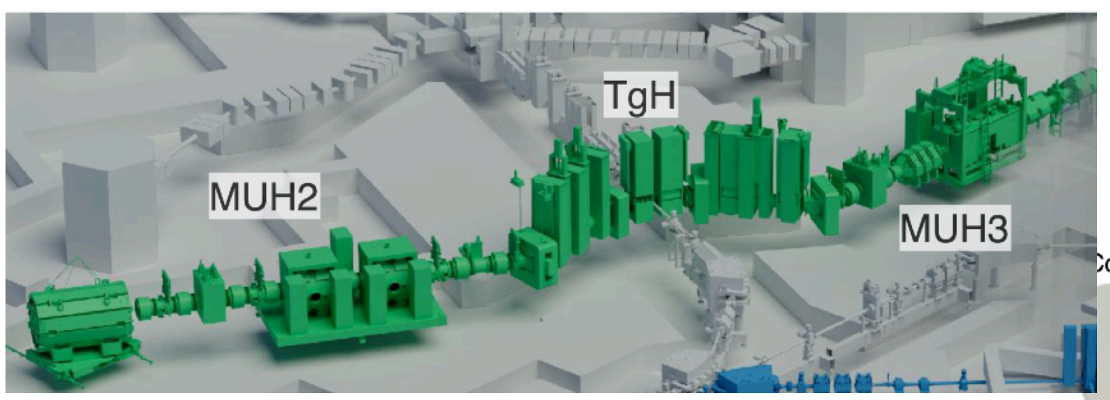


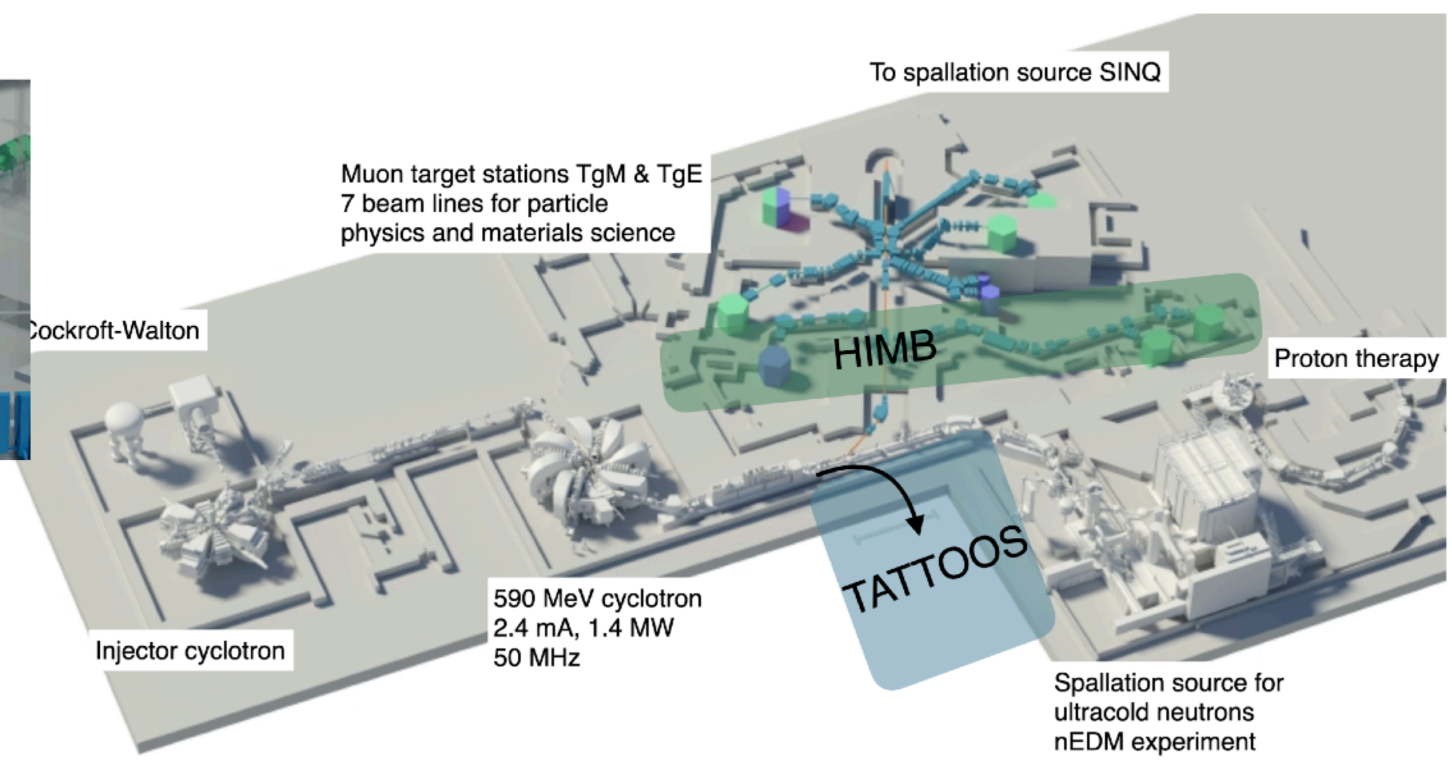


High Intensity Muon Beam

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

- **Phase II:** $\mathcal{B} <$ **10^{-16}** (90% CL) → not reachable with **πE5** beamline
- **High Intensity Muon Beam** (HIMB) at PSI:
  - Ground-breaking muon research (particle physics, condensed matter) at PSI for the next 20+ years
  - New target (TgH) and solenoid-based beamline (MUH2)
  - **10^{10} surface muons/s** at 28 MeV

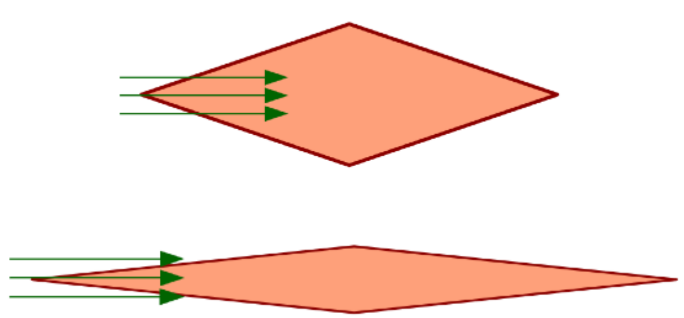


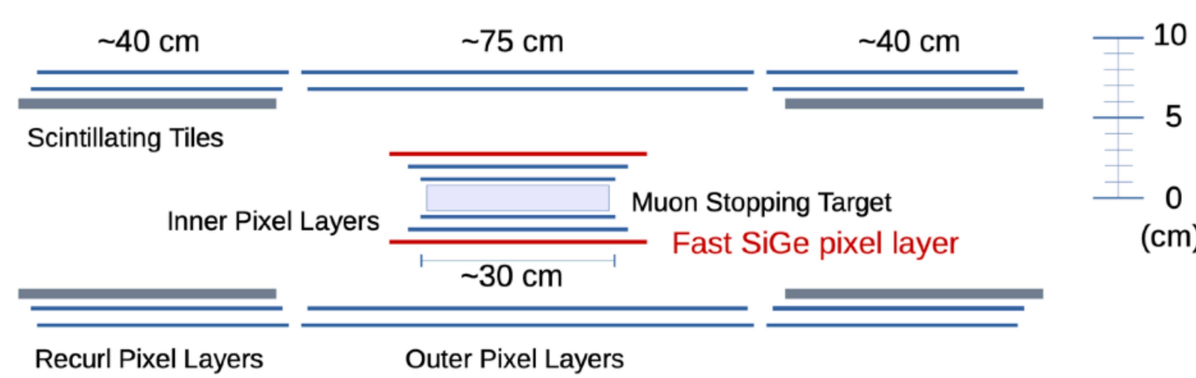


Phase II detector upgrades

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

- Higher beam emittance (x10):
  - higher **magnetic field** (2T) and/or new **moderator**
- Higher stopping rate, better accidental background (x400) suppression:
  - longer and narrower **target** (gaseous?)
- Higher occupancy, better timing:
  - **ultra-fast pixel** detector layer (<100 ps), closer to inner layers
- Larger acceptance, improved momentum resolution:
  - **elongated** pixel trackers, smaller radius, fifth layer
- Larger data rate (x20) and combinatorics:
  - faster readout, online data processing with more **powerful** filter farm





Conclusions

and outlook

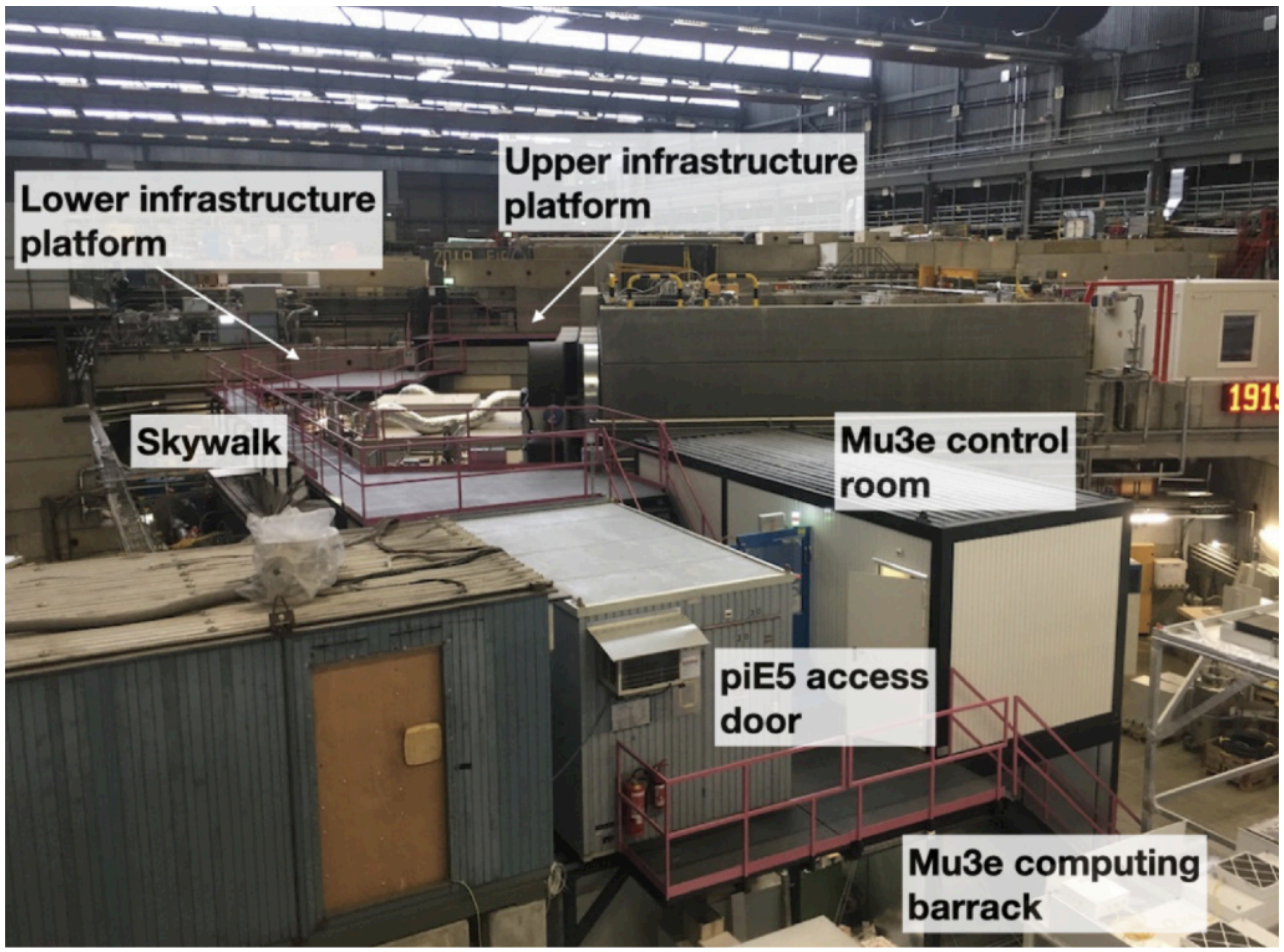
- Mu3e will search for the cLFV decay $\mu^+ \rightarrow e^+e^-e^+$ with a sensitivity of 10^{-16}
  - unique discovery potential for **new physics**
- It faces many technical **challenges**…
  - compact design, low material budget, fine granularity, high rates
- …with innovative **technologies**:
  - HV-MAPS, gaseous helium cooling, MuTRiG readout, GPUs
- We are now in **commissioning** phase:
  - two commissioning runs probed the production readiness
  - ongoing detector construction and QC
- The start of **phase I** data-taking ($B < 10^{-15}$) is expected in 2025
- Beam and detector upgrades are foreseen for **phase II** ($B < 10^{-16}$) starting in 2029

