The status of the MEGII and Mu3e experiments at PSI

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on behalf of the MEGII and Mu3e collaboration

PAUL SCHERRER INSTITUT
PSI

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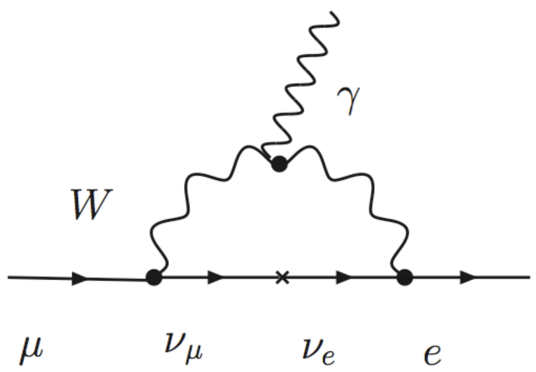
ICISE Quy Nhon, Vietnam

Overview

- charged Lepton Flavour Violation (cLFV) searches with muons at PSI
  - MEGII
  - Mu3e
- Outlook

The $\mu^+ \rightarrow e^+ \gamma$ decay as an example

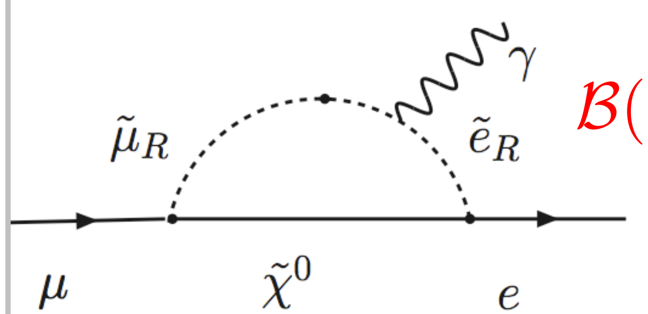
SM with massive neutrinos (Dirac)



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

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

The $\mu^+ \rightarrow e^+ \gamma$ decay as an example

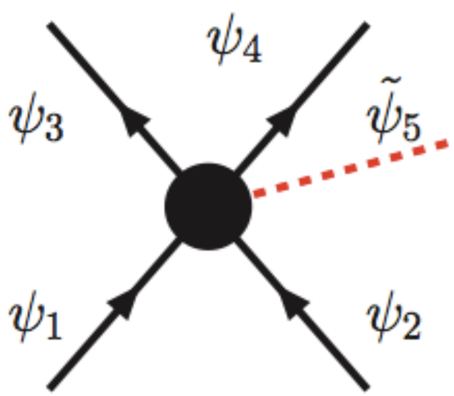
SM with massive neutrinos (Dirac)

The role of low energy physics:
a sensitive tool

- to unveil behind SM physics (virtual particles)

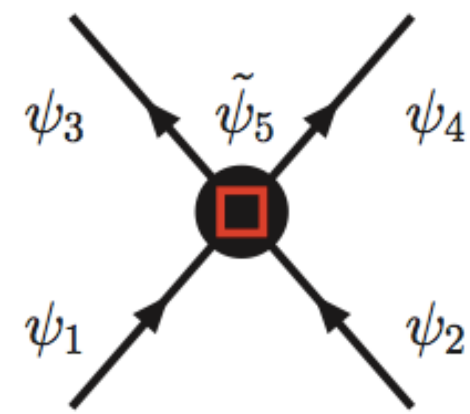
New Physics

Energy frontier

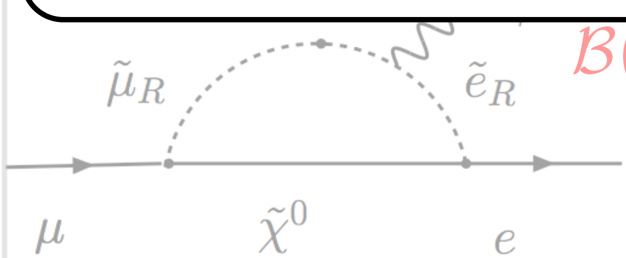


Real BSM particles

Precision and intensity frontier



Virtual BSM particles



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

an experimental evidence:
a clear signature of New Physics

The $\mu^+ \to e^+ \gamma$ decay as an example

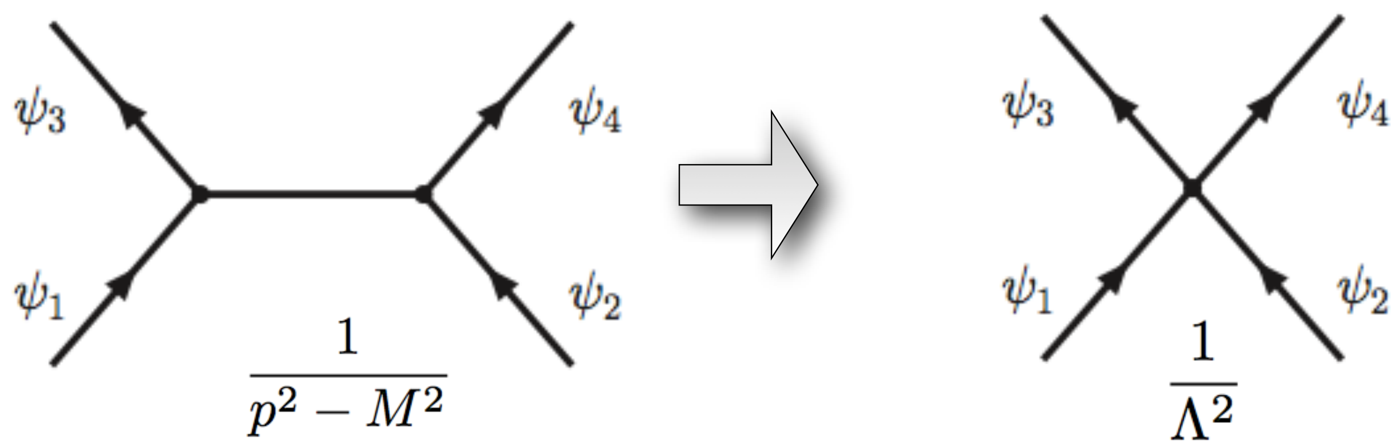
SM with massive neutrinos (Dirac)

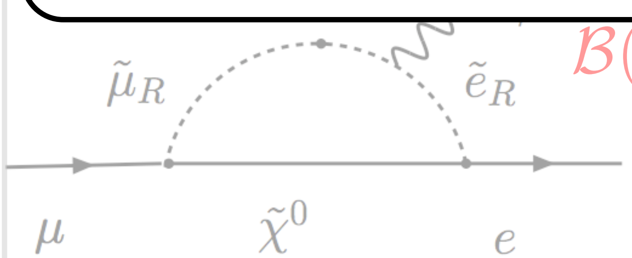
The role of low energy physics:
a sensitive tool

- to unveil behind SM physics (virtual particles)
- high energy scale probe (effective lagrangian)

New Physics

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





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

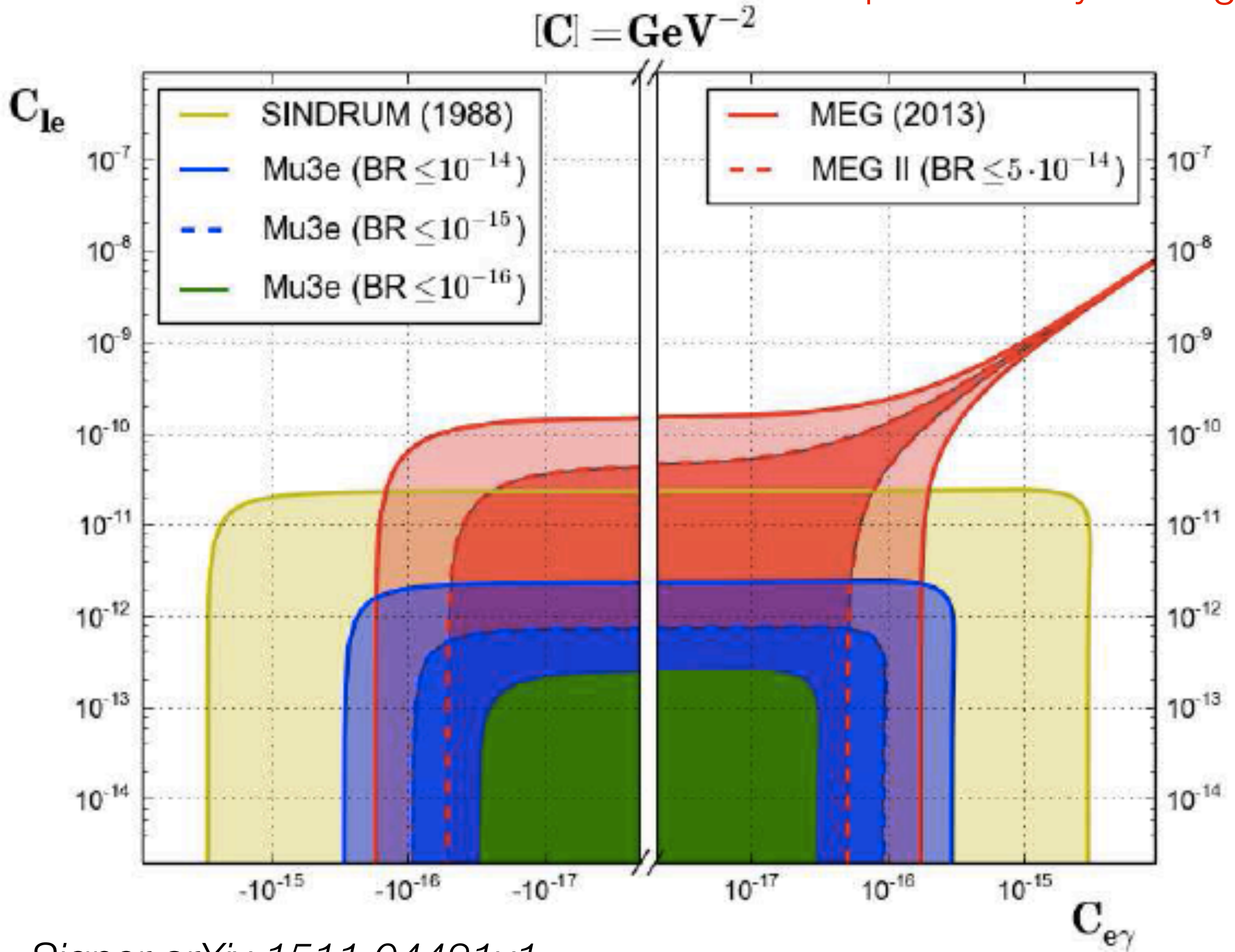
an experimental evidence:
a clear signature of New Physics

The $\mu^+ \to e^+ \gamma$ decay as an example

The role of low energy physics:

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

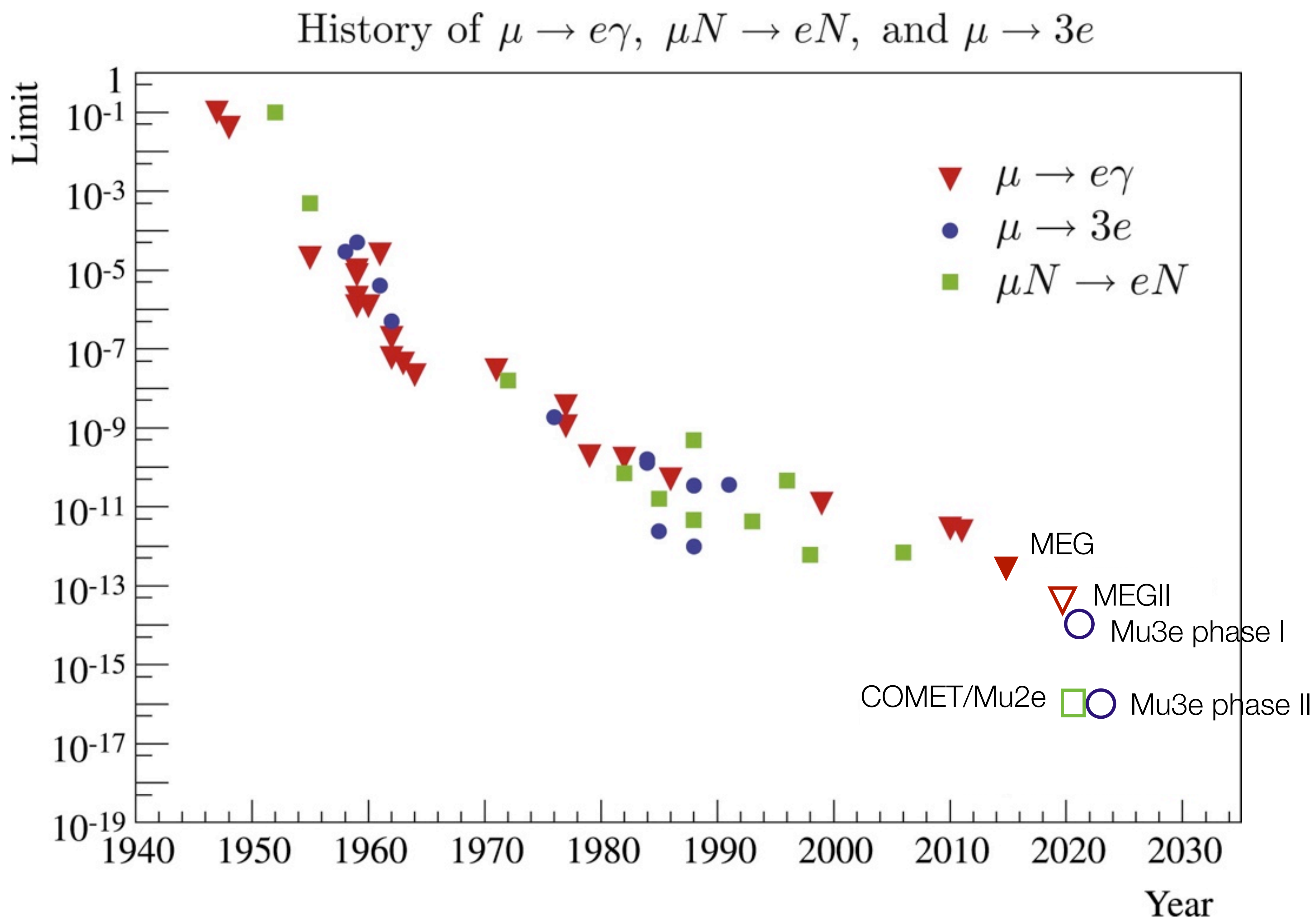
- effective lagrangian approach
  - a framework to combine constrains from low-energy (i.e. μ-> eγ) experiments with LFV searches at higher energies (Z bosons or H -> τμ)
  - complementarity among LFV channels



ref.: G.M. Pruna and A. Signer arXiv:1511.04421v1
G.M. Pruna and A. Signer JHEP 10 (2014) 014

see: S. Mihara, Nufact2016

cLFV searches with muons: status and future prospects



Why cLFV with muons?

