A Novel Experiment Searching for the Lepton Flavor Violating Decay

$\mu \rightarrow eee$

Dirk Wiedner, Heidelberg

On Behalf of the Mu3e Proto-Collaboration

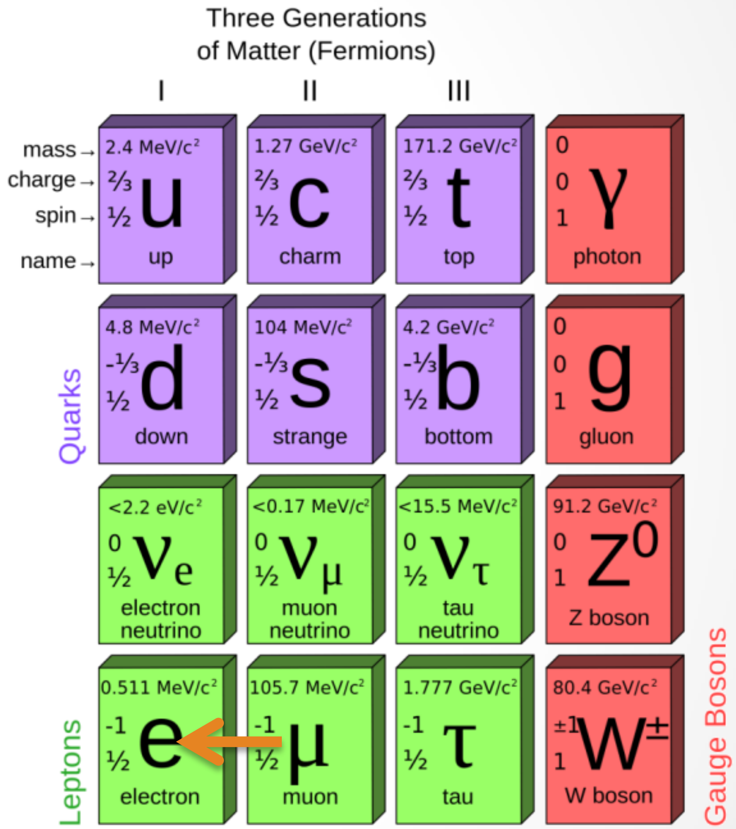
July 17th 2012

Overview

- Physics Motivation
- Mu3e Experiment
- HV-MAPS
- Construction
- Timing detectors
- DAQ
- Summary

Physics Motivation

Lepton flavor violation?



Standard model:

- No lepton flavor violation

Physics Motivation

Lepton flavor violation?

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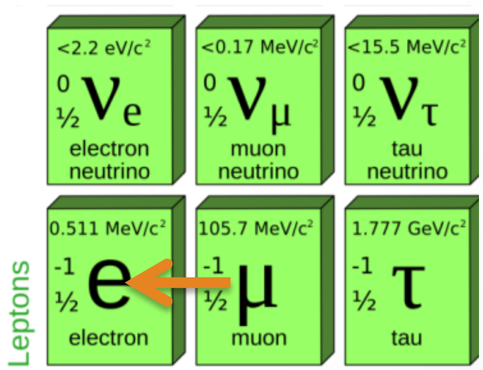
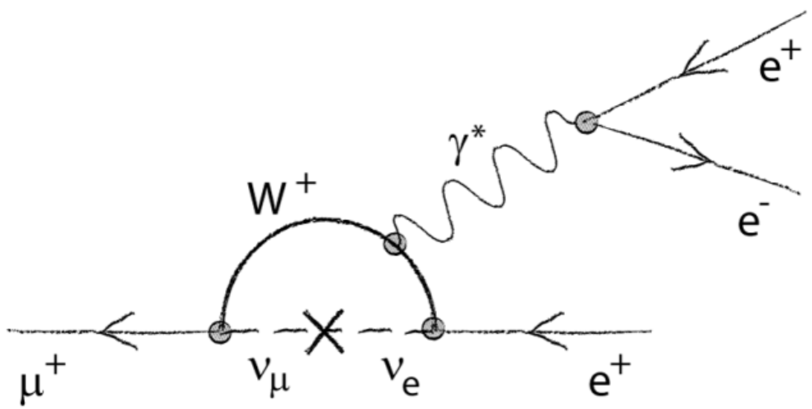


Physics Motivation

Lepton flavor violation: $\mu^+ \rightarrow e^+e^-e^+$

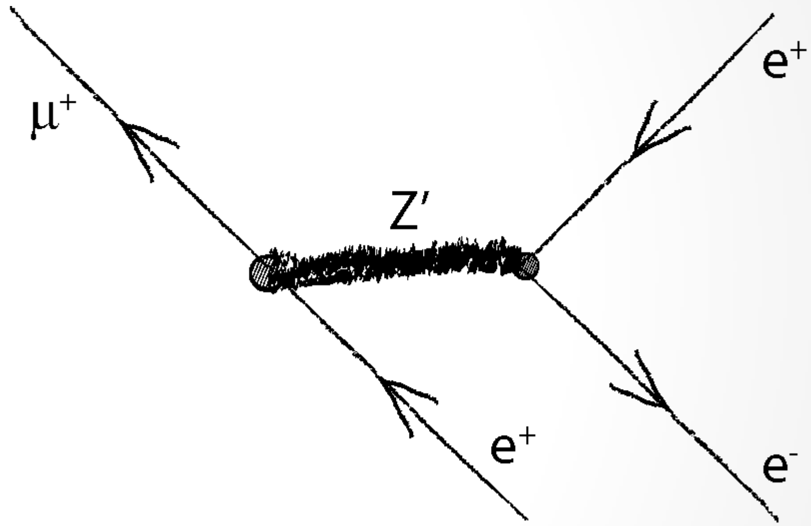


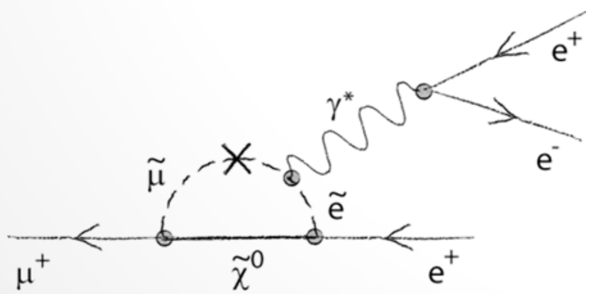
Standard model:

- No lepton flavor violation, but:
  - Neutrino mixing
  - Branching ratio $<10^{-50} \rightarrow$ unobservable

The Mu3e Signal

- μ→eee rare in SM
- Enhanced in:
  - Super-symmetry
  - Grand unified models
  - Left-right symmetric models
  - Extended Higgs sector
  - Large extra dimensions





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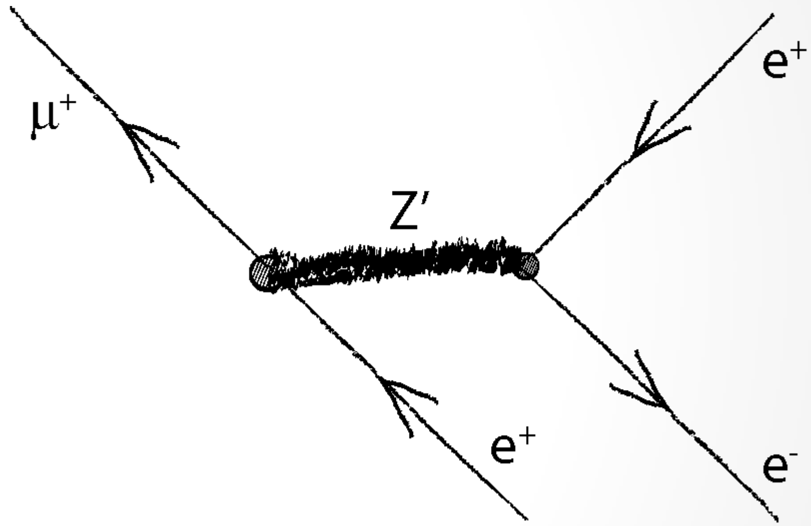
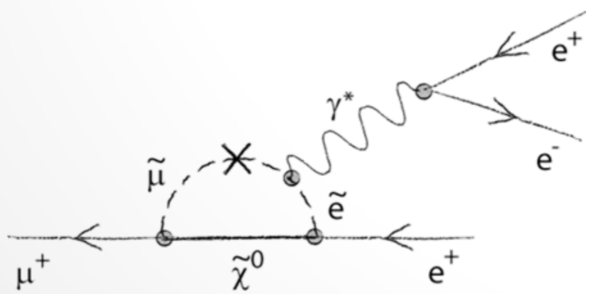
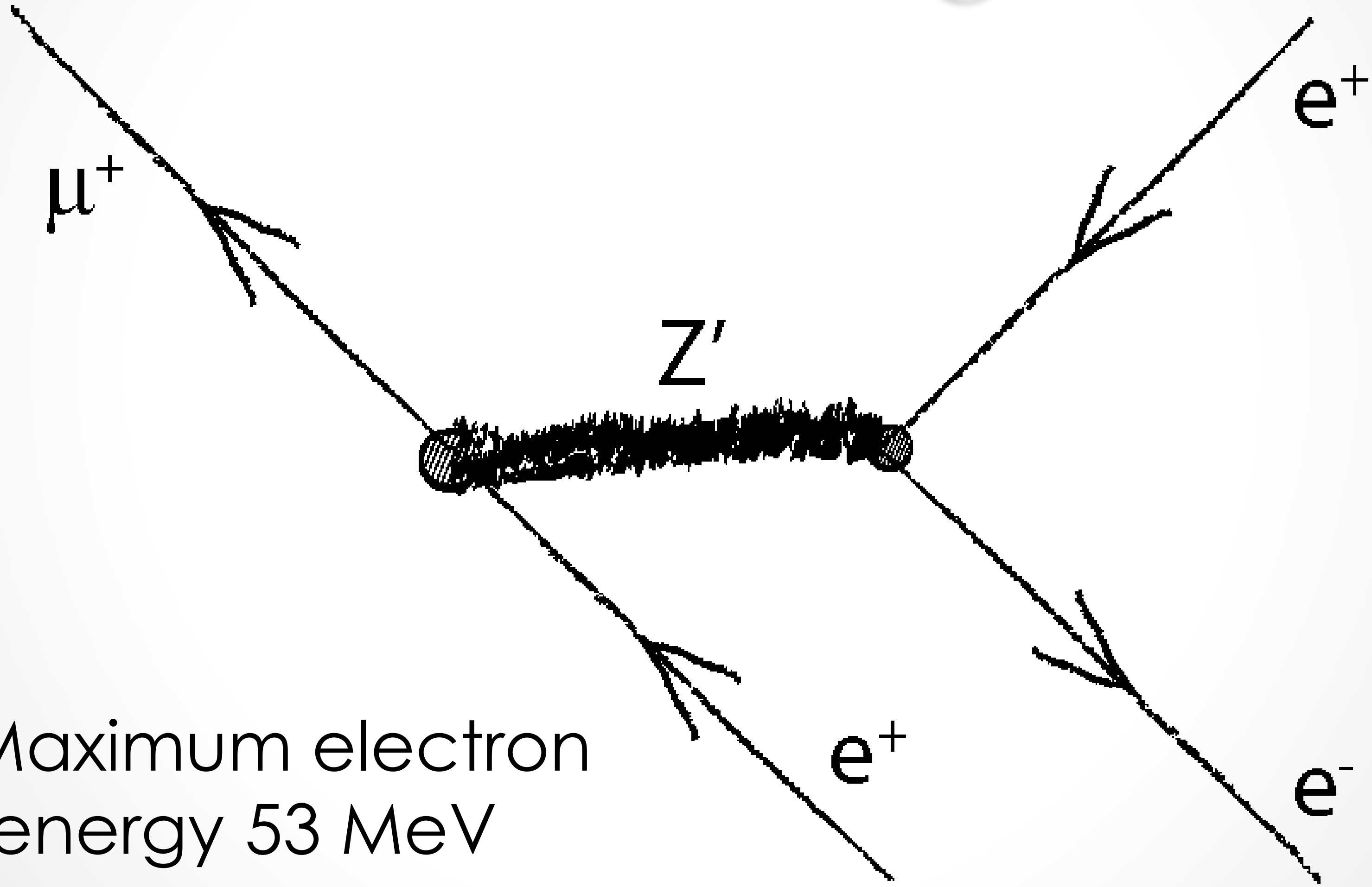




- ➢ Rare decay (BR<10^{-12}, SINDRUM)
- For BR O(10^{-16})
  - ➢ >10^{16} muon decays
  - ➢ High decay rates O(10^9 muon/s)

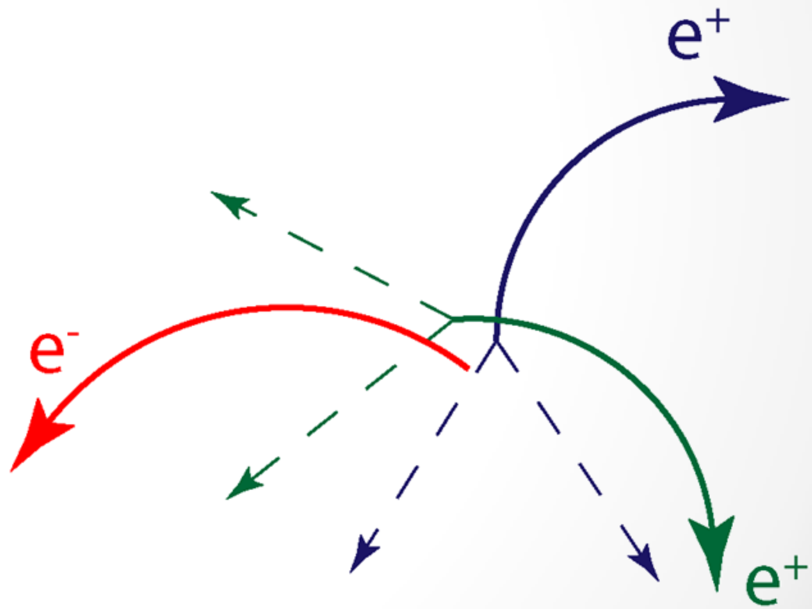
The Mu3e Signal



→Maximum electron energy 53 MeV

The Mu3e Background

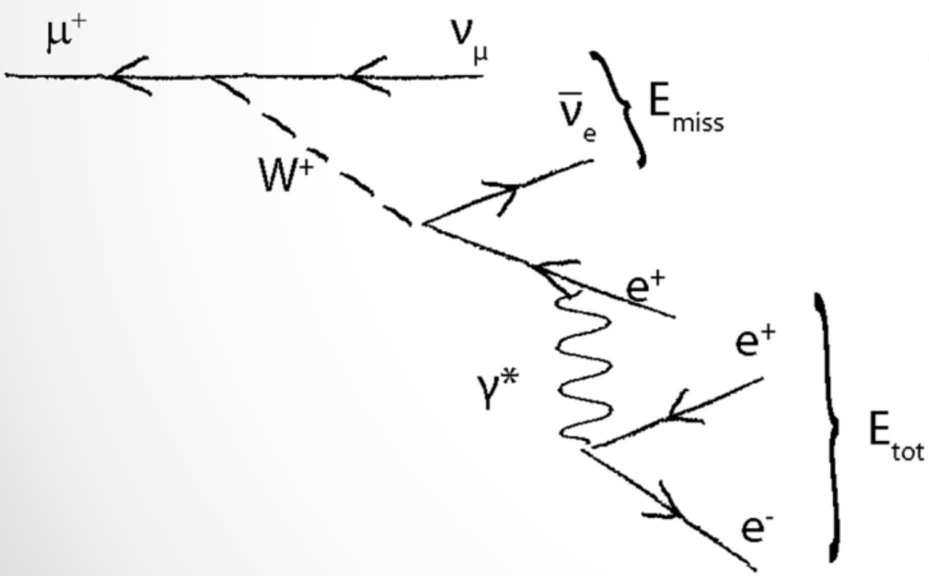
- Combinatorial background
  - $\mu^+ \rightarrow e^+\nu\nu$ & $\mu^+ \rightarrow e^+\nu\nu$ & e^+e^-
  - many possible combinations

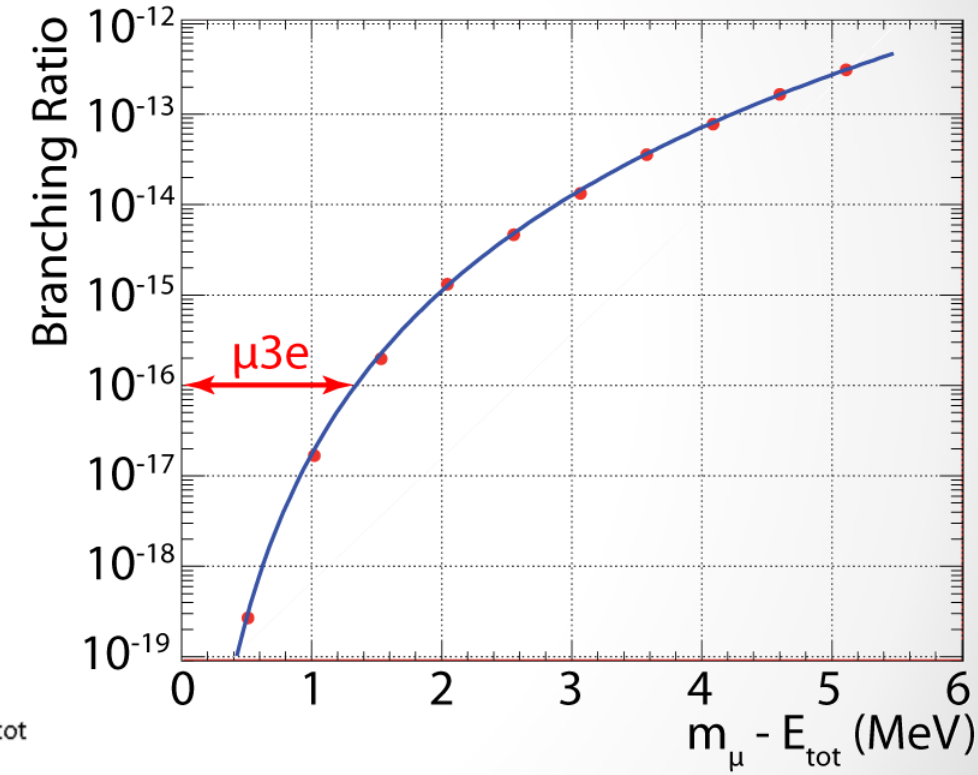


➢ Good time and
➢ Good vertex resolution required

The Mu3e Background

- $\mu^+ \to e^+ e^- e^+ \nu\nu$
  - Missing energy (ν)
  - ➢ Good momentum resolution





(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

Challenges

…

Challenges

- High rates
- Good timing resolution
- Good vertex resolution
- Excellent momentum resolution
- ➢ Extremely low material budget

