Mu3e experiment status and plans

Muon Precision Physics Workshop 2024
Liverpool, 14.11.2024

Paolo Beltrame for the Mu3e Collaboration

1. Physics introduction
2. Mu3e challenges
3. Mu3e physics reach, itinerary & plans
4. Summary & Outlook

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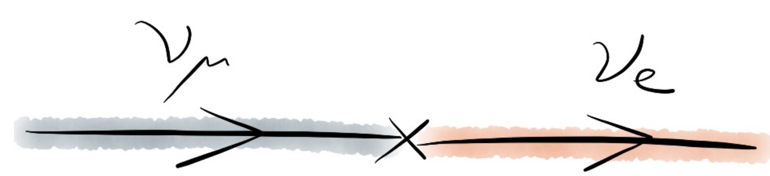
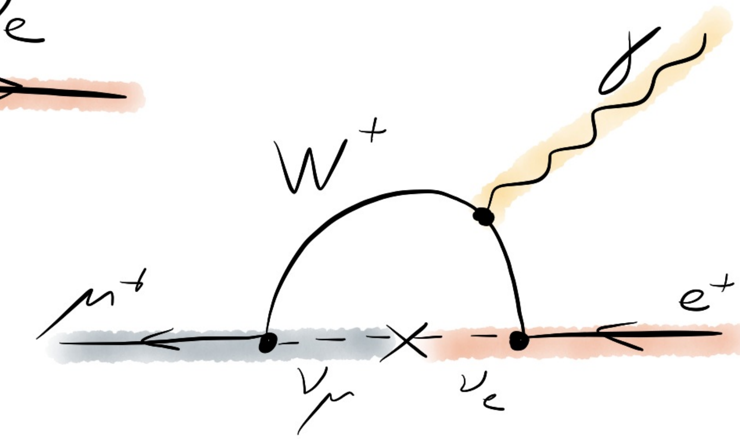
- Particle Physics (in 2024):
  - All particles in the Standard Model discovered
  - Very few lab measurements in tension with SM
  - SM known to be incomplete: Dark matter, baryon asymmetry, gravity, hierarchy,…

- Looking for New Physics
  - Lepton Flavour Violation:



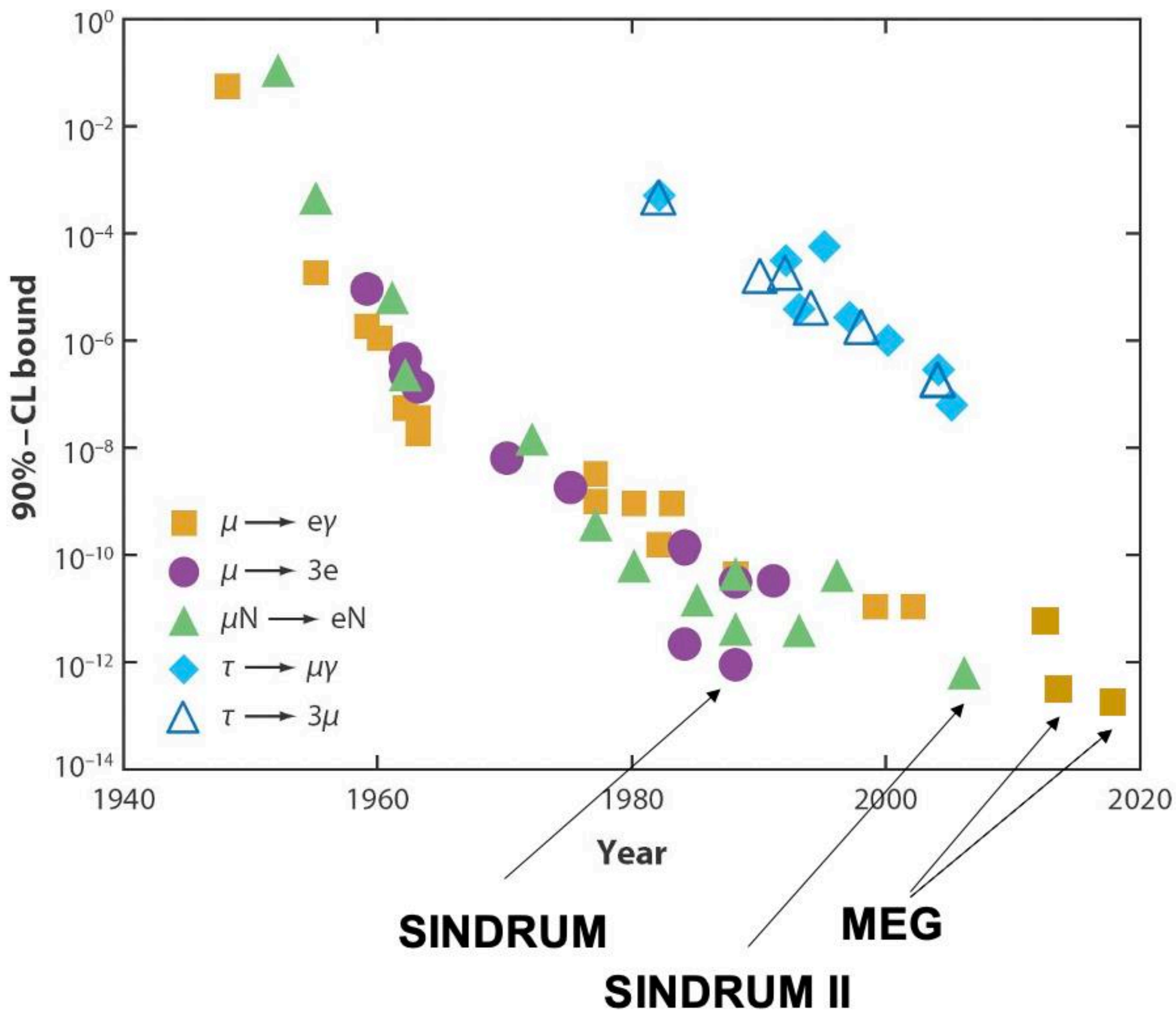
  - Charged Lepton Flavour Violation:



Heavily suppressed in the SM $(\Delta m^2_\nu/\Delta m^2_W)^2$
Branching fraction < 10^{-54}

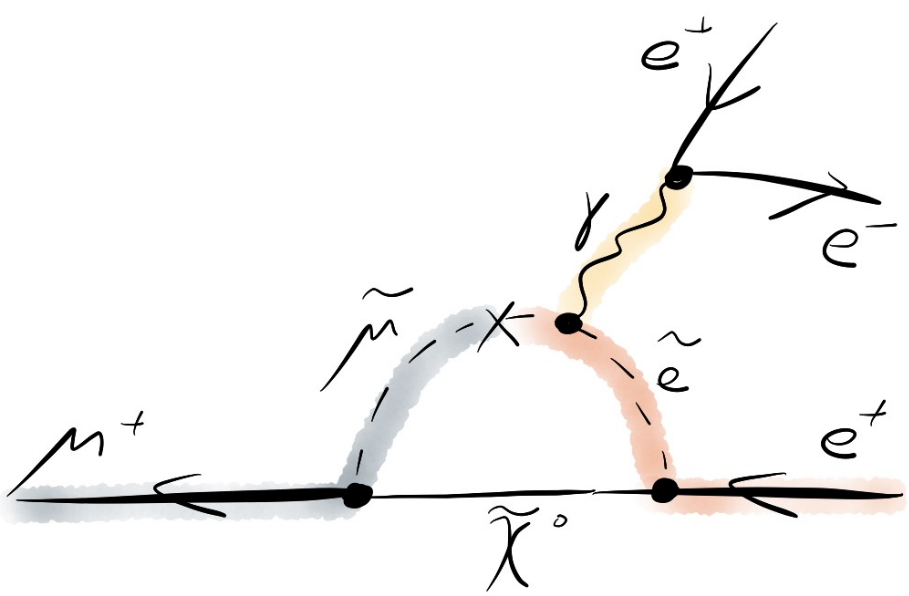
Best limits on LFV

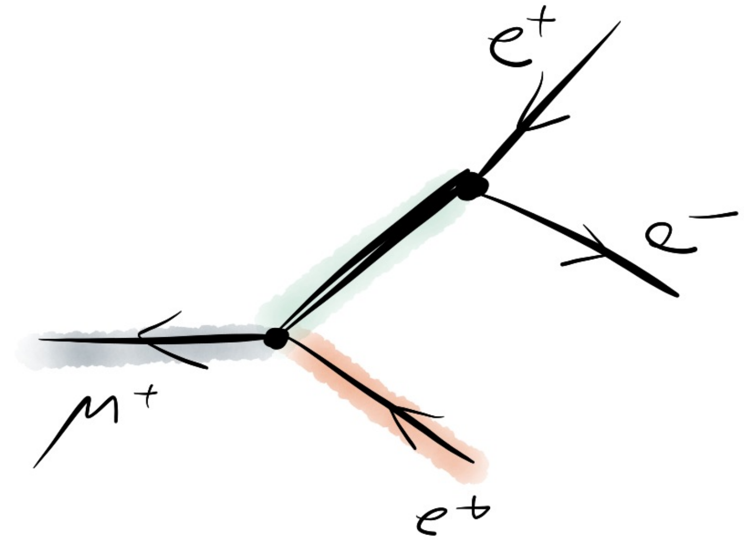
PSI muon experiments



New physics in $\mu^+ \to e^+e^+e^-$

- Loop diagrams
  - Supersymmetry
  - Little Higgs models
  - Seesaw models
  - GUT models (leptoquarks)
  - …
- Tree diagrams
  - Higgs triplet models
  - Extra heavy vector bosons (Z')
  - Extra dimensions (Kaluza-Klein tower)
  - …



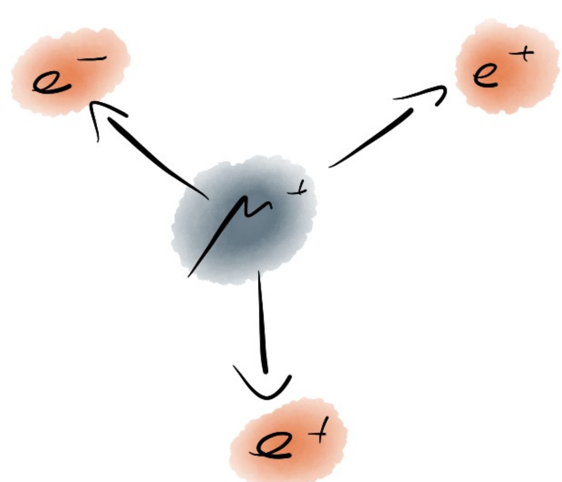


$\mu^+ \rightarrow e^+e^+e^-$ signal and background

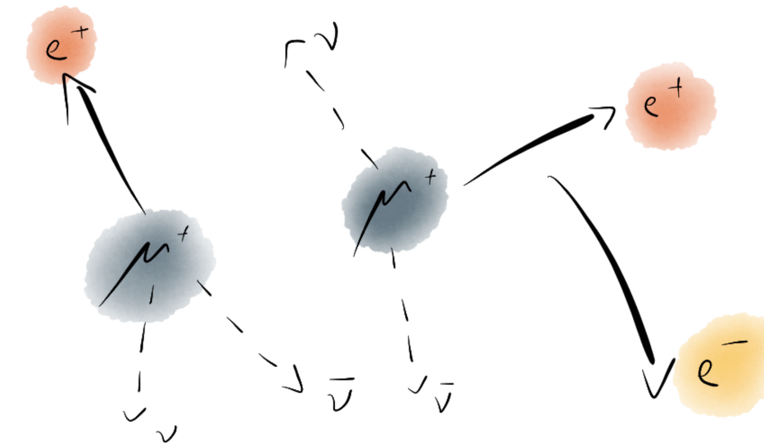
- Signal
  - Common vertex
  - $\sum \vec{p} = 0$
  - $\sum E = m_\mu$
  - $\sum t_{eee} = 0$

- Internal Conversion
  - Common vertex
  - $\sum \vec{p} \neq 0$
  - $\sum E < m_\mu$
  - $\sum t_{eee} = 0$

- Combinatorial
  - No common vertex
  - $\sum \vec{p} \neq 0$
  - $\sum E \neq m_\mu$
  - $\sum t_{eee} \neq 0$



→ momentum
and total energy resolution



→ time
and vertex resolution,
kinematic reconstruction

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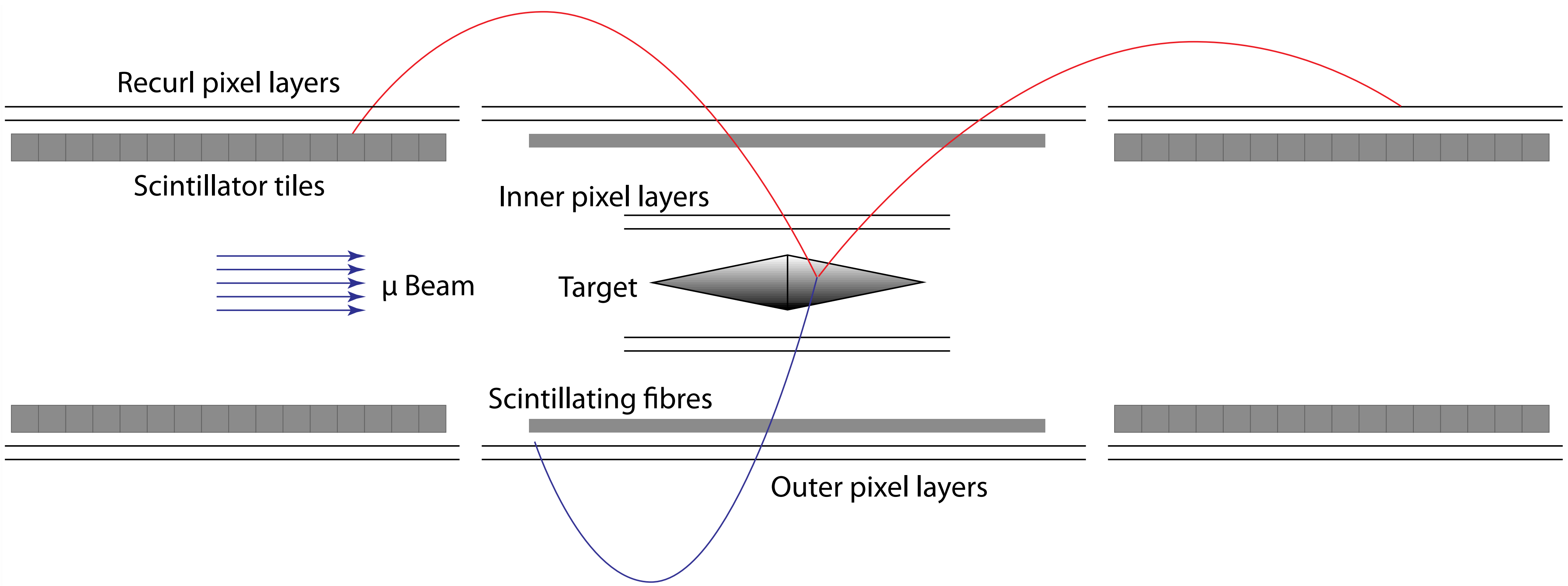
Experiment idea

- Muons decay at rest in target
- e^+/e^- start propagating in magnetic field
- two Si pixel layers vertex detector
- two more Si pixel layers and tracking
- Scintillating Fibres to differentiate e^+ from e^-
- Recurl tracking stations for optimal momentum resolution
- Scintillating Tiles for optimal timing resolution



Experimental challenges

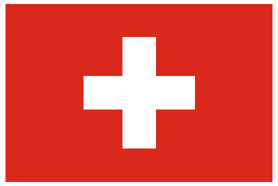
- multiple Coulomb scattering ➞ ultra-thin tracking layers
- high particles rates ➞ highly granular detectors and fast online reconstruction
- compact design ➞ high integration level (sensors, readout ASICs)

⇒ Innovative Technologies:

- High Voltage Monolithic Active Pixel Sensors (HV-MAPS) for tracking
- Ultra-thin pixel modules (0.1% X/X_0) and excellent spatial resolution (~30 μm)
- MuTRiG readout ASIC for timing detectors with ~30 *ps* time resolution
- Online filter farm based on Graphical Processing Units (2.3 x 10^6 *frames/s*)

Mu3e Collaboration

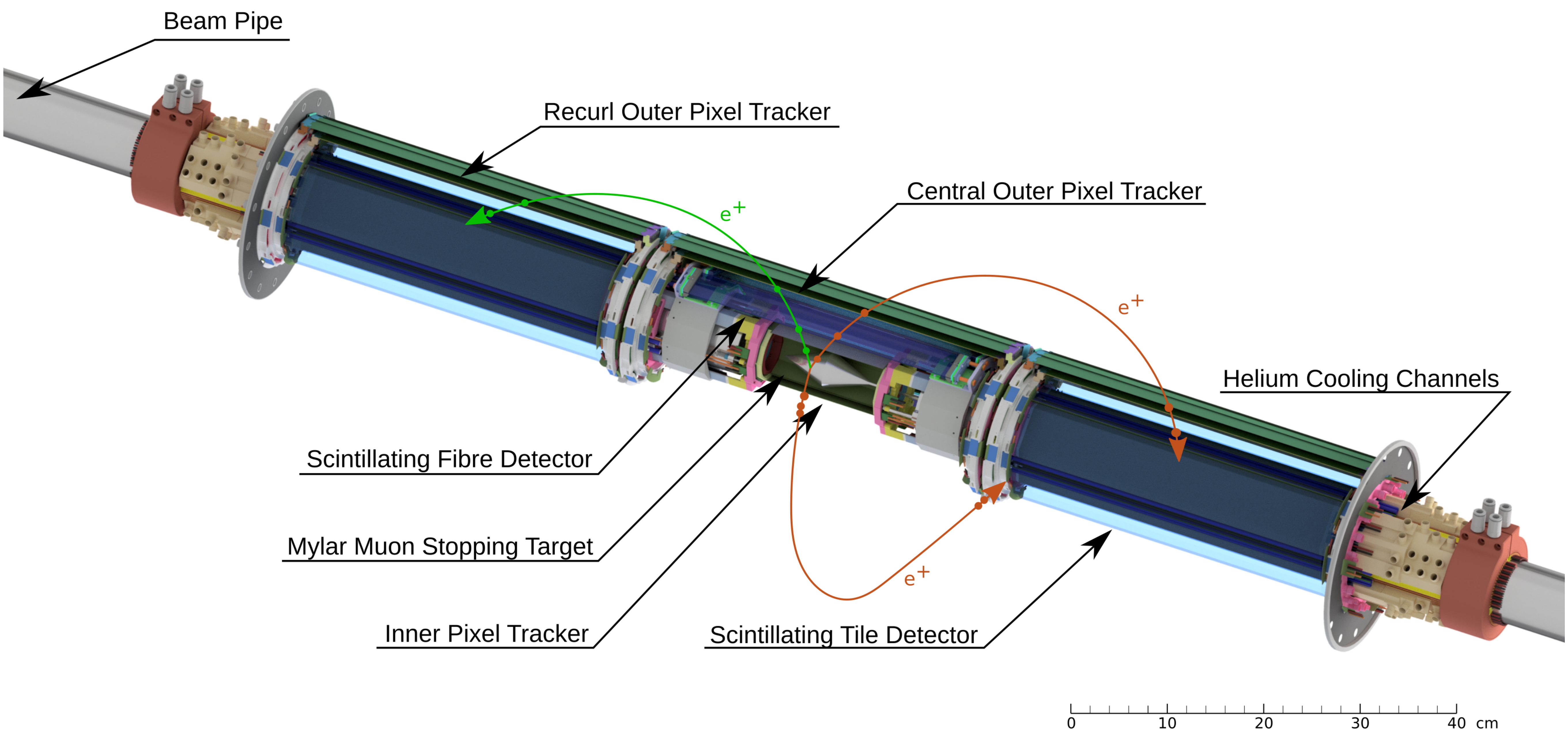
 Germany: University Heidelberg (KIP), University Heidelberg (PI), Karlsruhe Institute of Technology, University Mainz

 Switzerland: University of Geneva, Paul Scherrer Institute, ETH Zurich, University Zurich, [University of Applied Sciences Northwestern Switzerland] (associated partner)

 United Kingdom: Bristol University, Liverpool University, Oxford University, UC London

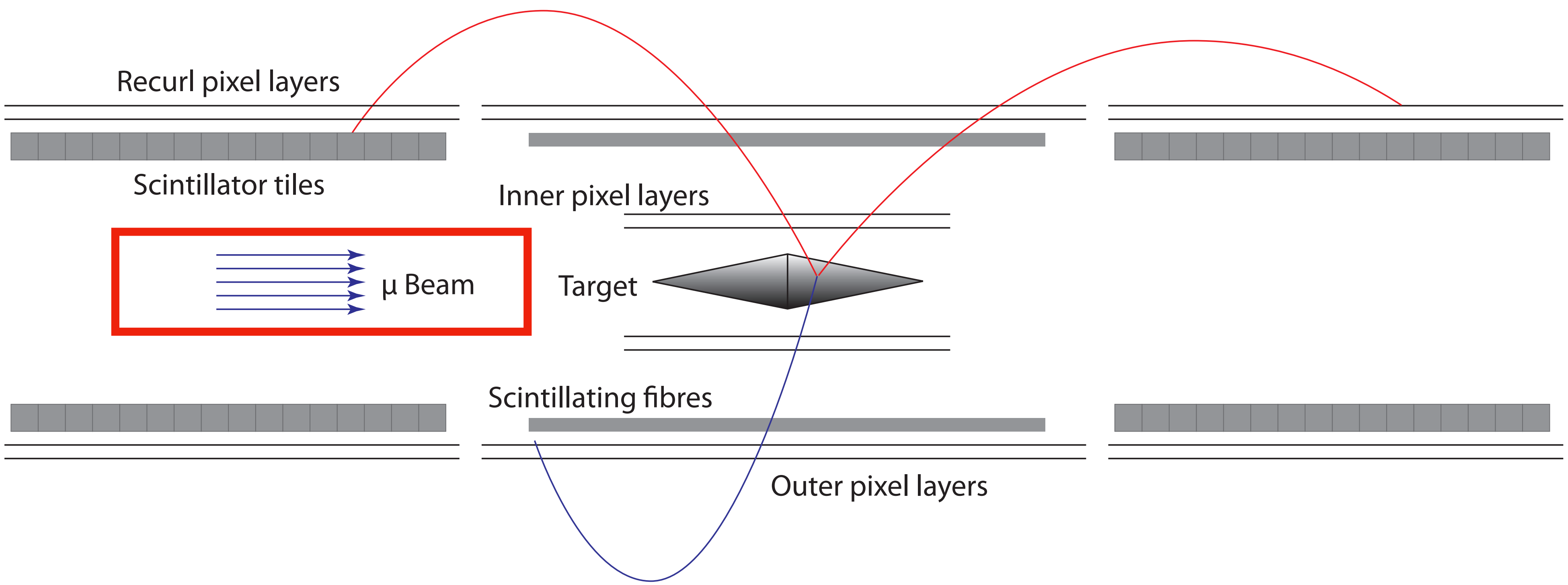
~85 members (~20 PhD students)

Mu3e



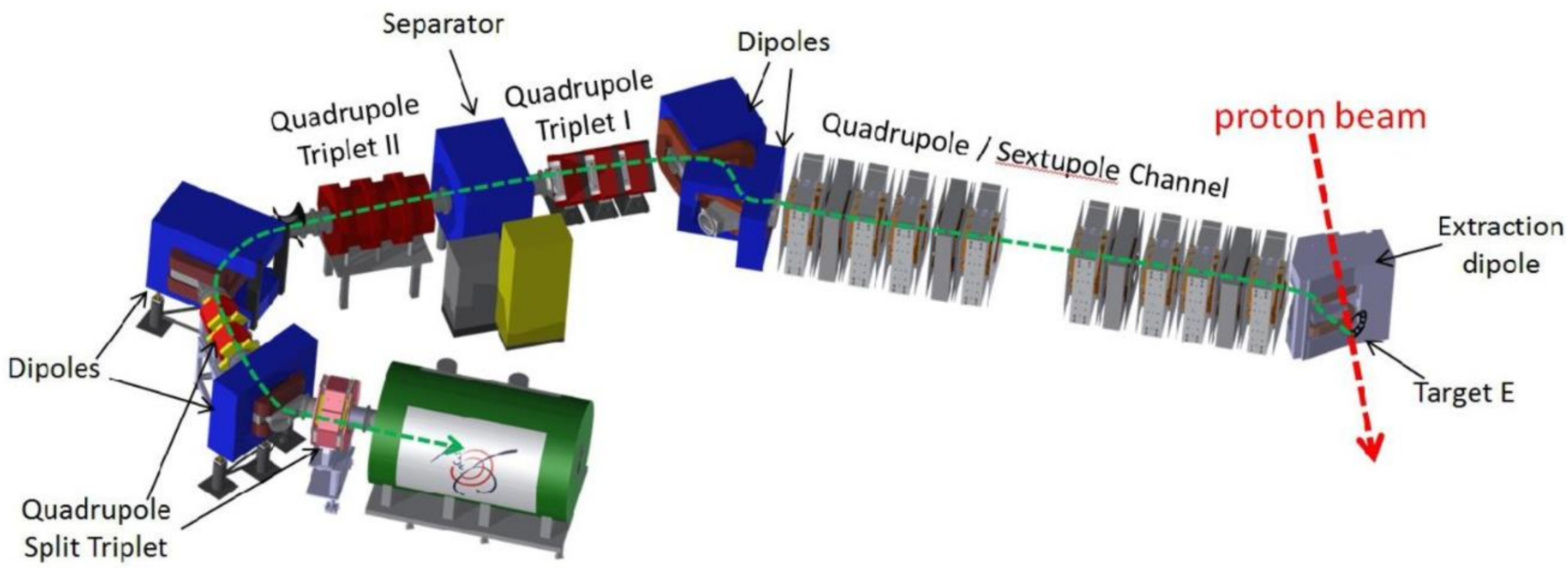
Beam Pipe
Recurl Outer Pixel Tracker
Central Outer Pixel Tracker
e+
e+
e+
Helium Cooling Channels
Scintillating Fibre Detector
Mylar Muon Stopping Target
Inner Pixel Tracker
Scintillating Tile Detector
0
10
20
30
40 cm

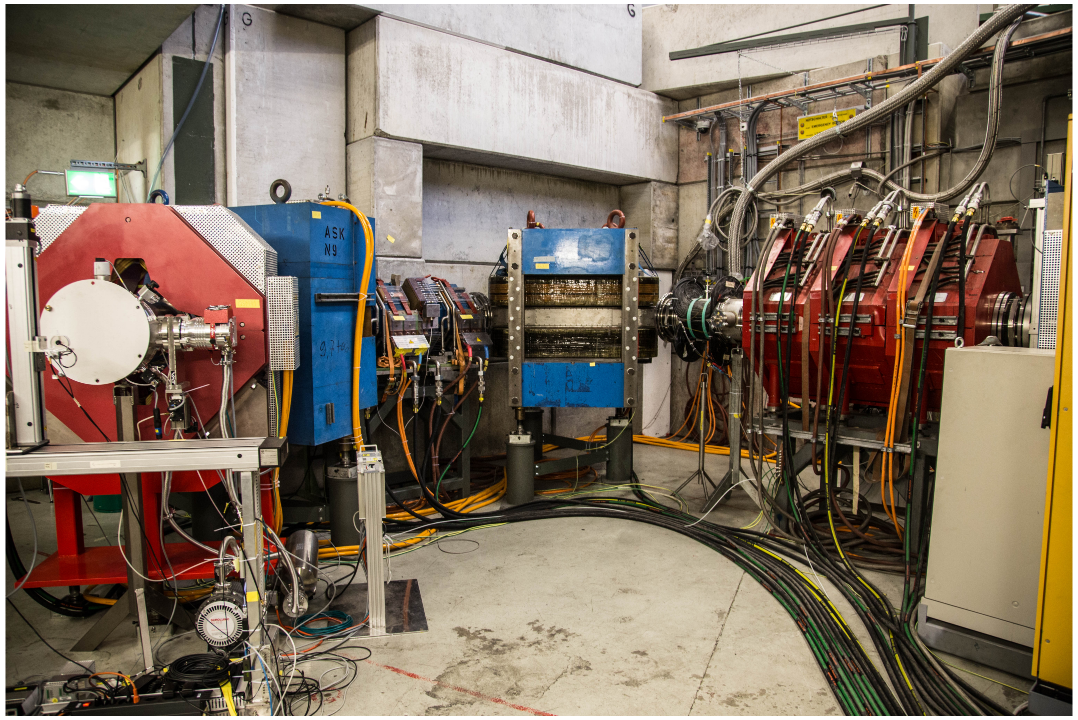
Muon beam


Recurl pixel layers
Scintillator tiles
Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers

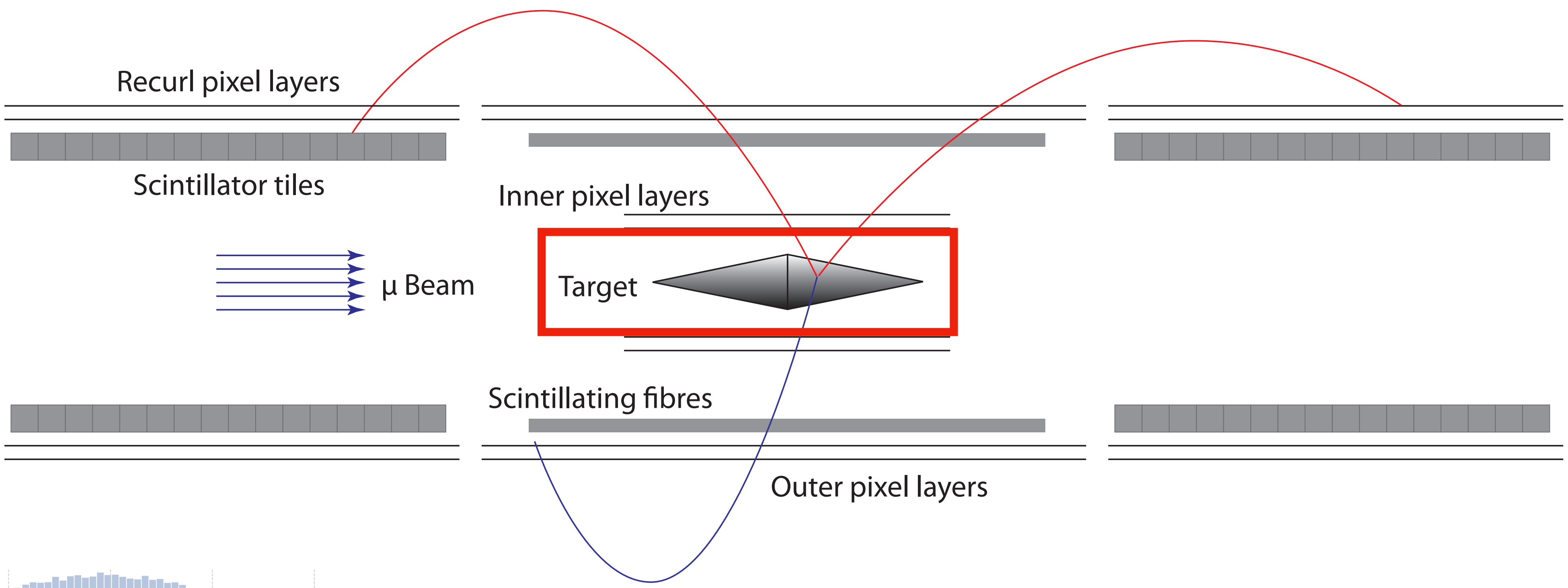
Muon beam

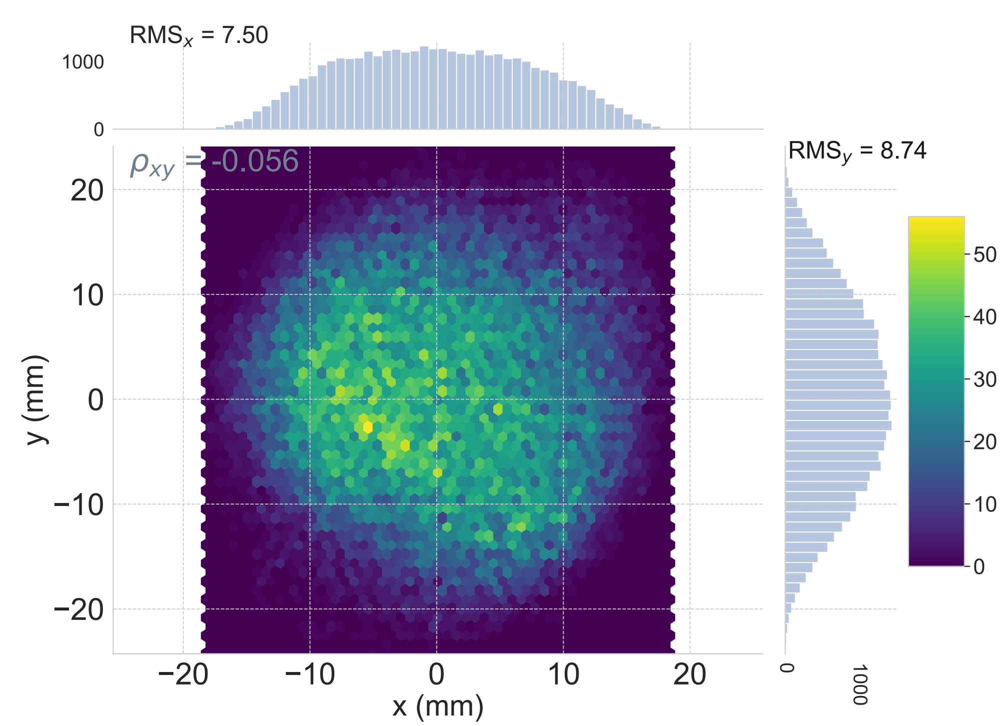
- S.E.S. of 10^{-15} (Phase I)
  → intensity frontier
  and continuous beam line
- HIPA accelerator
  at Paul Scherrer Institute
  (PSI) in Switzerland
  - 2.2 *mA* protons at 590 *MeV* (1.5 *MW*)
- World's most intense muon beam:
  - Low momentum muons ~28 *MeV*
  - πE5 beamline shared with MEG II
  - 10^8 *μ/s* stopped on Mu3e target