- Even if taus are the ideal probe for new physics via cLFV w. r. t. muons
  - Smaller GIM suppression
  - Expected stronger coupling to new physics
  - Many possible LFV decays
- Muons are currently the most sensitive probe to new physics via cLFV
  - Huge statistics

- **Best upper limit of any particle decay set by the MEG experiment**

$$B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13} \quad (2009\text{-}2011)$$

Ref. Phy. Rev. Lett. 110, 201801 (2013) see: M. Venturini, Nufact2016

MEG full data set result

EPJc (2016) 76:434

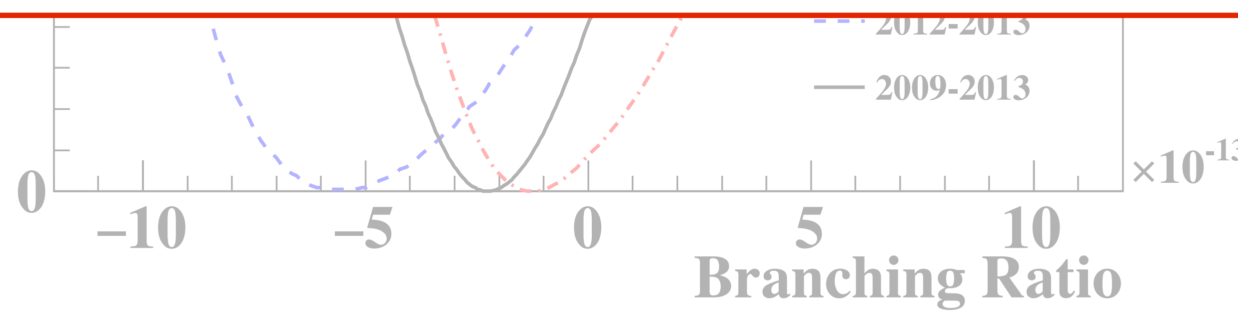
- profile likelihood ratios as a function of the BR: all consistent with a null-signal

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**



Muon-cLFV coincidence experiments

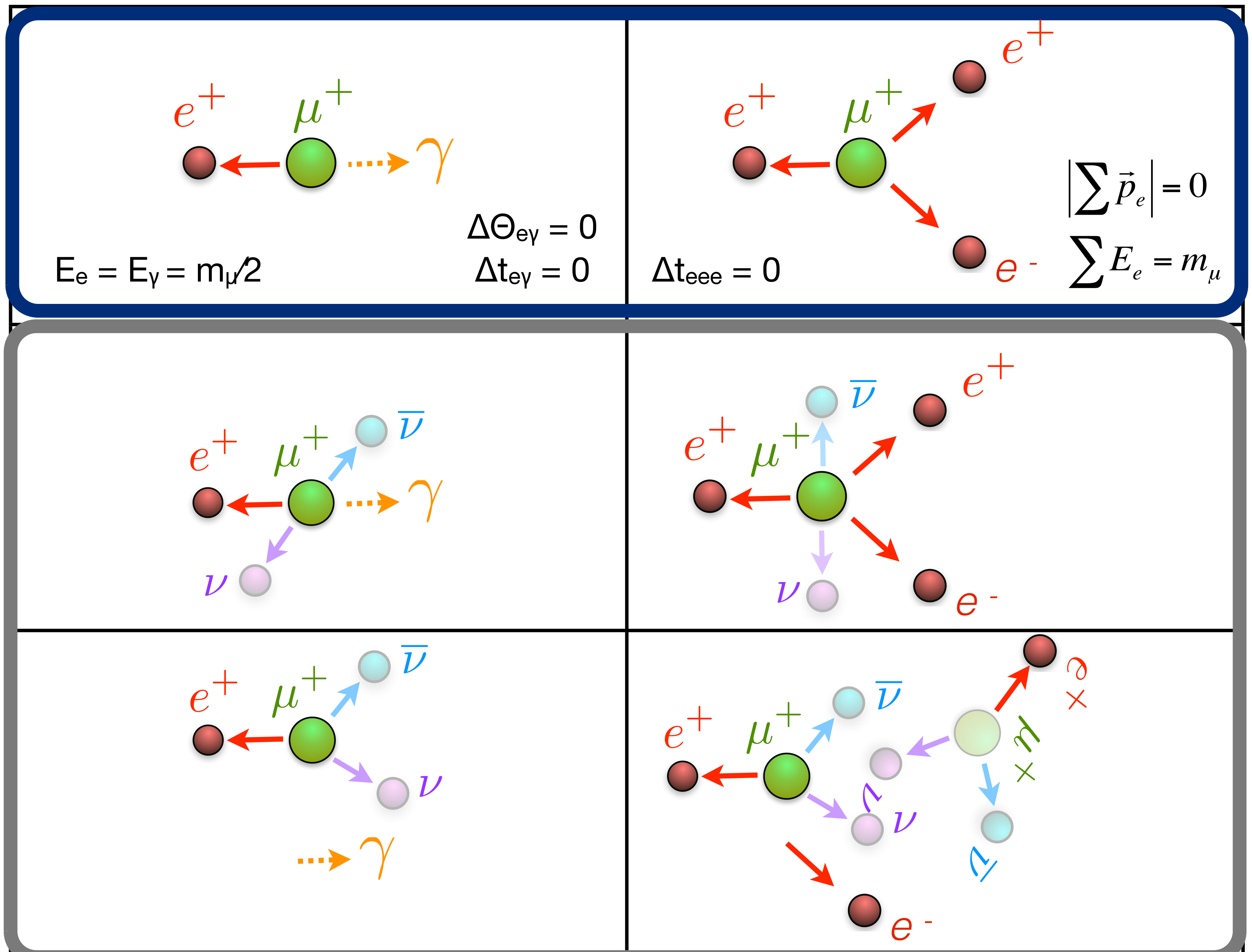
Gold channels: the $\mu^+ \to e^+ \gamma$ and $\mu^+ \to e^+ e^+ e^-$ decays

MEG and MEGII (CH) | **SINDRUM** and Mu3e (CH)

Signature

Correlated Background

Accidental Background



How the sensitivy can be pushed down?

Using the $\mu^+ \to e^+ \gamma$ search as an example

Current upper limit	future sensitivity
BR $(\mu^+ \to e^+ \gamma) < 4.2 \times 10^{-13}$ (MEG)	SES $(\mu^+ \to e^+ \gamma) \sim 5 \times 10^{-14}$ (MEGII)
BR $(\mu^+ \to e^+ e^+ e^-) < 1.0 \times 10^{-12}$ (SINDRUM)	SES $(\mu^+ \to e^+ e^+ e^-) \sim 10^{-16}$ (Mu3e)

high statistics

- More sensitive to the signal...

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

Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

high resolutions

- More effective on rejecting the background...

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

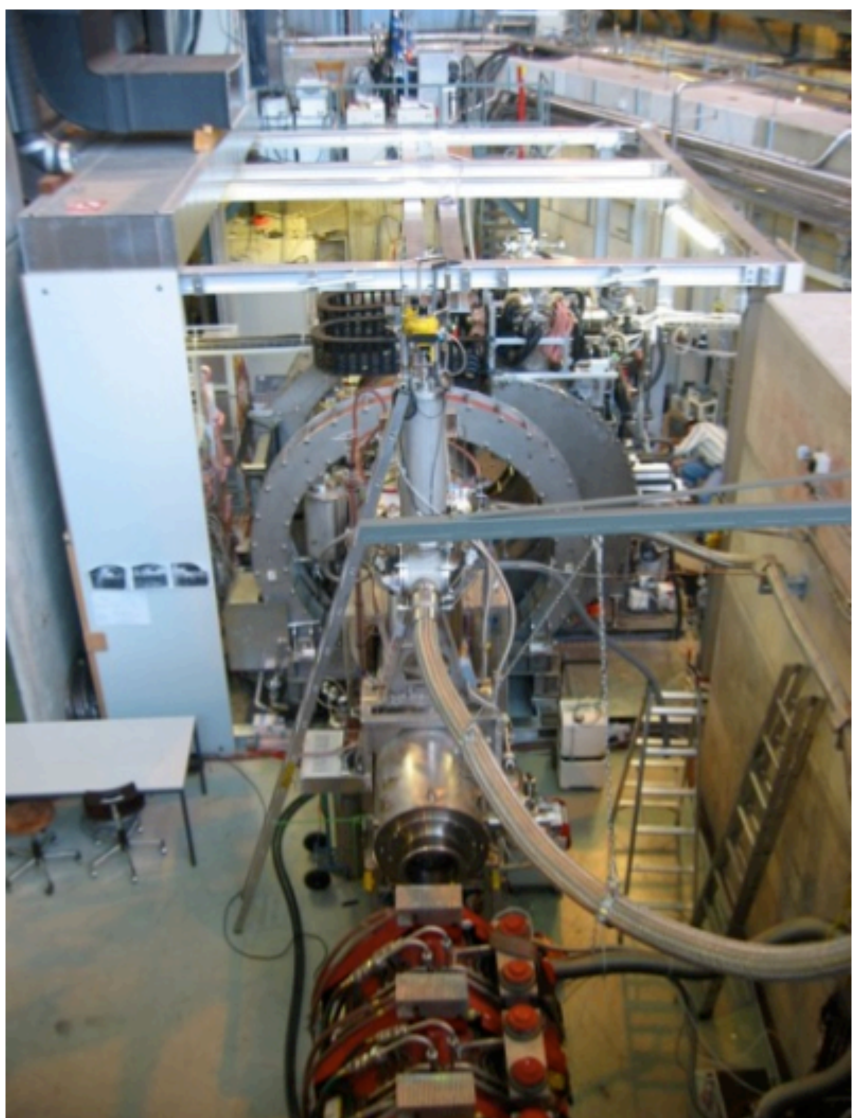
Momentum resolution
Energy resolution
Relative timing resolution
Relative angular resolution

The piE5 beam line

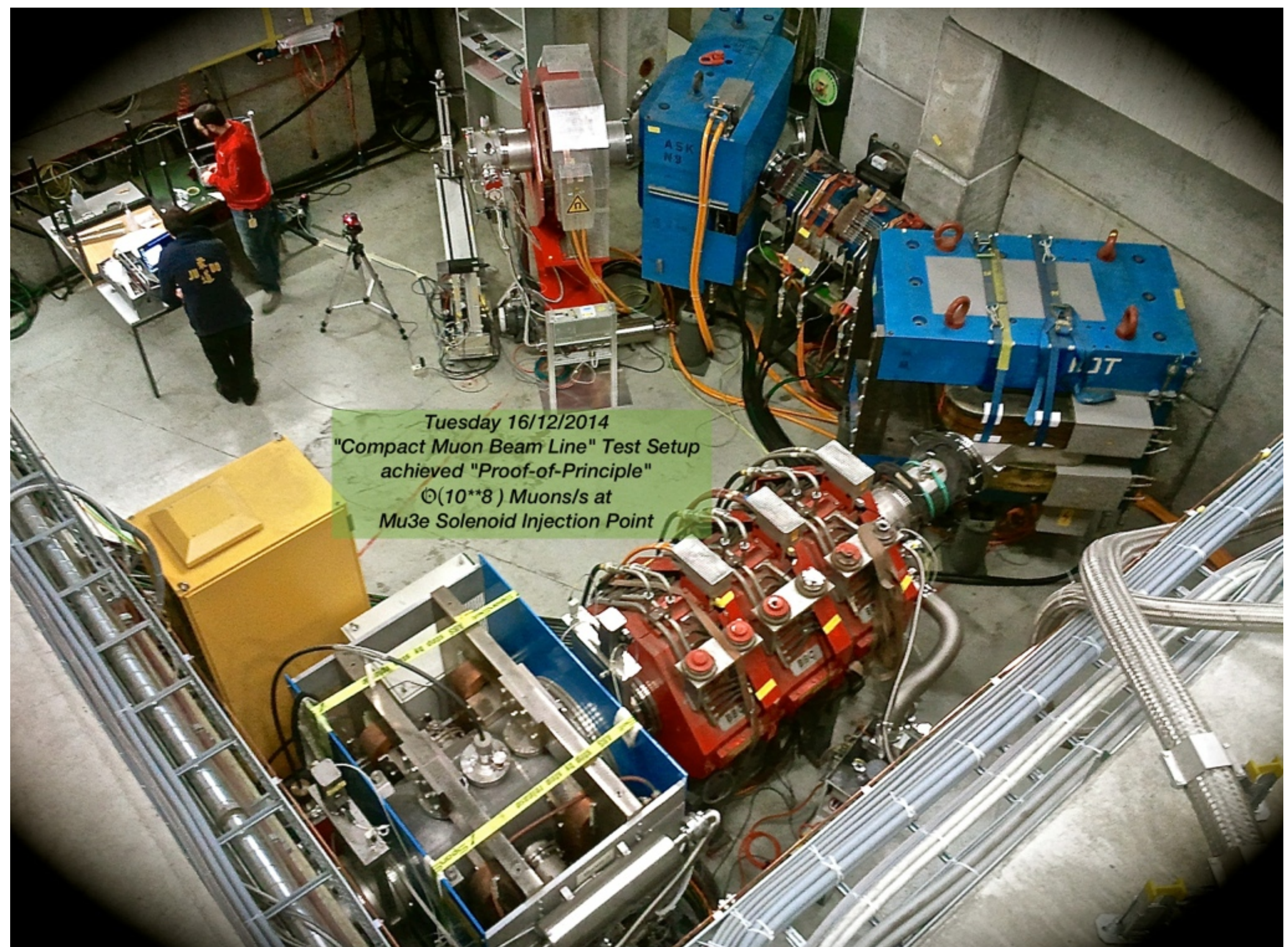
- MEGII and Mu3e (phase I) similar beam requirements:
  - Intensity O(10^8 muon/s), low momentum p = 28 MeV/c
  - Small straggling and good identification of the decay region

Only possible in piE5!