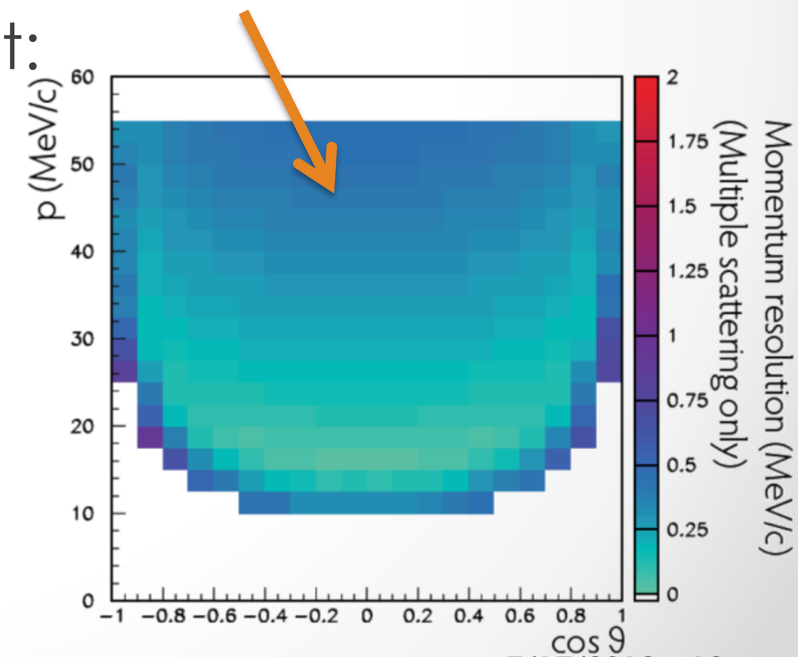
Challenges

- High rates: 10^9 μ/s
- Good timing resolution: 100 ps
- Good vertex resolution: ~100 μm
- Excellent momentum resolution: ~ 0.5 MeV/c^2

➢ Extremely low material budget:
  - ➢ 1×10^{-3} X_0 (Si-Tracker Layer)

➢ HV-MAPS spectrometer
  - ➢ 50 μm thin sensors
  - ➢ B ~1 T field

➢ + Timing detectors

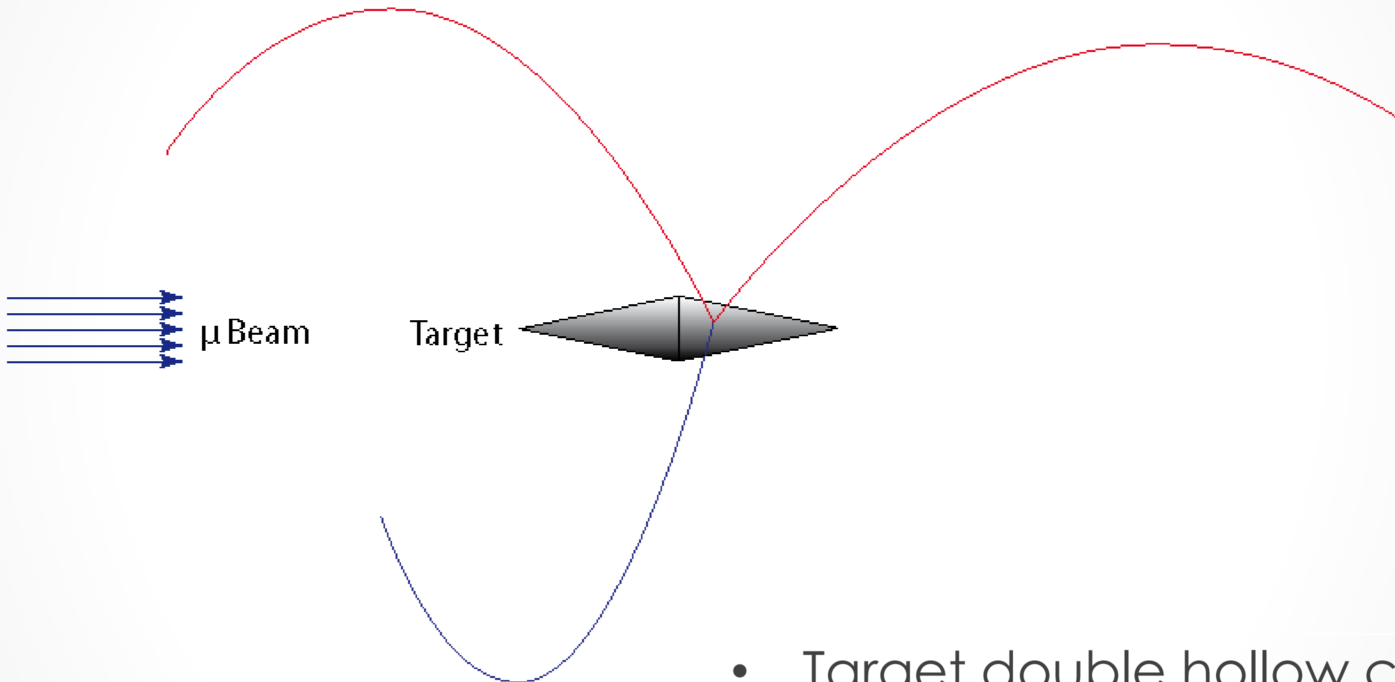


The Mu3e Experiment

- Muon beam O(10^9/s)
- Helium atmosphere
- 1 T B-field

- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber tracker
- Tile hodoscope

The Mu3e Experiment



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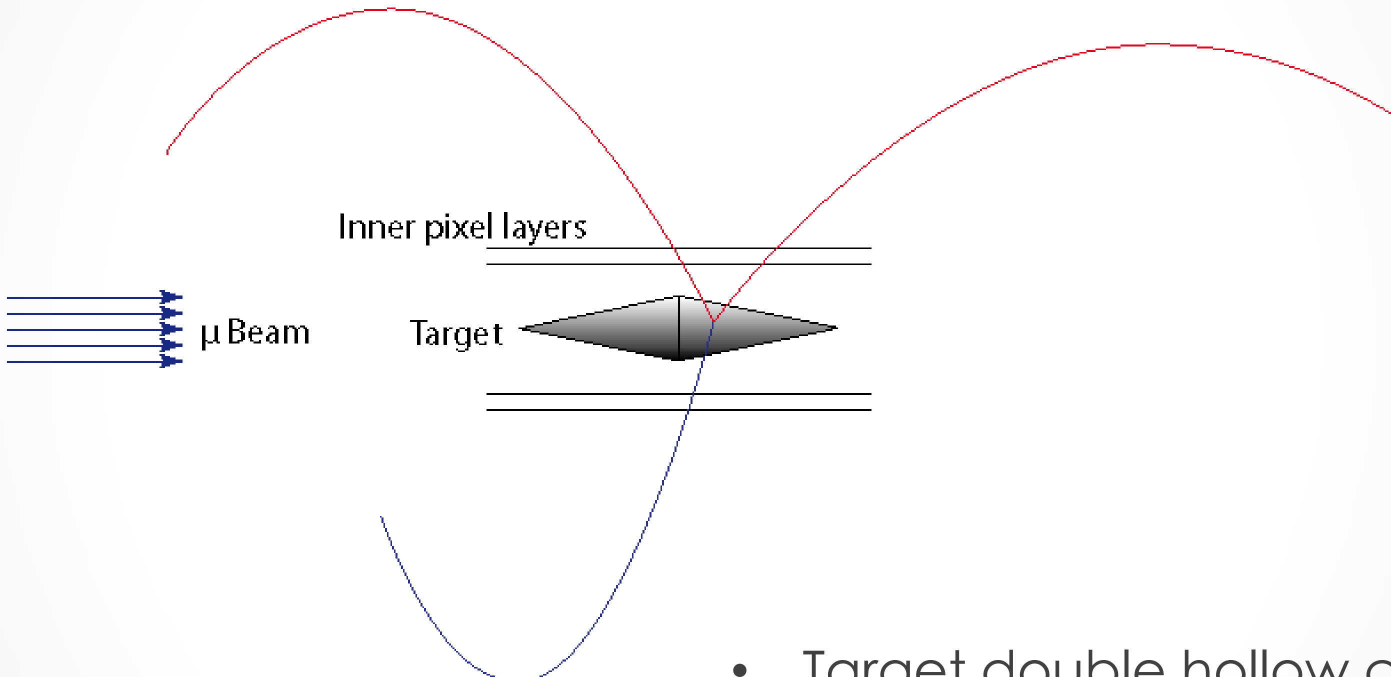

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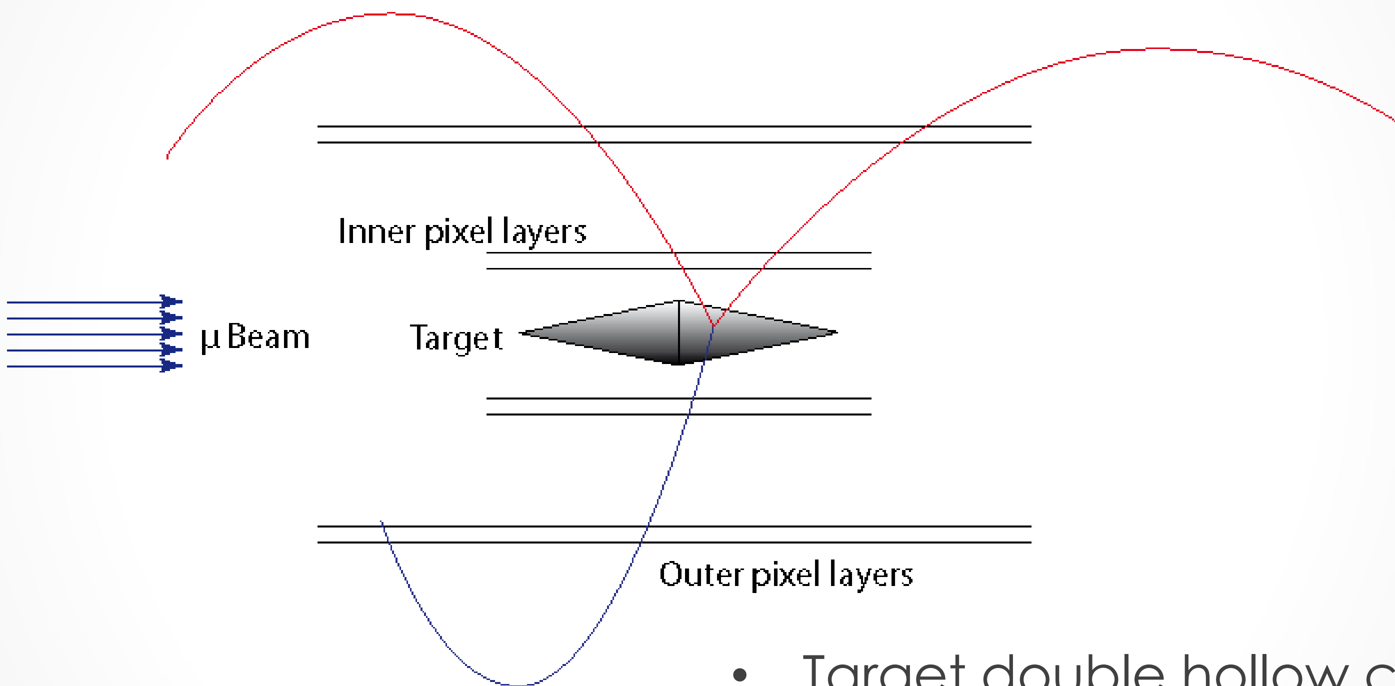

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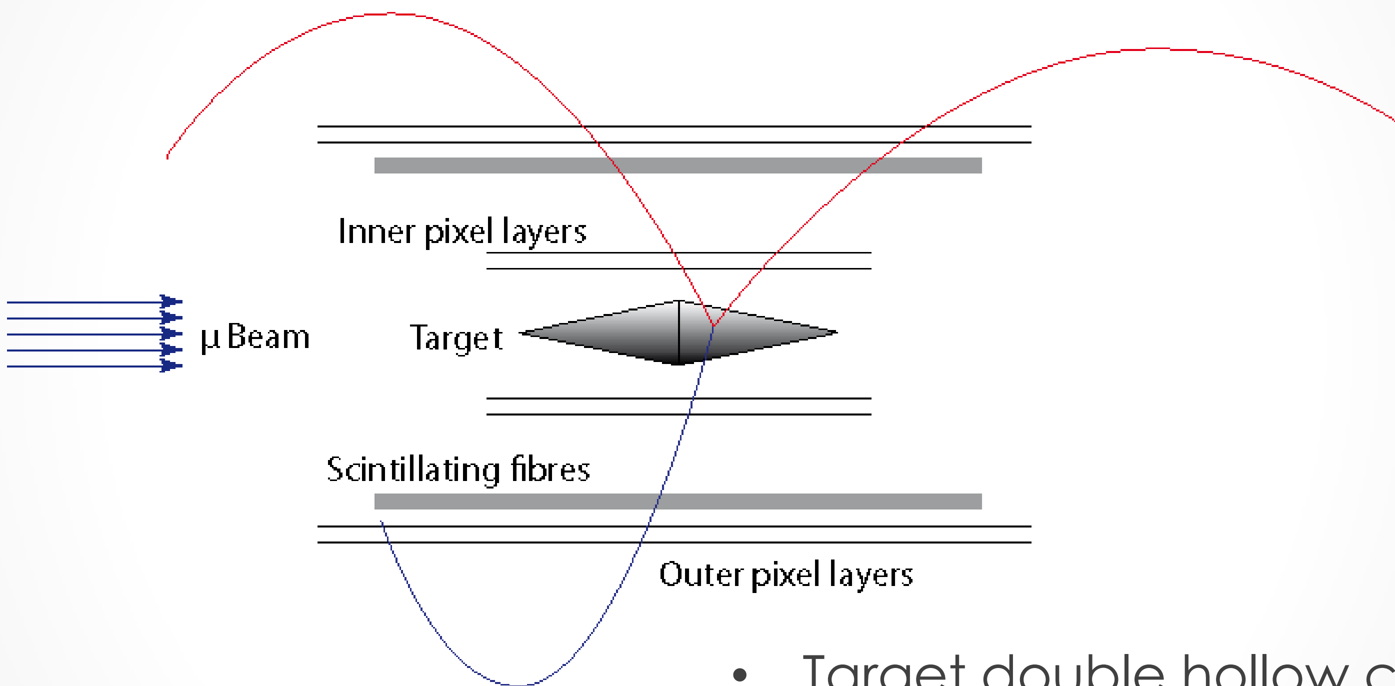

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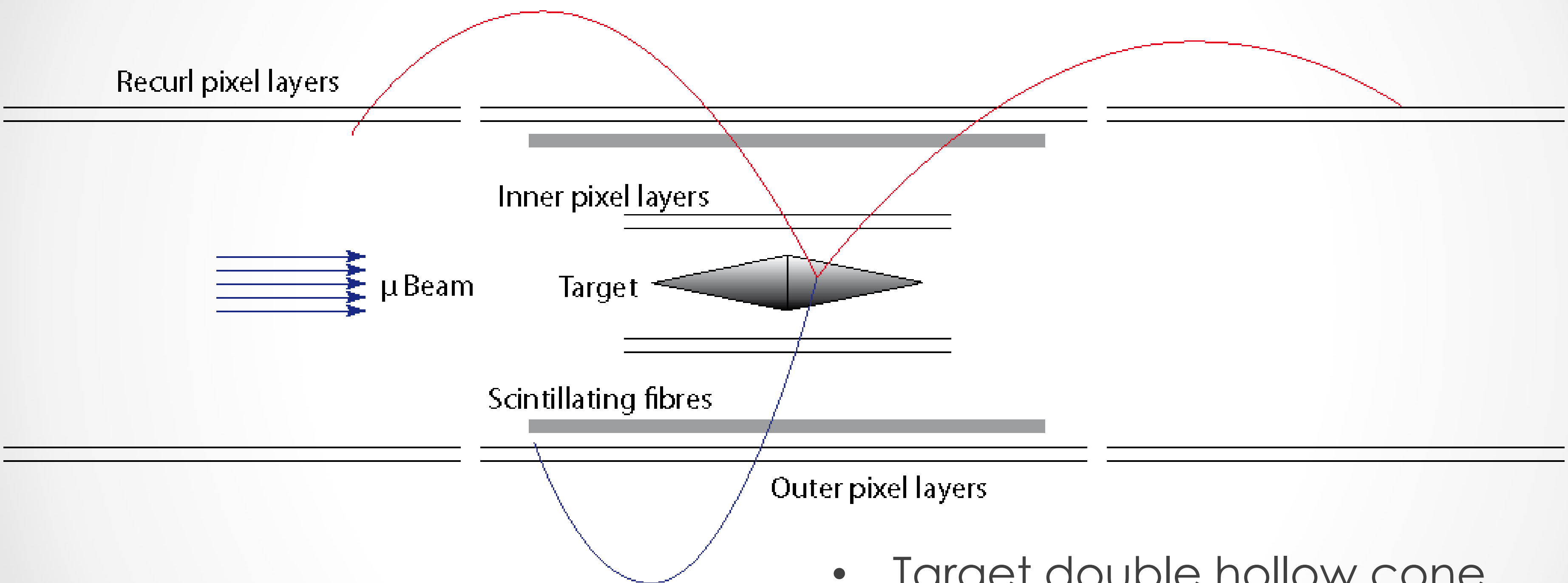

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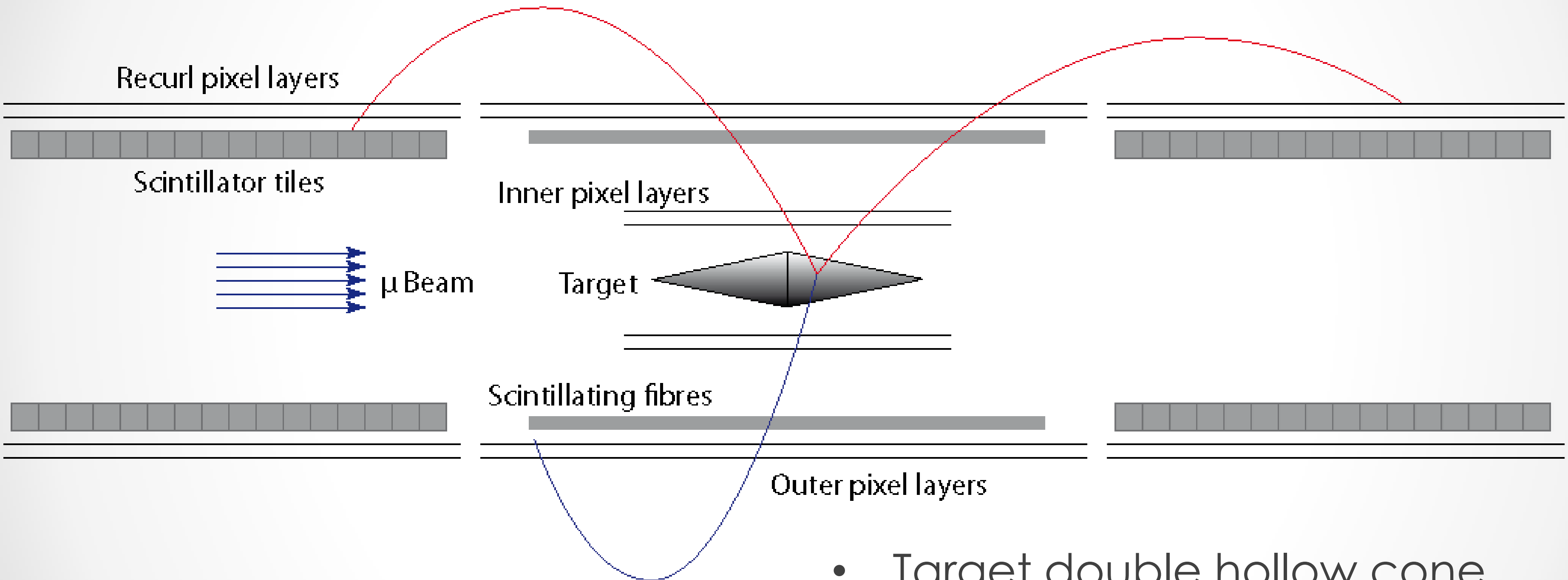

