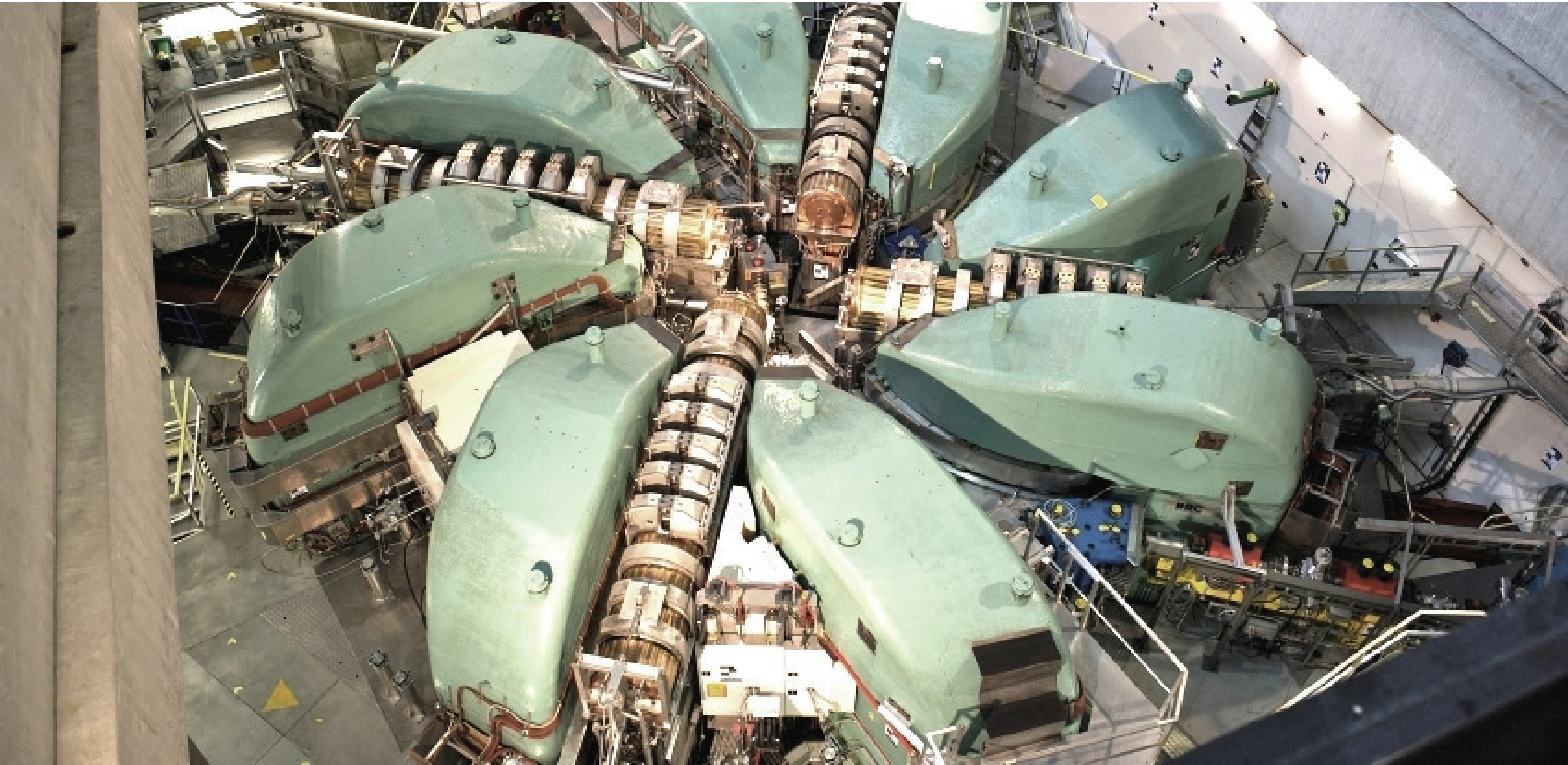
Muons - how to get high intensity

Paul Scherrer Institute in Villigen, Switzerland

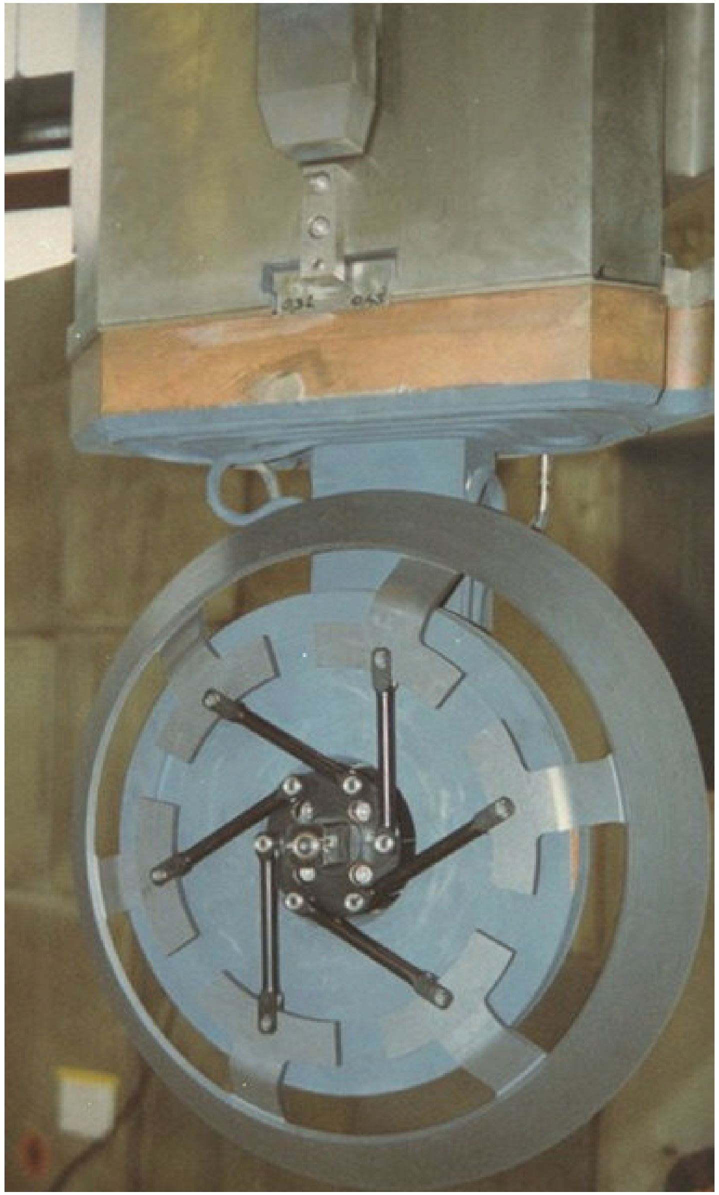
Example: Muons - how to get high intensity

Paul Scherrer Institute in Villigen, Switzerland

World's most intensive proton beam
2.2 mA at 590 MeV: 1.3 MW of beam power

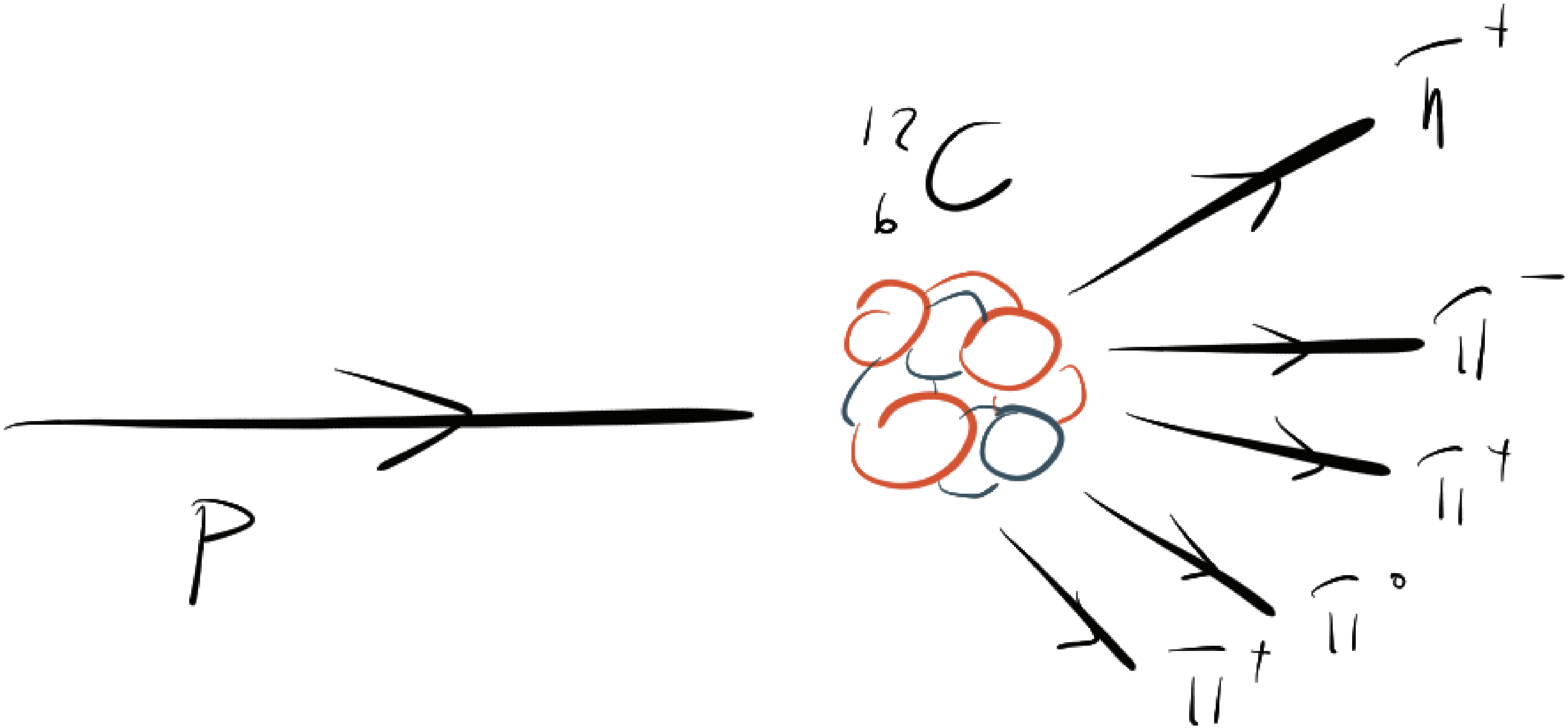


Example: Muons - how to get high intensity

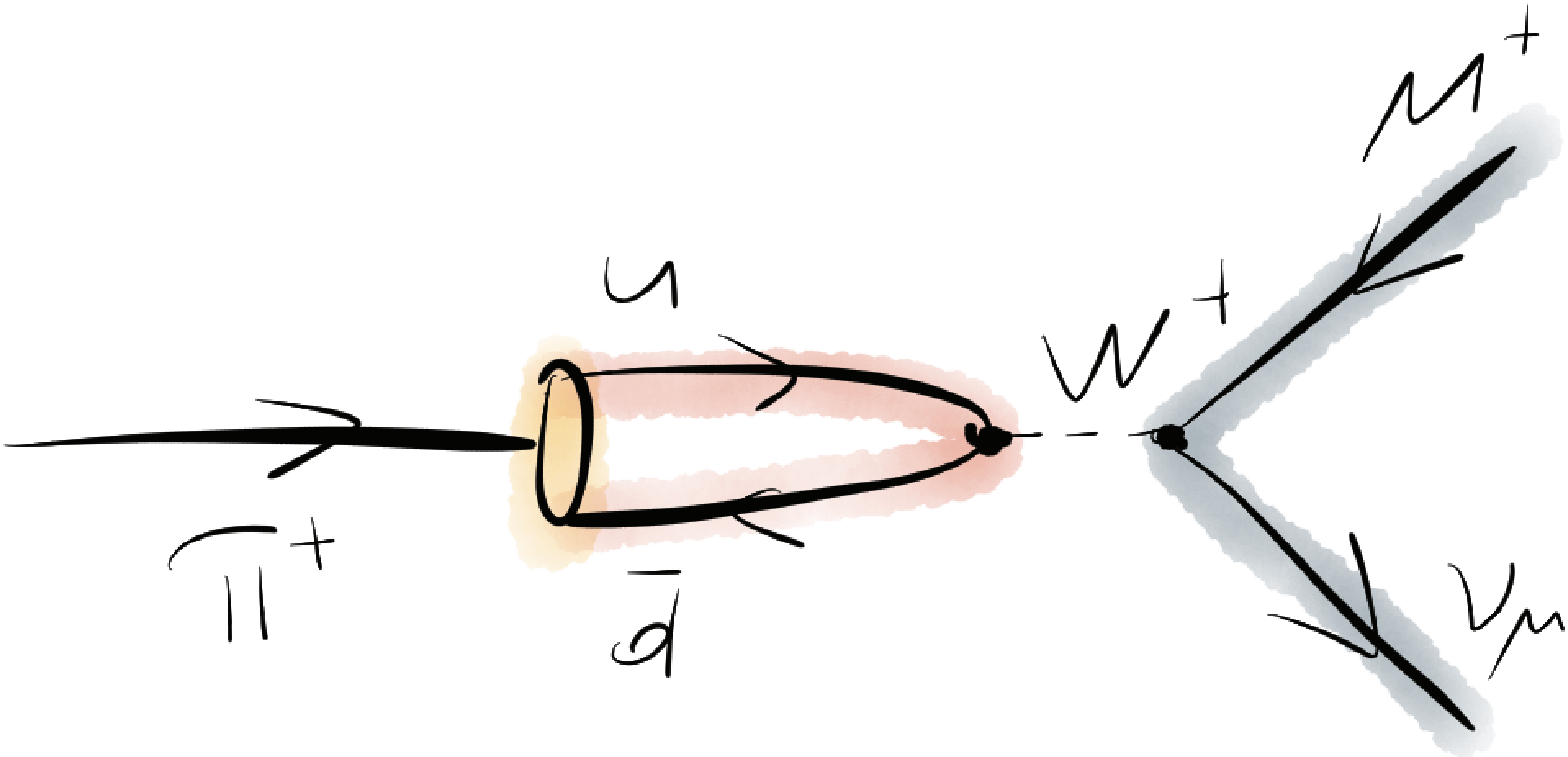


- Rotating carbon wheel as target
- Hit with proton beam

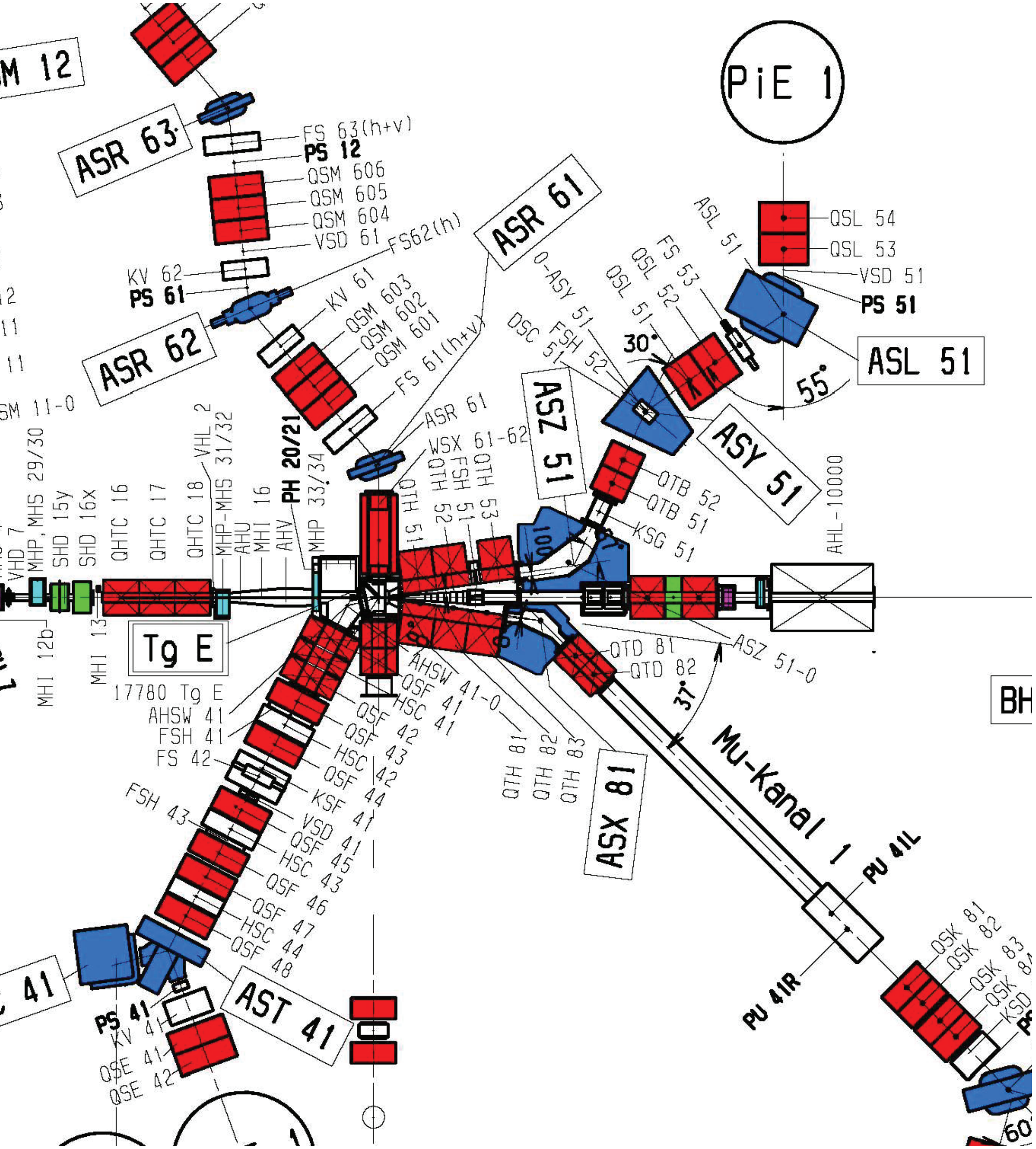
Pion production



Pion decay



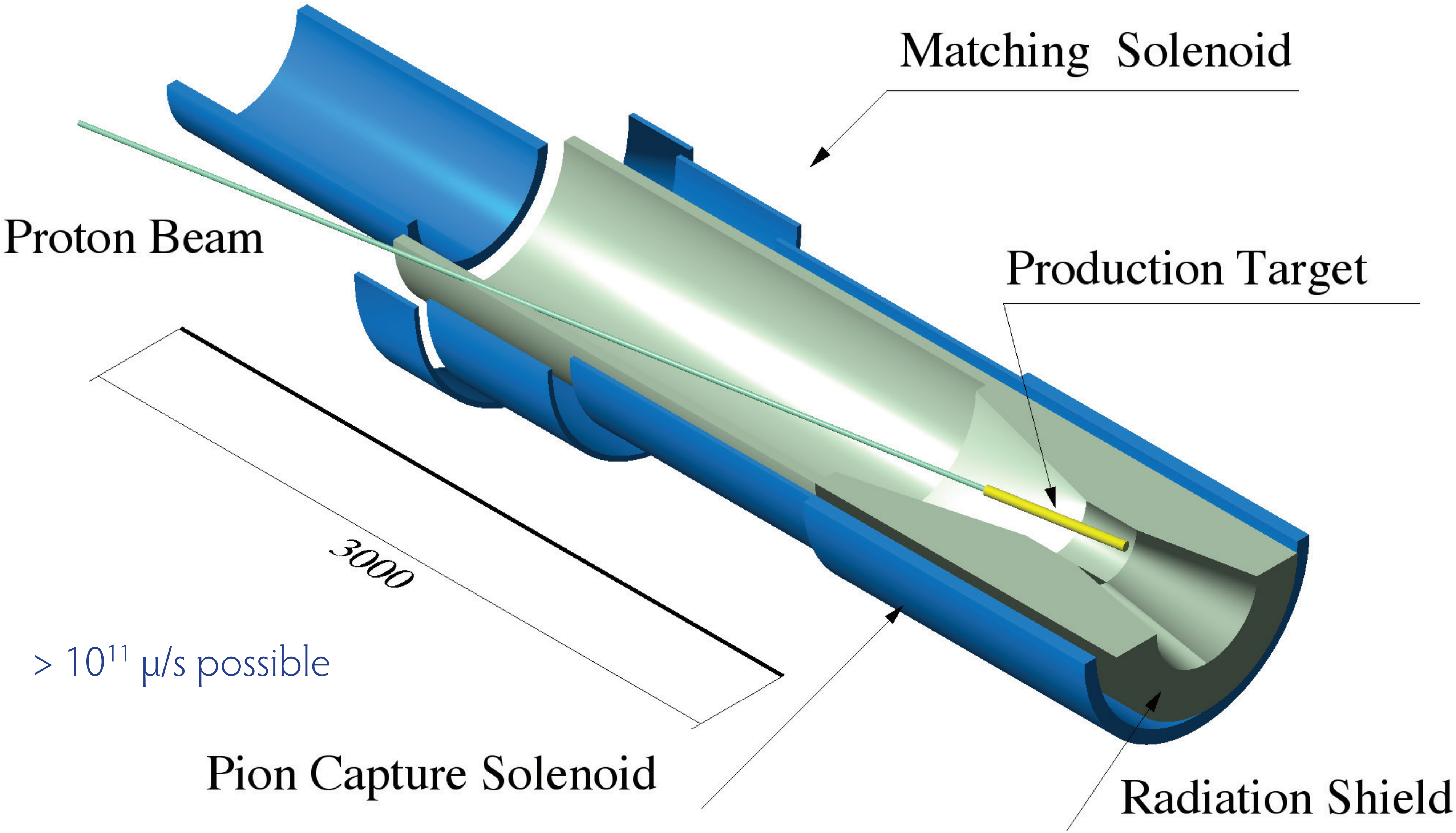
Muon beamlines



- Target serves many beamlines
- Usable intensity ~ 10^8 μ/s

How to get higher intensities?

Higher intensities - target in magnet

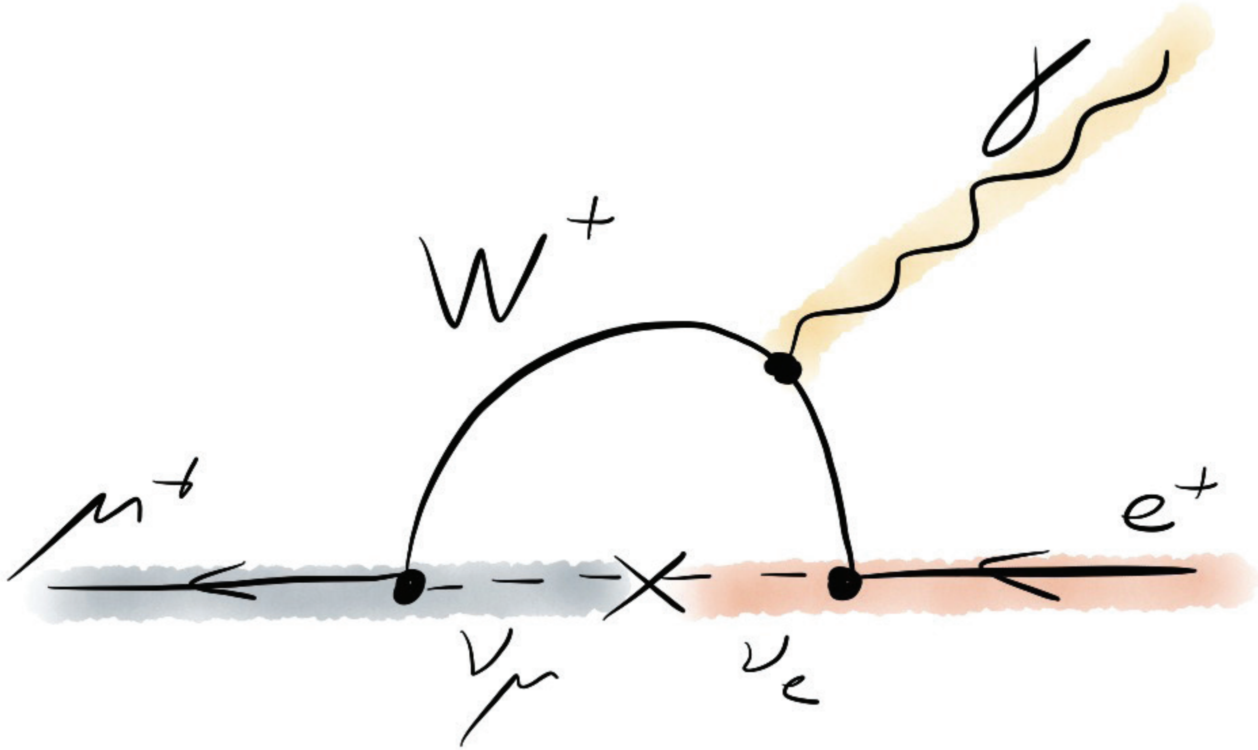


> 10^{11} μ/s possible

Gradient field: magnetic bottle
Capture most pions produced in target

Shielding of superconducting magnet very challenging

Lepton flavour violation experiments



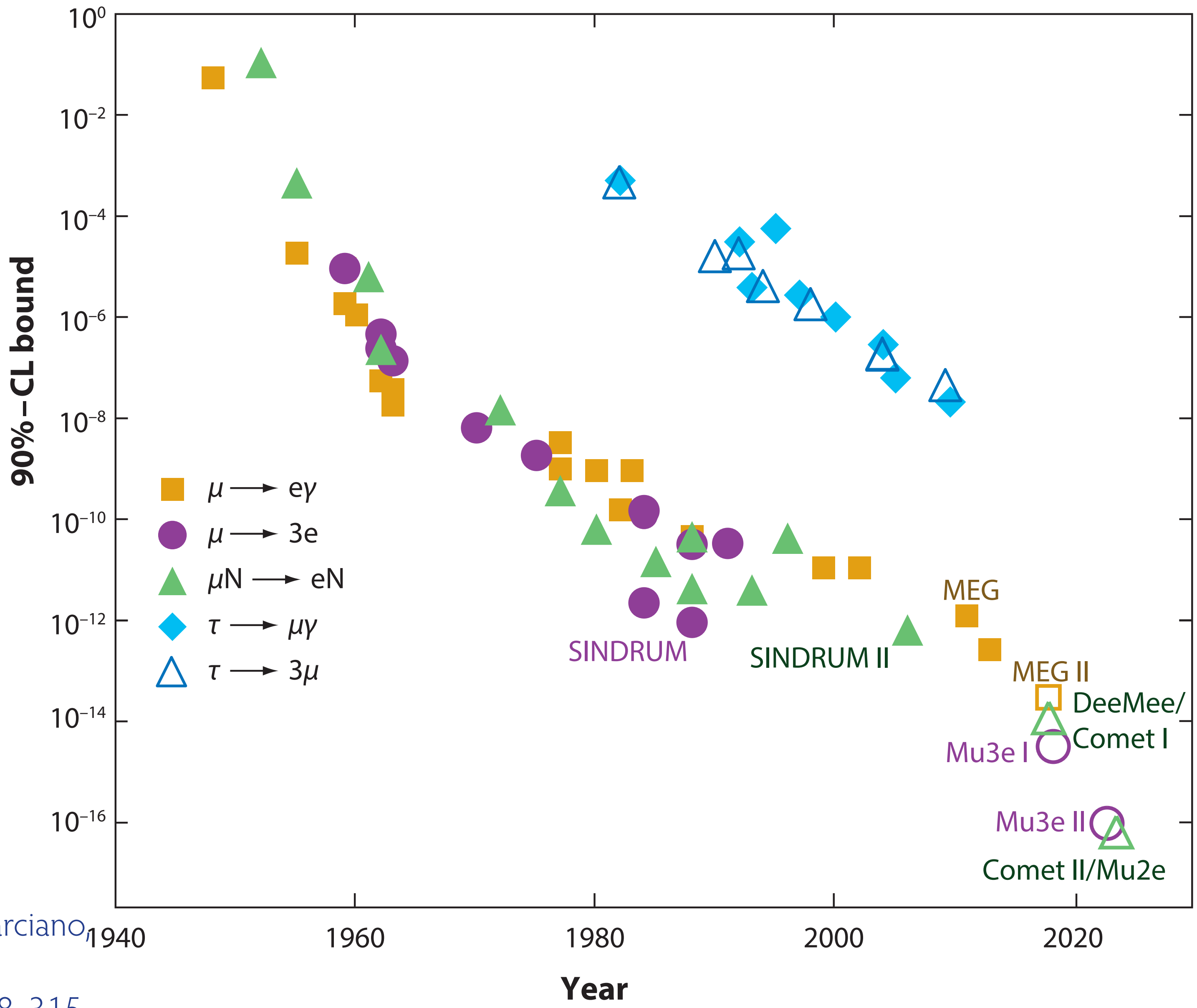
Standard Model branching fractions of

10^{-50ish}

Only limited by number of muons
and background suppression:

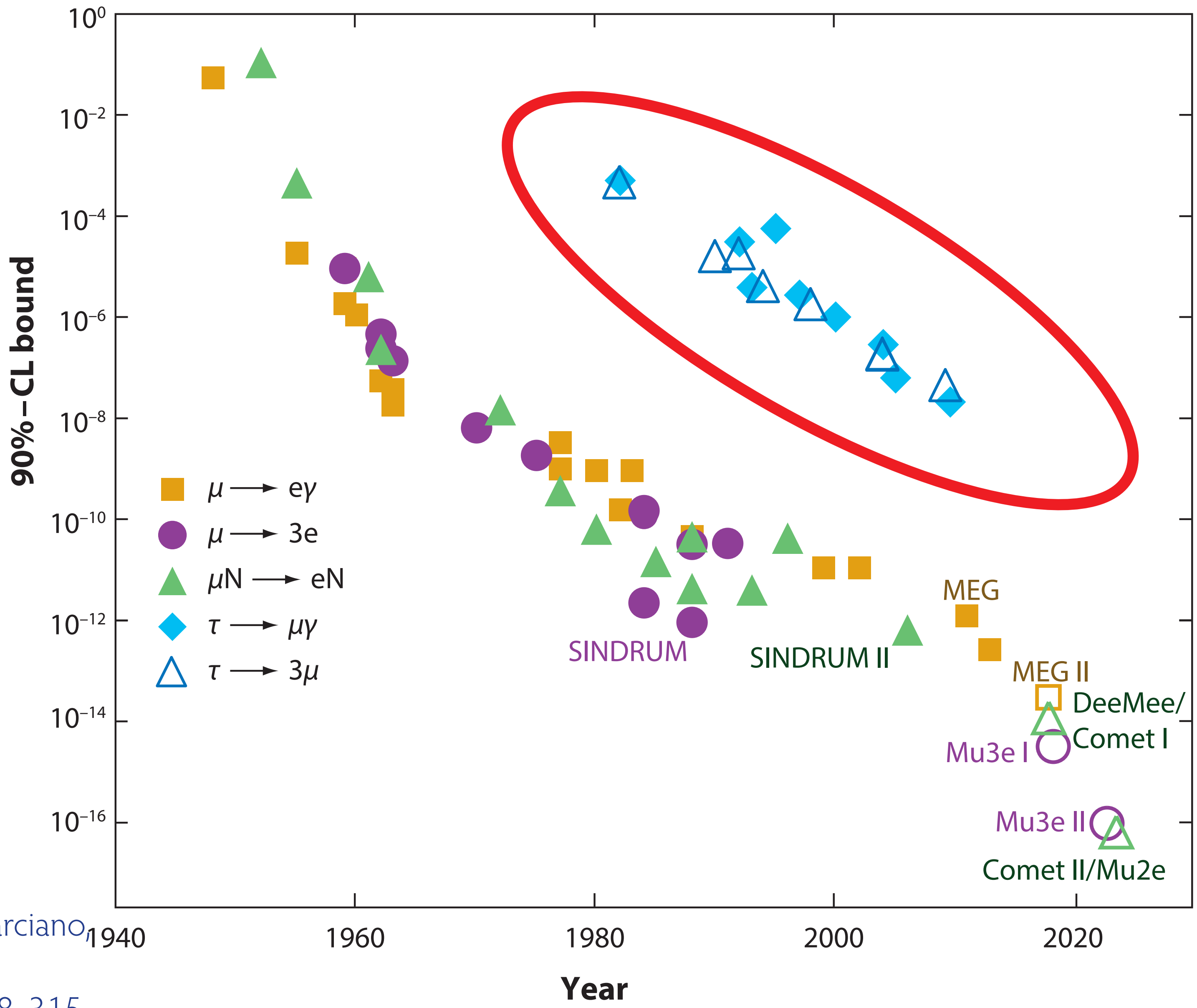
Experimental/technical challenge

History of LFV experiments



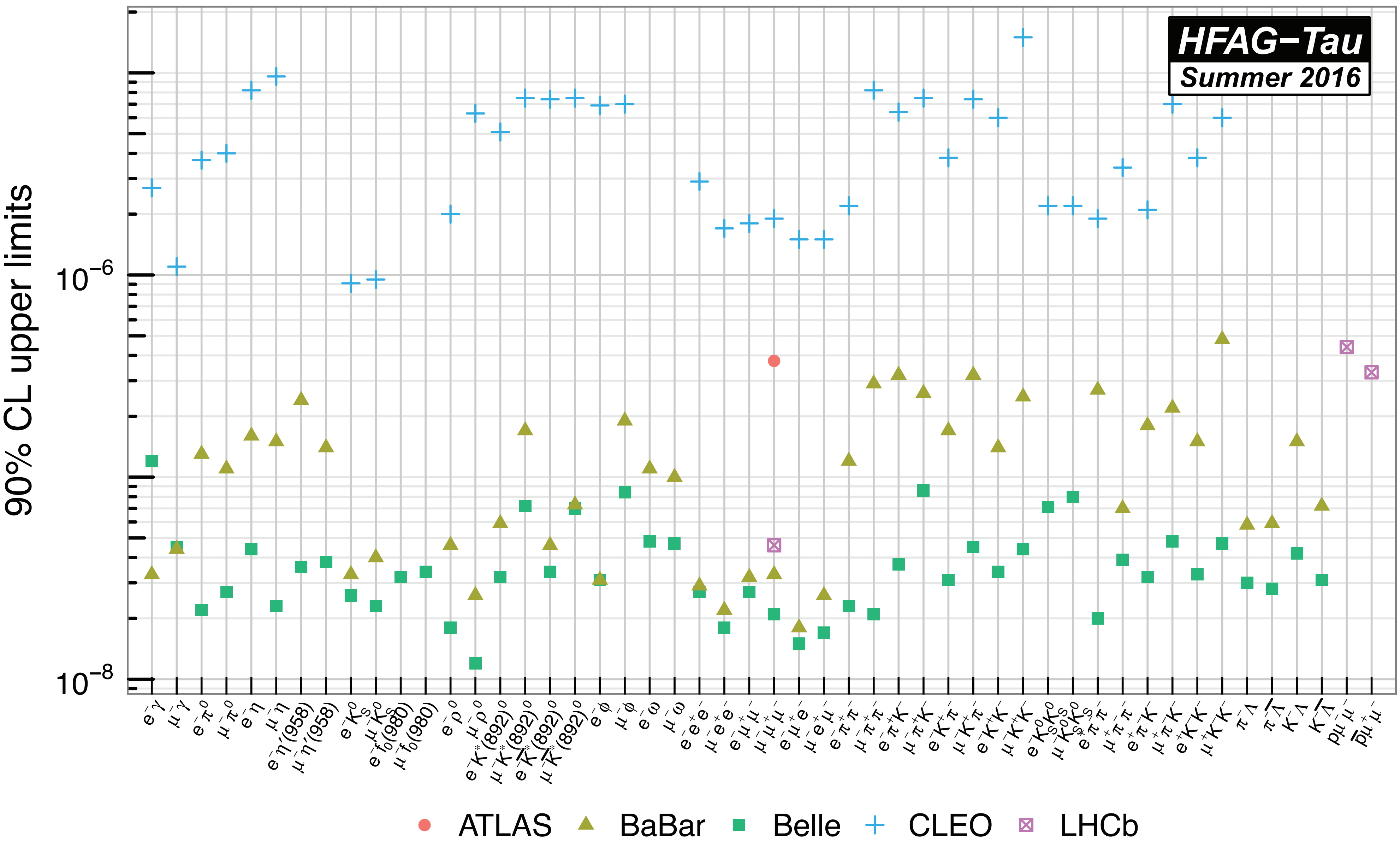
(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

History of LFV experiments

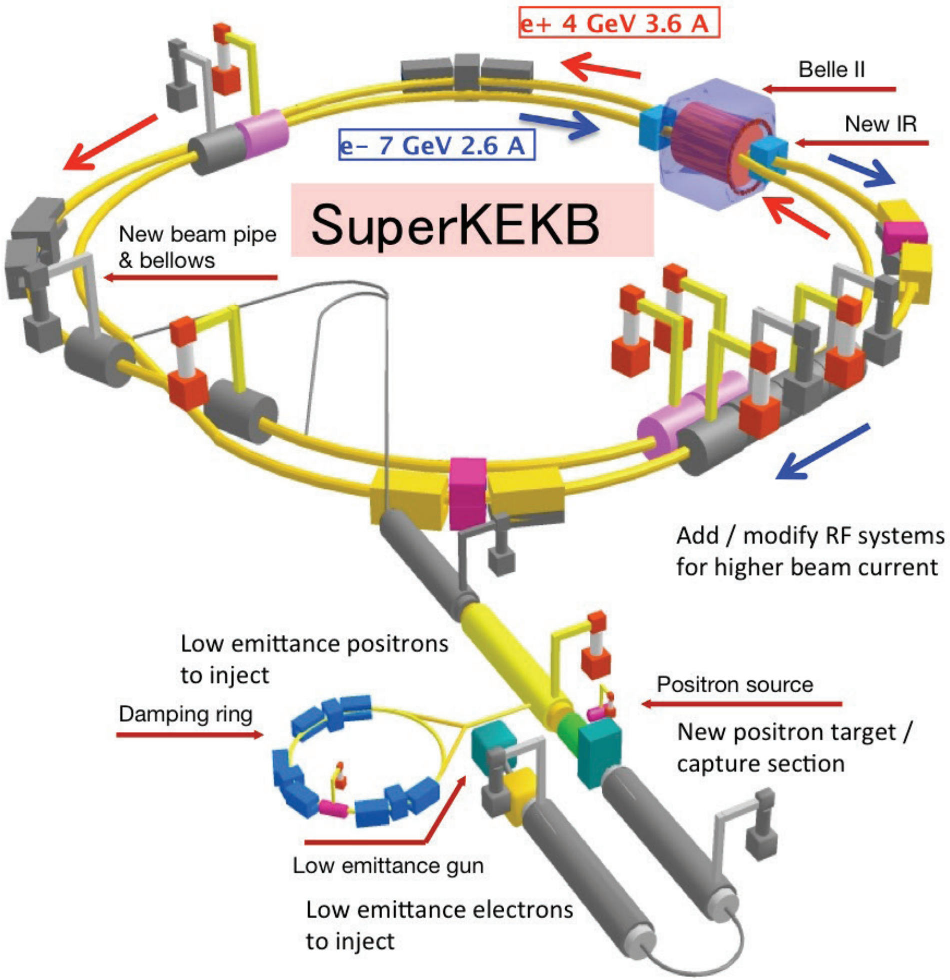


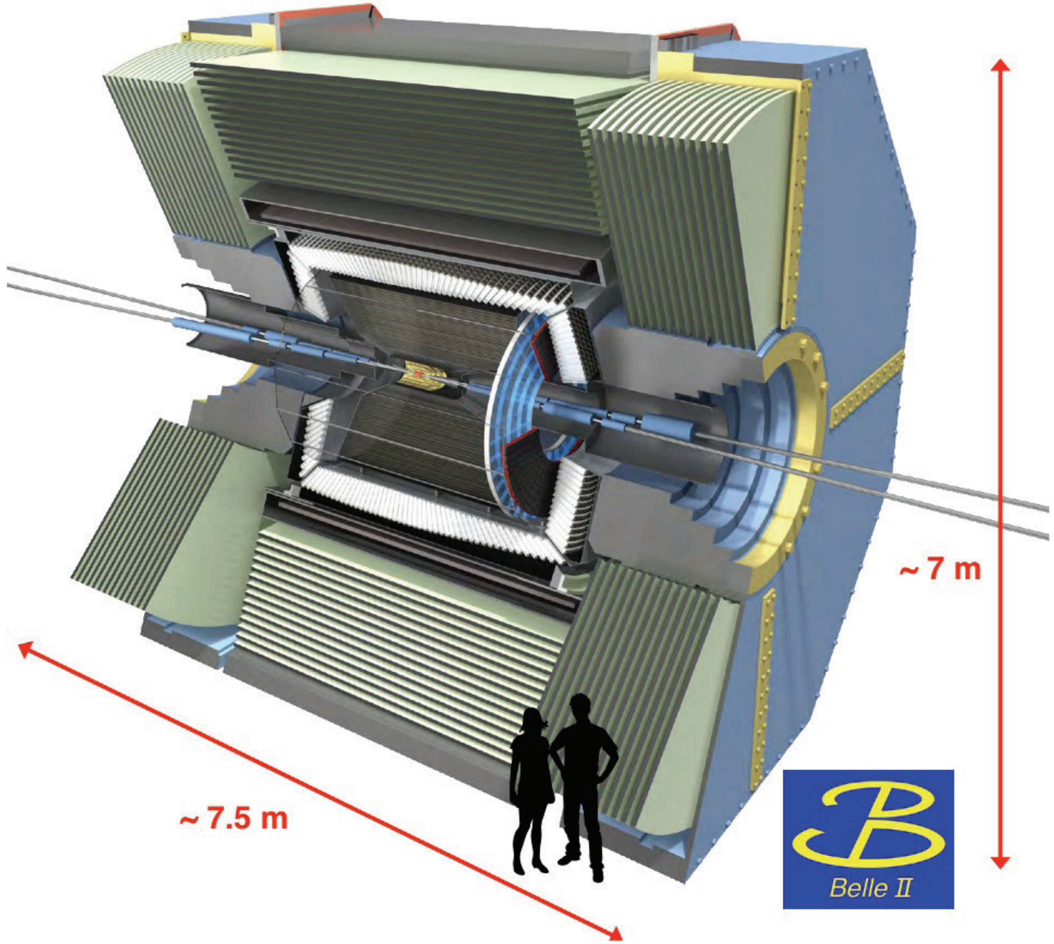
(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

Lepton flavour violating τ-decays



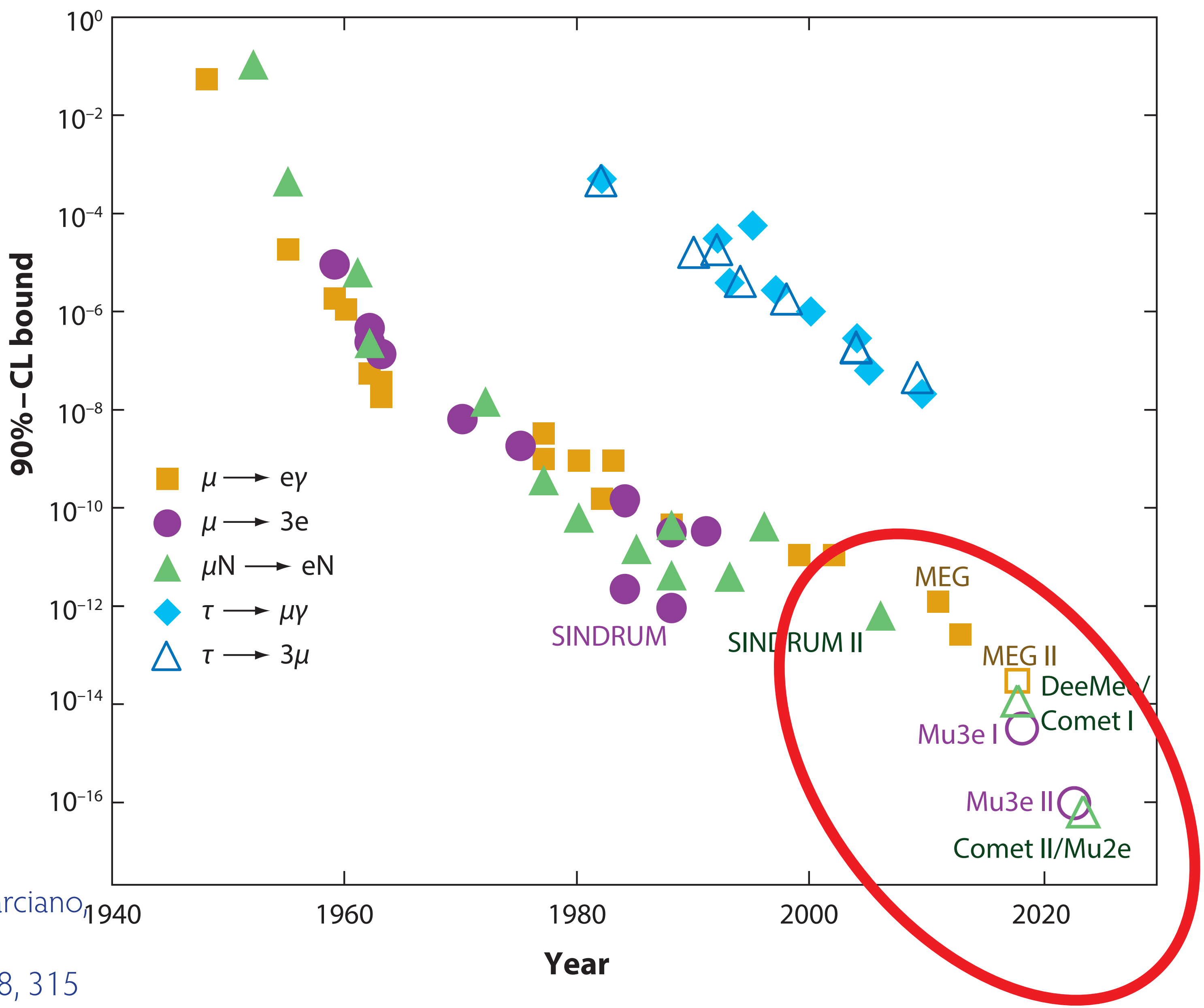
Belle II at Super KEKB





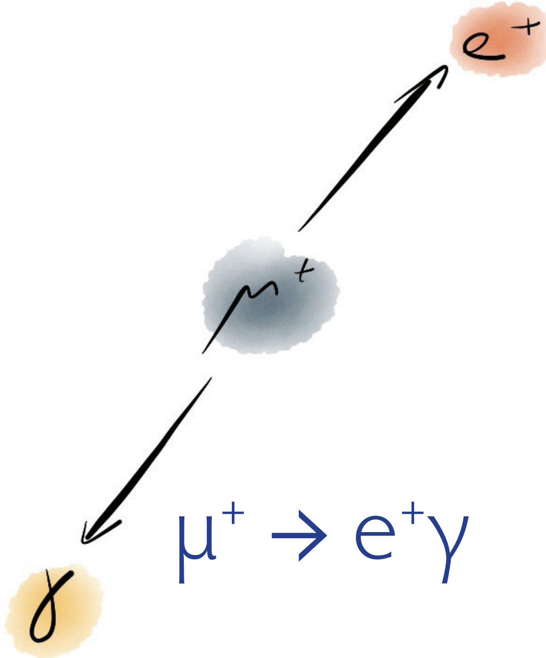
Expect 5× 10^{10} τ pairs - branching fractions of 10^{-9} achievable

