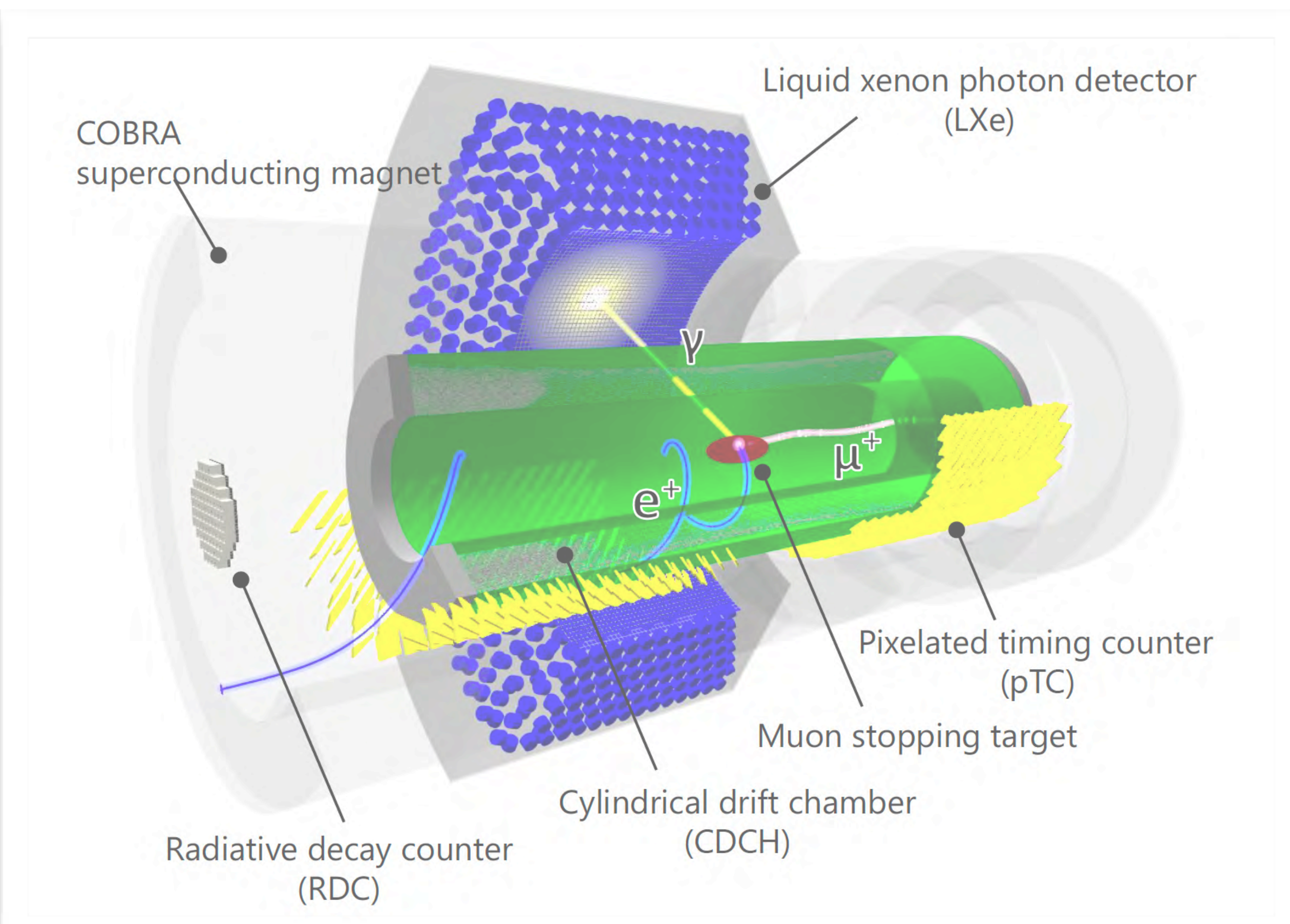
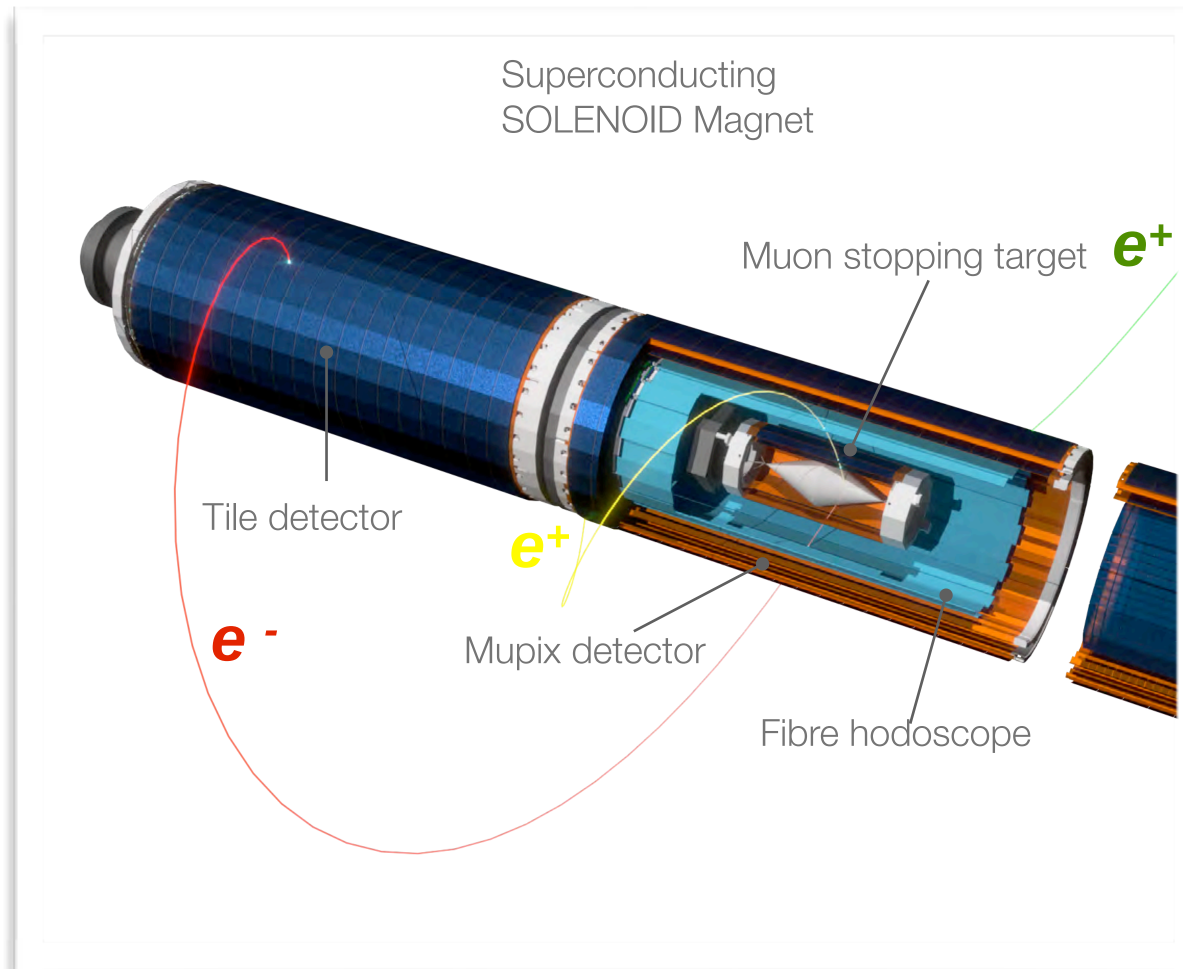
PAUL SCHERRER INSTITUT

Status of the MEGII and Mu3e experiments

Angela Papa, Paul Scherrer Institut
September 7-9, 2017
FCCP2017, Anacapri Italy





Content

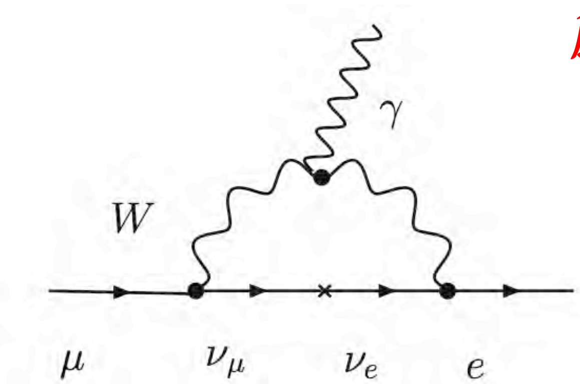
- Charged Lepton Flavour Violation (cLFV) search:
  The motivation

- cLFV with the MEGII and Mu3e experiments:
  The $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$ searches at PSI

  - Muon beams
  - Event signatures
  - The MEGII apparatus
  - The Mu3e apparatus

cLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

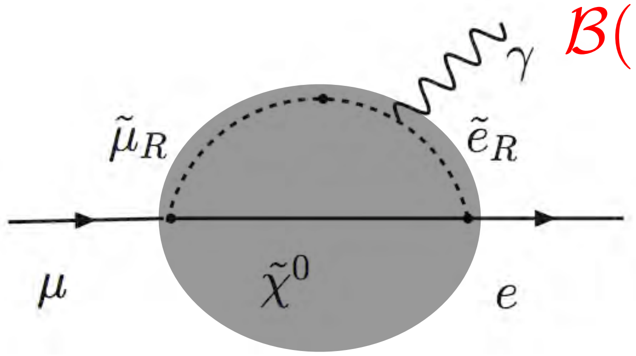


$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$

ν oscillations

too small to access experimentally

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



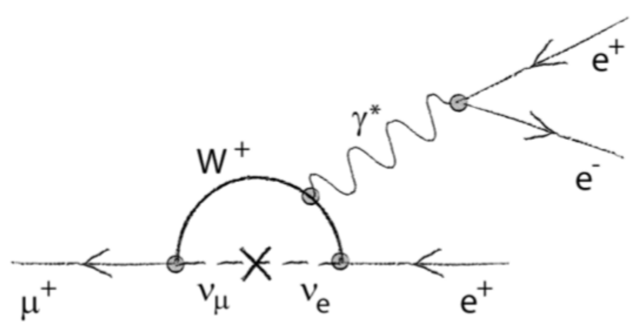
$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$

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

cLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

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



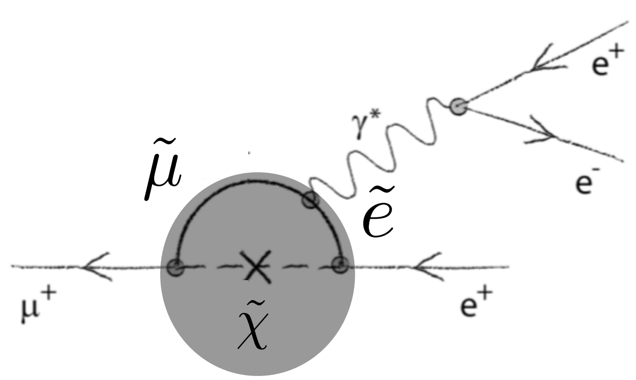
ν oscillations

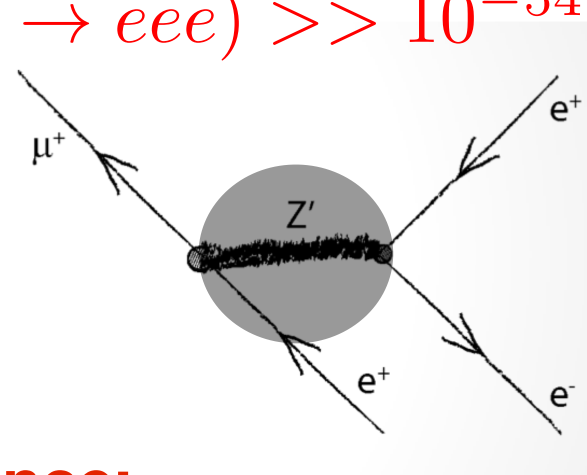
too small to access experimentally

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

i.e. EXTRA Z'

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





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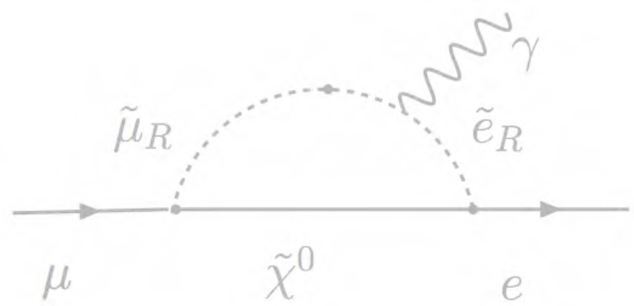
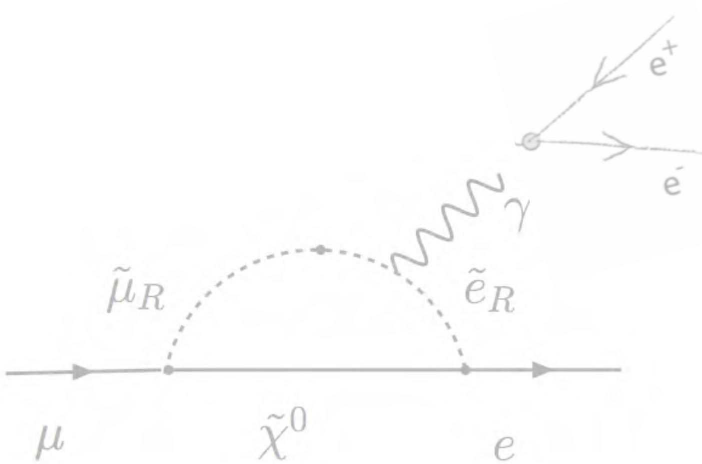
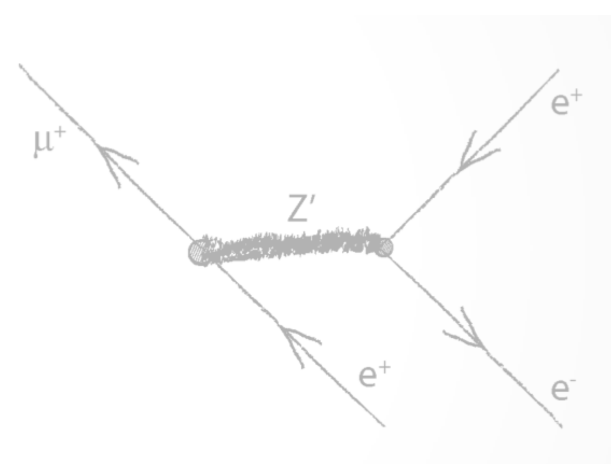
cLFV evidence: A clear signature of New Physics

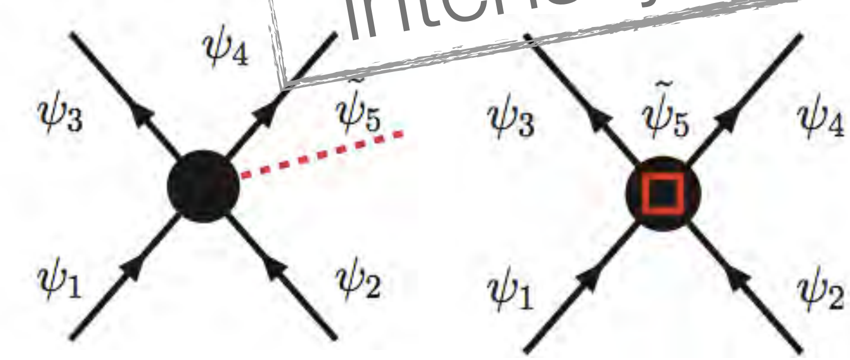






to unveil behind SM physics
via virtual particles

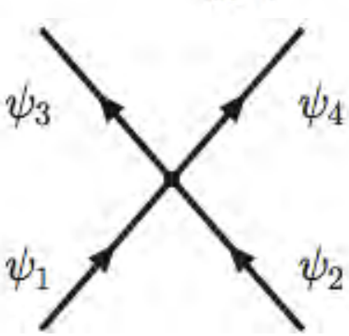
intensity frontier



to probe otherwise unreachable and unexploited new physics energy scale

high energy probe

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

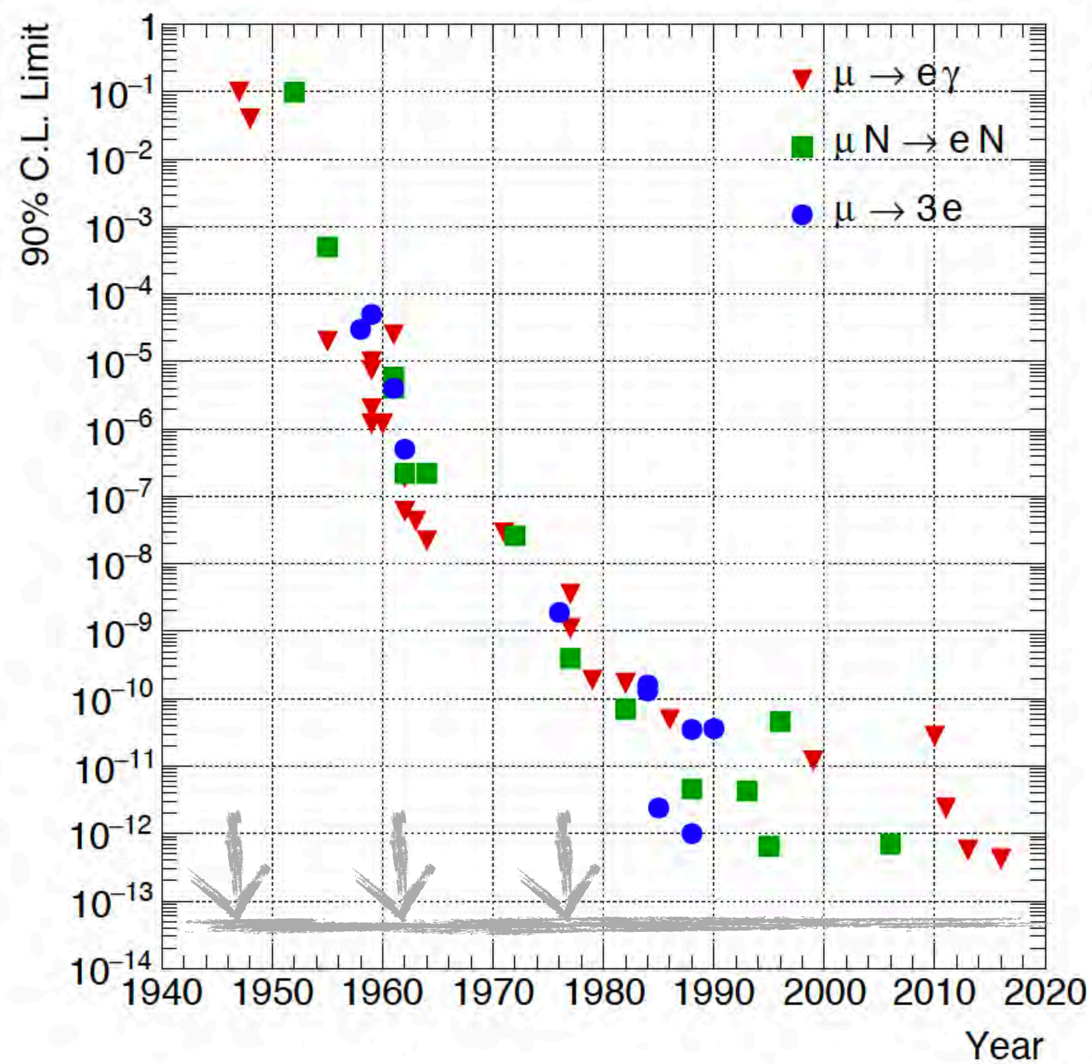


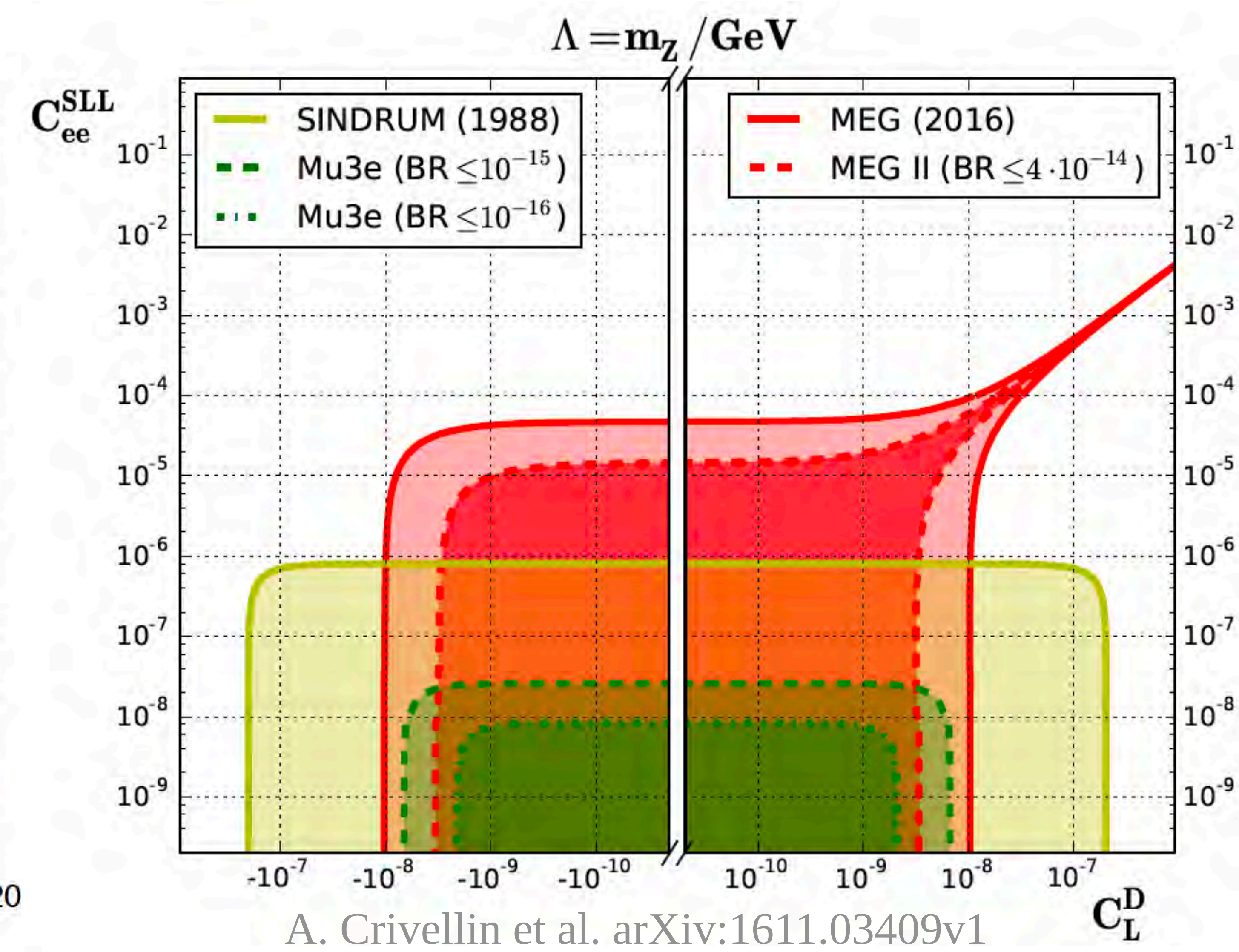
$$\frac{1}{\Lambda^2}$$

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:1611.03409v1

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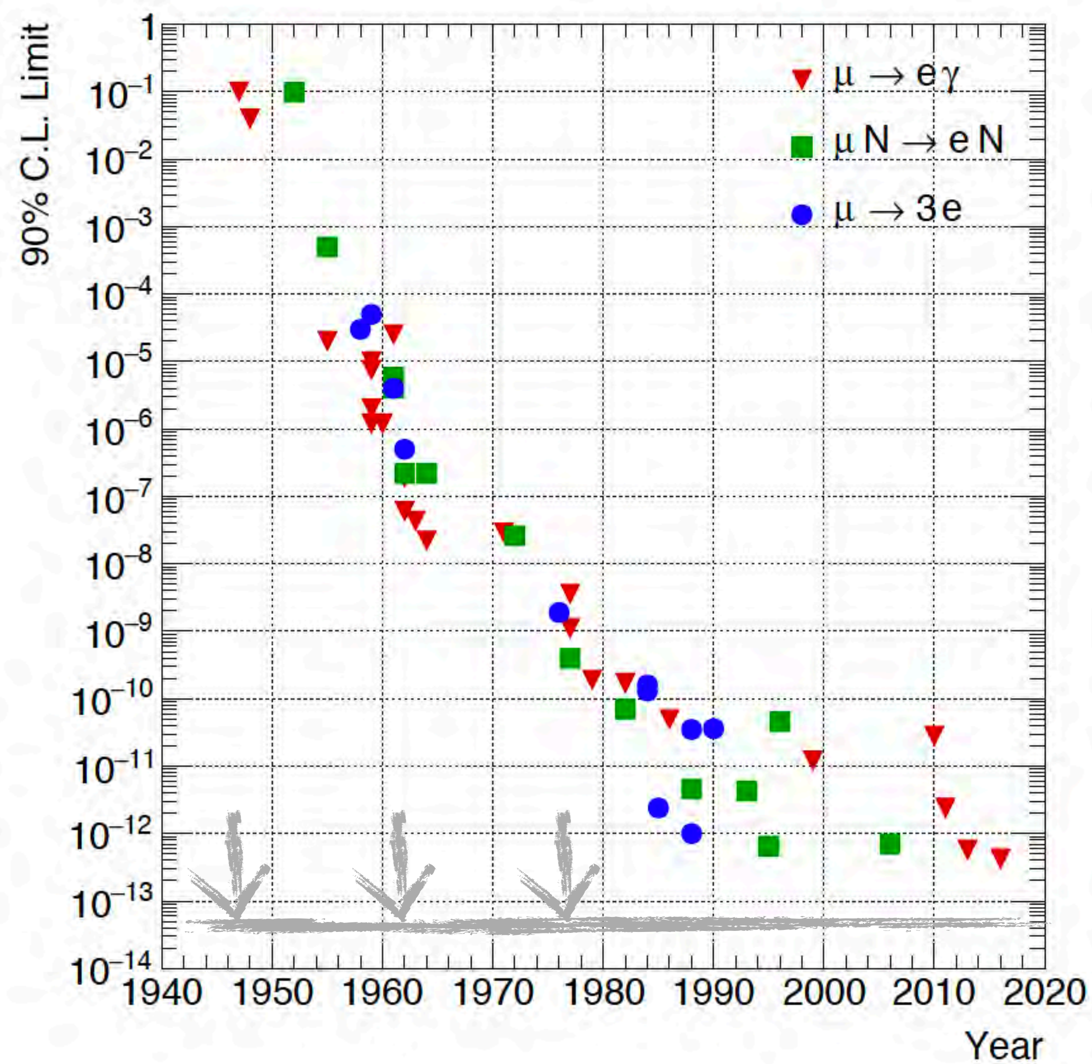
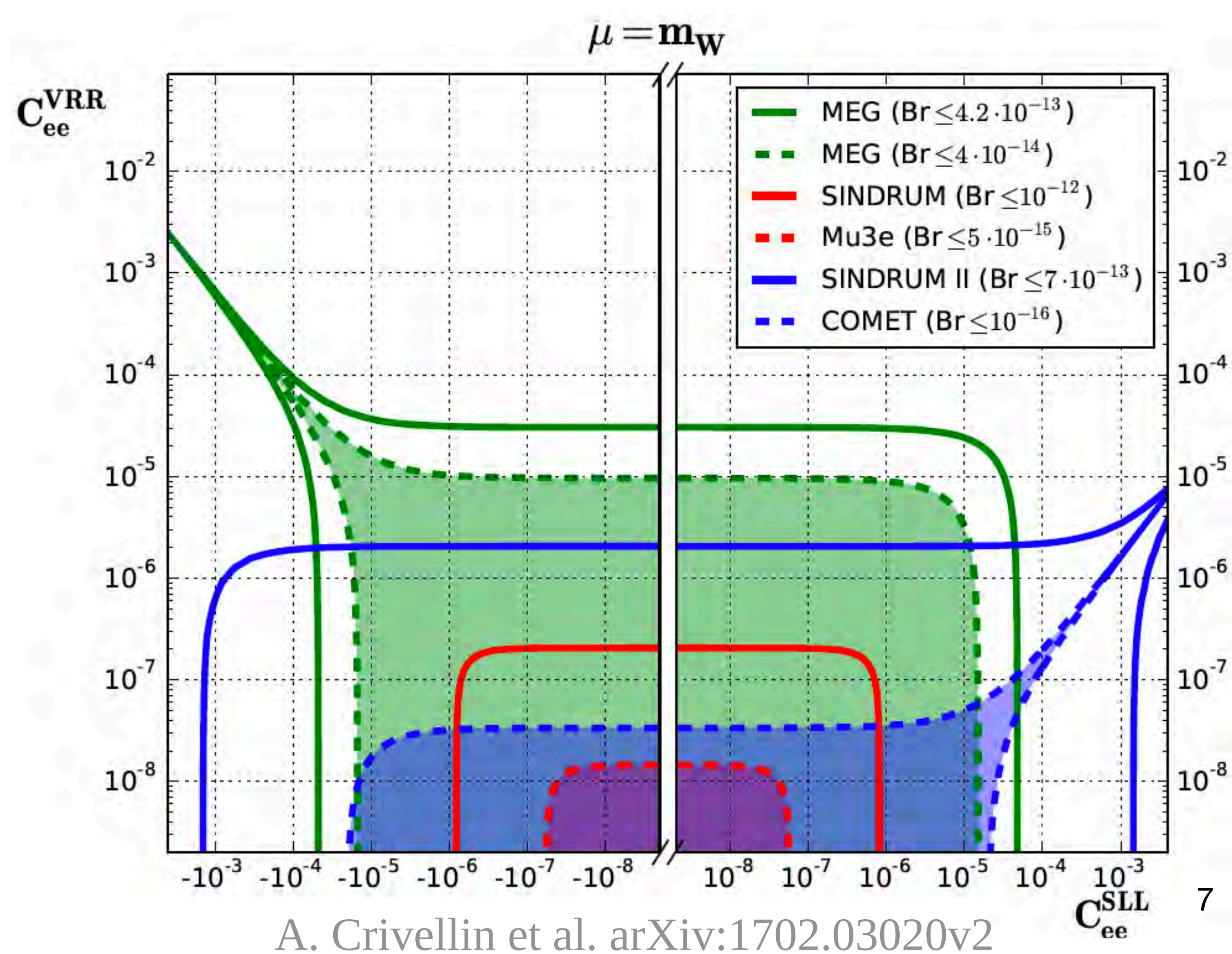


