Searching for charged lepton flavour violation in muon decays

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Flavour & Dark Matter
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JG|U

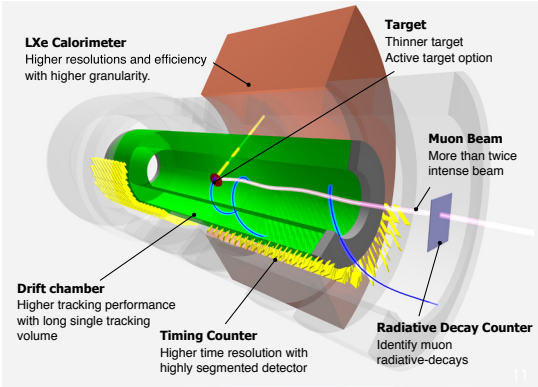
Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter

PRISMA

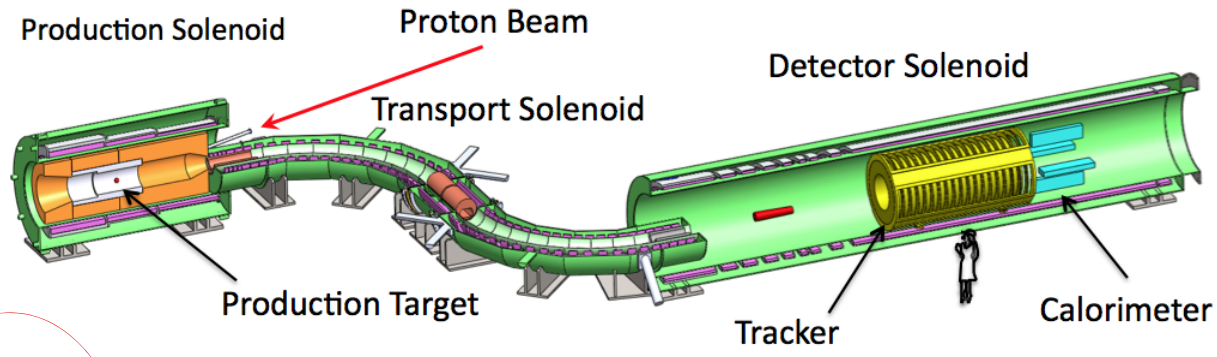
Overview

Charged lepton flavour violation experiments:

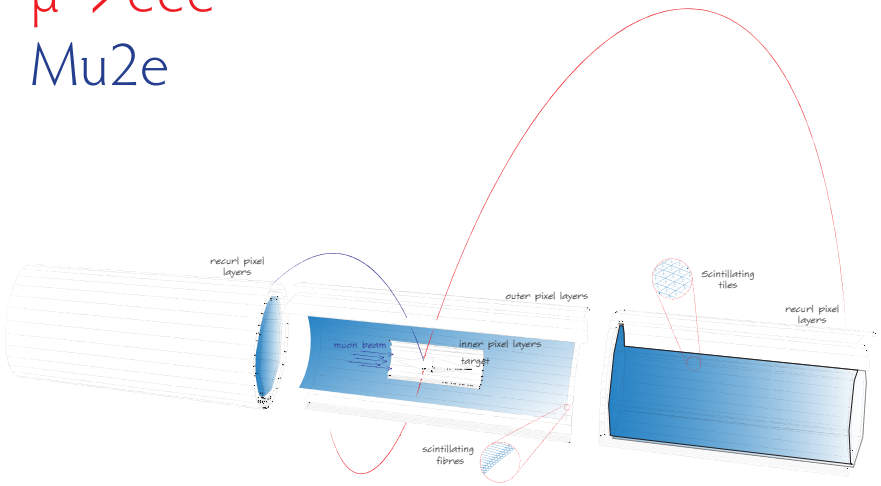
- μ → e γ
  MEG and MEG II



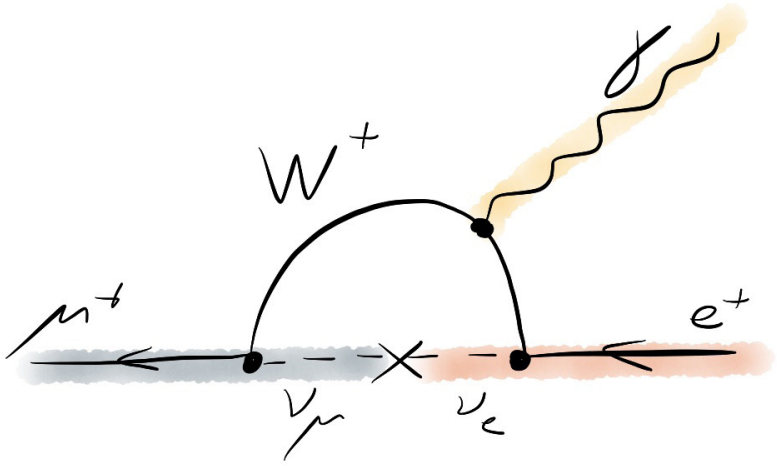
- μ to e conversion in Nuclei
  DeeMee, Comet, Mu2e



- μ → eee
  Mu2e



Lepton flavour violation experiments



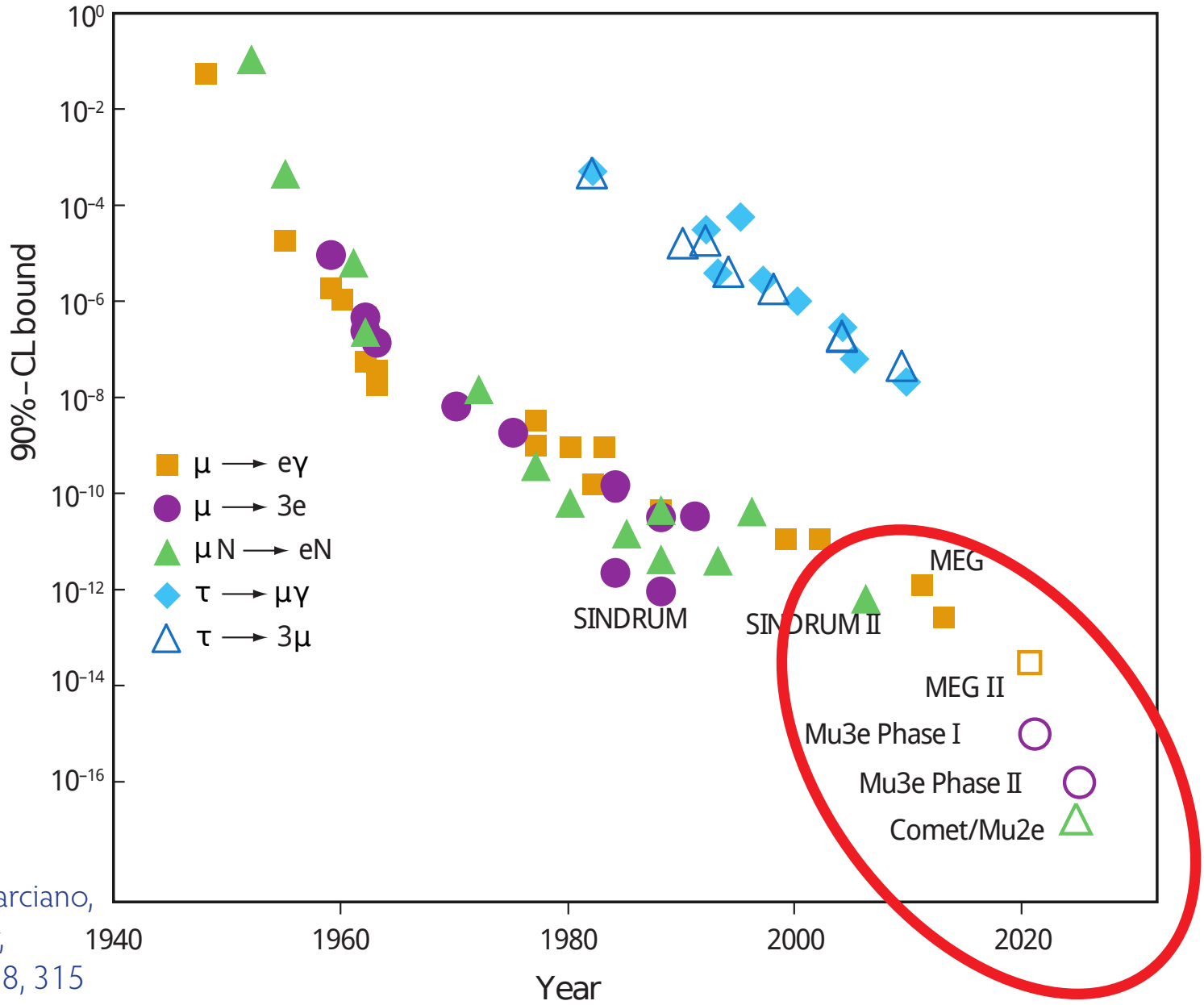
Standard Model branching fractions of

$10^{-50\text{ish}}$

Only limited by number of muons and background suppression:

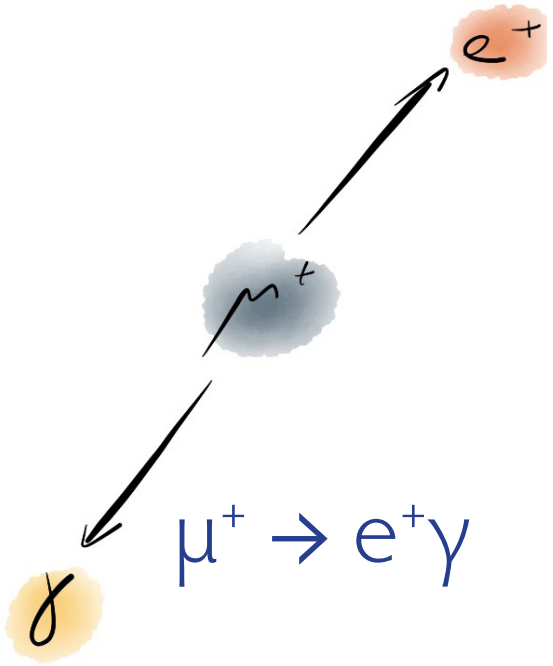
Experimental/technical challenge

History of cLFV experiments

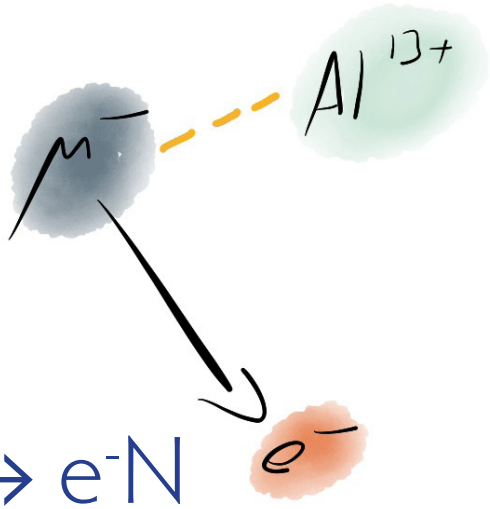


(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

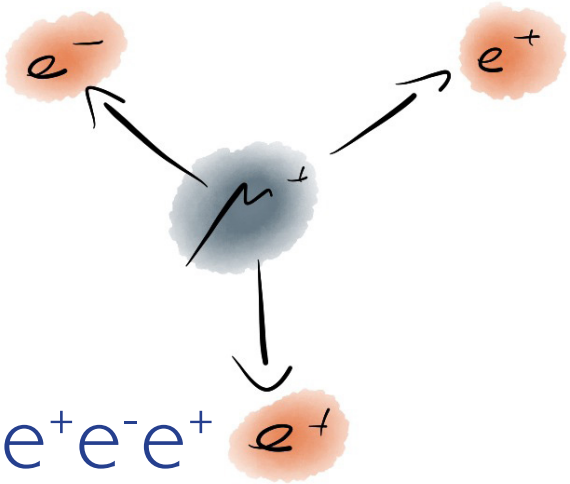
LFV Muon Decays



$\mu^+ \to e^+\gamma$

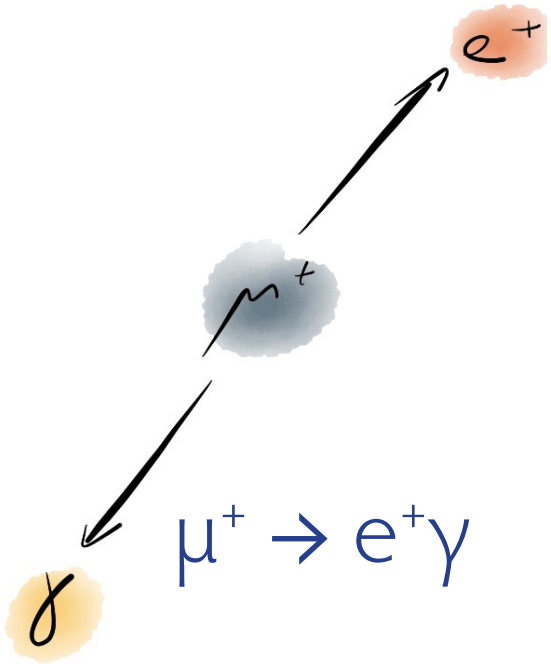


$\mu^- N \to e^- N$

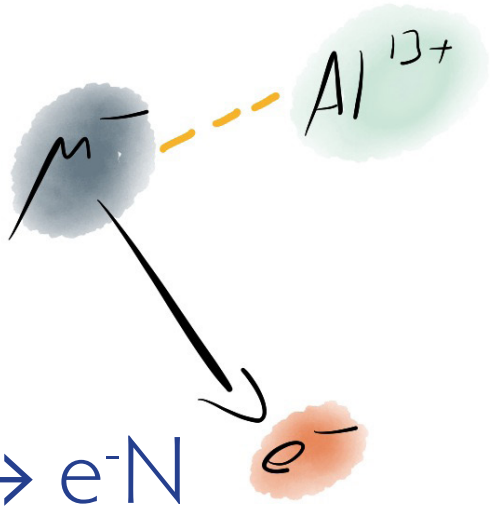


$\mu^+ \to e^+ e^- e^+$

LFV Muon Decays: Experimental Situation



$\mu^+ \to e^+\gamma$



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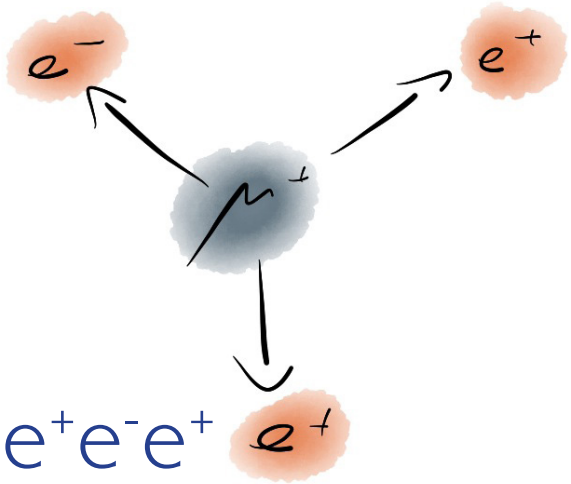


$\mu^+ \to e^+e^-e^+$

MEG (PSI)

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

(2016)

SINDRUM II (PSI)

$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$

(2006)

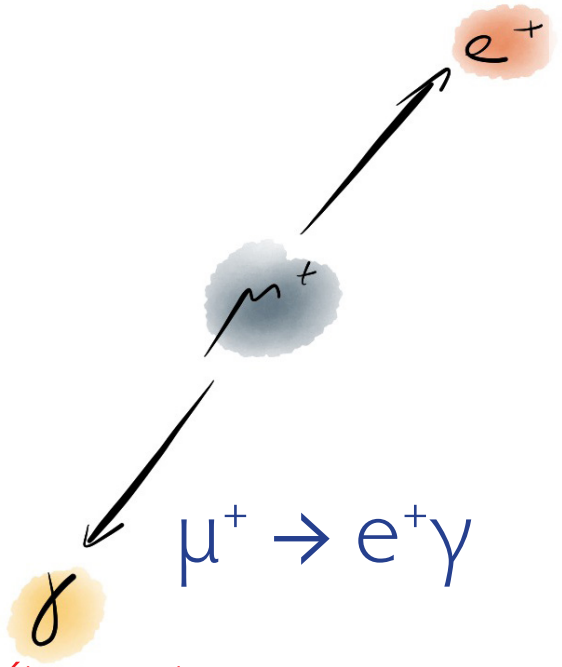
relative to nuclear capture

SINDRUM (PSI)

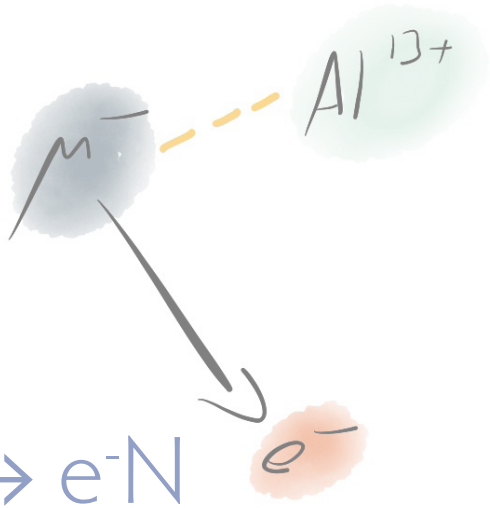
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$

(1988)

LFV Muon Decays: Experimental signatures



$\mu^+ \to e^+\gamma$



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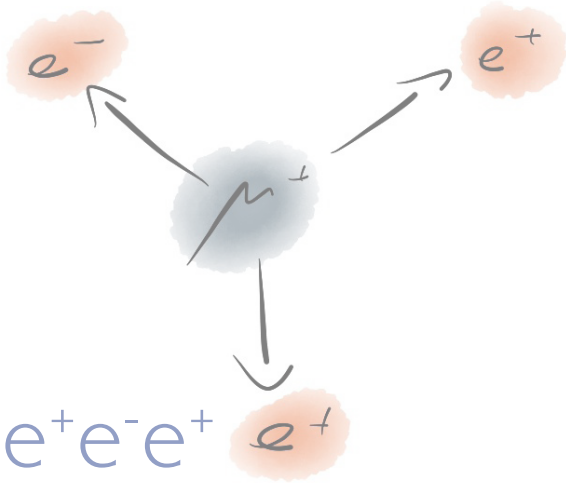
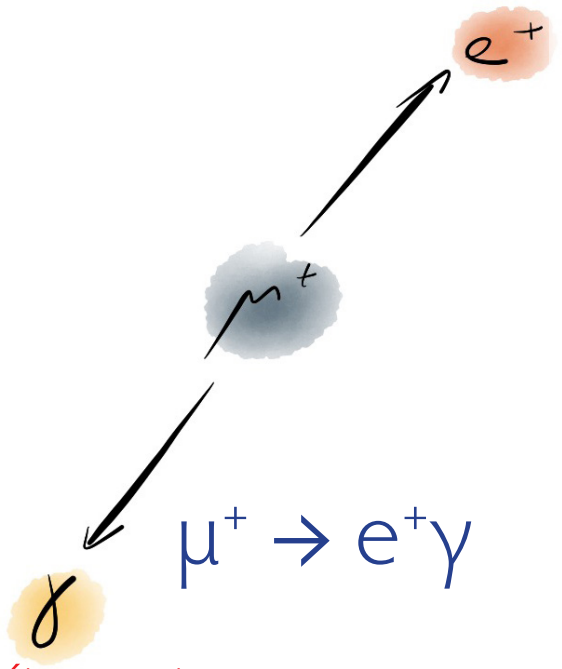


$\mu^+ \to e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

LFV Muon Decays: Experimental signatures



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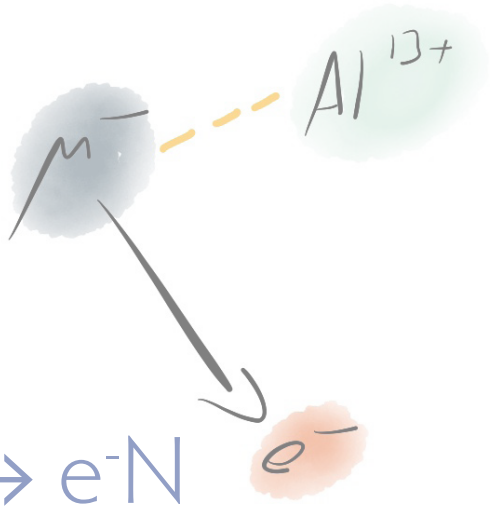

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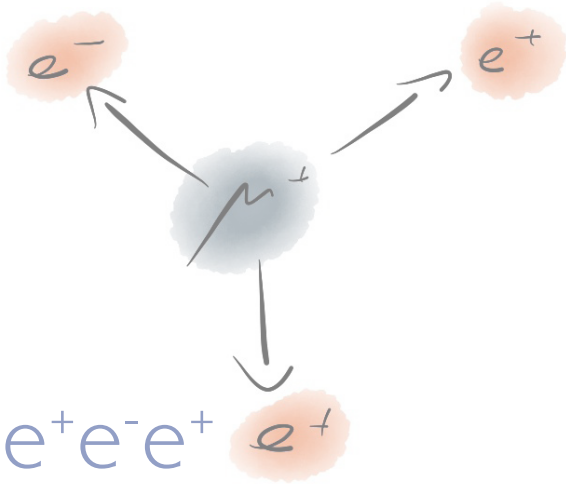


$\mu^+ \to e^+e^-e^+$

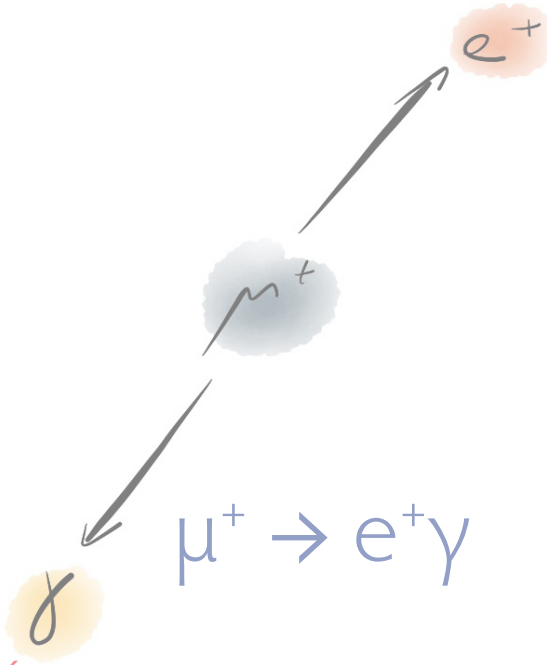
Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

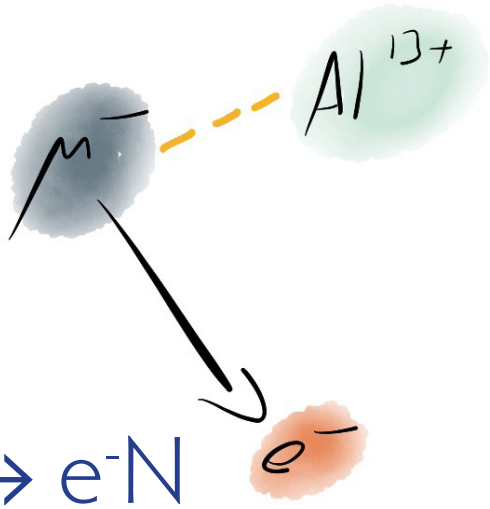
Background

- Accidental background
- Radiative decay

LFV Muon Decays: Experimental signatures



$\mu^+ \rightarrow e^+\gamma$



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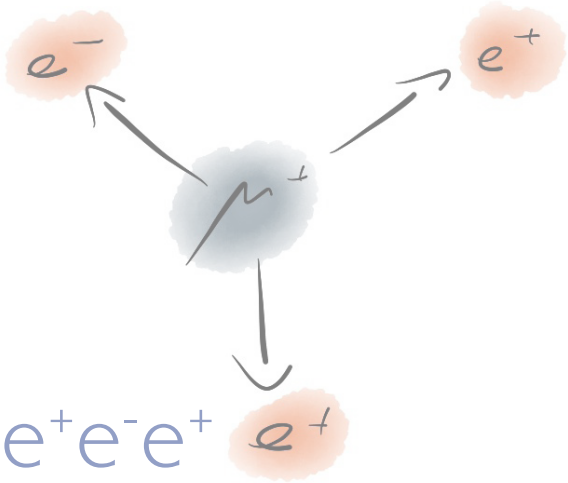


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

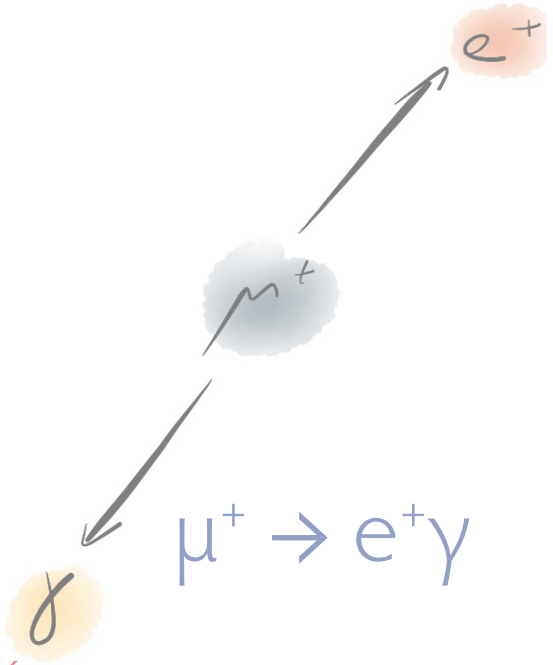
Background

- Accidental background
- Radiative decay

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

LFV Muon Decays: Experimental signatures



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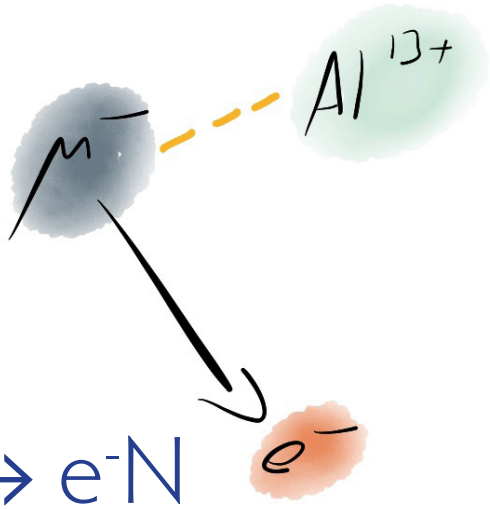

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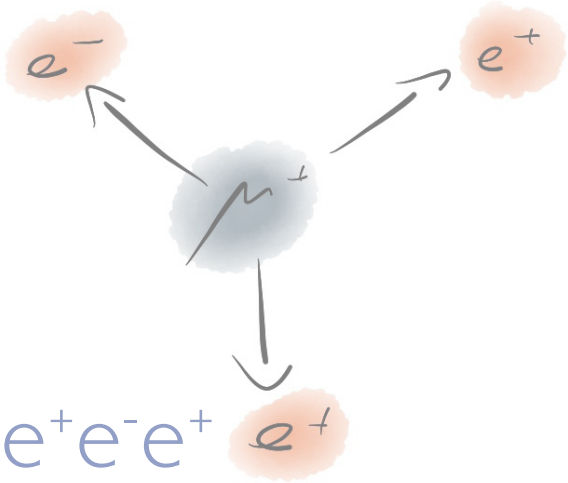


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background
- Radiative decay

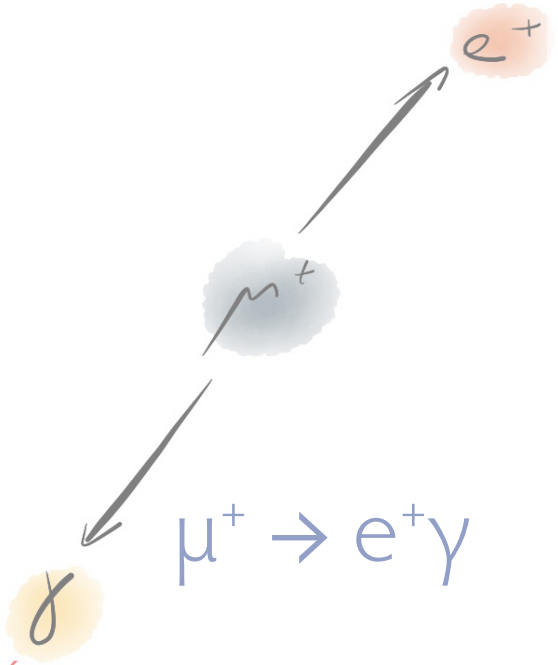
Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

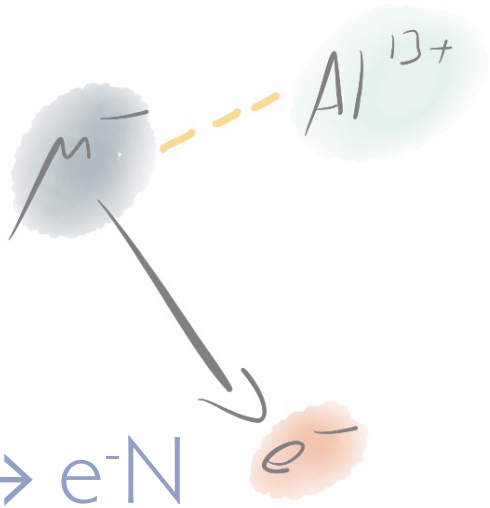
Background

- Decay in orbit
- Antiprotons, pions, cosmics

LFV Muon Decays: Experimental signatures



$\mu^+ \to e^+\gamma$



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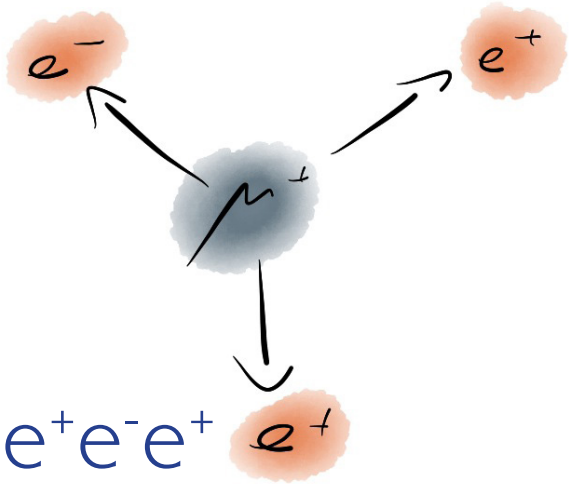


$\mu^+ \to e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background
- Radiative decay

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

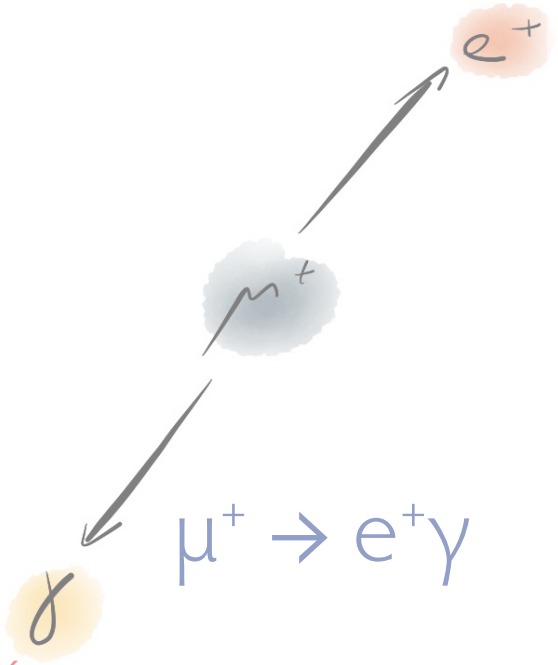
Background

- Decay in orbit
- Antiprotons, pions, cosmics

Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

LFV Muon Decays: Experimental signatures



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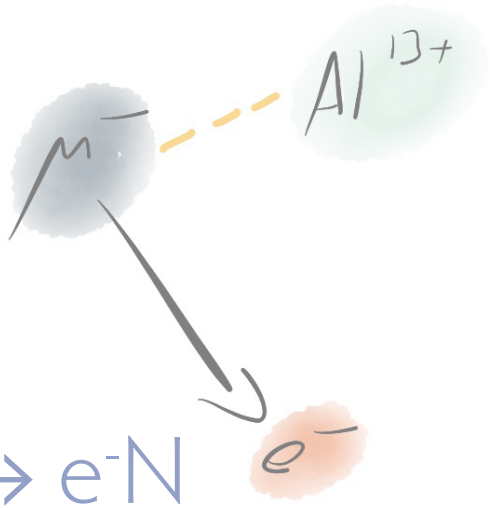
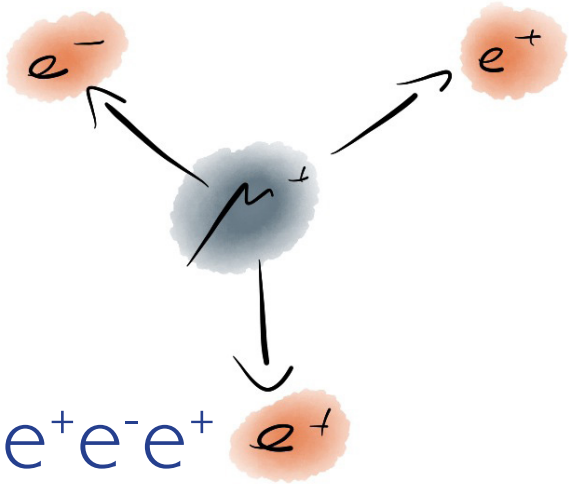


$\mu^-N \rightarrow e^-N$



$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background
- Radiative decay

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions, cosmics

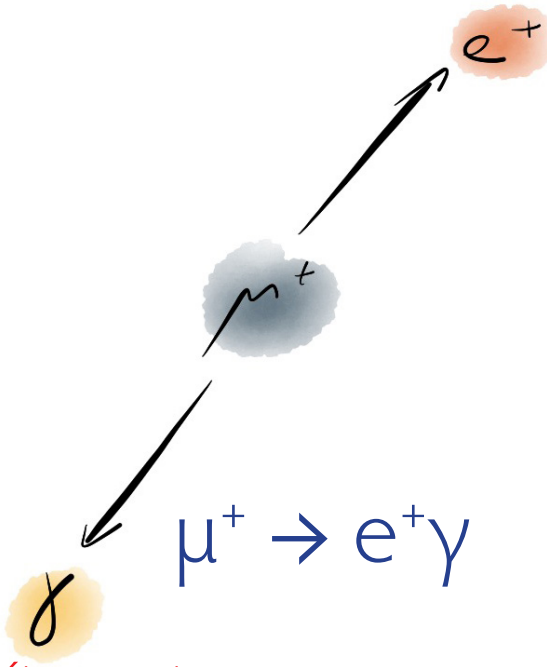
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

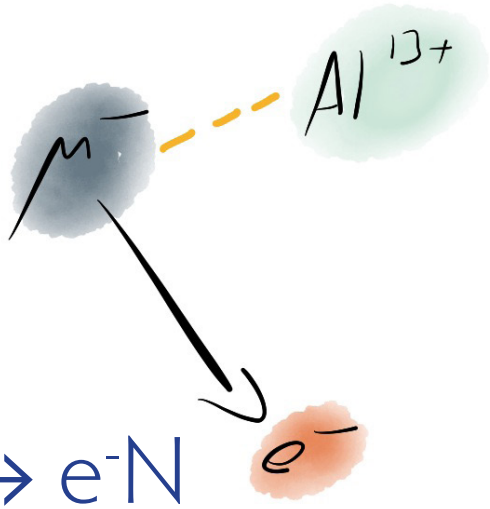
Background

- Internal conversion decay
- Accidental background

LFV Muon Decays: Experimental signatures



$\mu^+ \rightarrow e^+\gamma$



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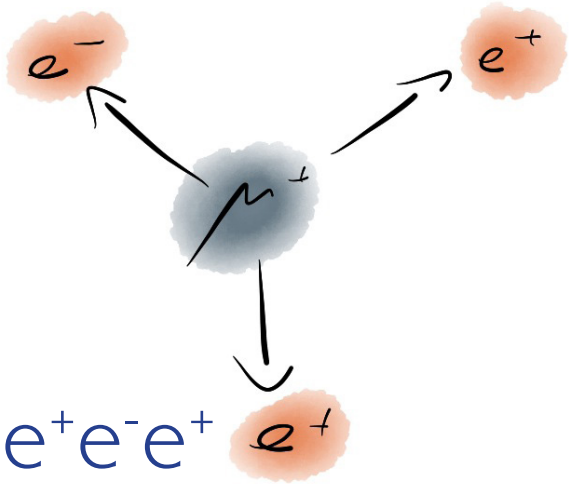


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background
- Radiative decay

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions, cosmics

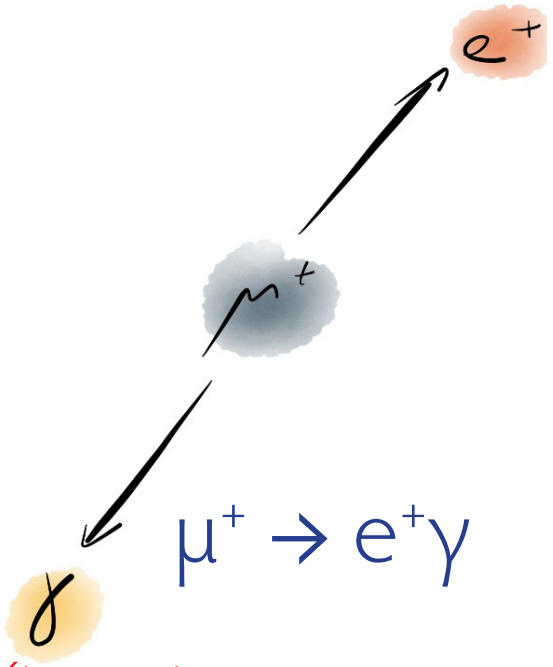
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

Background

- Internal conversion decay
- Accidental background

LFV Muon Decays: Experimental signatures



$\mu^+ \rightarrow e^+\gamma$

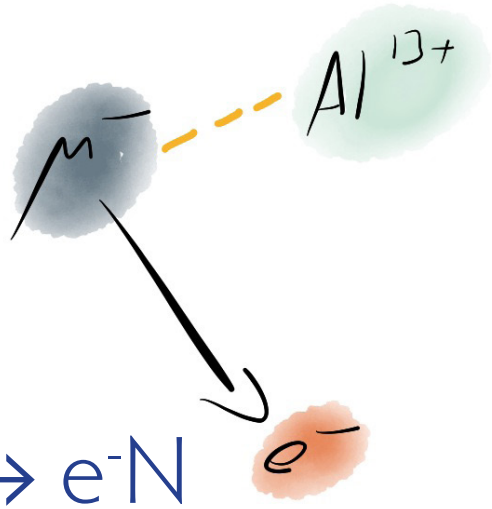
Kinematics

- 2-body decay
- Monoenerge
- Back-to-b

Backgro

- A al background

Continuous Beam



$\mu^-N \rightarrow e^-N$

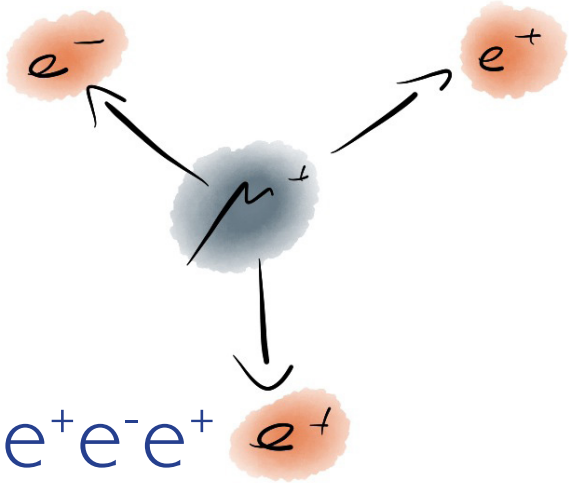
Kinematics

- Quasi 2-body d
- Monoenerge
- Single p etected

Backgro

- D orbit
- A protons, pions

Pulsed Beam



$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

Backgro

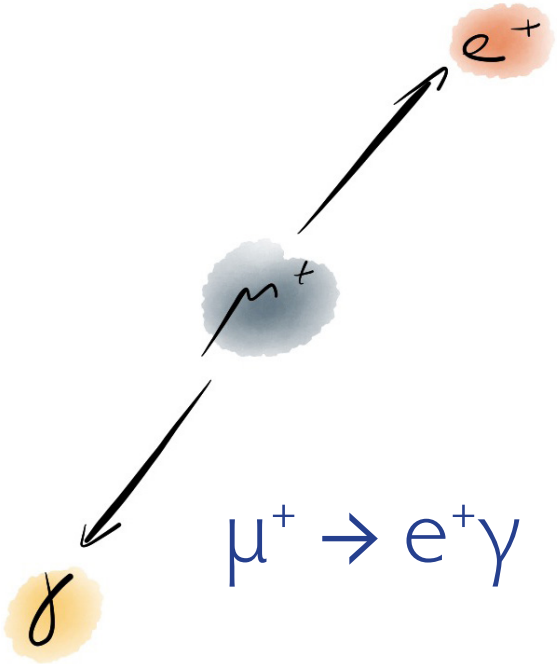
- R decay
- Ac dental background

Continuous Beam

Searching for $\mu \to e\gamma$ with

MEG and MEG II

MEG Signal and background



$\mu^+ \rightarrow e^+\gamma$

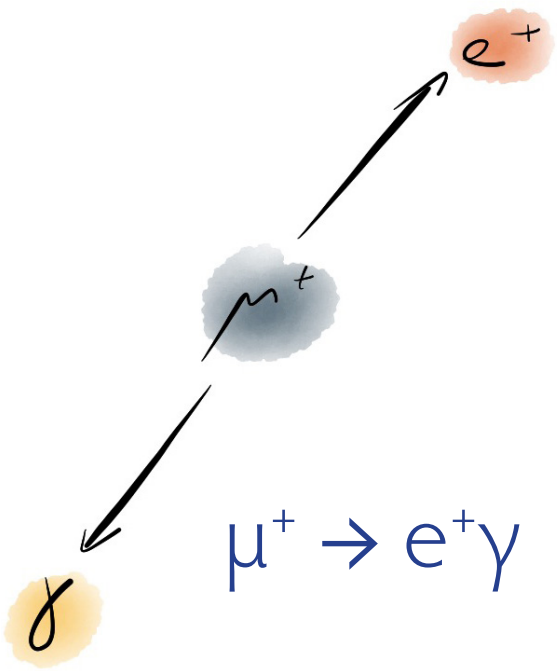
Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

