CLFV searches at PSI and future developments

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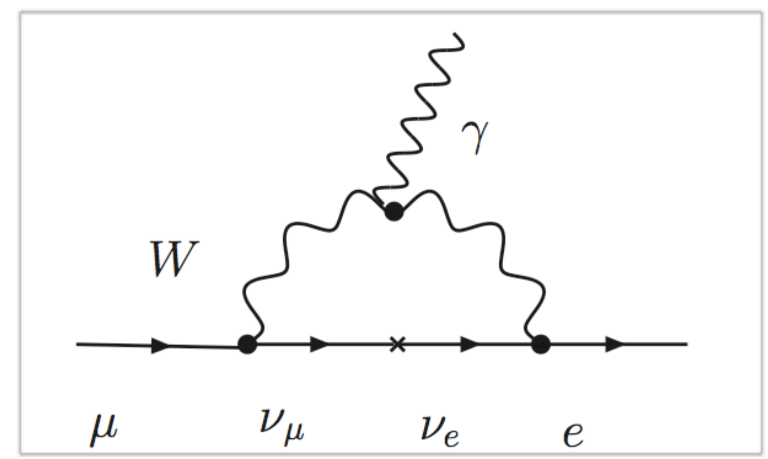
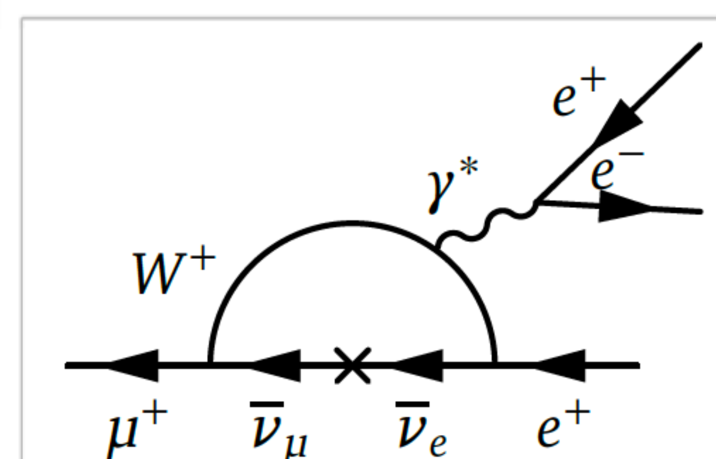
Physics Beyond Collider, 8-11 June 2020 (remote meeting)





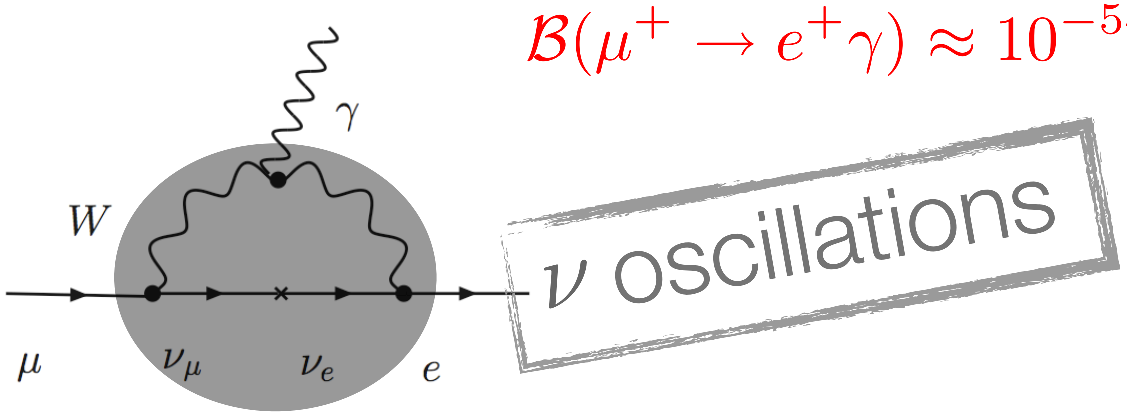
Content

- Introduction: Charged Lepton Flavour violations searches
- Status of the MEGII experiment
- Status of the Mu3e experiment
- The Most Intense DC Muon beams in the World: future prospects

Charged lepton flavour violation search: Motivation

SM with massive neutrinos (Dirac)

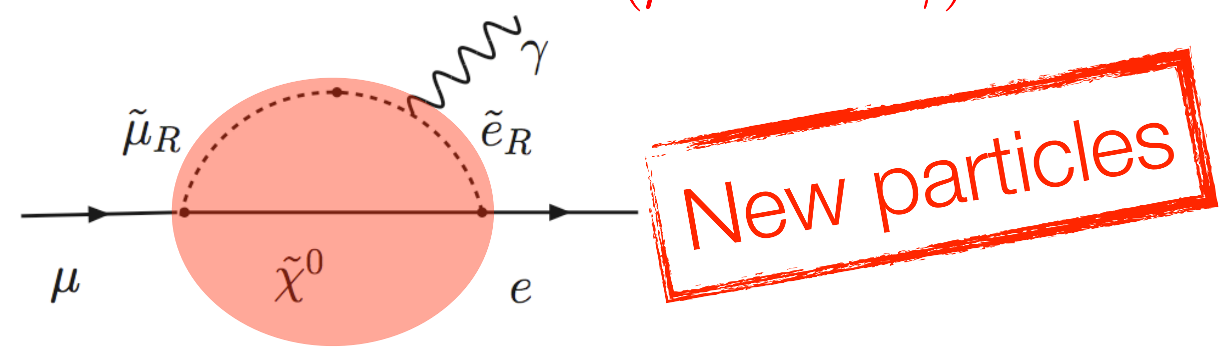
$$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$$



too small to access experimentally

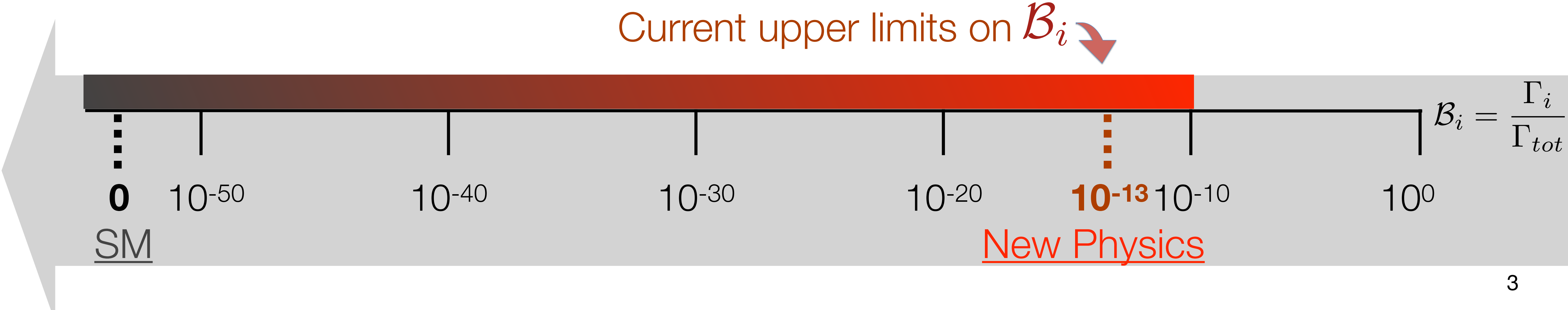
BSM

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



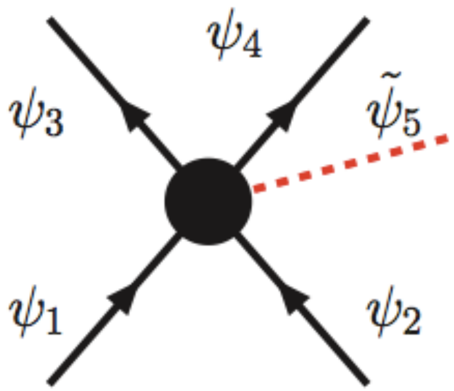
an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)

Current upper limits on $\mathcal{B}_i$



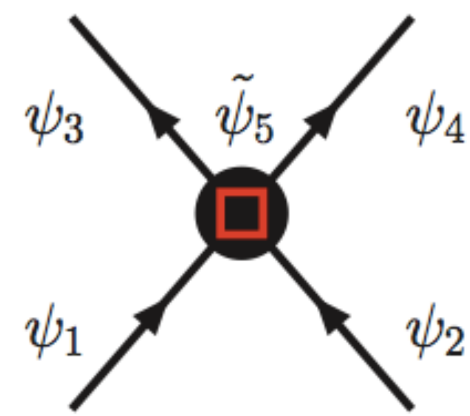
Complementary to “Energy Frontier”

Energy frontier



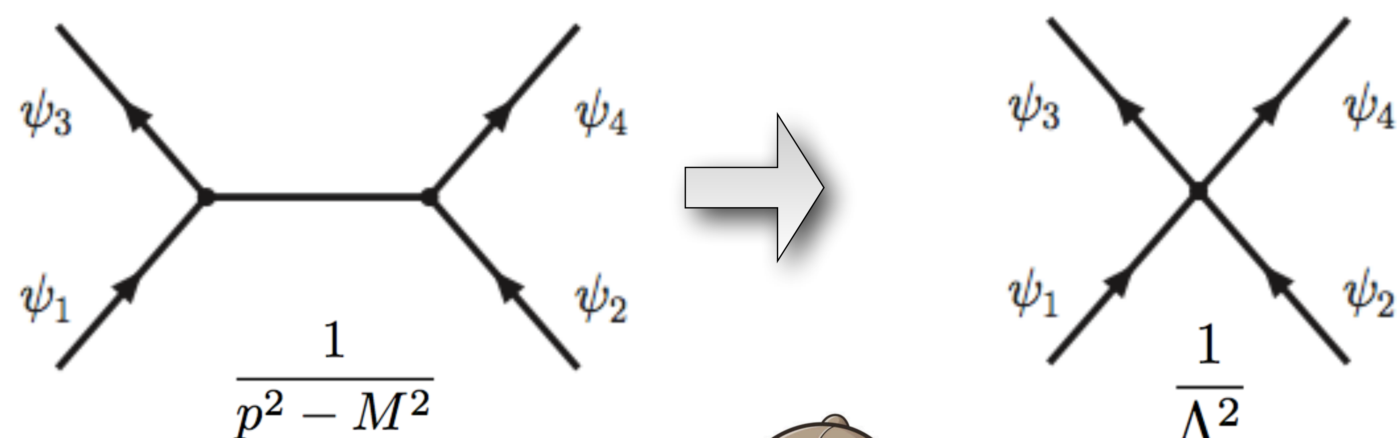
Real BSM particles

Precision and intensity frontier



Virtual BSM particles

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



Unveil new physics

Probe energy scale otherwise unreachable

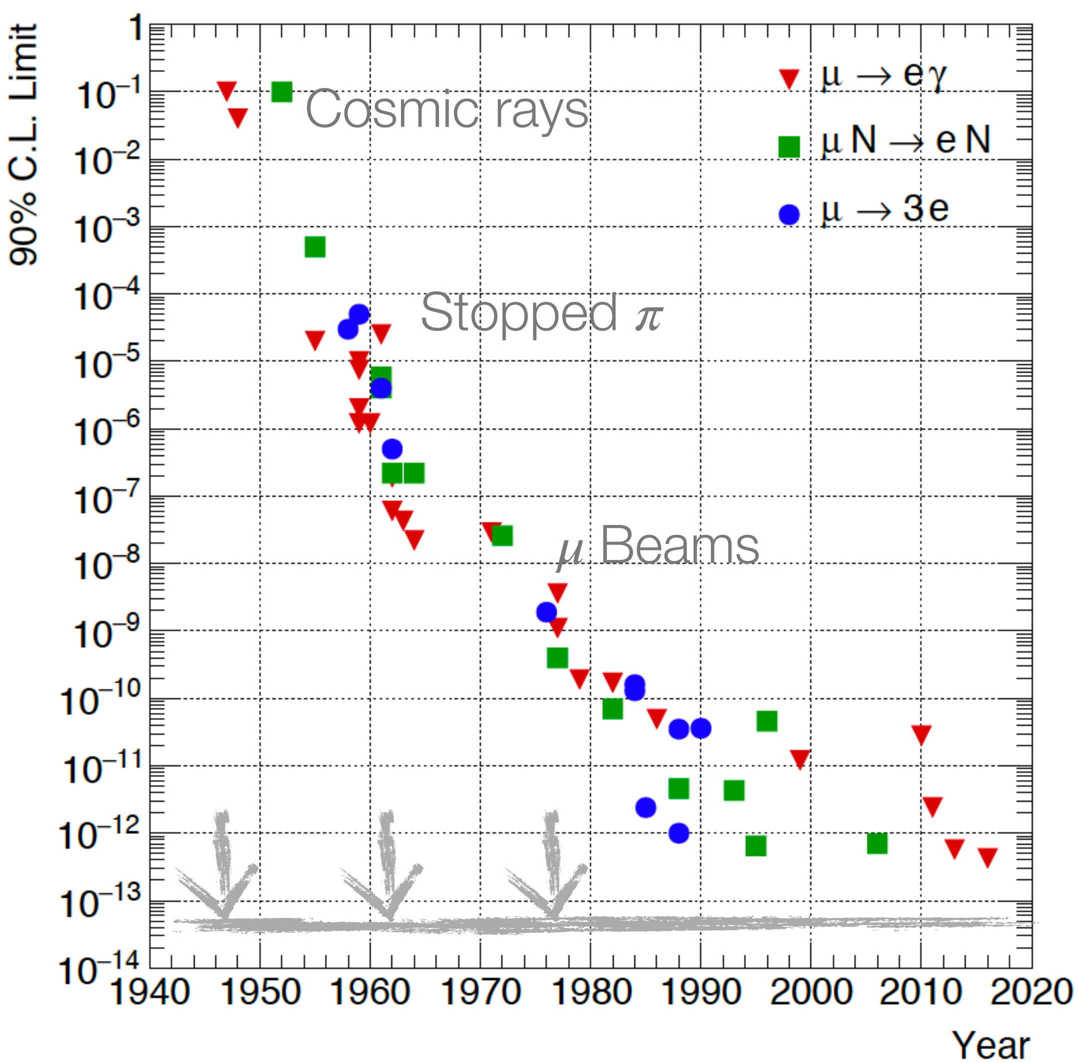
E > 1000 TeV

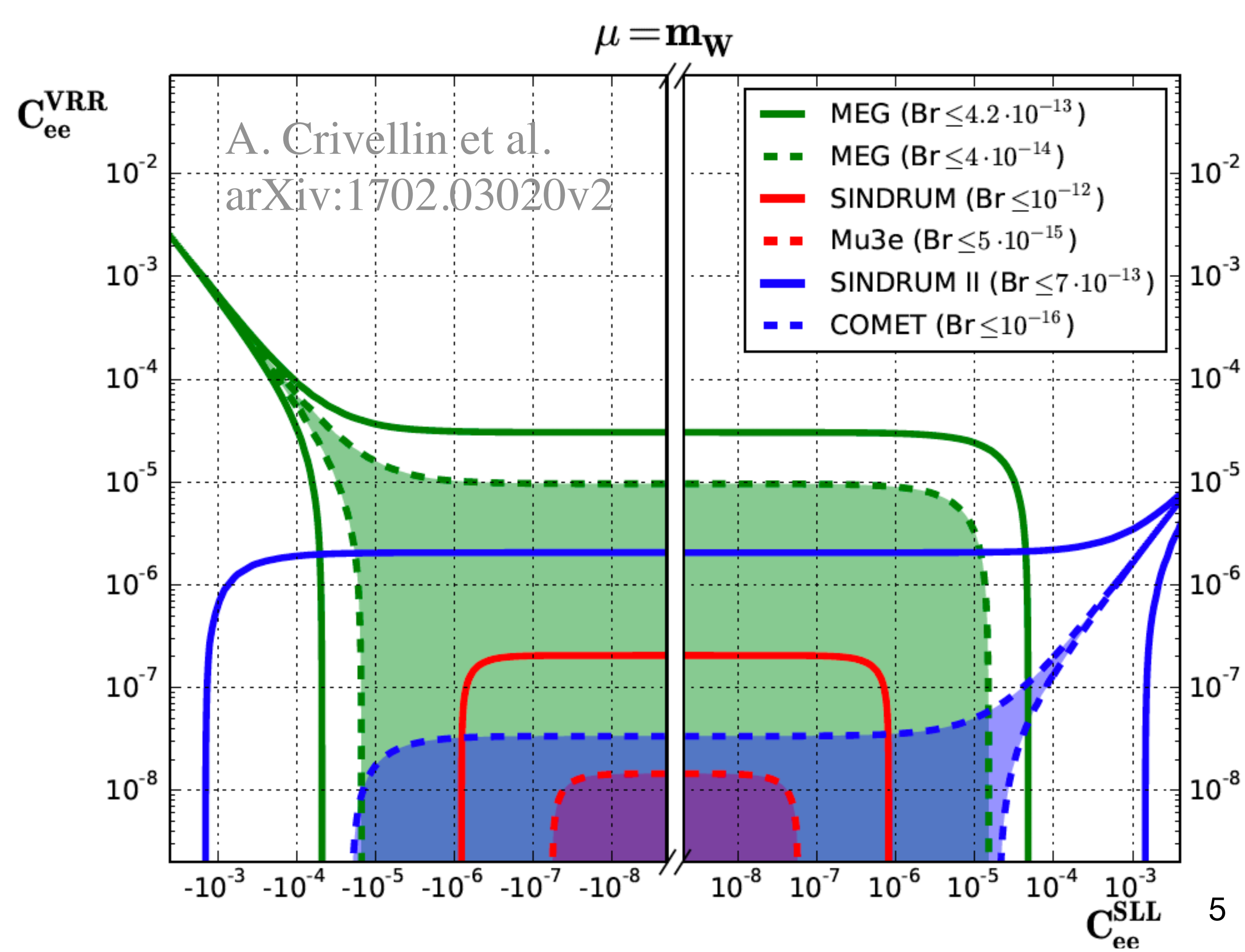
cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities:

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 4 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	few x 10^{-17}

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

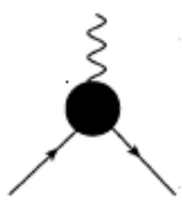
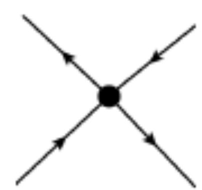


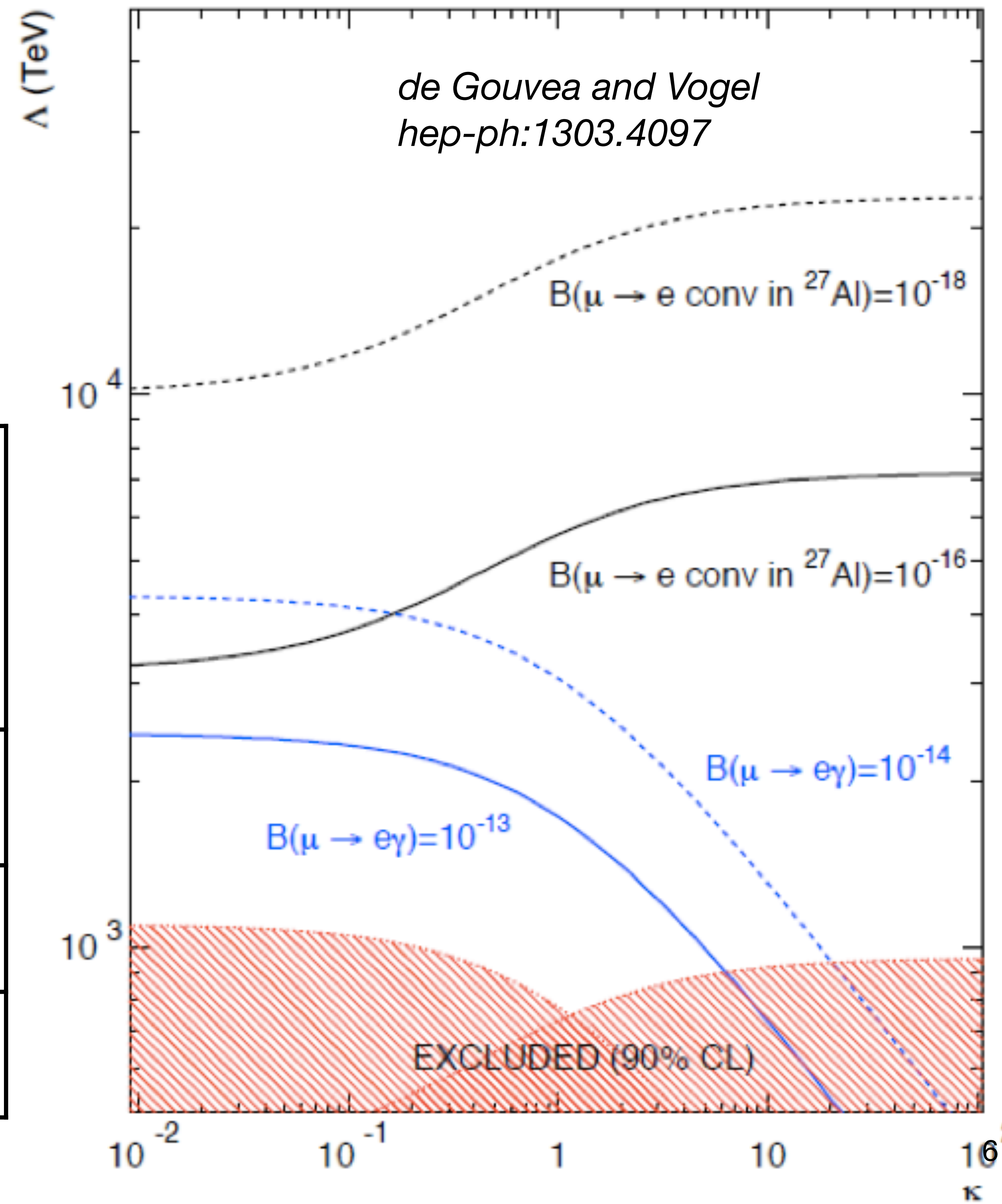


cLFV: “Effective” lagrangian with the k-parameter

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

Model independent lagrangian

$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$ 	$+ \frac{\kappa}{(\kappa+1)\Lambda^2} \times$ 
dipole term	contact term
$\mu \to e\gamma$	
$\mu \to eee$	
$\mu N \to eN$	



cLFV searches with muons: Status and prospects

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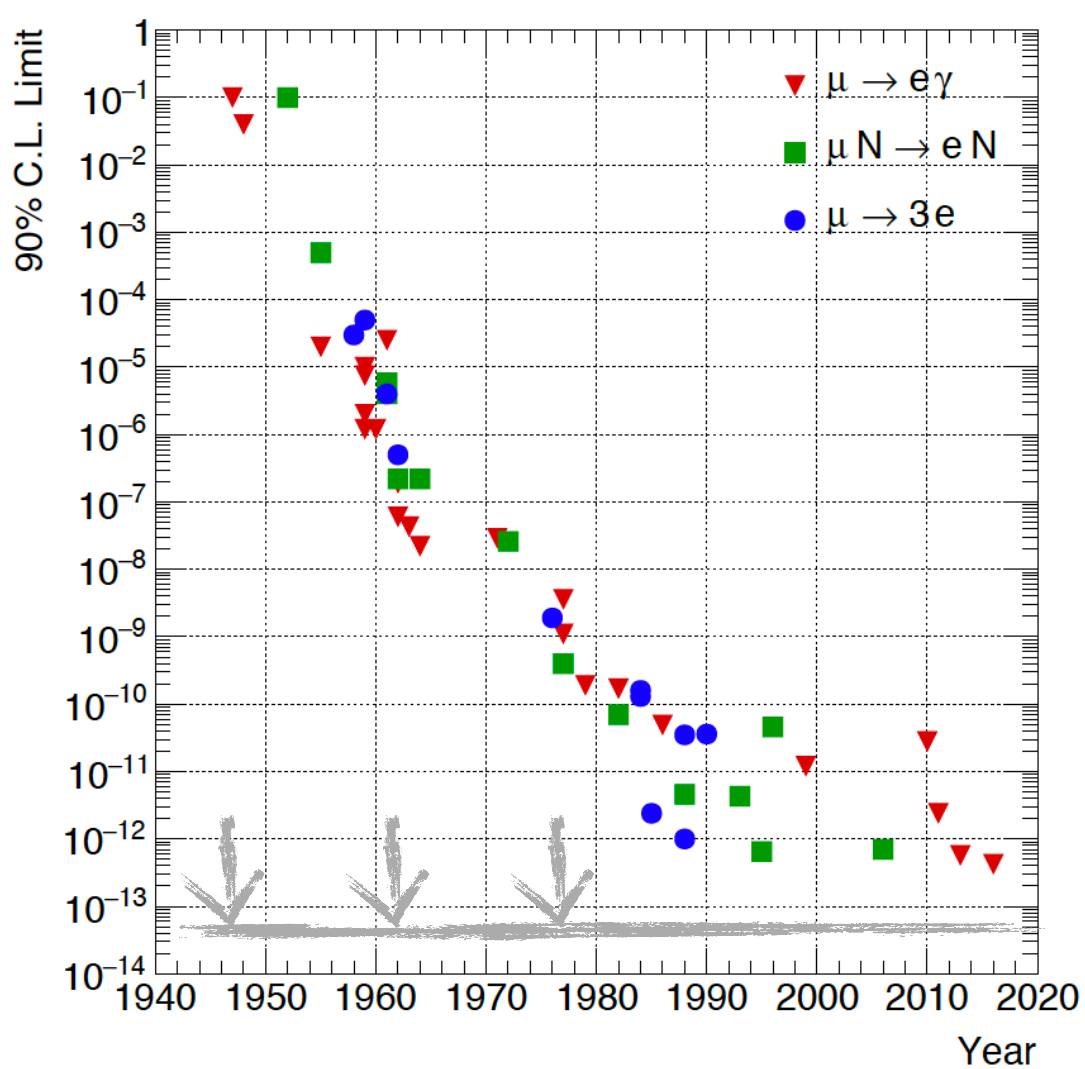
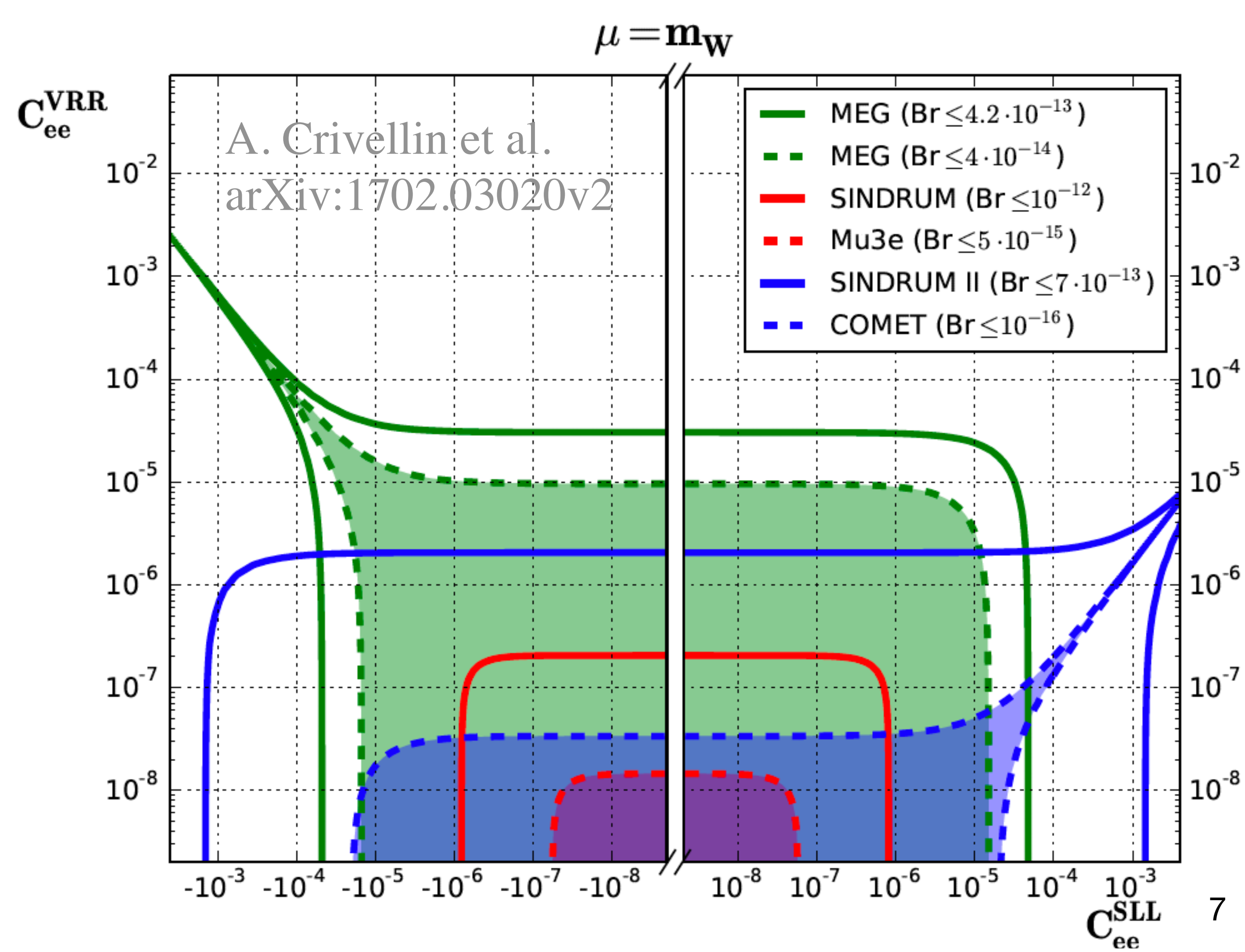




Beam features vs experiment requirements

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

DC or Pulsed?