MEG/MEGII Beam Line



Mu3e Compact Muon Beam Line



2013	2014	2015	2016	2017-20
Design	Construction	PreEng Run	Eng. Run	Run

MEGII detector concept

Sensitivity [2017-20] ~ 4 x 10^{-14}

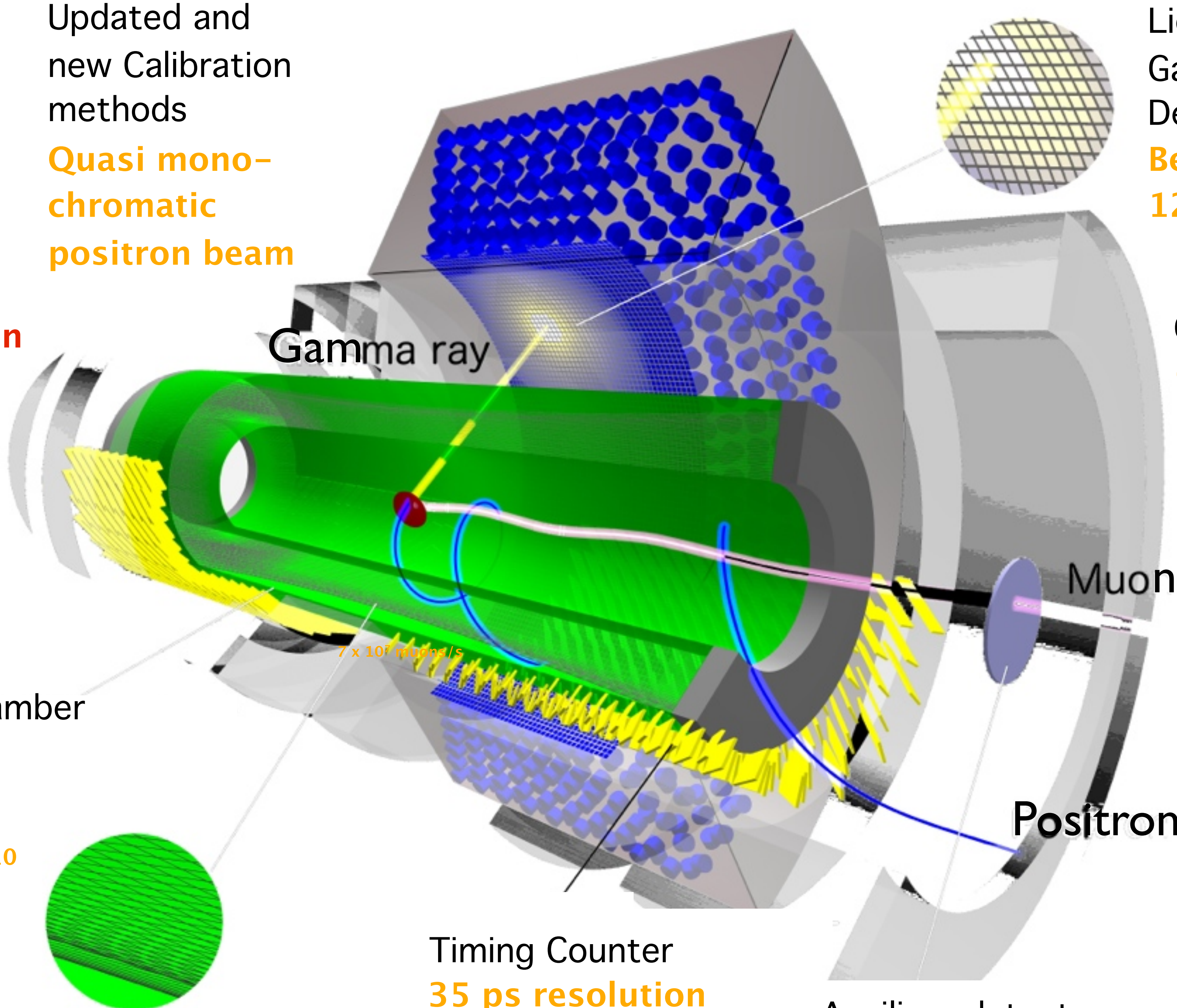
Wavedream
~9000 channels at 5GSPS

Updated and new Calibration methods
Quasi mono-chromatic positron beam

x2 resolution everywhere

Liquid Xenon Gamma-ray Detector
Better uniformity w/ 12x12 VUV SiPM

Cobra magnet
Gradient B field up to 1.3 T



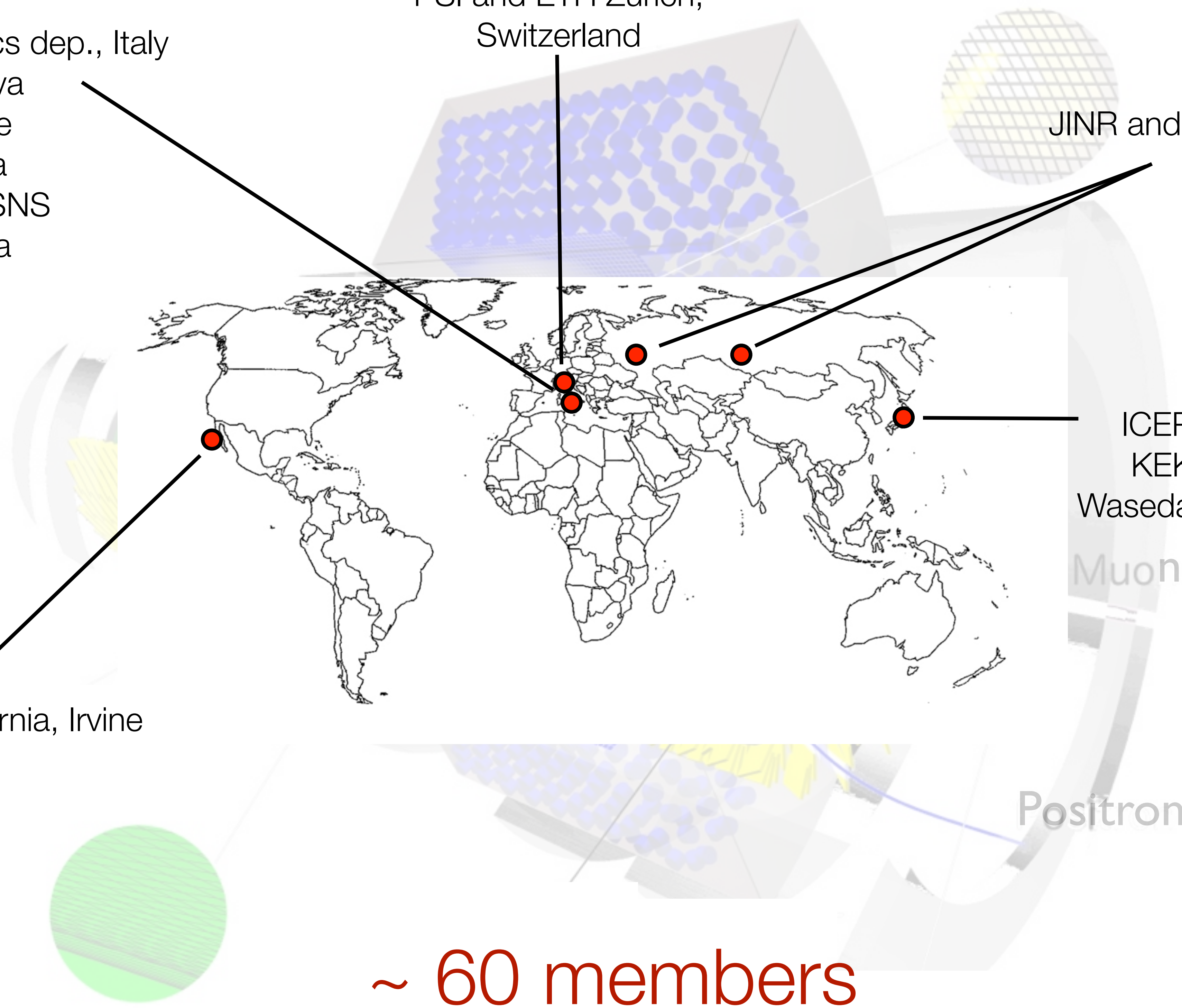
Muon Beam and target
Full available stopped beam intensity 7×10^7

Drift Chamber
Single volume $He:iC_4H_{10}$

Timing Counter
35 ps resolution w/ multiple hits

Auxiliary detectors
Background rejection

MEGII collaboration



~ 60 members

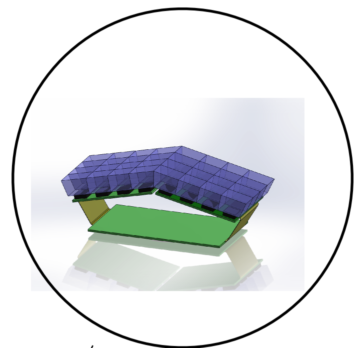
2013-5	2015-7	2017	2018-20
Design	Construction	Eng Run	Run

Sensitivity phase I [2018-20] ~ 10^{-15}
(Final sensitivity phase II [202x] ~ 10^{-16} needs 10^{9} muons/s)

Mu3e detector concept

Superconducting solenoid Magnet

Homogeneous field 1T

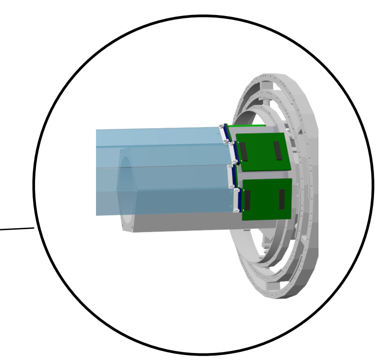


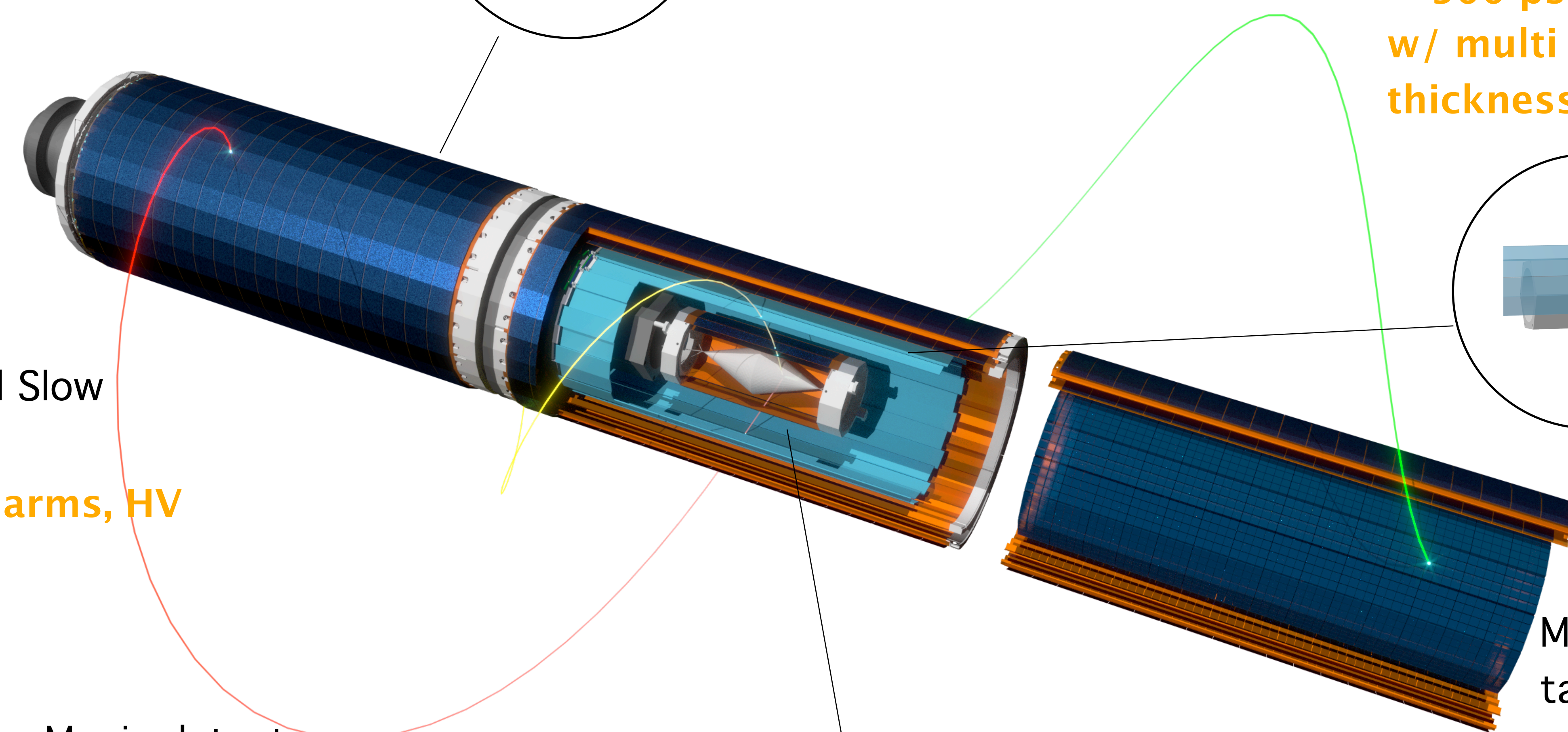
Tile detector

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.

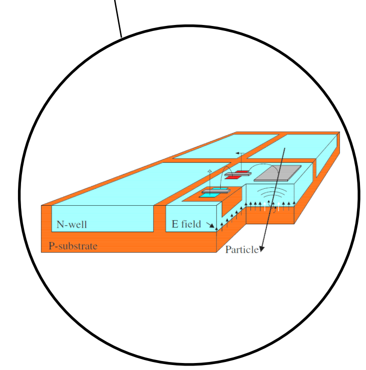
Muon Beam and target

Full available beam intensity 2×10^{8}

Mupix detector

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

1 layer: ~ 0.1% X_0



Mu3e collaboration

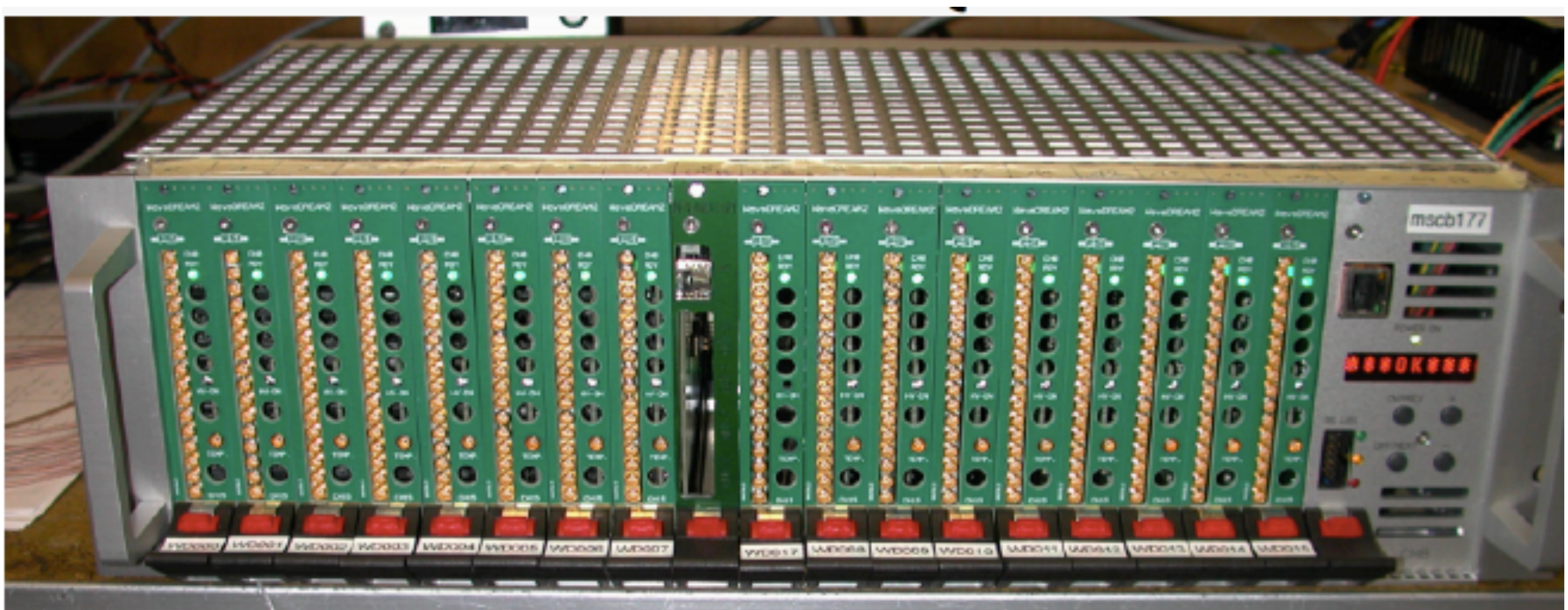
Switzerland:
PSI
ETH Zurich
Uni. of Geneve
Uni. of Zurich

Germany:
Karlsruhe Institut fur Technologie
J.G. Uni. Mainz
Uni. Heidelberg

~ 40 members

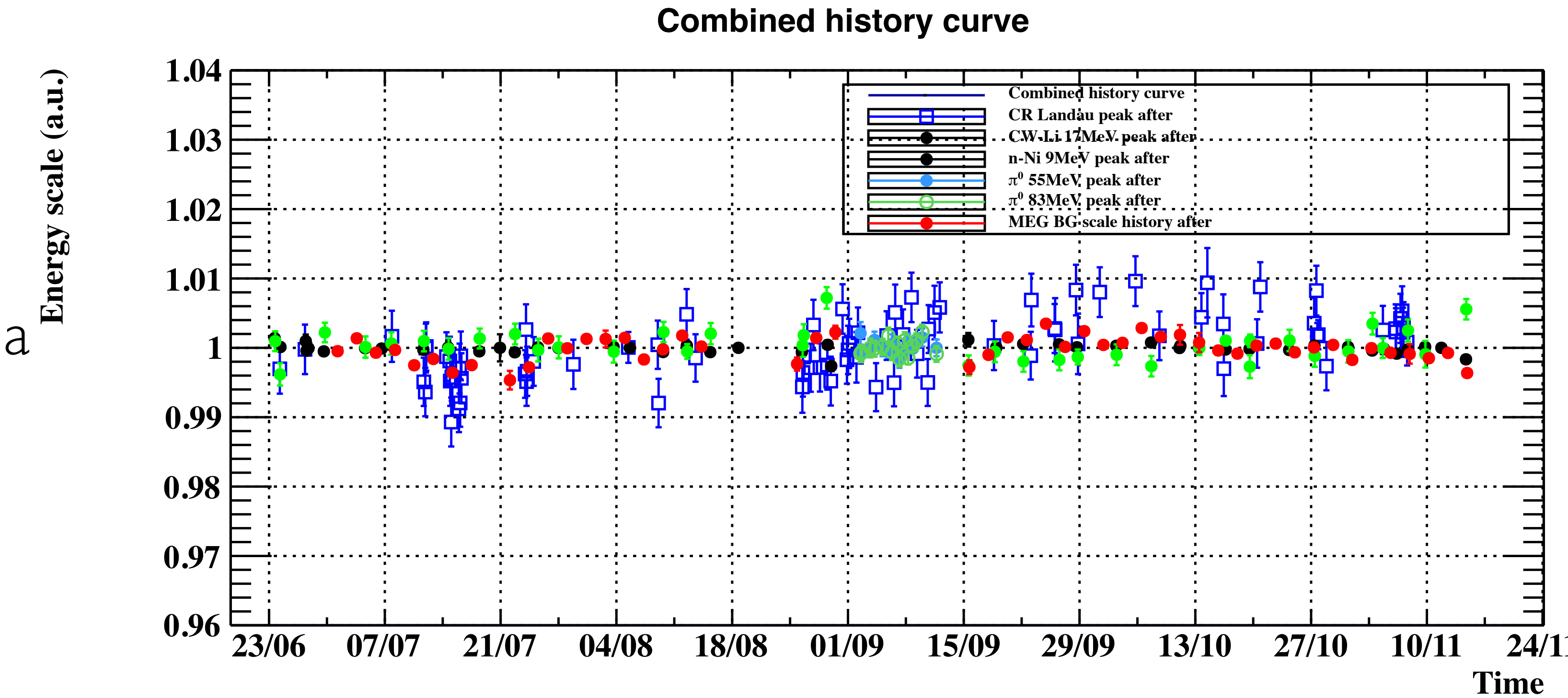
MEGII: The new electronic - DAQ and Trigger

- DAQ and Trigger
  - ~9000 channels (5 GSPS)
  - SiPM services included
- 256 channels delivered for the test beam/engineering run before summer and about 1000 channels available soon
- Trigger electronics and several trigger algorithms included and successfully delivered for the test beams/engineering run

