PAUL SCHERRER INSTITUT

Charged lepton flavour violation searches at PSI

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ECFA, Geneva (Switzerland)
16-17 November 2017

Content

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

- The Most Intense DC Muon Beams in the World:
  Present and future prospects

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

- cLFV searches worldwide and outlook

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

- The Most Intense DC Muon Beams in the World: Present and future prospects

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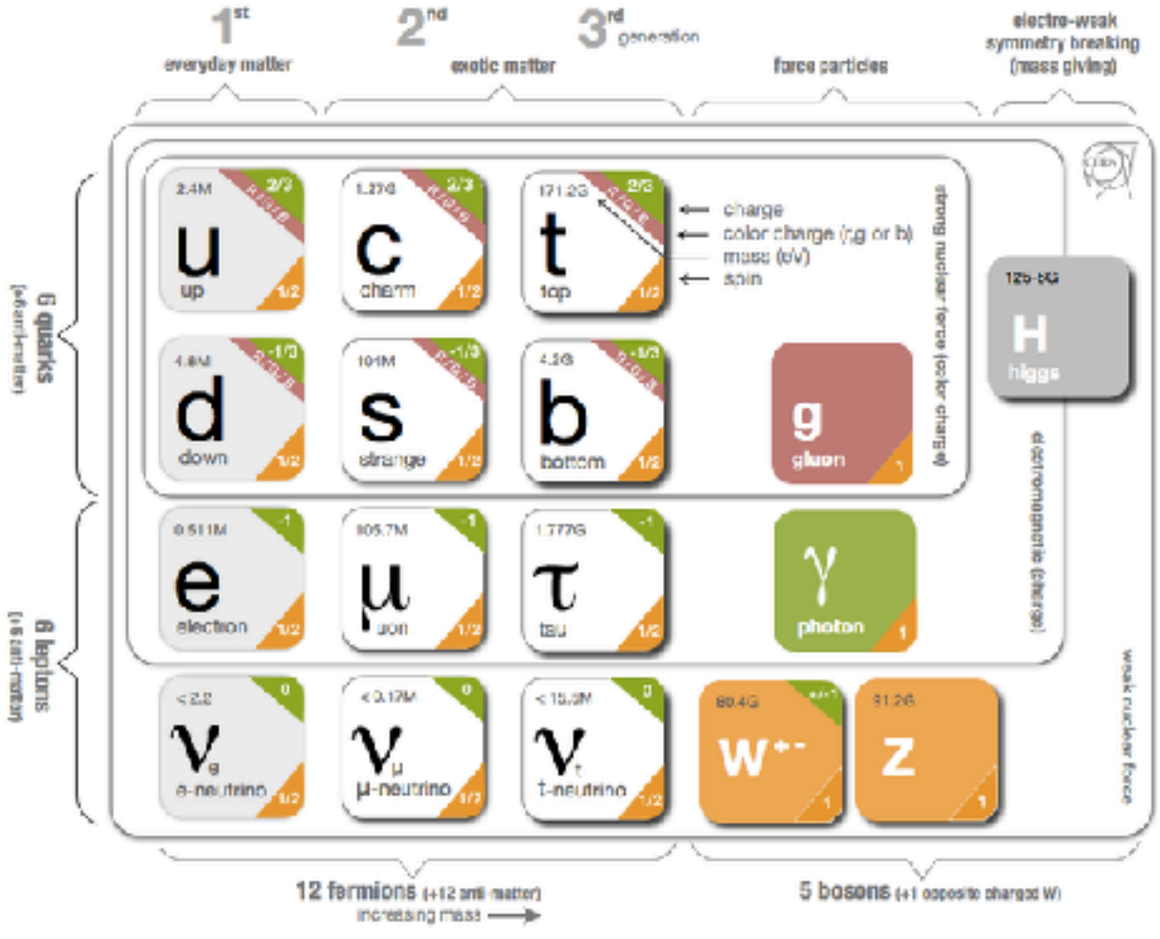
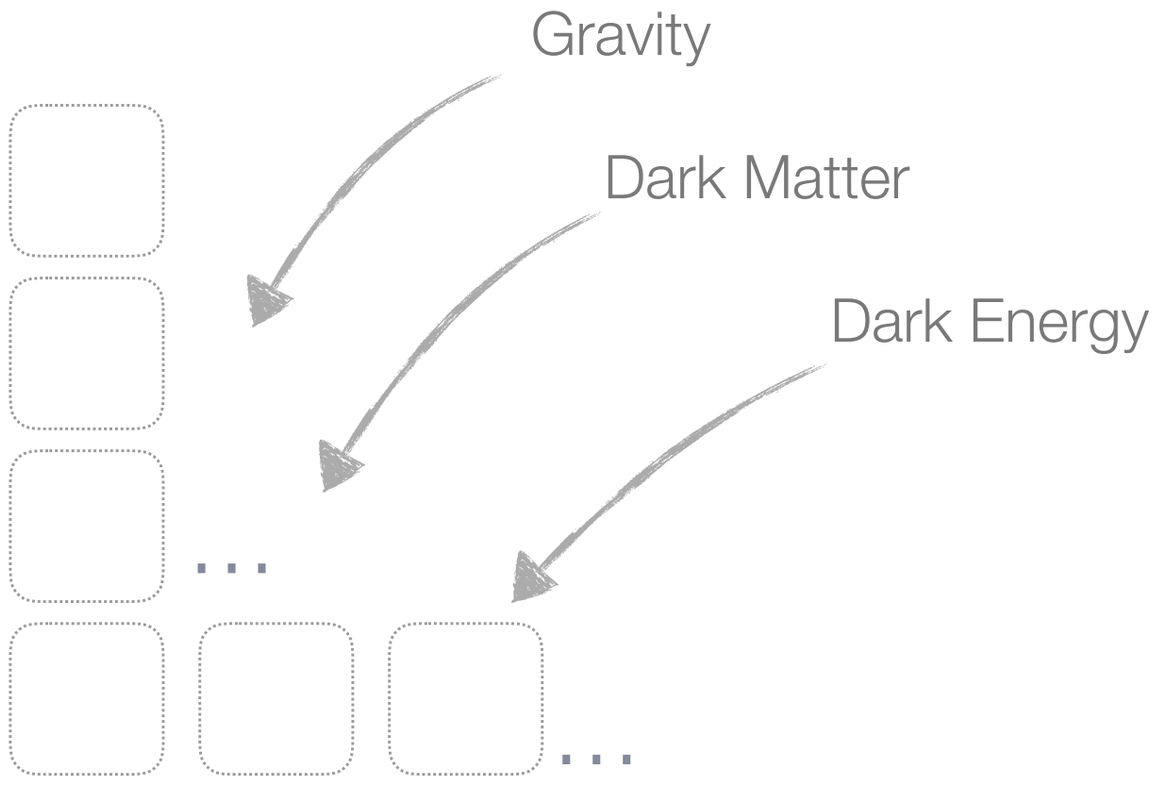
The role of the low energy precision physics

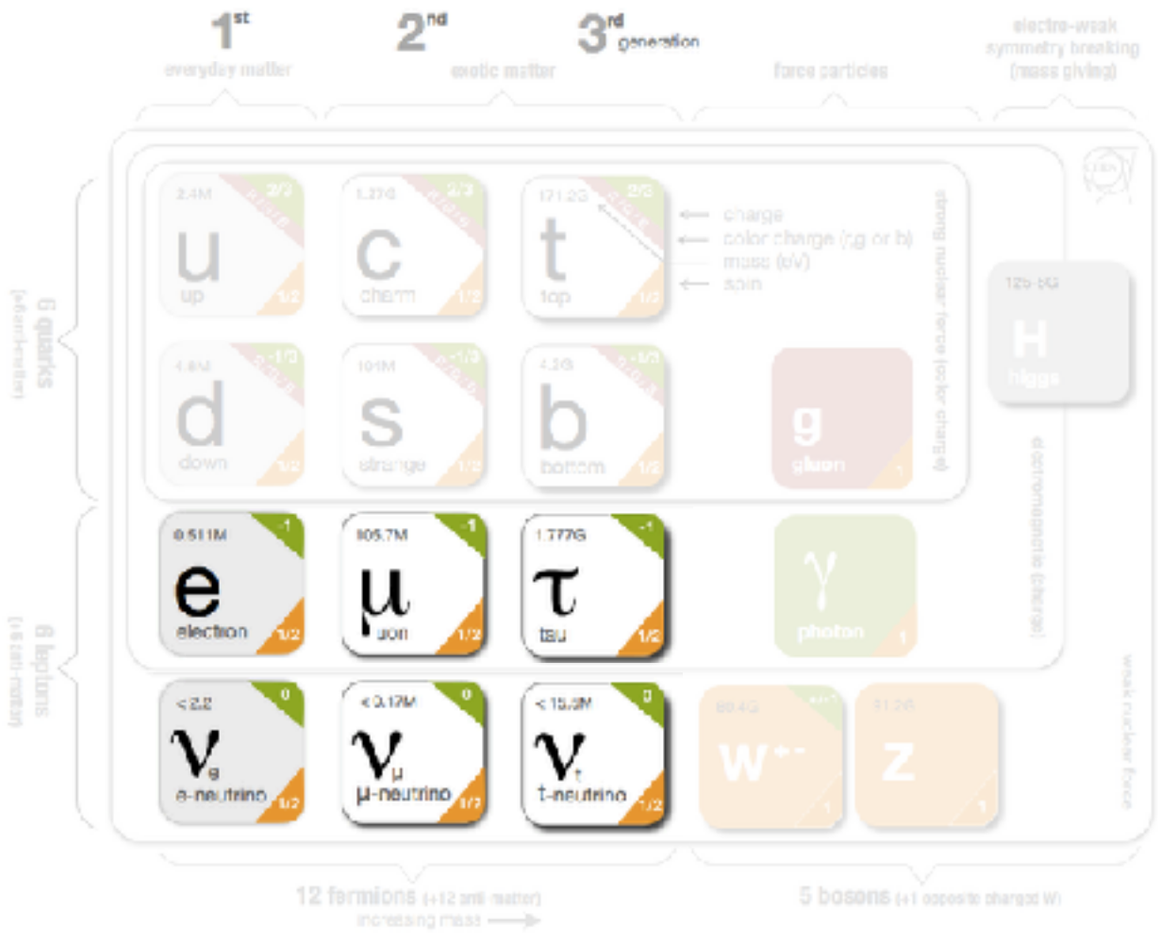
- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory





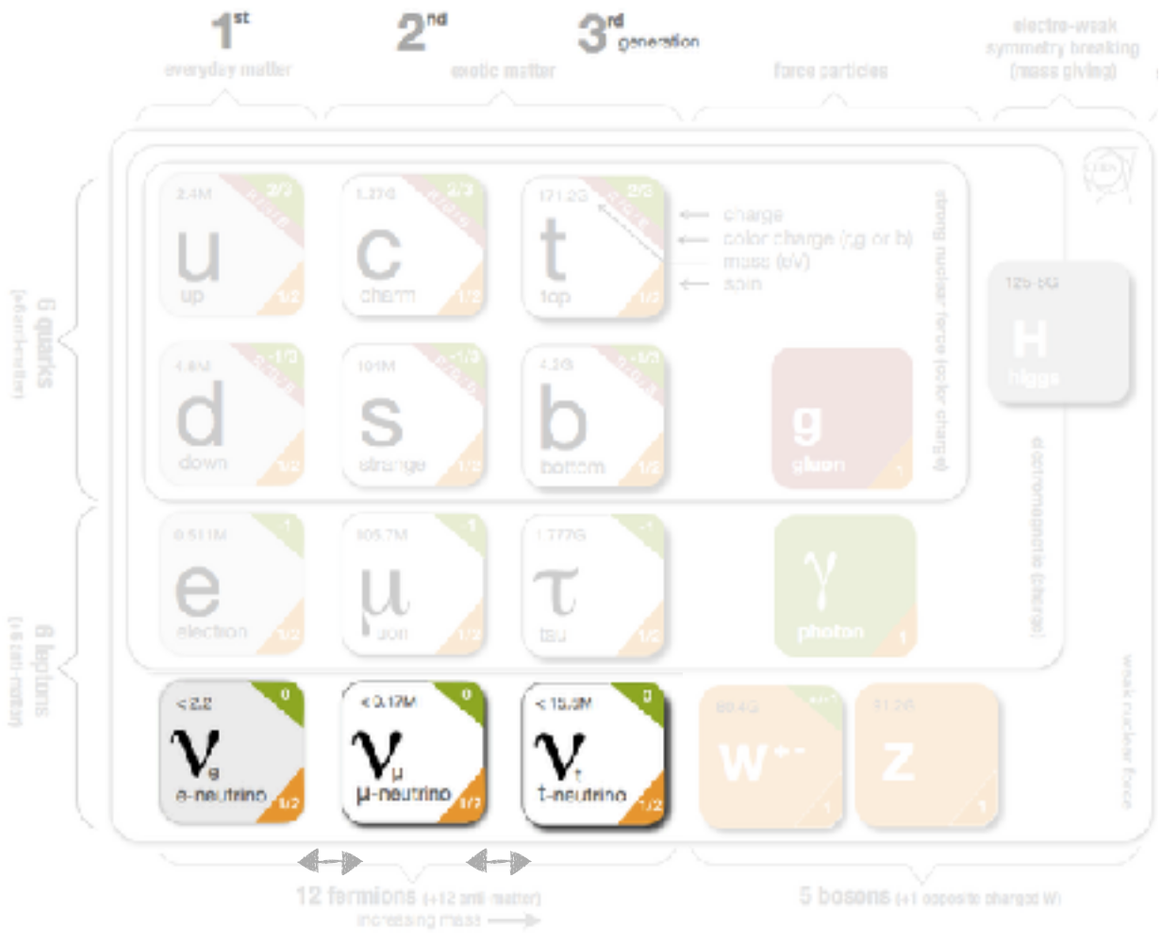
- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

Charged lepton flavour violation



Charged lepton flavour violation

- Neutrino oscillations: Evidence of physics Behind Standard Model (BSM)
  Neutral lepton flavour violation



$\Delta N_i \neq 0$ with i = 1,2,3

Charged lepton flavour violation

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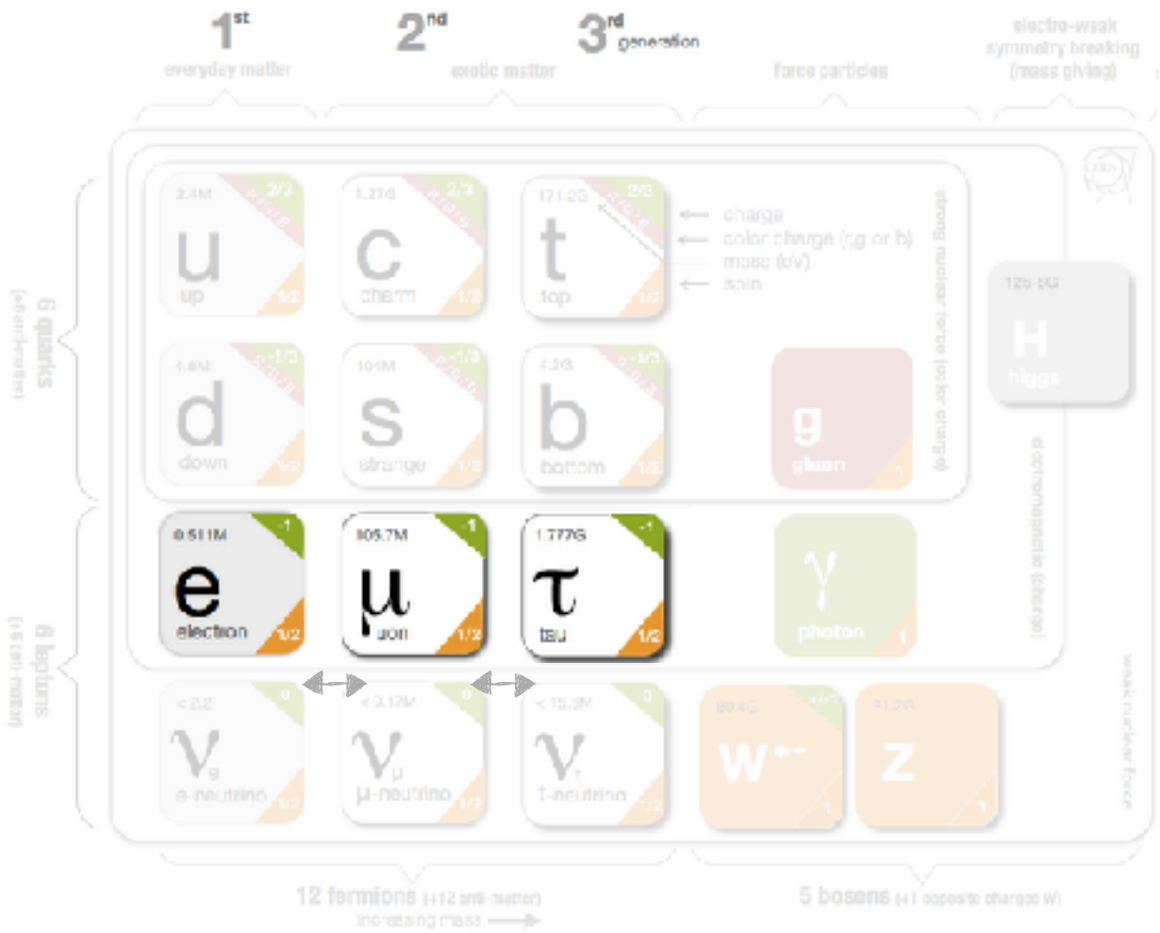


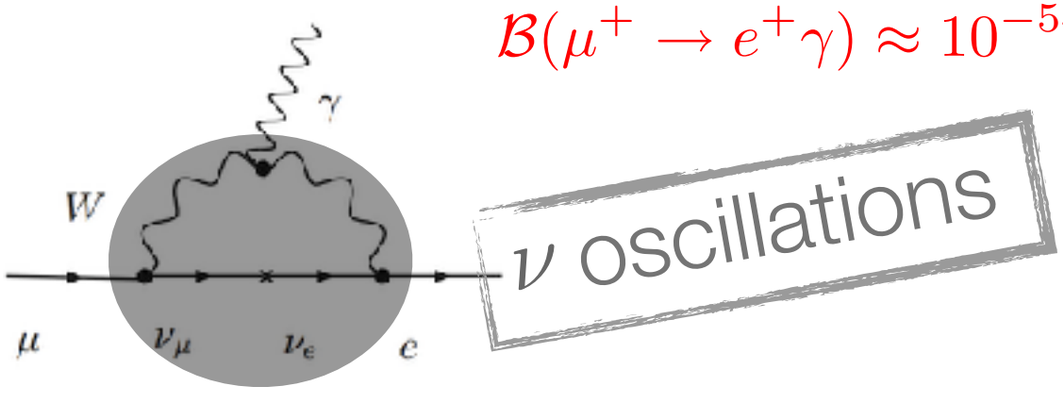
$$\Delta N_i \neq 0 \quad \text{with i = 1,2,3}$$

- Charged lepton flavour violation: NOT yet observed

Charged lepton flavour violation search: Motivation

SM with massive neutrinos (Dirac)

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

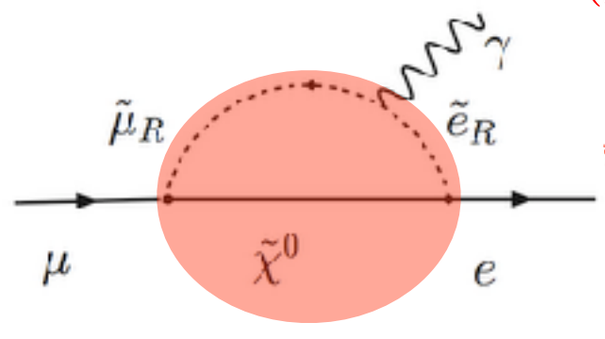


ν oscillations

too small to access experimentally

BSM

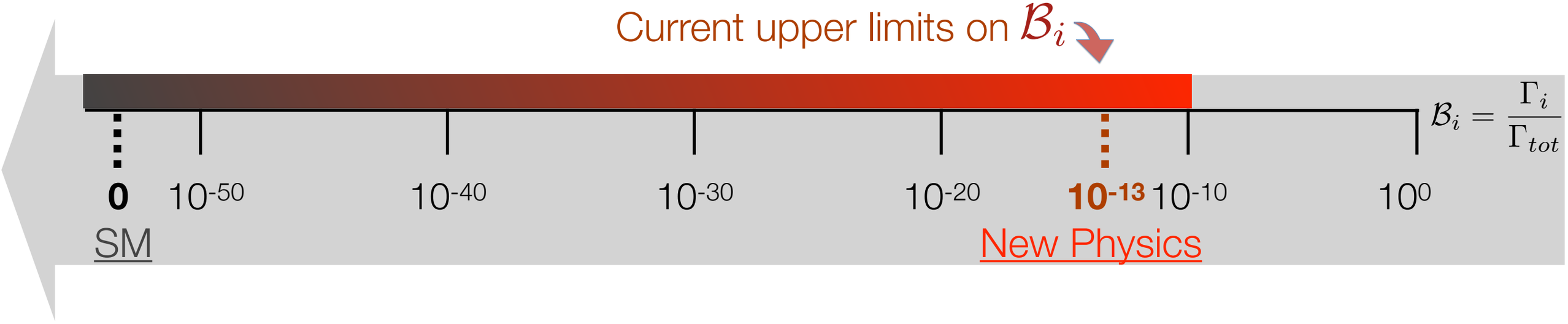
$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$



New particles

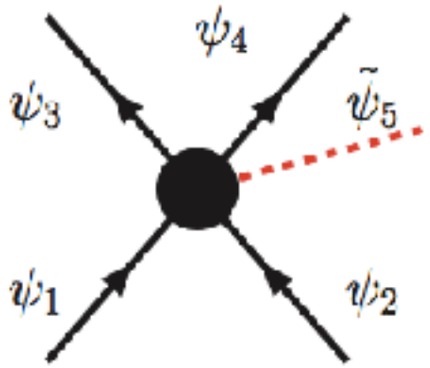
an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)

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



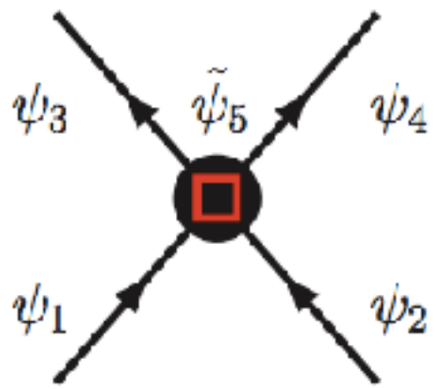
Complementary to “Energy Frontier”

Energy frontier



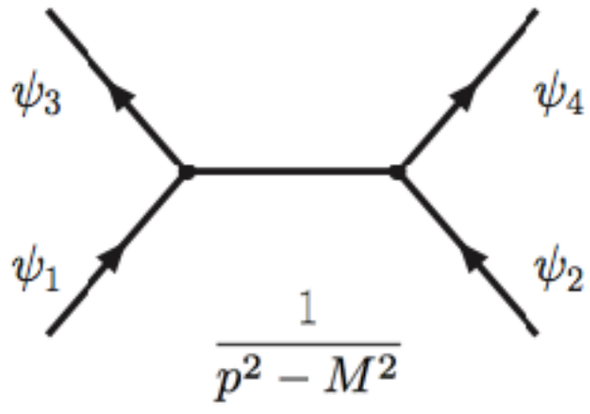
Real BSM particles

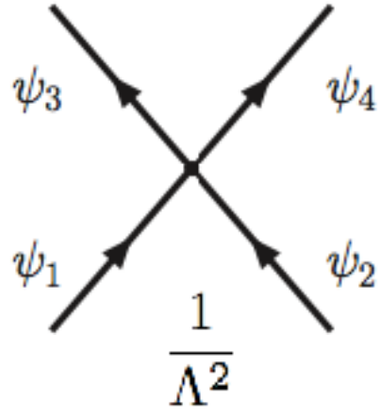
Precision and intensity frontier



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

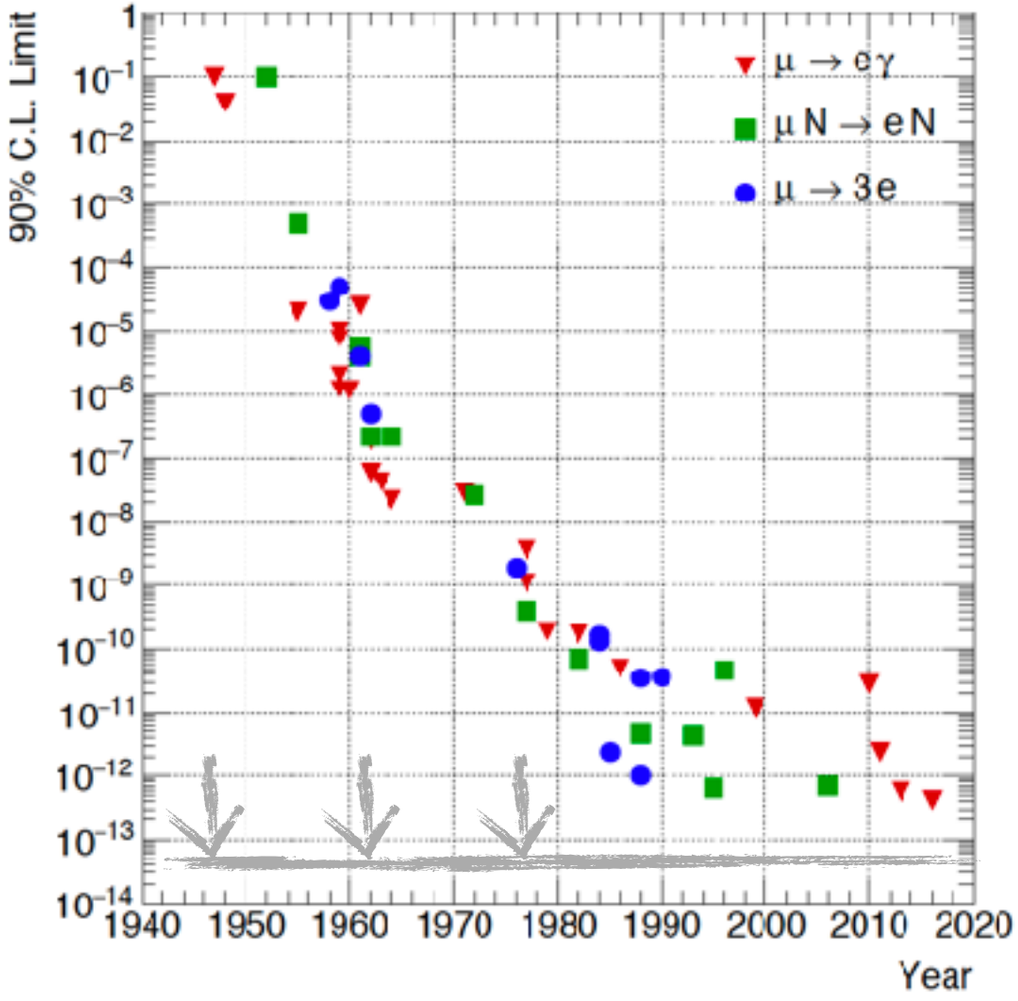
E > 1000 TeV

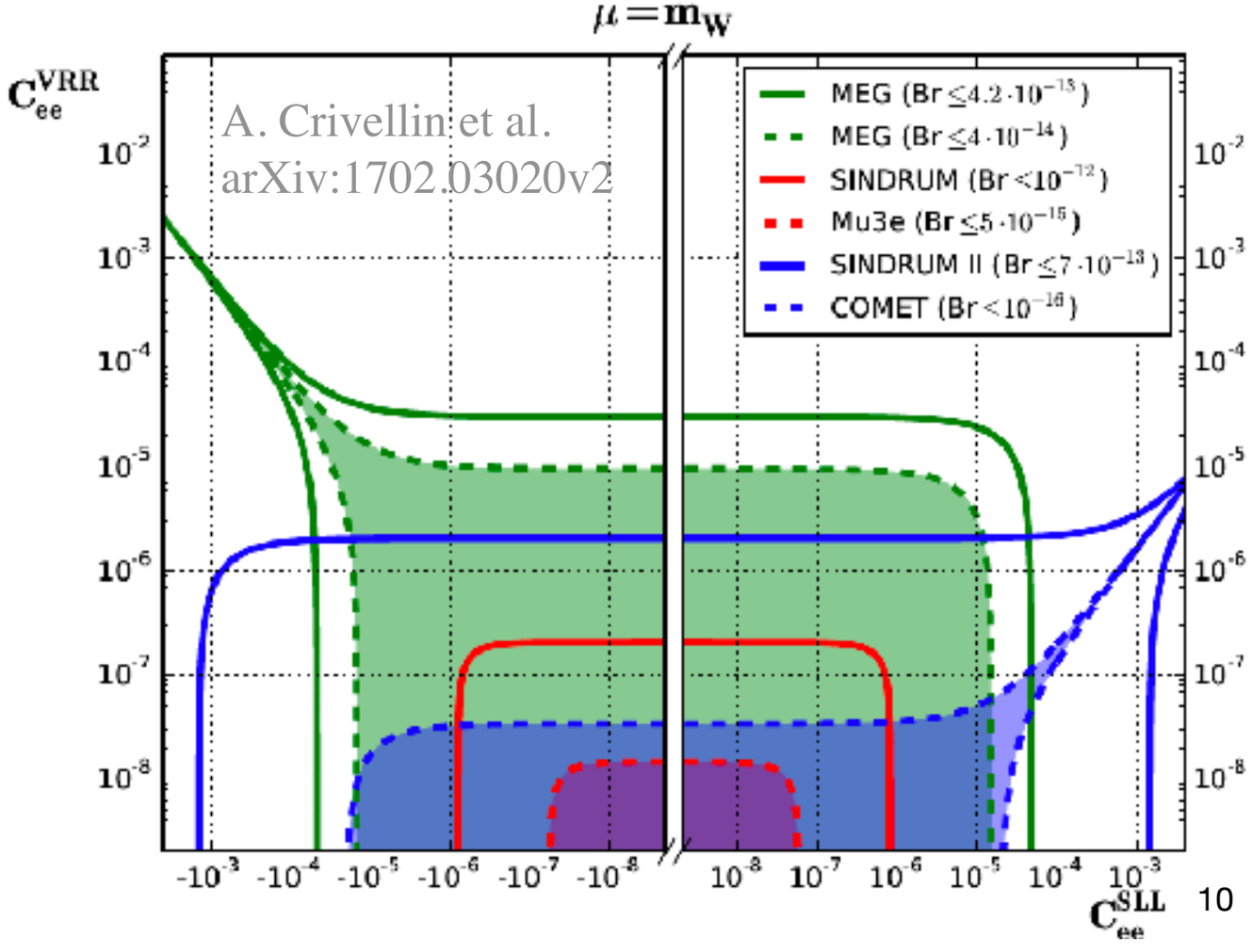
cLFV searches with muons: Status and prospects