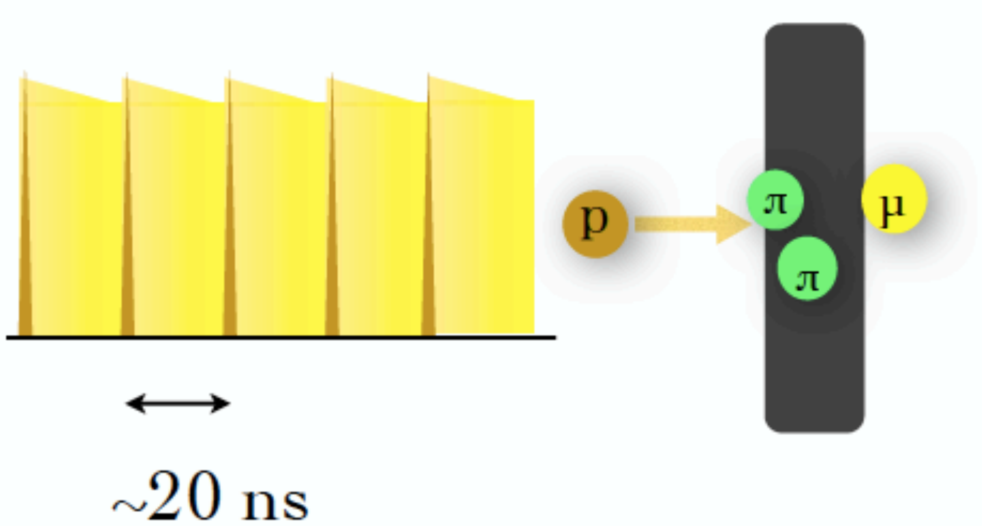
$I_{beam} \sim 10^8 - 10^{10}\ \mu/s$

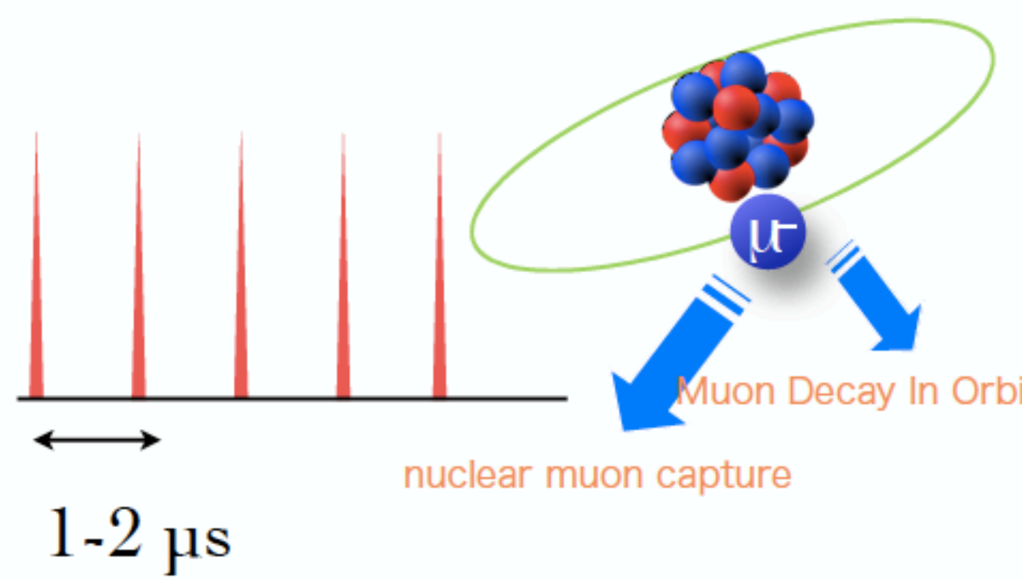
- DC beam for coincidence experiments
  - $\mu \rightarrow e \gamma$, $\mu \rightarrow e\ e\ e$

$I_{beam} \sim 10^{11}\ \mu/s$

- Pulse beam for non-coincidence experiments
  - μ-e conversion

@ PSI





@ JPARC, FERMILAB

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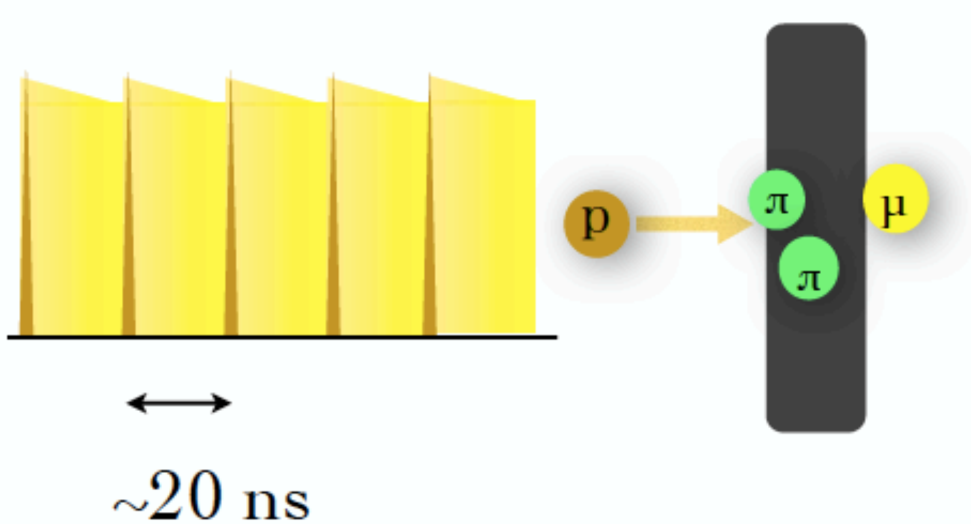
@ PSI

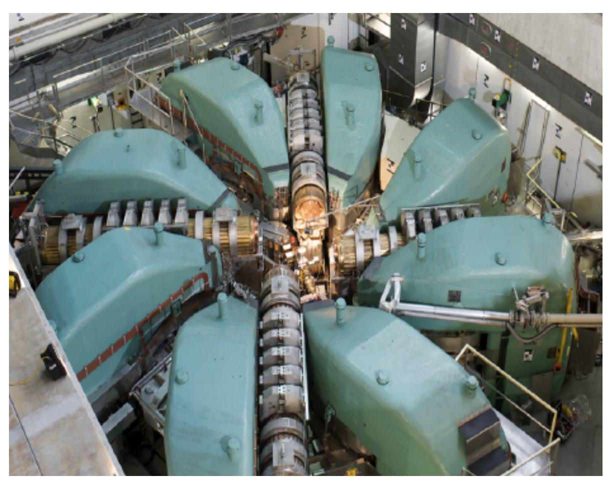


@ JPARC, FERMILAB

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

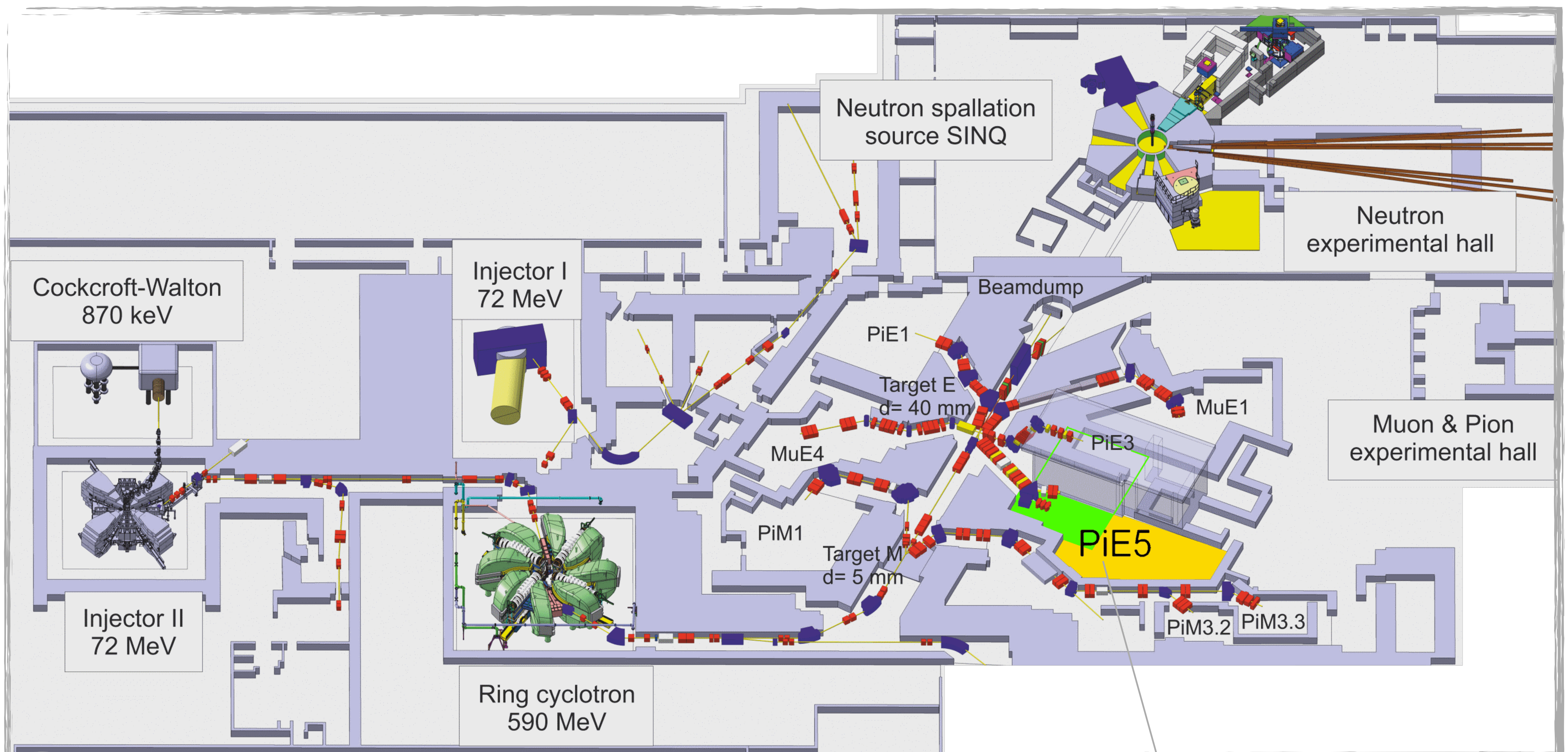


590 MeV proton
ring cyclotron
1.4 MW

PSI landscape

The world’s most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas



MEGII / Mu3e Experimental area

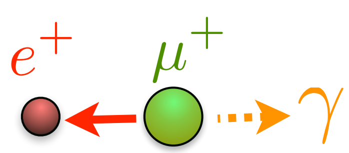
MEG: Signature, experimental setup and result

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365

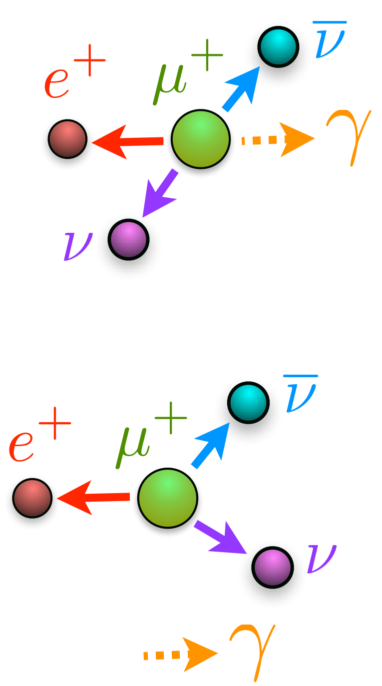
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

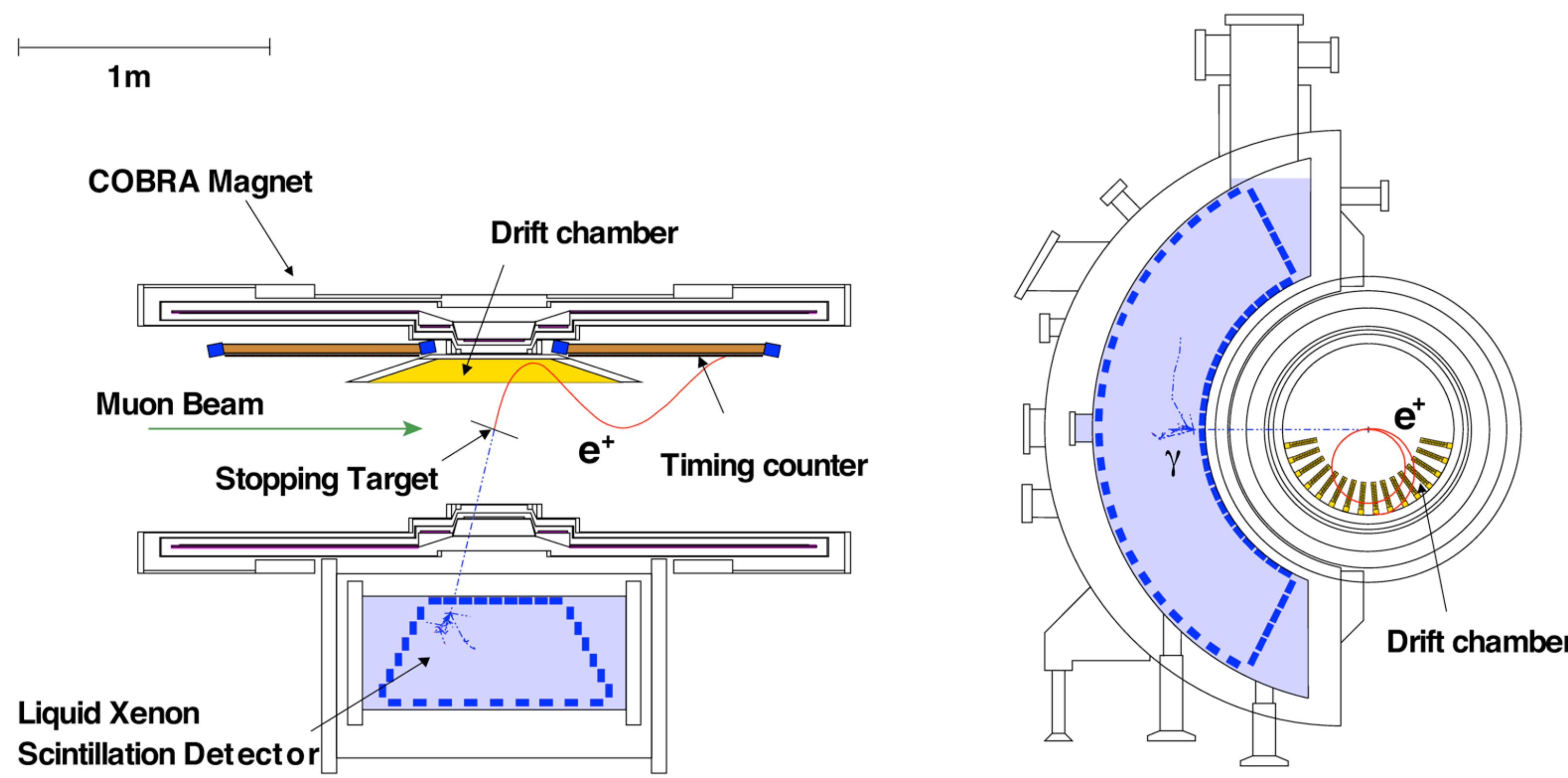
- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~10^{-13} (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow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

Signature



Backgrounds





Full data sample: 2009-2013

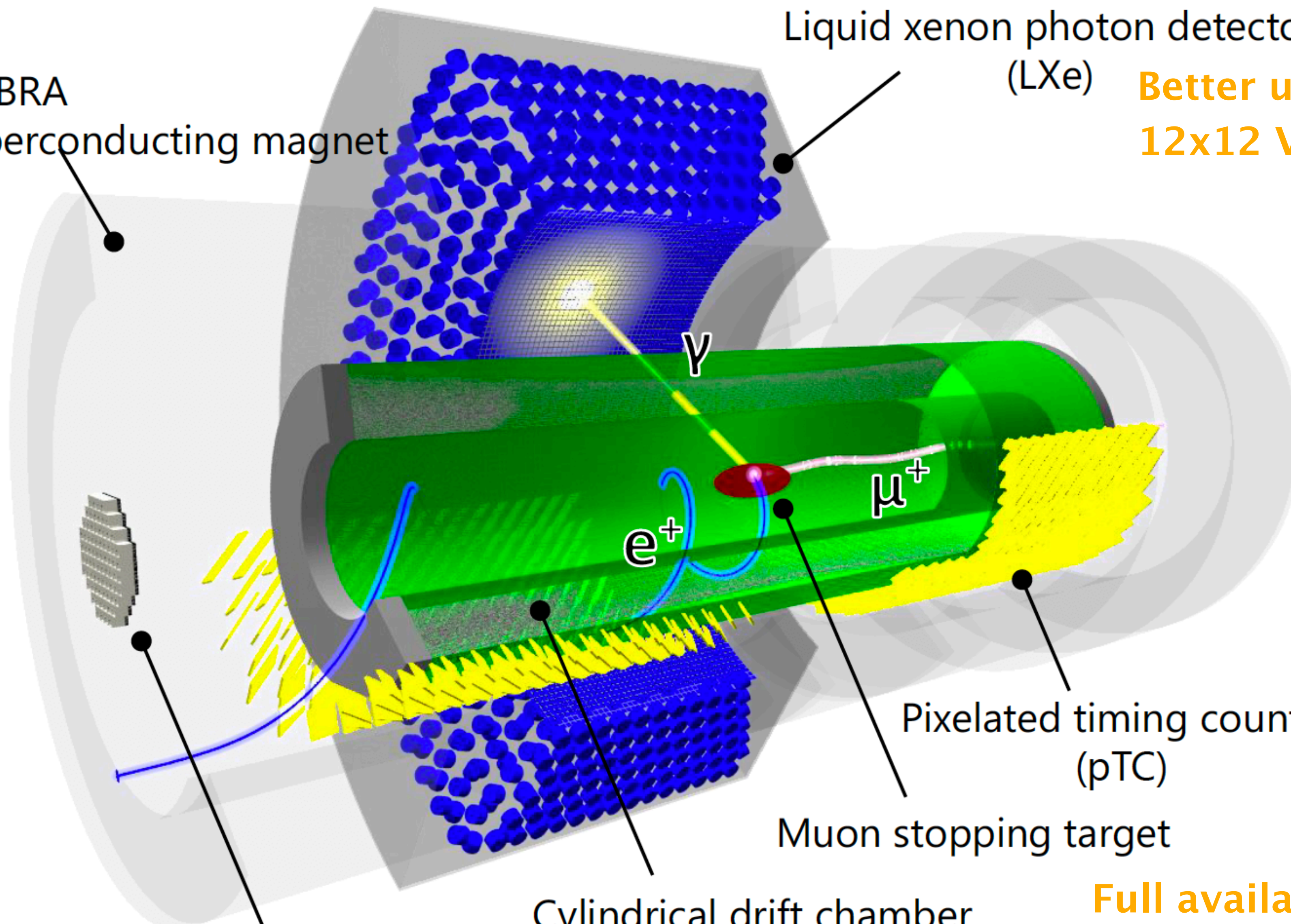
Best fitted branching ratio at 90% C.L.:

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

The MEGII experiment

New electronics:
Wavedream

~9000 channels at 5GSPS



Better uniformity w/ 12x12 VUV SiPM

x2 Resolution everywhere

x2 Beam Intensity

35 ps resolution w/ multiple hits

Updated and new Calibration methods

Quasi mono-chromatic positron beam

Background rejection

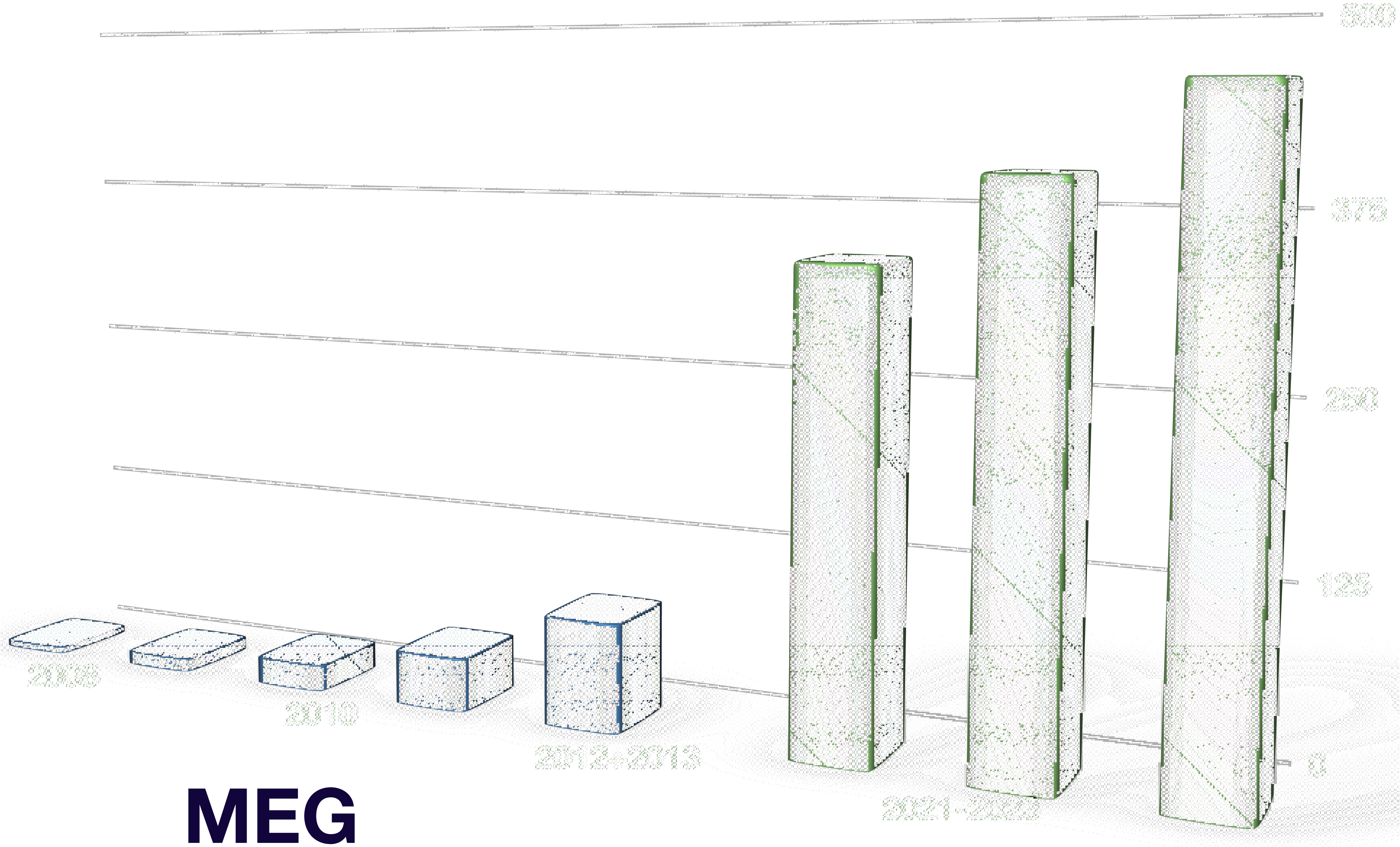
Single volume $He:iC_4H_{10}$

Full available stopped beam intensity 7×10^7

Where we will be

SES ~ 6×10^{-14}

k factor ($\times 10^{11}$)



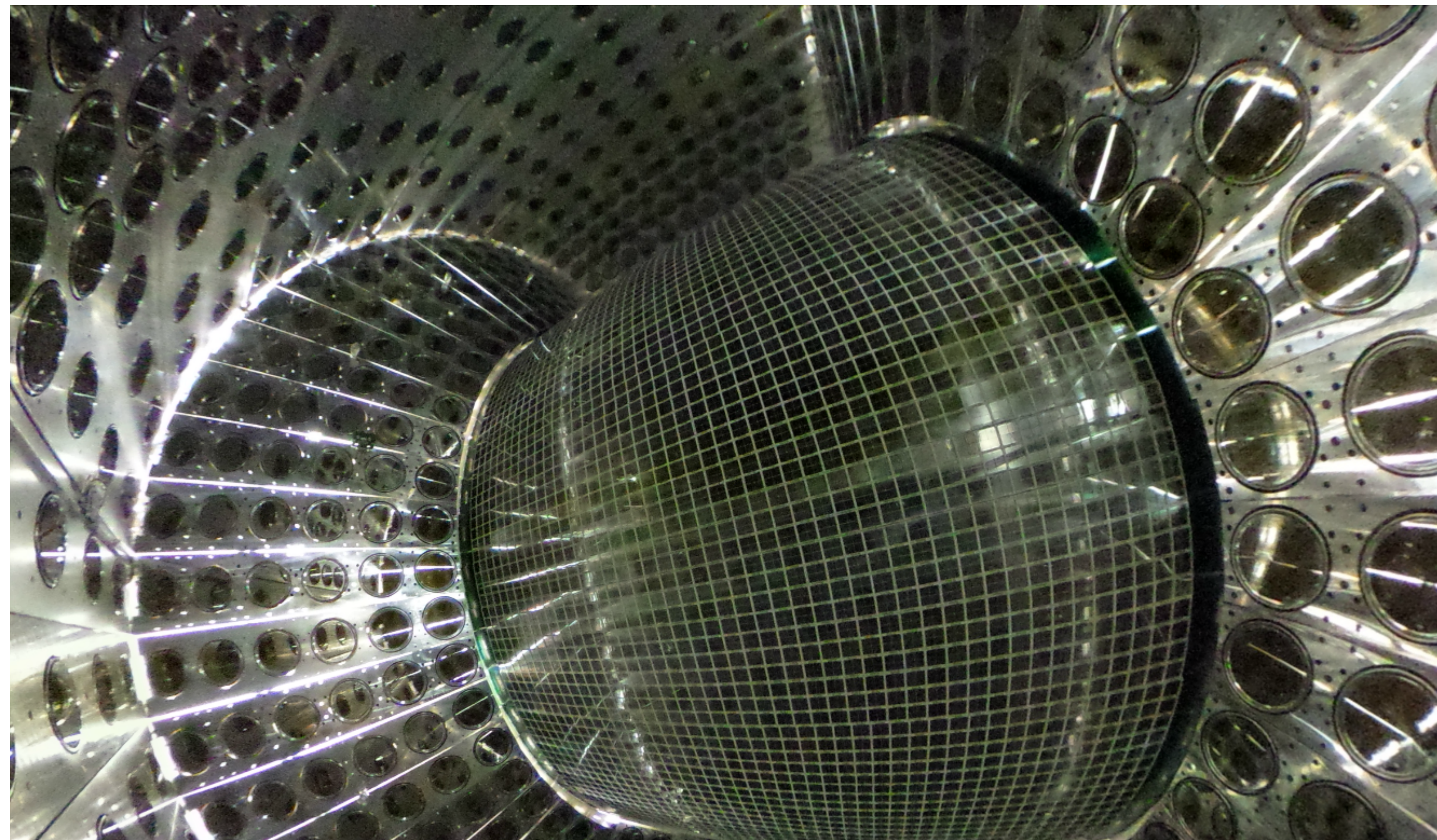
MEG

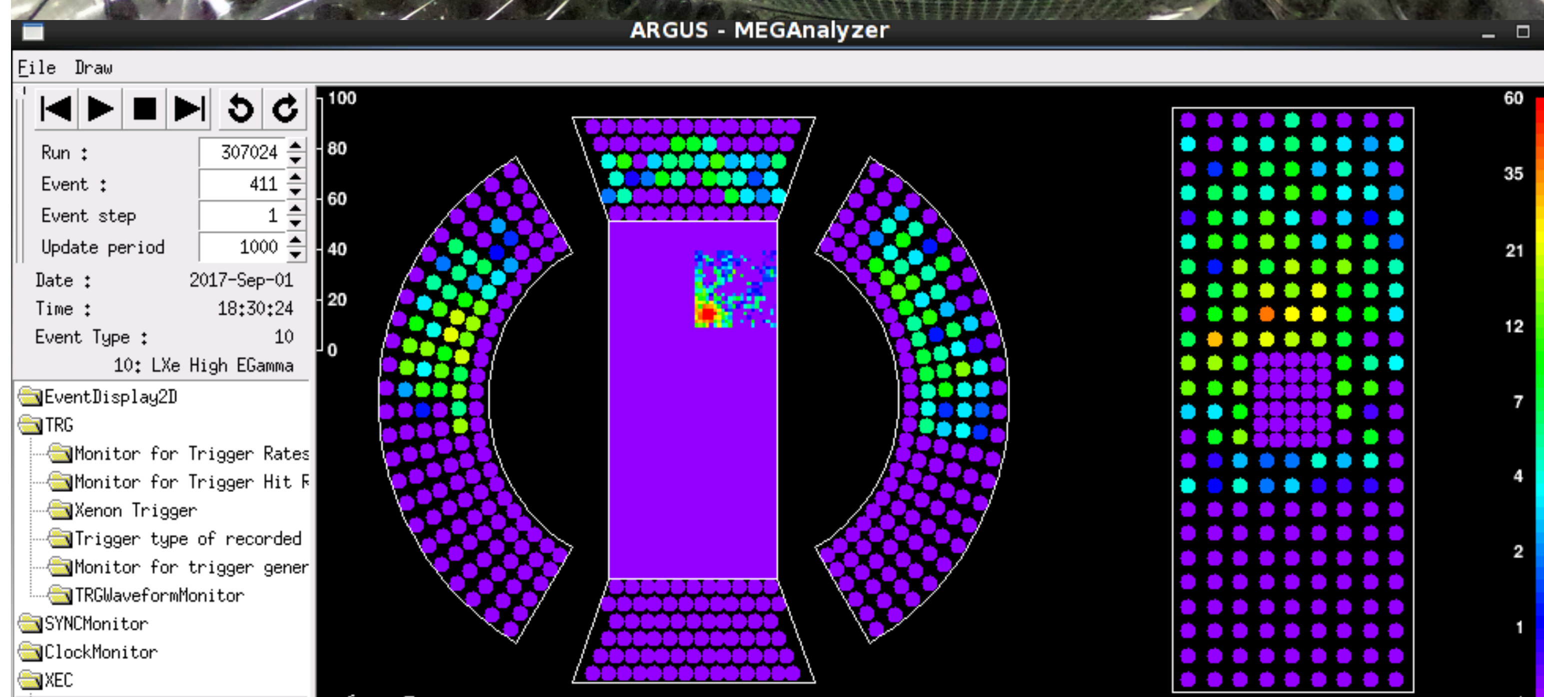
MEGII

MEGII: The upgraded LXe calorimeter

- Final aim: To confirm with data that the expected detector performances will be achieved and maintained over the time
- Xe Light Yield and purity
- Photosensor behaviour (gain, PDE/QE) at high beam intensity
- Evaluation of the gamma kinematical variables with the whole TDAQ: Energy (O(4000 channels)), Time and Positions. Low level noise crucial (i.e. coherent contribution)
- Current study: Based on a limited amount of channels

	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



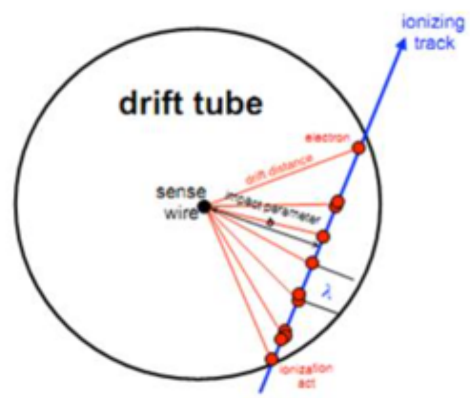


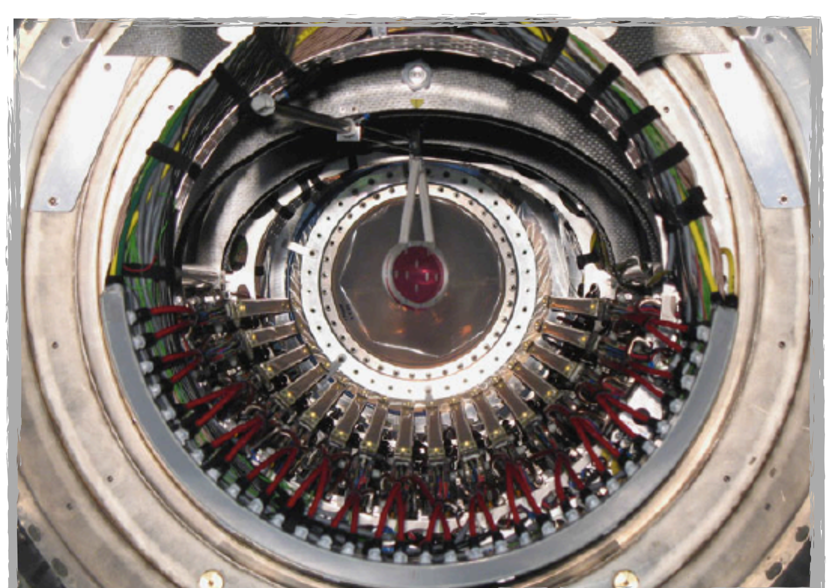
MEGII: The new single volume chamber

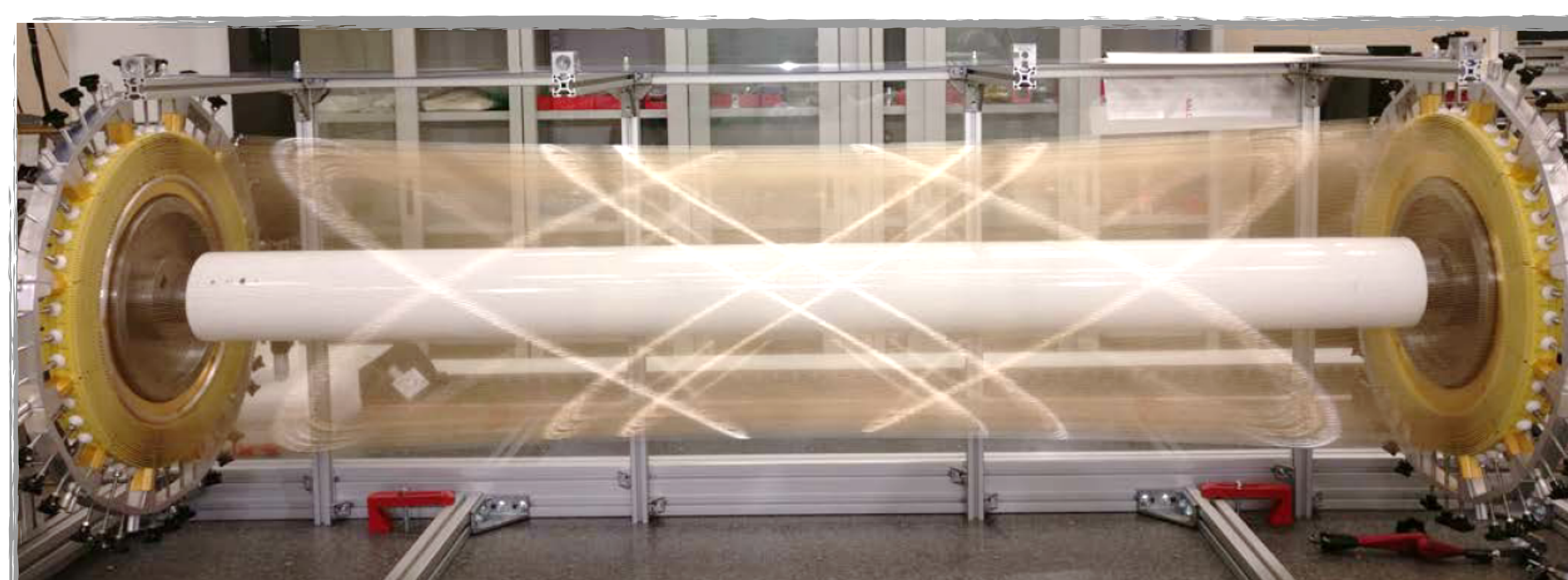
- Improved hit resolution: σ_r ~< 120 um (210 um)
- High granularity/Increased number of hits per track/cluster timing technique
- Less material (helium: isobutane = 90:10, 1.6×10^{-3} X_0)
- High transparency towards the TC
- Assembly: Completed!