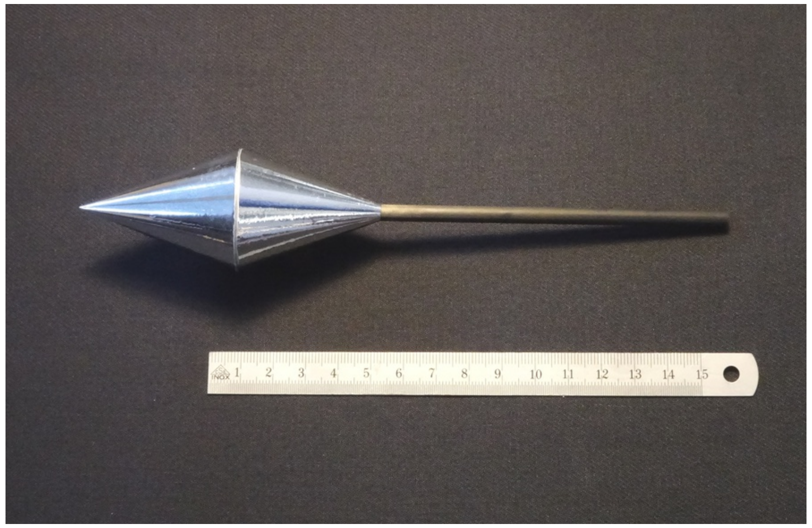
Stopping target and magnet

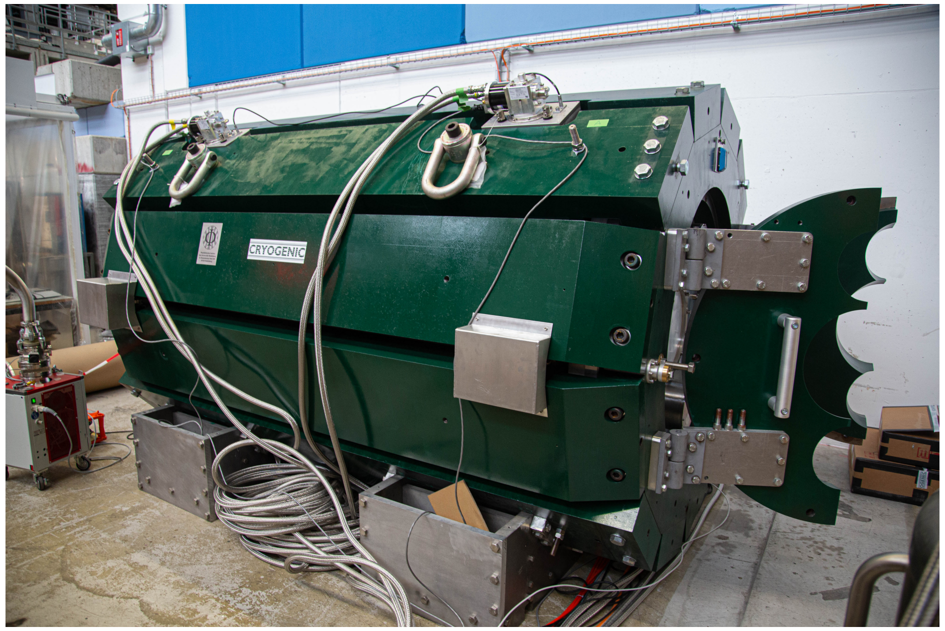




Stopping target and magnet

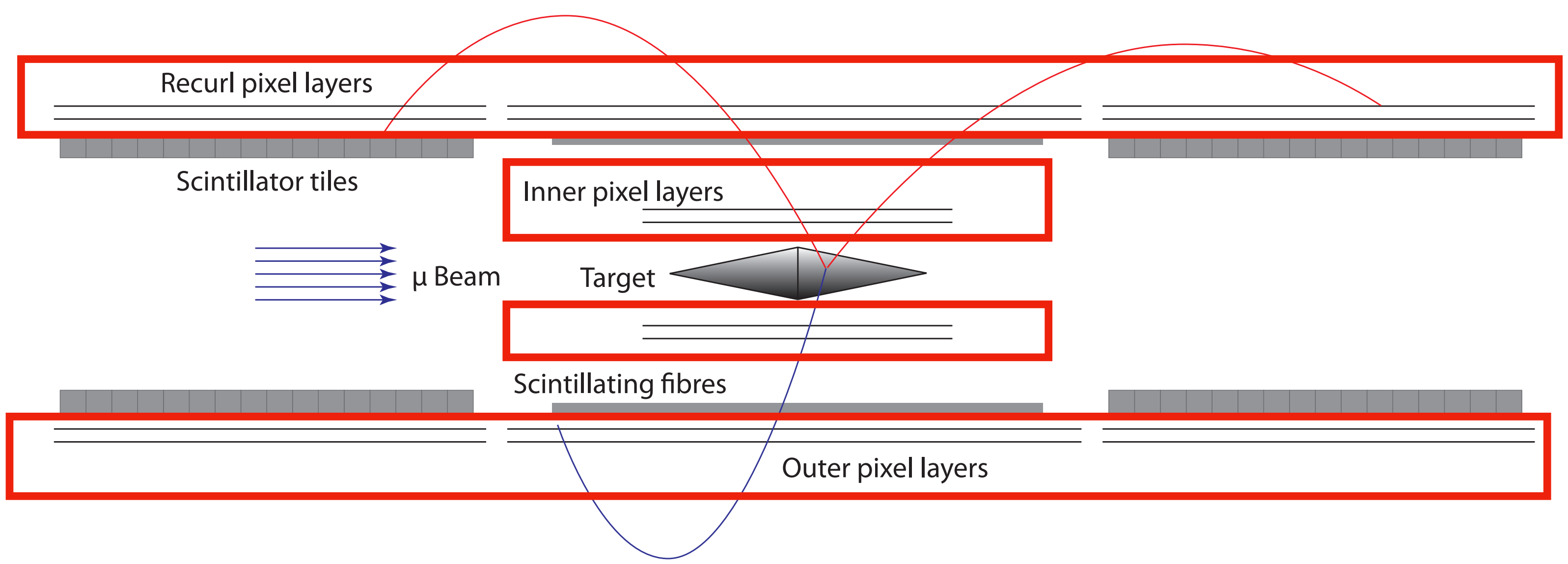
- Target
  (70 *μm* thick, 100 *mm* long, 19 *mm* radius):
  - Hollow: material budget traversed by decay particles minimized
  - Double-cone: decay vertices spread out in the longitudinal direction
  - Mylar: high stopping power



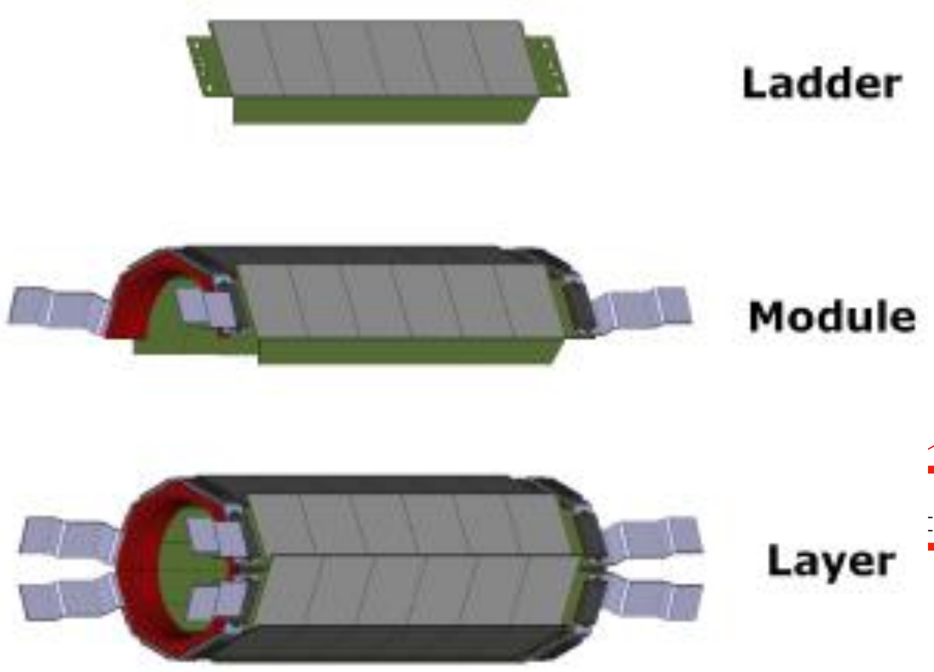


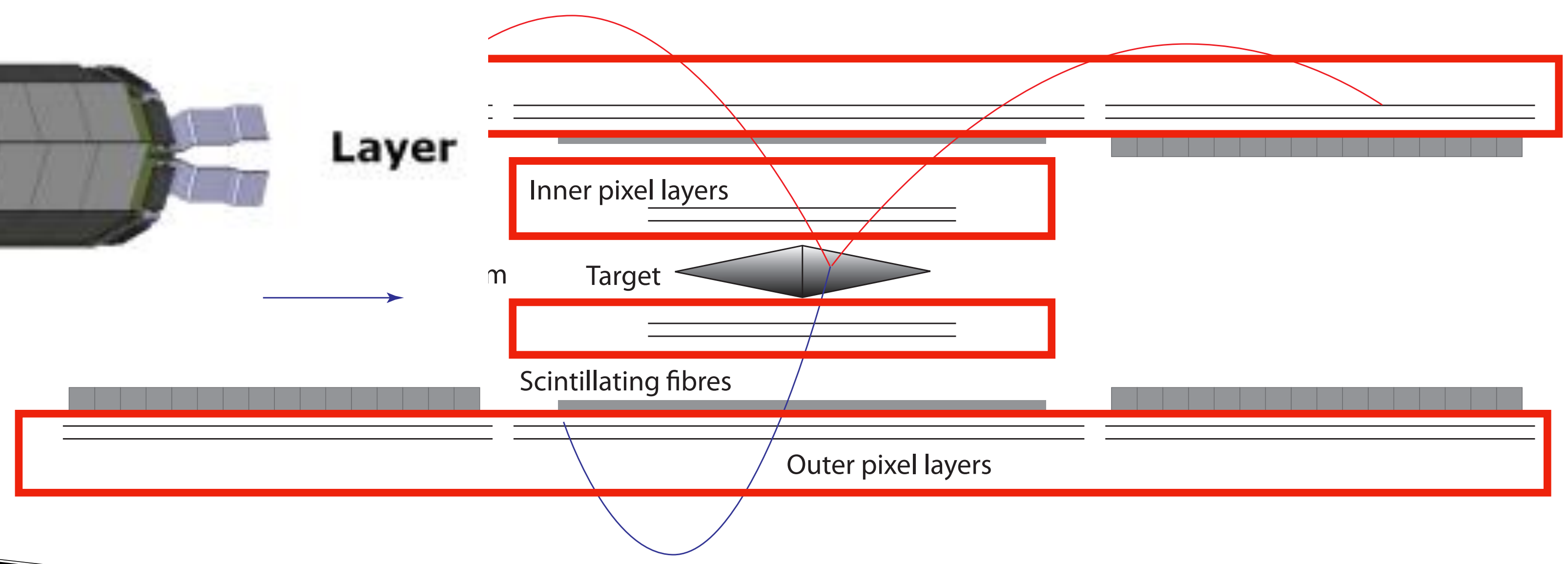
- Magnet
  Homogeneous, stable solenoidal superconducting magnet of 1 *T*
  - Precise momentum reconstruction with recurlers
  - Guides beam to target
  - Delivered at PSI and operational

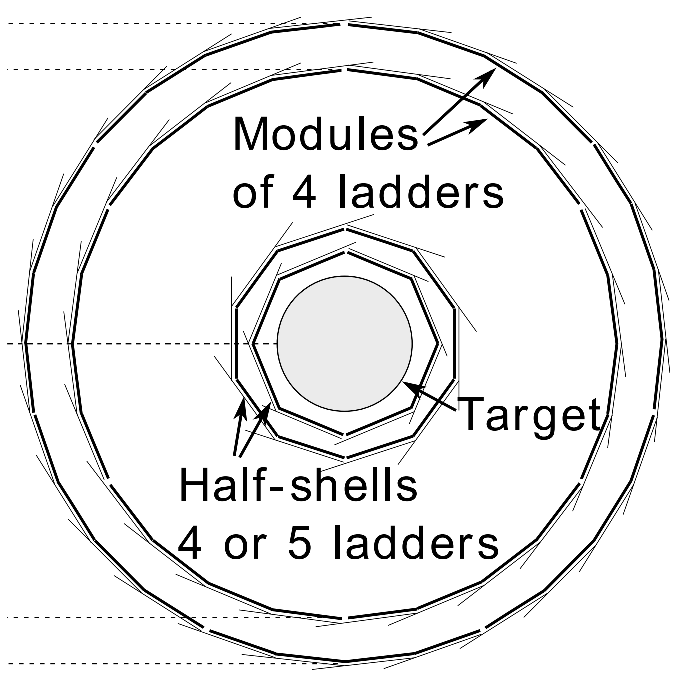
Pixel Detector



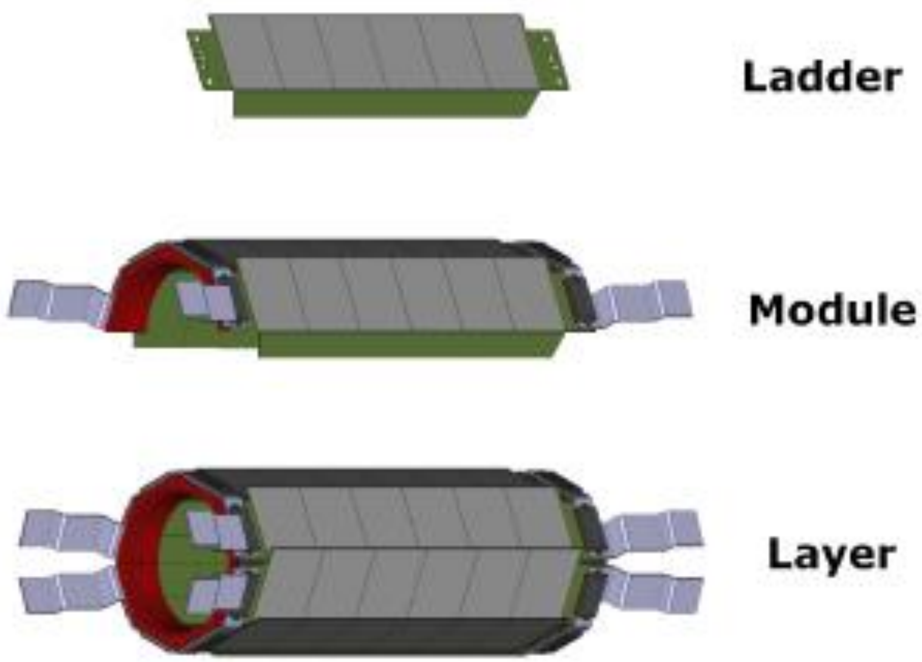
Pixel Detector

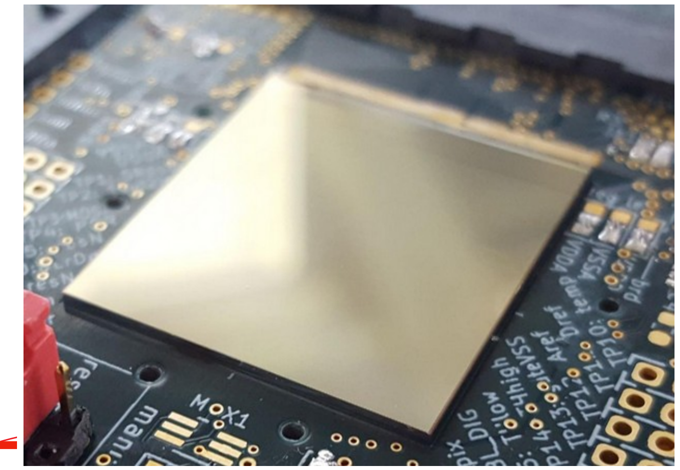


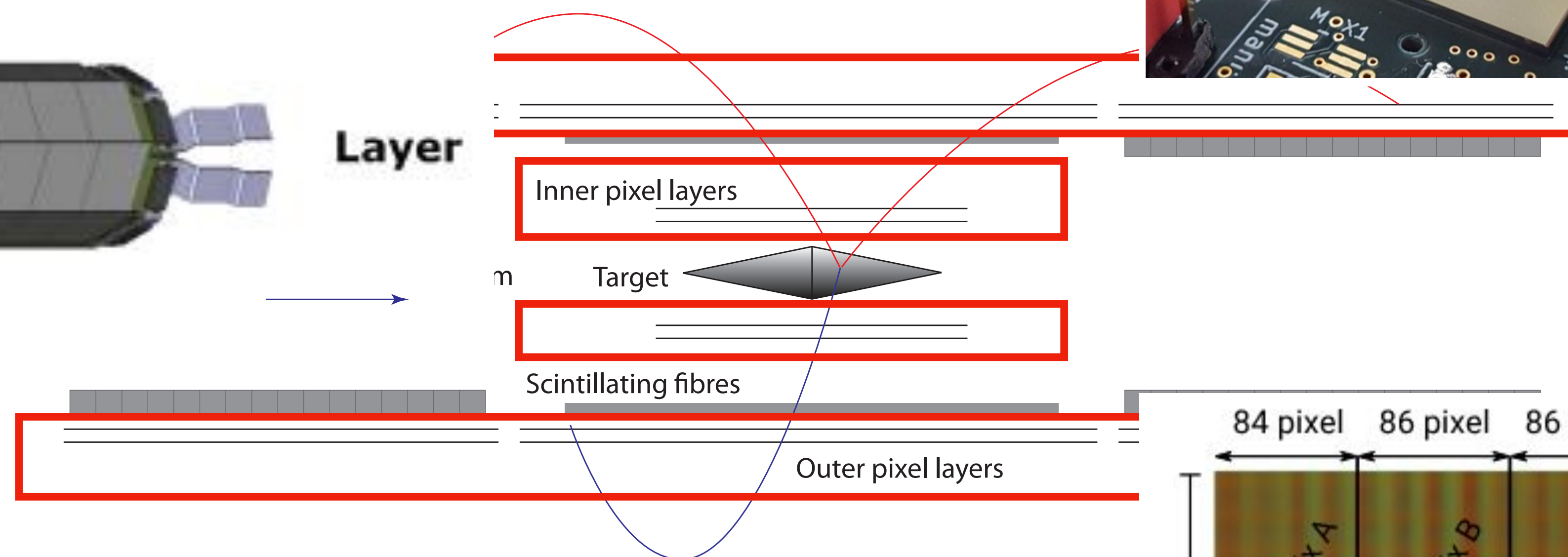


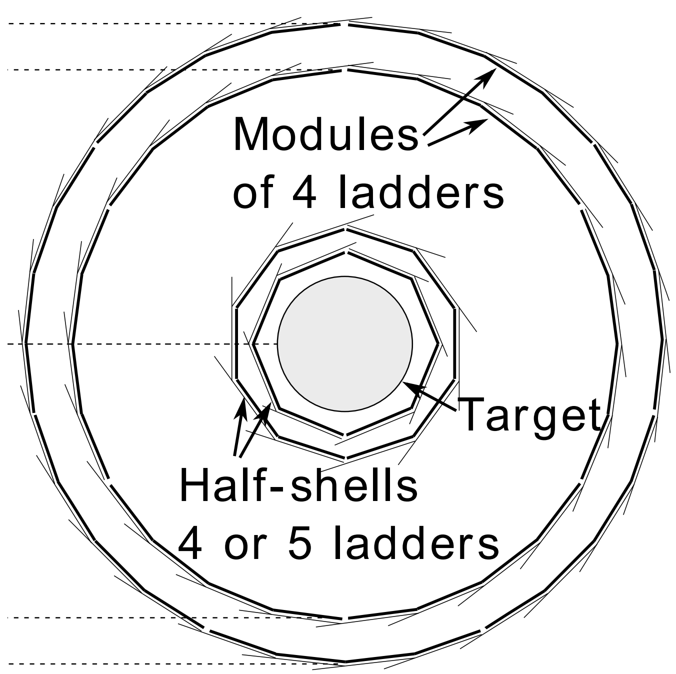


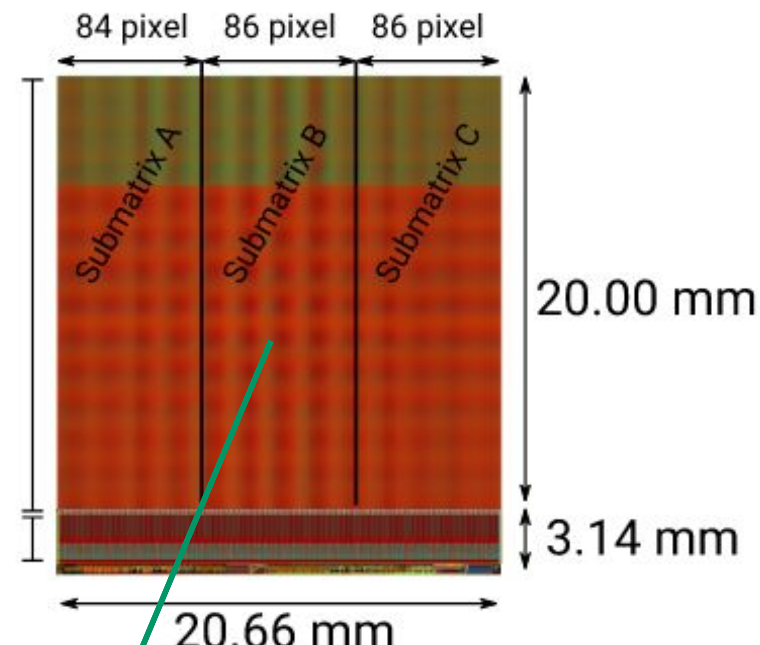
Pixel Detector







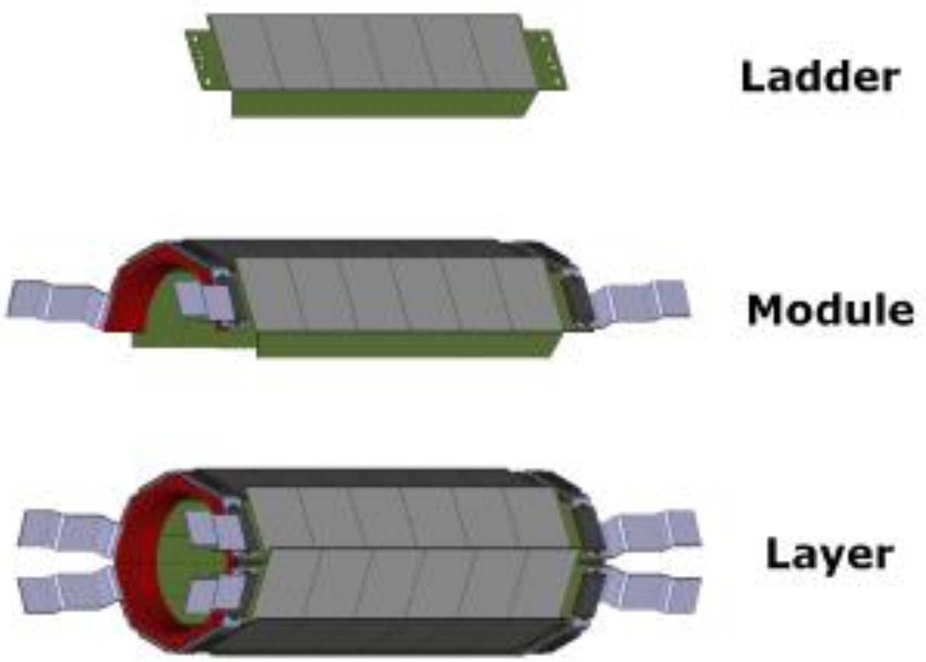




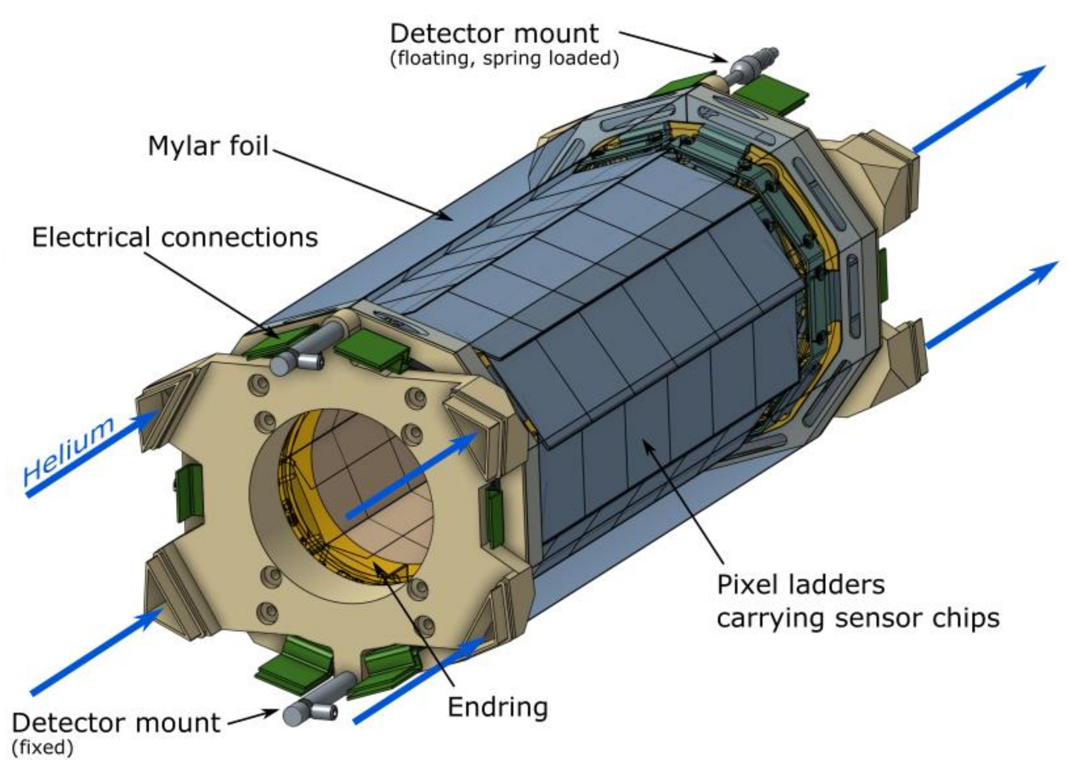
MuPIX: High Voltage Monolithic Active Pixel Sensors, pixels and the detector electronics are integrated into the same chip

Pixel Detector: mechanics

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



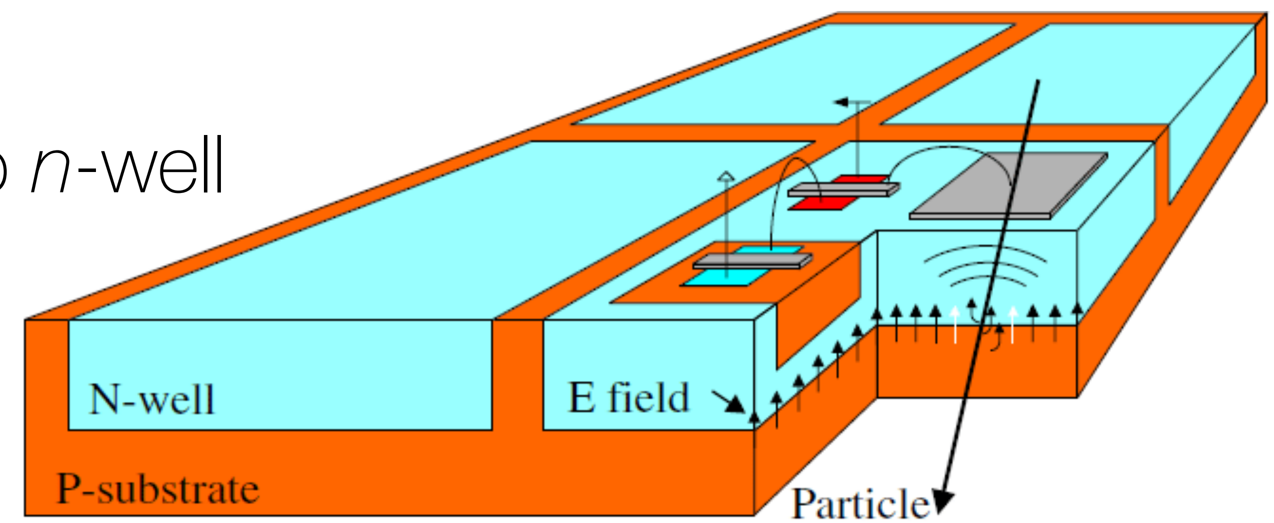
- Lightweight pixel tracker for vertex identification and momenta measurement
- Arranged in three stations (central, upstream, downstream)
- Minimal material budget (~1‰ X/X_0)
- 50 *g/s* 5 *kW* gaseous helium cooling



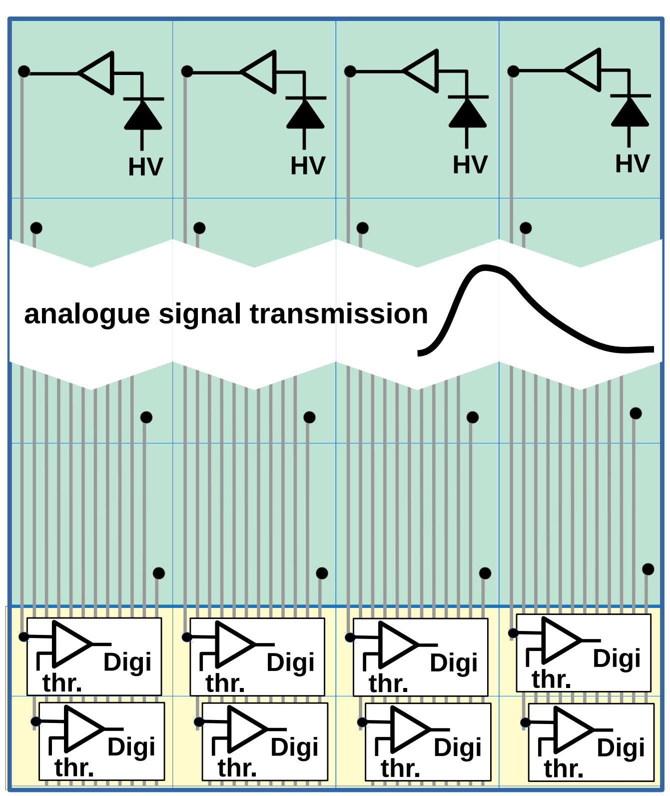
(HV-)MAPS

- Collect ionisation charge mainly via drift, time resolutions *O*(*ns*)
- Amplifier electronics inside the deep *n*-well
- Reverse biasing (≥ 60 V),
  → depletion zone ~30-40 *μm*
- Thinned to ~50 *μm* (~0.05% X/X_0)

I. Peric et al., NIM A 582 (2007) 876

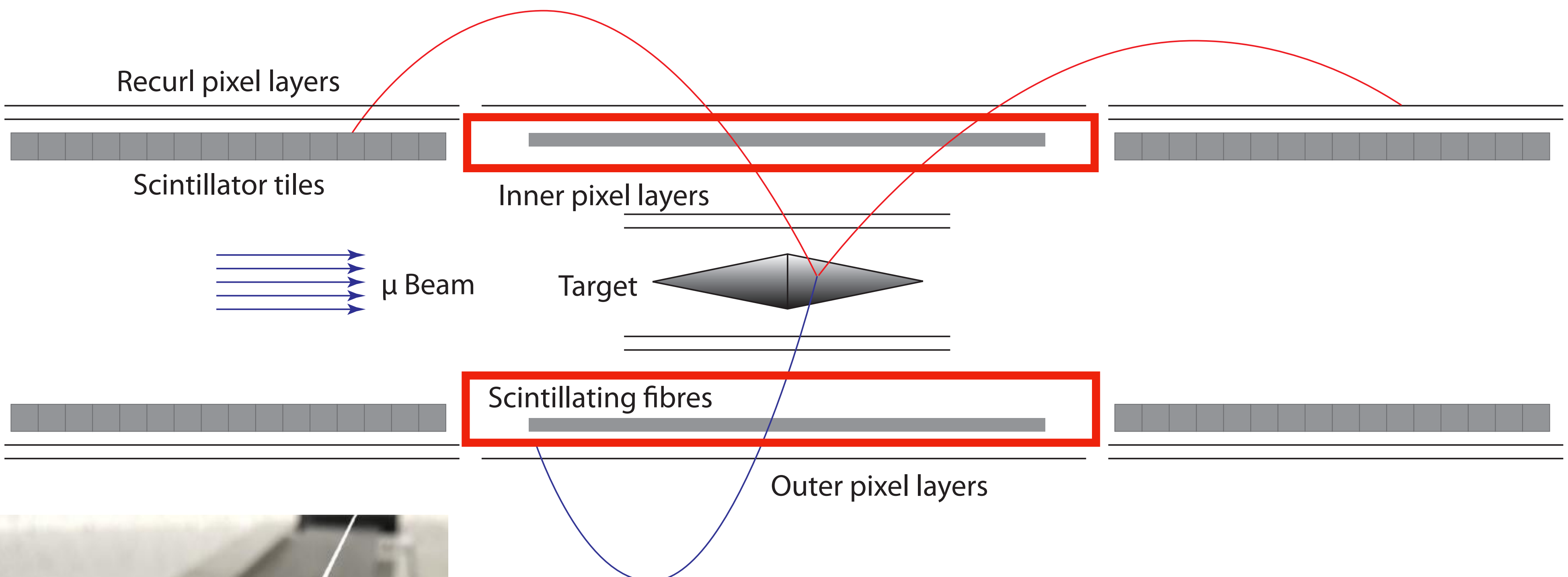


250x256 Pixels



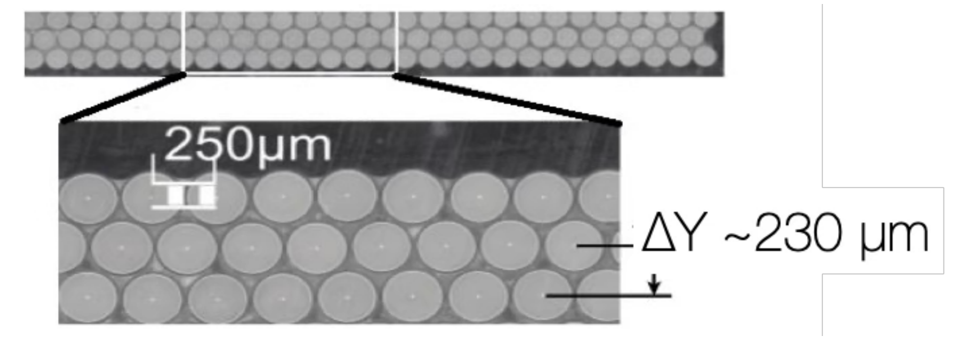
sensor dimensions [mm^2]	$\lesssim 21 \times 23$
sensor size (active) [mm^2]	$\approx 20 \times 20$
thickness [μm]	$\lesssim 50$
spatial resolution μm	$\lesssim 30$
time resolution [ns]	$\lesssim 20$
hit efficiency [%]	$\gtrsim 99$
#LVDS links (inner layers)	1 (3)
bandwidth per link [Gbit/s]	$\gtrsim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

