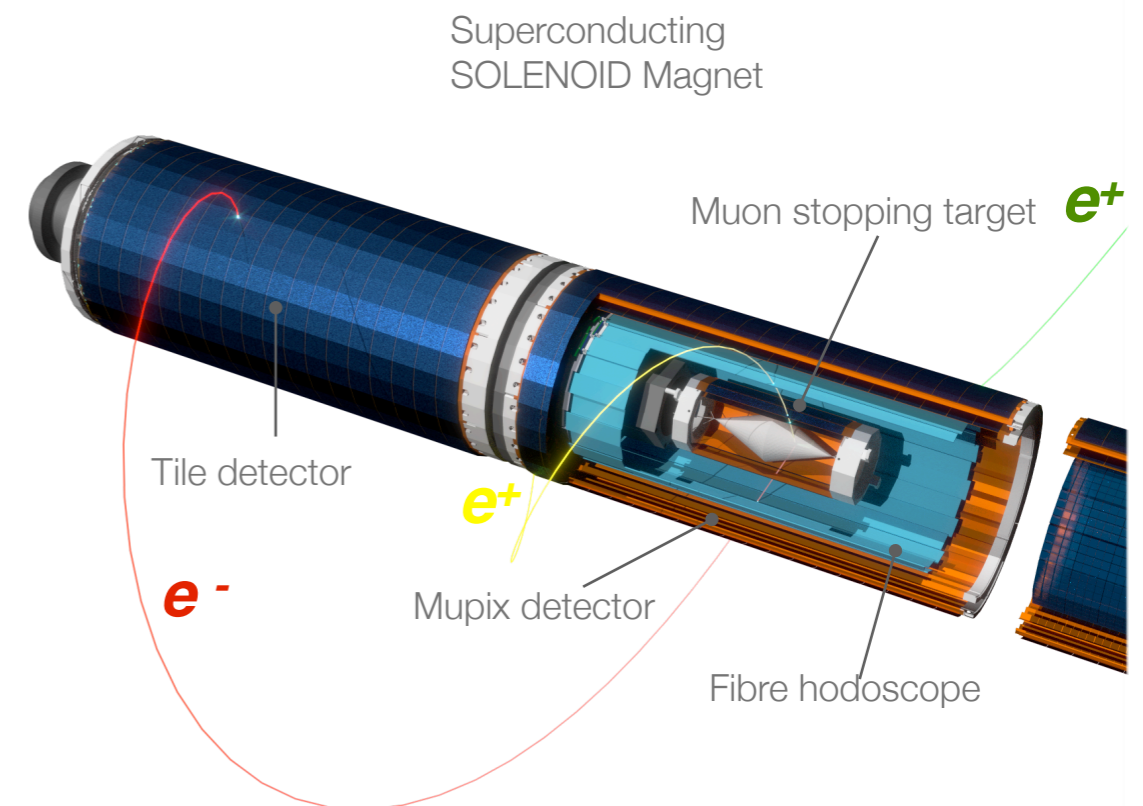
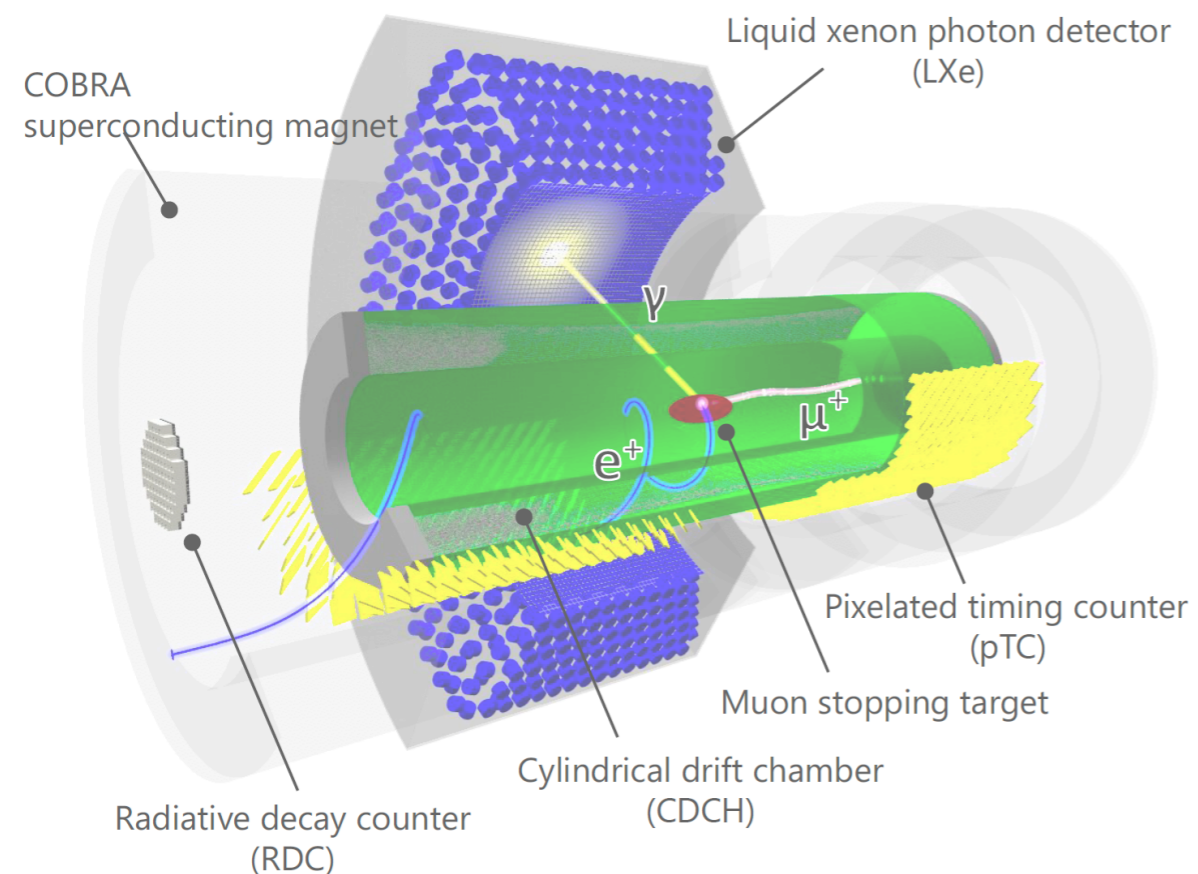


Status of the MEGII and Mu3e experiments

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

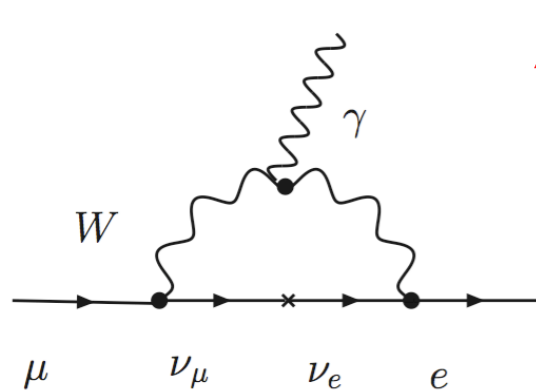


Content

- Charged Lepton Flavour Violation (cLFV) search:
The motivation
- cLFV with the MEGII and Mu3e experiments:
The $\mu^+ \rightarrow e^+ \gamma$ and $\mu^+ \rightarrow e^+ e^+ e^-$ 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)

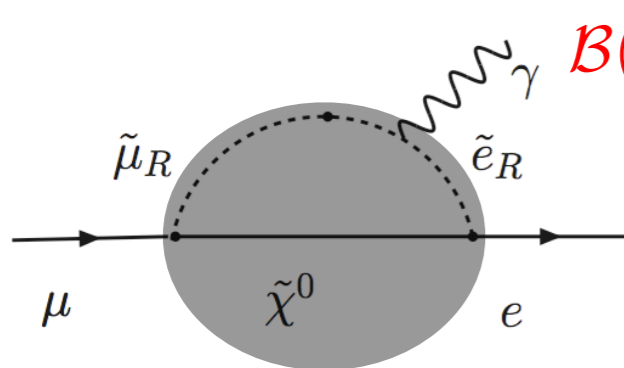


$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) \approx 10^{-54}$$

ν oscillations

too small to access experimentally

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



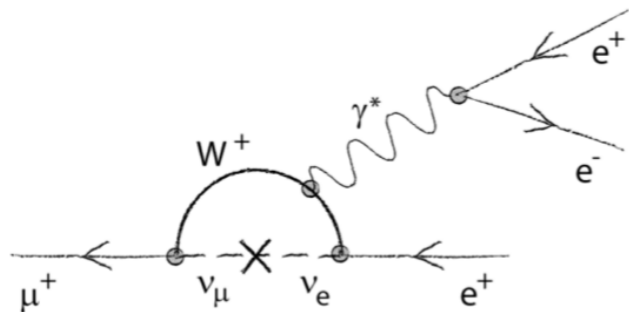
$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) \gg 10^{-54}$$

**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)

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



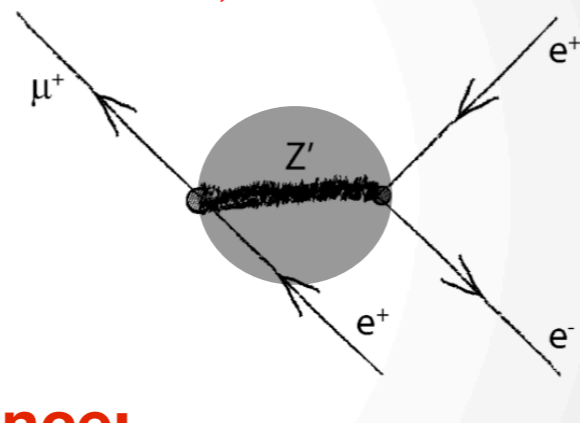
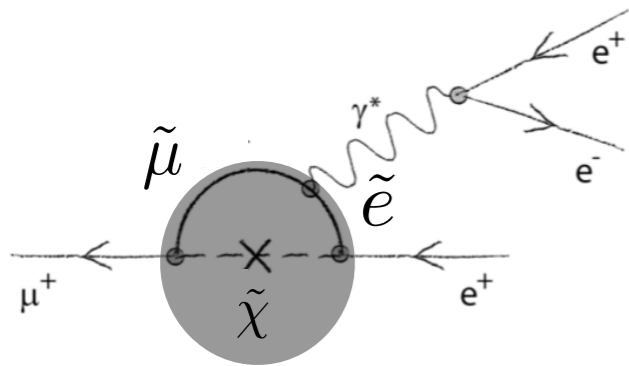
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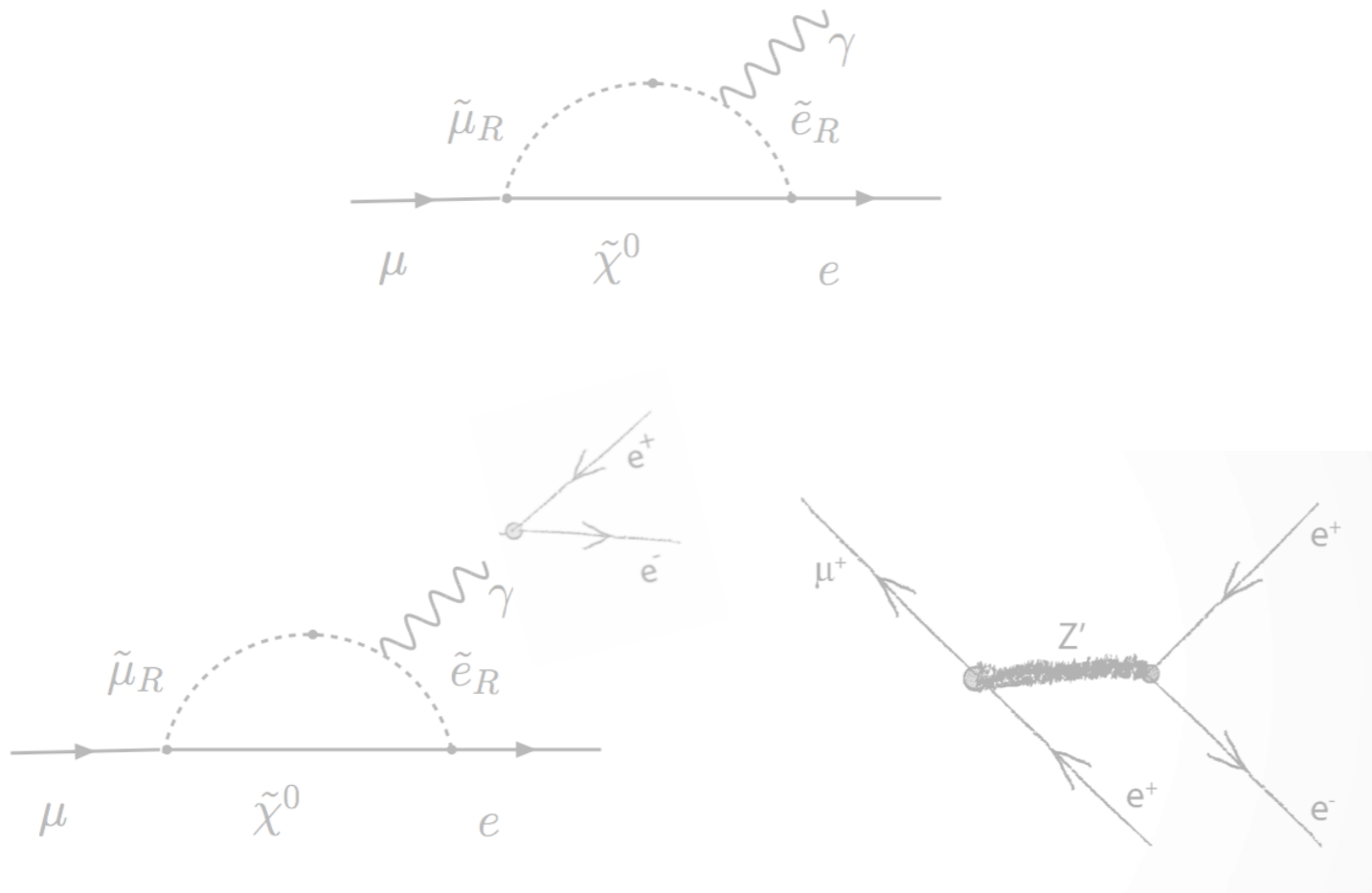
i.e. EXTRA Z'

$$BR(\mu \rightarrow eee) \gg 10^{-54}$$

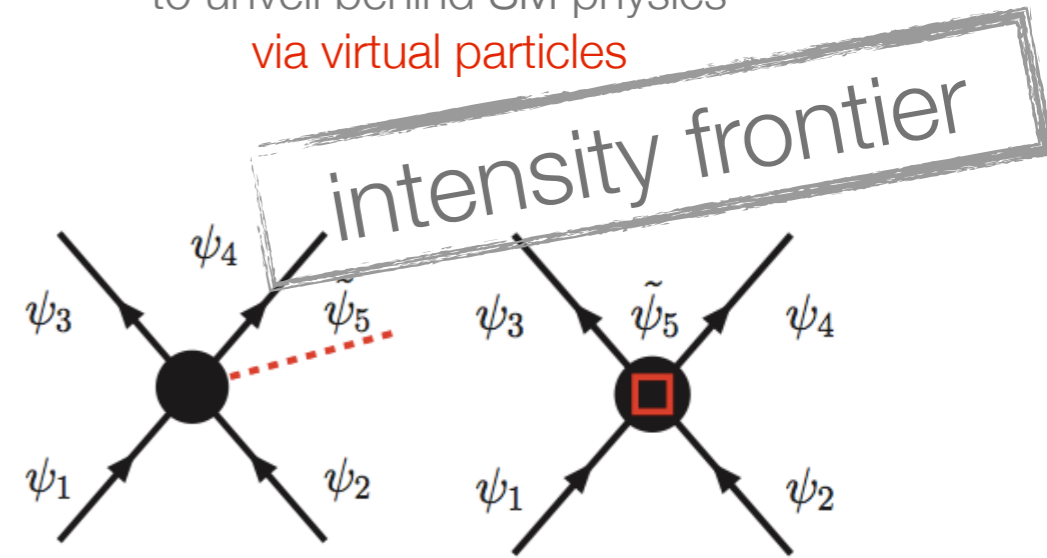


**an experimental evidence:
a clear signature of New Physics NP**
(SM background FREE)

cLFV evidence: A clear signature of New Physics



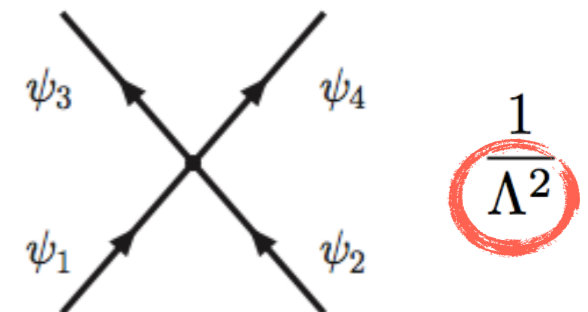
to unveil behind SM physics
via virtual particles



to probe otherwise unreachable and
unexploited new physics energy scale

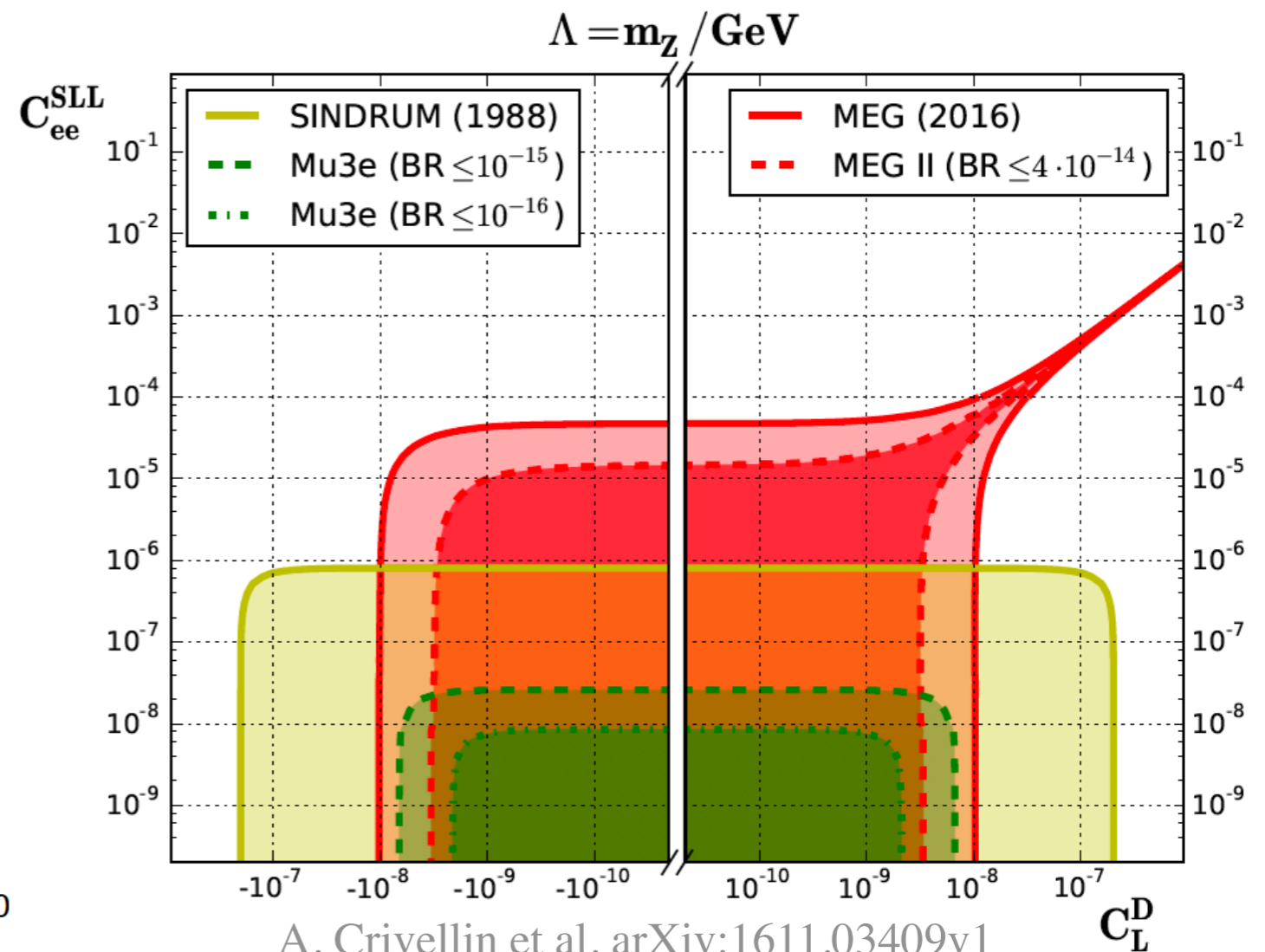
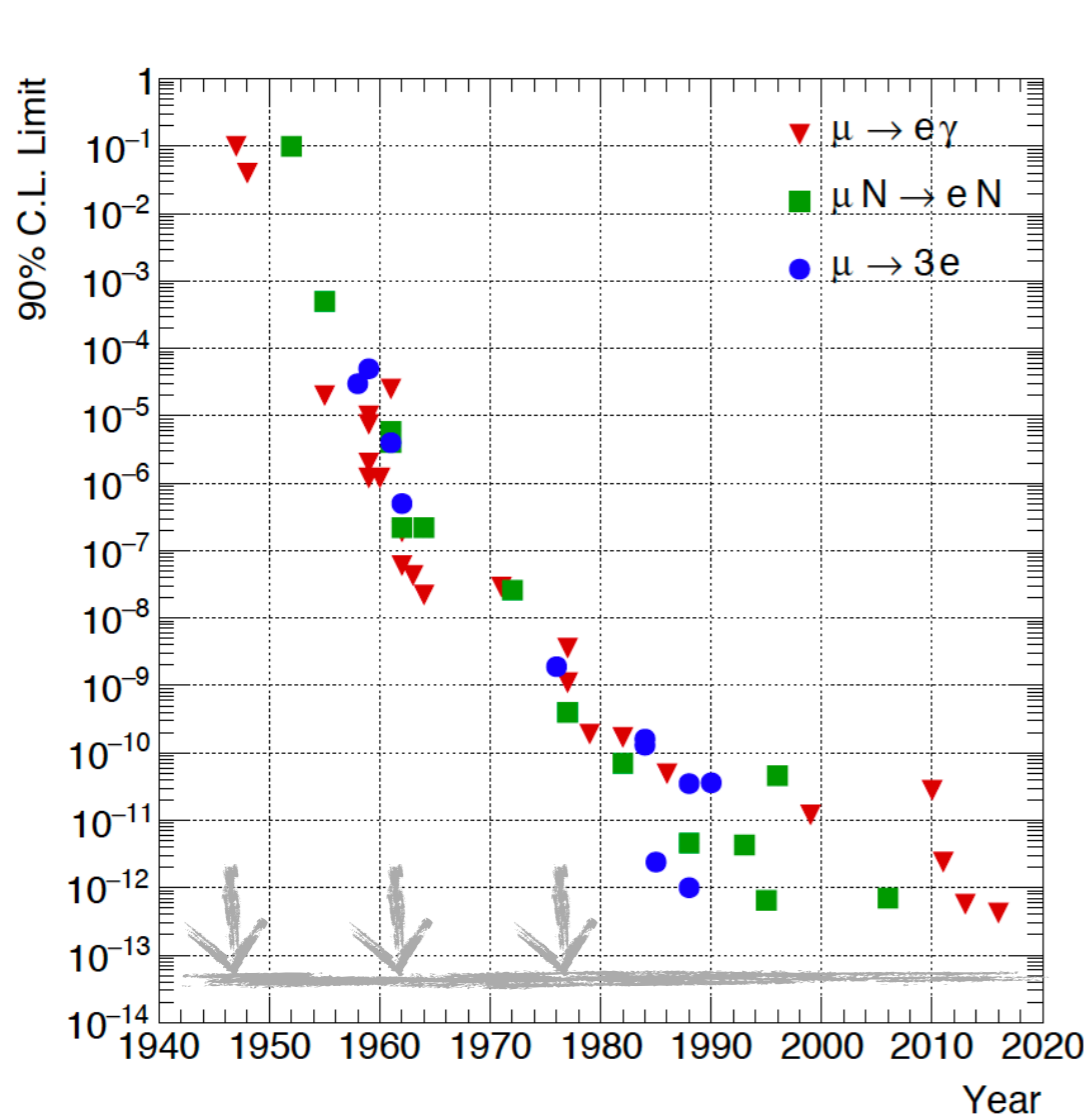
high energy probe

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



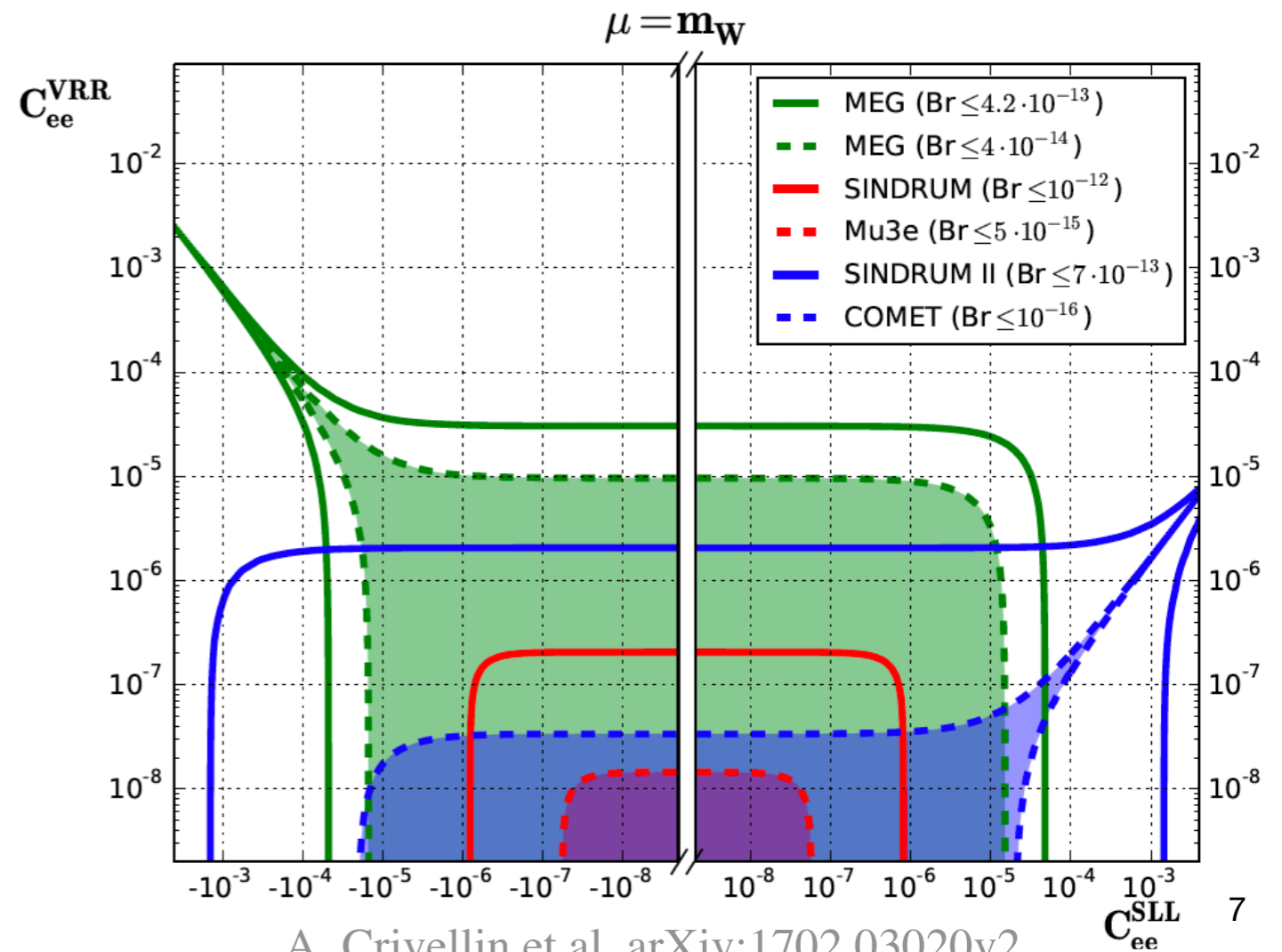
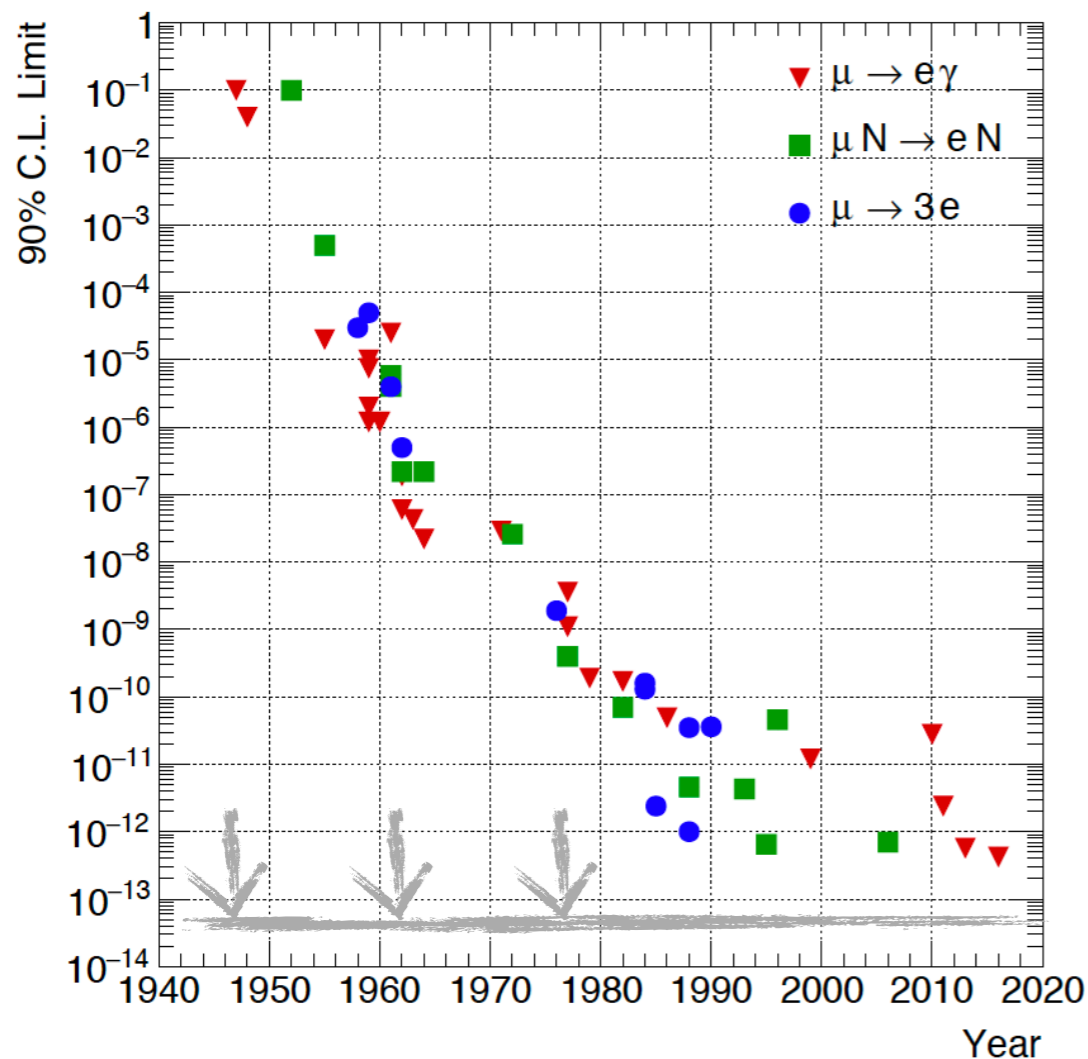
cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities: $BR(\mu \rightarrow e\gamma) < 4 \cdot 10^{-14}$; $BR(\mu \rightarrow eee) < 5 \cdot 10^{-15}$; $CR(\mu N \rightarrow eN') < 10^{-16}$
- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV



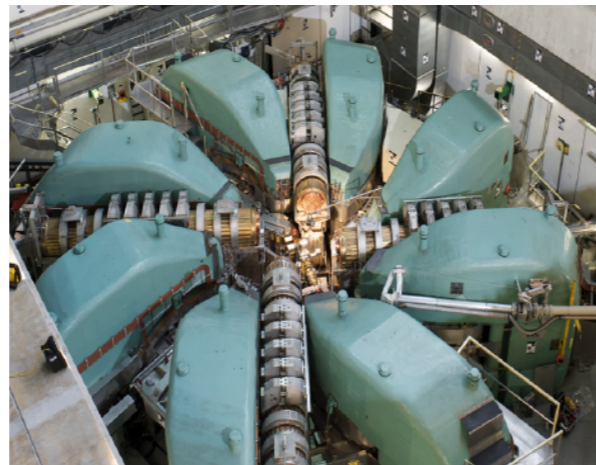
cLFV searches with muons: Status and prospects

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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



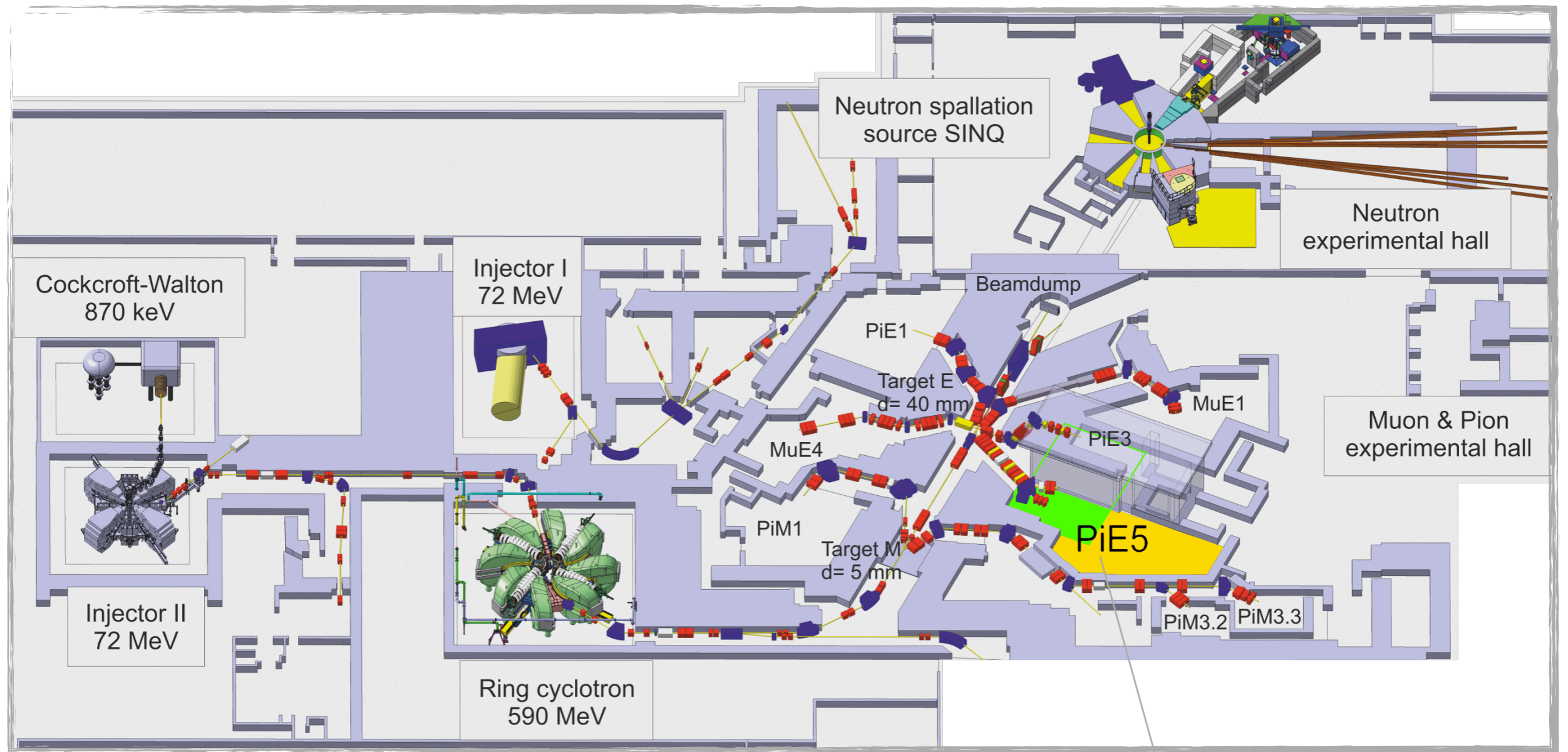
590 MeV proton
ring cyclotron
1.4 MW

PSI landscape



The world's most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas



MEGII / Mu3e Experimental area

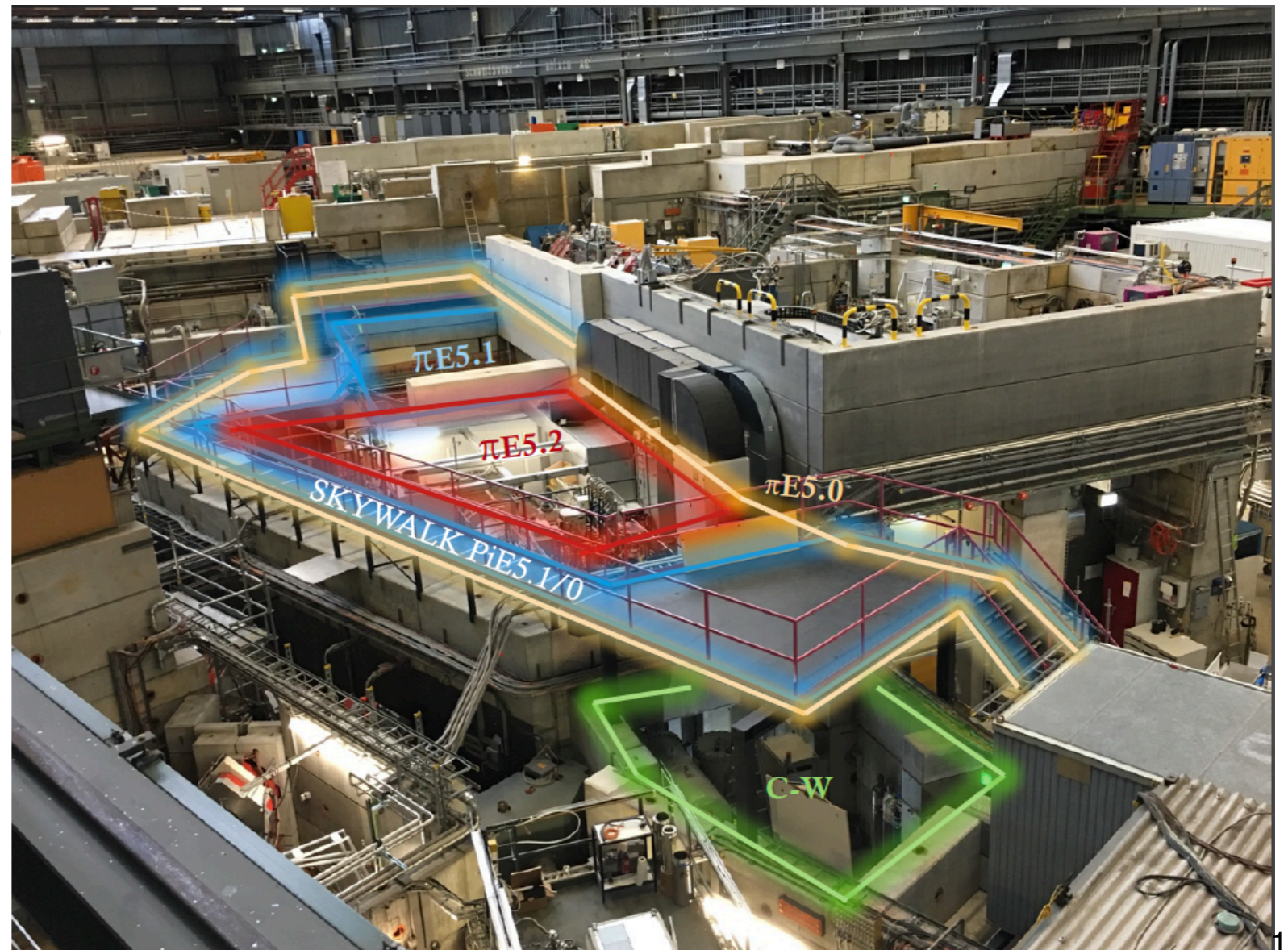
The MEGII and Mu3e experimental area: Pictures



Mu3e extra platforms

New

Overview piE5 area



New



Mu3e control room

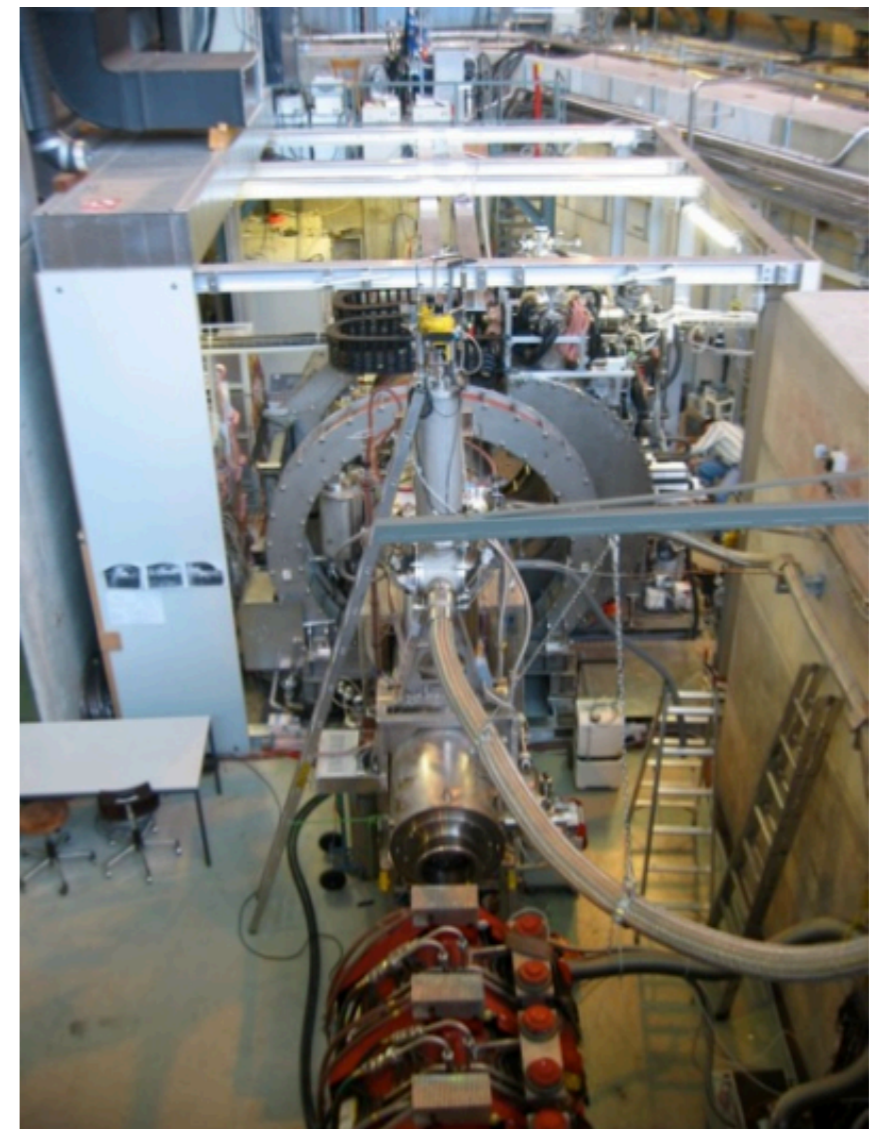
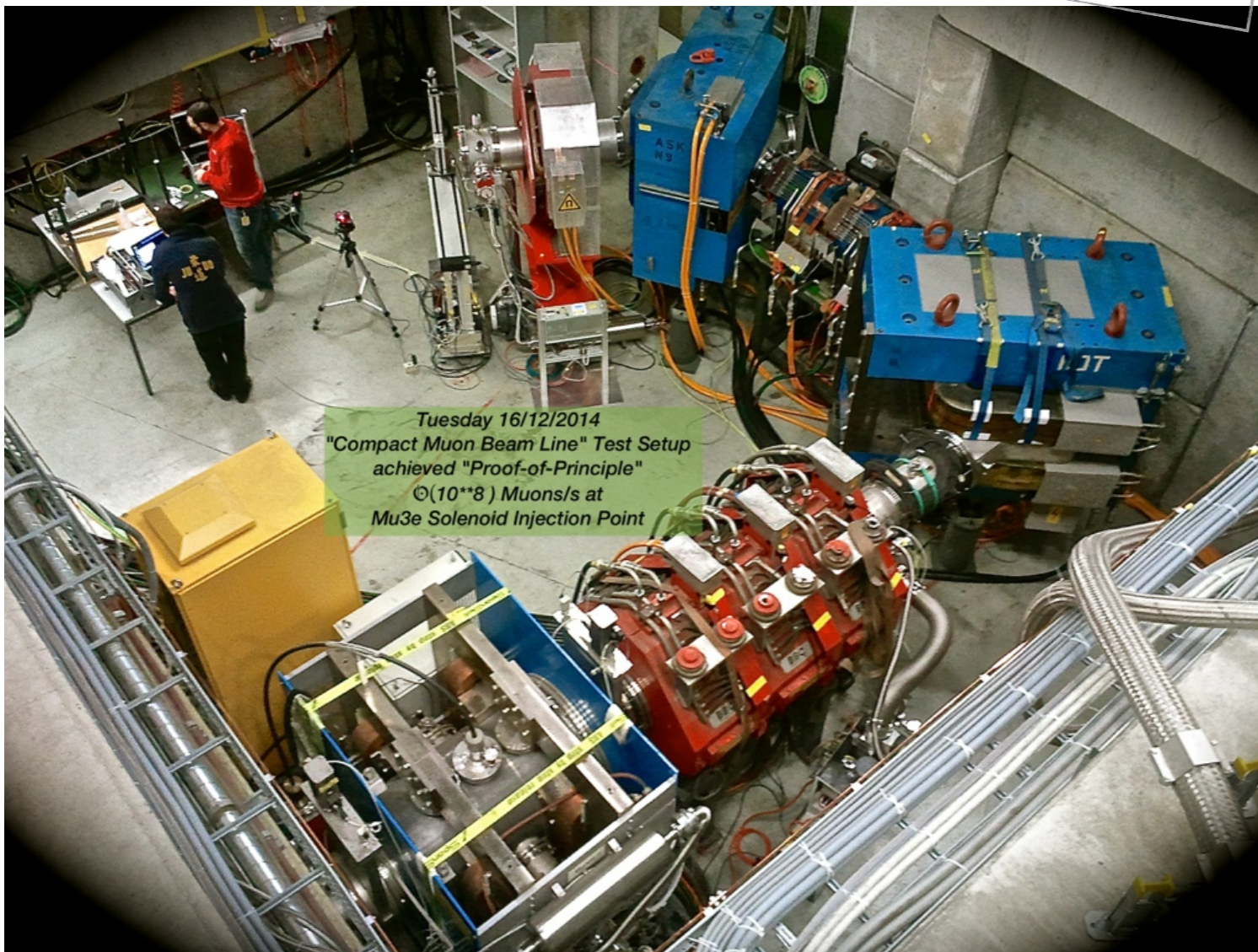
The MEGII and Mu3e beam lines

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

The Mu3e CMBL

New

The MEGII BL

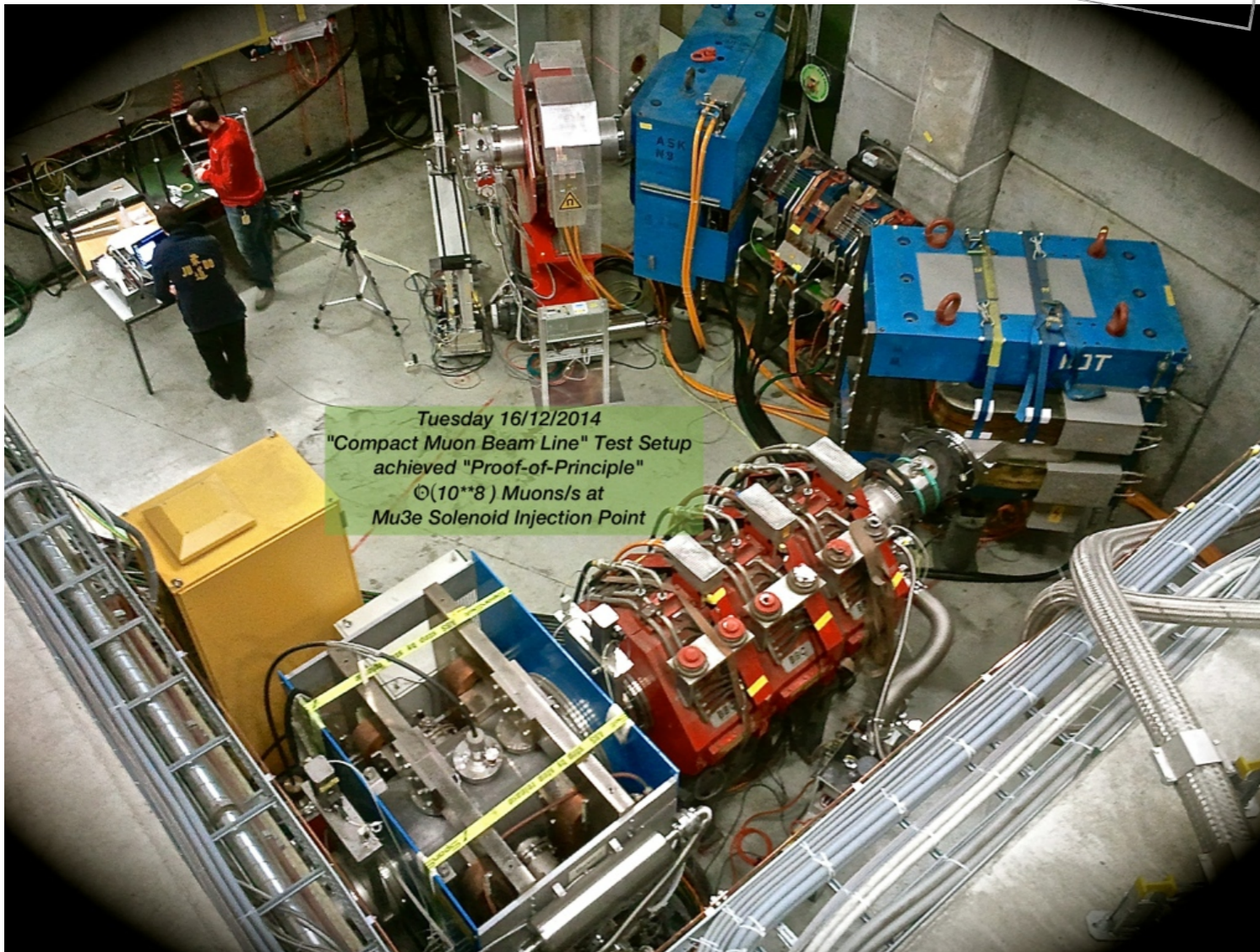


The compact beam line: Results

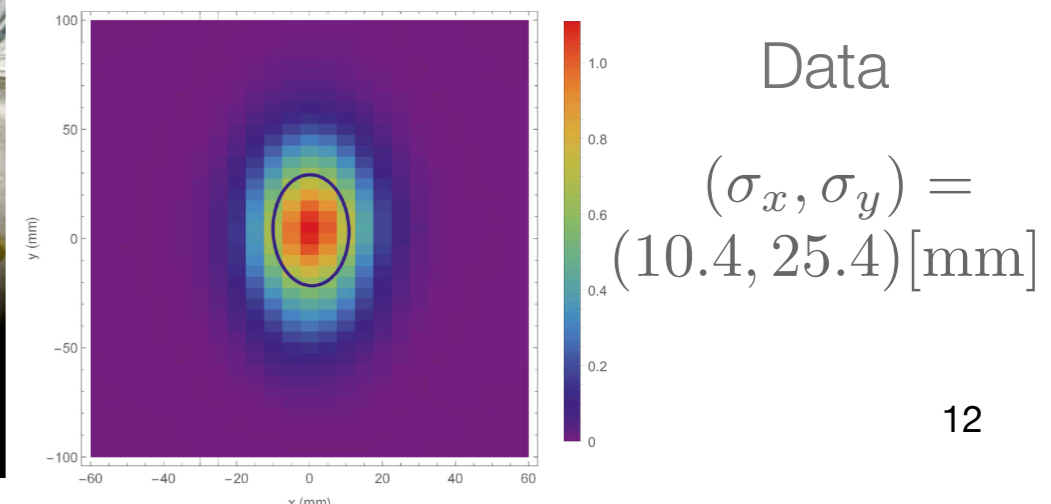
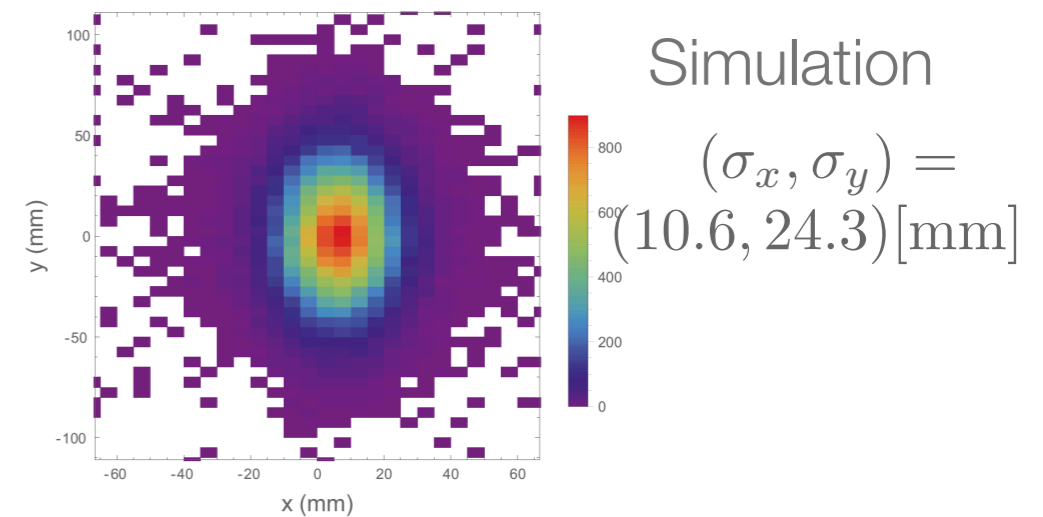
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The CMBL

New



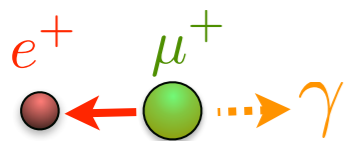
Beam at the injection Mu3e solenoid point