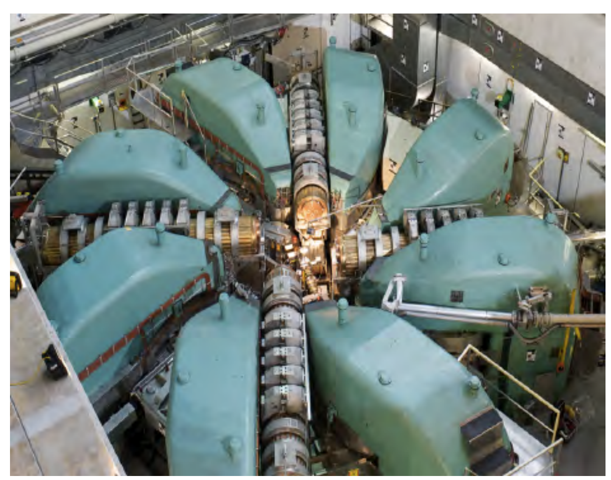


A. Crivellin et al. arXiv:1702.03020v2

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/Mu3e beam requirements:
  - Intensity O(10^8 muon/s), low momentum p = 29 MeV/c
  - Small straggling and good identification of the decay

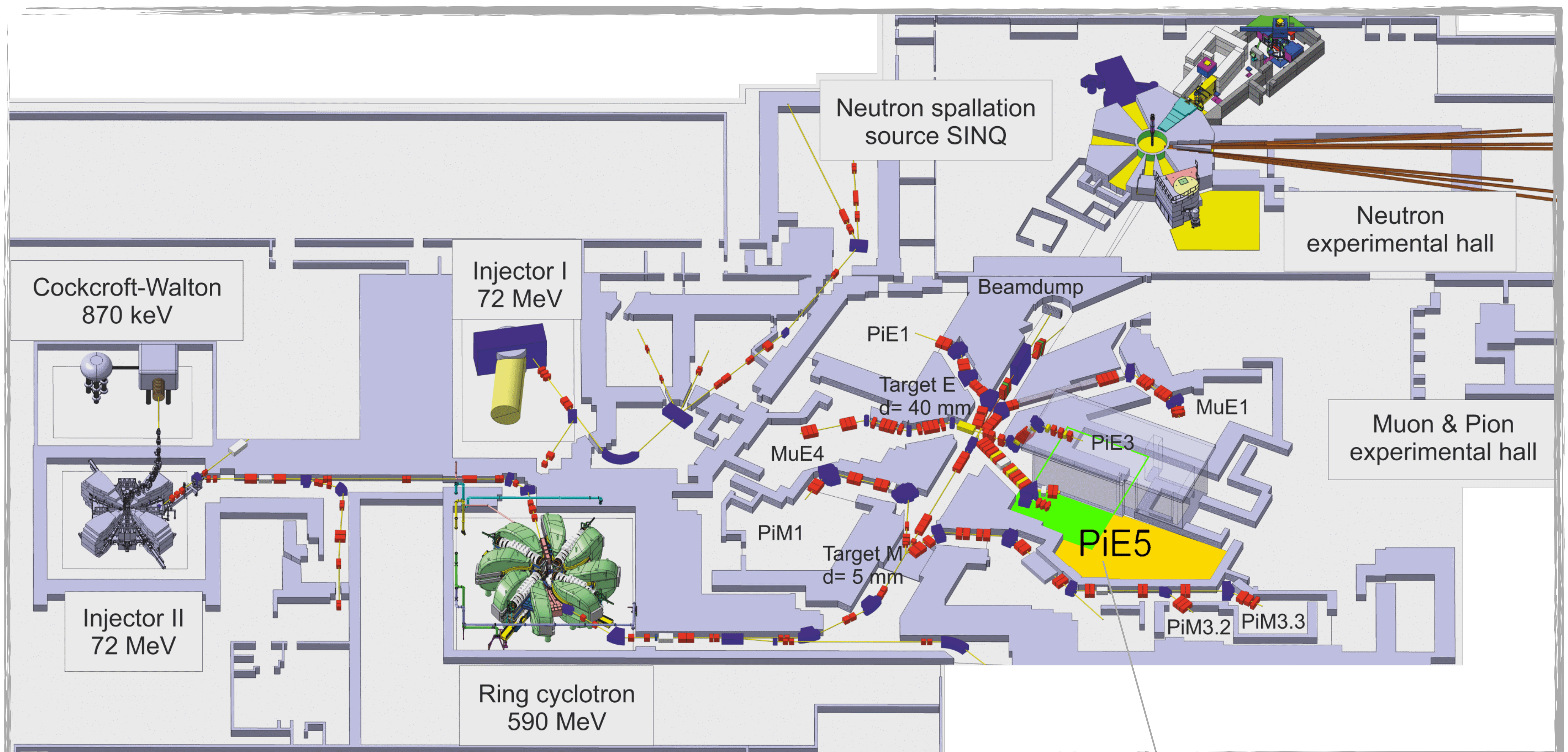


590 MeV proton
ring cyclotron
1.4 MW

PSI landscape

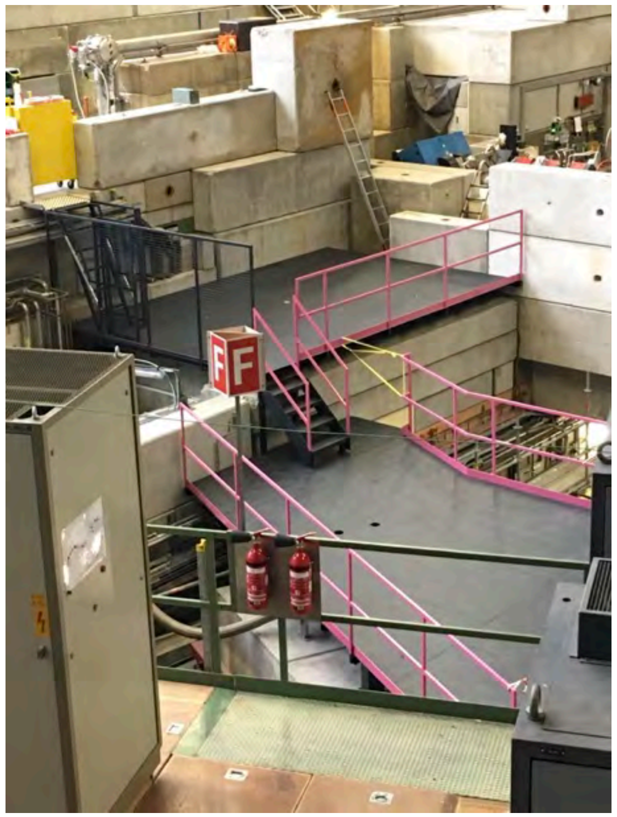
The world's most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas



MEGII / Mu3e Experimental area

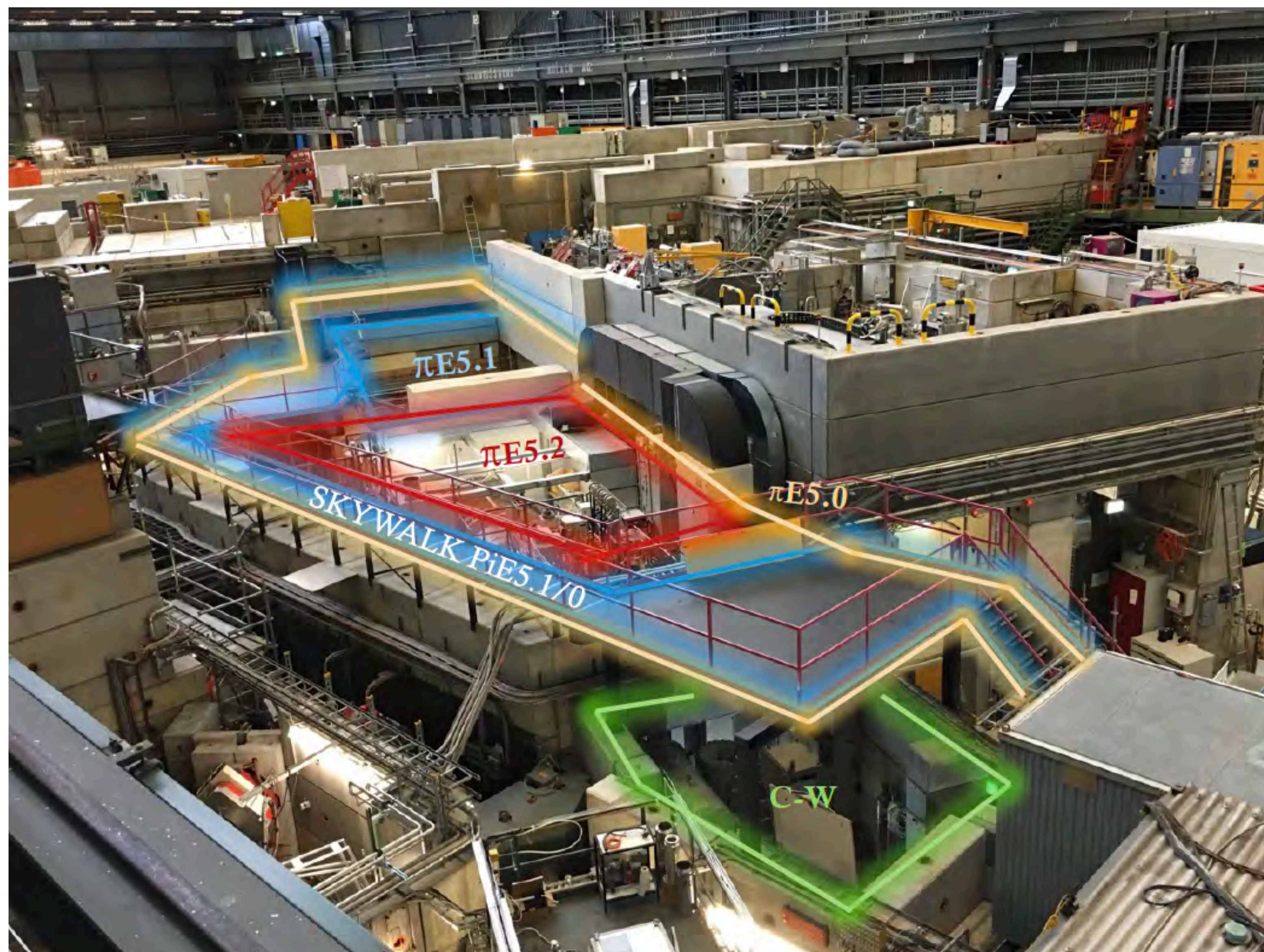
The MEGII and Mu3e experimental area: Pictures



New

Mu3e extra platforms

Overview piE5 area



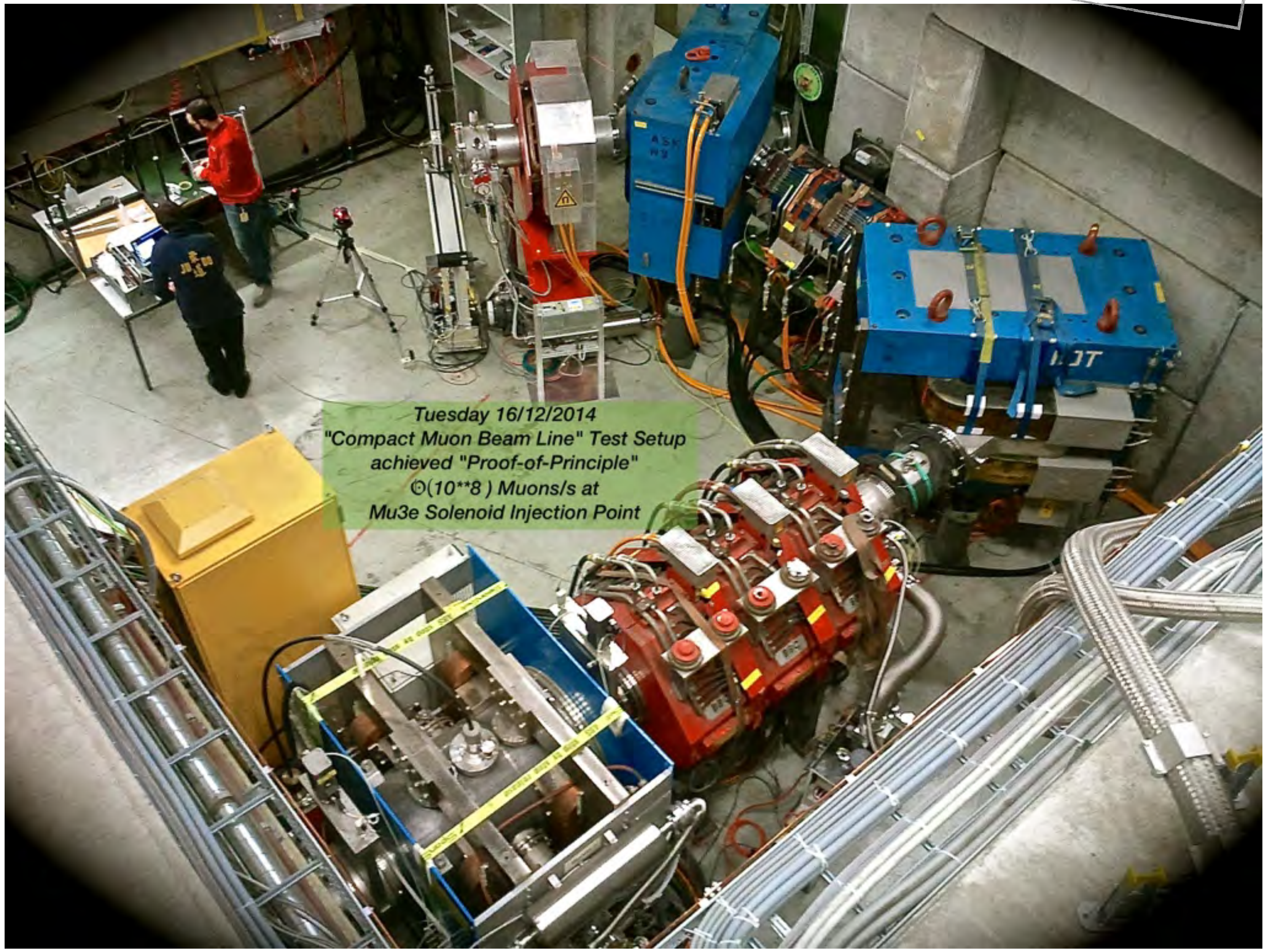
New

The MEGII and Mu3e beam lines

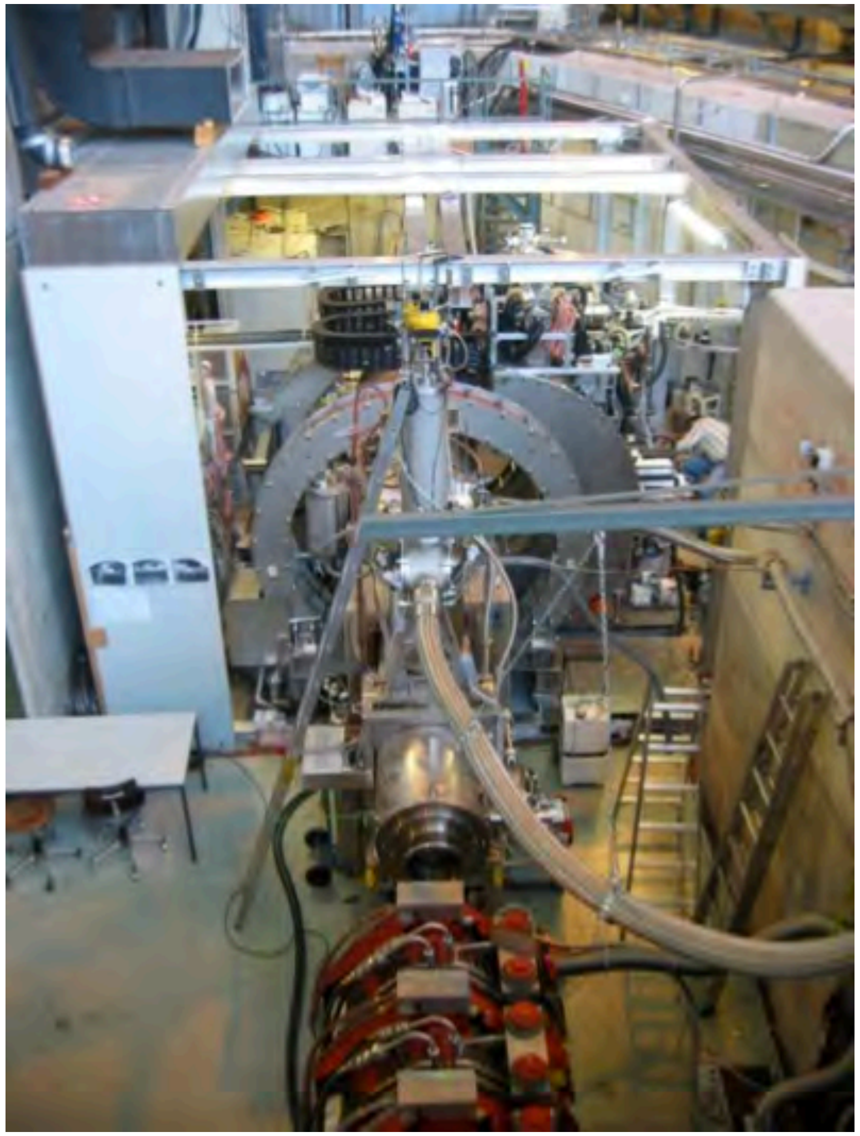
- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered 8.4 10^7 muon/s during 2016 test beam

New

The Mu3e CMBL



The MEGII BL

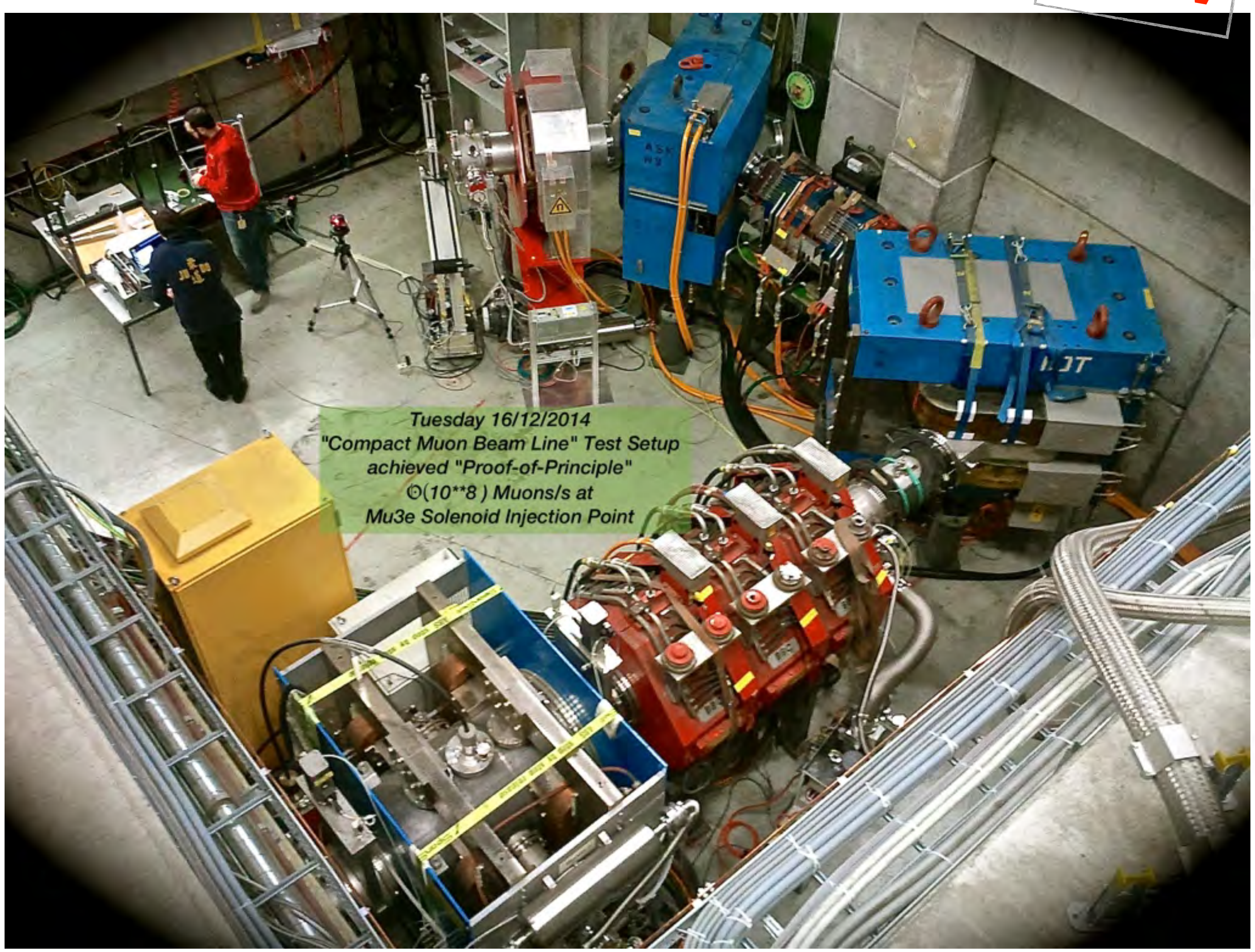


The compact beam line: Results

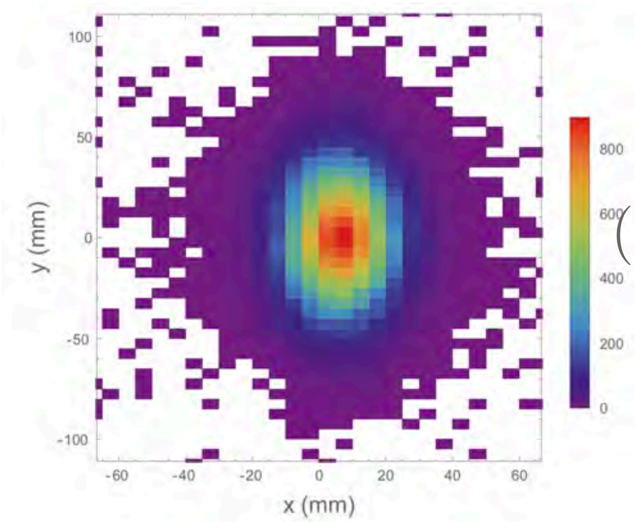
- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered 8.4 10^7 muon/s during 2016 test beam