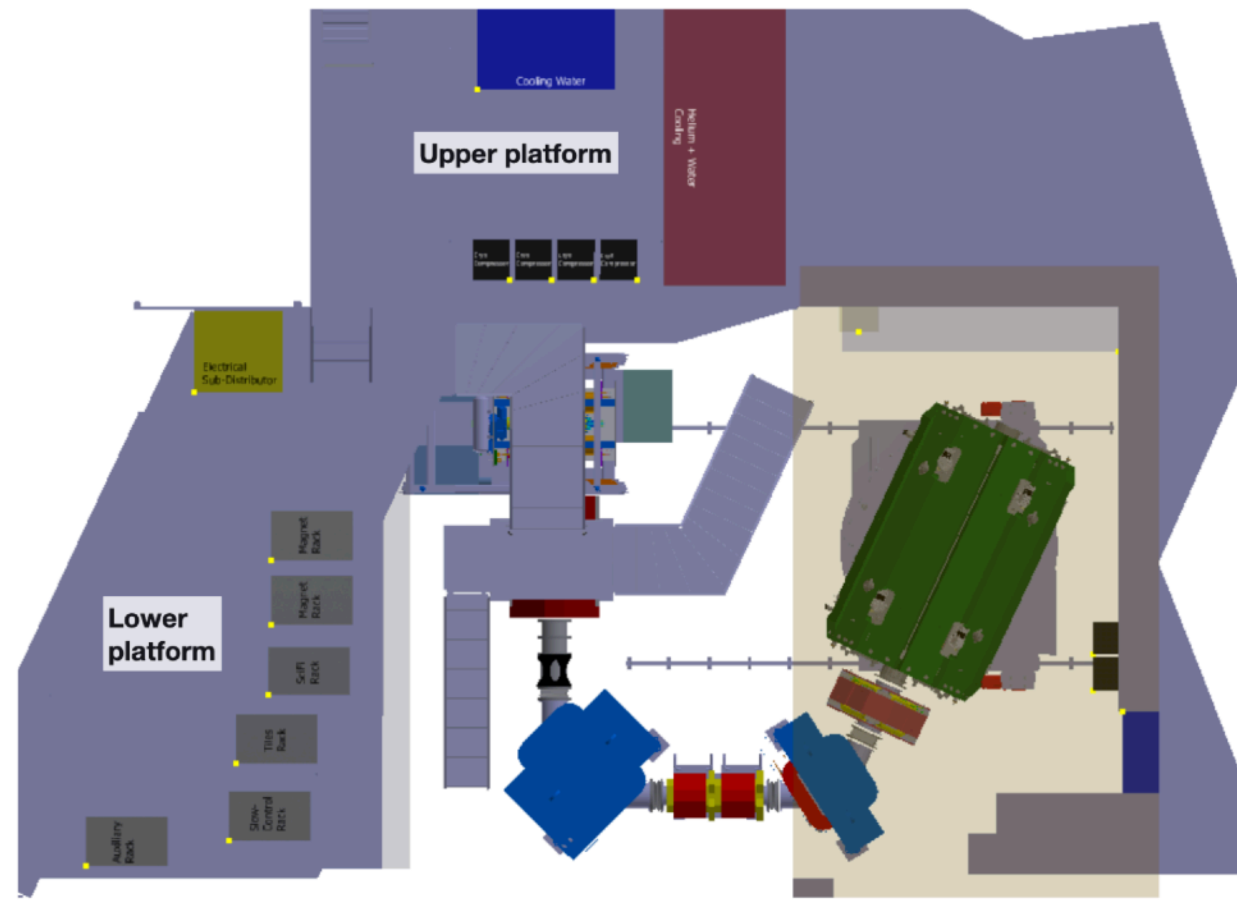
Thanks for listening!

Link to Technical Design Report
Link to HIMB physics case

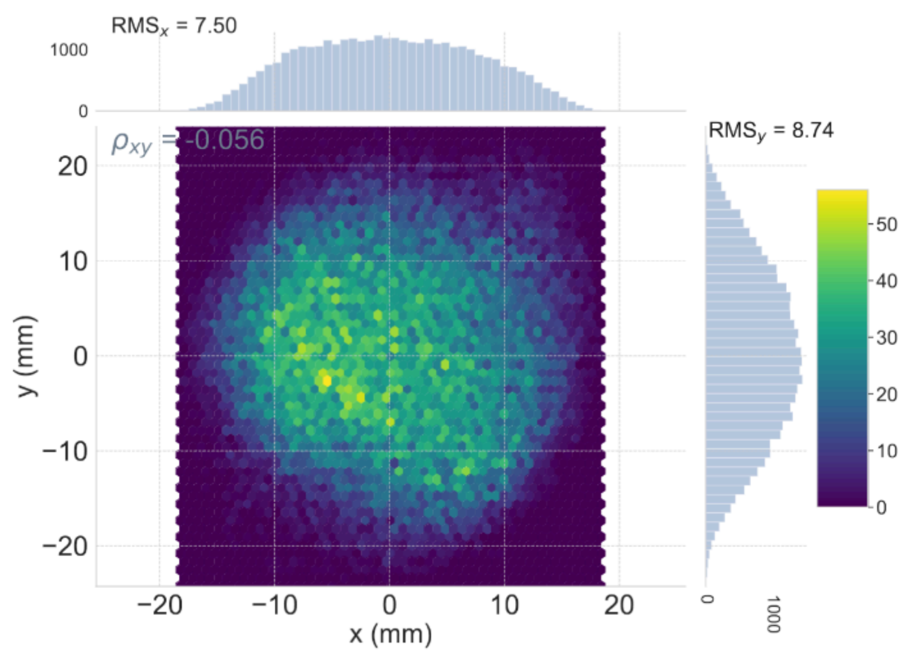
Back-up

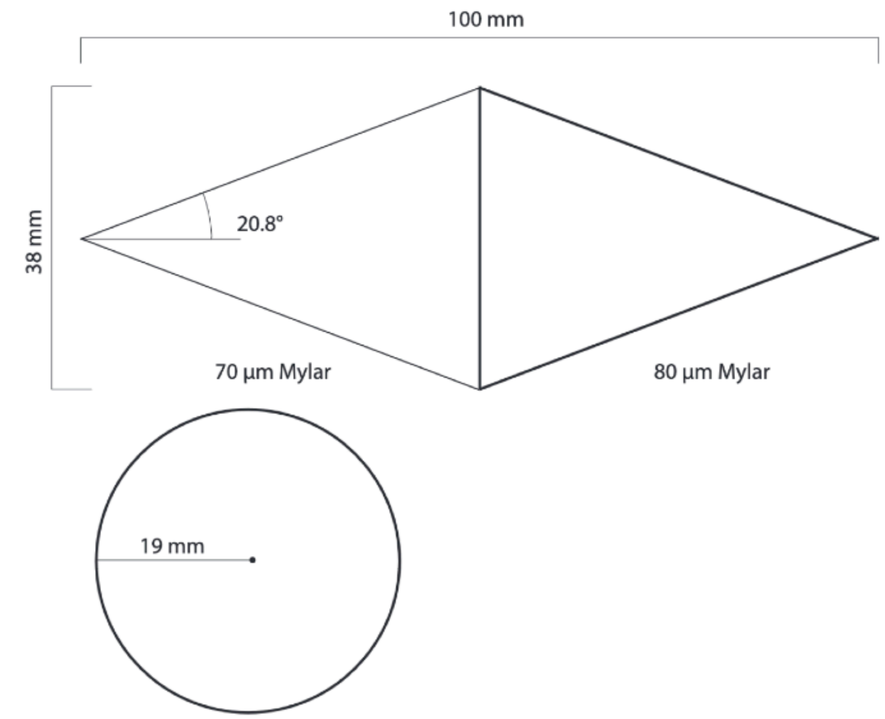
Area

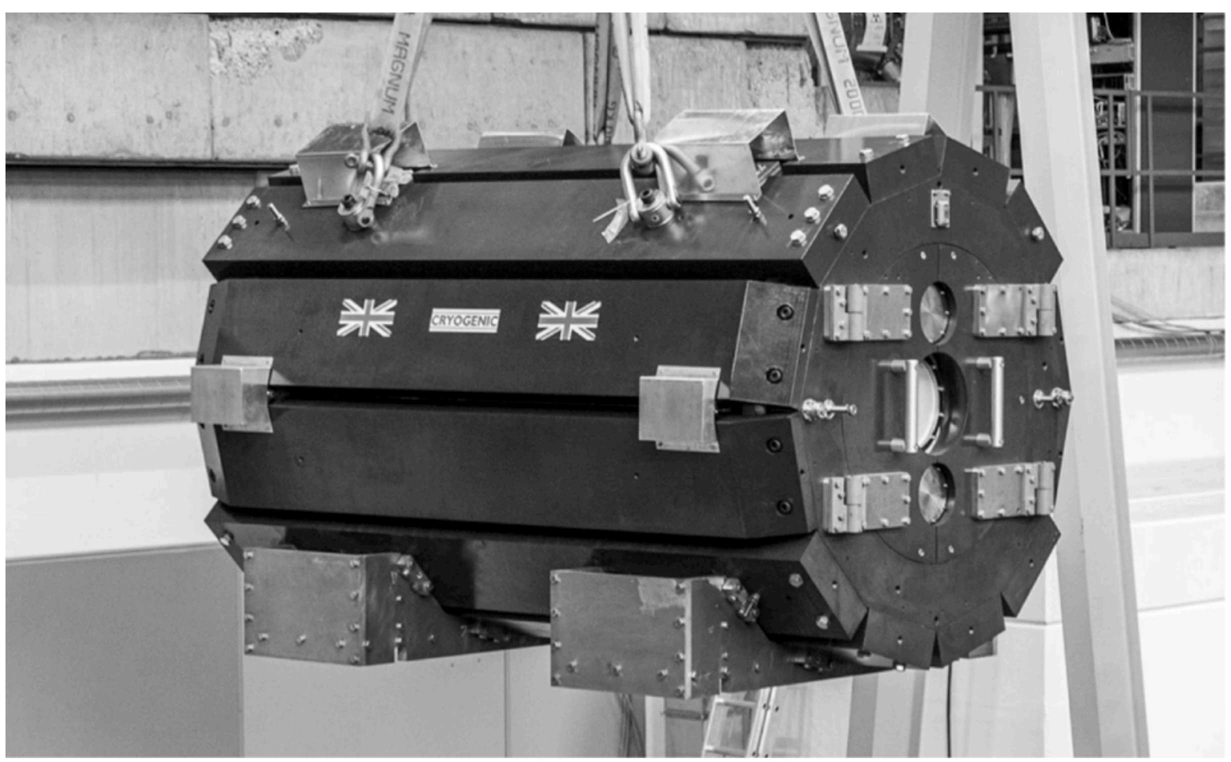

Lower infrastructure platform
Upper infrastructure platform
Skywalk
Mu3e control room
piE5 access door
Mu3e computing barrack


Cooling Water
Upper platform
Helium + Water Cooling
Electrical Sub-Distributor
Magnet Rack
Magnet Rack
SciFi Rack
Lower platform
Tiles Rack
Slow-Control Rack
Auxiliary Rack