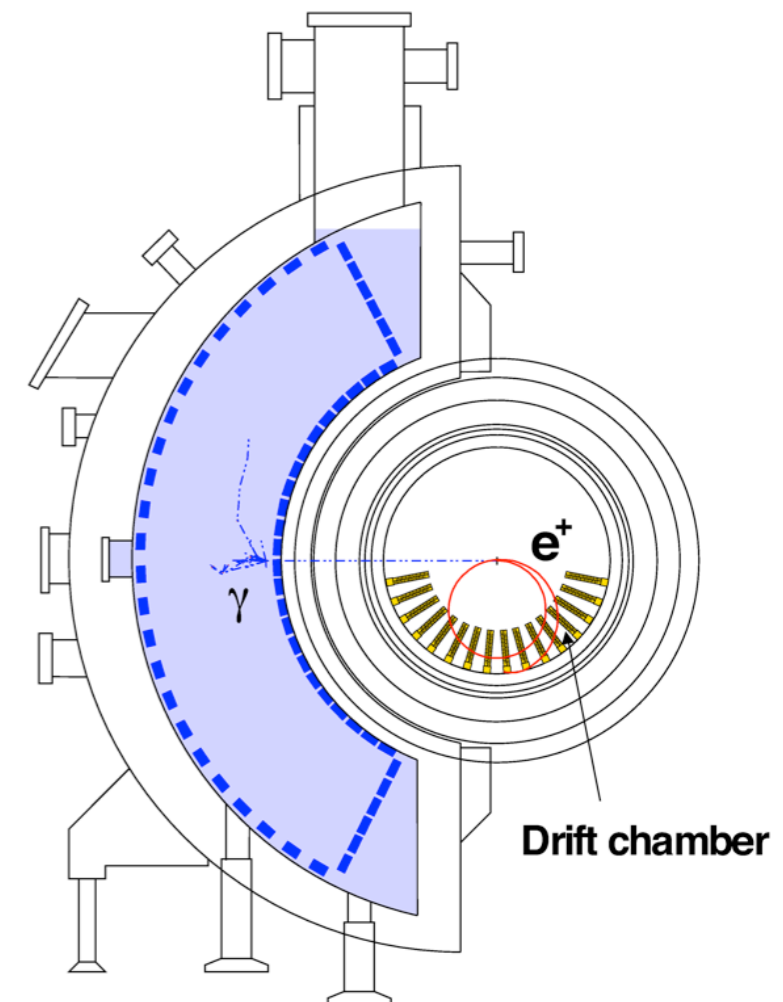
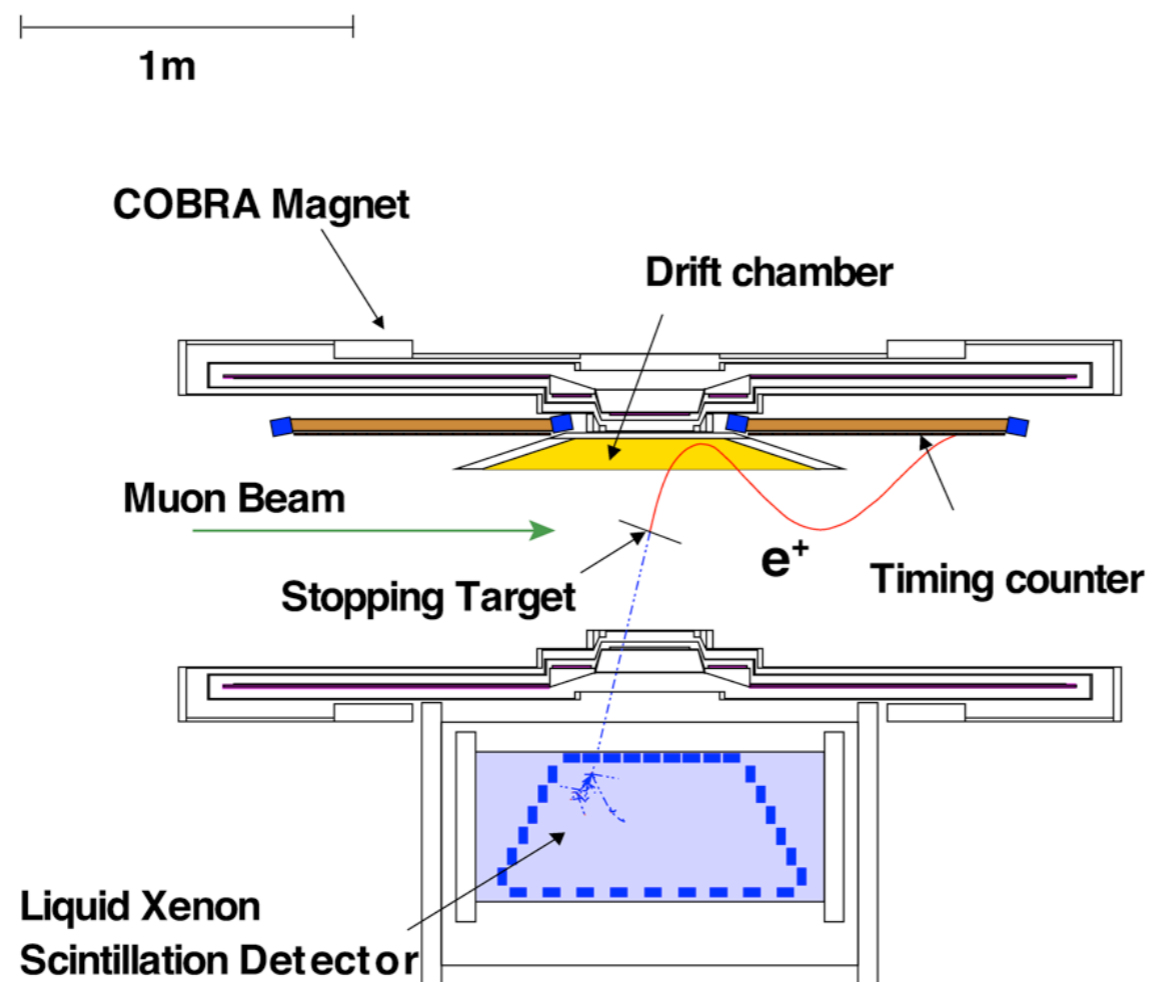
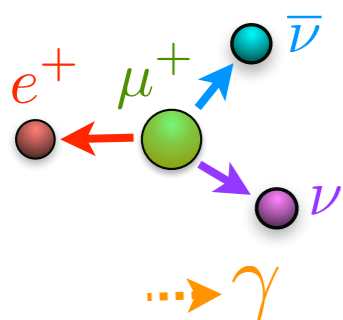
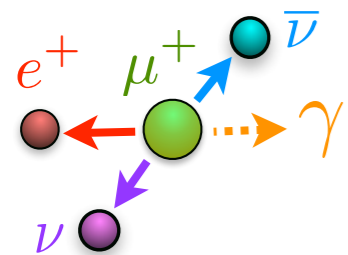
MEG: Signature and experimental setup

- 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_γ , E_e , t_{eg} , ϑ_{eg} , ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events

Signature



Backgrounds



MEG: The result

Since
March 8th 2016

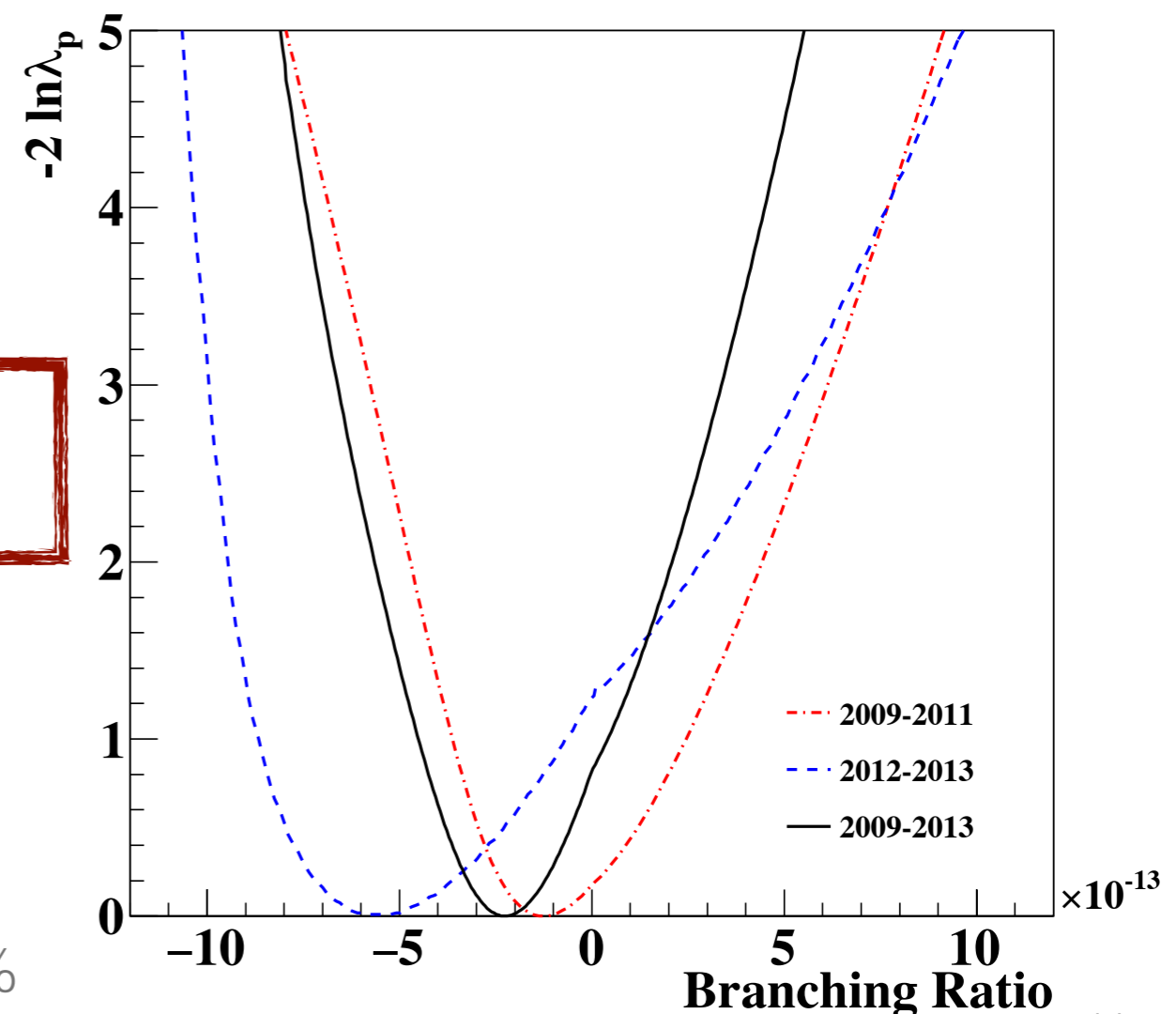
- Confidence interval calculated with Feldman & Cousins approach with profile likelihood ratio ordering
- Profile likelihood ratios as a function of the BR: all consistent with a null-signal hypothesis

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

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

From MEGA to MEG:
improvement by a factor ~ 30

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



How the sensitivity can be pushed down?

- More sensitive to the **signal**...

high statistics

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

Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

- More effective on rejecting the **background**...

high resolutions

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

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

The MEGII experiment

New electronics:
Wavedream

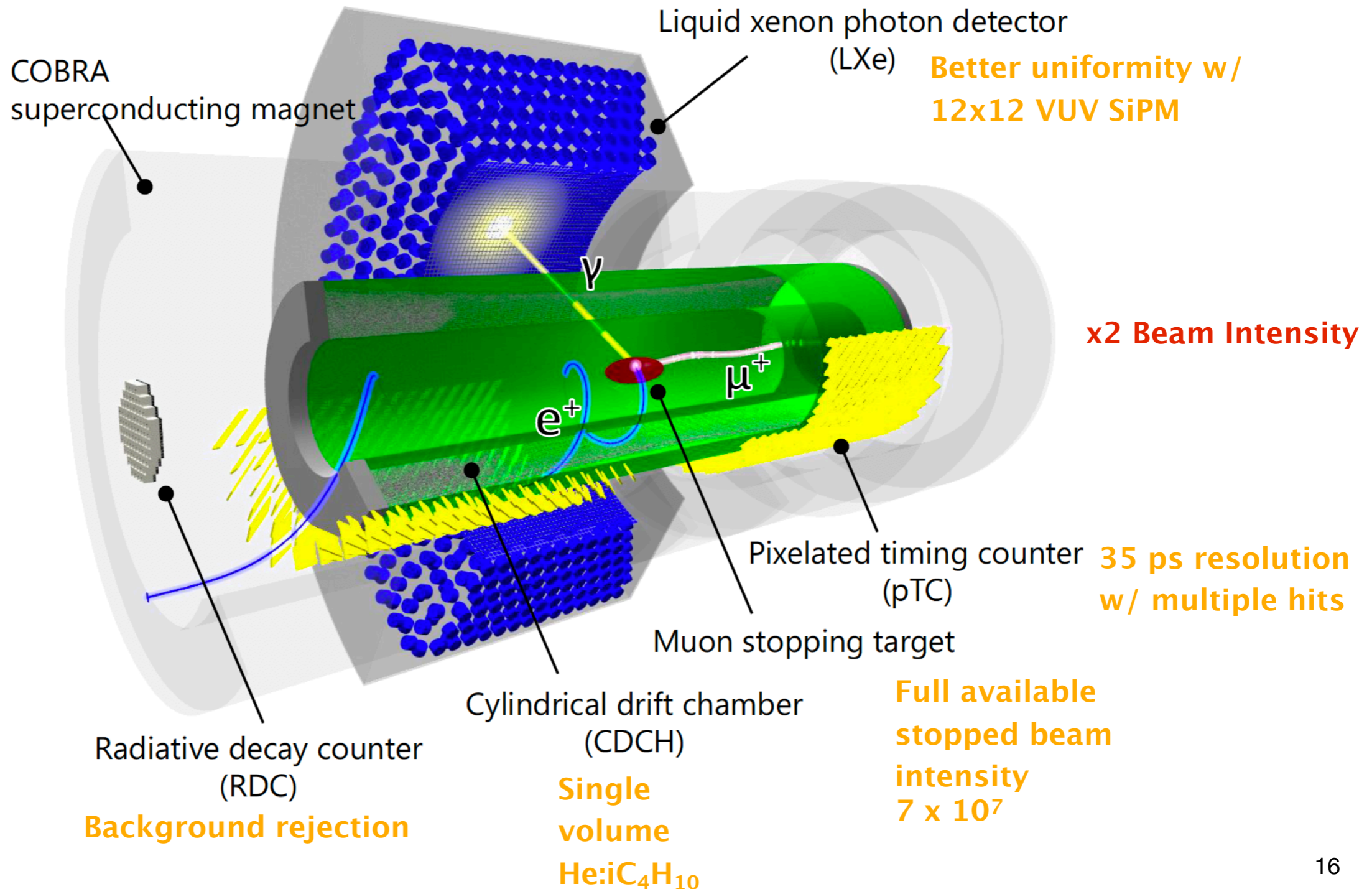
~9000
channels
at 5GSPS

x2 Resolution
everywhere

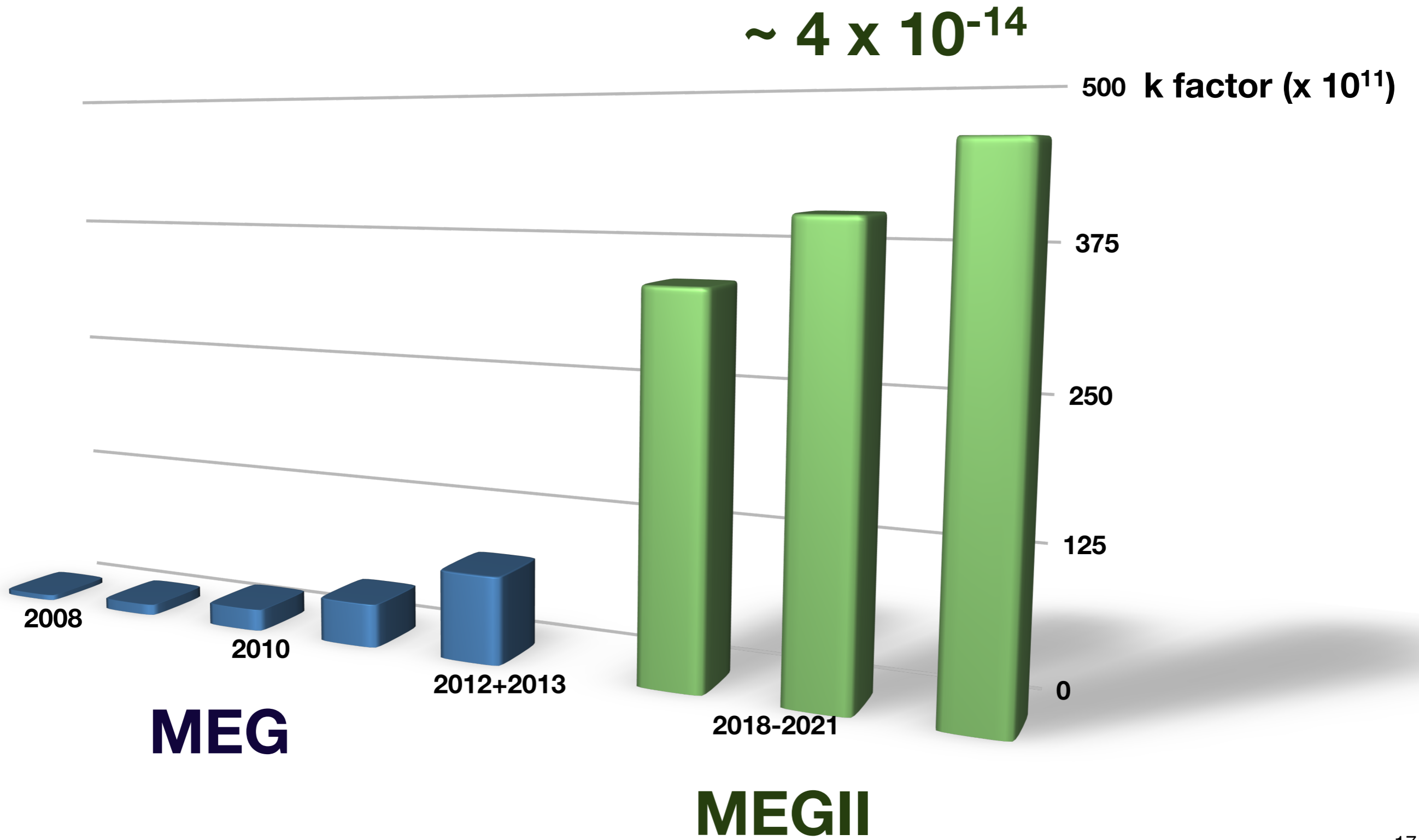
Updated and
new Calibration
methods

Quasi mono-
chromatic
positron beam

Background rejection

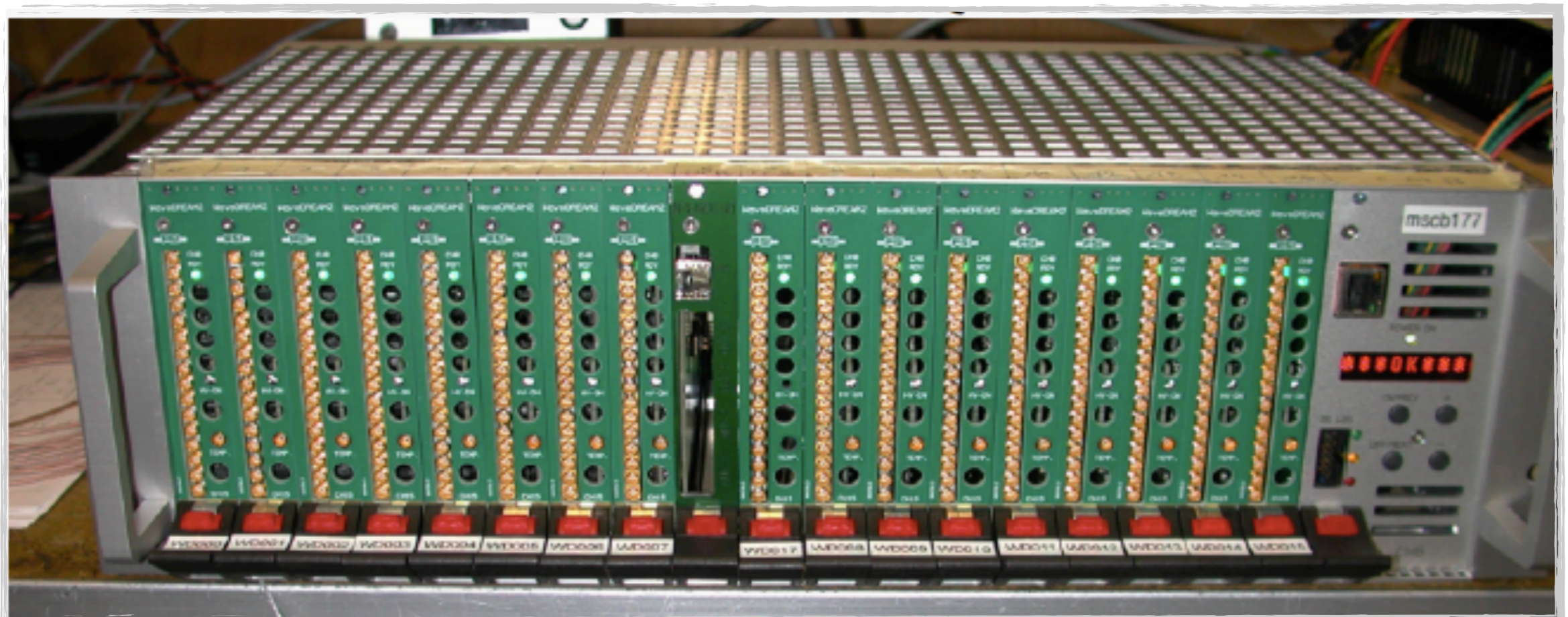


Where we will be



MEGII: The new electronic - DAQ and Trigger

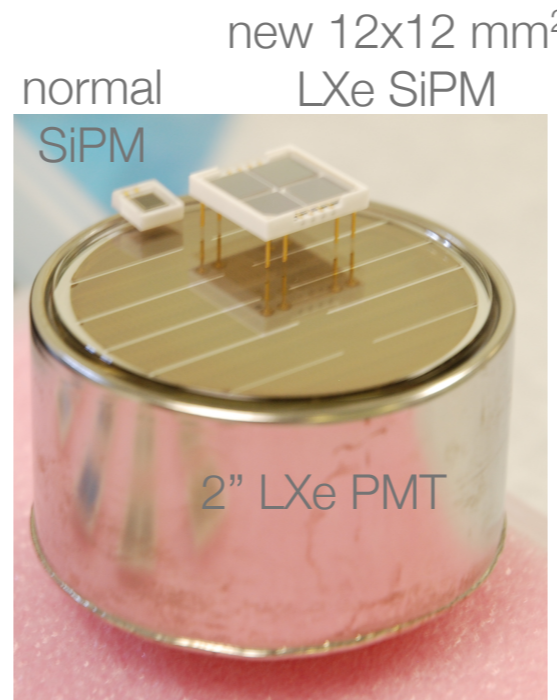
- DAQ and Trigger
 - ~9000 channels (5 GSPS)
 - Bias voltage, preamplifiers and shaping included for SiPMs
- 256 channels (1 crate) abundant tested during the 2016 pre-engineering run; >1000 channels available for the incoming 2017 pre-engineering run
- Trigger electronics and several trigger algorithms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



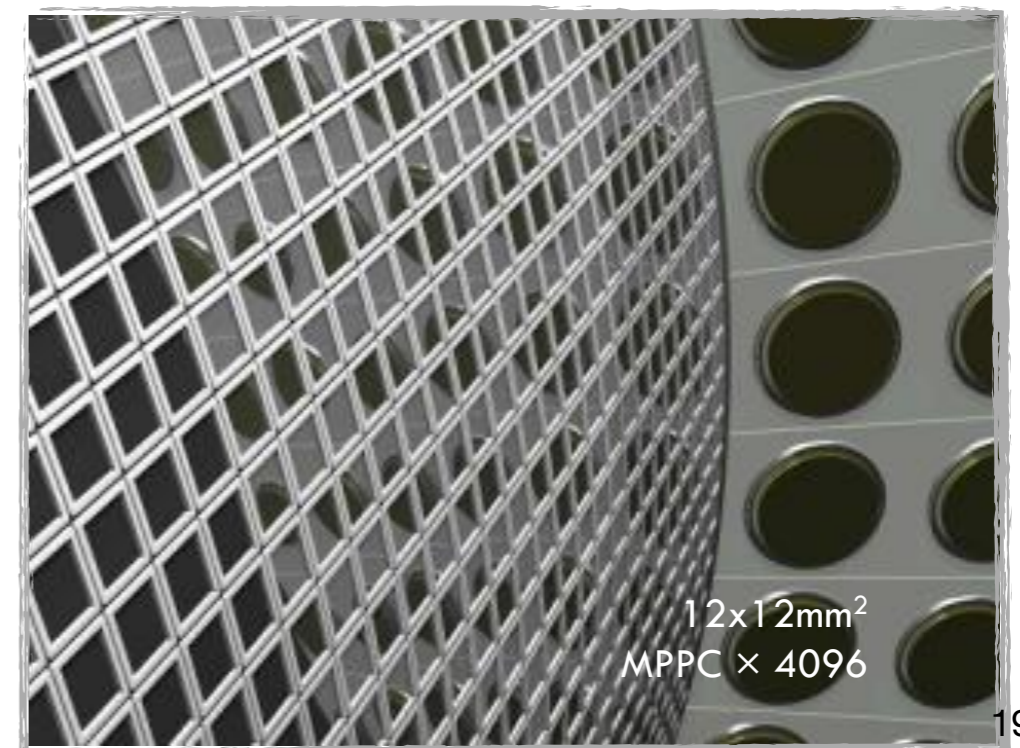
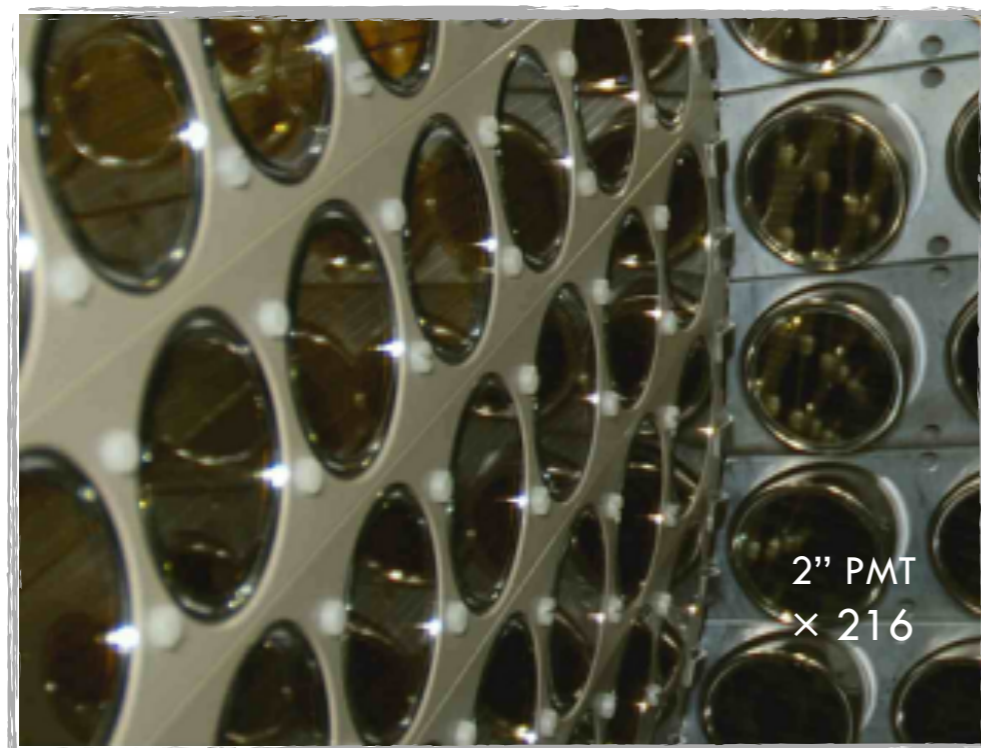
MEGII: The upgraded LXe calorimeter

- 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



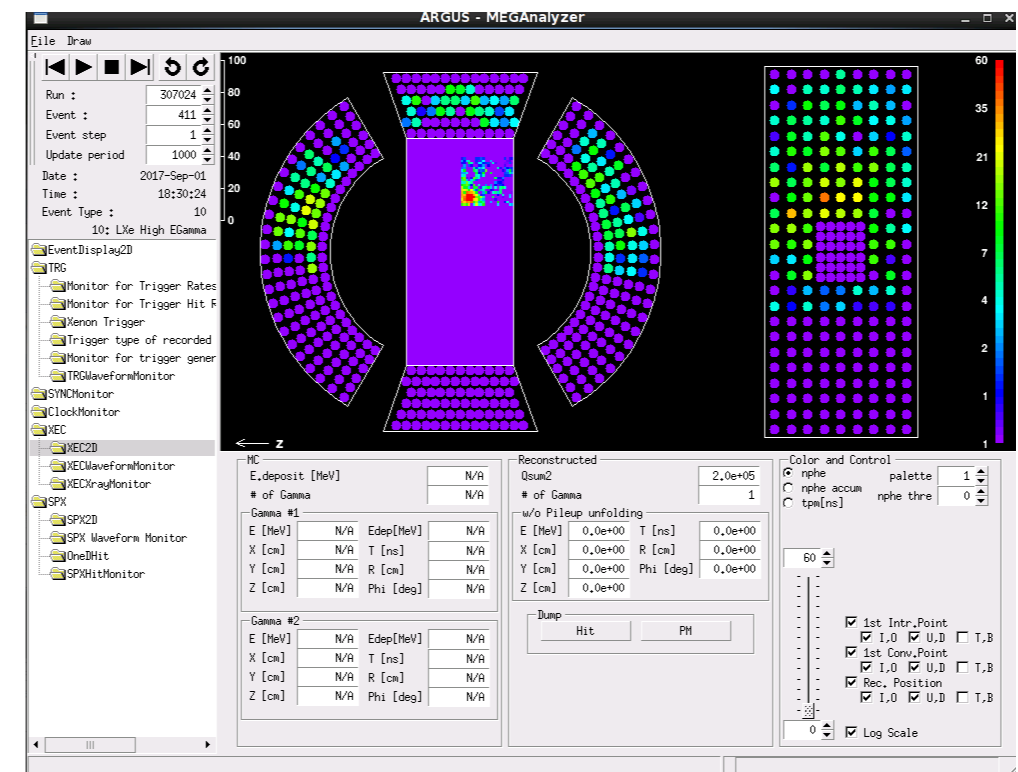
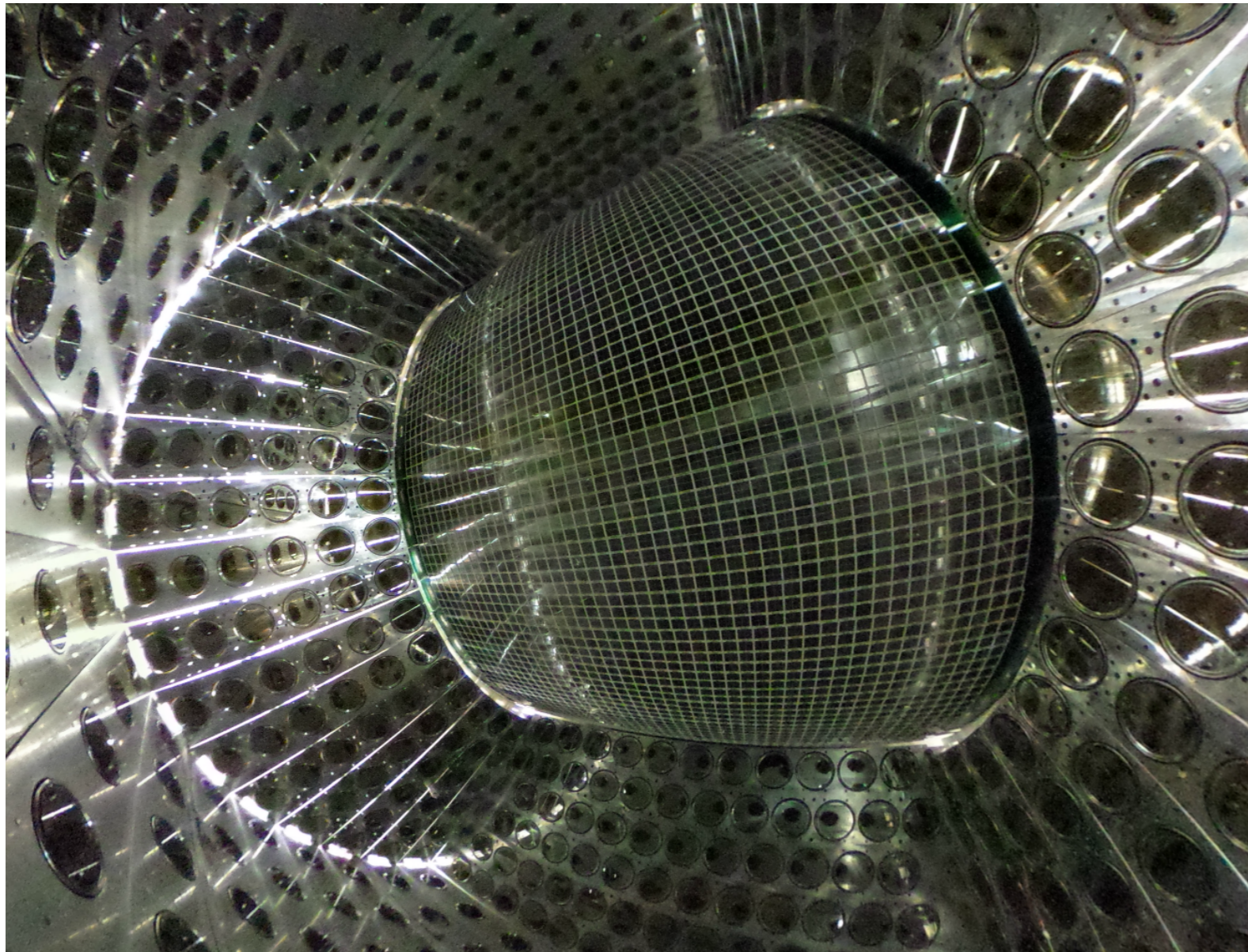
	MEG	MEGII
u [mm]	5	2.4
v [mm]	5	2.2
w [mm]	6	3.1
E [w<2cm]	2.4%	1.1%
E [w>2cm]	1.7%	1.0%
t [ps]	67	60



MEGII: The upgraded LXe calorimeter

Detector commissioning started !

