The Mu3e experiment

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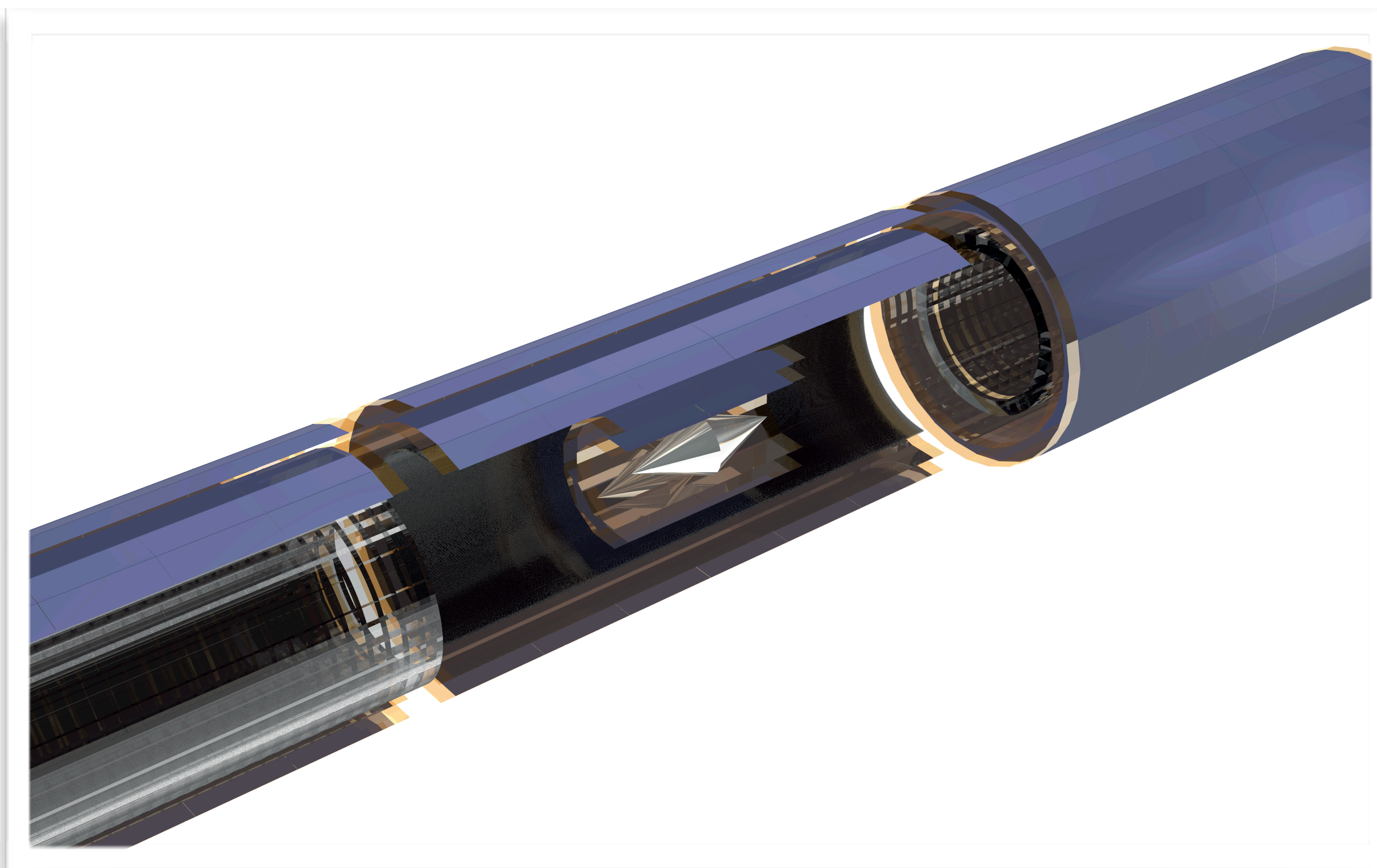


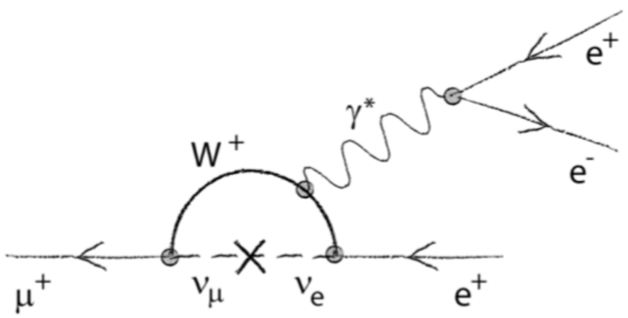
Content

- Charged Lepton Flavour Violation (cLFV) search:
  The motivation
- cLFV with the Mu3e experiment:
  The $\mu \rightarrow eee$ search
- The Mu3e experiment

cLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

$BR(\mu \to eee) \approx 10^{-54}$



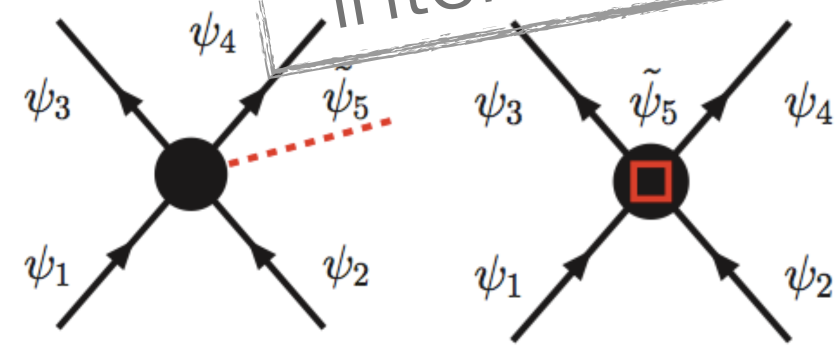
ν oscillations

too small to access experimentally

to unveil behind SM physics

via virtual particles

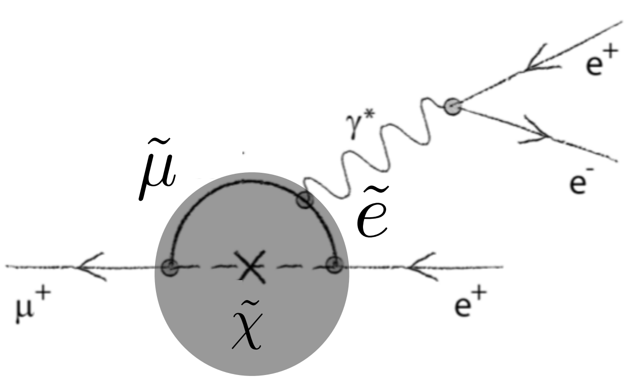
intensity frontier

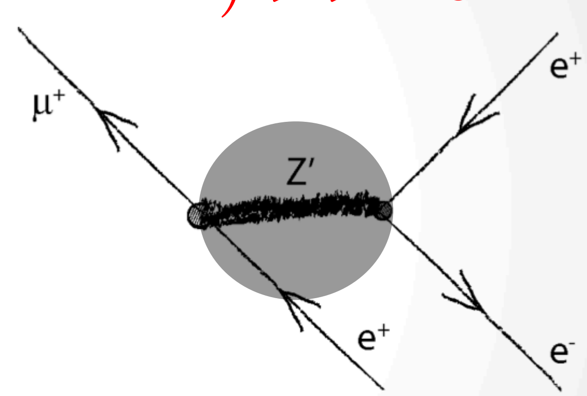


i.e. SU(5) SUSY-GUT or SO(10) SUSY-GUT

i.e. EXTRA Z'

$BR(\mu \to eee) >> 10^{-54}$

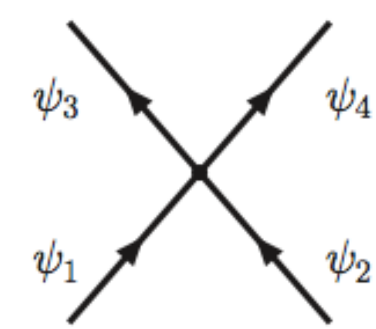




to probe otherwise unreachable and unexploited new physics energy scale

high energy probe

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



$\frac{1}{\Lambda^2}$

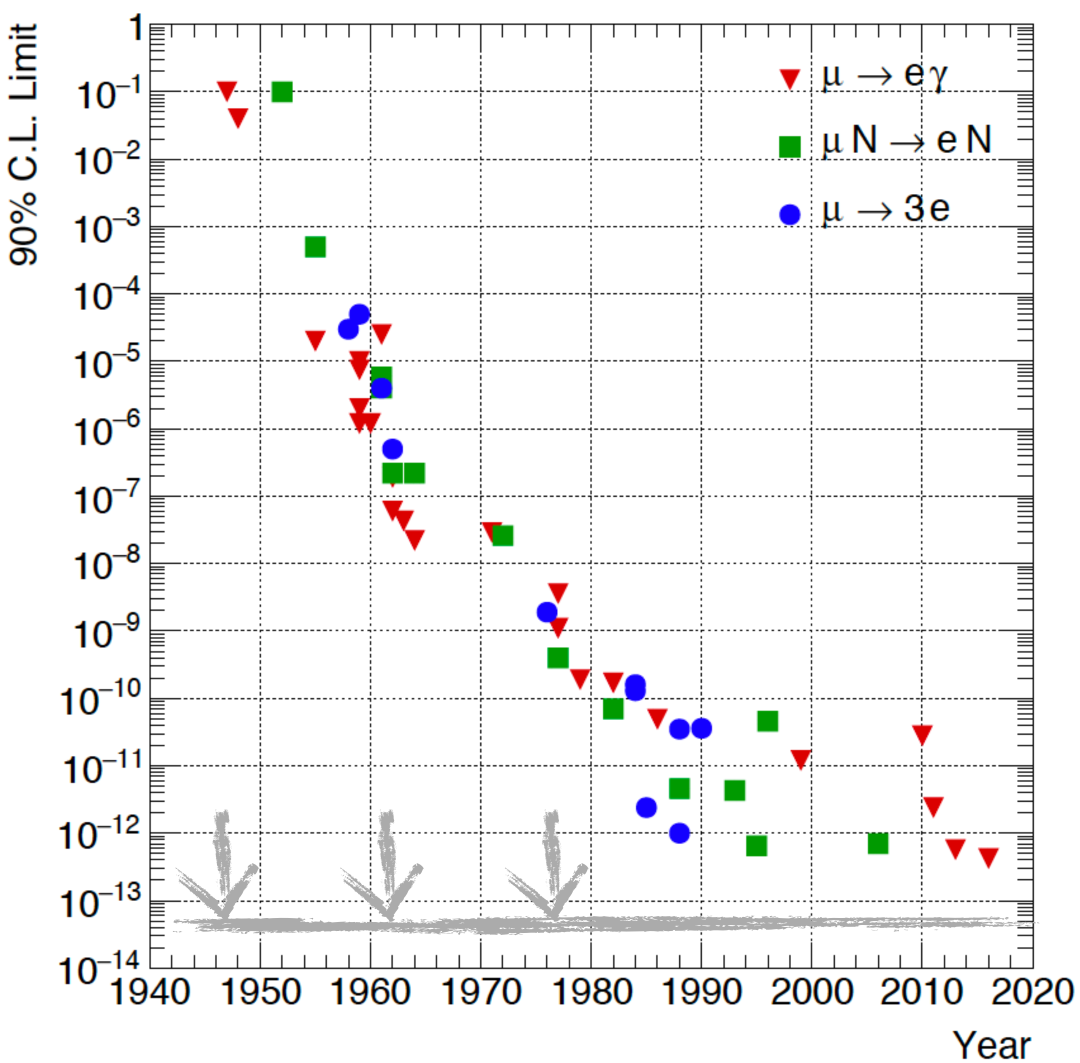
an experimental evidence:
a clear signature of New Physics NP

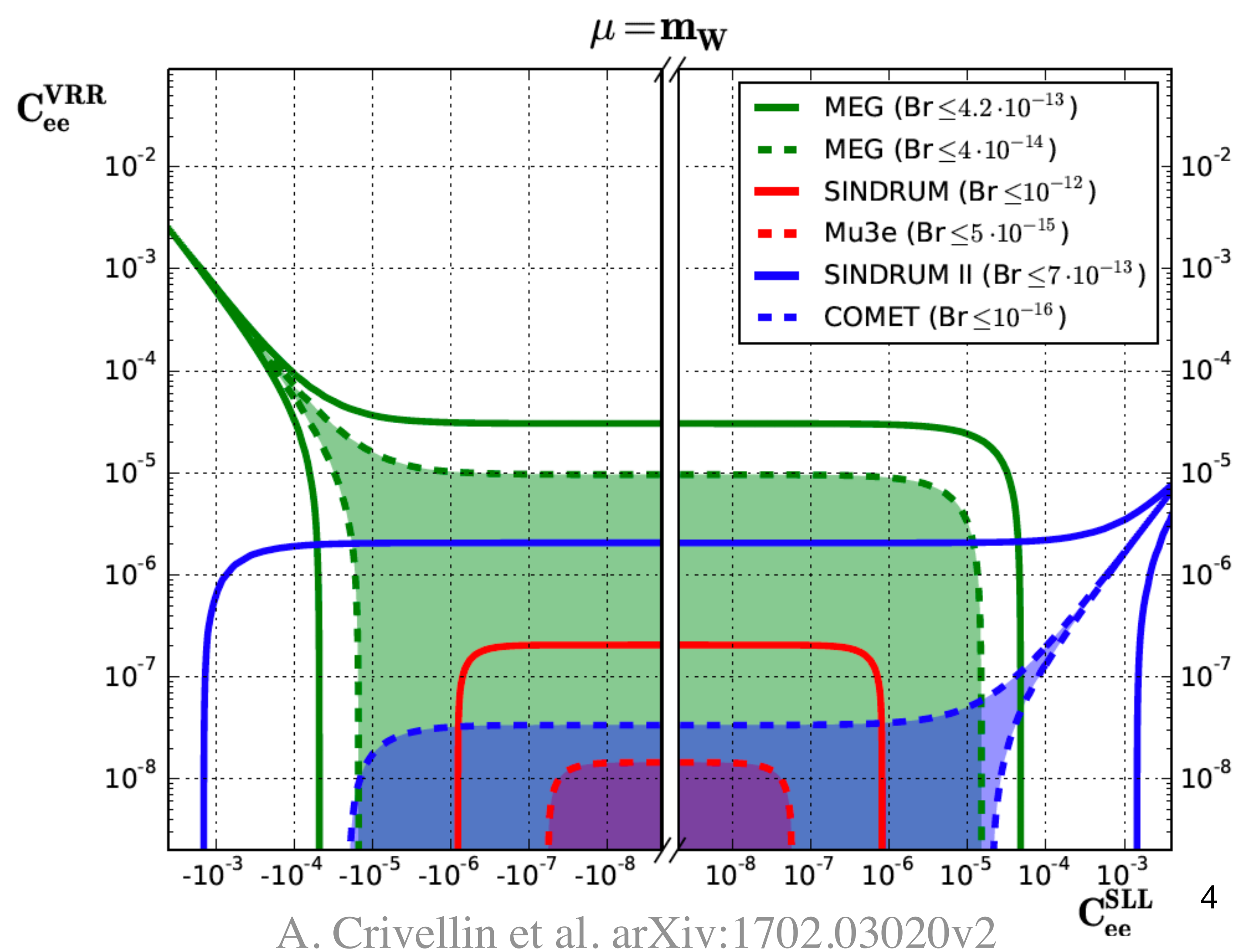
(SM background FREE)

cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities: BR($\mu \to e\gamma$) < 4 10^{-14} ; BR($\mu \to eee$) < 5 10^{-15}; CR($\mu N \to eN'$) < 10^{-16}

- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV





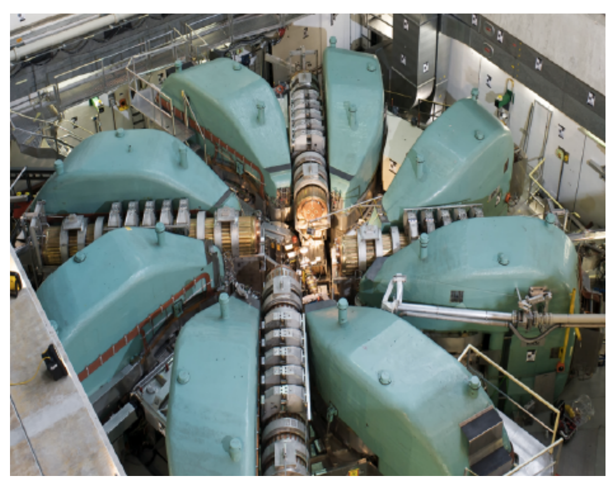
A. Crivellin et al. arXiv:1702.03020v2

The world’s most intense continuous muon beam

- PSI delivers the most intense continuous low momentum muon beam in the world (**Intensity Frontiers**)
- MEG/MEG II beam requirements:
  - Intensity O(10^8 muon/s), low momentum p = 29 MeV/c
  - Small straggling and good identification of the decay

- τ ideal probe for NP w. r. t. μ
  - Smaller GIM suppression
  - Stronger coupling
  - Many decays
- μ most sensitive probe
  - Huge statistics

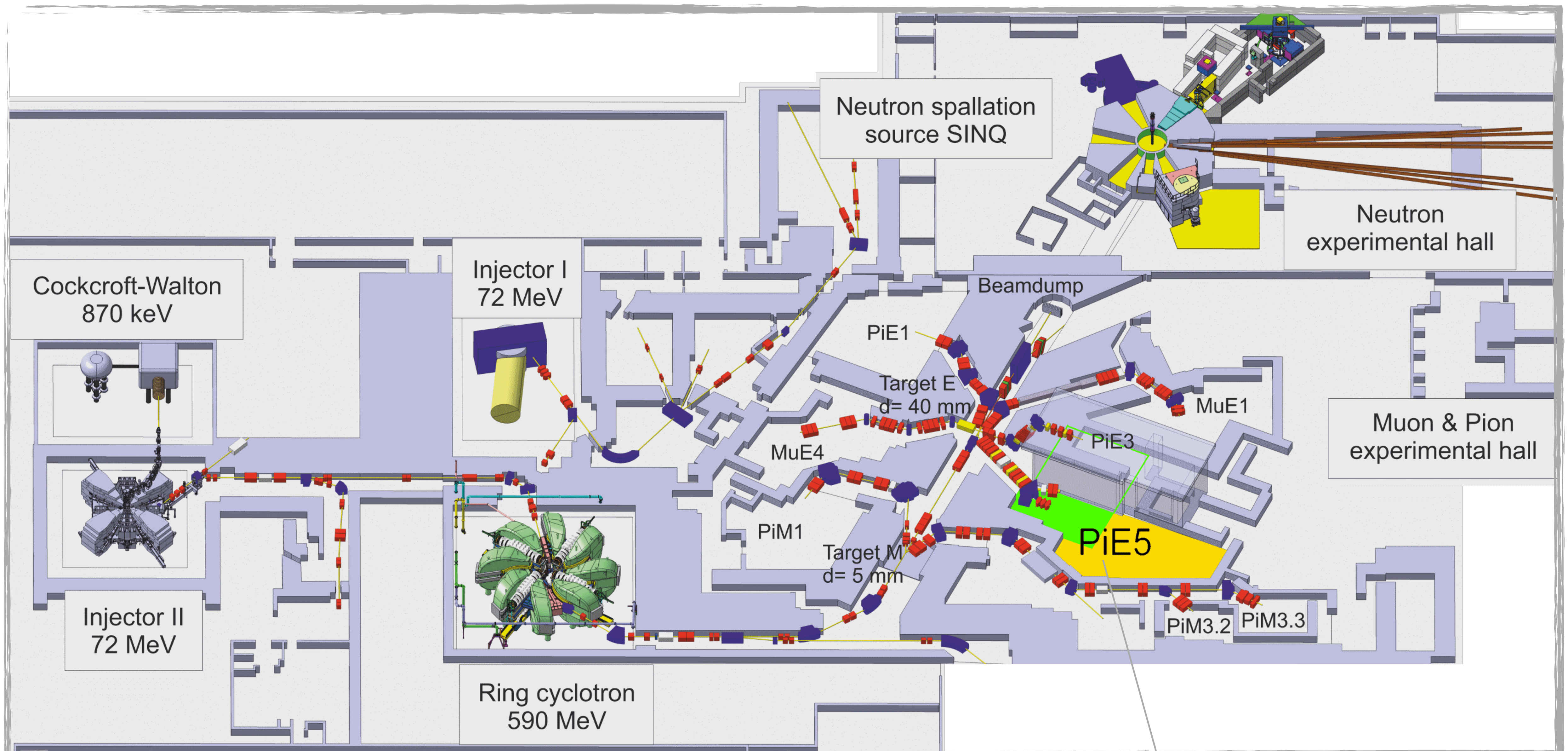
590 MeV proton
ring cyclotron
1.4 MW



PSI landscape

The world’s most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas

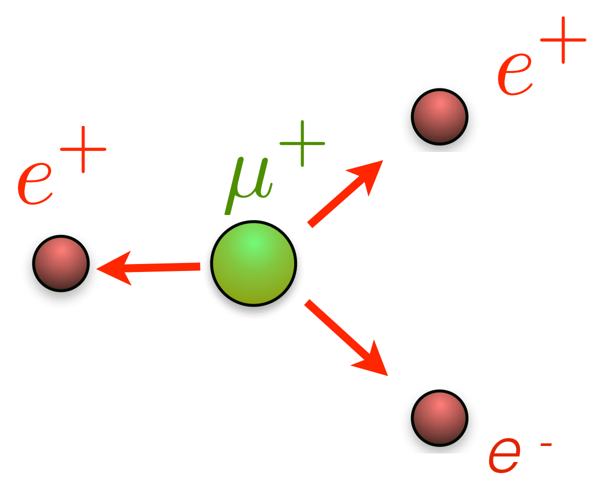


Mu3e Experimental area

Mu3e: The $\mu^+ \to e^+ e^+ e^-$ search

- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit BR($\mu^+ \to e^+ e^+ e^-$) ≤ 1 x 10^{-12} @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to eee$ events