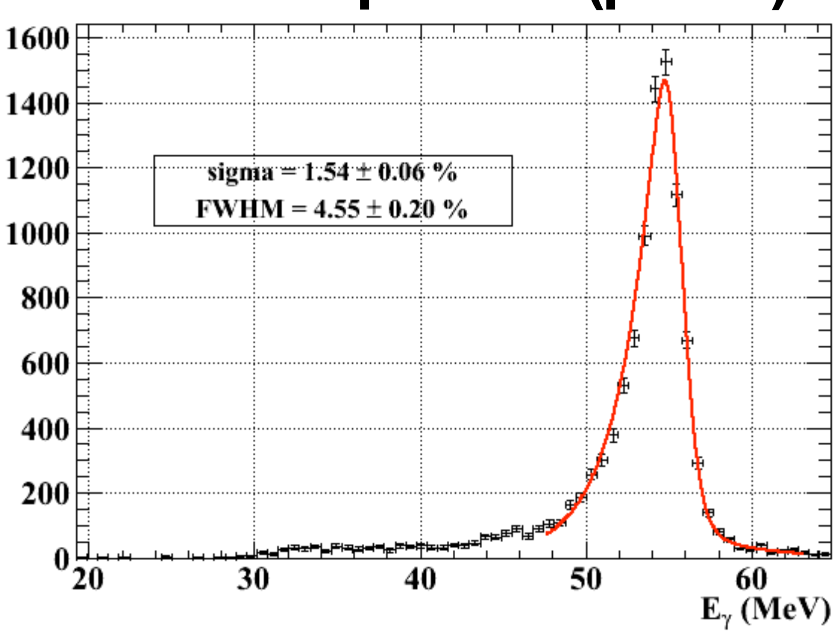


MEGII: The LXe calorimeter - MEG

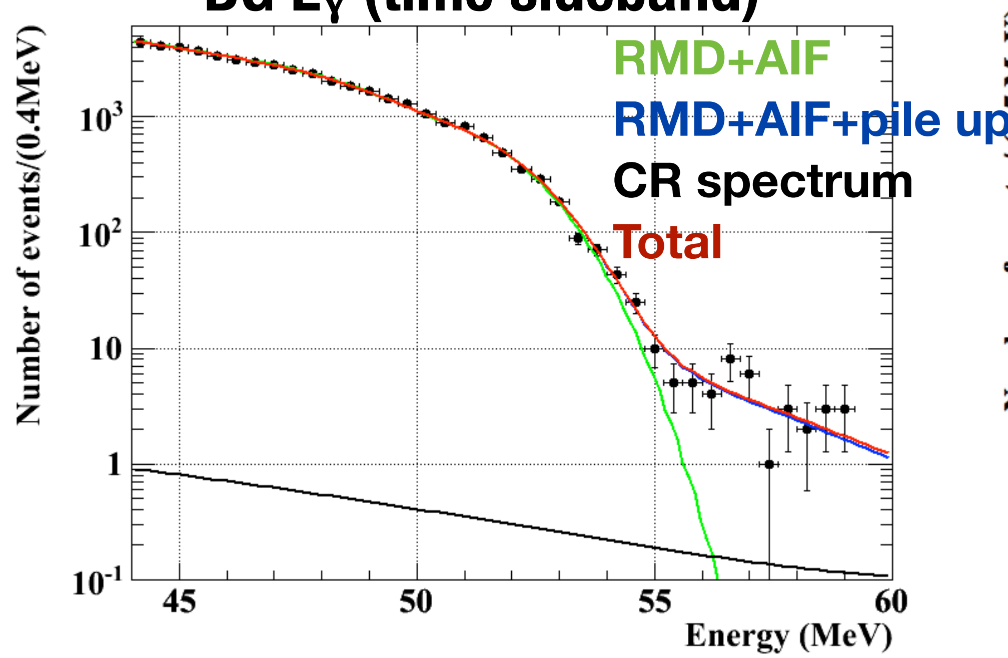
- Purity < 1 ppm and stable conditions over the time
- Energy (σ_E /E <2.5%) and timing resolutions(σ_t < 70 ps) never reached up to now with a unique detector at 52.8 MeV!
- Crucial ingredients:
  - waveform based analysis
  - calibration and monitoring methods



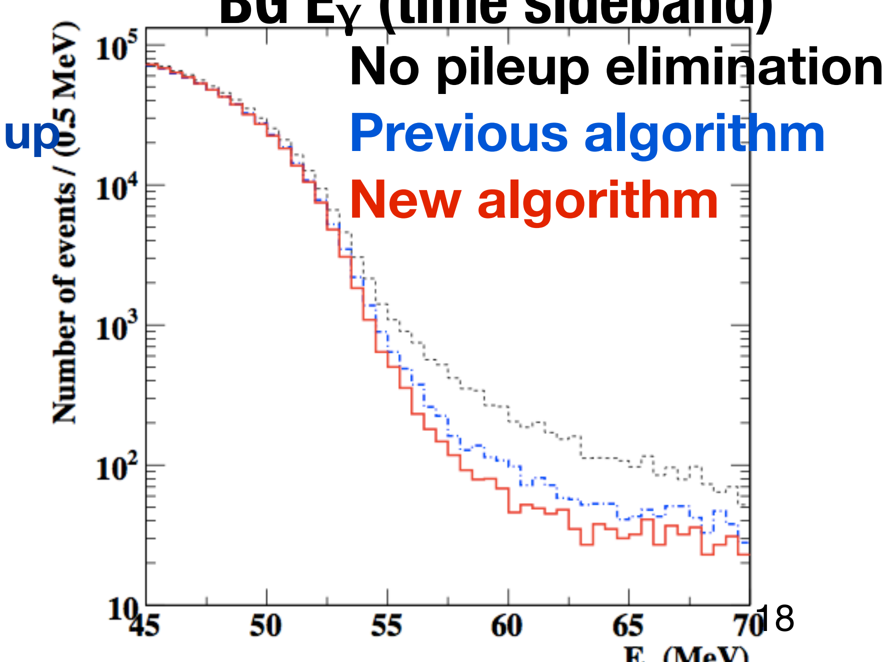
55 MeV spectrum (pi^0 run)



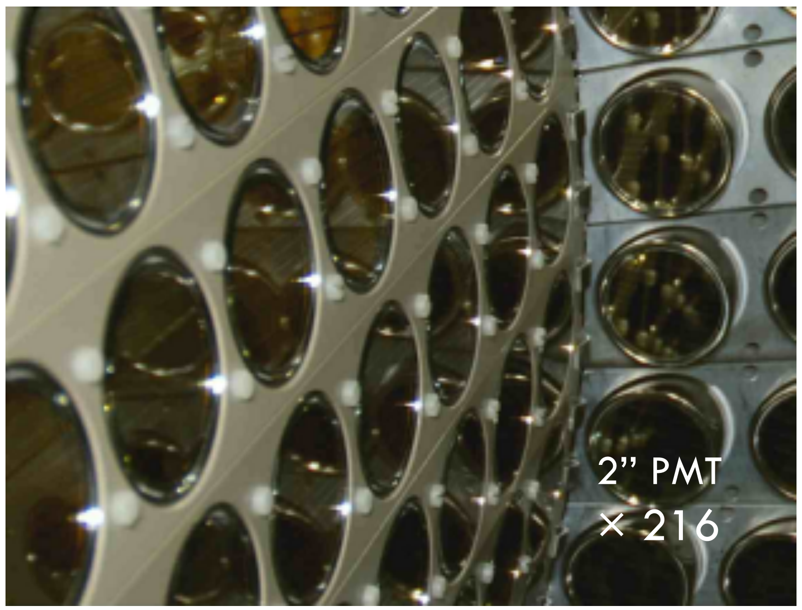
BG E_γ (time sideband)

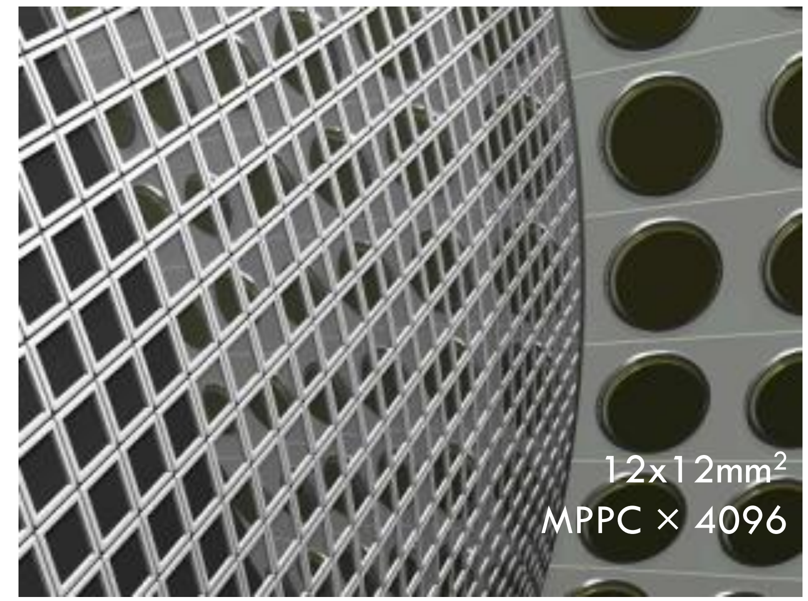


BG E_γ (time sideband)

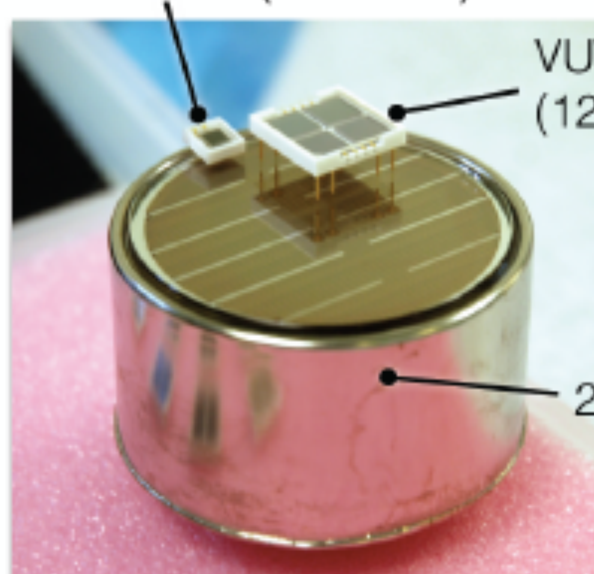


MEGII: The upgraded LXe calorimeter





new R&D: VUV SiPM

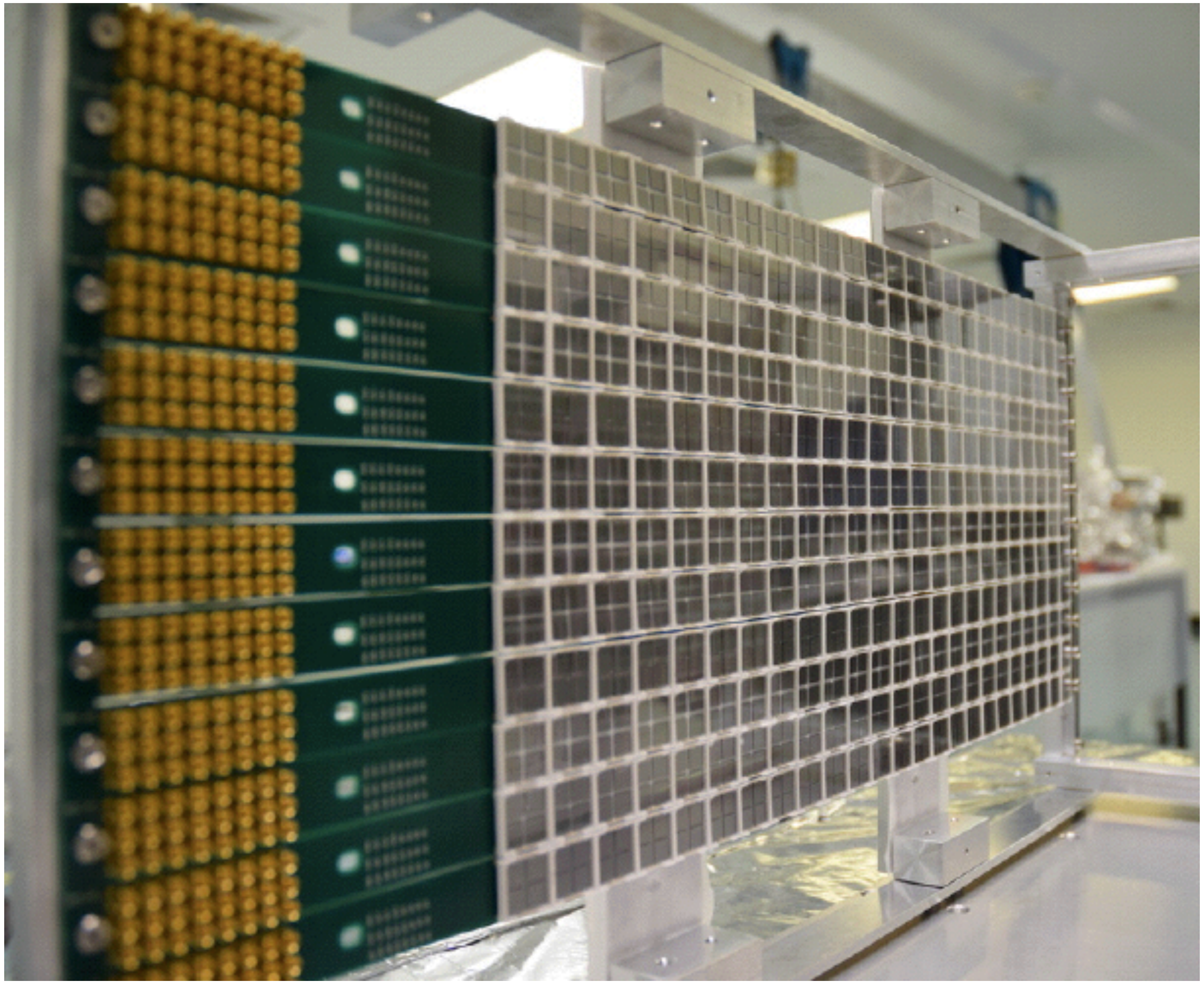


- Increased uniformity/ resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency

Resolution	MEGI	MEGII
u (mm)	5	2.4
v (mm)	5	2.2
w (mm)	6	3.1
E_γ (w<2cm)	2.4%	1.1%
E_γ (w>2cm)	1.7%	1.0%
t_γ (ps)	67	60

The MEGII calorimeter: Assembly

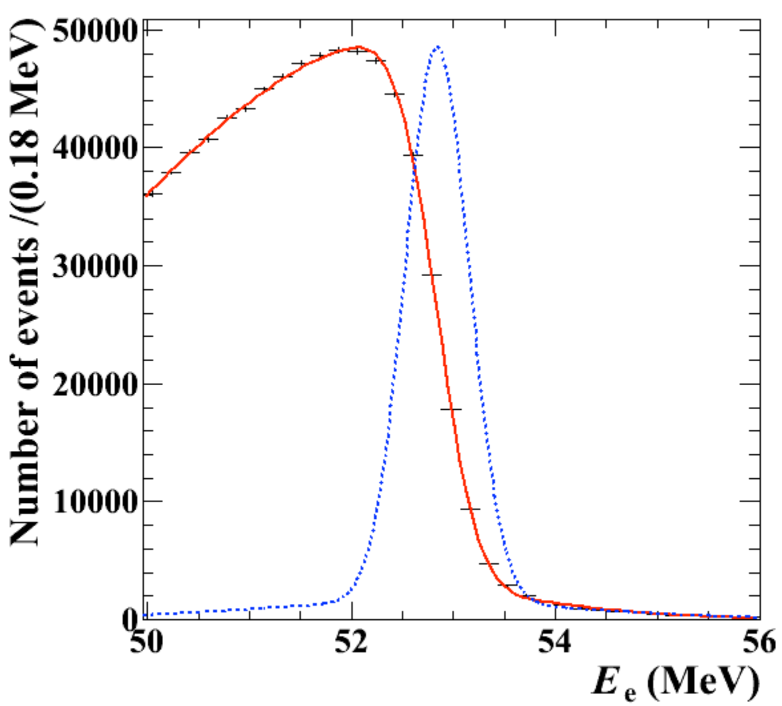
- All 4200 Hamamatsu VUV-sensitive 12x12 mm^2 SiPM (MPPC) were produced and succefully tested
- Detector assembly ongoing outside piE5 area
- Liquefaction, tests, purification and calibration inside piE5 area after summer