Beam, target, magnet

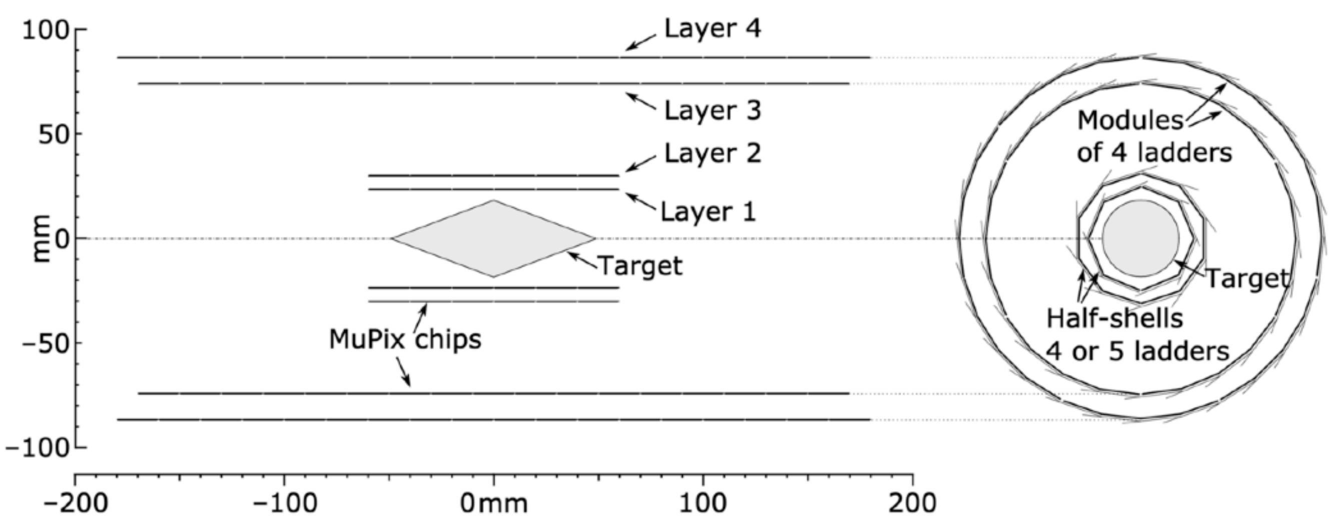


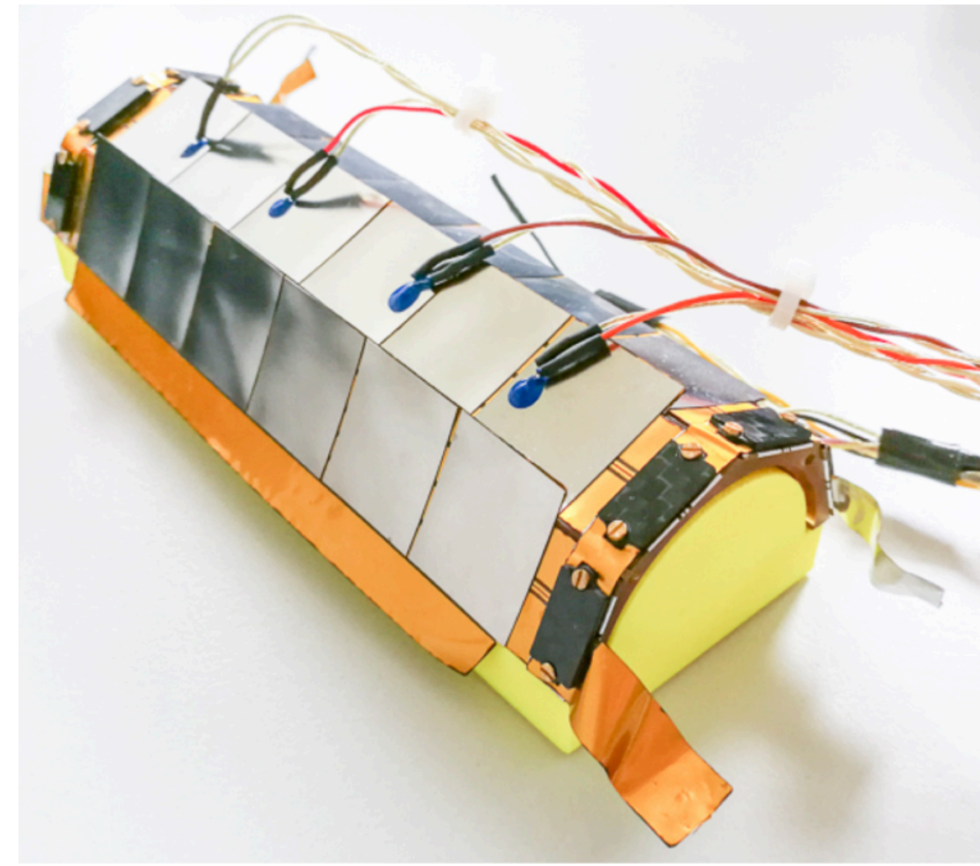


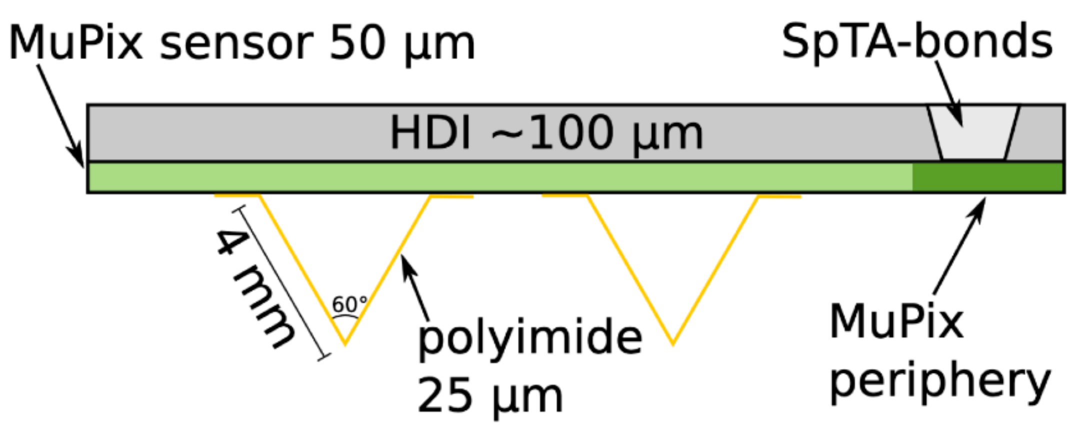


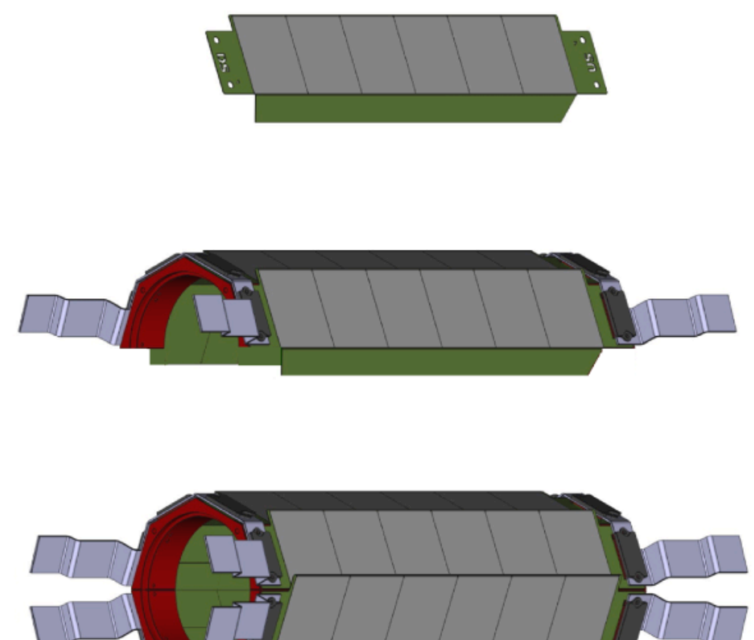
Magnet parameter	Value
nominal field	1.0 T
warm bore diameter	1.0 m
warm bore length	2.7 m
field inhomogeneity $\Delta B/B$	$\leq 10^{-3}$
field stability $\Delta B/B$ (100 days)	$\leq 10^{-4}$
field measurement accuracy $\Delta B/B$	$\leq 2.0 \cdot 10^{-4}$
outer dimensions: length	≤ 3.2 m
width	≤ 2.0 m
height	≤ 3.5 m

Pixel tracker





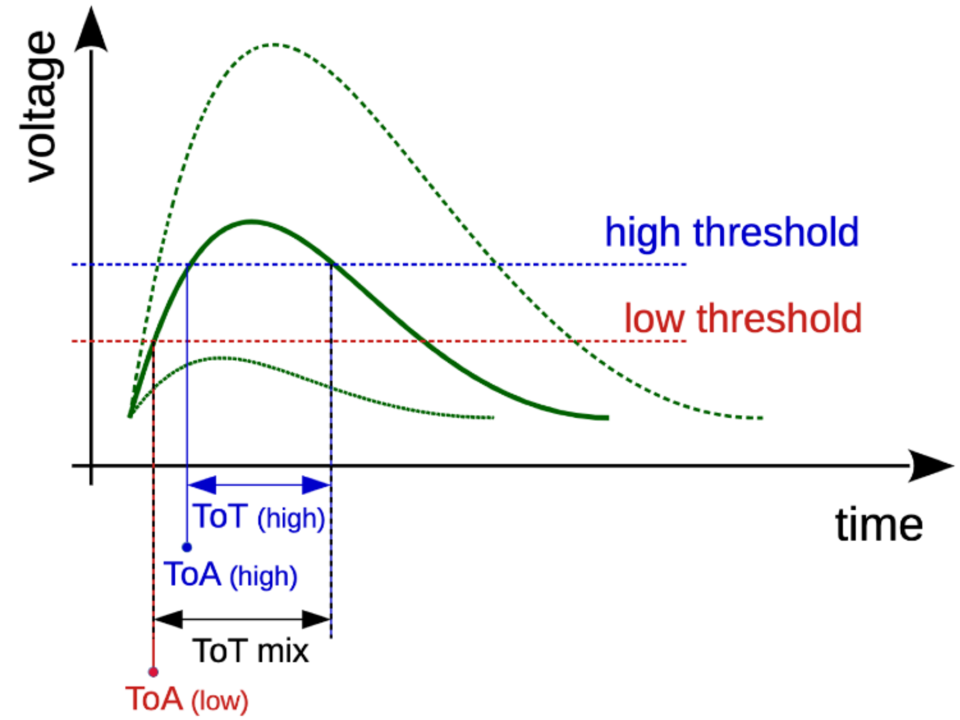




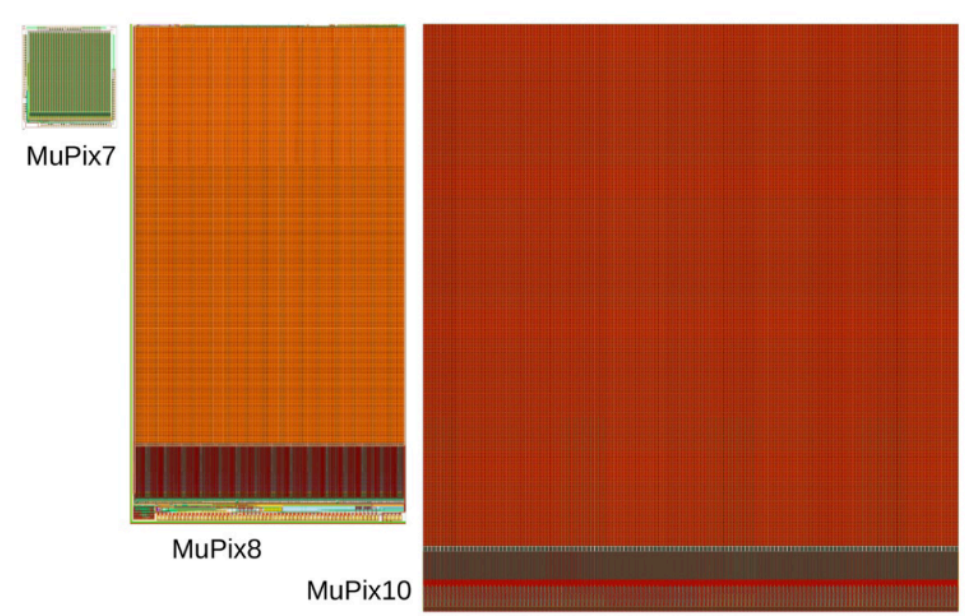
layer	1	2	3	4
number of modules	2	2	6	7
number of ladders	8	10	24	28
number of MuPix sensors per ladder	6	6	17	18
instrumented length [mm]	124.7	124.7	351.9	372.6
minimum radius [mm]	23.3	29.8	73.9	86.3

Pixel sensors

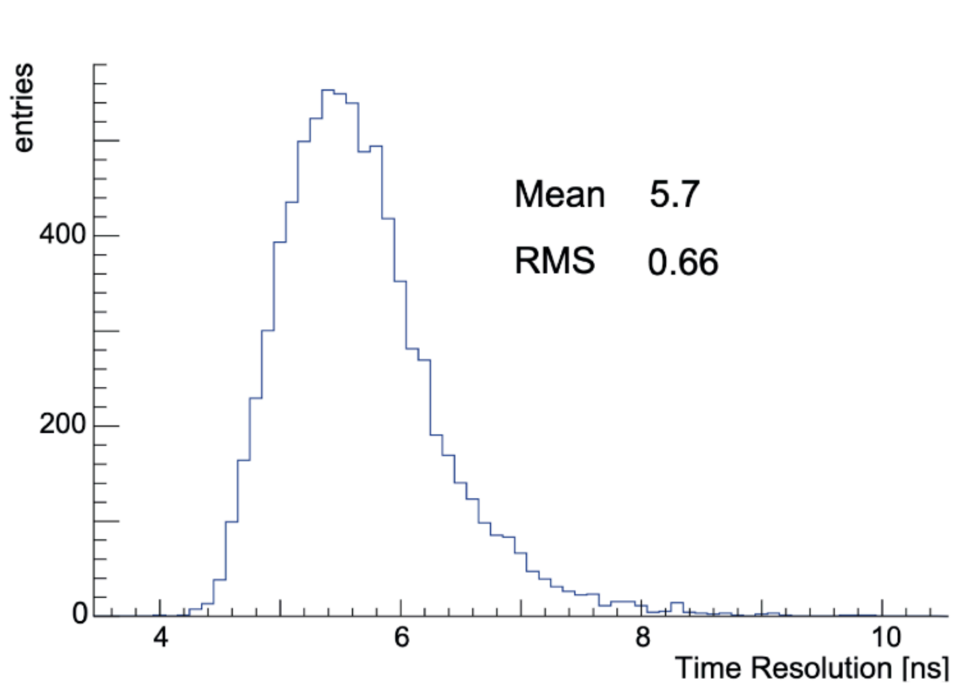
sensor dimensions [mm^2]	$\leq 21 \times 23$
sensor size (active) [mm^2]	$\approx 20 \times 20$
thickness [µm]	≤ 50
spatial resolution µm	≤ 30
time resolution [ns]	≤ 20
hit efficiency [%]	≥ 99
#LVDS links (inner layers)	1 (3)
bandwidth per link [Gbit/s]	≥ 1.25
power density of sensors [mW/cm^2]	≤ 350
operation temperature range [°C]	0 to 70