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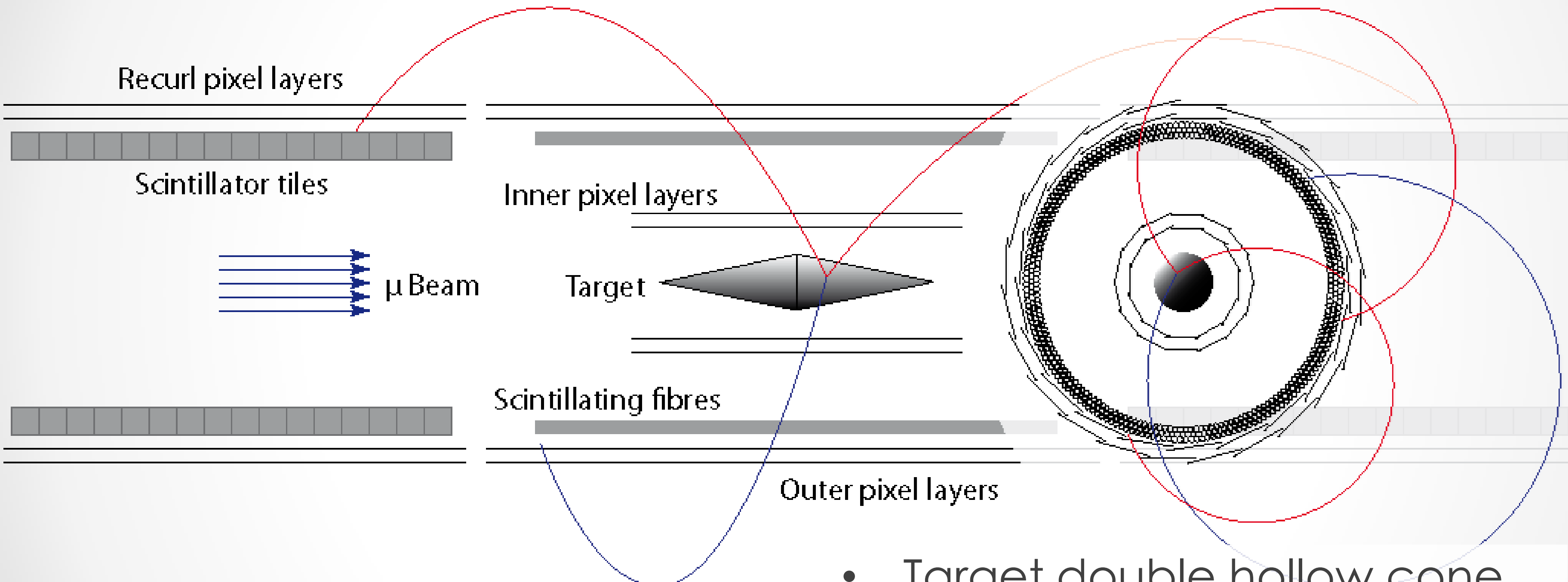

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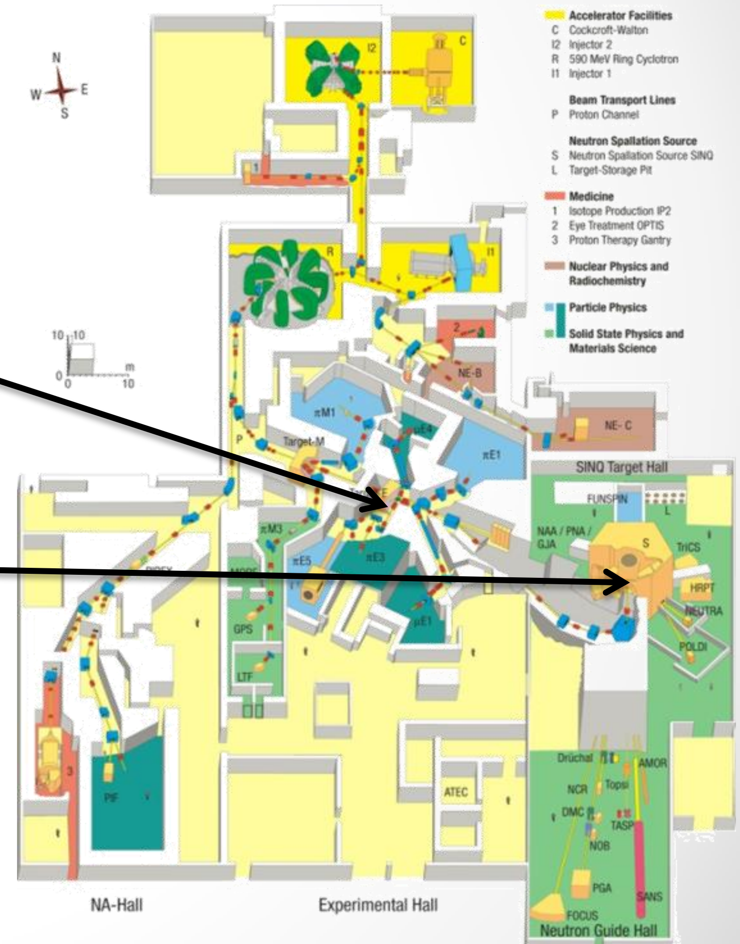
PSI μ-Beam

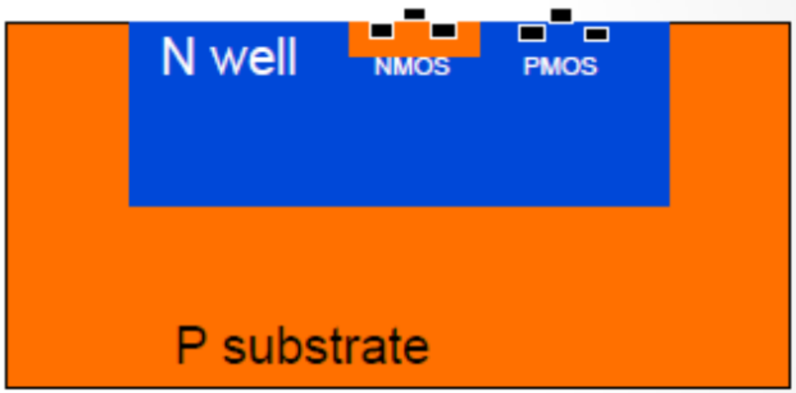
Paul Scherrer Institute Switzerland:

- 2.2 mA of 590 MeV/c protons
- Phase I:
  - Surface muons from target E
  - Up to a few 10^8 μ/s
- Phase II:
  - New beam line at the neutron source
  - Several 10^9 μ/s possible
  - ➢ $>10^{16}$ muon decays per year
  - ➢ BR 10^{-16} (90% CL)



HV-MAPS

- **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
- Pixel sensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased



by Ivan Peric

I. Peric, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876

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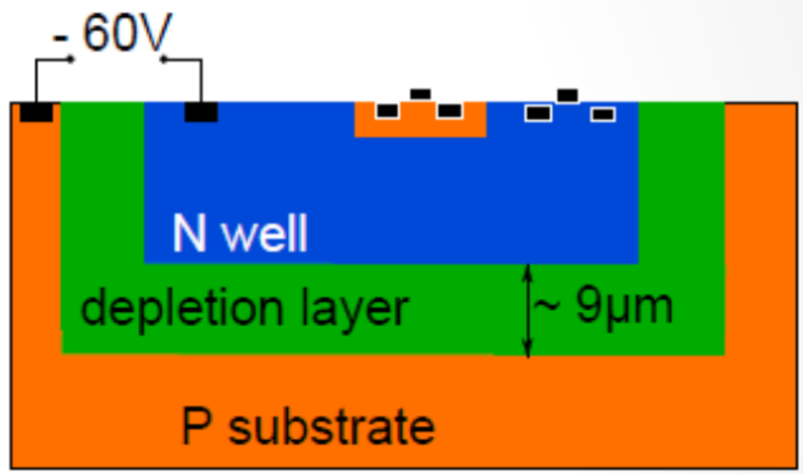
- Pixel sensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased ~60V
  - Depletion layer
  - Charge collection via drift
  - ➢ Fast O(100 ns) charge collection
  - Thinning to < 50 µm possible



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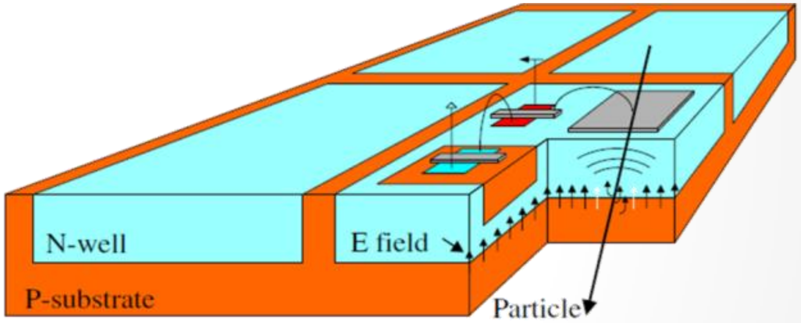
- Integrated readout electronics



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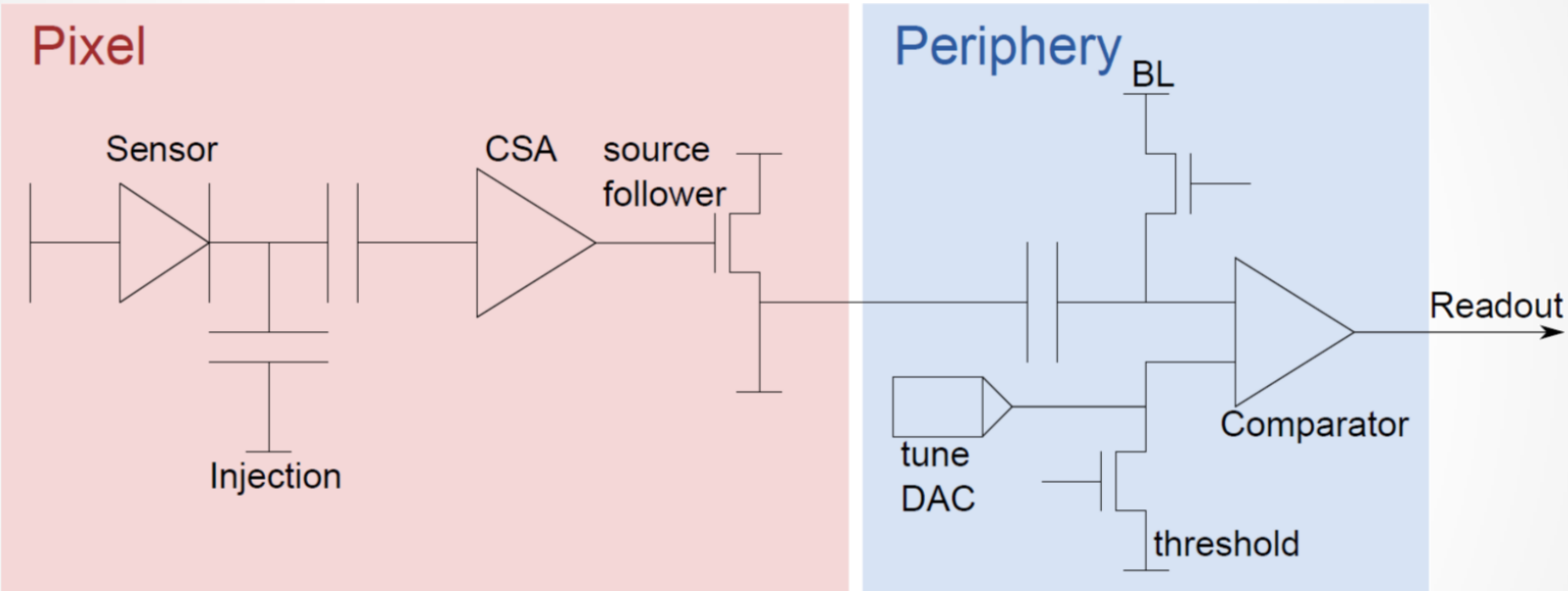
Sensor + Analog + Digital



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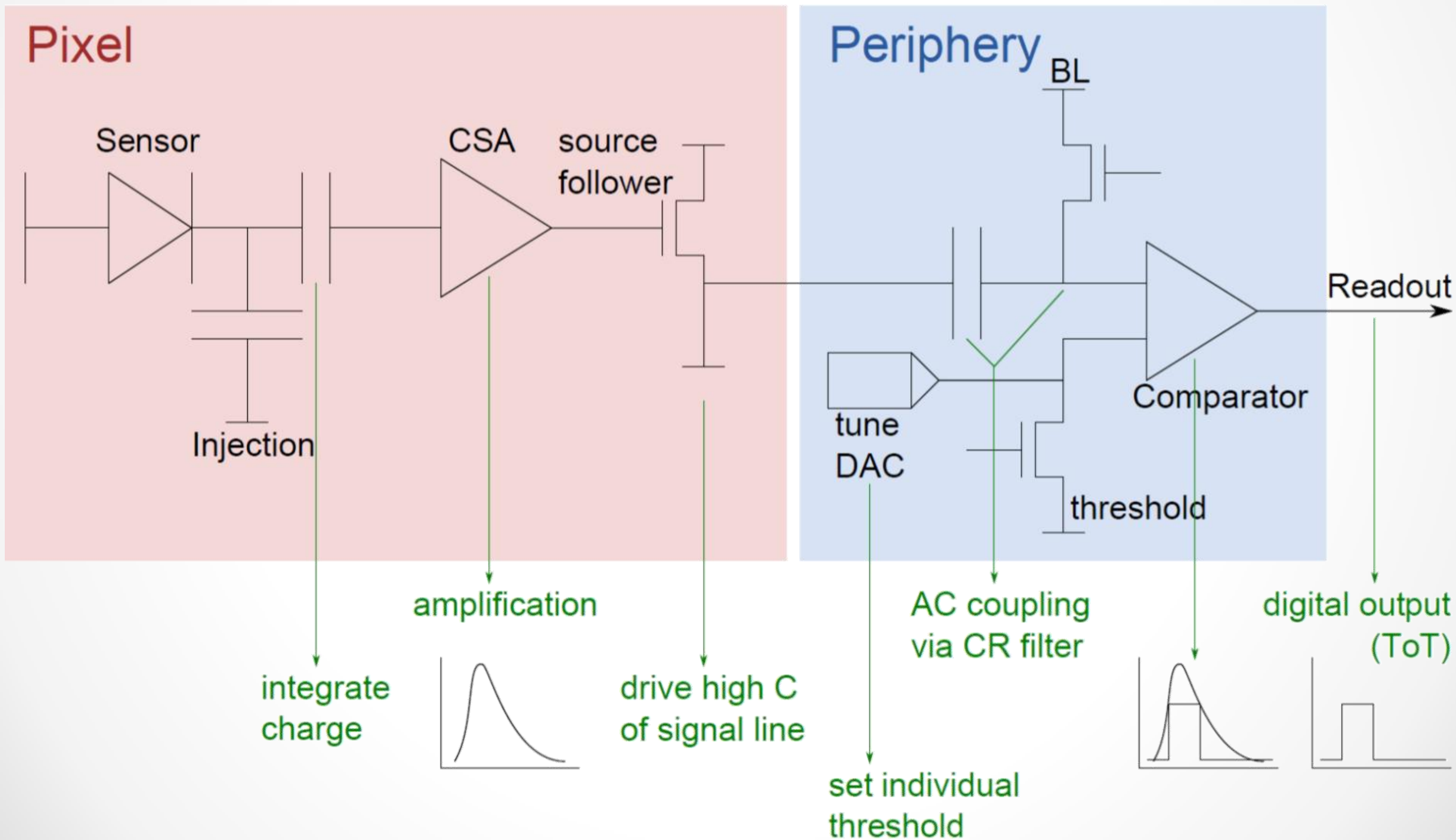
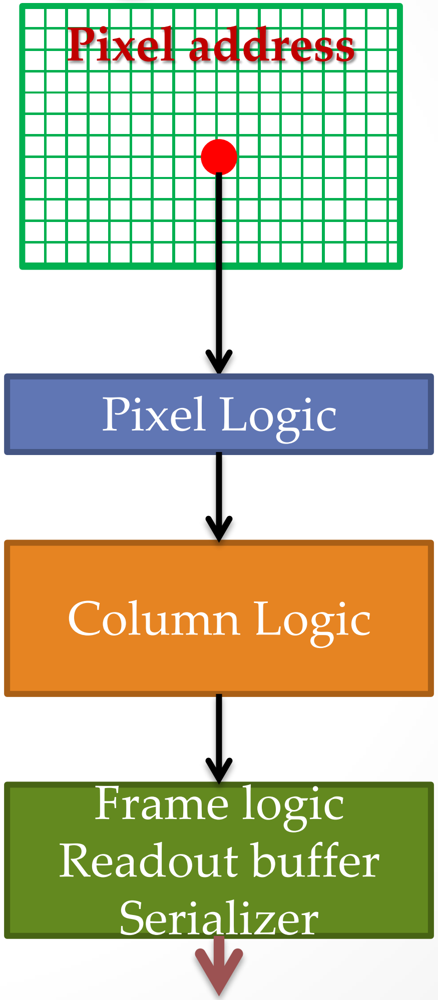


Digital Logic

- Pixel logic:
  - Address generation
  - Time stamp
  - Column bus logic
- Column logic
  - Priority logic
  - … using tri-state bus
  - Fifo buffer
- Chip wide logic
  - Data frame generation
- Serializer(s)
  - 800 Mbit/s LVDS



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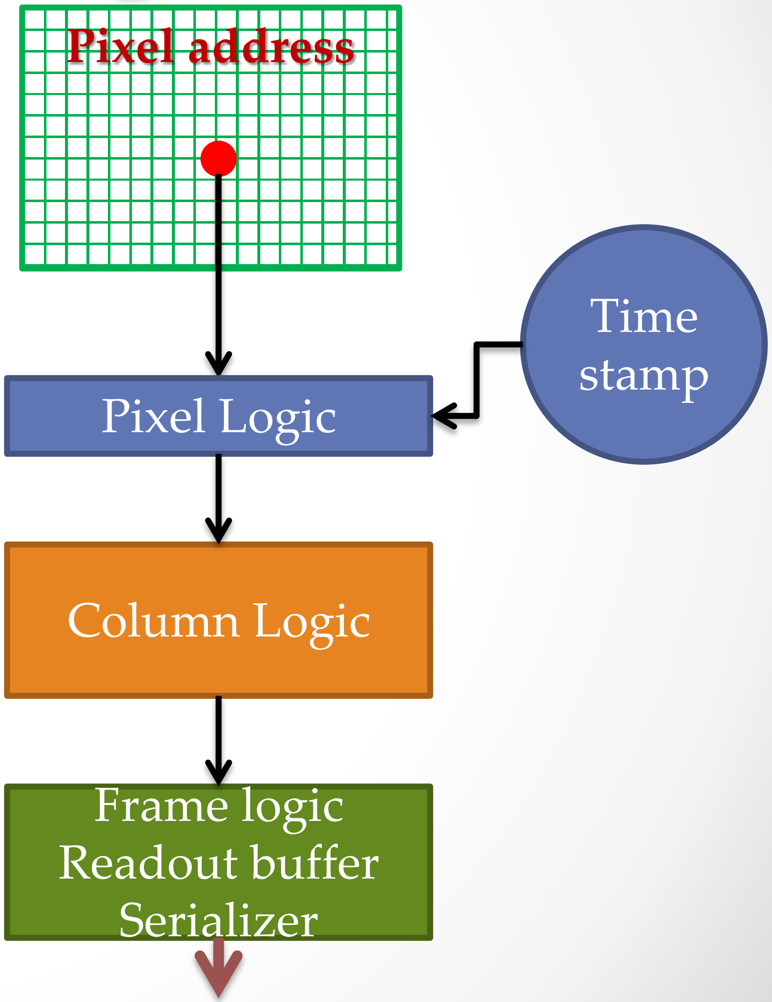