History of LFV experiments

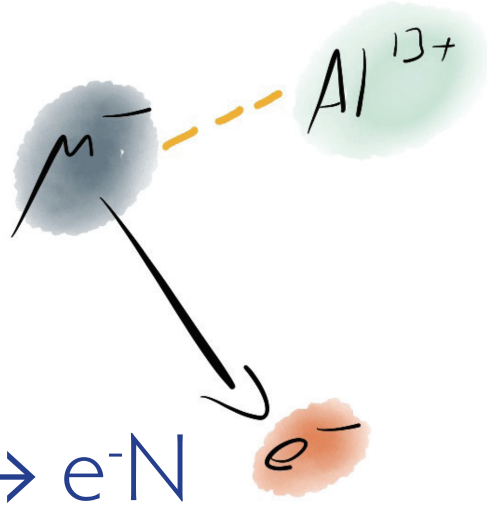


(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

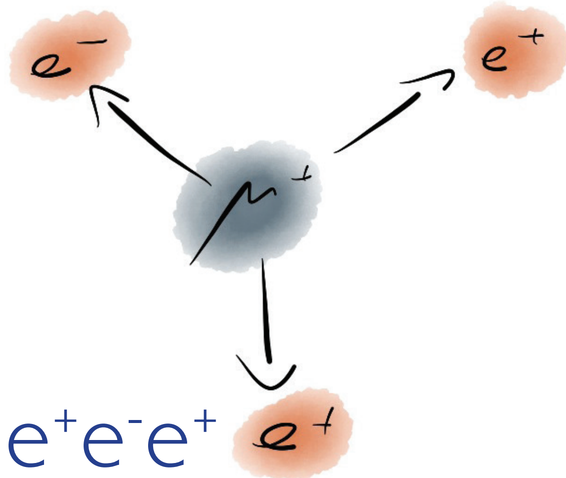
LFV Muon Decays



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

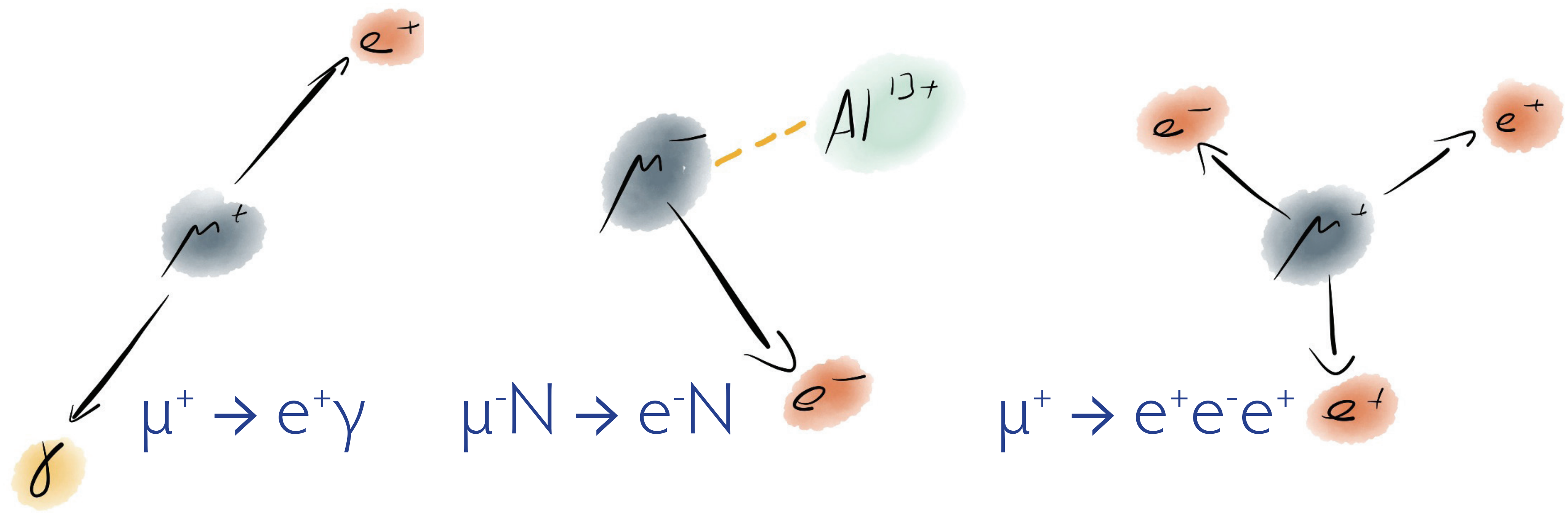


$\mu^- N \to e^- N$



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

LFV Muon Decays: Experimental Situation



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)

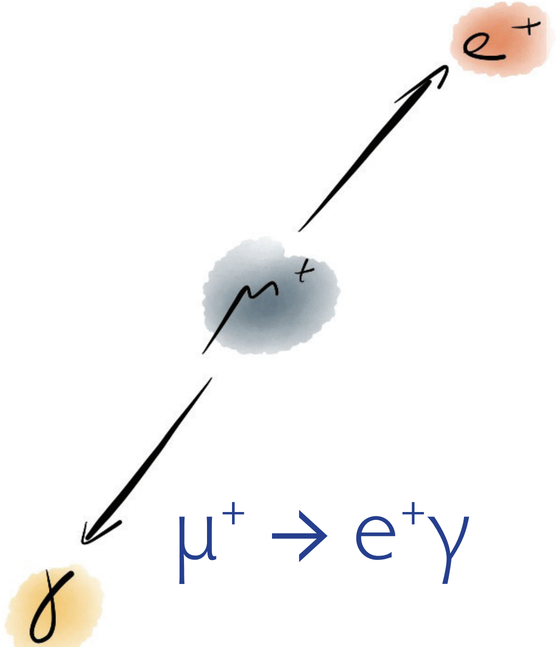
relative to nuclear capture

SINDRUM (PSI)

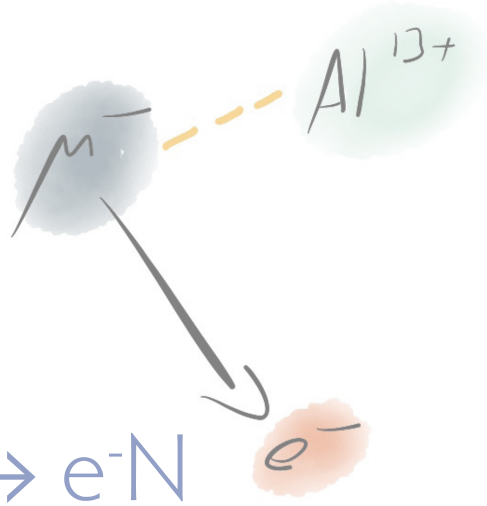
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$

(1988)

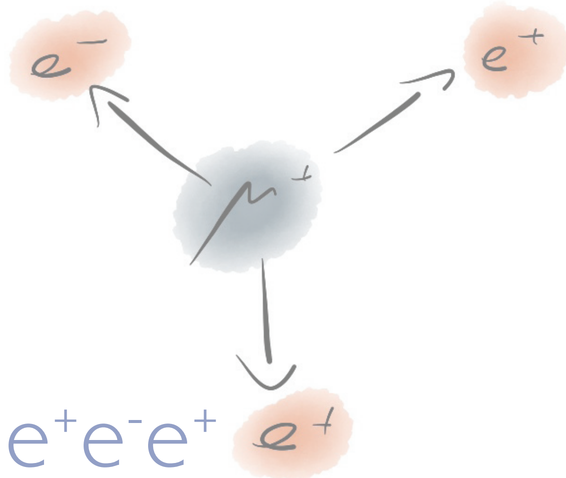
LFV Muon Decays: Experimental signatures



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



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

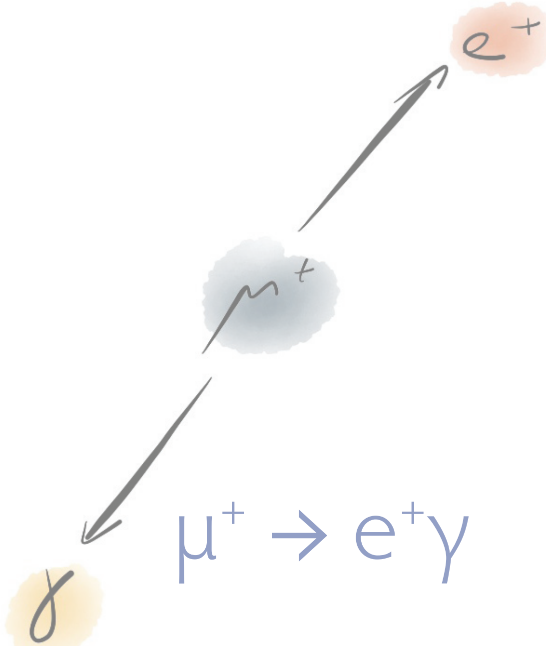


$\mu^+ \rightarrow e^+e^-e^+$

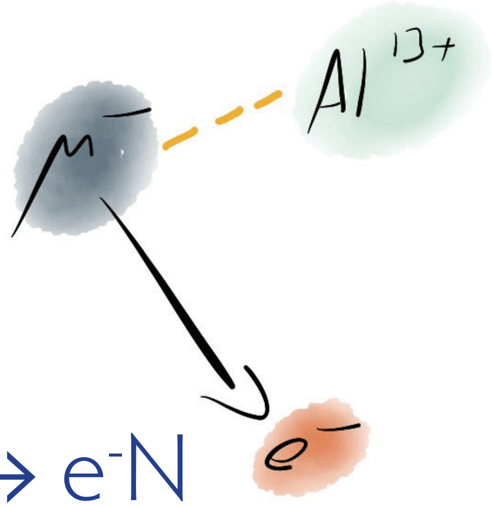
Kinematics

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

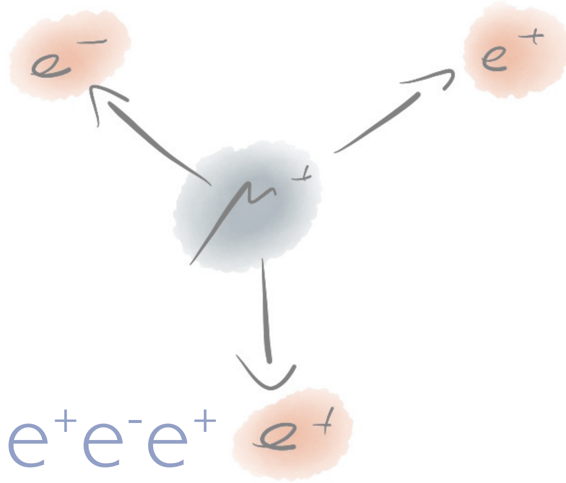
LFV Muon Decays: Experimental signatures



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



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



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

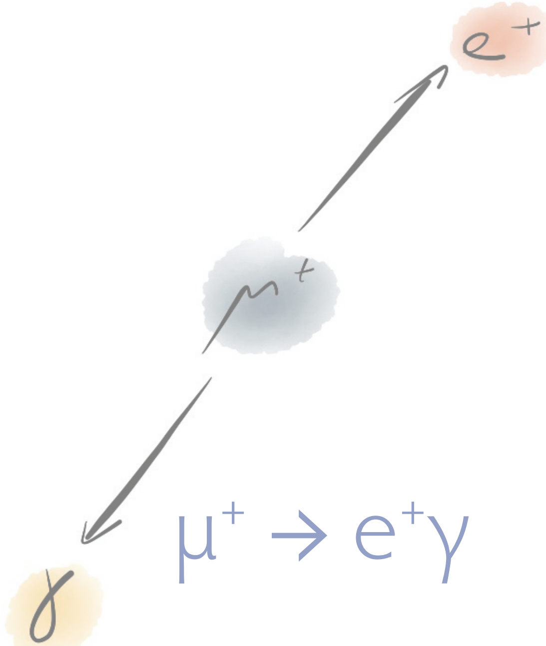
Kinematics

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

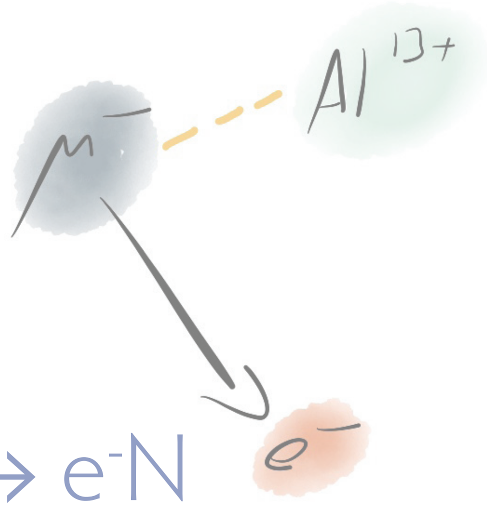
Kinematics

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

LFV Muon Decays: Experimental signatures



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



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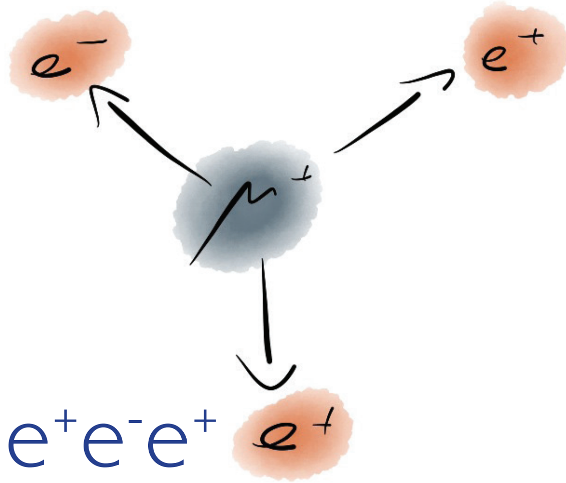


$\mu^+ \rightarrow e^+e^-e^+$

Kinematics

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

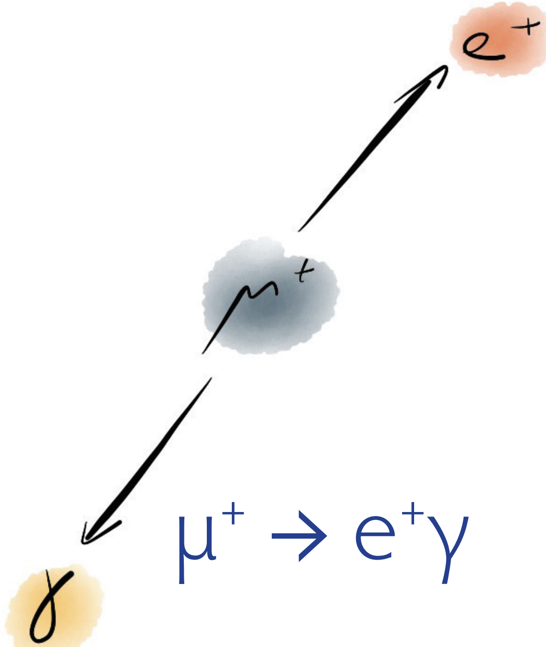
Kinematics

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

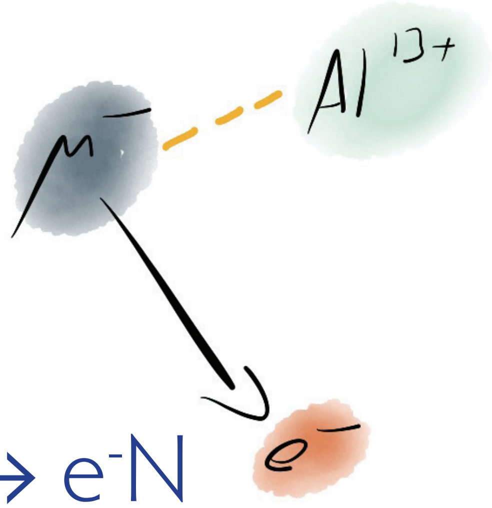
Kinematics

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

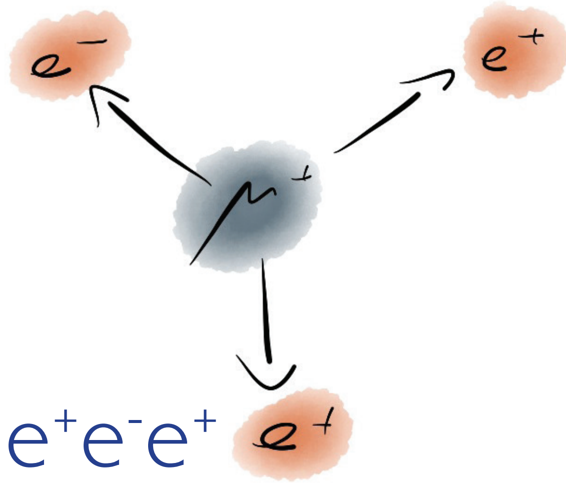
LFV Muon Decays: Experimental signatures



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



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



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

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

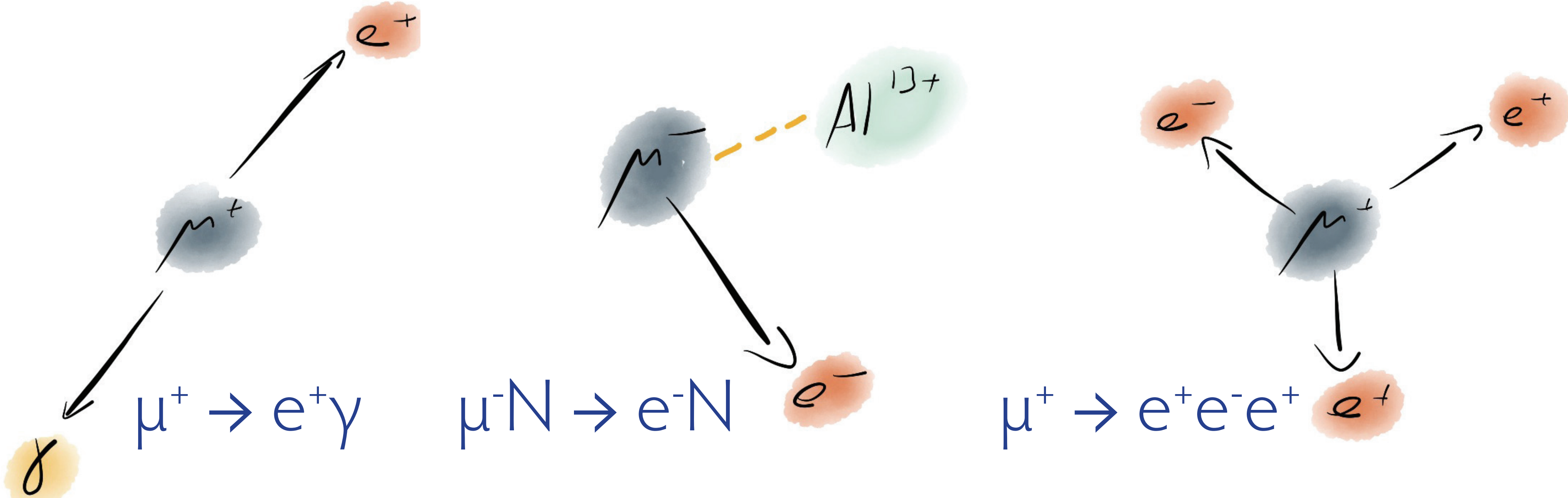
Kinematics

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

Background

- Internal conversion decay
- Accidental background

LFV Muon Decays: Experimental signatures



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

Kinematics

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

Backgro…

- A… …al background

Continuous Beam

Kinematics

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

Backgro…

- D… … orbit
- A… protons, pions

Pulsed Beam

Kinematics

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

Backgro…

- R… … decay
- Ac… …dental background

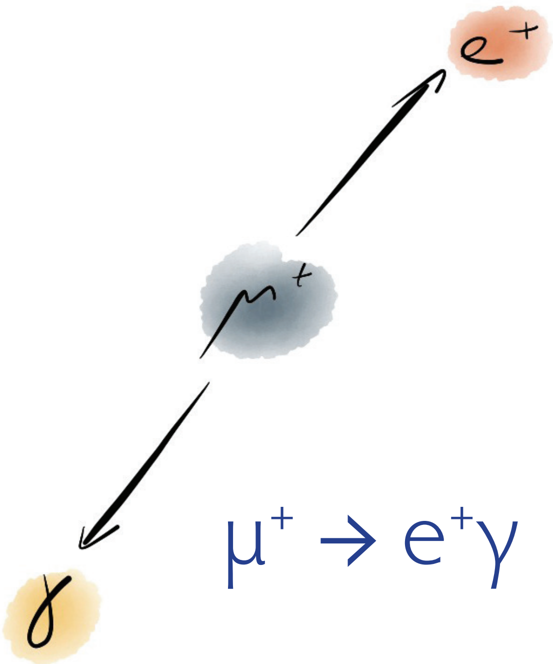
Continuous Beam

“Classic” technology and incremental upgrade

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

MEG

MEG Signal and background

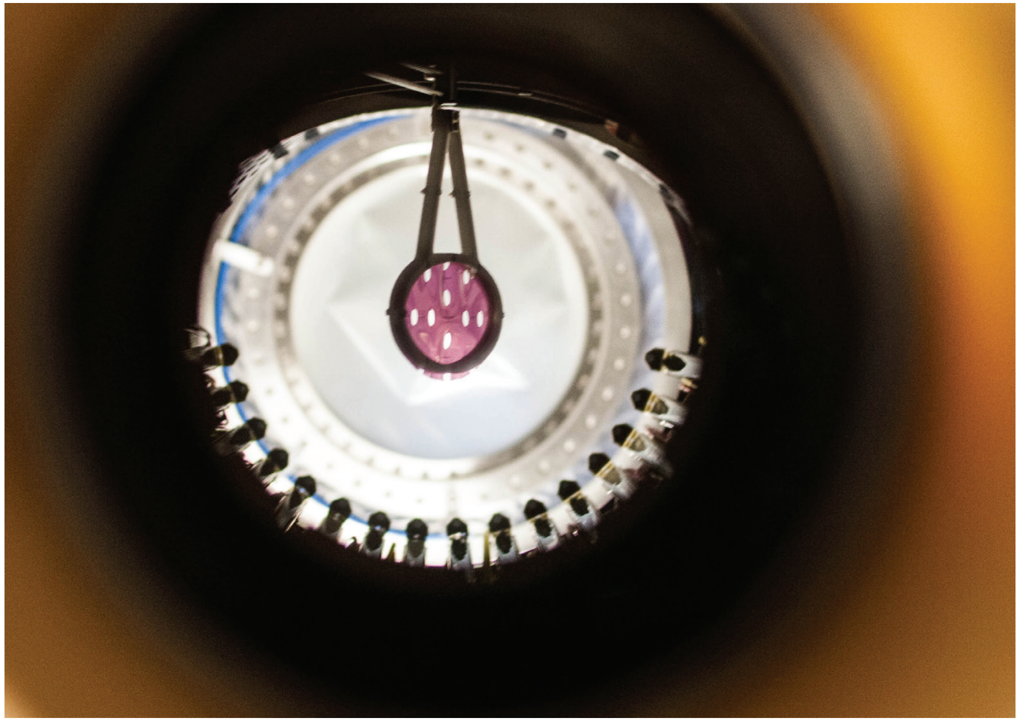


$\mu^+ \rightarrow e^+\gamma$

Kinematics

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

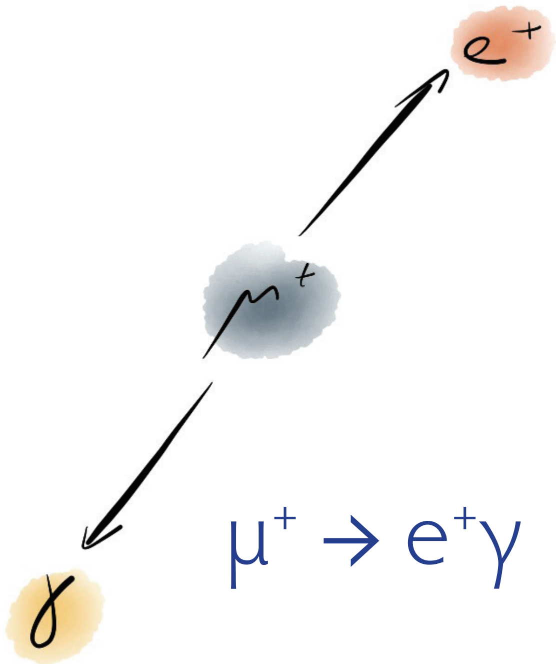
Rates and accidentals



- Muon lifetime 2.2 μs
- Single muon in target experiments limited to < 450'000 μ/s
- Corresponds to few 10^{12} μ decays a year

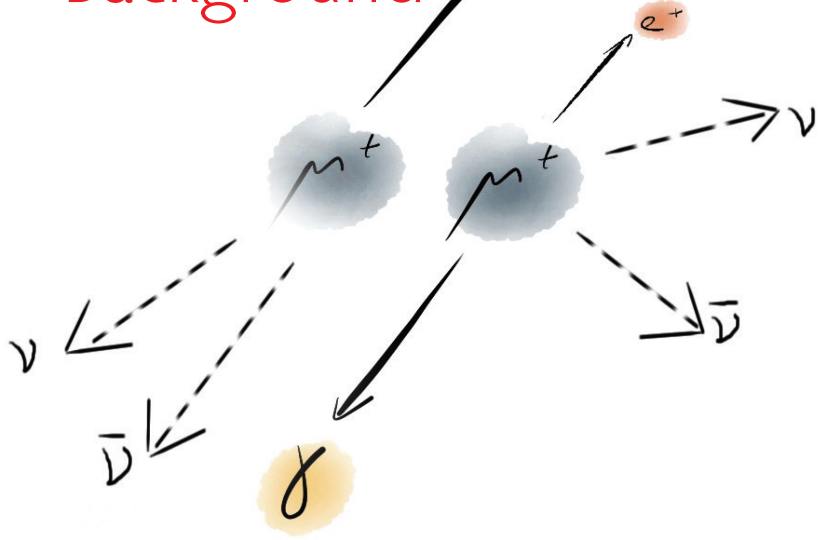
- New experiments operate at 10^{7}++ μ/s
- Many muons on target at any time
- Accidental background

MEG Signal and background



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

Accidental
Background

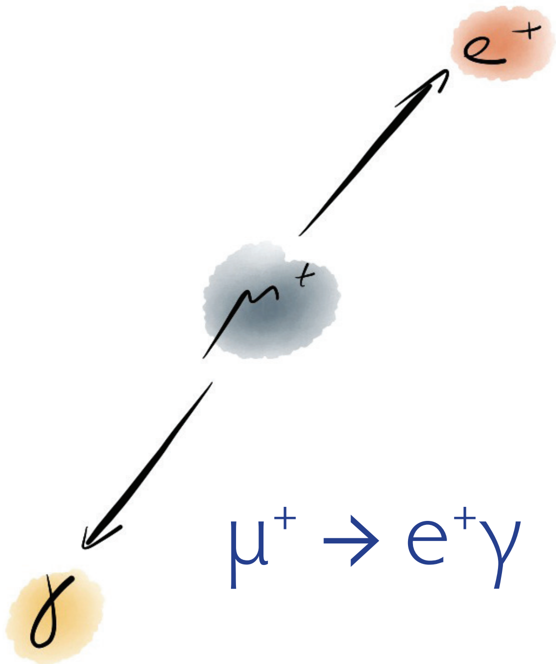


Kinematics

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

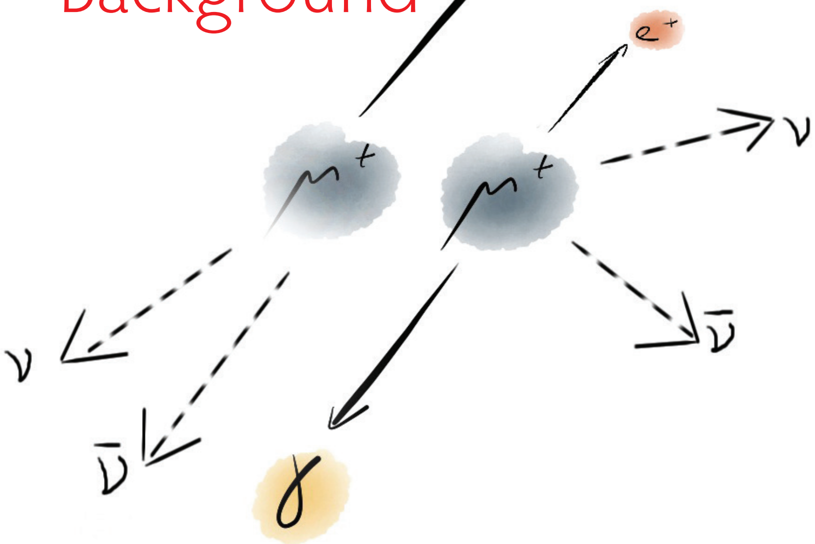
- Not exactly in time
- Not exactly same vertex
- e^+, γ energies somewhat off
- Not exactly back-to-back

MEG Signal and background

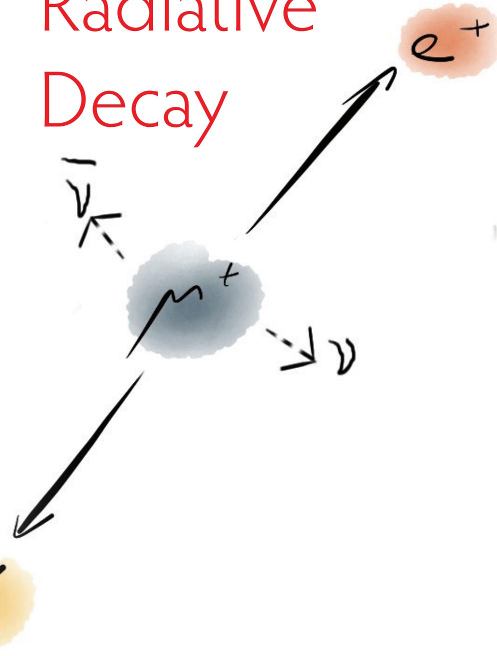


$\mu^+ \rightarrow e^+\gamma$

Accidental Background



Radiative Decay



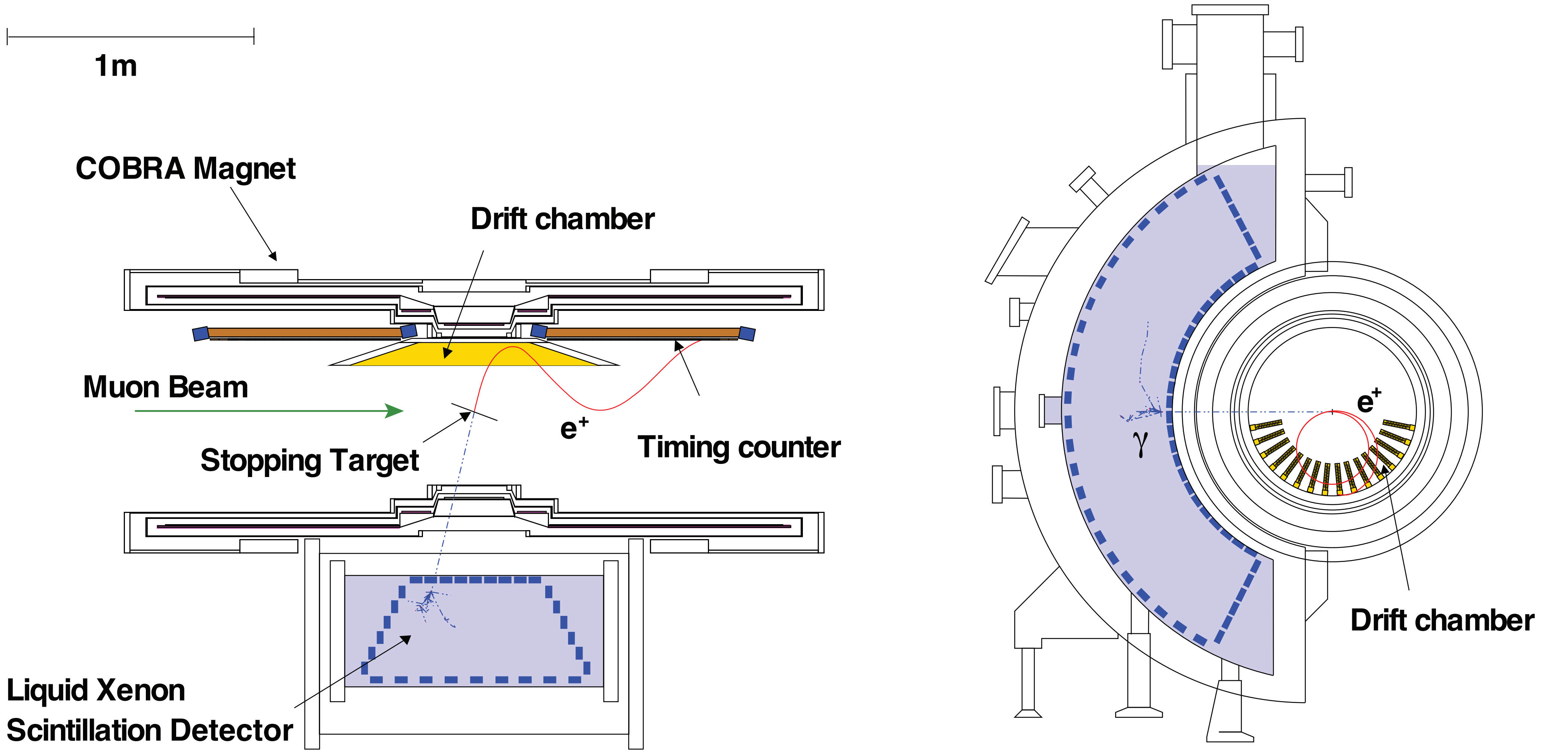
Kinematics

- 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

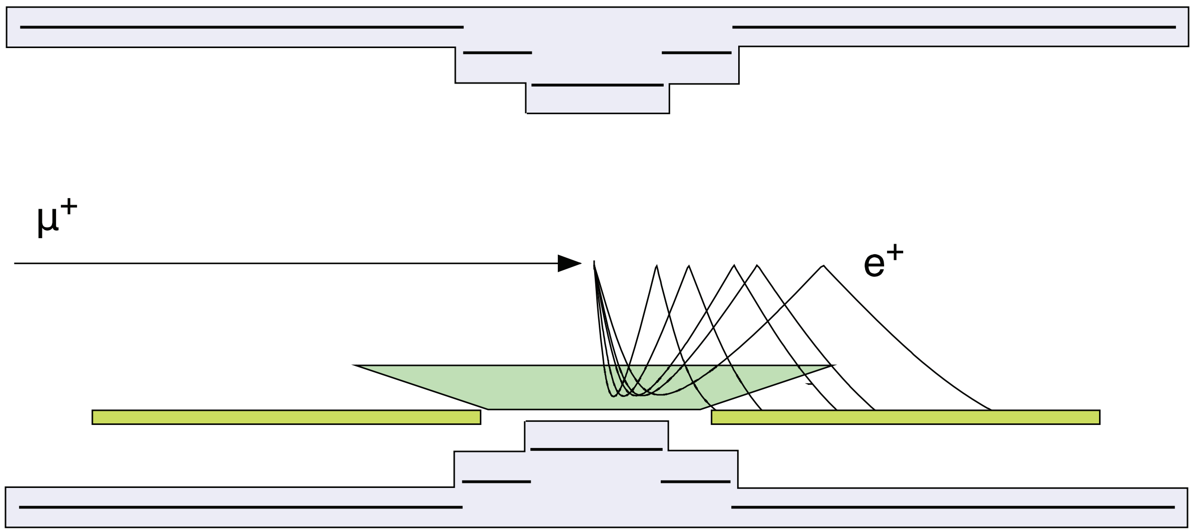
- e^+, γ energies somewhat off
- Not exactly back-to-back

The MEG Detector

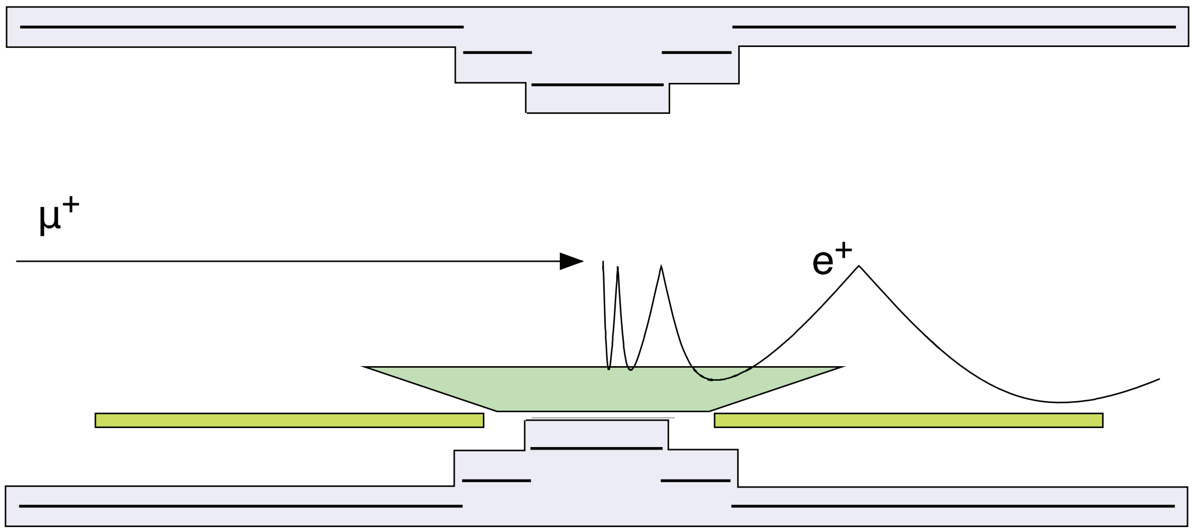


J. Adam et al. EPJ C 73, 2365 (2013)

COBRA Magnet

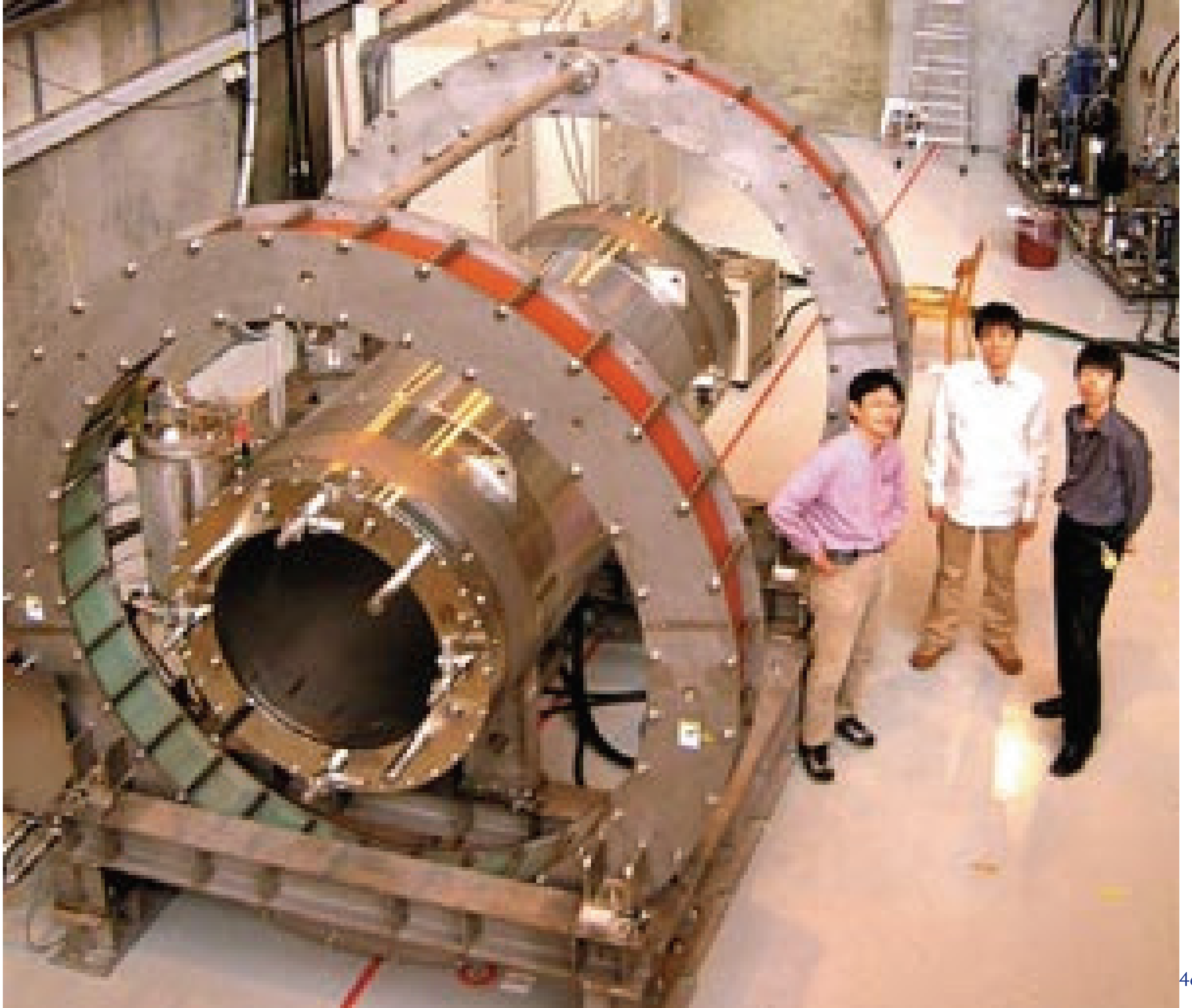


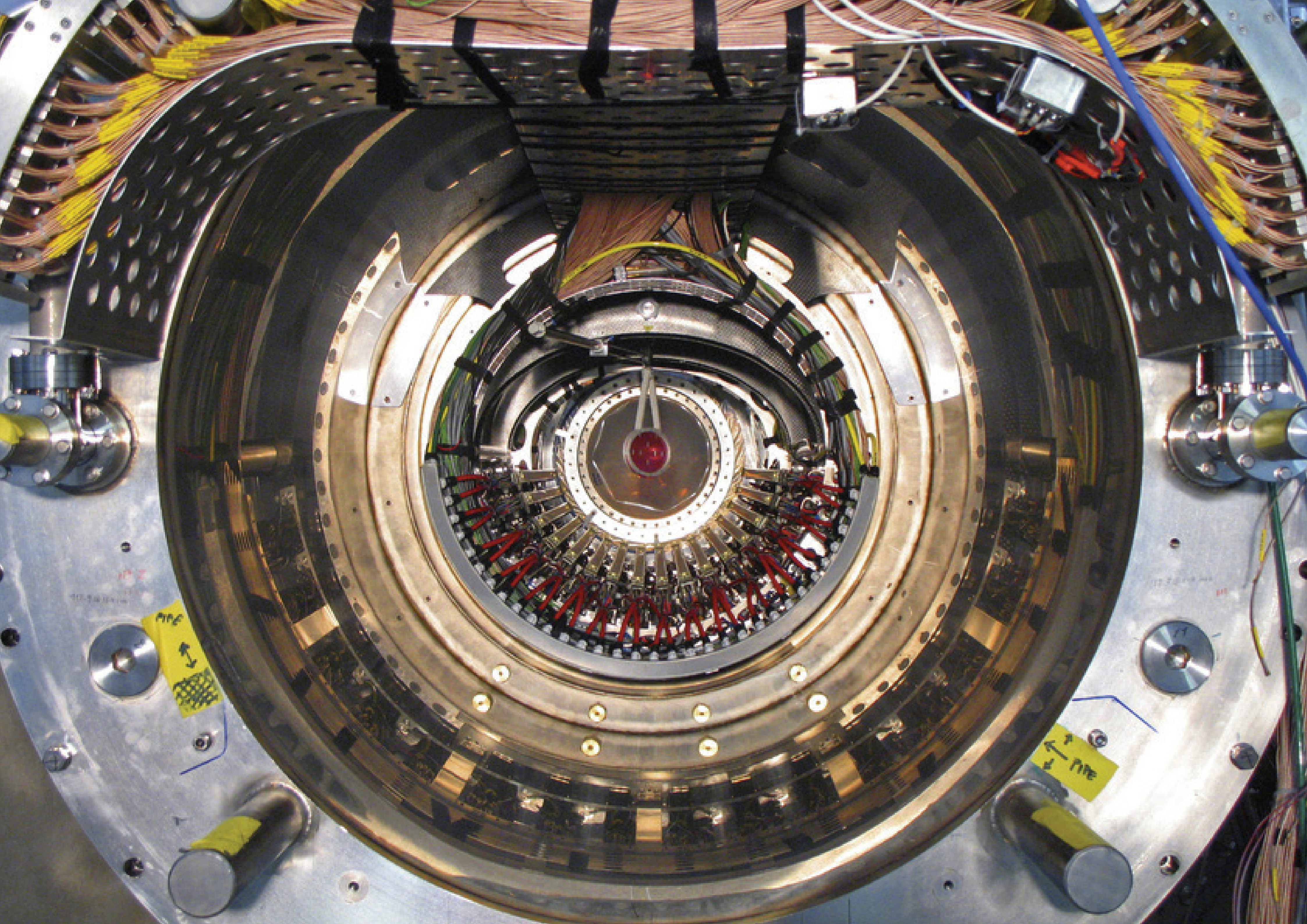
Gradient field gives constant bending radius independent of angle