New

The CMBL

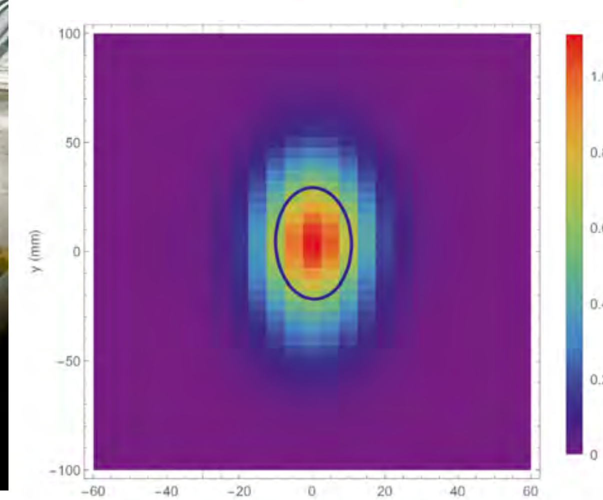


Beam at the injection Mu3e solenoid point



Simulation

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



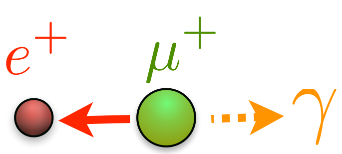
Data

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

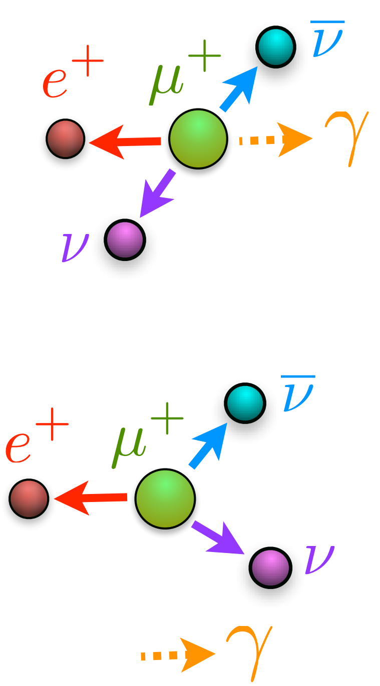
MEG: Signature and experimental setup

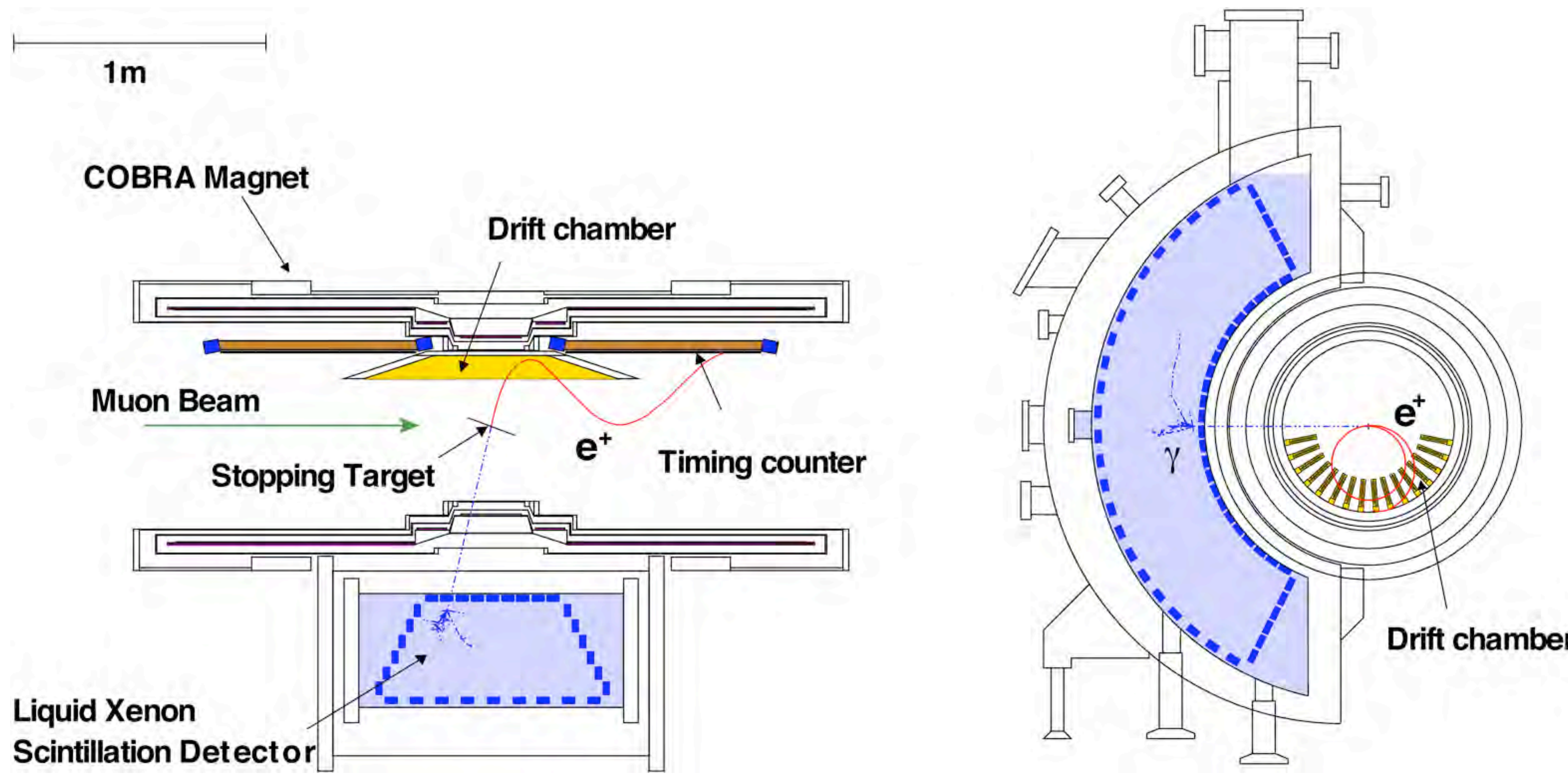
- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events

Signature



Backgrounds





A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

MEG: The result

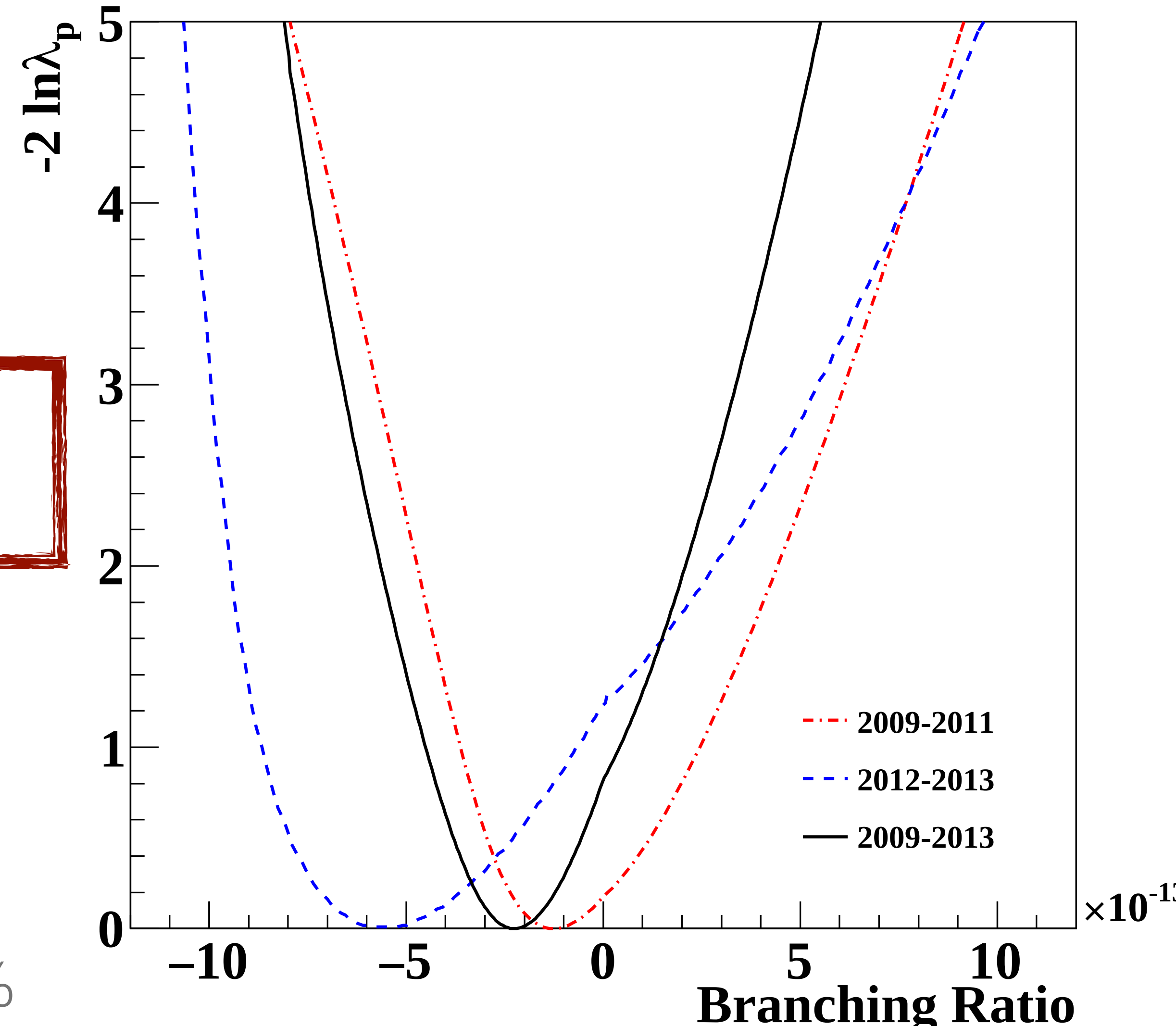
Since March 8th 2016

- Confidence interval calculated with Feldman & Cousin approach with profile likelihood ratio ordering
- Profile likelihood ratios as a function of the BR: all consistent with a null-signal hypothesis

Full data sample: 2009-2013
Best fitted branching ratio at 90% C.L.:

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

From MEGA to MEG:
improvement by a factor ~ 30



Systematic uncertainties: Target “alignment”: 5%
Other sources: < 1%

How the sensitivity can be pushed down?

high statistics

- More sensitive to the signal...

$$SES = \frac{1}{R \times T \times A_g \times \varepsilon(e^+) \times \varepsilon\,(gamma) \times \varepsilon(TRG) \times \varepsilon(sel)}$$

Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

high resolutions

- More effective on rejecting the background...

$$B_{acc} \sim R \times \Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2$$

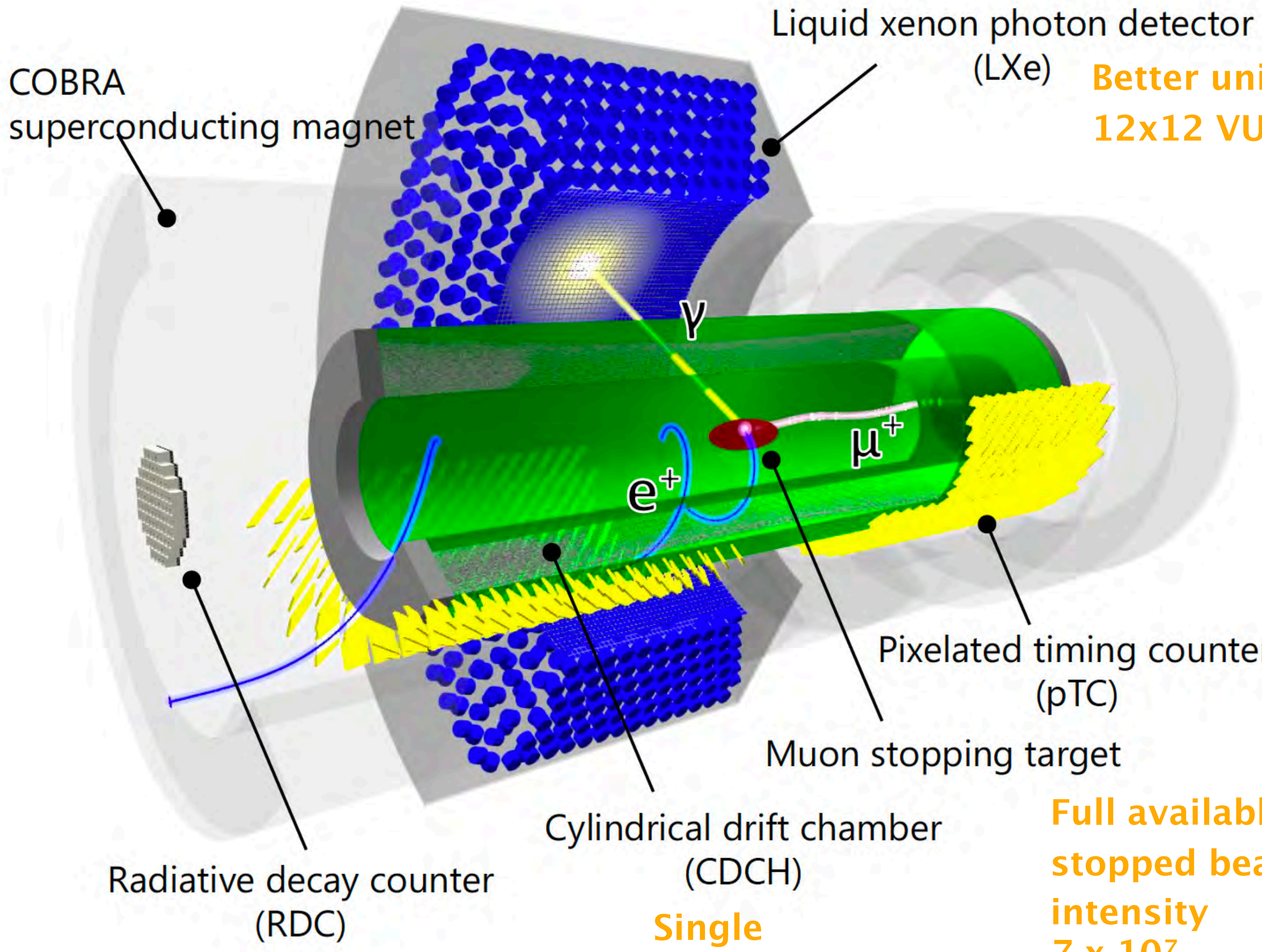
Positron Energy resolution
Gamma Energy resolution
Relative timing resolution
Relative angular resolution

A. Baldini et al. arXiv:1301.7225v2

The MEGII experiment

New electronics:
Wavedream

~9000 channels at 5GSPS



Better uniformity w/ 12x12 VUV SiPM

x2 Resolution everywhere

x2 Beam Intensity

Updated and new Calibration methods

Quasi mono-chromatic positron beam

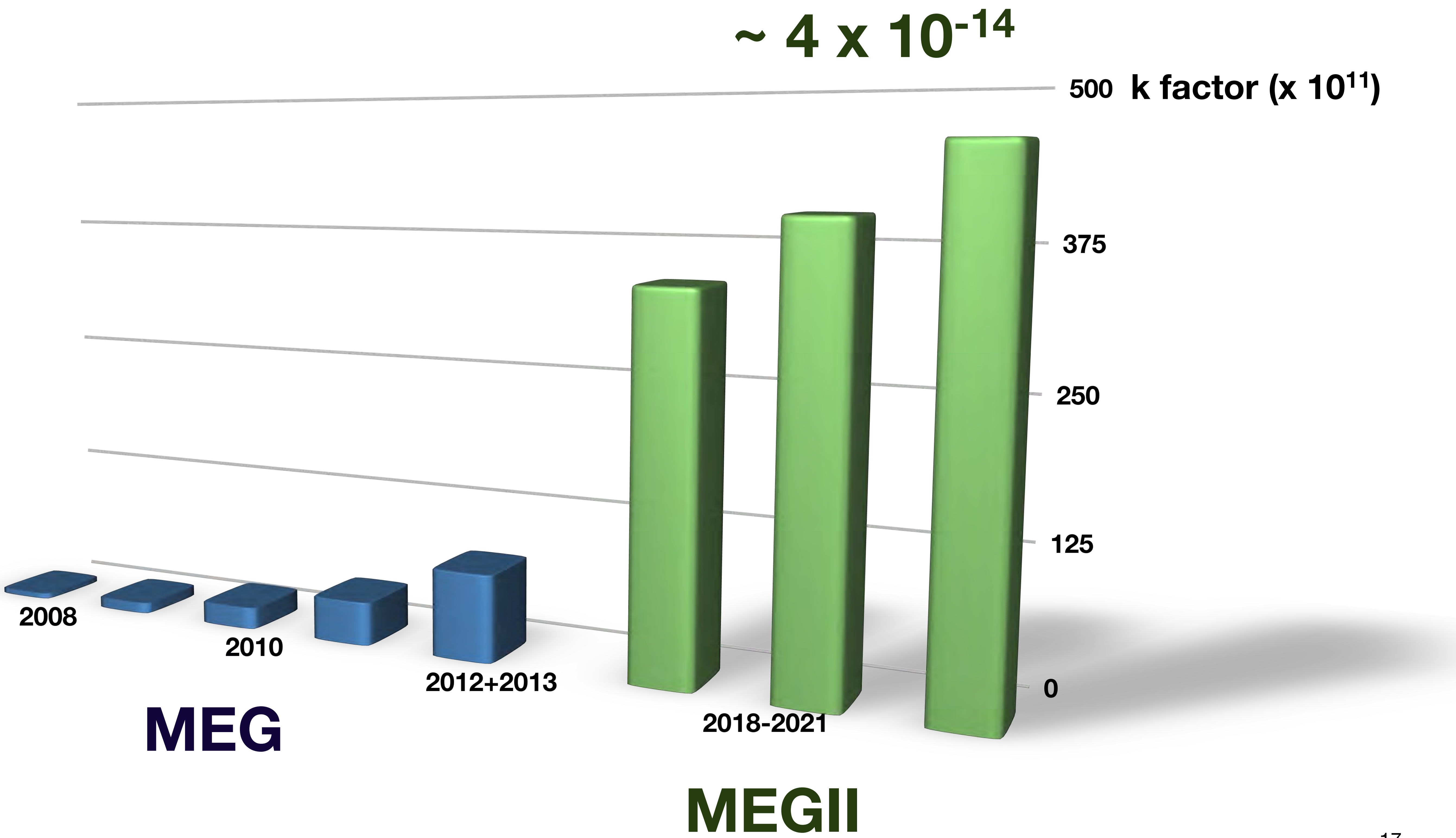
35 ps resolution w/ multiple hits

Background rejection

Single volume $He:iC_4H_{10}$

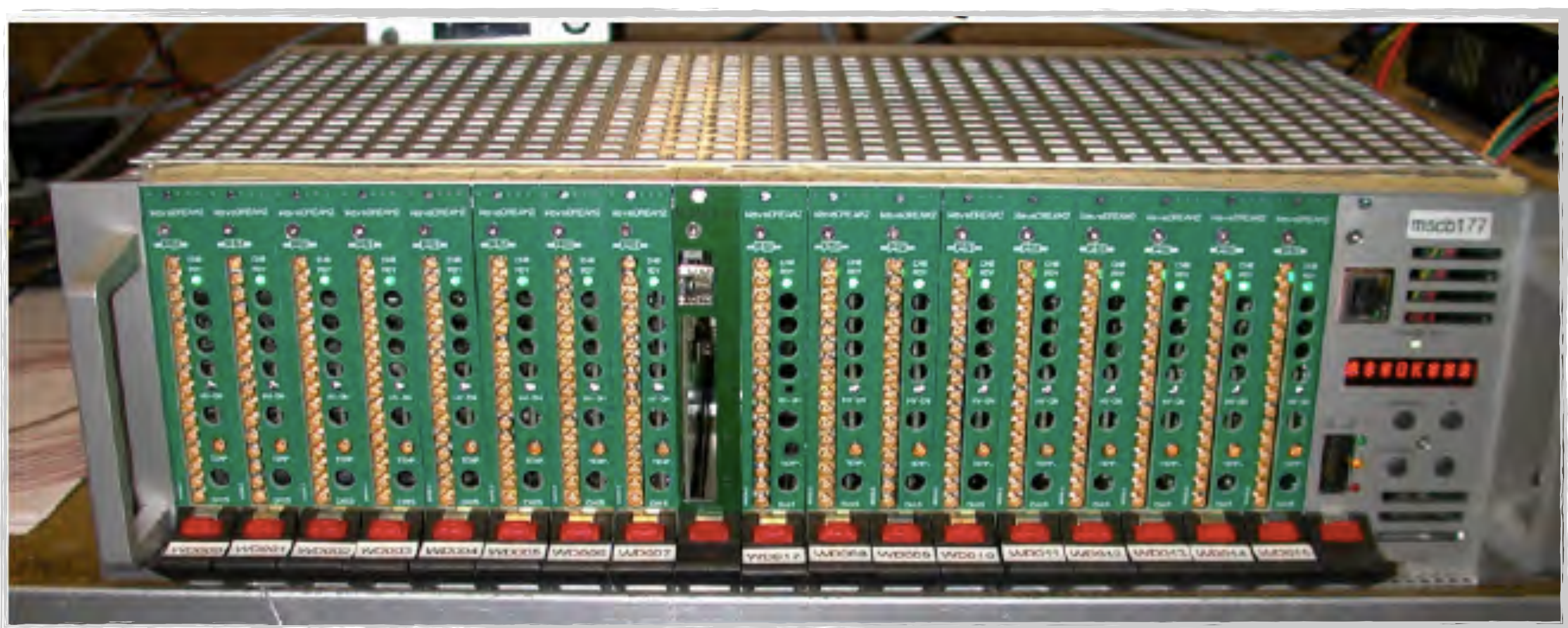
Full available stopped beam intensity 7×10^7

Where we will be



MEGII: The new electronic - DAQ and Trigger

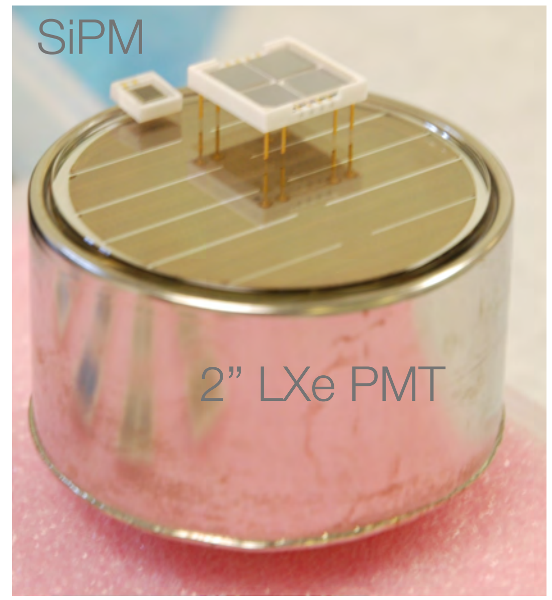
- DAQ and Trigger
  - ~9000 channels (5 GSPS)
  - Bias voltage, preamplifiers and shaping included for SiPMs
- 256 channels (1 crate) abundant tested during the 2016 pre-engineering run; >1000 channels available for the incoming 2017 pre-engineering run
- Trigger electronics and several trigger algorithms included and successfully delivered for the test beams/engineering runs



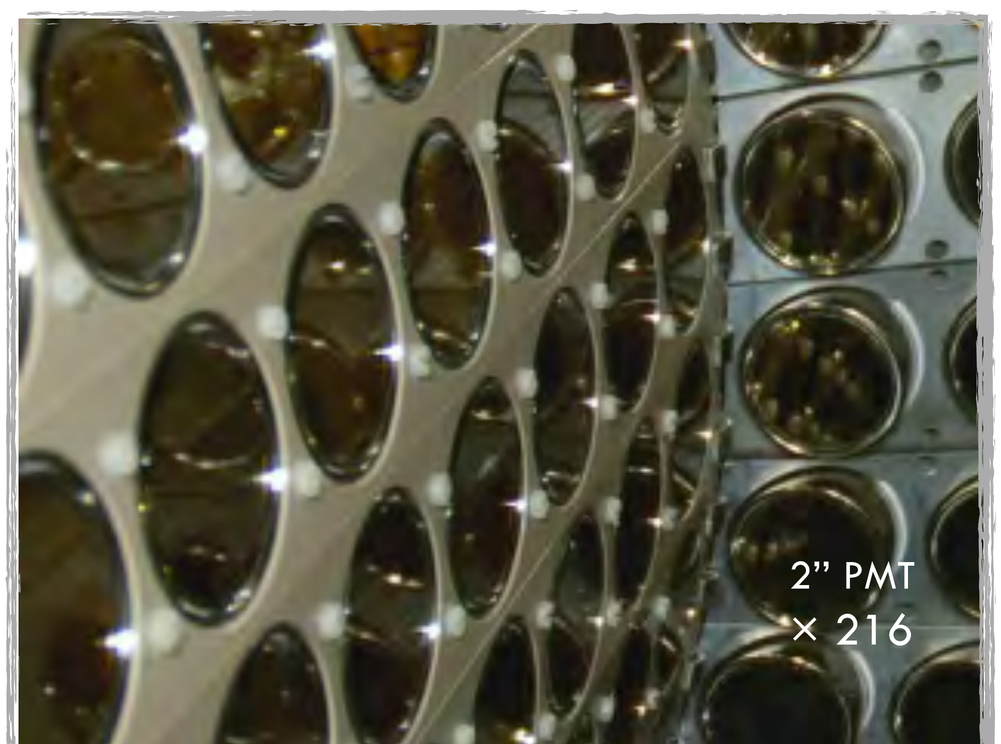
MEGII: The upgraded LXe calorimeter

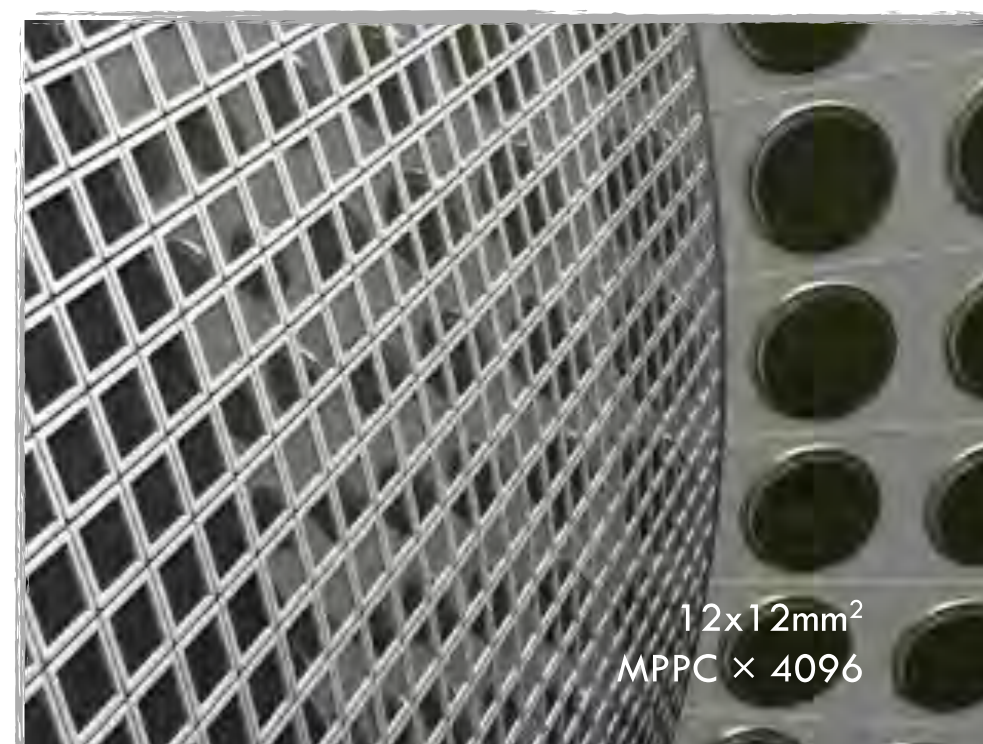
- Increased uniformity/resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency
- Assembly: Completed
- Detector filled with LXe
- Purification: Ongoing
- Monitoring and calibrations with sources: Started

New



	MEG	MEGII
u [mm]	5	2.4
v [mm]	5	2.2
w [mm]	6	3.1
E [w<2cm]	2.4%	1.1%
E [w>2cm]	1.7%	1.0%
t [ps]	67	60