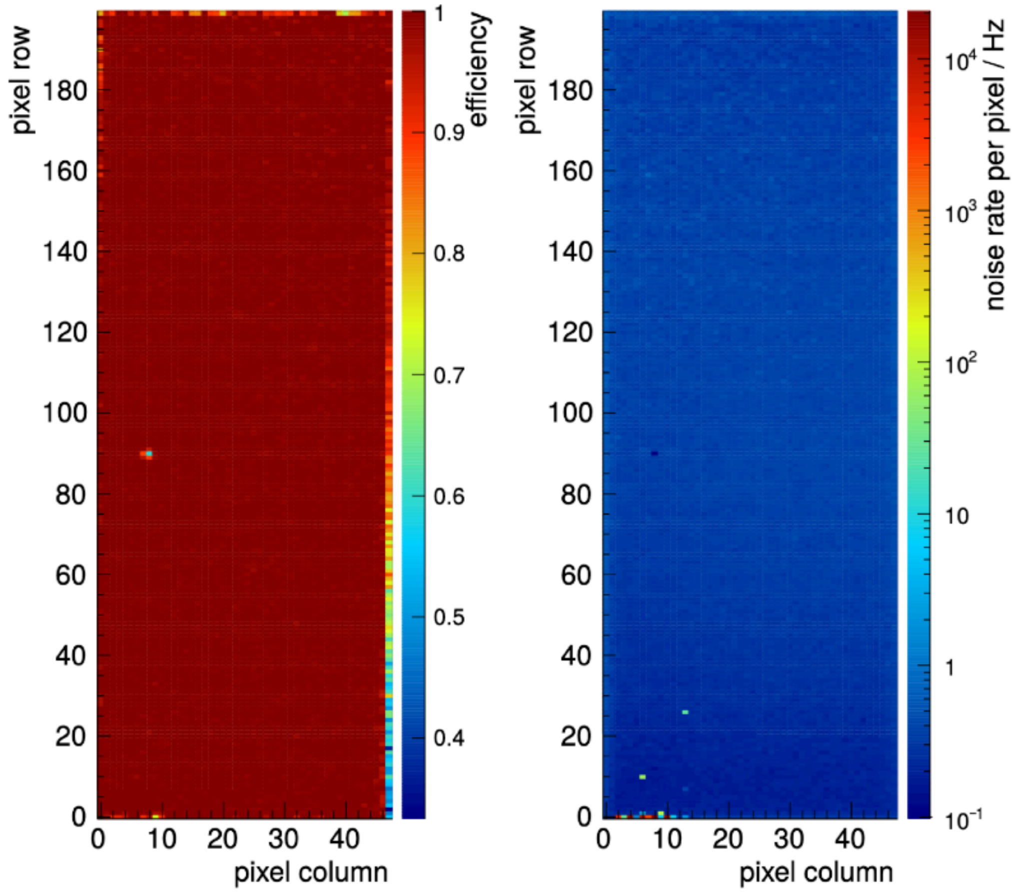


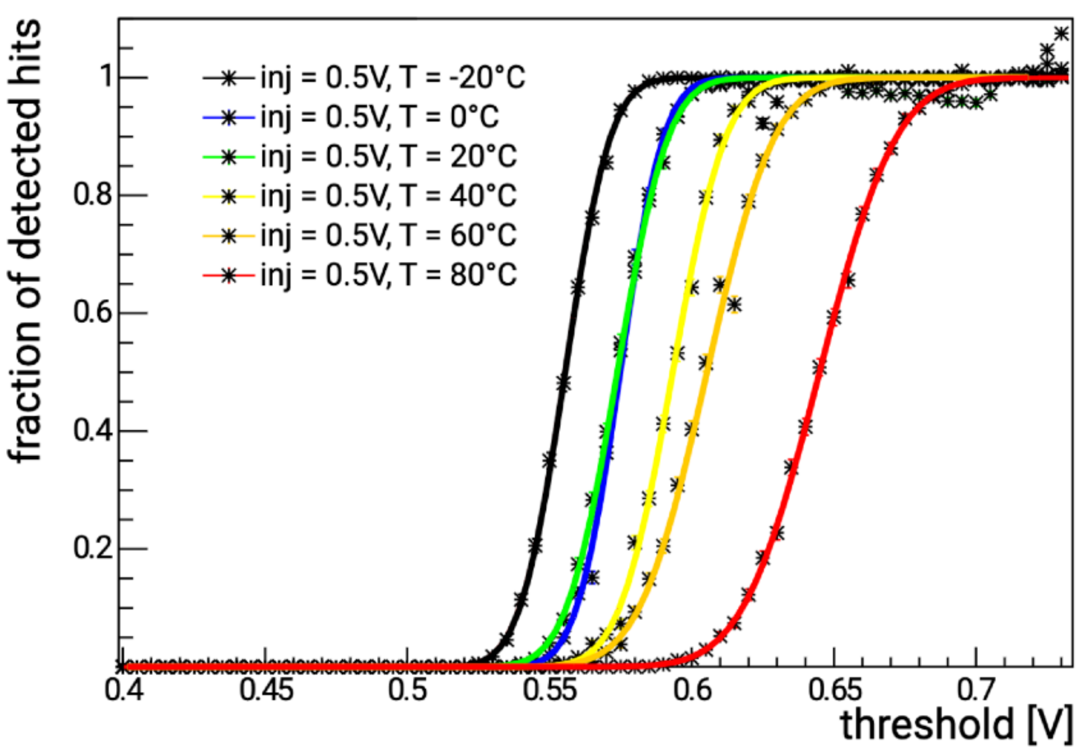
	Requirements	MuPix7	MuPix8	MuPix10
pixel size [µm^2]	80×80	103×80	81×80	80×80
sensor size [mm^2]	20×23	3.8×4.1	10.7×19.5	20.66×23.18
active area [mm^2]	20×20	3.2×3.2	10.3×16.0	20.48×20.00
active area [mm^2]	400	10.6	166	410
sensor thinned to thickness [µm]	50	50, 63, 75	63, 100	50, 100
LVDS links	$3 + 1$	1	$3 + 1$	$3 + 1$
maximum bandwidth[§] [Gbit/s]	3×1.6	1×1.6	3×1.6	3×1.6
timestamp clock [MHz]	≥ 50	62.5	125	625
RMS of spatial resolution [µm]	≤ 30	≤ 30	≤ 30	≤ 30
power consumption [mW/cm^2]	≤ 350	≈ 300[†]	$250 - 300$	≈ 200
time resolution per pixel [ns]	≤ 20	≈ 14	≈ 13 (6*)	not meas.[‡]
efficiency at 20 Hz/pix noise [%]	≥ 99	99.9	99.9	99.9
noise rate at 99 % efficiency [Hz/pix]	≤ 20	< 10	< 1	< 1
amplifier type	no spec.	PMOS	PMOS	PMOS
amplifier stages	no spec.	2	1	1
timestamp representation	no spec.	8 bit	10 bit	11 bit
ToT representation	no spec.	-	6 bit	5 bit
ring transistors (irradiation tolerant)	no spec.	no	yes	yes
approx. substrate resistivity[¶] [Ω cm]	no spec.	≈ 20	$\approx 20, 80, 200$	≈ 200