- 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}	< 10^{-16}

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





cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities: **Set at PSI**

	Current upper limit	Future sensitivity
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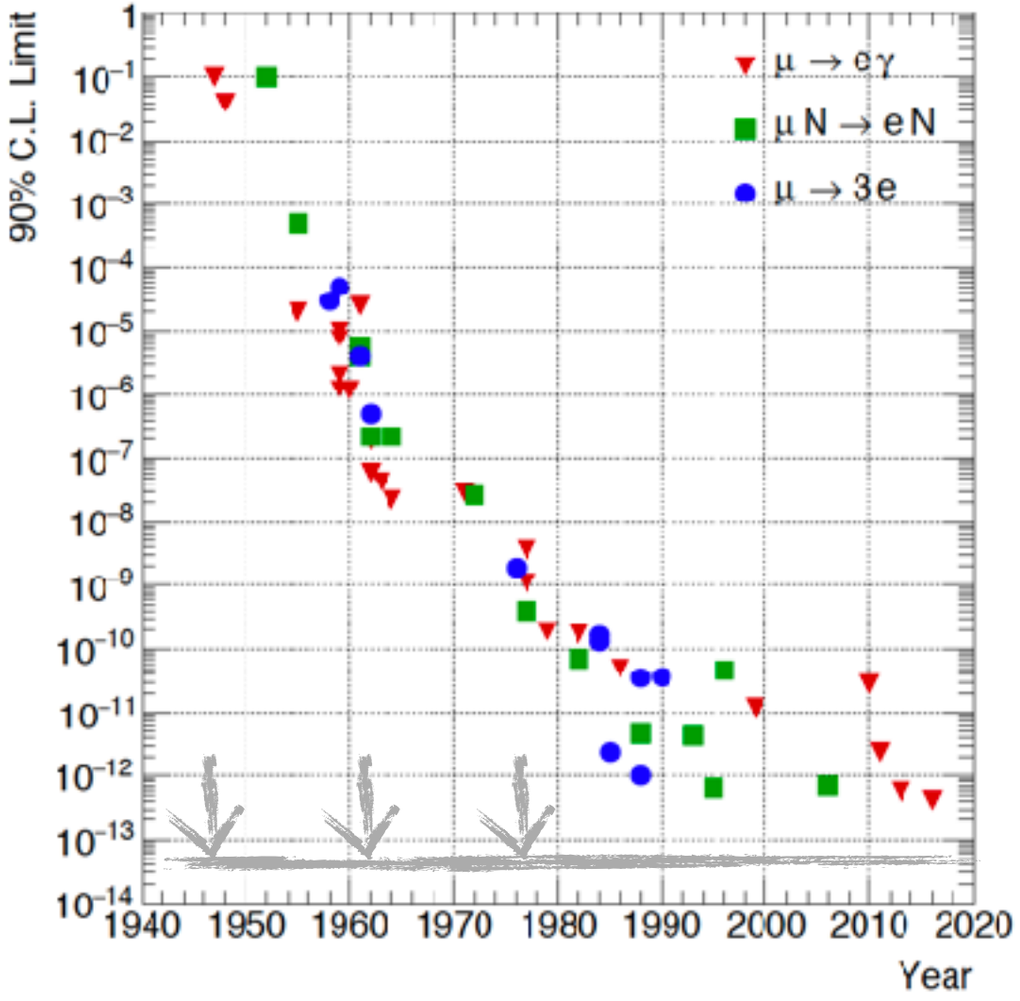

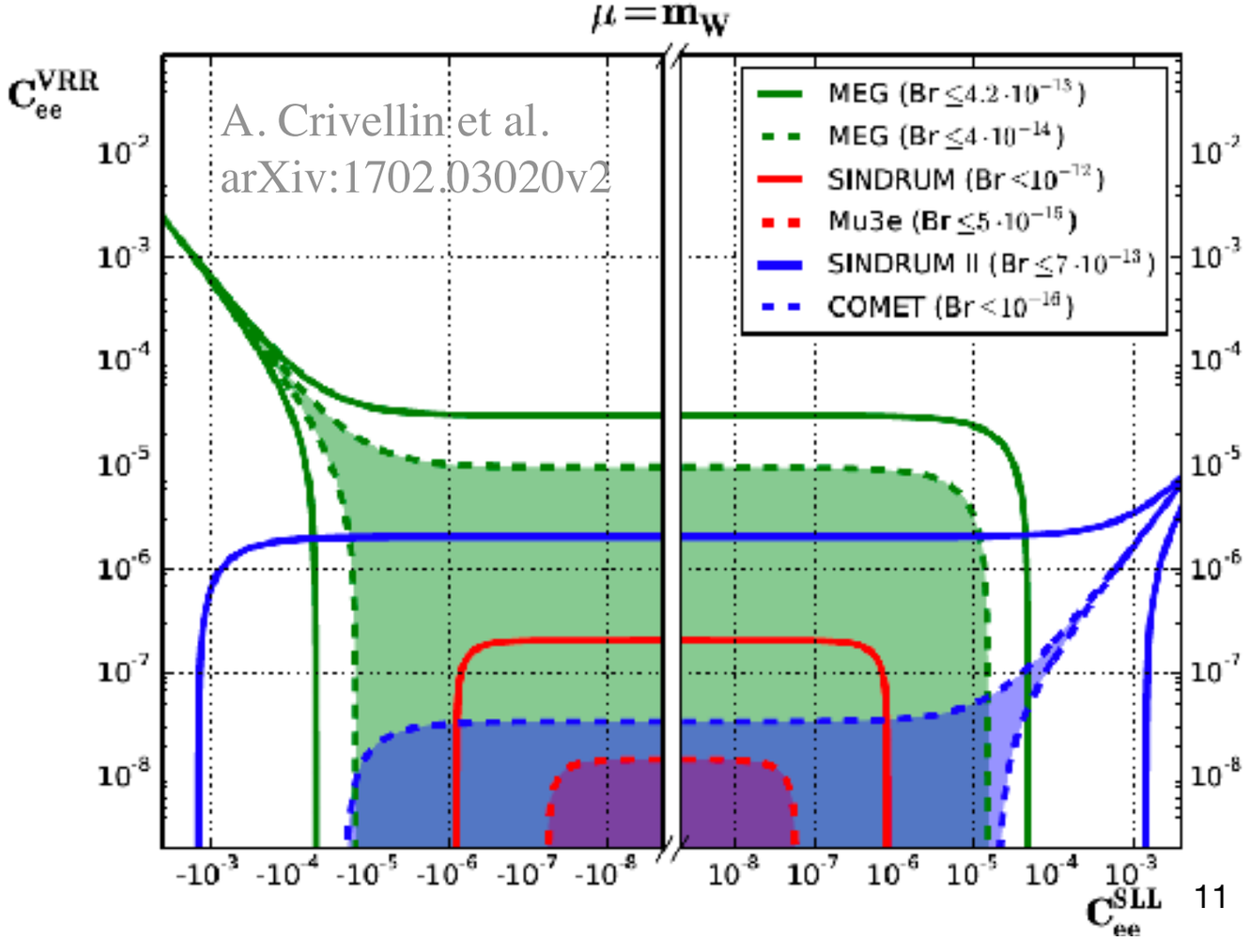

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Beam features vs experiment requirements

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

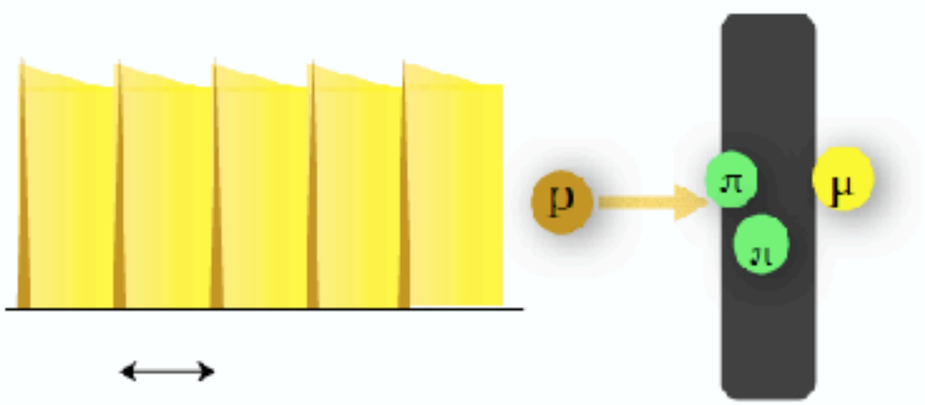
$I_{beam} \sim 10^8 - 10^{10}$ μ/s

DC or Pulsed?

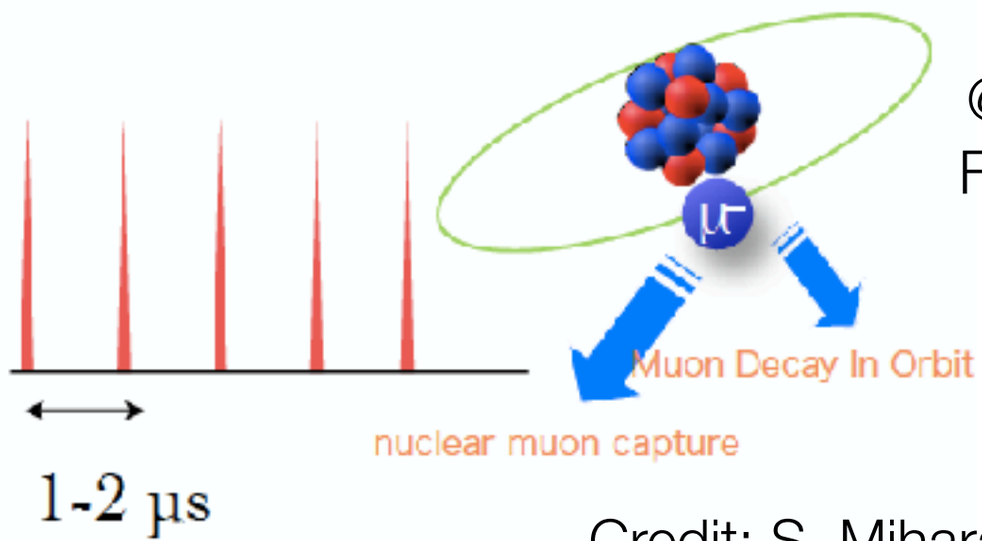
$I_{beam} \sim 10^{11}$ μ/s

- DC beam for coincidence experiments
  - $\mu \to e\gamma$, $\mu \to e\,e\,e$
- Pulse beam for non-coincidence experiments
  - μ-e conversion

@ PSI



@ JPARC, FERMILAB



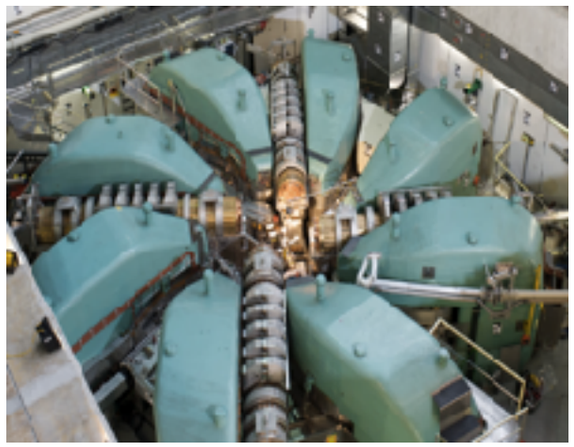
Credit: S. Mihara

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

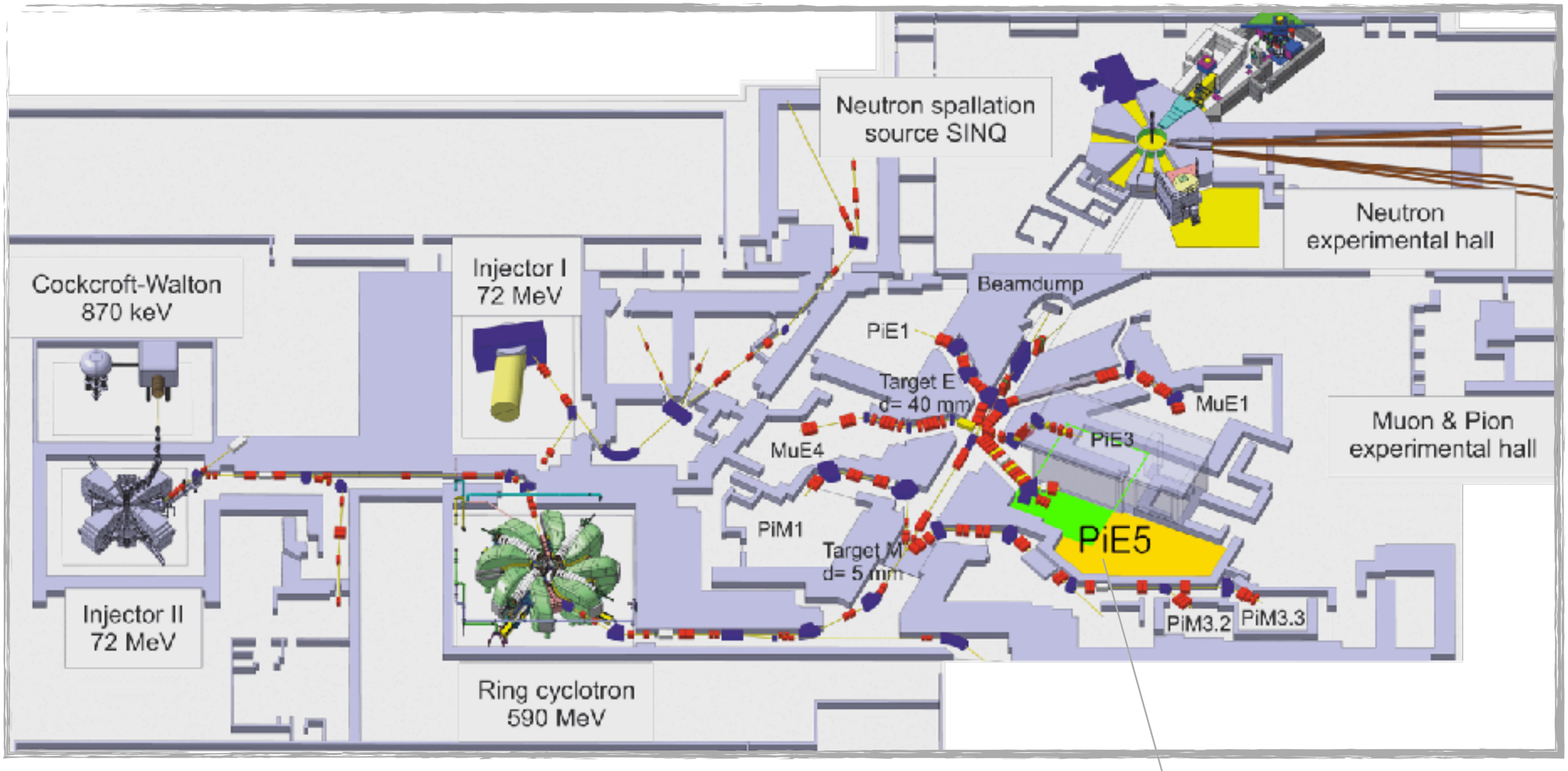
590 MeV proton ring cyclotron
1.4 MW



PSI landscape

The world’s most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas

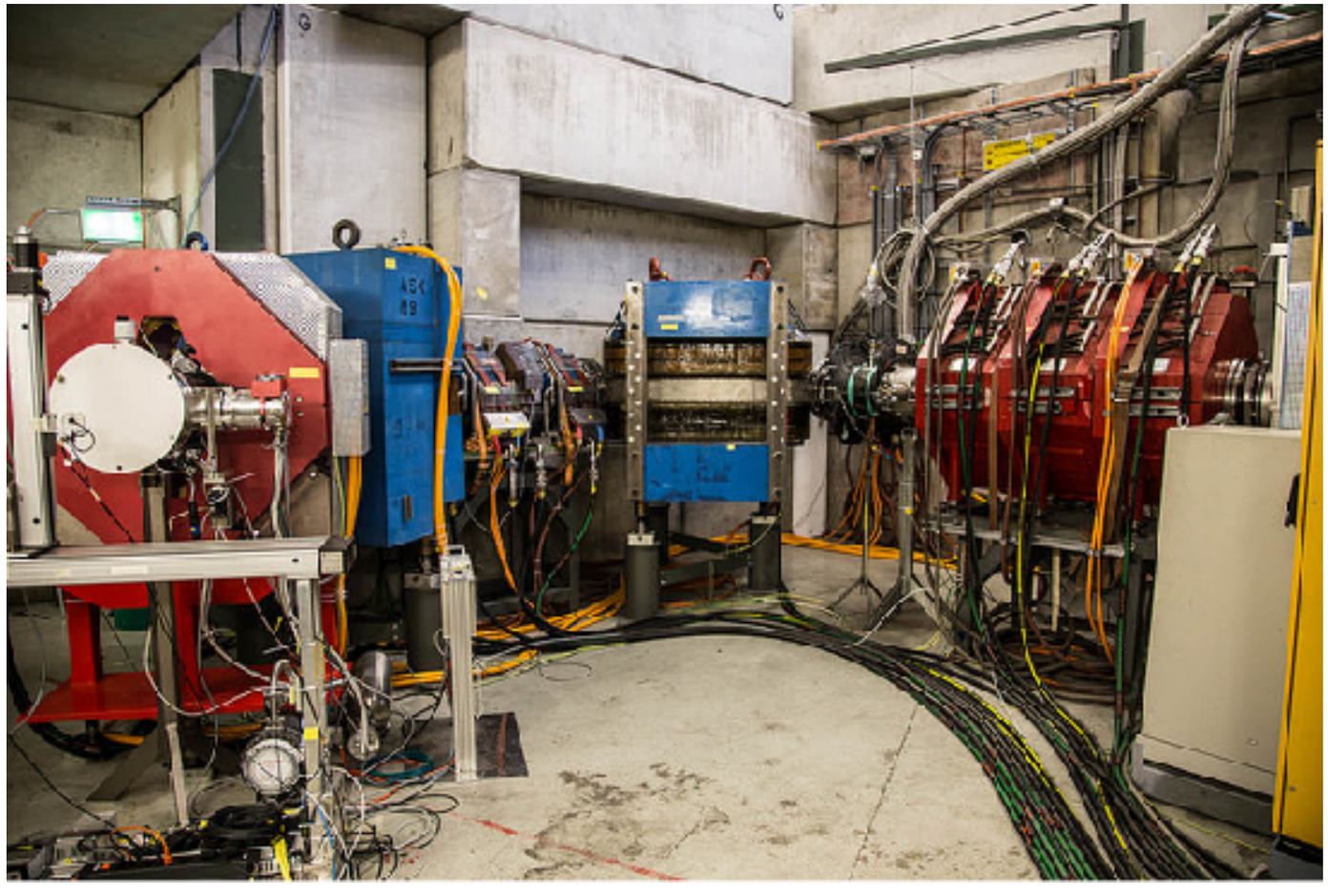


MEGII / Mu3e Experimental area

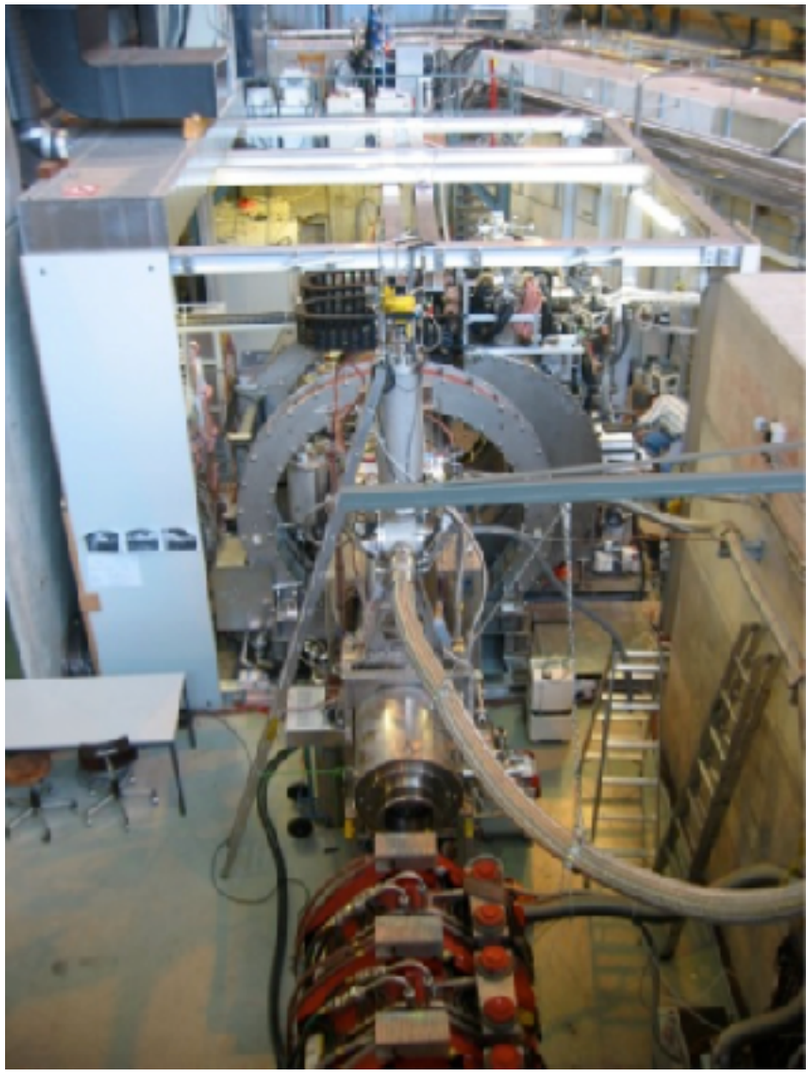
The MEGII and Mu3e beam lines

- 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

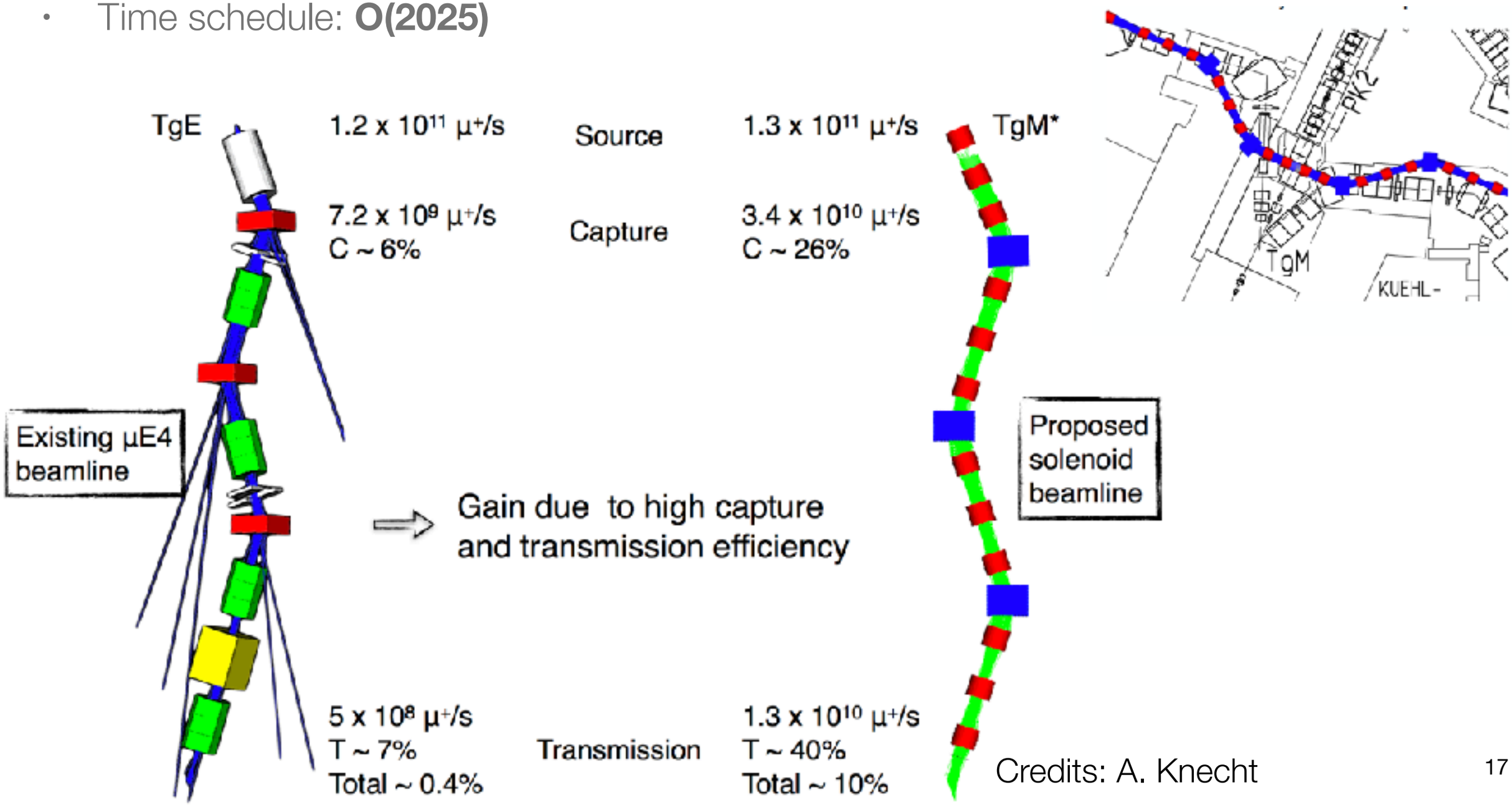


The MEGII BL



The HiMB project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Slanted E target test ("towards the new M-target"): planned for **next year**
- Time schedule: **O(2025)**



Credits: A. Knecht

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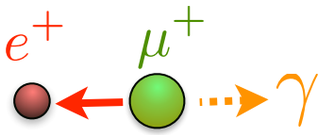
A. Baldini et al. (MEG Collaboration),
Eur. Phys. J. C73 (2013) 2365