Signature

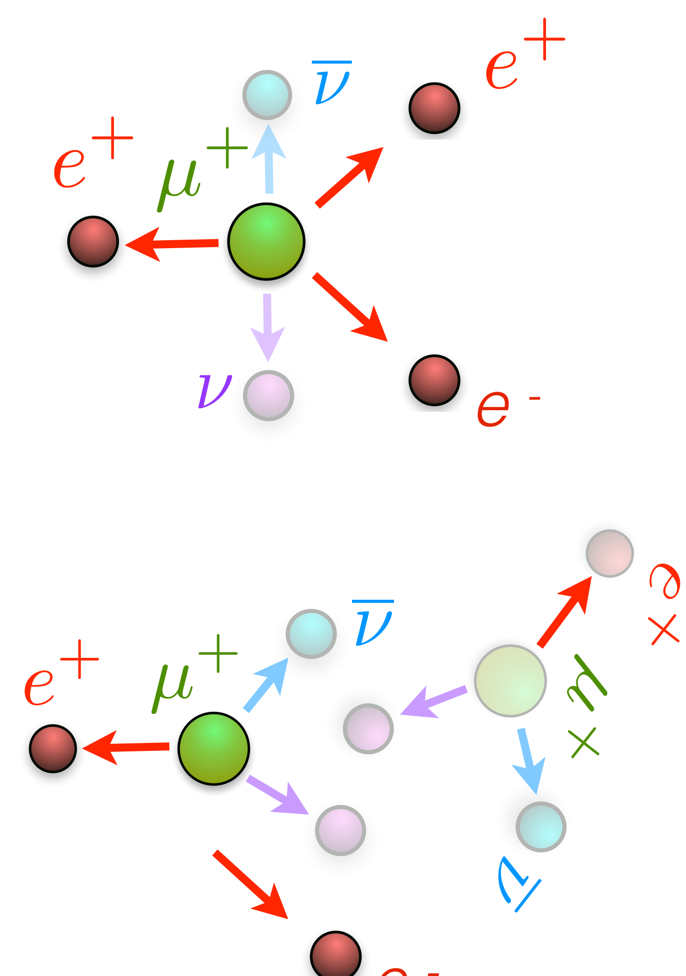


$$\Delta t_{eee} = 0$$

$$\Sigma \overline{p}_e = 0$$

$$\Sigma E_e = m_\mu$$

Background



Mu3e: Requirements

Signal

1. $\mu \rightarrow eee$

- Rare decay search: Intense muon beam O(10*8 muon/s) for phase I
- High occupancy: High detector granularity
- Three charged particles in the final state: allowing for high detector performances vs the case of having neutral particle

Background

1. $\mu \rightarrow eee\nu\nu$

- Missing energy: Excellent momentum resolution

2. $\mu \rightarrow e\nu\nu, \mu \rightarrow e\nu\nu\,,\, e^+e^-$

- Coincidence and vertex: High timing and position resolutions

The Mu3e experiment: Schematic 3D

Superconducting solenoid Magnet

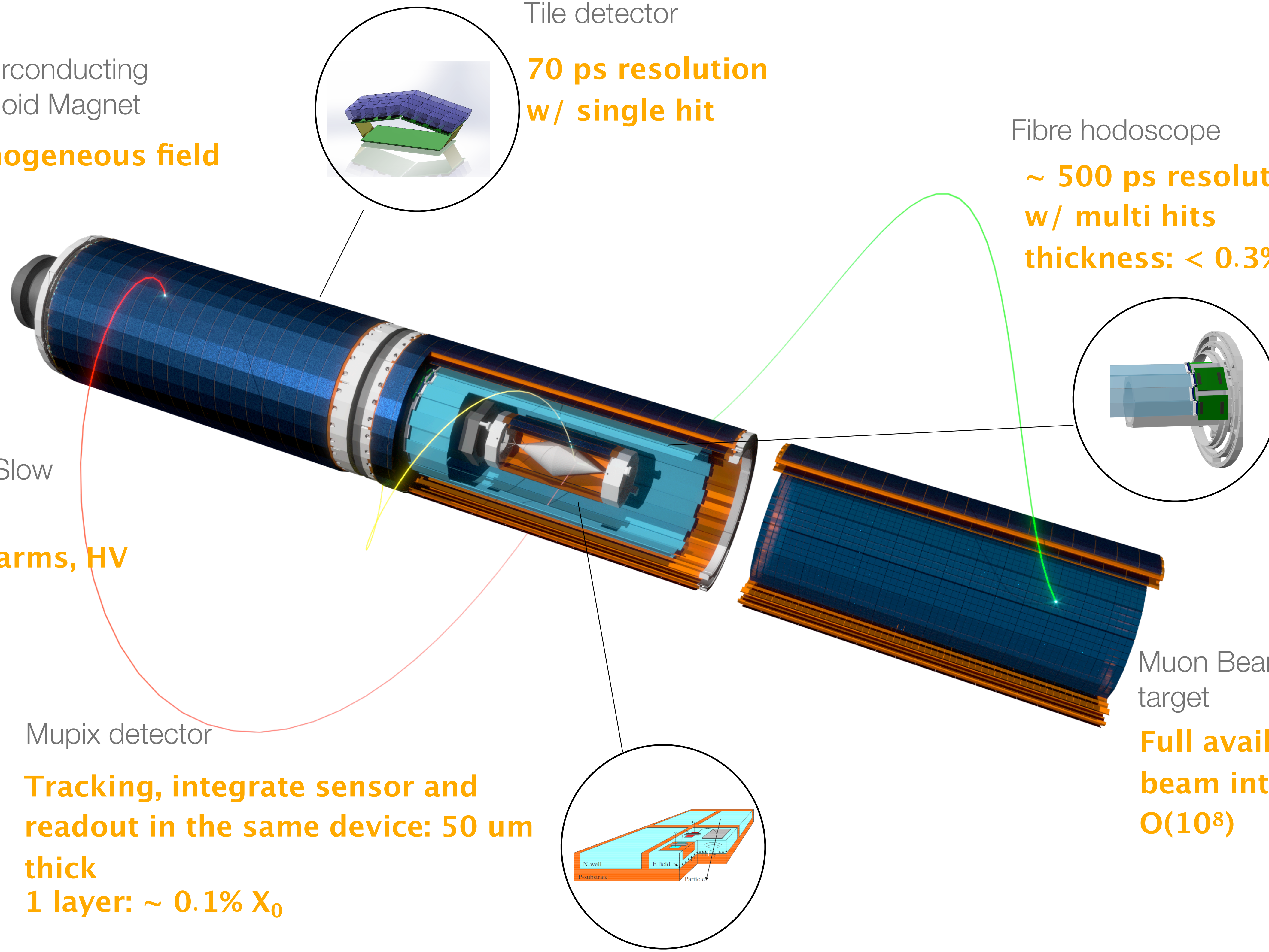
Homogeneous field 1T

Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

~ 500 ps resolution w/ multi hits thickness: < 0.3% X_0



MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

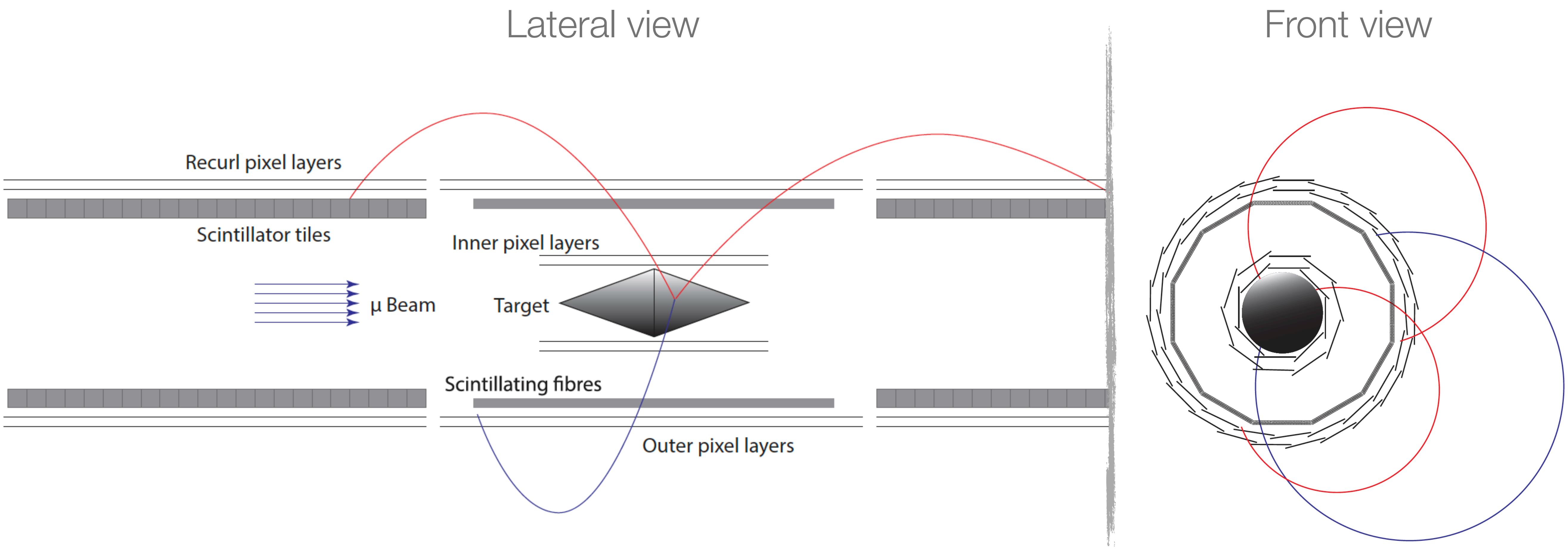
Muon Beam and target

Full available beam intensity $O(10^8)$

Mupix detector

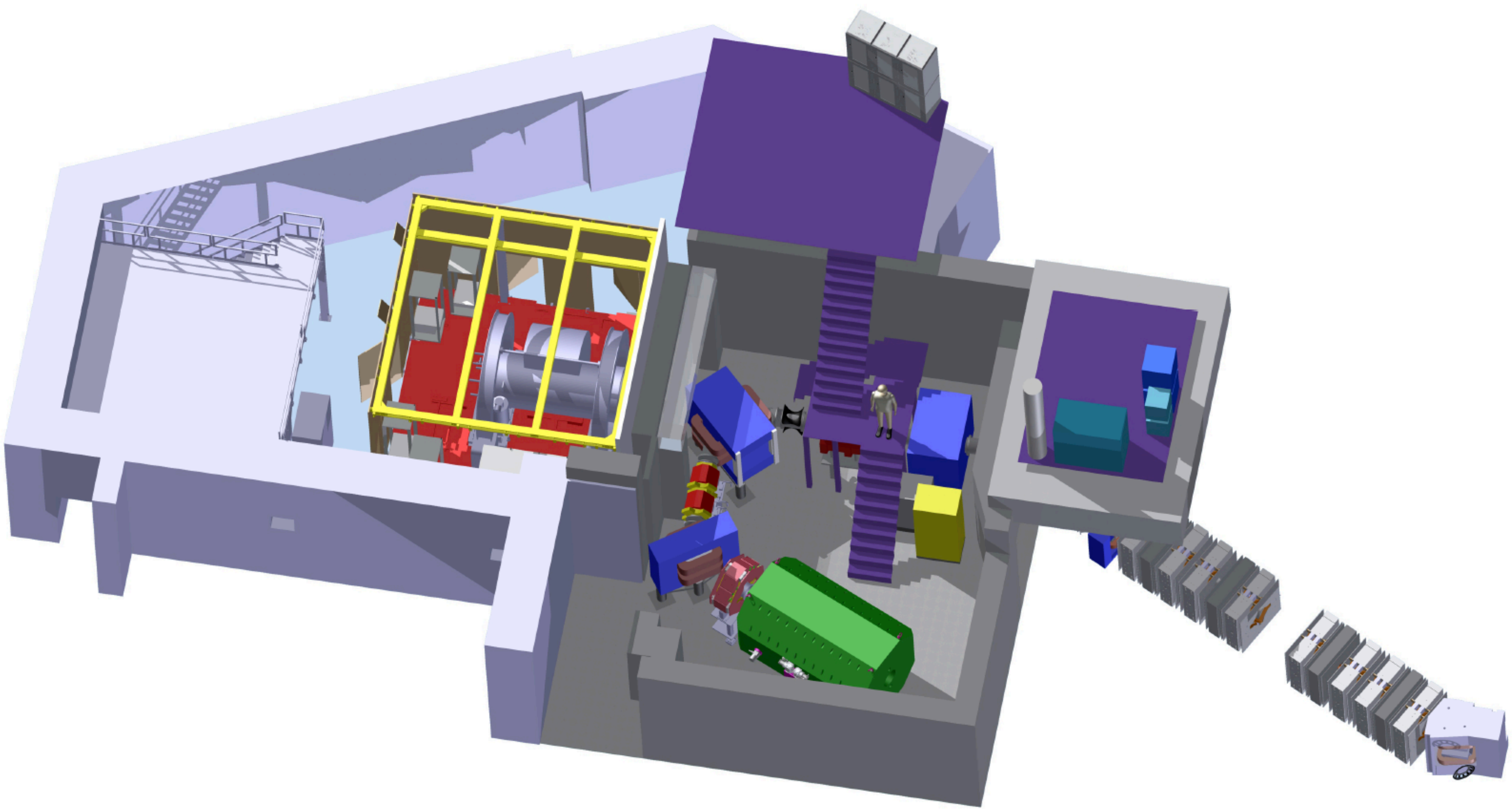
Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X_0

The Mu3e experiment: Schematic 2D

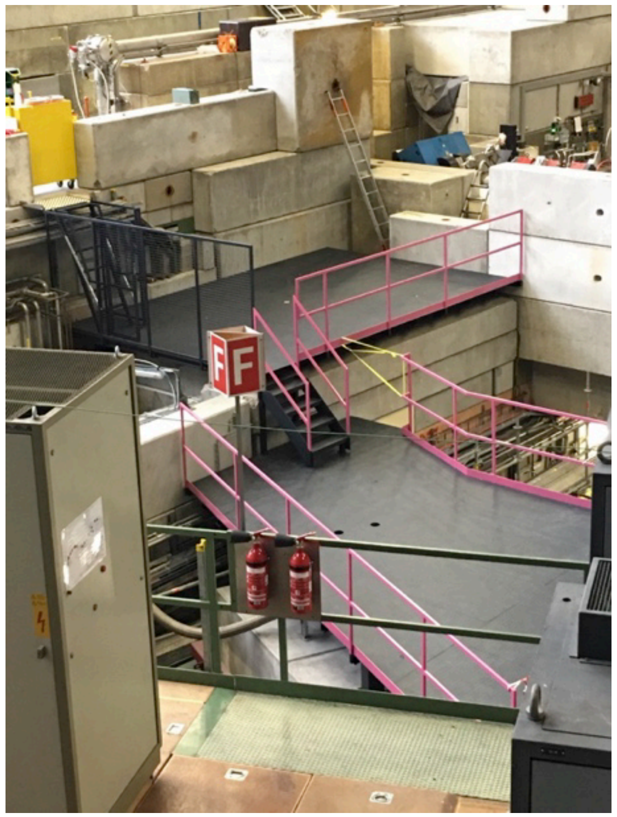


The experimental area

- MEGII and Mu3e will share the same main beam line: A new infrastructure has been built to accomodare both experiment

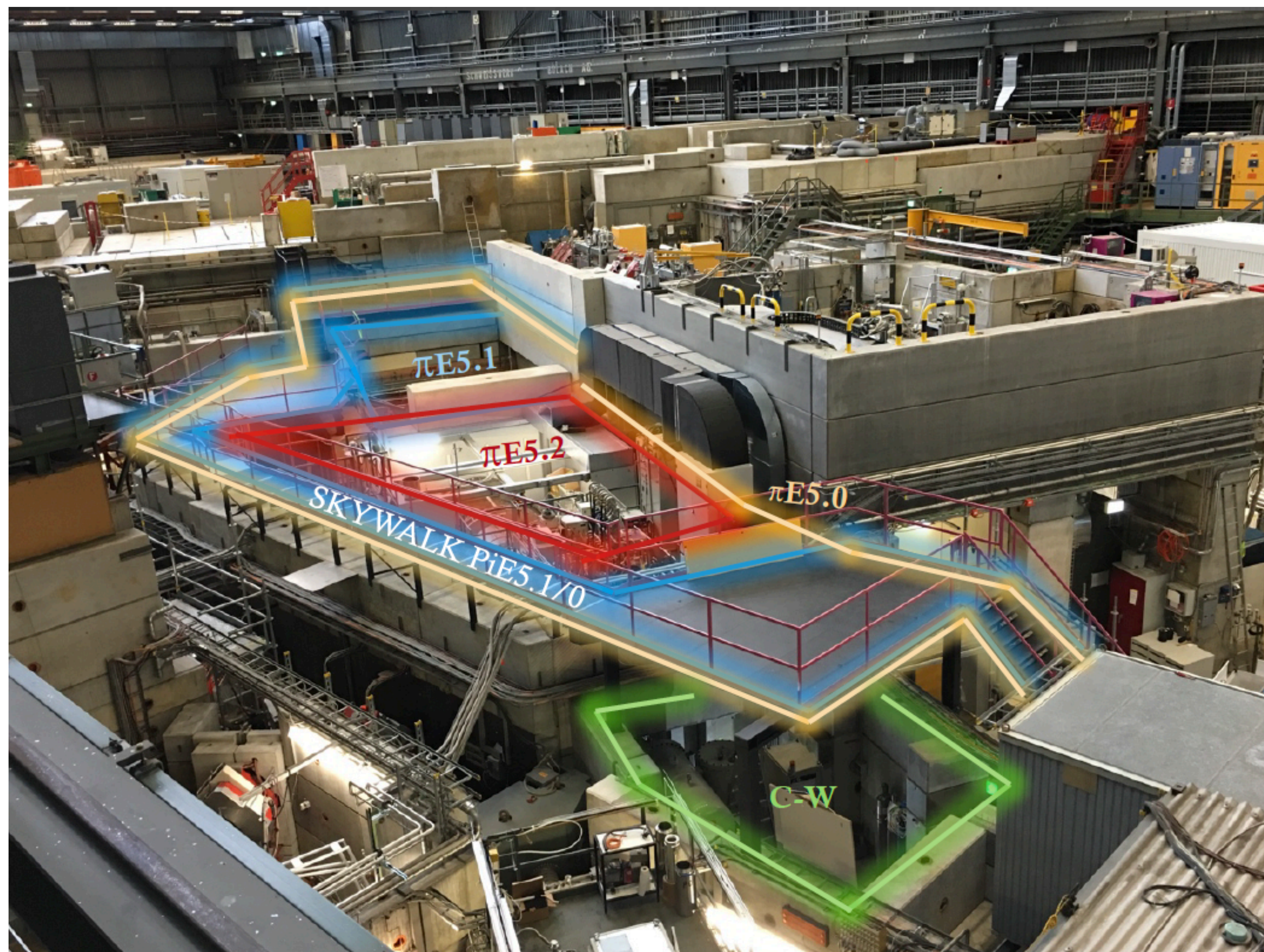


The experimental area: Pictures



Mu3e extra platforms

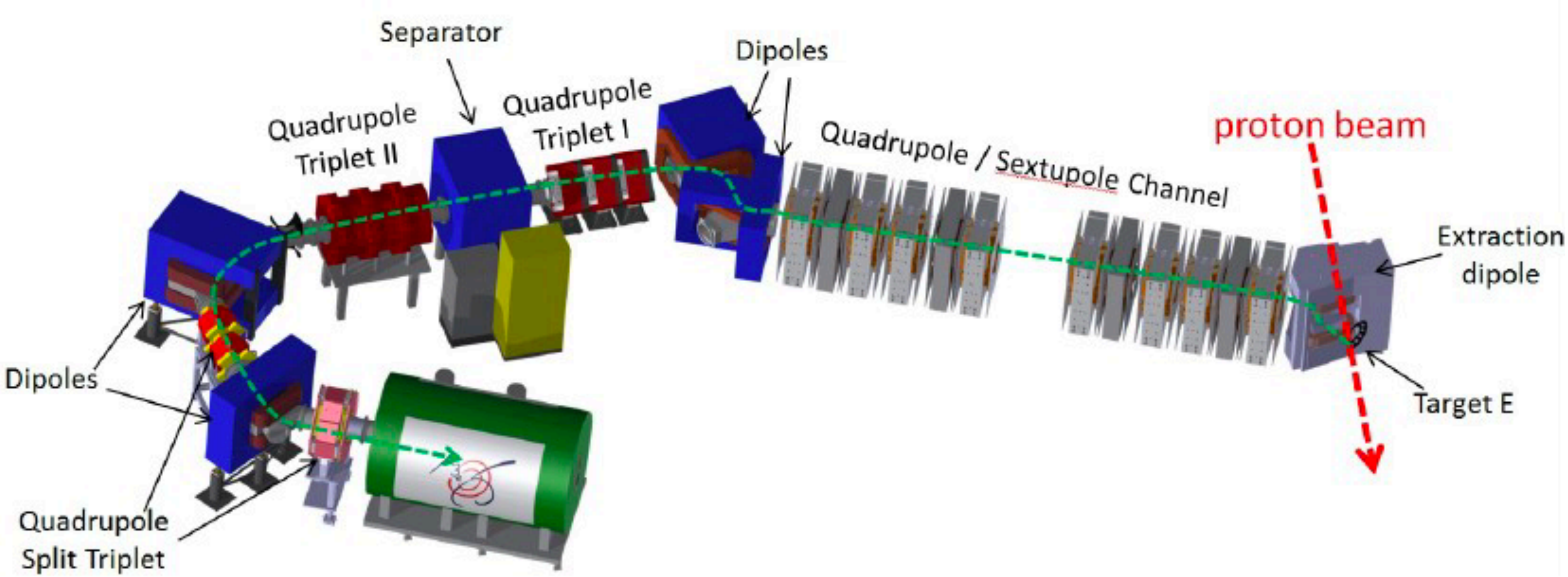
Overview piE5 area



The compact beam line

- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Aim: To deliver O(10^8) muon/s

