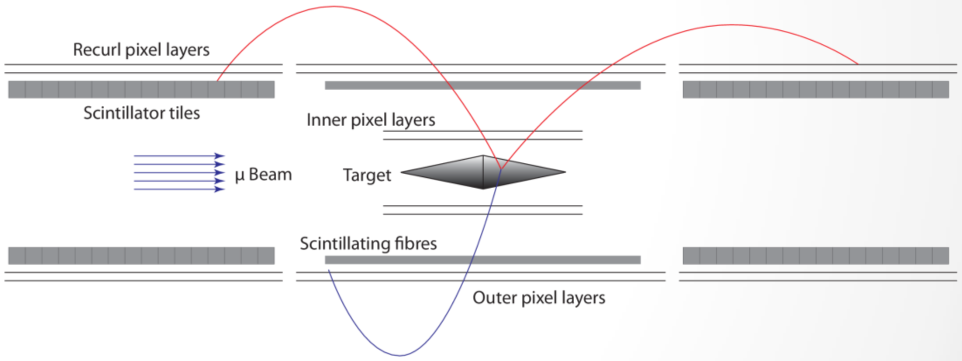
The Mu3e Experiment

Dirk Wiedner, Heidelberg
On Behalf of the Mu3e Collaboration

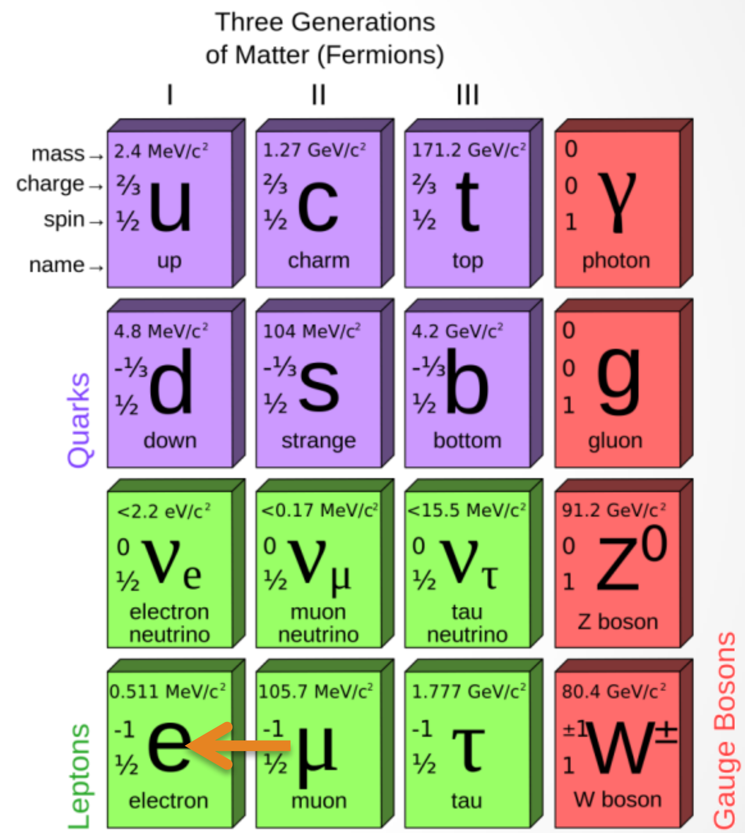
Overview

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



Physics Motivation

Lepton flavor violation?



Standard model:

- No lepton flavor violation

Physics Motivation

Lepton flavor violation?

Standard model:

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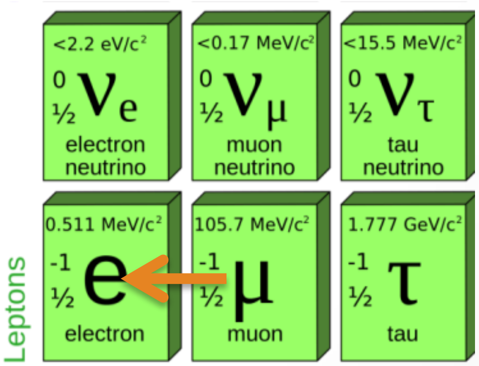
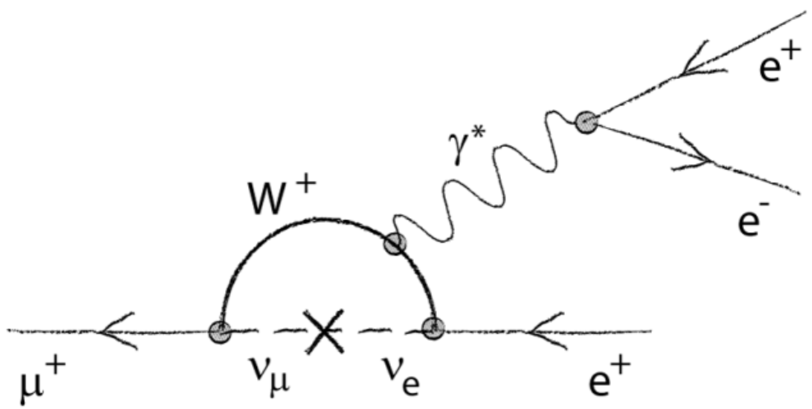


Physics Motivation

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

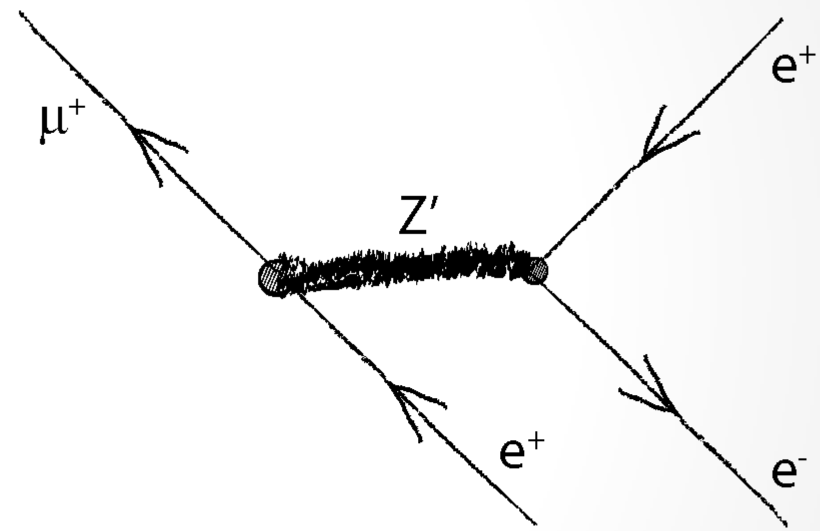


Standard model:

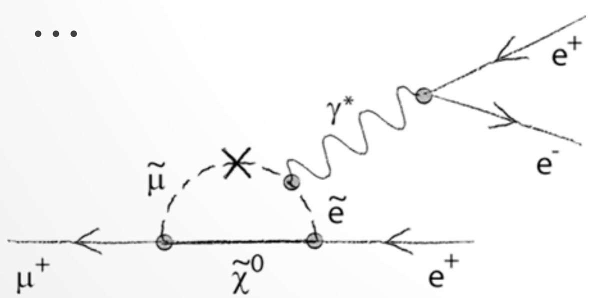
- No lepton flavor violation, but:
  - Neutrino mixing
  - Branching ratio $<10^{-54} \rightarrow$ unobservable

The Mu3e Signal

- $\mu^+ \rightarrow e^+ e^- e^+$ rare in SM
- Enhanced in:
  - Super-symmetry
  - Grand unified models
  - Left-right symmetric models
  - Extended Higgs sector
  - Large extra dimensions
  - …



Tree level



SUSY

The Mu3e Signal

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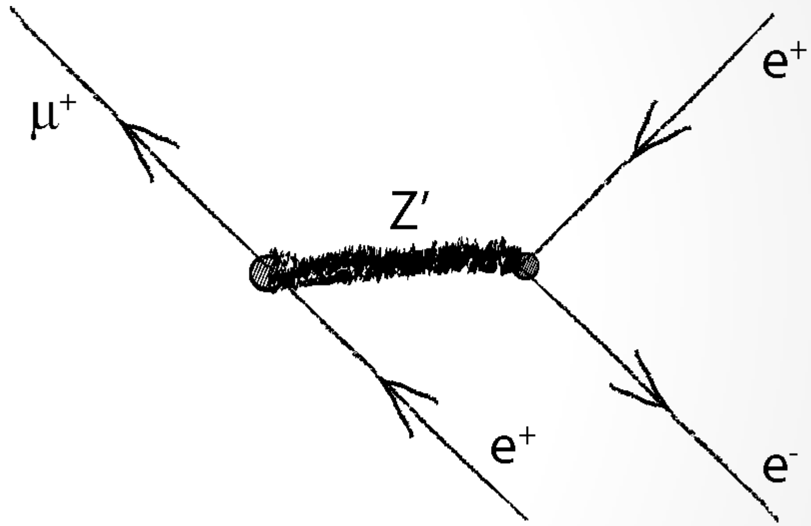
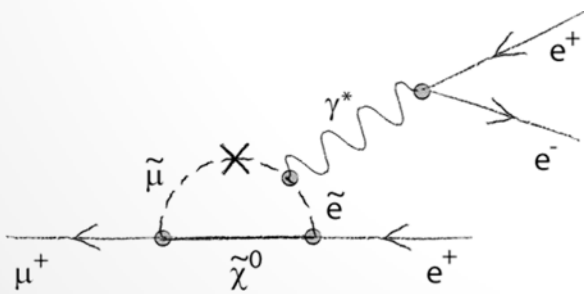
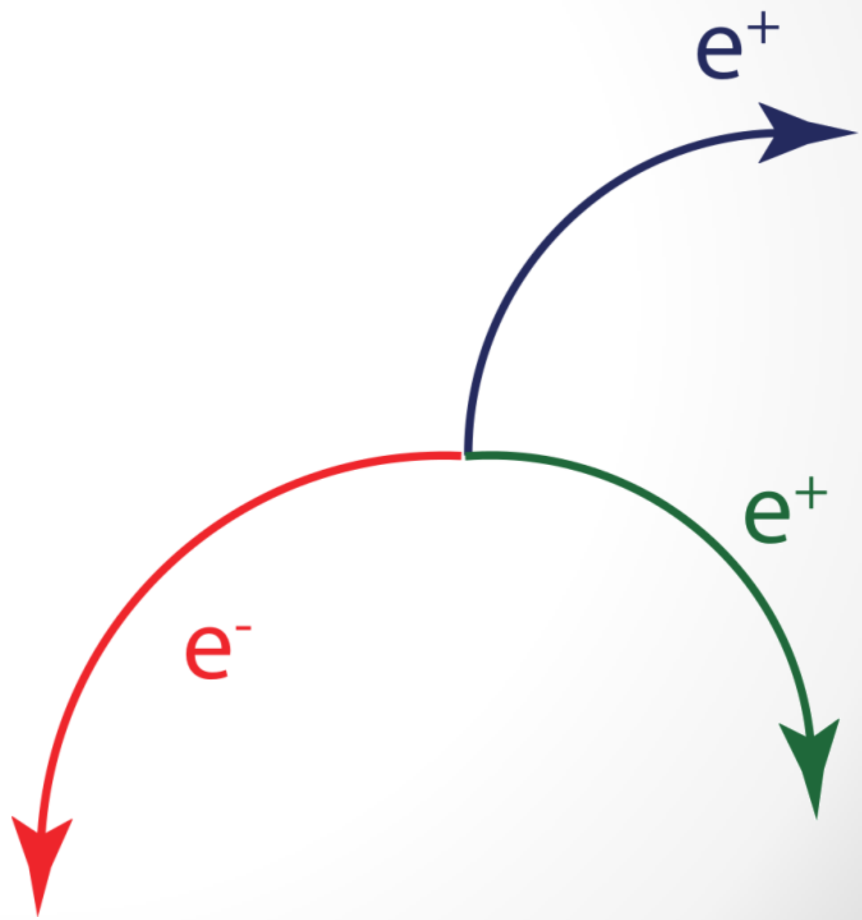




- Rare decay (BR<10^{-12}, SINDRUM)
- For BR O(10^{-15})
  - >10^{15} muon decays
  - High decay rates O(10^{8} muon/s)

The Mu3e Signal



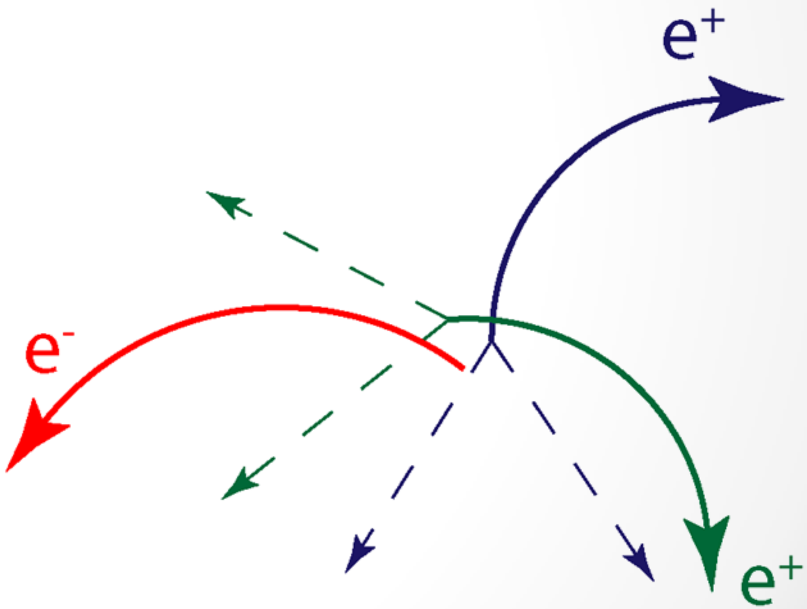
→Maximum electron energy 53 MeV

The Mu3e Background

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

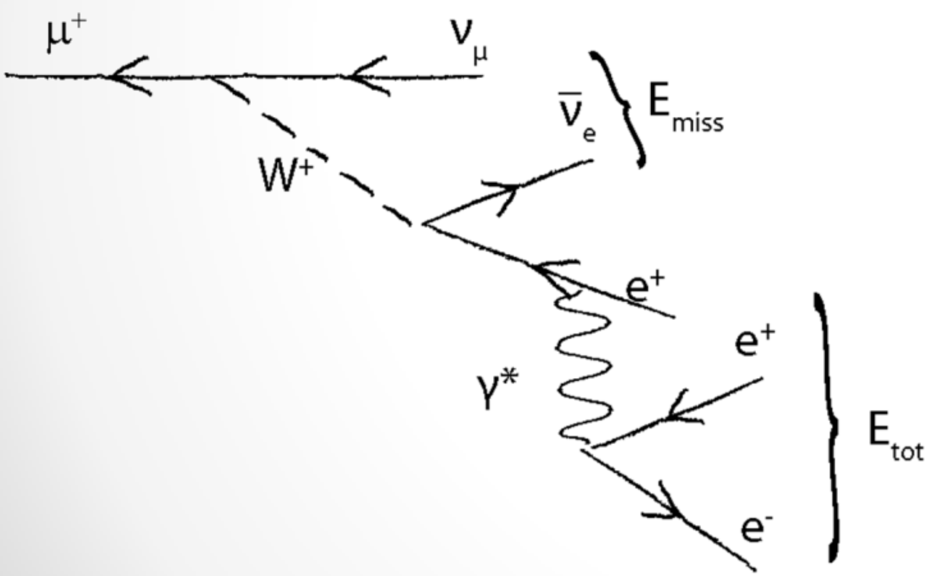
➢ Good time and

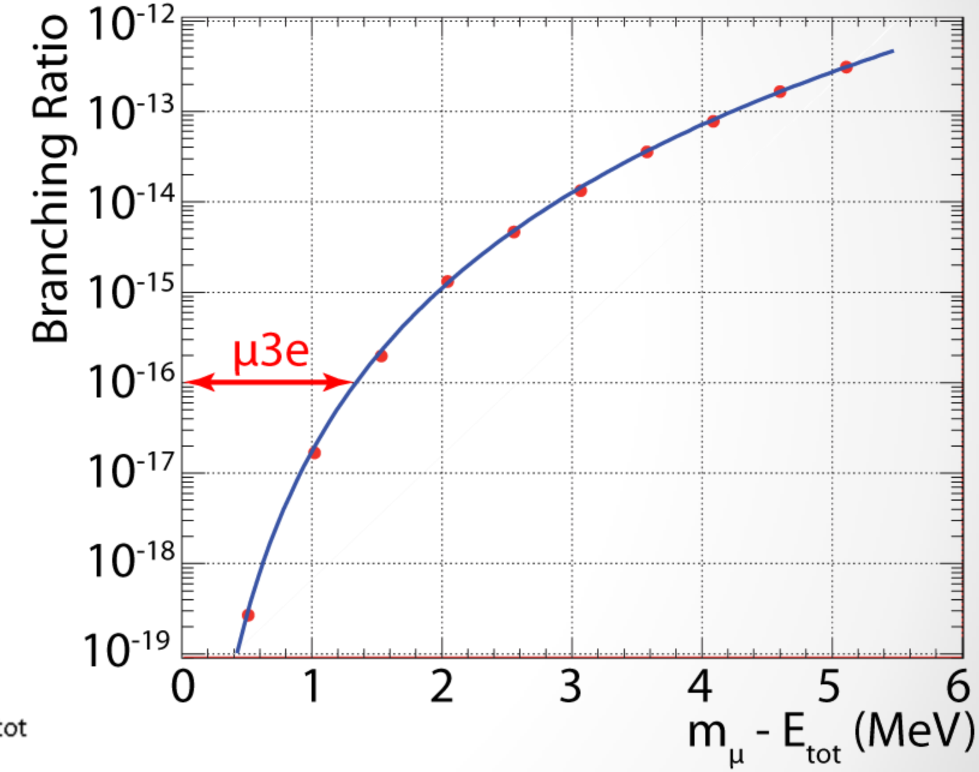
➢ Good vertex resolution required



The Mu3e Background

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





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

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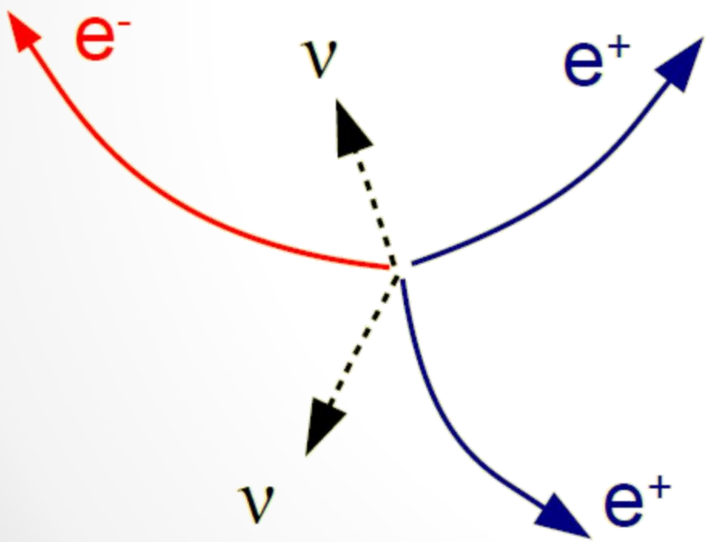

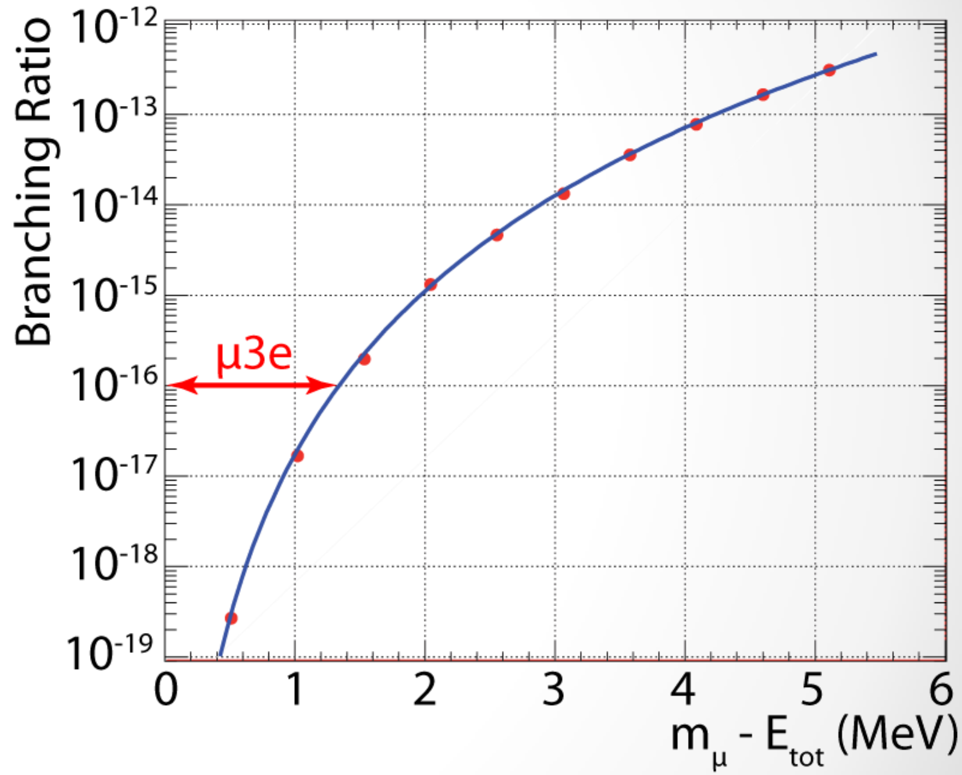

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Challenges

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Challenges

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

Challenges

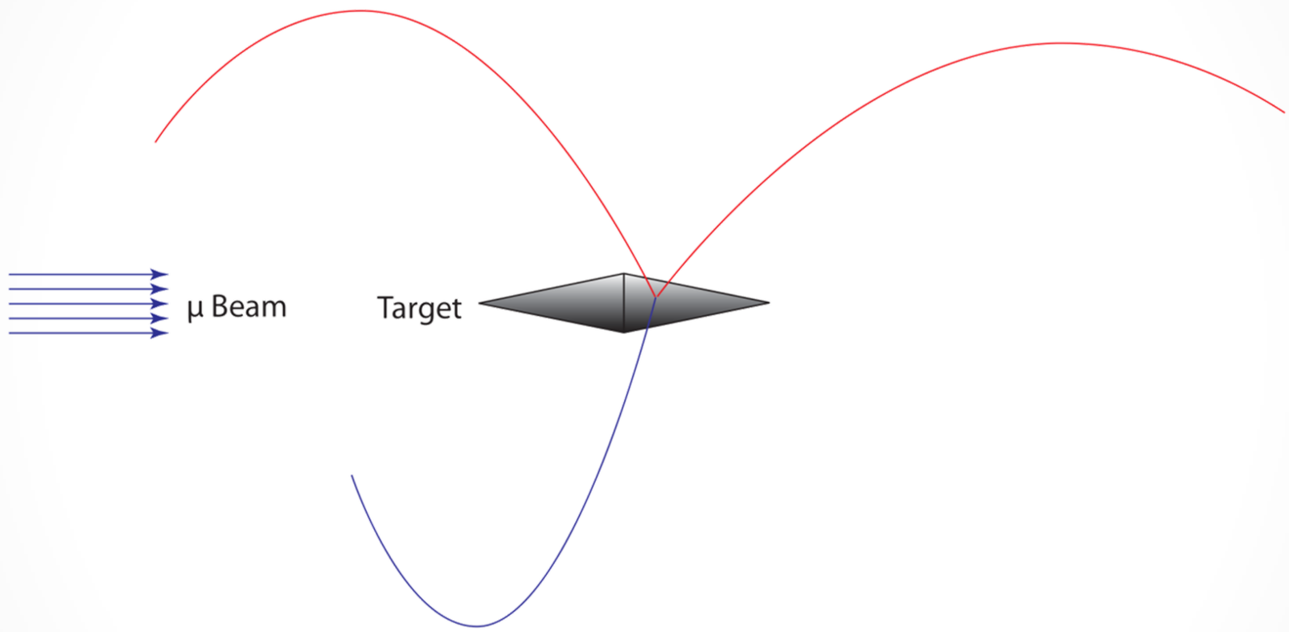
- High rates: 10^8 μ/s
- Good timing resolution: 100 ps
- Good vertex resolution: ~200 μm
- Excellent momentum resolution: ~ 0.5 MeV/c^2

➢ Extremely low material budget:
  - ➢ $1x10^{-3} X_0$ (Si-Tracker Layer)

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

➢ + Timing detectors

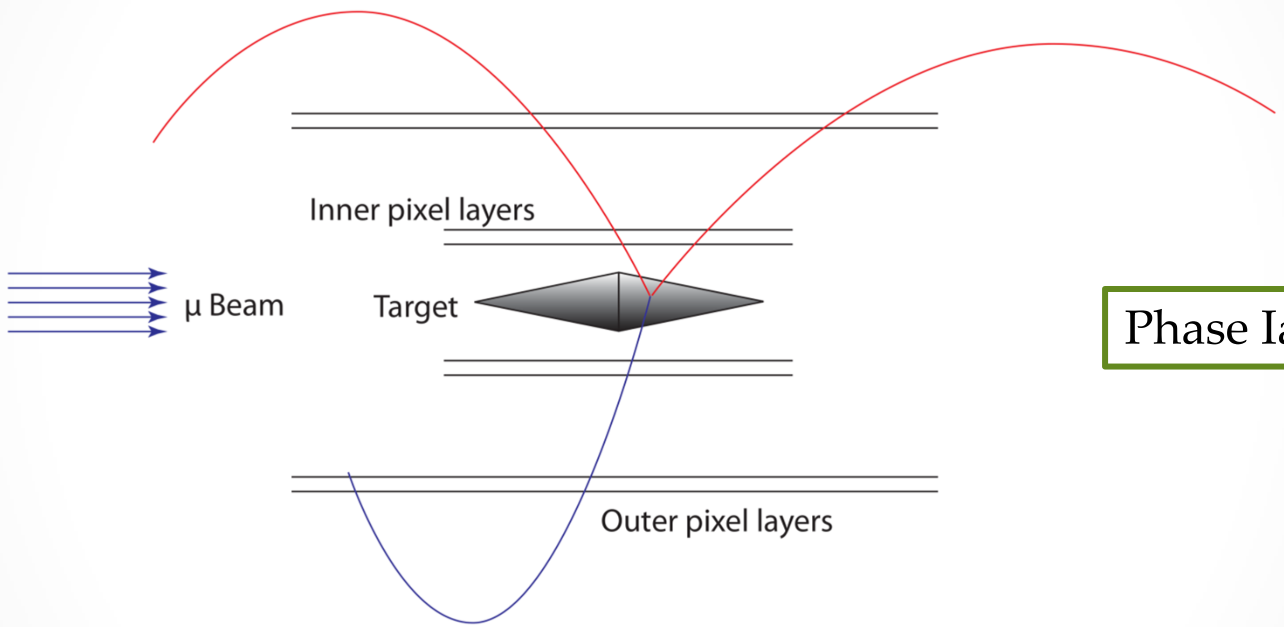
The Mu3e Experiment



- Muon beam O(10^8/s)
- Helium atmosphere
- 1 T B-field

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

The Mu3e Experiment



Phase Ia

- Muon beam O(10^8/s)
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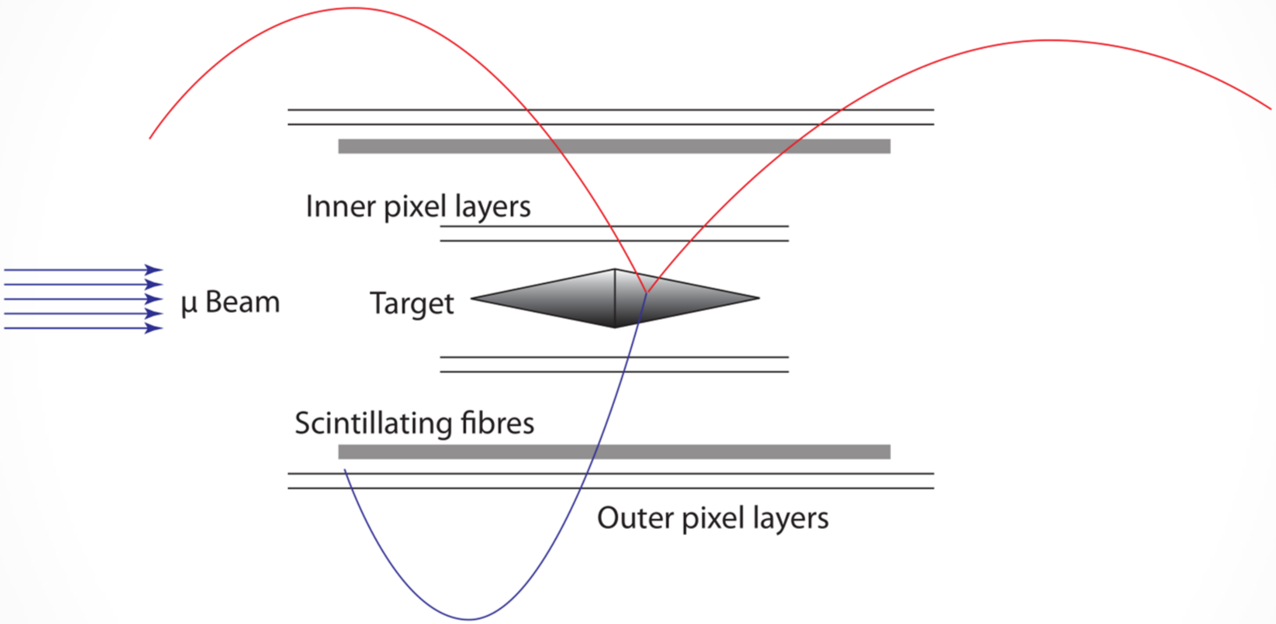
The Mu3e Experiment



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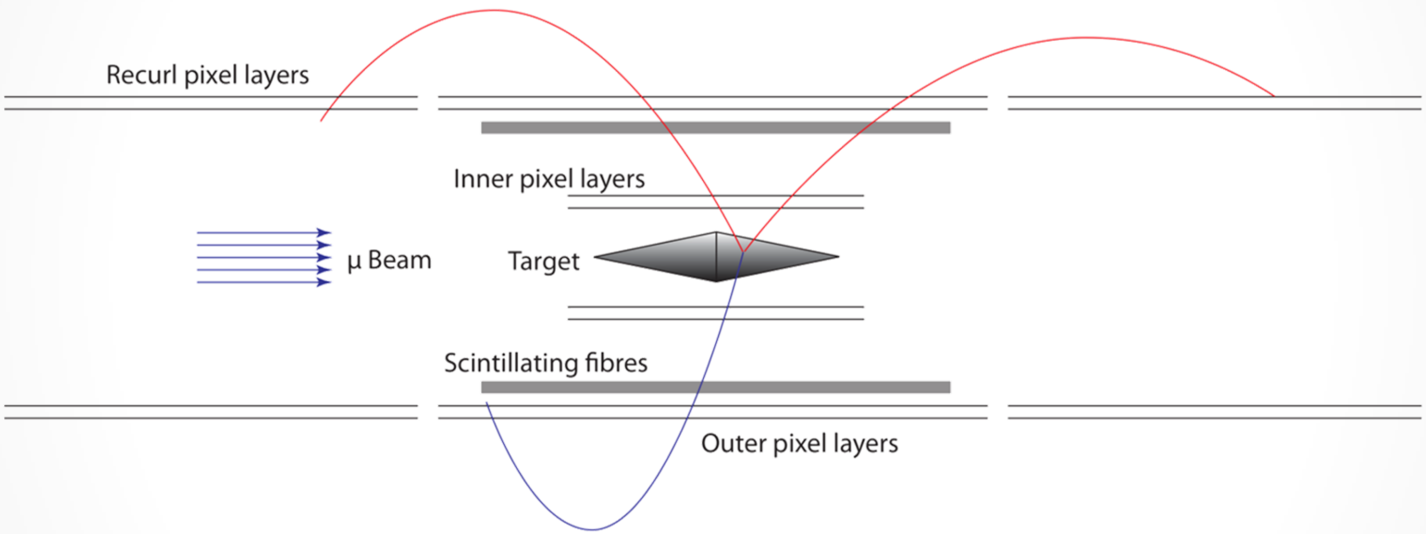
The Mu3e Experiment



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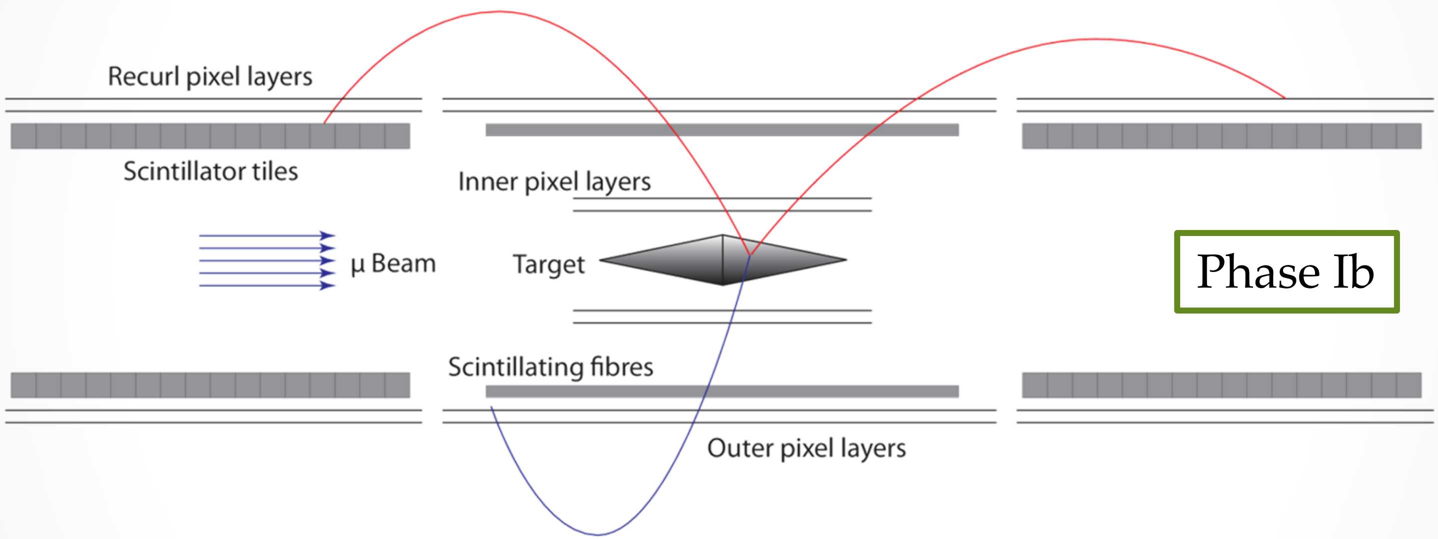
The Mu3e Experiment