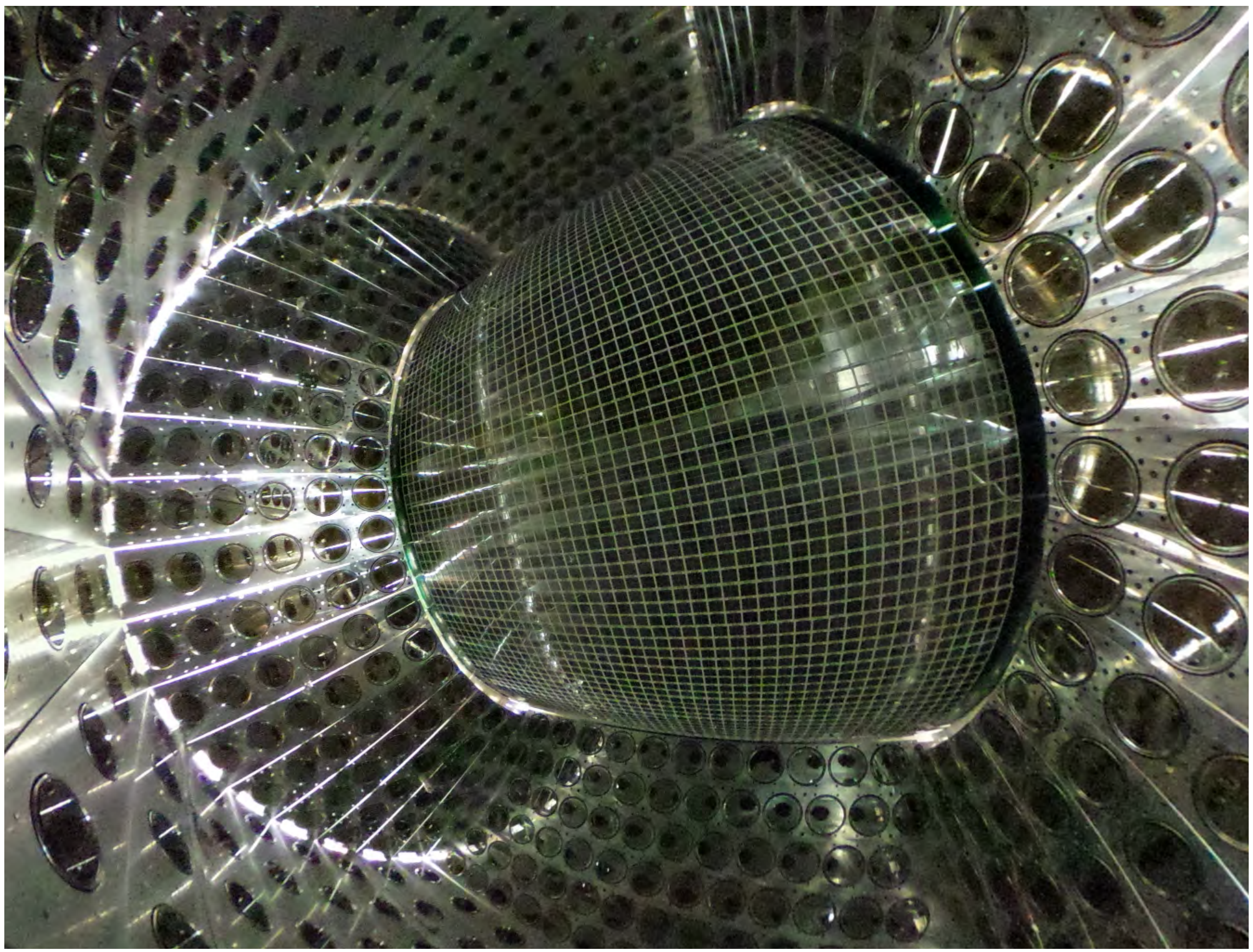


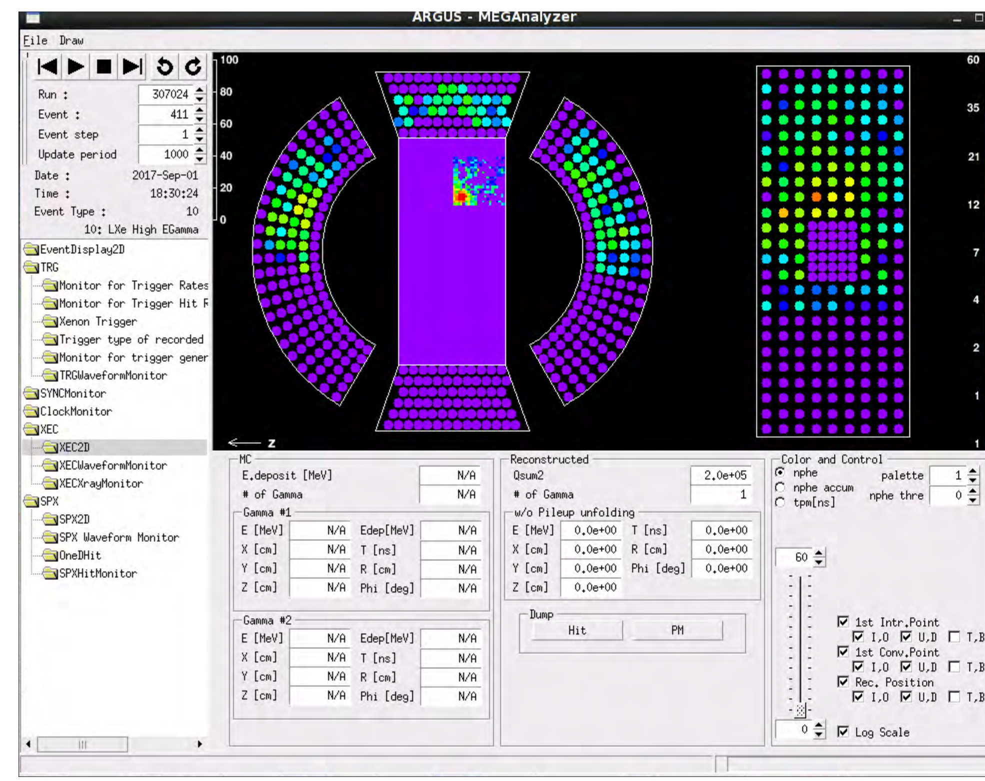


MEGII: The upgraded LXe calorimeter

Detector commissioning started !

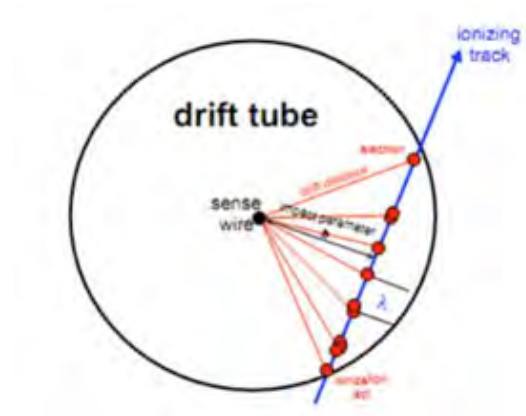
New





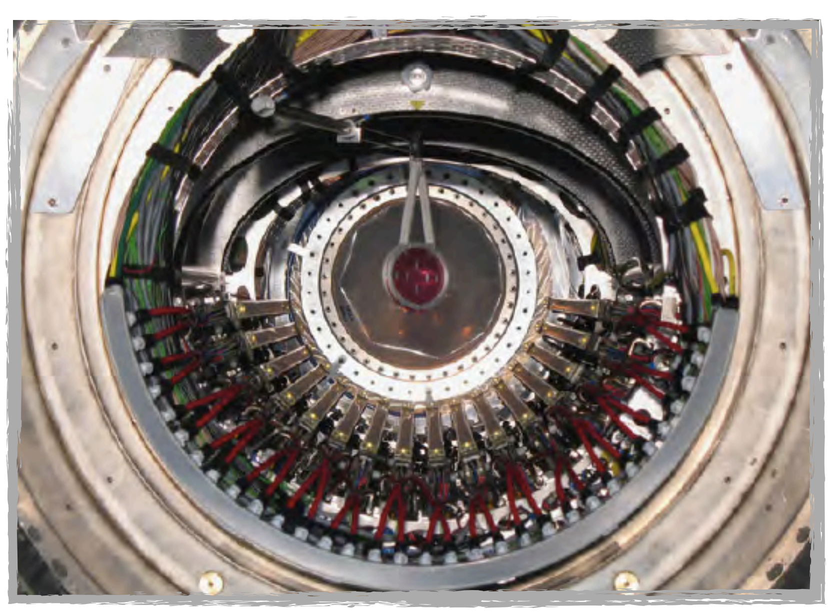
MEGII: The new single volume chamber

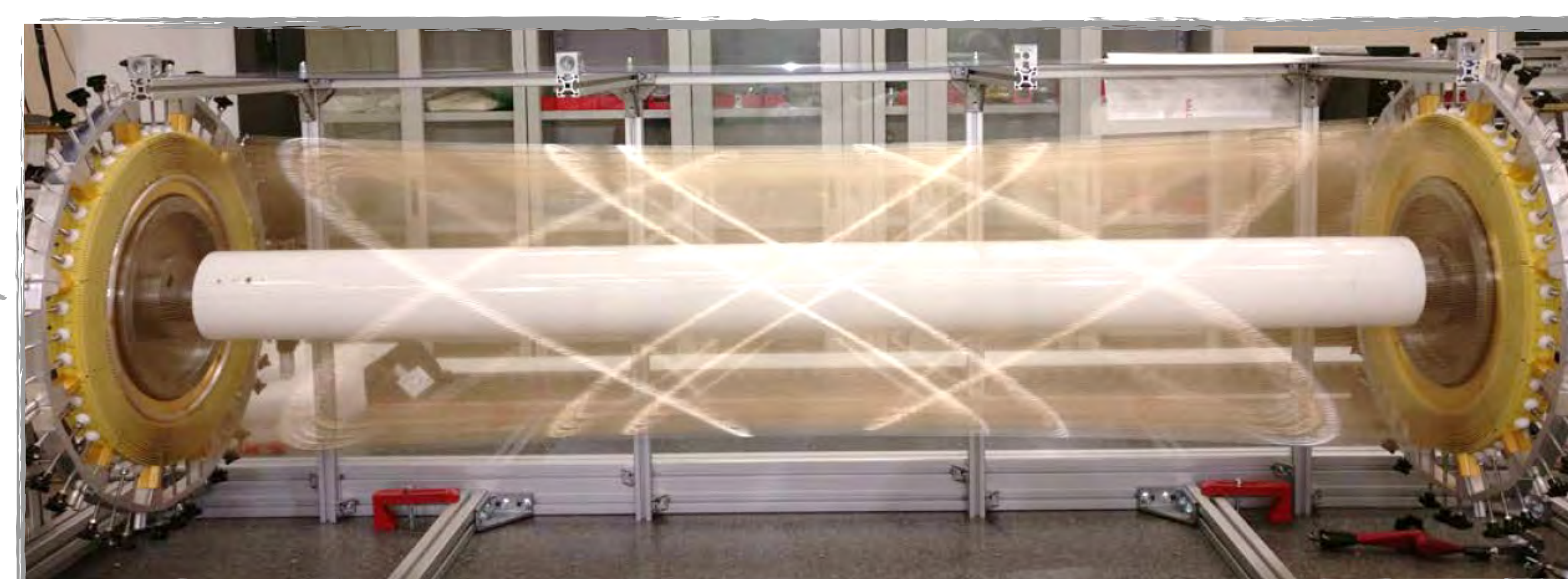
- Improved hit resolution: σ_r ~< 120 um (210 um)
- High granularity/Increased number of hits per track/cluster timing technique
- Less material (helium: isobutane = 90:10, 1.6×10^{-3} X_0)
- High transparency towards the TC
- Assembly: ~ 70% (wiring ~ 80%)



	MEG	MEGII
p [keV]	306	80
θ [mrad]	9.4	6.3
ϕ [mrad]	8.7	5.0
ϵ [%]*	40	70

(*) It includes also the matching with the Timing Counter





MEGII: The new single volume chamber

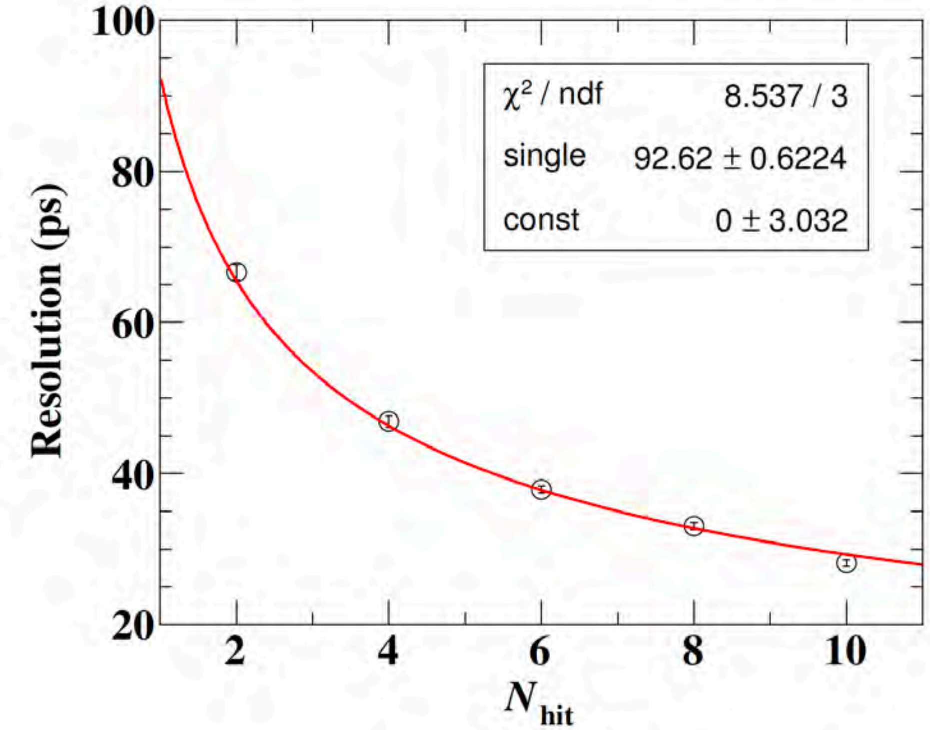
New

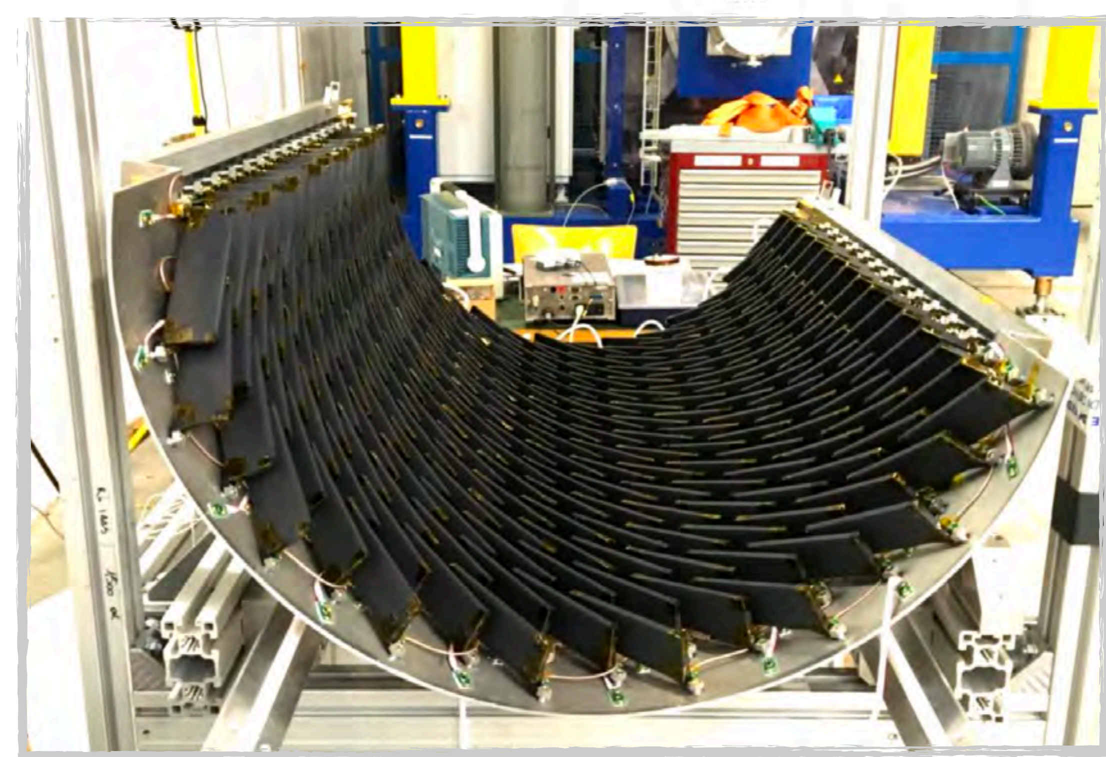
DCH Mock-up Ready!

MEGII: the pixelized Timing Counter

- Higher granularity: 2 x 256 of BC422 scintillator plates (120 x 40 (or 50) x 5 mm^3) readout by AdvanSiD SiPM ASD-NUM3S-P-50-High-Gain
- Improved timing resolution: from 70 ps to 35 ps (multi-hits)
- Less multiple scattering and pile-up
- Assembly: Completed **New**
- Expected detector performances confirmed with data

Pilot run 2016

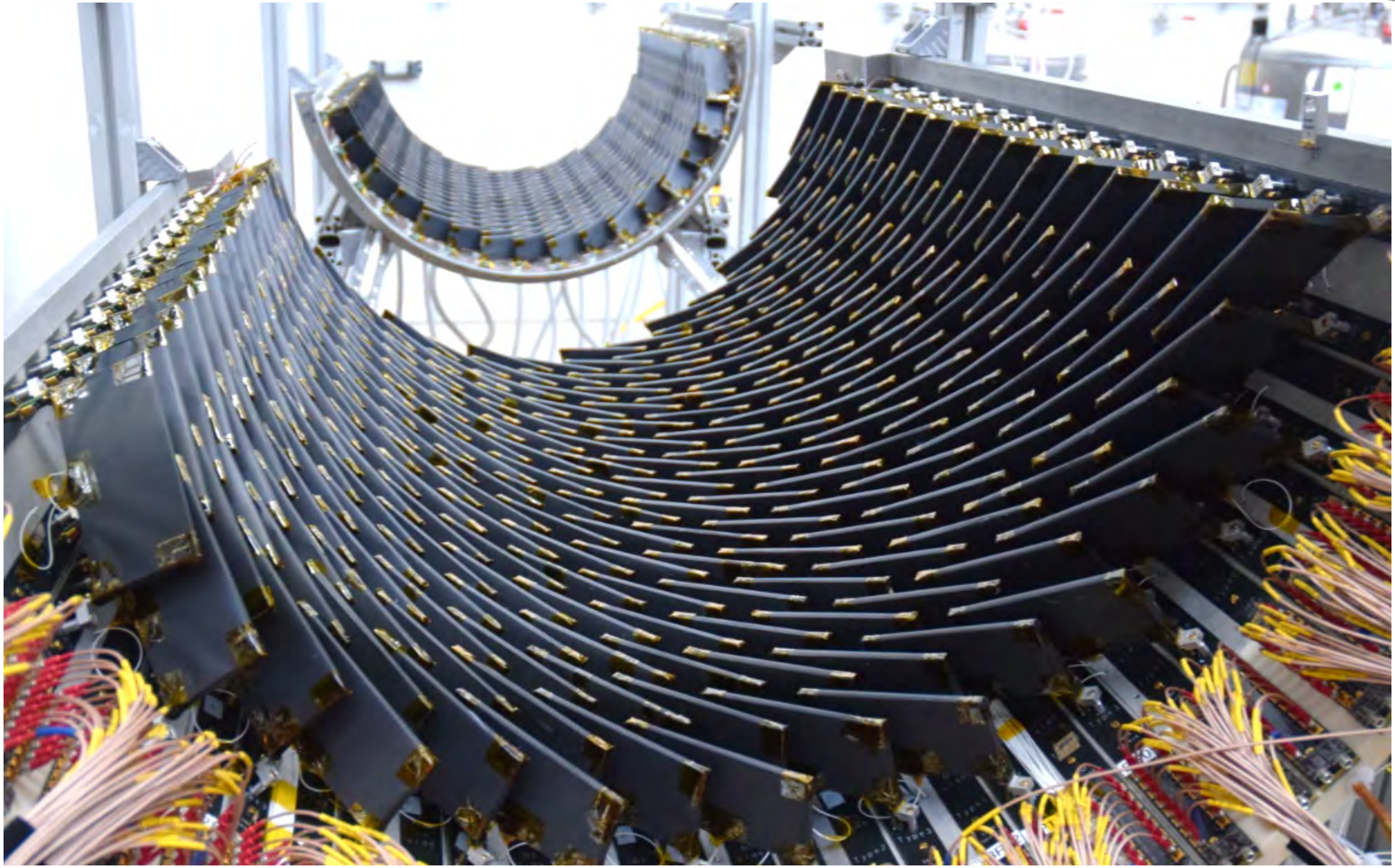




MEGII: the pixelized Timing Counter

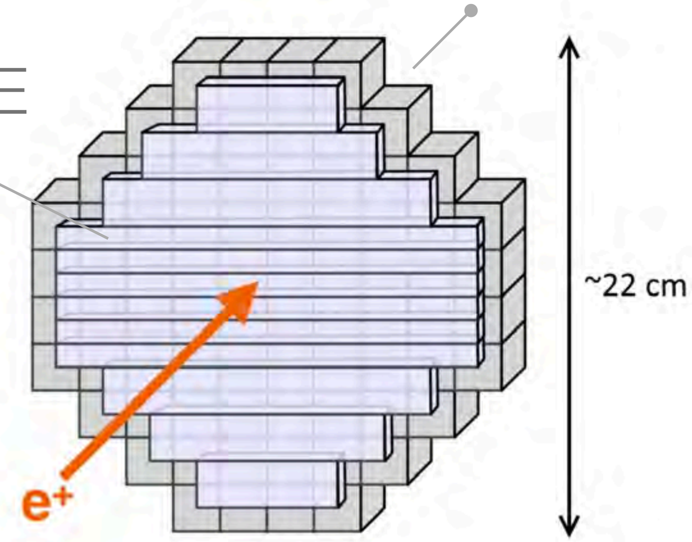
New

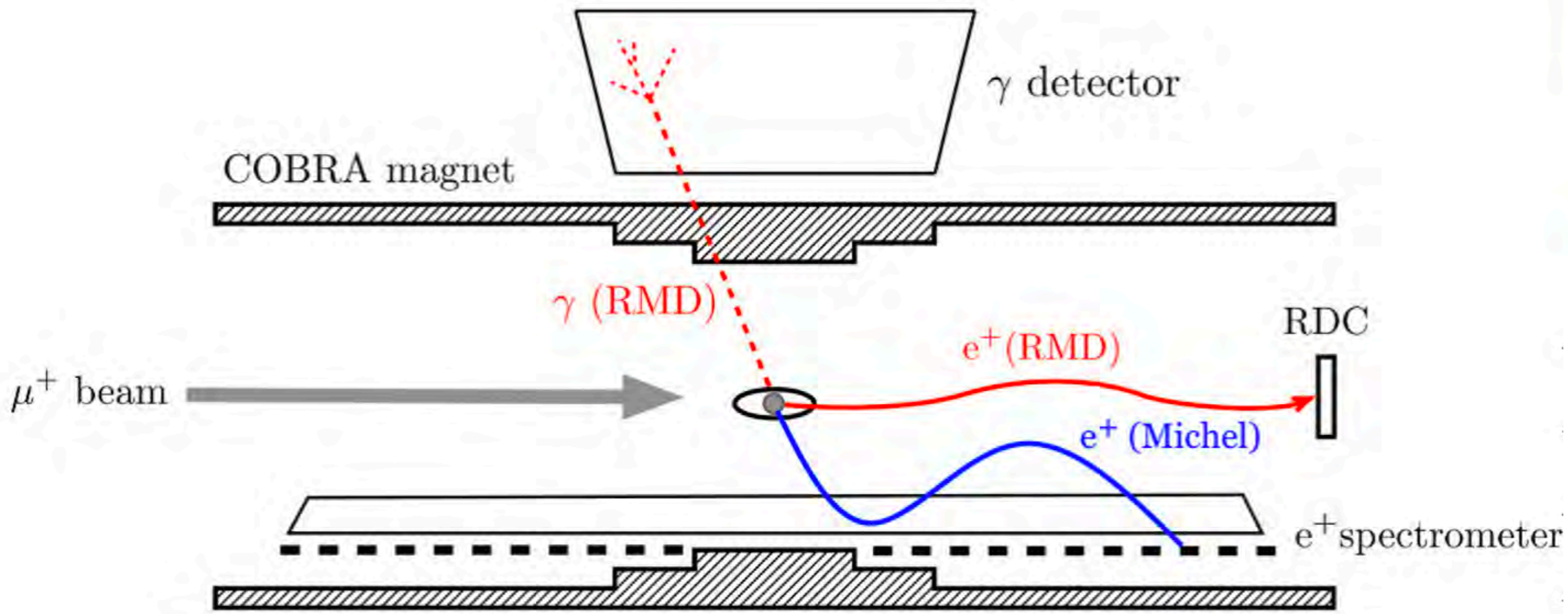
Ready to be inserted inside Cobra !