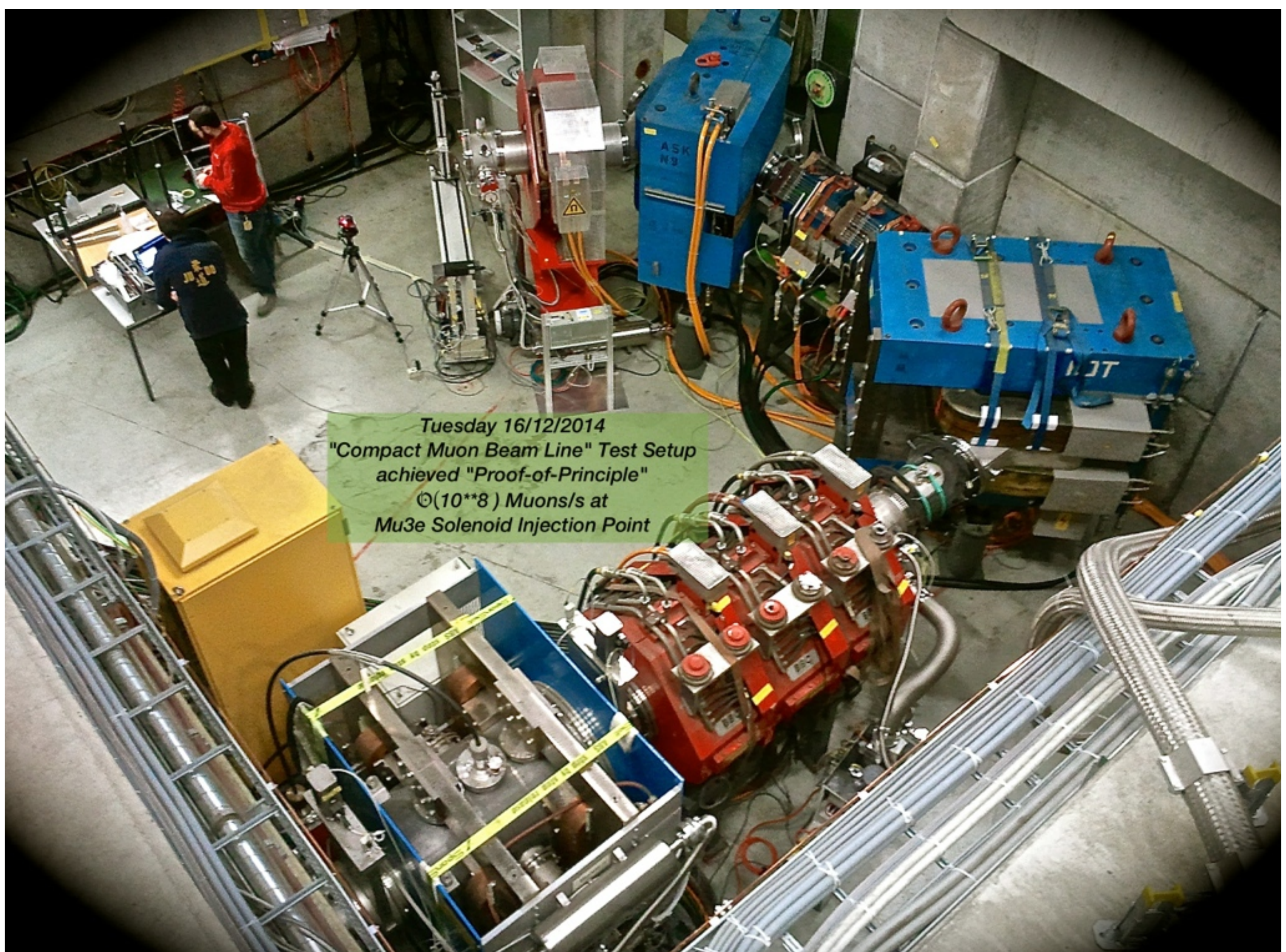
The CMBL



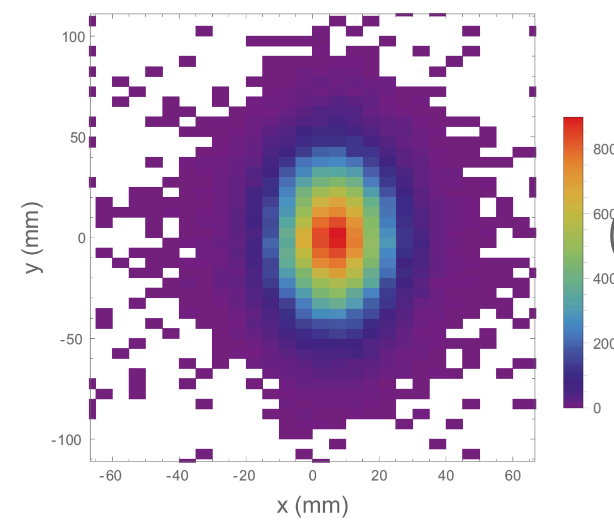
The compact beam line: Pictures and results

- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered 8.4 10^7 muon/s during 2016 test beam

The CMBL

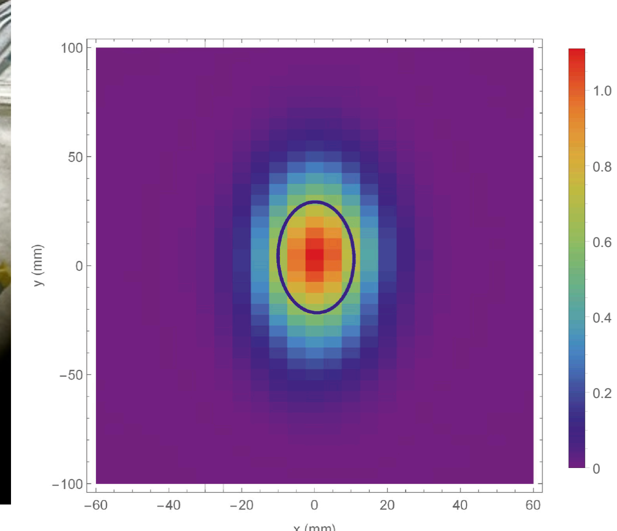


Beam at the injection Mu3e solenoid point



Simulation

$$(\sigma_x, \sigma_y) = (10.6, 24.3)[\mathrm{mm}]$$



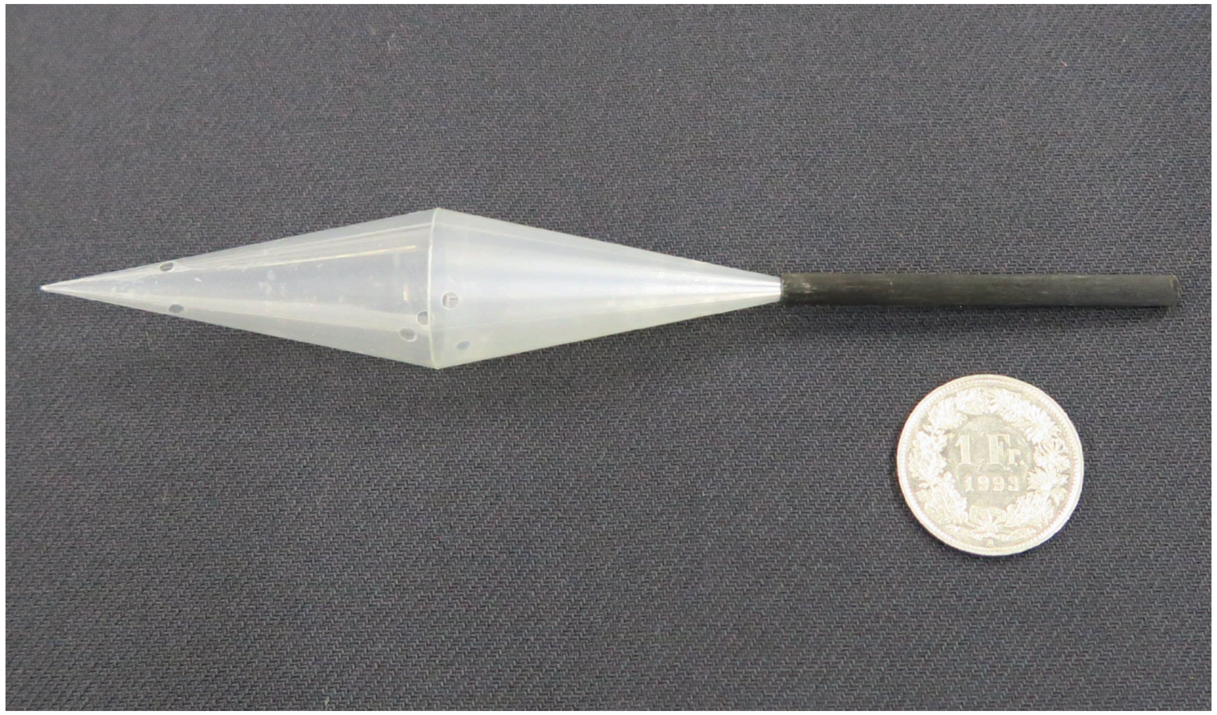
Data

$$(\sigma_x, \sigma_y) = (10.4, 25.4)[\mathrm{mm}]$$

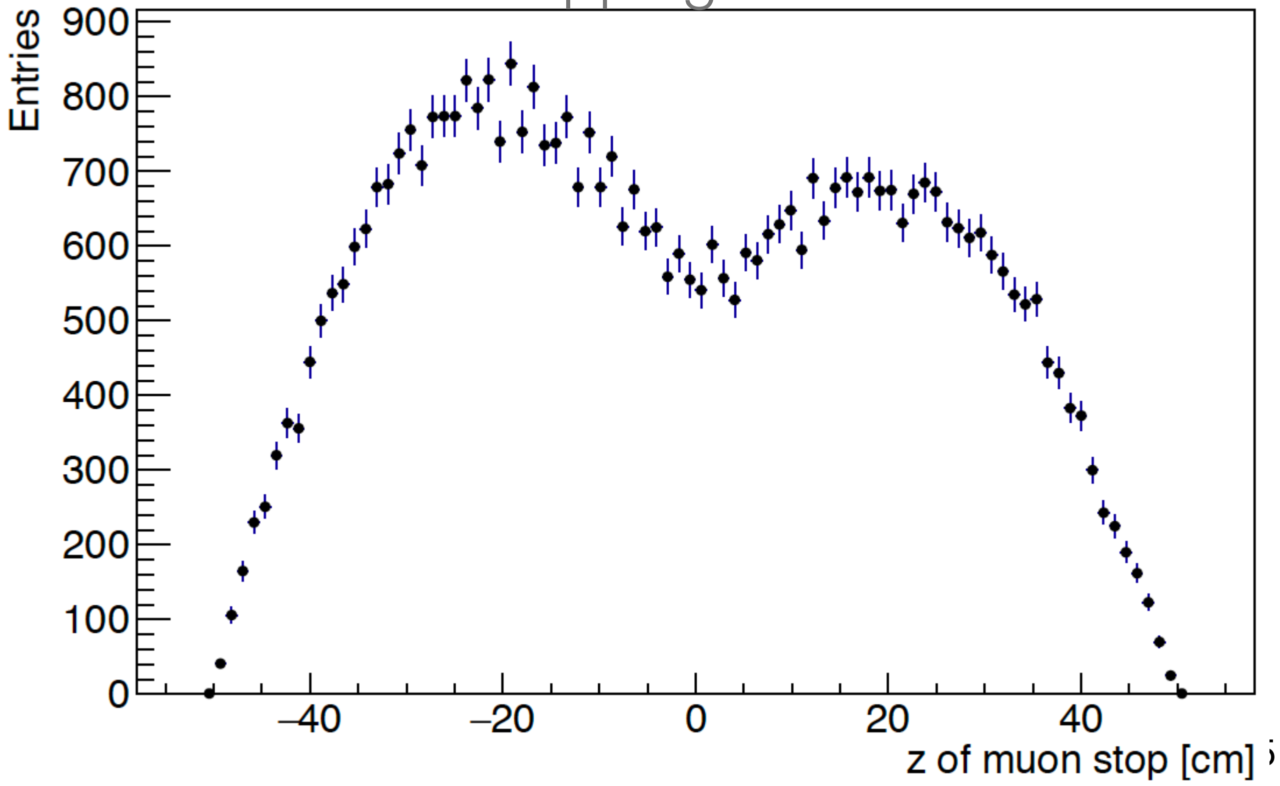
The target

- Mylar double hollow cone
- Large target area (L = 100 mm, R = 19 mm; A ~ XXX mm^2)
- Low material budget: (asymmetric structure: US 75 um, DS 85 um)
- Stopping efficiency: ~ 83%
- Vertex separation ability (tracking) < 200 um

Target prototype



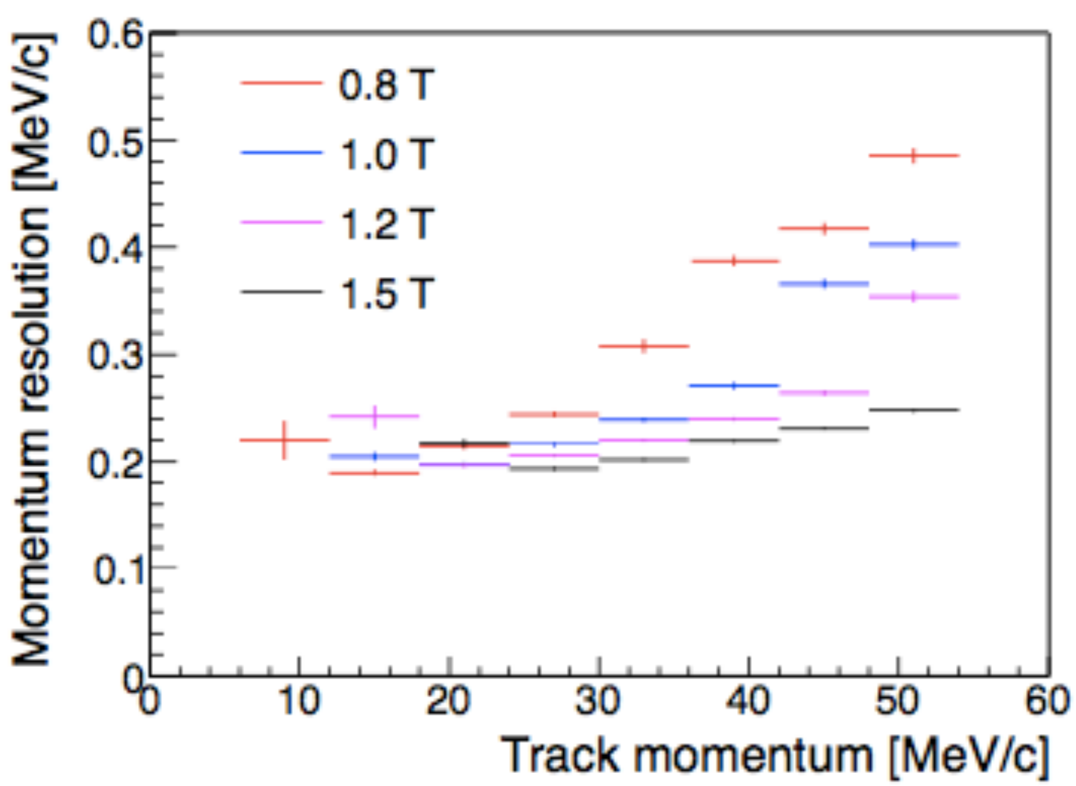
Simulation: Stopping distribution

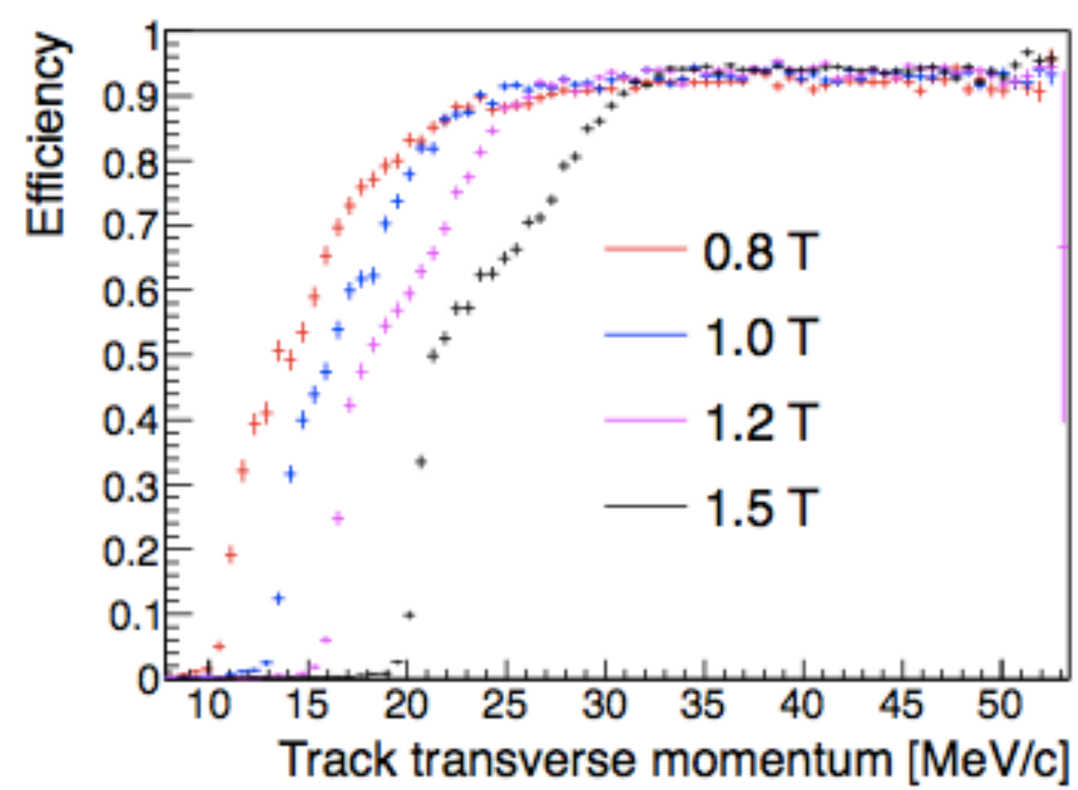


The magnet: The characteristics

- Superconducting Solenoidal magnet: Precise momentum determination, beam transport to the target
- Field Intensity: 1T
- Field description: $dB/B \leq 10^{-4}$
- Field stability: $dB/B(100\ d) \leq 10^{-4}$
- Dimensions: L < 3.2 m, W < 2.0 m, H < 3.5 m