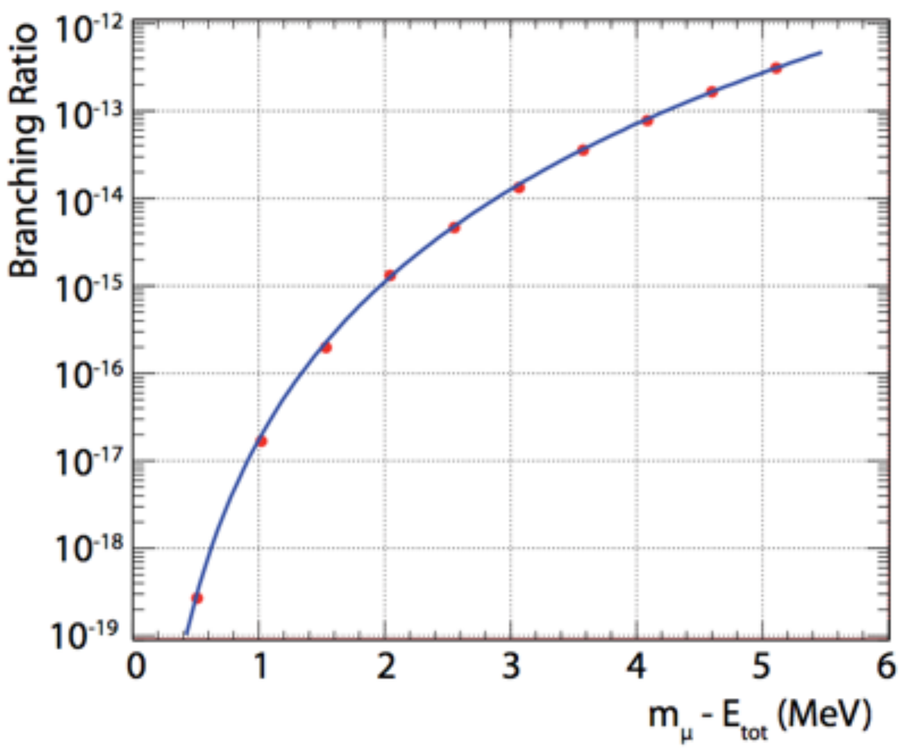


Positron/electron detector requirements

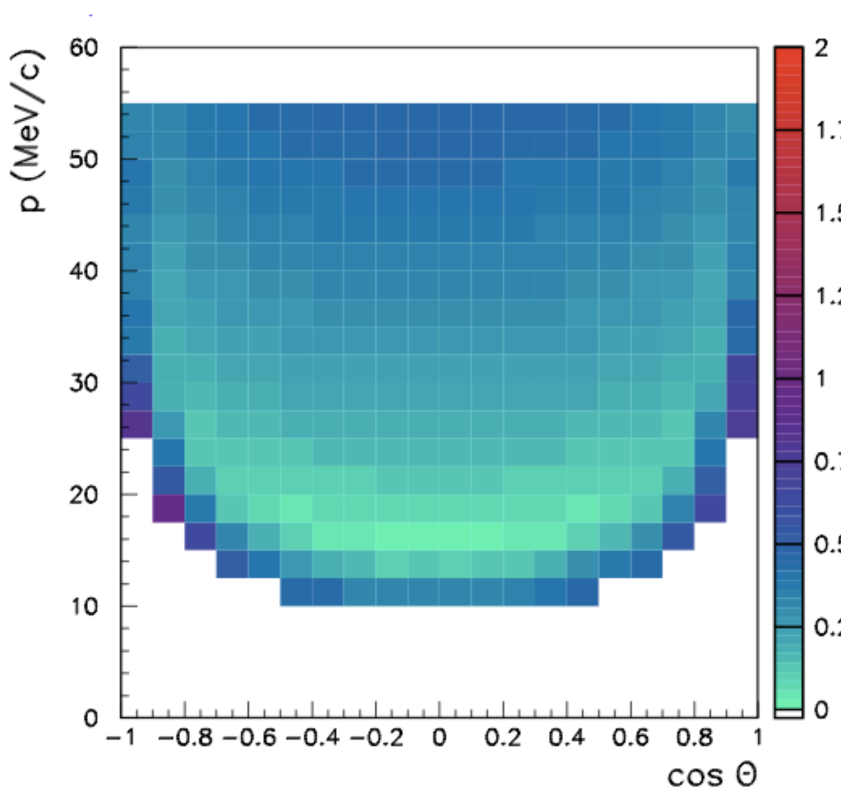
- High detection efficiency and acceptance (10 - 60 MeV/c)
- High rate capability
- High momemtum resolutions
  - good hit resolutions
  - low mass

MEG/MEGII

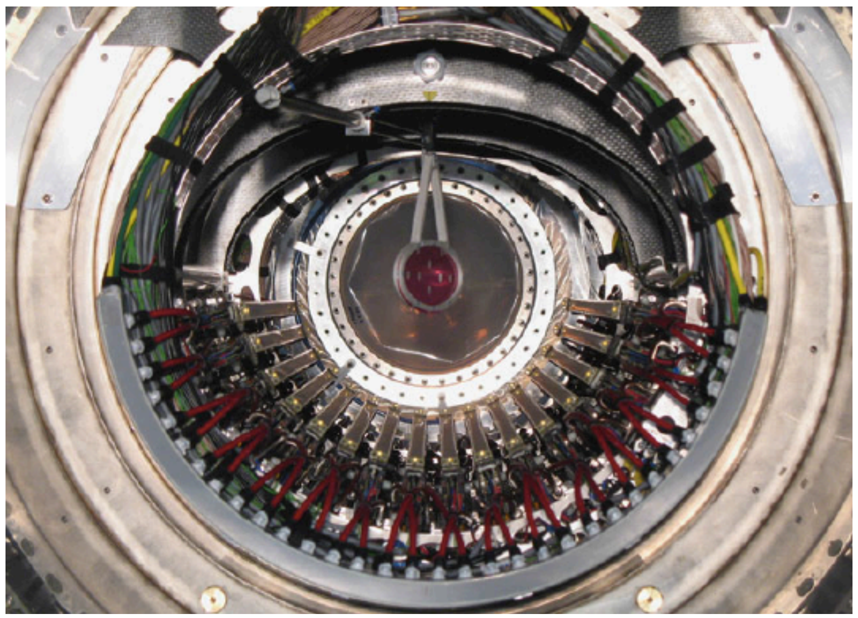


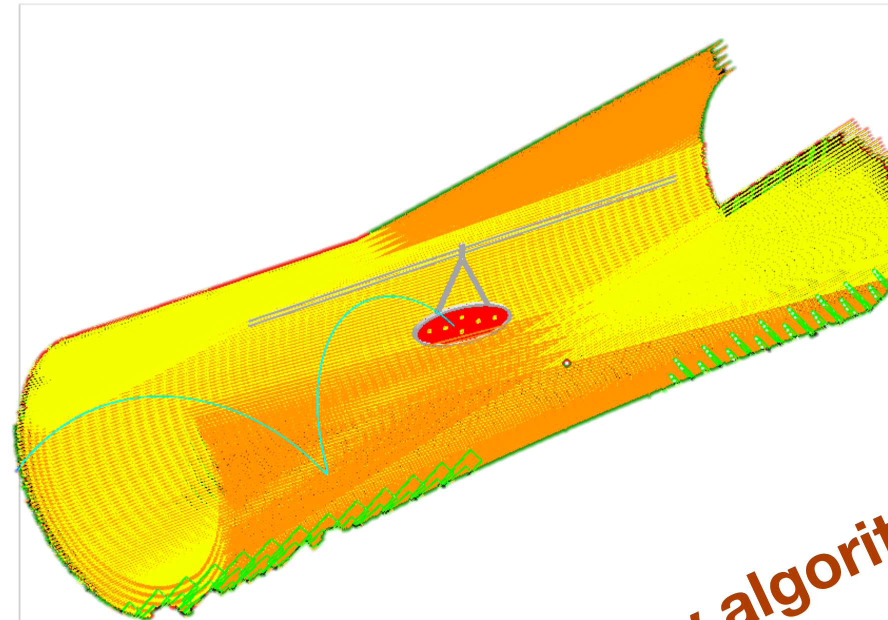


Mu3e

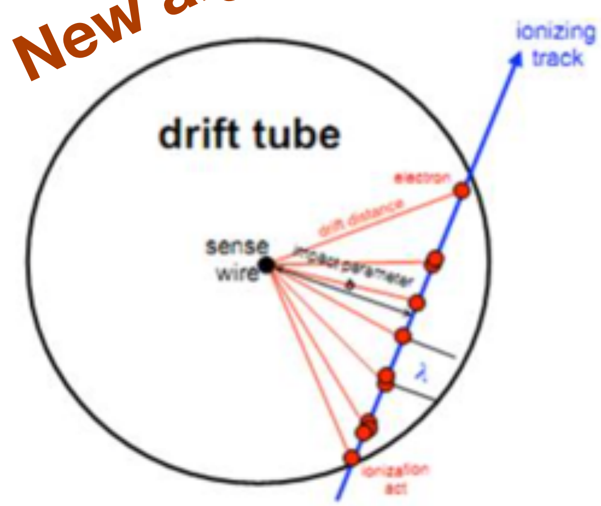


The MEGII spectrometer: a single volume chamber





New algorithms

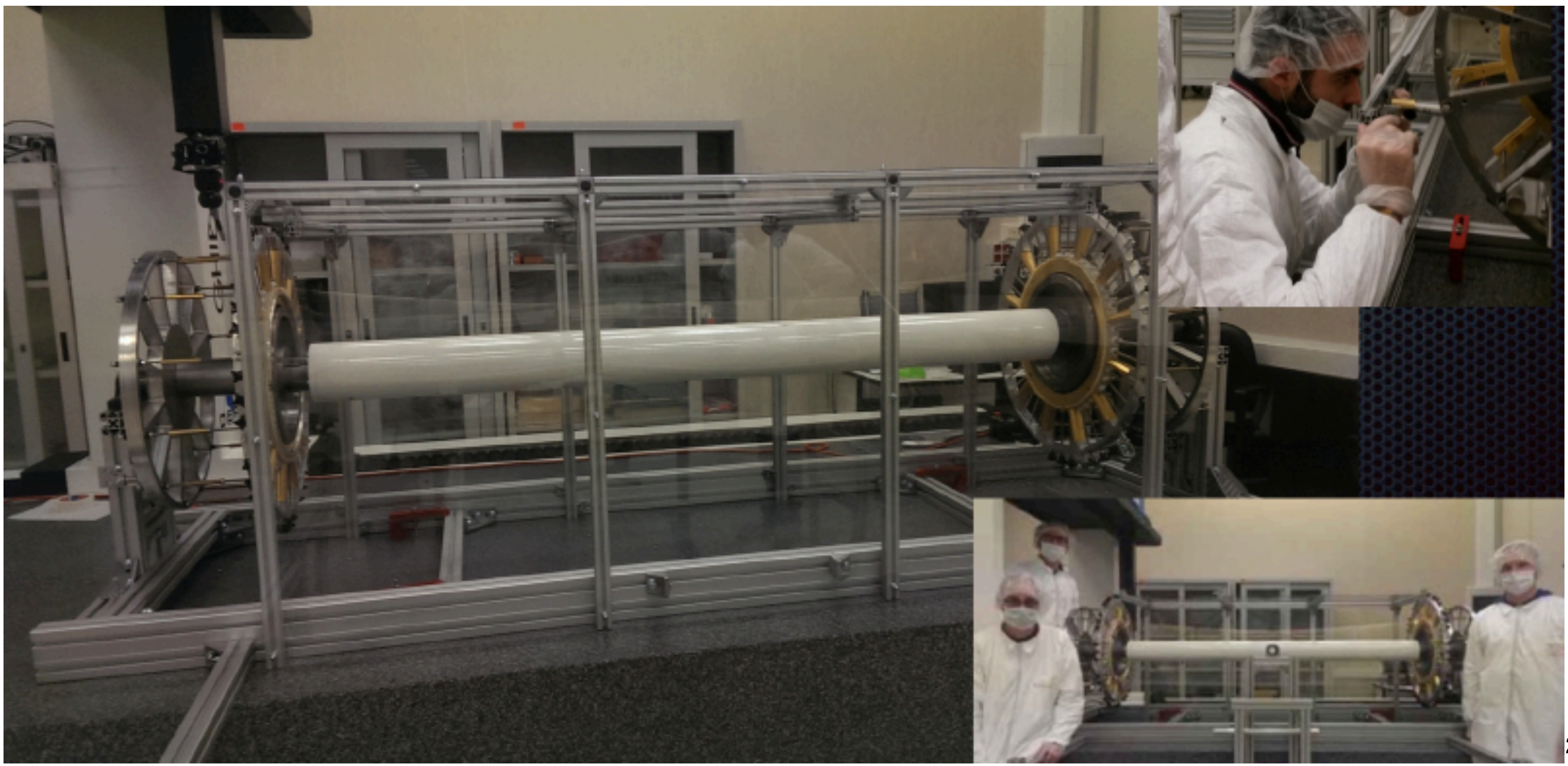


- Improved hit resolutions σ_r = 120 um, σ_z = 170 um (210, 800 um)
- High granularity/Increased number of hits per track/cluster timing technique
- Less material (helium:isobutane = 85:15, $1.6\times10^{-3}\,X_0$)
- High transparency towards the TC

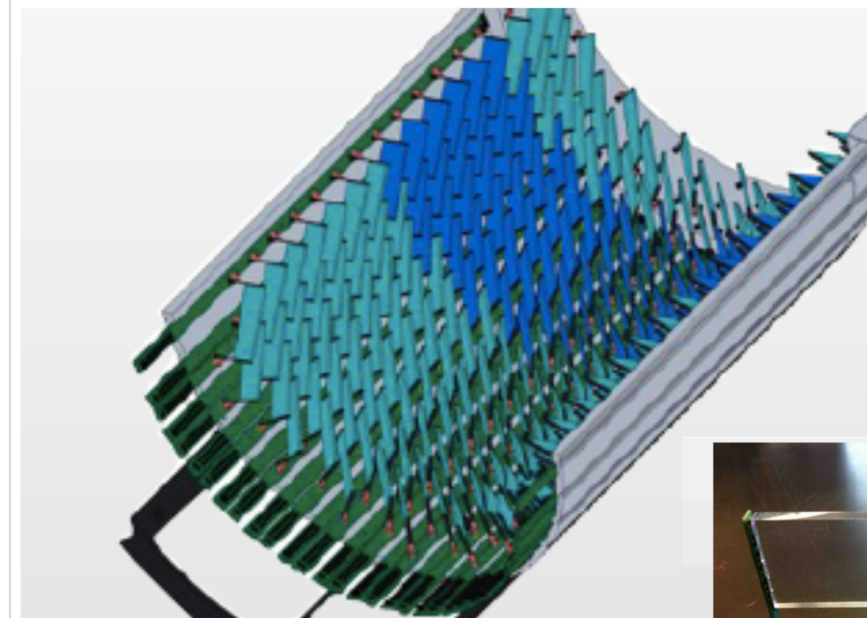
Resolutions	MEG	MEG II
p_e (keV)	306	130
ϑ_e(mrad)	9.4	5.3
φ_e(mrad)	8.7	4.8
e^+ efficiency (%)	40	88

The single volume chamber: Wiring

- Carbon fibre structure test successful
- Construction going on: wiring and assembly
- To be delivered to PSI end of this year/begging of next one

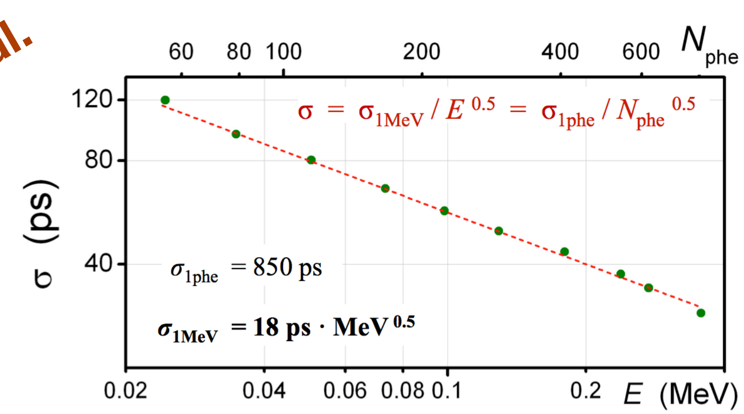


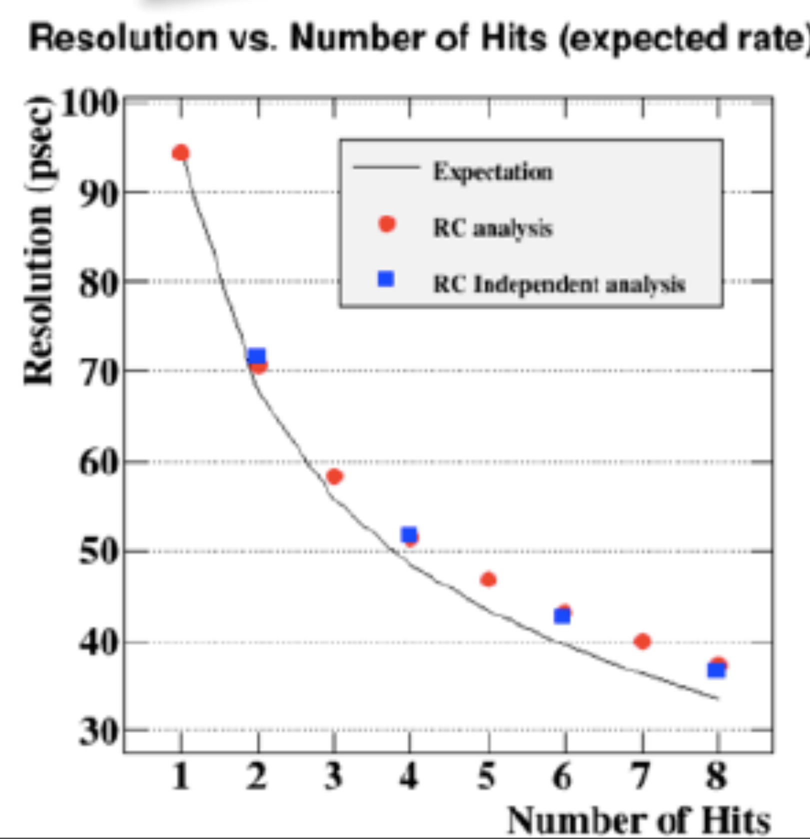
The MEGII spectrometer: the pixelized Timing Counter