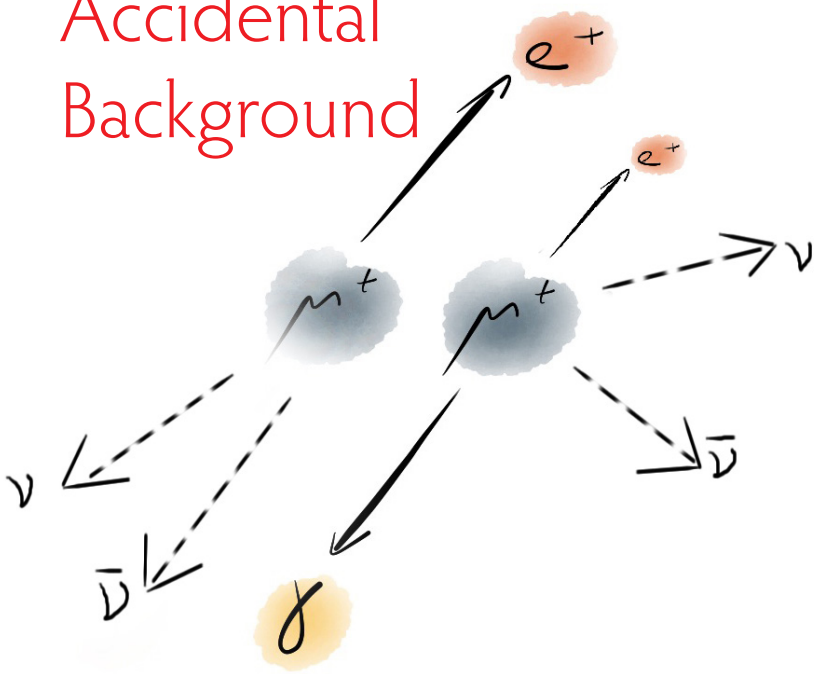
Measure

- Photon energy
- Positron momentum
- Opening angle (in two projections)
- Time difference

MEG Signal and background



Accidental Background

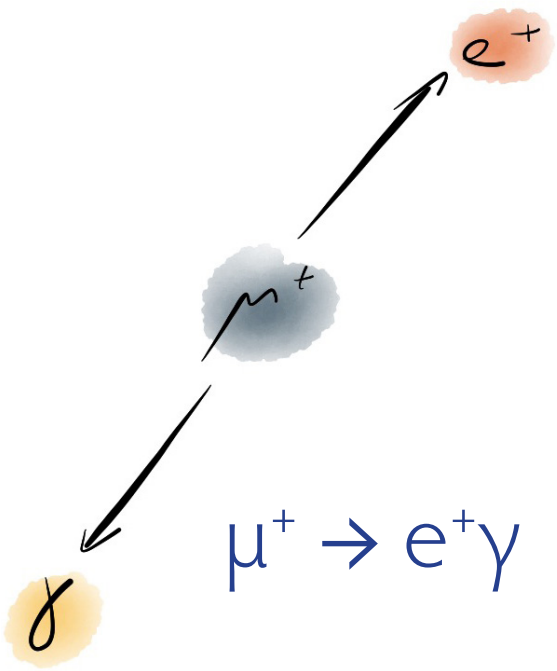


Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

- Not exactly in time
- Not exactly same vertex
- e^+, γ energies somewhat off
- Not exactly back-to-back

MEG Signal and background



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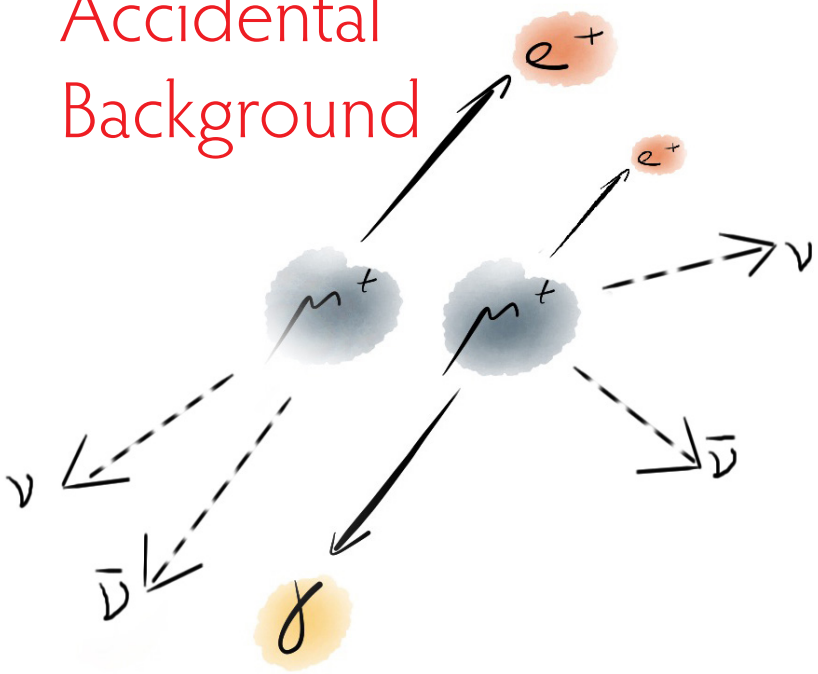
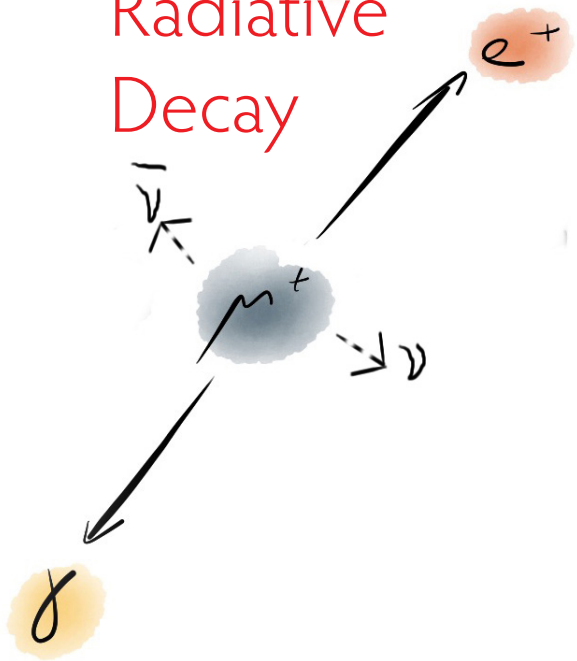


Radiative Decay



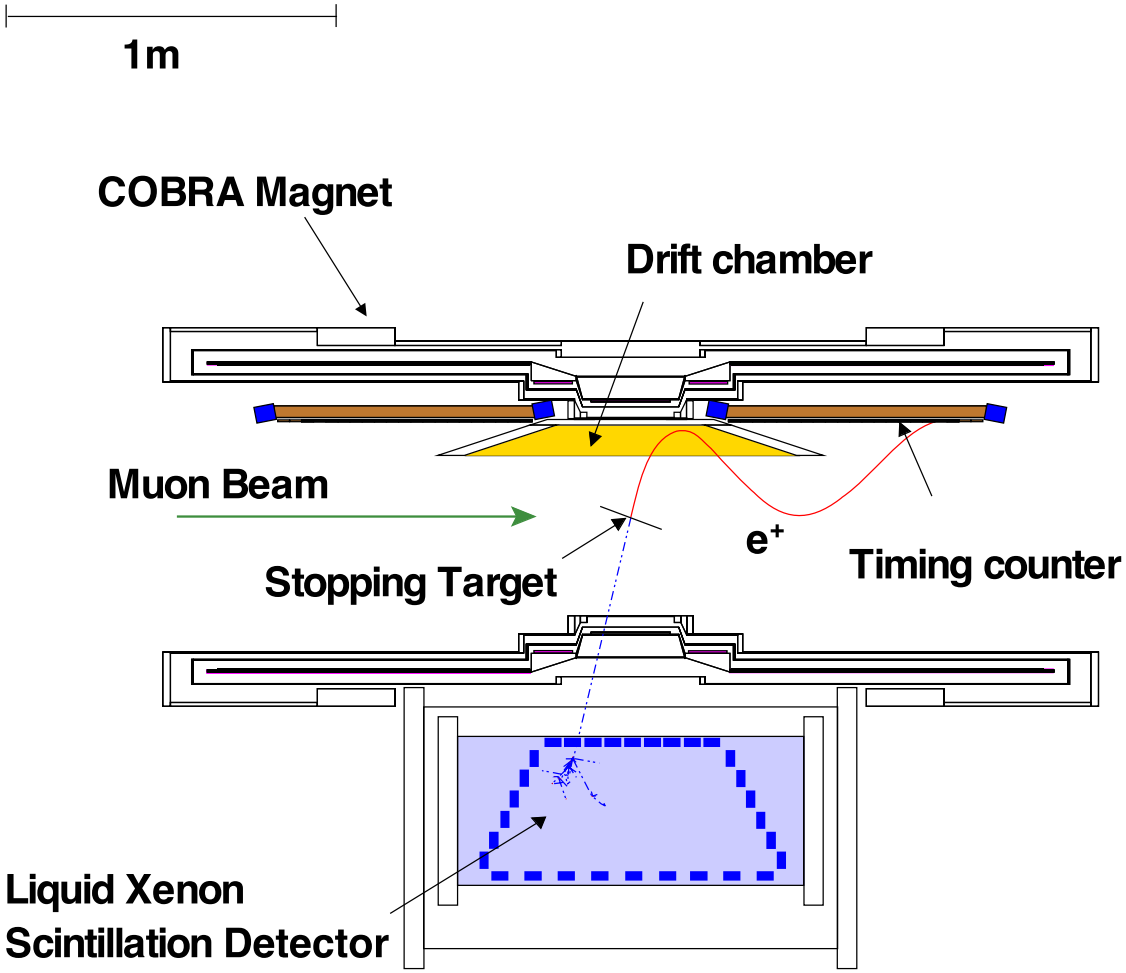
Kinematics

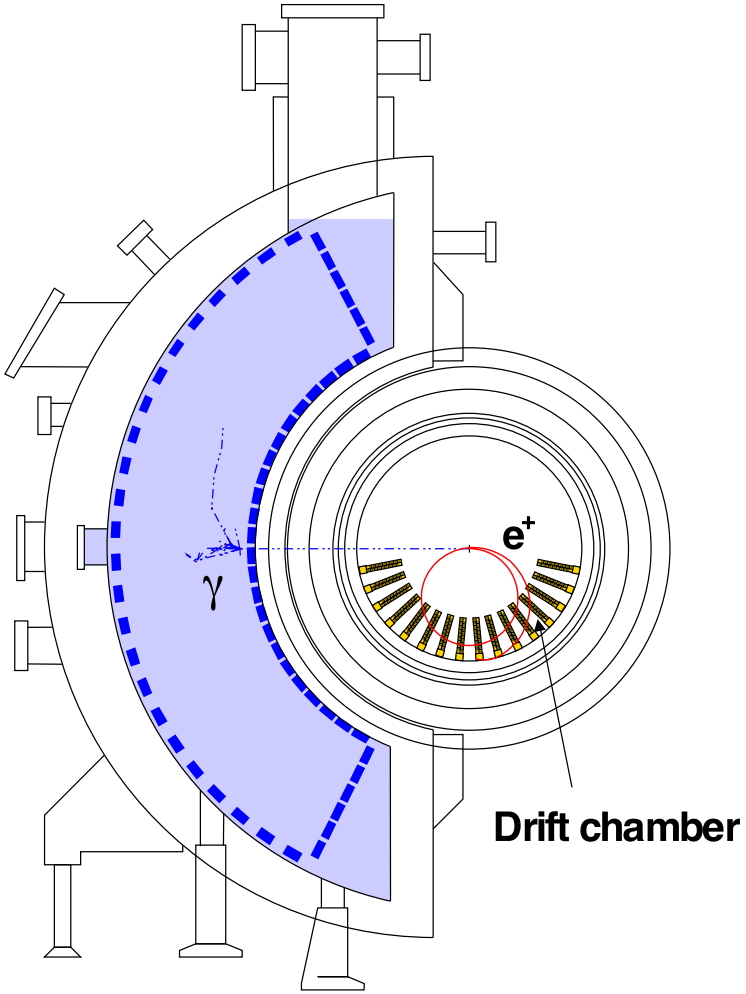
- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

- Not exactly in time
- Not exactly same vertex
- e^+, γ energies somewhat off
- Not exactly back-to-back

- e^+, γ energies somewhat off
- Not exactly back-to-back

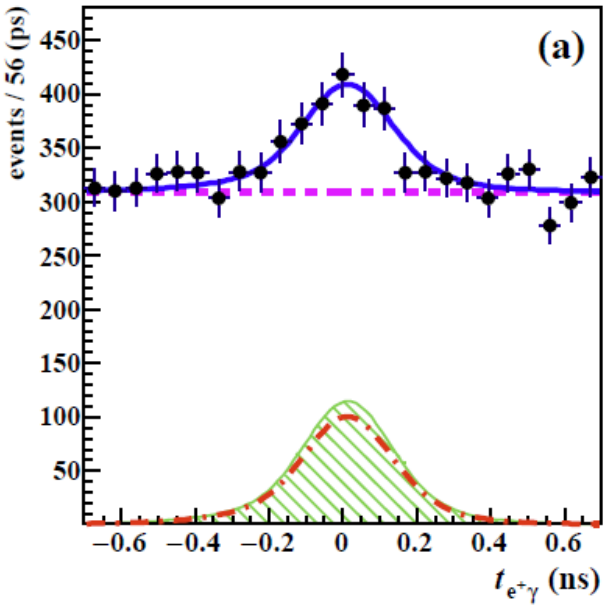
The MEG Detector

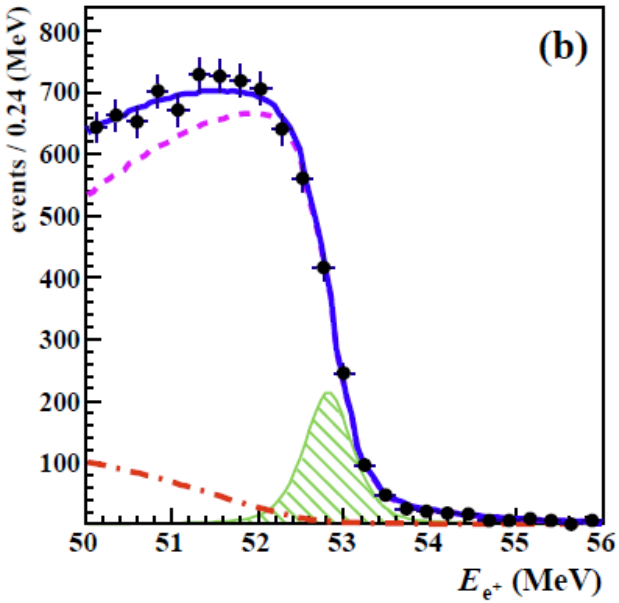


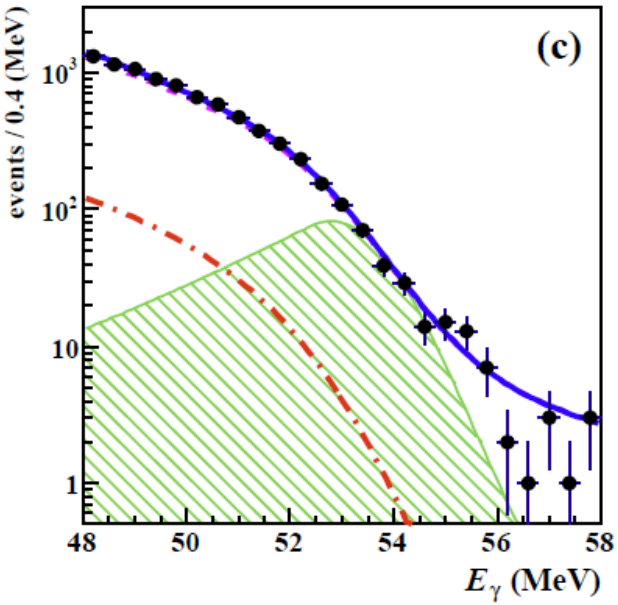


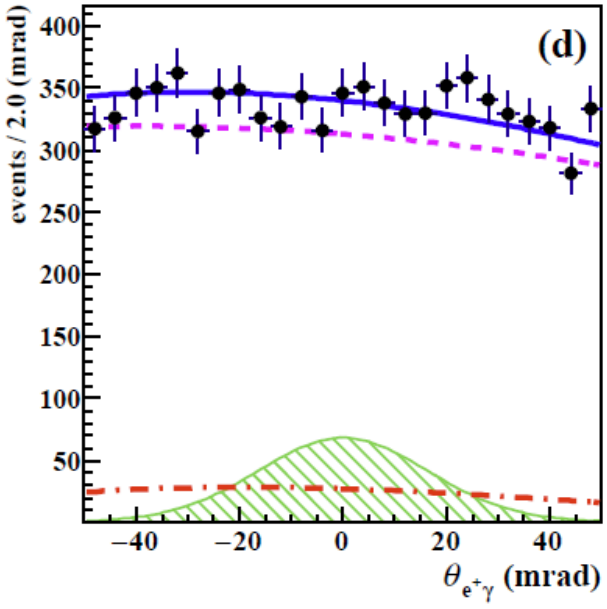
J. Adam et al. EPJ C 73, 2365 (2013)

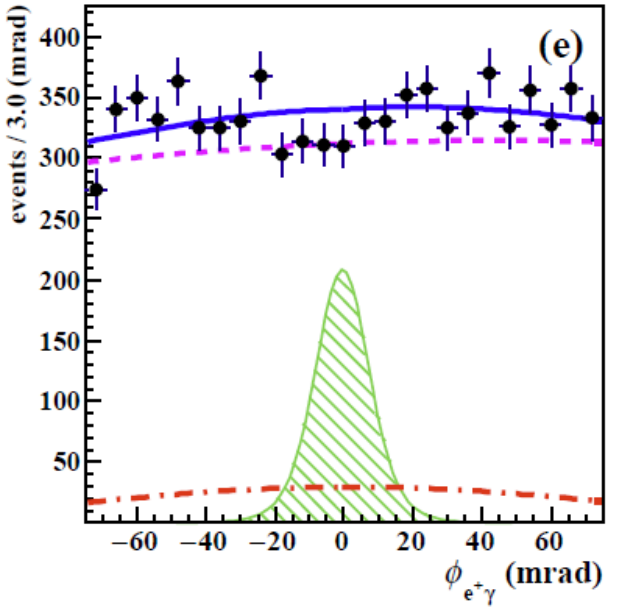
MEG Results

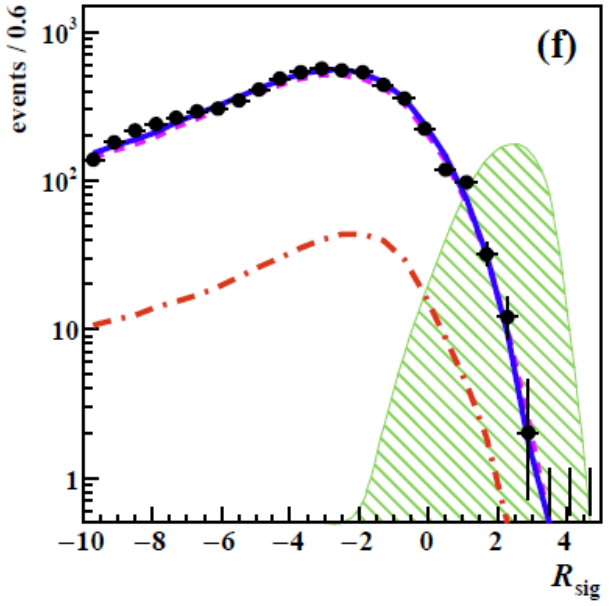

(a)
events / 56 (ps)
$t_{e^+\gamma}$ (ns)


(b)
events / 0.24 (MeV)
E_{e^+} (MeV)


(c)
events / 0.4 (MeV)
E_γ (MeV)


(d)
events / 2.0 (mrad)
$\theta_{e^+\gamma}$ (mrad)


(e)
events / 3.0 (mrad)
$\phi_{e^+\gamma}$ (mrad)

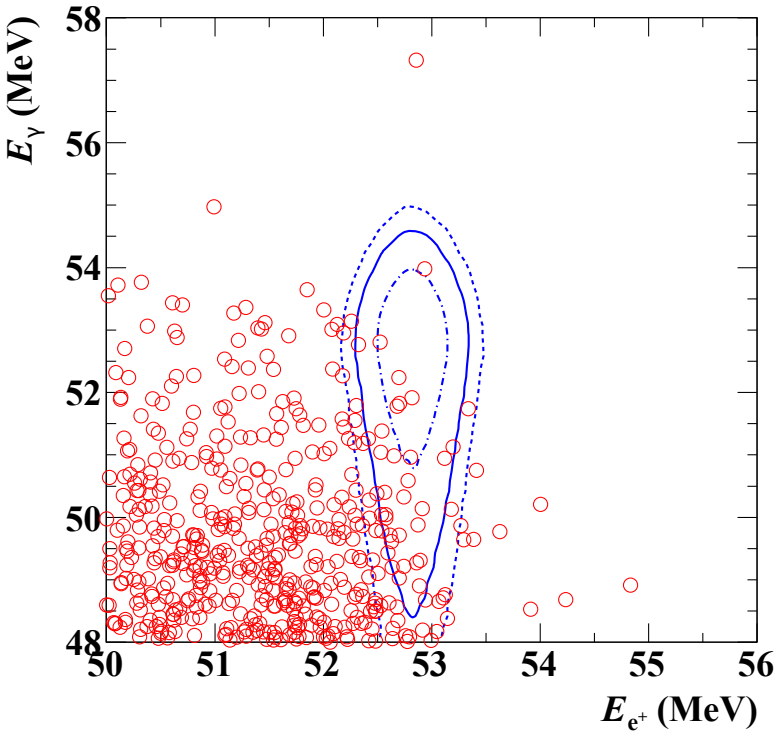

(f)
events / 0.6
R_{sig}

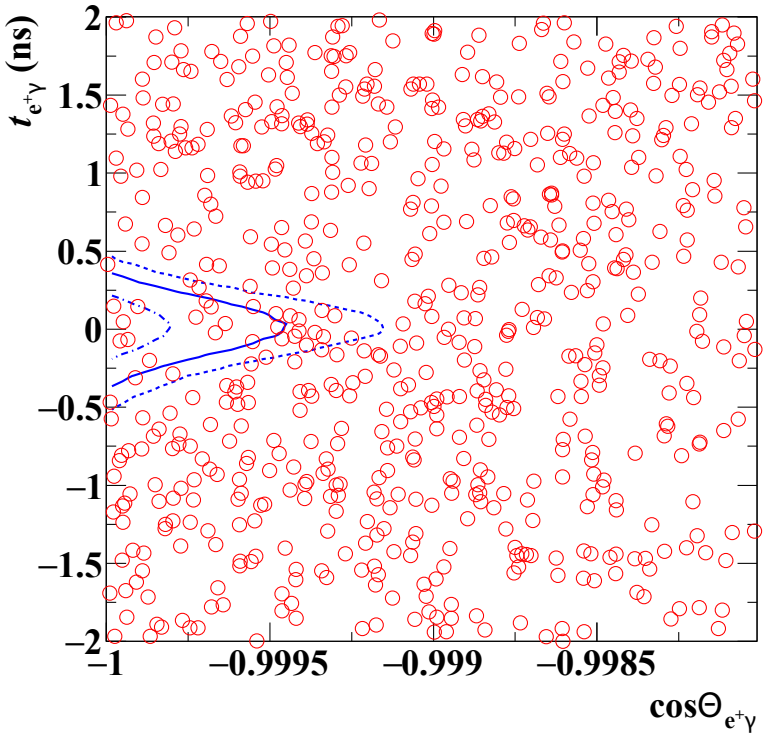
MEG Results

- 2009-2013 data
- Blue: Signal PDF, given by detector resolution
- No signal seen
- Upper limit at 90% CL:

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

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





How the sensitivity can be pushed down?

Angela Papa (Mainz Seminar)

- More sensitive to the signal...

high statistics

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

Beam rate

Acquisition time

Geometrical acceptance

Detector efficiency

Selection efficiency

- More effective on rejecting the background...

high resolutions

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

Positron Energy resolution

Gamma Energy resolution

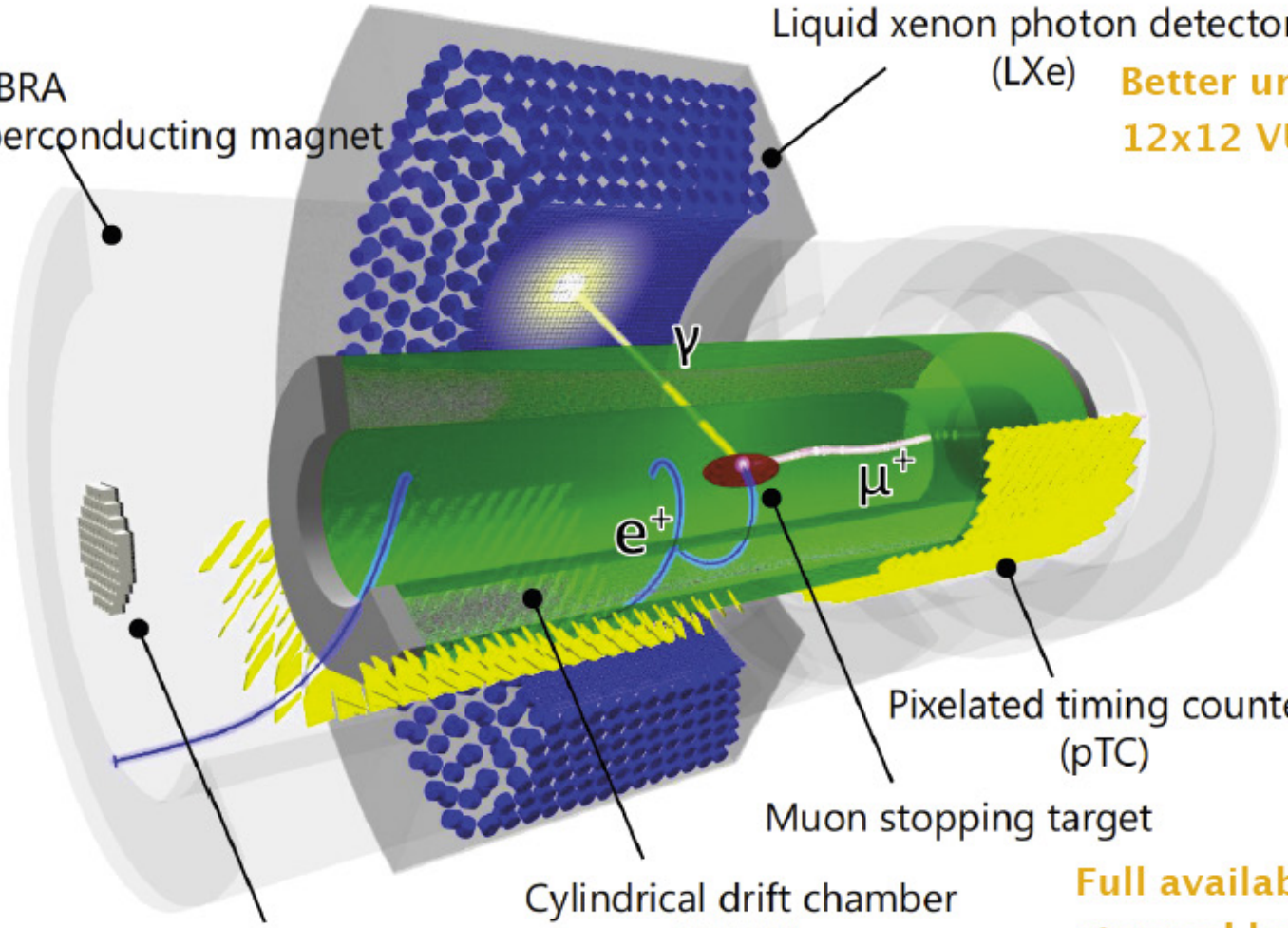
Relative timing resolution

Relative angular resolution

MEG II

New electronics:
Wavedream

~9000 channels at 5GSPS



x2 Resolution everywhere

x2 Beam Intensity

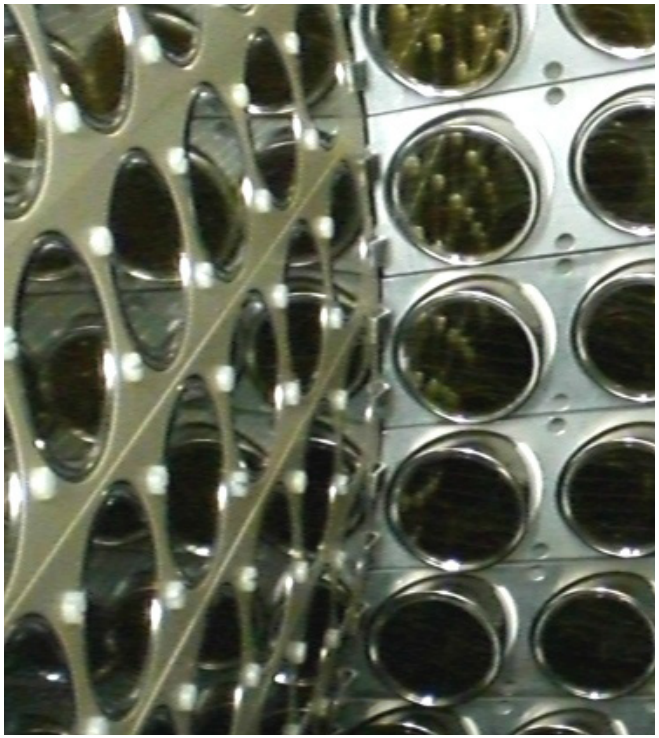
Updated and new Calibration methods

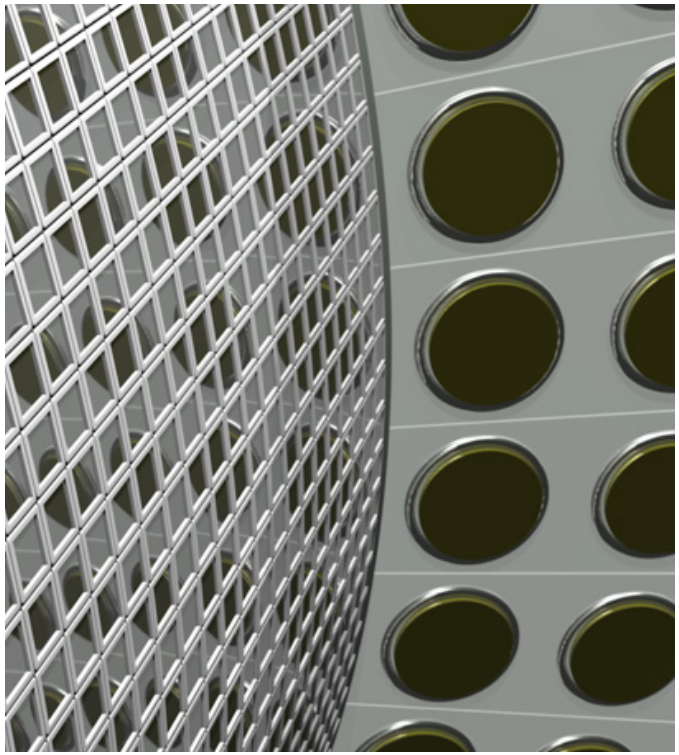
Quasi mono-chromatic positron beam

Angela Papa, NuFact 2018

MEG II - Calorimeter

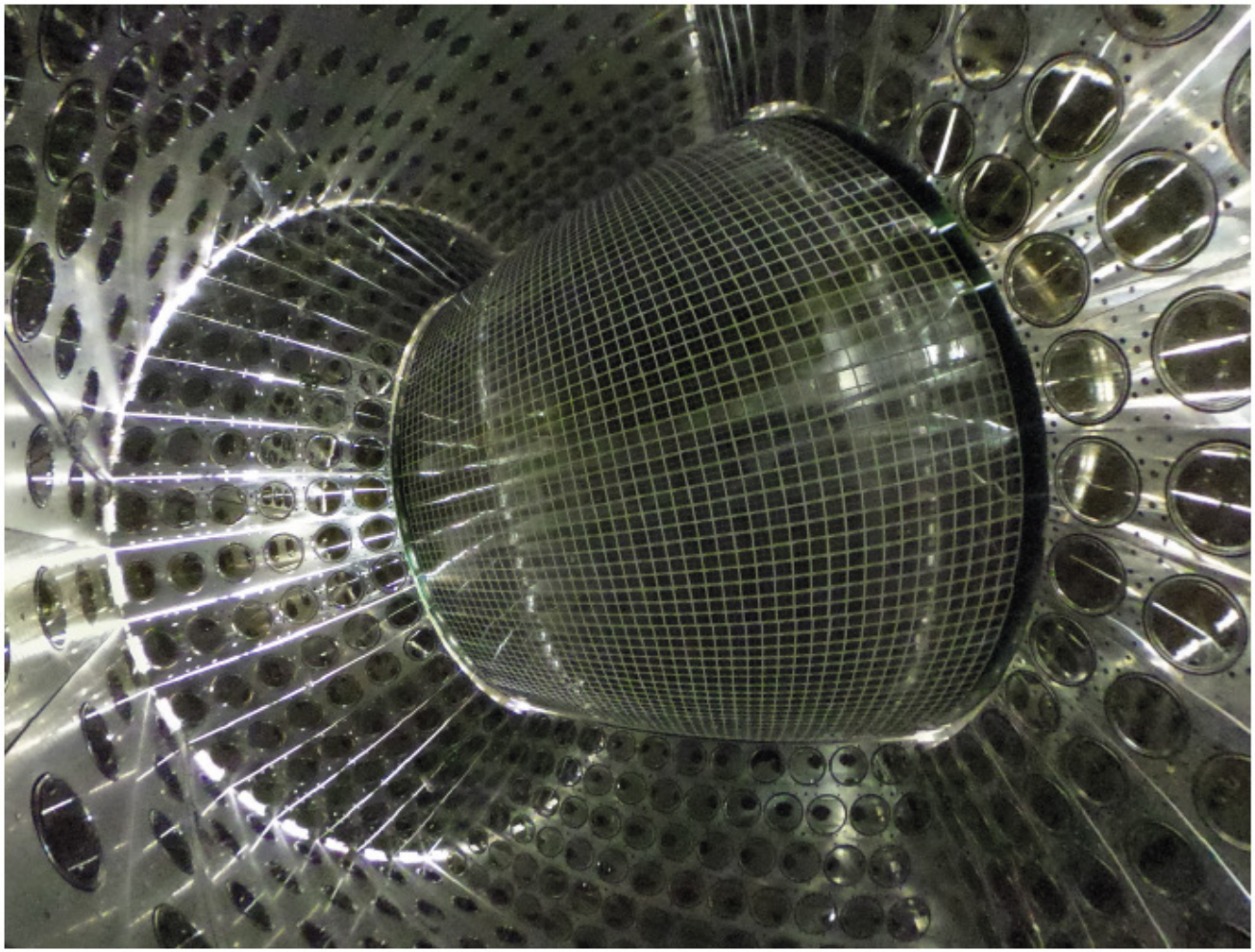
- ~4000 VUV sensitive SiliconPMs on entry face (new development with Hamamatsu)
- Better position and energy resolution
- Better efficiency



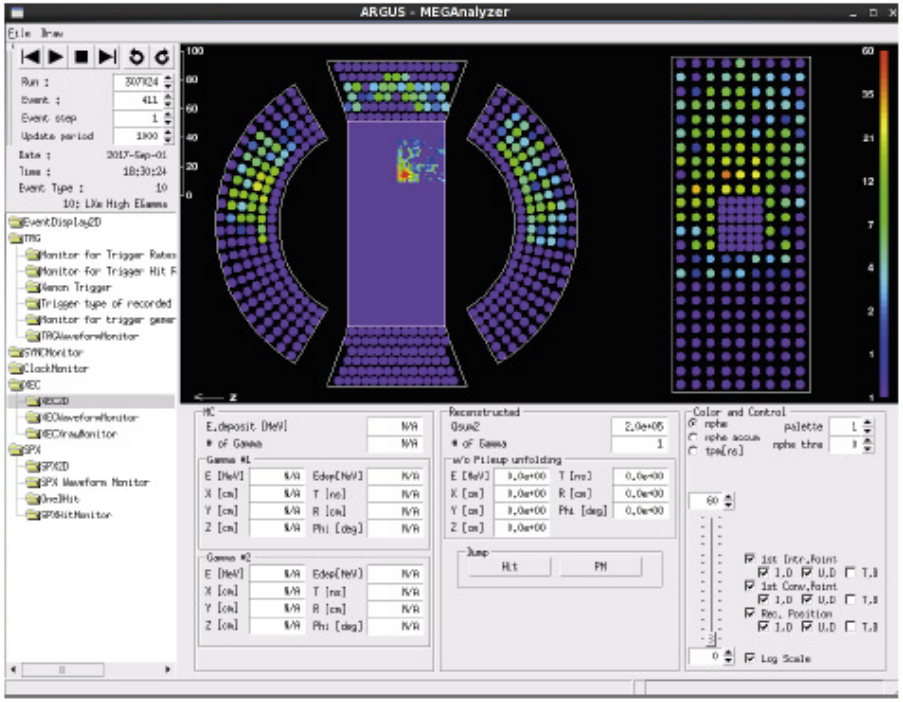


MEG II - Calorimeter

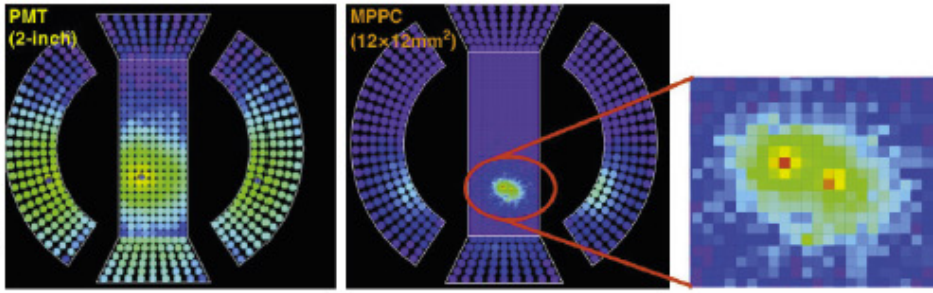
Detector commissioning started ! **New**



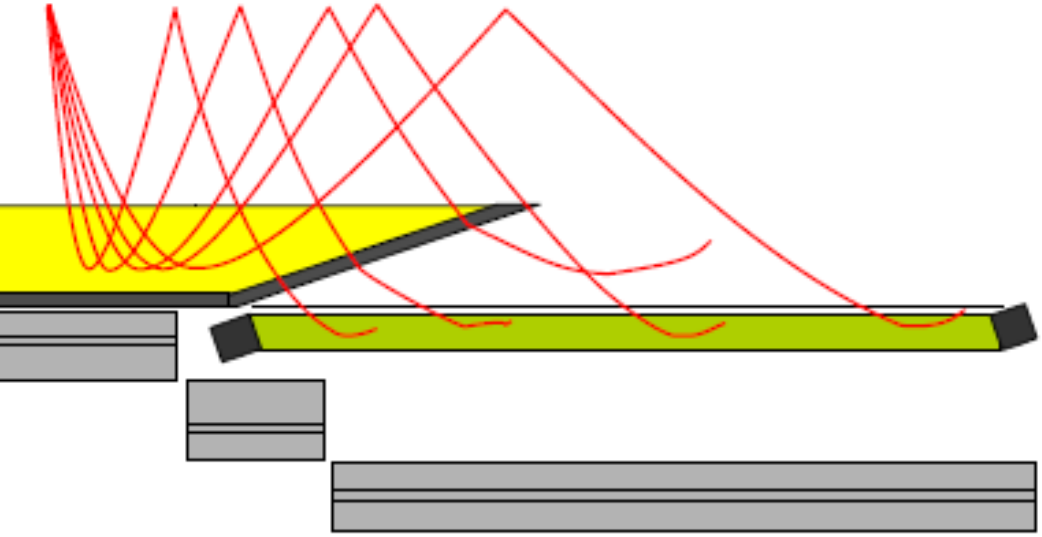
Data

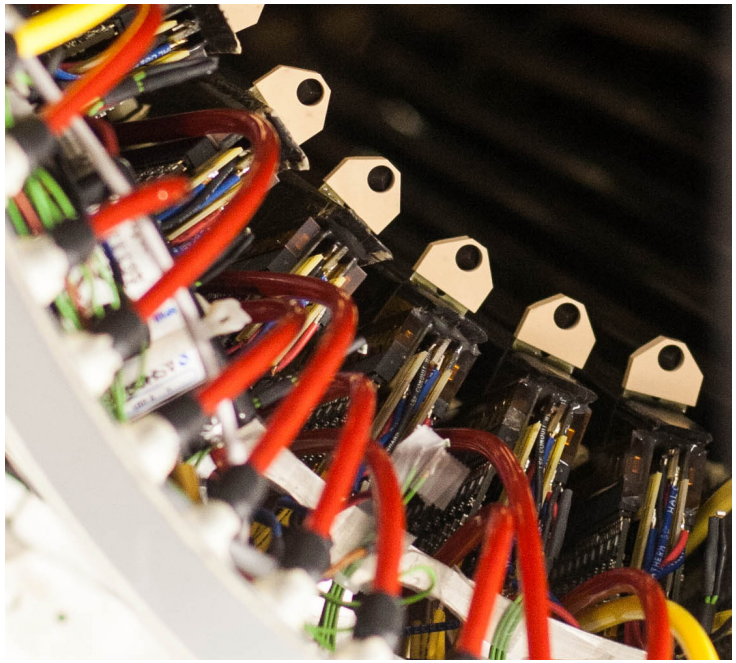


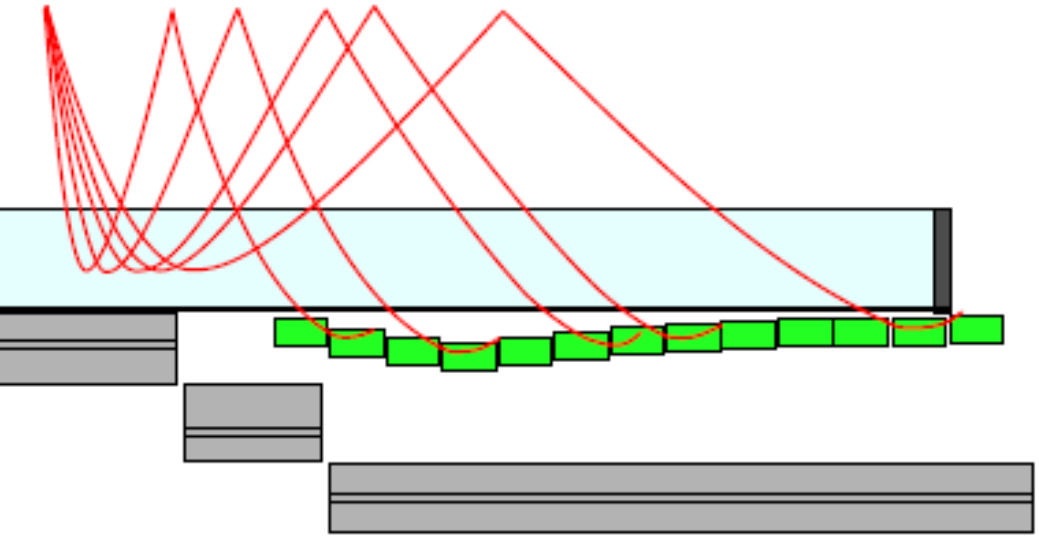
MC simulation



MEG II - Drift Chamber





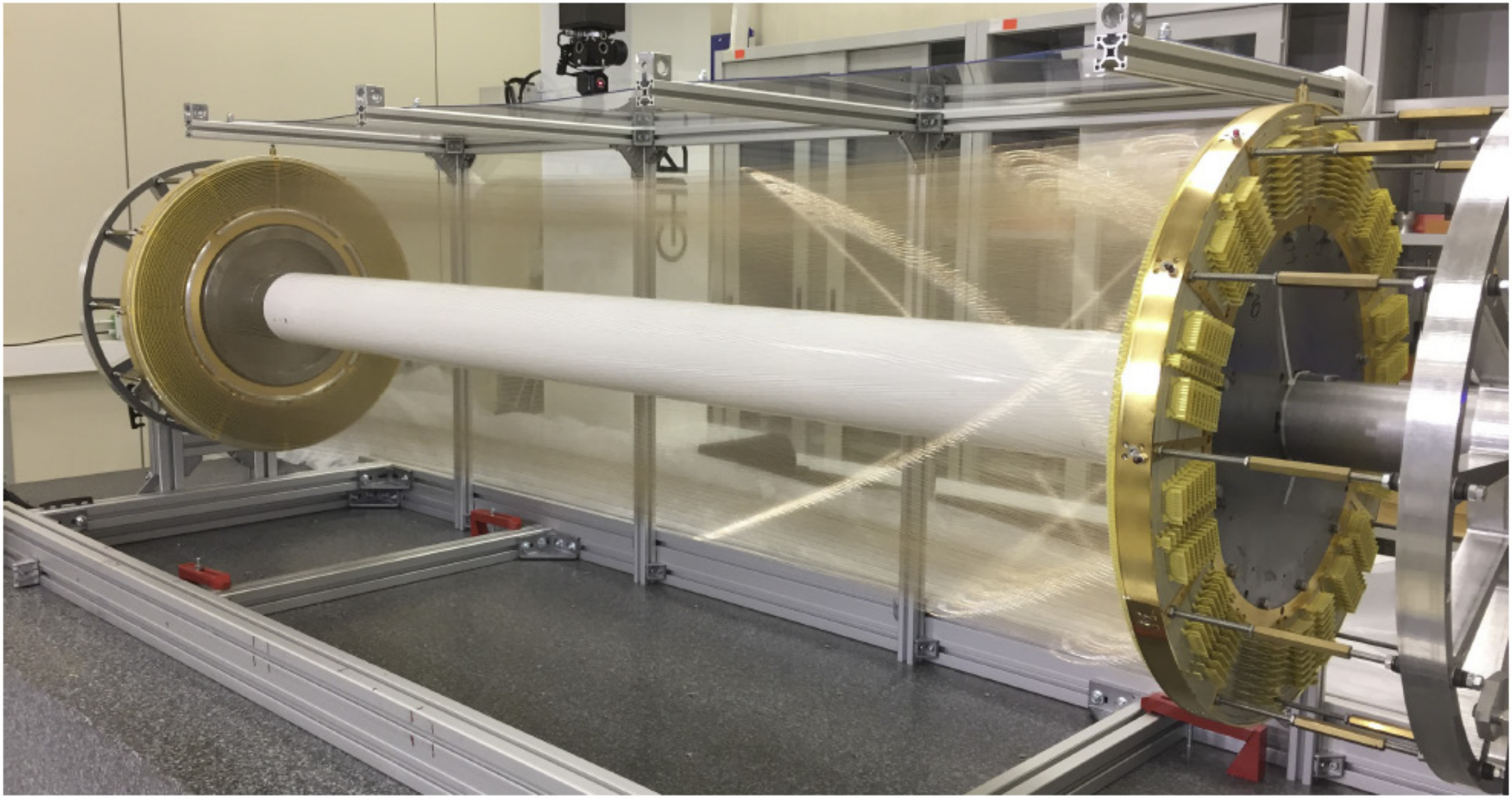


- New single volume drift chamber
- Lower Z gas mixture
- More space points per track
- Better rate capability
- Less material in front of timing counters