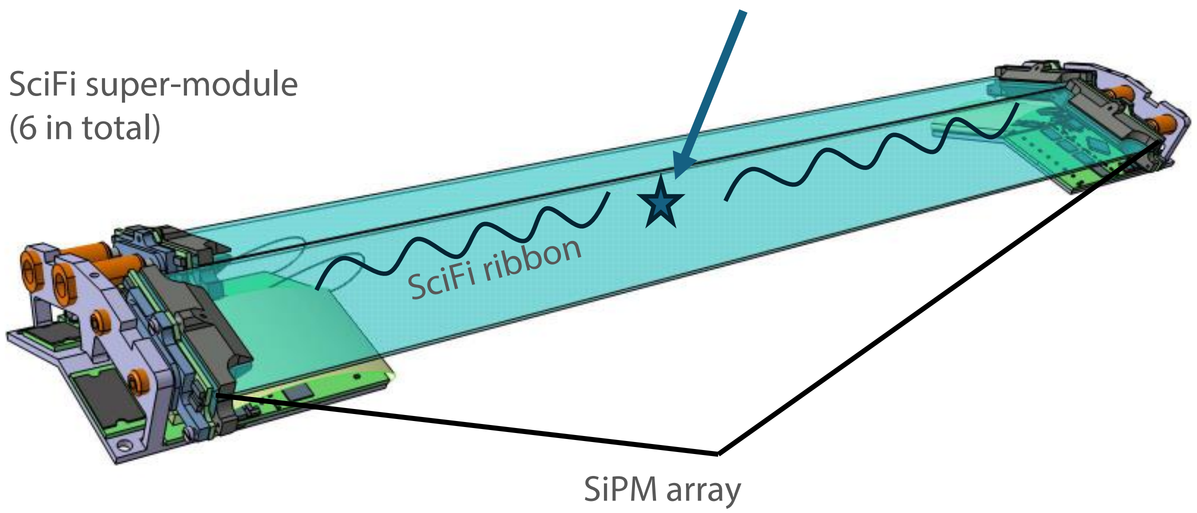
Time Sensor: Sci Fi

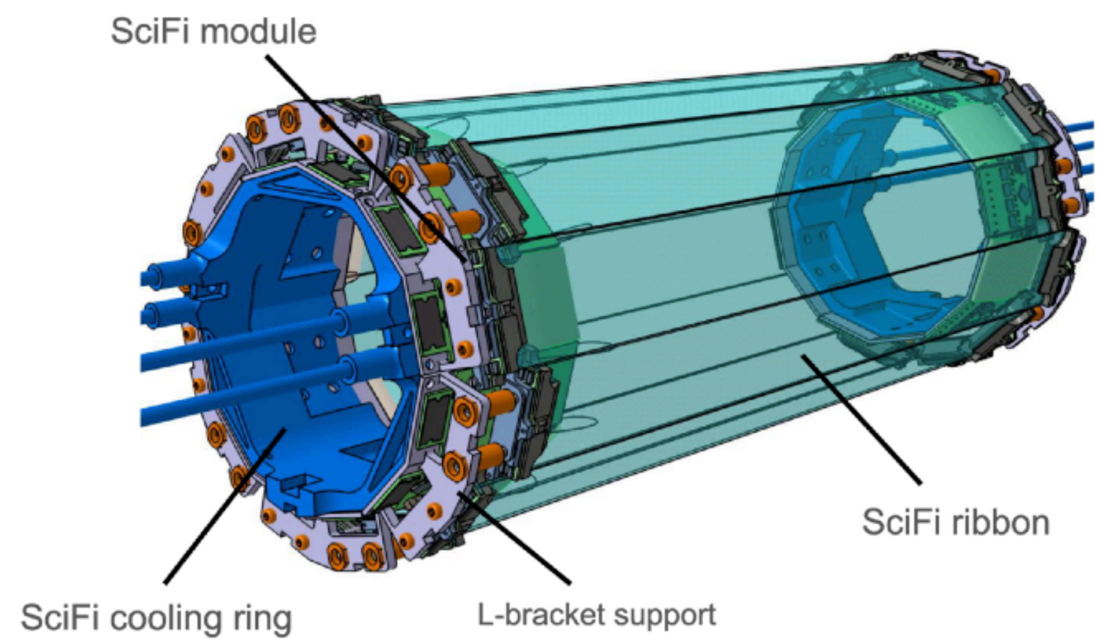


Time Sensor: Sci Fi

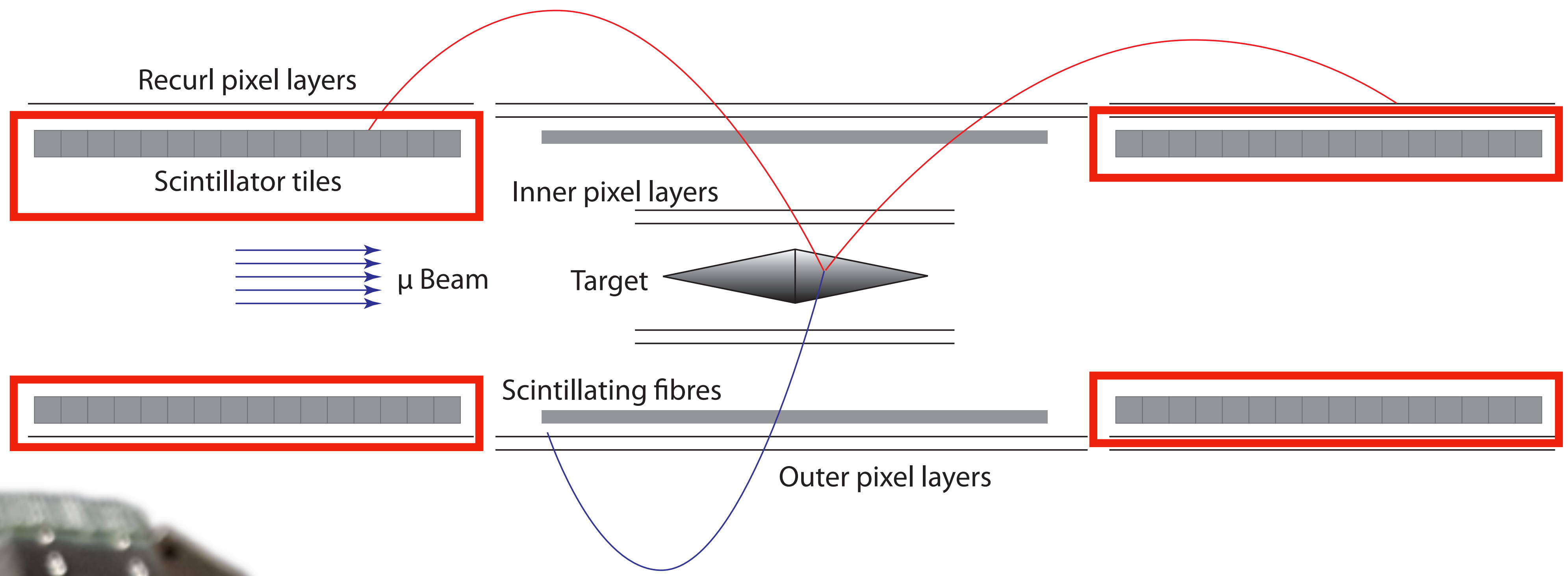
- Suppress combinatorial background and enable charge identification
  - 3 layers of 250 µm staggered fibres
  - 12 long fibre ribbons covering 4π
  - 1 ribbon = 720 *µm* thick, 0.2% X/X_0
  - 250 *ps* time resolution
  - Liquid cooling (SilOil, -20°) through the Cooling Ring (CR).
- Each ribbon has SiPM arrays at its ends and dedicated ASIC
- 256 channels per ribbon, 3072 for SciFi

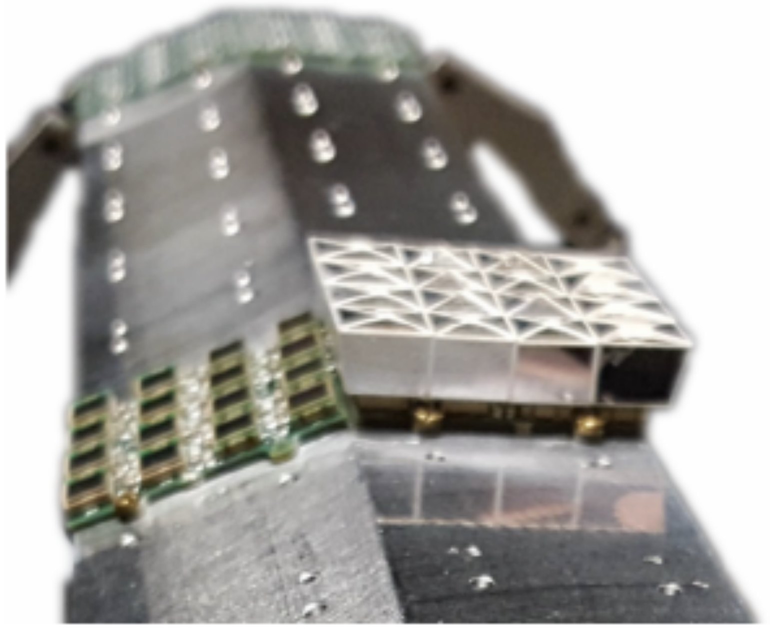


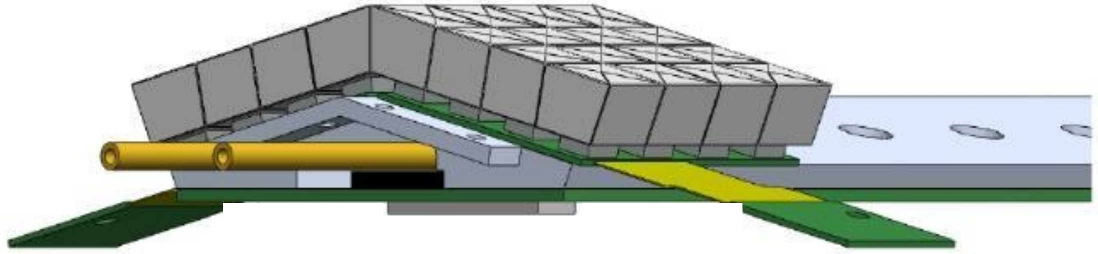




Time Sensor: Sci Tiles

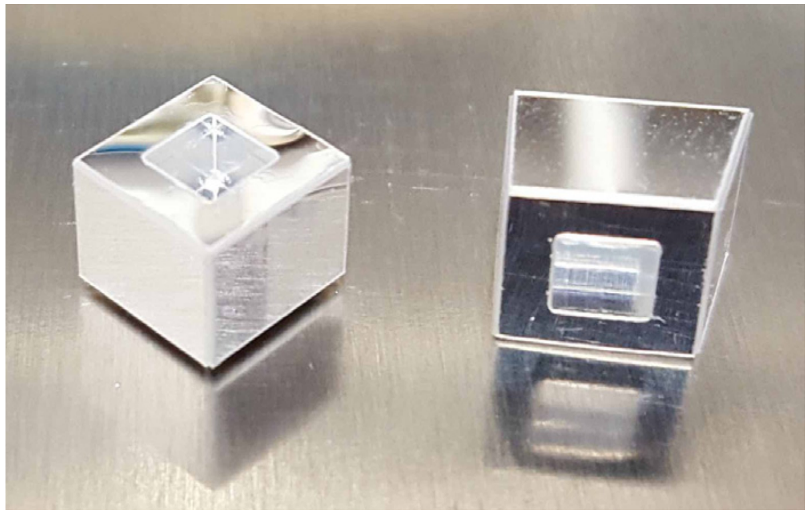


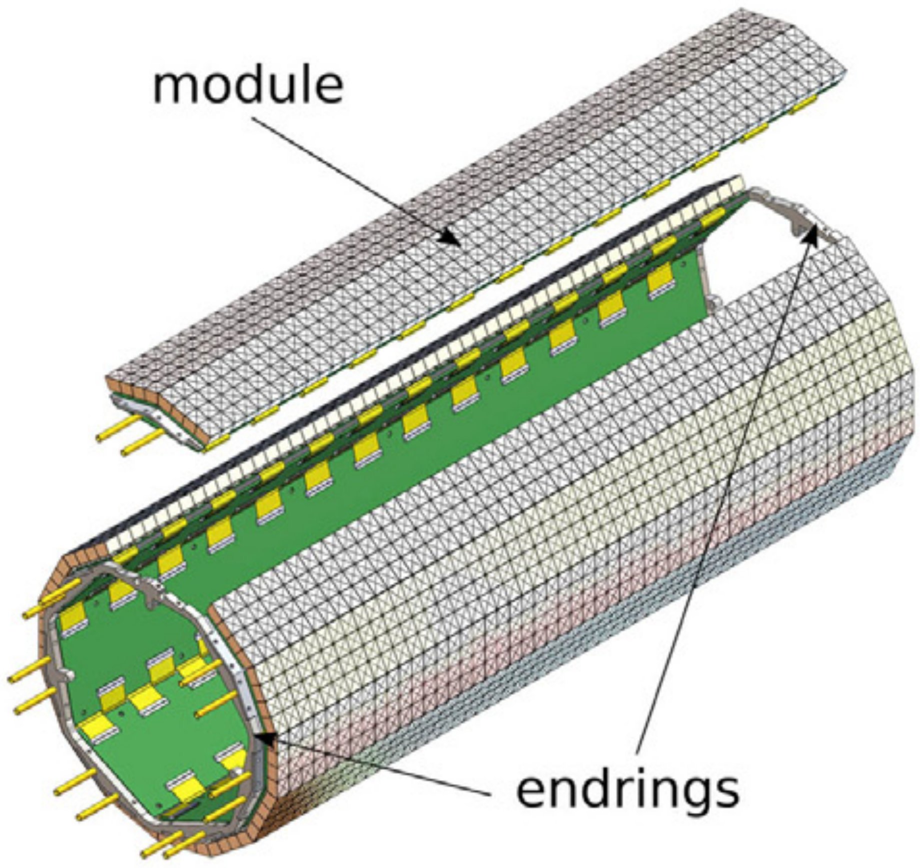


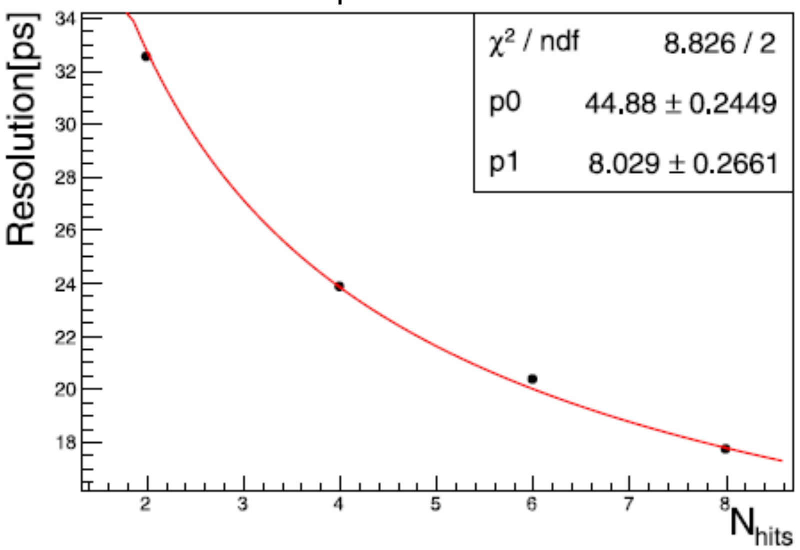


Time Sensor: Sci Tiles

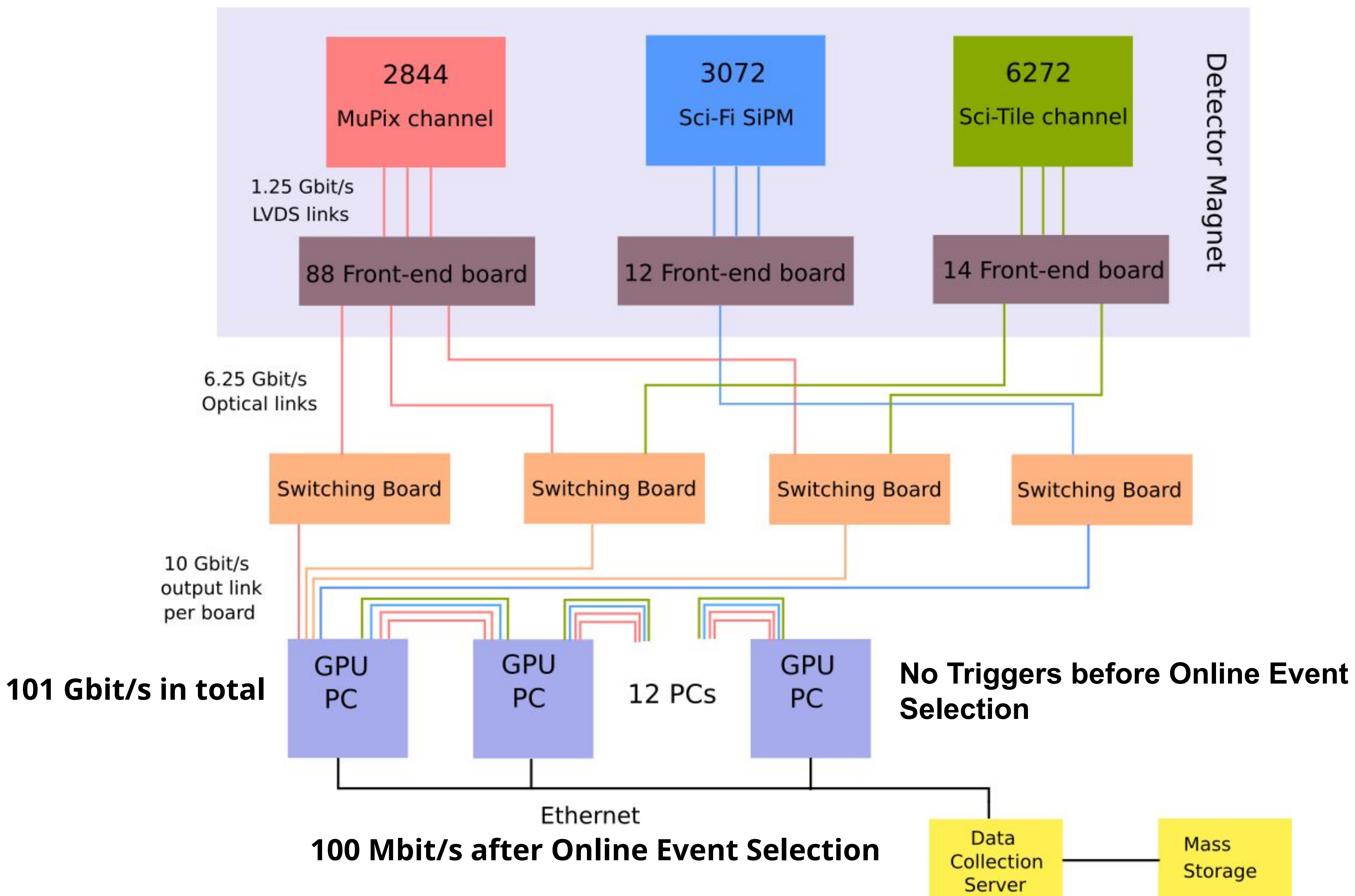
- No tight space constraints on detector volume
  - Cylindric, at recurling stations, internally to the outer pixel detector
  - Highly segmented (6 x 6 x 5 *mm*^{3}) in ~6k tiles
  - Individually wrapped in ESR foil to minimize crosstalk
  - Efficiency > 99%, time resolution ~40 *ps*
- Readout with SiPM and dedicated ASIC
- Extensively tested in demonstrator modules
- First final modules produced







Data Acquisition System



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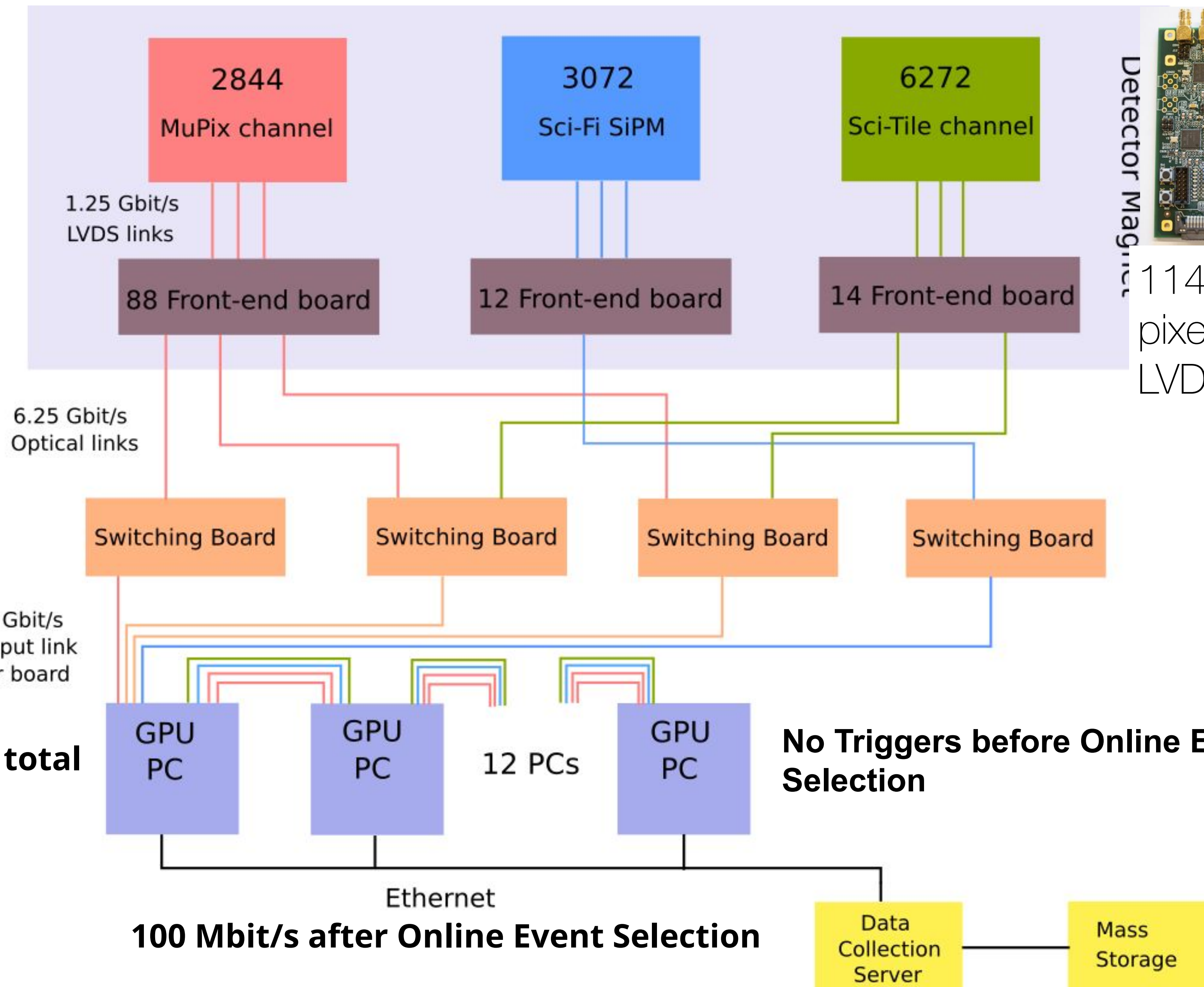
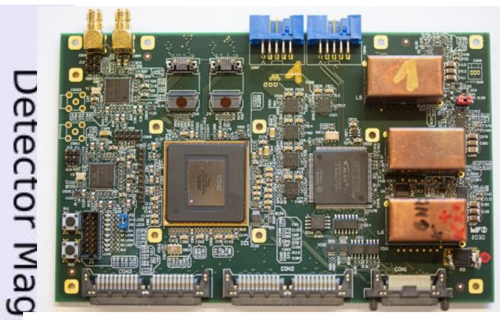




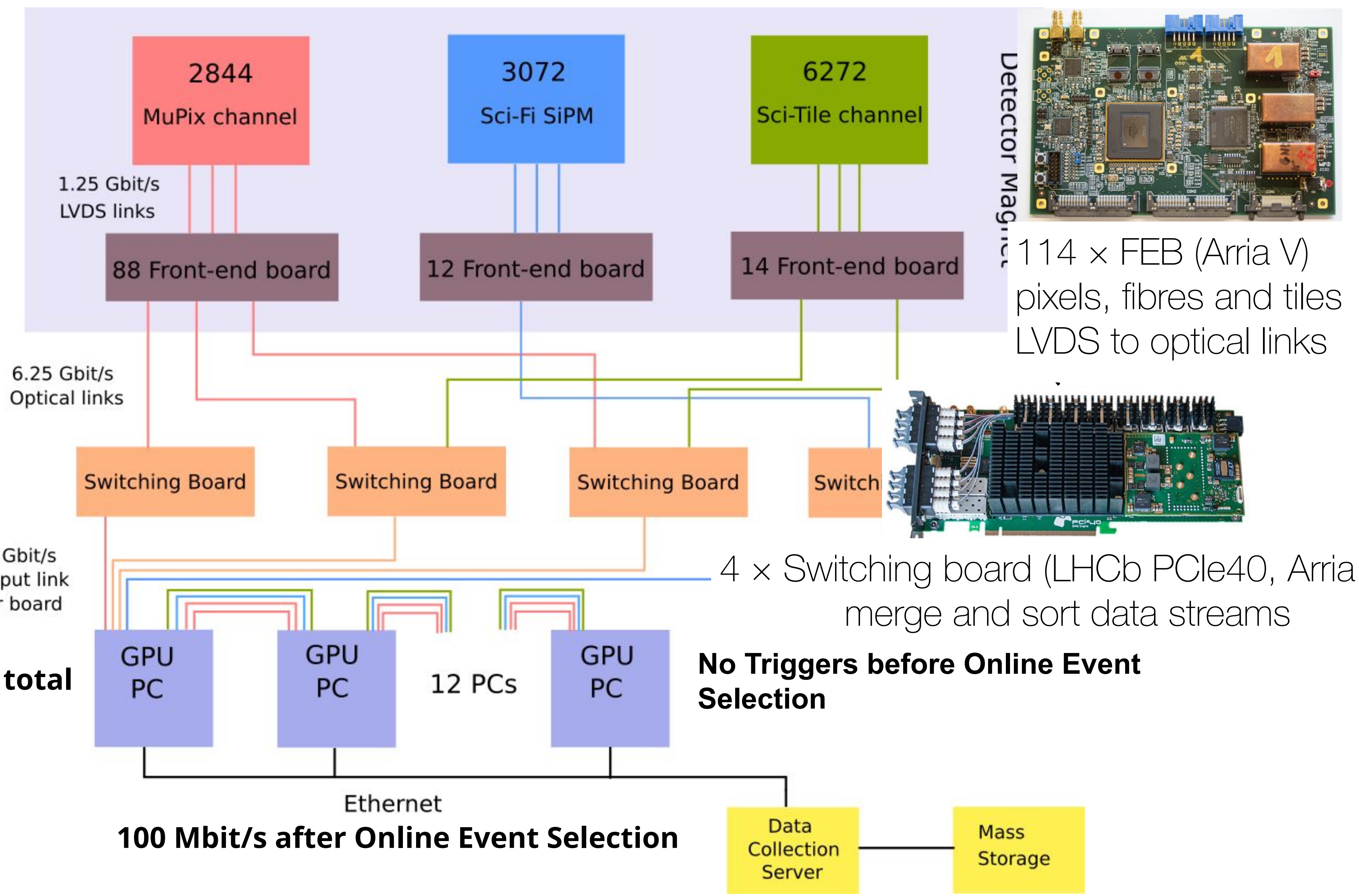
114 × FEB (Arria V)
pixels, fibres and tiles
LVDS to optical links

101 Gbit/s in total

No Triggers before Online Event Selection

100 Mbit/s after Online Event Selection

Data Acquisition System



114 × FEB (Arria V)
pixels, fibres and tiles
LVDS to optical links

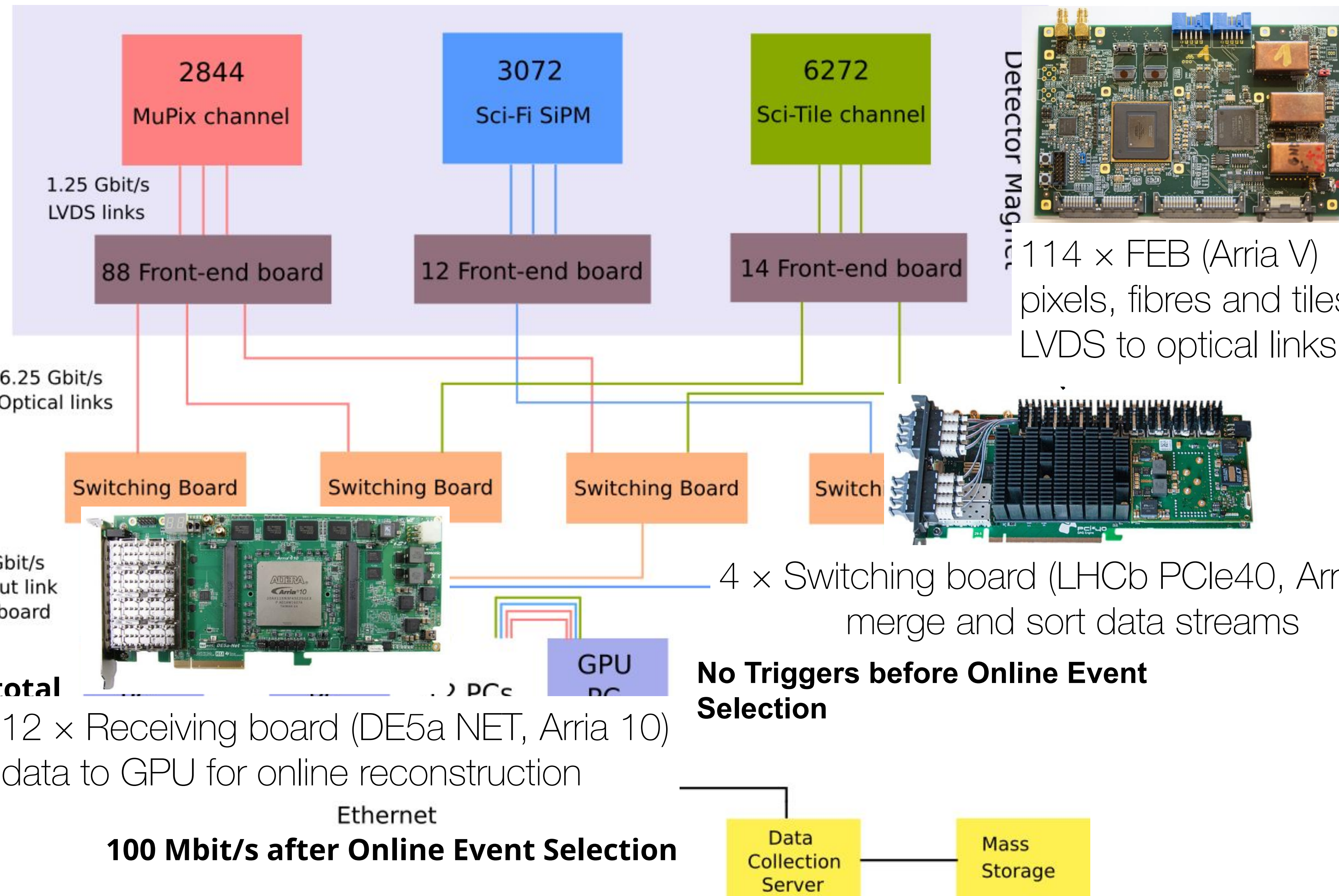
4 × Switching board (LHCb PCIe40, Arria 10)
merge and sort data streams

101 Gbit/s in total

No Triggers before Online Event Selection

100 Mbit/s after Online Event Selection

Data Acquisition System



114 × FEB (Arria V)
pixels, fibres and tiles
LVDS to optical links

4 × Switching board (LHCb PCIe40, Arria 10)
merge and sort data streams

No Triggers before Online Event Selection

101 Gbit/s in total

Chain of 12 × Receiving board (DE5a NET, Arria 10)
Transfer data to GPU for online reconstruction