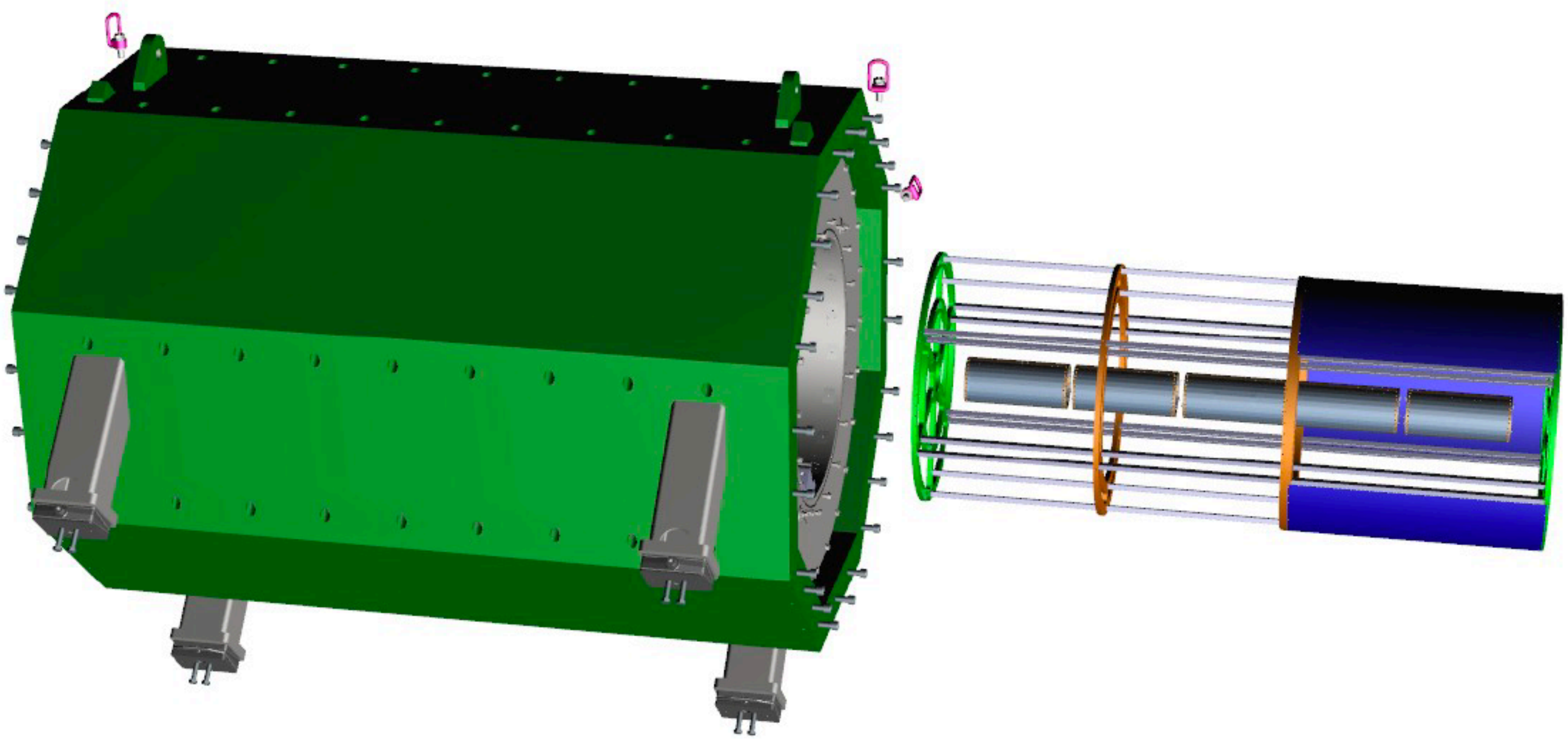
Simulation





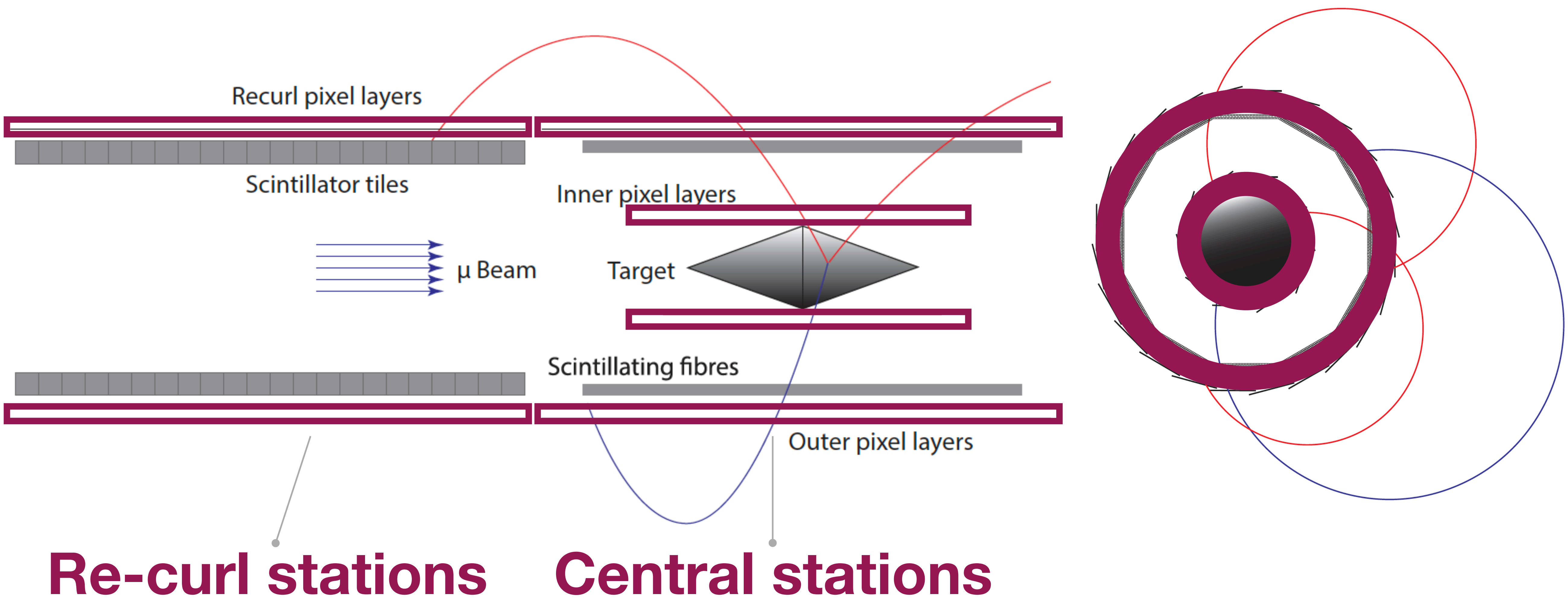
The magnet: Status

- Contract with DANFYSIK in July 2015
- Delivery including the commissioning of the magnet at PSI originally foreseen for December 2016. Contract cancel in January 2017
- Current status: In contact several companies. New delivering date: beginning 2019



The pixel tracker: Overview

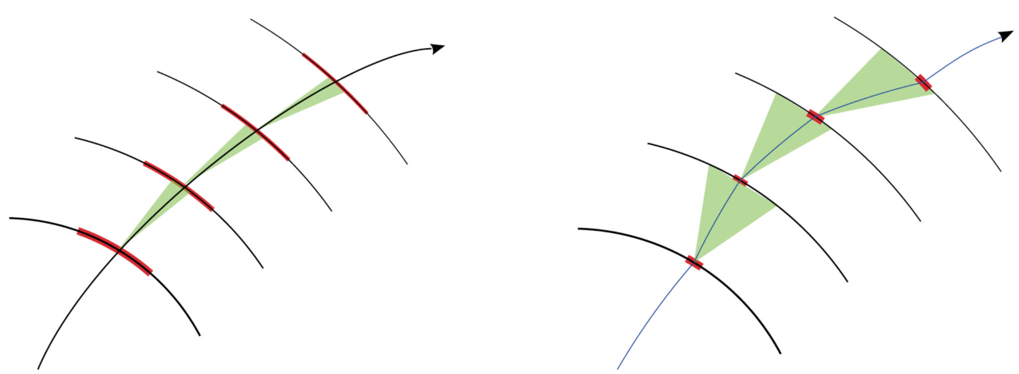
- Central tracker: Four layers; Re-curl tracker: Two layers



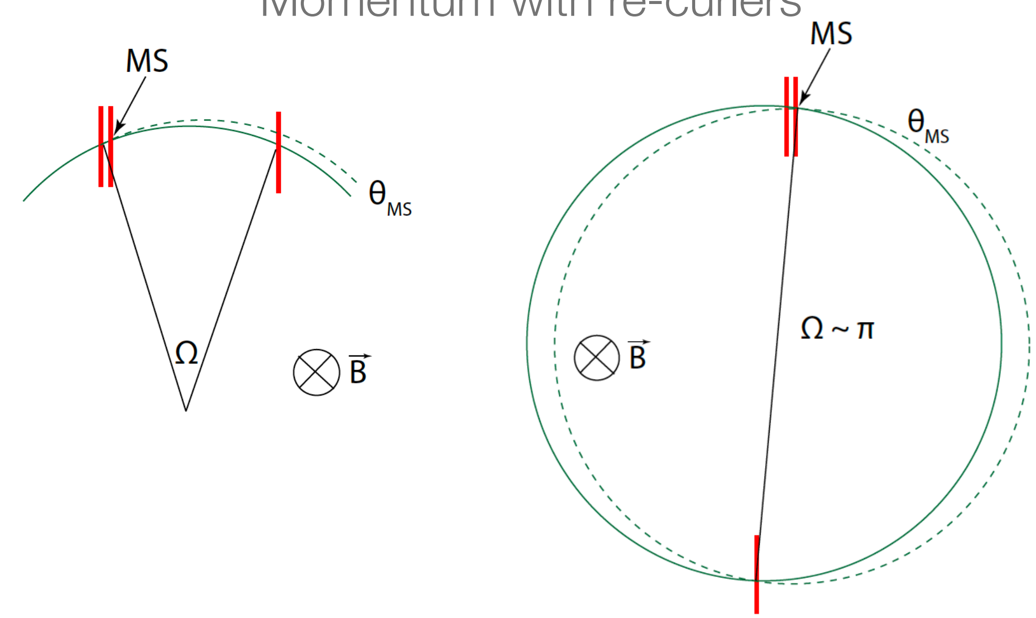
The pixel tracker: The principle

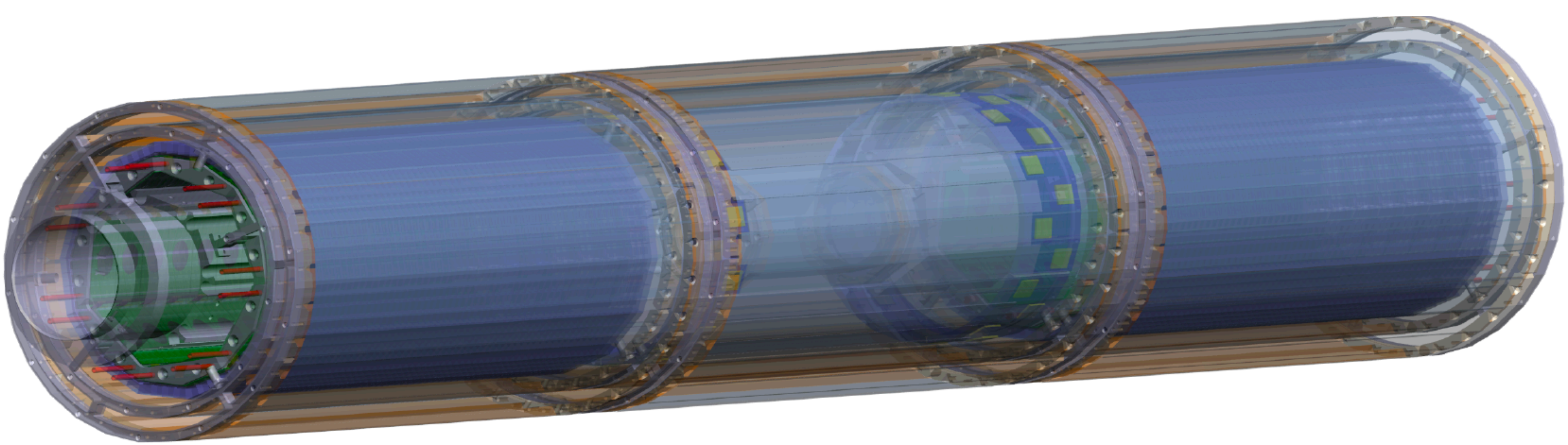
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime

Tracking in the spacial and scattering dominated regime



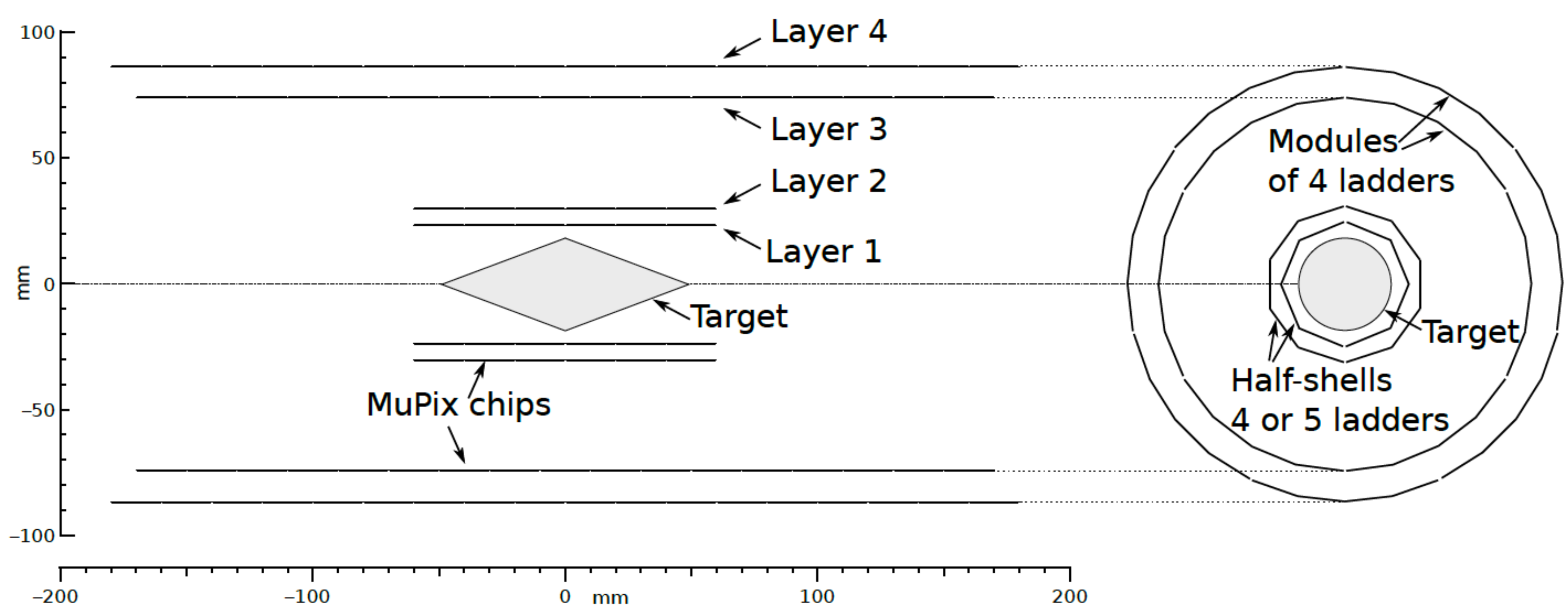
Momentum with re-curlers





The pixel tracker: The geometry

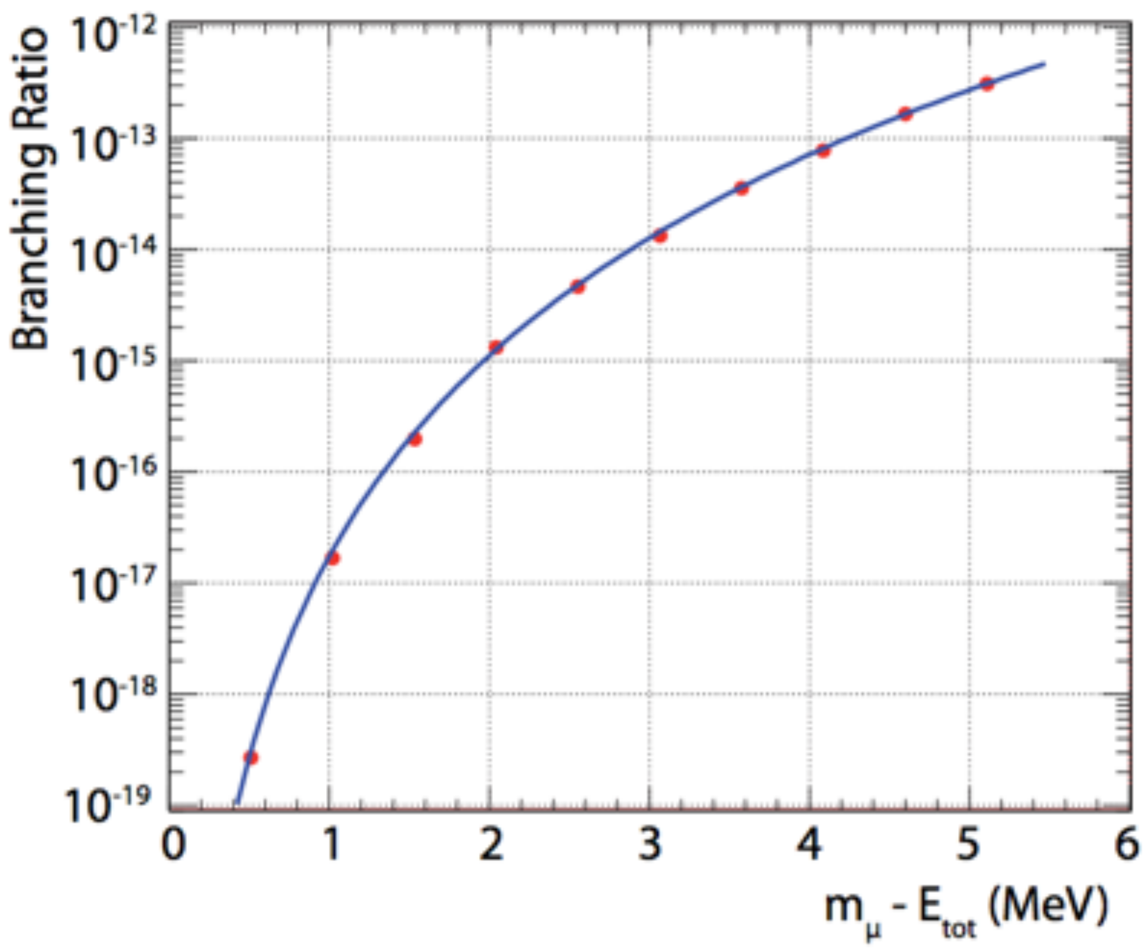
- Central tracker: Four layers; Re-curl tracker: Two layers

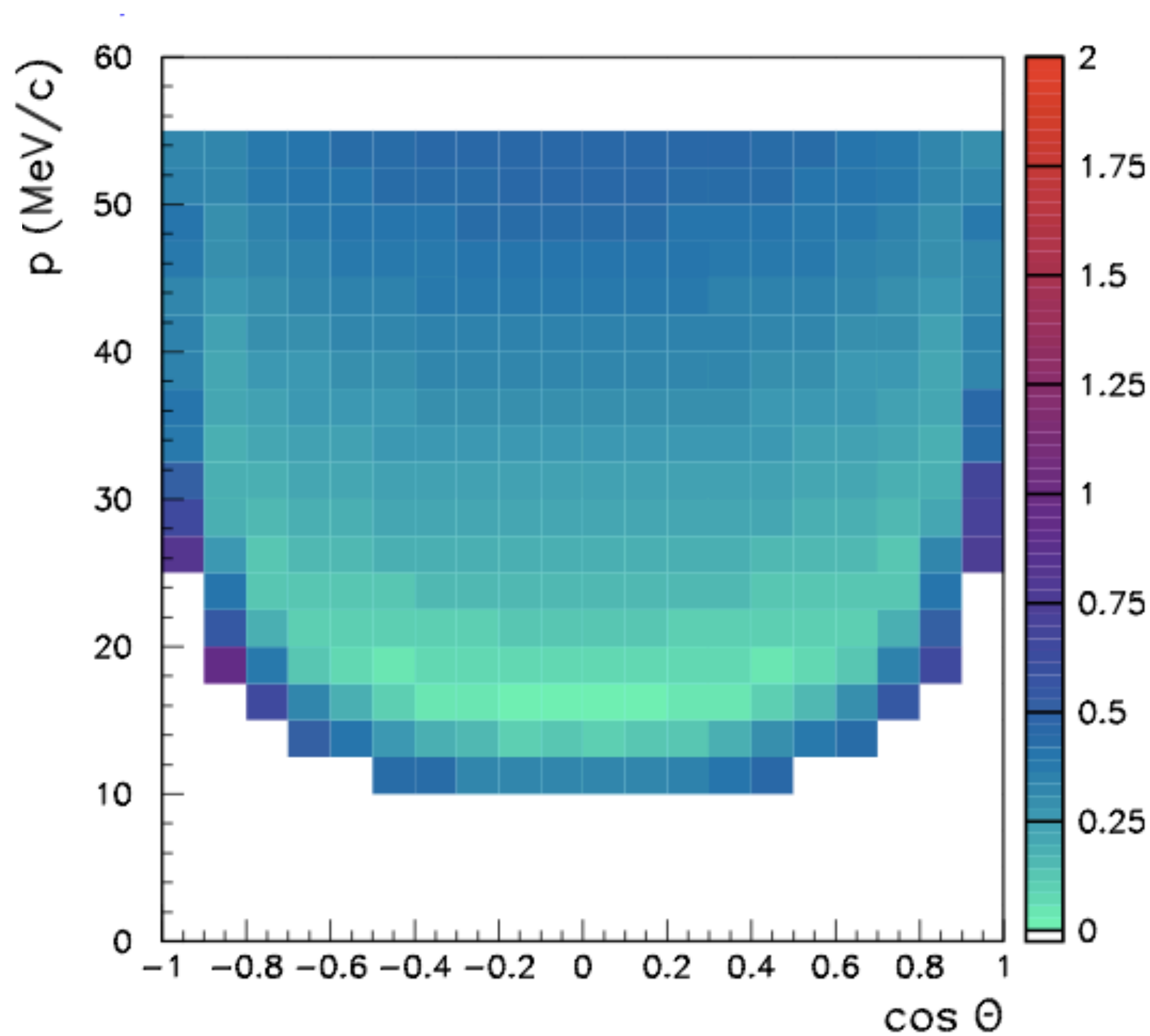


The central tracker. Re-curl stations copies of layer 3/4 , extending in z

The pixel tracker: The performances

- Momentum resolution: < 0.5 MeV/c over a large phase space
- Geometrical acceptance: ~ 70%
- X/X_0 per layer: ~ 0.011%
- Vertex resolution: < 200 μm



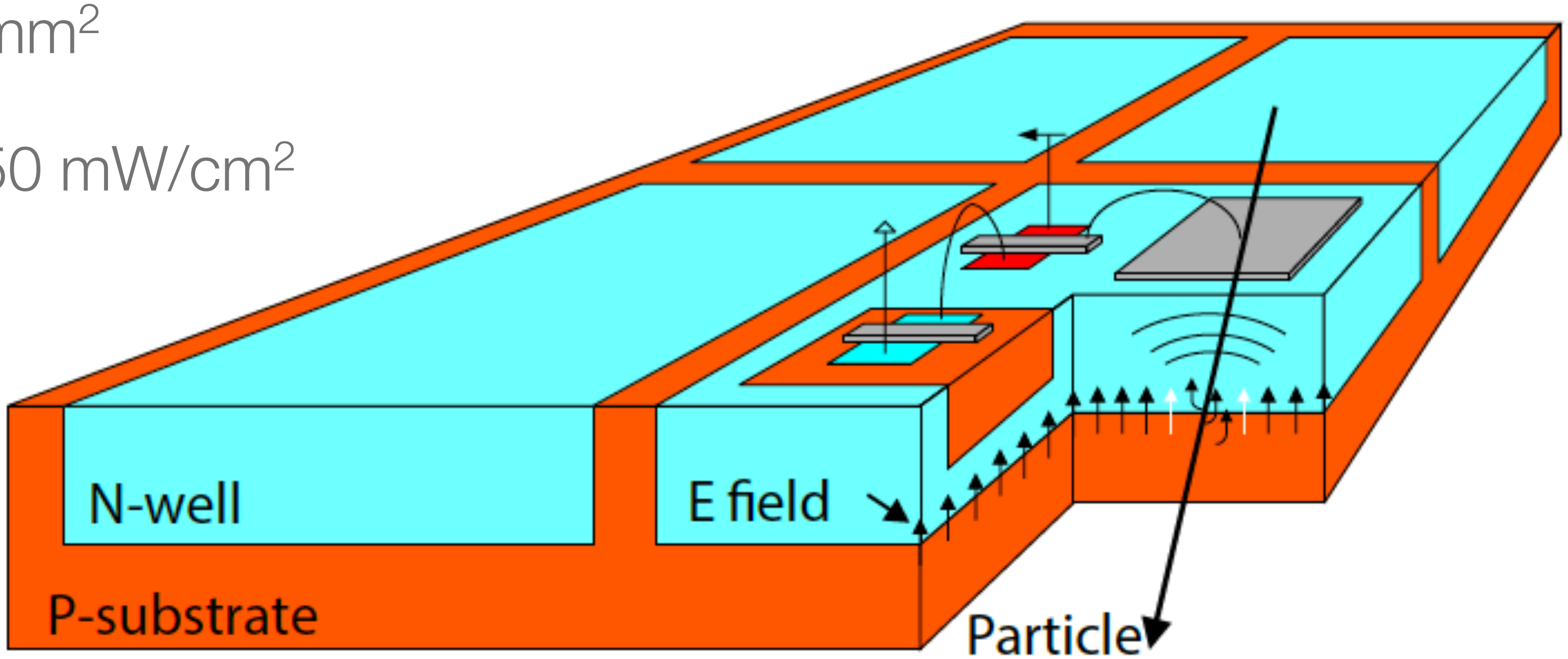


The pixel tracker: The sensors

- Pixel dimension: 80 x 80 μm^2
- Thickness: 50 μm
- Sensor and readout integrated on the same device
- Efficiency: > 99 %
- Time resolution: < 20 ns
- Active area chip: 20 x 20 mm^2
- Power consumption : < 350 mW/cm^2