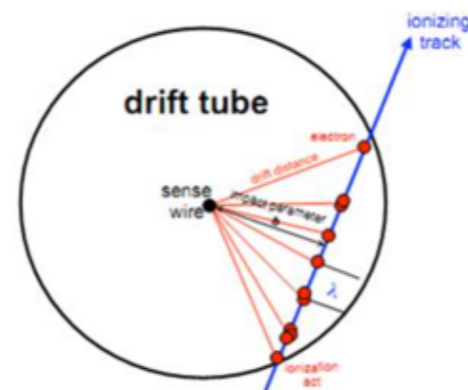
New



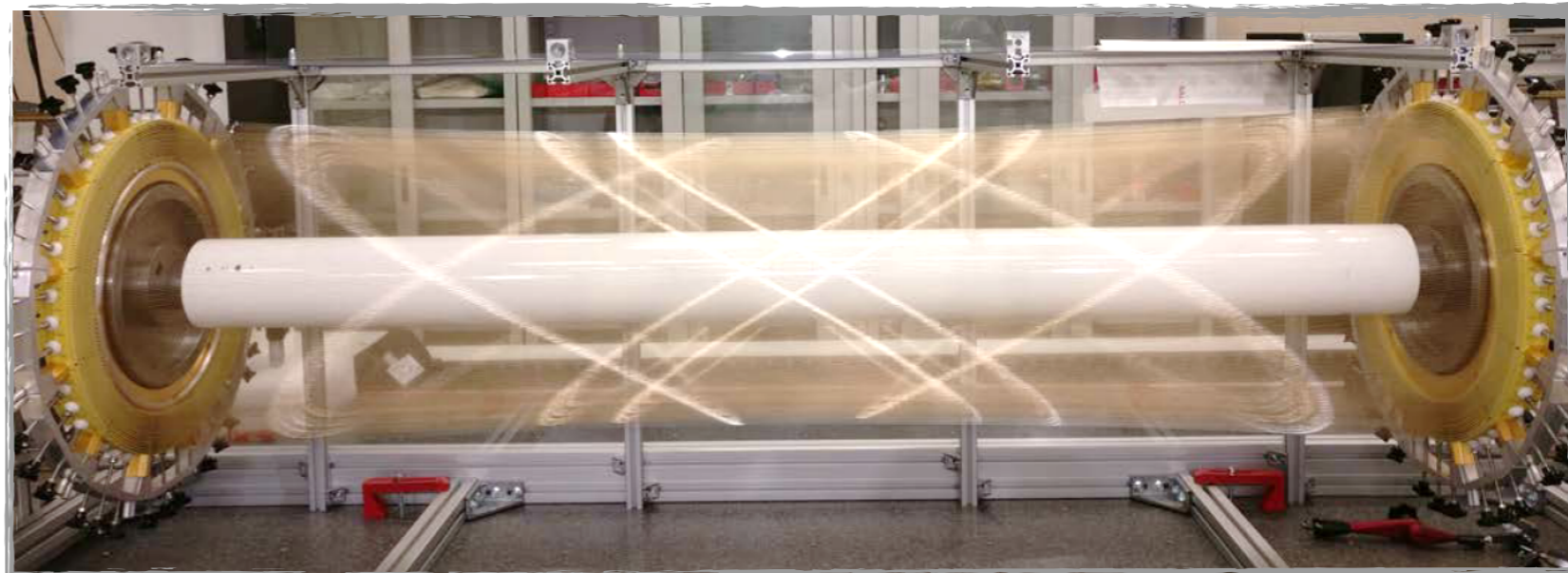
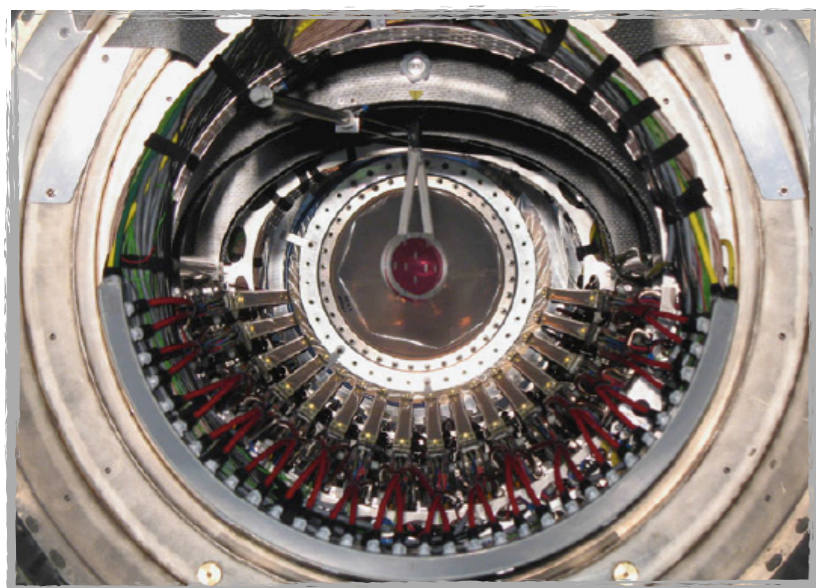
MEGII: The new single volume chamber

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

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



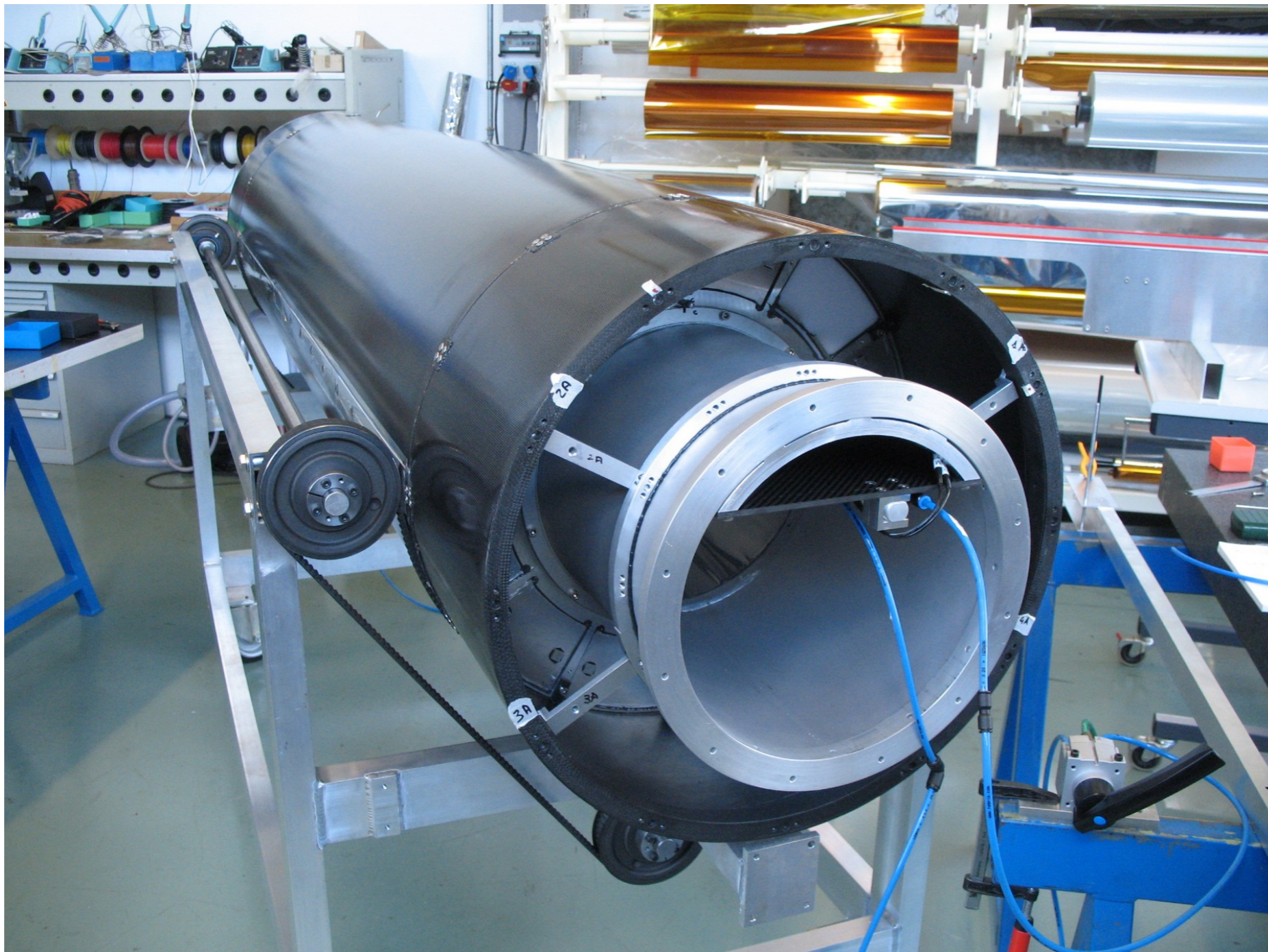
(*) It includes also the matching with the Timing Counter



MEGII: The new single volume chamber

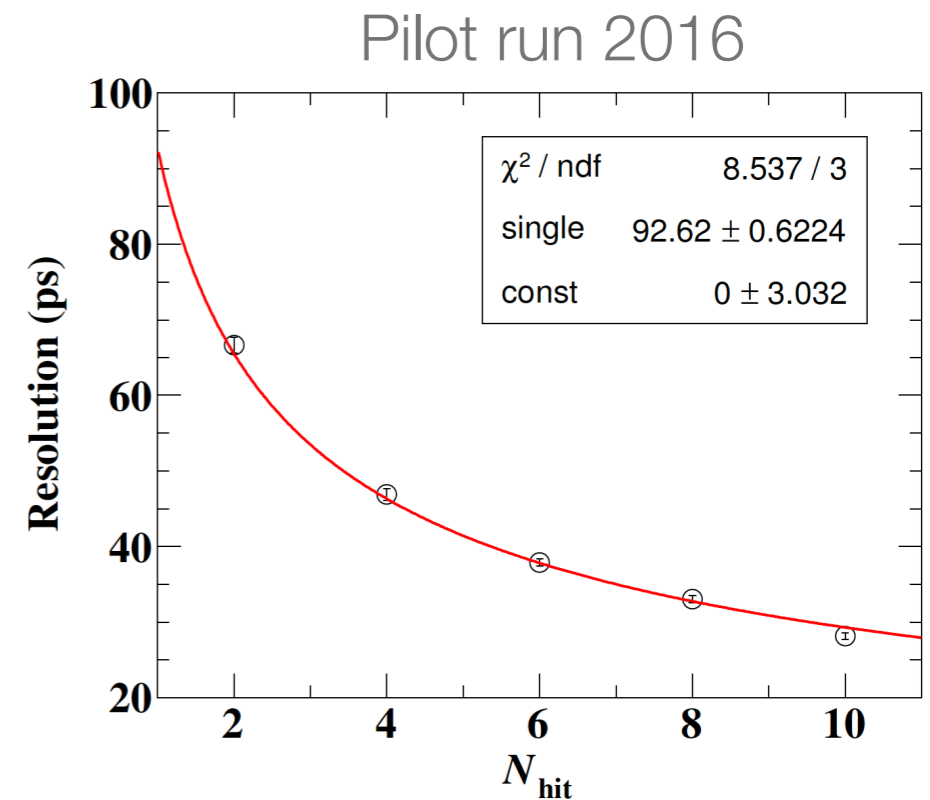
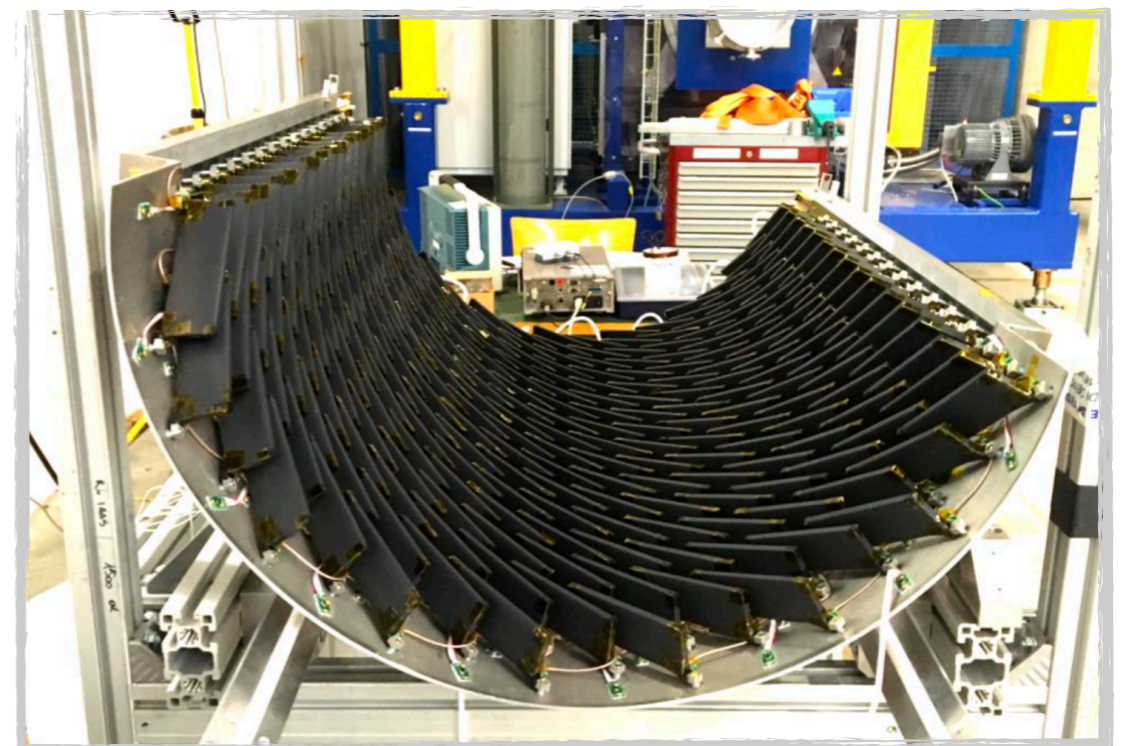
DCH Mock-up Ready!

New



MEGII: the pixelized Timing Counter

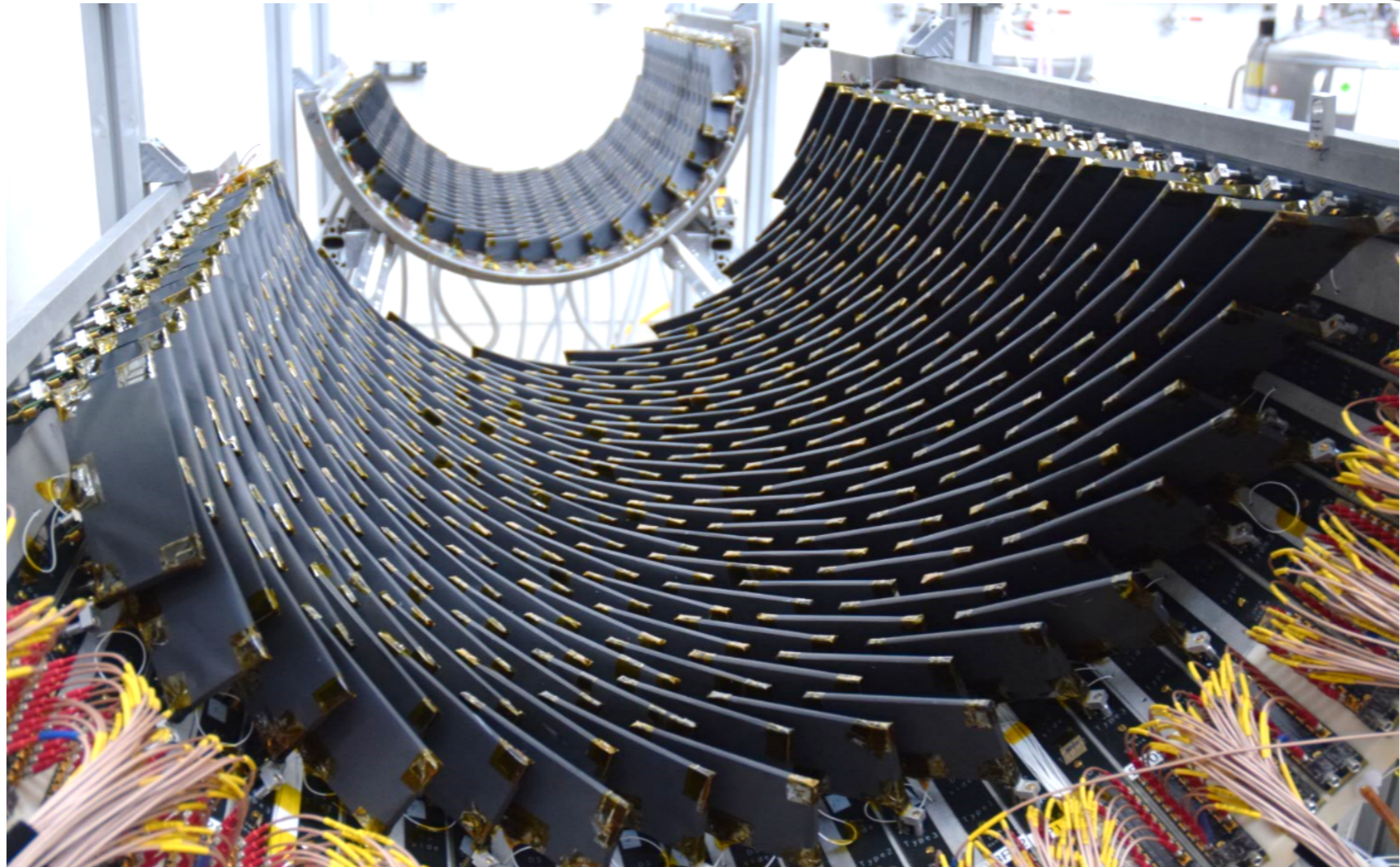
- Higher granularity: 2 x 256 of BC422 scintillator plates (120 x 40 (or 50) x 5 mm³) readout by AdvanSiD SiPM ASD-NUM3S-P-50-High-Gain
- Improved timing resolution: from 70 ps to 35 ps (multi-hits)
- Less multiple scattering and pile-up
- Assembly: Completed **New**
- Expected detector performances confirmed with data



MEGII: the pixelized Timing Counter

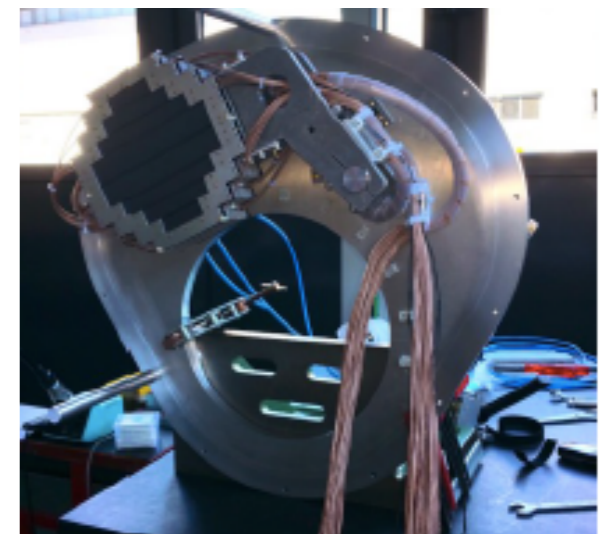
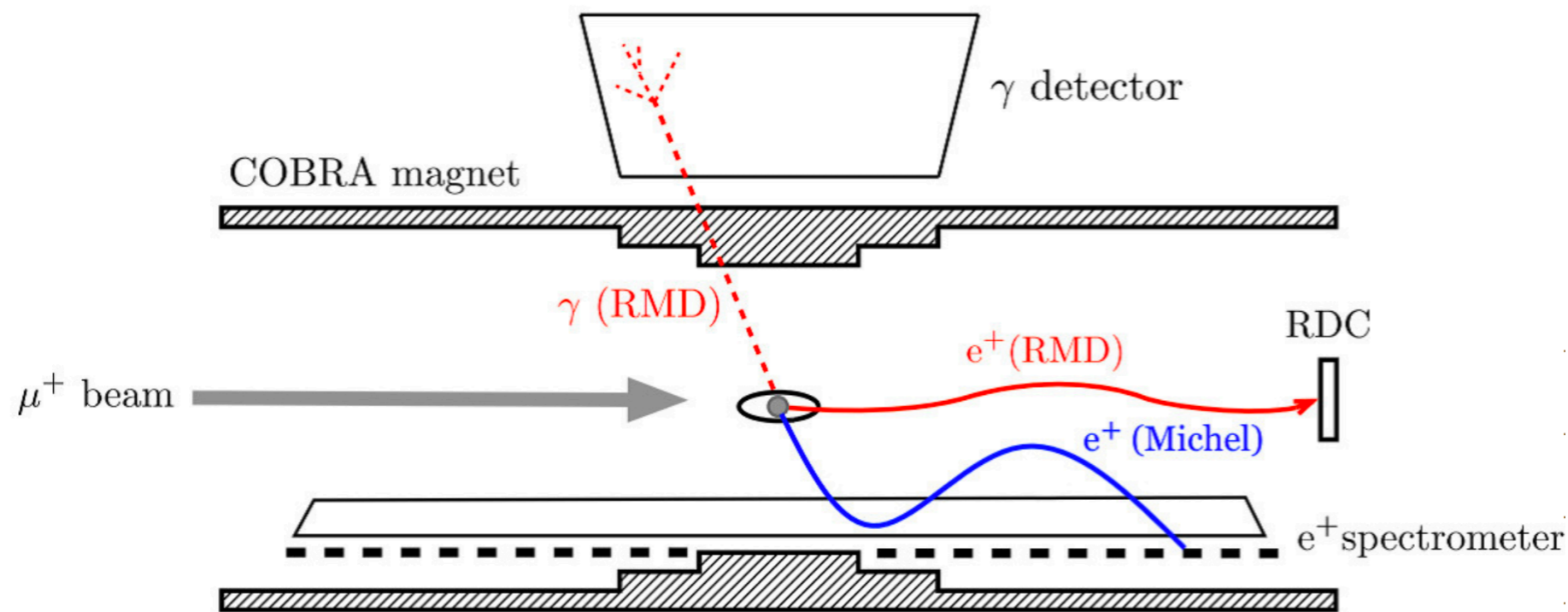
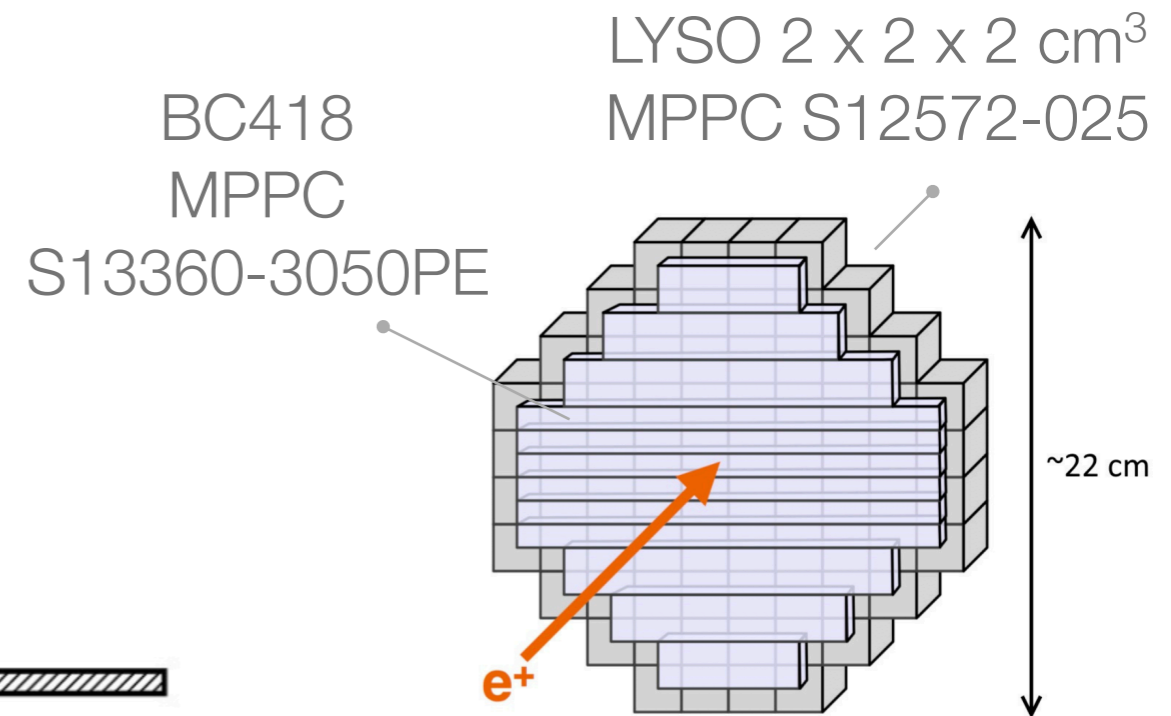
Ready to be inserted inside Cobra !