100 Mbit/s after Online Event Selection

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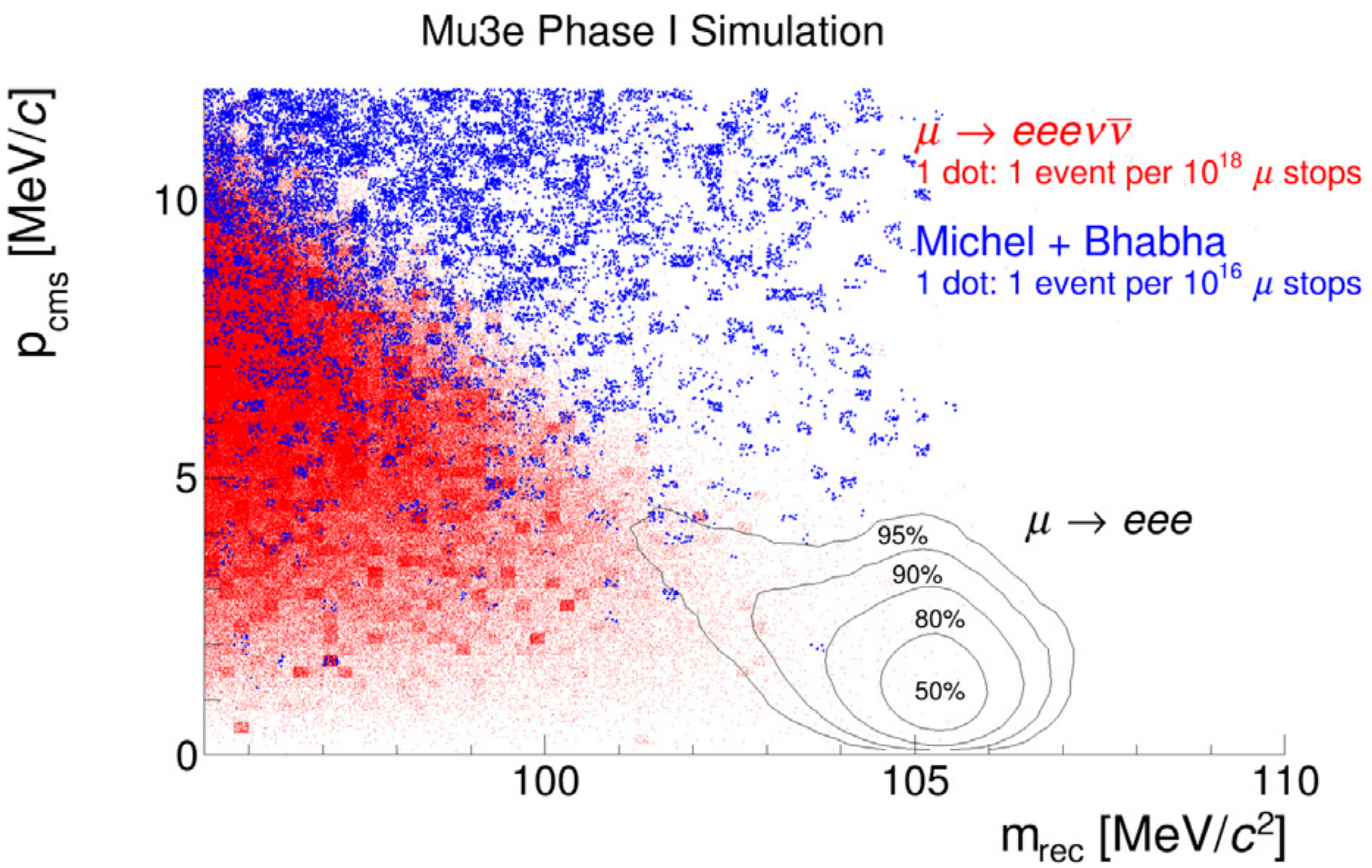
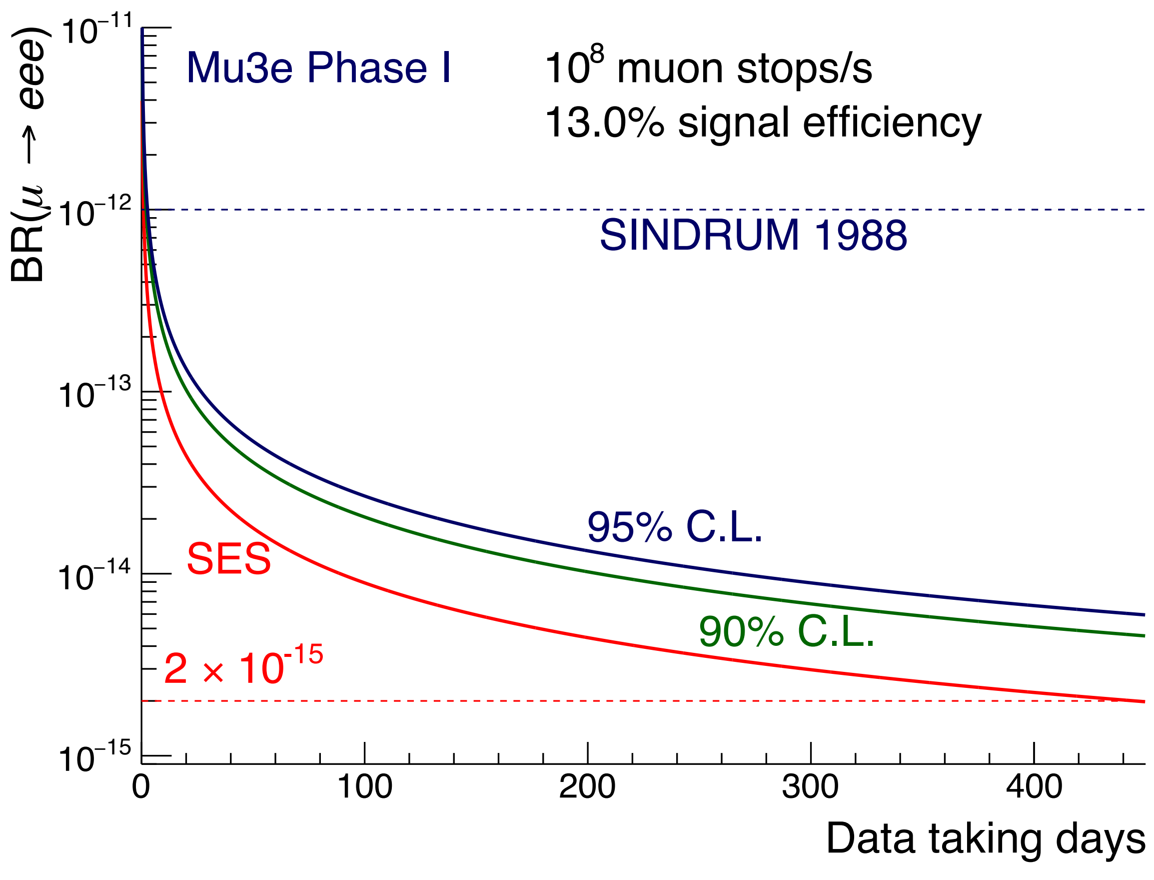
Hofstadter's Law:

It always takes longer than you expect,
even when you take into account Hofstadter's Law

Mu3e Physics reach

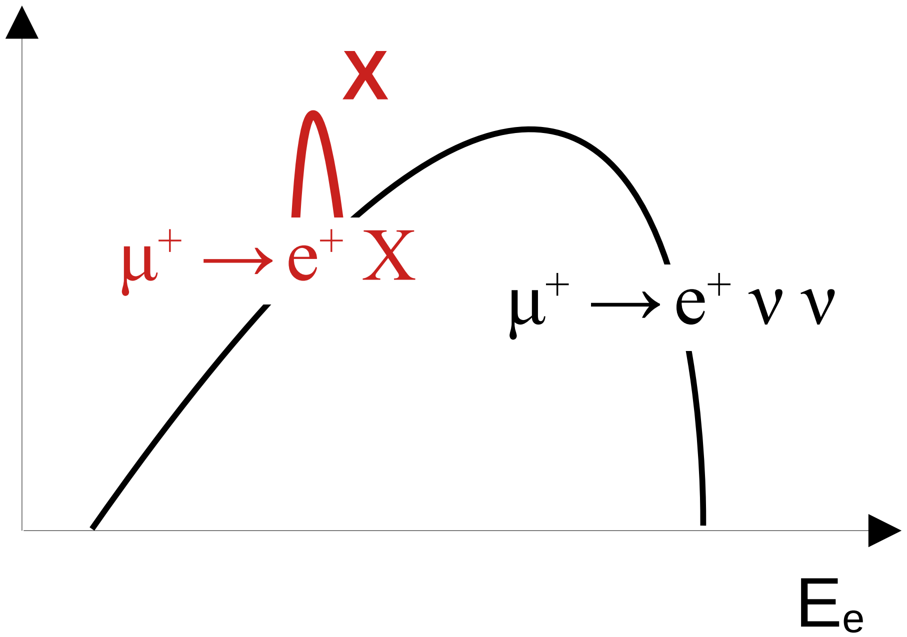
- Mu3e Phase I: $B(\mu \rightarrow eee) \leq 2 \times 10^{-15}$ (90% *CL*)
- Simulated full Phase I data taking:
  - Background-free measurement for > 2.5×10^{15} muon stops
  - ~300 days of continuous running at 1×10^{8} *μ/s*





Other Ideas for Mu3e Physics

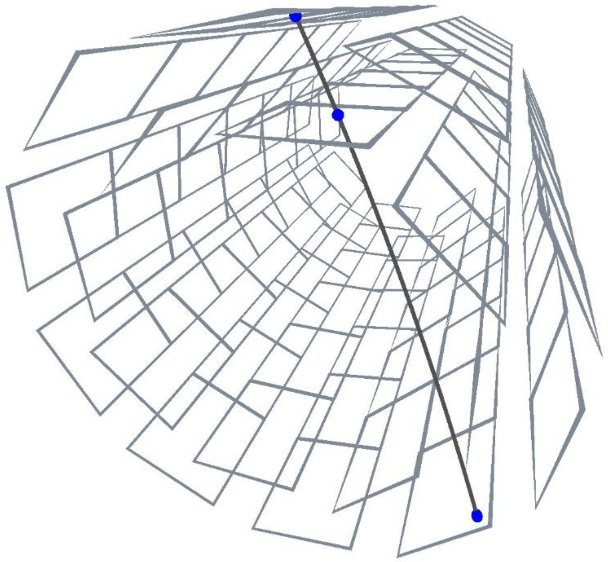
- Search for light cLFV particles: $\mu \to eX$
  - X invisible → peak in Michel spectrum
  - $X \to ee$ at displaced vertex or $\mu \to eee$ signature
    - special search strategy and upgrade of online filter farm

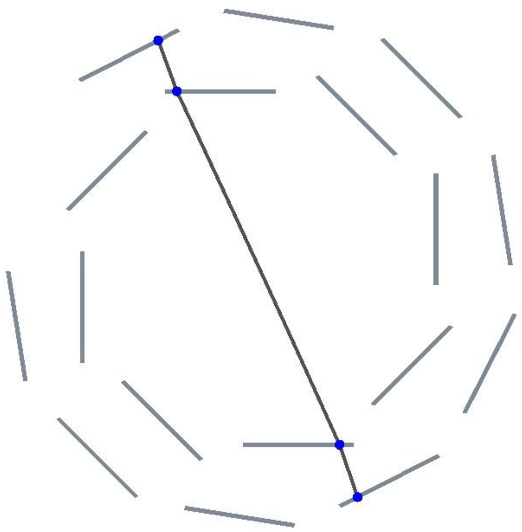


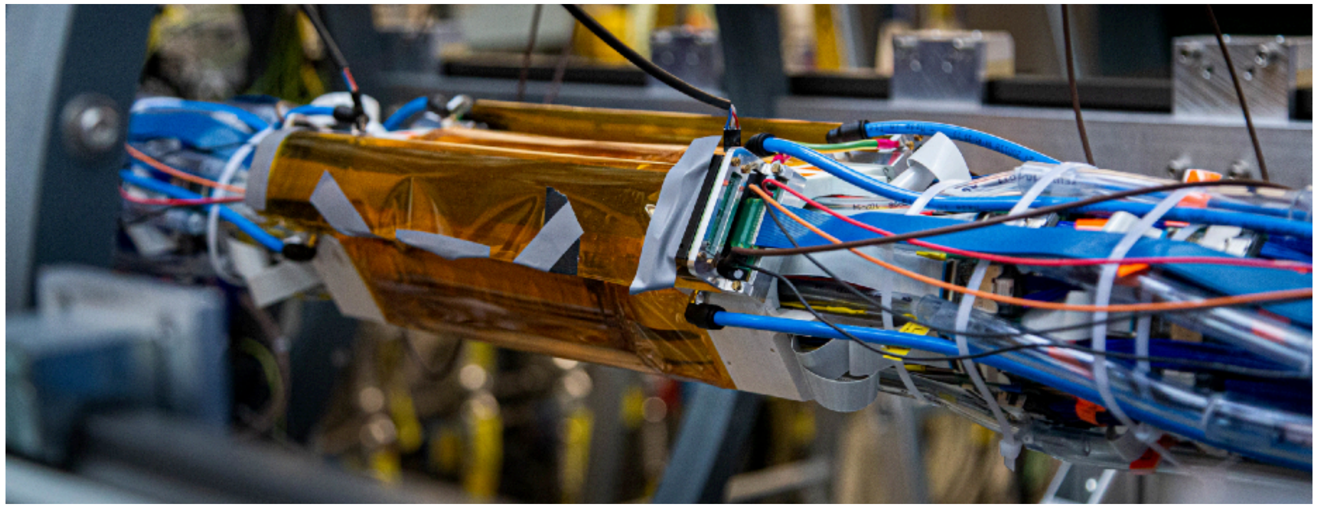
- Search for dark photons: $\mu \to e\nu\nu A'$
  - A' invisible → no chance for detection
  - $A' \to ee$ at displaced vertex or peak in the ee inv. mass spectrum of $\mu \to eee\nu\nu$ events
- Search for cLFV in: $\mu \to e\gamma$
  - Mu3e is a tracking detector and is able to detect converted photons $\gamma \to ee$ using dedicated converter layers
  - "Beyond Phase II"

Mu3e Integration

- 2021-2022 Detector Integration
  - Integration and cosmic runs (PSI, 2021/22), test beam campaigns, thermo-mechanical mock-ups…
  - Combined vertex-SciFi and vertex-SciTiles operation
  - Integration of services, cooling and DAQ
  - Hardware validation in magnet and beam
  - Reconstruction of cosmic tracks, recurl electrons, sub-detector correlations,…

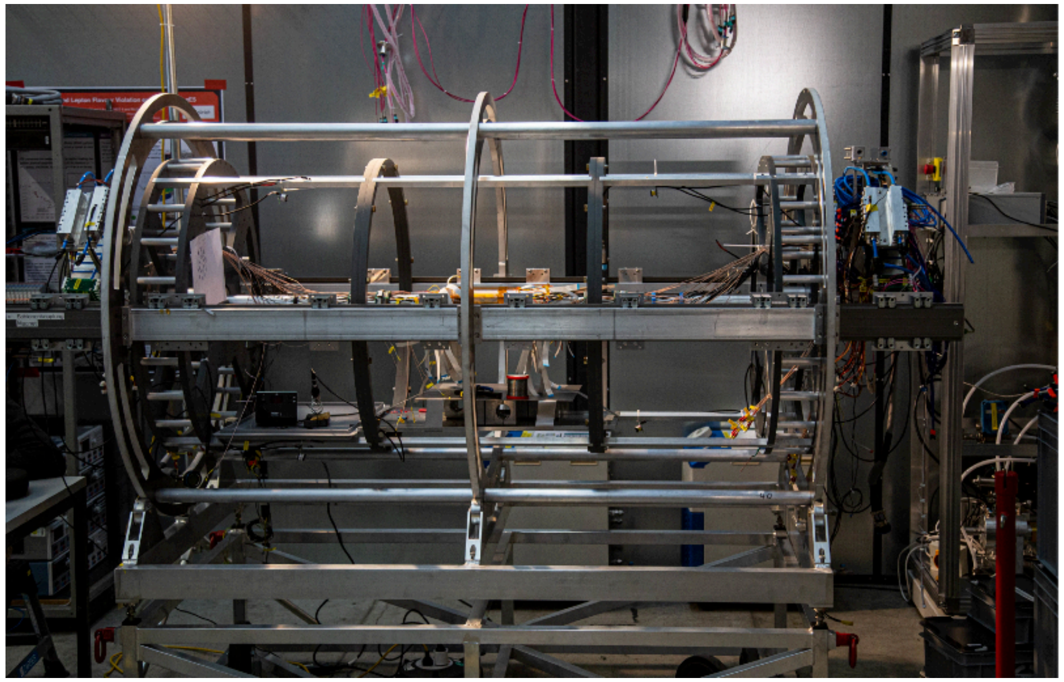


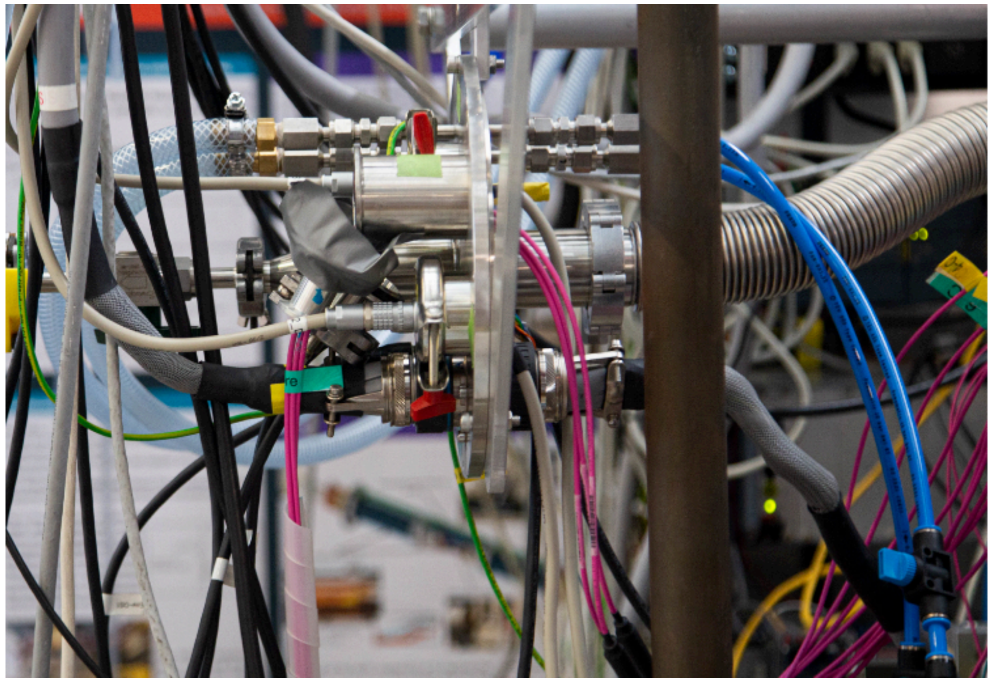




Mu3e Construction

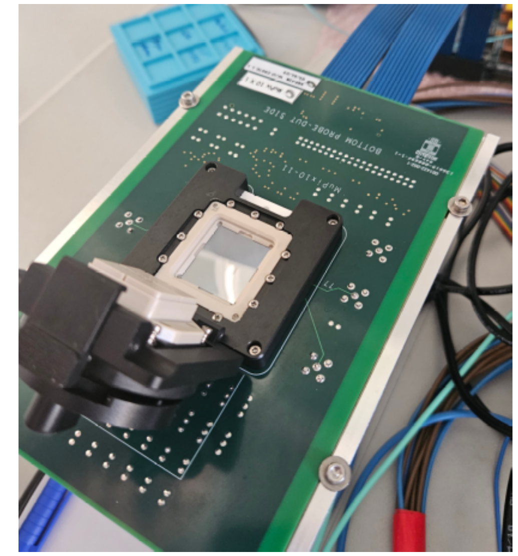
- 2022-2023 Detector development
  - Operational MuPix11 sensor, validation of MuTRiG3
  - Integration of pixel, tile and SciFi readout with final hardware
- 2022-2023 Detector construction
  - Phase I detector construction has started
  - Permanent staging area at PSI for installation
  - Consolidating production and QC pipelines

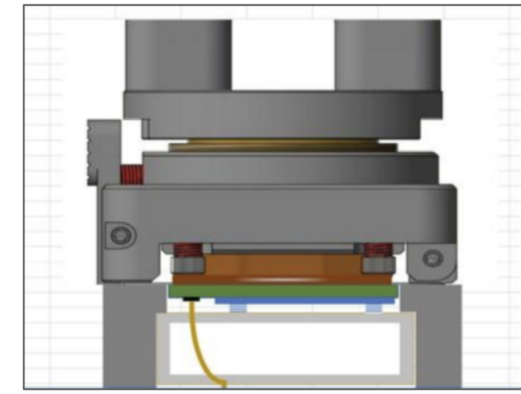




Mu3e itinerary (2024)

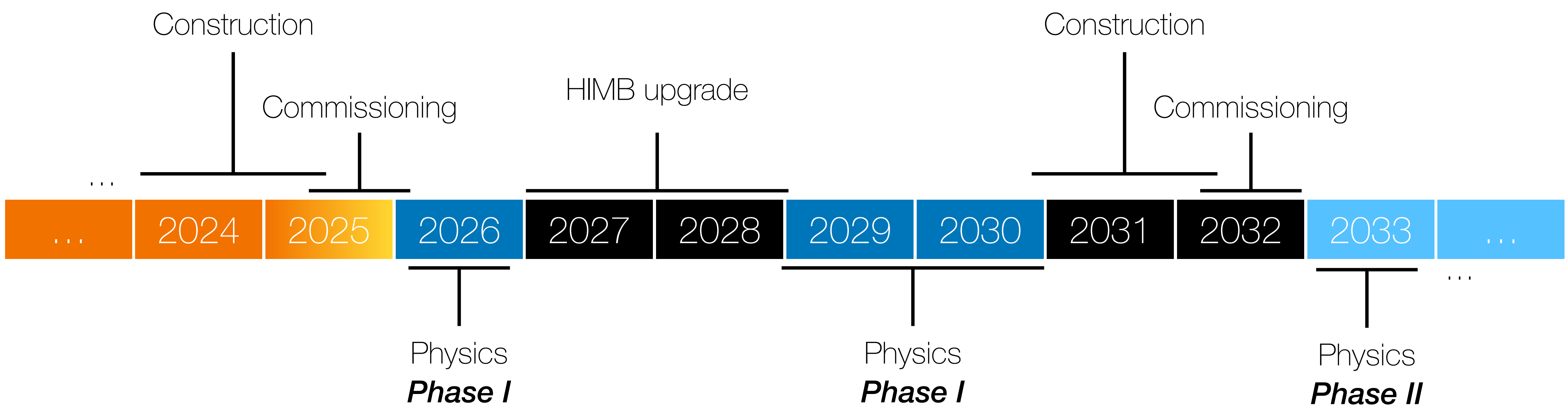
- MuPix
  - After 11 year R&D period over…
  - Inner pixels installation in progress
  - Two layer vertex detector to be installed (end of the year)
  - Outer Pixel Modules
    - Active area in total 1.2 m^2 (~3000 sensors)
    - All individual MuPix to be qualified ~10000 sensors to be tested





- SciFi and Tile
  - Mid 2024: Integration of one station into the experiment
- DAQ
  - operational with different detector types
- Helium gas cooling installed
- Cosmic Run with final 2 layer detector (end of 2024)

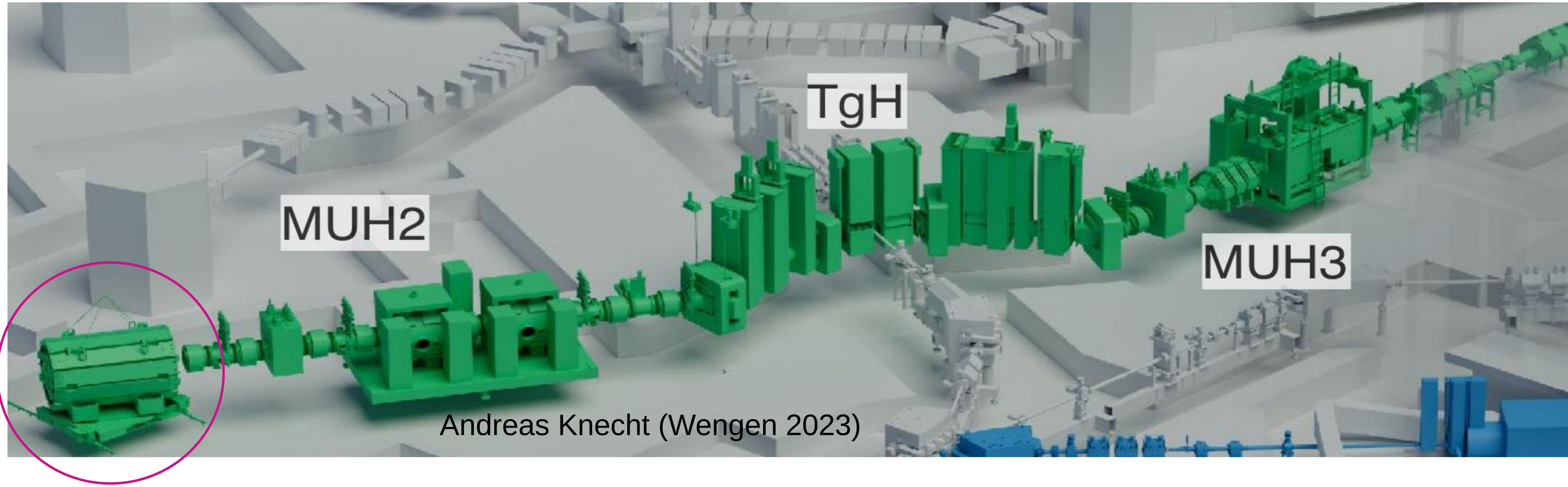
Mu3e Phase I → Phase II



Phase	$B(\mu \to eee)$	Beam-line
I	$< 2 \times 10^{-15}$	10^8 μ/s (PiE5)
II	$< 10^{-16}$	2×10^9 μ/s (HIMB)

High Intensity Muon Beam-line (HIMB)

2027-2028



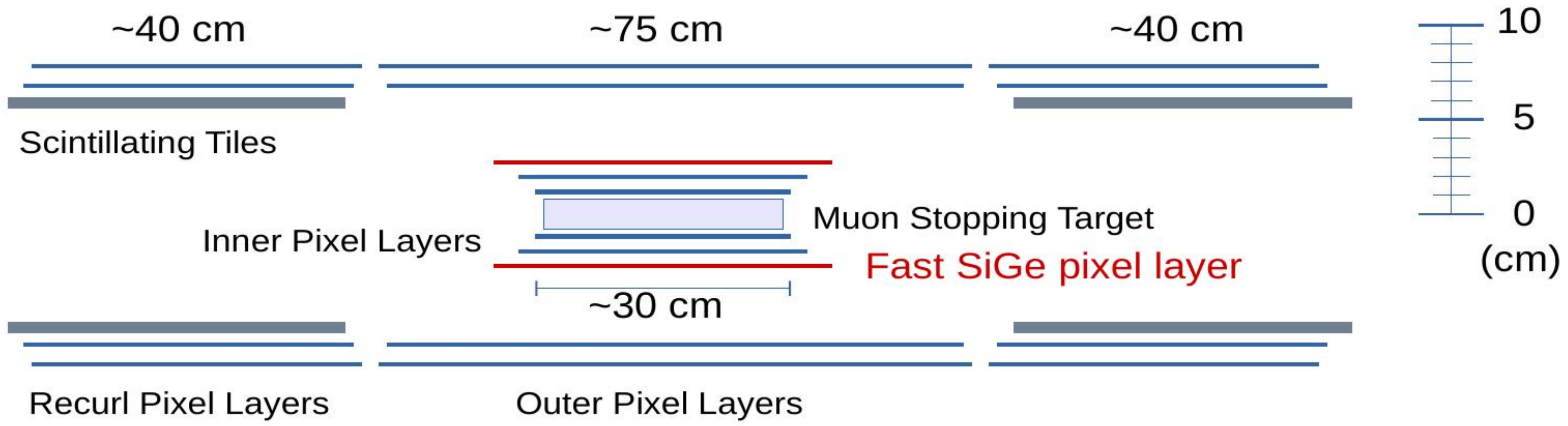
Mu3e

Main user (particle Physics) will be Mu3e

~20 times higher muon stopping rate ⇒ Mu3e Phase II

accidental background will increase by factor 400 = 20^2

Sketch of Mu3e Phase II



- Longer stopping target to reduce accidentals: 10 $cm \Rightarrow$ 30 cm
- Thinner and smaller vertex detector to improve pointing resolution
- Longer pixel detector modules to match longer muon stopping target
- SciFi timing detector replaced with Ultra Fast Silicon Pixel Detector (UFSPD)
- Increase readout bandwidth at front end
- Increase magnetic field from B = 1 T to B = 2 T (option) to increase resolution and acceptance

Summary & Outlook

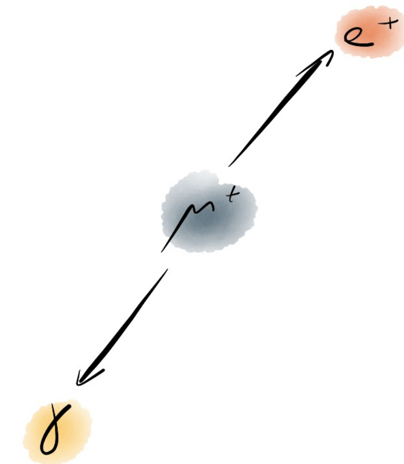
- Mu3e will search for the cLFV decay $\mu \rightarrow eee$ with a sensitivity of 10^{-16}
- It faces many technical challenges: compact design, low material budget, fine granularity, high rates
- …with innovative technologies: HV-MAPS, gaseous helium cooling, MuTRiG readout, GPUs…
- We are now in commissioning phase:
- Mu3e Phase I detector will be completed in 2025 (optimistically) and ready for data taking in 2026 → S.E.S. ~10^{-15}
- … Detector and beam upgrades are expected in 2033

Back up

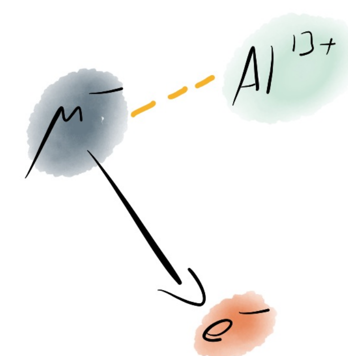
Charged Lepton Flavour Violation

Muons lead the search

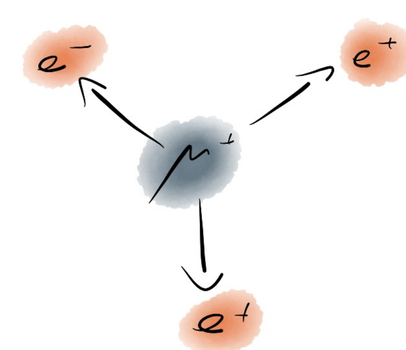
- $\mu^+ \rightarrow e^+\gamma$ MEG (PSI) ➞ MEG II
  B($\mu^+ \rightarrow e^+\gamma$) < 3.1 x 10^{-13} (2024)



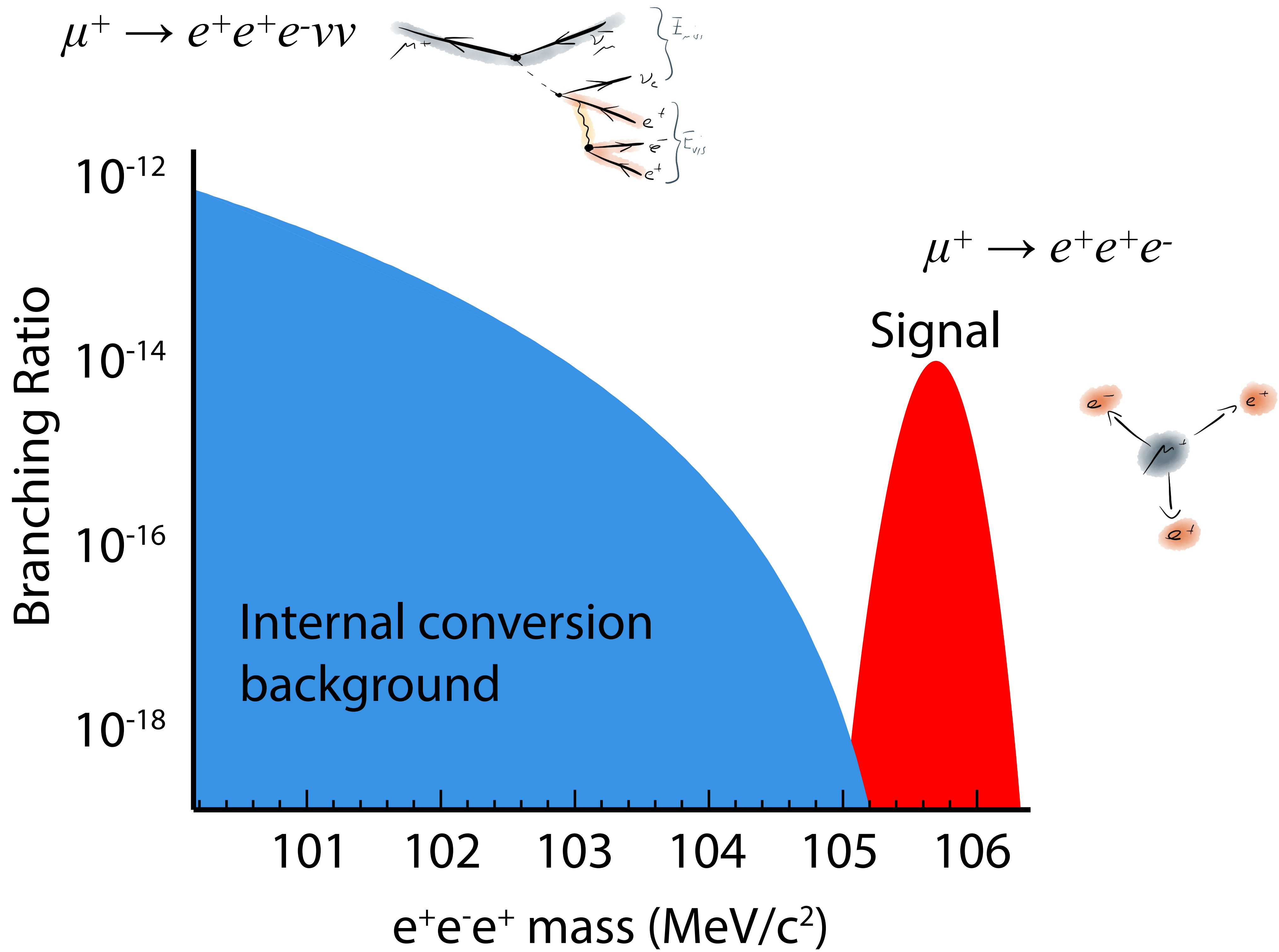
- $\mu^- N \rightarrow e^- N$ SINDRUM II (PSI) ➞ Mu2e/Comet
  B($\mu^- Au \rightarrow e^- Au$) < 7 x 10^{-13} (2006)



- $\mu^+ \rightarrow e^+e^+e^-$ SINDRUM I (PSI) ➞ Mu3e
  B($\mu^+ \rightarrow e^+e^+e^-$) < 1.0 x 10^{-12} (1988)