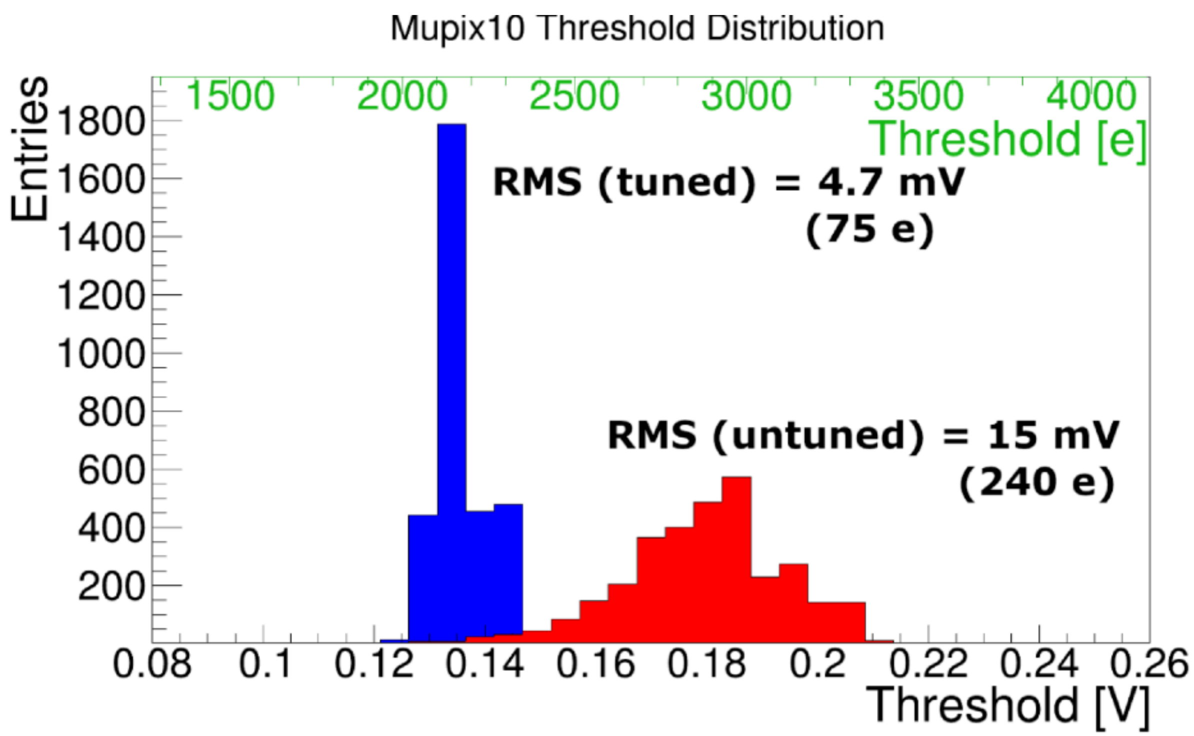


Pixel sensors

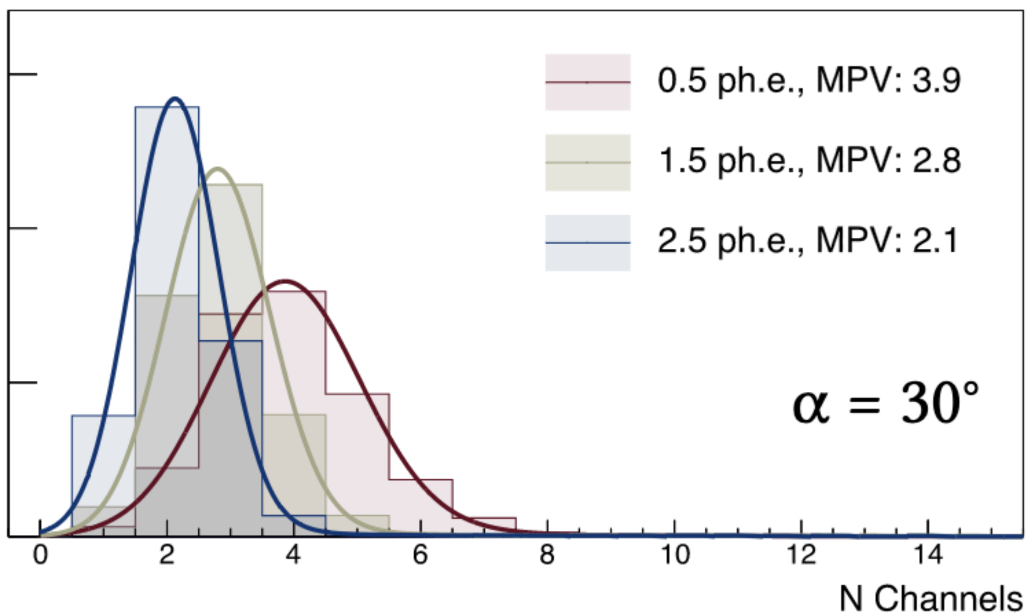


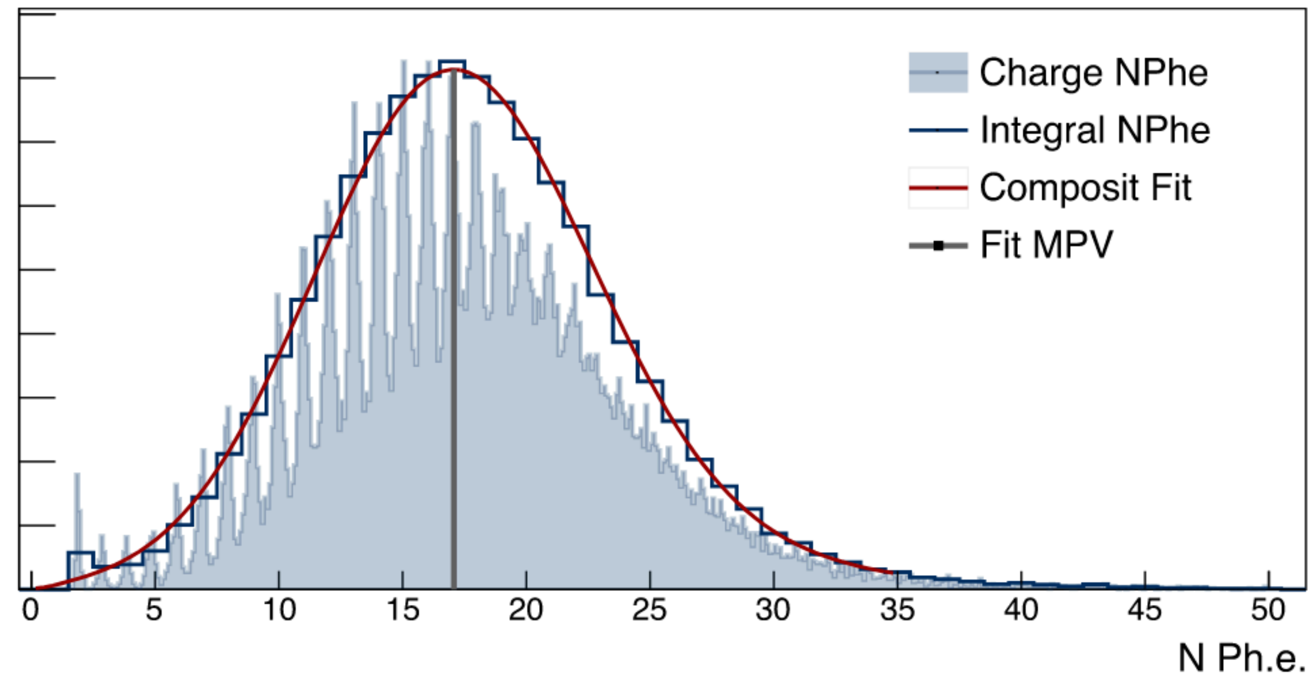


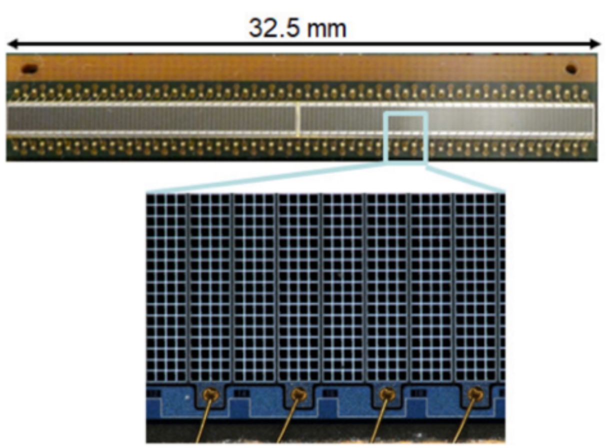


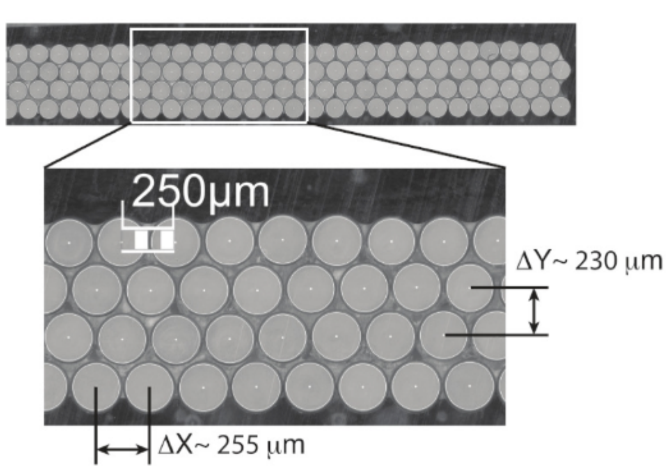


SciFi





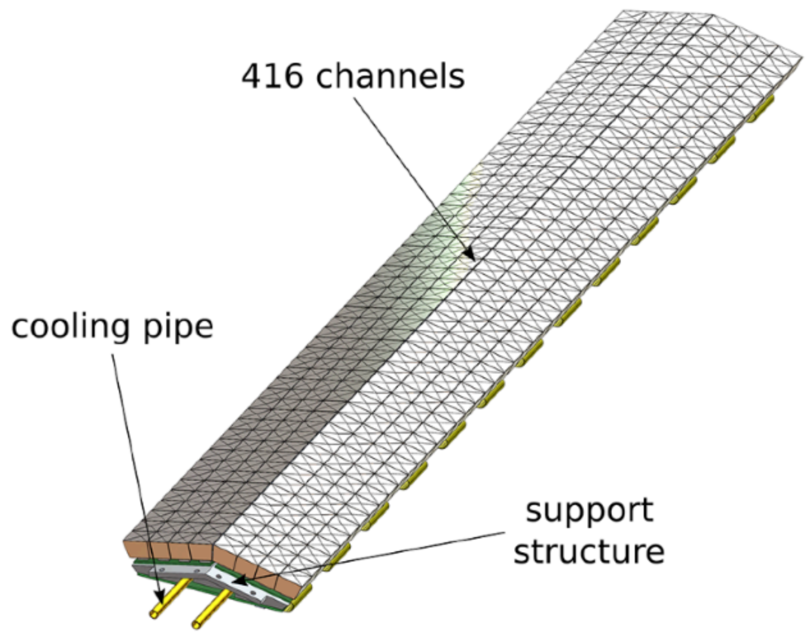


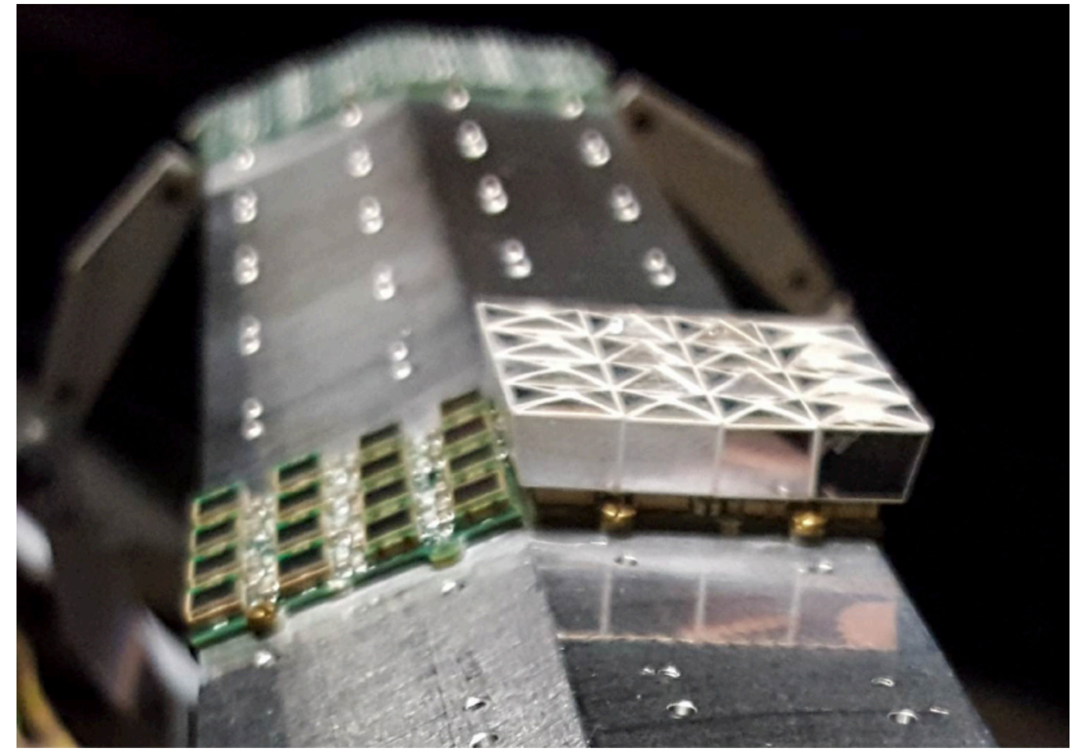


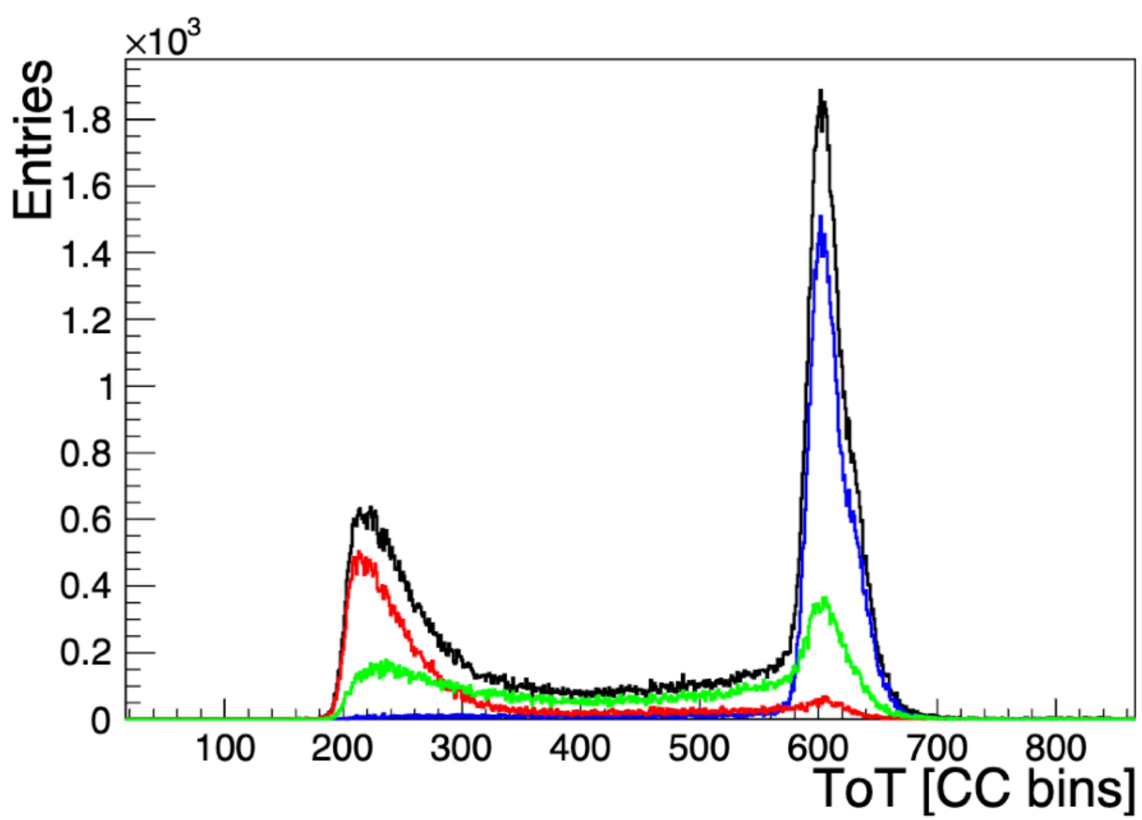
characteristic	value
cross-section	round
emission peak [nm]	450
decay time [ns]	2.8
attenuation length [m]	>4.0
light yield [ph/MeV]	n/a (*high*)
trapping efficiency [%]	5.4
cladding thickness [%]	3 / 3
core	Polystyrene (PS)
inner cladding	Acrylic (PMMA)
outer cladding	Fluor-acrylic (FP)
refractive index	1.59/1.49/1.42
density [g/cm^3]	1.05/1.19/1.43