MEGII: The Radiative Decay Counter

- Added a new auxiliary detector for background rejection purpose. Impact into the experiment: Improved sensitivity by 20%
- Commissioning during the 2016 pre-engineering run
- Status: Ready



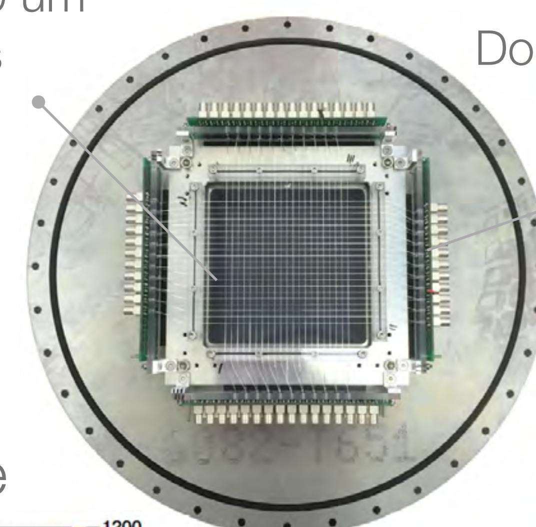


MEGII: new calibration methods and upgrades

- CEX reaction: $p(\pi^-,\pi^0)n$, $\pi^0 \rightarrow \gamma\gamma$
- 1MV Cockcroft-Walton accelerator
- Pulsed D-D Neutron generator
- NEW: Mott scattered positron beam to fully exploit the new spectrometer
- NEW: SciFi beam monitoring. Not invasive, ID particle identification, vacuum compatible, working in magnetic field, online beam monitor (beam rate and profile)
- NEW: Luminophore (CsI(Tl) on Lavsan/Mylar equivalent) to measure the beam properties at the Cobra center
- NEW: LXe X-ray survey
- NEW: Laser system for the pTC

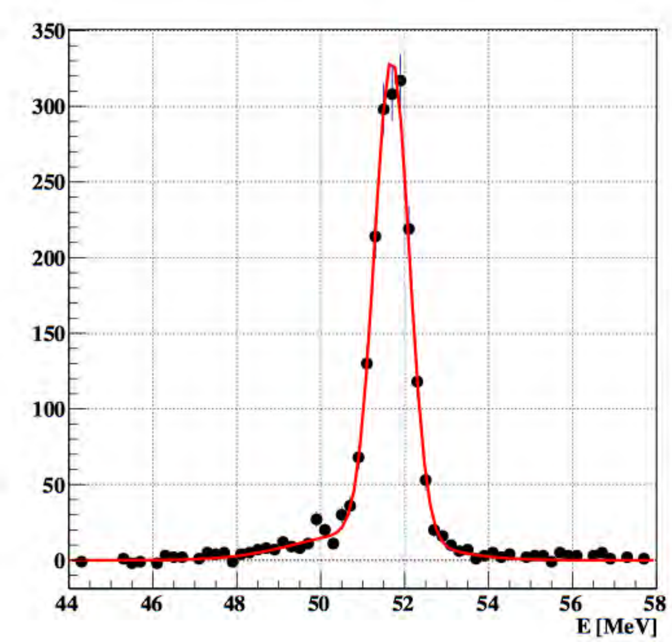
MC BCF12 250 x 250 um^2 scintillating fibers

Double readout: MPPC S13360-3050C



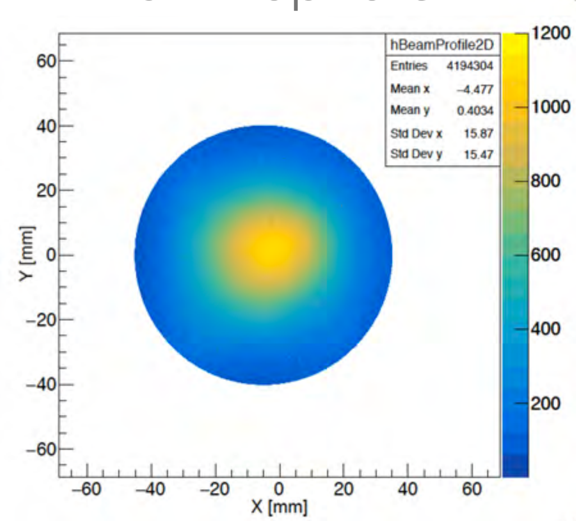
SciFi

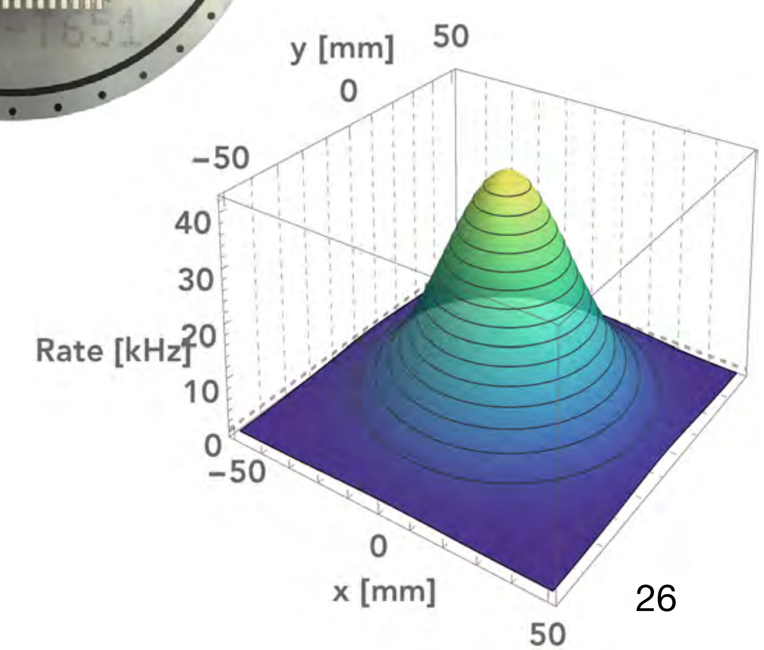
Monochromatic e-line



pTC's laser

Luminophore

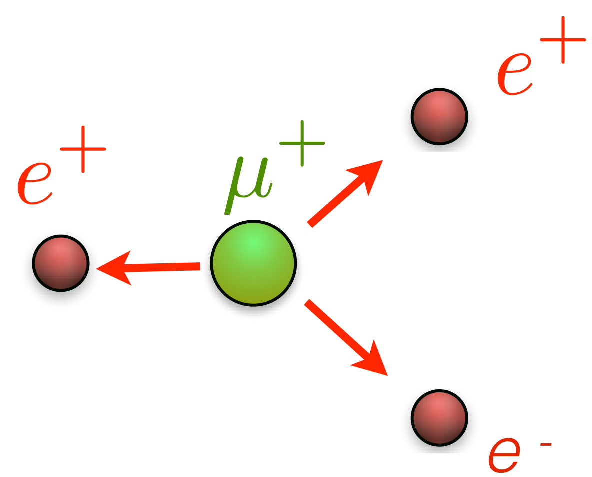




Mu3e: The $\mu^+ \rightarrow e^+ e^+ e^-$ search

- 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 $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables $(E_e, t_e, \text{vertex})$ to characterize $\mu \rightarrow eee$ events

Signature

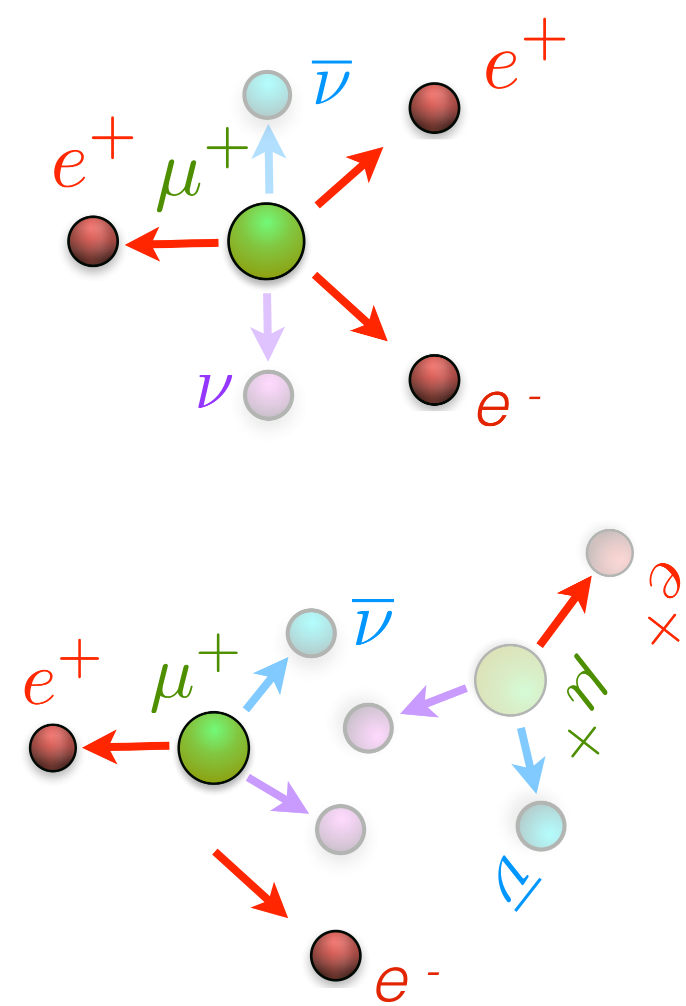


$$\Delta t_{eee} = 0$$

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

$$\Sigma E_e = m_\mu$$

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

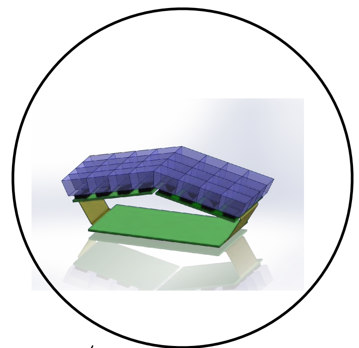
2. $\mu \rightarrow e\nu\nu, \mu \rightarrow e\nu\nu\,, e^+e^-$

- Coincidence and vertex: High timing and position resolutions

The Mu3e experiment: Schematic 3D

Superconducting solenoid Magnet

Homogeneous field
1T

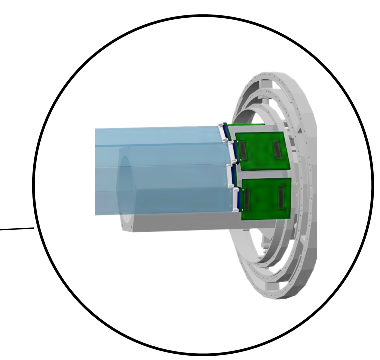


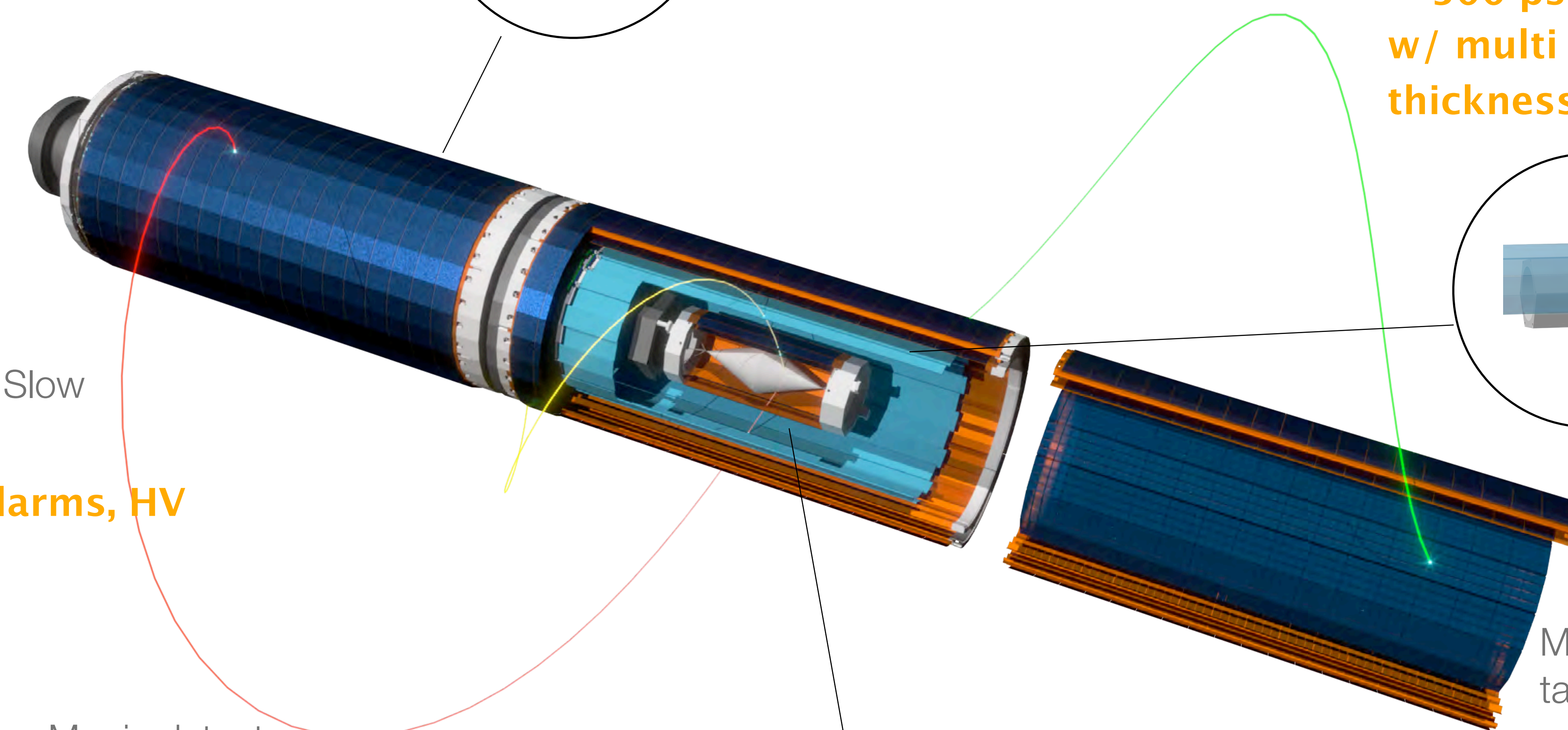
Tile detector

70 ps resolution
w/ single hit

Fibre hodoscope

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





MIDAS DAQ and Slow Control

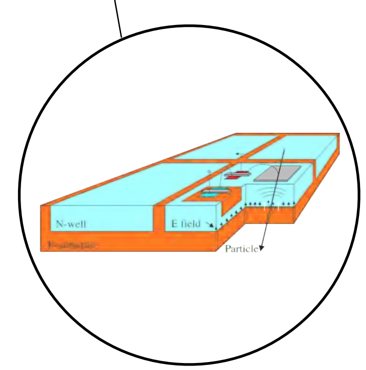
Run, history, alarms, HV etc.

Muon Beam and target

Full available beam intensity O(10^8)

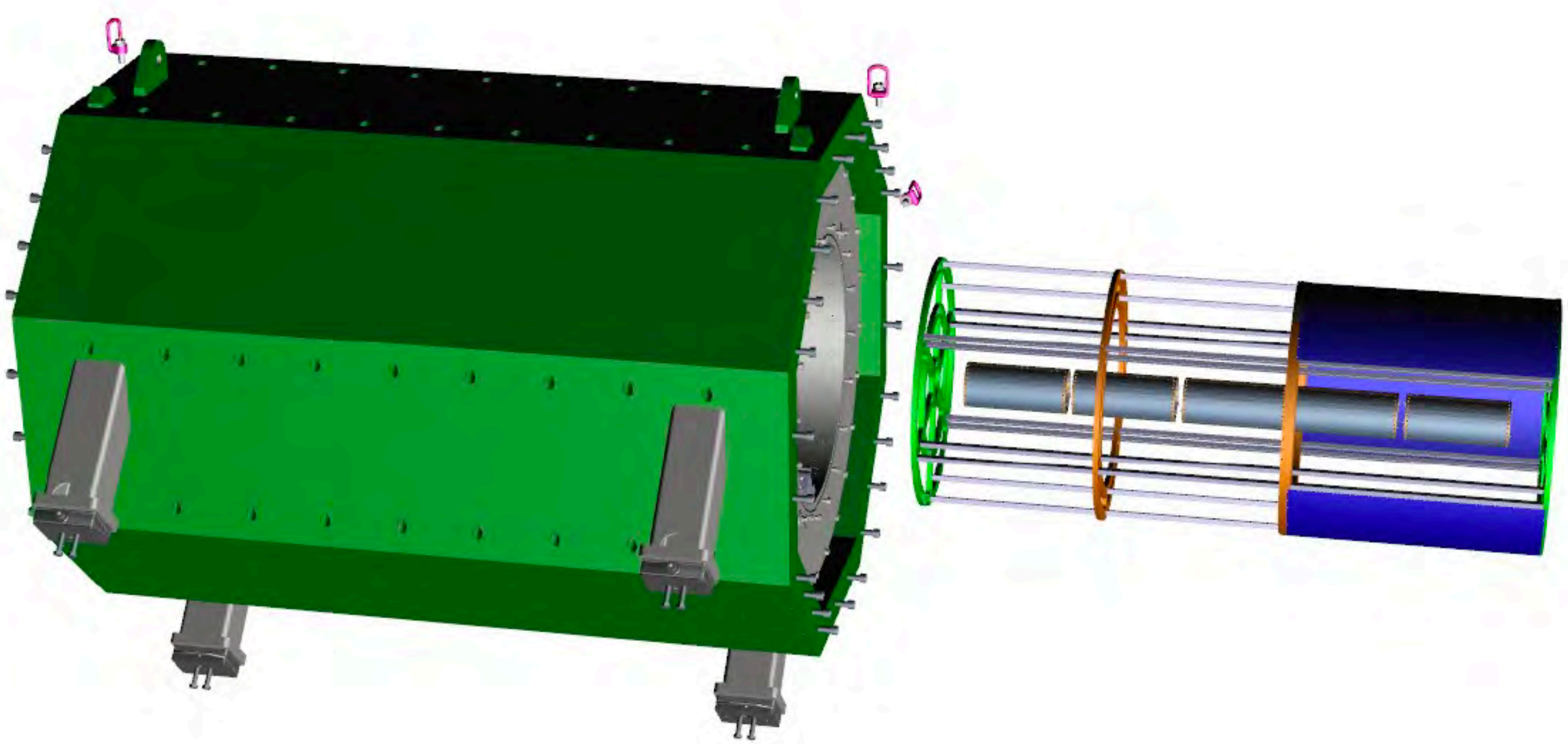
Mupix detector

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

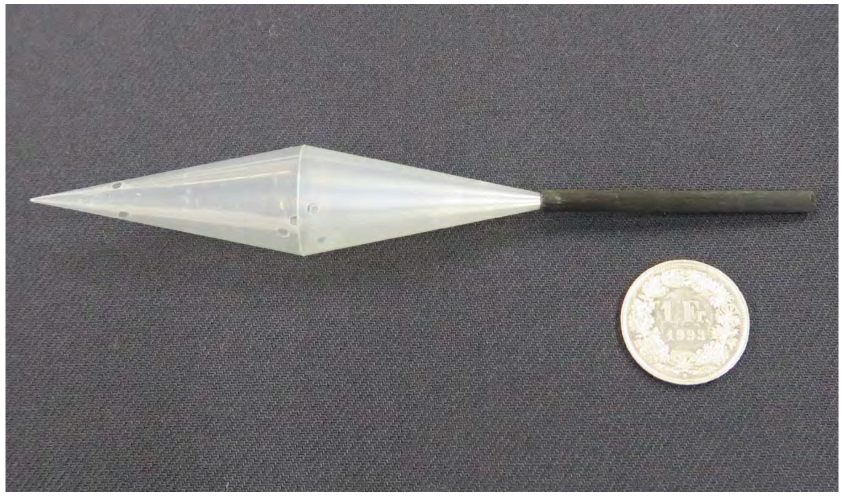


Target and magnet: Status

- Target: Mylar double hollow cone (L = 100 mm, R = 19 mm), Stopping efficiency: ~ 83%, Vertex separation ability (tracking) < 200 um
- Magnet: 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

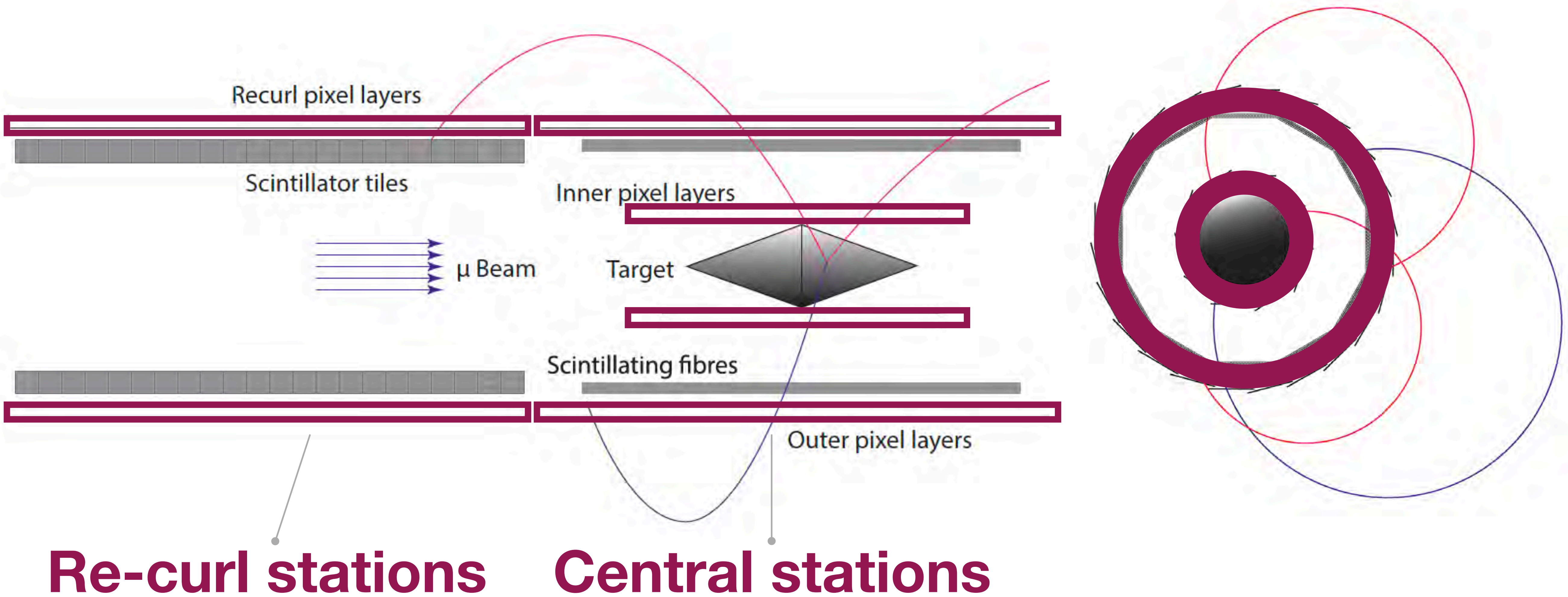


Target prototype



The pixel tracker: Overview

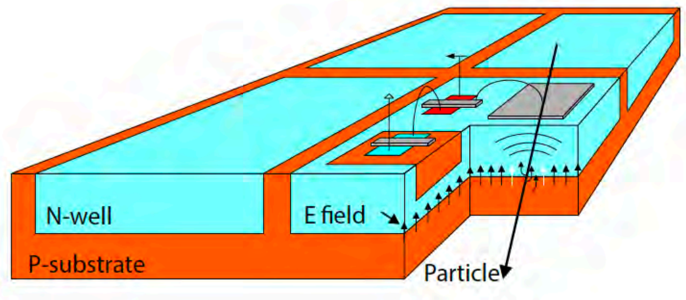
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime
- Momentum resolution: < 0.5 MeV/c over a large phase space; Geometrical acceptance: ~ 70%; X/X_0 per layer: ~ 0.011%



The pixel tracker: The MuPix prototypes

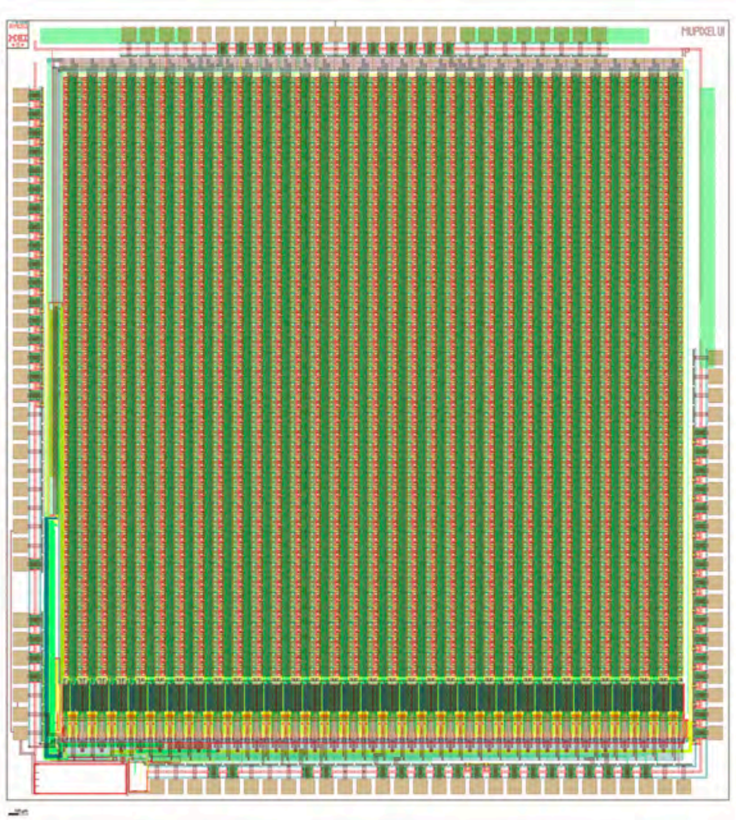
- Based on HV- MAP: Pixel dimension: 80 x 80 μm^2 , Thickness: 50 μm , Time resolution: < 20 ns, Active area chip: 20 x 20 mm^2 , Efficiency: > 99 %, Power consumption : < 350 mW/cm^2
- MuPix 7: The first small-scale prototype which includes all Mu3e functionalities

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

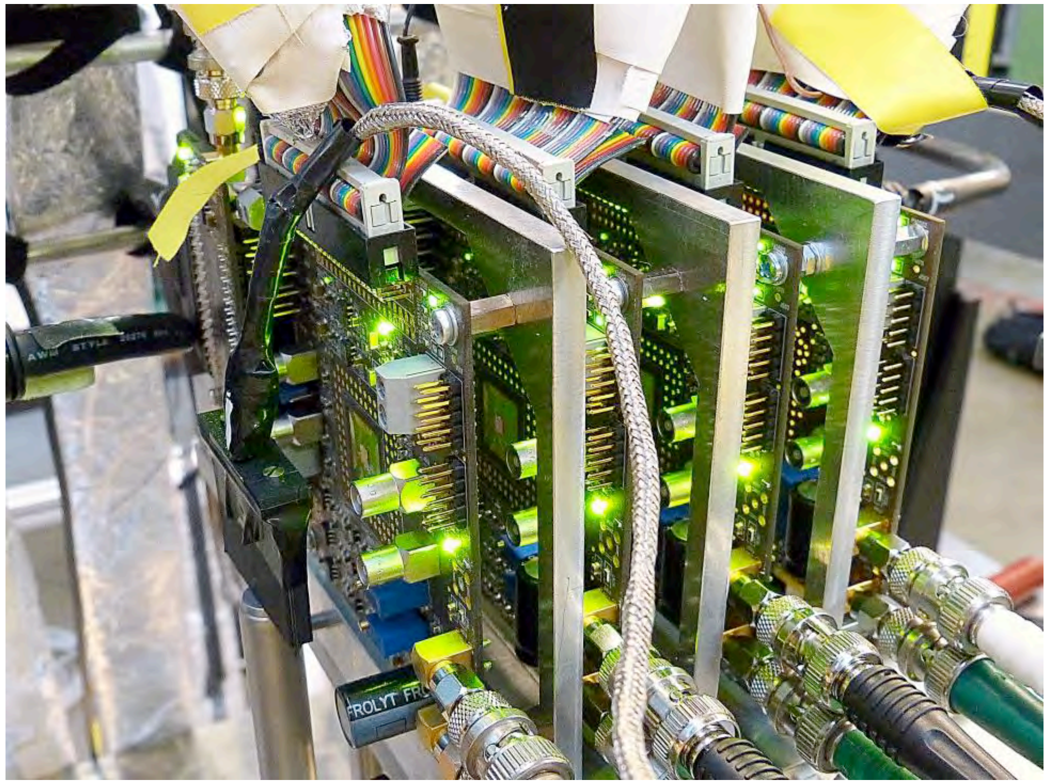


Prototype	Active Area [mm^2]
MuPix1	1.77
MuPix2	1.77
MuPix3	9.42
MuPix4	9.42
MuPix6	10.55
MuPix7	10.55

MuPix7



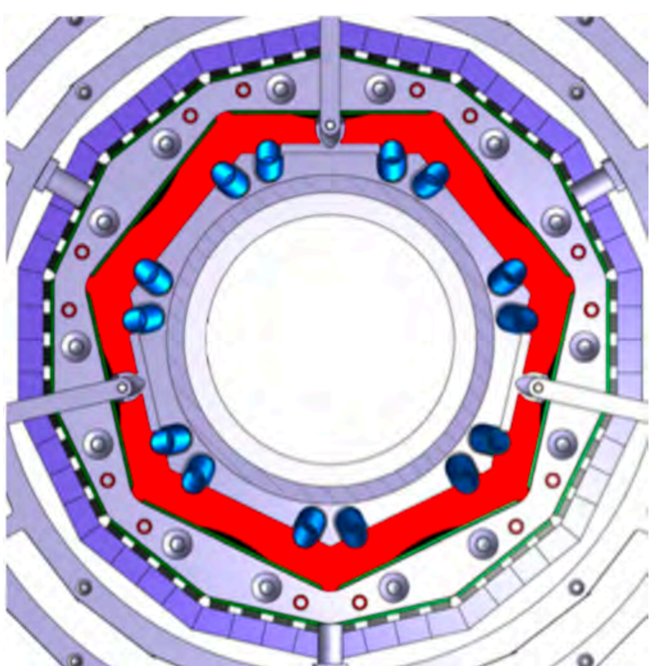
Extensively tested along beams

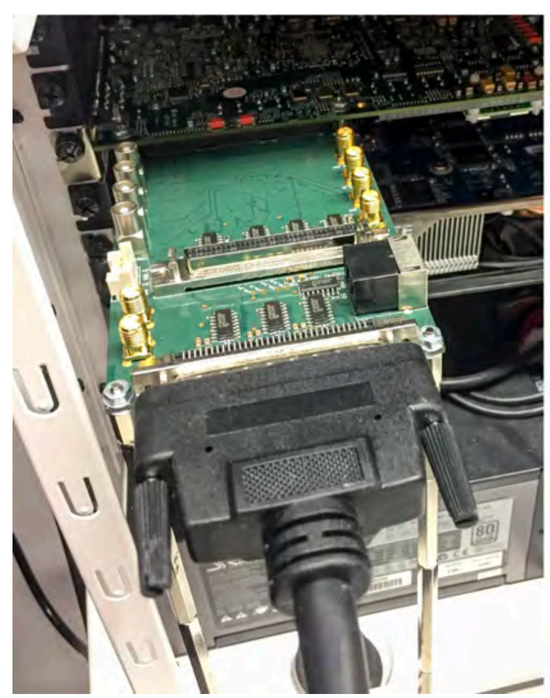


The pixel tracker: Current and future plan

- 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 ! **New**
  - MuPix 9, small test chip for: Slow Control, voltage regulators and other test circuits; Submission is happening right now
  - MuPix 10, the final version for Mu3e: Active area from 160 mm^2 to 380 mm^2