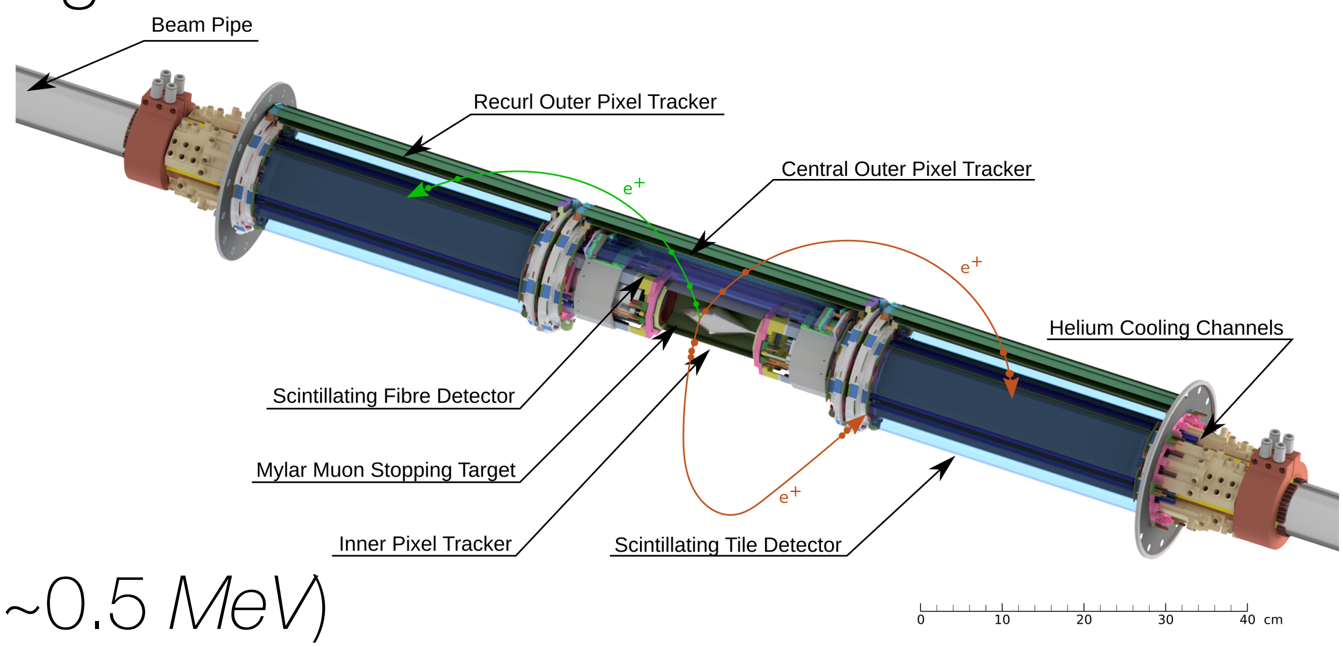


Signal vs. Internal Conversion



Mu3e

- High muon rates (10^8 μ/s)
  - high granularity and fast processing
- Compact design
  - high integration level (sensors, readout ASICs)
- Internal conversion
  - excellent momentum resolution (~0.5 *MeV*)
- Accidental background
  - good timing (~100 *ps*) and vertex resolution (~0.2 *mm*)
- Low energy electrons
  - low material budget and recurl tracking stations



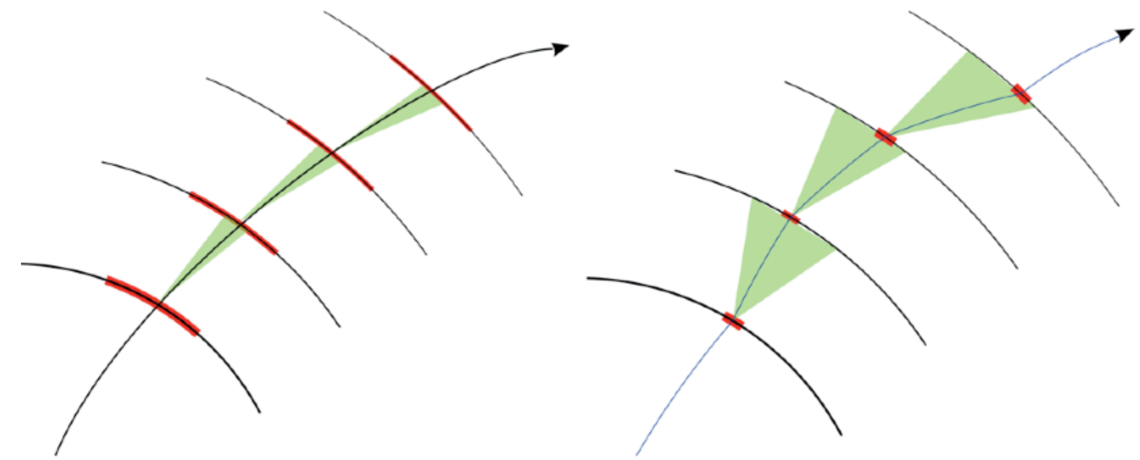
Momentum measurement

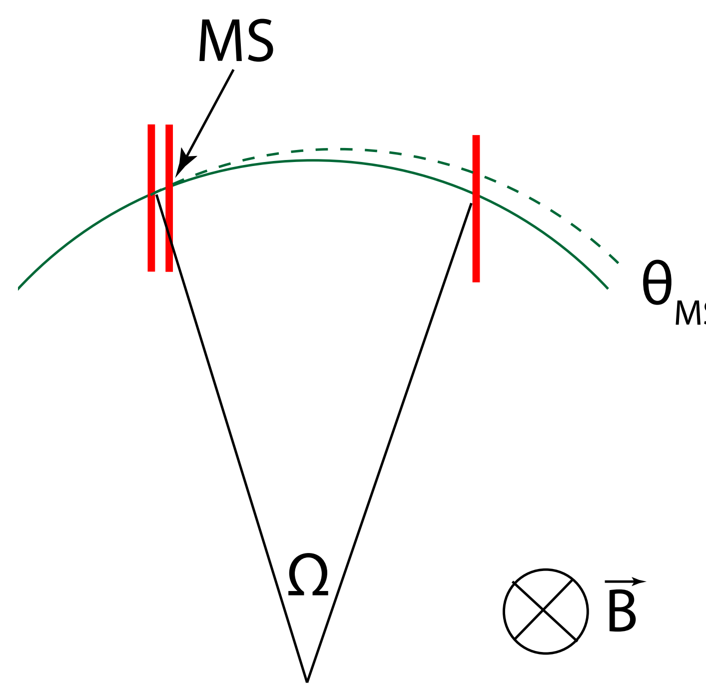
and multiple scattering

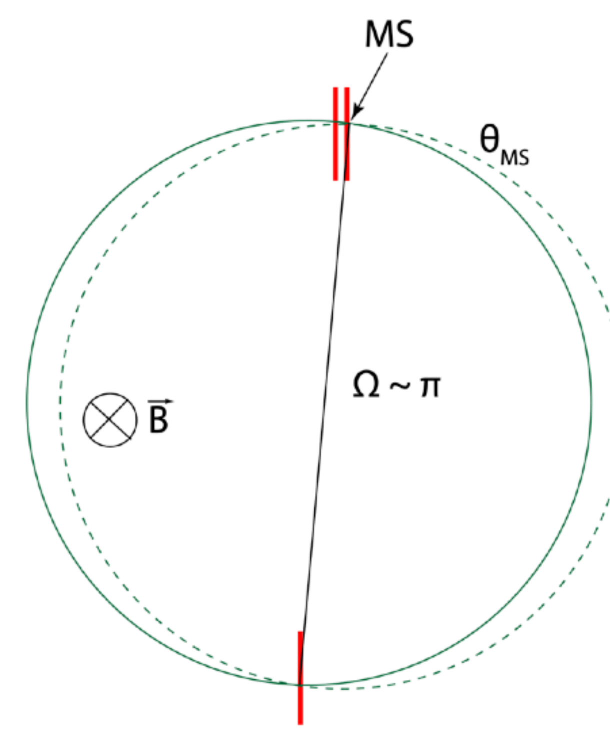
- Muon decays at rest into **low energy** electrons and positrons (<53 MeV)
- Apply strong magnetic field (**1T**) and measure the curvature of the particles
- Momentum resolution in the low energy regime is dominated by **multiple scattering**, not detector resolution
- At first order:

$$\frac{\sigma_{\mathrm{p}}}{\mathrm{p}} \sim \frac{\theta_{\mathrm{MS}}}{\Omega}$$

- Recover momentum resolution:
  - Low **material** budget
  - Large lever arm (**recurlers**)
  - Scattering in track **reconstruction**

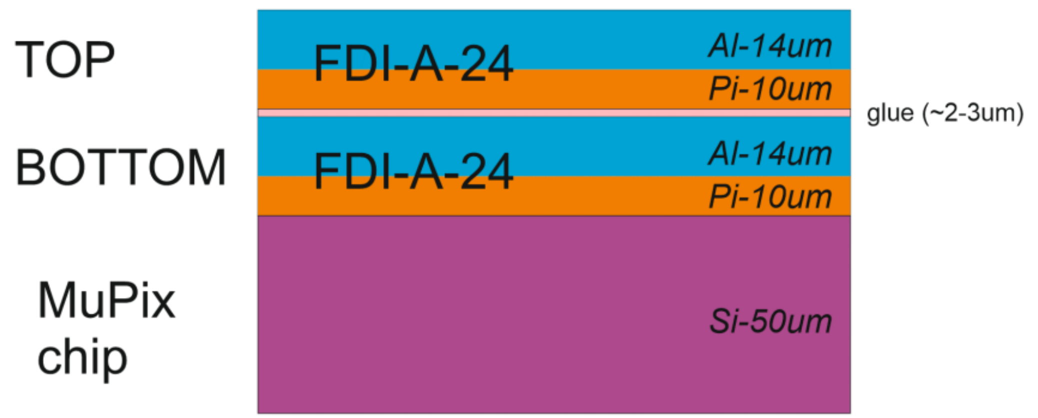






Tracking design

Mu3e low-material budget detector i.e., thickness X/Xo $\sim 0.115\%$ per layer.

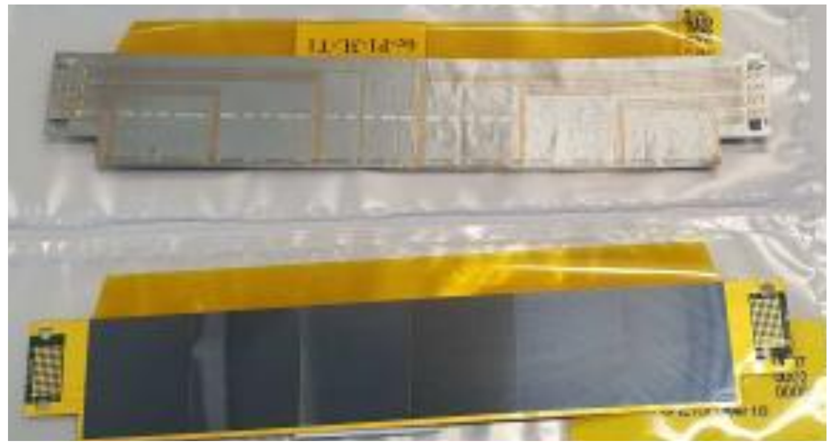


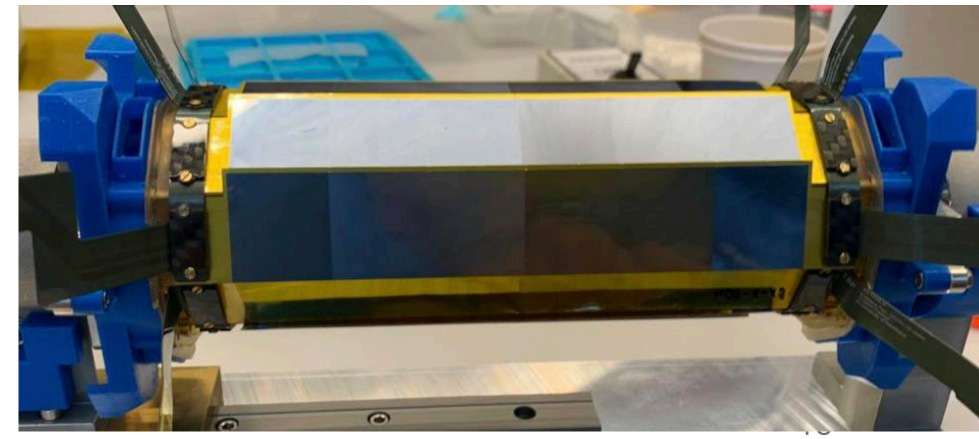
High-Voltage Monolithic Active Pixel Sensors MuPix
50μm thickness (or 0.054%X_o).

The High-Density Interconnect
Flex tape made of 2X14 μm Al layers.

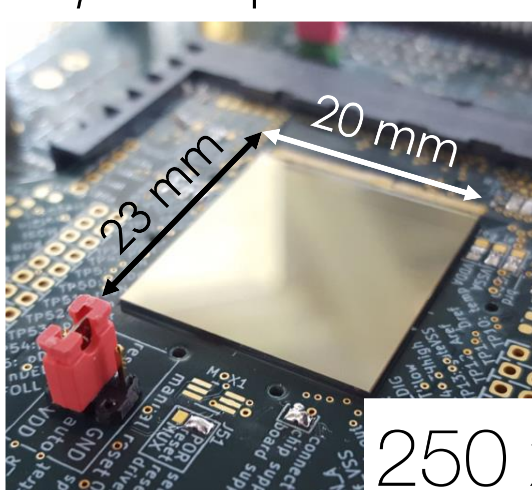
- **Mechanics**: the support of our detector ladder is a HDI flex thinner than a human hair.
- **Electronics**: high-density of traces in the HDI flex circuit (data lines, power, bias, for 18 chips).
- **HDI-production**: long fragile HDI flex, shrinking of the material, layers misalignment.
- **Tooling**: proper tooling for handling flex tapes and chips.

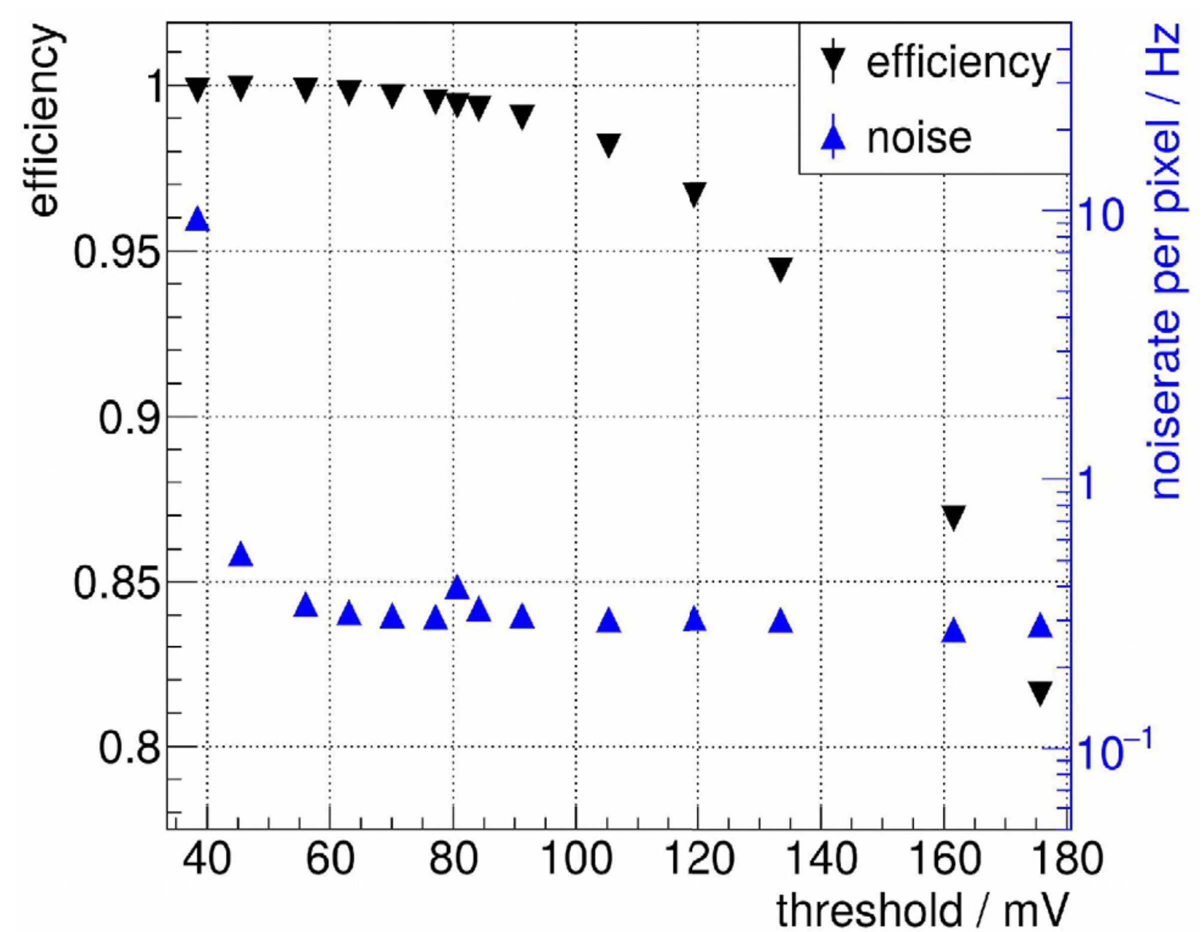
Pixel Detector: MuPix





- ~11 year R&D time… Final version (MuPix11) operational
- Developed a series of MuPix, extensively tested
  - Efficiency >99%,
    time resolution <20 *ns*
    ~23 *μm* spatial resolution





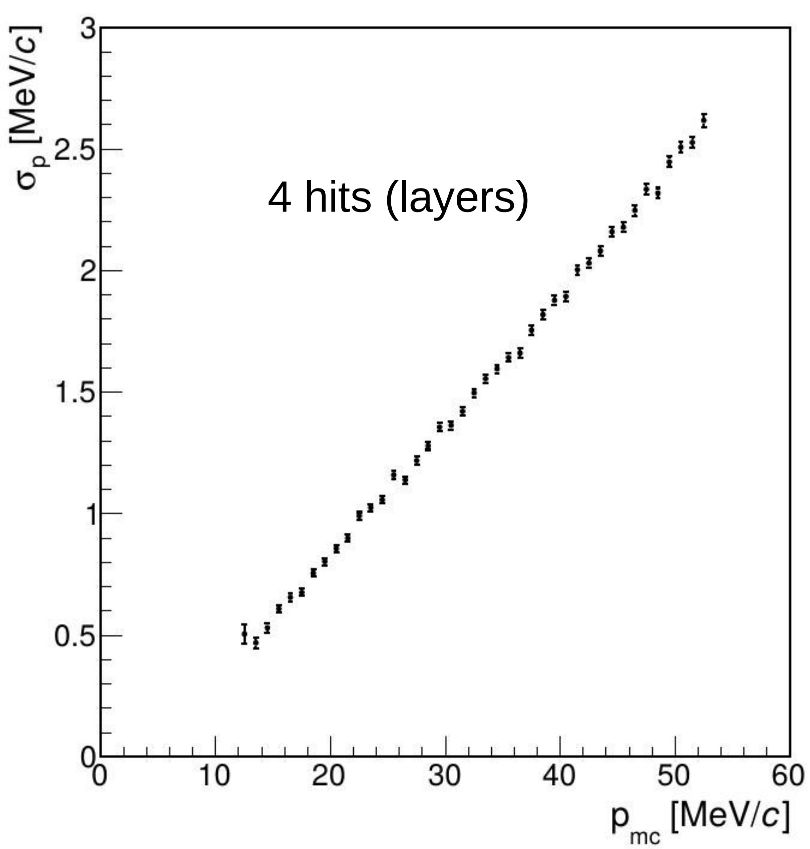
250 x 256 Pixels

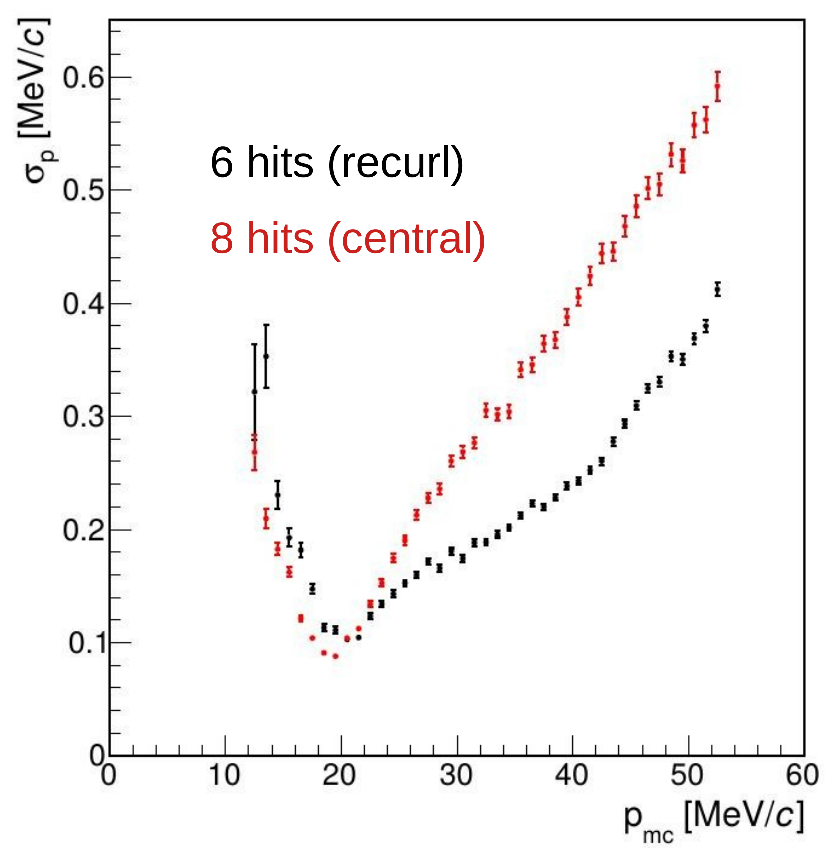
P. Beltrame, UoL - Mu3e Coll.

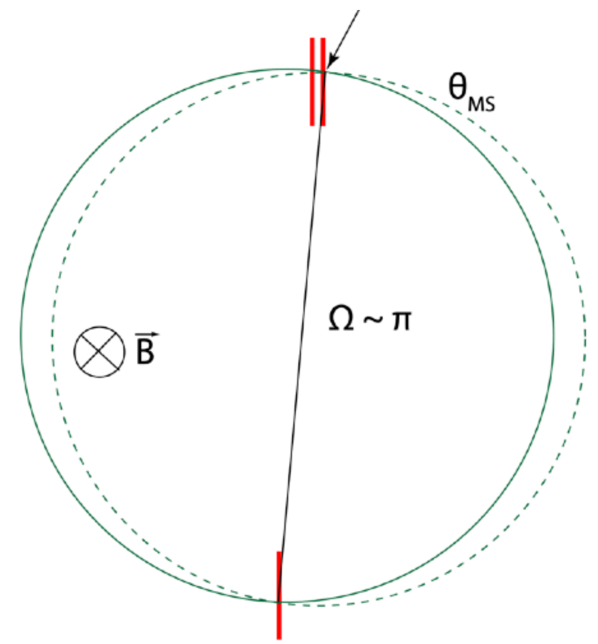
Mu3e Phase I

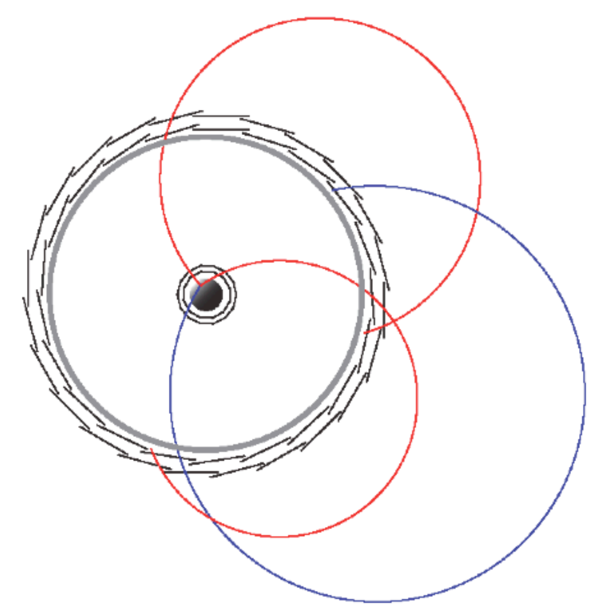
Momentum resolution

- Simulation of momentum resolution with Geant4
- Reconstruction of recurlers pays off
- Improvement in resolution up to a **factor 10**

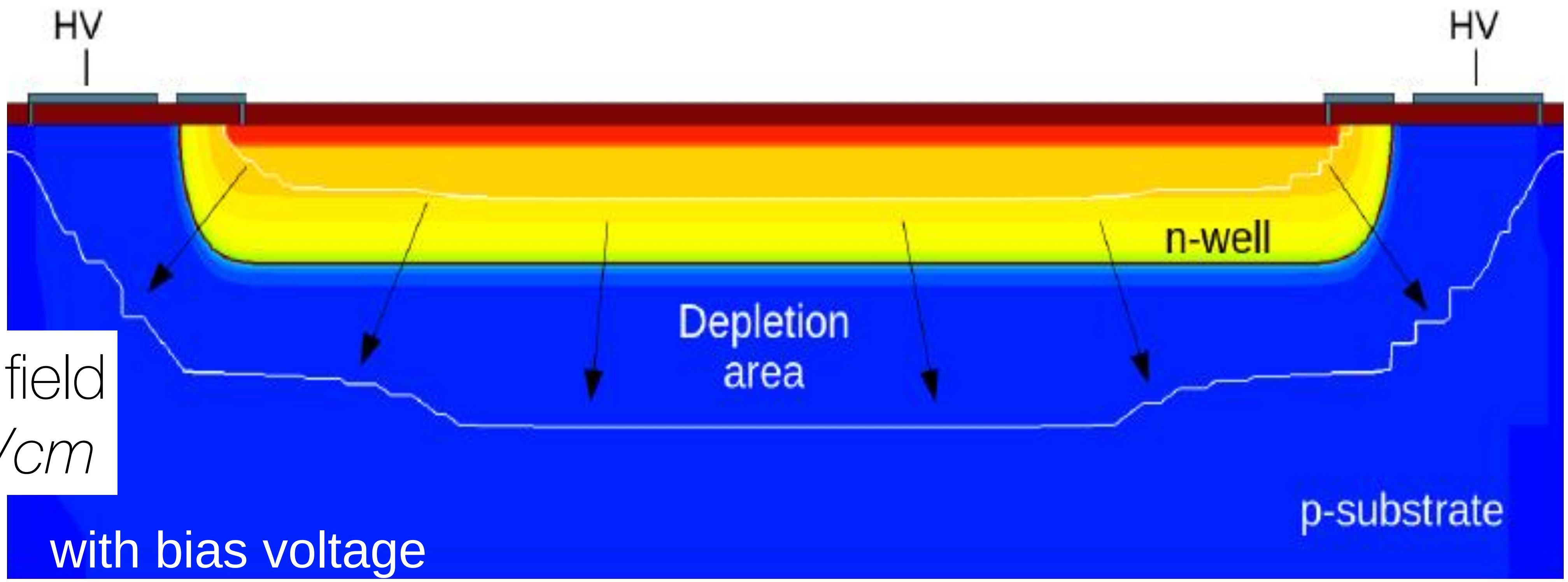








HV-MAPS Charge Collection



electrical field
up 10^5 *V/cm*

"depleted MAPS"

Depletion depth: $d \propto \sqrt{\rho \cdot U}$

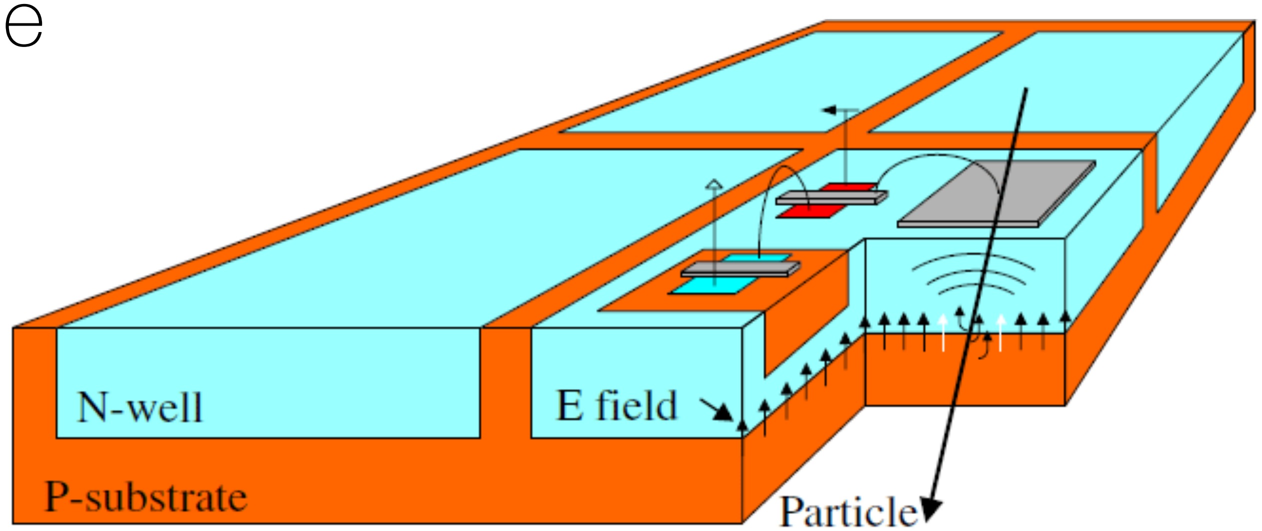
Electric field: $E \propto \sqrt{U/\rho}$

U = voltage

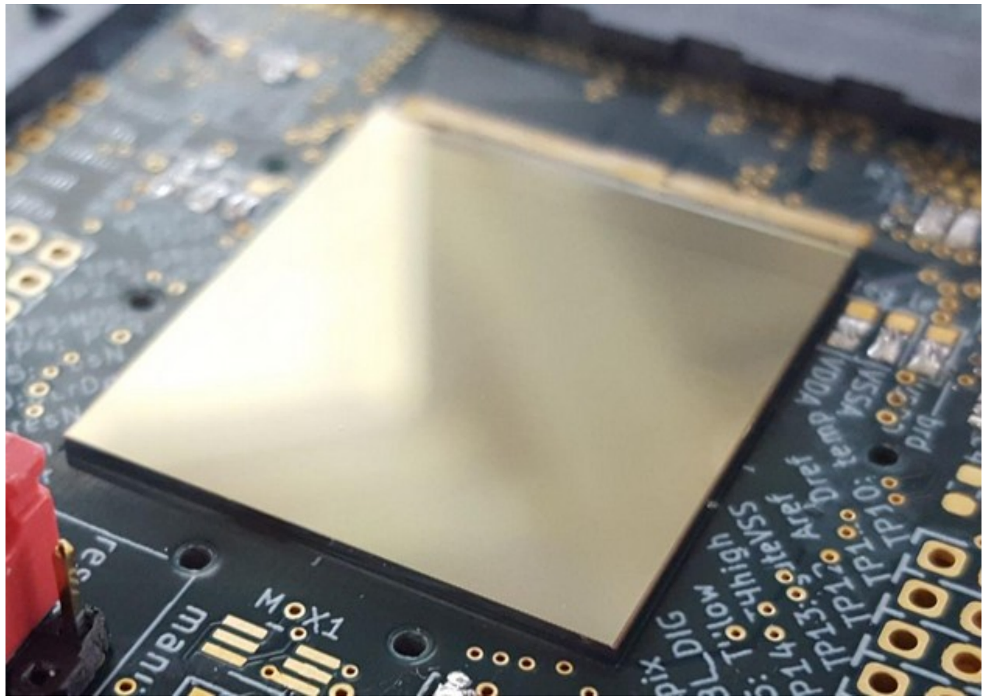
ρ = substrate resistivity

HV-MAPS

- Monolithic: Readout and active volume on same chip
- Characteristic:
  - Diode realised as deep n-well in p-substrate reversely biased up to -140 *V*
  - Fast charge collection via drift in depleted volume
  - $\vec{j} = qD\nabla n + qn\mu\vec{E}$
  - $\tau_{coll}^{-1} = \tau_{diff}^{-1} + \tau_{drift}^{-1}$
    - Fast charge in depleted volume collected via drift
    - Diffusion in non depleted volume

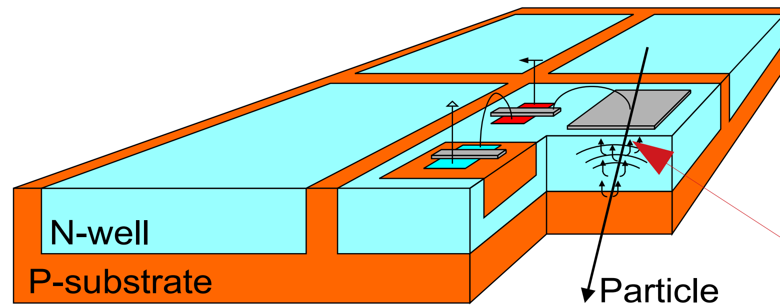


High Voltage-Monolithic Active Pixel Sensors



High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)

I.Peric, et al., NIM A 582 (2007) 876



transistor logic embedded in N-well ("smart diode array")

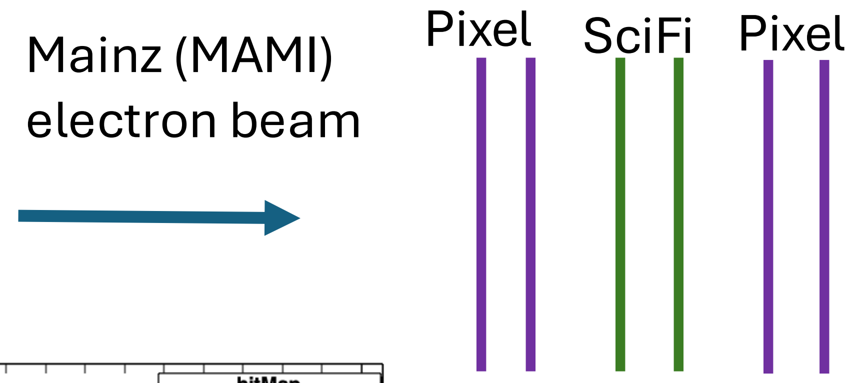
charge collection by drift!