MEG II - Drift Chamber

- Assembly completed

Angela Papa, NuFact 2018

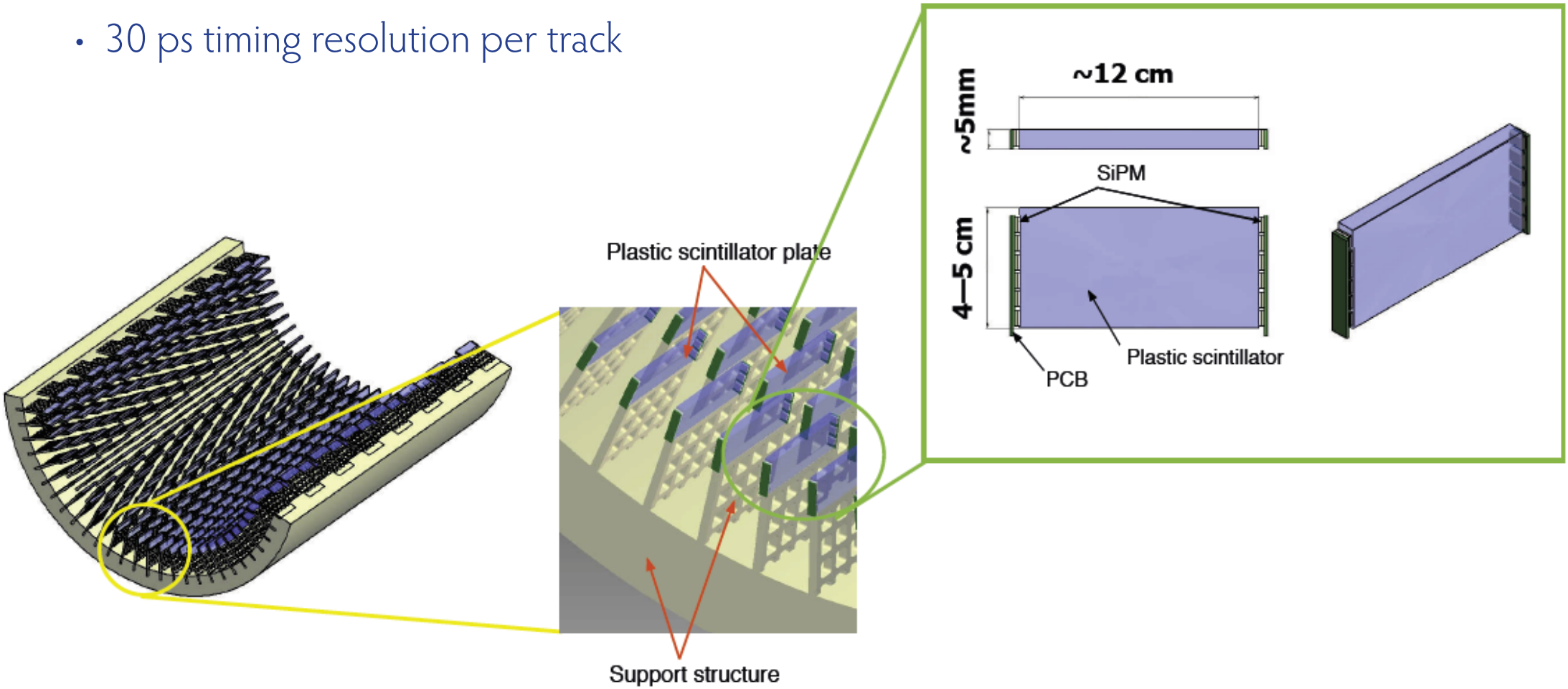


MEG II - Drift Chamber

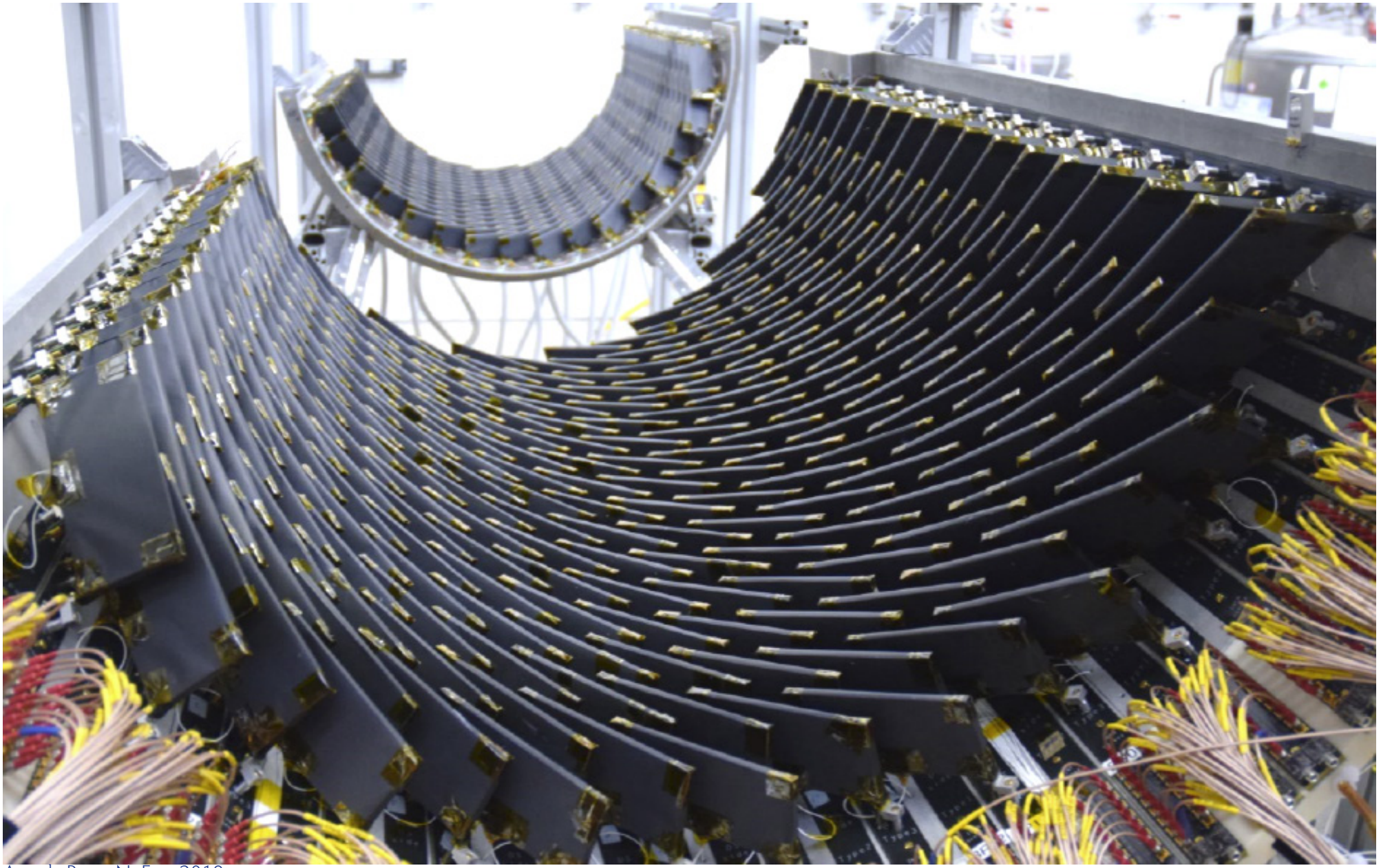
- Assembly completed
- at PSI

MEG II - Timing Counter

- Many small scintillators
- Read-out by SiliconPMs
- On average eight counters hit by track
- 30 ps timing resolution per track

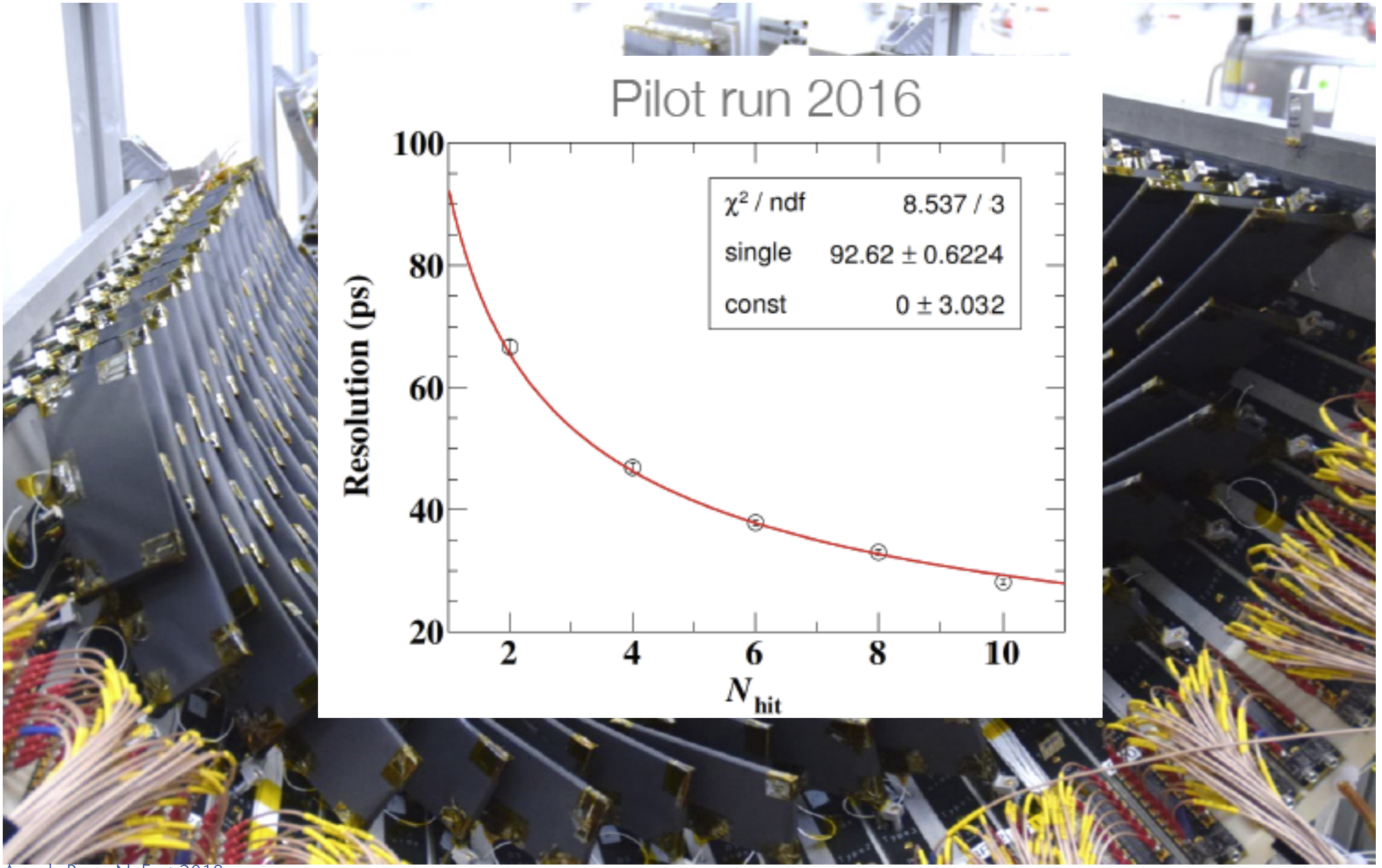


MEG II - Timing Counter



Angela Papa, NuFact 2018

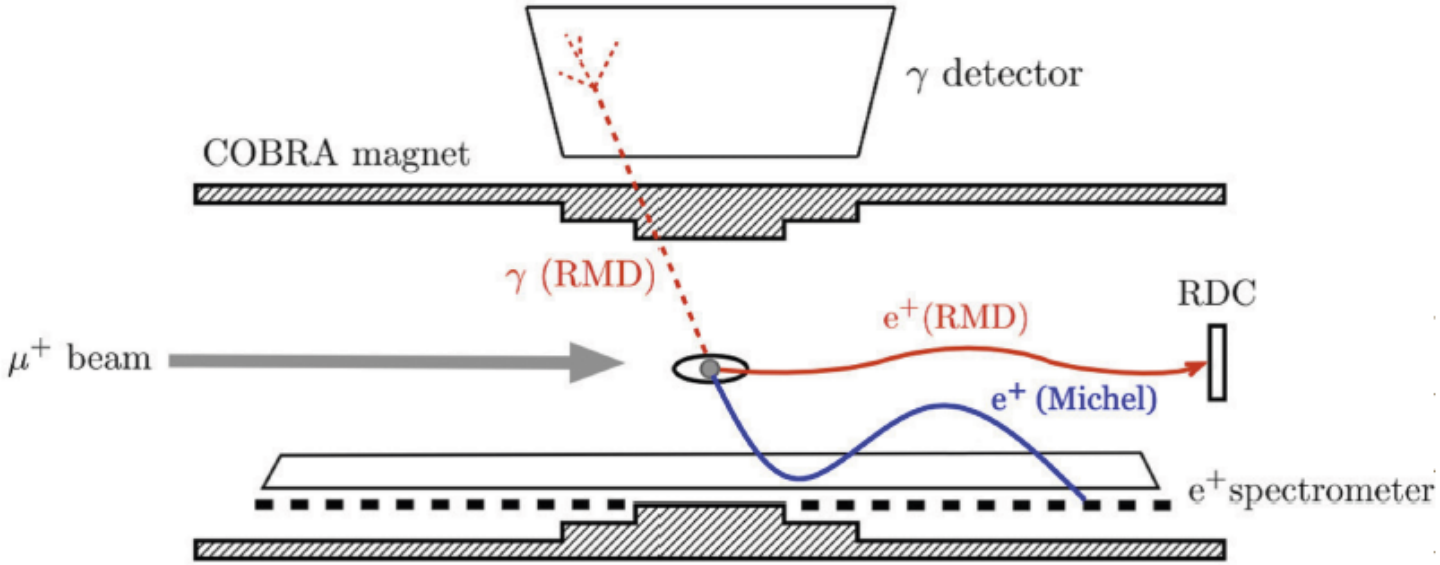
MEG II - Timing Counter

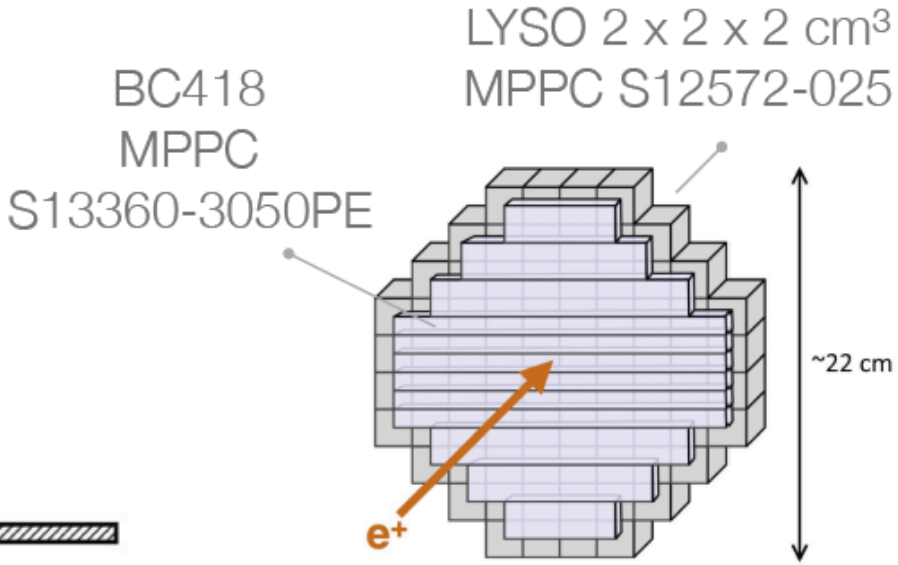


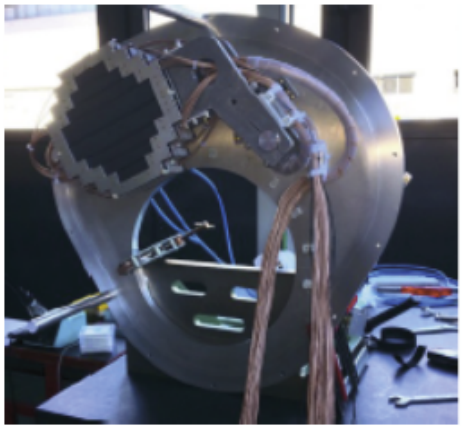
Angela Papa, NuFact 2018

MEG II - Radiative Decay Counter

- Detect low energy positrons from radiative decays with high energy gammas



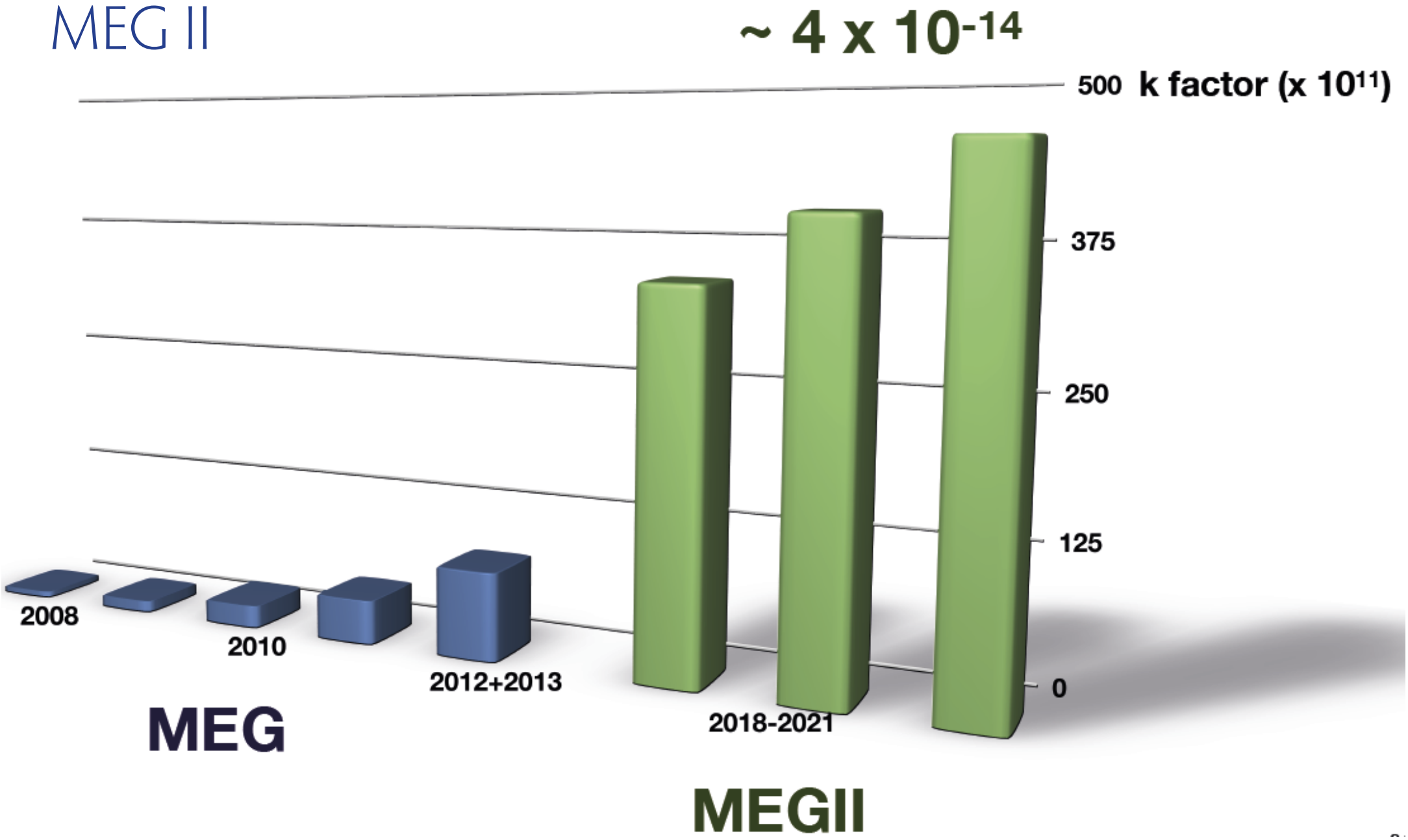




Angela Papa, NuFact 2018

Where we will be

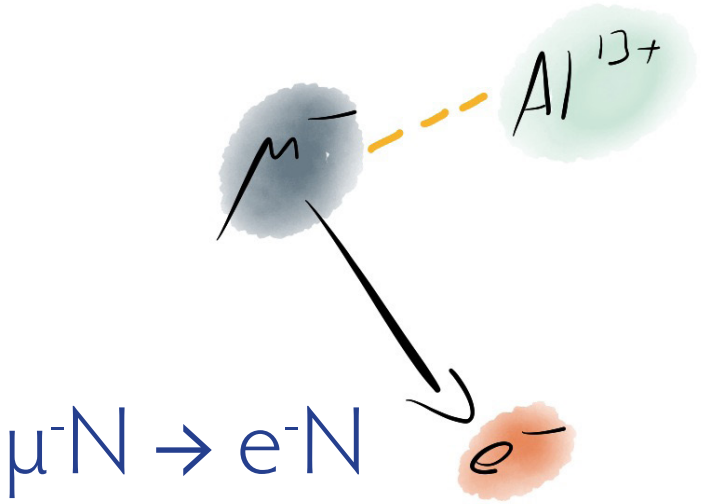
MEG II



Searching for μ → e conversion with

Mu2e, DeeMee, COMET, PRISM

Conversion Signal and Background



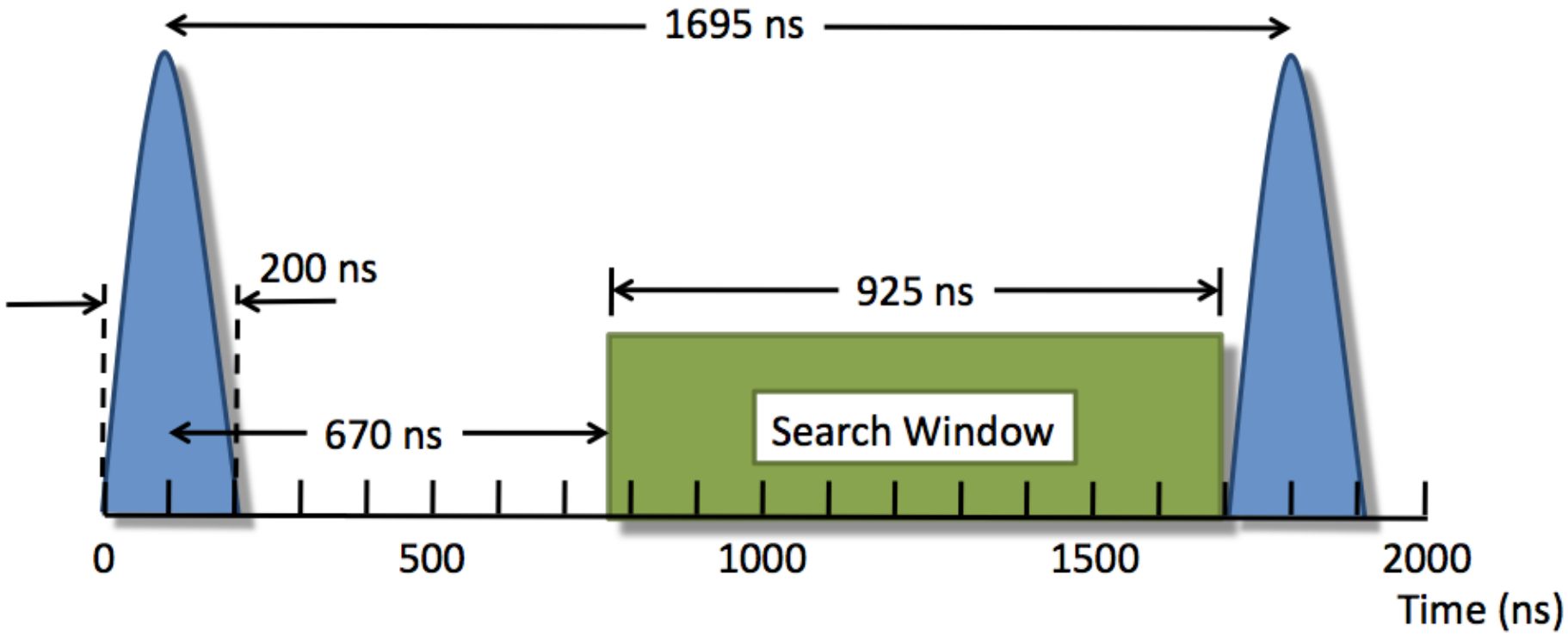
- Single 105 MeV/c electron observed

Backgrounds:

Anything that can produce a 105 MeV/c electron

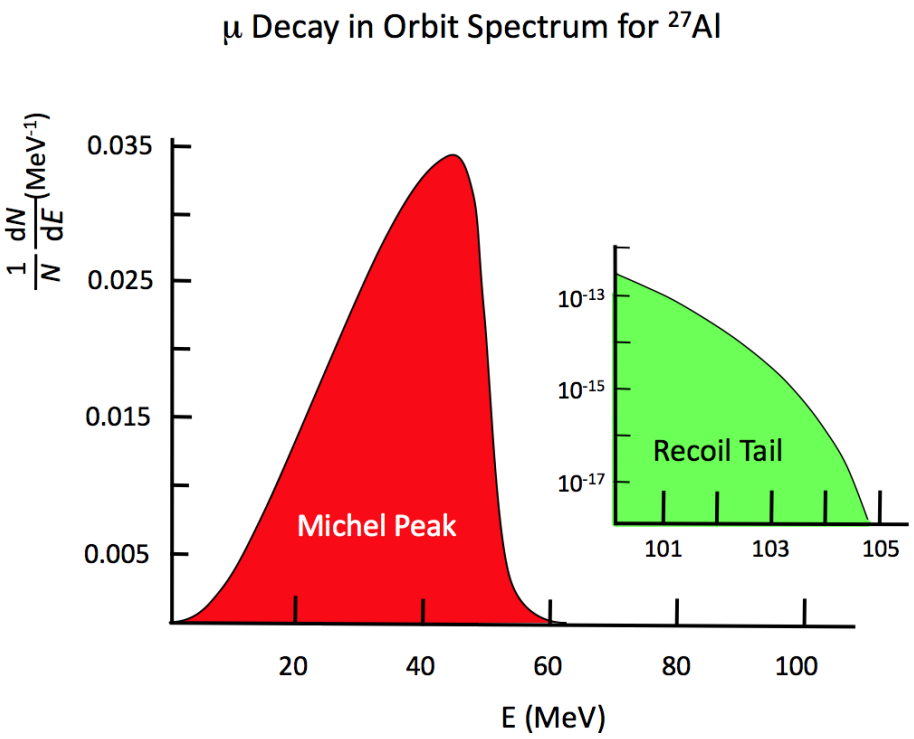
- Primary proton beam
- Decay in Orbit (DIO)
- Nuclear capture (AlCap effort at PSI)
- Cosmics

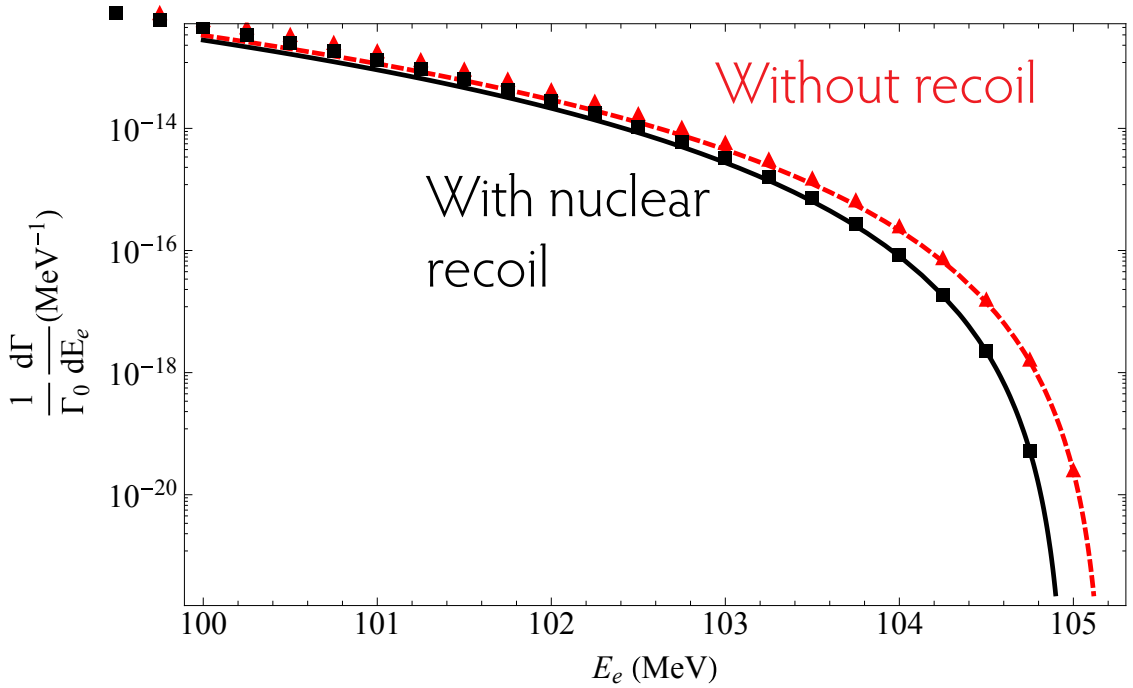
Beam induced background



- Proton beam produces pions, photons, (antiprotons) etc.
- Wait until things become better...
- Makes it hard to use high Z targets

Deacy-in-orbit background





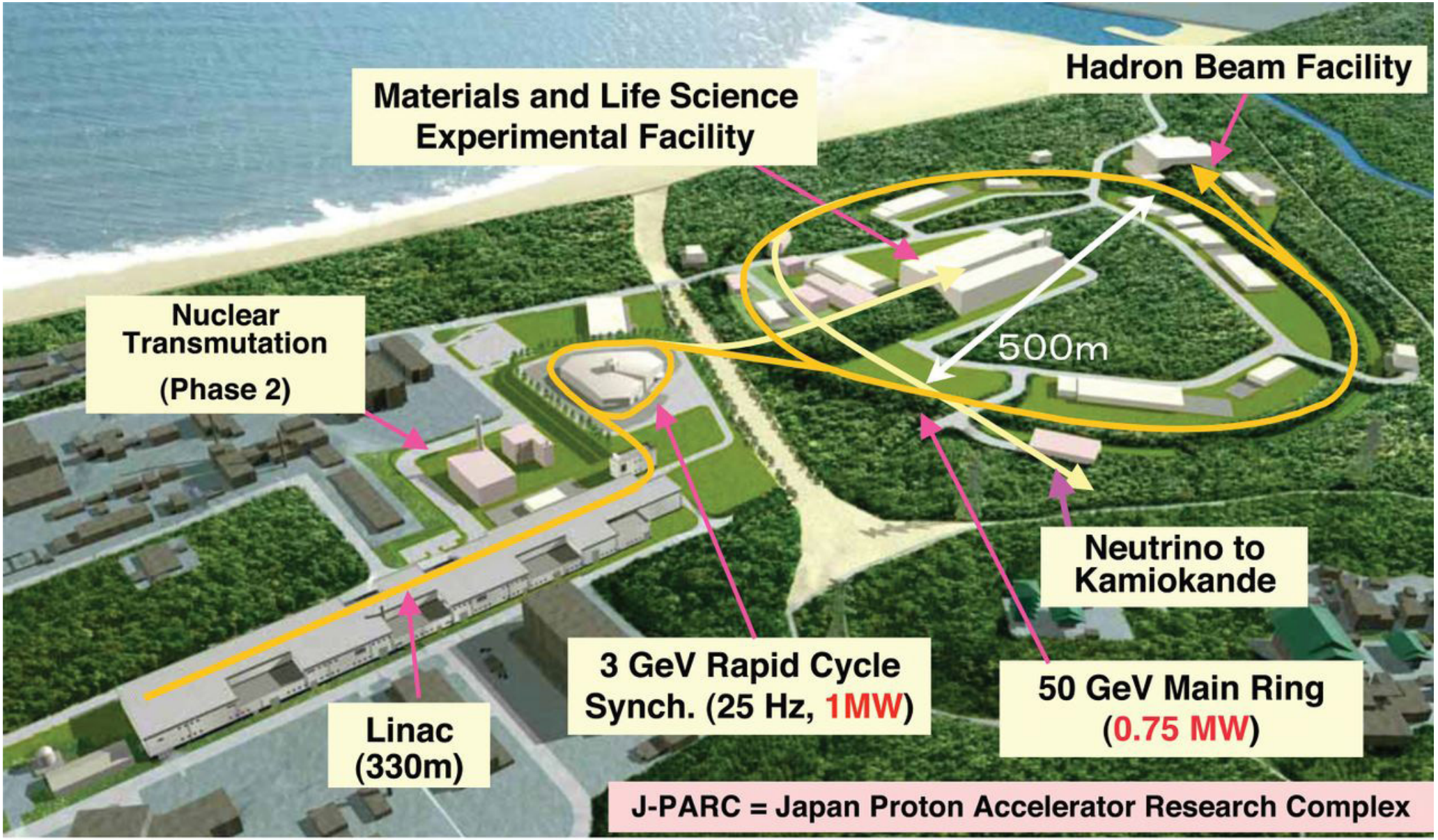
- Nuclear recoil allows for electron energies above $m_\mu/2$
- Calculation by Czarnecki, Garcia i Tormo and Marciano, Phys. Rev. D84 (2011)
- Requires excellent momentum resolution

Muons from Fermilab...

