# Status of the Mu3e experiment at PSI

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July 10th - July 17th, Ghent, Belgium
**EPS 2019**

# Content

- Charged Lepton Flavour Violation (cLFV) search:
  The motivation

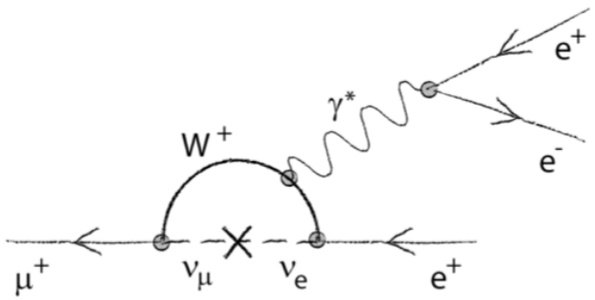
- cLFV with the Mu3e experiment:
  The $\mu \to eee$ search

- The Mu3e experiment

# cLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

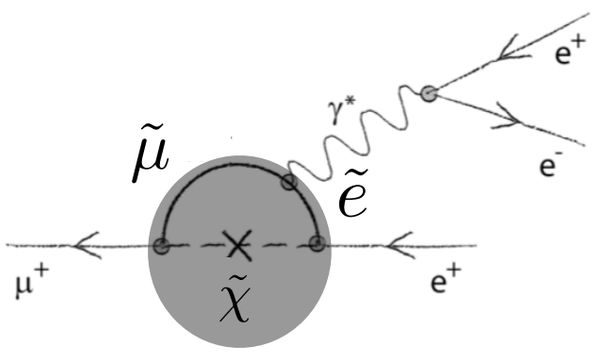
$$BR(\mu \to eee) \approx 10^{-54}$$




$\nu$ oscillations

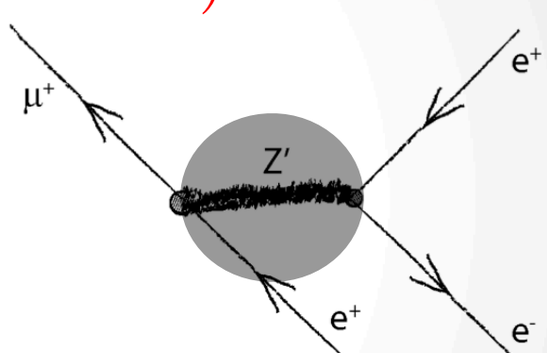
too small to access experimentally

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




i.e. EXTRA Z'

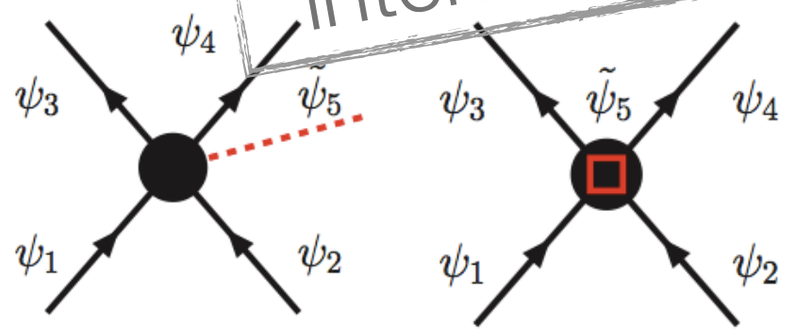
$$BR(\mu \to eee) >> 10^{-54}$$




**an experimental evidence:**
**a clear signature of New Physics NP**
(SM background FREE)

to unveil behind SM physics
via virtual particles

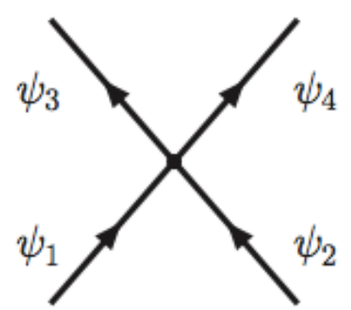
intensity frontier




to probe otherwise unreachable and
unexploited new physics energy scale

high energy probe

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




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

# cLFV: “Effective” lagrangian with the k-parameter

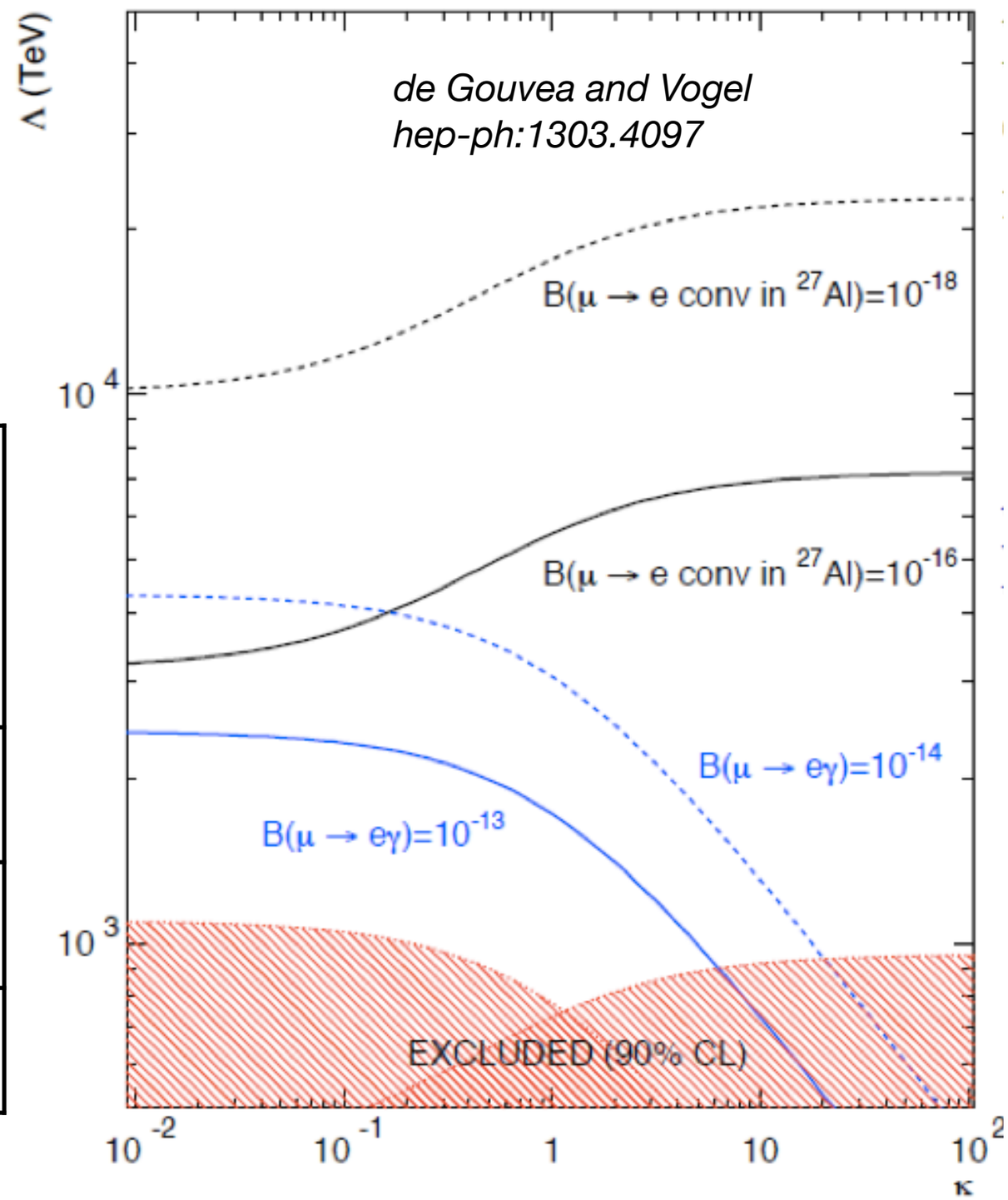
- Due to the **extremely-low** accessible **branching ratios**, muon cLFV can strongly **constrain** new physics models and scales

Model independent lagrangian

$$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times \quad + \quad \frac{\kappa}{(\kappa+1)\Lambda^2} \times$$



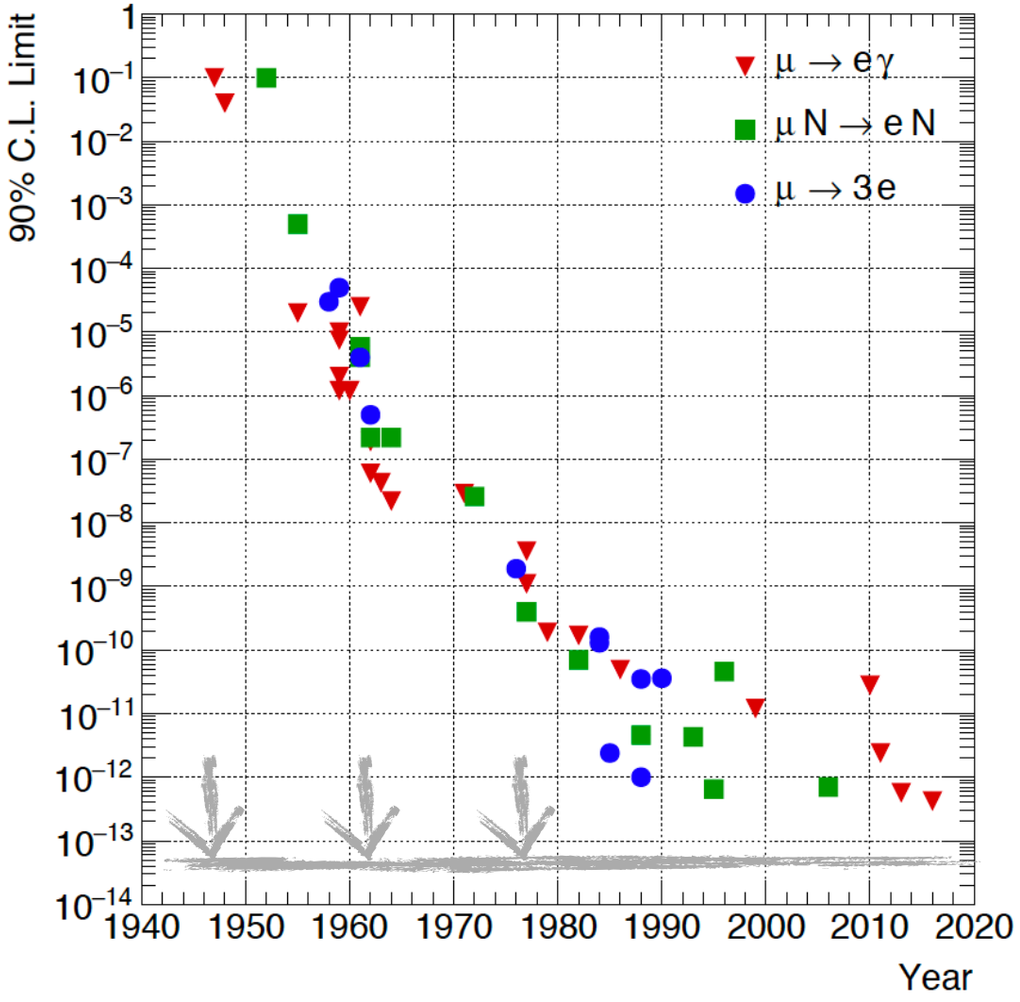
| dipole term | contact term |
|---|---|
| $\mu \to e\gamma$ | |
| $\mu \to eee$ | |
| $\mu N \to eN$ | |