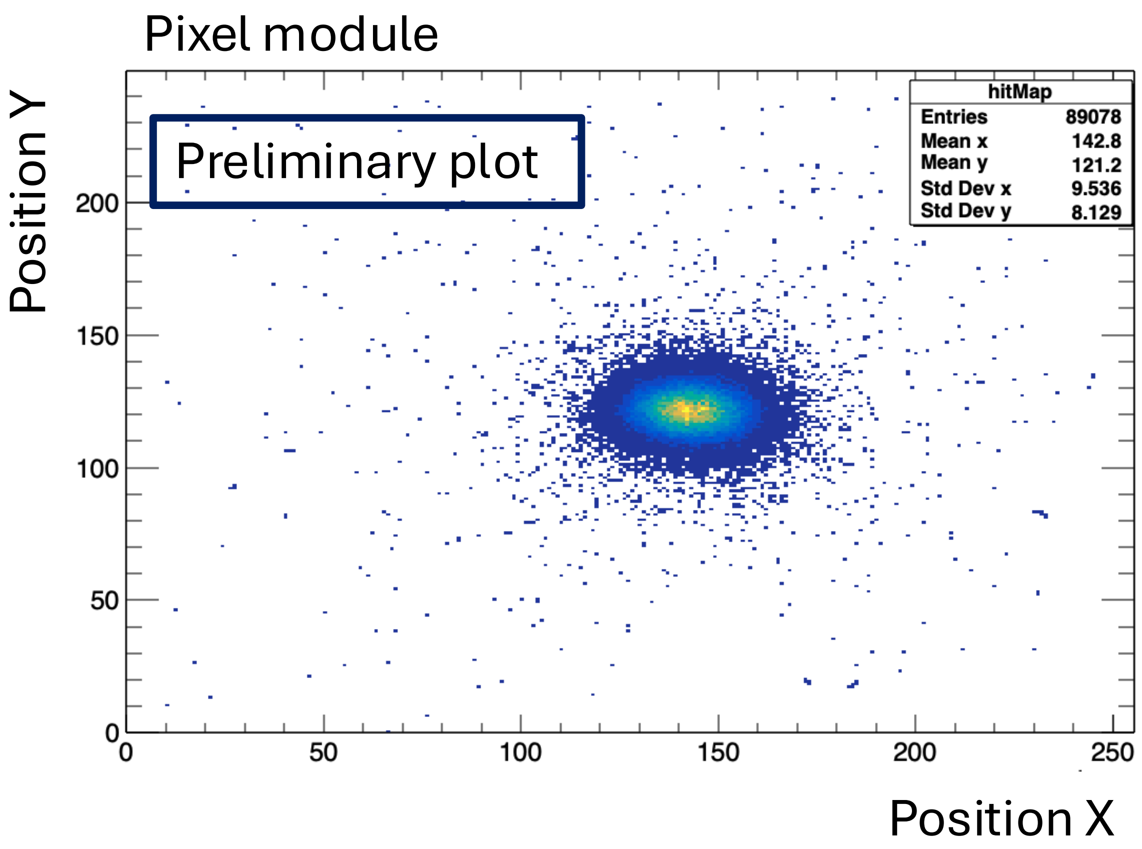
active sensor → hit finding & digitisation & zero suppression & readout

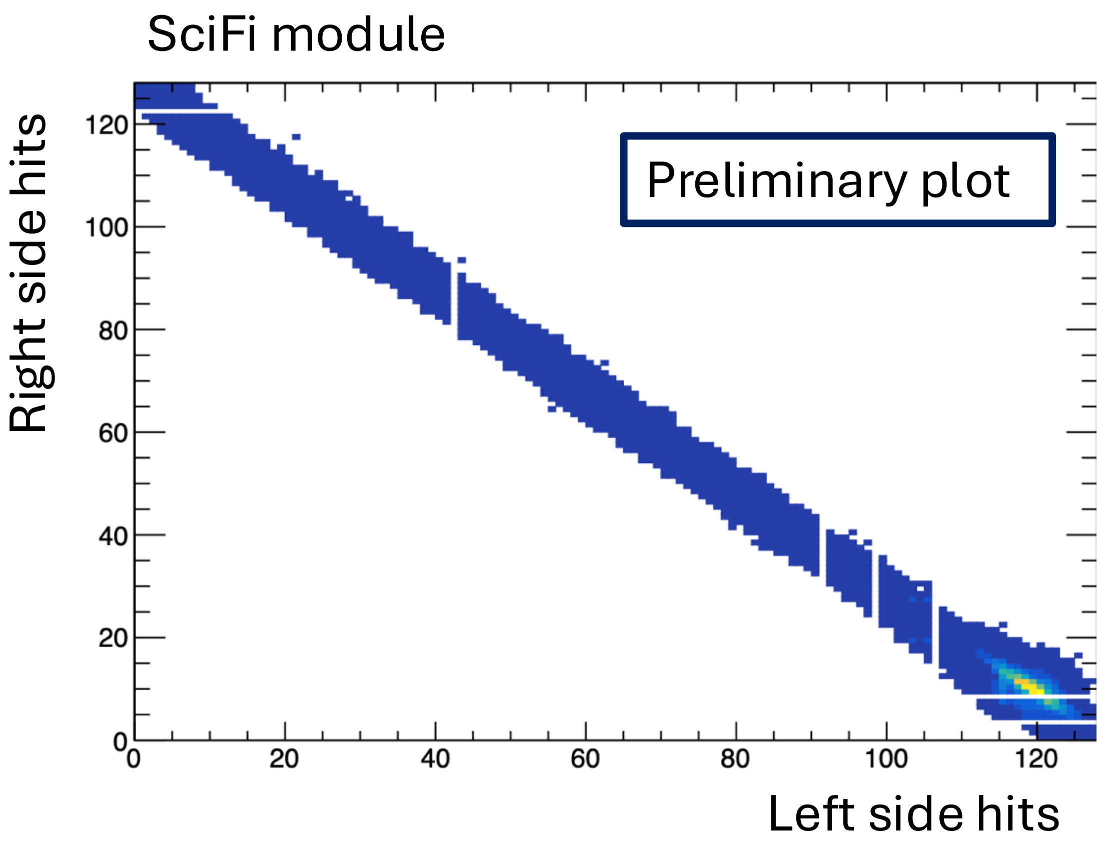
- low noise O(75-100e^-) → low threshold
- small depletion region of ≤ 30 μm → thin sensor ~50 μm
- HV-CMOS (60 - 120 V) process → fast charge collection
- industrial standard process → low production costs
- continuous and fast readout (serial link) → high rate applications

Beam test results

SciFi qualification with MuTRiG ASICs

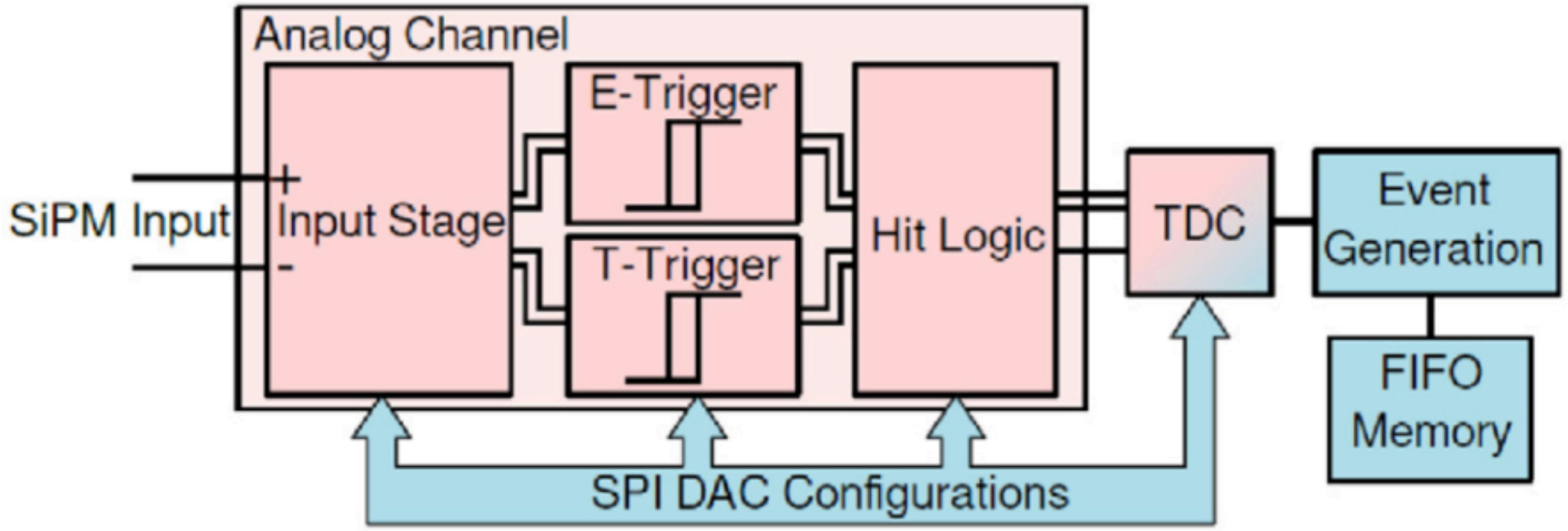






Time Sensor: Read Out

- Both timing detectors are read out with MuTRiG ASICs:
    - Custom readout ASIC for fast SiPM readout
    - High resolution TDC (50 *ps*) and rate acceptance (~1 *MHz*/channel)
    - Separate time and energy thresholds
    - Clustering (coincidence) logic on-chip
    - Tunable output event structure
- Final version (MuTRiG3) under validation



Mu3e DAQ Chain & Filter

Search for mu3e does not allow for on-detector trigger

Instead: Online filter using GPUs

3 Layers in DAQ chain:

- Hit Data sorting & Concentration
- Assembly of time slices
- Distribute & filter on GPUs:
    - Track reconstruction in central pixel detector
    - vertex finding
    - O(100) reduction
- (Write candidate events to disk)

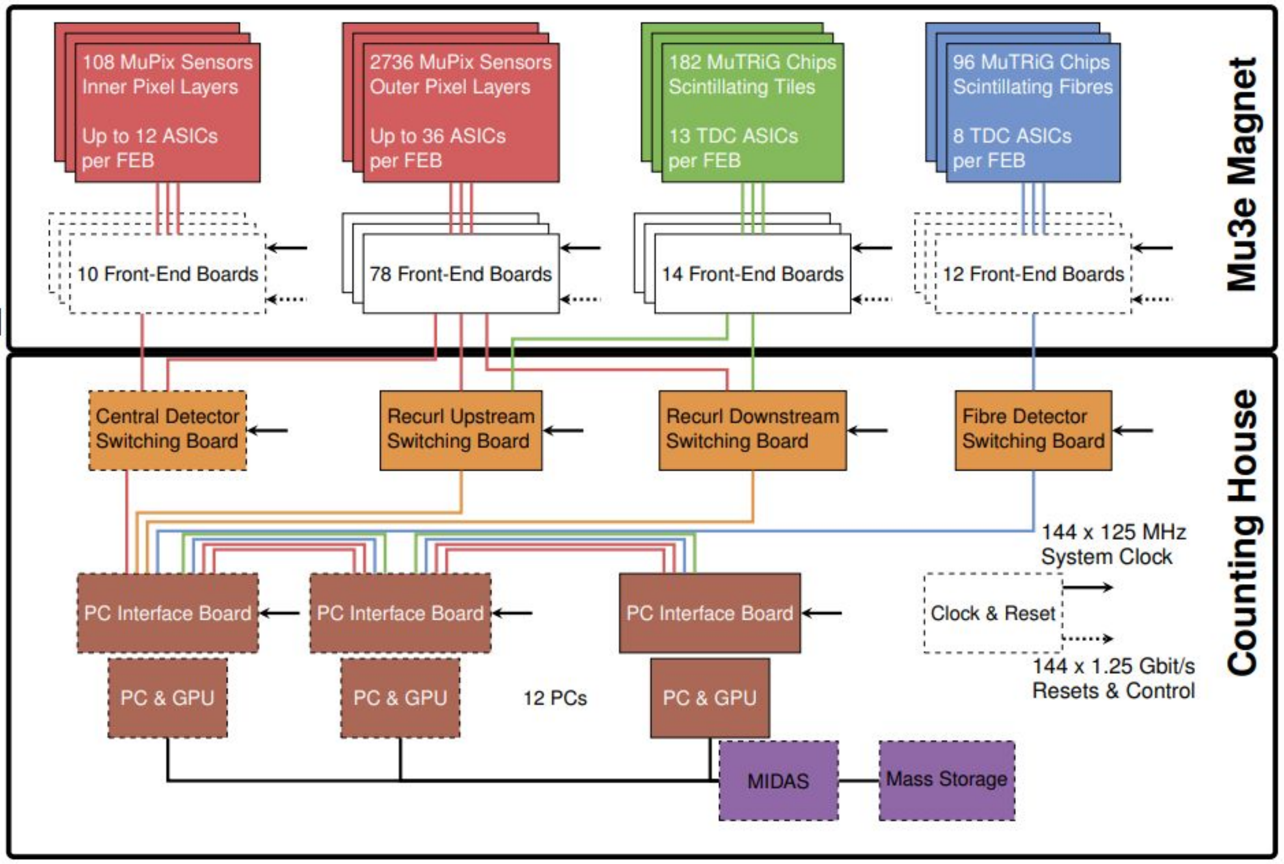
up to 3 x $1.25\,\mathrm{Gbit/s}$ LVDS links per ASIC

1-2 x $6.25\,\mathrm{Gbit/s}$ optical link per board

2-8 x $10\,\mathrm{Gbit/s}$ optical links per board

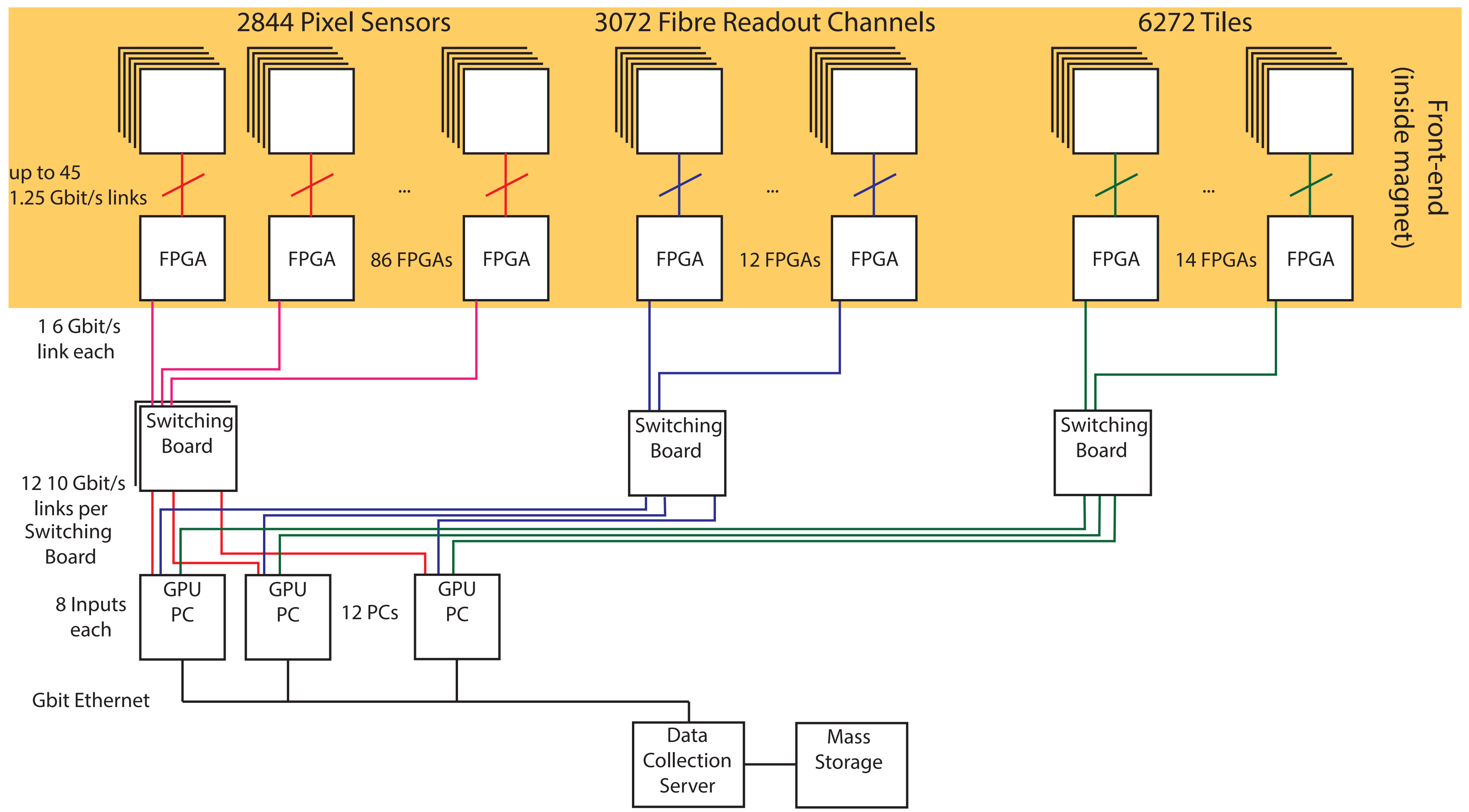
16 inputs per Farm FPGA

Gbit Ethernet



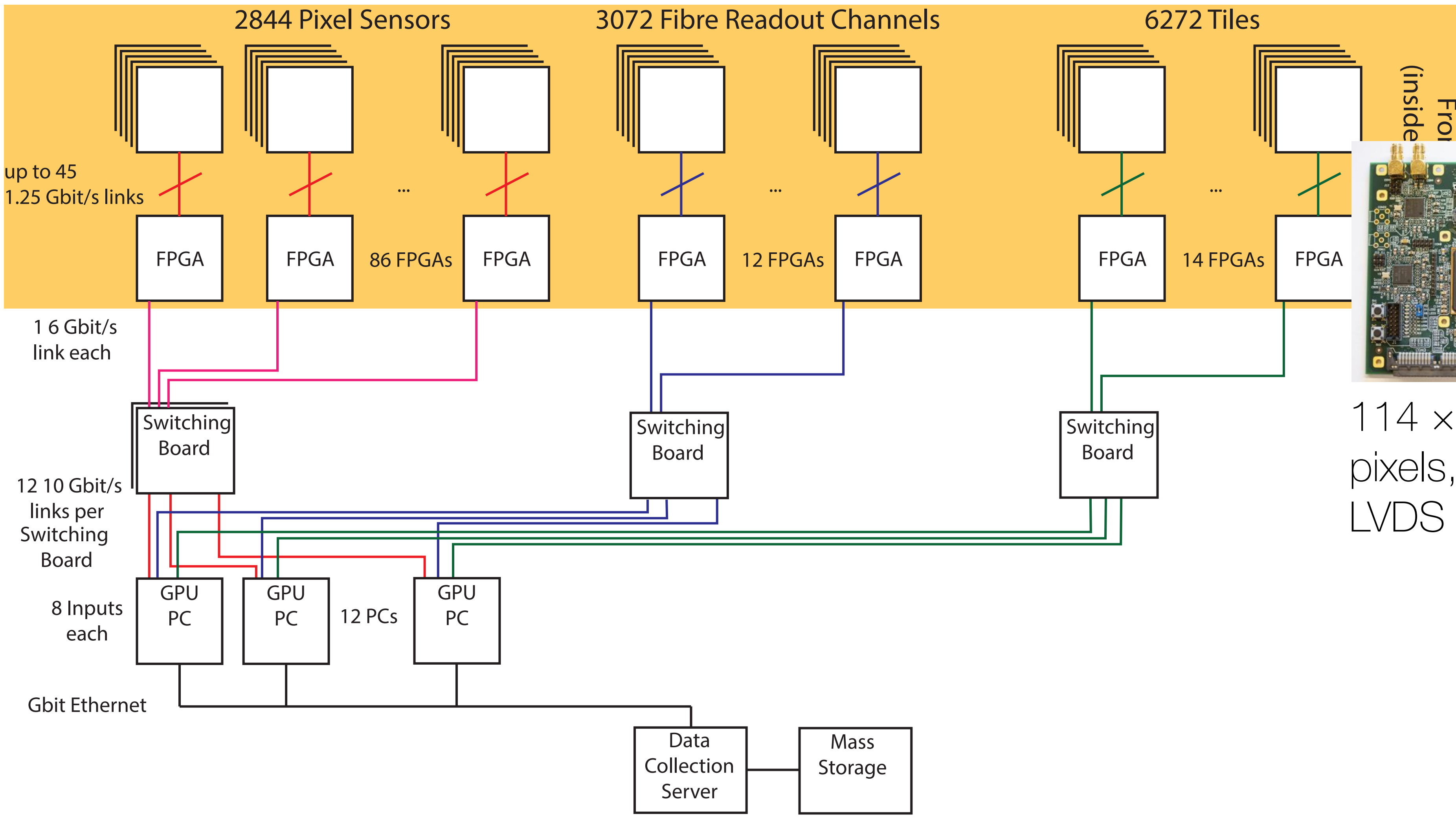
23

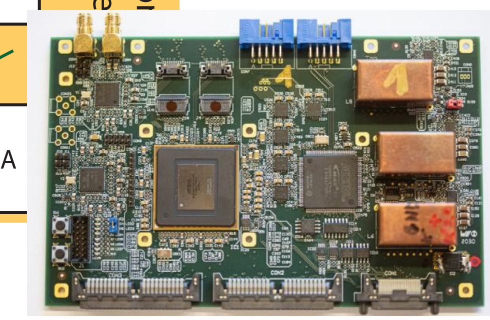
Data Acquisition System



- No hardware trigger → detectors continuously send zero-suppressed hit information
- Intel FPGAs: two main (Arria V and Arria 10), one auxilary (MAX 10)
- Three boards (FEB, SWB/PCIe40 and Farm/DE5a)
- Several firmware configurations (MuPix/SciFi/AsciTile, DDR3/4, test stands)

Data Acquisition System





114 × FEB (Arria V)
pixels, fibres and tiles
LVDS to optical links

- No hardware trigger → detectors continuously send zero-suppressed hit information
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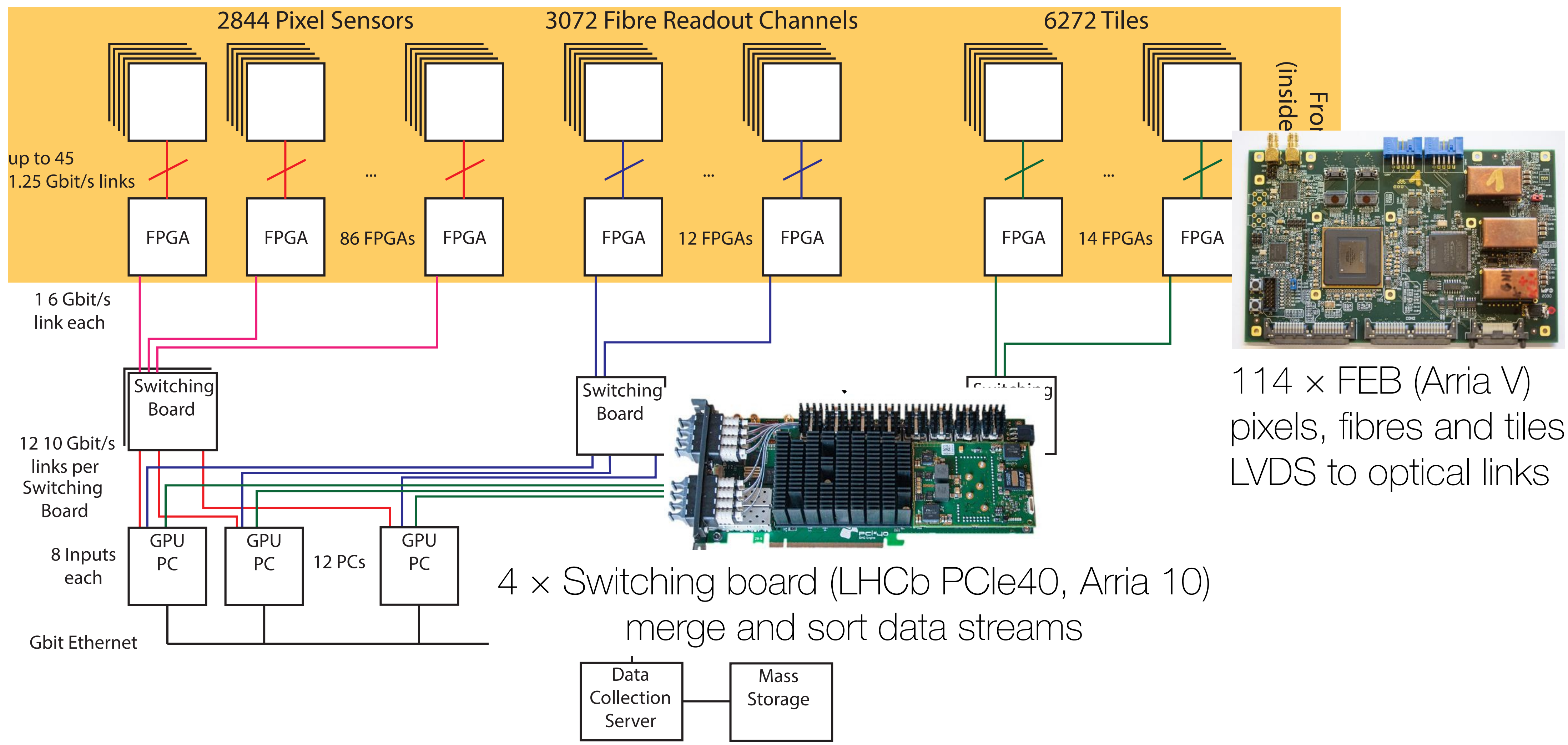

114 × FEB (Arria V)
pixels, fibres and tiles
LVDS to optical links

4 × Switching board (LHCb PCIe40, Arria 10)
merge and sort data streams

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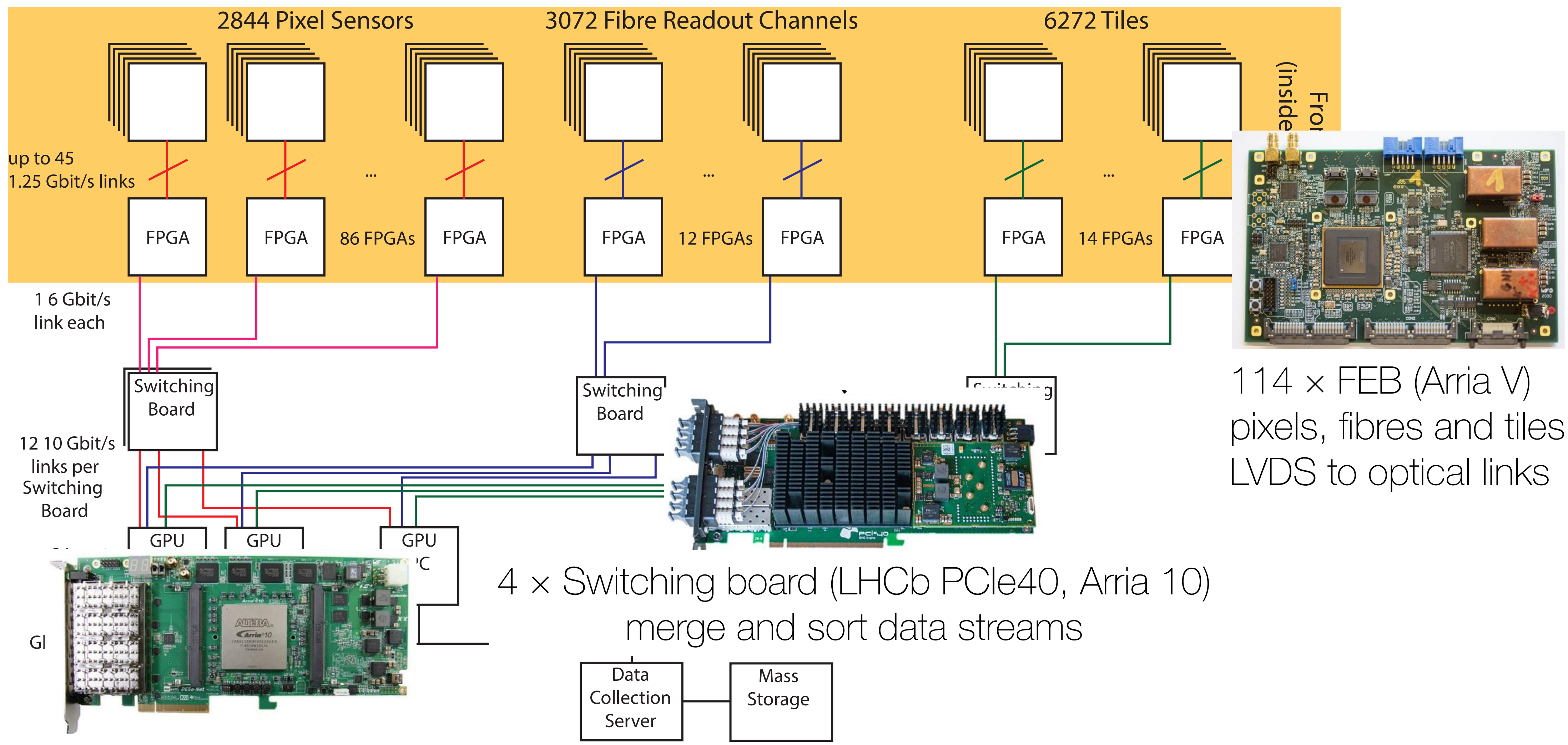

114 × FEB (Arria V)
pixels, fibres and tiles
LVDS to optical links

4 × Switching board (LHCb PCIe40, Arria 10)
merge and sort data streams

Chain of 12 × Receiving board (DE5a NET, Arria 10)
Transfer data to GPU for online reconstruction

- No hardware trigger → detectors continuously send zero-suppressed hit information
- Intel FPGAs: two main (Arria V and Arria 10), one auxilary (MAX 10)
- Three boards (FEB, SWB/PCIe40 and Farm/DE5a)
- Several firmware configurations (MuPix/SciFi/AsciTile, DDR3/4, test stands)

Mu3e Data Acquisition

- Trigger-less continuous readout
- Front-end board bandwidth requirements:
  - MuPix: 1.3 *MHz/cm²*, maximum hit band-width of 740 *Mbit/s*, equivalent to 23 x 10^6 32 bit hits per link per second
  - SciFi: estimated from the simulation as 620 *kHz*, with a hit size of 28 bits, 32 channels per ASIC, this uses about 700 *Mbit/s*

Subdetector	Max. hit rate/FPGA MHz	Hit size Bits	Bandwidth needed Gbit/s	FPGAs
Pixels	58	48	4.6	88
Fibres	28	48	2.3	12
Tiles	15	48	1.2	14

- Switching board bandwidth requirements

Mu3e Bandwidth

Subdetector	Max. hit rate/FPGA MHz	Hit size Bits	Bandwidth needed Gbit/s	FPGAs
Pixels	58	48	4.6	88
Fibres	28	48	2.3	12
Tiles	15	48	1.2	14

	Rate MHz	Bandwidth Gbit/s
Central Pixels	905	58
Upstream Recurl	191	12
Downstream Recurl	131	8.4
Fibres	337	21.5
Total	1564	100

Mu3e "Crisis" and Delays

2017: Termination of Mu3e magnet contract after 2 years
—> changed producer

2018: 180nm HV-CMOS process abandoned by austriamicrosystems
—> fab change

2019: Main Engineer in Oxford (Kirk Arndt) passed away

2020: Covid19 pandemic …

2021: Production stop of Frontend Boards (main Mu3e electronics) due to delivery problems (e.g. FPGAs) for more than two years

2022: Pixel Tracker flexprint production in Kharkiv stopped for ~1 year because of Ukraine war

… many other smaller problems

Mu3e “Crisis” and Delays

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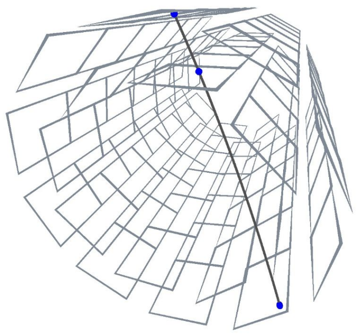
2022: Pixel Tracker flexprint production in Kharkiv stopped for ~1 year because of Ukraine war

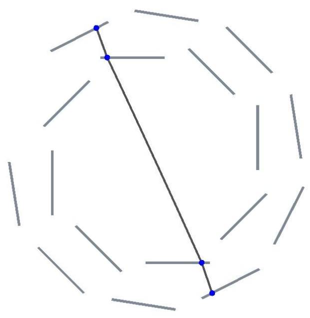
… many other smaller problems

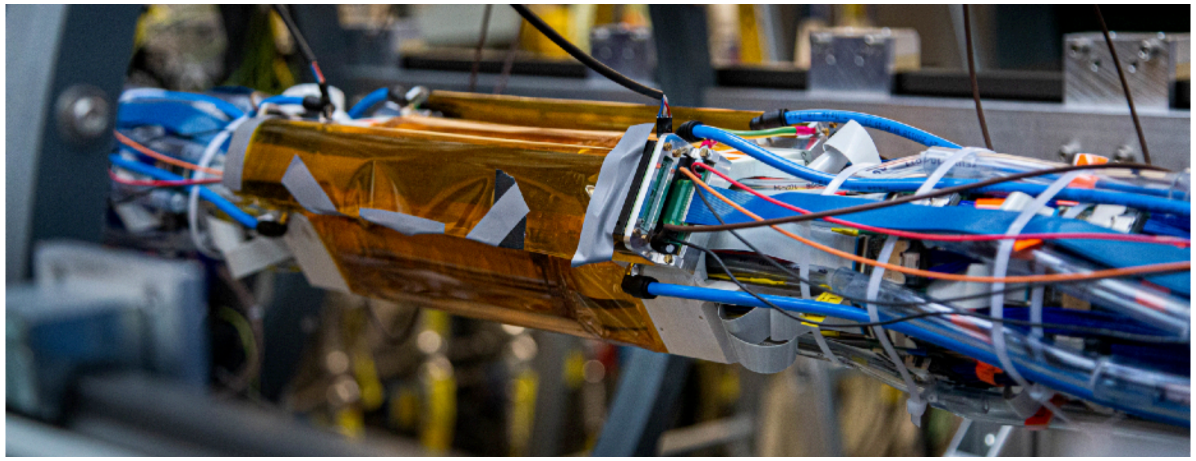
Mu3e collaboration was (and still is) very optimistic