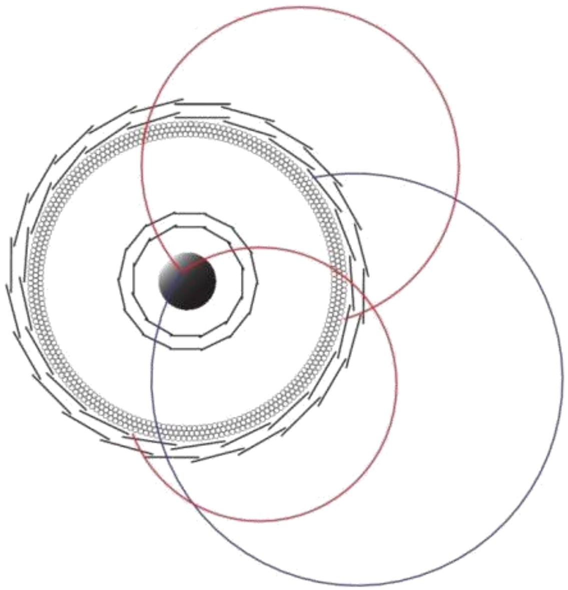


Phase Ib

- Muon beam O(10^8/s)
- Helium atmosphere
- 1 T B-field

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

The Mu3e Experiment



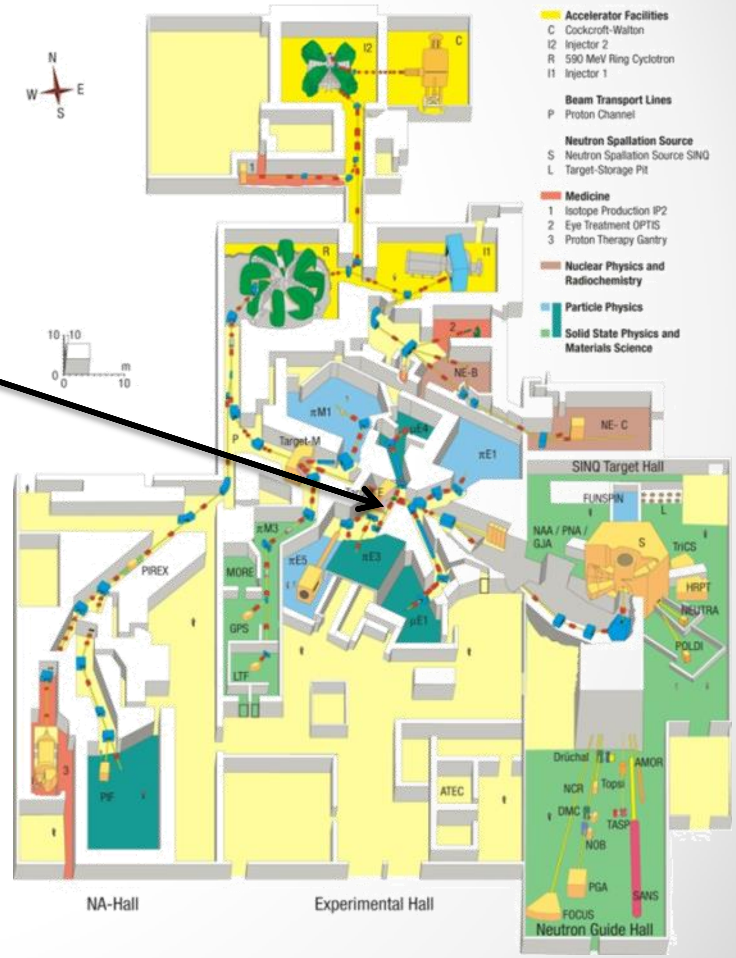
- Muon beam O(10^8/s)
- Helium atmosphere
- 1 T B-field

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

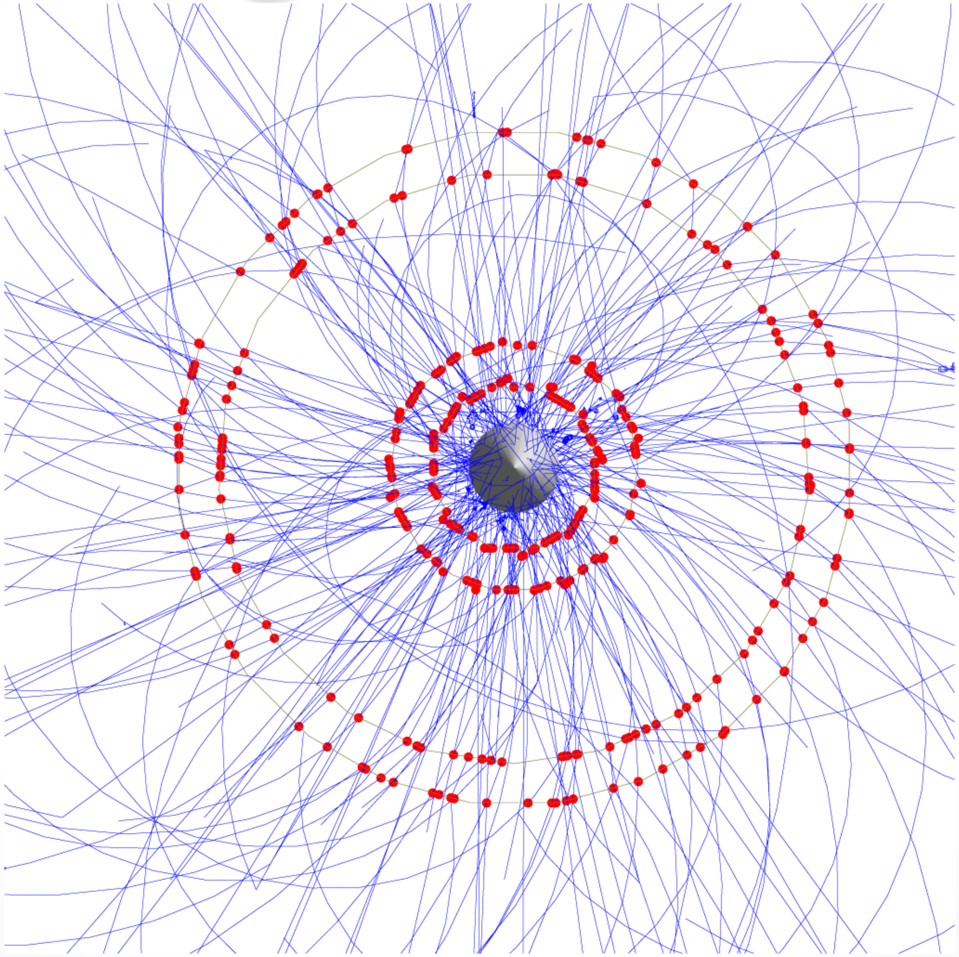
PSI μ-Beam

Paul Scherrer Institute Switzerland:

- 2.2 mA of 590 MeV/c protons
- Phase I:
    - Surface muons from target E
    - Up to a ~10^8 μ/s
- ➢ >10^{15} muon decays per year
- ➢ BR 10^{-15} (90% CL)

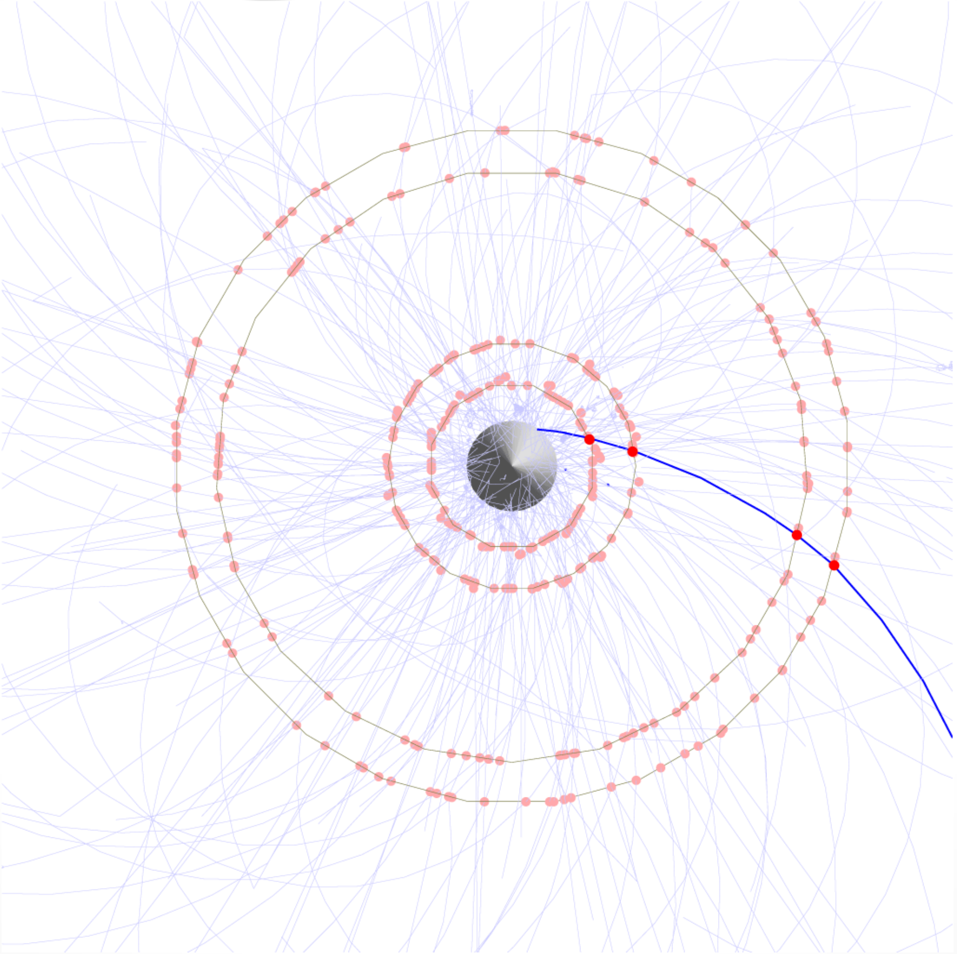


Timing Detectors



50 ns

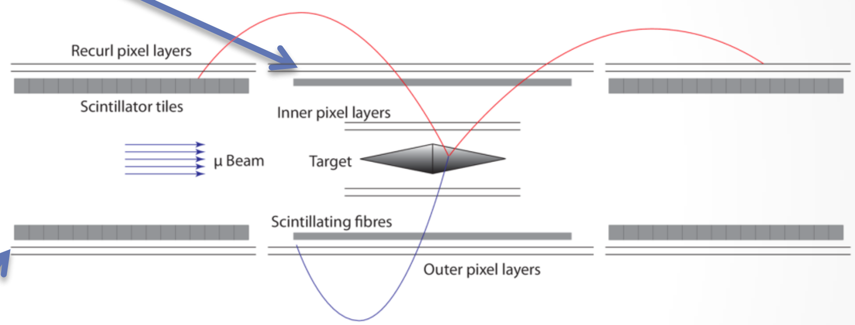
Timing Detectors

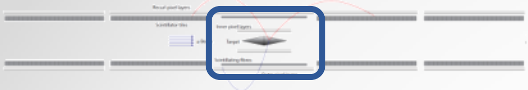


0.1 ns

Timing Detectors

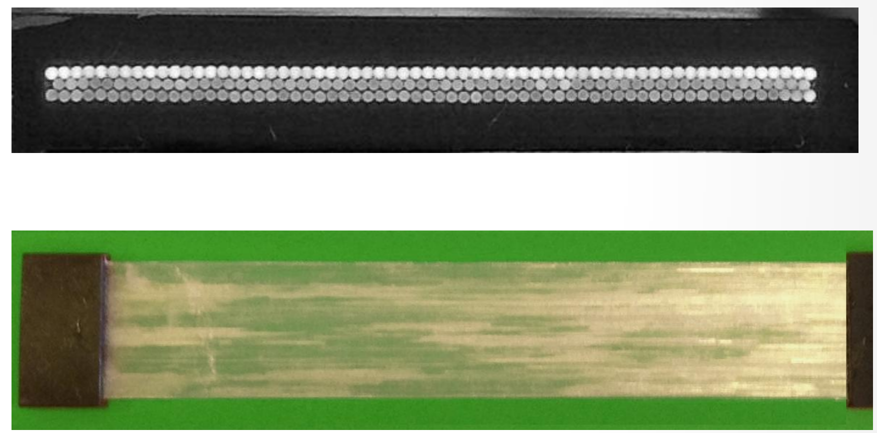
- Fiber detector
  - Before outer pixel layers
  - 250 μm scintillating fibers
  - SiPMs
  - ≤ 1 ns resolution
- Tile detector
  - After recurl pixel layers
  - 6.5 x 6.0 x 5.0 mm^3
  - SiPMs
  - ≤ 100 ps resolution





Fiber Detector

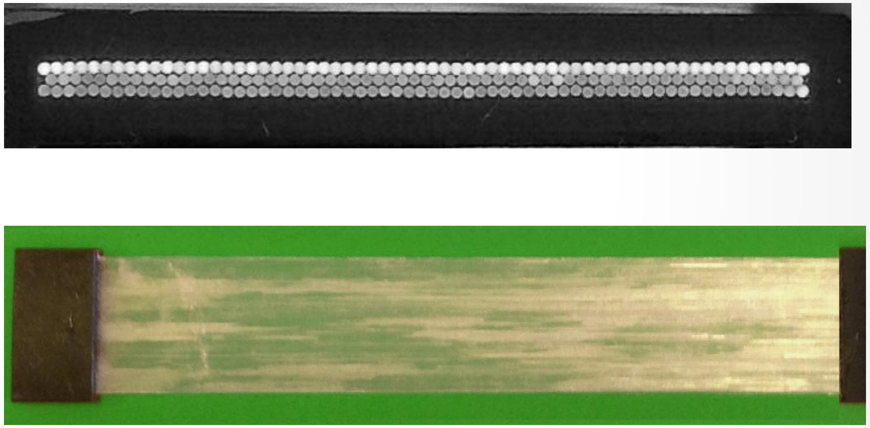
- Fiber ribbon modules
  - 16 mm wide
  - 290 mm long
  - 3 layers fibers of 250 µm dia.
  - 6 MuSTiC readout chips



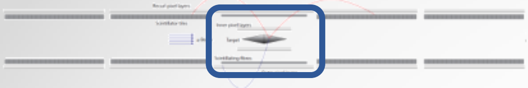
Scintillating fiber ribbons

Fiber Detector

- Total fiber detector:
  - 24 ribbon-modules
  - 144 read-out chips
  - 4536 fibers

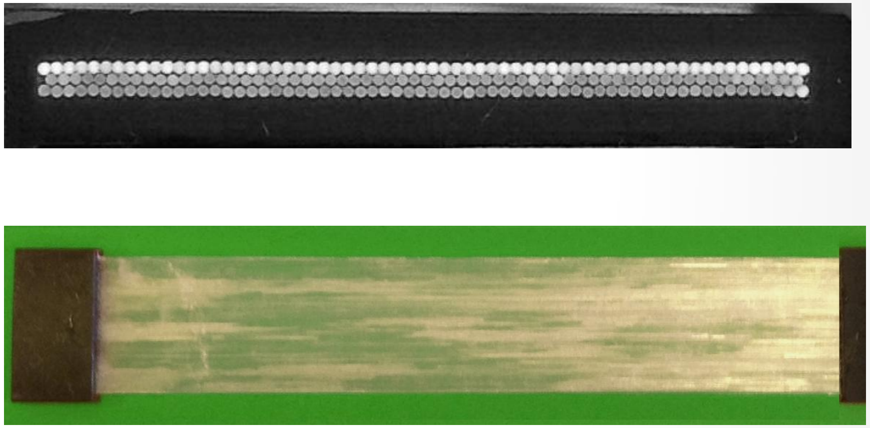


Scintillating fiber ribbons

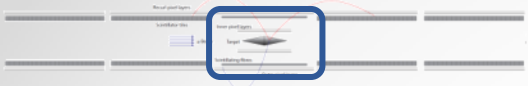


Fiber Detector

- Prototype ribbons built:
  - 3 and 4 layers
  - 16 mm wide
  - 360 mm long
- CAD in progress

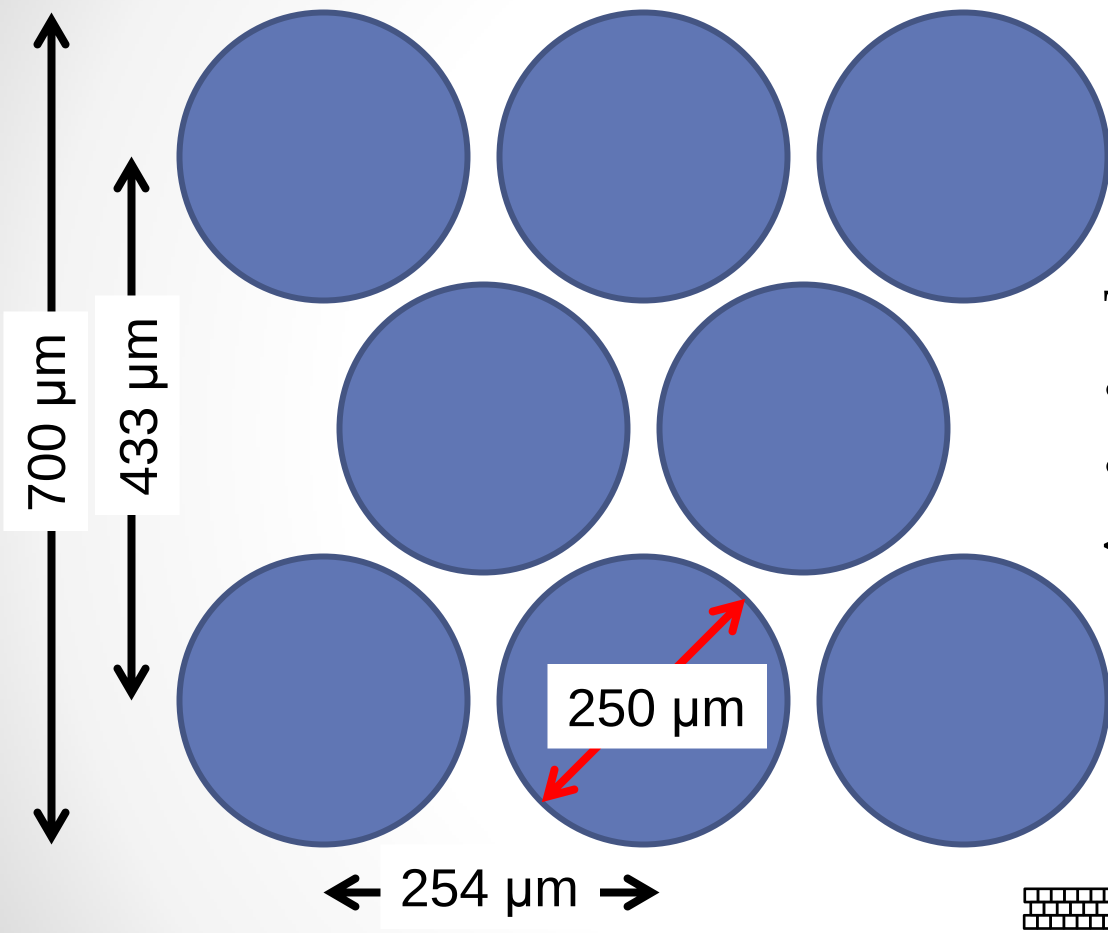


Scintillating fiber ribbons



Details …

staggered layers

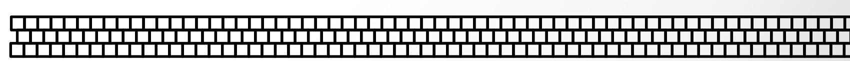


Thickness:

- theoretical ~ 683 µm
- measured ~ 750 µm

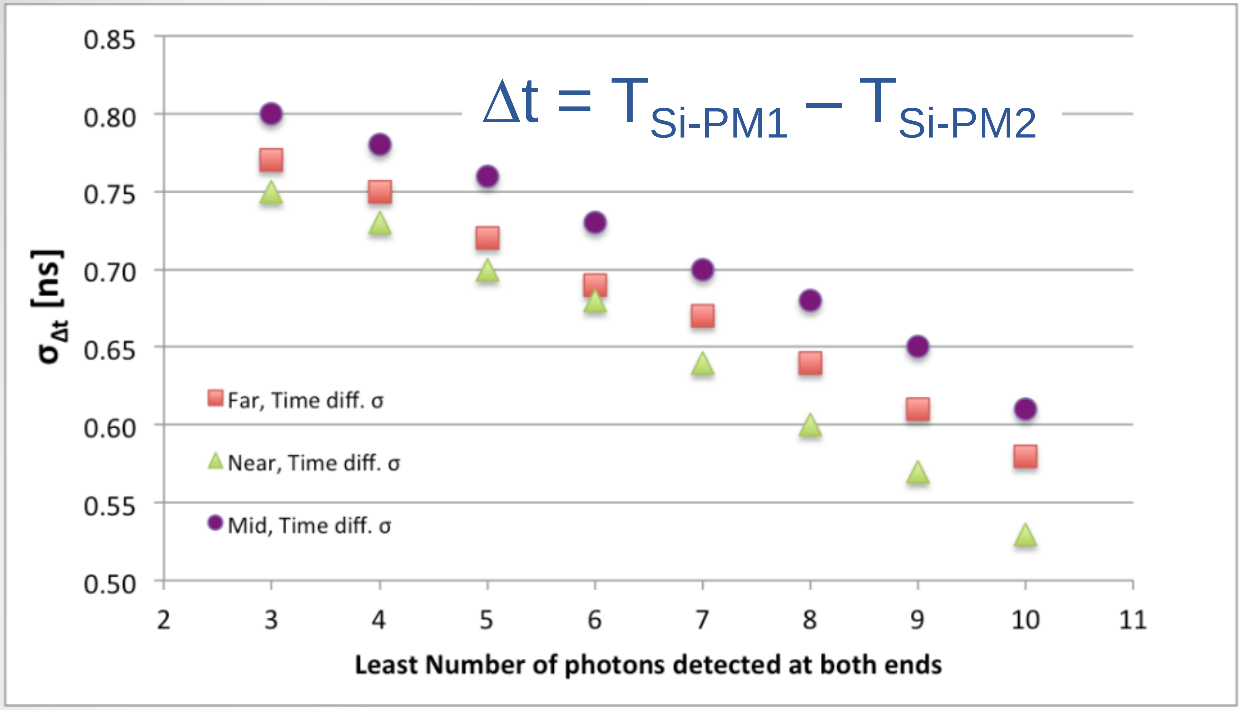
< 1 g of glue / ribbon

Alternative:
Square shape fibers



Horizontal gap between fibers ~ 4 µm

Time Resolution



$\sigma_{\Delta t} \approx 800$ ps
with at least 3 γ detected
(~95 % efficient)

$\Rightarrow \sigma_{MT} \approx 400$ ps $\geq 3\ \gamma$

reproducible results

- Time resolution does not show 1 / √n behavior:

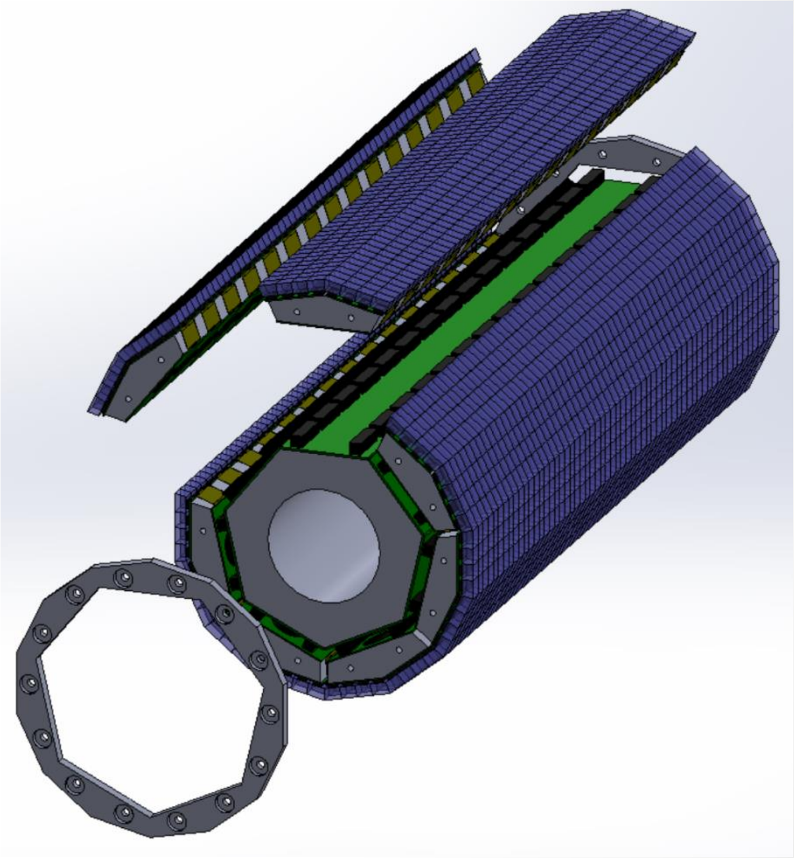
⇒ improve on timing algorithm!

- Si-PM transit time spread ~100 ps has almost no effect

- Real issue: time in all ~9k channels to few 100 ps

Tile Detector

- Scintillating tiles
  - 6.5 x 6.0 x 5.0 mm^3
- 7 Tile Modules per station
  - 480 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through STiC



Sketch of Tile detector station

Tile Detector

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  - 6.5 x 6.0 x 5.0 mm^3
- 7 Tile Modules per station
  - 480 tiles/module
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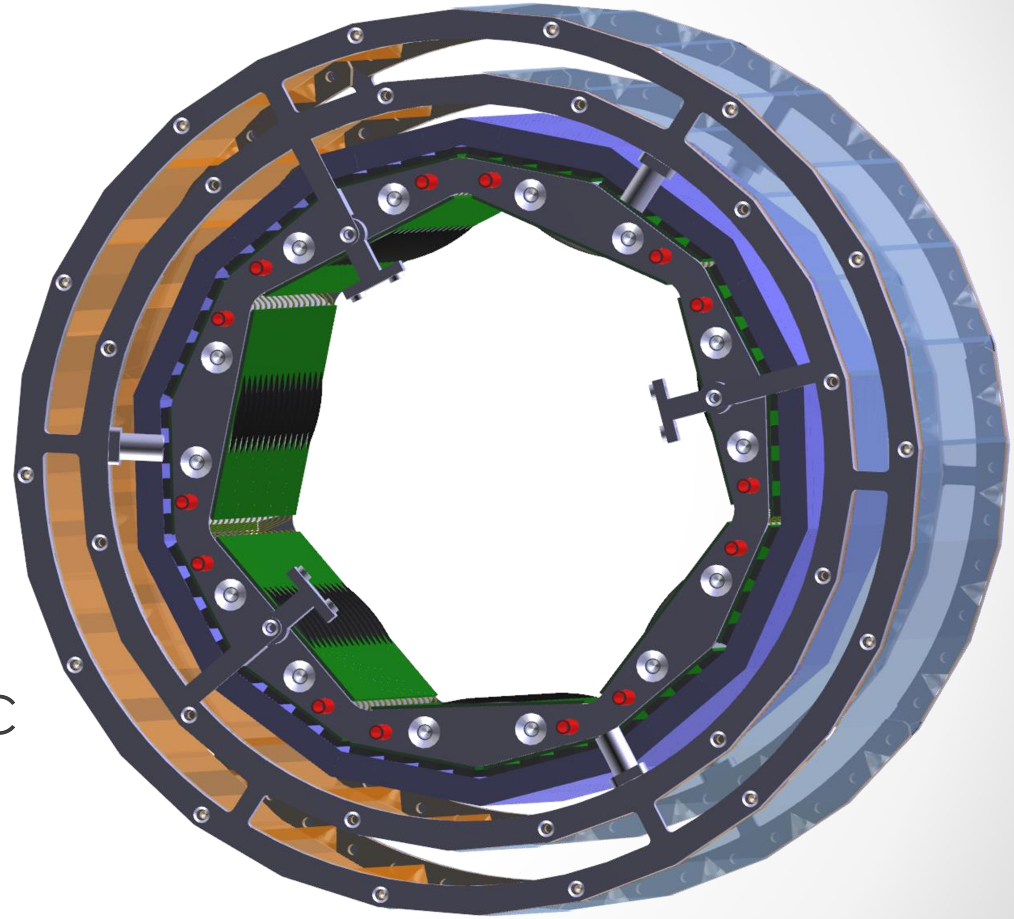
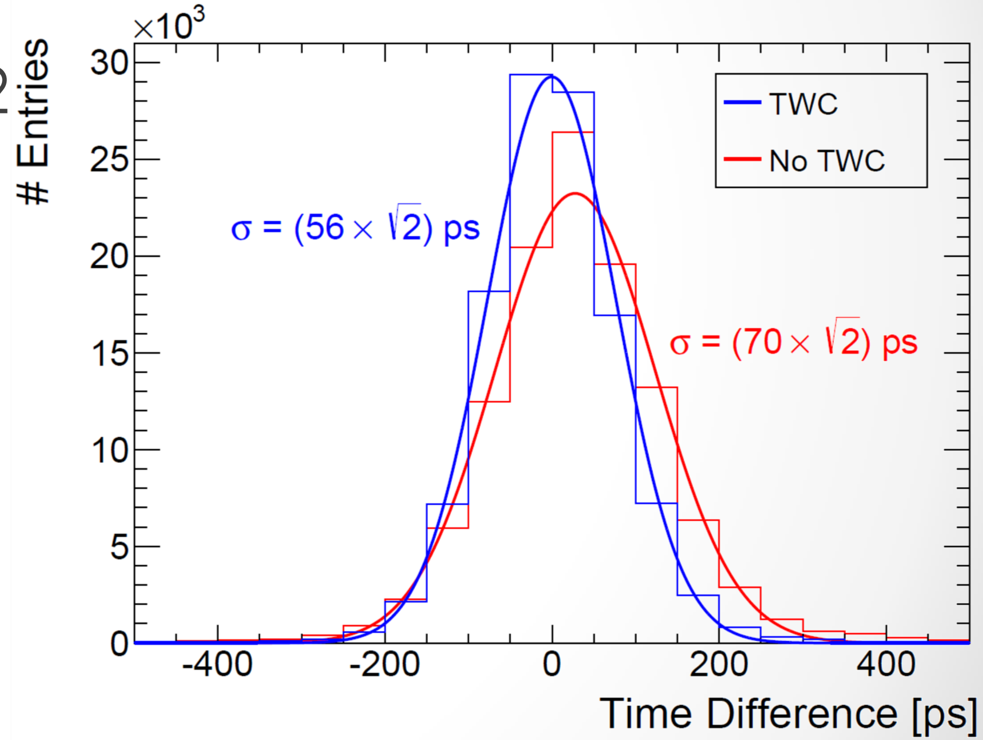
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through MuSTiC



CAD of Tile Detector integration

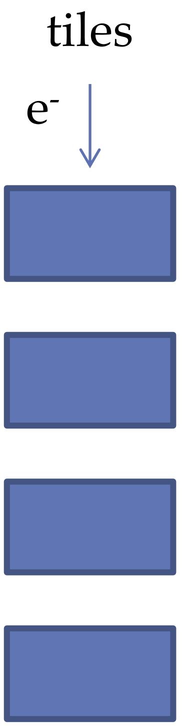
Time Resolution

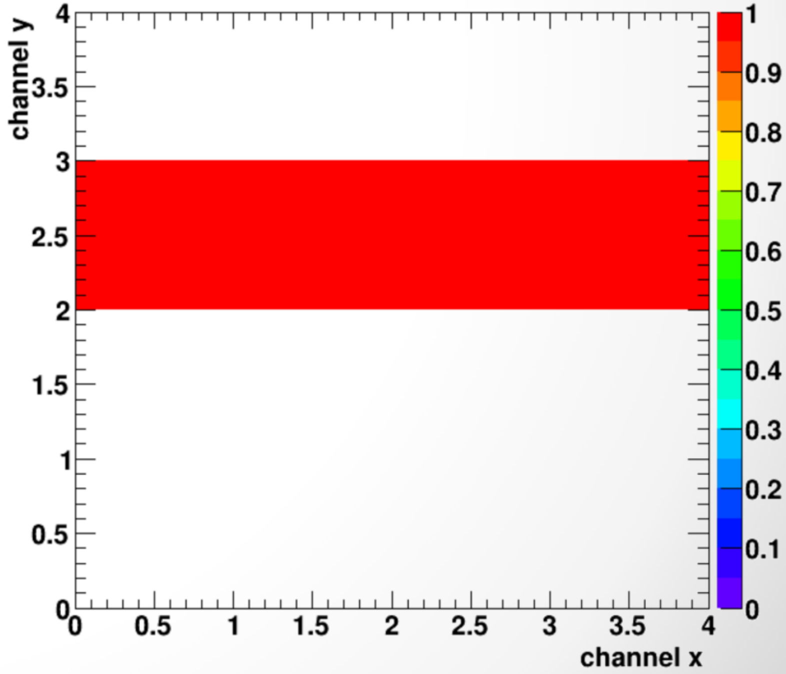
- Coincidence between 2 tiles in a row
- Time resolution ≈ 70 ps
- Time-walk effect ≈ 14 ps
- Only small dependence on chip settings