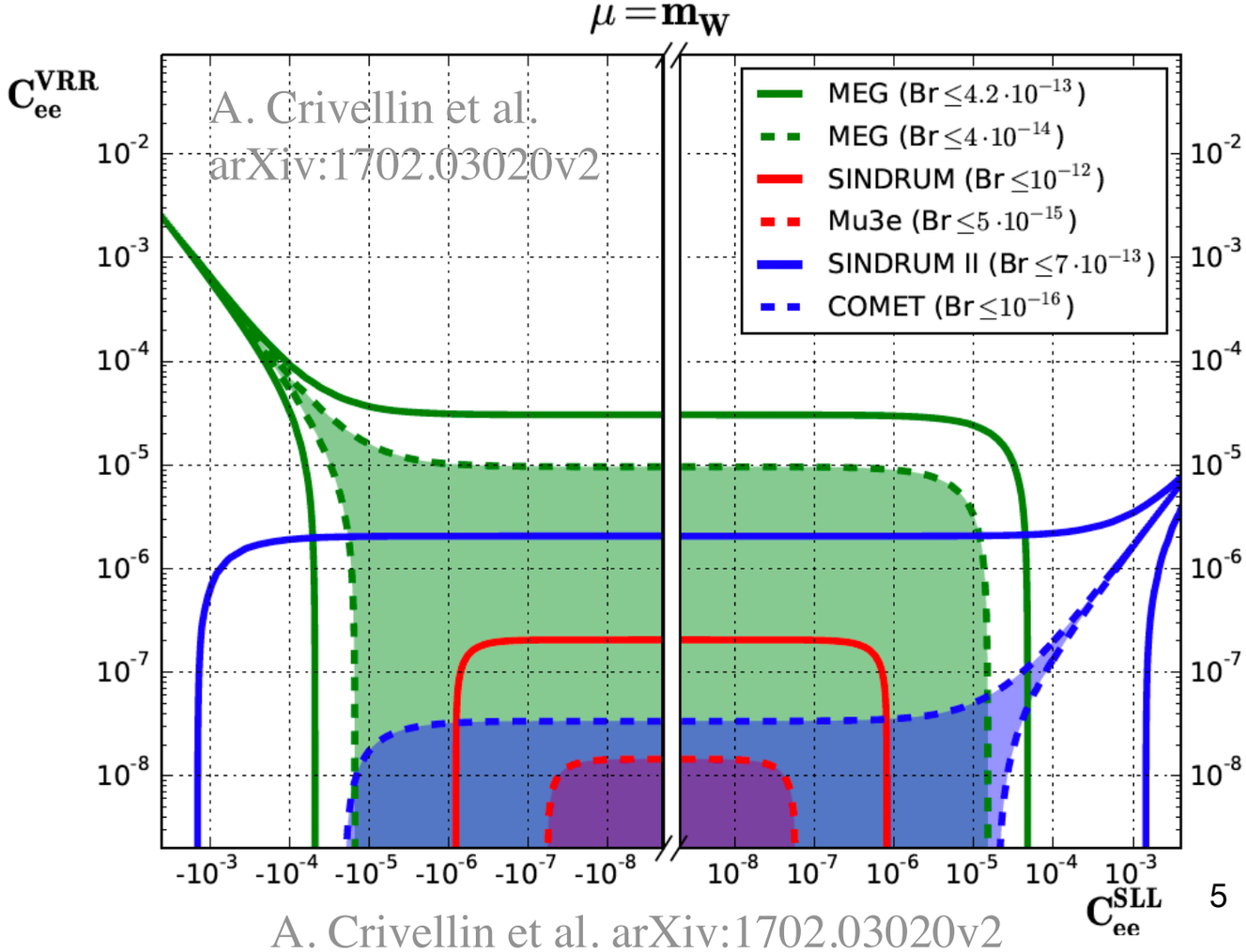


# cLFV searches with muons: Status and prospects

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

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



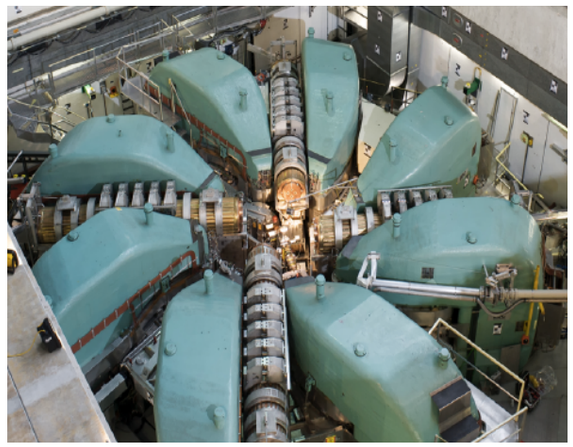

A. Crivellin et al. arXiv:1702.03020v2

# The world's most intense continuous muon beam

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

- 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

590 MeV proton ring cyclotron
**1.4 MW**

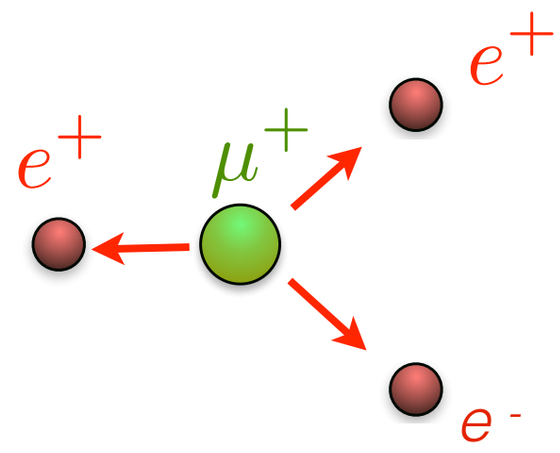


**PSI landscape**

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

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

Signature

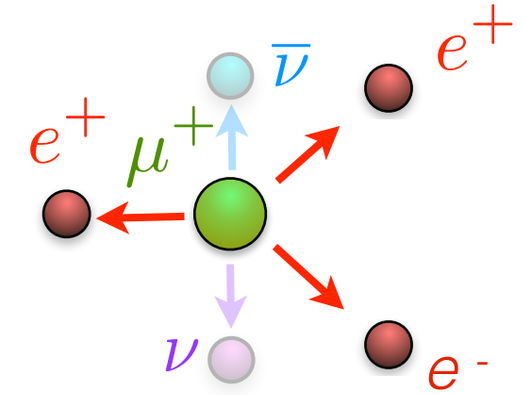


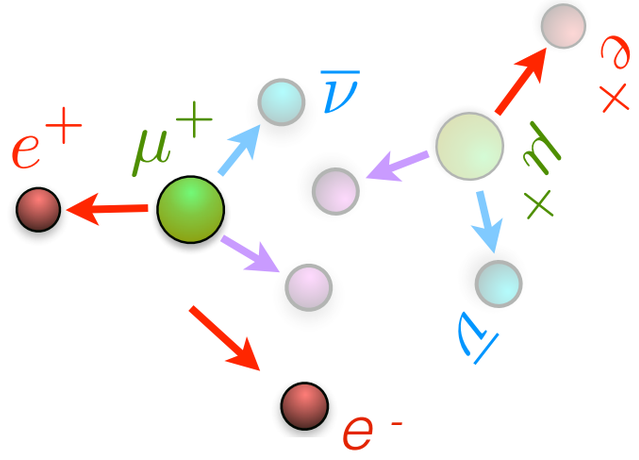

$\Delta t_{eee} = 0$

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

$\Sigma E_e = m_\mu$

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: 3D schematic view

Superconducting solenoid Magnet

**Homogeneous field 1T**

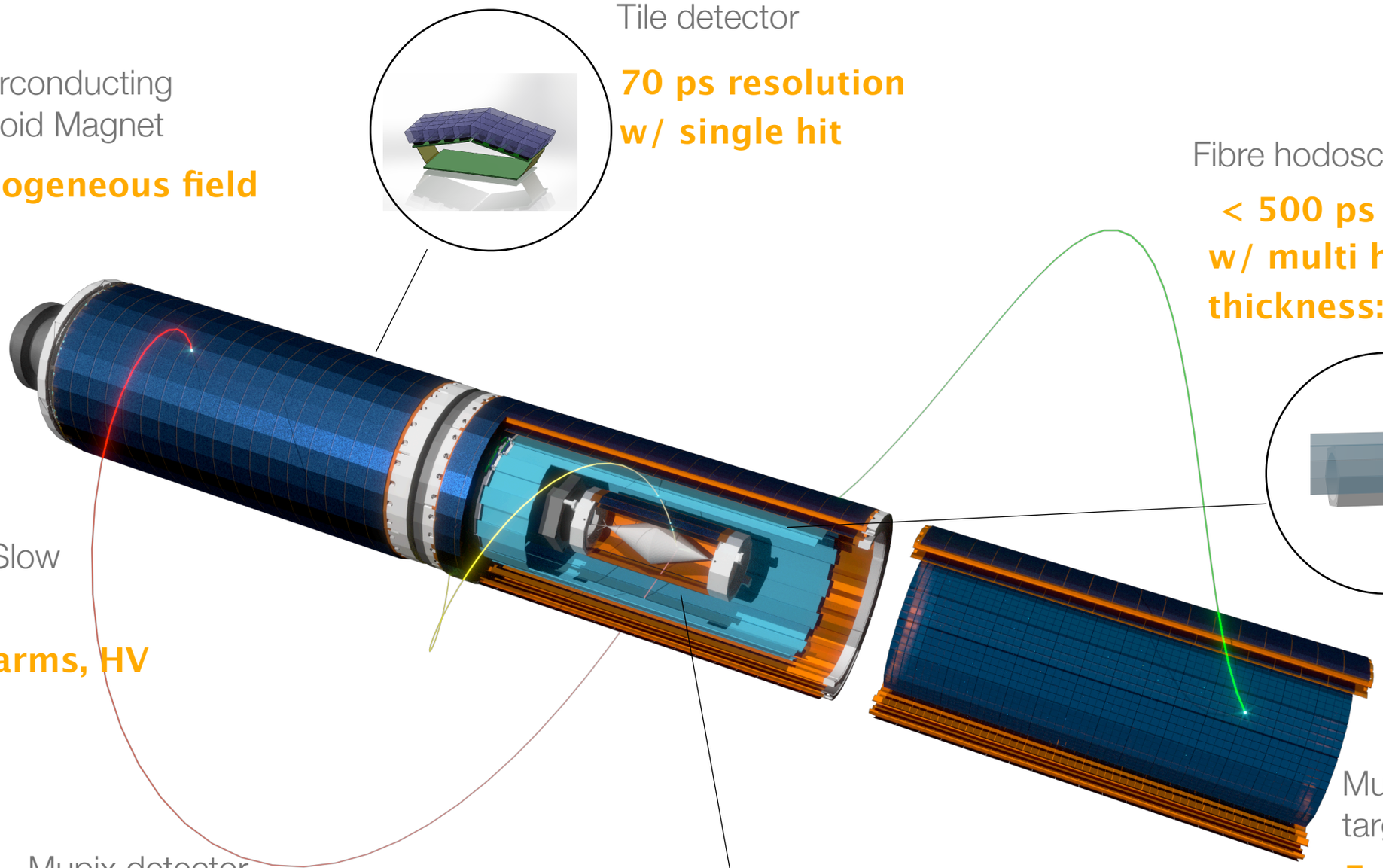
Tile detector

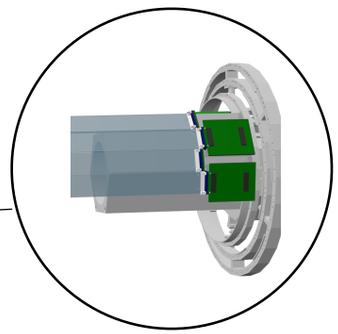
**70 ps resolution w/ single hit**

Fibre hodoscope

**< 500 ps resolution w/ multi hits**

**thickness: < 0.3% $X_0$**





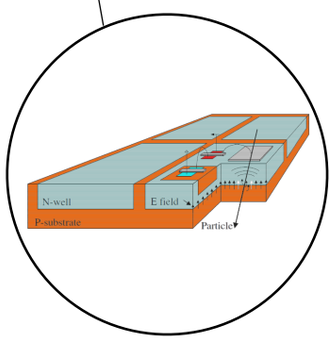
MIDAS DAQ and Slow Control

**Run, history, alarms, HV etc.**

Mupix detector

**Tracking, integrate sensor and readout in the same device: 50 um thick**

**1 layer: ~ 0.1% $X_0$**



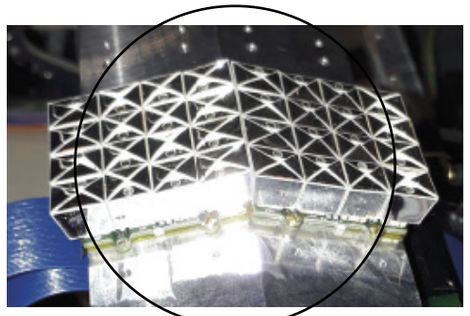

Muon Beam and target

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

# The Mu3e experiment: R&D completed. Prototyping phase

Superconducting solenoid Magnet

**Homogeneous field 1T**



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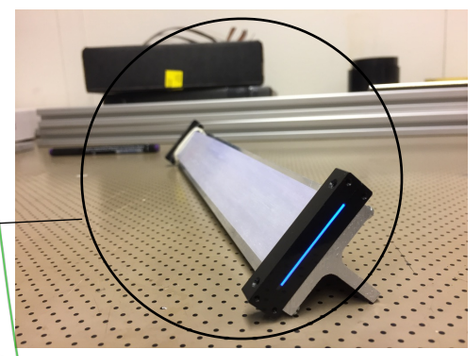

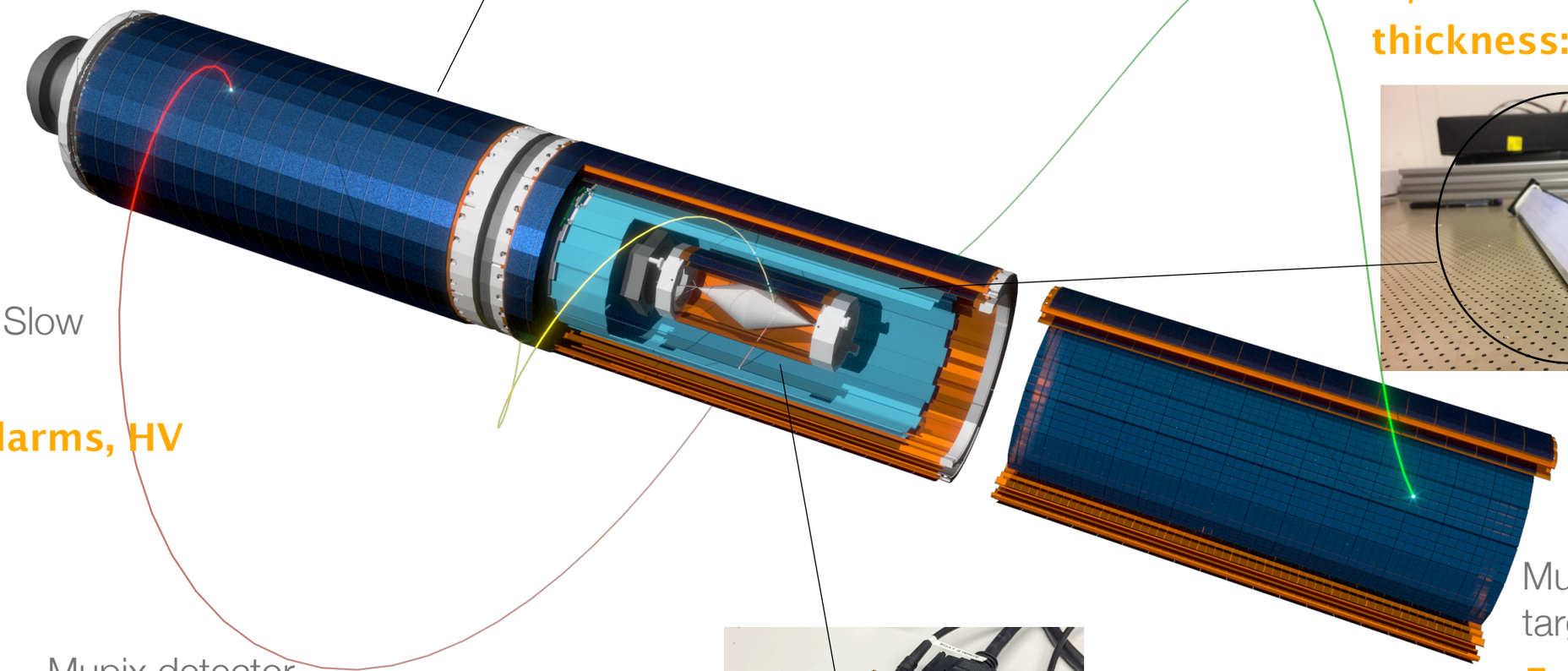

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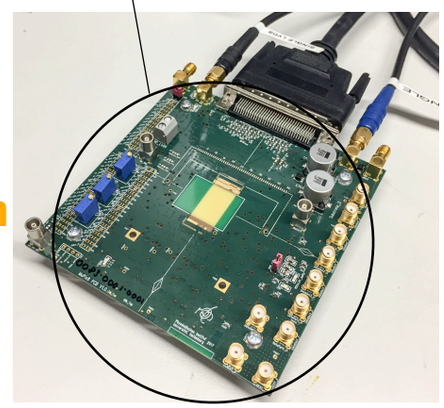
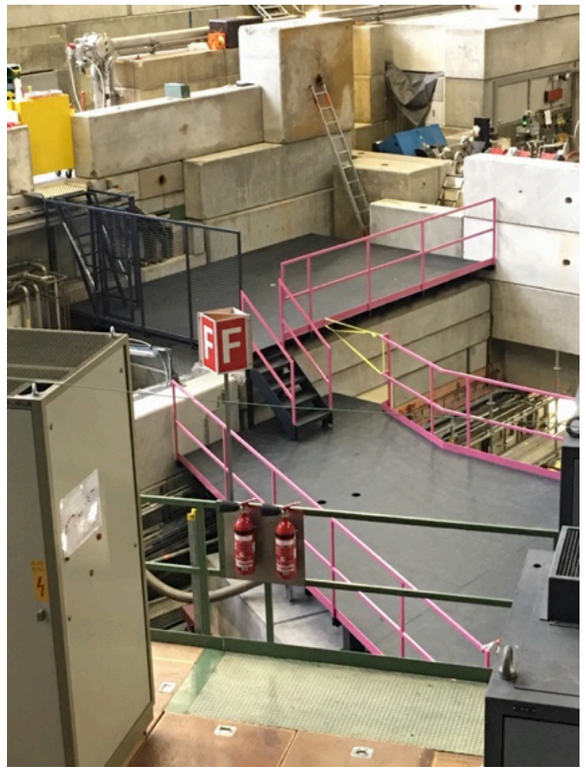