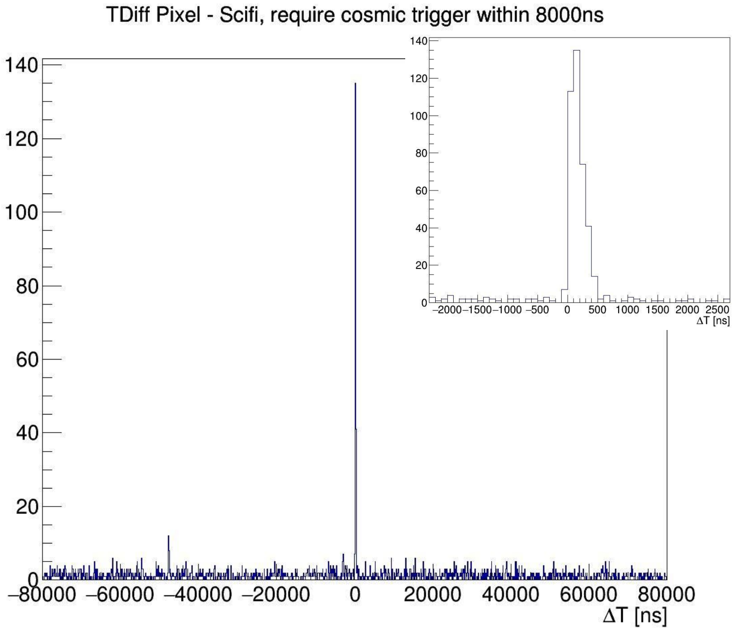
Mu3e integration: 2021-2022

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



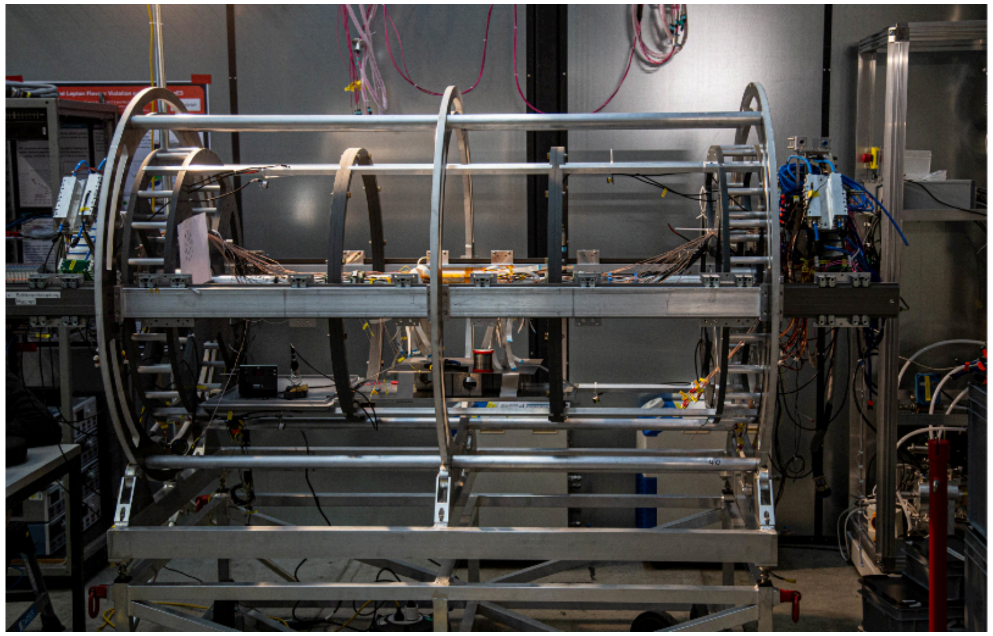


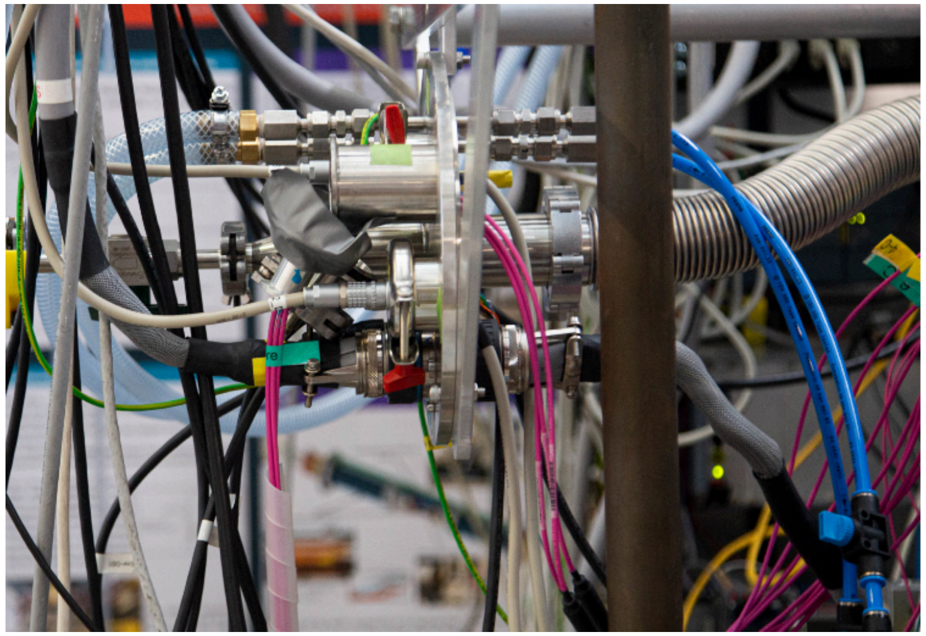




Mu3e construction: 2022-2023

- Detector development:
  - Operational MuPix11 sensor, validation of MuTRiG3 ongoing
  - Integration of pixel, tile and SciFi readout with final hardware
- Detector construction:
  - Phase I detector construction has started
  - Permanent staging area at PSI for installation
  - Consolidating production and QC pipelines

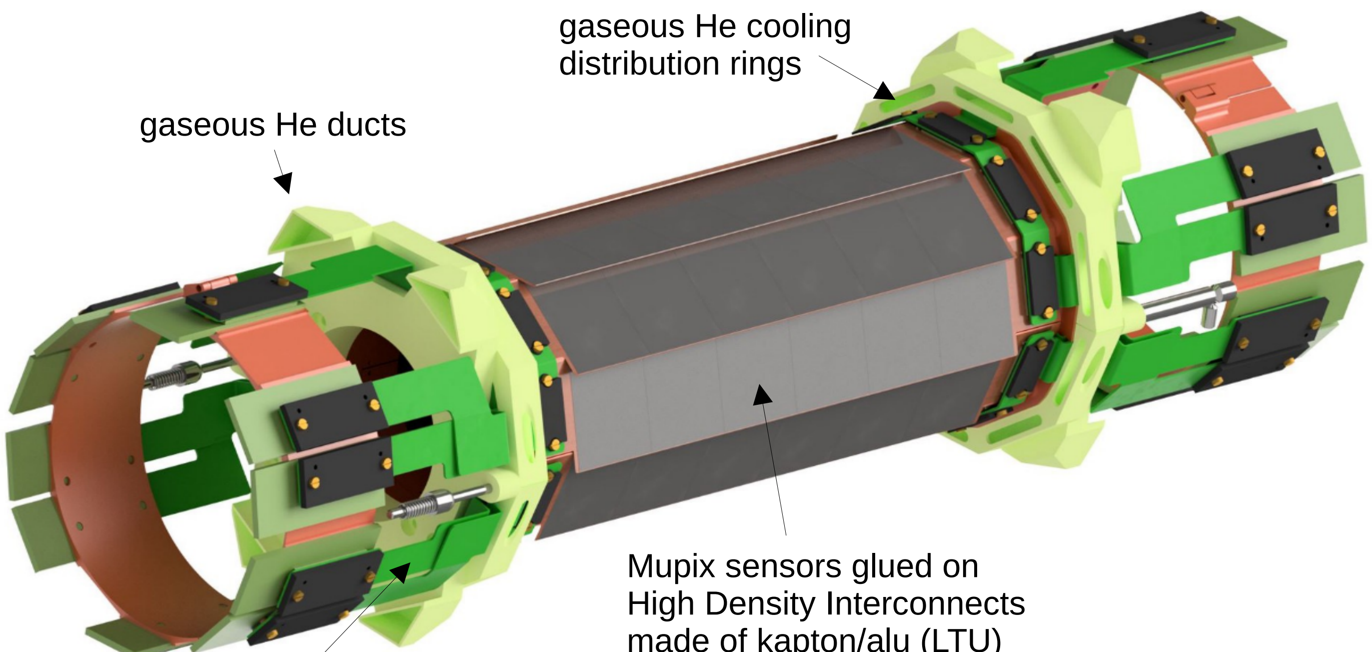




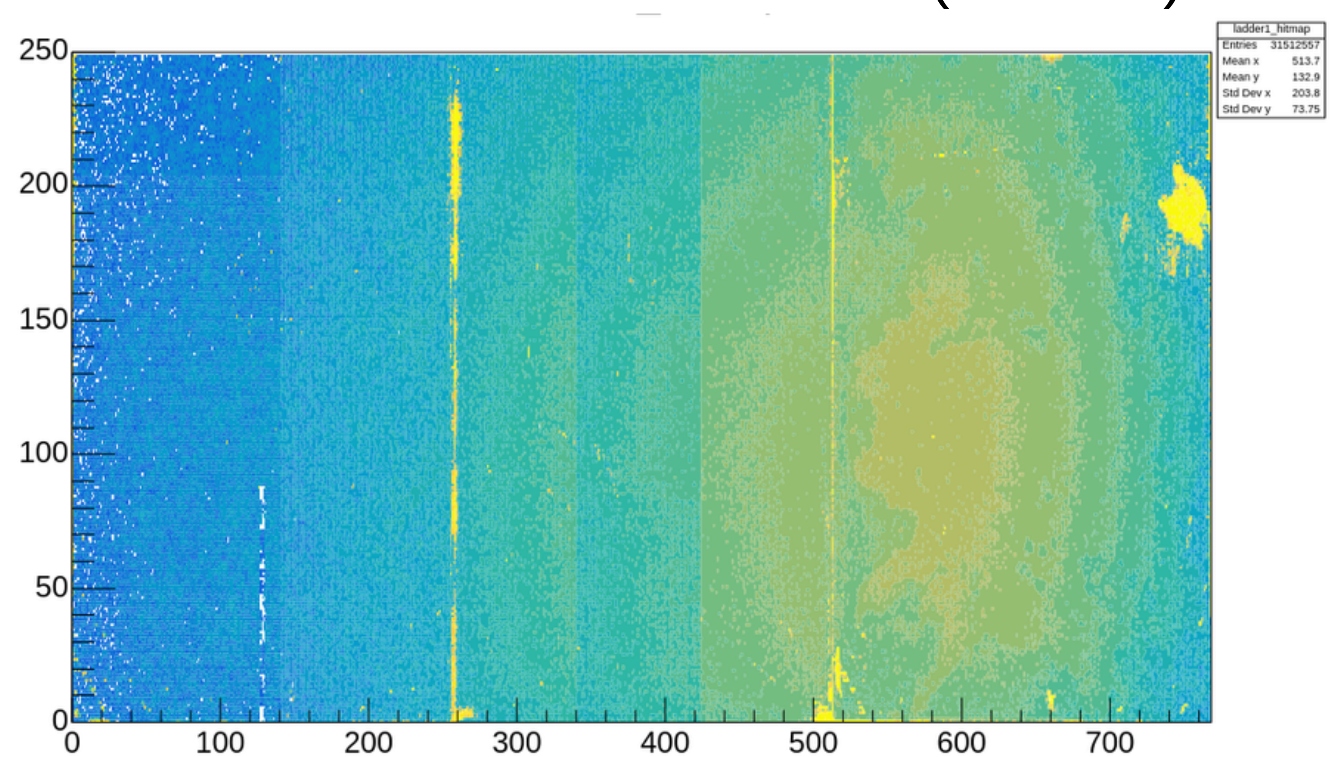
Mu3e Vertex Detector

2023 (final design)

Ultra-light design:
the mass of one vertex ladder is <1 *g*
radiation lengths: $X/X_0 \simeq 1.1 \cdot 10^{-3}$

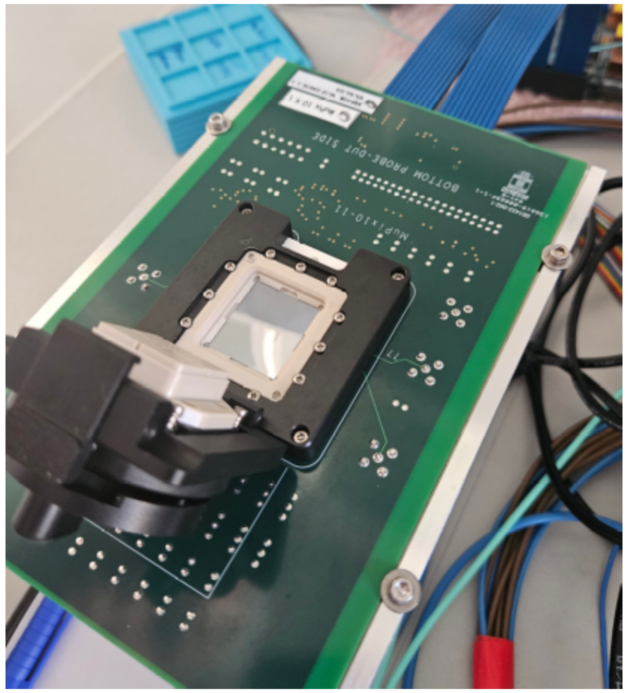


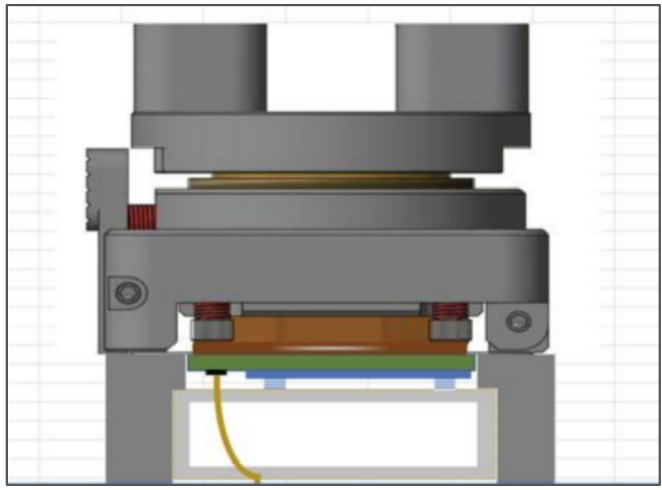
Half-Ladder in PSI testbeam (Oct. '23)



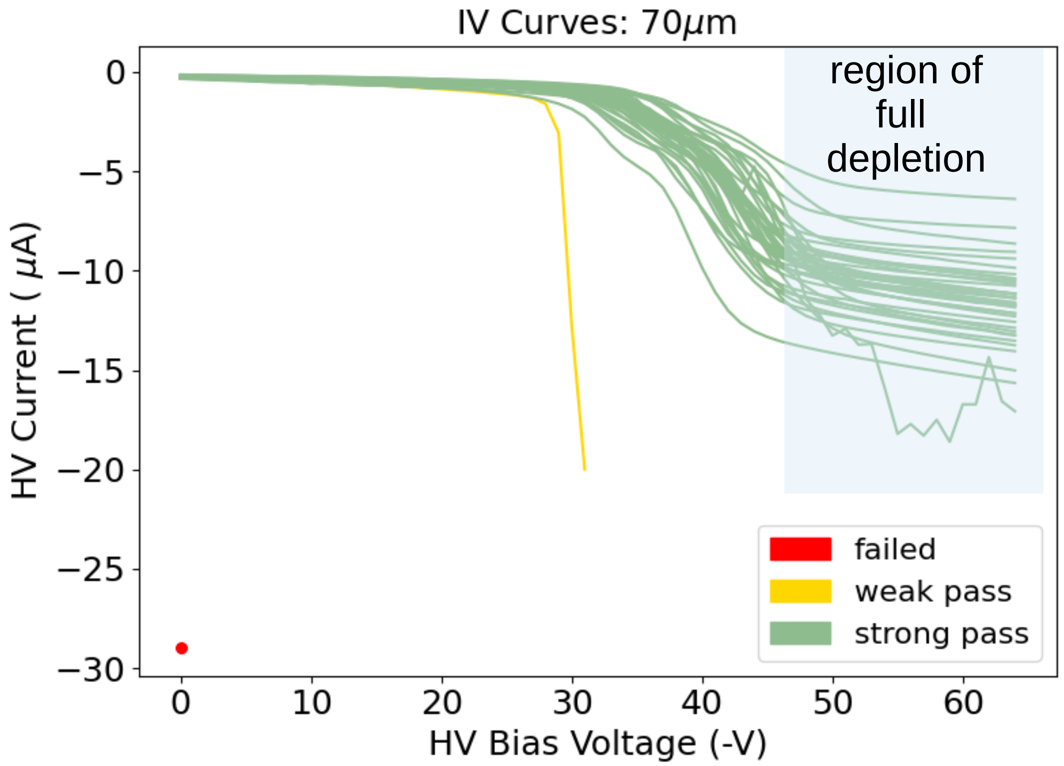
Mu3e Outer Pixel Detector

- Production of Outer Pixel Modules is automated to a large extend
  → active area in total 1.2 m^2 (~3000 sensors)
- Single chip probe station
  - All individual MuPix sensors to be qualified before ladder construction (gluing)
    ~10000 sensors to be tested

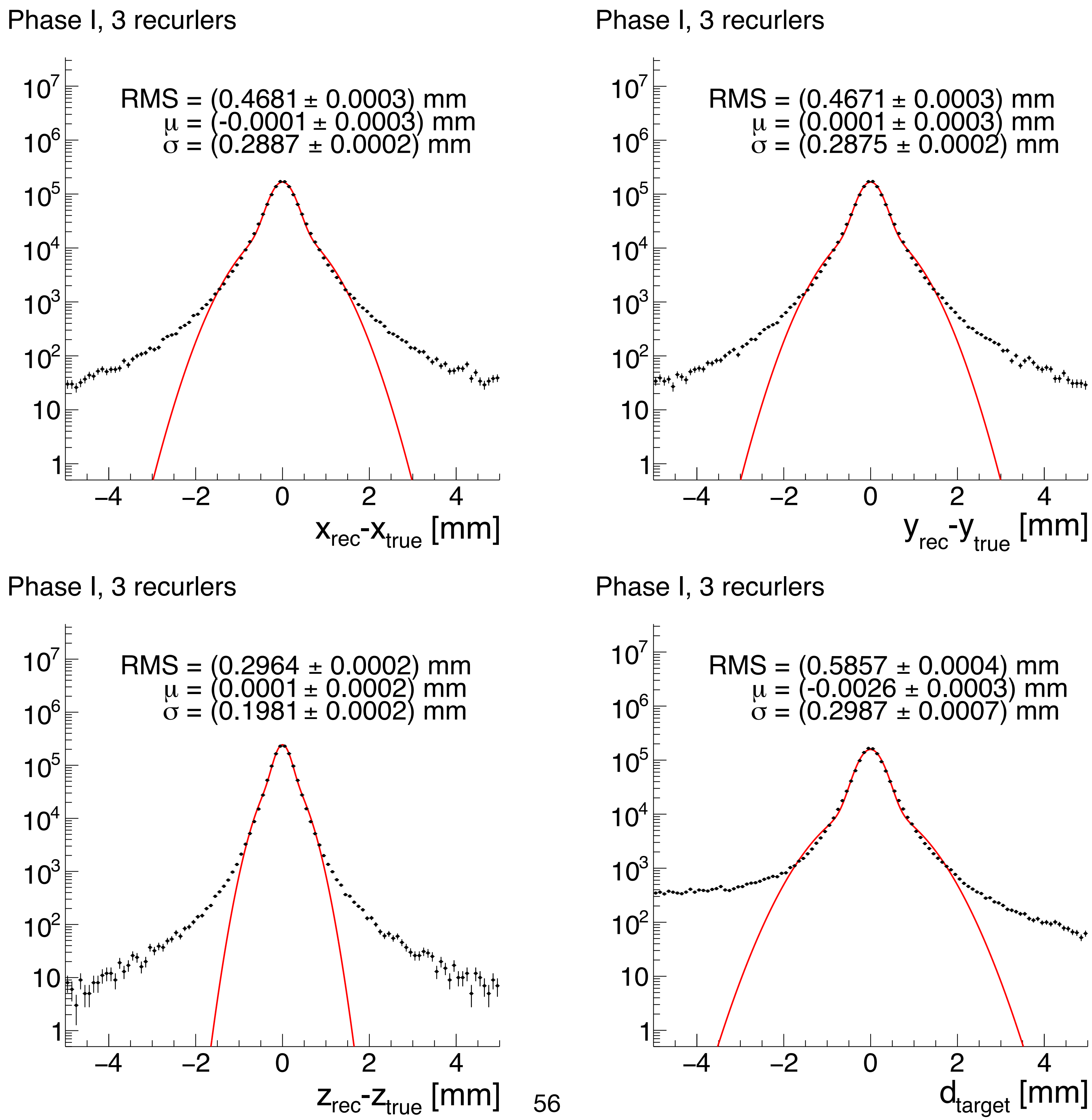




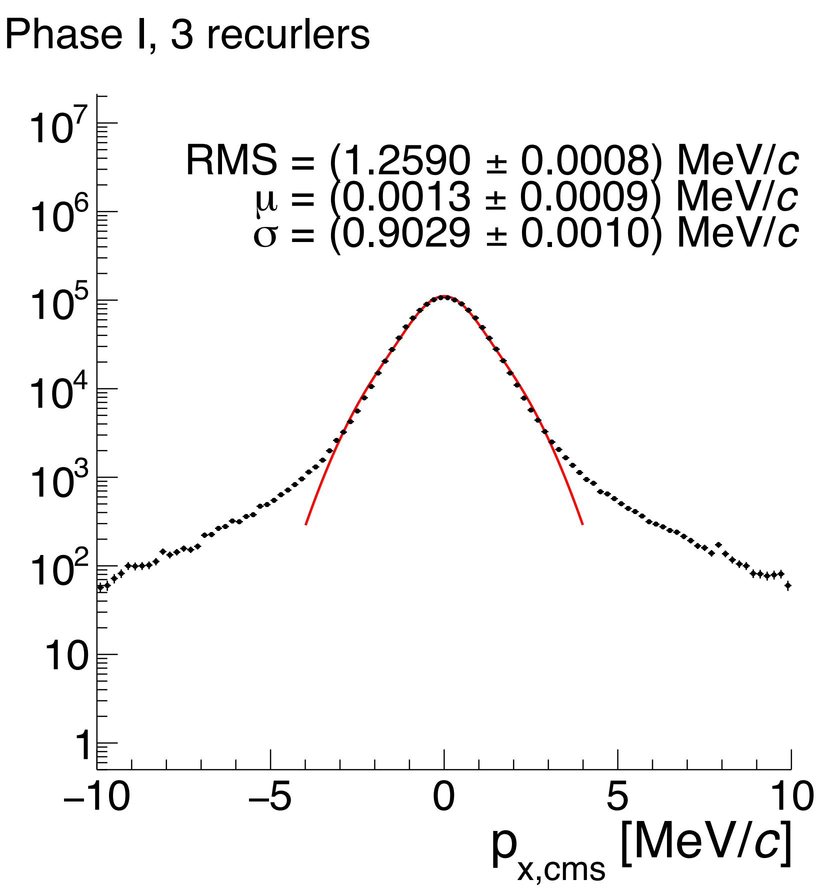
- Measured Current Voltage diagrams
- other parameters:
  - power consumption
  - voltage levels
  - data links

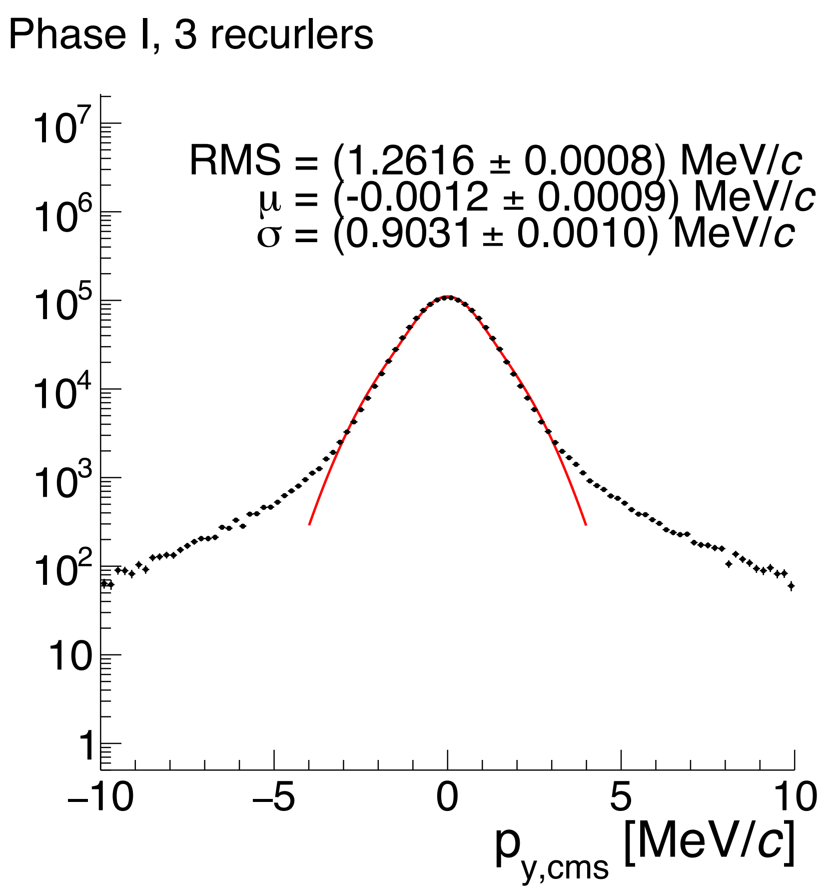


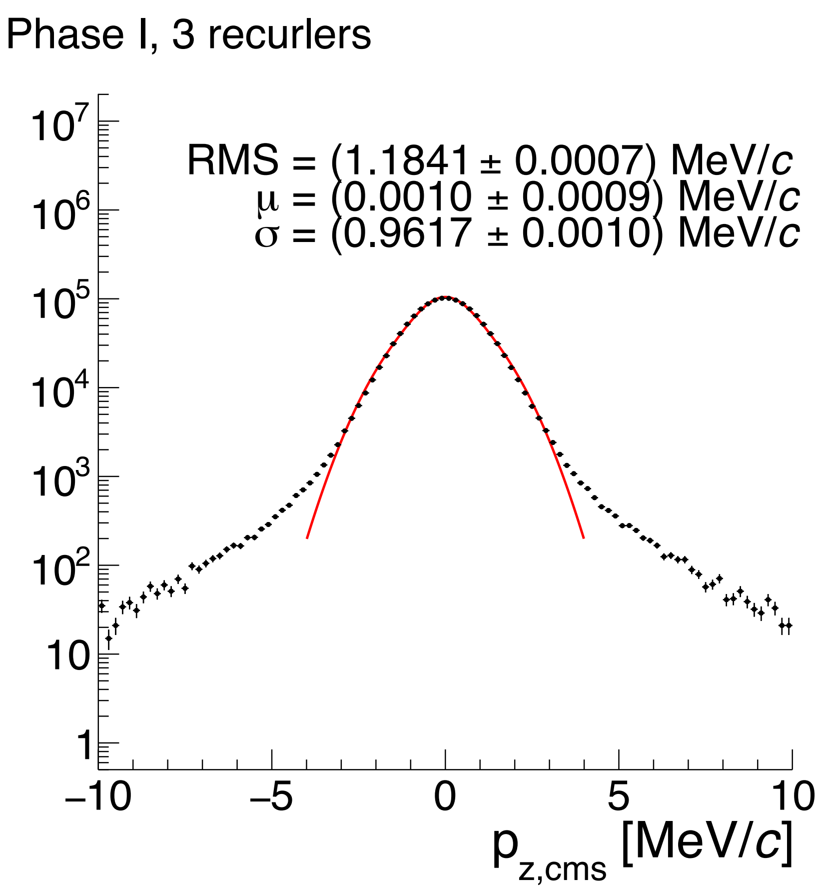
Vertex resolution



Momentum resolution

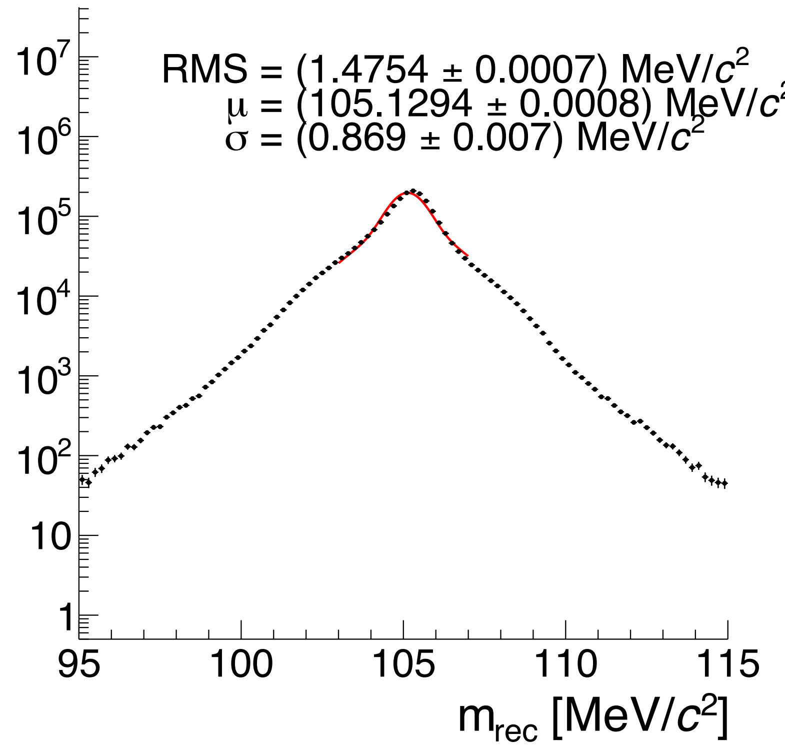




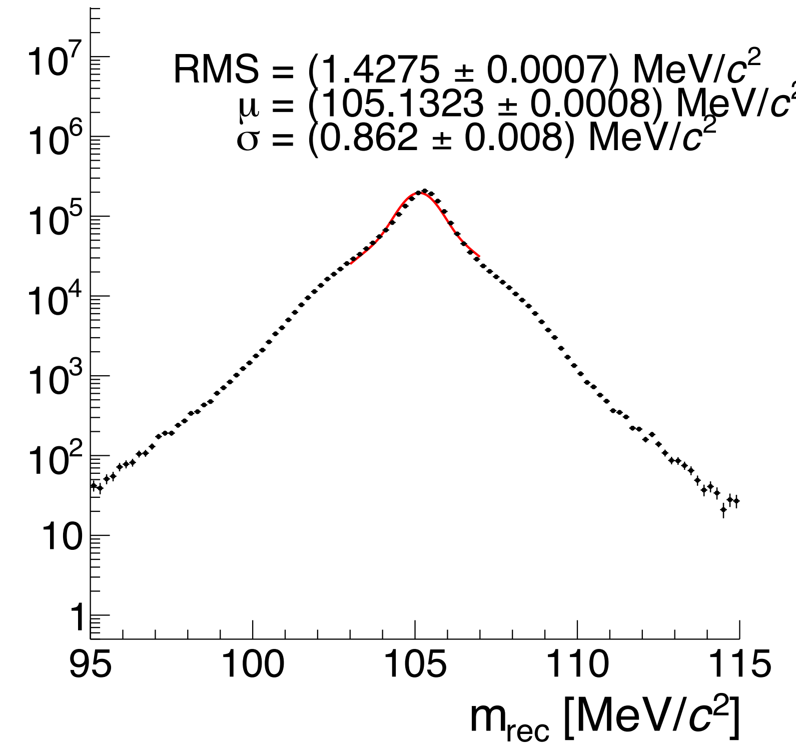


Muon mass reconstruction

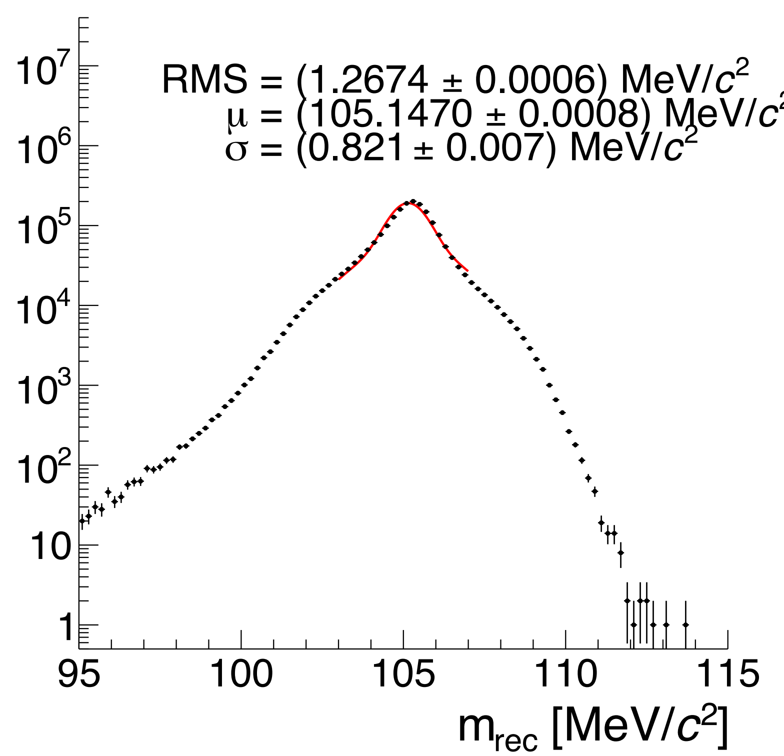
Phase I, all tracks



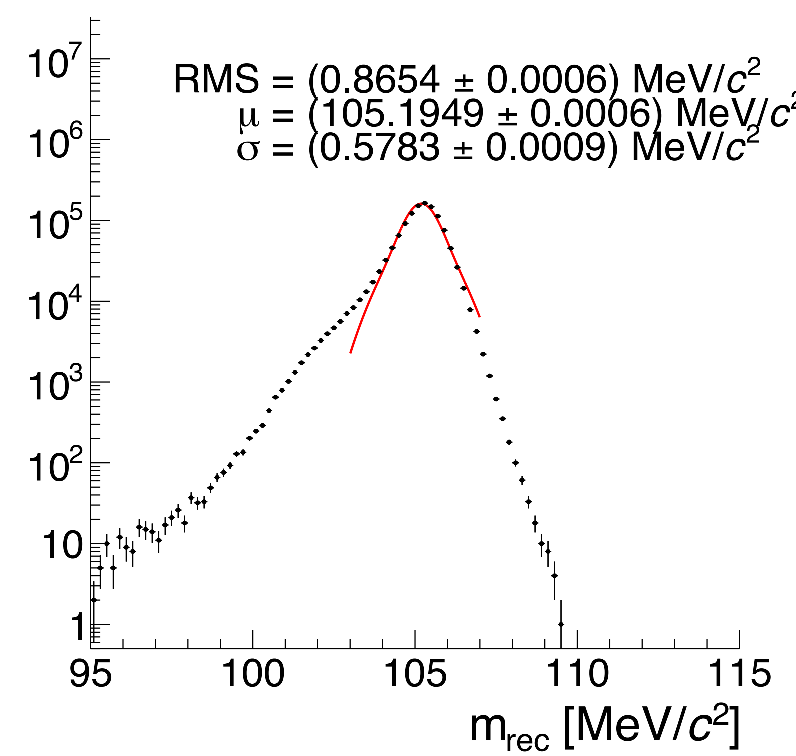
Phase I, ≥ 1r ecurler



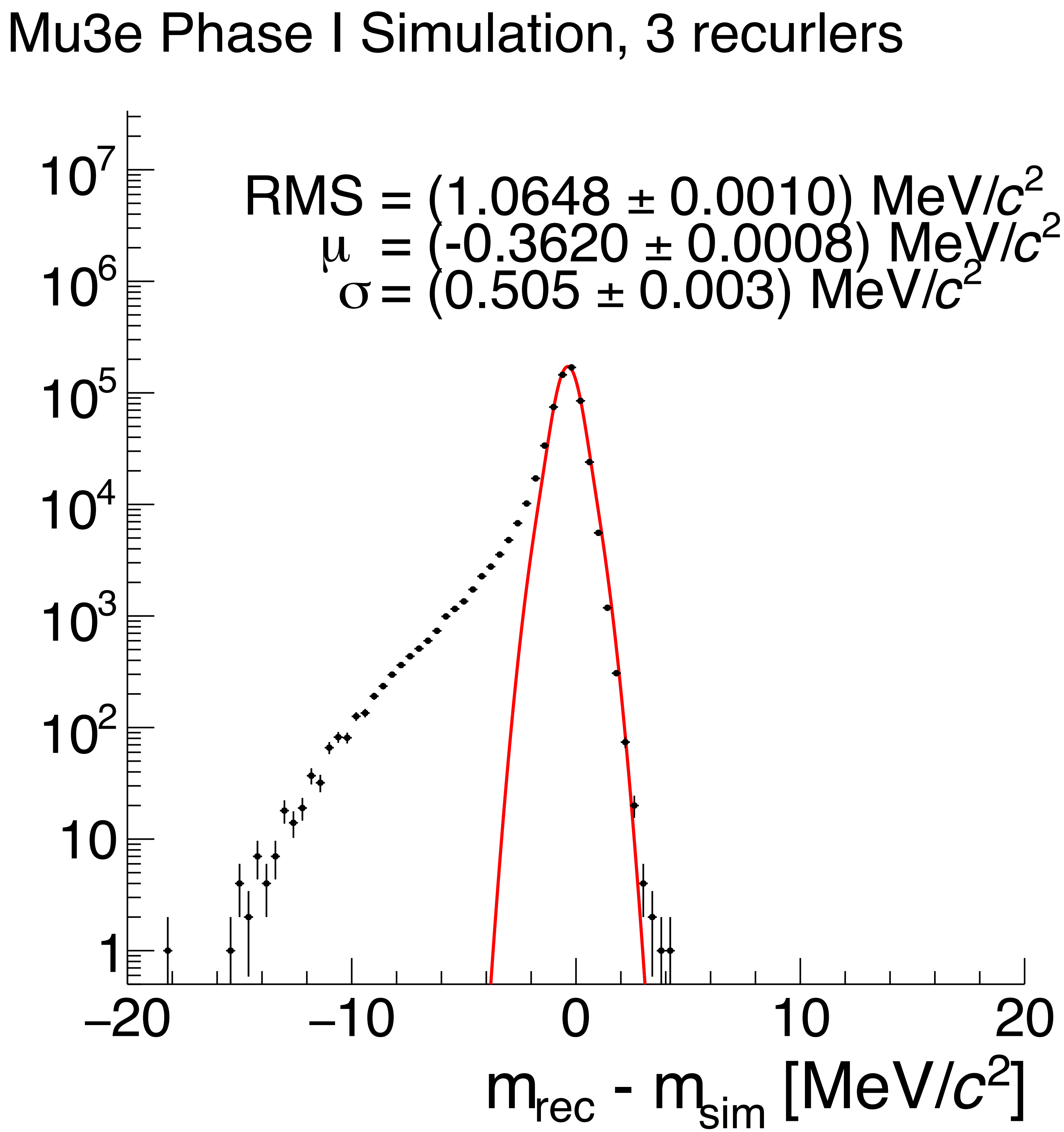
Phase I, ≥ 2 recurlers



Phase I, 3 recurlers



Mass reconstruction resolution



Mu3e Plans for 2024 and further

- Achievements so far:
  - DAQ operational with different detector types
  - Cooling for detectors
  - Pixel, SciFi, SciTile → First modules installed

