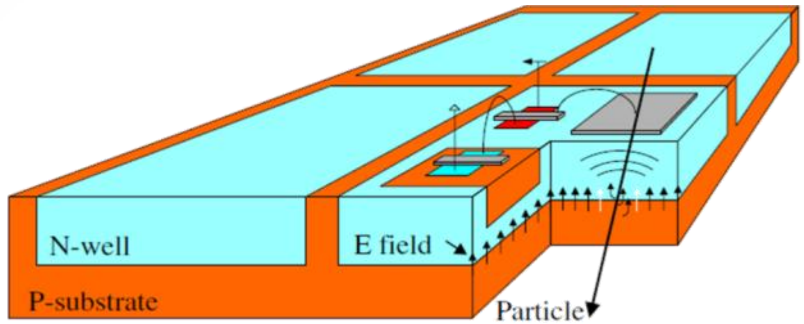



# HV-MAPS

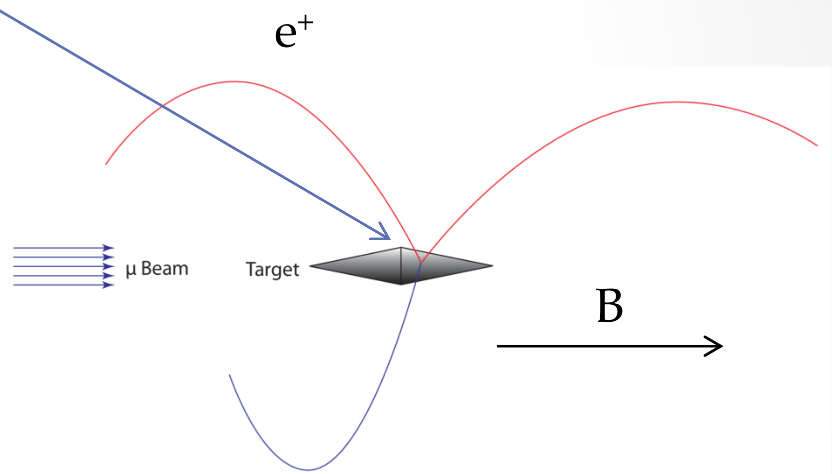
Dirk Wiedner
Physikalisches Institut
der Universität Heidelberg
on behalf of the Mu3e silicon detector collaboration

# From Tracking to Pixel Sensors

• • •

# Tracking

- Decay point
  - Primary vertex:
  - Tracks of decay products point to primary vertex
- Momentum
  - Charged particles are bend in magnetic fields
  - Curvature → momentum
- Particle identification
  - Match information of sub-detectors



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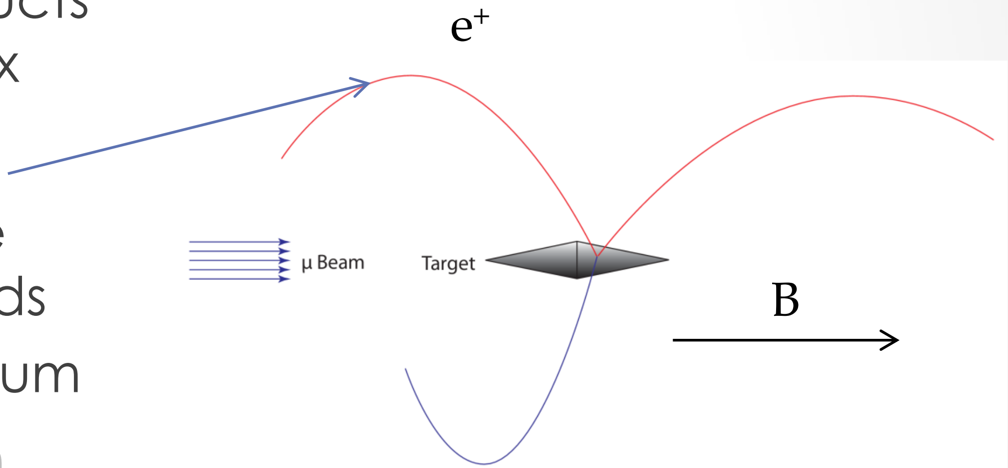
  - Secondary vertex



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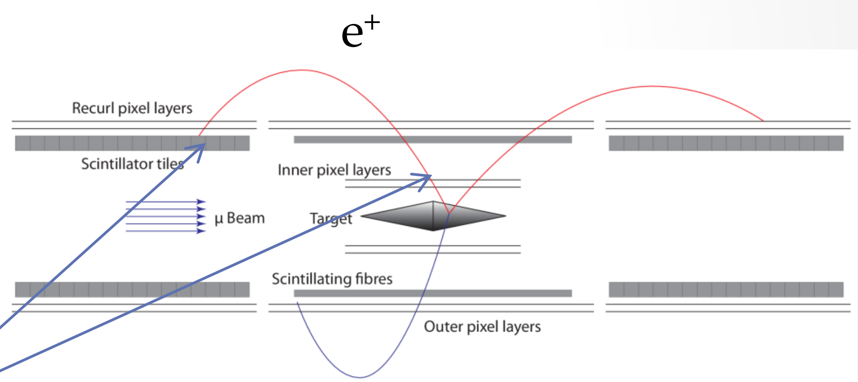
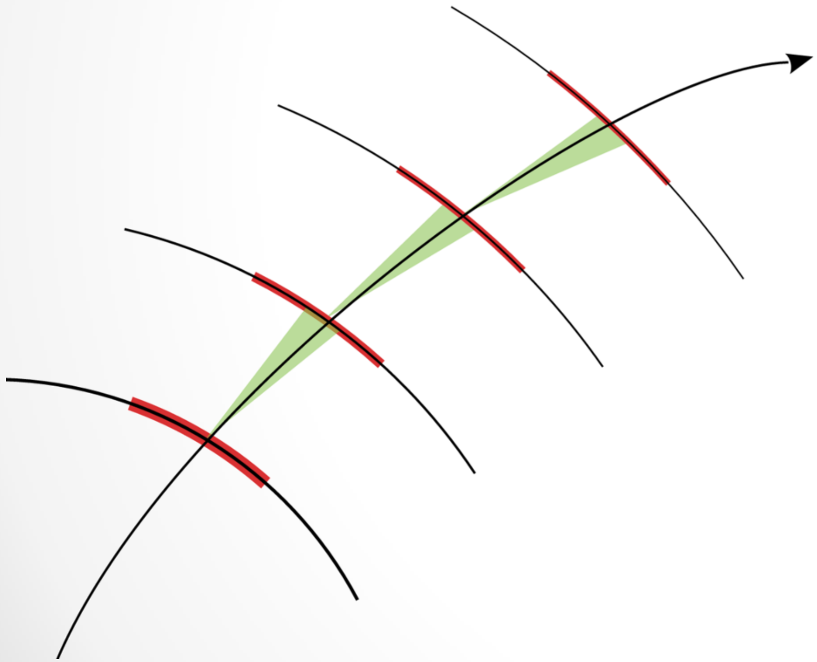
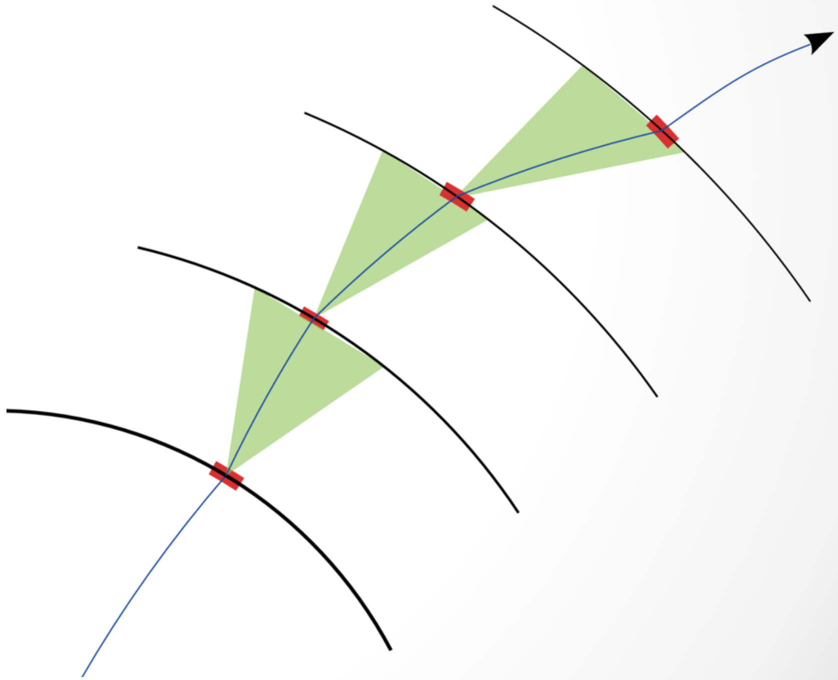


# Tracking resolution

Cell size dominated



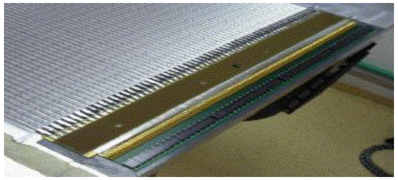
Scattering dominated



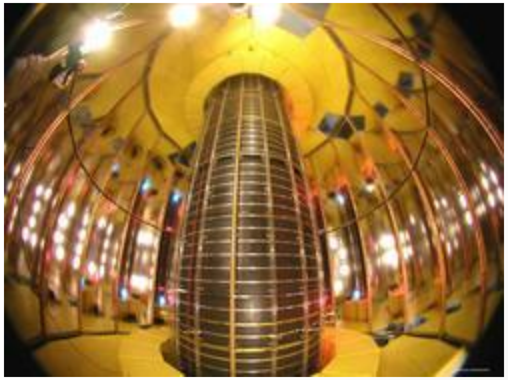
# Tracking Detectors

- Gas detectors
  - Wire chamber
  - Straw tubes
  - Time Projection Chamber
  - …
- Silicon detectors
  - Silicon strip
  - Silicon pixel
  - …
- Scintillating fiber trackers

CDF central wire chamber



LHCb outer tracker straw tubes



ALICE TPC

# Tracking Detectors

- Gas detectors
  - Wire chamber
  - Straw tubes
  - Time Projection Chamber
  - …
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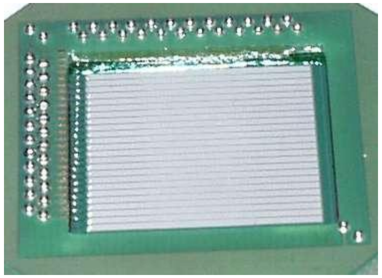
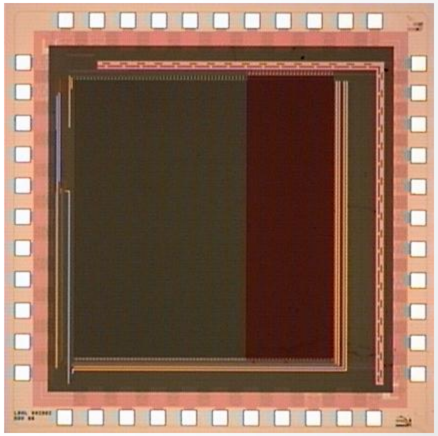
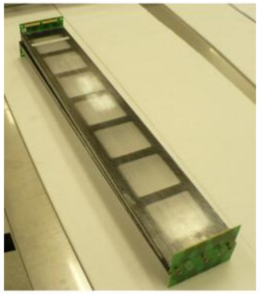
  - Silicon strip
  - Silicon pixel
  - …
- Scintillating fiber trackers



Silicon strip prototype (NRL)



Pixel chip (Berkley)



SciFi (RWTH)

# Which type of detector is best?

Gas detectors

- Cheap
  - Large surface possible
- Light weight
  - Low multiple scattering
- Well known technology
  - Production at institute
- Low power
  - Amplifiers outside active volume
- – Ageing
  - – Gas contents react chemically
- – Little granularity
  - – Spatial resolution limited
- – Some types are slow

Silicon detectors

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**Silicon detectors**

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## Silicon detectors

- ✚ Very good resolution
- ✚ Fine granularity
  - ✚ Pixel: 15 x 15 $\mu m^2$
- ✚ Radiation hard
  - ✚ $10^{16}$ 1MeV neutron eq. /$cm^2$
- ✚ Fast
  - ✚ Drift Charge Collection
- – High power
  - – Pre-amplifiers in active volume
- – Expensive
- – More material than gas chambers
  - – Multiple scattering
- – Production by outside company

# Which type of detector is best?

## Gas detectors

- + Cheap
  - + Large surface possible
- + Light weight
  - + Low multiple scattering
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  - − Pre-amplifiers in active volume
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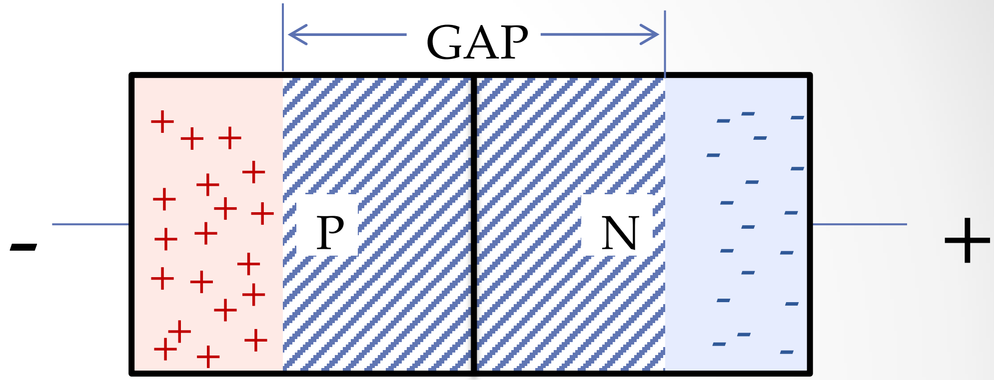
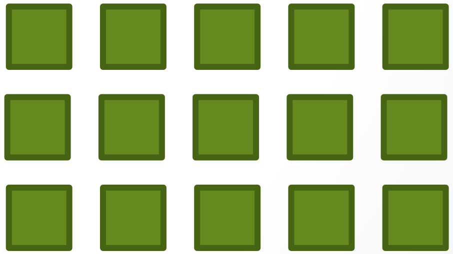
# Silicon detectors

- PN-Diode
  - Fully depleted
  - 100-500V




- Silicon Strip
  - O(10) cm long
  - O(50) µm wide
  - Extra readout chip

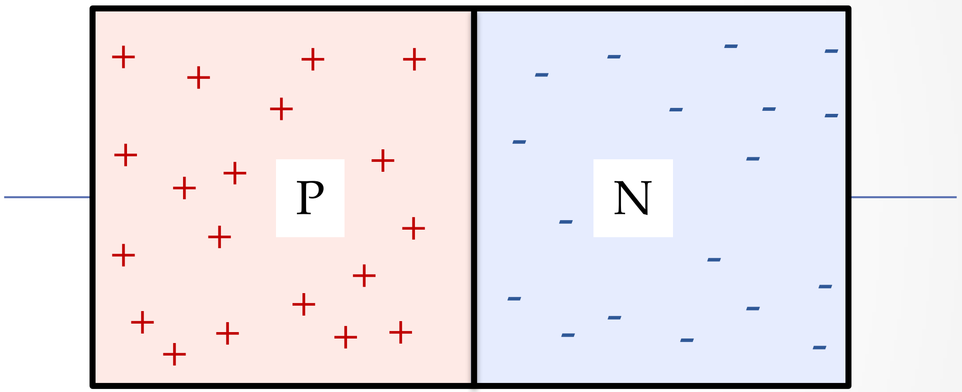
- Silicon Pixel
  - Ca. 50 x 50 $\mu m^2$
  - Hybrid – extra readout
  - Monolithic – integrated readout



# Working Principle of Silicon Detectors

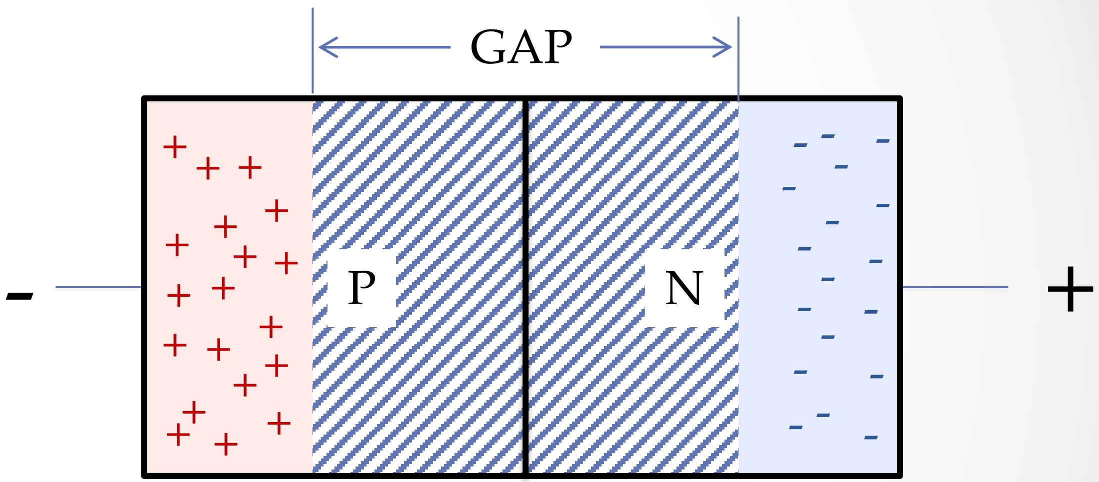
# PN-Junction

- PN-Diode



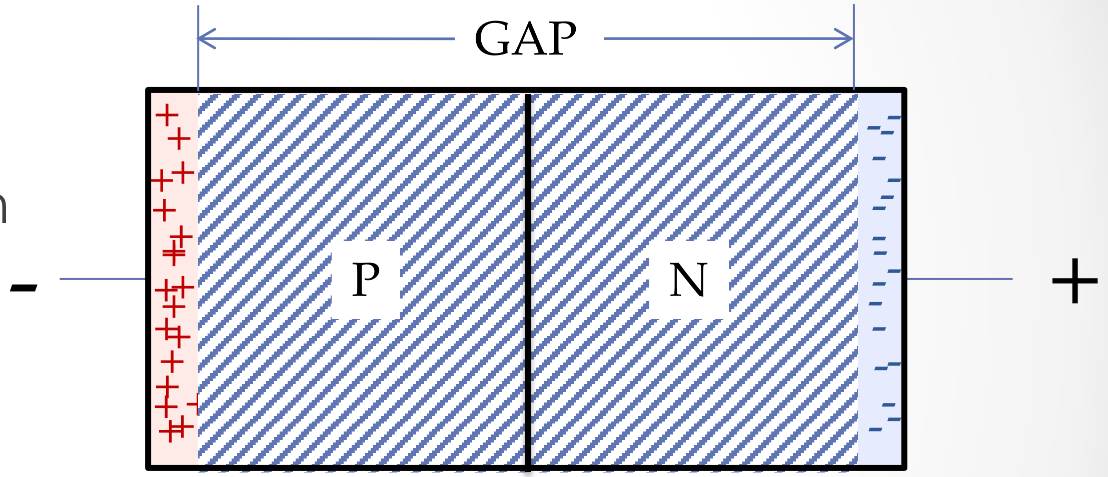
# Depletion Zone

- PN-Diode
- Reverse voltage
  - Depletion zone



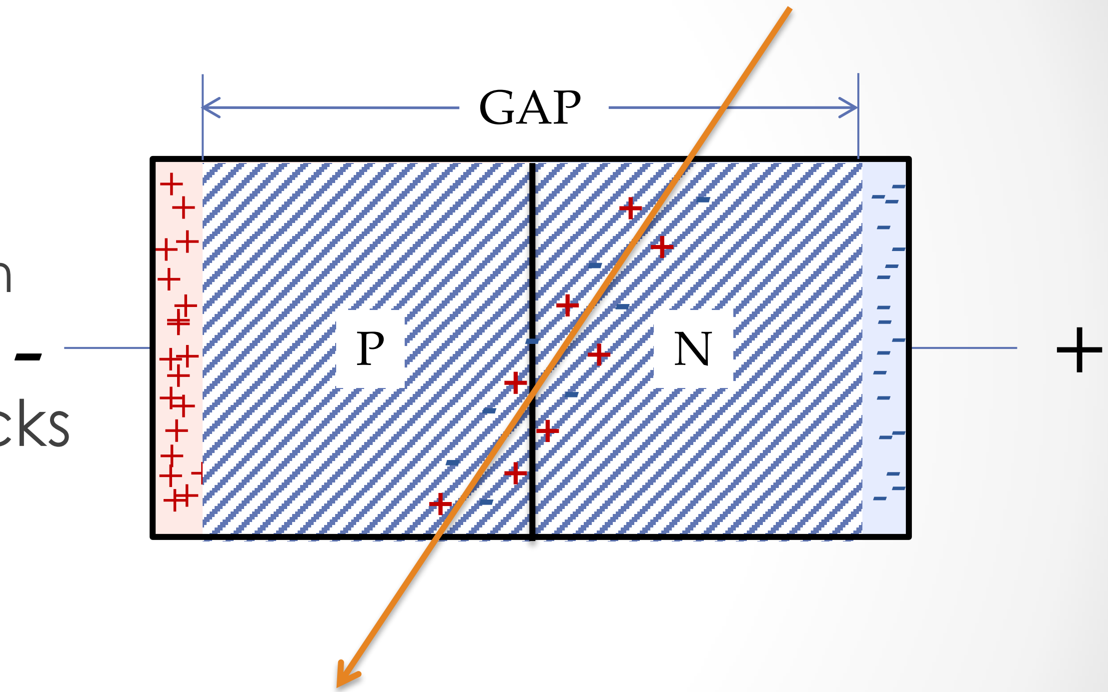
# Depletion Zone

- PN-Diode
- Reverse voltage
  - Depletion zone
  - Full depletion for high efficiency



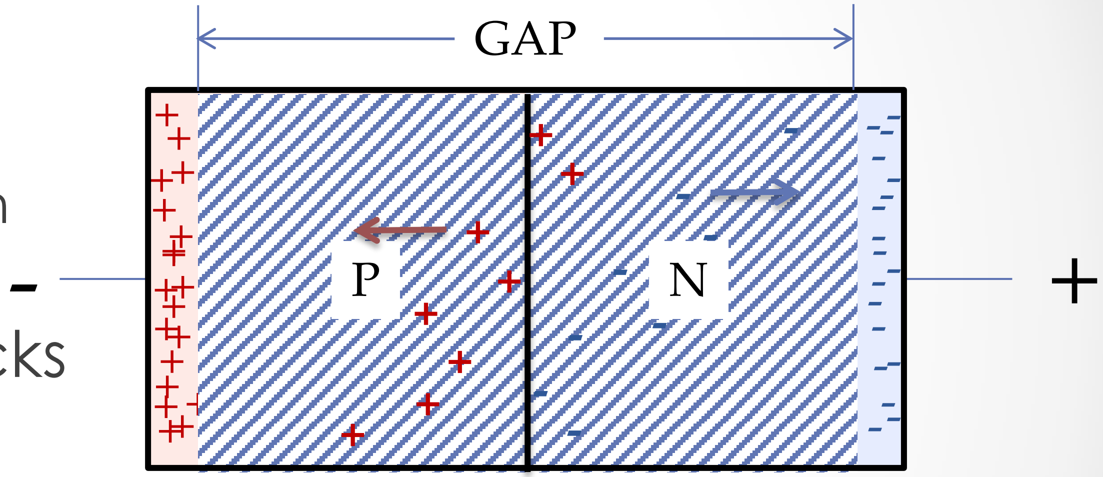
# Charged Particle Track

- PN-Diode
- Reverse voltage
  - Depletion zone
  - Full depletion for high efficiency
- Charge particle tracks
  - electron hole pairs



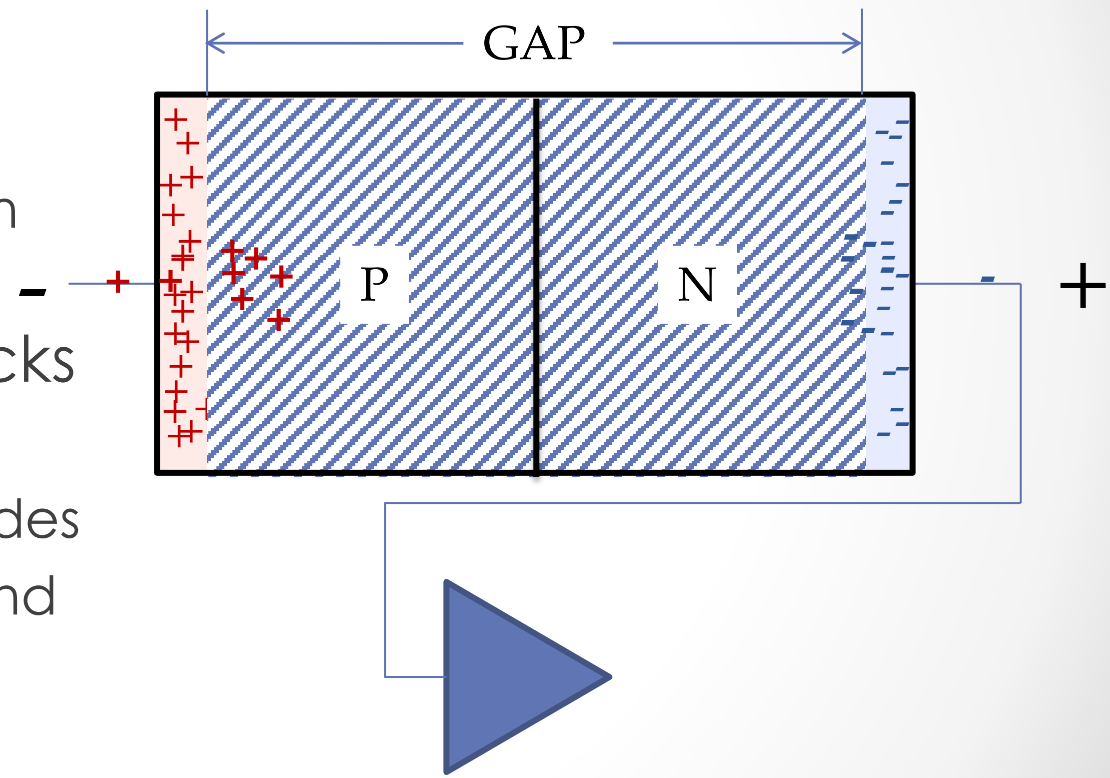
# Charge Drift

- PN-Diode
- Reverse voltage
  - o Depletion zone
  - o Full depletion for high efficiency
- Charge particle tracks
  - o electron hole pairs
  - o Drift towards electrodes
    - Diffusion much slower



# Charge Collection

- PN-Diode
- Reverse voltage
  - Depletion zone
  - Full depletion for high efficiency
- Charge particle tracks
  - electron hole pairs
  - Drift towards electrodes
  - Charge collection and pre-amplification



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**Gas detectors**

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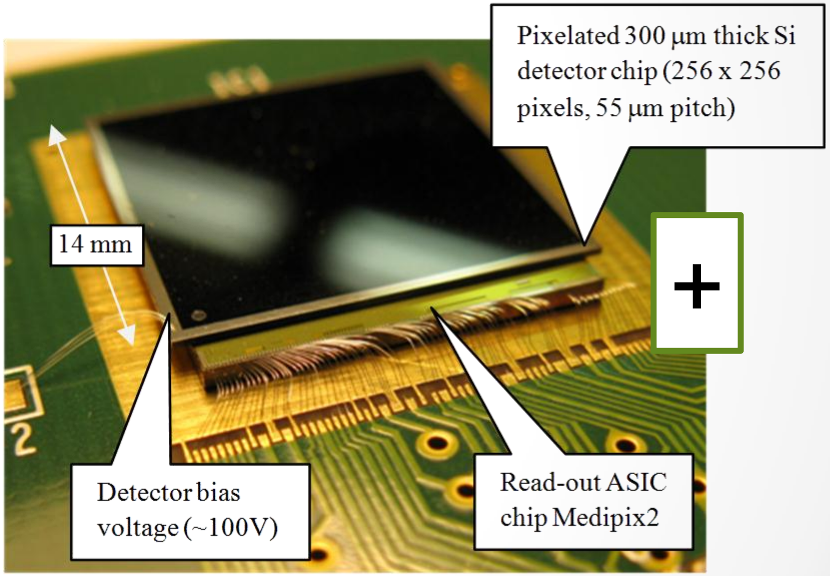
- + Light weight
- + Well known technology
- + Low power
- − Ageing
- − Little granularity
- − Some types are slow

**Silicon detectors**

- + Very good resolution
- + Fine granularity
- + Radiation hard
- + Fast
- − High power
- − Expensive
- − More material than gas chambers
- − Production by outside company

# Hybrid Silicon Pixel

- Very good resolution
- Fine granularity
  - Pixel: 55 x 55 μm$^2$
- Radiation hard
  - $10^{16}$ 1MeV neutron eq. /cm$^2$
- Fast
  - Drift Charge Collection




MediPix (Michal Platkevič Uni Prag)

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  - Pixel: 55 x 55 $\mu m^2$
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  - $10^{16}$ 1MeV neutron eq. /$cm^2$
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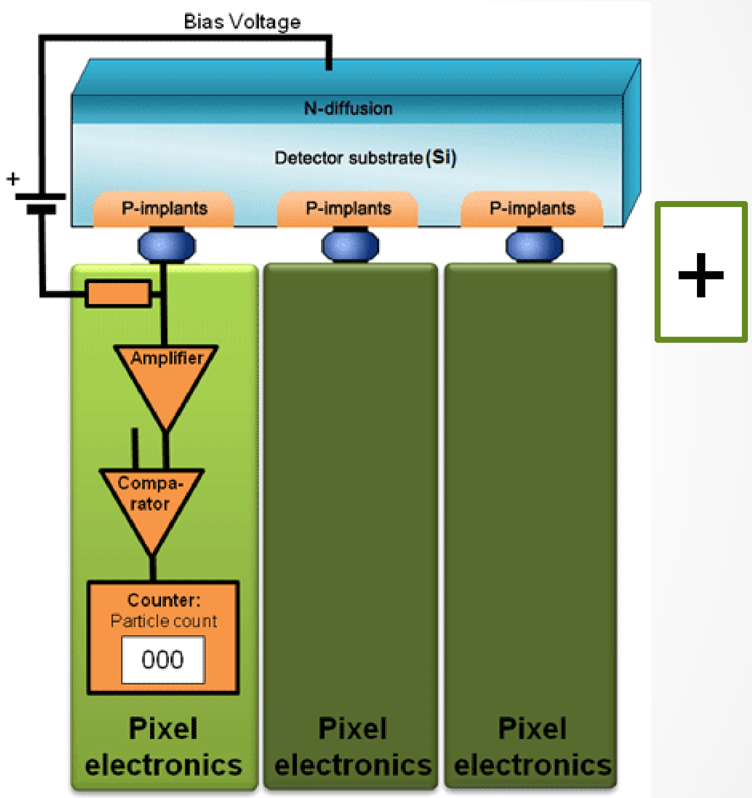
  - Drift Charge Collection
- – High power
  - – Pre-amplifiers in active volume
- – Expensive
- – **More material than gas chambers**
  - – **Multiple scattering**
- – Production by outside company




MediPix (Michal Platkevič Uni Prag)

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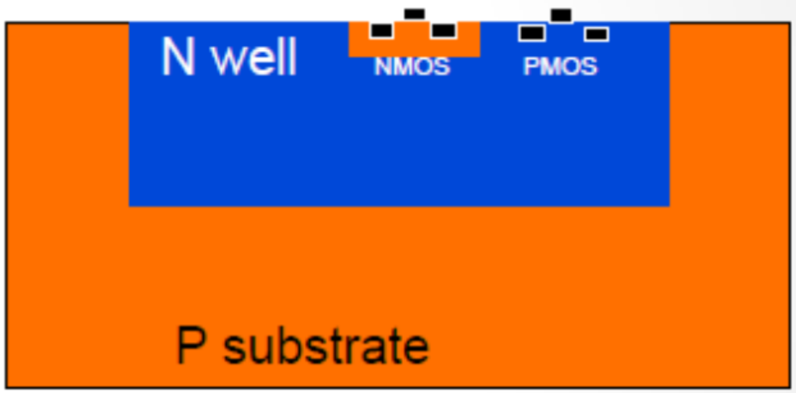
# HV-MAPS

# HV-MAPS

- **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
- HV-CMOS technology
- Reversely biased

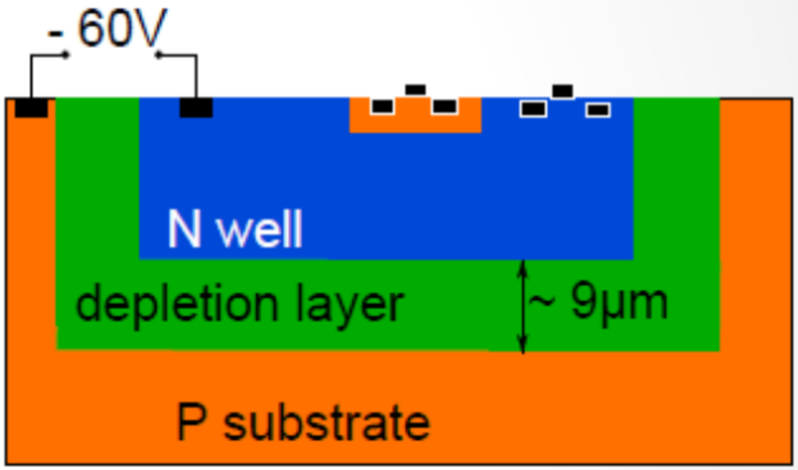



**by Ivan Peric**

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

# HV-MAPS

- **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
- HV-CMOS technology
- Reversely biased ~60V
  - Charge collection via drift
  - ➢ Fast O(10 ns)
  - Thinning to < 50 µm possible

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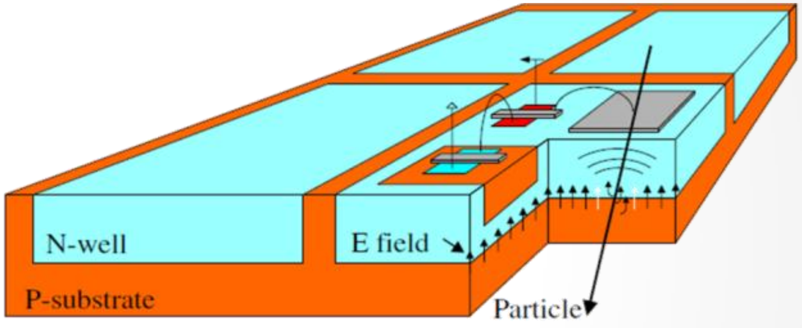
- **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
- HV-CMOS technology
- Reversely biased ~60V
  - o Charge collection via drift
  - ➢ Fast O(10 ns)
  - o Thinning to < 50 µm possible
- Integrated readout electronics
  - o Pre-amplifier
  - o Digital readout
    - Discriminator
    - Time stamp and address
    - Zero suppression

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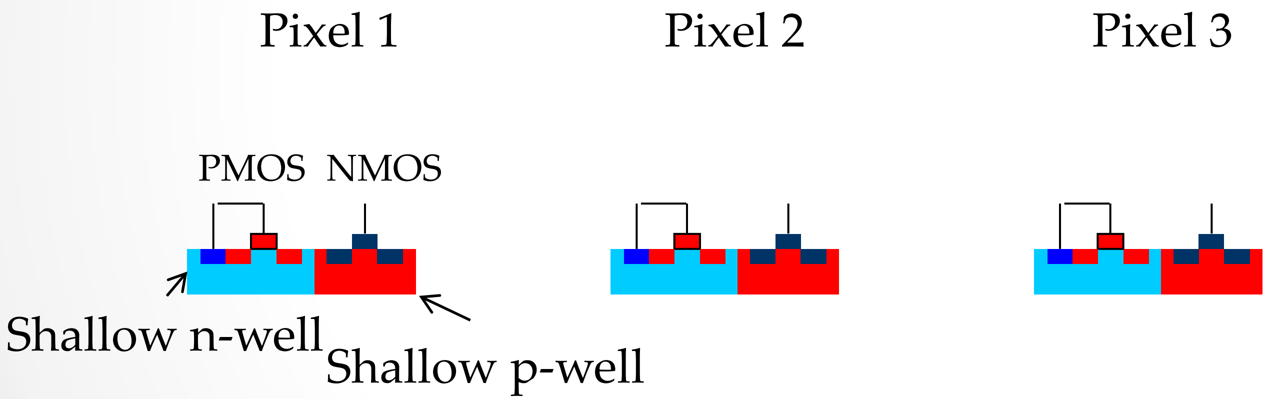
I. Peric, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876

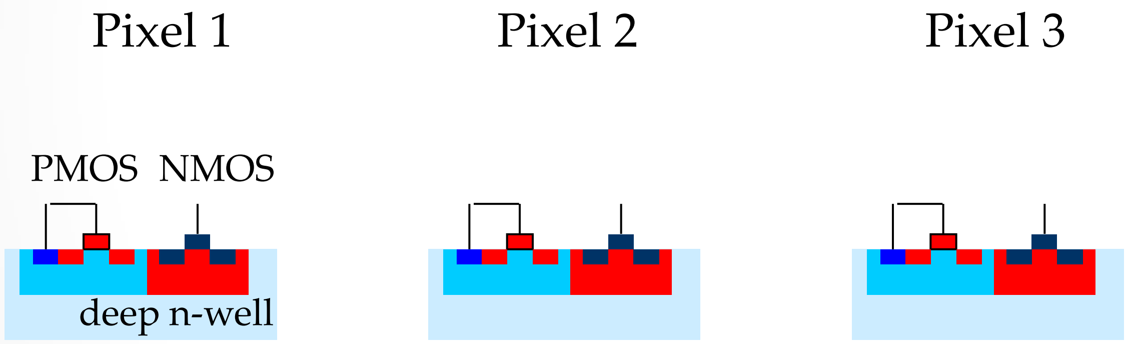
# HV CMOS detectors

- Monolithic active pixel sensor.
- Pixel electronics based on CMOS.
- Implemented in commercial technologies.
- PMOS and NMOS transistors are placed inside the shallow n- and p-wells.



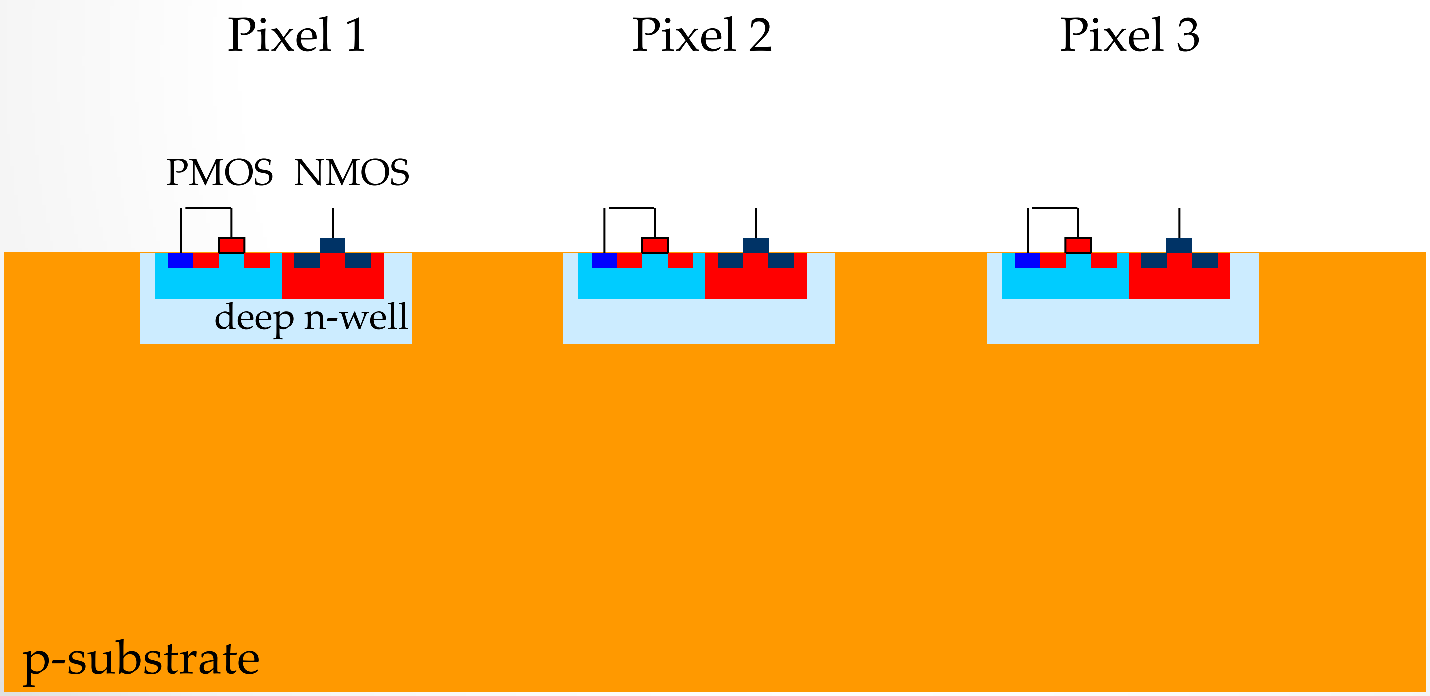
# HV CMOS detectors

- A deep n-well surrounds the electronics of every pixel.



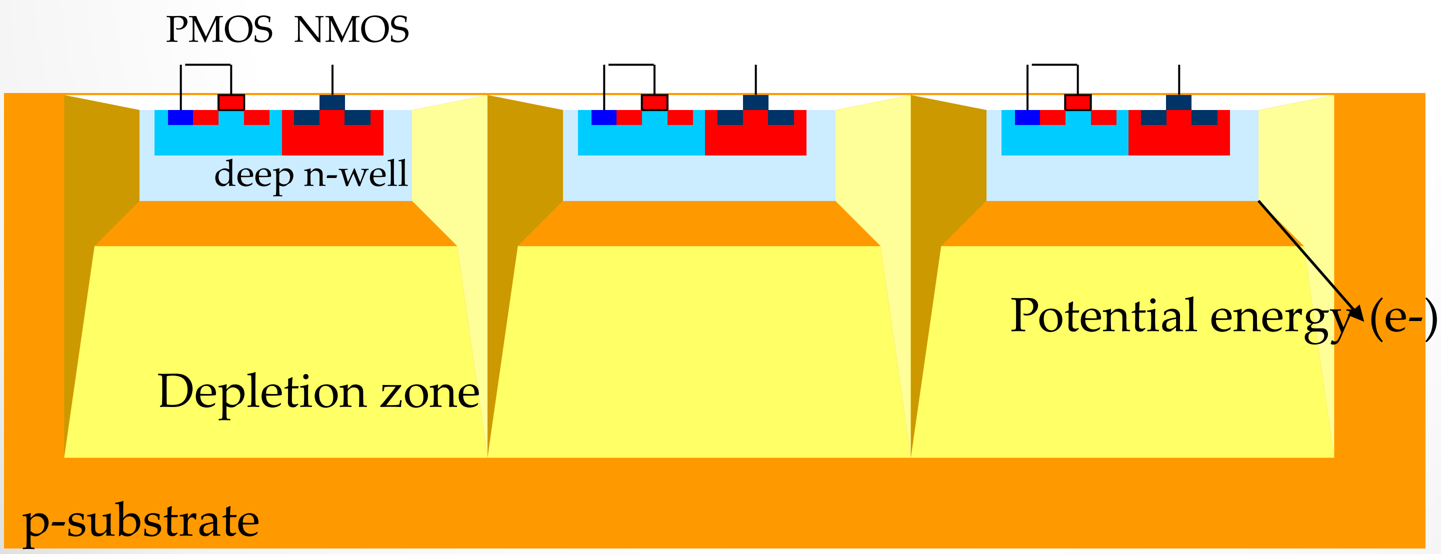
# HV CMOS detectors

- The deep n-wells isolate the pixel electronics from the p-type substrate.



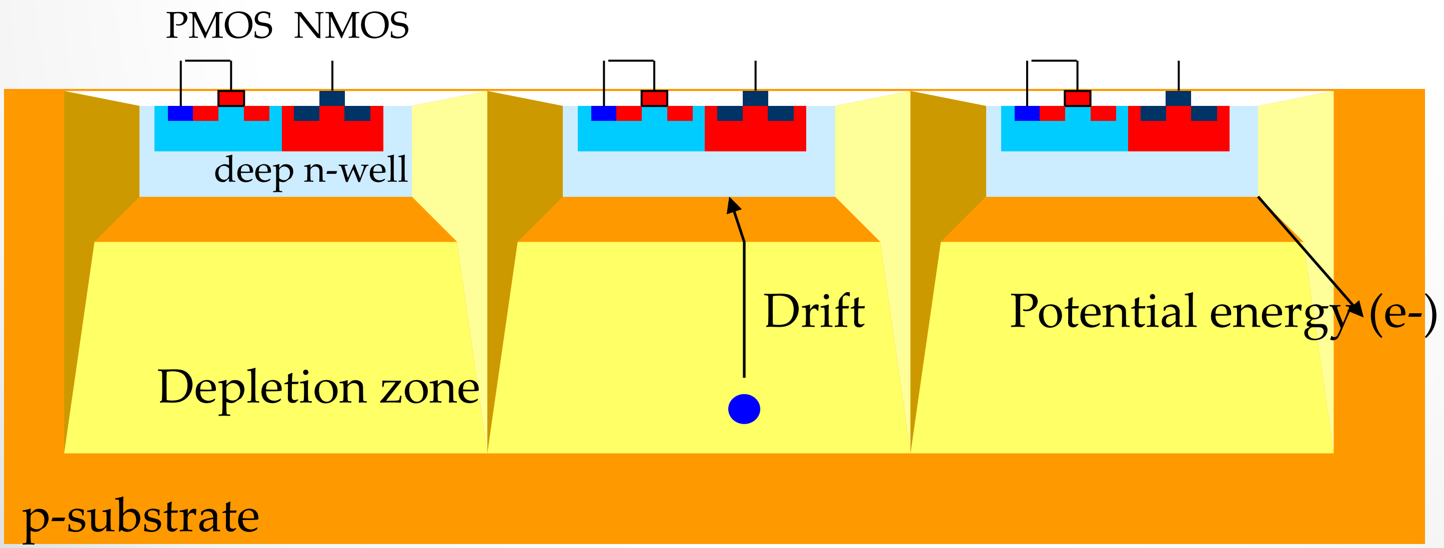
# HV CMOS detectors

- The substrate can be biased low without damaging the transistors.
- In this way the depletion zones in the volume around the n-wells are formed.
- => Potential minima for electrons



# HV CMOS detectors

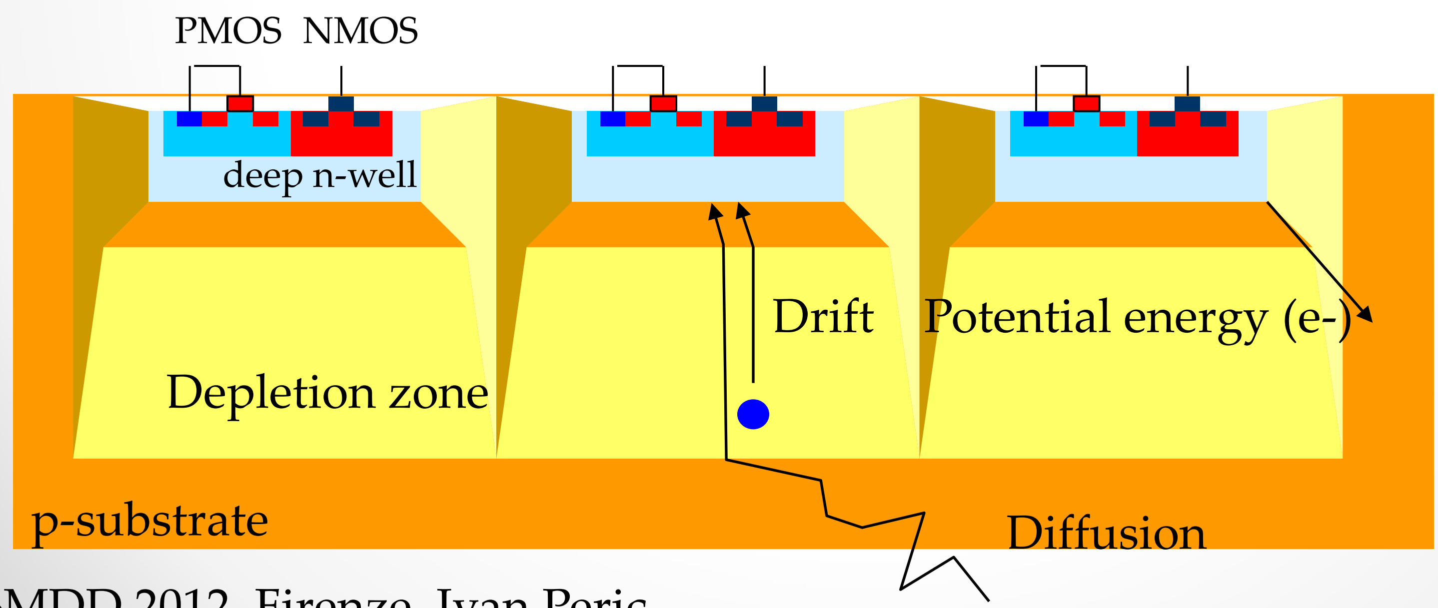
- Charge collection occurs by drift
  - main part of the signal




RESMDD 2012, Firenze, Ivan Peric

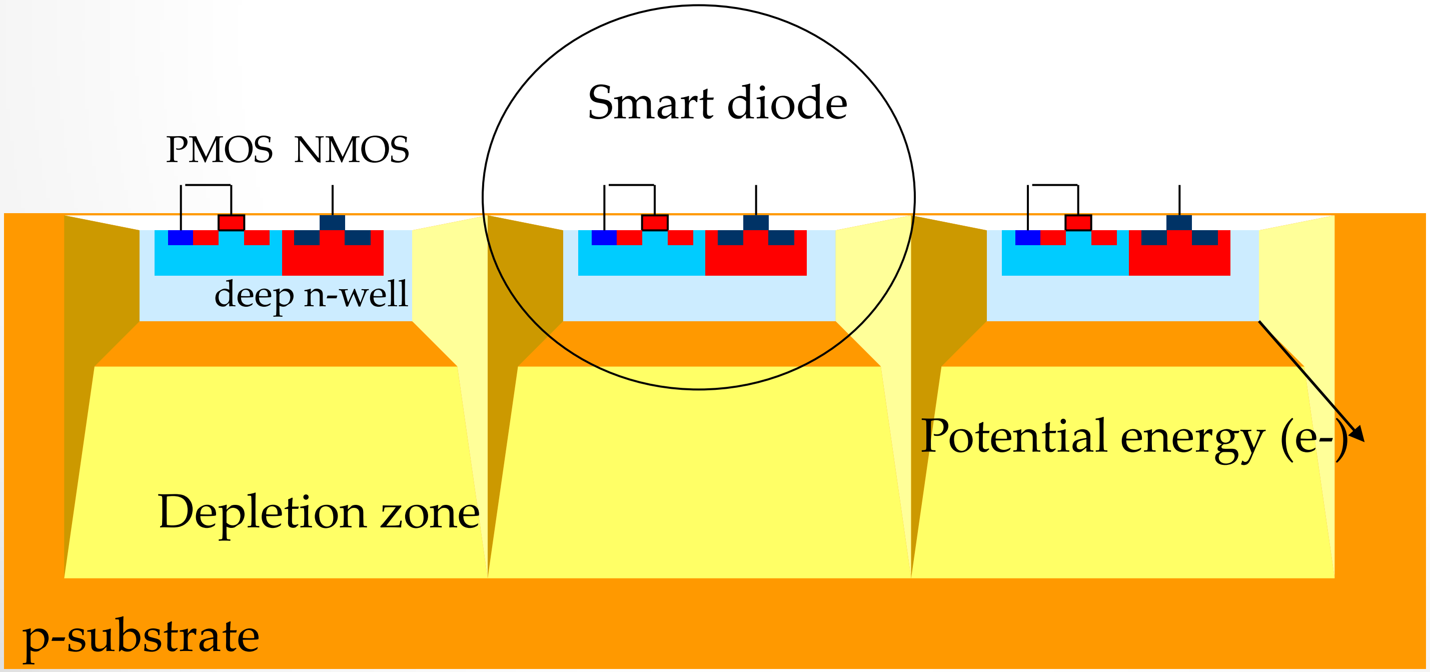
# HV CMOS detectors

- Charge collection occurs by drift
  - main part of the signal
- Additional charge collection by diffusion.



# HV CMOS detectors

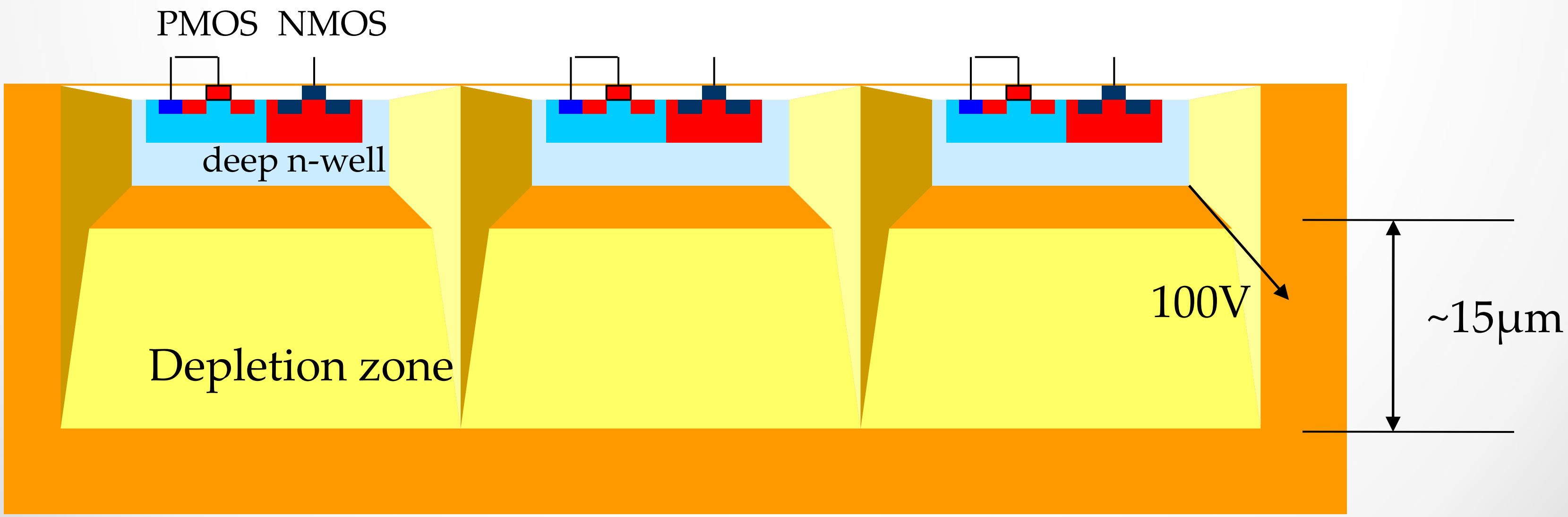
- HVCMOS sensors can be implemented in **any** CMOS technology
  - that has a **deep-n-well surrounding low voltage p-wells**.
  - We have successfully used TSMC 65nm: **2.5 µm** pixels.
- We expect the best results in **high-voltage** technologies:
  - These technologies have **deeper n-wells** and
  - the substrates of **higher resistances** than the LV CMOS.




RESMDD 2012, Firenze, Ivan Peric

# HV CMOS detectors

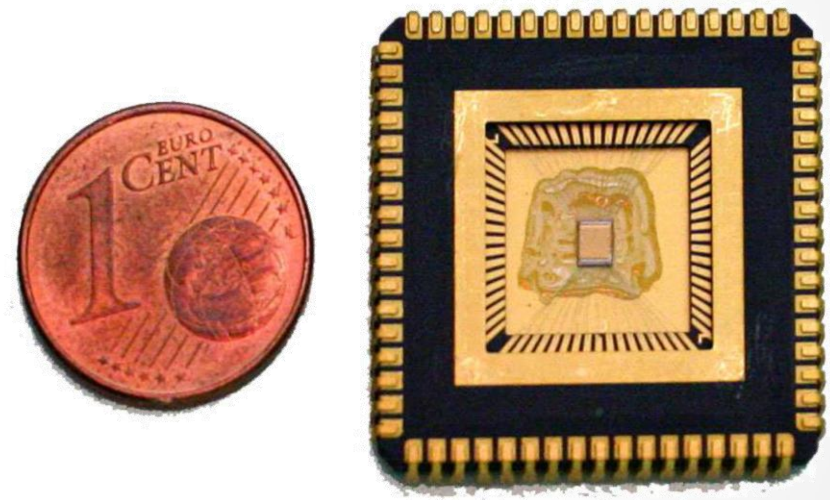
- Example AMS 350 nm HVCMOS:
  - Typical reverse bias voltage is 60-100 V and
  - the depleted region depth ~15 μm.
- 20 Ωcm substrate resistance ->
  - acceptor density ~ $10^{15}$ $cm^{-3}$.
- E-field: 100 V/15 μm or 67 kV/cm or 6.7 V/μm.



# Chip Prototypes

# Chip Prototypes

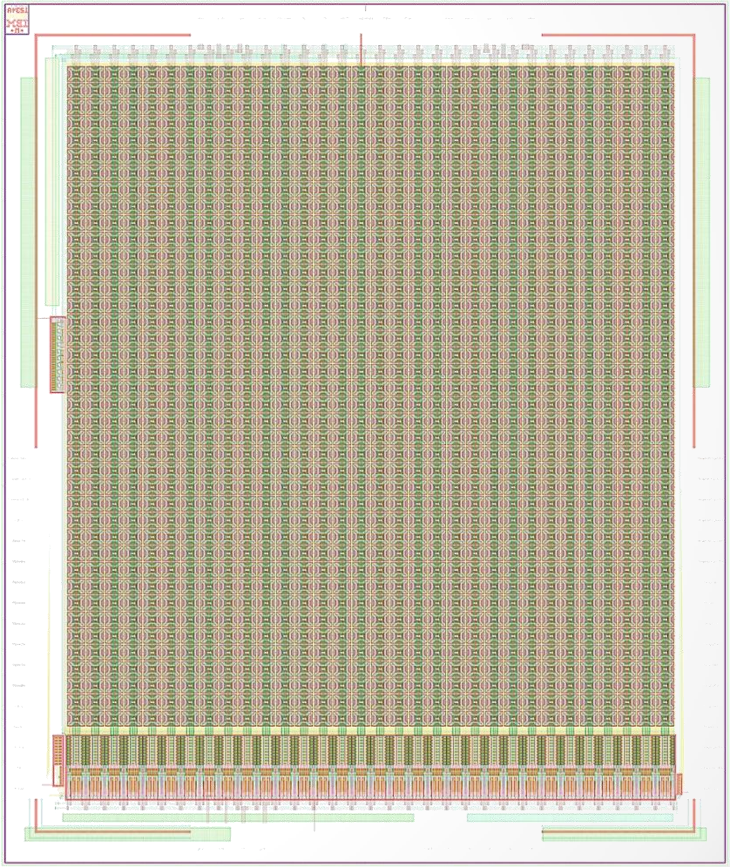
- 180 nm HV-CMOS
- Pixel matrix:
  - 42 x 36 pixels
  - 30 x 39 μm² each
- Ivan Peric ZITI
  - Analog part almost final
  - Digital part under development




MuPix2

# Chip Prototypes

- 180 nm HV-CMOS
- Pixel matrix:
  - 40 x 32 pixels
  - 92 x 80 $\mu m^2$ each
- Ivan Peric ZITI
  - Analog part almost final
  - Digital part under development



MuPix3

# Chip Prototypes

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- Ivan Peric ZITI
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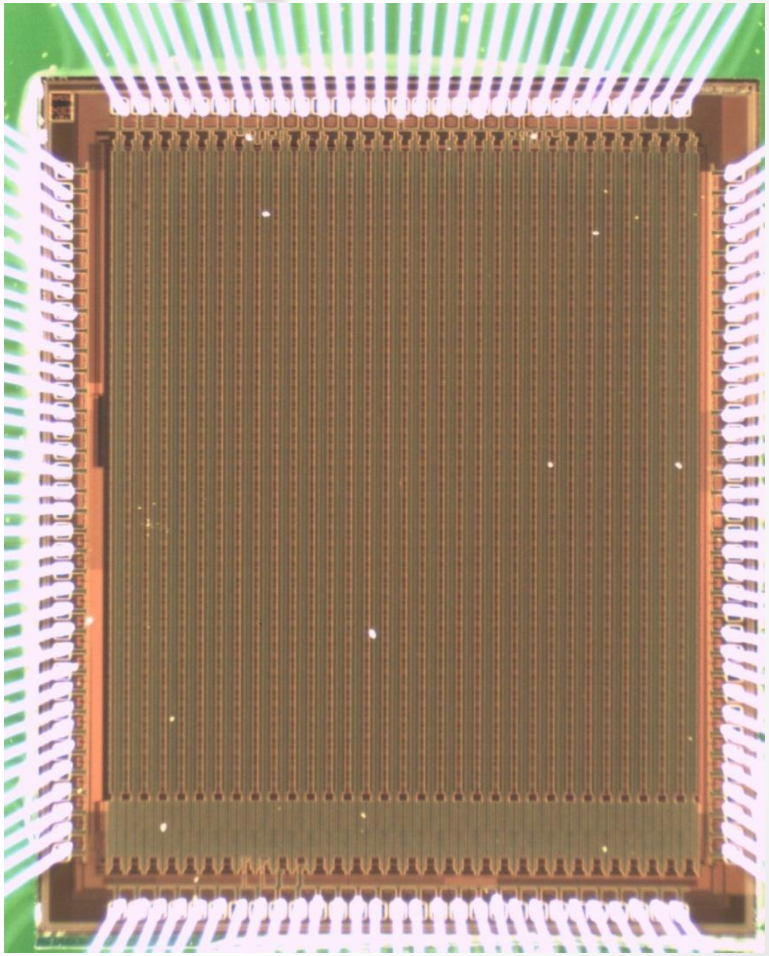
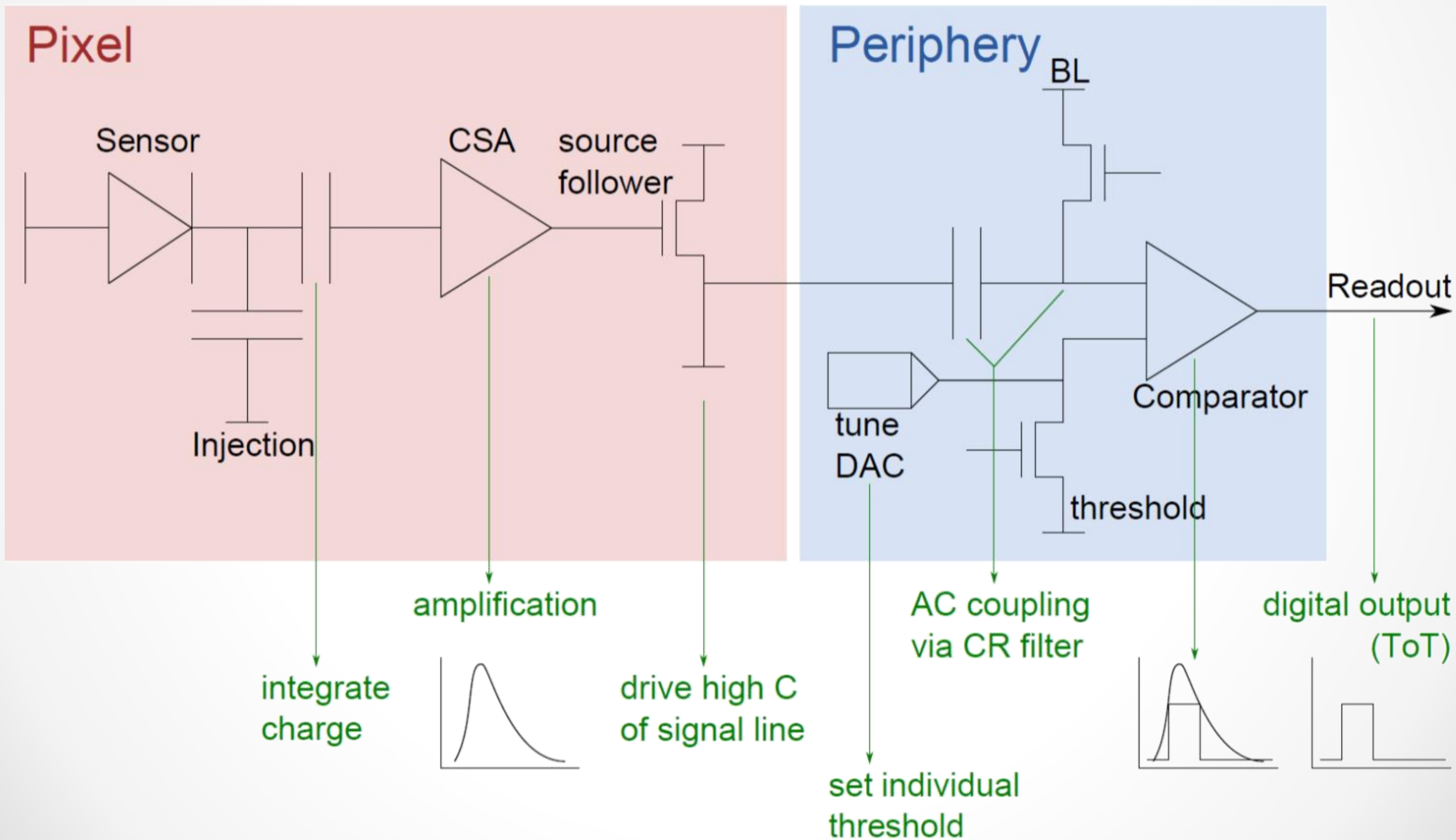
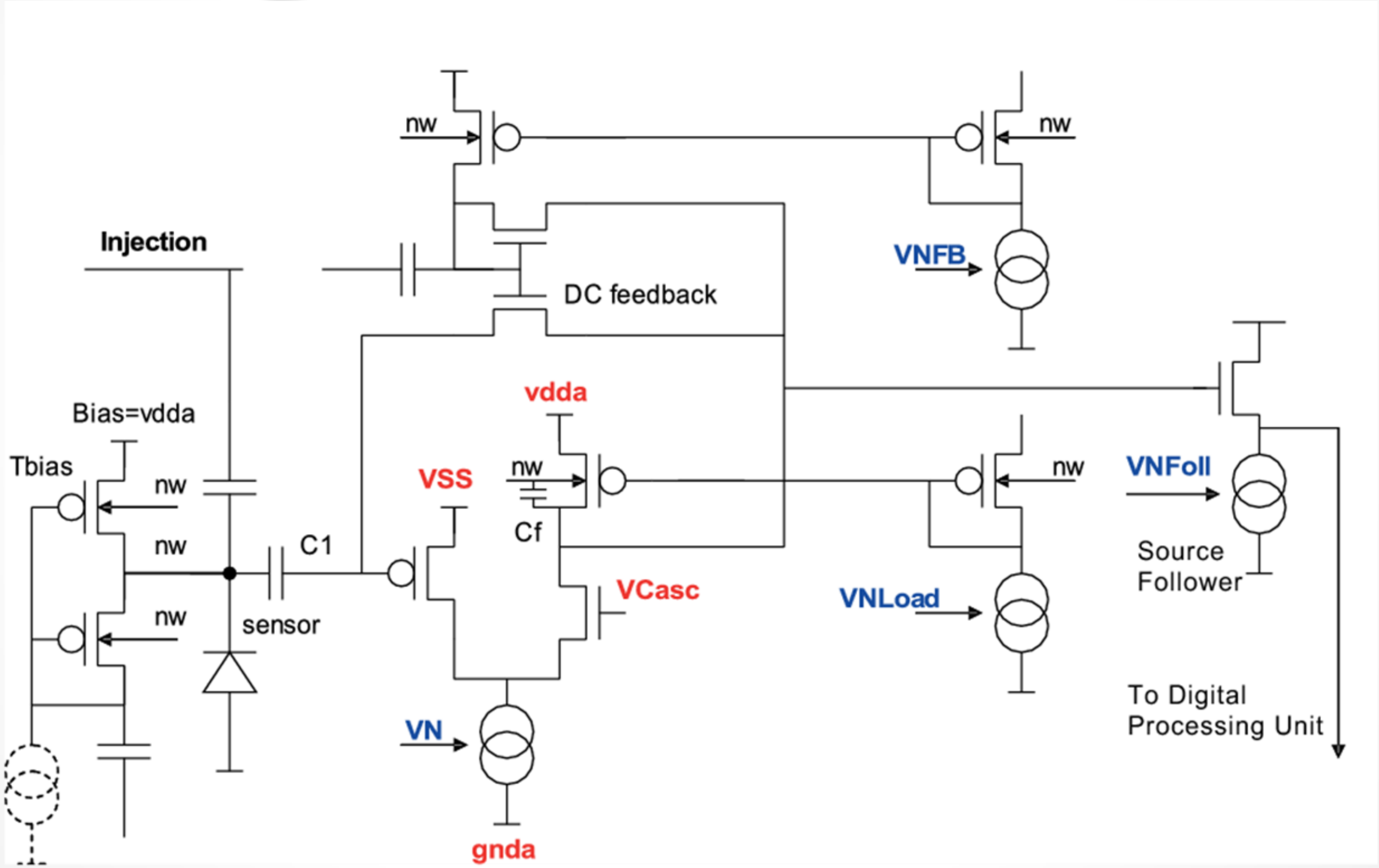


MuPix3

# Sensor + Analog + Digital



# Analog Electronics MuPix

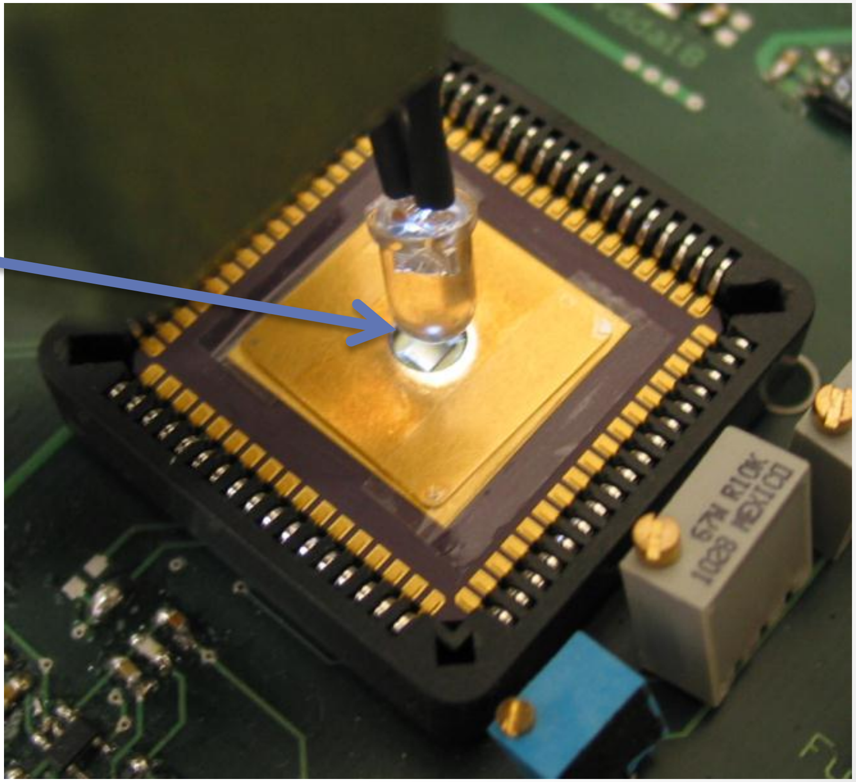


# Test Results

Taken from: A.-K. Perrevoort,
Characterization of High-Voltage Monolithic Active Pixel Sensors
for the Mu3e Experiment,
Master's thesis, University of Heidelberg, 2012.

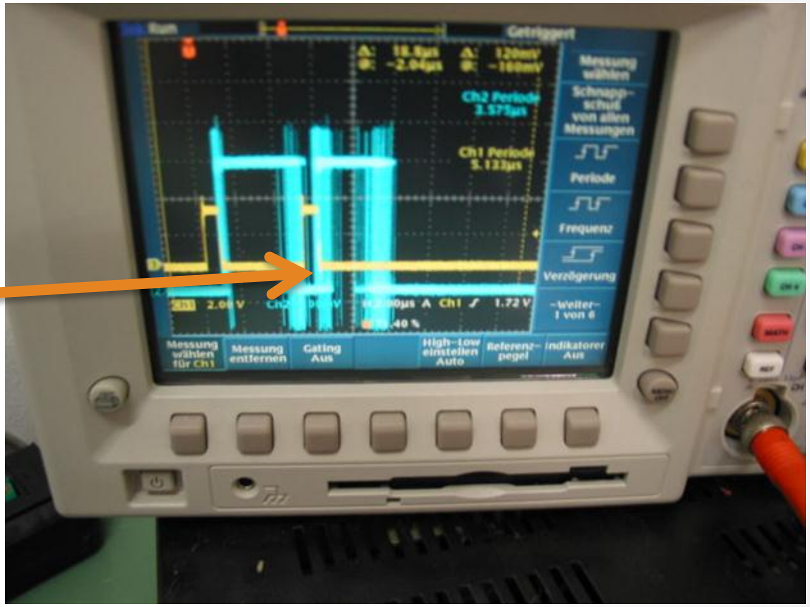
# Timing Tests

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



# Timing Tests

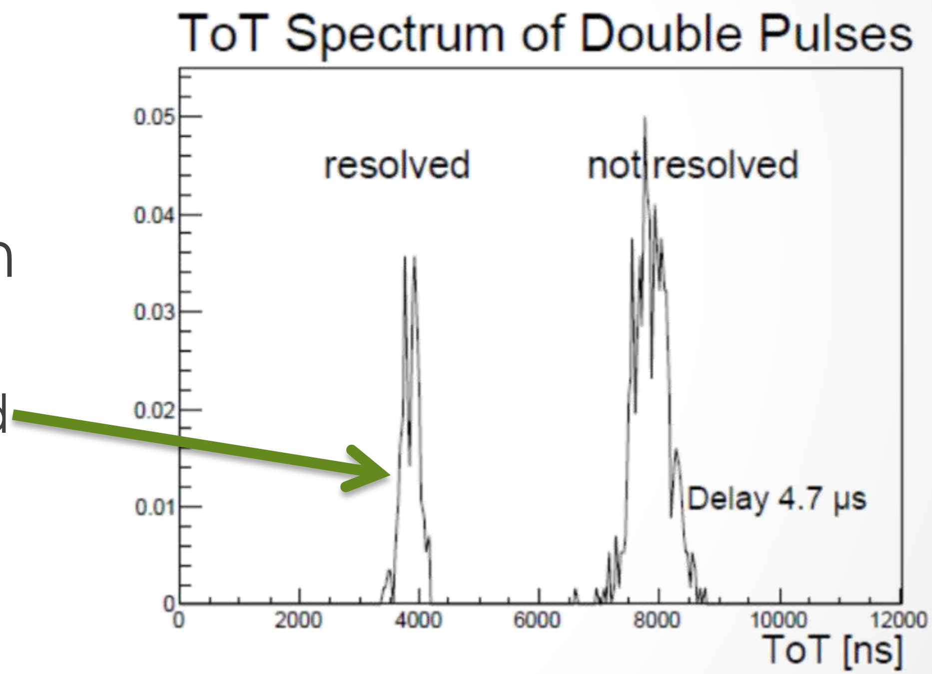
- LED pulsed sensor
- Double pulse resolution
    - Visible in oscilloscope




A.-K. Perrevoort

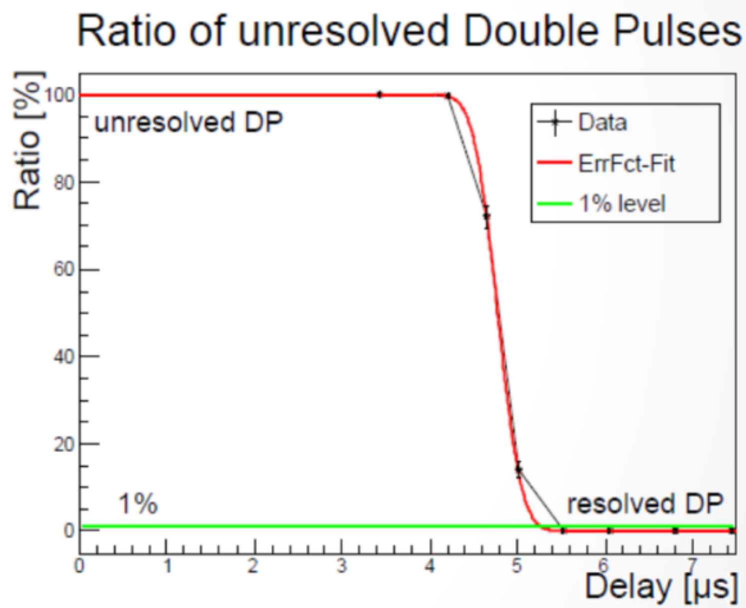
# Timing Tests

- LED pulsed sensor
- Double pulse resolution
  - Visible in oscilloscope
  - … or time over threshold



# Double Pulse Resolution

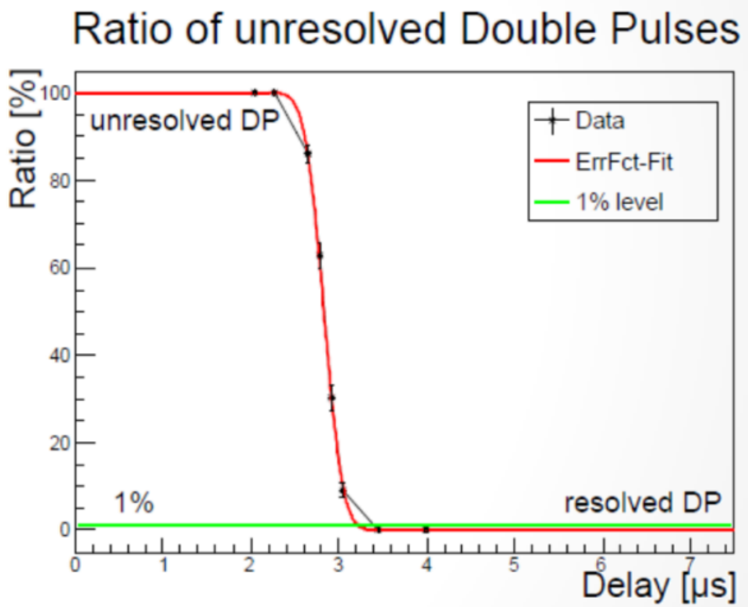
- Ratio of
  - resolved to
  - unresolved double pulses
- 5.27 ± 0.01 μs




A.-K. Perrevoort

# Double Pulse Resolution

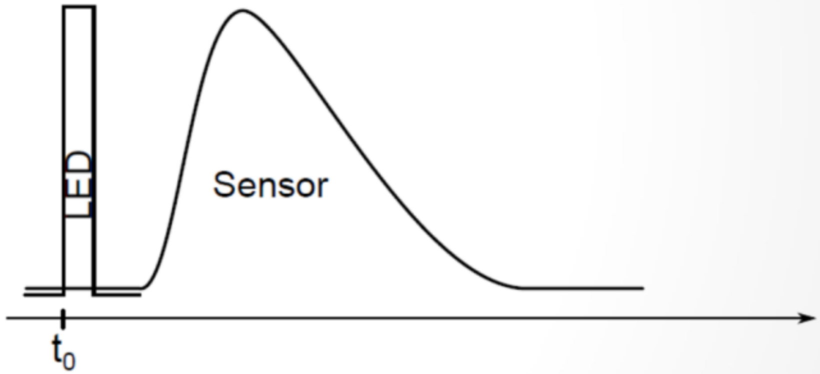
- Ratio of
  - resolved to
  - unresolved double pulses
- Default: 5.27 ± 0.01 µs
- ➢ Pixel bias current adjustment
- ➢ Optimized: 3.23 ± 0.01 µs
  - ➢ Further reduction required




A.-K. Perrevoort

# Pulse Shape

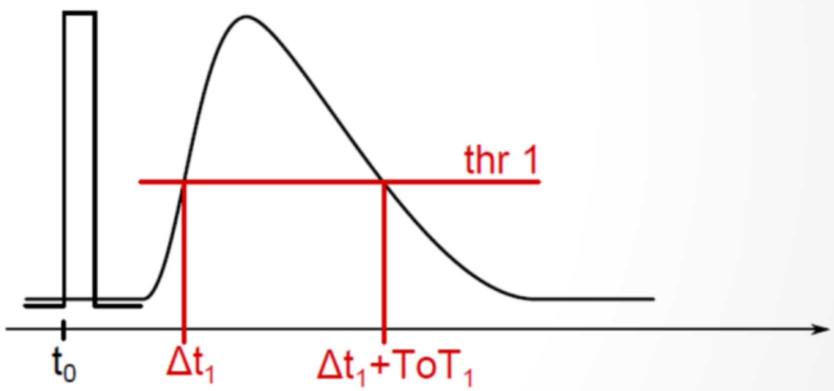
- LED setup
- Test pulse latency
- + time over threshold




A.-K. Perrevoort

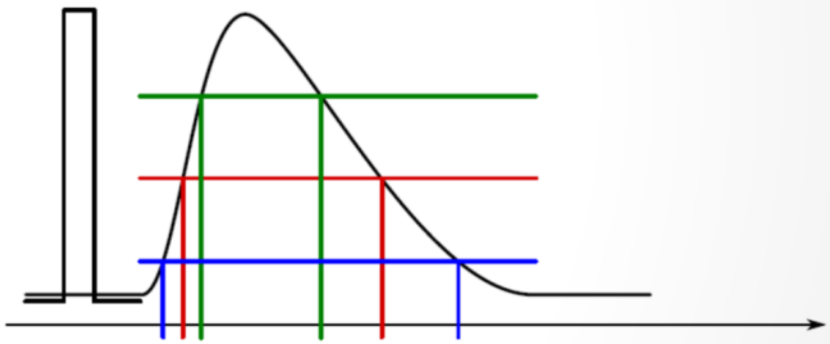
# Pulse Shape

- LED setup
- Test pulse latency
- + time over threshold



# Pulse Shape

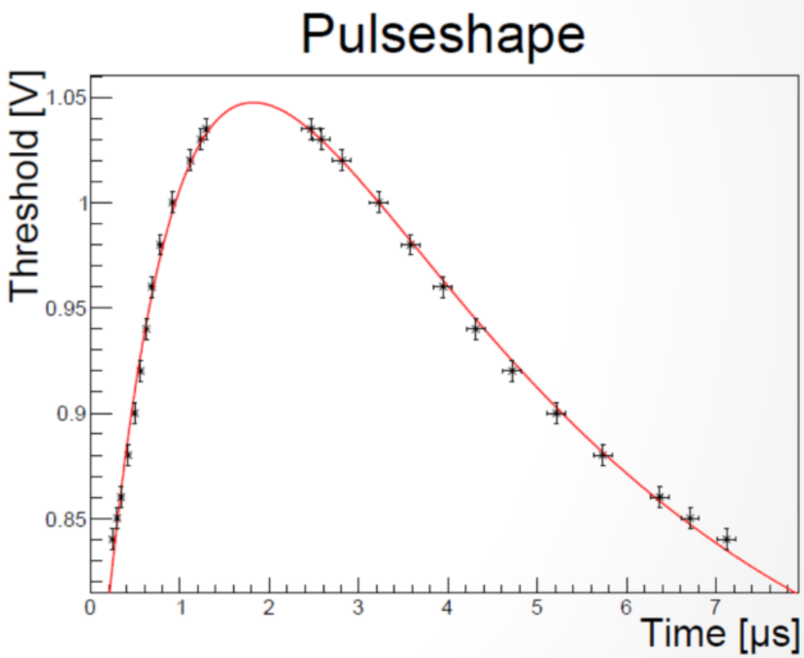
- LED setup
- Test pulse latency
- + time over threshold
- … for different thresholds



# Pulse Shape

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

➢ faster shaping needed

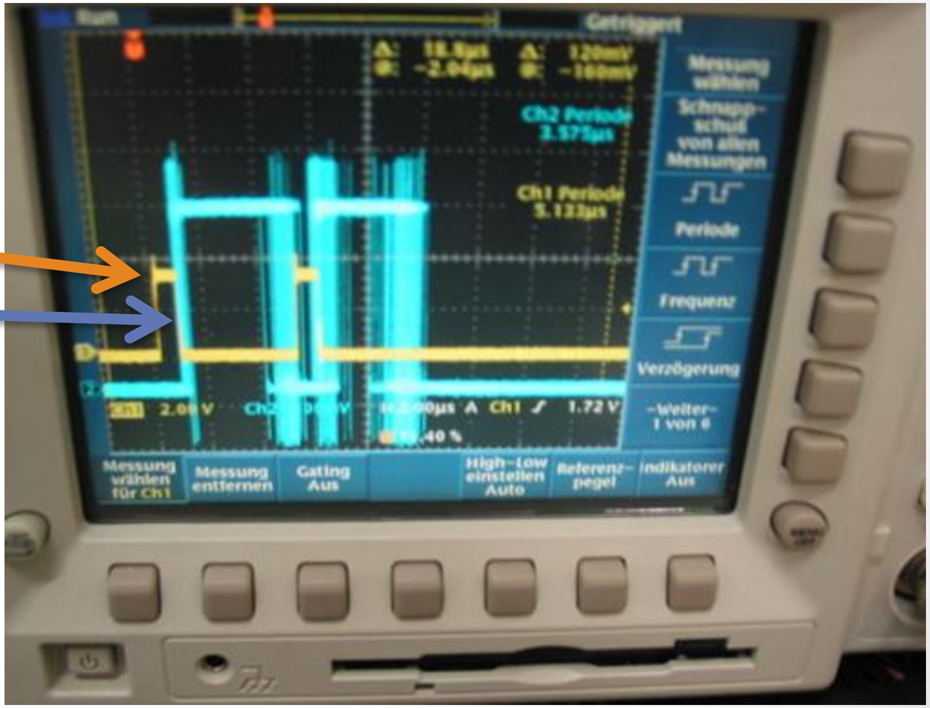



A.-K. Perrevoort

# Timing: Latency jitter

- Precise timing important for:
  - High occupancy
  - Short readout frames
- Latency between
  - signal-pulse and
  - pixel response

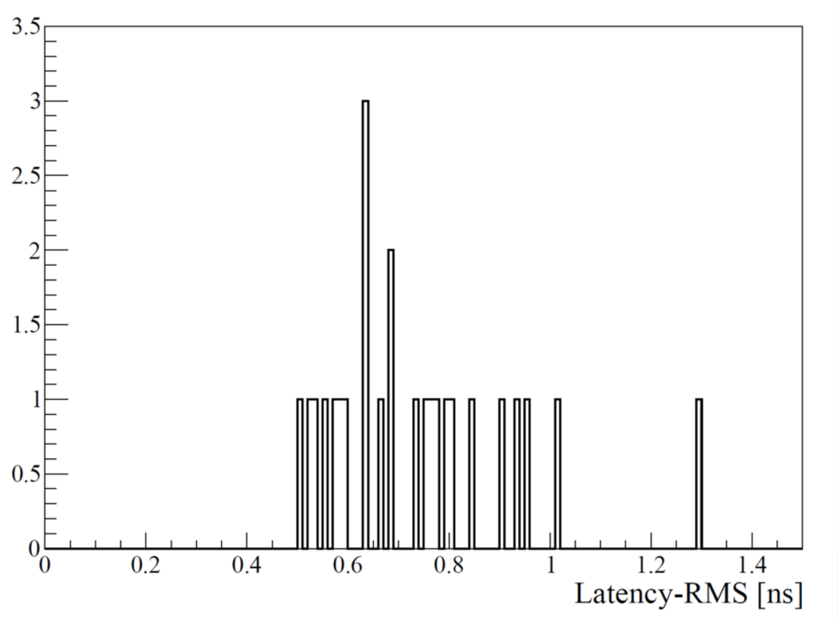
…should be constant



# Timing: Latency jitter

- Latency between
  - test-pulse and pixel response
  - ➢ Latency 59.37 ± 1.63 ns
  - ➢ Latency jitter **0.74 ± 0.18 ns**
- ➢ **Fast**
- But: Pulse height dependency
- ➢ Measure Time over Threshold
  - ➢ Pulse height
  - ➢ Time correction

Latency jitter distribution

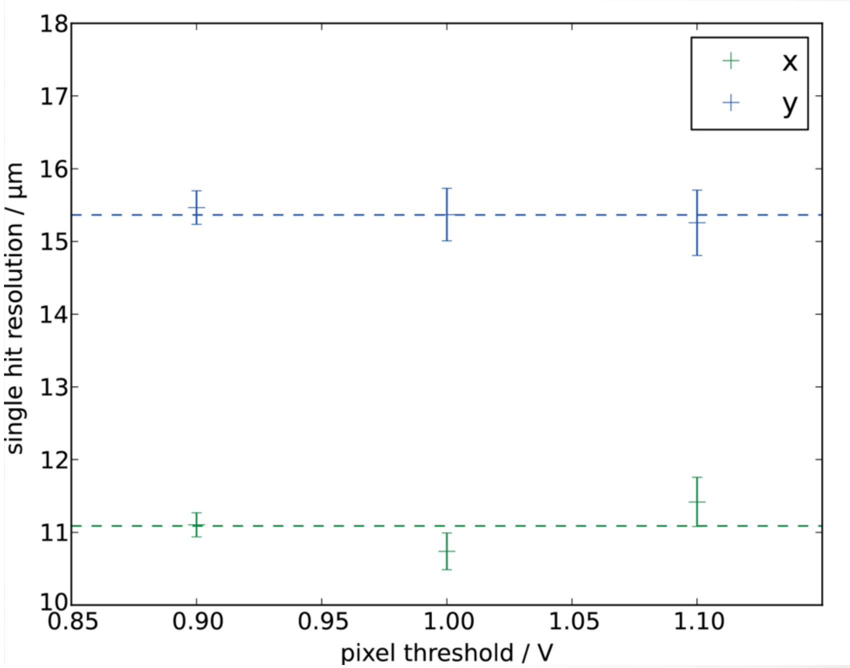



A.-K. Perrevoort

# Pixel resolution

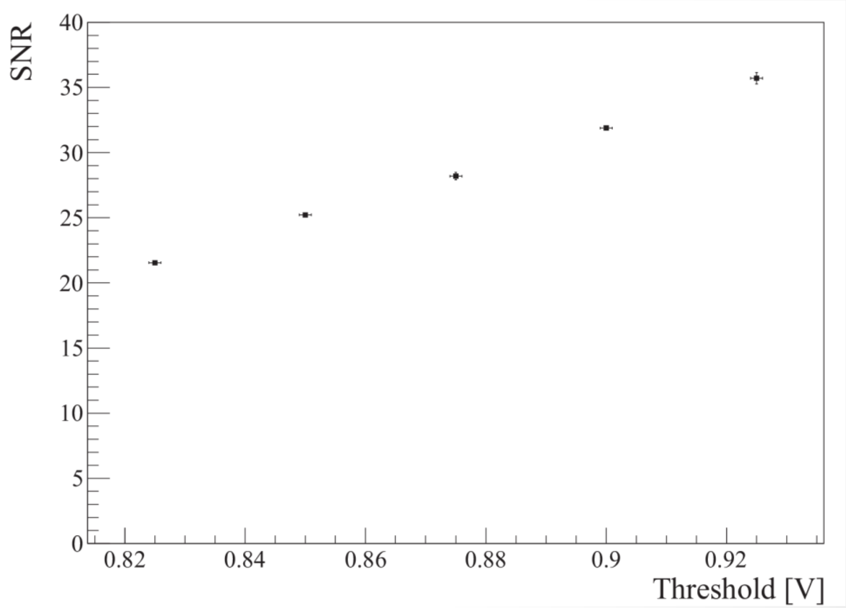
- MuPix2 prototype
- 170 GeV pion beam
- Used TimePix-telescope
- Pixel size:
  - 30 µm in x
  - 39 µm in y
- Resolution:
  - 11 µm in x
  - 15 µm in y

➢ Good resolution



# Signal to noise ratio

- Pre-amplifier at pixel
  - Low capacitance
  - Low noise
- ➢ Good signal to noise
- X-talk from digital readout possible
  - Digital part on fringe
- Radiation damage increases noise…

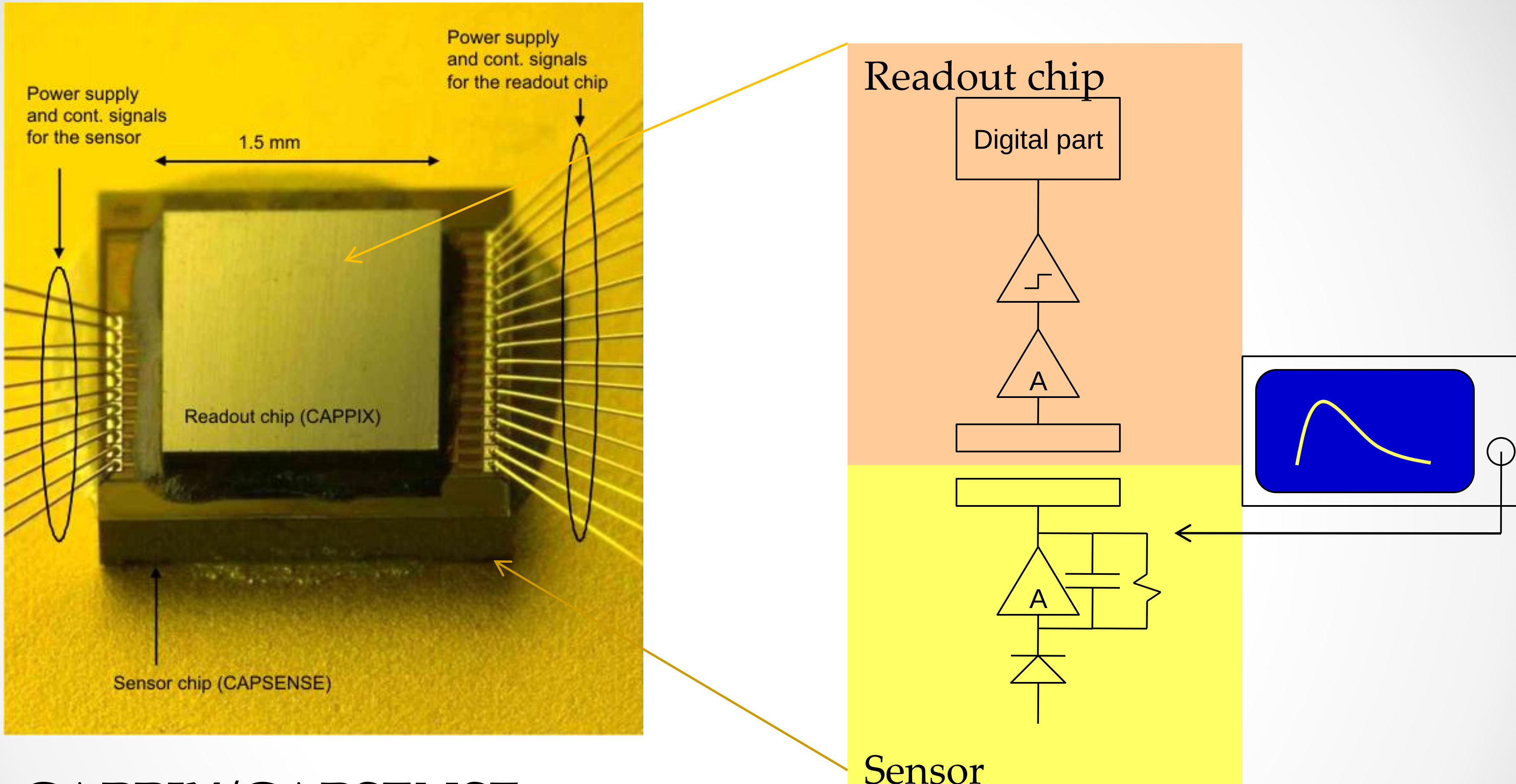


# Proton irradiation

KIT (Karlsruhe) $10^{15}$ $n_{eq}/cm^2$

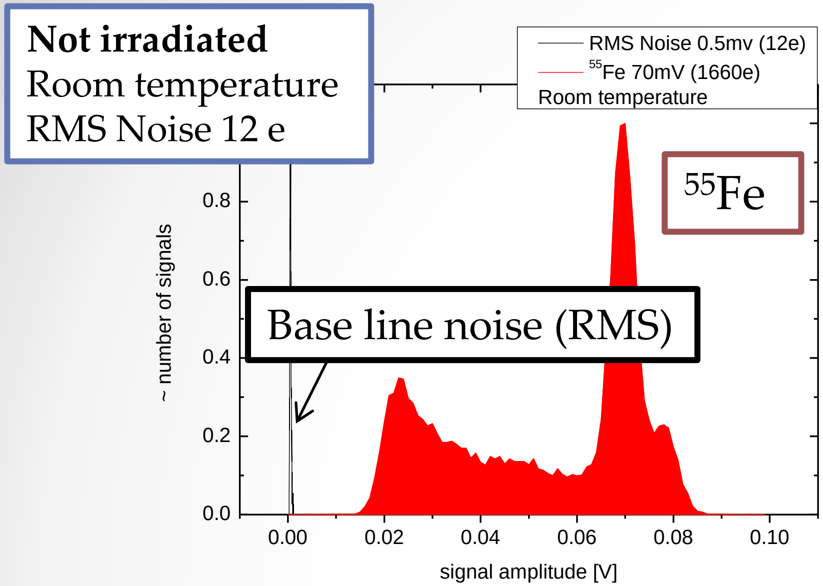
**RESMDD 2012, Firenze, Ivan Peric**

# Irradiated device: CCPD2




CAPPIX/CAPSENSE
edgeless CCPD
50x50 μm pixel size

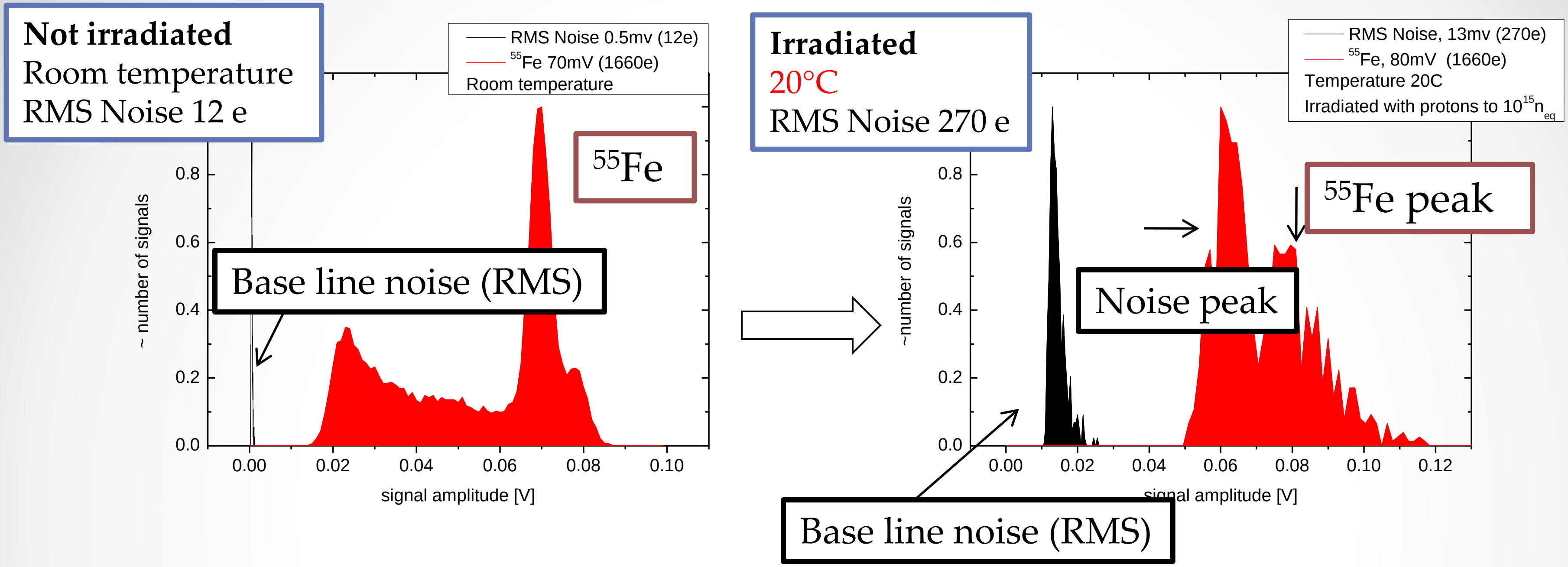
# Irradiation with protons at KIT $10^{15}$ $n_{eq}/cm^2$



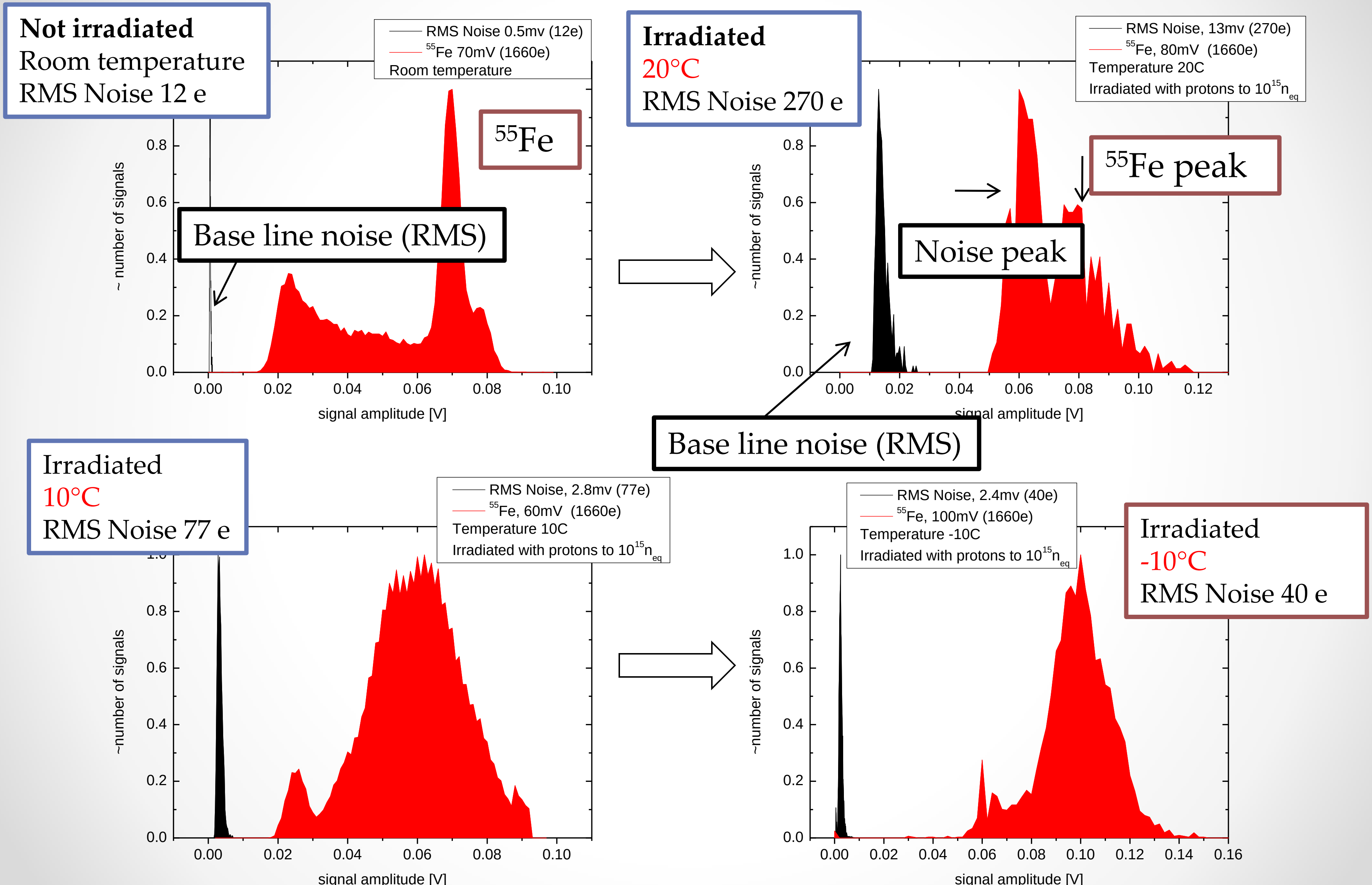



RESMDD 2012, Firenze, Ivan Peric

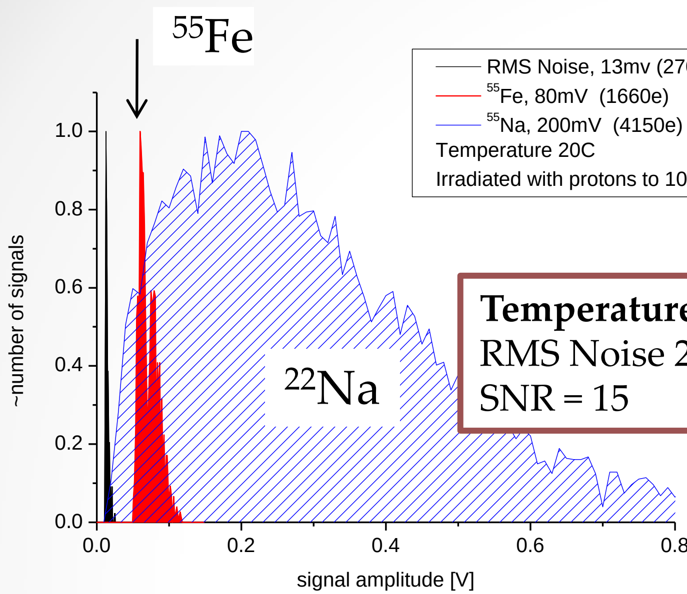
# Irradiation with protons at KIT $10^{15}$ $n_{eq}/cm^2$



# Irradiation with protons at KIT $10^{15}$ $n_{eq}/cm^2$



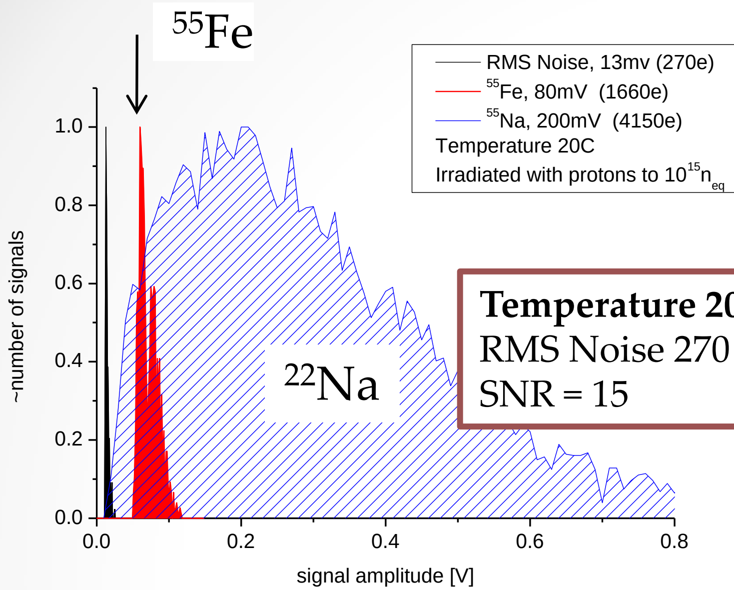
# Irradiation with protons at KIT $10^{15}$ $n_{eq}/cm^2$



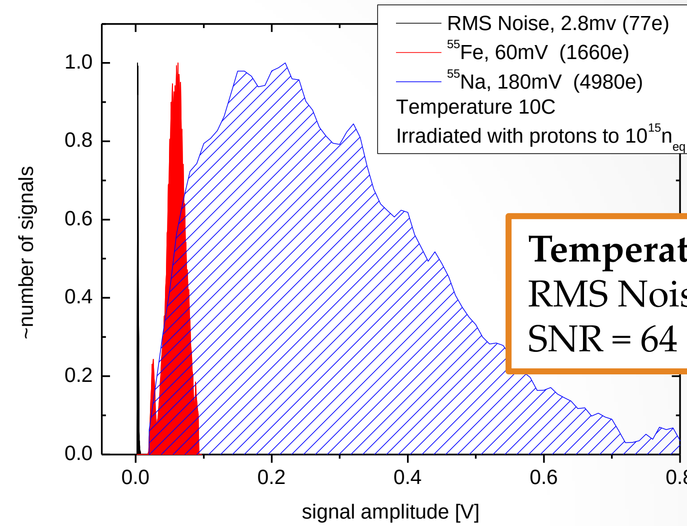

**Temperature 20°C**
RMS Noise 270 e
SNR = 15

$^{55}$Fe and $^{22}$Na spectrum, RMS noise

# Irradiation with protons at KIT $10^{15}$ $n_{eq}/cm^2$

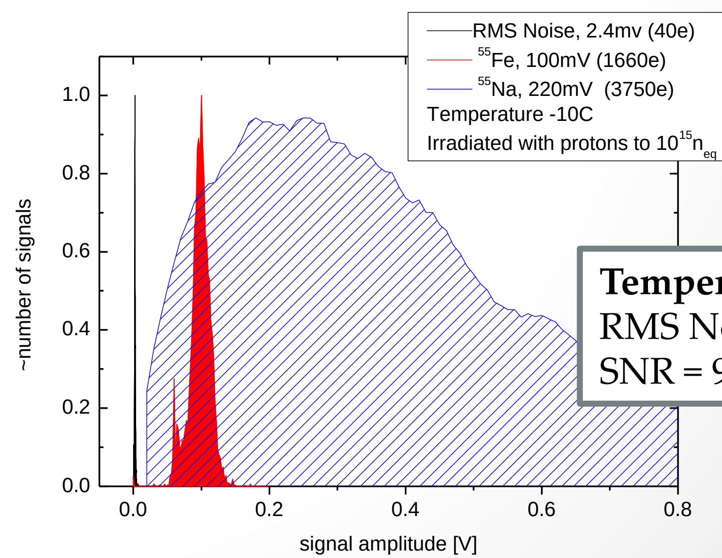



**Temperature 20°C**
RMS Noise 270 e
SNR = 15



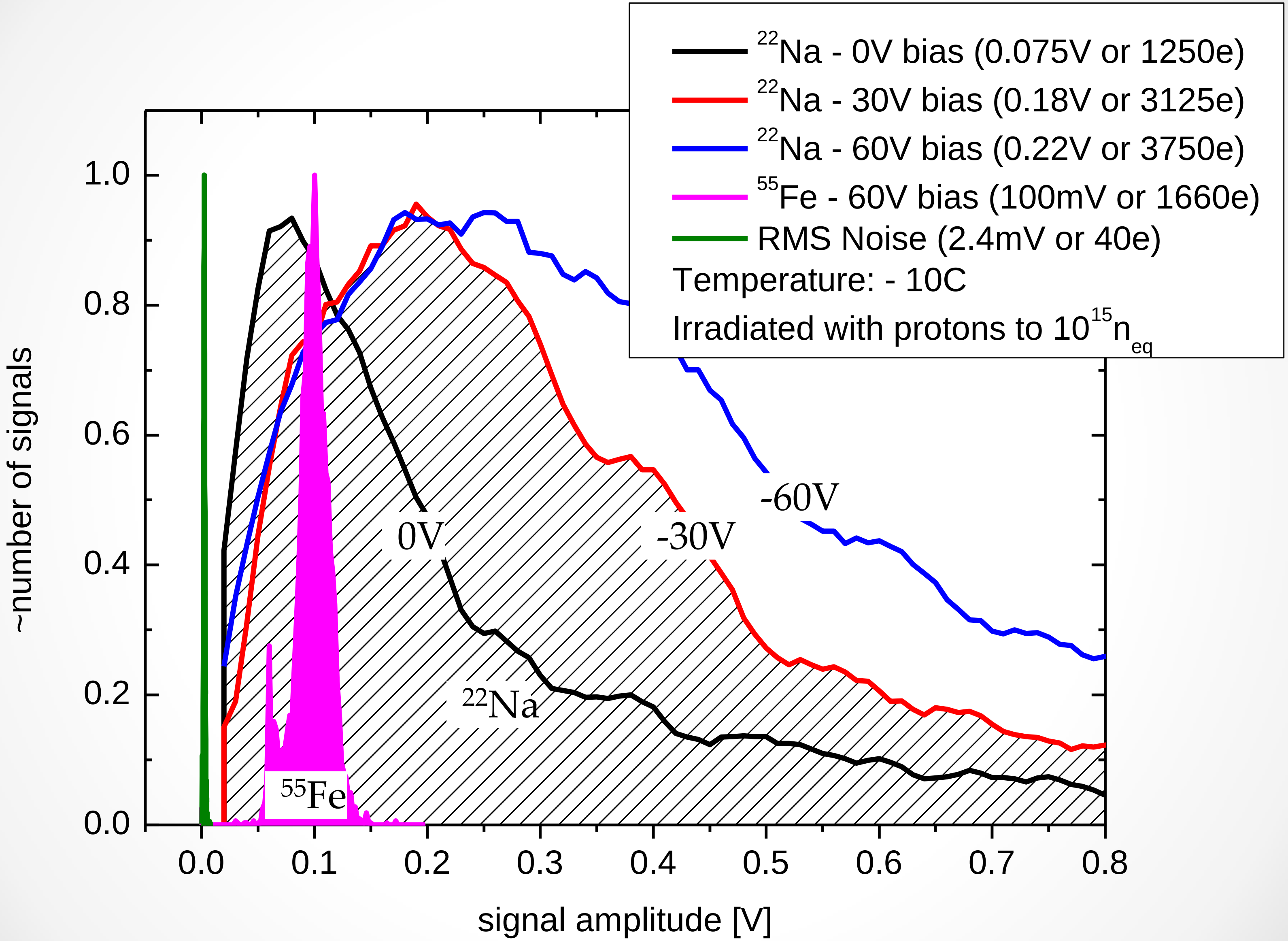

**Temperature 10°C**
RMS Noise 77 e
SNR = 64

$^{55}Fe$ and $^{22}Na$ spectrum, RMS noise




**Temperature -10°C**
RMS Noise 40 e
SNR = 93

# Irradiation with protons at KIT ($10^{15}$ $n_{eq}/cm^2$)






RESMDD 2012, Firenze, Ivan Peric

# Radiation hardness

- Irradiation test of HVCMOS sensors with:
  - **neutrons** $10^{14}$ $n_{eq}$ at Munich,
  - **protons** $10^{15}$ $n_{eq}$ and 8 x $10^{15}$ $n_{eq}$ - 380 MRad at KIT and PS
  - **x-rays** 50MRad at KIT
- Two main effects are observed:
  - **Reduction** of the secondary **signal** part that is collected by diffusion
  - **Increase** of **leakage current**
- Good SNR can be achieved after irradiation
  - if the sensors are **cooled** to ~ 0°C
- Charge multiplication factor can further increase SNR

➢ Although we still do not understand all effects, the HVCMOS sensors seem to have a high radiation tolerance.

# HV MAPS Properties

- Good resolution
- Fine granularity
- Radiation hard
- Fast
- Cheap
- Similar radiation length as gas detectors
- Medium power
- Production by outside company

# HV MAPS Properties

### Gas detectors

- ✚ Cheap
- ✚ Light weight
- ✚ Well known technology
- ✚ Low power
- – Ageing
- – Little granularity
- – Some types are slow

### Silicon detectors

- ✚ Very good resolution
- ✚ Fine granularity
- ✚ Radiation hard
- ✚ Fast
- – High power
- – Expensive
- – Production by outside company
- – More material than gas detectors

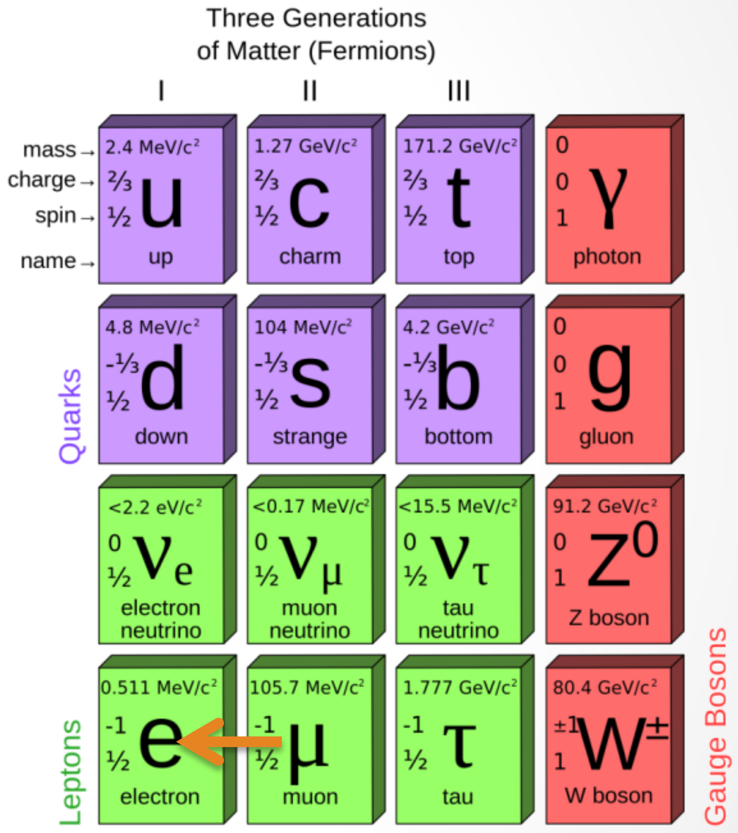
### **HV-MAPS**

- ✚ Good resolution
- ✚ Fine granularity
- ✚ Radiation hard
- ✚ Fast
- ✚ Cheap
- ✚ Similar material as gas chambers
- ▪ Medium power
- – Production by outside company

# HV-MAPS Based Detector: Mu3e Tracker

# Physics Motivation

Lepton flavor violation?

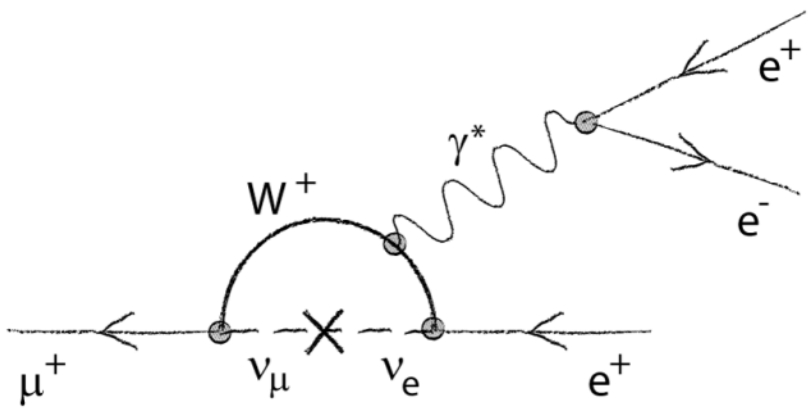



Standard model:

- No lepton flavor violation

# Physics Motivation

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

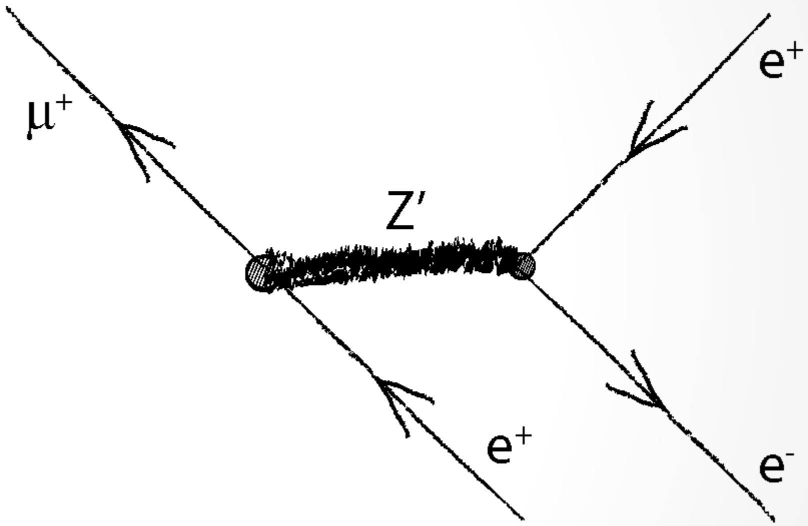


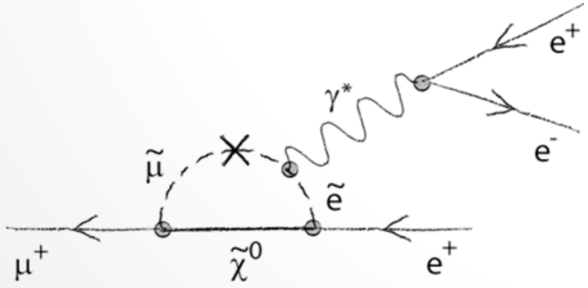

Standard model:

- 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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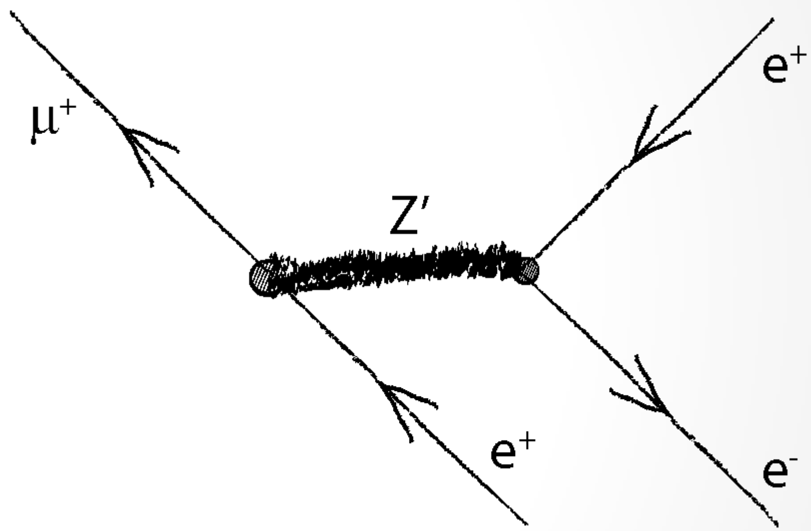
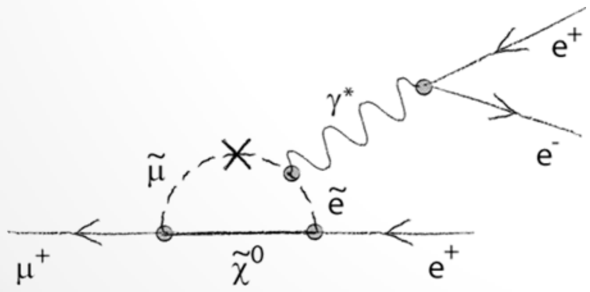
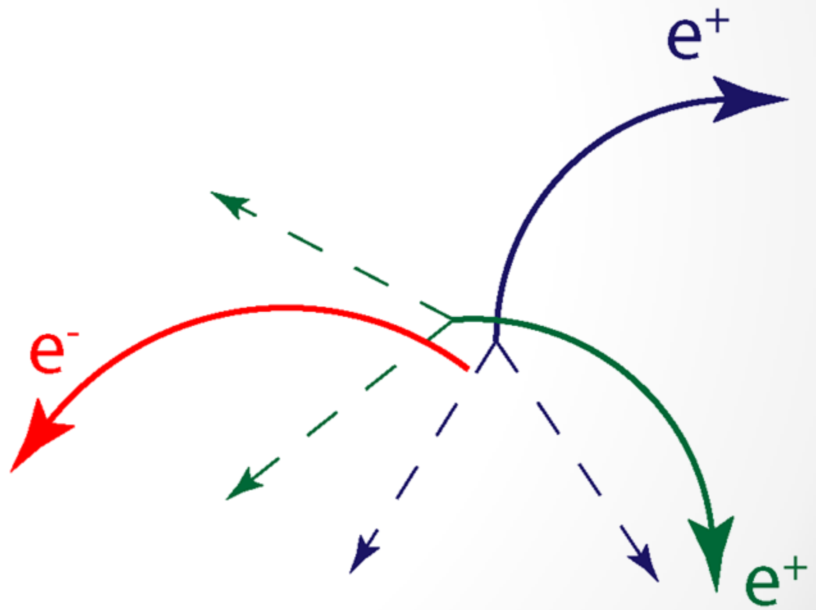



- Rare decay (BR<$10^{-12}$, SINDRUM)
- For BR O($10^{-16}$)
  - >$10^{16}$ muon decays
  - **High decay rates O($10^{9}$ muon/s)**

# The Mu3e Background

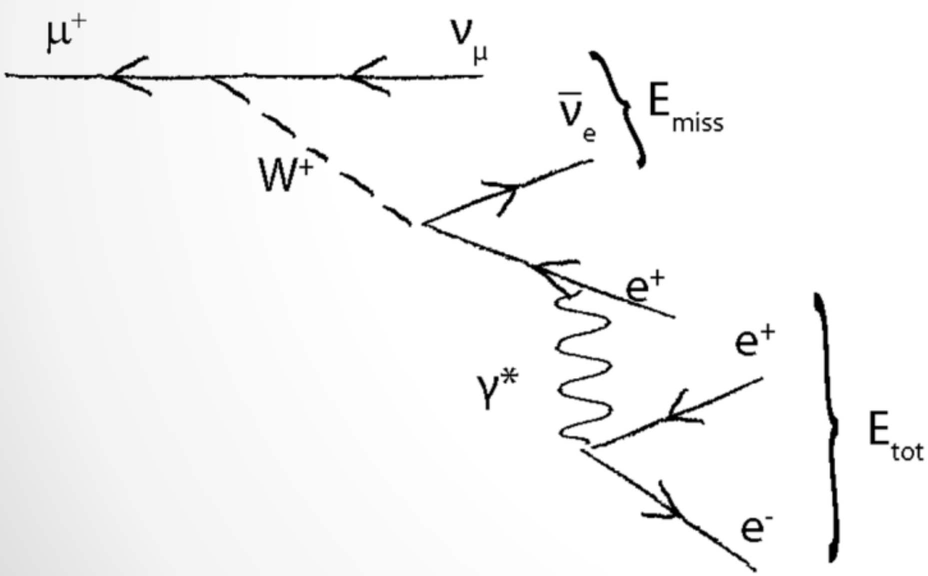
- Combinatorial background
  - $\mu^+ \to e^+ \nu\nu$ & $\mu^+ \to e^+ \nu\nu$ & $e^+ e^-$
  - many possible combinations

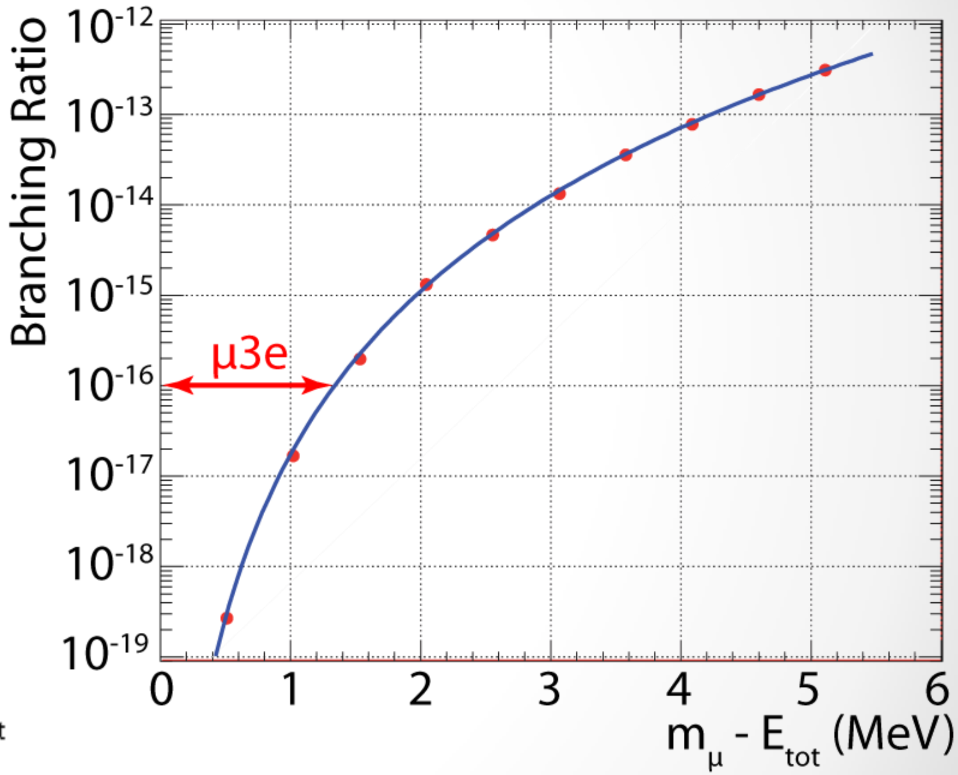



- **Good time and**
- **Good vertex resolution required**

# The Mu3e Background

- $\mu^+ \rightarrow e^+ e^- e^+ \nu\nu$
  - o Missing energy ($\nu$)
  - ➢ **Good momentum resolution**




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

# Challenges

- High rates
- Good timing resolution
- Good vertex resolution
- Excellent momentum resolution

➢ Extremely low material budget

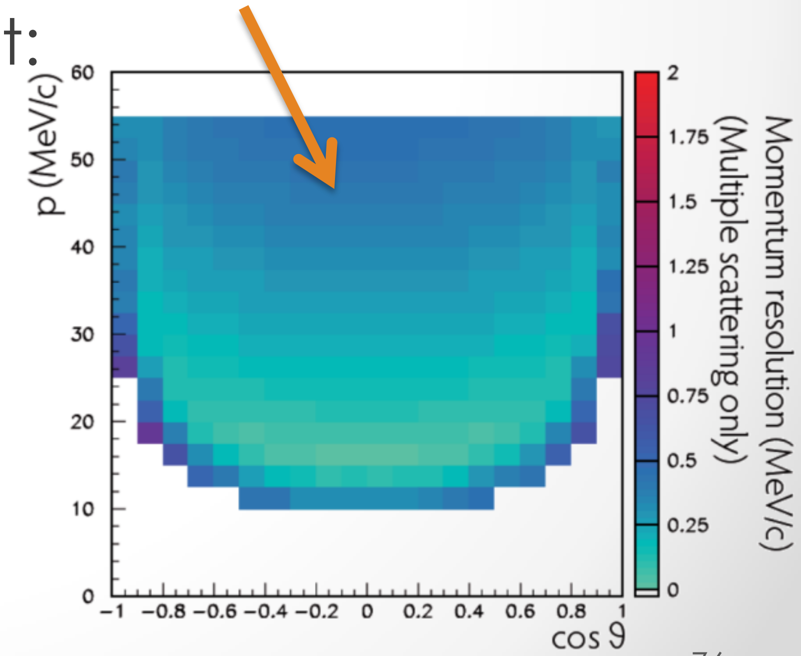
# Challenges

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

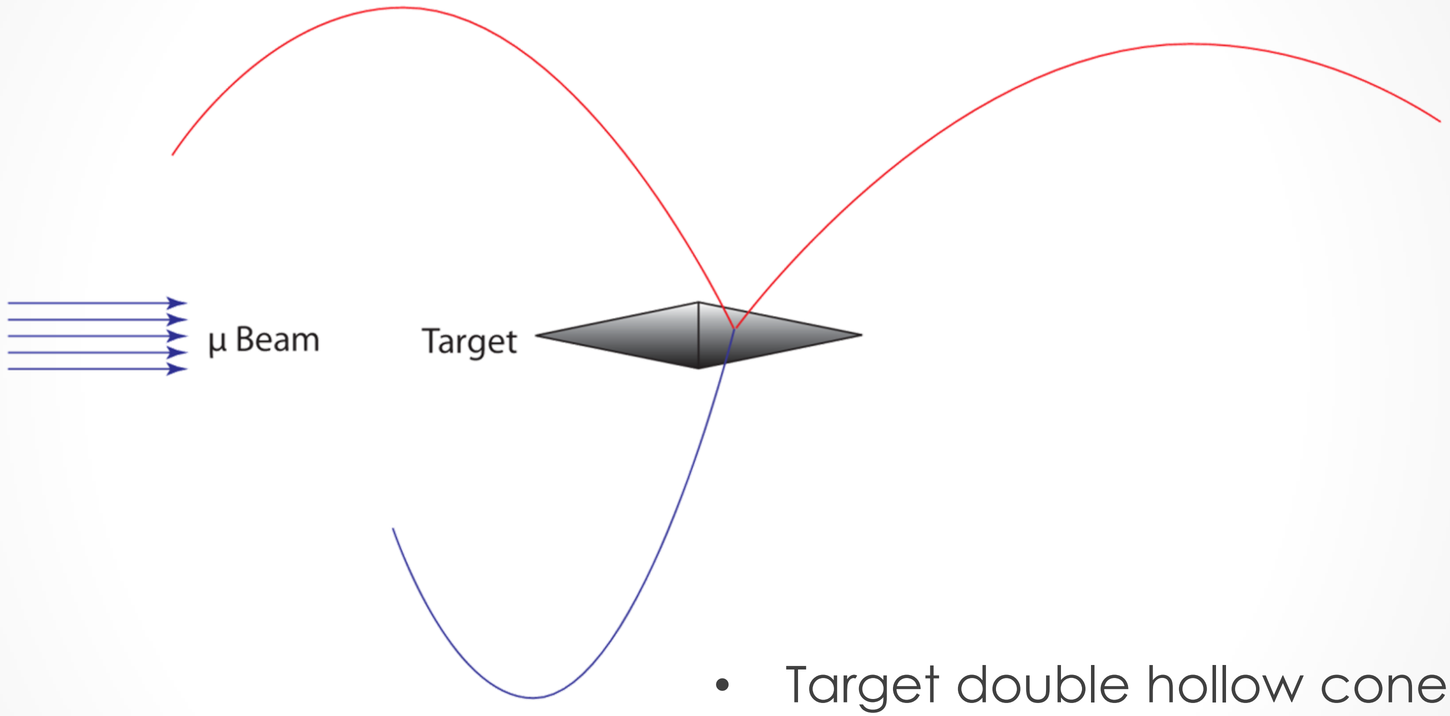
➢ Extremely low material budget:
  - ➢ $1 \times 10^{-3}$ $X_0$ (Si-Tracker Layer)

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

➢ + Timing detectors



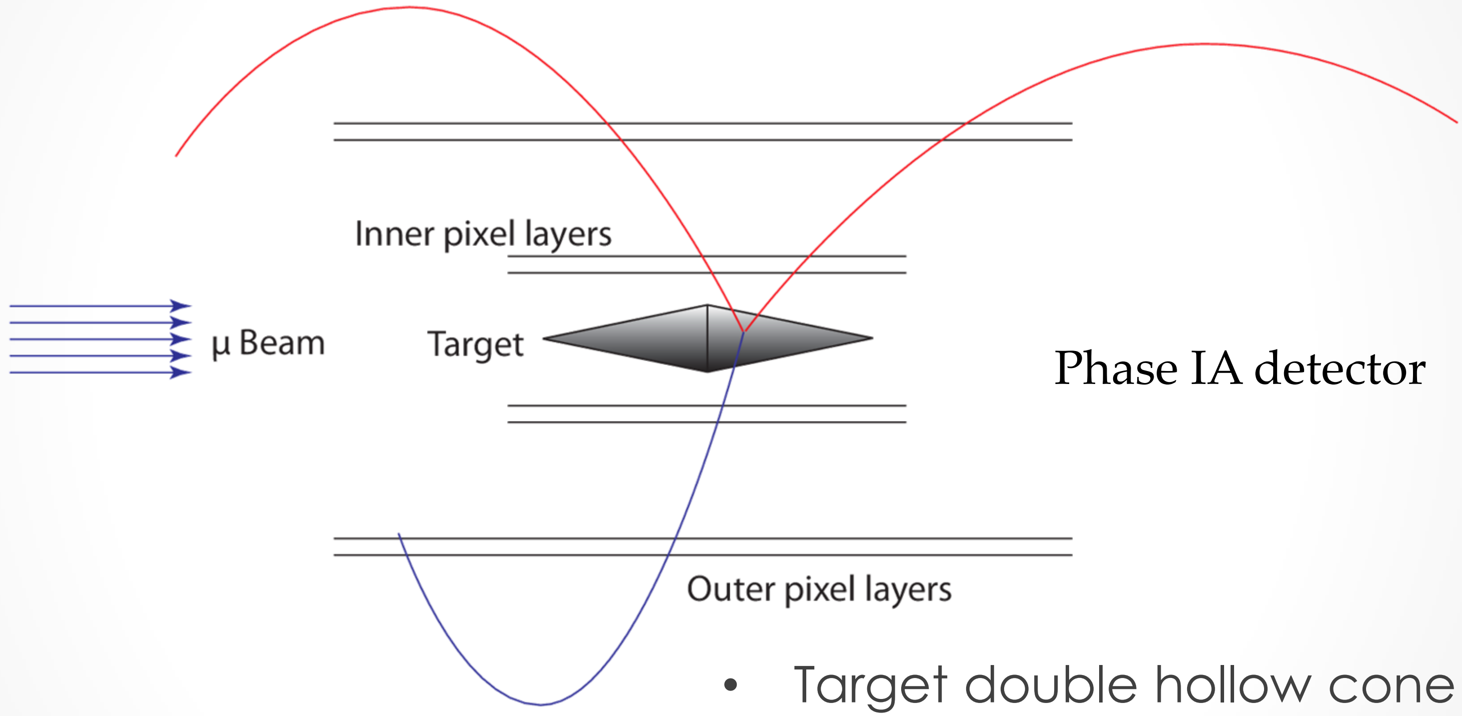
# The Mu3e Experiment




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

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

# The Mu3e Experiment

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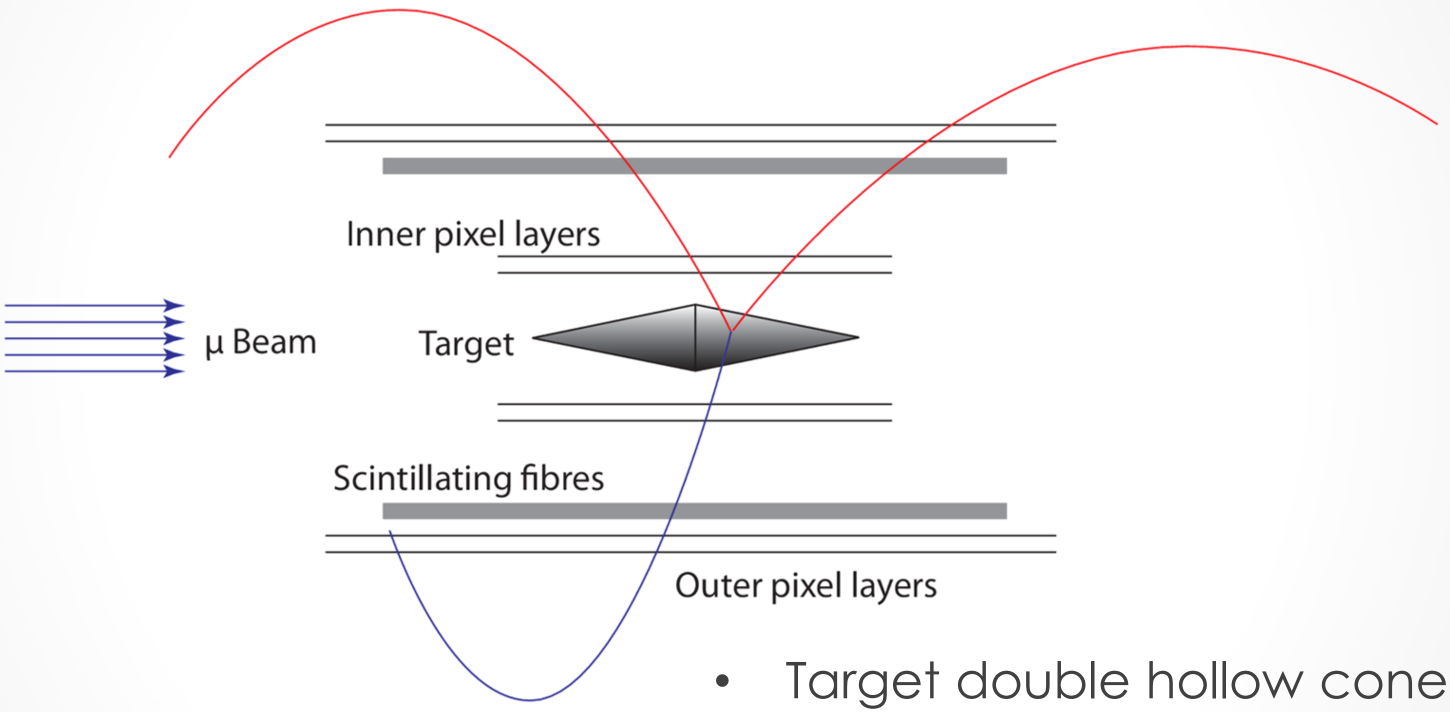


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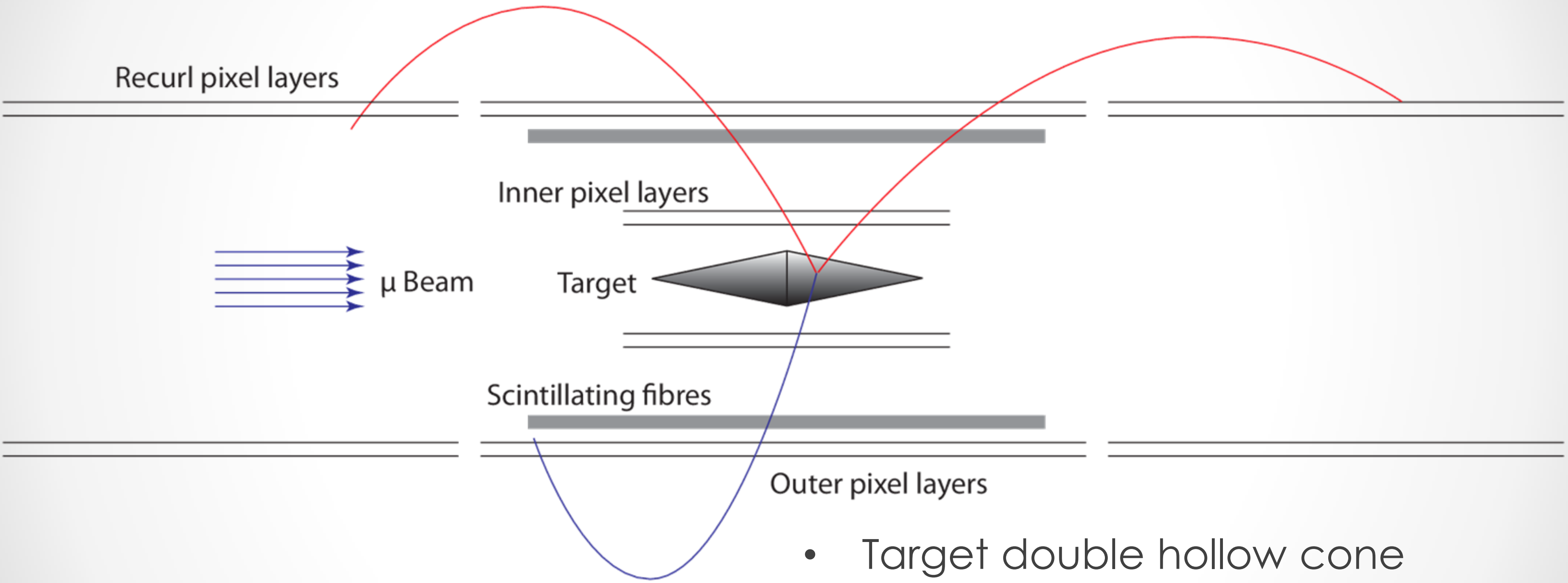


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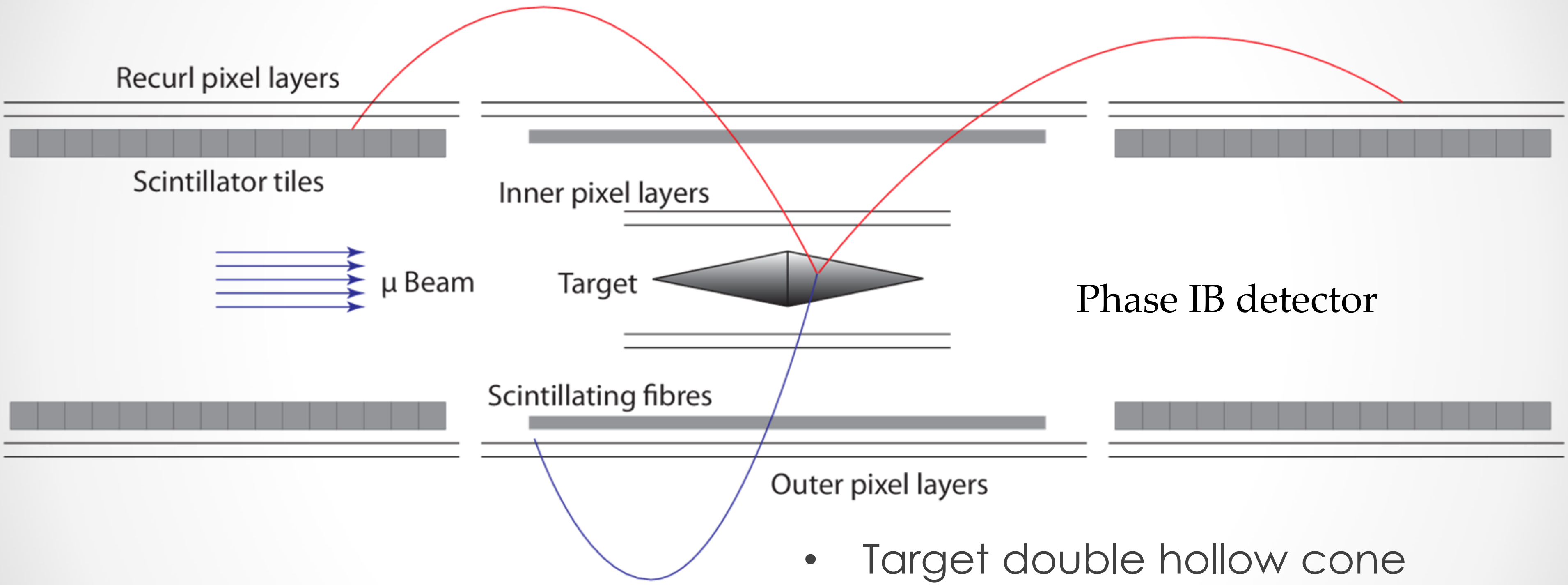


Phase IB detector

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

- Target double hollow cone
- Silicon pixel tracker
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- Recurl station
- Tile hodoscope

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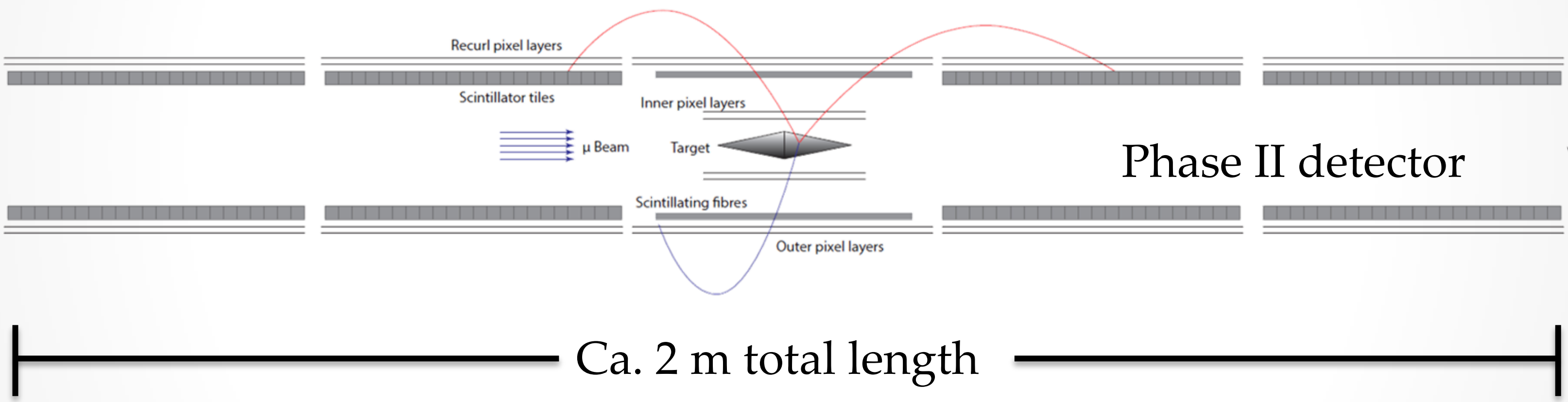


- Muon beam O($10^9$/s)
- Helium atmosphere
- 1 T B-field

- Target double hollow cone
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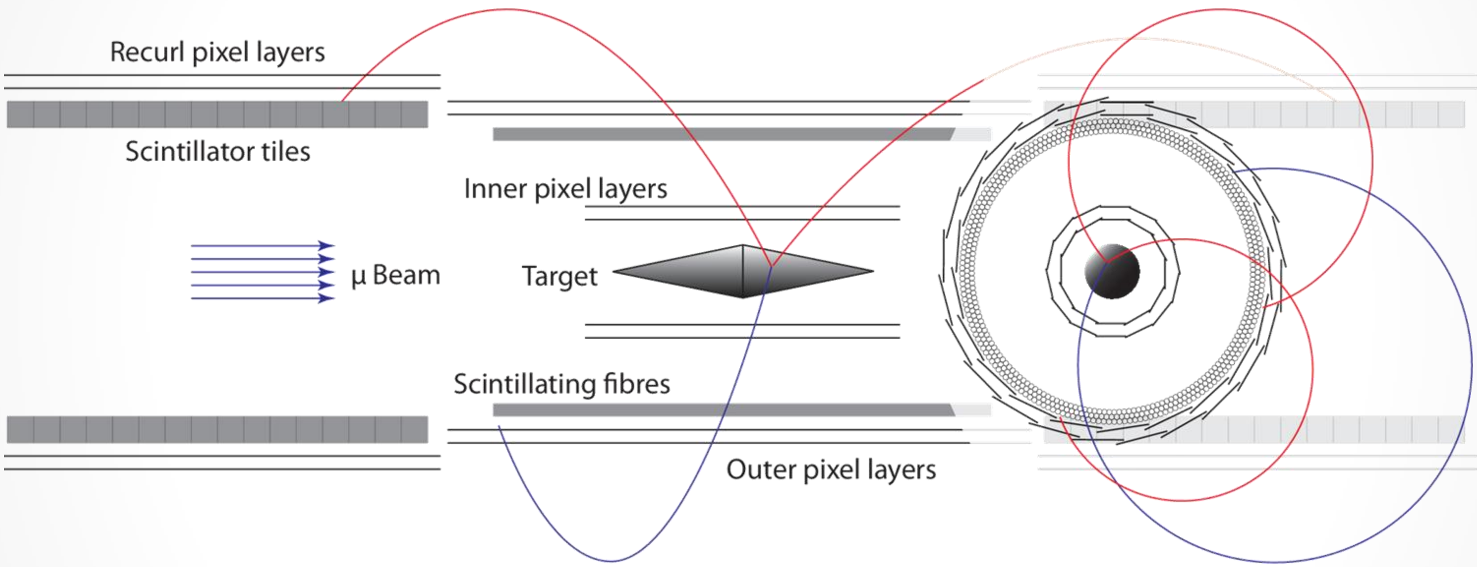
# The Mu3e Experiment




- Muon beam O(10$^9$/s)
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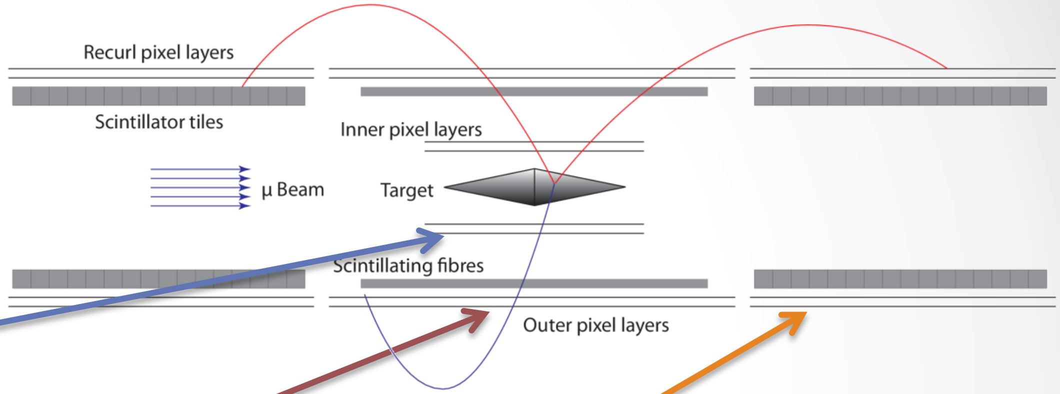
# Mu3e Silicon Detector



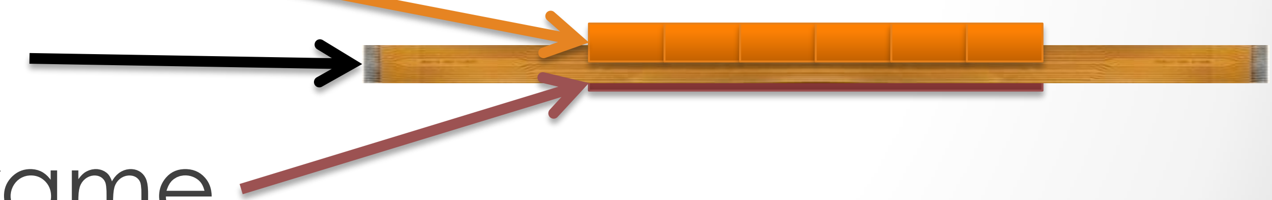

- Conical target
- Inner double layer
  - 12 and 18 sides of 1 x 12 cm
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm
- Re-curl layers
  - 24 and 28 sides of 2x 72 cm
  - Both sides (x2)

180 inner sensors
4680 outer sensors
➢ 274 752 000 pixel

# Lightweight Detector

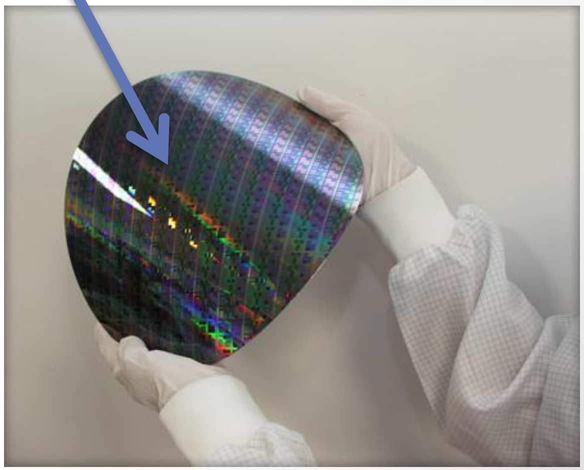
# Material

- HV-MAPS
- Flex print
- Kapton Frame



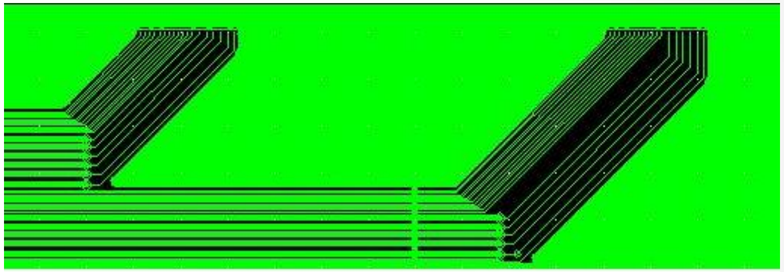
# Thinning

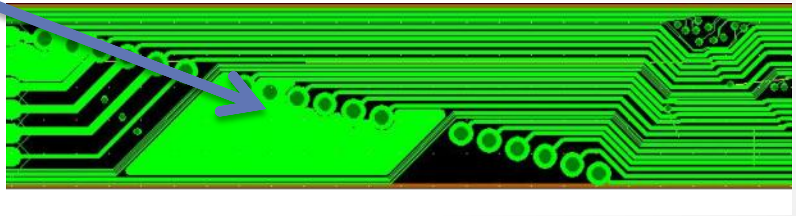
- 50 µm Si-wafers
  - Commercially available
  - HV-CMOS 75 µm (AMS)
- Single die thinning
  - For chip sensitivity studies
  - < 50 µm desirable
  - In house grinding?
  - ➢ Local company



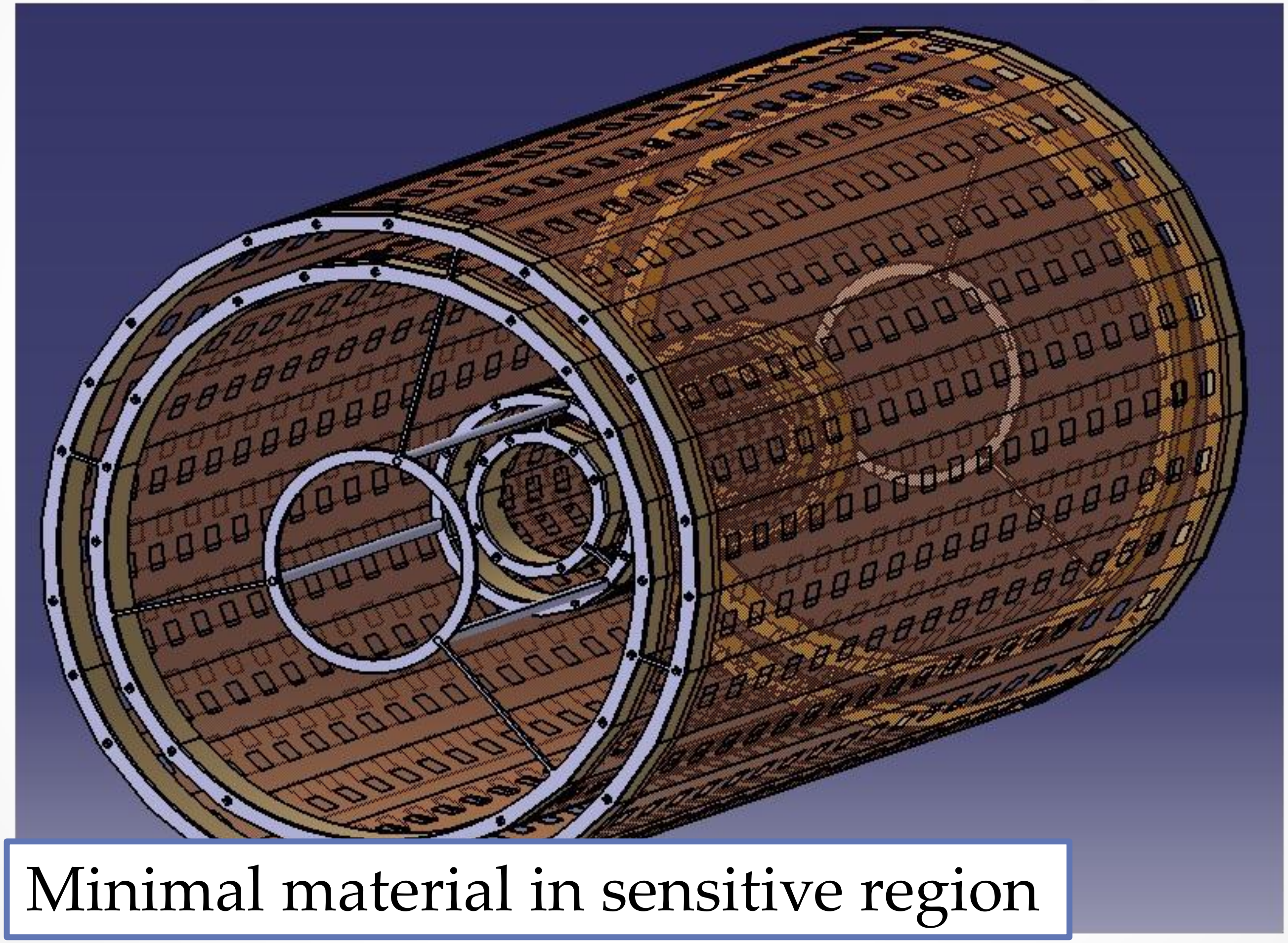
# Flex Print

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



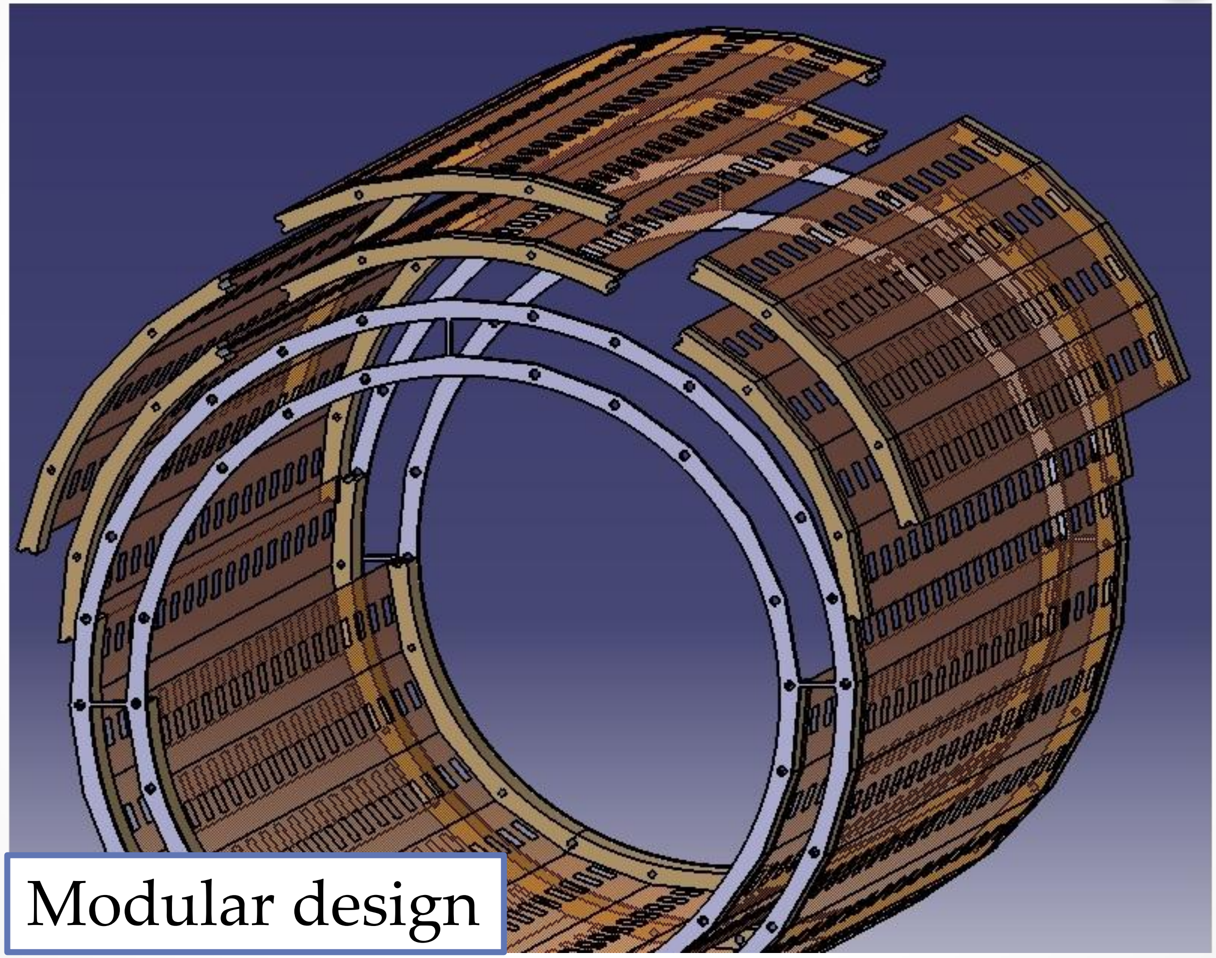


# Outer Double Layer



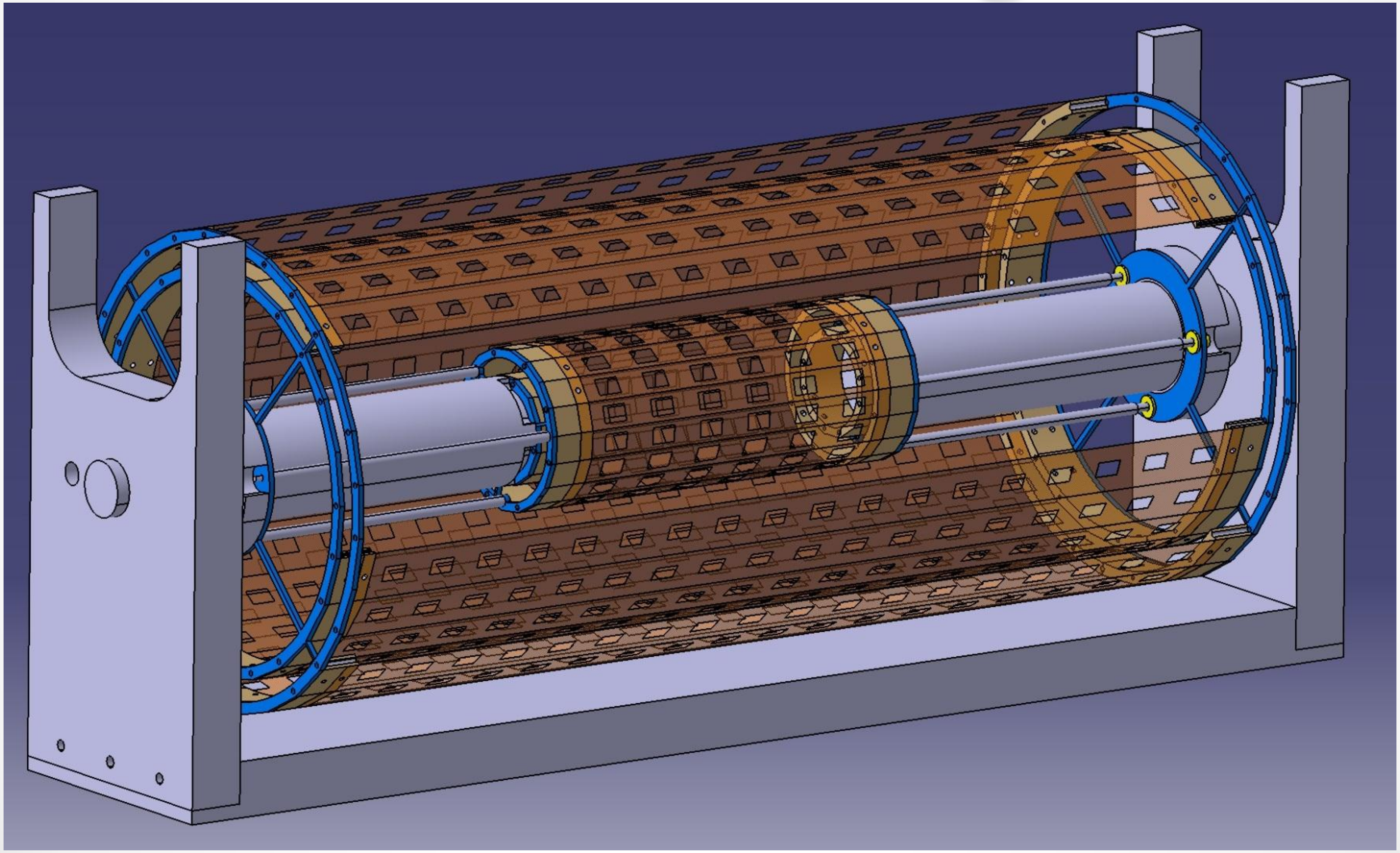
Minimal material in sensitive region

# Outer Doublet Design



Modular design

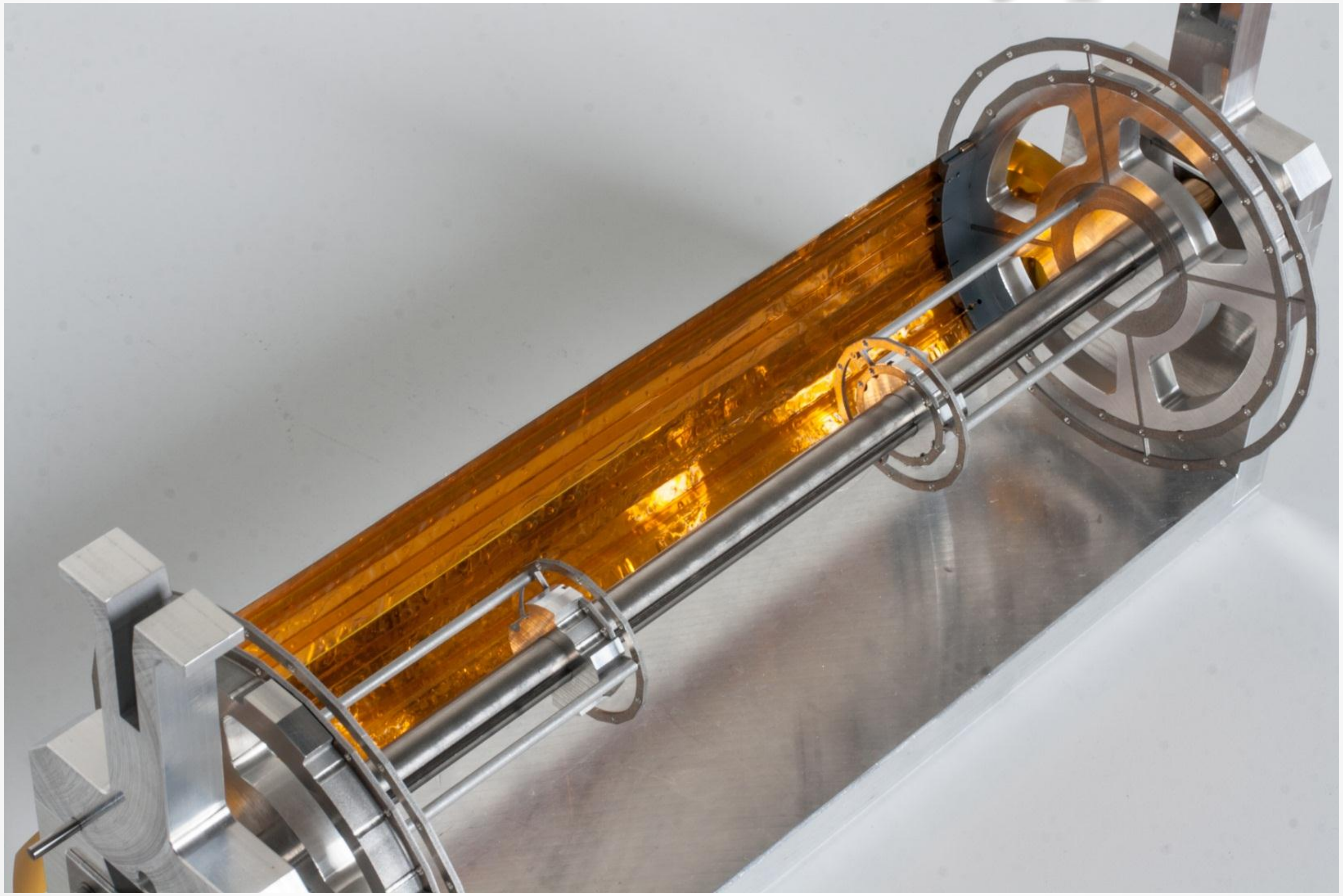
# Station Design



# Inner Double Layer

Very stable self supporting structure

# Station Prototype

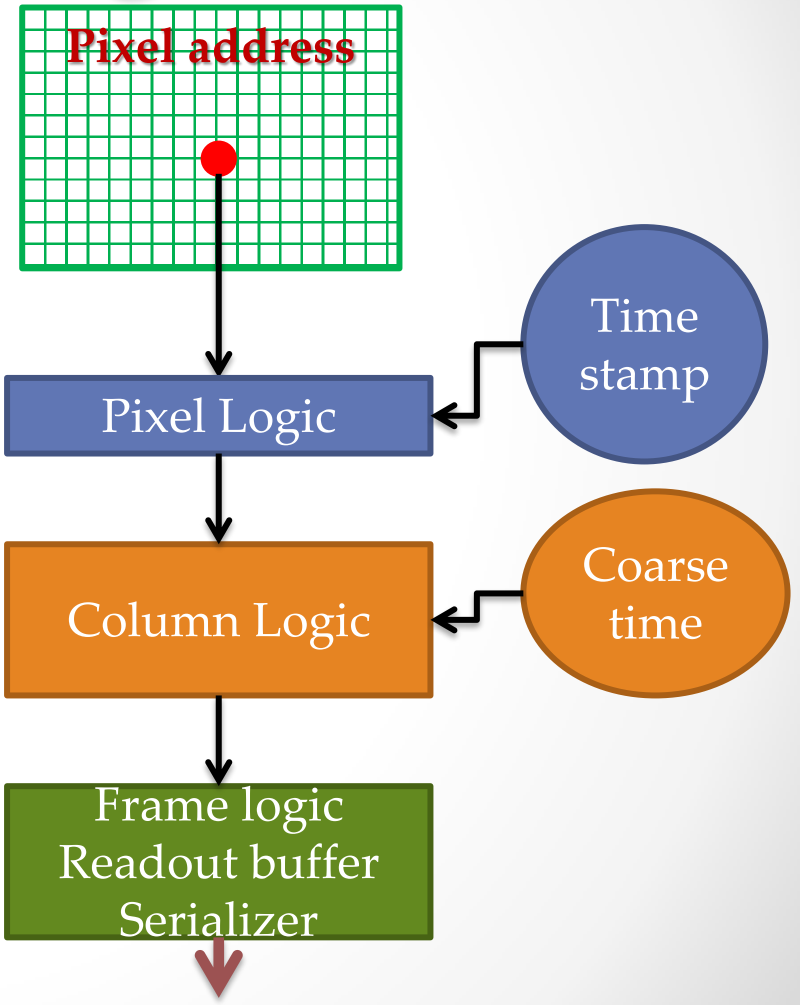


# Mu3e
# 1Tbit/s Readout

# Digital Logic

Zero suppressed readout:

- 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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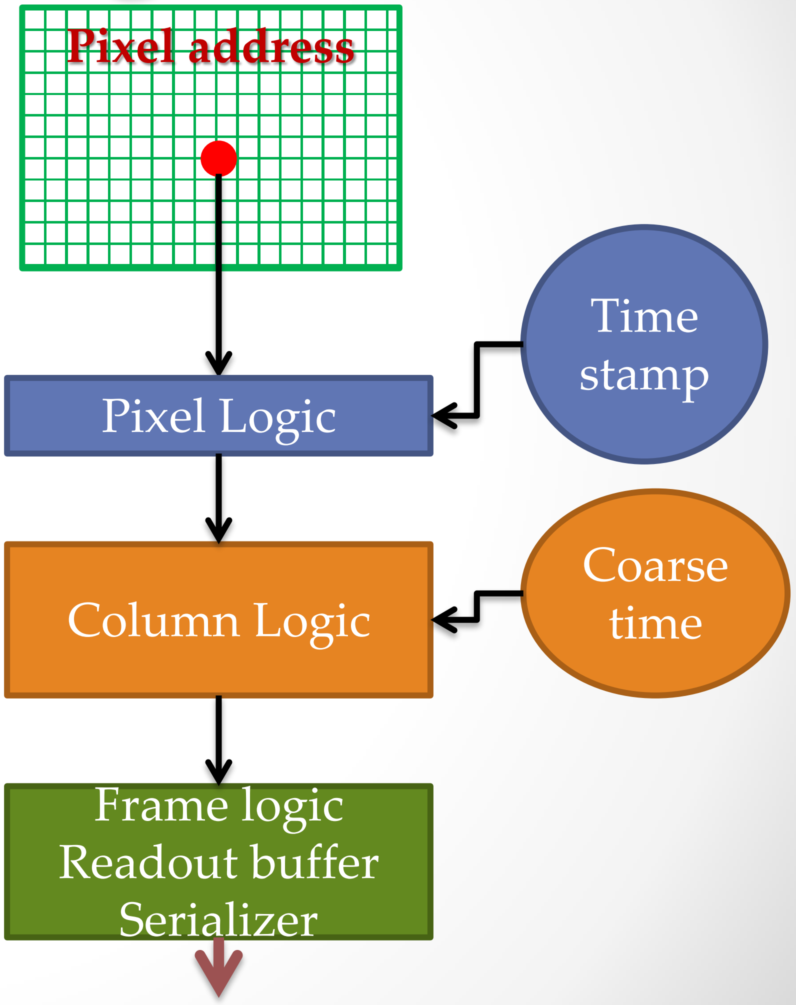

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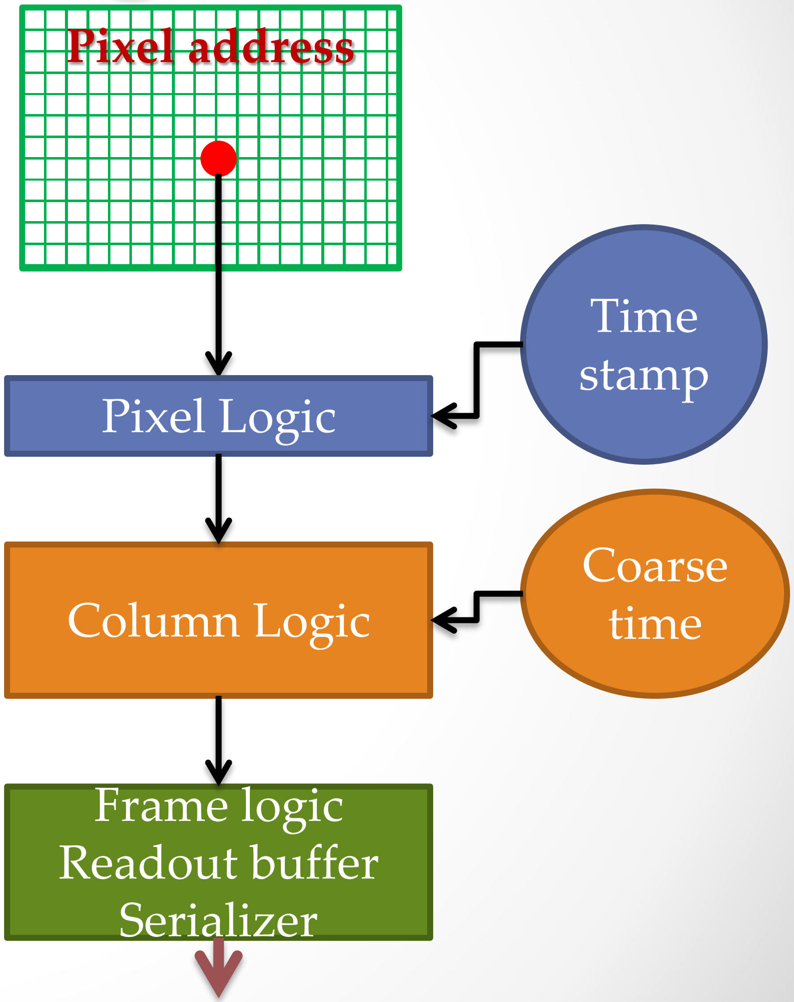
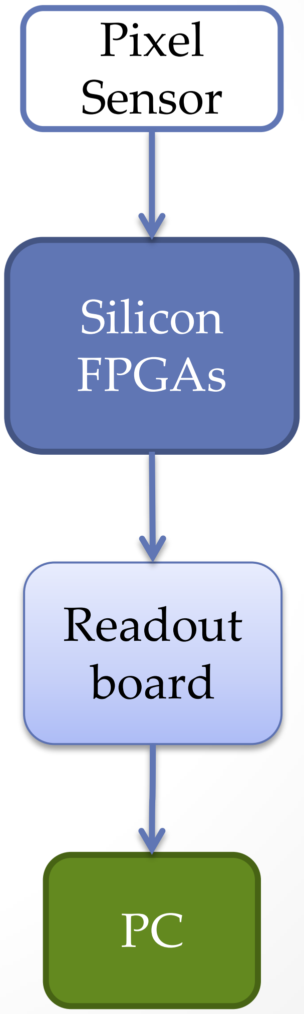


# Data Acquisition

- 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



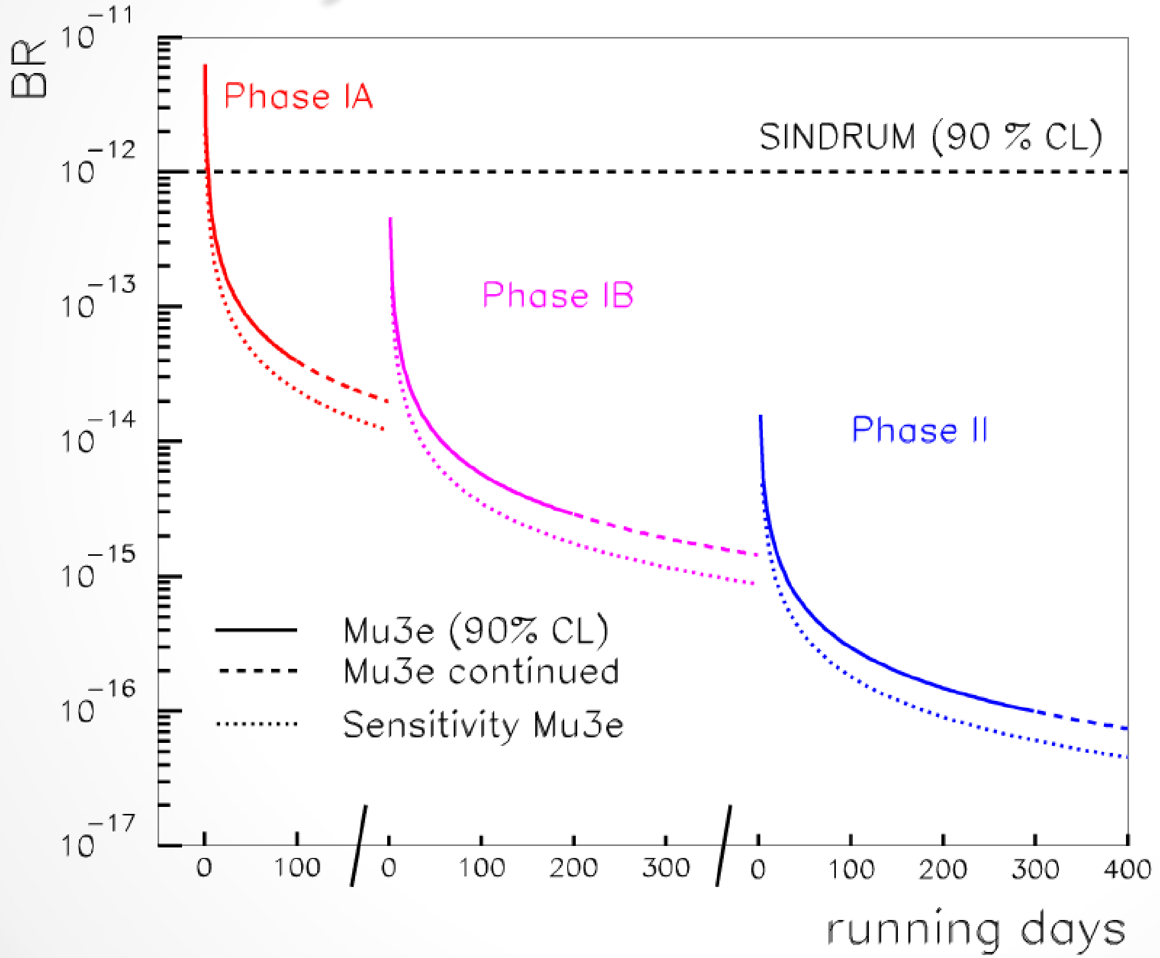
# Event Filter Farm

- Trigger less 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

# Projected Sensitivity



# Schedule

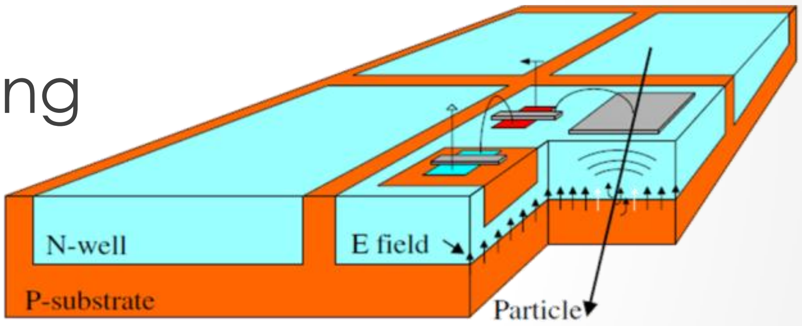
- **2012 Letter of intent** to PSI, tracker prototype, technical design, research proposal
- **2013** Detector **construction**
- **2014** Installation and **commissioning** at PSI
- **2015** Data taking at up to a few **$10^8$ μ/s**
- **2016+** Construction of **new beam-line** at PSI
- **2017++** Data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

# Institutes

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

# Summary

- High Voltage Monolithic Active Pixel Sensors combine good properties of
  - Gas detectors
  - Hybrid silicon detectors
- First prototypes look promising
  - Low noise
  - Fast
  - Radiation hard

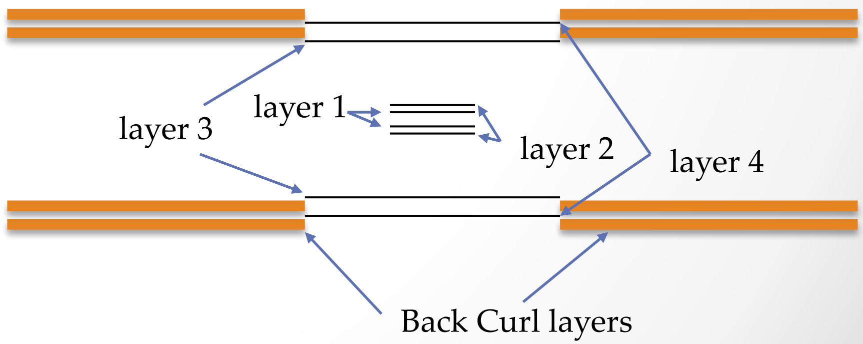



- First HV-MAPS detector system for Mu3e experiment

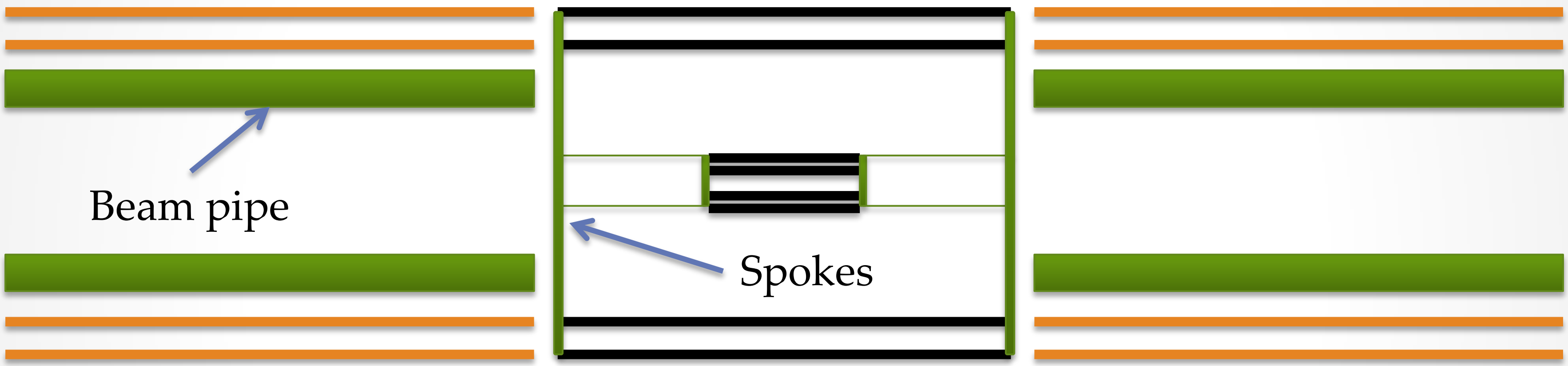
# Backup Slides

# 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 $\Theta_{min}$ = 22.9°
  - $X_0$= 21.1e-4



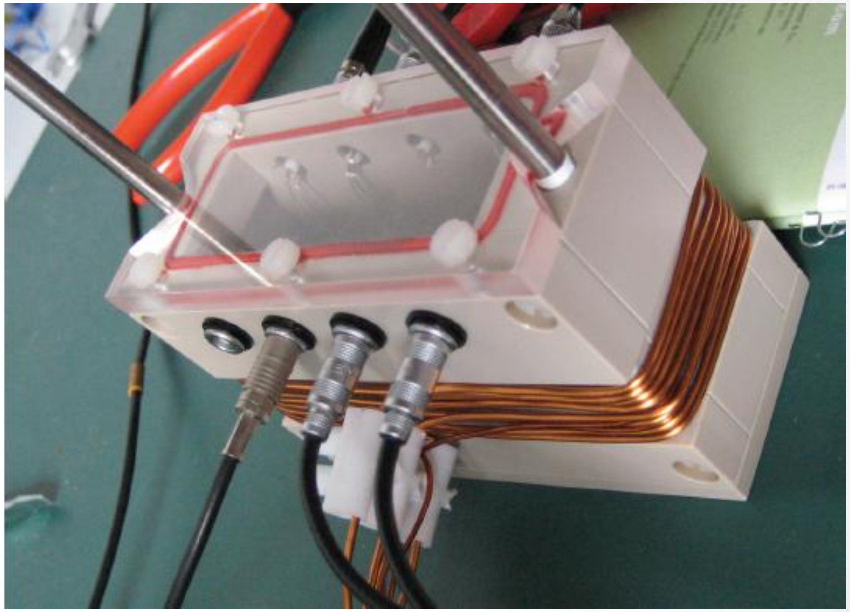
# Frame Support




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

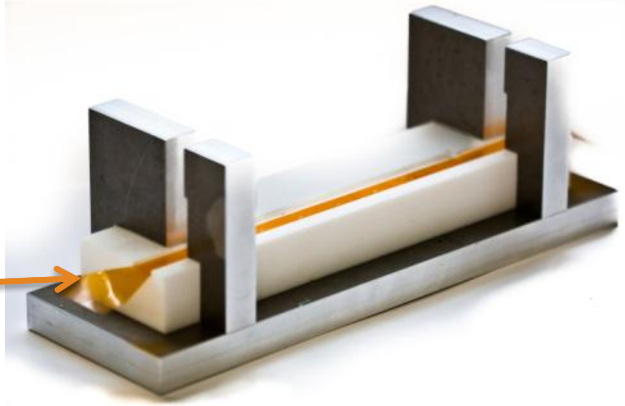
# Cooling

- 2 $m^2$ silicon detector
- Up to 200mW/$cm^2$
- ➢ ≤ 4 kW cooling
- 60 °C maximum
- Gaseous helium
- Laminar flow
- Tests:
    - Inductive heating
    - Aluminum foil



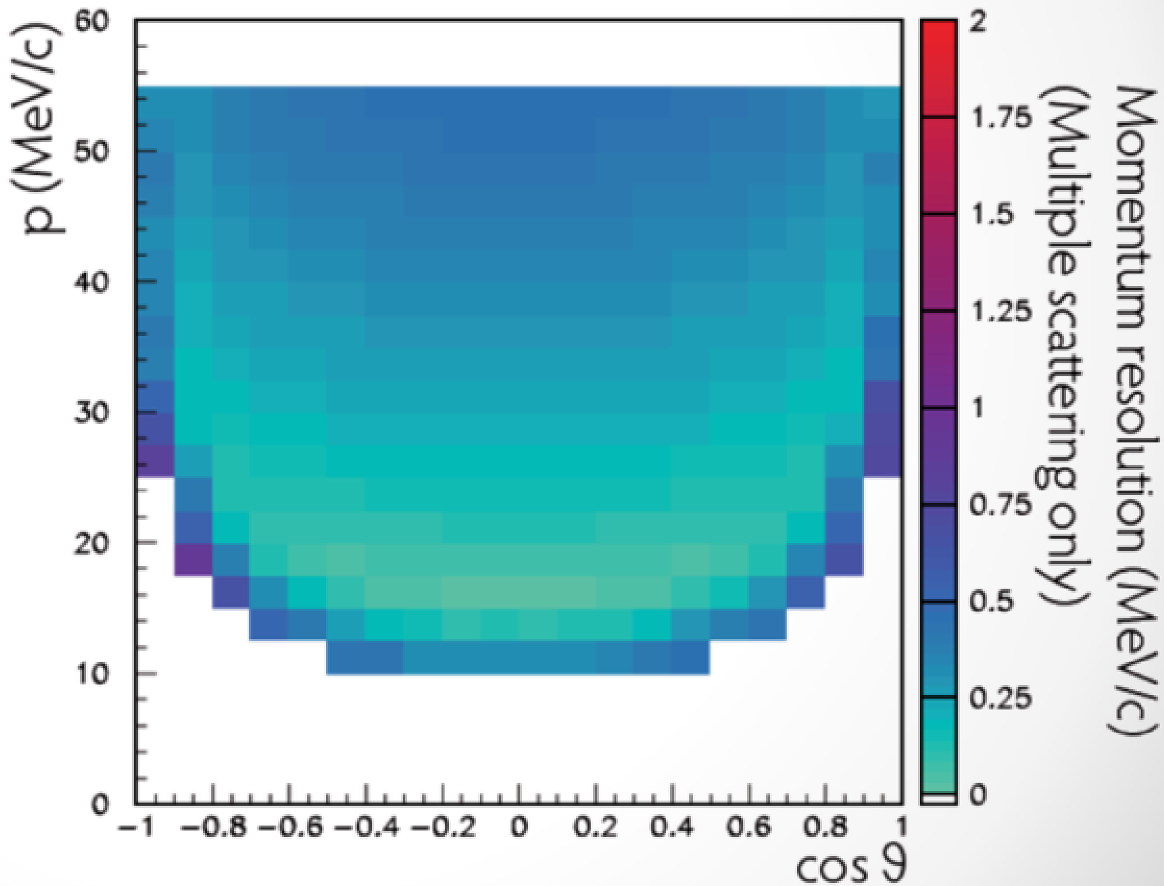
# Tools

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

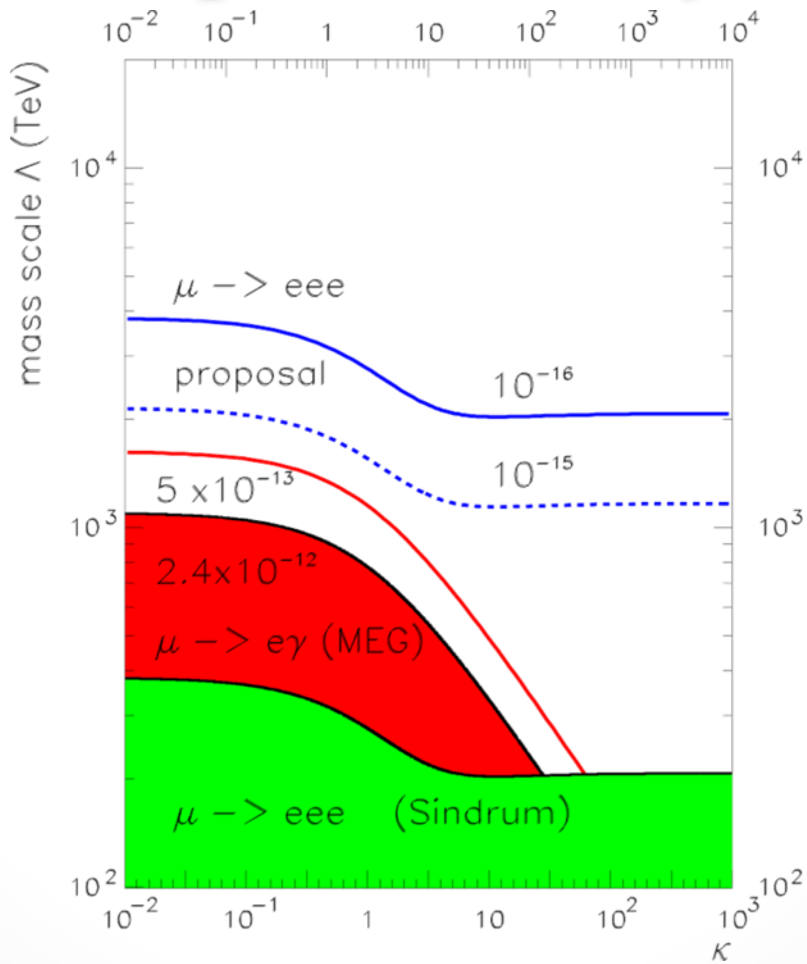


# Momentum Resolution

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



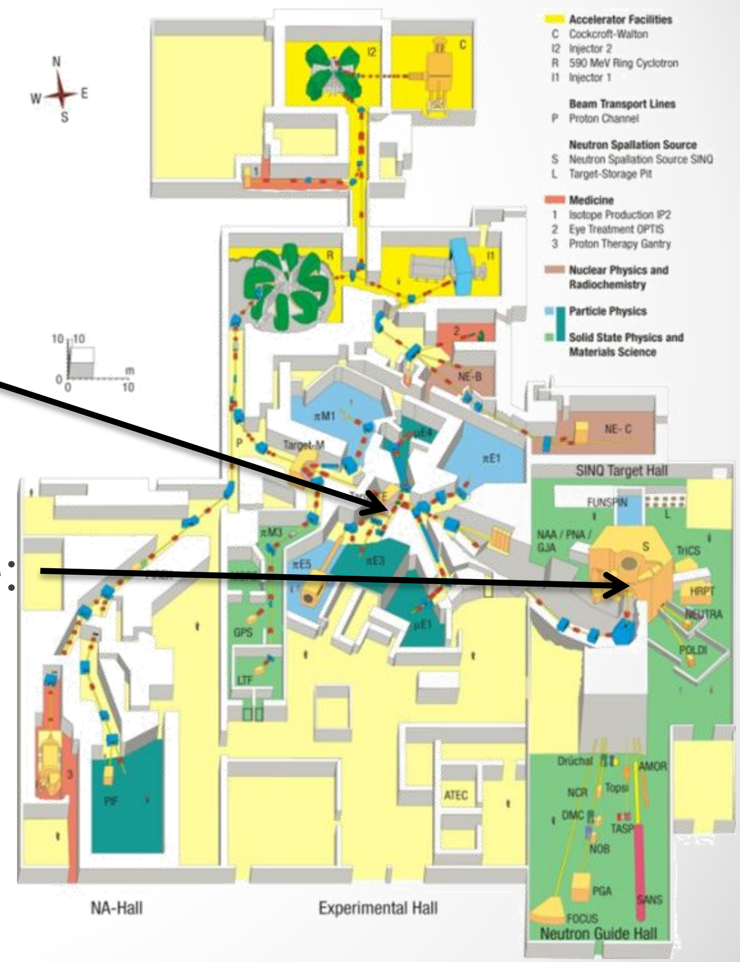
# Mu3e complementary to MEG



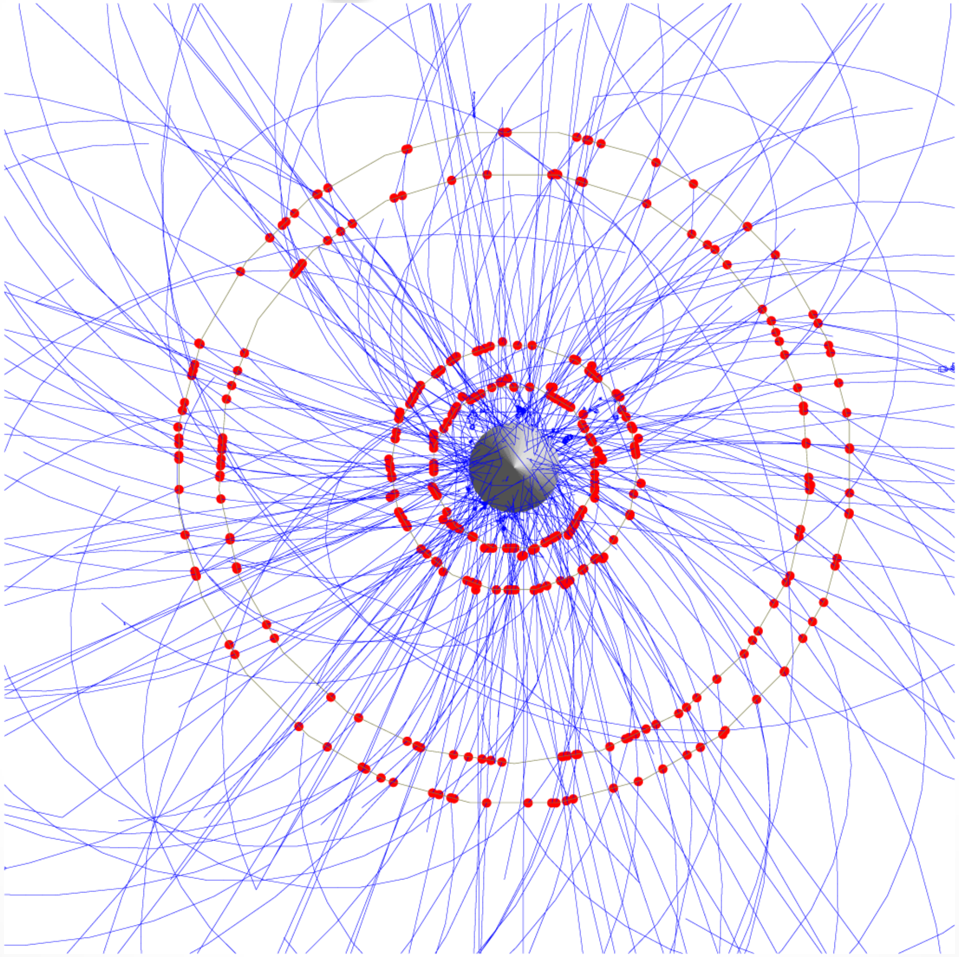
# PSI μ-Beam

Paul Scherrer Institute Switzerland:

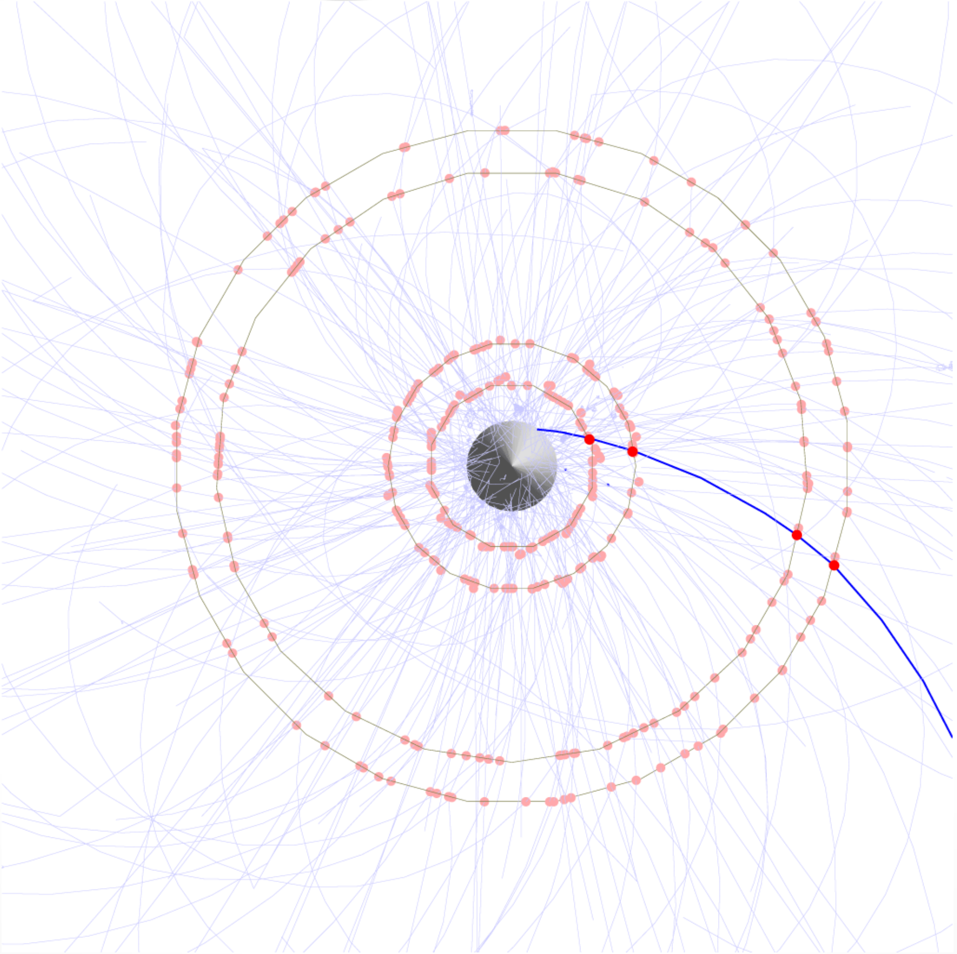
- 2.2 mA of 590 MeV/c protons
- Phase I:
  - Surface muons from target E
  - Up to a few $10^8$ μ/s
- Phase II:
  - New beam line at the neutron source: HIMB project (2y application)
  - Several $10^9$ μ/s possible
  - ➢ $>10^{16}$ muon decays per year
  - ➢ BR $10^{-16}$ (90% CL)



# Timing Detectors

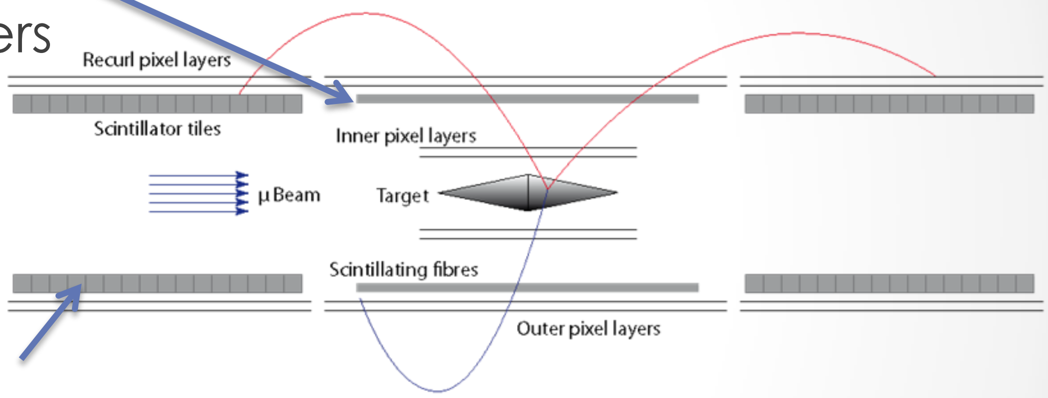


# Timing Detectors



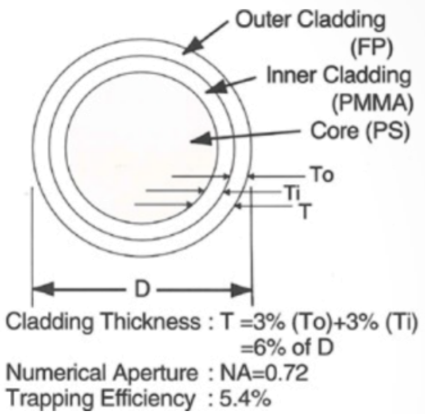
# Timing Detectors

- 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

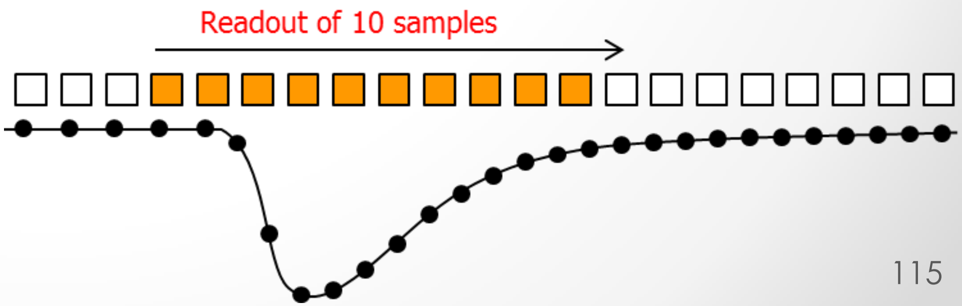


# Fiber Hodoscope

- 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

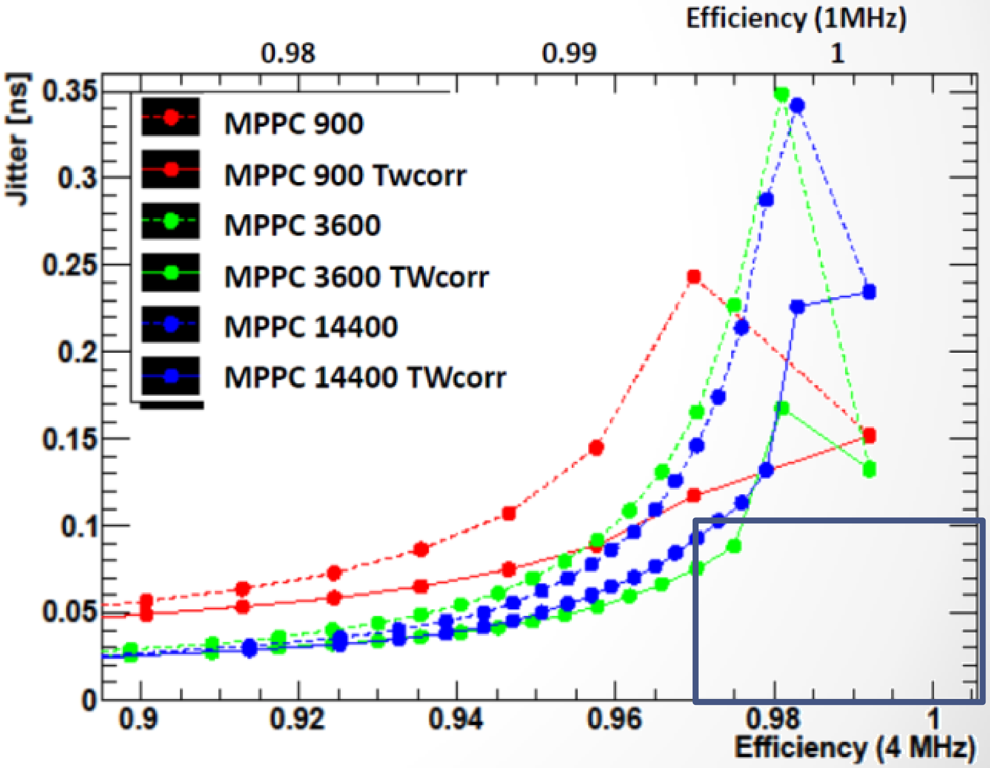






# Tile Detector

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



# 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