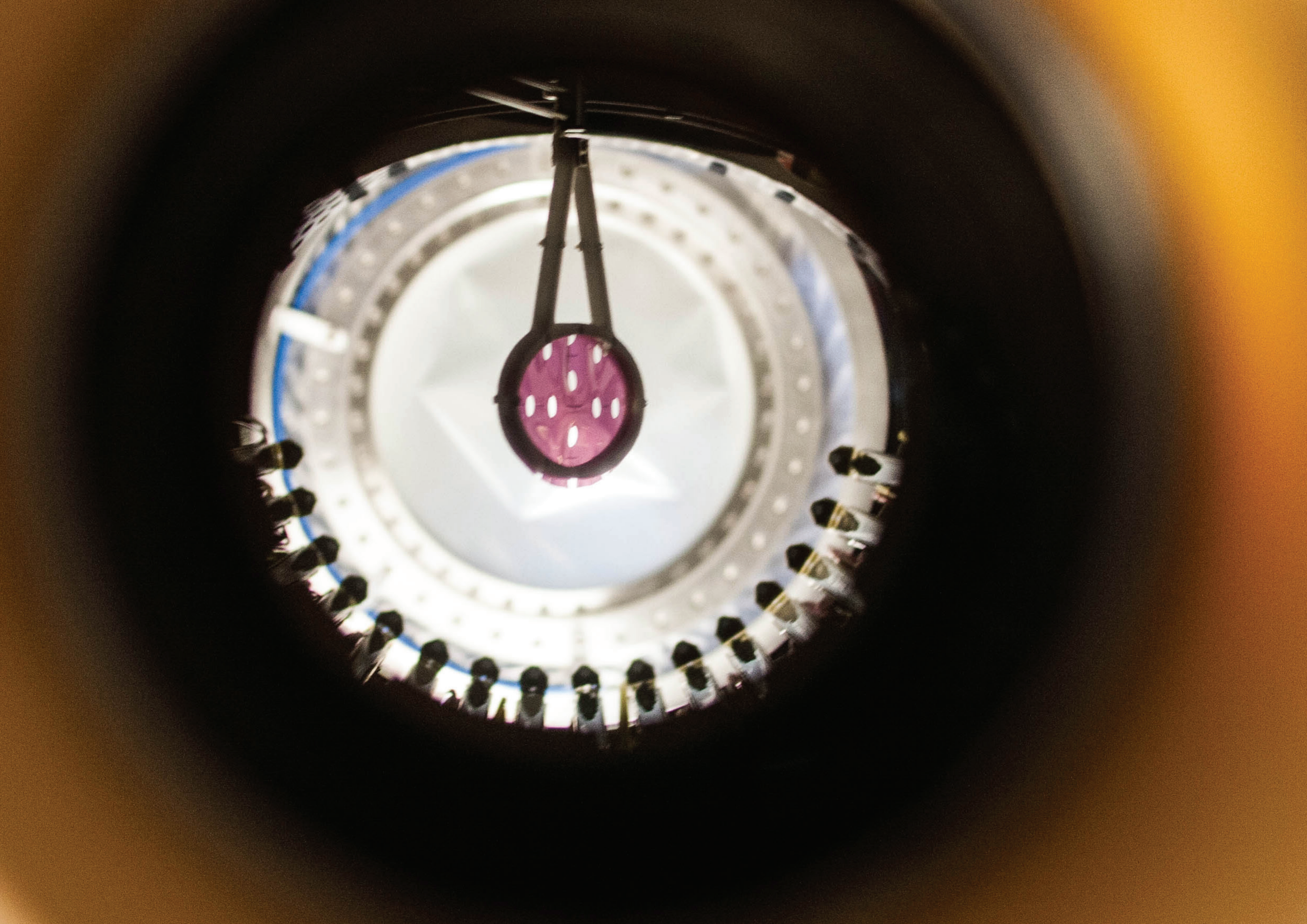


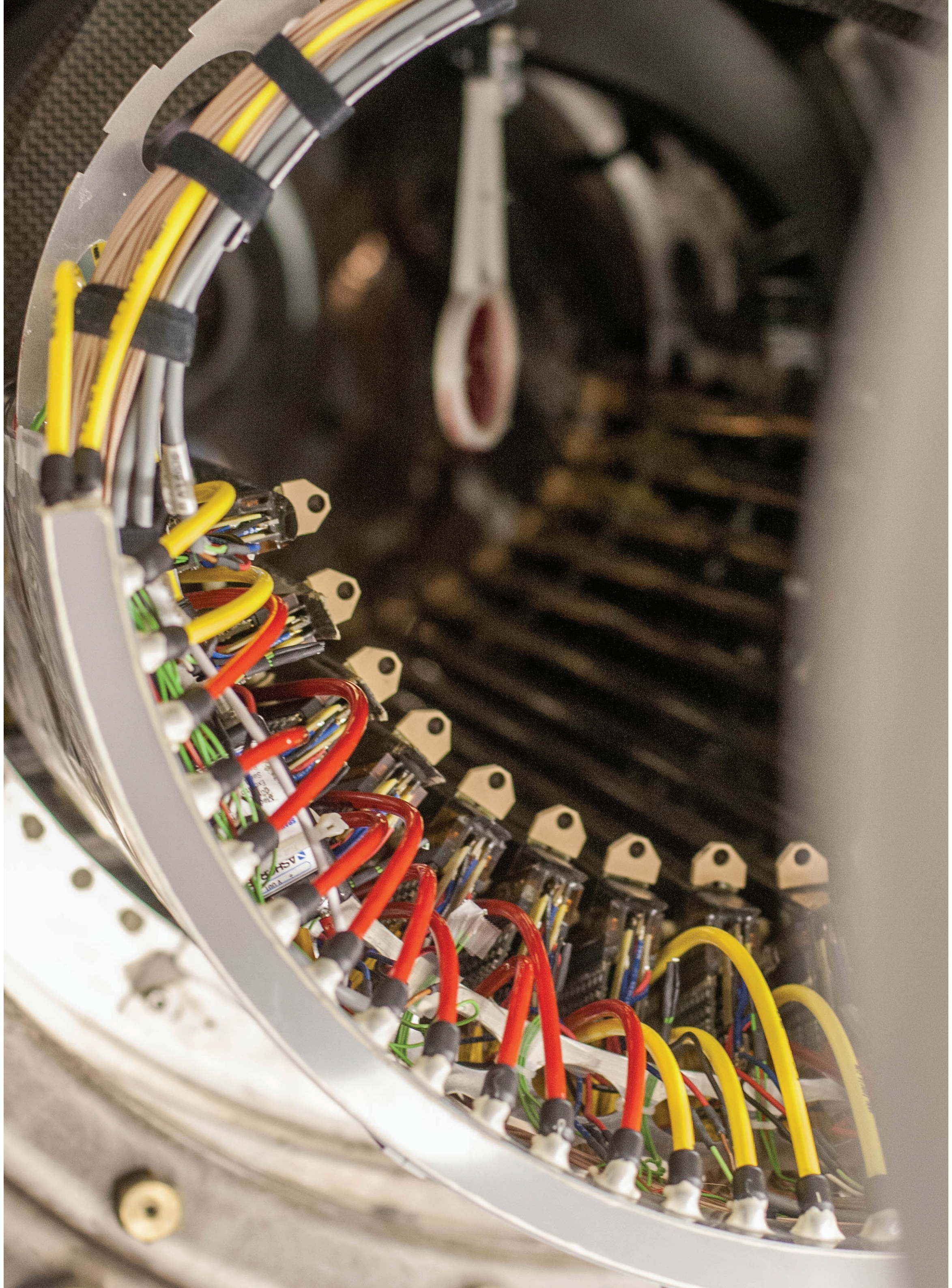
Fast sweep of curlers

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

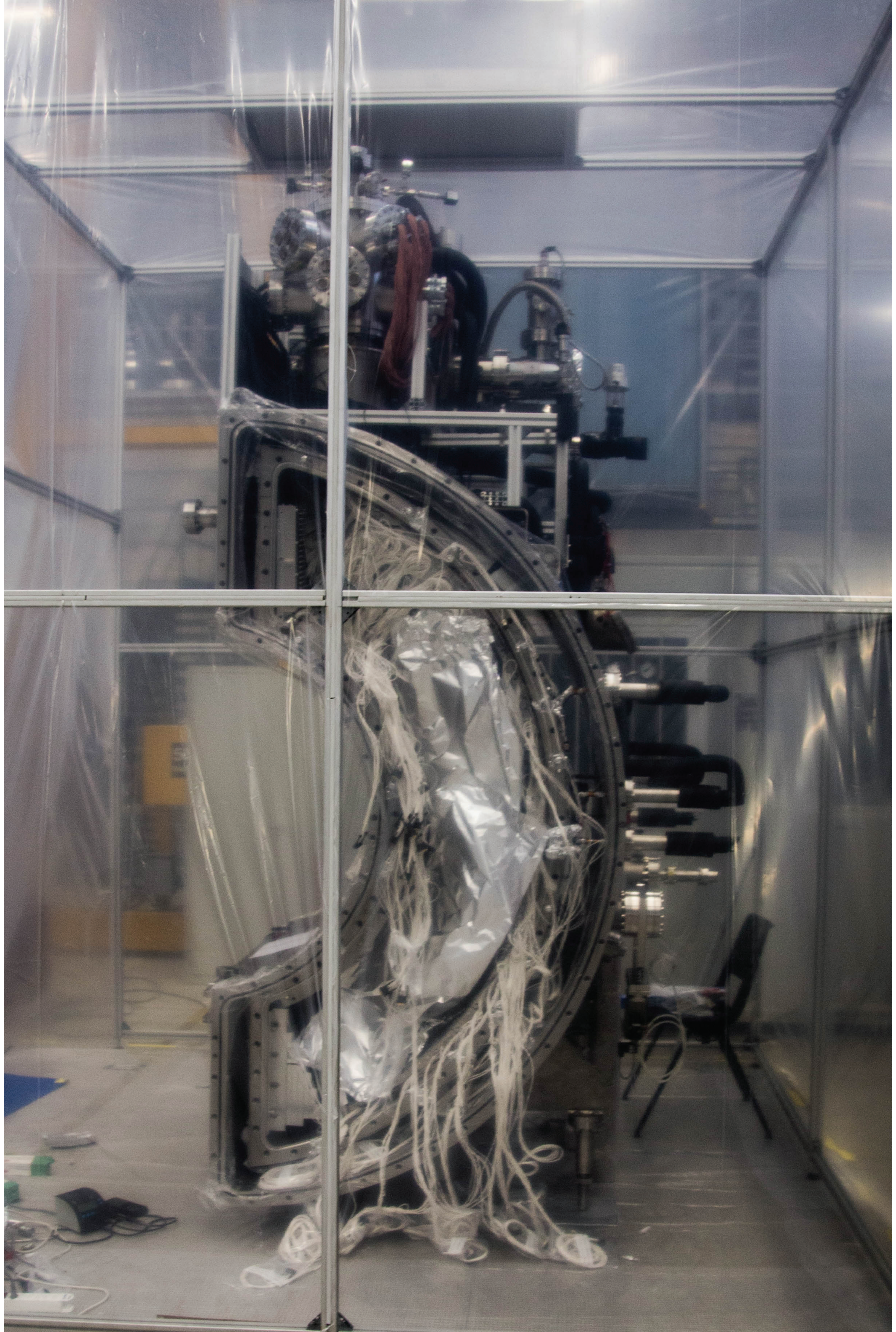



PIPE
PIPE






1039
RA 1397
RA 1029

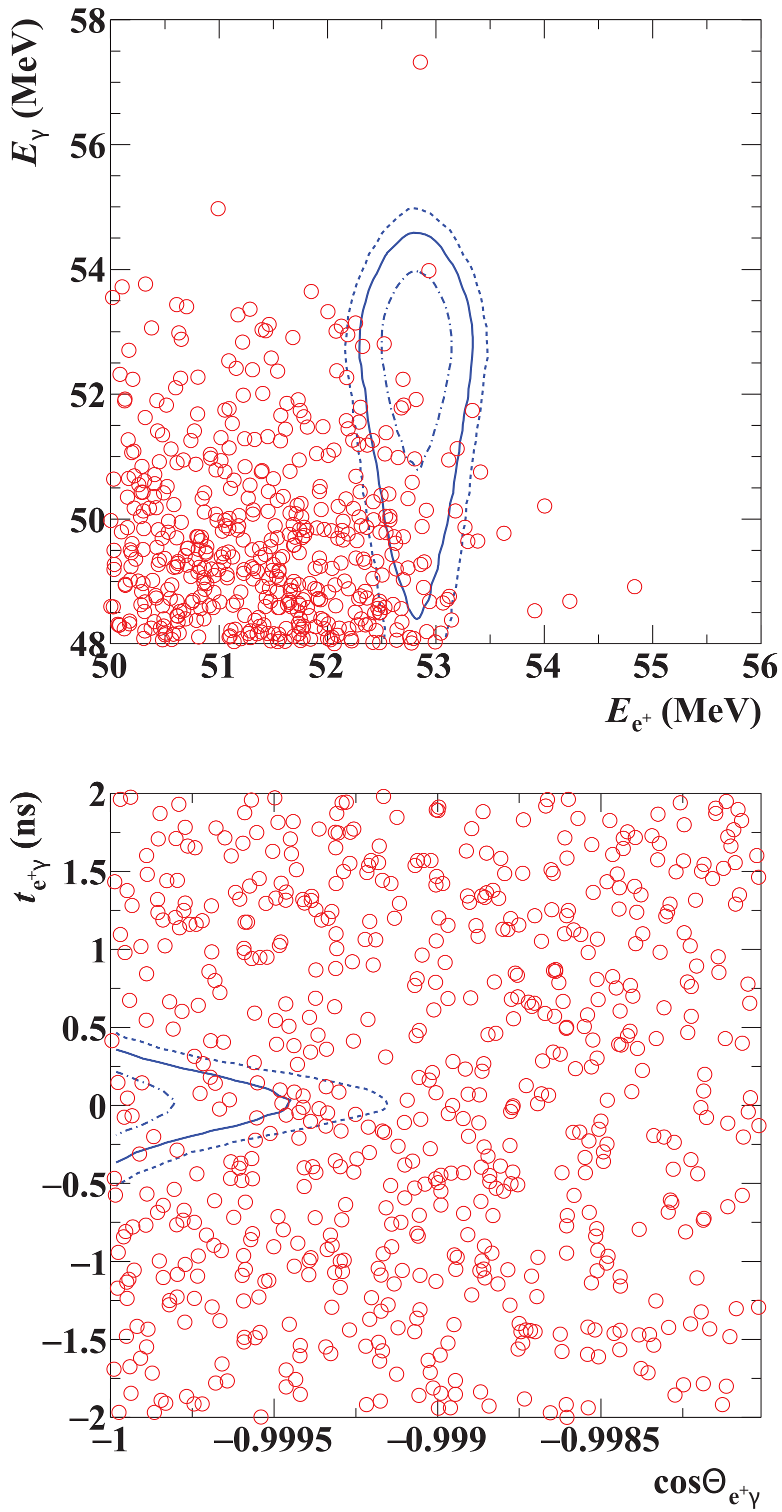


MEG Results

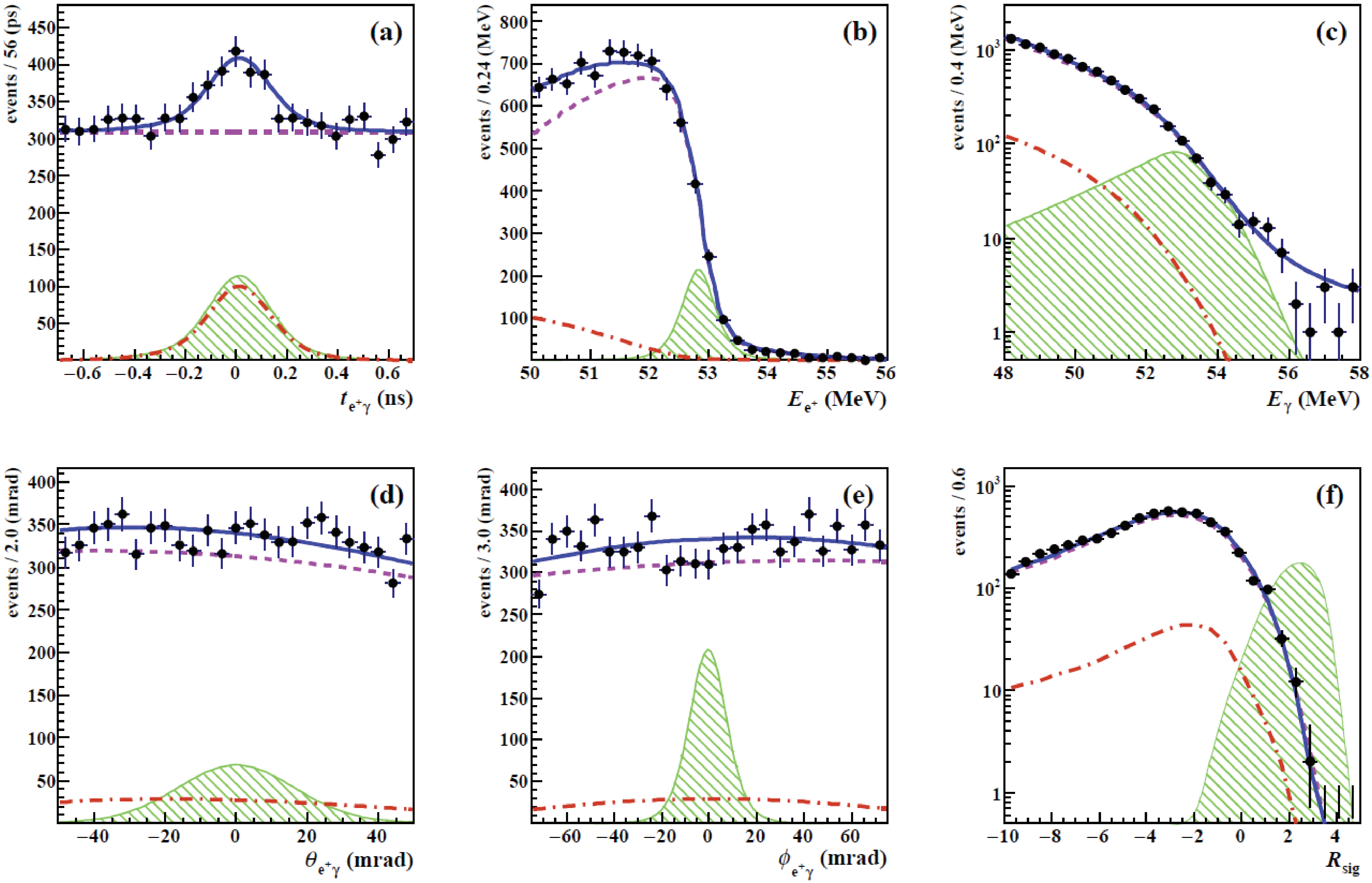
- 2009-2013 data
- Blue: Signal PDF, given by detector resolution
- No signal seen
- Upper limit at 90% CL:

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

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



MEG Resolutions



How the sensitivity can be pushed down?

Angela Papa (Mainz Seminar)

high statistics

- More sensitive to the signal...

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

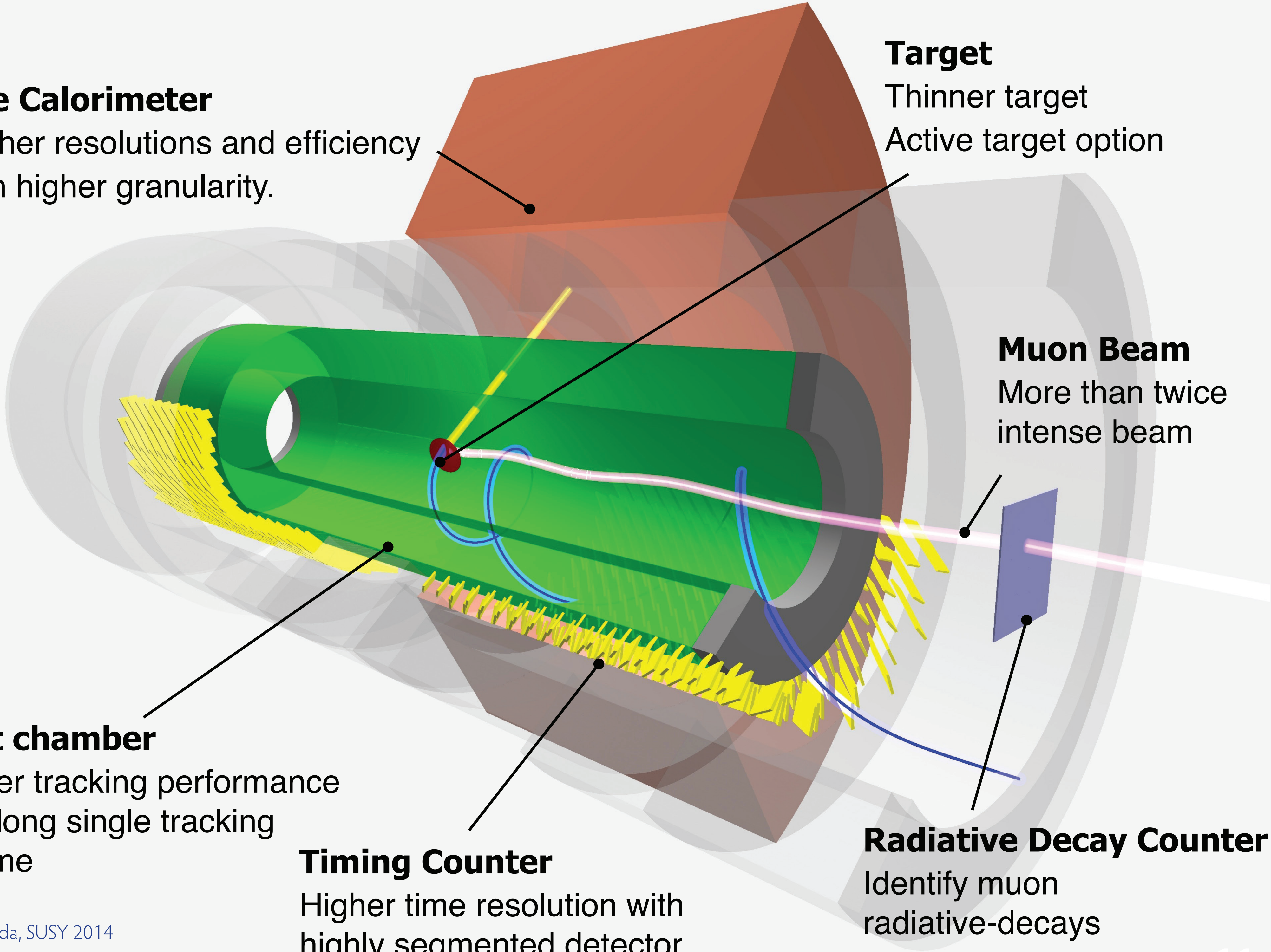
Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

high resolutions

- More effective on rejecting the background...

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

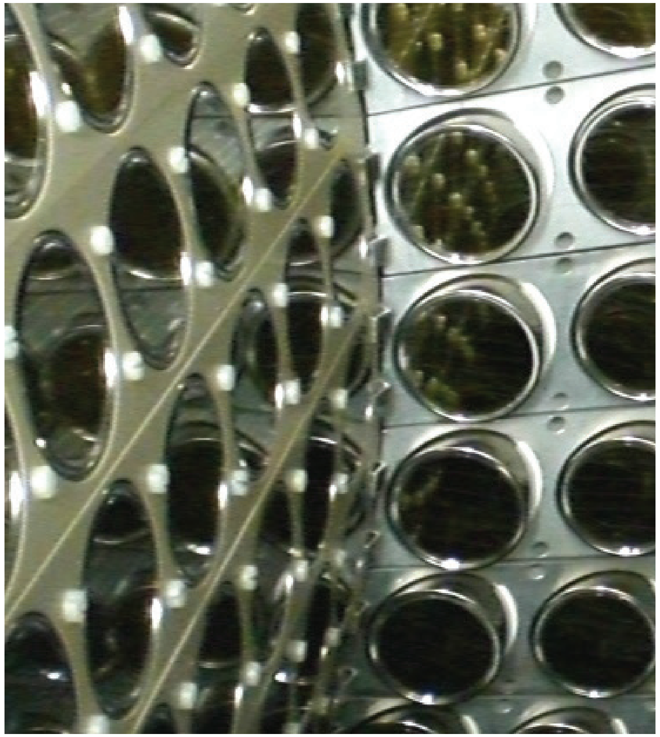
Positron Energy resolution
Gamma Energy resolution
Relative timing resolution
Relative angular resolution

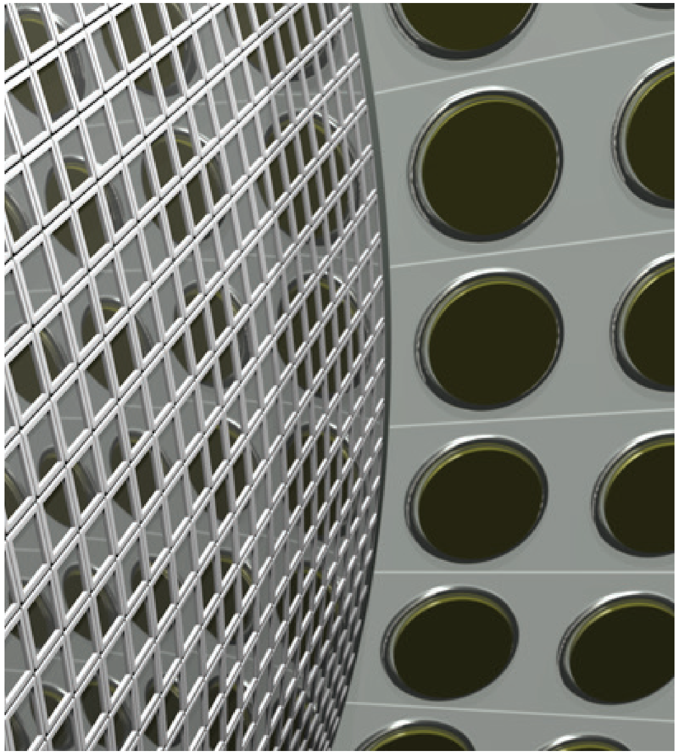


LXe Calorimeter
Higher resolutions and efficiency with higher granularity.
Target
Thinner target
Active target option
Muon Beam
More than twice intense beam
Drift chamber
Higher tracking performance with long single tracking volume
Timing Counter
Higher time resolution with highly segmented detector
Radiative Decay Counter
Identify muon radiative-decays

MEG Upgrade - Calorimeter

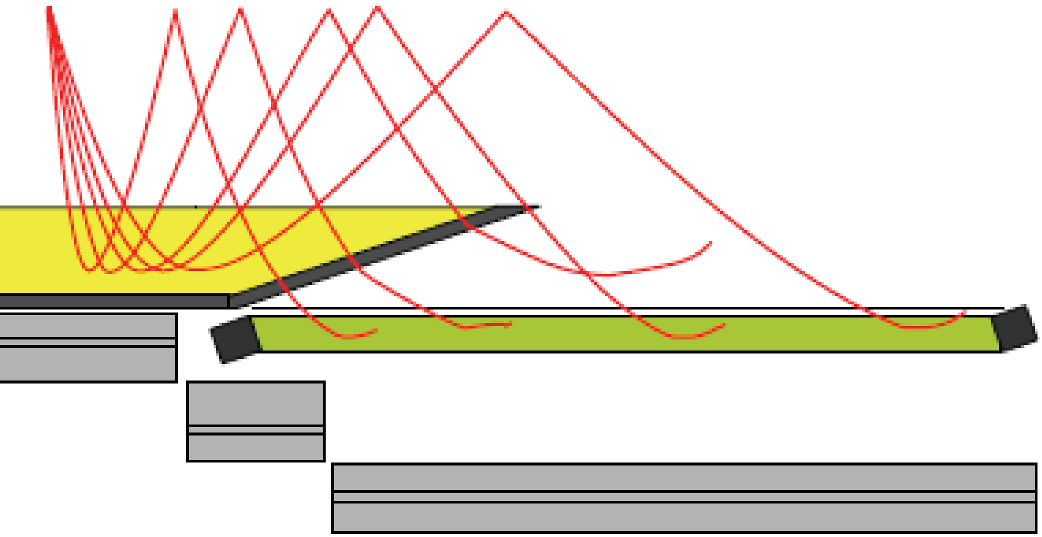
- ~4000 VUV sensitive SiliconPMs on entry face (new development with Hamamatsu)
- Better position and energy resolution
- Better efficiency

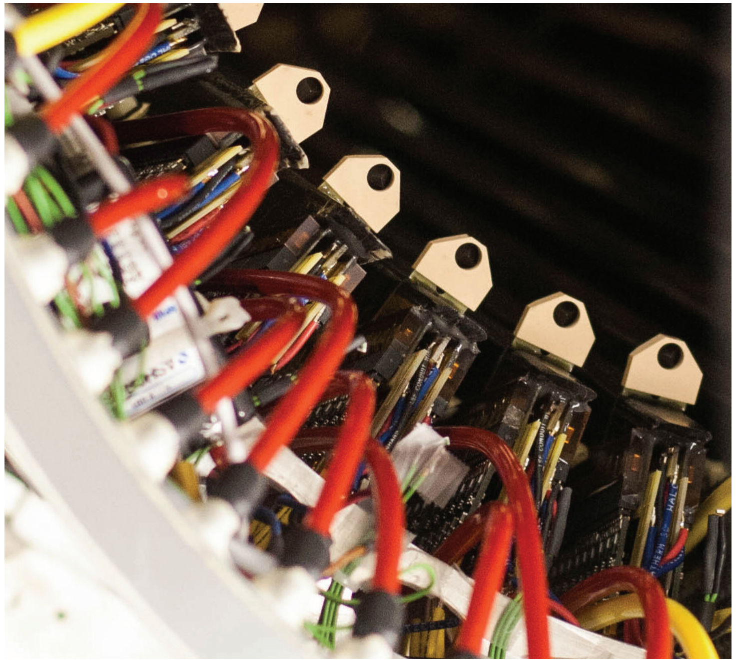


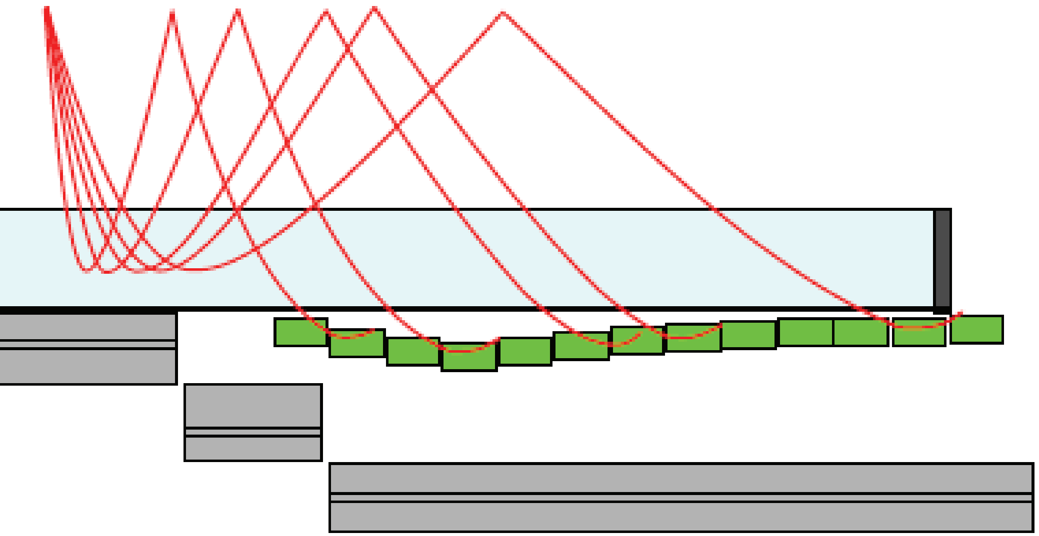


Ryu Sawada, SUSY 2014

MEG Upgrade - Drift Chamber



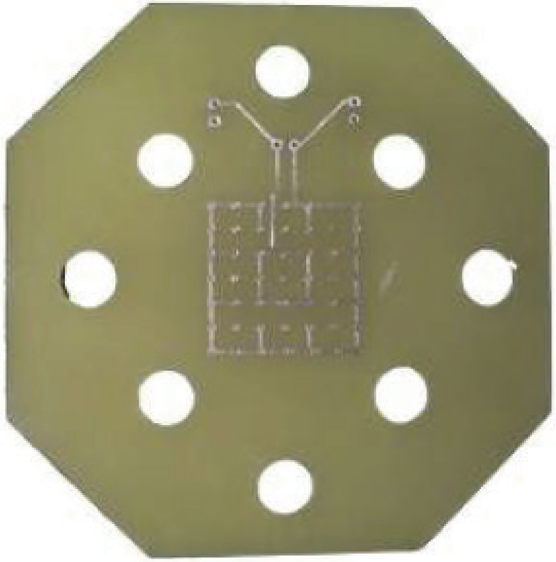


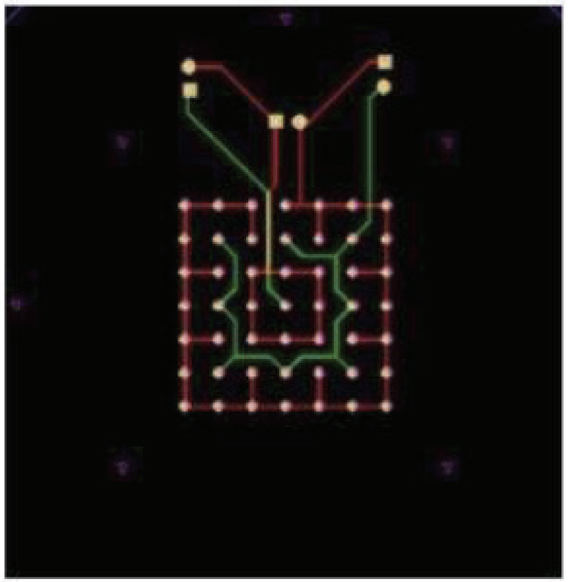


- New single volume drift chamber
- Lower Z gas mixture
- More space points per track
- Better rate capability
- Less material in front of timing counters

Ryu Sawada, SUSY 2014

MEG Upgrade - Drift Chamber Ageing





MEG Upgrade - Drift Chamber Ageing

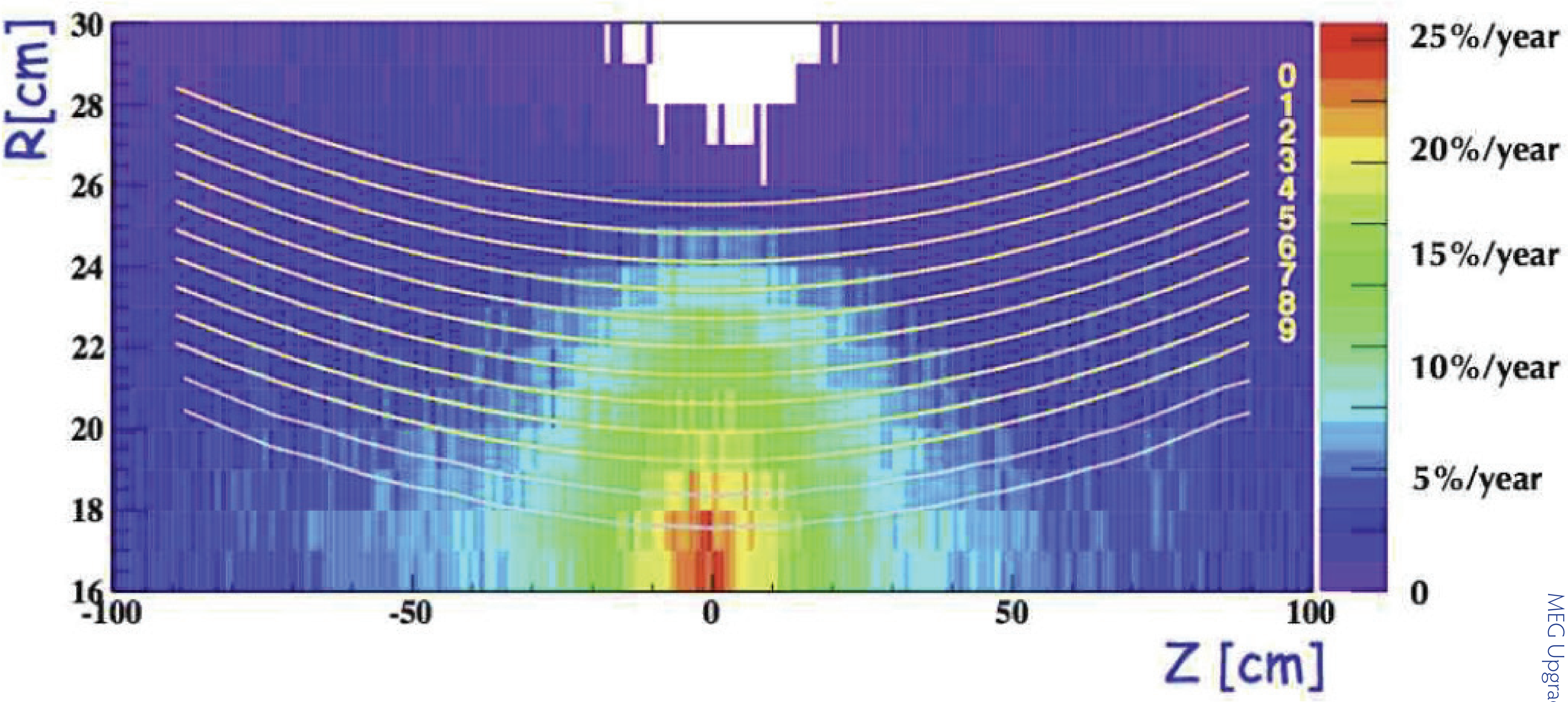
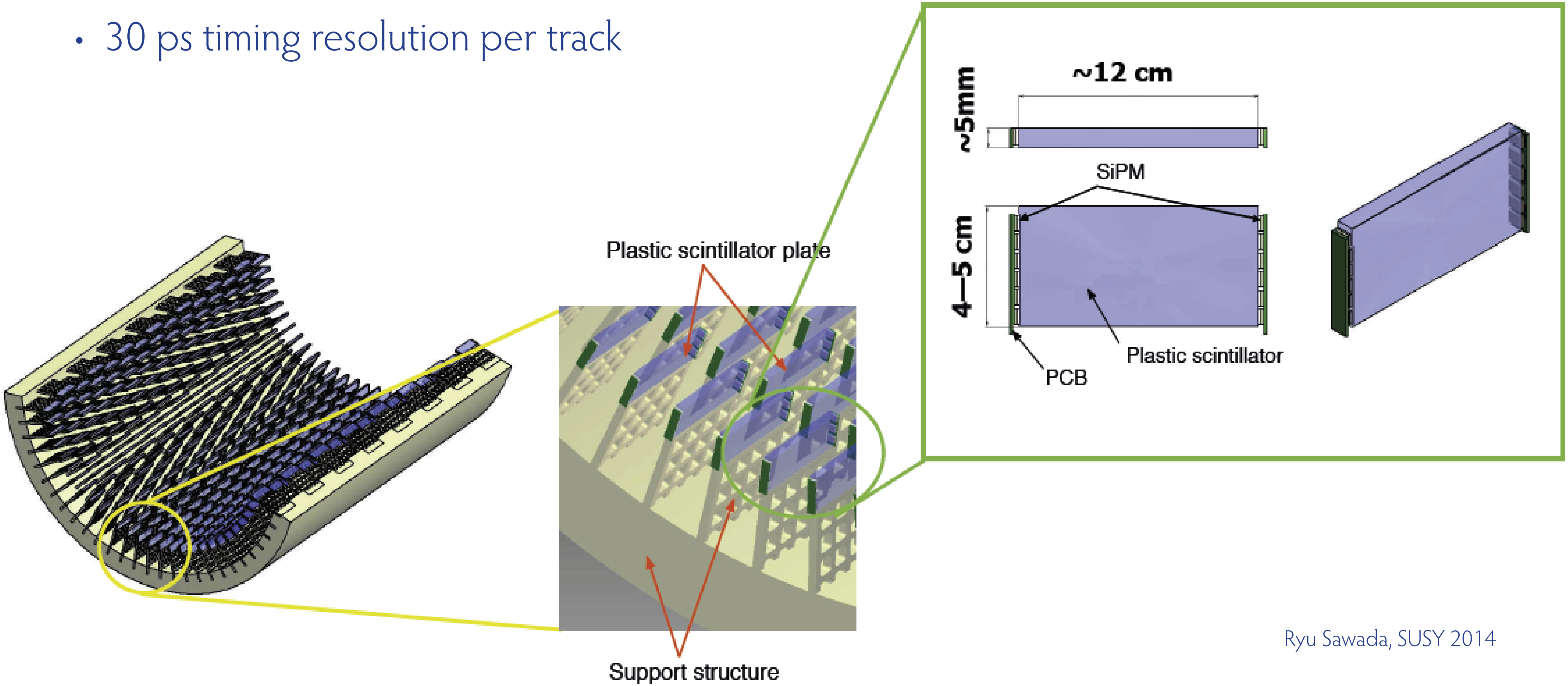


FIG. 24: Gain drop in 1-year od DAQ time at 7×10^7 μ^+/sec.