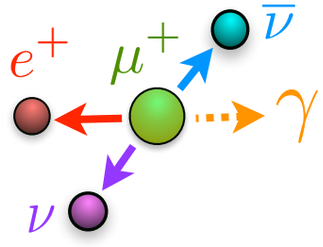
MEG: Signature and experimental setup

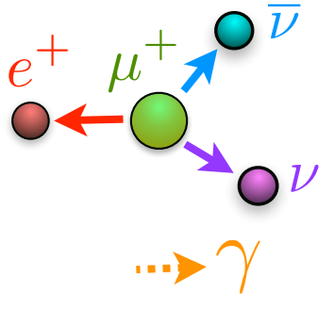
- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~10^{-13} (previous upper limit BR($\mu^+ \rightarrow e^+ \gamma$) ≤ 1.2 x 10^{-11} @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$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

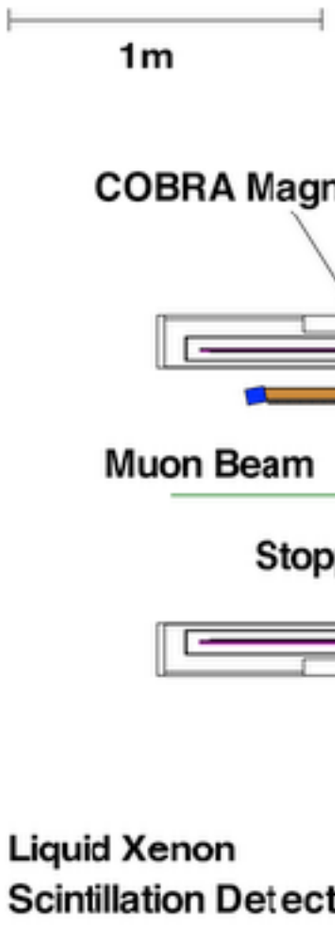
Signature

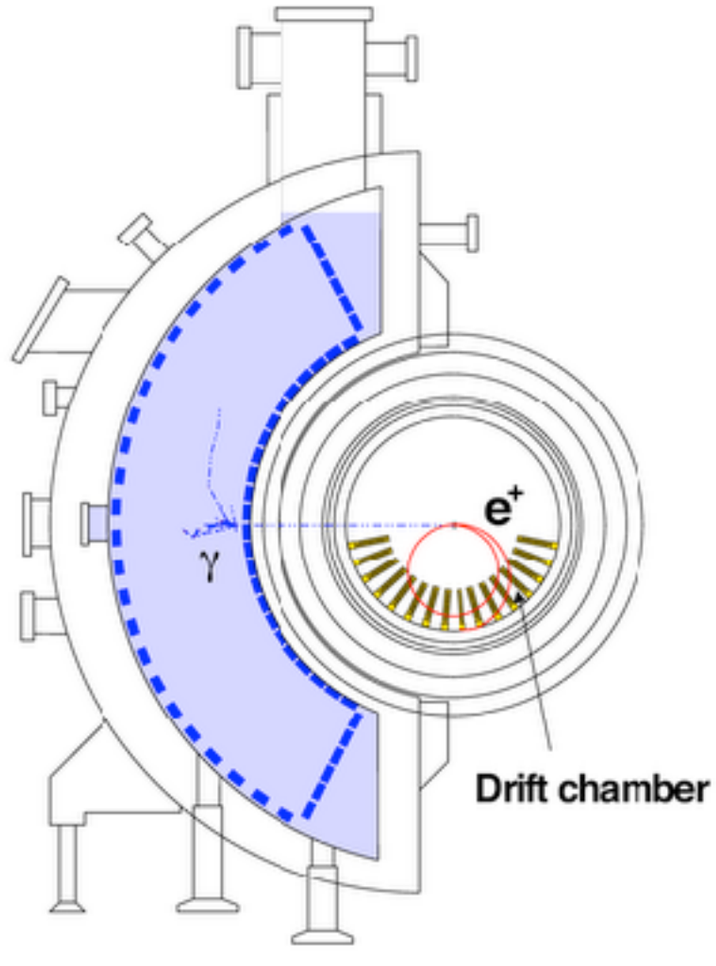


Backgrounds









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

MEG: The result

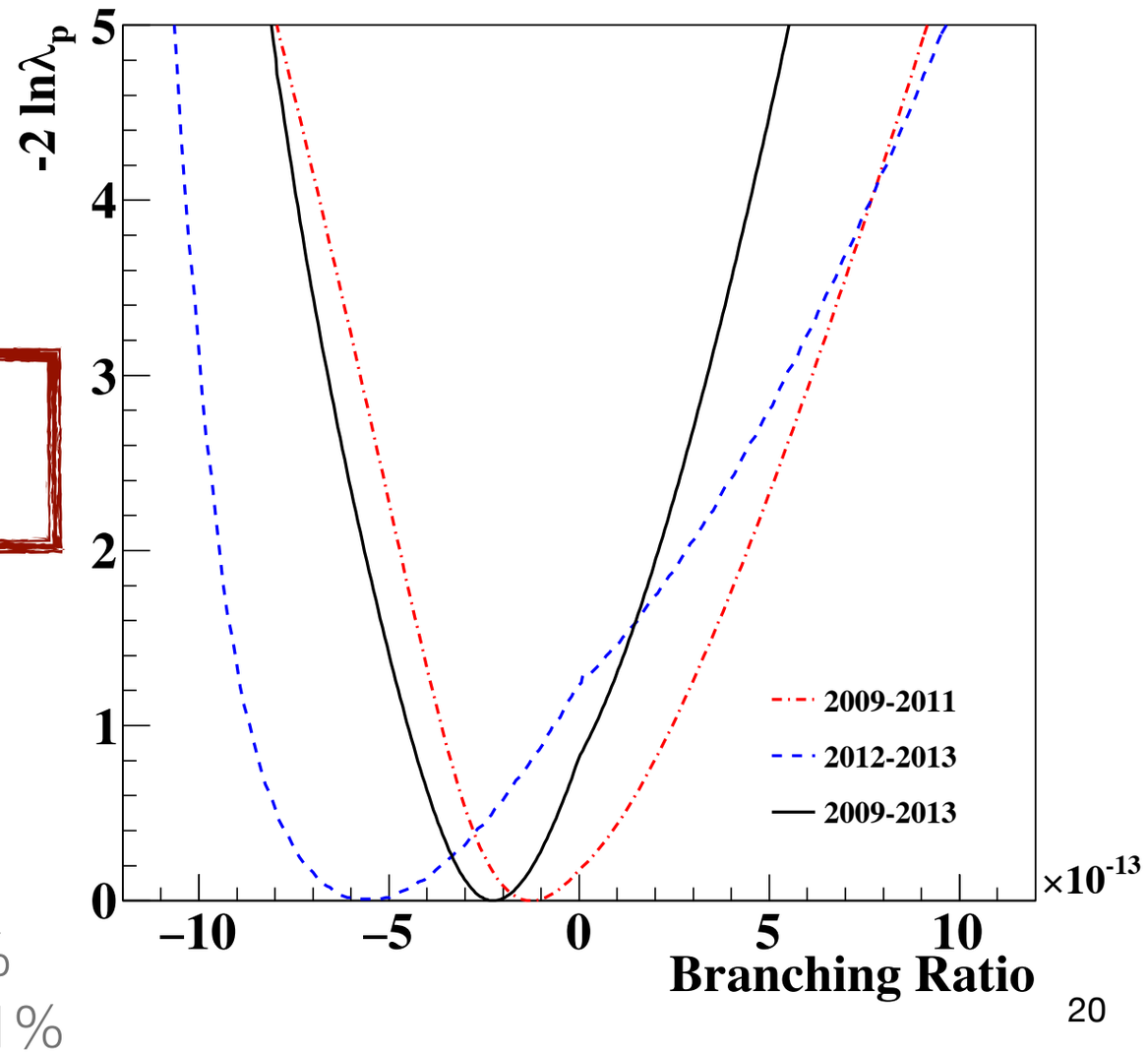
- Confidence interval calculated with Feldman & Cousin approach with profile likelihood ratio ordering
- Profile likelihood ratios as a function of the BR: all consistent with a null-signal hypothesis

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

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

From MEGA to MEG:

improvement by a factor ~ 30



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

How the sensitivity can be pushed down?

- More sensitive to the signal...

high statistics

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

R: Beam rate; T: Acquisition time; A_g: Geometrical acceptance; $\varepsilon(e^+)$: Detector efficiency; $\varepsilon(sel)$: Selection efficiency

- More effective on rejecting the background...

high resolutions

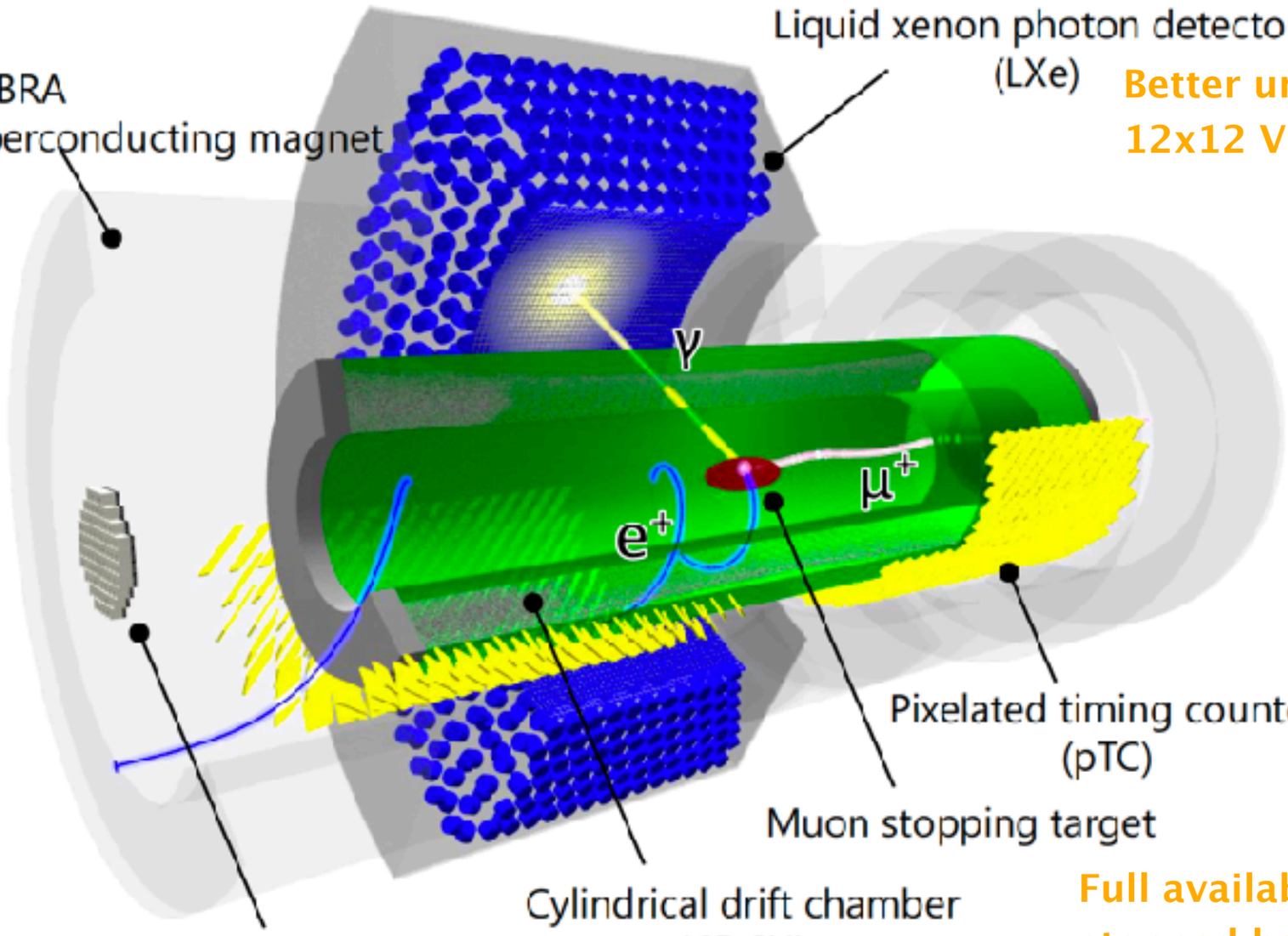
$$B_{acc} \sim R \times \Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2$$

ΔE_e: Positron Energy resolution; ΔE_{gamma}: Gamma Energy resolution; ΔT_{egamma}: Relative timing resolution; $\Delta \Theta_{egamma}$: Relative angular resolution

The MEGII experiment

New electronics:
Wavedream

~9000 channels at 5GSPS



Better uniformity w/ 12x12 VUV SiPM

x2 Resolution everywhere

x2 Beam Intensity

Updated and new Calibration methods

Quasi mono-chromatic positron beam

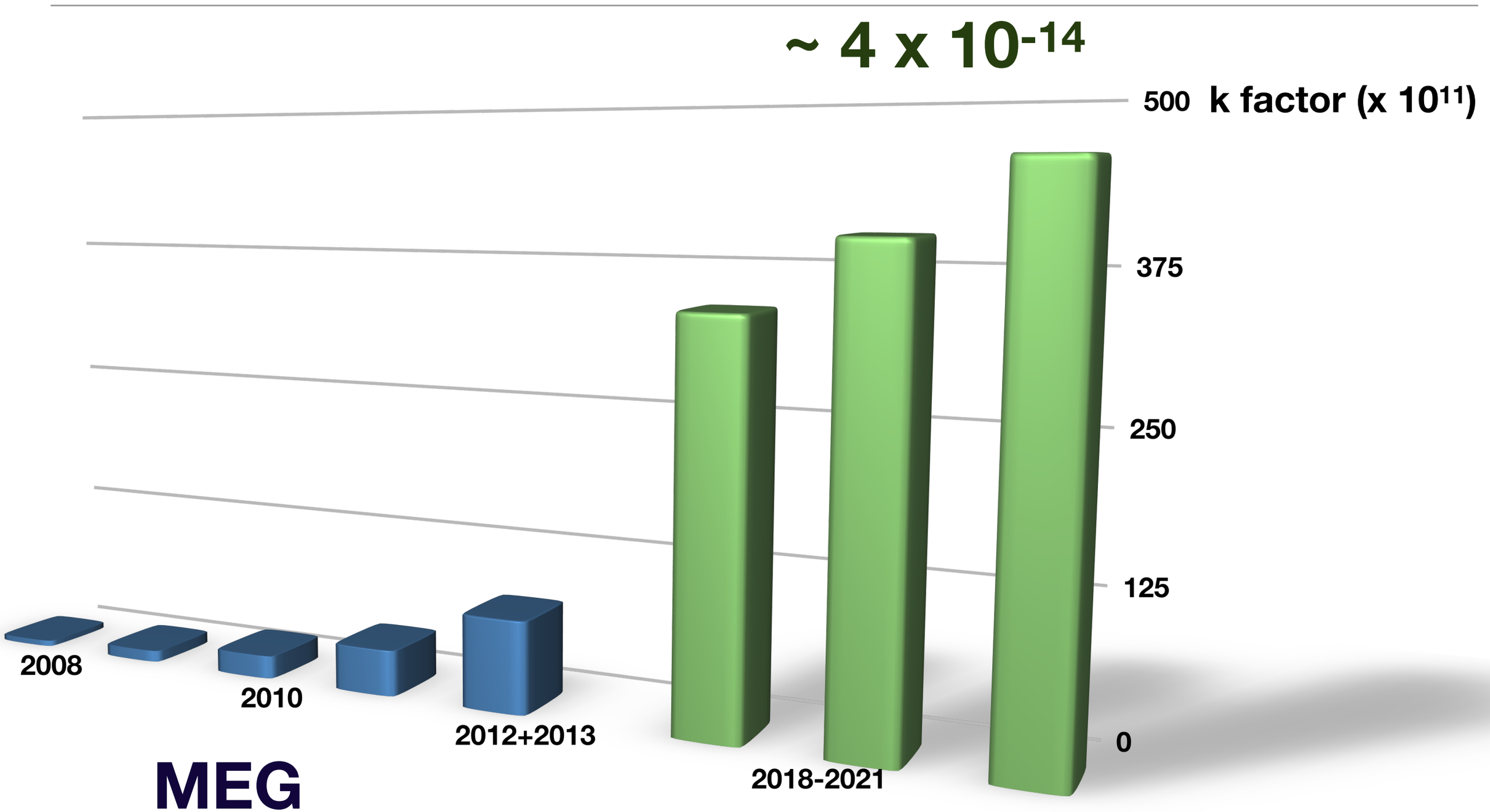
35 ps resolution w/ multiple hits

Full available stopped beam intensity
7×10^7

Background rejection

Single volume
He:iC_4H_{10}

Where we will be



The MEGII experiment: Status

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Wavedream

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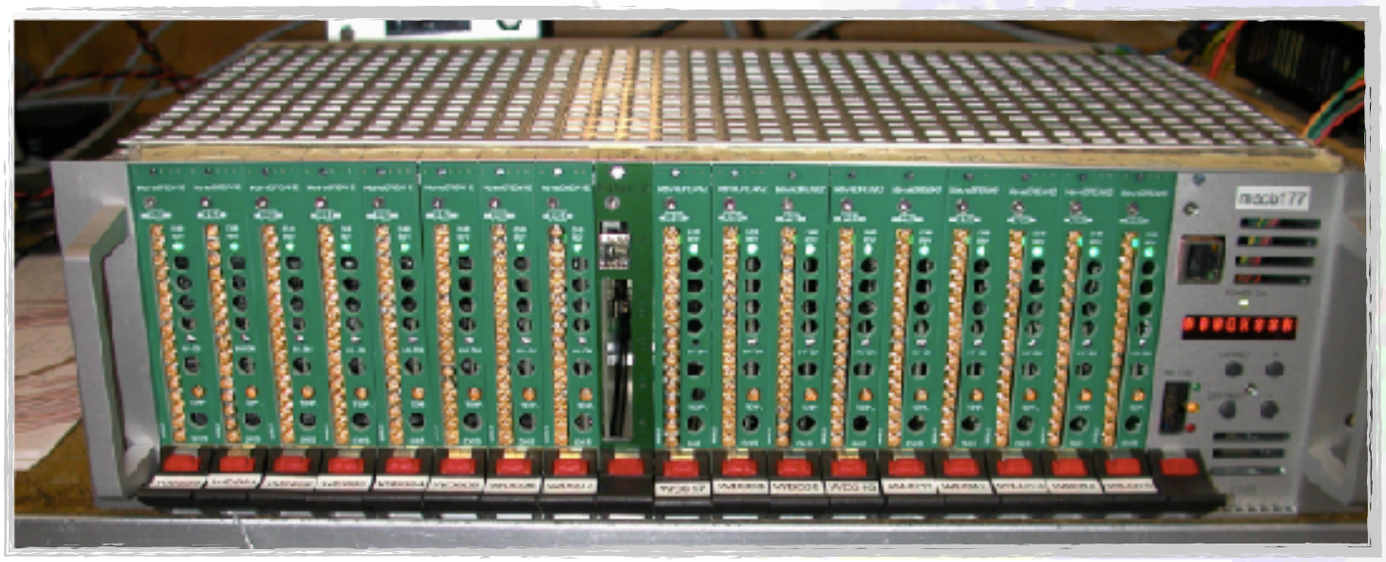
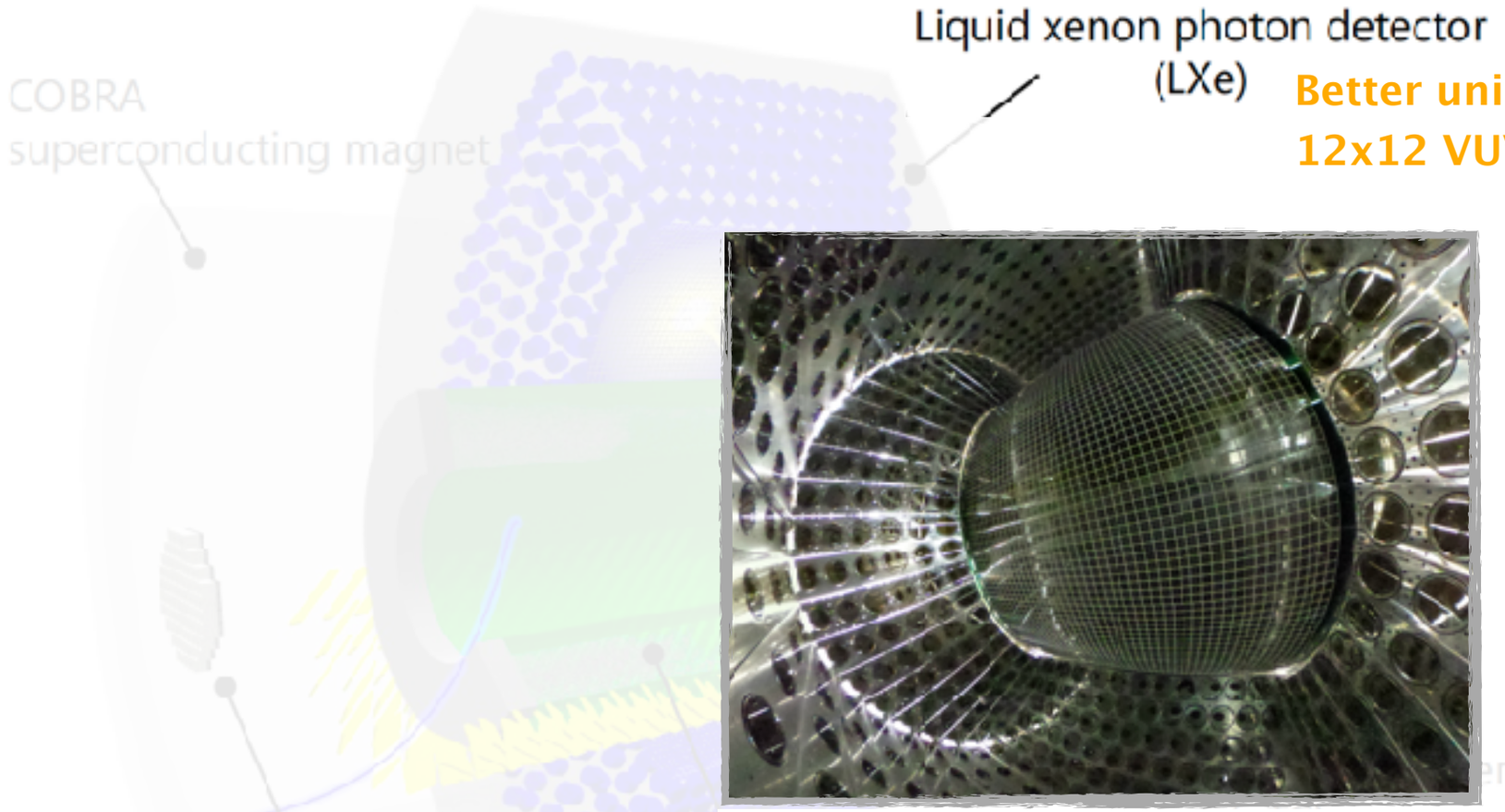


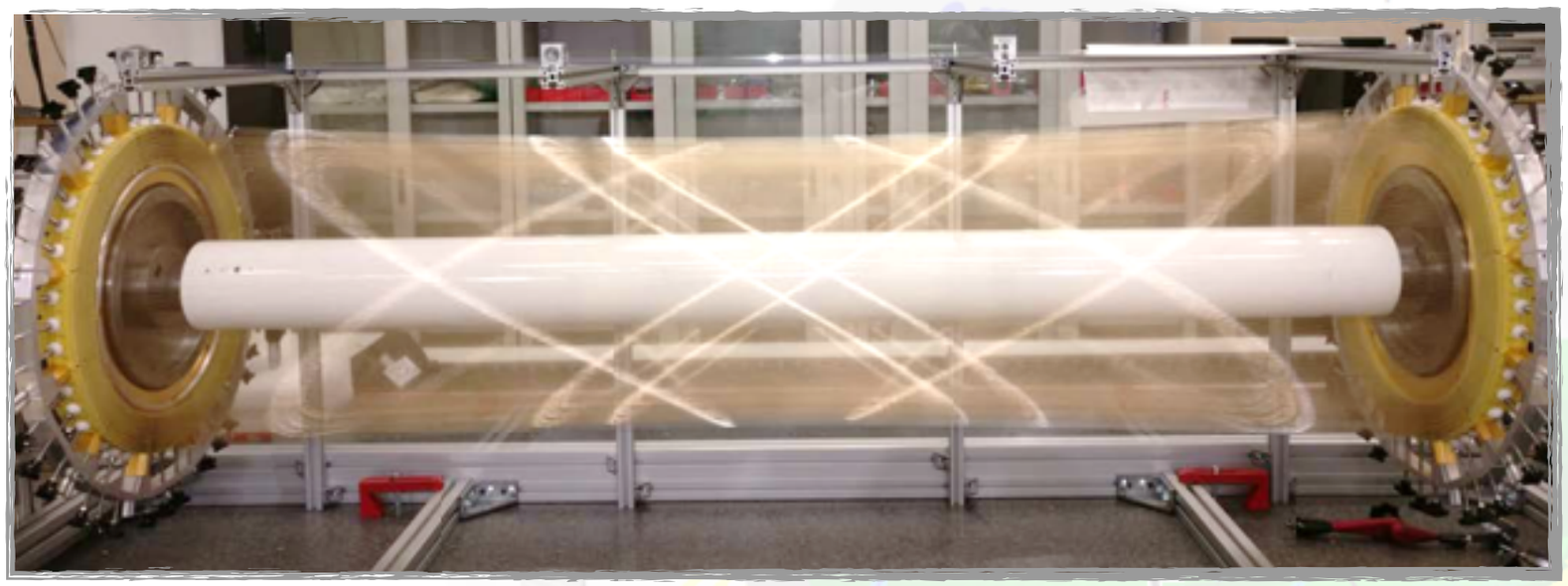
- **>1000 channels available for the incoming 2017 pre-engineering run**
- **For SiPM: bias voltage, pre-amp and shaping included**

The MEGII experiment: Status



- 900 LXe
- ~ 4000 Photosensors = SiPM and PMT directly immersed in the Xe
- Construction and assembly completed
- Commissioning phase started (with reduced number of electronics channels)

The MEGII experiment: Status



- **Low material budget detector: < 0.0016 X_0**
- **In construction (Assembly: 70%, wiring: 80%)**
- **Mock-up installed in Cobra**
- **Gas system: commissioning phase**

Liquid xenon photon detector
(LXe)

Pixelated timing counter
(pTC)

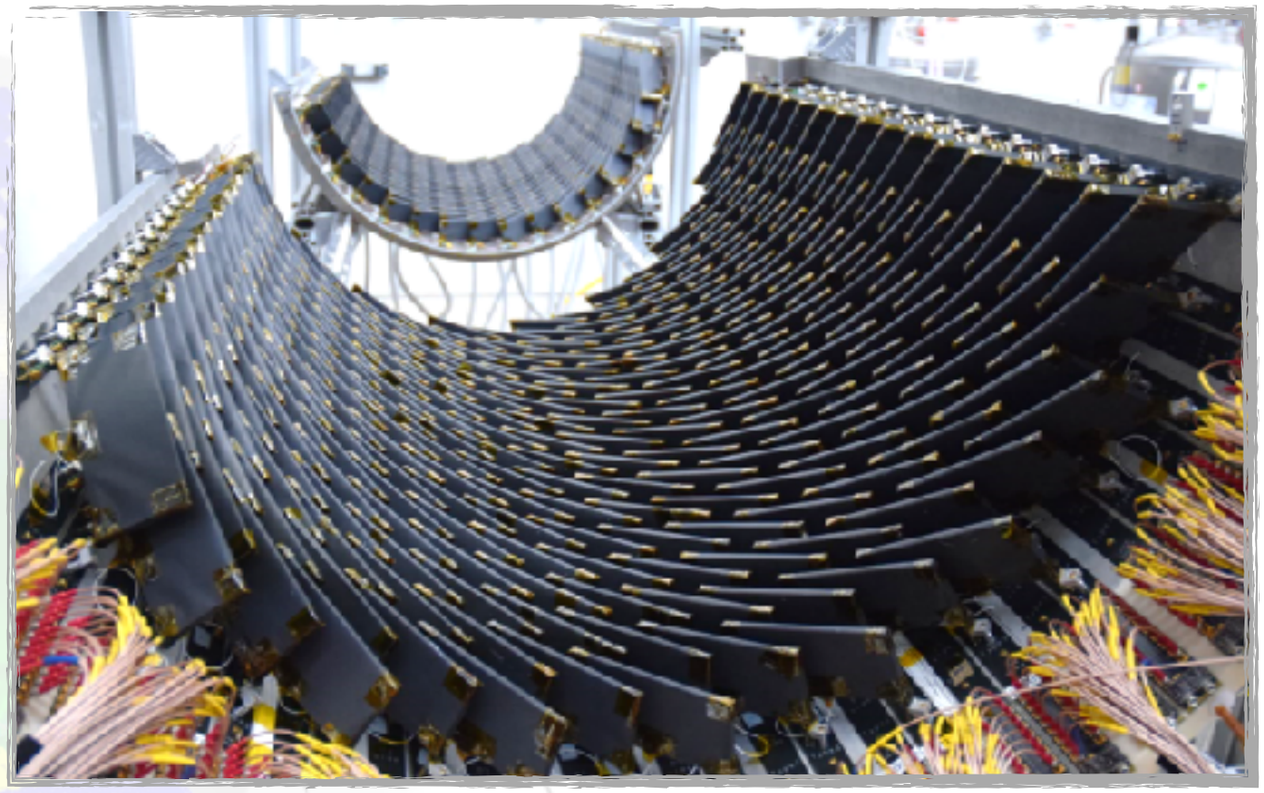
Muon stopping target

Radiative decay counter
(RDC)