Ivan Peric, Nucl.Instrum.Meth. A582 (2007) 876-885

HV-MAP

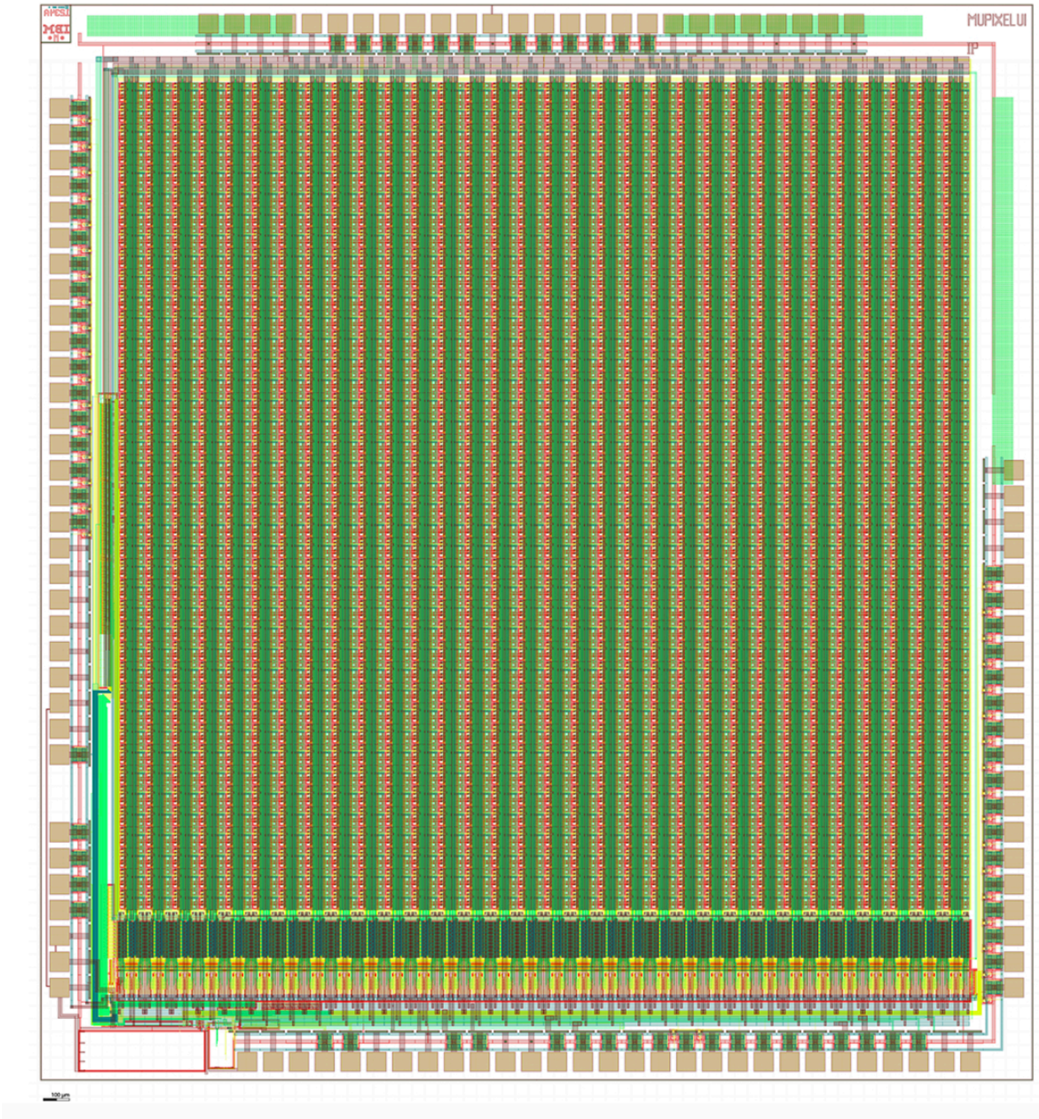


The pixel tracker: The MuPix prototypes

- Rapid development
- MuPix 7: The first small-scale prototype which includes all Mu3e functionalities

Prototype	Active Area [mm^2]
MuPix1	1.77
MuPix2	1.77
MuPix3	9.42
MuPix4	9.42
MuPix6	10.55
MuPix7	10.55

MuPix7

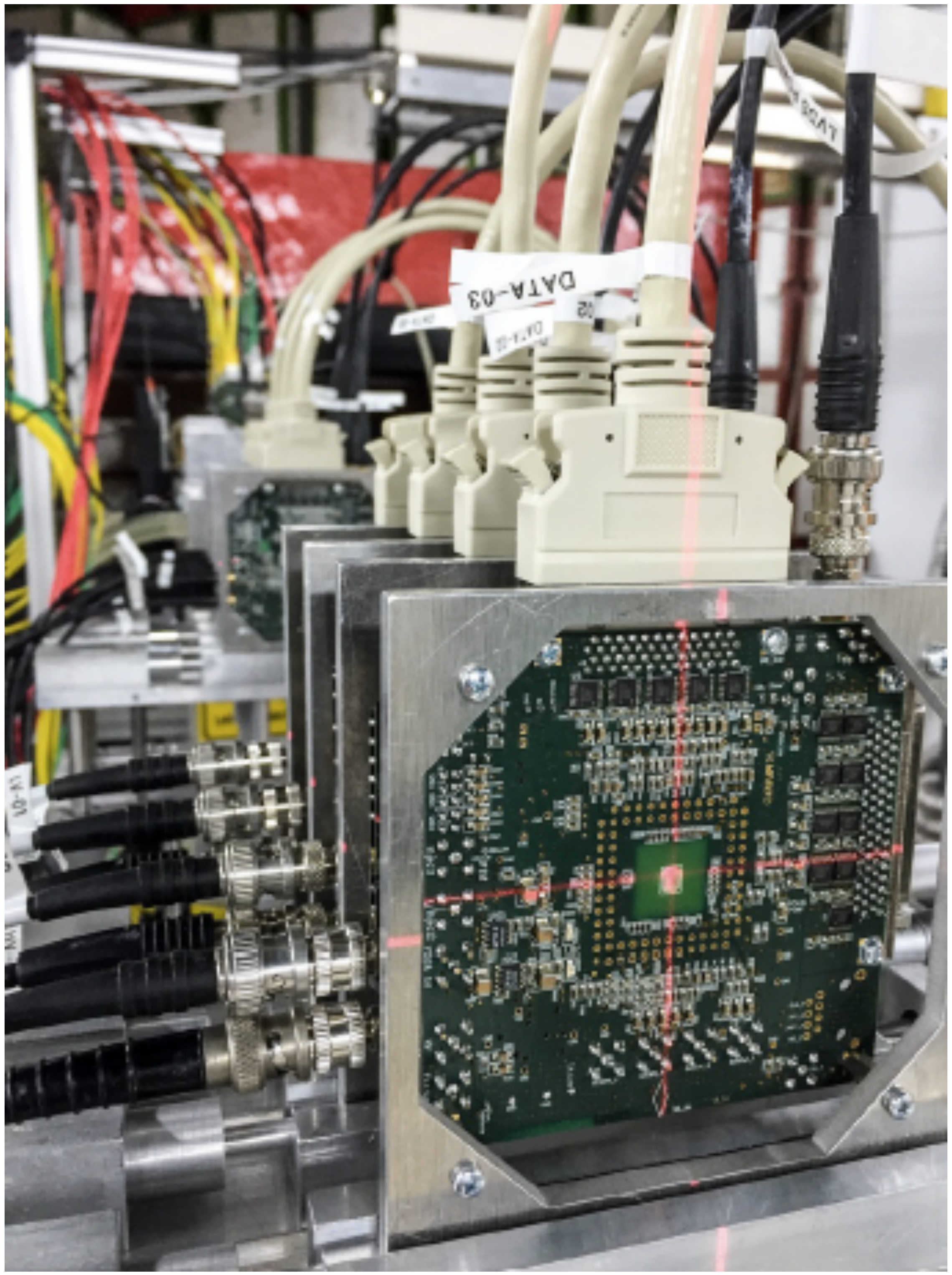


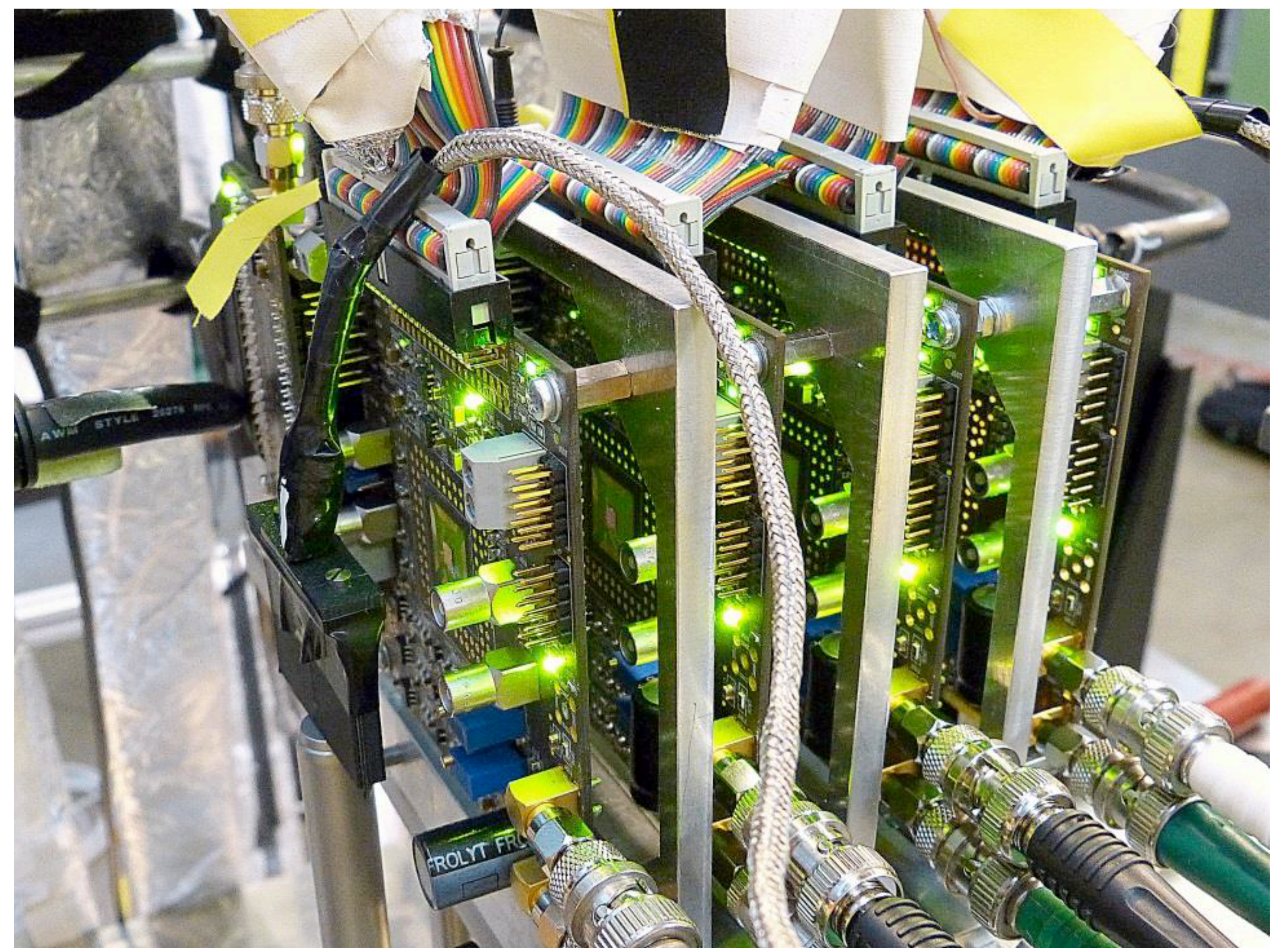
Prototypes: Current and future plan

- After an extensive test beam campaign, achieved milestones
  - A fully functional HV-MAPS chip, 3x3 mm^2
  - Operation at high rates: 300 kHz at PSI; up to 1 MHz at SPS
  - Crosstalk on setup under control, on chip seen. Mitigation plan exists (MuPix8)
  - Routinely operated systems of up to 8 chips in test beams reliably
  - Data processing of one telescope at full rate on GPU demonstrated

- Next steps
  - MuPix 8, the first large area prototype: from O(10) mm^2 to 160 mm^2
  - Tested soon from this summer
  - MuPix 9, small test chip for: Slow Control, voltage regulators and other test circuits
  - MuPix 10, the final version for Mu3e: Active area from 160 mm^2 to 380 mm^2

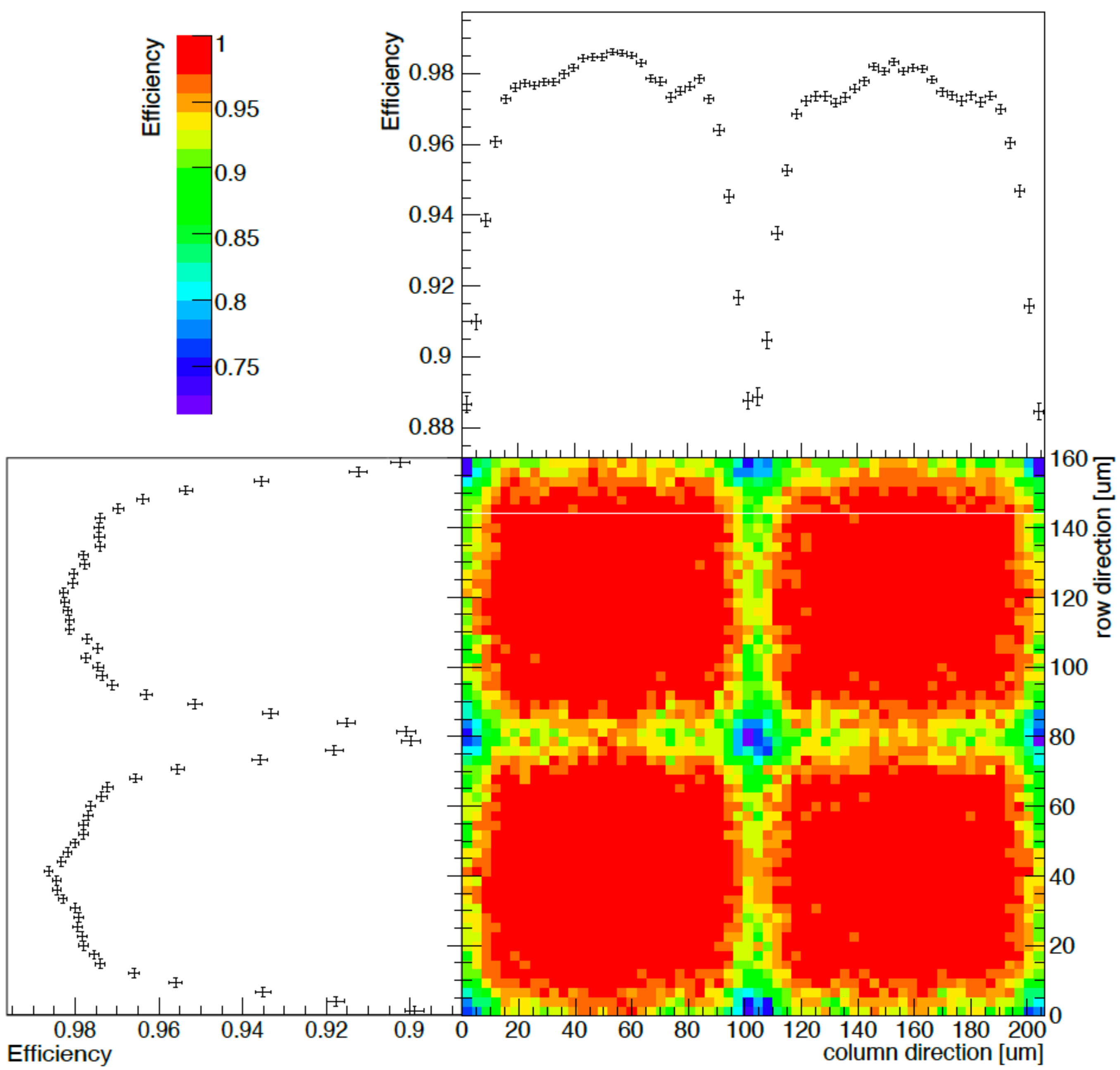
Prototypes: Pictures





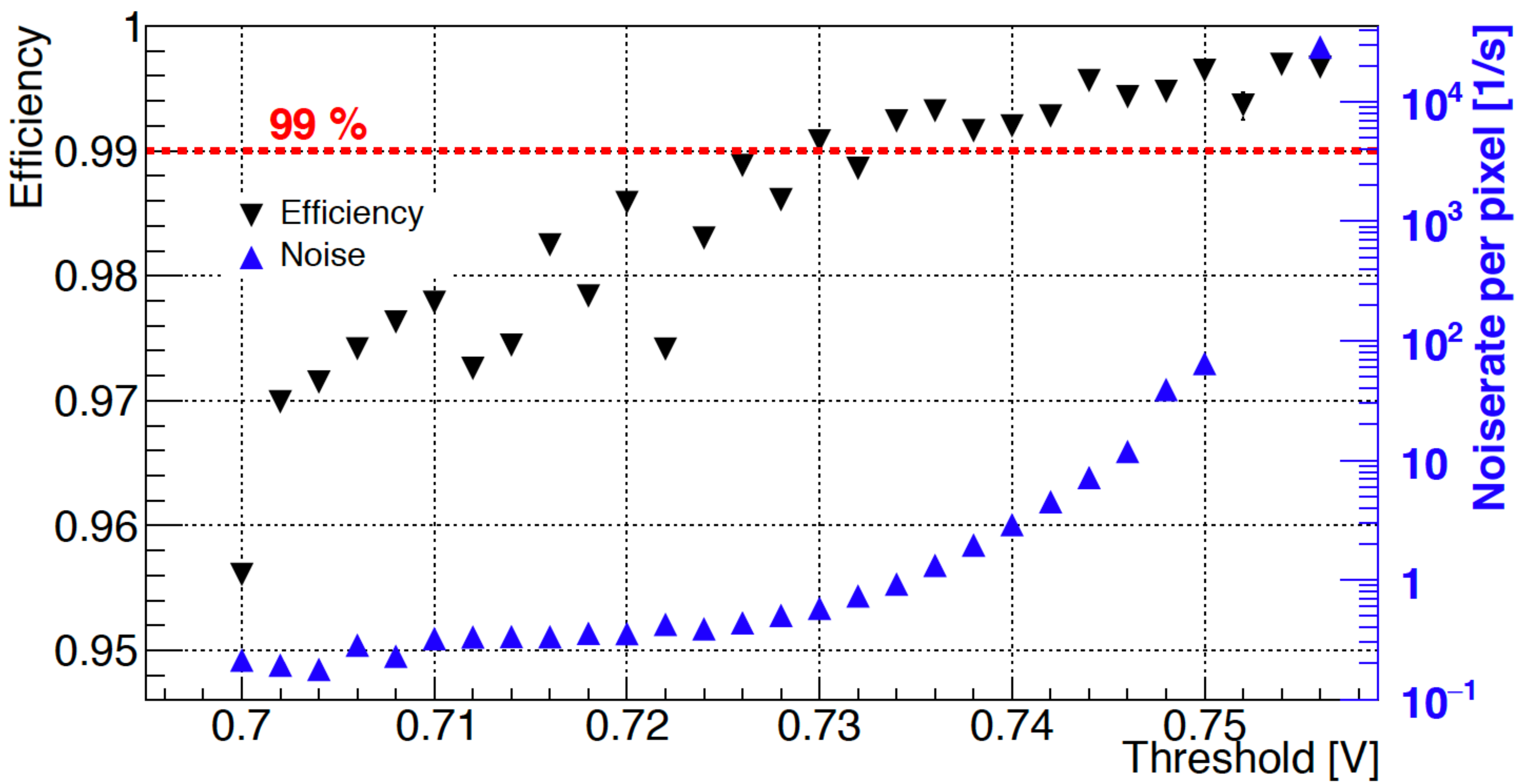
Prototypes: Results

- Hit map efficiency. MuPix7: 2 x 2 pixel array. Bias voltage: -40 V
- 4 GeV electrons