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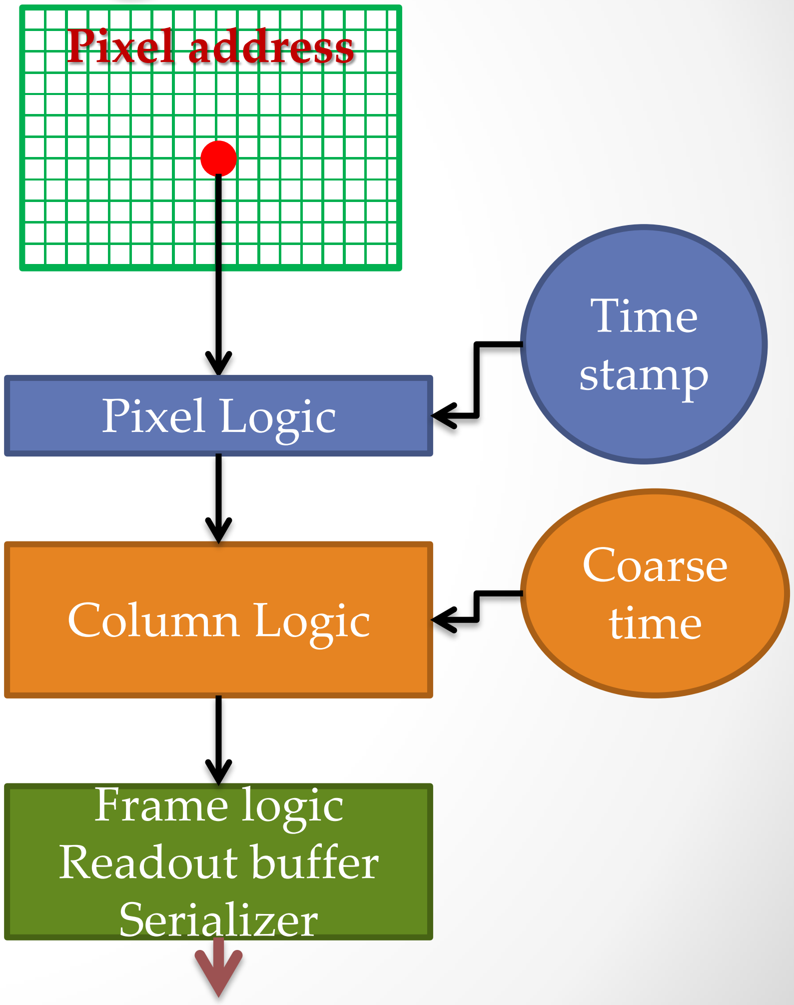

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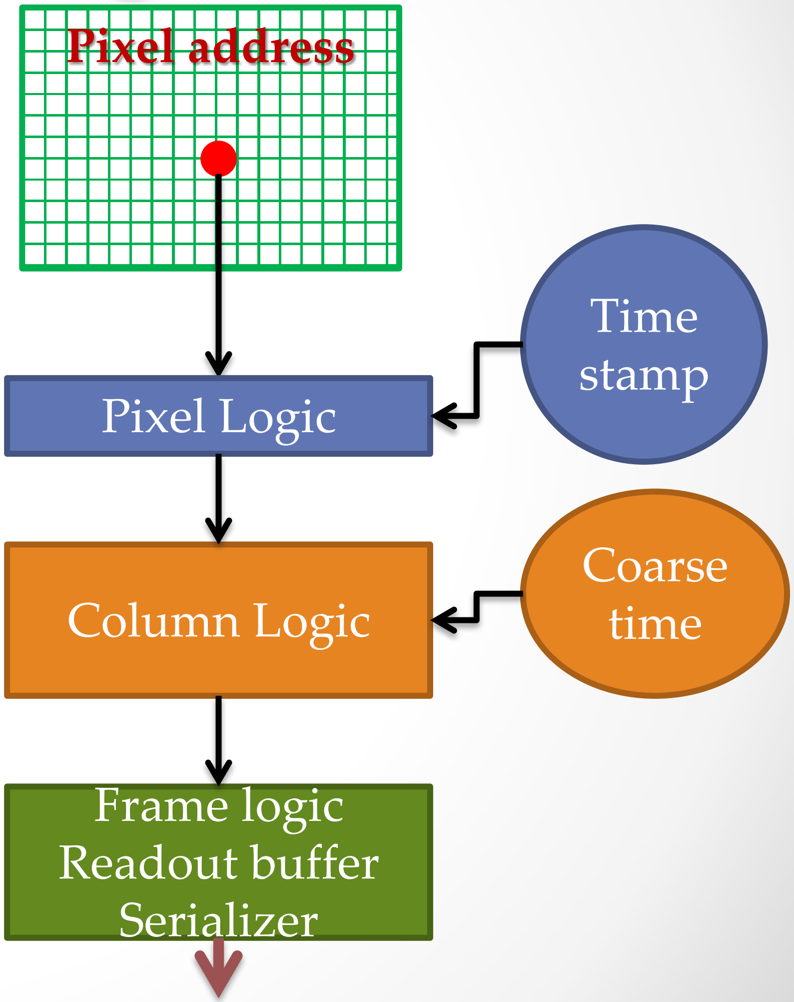

Test Results

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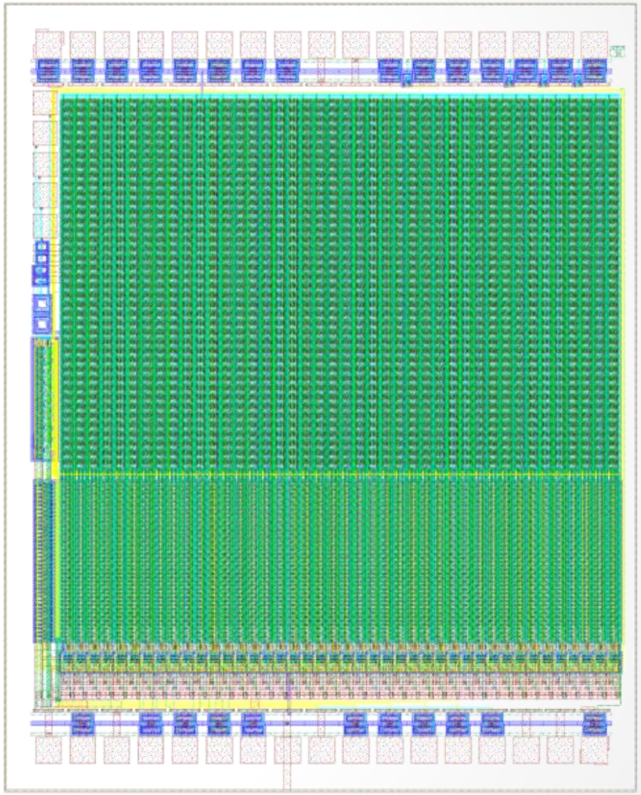
Current Chip Prototype

- 180 nm HV-CMOS
- Pixel matrix:
  - 42 x 36 pixel
  - 39 x 30 μm^2 each
- Ivan Peric ZITI
  - Analog part almost final
  - Digital part in next submission



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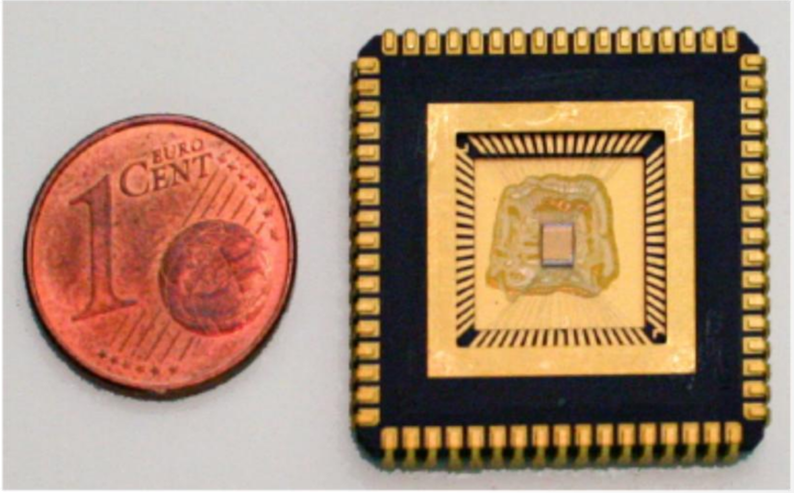
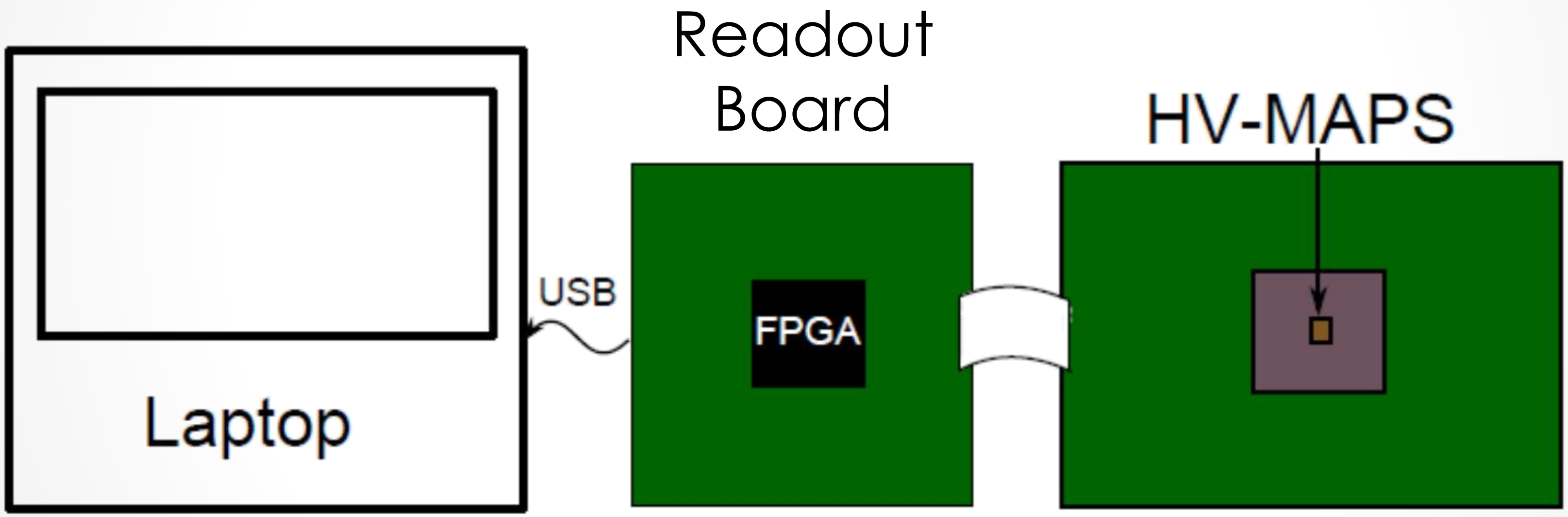


Test Setup



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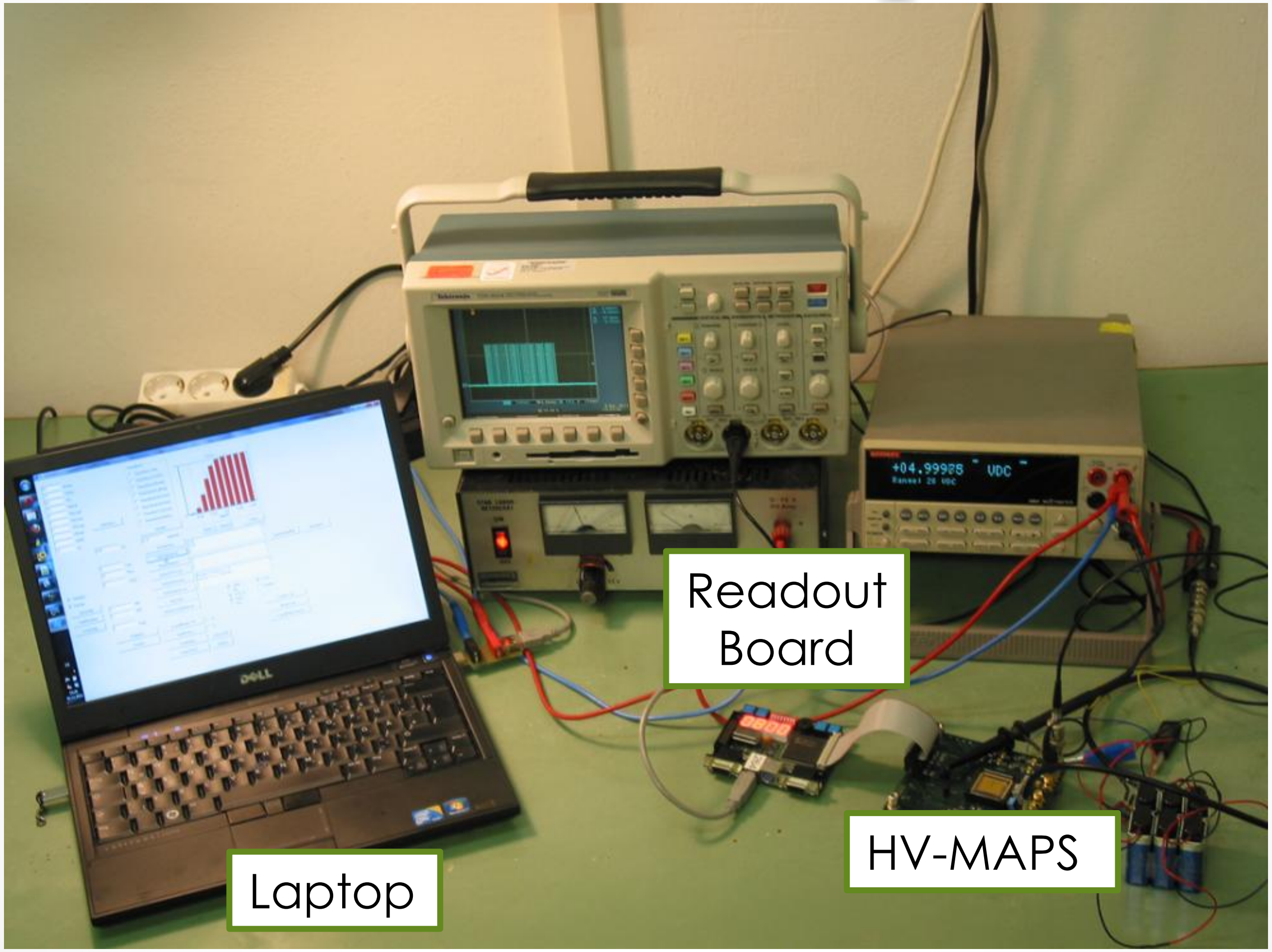

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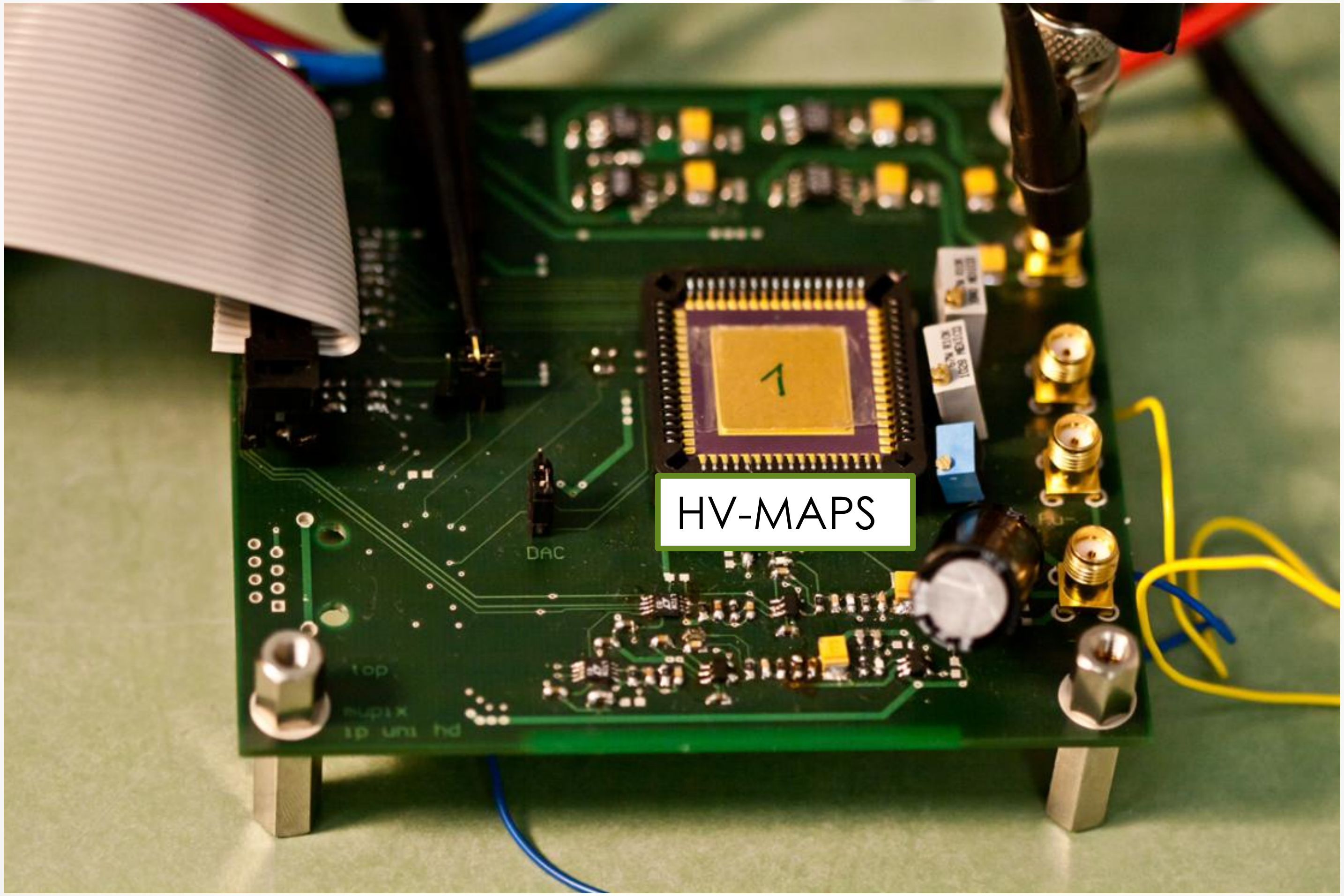
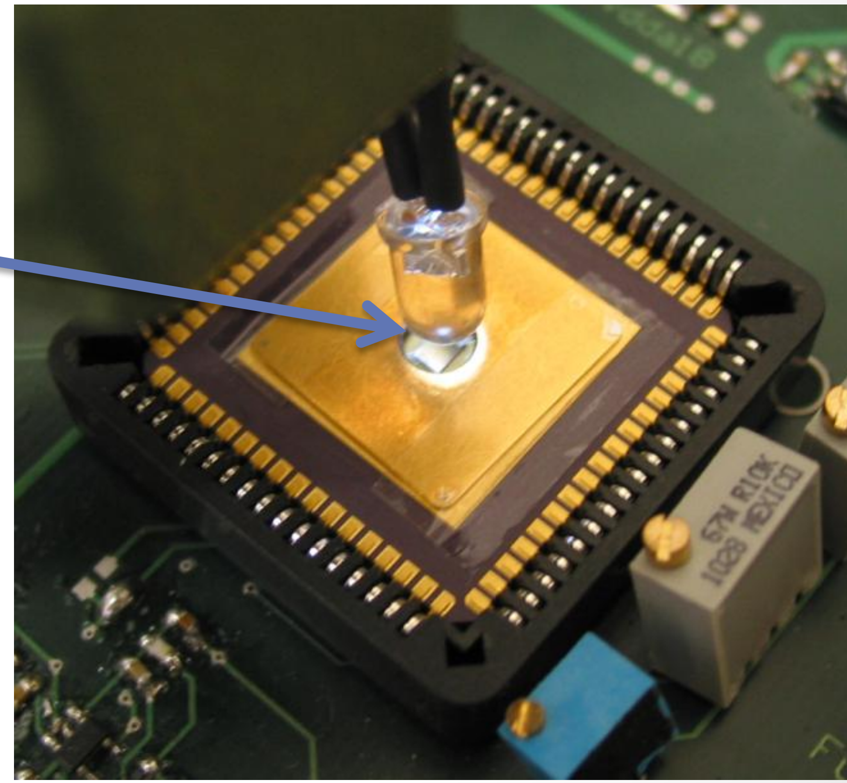