Muon Beam and target

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

# The MEGII and Mu3e experimental area: Pictures



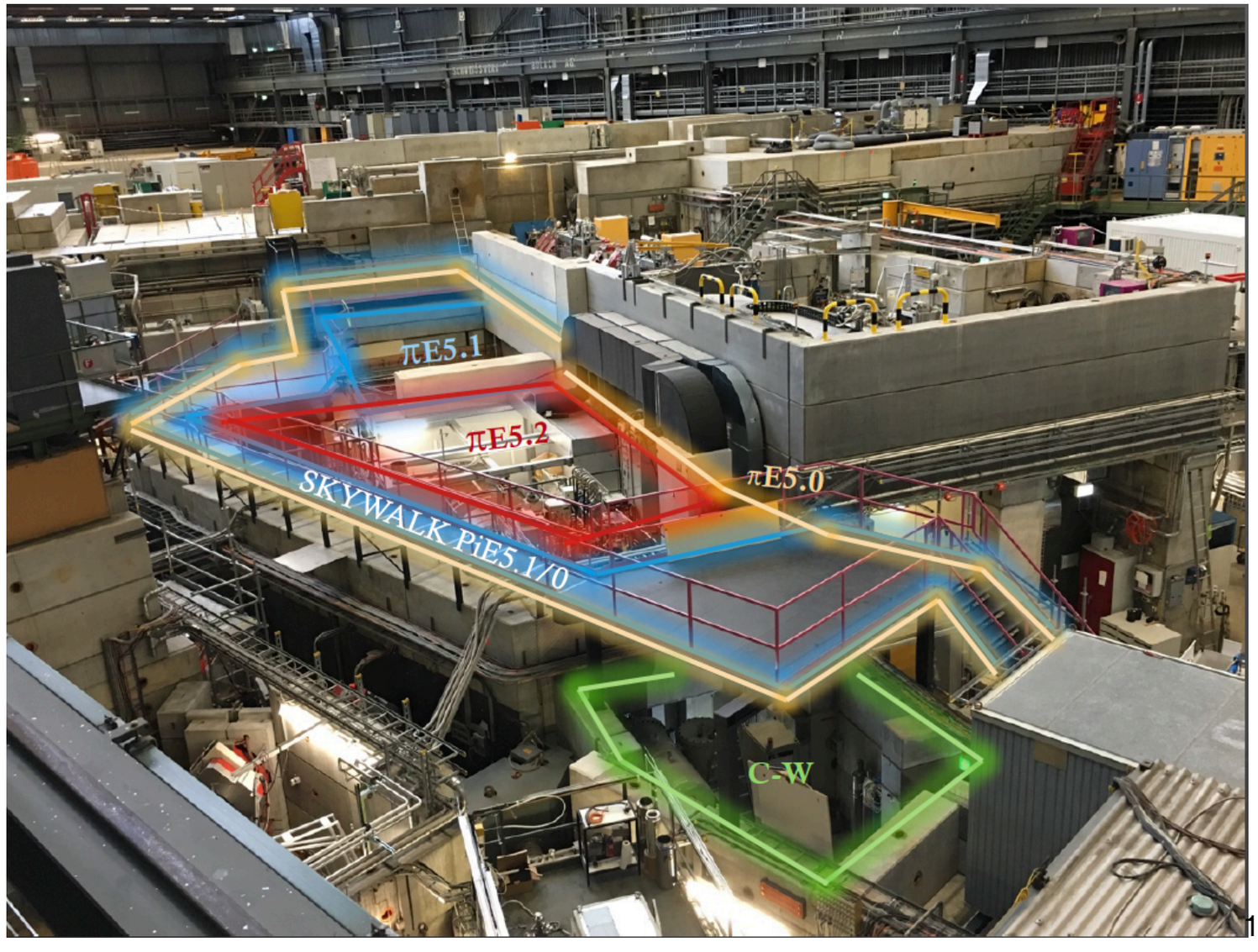

## Mu3e extra platforms

New

New

Mu3e control room

## Overview piE5 area



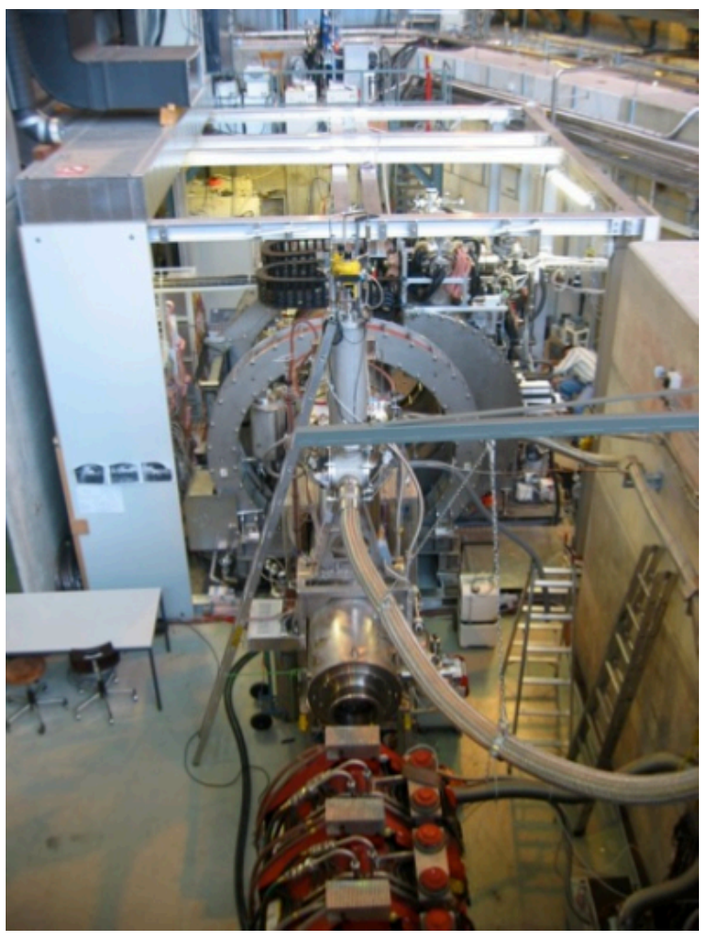
# The MEGII and Mu3e beam lines

- MEGII and Mu3e (phase I) similar beam requirements:
  - **Intensity O($10^8$ muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered 8 x $10^7$ muon/s during 2016 test beam

The Mu3e CMBL **New**



The MEGII BL

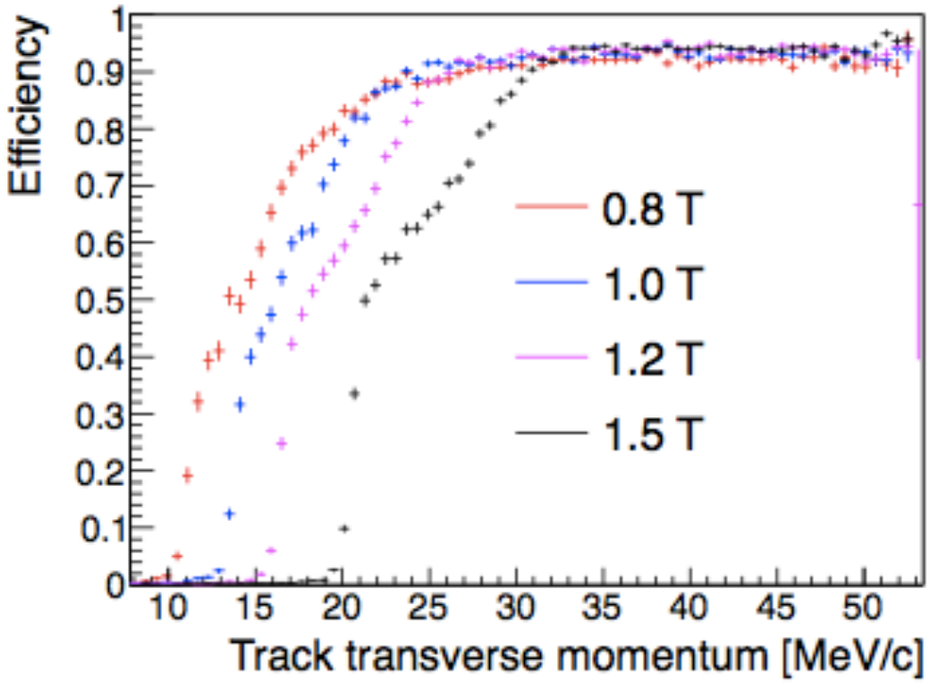


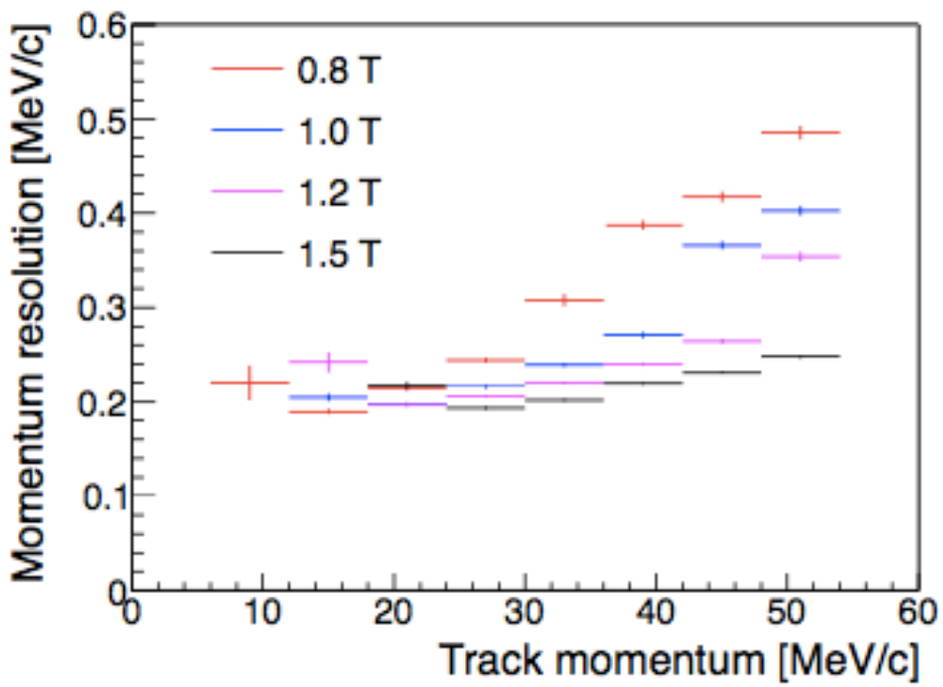
# Target and magnet: Status

- Target: Mylar double hollow cone (L = 100 mm, R = 19 mm), Stopping efficiency: ~ 83%, Vertex separation ability (tracking) < 200 um
- Magnet from Cryogenic. Delivering Time at PSI: This year
- 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