- Re-use part of the Tevatron infrastructure
- Proton pulses every 1700 ns
- $> 10^{10}$ μ/s

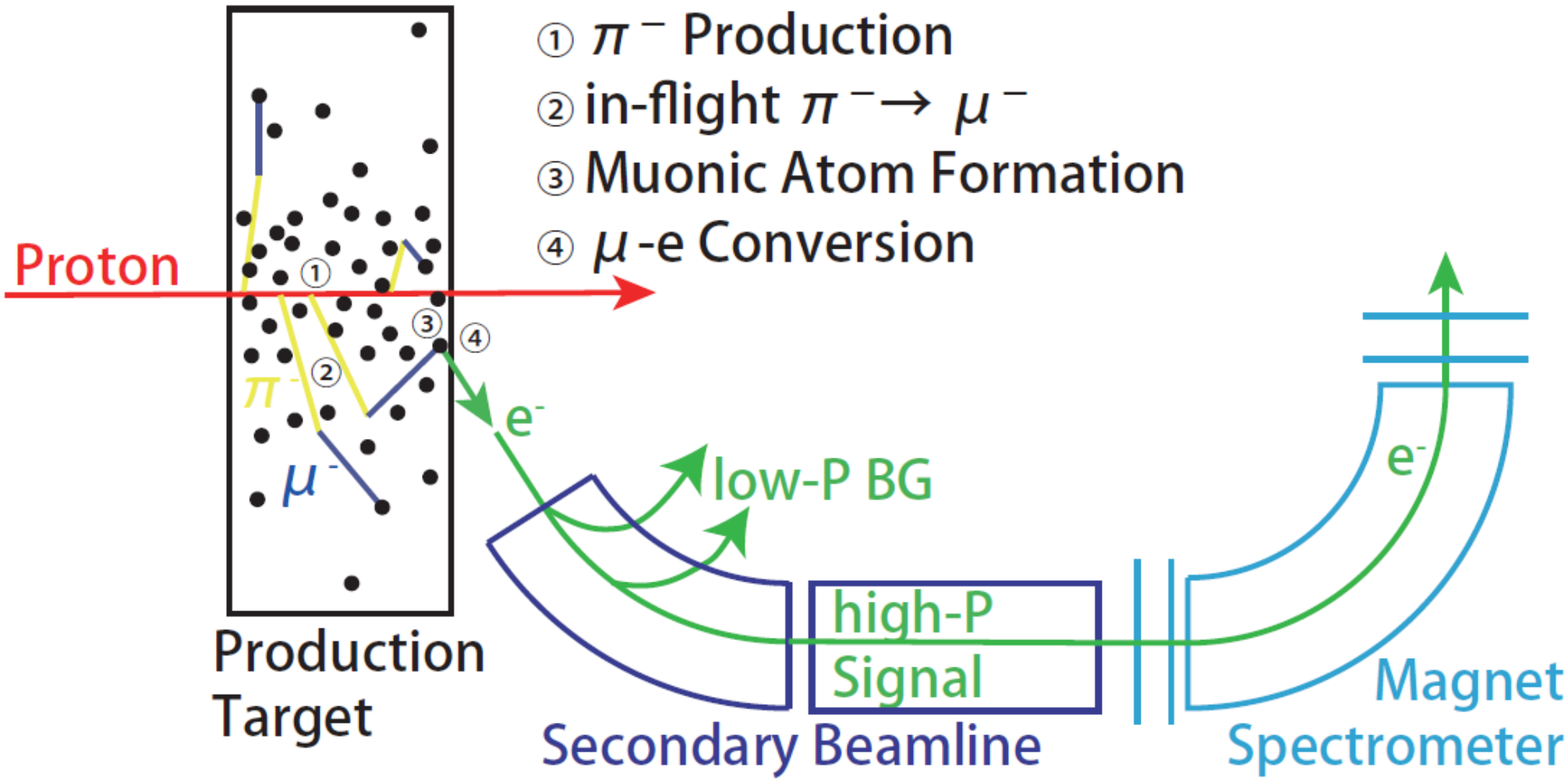
- PIP-II would give another 2 orders of magnitude at an energy below the antiproton threshold

... and J-PARC



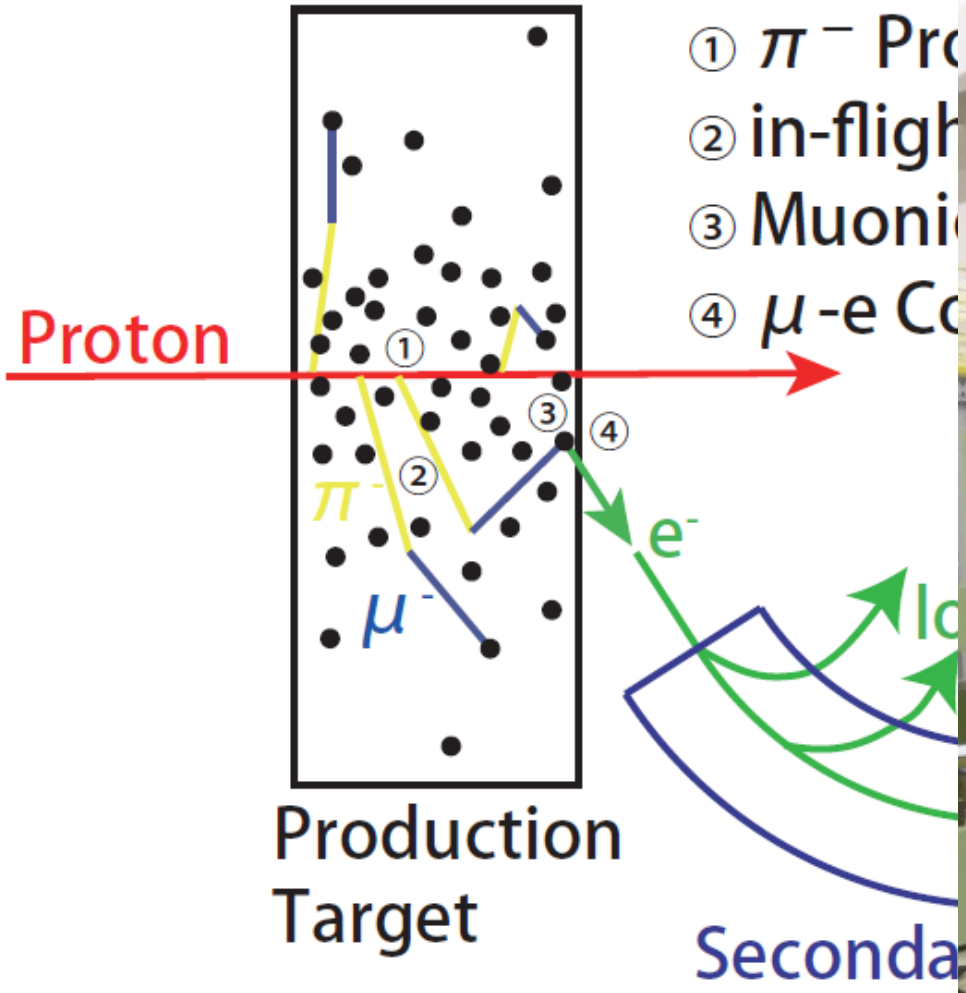
- 10^{11} μ/s from 8 GeV/c protons

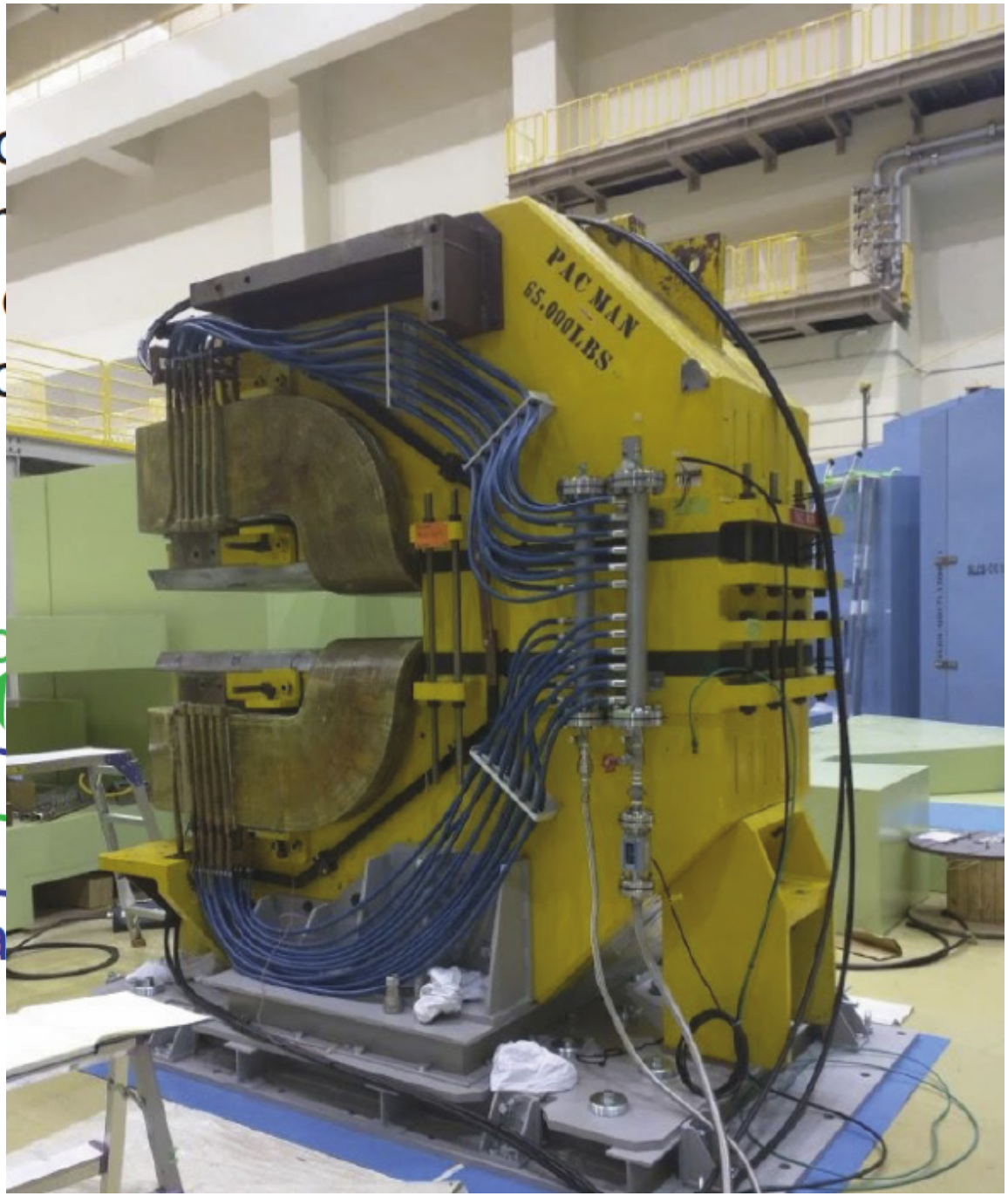
Experimental concept - DeeMee



Yohei Nakatsugawa, NuFACT2014

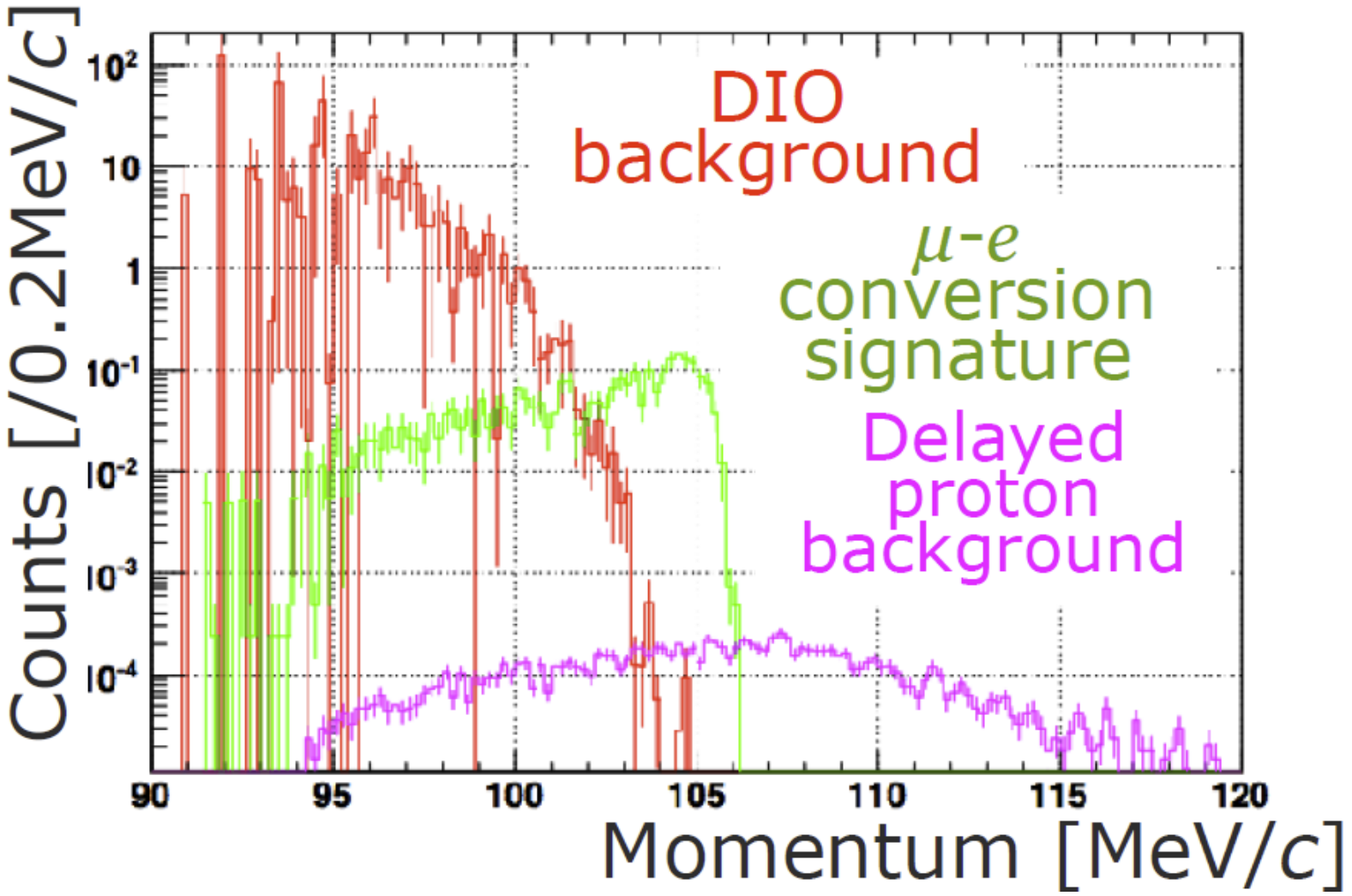
Experimental concept - DeeMee





Sensitivity - DeeMee

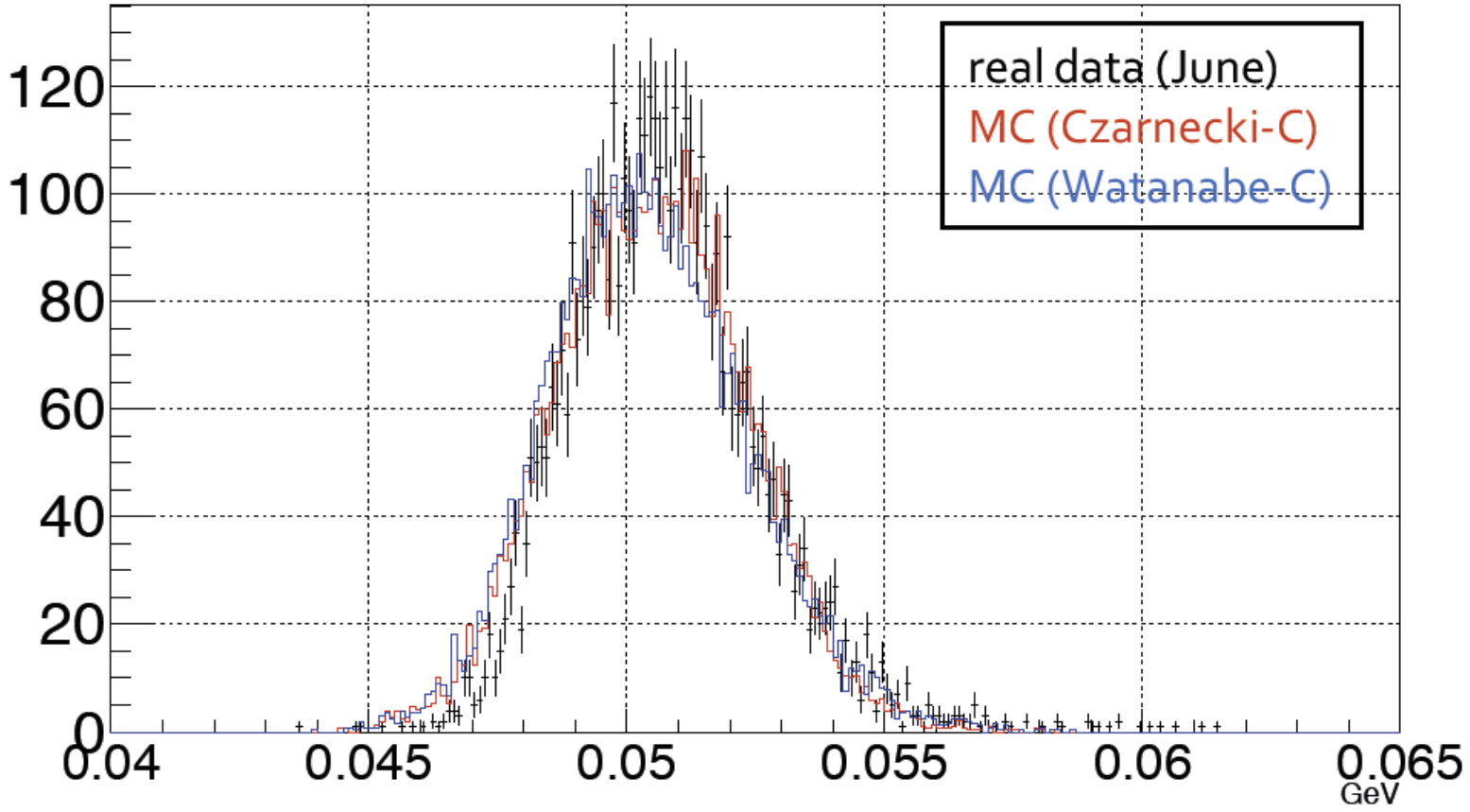
- Expect 2.1×10^{-14} single event sensitivity for one year running
- Beamline under construction