Cylindrical drift chamber
(CDCH)

Single volume He:iC_4H_{10}

The MEGII experiment: Status

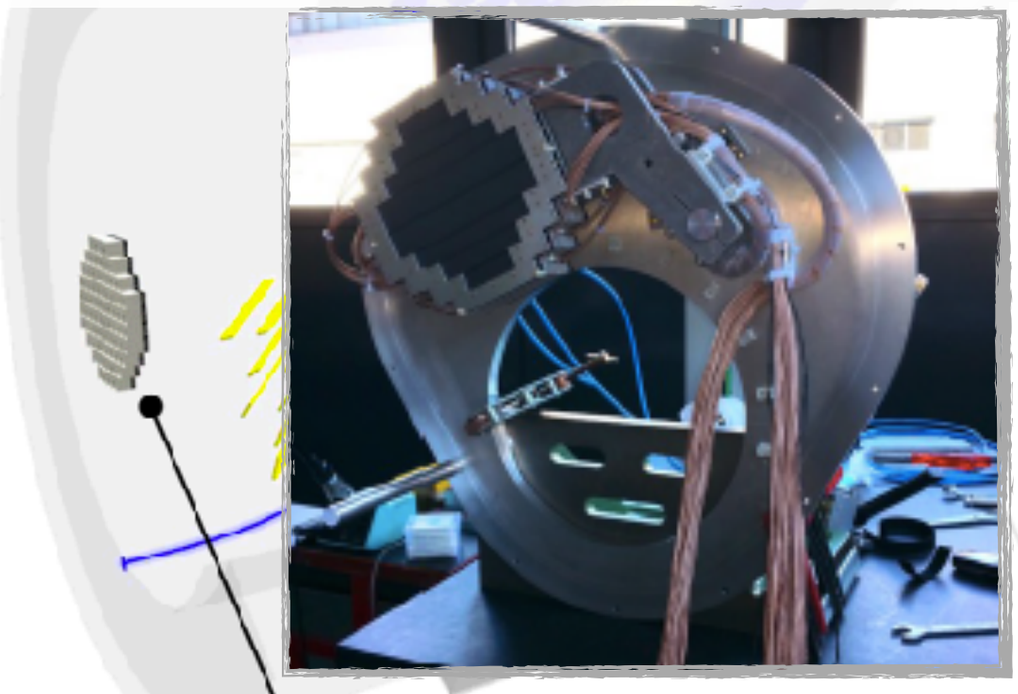


Pixelated timing counter
(pTC)

35 ps resolution w/ multiple hits

- **2 x 256 of BC422 scintillator plates (120 x 40 (or 50) x 5 mm^3) readout by AdvanSiD SiPM ASD-NUM3S-P-50-High-Gain**
- **Full detector: Commissioning phase**

The MEGII experiment: Status

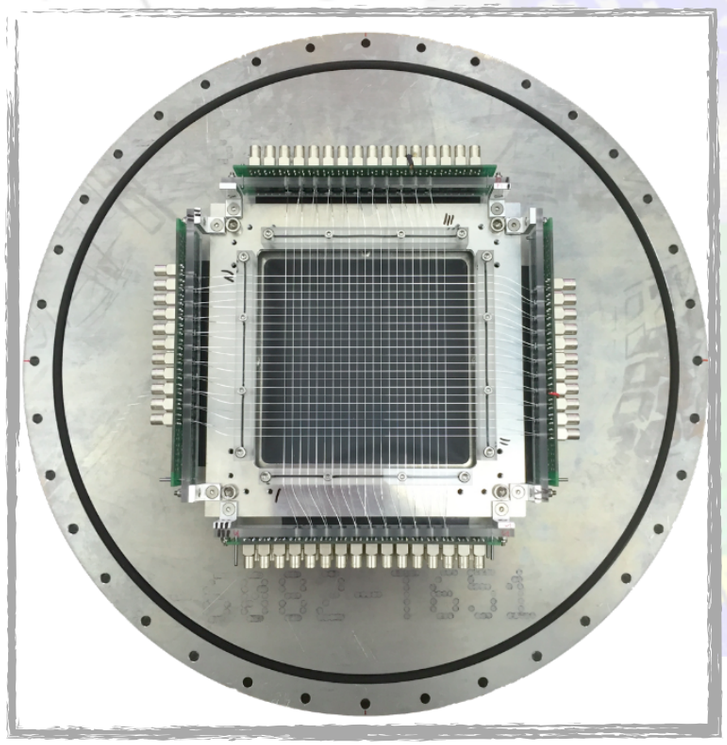


- **BC418 + MPPC S13360-3050PE**
- **LYSO 2 x 2 x 2 cm^3 + MPPC S12572-025**
- **Commissioning: pre-engineering run 2016**
- **Ready**

Radiative decay counter
(RDC)

Background rejection

The MEGII experiment: Status



Updated and new Calibration methods

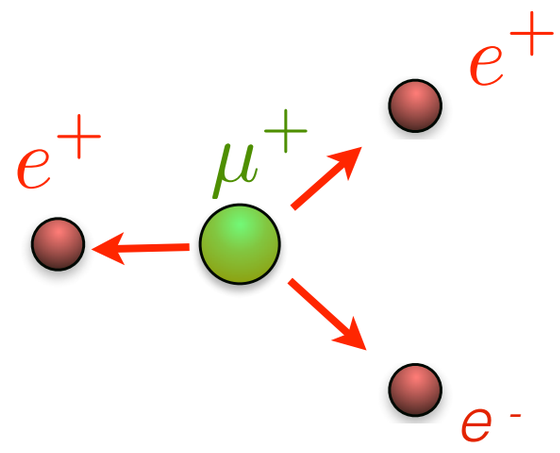
Quasi mono-chromatic positron beam

- **MC BCF12 250 x 250 um² scintillating fibers + MPPC S13360-3050C**
- **Commissioning: pre-engineering run 2016**
- **Movable configuration: in preparation**

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

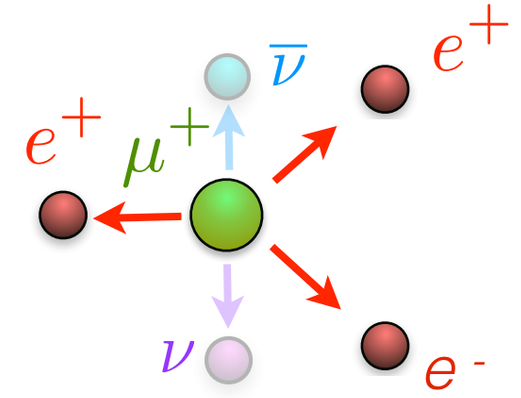
- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit BR($\mu^+ \to e^+ e^+ e^-$) ≤ 1 x 10^{-12} @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to$ eee events

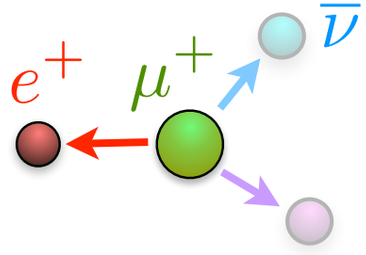
Signature

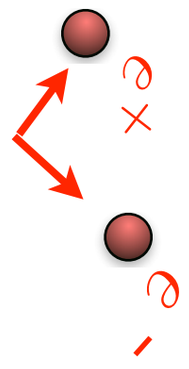


$\Delta t_{eee} = 0$ $\quad \Sigma \vec{p}_e = 0$ $\quad \Sigma E_e = m_\mu$

Background







The Mu3e experiment: Schematic 3D

Superconducting solenoid Magnet

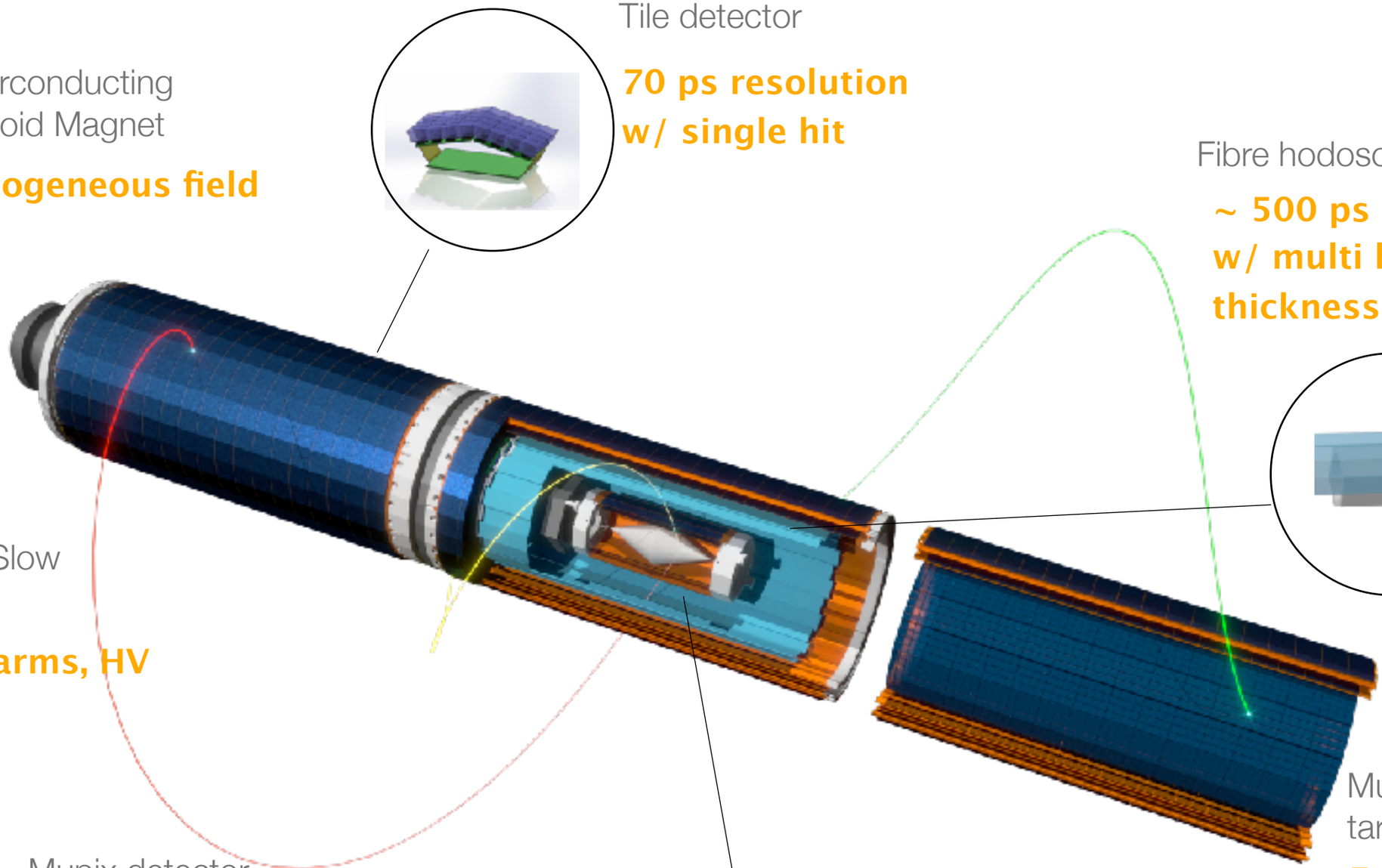
Homogeneous field 1T

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.

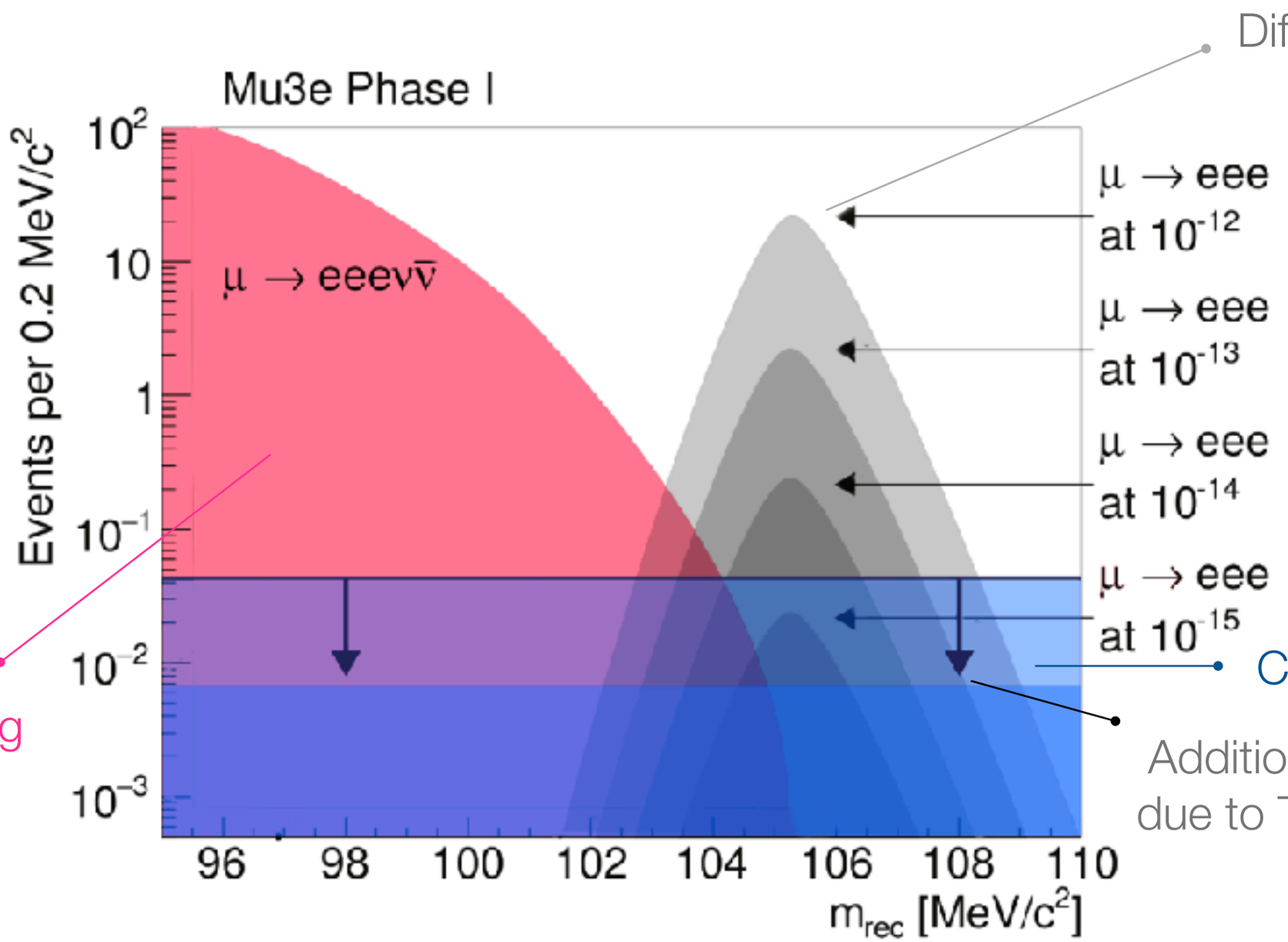
Mupix detector

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

Muon Beam and target

Full available beam intensity O(10^8)

Where we will be



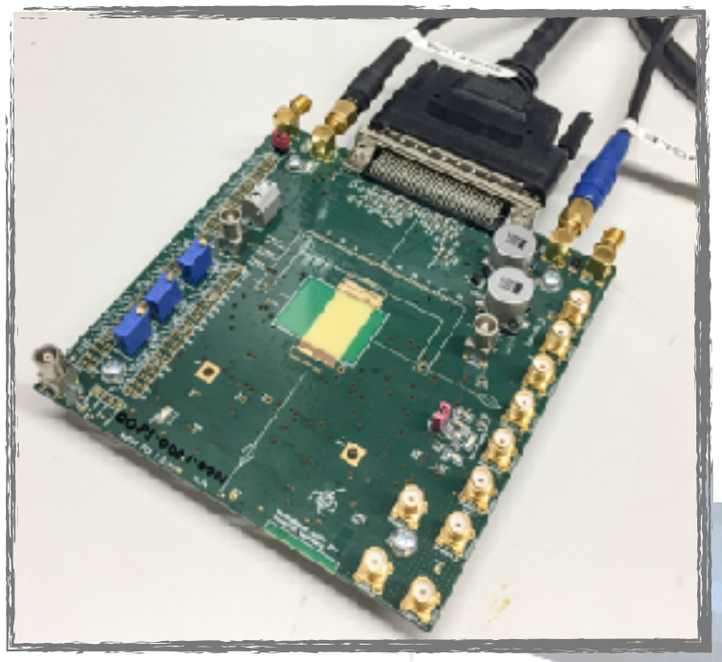
Different signal BR

Irreducible Bkg

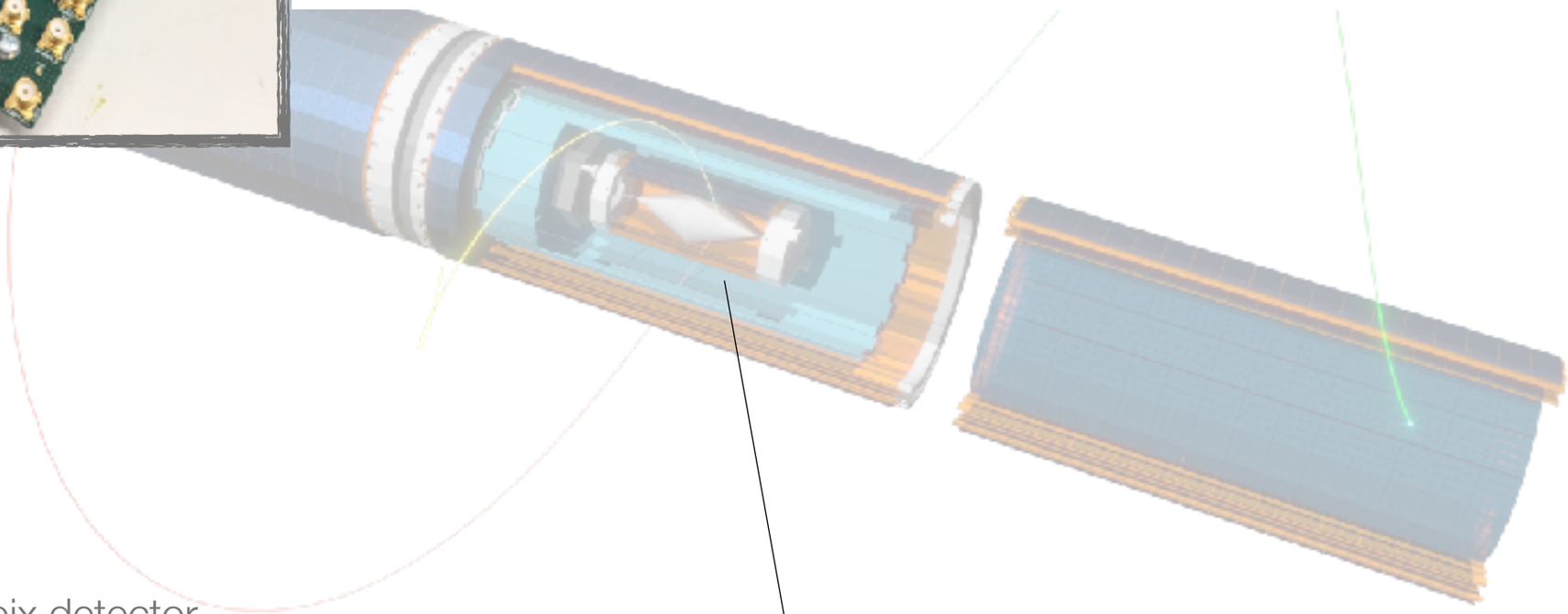
Combinatorial Bkg

Additional suppression due to Timing detectors

The Mu3e experiment: Status

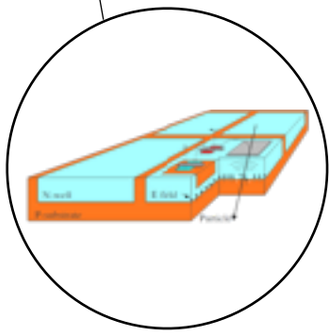


- **Extensive test beam campaign**
- **Long and rapid prototyping development**
- **MuPix 7: Fully functional HV-MAPS chip, 3x3 mm²**
- **MuPix 8: The first large area prototype, 160 mm² . Delivered**

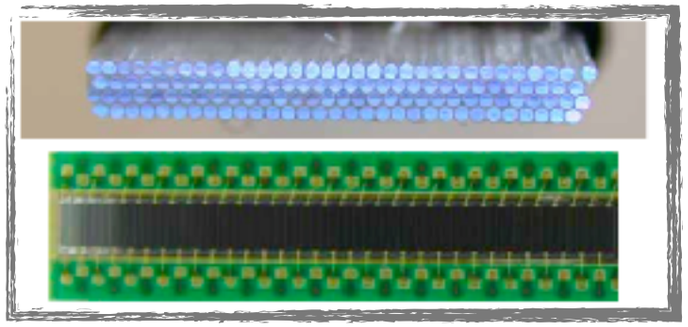


Mupix detector

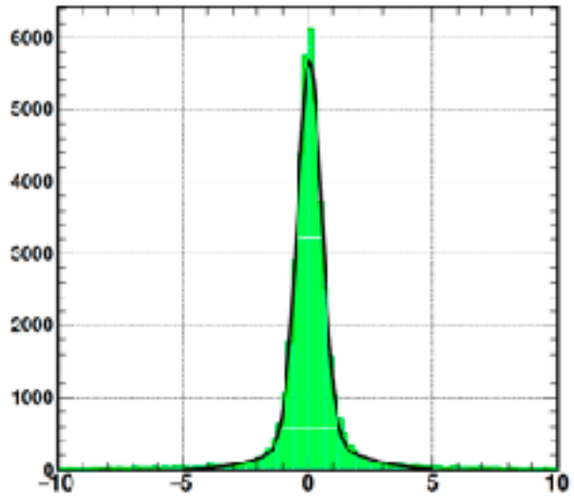
Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X_0



The Mu3e experiment: Status



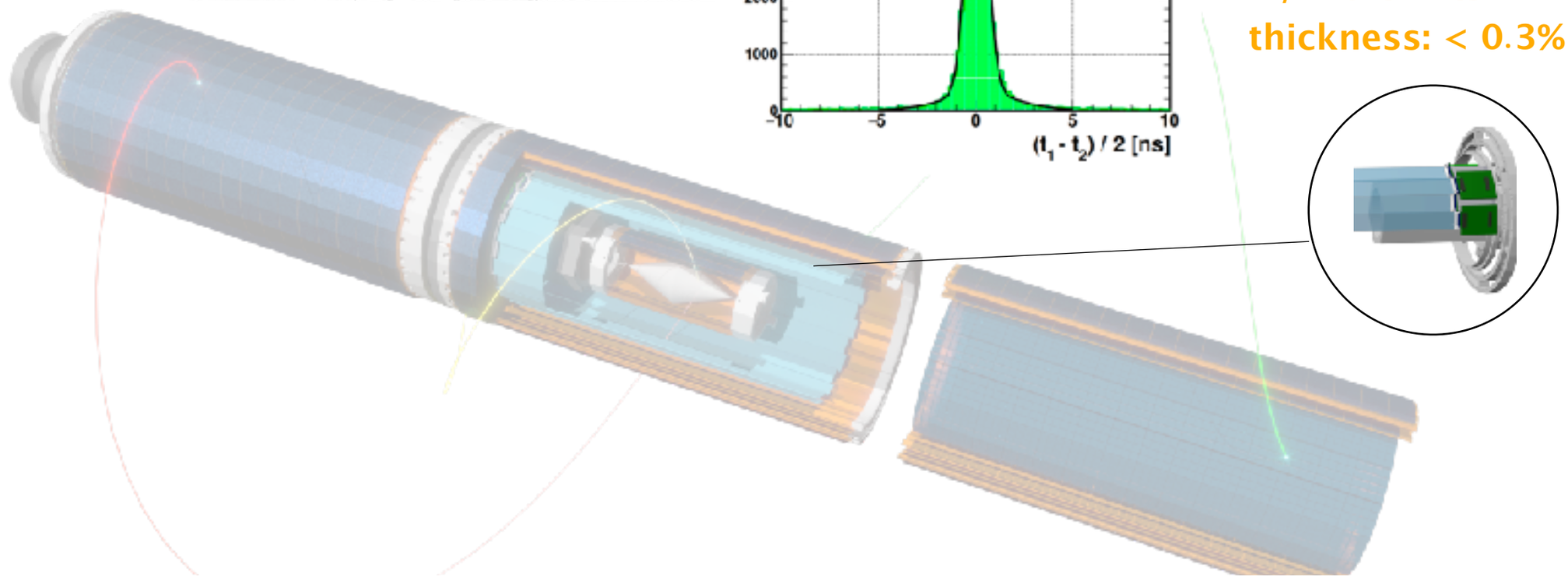
Time resolution O(500) ps



Fibre hodoscope

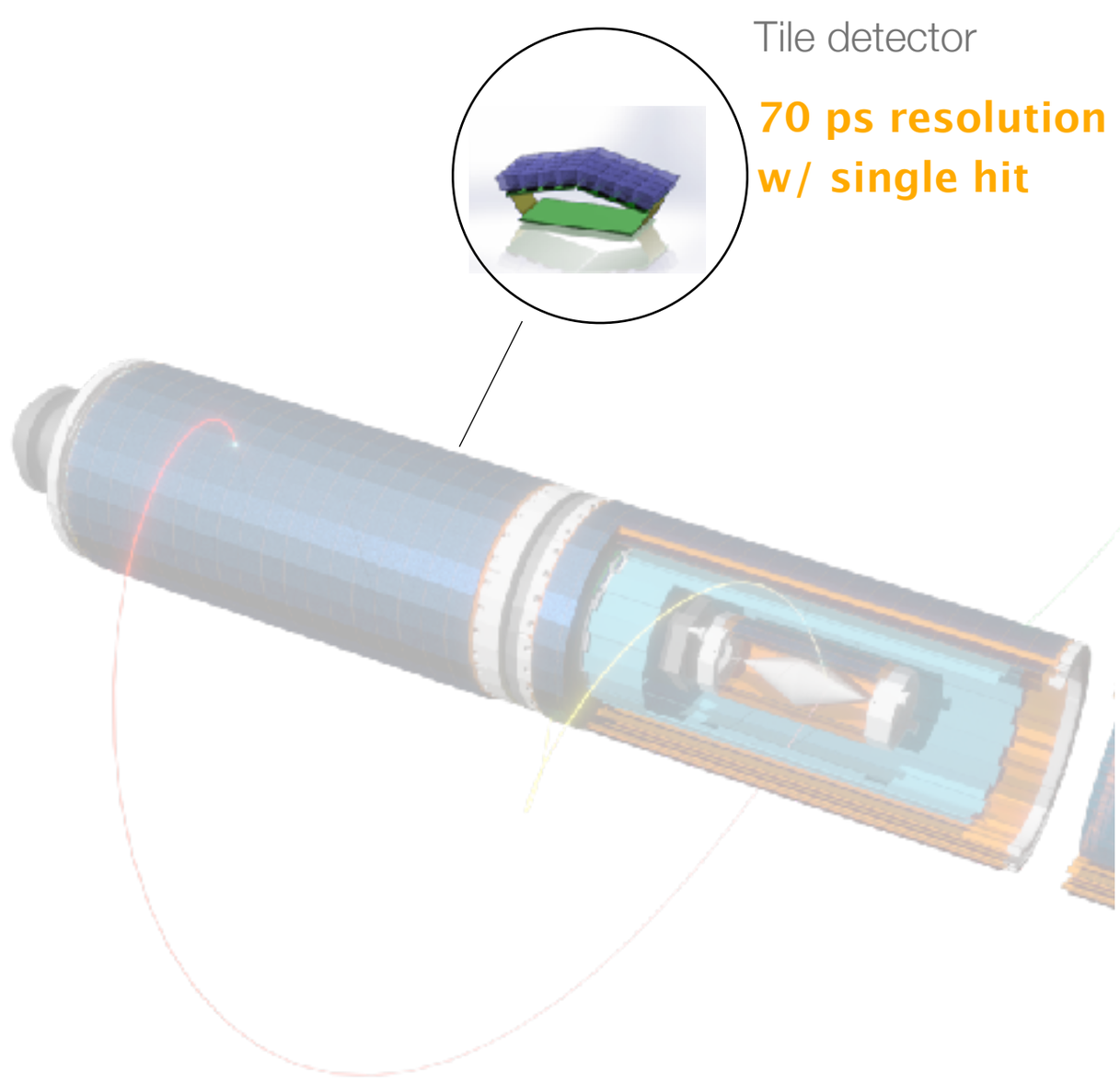
~ 500 ps resolution w/ multi hits

thickness: < 0.3% X_0



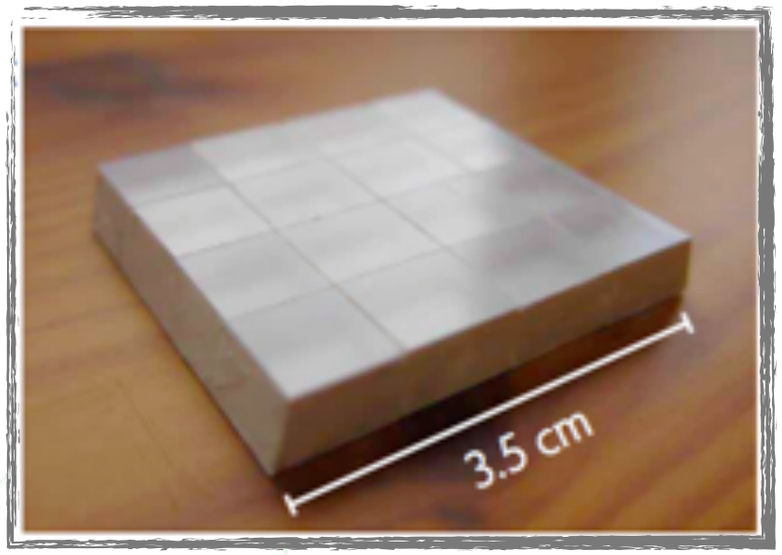
- **Extensive studied configurations and options (250 um fibres + MPPC array)**
- **Achieved detector performances (eff > 95%, σ ~ O(500) ps)**
- **Design: finalising phase**
- **Readout electronics: in preparation/to be tested soon**