	MEG	MEGII
p [keV]	306	100
θ [mrad]	9.4	6.3
ϕ [mrad]	8.7	5.0
ϵ [%]*	40	70

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



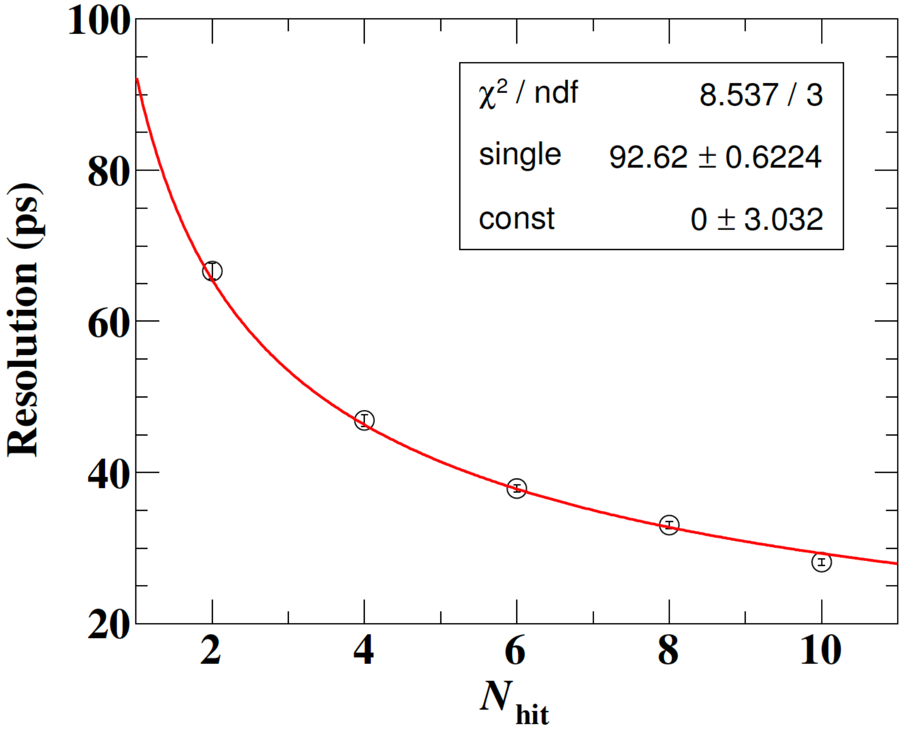


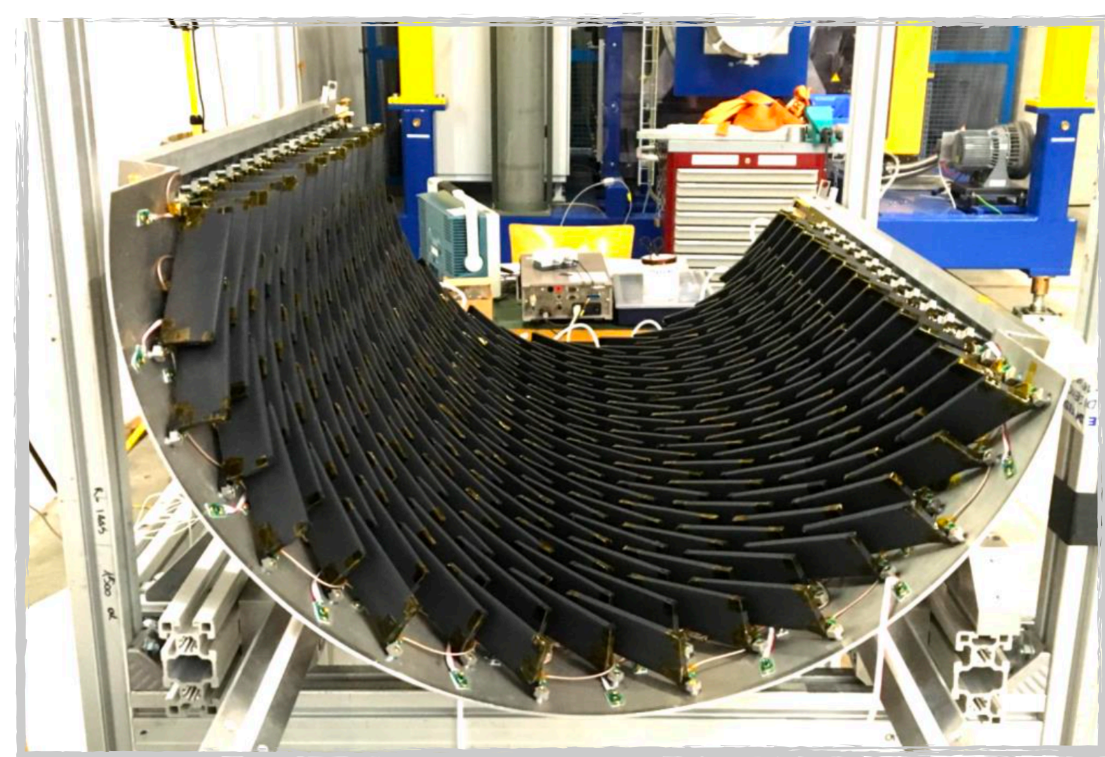


MEGII: the pixelized Timing Counter

- 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
- Expected detector performances confirmed with data

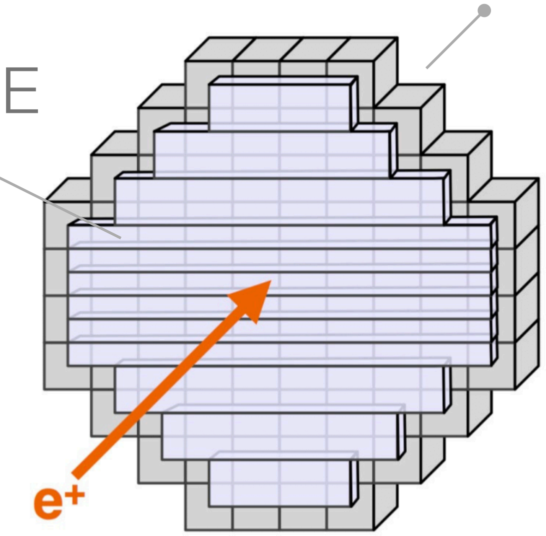
Pilot run 2016

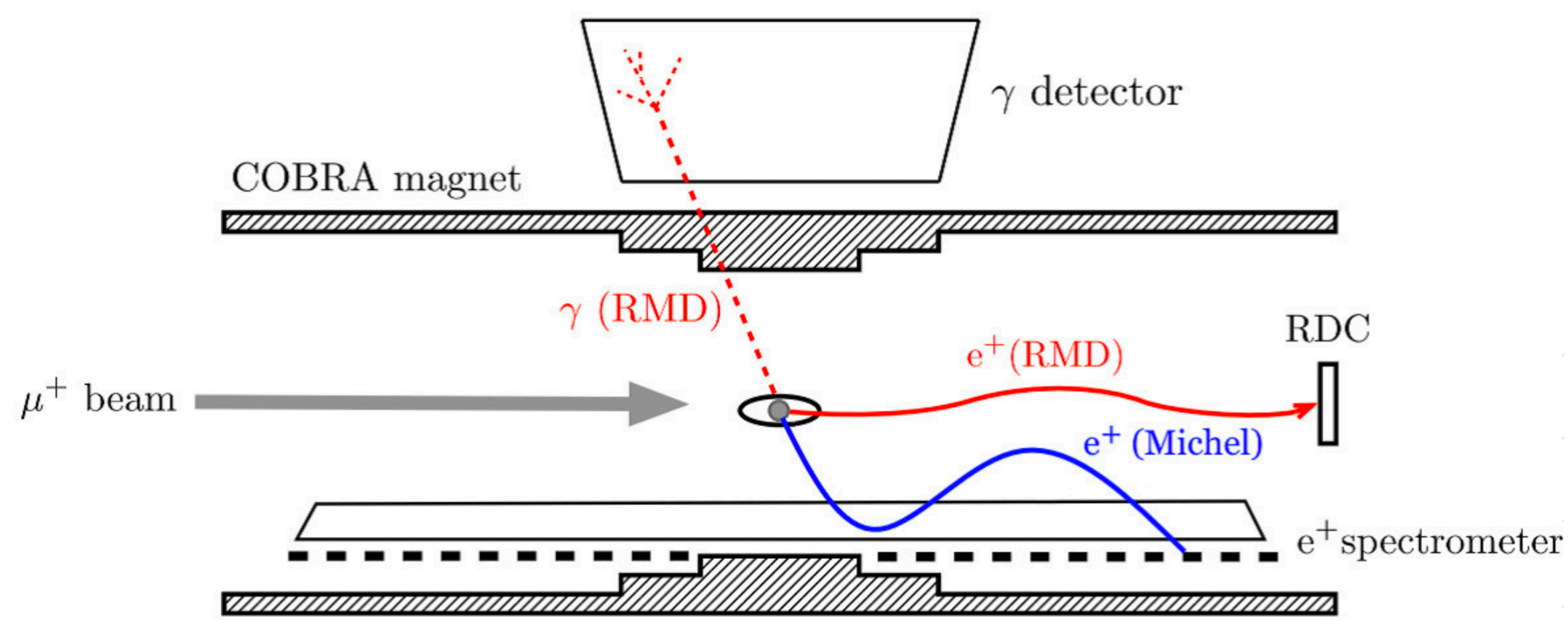


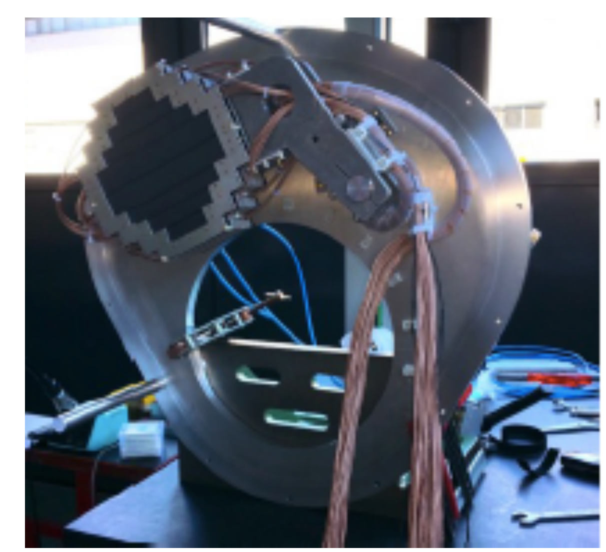


MEGII: The Radiative Decay Counter

- 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

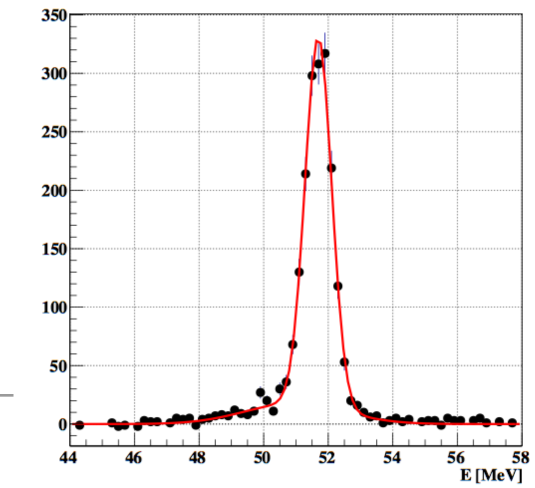


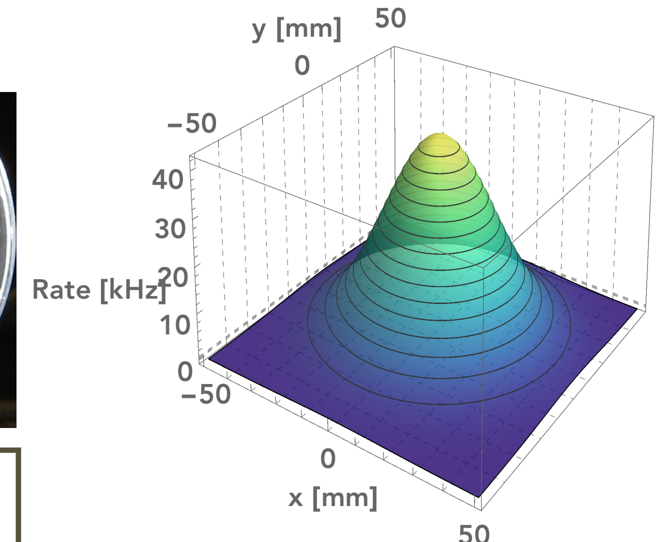


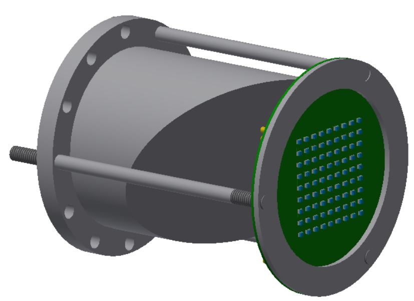


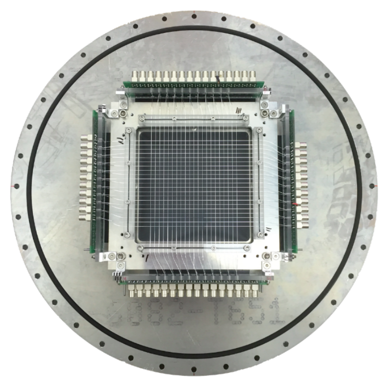
MEG/II: The calibration methods

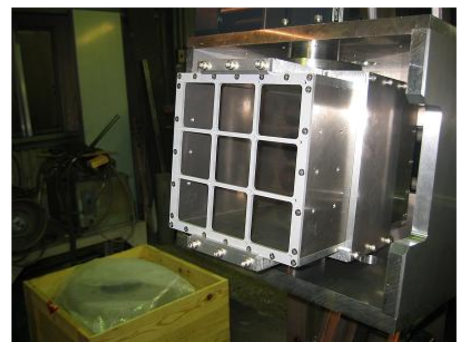
- Multiple calibration and monitoring methods: detector resolution and stability are the key points in the search for rare events over the background

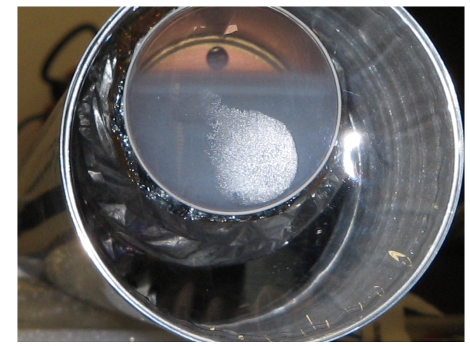




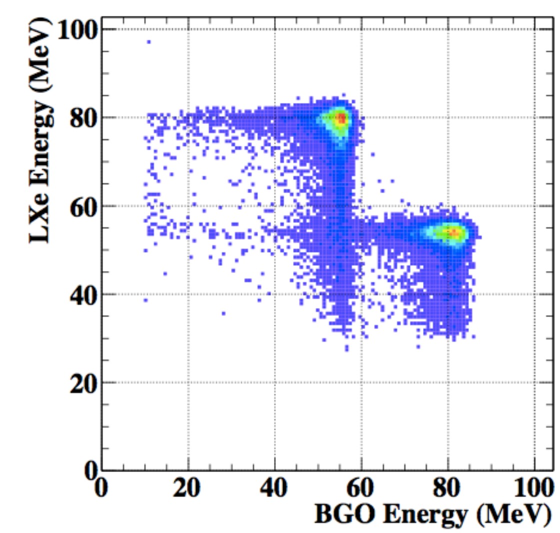


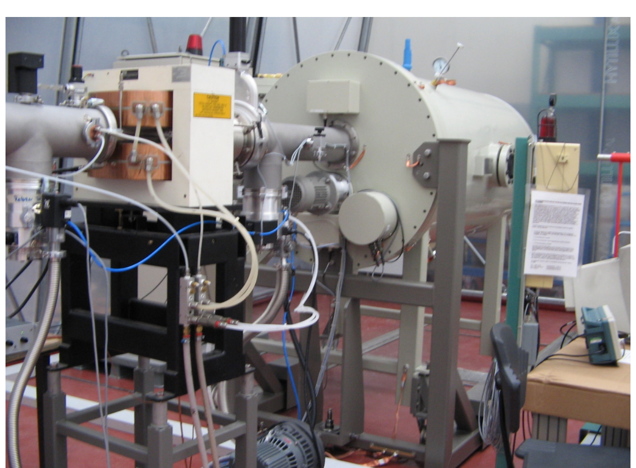


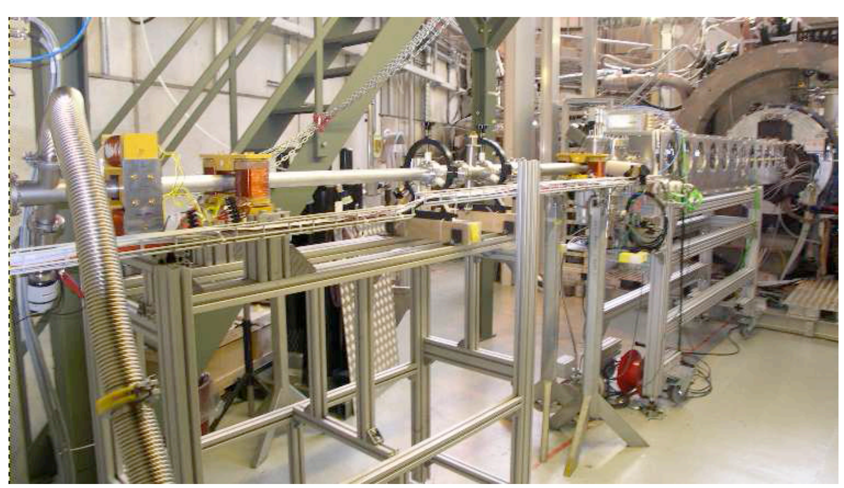


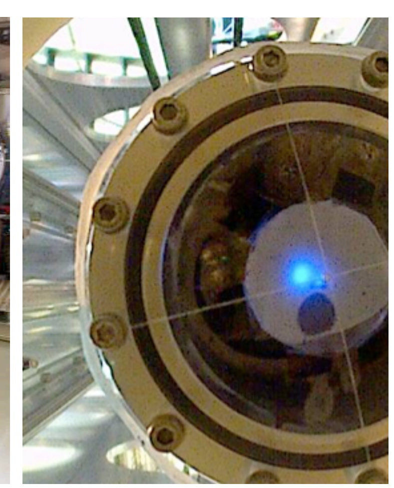


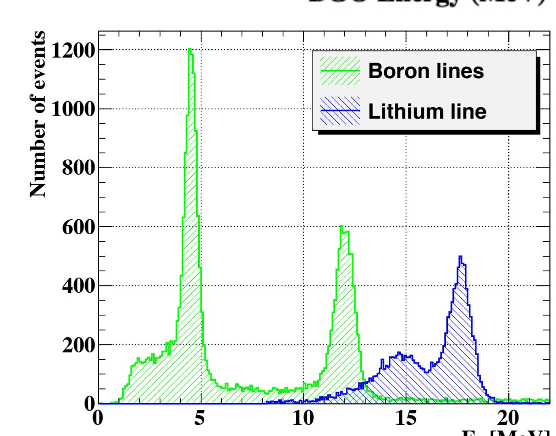
Process		Energy (MeV)	Frequency
CEX reaction	$p(\pi^-, \pi^0)n, \pi^0 \to \gamma\gamma$	55, 83	annually
C-W accelerator	$^7Li(p, \gamma_{17.6})^8Be$	17.6	weekly
	$^{11}B(p, \gamma_{11.6})^{12}C$	4.4&11.6	weekly
Neutron Generator	$^{58}Ni(n, \gamma_9)^{59}Ni$	9	daily
Mott Positrons	$p(e^+, e^+)p$	53	annually





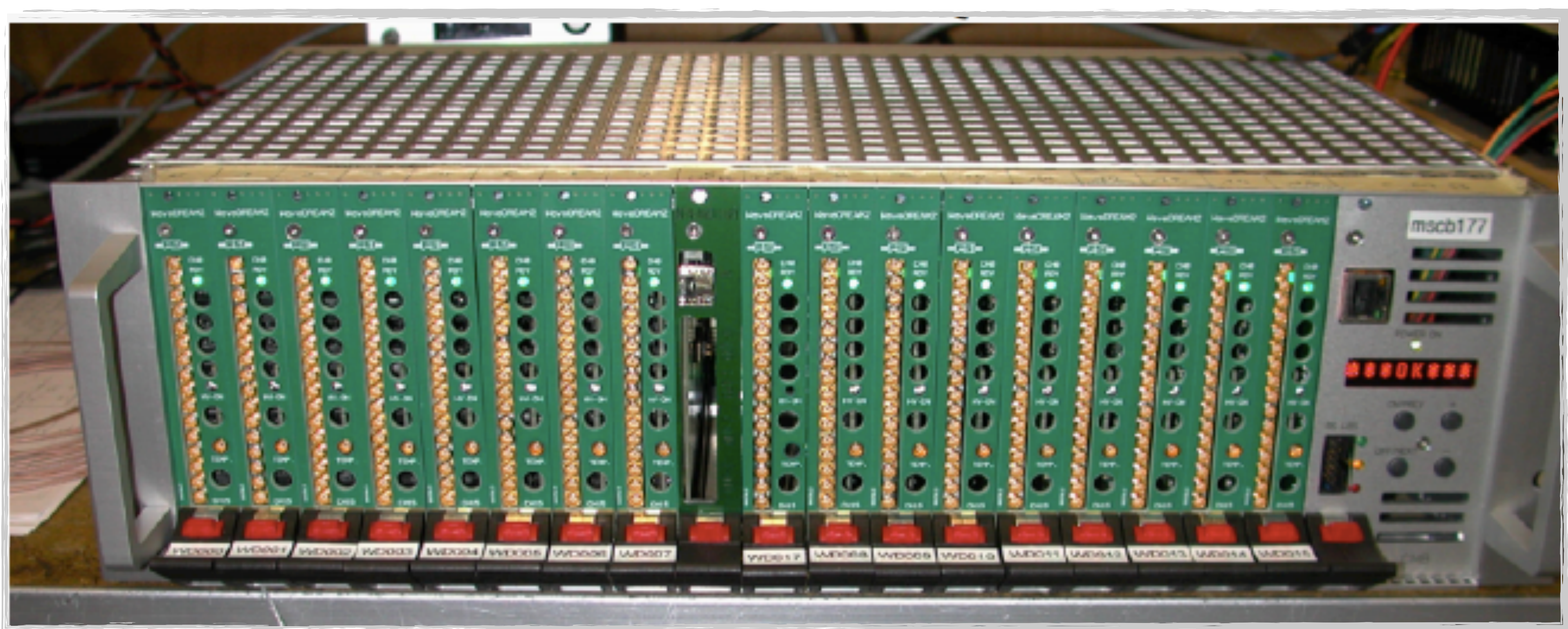






MEGII: The new electronic - DAQ and Trigger

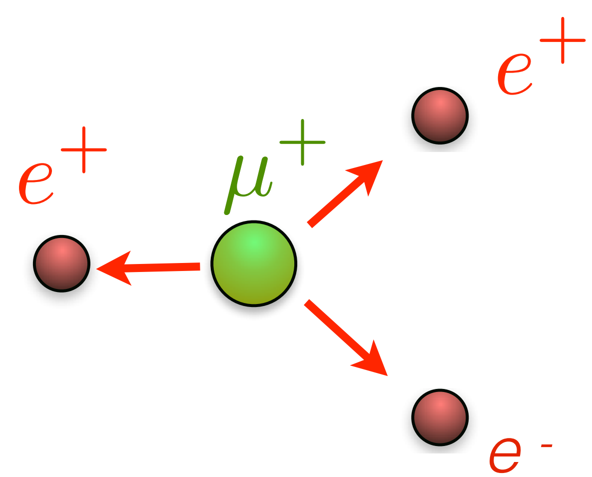
- DAQ and Trigger
  - ~9000 channels (5 GSPS)
  - Bias voltage, preamplifiers and shaping included for SiPMs
- 256 channels (1 crate) abundant tested during the 2016 pre-engineering run; >1000 channels available for the 2017, 2018 and 2019 pre-engineering runs
- Trigger electronics and several trigger algorithms included and successfully delivered for the test beams/engineering runs



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

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

Signature

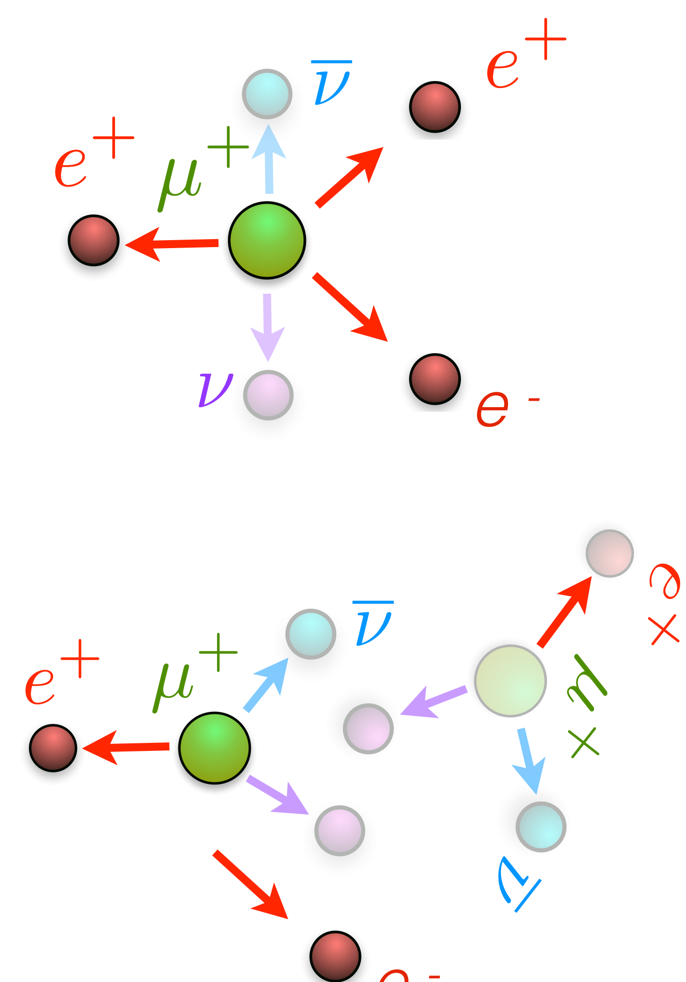


$$\Delta t_{eee} = 0$$

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

$$\Sigma E_e = m_\mu$$

Background



Mu3e: Requirements

Signal

1. $\mu \rightarrow eee$

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

Background

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

- Missing energy: Excellent momentum resolution

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

- Coincidence and vertex: High timing and position resolutions

The Mu3e experiment: Schematic 3D

Superconducting solenoid Magnet

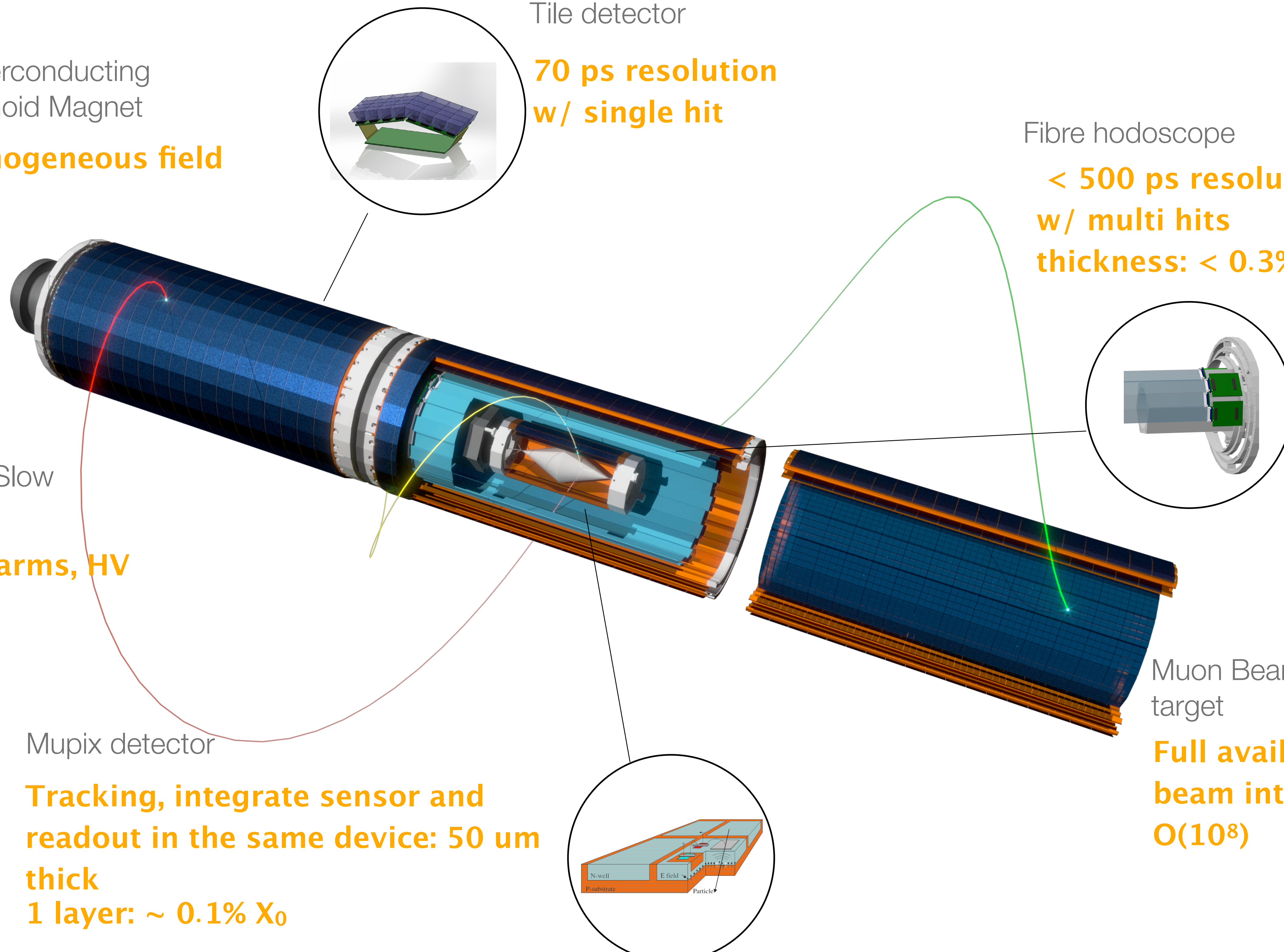
Homogeneous field
1T

Tile detector

70 ps resolution
w/ single hit

Fibre hodoscope

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



MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Muon Beam and target

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

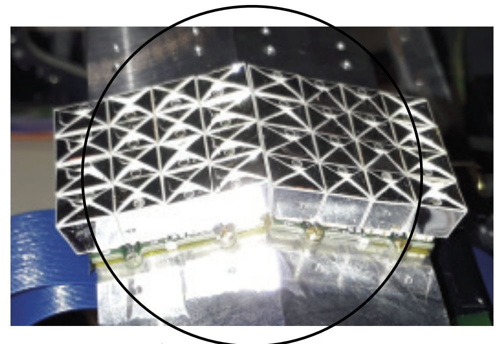
Mupix detector

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

The Mu3e experiment: R&D completed. Prototyping phase

Superconducting solenoid Magnet

Homogeneous field 1T

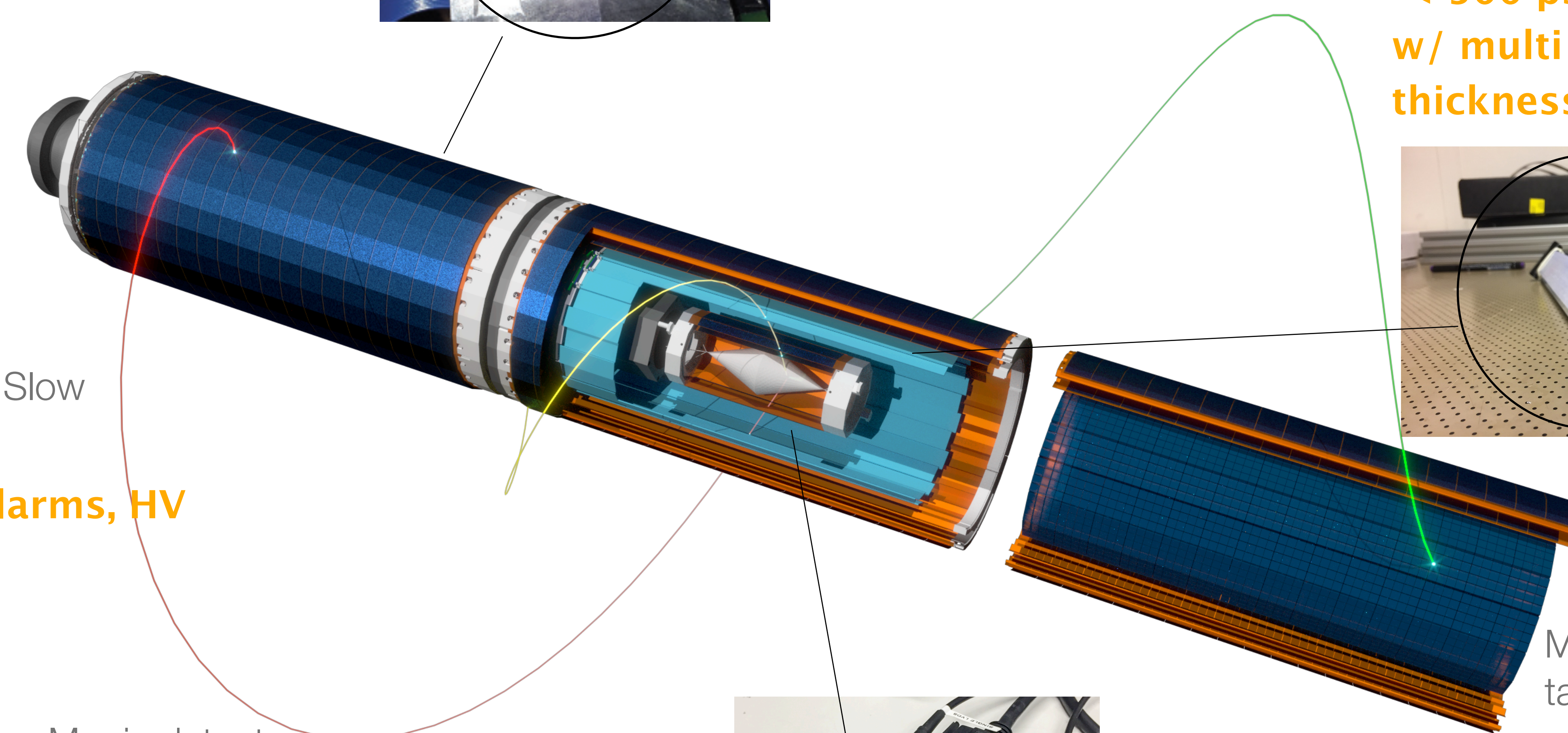


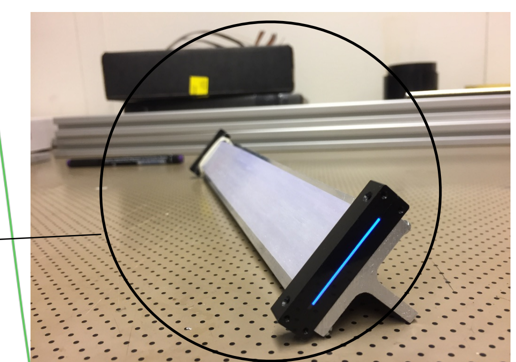
Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

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





MIDAS DAQ and Slow Control

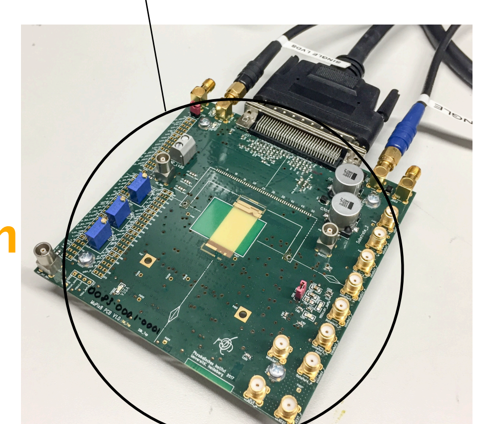
Run, history, alarms, HV etc.