Natsuki Teshima, NuFACT2017

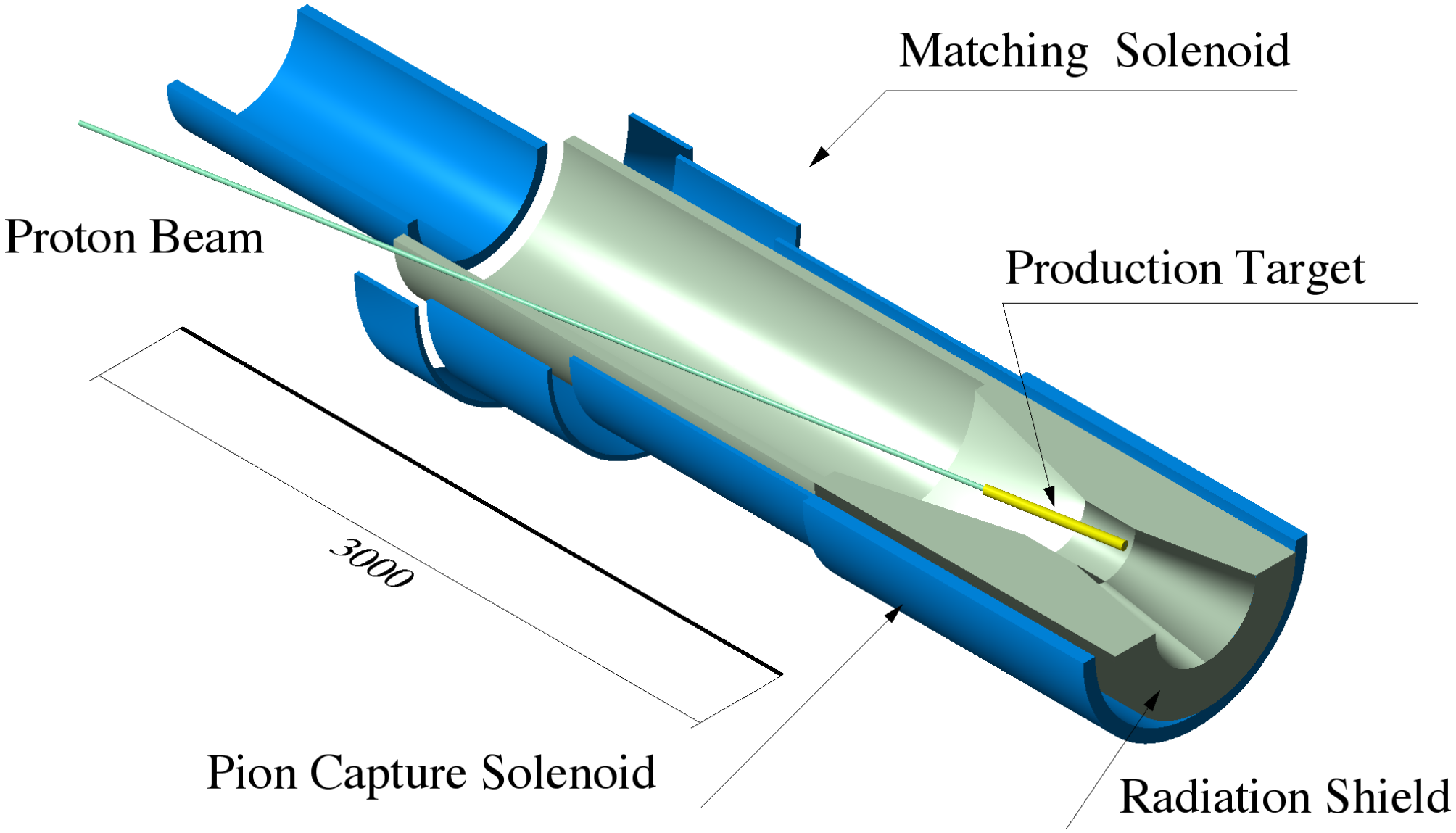
First DIO Measurement - DeeMee

- Very first measurements:
  Different setup and different beamline



Dakai Nagao,
NuFACT2018

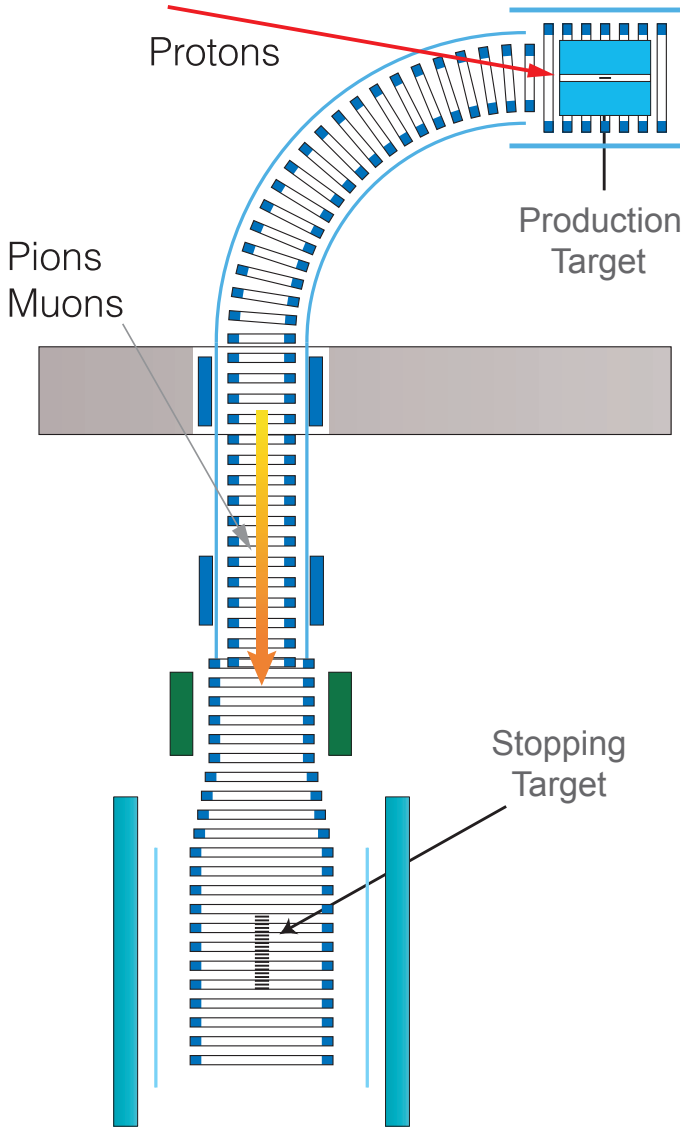
Production target inside a solenoid



Capture most pions produced in target

Shielding of superconducting magnet very challenging

Experimental layout - COMET Phase I



Pion Capture Section

High solenoidal field

Capture pions with large solid angle

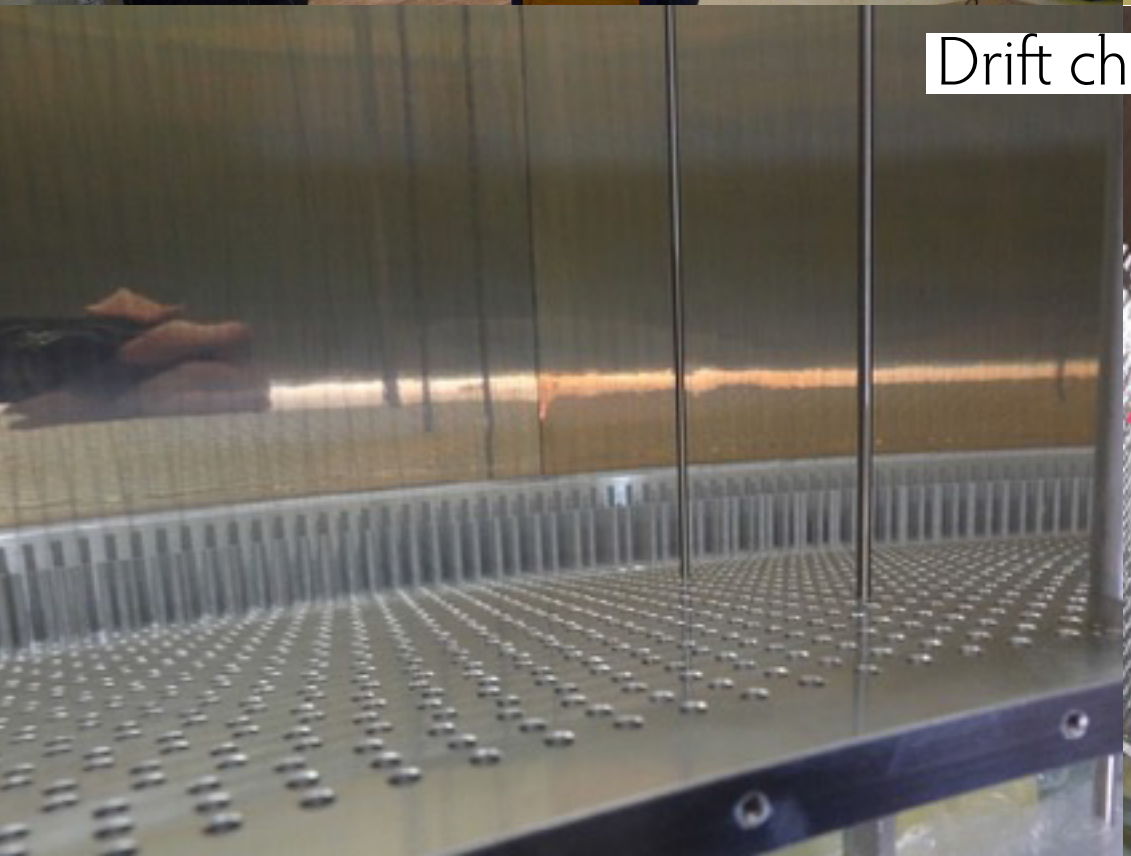
Pion-Decay and Muon-Transport Section

Detector Section

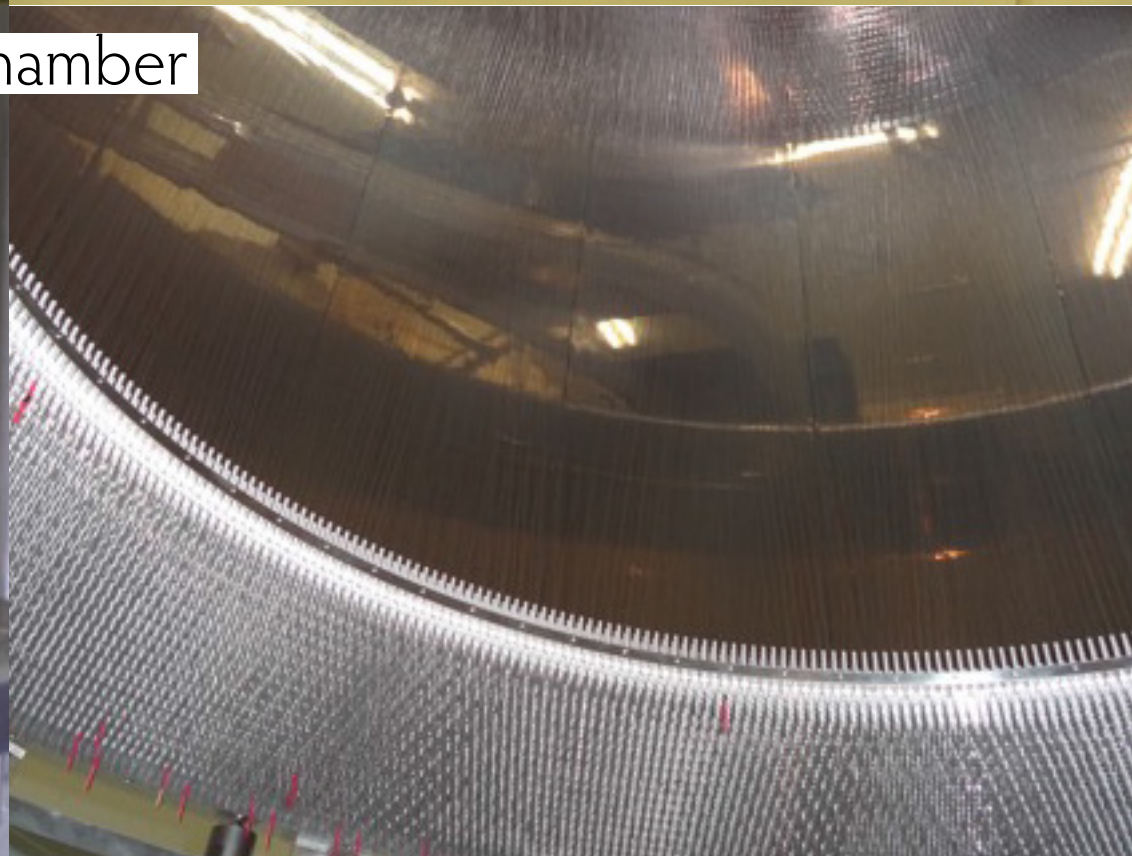
Comet CDR

Y. Kuno

Curved solenoid

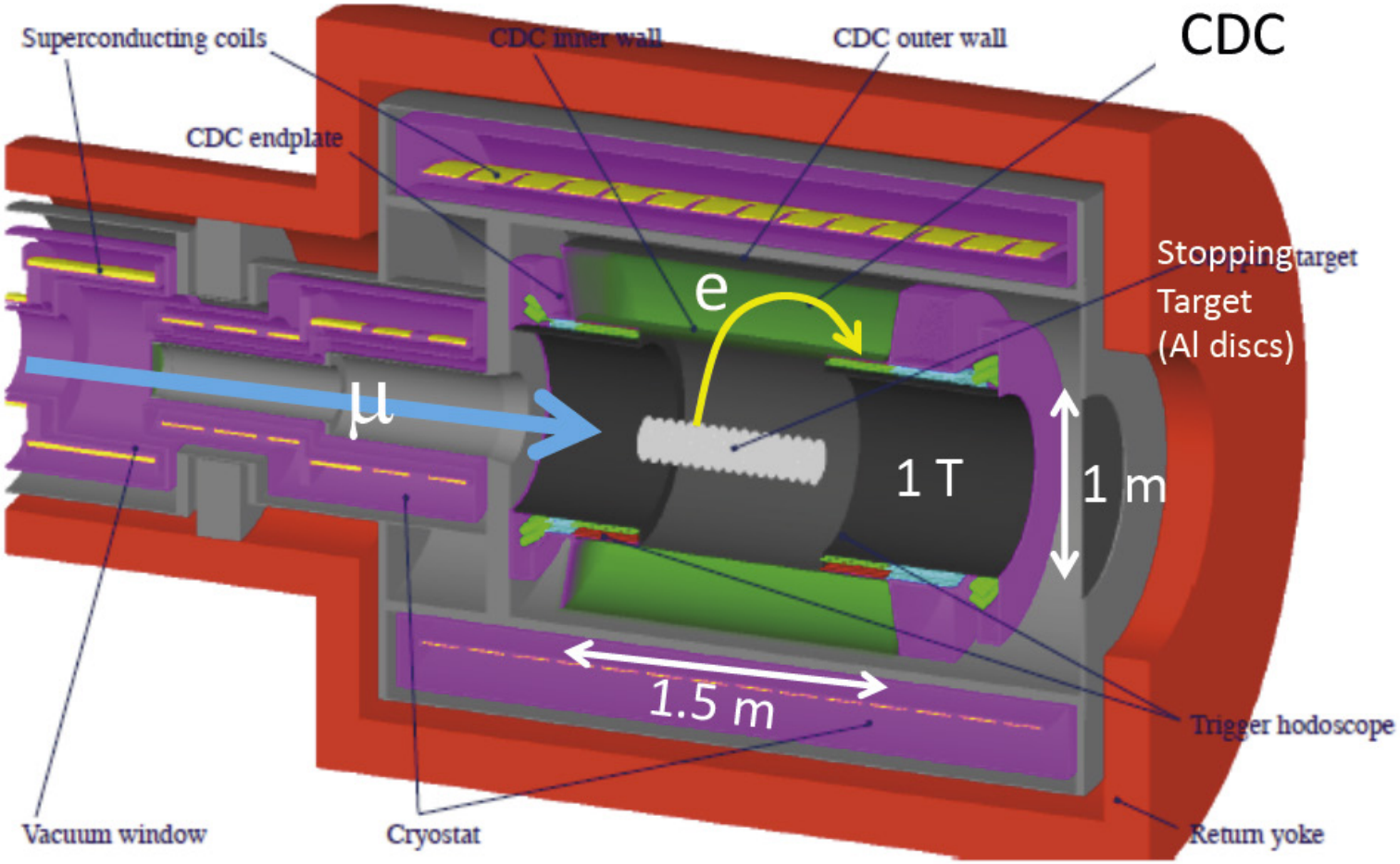


Drift chamber



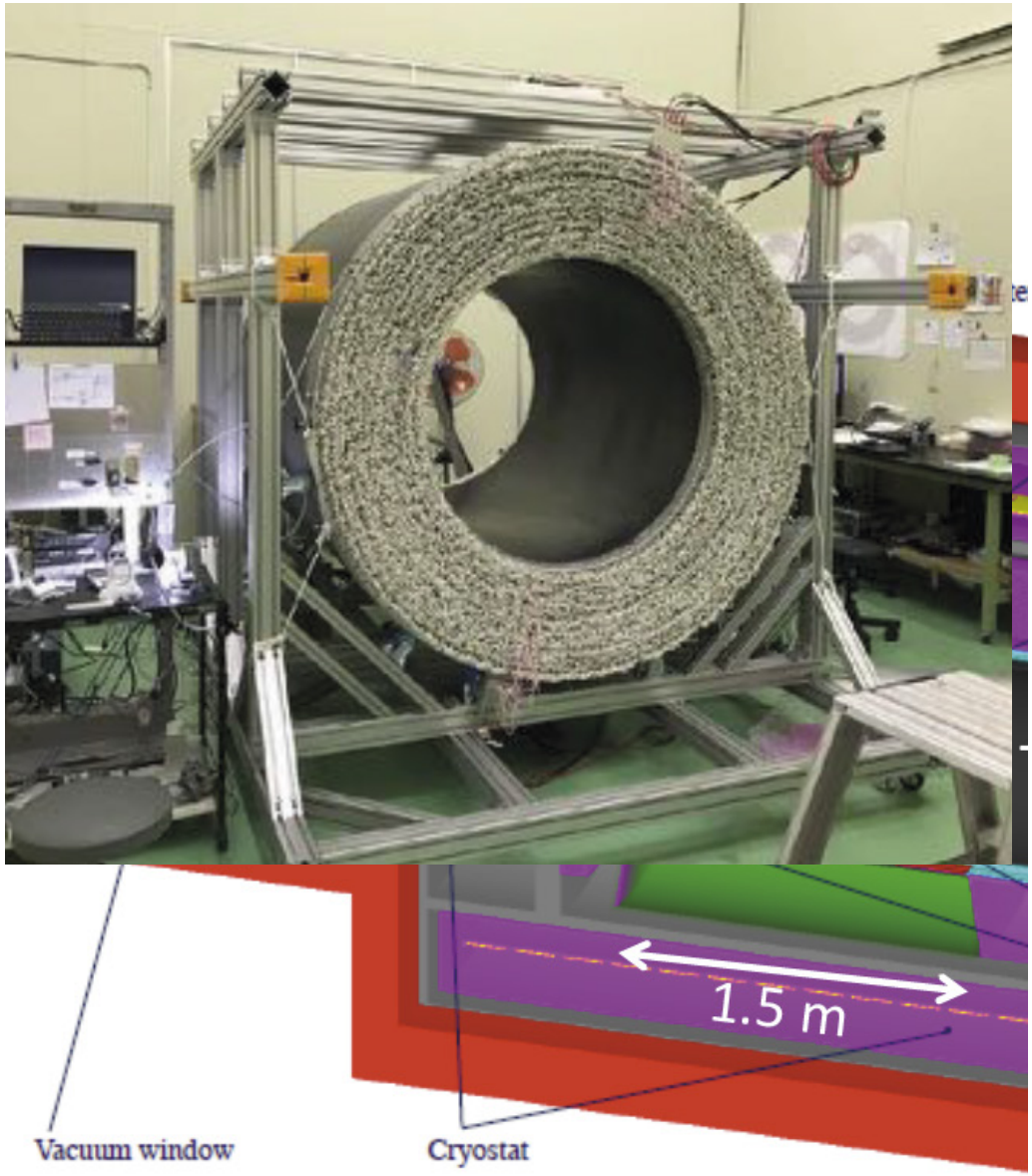
Cylindrical Detector System

- Large drift chamber for momentum measurements
- Trigger hodoscope



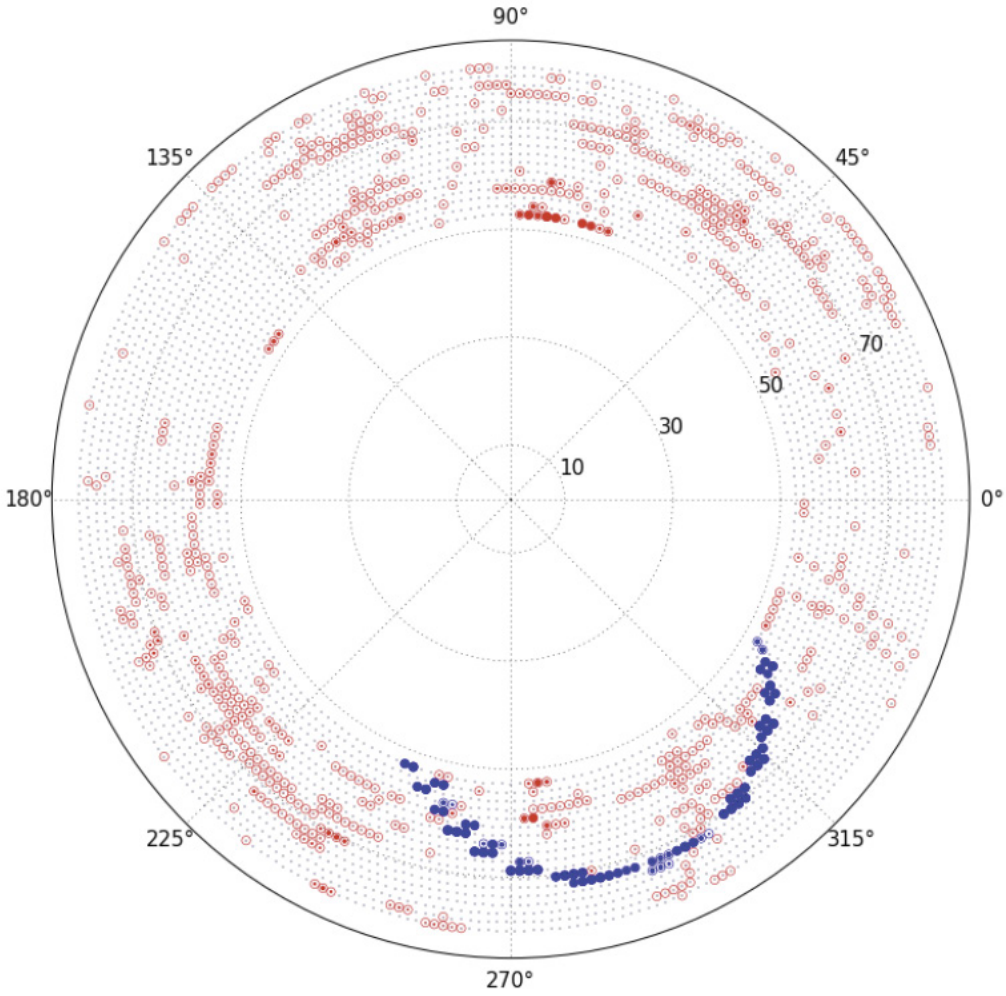
Manabu Moritsu, NuFACT2018

Cylindrical Detector System

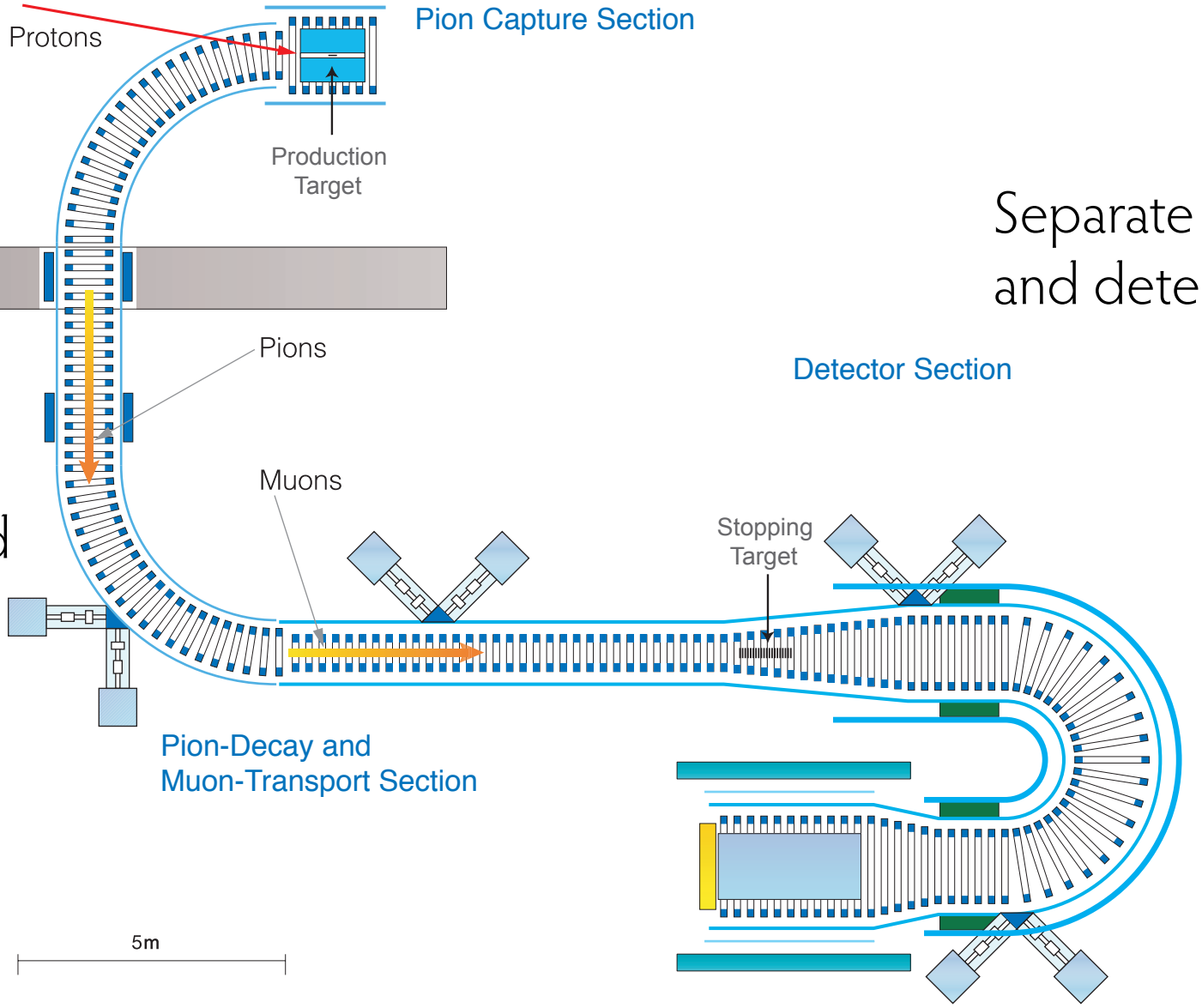


Manabu Moritsu, NuFACT2018

- Large drift chamber for momentum measurements
- Trigger hodoscope



Experimental layout - COMET Phase II

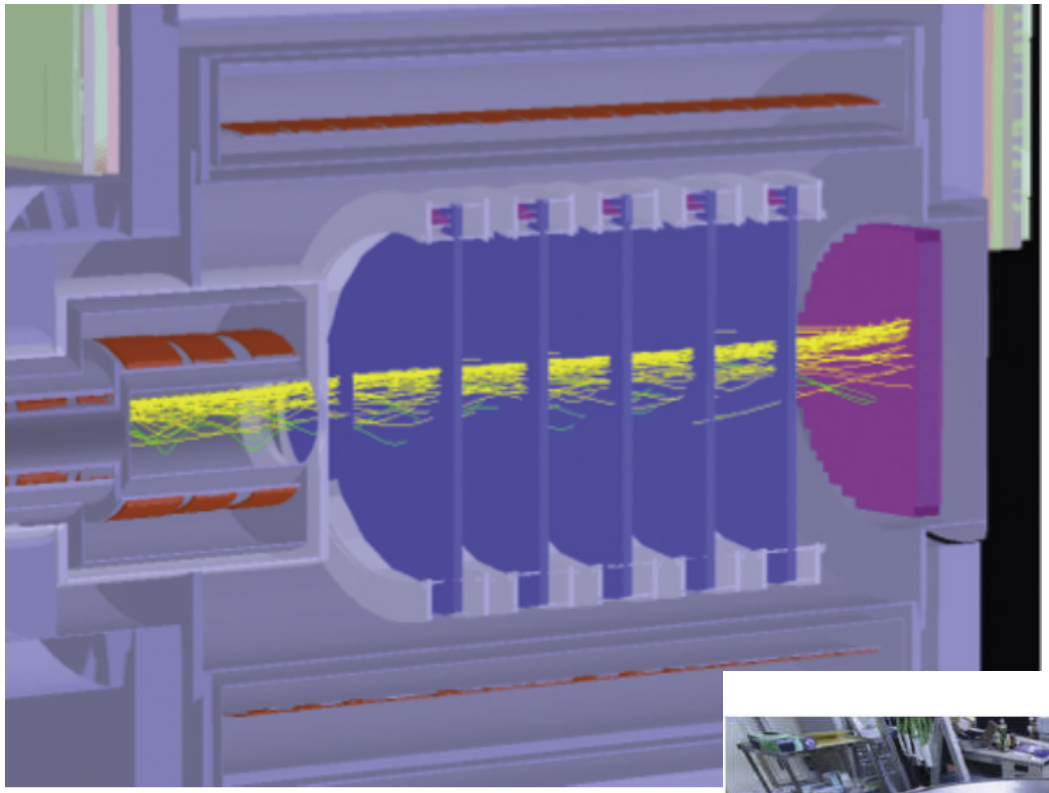


Separate muon decay and detector region

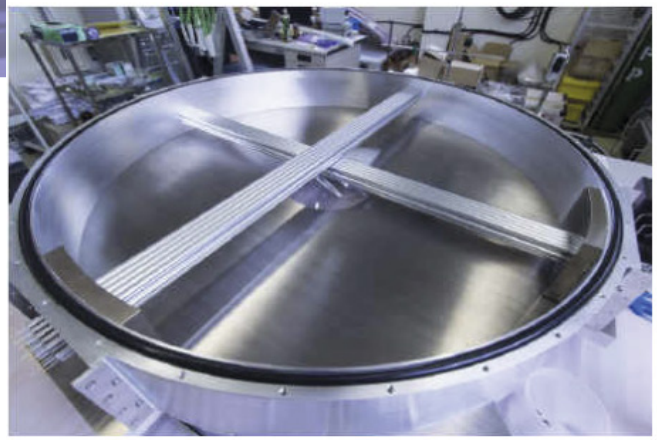
One more bend

Comet CDR

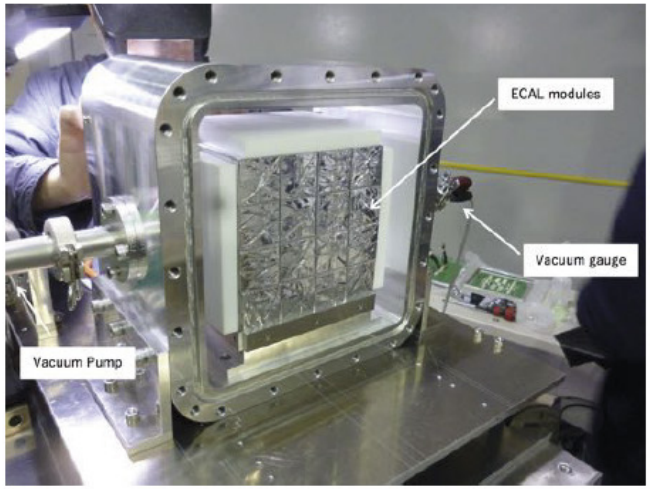
COMET Phase II Detector System



- Straw tubes in vacuum
- LYSO calorimeter



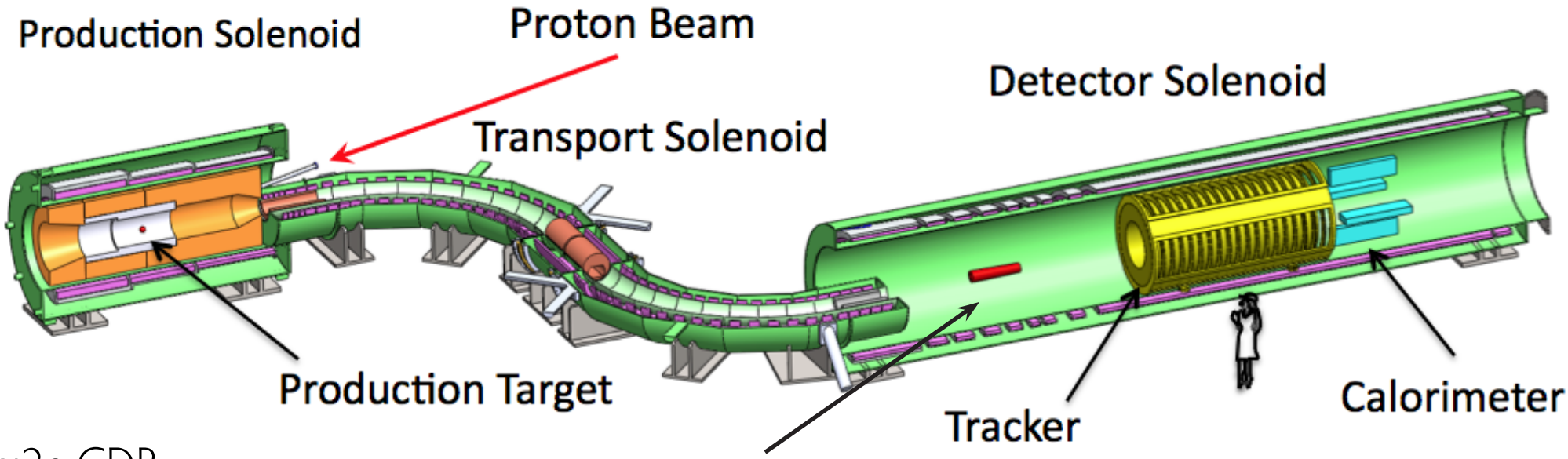
Straw Tracker prototype



ECAL prototype

Manabu Moritsu,
NuFACT2018

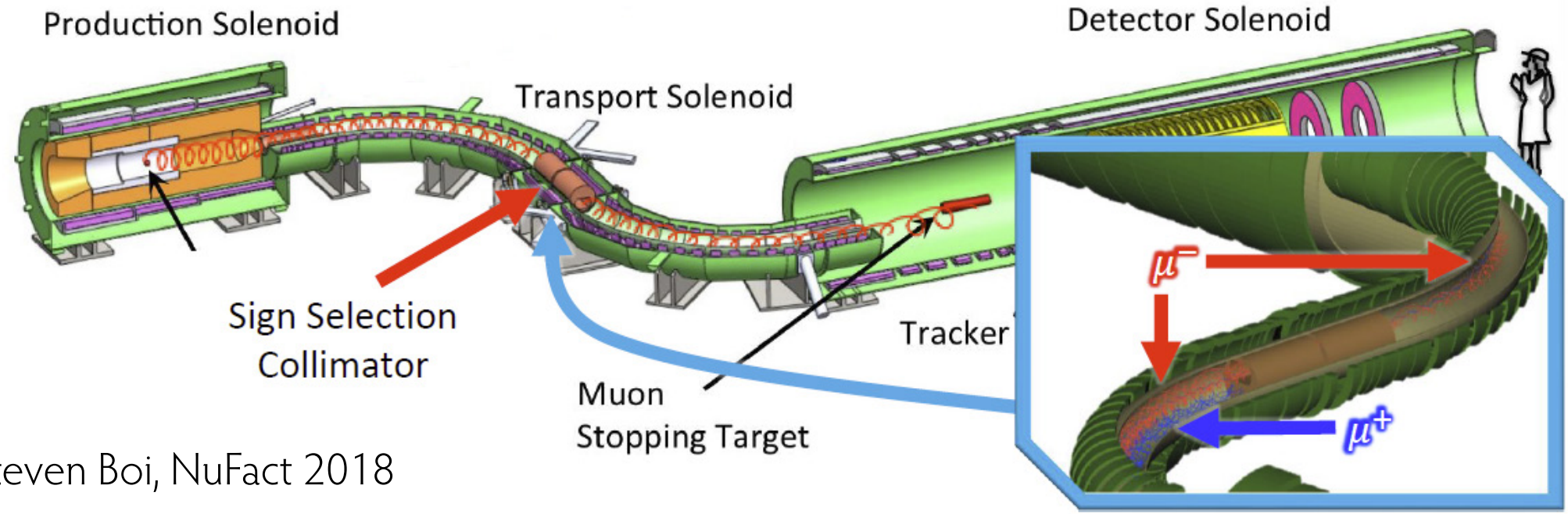
Experimental layout - Mu2e



Mu2e CDR

- Separate muon production and conversion target
- Not shown: cosmic ray veto and absorbers

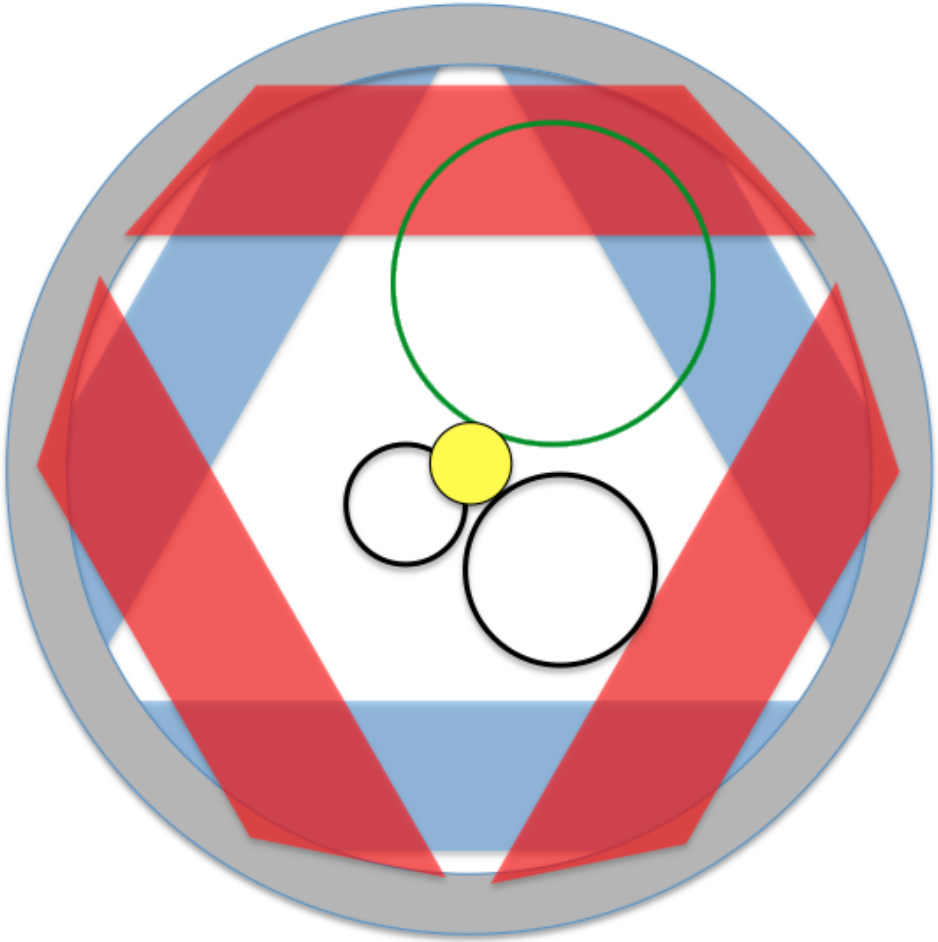
Experimental layout - Mu2e

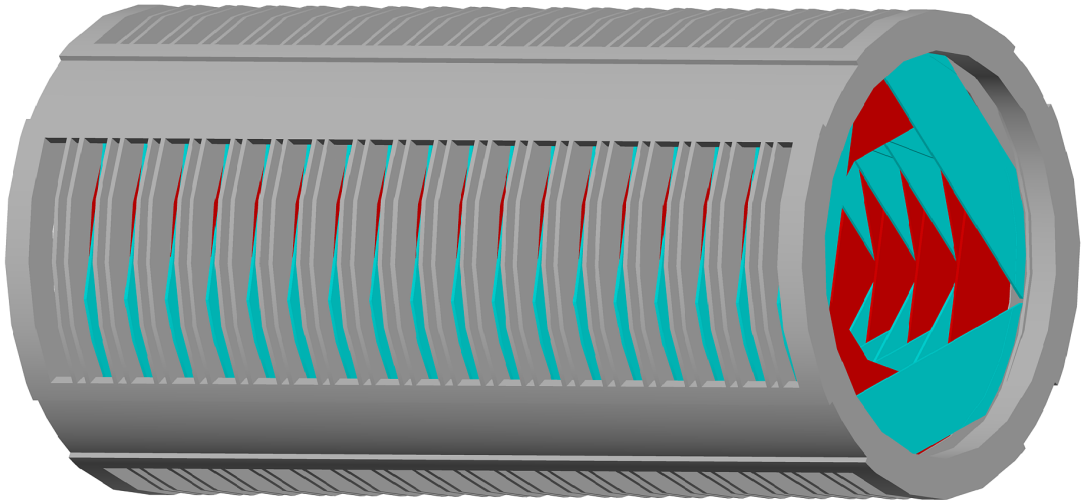


Steven Boi, NuFact 2018

- Charge selection in curved solenoid

Mu2e Tracker

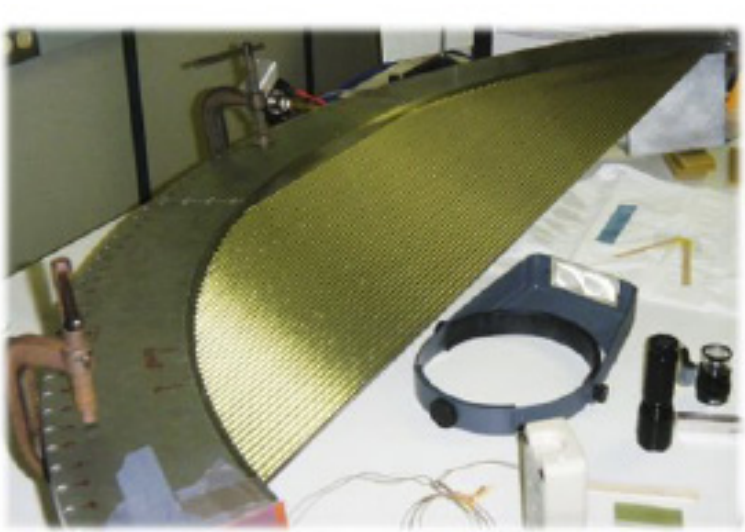


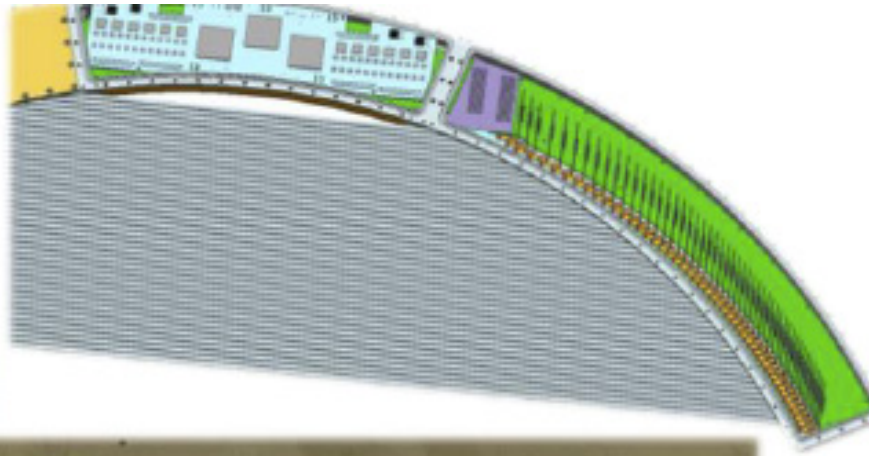


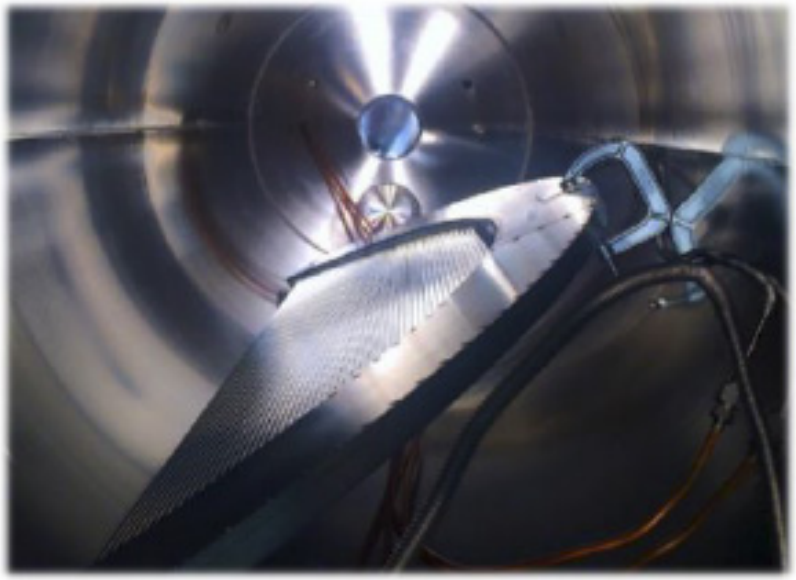
- Straw tubes in vacuum
- Outside of radius of Michel electrons

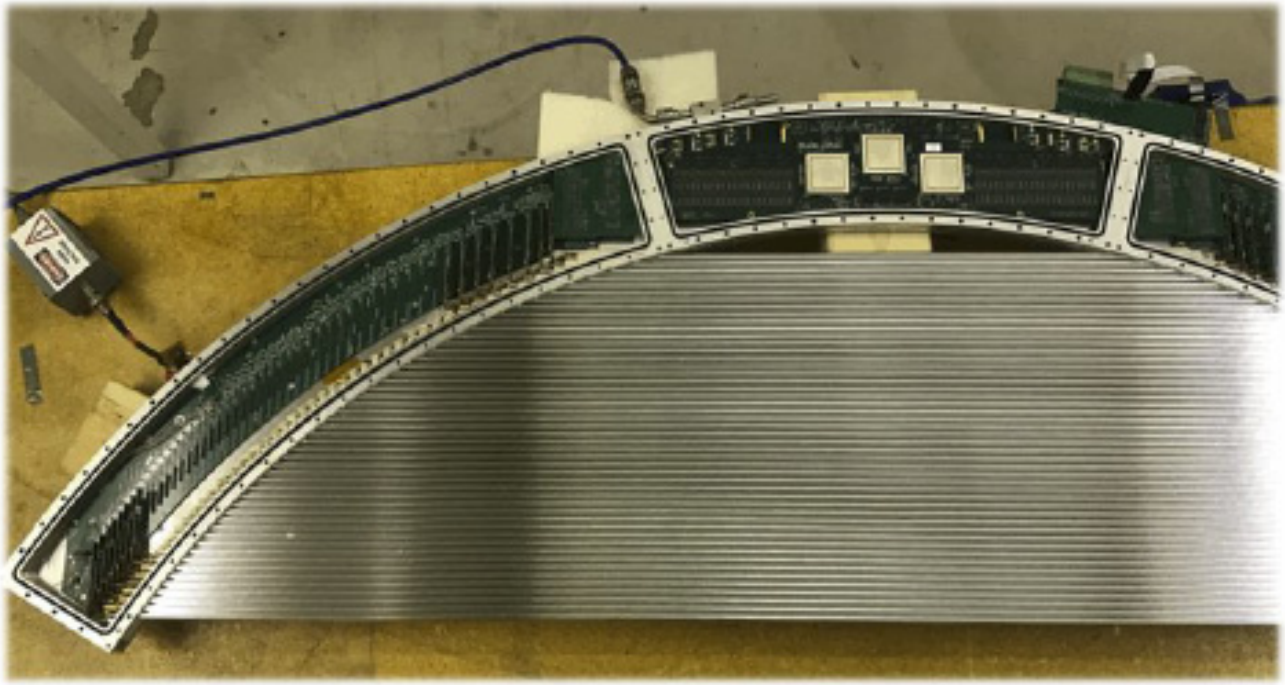
Mu2e CDR

Mu2e Tracker



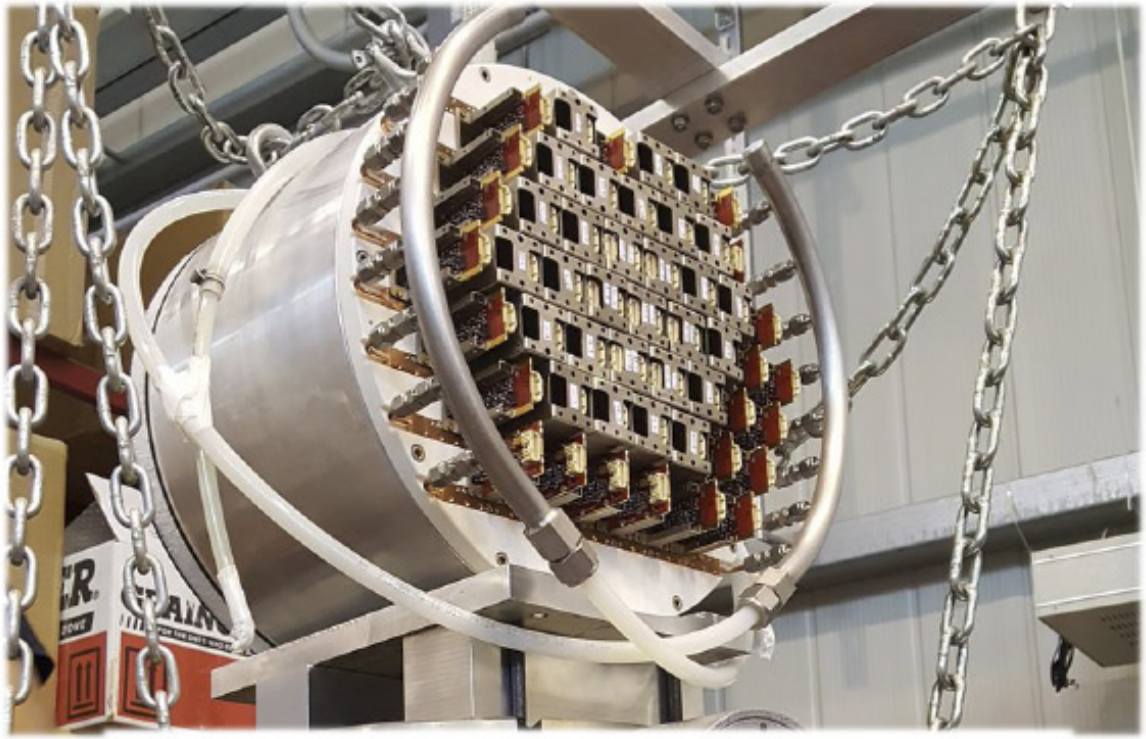


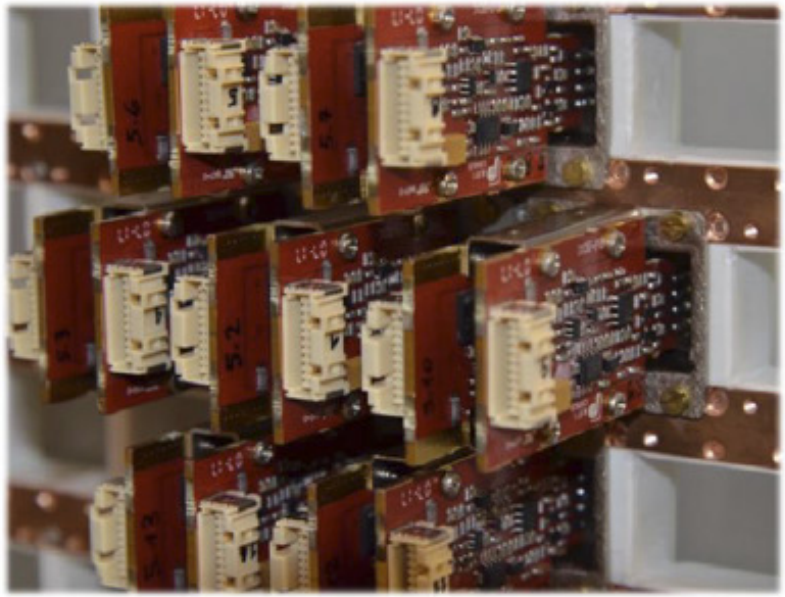


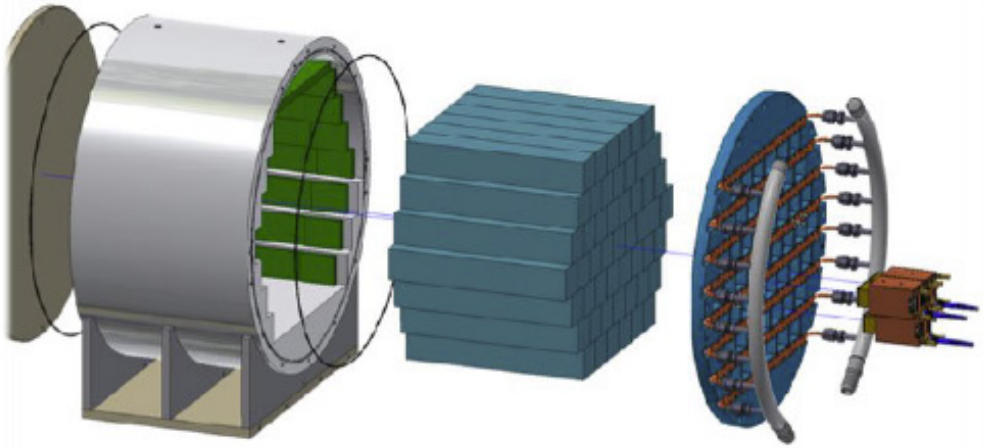


Steven Boi, NuFact 2018

Mu2e Calorimeter



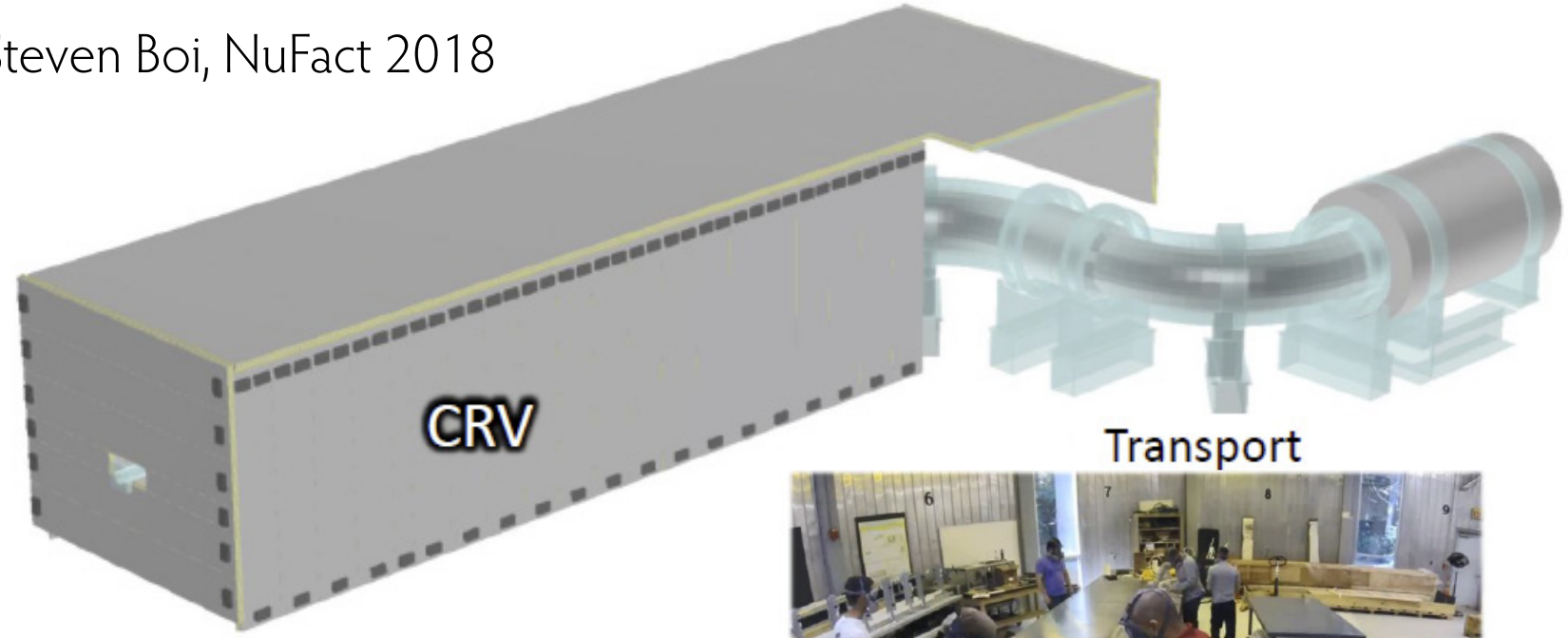




Steven Boi, NuFact 2018

Mu2e Cosmic Ray Veto

Steven Boi, NuFact 2018



Production Solenoid

Transport

- Without veto:
  ~ 1 signal-like event/day

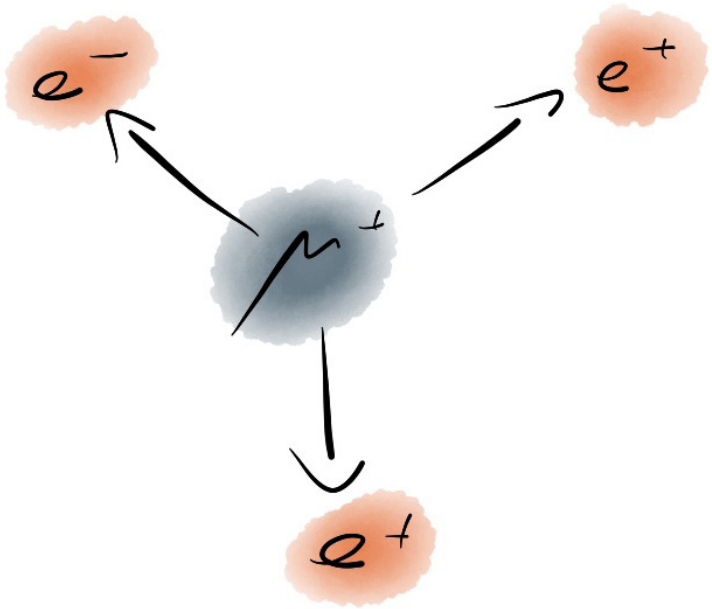
Conversion: Expected sensitivities

- J-PARC: Comet/DeeMee Fermilab: Mu2e
- Comet Phase I and DeeMee might get to ~10^{-14} as early as 2019
- Both Comet Phase II and Mu2e will start around 2022
- Should get single event sensitivities well below 10^{-16}
- Paths to 10^{-18} being explored

Searching for $\mu^+ \to e^+e^-e^+$ with

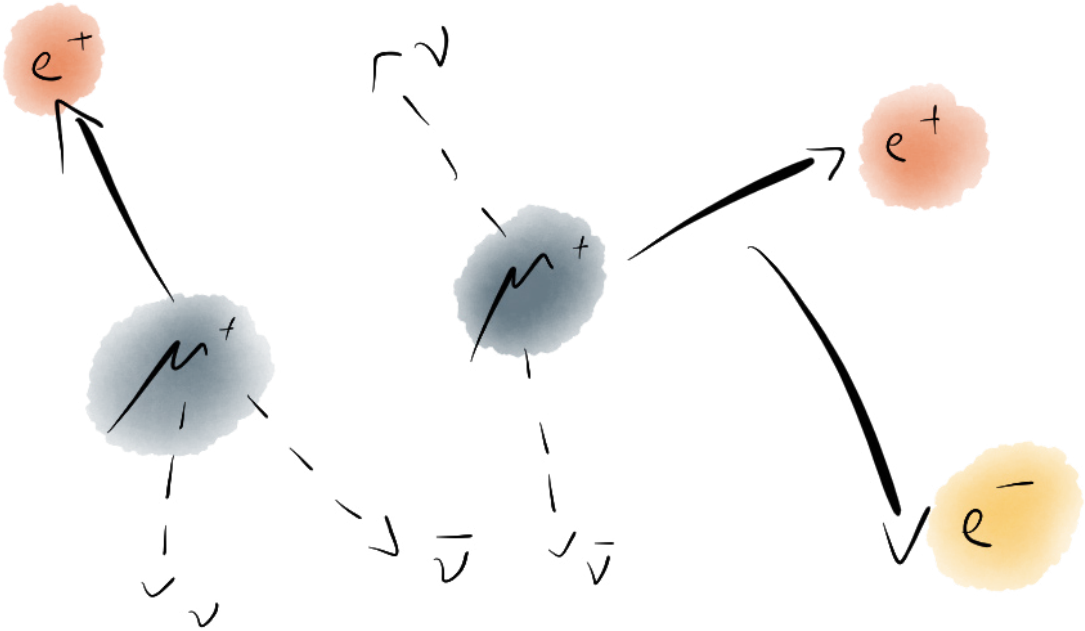
Mu3e

The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma\, p_e = m_\mu$
- Maximum momentum: $\frac{1}{2}\, m_\mu = 53$ MeV/c

Accidental Background



- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha (electron-positron) scattering,
  - Mis-reconstruction

- Need very good timing, vertex and momentum resolution

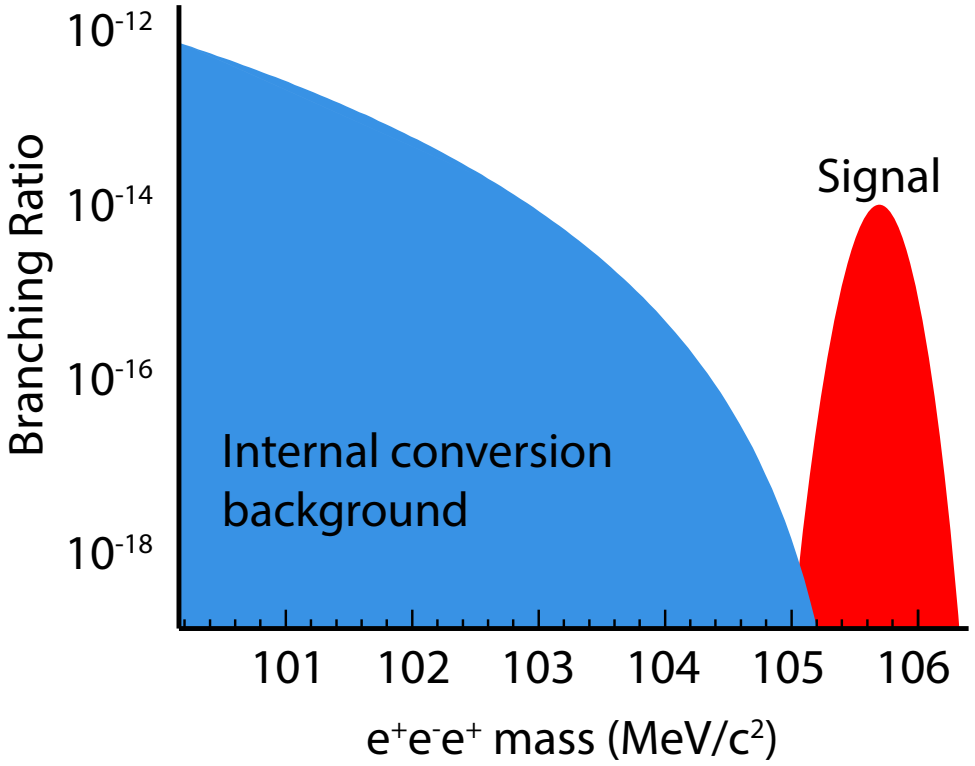
Internal conversion background

- Need excellent momentum resolution

- Allowed radiative decay with internal conversion:

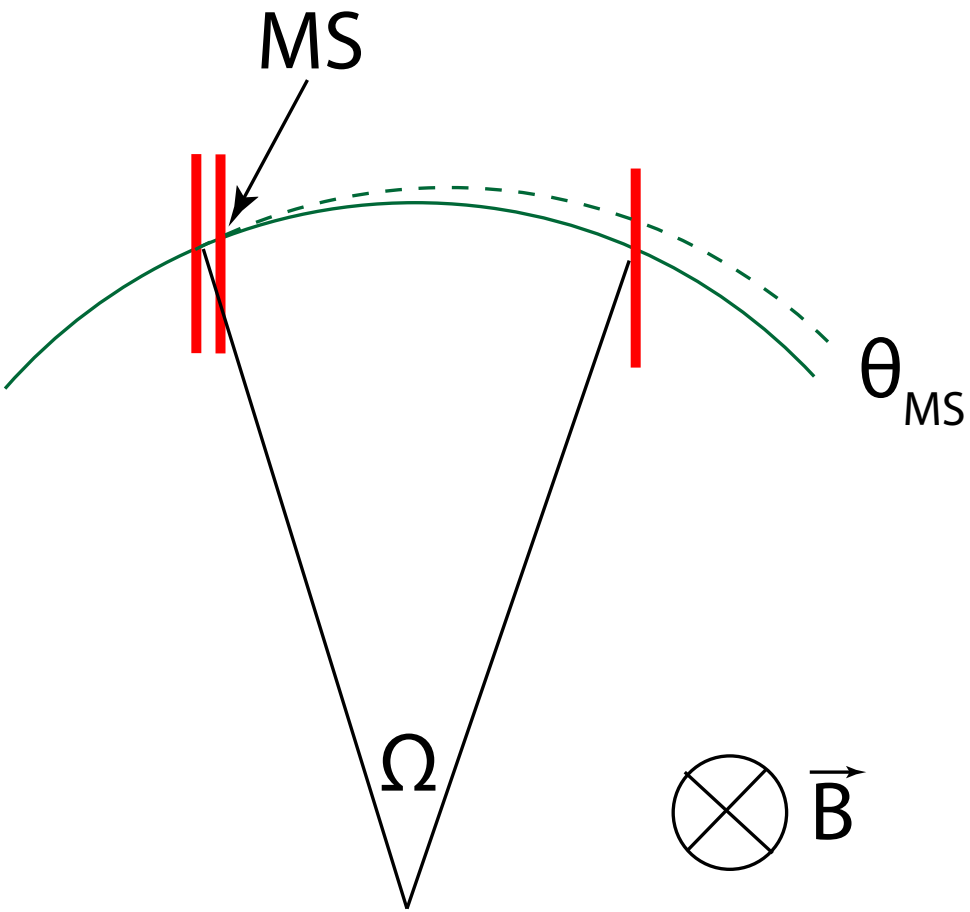
$$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$$

- Only distinguishing feature: Missing momentum carried by neutrinos



Need excellent momentum resolution
for very low momentum electrons

Momentum measurement

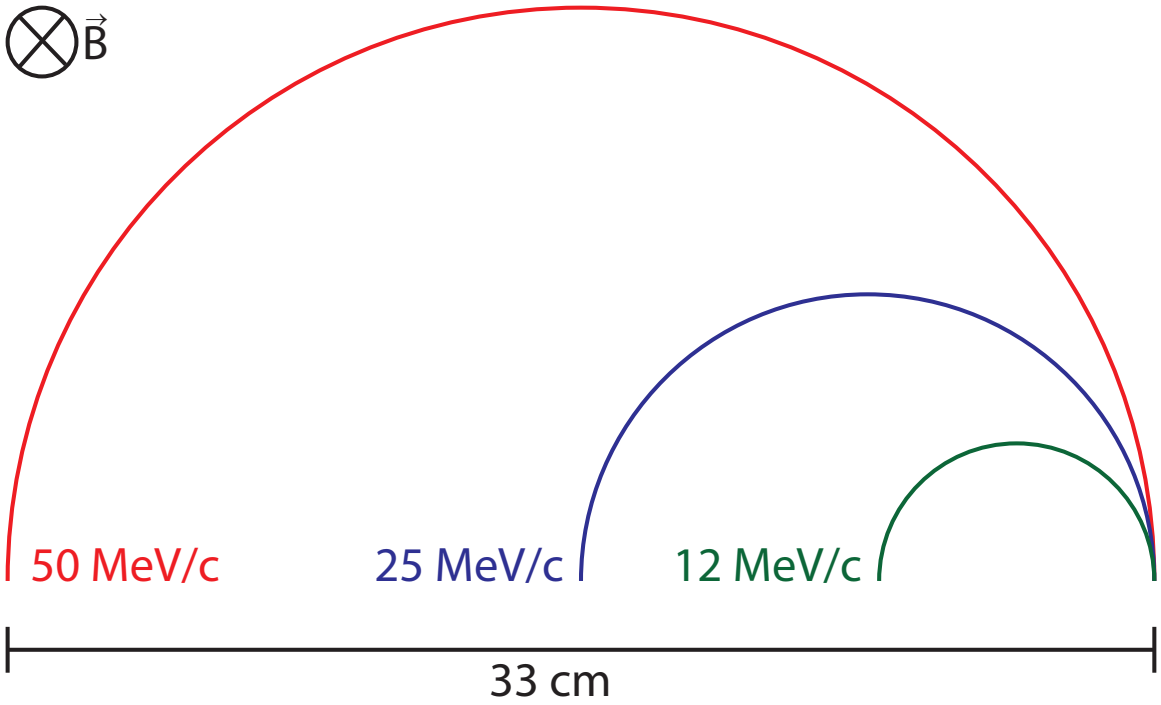


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

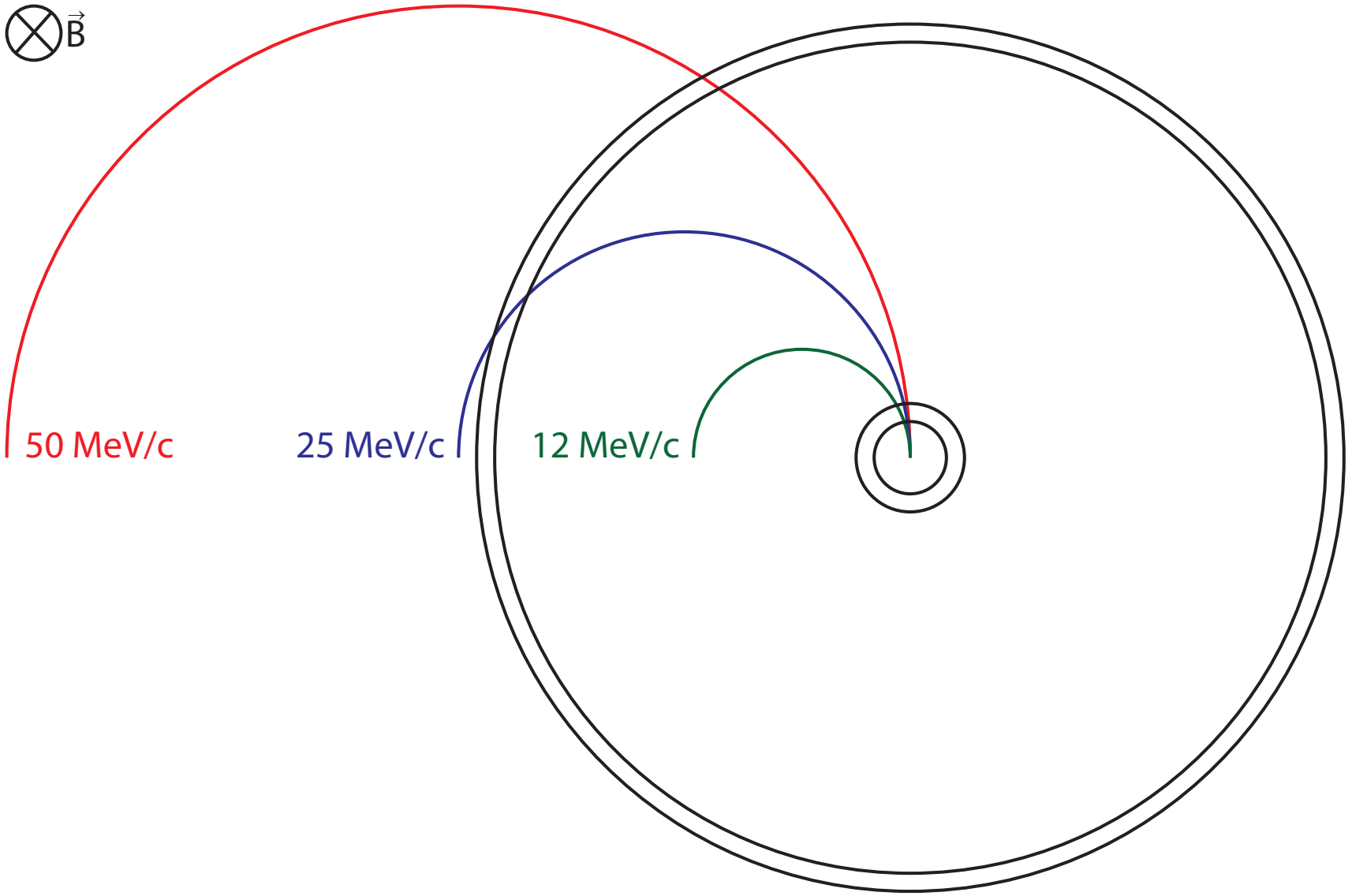
$$\sigma_{P}/_{P} \sim \theta_{MS}/_{\Omega}$$