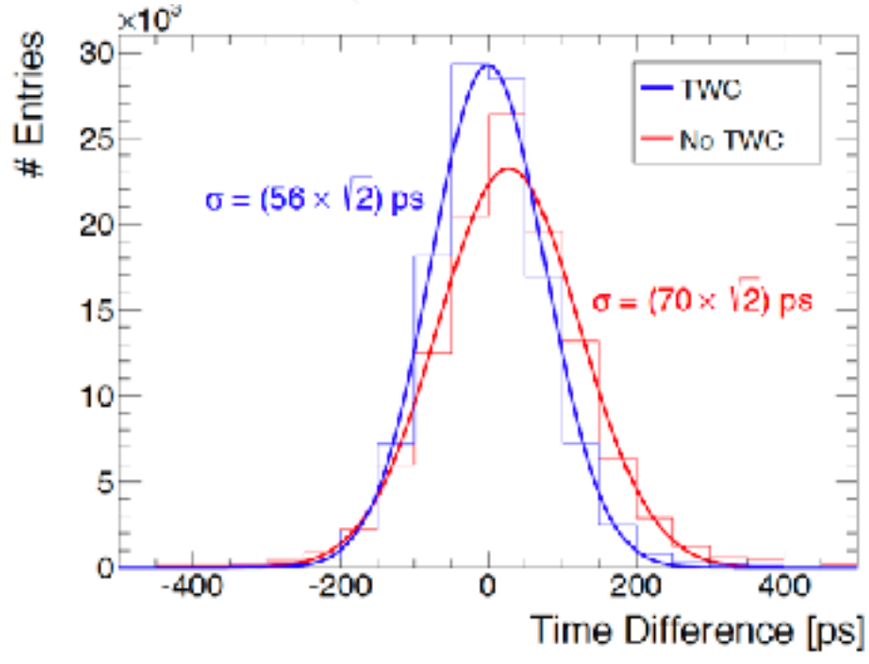
The Mu3e experiment: Status



Tile detector

70 ps resolution
w/ single hit





- **Full detection efficiency (> 99 %) and timing resolution O (60) ps**
- **4 x 4 channel BC408 (7. 5 x 8. 5 x 5. 0 mm³) + Hamamatsu S10362-33-050C (3 x 3 mm²)**
- **Readout: MuTRiG; Commissioning phase**

cLFV search landscape

Muons ~ 250

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

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

Kaons ~ 100

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

cLFV @ LHC ~ 250

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

Taus ~ 250

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

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 $\mu \to e \gamma$

Outlooks

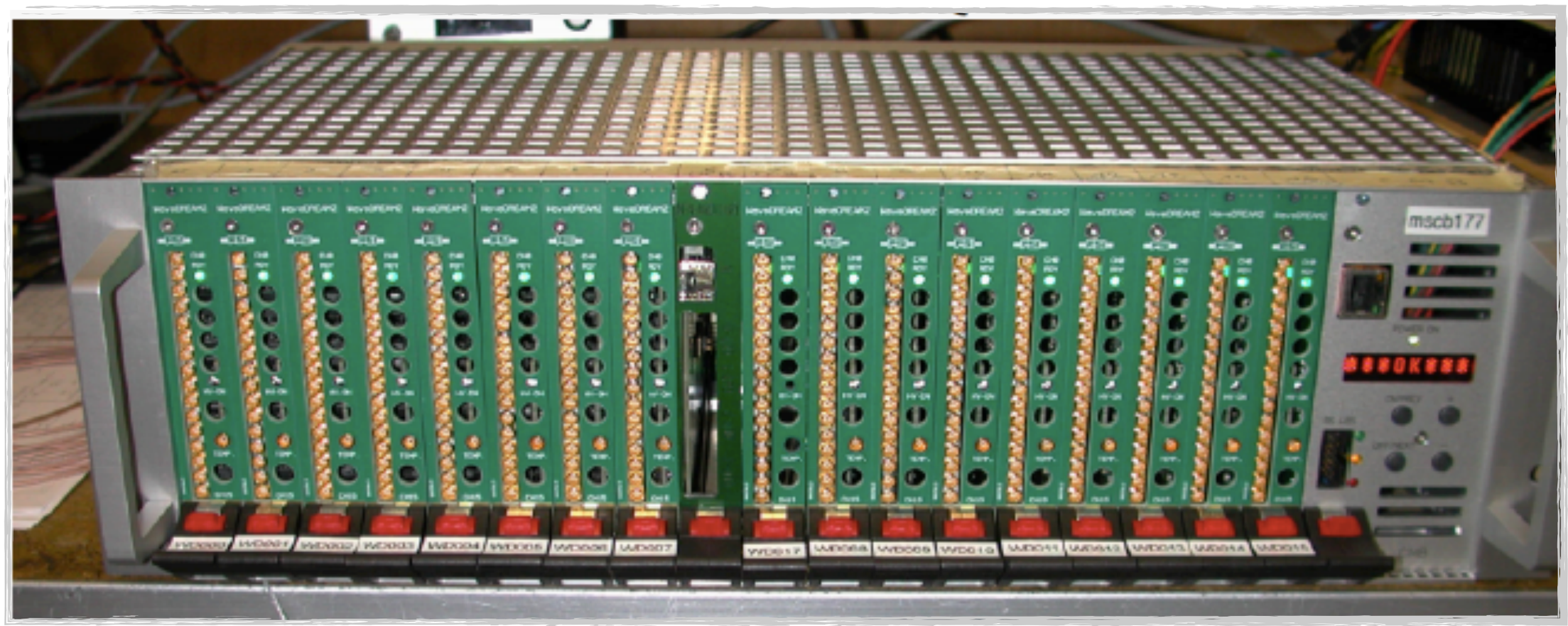
- The MEG experiment has set a new upper limit for the branching ratio of **$B(\mu^+ \to e^+ \gamma) < 4.2 \times 10^{-13}$** at 90% C.L. (a factor 30 improvement with respect to the previous MEGA experiment and also the strongest bound on any forbidden decay particle)
- An upgrade of the apparatus is ongoing: MEGII is expect to start next year the full engineering run followed by a physics run aiming at a sensitivity **down to 4×10^{-14}**
- The Mu3e experiment **is completely based on new detector technologies** and strongly connected with new beam line projects (**HiMB** at PSI aiming at 10^{10} muon/s) for a final sensitivity **down to few x 10^{-16}**
- The R&D phase for all sub-detectors and beam line has been concluded proving that the expected detector performances can be achieved. Construction and characterisation of all sub-detector prototype are extensively ongoing
- A full engineering run is expected for 2019 followed by data acquisition

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

Back-up

MEGII: The new electronic - DAQ and Trigger

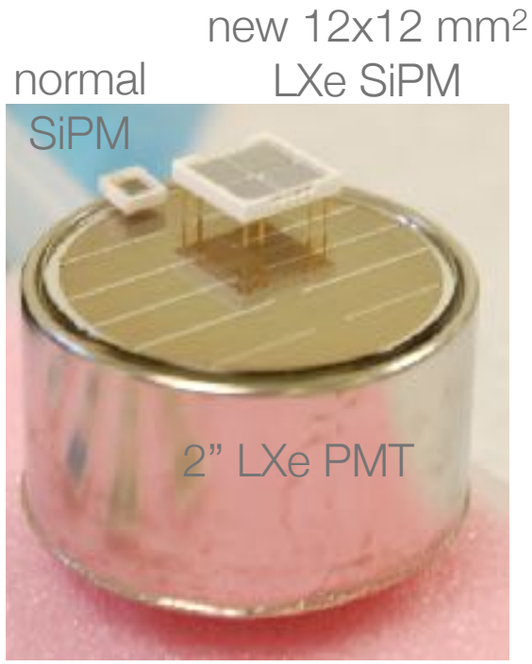
- DAQ and Trigger
  - ~9000 channels (5 GSPS)
  - Bias voltage, preamplifiers and shaping included for SiPMs
- 256 channels (1 crate) abundant tested during the 2016 pre-engineering run; >1000 channels available for the incoming 2017 pre-engineering run
- Trigger electronics and several trigger algorithms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



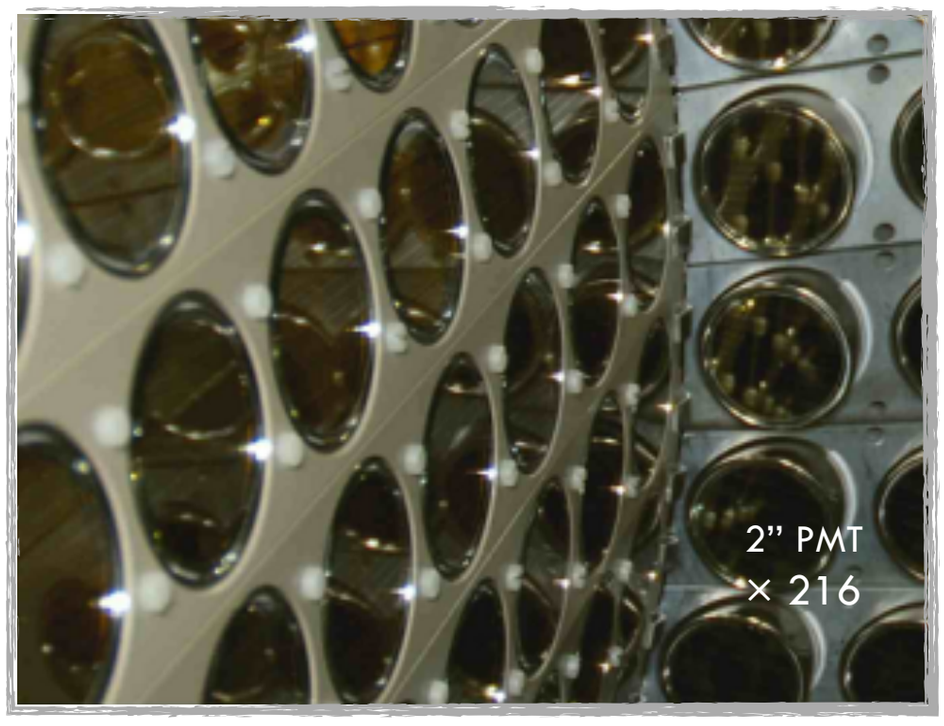
MEGII: The upgraded LXe calorimeter

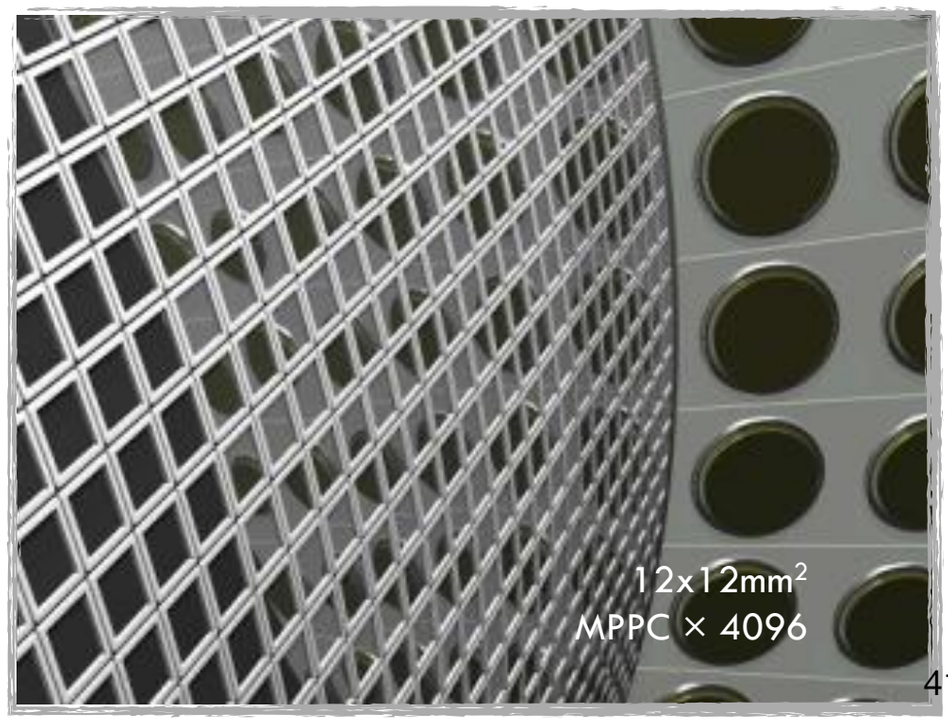
- Increased uniformity/resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency
- Assembly: Completed
- Detector filled with LXe
- Purification: Ongoing
- Monitoring and calibrations with sources: Started

New



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

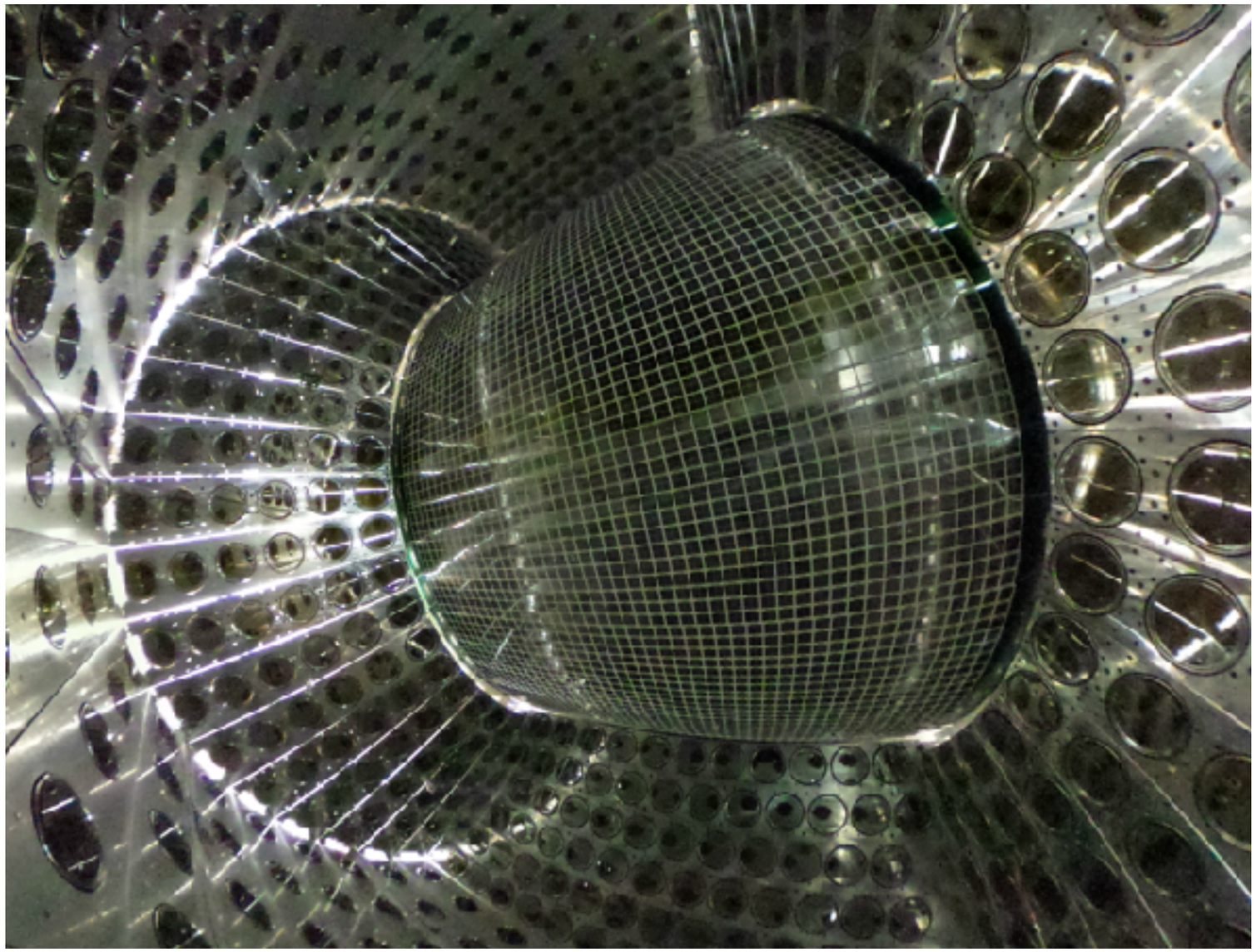


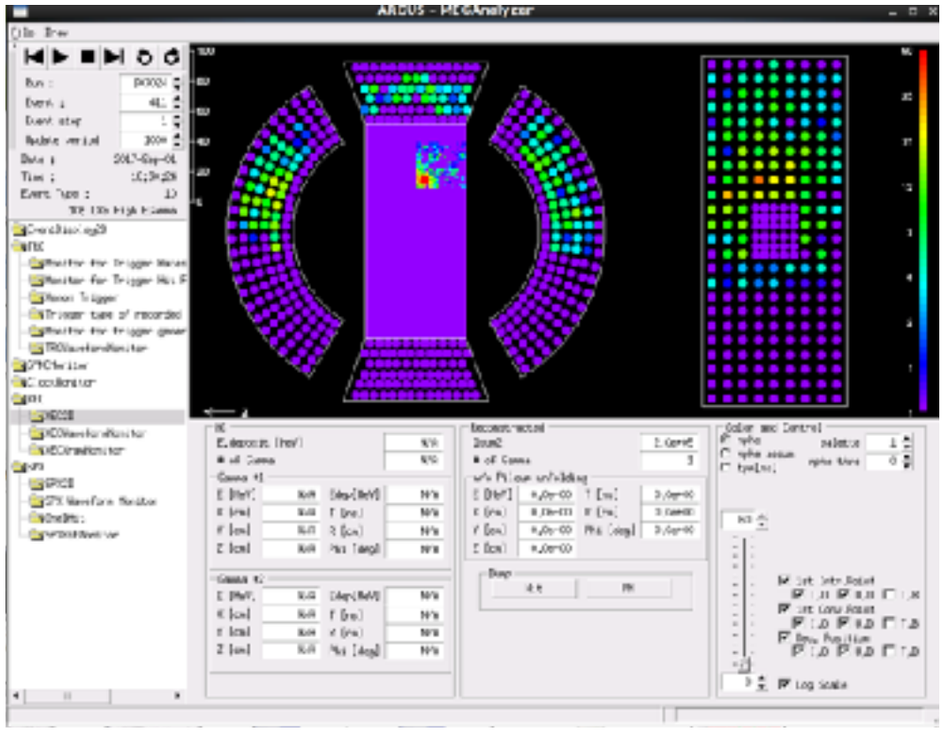


MEGII: The upgraded LXe calorimeter

Detector commissioning started !

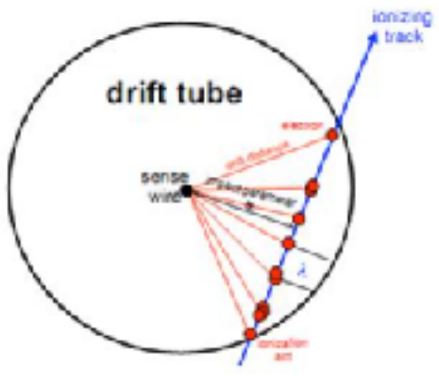
New





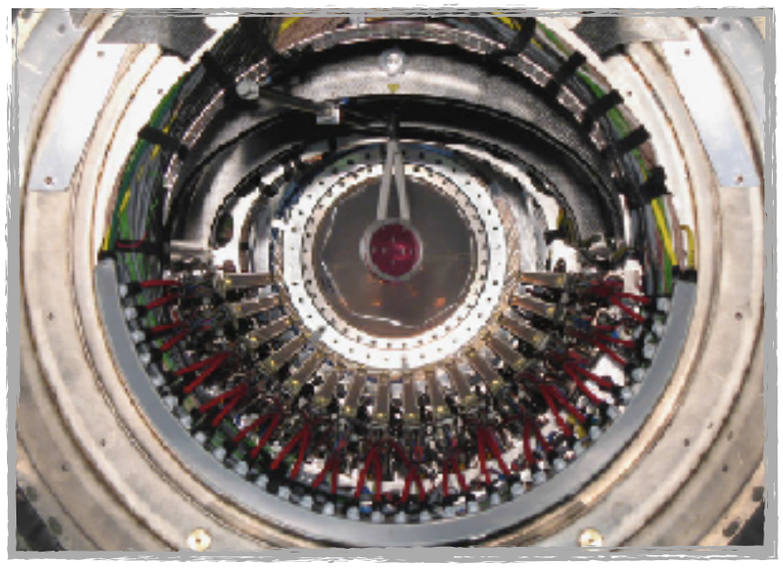
MEGII: The new single volume chamber

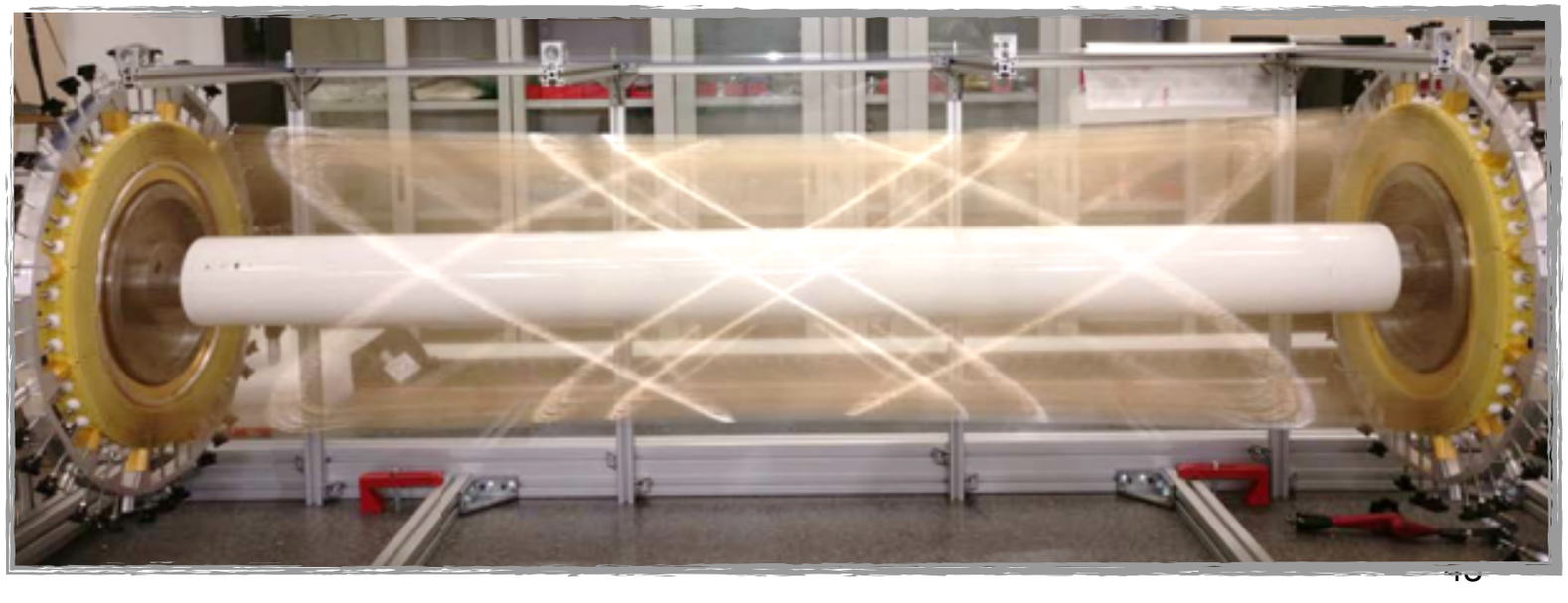
- Improved hit resolution: σ_r ~< 120 um (210 um)
- High granularity/Increased number of hits per track/cluster timing technique
- Less material (helium: isobutane = 90:10, 1.6×10^{-3} X_0)
- High transparency towards the TC
- Assembly: ~ 70% (wiring ~ 80%)



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

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





MEGII: The new single volume chamber

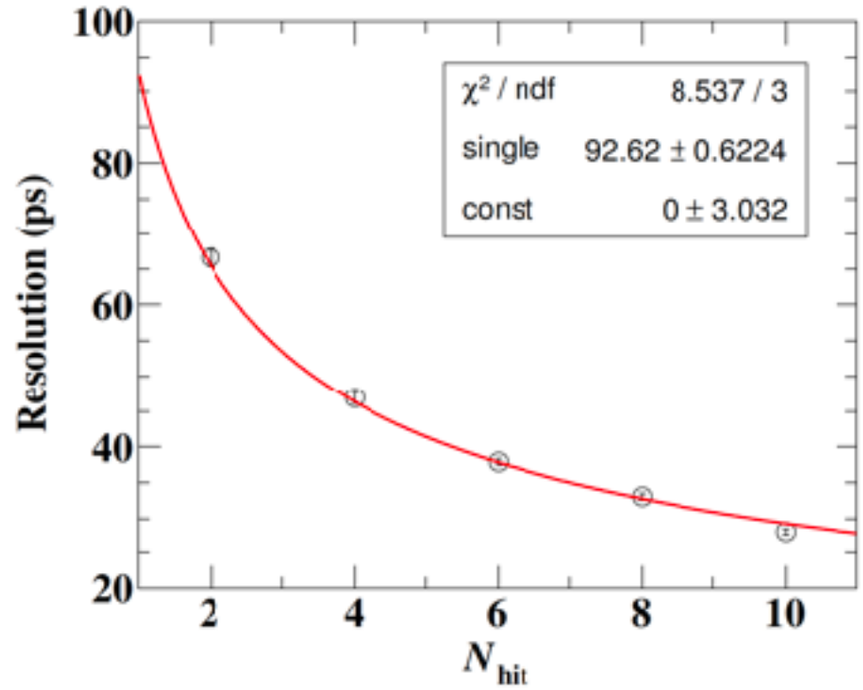
New

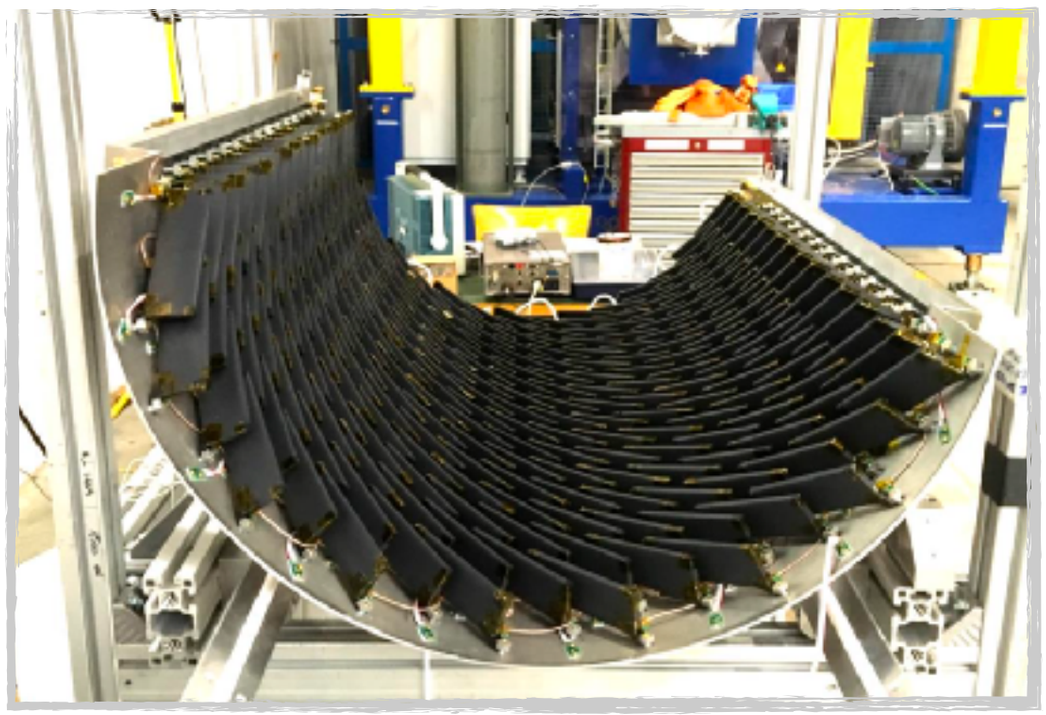
DCH Mock-up Ready!