Muon Beam and target

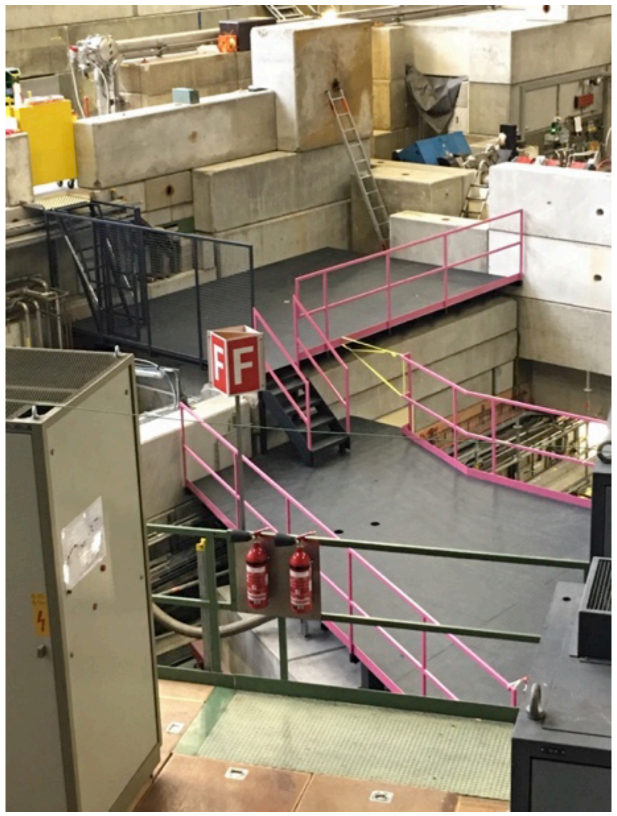
Full available beam intensity O(10^8)

Mupix detector

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

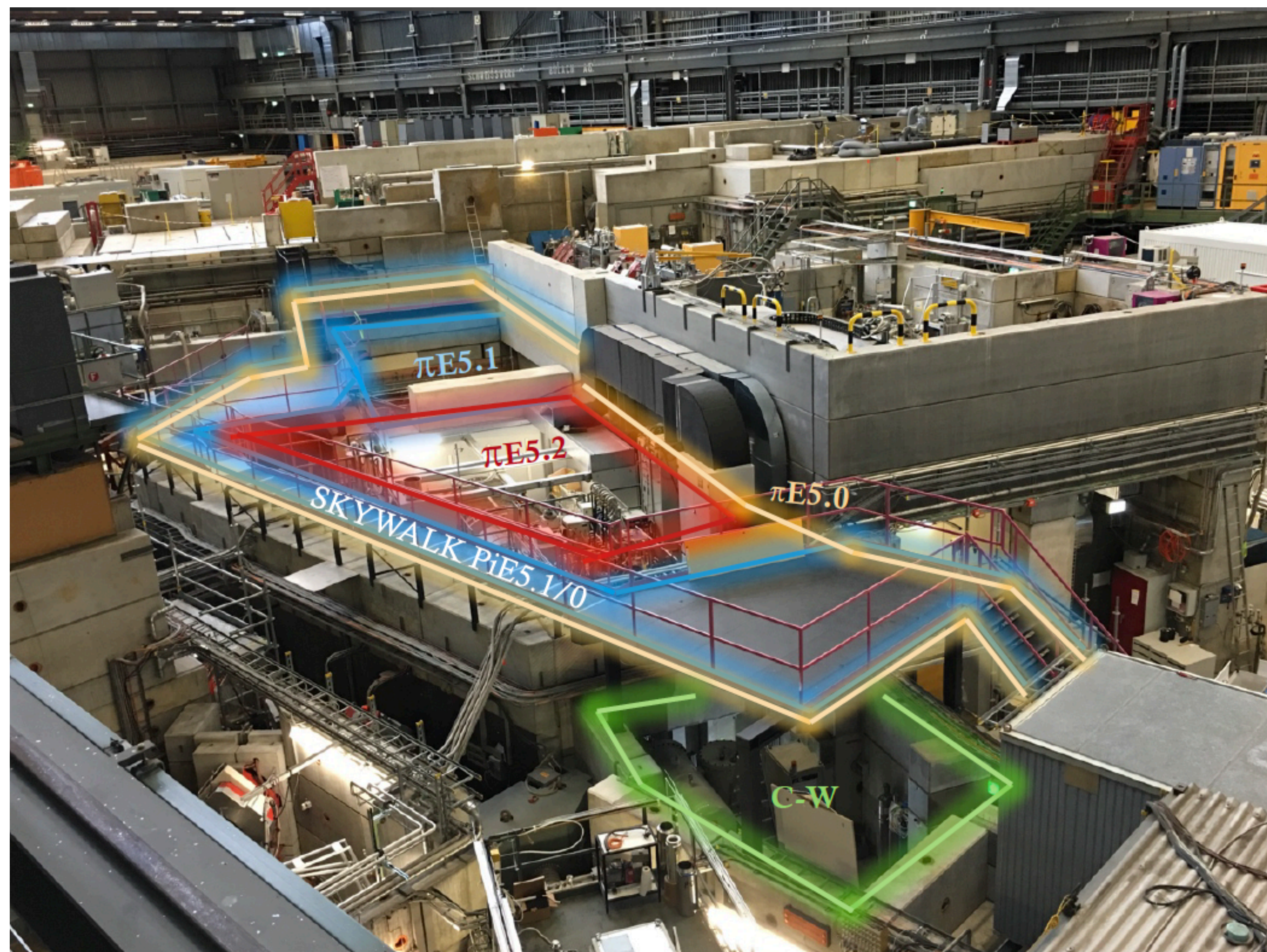


The MEGII and Mu3e experimental area: Pictures



Mu3e extra platforms

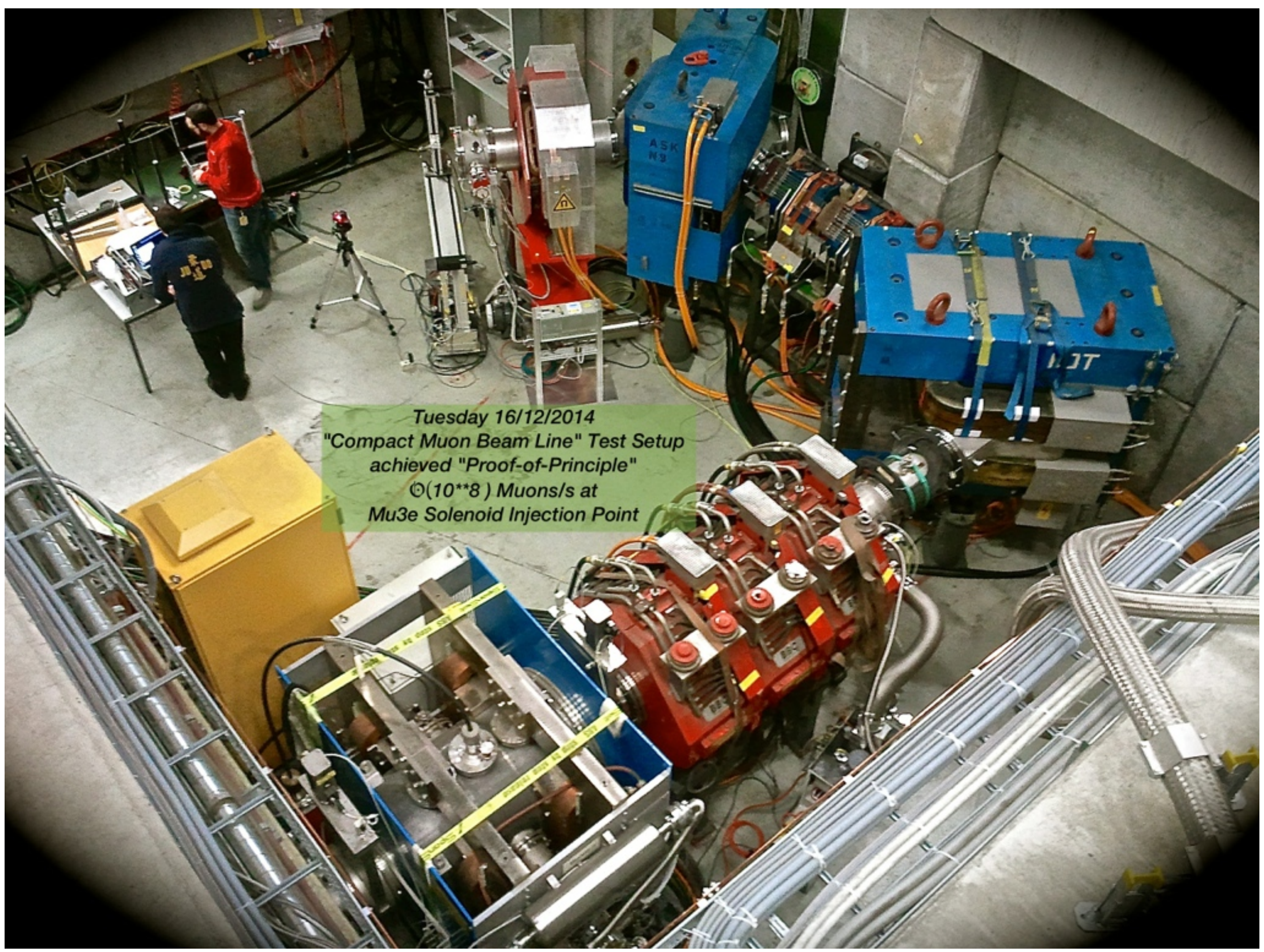
Overview piE5 area



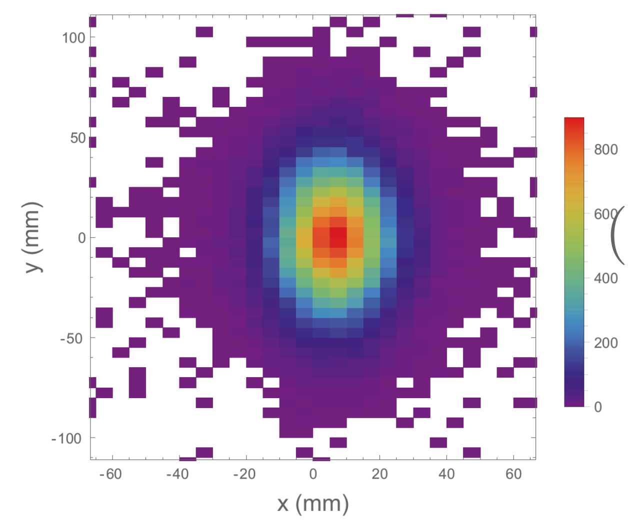
The compact muon beam line: Results

- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered 8 10^7 muon/s during 2016 test beam

The CMBL

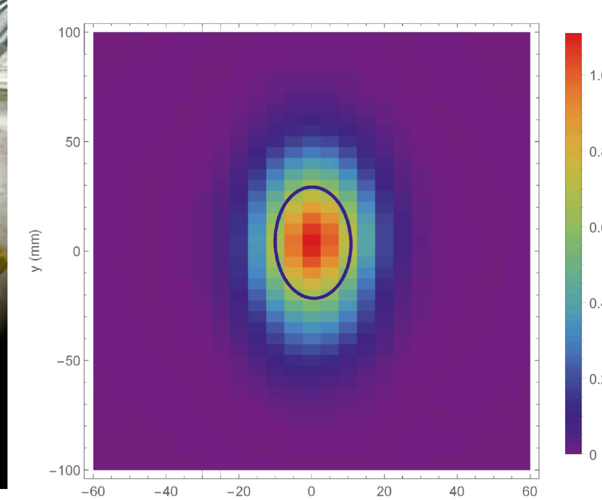


Beam at the injection Mu3e solenoid point



Simulation

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

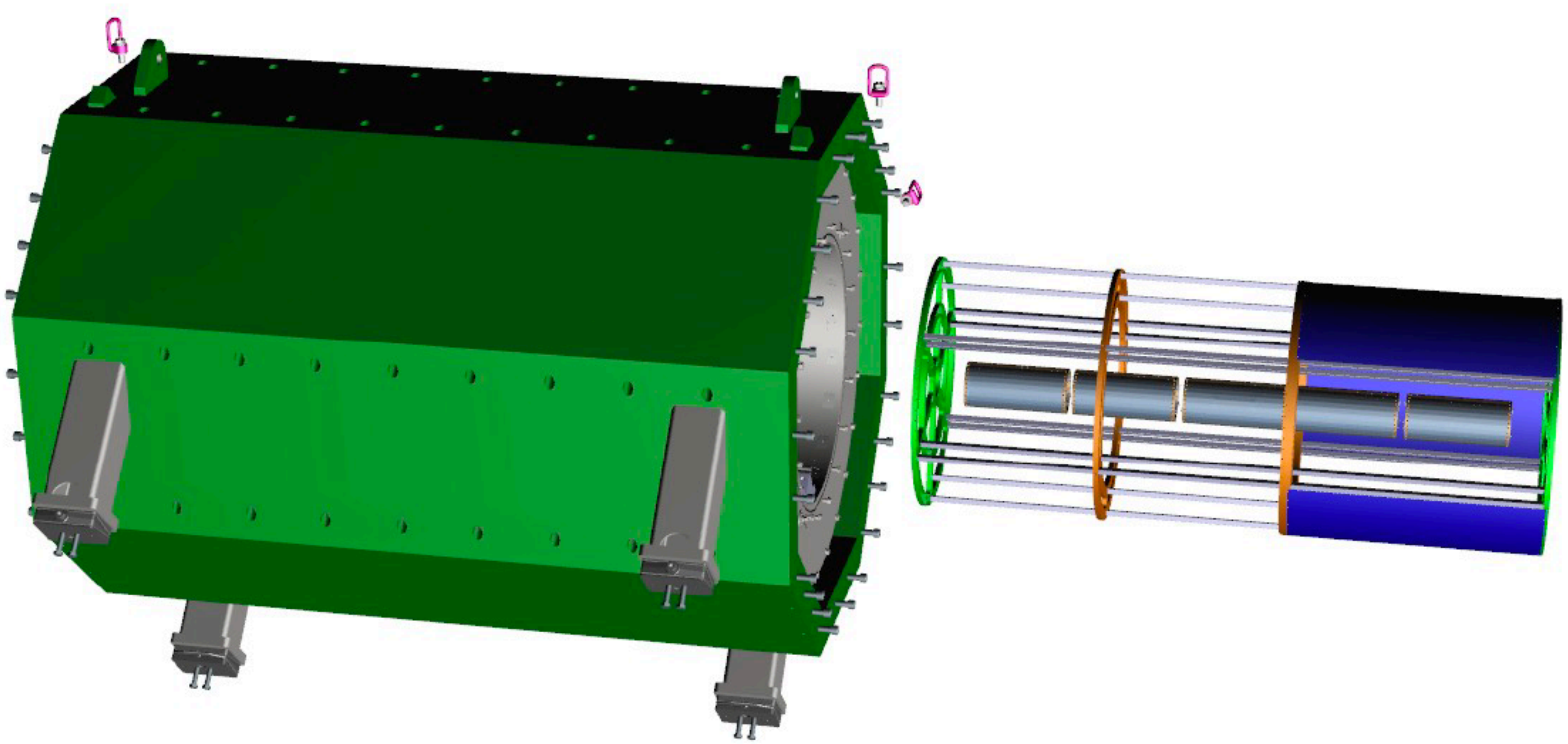


Data

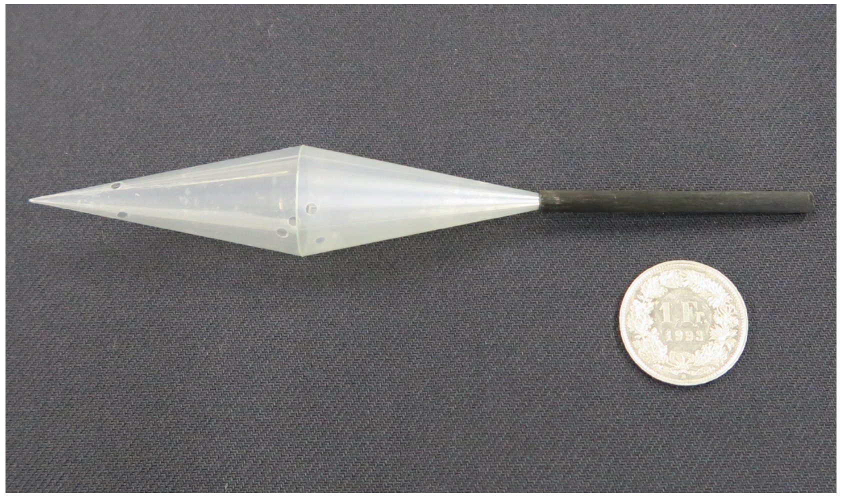
$$(\sigma_x, \sigma_y) = (10.4, 25.4)[\mathrm{mm}]$$

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: in fall this year
- Field Intensity: 1T; Field description: $dB/B \leq 10^{-4}$; Field stability: $dB/B(100\ d) \leq 10^{-4}$

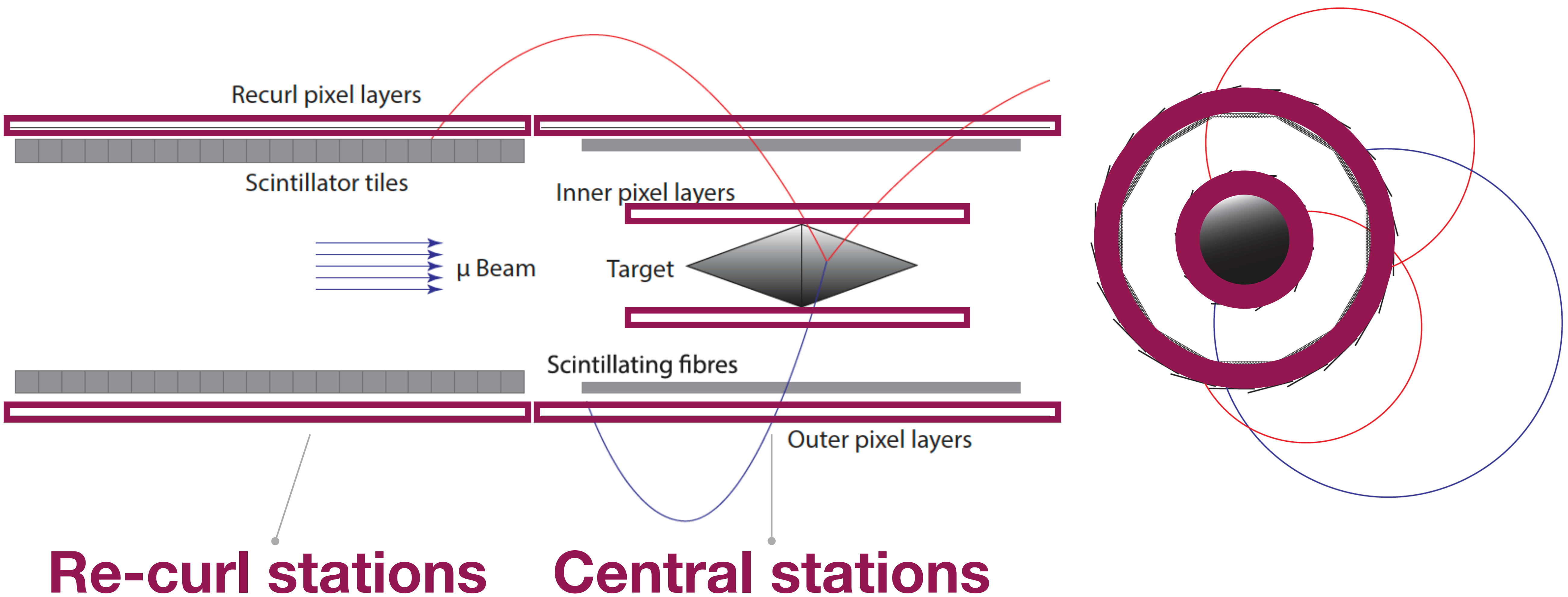


Target prototype



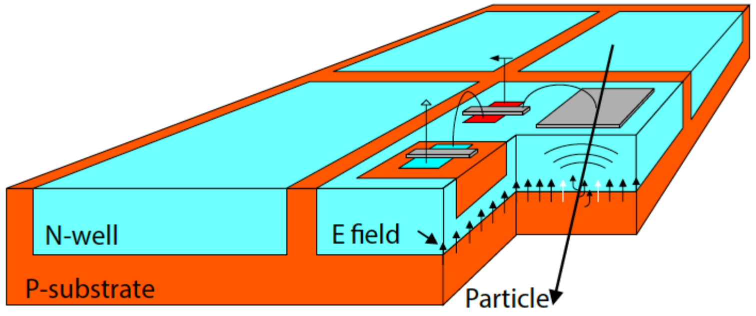
The pixel tracker: Overview

- 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%



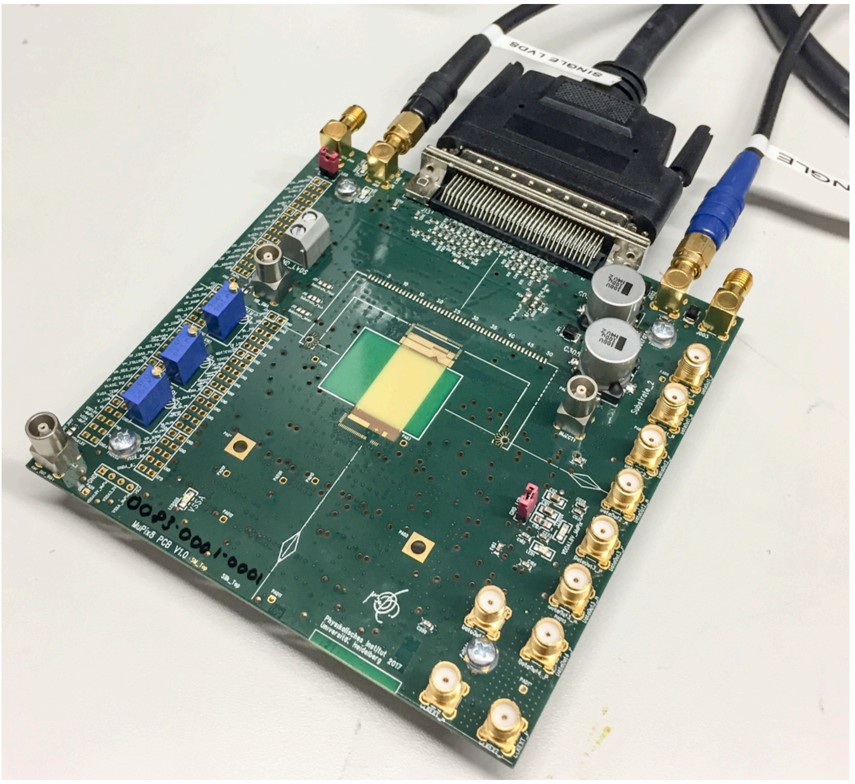
The pixel tracker: The MuPix prototypes

- 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
- 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. 2019 year test beam campaign
- MuPix 10, the final version for Mu3e: 380 mm^2

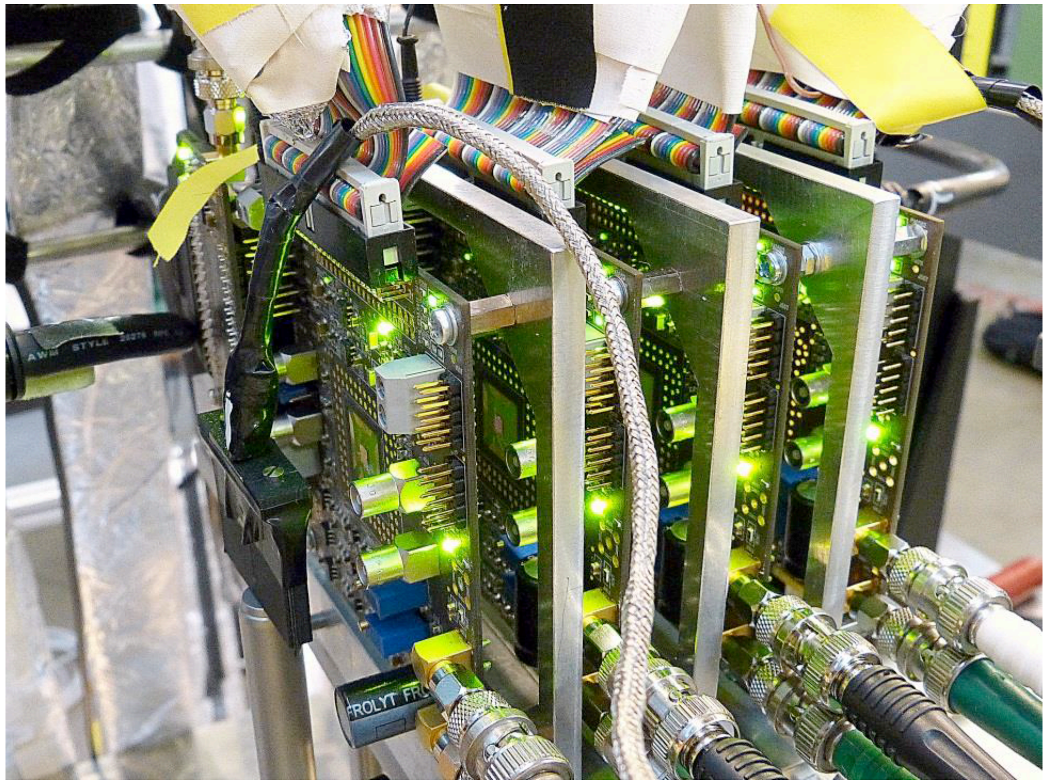


Prototype	Active Area [mm^2]
MuPix1	1.77
MuPix2	1.77
MuPix3	9.42
MuPix4	9.42
MuPix6	10.55
MuPix7	10.55

MuPix8

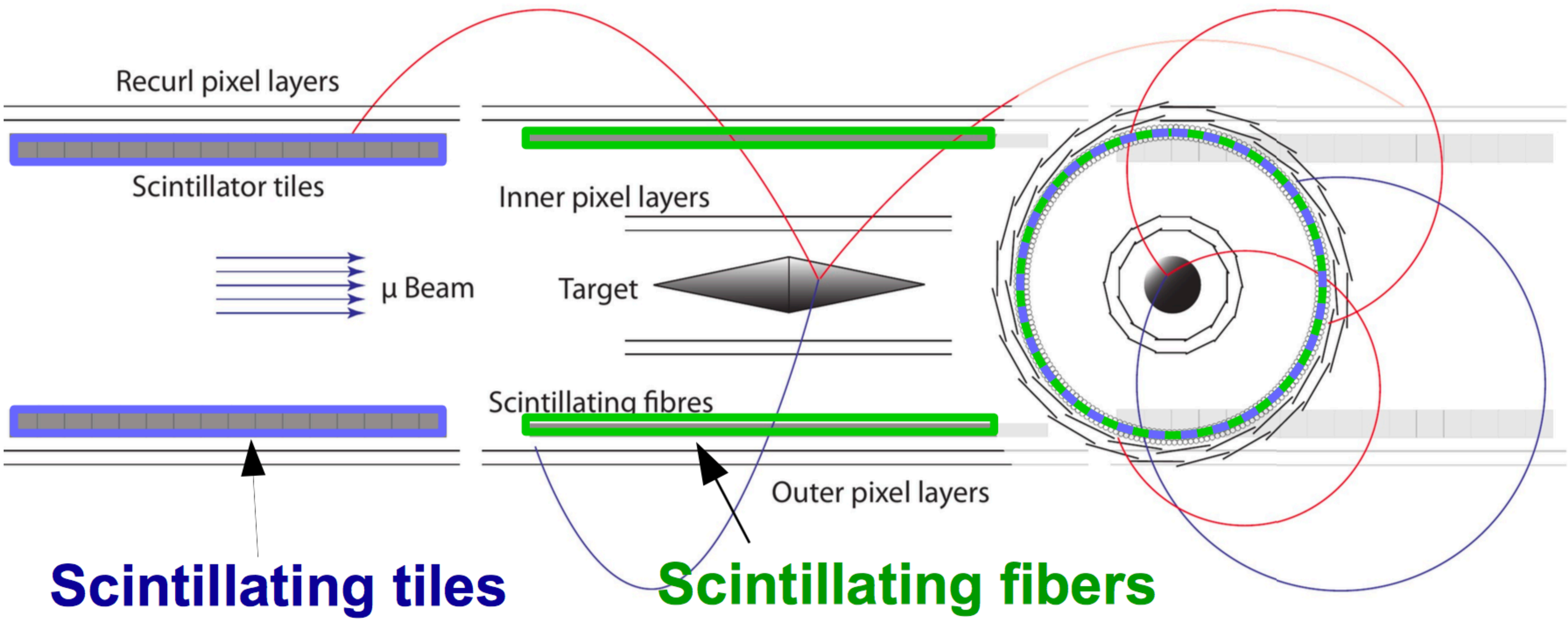


Mupix 7 telescope



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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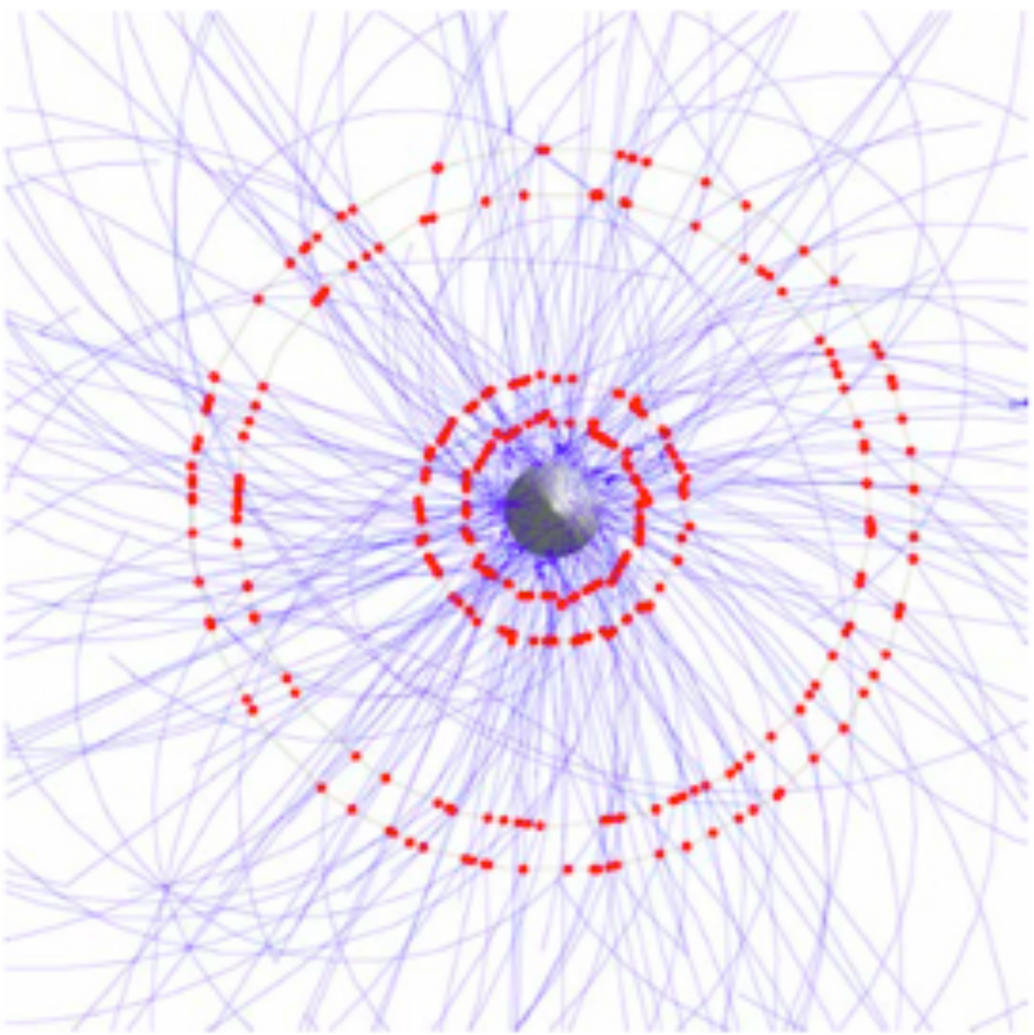
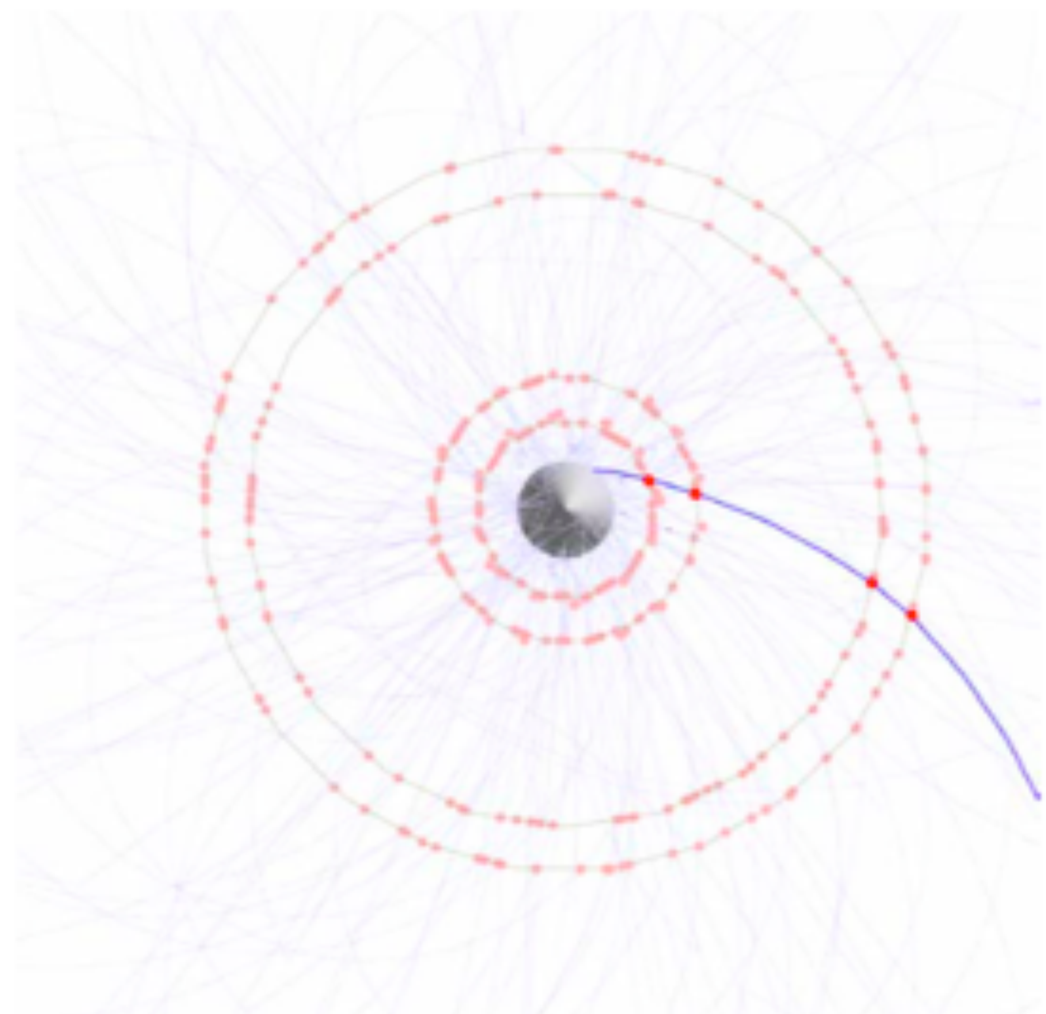