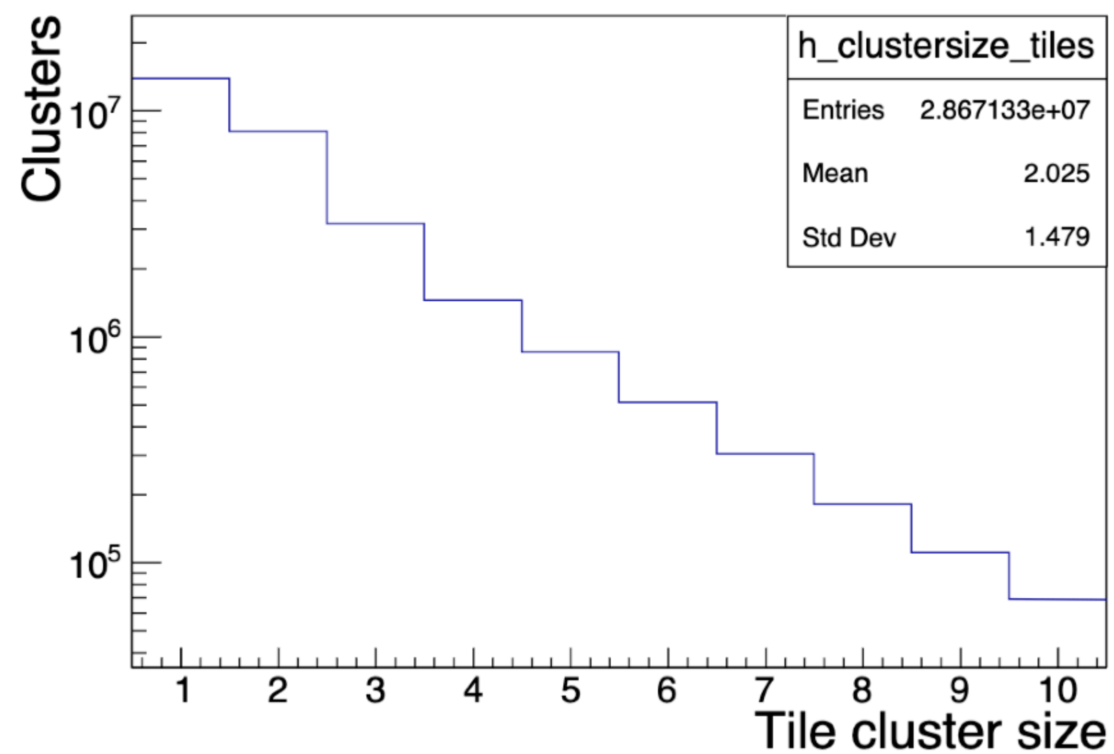
characteristic	value
breakdown voltage	52.5 V
variation per sensor	$\pm$250 mV
variation between sensors	$\pm$500 mV
temperature coefficient	53.7 mV/K
gain	$3.8 \cdot 10^6$
direct crosstalk	3 %
delayed crosstalk	2.5 %
after-pulse	0 %
peak PDE	48 %
max PDE wavelength	450 nm
mean quench resistance R_Q	490 kΩ at 25 °C
recovery time τ_{recovery}	(68.9 ± 2.1) ns
short component τ_{short}	< 1 ns
long component τ_{long}	(50.1 ± 4.1) ns

SciTiles


416 channels
cooling pipe
support
structure

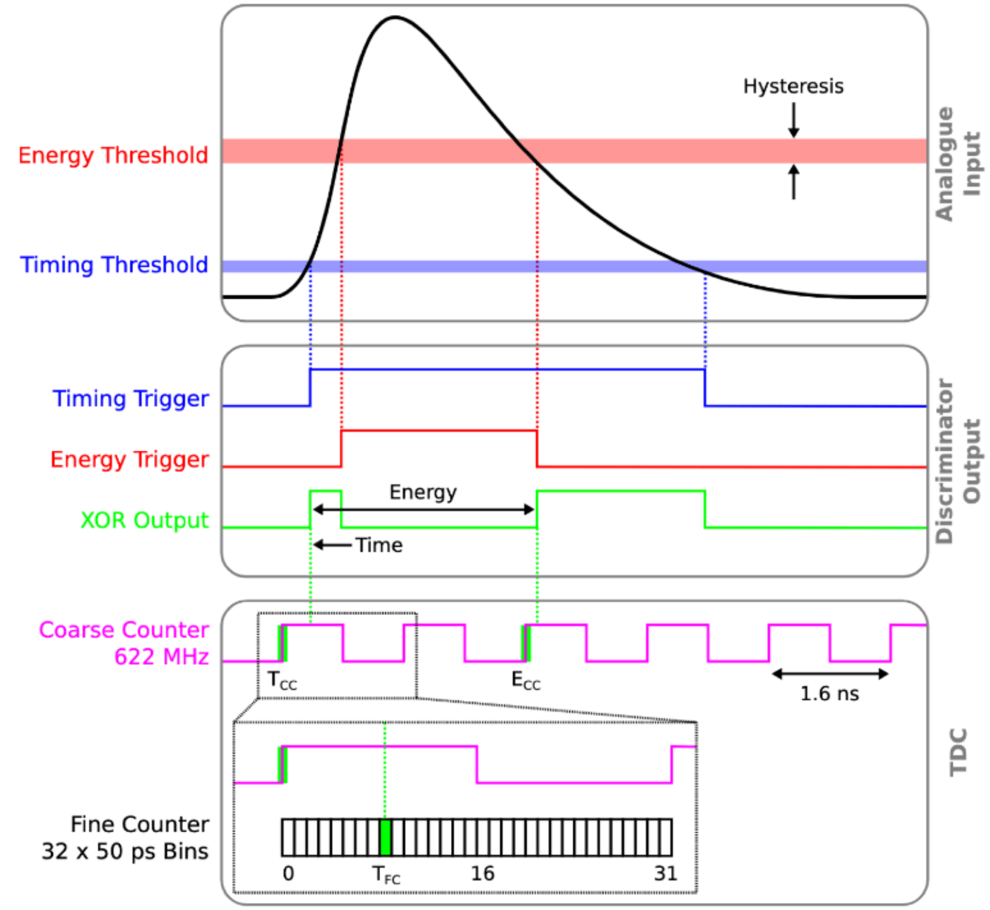


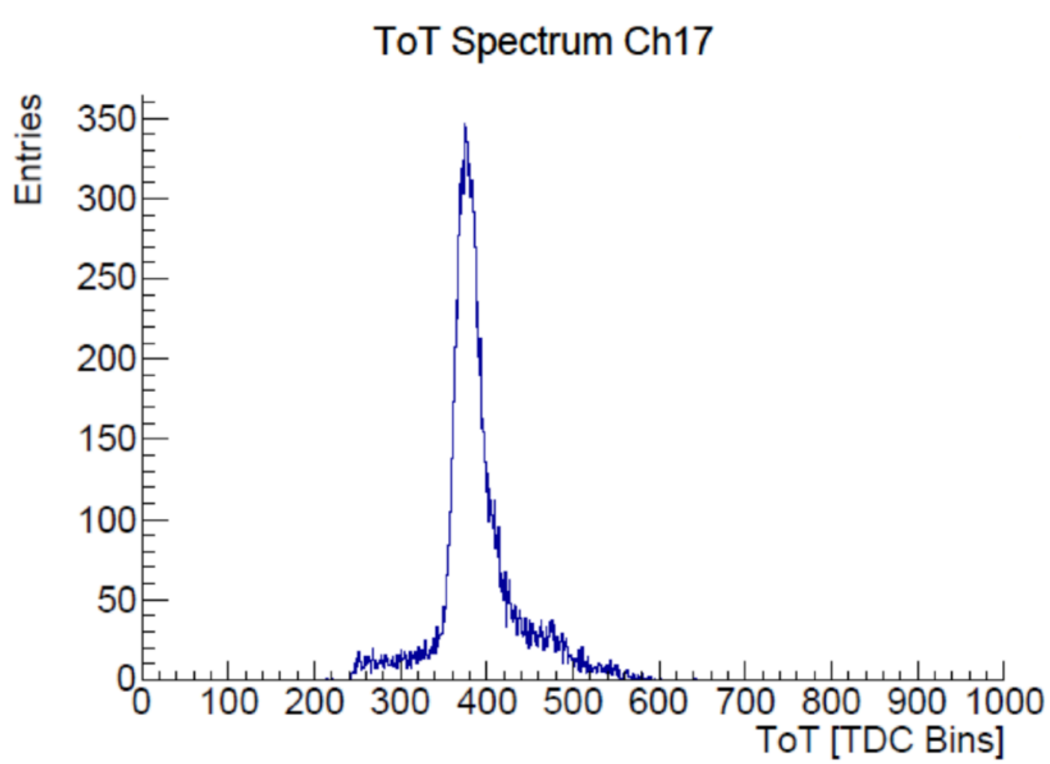

×10³
Entries
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
700
800
ToT [CC bins]

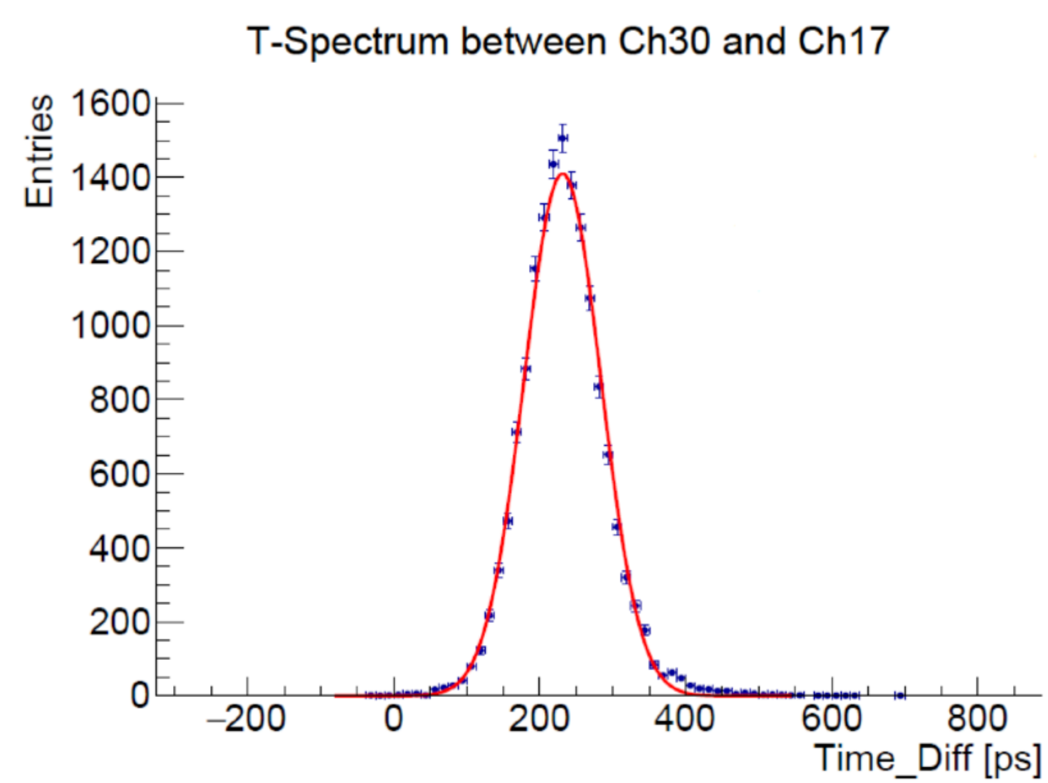

h_clustersize_tiles
Entries 2.867133e+07
Mean 2.025
Std Dev 1.479
Clusters
10⁷
10⁶
10⁵
1
2
3
4
5
6
7
8
9
10
Tile cluster size

MuTRiG

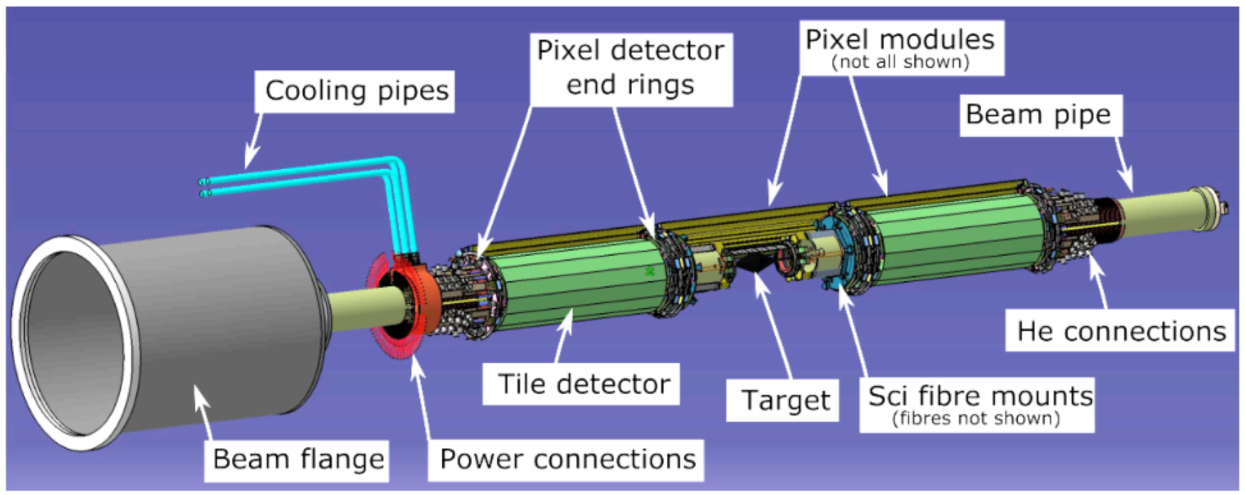
	STiCv3.1	MuTRiG
number of channels	64	32
LVDS speed [Mbit/s]	160	1250
8b/10b encoding	yes	yes
event size [bit]		
standard event	48	47
short event	-	27
event rate / chip [MHz]		
standard event	∼2.6	∼20
short event	-	∼38
event rate / channel [kHz]		
standard event	∼40	∼650
short event	-	∼1200
power per channel [mW]	35	35
size [mm x mm]	5x5	5x5
number of PLLs	2	1