- Precision requires large lever arm (large bending angle Ω) and low multiple scattering θ_{MS}

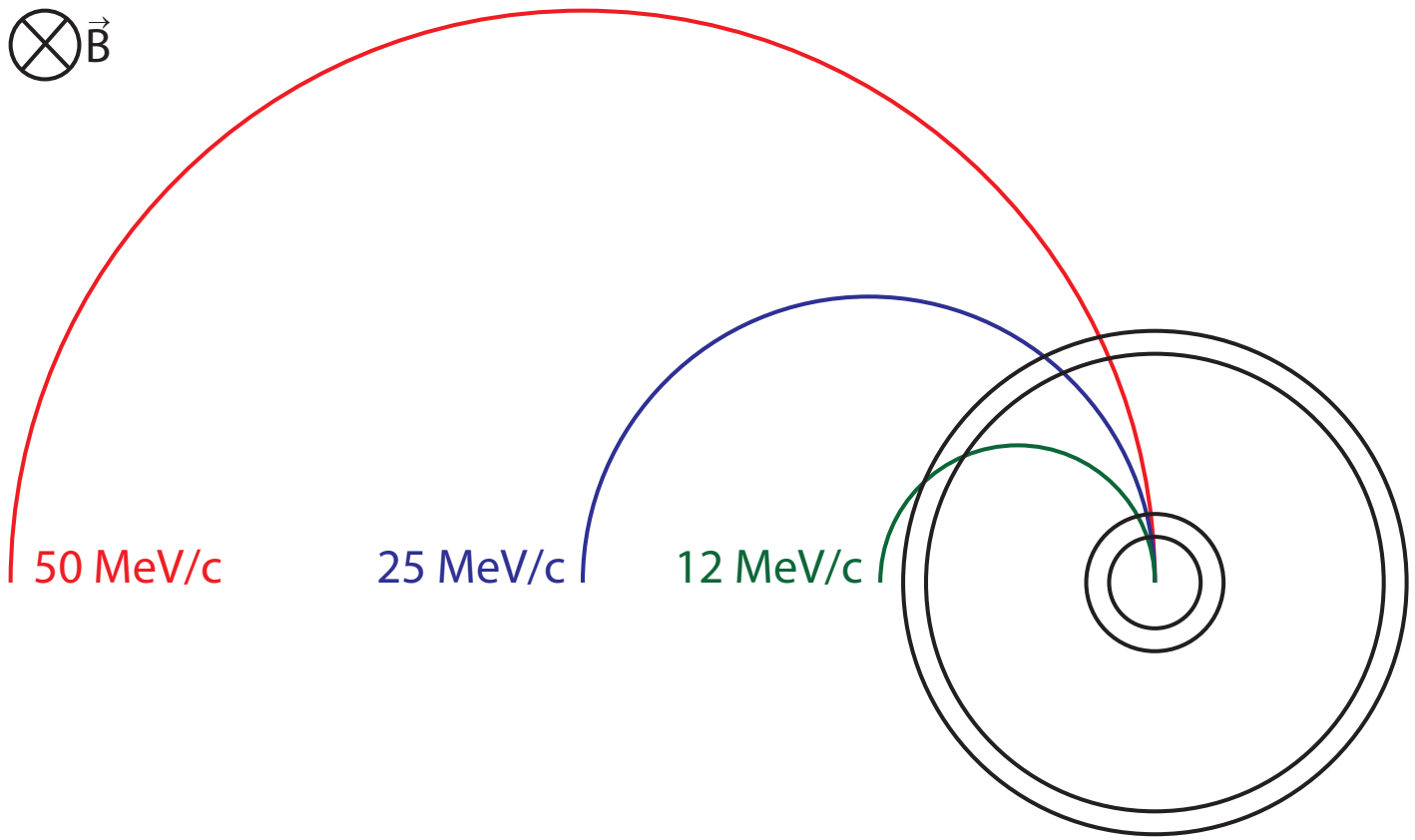
Precision vs. Acceptance



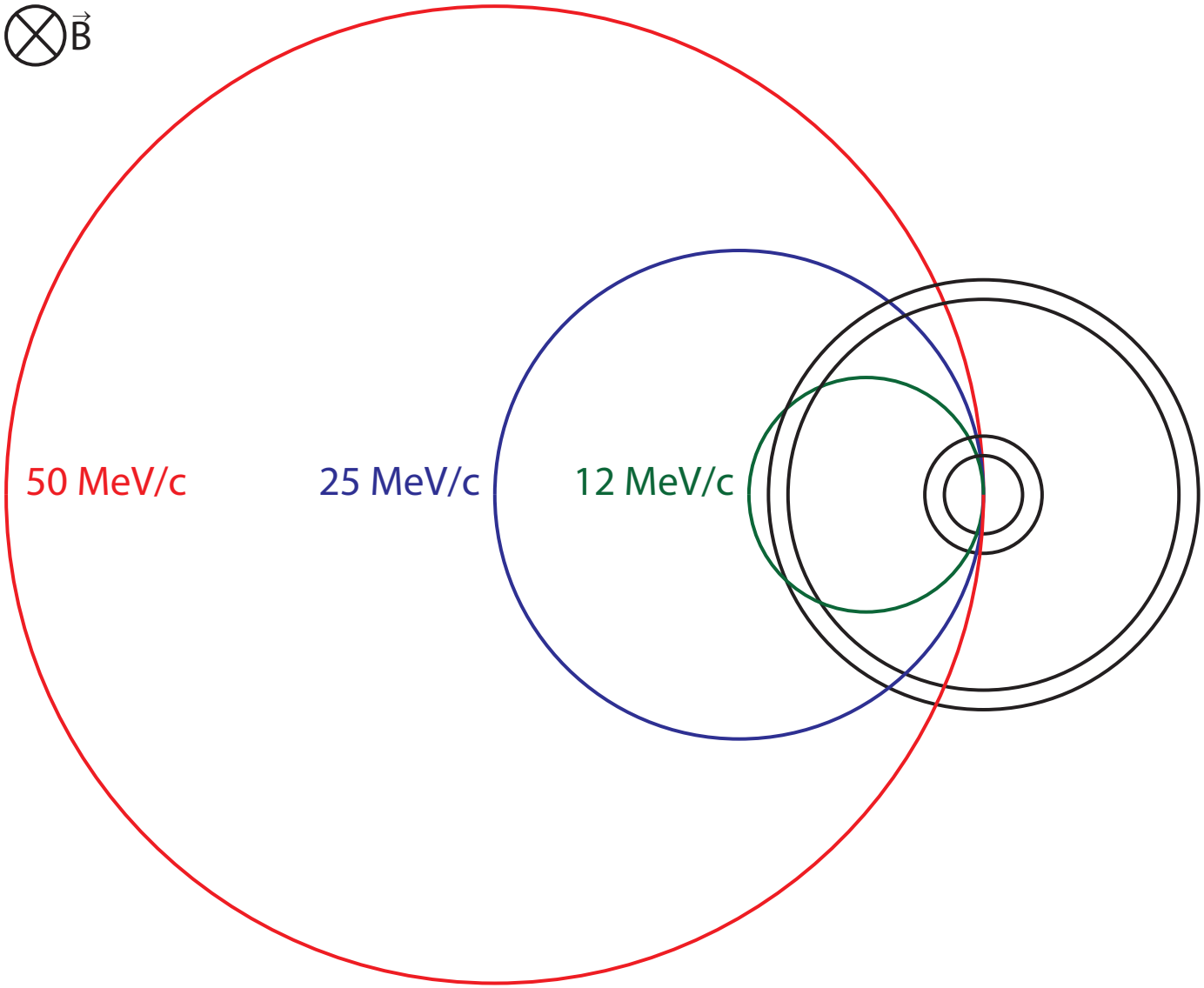
Precision vs. Acceptance



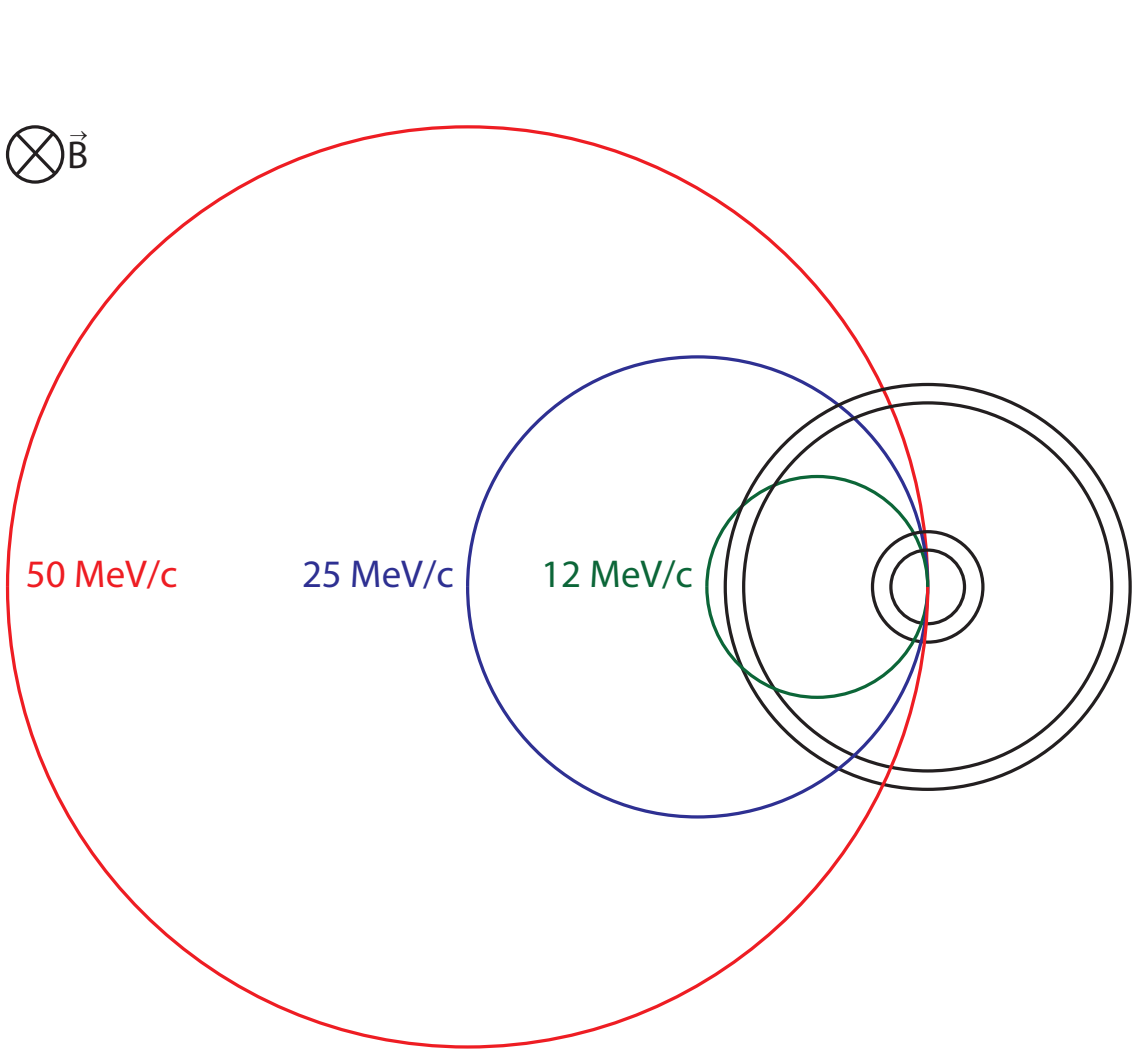
Precision vs. Acceptance

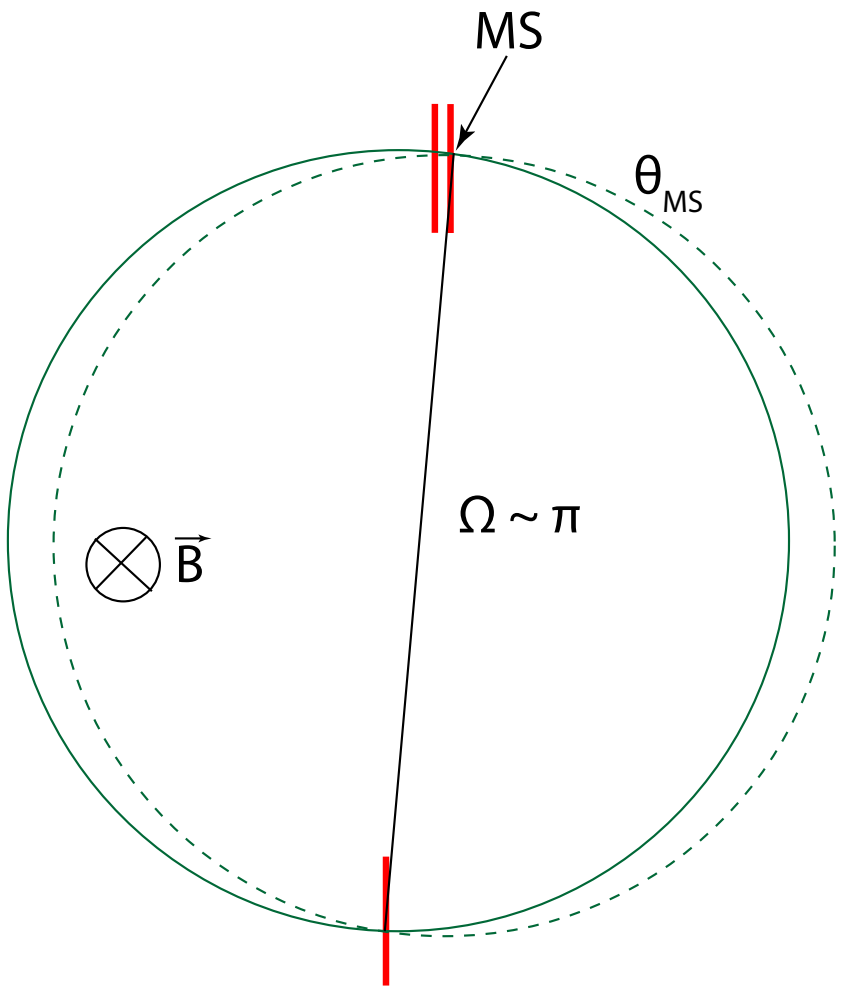


Precision vs. Acceptance

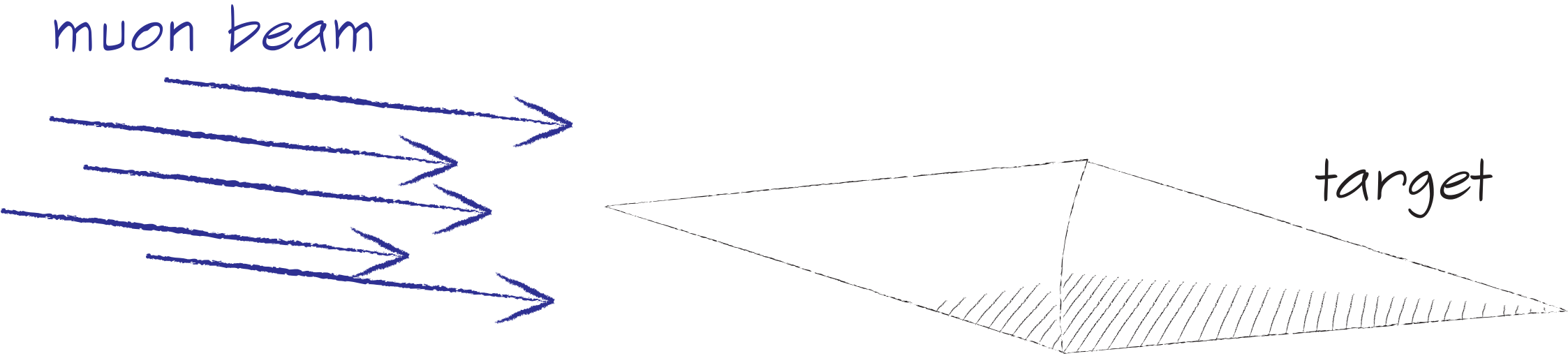


Precision vs. Acceptance

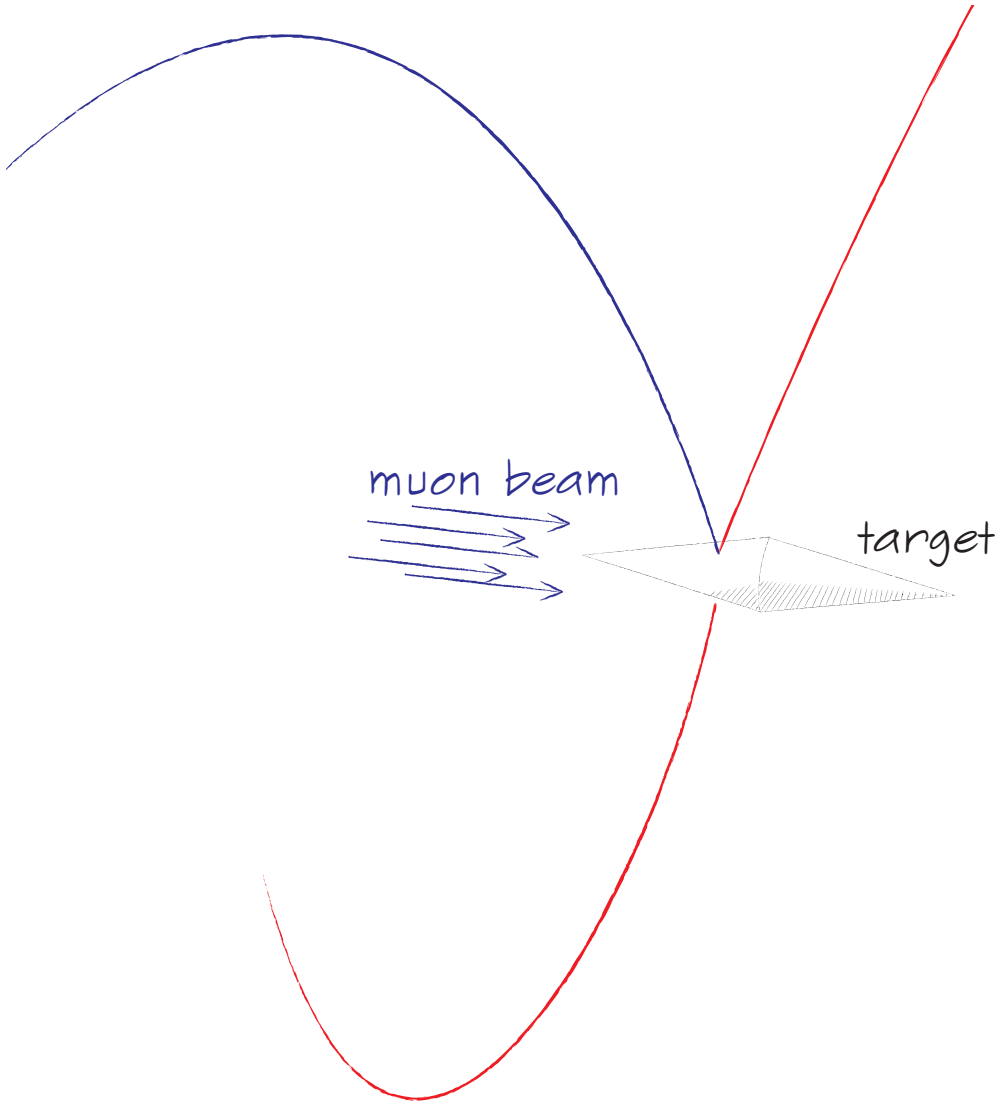




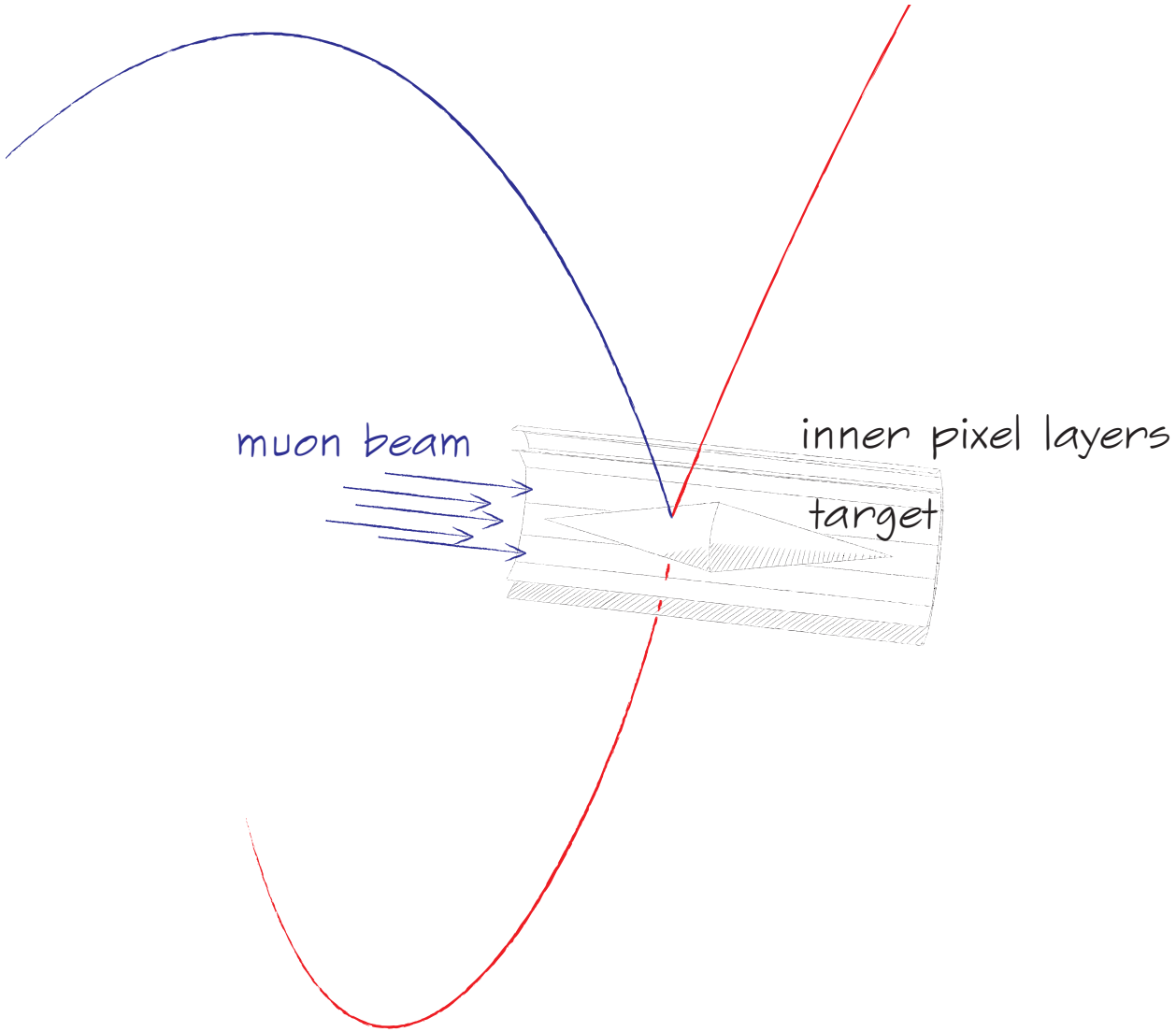
Detector Design



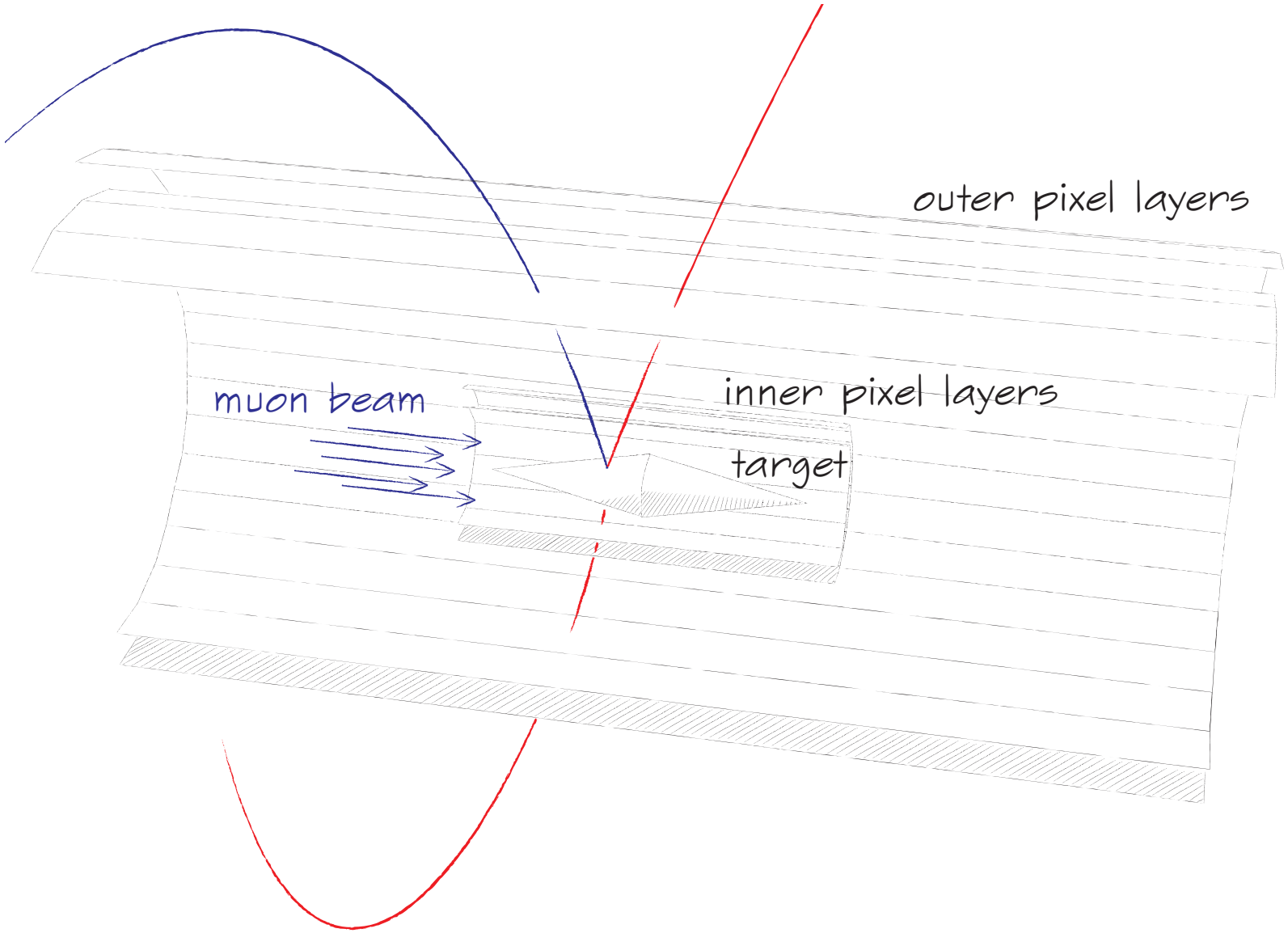
Detector Design



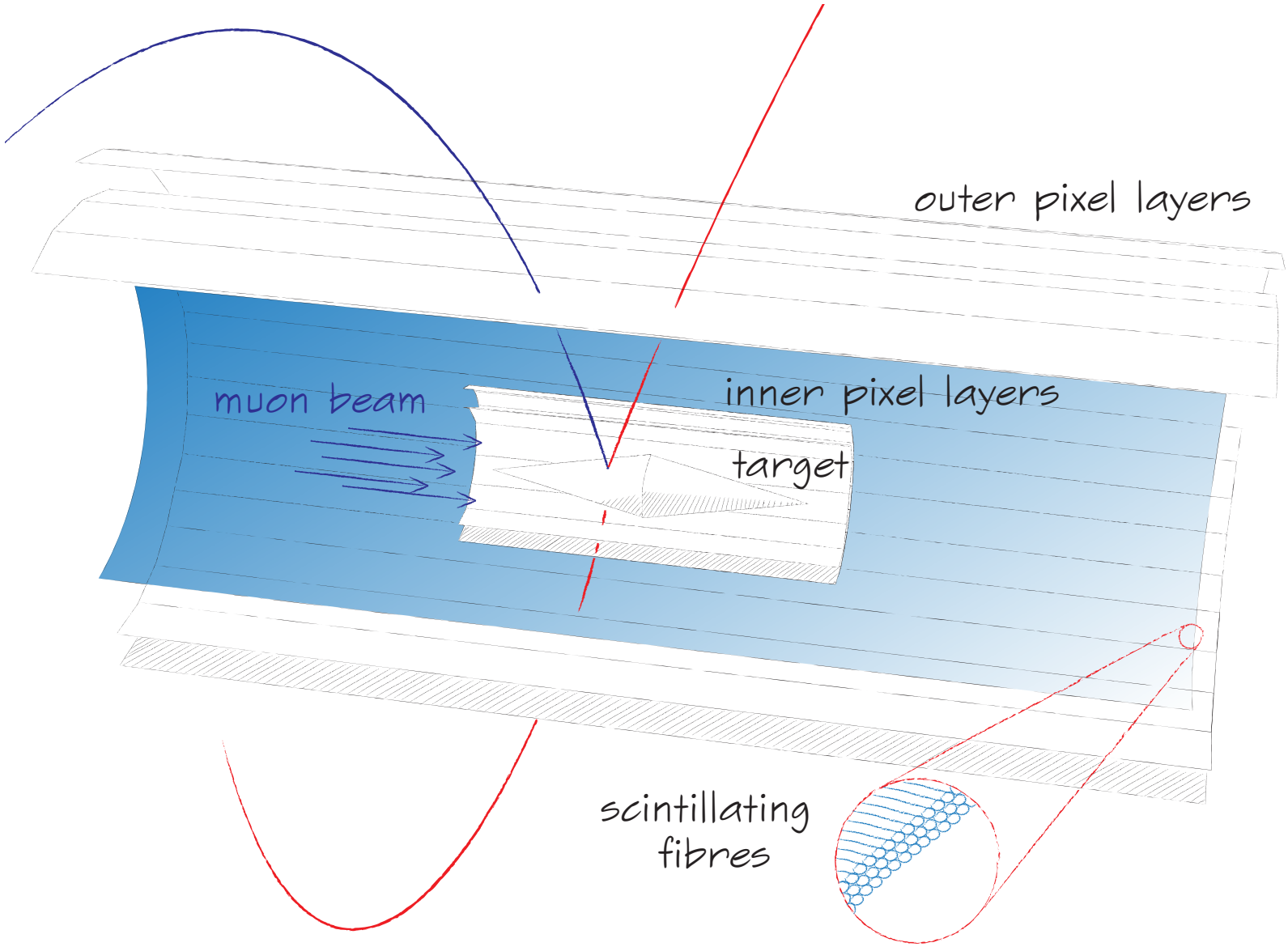
Detector Design



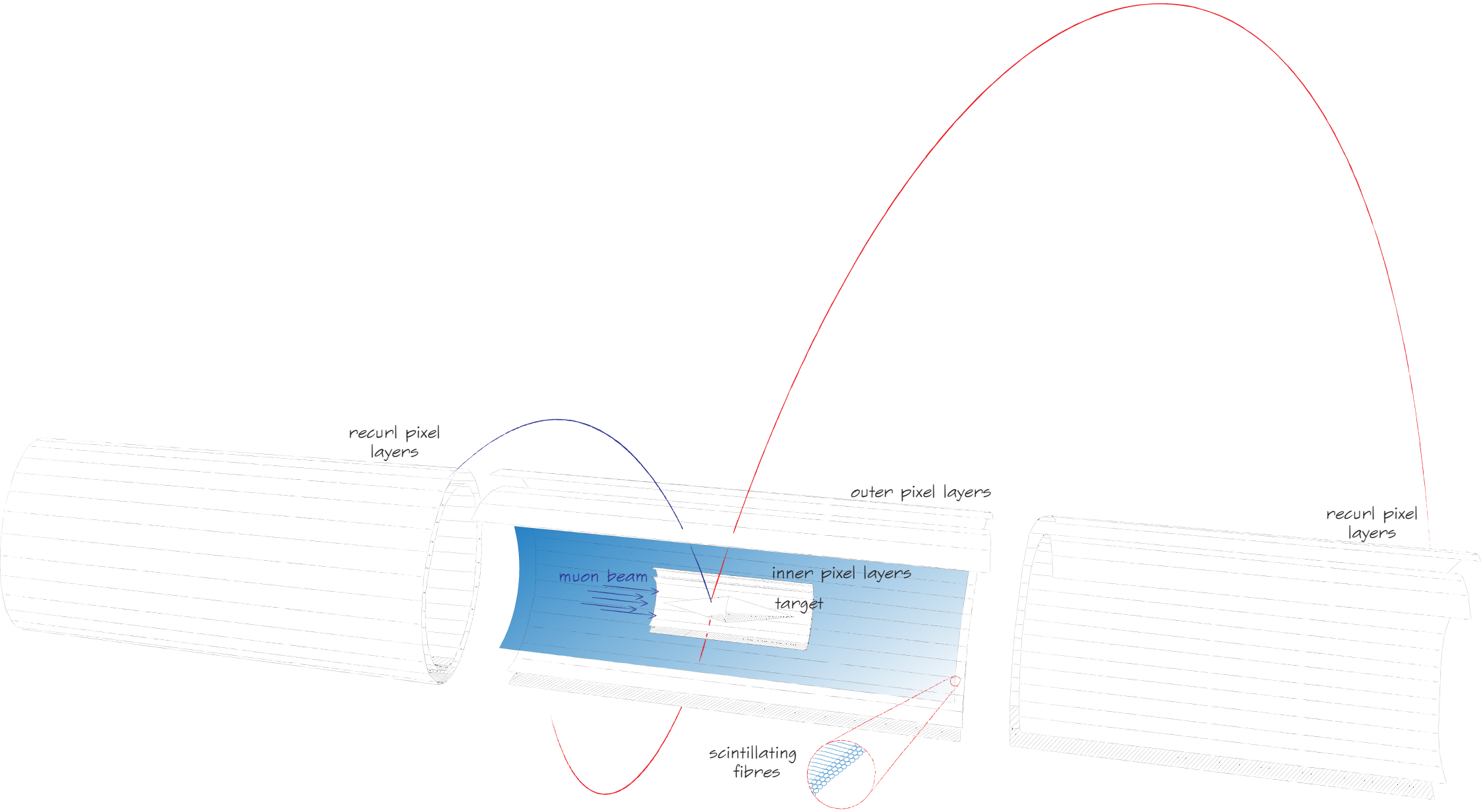
Detector Design



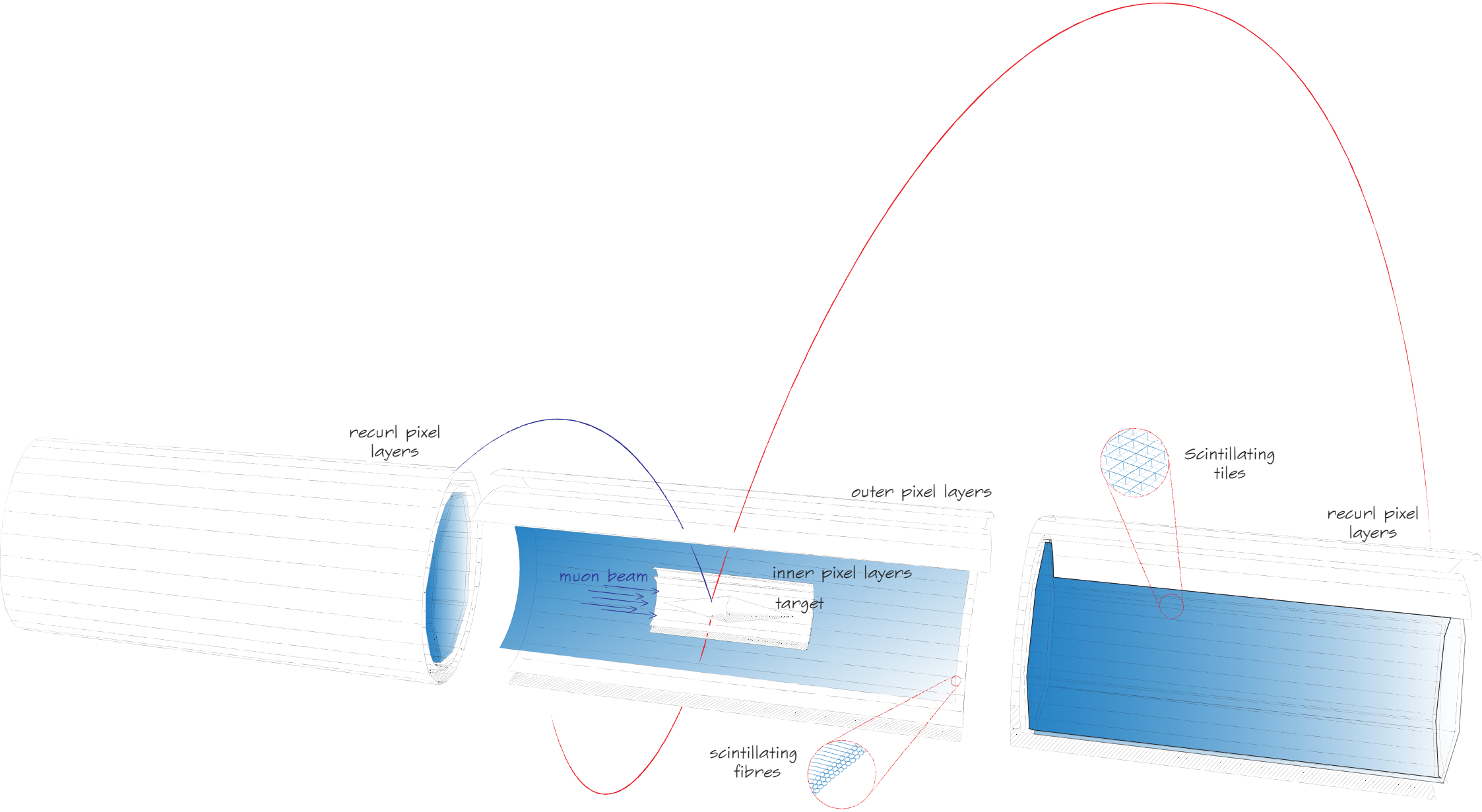
Detector Design



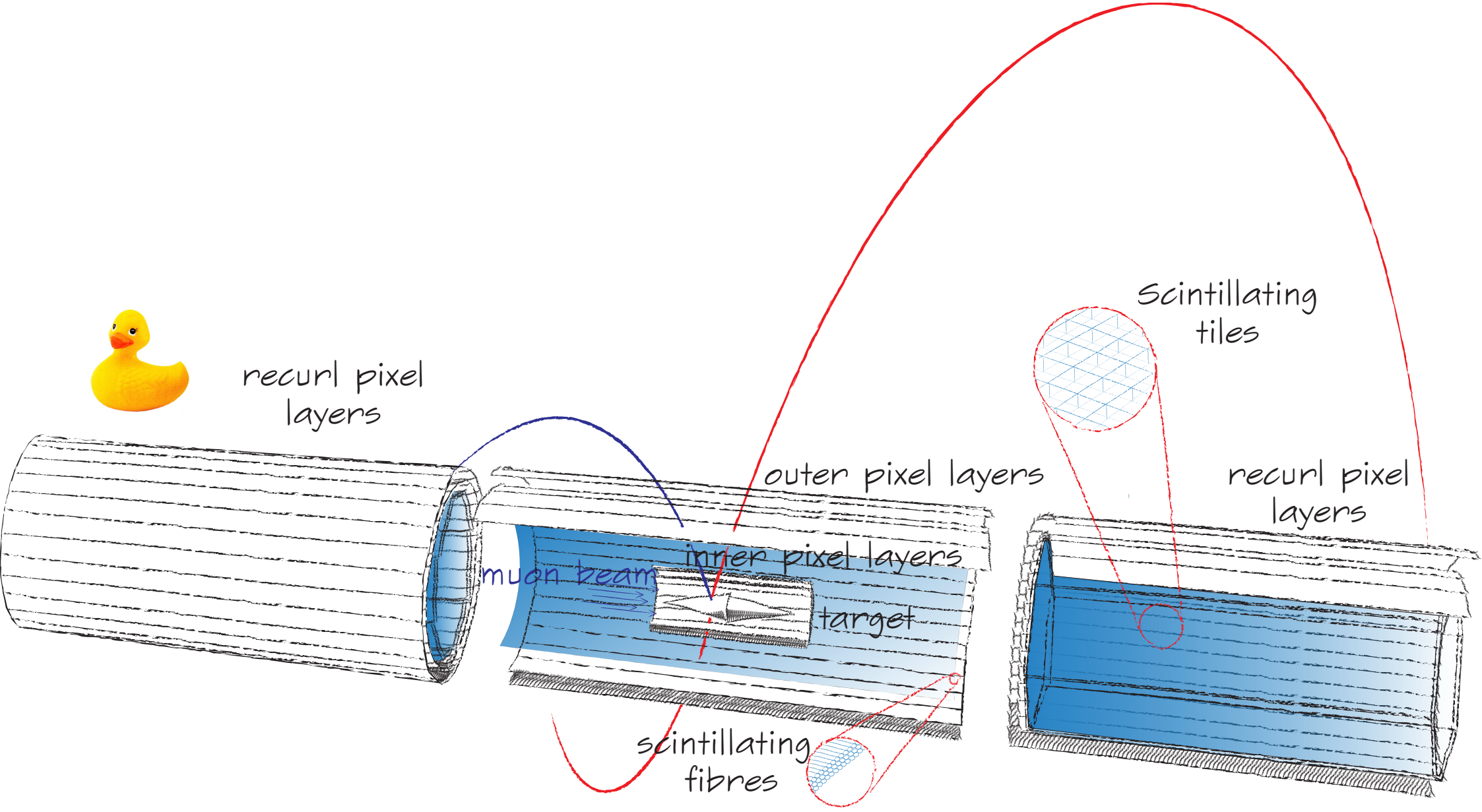
Detector Design



Detector Design



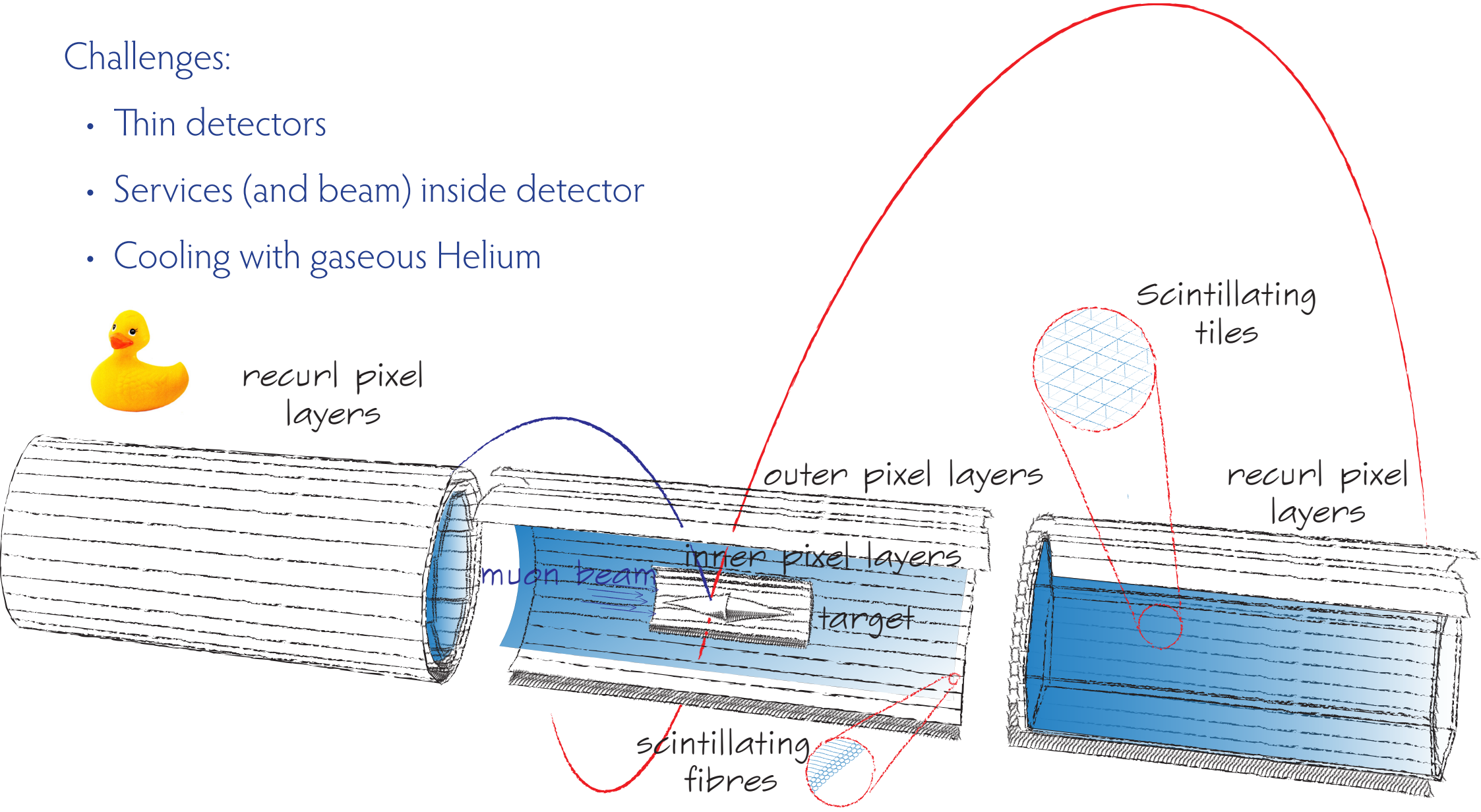
Detector Design



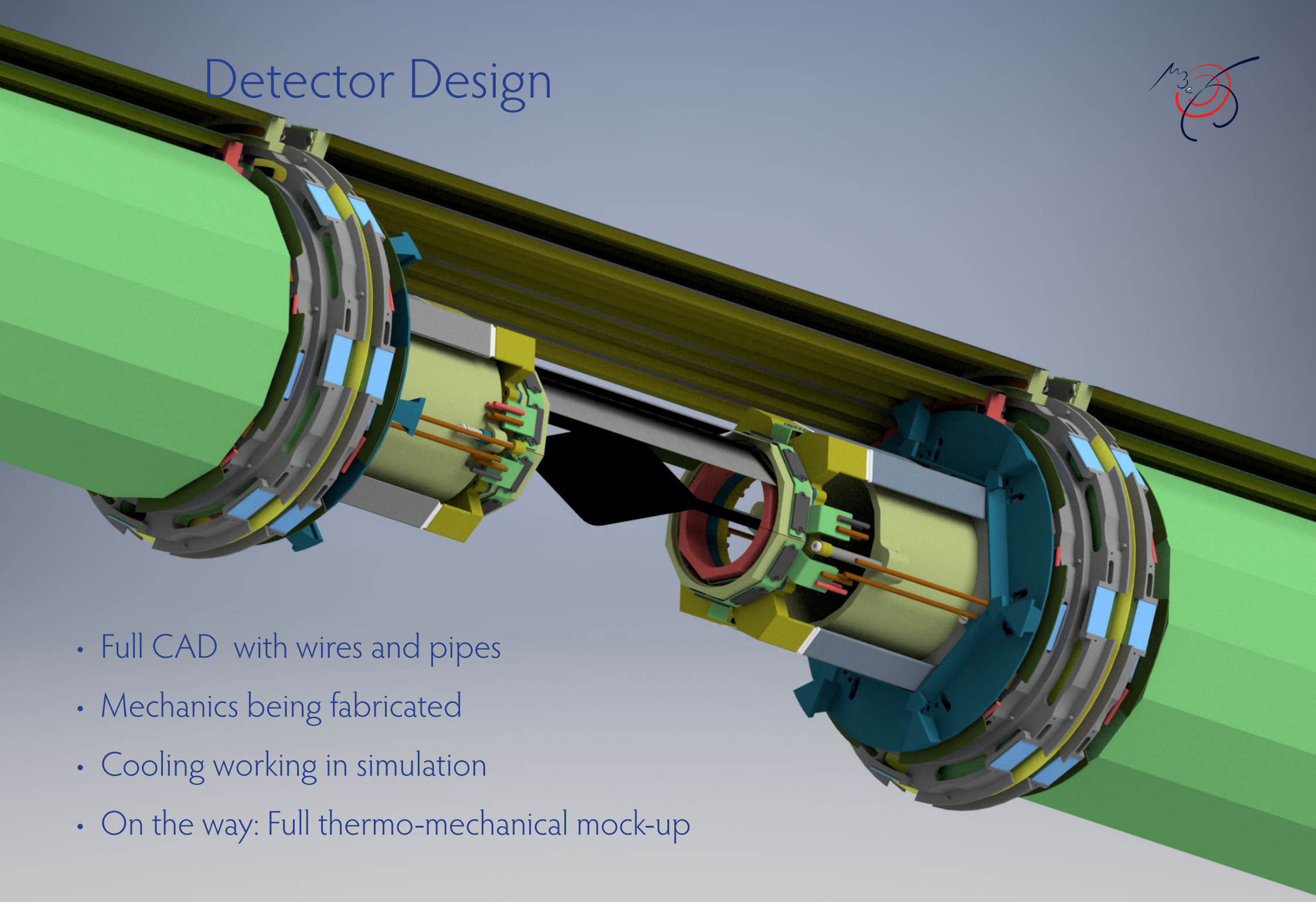
Detector Design

Challenges:

- Thin detectors
- Services (and beam) inside detector
- Cooling with gaseous Helium



Detector Design



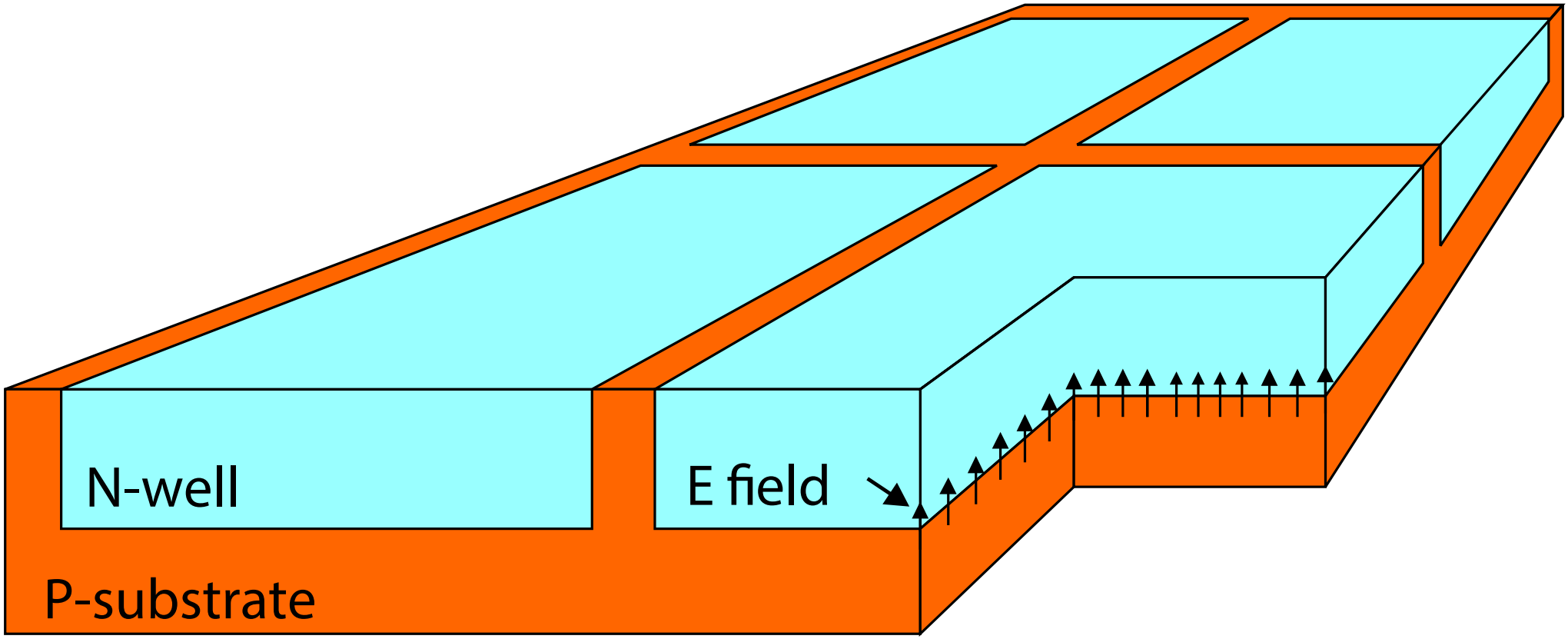
- Full CAD with wires and pipes
- Mechanics being fabricated
- Cooling working in simulation
- On the way: Full thermo-mechanical mock-up

Very thin and fast silicon pixel sensors: HV-MAPS

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)



Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