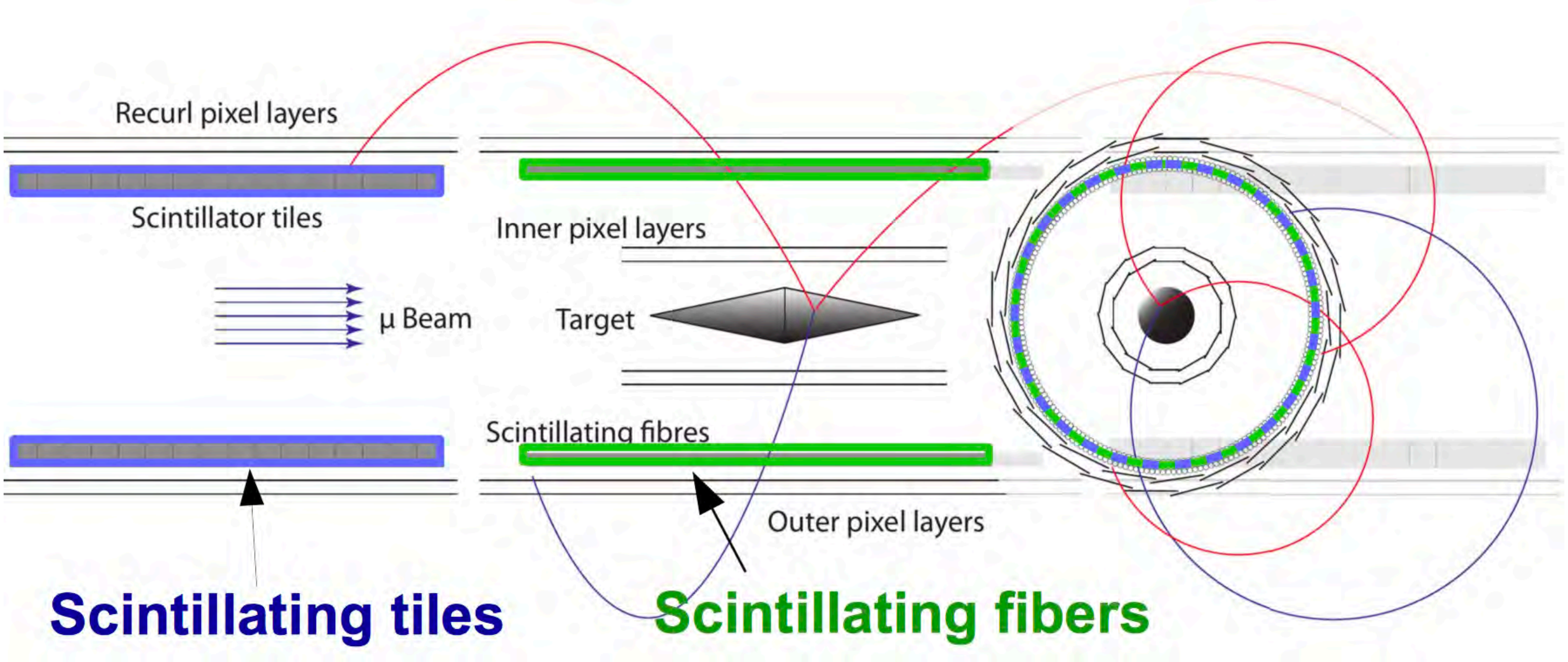




MuPix8 **New**

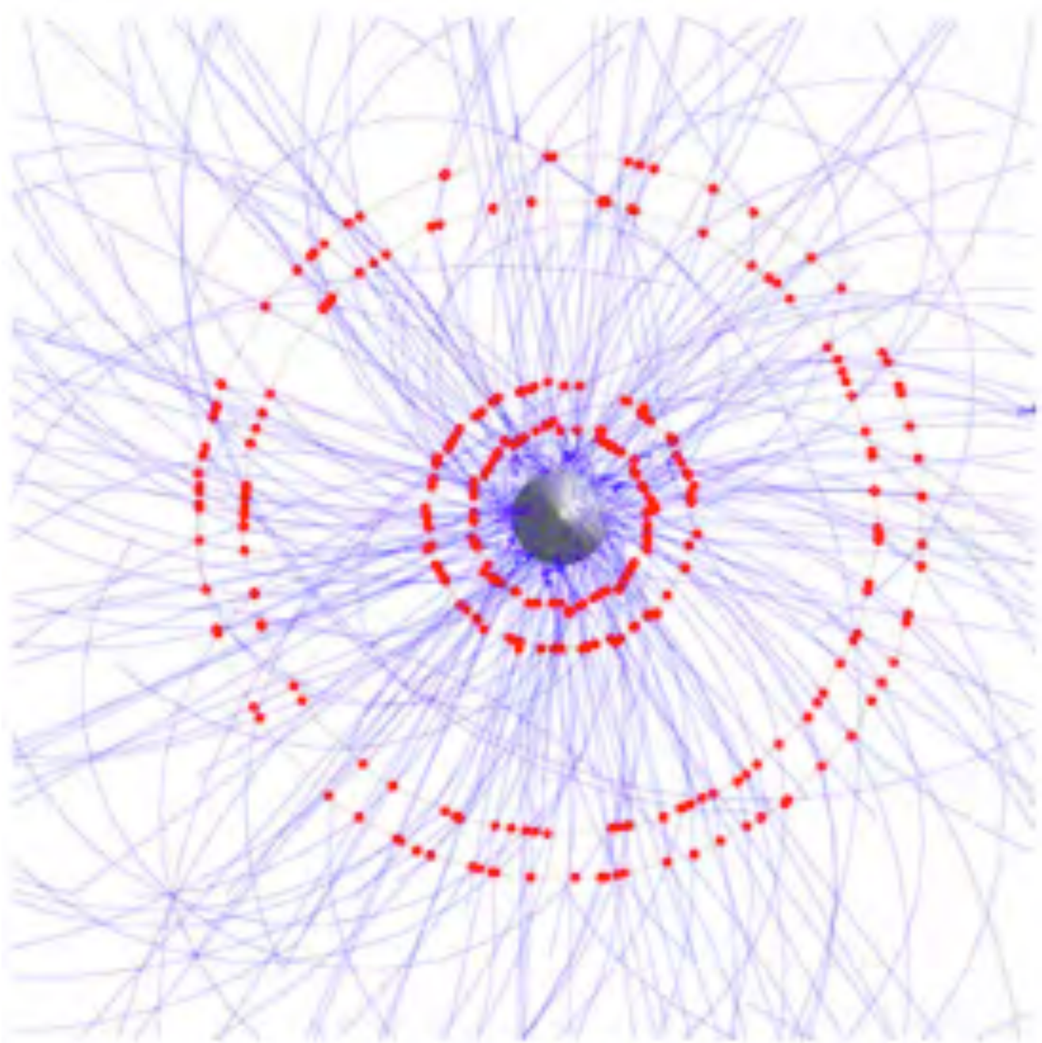
The timing detectors: Fibers and tiles

- 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%)

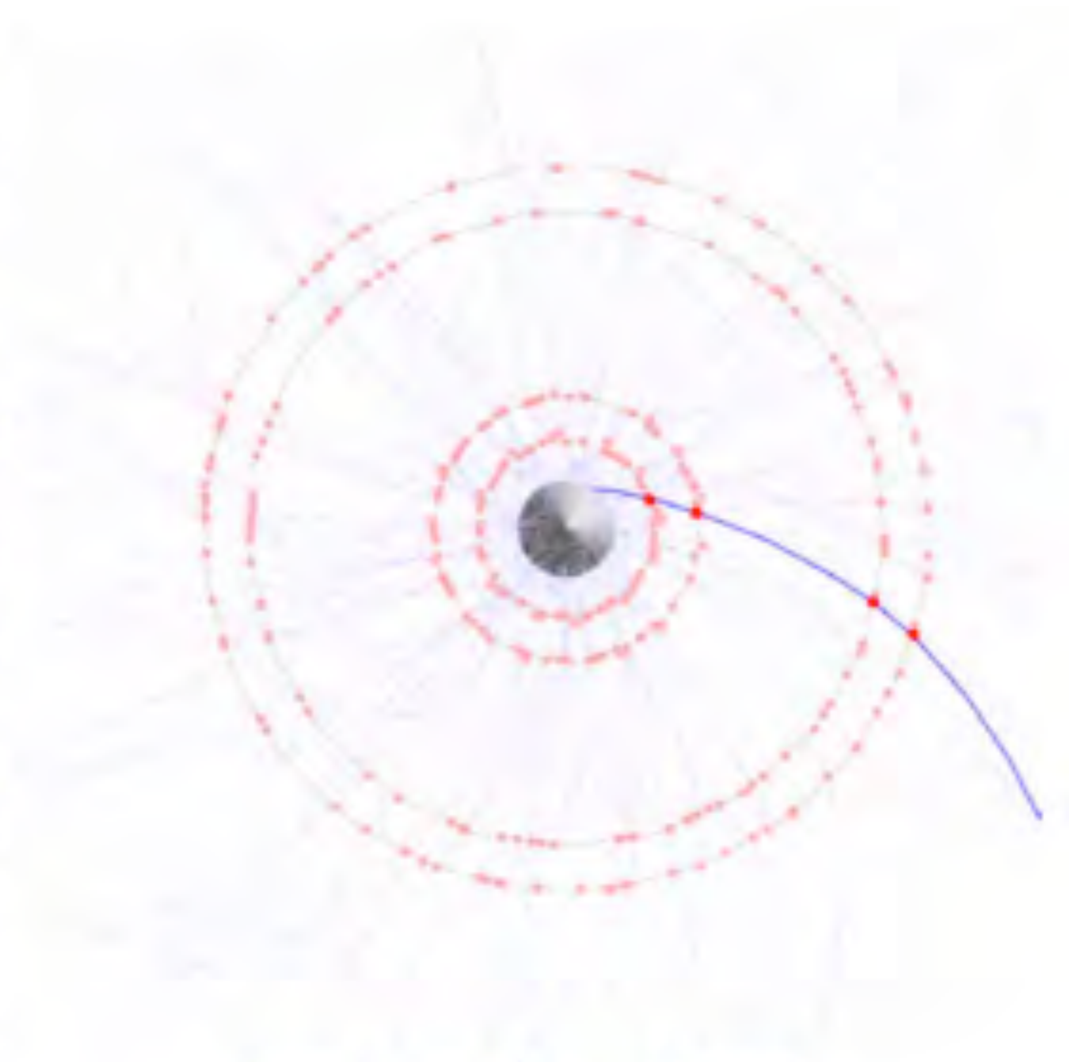


The timing detectors: Fibers and tiles

- 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%)



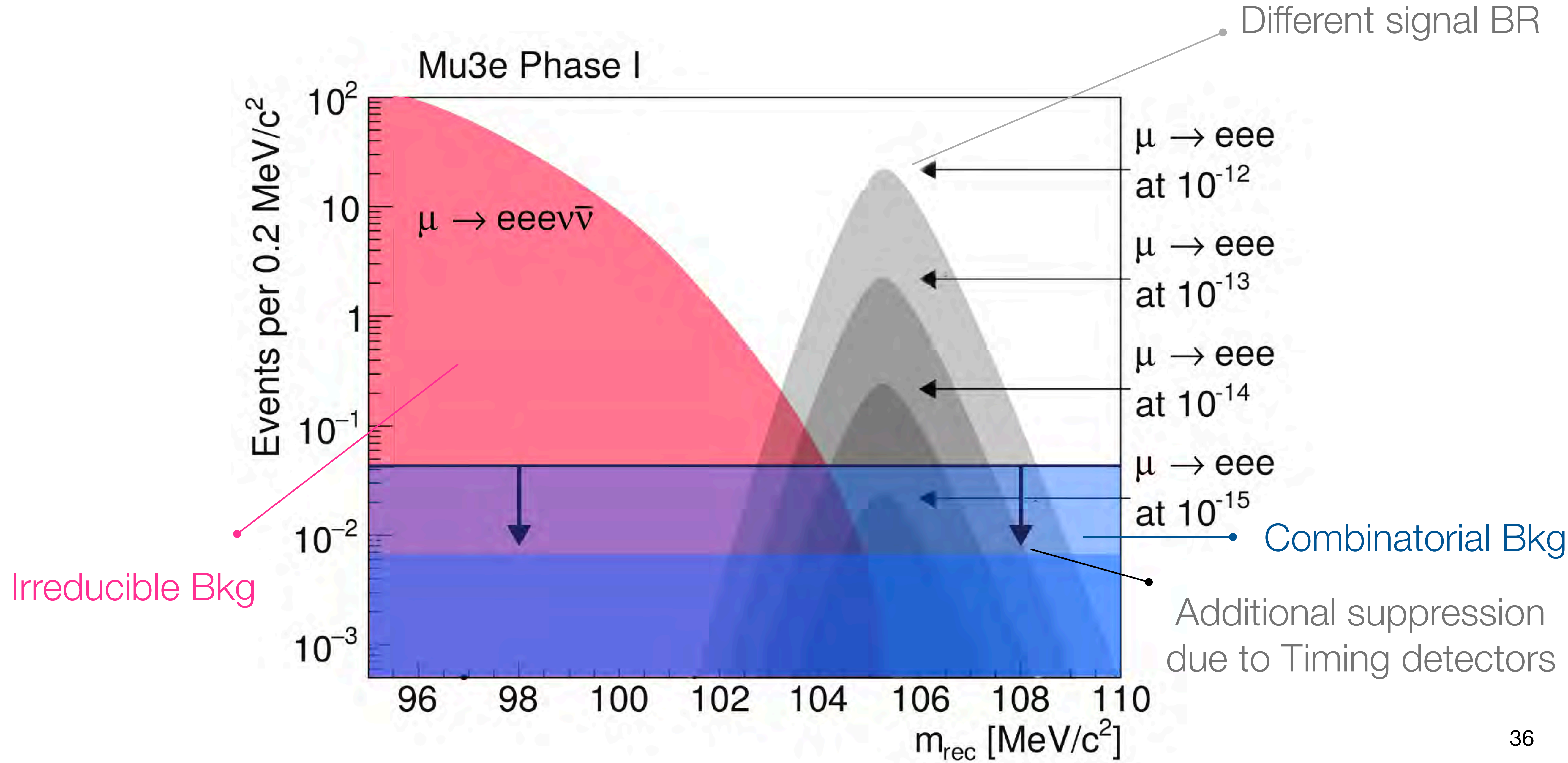
Pixels: O(50 ns)



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

The timing detectors: Impact

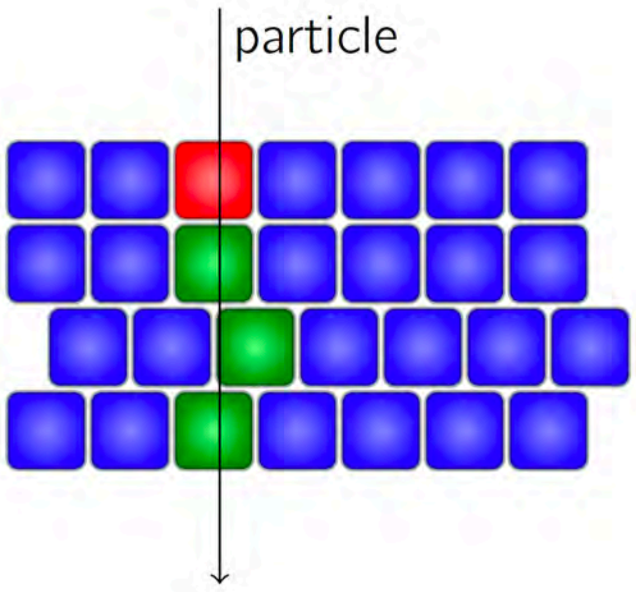
- Precise timing measurement: Critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
  - Scintillating tiles O(100 ps), full detection efficiency (>99%)



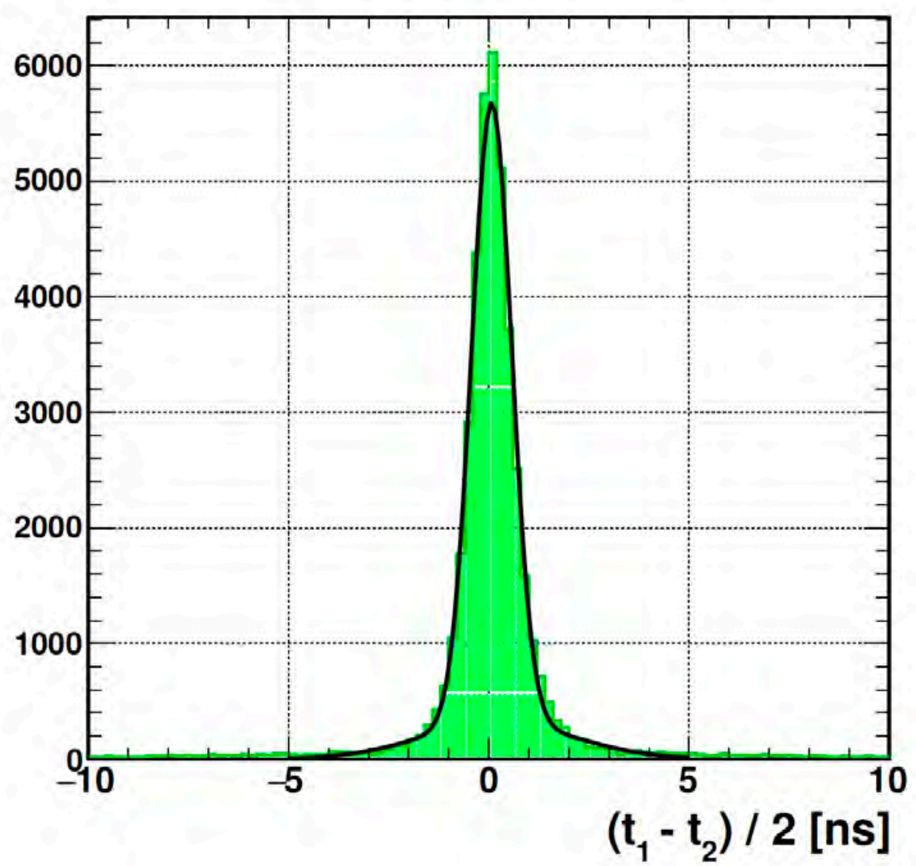
SciFi prototypes: Results

- 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

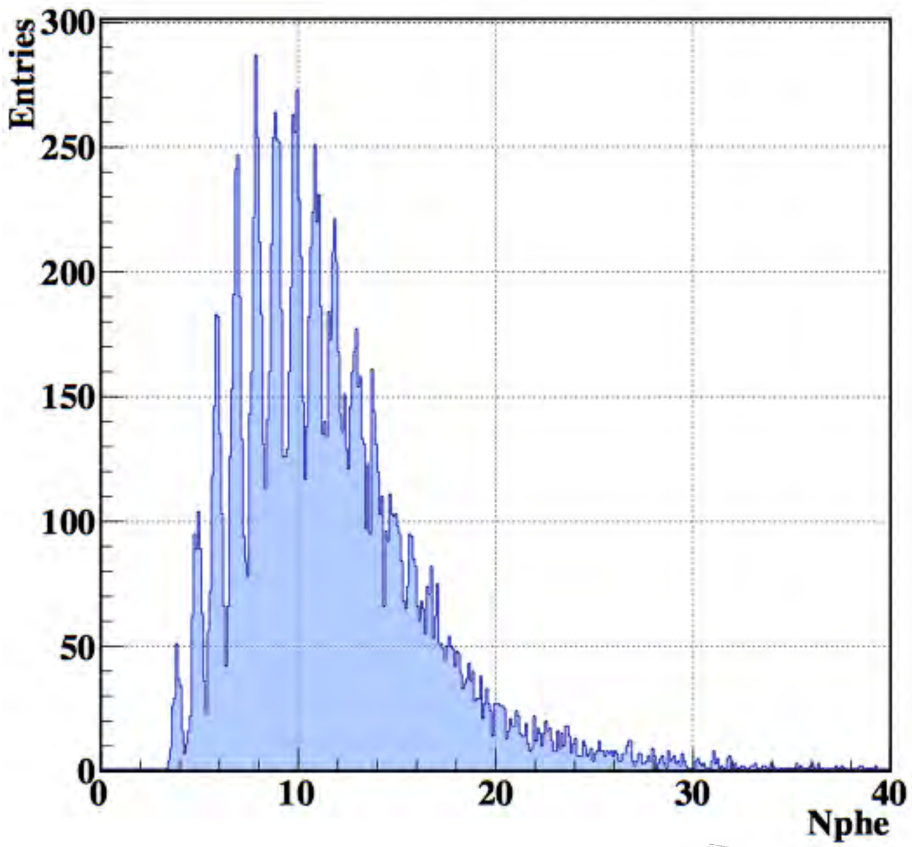
Trigger
offline selection:
hits in 3 layers



3 layer time resolution O(550) ps



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

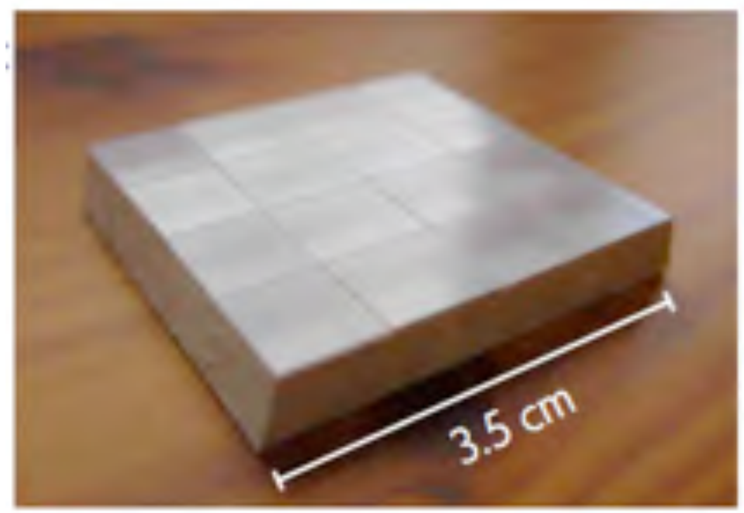


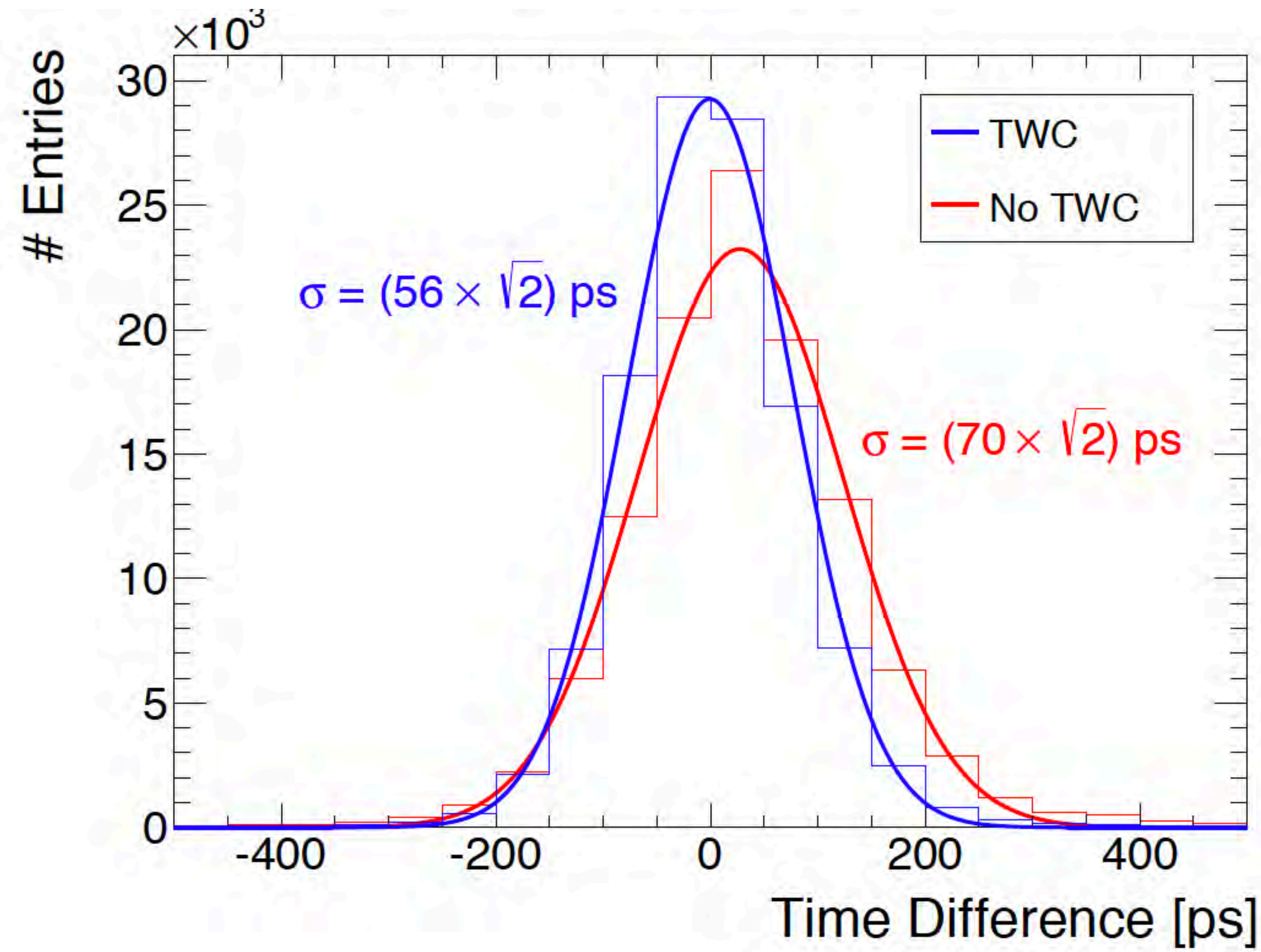
New

Very promising results from summer test beams with also with "new" fibres: SCSF 78 MJ, clear; SCSF 78 MJ, with 20% TiO_2; NOL 11, clear; NOL 11, with 20% TiO_2; SCSF 81 MJ, with 20% TiO_2

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





Outlooks

- The MEG experiment has set a new upper limit for the branching ratio of **$B(\mu^+ \rightarrow e^+ \gamma) < 4.2 \times 10^{-13}$** at 90% C.L. (a factor 30 improvement with respect to the previous MEGA experiment and also the strongest bound on any forbidden decay particle)
- An upgrade of the apparatus is ongoing: MEGII is expect to start next year the full engineering run followed by a physics run aiming at a sensitivity **down to 4×10^{-14}**

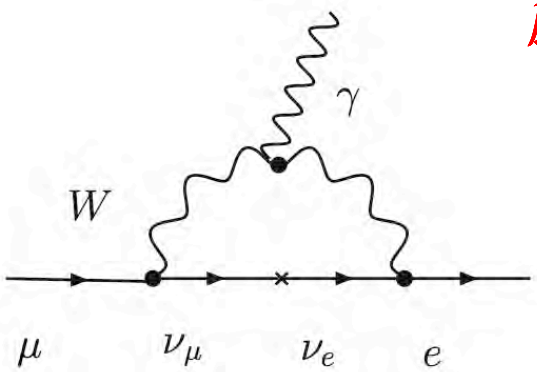
- The Mu3e experiment **is completely based on new detector technologies** and strongly connected with new beam line projects (**HiMB** at PSI aiming at 10^9 muon/s) for a final sensitivity **down to few $\times 10^{-16}$**
- The R&D phase for all sub-detectors and beam line has been concluded proving that the expected detector performances can be achieved. Construction and characterisation of all sub-detector prototype are extensively ongoing
- A full engineering run is expected for 2019 followed by data acquisition