- Higher granularity: 2 x 256 of scintillator plates (120 x 50 x 5 mm^3) readout by SiPMs
- Improved timing resolution: from 70 ps to 35 ps
- Less multiple scattering and pile-up

A. Stoykov et al.
μSR PSI



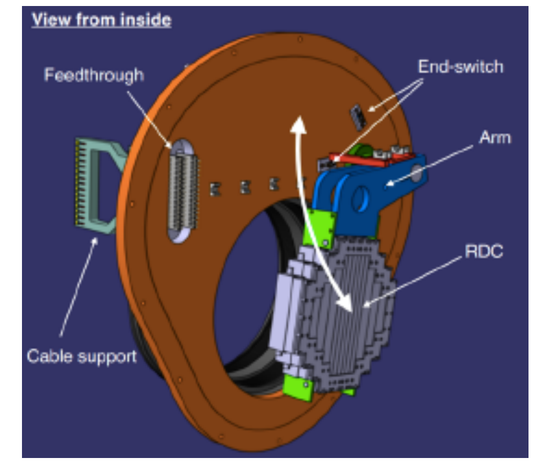


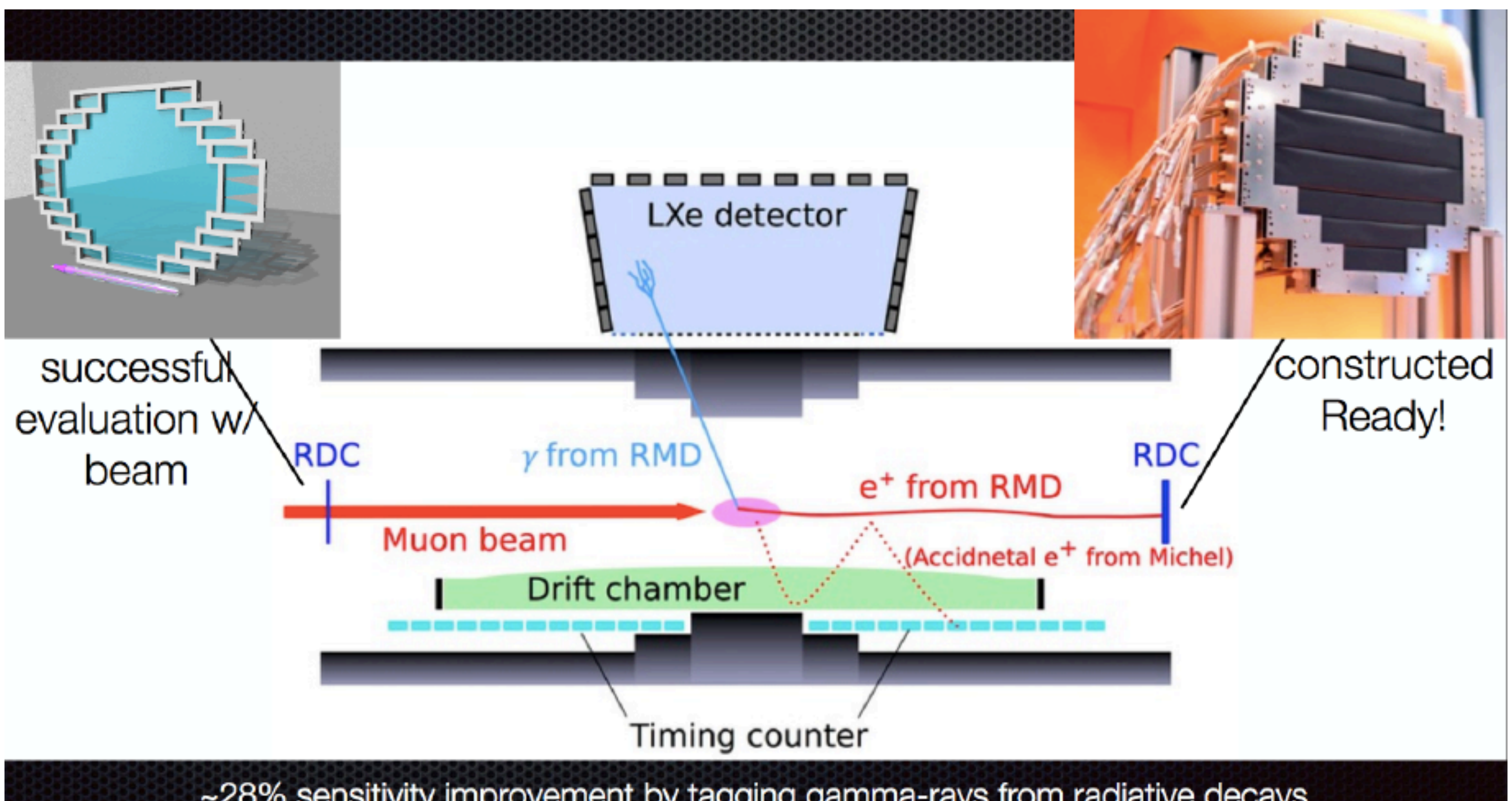
The pixelized Timing Counter: commissioning

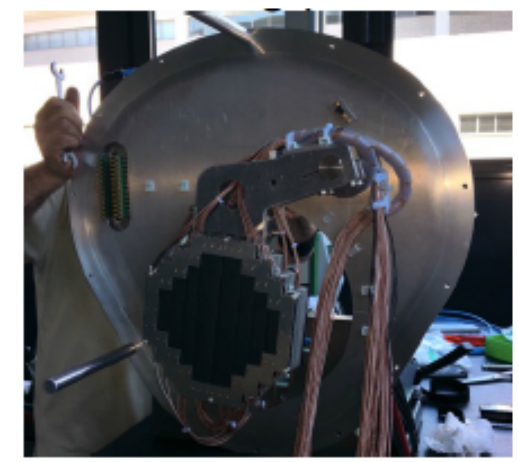
- Successful engineering run in June/July 2016 (one quarter of the new TC)
- Detector performances fully achieved along the beam line
- To be completed and commissioned by this year

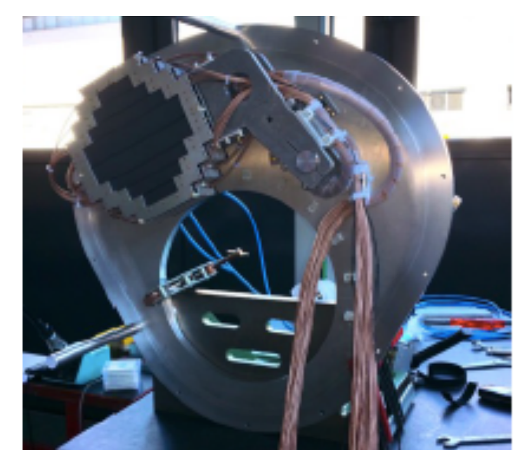
MEGII: new auxiliary detectors

- Commissioned during the engineering run in June/July 2016
- DS Detector status: Ready!
- US Detector under study/ in preparation





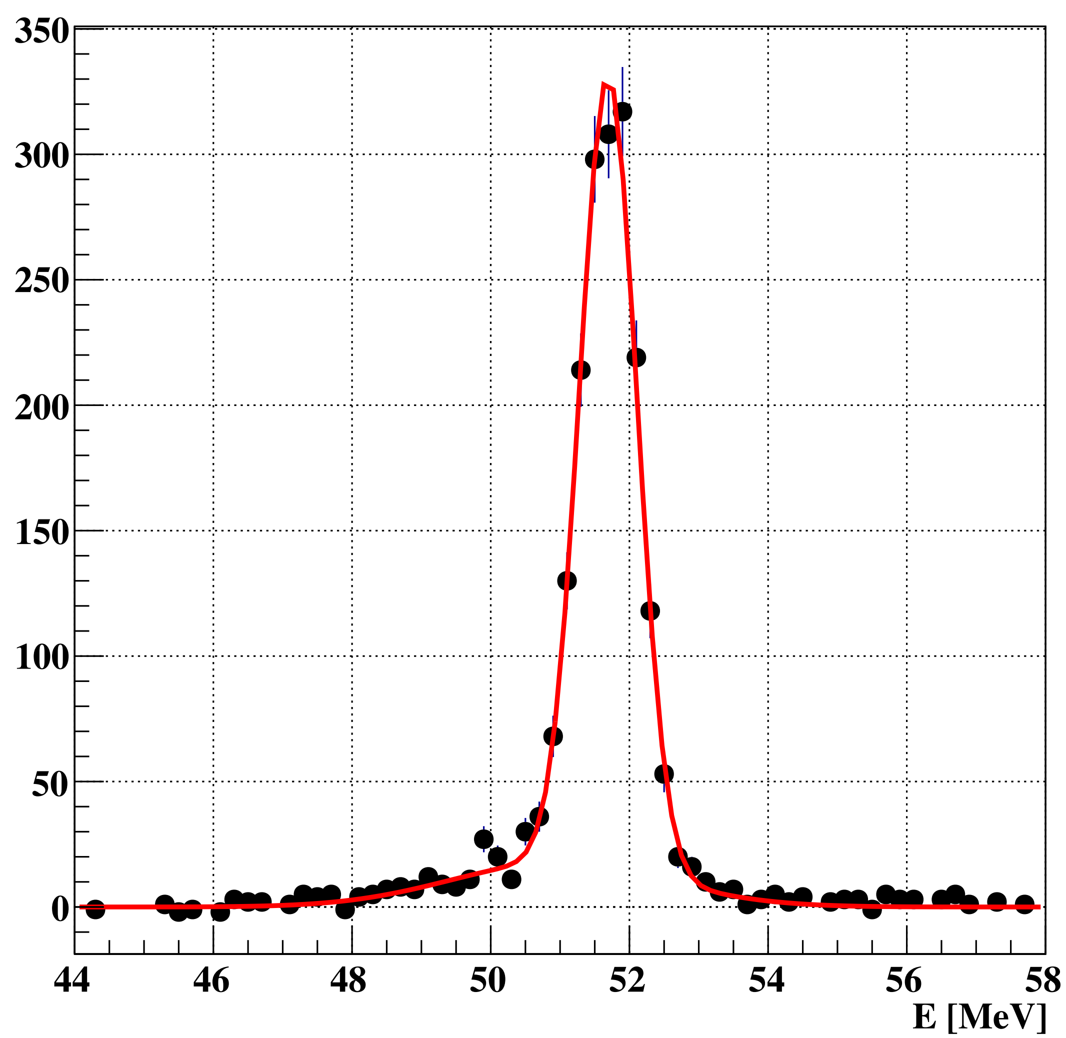


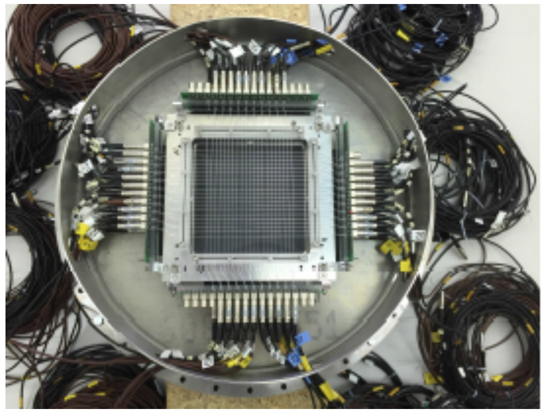


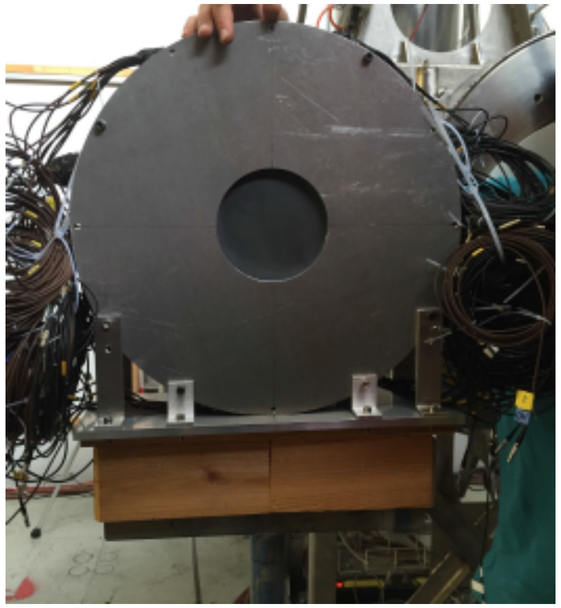
MEGII: new calibration methods and upgrades

- CEX reaction: $p(\pi^- ,\pi^0)n$, π^0 $\gamma\gamma$
- 1MV Cockcroft-Walton accelerator
- Pulsed D-D Neutron generator
- NEW: Mott scattered positron beam to fully exploit the new spectrometer !
- NEW: not invasive, ID particle identification, vacuum compatible, working in magnetic field,

online beam monitor (beam rate and profile)

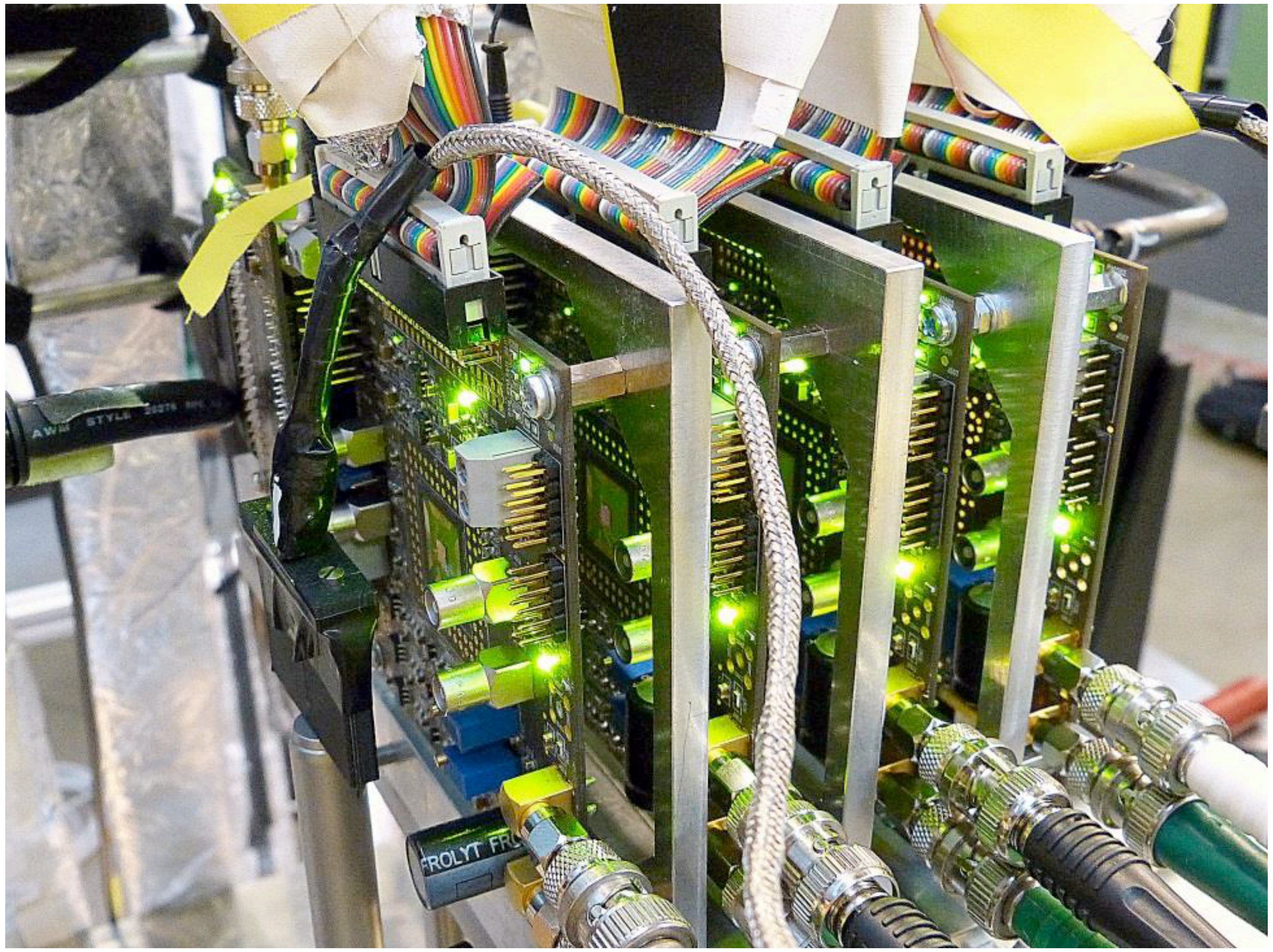






Mu3e: The Mupix tracker detector

- Based on the High Voltage Monolithic Active Pixel Sensors (HV-MAPs)
- HV-CMOS technology
- Reverserly biased ~60 V
    - charge collection via drift
    - fast <1ns
    - thinning to ~50 μm
- Integrated readout electronics
- Full detection efficiency (> 99%)
- High rate capability (> 1 MHz)
- Timing resolution < 17 ns