MEGII: the pixelized Timing Counter

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

Pilot run 2016

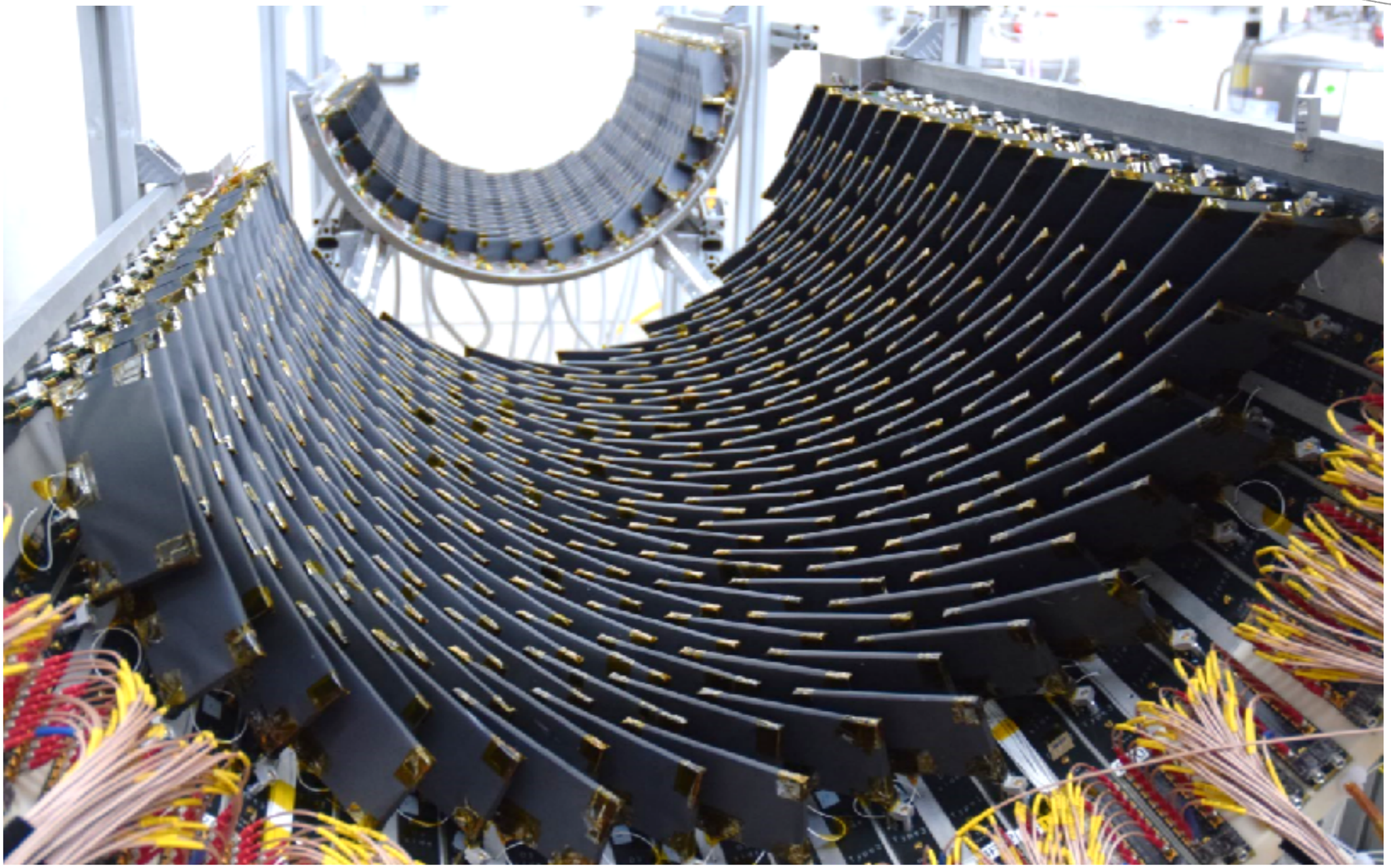




MEGII: the pixelized Timing Counter

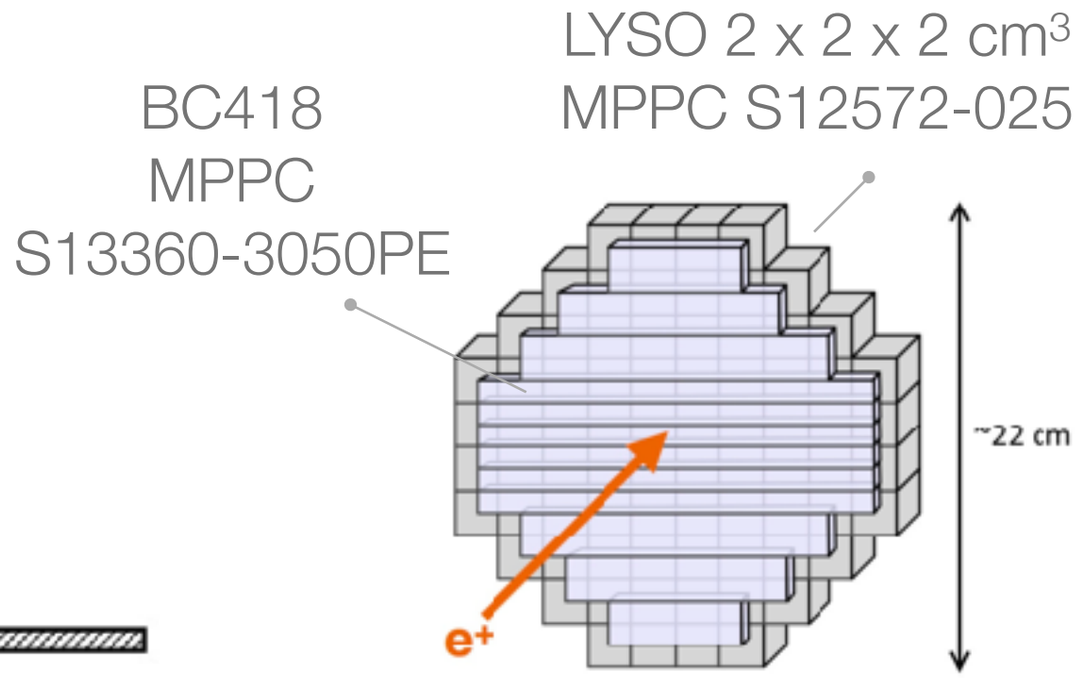
Ready to be inserted inside Cobra !

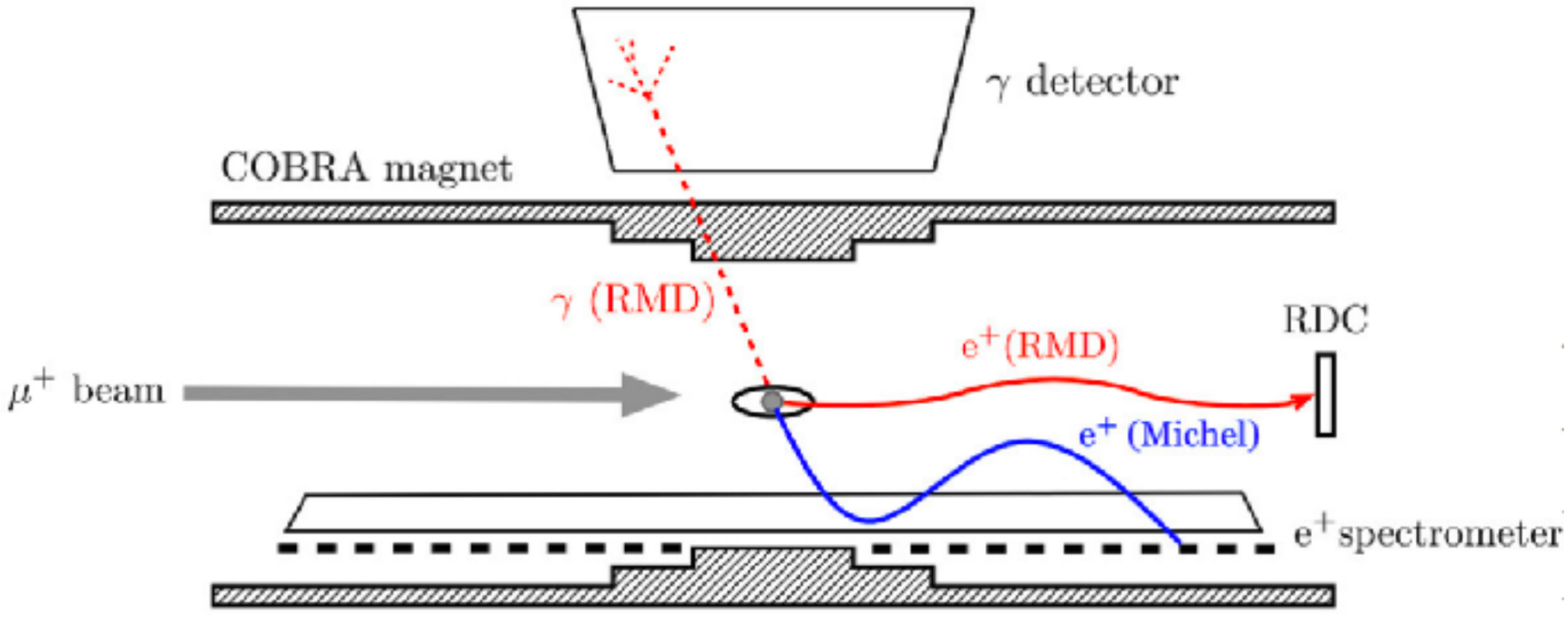
New

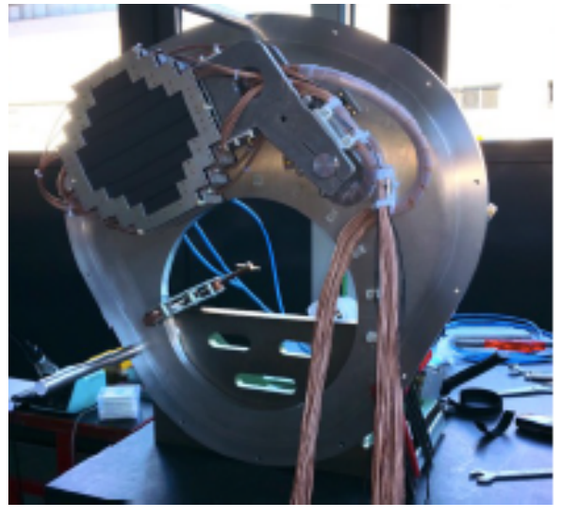


MEGII: The Radiative Decay Counter

- 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



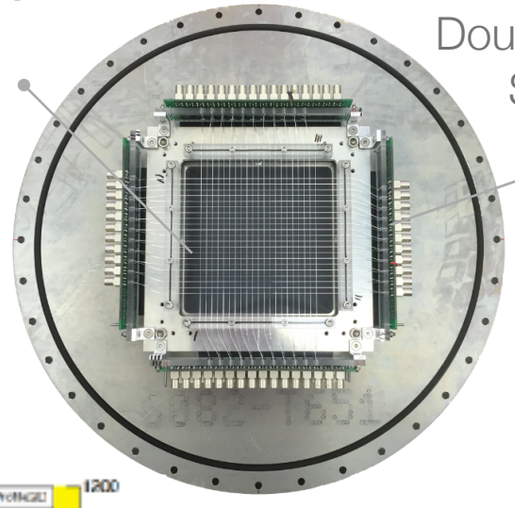




MEGII: new calibration methods and upgrades

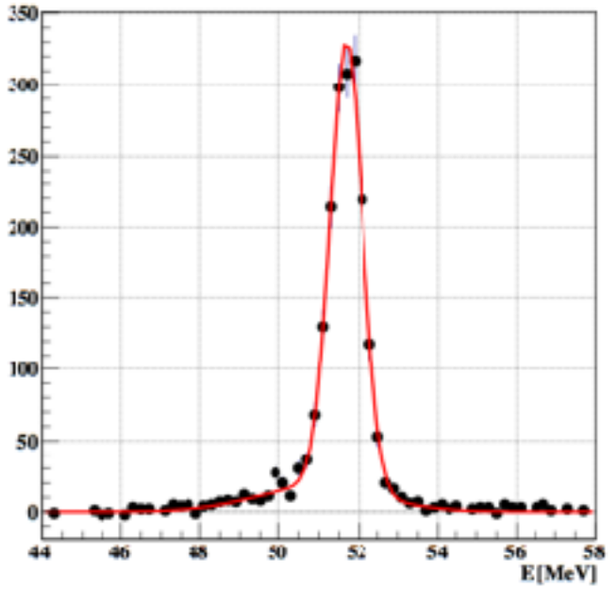
- CEX reaction: $p(\pi^-, \pi^0)n$, $\pi^0 \rightarrow \gamma\gamma$
- 1MV Cockcroft-Walton accelerator
- Pulsed D-D Neutron generator
- NEW: Mott scattered positron beam to fully exploit the new spectrometer
- NEW: SciFi beam monitoring. Not invasive, ID particle identification, vacuum compatible, working 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 um^2 scintillating fibers



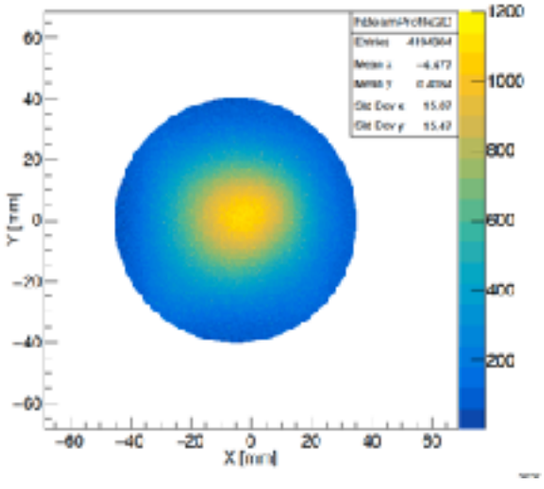
Double readout: MPPC S13360-3050C

Monochromatic e-line

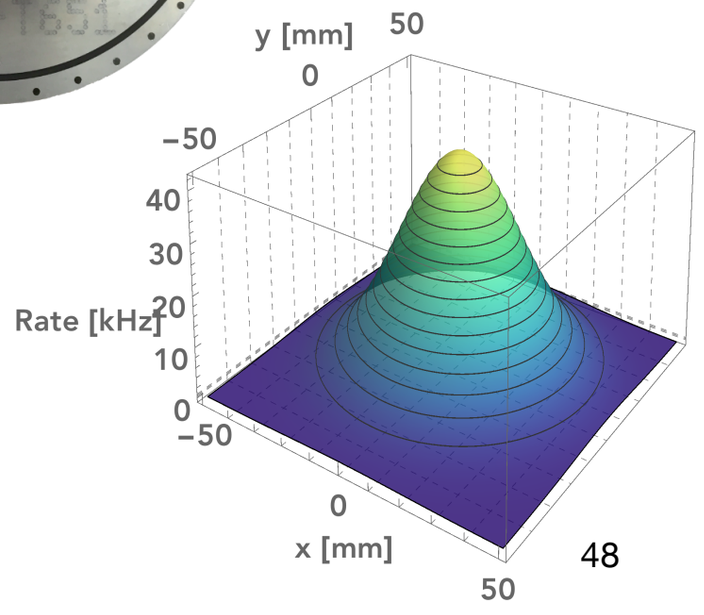


pTC's laser

Luminophore

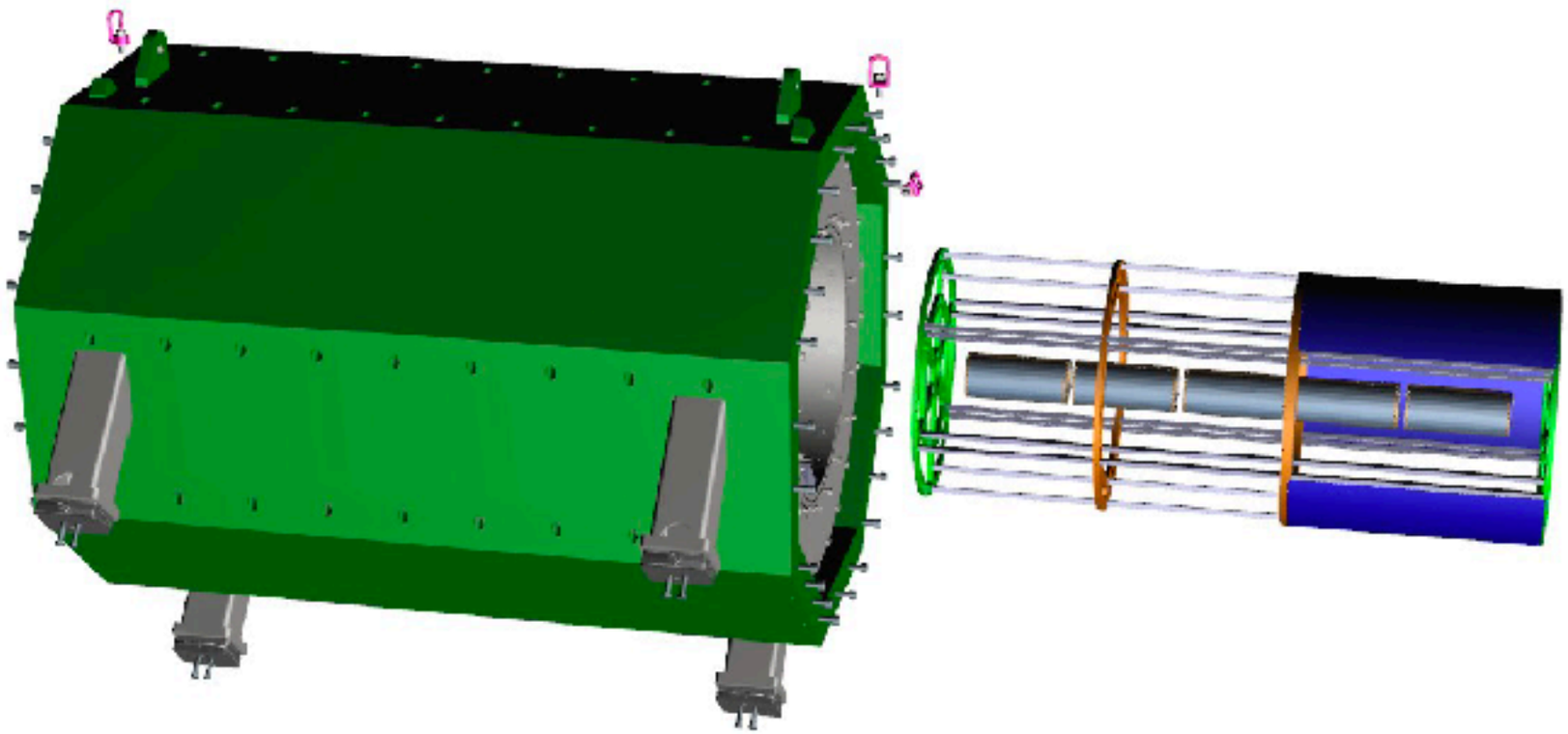


SciFi

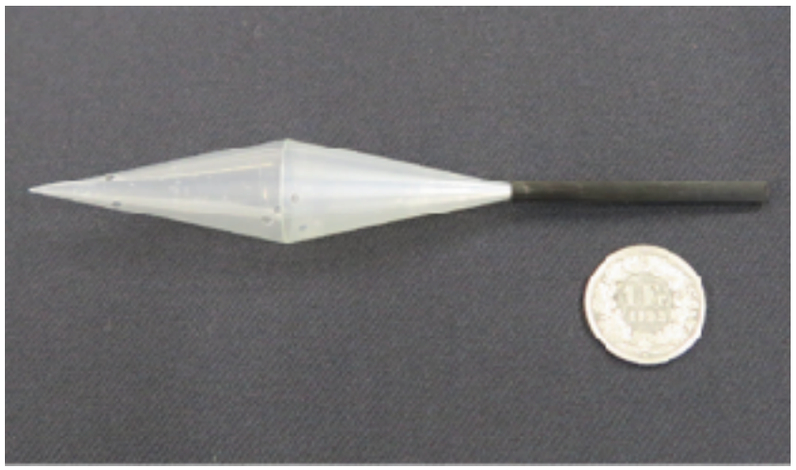


Target and magnet: Status

- Target: Mylar double hollow cone (L = 100 mm, R = 19 mm), Stopping efficiency: ~ 83%, Vertex separation ability (tracking) < 200 um
- Solenoid Magnet: Delivering time 2019

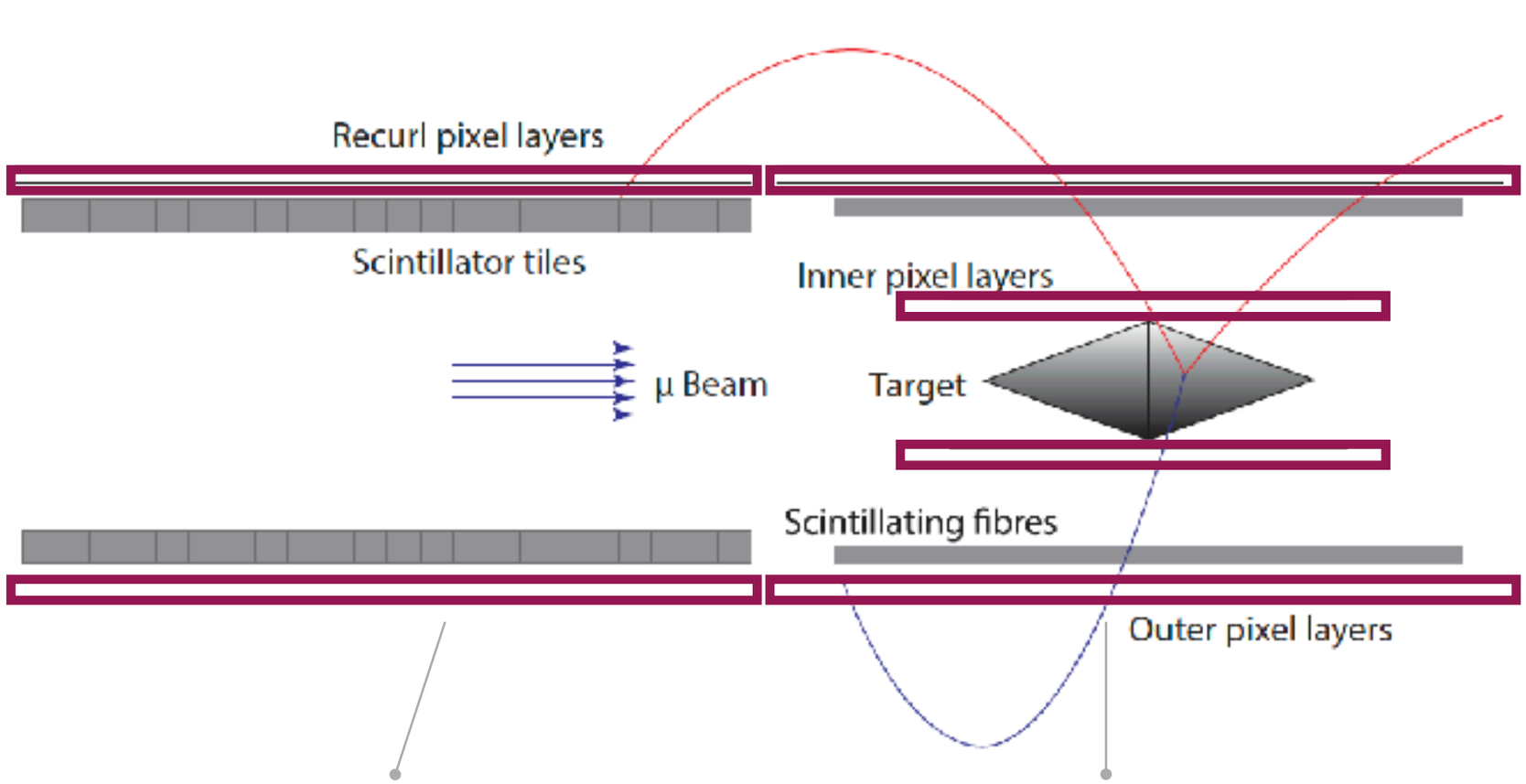


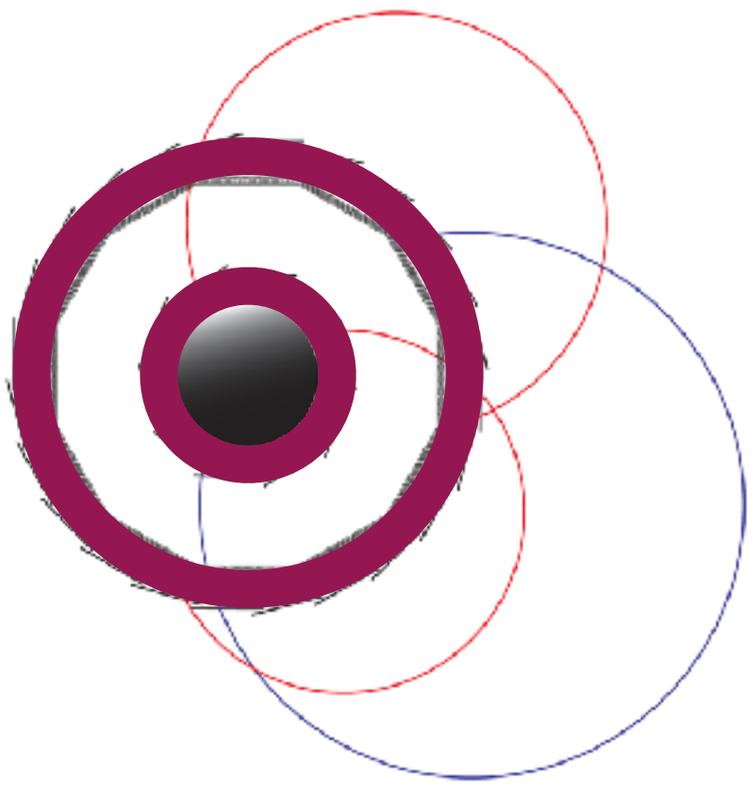
Target prototype



The pixel tracker: Overview

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



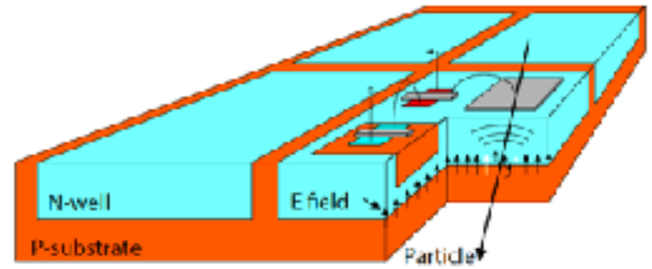


Re-curl stations **Central stations**

The pixel tracker: The MuPix prototypes

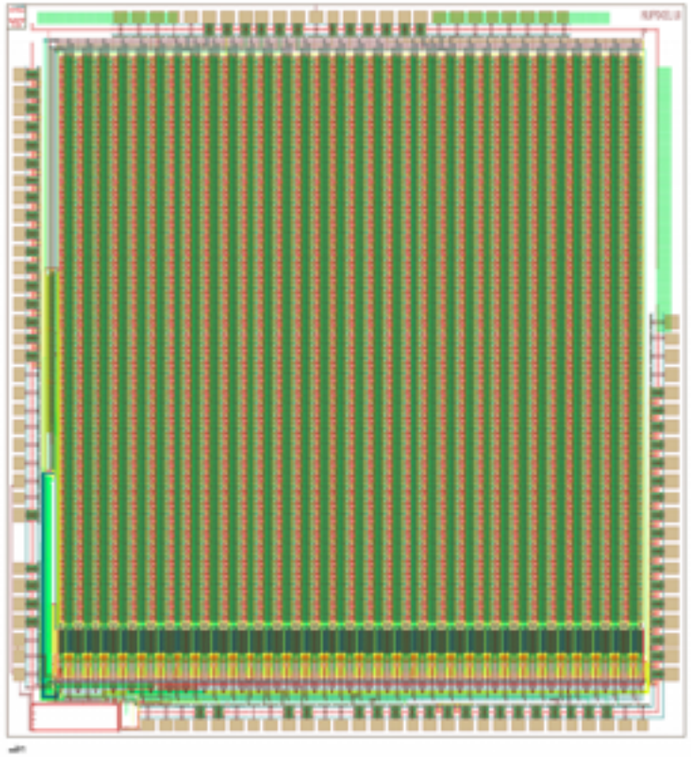
Ivan Peric, Nucl.Instrum.Meth. A582 (2007) 876-885