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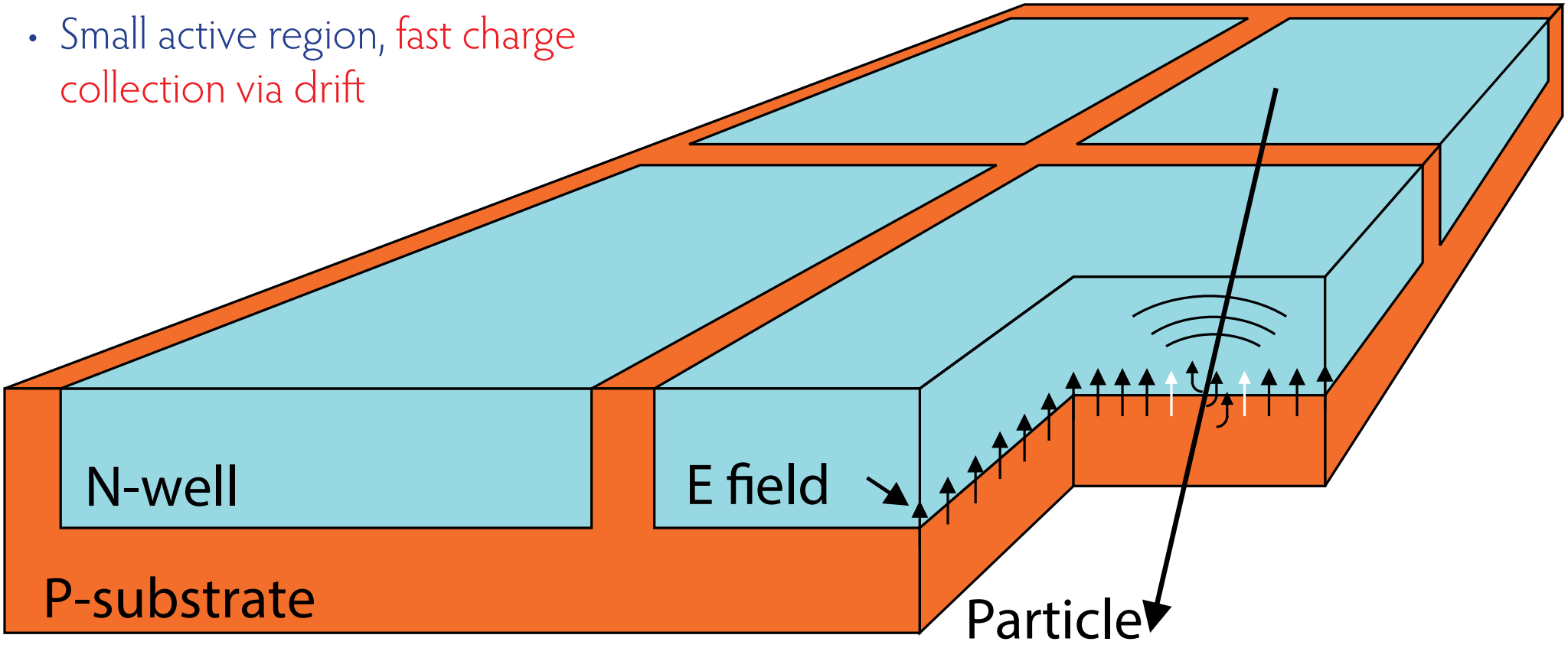


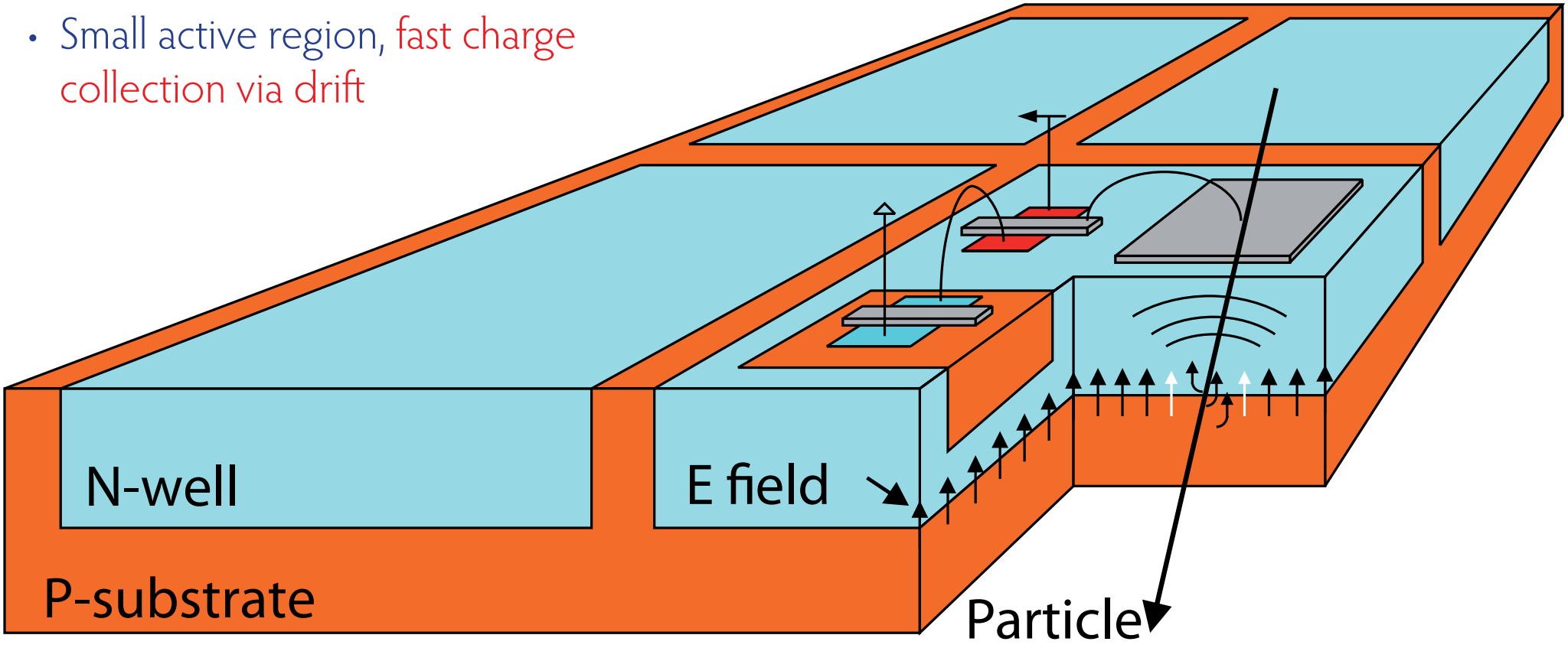
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift

- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 µm

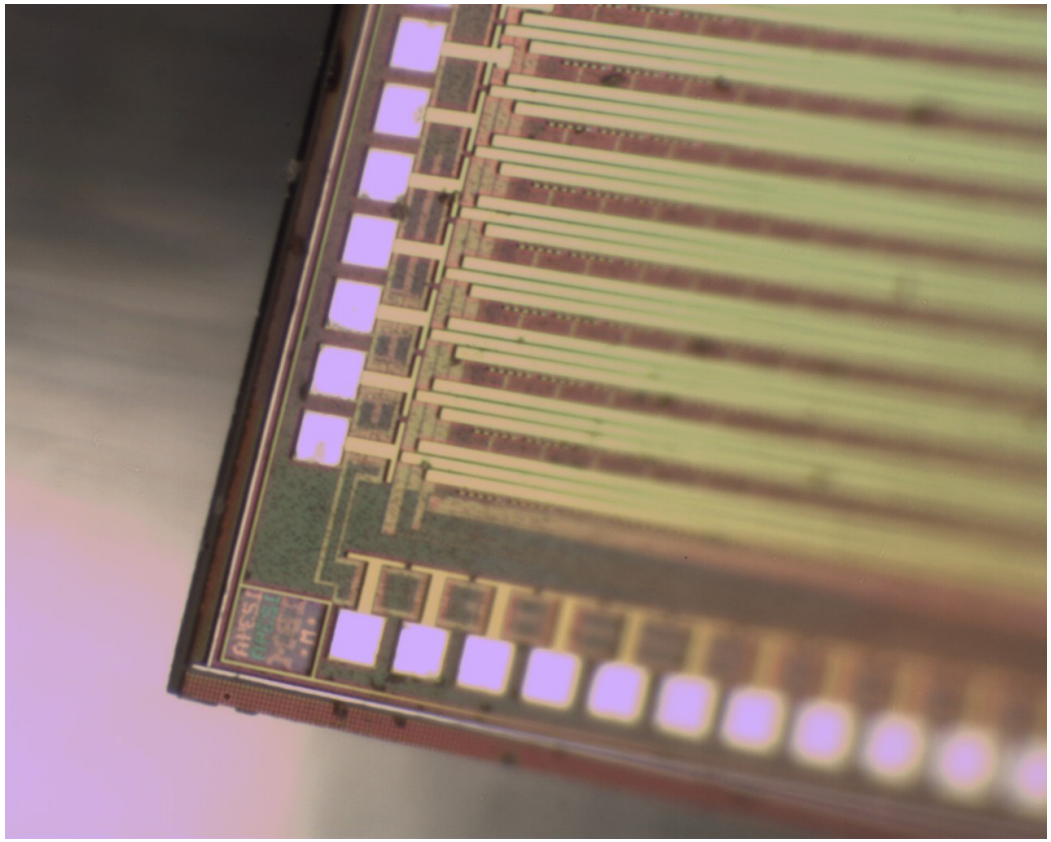
(I.Perić, NIM A 582 (2007) 876)



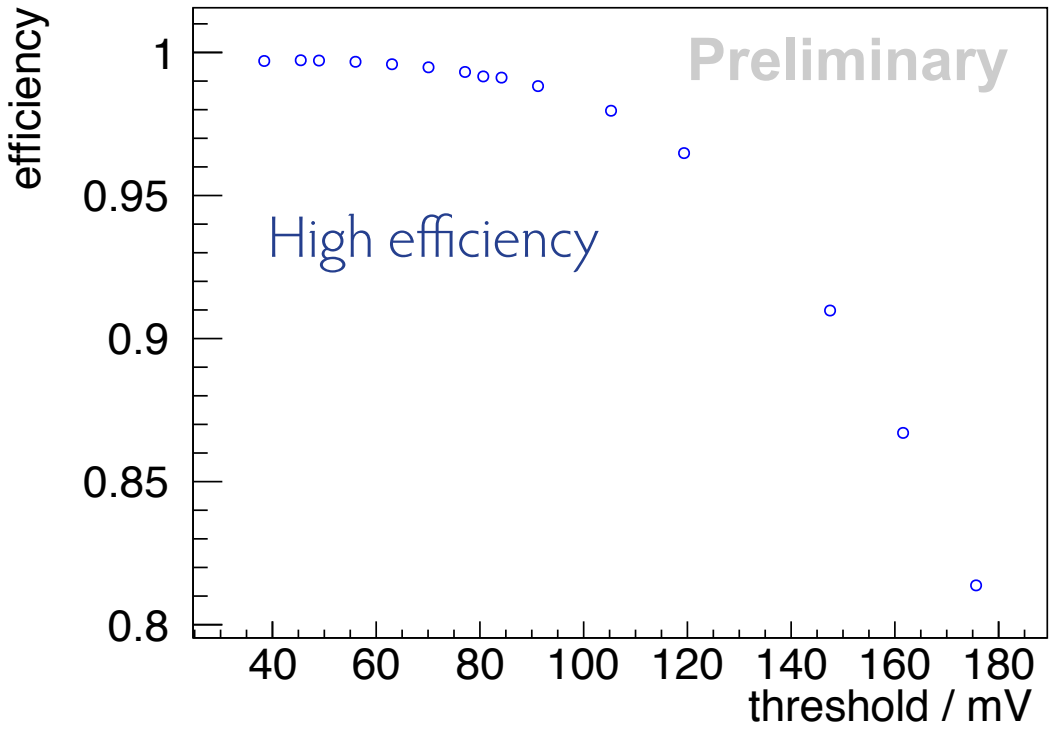
The MuPix Prototypes

Developed a series of HV-MAPS prototypes

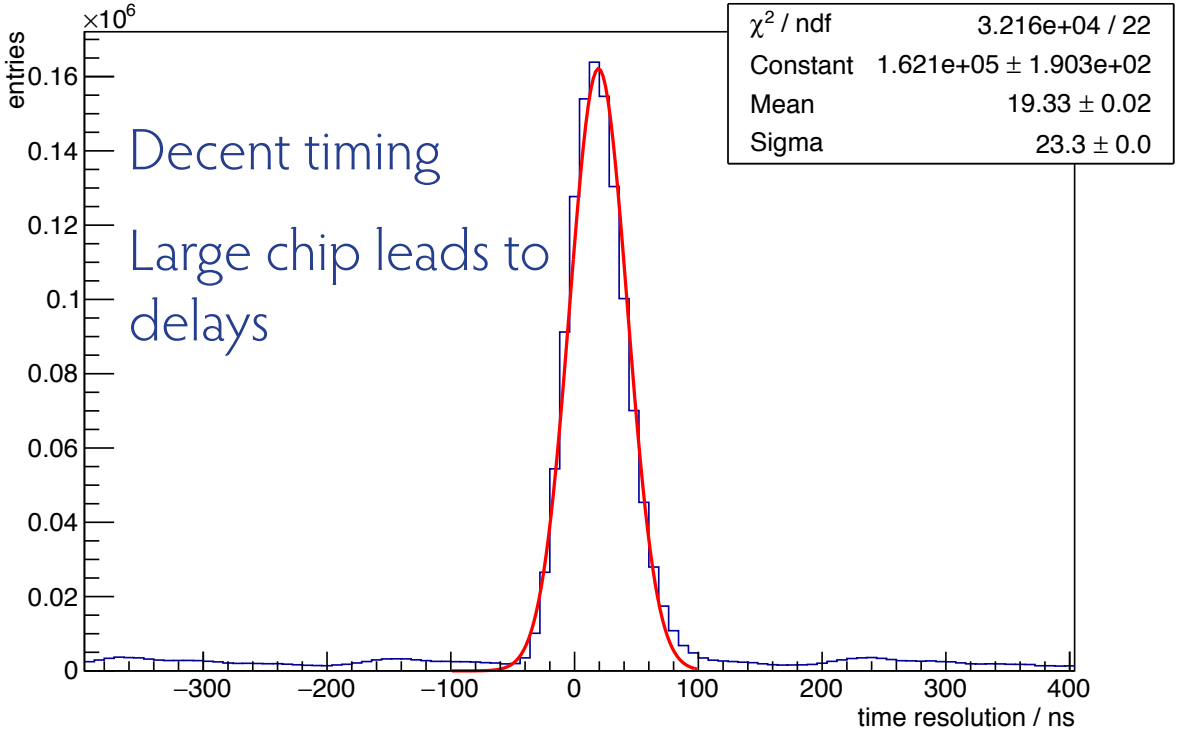
- Goal: Detection and signal processing with just 50 µm silicon
- 6th chip, MuPix7, is a full system-on-a-chip
- Well characterized, working very nicely
- Now: Going "big" 2 x 1 cm^2 MuPix8 with 80 by 80 µm pixels under test



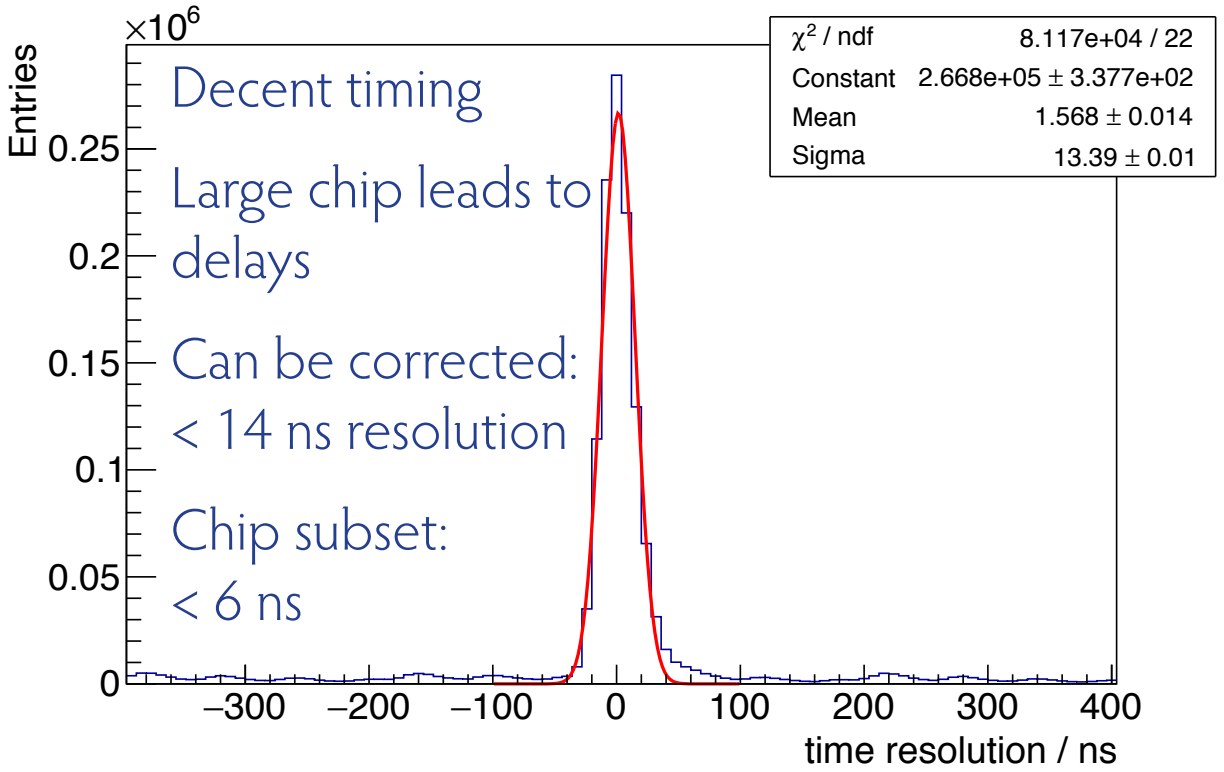
MuPix8: First results



MuPix8: First results

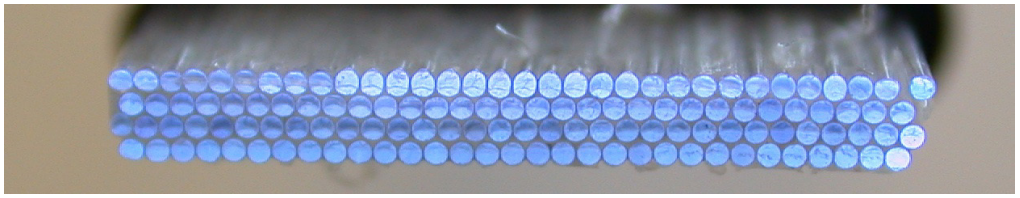


MuPix8: First results



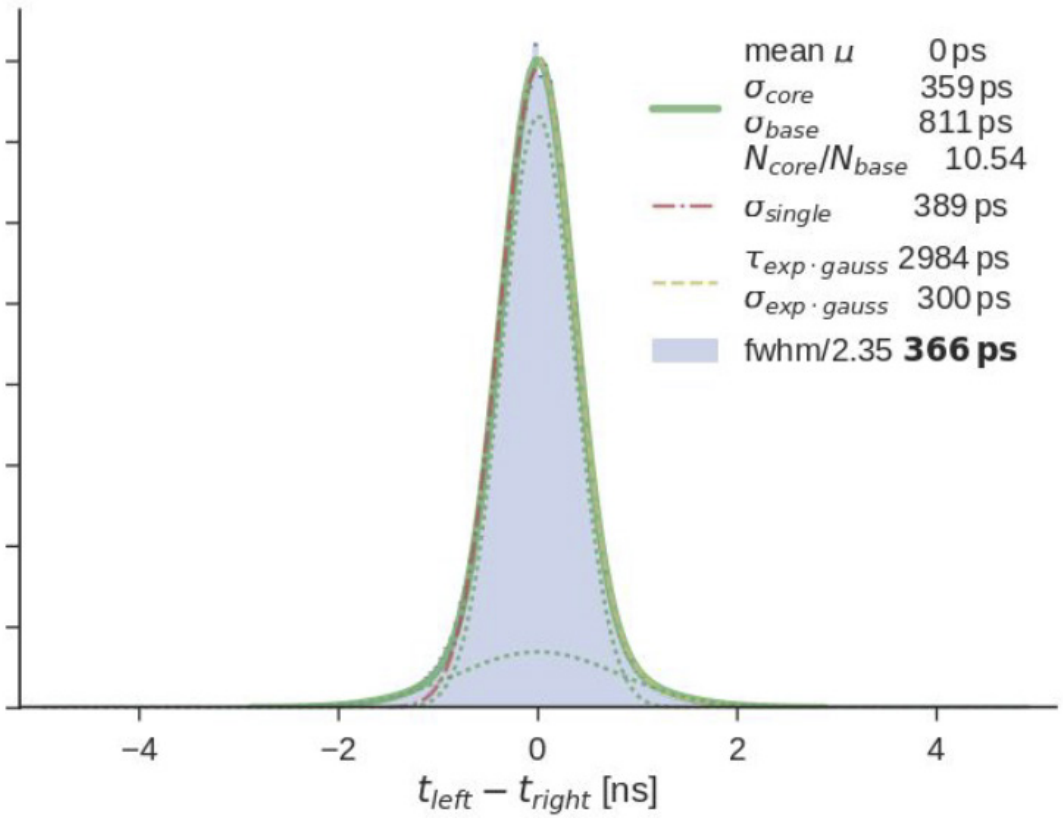
Better timing:
Scintillating fibres and tiles

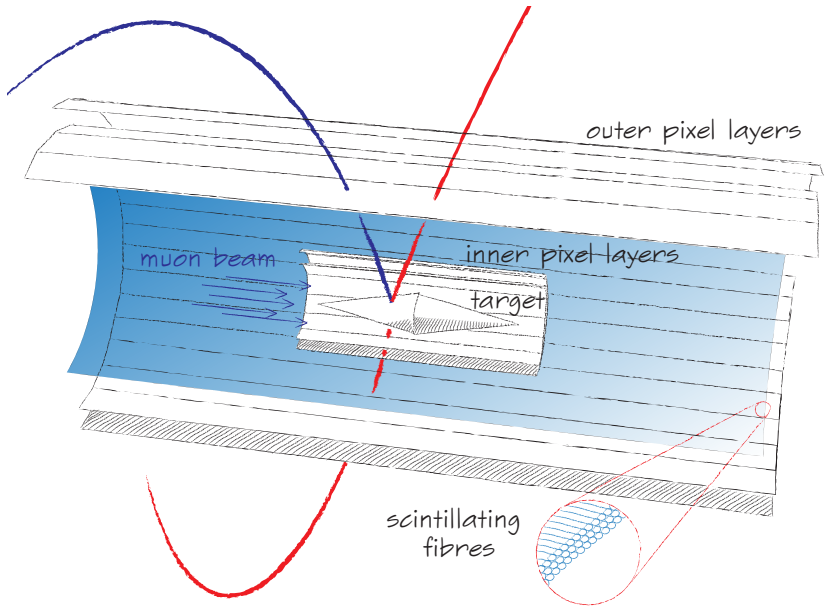
Timing Detector: Scintillating Fibres



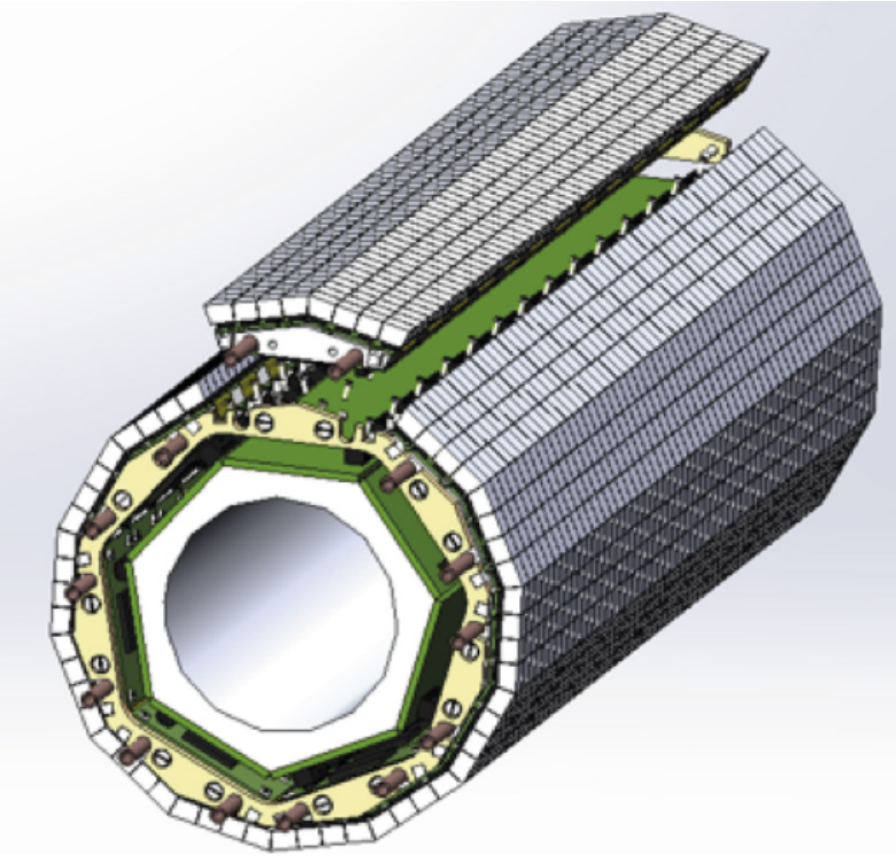
- 4 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)

Timing resolution < 400 ps including ASIC (using a Sr^{90} source)

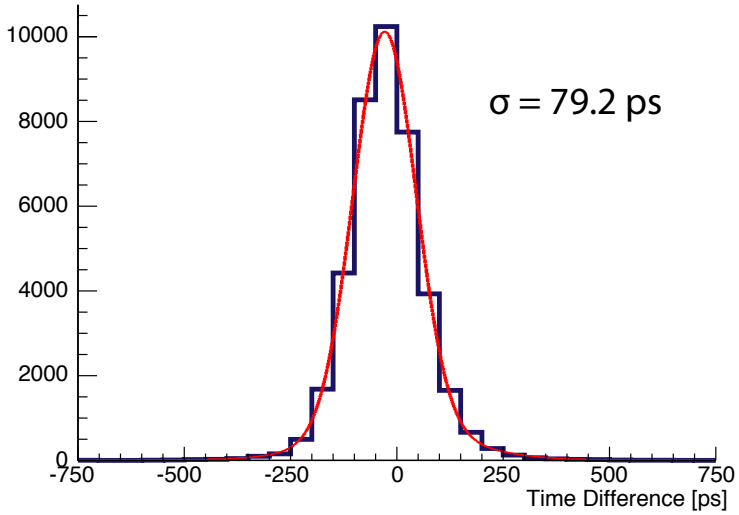


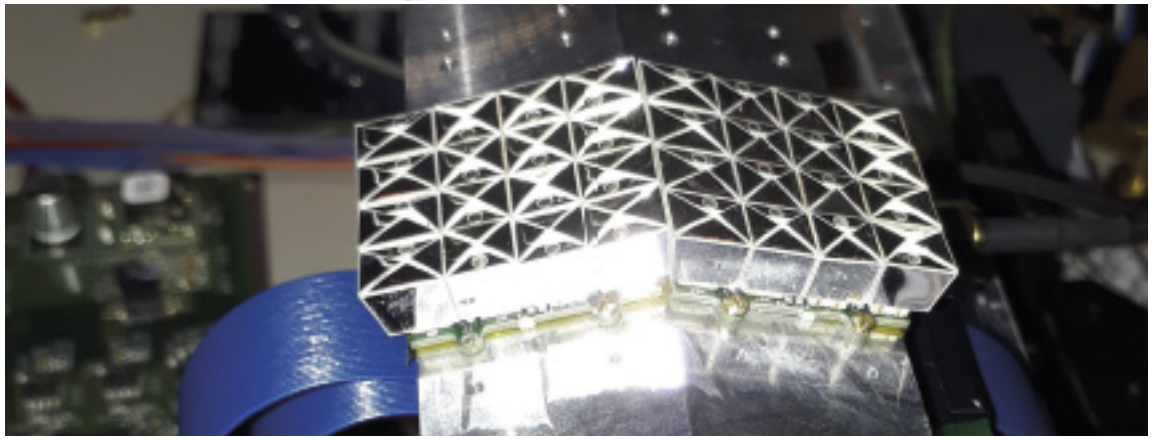


Timing Detector: Scintillating tiles



- ~ 0.5 cm^3 scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)





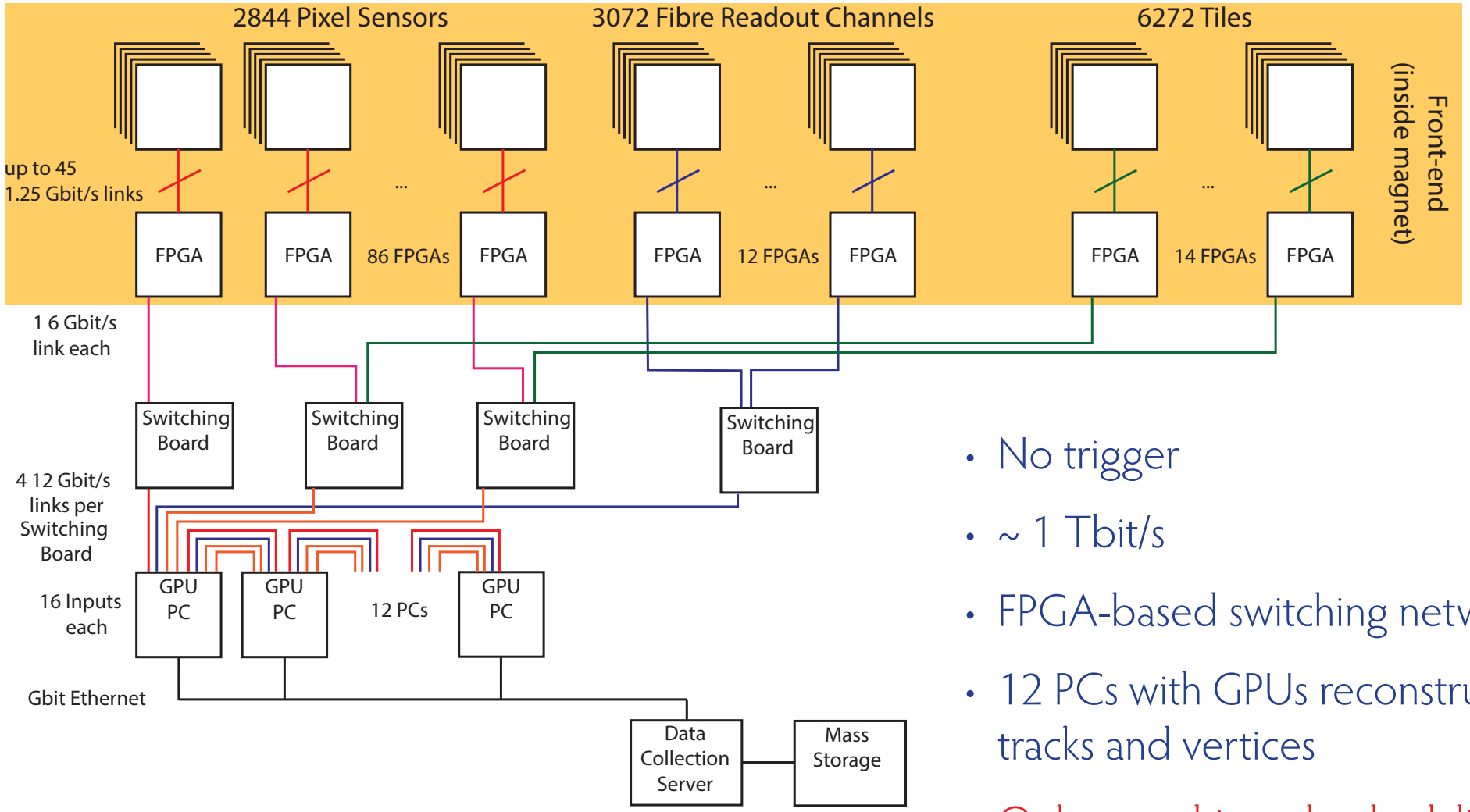
- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution better 80 ps