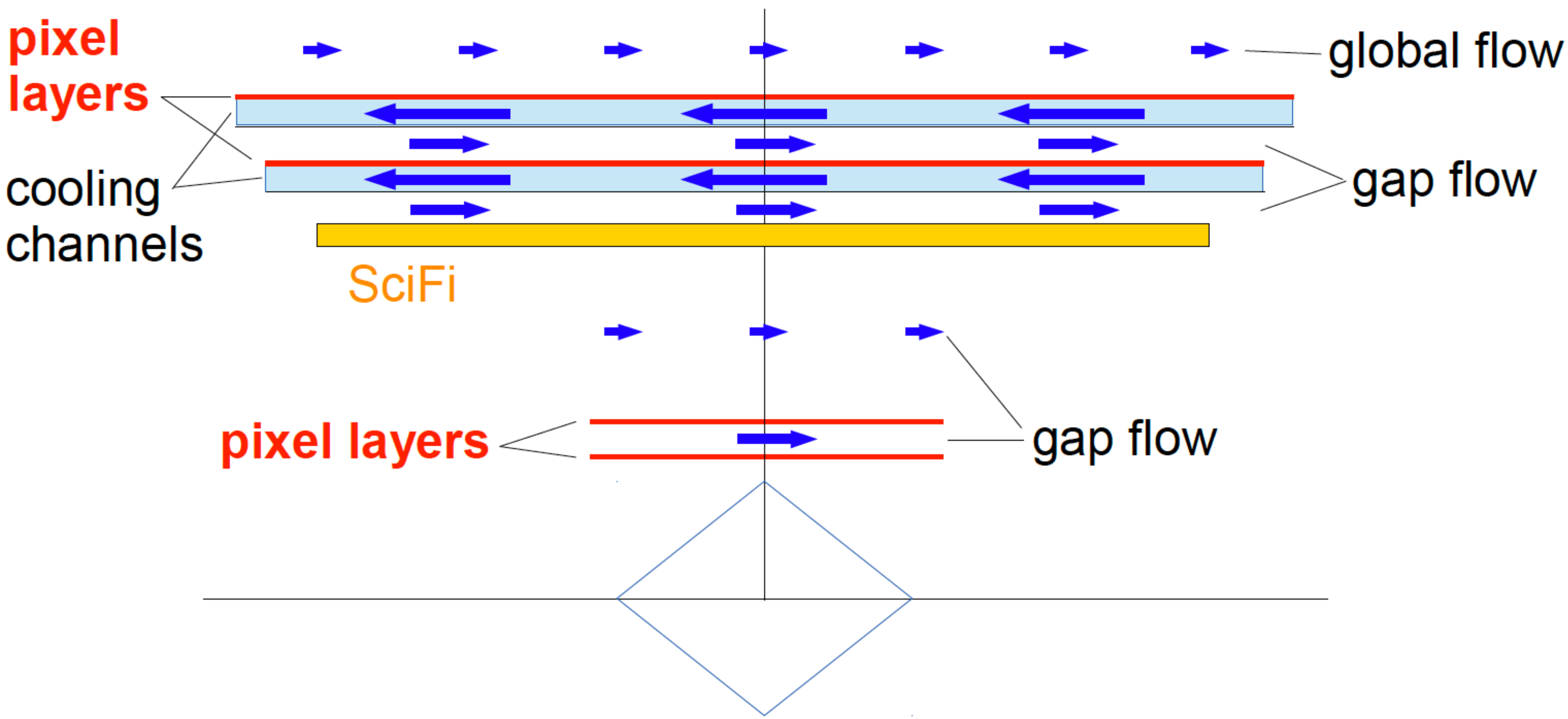
Prototypes: Results

- Hit efficiency and noise as a function of the charge threshold. MuPix7: 2 x 2 pixel array. Bias voltage: -85 V
- 4 GeV electrons



Detector cooling

- Cooling done using He gas flow (velocity~ [5-20 m/s])
- Power consumption: 250 mW/cm^2
- Maximum sensor temperature: < 70 ^{0}C (total power consumption ~ 4.55 kW)



Detector cooling: Pictures

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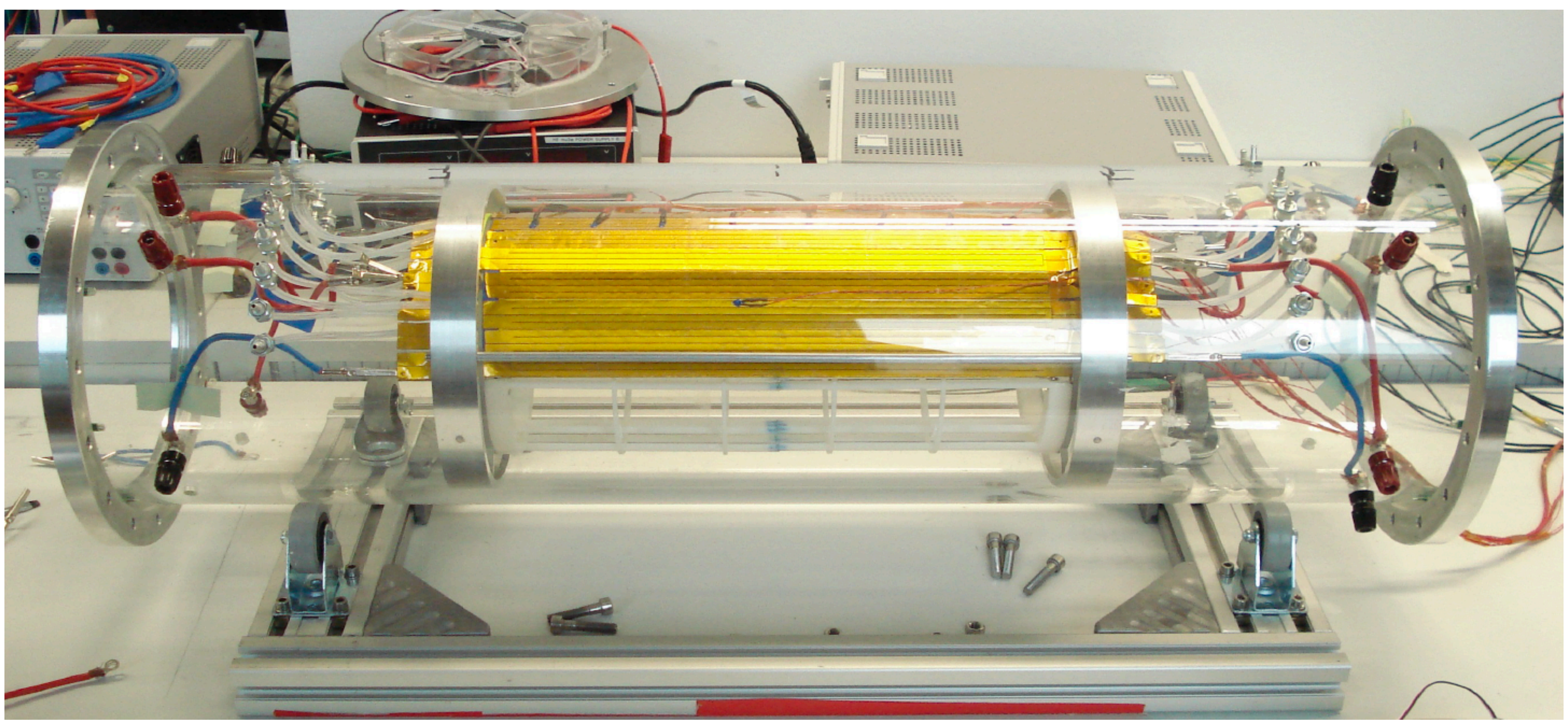
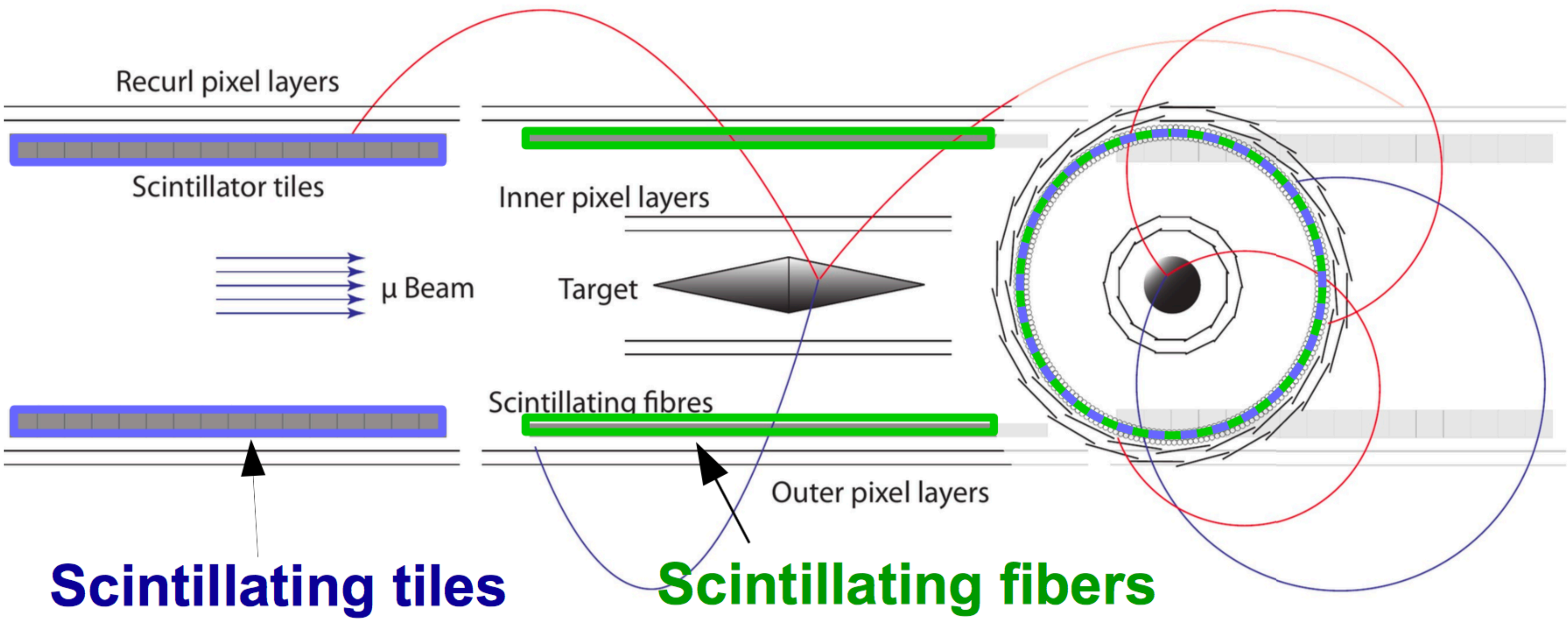


The timing detectors: Fibers and tiles

- Precise timing measurement: Critical to reduce the accidental BGs
    - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
    - Scintillating tiles O(100 ps), full detection efficiency (>99%)



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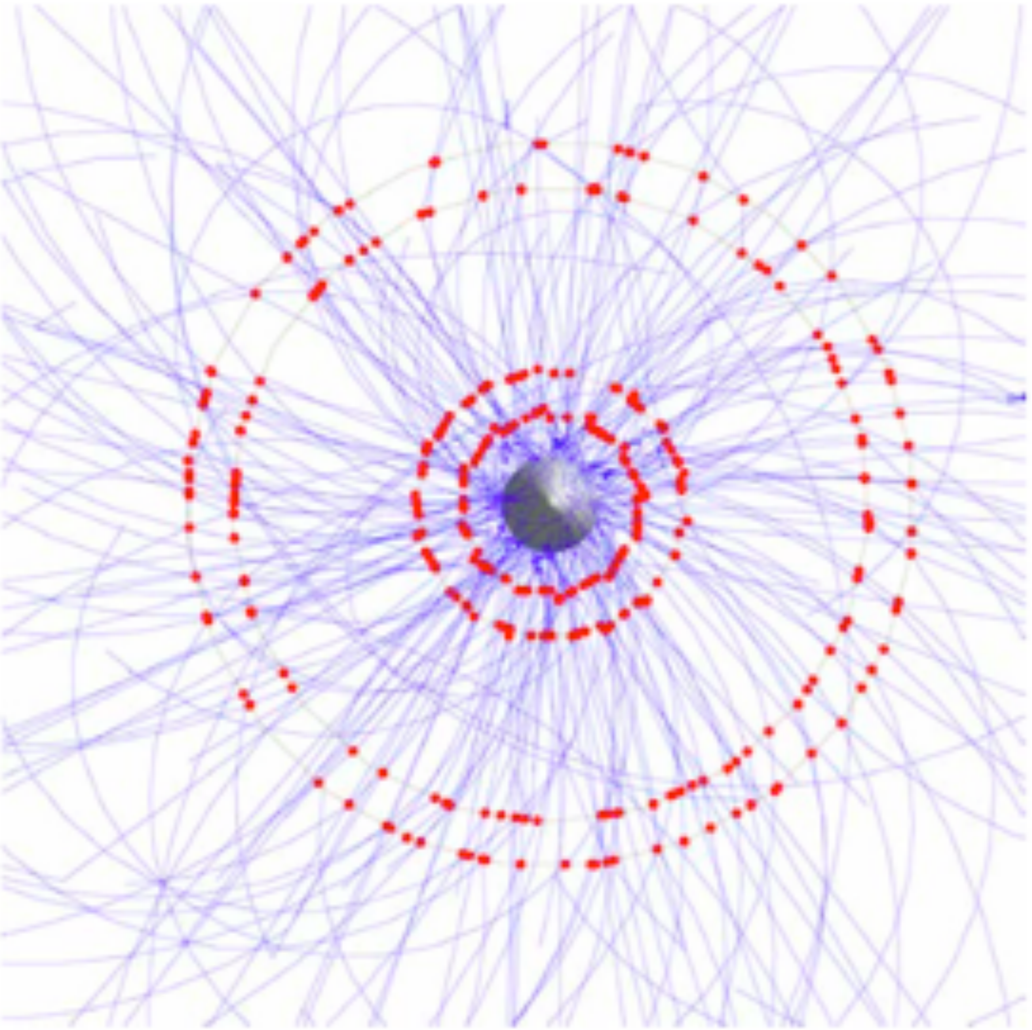
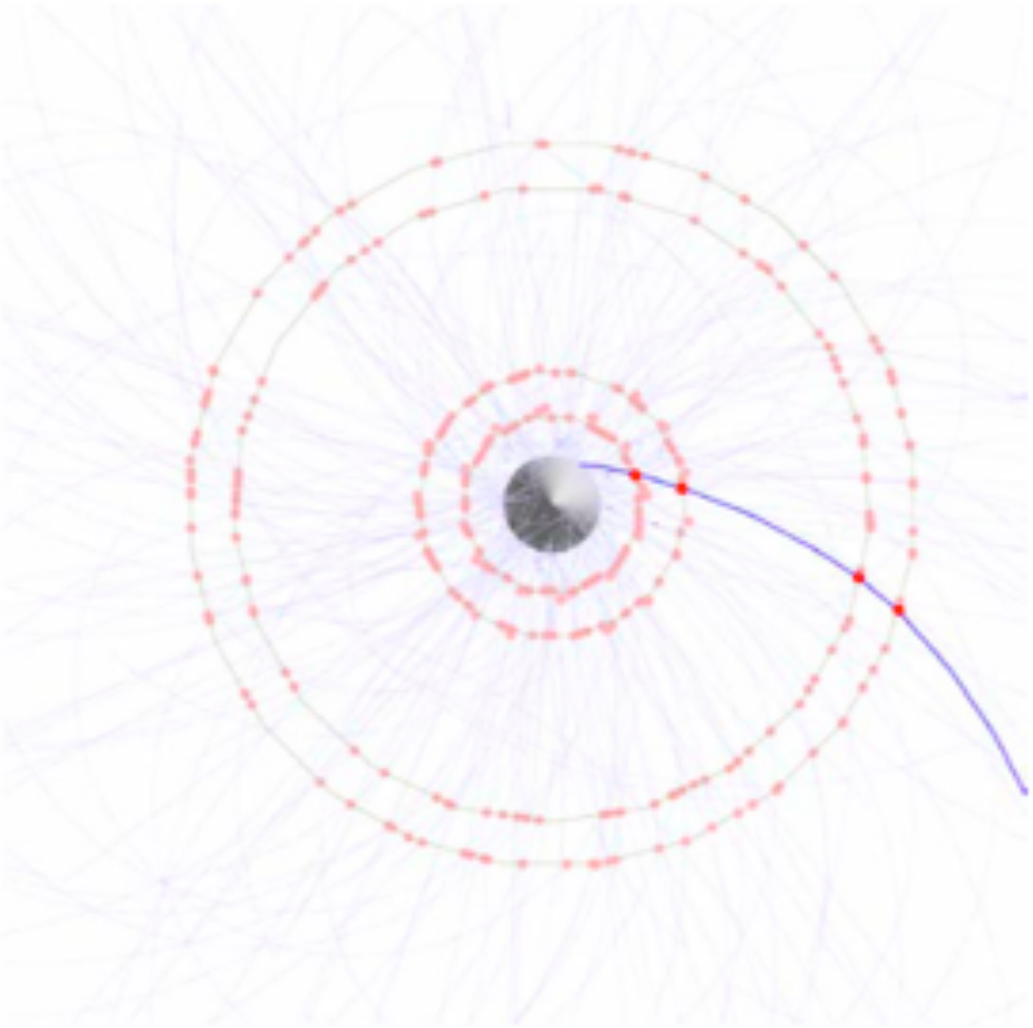


Pixels: O(50 ns)



Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

The timing detectors: Impact

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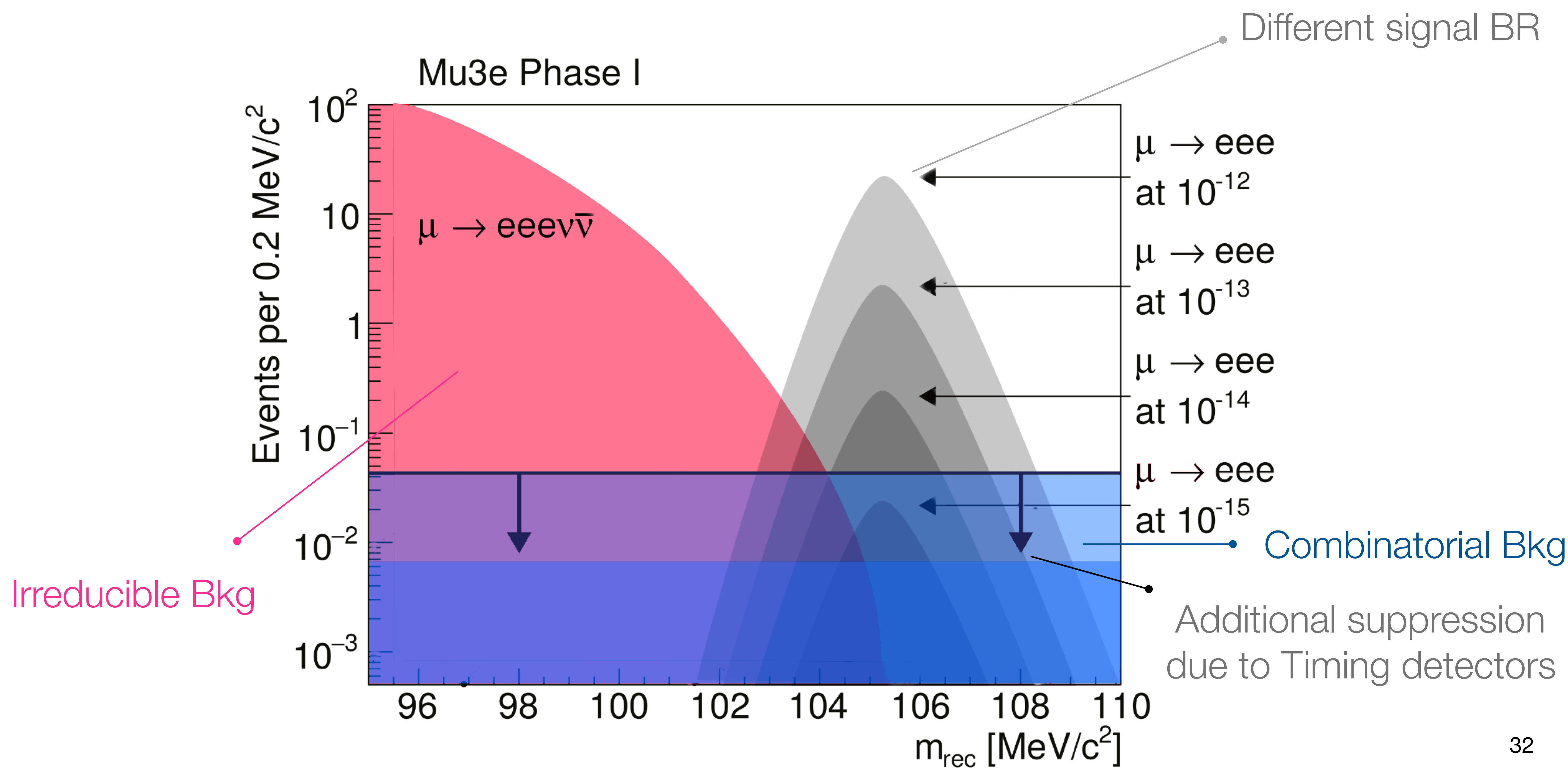
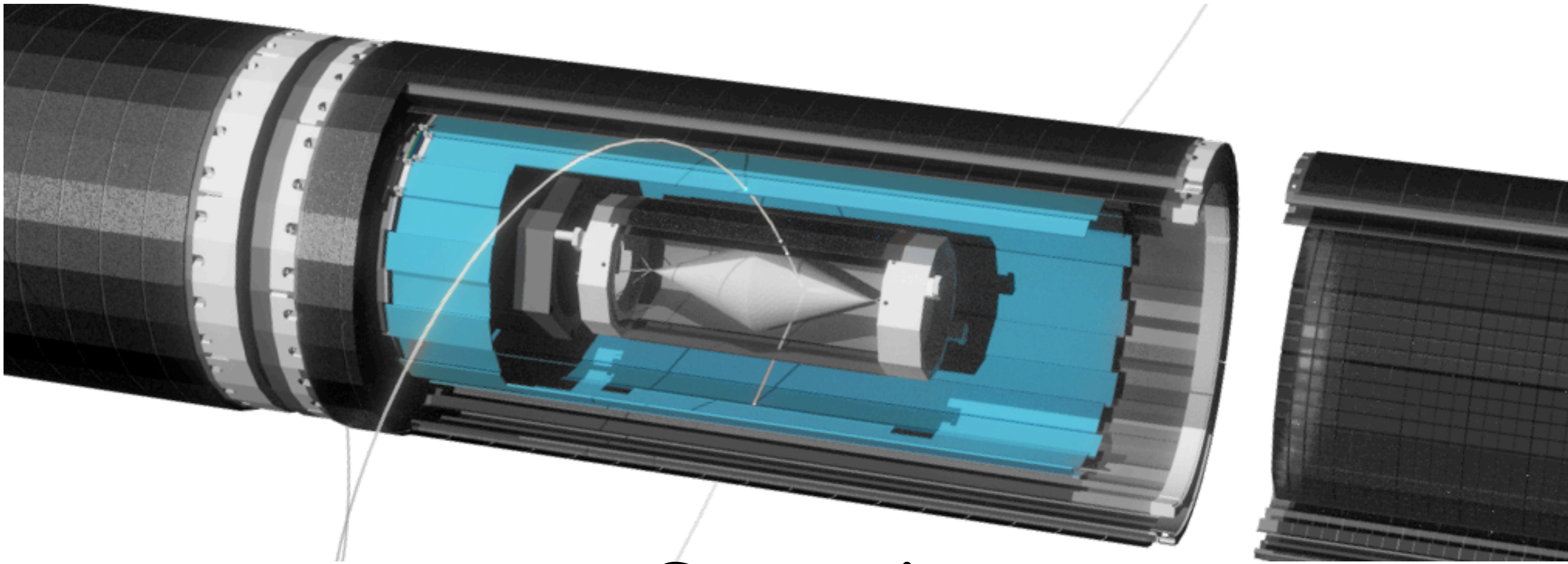