- Based on HV- MAP: Pixel dimension: 80 x 80 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

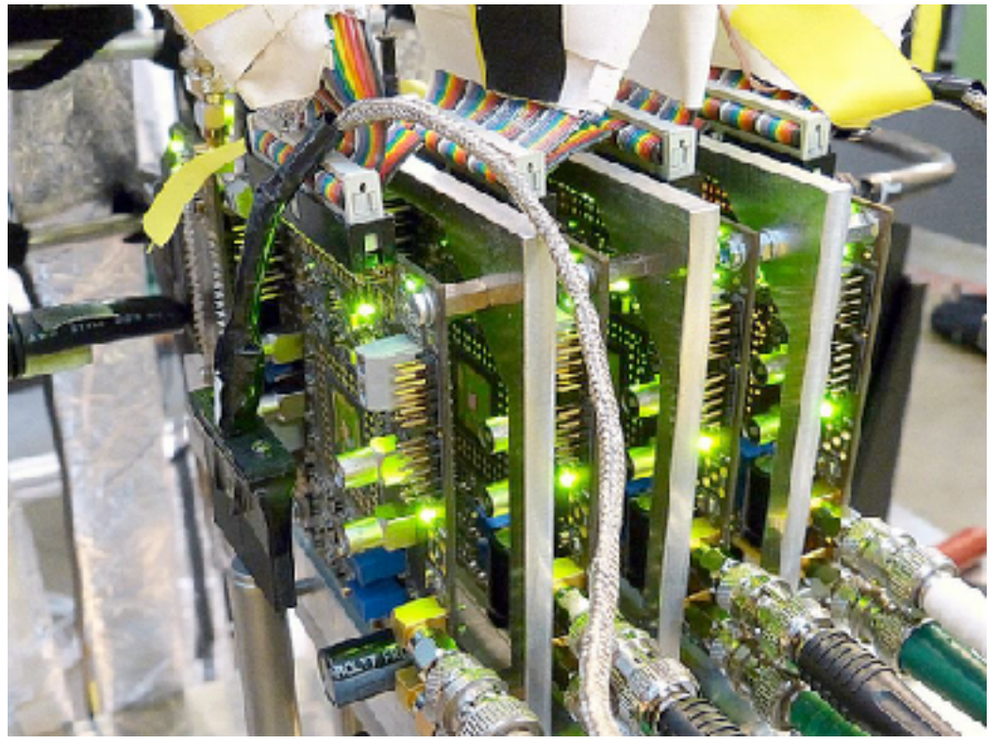


Prototype	Active Area [mm^2]
MuPix1	1.77
MuPix2	1.77
MuPix3	9.42
MuPix4	9.42
MuPix6	10.55
MuPix7	10.55

MuPix7



Extensively tested along beams



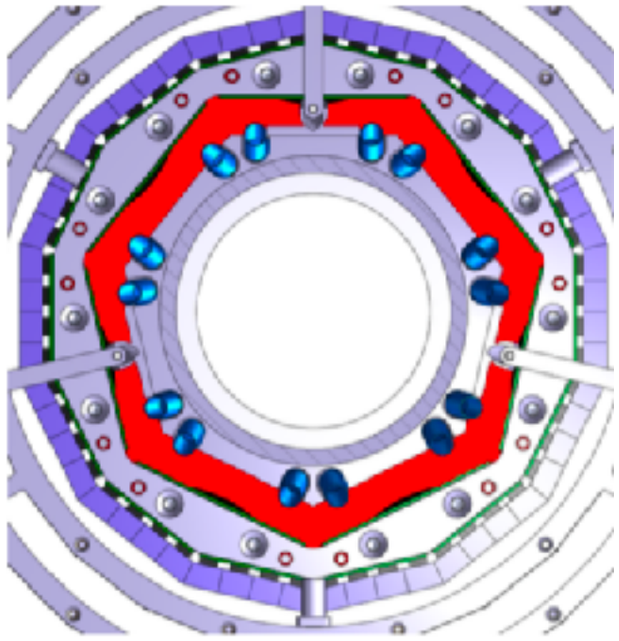
The pixel tracker: Current and future plan

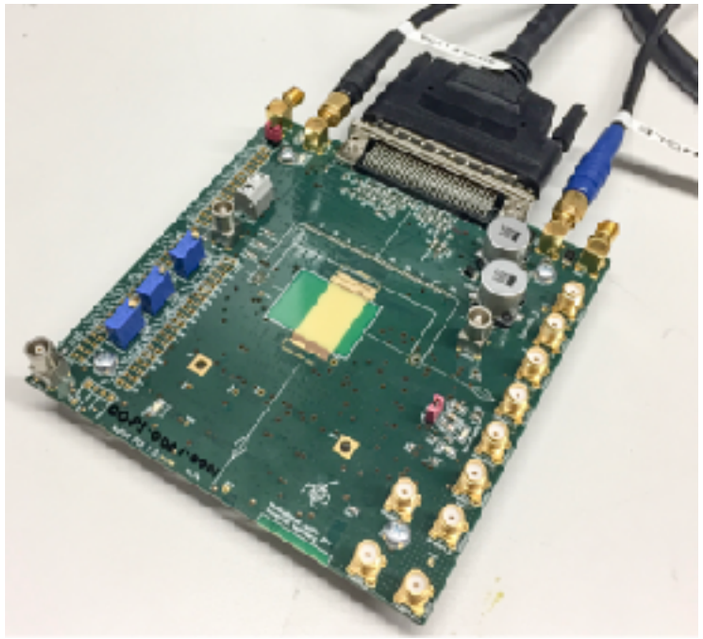
- After an extensive test beam campaign, achieved milestones
  - A fully functional HV-MAPS chip, 3x3 mm^2, Operation at high rates: 300 kHz at PSI; up to 1 MHz at SPS
  - Crosstalk on setup under control, on chip seen. Mitigation plan exists (MuPix8), Routinely operated systems of up to 8 chips in test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

- Next steps
  - MuPix 8, the first large area prototype: from O(10) mm^2 to 160 mm^2 : Ready !
  - 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

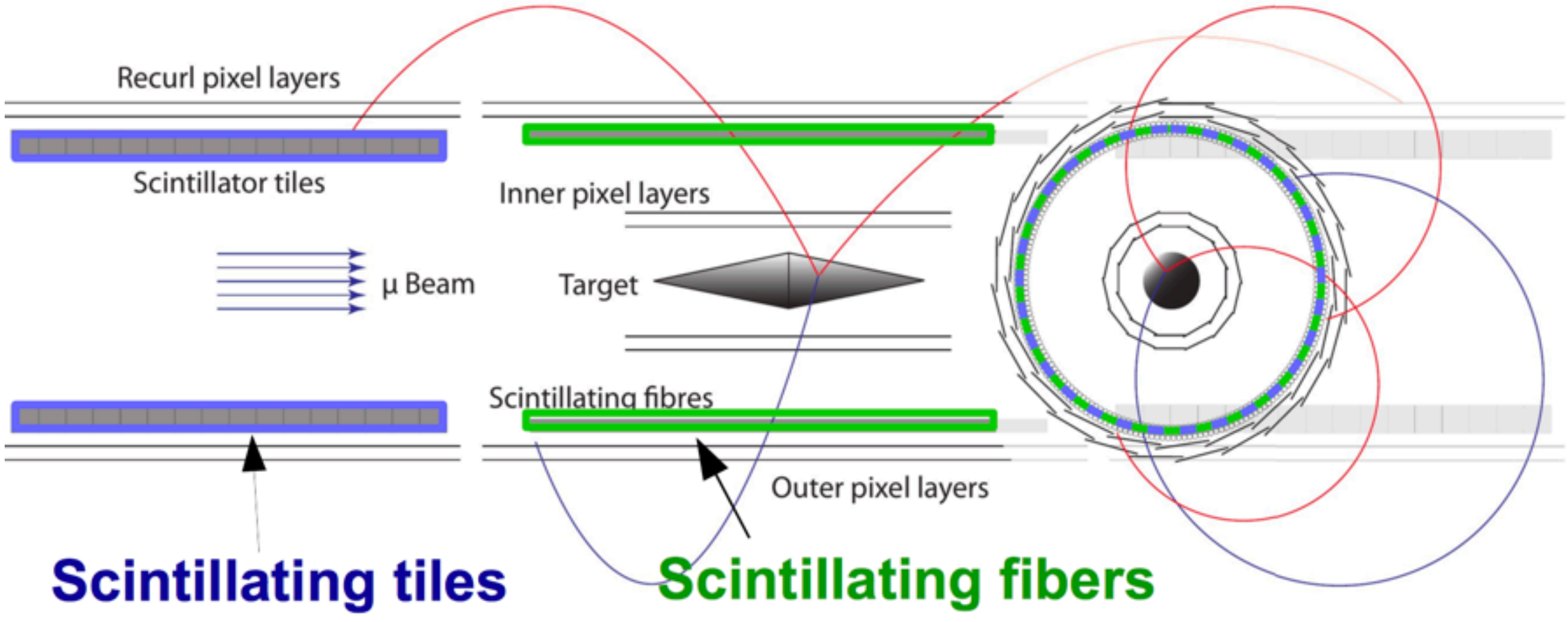




New

The timing detectors: Fibers and tiles

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



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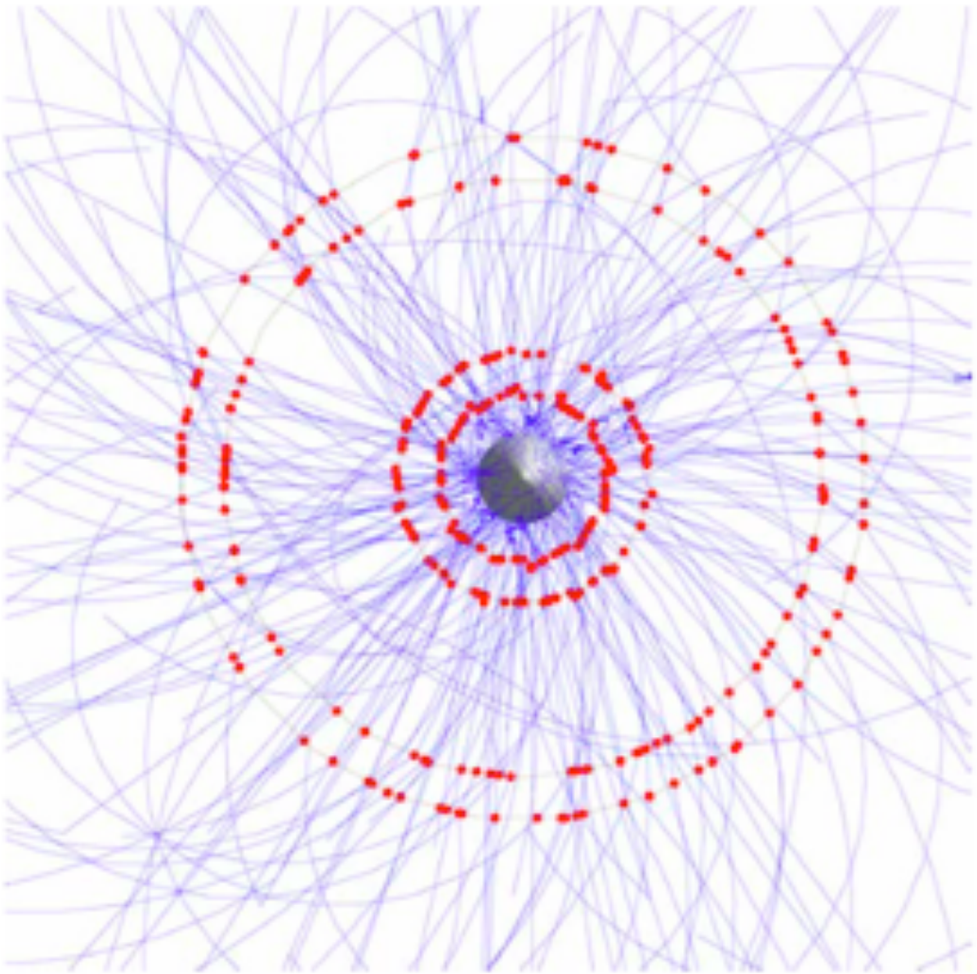
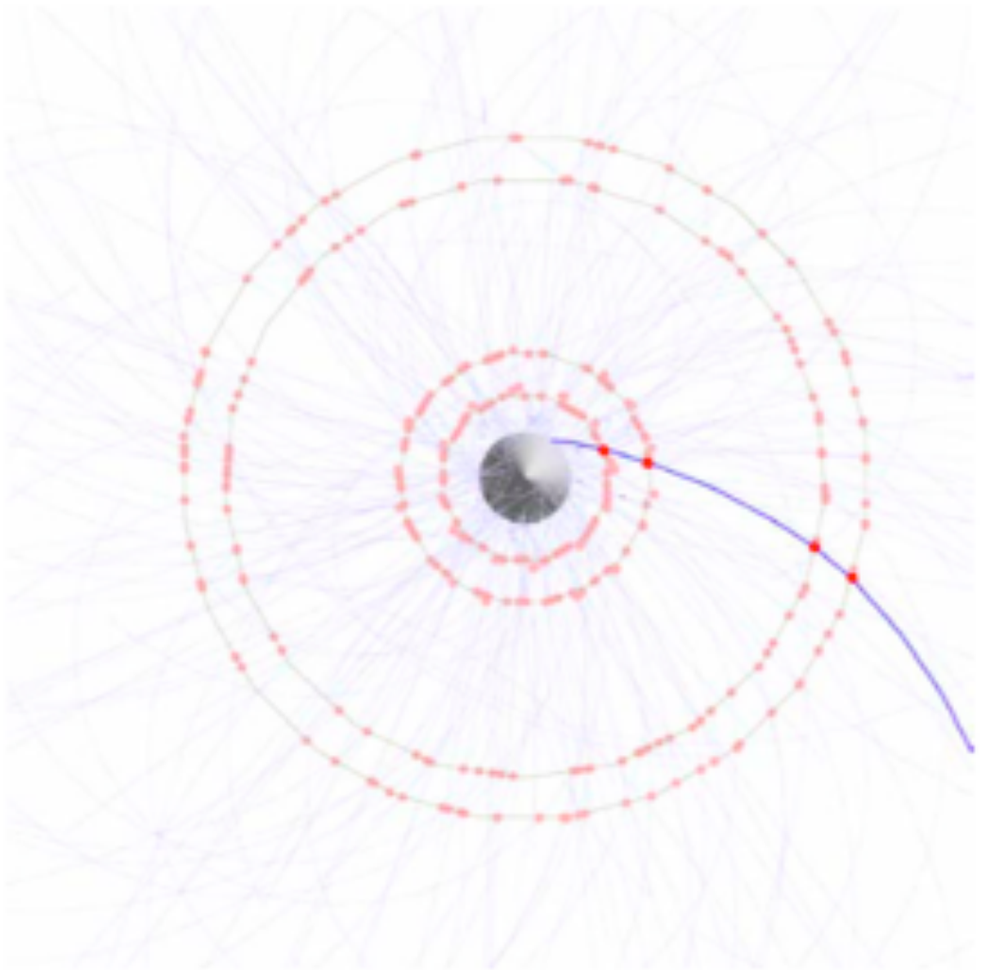


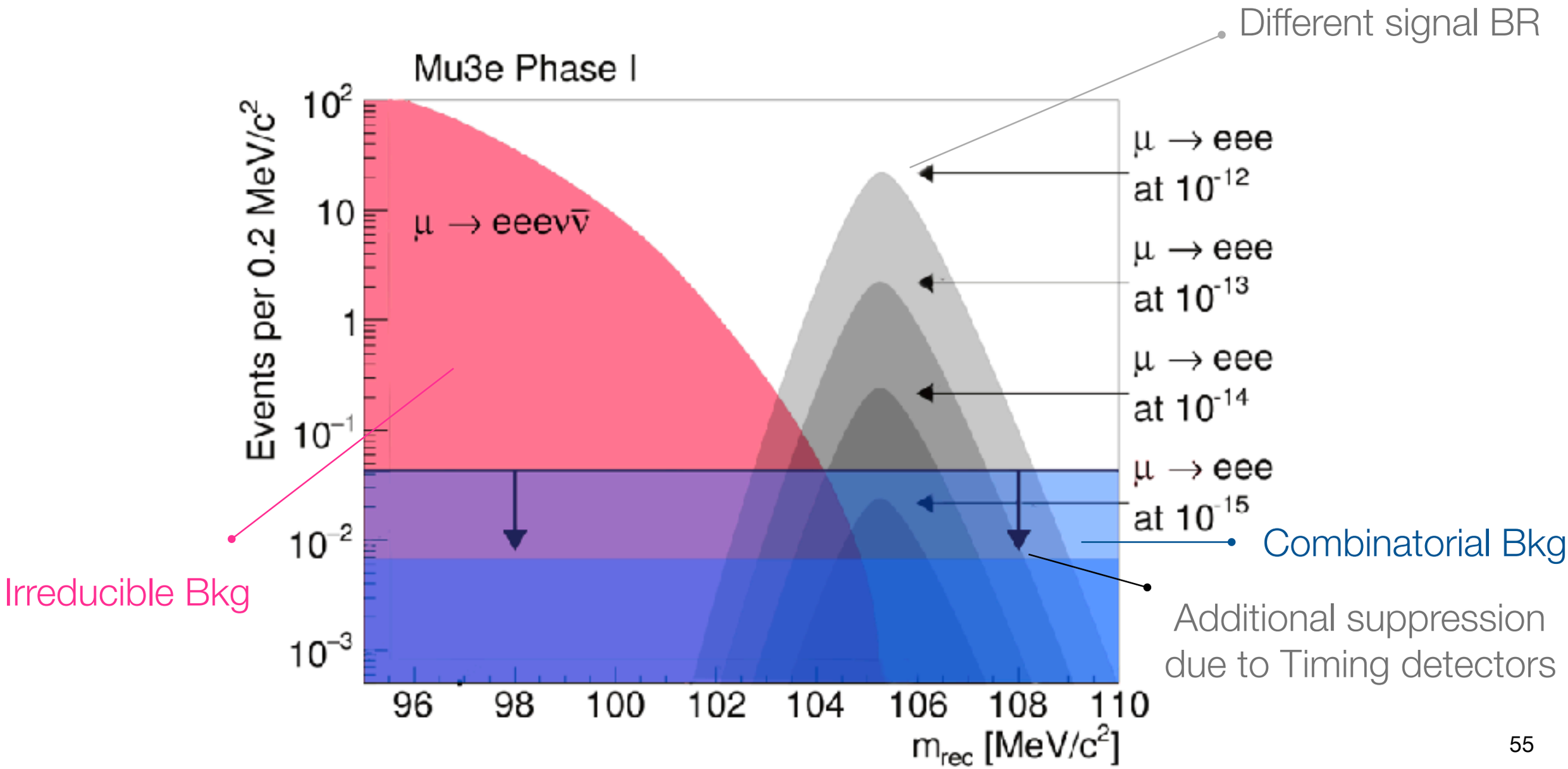
Pixels: O(50 ns)



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

The timing detectors: Impact

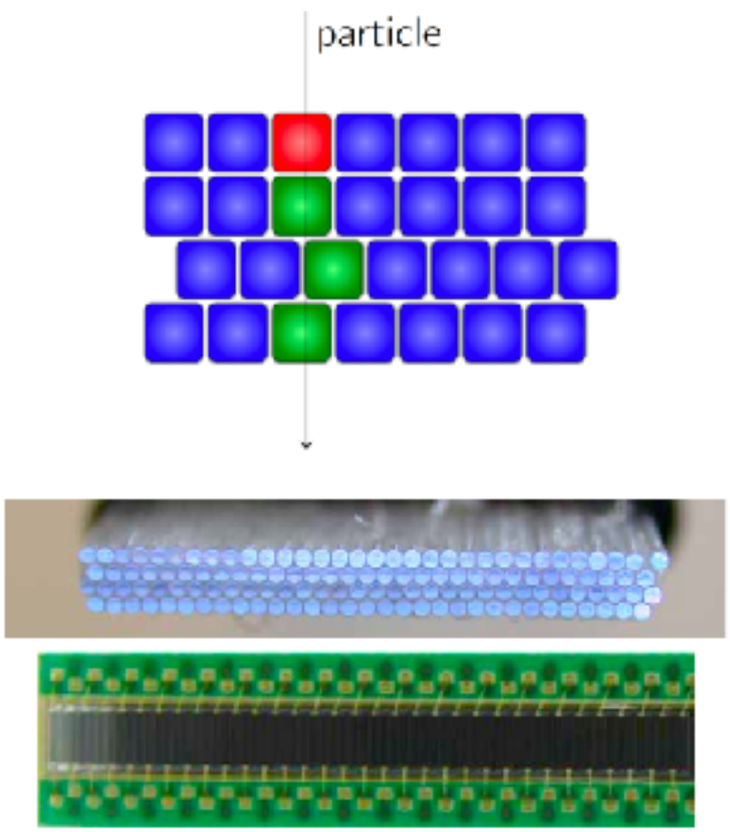
- Precise timing measurement: Critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
  - Scintillating tiles O(100 ps), full detection efficiency (>99%)



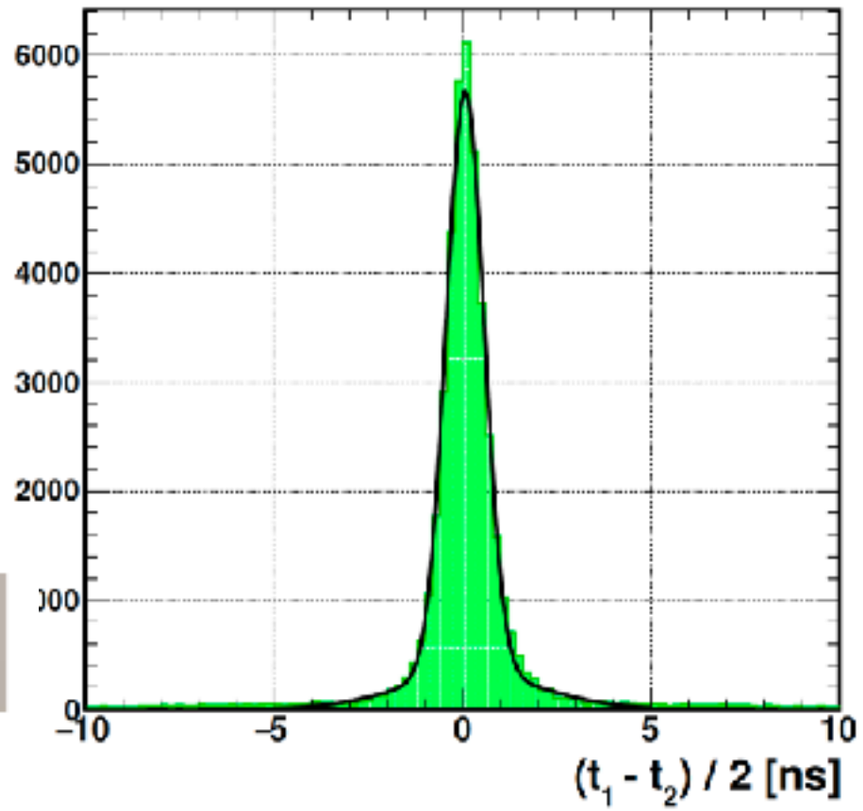
SciFi prototypes: Results

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

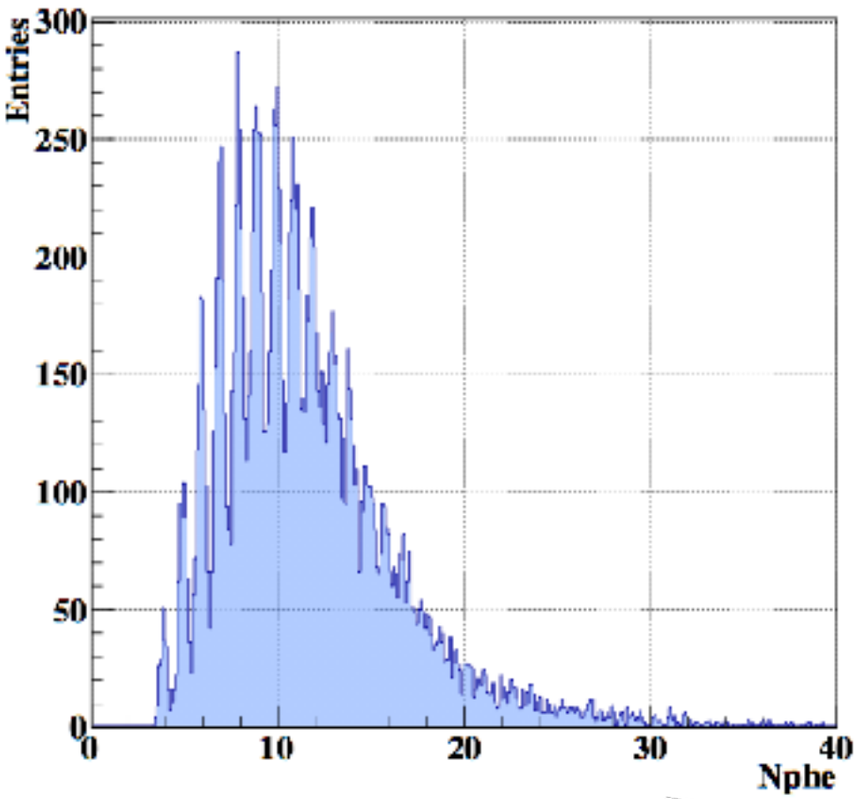
Trigger
offline selection:
hits in 3 layers