MEG Upgrade Proposal

MEG Upgrade - Timing Counter

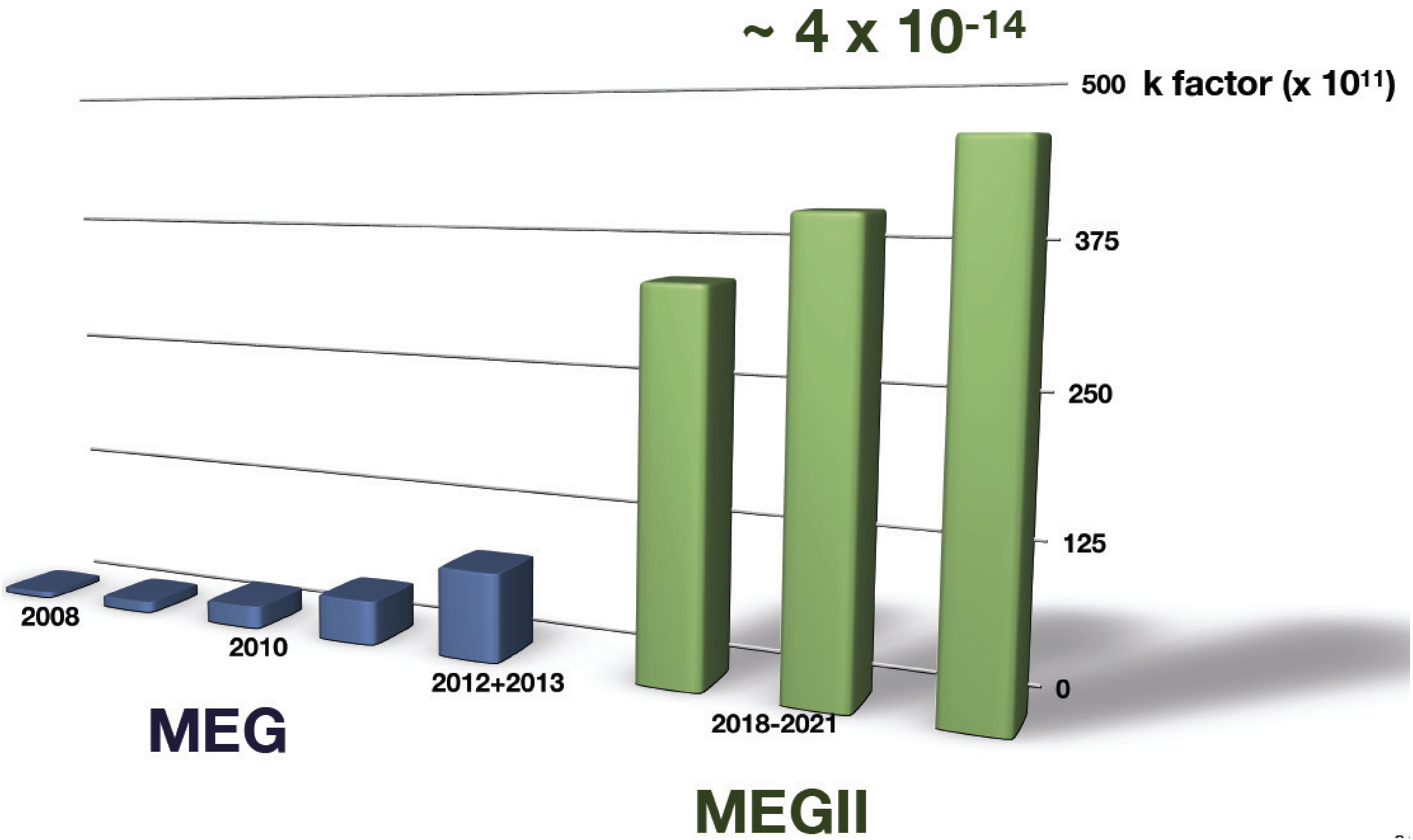
- Many small scintillators
- Read-out by SiliconPMs
- On average eight counters hit by track
- 30 ps timing resolution per track



Ryu Sawada, SUSY 2014

Where we will be

Angela Papa (Mainz Seminar)

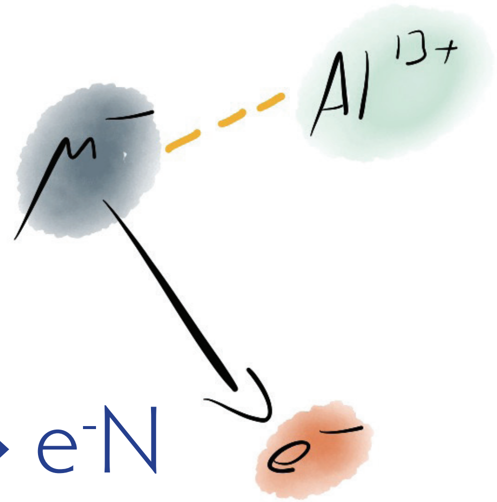


High rates without seeing high rates

Searching for $\mu \rightarrow e$ conversion with

Mu2e, DeeMee, COMET, PRISM

Conversion Signal and Background



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

- Single 105 MeV/c electron observed

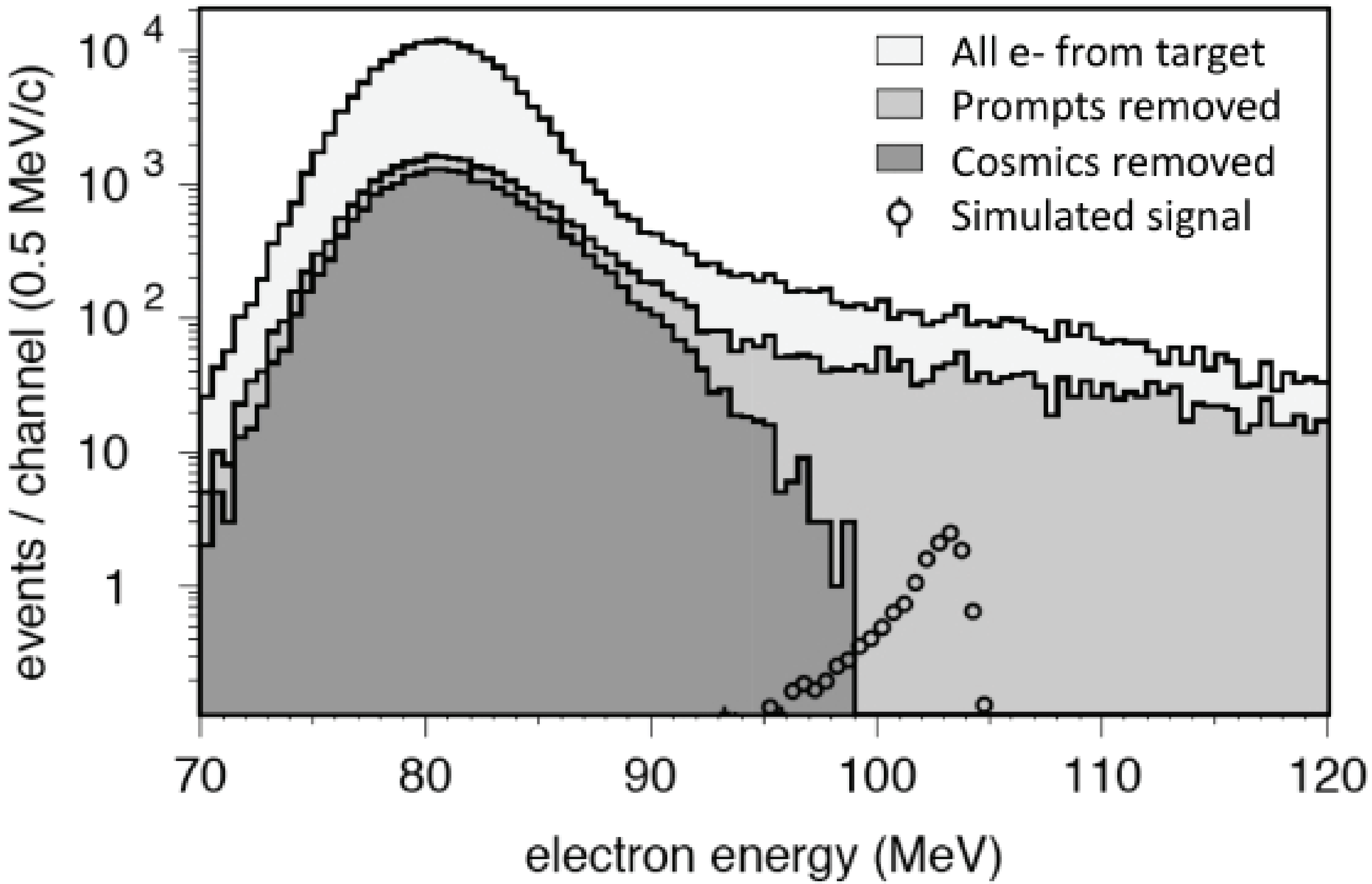
Backgrounds:

Anything that can produce a 105 MeV/c electron

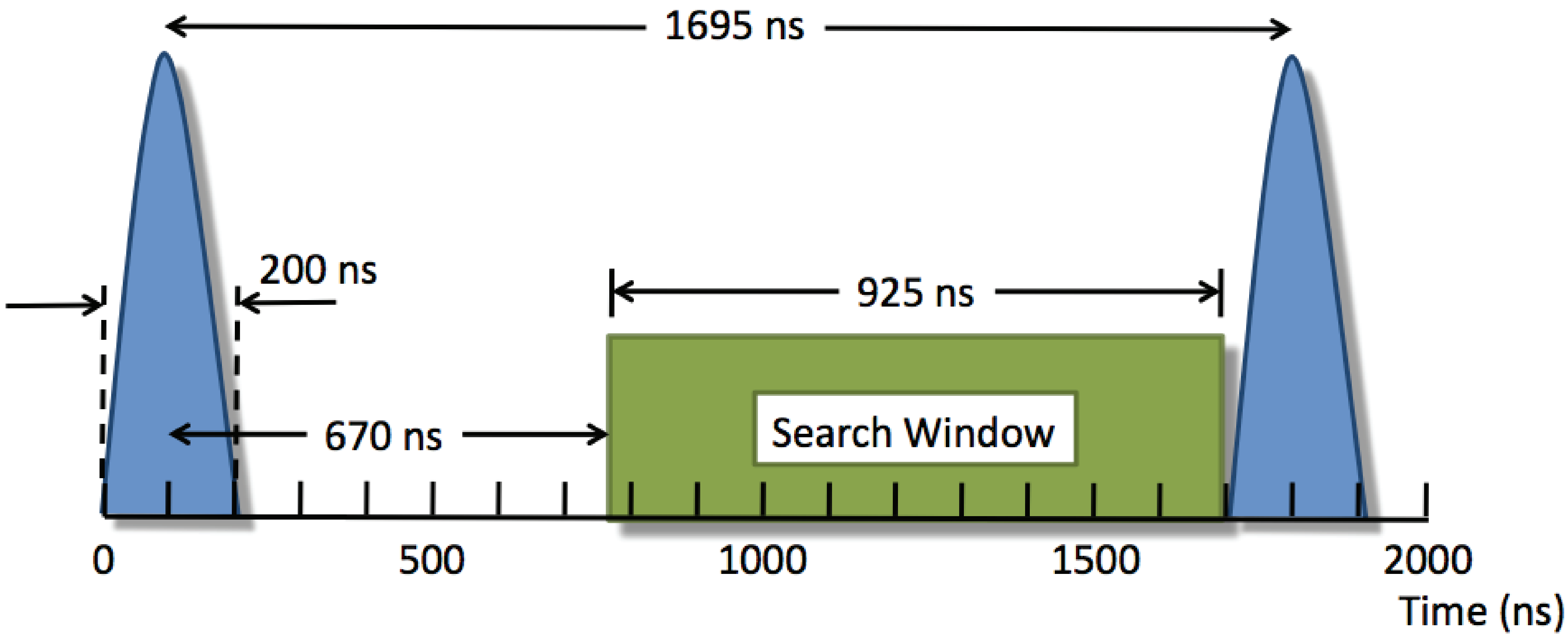
- Primary proton beam
- Decay in Orbit (DIO)
- Nuclear capture (AlCap effort at PSI)
- Cosmics

Limitations of last experiment: SINDRUM II

- Beam induced background
- Muon rates



Beam induced background



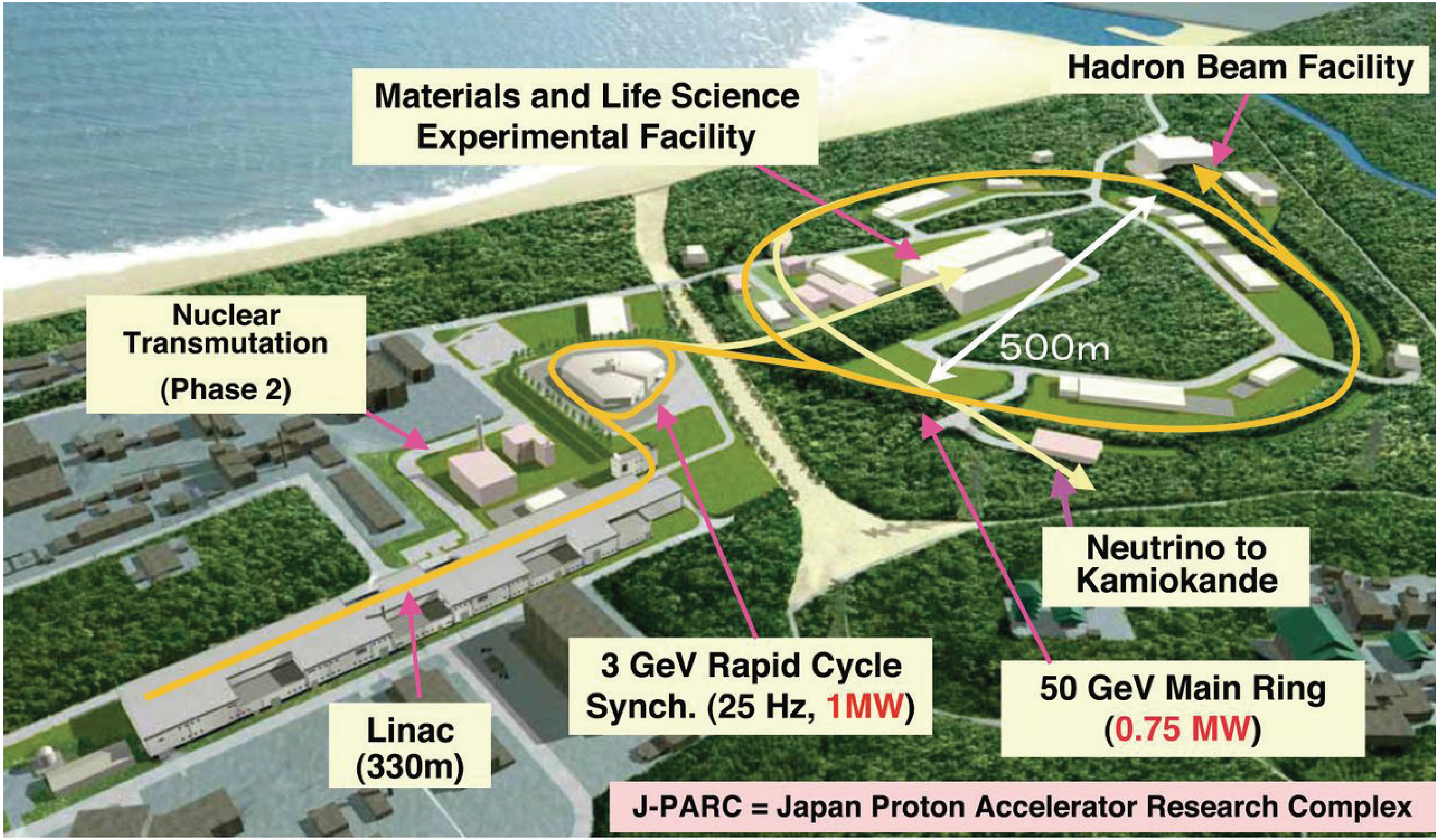
- Proton beam produces pions, photons, (antiprotons) etc.
- Wait until things become better...

Muons from Fermilab...

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

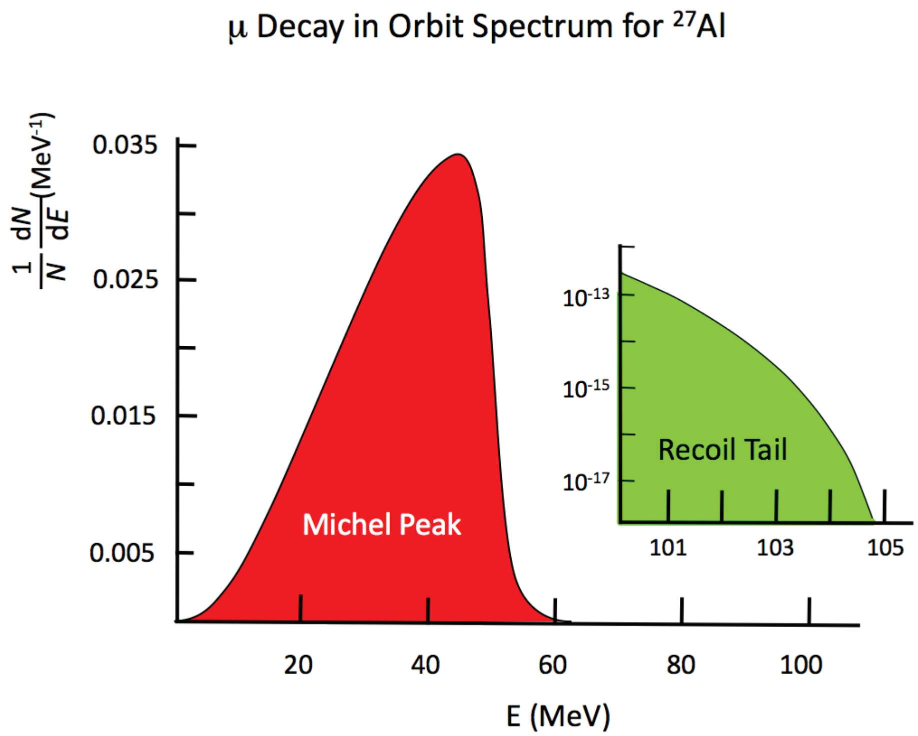
- Project X would give another 2 orders of magnitude at an energy below the antiproton threshold

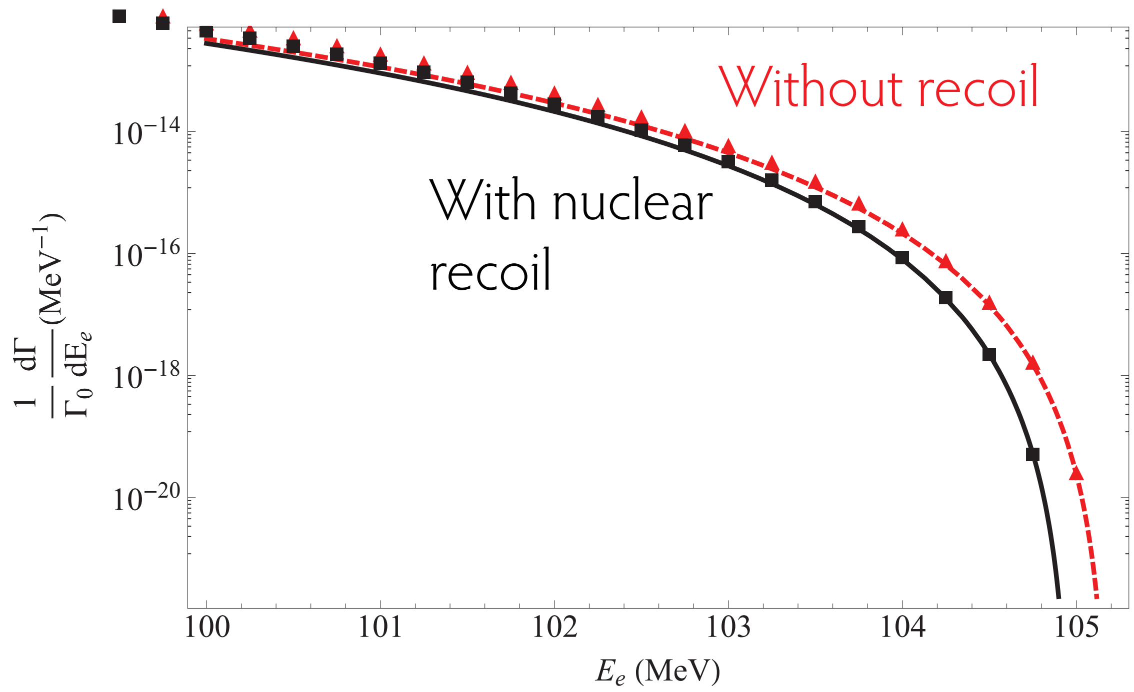
… and J-PARC



- 10^{11} μ/s from 8 GeV/c protons

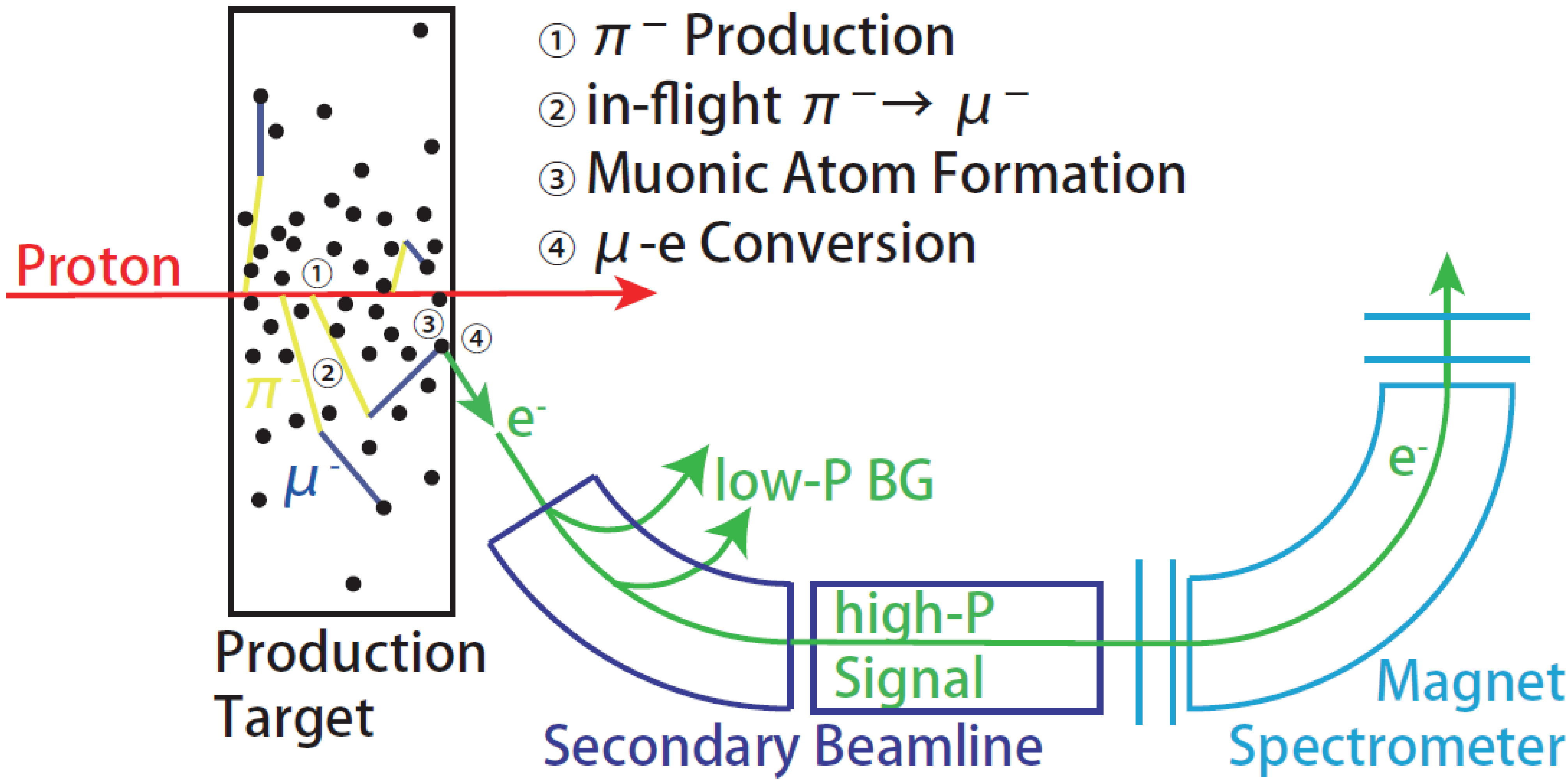
Deacy-in-orbit background





- 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

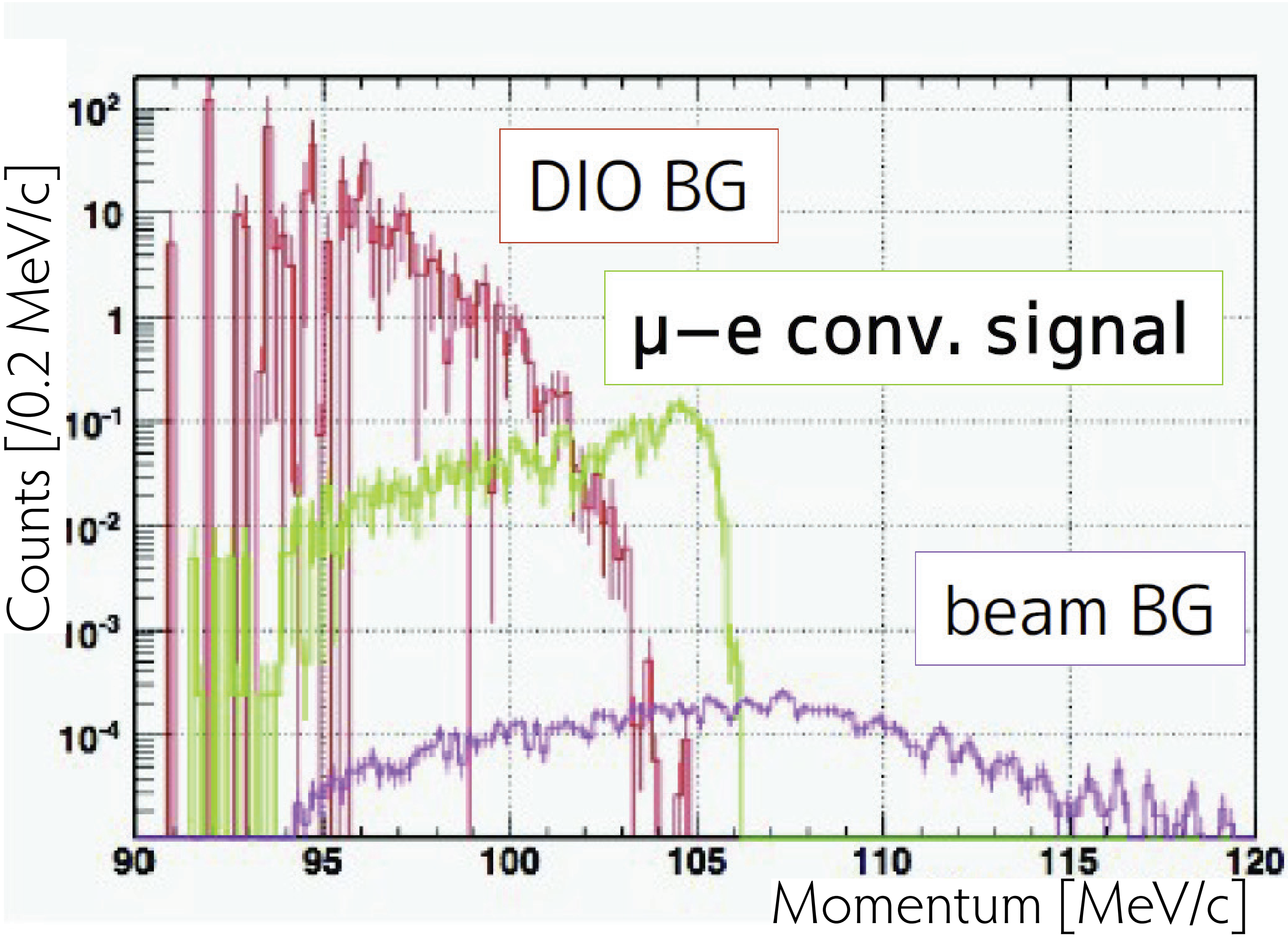
Experimental concept - DeeMee



Yohei Nakatsugawa, NuFACT2014

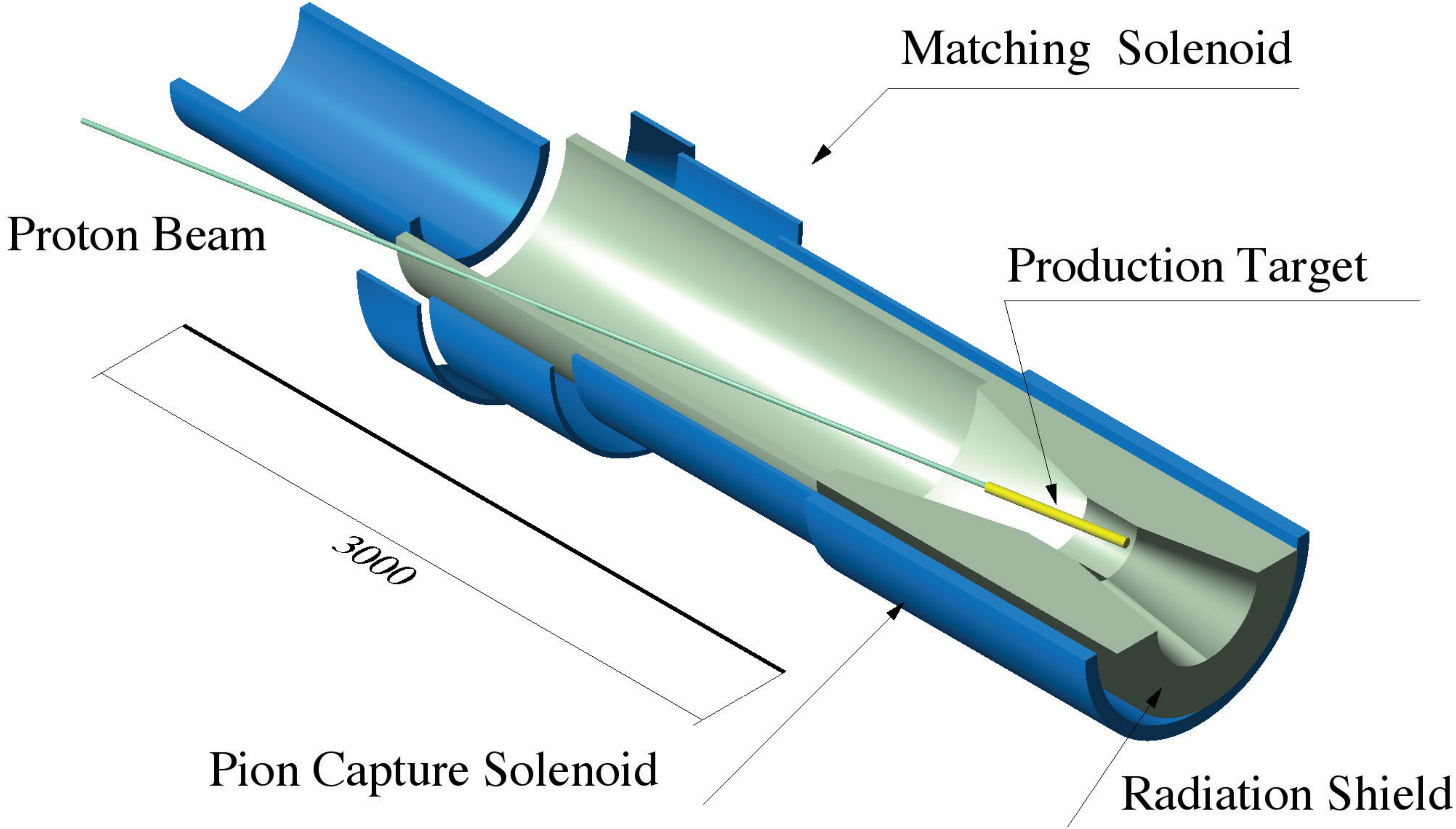
Sensitivity - DeeMee

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



Yohei Nakatsugawa, NuFACT2014

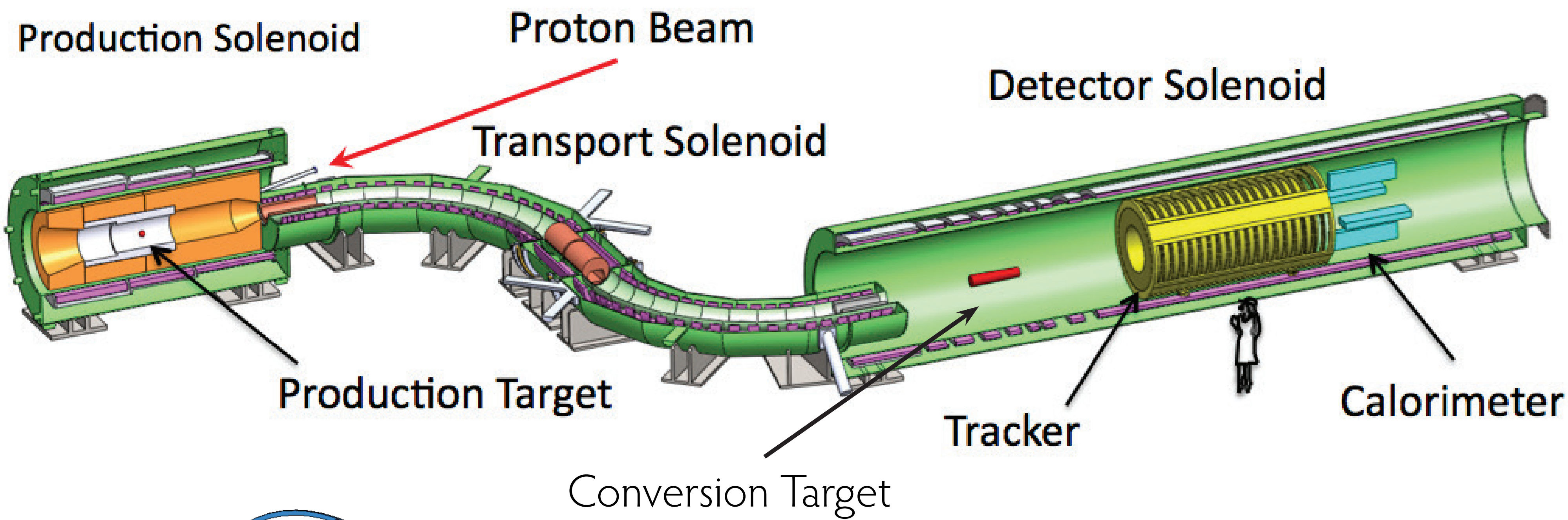
Production target inside a solenoid

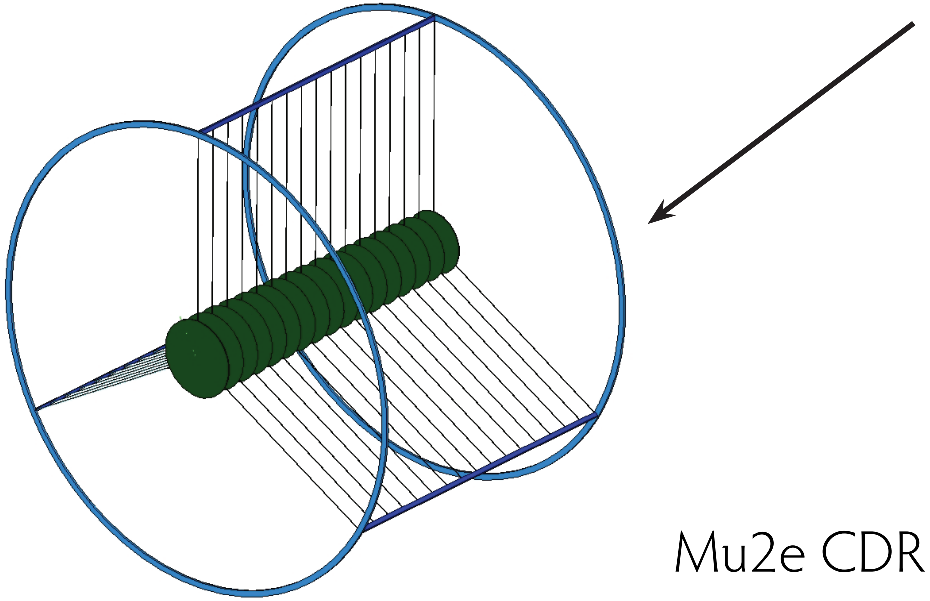


Capture most pions produced in target

Shielding of superconducting magnet very challenging

Experimental layout - Mu2e

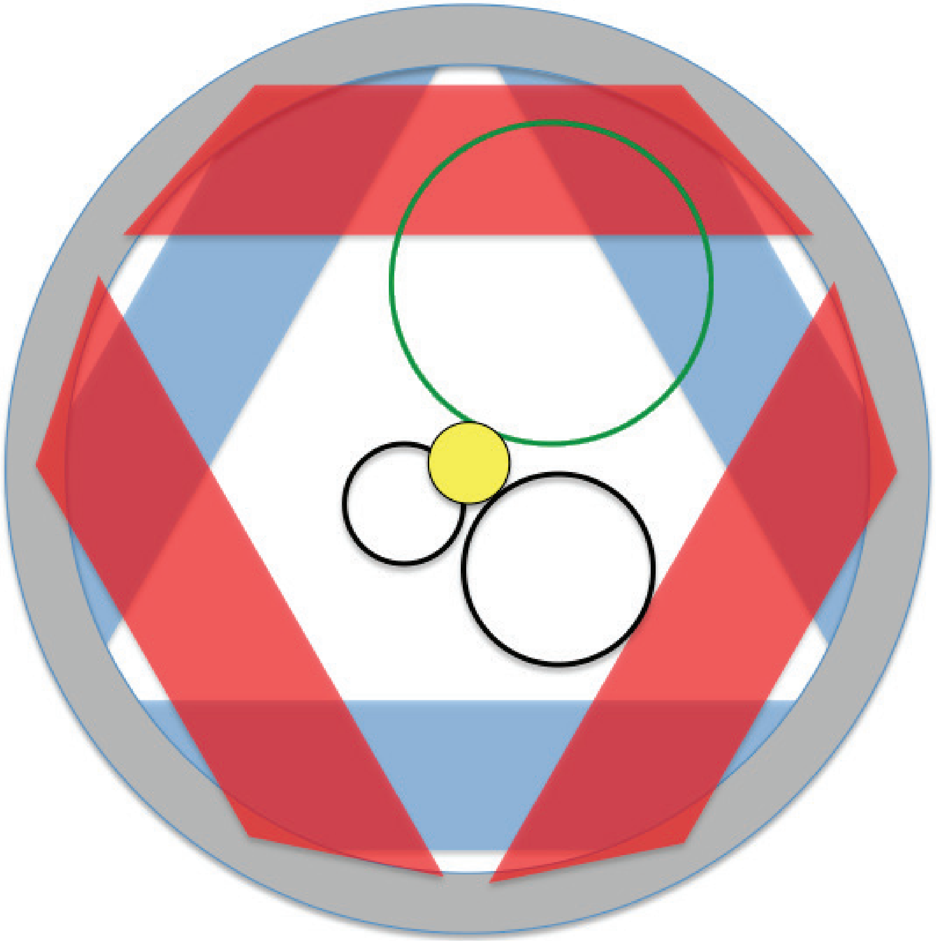


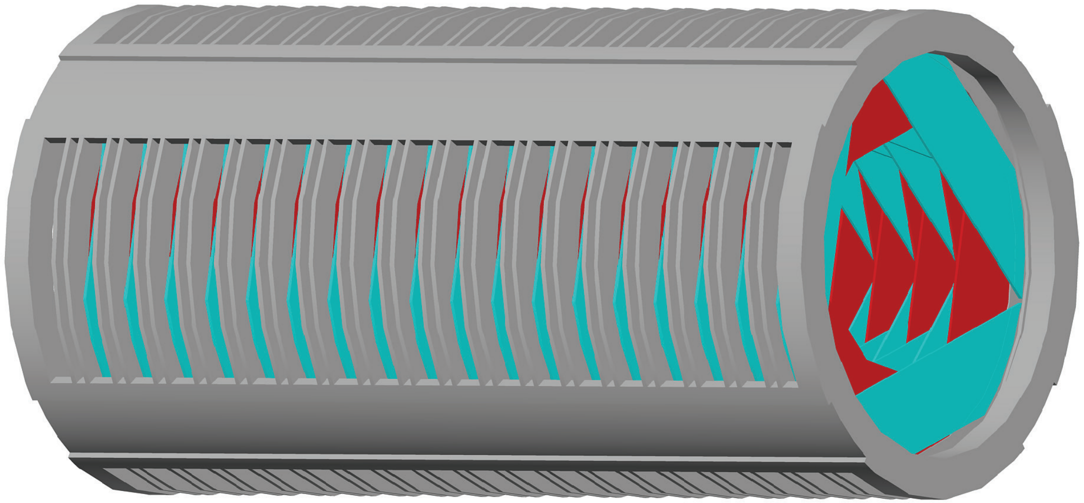


Mu2e CDR

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

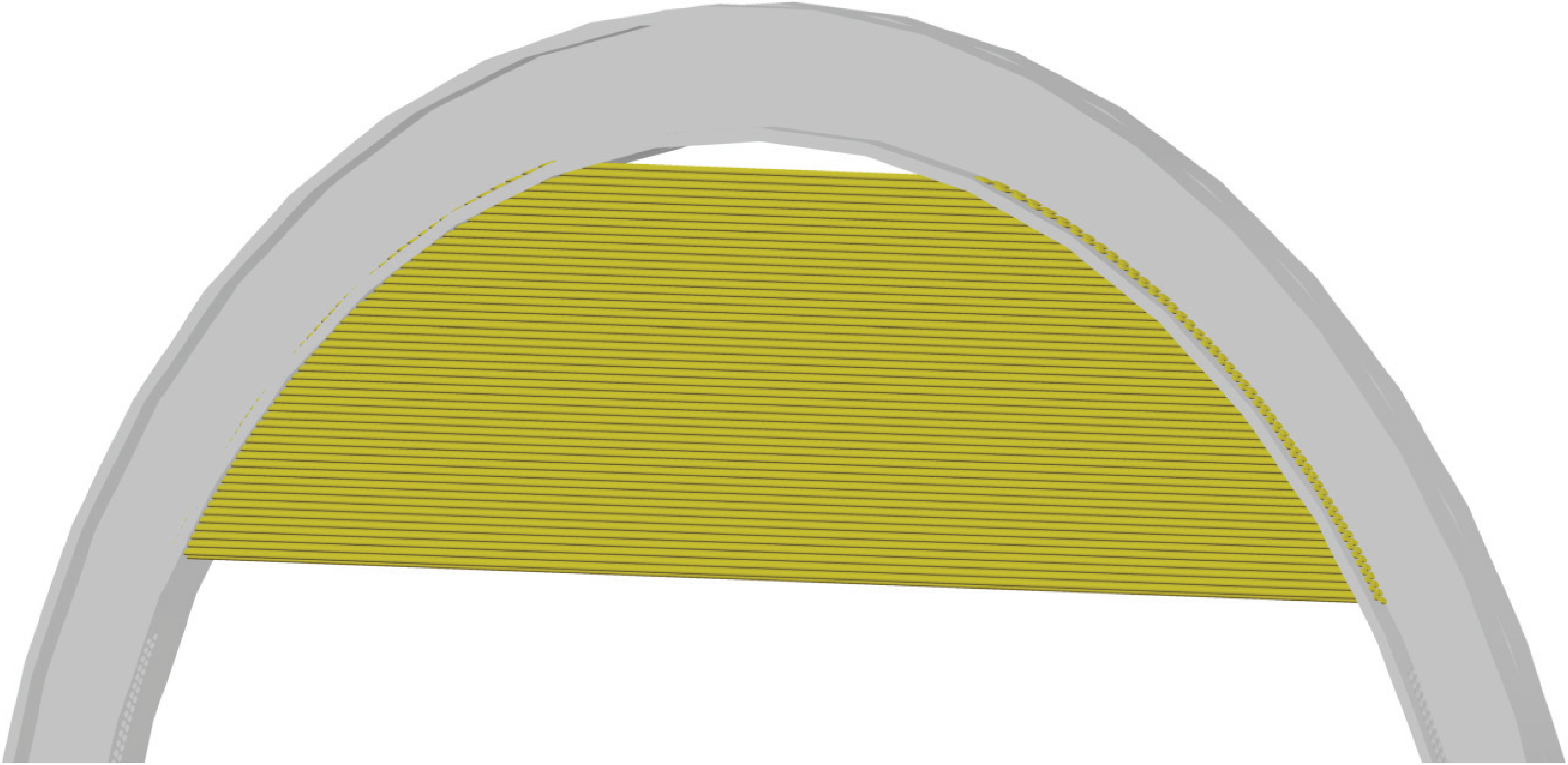
Mu2e Tracker

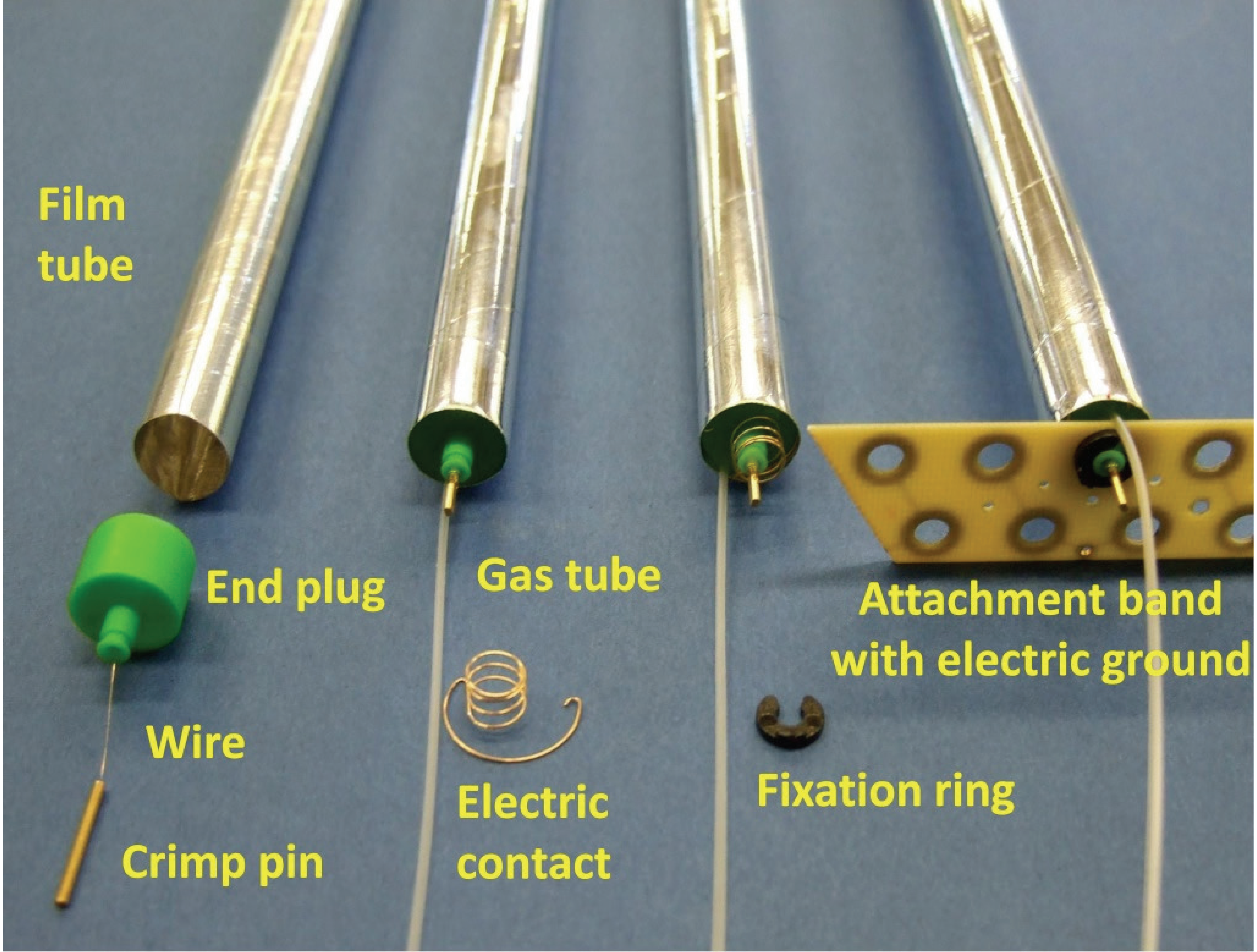




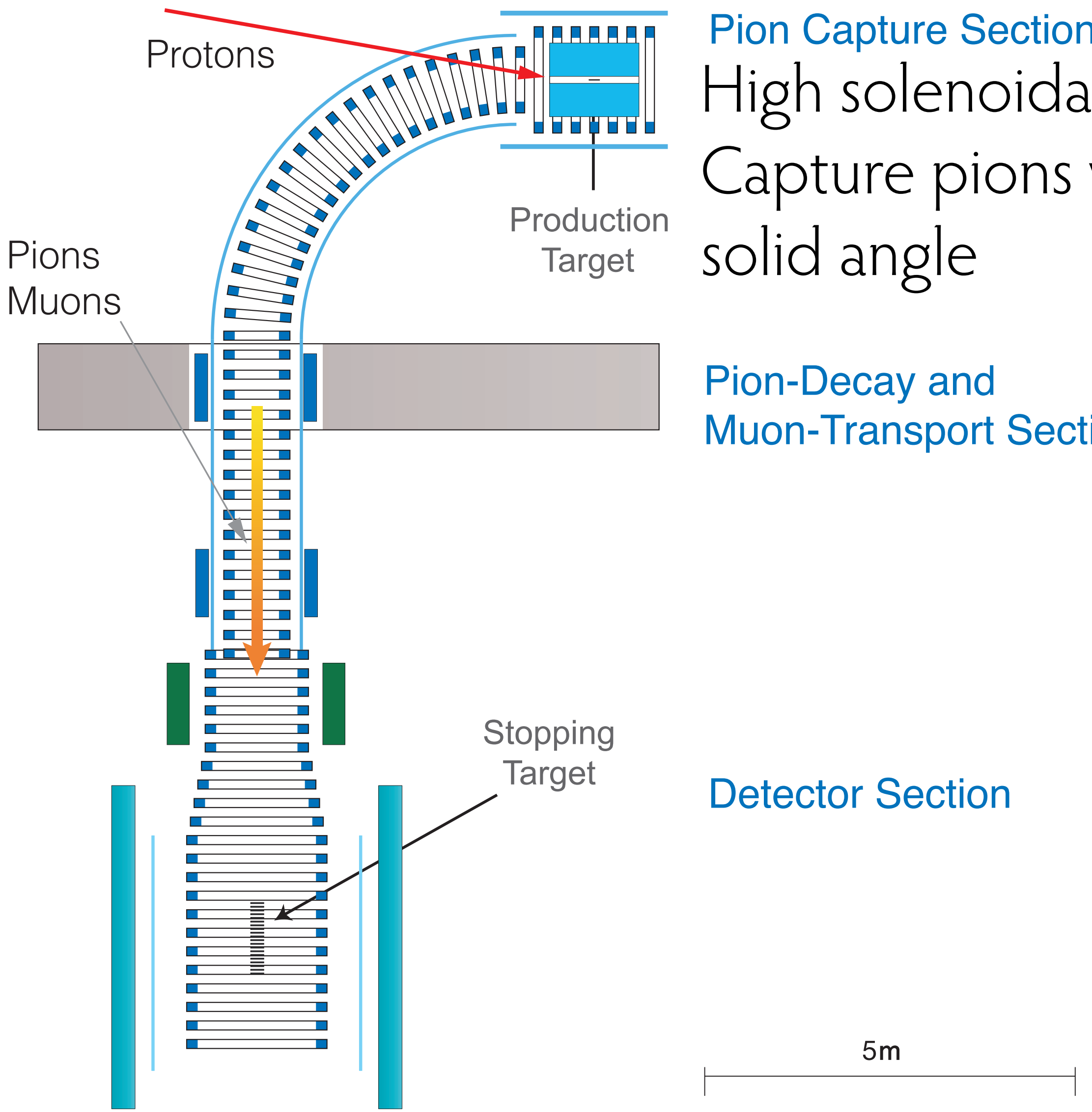
- Straw tubes in vacuum
- Outside of radius of Michel electrons