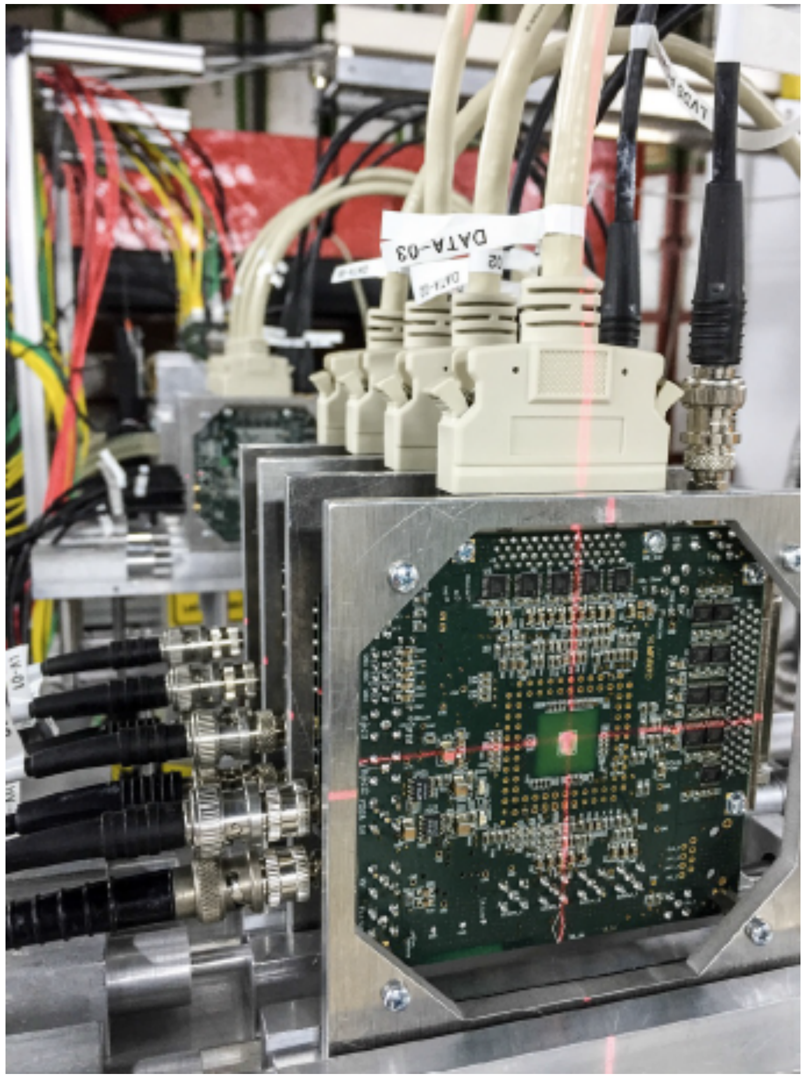


Mu3e: The Mupix R&D history

Several generations of MuPix chips realised:

Version	Year	Main features
MuPix1/2	2011/12	Analog prototype chips
MuPix3	2013	First digital readout
MuPix4	2013	Working digital readout and time-stamping
MuPix6	2014	Readout bugs fixed, double-staged preamplifier
MuPix7	2014	Fast serial readout (1.25 Gbit/s), internal state machine, internal clock generation

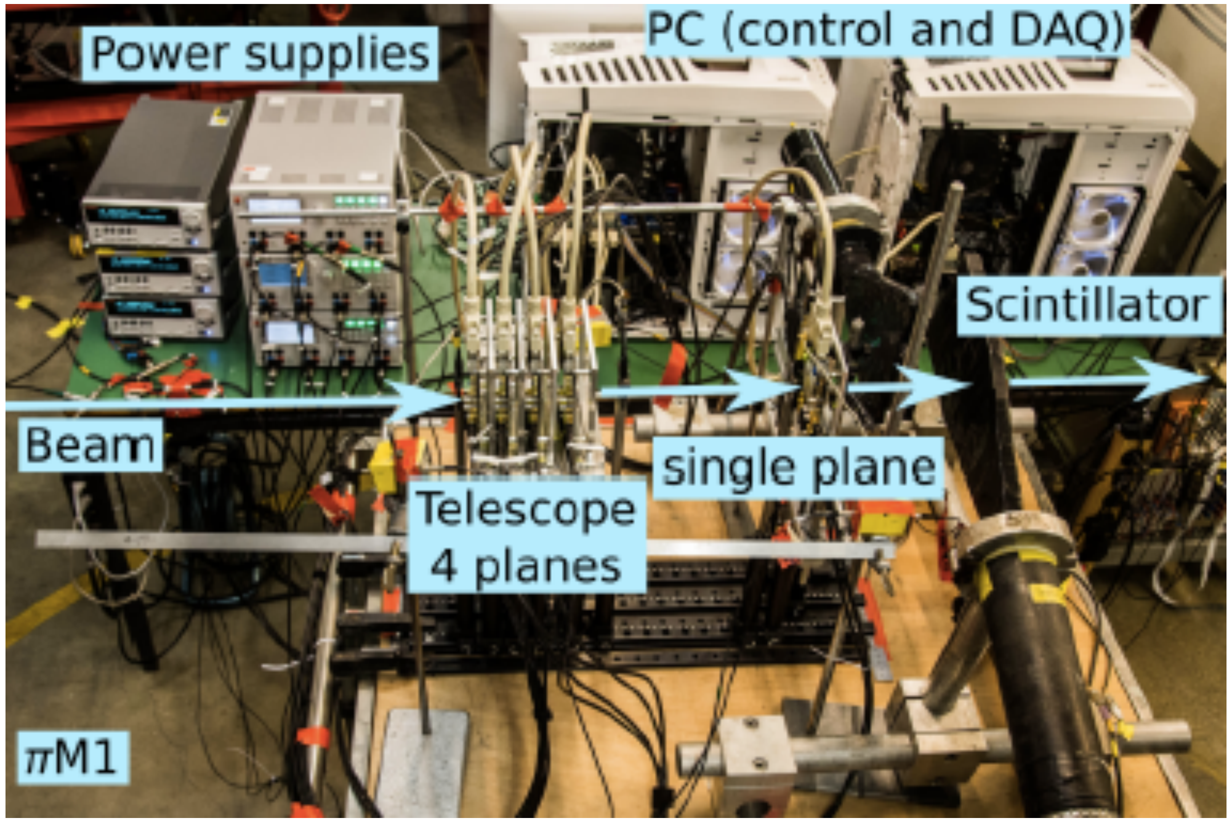
MuPix3–7 have an area of $3 \times 3\text{mm}^2$. MuPix7 pixel size: $103 \times 80\,\mu\text{m}^2$.



Mu3e: The Mupix status

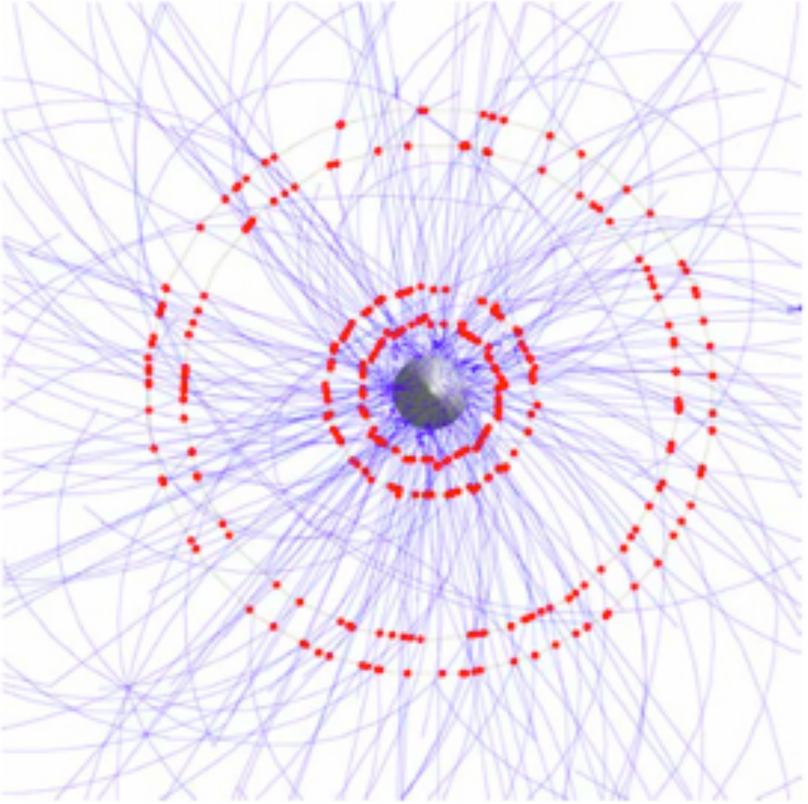
- After an extensive test beam campaign, achived milestones
  - A fully functional HV-MAPS chip, 3x3 mm^2
  - Operation at high rates: 300 kHz at PSI; up to 1 MHz at SPS
  - Crosstalk on setup under control, on chip seen. Mitigation plan exists (Mupix8)
  - Routinely operated systems of up to 8 chips in testbeams reliably
  - Data processing of one telescope at full rate on GPU demostrated

- Next steps
  - Mupix 8: from 3x3 mm^2 to 20x20 mm^2
  - Submission deadline: June 2016

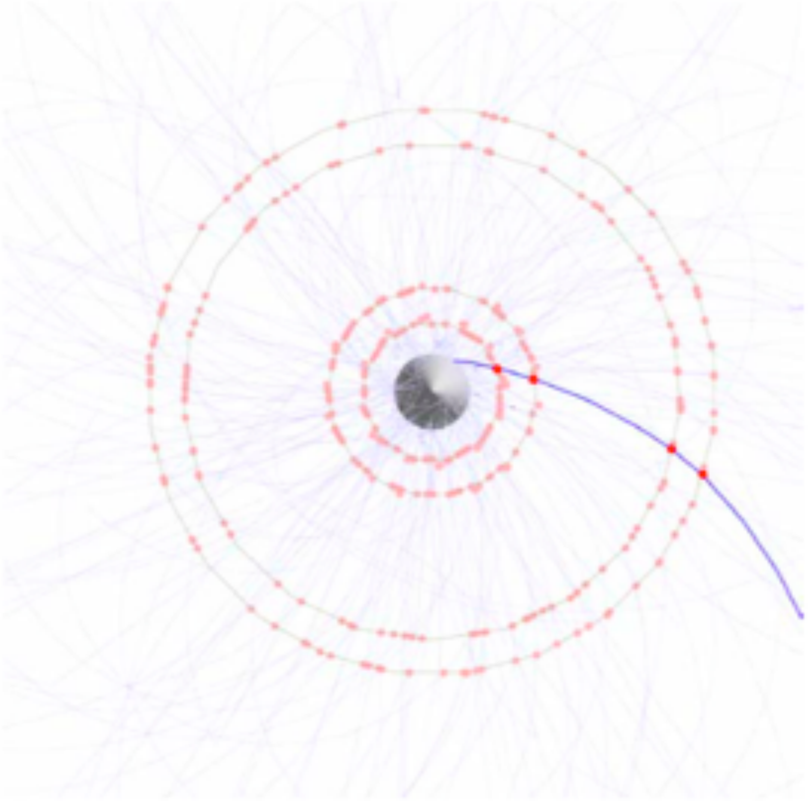


Mu3e: The timing detector - Tiles and SciFi

- Precise timing measurement is 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%)



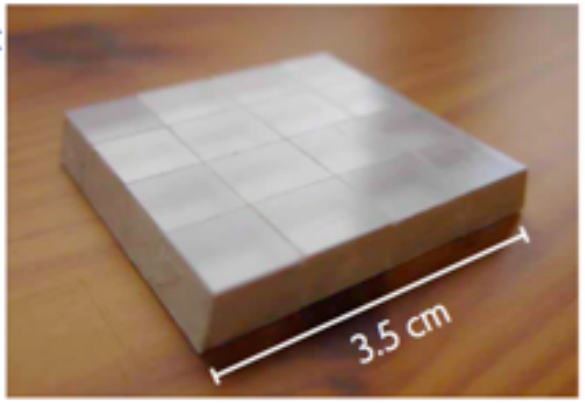
Pixels: O(50 ns)

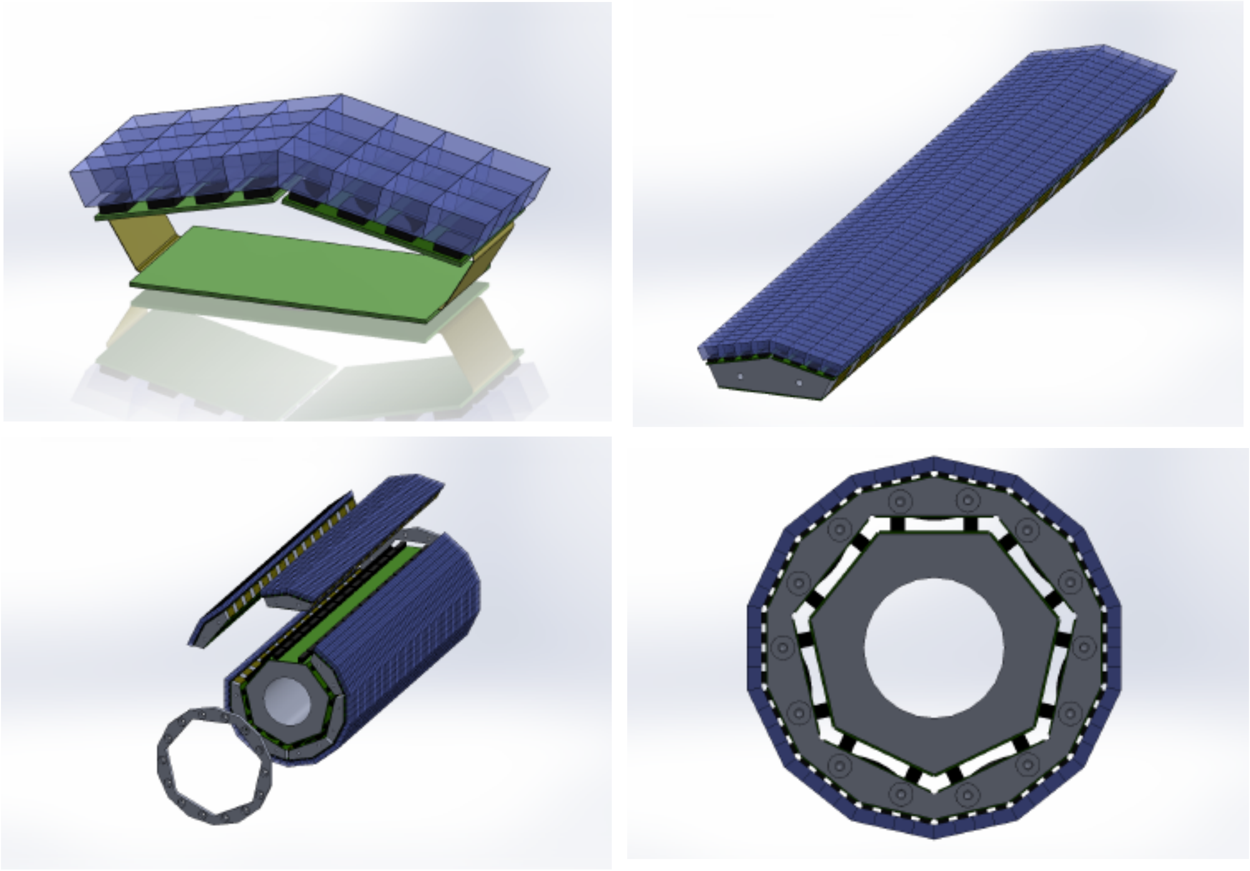


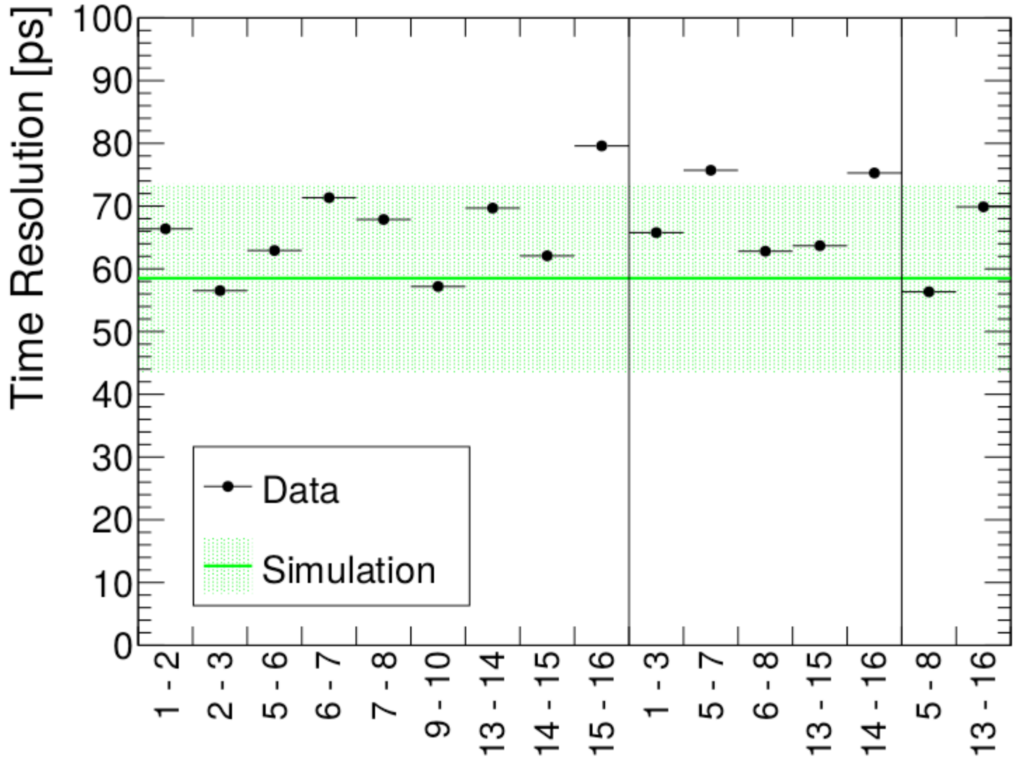
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