3 layer time resolution O(550) ps



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

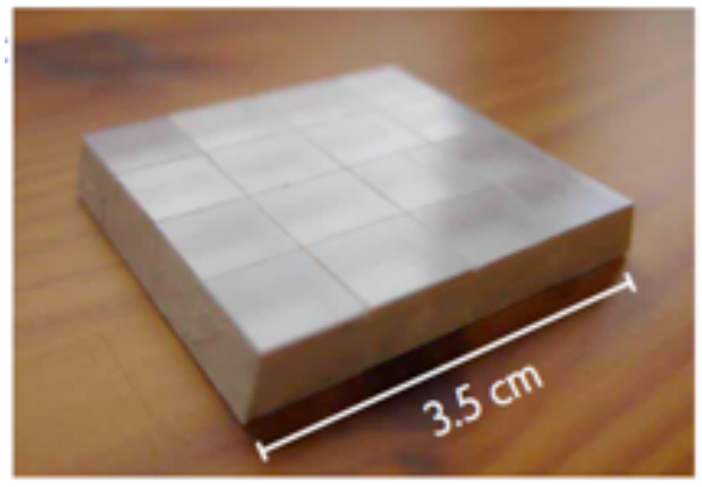


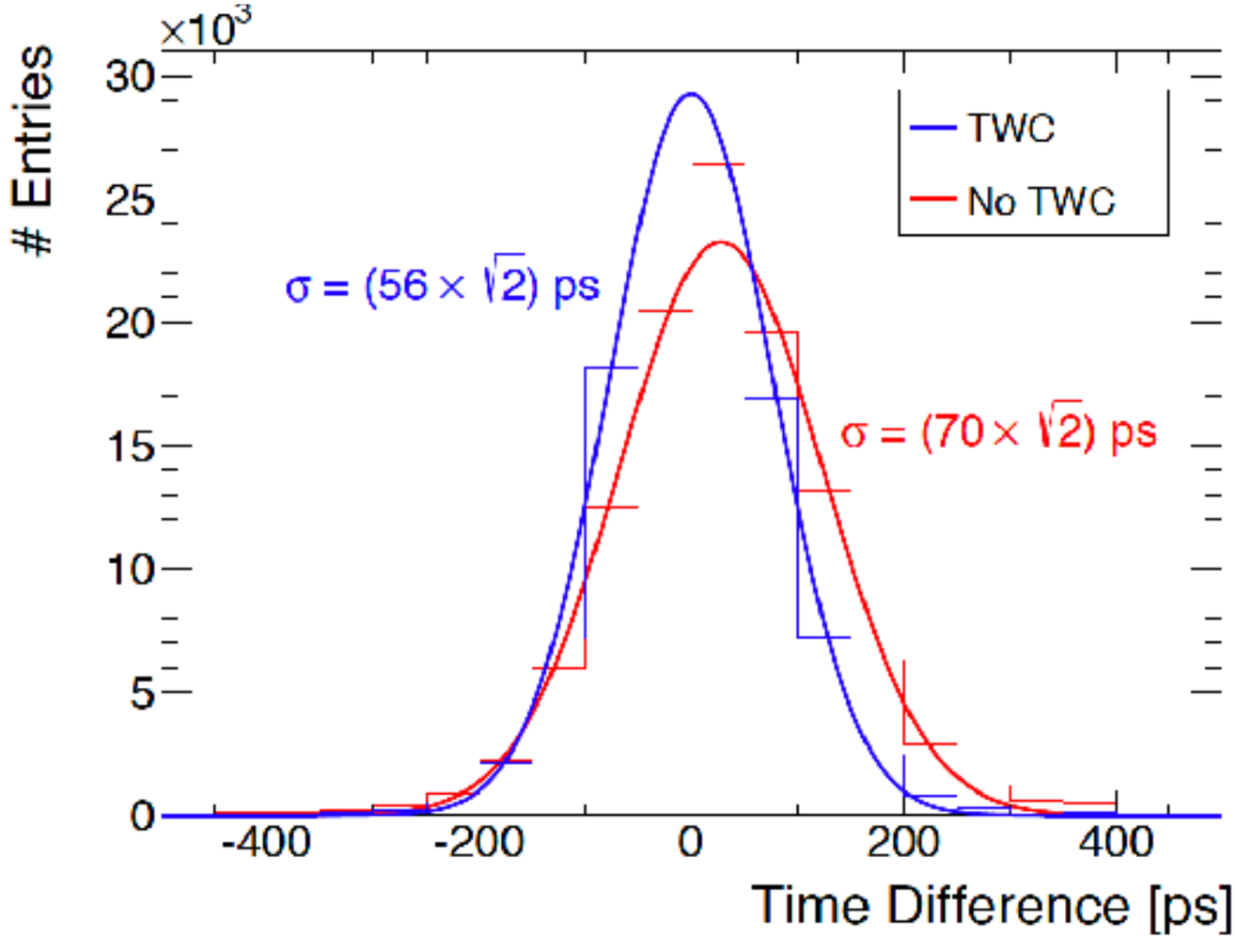
New

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

Tile Prototype: Results

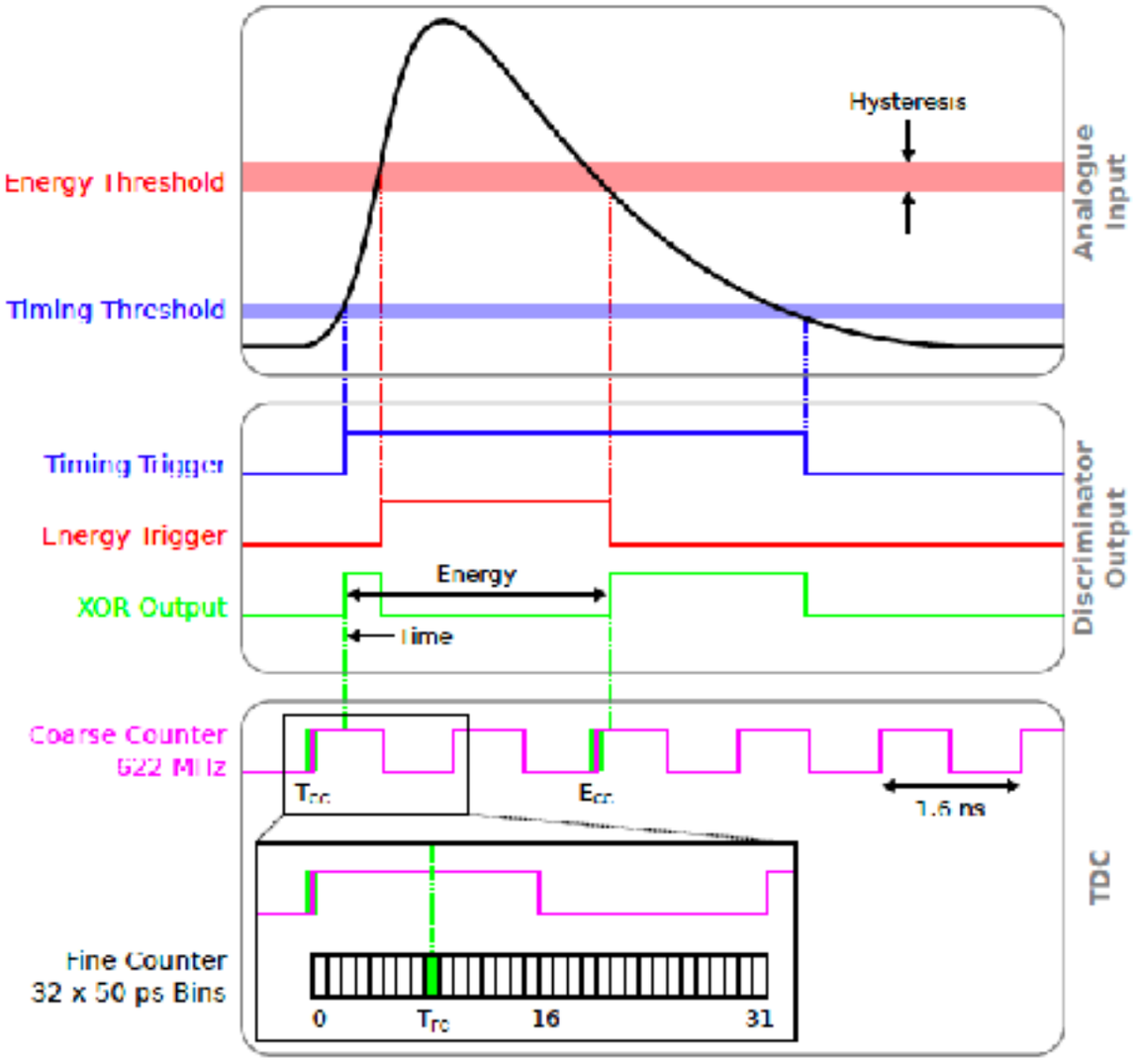
- Mu3e requirements fulfilled: Full detection efficiency (> 99 %) and timing resolution O (60) ps
- 4 x 4 channel BC408
- 7. 5 x 8. 5 x 5. 0 mm^3
- Hamamatsu S10362-33-050C (3 x 3 mm^2)
- readout with STiC2





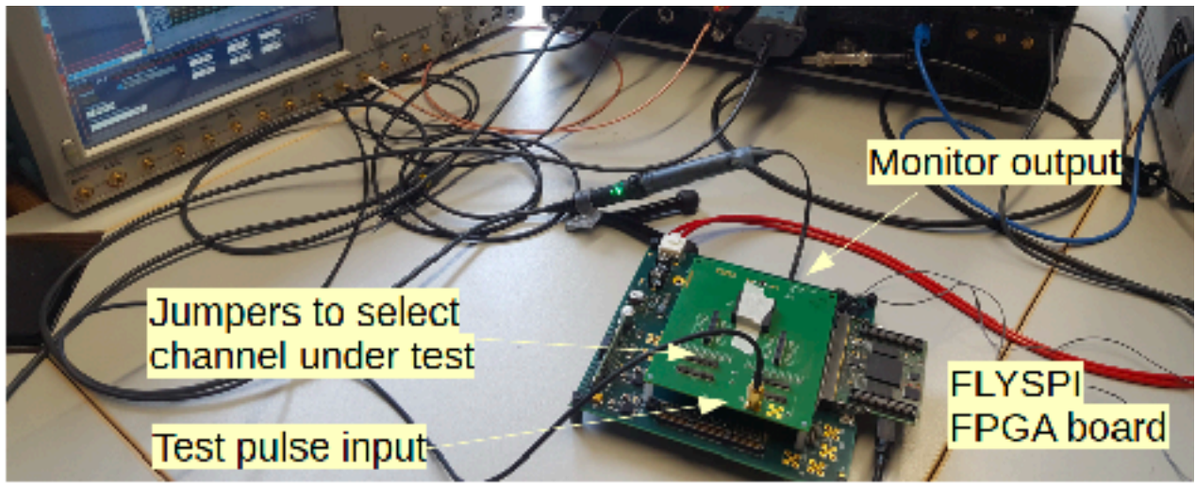
Timing detector electronics: MuTRiG

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



	STiC3.1 in use	**MuTRiG** received end Jan.
number of channels	64	32
LVDS speed [Mbit/s]	160	1250
event size [bit]	48	47
time mode	-	26
event rate / chip [MHz]	~2.6	~20
time mode	-	~38
event rate / ch [kHz]	~40	~650
time mode	-	~1200
power per channel [mW]	35	35
size [mm x mm]	5x5	5x5
number of PLLs	2	1

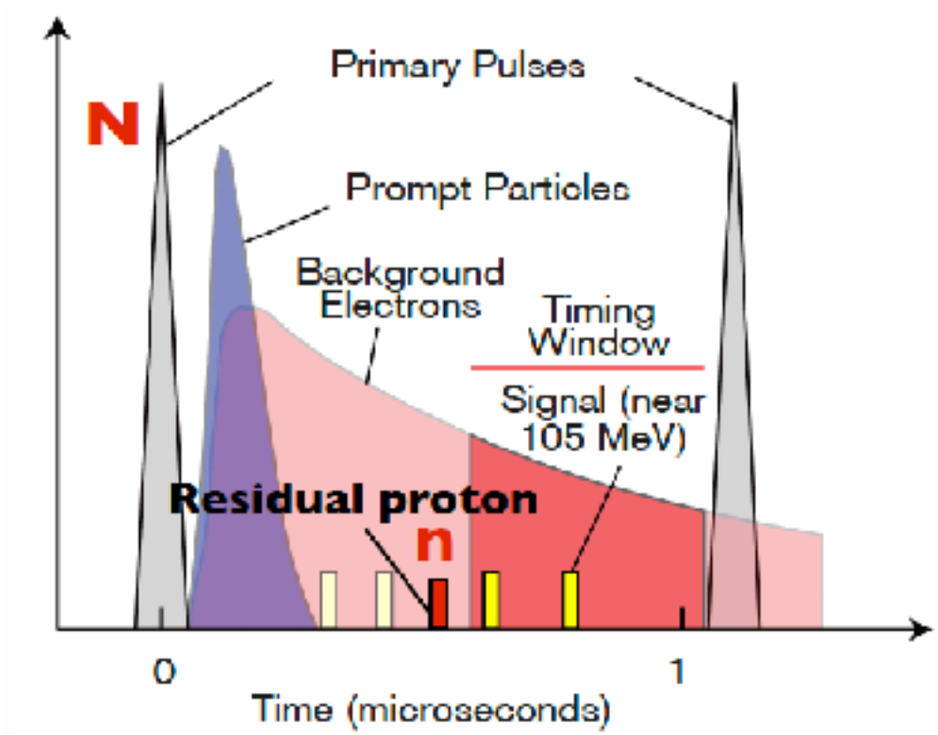
New

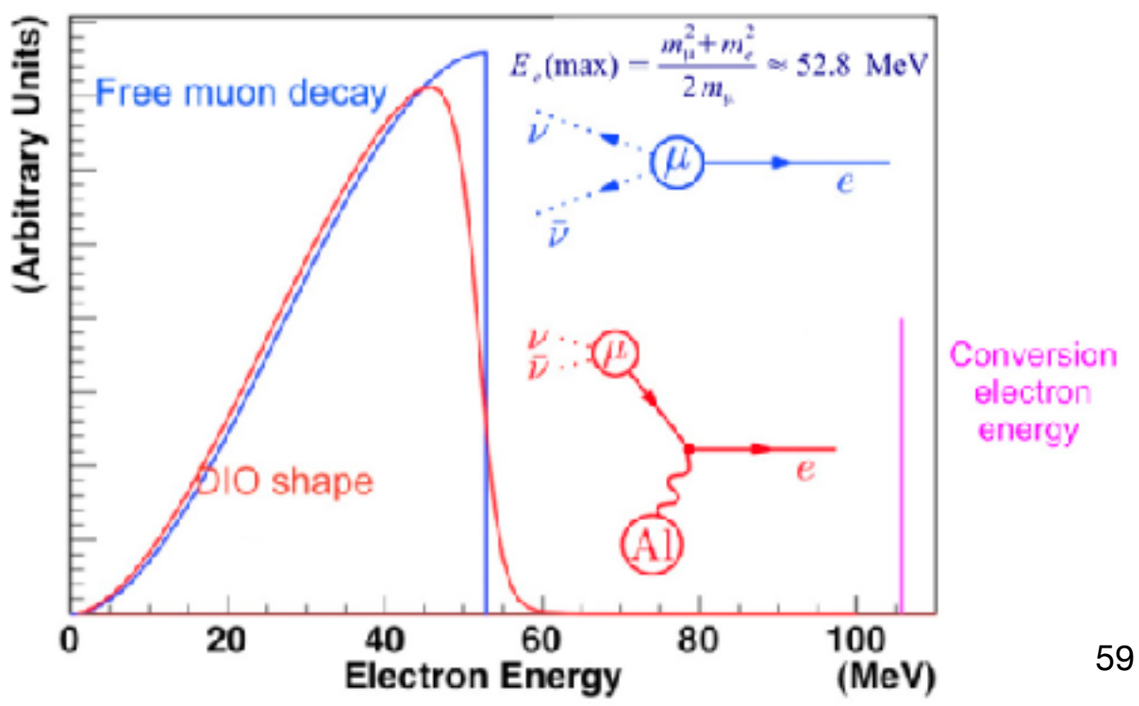


μ⁻ N → e⁻ N experiments

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

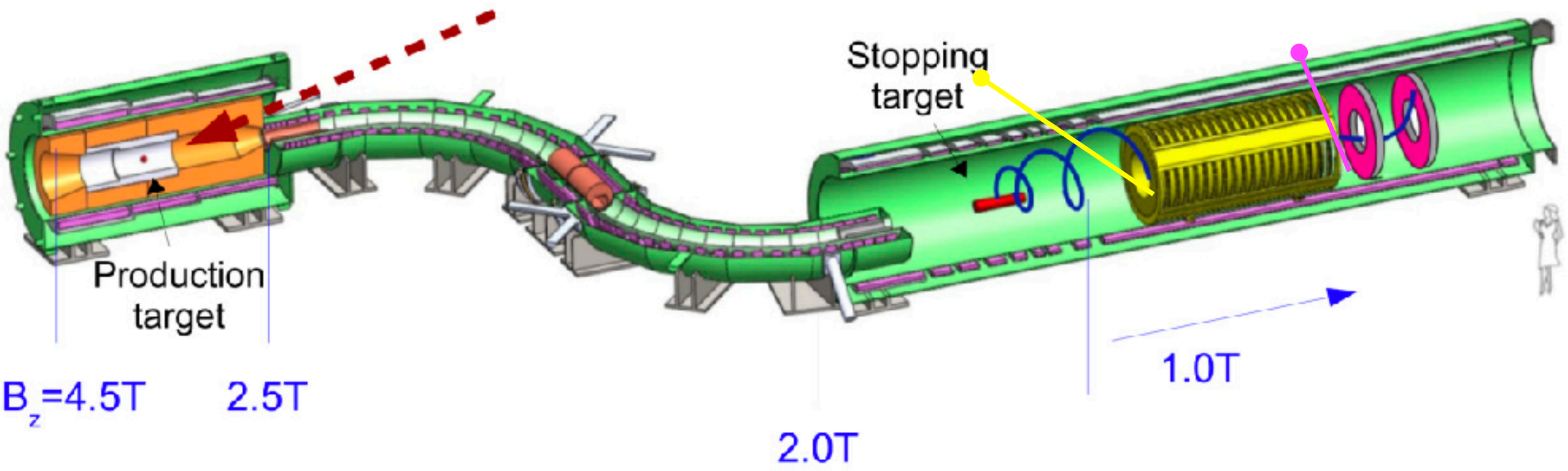
- Signal of mu-e conversion is single mono-energetic electron
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Stop a lot of muons! O(10^{18})
- Use timing to reject beam backgrounds (extinction factor 10^{-10})
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime
- Good energy resolution and Particle ID to defeat muon decay in orbit
- Veto Counters to tag Cosmic Rays





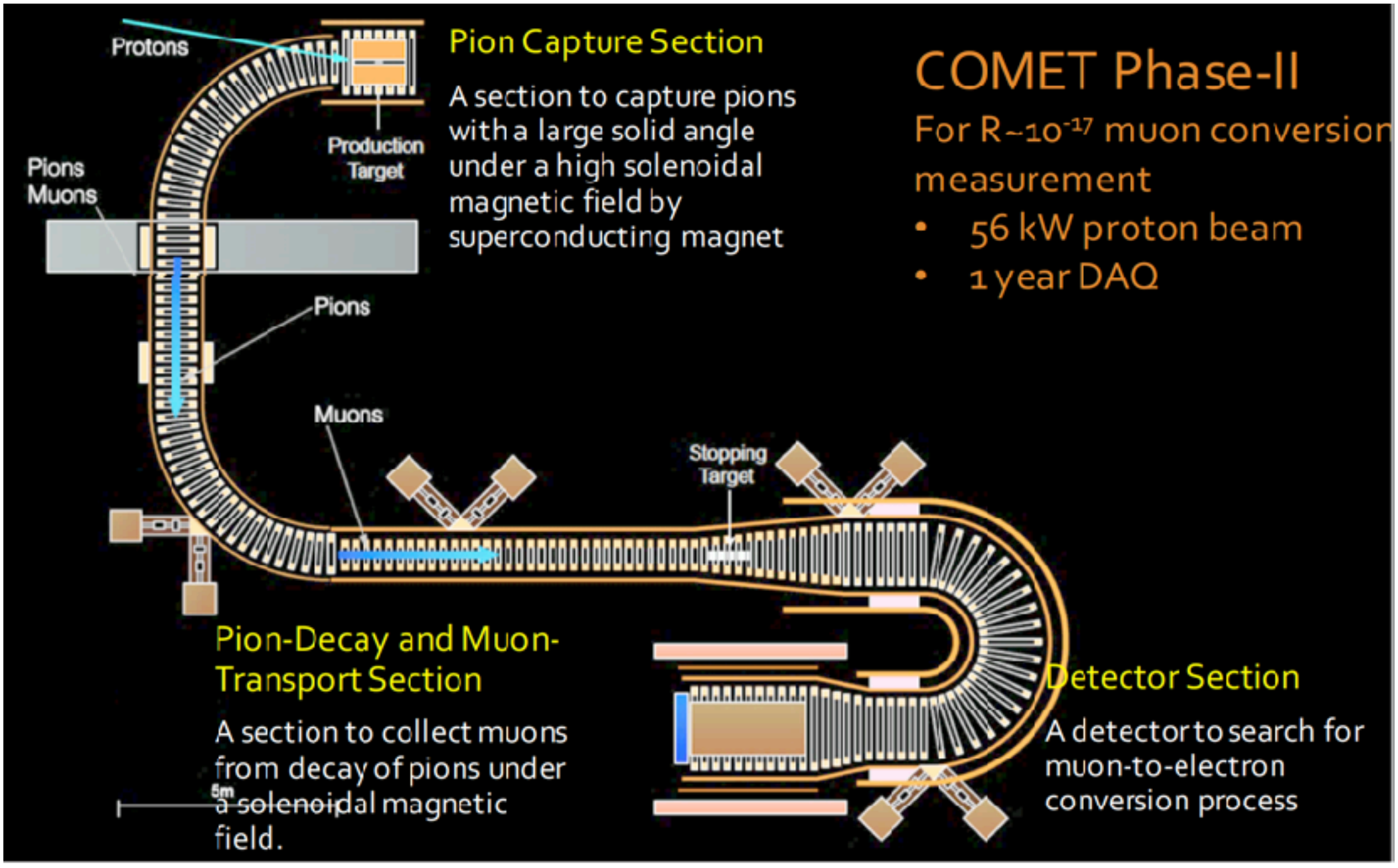
The Mu2e experiment

- Three superconducting solenoids: Production, Transport and Detector solenoids
- Muons stop in thin aluminum foils
- High precision straw tracker for momentum measurement
- Electromagnetic calorimeter for PID
- Scintillators for the Veto



The COMET experiment

- Stage phase approach: ultimate sensitivity with phase II [Data taking in: 2021/2022]



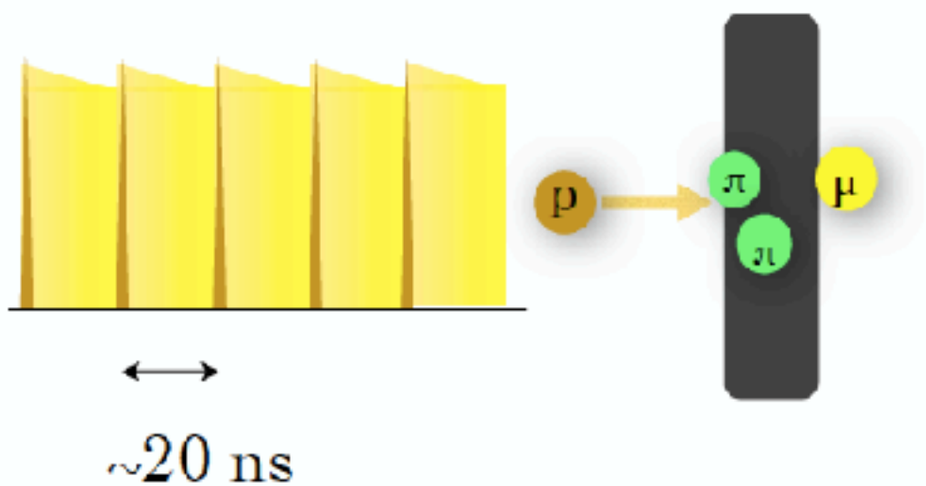
Beam features vs experiment requirements

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

$I_{beam} \sim 10^8$ μ/s

DC or Pulsed?

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



Present at PSI

Beam features vs experiment requirements

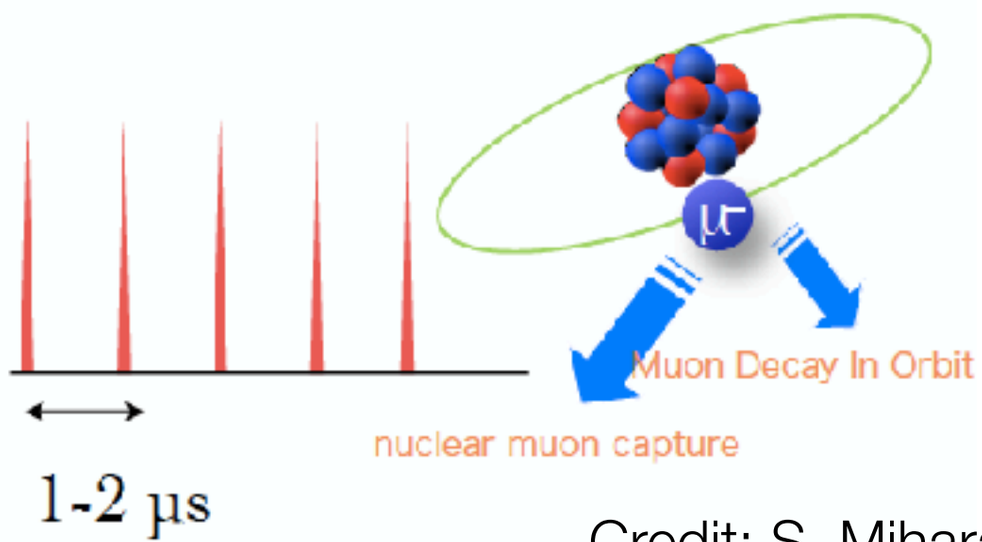
- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

DC or Pulsed?

In construction and available soon: at JPARC and FERMILAB

$I_{beam} \sim 10^{11}$ μ/s

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



Credit: S. Mihara

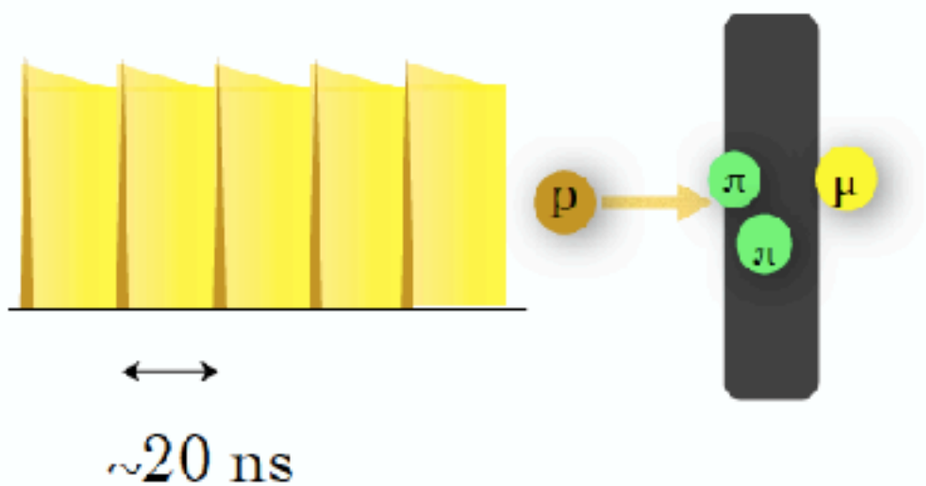
Beam features vs experiment requirements

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

$I_{beam} \sim 10^8 - 10^{10}$ μ/s

DC or Pulsed?

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



Future at PSI

Credit: S. Mihara