Mu2e CDR




Film
tube
End plug
Wire
Crimp pin
Gas tube
Electric
contact
Fixation ring
Attachment band
with electric ground

Experimental layout - COMET Phase I



Pion Capture Section

High solenoidal field

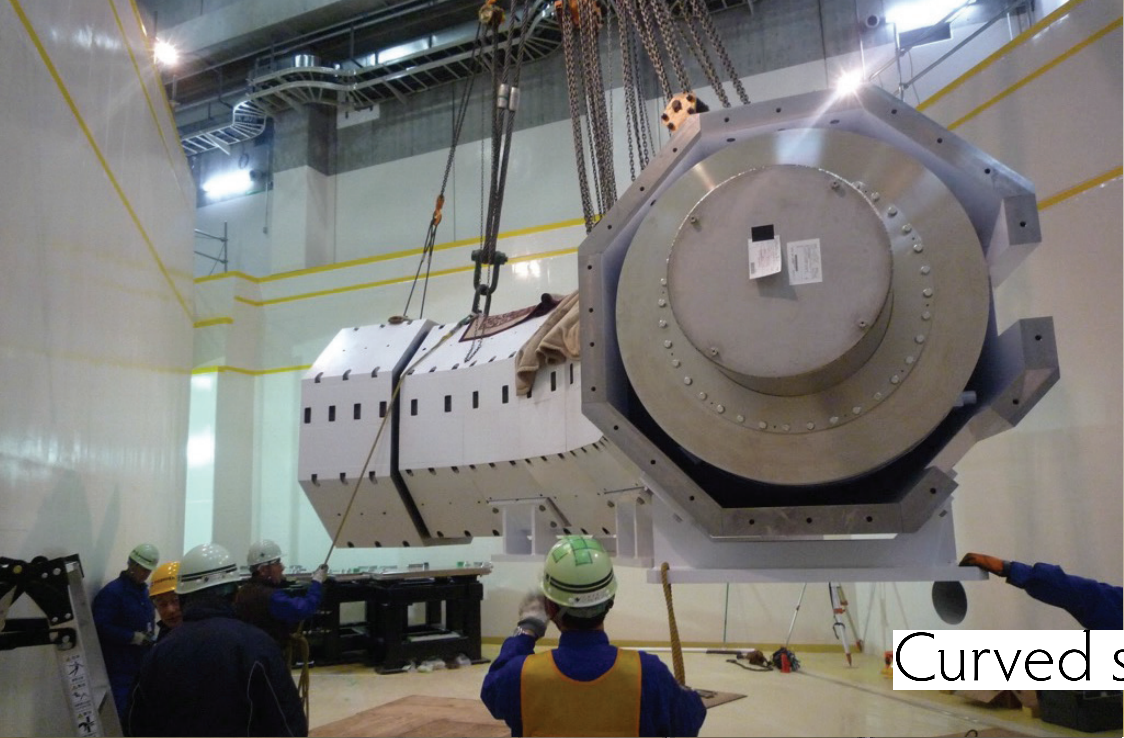
Capture pions with large solid angle

Pion-Decay and Muon-Transport Section

Detector Section

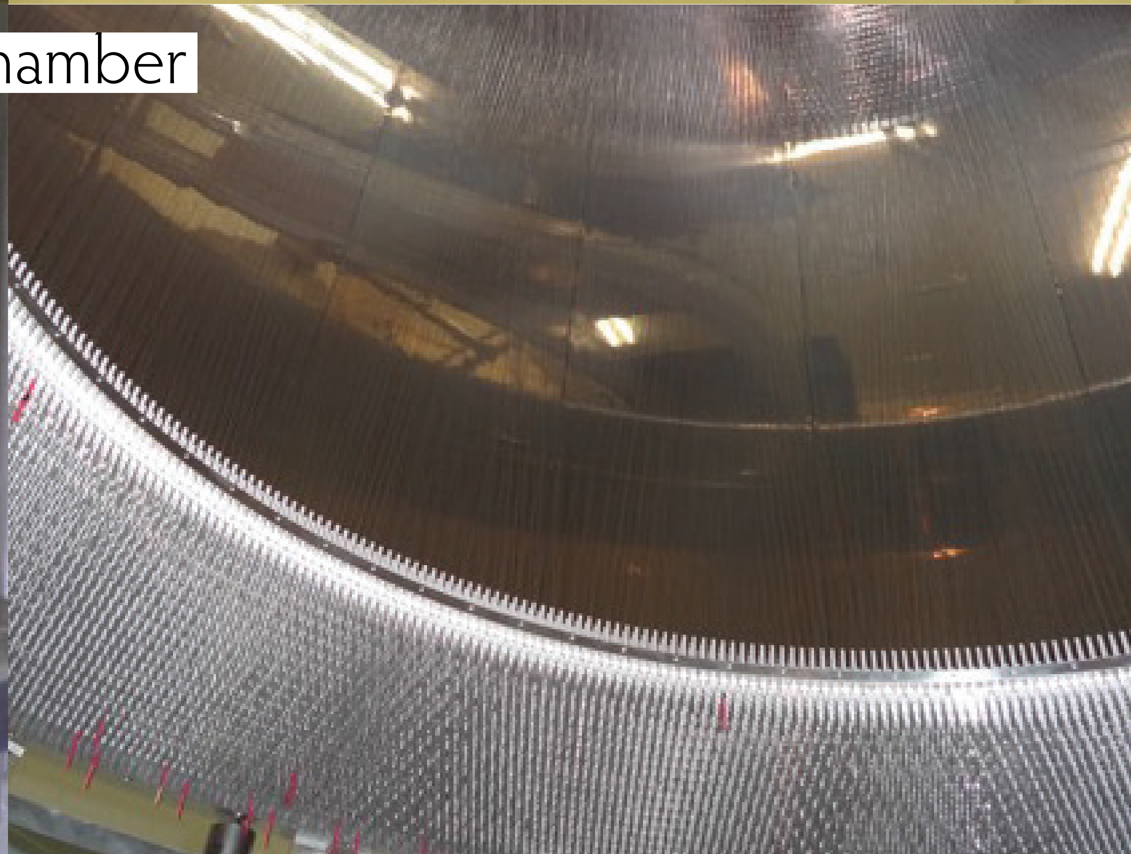
Comet CDR

Y. Kuno

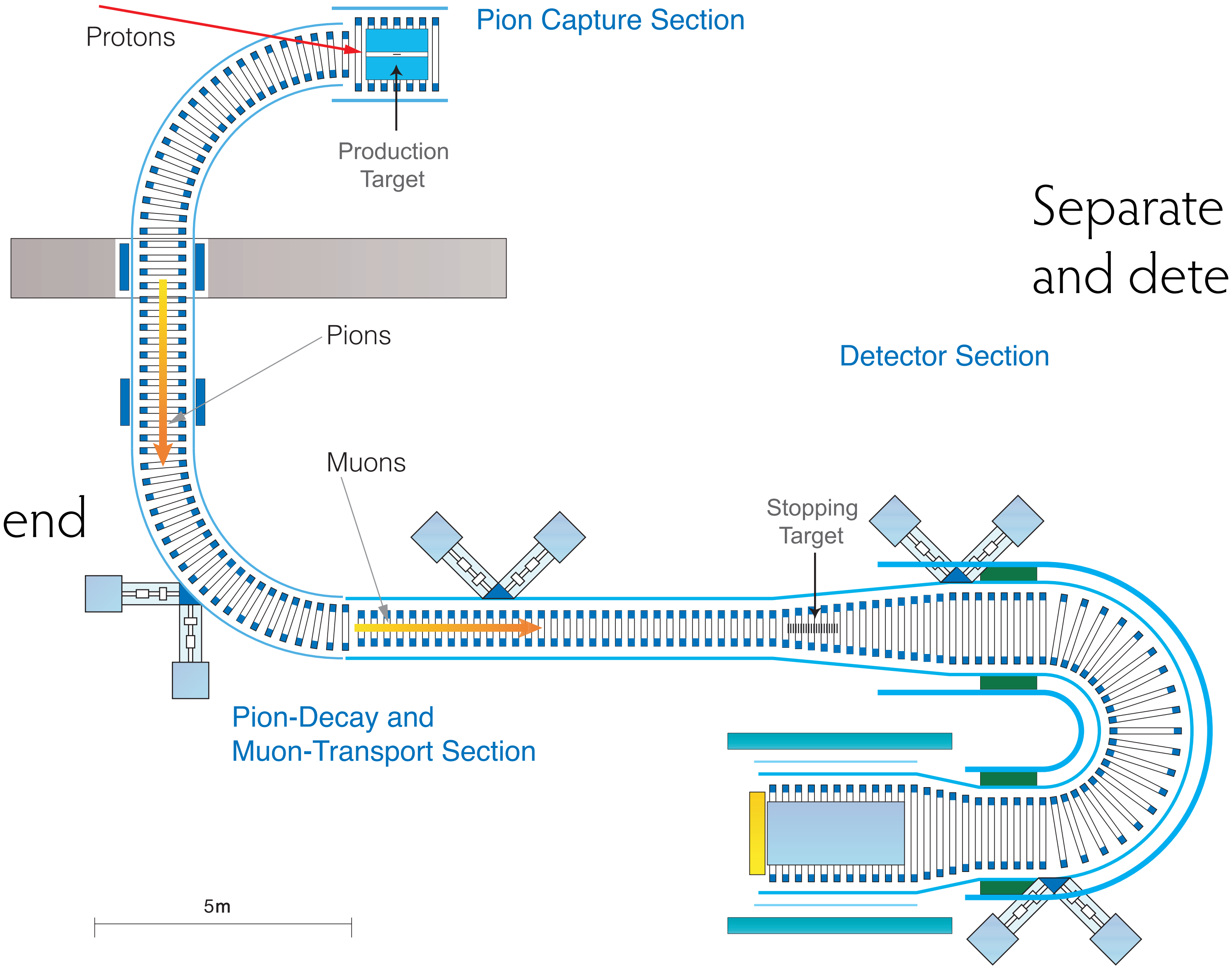


Curved solenoid

Drift chamber



Experimental layout - COMET Phase II



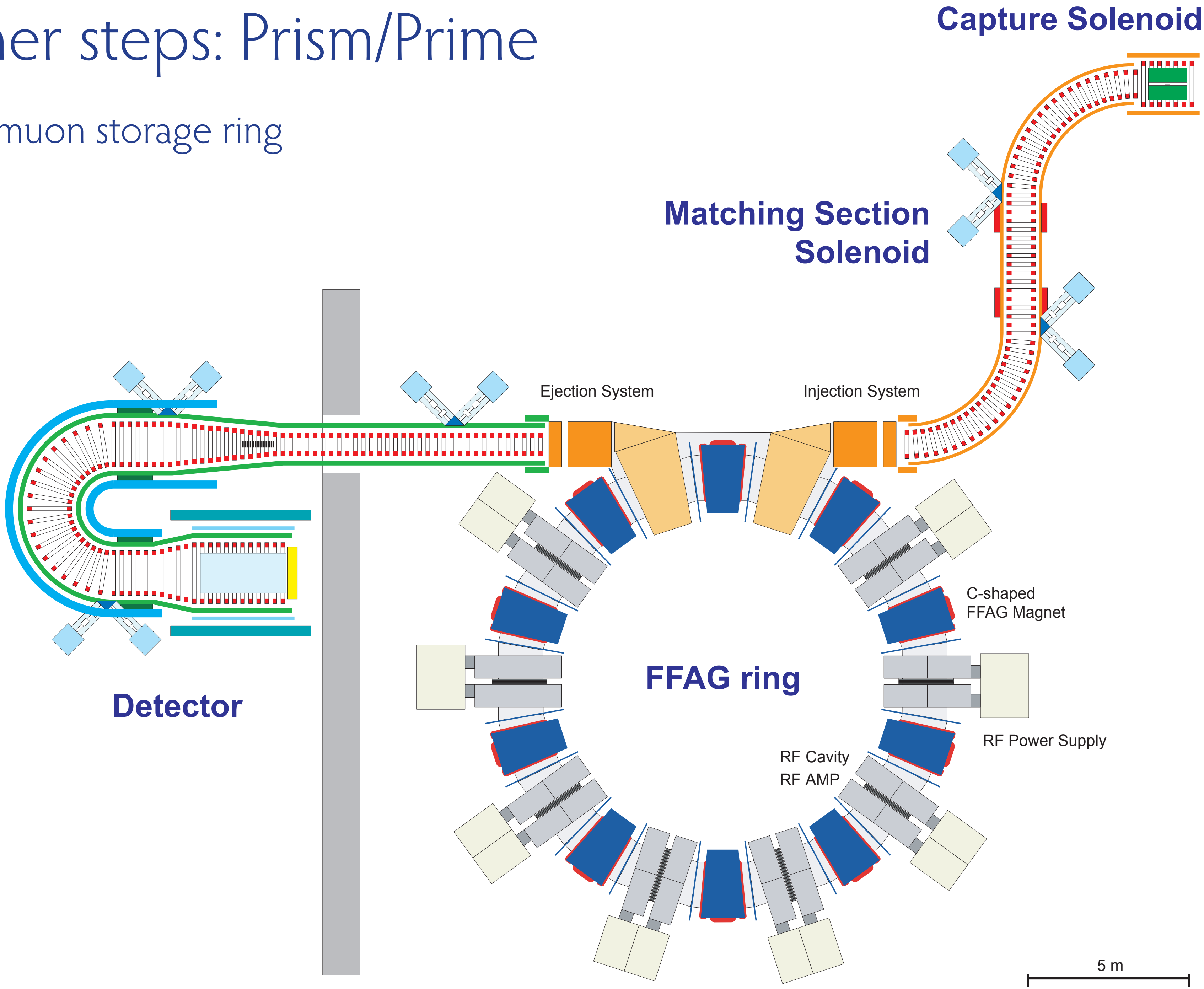
Separate muon decay and detector region

One more bend

Comet CDR

Further steps: Prism/Prime

Add a muon storage ring



Conversion: Expected sensitivities

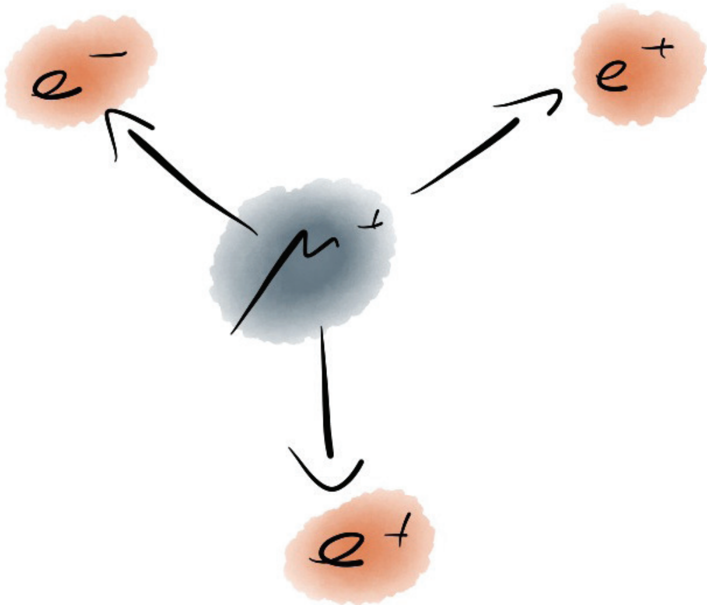
- Comet Phase I and DeeMee might get to $\sim 10^{-14}$ as early as 2019
- Both Comet Phase II and Mu2e will start around 2020
- Should get single event sensitivities well below 10^{-16}
- Prism/Prime and Mu2e with Project X explore paths to 10^{-18}

Tracking it all:

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

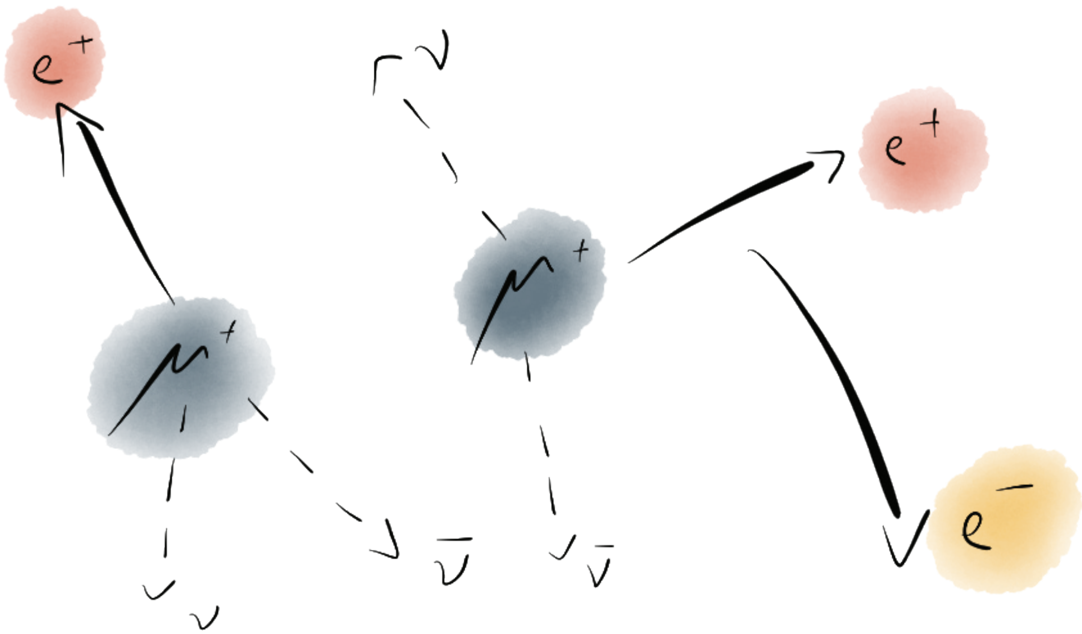
Mu3e

The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma\, p_e = m_\mu$
- Maximum momentum: ½ m_μ = 53 MeV/c

Accidental Background



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

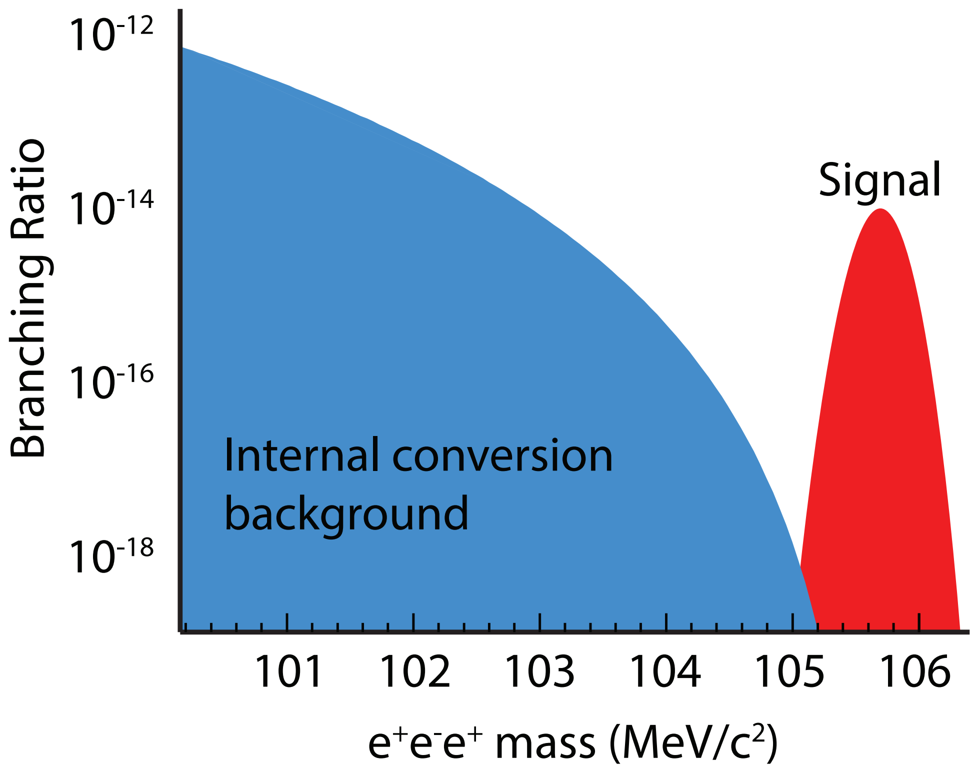
- Need very good timing, vertex and momentum resolution

Internal conversion background

- Allowed radiative decay with internal conversion:

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

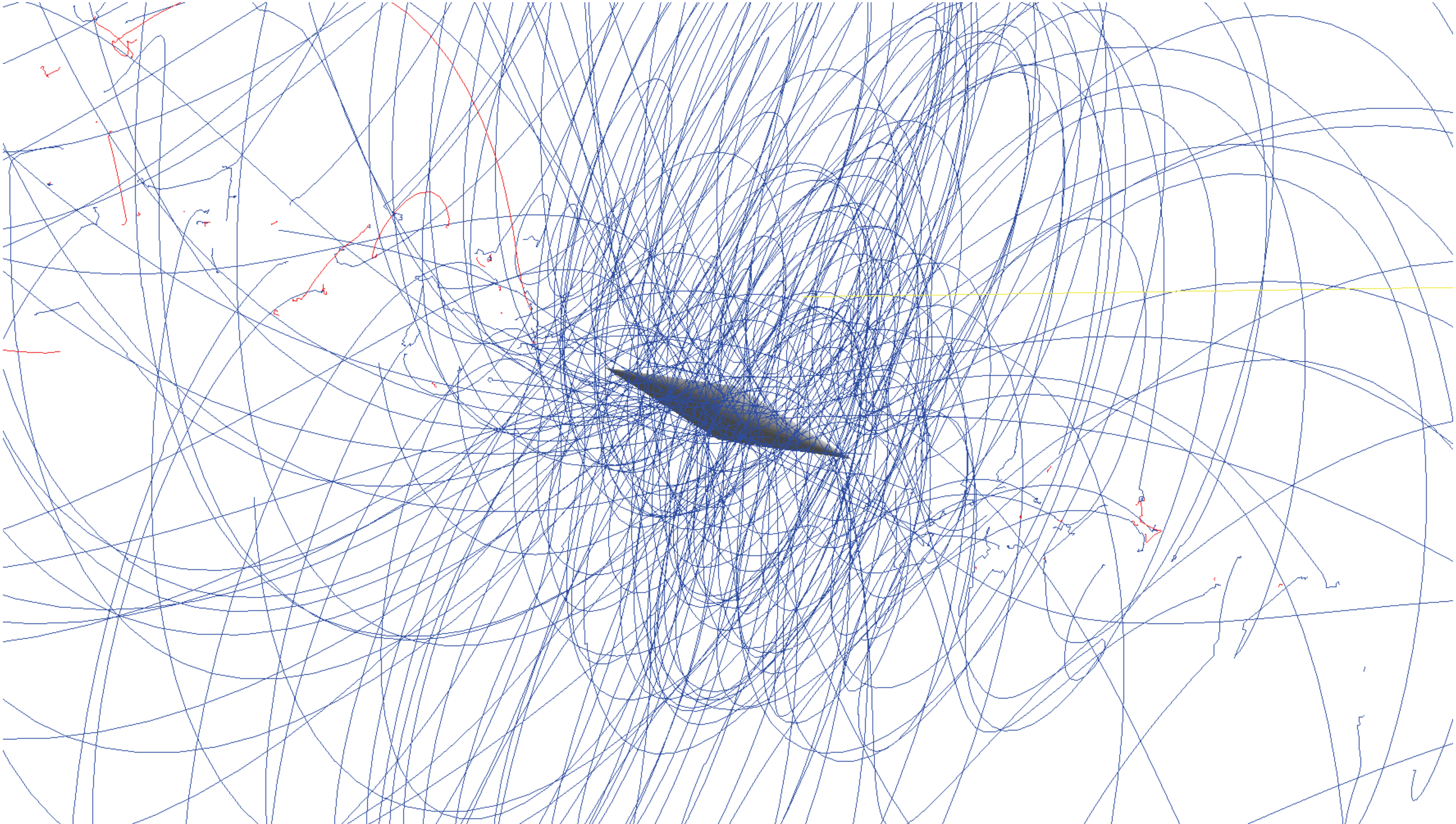
- Only distinguishing feature: Missing momentum carried by neutrinos



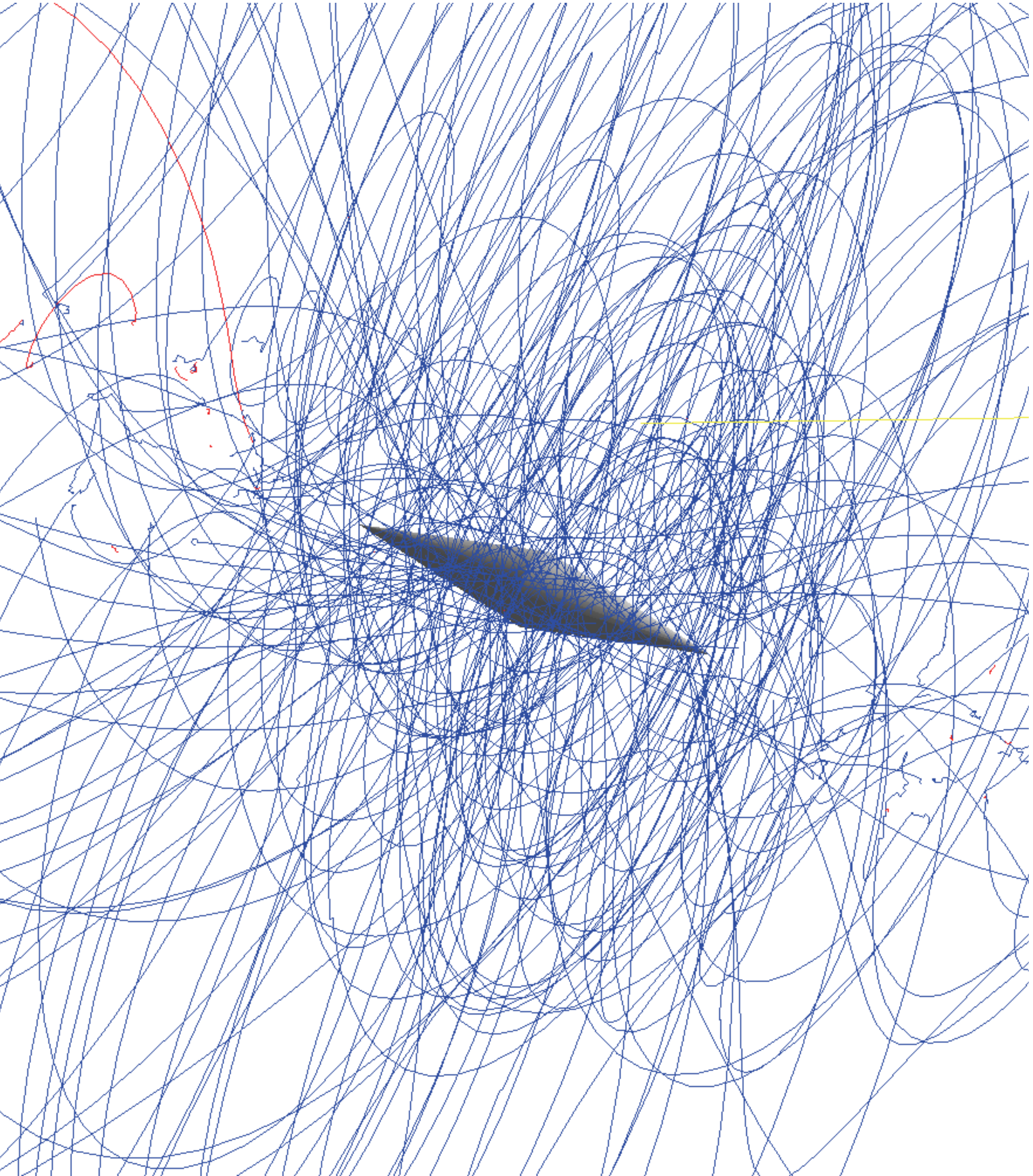
- Need excellent momentum resolution

2 Billion Muon Decays/s

50 ns, 1 Tesla field

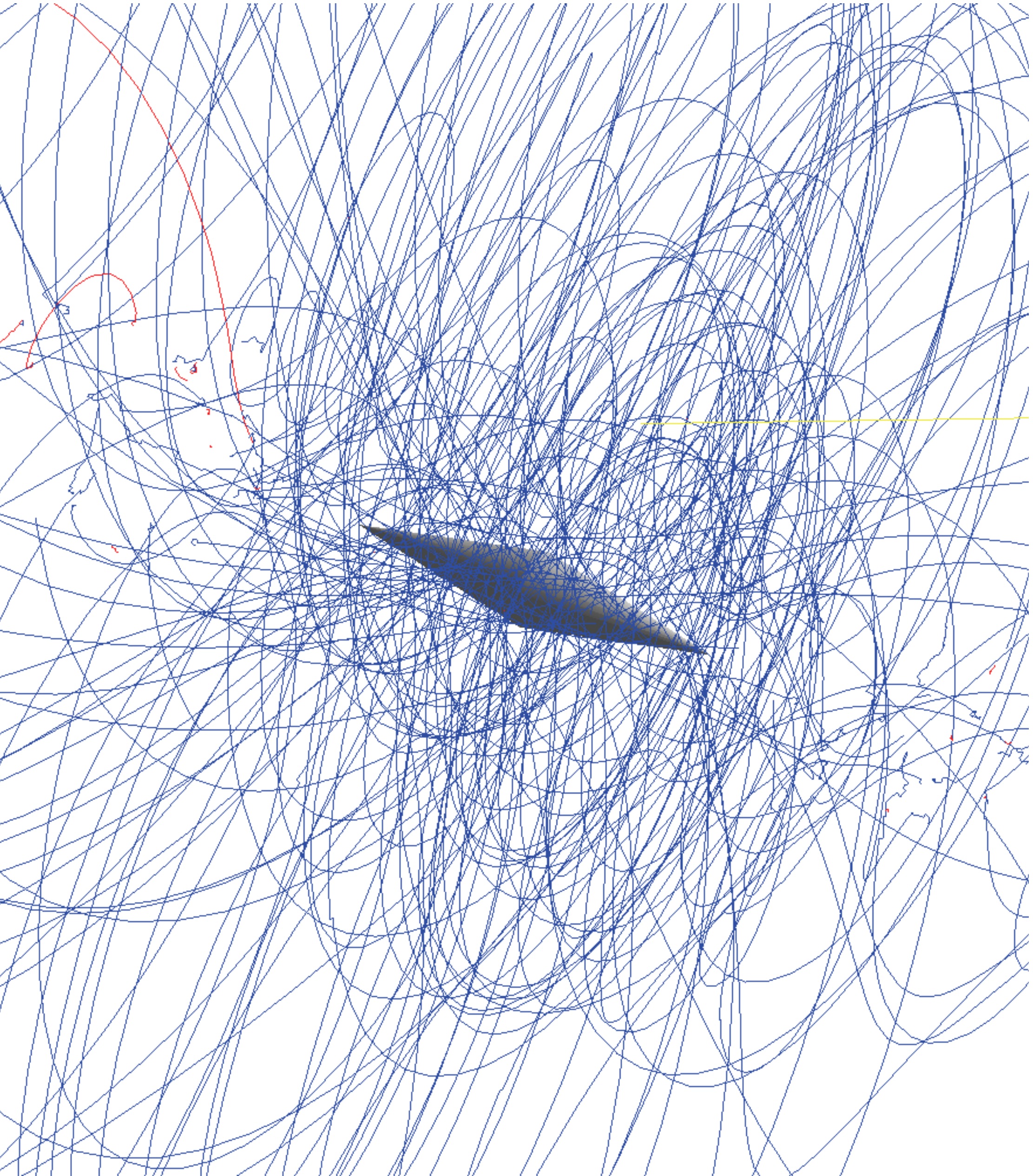


Detector Technology



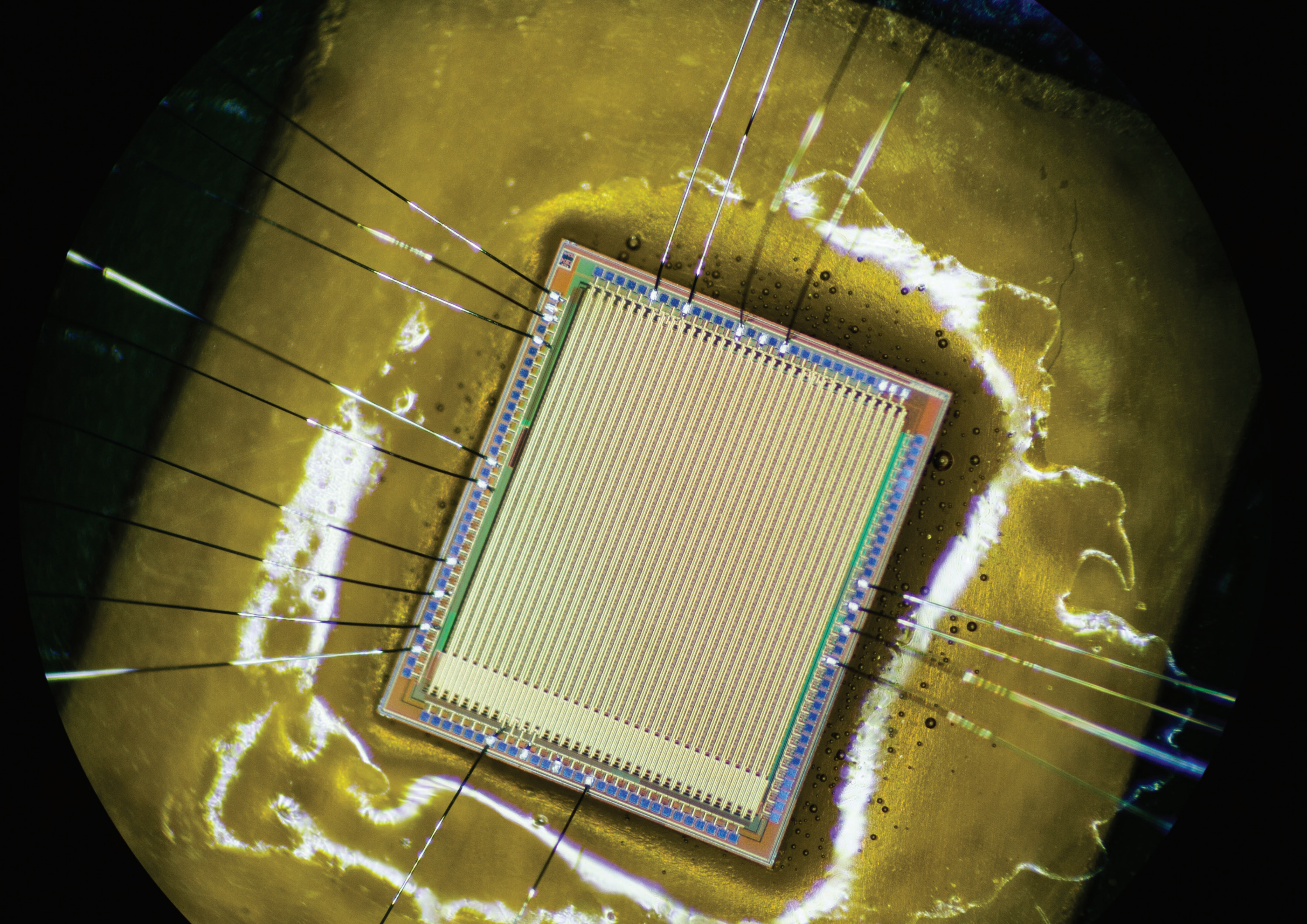
- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

Detector Technology



- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

- Gas detectors do not work (space charge, aging, 3D)
- Silicon strips do not work (material budget, 3D)
- Hybrid pixels (as in LHC) do not work (material budget)