- **cLFV remains one of the most exiting place where to search for new physics**

Backup

cLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

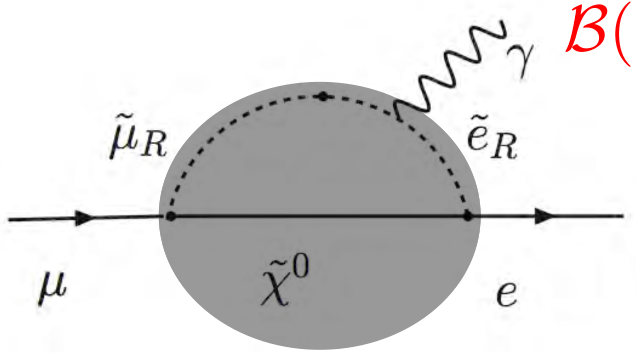


$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$

ν oscillations

too small to access experimentally

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

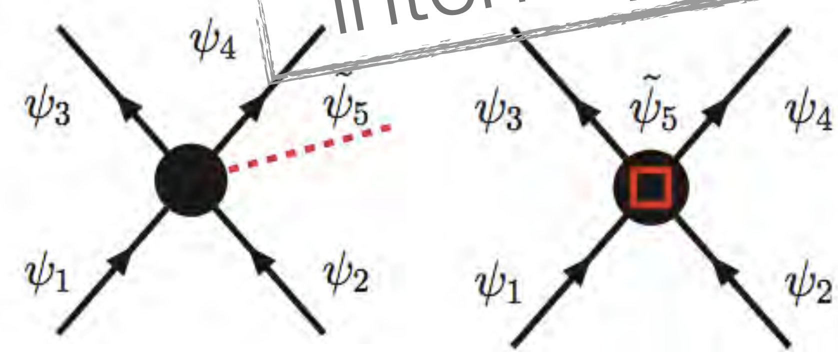


$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$

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

to unveil behind SM physics
via virtual particles

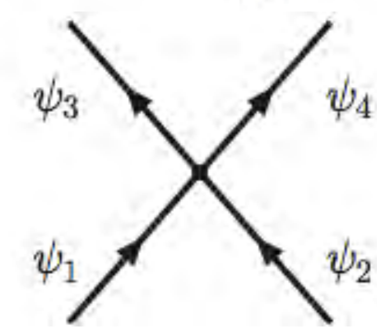
intensity frontier



to probe otherwise unreachable and
unexploited new physics energy scale

high energy probe

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

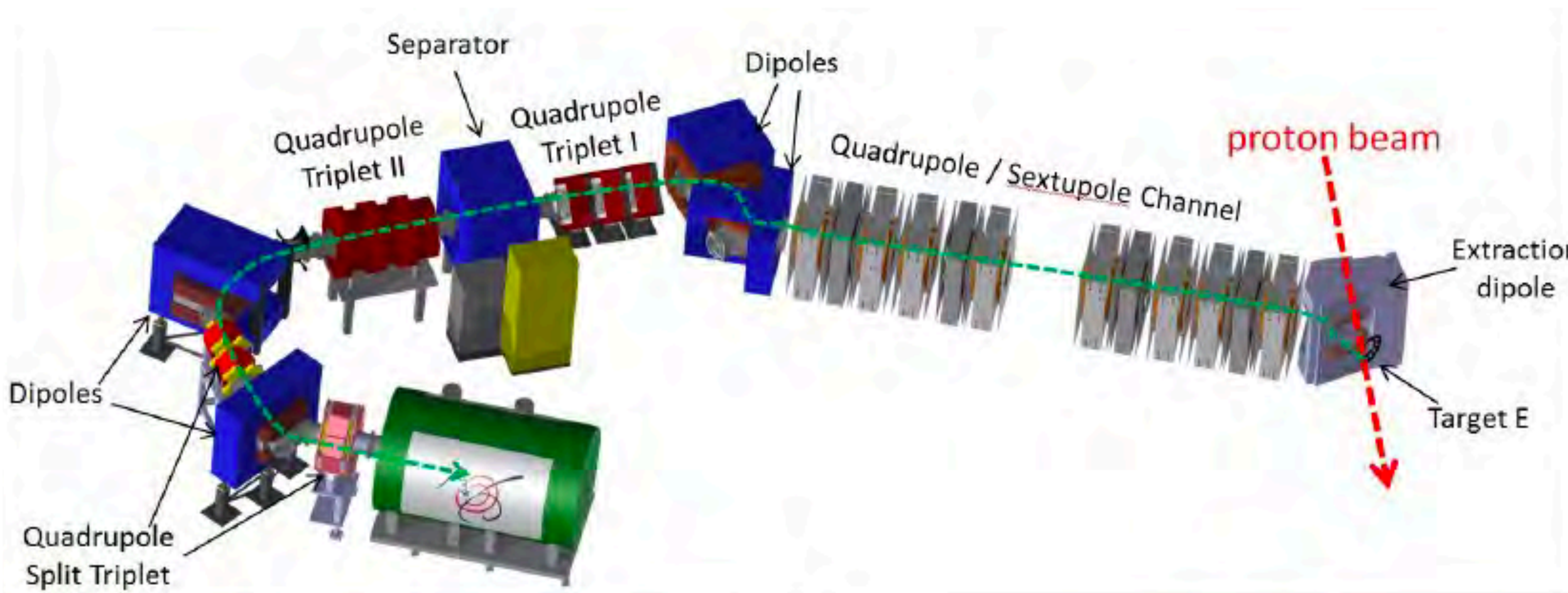


$\frac{1}{\Lambda^2}$

The compact beam line

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

The CMBL

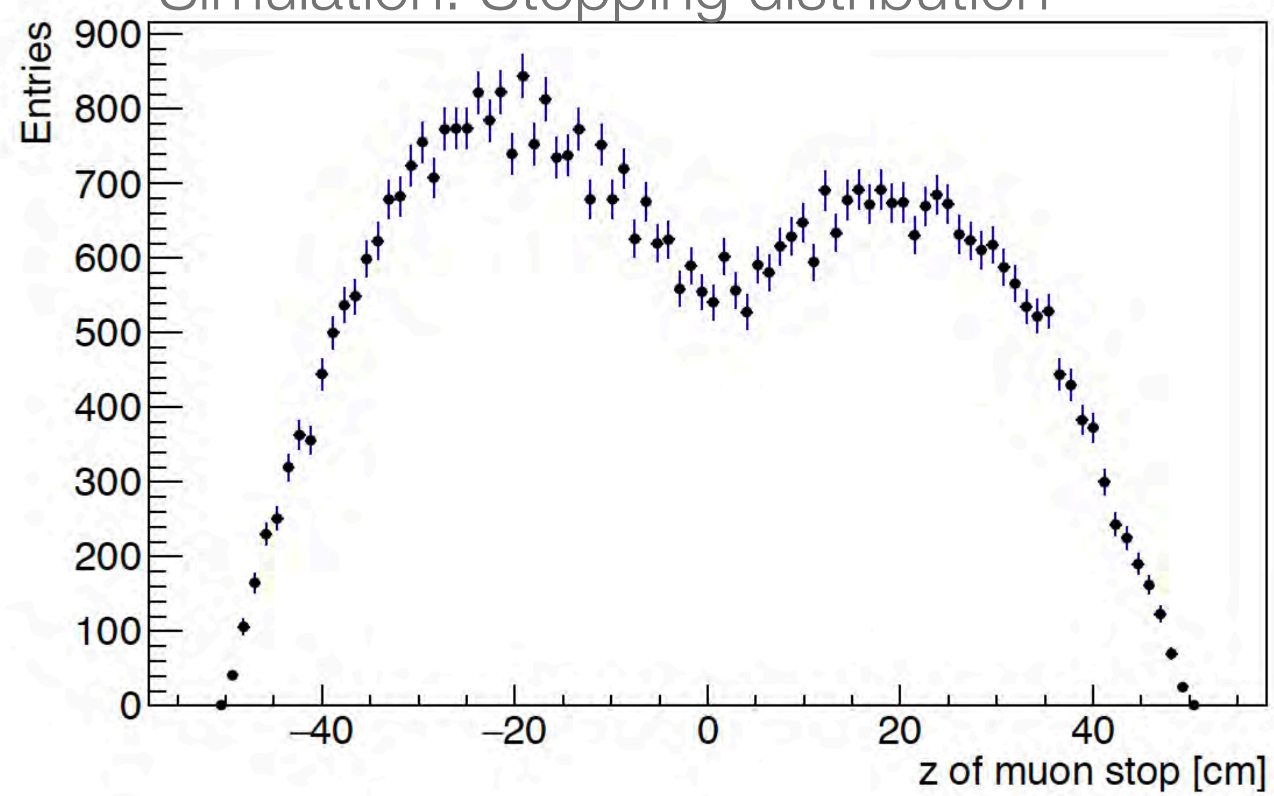


The target

- 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

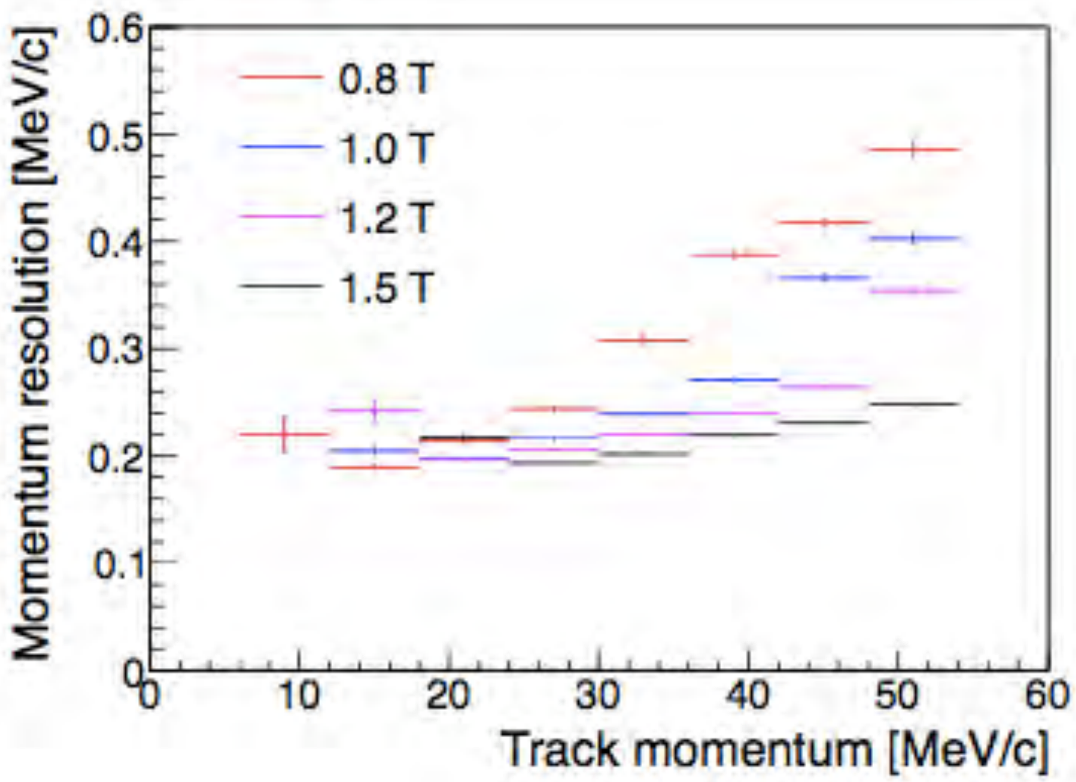
Simulation: Stopping distribution

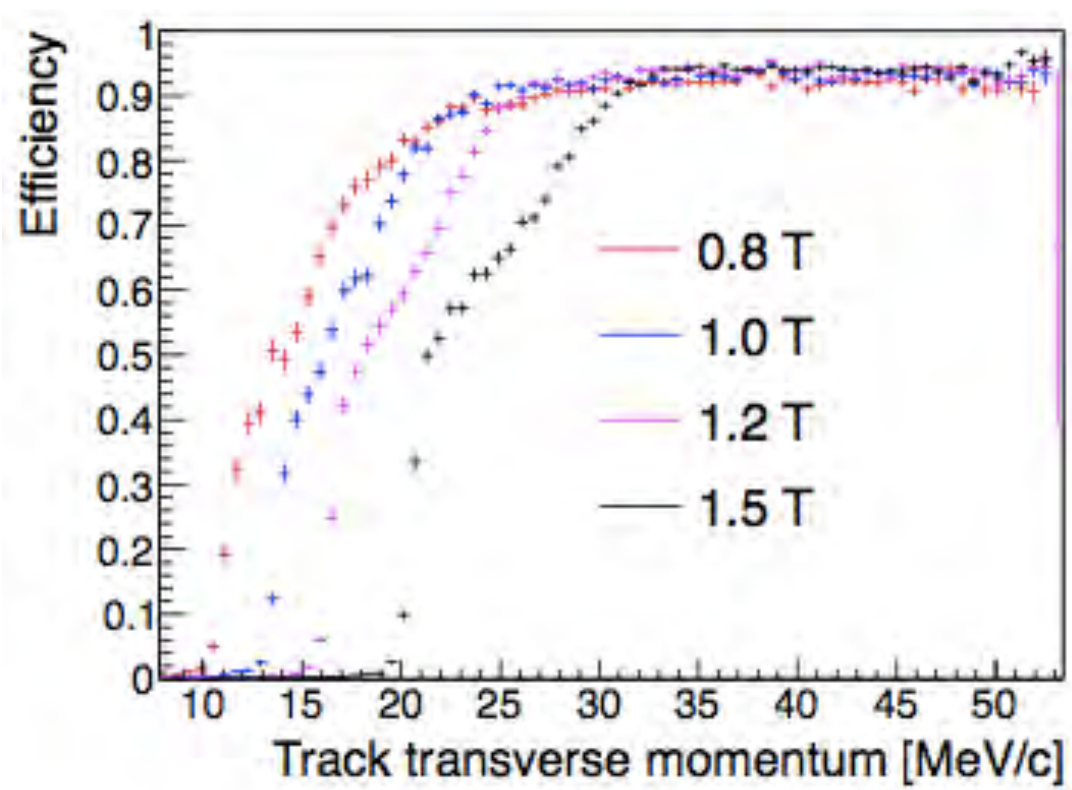


The magnet: The characteristics

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

Simulation

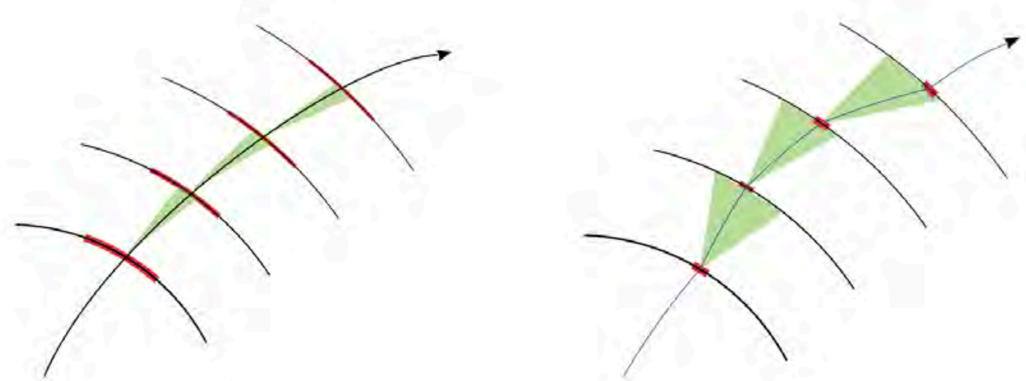




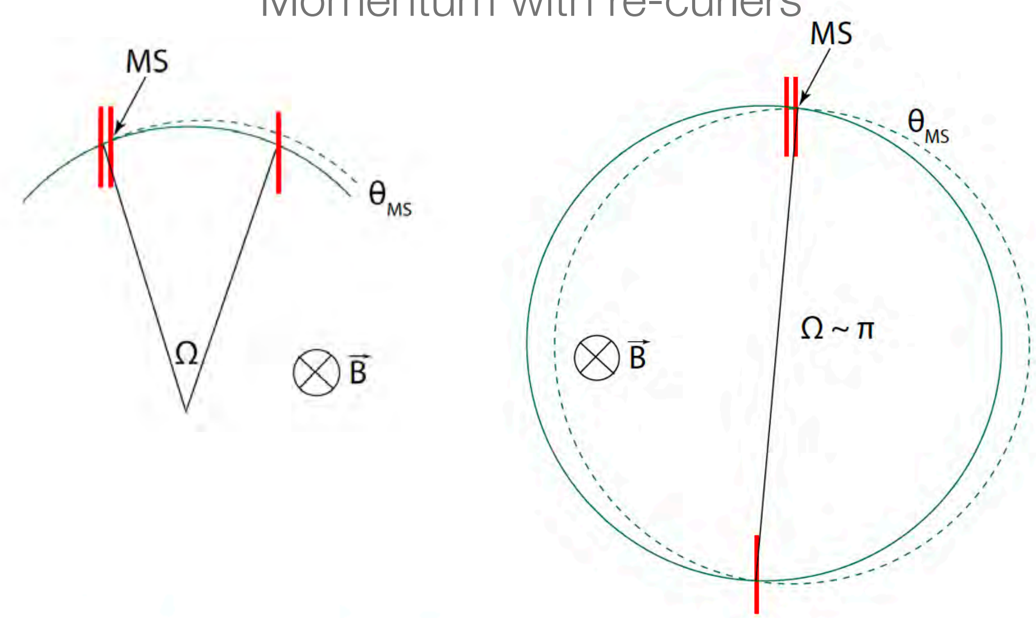
The pixel tracker: The principle

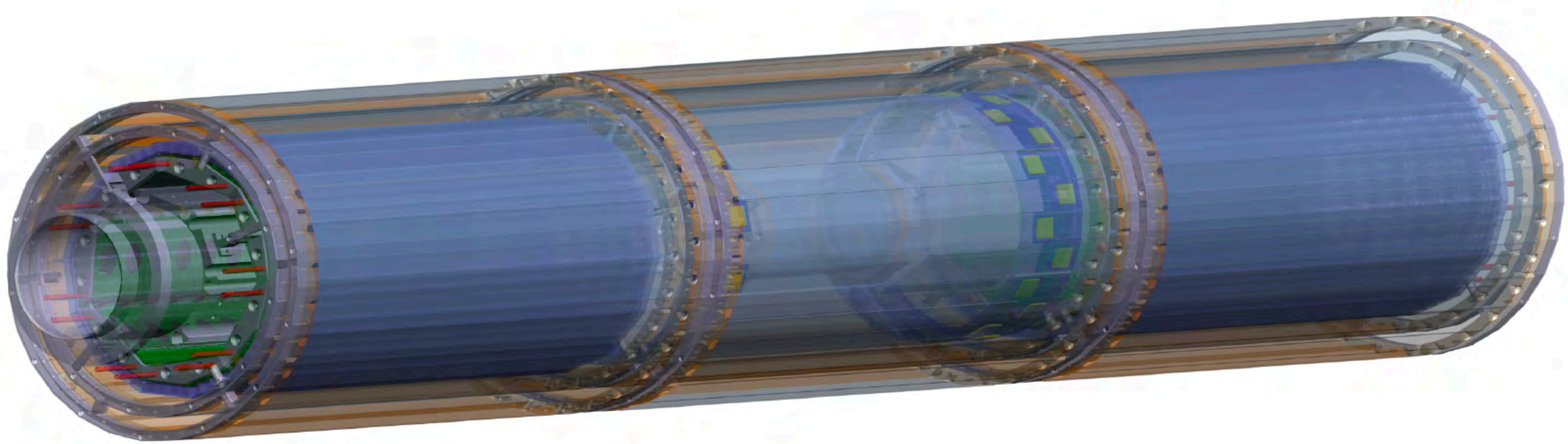
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime

Tracking in the spacial and scattering dominated regime



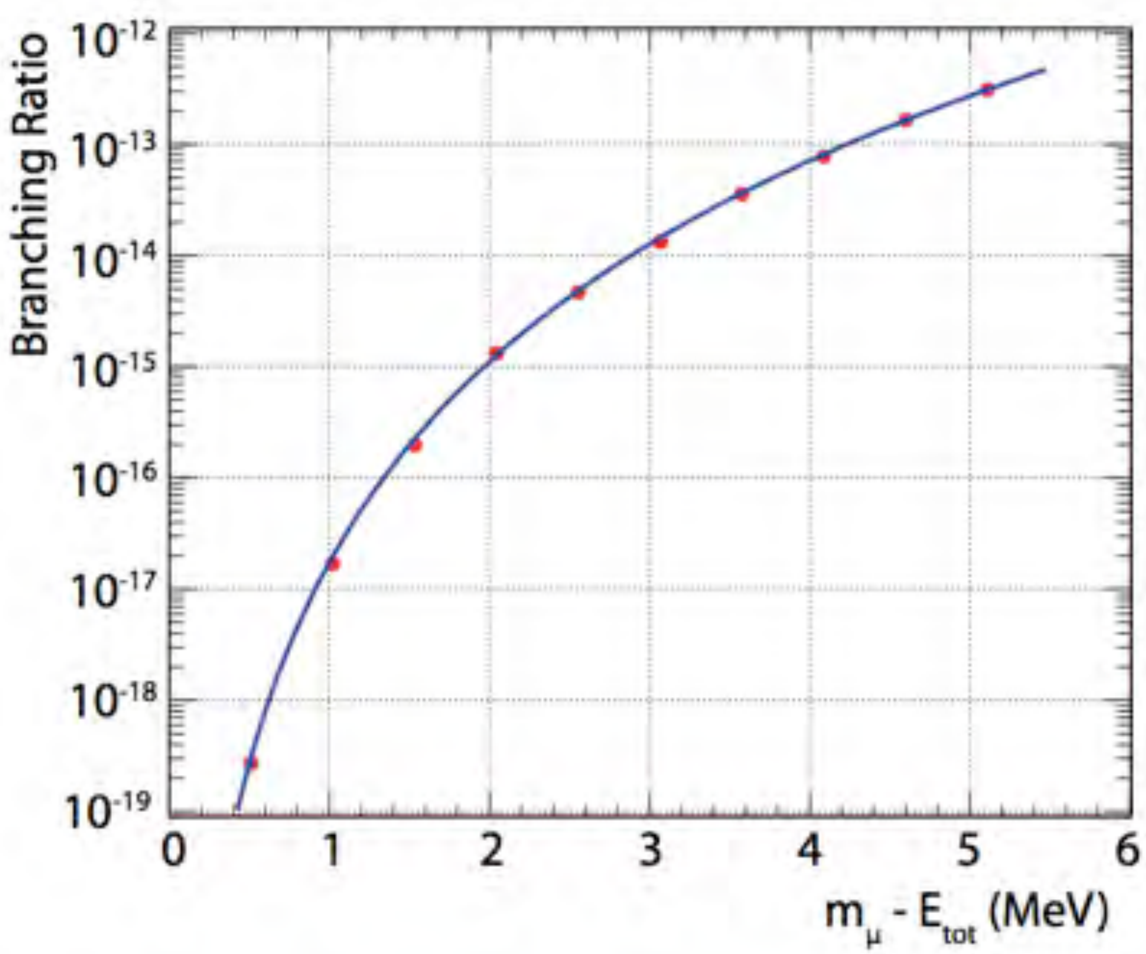
Momentum with re-curlers

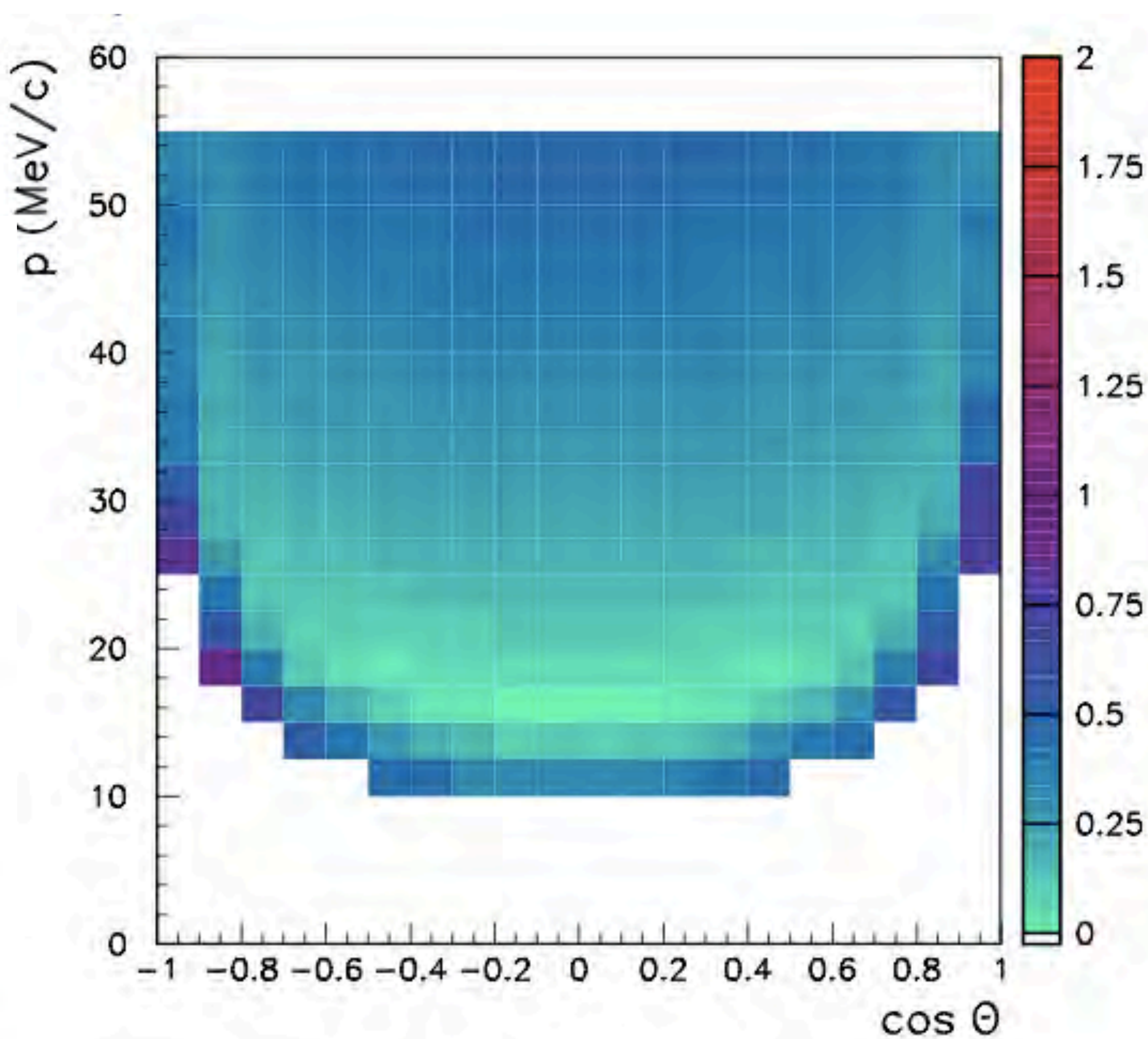




The pixel tracker: The performances

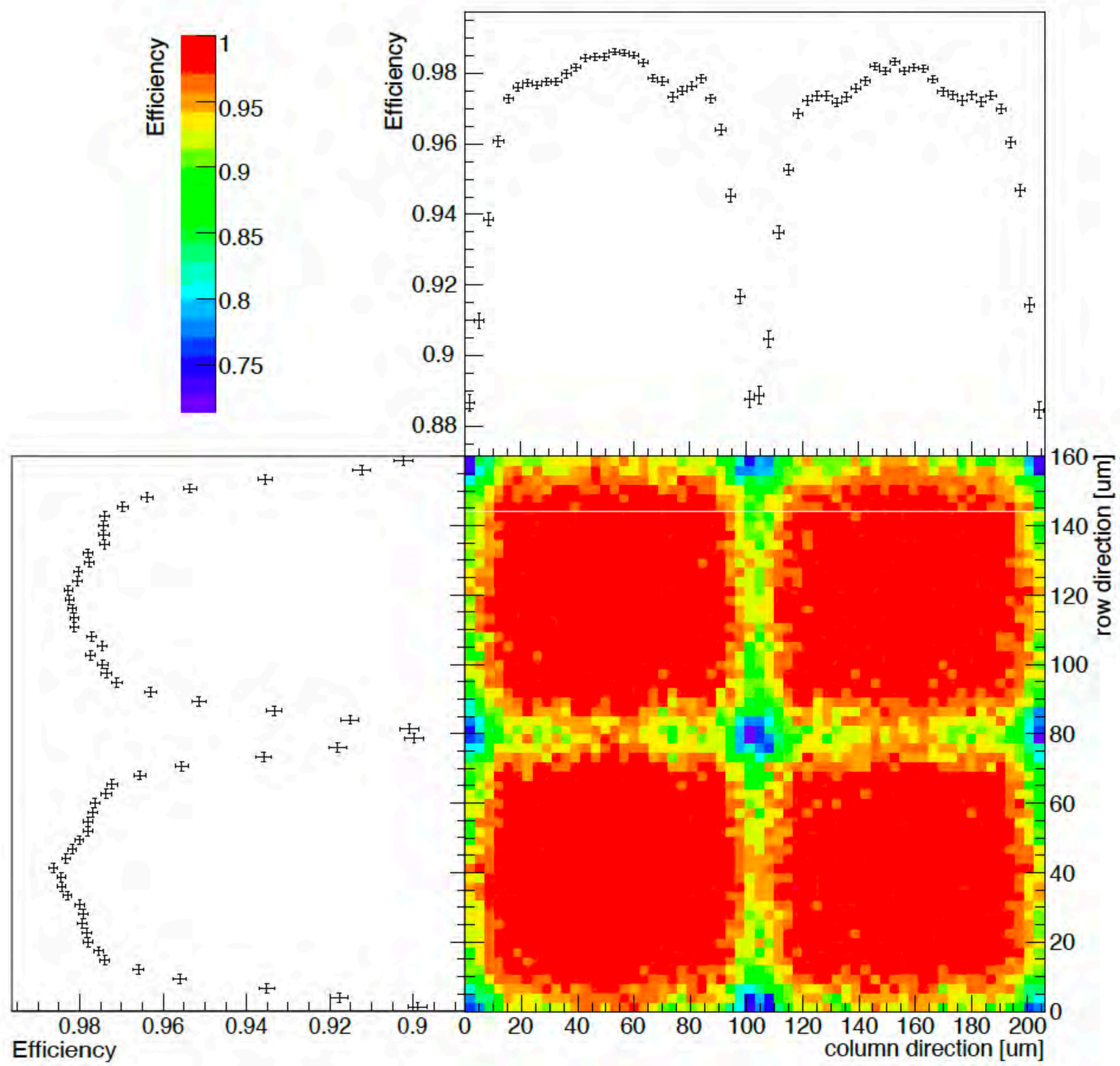
- Momentum resolution: < 0.5 MeV/c over a large phase space
- Geometrical acceptance: ~ 70%
- X/X_0 per layer: ~ 0.011%
- Vertex resolution: < 200 μm