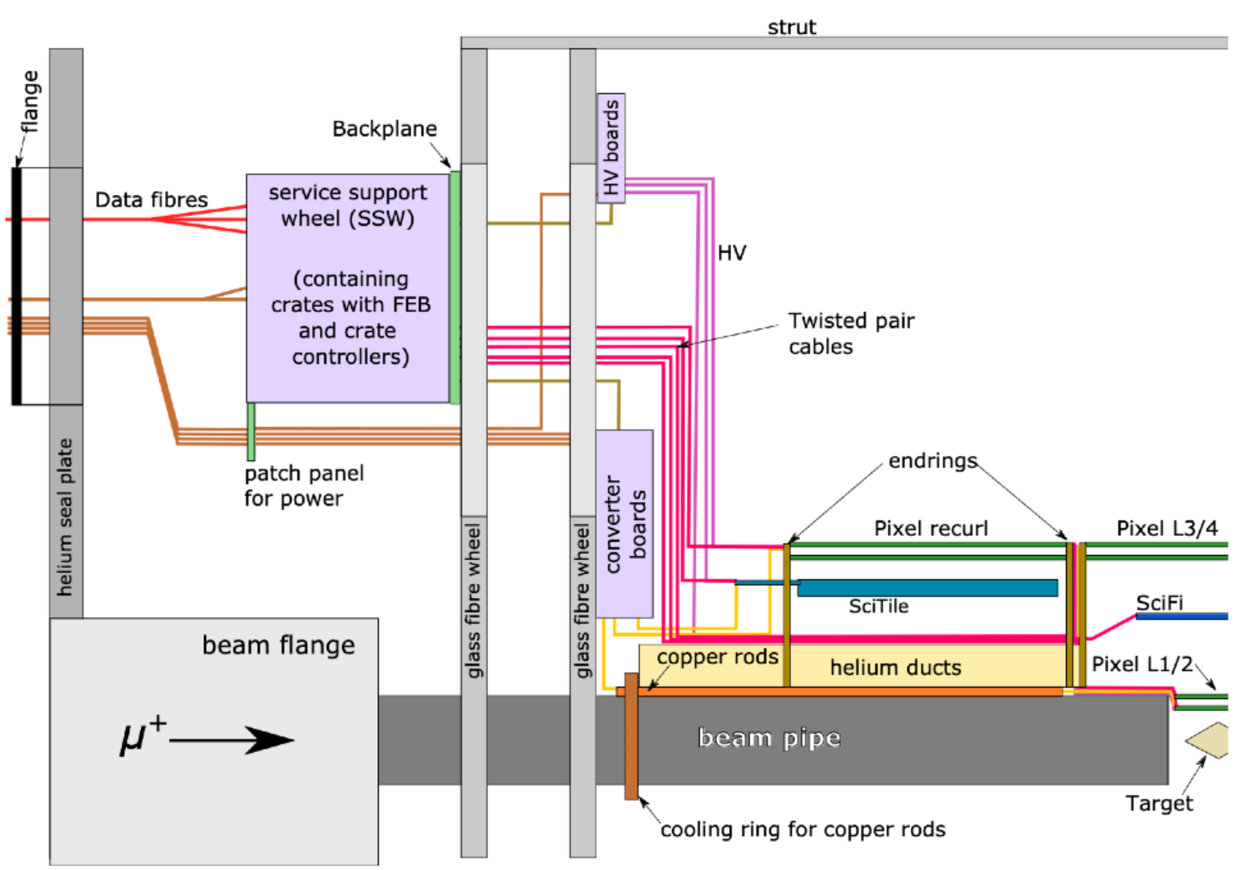


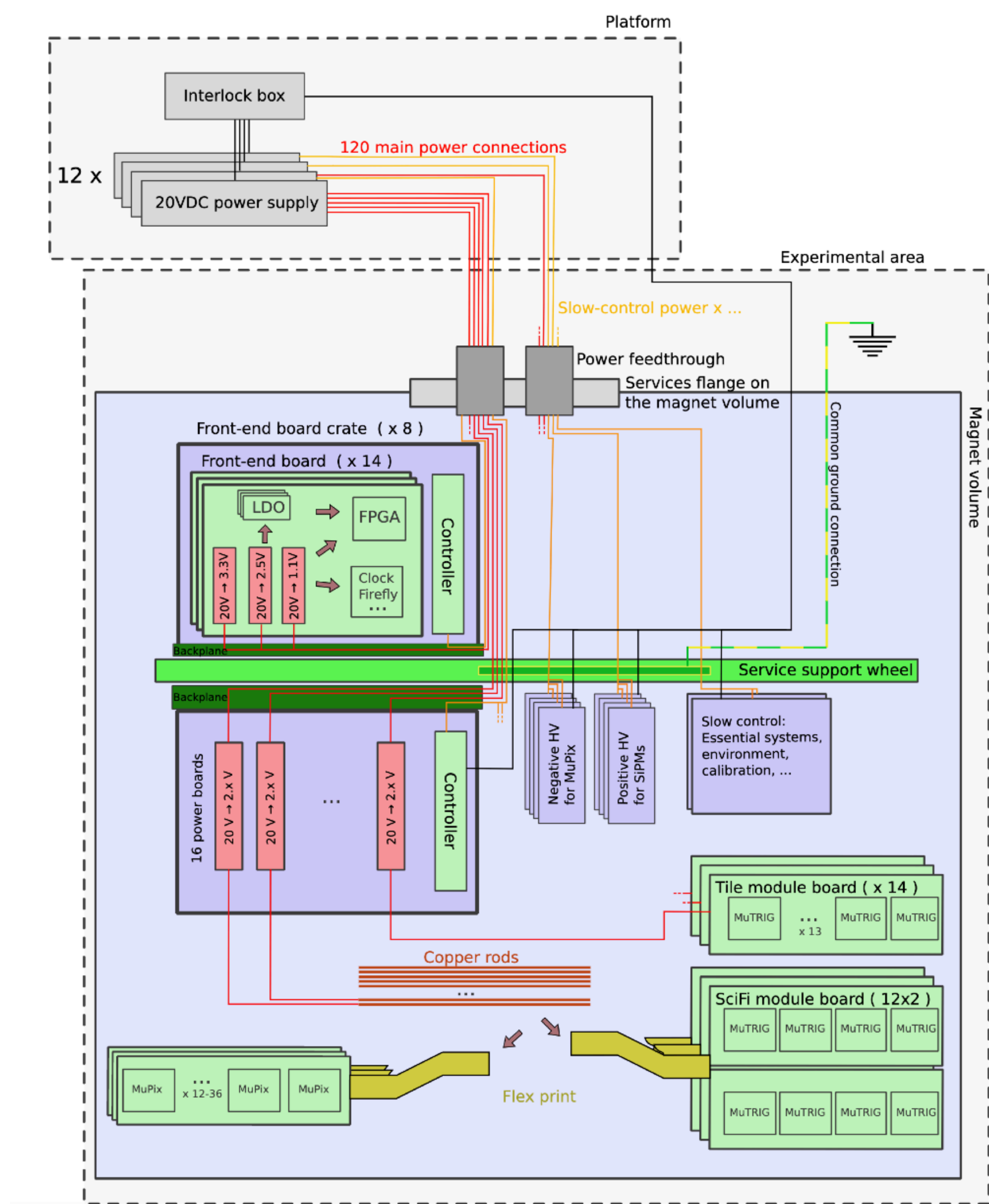




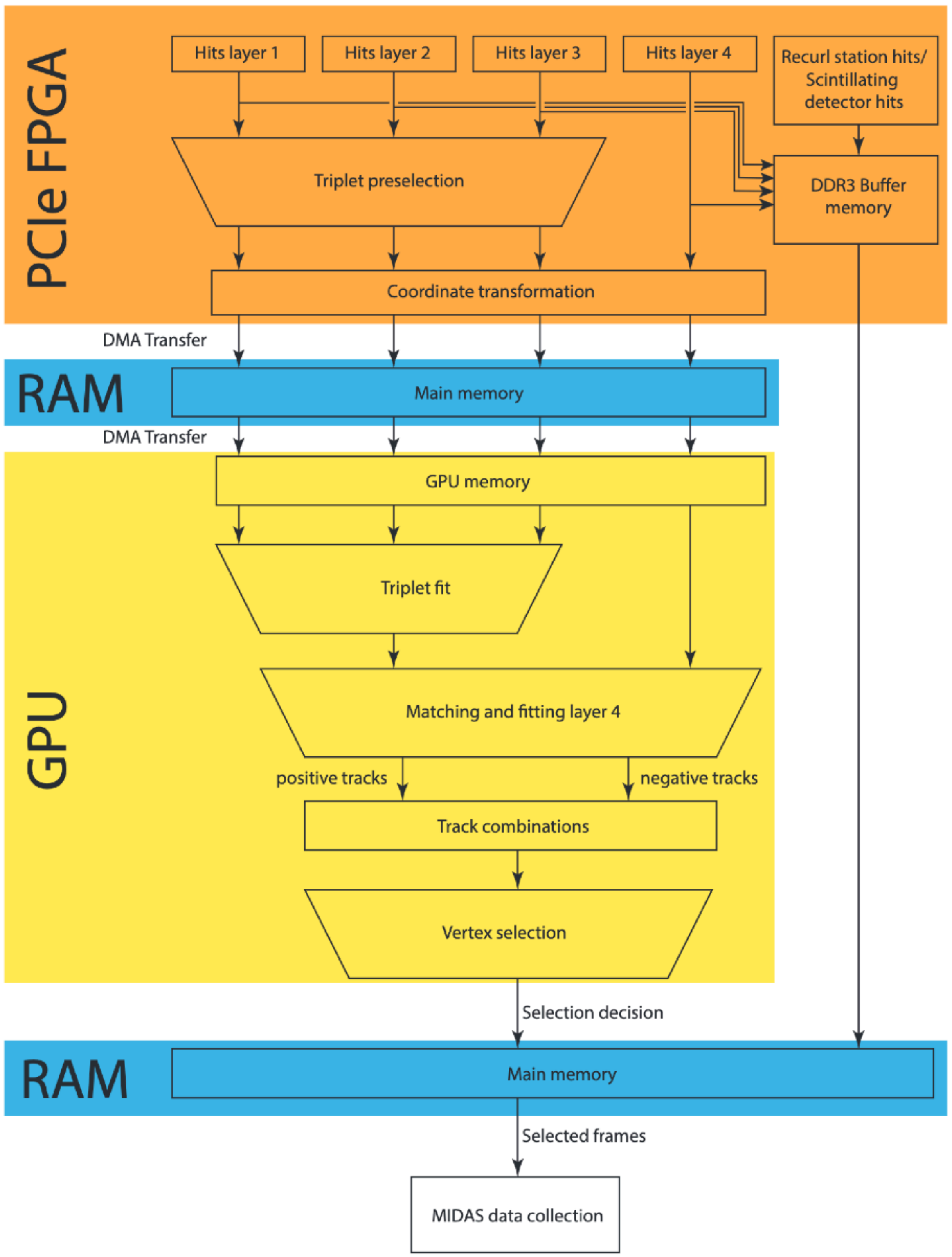
Mechanics and power



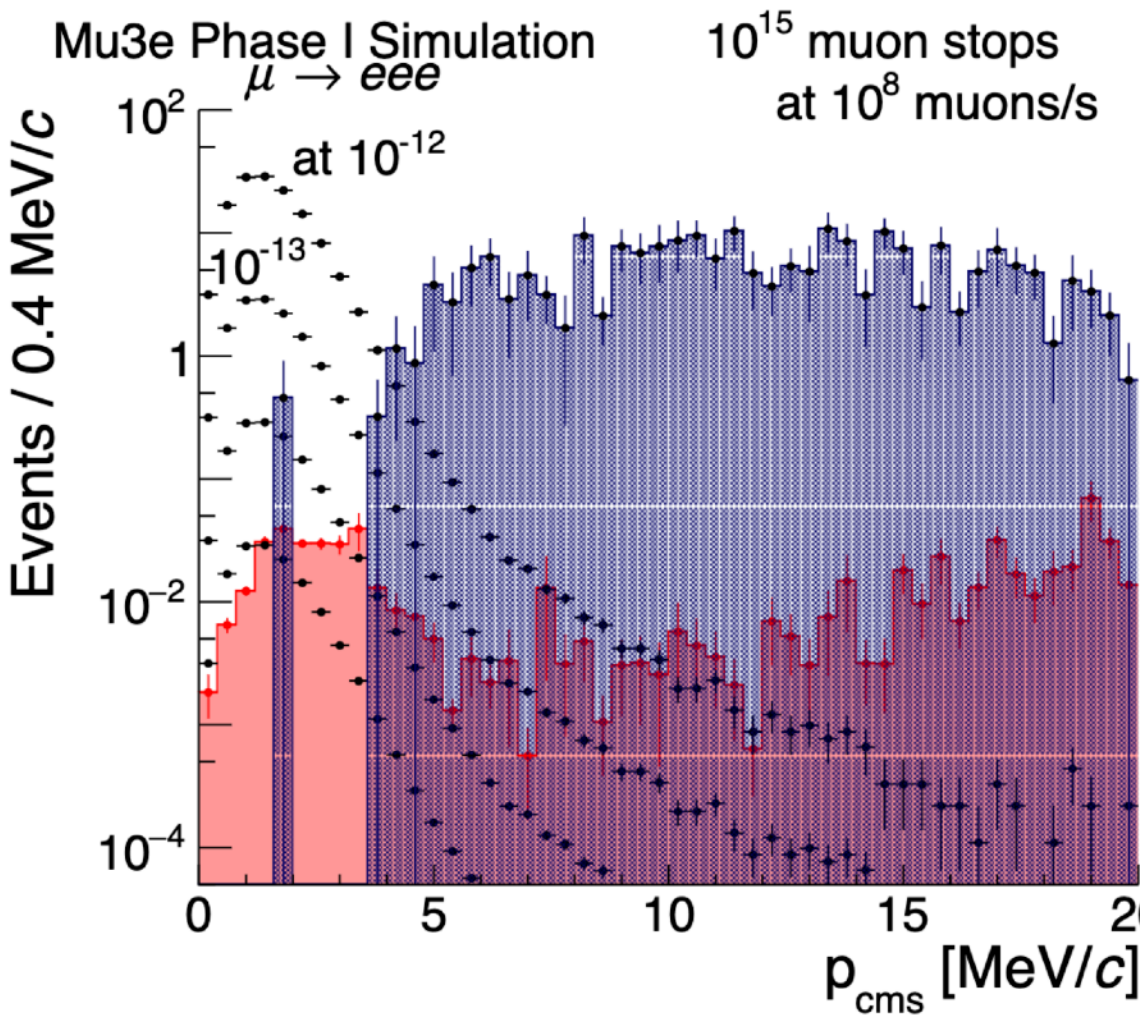




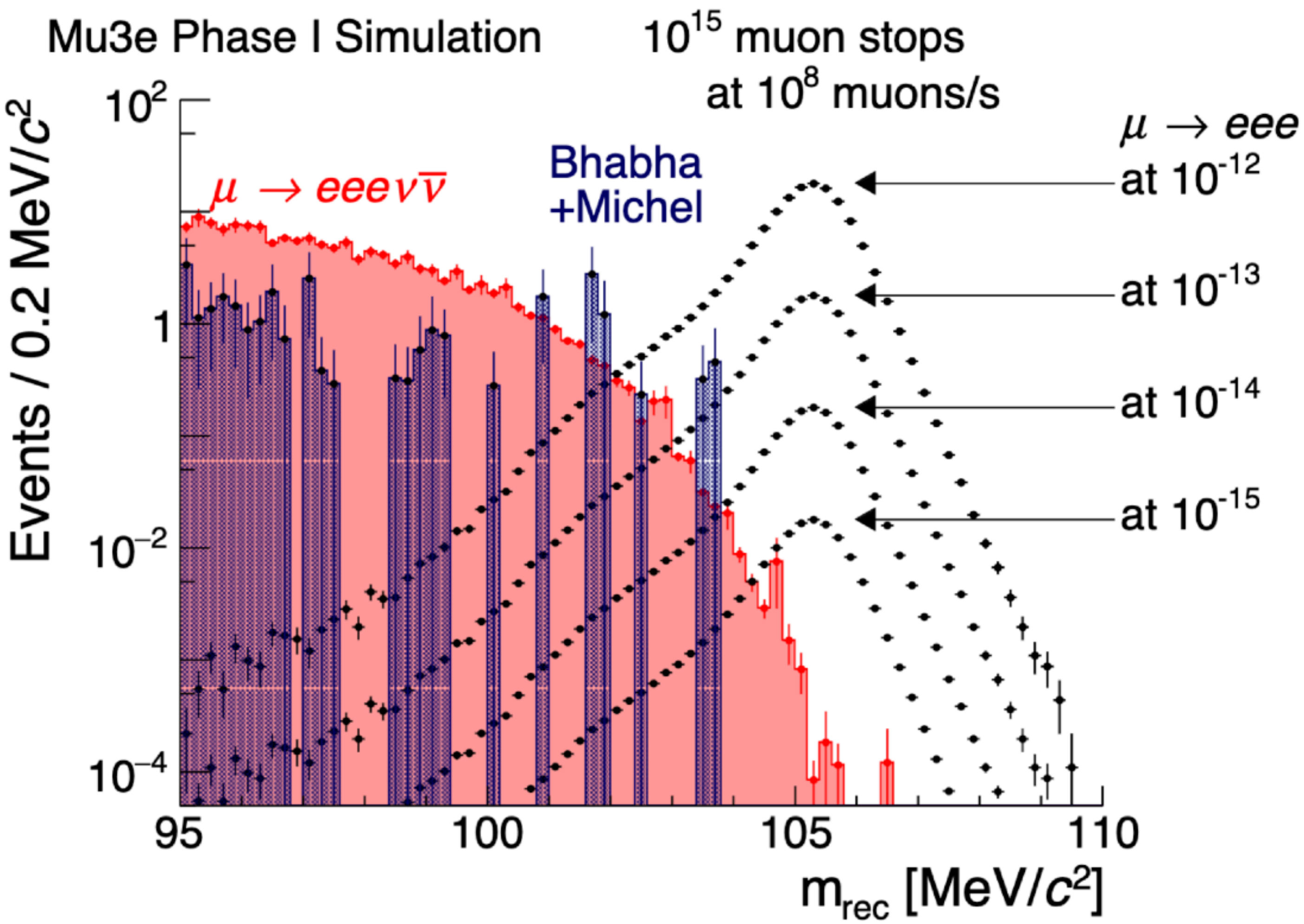
Online reconstruction



Simulation



Mu3e Phase I Simulation
10^{15} muon stops
at 10^8 muons/s
$\mu \to eee$
at 10^{-12}
10^{-13}
Events / 0.4 MeV/c
p_{cms} [MeV/c]



Mu3e Phase I Simulation
10^{15} muon stops
at 10^8 muons/s
$\mu \to eee$
at 10^{-12}
at 10^{-13}
at 10^{-14}
at 10^{-15}
$\mu \to eee\nu\bar{\nu}$