The Fiber detector (SciFi): Overview



Parts

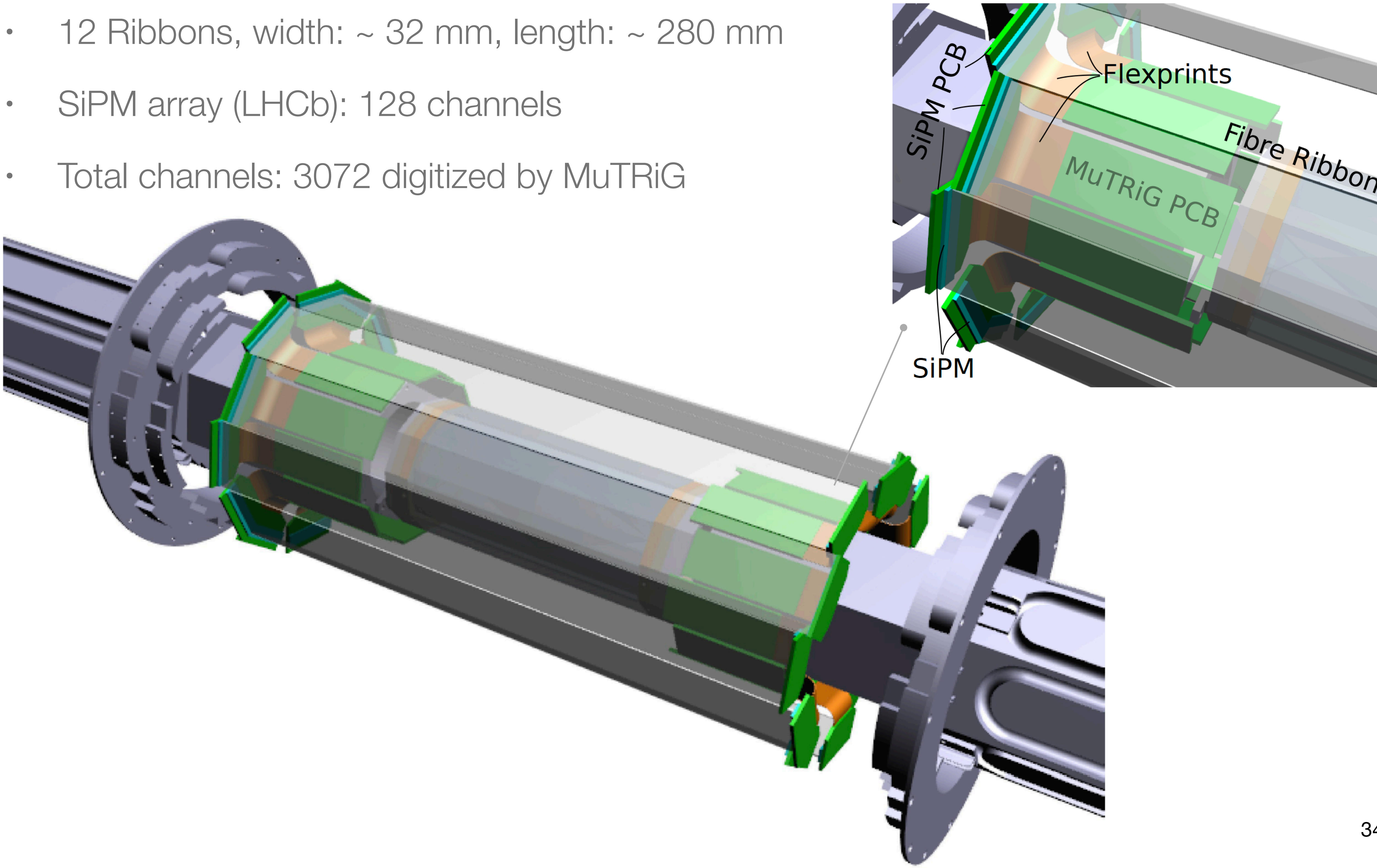
- cylindrical at ~ 6 cm (radius);
- length of 28-30 cm;
- 3 layers of round or square
- multi-clad 250 μm fibres
- fibres grouped onto SiPM array
- MuSTiC readout

Constraints

- high detection efficiency ε > 95%
- time resolution σ < 1 ns
- < 900 μm total thickness
- < 0.4 % X_0
- rate up to 250 KHz/fibre
- very tight space for cables, electronics and cooling

The Fiber detector (SciFi): 3D view

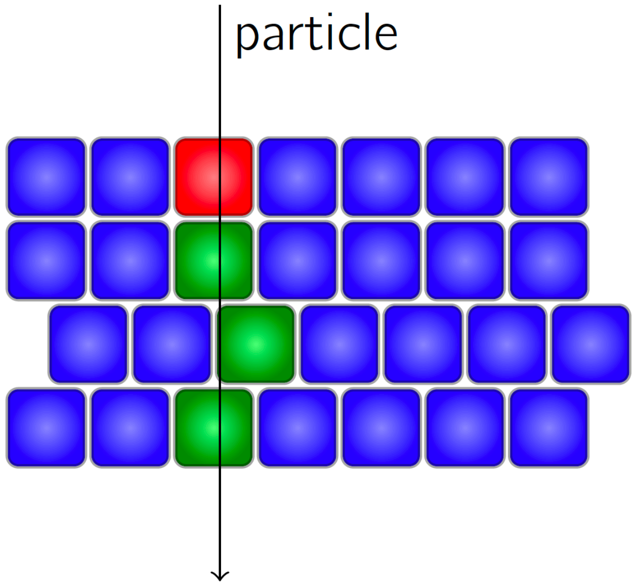
- 12 Ribbons, width: ~ 32 mm, length: ~ 280 mm
- SiPM array (LHCb): 128 channels
- Total channels: 3072 digitized by MuTRiG



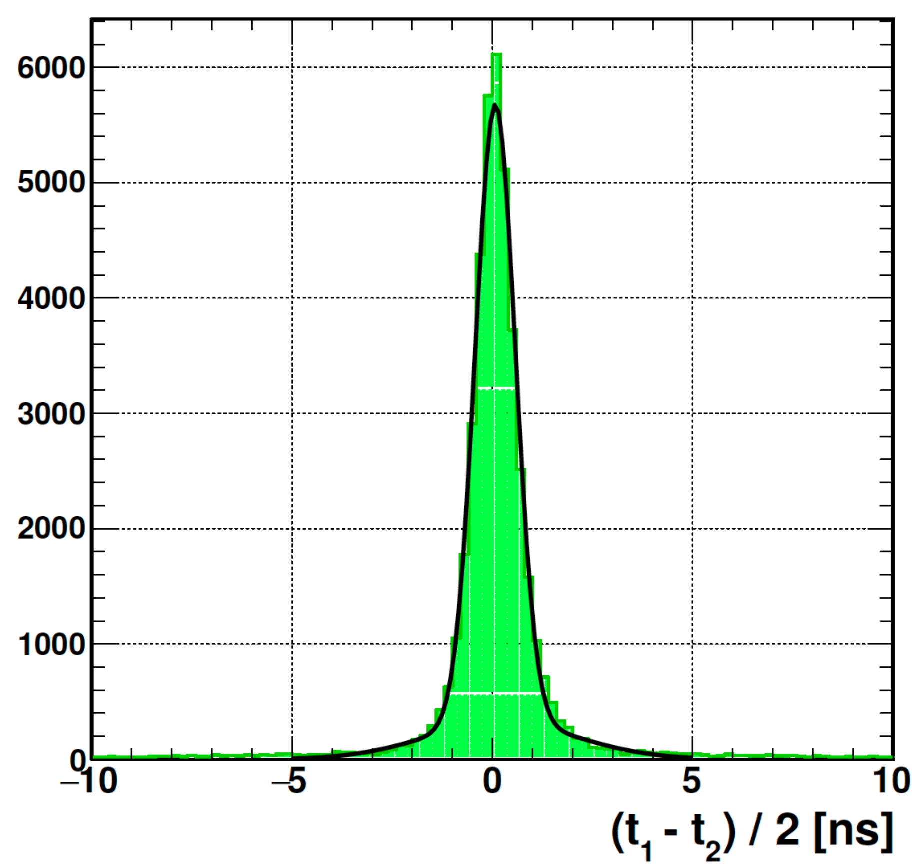
SciFi prototypes: Results

- Confirmed full detection efficiency (> 96 % @ 0.5 thr in Nphe) and timing performances for multi-layer configurations (square and round fibres) with several prototypes: individual and array readout with standalone and prototyping (STiC) DAQ

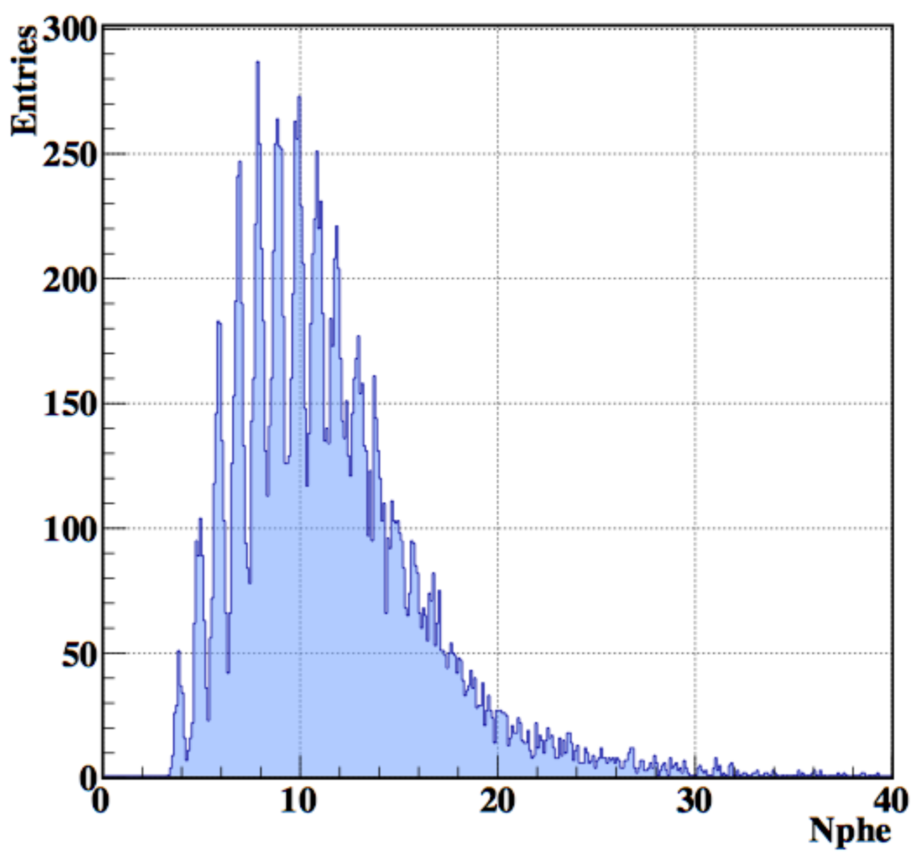
Trigger
offline selection:
hits in 3 layers



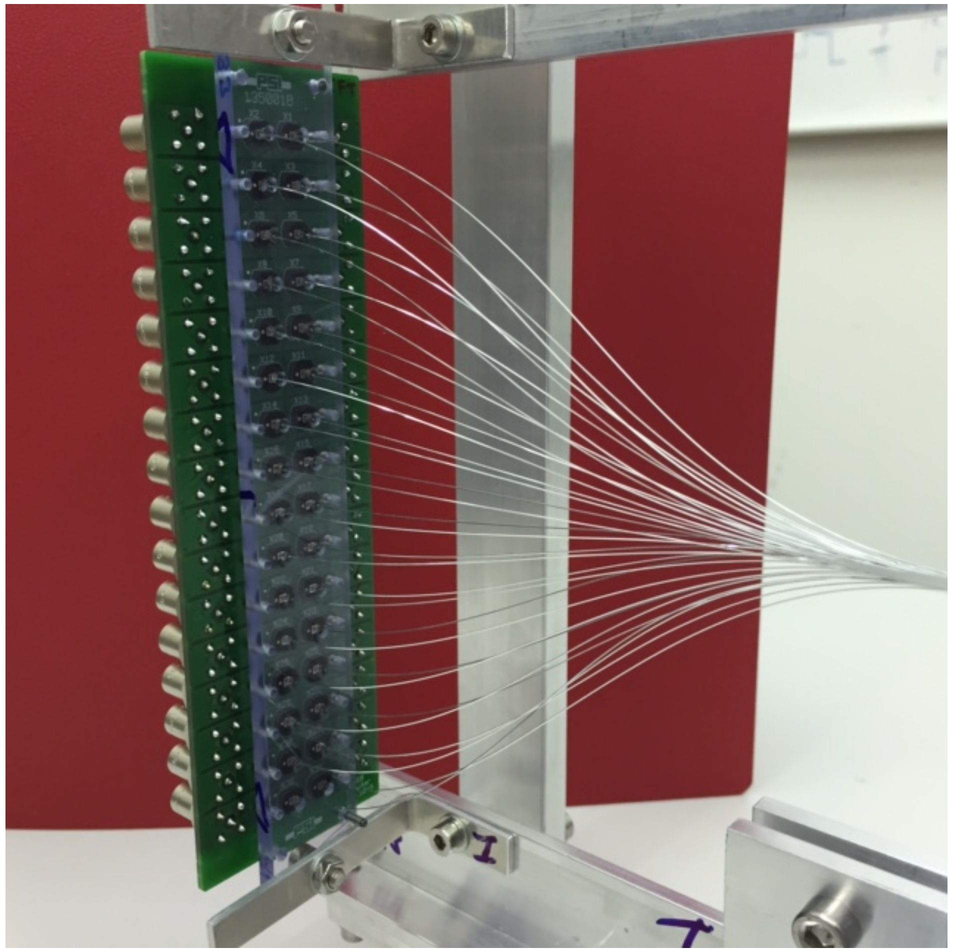
3 layer time resolution O(550) ps

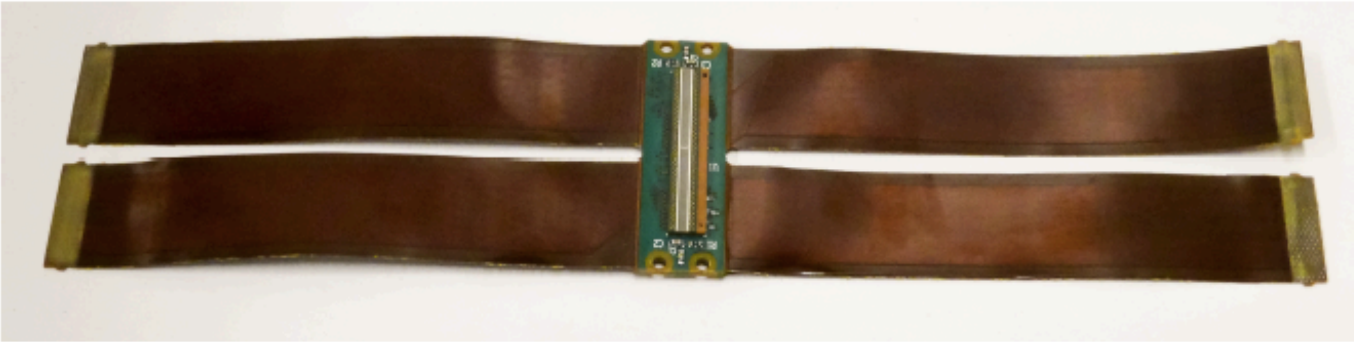


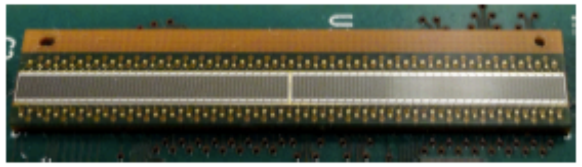
3 layer offline array charge collection (thr > 1.5 Nphe)