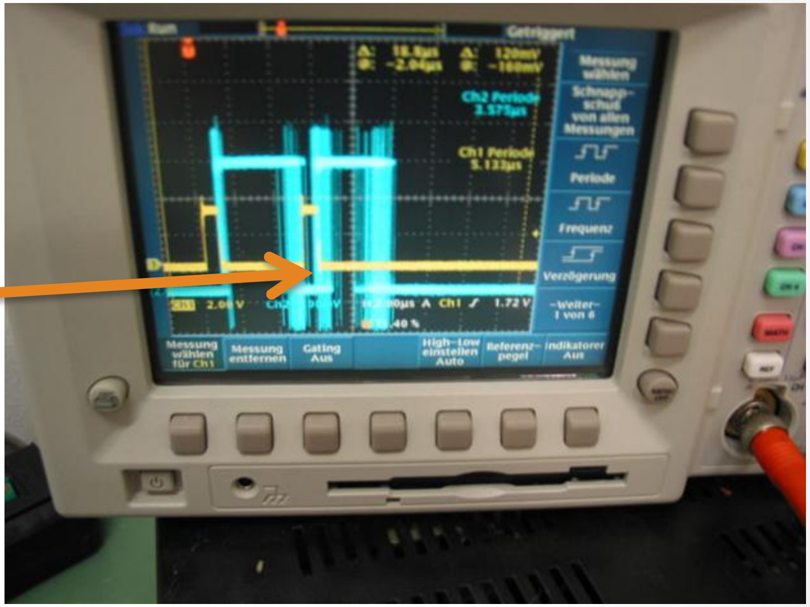
Timing Tests

- Timing critical
  - 10^9 μ/s
  - ➢ O(10 ns) resolution
- LED pulsed sensor
- Double pulse resolution



Timing Tests

- LED pulsed sensor
- Double pulse resolution
  - Visible in oscilloscope



Timing Tests

- LED pulsed sensor
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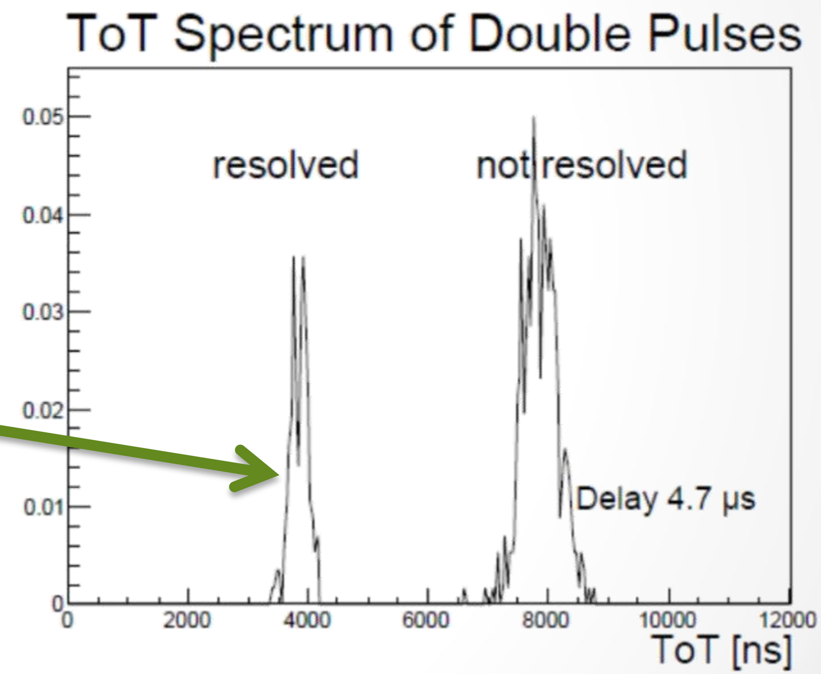
  - … or time over threshold



Double Pulse Resolution

- Ratio of
  - resolved to
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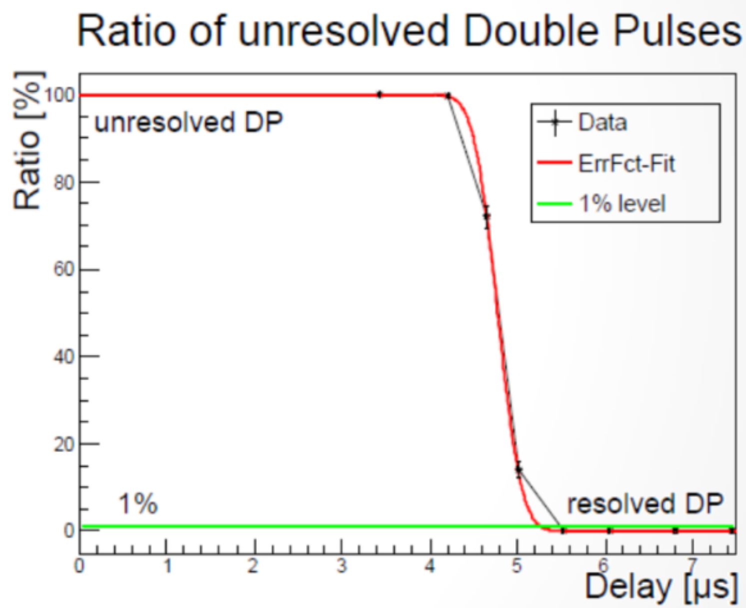
- Default: 5.27 ± 0.01 µs



Double Pulse Resolution

- Ratio of
  - resolved to
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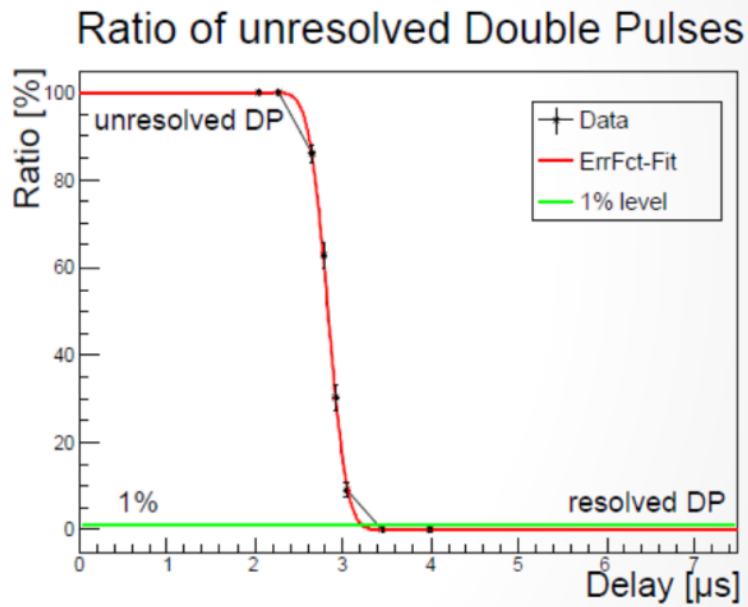
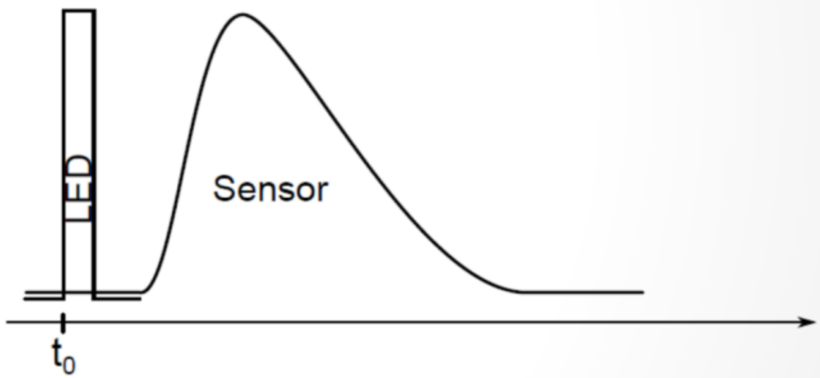
- Default: 5.27 ± 0.01 μs
- ➢ Pixel bias current adjustment
- ➢ Optimized: 3.23 ± 0.01 μs
  - ➢ Further reduction required



Pulse Shape

- LED setup
- Test pulse latency
- + time over threshold
- … for different thresholds



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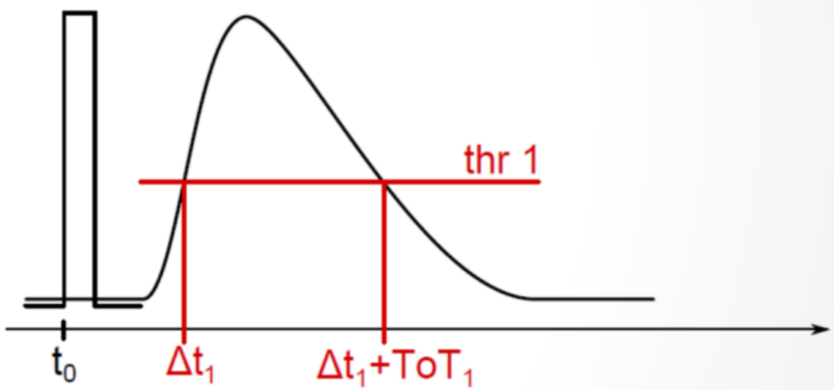

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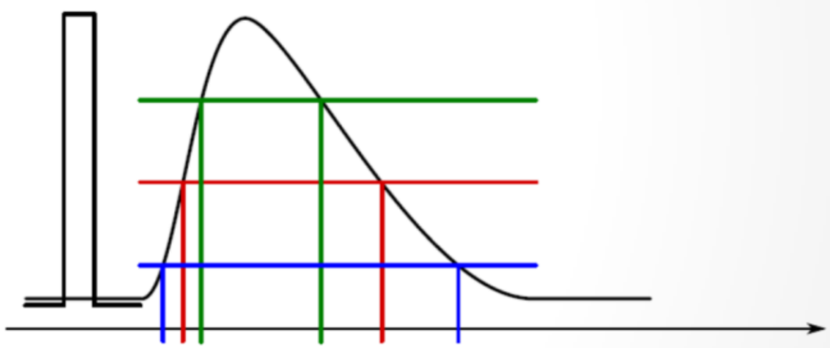

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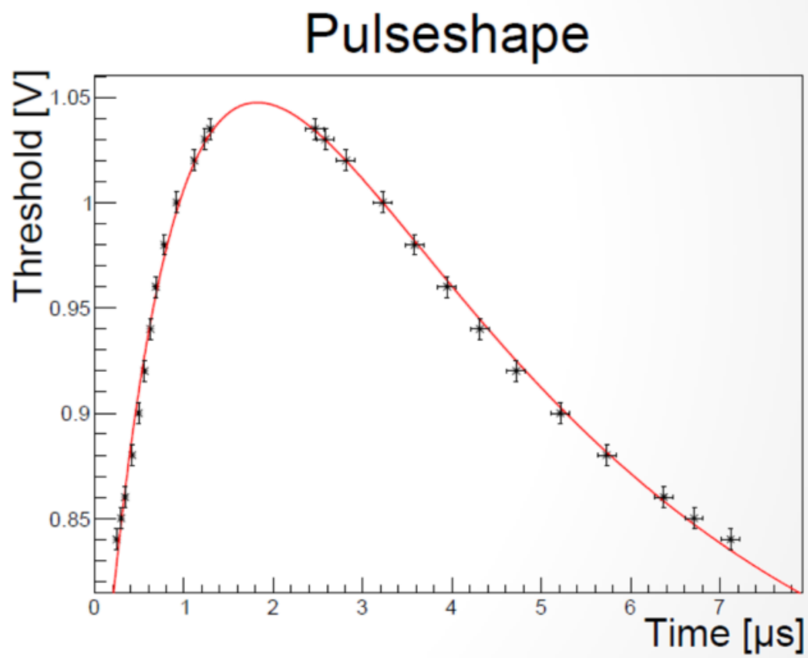
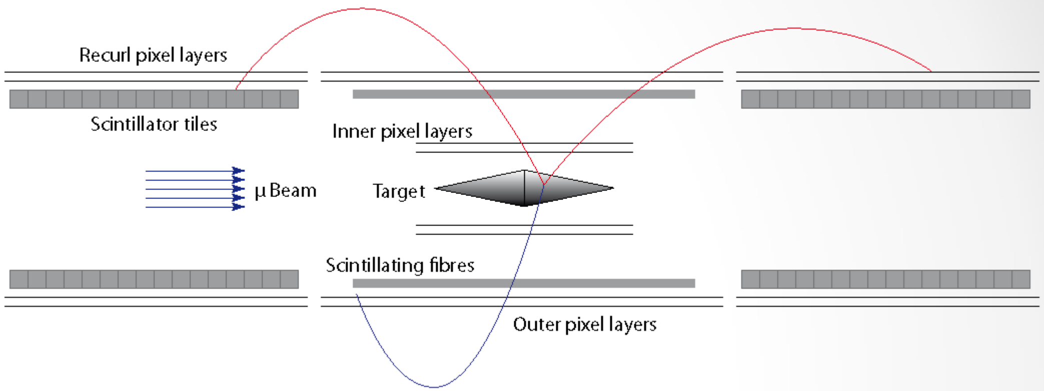
➢ faster shaping needed



Construction

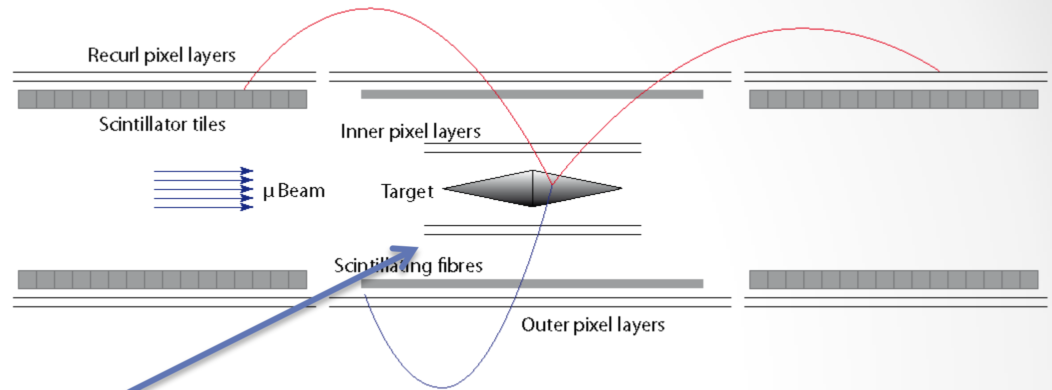
…

Mu3e Silicon Detector



- Conical target
- Inner double layer
  - 12 and 18 sides of 1 x 12 cm
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm
- Re-curl layers
  - 24 and 28 sides of 2x 72 cm
  - Both sides (x2)

Mu3e Silicon Detector



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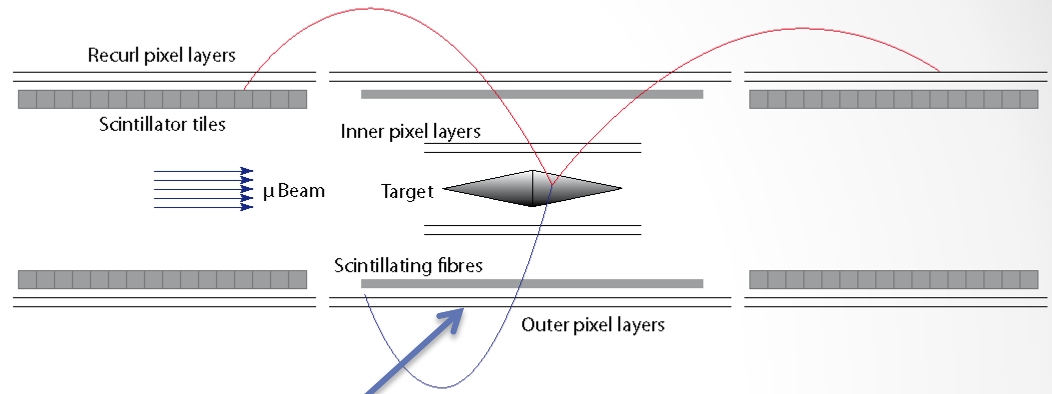

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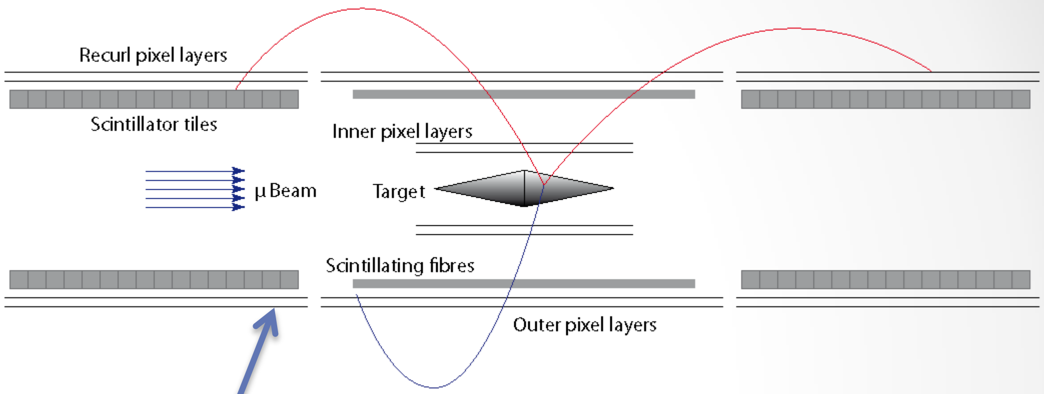

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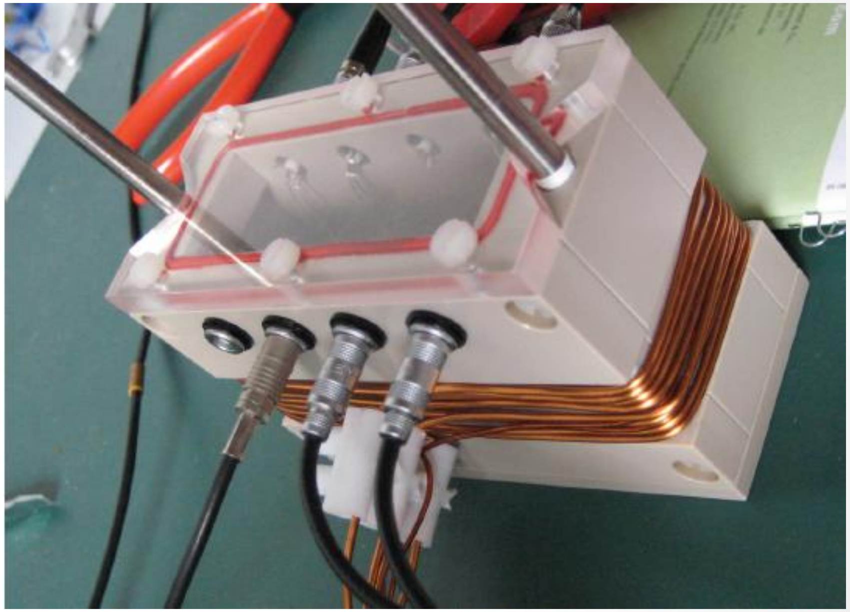
180 inner sensors
4680 outer sensors
➢ 274 752 000 pixel