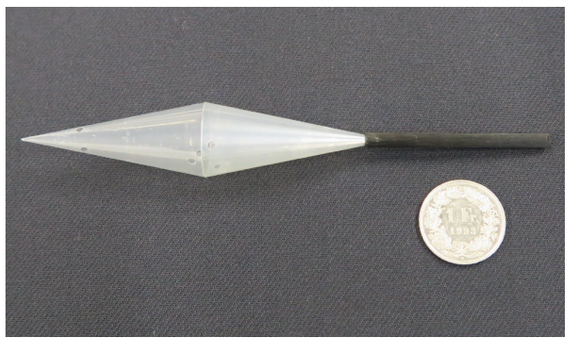
New

BField Simulation



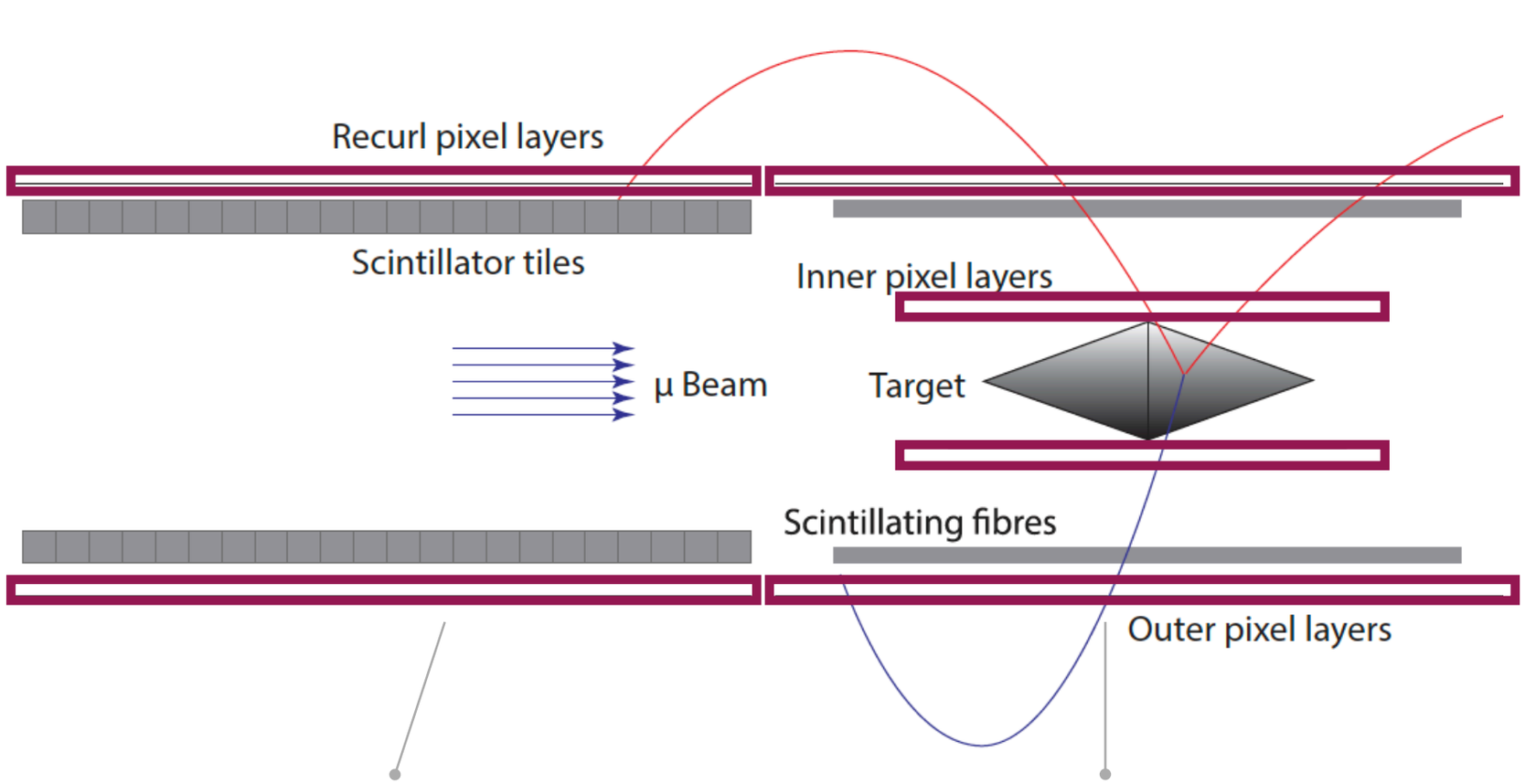



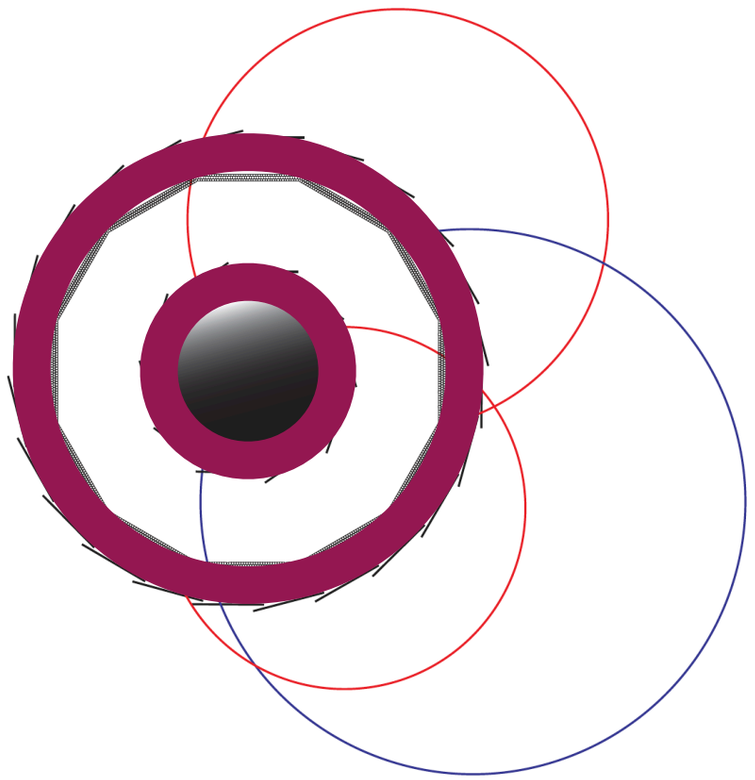

Target prototype



# The pixel tracker: Overview

- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime
- Momentum resolution: < 0.5 MeV/c over a large phase space; Geometrical acceptance: ~ 70%;  $X/X_0$ per layer: ~ 0.011%



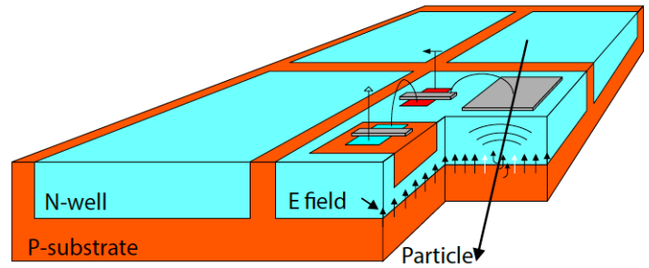



**Re-curl stations** **Central stations**

# The pixel tracker: The MuPix prototypes

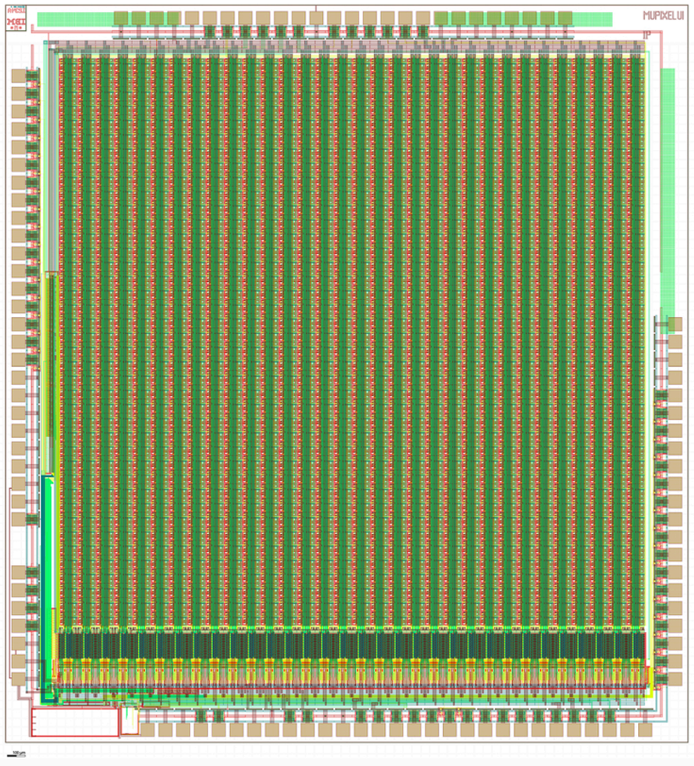
Ivan Peric, Nucl.Instrum.Meth. A582 (2007) 876-885

- Based on HV- MAP: Pixel dimension: 80 x 80 $\mu m^2$ , Thickness: 50 µm , Time resolution: < 20 ns, Active area chip: 20 x 20 $mm^2$ , Efficiency: > 99 %, Power consumption : < 350 $mW/cm^2$
- MuPix 7: The first small-scale prototype which includes all Mu3e functionalities

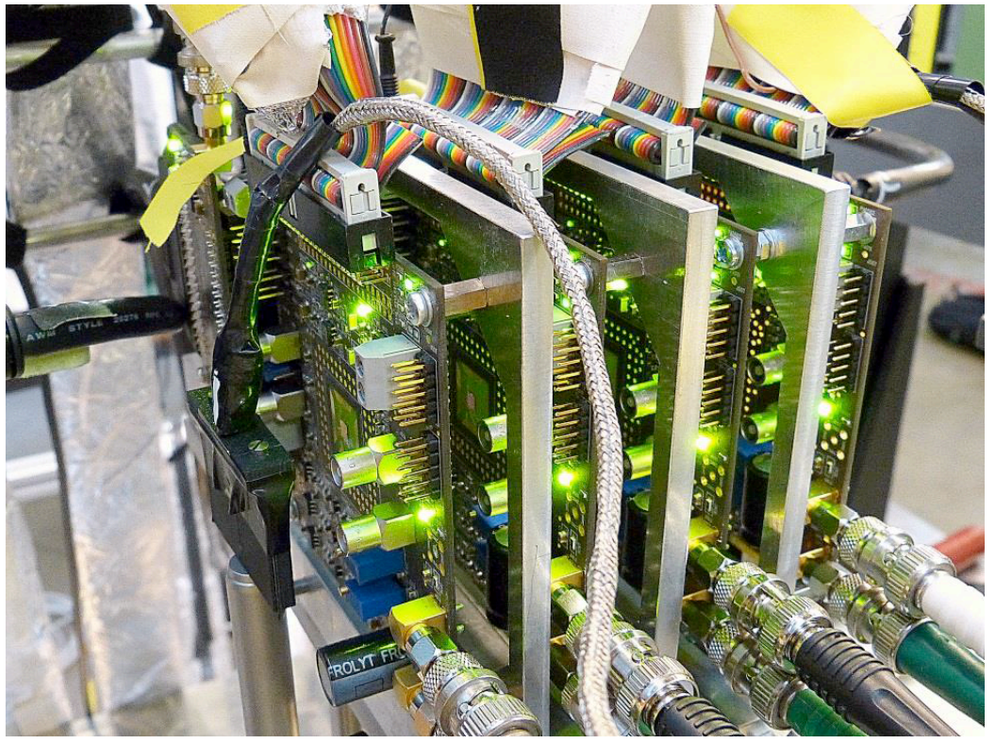



| Prototype | Active Area [$mm^2$] |
|---|---|
| MuPix1 | 1.77 |
| MuPix2 | 1.77 |
| MuPix3 | 9.42 |
| MuPix4 | 9.42 |
| MuPix6 | 10.55 |
| MuPix7 | 10.55 |

## MuPix7



## Extensively tested along beams



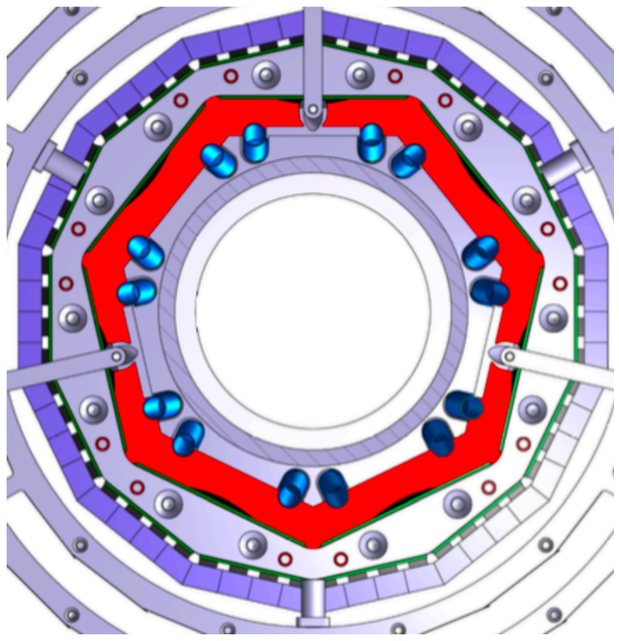
# The pixel tracker: Current and future plan

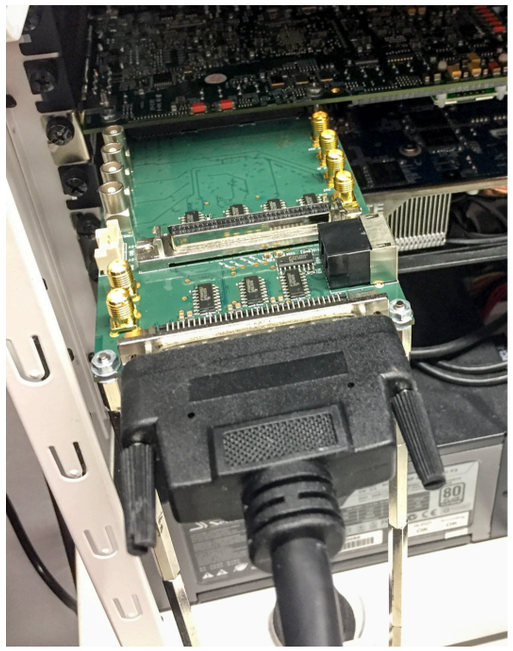
- After an extensive test beam campaign, achieved milestones
  - A fully functional HV-MAPS chip, 3x3 $mm^2$, Operation at high rates: 300 kHz at PSI; up to 1 MHz at SPS
  - Crosstalk on setup under control, on chip seen. Mitigation plan exists (MuPix8), Routinely operated systems of up to 8 chips in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

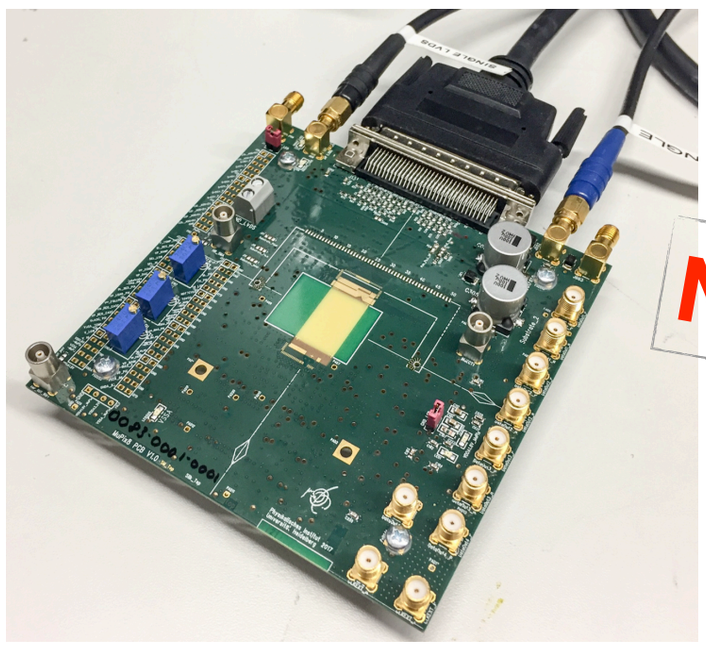
- Next steps
  - MuPix 8, the first large area prototype: from O(10) $mm^2$ to 160 $mm^2$ : Ready and extensively tested!
  - MuPix 9, small test chip for: Slow  Control, voltage regulators and other test circuits. This year test beam campaign
  - MuPix 10, the final version for Mu3e: 380 $mm^2$