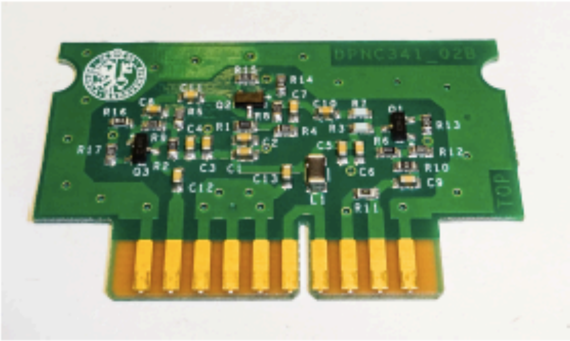


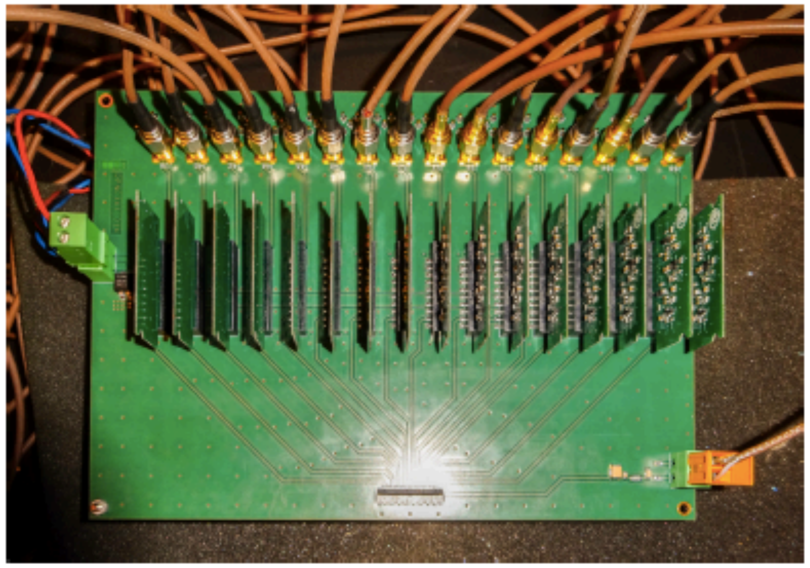
SciFi prototypes: Pictures

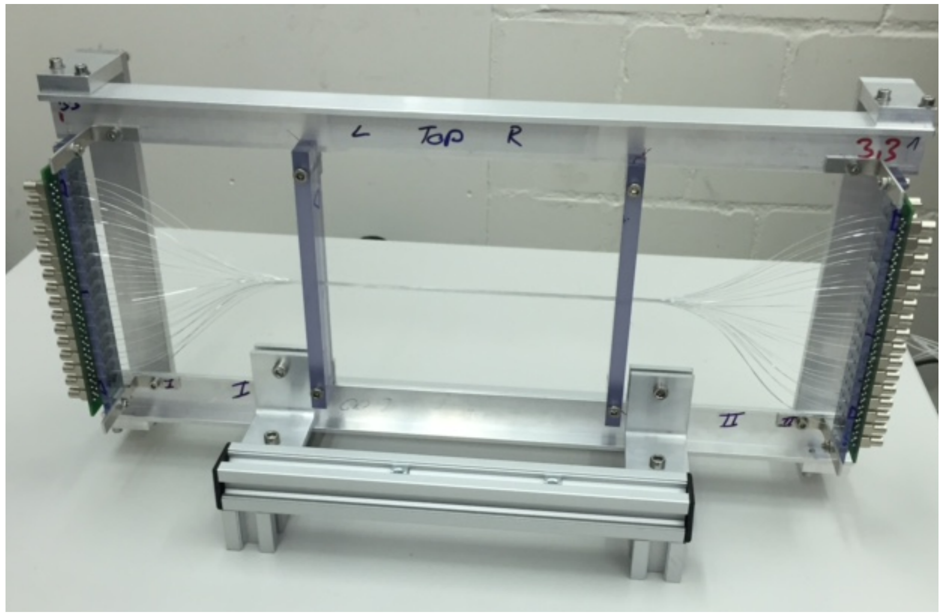


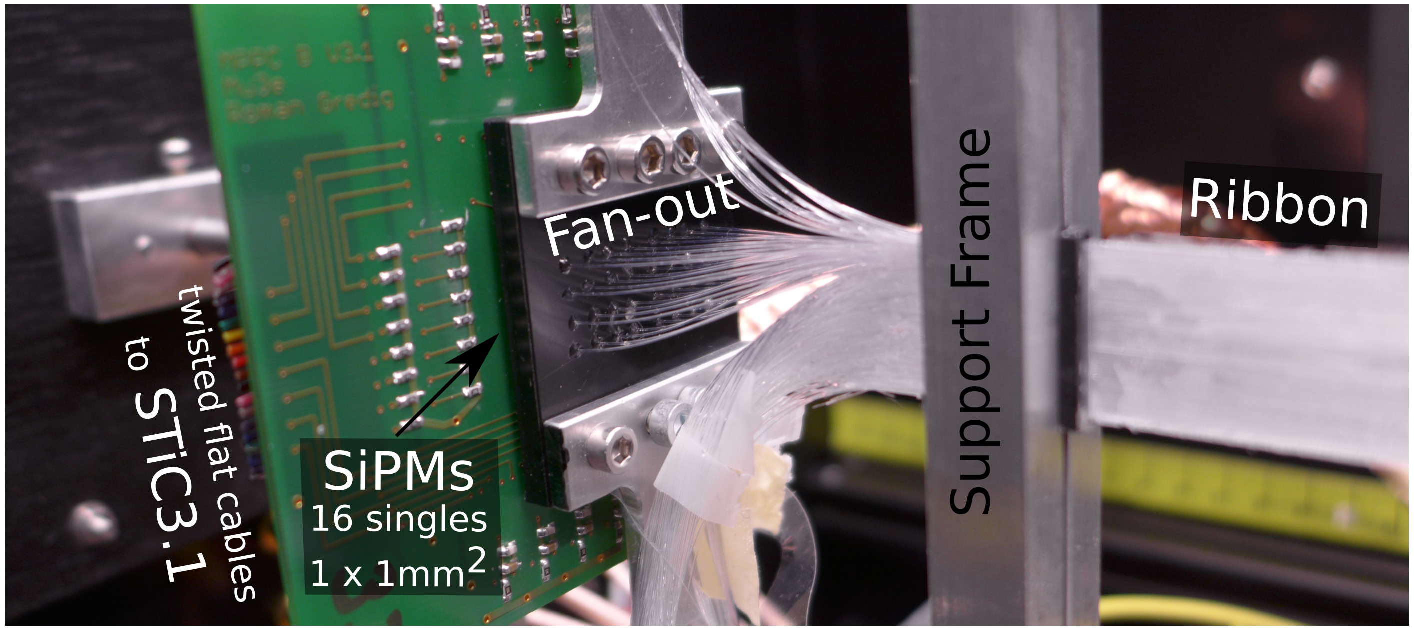






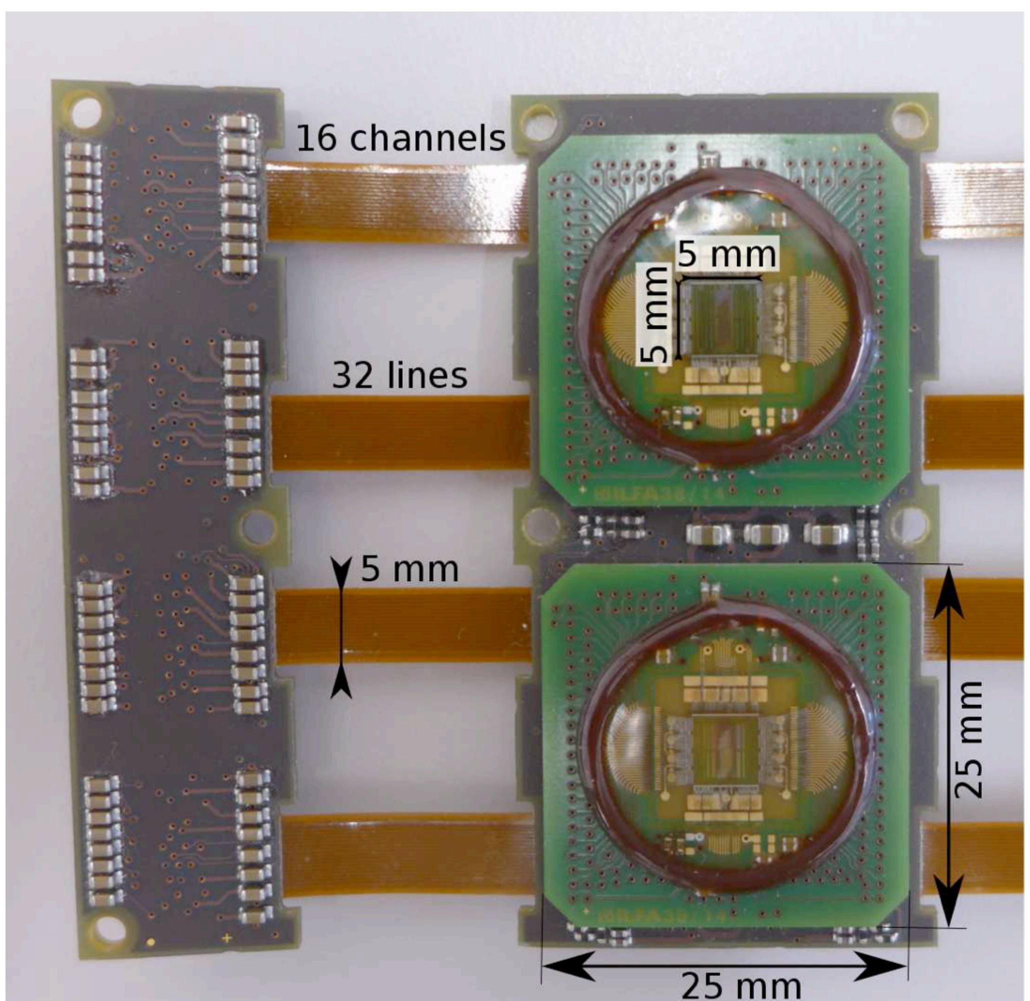






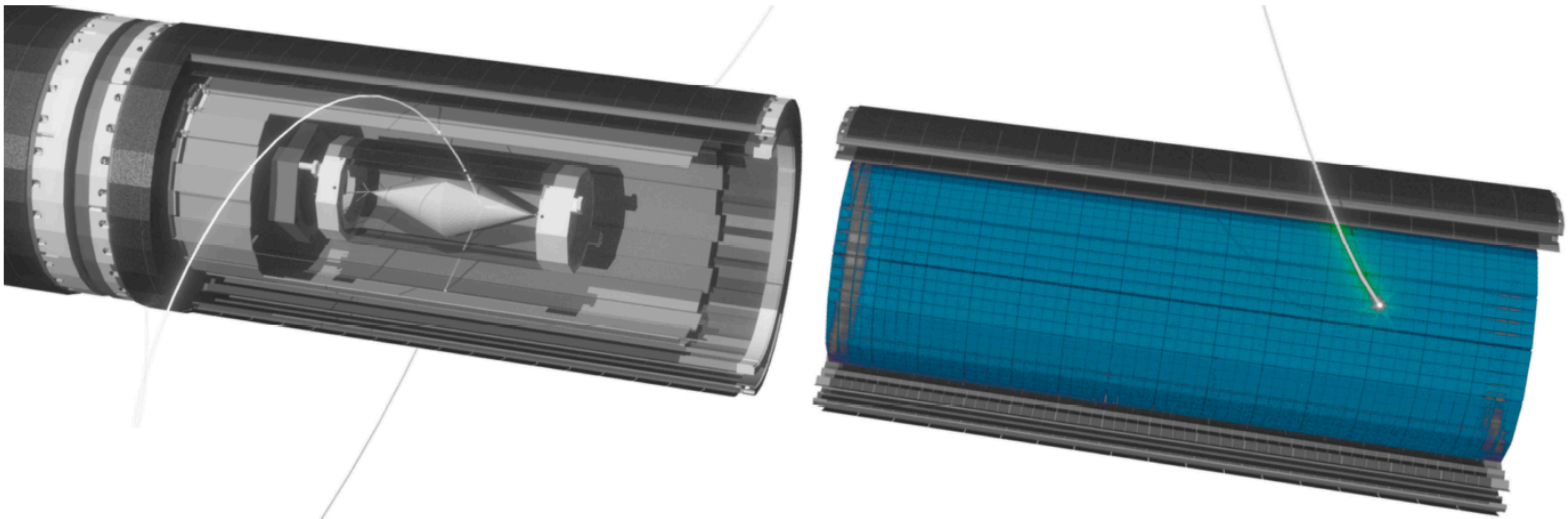
SciFi: Electronics readout, MuTRiG

- Requirements:
    - 3072 channels
    - O(1000) kHz/channel
    - < 100 ps time information [charge beneficial, possibly 2nd threshold]
    - very tight space constraints (48 ASICs)



STiC3.1	MuTRiG
Tested	in development ready for summer
64 channels	32 channels
160 Mbit/s links	1250 Mbit/s links
~40 kevents/s	~1200 kevents/s
no charge for fibre signals	possibly 2nd threshold

The Tile detector: Overview



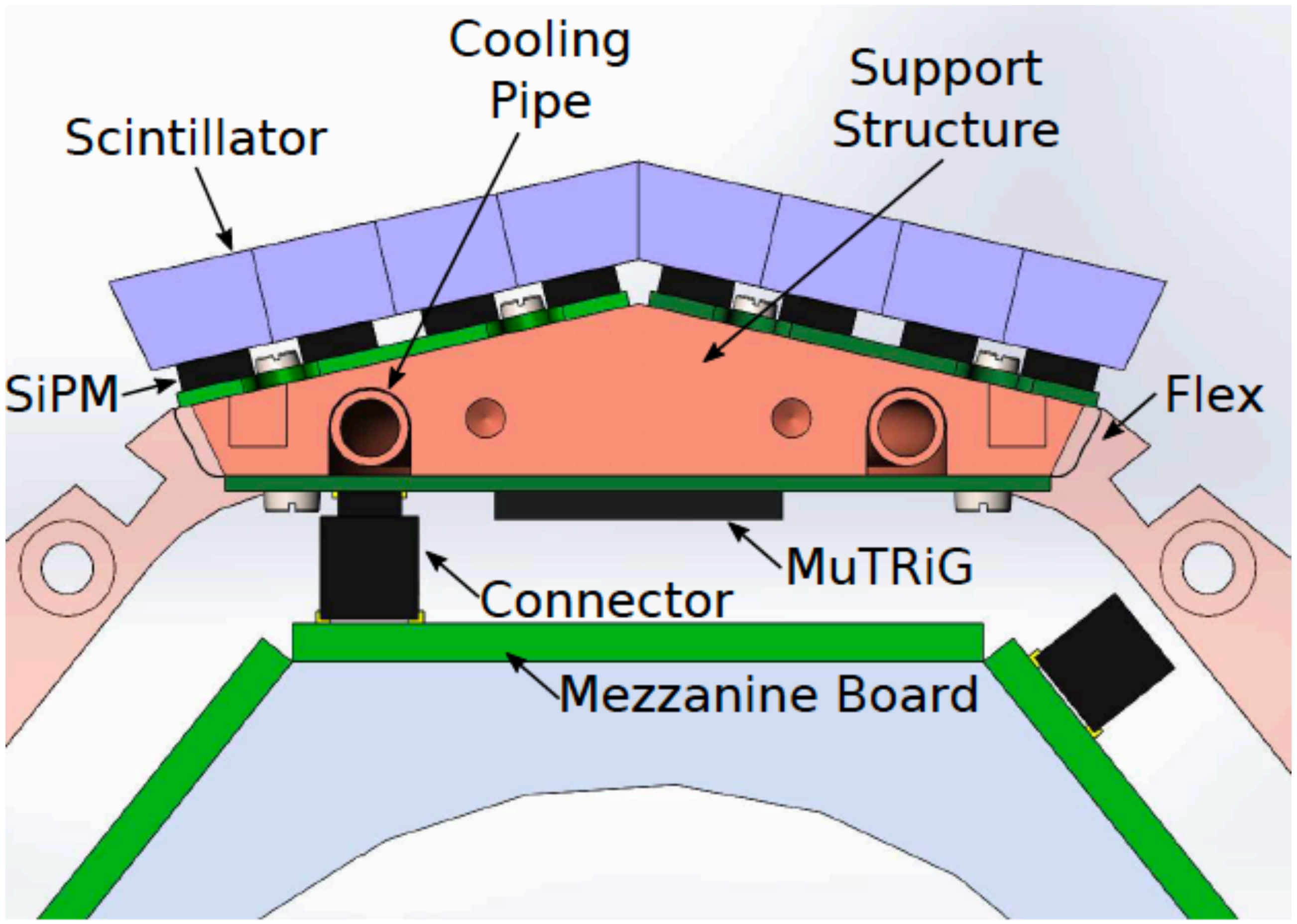
Parts

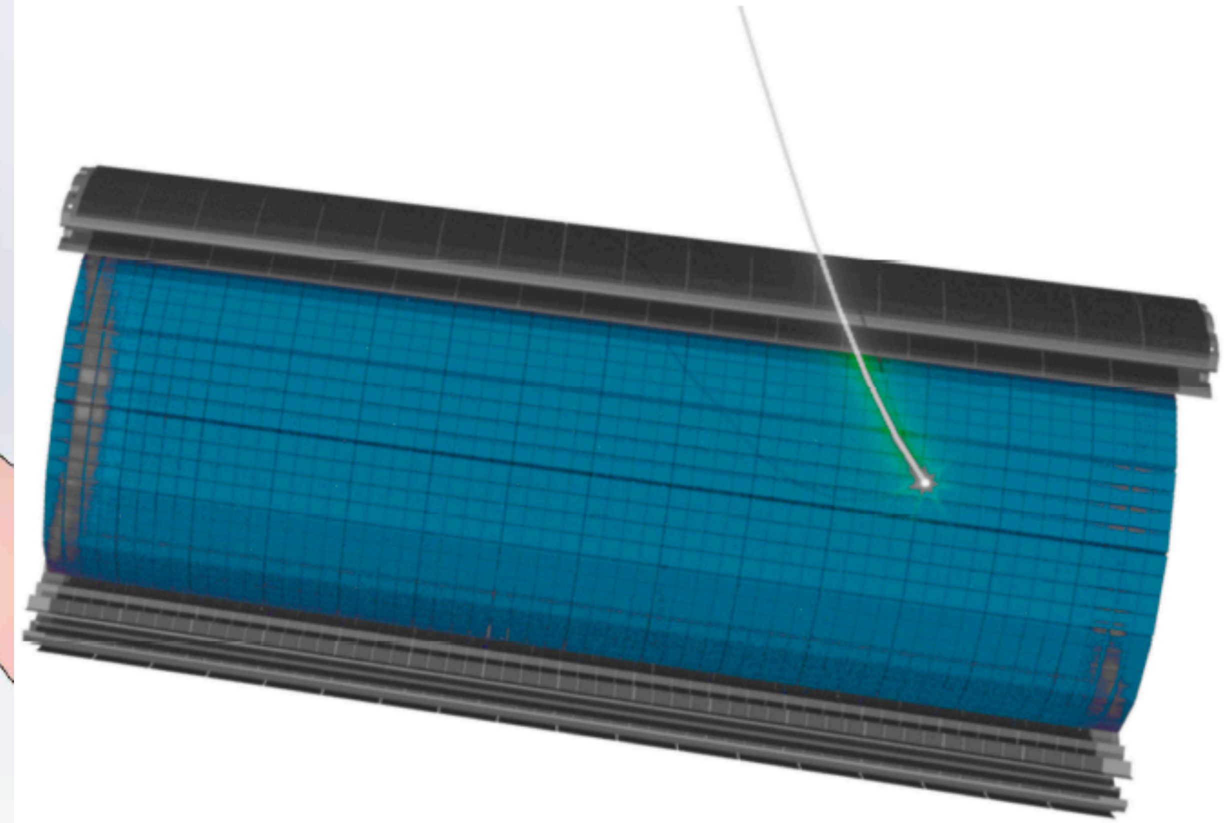
- cylindrical at ~ 6 cm (radius)
- length of 36.4 cm
- 56 x 56 tiles of 6.5 x 6.5 x 5 mm^3
- 3 x 3 mm^2 single SiPM per tile
- Mixed mode ASIC: MuTRiG

Requirements

- high detection efficiency $\varepsilon > 95\%$
- time resolution $\sigma < 100$ ps
- rate up to 50 KHz per tile/channel

The Tile detector: Overview





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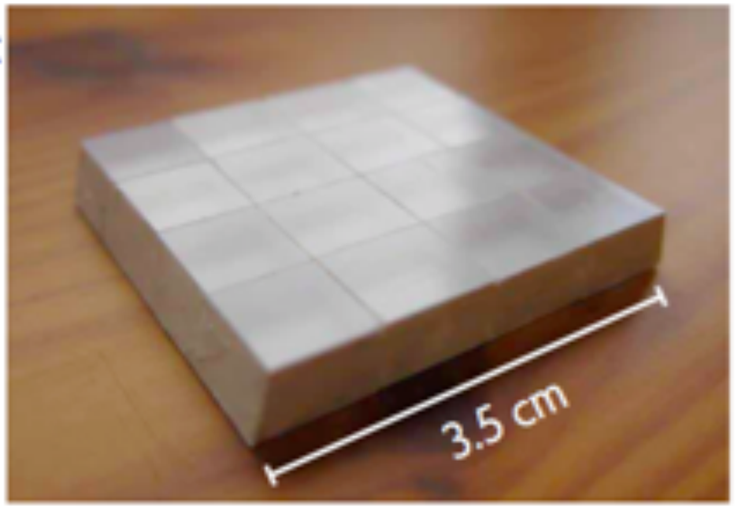
- Mixed mode ASIC: MuTRiG

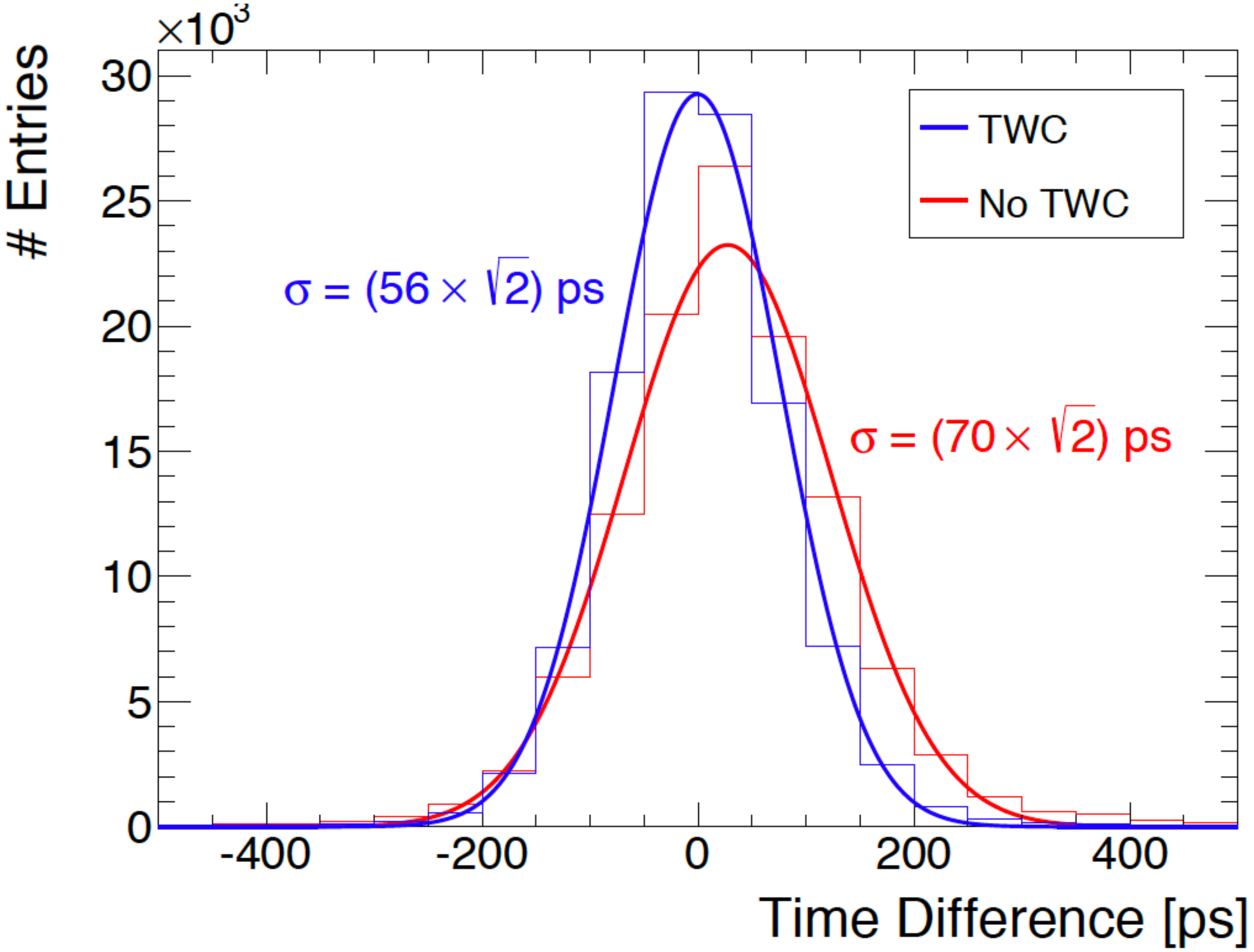
Requirements

- high detection efficiency $\varepsilon > 95\%$
- time resolution $\sigma < 100$ ps
- rate up to 50 KHz per tile/channel

Prototype: Results

- Mu3e requirements fulfilled: Full detection efficiency (> 99 %) and timing resolution O (60) ps
- 4 x 4 channel BC408
- 7. 5 x 8. 5 x 5. 0 mm^3
- Hamamatsu S10362-33-050C (3 x 3 mm^2)
- readout with STiC2





Conclusions

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-15}$ (Phase I) up to down $\sim 10^{-16}$ (Phase II). Previous upper limit $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment
- The Mu3e experiment is completely based on new detector technologies and strongly connected with new beam line projects (HiMB at PSI aiming at 10^9 muon/s)
- The R&D phase for all sub-detectors and beam line has been concluded proving that the expected detector performances can be achieved
- Construction and characterisation of all sub-detector prototype are extensively ongoing
- A full engineering run is expected for 2019 followed by data acquisition

Backup slides