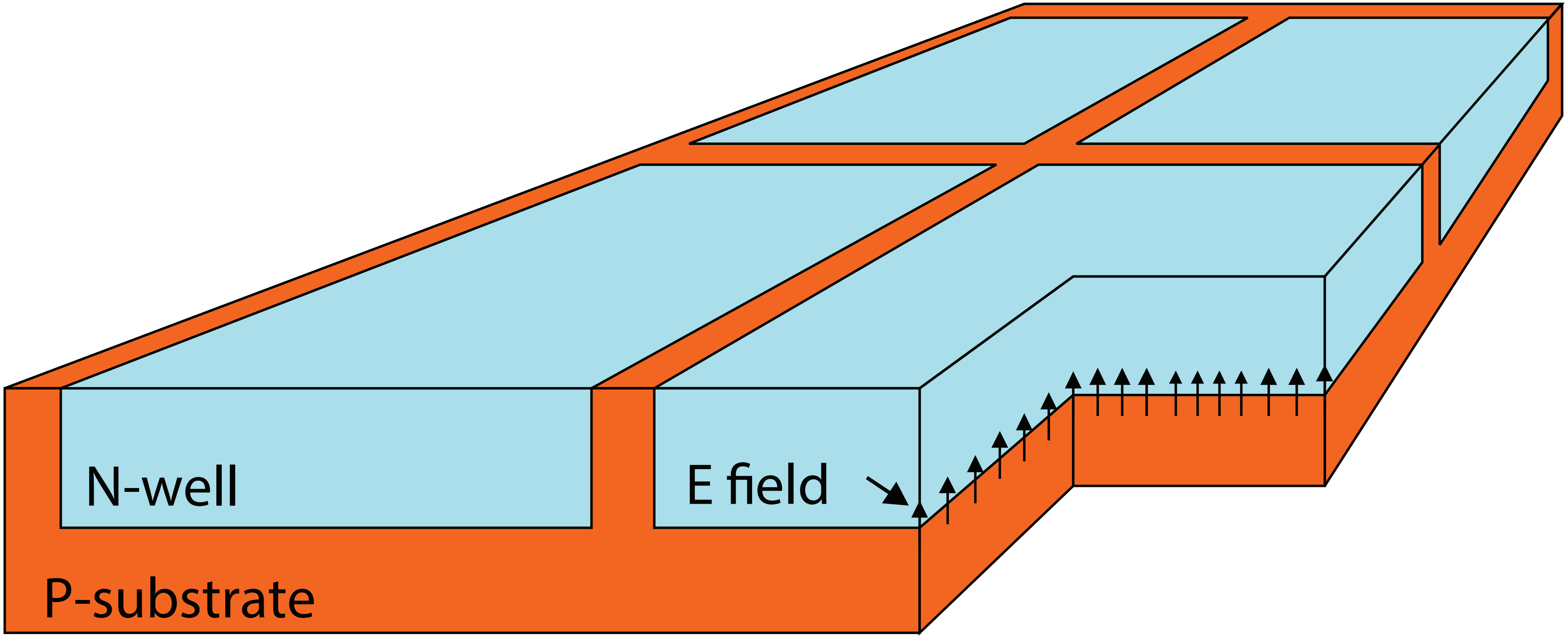


High-Voltage
Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

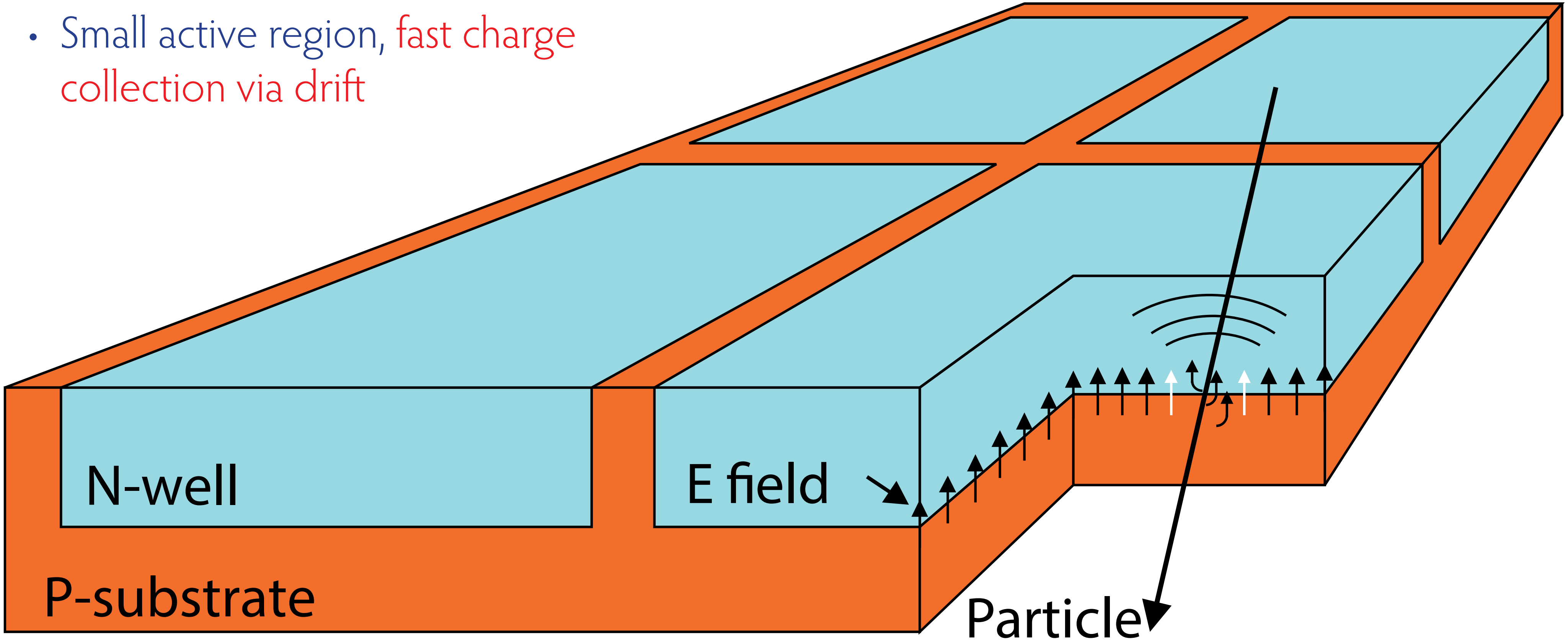
- Use a high voltage commercial process (automotive industry)



Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

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



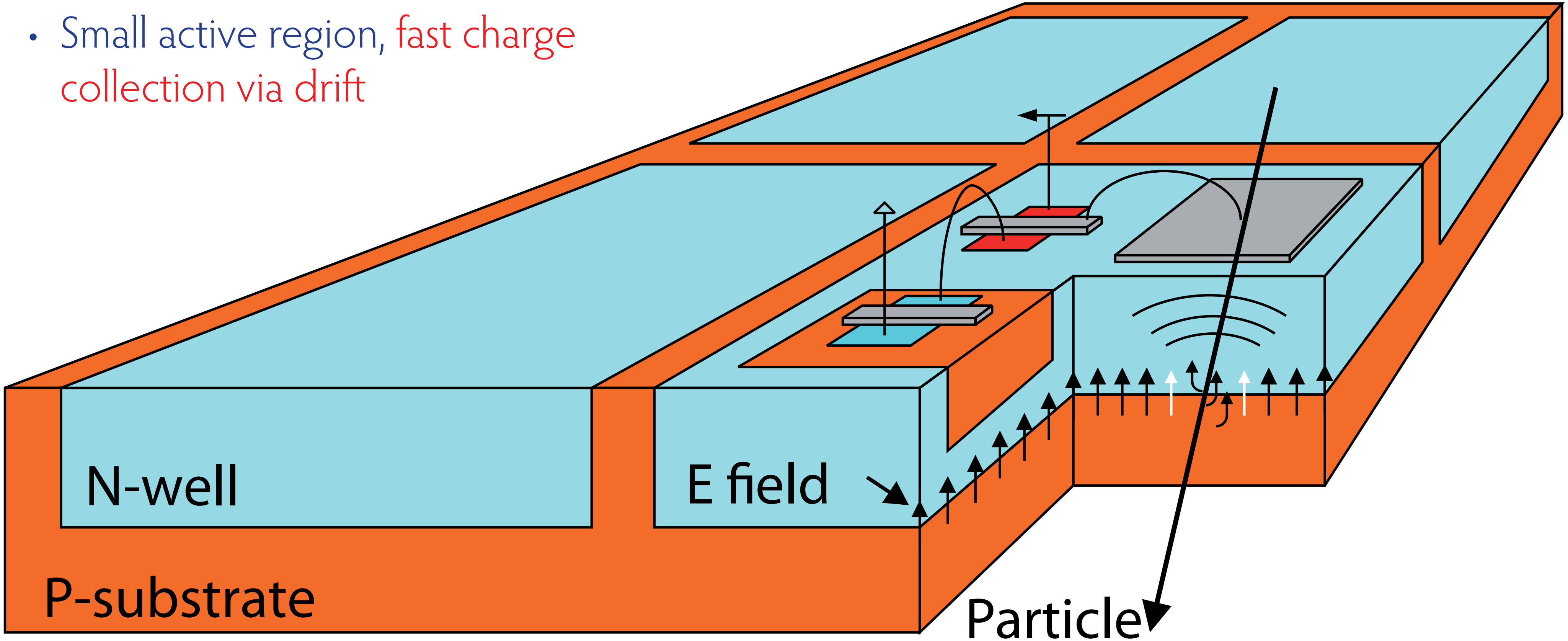
Fast and thin sensors: HV-MAPS

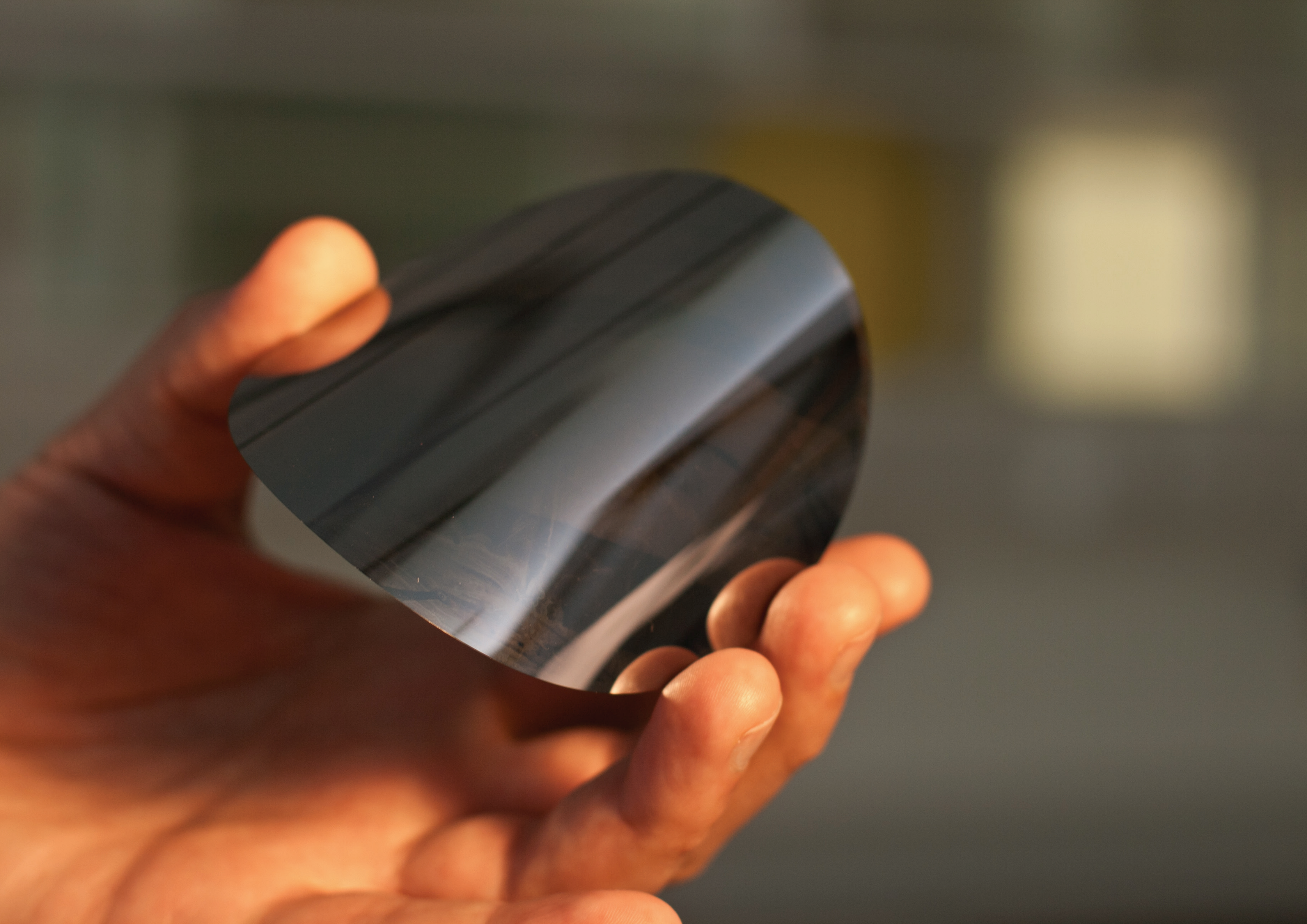
High voltage monolithic active pixel sensors - Ivan Perić

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

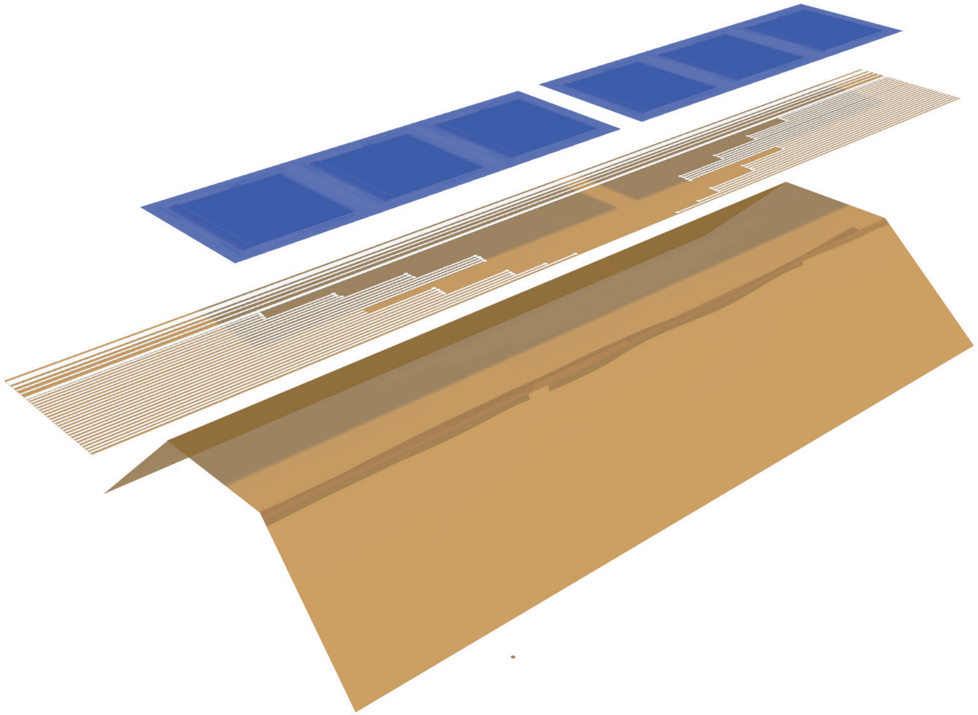
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 μm

(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)





Mechanics

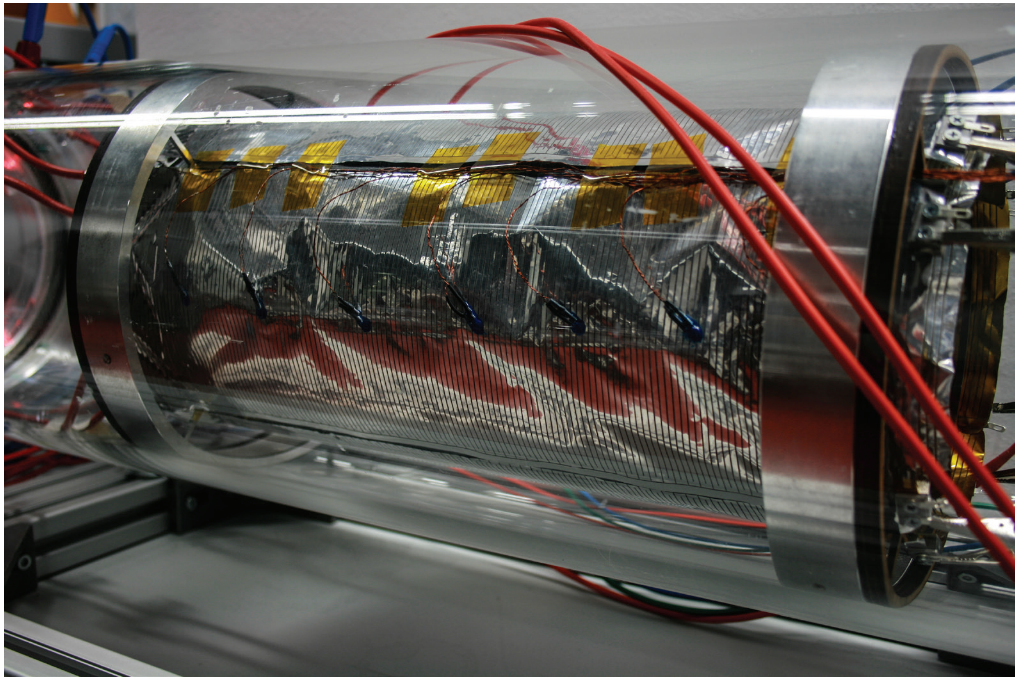


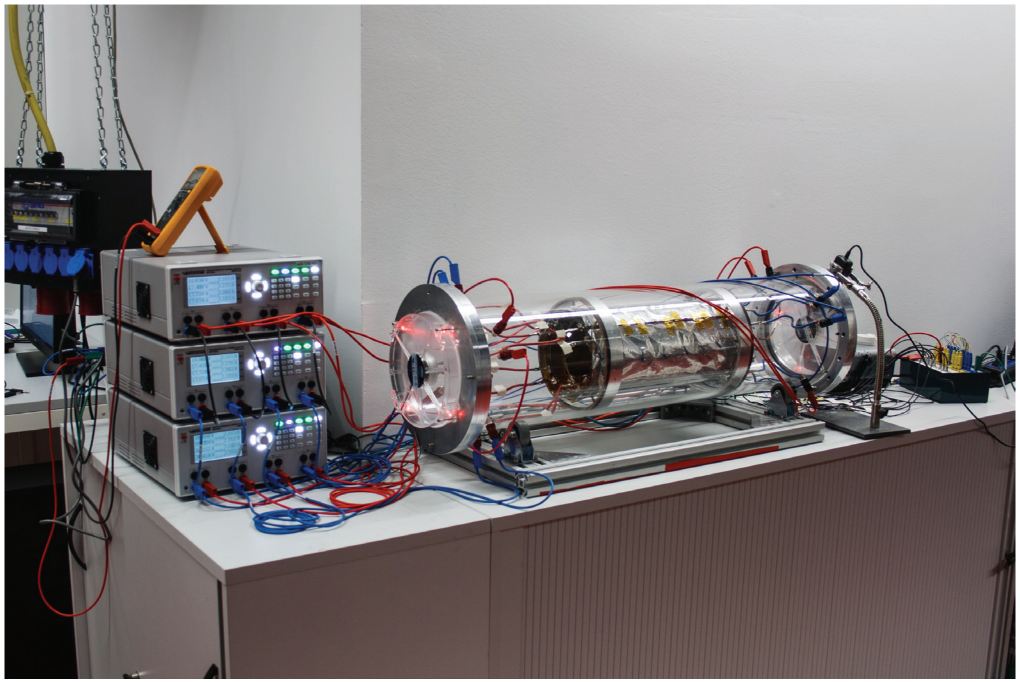
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- About 1‰ of a radiation length per layer

Cooling

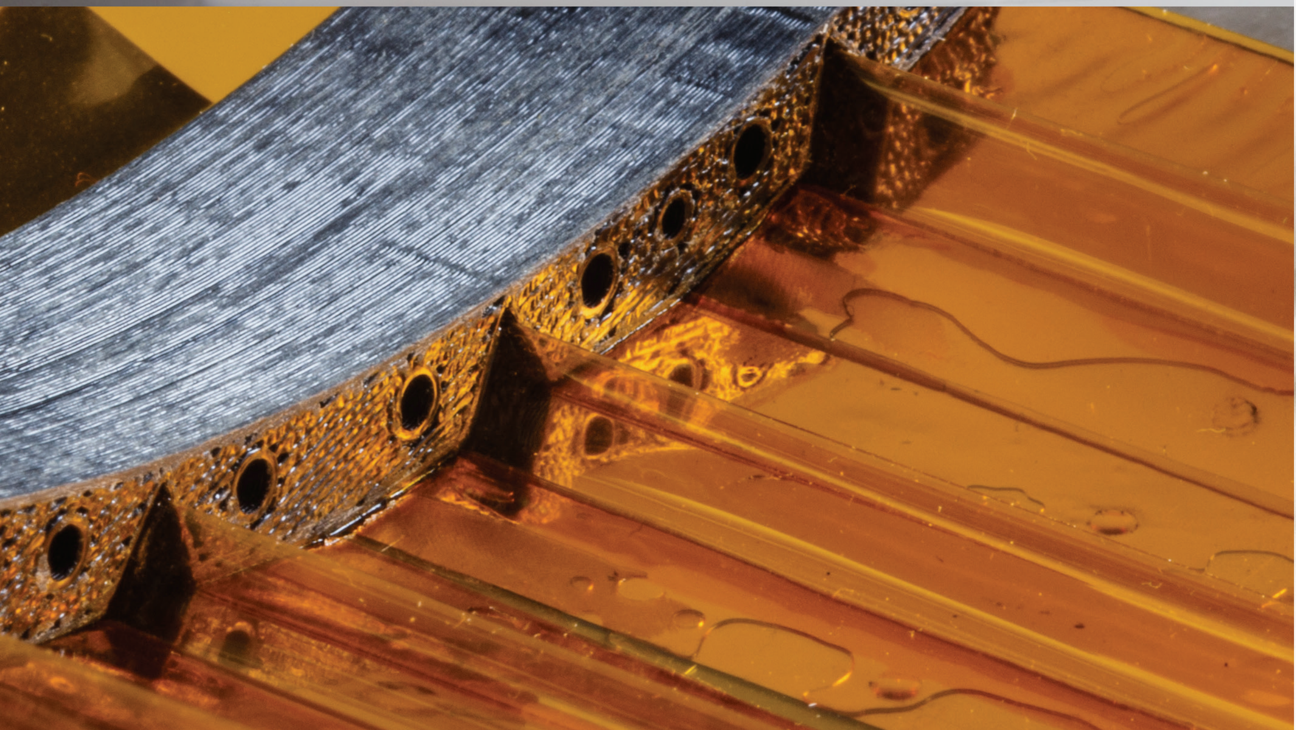
- Add no material:
  Cool with gaseous Helium
  (low scattering, high mobility)
- ~ 250 mW/cm^2 - total ~3 kW
- Simulations: Need ~ several m/s flow

- Full scale heatable prototype built
- 36 cm active length
- Vibrations studied using Michelson-Interferometer
- Can keep temperature below 70°C

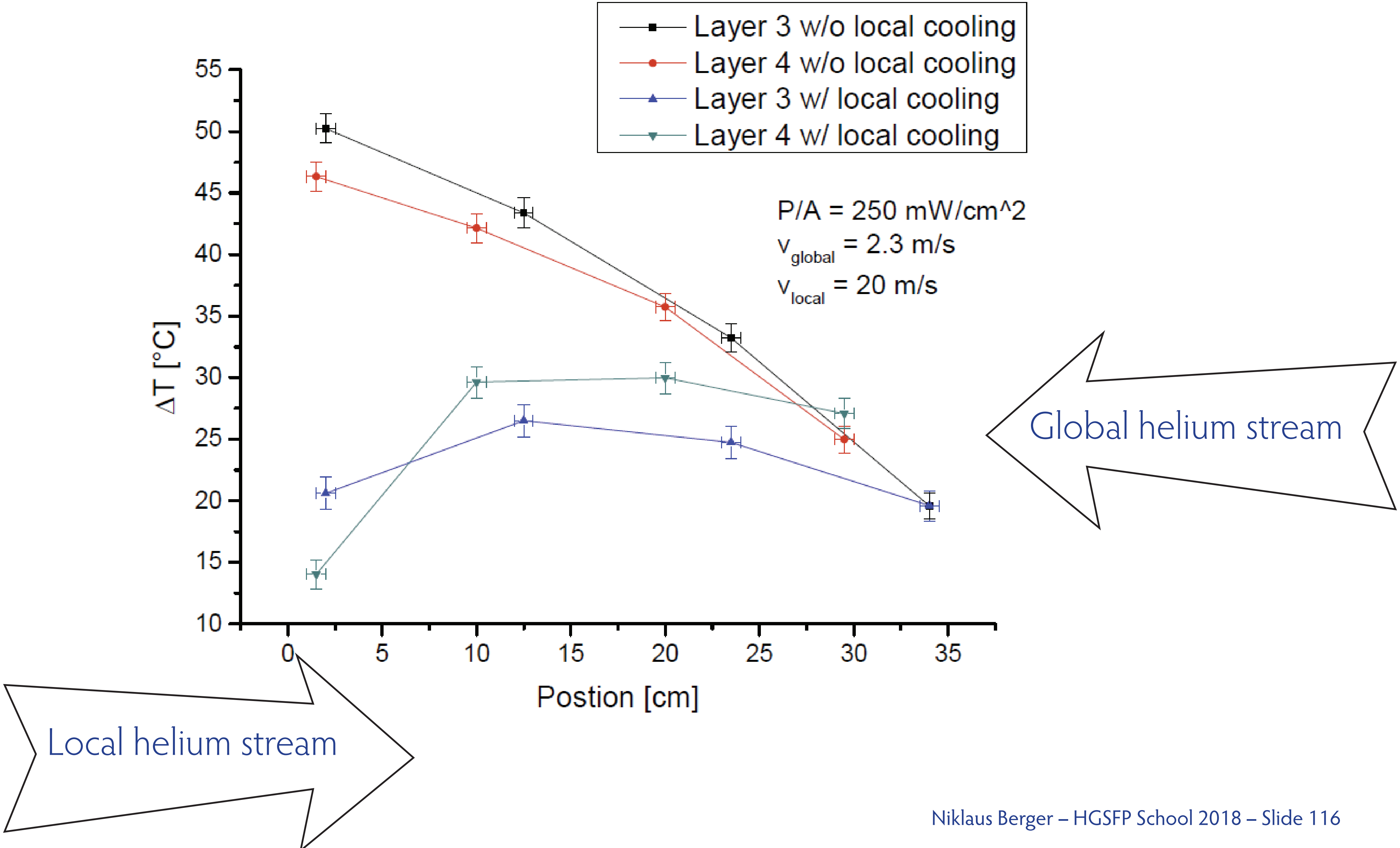





Ring 4
vorne

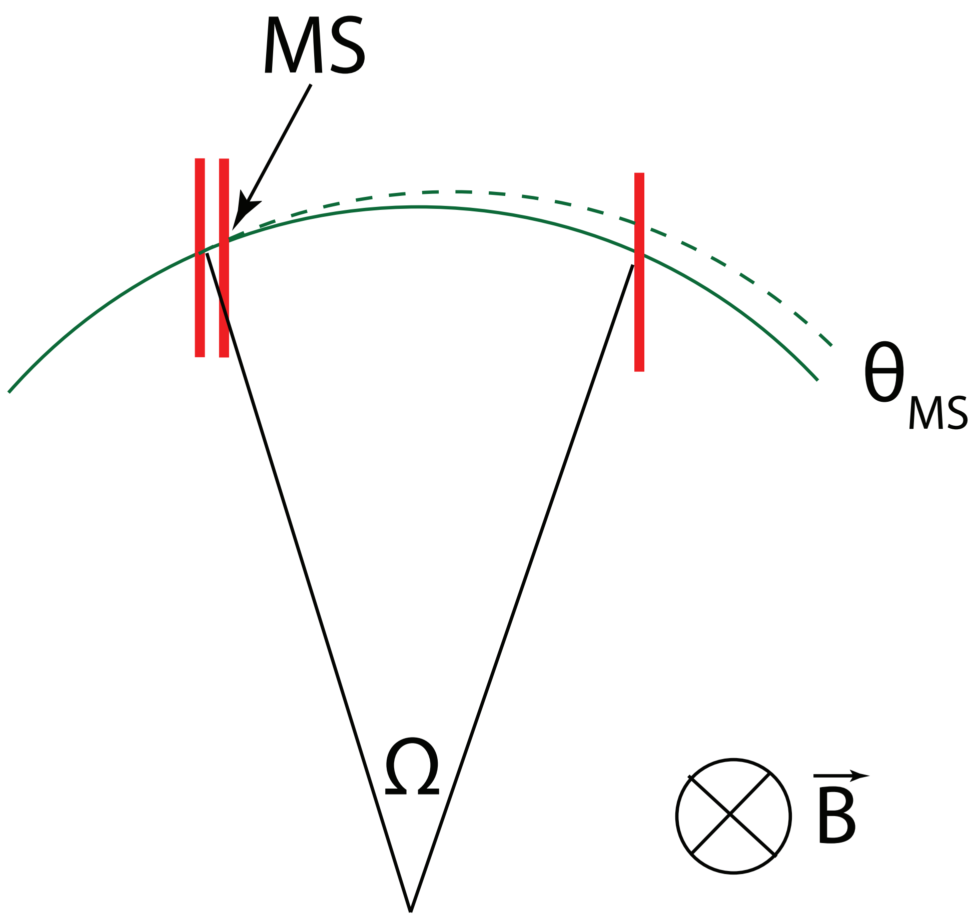


Cooling tests



How to build the detector?

Momentum measurement

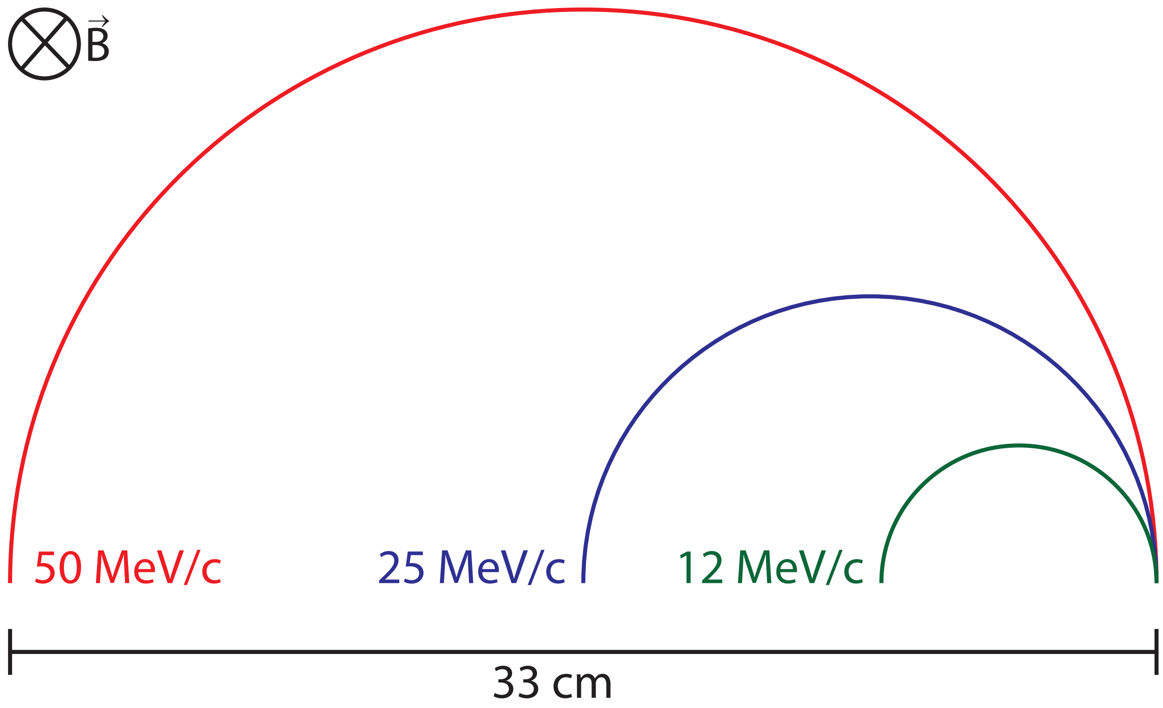


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

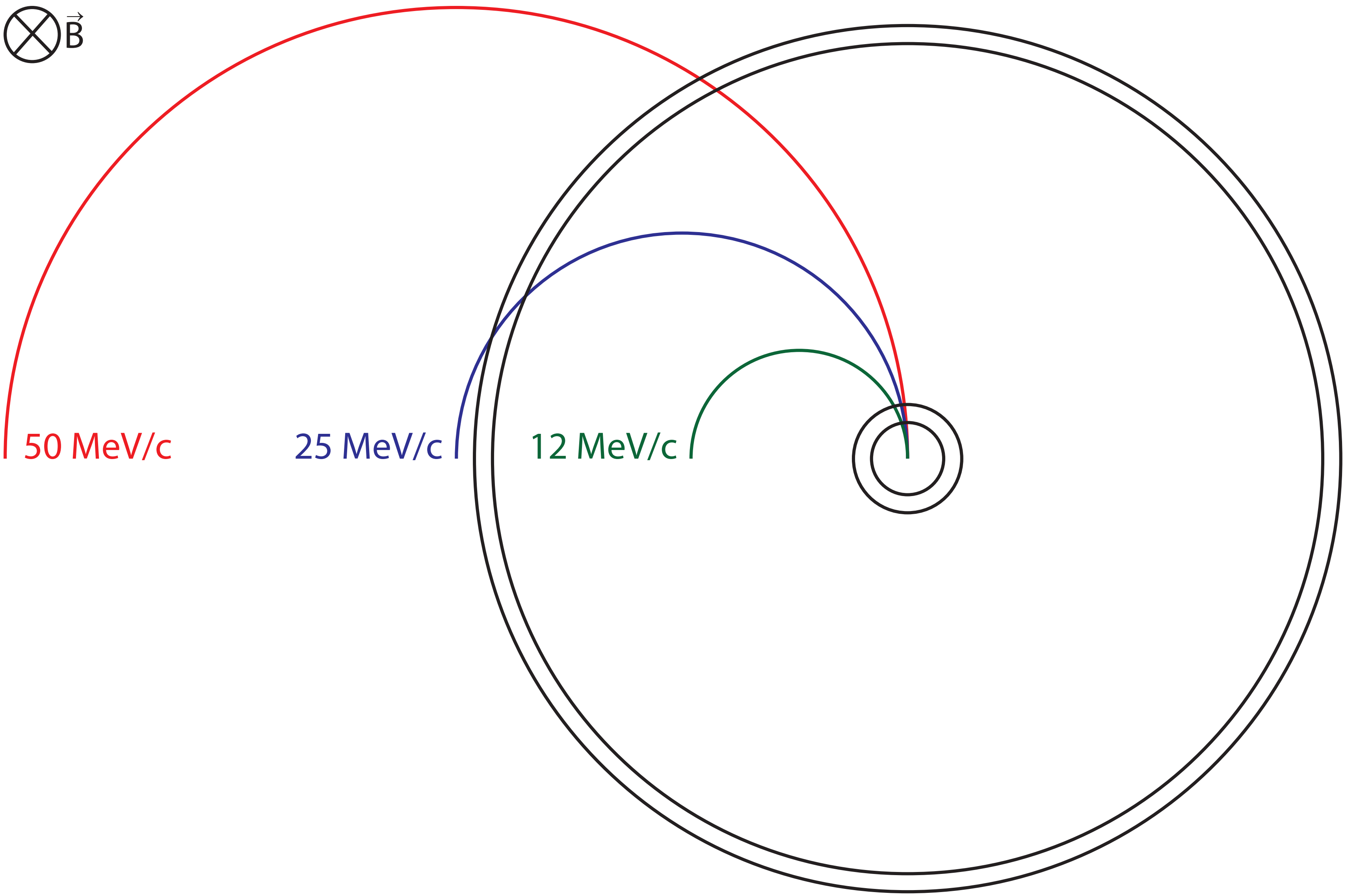
$$\sigma_P/_P \sim \theta_{MS}/_\Omega$$