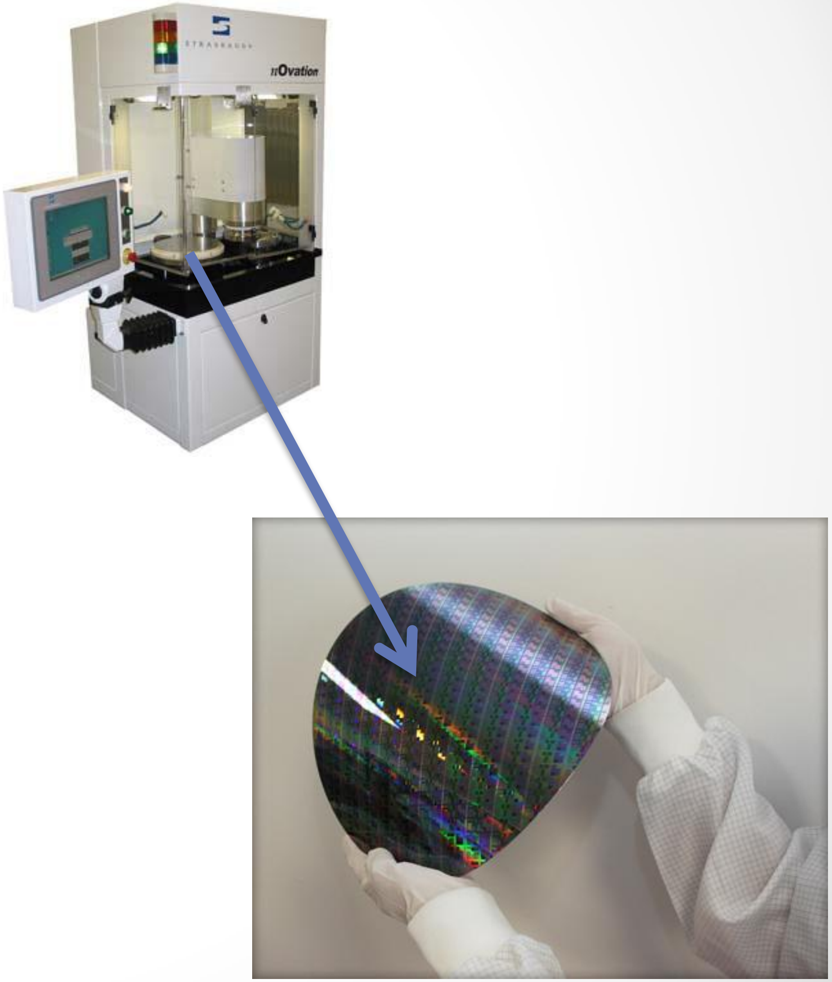
Cooling

- 2 m^2 silicon detector
- Up to 200mW/cm^2
- 60 °C maximum
- Gaseous helium
- Laminar flow
- Tests:
  - Inductive heating
  - Aluminum foil



Thinning

- 50 µm Si-wafers
  - Commercially available
  - HV-CMOS 75 µm (AMS)
- Single die thinning
  - For chip sensitivity studies
  - < 50 µm desirable
  - In house grinding?



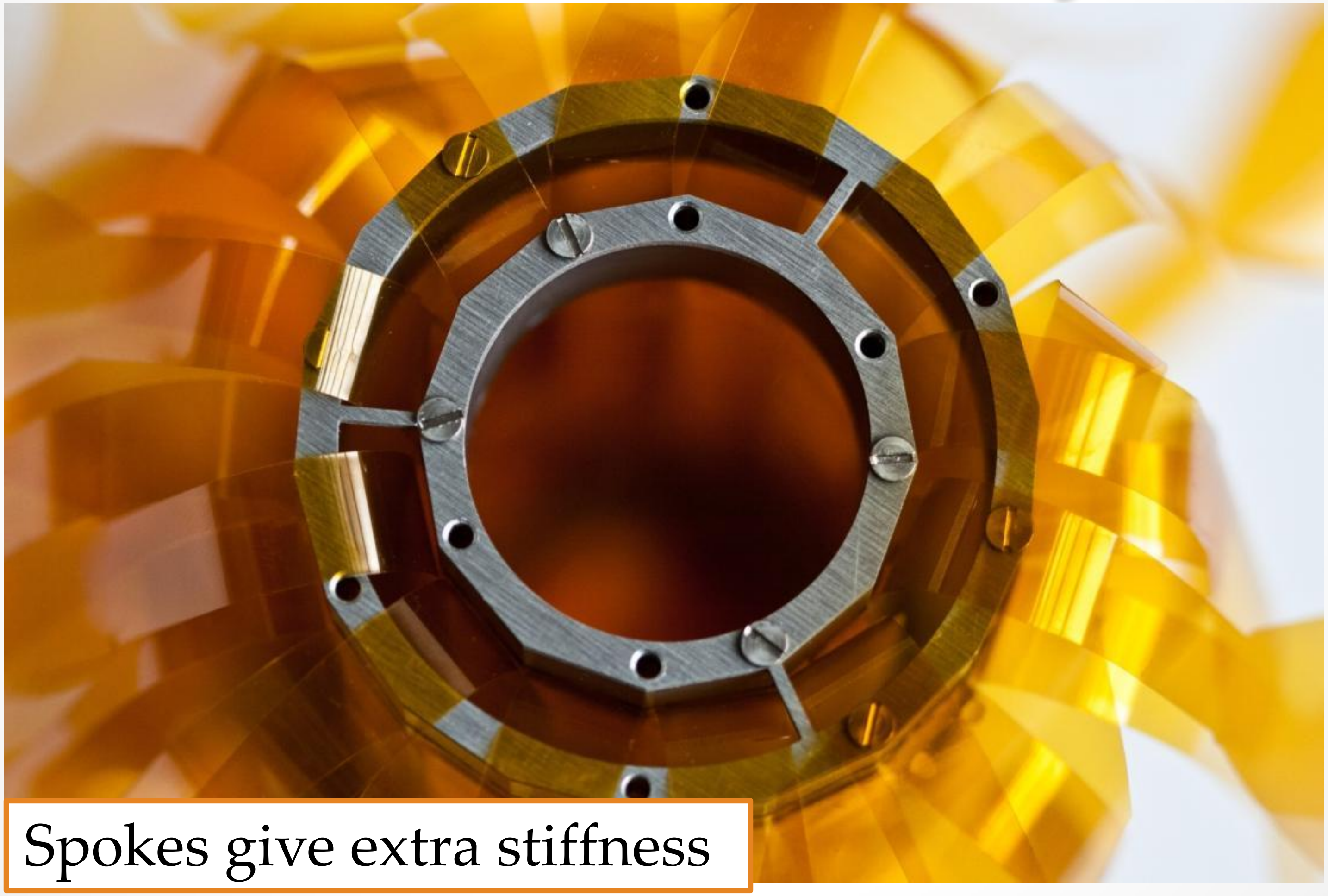
Material

- HV-MAPS
- Flex print
- Kapton Frame

Inner Double Layer

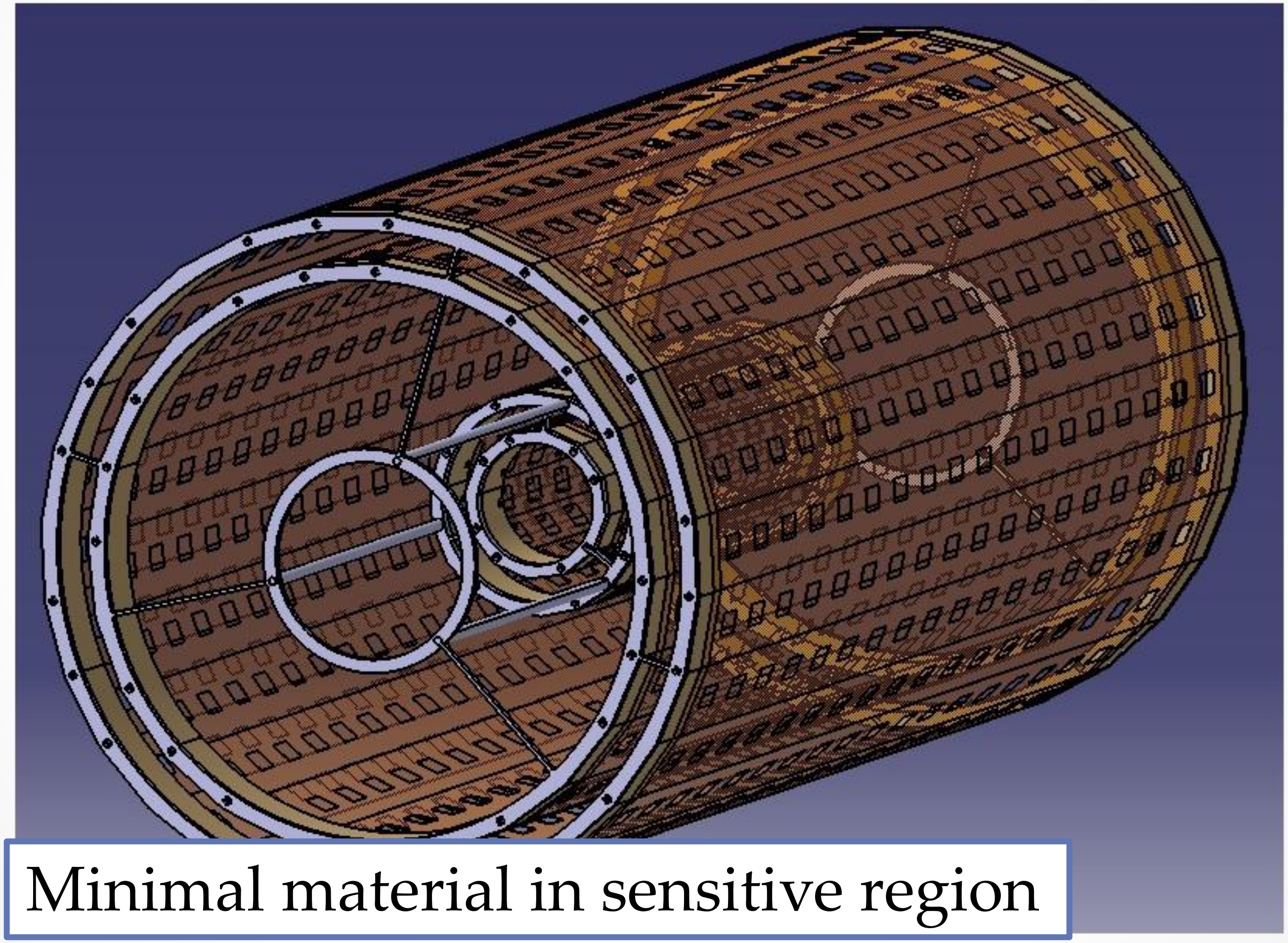
Very stable self supporting structure

Inner Double Layer



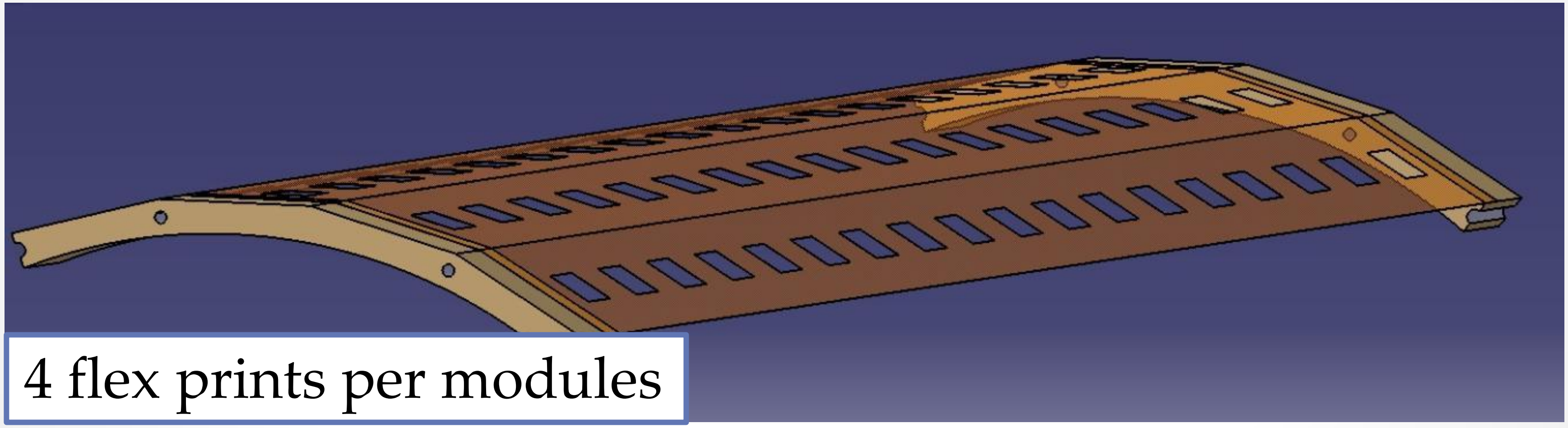
Spokes give extra stiffness

Outer Double Layer



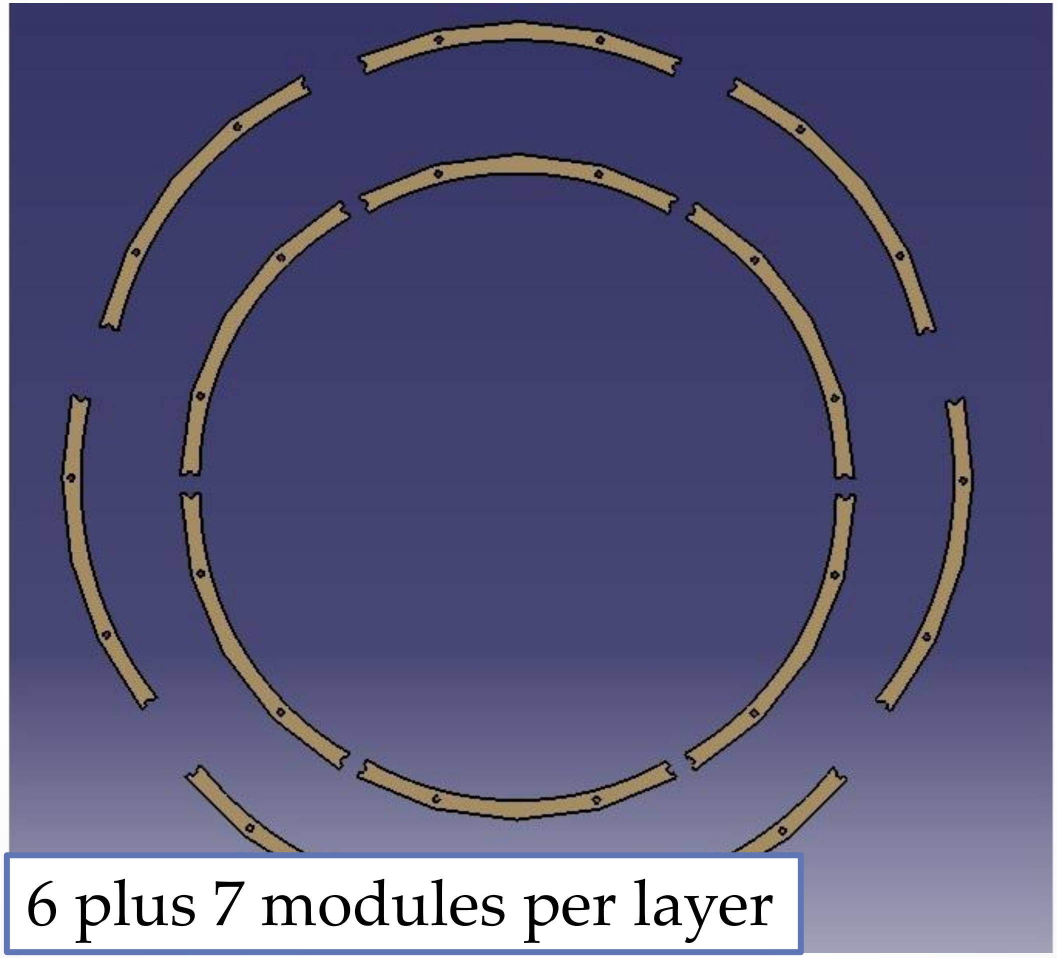
Minimal material in sensitive region

Outer Double Layer



4 flex prints per modules

End Pieces

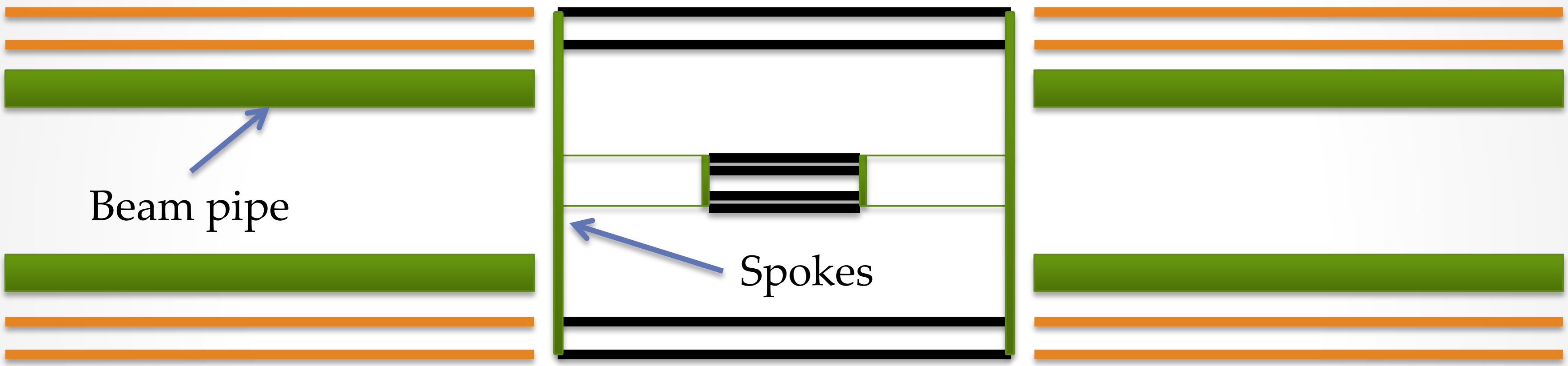


6 plus 7 modules per layer

End Pieces

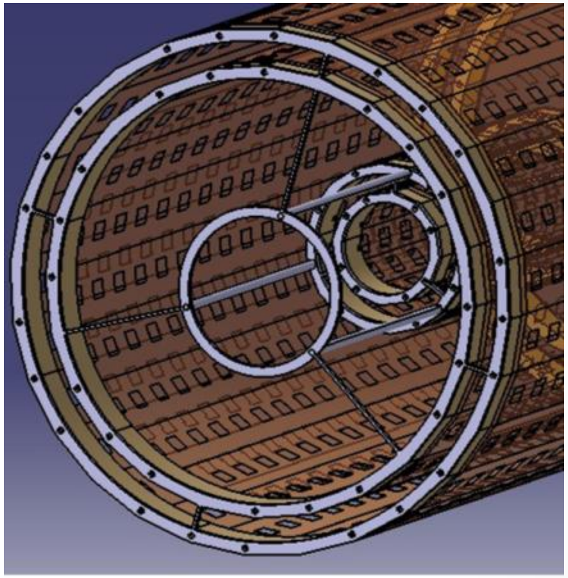
- End pieces for modules
  - PVC
  - PEEK in future?
- Production done