New



MEGII: The Radiative Decay Counter

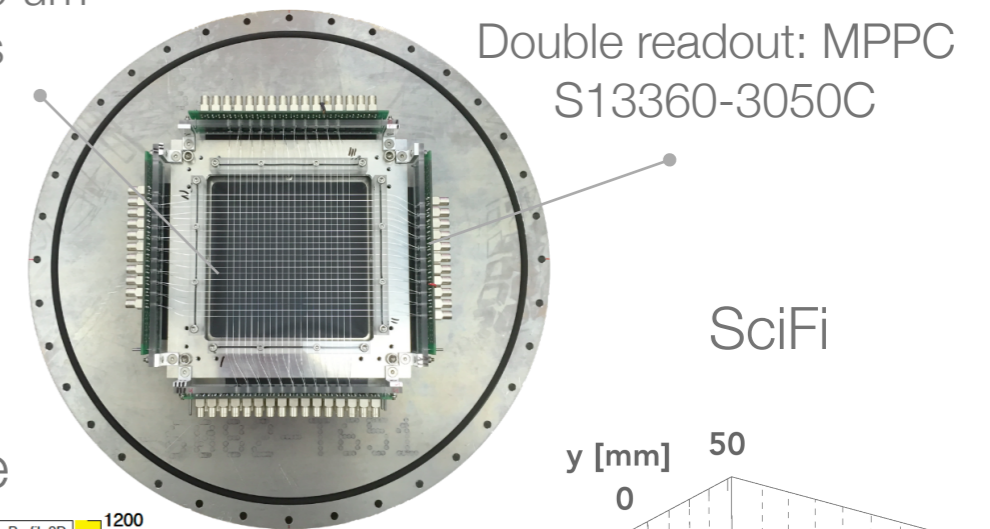
- Added a new auxiliary detector for background rejection purpose. Impact into the experiment: Improved sensitivity by 20%
- Commissioning during the 2016 pre-engineering run
- Status: Ready



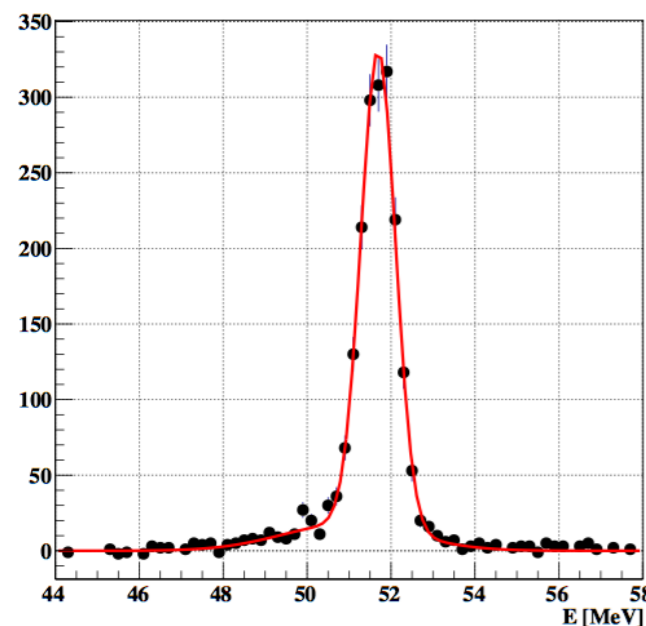
MEGII: new calibration methods and upgrades

- 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 μm^2
scintillating fibers



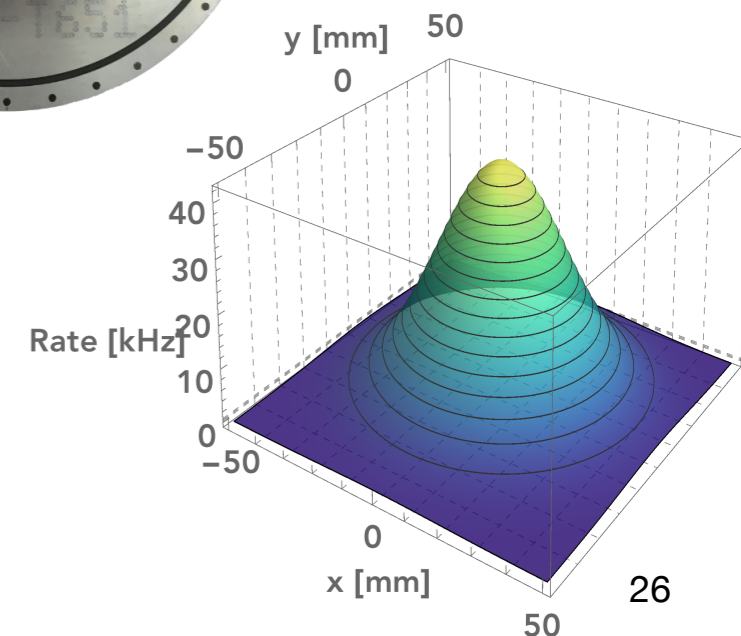
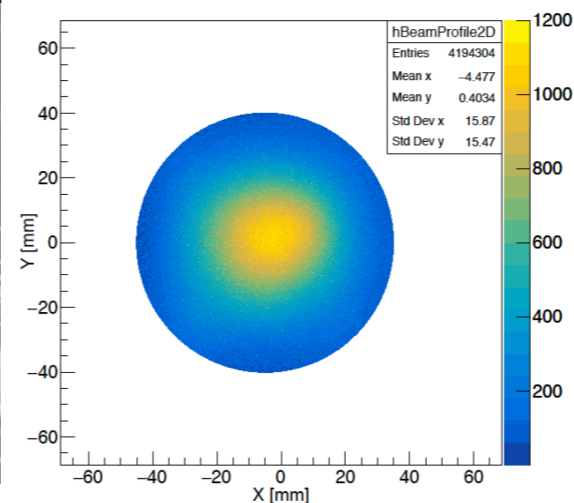
Monochromatic e-line



pTC's laser



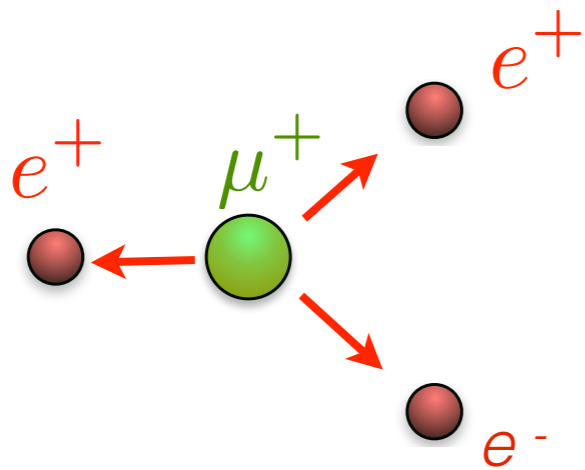
Luminophore



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

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-15}$ (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)
- Observables (E_e , t_e , **vertex**) to characterize $\mu \rightarrow eee$ events

Signature

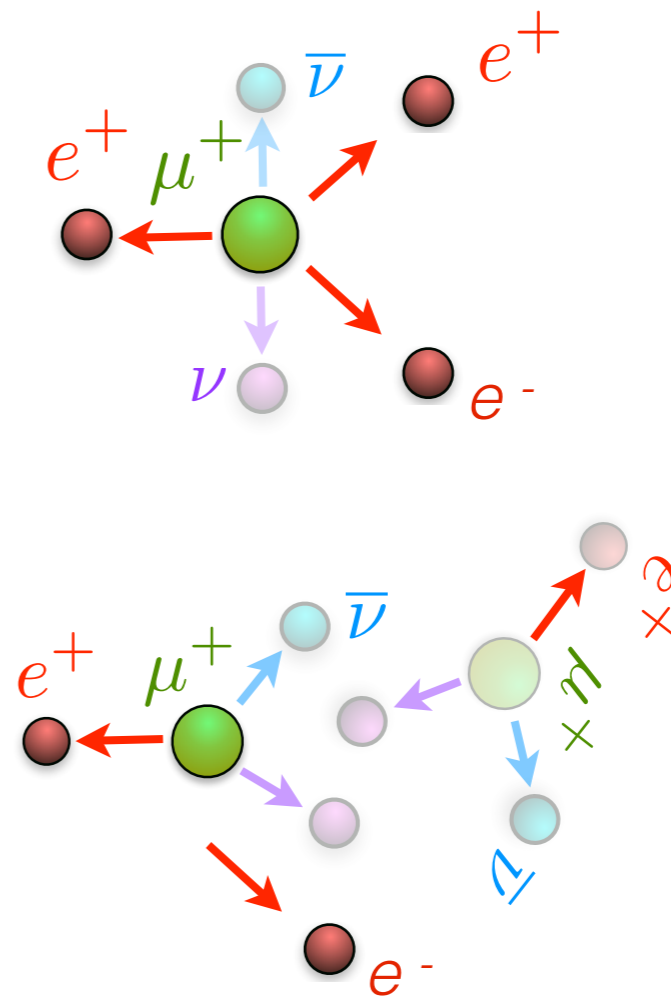


$$\Delta t_{eee} = 0$$

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

$$\Sigma E_e = m_\mu$$

Background



Mu3e: Requirements

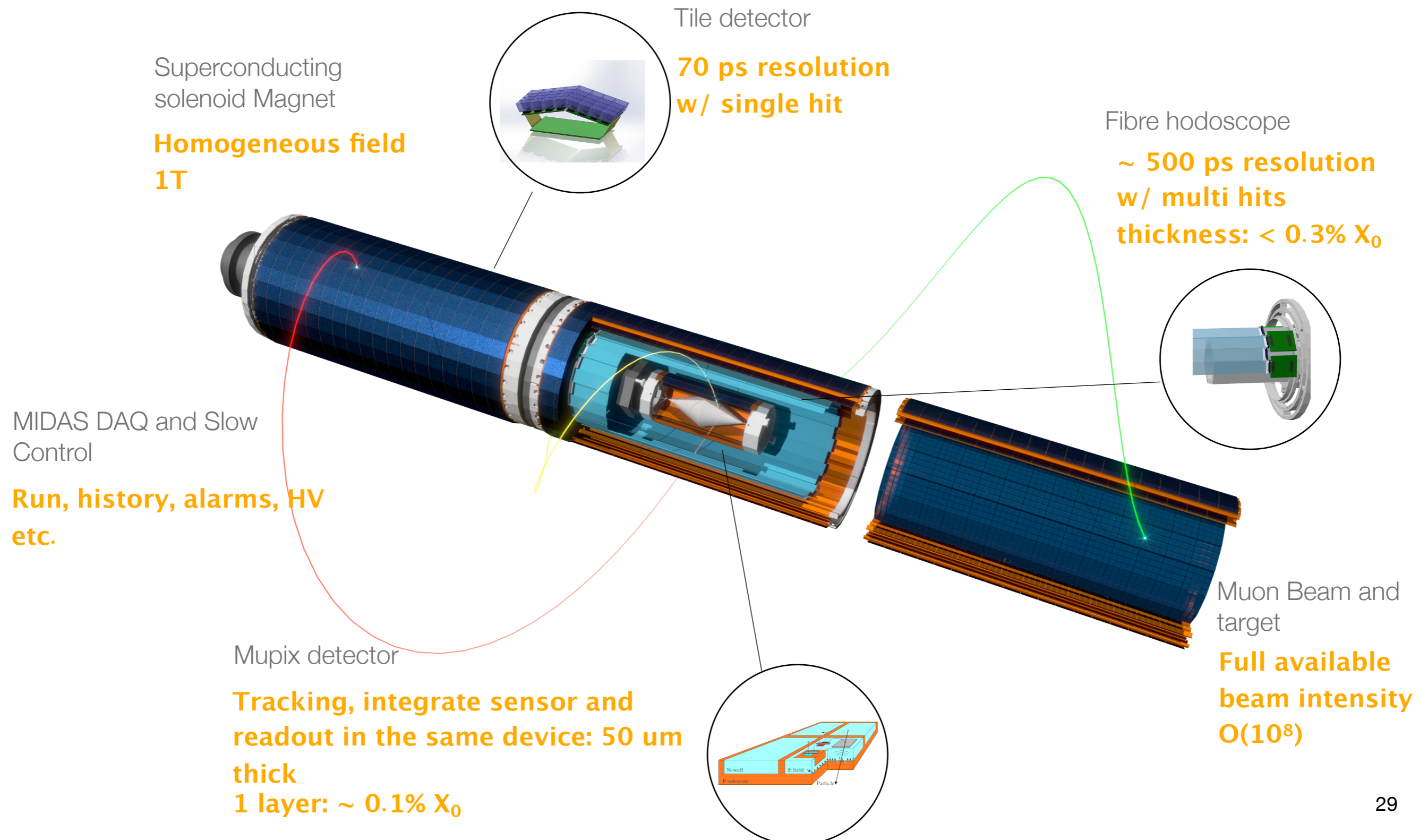
Signal

1. $\mu \rightarrow eee$
 - Rare decay search: Intense muon beam $O(10^8 \text{ muon/s})$ 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

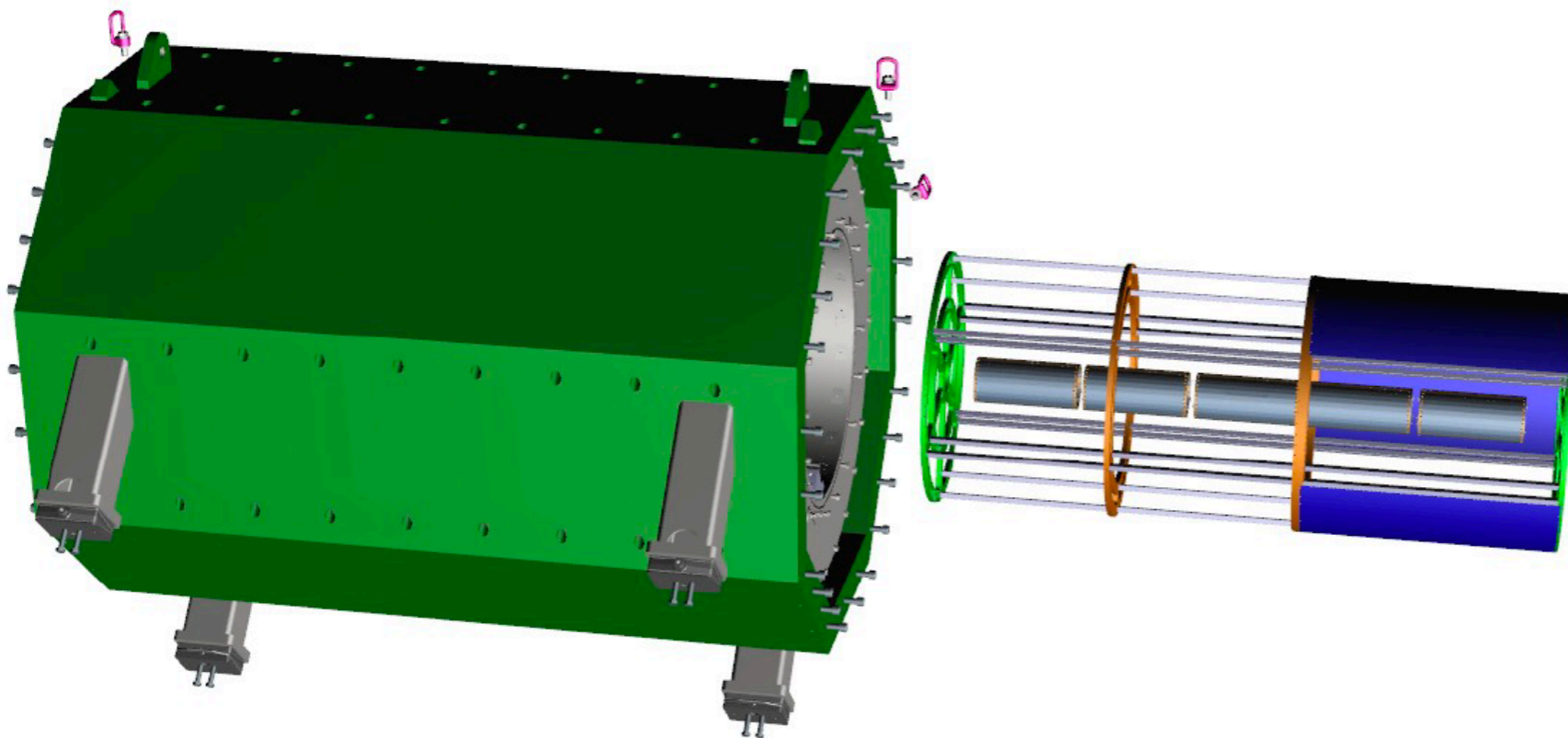
1. $\mu \rightarrow eee\nu\nu$
 - Missing energy: Excellent momentum resolution
2. $\mu \rightarrow e\nu\nu, \mu \rightarrow e\nu\nu, e^+e^-$
 - Coincidence and vertex: High timing and position resolutions

The Mu3e experiment: Schematic 3D

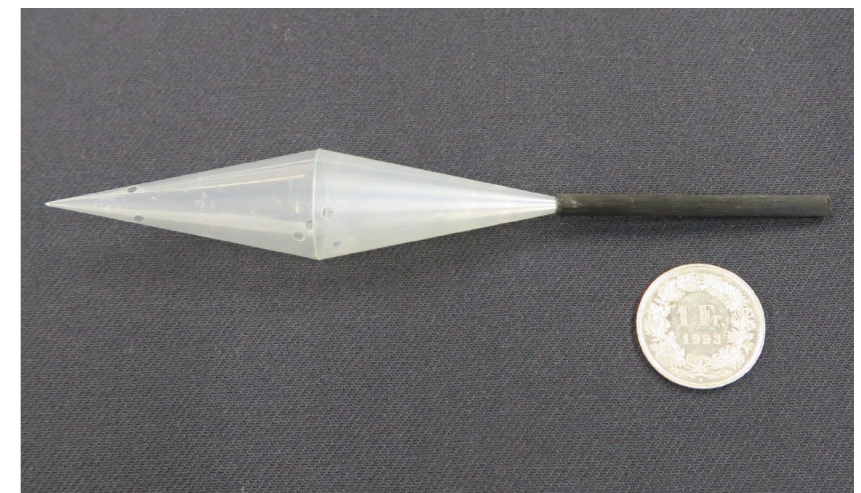


Target and magnet: Status

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

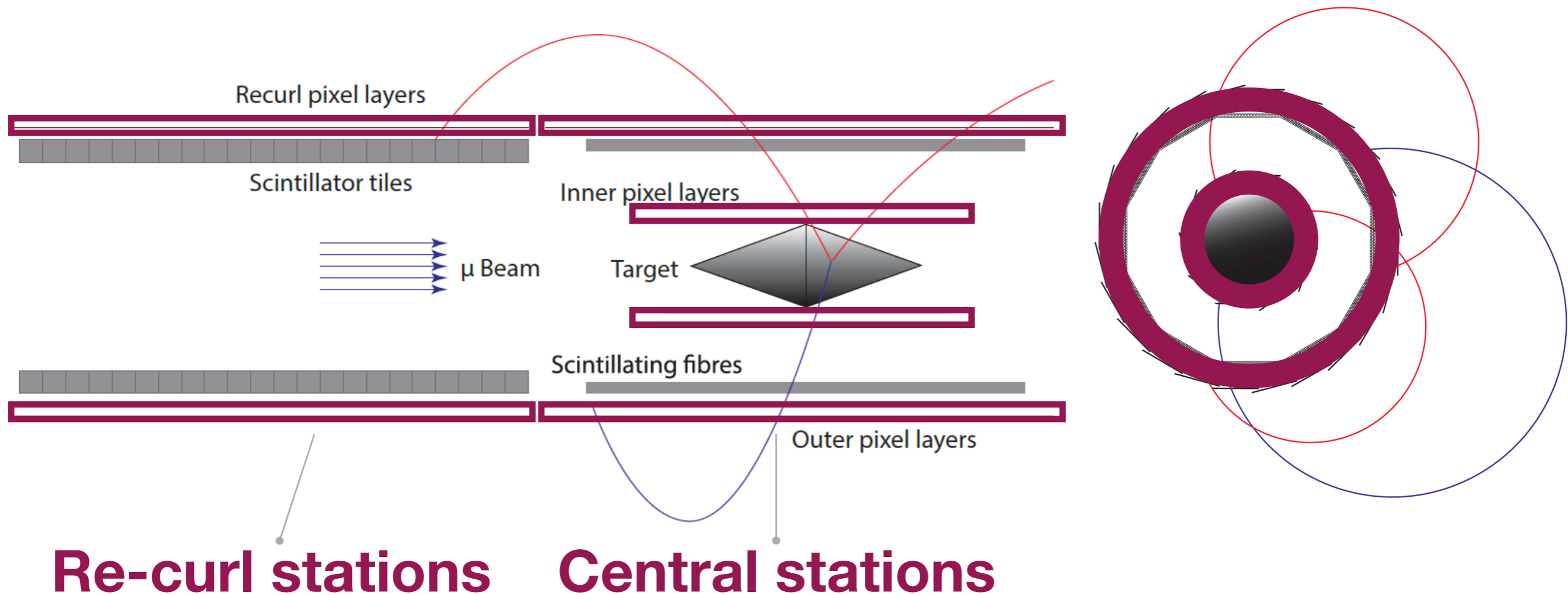


Target prototype



The pixel tracker: Overview

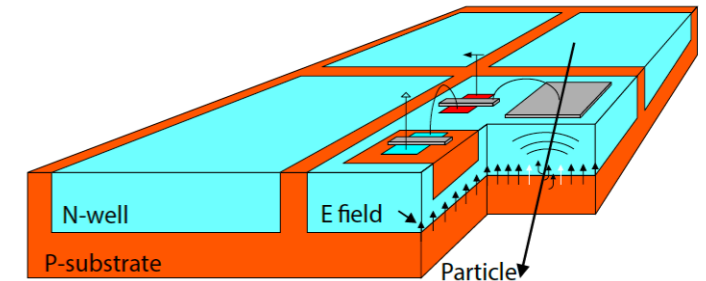
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime
- Momentum resolution: $< 0.5 \text{ MeV}/c$ over a large phase space; Geometrical acceptance: $\sim 70\%$; X/X_0 per layer: $\sim 0.011\%$



The pixel tracker: The MuPix prototypes

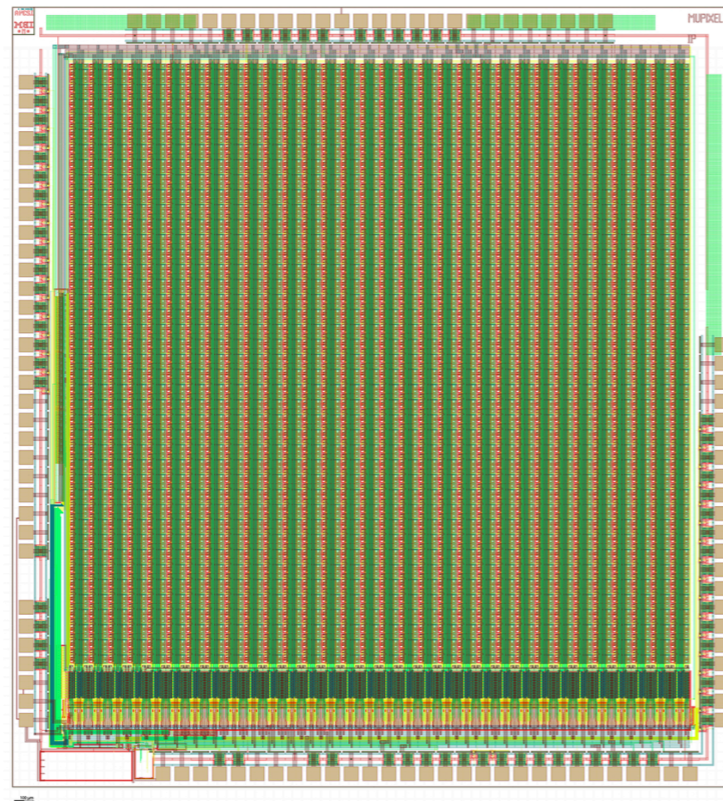
Ivan Peric, Nucl.Instrum.Meth. A582 (2007) 876-885

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

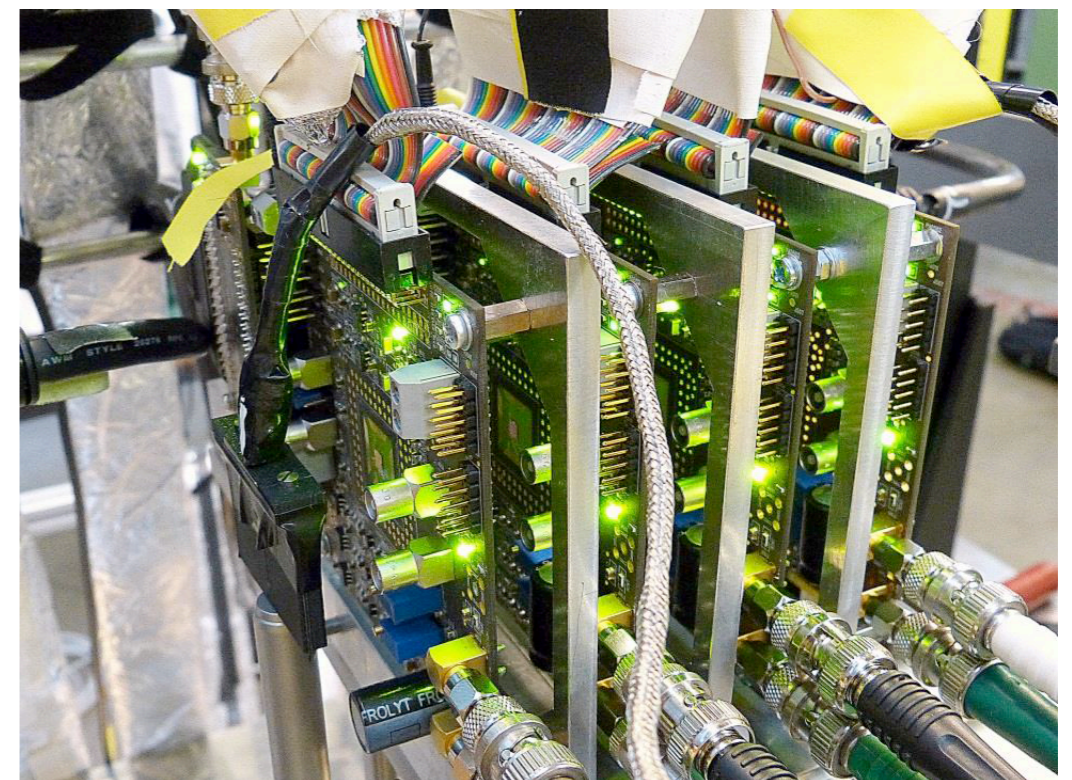


Prototype	Active Area [mm ²]
MuPix1	1.77
MuPix2	1.77
MuPix3	9.42
MuPix4	9.42
MuPix6	10.55
MuPix7	10.55

MuPix7



Extensively tested along beams



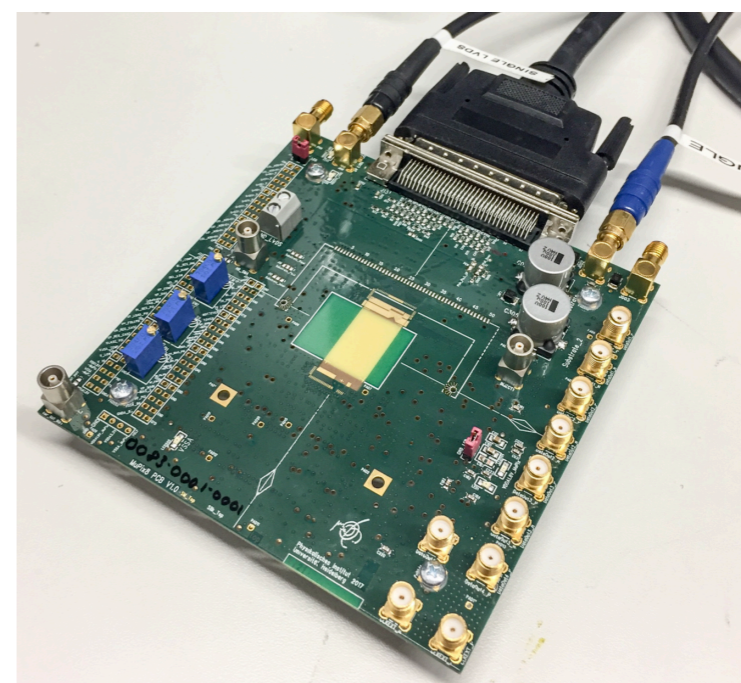
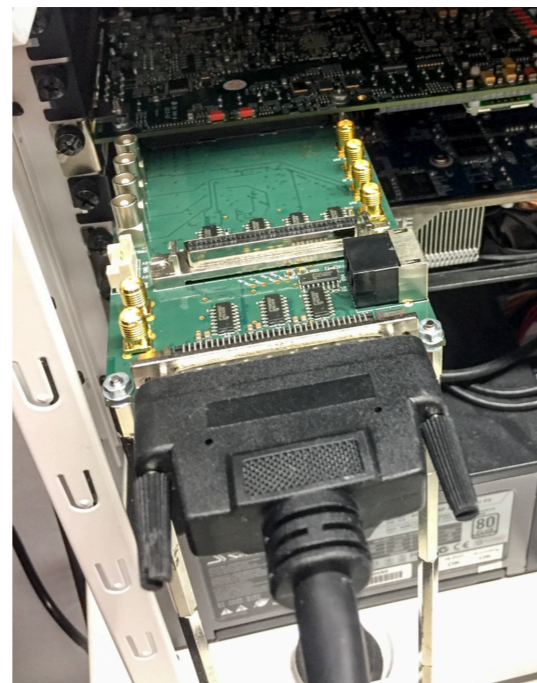
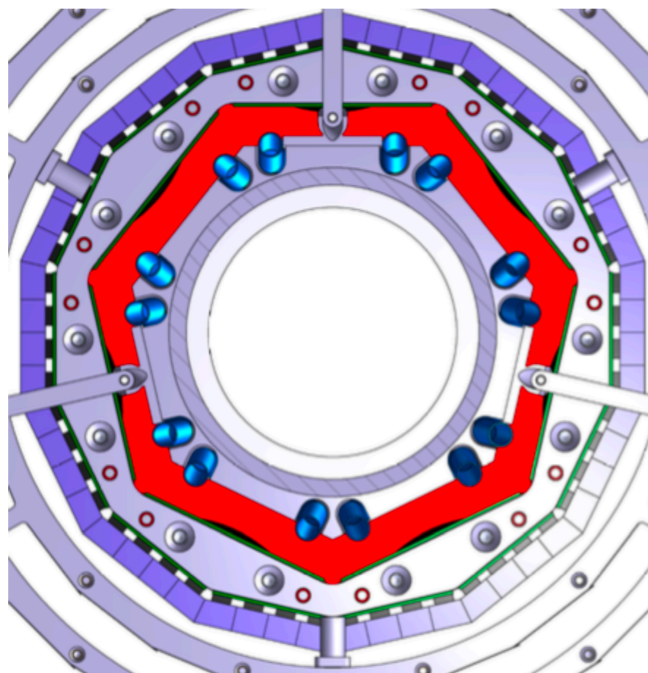
The pixel tracker: Current and future plan