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

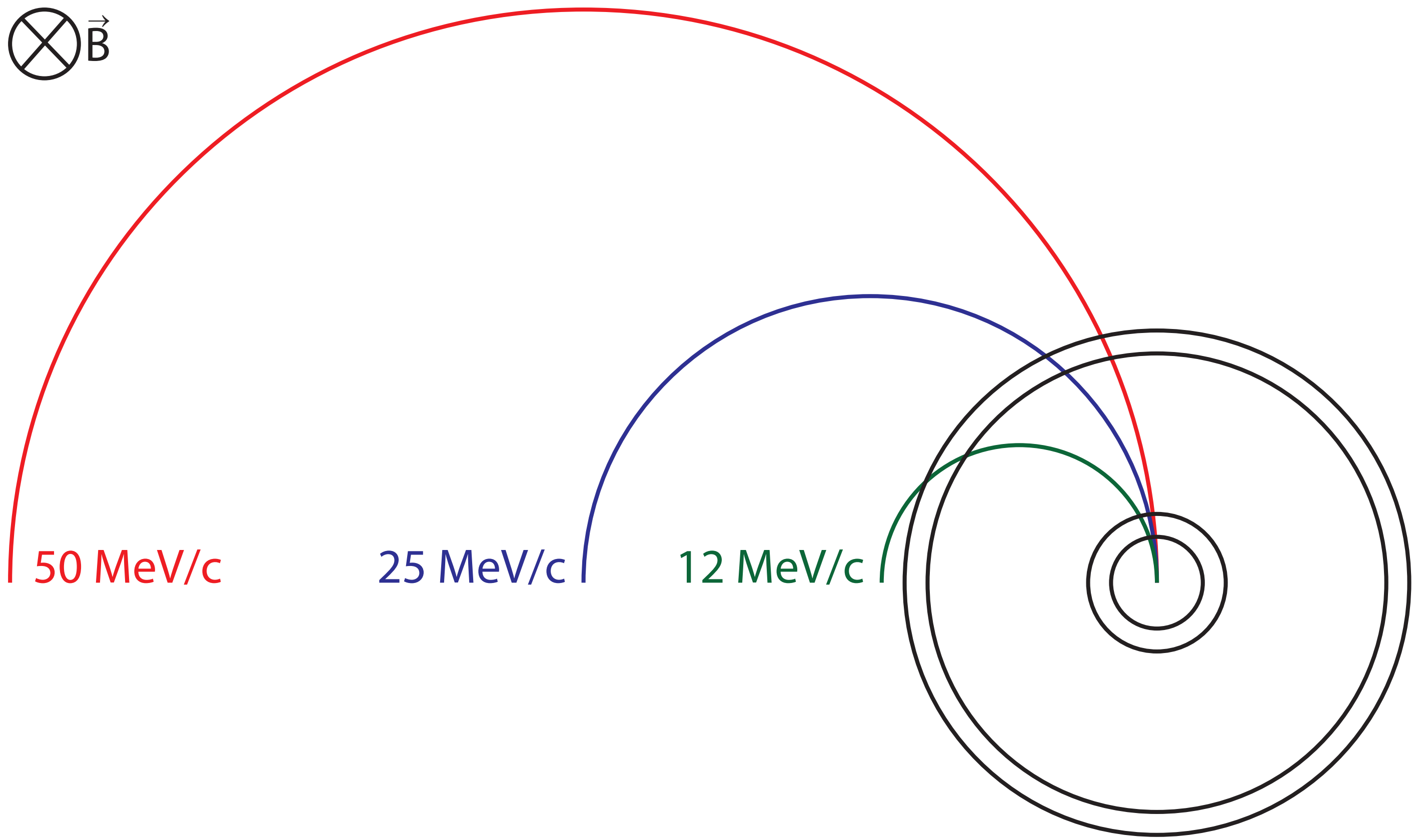
Precision vs. Acceptance



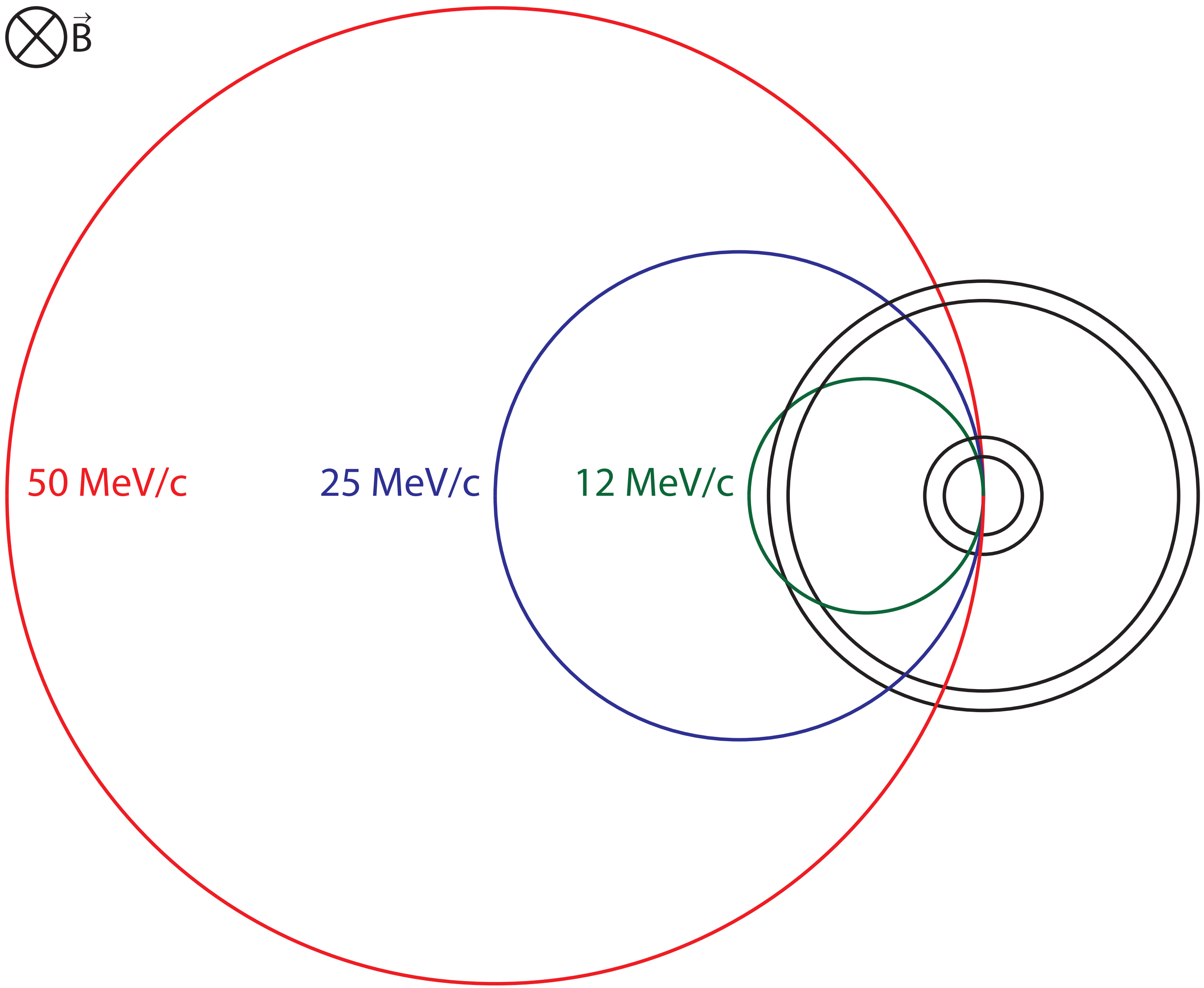
Precision vs. Acceptance



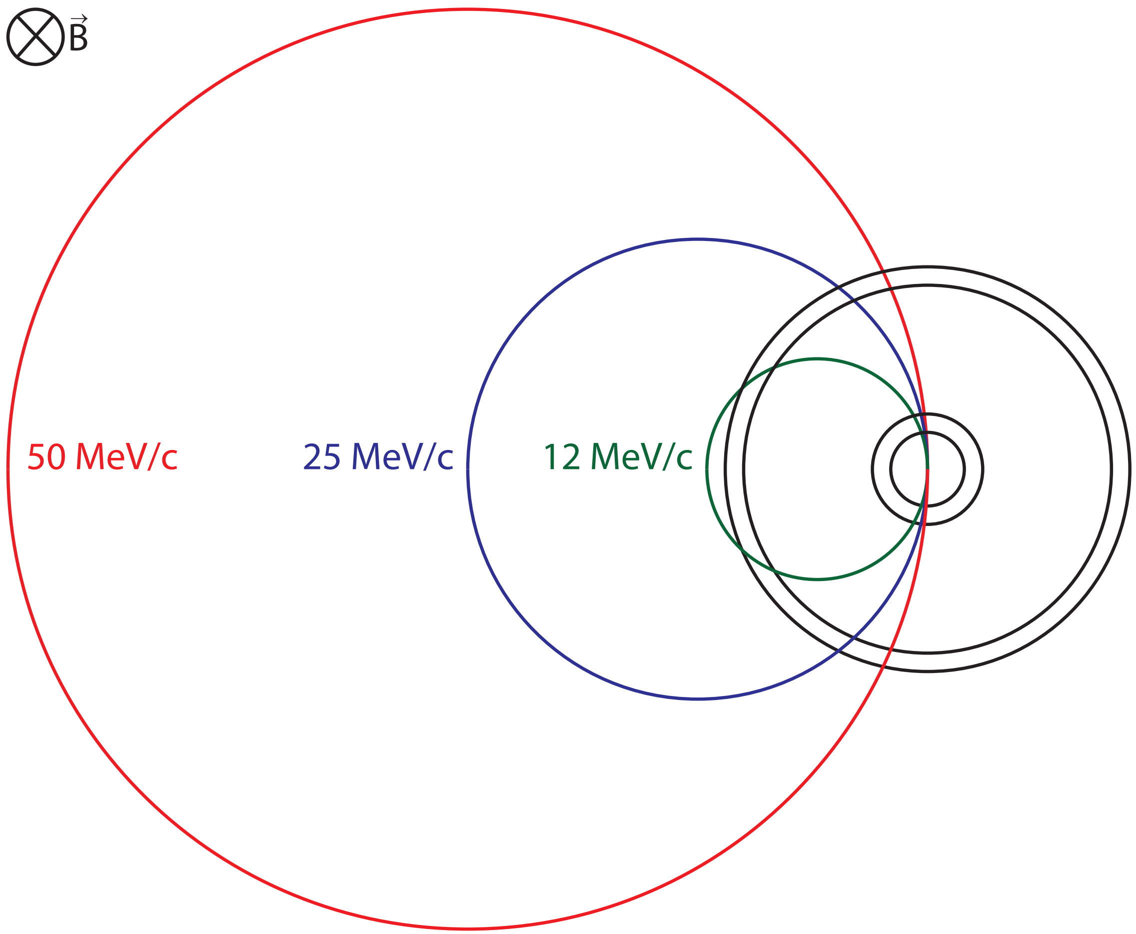
Precision vs. Acceptance

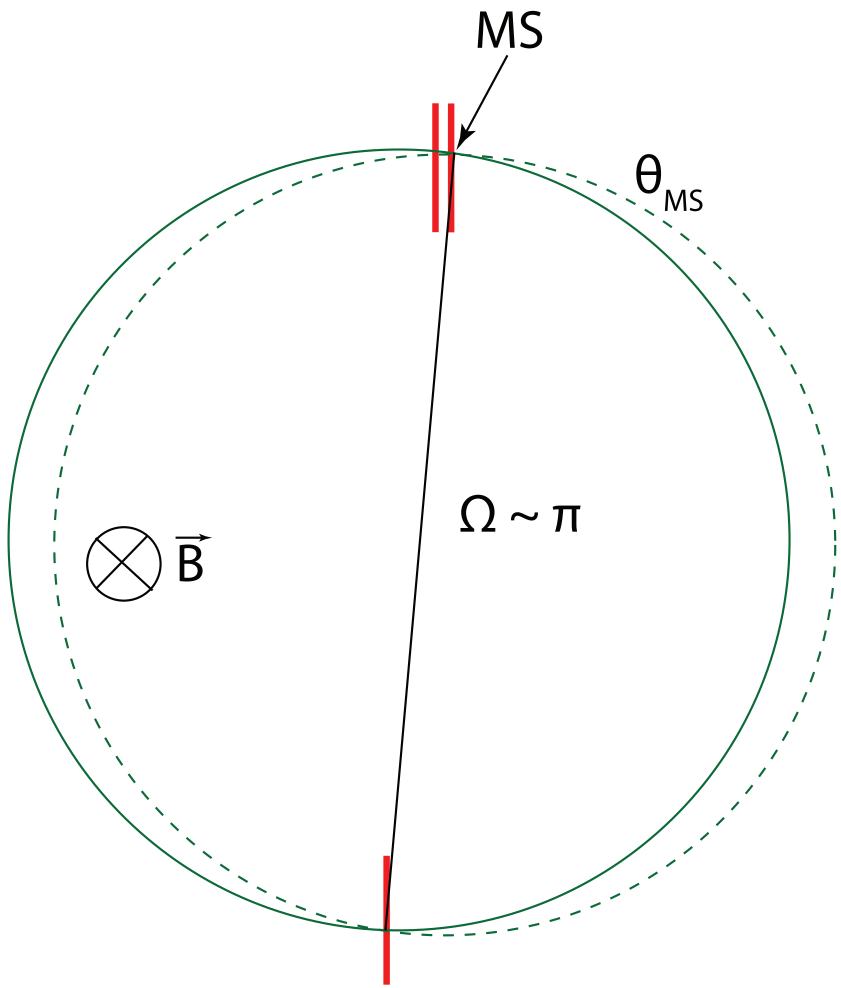


Precision vs. Acceptance

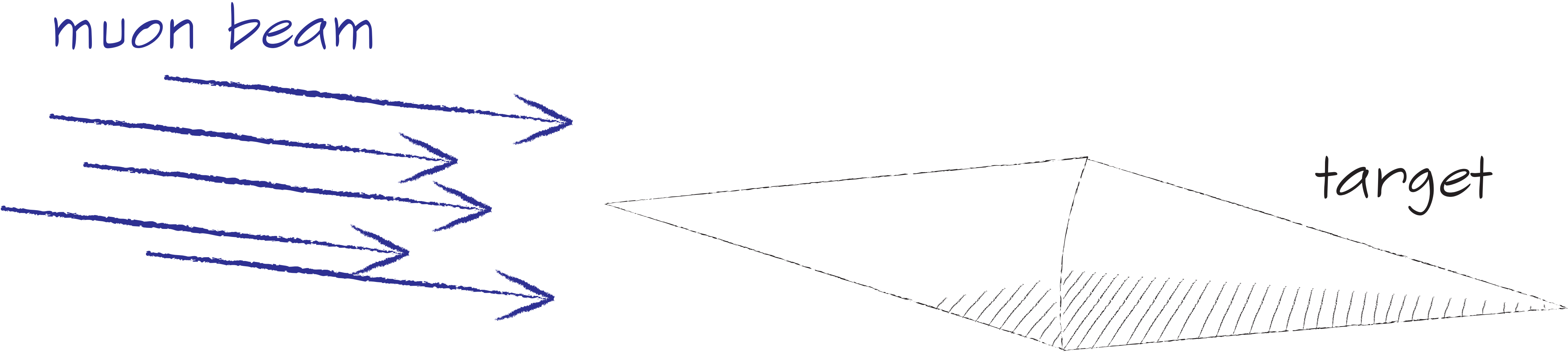


Precision vs. Acceptance

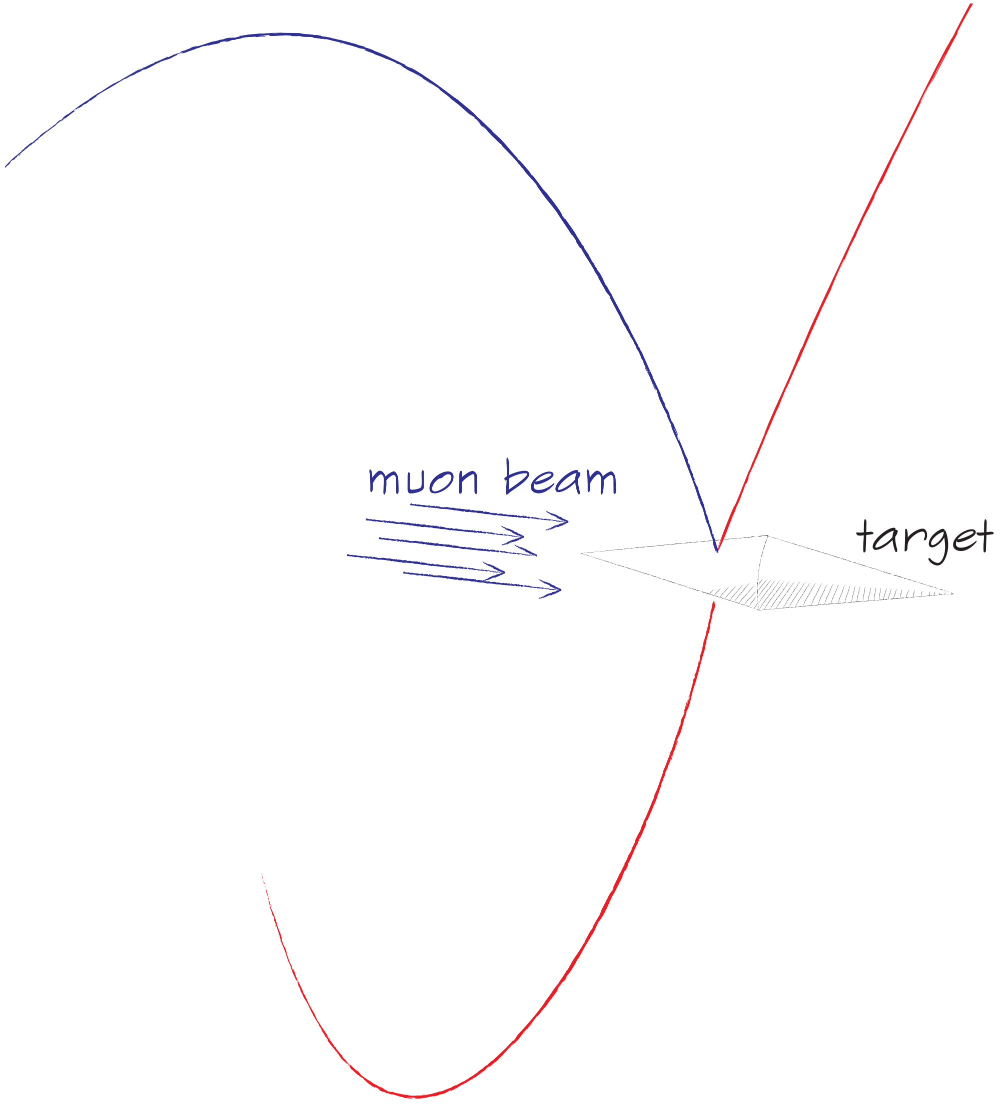




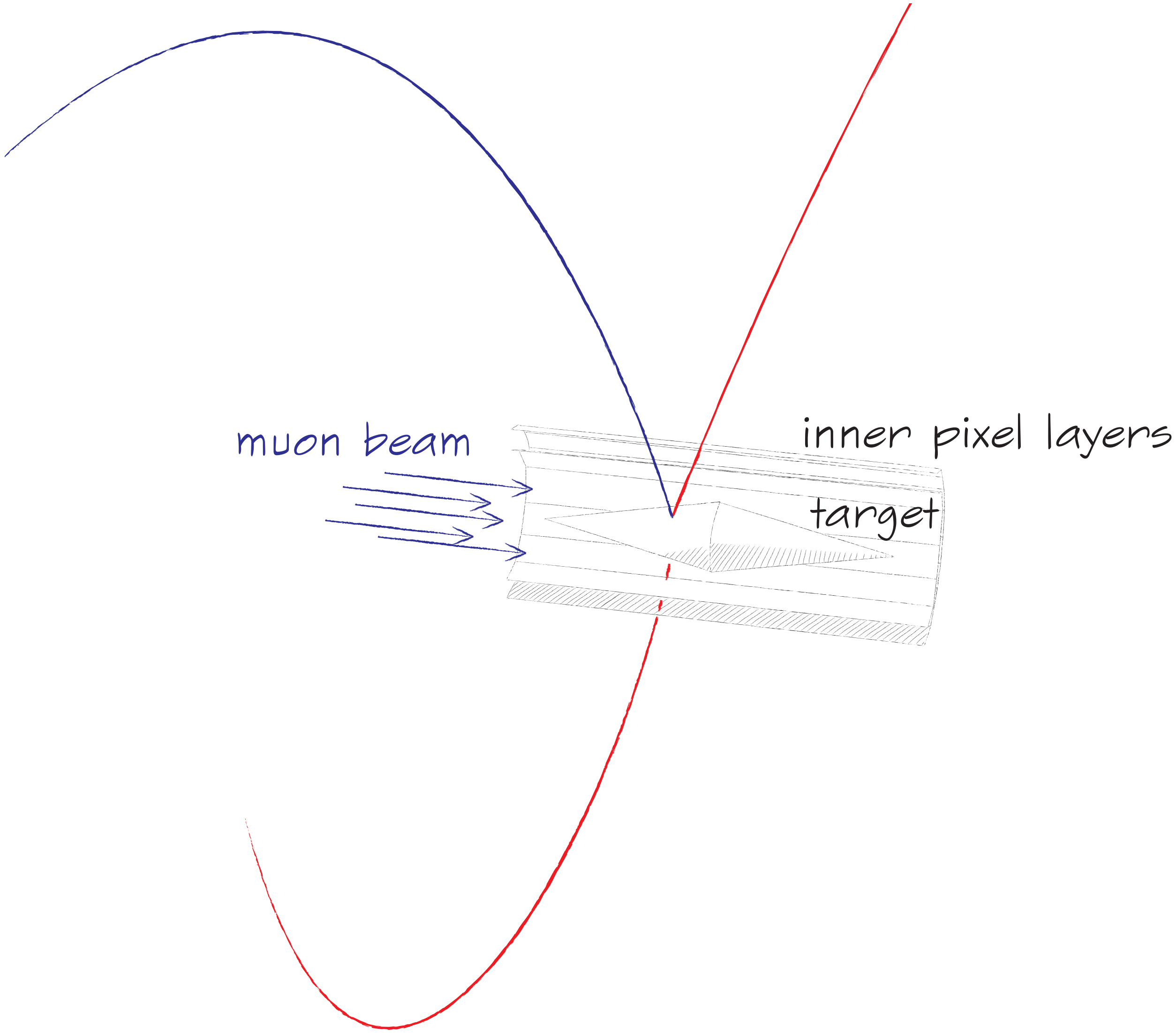
Detector Design



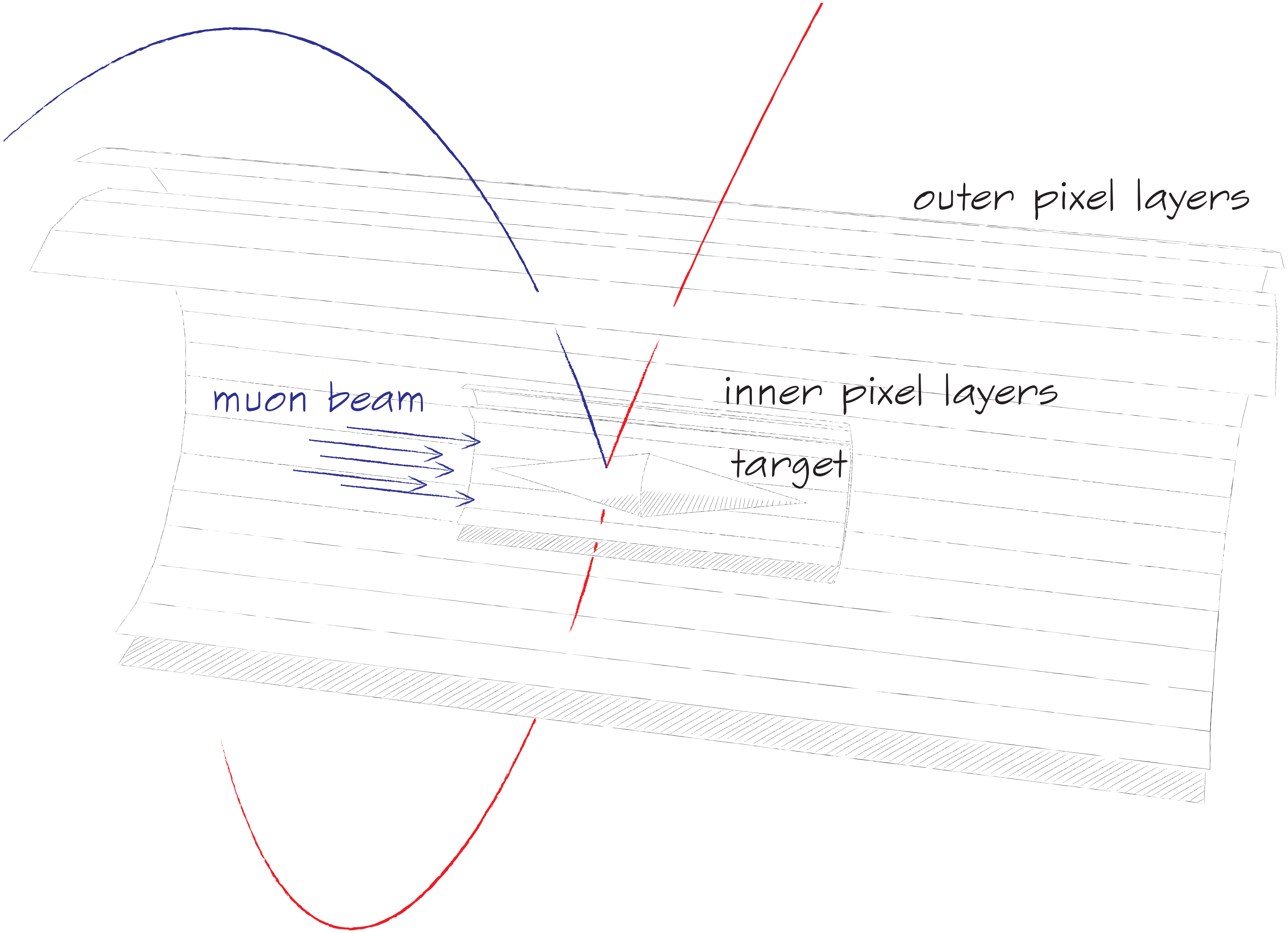
Detector Design



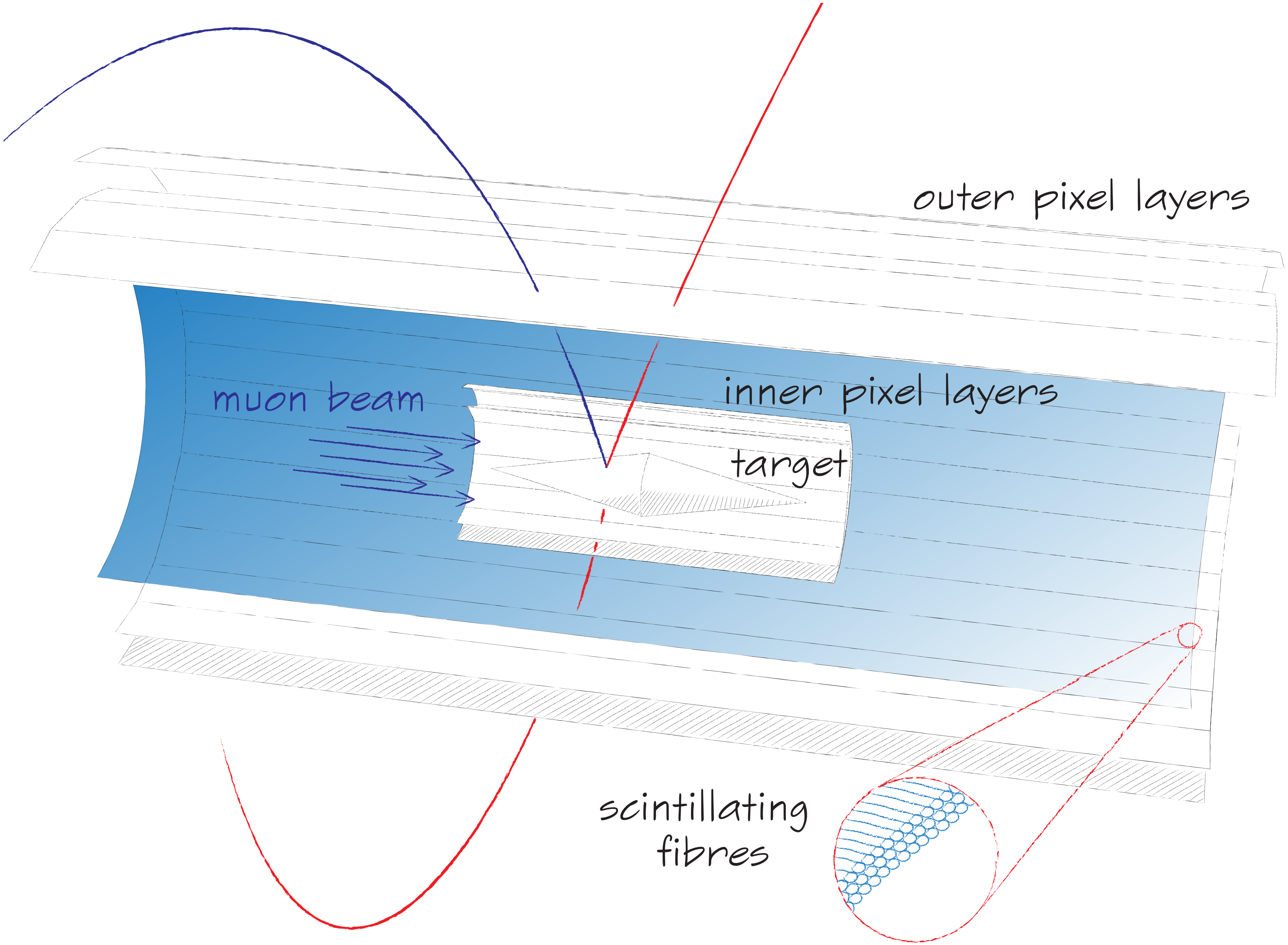
Detector Design



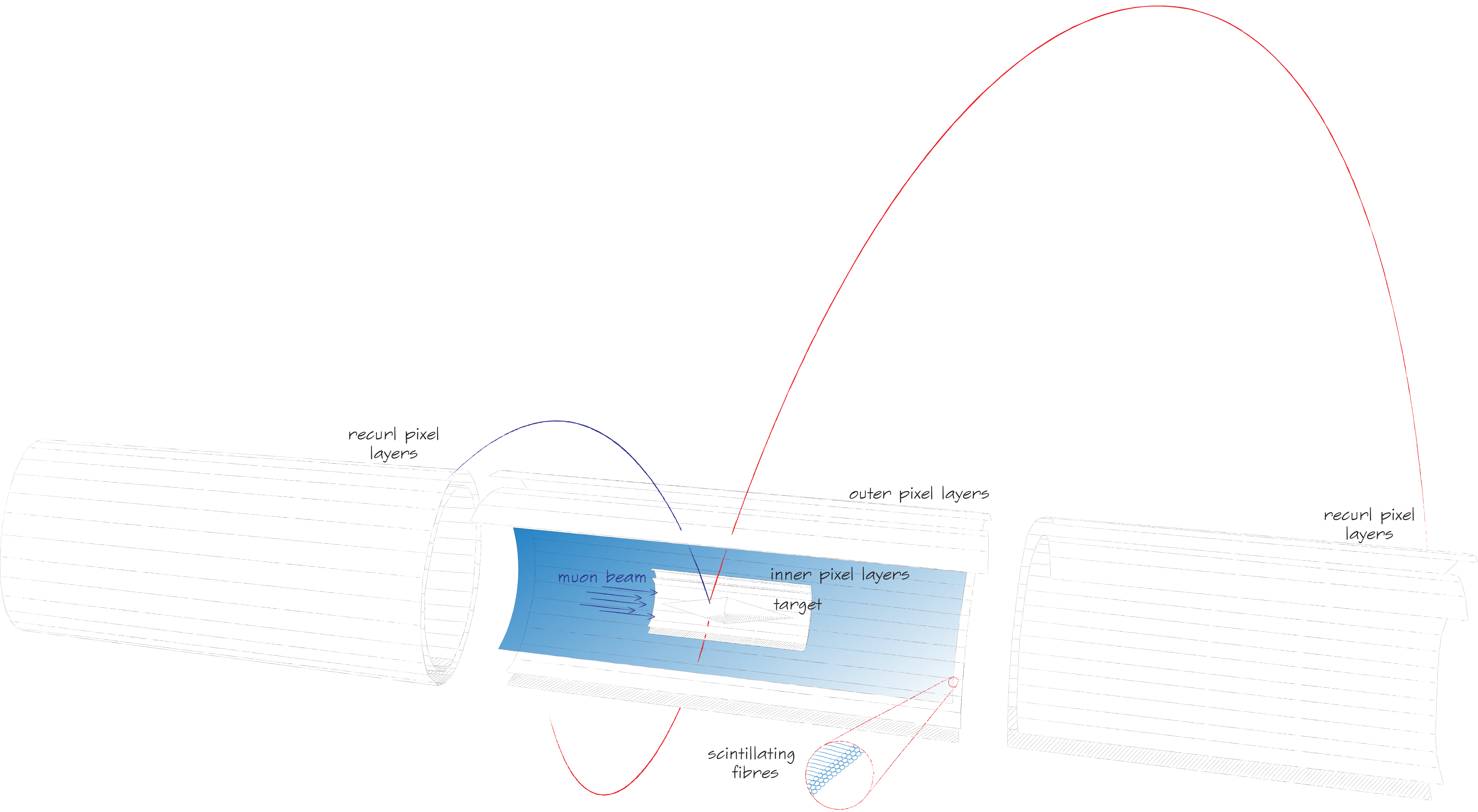
Detector Design



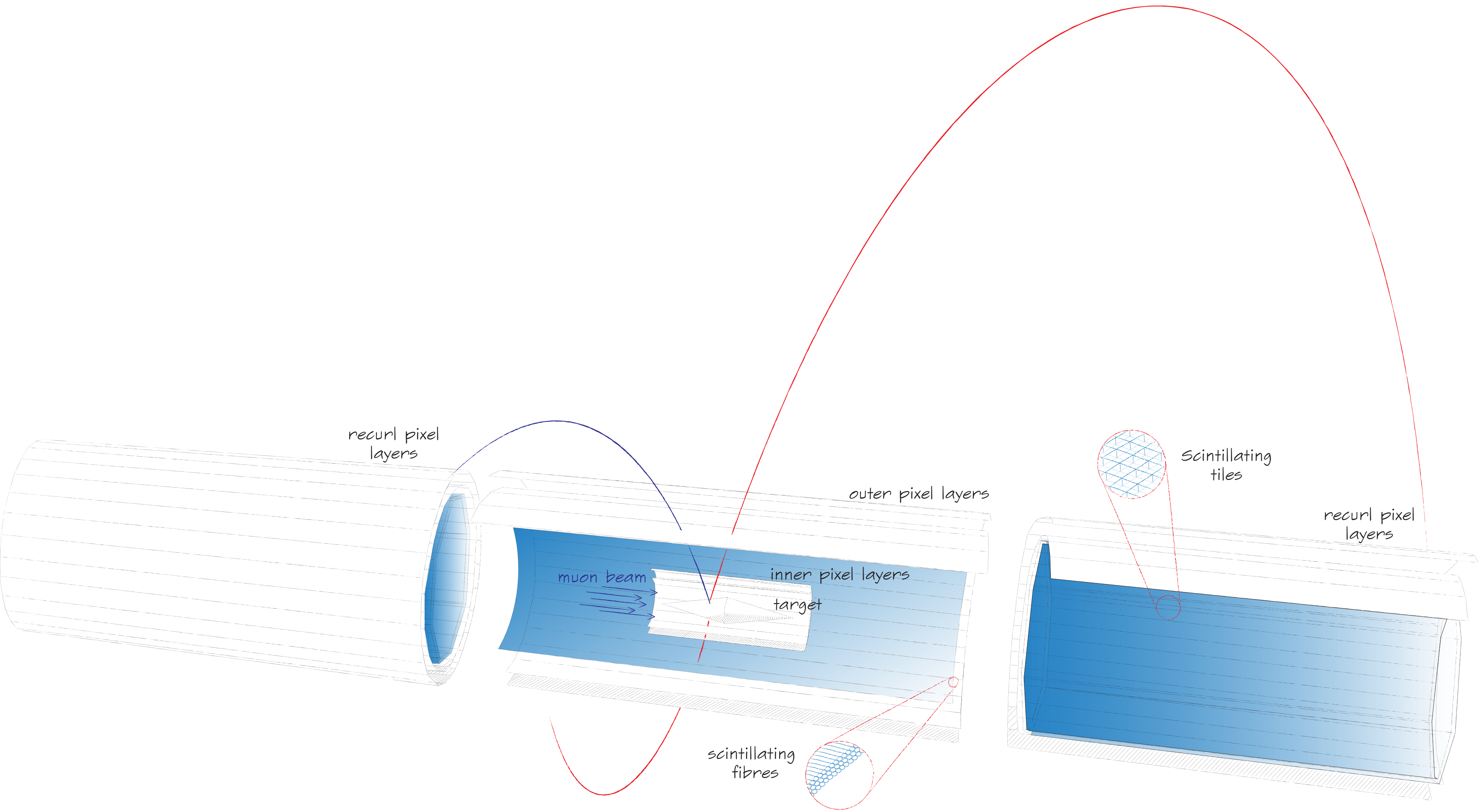
Detector Design



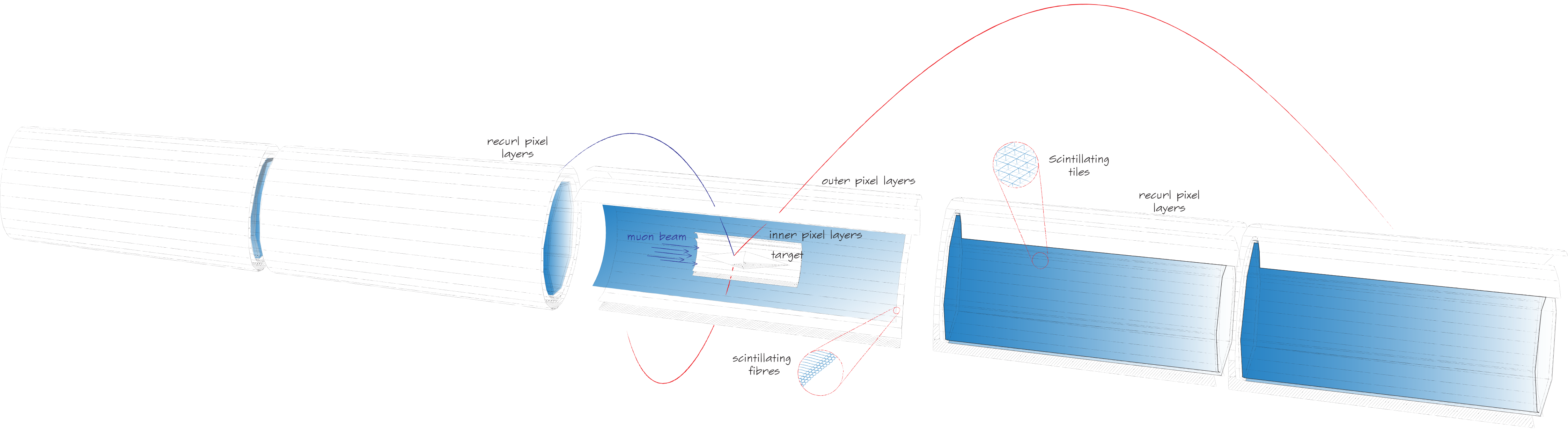
Detector Design



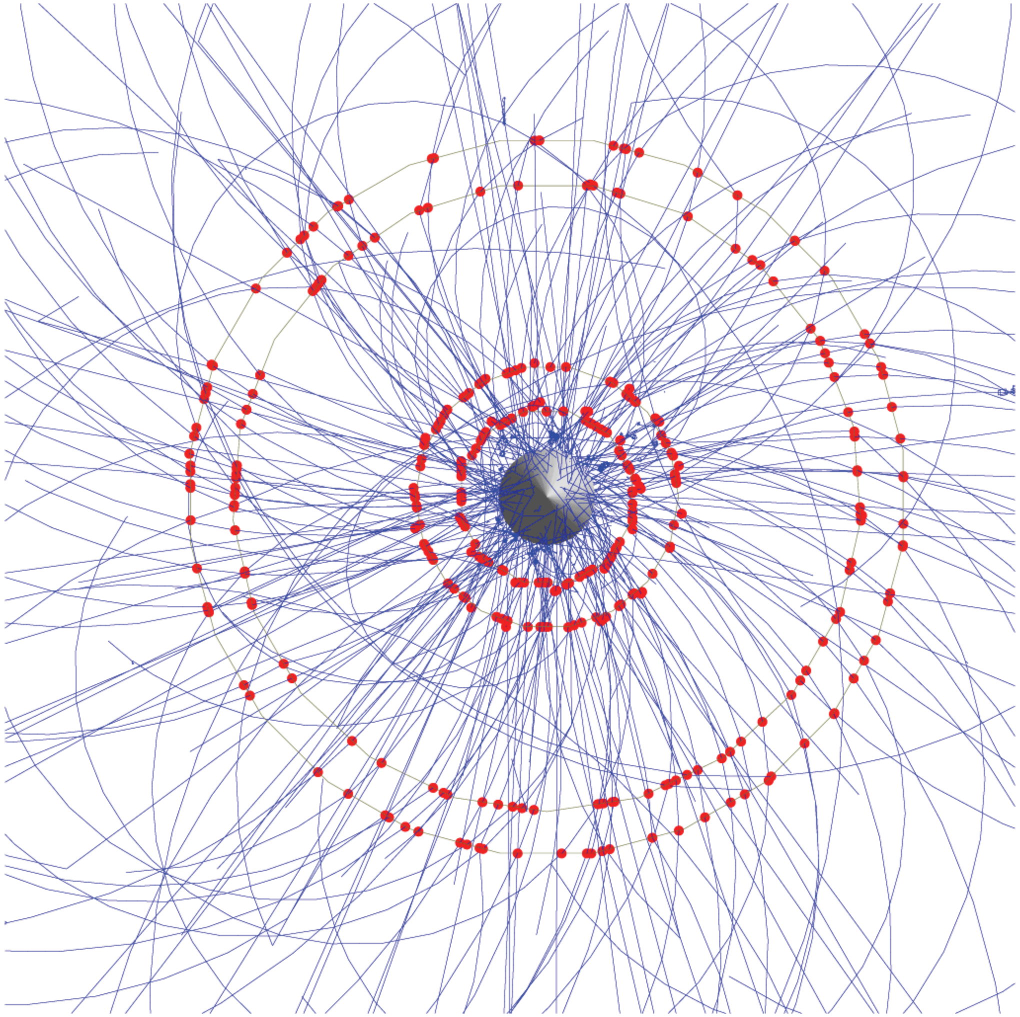
Detector Design



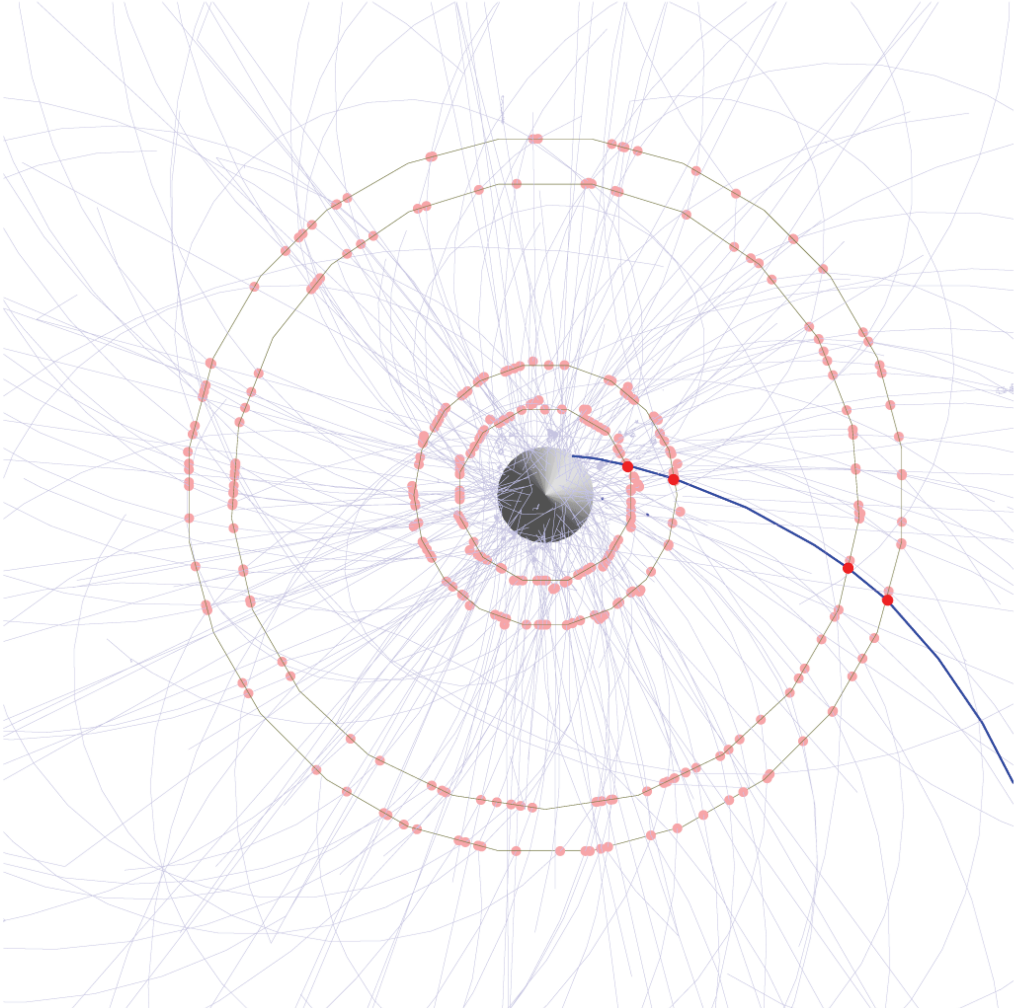
Detector Design



Timing measurements



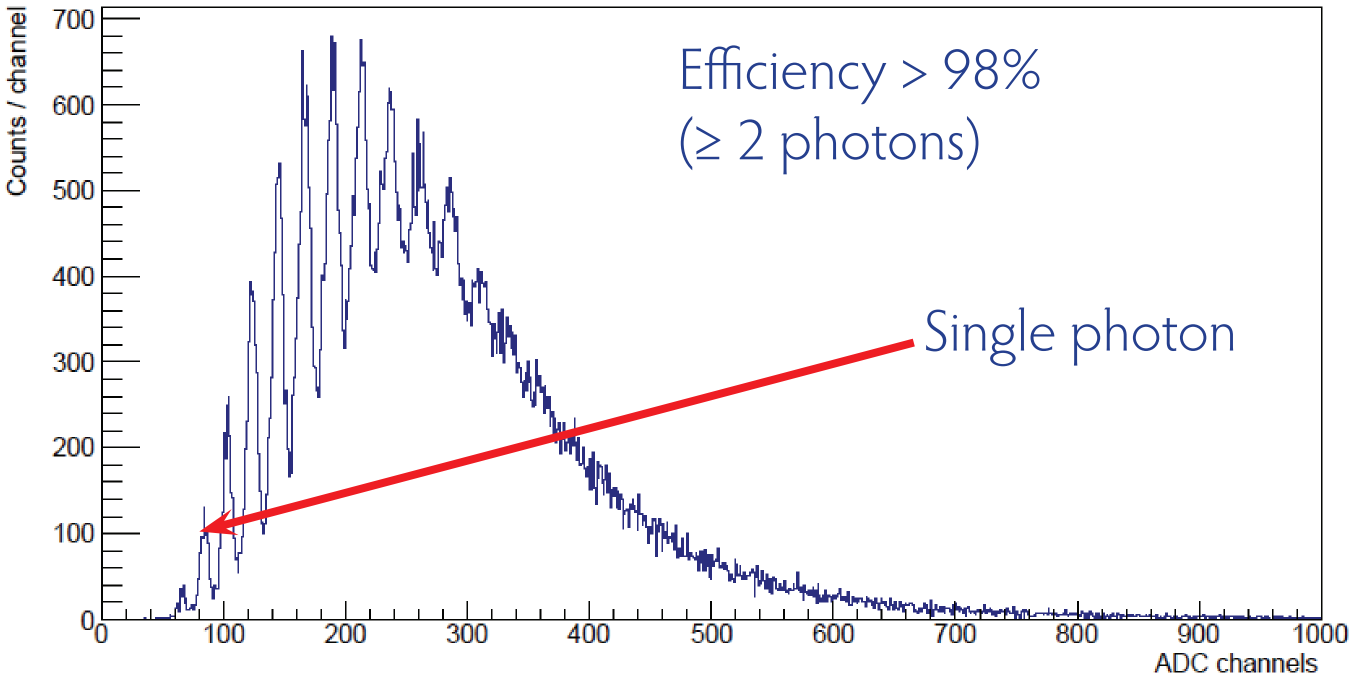
Pixels: O(50 ns)



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

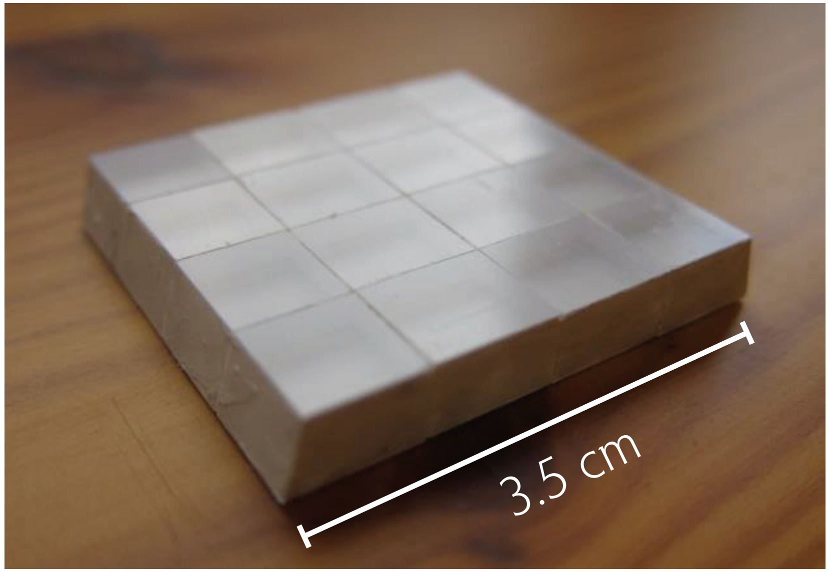
Timing Detector: Scintillating Fibres

- 3 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)
- Timing resolution $\mathcal{O}$(0.5 - 1 ns)