Bhabha
+Michel
Events / 0.2 MeV/c^2
m_{rec} [MeV/c^2]

Other searches with Mu3e

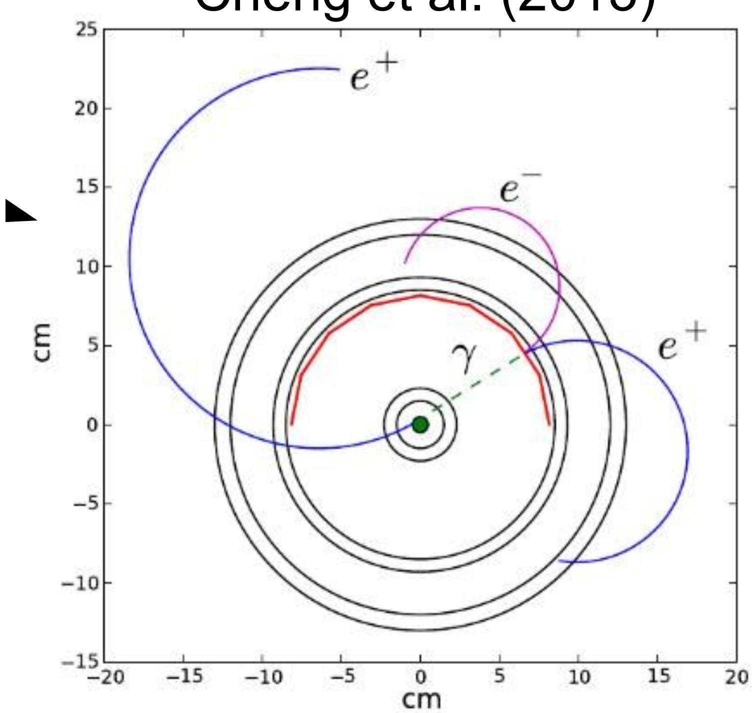
Unprecedented muon dataset (>10^{16}) can be exploited in online searches:

μ→eγ

(with converted photons)

Good accidental background suppression

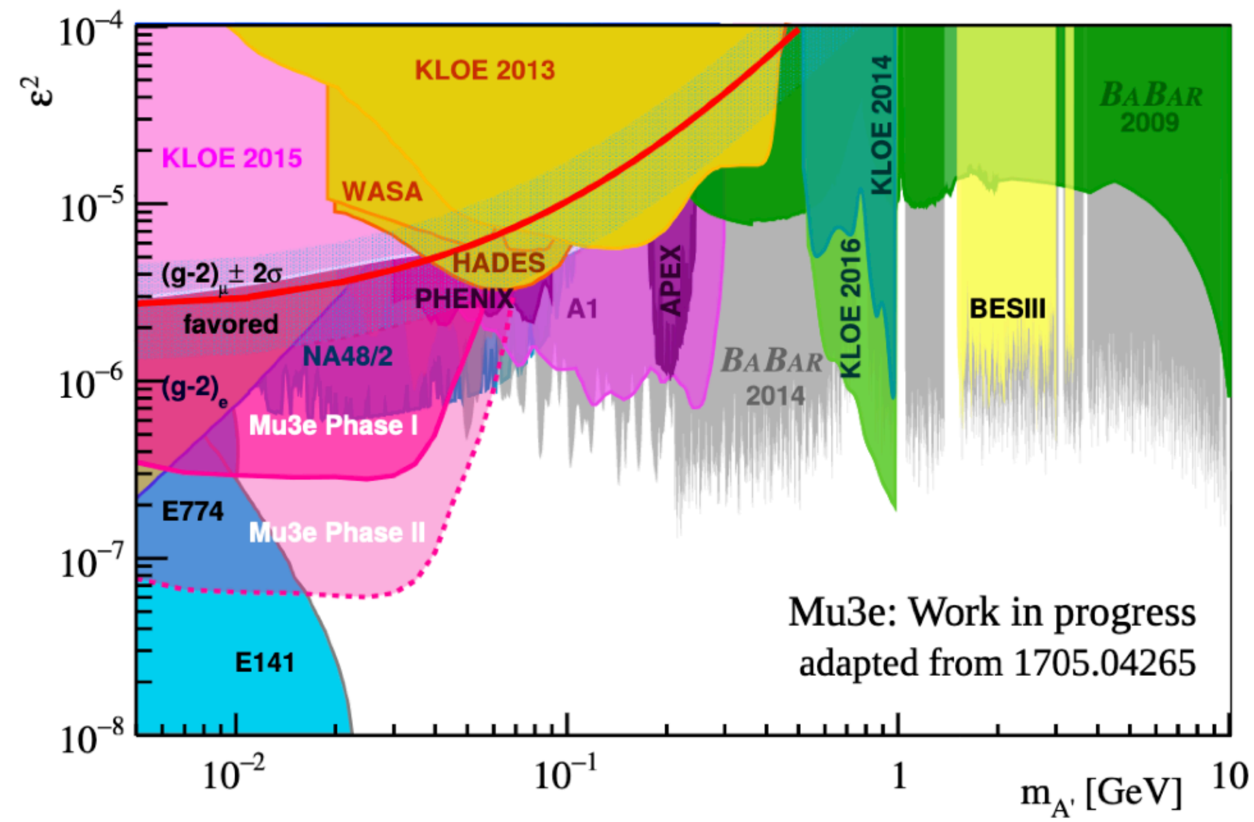
Cheng et al. (2013)

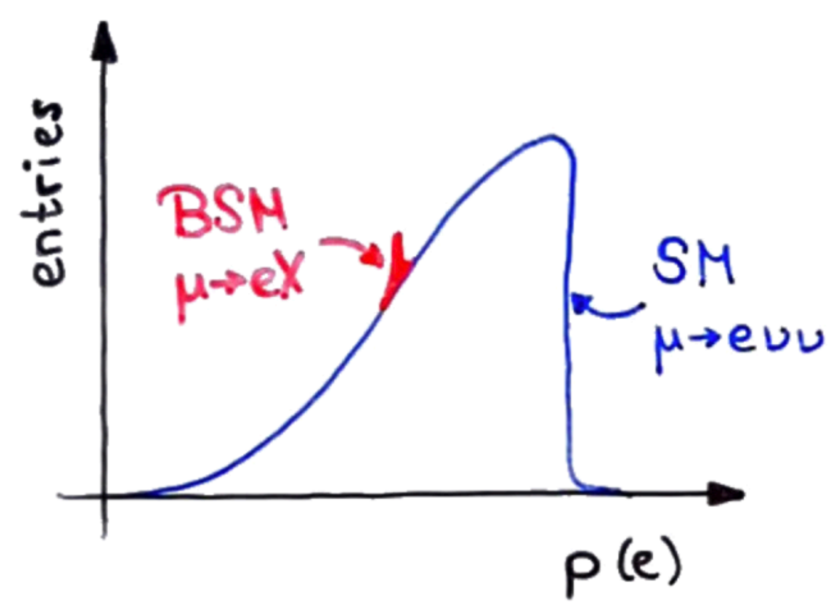


μ→eννA'

(dark matter photons)

e^+/e^- resonance





μ→eX

(X unobserved)

monoenergetic e^+

ex. familons (Goldstone boson from spontaneously broken flavor symmetry)