Mu3e: Tiles - R&D completed

- Detector perfomances fully achived: 100% detection efficiency and timing resolution < 100 ps (~ 70 ps)



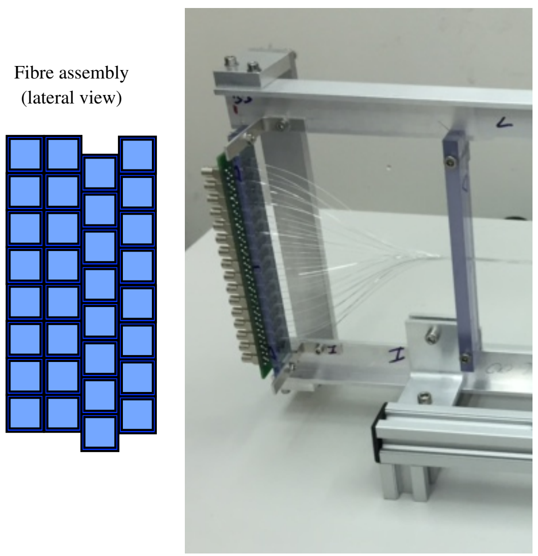


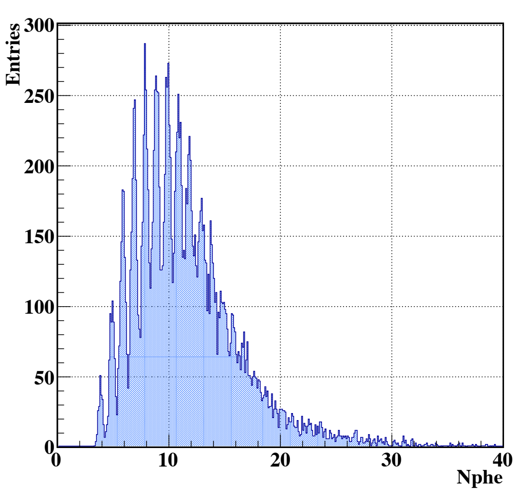


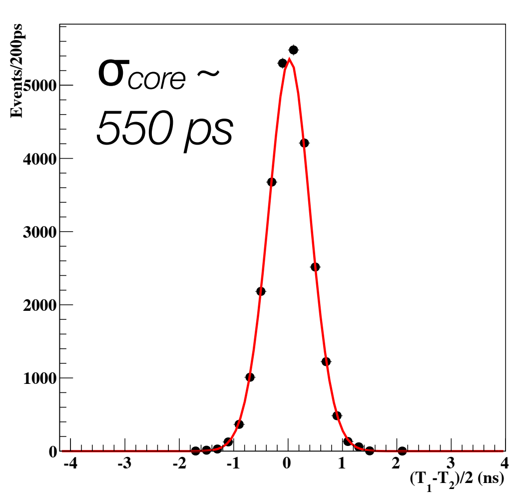
Mu3e: SciFi R&D status

Fibres:

confirmed full detection efficiency and timing performances for multi-layer configurations (square and round fibres) with several prototypes

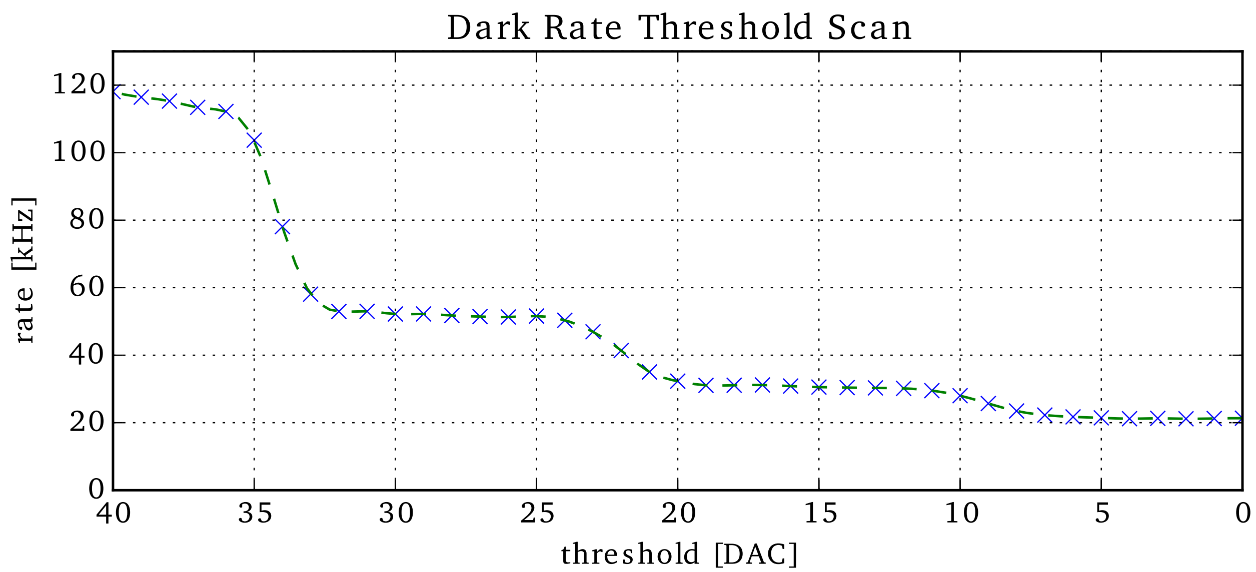




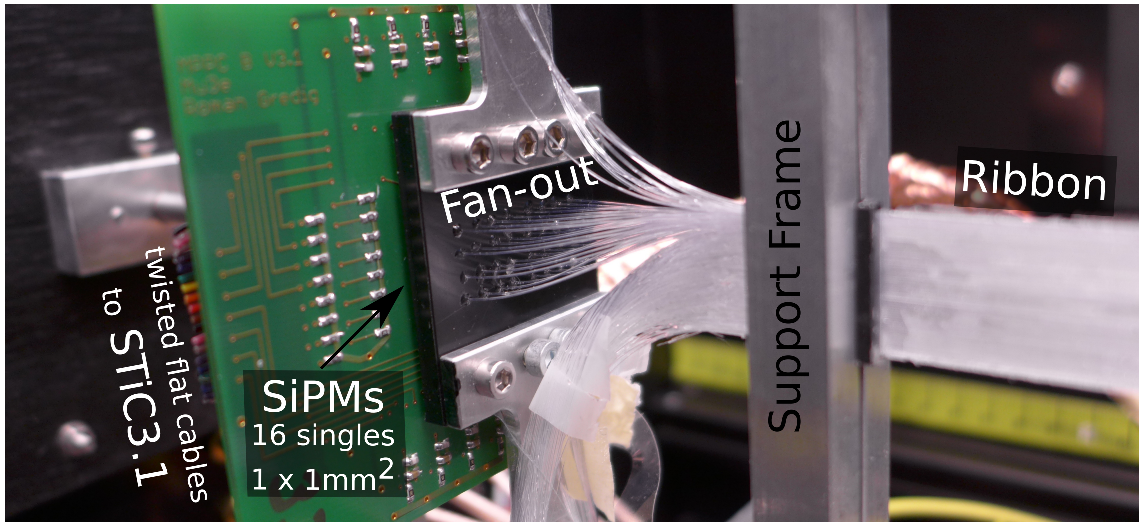


Electronics STiC3.1:

confirmed standalone DAQ measurements of round prototype

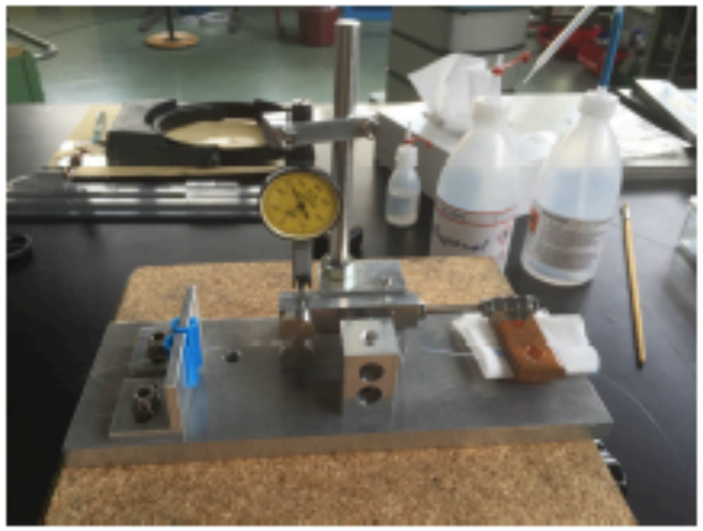


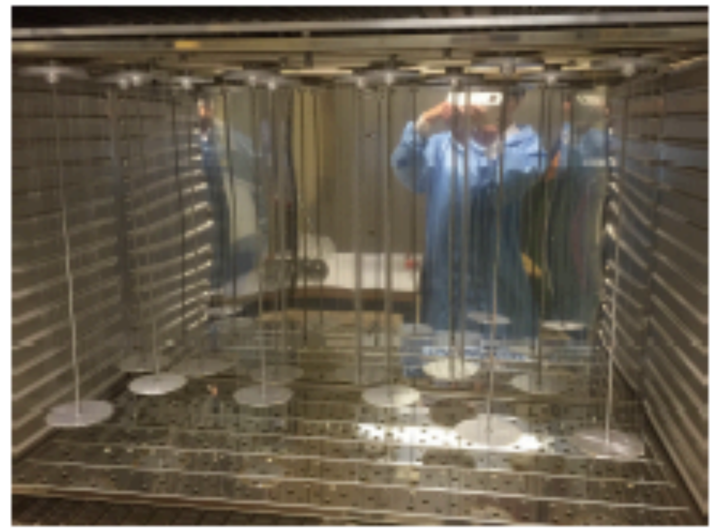
STiC3.1 threshold scan with dark counts

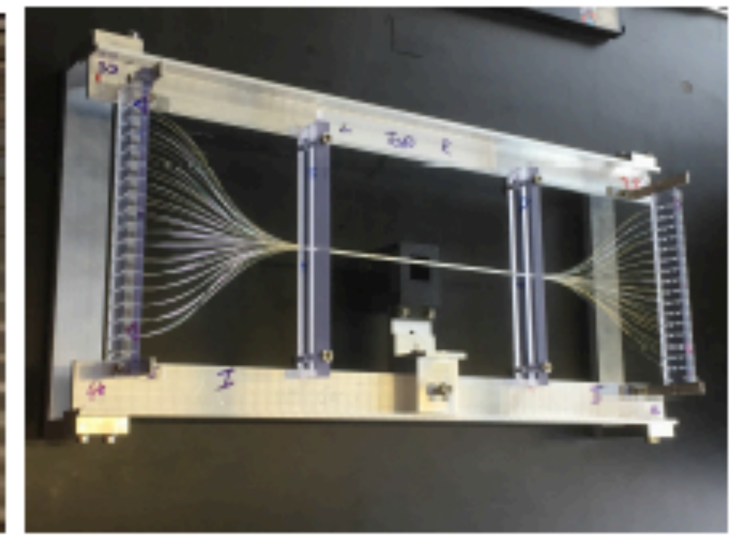


Round fibre prototype connected to STiC

Mu3e: SciFi chain production



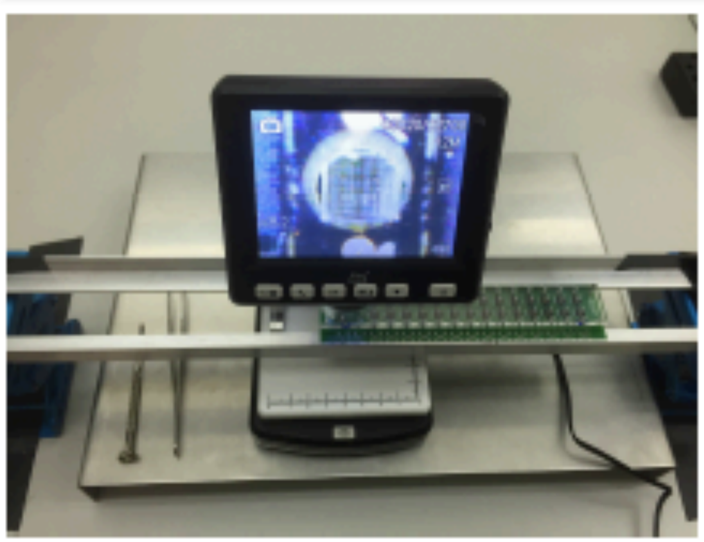


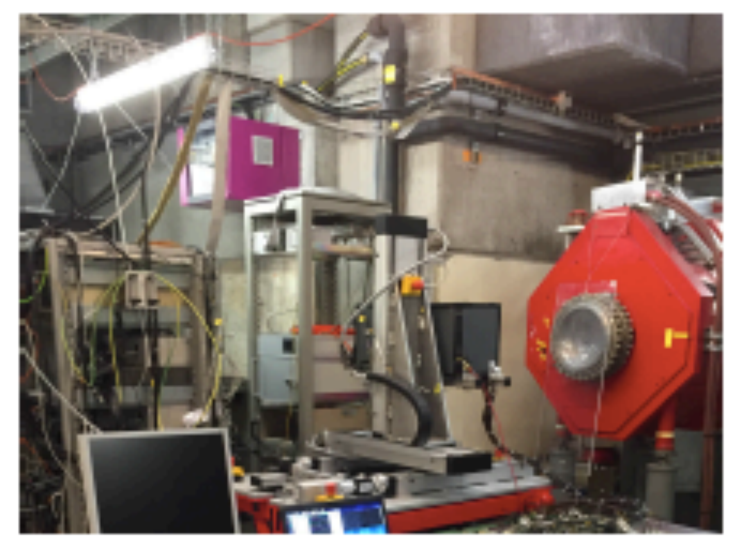


Fiber selection

Fiber coating

Fiber mounting





SiPM alignment

SiPM/ Preamp characterization

Measurement

Outlook

- cLFV processes are among the most clean where to search for new physics
  - muon cLFV: most cLFV sensitive channels
  - complementarity for unveling the driven physics associated with them
- PSI and collaborating Institutions are leading such a researches based on continuous high intensity muon beams (MEG, MEGII, Mu3e, HiMB, muCool...)
- The MEGII preparation is underway: all sub-detectors expected to be ready and installed by the middle of next year
- The Mu3e R&D is ongoing: a first pre-engineering run expected by the end of next year