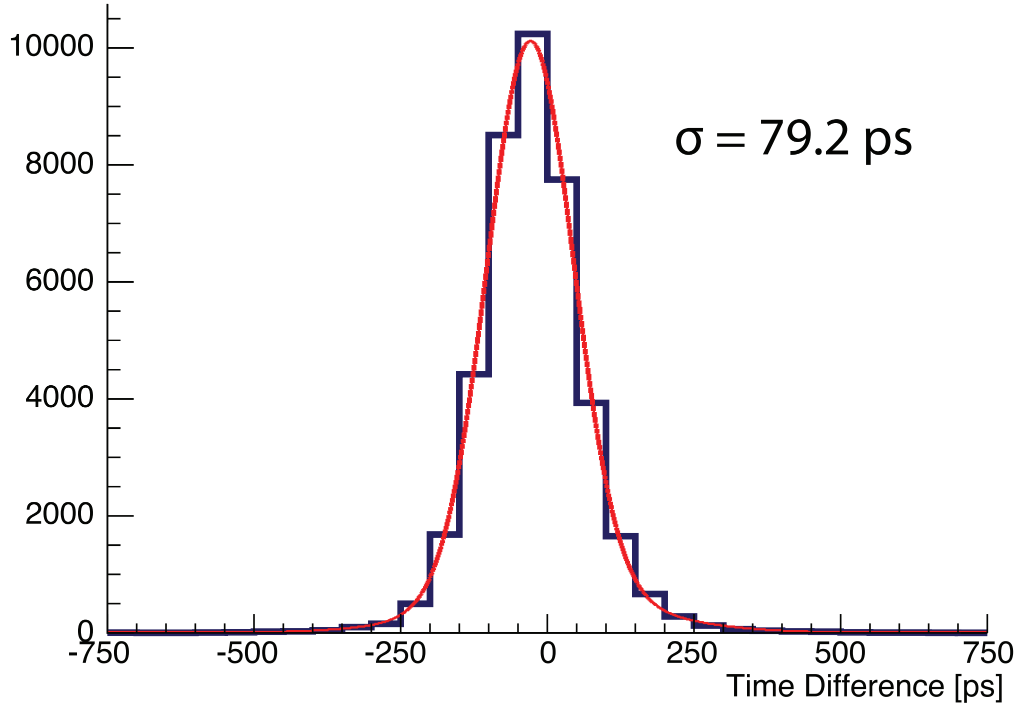


Timing Detector: Scintillating tiles

Front



Back

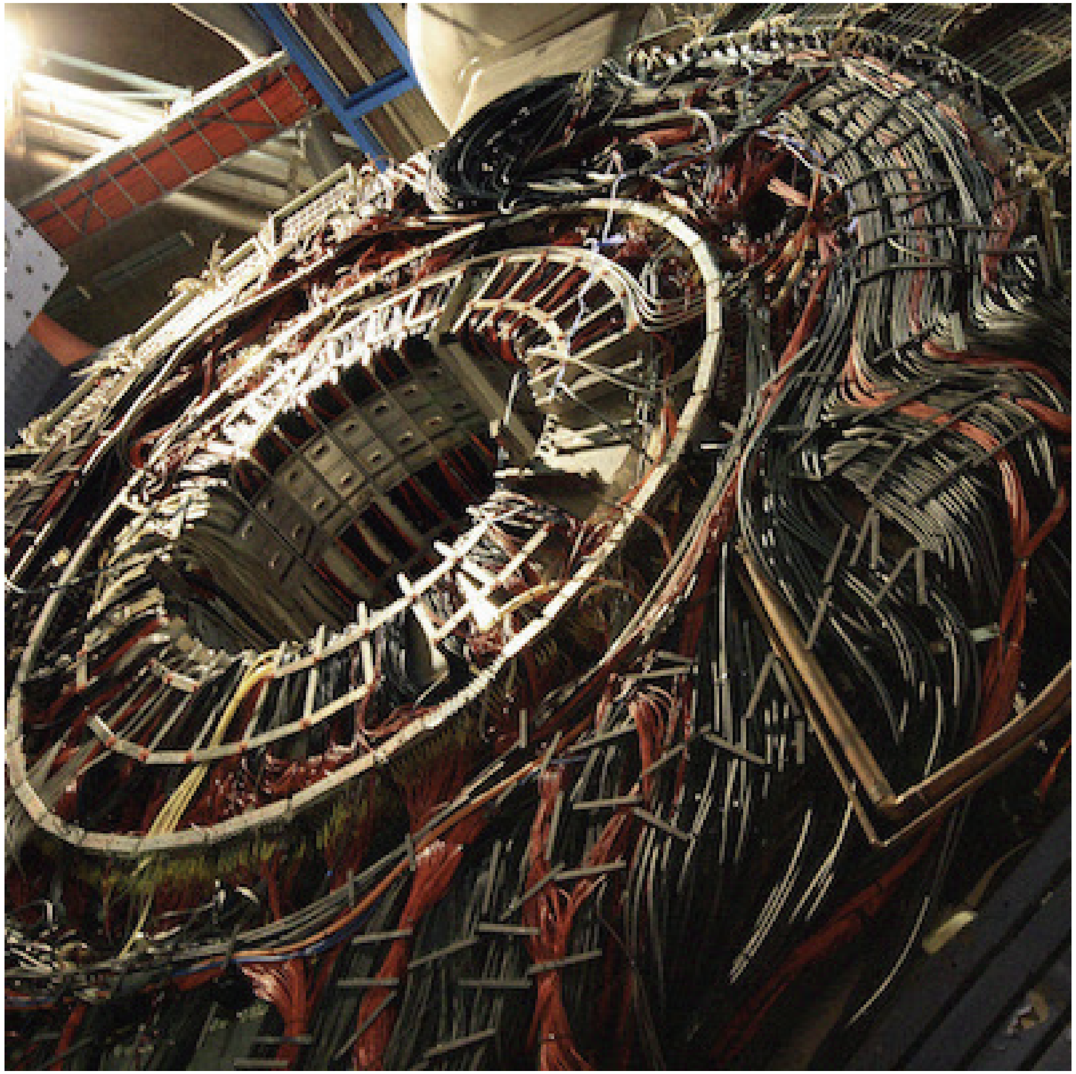


- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution ~ 80 ps

Mu3e data acquisition

Streaming Readout

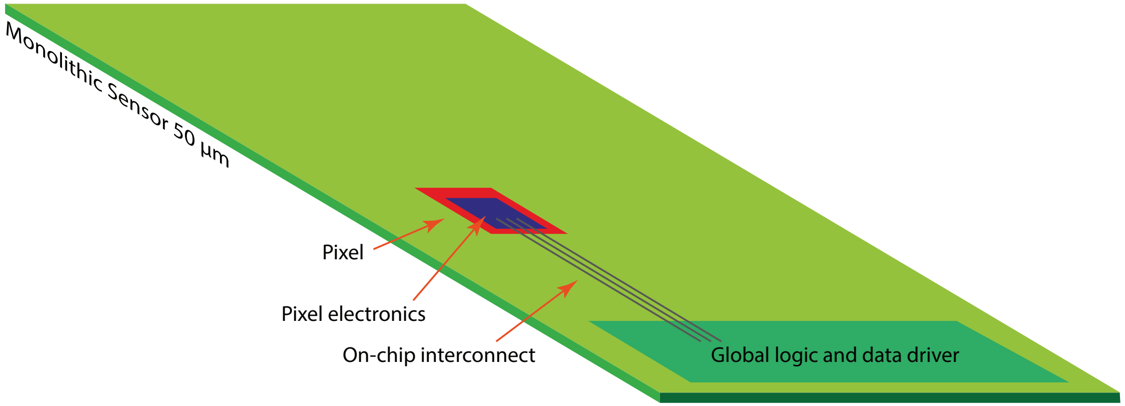
Getting data out

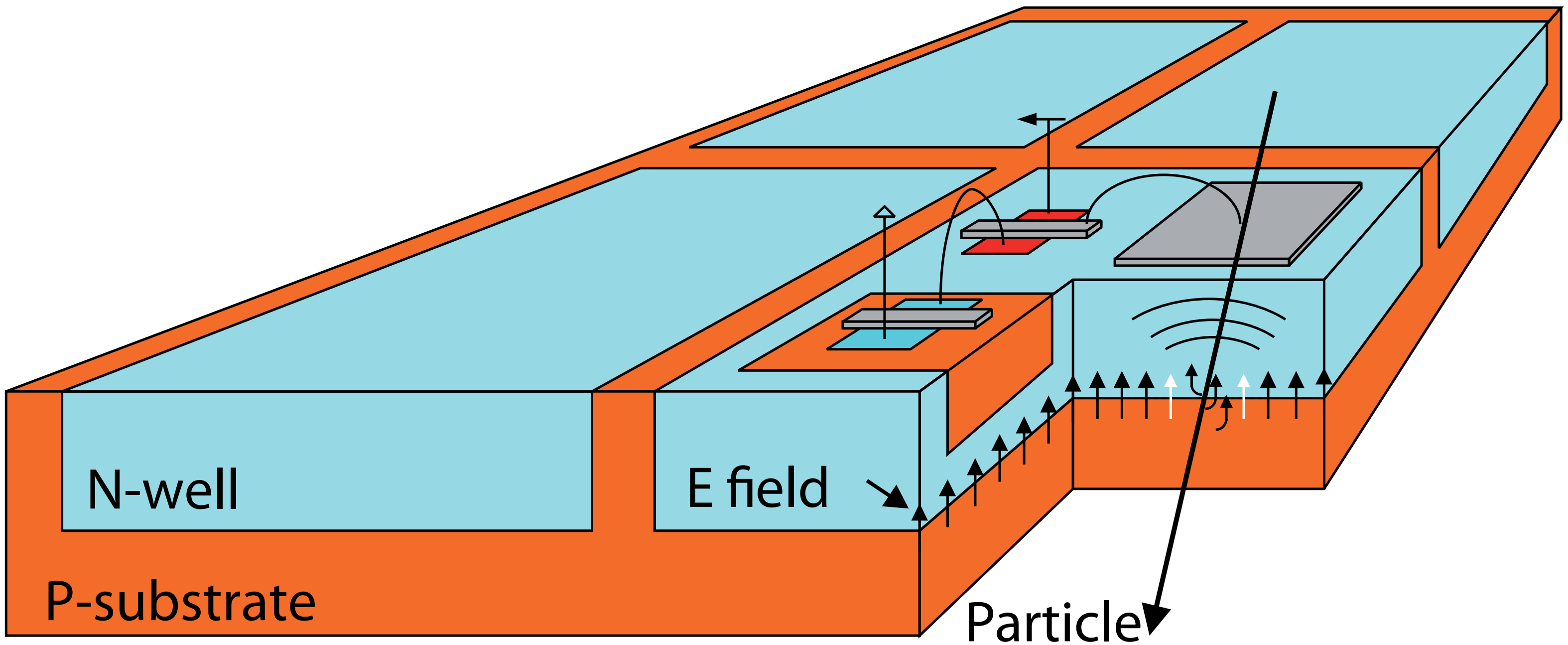


- No space, cooling, power in detector for
  buffer,
  digitalization,
  trigger electronics

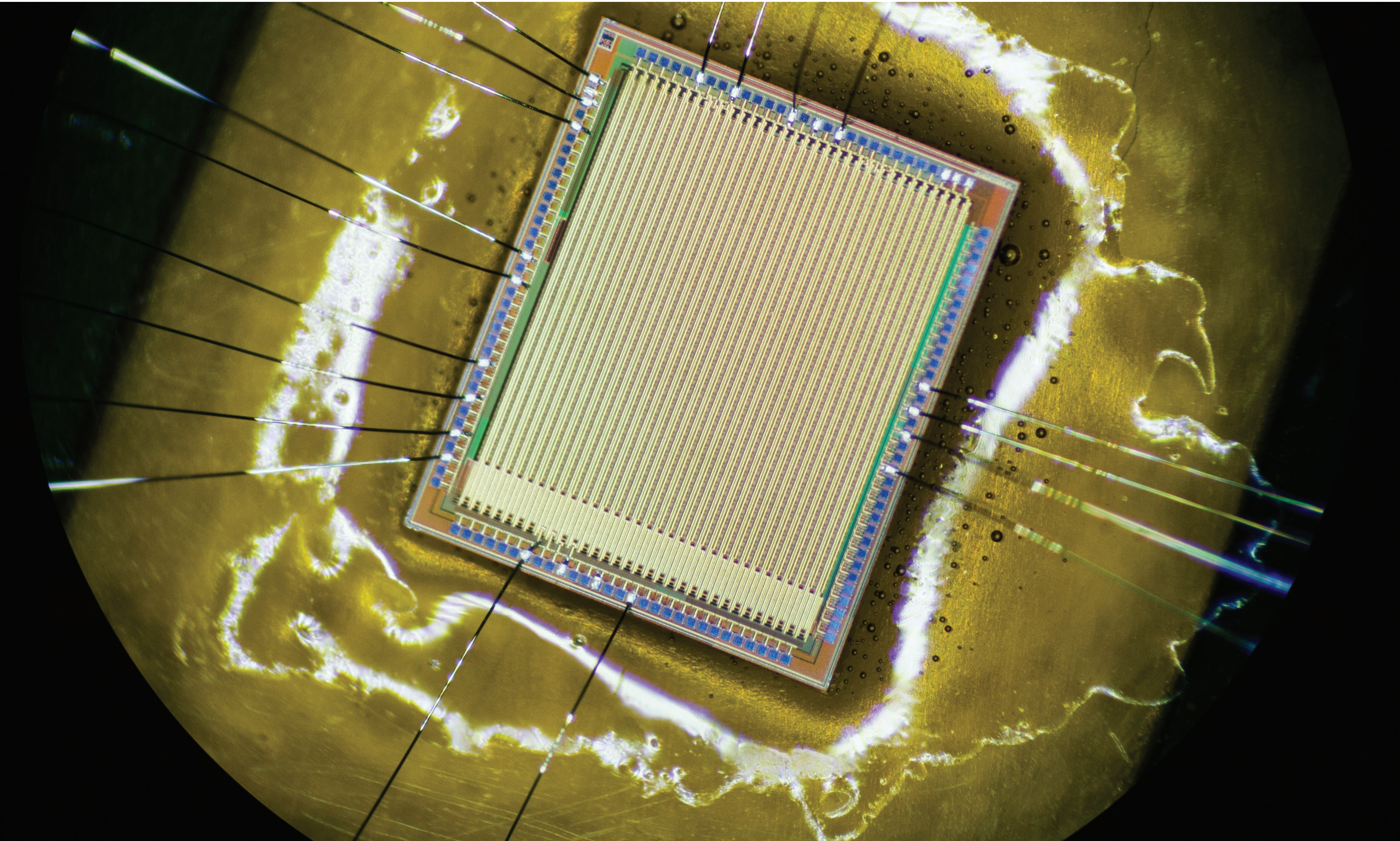
- Really?

Use custom integrated circuits!

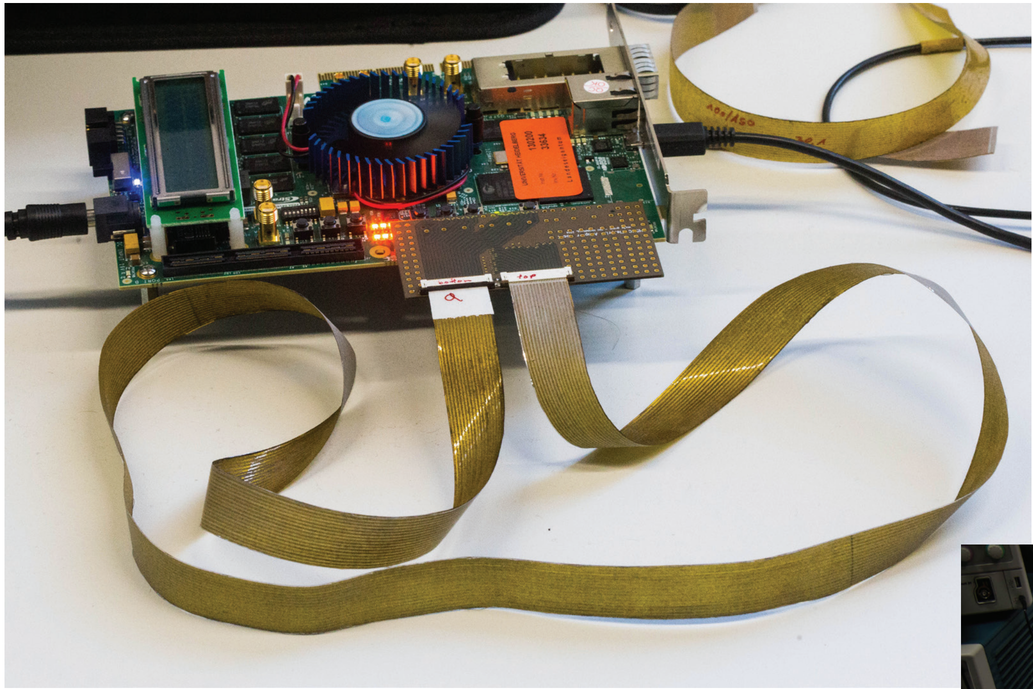




Digital electronics is tiny....

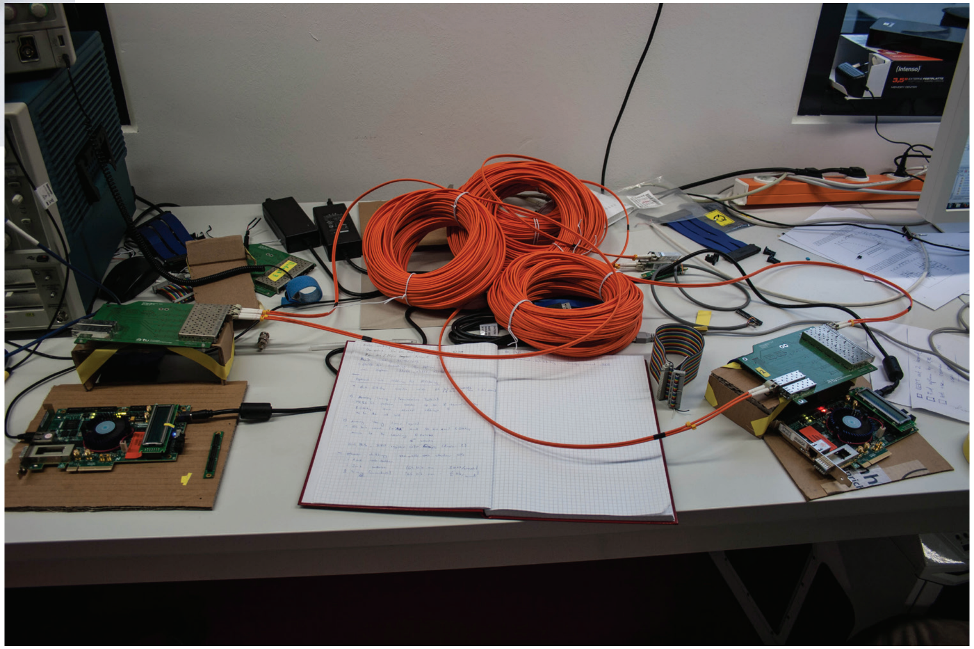


Fast links on thin cables

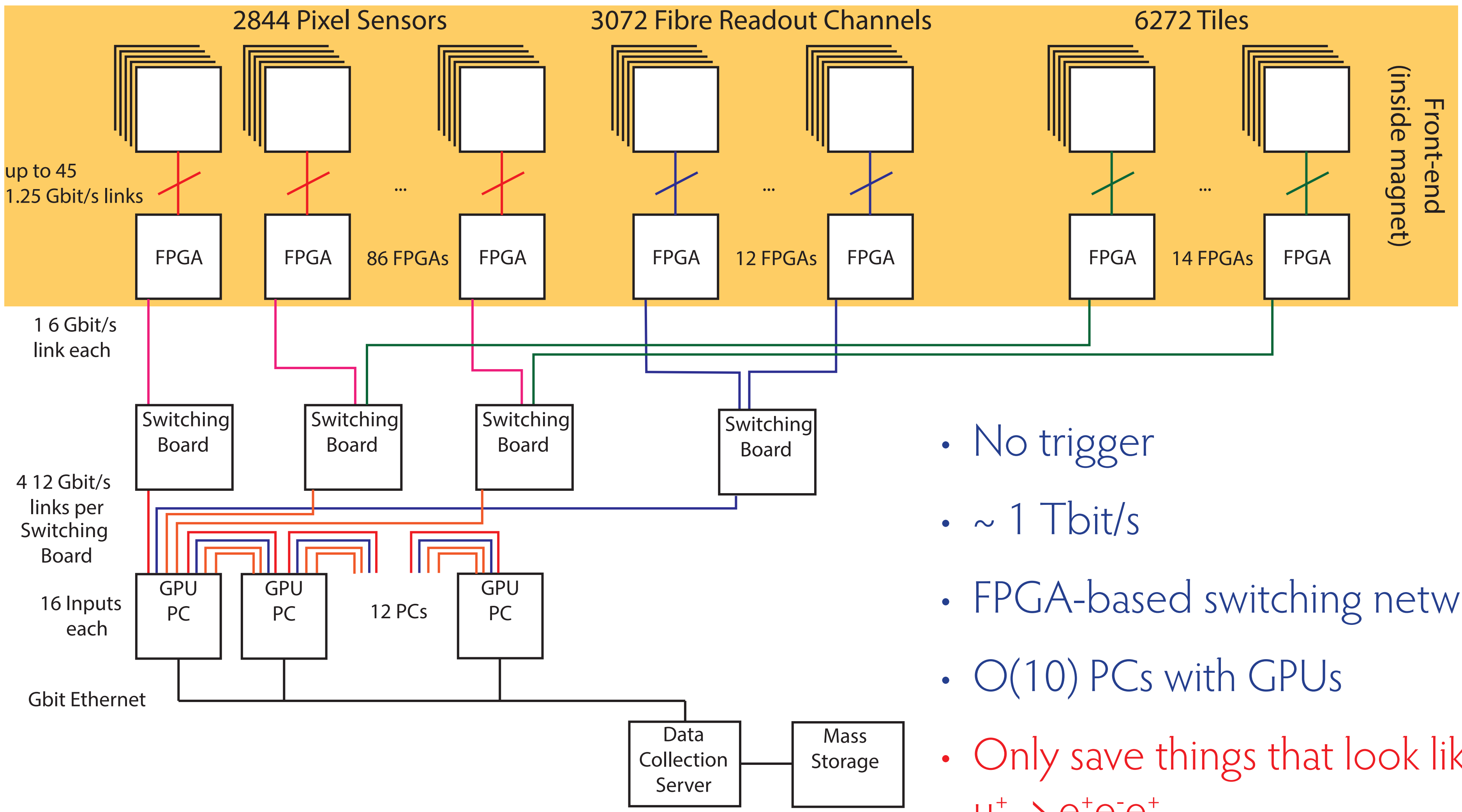


- Up to 1.6 GBit/s over one differential pair to an FPGA

- Multiplex data and send via optical link 10 GBit/s easy, more possible

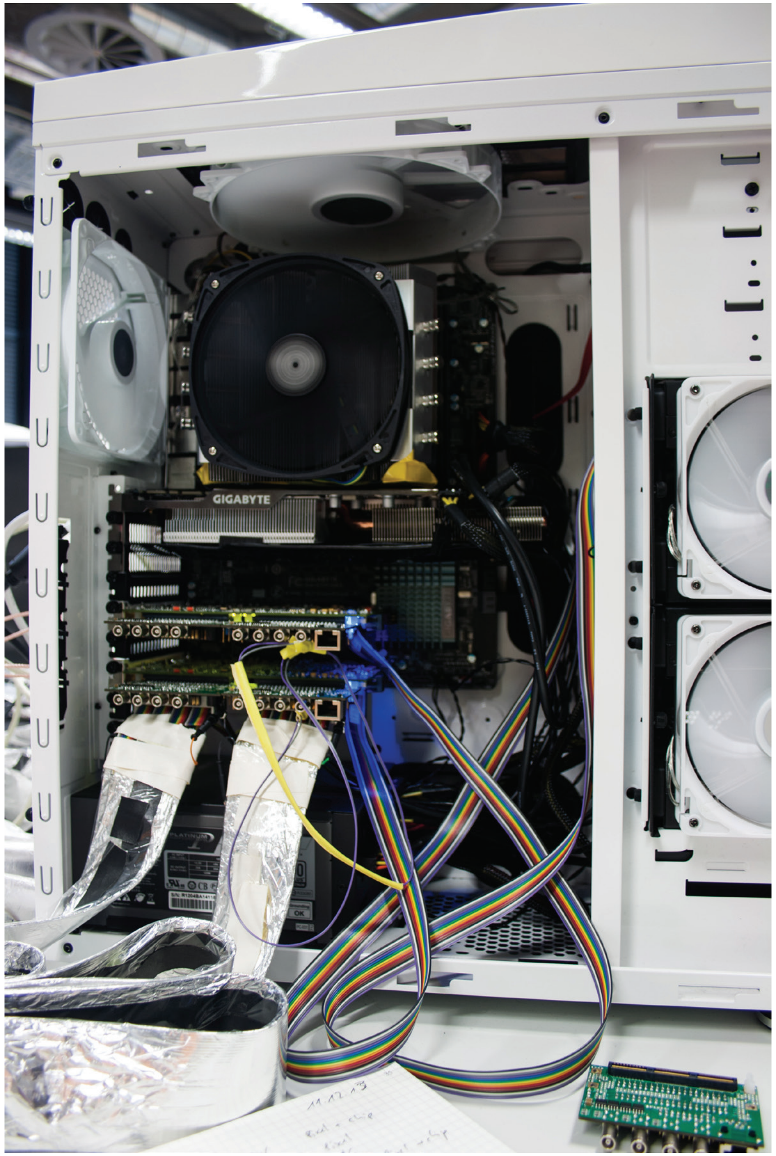


Data Acquisition



- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(10) PCs with GPUs
- Only save things that look like $\mu^+ \to e^+e^-e^+$
- Or: Additional selection

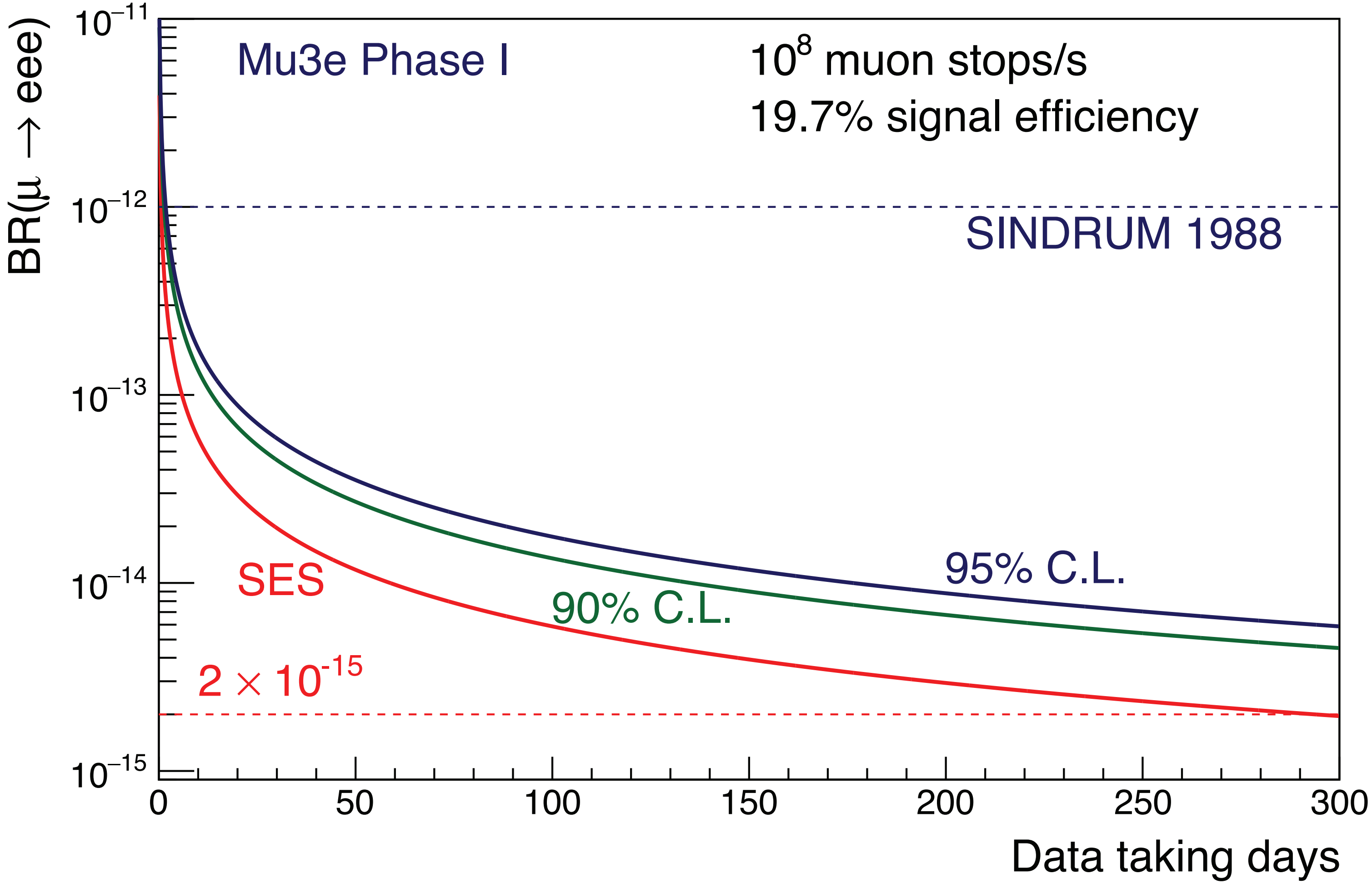
Online filter farm



Online software filter farm

- PCs with FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- 10^9 3D track fits/s achieved
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

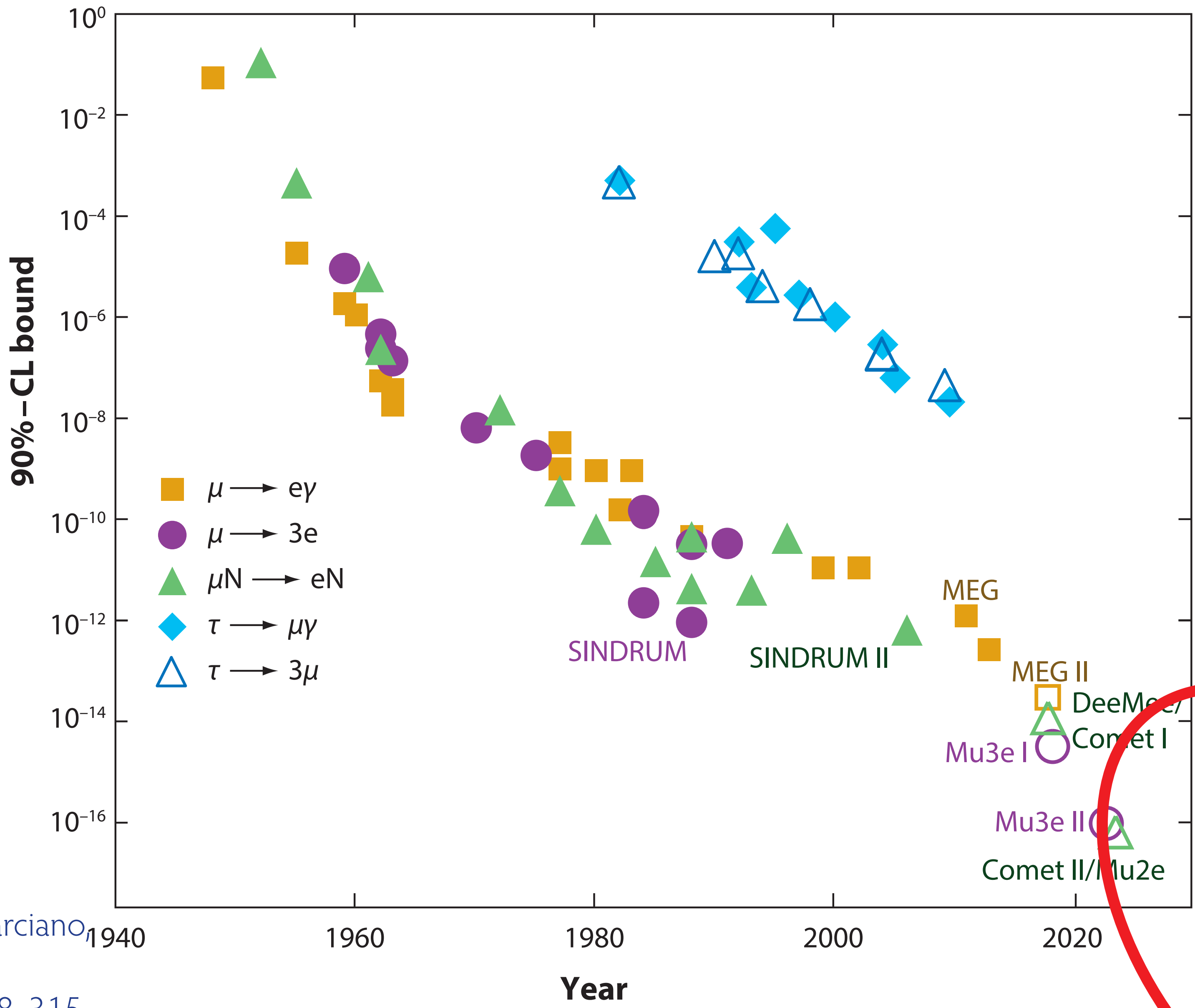
Sensitivity - Mu3e Phase I



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

Going further?

History of LFV experiments



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

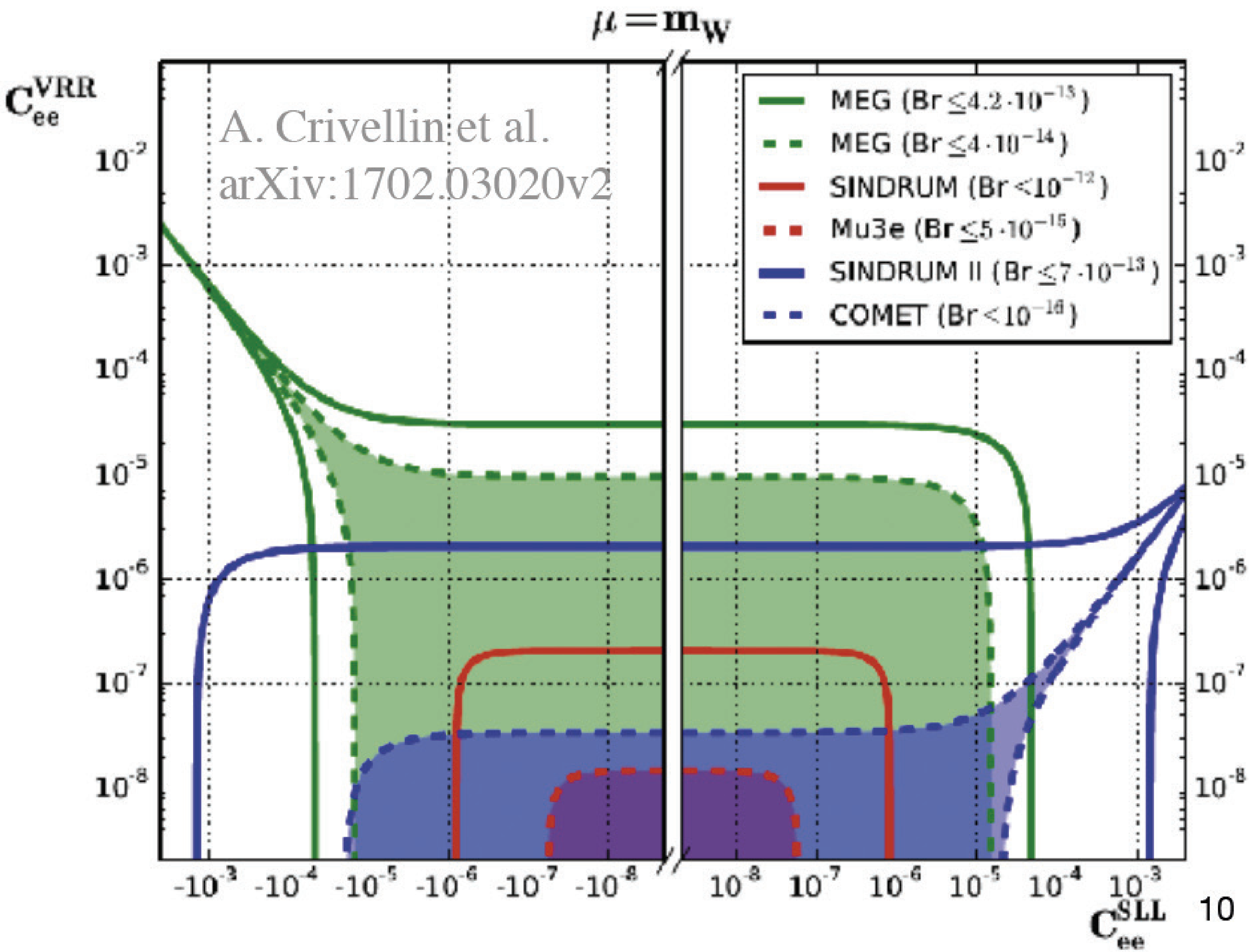
Beyond 10^{-16}

- No point if we find something before

- Requires new technologies, new beams

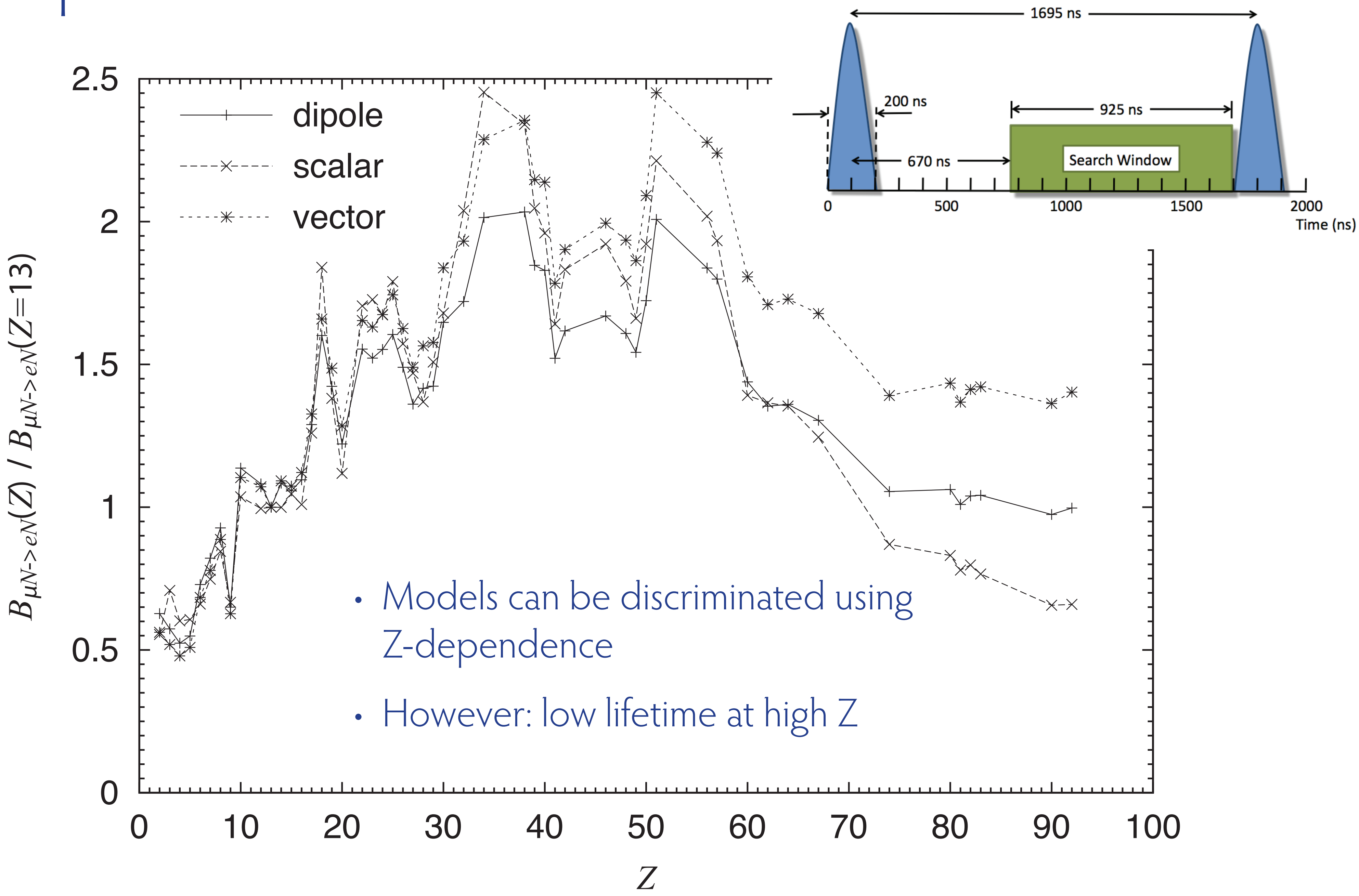
- Start thinking now...

If we find something...



μ = m_W
C_ee^VRR
A. Crivellin et al.
arXiv:1702.03020v2
MEG (Br ≤ 4.2·10^-13)
MEG (Br ≤ 4·10^-14)
SINDRUM (Br < 10^-12)
Mu3e (Br ≤ 5·10^-15)
SINDRUM II (Br ≤ 7·10^-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
10

Z-dependence

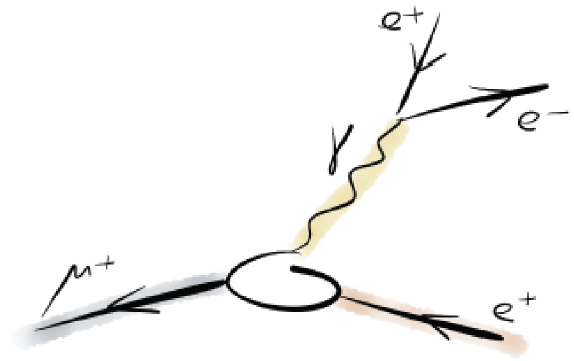


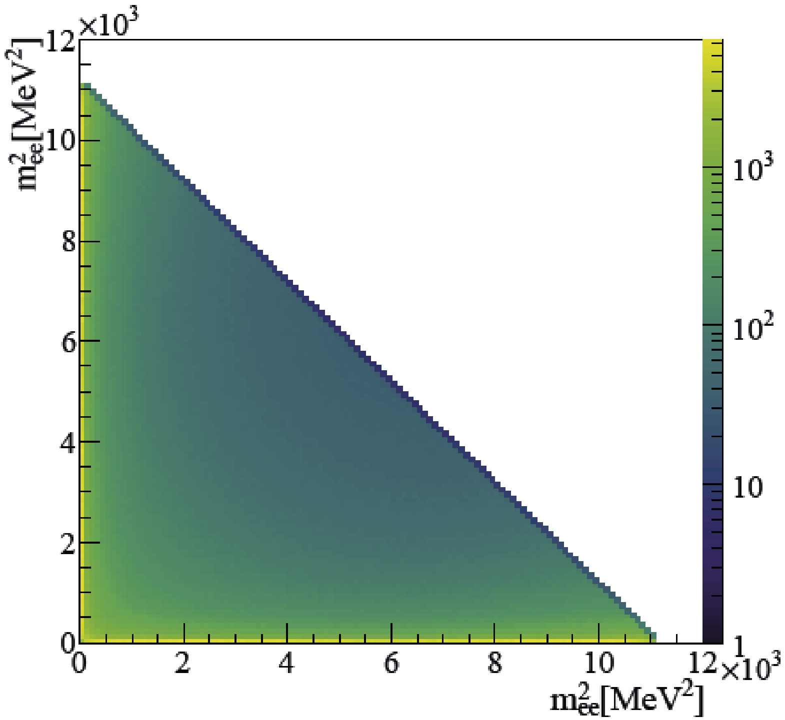
- Models can be discriminated using Z-dependence
- However: low lifetime at high Z

Decay distributions!

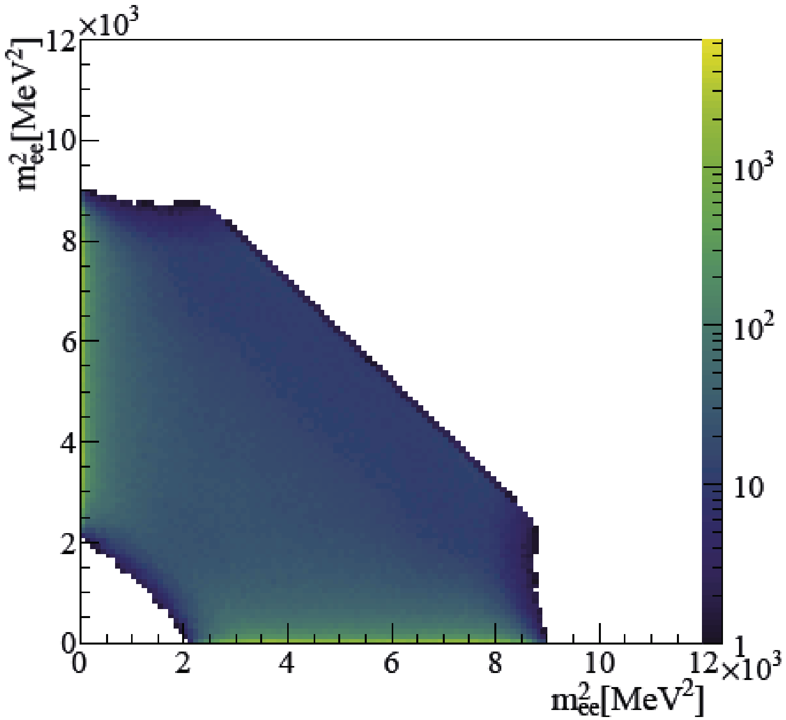
Dipole operator $em_\mu A_L \overline{\mu_L} \sigma^{\mu\nu} e_R F_{\mu\nu}$

Efficiency is 13 %





Generated distribution



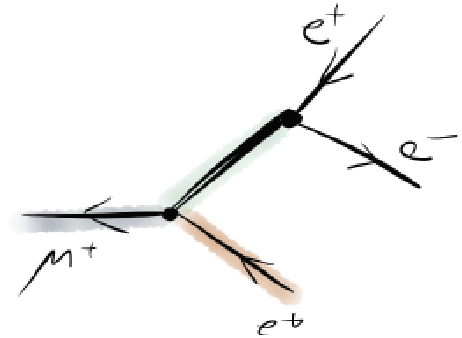
After reconstruction and vertex fit

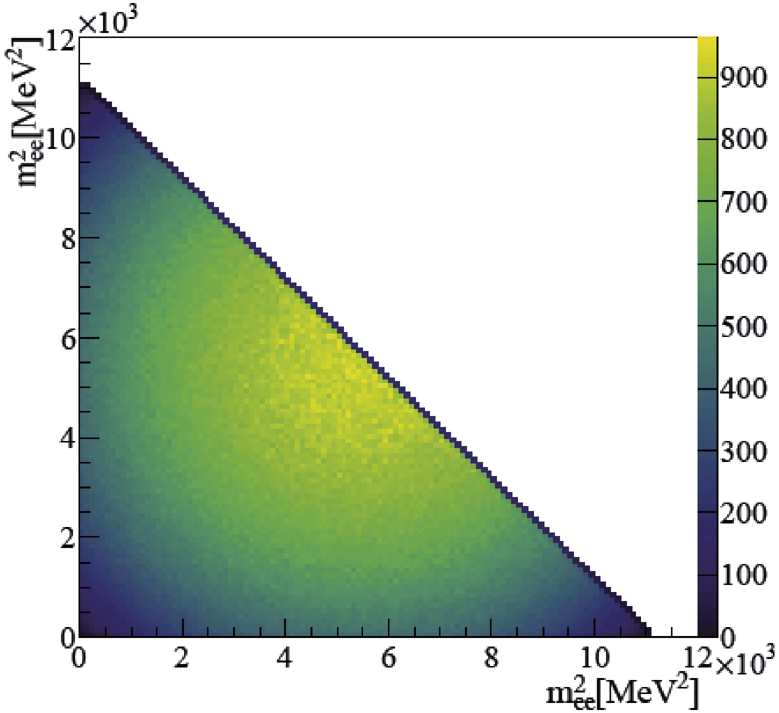
Ann-Kathrin Perrevoort

Decay distributions!

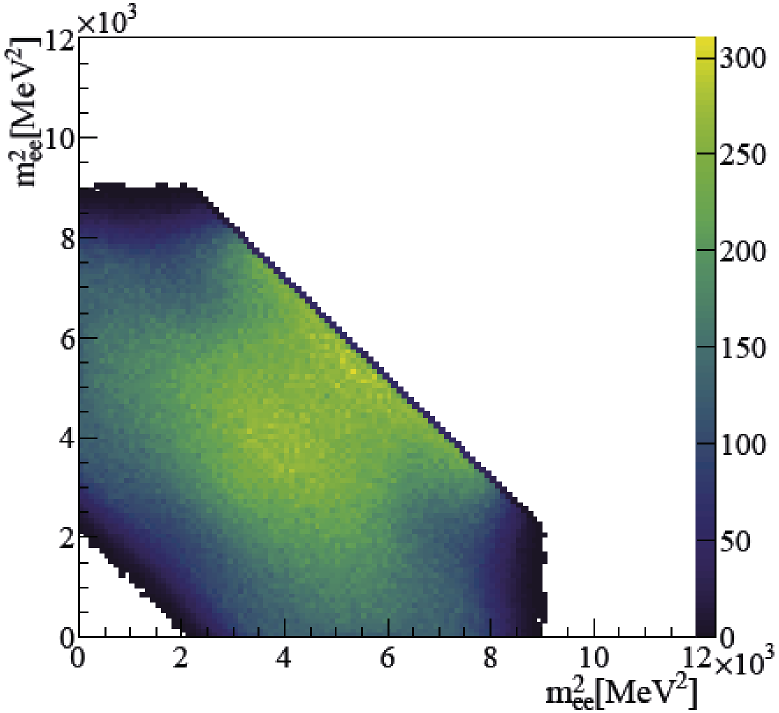
Vector 4-fermion operator $(\overline{\mu_R}\gamma^\mu e_R)(\overline{e_R}\gamma^\mu e_R)$

Efficiency is 22 %





Generated distribution



After reconstruction and vertex fit

Ann-Kathrin Perrevoort