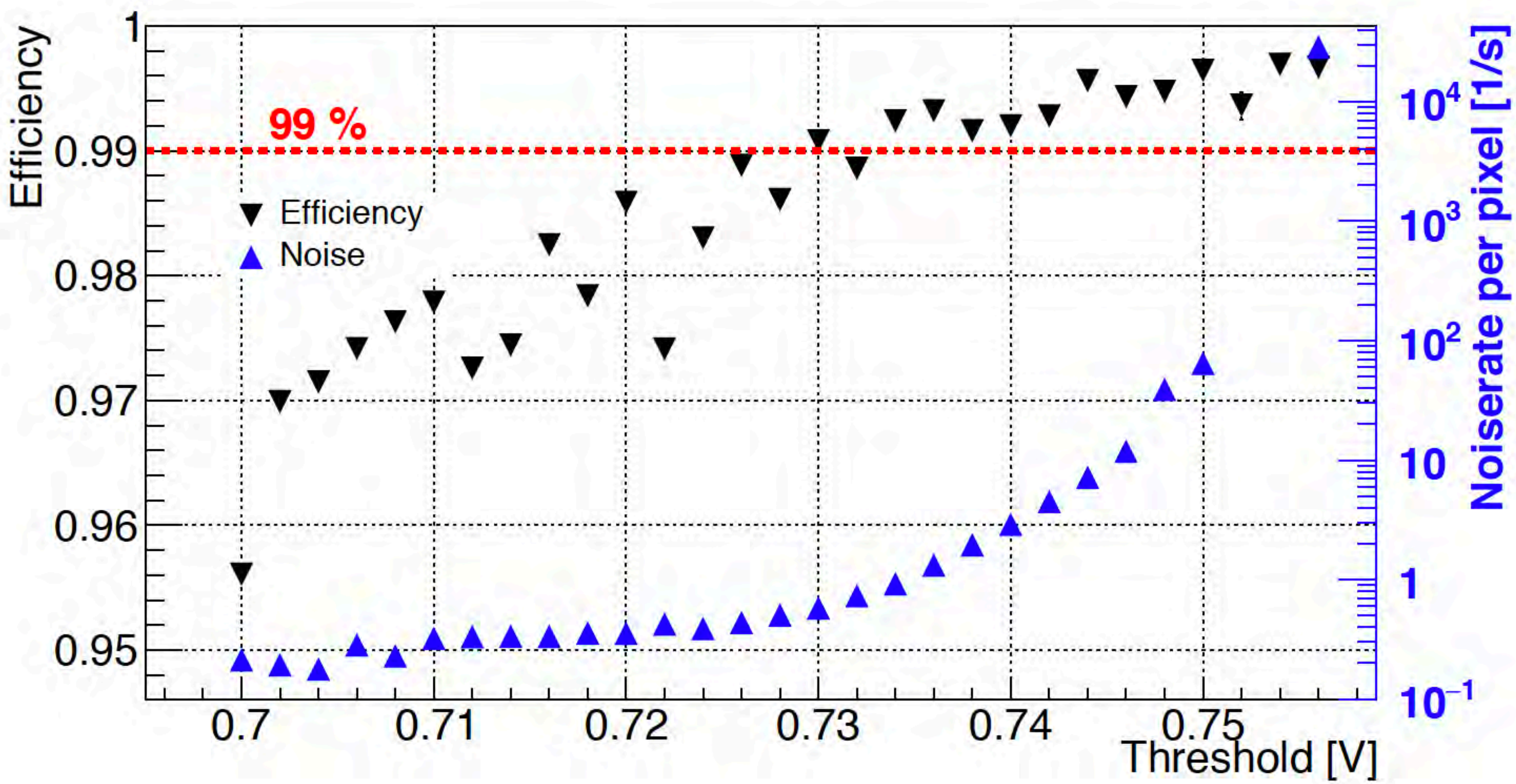
Prototypes: Results

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

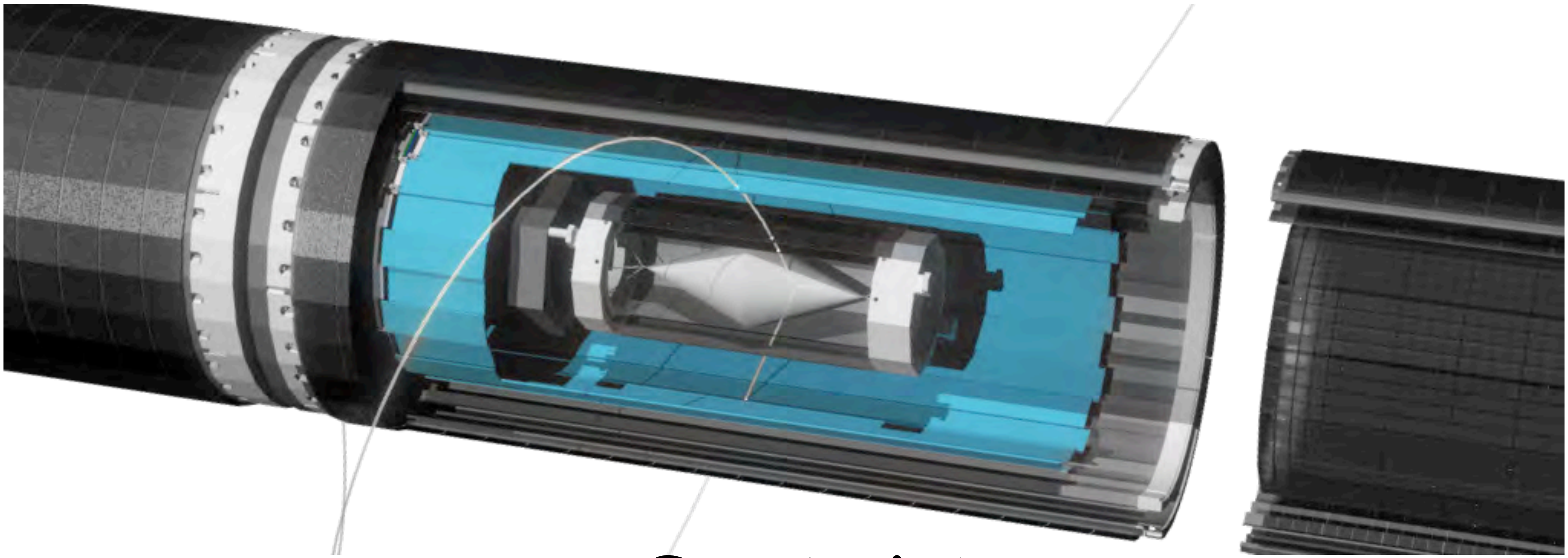


Prototypes: Results

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



The Fiber detector (SciFi): Overview



Parts

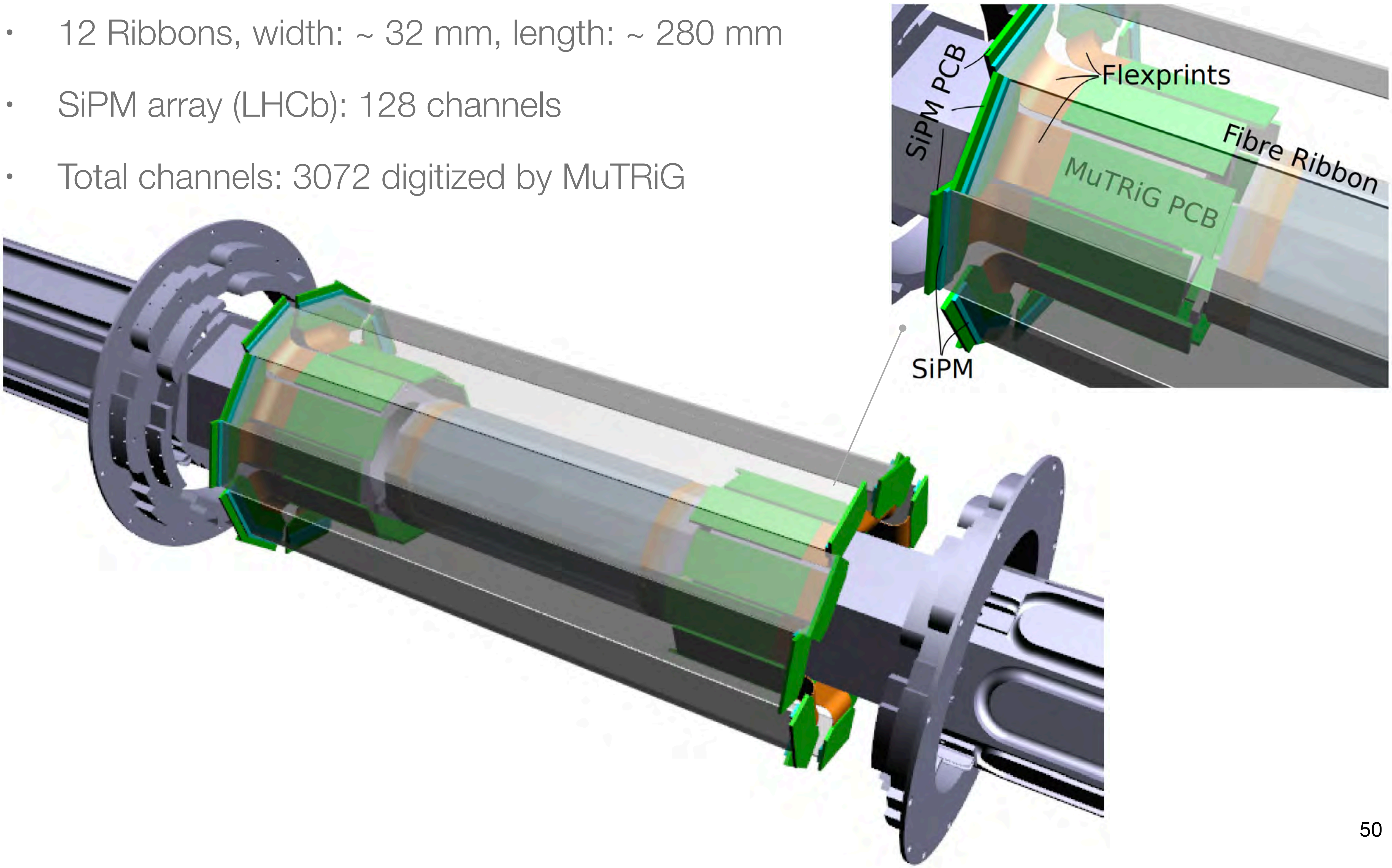
- cylindrical at ~ 6 cm (radius);
- length of 28-30 cm;
- 3 layers of round or square
- multi-clad 250 μm fibres
- fibres grouped onto SiPM array
- MuSTiC readout

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

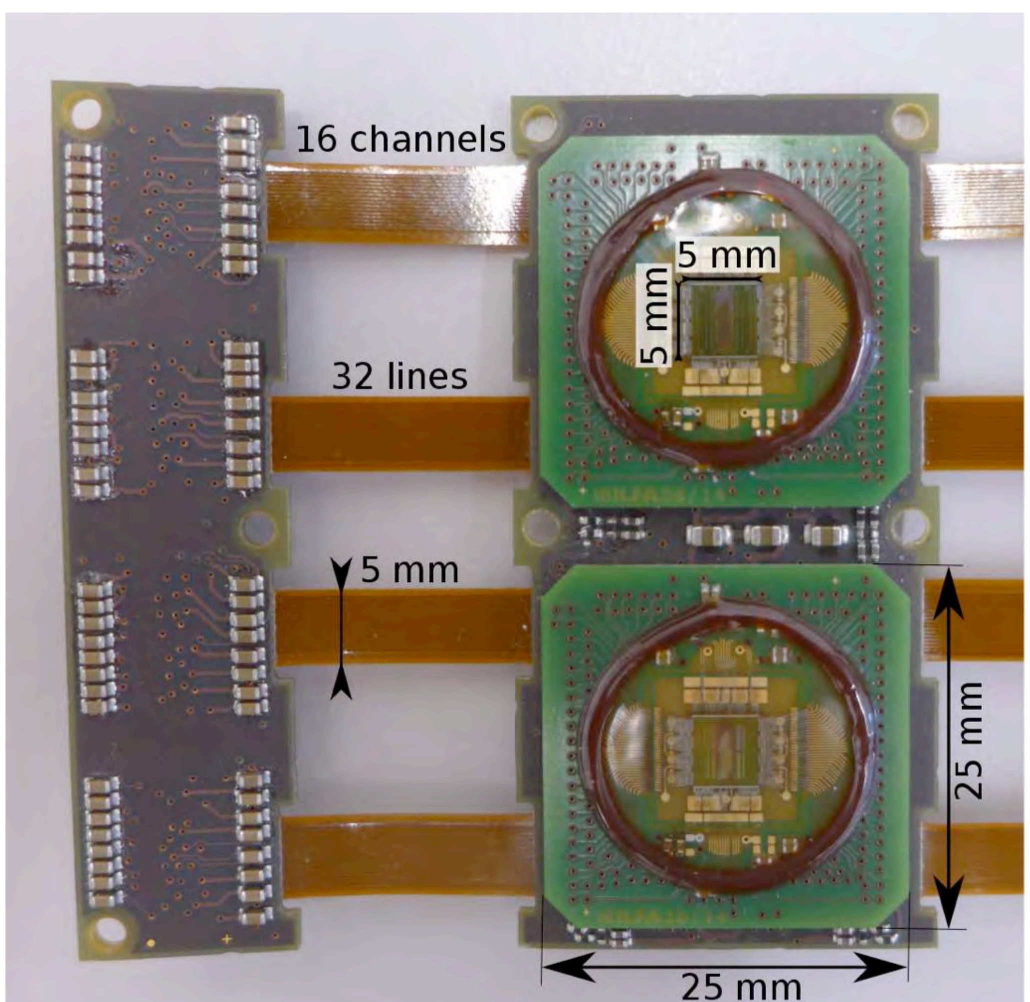
The Fiber detector (SciFi): 3D view

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



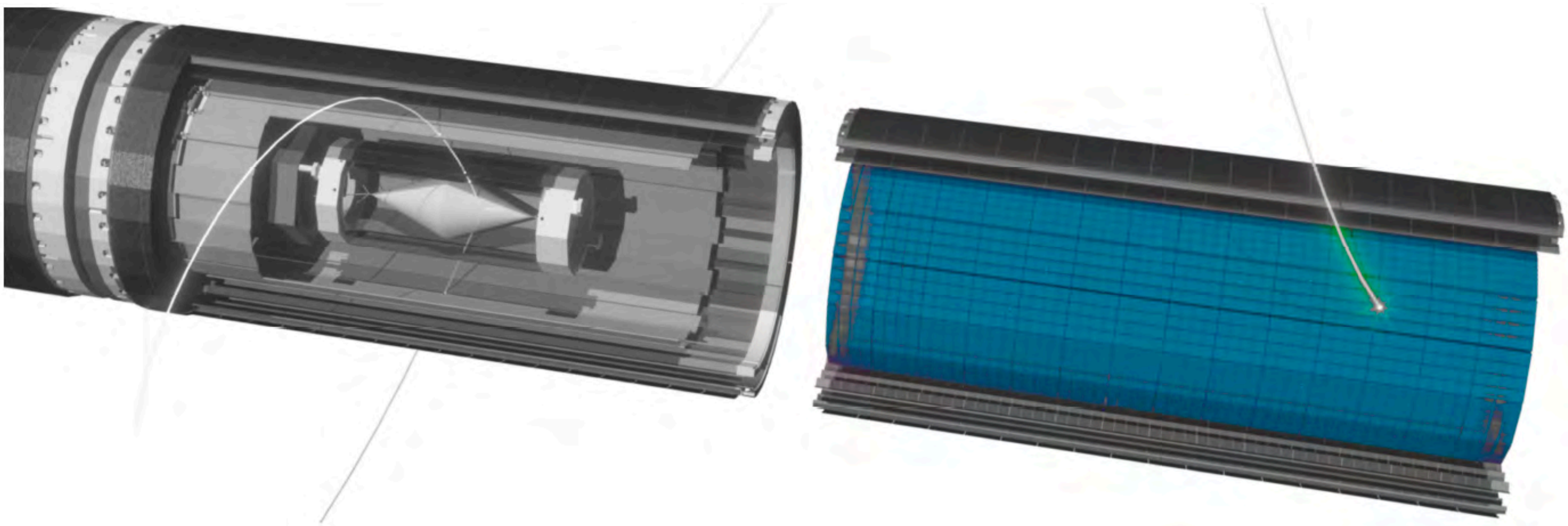
SciFi: Electronics readout, MuTRiG

- 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



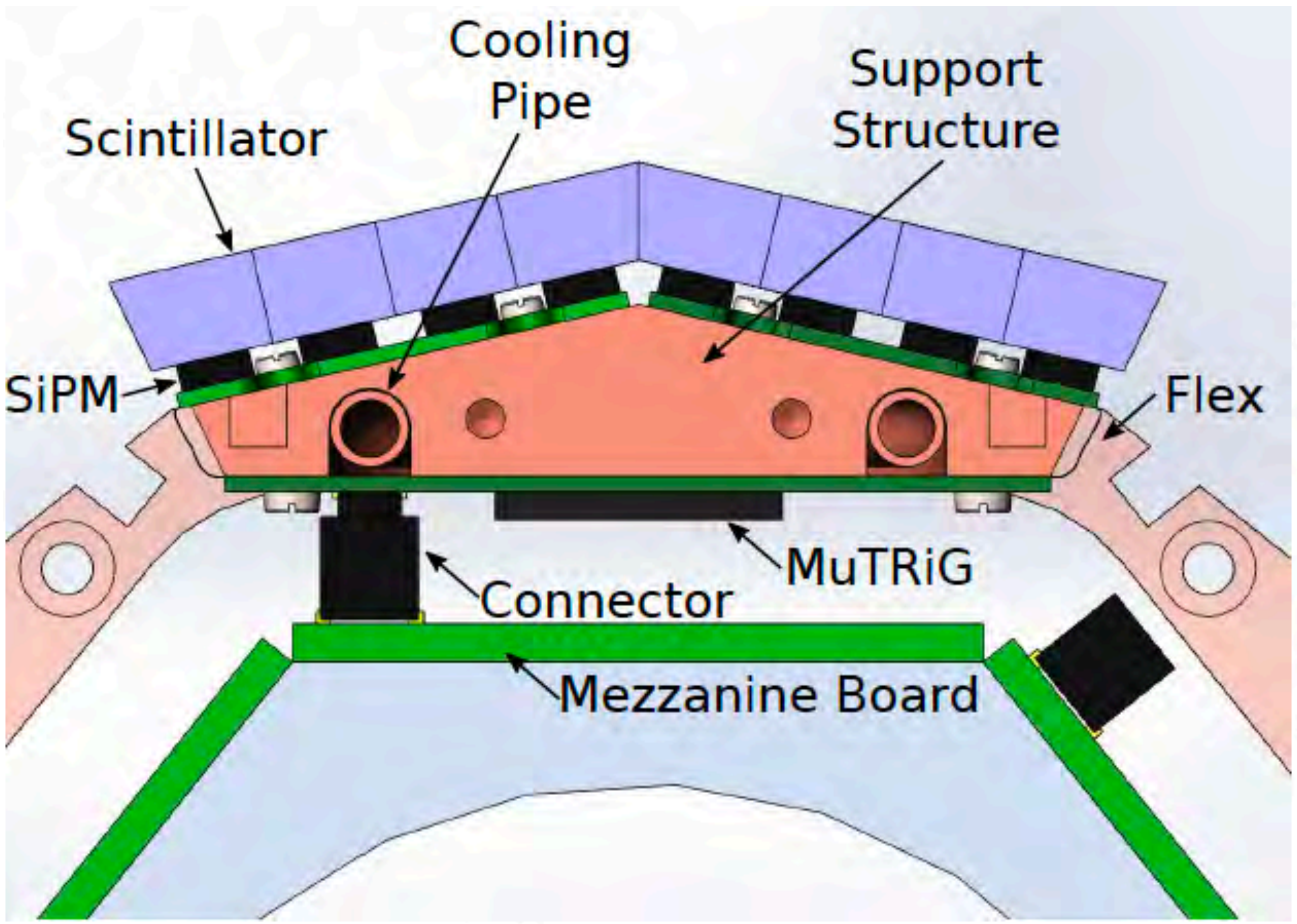
Parts

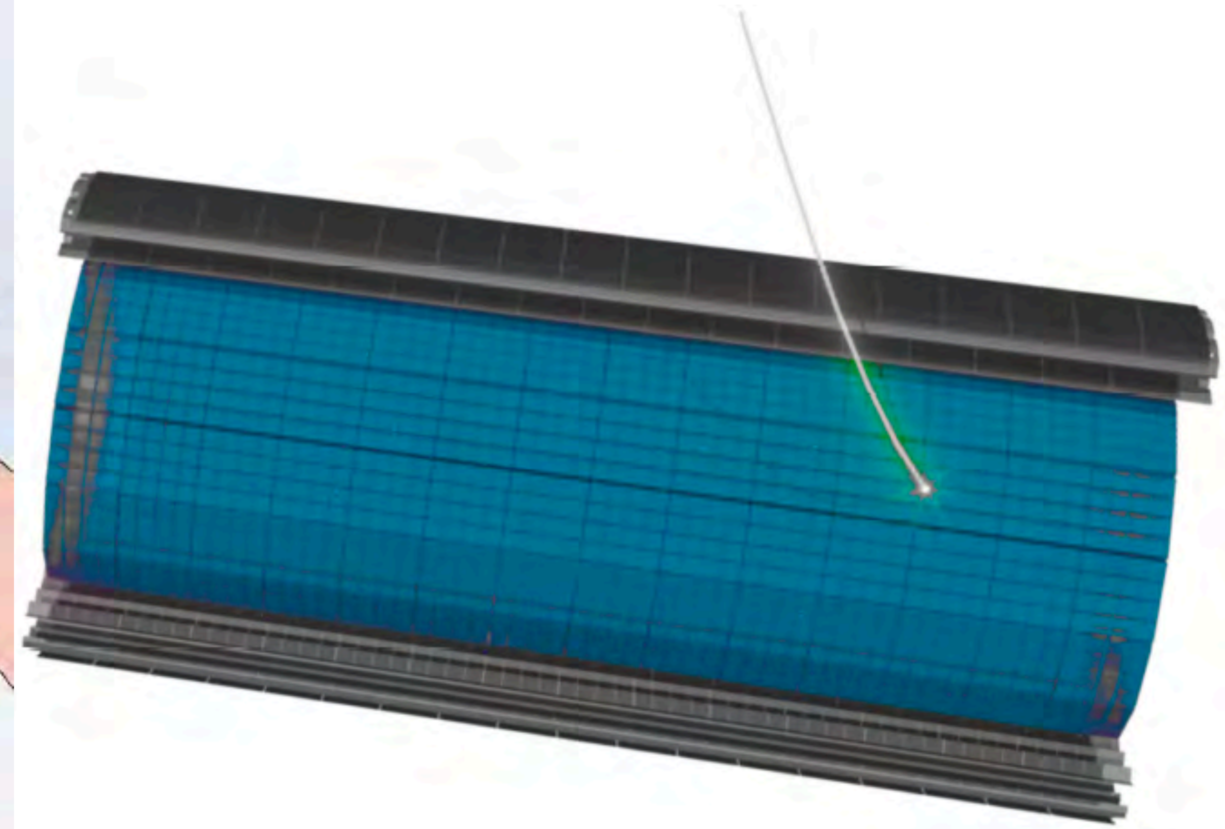
- cylindrical at ~ 6 cm (radius)
- length of 36.4 cm
- 56 x 56 tiles of 6.5 x 6.5 x 5 mm^3
- 3 x 3 mm^2 single SiPM per tile
- Mixed mode ASIC: MuTRiG

Requirements

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

The Tile detector: Overview





Parts

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- 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

MuTRiG

MuTRiG commissioning started !

New