- After an extensive test beam campaign, achieved milestones
 - A fully functional HV-MAPS chip, $3 \times 3 \text{ mm}^2$. 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 $O(10) \text{ mm}^2$ to 160 mm^2 : Ready !
 - 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

New

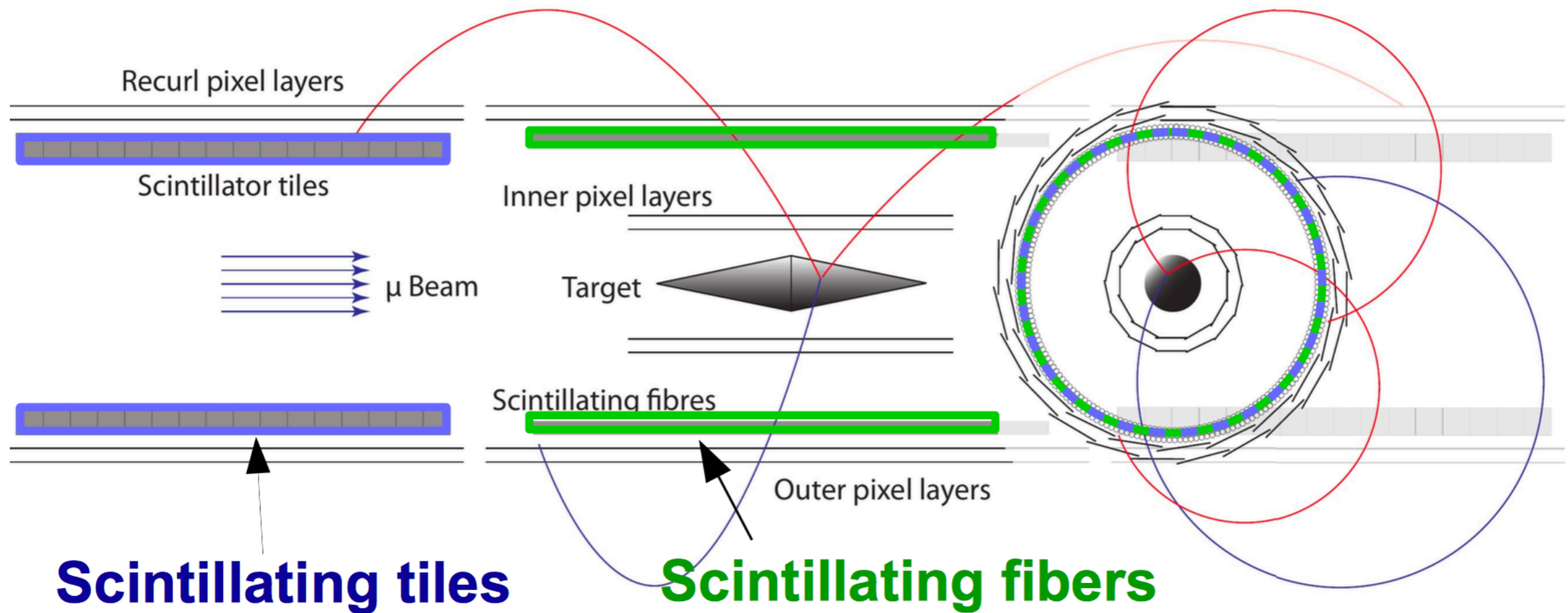
MuPix8

New



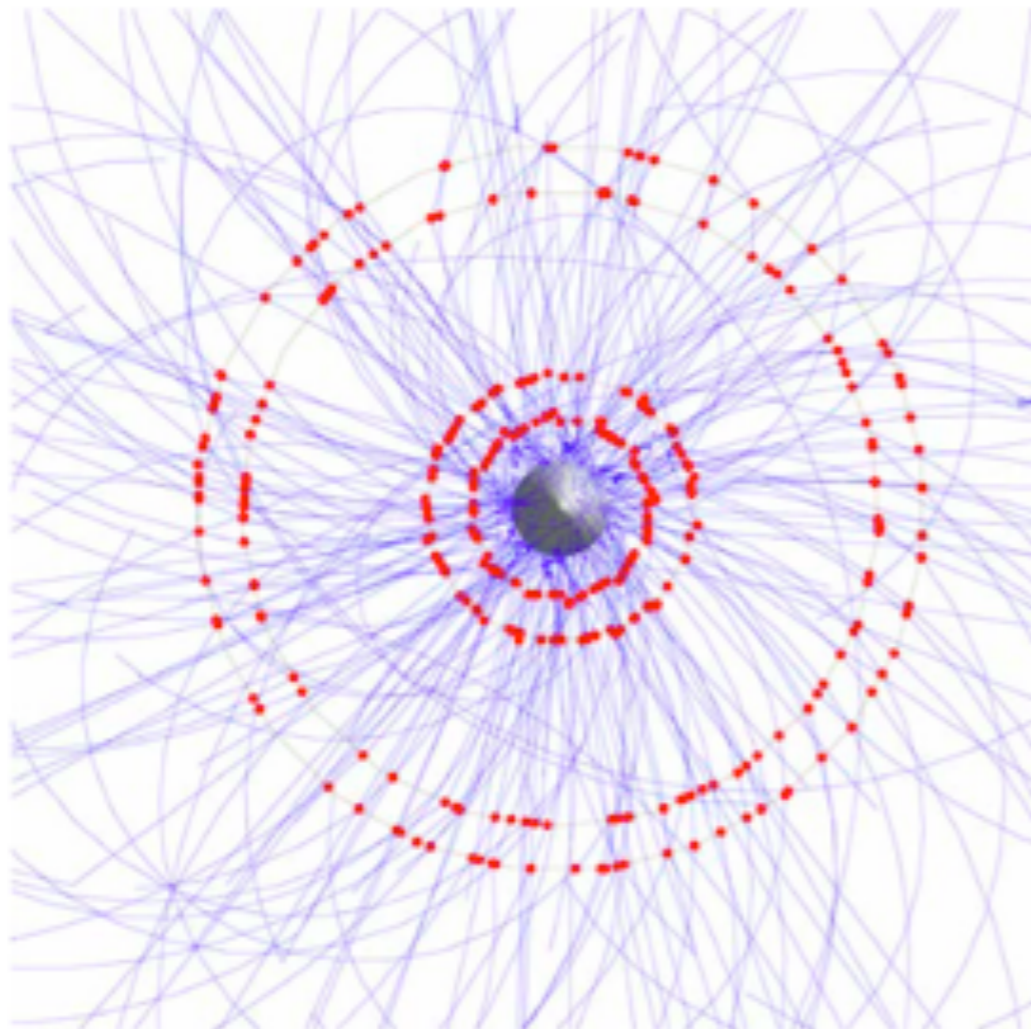
The timing detectors: Fibers and tiles

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

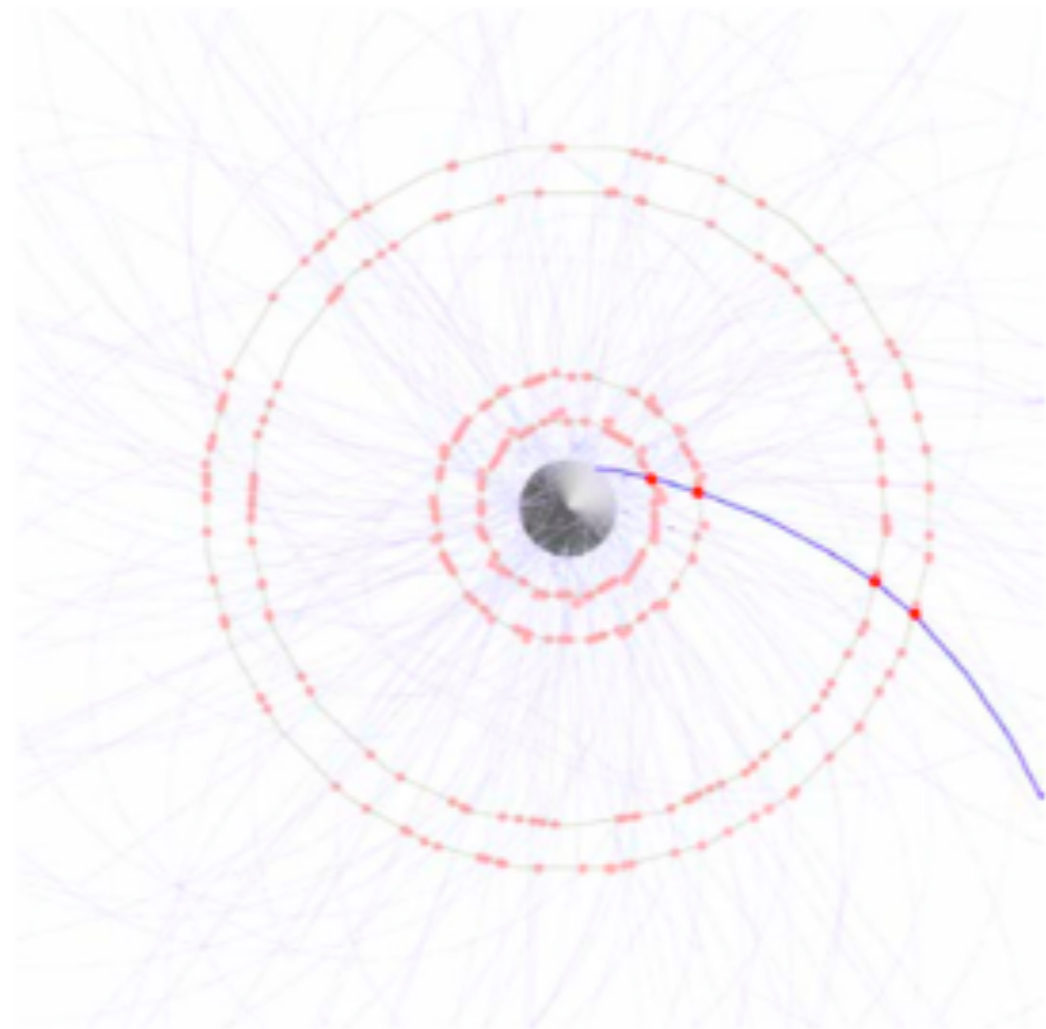


The timing detectors: Fibers and tiles

- Precise timing measurement: Critical to reduce the accidental BGs
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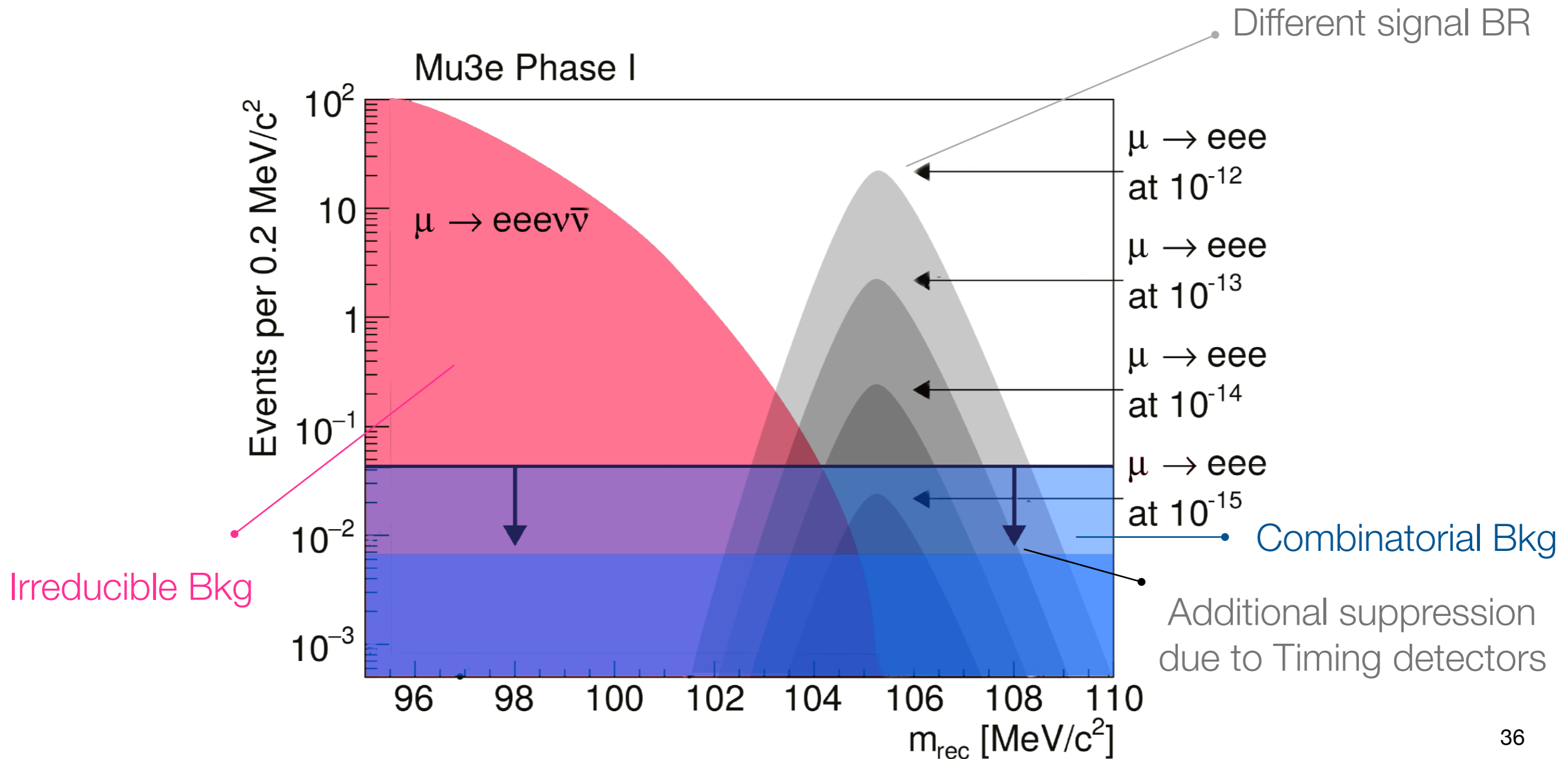
Pixels: $O(50 \text{ ns})$



Scintillating fibres $O(1 \text{ ns})$;
Scintillating tiles $O(100 \text{ ps})$

The timing detectors: Impact

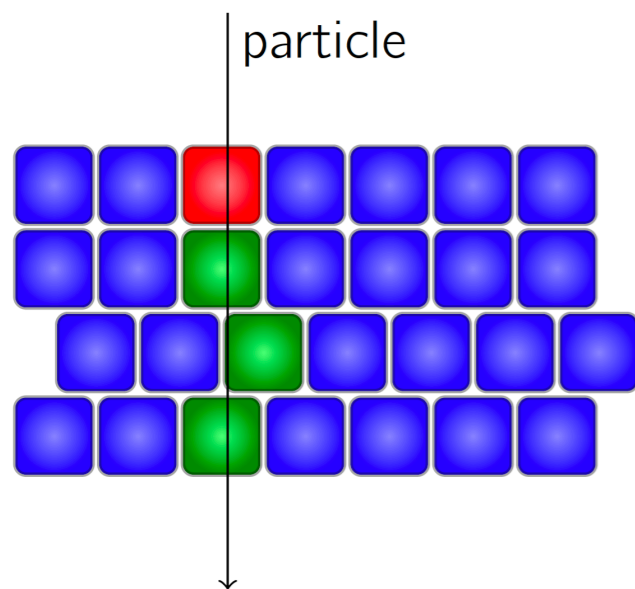
- Precise timing measurement: Critical to reduce the accidental BGs
 - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
 - Scintillating tiles O(100 ps), full detection efficiency (>99%)



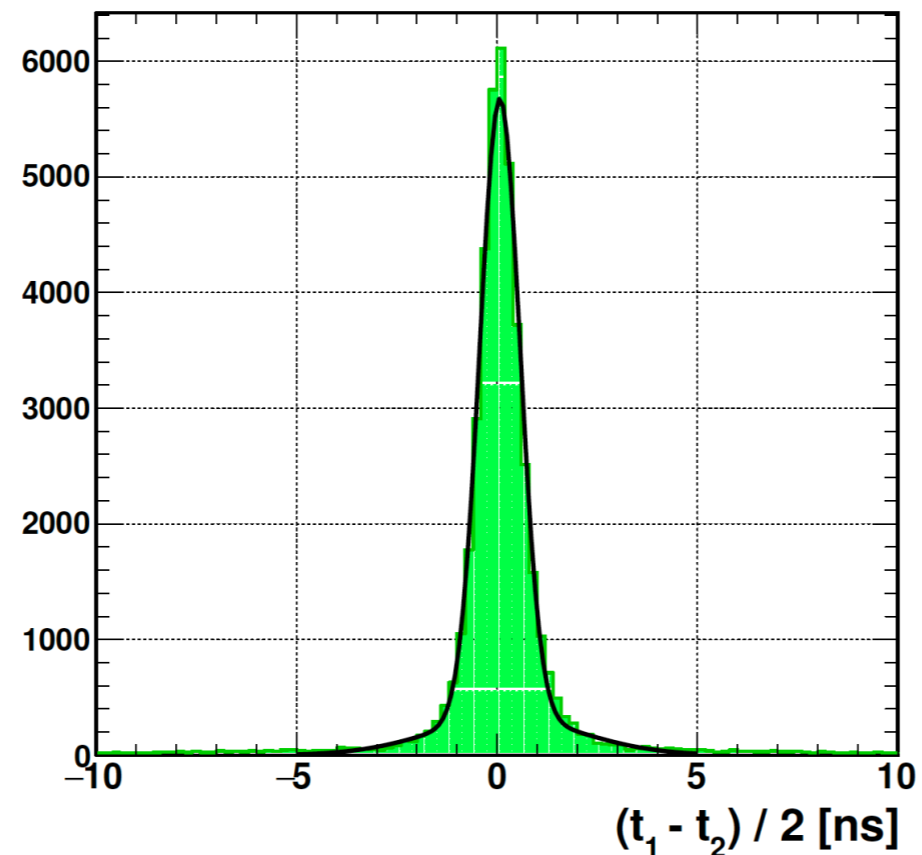
SciFi prototypes: Results

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

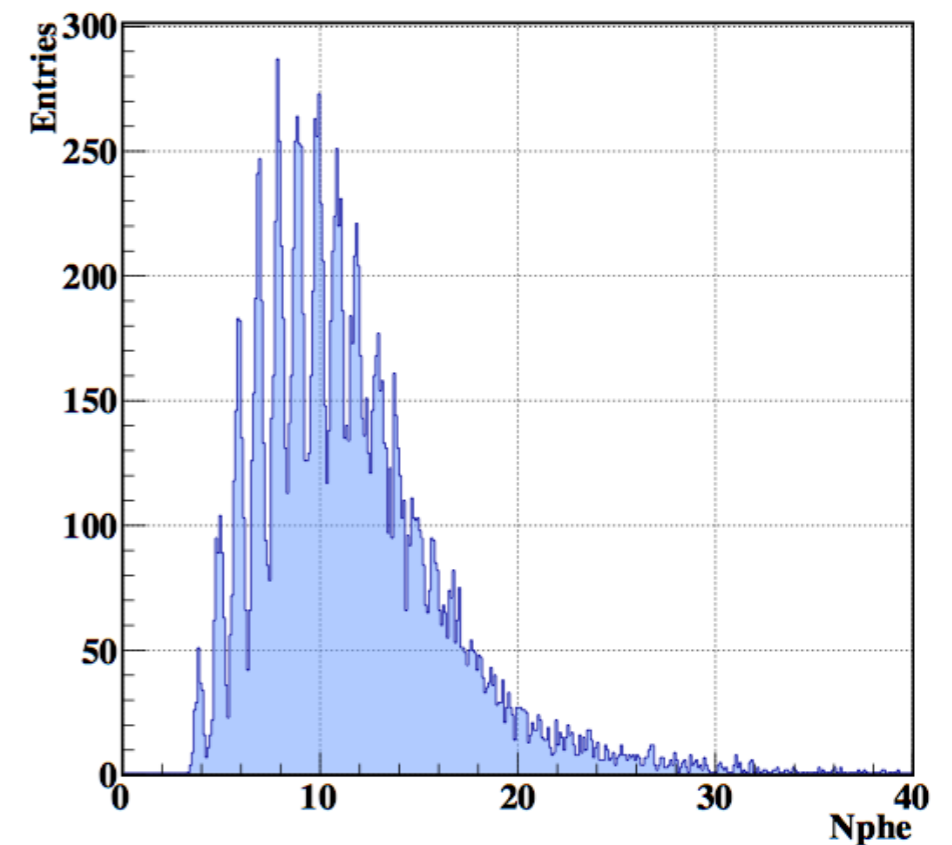
Trigger
offline selection:
hits in 3 layers



3 layer time resolution $O(550)$ ps



3 layer offline array charge collection (thr $> 1.5 N_{phe}$)

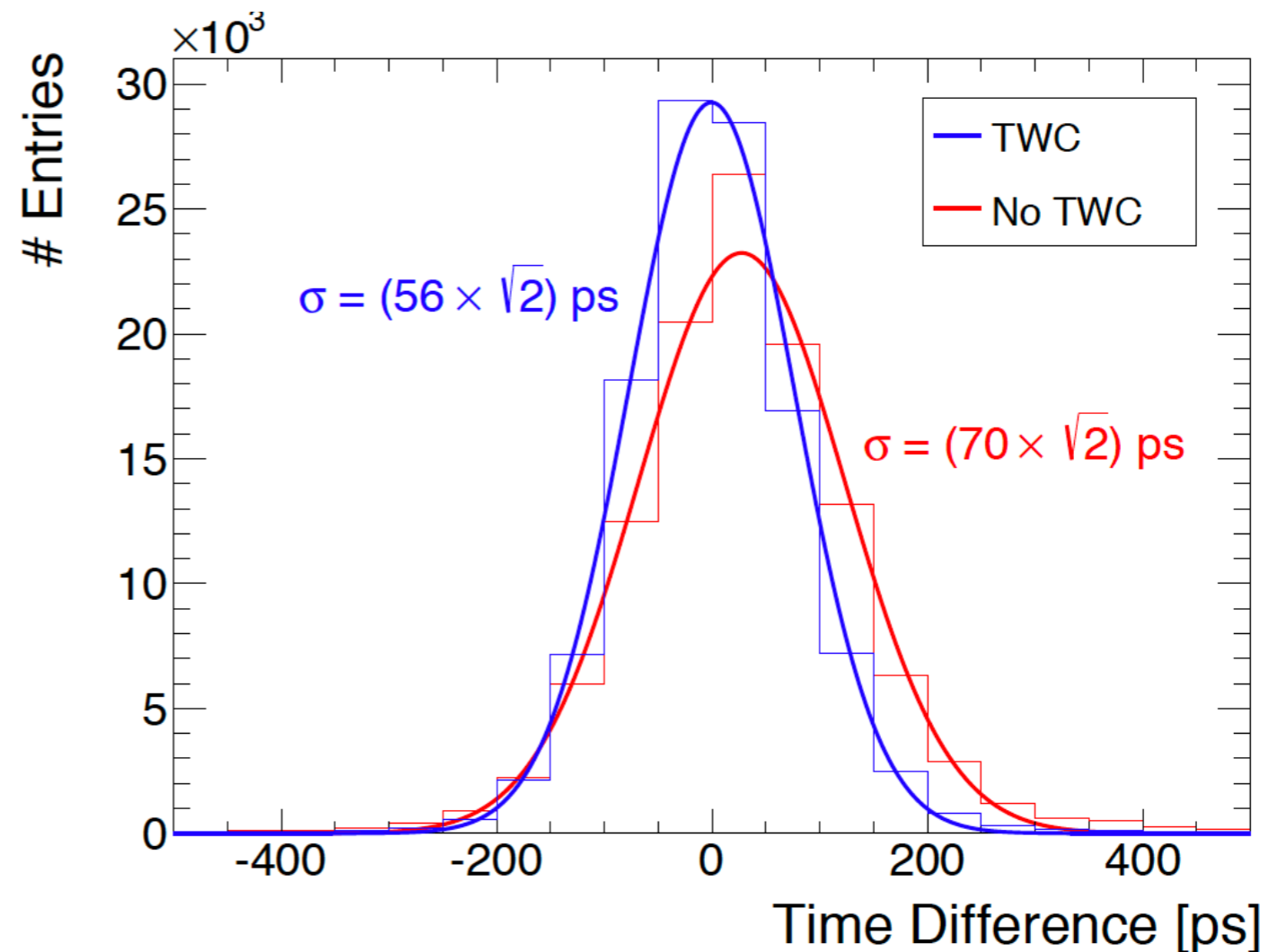
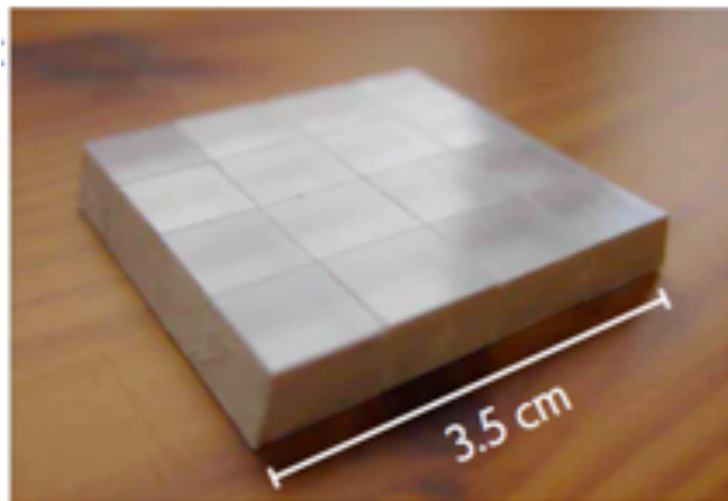


Very promising results from summer test beams with also with “new” fibres: SCSF 78 MJ, clear; SCSF 78 MJ, with 20% TiO₂; NOL 11, clear; NOL 11, with 20% TiO₂; SCSF 81 MJ, with 20% TiO₂

New

Tile Prototype: Results

- Mu3e requirements fulfilled: Full detection efficiency ($> 99\%$) and timing resolution σ (60) ps
- 4 x 4 channel BC408
- $7.5 \times 8.5 \times 5.0 \text{ mm}^3$
- Hamamatsu S10362-33-050C ($3 \times 3 \text{ mm}^2$)
- readout with STiC2



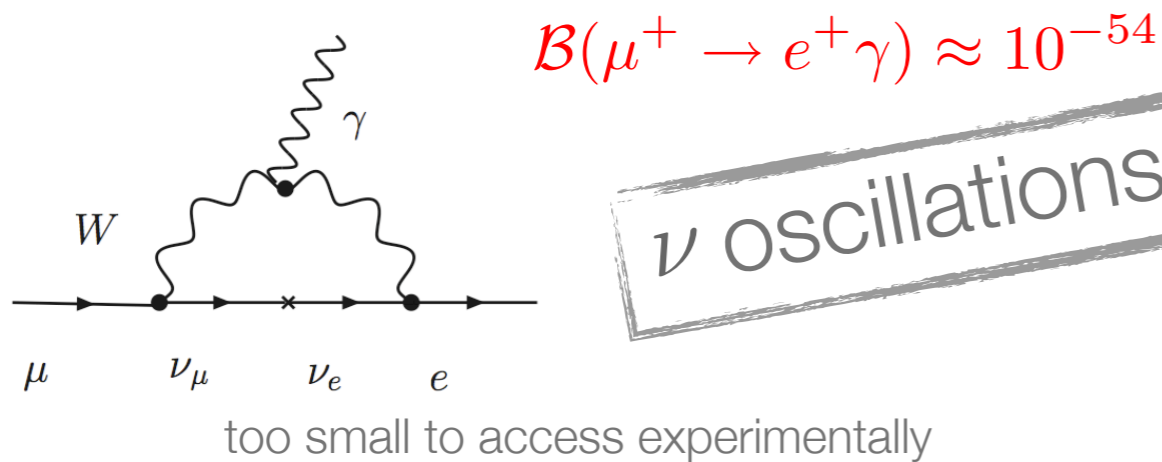
Outlooks

- 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 expected 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 exciting place where to search for new physics**