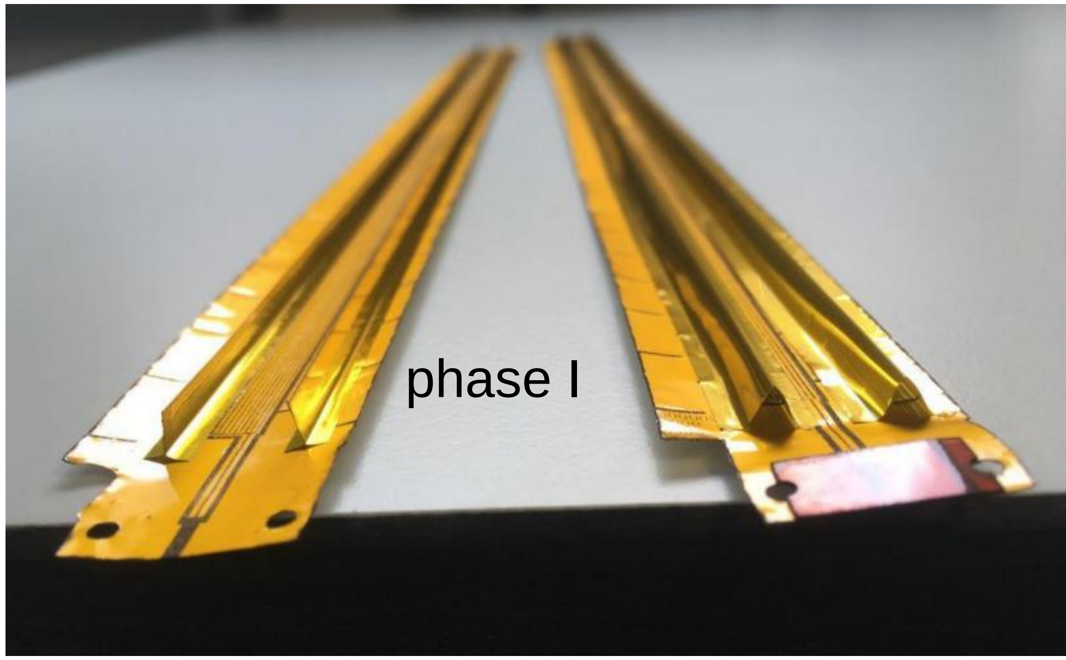
- Aims for rest of the year:
  - Cosmic run
  - Complete experimental chain
  - Detector installation
  - Data taking (beginning of next year)

Nov/Dec 2024	2025	2026
Cosmic run with inner pixel and SciFi	Full detector commissioning	Physics data taking

Long Ultra-Light Pixel Tracker modules

- Mu3e Phase I:
  - world record for building the lightest pixel tracking detect ever
  - 36cm long pixel modules hanging “freely”

Is this the physical limit or can we build even longer modules at even more reduced weight?



The Bandwidth Challenge

- Hit occupancy is highest for inner pixel layers
- Phase I hit rate of 1.5 MHz/cm^2 increases to 30 MHz/cm^2 for Phase II w/o design changes (x20)
- Elongated muon stopping target reduces hit occupancy but at the same time the number of recurling tracks increases

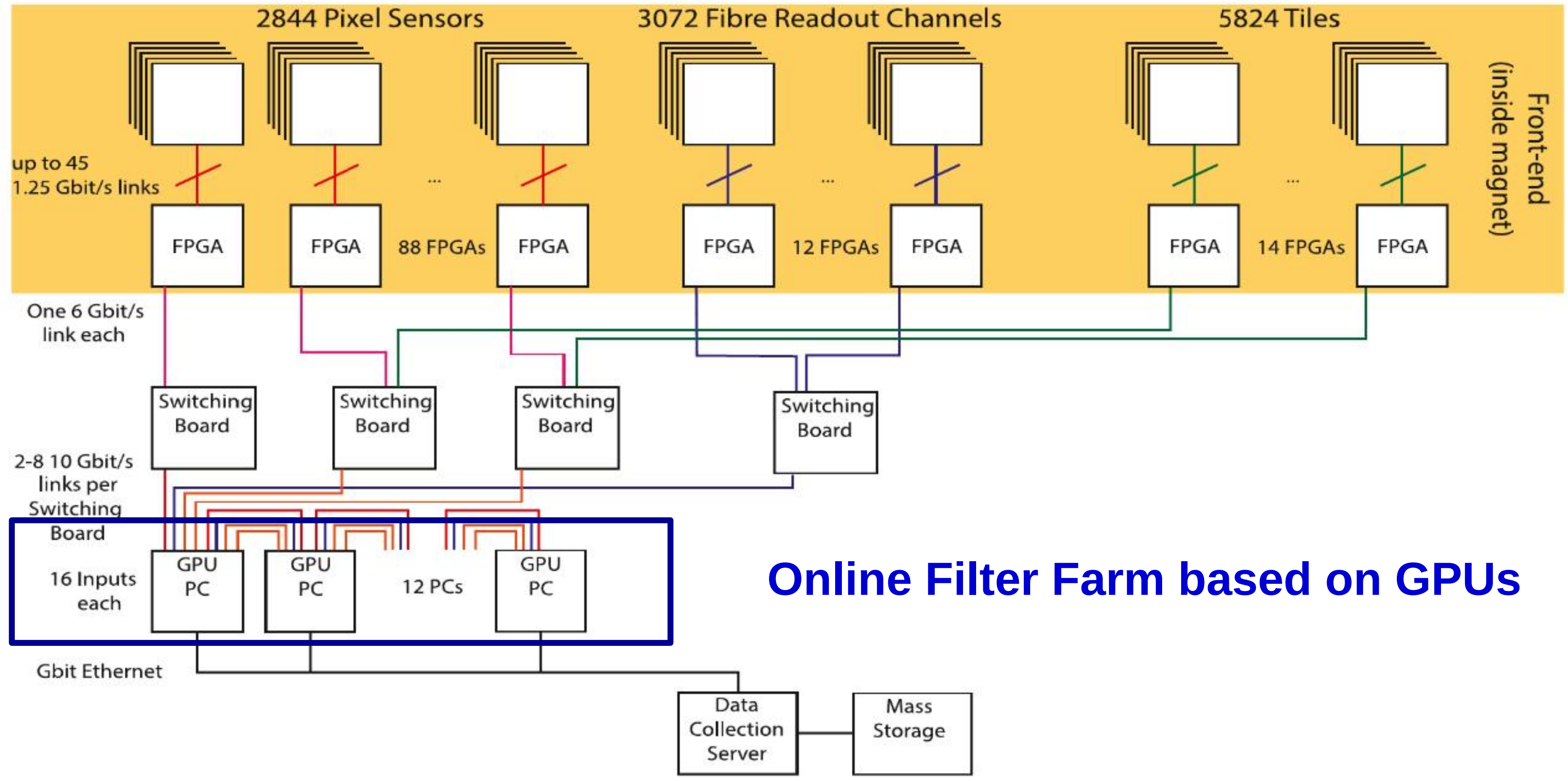
Consequences:

1. Phase II MuPix sensors will require a much higher readout bandwidth!
2. Total hit rate will increase by almost 2 orders of magnitude!

Further Improvements for Phase II

- **Serial powering** of detector modules to reduce cables and to free some space
- **Upgrade Filter Farm** (+GPUs, + FPGAs) to tackle the drastically increased combinatorial problem in the online track reconstruction

Mu3e Detector

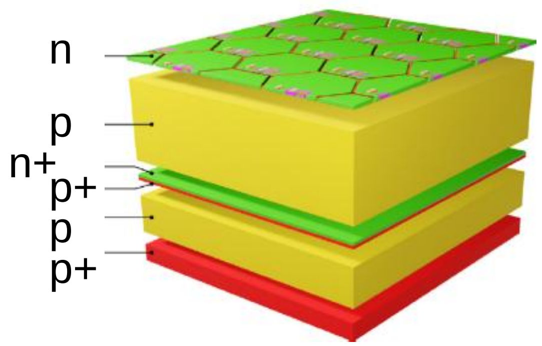


Online Filter Farm based on GPUs

Most important we want to learn from the phase I experience (design, production and operation)

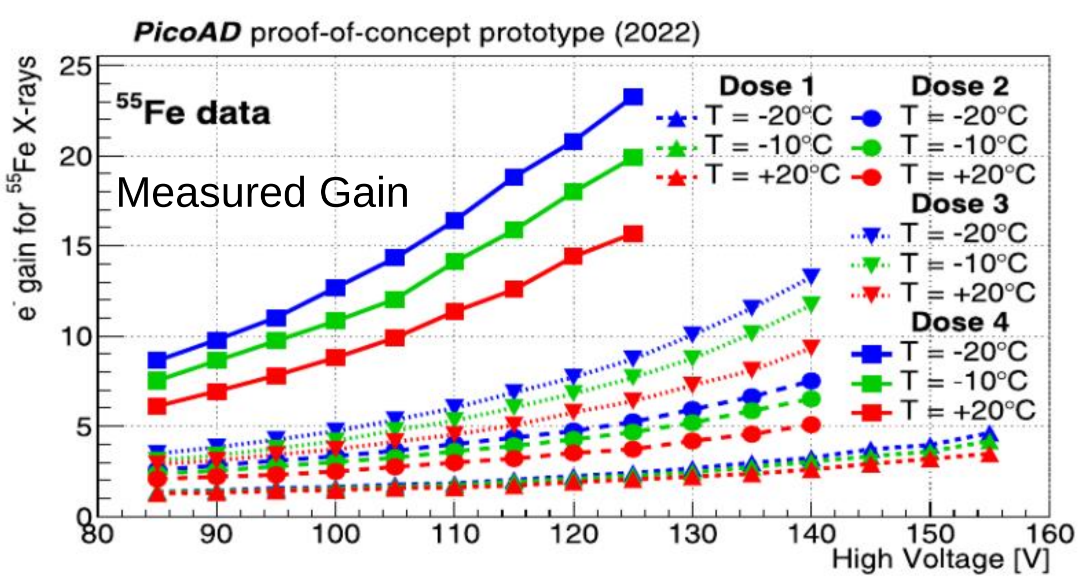
Ultra Fast Monolithic Silicon Pixel Prototypes

Gain Layer for HV-MAPS



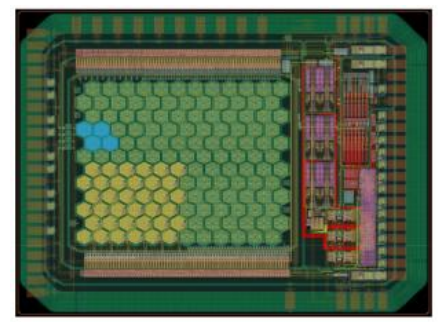
$\sigma_t < 20\ ps$

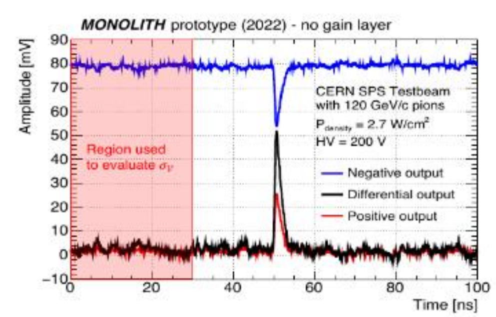
Gain layer

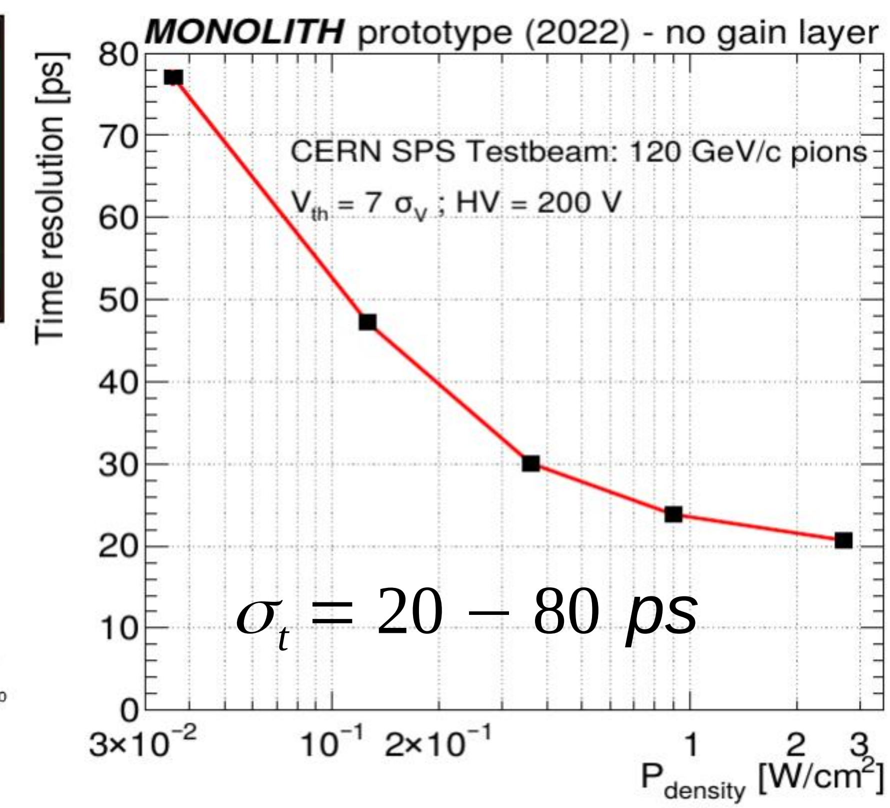


M.Milanesio et al., *Gain measurements of the first proof-of-concept PicoAD prototype with a 55 Fe X-ray radioactive source,* NIMA 1046 (2023) 167807

High Power Amplifier with SiGe Bipolar Transistors







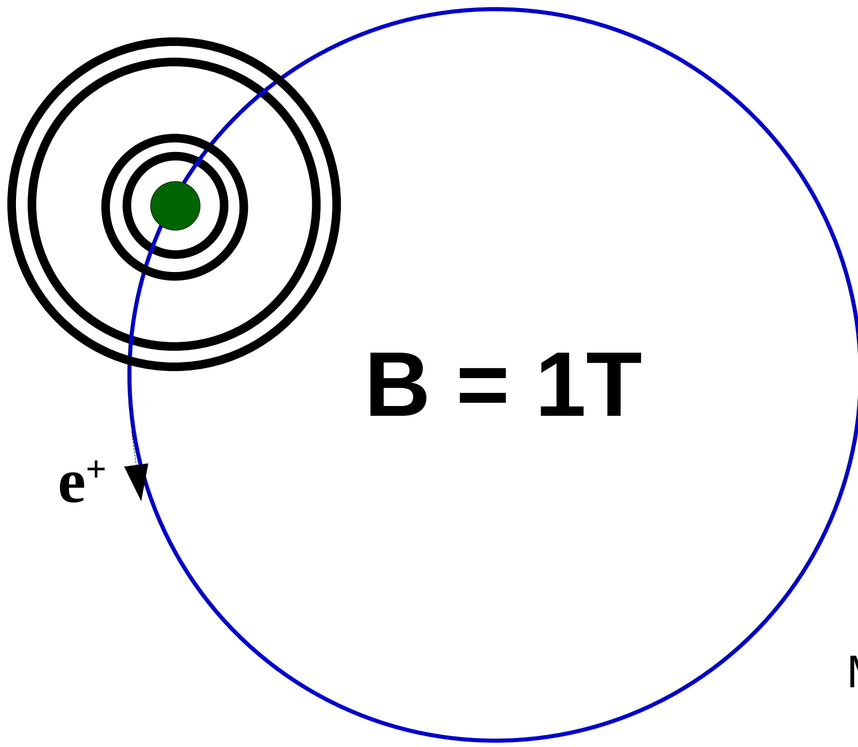
S. Zambito et al., 20 ps time resolution with a fully-efficient monolithic *silicon pixel detector without internal gain layer,* 2023 JINST 18 P03047

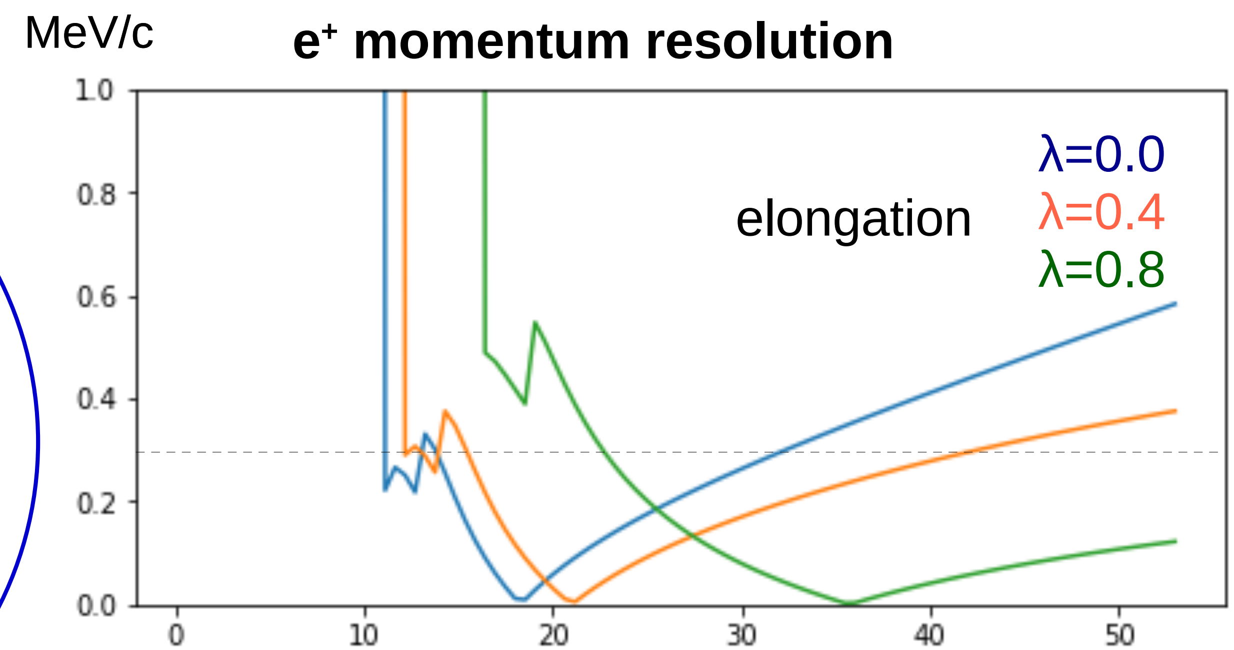
Warning! A fast prototype sensor does not make a full detector!
≥ ~5 years R&D needed for fully monolithic sensor (from my experience)

Phase II Detector Design Studies

Phase I with 4 layers

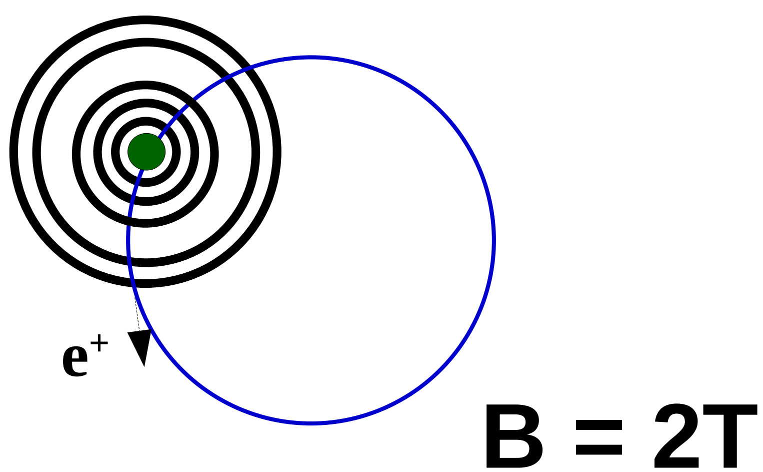
radii:
- 23 mm
- 30 mm
- 74 mm
- 86 mm

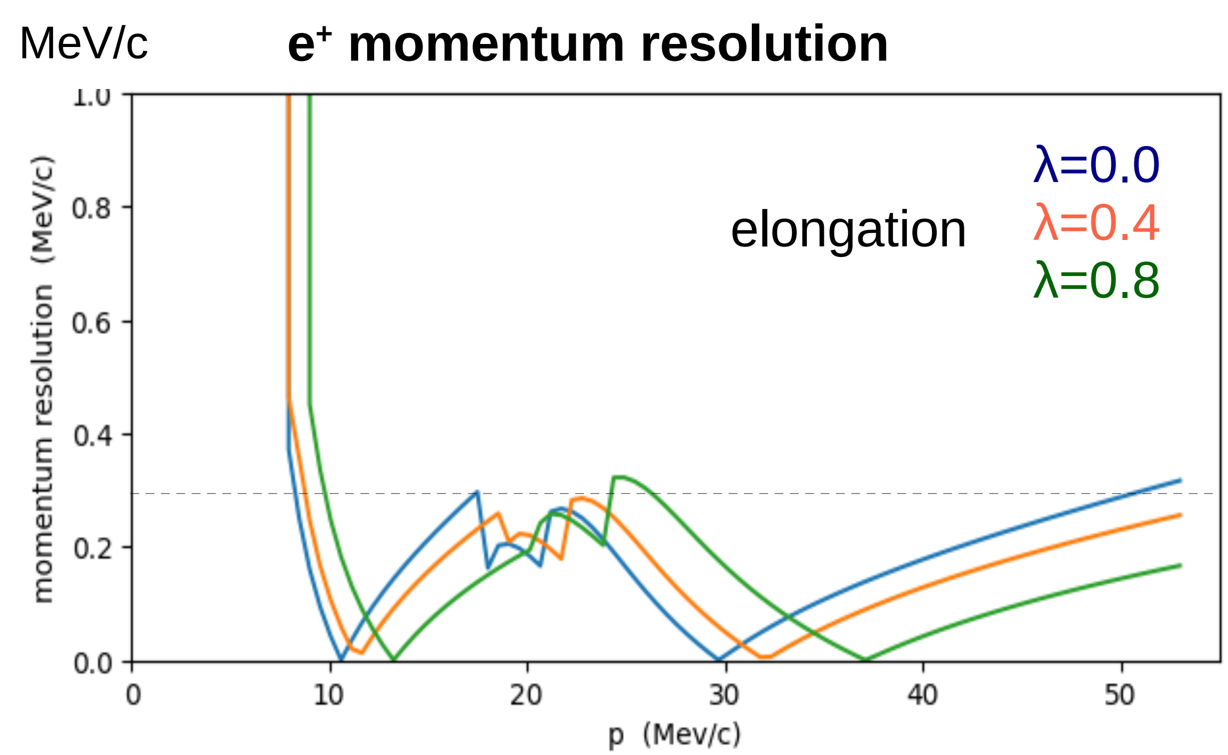




Phase II with 5 layers

radii:
- 15 mm
- 20 mm
- 25 mm
- 60 mm
- 70 mm





studies are ongoing

Beyond Phase II

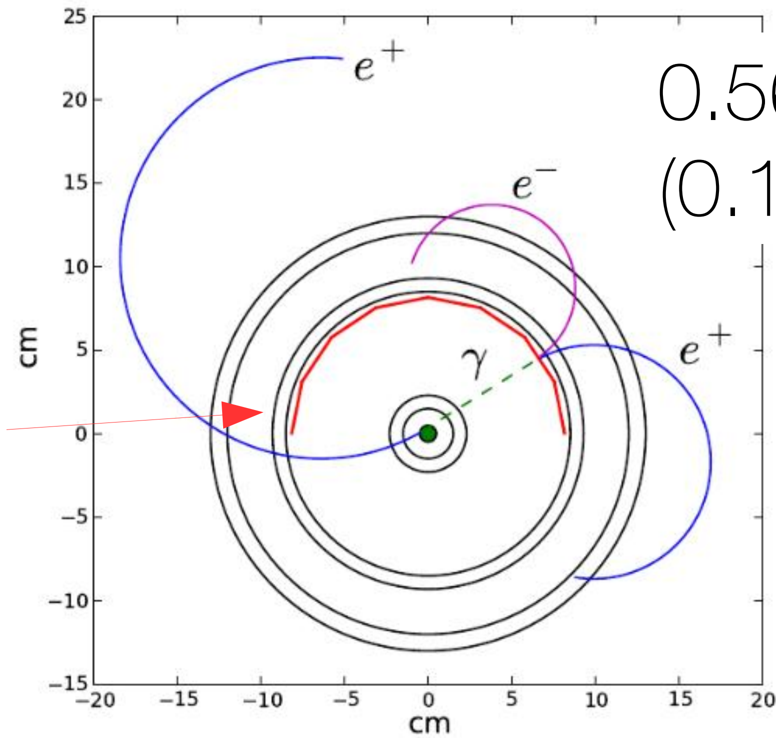
- Modified detector to also search for $\mu^+ \to e^+\gamma\ (\gamma \to e^+e^-)$
  - Master formula for accidental background:

$$B_{acc} \sim R_\mu \sigma(t_{e\gamma})\sigma(\theta_{e\gamma})^2\sigma(p)\sigma(E_\gamma)^2$$

MEG2 LXe calorimeter: $\sigma \approx 1\ MeV$

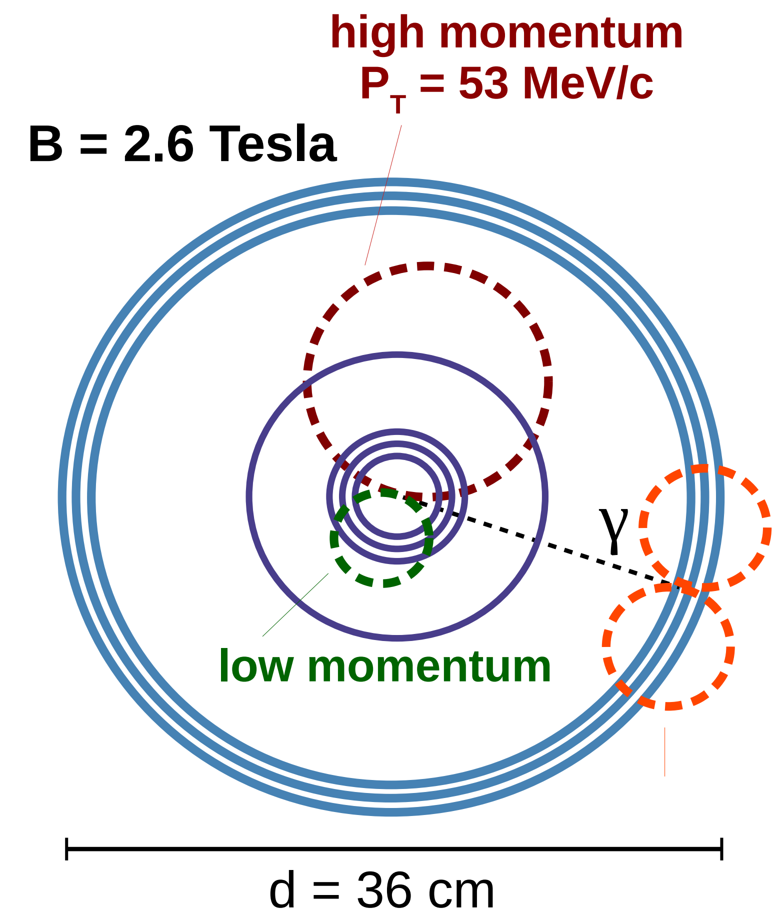
  - Better photon energy resolutions by measuring converted photons
  - Penalty: significant loss of rate
  - Photon converter design is well motivated if there are plenty of muons (→ HIMB project)

Disadvantages of the simulated design:
- only half the phase space covered by converter
- converter compromises "normal" track reconstruction
- photons to be reconstructed in a sea of Michel electrons



0.56 *mm* lead ($0.1\ X_0$)

Beyond Phase II

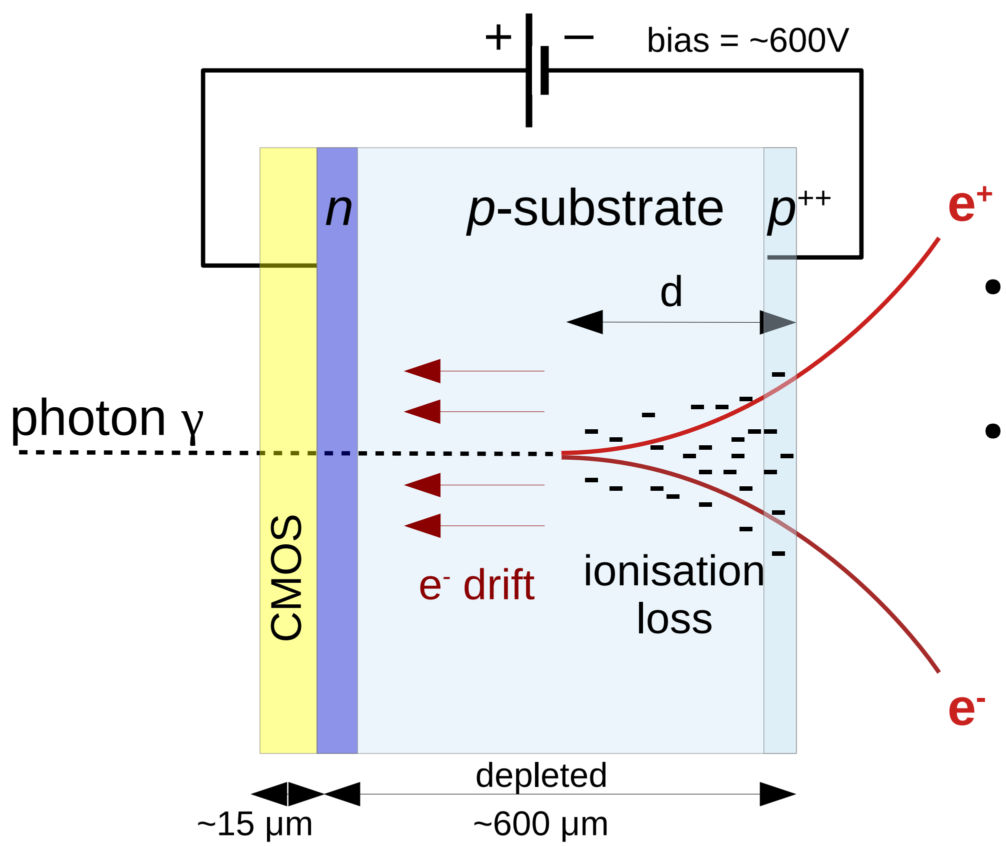


Mu3e-gamma proposal

→ studied for HIMB Science Case arXiv:2111.05788

Features:

- Michel electrons do not reach converter layers (**no BG**)
- Michel electrons have an excellent momentum resolution of ~ 100 keV due to high magnetic field (**B=2.6T**)
- Photons are detected in **Active Silicon Sensor Converters**



- Energy resolution of converted photons is usually given by **energy loss** of e+ and e- pair in converter.
- An active converter measures this energy loss!

→ expected energy resolution: $\sigma(E_\gamma) = 100-200\ keV$

The same setup can also be used to search for displaced decays of X → ee or A' → ee