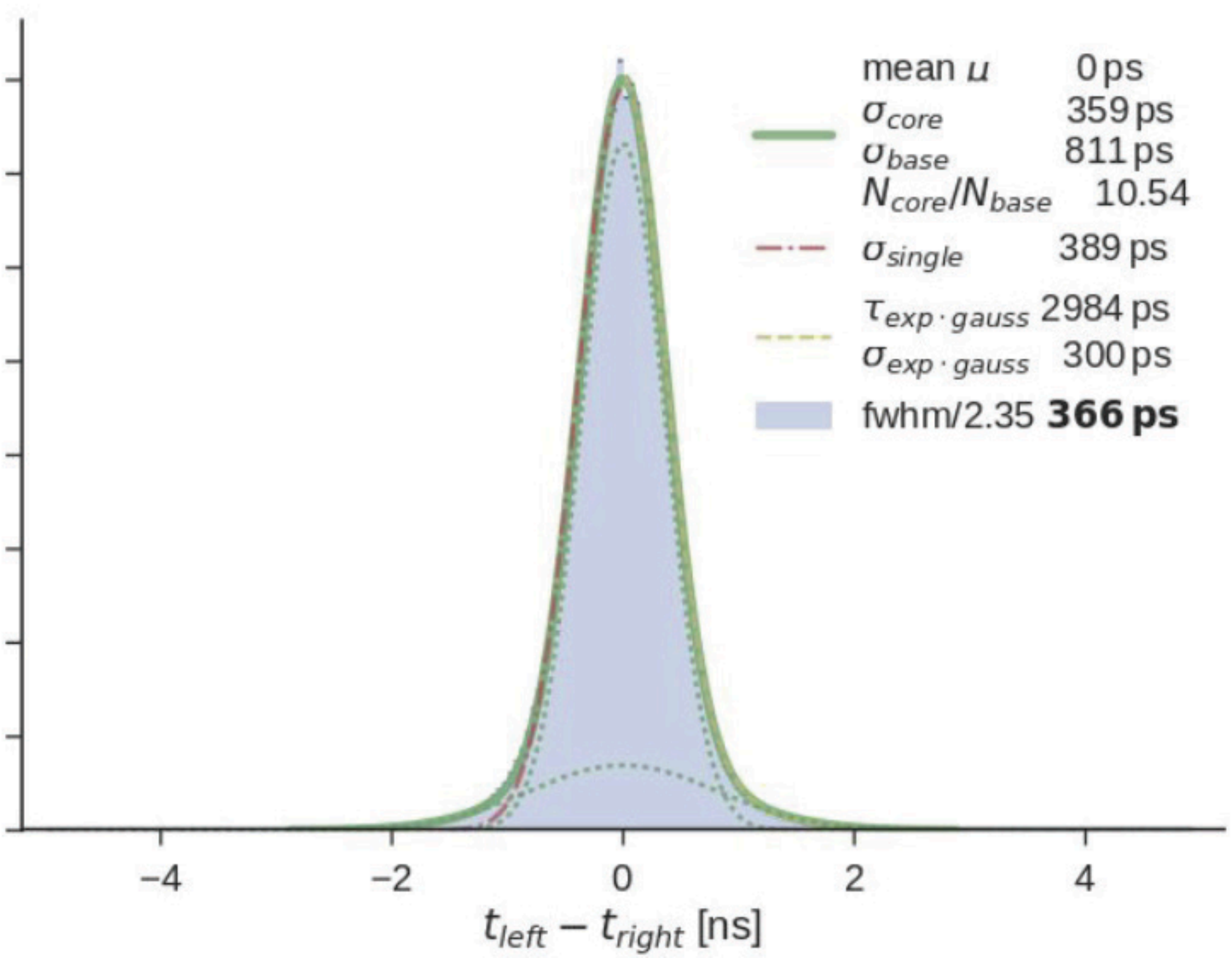
Pixels: O(50 ns)



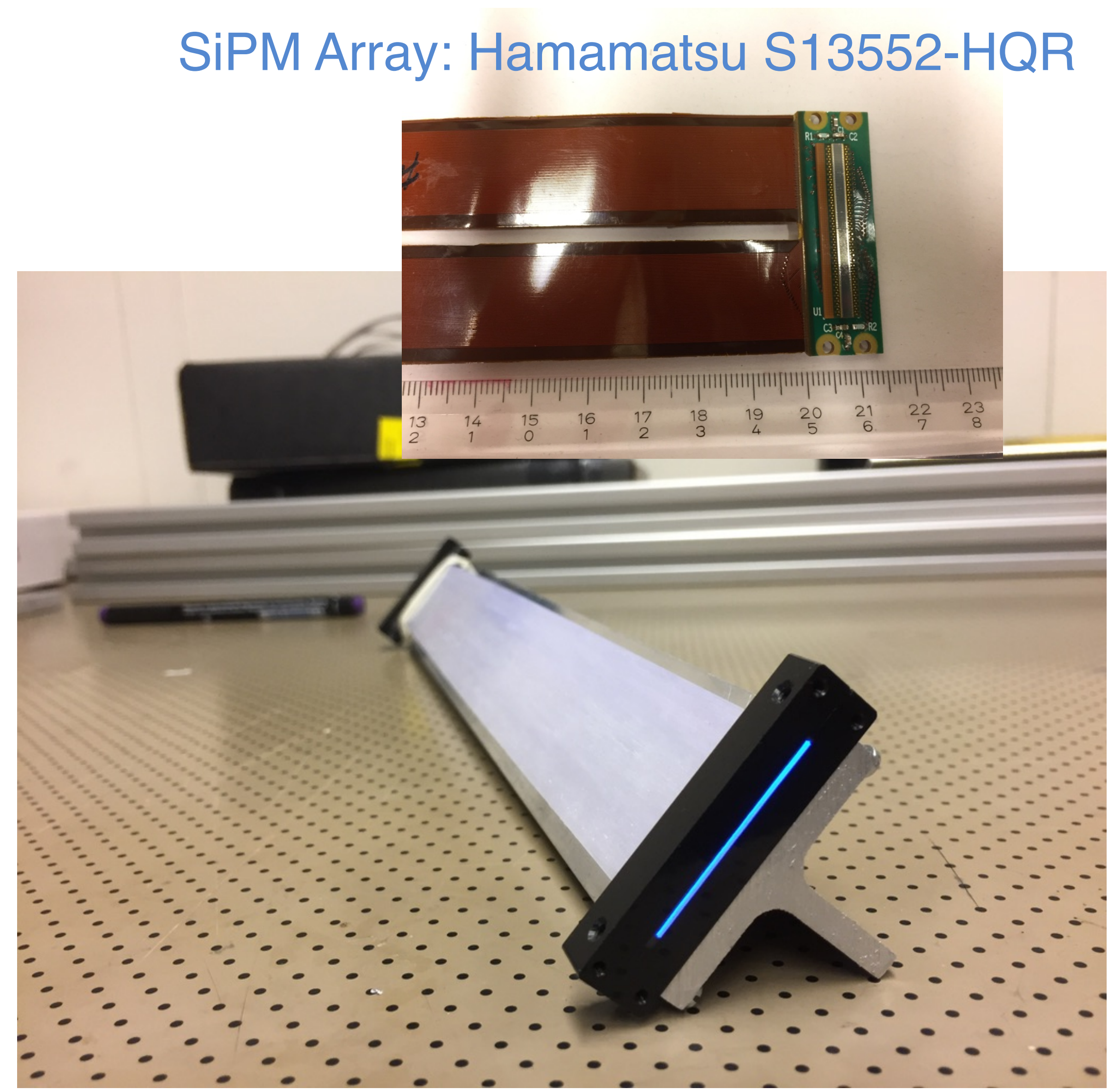
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

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

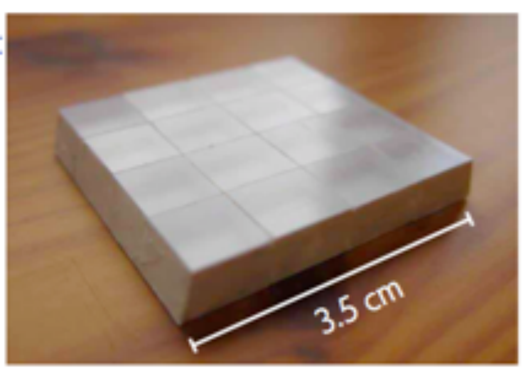


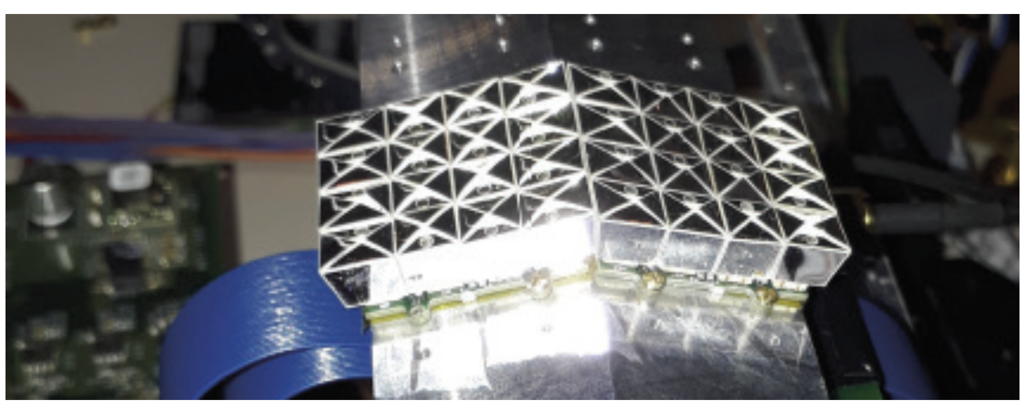
SiPM Array: Hamamatsu S13552-HQR

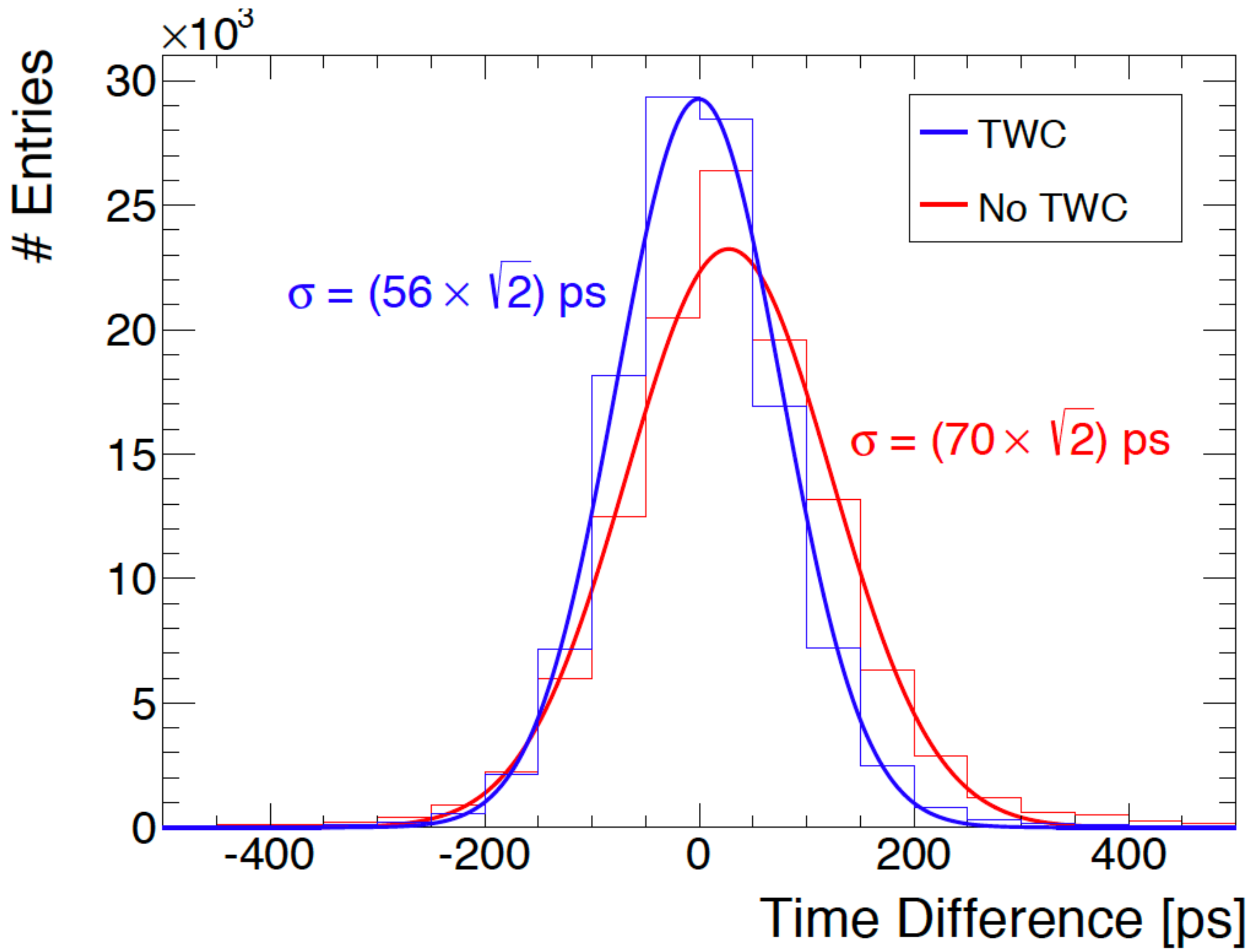


Tile Prototype: Results

- 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





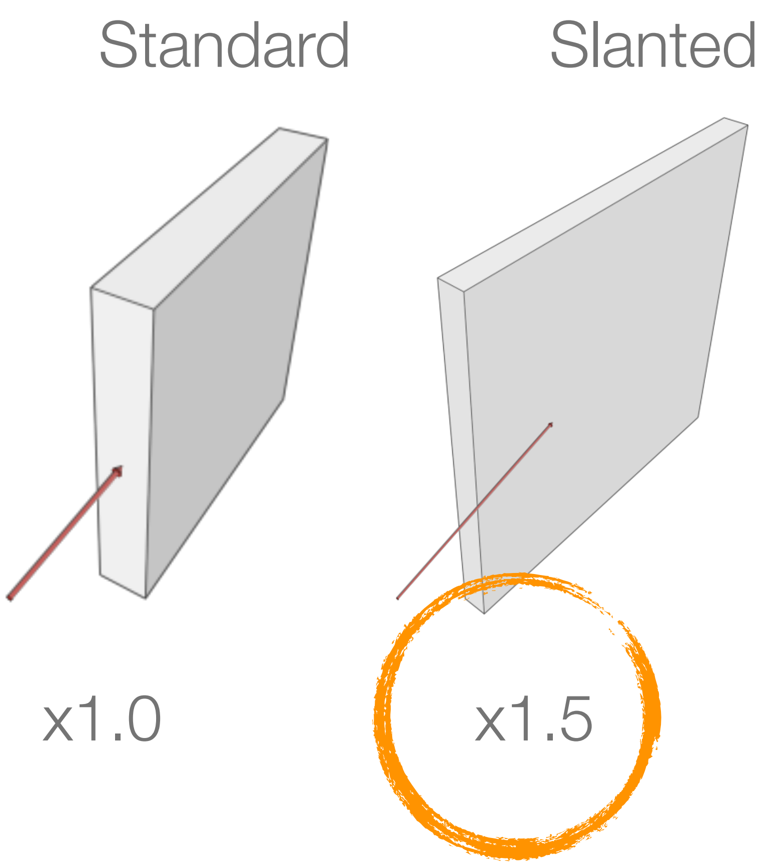


The High intensity Muon Beam (HiMB) project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Strategy:
  - Target optimization
  - Beam line optimization
- Time schedule: **O(2025)**

The High intensity Muon Beam (HiMB) project at PSI

- Target optimization
  - **Target geometry and alternate materials**
    - Search for higher muon yield

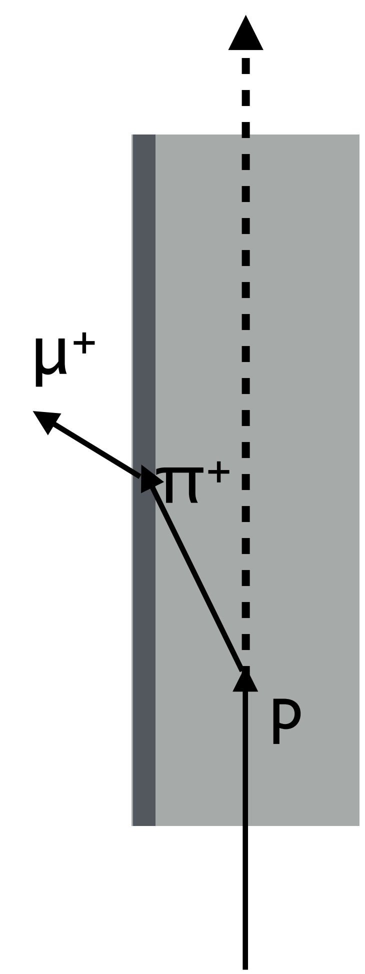


$$\text{relative } \mu^+ \text{yield} \propto \pi^+ \text{stop density} \cdot \mu^+ \text{Range} \cdot \text{length}$$

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_x (Z/A)_x}$$

$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

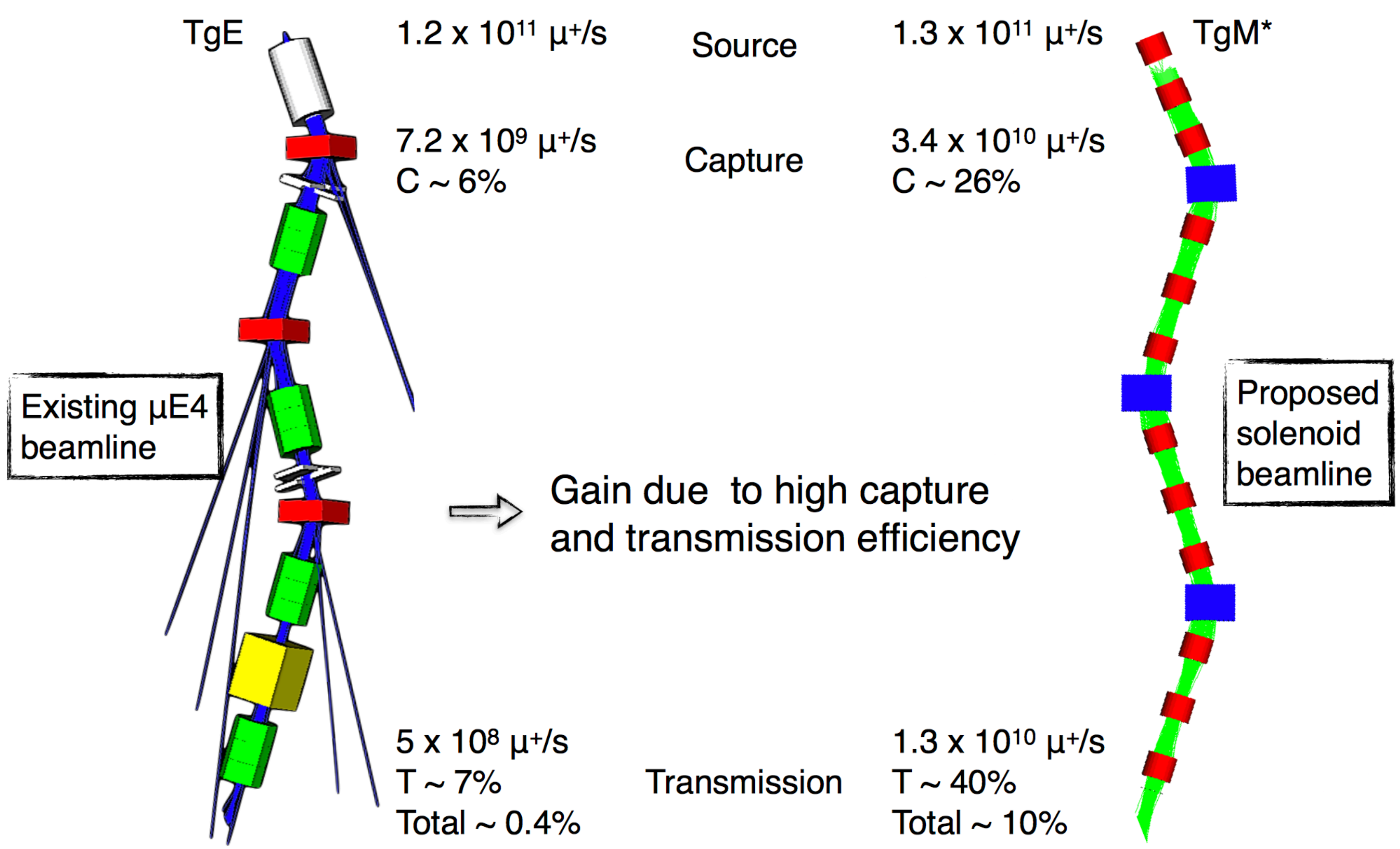
$$\propto \frac{1}{Z^{2/3}}$$



- **50%** of muon beam intensity gain, would corresponds to effectively raising the proton beam power at PSI by **650 kW**, equivalent to a beam power of almost **2 MW** without the additional complications such ad increased energy and radiation deposition into the target and its surroundings

The High intensity Muon Beam (HiMB) project at PSI

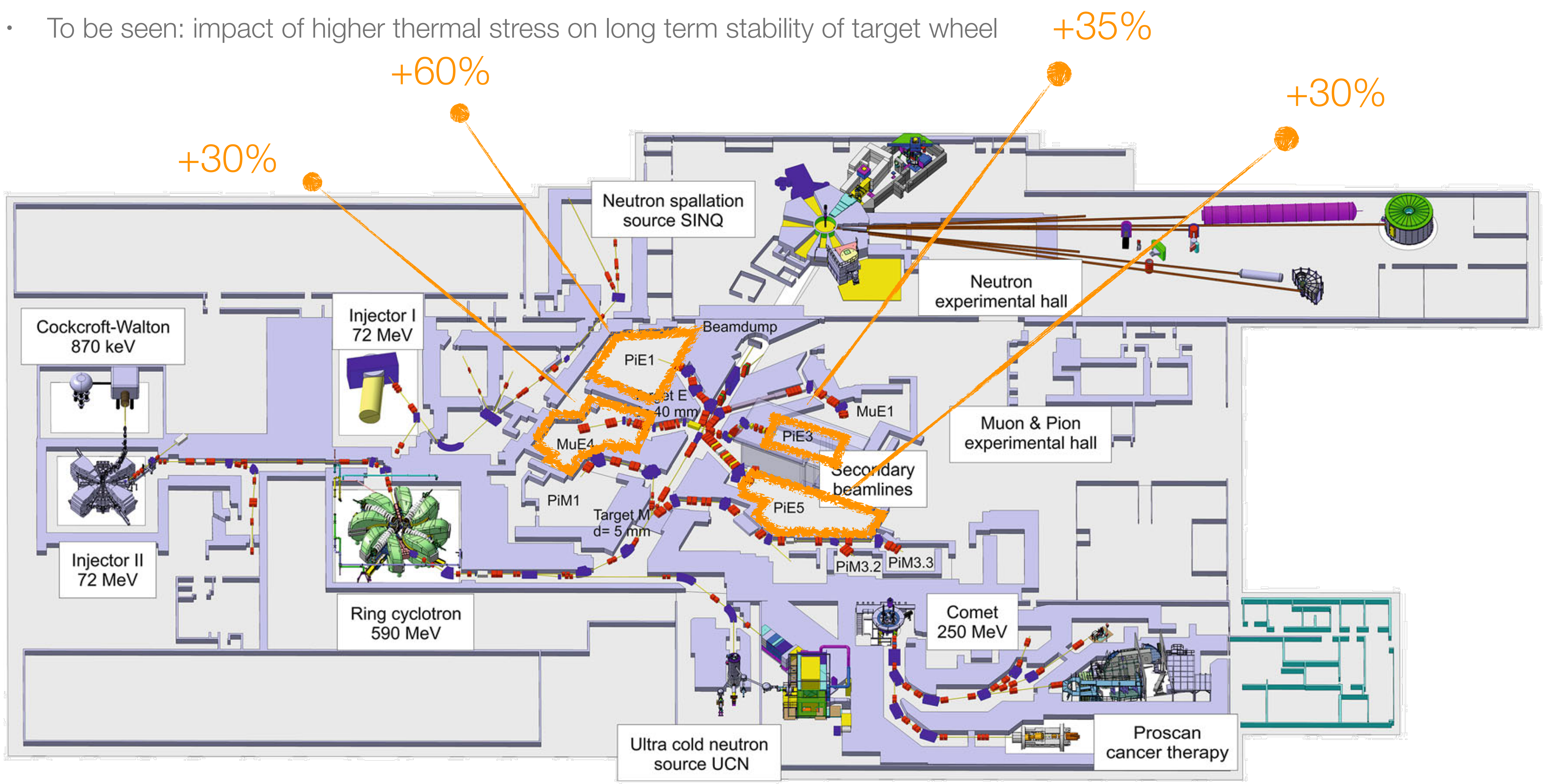
- Beam line optimisation
  - **Increased capture and transmission**



- Put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**

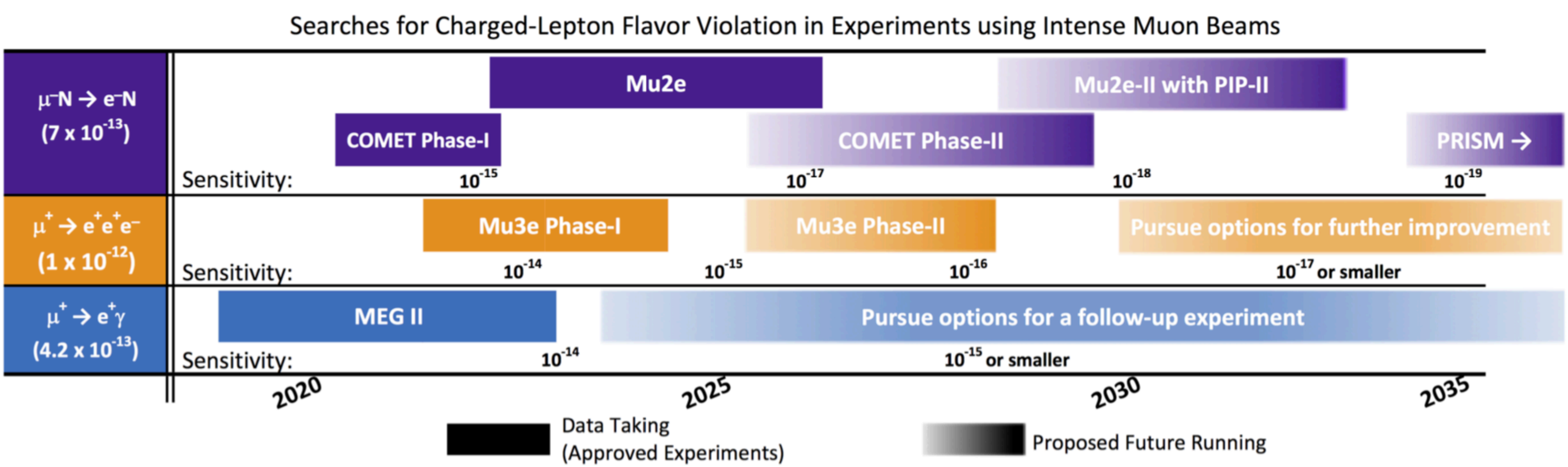
Slanted target: Prototype test in 2019

- Expected 30-60% enhancement
- Measurements successfully done in different experimental areas in fall 2019
- Analysis still undergoing: increased muon yield CONFIRMED!
- To be seen: impact of higher thermal stress on long term stability of target wheel



Outlooks

- **cLFV remains one of the most exciting place where to search for new physics**
- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
  - MEGII and Mu3e will search also for more exotic processes
  - **In evidence**: first direct search of $\mu \rightarrow eX$, $X \rightarrow \gamma\gamma$ with the MEG experiment, **arXiv:2005.00339**
- HiMB, a new beam line project at PSI, aims at delivering surface high intensity muon beams O(10^{10} muon/s)
  - Opening the door to interesting physics opportunities for particle physics and materials science using high-intensity and high-brightness muon beams (Mu3e Phase II, muEDM, MuSR, muonium spectroscopy, …)

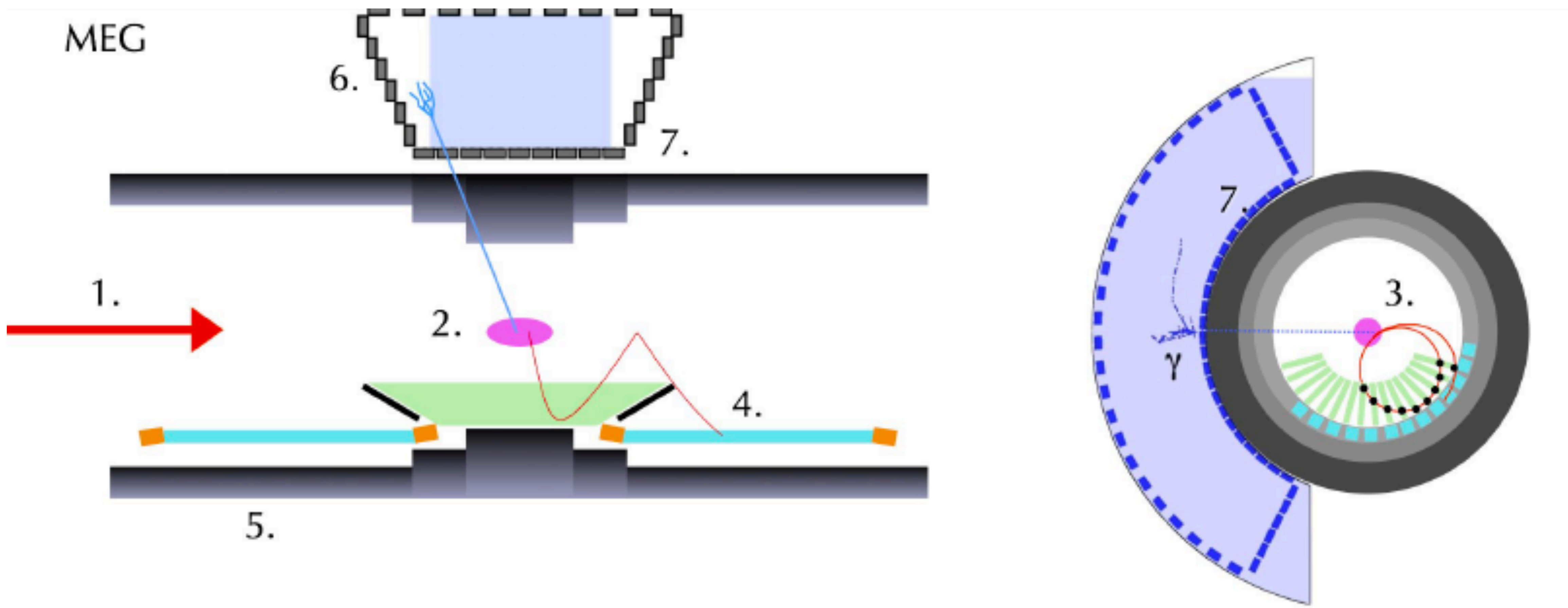


Thanks for your attention!