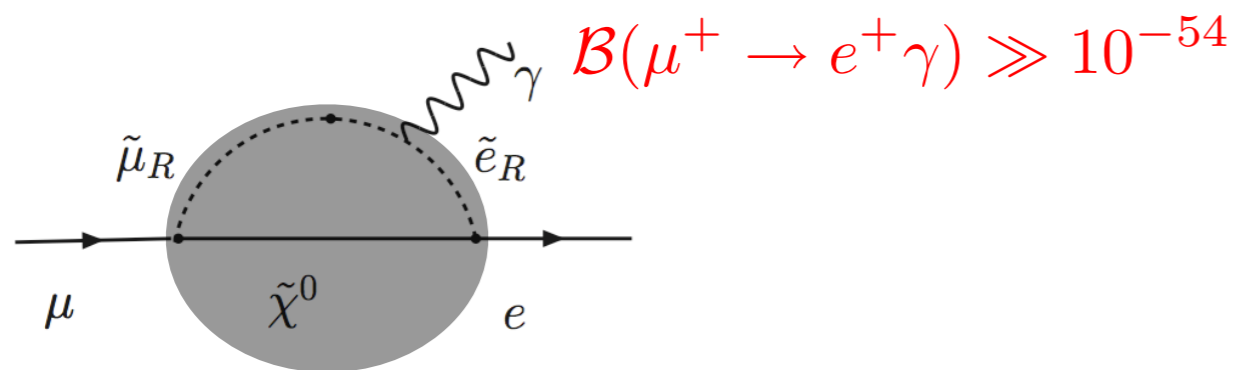
Backup

cLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

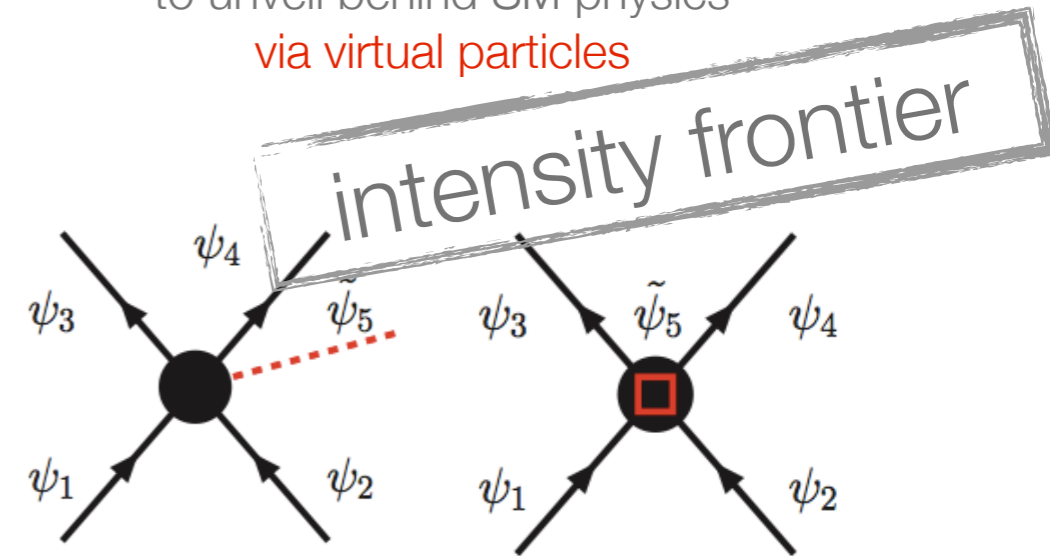


i.e. SU(5) SUSY-GUT or SO(10) SUSY-GUT



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

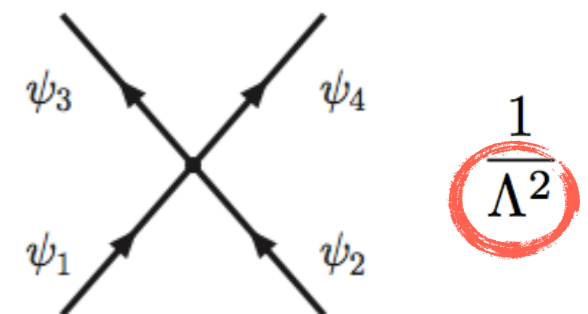
to unveil behind SM physics
via virtual particles



to probe otherwise unreachable and
unexploited new physics energy scale

high energy probe

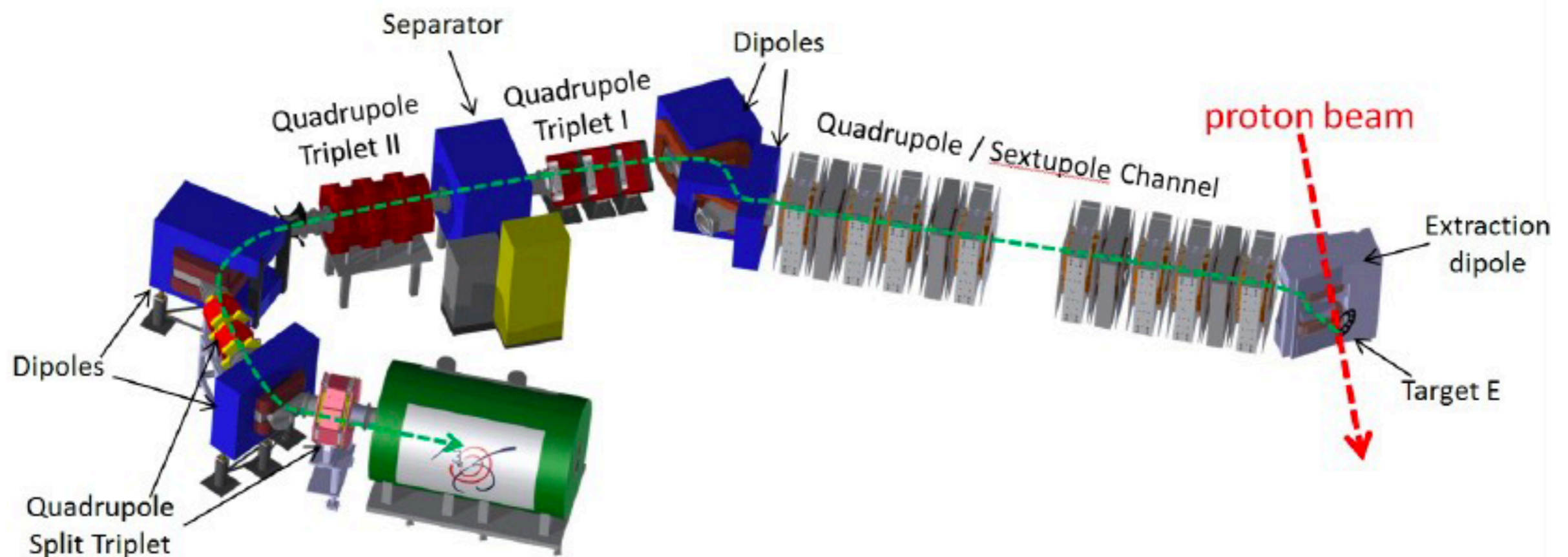
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



The compact beam line

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

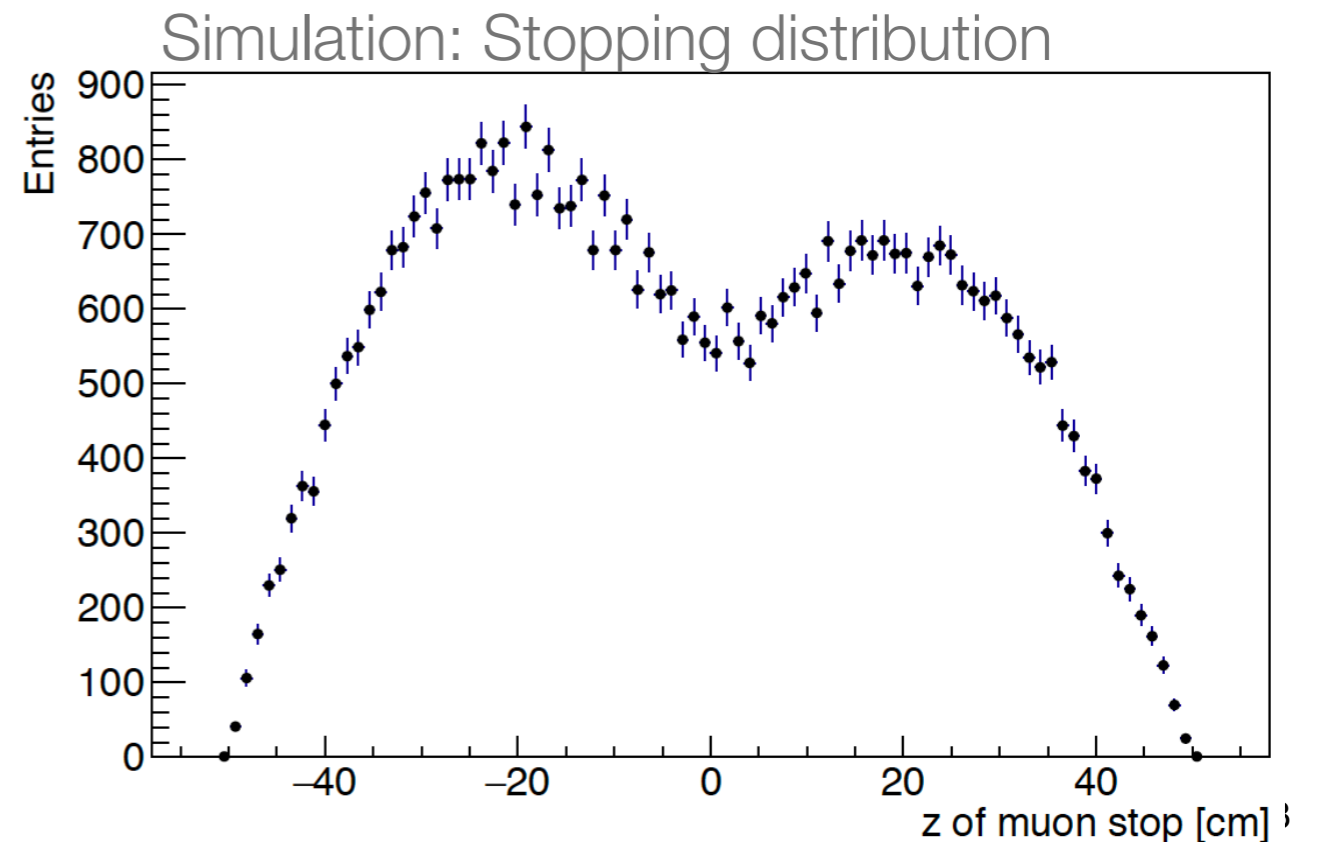
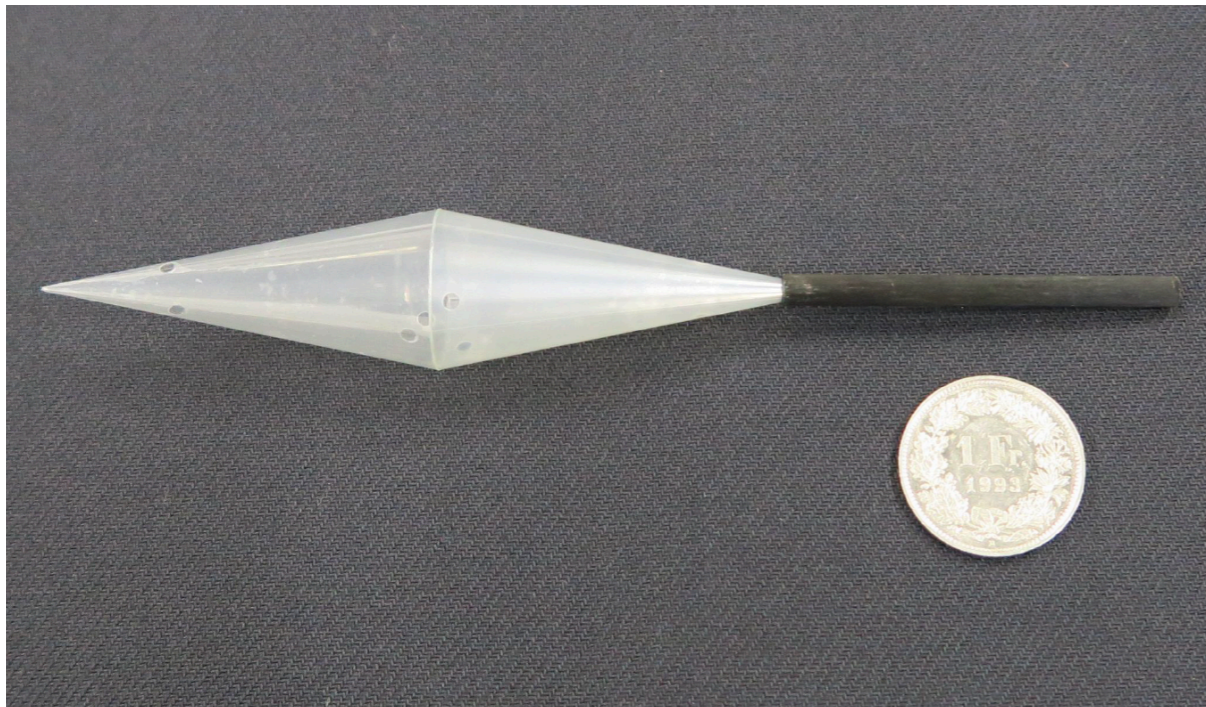
The CMBL



The target

- Mylar double hollow cone
- Large target area ($L = 100$ mm, $R = 19$ mm; $A \sim \text{XXX}$ mm²)
- Low material budget: (asymmetric structure: US 75 μm , DS 85 μm)
- Stopping efficiency: $\sim 83\%$
- Vertex separation ability (tracking) < 200 μm

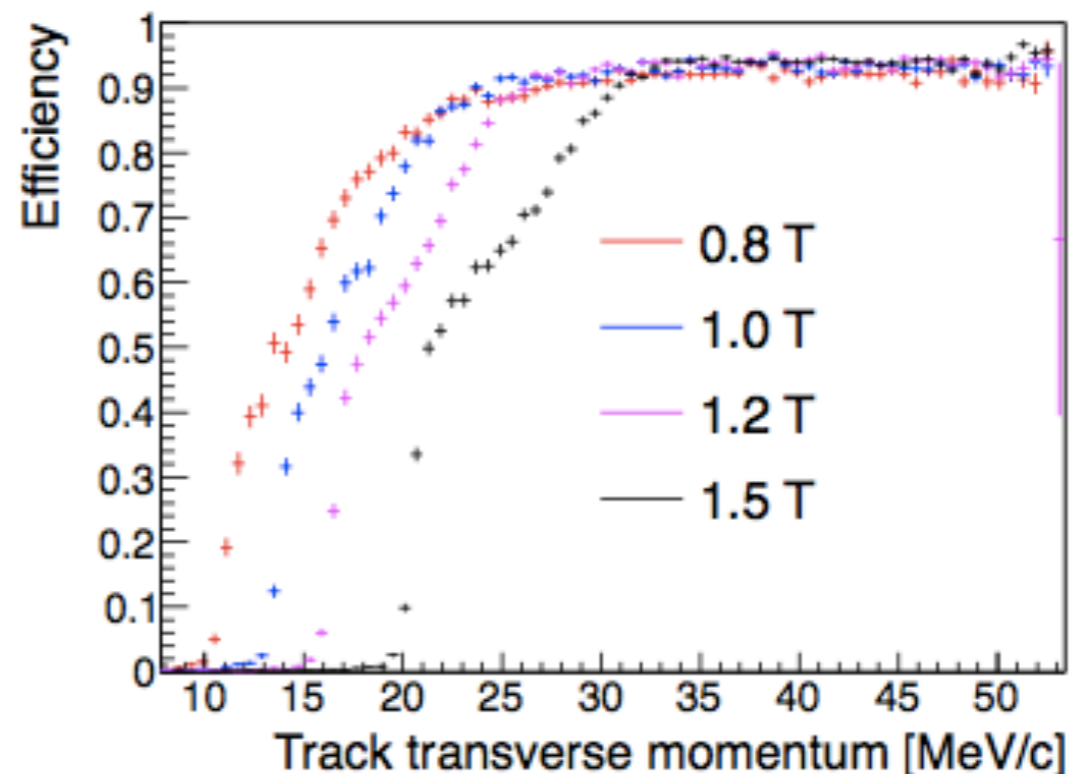
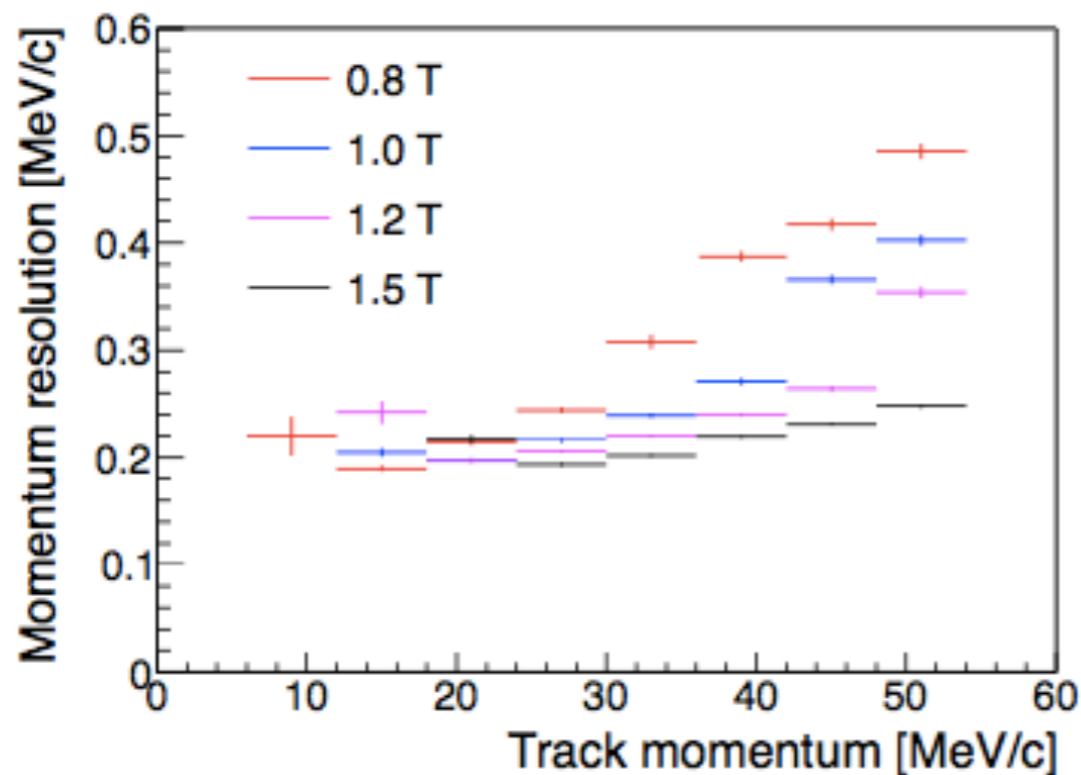
Target prototype



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: $dB/B(100 \text{ d}) \leq 10^{-4}$
- Dimensions: $L < 3.2 \text{ m}$, $W < 2.0 \text{ m}$, $H < 3.5 \text{ m}$

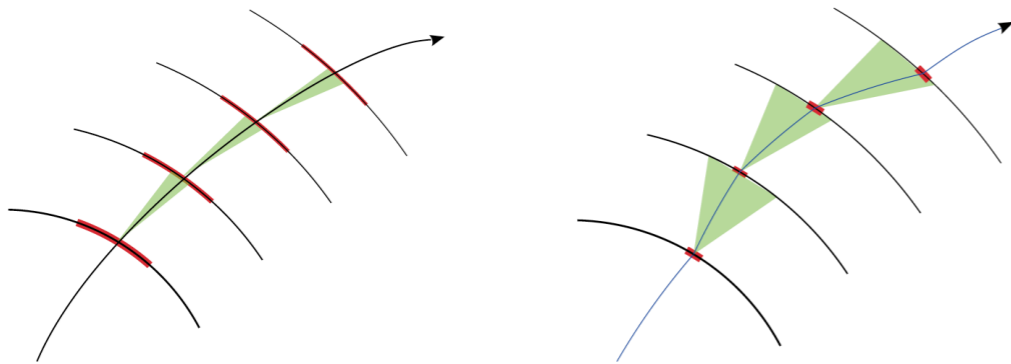
Simulation



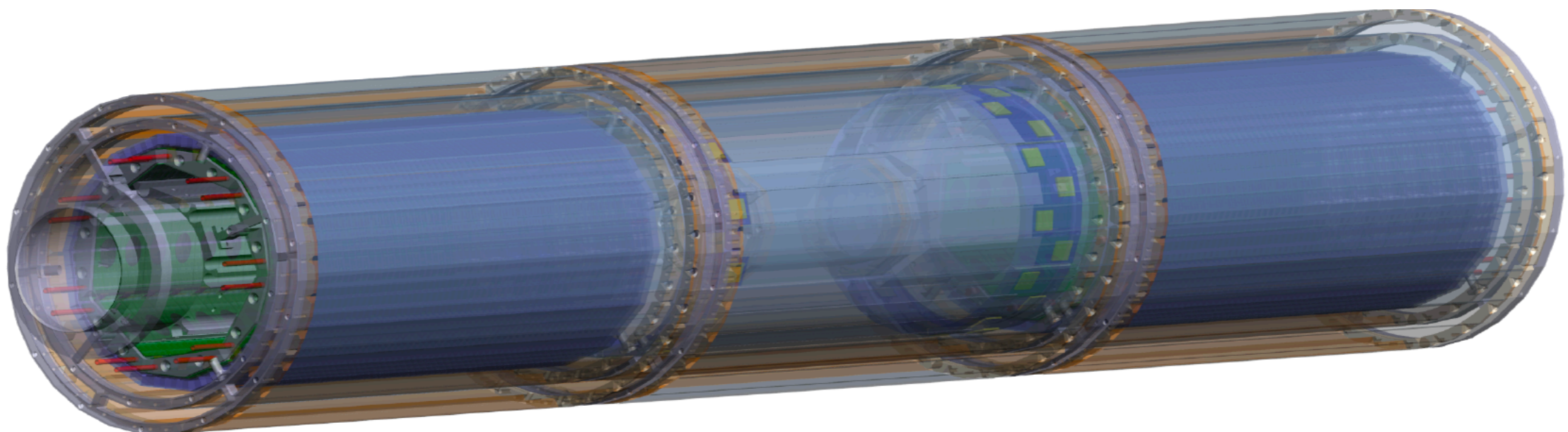
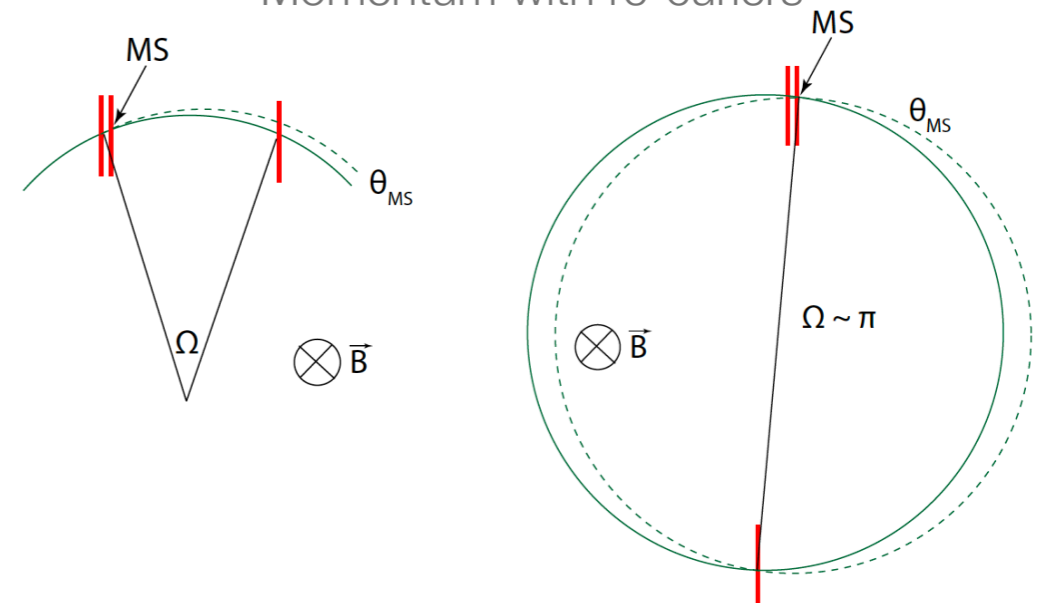
The pixel tracker: The principle

- 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

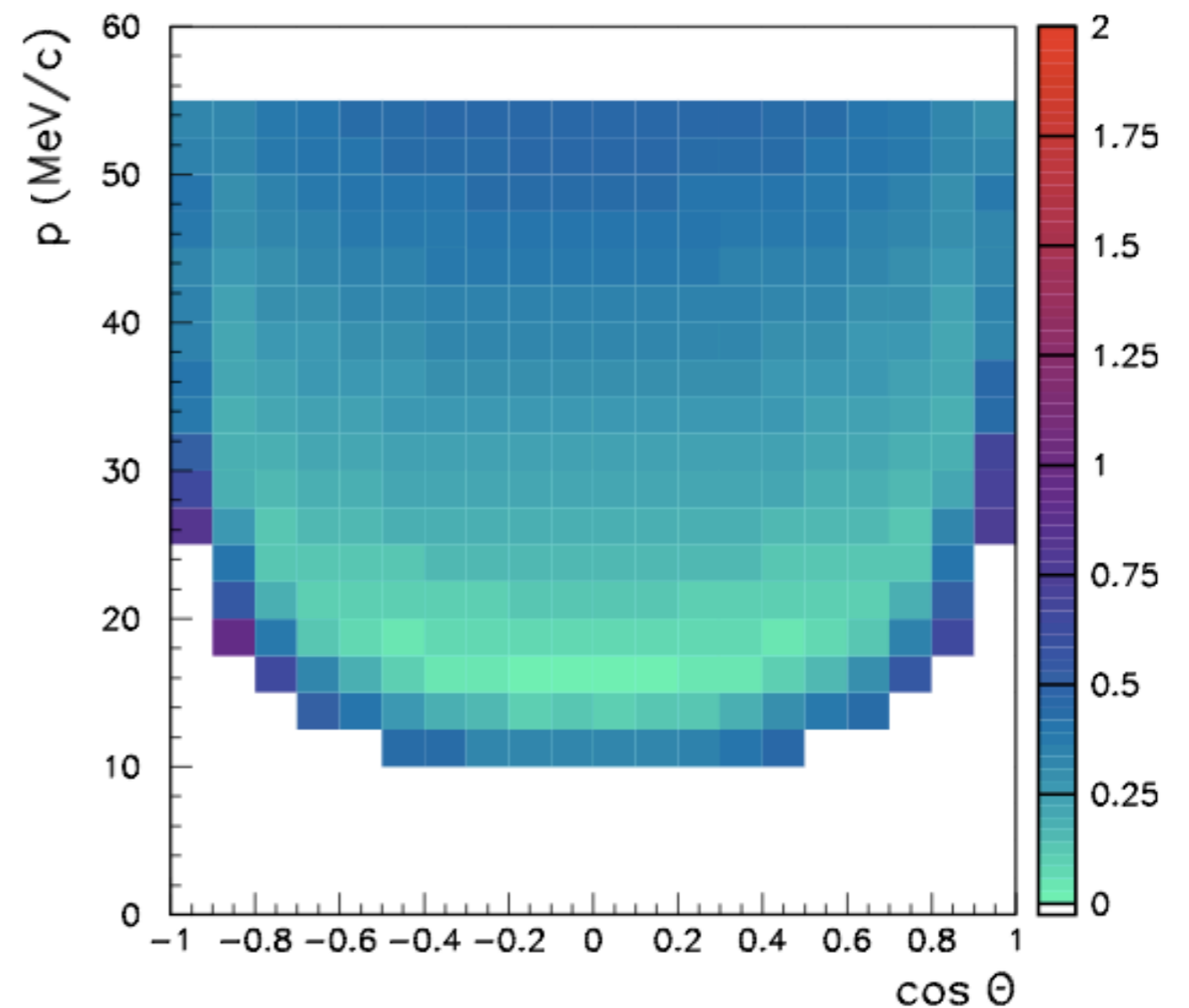
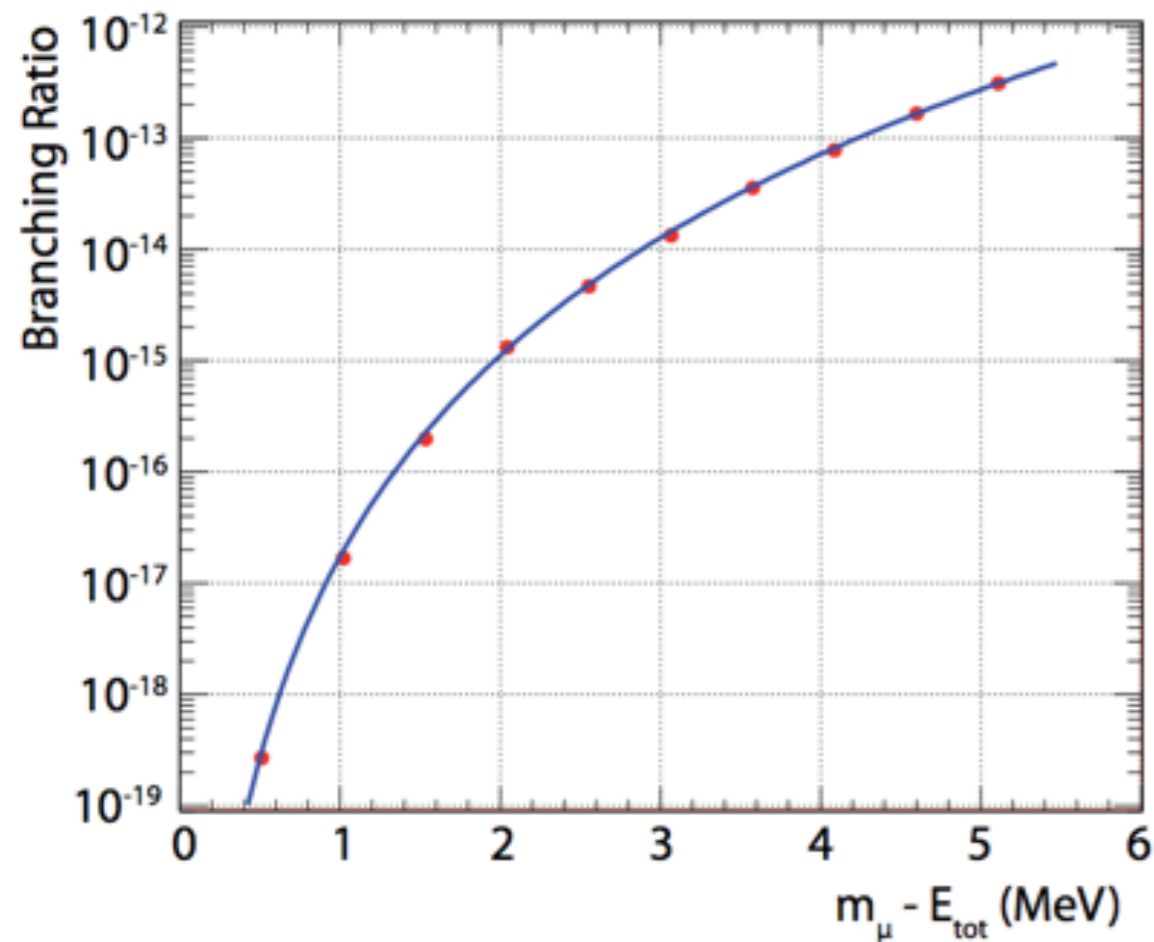