Phased experiment:

Phase I uses the existing PiE5 beam line at PSI,
shared with MEG II, 10^8 muons/s

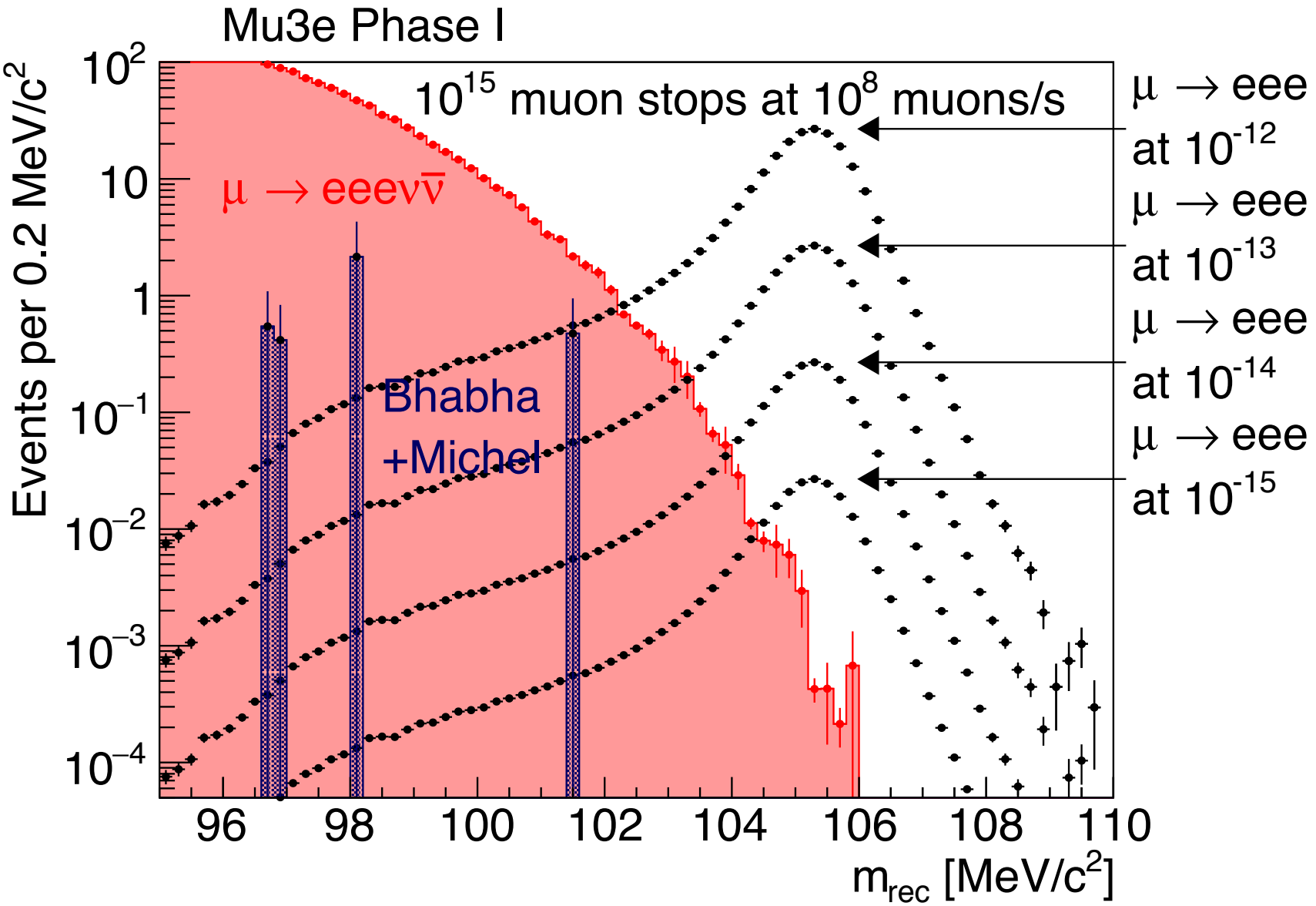
Phase II requires a High Intensity Muon Beamline
(HiMB, > $2 \cdot 10^9$ muons/s)

Phase I Data Acquisition and Filter Farm

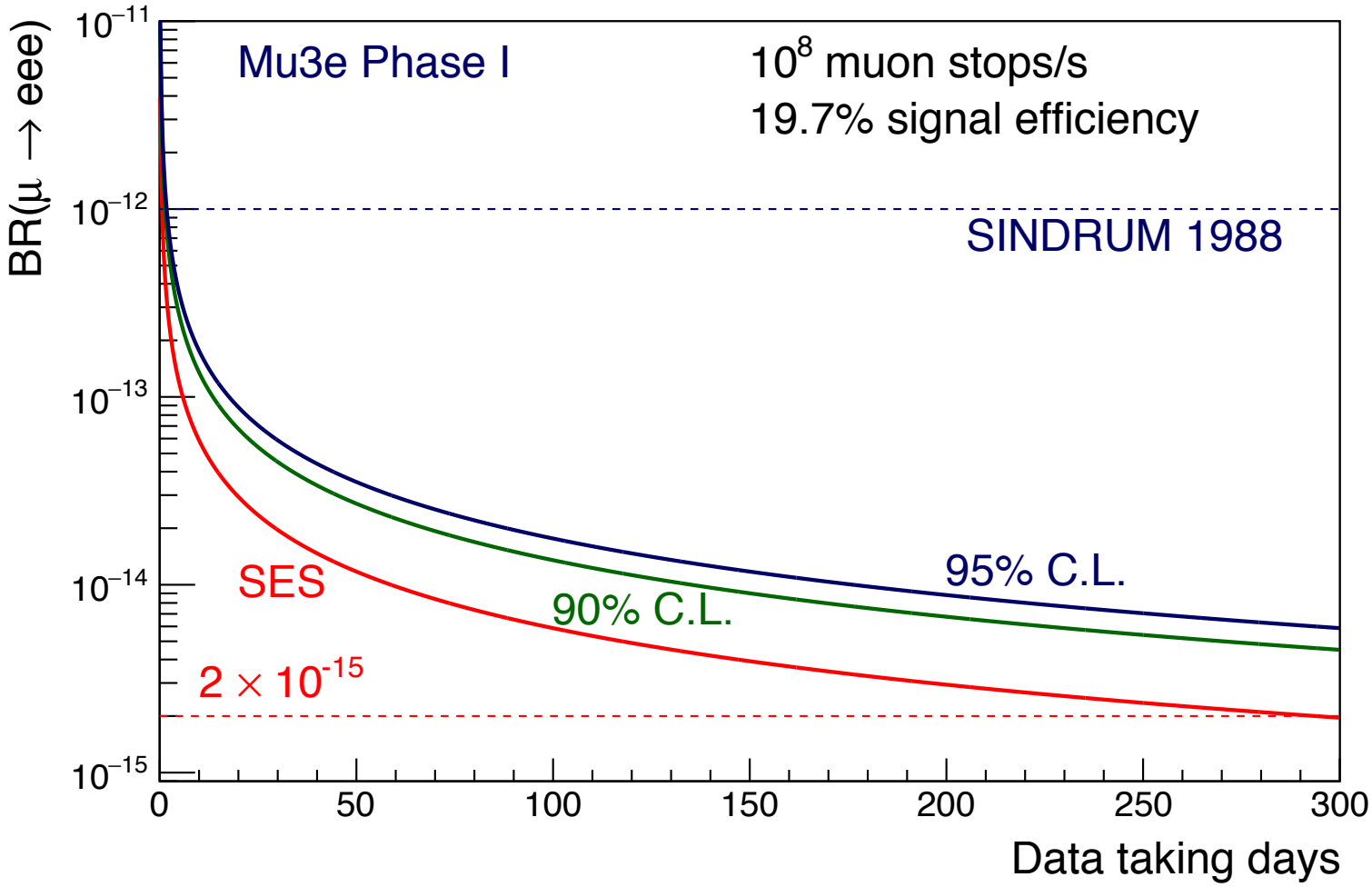


- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- 12 PCs with GPUs reconstruct tracks and vertices
- Only save things that look like $\mu^+ \rightarrow e^+e^-e^+$

Phase I Performance Simulation

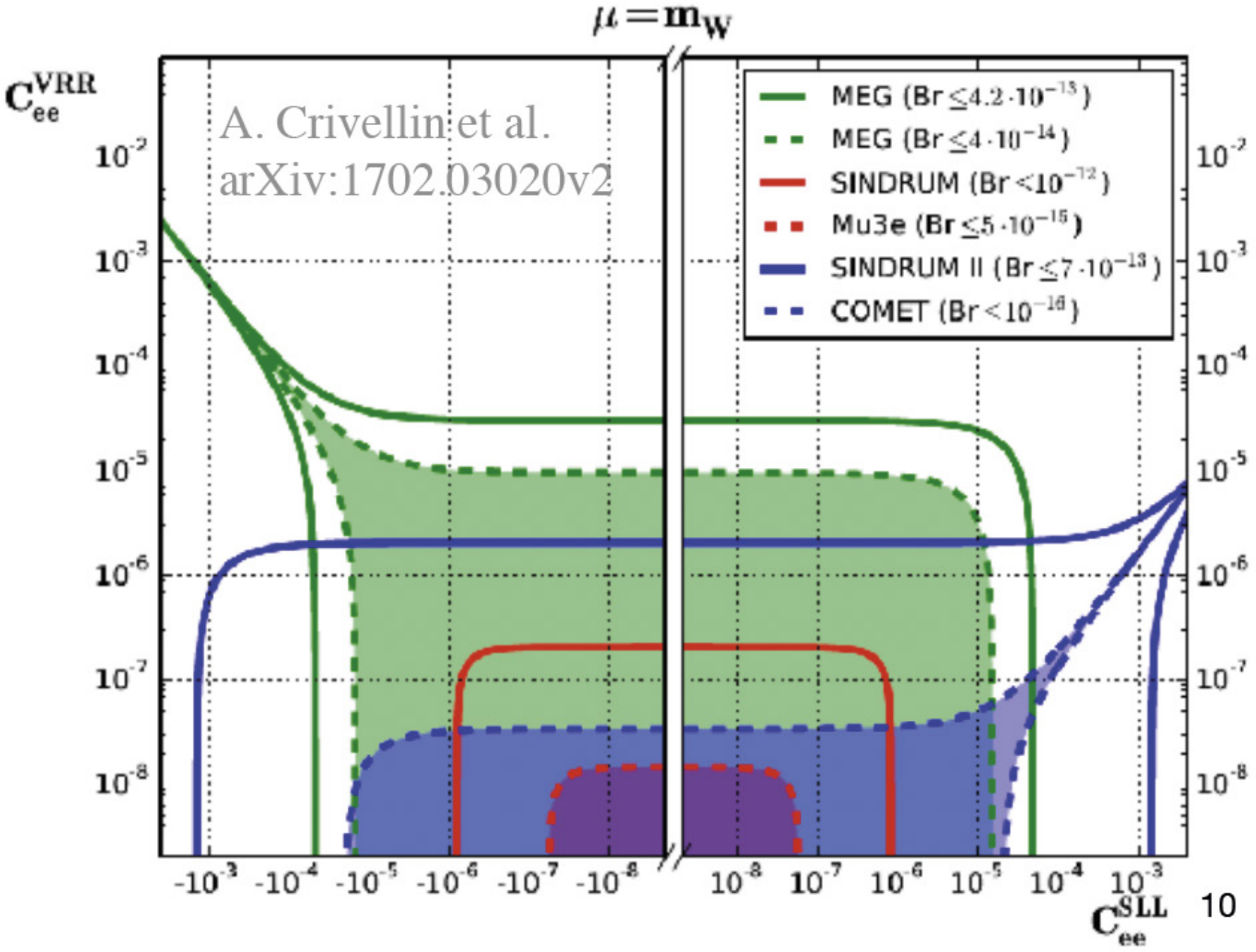


Sensitivity - Mu3e Phase I

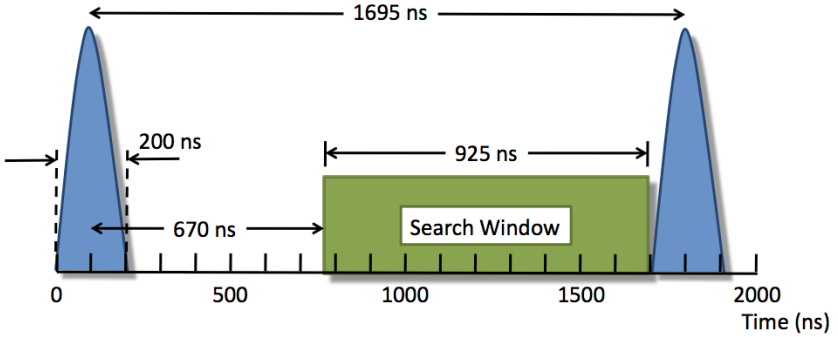


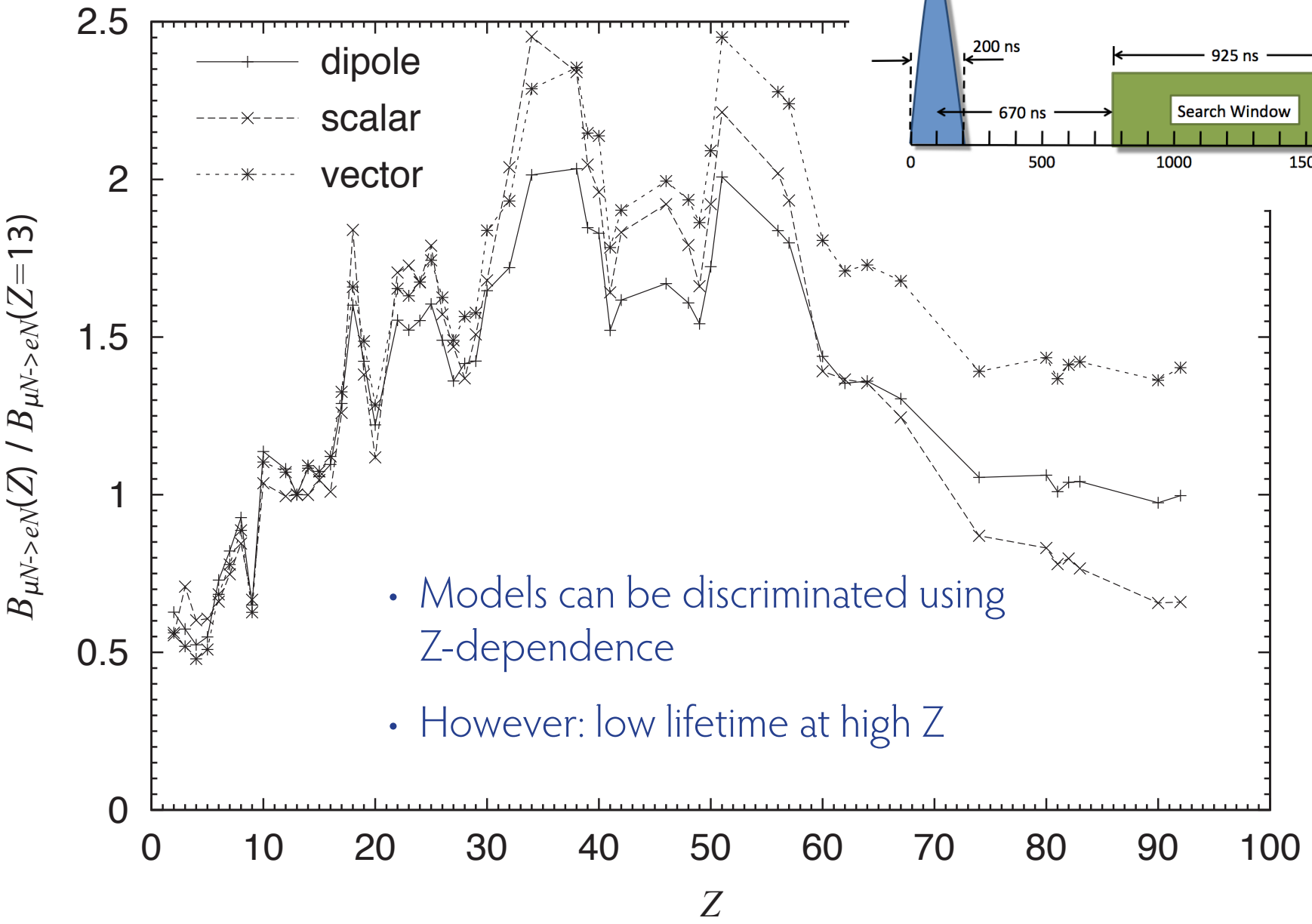
- Start 2020
- Phase II with a high intensity muon beam line at PSI under study

If we find something...


$\mu = m_W$
C_{ee}^{VRR}
A. Crivellin et al.
arXiv:1702.03020v2
MEG (Br $\leq 4.2 \cdot 10^{-13}$)
MEG (Br $\leq 4 \cdot 10^{-14}$)
SINDRUM (Br $< 10^{-12}$)
Mu3e (Br $\leq 5 \cdot 10^{-15}$)
SINDRUM II (Br $\leq 7 \cdot 10^{-13}$)
COMET (Br $< 10^{-16}$)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
-10^{-3} -10^{-4} -10^{-5} -10^{-6} -10^{-7} -10^{-8}
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3}
C_{ee}^{SLL}

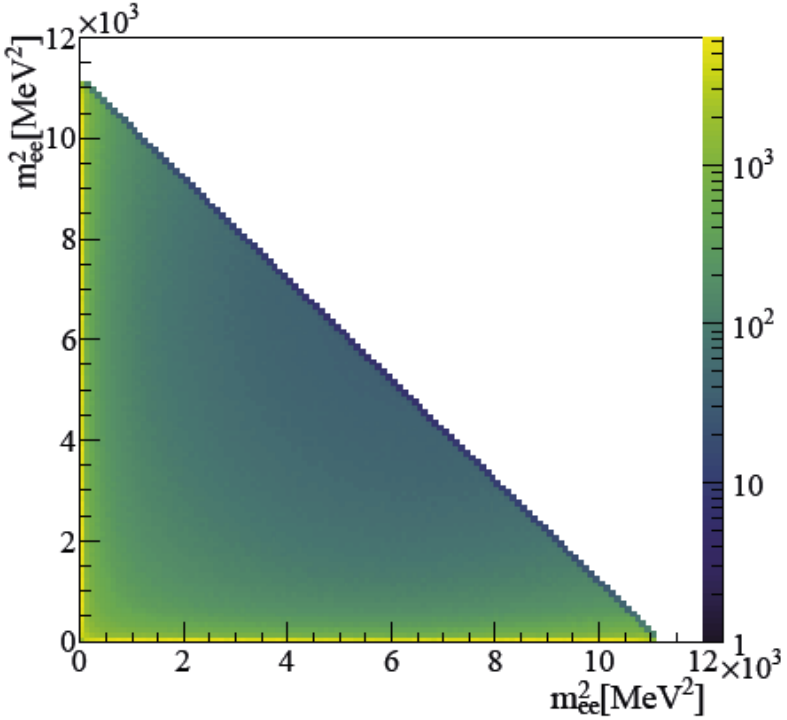
Conversion: Z-dependence

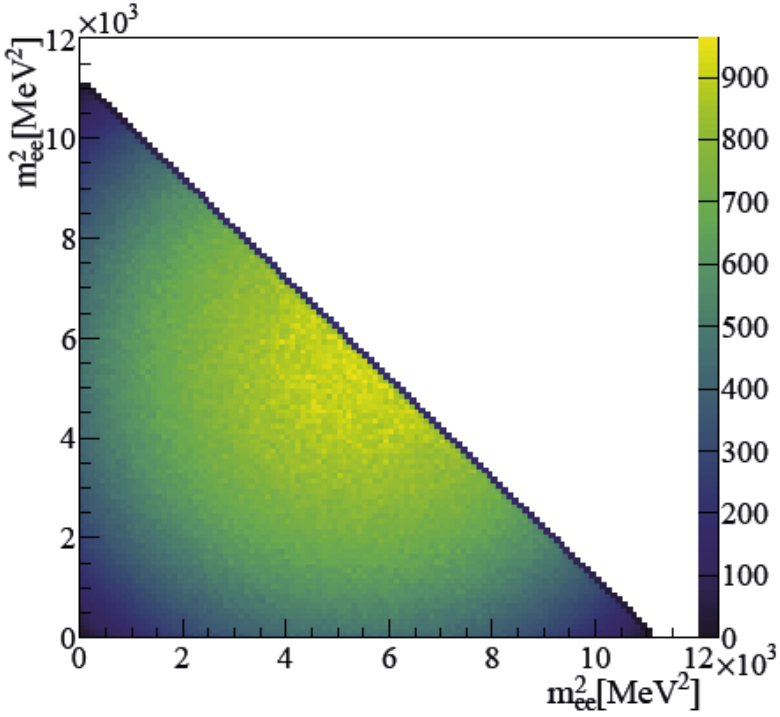




- Models can be discriminated using Z-dependence
- However: low lifetime at high Z

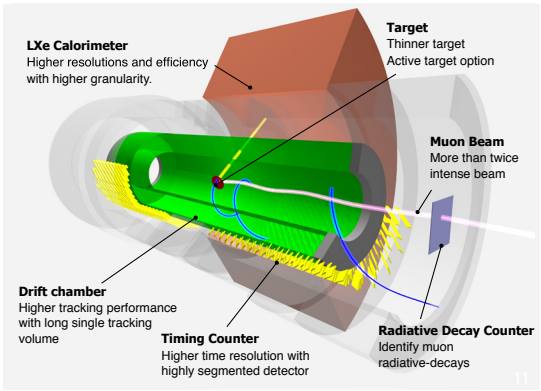
Mu3e: Decay distributions!

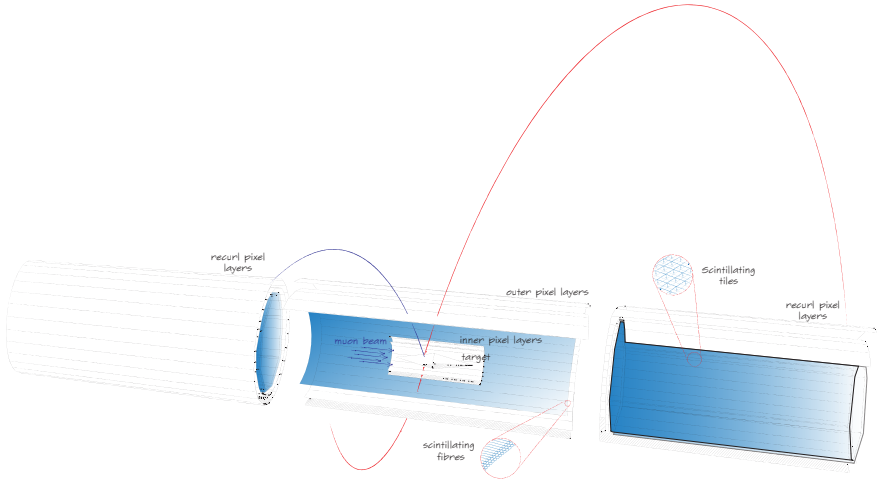


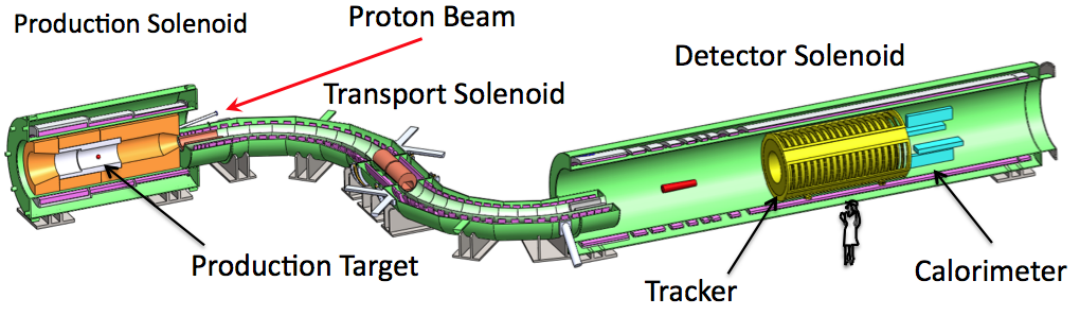


Summary

- Exciting range of experiments going on-line:
  New lepton flavour violation limits upcoming
- MEG II starting engineering run now, data taking from next year
- DeeMee and Comet Phase I almost ready
- Mu3e Phase I starting 2020
- Mu2e and Comet Phase II from 2022
- More things we can do: Ann-Kathrin

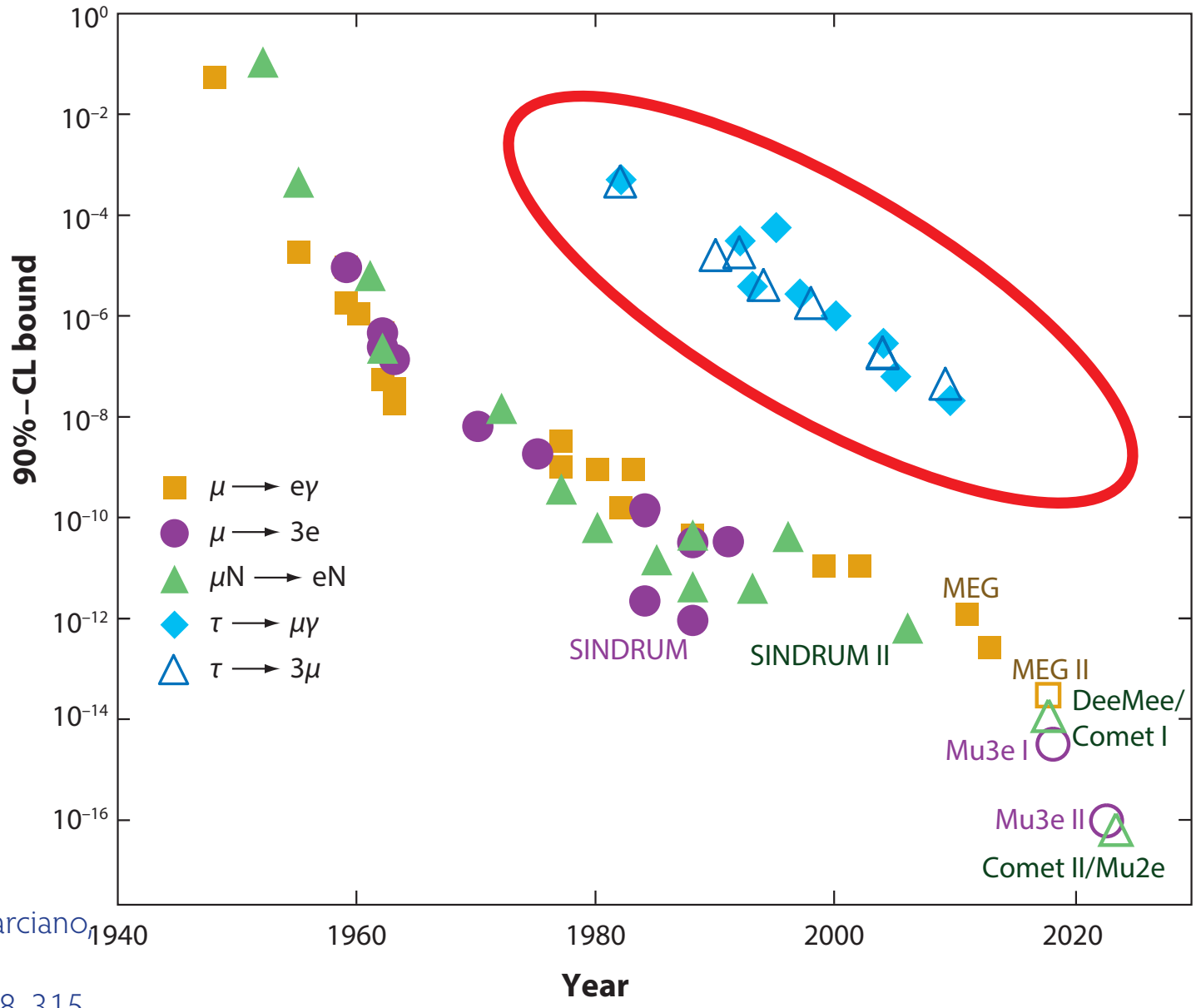






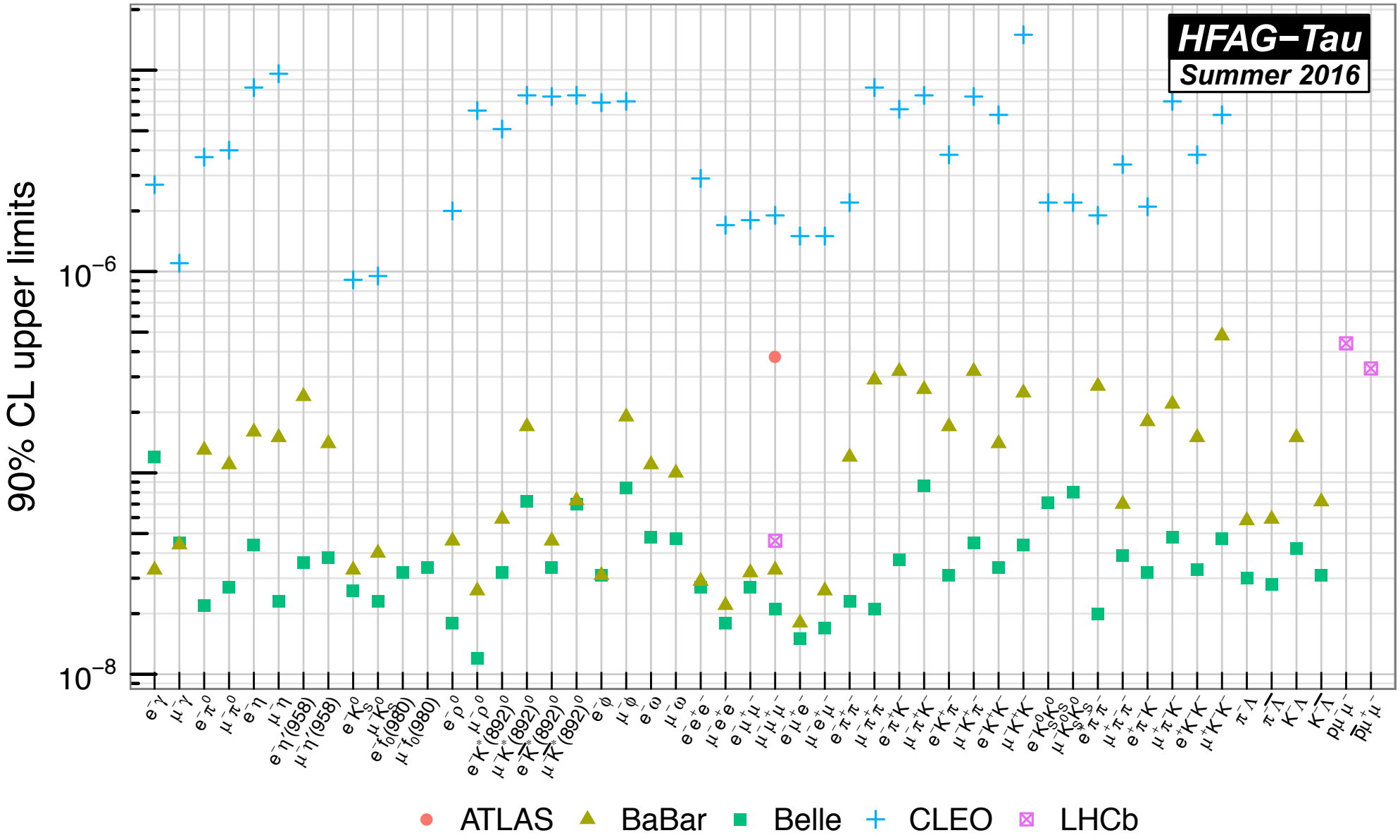
Backup Material

History of LFV experiments

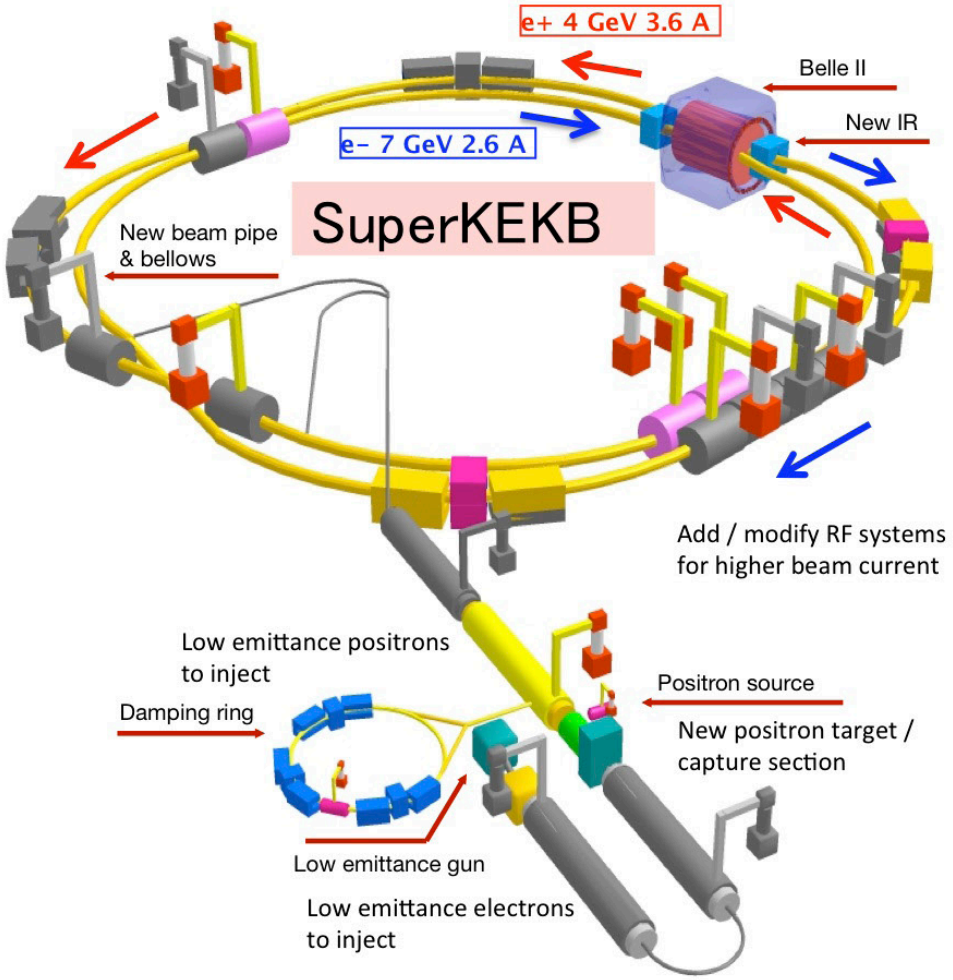


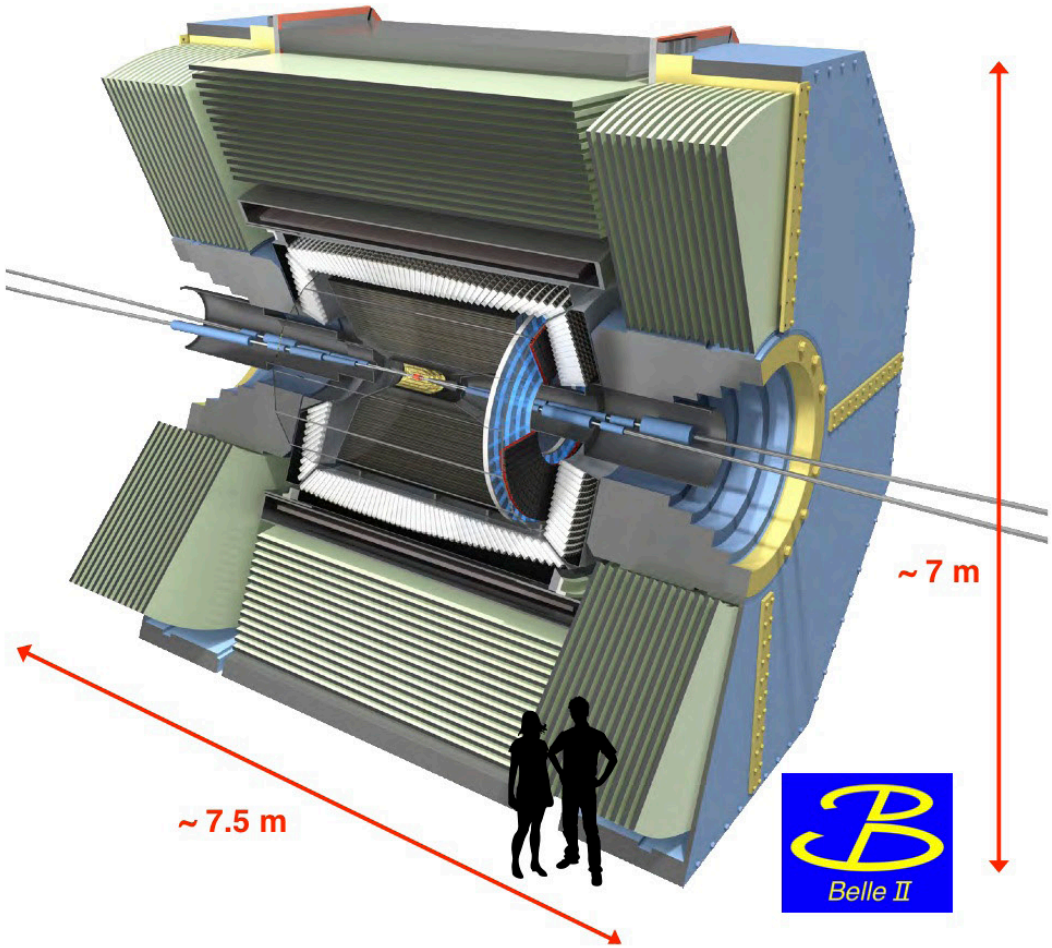
(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

Lepton flavour violating τ-decays



Belle II at Super KEKB

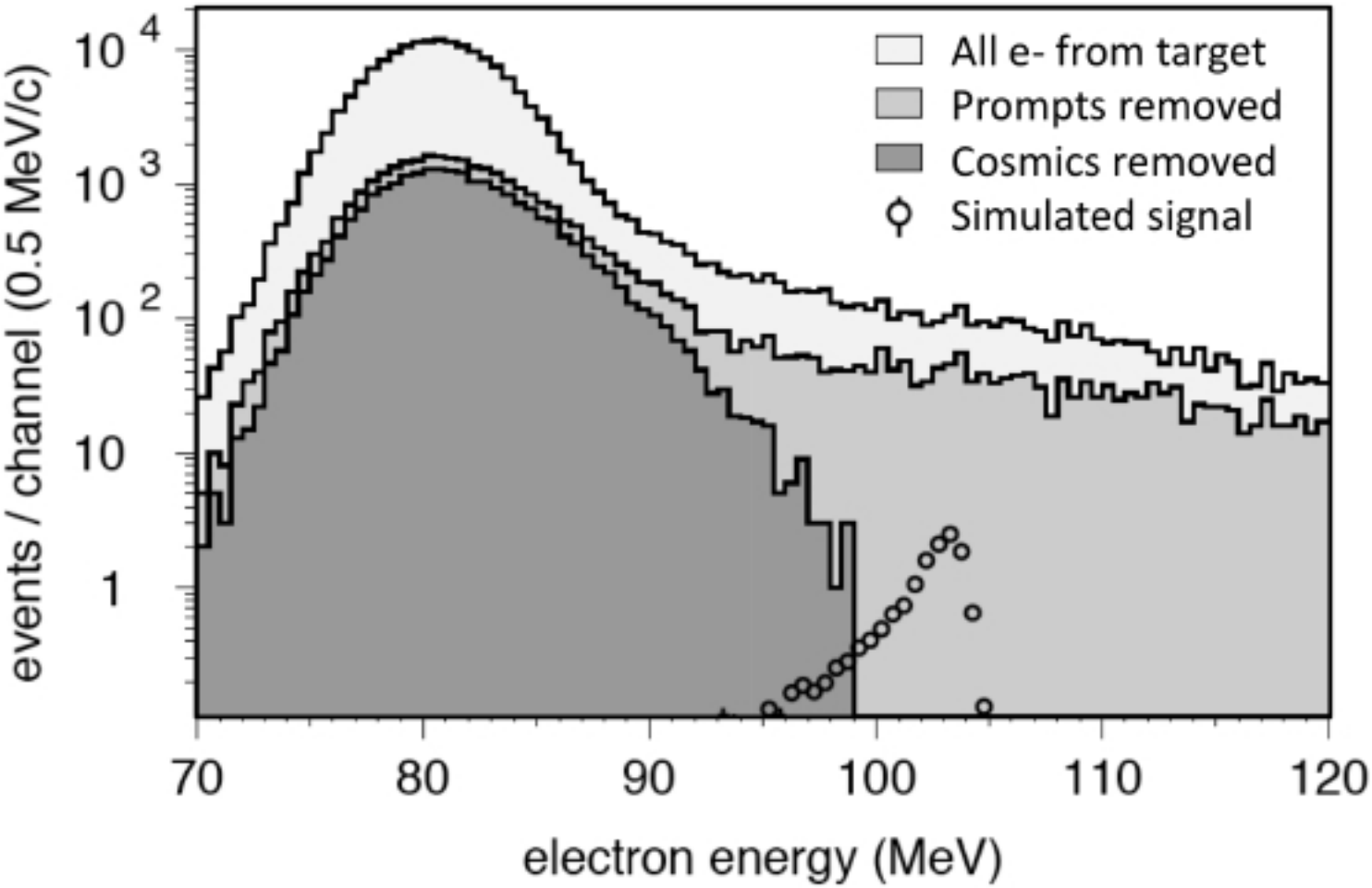




Expect 5× 10^{10} τ pairs - branching fractions of 10^{-9} achievable

Limitations of last experiment: SINDRUM II

- Beam induced background
- Muon rates



Further steps: Prism/Prime

Add a muon storage ring