Frame Support



- Support design light weight
  - Spokes combine all separate modules
  - Connected by metal beams
  - … running in bushings

Frame Support



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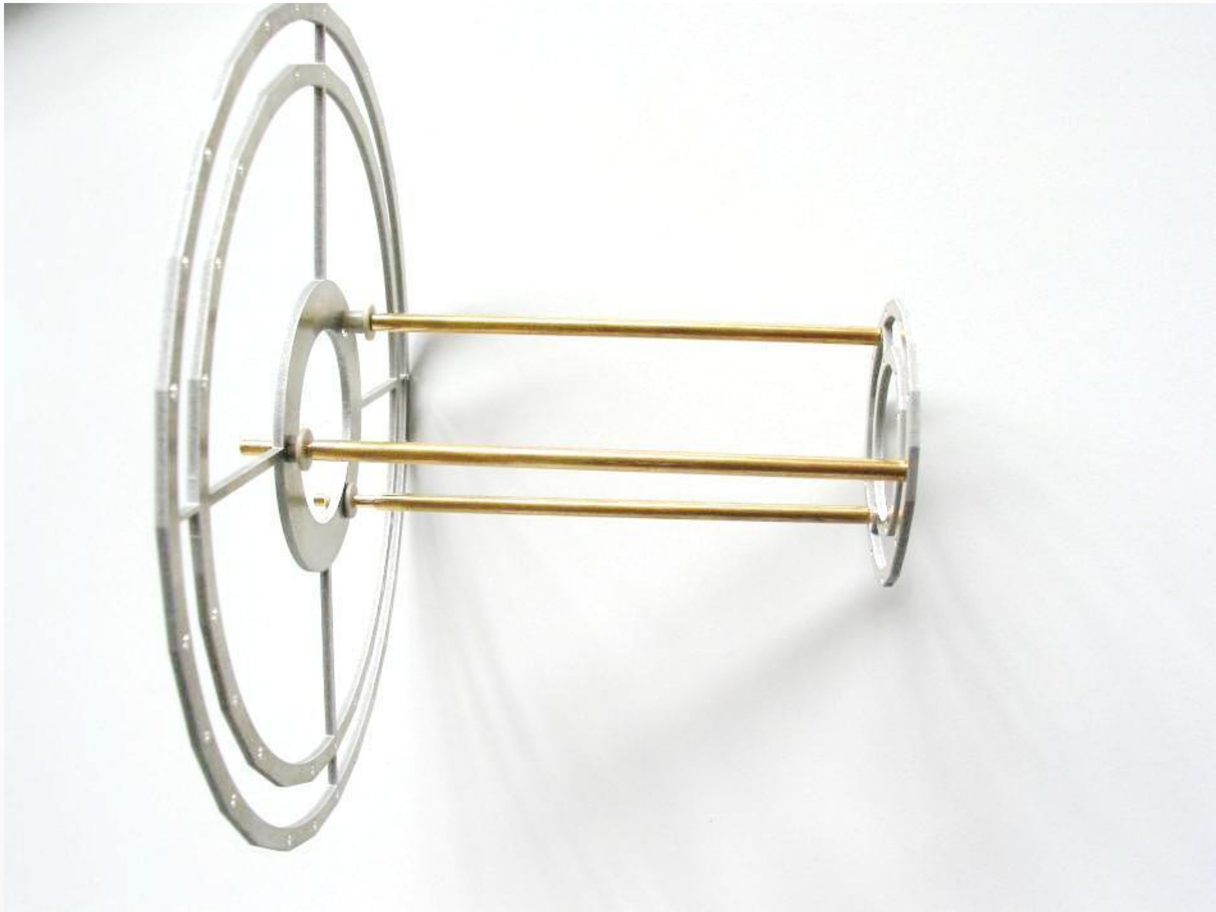
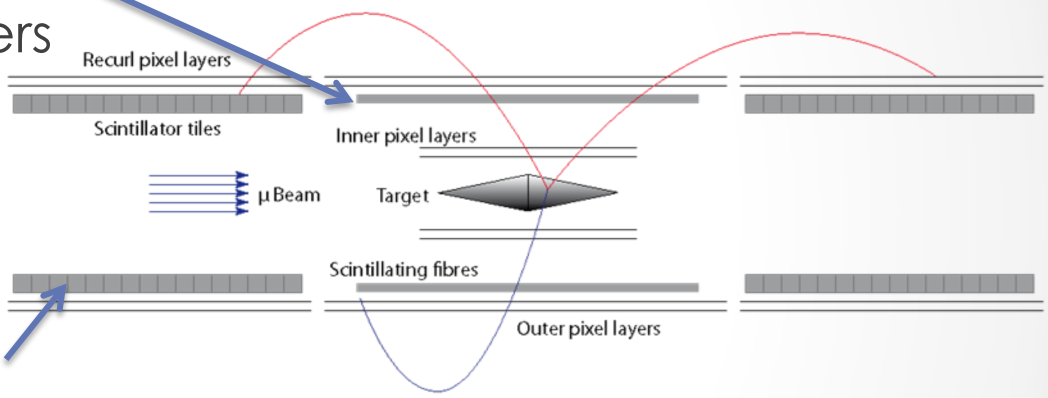
Spoke Assembly

Spoke Assembly



Timing Detectors

- Fiber hodoscope
  - Before outer pixel layers
  - 250 μm scintillating fibers
  - SiPMs
  - 1 ns resolution
- Tile detector
  - After recurl pixel layers
  - 1x1 cm^2 scintillating tiles
  - SiPMs
  - 100 ps resolution



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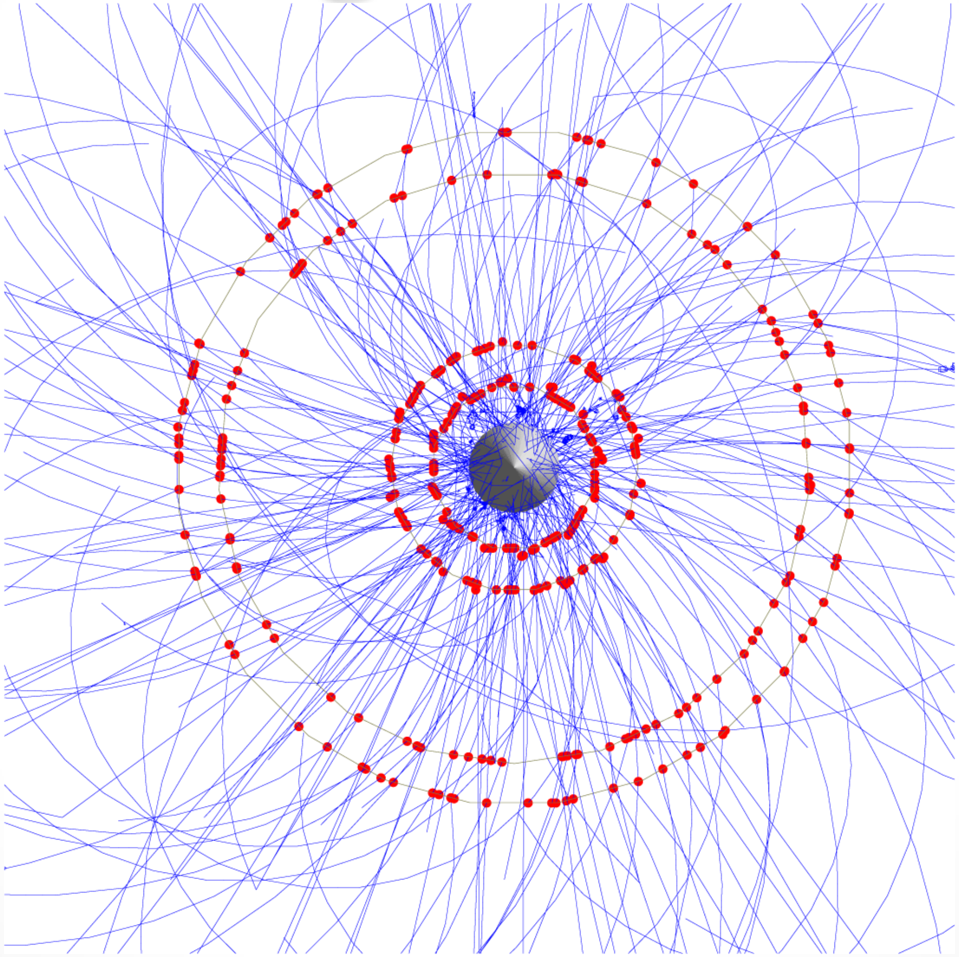

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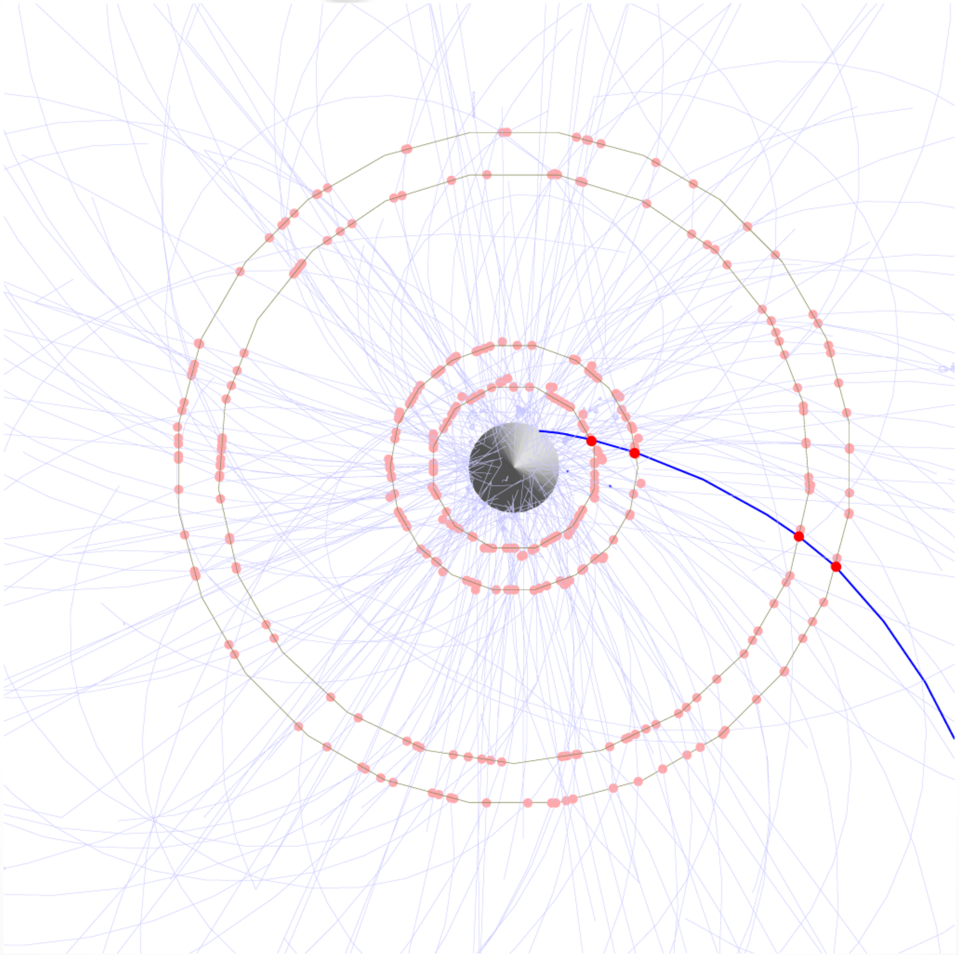

Fiber Hodoscope

- 250 μm scintillating fibers
  - Kuraray SCSF-81M
  - double cladding
  - 7500 in total
- Very high occupancies:
  - 24% in 50ns time frame
- Sampling readout
  - SiPM
  - DRS5 chip
  - From Stefan Ritt, PSI

Kuraray

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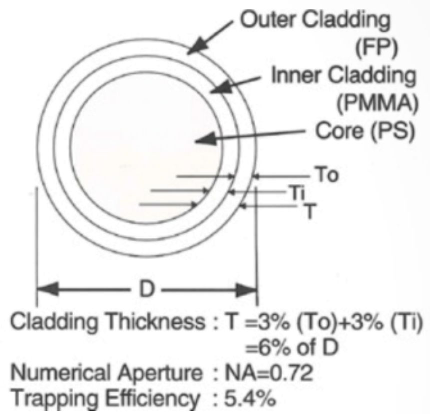

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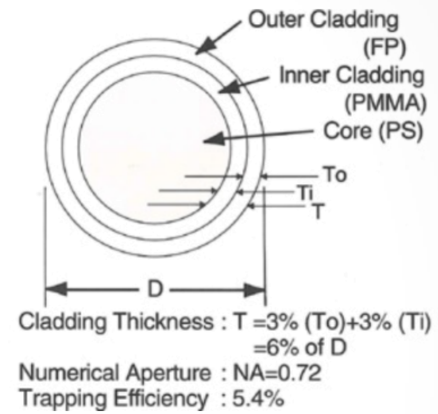
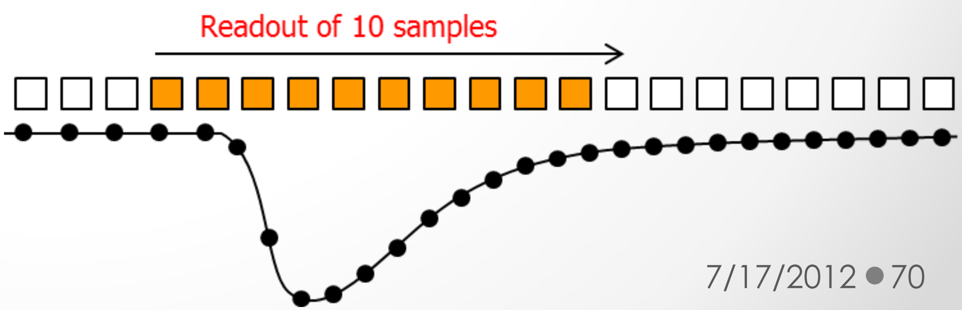
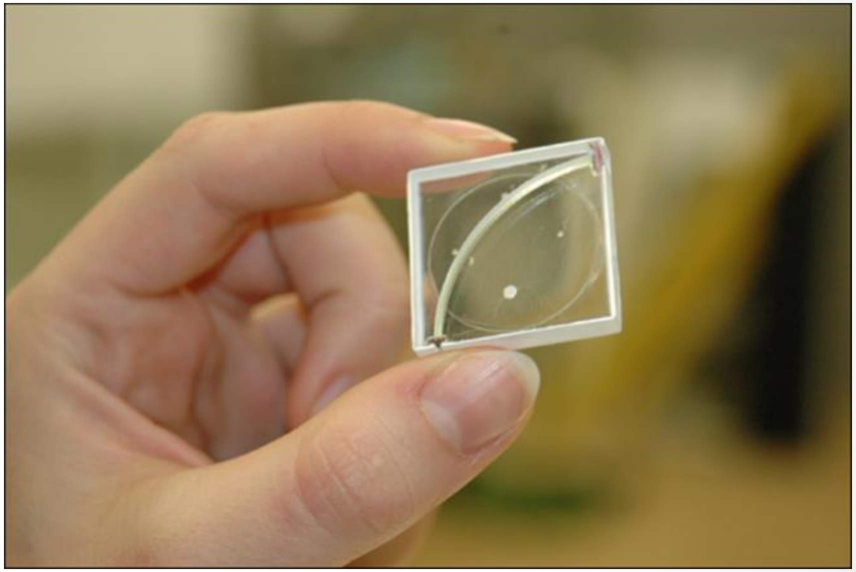




Tile Detector

- 1x1 cm^2 scintillating tiles
  - O(7000)
- GosSip simulation
  - MPPC with 3600 pixels
  - 100 ps resolution (RMS)
  - 97% efficiency



Kirchhoff-Institut für Physik

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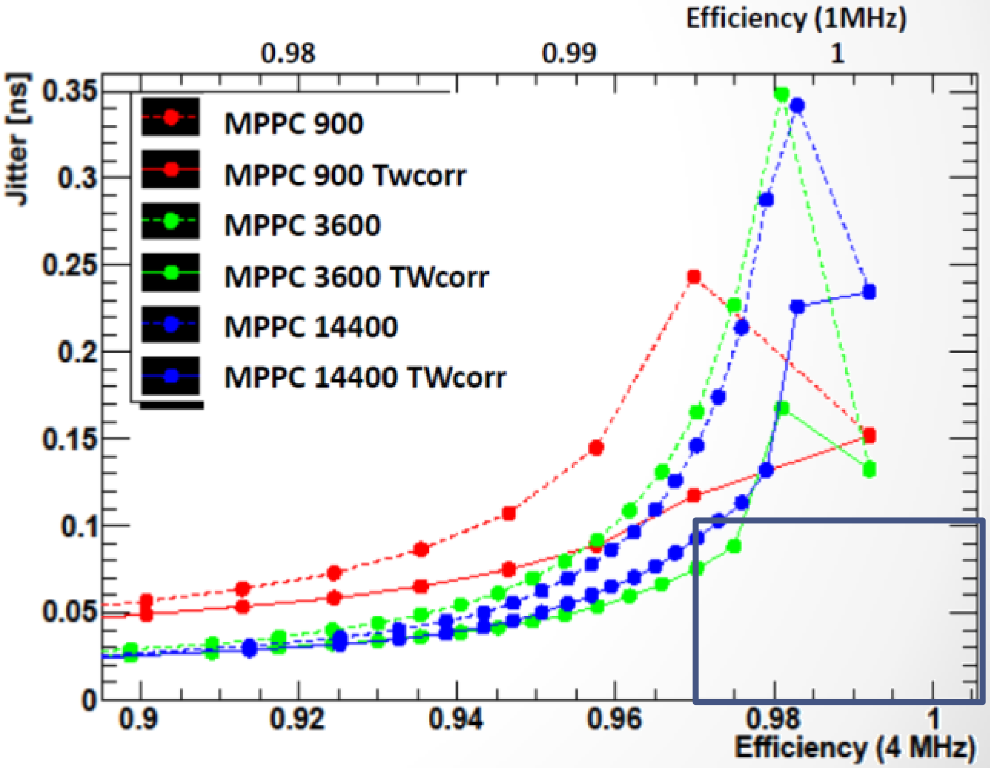
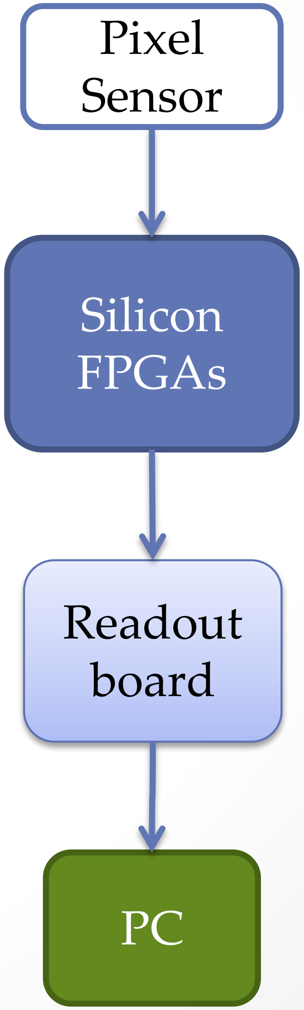


Data Acquisition

- 2.5 GHz muon decays
- 50 ns readout frames
- O(5000) pixel chips
    - 800 Mb/s readout links
- O(7500) scintillating fibers
- O(7000) timing tiles
    - DRS readout
- 3 layers switching FPGAs
    - Optical data links
- Online filtering