Momentum with re-curlers



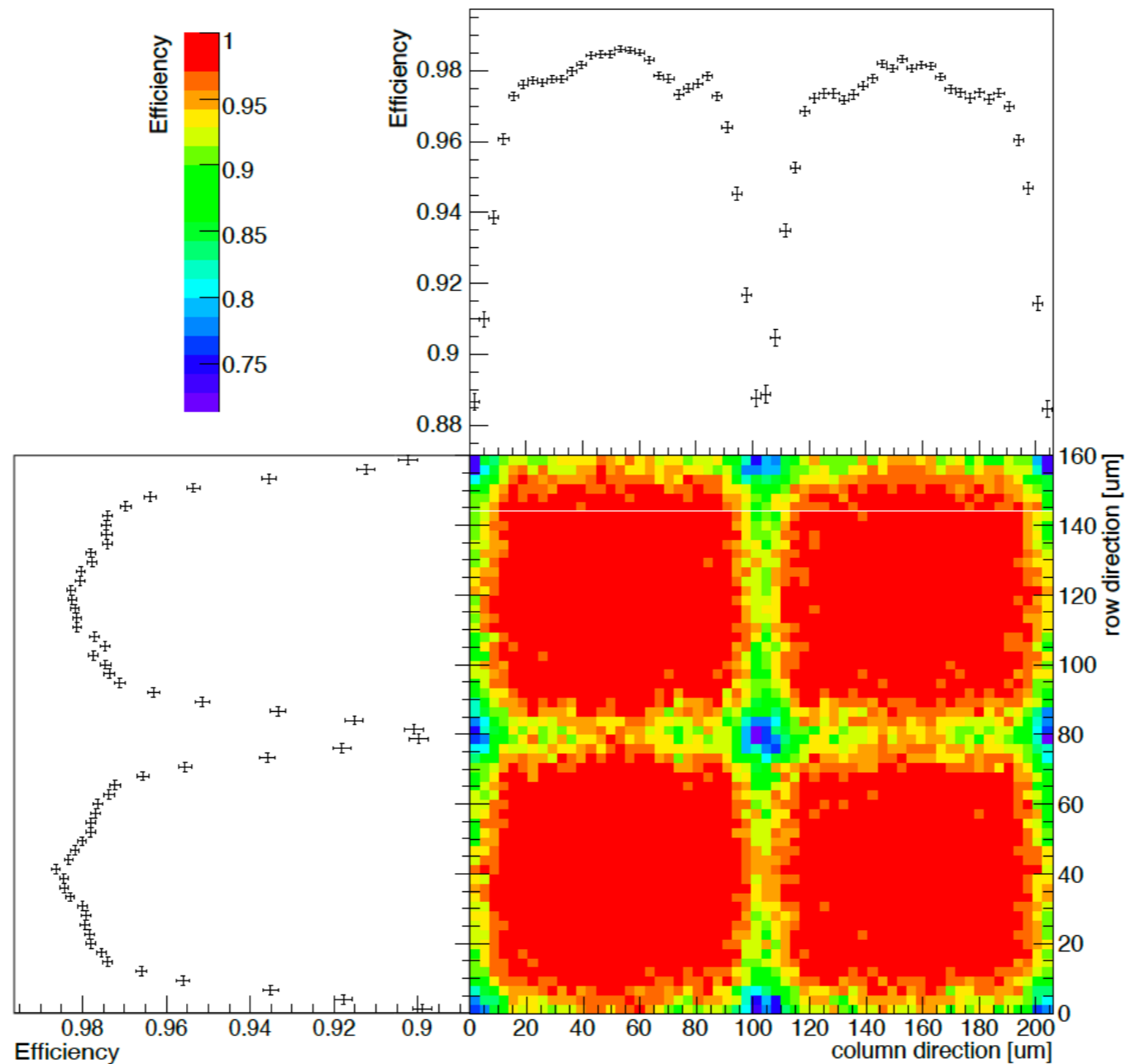
The pixel tracker: The performances

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



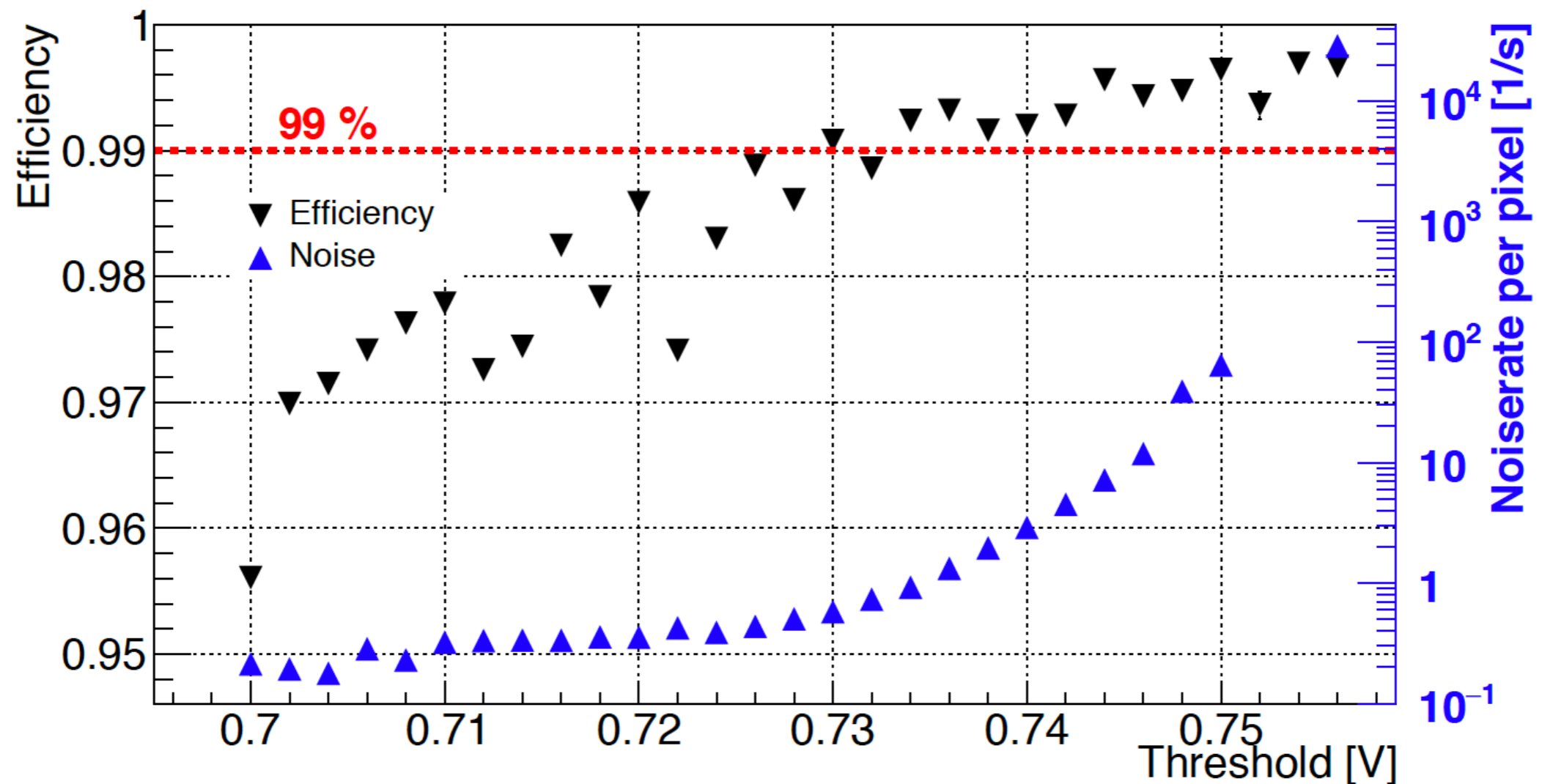
Prototypes: Results

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

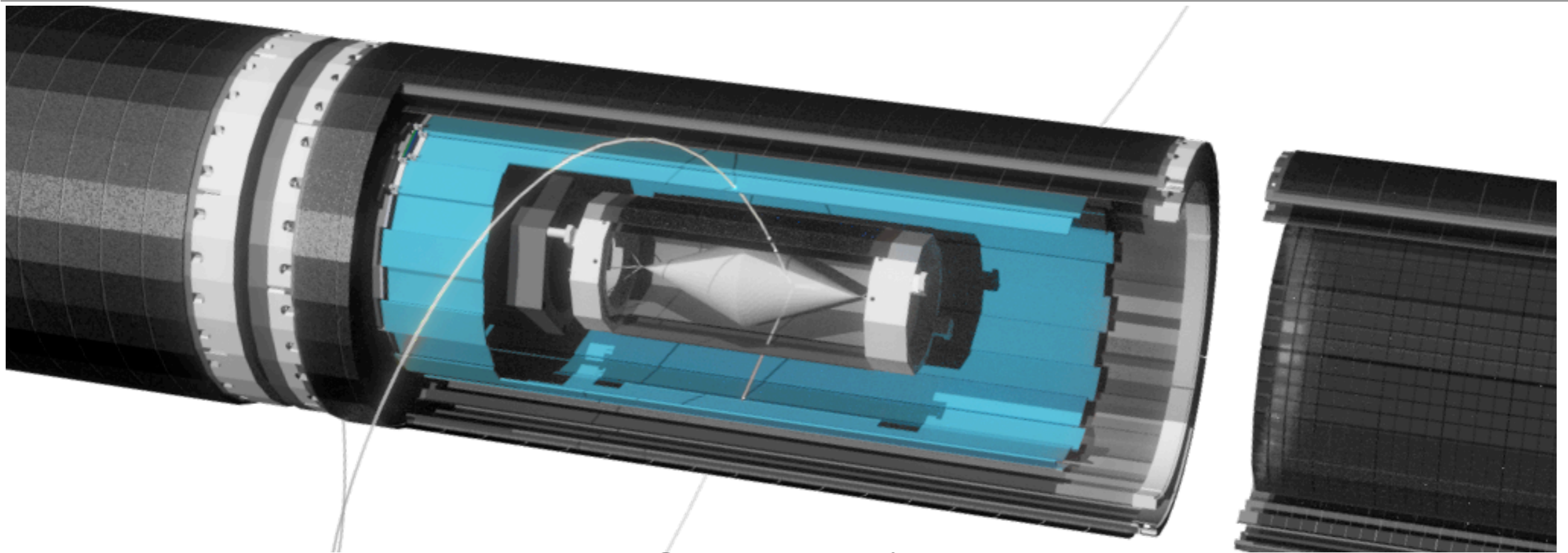


Prototypes: Results

- 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

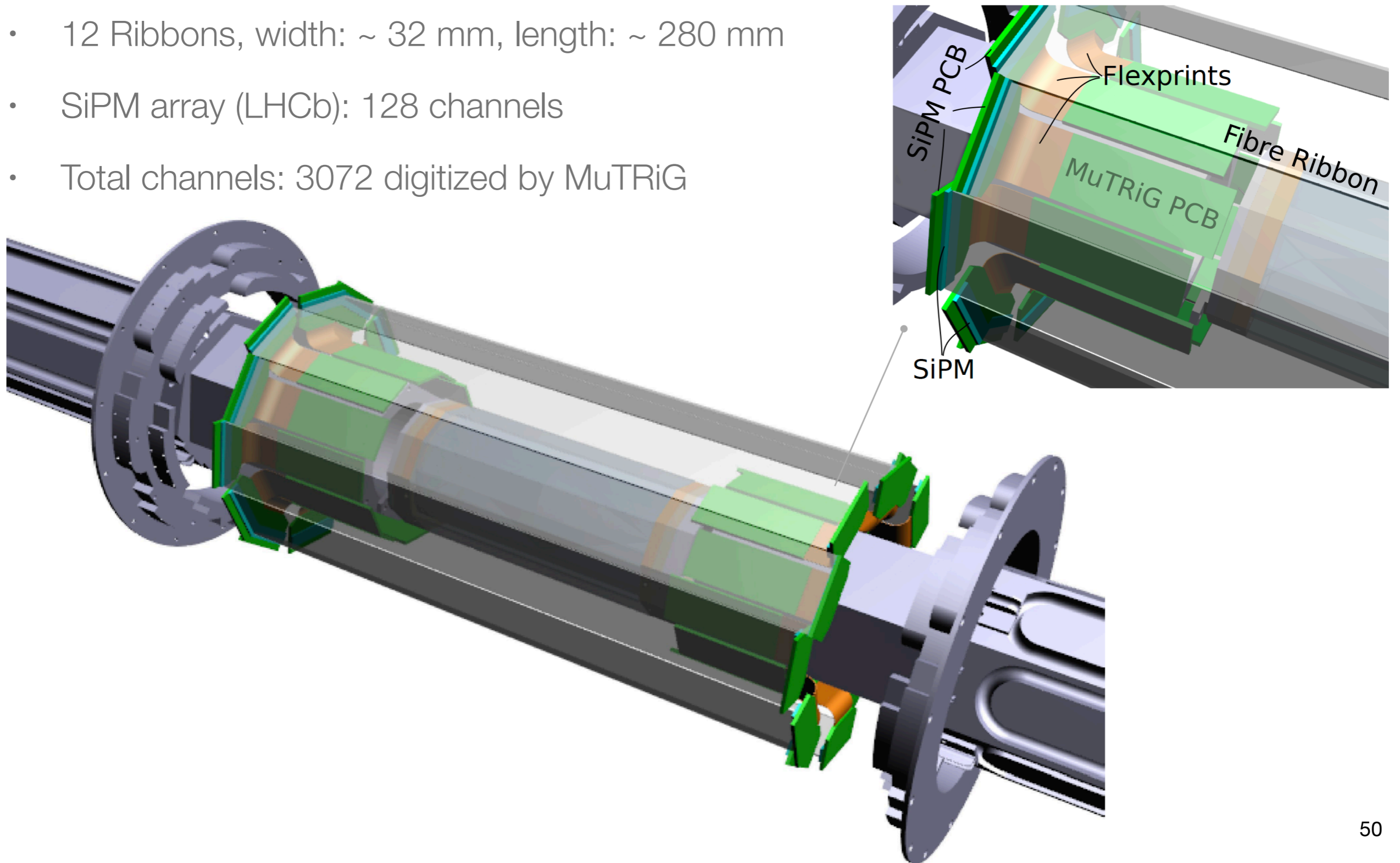
- cylindrical at ~ 6 cm (radius);
- length of 28-30 cm;
- 3 layers of round or square
- multi-clad $250 \mu\text{m}$ fibres
- fibres grouped onto SiPM array
- MuSTiC readout

Constraints

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

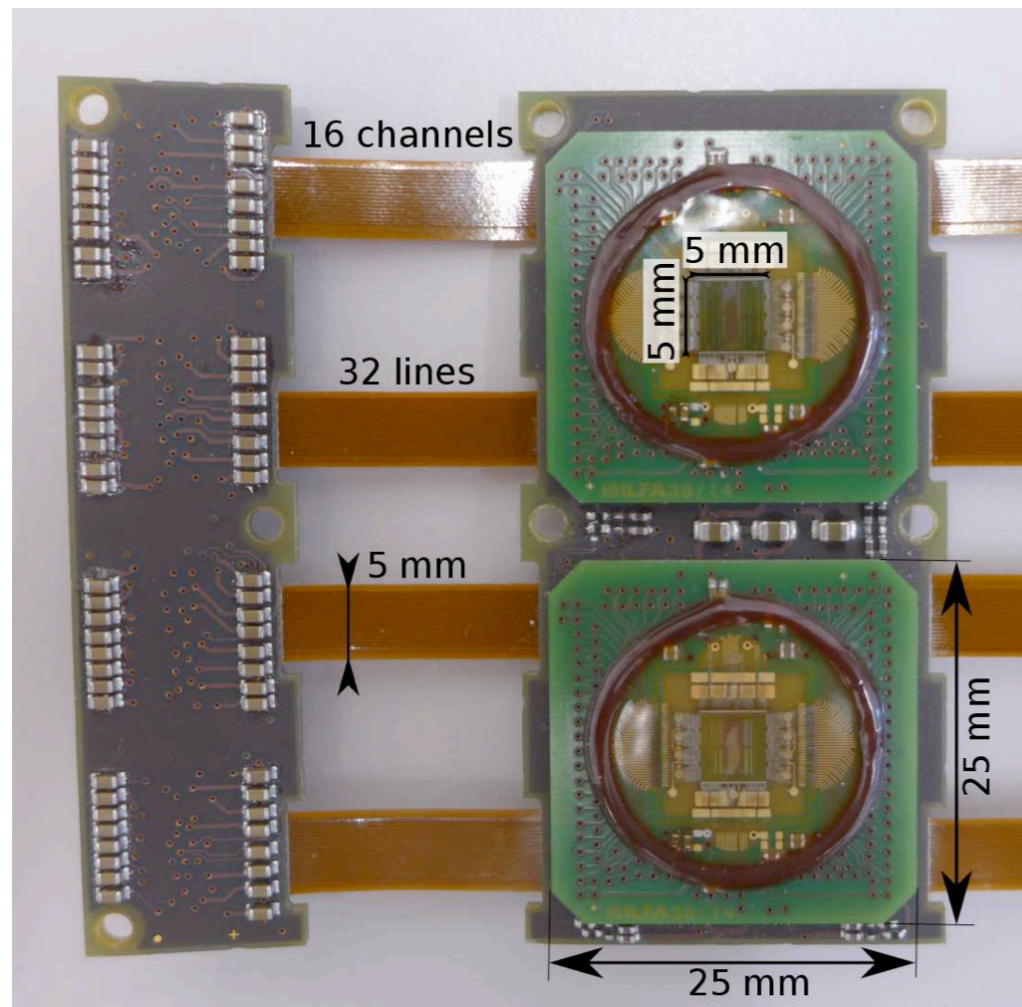
The Fiber detector (SciFi): 3D view

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



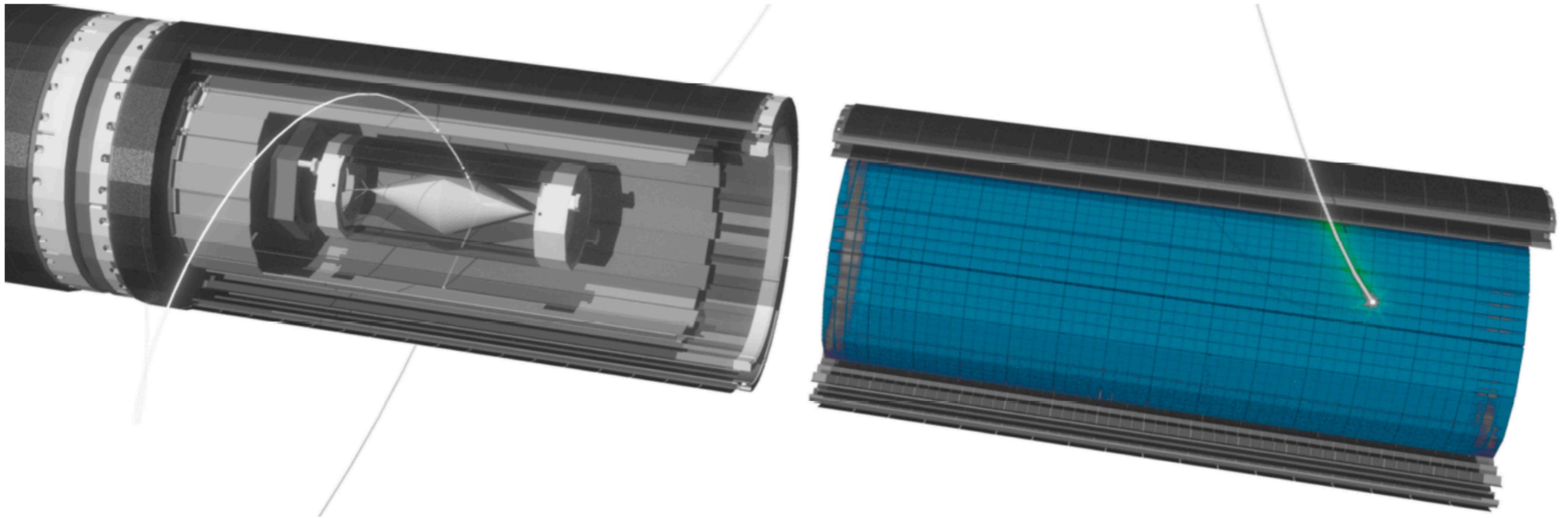
SciFi: Electronics readout, MuTRiG

- 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



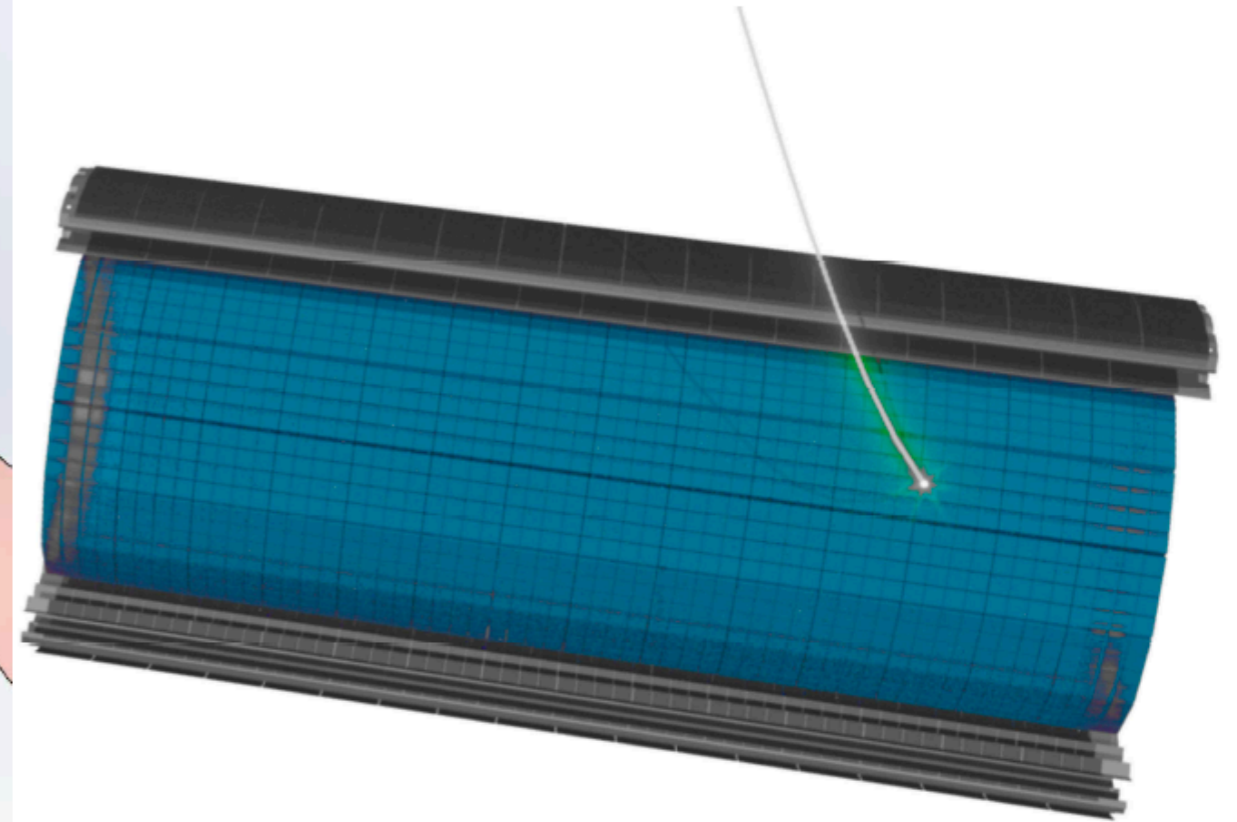
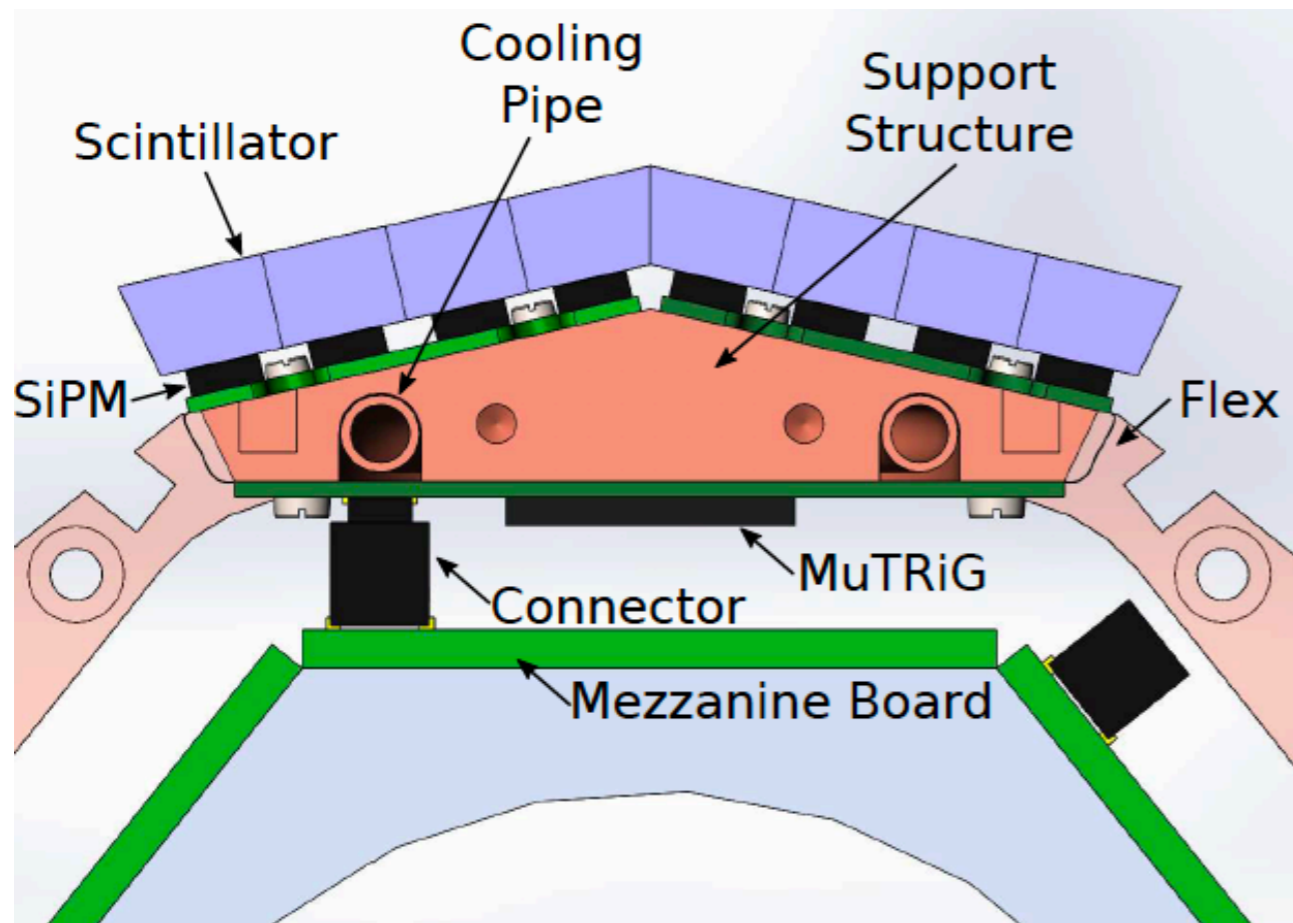
Parts

- cylindrical at ~ 6 cm (radius)
- length of 36.4 cm
- 56 x 56 tiles of $6.5 \times 6.5 \times 5$ mm³
- 3 x 3 mm² 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

- cylindrical at ~ 6 cm (radius)
- length of 36.4 cm
- 56×56 tiles of $6.5 \times 6.5 \times 5$ mm³
- 3×3 mm² 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