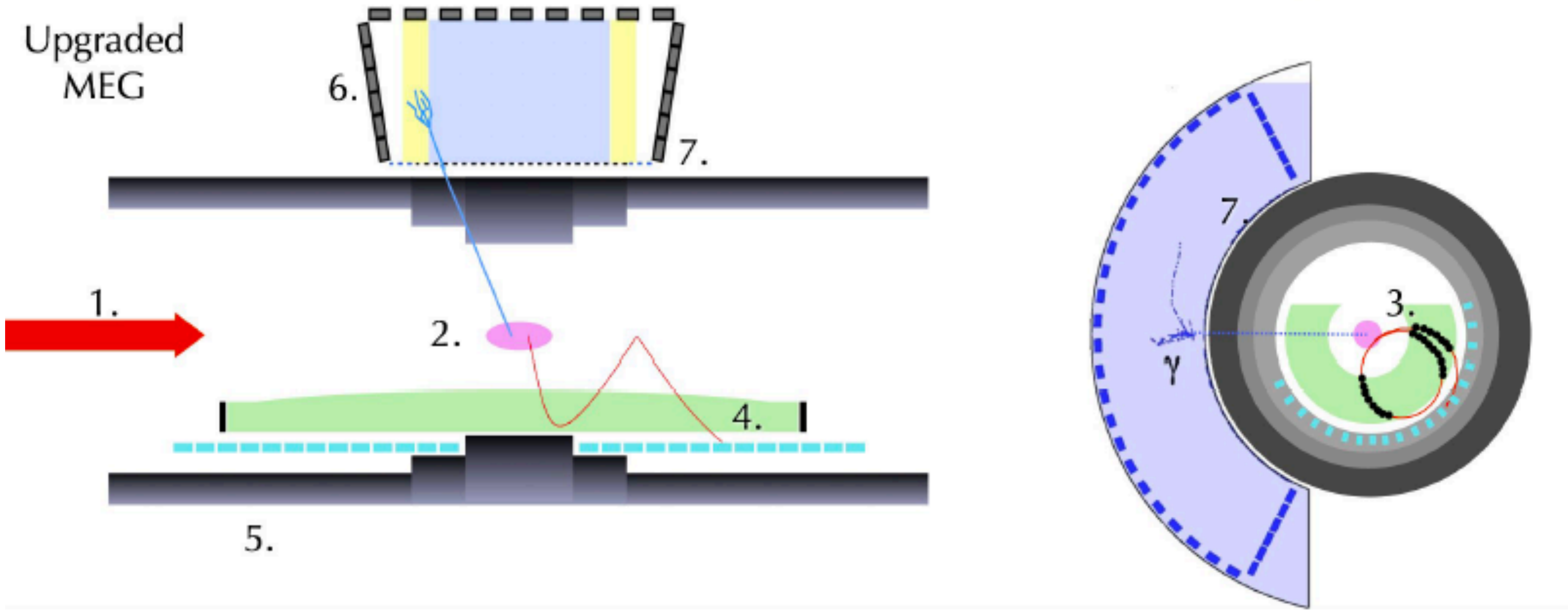
Credits: MEGII,Mu3e and HiMB

Back-up

The MEG experiment vs the MEGII experiment



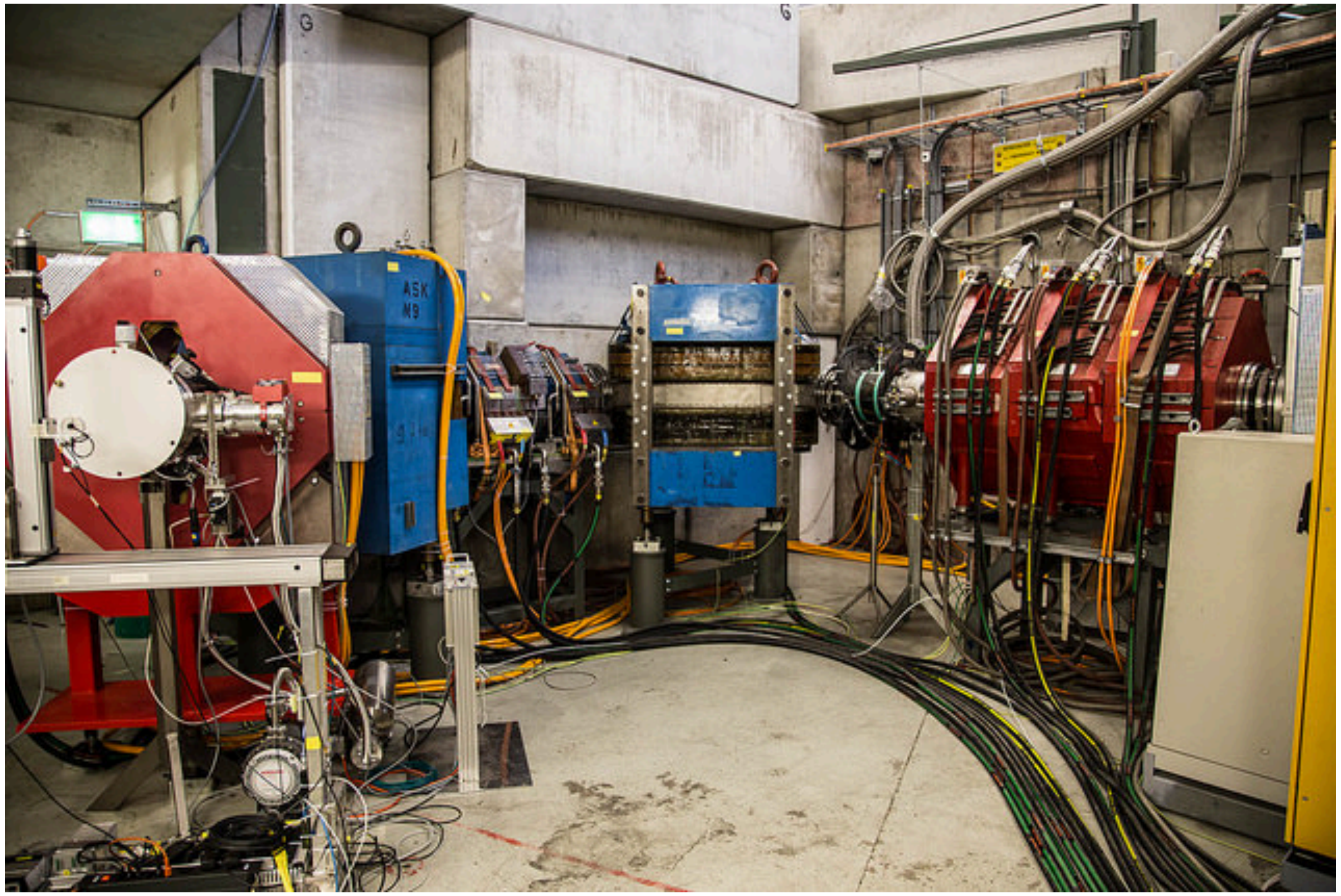
The MEG experiment vs the MEGII experiment



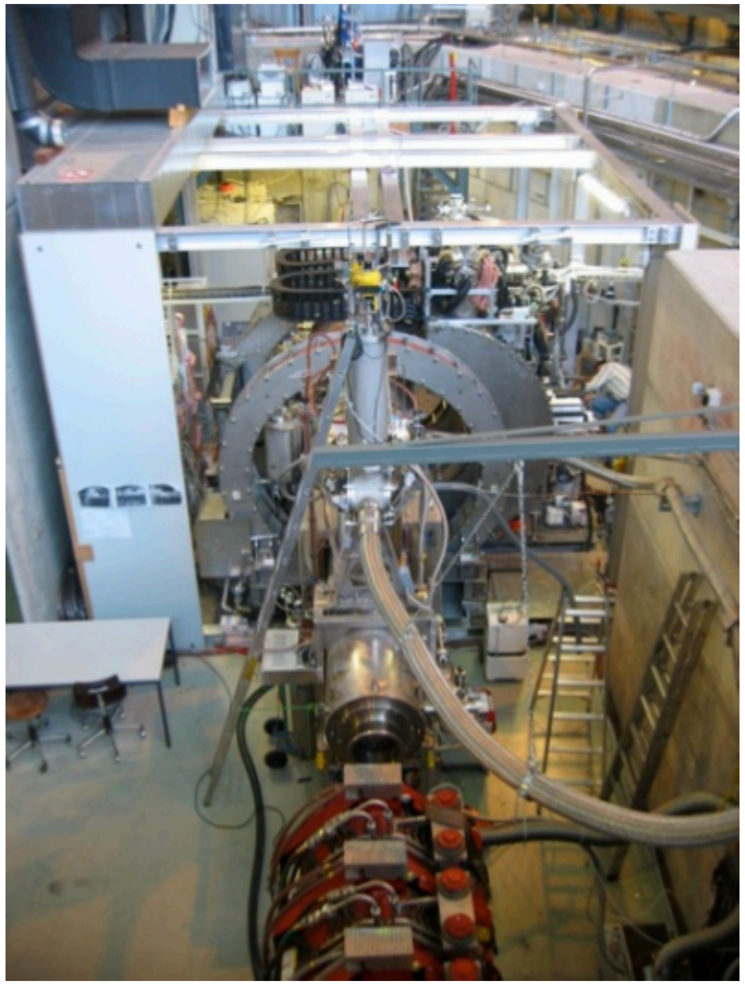
The MEGII and Mu3e beam lines

- 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

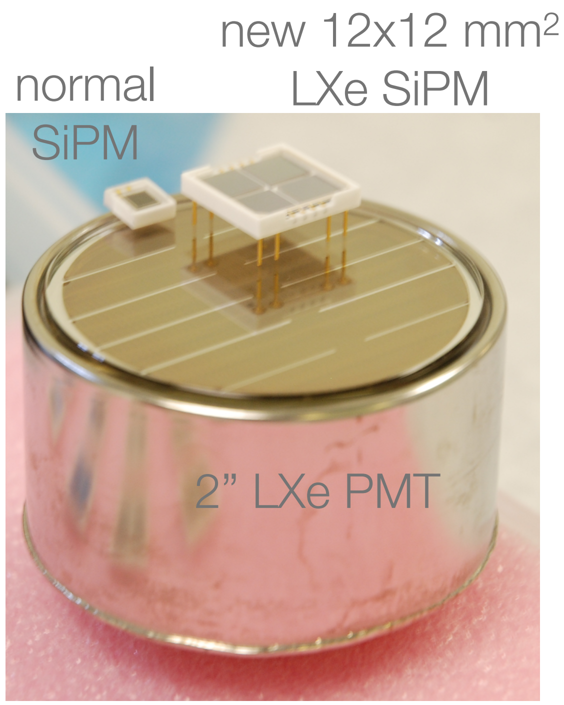


The MEGII BL

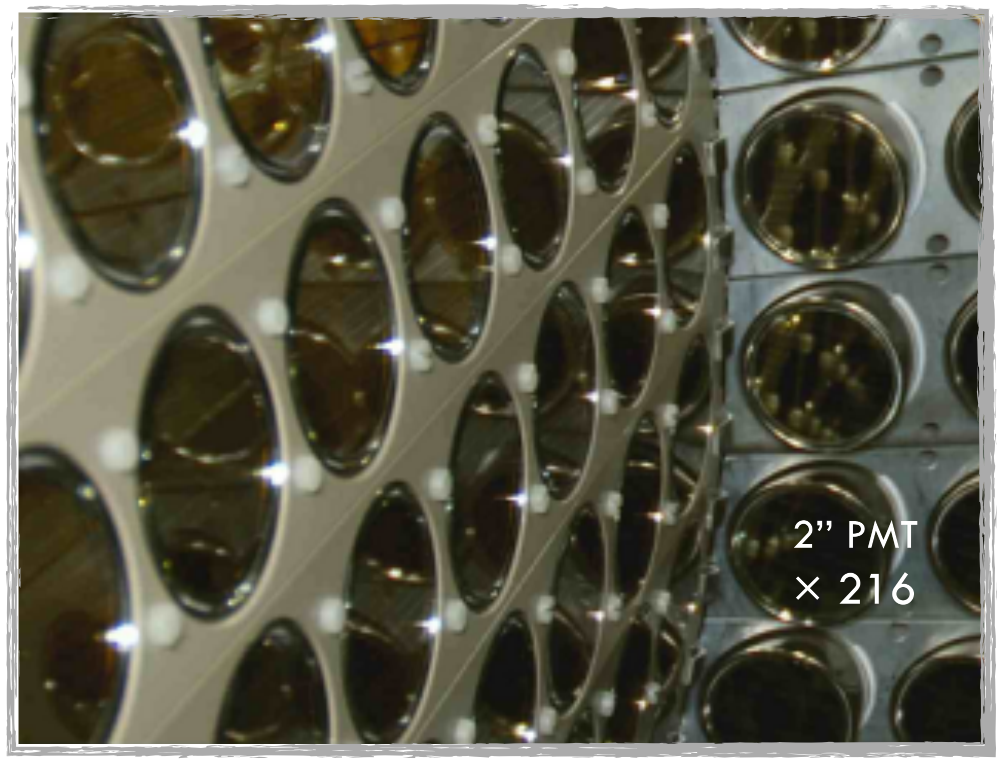


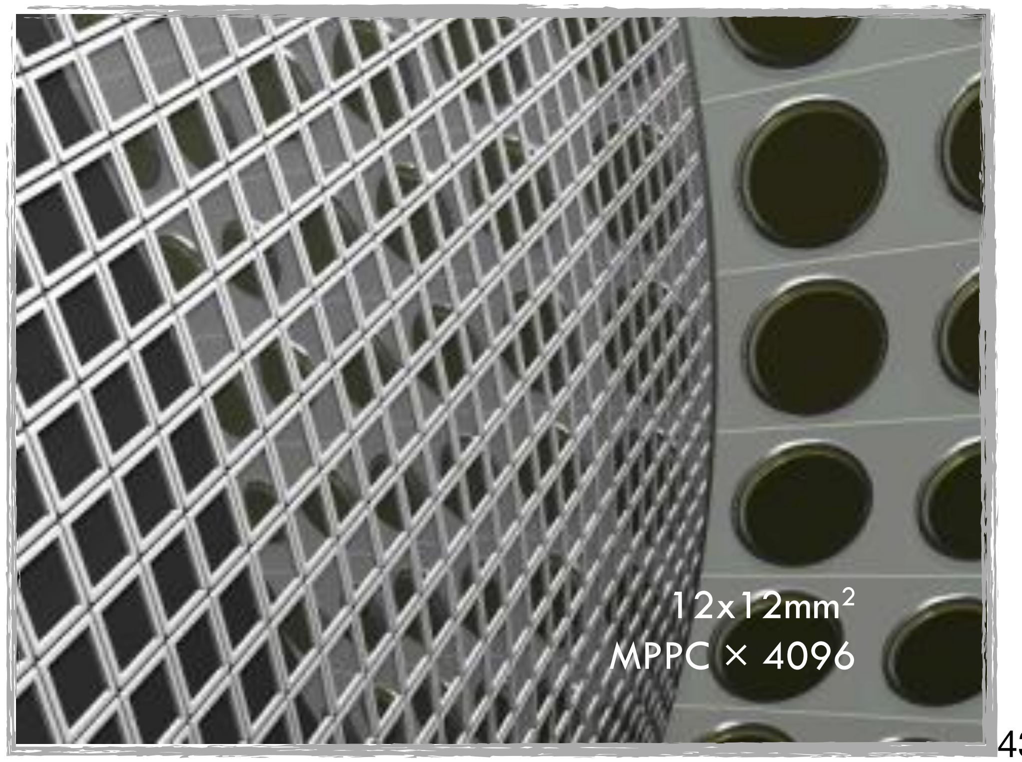
MEGII: The upgraded LXe calorimeter

- Increased uniformity/resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency
- Assembly: Completed
- Detector filled with LXe
- Construction completed in 2017



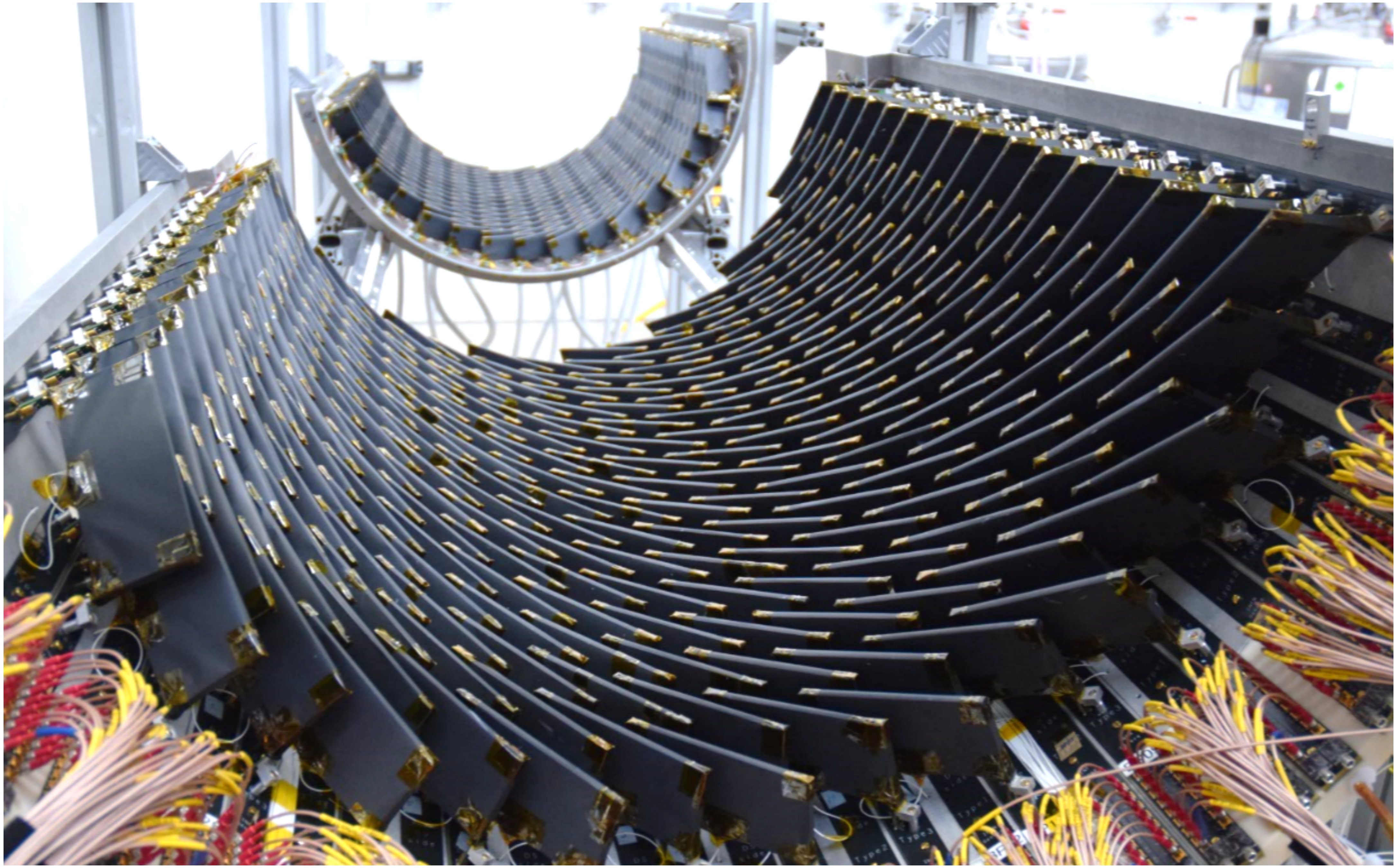
	MEG	MEGII
u [mm]	5	2.4
v [mm]	5	2.2
w [mm]	6	3.1
E [w<2cm]	2.4%	1.1%
E [w>2cm]	1.7%	1.0%
t [ps]	67	60





MEGII: the pixelized Timing Counter

Ready for the MEGII physics run !

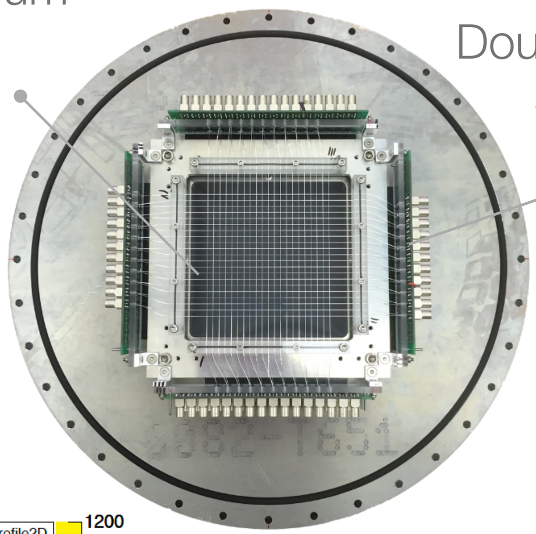


MEGII: new calibration methods and upgrades

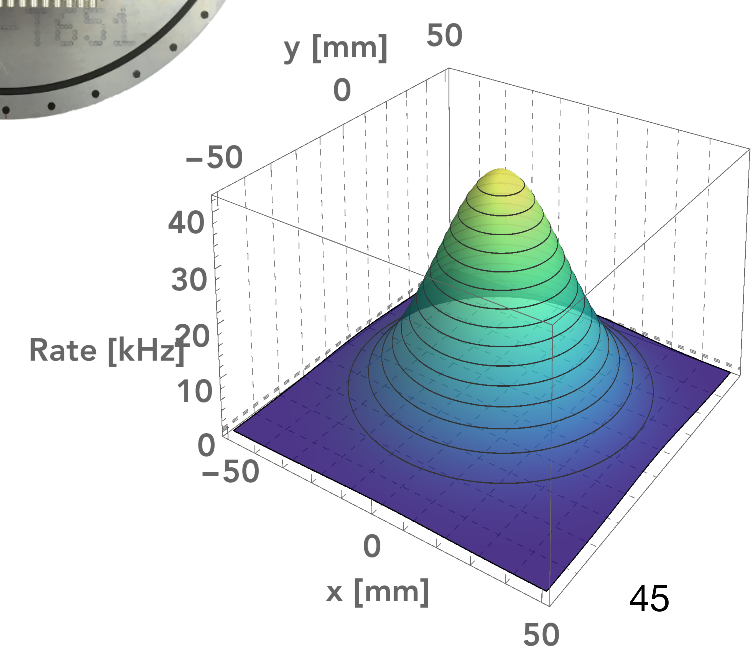
- CEX reaction: $p(\pi^-, \pi^0)n$, $\pi^0 \rightarrow \gamma\gamma$
- 1MV Cockcroft-Walton accelerator
- Pulsed D-D Neutron generator
- NEW: Mott scattered positron beam to fully exploit the new spectrometer
- NEW: SciFi beam monitoring. Not invasive, ID particle identification, vacuum compatible, working 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

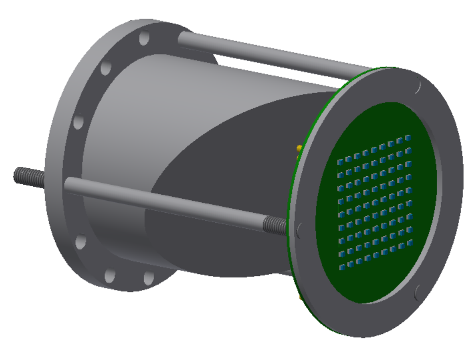
Double readout: MPPC S13360-3050C



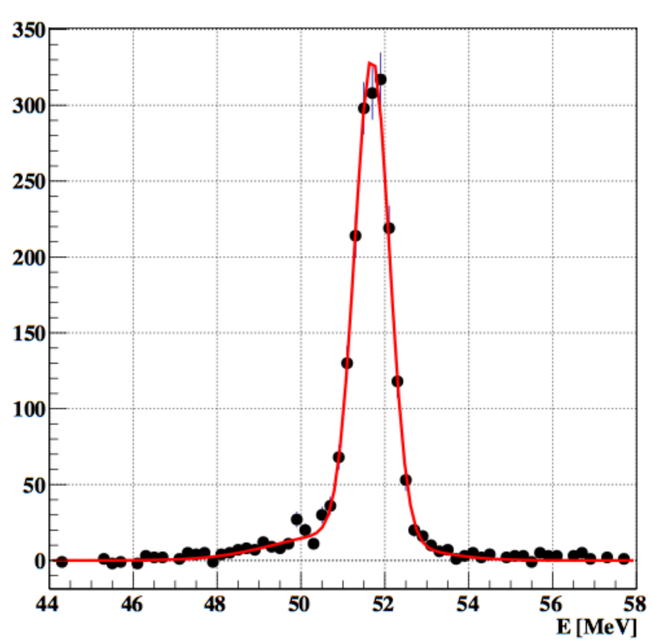
SciFi



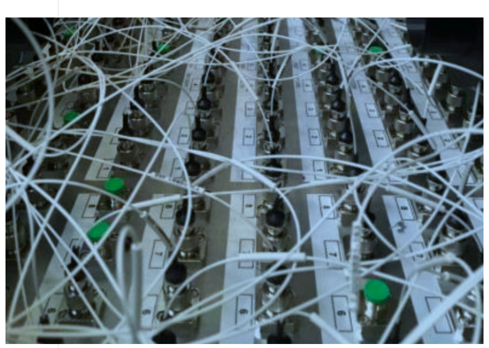
MatriX



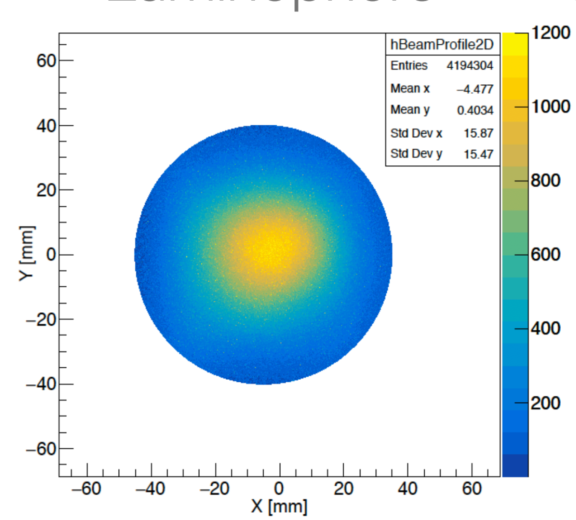
Monochromatic e-line



pTC's laser



Luminophore



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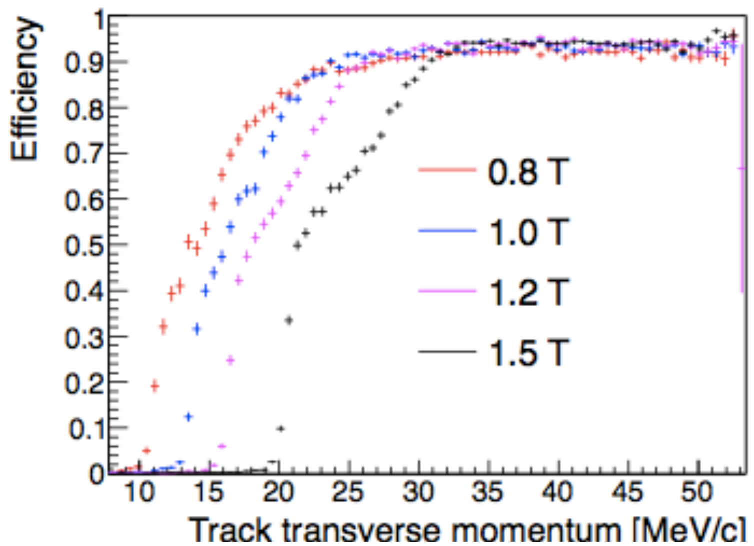
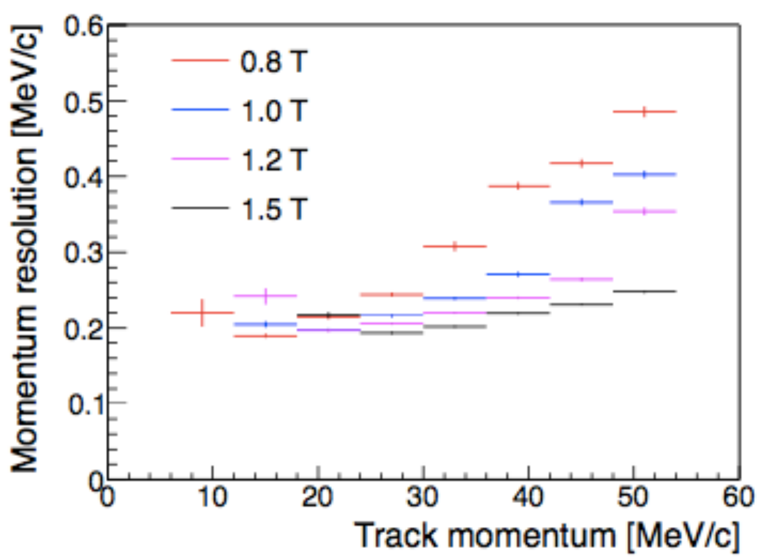
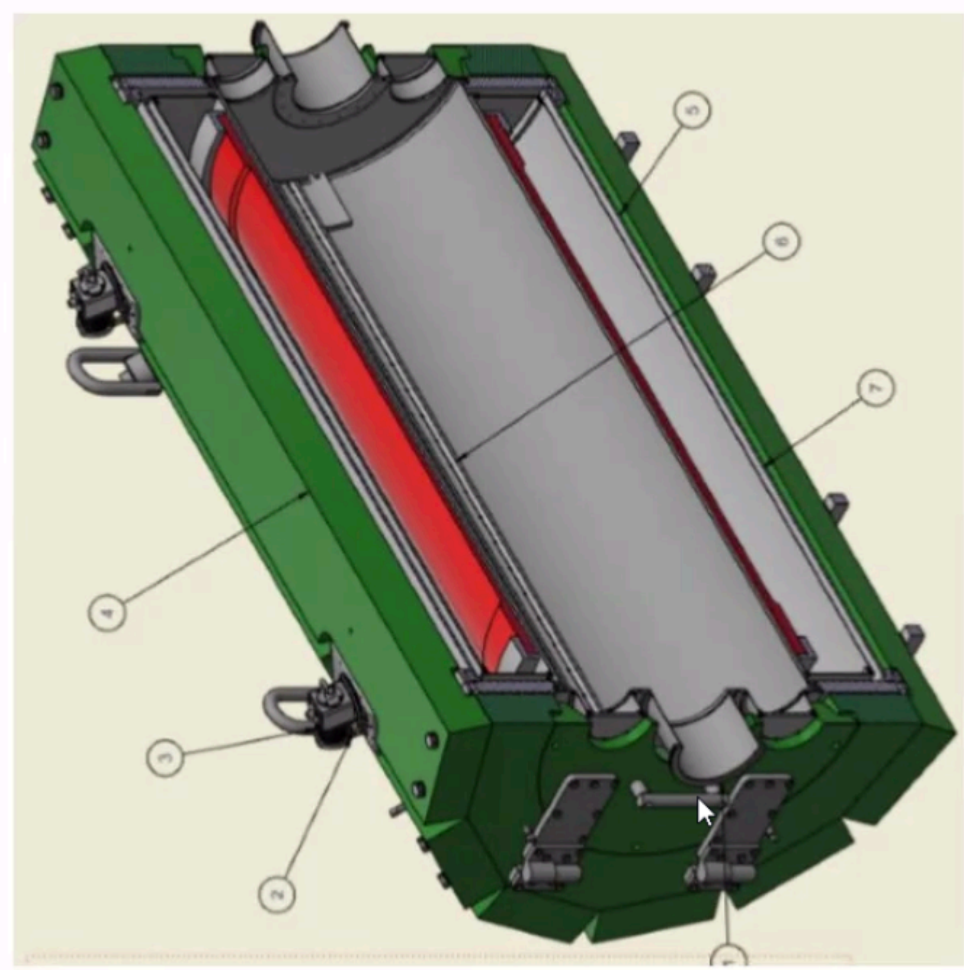
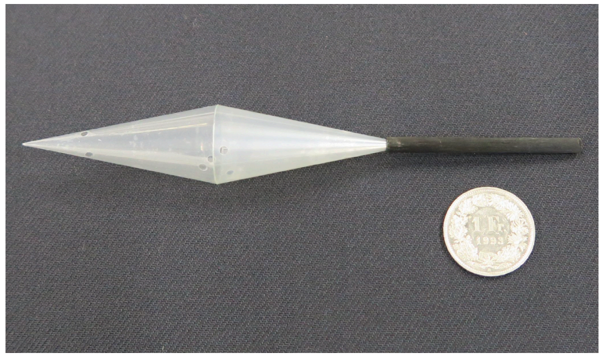
- Magnet from Cryogenic. Delivering Time at PSI: This year **New**
- Field Intensity: 1T; Field description: $dB/B \leq 10^{-4}$; Field stability: $dB/B(100\ d) \leq 10^{-4}$
- Dimensions: L < 3.2 m, W < 2.0 m, H < 3.5 m