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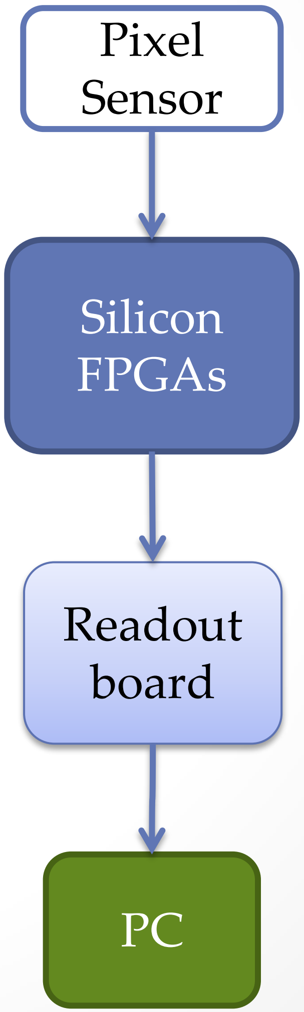
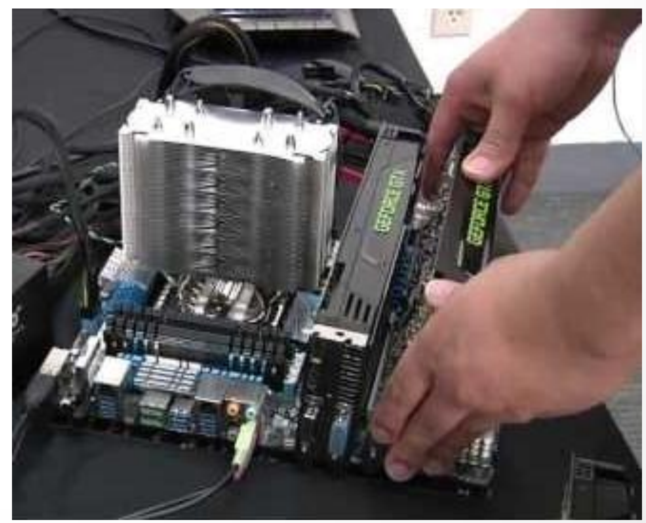


Event Filter Farm

- Triggerless readout
- GPU computers
  - o PCIe FPGA/optical input
  - o Tflop/s GPU
- 10x faster than CPU
  - – Requires custom code
  - + Makes farm affordable

Optical mezzanine connectors



GPU computer

Schedule

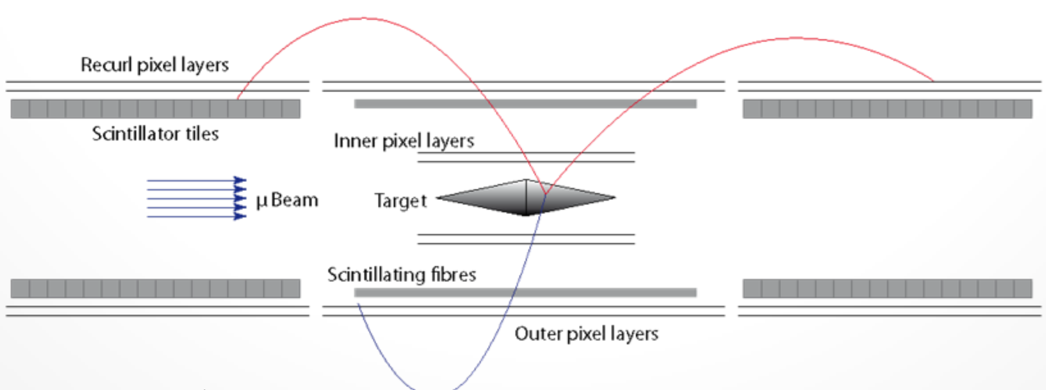
- **2012 Letter of intent** to PSI, tracker prototype, technical design, technical design report
- **2013** Detector **construction**
- **2014** Installation and **commissioning** at PSI
- **2015** Data taking at up to a few **10^8 μ/s**
- **2016+** Construction of **new beam-line** at PSI
- **2017++** Data taking at up to **$3 \cdot 10^9$ μ/s**

Institutes

- Mu3e proto-collaboration:
  - DPNC Geneva University
  - Paul Scherrer Institute
  - Particle Physics ETH Zürich
  - Physics Institute Zürich University
  - Physics Institute Heidelberg University
  - ZITI Mannheim
  - KIP Heidelberg

Summary

- Mu3e searches for lepton flavor violation
- > 10^{16} μ-decays → BR < 10^{-16} (90% CL)
- Silicon tracker with ~275M pixel
- HV-MAPS 50 μm thin
- Two SiPM based timing systems
- Prototypes look encouraging

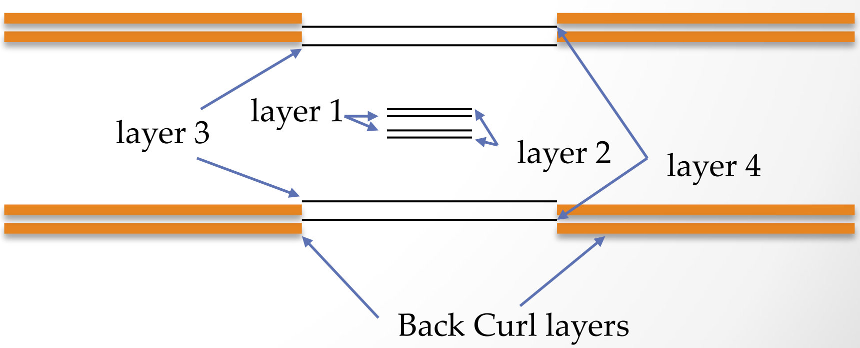


Backup Slides

…

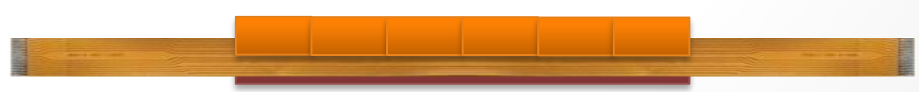
Si-Layer Rad Length

- Radiation length per layer
  - 2x 25 µm Kapton
    - X_0= 1.75e-4
  - 15 µm thick aluminum traces (50% coverage)
    - X_0= 8.42e-5
  - 50 µm Si MAPS
    - X_0= 5.34e-4
  - 10 µm adhesive
    - X_0= 2.86e-5
- Sum: 8.22e-4 (x4 layers)
  - For Θ_{min} = 22.9°
  - X_0= 21.1e-4



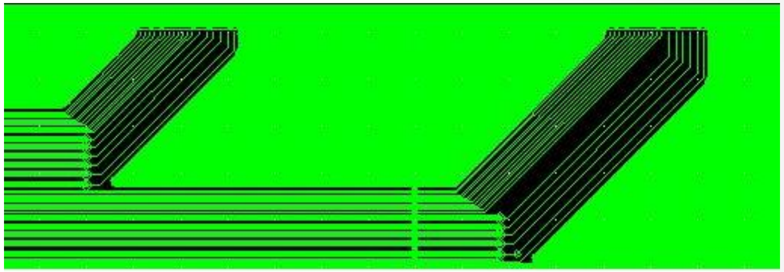
MAPS Tiles

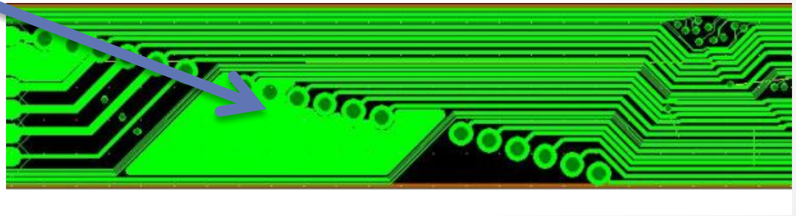
- MAPS
  - 2 cm x 1 cm for inner layers
  - 2 cm x 2 cm for outer layers
  - Pixel size 80 μm x 80 μm
- Size defined by reticle: 2 cm x 2 cm
  - Cut 6 cm x 2 cm stripes from wafer
  - Bond to flex print
  - Mount sensor-equipped flex print on carrier



Flex Print

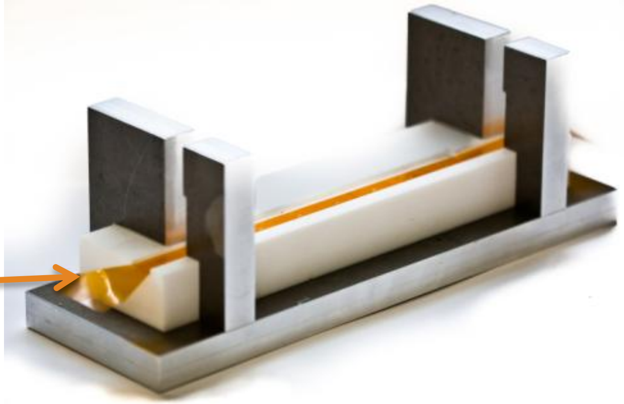
- Single Layer in active region
- Multilayer in “cable” end
- LVDS buffers at edge





Tools

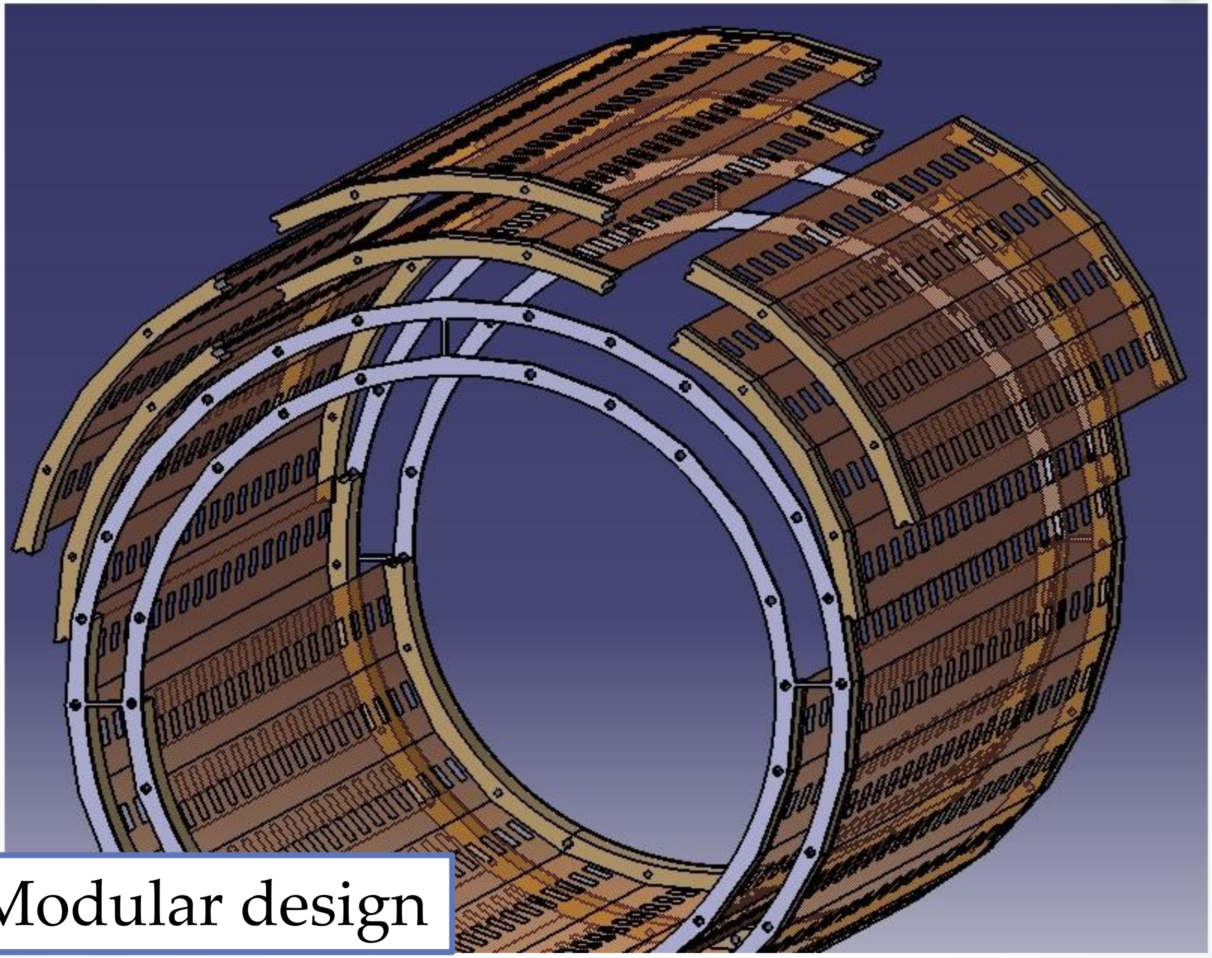
- Kapton-Frame tools:
  - Sensor on Flex print
    - Gluing groove
    - Vacuum lift
  - Tools are tested with
    - 25 μm Kapton foil
    - 50 μm glass



Inner Double Layer

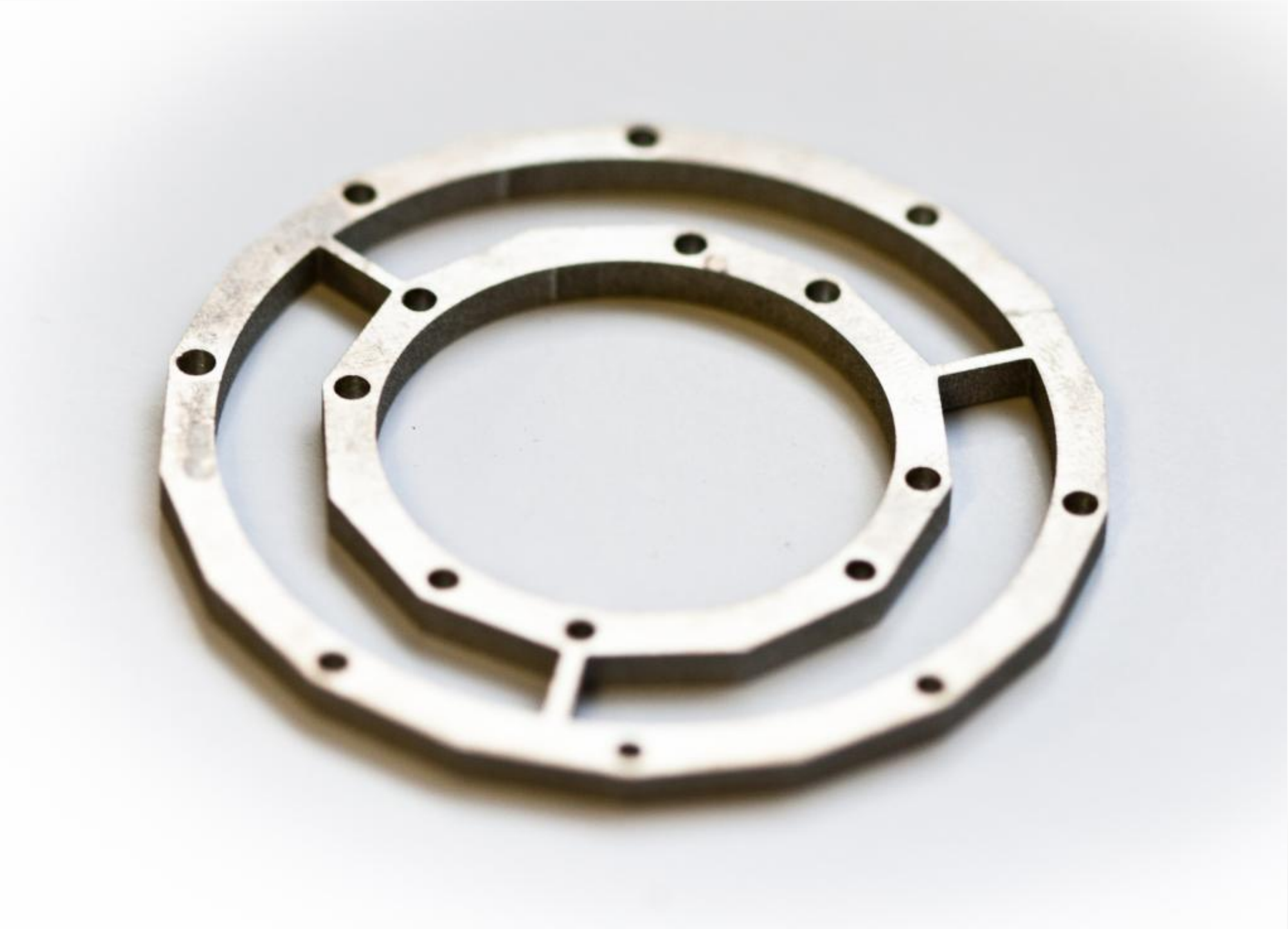
25 μm Kapton frame
+ 25 μm Kapton strip
+ 50 μm glass

Outer Doublet Design

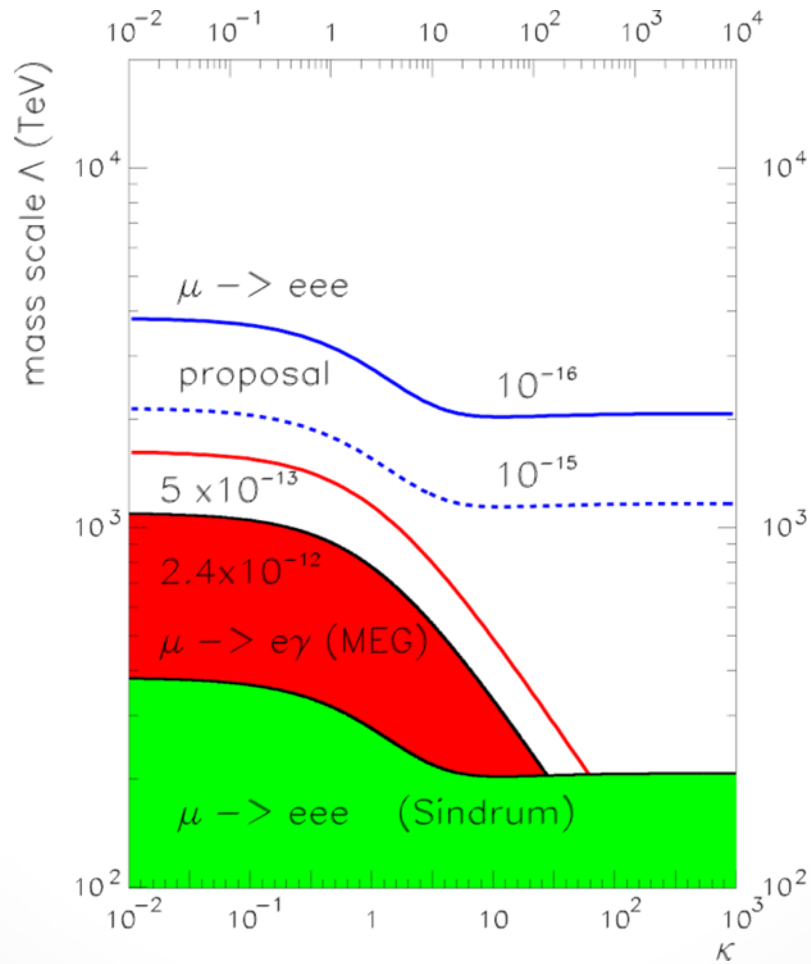


Modular design

Spokes Between Layers 1+2



Mu3e vs. MEG



mass scale Λ (TeV)
μ −> eee
proposal
10^{-16}
10^{-15}
5×10^{-13}
2.4×10^{-12}
μ −> eγ (MEG)
μ −> eee (Sindrum)
κ

Momentum Resolution

- Multiple scattering only
- Current design:
  - 50 µm silicon
  - 50 µm Kapton
  - Helium gas cooling
  - 3 layer fiber tracker