New

MuPix8





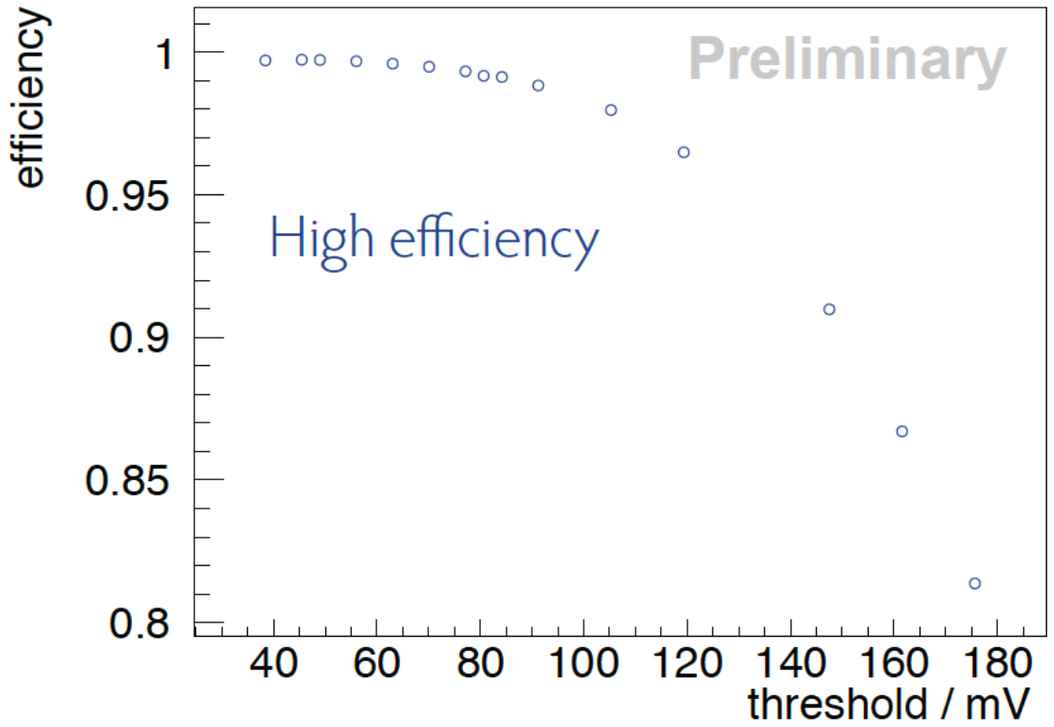


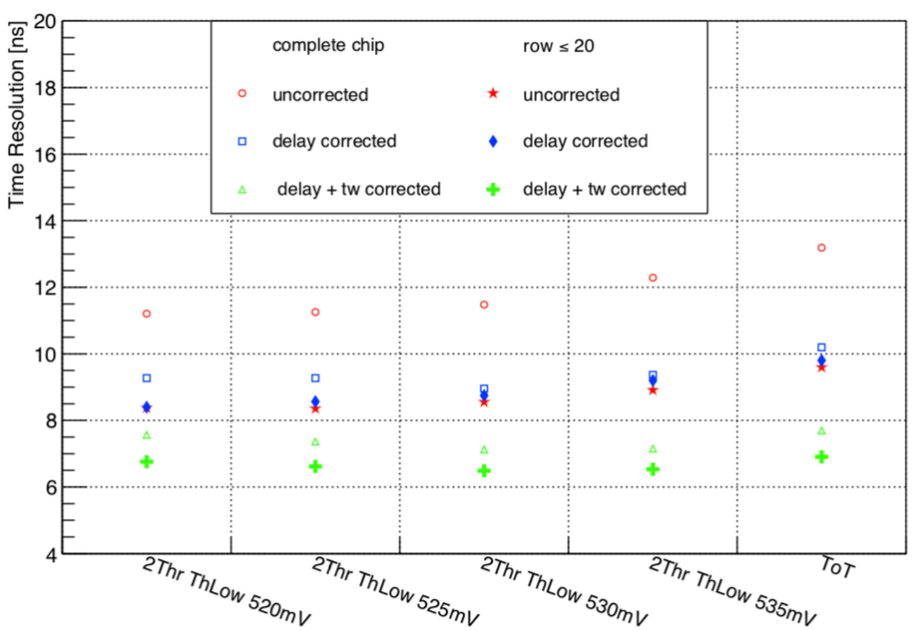
New

H. Augustin wt al. Nucl. Instr. Meth., A936 681 (2019)
H. Augustin et al. arXiv:1905.09309

# MuPix 8: First Results

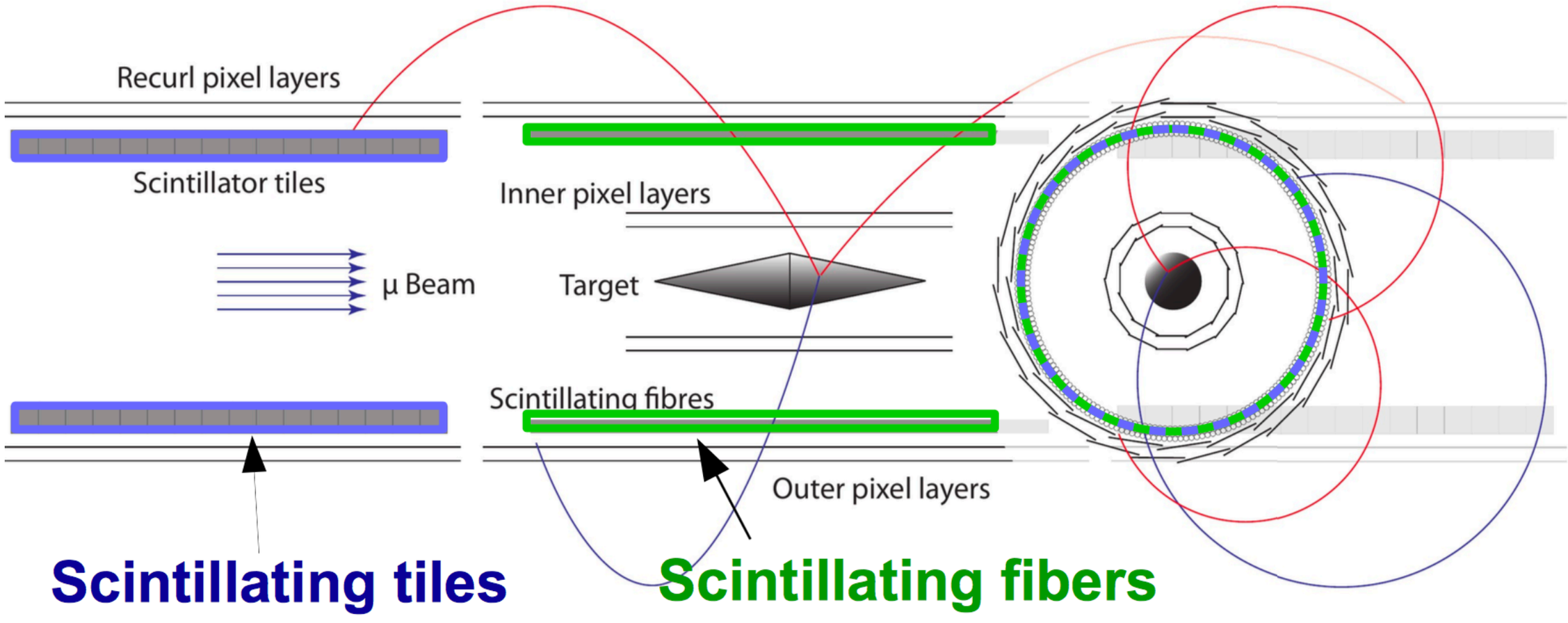
- Extensive beam test performed during 2018
- Some preliminary results

# 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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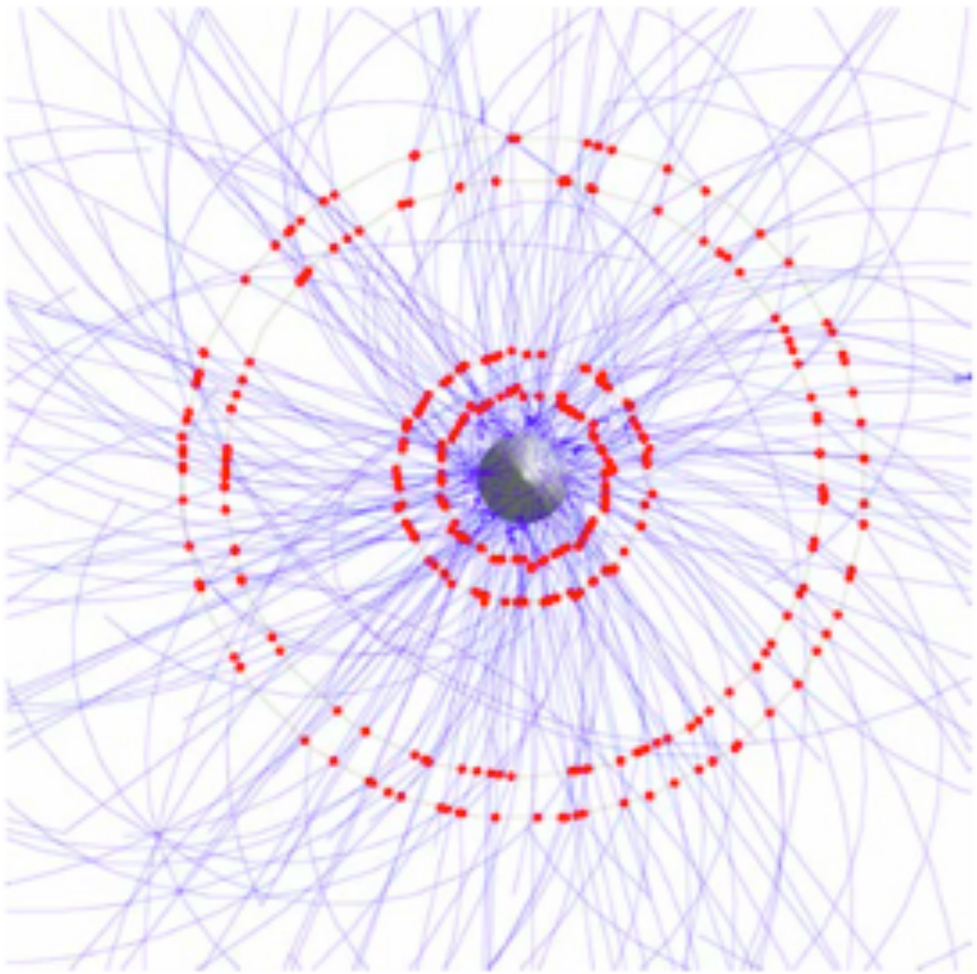
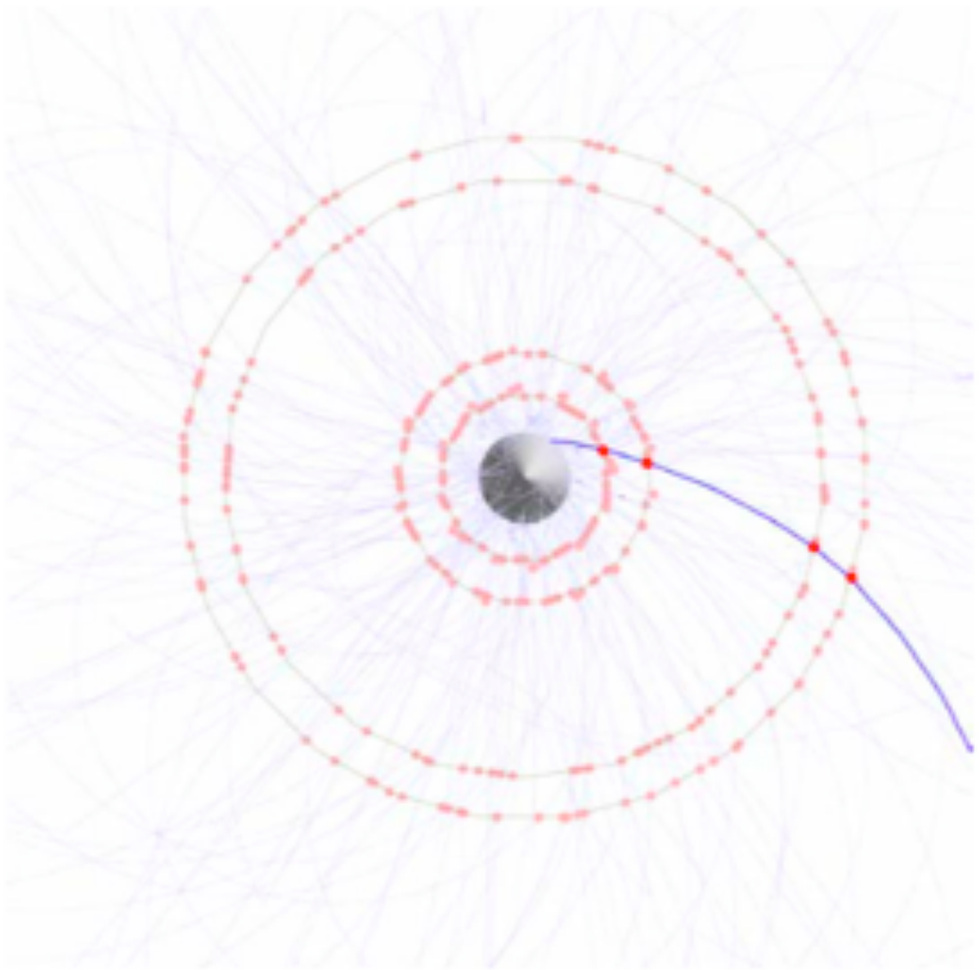


Pixels: O(50 ns)



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

# The timing detectors: Impact

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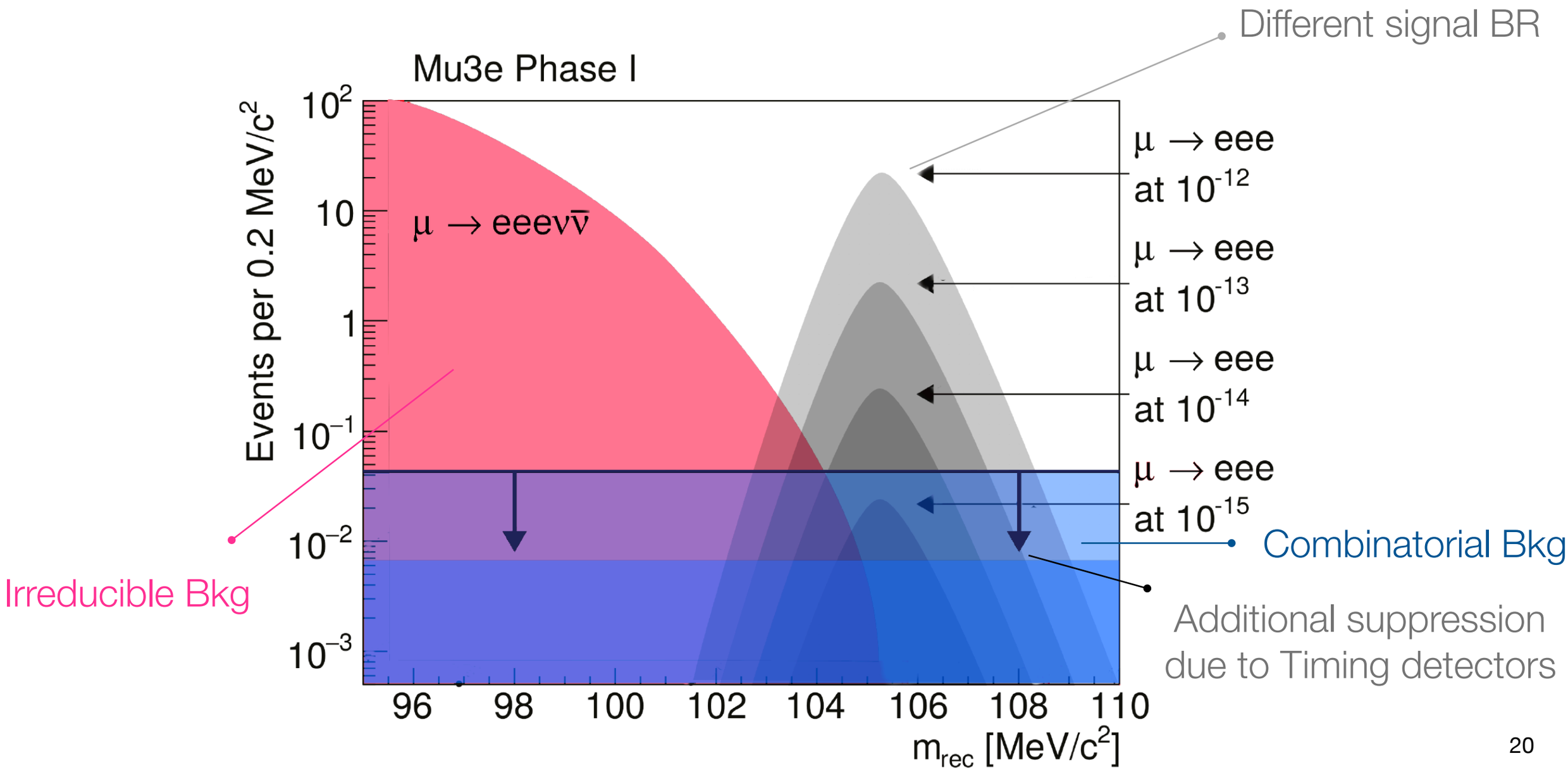
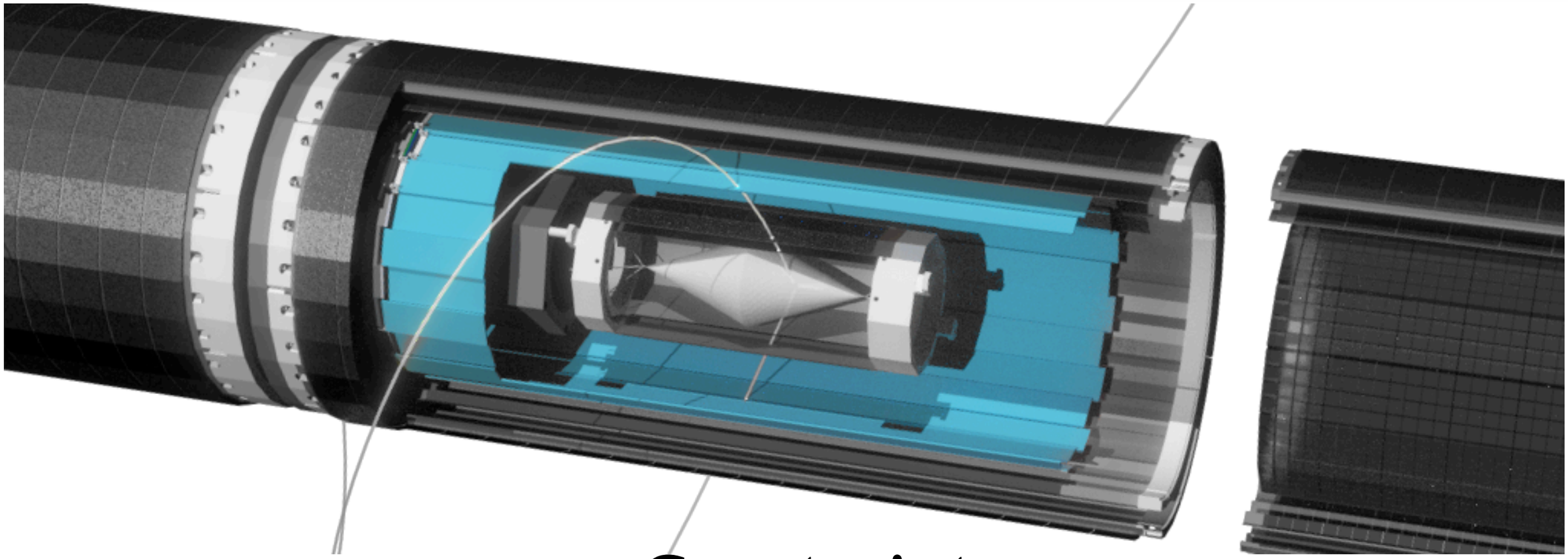


# The Fiber detector (SciFi): Overview



## Parts

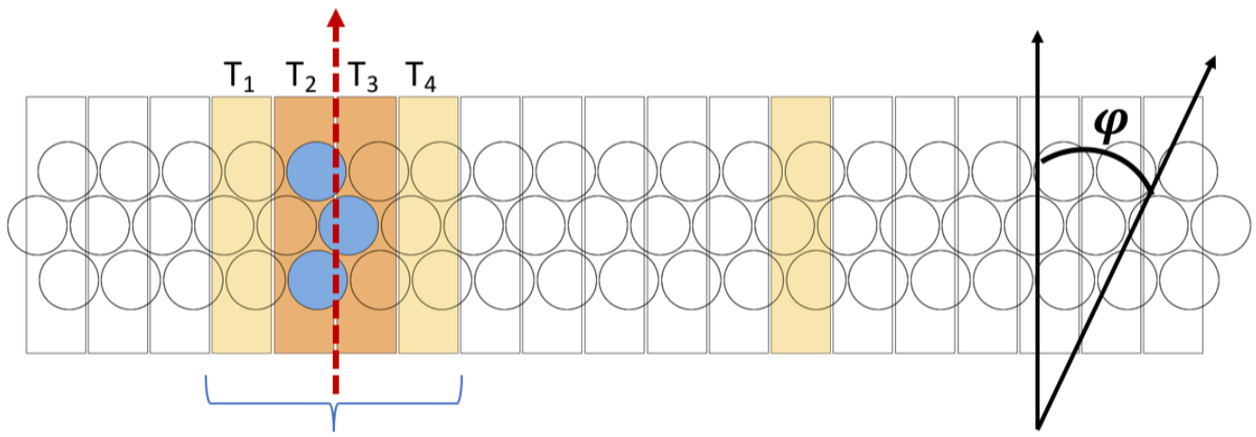
- cylindrical at ~ 6 cm (radius);
- length of 28-30 cm;
- 3 layers of round or square
- multi-clad 250 μm fibres
- fibres grouped onto SiPM array
- MuSTiC readout

## Constraints

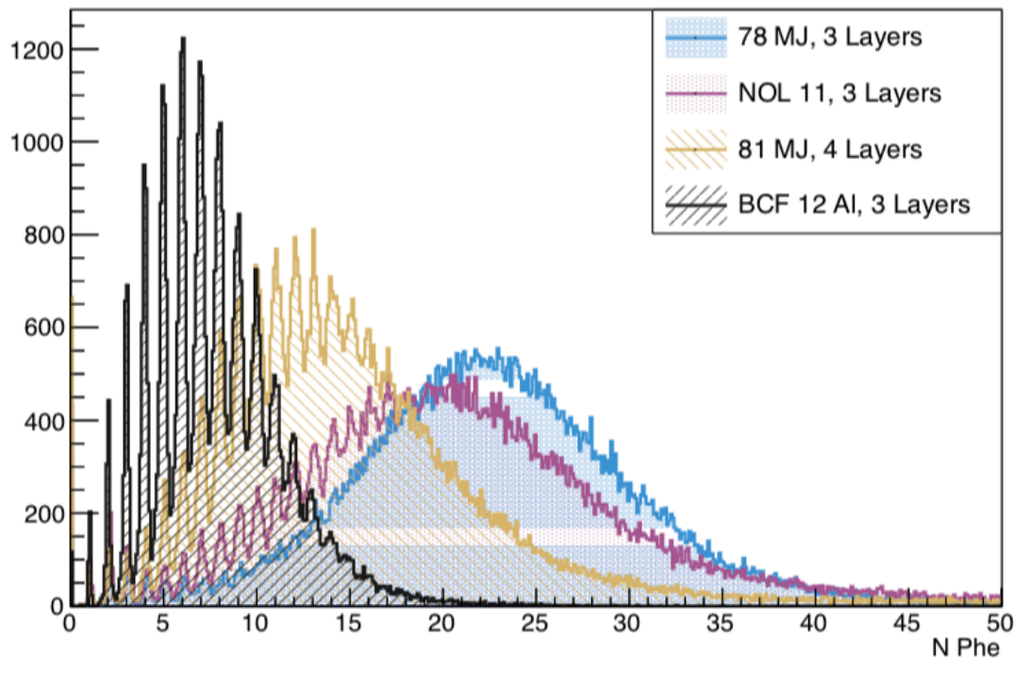
- high detection efficiency $\varepsilon > 95\%$
- time resolution $\sigma < 1$ ns
- < 900 μm total thickness
- < 0.4 % $X_0$
- rate up to 250 KHz/fibre
- very tight space for cables, electronics and cooling

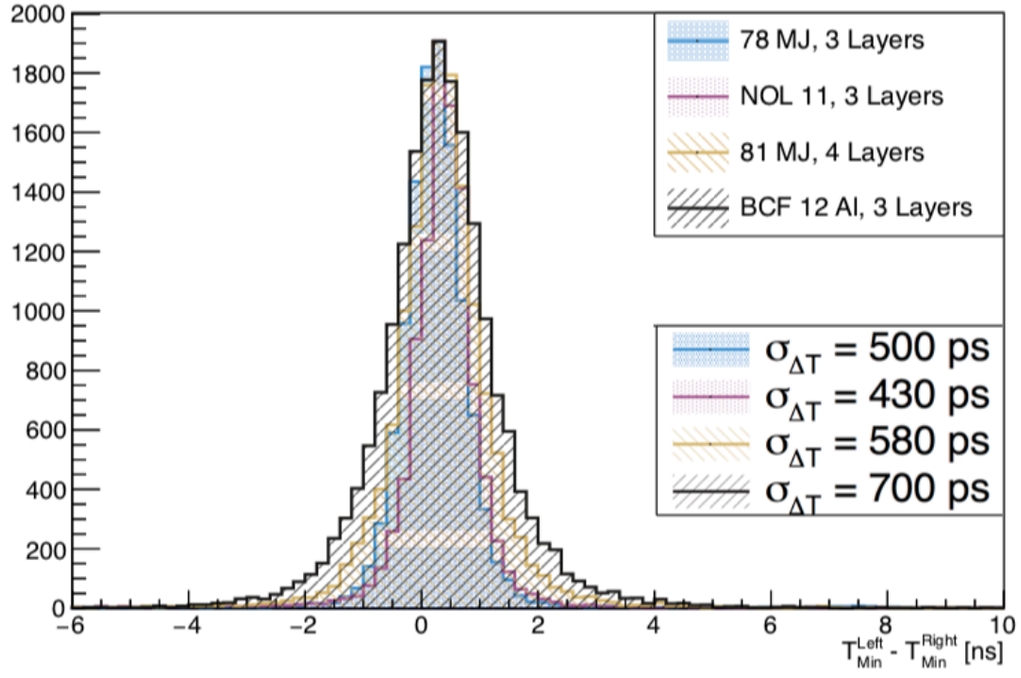
# SciFi prototypes: Results

- Studied a variety of fibres (SCSF 78 MJ, clear; SCSF 78 MJ, with 20% TiO2; NOL 11, clear; NOL 11, with 20% TiO2; SCSF 81 MJ, with 20% TiO2; BCF12 clear;  BCF12, with 100 nm Al deposit)
- 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




New



# SciFi prototypes: Results

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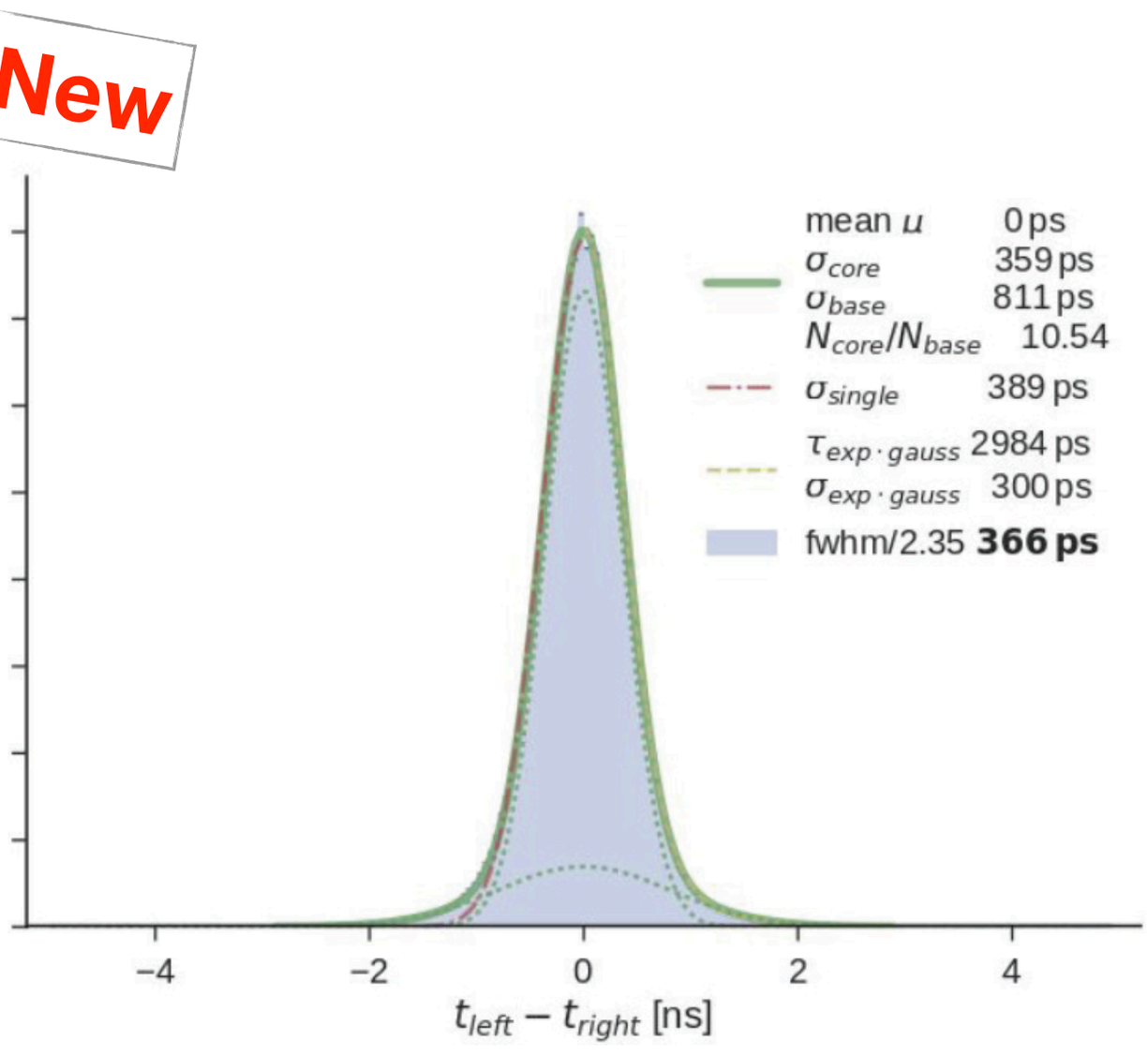
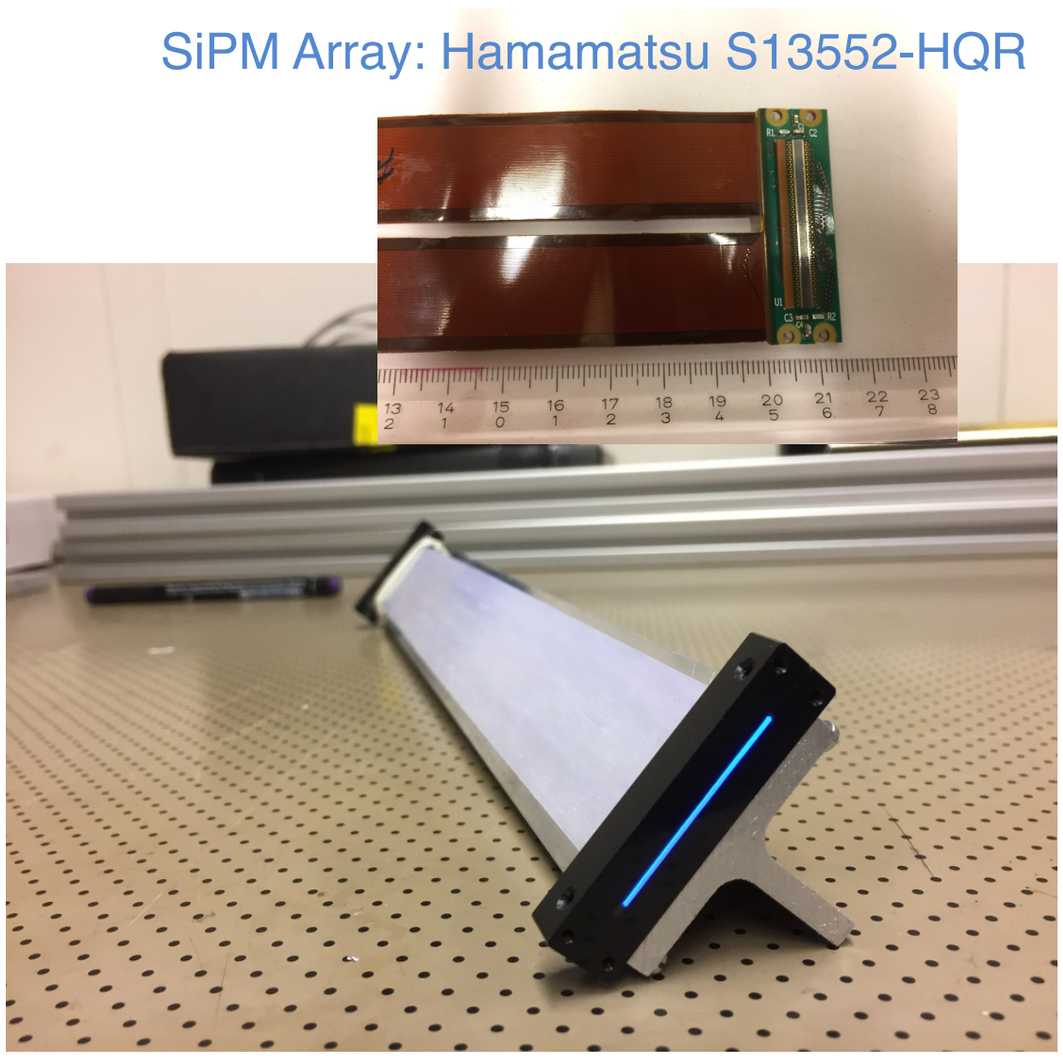
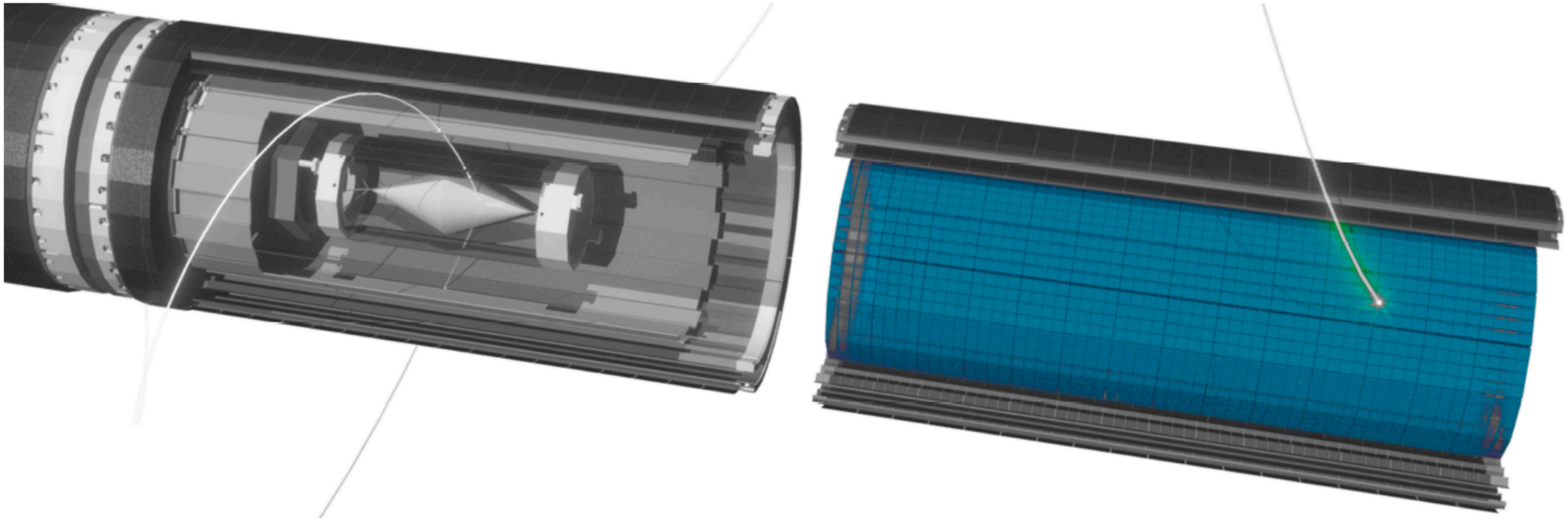
New




SiPM Array: Hamamatsu S13552-HQR



# The Tile detector: Overview



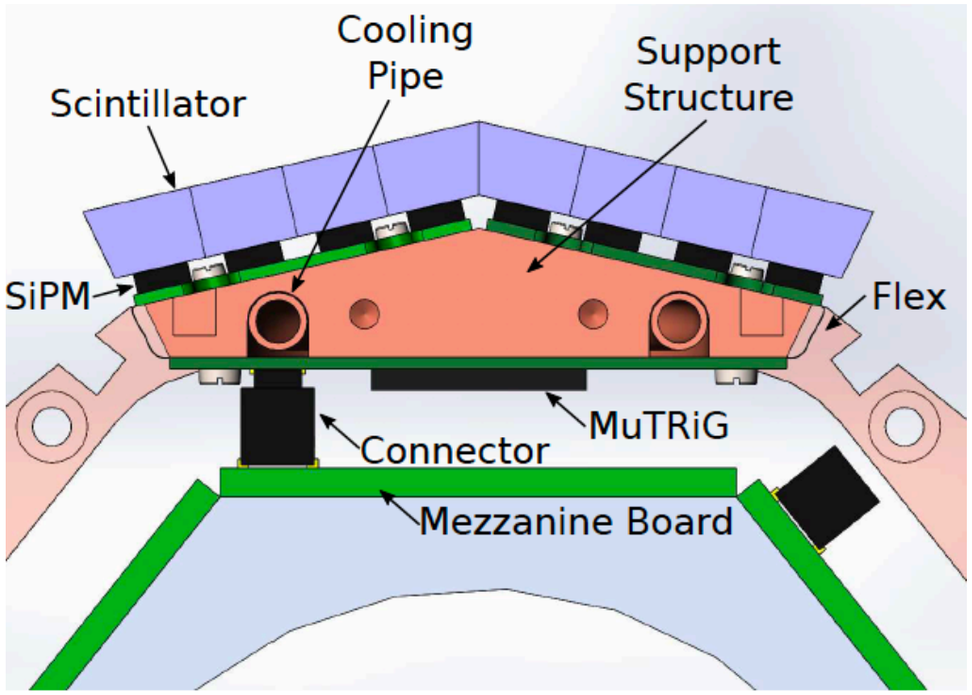
## Parts

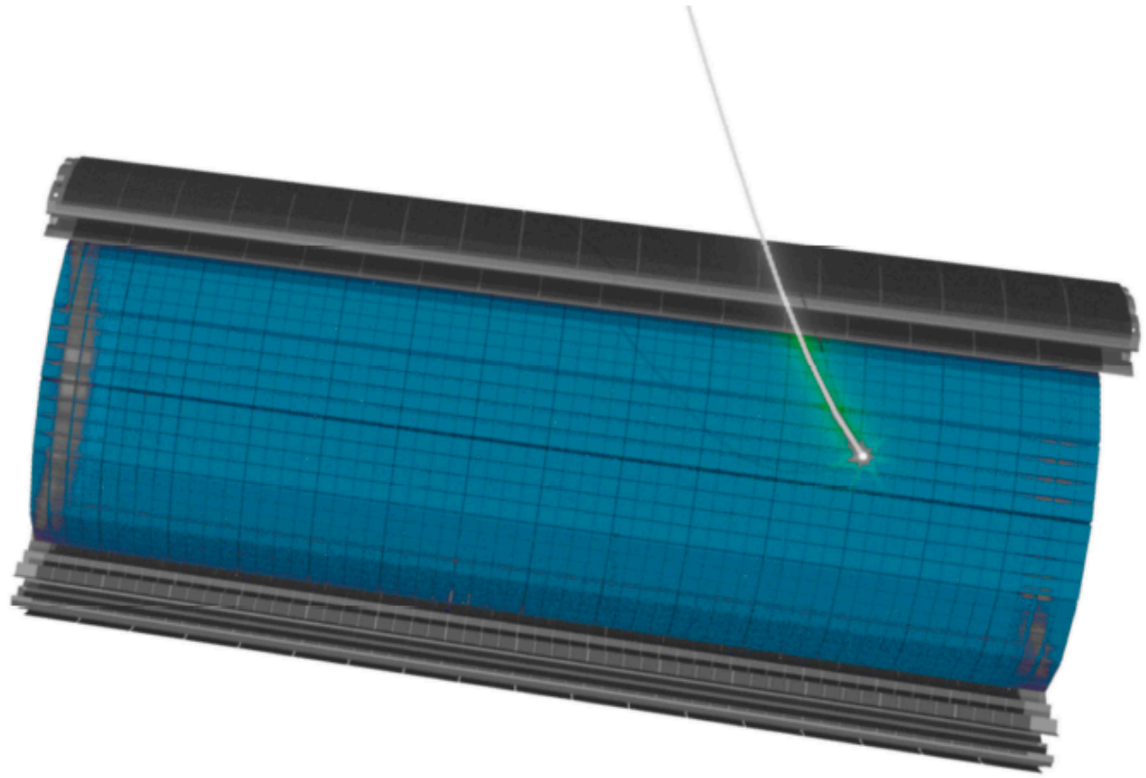
- cylindrical at ~ 6 cm (radius)
- length of 36.4 cm
- 56 x 56 tiles of 6.5 x 6.5 x 5 $mm^3$
- 3 x 3 $mm^2$ single SiPM per tile
- Mixed mode ASIC: MuTRiG

## 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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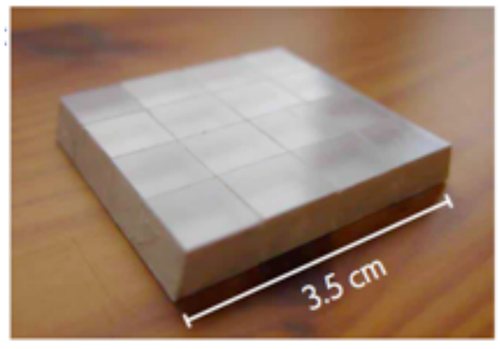
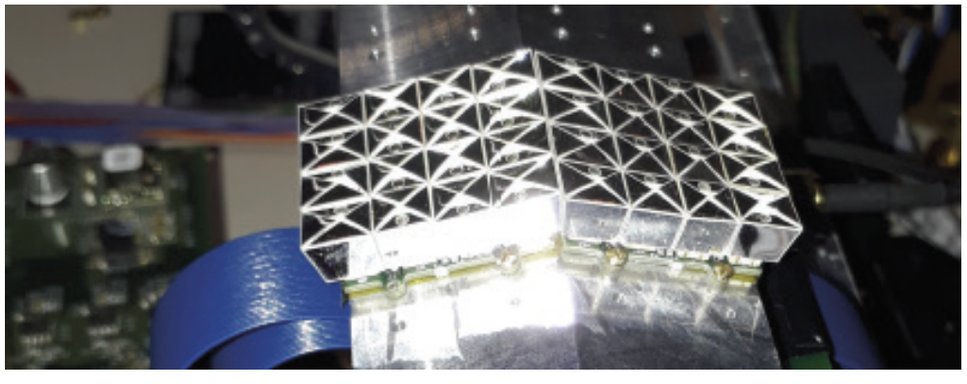
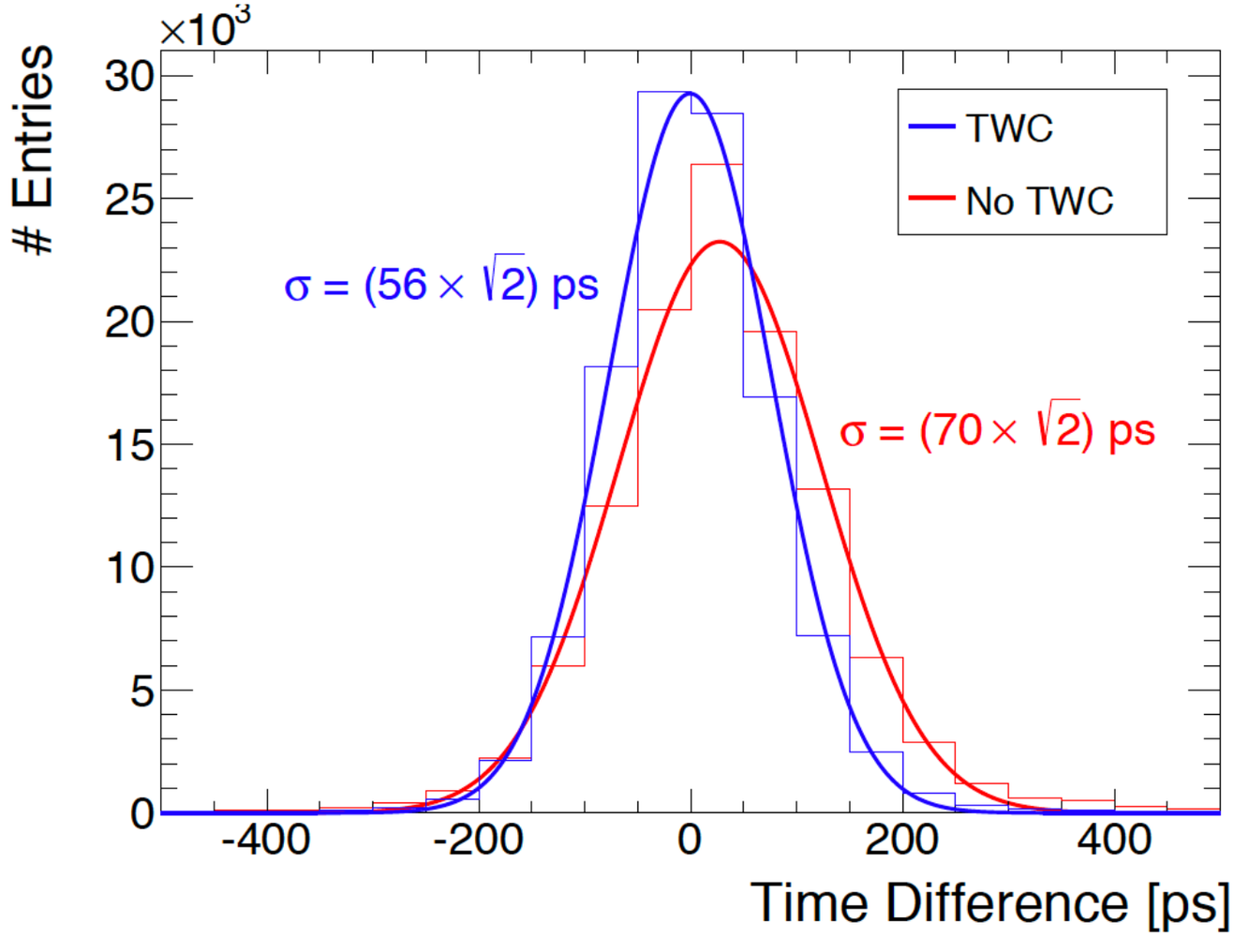
# Tile Prototype: Results

- 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



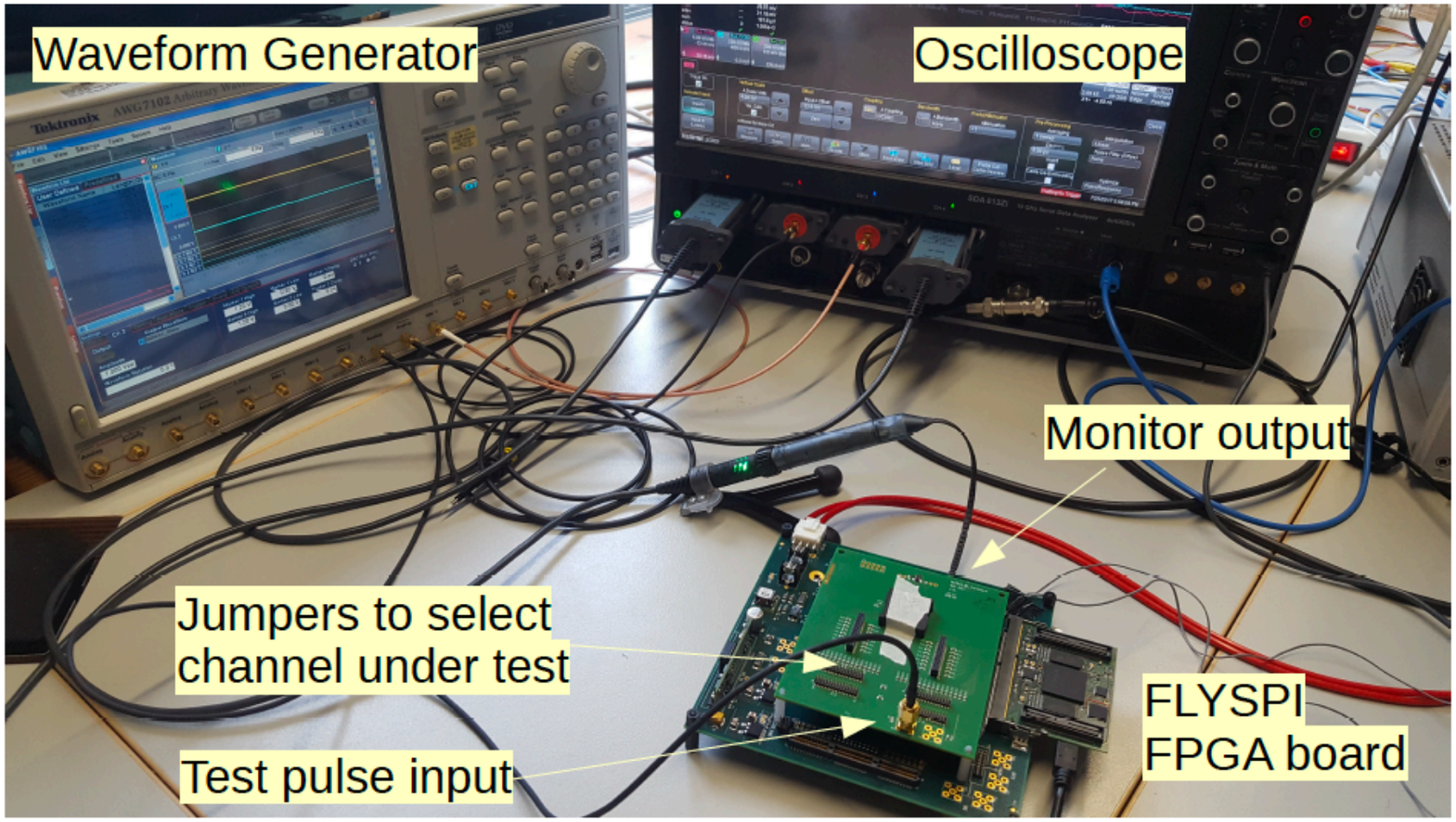



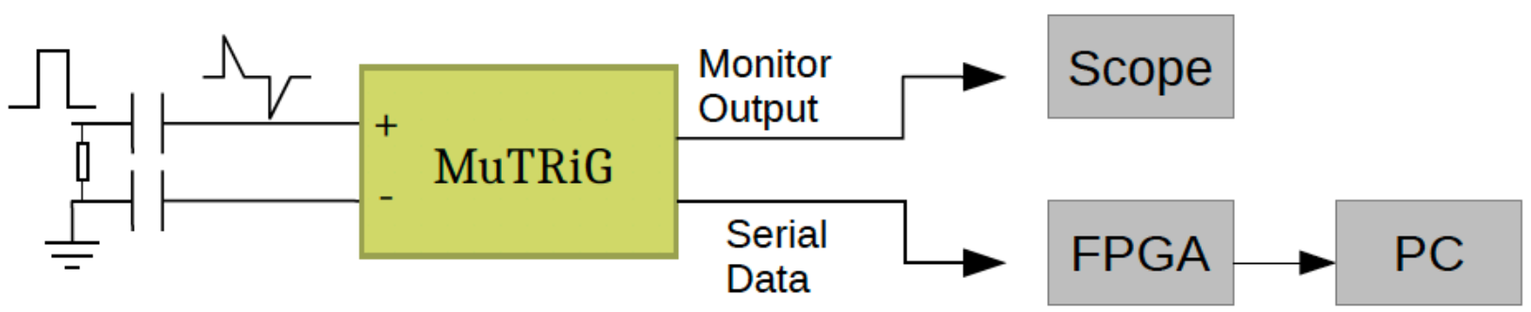


# MuTRiG

- Mixed mode, ~ 50 ps timestamps, high impedance, optional differential
- Commissioning started!

New



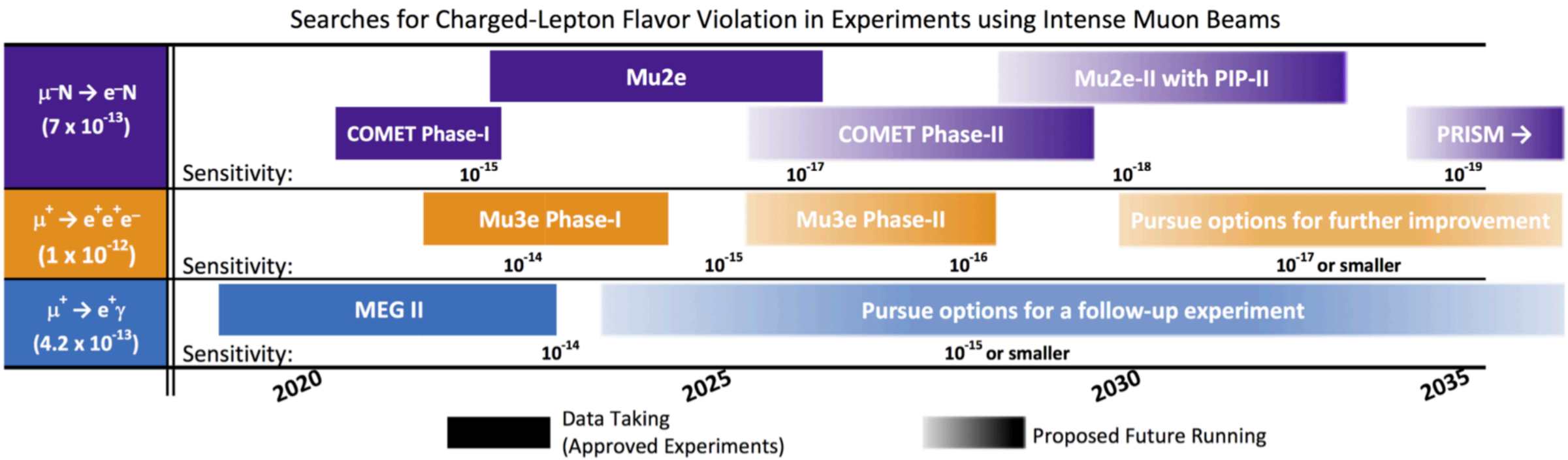
# Outlooks

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of **~$10^{-15}$** (Phase I) up to down **~$10^{-16}$** (Phase II). Previous upper limit **BR($\mu^+ \rightarrow e^+ e^+ e^-$) ≤ 1 x $10^{-12}$ @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) for a final sensitivity **down to few x $10^{-16}$**
- 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
- Pre- and full- engineering runs are expected for 2020-21 followed by data acquisition

A.M. Baldini et al. arXiv:1812.06540v1

# Final remarks

- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
- **cLFV remains one of the most exciting place where to search for new physics**
- Submitted inputs to the European Strategy Committee




Thanks for your attention!