The coil and the shield surrounding it.*



Target prototype

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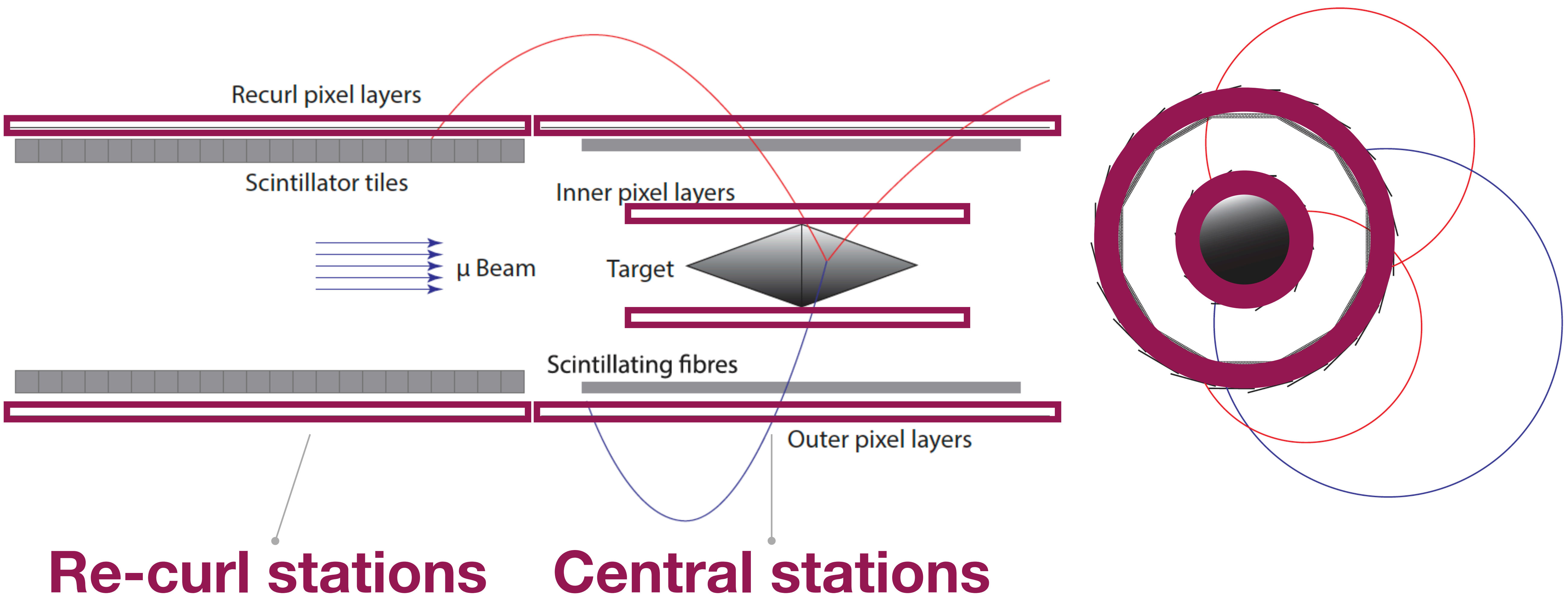
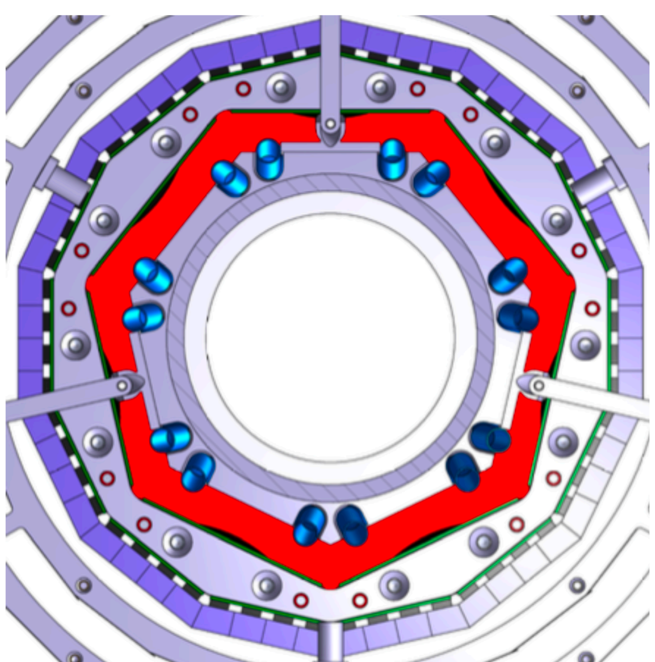
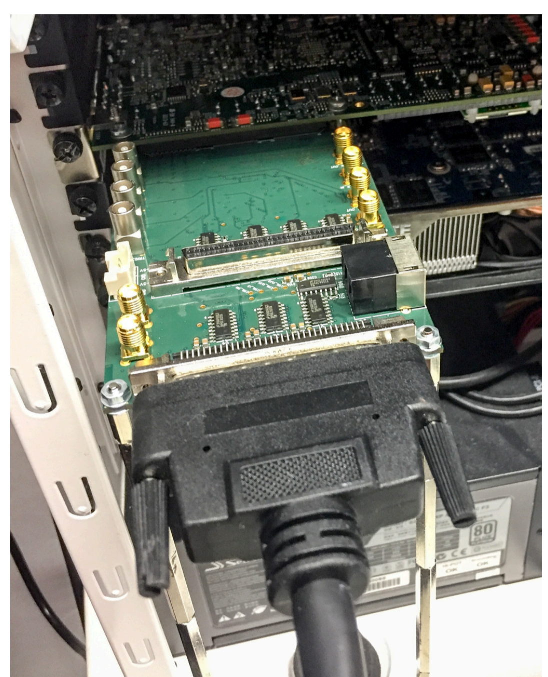


The pixel tracker: Current and future plan

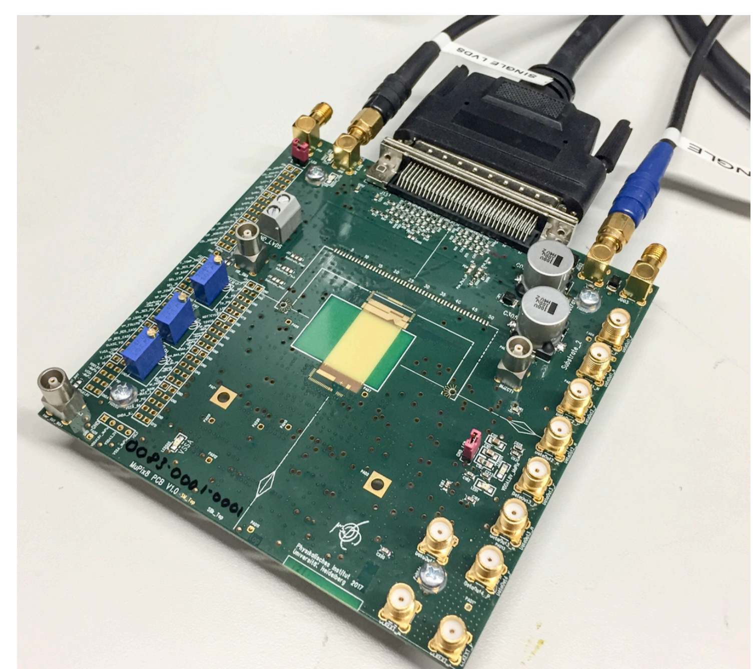
- After an extensive test beam campaign, achieved milestones
  - A fully functional HV-MAPS chip, 3x3 mm^2, Operation at high rates: 300 kHz at PSI; up to 1 MHz at SPS
  - Crosstalk on setup under control, on chip seen. Mitigation plan exists (MuPix8), Routinely operated systems of up to 8 chips in test 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. 2019 year test beam campaign
  - MuPix 10, the final version for Mu3e: 380 mm^2





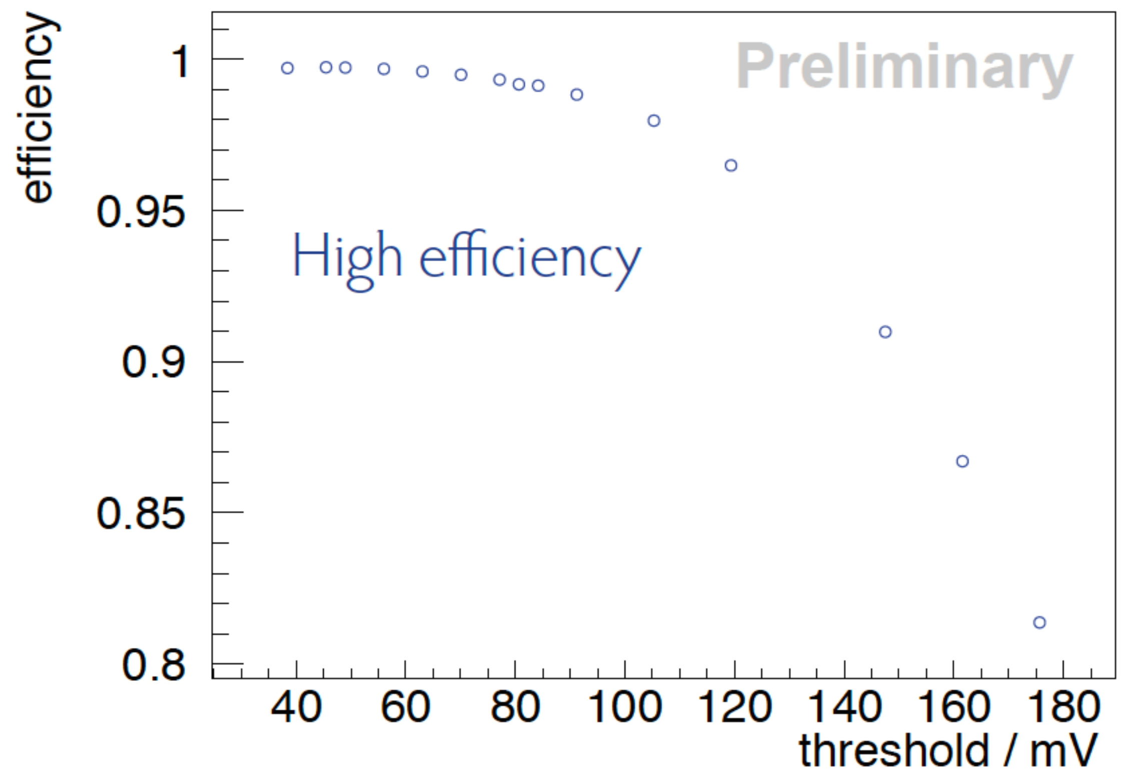
MuPix8

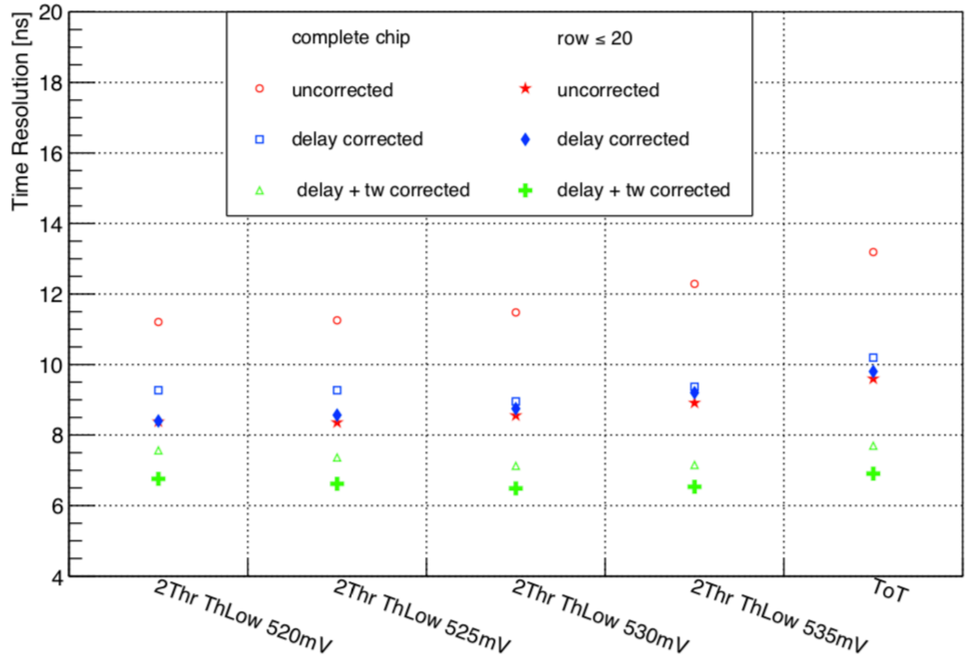


H. Augustin wt al. Nucl. Instr. Meth., A936 681 (2019)
H. Augustin et al. arXiv:1905.09309

MuPix 8: First Results

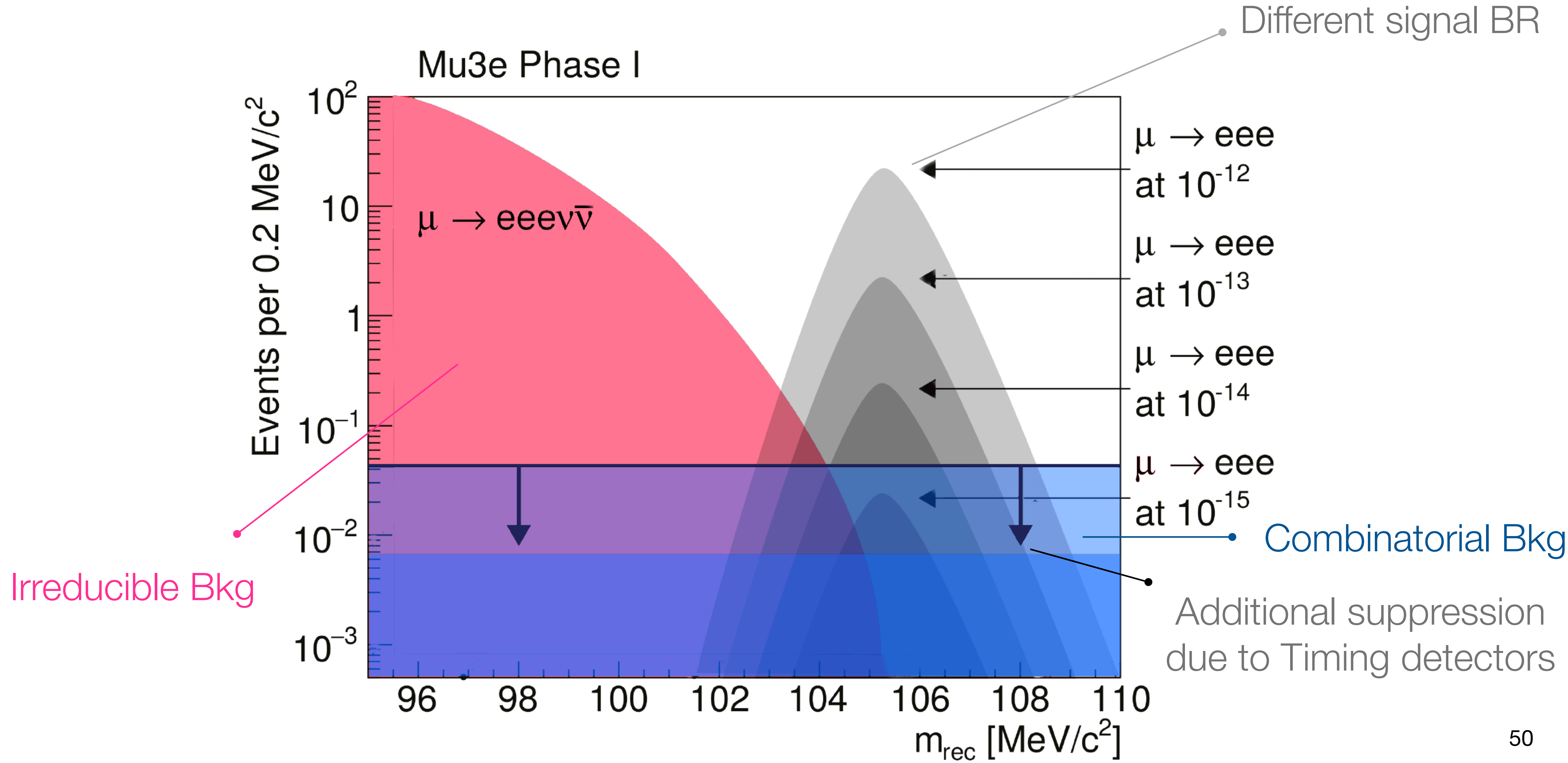
- Extensive beam test performed during 2018
- Some preliminary results



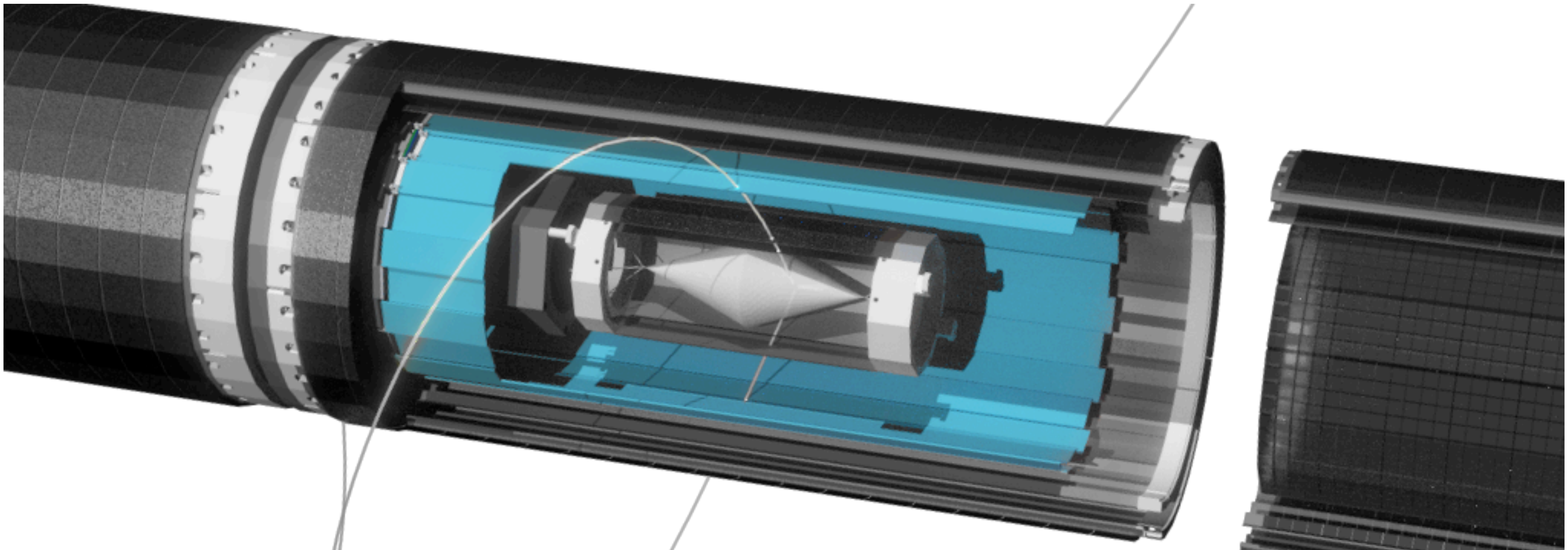


The timing detectors: Impact

- 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%)



The Fiber detector (SciFi): Overview



Parts

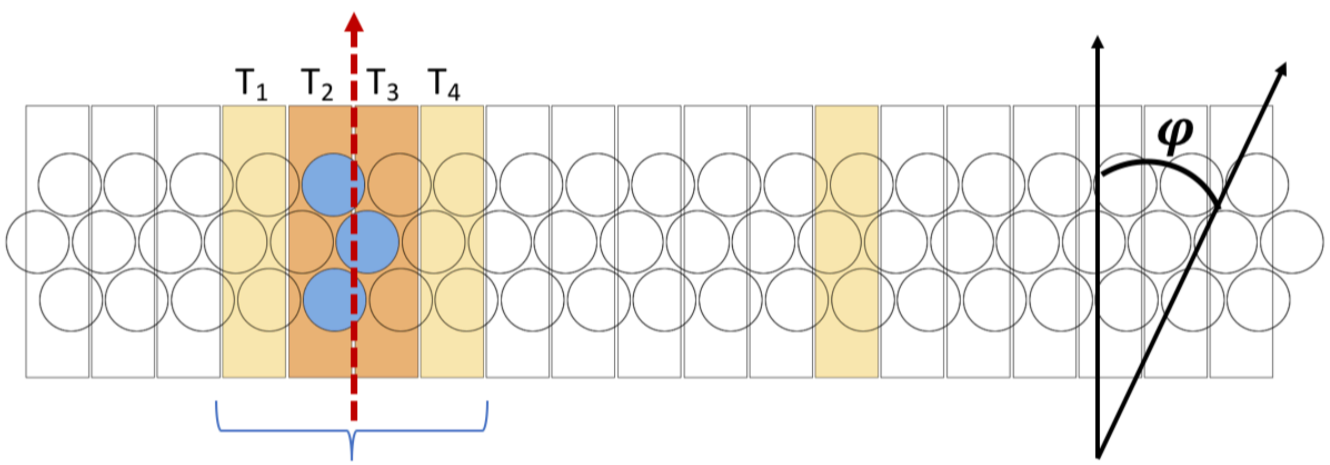
- cylindrical at ~ 6 cm (radius);
- length of 28-30 cm;
- 3 layers of round or square
- multi-clad 250 μm fibres
- fibres grouped onto SiPM array
- MuSTiC readout

Constraints

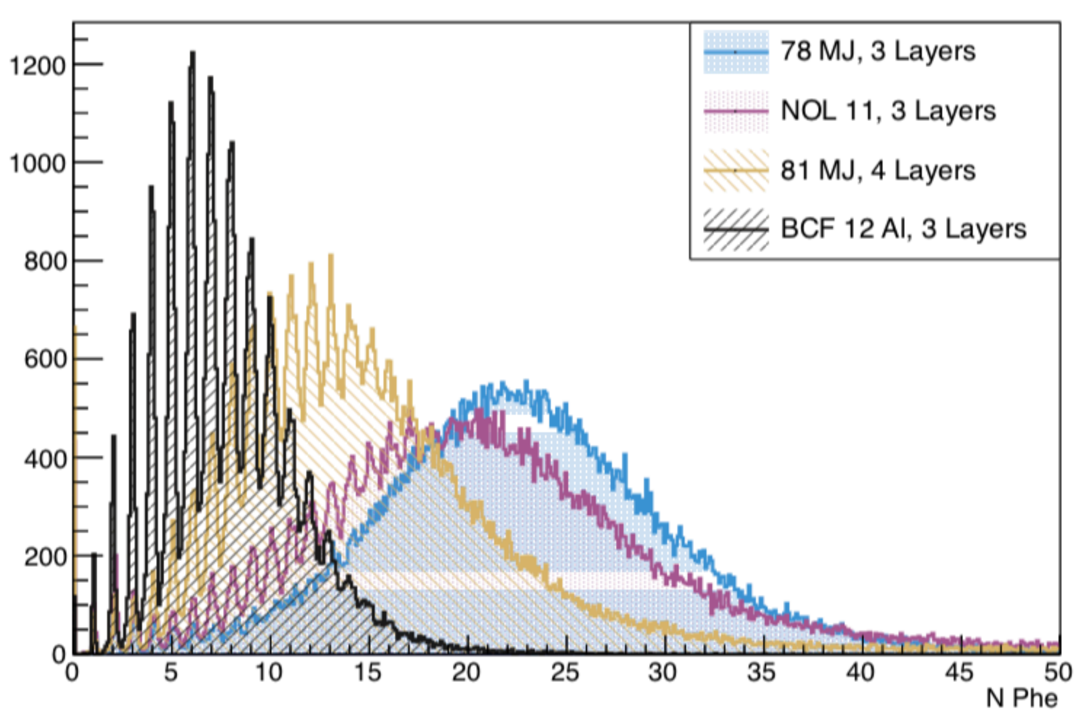
- high detection efficiency ε > 95%
- time resolution σ < 1 ns
- < 900 μm total thickness
- < 0.4 % X_0
- rate up to 250 KHz/fibre
- very tight space for cables, electronics and cooling

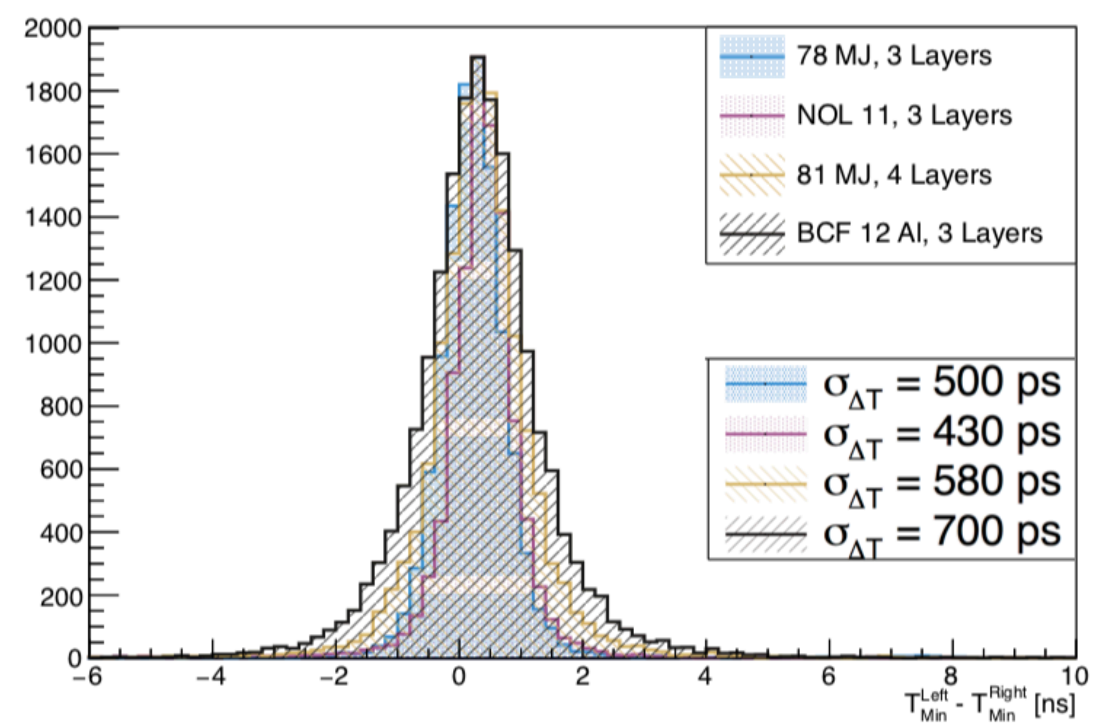
SciFi prototypes: Results

- 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

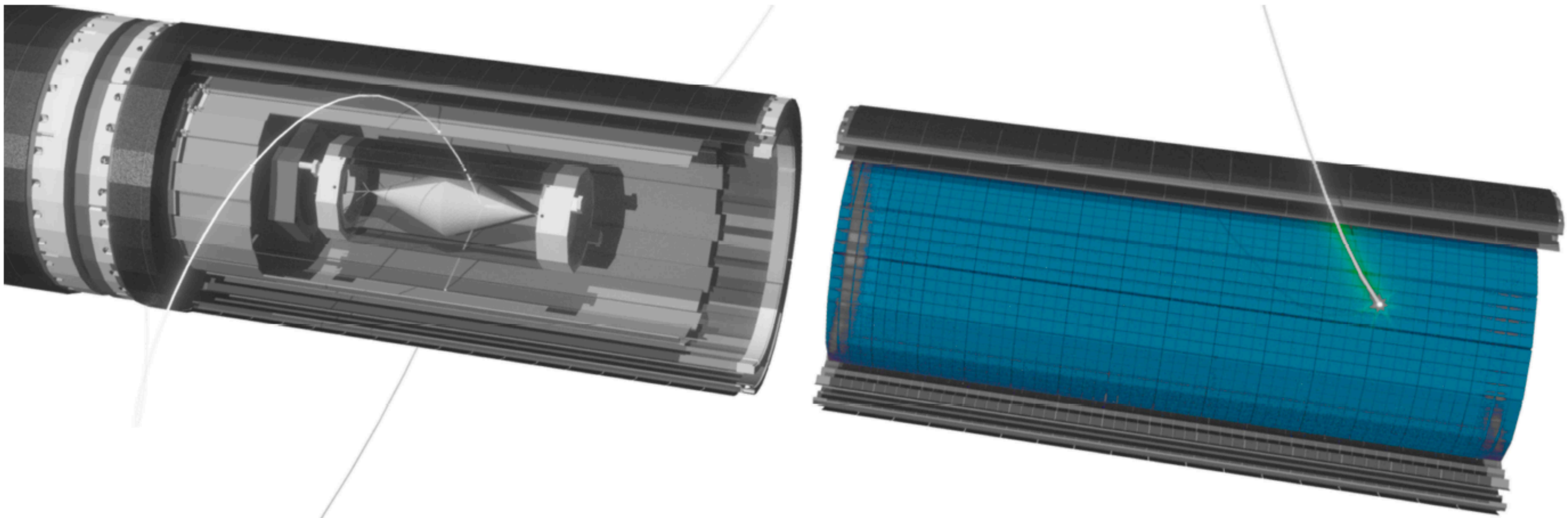


New





The Tile detector: Overview



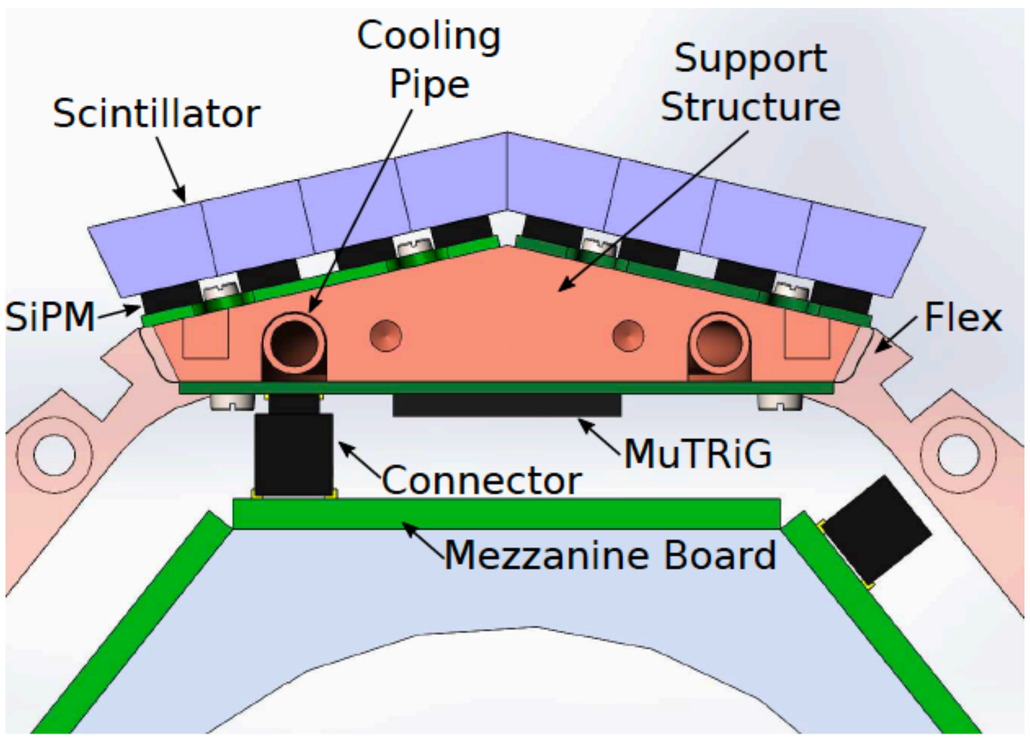
Parts

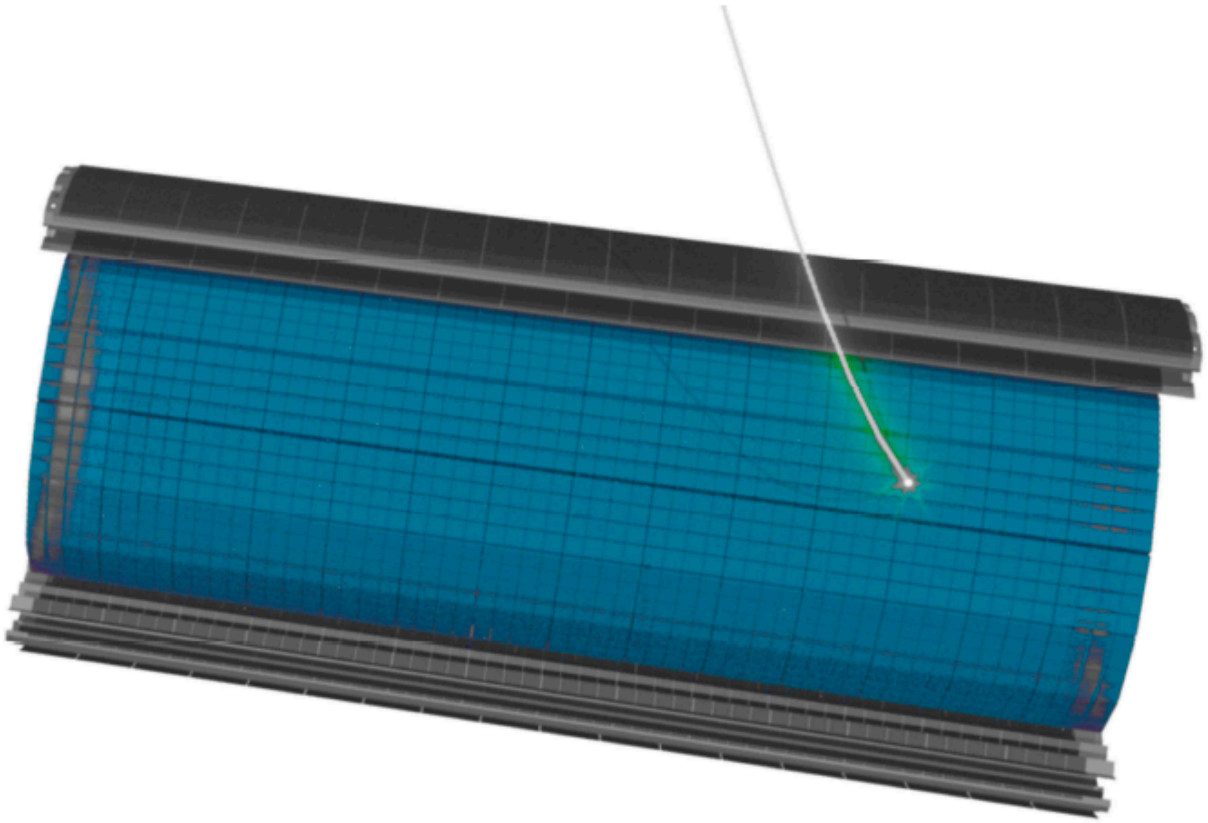
- cylindrical at ~ 6 cm (radius)
- length of 36.4 cm
- 56 x 56 tiles of 6.5 x 6.5 x 5 mm^3
- 3 x 3 mm^2 single SiPM per tile
- Mixed mode ASIC: MuTRiG

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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- Mixed mode ASIC: MuTRiG