Efficiency

- Require hit in first & last column
- Look for hit in middle channel
- Efficiency > 99.5%





Pixel Sensors

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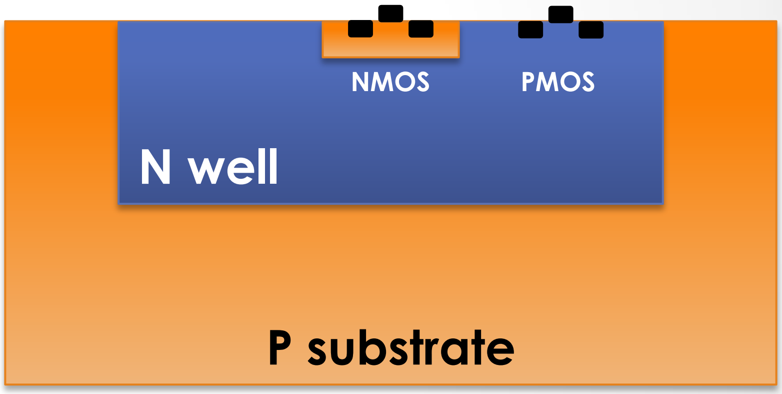
HV-MAPS

- **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 Perić

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

HV-MAPS

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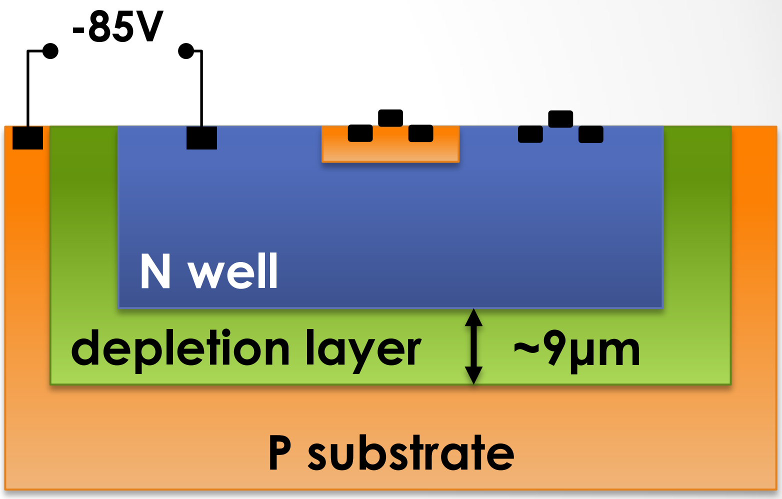
- Pixel sensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased ~85V
  - Depletion layer
  - Charge collection via drift
  - ➢ Fast <1 ns charge collection
  - Thinning to < 50 µm possible



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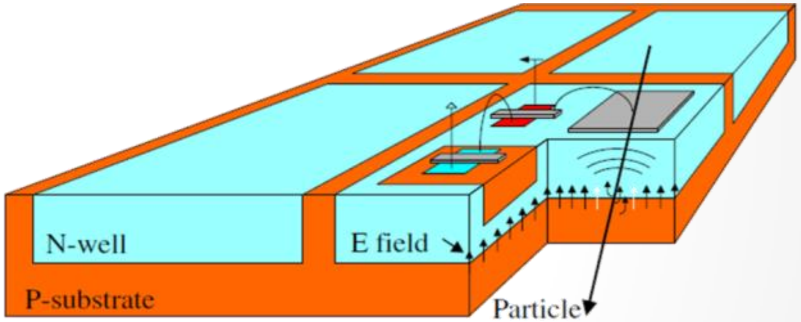
  - Thinning to < 50 µm possible
- Integrated readout electronics



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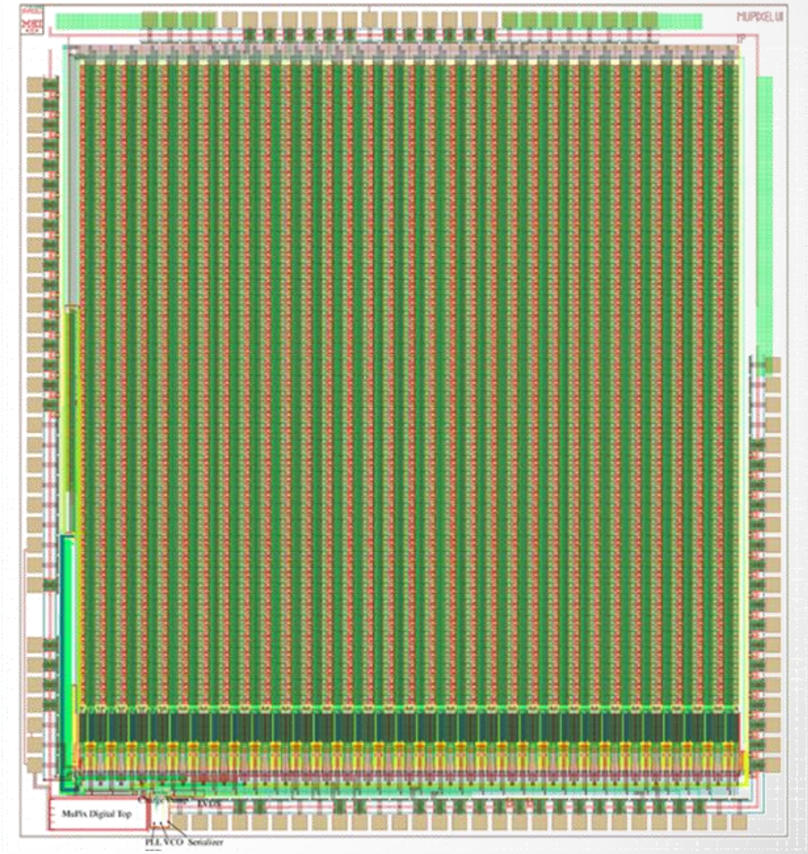
Chip Prototypes

MuPix7

- 180 nm HV-CMOS
- Pixel matrix:
  - 40 x 32 pixels
  - 103 x 80 μm^2 each
- Ivan Perić
  - Analog part
    - Small pixel capacitance
    - Temperature tolerant
  - Digital part
    - Full system on chip



HV-MAPS Test Results

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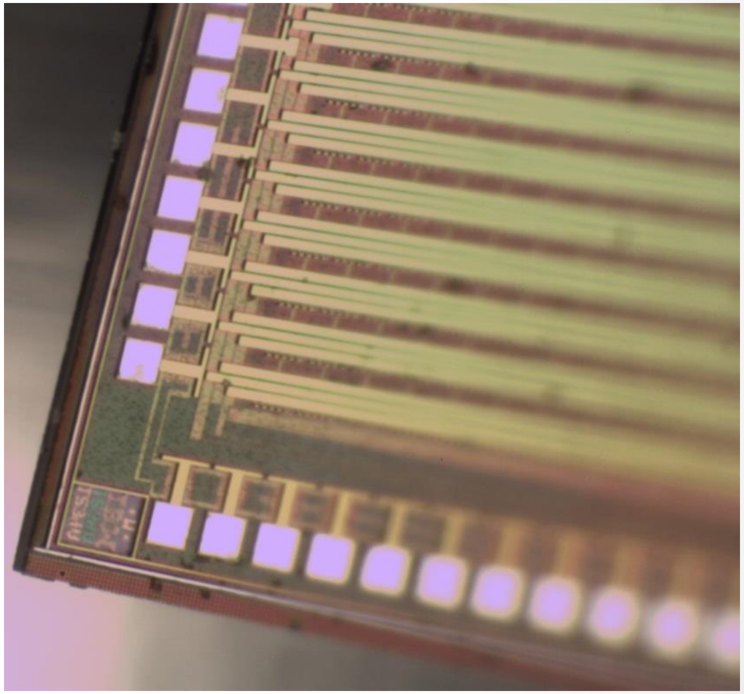
Thinned Sensors

- Prototypes thinned:
  - MuPix4 thinned to 50μm
  - MuPix7 thinned to 50, 62, 75μm
- Good performance of thin chips
  - In lab
  - In particle beam

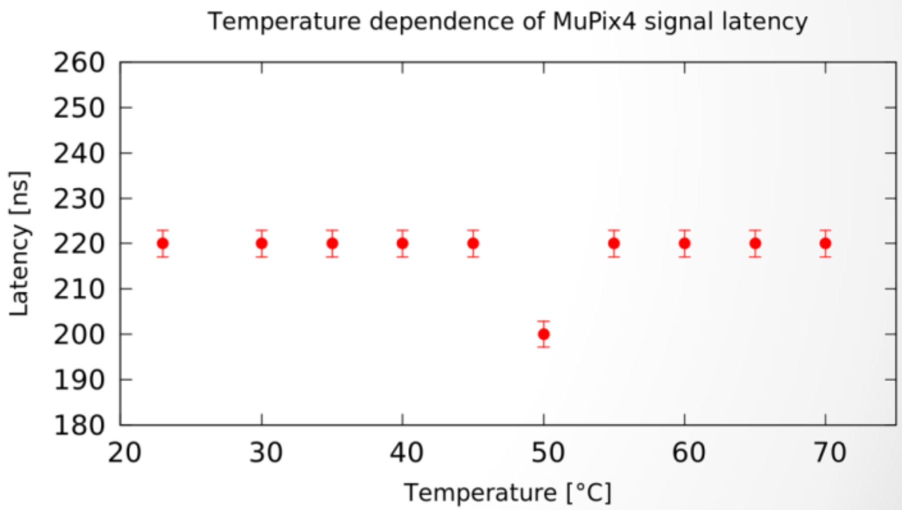


MuPix4 thinned to 50μm

Temperature Dependence

- MuPix4 prototype
- Latency measurement
  - LED pulse to Pixel discriminator output
- Setup in Oven
  - 23°C to 70°C

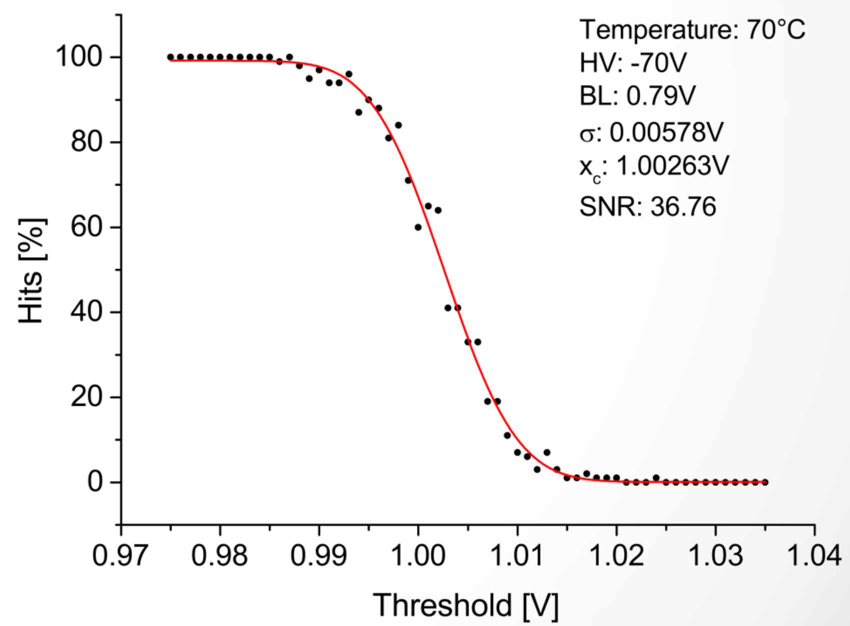
➢ Very **little temperature dependence**
  - ➢ O(10ns) in latency
  - ➢ Within resolution of setup



Signal to Noise

- MuPix4
- Signal
  - Test-pulse
  - Calibrated to ^{90}Sr source
  - 70°C
  - HV = -70V
- Noise
  - S-curve fit
  - X-checked with
    - Threshold scan
    - Close to baseline

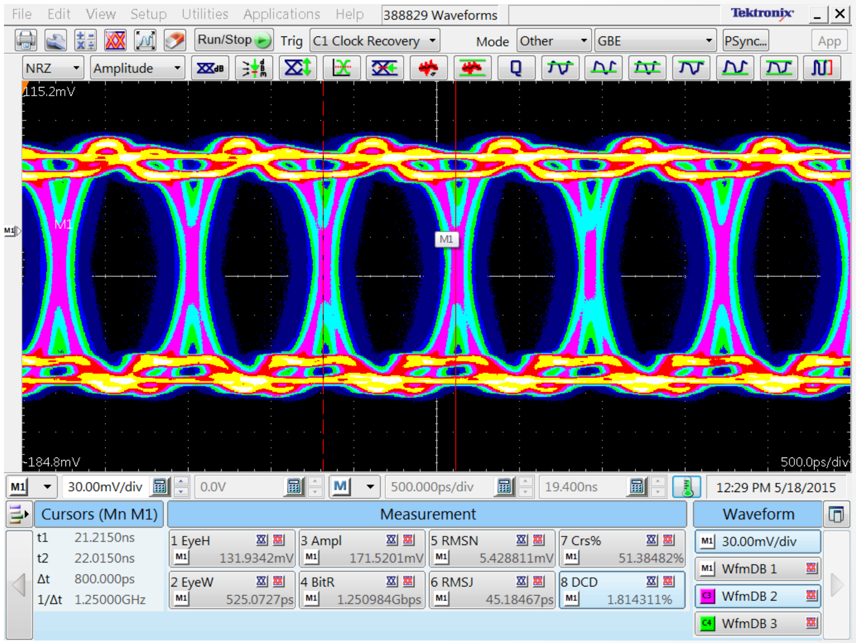
➢ **S/N = 36.8**



Chip Readout

On Chip:

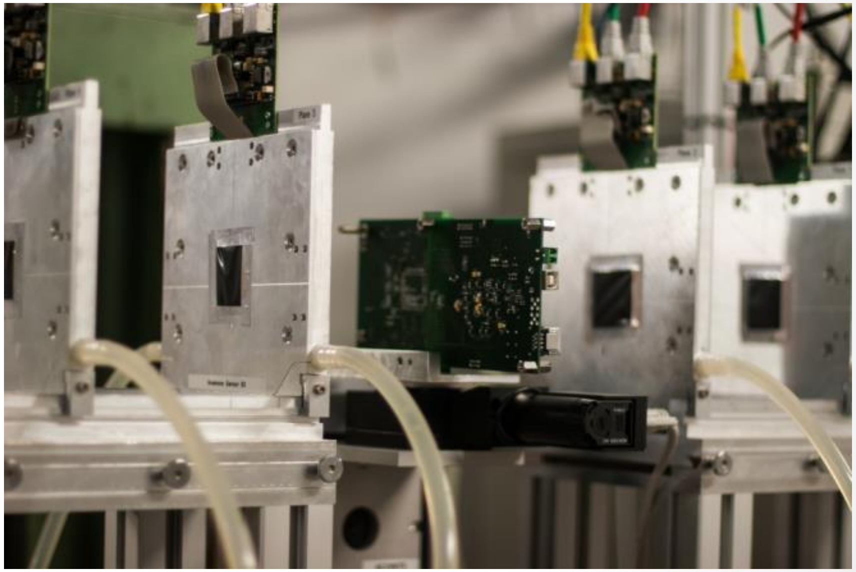
- Zero suppression
- Read-out state machine
- PLL and VCO
- Fast serializer
- ➢ 1.25 Gbit/s LVDS output



Eye diagram MuPix7

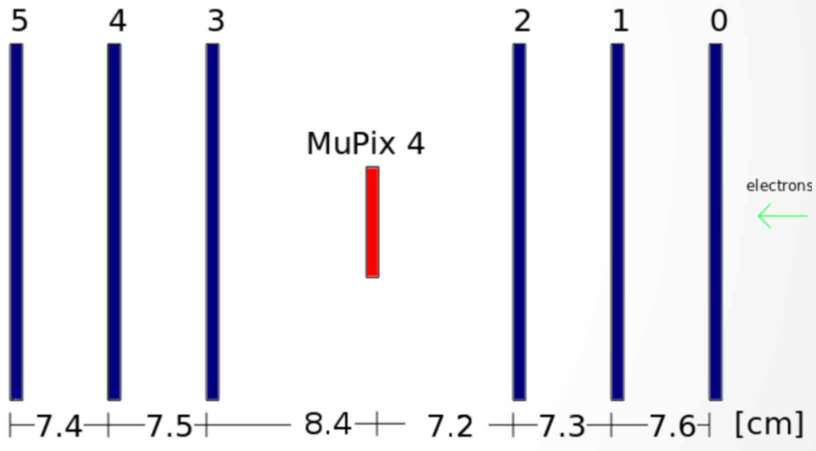
Test beams

- 14 test beam campaigns 2012 - 15:
  - SPS
  - DESY
  - PSI
  - MAMI



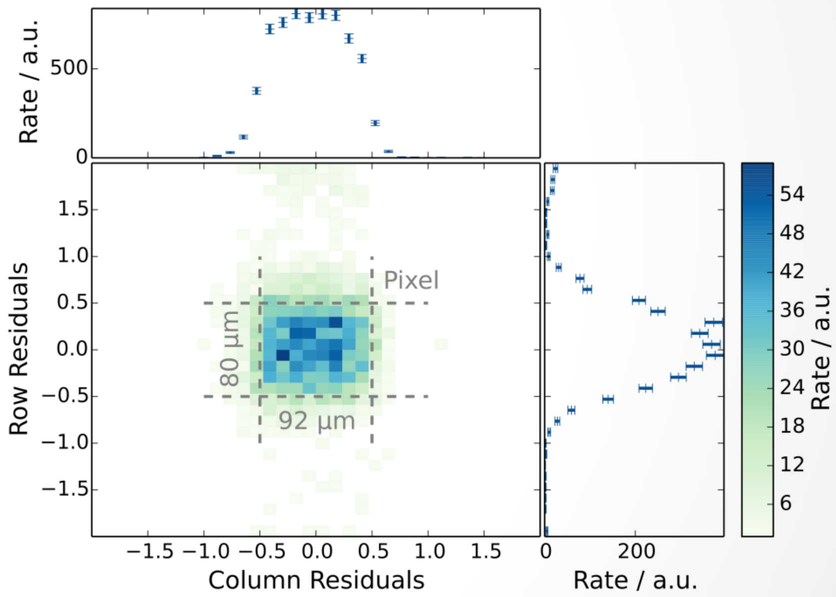
Setup February Test-Beam

- DESY, February 2014
- Beam-line T22
  - up to **6 GeV** electrons
- Aconite telescope
- MuPix4 prototype
- Readout setup from Ivan Perić



Spatial Resolution

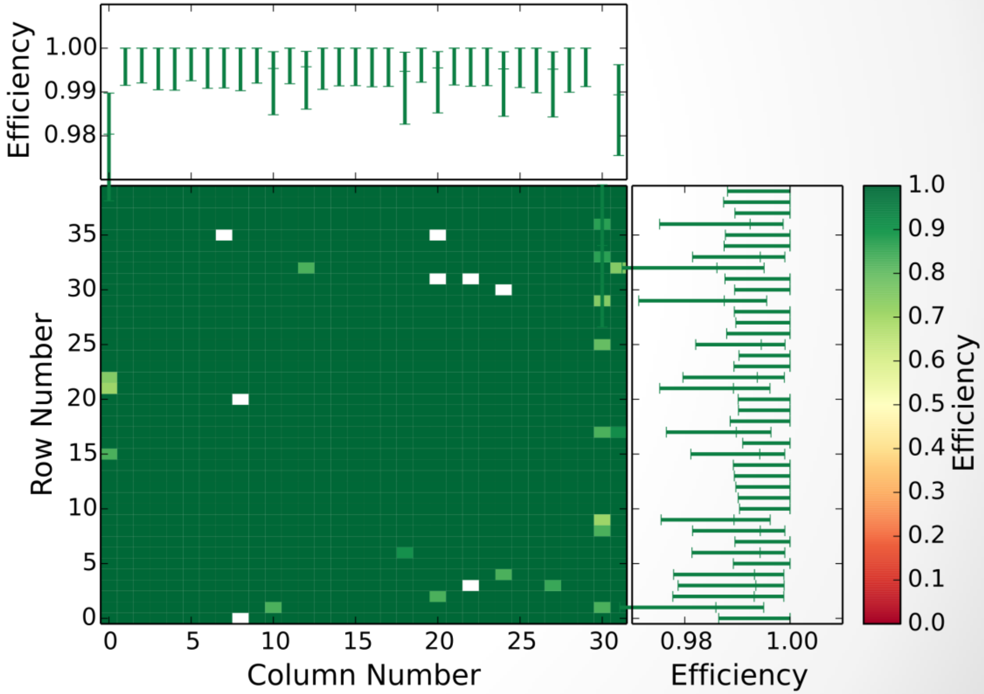
- Pixel size 80 µm x 92 µm
- Measured track residuals:
  - RMS x = **28 µm**
  - RMS y = **29 µm**



Pixel Residuals

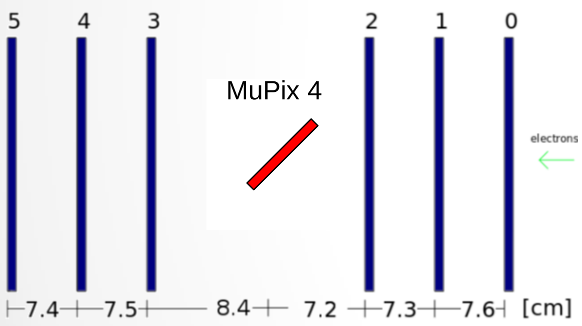
Efficiencies

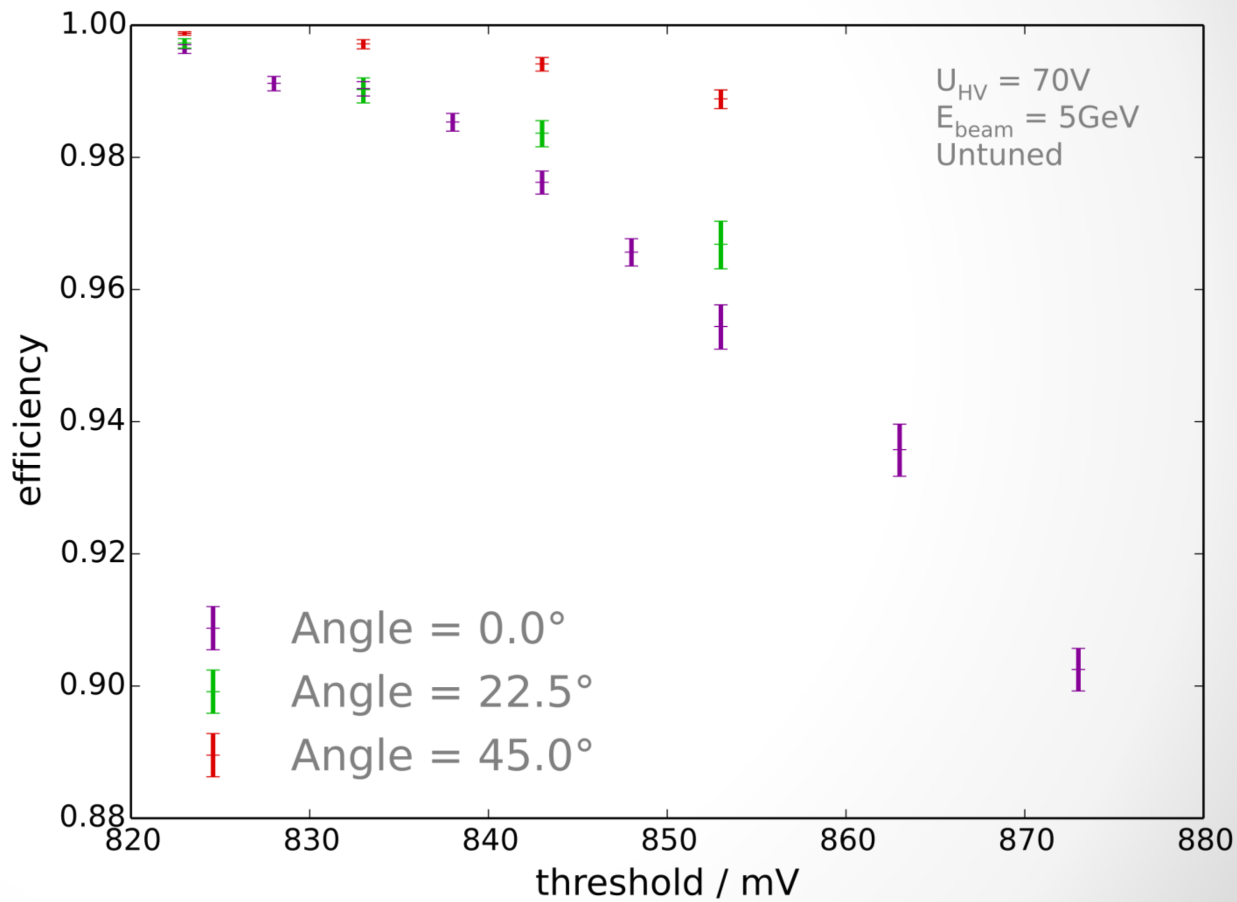
- **>99.5% efficiency**
  - 5 GeV electrons
  - 45° angle
  - Individual pixel thresholds
    - Threshold tune from pixel efficiencies in previous test beam



MuPix4 Efficiency

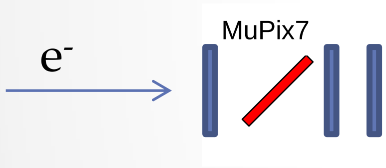
Threshold Scans for 0° to 45°



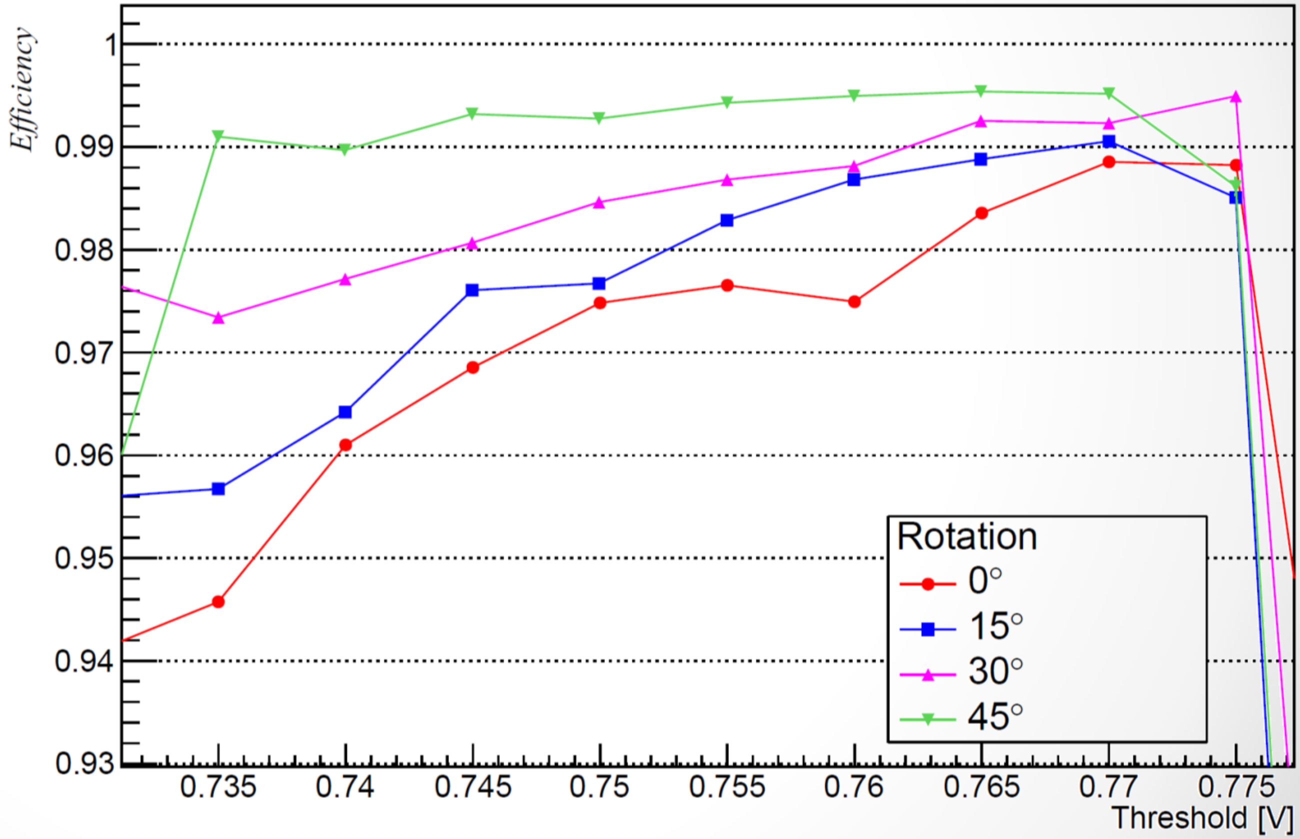


DESY February 2014

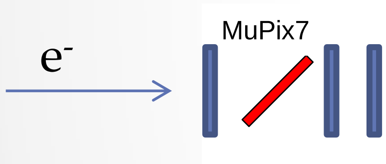
Threshold Scans for 0° to 45°



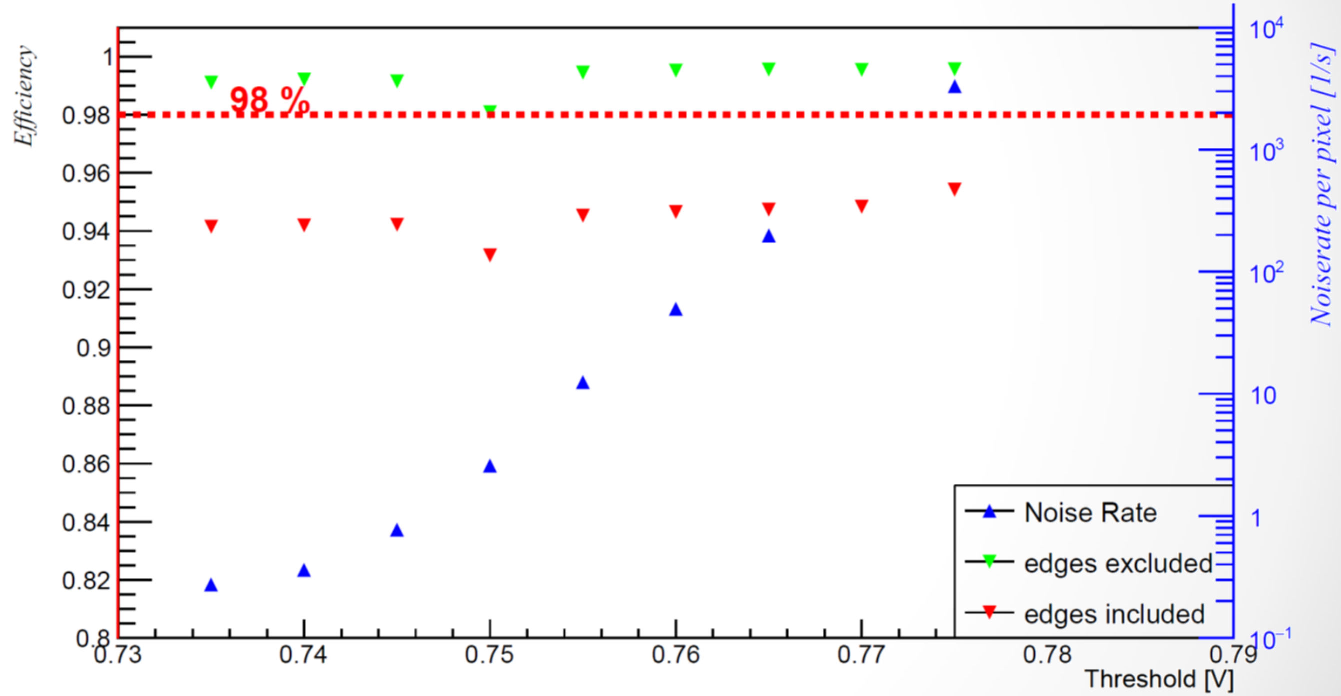
DESY October 2015



Threshold Scans for 0° to 45°

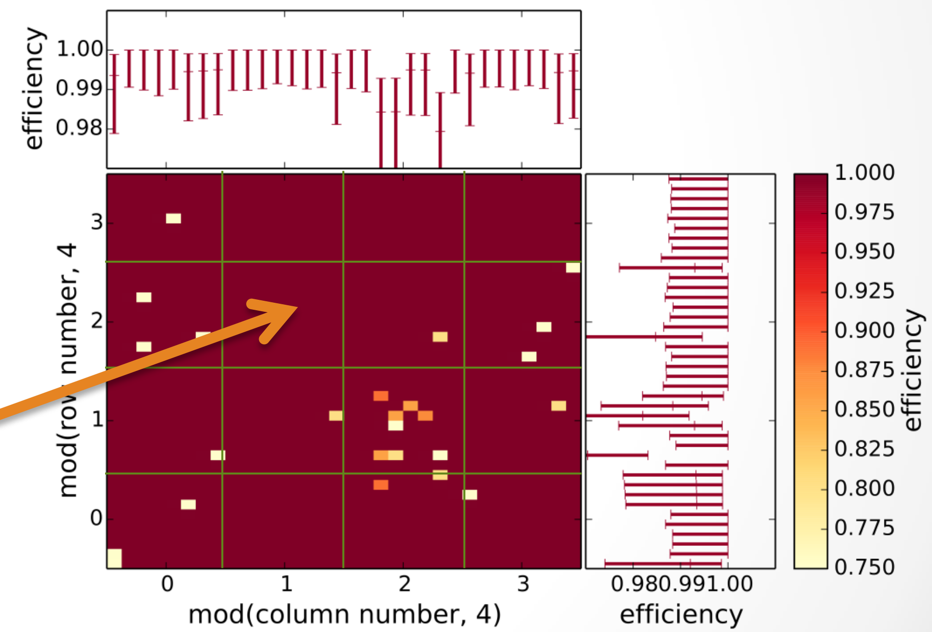


DESY October 2015



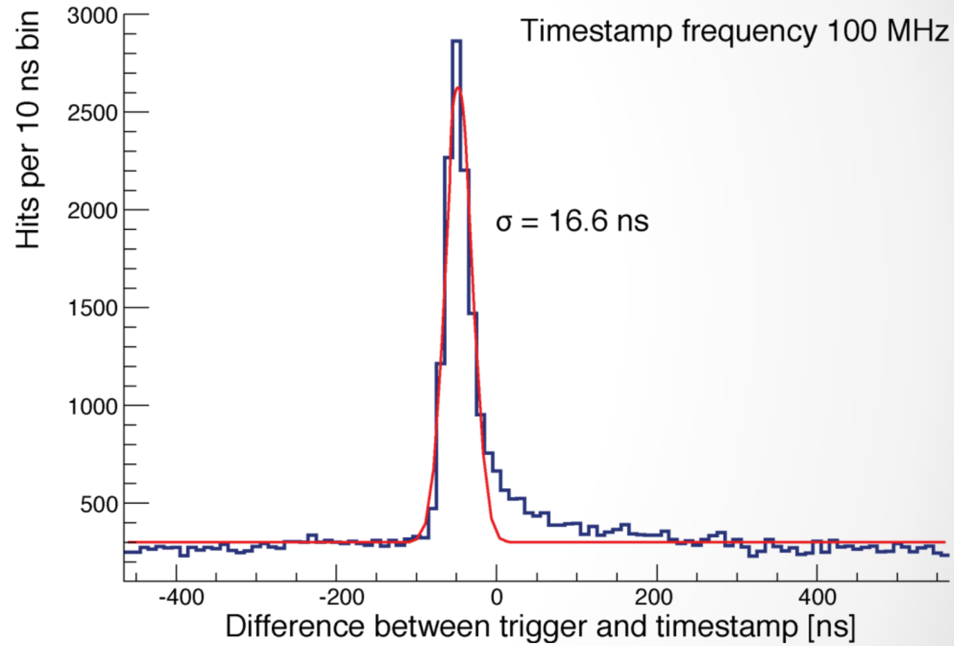
Sub-Pixel Efficiencies

- Chip folded back to 4 x 4 pixel area
- Resolution limited
- Overall high efficiency
- No pixel substructure (within resolution)



Time Stamps

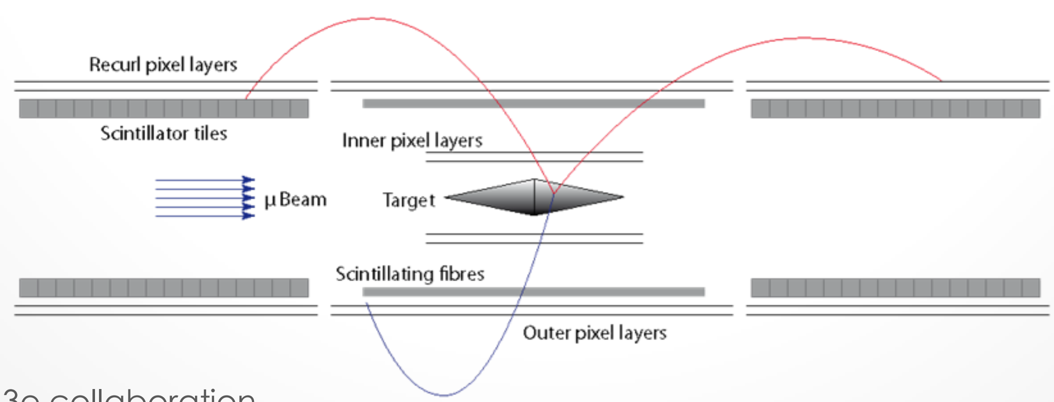
- MuPix4 prototype
- External grey counter
  - At 100 MHz
- Time stamp recorded by MuPix4 sensor
  - For each pixel
- **Time resolution O(17 ns)**
  - Non-negligible setup contribution



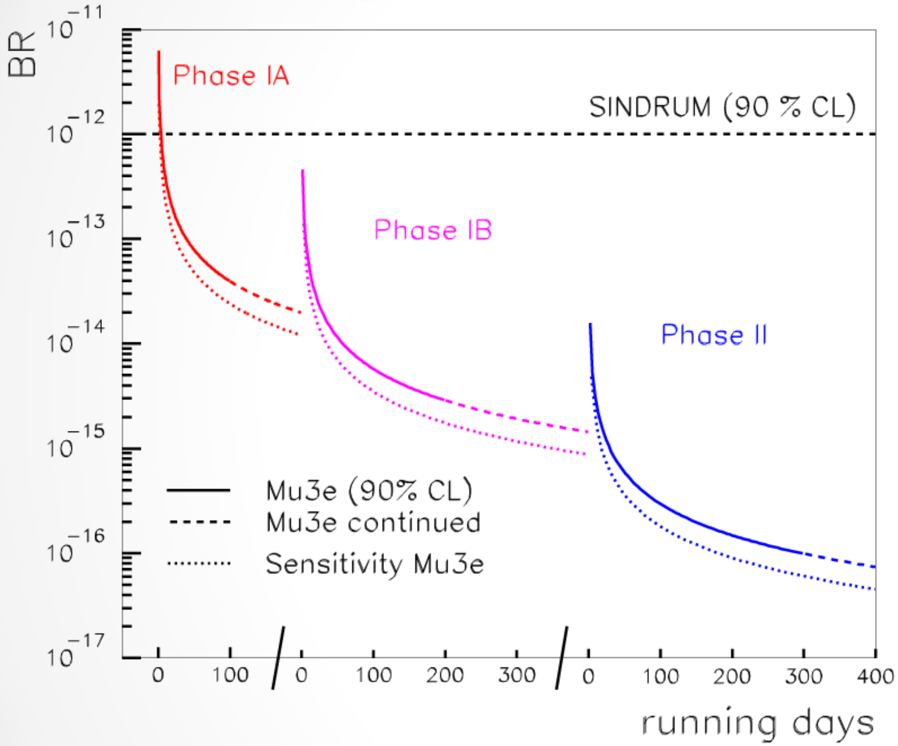
Time Resolution of Pixels

Summary

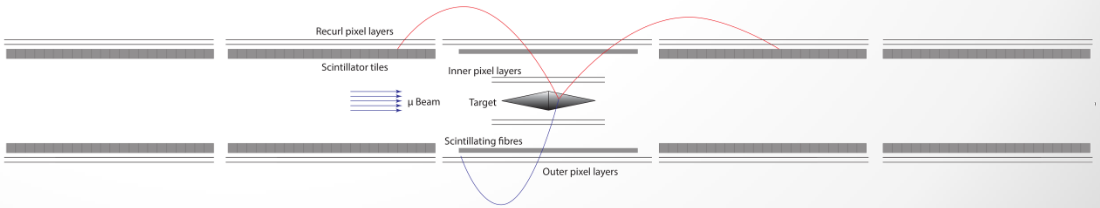
- Mu3e searches for lepton flavor violation
- > 10^{15} μ-decays → BR < 10^{-15} (90% CL)
- Two SiPM based timing systems
- Silicon tracker with ~182M pixel
- HV-MAPS 50 μm thin
- Prototypes look encouraging



Outlook: Projected Sensitivity



- Phase II 10^{-16}



Institutes

- Mu3e-collaboration:
  - DPNC Geneva University
  - Paul Scherrer Institute
  - Particle Physics ETH Zürich
  - Physics Institute Zürich University
  - Physics Institute Heidelberg University
  - Institute for Nuclear Physics Mainz University
  - IPE Karlsruhe
  - KIP Heidelberg

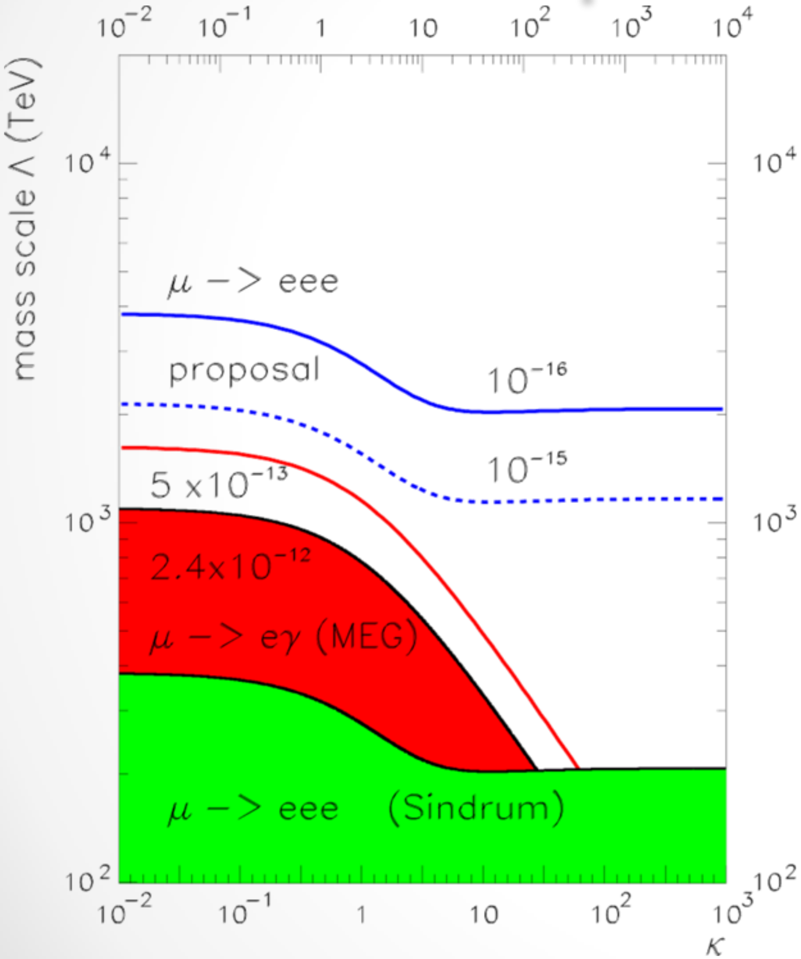
Backup Slides

…

Motivation Backup

…

μ→eee vs. μ→eγ

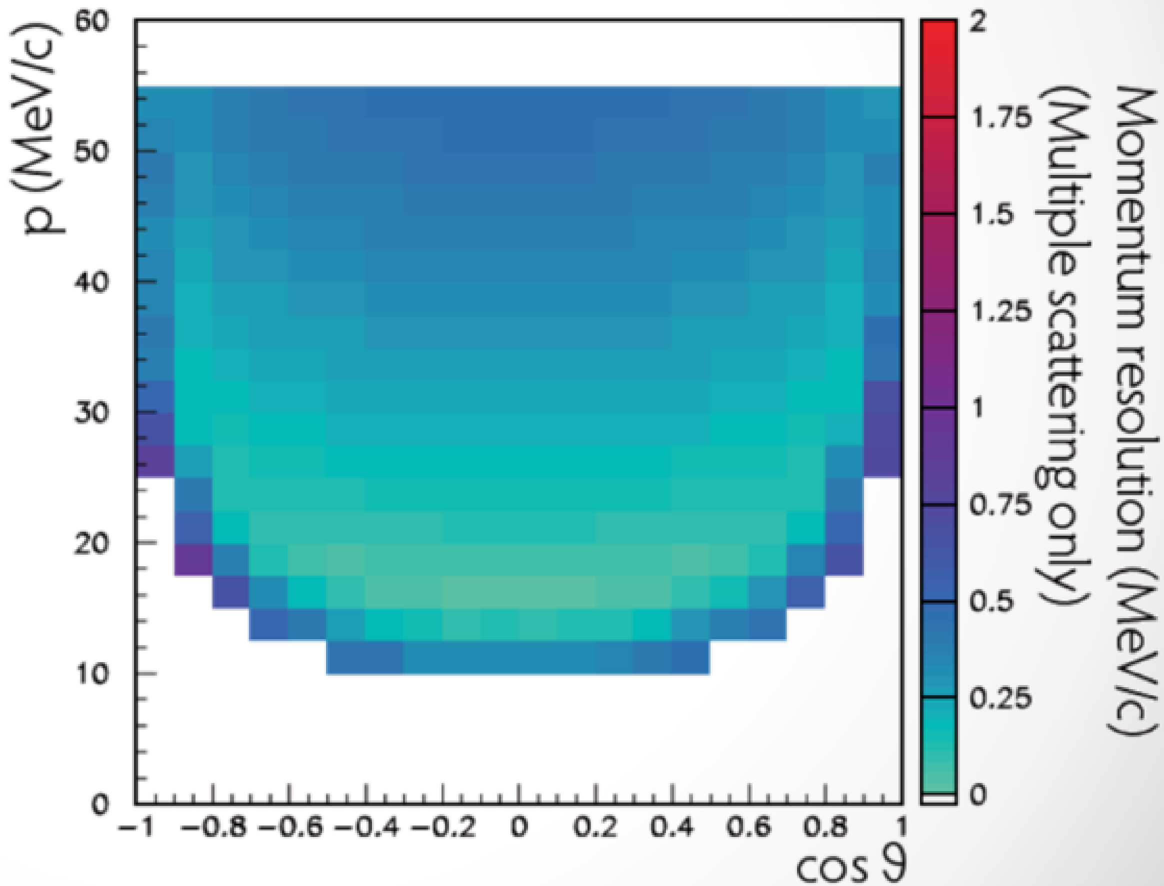


$$L_{LFV} = \left[\frac{m_\mu}{(\kappa+1)\Lambda^2}\,\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu}\right]_{\gamma-\text{penguin}} + \left[\frac{\kappa}{(\kappa+1)\Lambda^2}\,(\overline{\mu_L}\gamma^\mu e_L)\,(\overline{e_L}\gamma_\mu e_L)\right]_{\text{tree}}$$

A. de Gouvêa,
"(Charged) Lepton Flavor Violation",
Nucl. Phys B. (Proc. Suppl.),
188 303–308, 2009.

Momentum Resolution

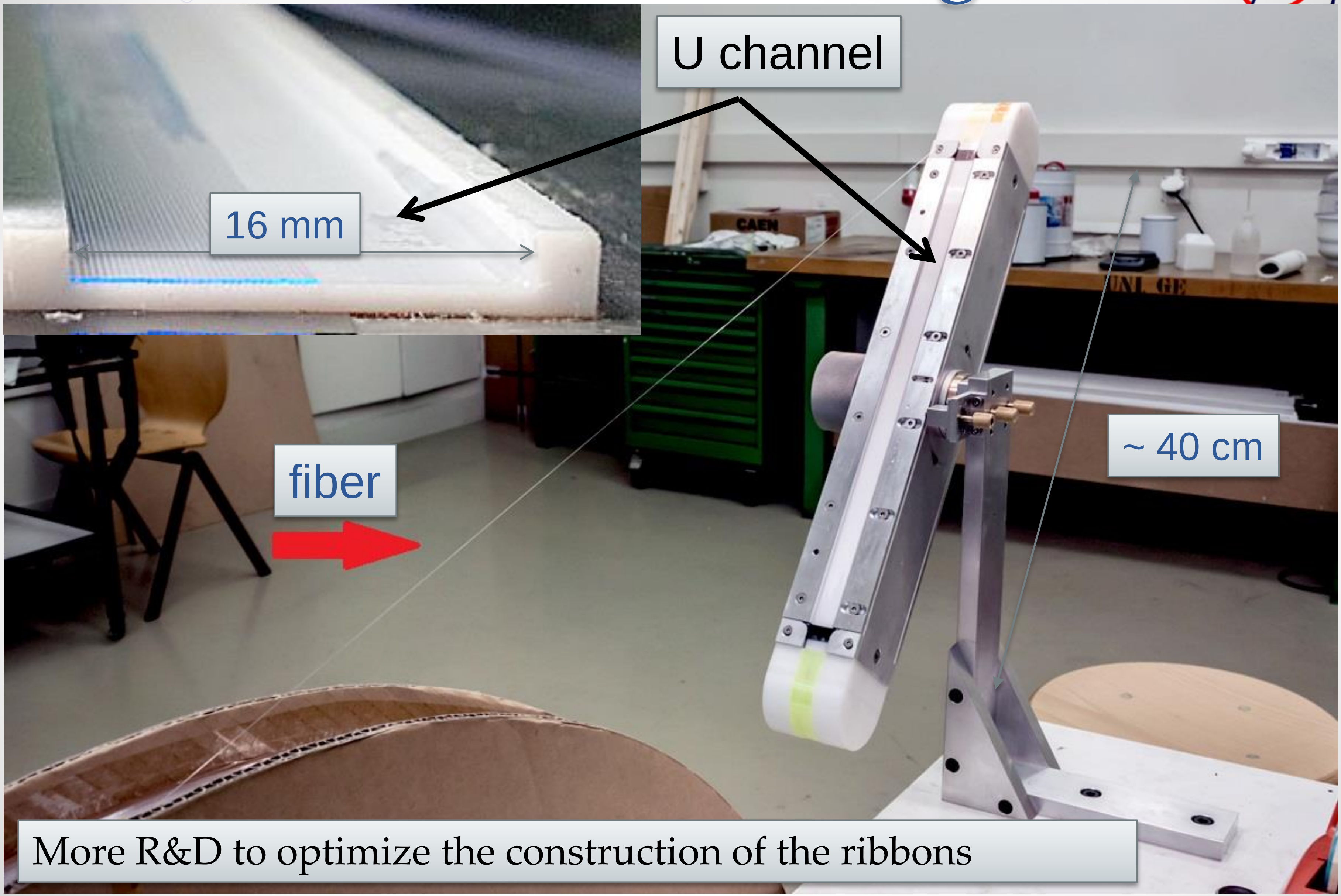
- Multiple scattering only
- Current design:
  - 50 µm silicon
  - 50 µm Kapton
  - Helium gas cooling
  - 3 layer fiber detector



SciFi Backup

…

Fiber Winding Tool

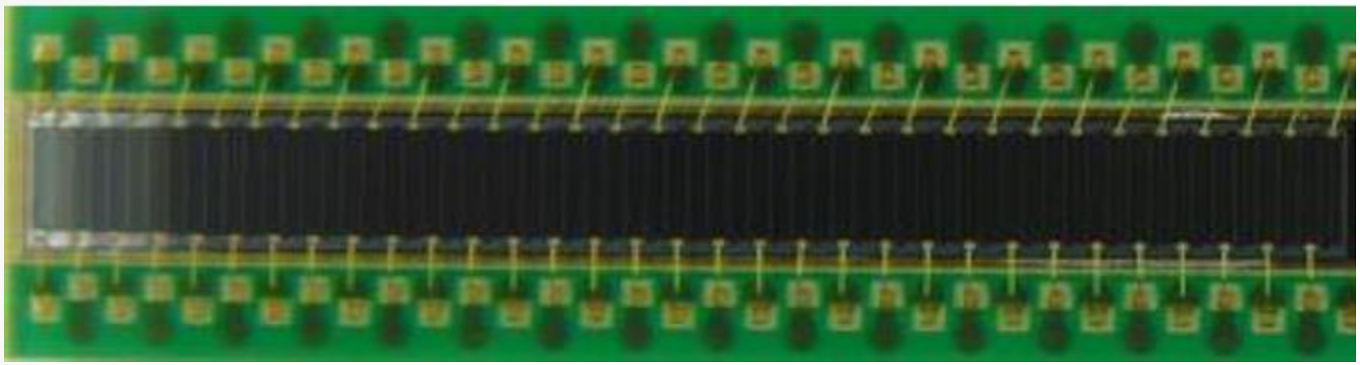


More R&D to optimize the construction of the ribbons

Readout of Fibers

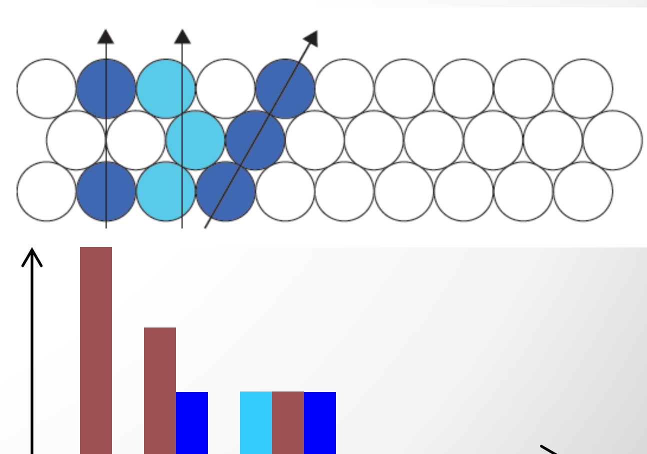
Si-PMs (MPPCs) at both fiber ends

SciFi column readout with Si-PM arrays



LHCb type detector

- 64 channel monolithic device (custom design)
- ~250 µm effective "pitch"
- 50 µm × 50 µm pixels
- Grouped in 0.25 mm × 1 mm vertical columns
- Common bias voltage



Readout of Fibers

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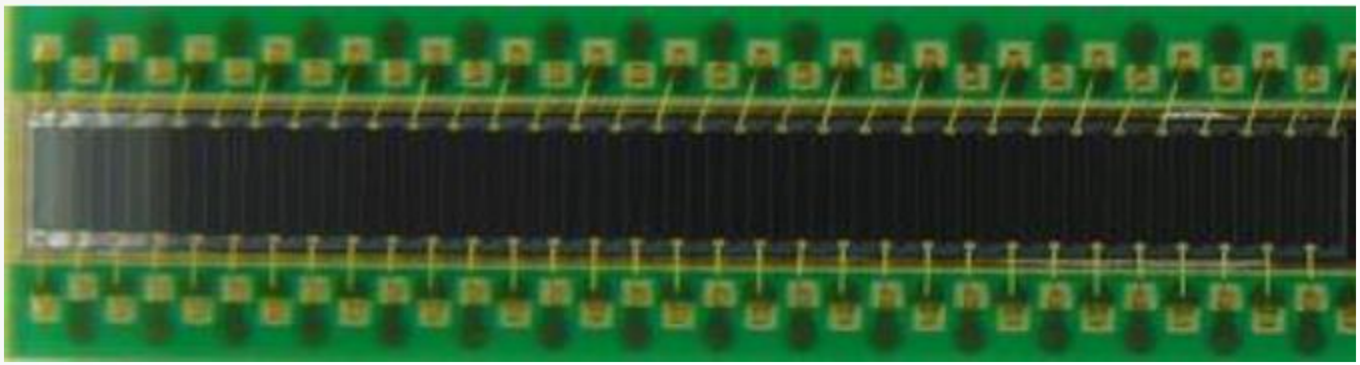
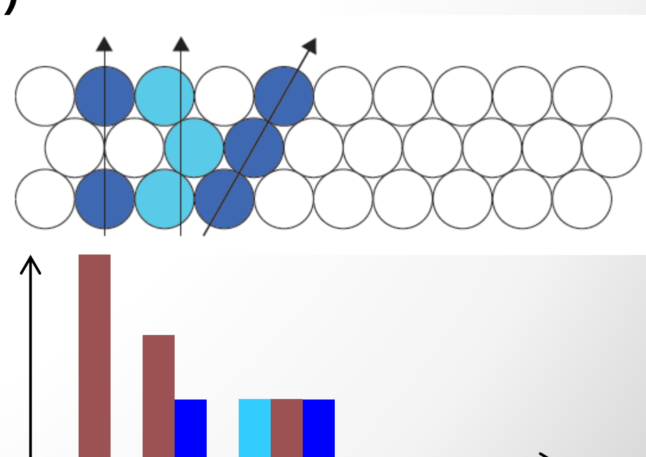
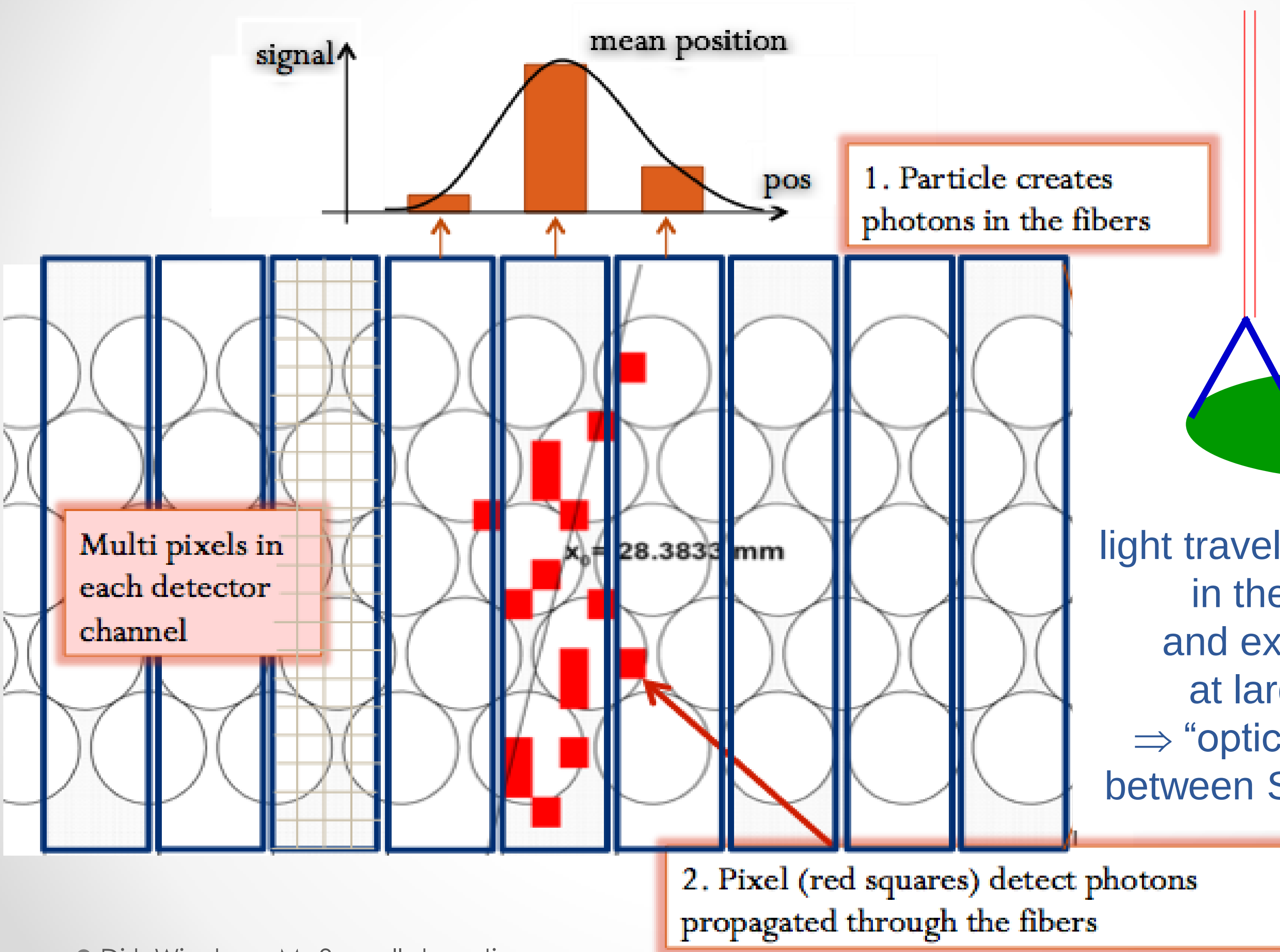


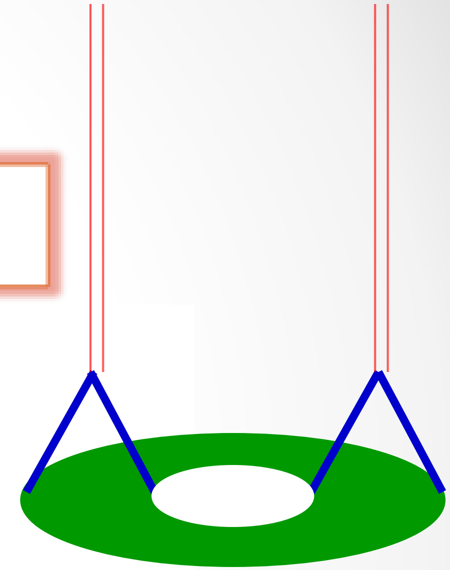
LHCb type detector

- ☺Reduced # of readout channels (2×64)
- ☺Easy, direct coupling
- ☹ Higher occupancy
- ☹ “Optical” cross talk

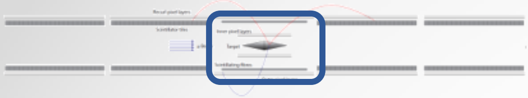


SciFi Column Readout





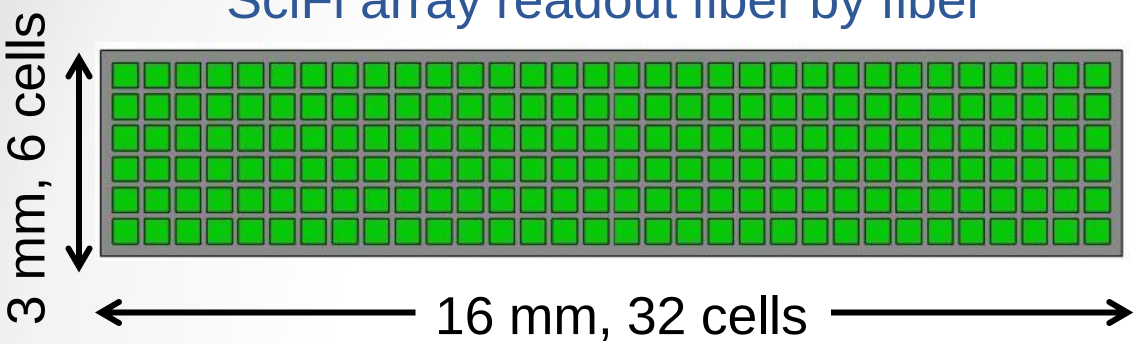
light travels preferentially in the cladding and exits the fiber at large angles
⇒ "optical" cross talk between Si-PM columns

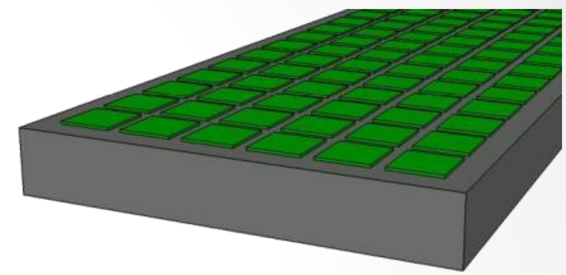


Readout of Fibers

Si-PMs (MPPCs) at both fiber ends

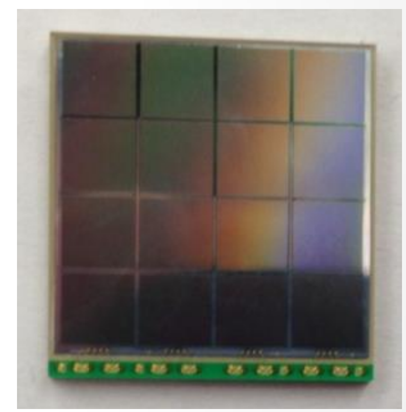
SciFi array readout fiber by fiber



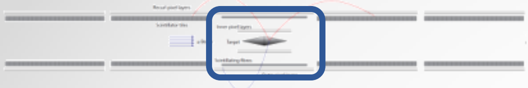


Monolithic device

- Custom design ongoing with Hamamatsu
- 6 × 32 independent readout cells
- 50 µm × 50 µm pixels grouped in
- 0.4 mm × 0.4 mm cells with 0.1 mm spacing
- Common bias for each cell (~0.5 V)



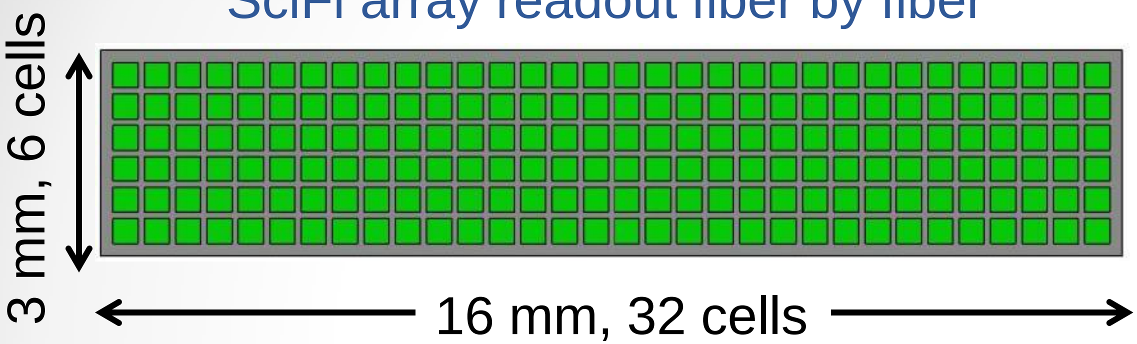
Example of Hamamatsu Si-PM array S12642-0404 sensor 4 × 4 ch. (3×3 mm^2)

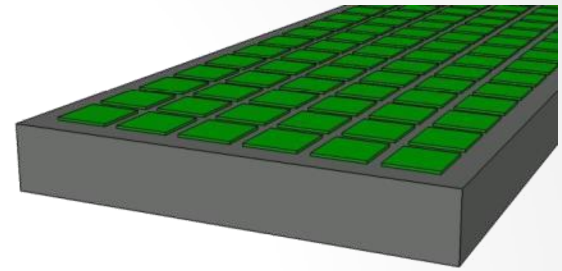


Readout of Fibers

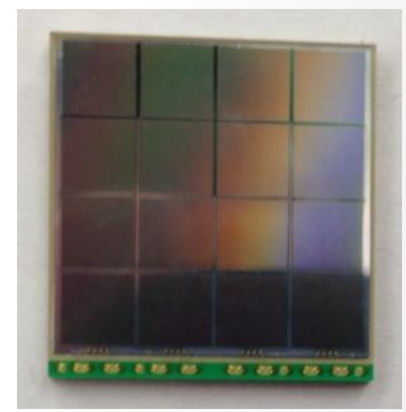
Si-PMs (MPPCs) at both fiber ends

SciFi array readout fiber by fiber





- ☺ Lowest possible occupancy
- ☺ No “optical” cross talk
- ☺ Less dark rate
- ☺ Can also be used for tracking?
- ☹ Increased # of readout channels (2 × 192)
- ☹ Few photons / fiber (cell)



Example of Hamamatsu Si-PM array S12642-0404 sensor 4×4 ch. (3×3 mm^2)

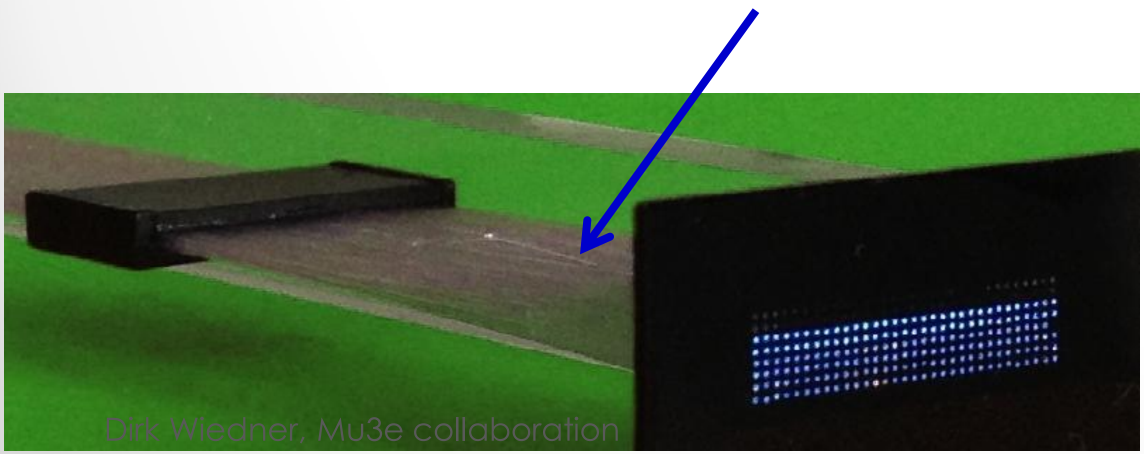
Single Fiber Readout

Fibers glued with photo-device geometry
500 μm center to center

Si-PM array directly coupled to fibers

Estimated rate ~ 200 kHz for 2017 run

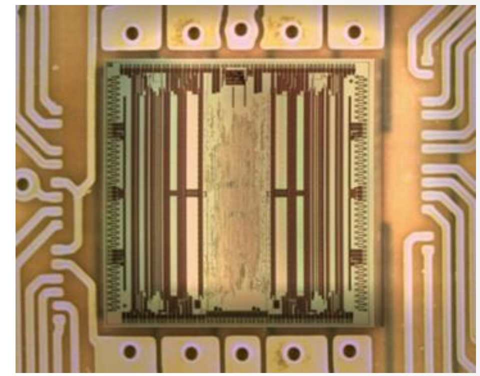
"fan-out" between straight section and socket



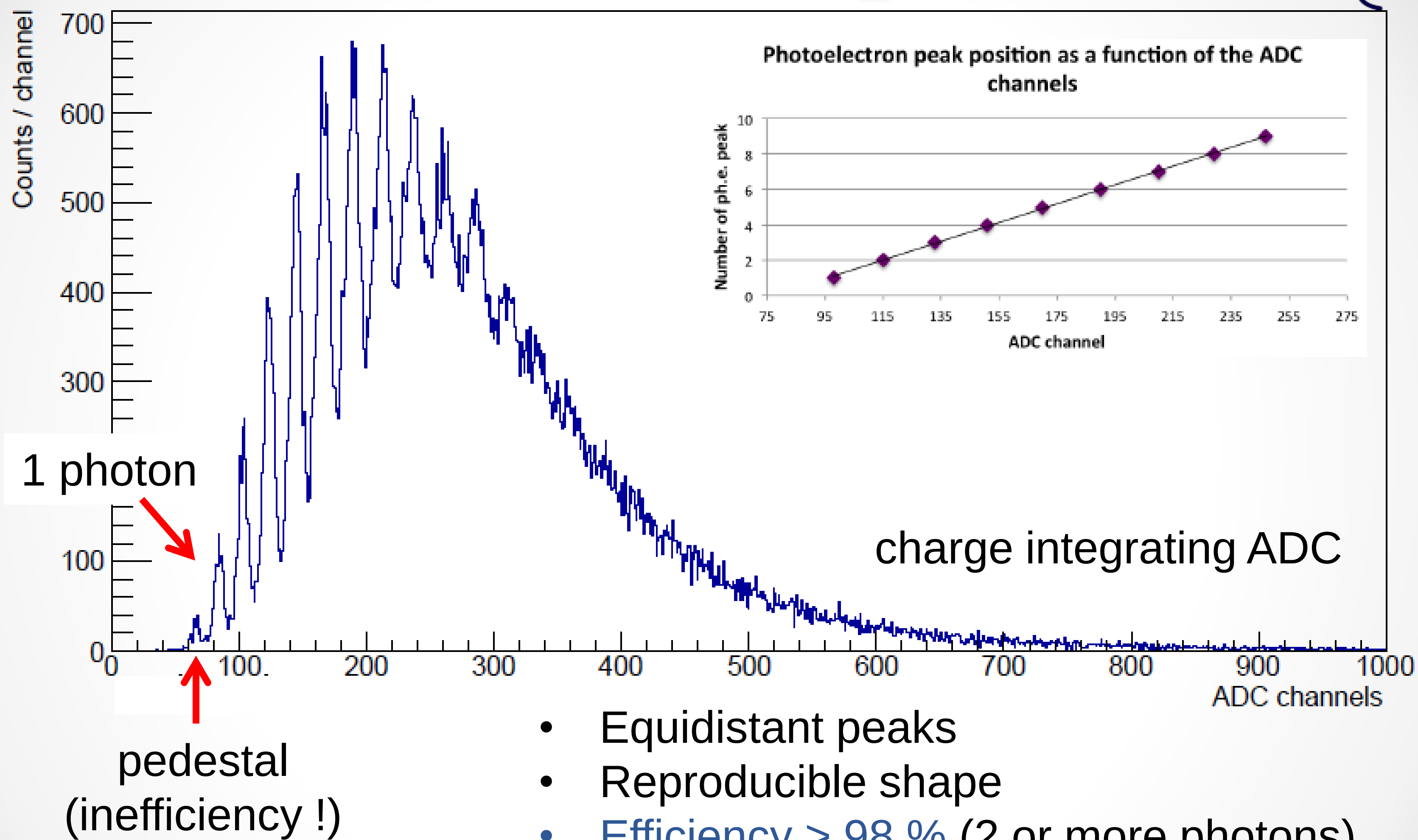
Alternative:
LHCb type detector

Readout Electronics

- **MuSTiC** ASIC (KIP)
- Fulfills SciFi requirements
  - o Compact design
    - Installation very close to Si-PM arrays
  - o 64 channels
    - 6 chips / Si-PM array
    - Assuming MuSTIC can sustain ~10 MHz hit-rate
- Performance to be tested
  - o In particular for low photon yield

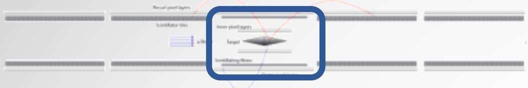


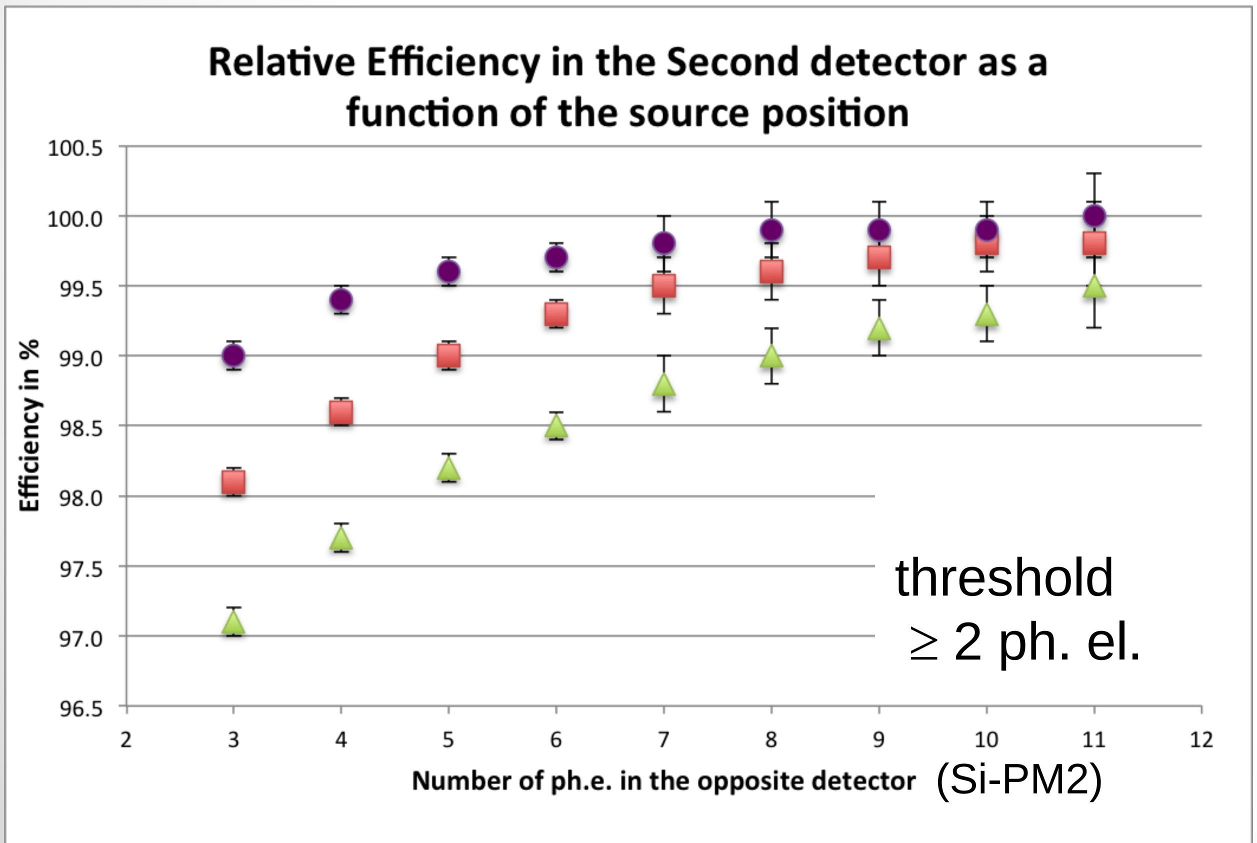
ADC Spectra



- Equidistant peaks
- Reproducible shape
- Efficiency > 98 % (2 or more photons)
- Consistent with light propagation simulations
- Distance between peaks → amplification

Efficiency





Small efficiency drop for source far from Si-PM

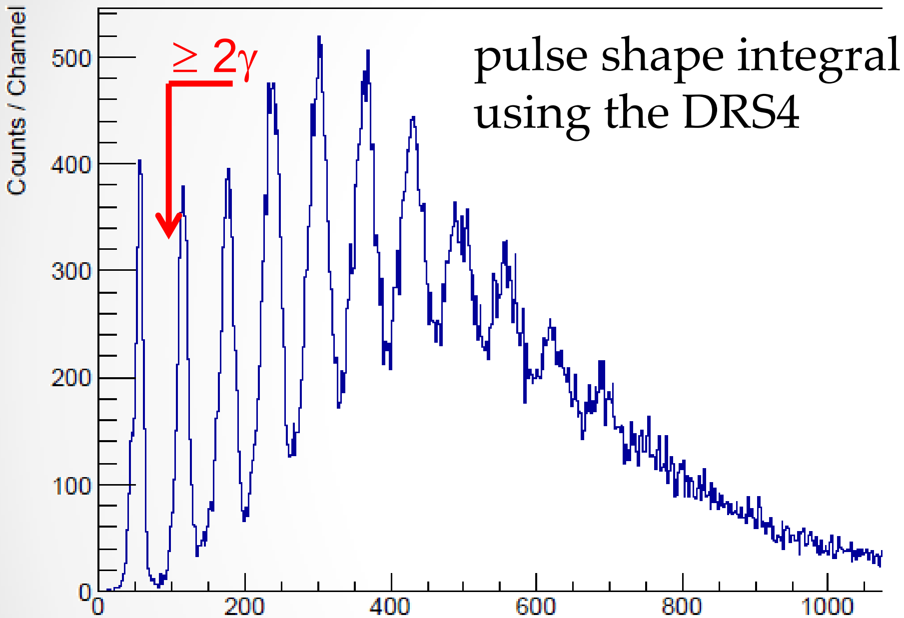
Vs. photons in opposite detector

Detection efficiency of Si-PM1 increases With # photons in Si-PM2

Calibration

Calibrate in situ:

Alignment, energy (thresholds), timing



Energy:

Use ADC spectra

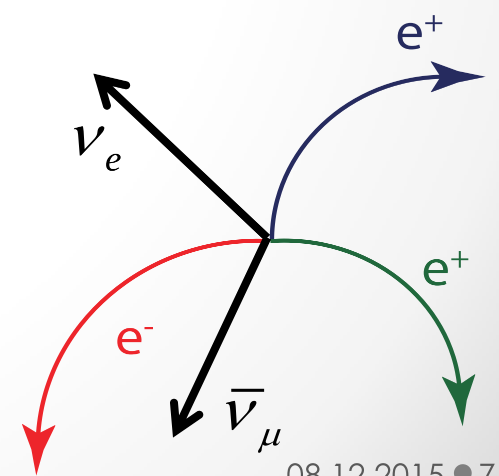
Distance between peaks

$\rightarrow$ Amplification

Set discriminator thresholds (> nγ)

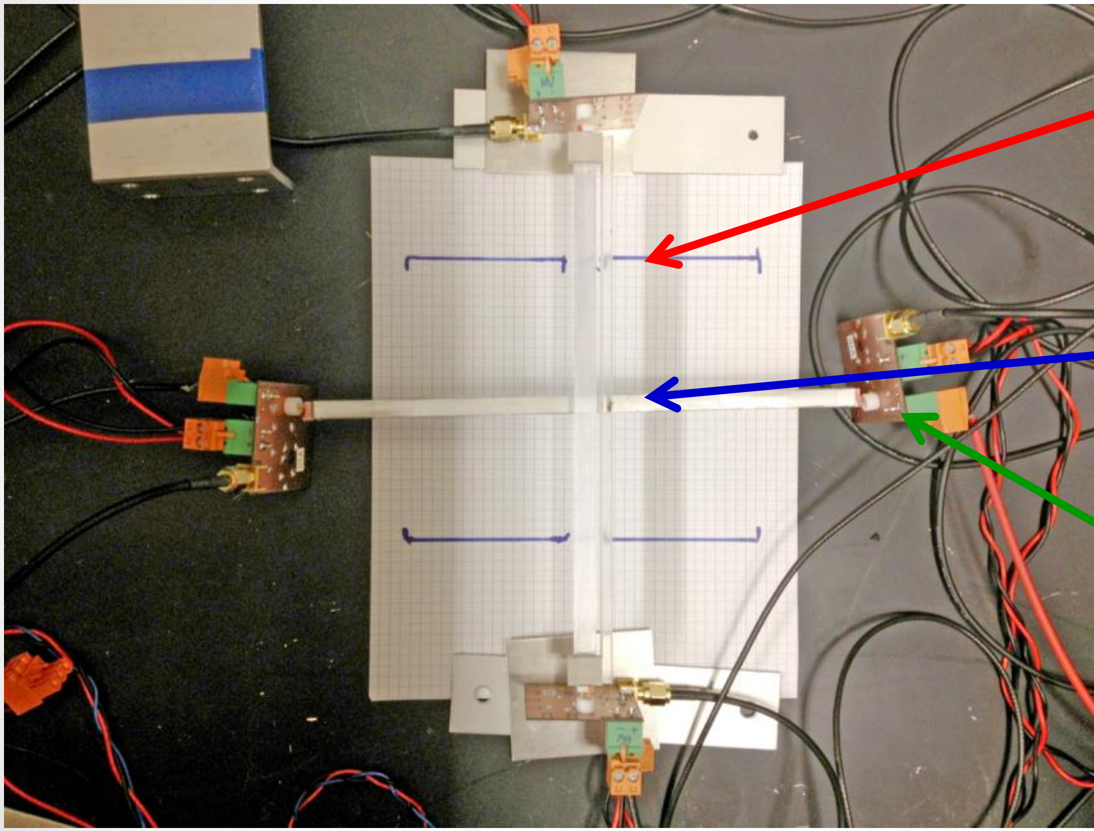
Timing:

- use the decay $\mu^+ \rightarrow e^+ e^- e^+ \nu \nu$
- 3 prongs produced at the same time
- For 10^7 μ decays / s in one day
- 10^7 decays assuming 33% eff.



Test Set-Up

Tests with collimated β source (Sr)
β electrons cross the ribbon at 90^0

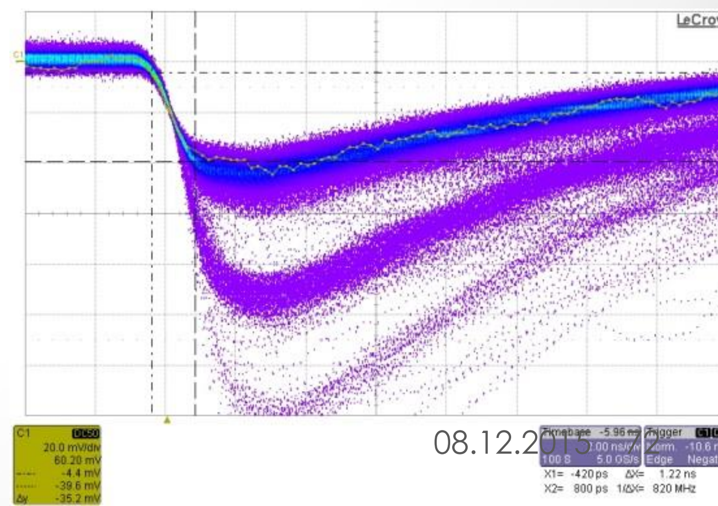


8 mm wide 200 mm long
3 layer SciFI ribbon

Readout with 3×3 mm^2 Si-PMs
Si-PMs glued on SciFi ribbon

Trigger scintillator:
- 6×6 mm^2 square bar
- Readout with same Si-PMs

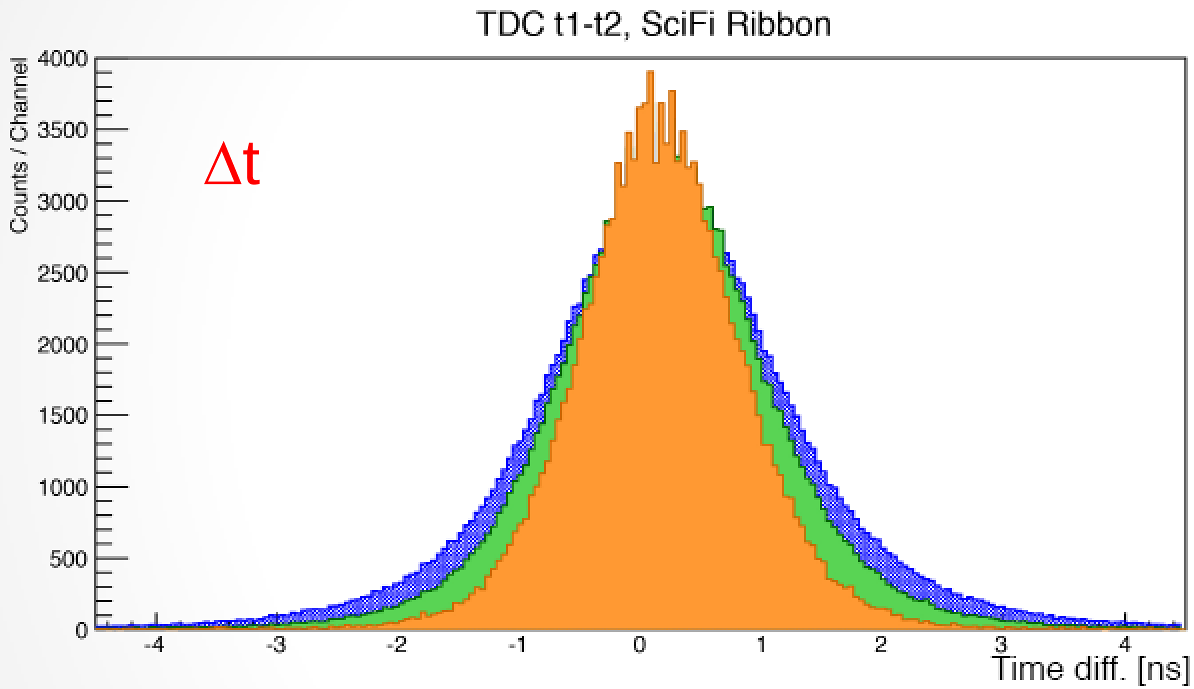
Fast (~1 ns) transistor based



Complete the studies
by testing prototypes in a beam
→ February DESY Test Beam

Timing

- Time difference Δt between Si-PM1 and Si-PM2
  - Rise-time compensated discriminators



different colors : different # of detected photons (see next slides)

Time resolution σ of each Si-PM : $\Delta t / \sqrt{2}$

Time resolution of Mean Time : $\sigma_{MT} = \sigma / \sqrt{2} = \Delta t / 2$

For same σ, i.e. similar # of detected photons on each side

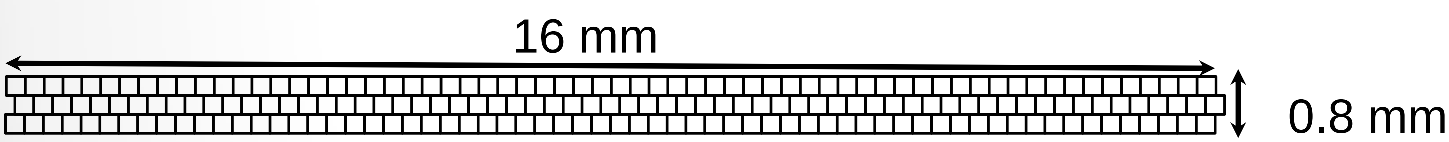
Mean time does not depend on impact position

Alternative Design with Square Fibers

3 layers of 250 μm square double cladding scint. fibers

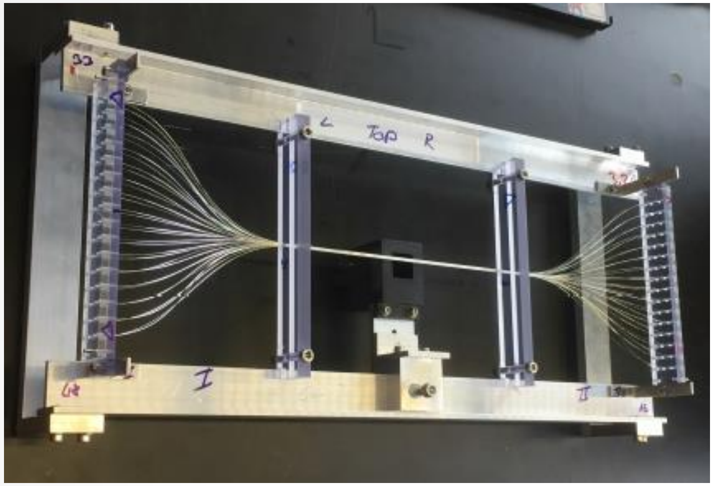
64 fibers/layer

Single fiber Al coating (minimum "optical" cross-talk)



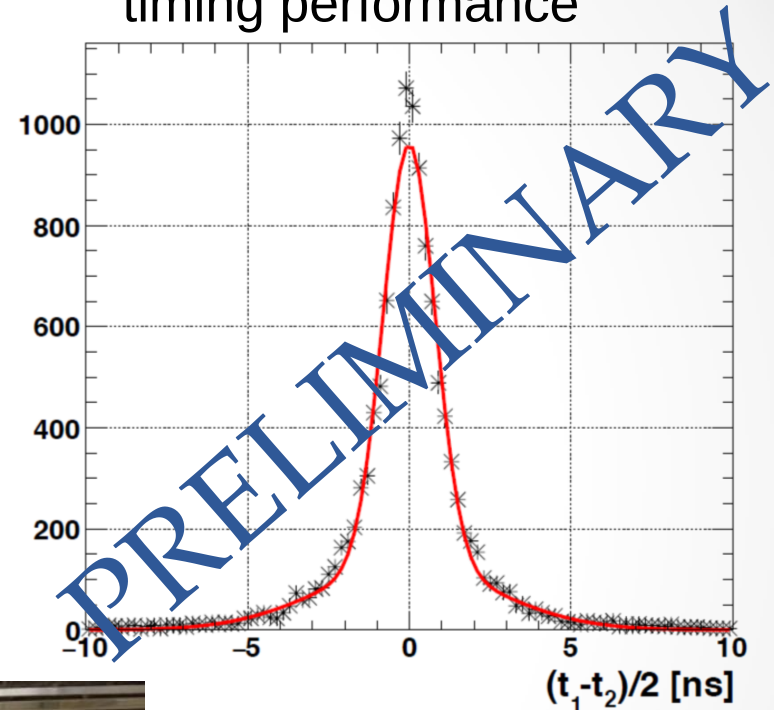
Testing Square Fibers

Fiber test setup developed at PSI



250 µm square fiber

timing performance



Cross talk:

By sputtering 30 nm Al coating on the fiber cross talk < 1% was achieved

0.5 Nphe threshold

σcore ~ 800 ps

σtail ~ 2.8 ns

fcore ~ 65 %

Conclusions SciFi

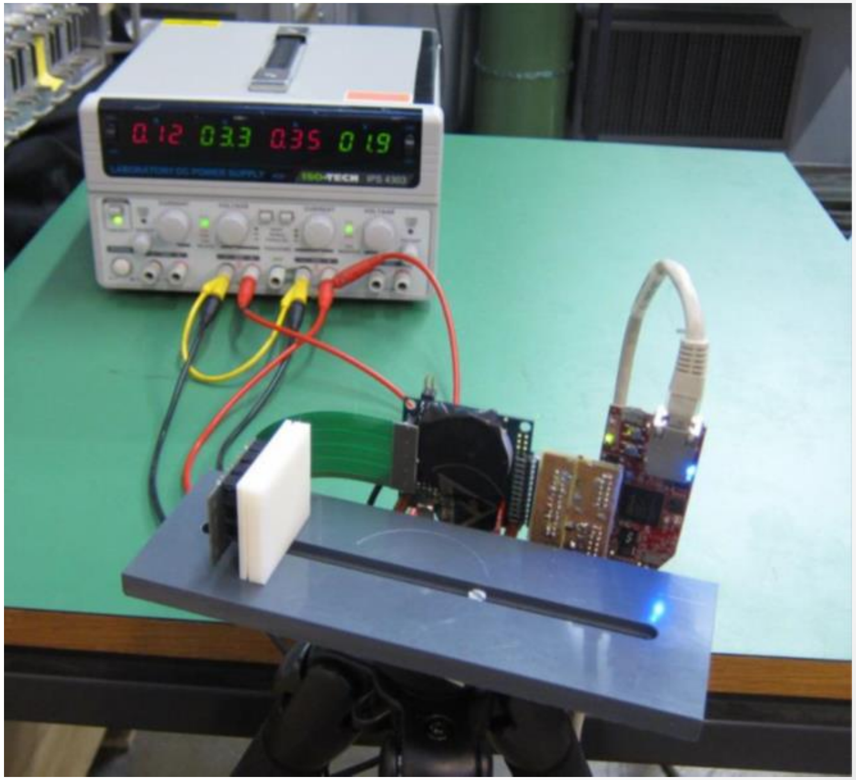
- Timing requirements (resolution < 1 ns) fulfilled
- Good agreement between simulations and measurements
    - Light propagation
- Further characterizations ongoing or planned
    - B-source and beam:
    - Test of single fiber readout with commercially available Si-PMs
    - Cross talk between fibers
    - Rate capabilities
    - Readout electronics

- Further studies under way to optimize construction of detector

Tile Detector
Backup

Tile Detector

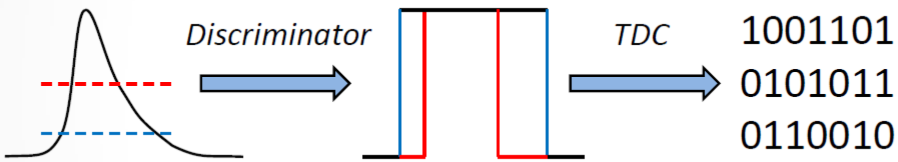
- Scintillating tiles
  - 6.5 x 6.0 x 5.0 mm^3
- 7 Tile Modules per station
  - 480 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through STiC



Tile detector 4 x 4 prototype

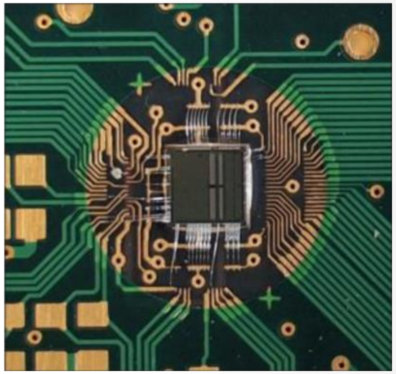
STiC Readout

- Developed at KIP for EndoTOFPET-US
  - Optimized for ToF applications
- Key features:
  - Digital timing & energy information

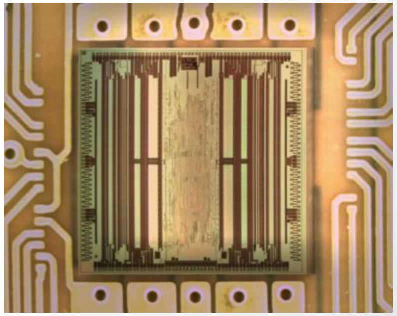


  - 64 channels (version 3.0)
  - 50 ps TDC bins
  - SiPM bias tuning
  - SiPM tail cancelation possibility (version 3.0)
  - Currently ≈ 1 MHz hit rate / chip
  - Up to ≈ 20 MHz in future version
- Version 2.0 successfully operated in test-beam

STiC 2.0



STiC 3.0



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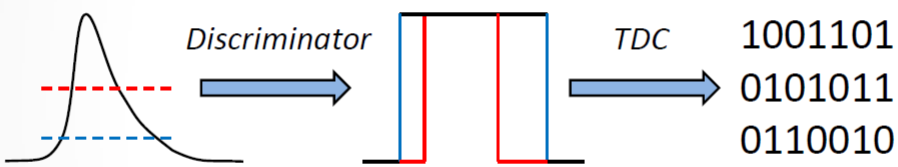

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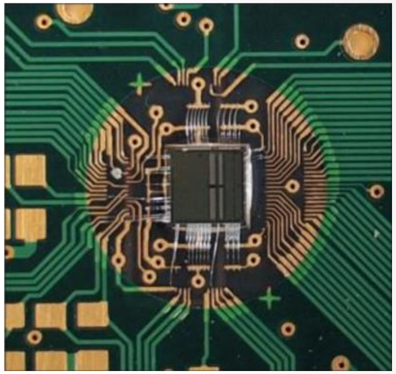
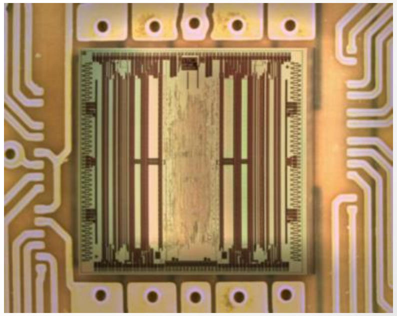
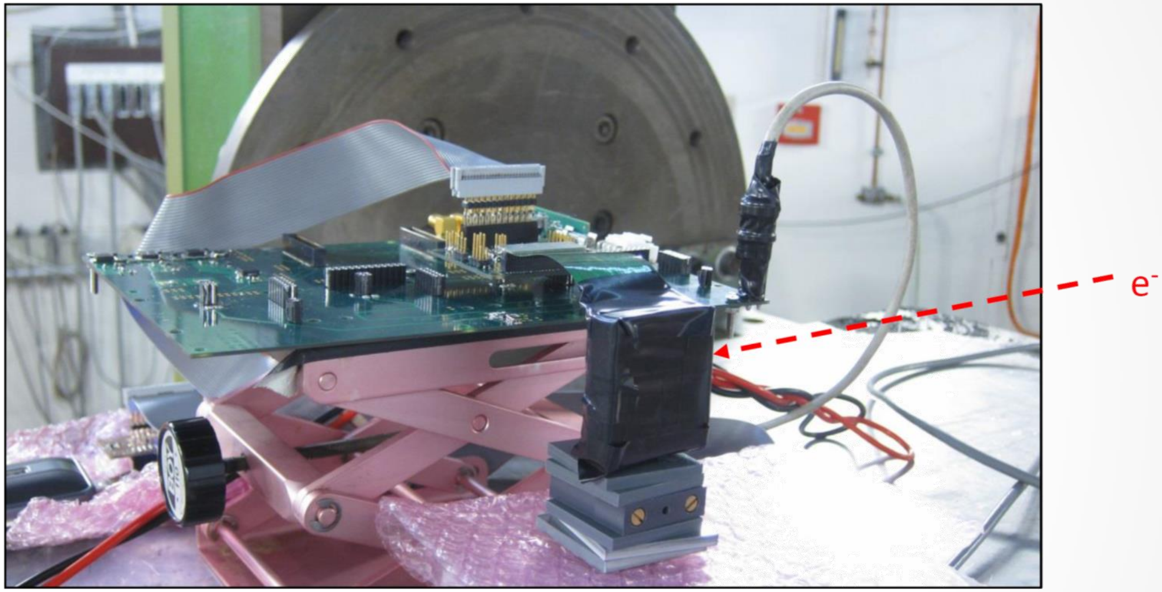


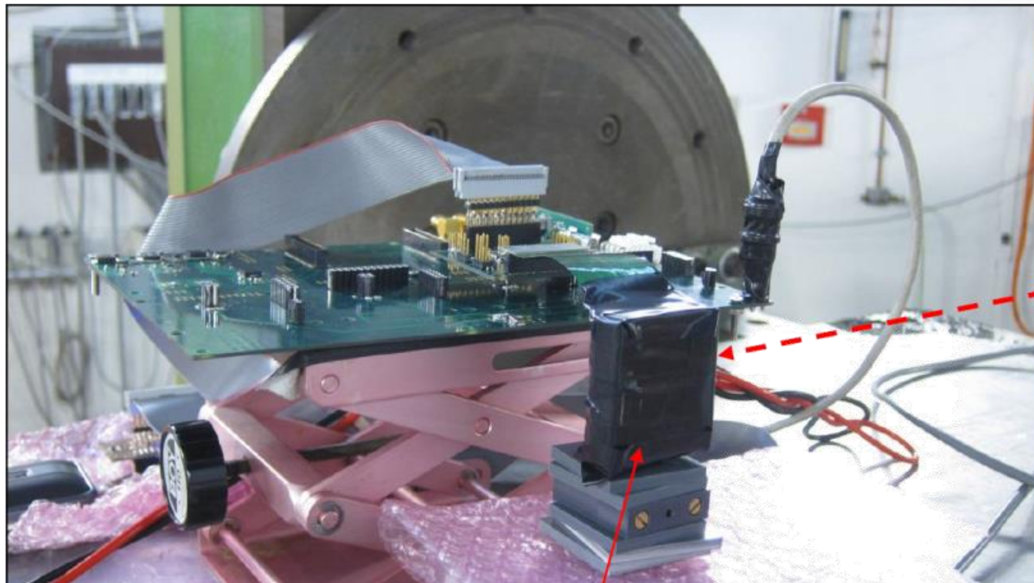
STiC 3.0

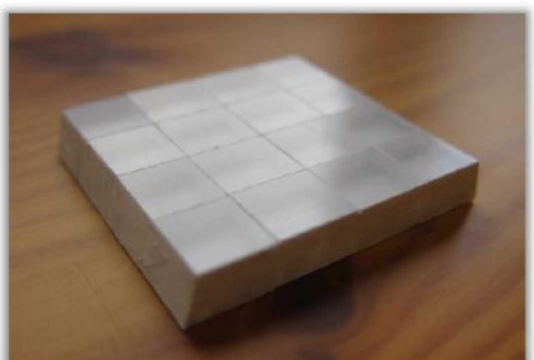


STiC Test Beam

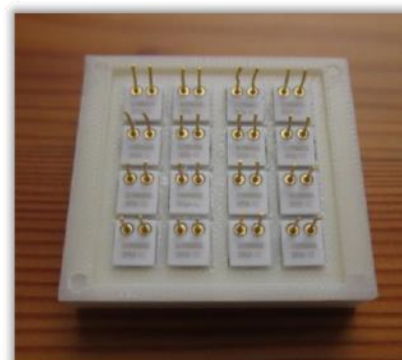


STiC Test Beam



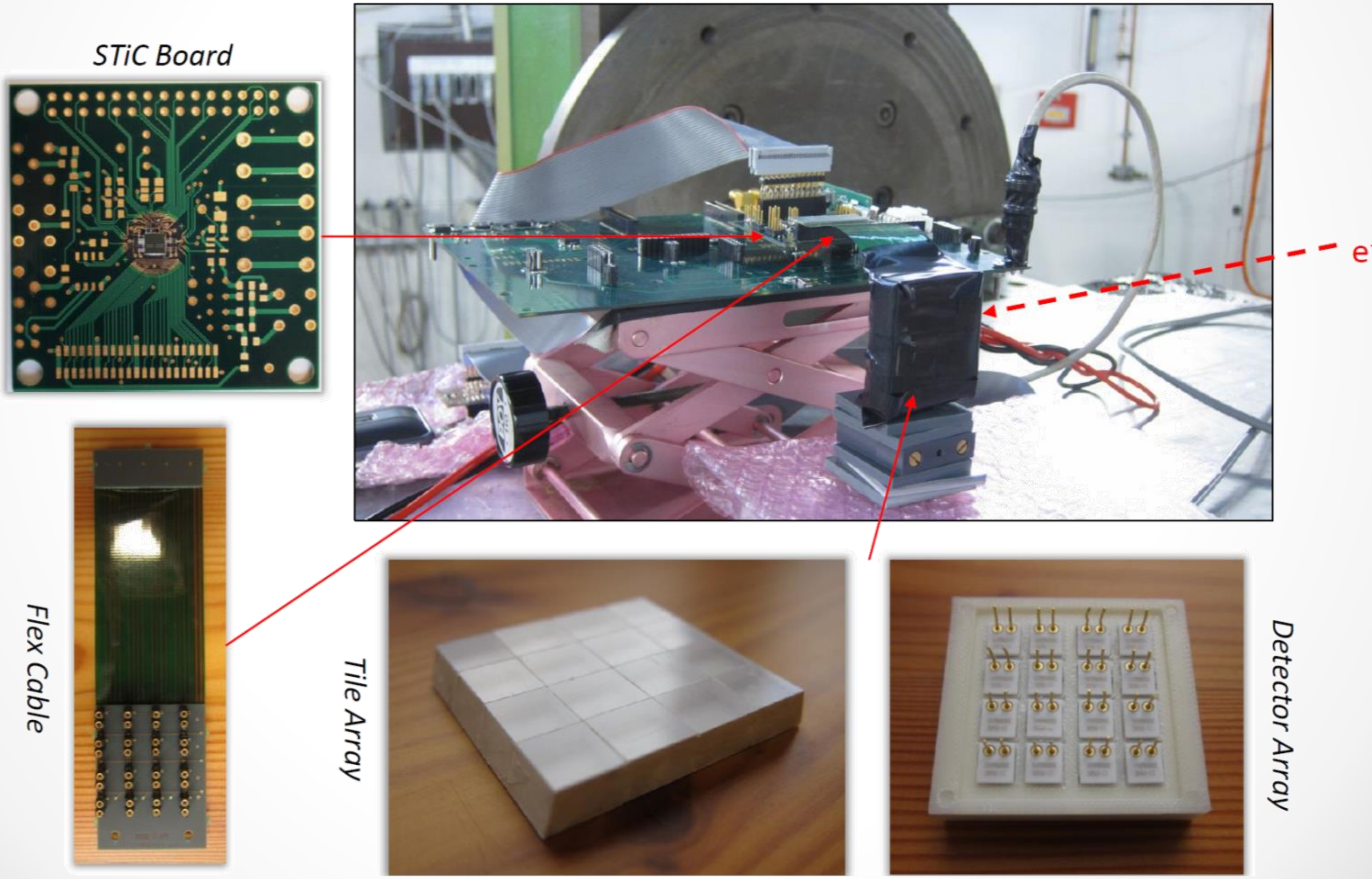


Tile Array



Detector Array

STiC Test Beam

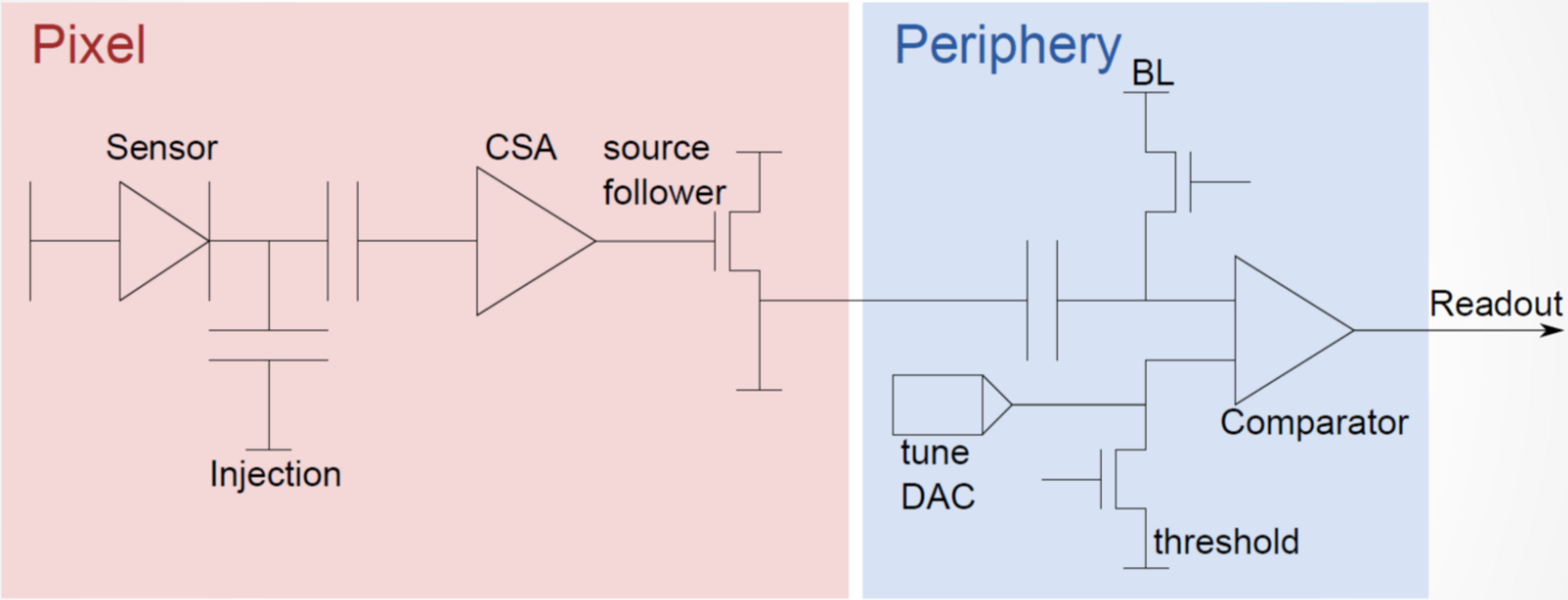


HV-MAPS Backup

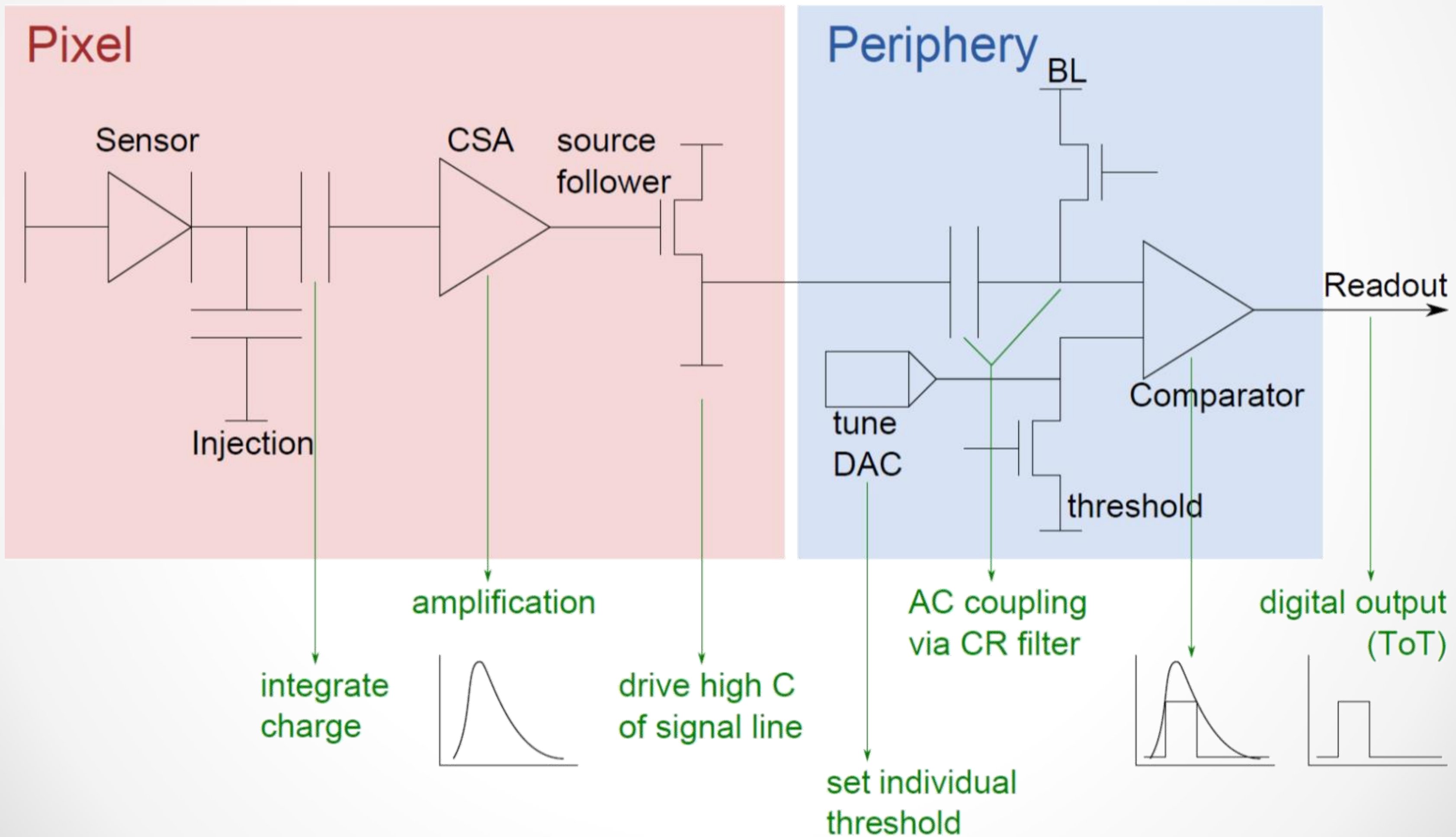
Prototype Overview

Prototype	Active Area	Functionality	Bugs	Improvements
MuPix1	1.77 mm^2	Sensor + analog	Comparator **"ringing"**	First MuPix prototype
MuPix2	1.77 mm^2	Sensor + analog	**Temperature** dependence	**No ringing**
MuPix3	9.42 mm^2	Sensor, analog, dig.	bad pixel **on/off**,	**First** part of **dig.** readout
MuPix4	9,42 mm^2	Sensor, analog, dig.	Zero time-stamp and **row address** for 50% of pixels	Working digital readout, **timestamp**, temperature stable
MuPix6	10.55 mm^2	Sensor, analog, dig.	?	Removed zero time-stamp and address bug
MuPix7	10.55 mm^2	System on Chip	?	Fast serial readout

Sensor + Analog + Digital

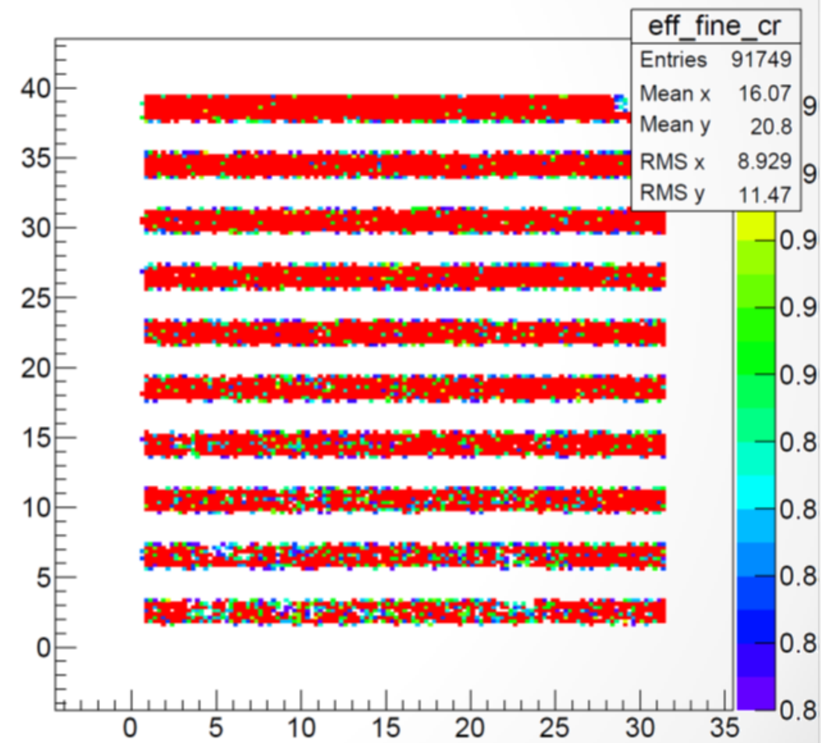


Sensor + Analog + Digital



Digital Readout Feature

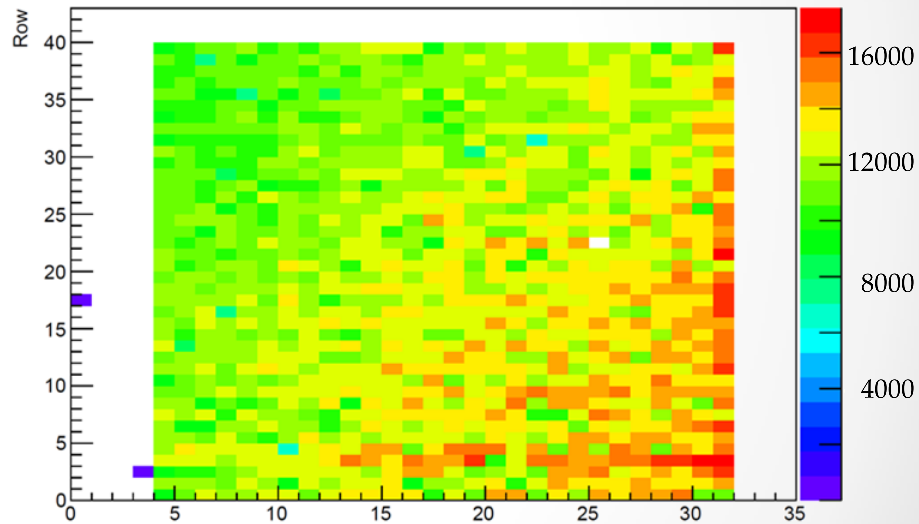
- Artifact from readout protocol:
  - Pixel RAM-cells reset before readout
  - ➢ Bug effects only row address and time stamp
  - ➢ 50% of pixels effected
  - ➢ Pixel efficiency also good for affected rows



Efficiency
Only hits with full address

Digital Readout Feature

- Artifact from readout protocol:
  - Pixel RAM-cells reset before readout
  - Bug effects only row address and time stamp
  - 50% of pixels effected
  - Pixel efficiency also good for affected rows
- **Bug fixed since MuPix6**

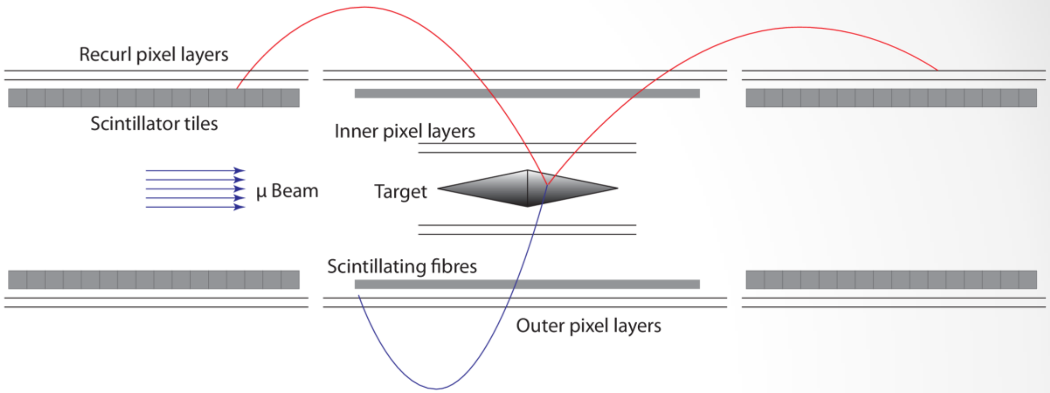


Hit map for MuPix6

Mechanics Backup

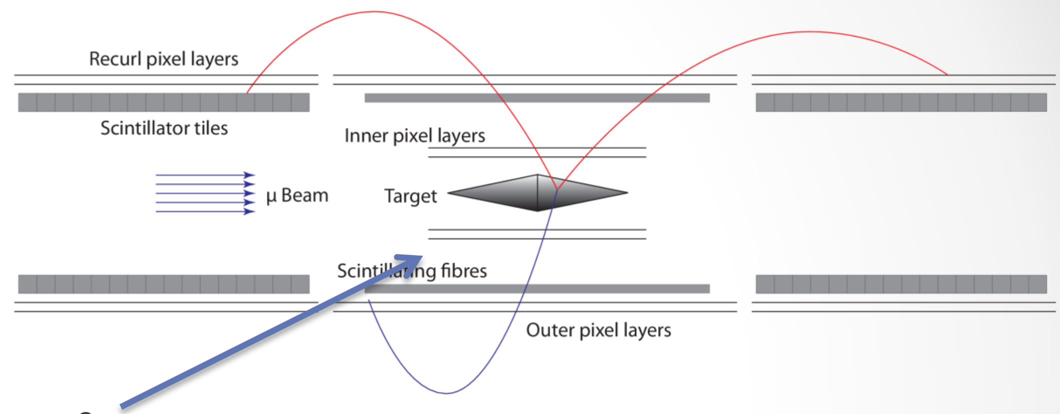
…

Mu3e Silicon Detector



- Conical target
- Inner double layer
  - 8 and 10 sides of 2 x 12 cm^2
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm^2
- Re-curl layers
  - 24 and 28 sides of 2x 36 cm^2
  - Both sides

Mu3e Silicon Detector



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- Inner double layer
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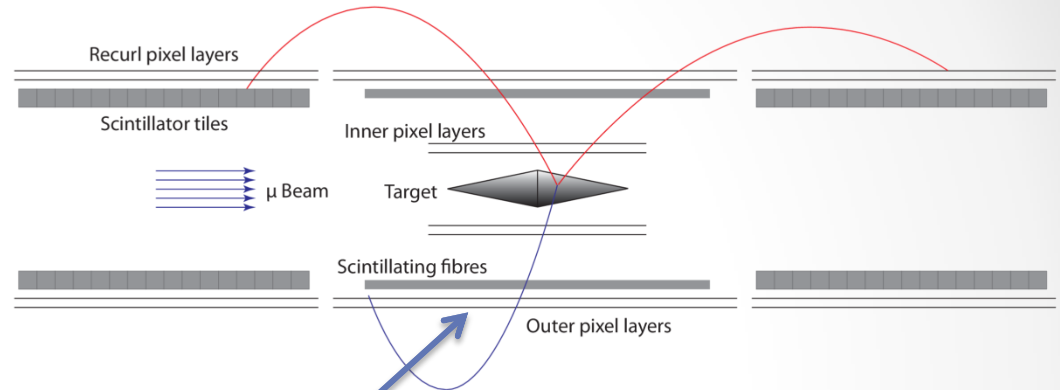
Mu3e Silicon Detector



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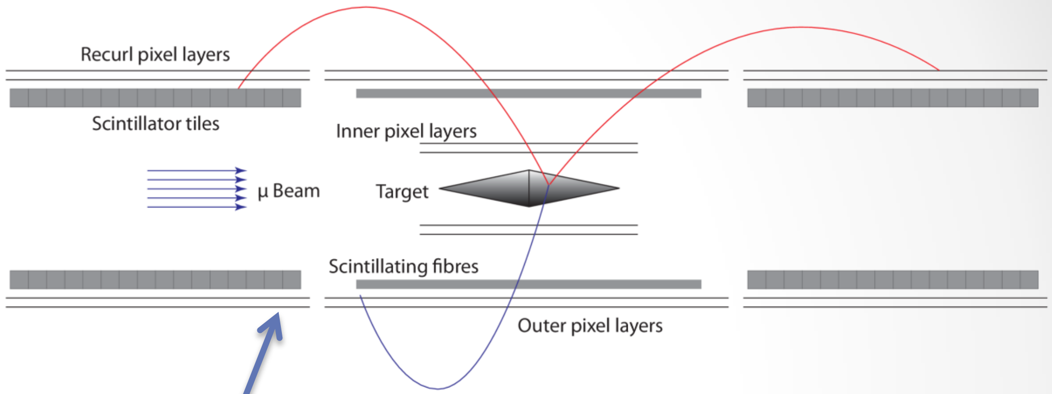
  - Both sides

Mu3e Silicon Detector

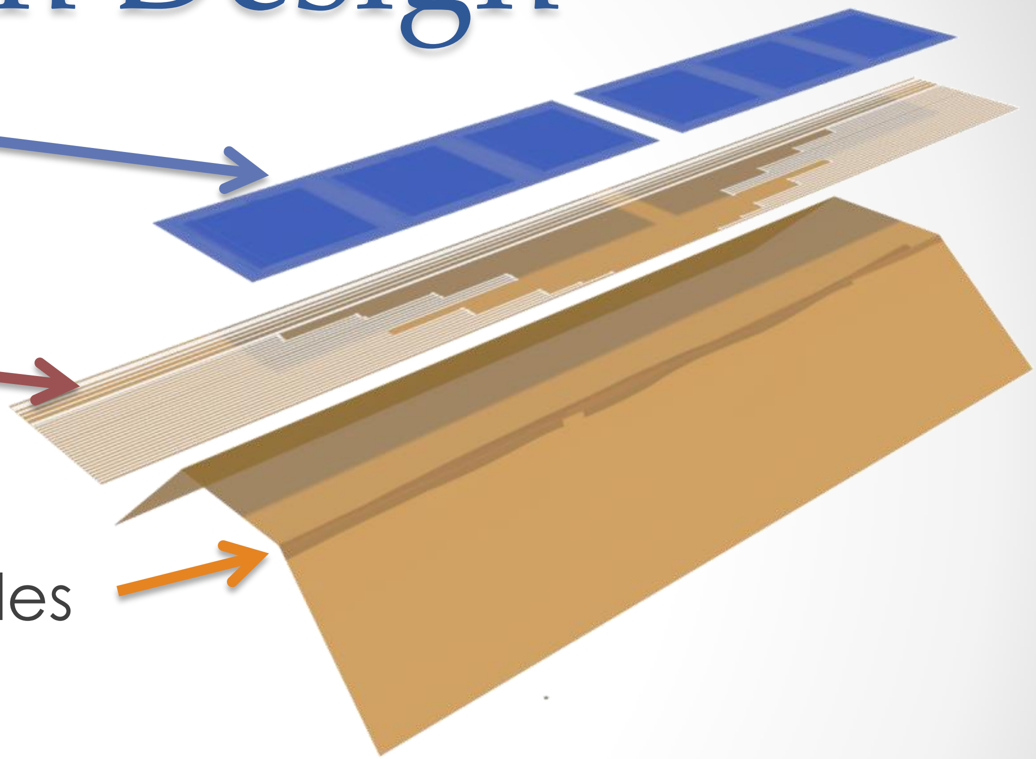


- Conical target
- Inner double layer
  - 8 and 10 sides of 2 x 12 cm^2
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm^2
- Re-curl layers
  - 24 and 28 sides of 2 x 36 cm^2
  - Both sides

108 inner sensors
2808 outer sensors
➢ 182 250 000 pixel

Sandwich Design

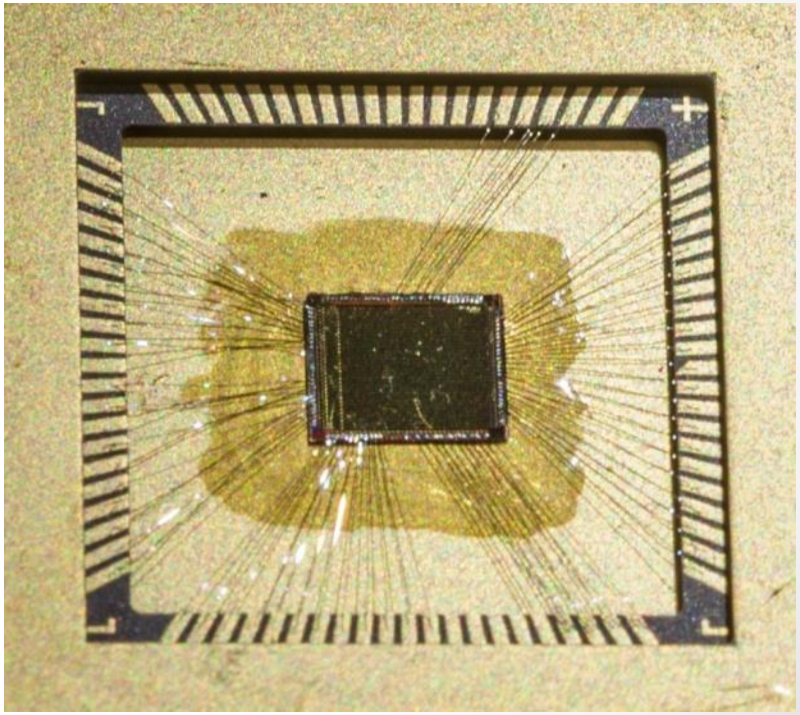
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



0.1% of X_0

Thinned Pixel Sensors

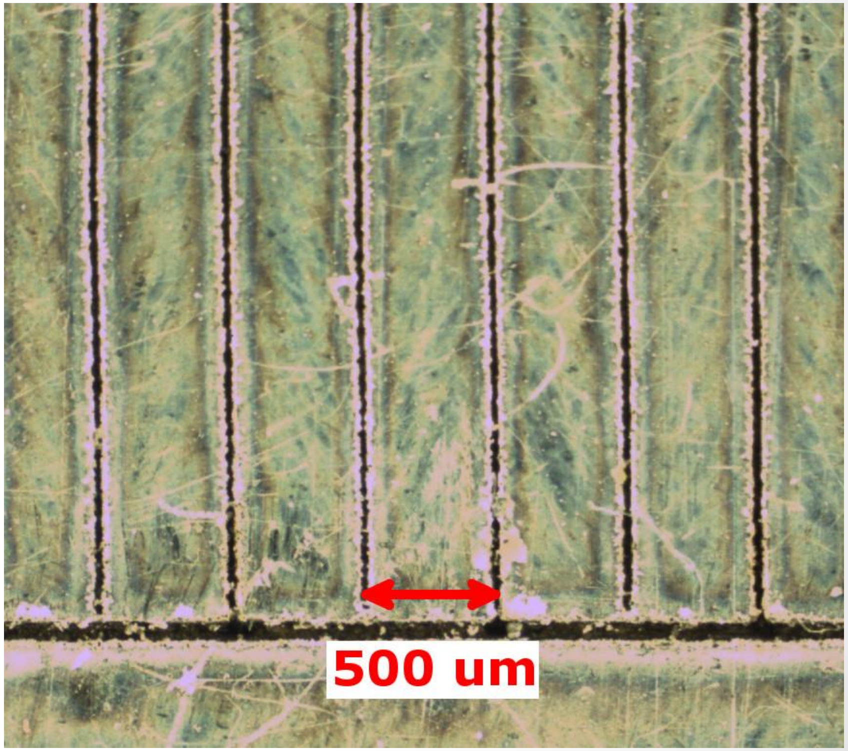
- **HV-MAPS***
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



MuPix3 thinned to < 90µm

Kapton™ Flex Print

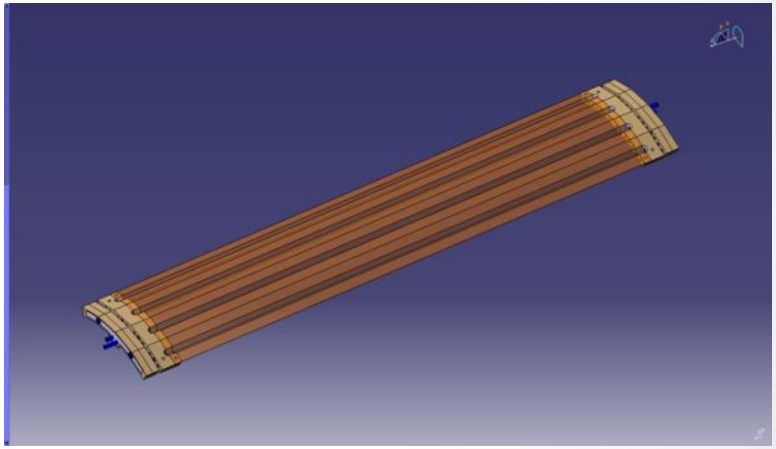
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- **Kapton™ flex print**
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



Laser-cut flex print prototype

Pixel Modules

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm²
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors

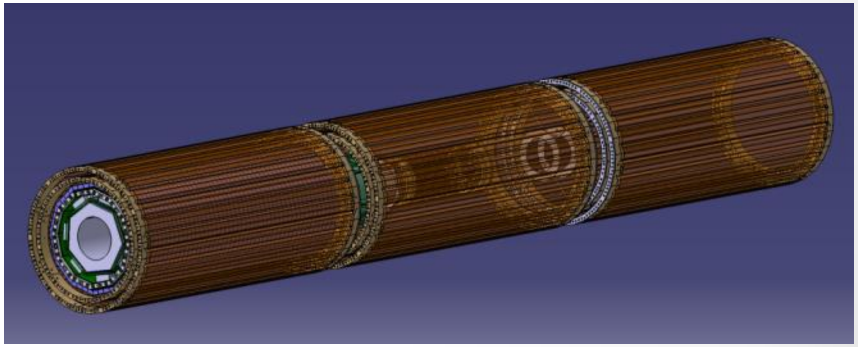


CAD of Kapton™ frames

Overall Design

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors

- Two halves for layers 1+2
- 6 modules in layer 3
- 7 modules in layer 4



CAD of Kapton™ frames

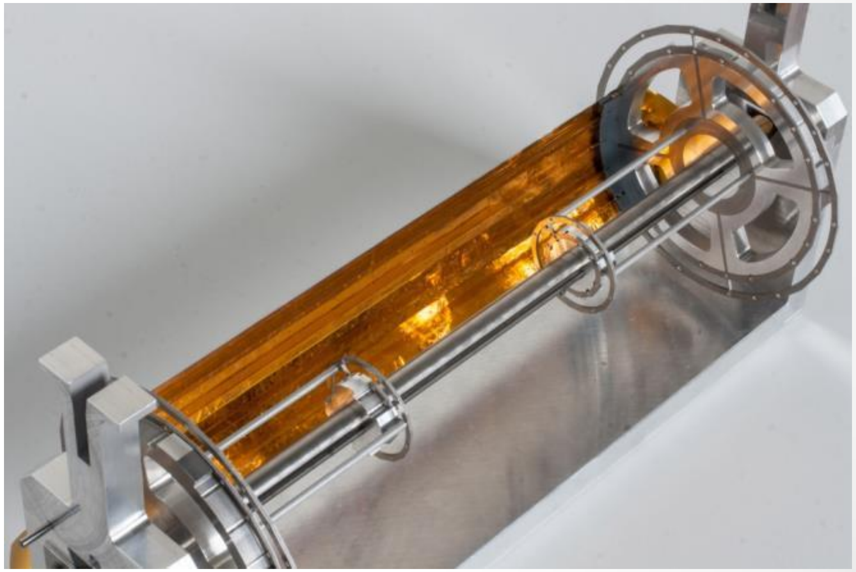
Inner Layers

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors

Vertex Prototype
with 100 µm Glass

Outer Module

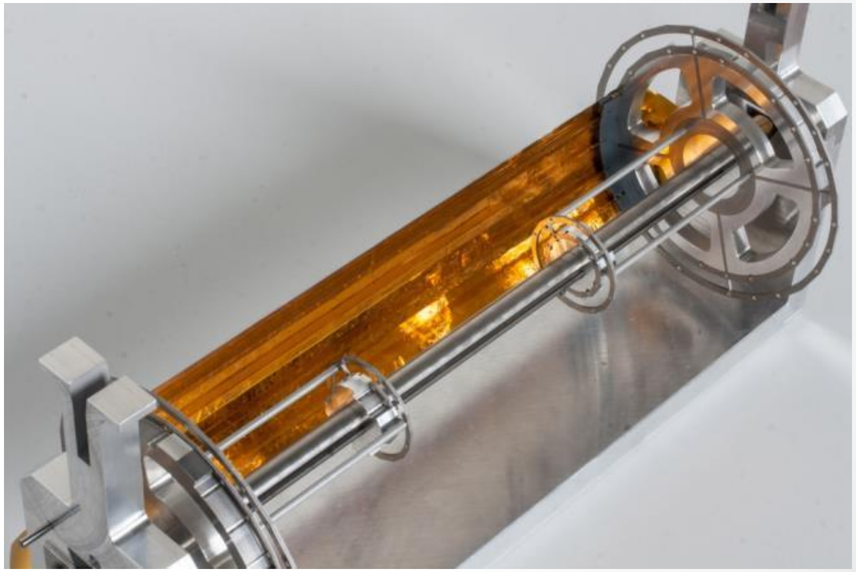
- HV-MAPS
  - Thinned to 50 μm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 μm Kapton™
  - 12.5 μm Alu traces
- **Kapton™ Frame Modules**
  - 25 μm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors



Layer 3 Prototype in Assembling Frame with 50 μm Glass

Detector Frame

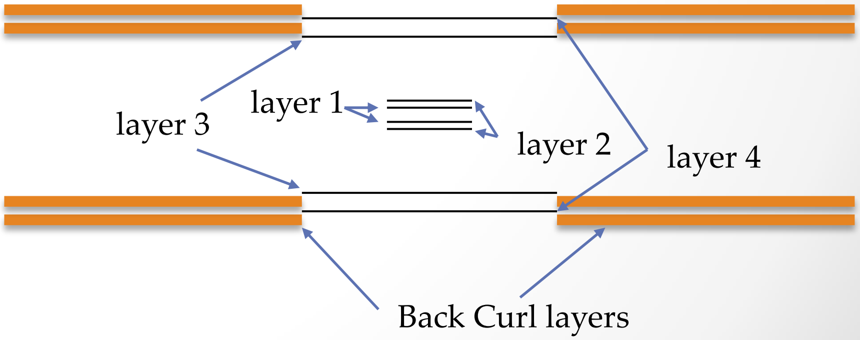
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- **Alu end wheels**
  - Support for all detectors



Layer 3 Prototype in Assembling Frame with 50 µm Glass

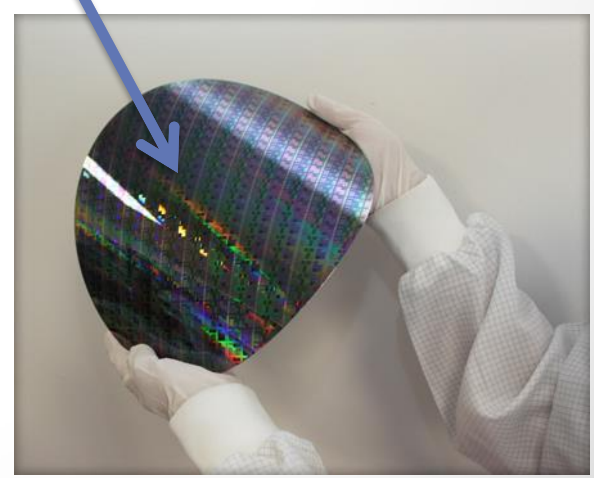
Pixel-Layer Rad. Length

- Radiation length per layer
  - 4× 25 μm Kapton
    - X_0= 0.35‰
  - 3×15 μm thick aluminum traces (50% coverage)
    - X_0= 0.25‰
  - 50 μm Si MAPS
    - X_0= 0.54‰
  - 20 μm adhesive
    - X_0= 0.05‰
- Sum: 1.19‰ (x4 layers)



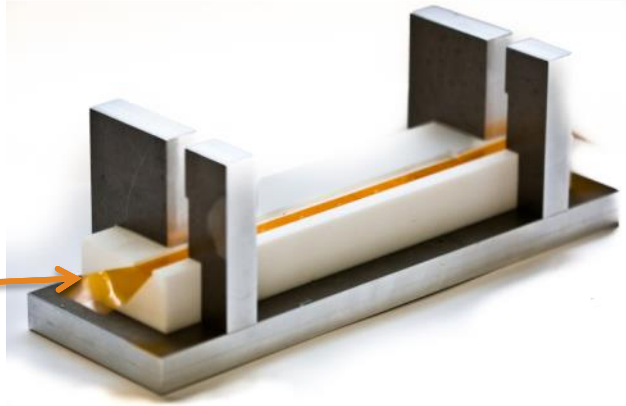
Thinning

- 50 µm Si-wafers
  - Commercially available
  - HV-CMOS 50 µm (AMS)
  - 50 µm for MuPix4 and MuPix7
- Single die thinning
  - For chip sensitivity studies
  - < 50 µm desirable



Tools

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

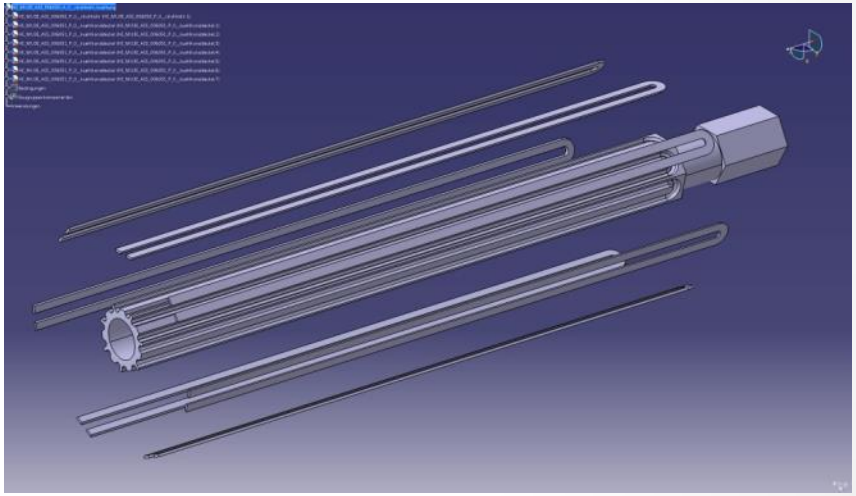


Cooling Backup

…

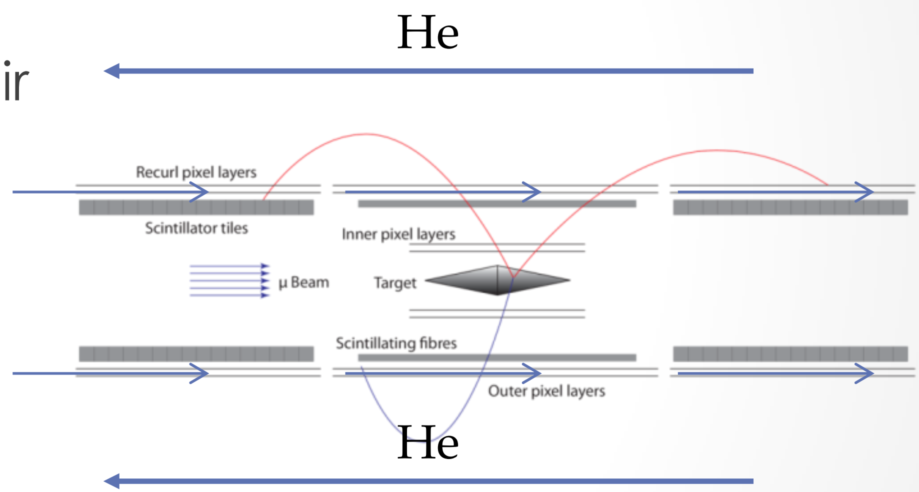
Liquid Cooling

- Beam pipe cooling
  - With cooling liquid
  - 5°C temperature
  - Significant flow possible
- For electronics
  - FPGAs
  - Power regulators
  - Mounted to cooling plates
- Total power several kW



He Cooling

- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - Distribution in Frame
    - V-shapes
    - Outer surface



$$400\text{mW/cm}^2 \times 11664\text{cm}^2 \approx 4.7\text{ KW}$$

He Cooling

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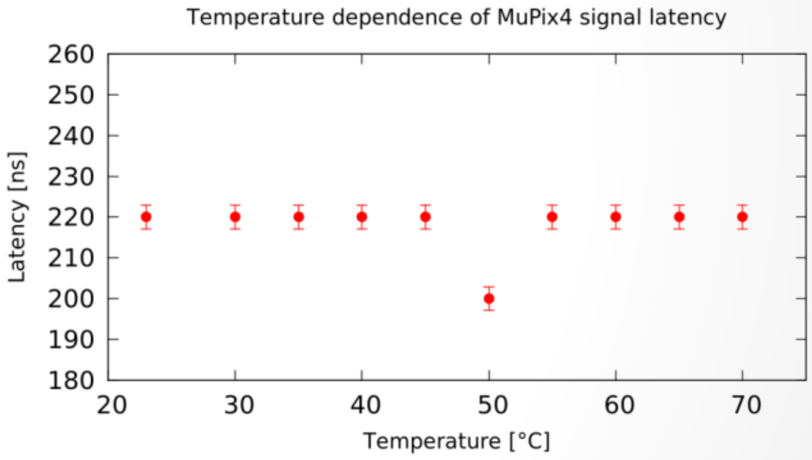
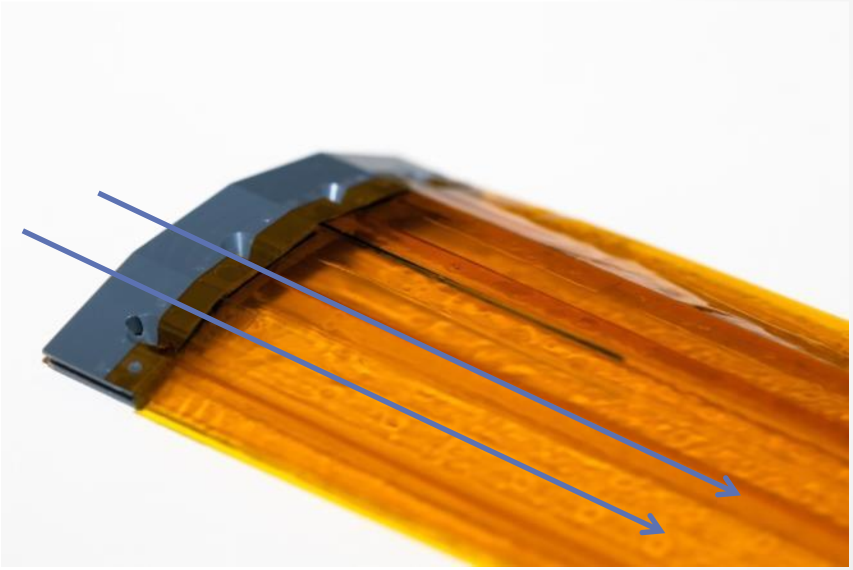


Temperatures between 20°C to 70°C ok.

He Cooling

- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- **Local flow for Tracker**
  - Distribution in Frame
    - V-shapes
    - Outer surface



He Cooling

- Gaseous He cooling
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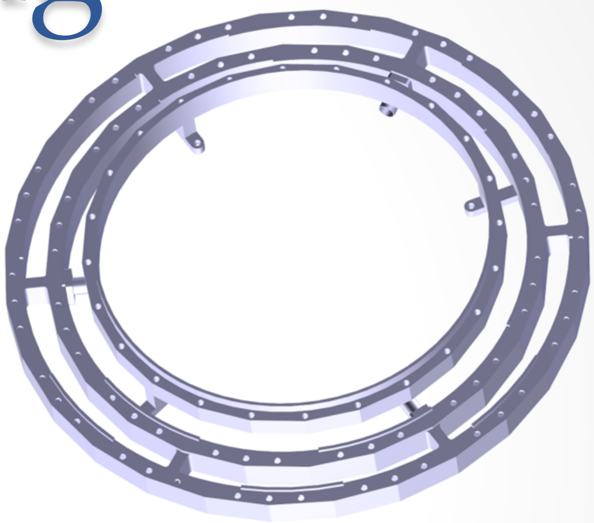
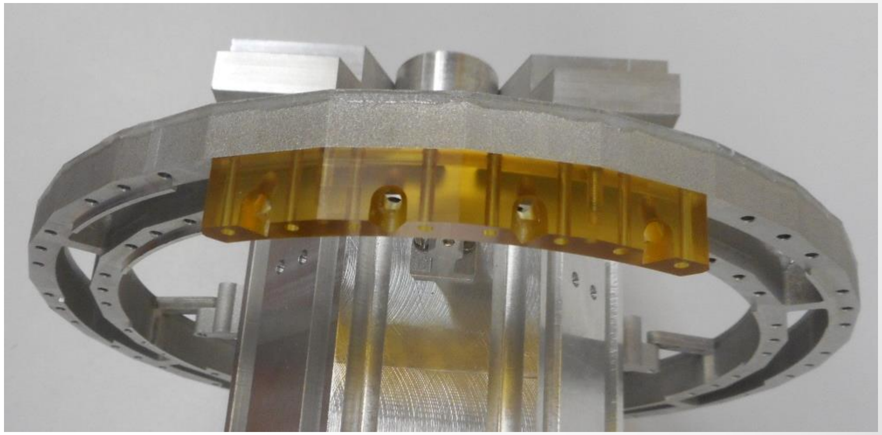
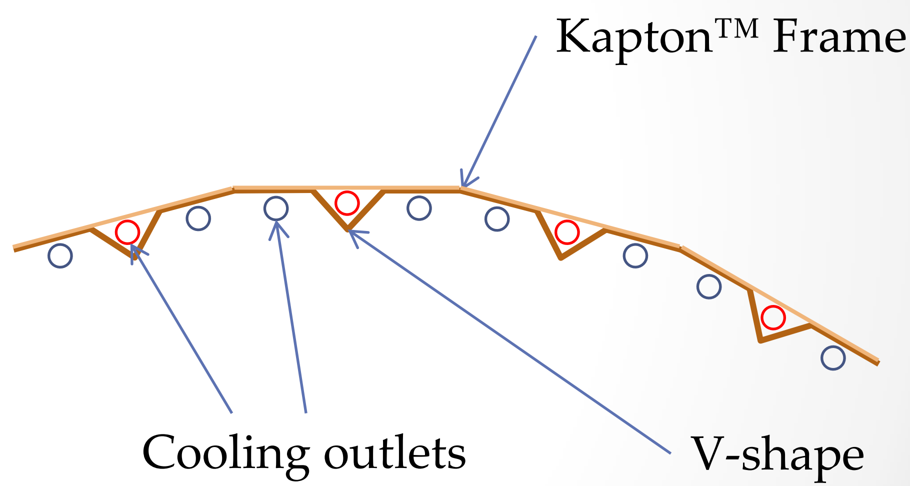
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - **Distribution in Frame**
    - V-shapes
    - Outer surface



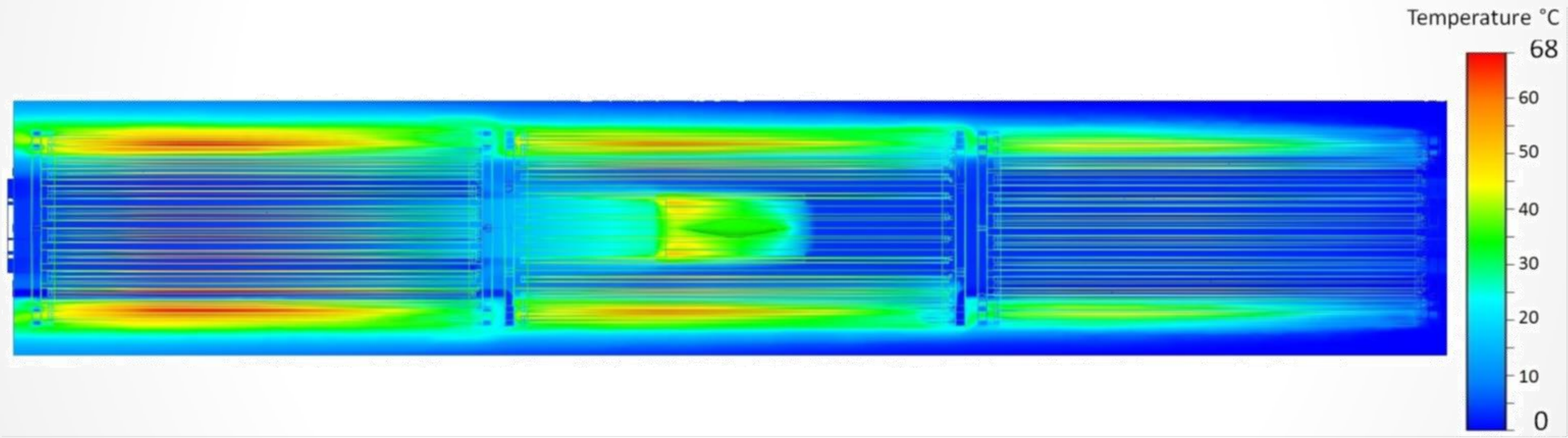


He Cooling

- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - Distribution to Frame
    - **V-shapes**
    - **Outer surface**



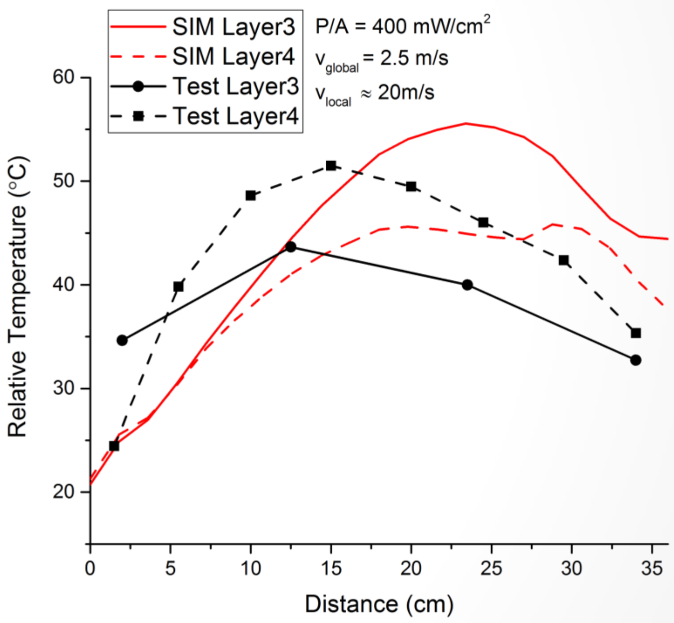
Simulation



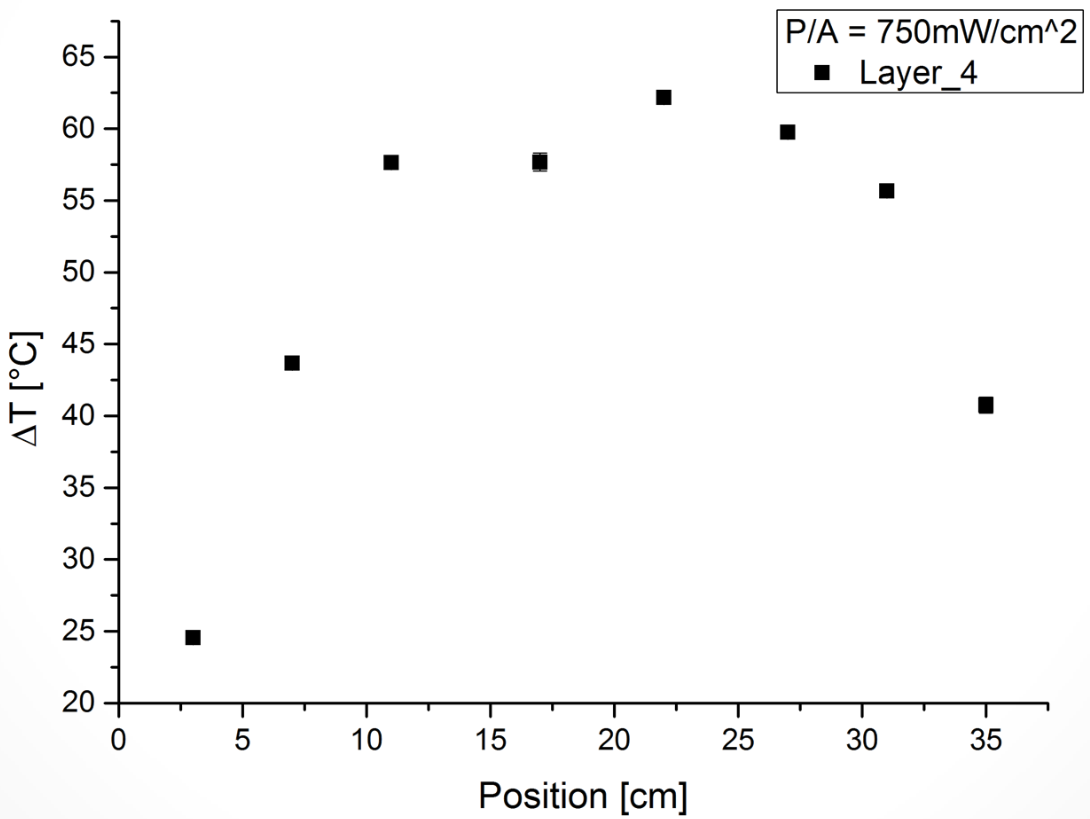
He cooling
400mW/cm^2

Test Results

- 1:1 Prototype
  - Layer 3+4 of silicon tracker
  - Ohmic heating 400mW/cm²
- Cooling He
  - at several m/s
- Temperature sensors attached to foil
  - LabVIEW readout
- **First results promising**
  - **ΔT < 60°K**
  - **No sign of vibration in air**



He Cooling
750 mW/cm²

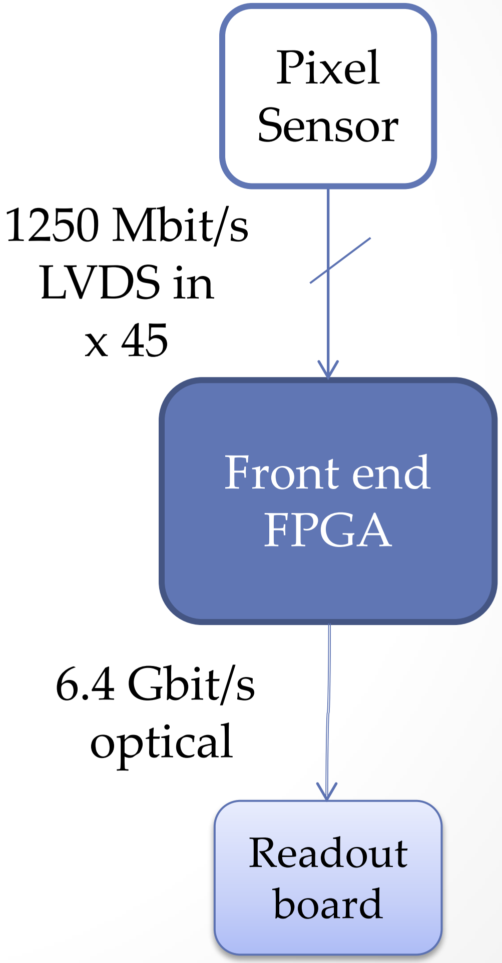


DAQ Backup

...

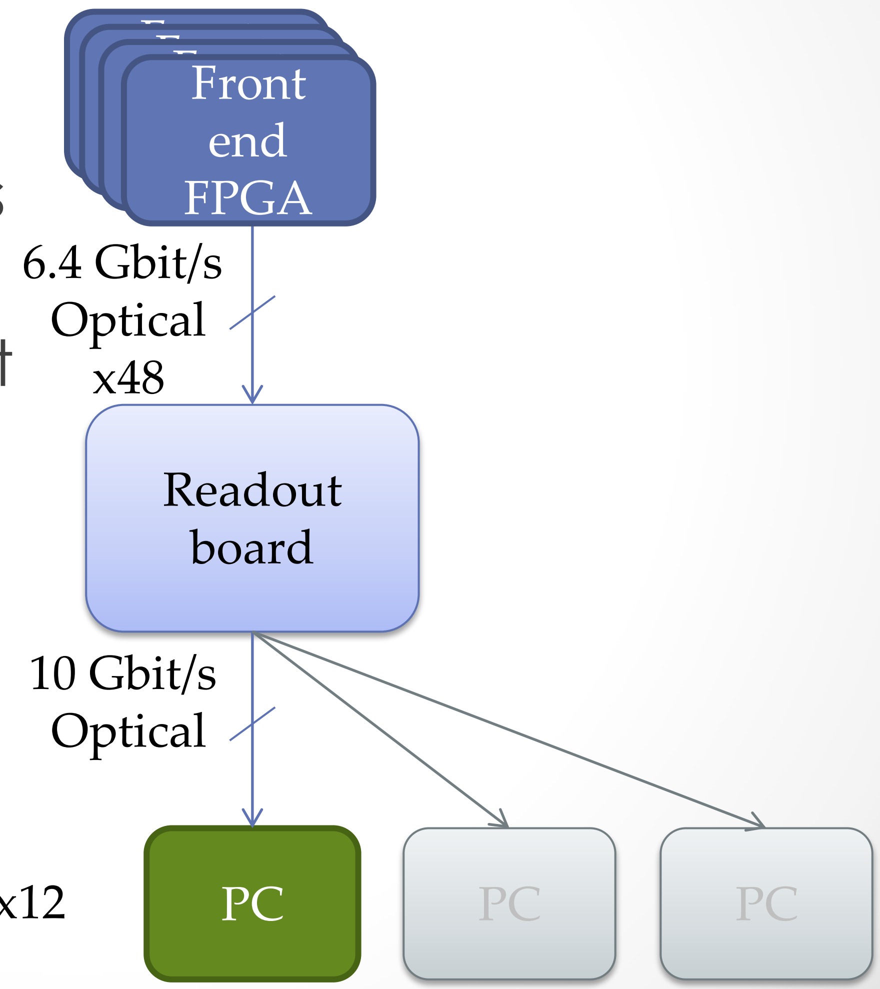
Front End FPGAs

- FPGAs on detector (?)
  - 90 (+26) pieces
- Receive sensor data
  - 36-45 LVDS inputs
- 6.4 Gbit/s outputs
  - 8 optical links
  - … to counting house



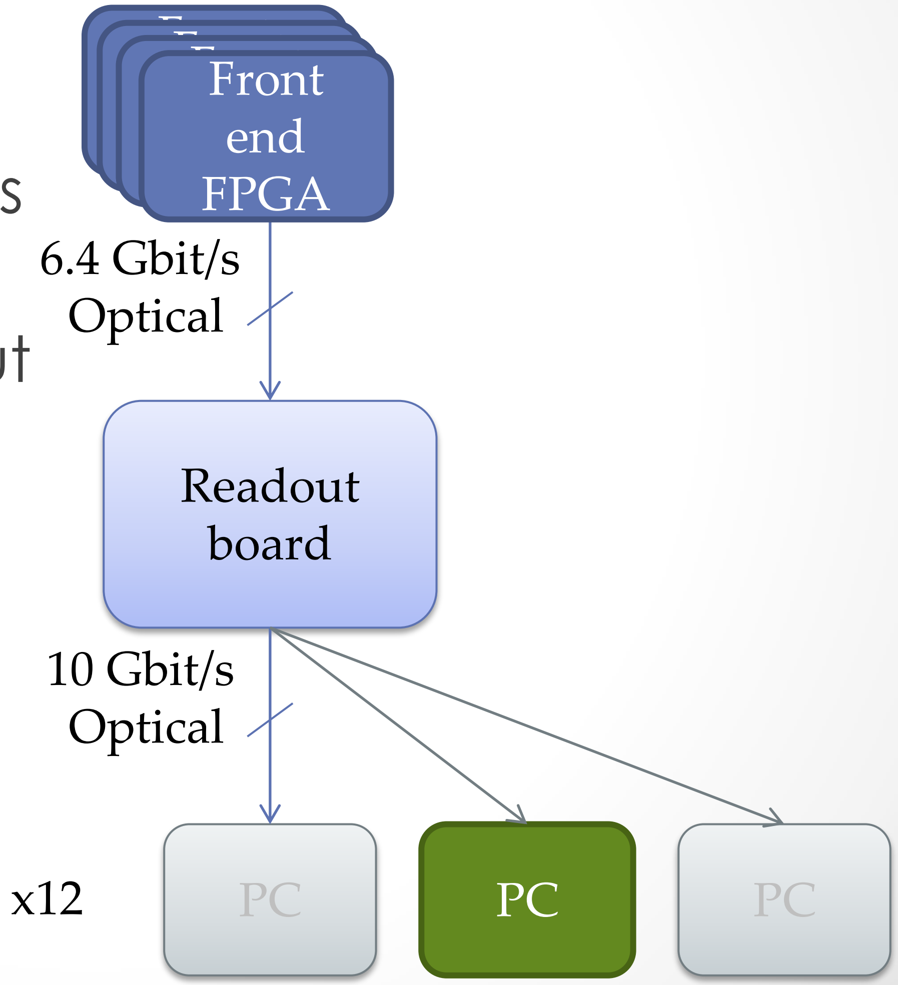
Readout Board

- FPGA readout boards
  - per sub-detector
- 6.4 Gbit/s optical inputs
  - 16-48 inputs
- 10 Gbit/s optical output
  - 12 outputs to PCs
- Switching network
  - One output per PC



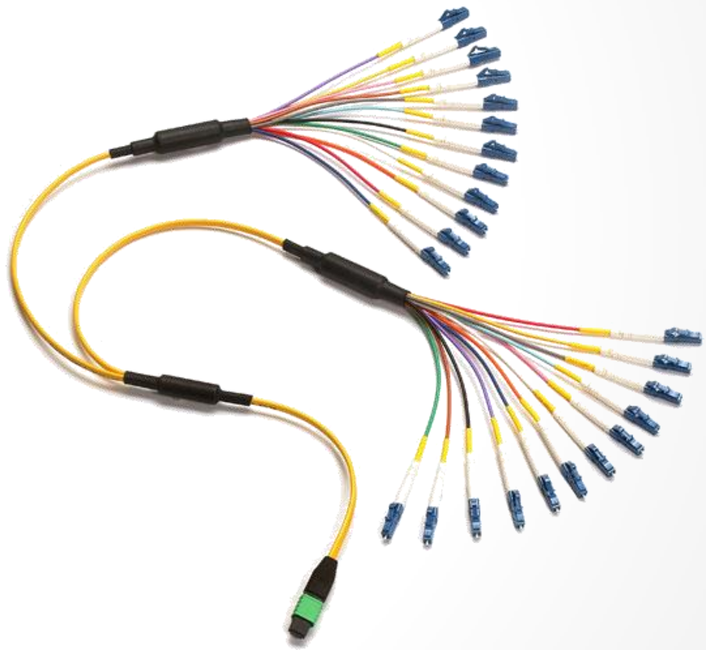
Readout Board

- FPGA readout boards
  - 4 per sub-detector
- 6.4 Gbit/s optical inputs
  - 16-48 inputs
- 10 Gbit/s optical output
  - 12 outputs to PCs
- Switching network
  - One output per PC



Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 400 – 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - … to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



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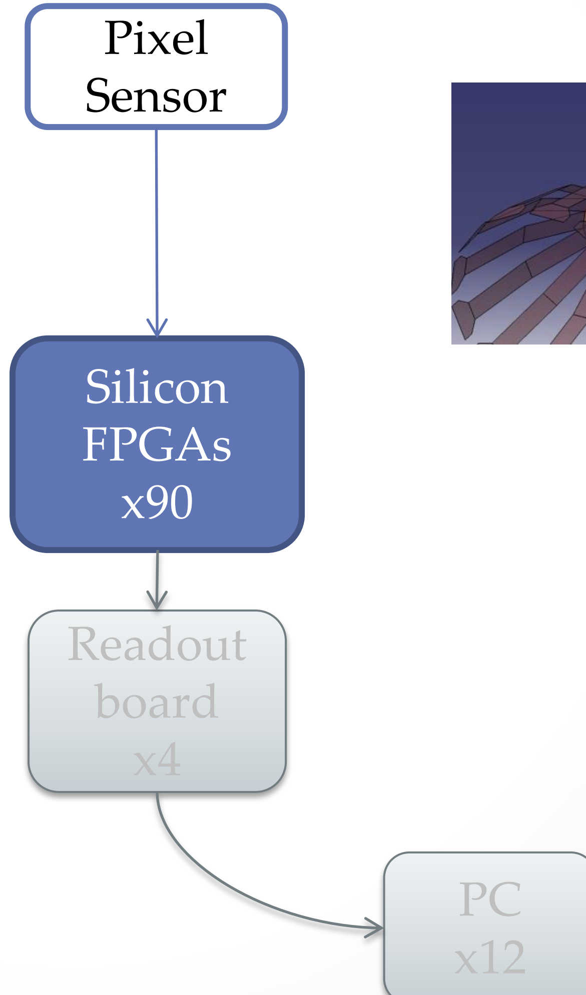
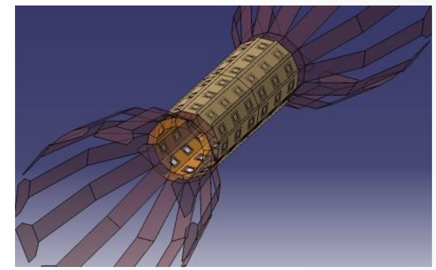
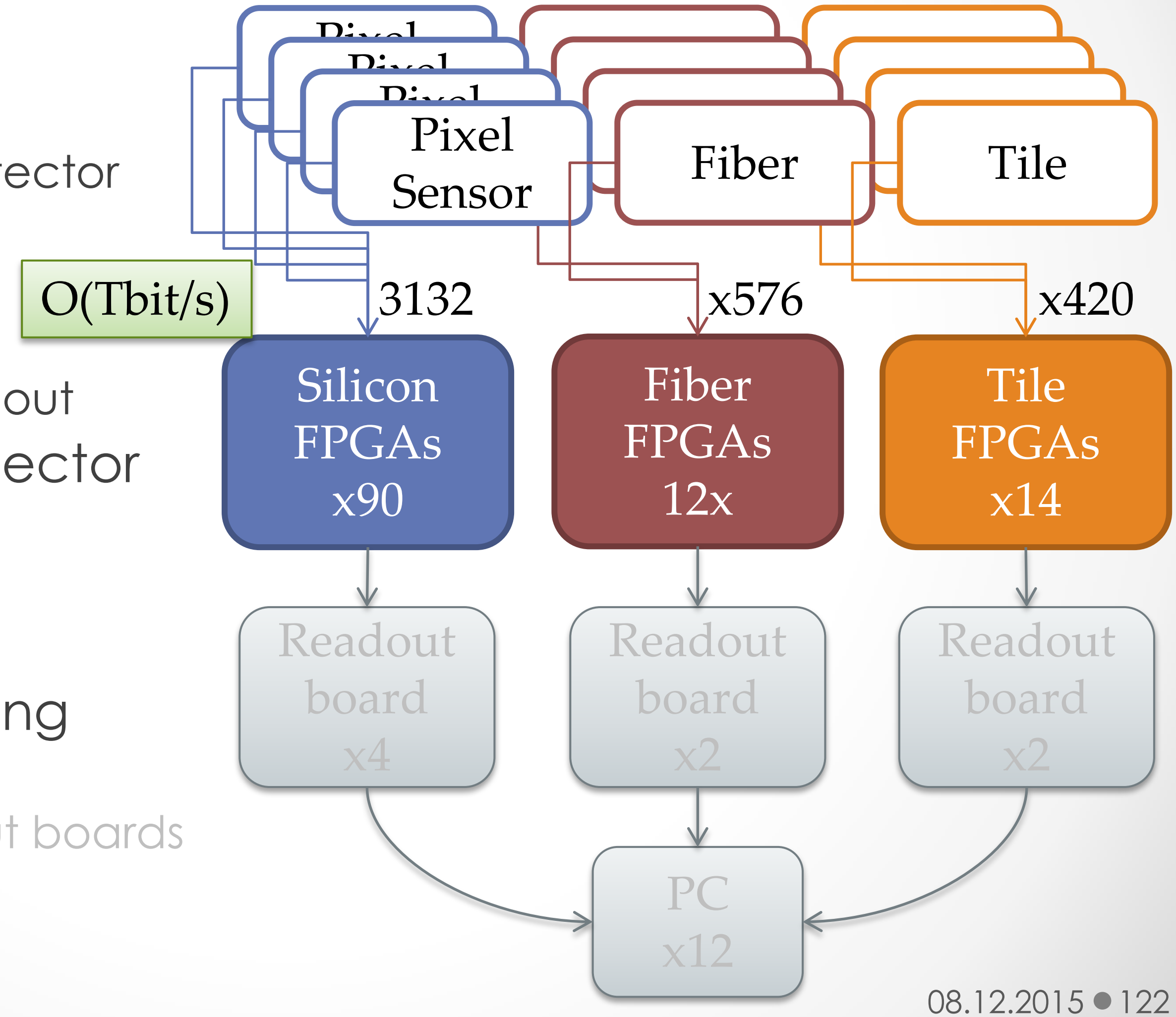
  - Front end FPGAs
  - … to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm





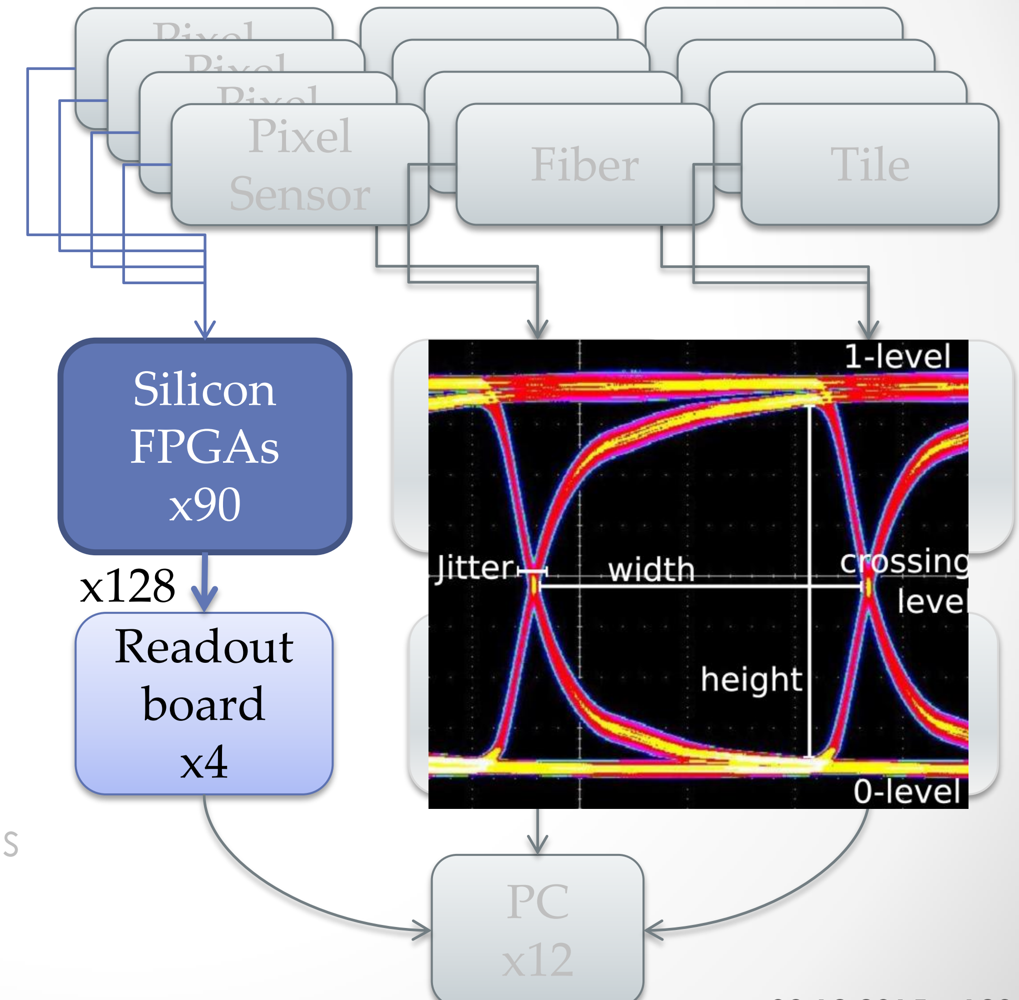
Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 400 – 800 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - … to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 400 – 800 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - … to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 400 – 800 Mbit/s
    - LVDS
  - Timing detector readout
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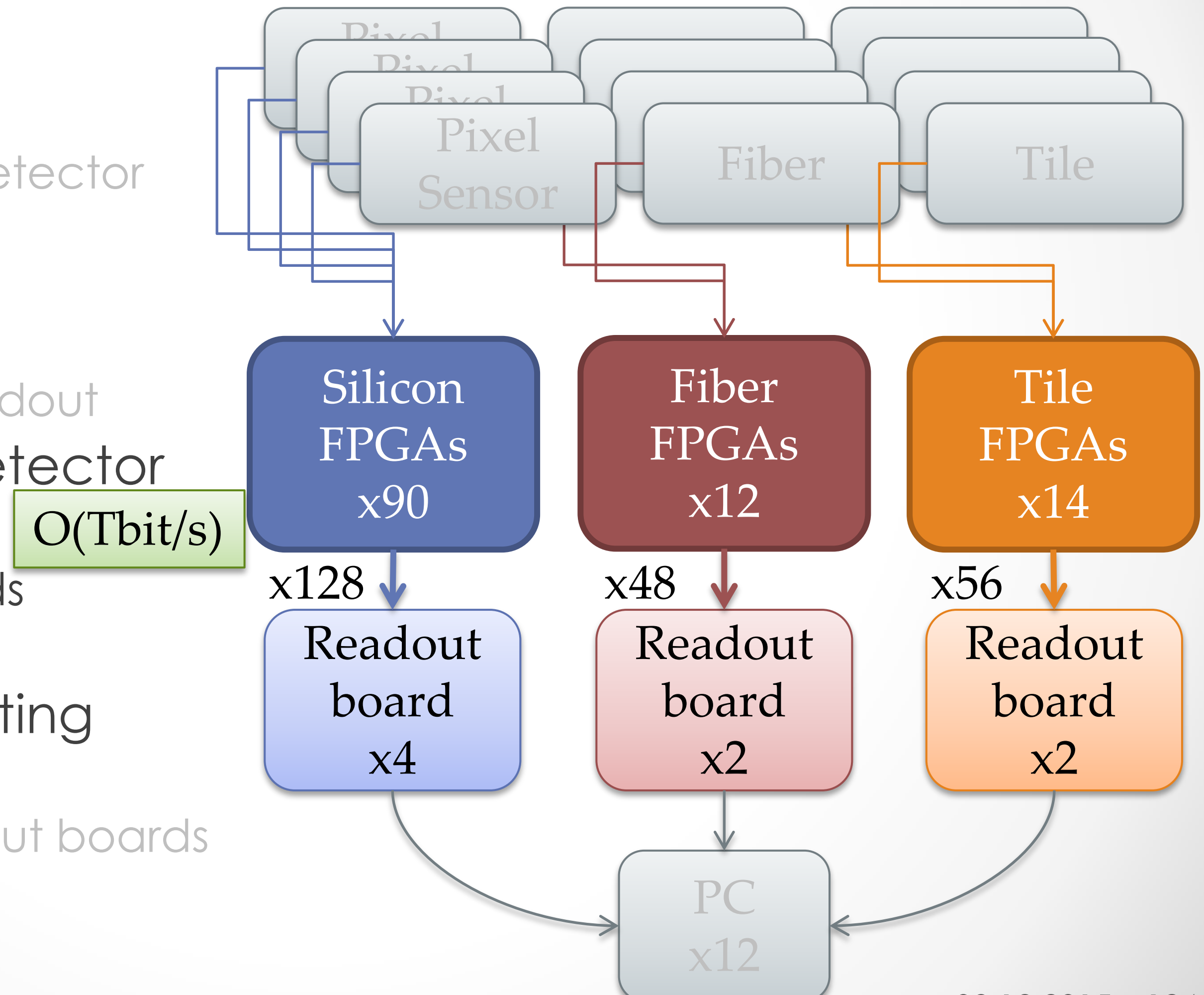
  - Front end FPGAs
  - … to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
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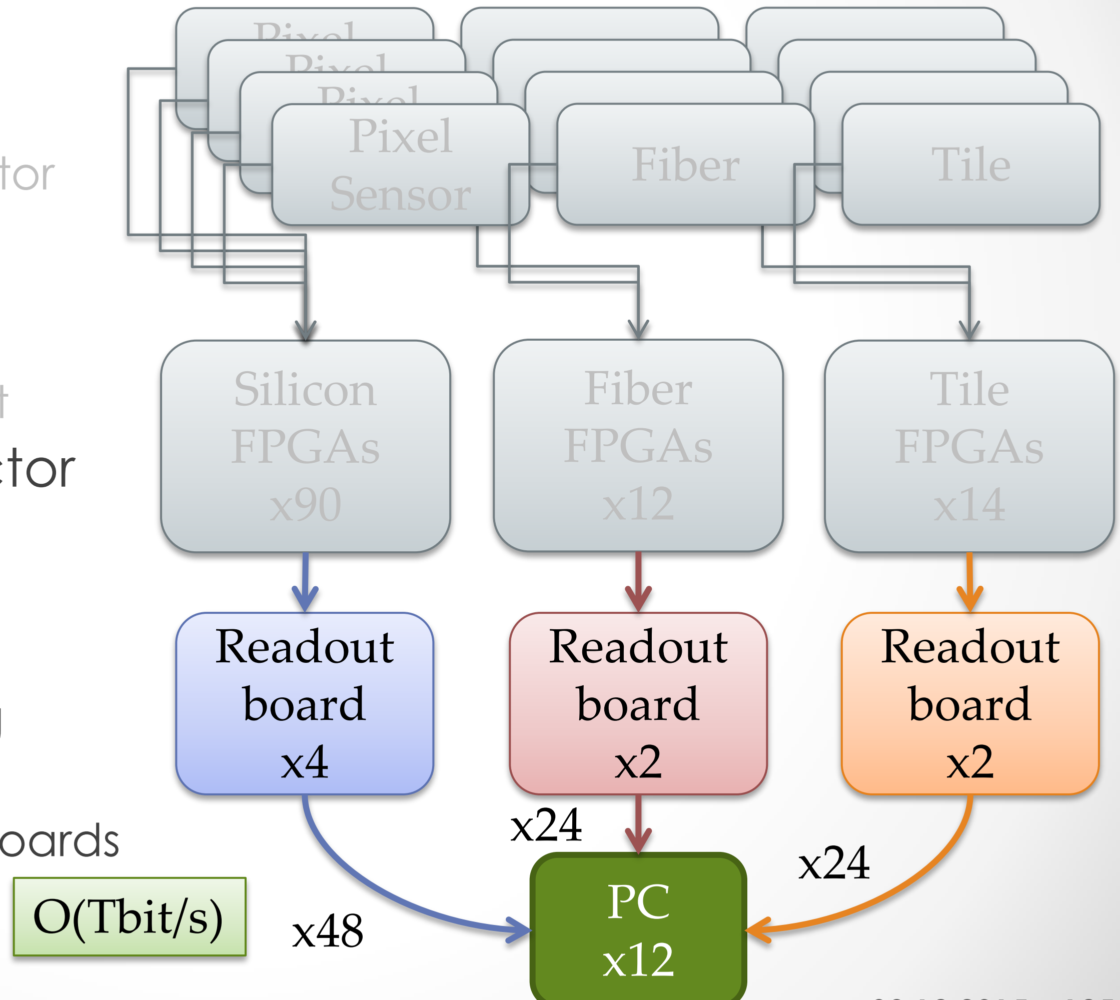


GPU-PC

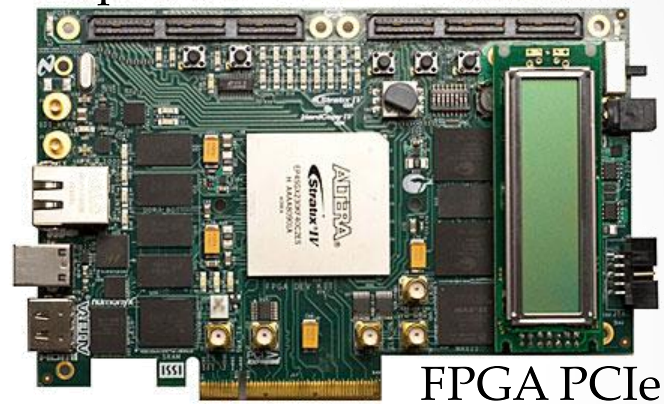
- PC with GPU
- 10 Gbit/s Fiber input
  - 8 inputs from sub-detectors
- Data filtering
  - Timing Filter on FPGA
  - Track filter on GPU
  - Data to tape < 100 MB/s

GPU computer

GPU-PC

- PC with GPU
- 10 Gbit/s Fiber input
  - 8 inputs from sub-detectors
- Data filtering
  - Timing Filter on FPGA
  - Track filter on GPU
  - Data to tape < 100 MB/s

Optical mezzanine connectors



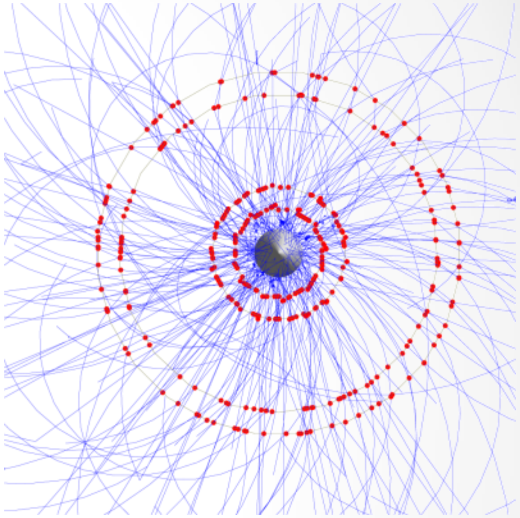
FPGA PCIe board

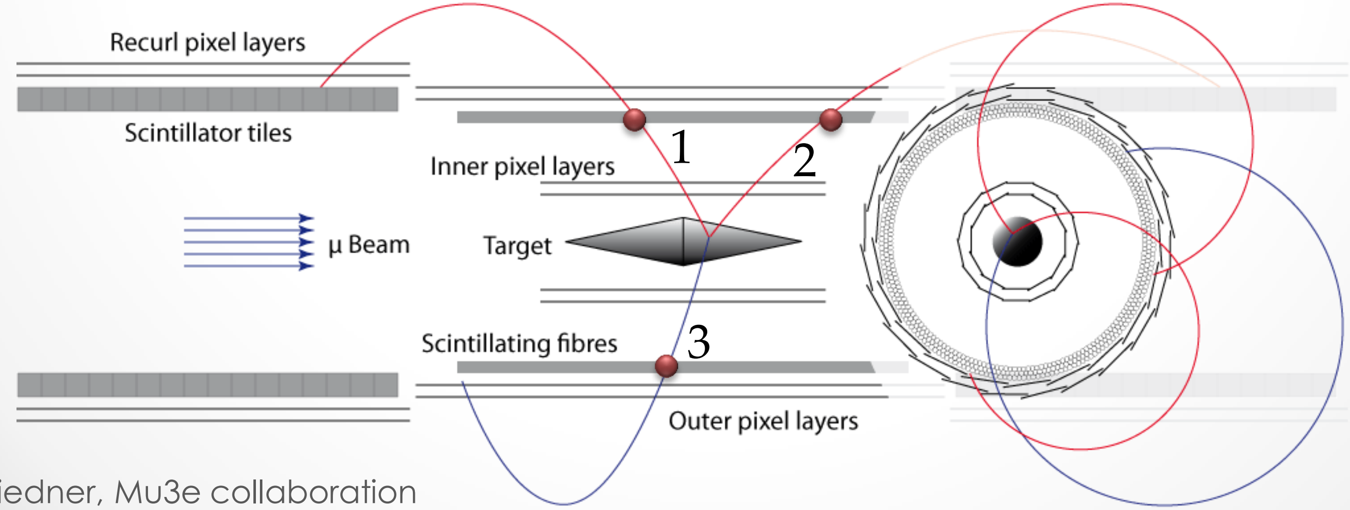
GPU computer

Timing Filter

Under discussion

- Entire event on PCIe FPGA
- Tile and Fiber data
  - Easy to match
  - Look for three tracks
- Reject data without three hits
  - … inside time interval





Timing Filter

Under discussion

- Entire event on PCIe FPGA
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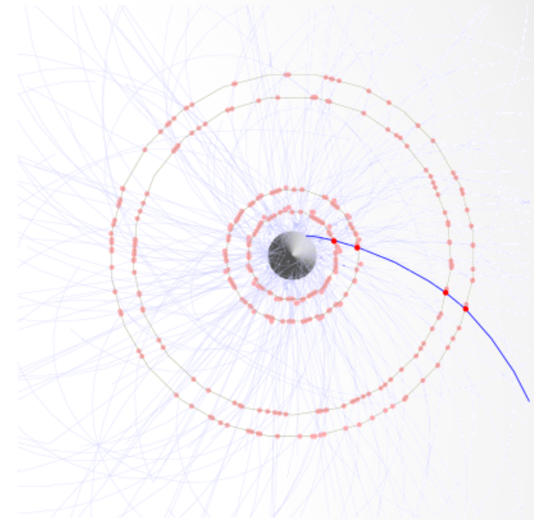
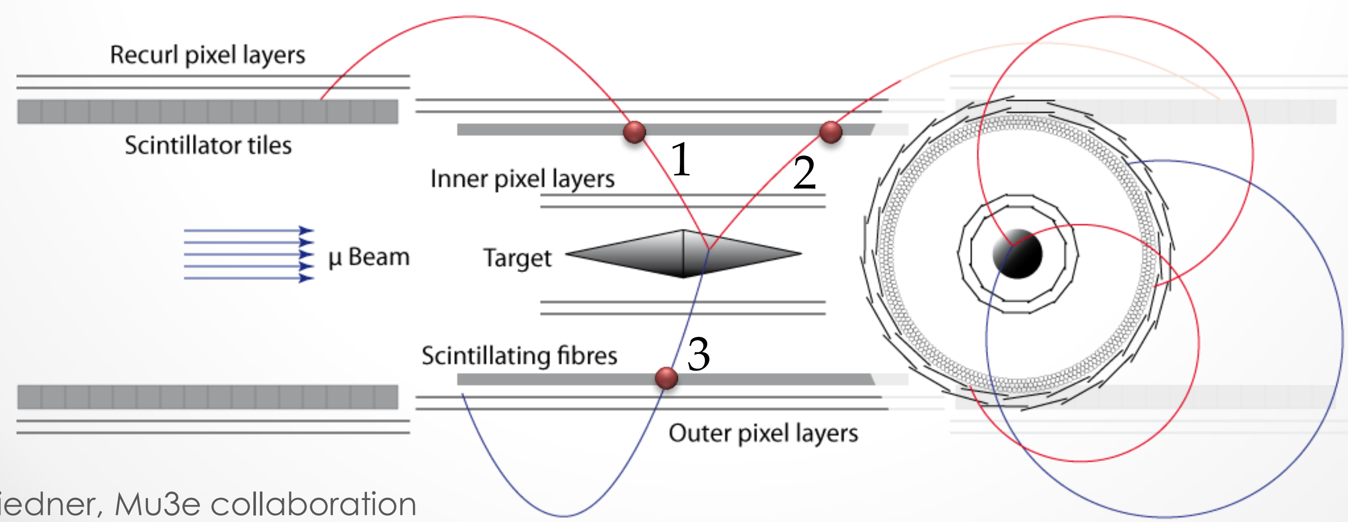
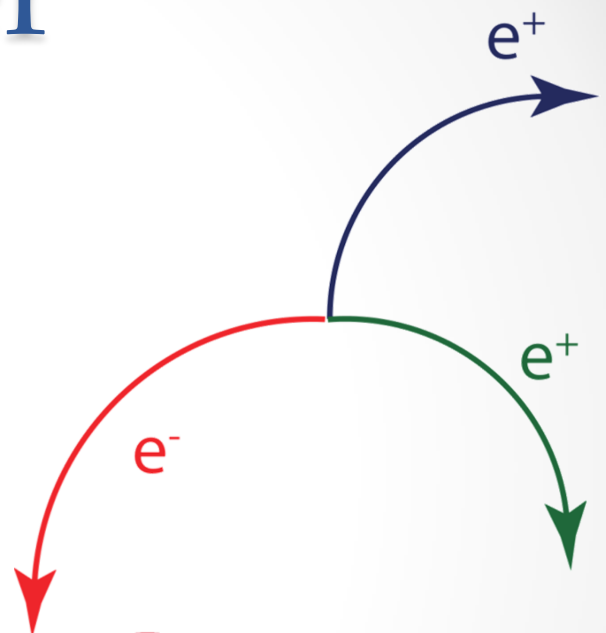
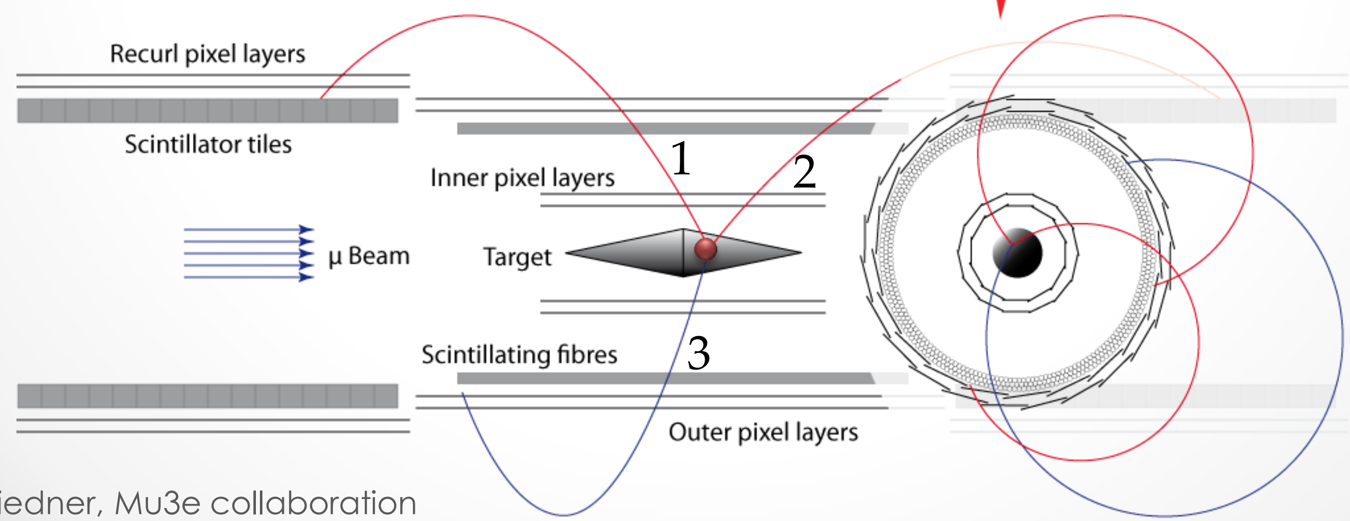




Vertex Filter

- Entire event on GPU
- Large target
  - o Large spread of muons
  - o Easy vertex separation
- Reject data without three tracks
  - o … inside area interval on target





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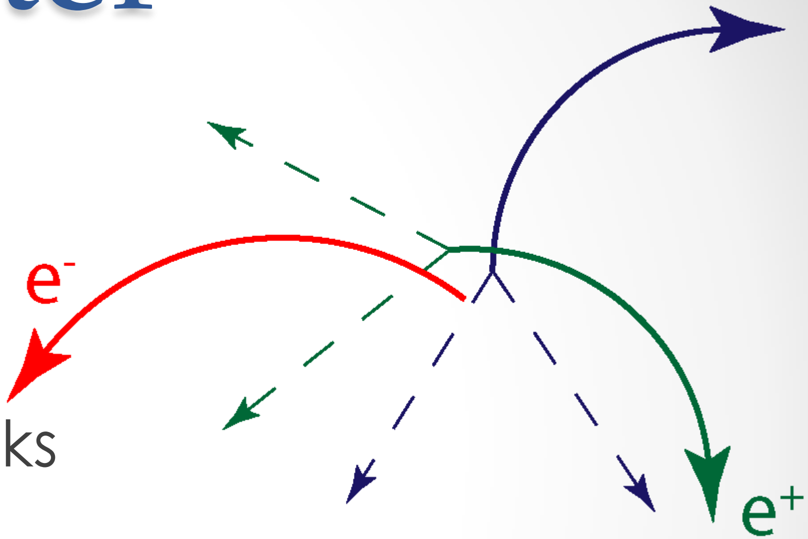

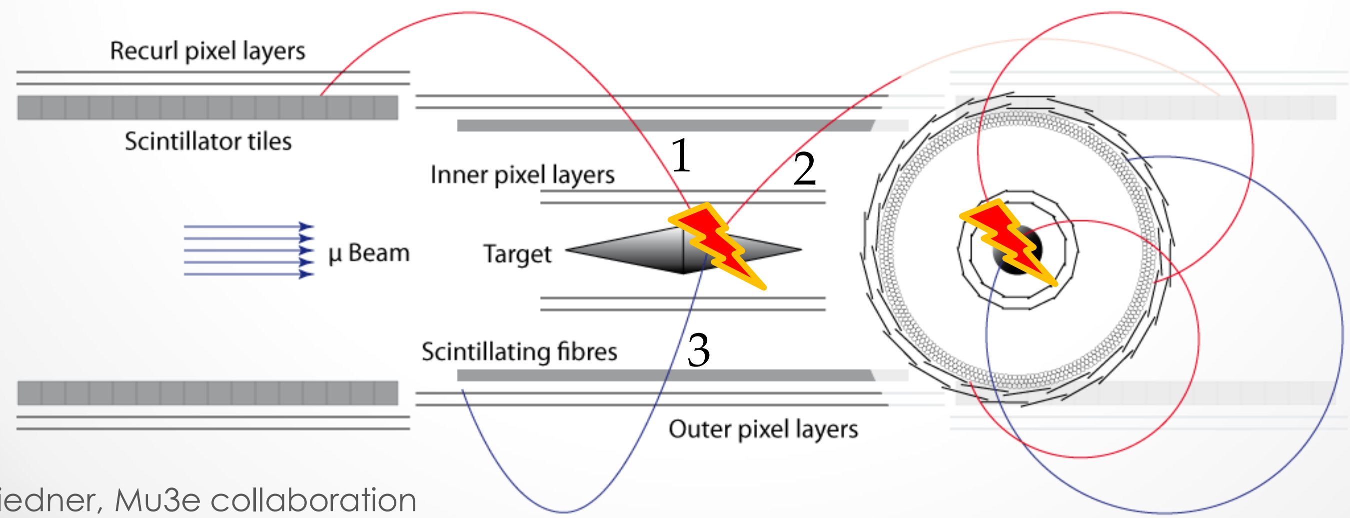

Schedule

- **2012 Letter of intent** to PSI, research proposal
- **2013-16** Detector **R&D**
- **2017** Detector **construction**
- **2018** Installation and **commissioning** at PSI
- **2019** Data taking at up to a few **10^8 μ/s**