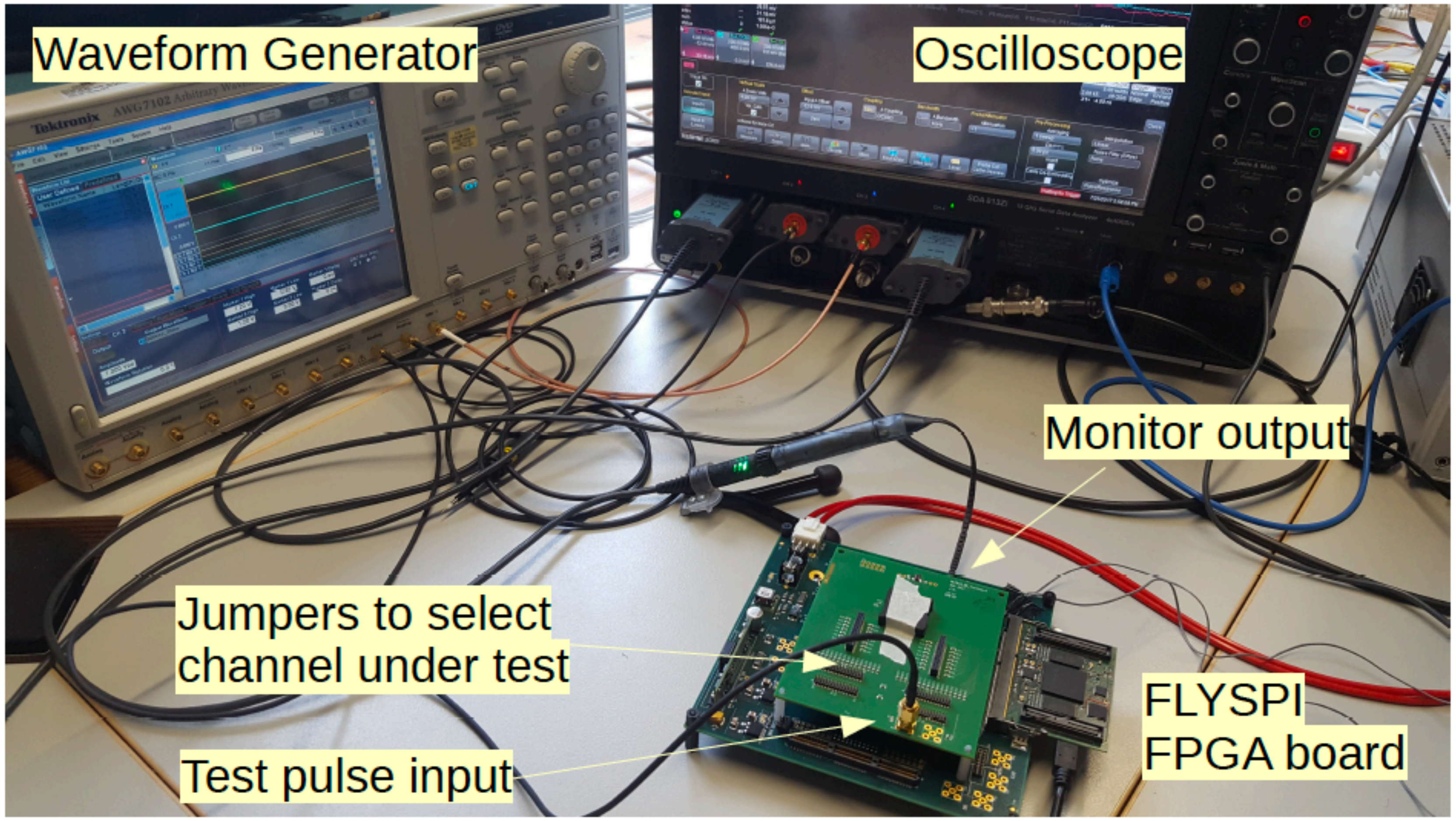
Requirements

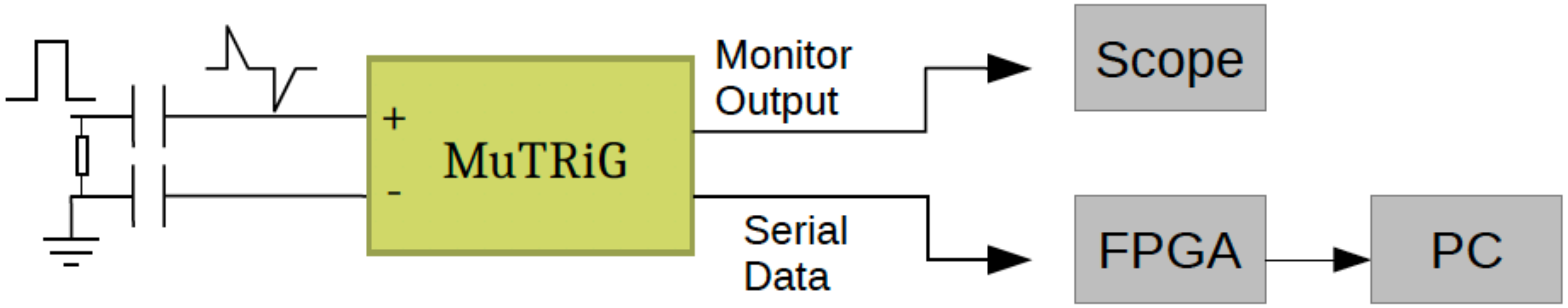
- high detection efficiency $\varepsilon > 95\%$
- time resolution $\sigma < 100$ ps
- rate up to 50 KHz per tile/channel

MuTRiG

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

New





The High intensity Muon Beam (HiMB) project at PSI

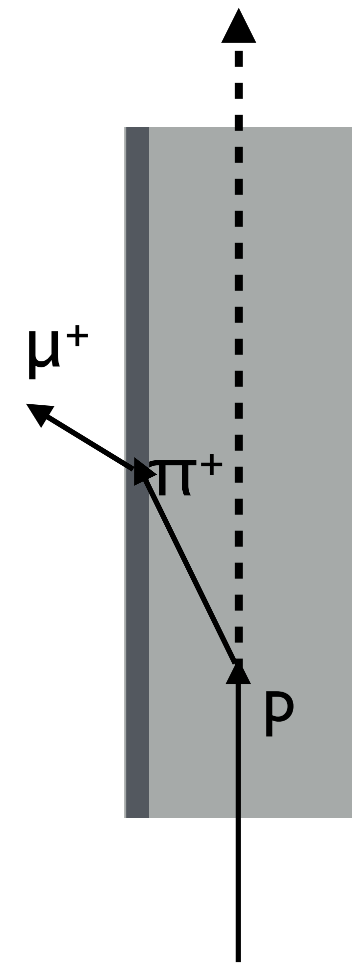
- Back to standard target to exploit possible improvements towards high intensity beams:
  - **Target geometry and alternate materials**
    - Search for high pion yield materials -> higher muon yield

$$\textit{relative}\ \mu^+ \textit{yield} \propto \pi^+ \textit{stop density} \cdot \mu^+ \textit{Range} \cdot \textit{length}$$

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_X (Z/A)_X}$$

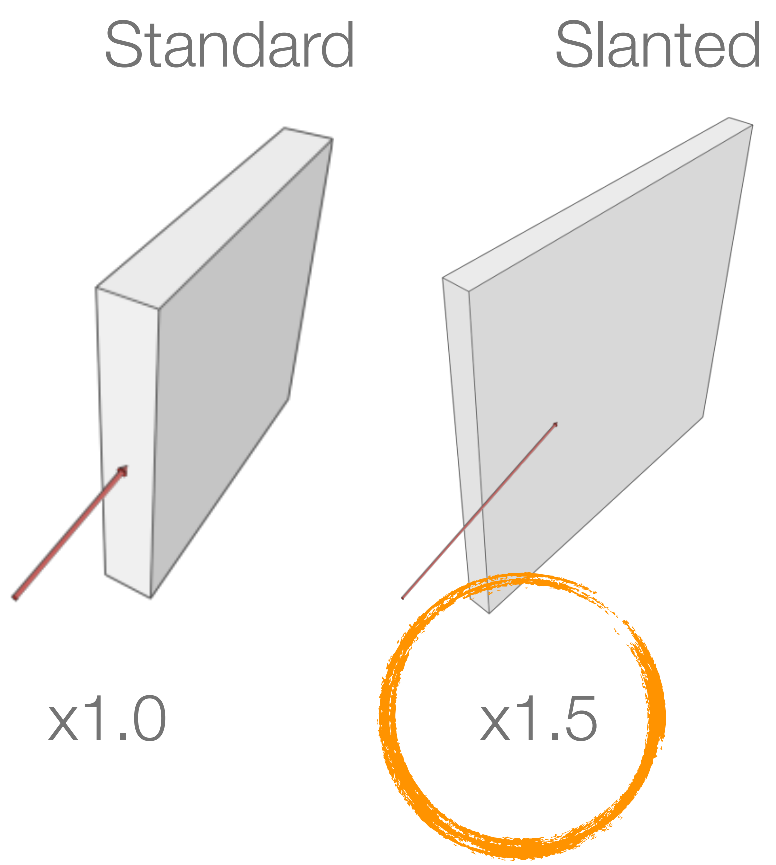
$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

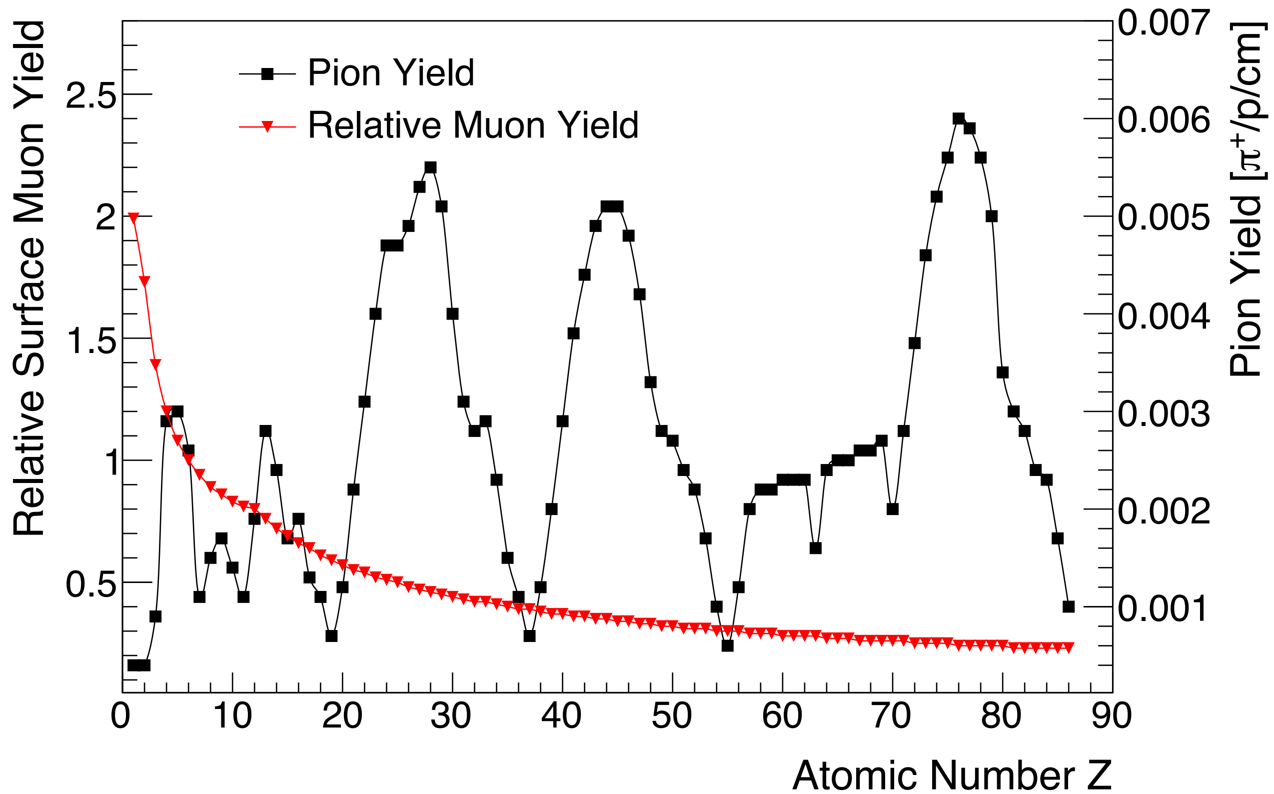
$$\propto \frac{1}{Z^{2/3}}$$



The High intensity Muon Beam (HiMB) project at PSI

- Target optimization
  - **Target geometry and alternate materials**
    - Search for high pion yield materials -> higher muon yield





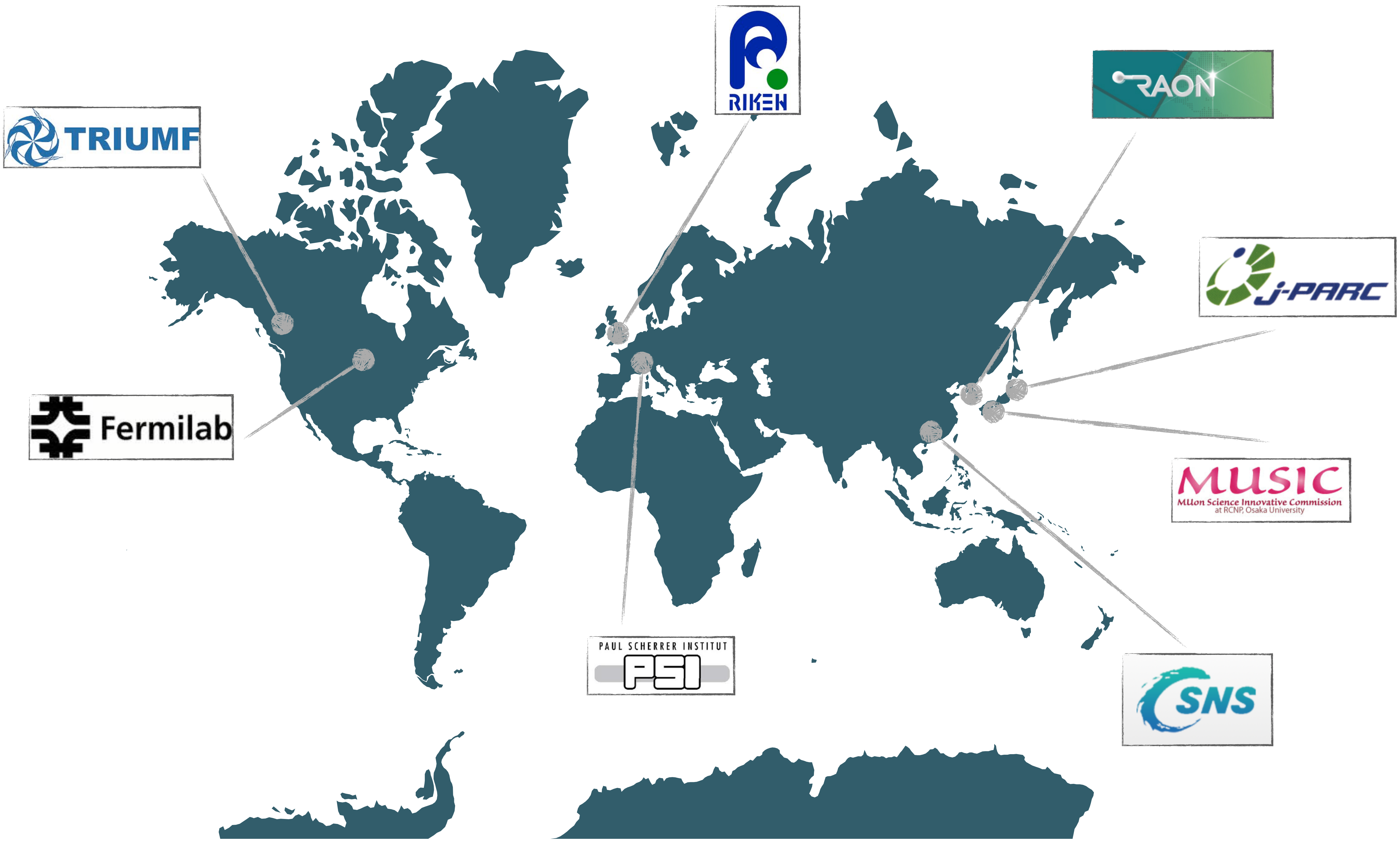
- **50%** of muon beam intensity gain, would corresponds to effectively raising the proton beam power at PSI by **650 kW**, equivalent to a beam power of almost **2 MW** without the additional complications such ad increased energy and radiation deposition into the target and its surroundings

L. Calibbi and G. Signorelli, il Nuovo Cimento **41** (2018) 71

DC and Pulsed muon beams - present and future

Laboratory	Beam Line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH) (590 MeV, 1.3 MW)	$\mu E4, \pi E5$ HiMB at EH	$2 \div 4 \times 10^8$ (μ^+) $\mathcal{O}(10^{10})$ (μ^+) (>2018)	
J-PARC (Japan) (3 GeV, 210 kW) (8 GeV, 56 kW)	MUSE D-Line MUSE U-Line COMET		$3 \times 10^7 (\mu^+)$ $6.4 \times 10^7 (\mu^+)$ $1 \times 10^{11} (\mu^-)$(2020)
FNAL (USA) (8 GeV, 25 kW)	Mu2e		$5 \times 10^{10} (\mu^-)$(2020)
TRIUMF (Canada) (500 MeV, 75 kW)	M13, M15, M20	$1.8 \div 2 \times 10^6 (\mu^+)$	
RAL-ISIS (UK) (800 MeV, 160 kW)	EC/RIKEN-RAL		$7 \times 10^4 (\mu^-)$ $6 \times 10^5 (\mu^+)$
KEK (Tsukuba, Japan) (500 MeV, 25 kW)	Dai Omega		$4 \times 10^5 (\mu^+)$(2020)
RCNP (Osaka, Japan) (400 MeV, 400 W)	MuSIC	$10^4 (\mu^-) \div 10^5 (\mu^+)$ $10^7 (\mu^-) \div 10^8 (\mu^+)$(>2018)	
JINR (Dubna, Russia) (660 MeV, 1.6 kW)	Phasotron	$10^5 (\mu^+)$	
RISP (Korea) (600 MeV, 0.6 MW)	RAON	$2 \times 10^8 (\mu^+)$(>2020)	
CSNS (China) (1.6 6eV, 4 kW)	HEPEA	$1 \times 10^8 (\mu^+)$(>2020)	

DC and Pulsed muon beams - present and future



MEGII: The new single volume chamber

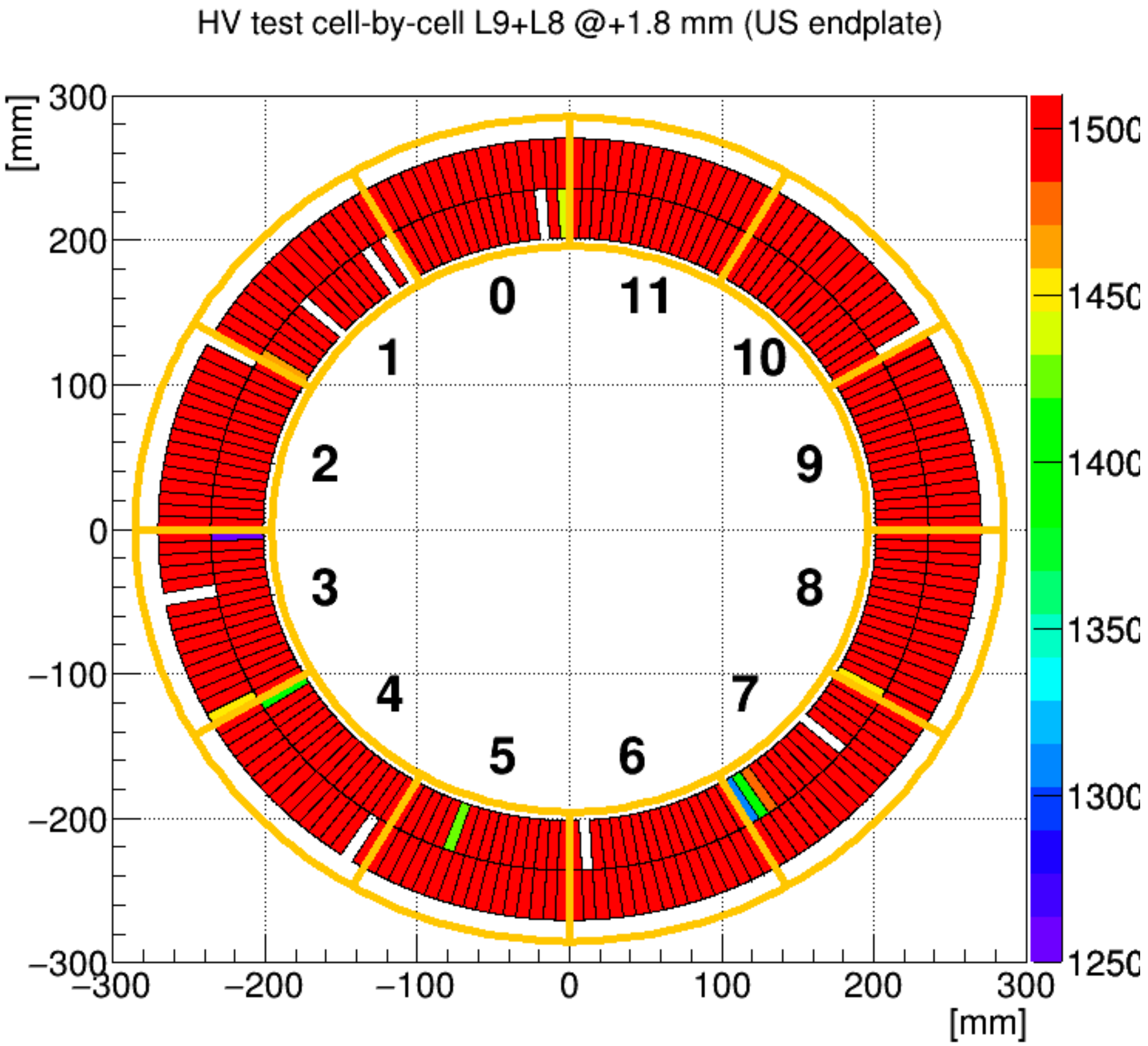
HV test @ +1.8 mm

Layer	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
9 (1500 V)	1500	1500	1500	1500	1500	1430	1500	1500	1500	1500	1500	1500
8 (1510 V)	1510	1510	1510	1500	1510	1510	1510	1510	1510	1510	1510	1510
7 (1520 V)	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520	1520
6 (1530 V)	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530
5 (1540 V)	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540	1540
4 (1550 V)	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550
3 (1560 V)	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560	1560
2 (1570 V)	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570	1570
1 (1580 V)	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580

MEGII: The new single volume chamber

RESULTS

- Safety HV values
  - $27/384$ cells (20 for L9 + 7 for L8) don't reach it (7 %)
  - $8/27$ cells (6 for L9 + 2 for L8) almost reach it
    - $5 \div 20$ V discrepancy
- Working point
  - $12/384$ cells (8 for L9 + 4 for L8) don't reach it (3 %)
  - $11/12$ cells (6 for L9 + 4 for L8) have permanent shorts

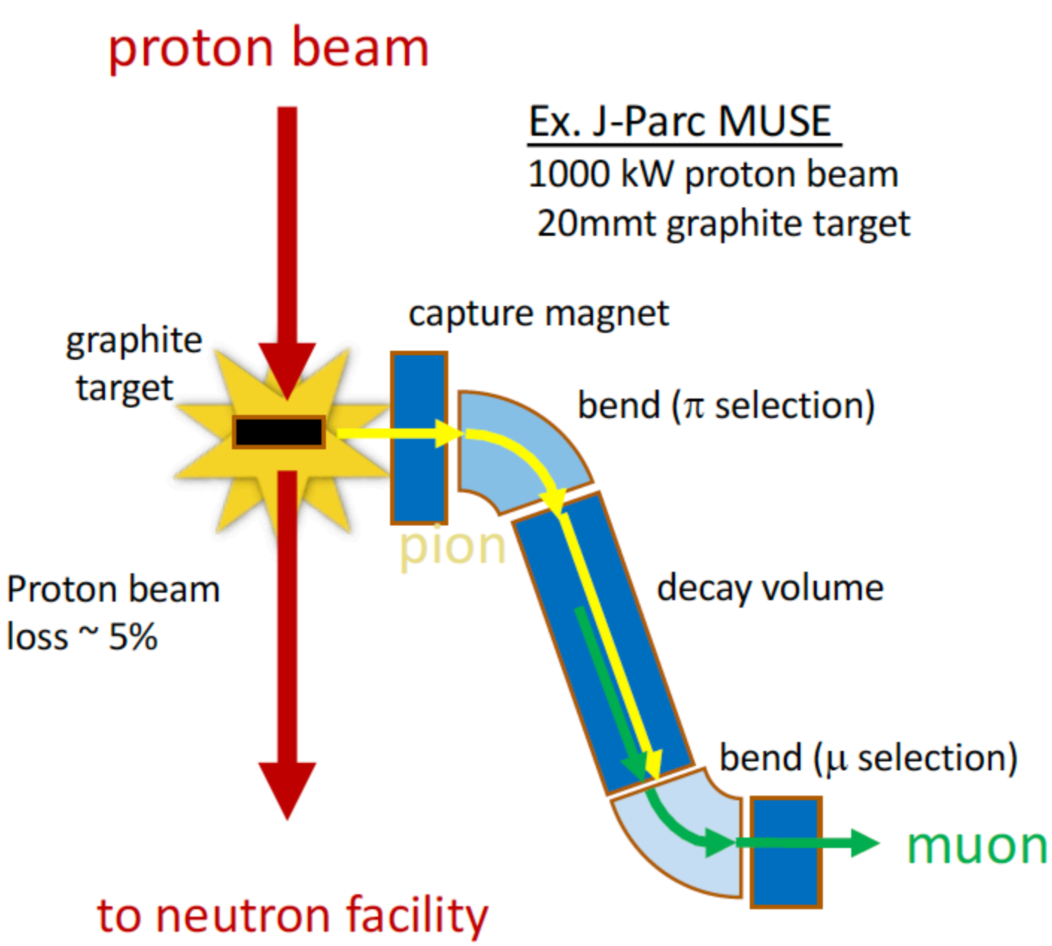


CDCH @ +5.6 mm elongation fulfils the MEGII requirements

MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

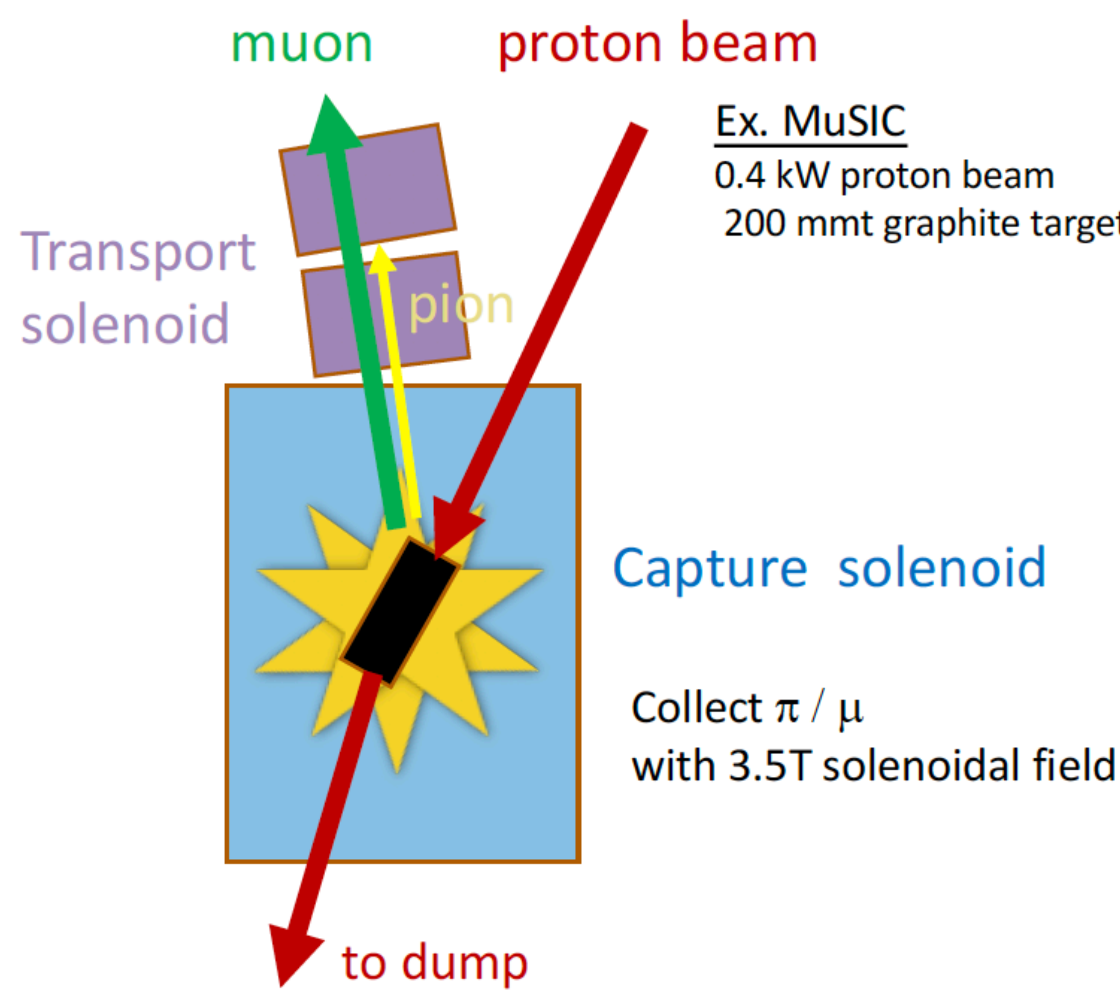
- Aim: O(**10^8** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam

Conventional muon beamline



- Thin target (~ 20mmt)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

MuSIC beamline



- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion / muon momentum)

cLFV search landscape

Rough estimate of numbers of researchers, in total ~ 850 (with some overlap)

Muons

~ 250

- MEG, PSI
- MEGII, PSI
- Mu3e, PSI
- DeeMee, J-PARC
- MuSiC, Osaka
- Mu2e, FNAL
- COMET, J-PARC
- PROJECT X, FNAL
- PRIME, J-PARC

Taus

~ 250

- BABAR, PEPII
- BELLE/BELLE II, KEKB/SuperKEKB

Kaons

~ 100

- NA48,CERN
- NA62,CERN
- KOTO, J-PARC

cLFV @ LHC

~ 250

- ATLAS,CERN
- CMS,CERN
- LHCb, CERN

J/ψ @ BEPCII

~ 100

- BESIII, Beijing

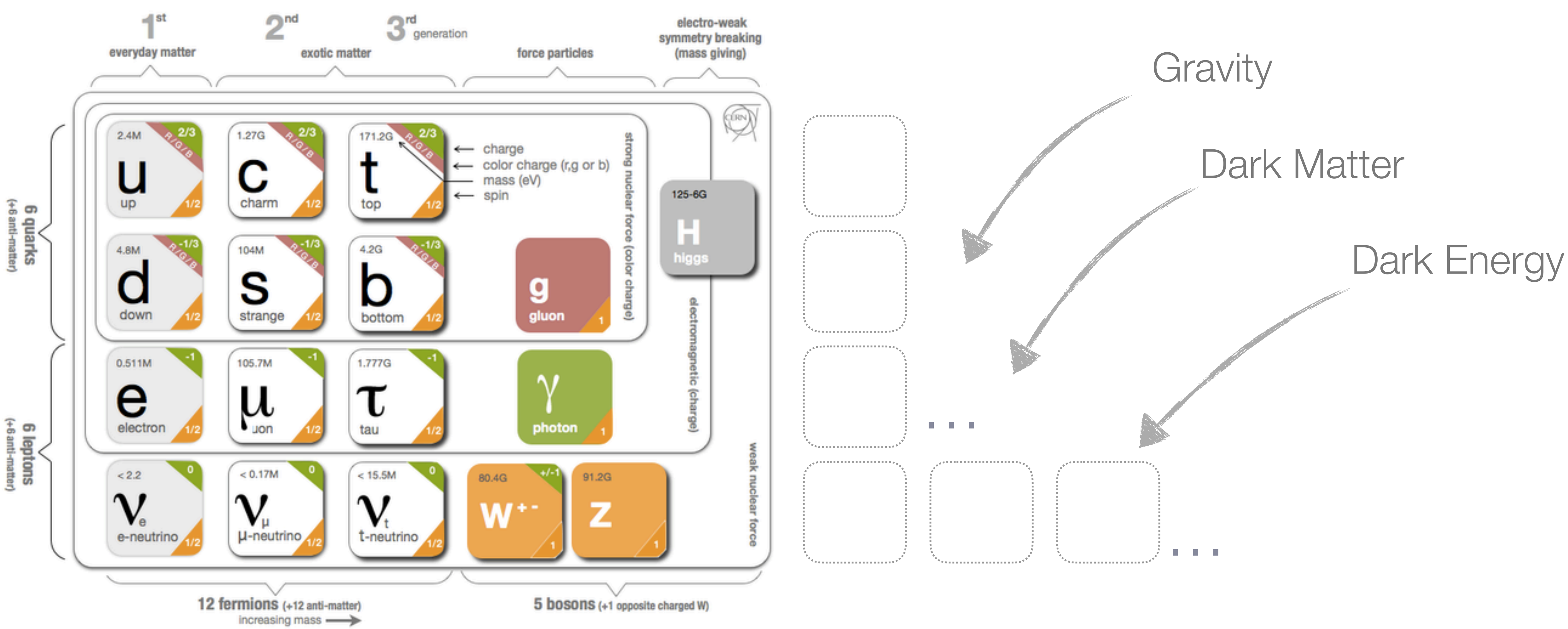
cLFV best upper limits

Process	Upper limit	Reference	Comment
$\mu^+ \to e^+ \gamma$	4.2×10^{-13}	arXiV:1605.05081	MEG
$\mu^+ \to e^+ e^+ e^-$	1.0×10^{-12}	Nucl. Phy. B299 (1988) 1	SINDRUM
$\mu^- N \to e^- N$	7.0×10^{-13}	Eur. Phy. J. c 47 (2006) 337	SINDRUM II
$\tau \to e \gamma$	3.3×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau \to \mu \gamma$	4.4×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau^- \to e^- e^+ e^-$	2.7×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^- \mu^+ \mu^-$	2.1×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^+ e^- e^-$	1.5×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$Z \to \mu e$	7.5×10^{-7}	Phy. Rev. D 90 (2014) 072010	Atlas
$Z \to \mu e$	7.3×10^{-7}	CMS PAS EXO-13-005	CMS
$H \to \tau \mu$	1.85×10^{-2}	JHEP 11 (2015) 211	Atlas (*)
$H \to \tau \mu$	1.51×10^{-2}	Phy. Let. B 749 (2015) 337	CMS
$K_L \to \mu e$	4.7×10^{-12}	PRL 81 (1998) 5734	BNL

* $B(H \to \mu e) < O(10^{-8})$ from $\mu \to e \gamma$

The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale