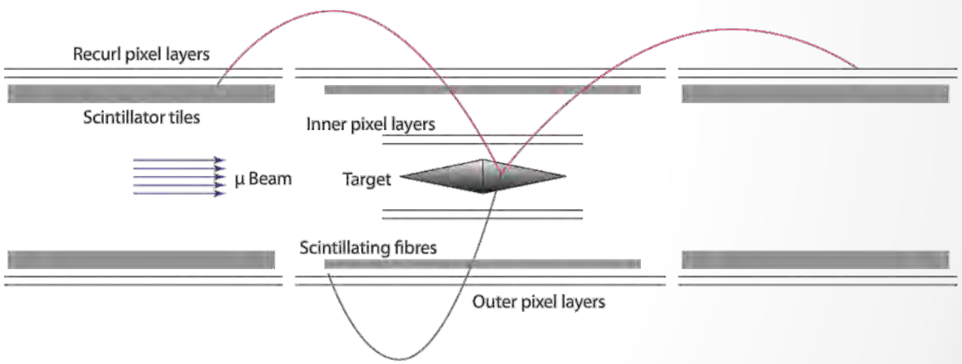
The Mu3e Experiment

Dirk Wiedner, Heidelberg
On Behalf of the Mu3e Collaboration
22nd October 2014

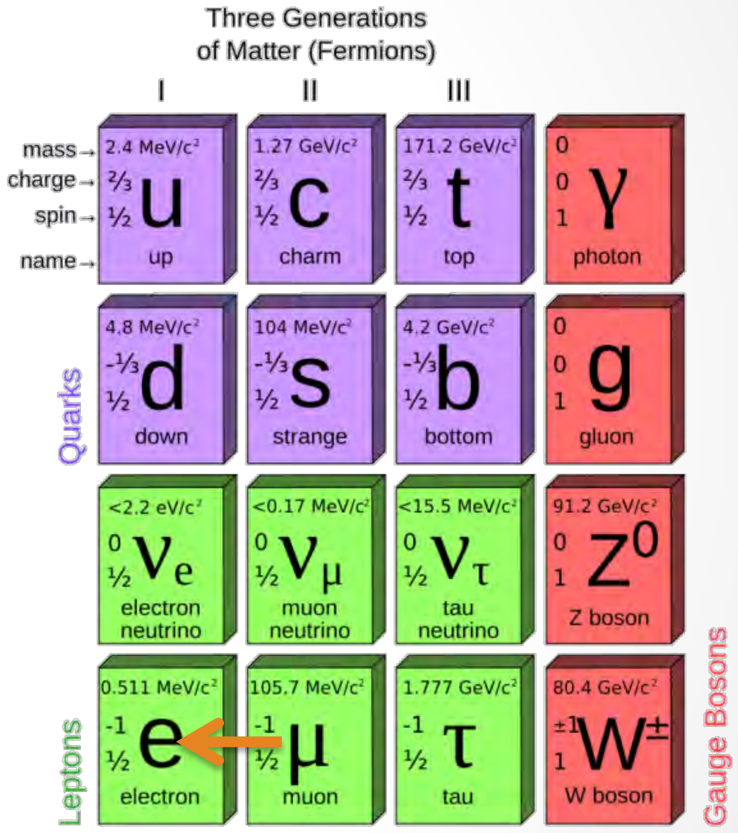
Overview

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



Physics Motivation

Lepton flavor violation?



Standard model:

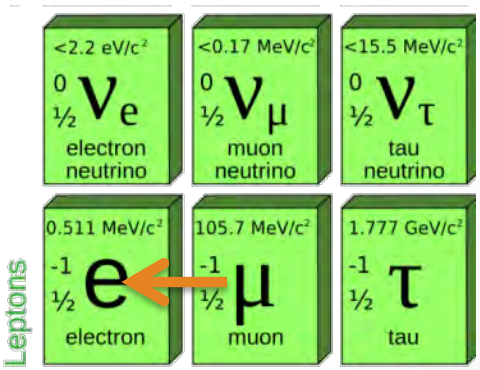
- No lepton flavor violation

Physics Motivation

Lepton flavor violation?

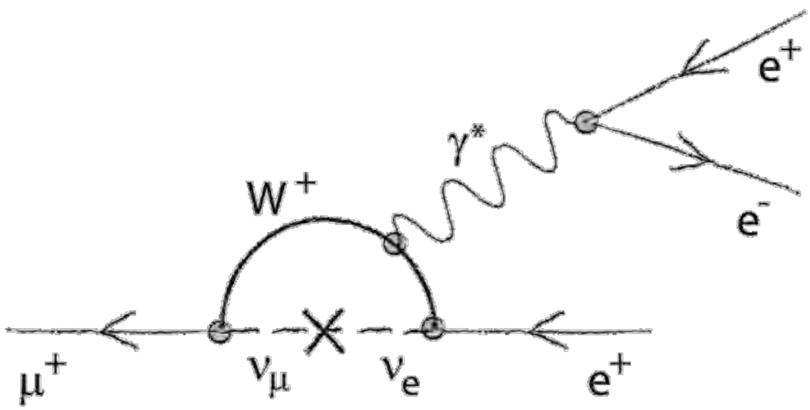
Standard model:

- No lepton flavor violation



Physics Motivation

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

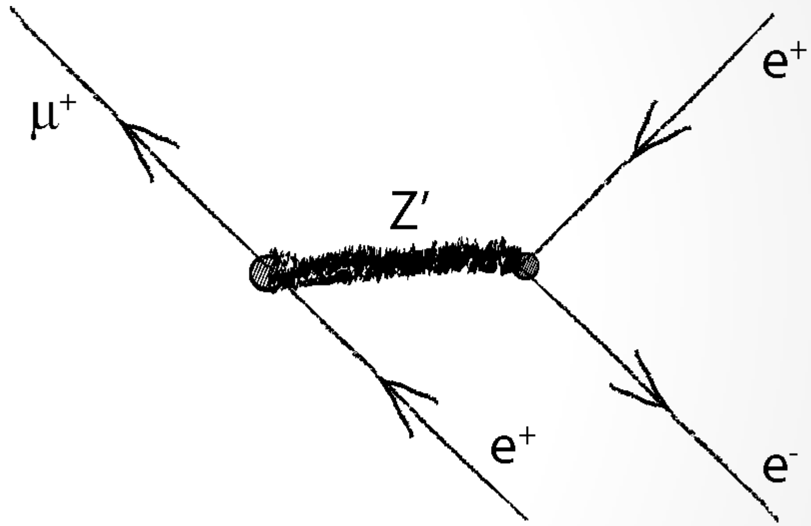


Standard model:

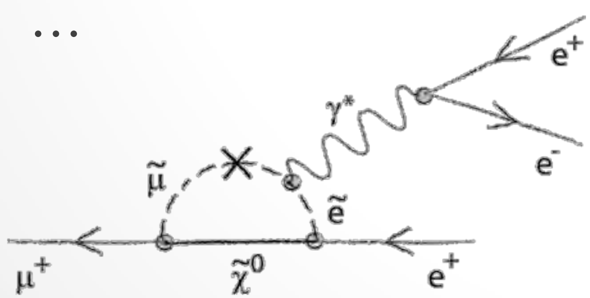
- No lepton flavor violation, but:
  - Neutrino mixing
  - Branching ratio $<10^{-54}$ $\rightarrow$ unobservable

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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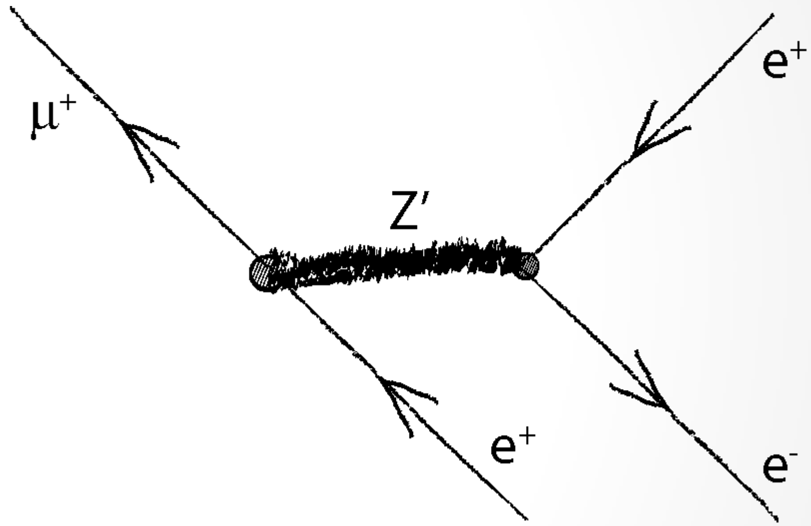
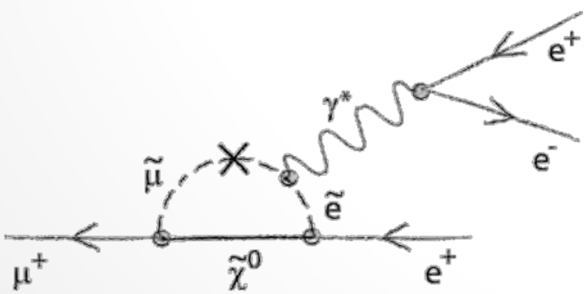
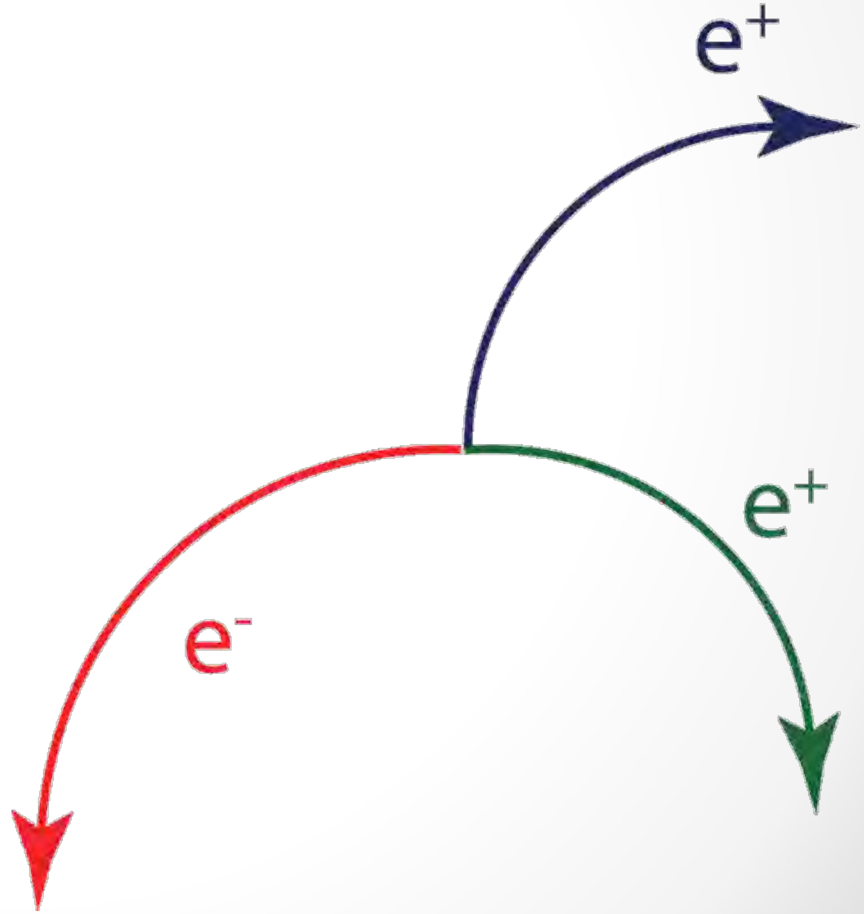




- ➢ Rare decay (BR<10^{-12}, SINDRUM)
- For BR O(10^{-16})
  - ➢ >10^{16} muon decays
  - ➢ High decay rates O(10^{9} muon/s)

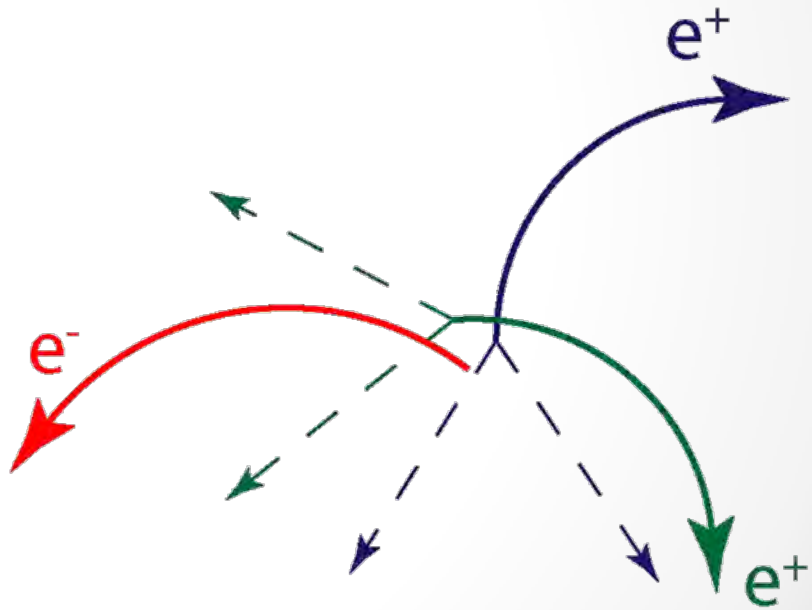
The Mu3e Signal



→Maximum electron energy 53 MeV

The Mu3e Background

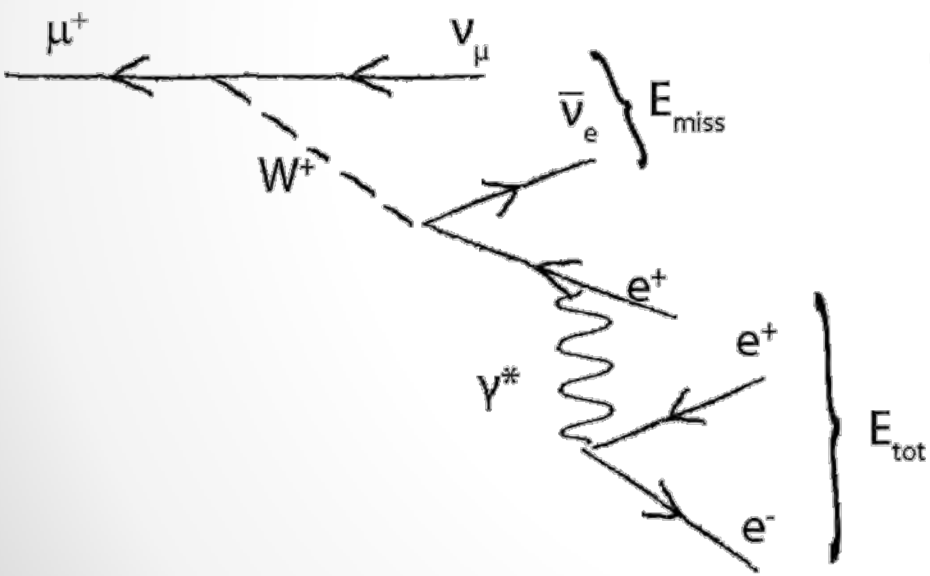
- Combinatorial background
  - $\mu^+ \rightarrow e^+ \nu\nu$ & $\mu^+ \rightarrow e^+ \nu\nu$ & $e^+ e^-$
  - many possible combinations

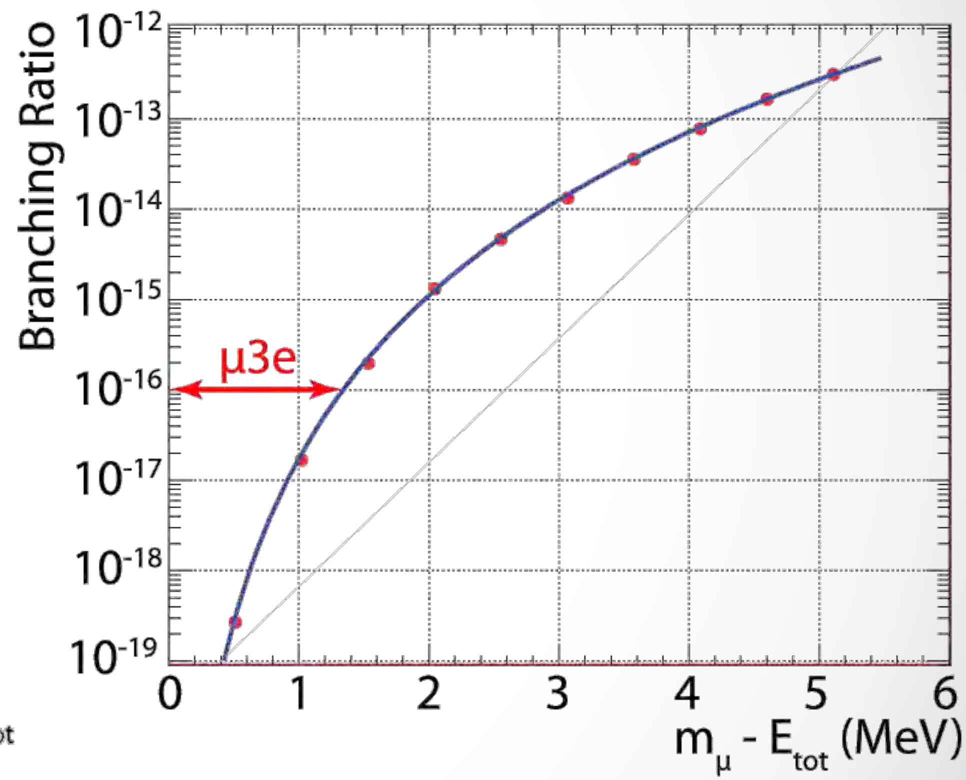


- ➢ Good time and
- ➢ Good vertex resolution required

The Mu3e Background

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





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

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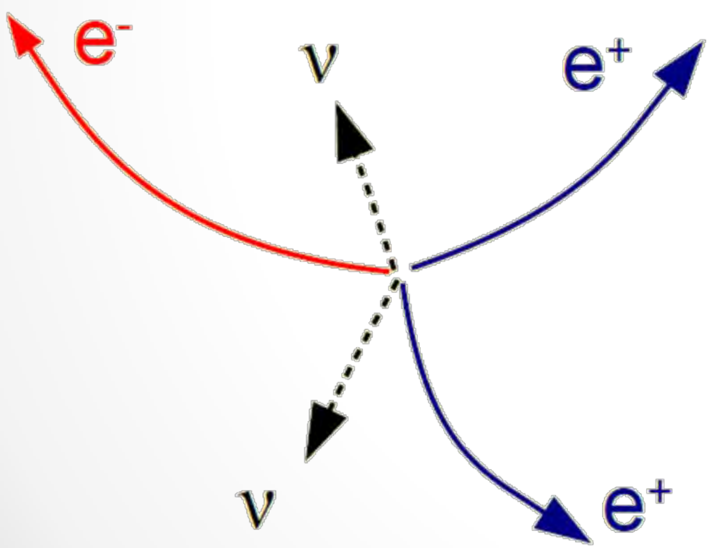

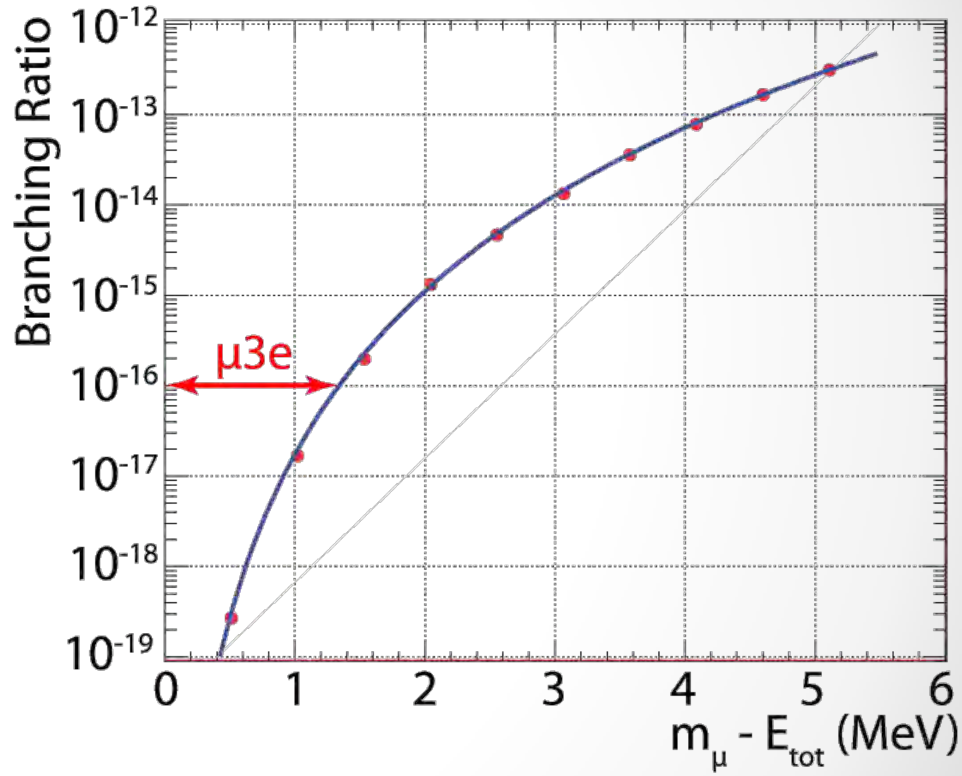

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Challenges

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Challenges

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

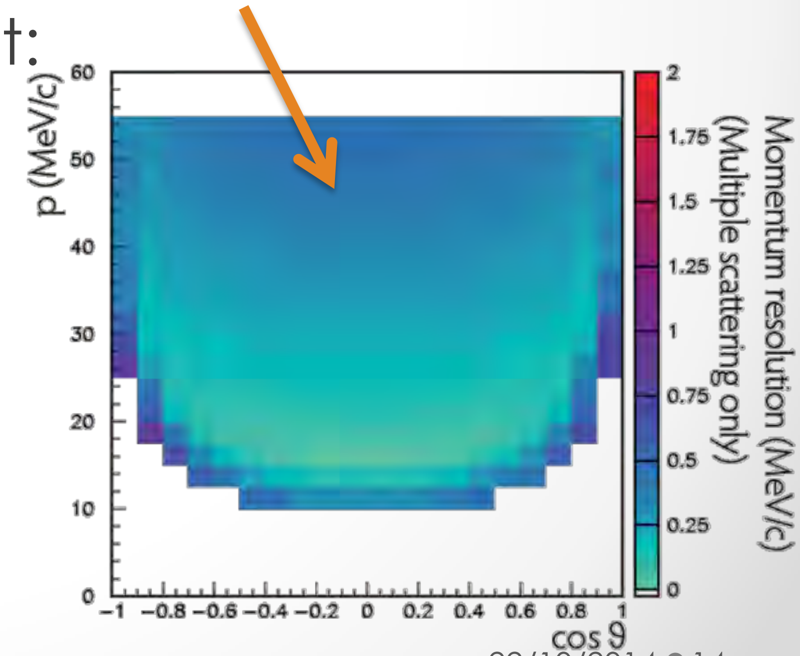
Challenges

- High rates: 10^9 μ/s
- Good timing resolution: 100 ps
- Good vertex resolution: ~200 μm
- Excellent momentum resolution: ~ 0.5 MeV/c²

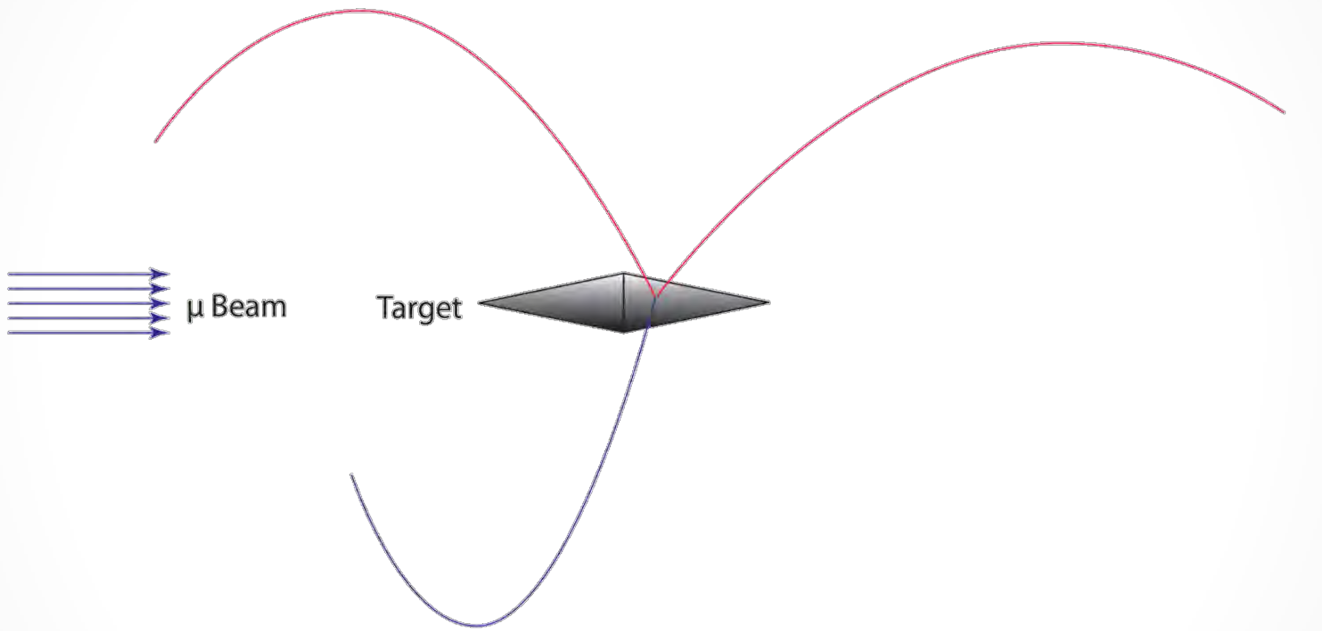
➢ Extremely low material budget:
  - ➢ 1×10^{-3} X_0 (Si-Tracker Layer)

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

➢ + Timing detectors



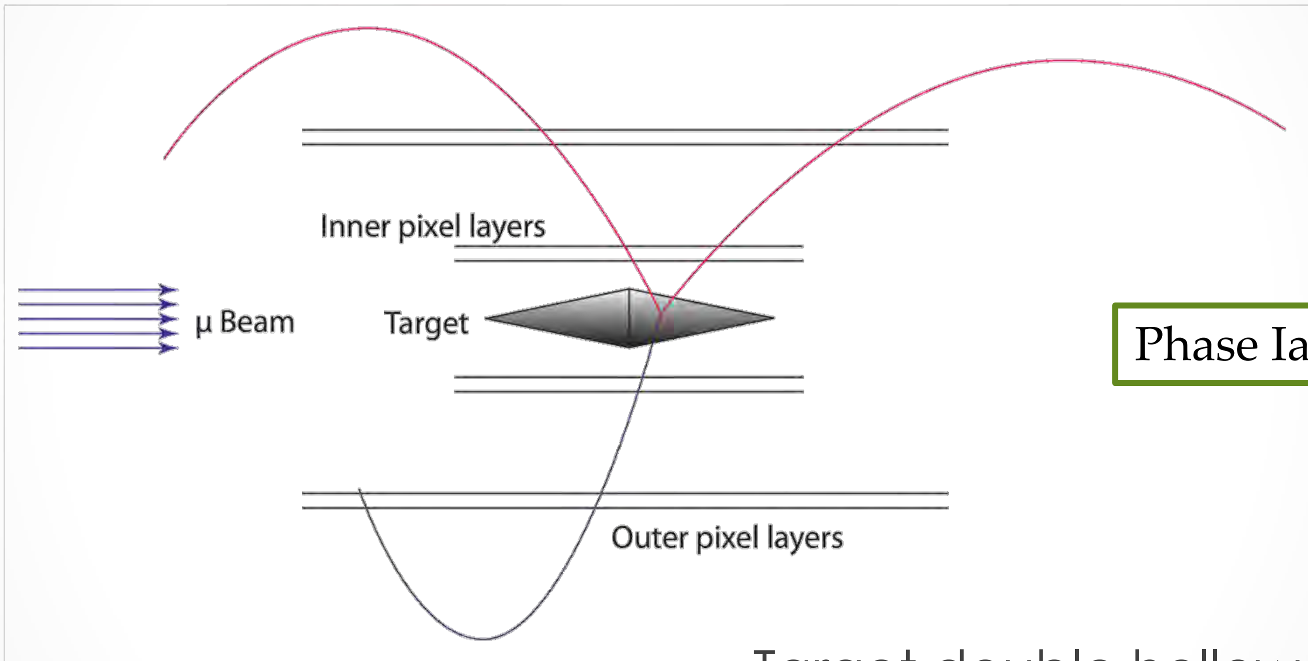
The Mu3e Experiment



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

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

The Mu3e Experiment



Phase Ia

- Muon beam O(10^9/s)
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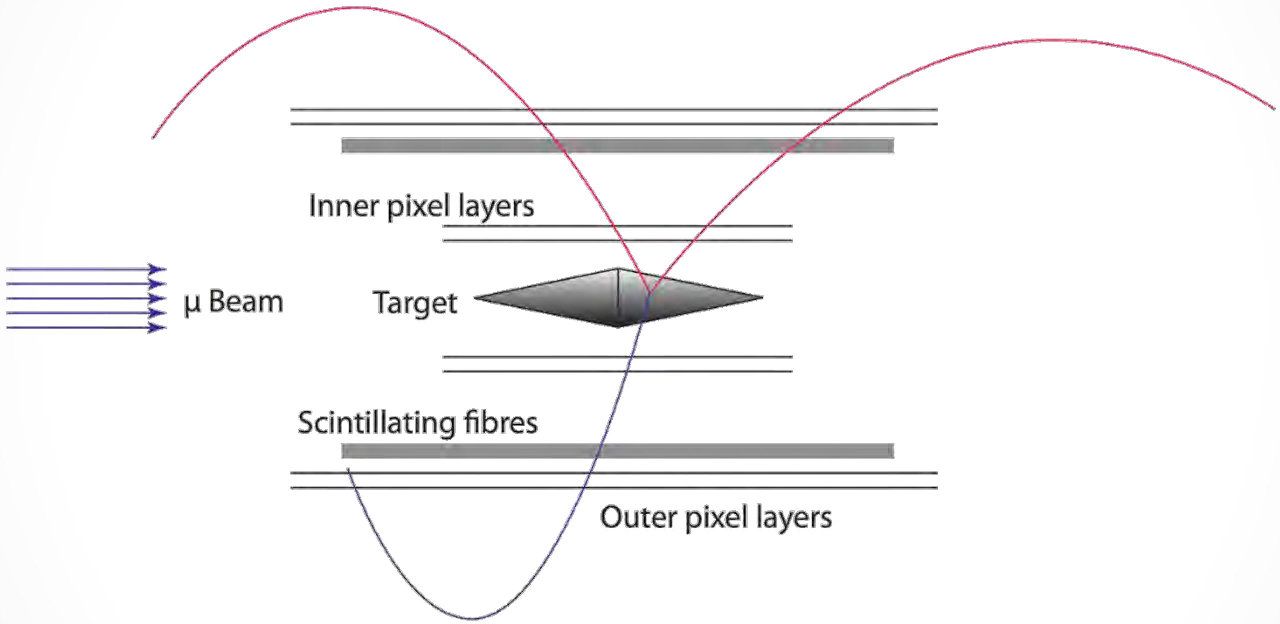

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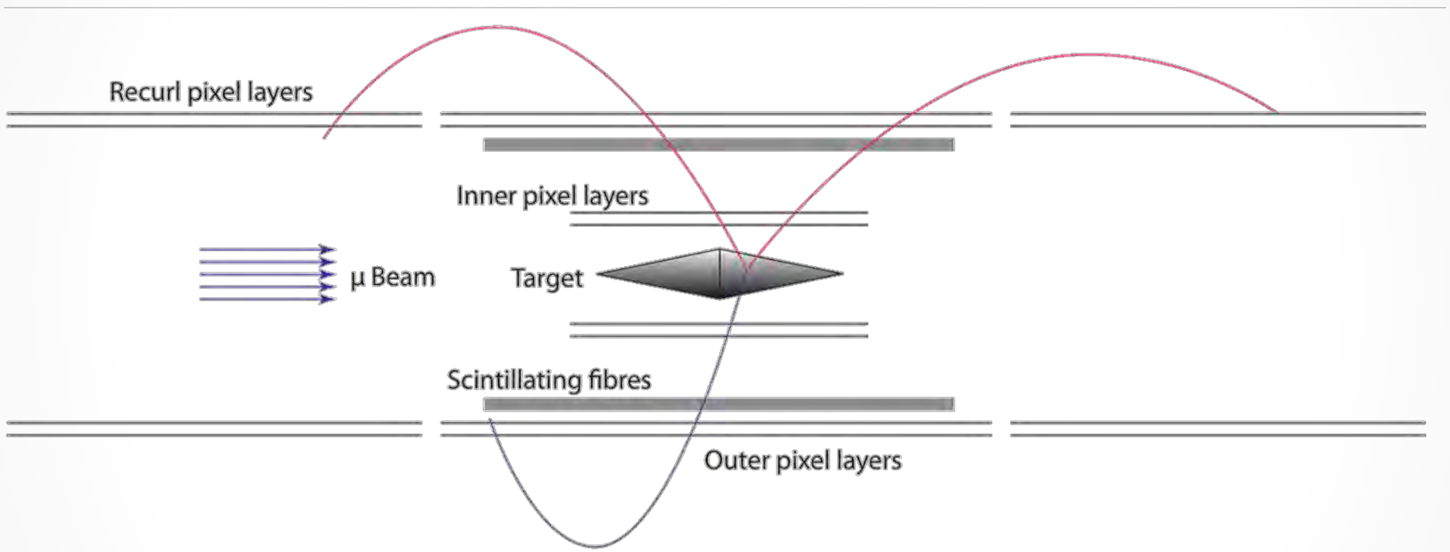

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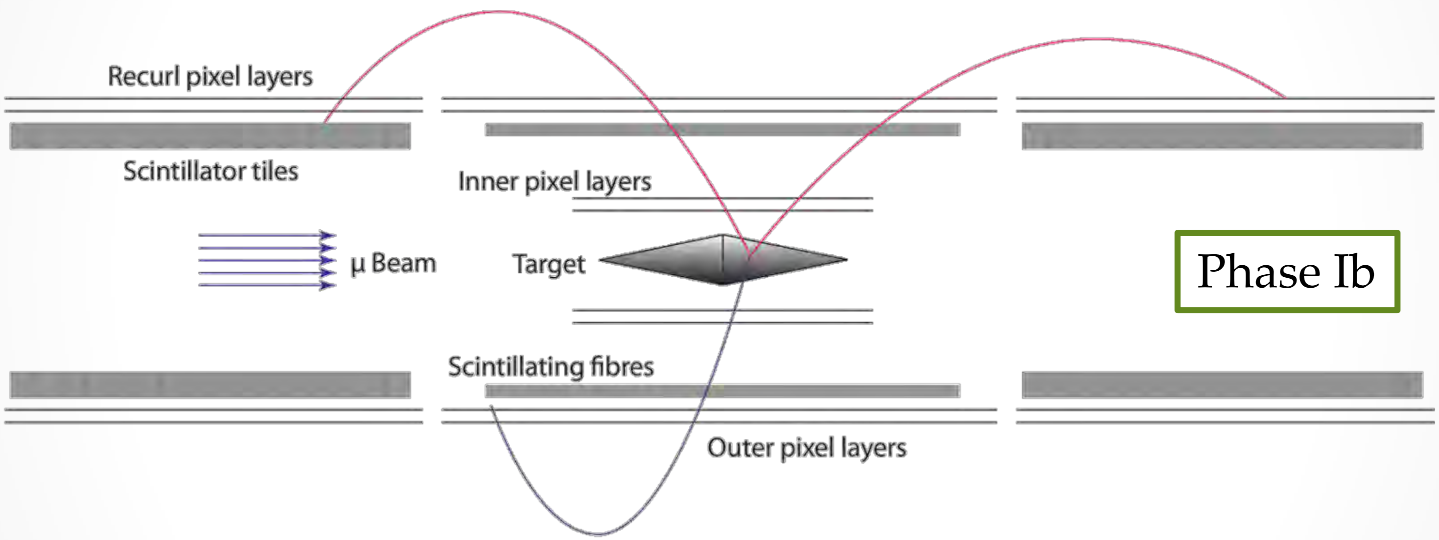
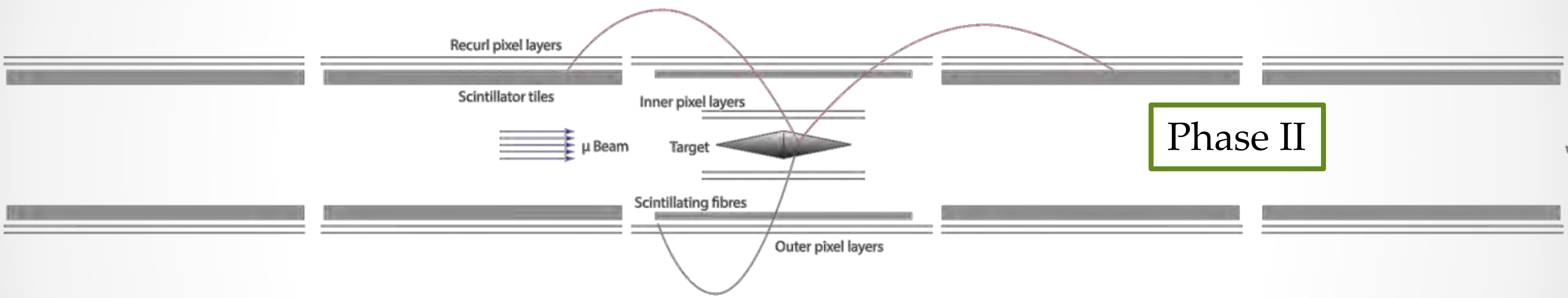


Phase Ib

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

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

The Mu3e Experiment



- Muon beam $O(10^9/s)$
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- Target double hollow cone
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- Tile detector

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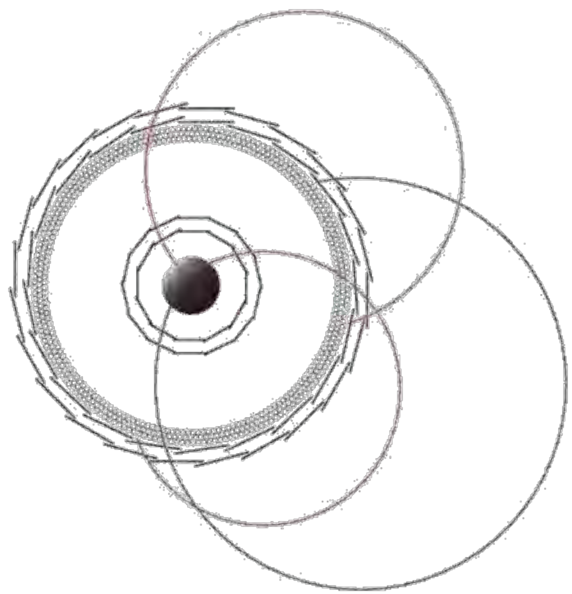


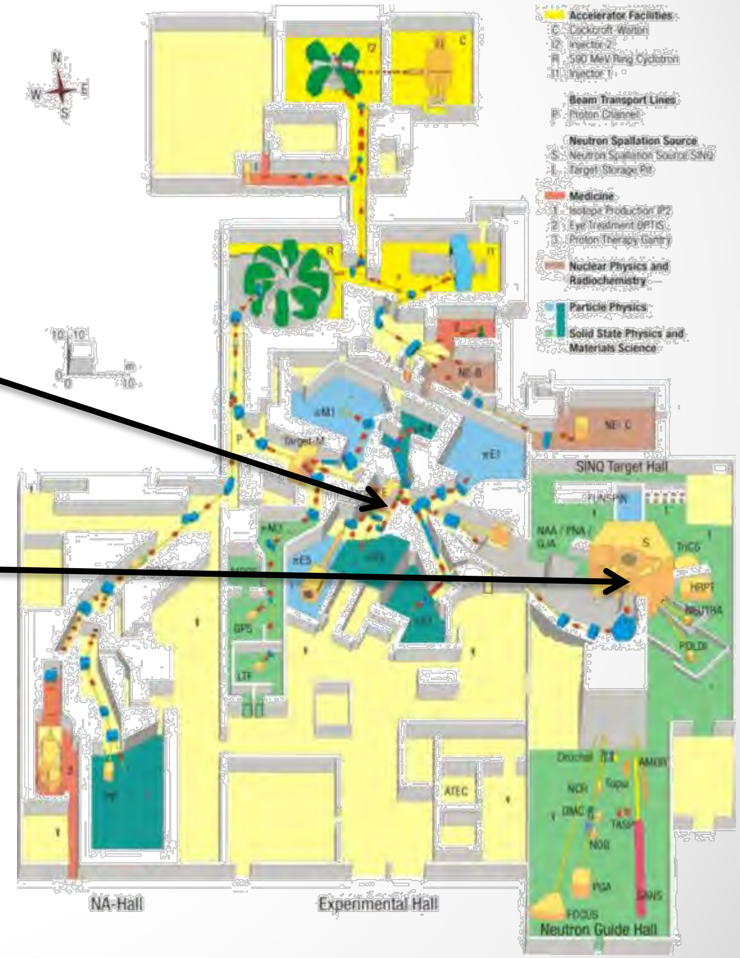
- Muon beam $O(10^9/s)$
- Helium atmosphere
- 1 T B-field

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

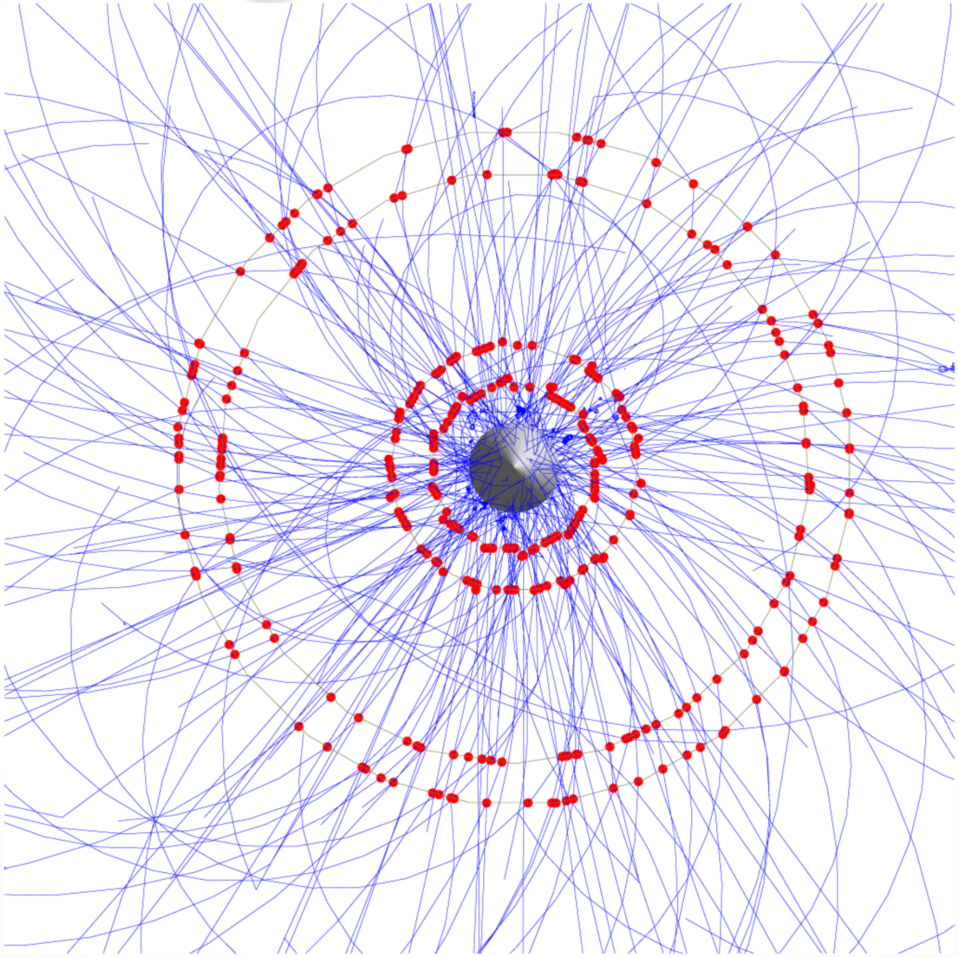
PSI μ-Beam

Paul Scherrer Institute Switzerland:

- 2.2 mA of 590 MeV/c protons
- Phase I:
  - o Surface muons from target E
  - o Up to a ~10^8 μ/s
- Phase II:
  - o New beam line at the neutron source:
    - **H**igh **i**ntensity **M**uon **B**eam
  - o Several 10^9 μ/s possible
  - ➢ >10^{16} muon decays per year
  - ➢ BR 10^{-16} (90% CL)

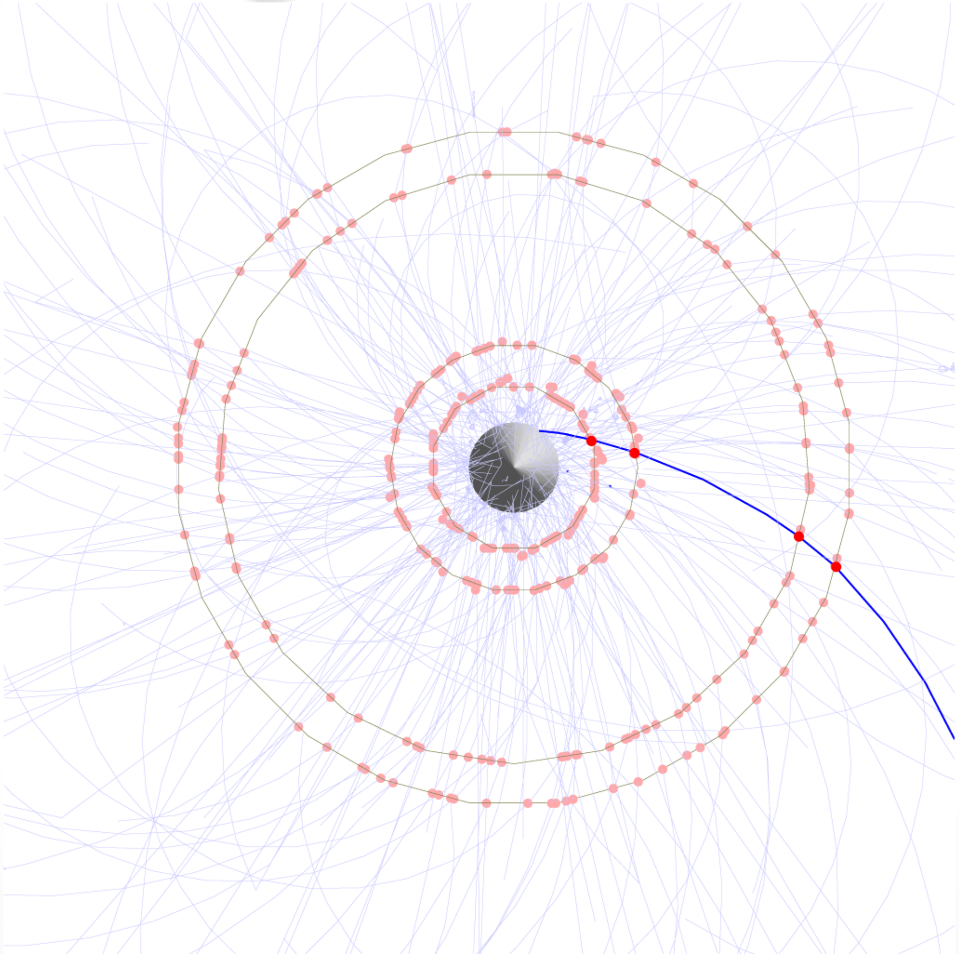


Timing Detectors



50 ns

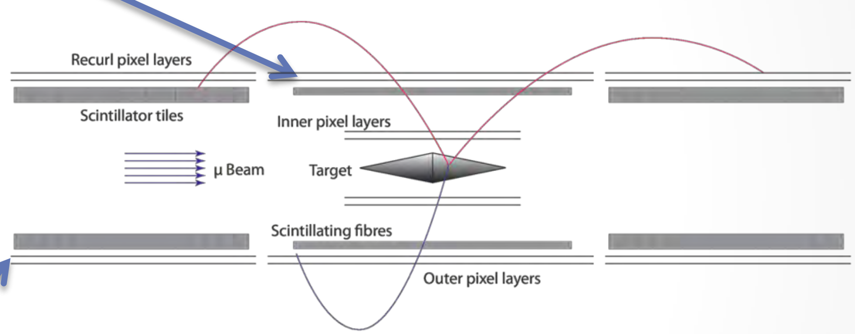
Timing Detectors

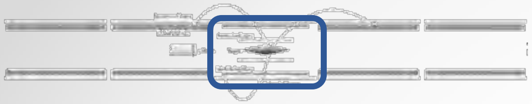


0.1 ns

Timing Detectors

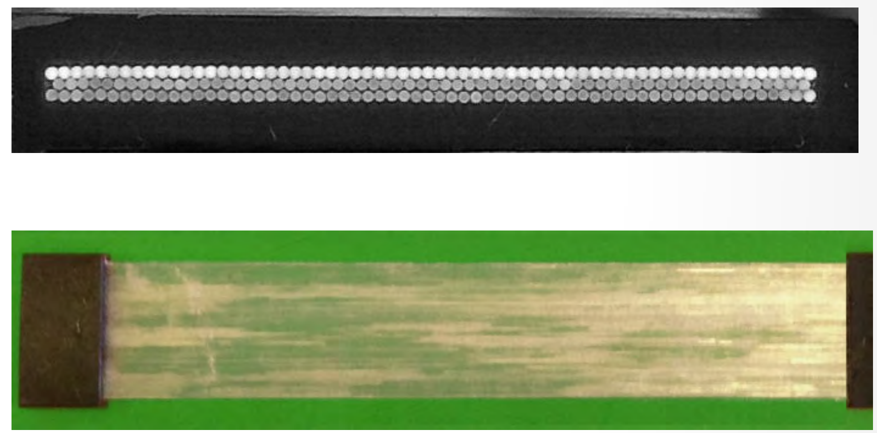
- Fiber detector
  - Before outer pixel layers
  - 250 µm scintillating fibers
  - SiPMs
  - ≤ 1 ns resolution
- Tile detector
  - After recurl pixel layers
  - 8.5 x 7.5 x 5 mm^3
  - SiPMs
  - ≤ 100 ps resolution



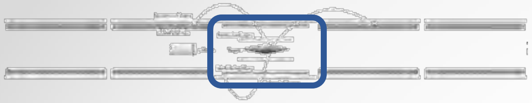


Fiber Detector

- Fiber ribbon modules
  - o 16 mm wide
  - o 360 mm long
  - o 3 or 4 layers fibers of 250 µm dia.
  - o 6 STiC readout chips

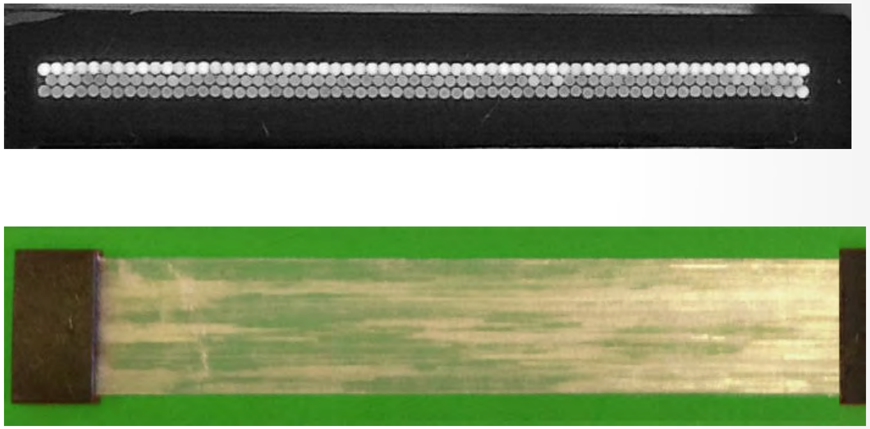


Scintillating fiber ribbons

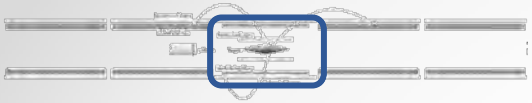


Fiber Detector

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



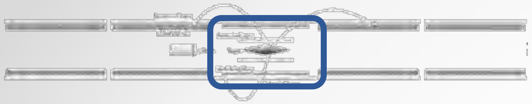
Scintillating fiber ribbons



Fiber Detector

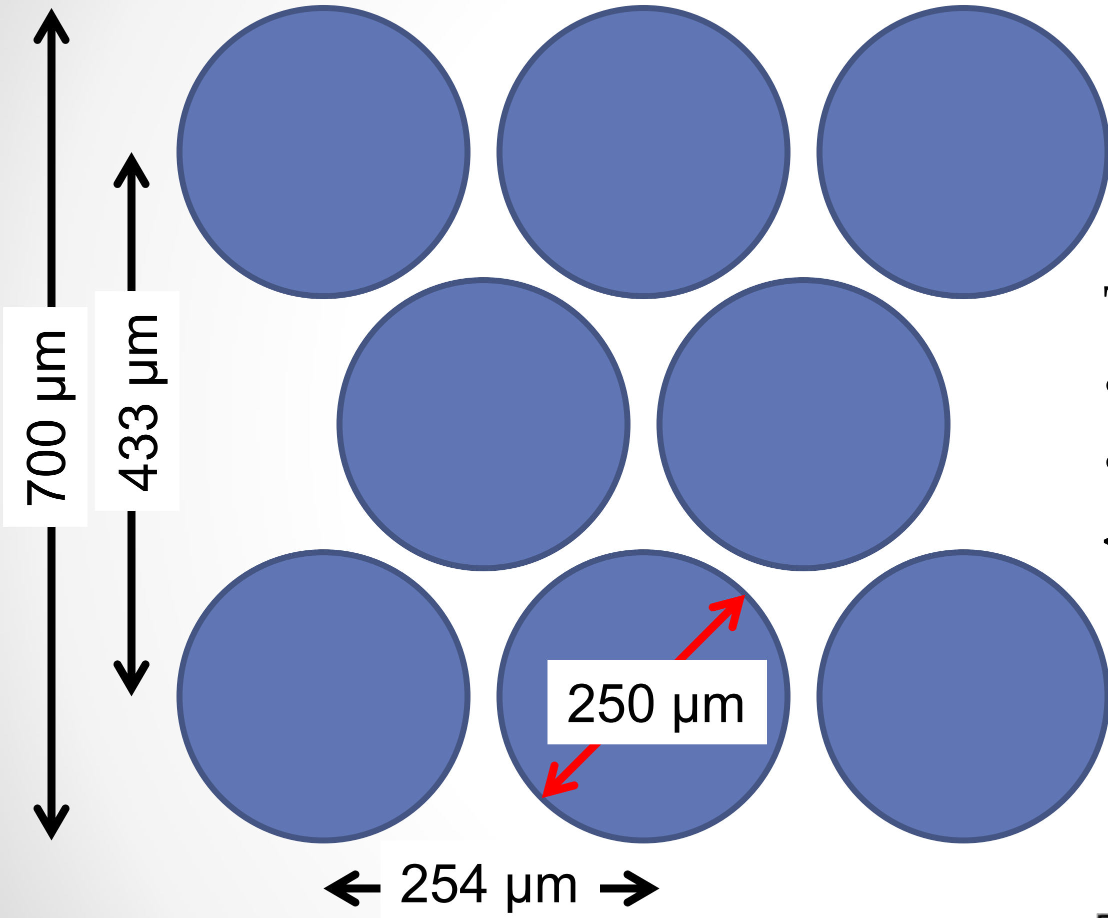
- Prototype ribbons built:
  - 3 and 4 layers
  - 16 mm wide
  - 360 mm long
- CAD in progress

Scintillating fiber ribbons



Details …

staggered layers



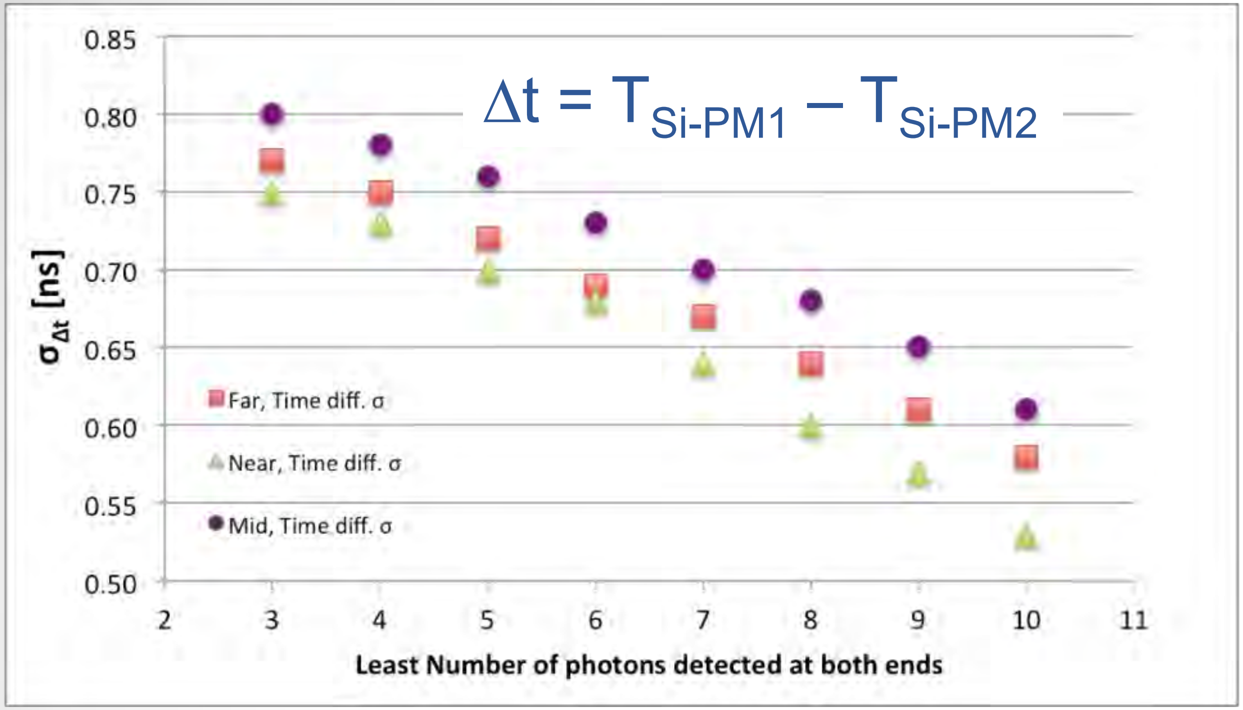
Thickness:
- theoretical ~ 683 µm
- measured ~ 750 µm

< 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 $1 / \sqrt{n}$ behavior:

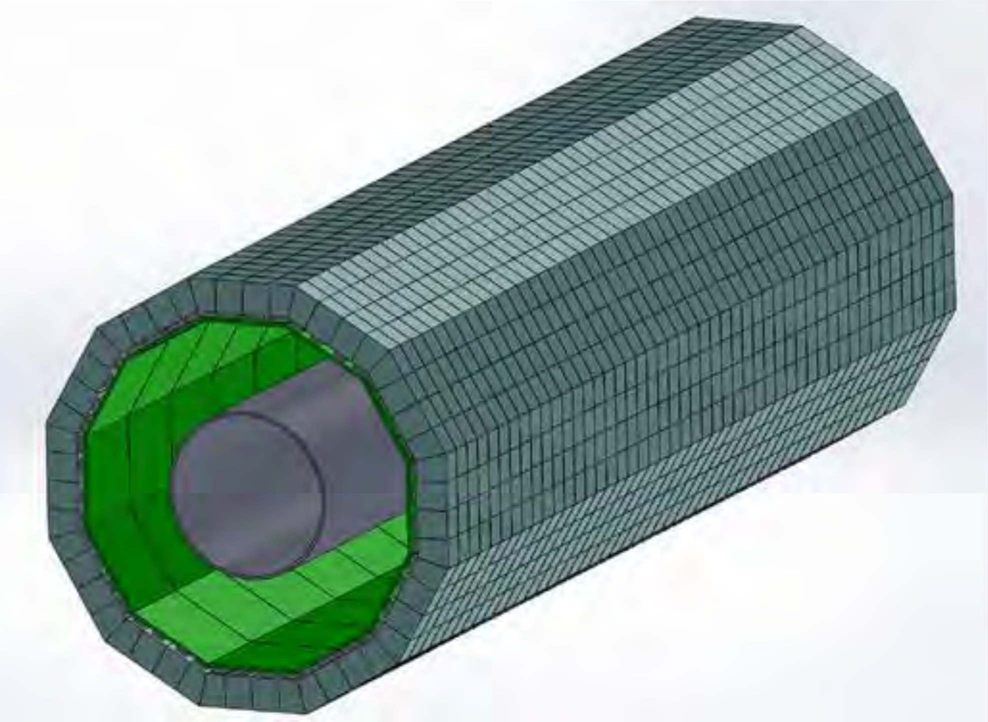
$\Rightarrow$ improve on timing algorithm!

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

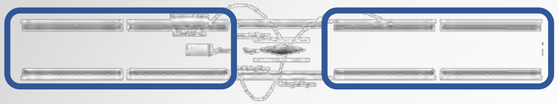
- Real issue: time in all ~9k channels to few 100 ps

Tile Detector

- Scintillating tiles
  - 8.5 x 7.5 x 5 mm^3
- 12 Tile Modules per station
  - 192 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through STiC



Sketch of Tile detector station



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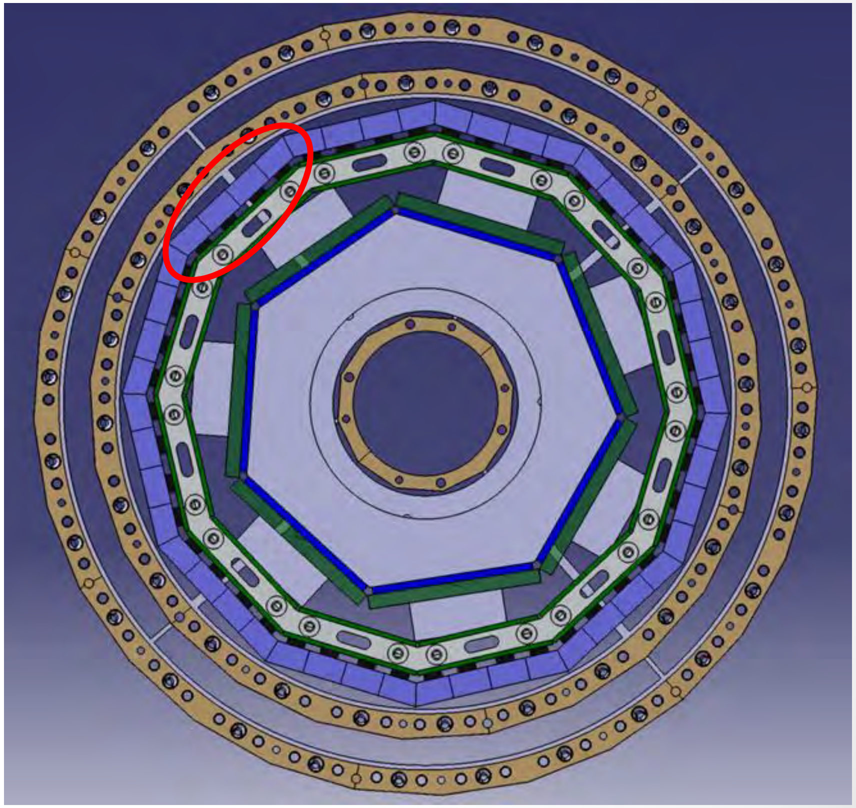
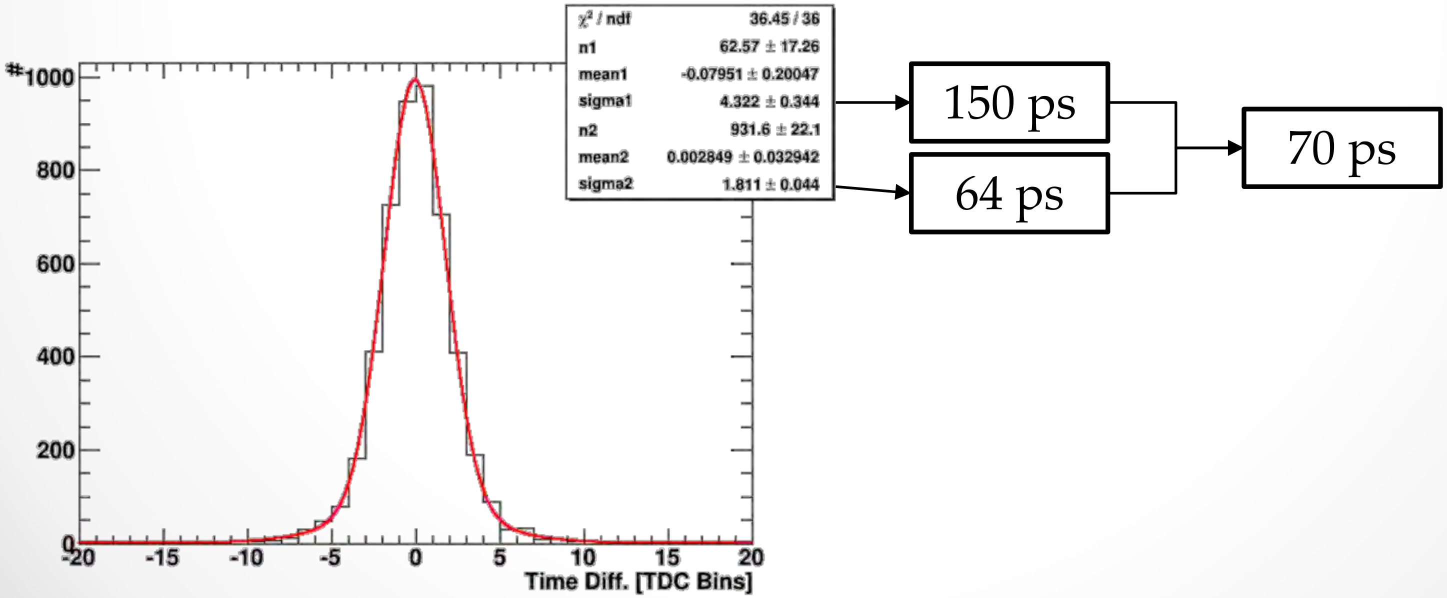


CAD of Tile Detector integration

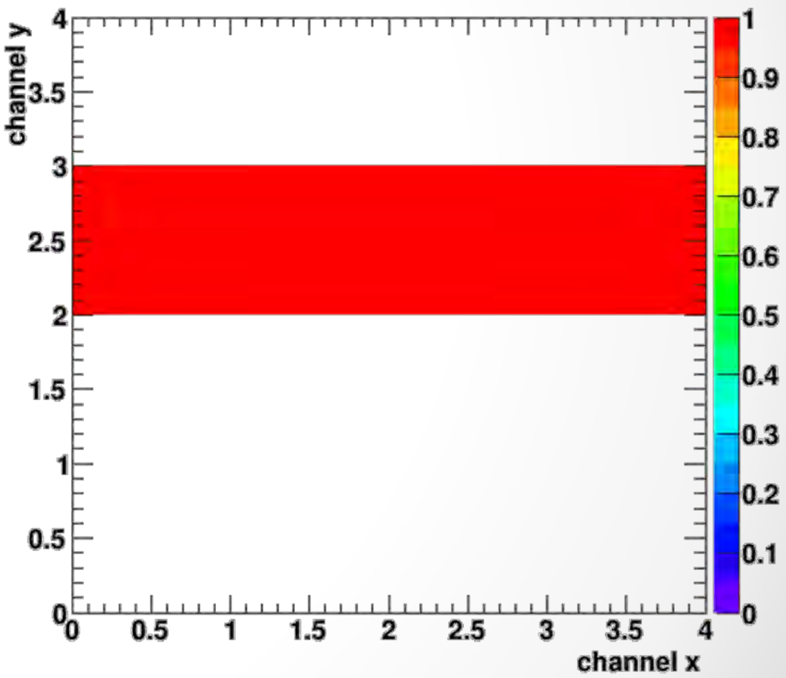
Time Resolution

- Coincidence between 2 tiles in a row
- Time resolution ≈ 70 ps
- Time-walk effect ≈ 5 % (4 ps)
- Only small dependence on chip settings



Efficiency

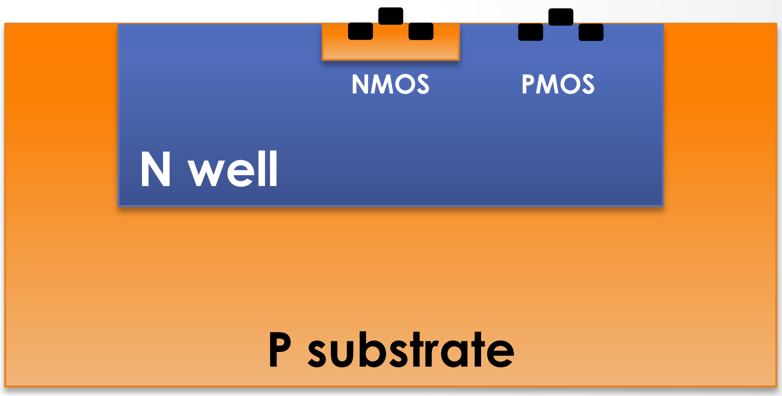
- Require hit in first & last column
- Look for hit in middle channel
- Efficiency > 99.5%
- Bad time values for ≈ 40% of hits
  - Known bug in STiC 2.0
  - Will be fixed in STiC 3.0



Pixel Sensors

HV-MAPS

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



by Ivan Peric

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

HV-MAPS

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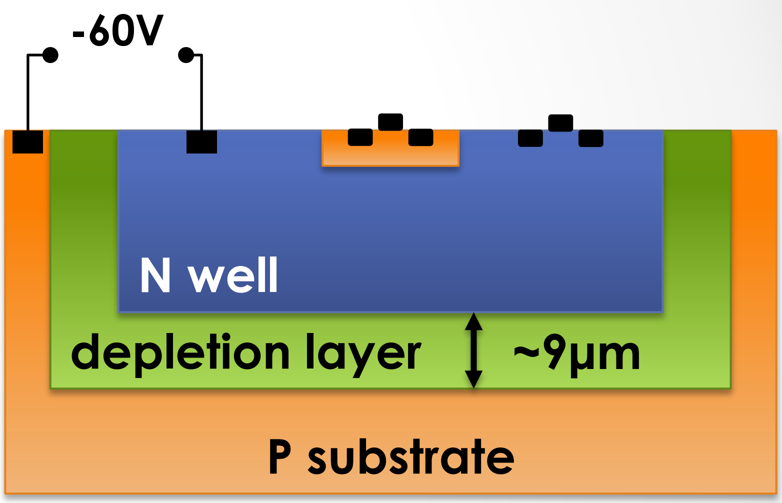
- Pixel sensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased ~60V
  - Depletion layer
  - Charge collection via drift
  - ➢ Fast <1 ns charge collection
  - Thinning to < 50 µm possible



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  - o Depletion layer
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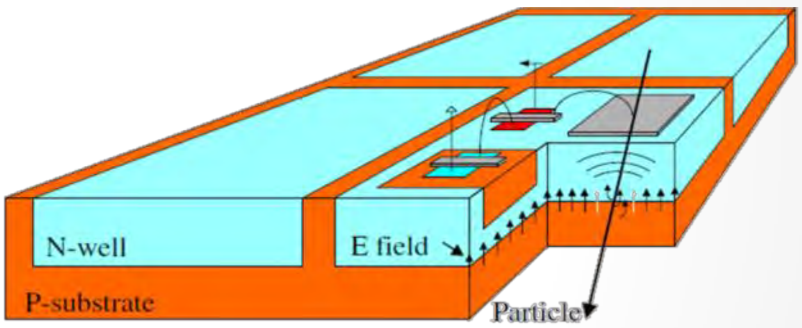
  - ➢ Fast <1 ns charge collection
  - o Thinning to < 50 µm possible
- Integrated readout electronics



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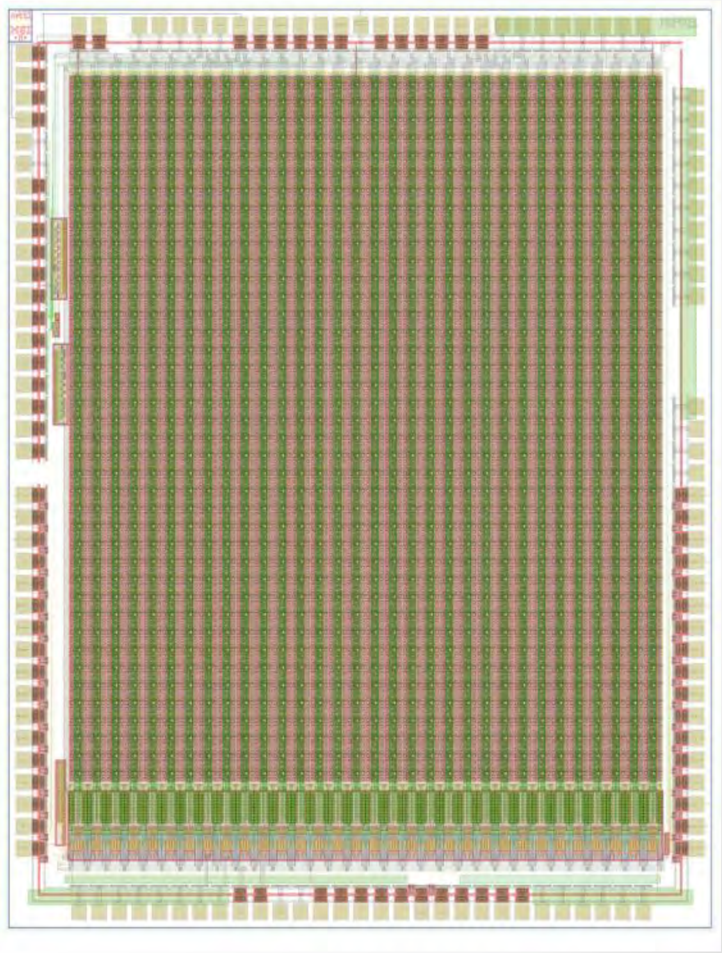
Chip Prototypes

MuPix4

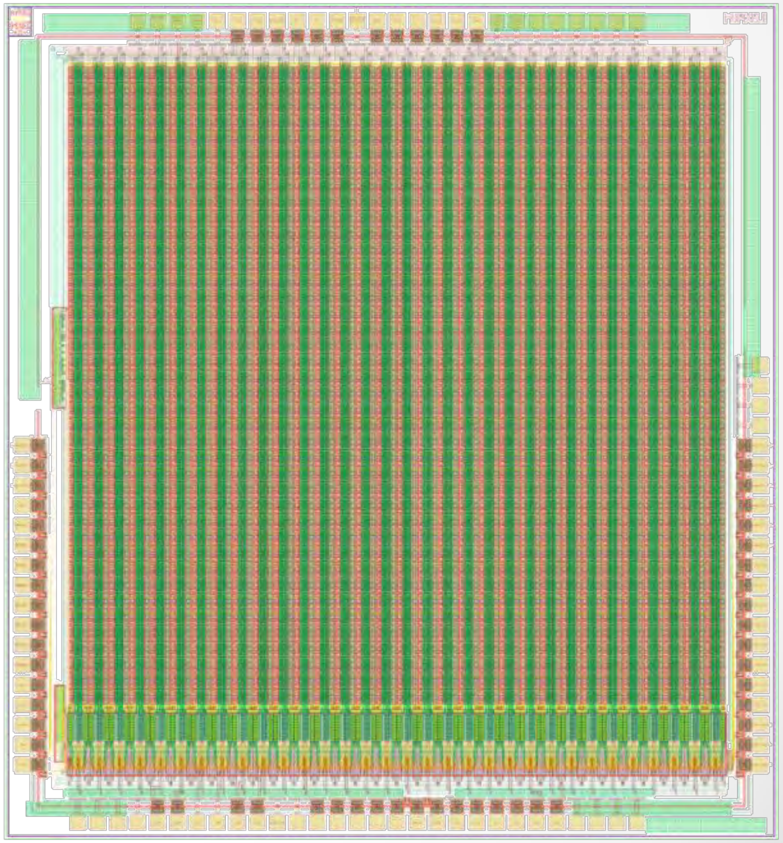
- 180 nm HV-CMOS
- Pixel matrix:
  - 40 x 32 pixels
  - 92 x 80 μm^2 each
- Ivan Perić ZITI
  - Analog part
    - Small pixel capacitance
    - Temperature tolerant
  - Digital part
    - Mostly ready



Chip Prototypes

MuPix6

- 180 nm HV-CMOS
- Pixel matrix:
  - o 40 x 32 pixels
  - o 103 x 80 μm² each
- Ivan Perić ZITI
  - o Analog part
    - Small pixel capacitance
    - Temperature tolerant
  - o Digital part
    - Mostly ready

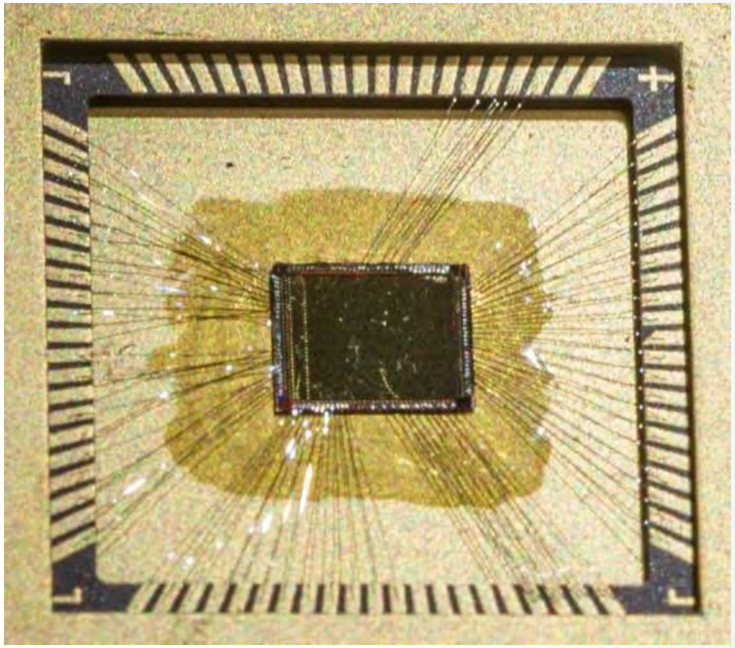


HV-MAPS
Test Results

…

Thinned Sensors

- Single dies thinned:
  - MuPix2 thinned to < 80µm
  - MuPix3 thinned to < 90µm
  - MuPix4 thinned to 50µm
- Good performance of thin chips
  - In lab
  - In particle beam



MuPix3 thinned < 90µm

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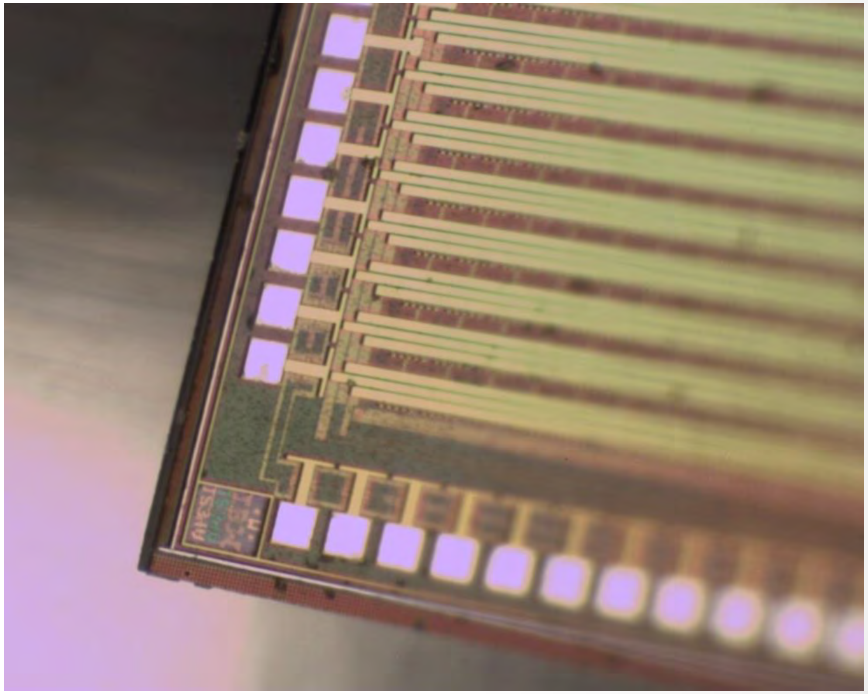
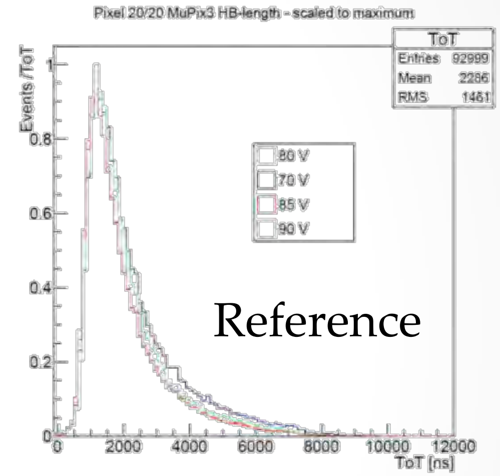


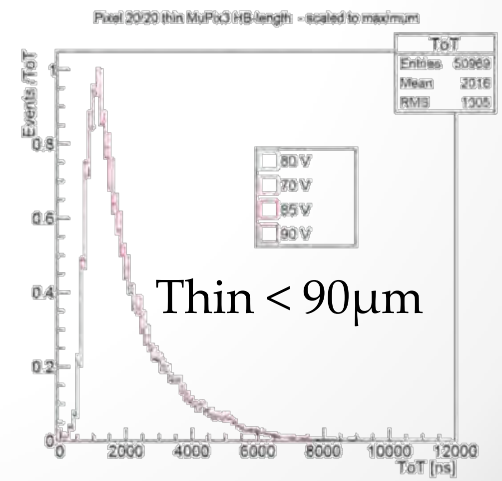
MuPix4 thinned to 50μm

Thinned Sensors

- Single dies thinned:
  - MuPix2 thinned to < 80µm
  - MuPix3 thinned to < 90µm
  - MuPix4 thinned to 50µm
- Good performance of thin chips
  - In lab
  - In particle beam
- Similar Time over Threshold (ToT)
  - PSI test-beam
  - PiM1 beam-line
  - 193 MeV π^+

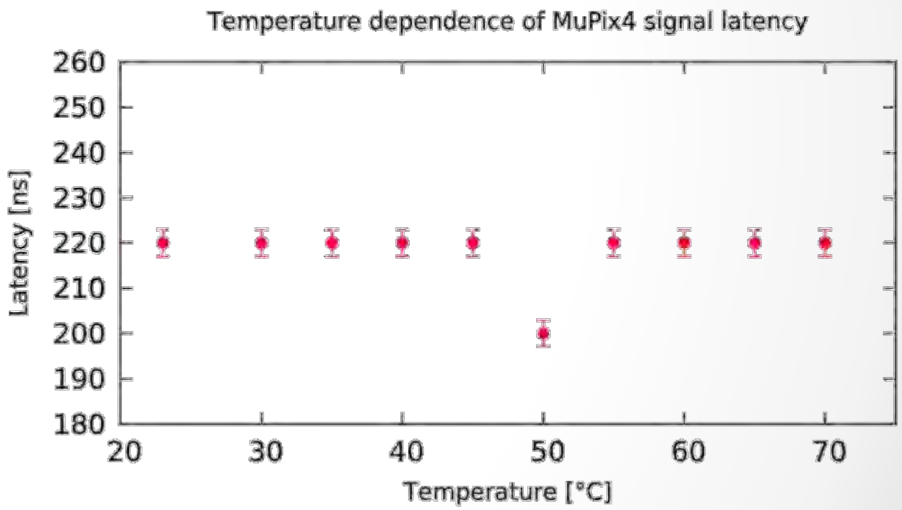
Time Over Threshold





Temperature Dependence

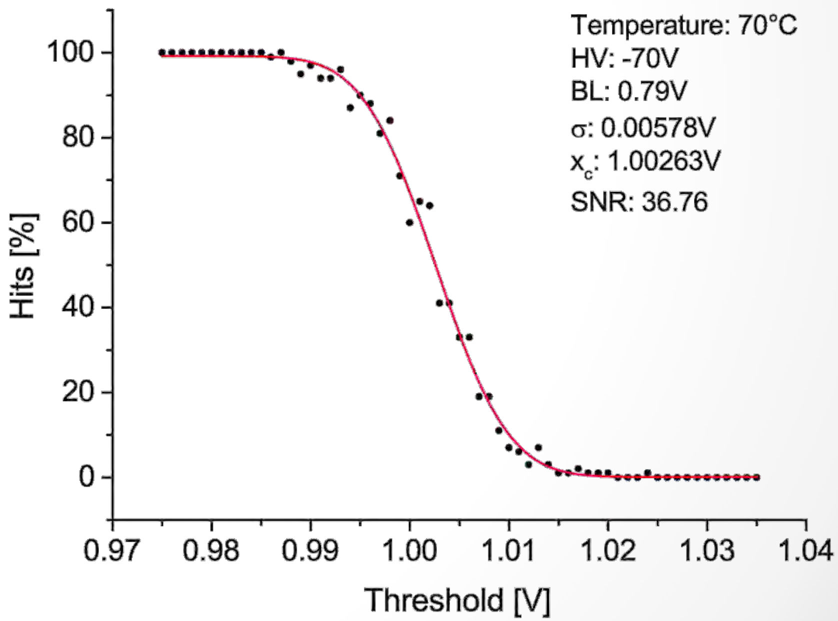
- MuPix4 prototype
- Latency measurement
  - o LED pulse to…
  - o Pixel discriminator output
- Setup in Oven
  - o Temperature between 23°C and 70°C
- ➢ Very **little temperature dependence**
  - ➢ O(10ns) in latency
  - ➢ Within resolution of setup



Signal to Noise

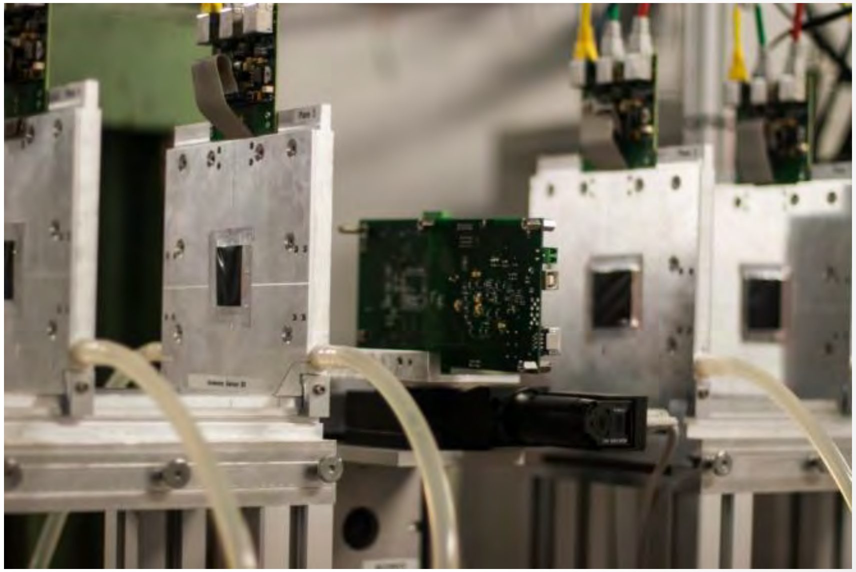
- MuPix4 prototype
- Signal
  - Test-pulse
  - Calibrated to ^{90}Sr source
  - At 70°C in oven
  - HV = -70V
- Noise
  - Taken from S-curve
  - Error function fit
  - X-checked with
    - Threshold scan
    - Close to baseline

➢ **S/N = 36.8**



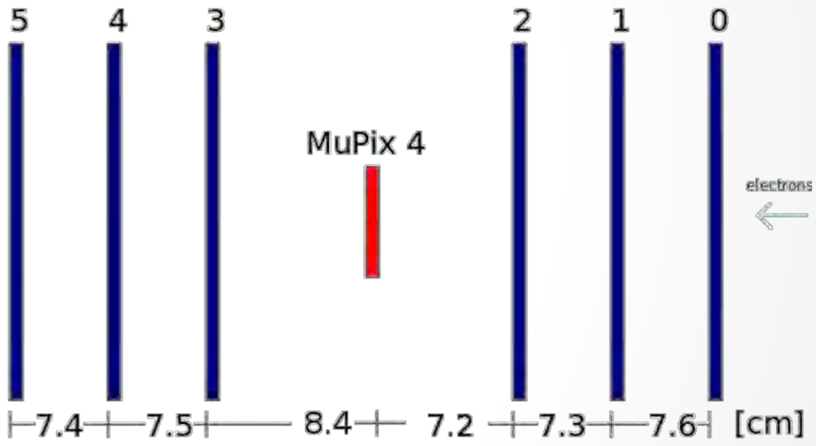
Test beams

- Eight test beam campaigns in 2013-14:
  - March DESY
  - June DESY
  - September PSI
  - October DESY
  - **February ’14 DESY**
  - June PSI
  - July PSI
  - October PSI



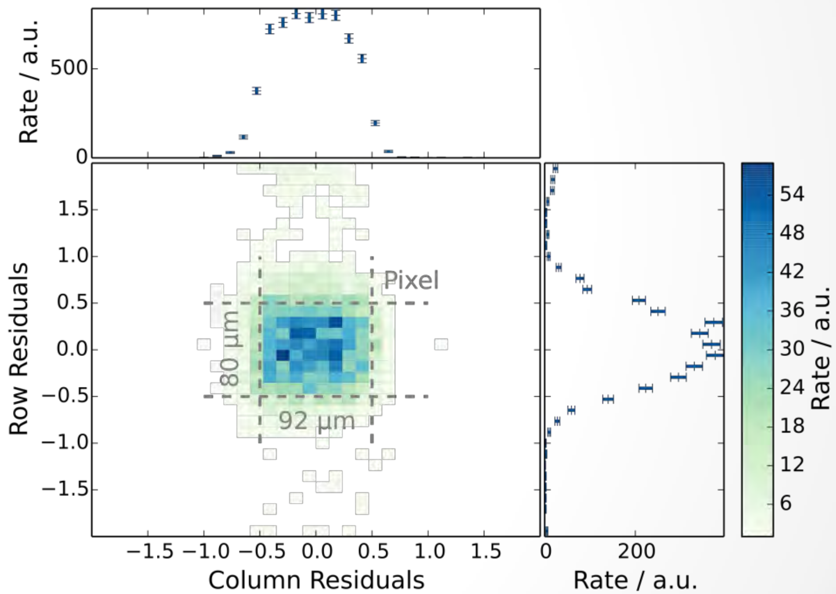
Setup February Test-Beam

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



Spatial Resolution

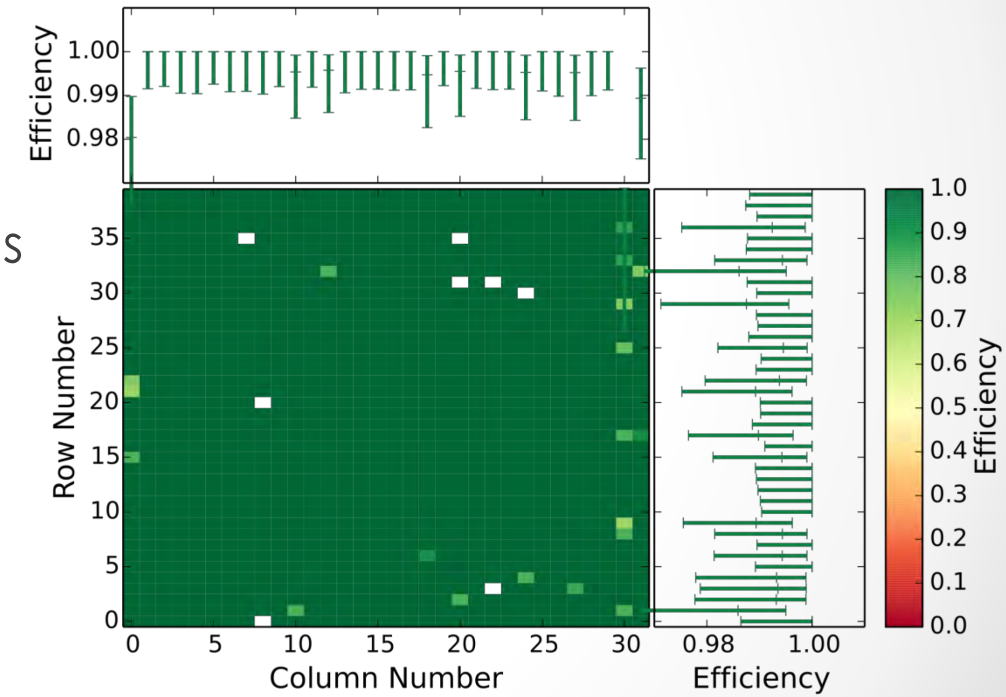
- Pixel size 80 µm x 92 µm
- Measured track residuals:
  - RMS x = **28 µm**
  - RMS y = **29 µm**



Pixel Residuals

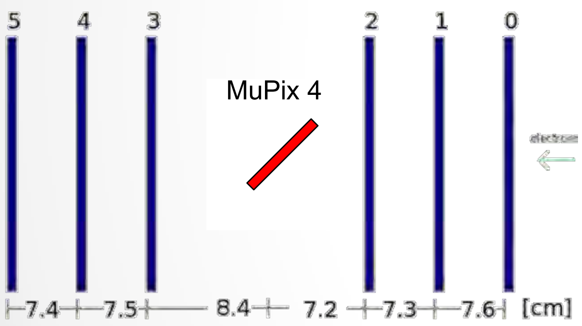
Efficiencies

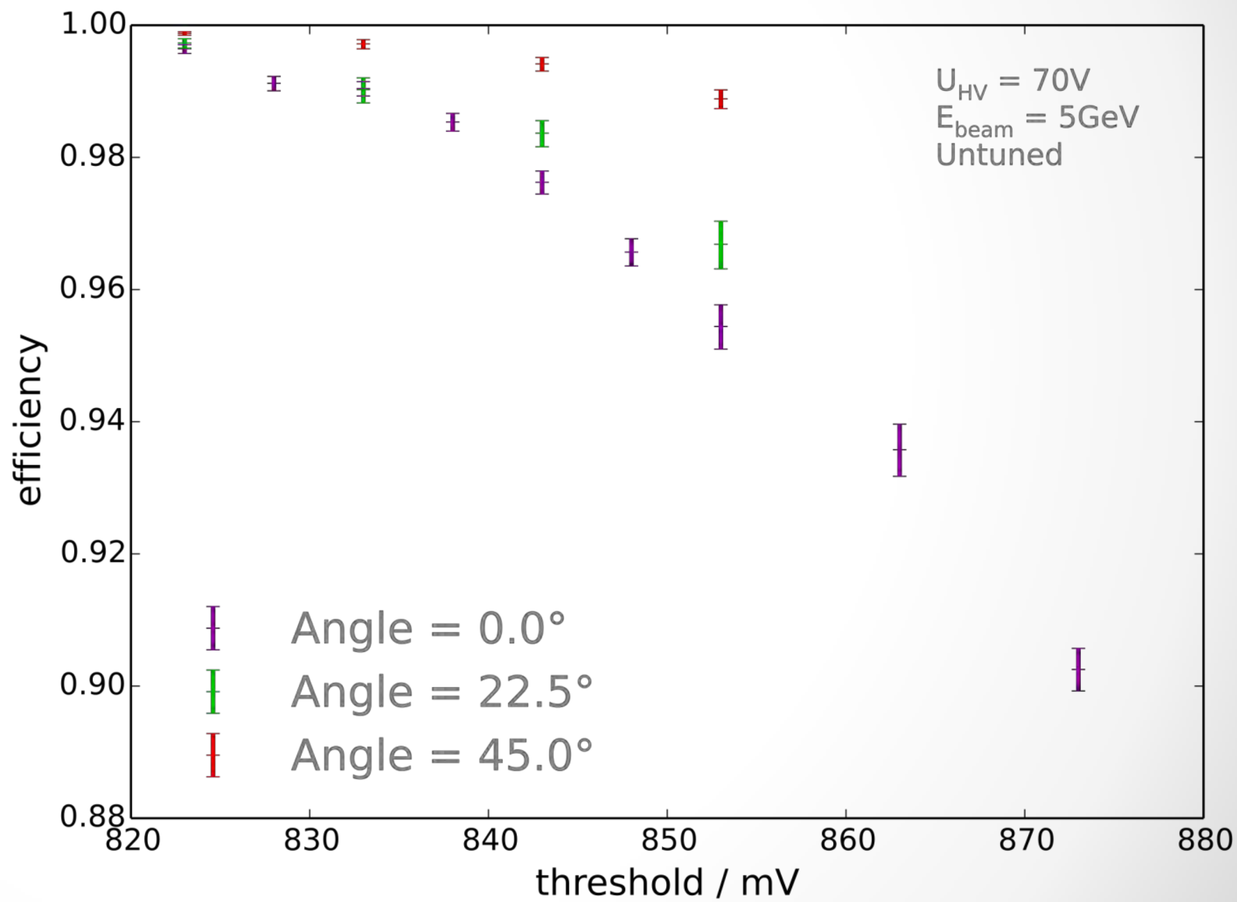
- **>99.5% efficiency**
  - 5 GeV electrons
  - 45° angle
  - Individual pixel thresholds
    - Threshold tune from pixel efficiencies in previous test beam



MuPix4 Efficiency

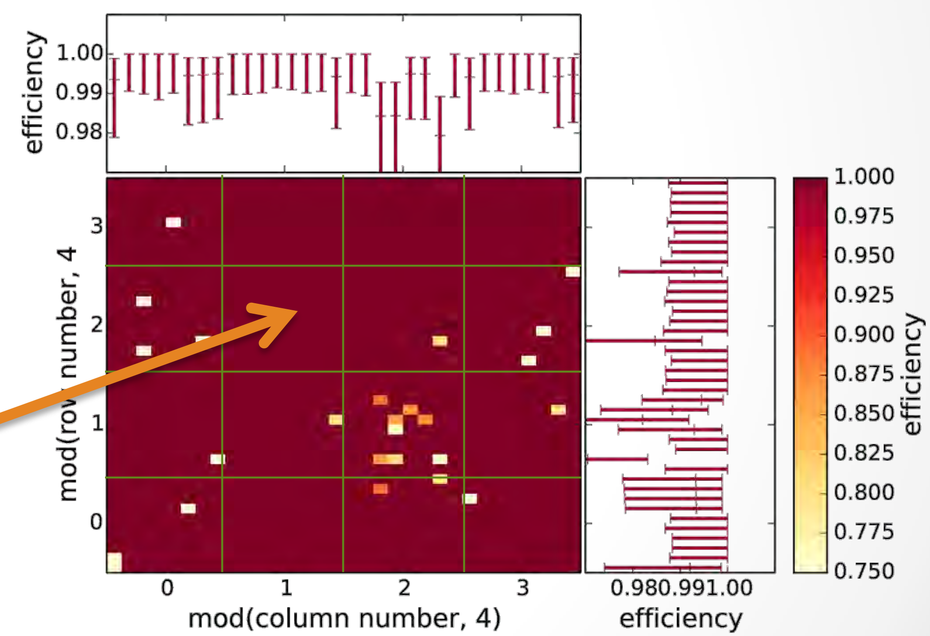
Threshold Scans for 0° to 45°





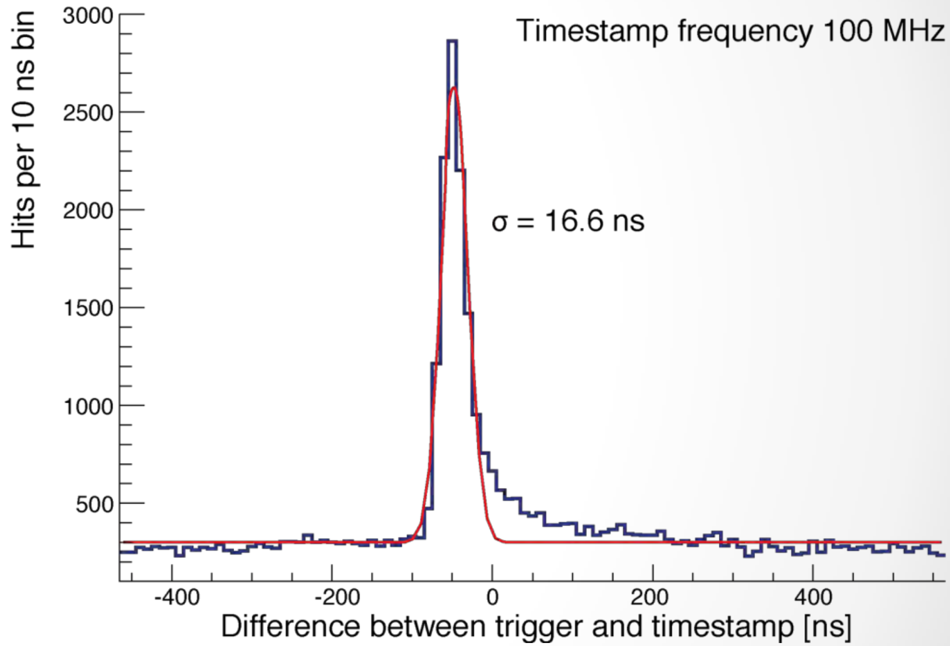
Sub-Pixel Efficiencies

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



Time Stamps

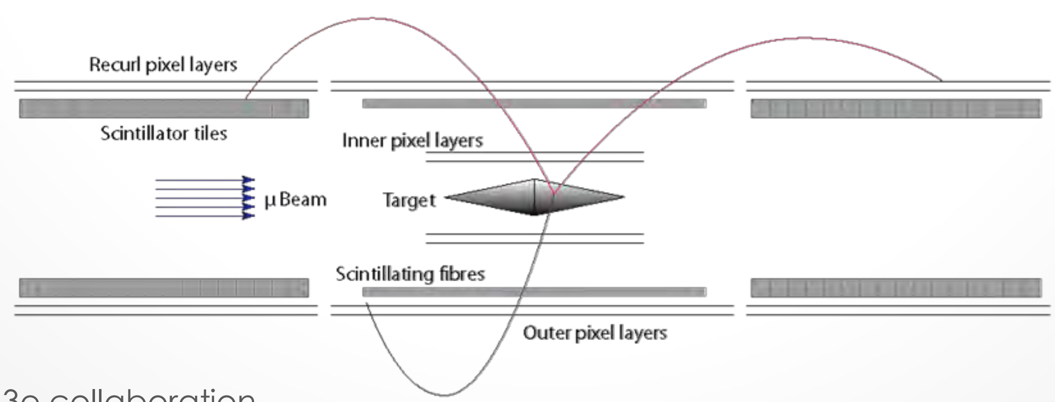
- MuPix4 prototype
- External grey counter
  - At 100 MHz
- Time stamp recorded by MuPix4 sensor
  - For each pixel
- **Time resolution O(17 ns)**
  - Non-negligible setup contribution



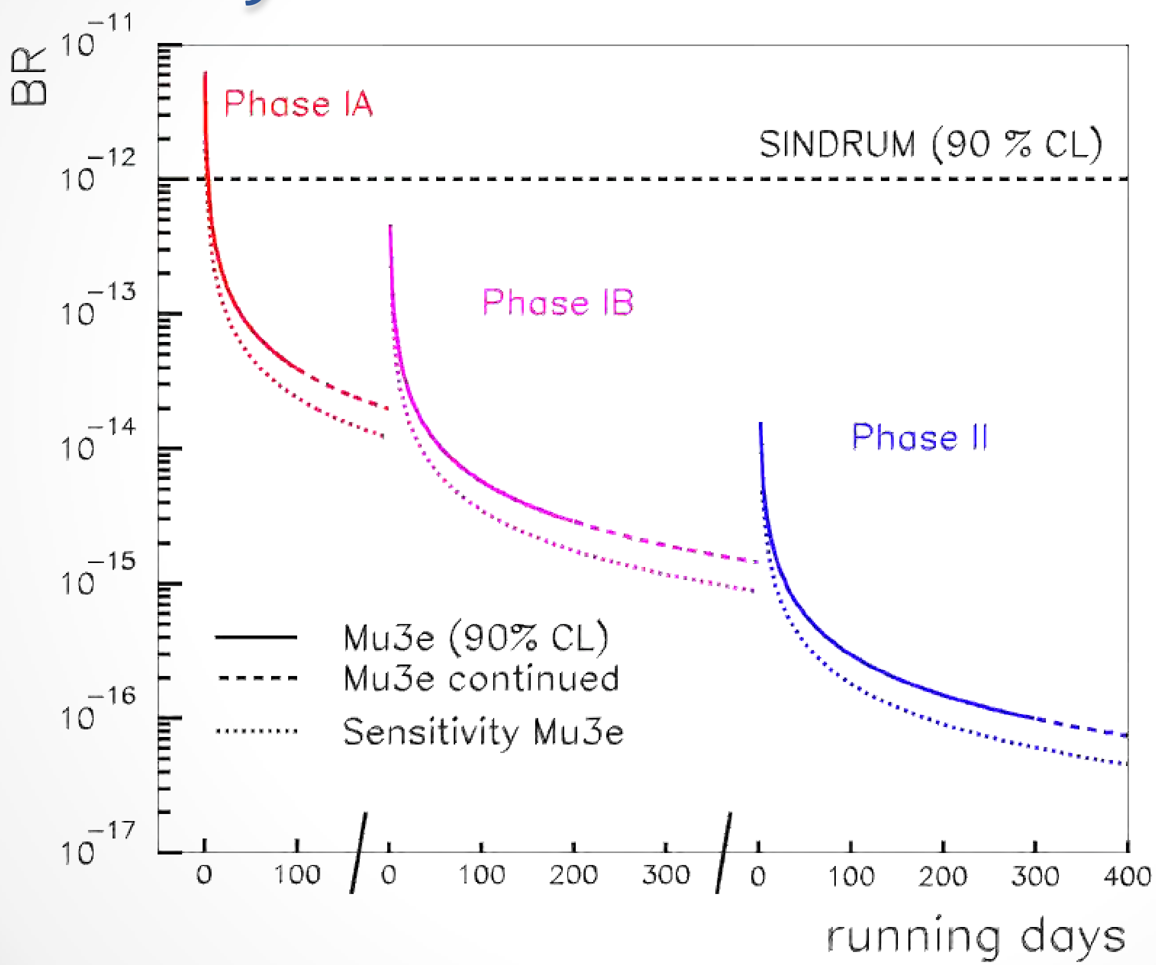
Time Resolution of Pixels

Summary

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



Outlook: Projected Sensitivity



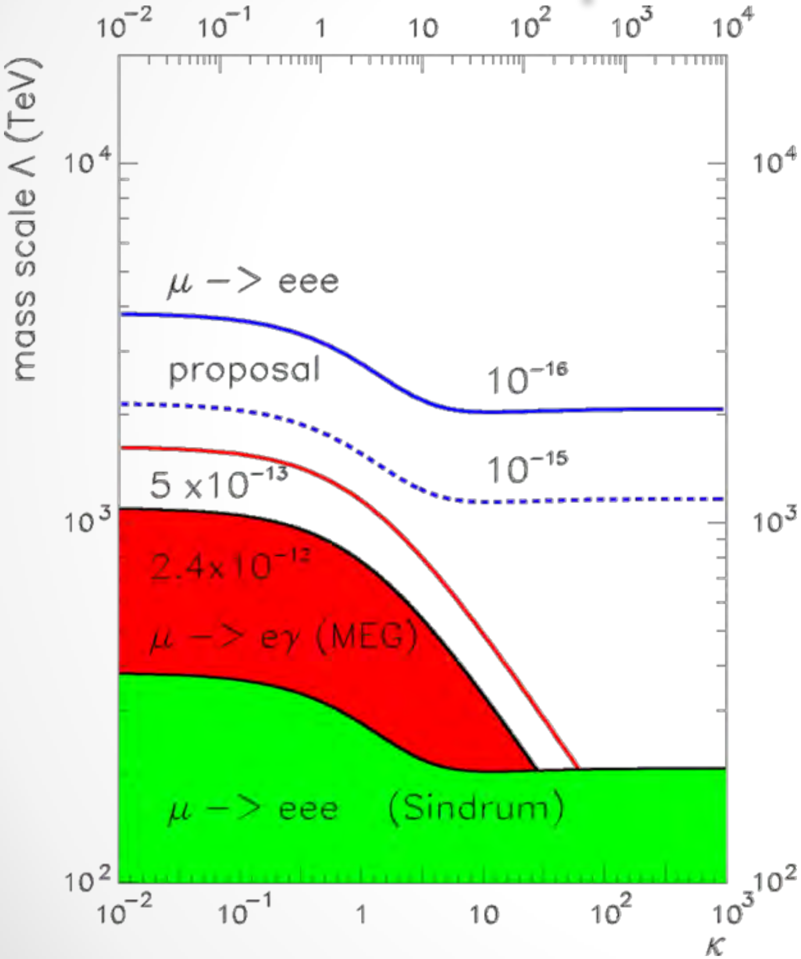
Institutes

- 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

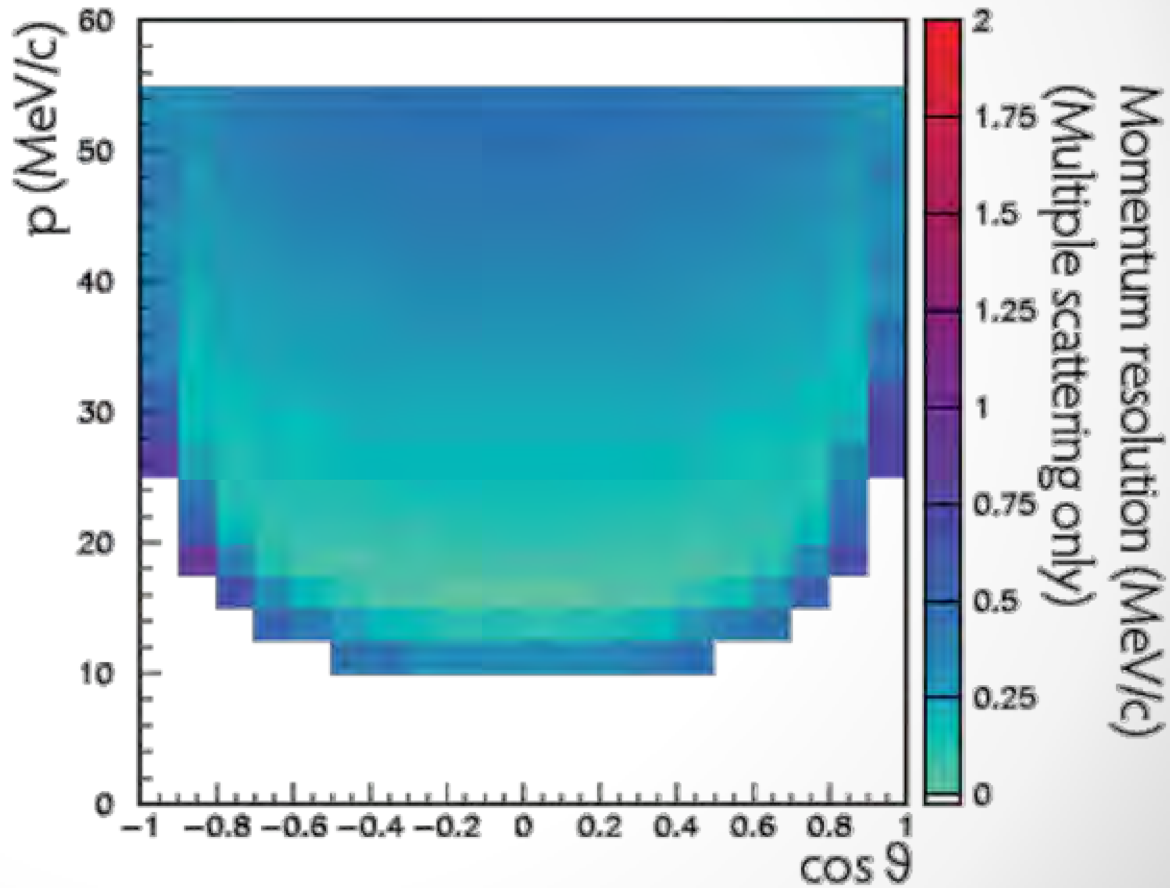


$$L_{LFV} = \left[\frac{m_\mu}{(\kappa+1)\Lambda^2}\,\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu}\right]_{\gamma-\text{penguin}} + \left[\frac{\kappa}{(\kappa+1)\Lambda^2}\,(\overline{\mu_L}\gamma^\mu e_L)\,(\overline{e_L}\gamma_\mu e_L)\right]_{\text{tree}}$$

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

Momentum Resolution

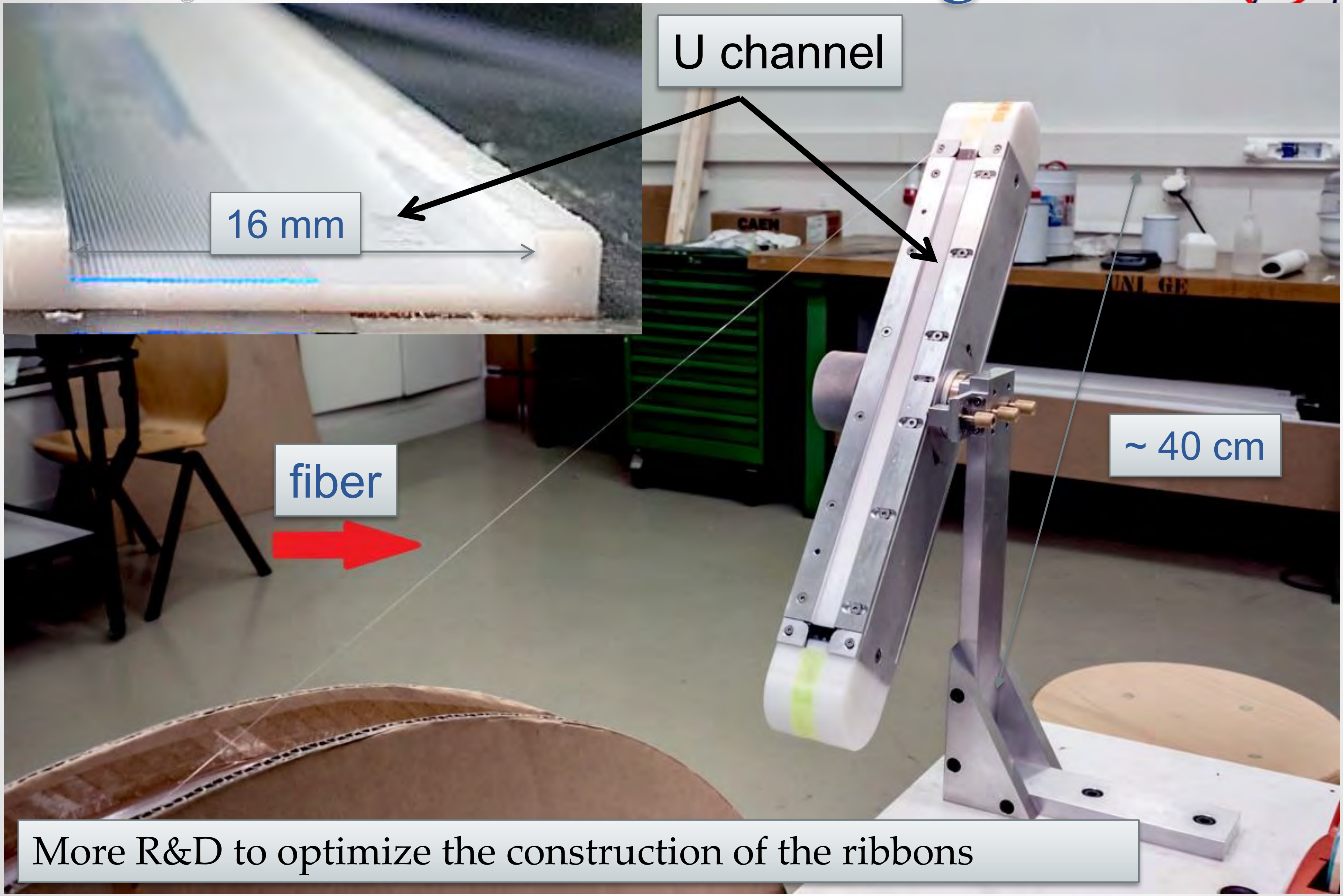
- Multiple scattering only
- Current design:
  - 50 µm silicon
  - 50 µm Kapton
  - Helium gas cooling
  - 3 layer fiber detector



SciFi Backup

…

Fiber Winding Tool

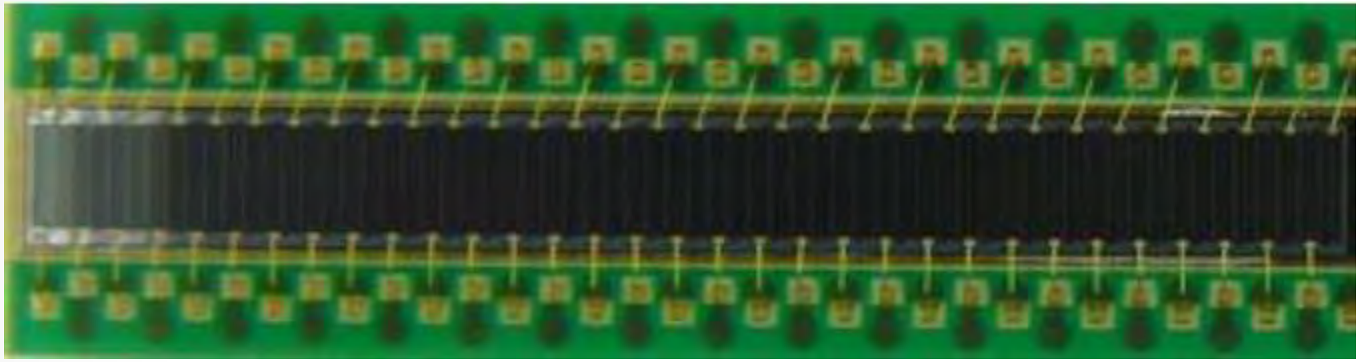


More R&D to optimize the construction of the ribbons

Readout of Fibers

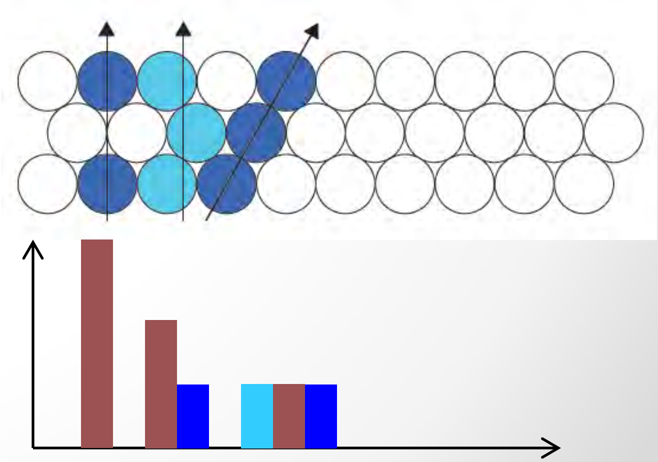
Si-PMs (MPPCs) at both fiber ends

SciFi column readout with Si-PM arrays



LHCb type detector

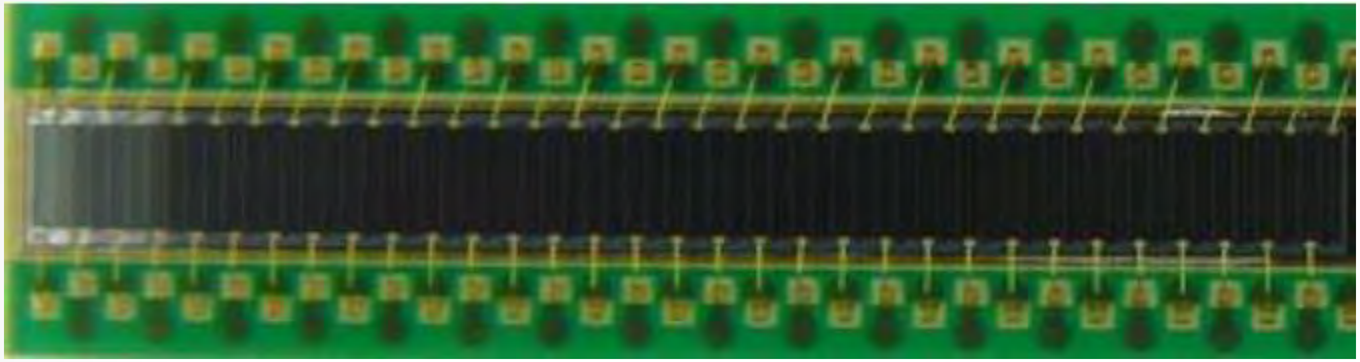
- 64 channel monolithic device (custom design)
- ~250 micron effective "pitch"
- 50 μm $\times$ 50 μm pixels
- Grouped in 0.25 mm $\times$ 1 mm vertical columns
- Common bias voltage



Readout of Fibers

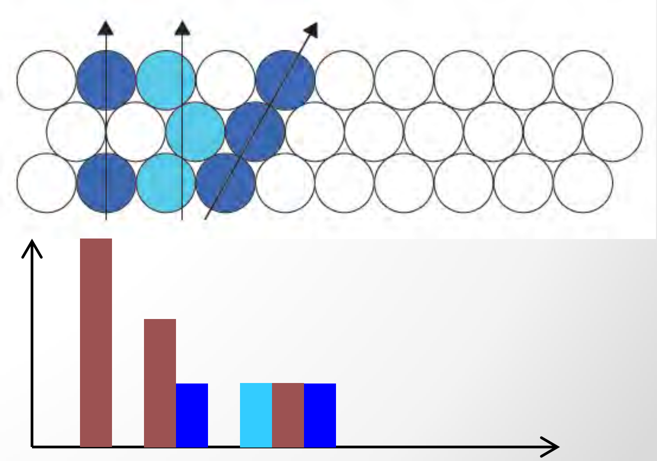
Si-PMs (MPPCs) at both fiber ends

SciFi column readout with Si-PM arrays

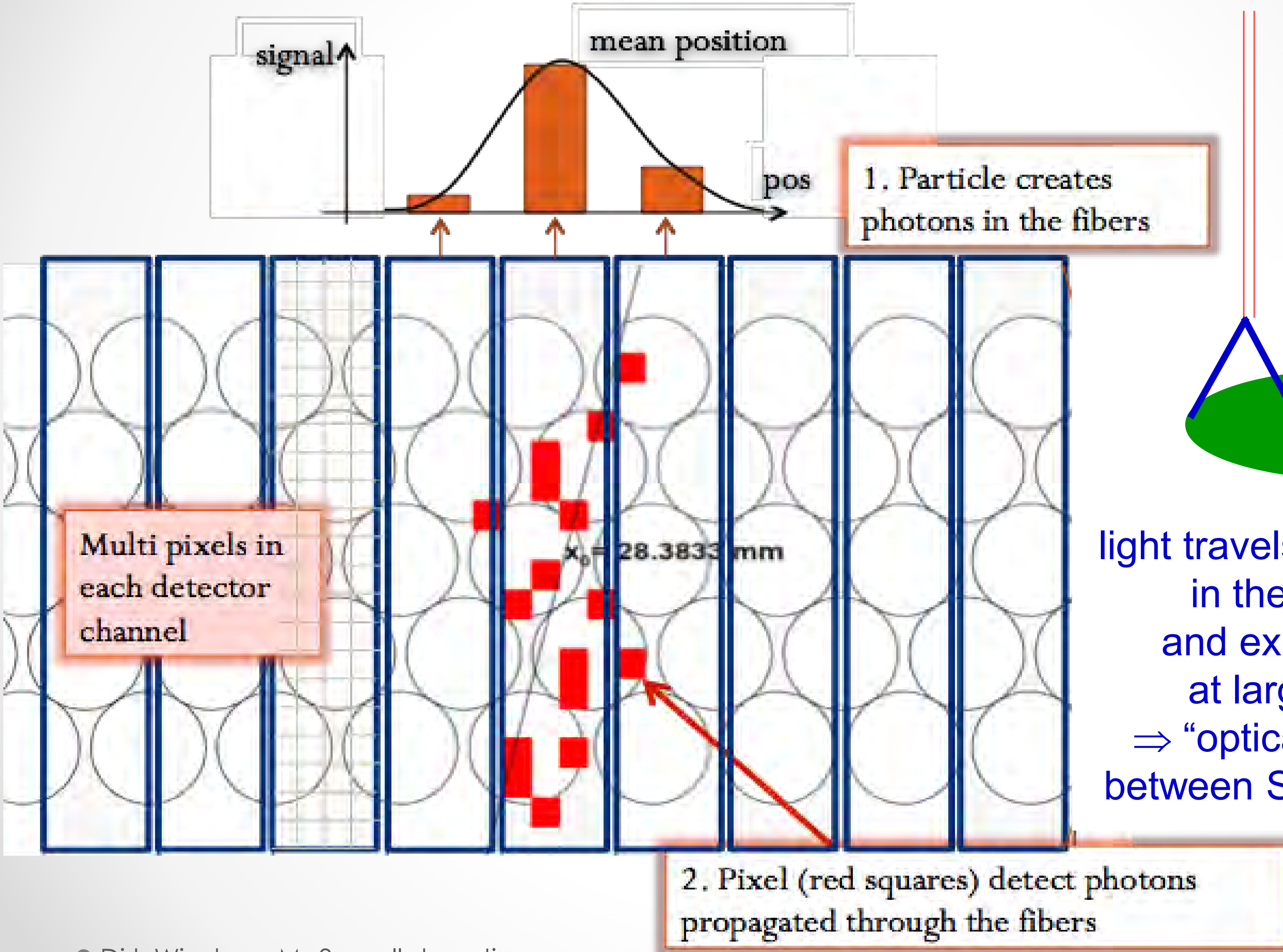


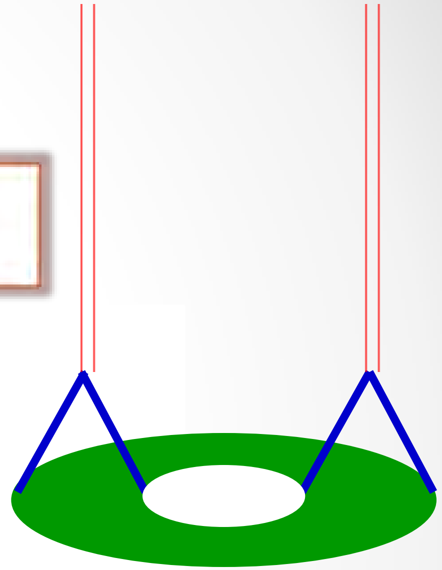
LHCb type detector

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

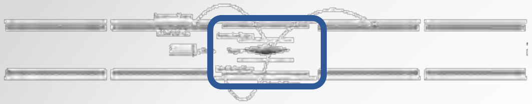


SciFi Column Readout





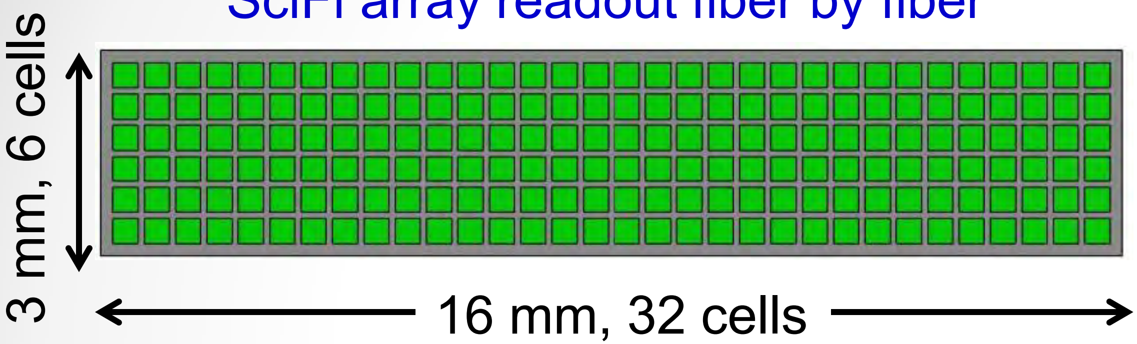
light travels preferentially in the cladding and exits the fiber at large angles
⇒ "optical" cross talk between Si-PM columns

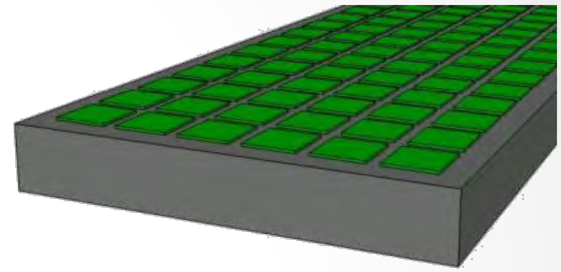


Readout of Fibers

Si-PMs (MPPCs) at both fiber ends

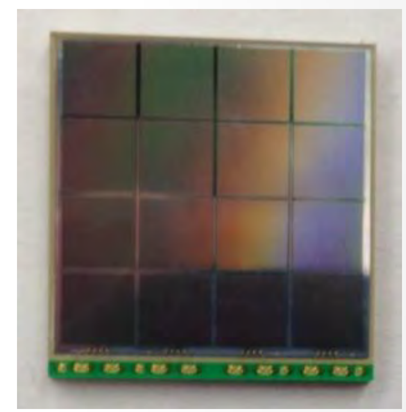
SciFi array readout fiber by fiber



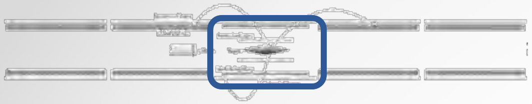


Monolithic device

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



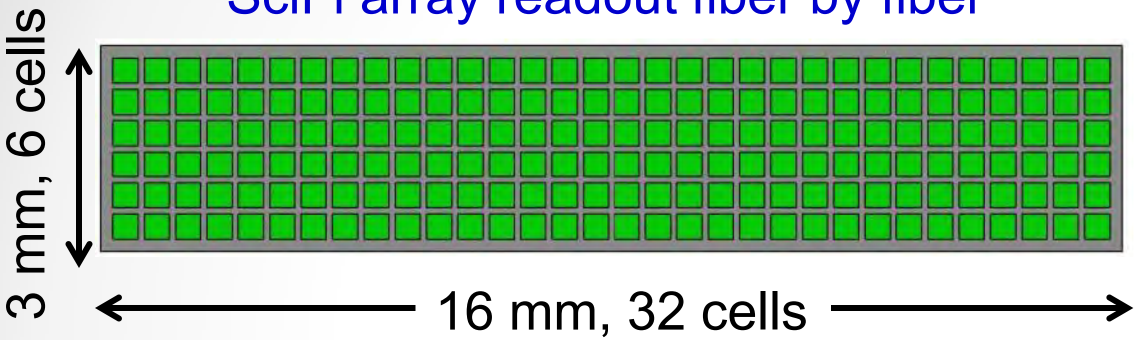
Example of Hamamatsu Si-PM array S12642-0404 sensor 4×4 ch. ($3 \times 3\ mm^2$)

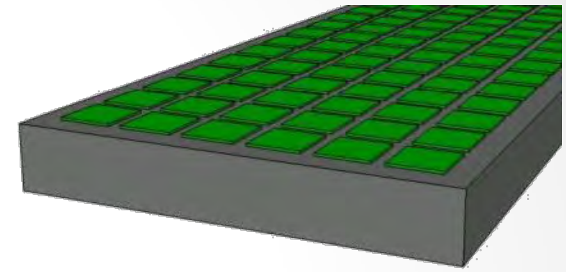


Readout of Fibers

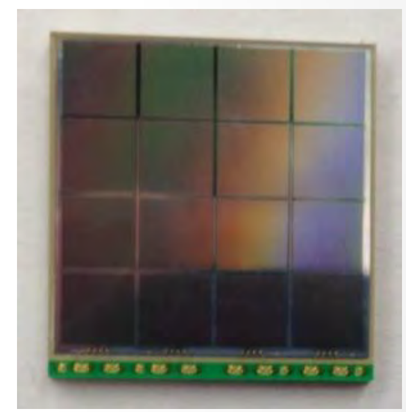
Si-PMs (MPPCs) at both fiber ends

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

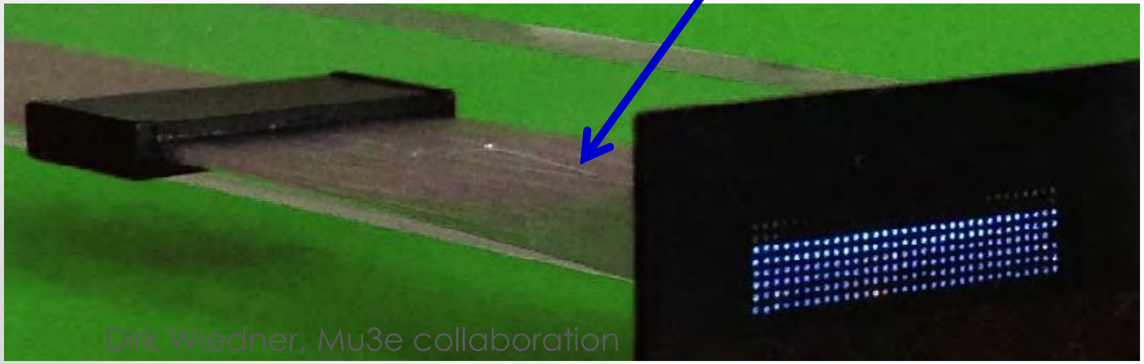
Fibers glued with photo-device geometry
500 μm center to center

Si-PM array directly coupled to fibers

Estimated rate ~ 200 kHz for 2016 run

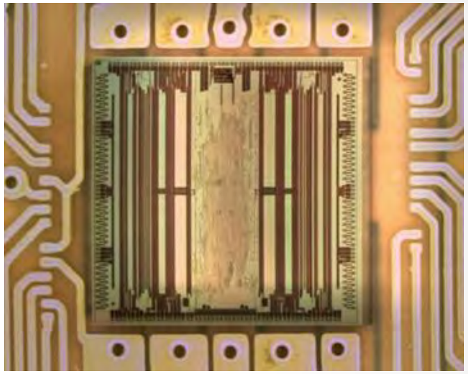
“fan-out” between straight section and socket

Alternative:
LHCb type detector

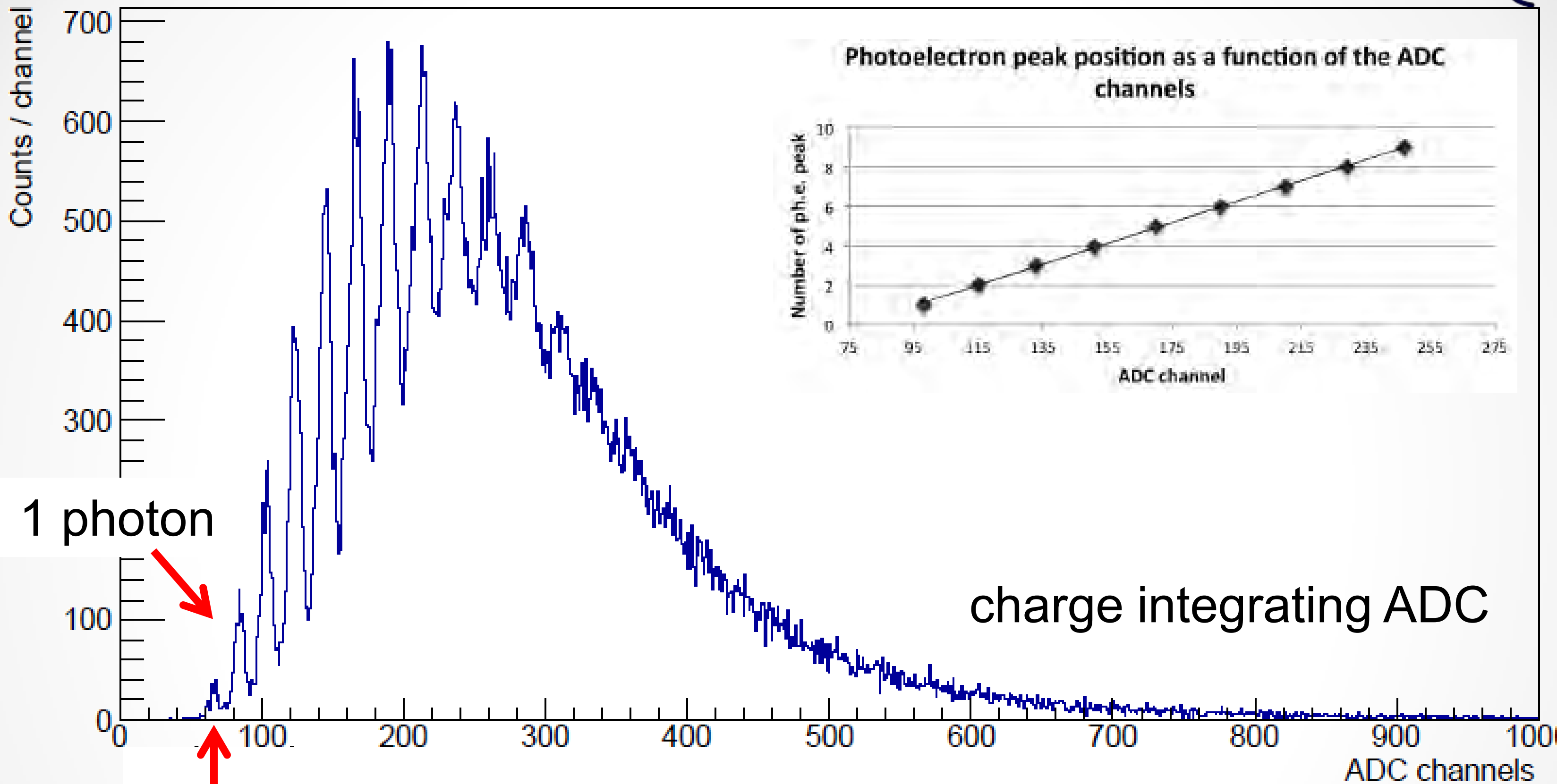


Readout Electronics

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



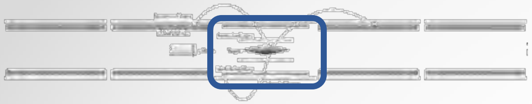
ADC Spectra

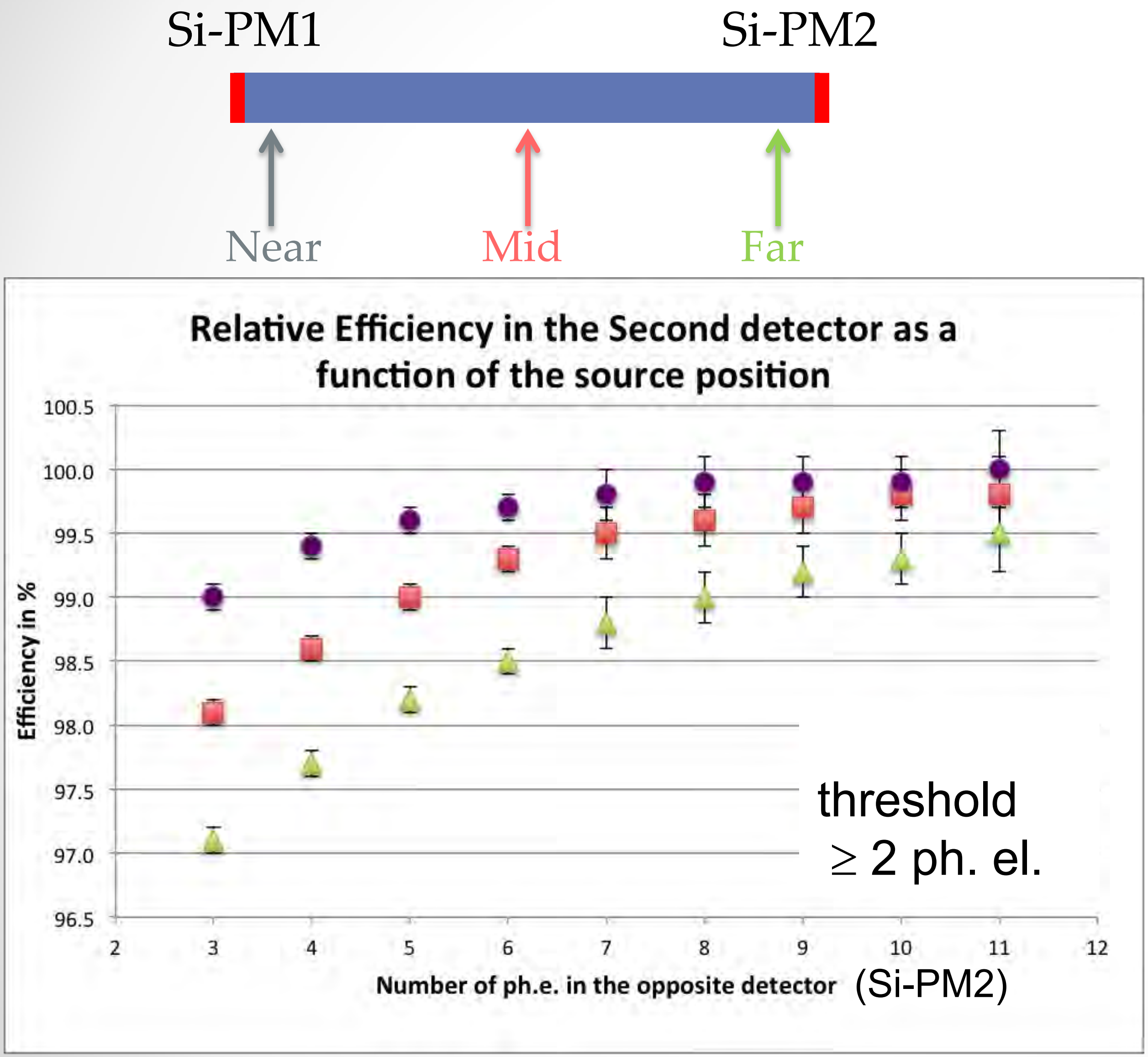


pedestal
(inefficiency !)

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

Efficiency



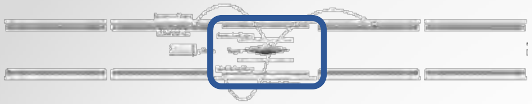


Small efficiency drop for source far from Si-PM

Vs. photons in opposite detector

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

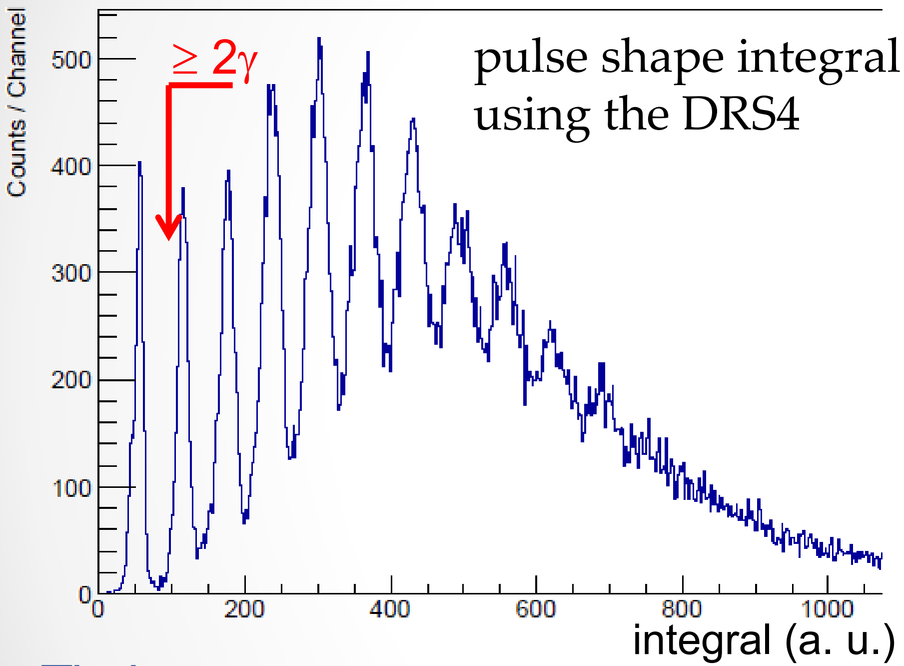
t.b.d. with 360 mm ribbons



Calibration

Calibrate in situ:

Alignment, energy (thresholds), timing



Energy:

Use ADC spectra

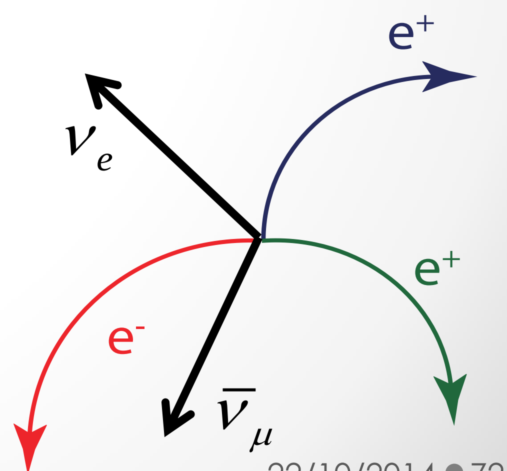
Distance between peaks

$\rightarrow$ Amplification

Set discriminator thresholds (> nγ)

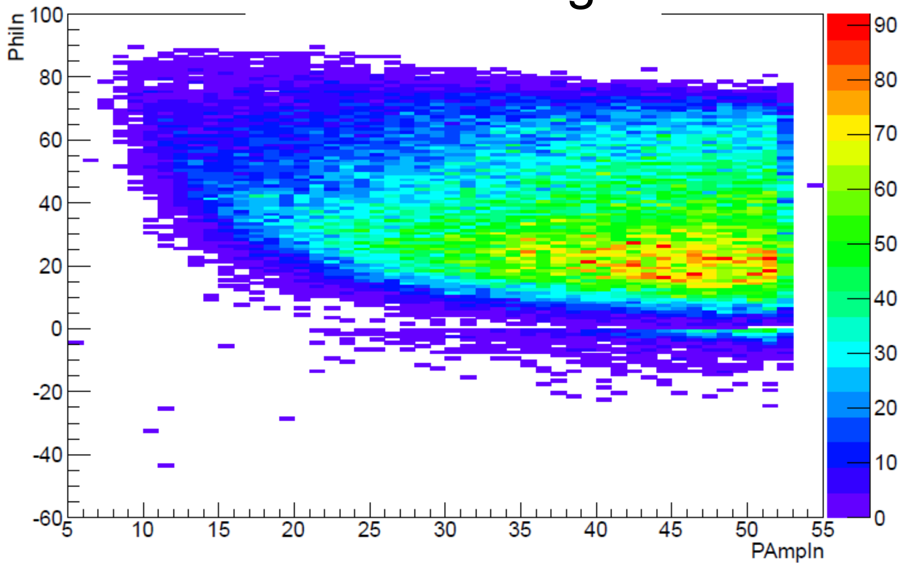
Timing:

- 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.

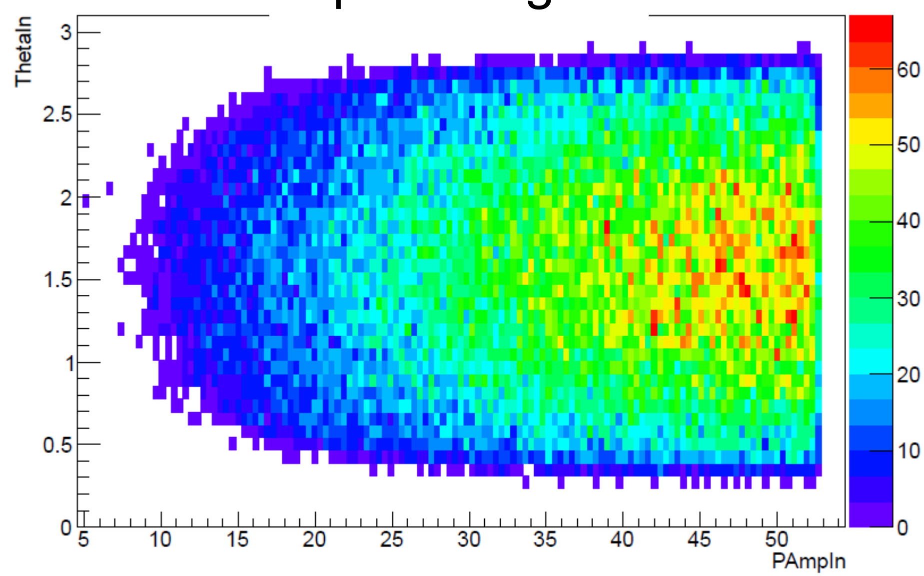


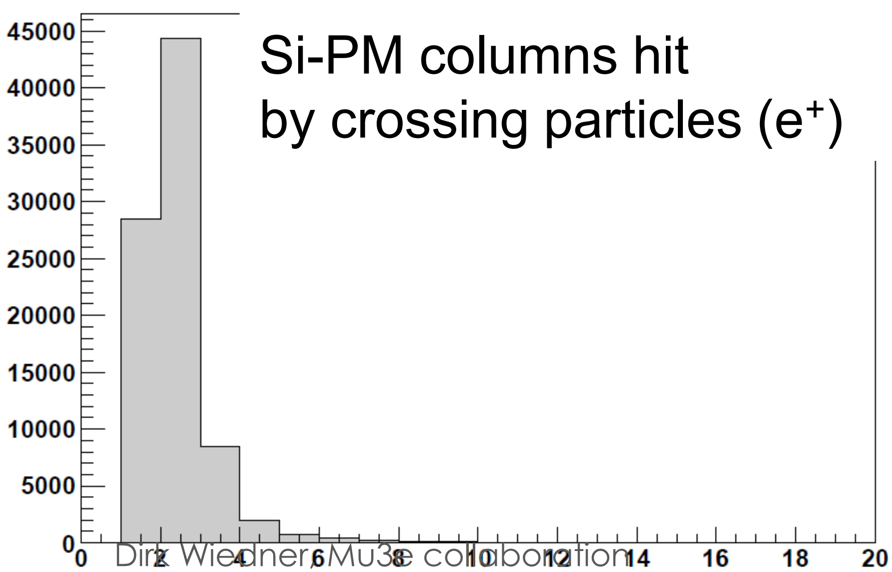
Crossing Angles

azimuthal angle



polar angle





occupancy :

ideal case : 100 kHz (PHASE I)
(1500 ch / 1.5×10^8 μ decays / s)

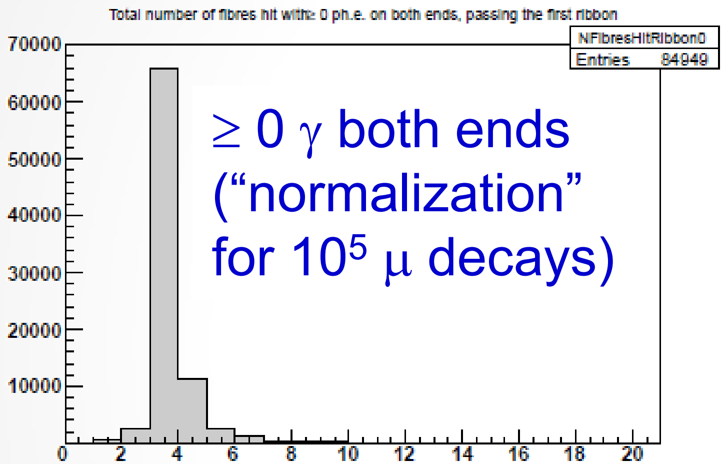
total # tracks $2.5 \times$ larger

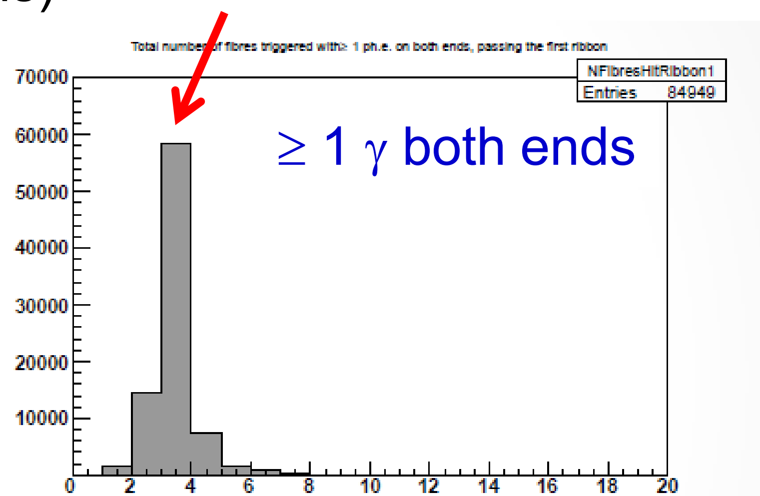
on average 2.5 Si-PM "columns" hit

estimated rate > 500 kHz

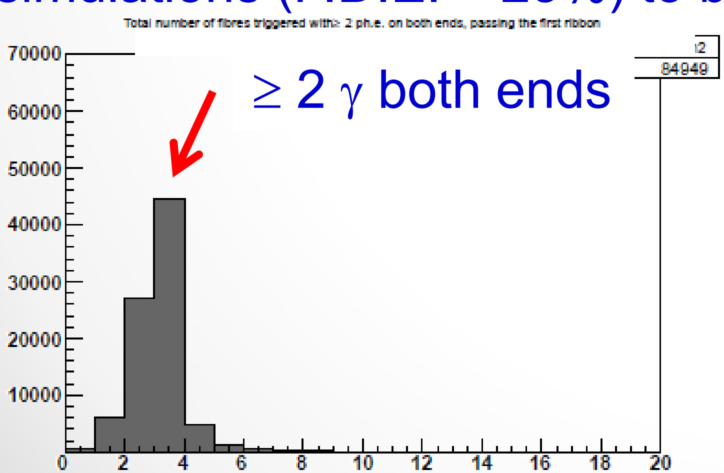
“Triggering”

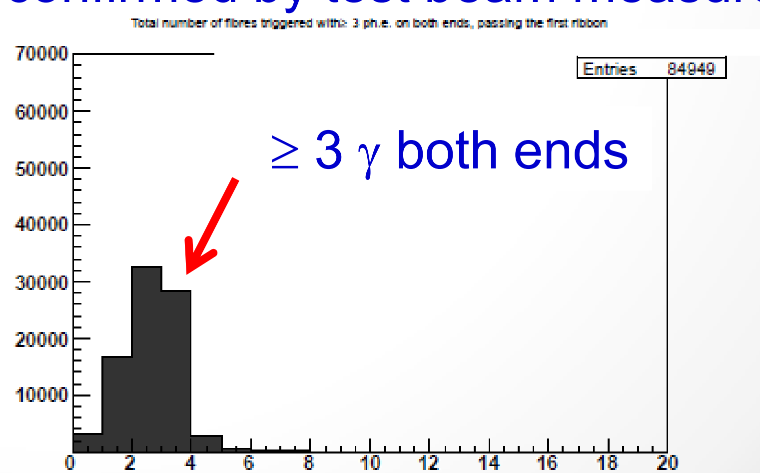
of fibers hit by a particle crossing the SciFi array (simulation)
as a function of detected photons at each fiber end
(assume 25% P. D. E. in simulations)





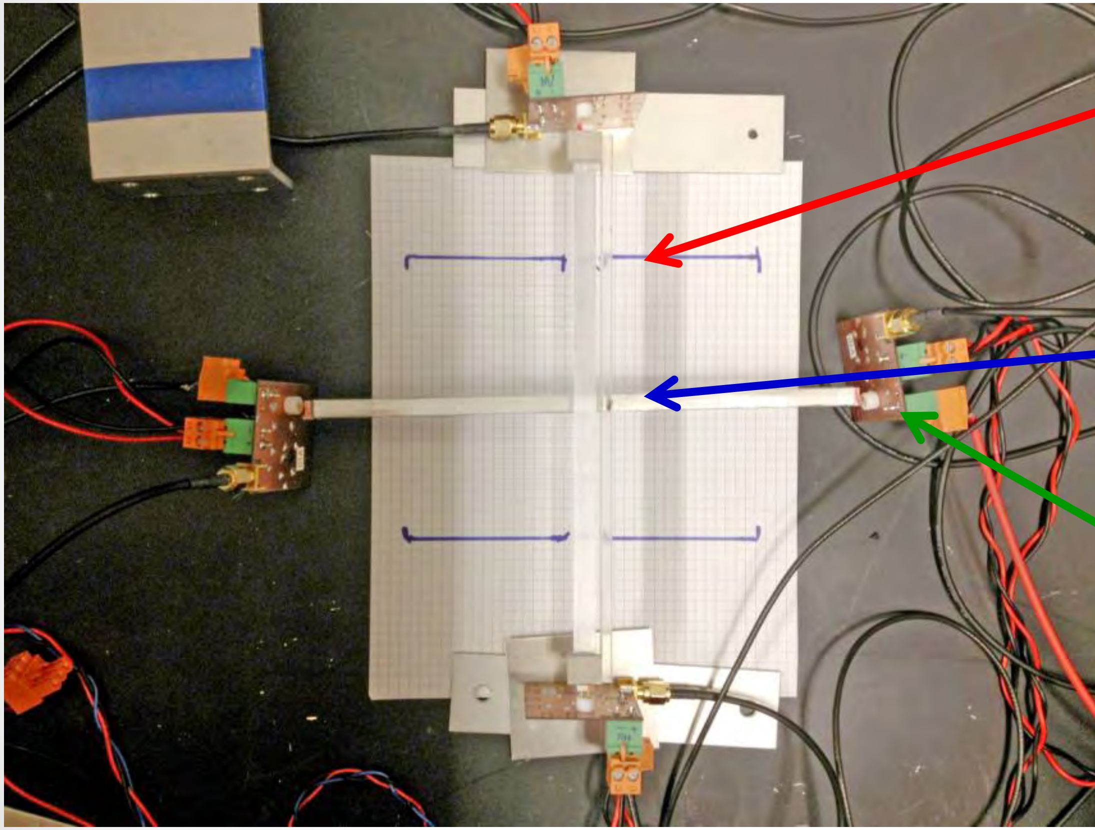
simulations (P.D.E. = 25%) to be confirmed by test beam measurements





Test Set-Up

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

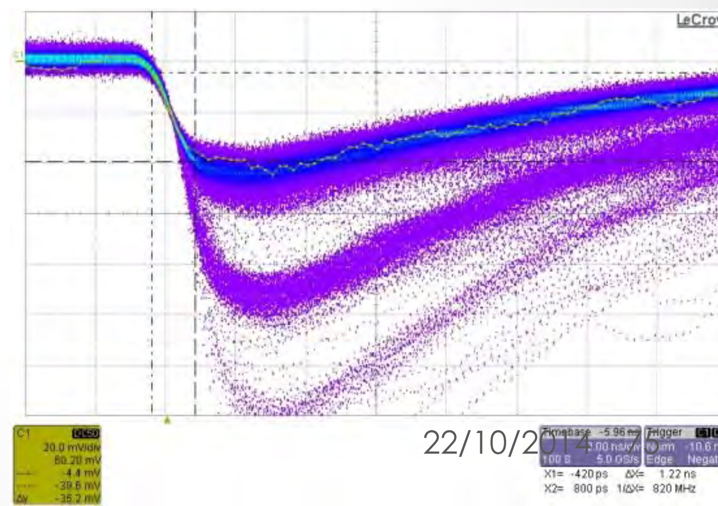


8 mm wide 200 mm long
3 layer SciFI ribbon

Readout with 3×3 mm² Si-PMs
Si-PMs glued on SciFi ribbon

Trigger scintillator:
- 6×6 mm² square bar
- Readout with same Si-PMs

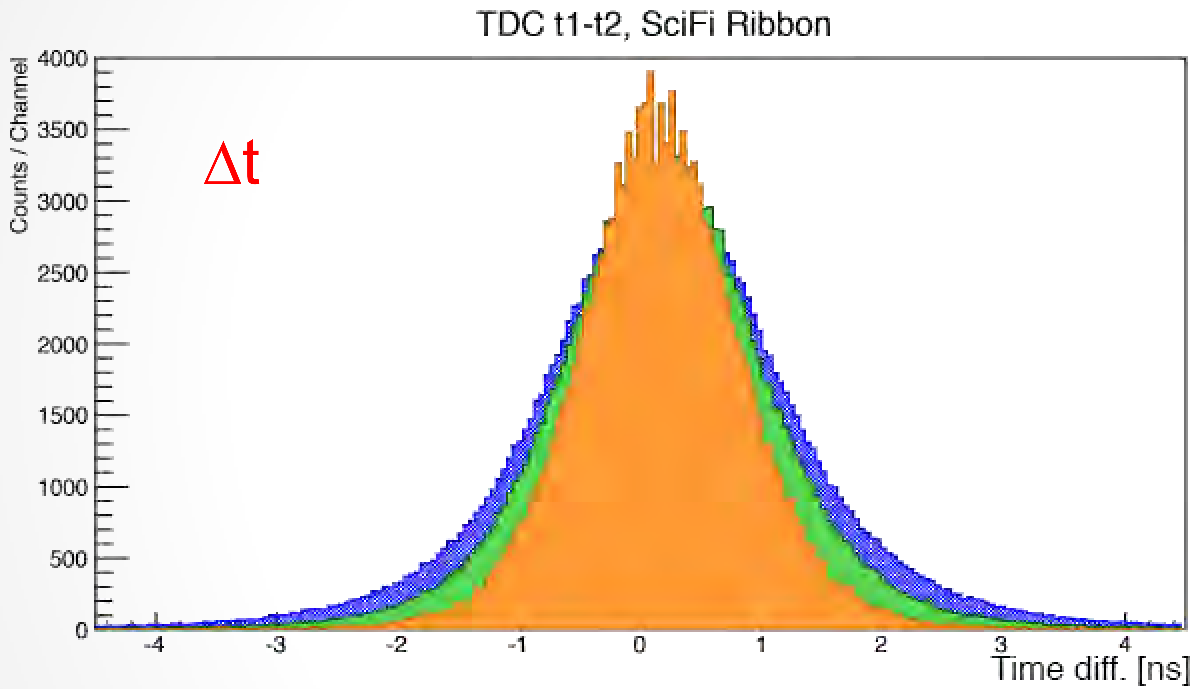
Fast (~1 ns) transistor based



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 : $\sigma_{MT} = \sigma / \sqrt{2} = \Delta t / 2$

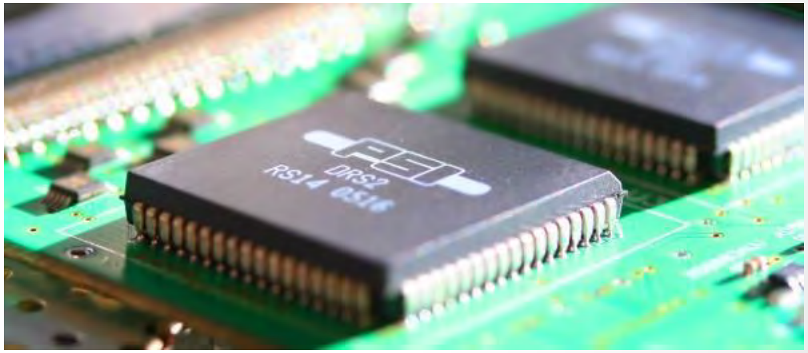
For same σ, i.e. similar # of detected photons on each side

Mean time does not depend on impact position

DRS5-Chip Readout

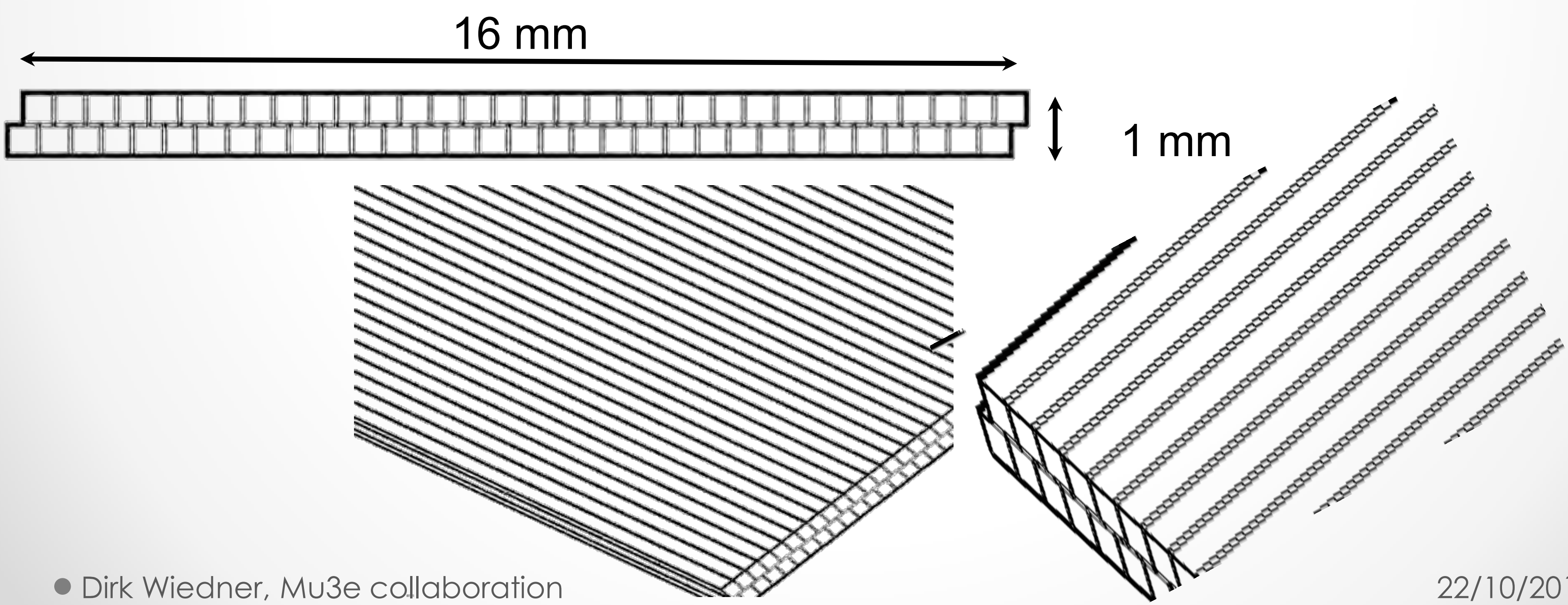
Alternative
To STiC

- Developed at PSI – successor to DRS4
- Currently in development
- Key features:
  - Sampling speed up to 10 GSPS
  - Bandwidth > 3 GHz
  - 8 (16?) channels
  - Dead-time less readout mode
  - Up to 5 MHz hit rate
- DRS4 successfully operated in test-beam



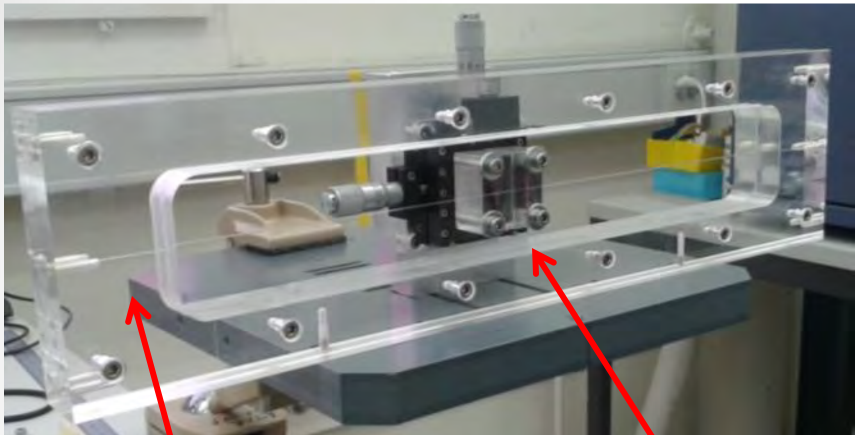
Alternative Design with Square Fibers

- 2 staggered layers of 500 μm square double cladding scint. fibers from Saint Gobain
  - BCF12: λ_{peak} ~435nm, τ_{decay}~3.2ns, L_{att} ~ 2.7 m / BCF20: λ_{peak} ~492nm, τ_{decay}~2.7ns, L_{att} > 3.5 m
- 32 fibers/layer
- **OR** 250 μm square double cladding scint. fibers
- Single fiber Al coating (minimum / negligible "optical" cross-talk)
- To reduce thickness and occupancy thinner fibers would be required



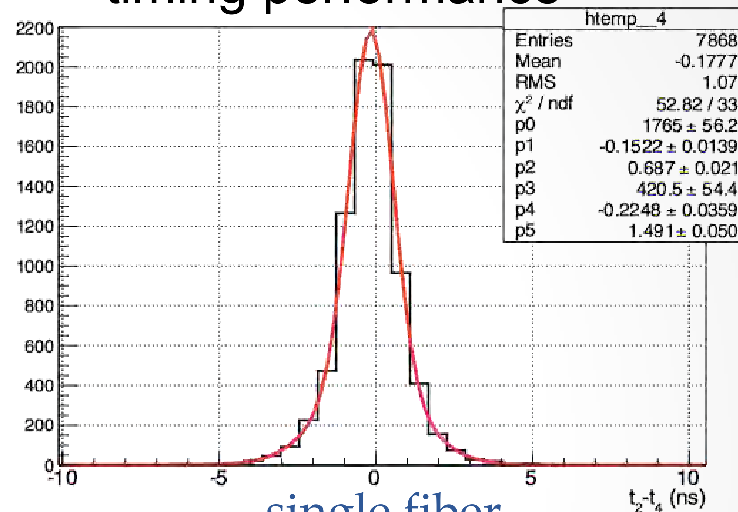
Testing Square Fibers

Fiber test setup developed at PSI



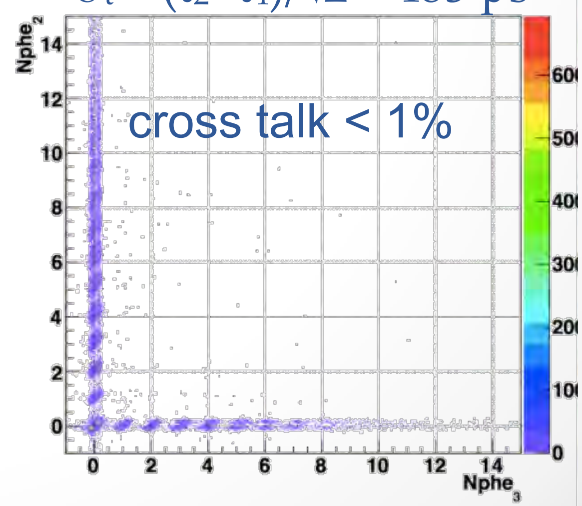
500 μm square fiber β source

timing performance



single fiber

$\sigma_t = (t_2 - t_4)/\sqrt{2} \sim 485$ ps



Cross talk:

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

Conclusions SciFi

- Timing requirements (resolution < 1 ns) fulfilled
  - in lab with β source (resolution < 500 ps)

- Good agreement between simulations and measurements
  - light propagation

- Further characterizations ongoing or planned
  - β 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

- About 6 months to complete detector studies

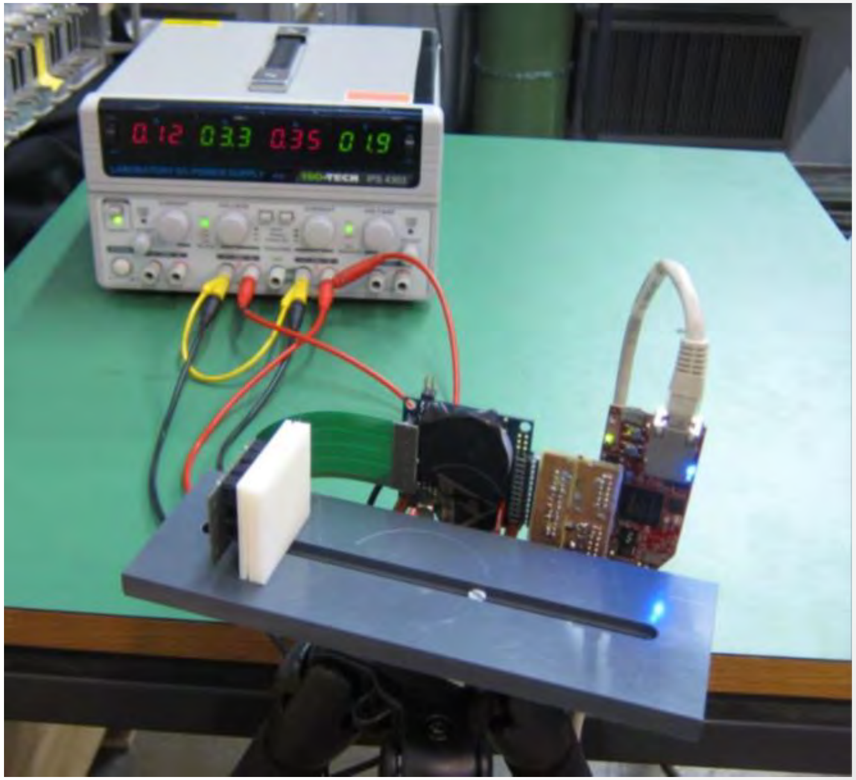
→ 6 more months to finalize design

→ construction of detector about 6 months

Tile Detector Backup

Tile Detector

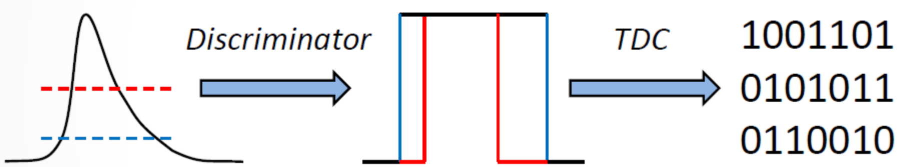
- Scintillating tiles
    - 8.5 x 7.5 x 5 mm^3
- 12 Tile Modules per station
    - 192 tiles/module
    - Attached to end rings
- SiPMs attached to tiles
    - Front end PCBs below
    - Readout through STiC



Tile detector 4 x 4 prototype

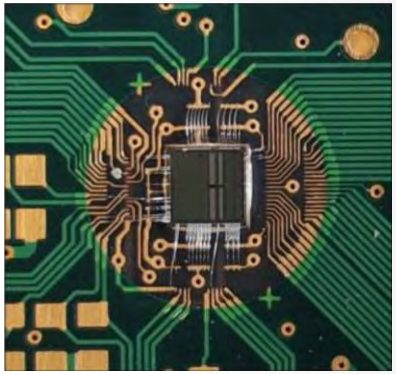
STiC Readout

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

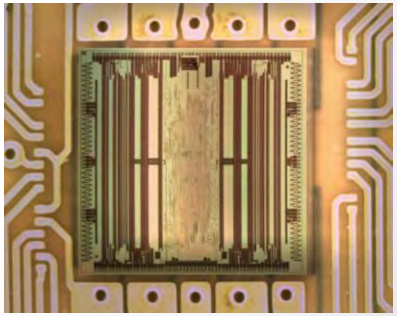


  - 64 channels (version 3.0)
  - 50 ps TDC bins
  - SiPM bias tuning
  - SiPM tail cancelation possibility (version 3.0)
  - Currently ≈ 1 MHz hit rate / chip
  - Up to ≈ 20 MHz in future version
- Version 2.0 successfully operated in test-beam

STiC 2.0



STiC 3.0



STiC Readout

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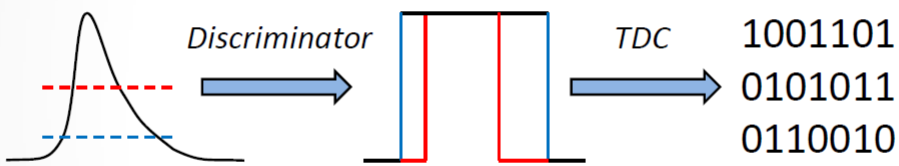

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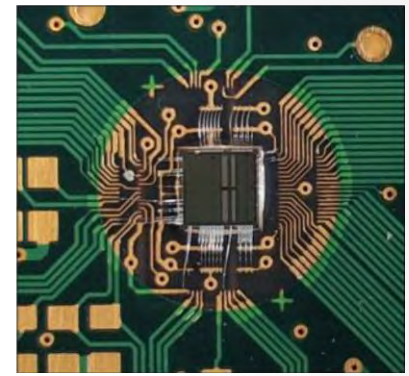

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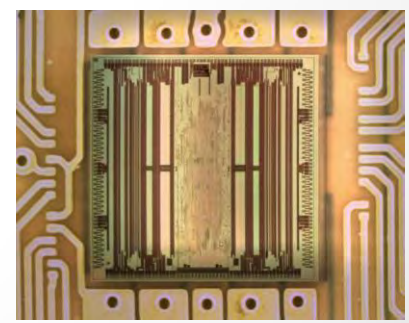
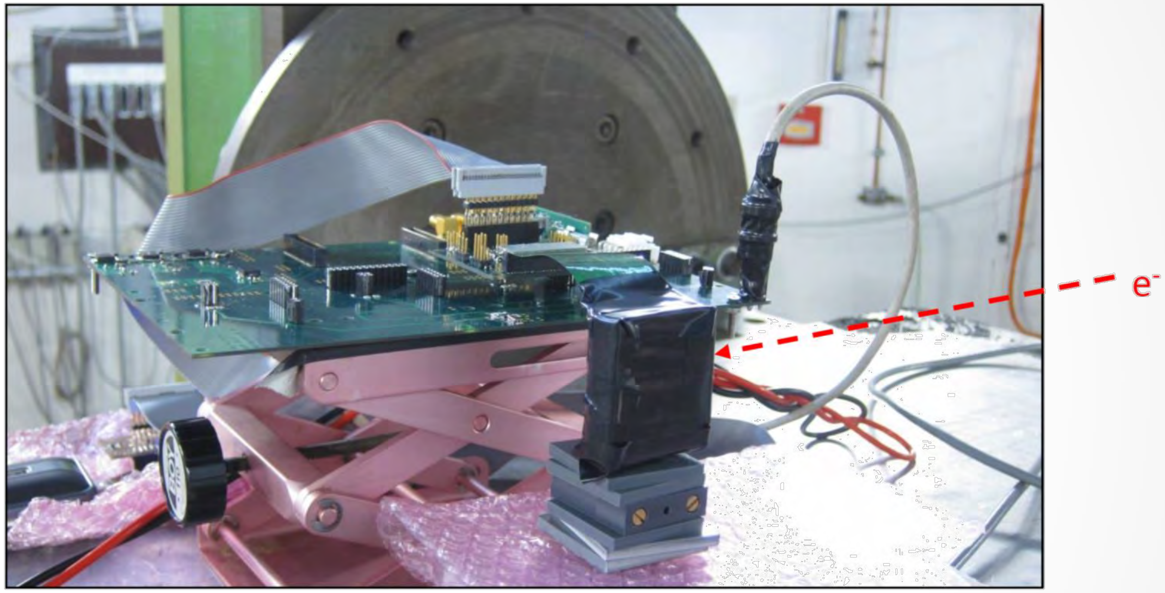


STiC Test Beam



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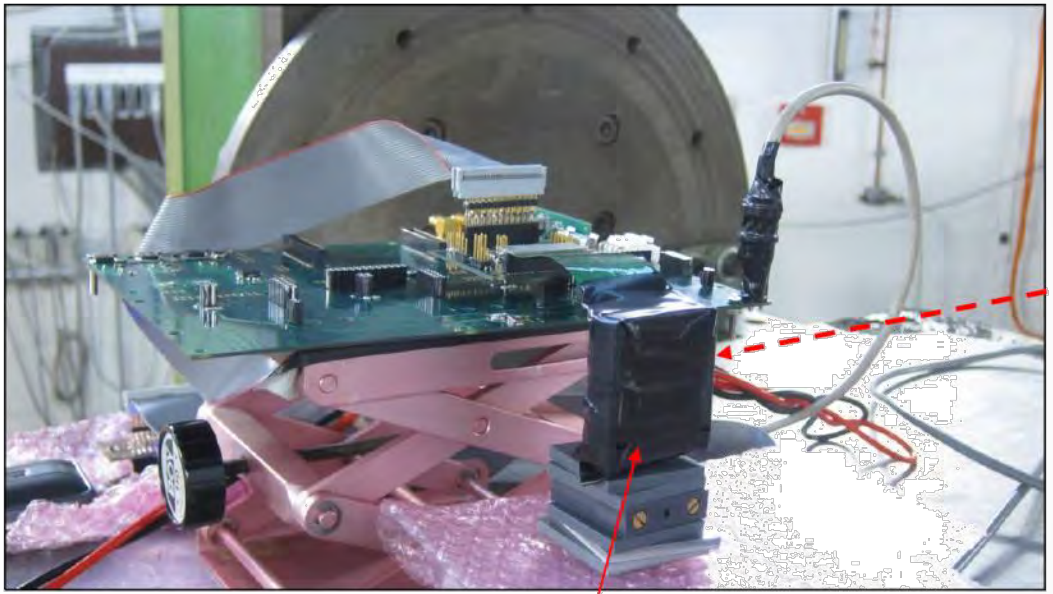
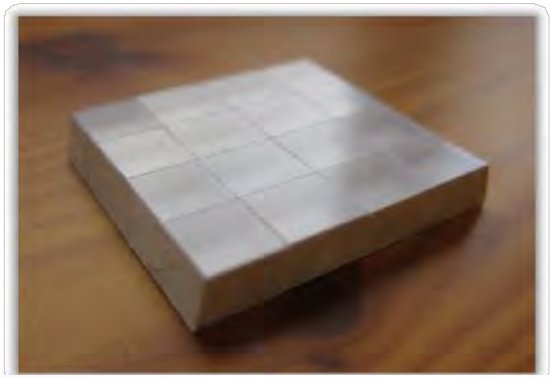
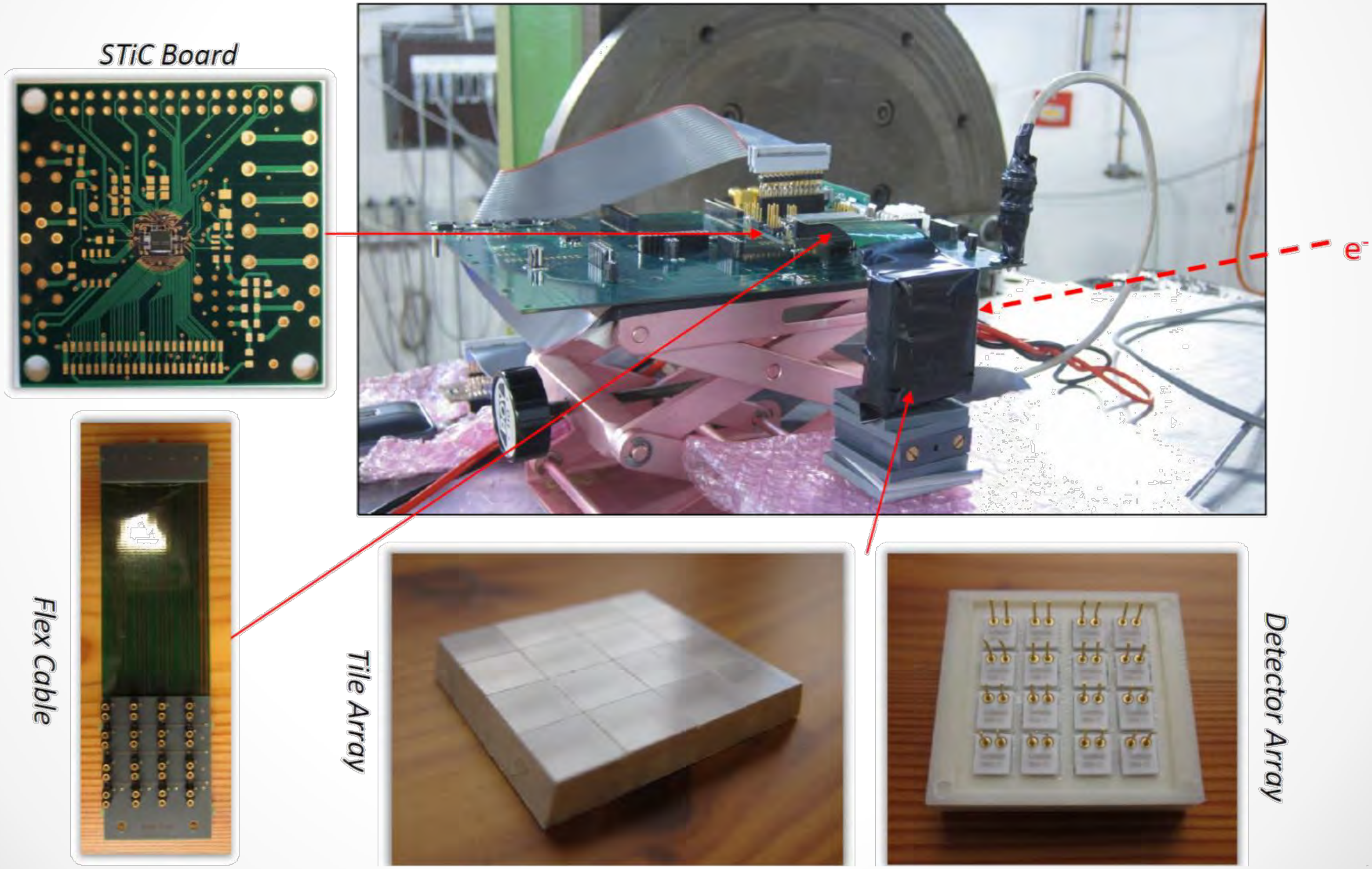


Tile Array



Detector Array

STiC Test Beam



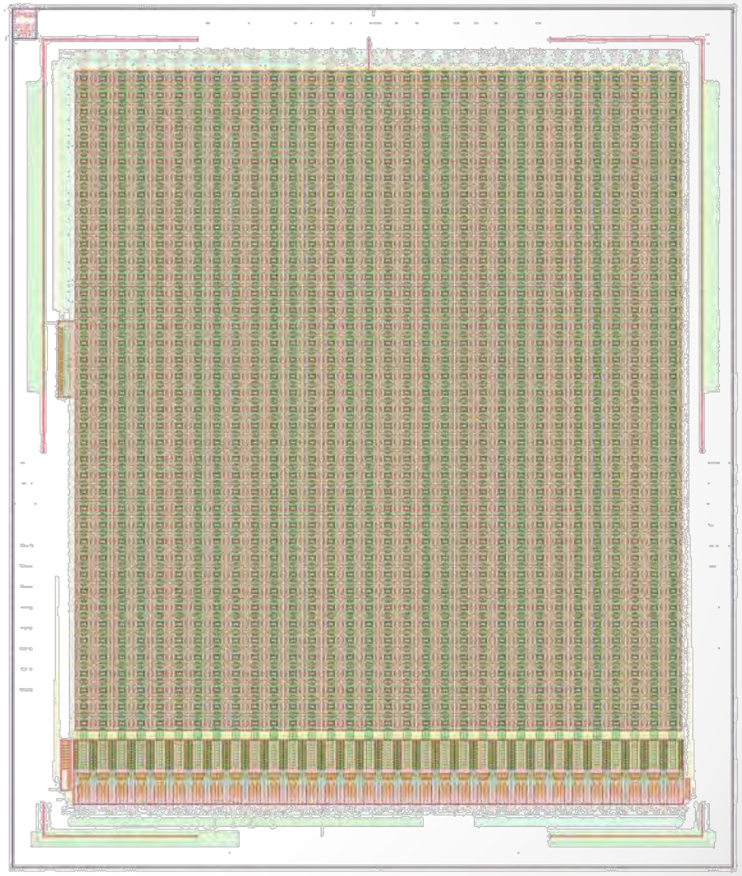
HV-MAPS Backup

…

Chip Prototypes

MuPix3

- 180 nm HV-CMOS
- Pixel matrix:
  - 40 x 32 pixels
  - 92 x 80 μm^2 each
- Ivan Perić ZITI
  - Analog part almost final
  - Digital part under development
  - Bug in pixel on/off



Chip Prototypes

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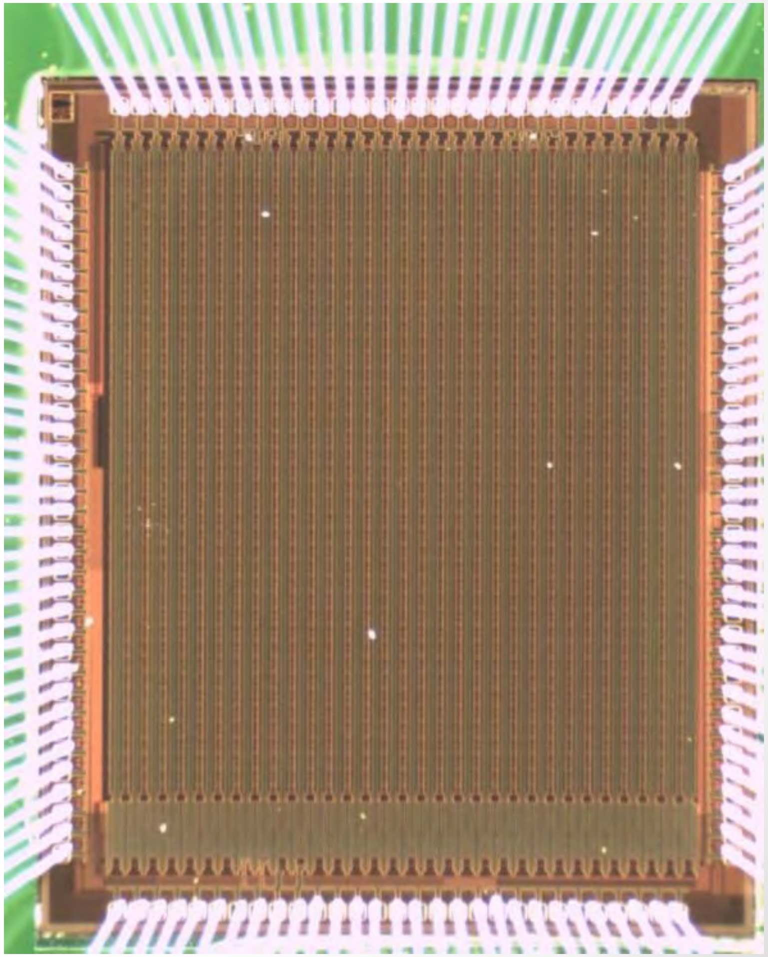
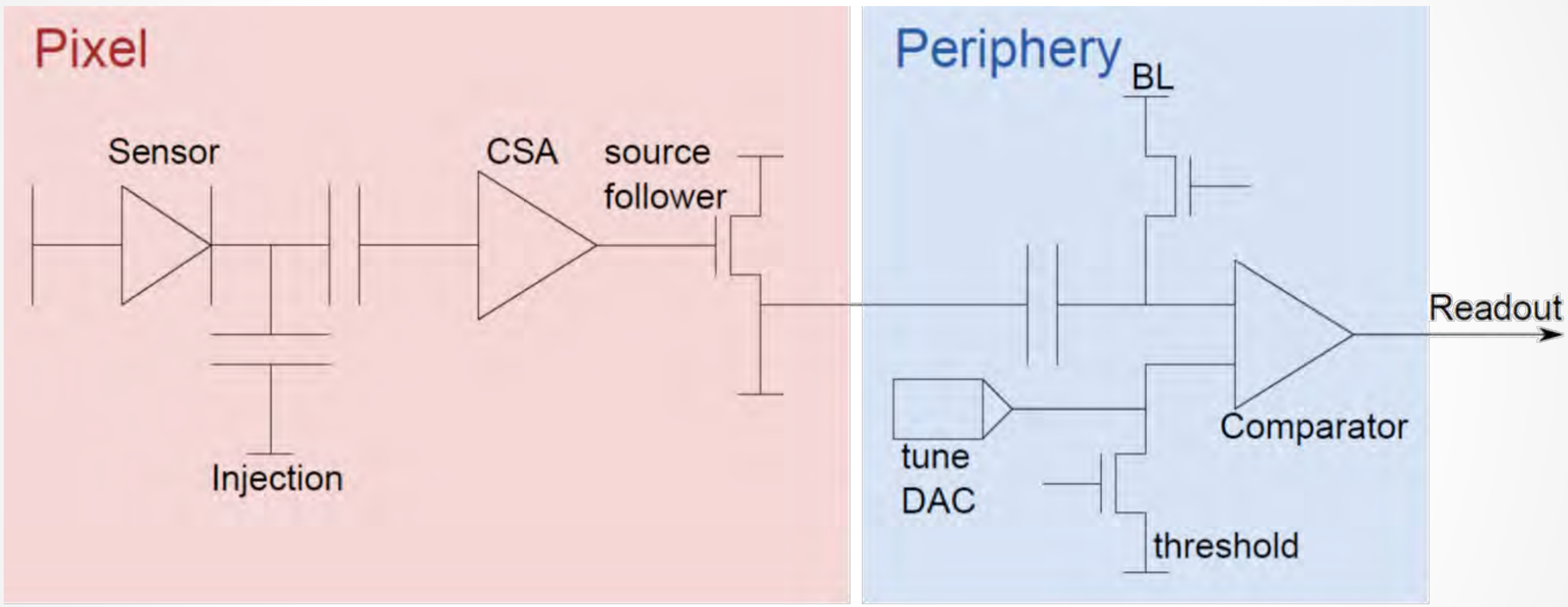


Prototype Overview

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	First working digital readout, **first timestamp**, temperature stable
MuPix6	10.55 mm^2	Sensor, analog, dig.	?	Removed zero time-stamp and address bug

Sensor + Analog + Digital



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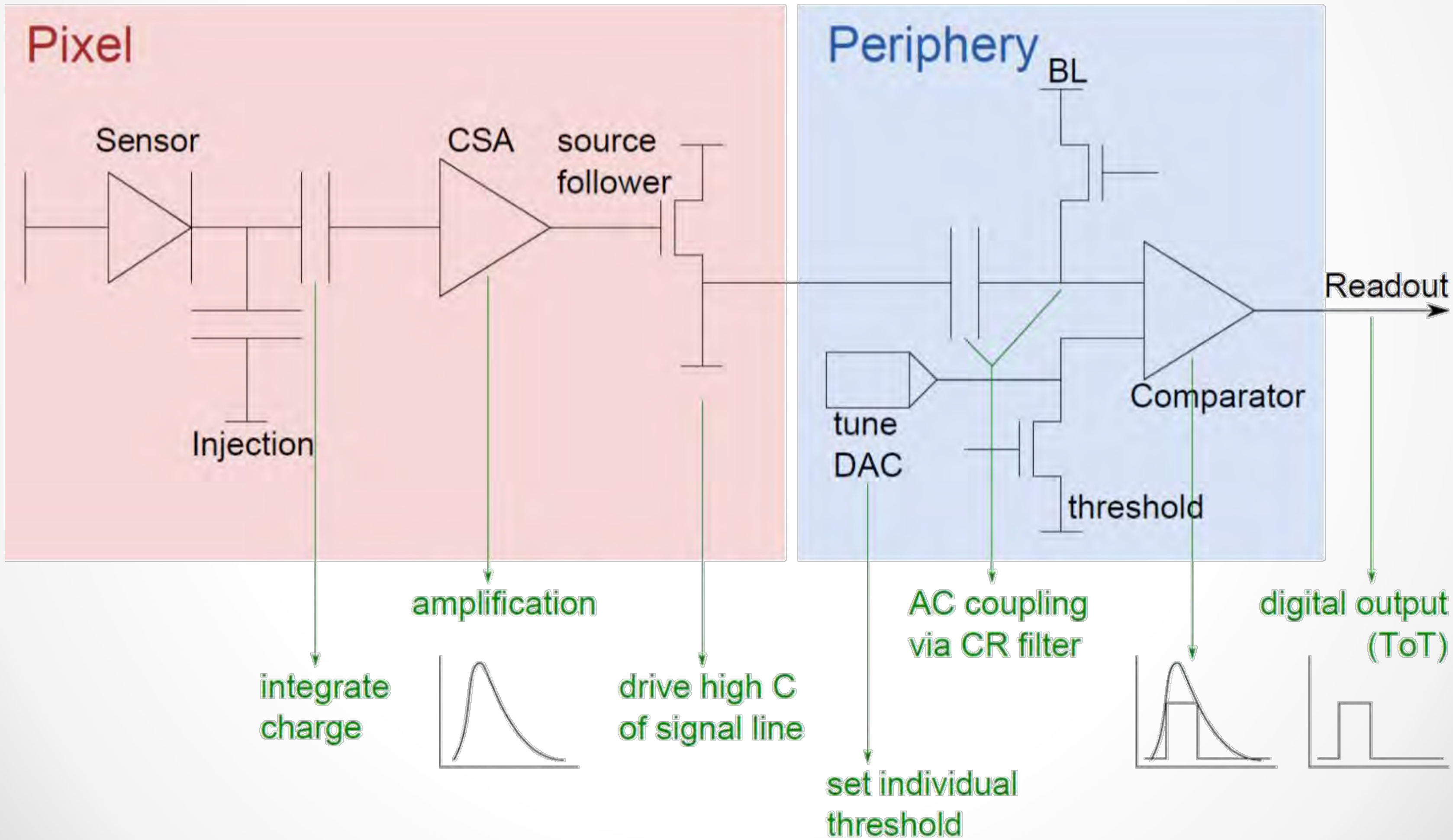
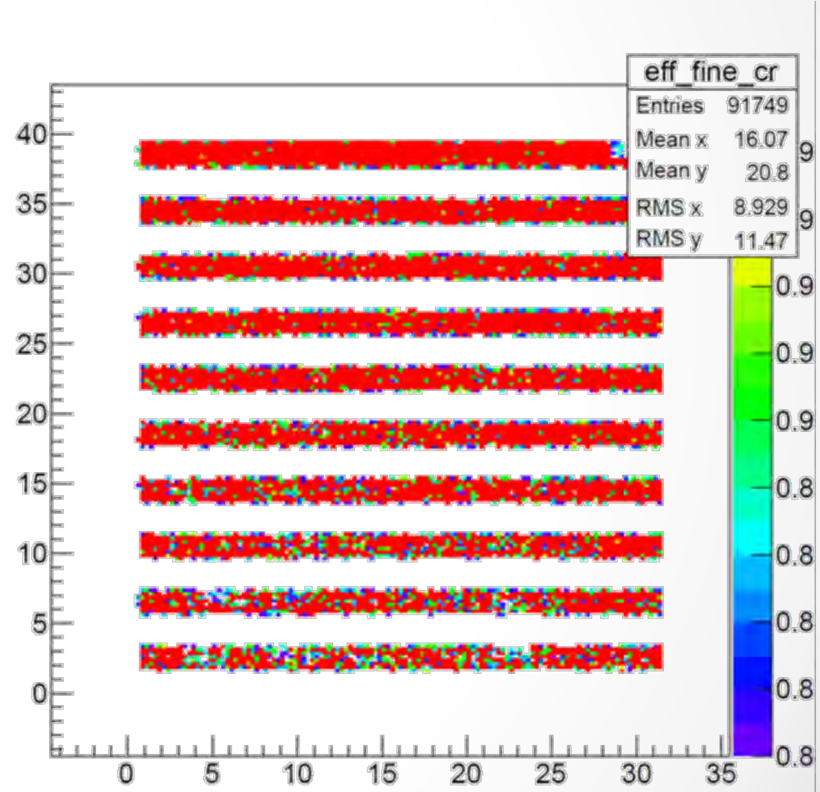


Digital Readout Feature

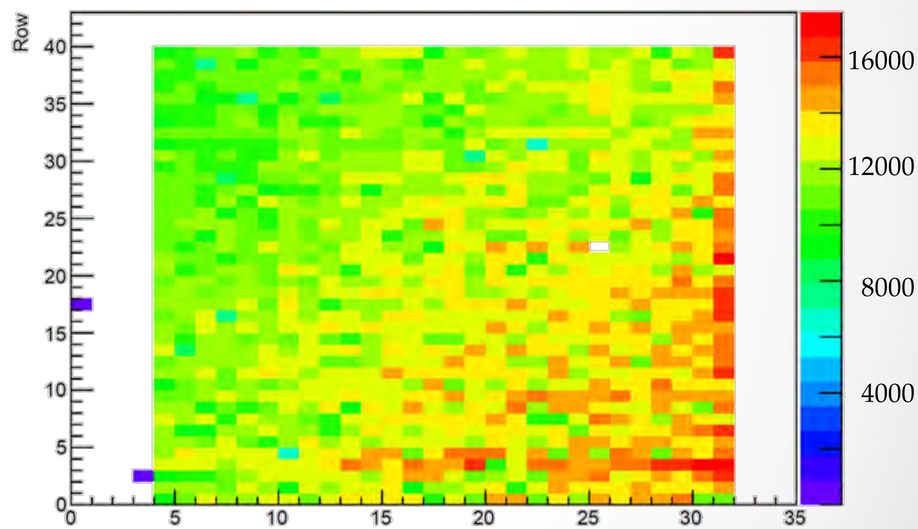
- Artifact from readout protocol:
  - Pixel RAM-cells reset before readout
  - ➢ Bug effects only row address and time stamp
  - ➢ 50% of pixels effected
  - ➢ Pixel efficiency also good for affected rows



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 for MuPix6**

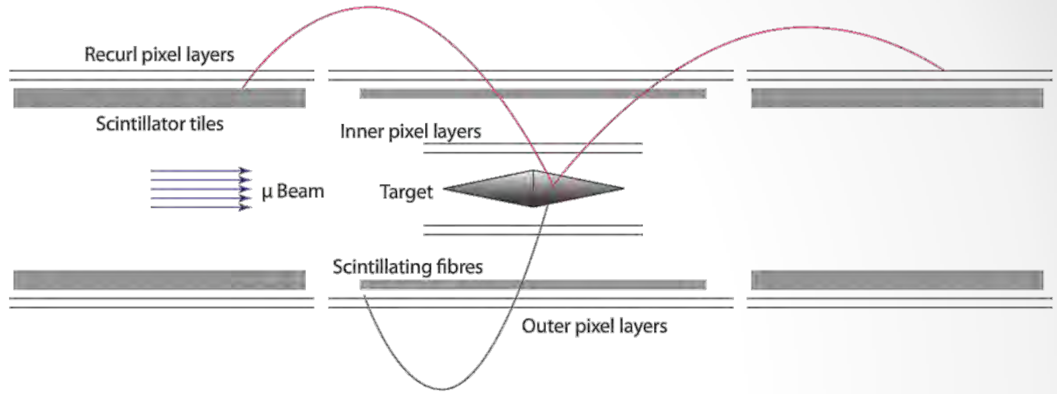


Hitmap for MuPix6

Mechanics Backup

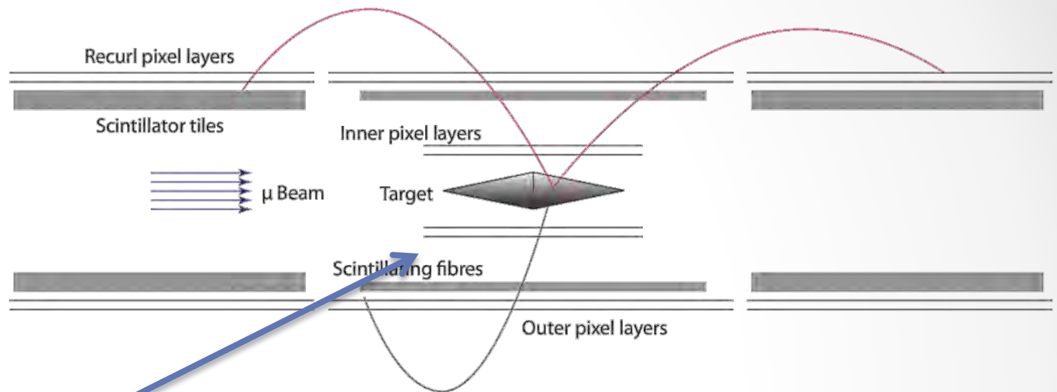
• • •

Mu3e Silicon Detector



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

Mu3e Silicon Detector



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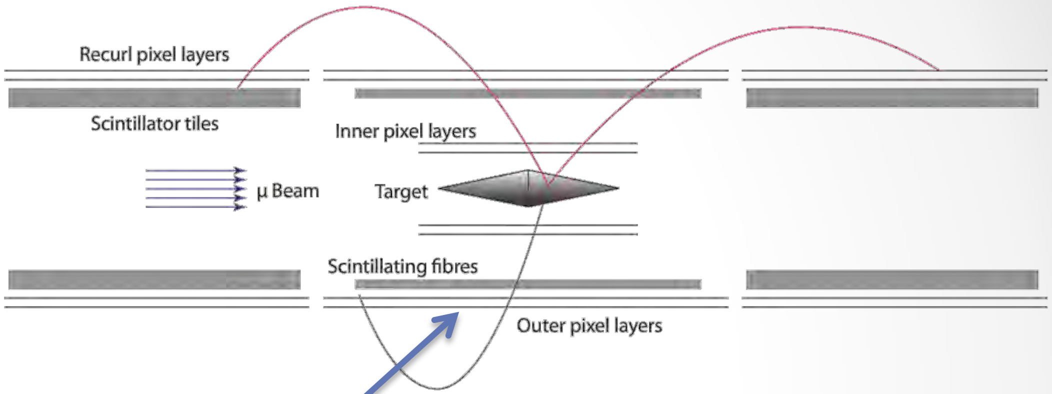

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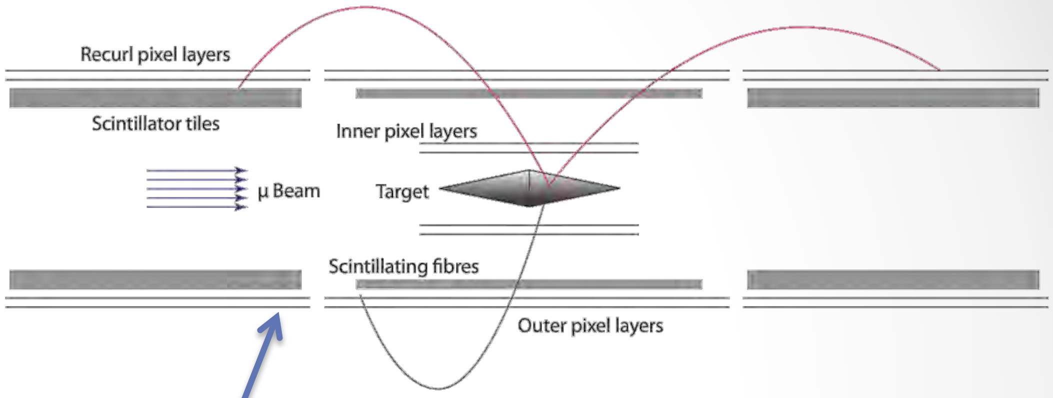
Mu3e Silicon Detector



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  - 12 and 18 sides of 1 x 12 cm
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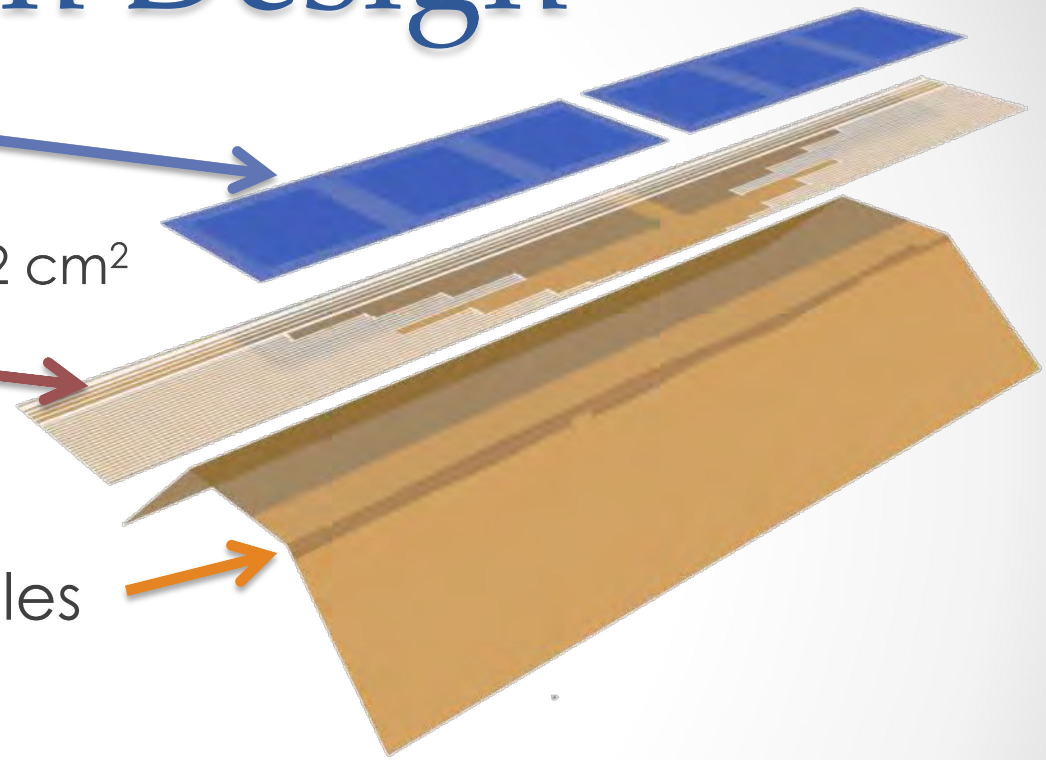
  - 24 and 28 sides of 2 x 36 cm
- Re-curl layers
  - 24 and 28 sides of 2x 72 cm
  - Both sides (x2)

180 inner sensors
4680 outer sensors
➢ 274 752 000 pixel

Sandwich Design

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm^2 or 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 1 x 2 cm^2 or 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
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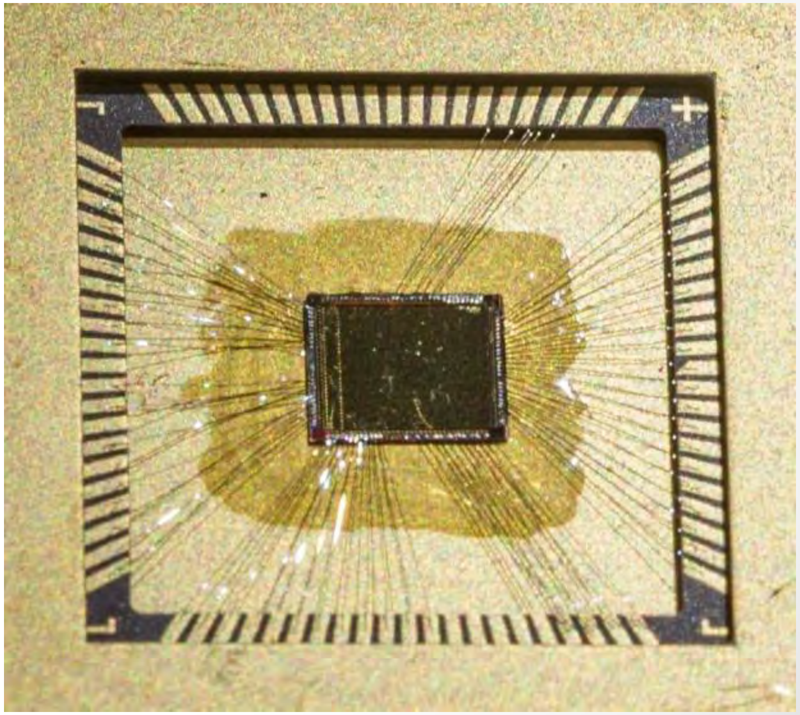
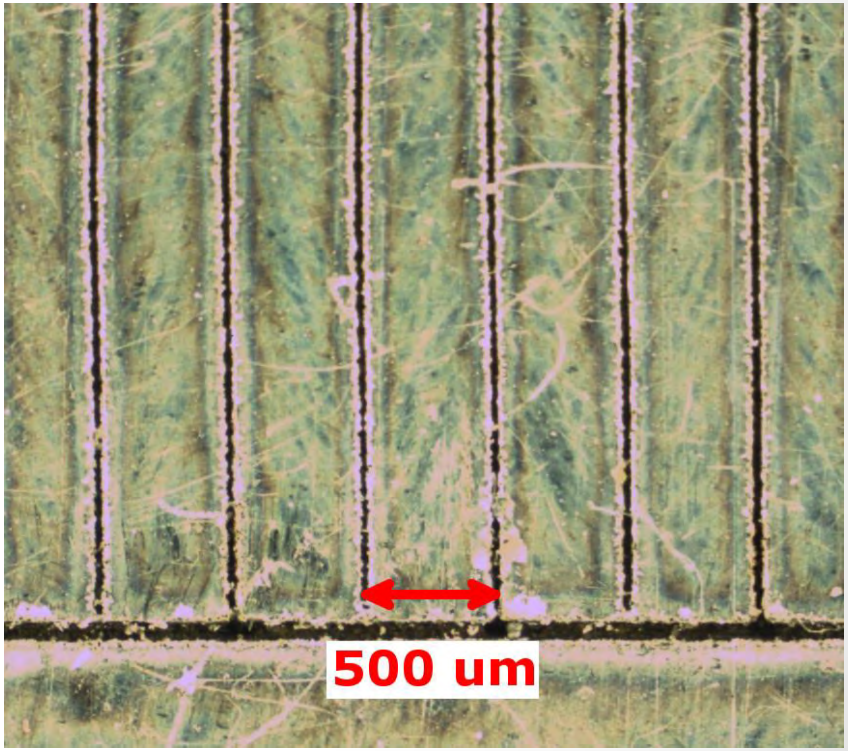
  - Support for all detectors



MuPix3 thinned to < 90µm

Kapton™ Flex Print

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm² or 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



Laser-cut flex print prototype

Pixel Modules

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm² or 2 x 2 cm²
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - Self supporting
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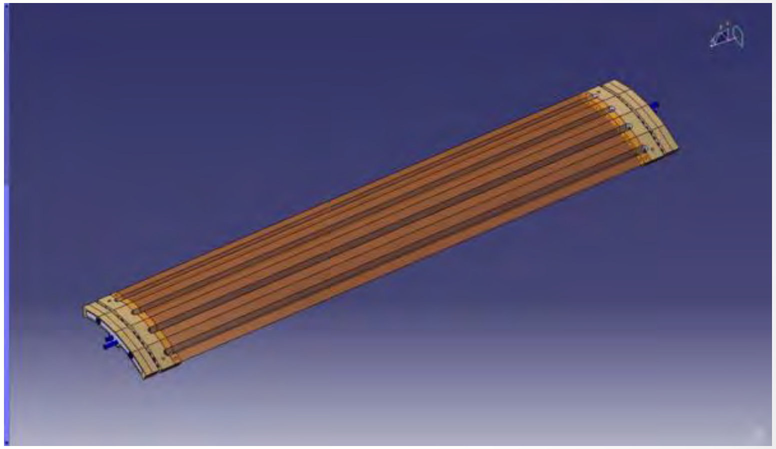
  - Support for all detectors

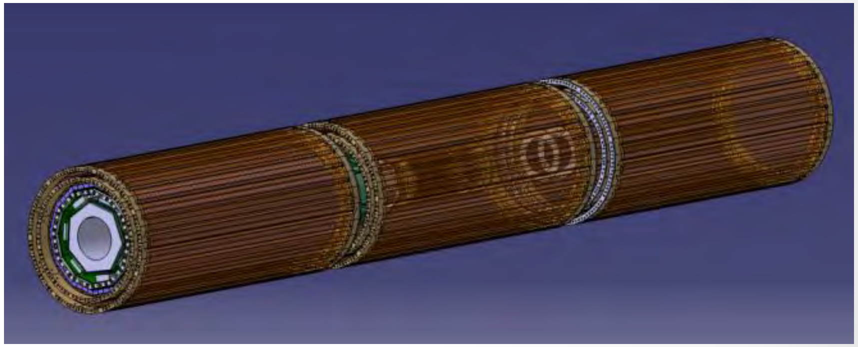


CAD of Kapton™ frames

Overall Design

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm^2 or 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

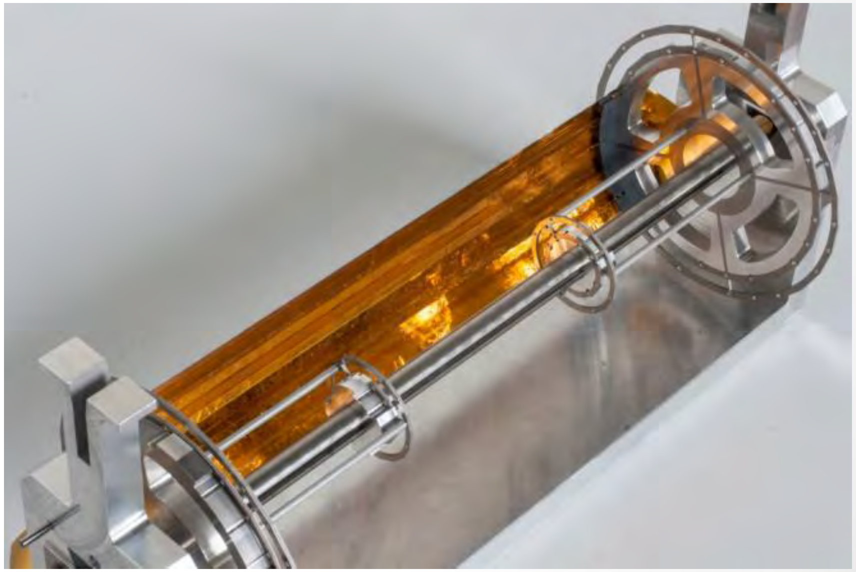
Inner Layers

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm² or 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

Vertex Prototype
with 100 µm Glass

Outer Module

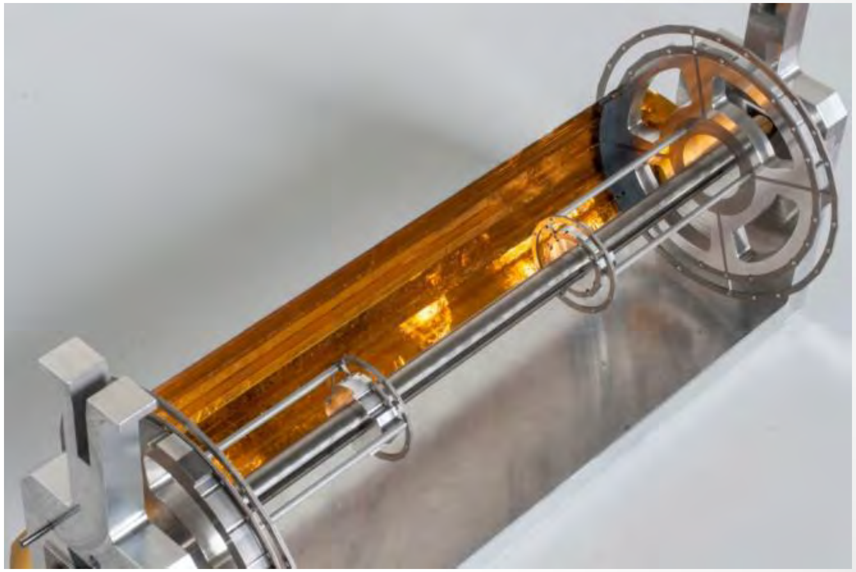
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm^2 or 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors



Layer 3 Prototype in Assembling Frame with 50 µm Glass

Detector Frame

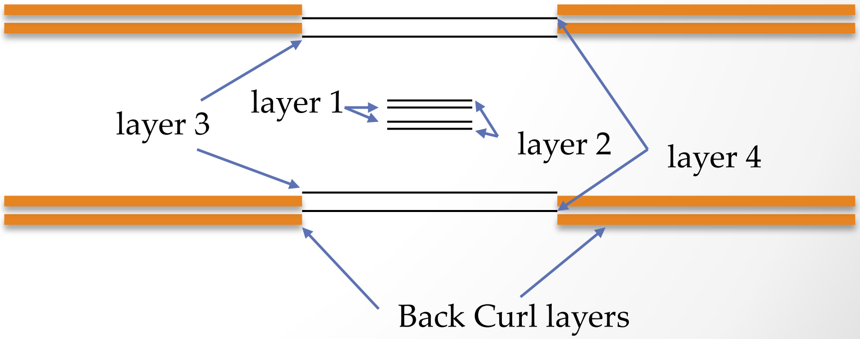
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm^2 or 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 12.5 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- **Alu end wheels**
  - Support for all detectors



Layer 3 Prototype in Assembling Frame with 50 µm Glass

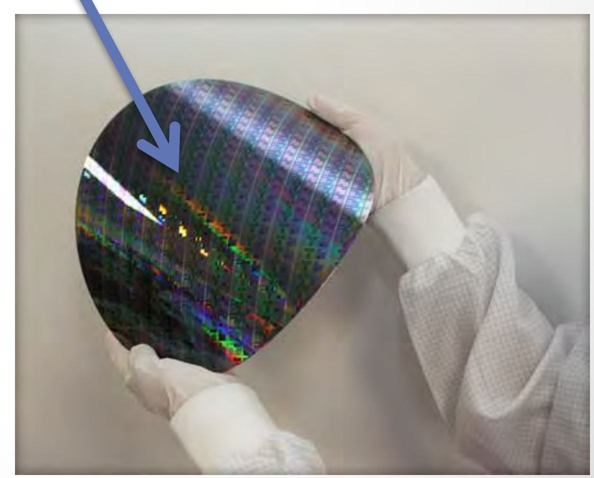
Si-Layer Rad Length

- Radiation length per layer
  - 2x 25 µm Kapton
    - X_0= 0.175‰
  - 15 µm thick aluminum traces (50% coverage)
    - X_0= 0.0842‰
  - 50 µm Si MAPS
    - X_0= 0.534‰
  - 10 µm adhesive
    - X_0= 0.0286‰
- Sum: 0.822‰ (x4 layers)
  - For Θ_{min} = 22.9°
  - X_0= 2.11‰



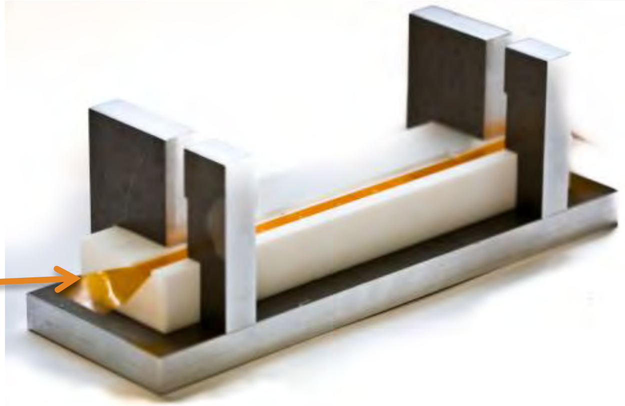
Thinning

- 50 µm Si-wafers
  - Commercially available
  - HV-CMOS 50 µm (AMS)
  - 50 µm for MuPix4
- 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

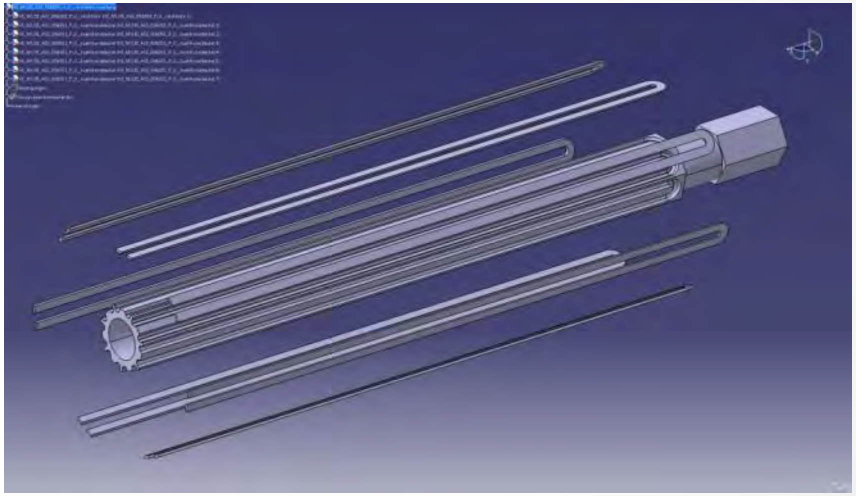


Cooling Backup

…

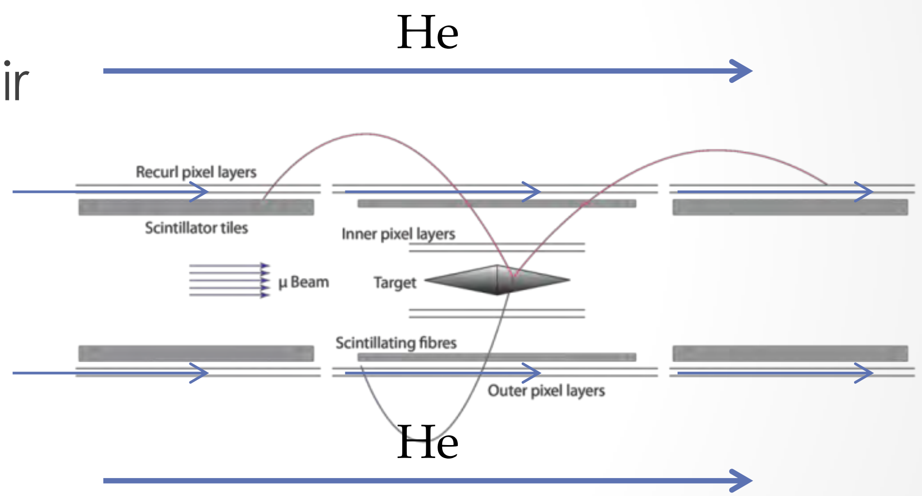
Liquid Cooling

- Beam pipe cooling
  - With cooling liquid
  - 5°C temperature
  - Significant flow possible
  - … using grooves in pipe
- For electronics
  - FPGAs and
  - 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 to Frame
    - V-shapes
    - Outer surface



$150\text{mW/cm}^2 \times 19080\text{cm}^2$
$= 2.86$ KW

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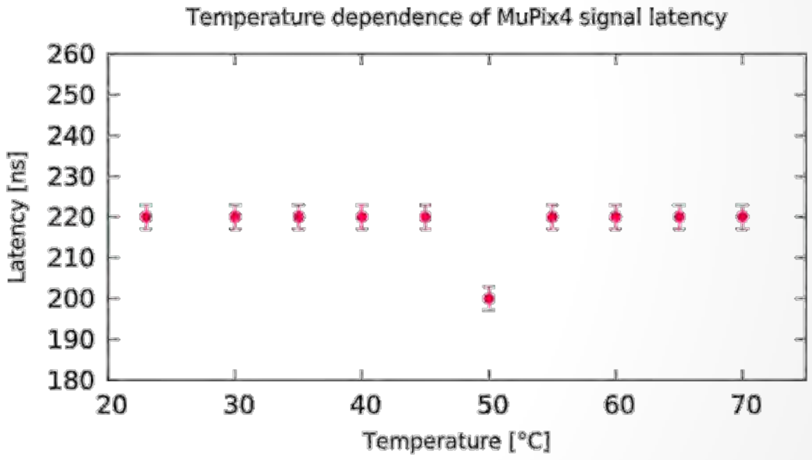

Temperatures between 20°C to 70°C ok.

He Cooling

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- **Local flow for Tracker**
  - Distribution to Frame
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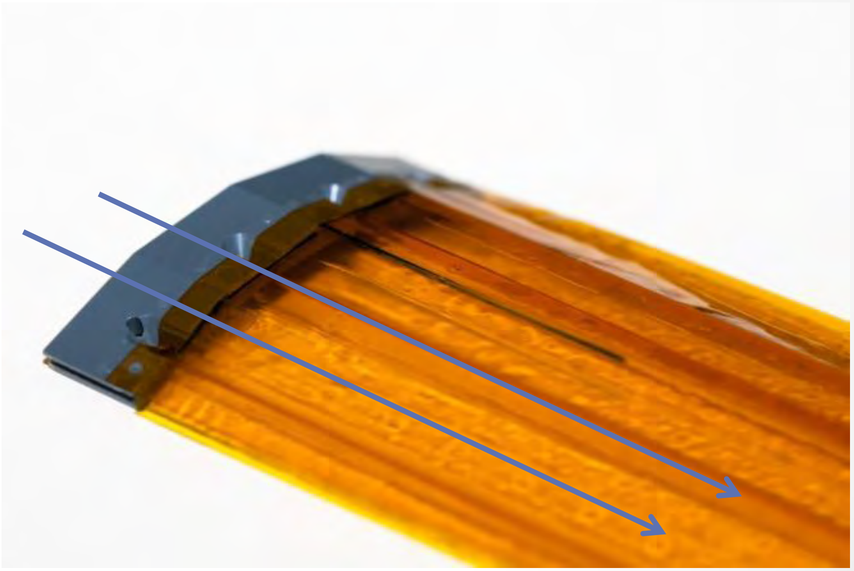

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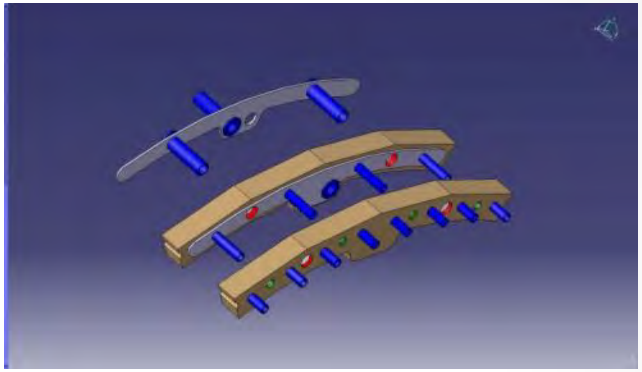

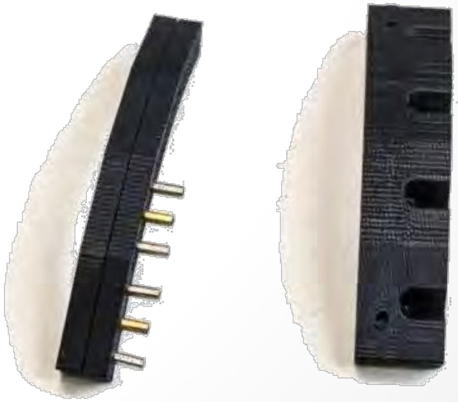

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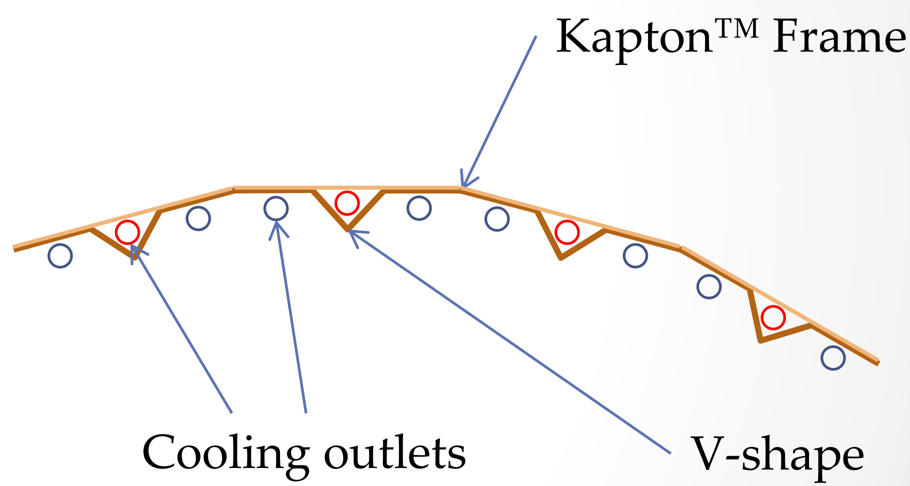
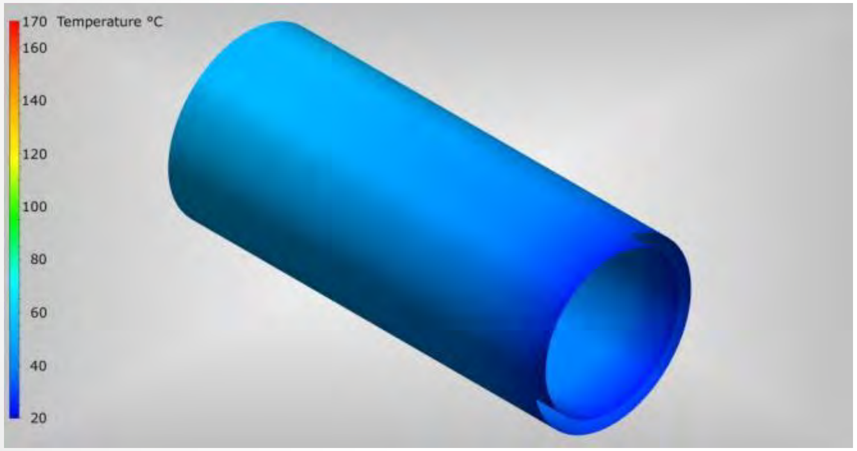
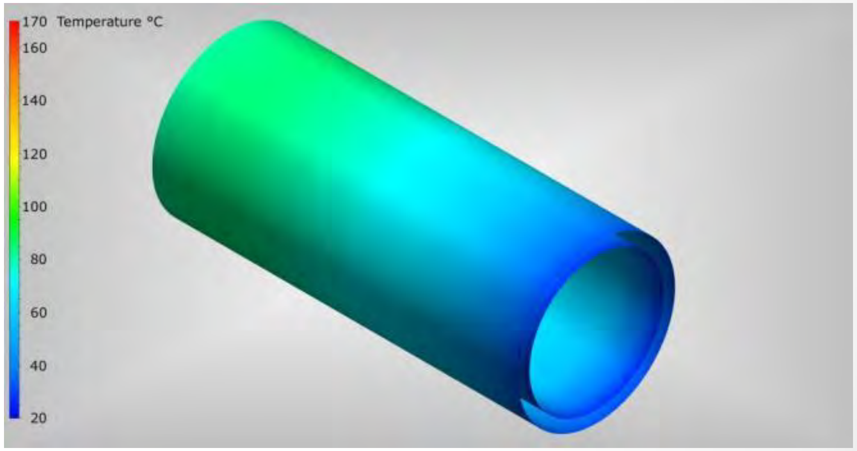


Comparison Simulation He and Air

He | Air

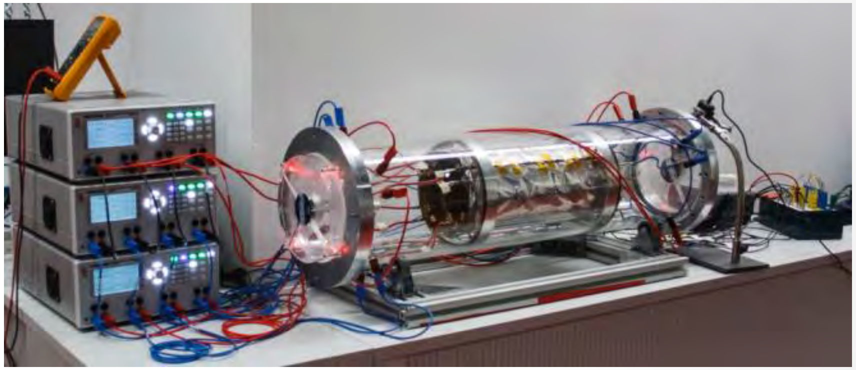




$$v = 4.0\ ^{m}/_{s}$$

Tests

- **Full scale prototype**
  - Layer 3+4 of silicon tracker
  - Ohmic heating (150mW/cm^2)
  - 561.6 W for layer 3 +4
  - … of Aluminum-Kapton™
- Cooling with external fan
  - **Air** at several m/s



- Temperature sensors attached to foil
  - LabView readout
- First results promising
  - $\Delta T < 60°K$

Tests

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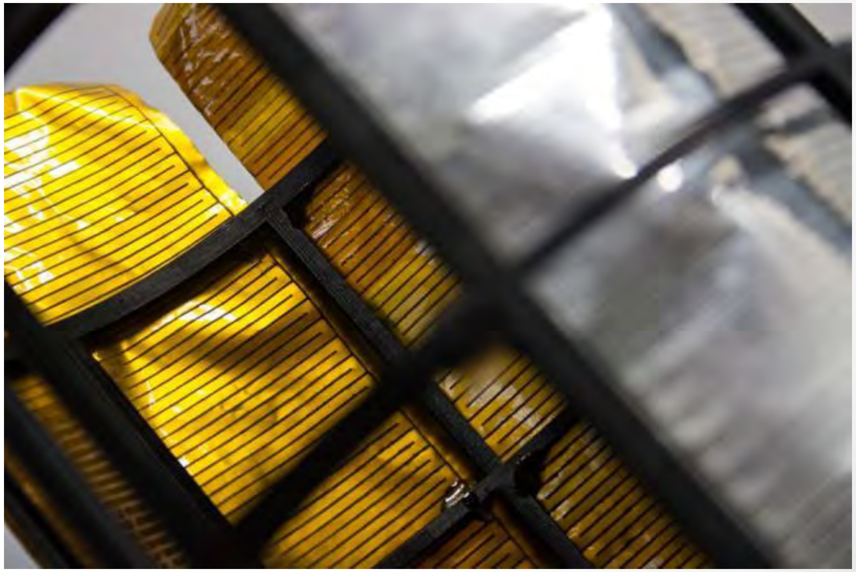
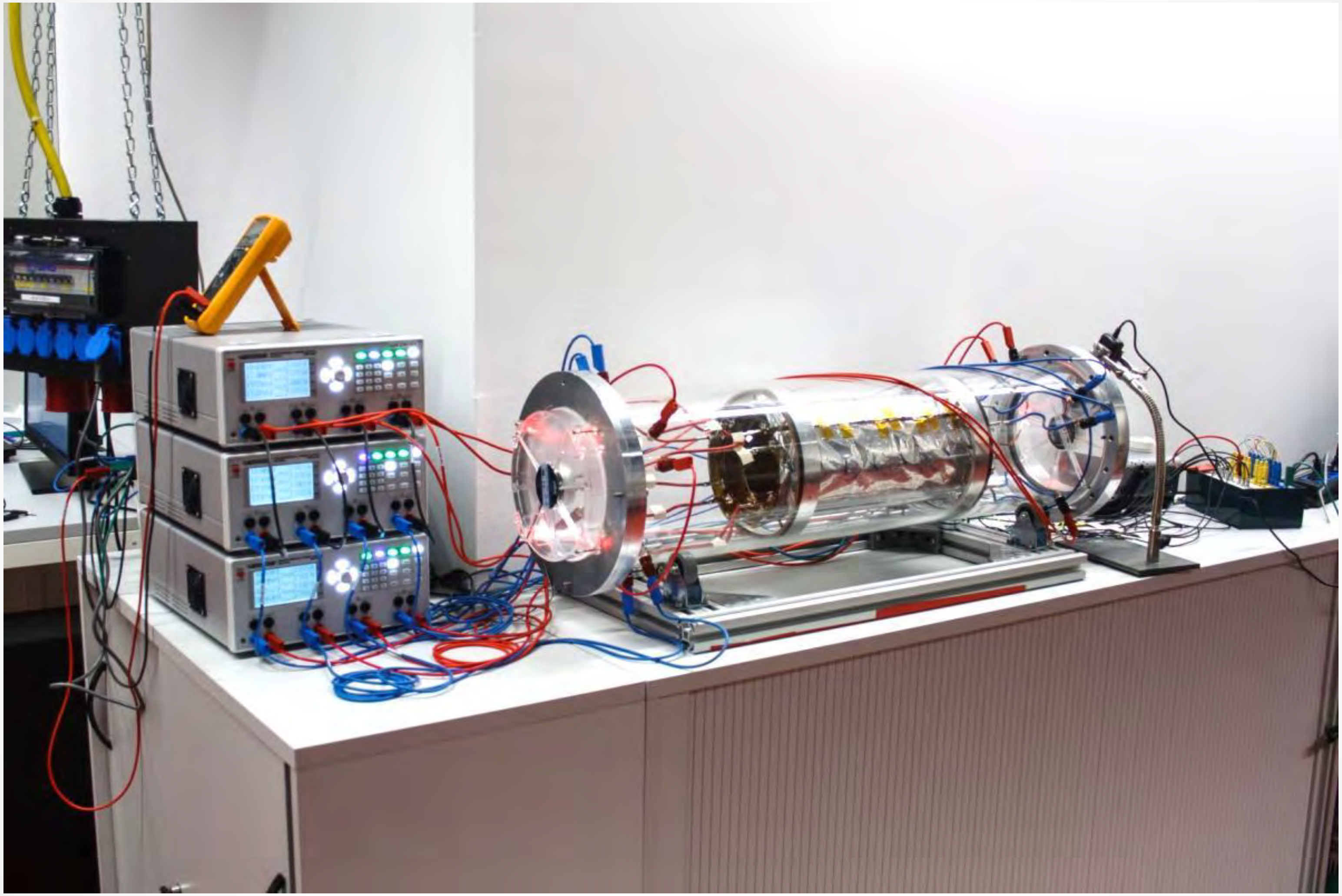


Tests



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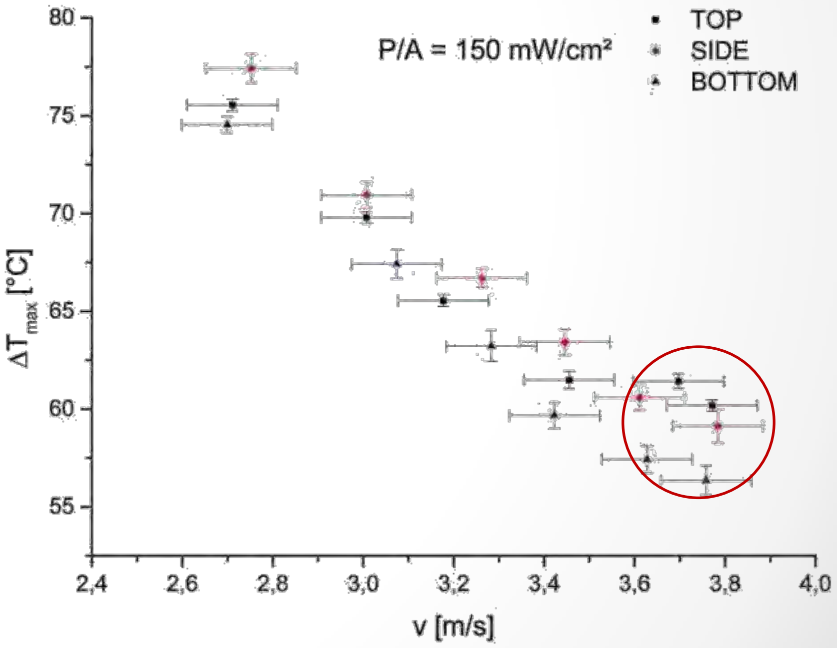
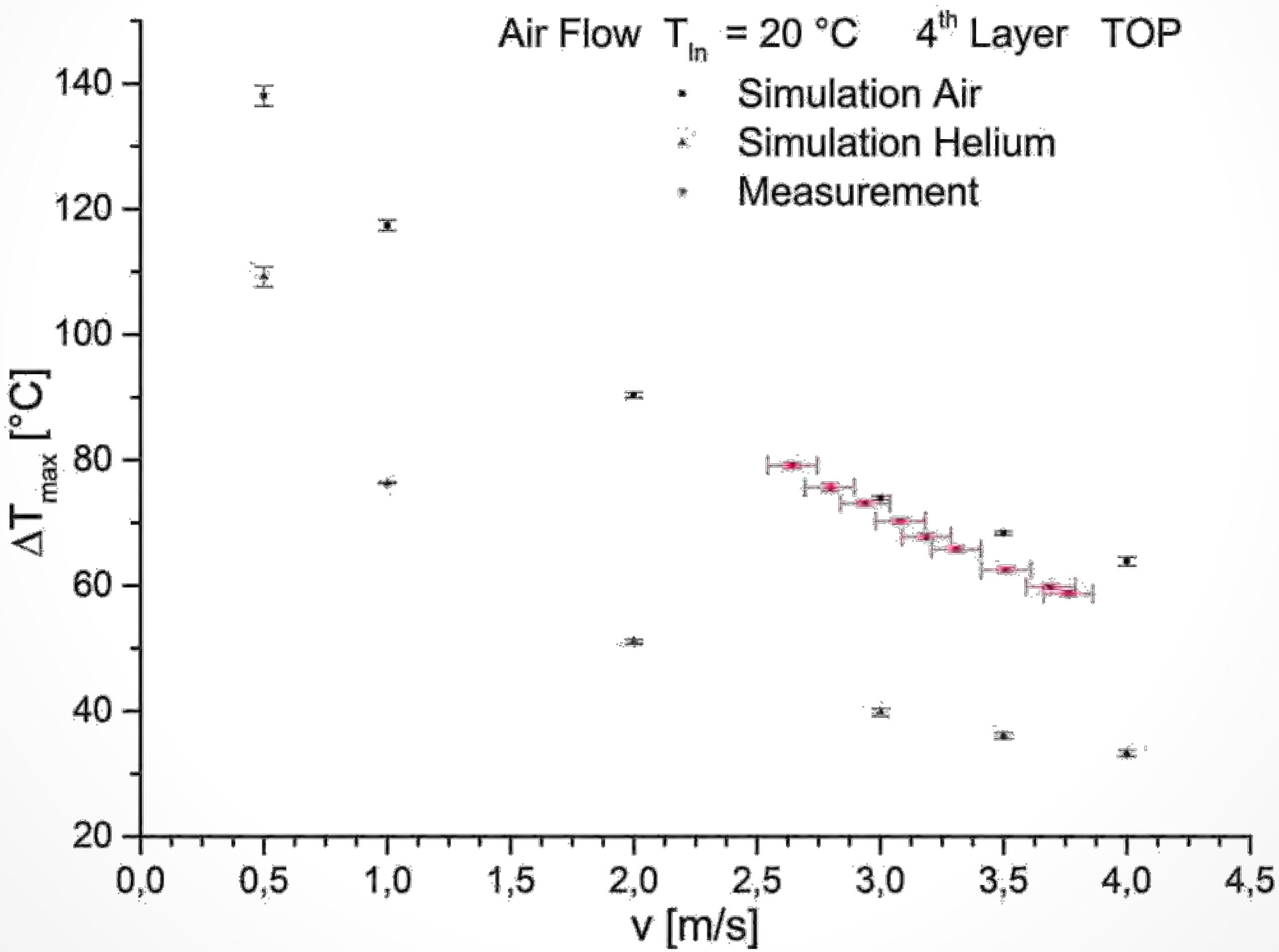
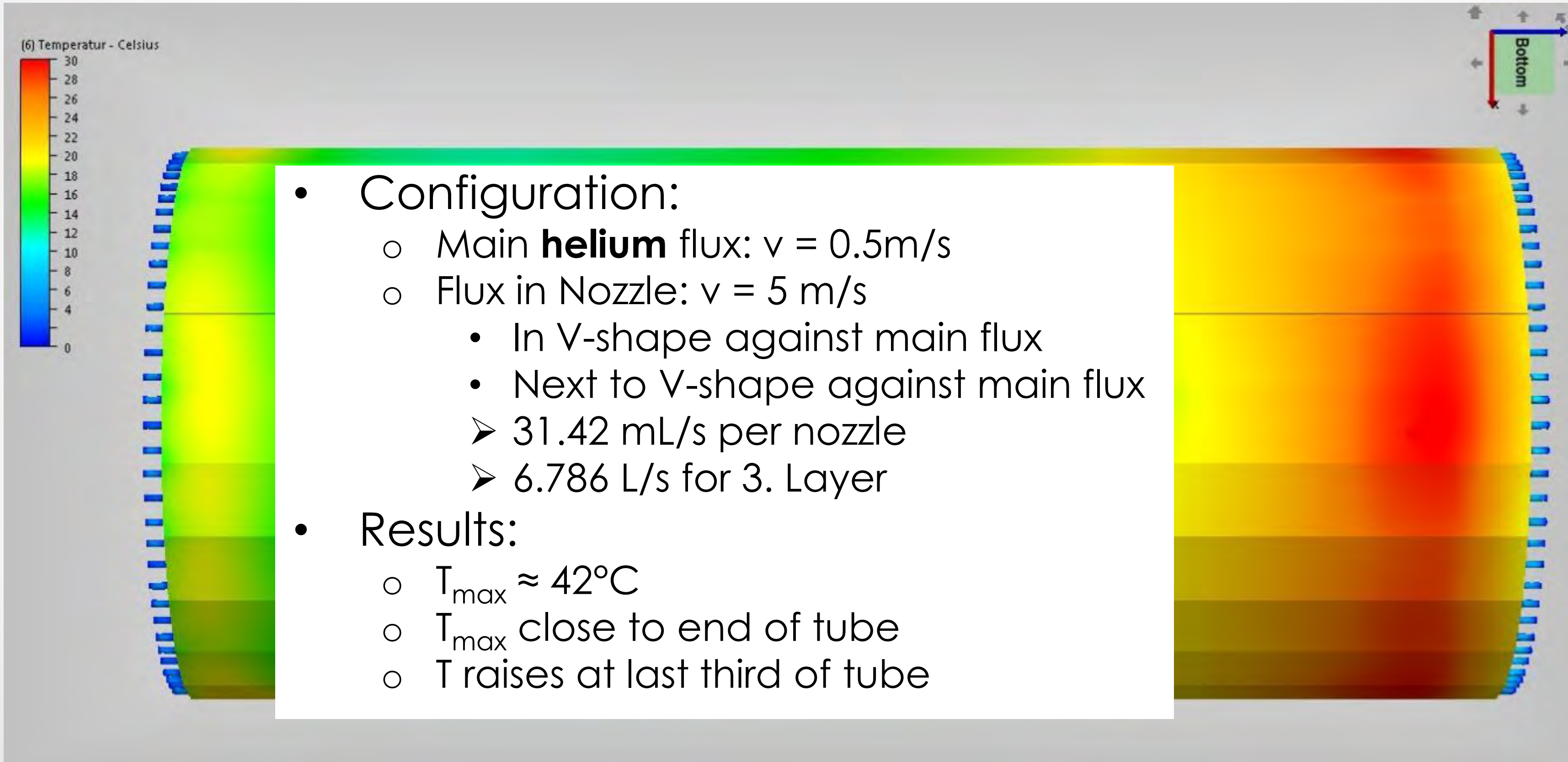
  - … of Aluminum-Kapton™
- Cooling with external fan
  - Air at several m/s
- Temperature sensors attached to foil
  - LabView readout
- **First results promising**
  - **ΔT < 60°K**
  - ➢ **No sign of vibration in air**



Comparison Simulation and Tests

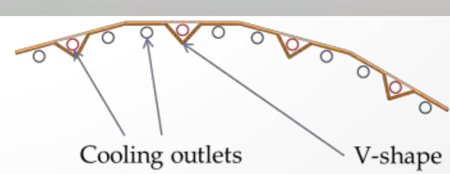


Simulation with V-shape cooling



- Configuration:
  - Main **helium** flux: v = 0.5m/s
  - Flux in Nozzle: v = 5 m/s
    - In V-shape against main flux
    - Next to V-shape against main flux
    - ➢ 31.42 mL/s per nozzle
    - ➢ 6.786 L/s for 3. Layer
- Results:
  - $T_{max} \approx 42°C$
  - T_{max} close to end of tube
  - T raises at last third of tube

→ Extra Improvement using V-shapes as cooling channels



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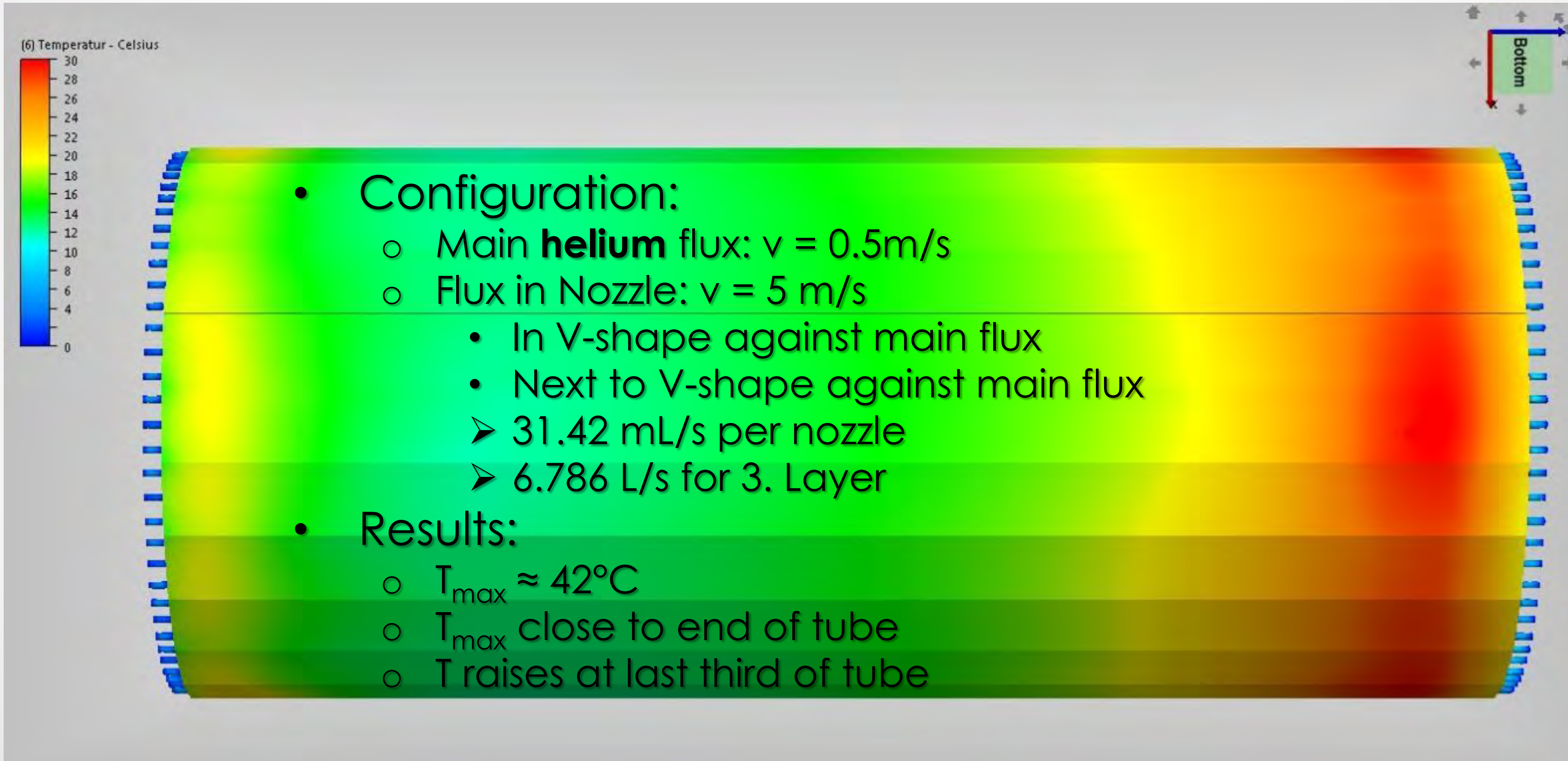

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- Results:
  - T_{max} ≈ 42°C
  - T_{max} close to end of tube
  - T raises at last third of tube

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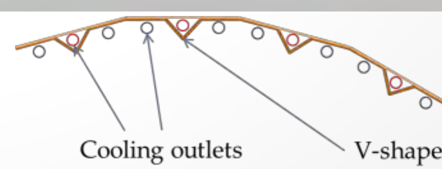
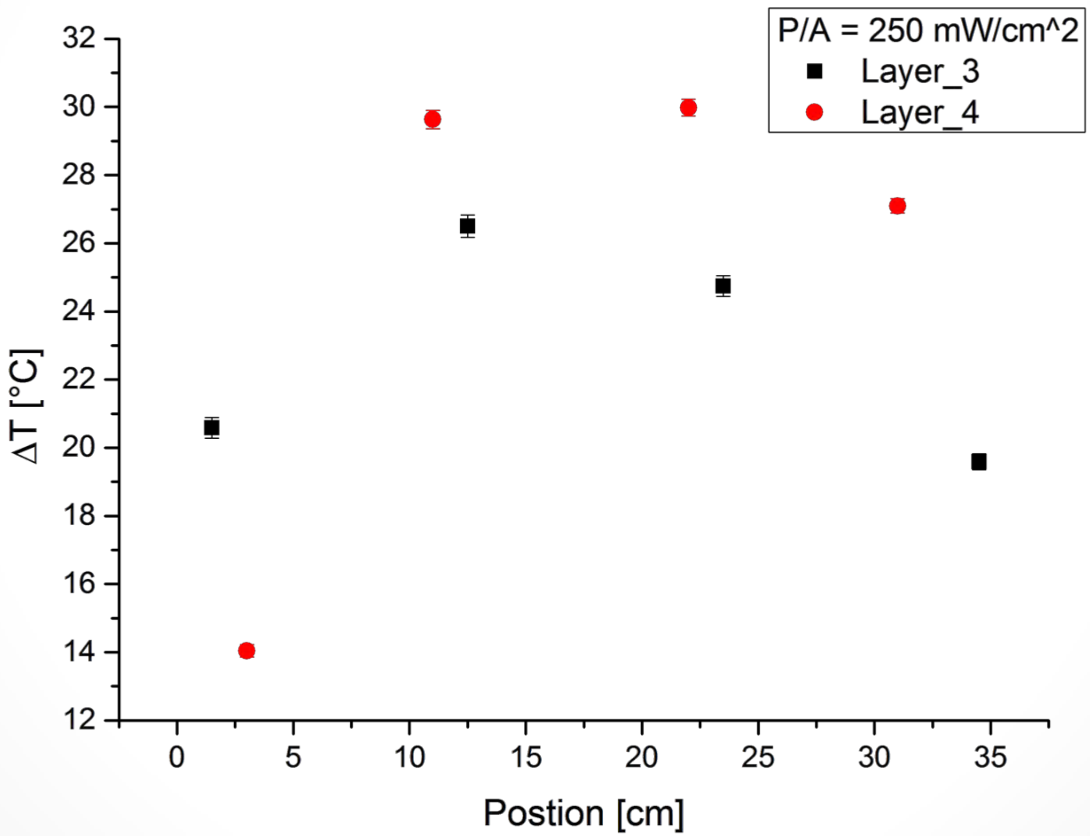
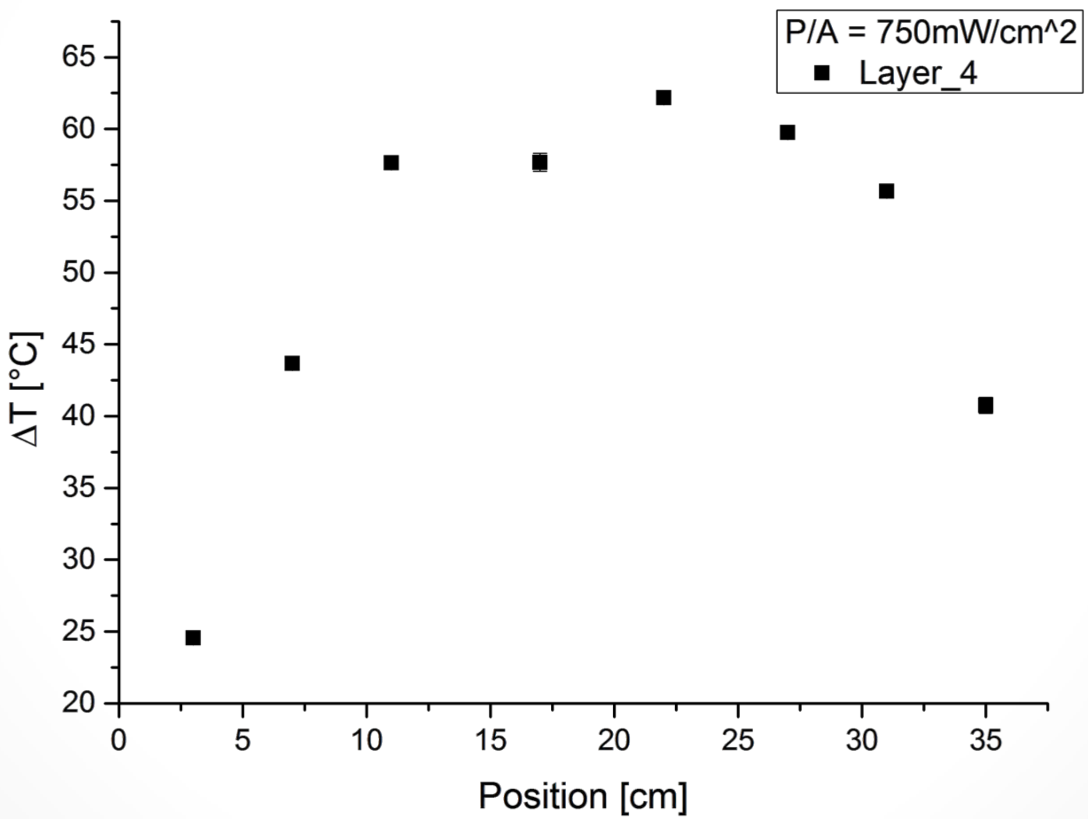


He Cooling 250 mW/cm^2



He Cooling 750 mW/cm^2

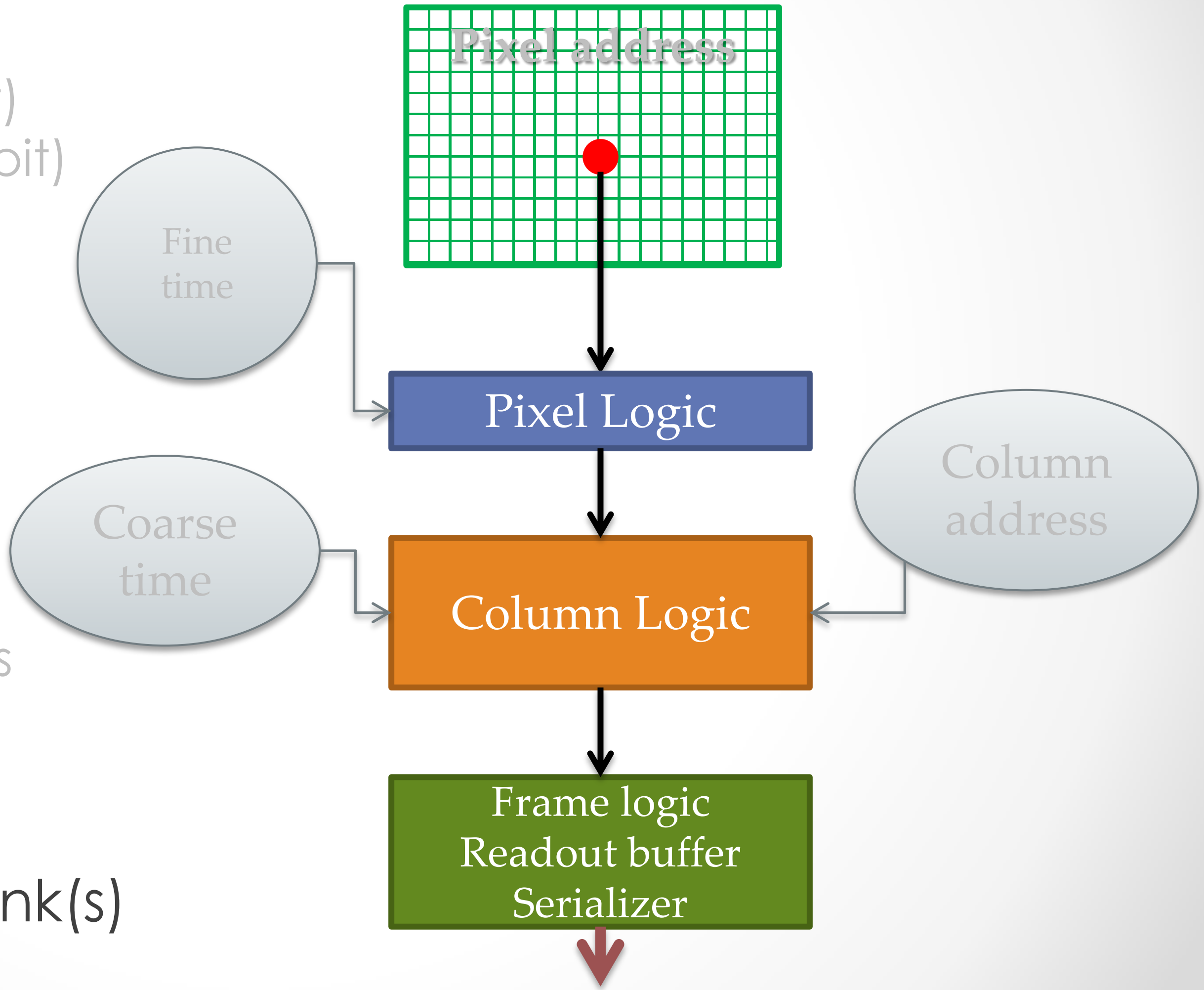


DAQ Backup

…

Pixel Readout Scheme

- Pixel logic
  - Pixel address (8 bit)
  - Frame number (4 bit)
  - 50 ns frames
- Column logic
  - Pixel data
  - Column address
  - Coarse time
- Frame logic
  - Super Frame
  - Contains 16 x 50 ns readout frames
  - + Sensor header
- Readout buffer
- Serializer and fast link(s)



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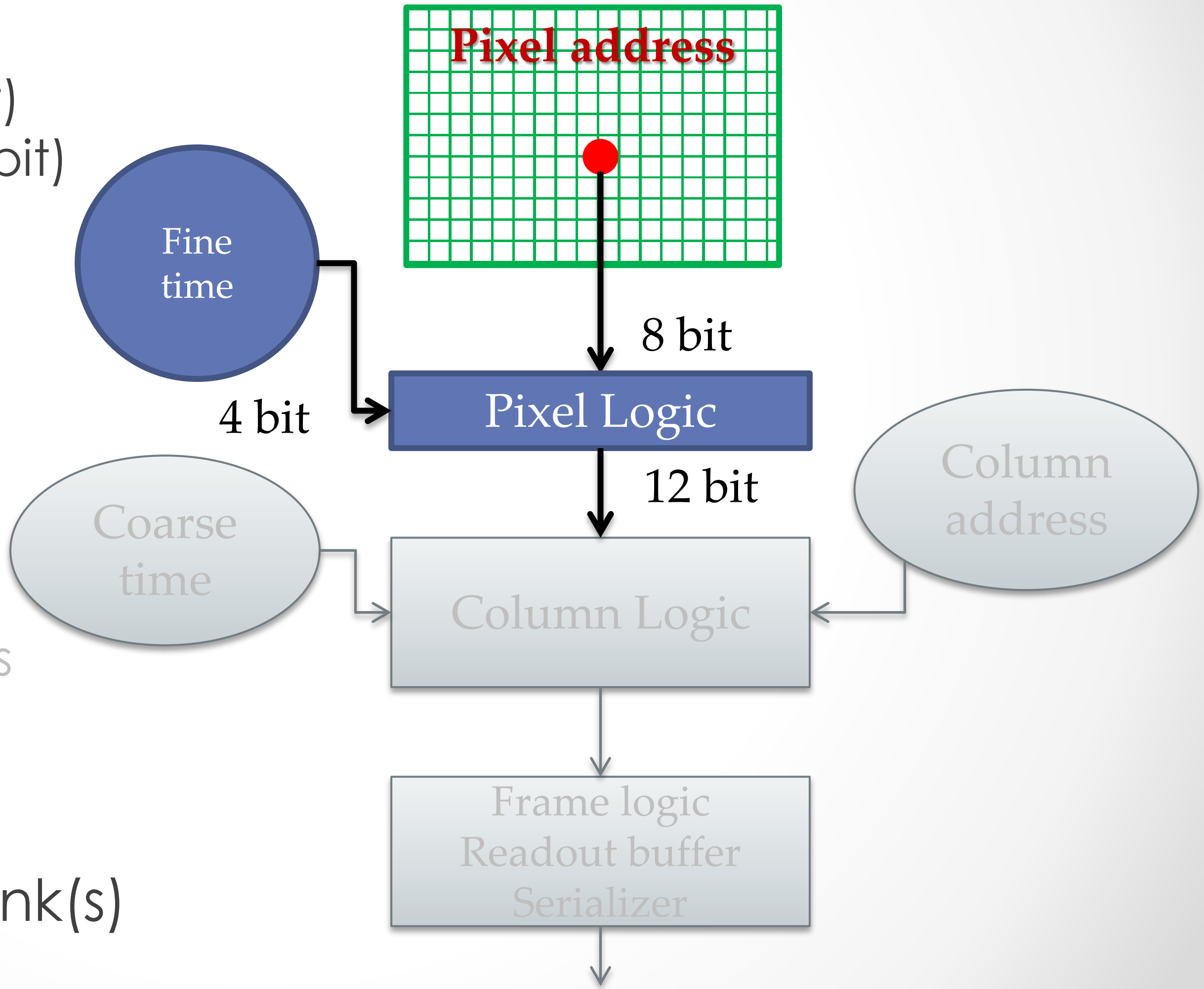

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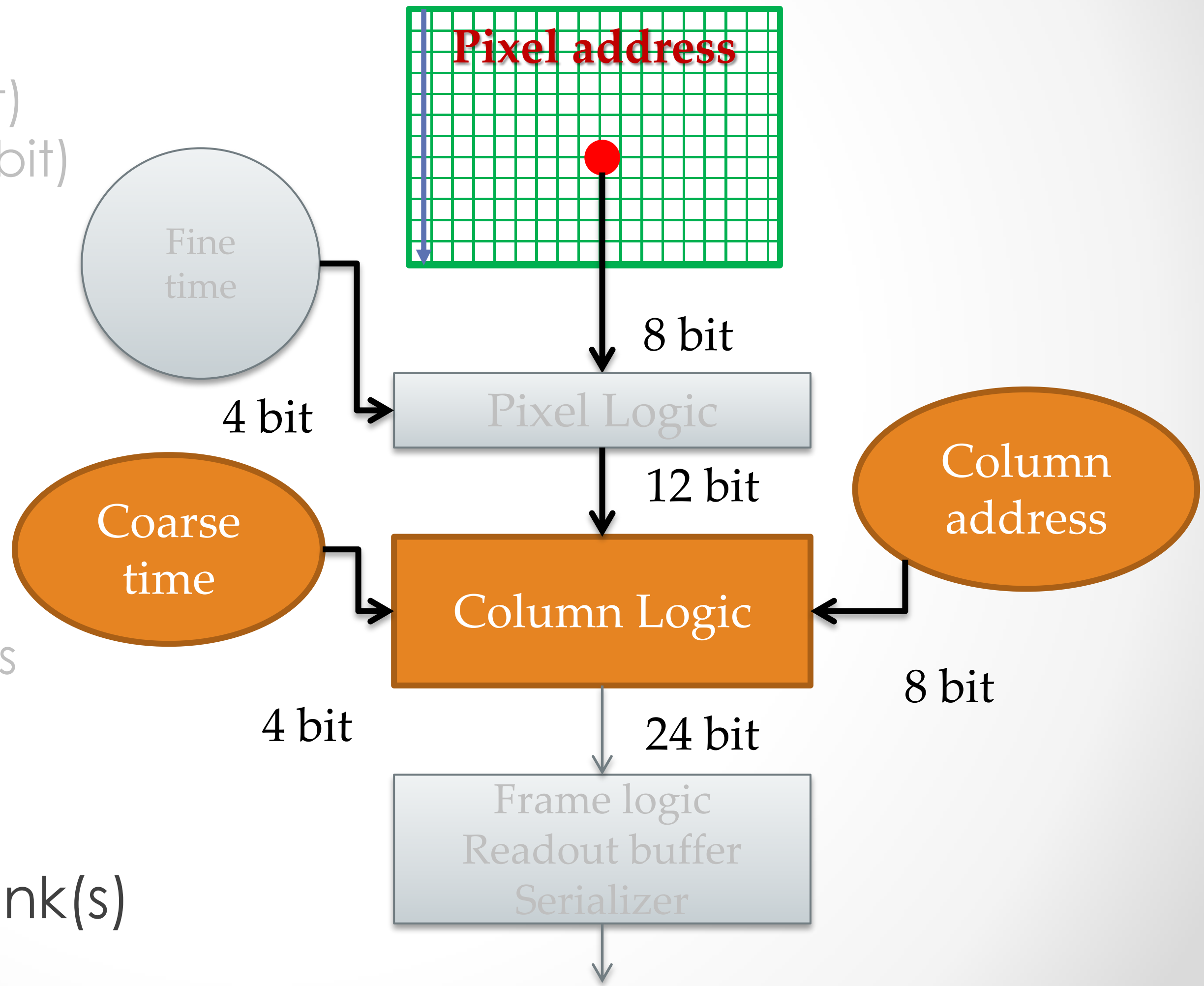

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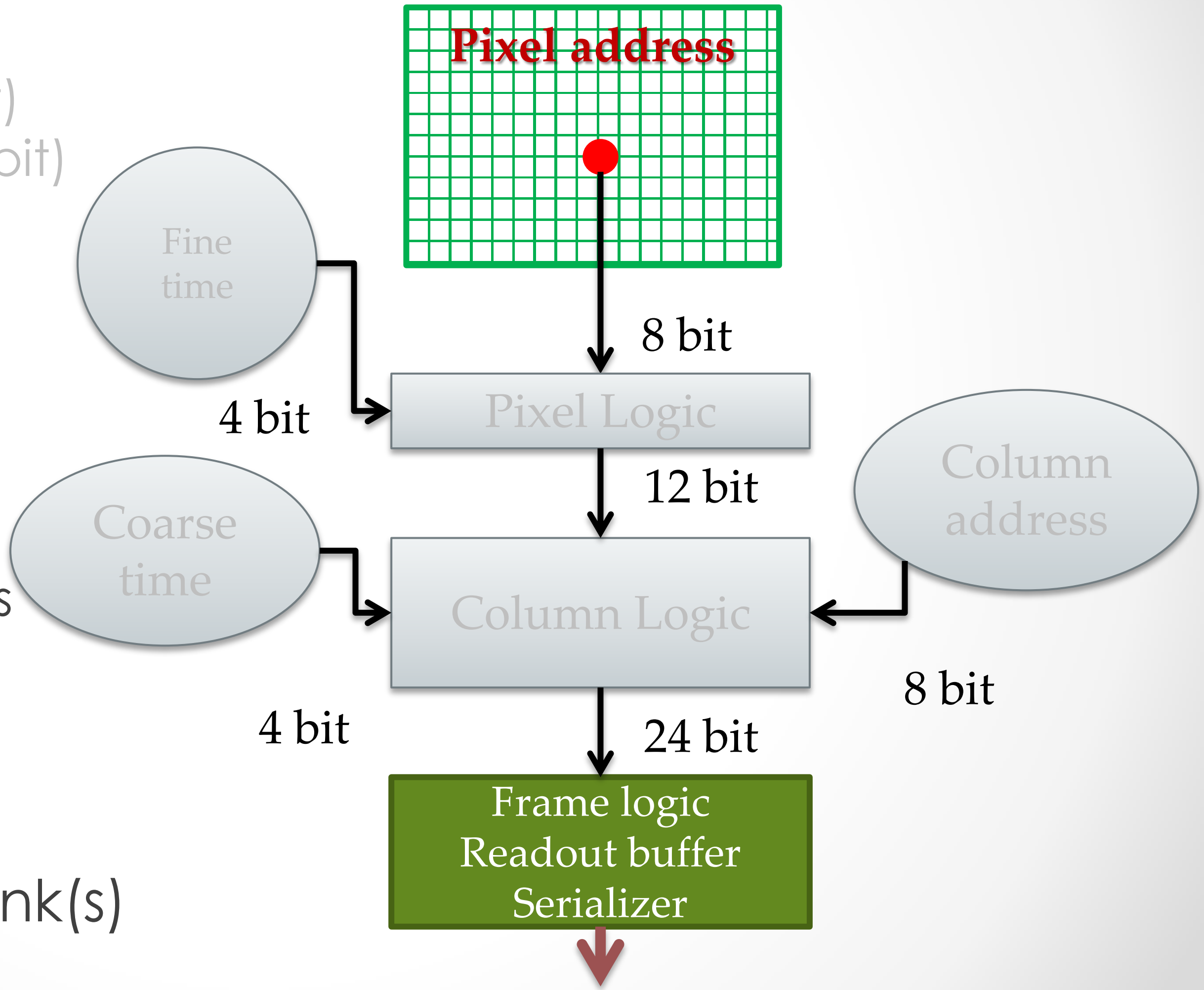
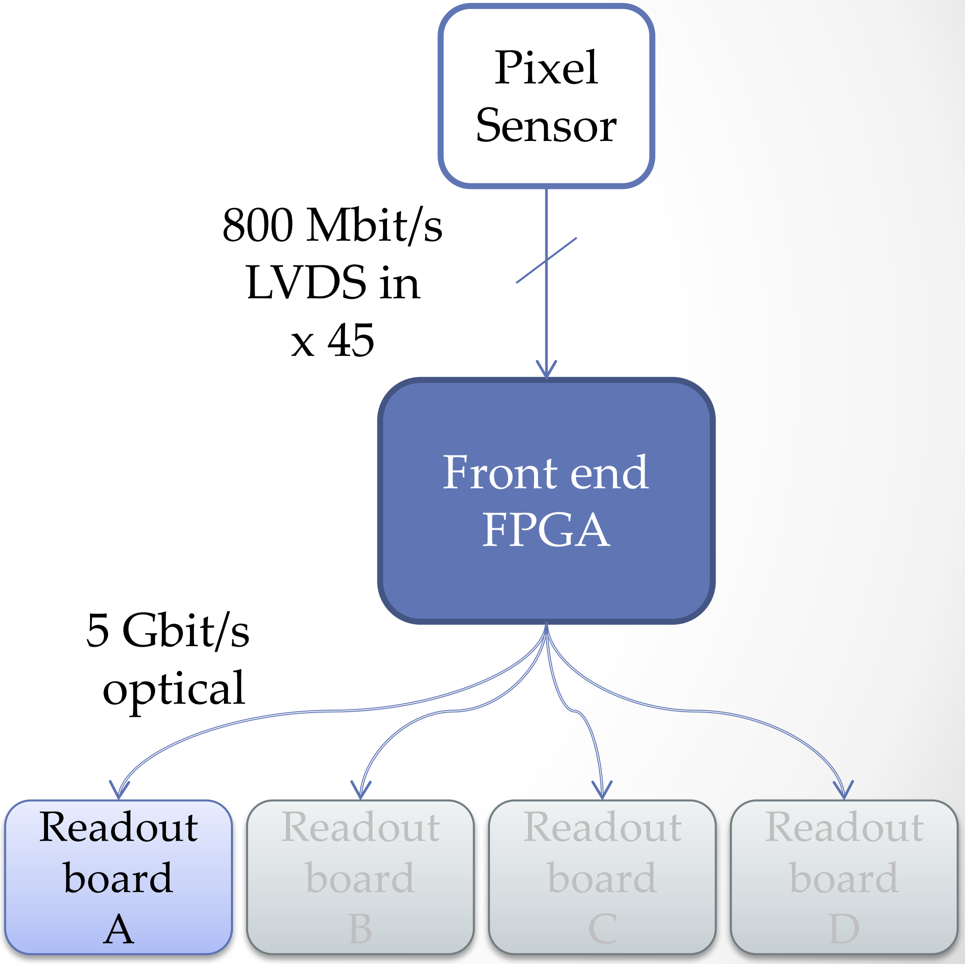


3 x serial @ 800 Mb/s

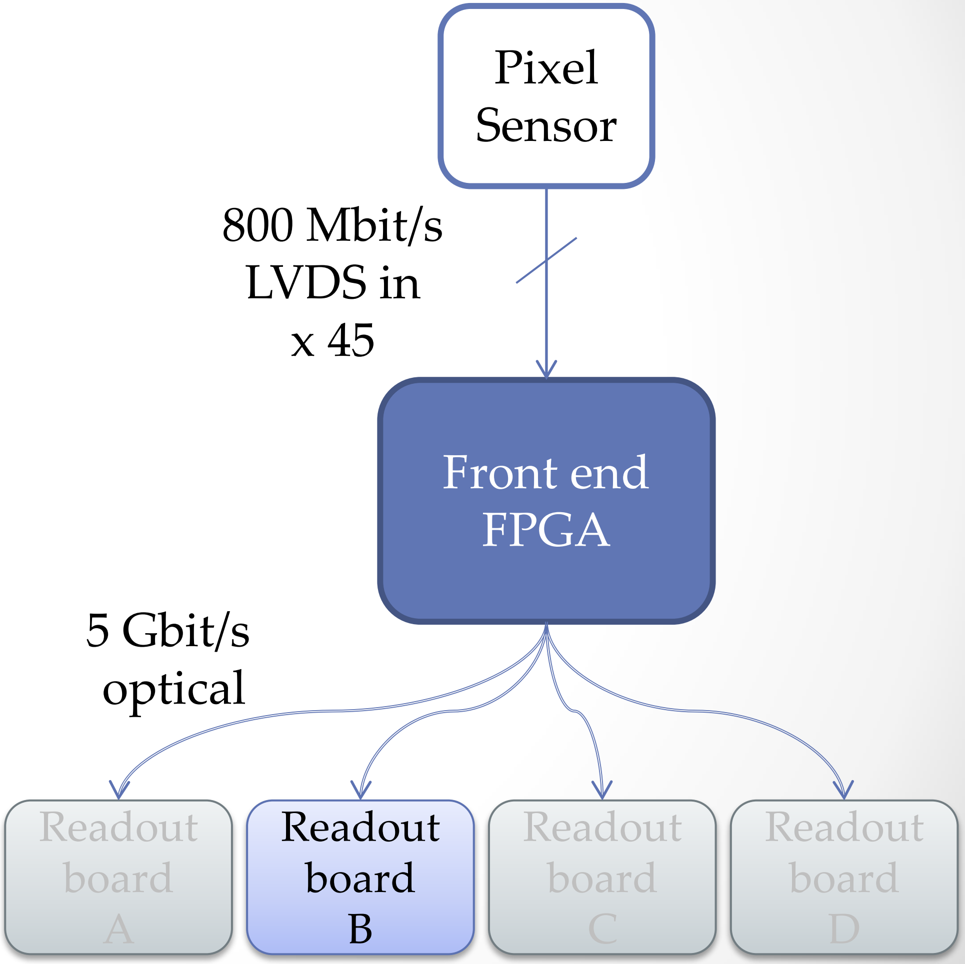
Front End FPGAs

- FPGAs on detector
  - 90 (+96) pieces
- Receive sensor data
  - 36-45 LVDS inputs
- 5 Gbit/s outputs
  - 8 optical links
  - … to counting house
- Switching data between readout boards farms A-D



Front End FPGAs

- FPGAs on detector
  - 90 (+96) pieces
- Receive sensor data
  - 45 LVDS inputs
- 5 Gbit/s outputs
  - 8 optical links
  - … to counting house
- Switching data between readout boards farms A-D



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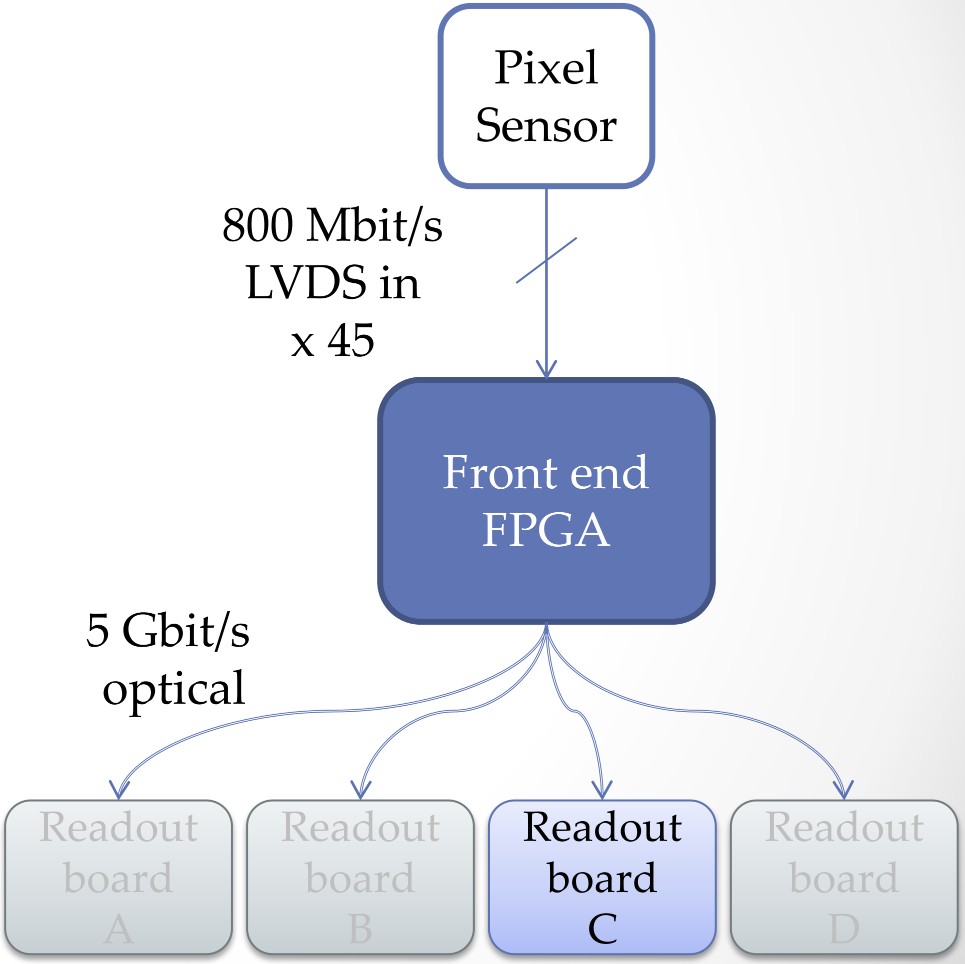

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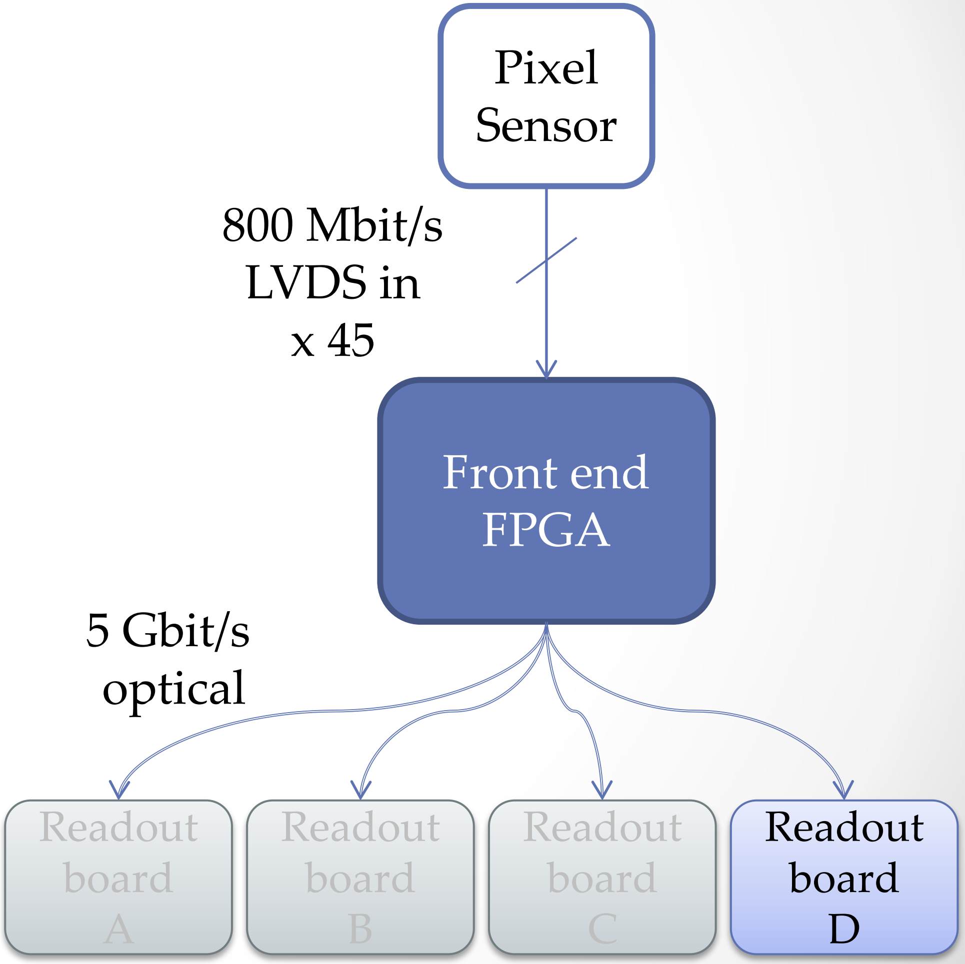
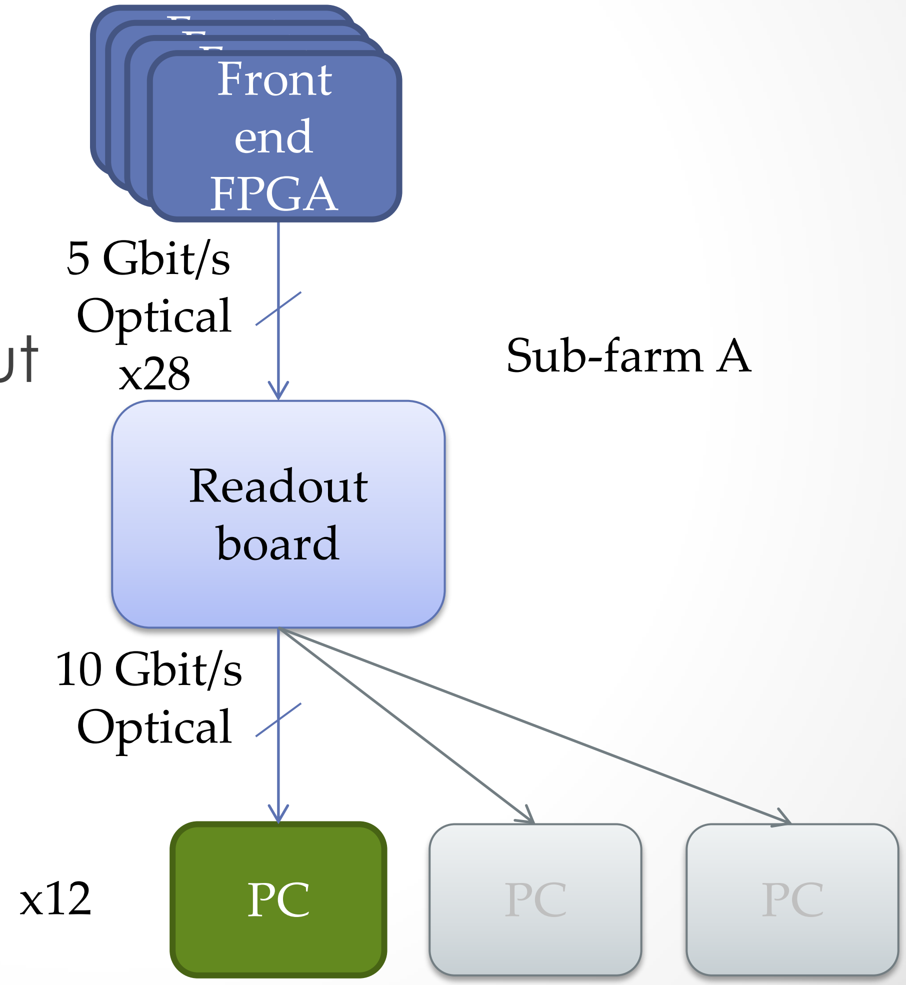


Readout Board

- FPGA readout boards
  - 4 per sub-detector
- 5 Gbit/s optical inputs
  - 16-28 inputs
- 10 Gbit/s optical output
  - 12 outputs to PCs
- Switching network
  - A-D sub-farms
  - One output per PC



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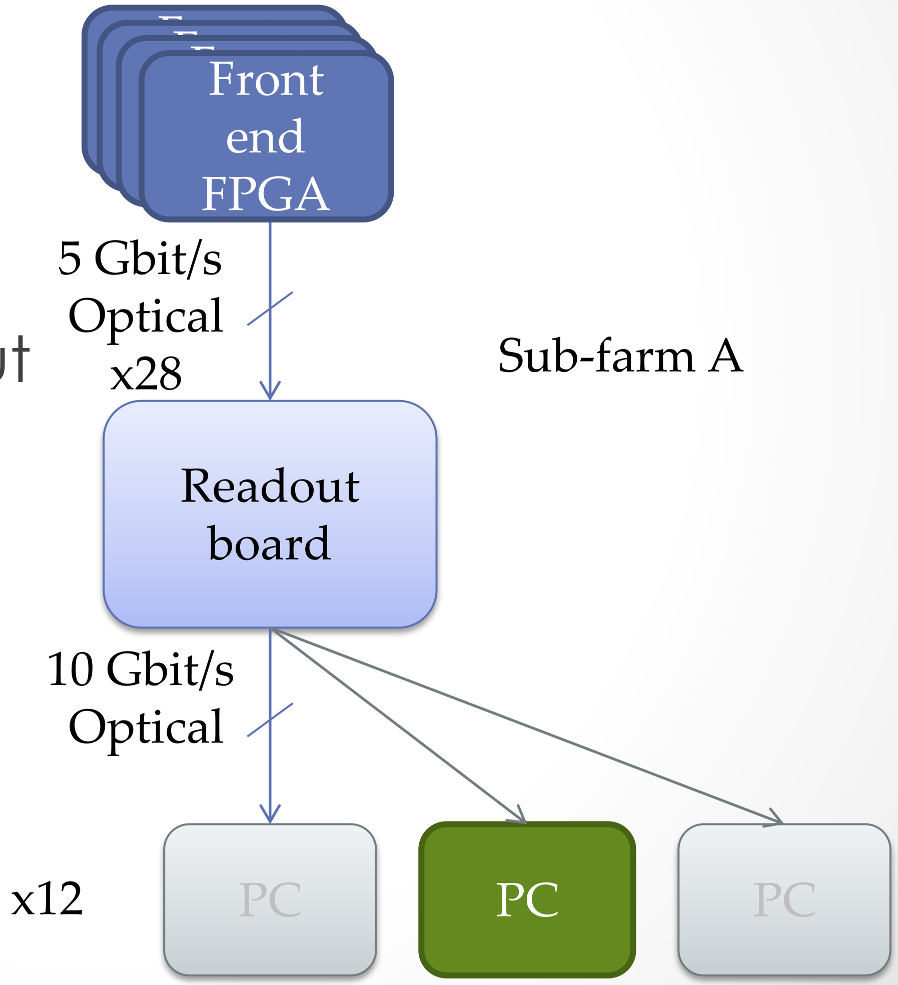
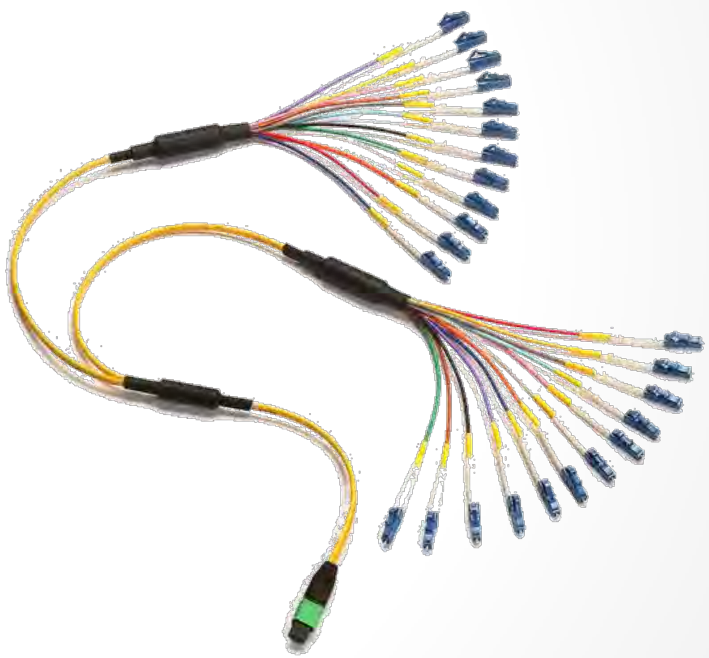


Trigger-less DAQ

- 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
  - 5 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



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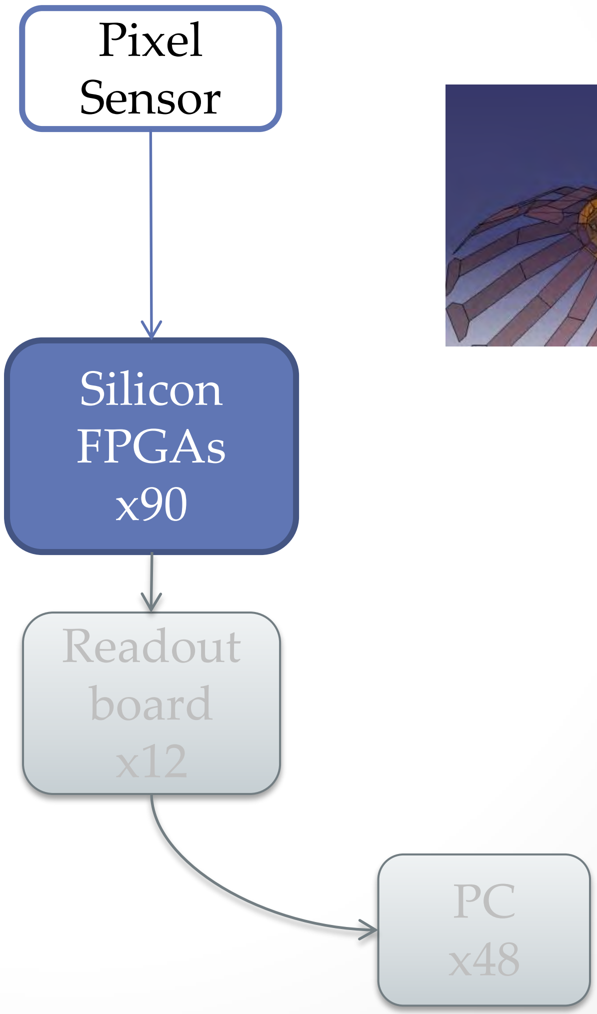

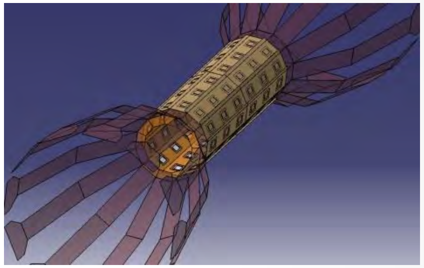

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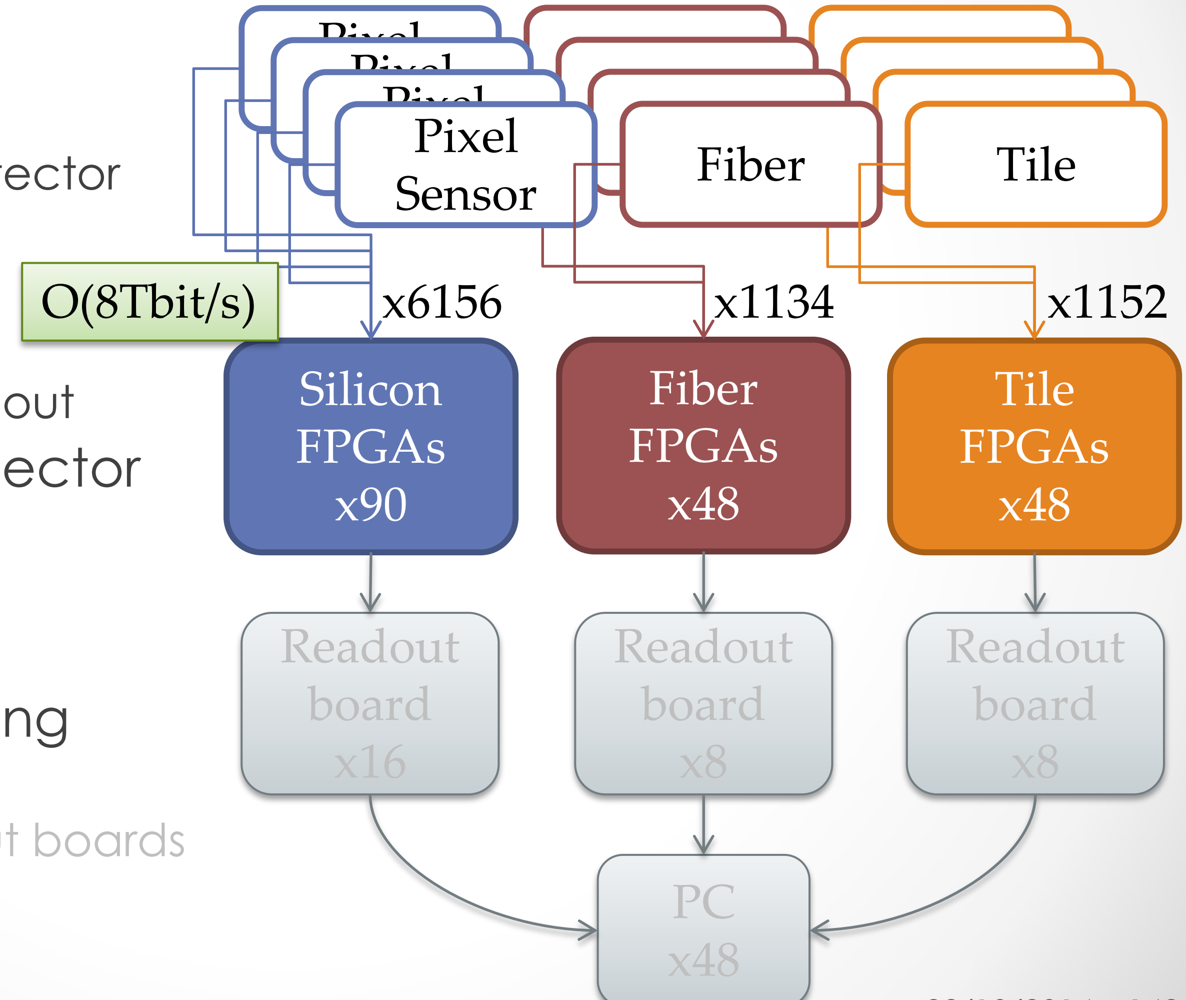

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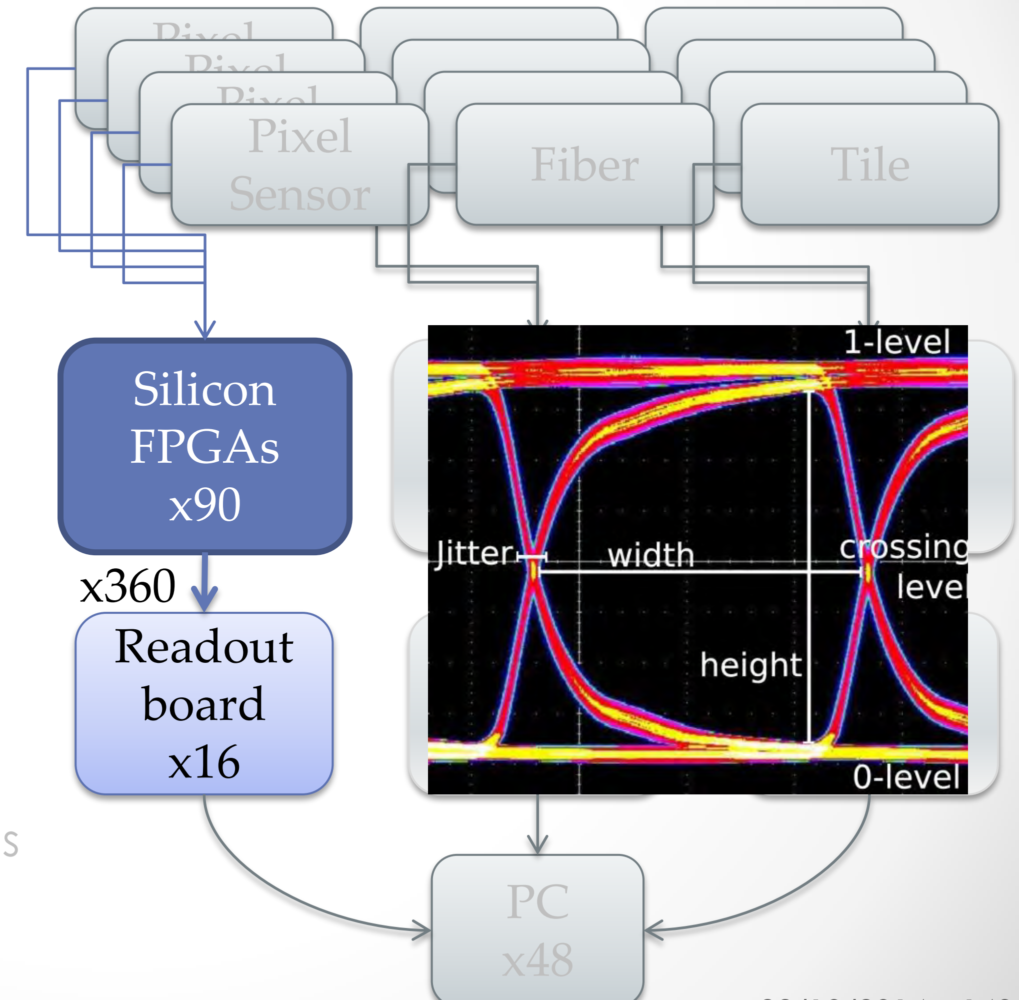

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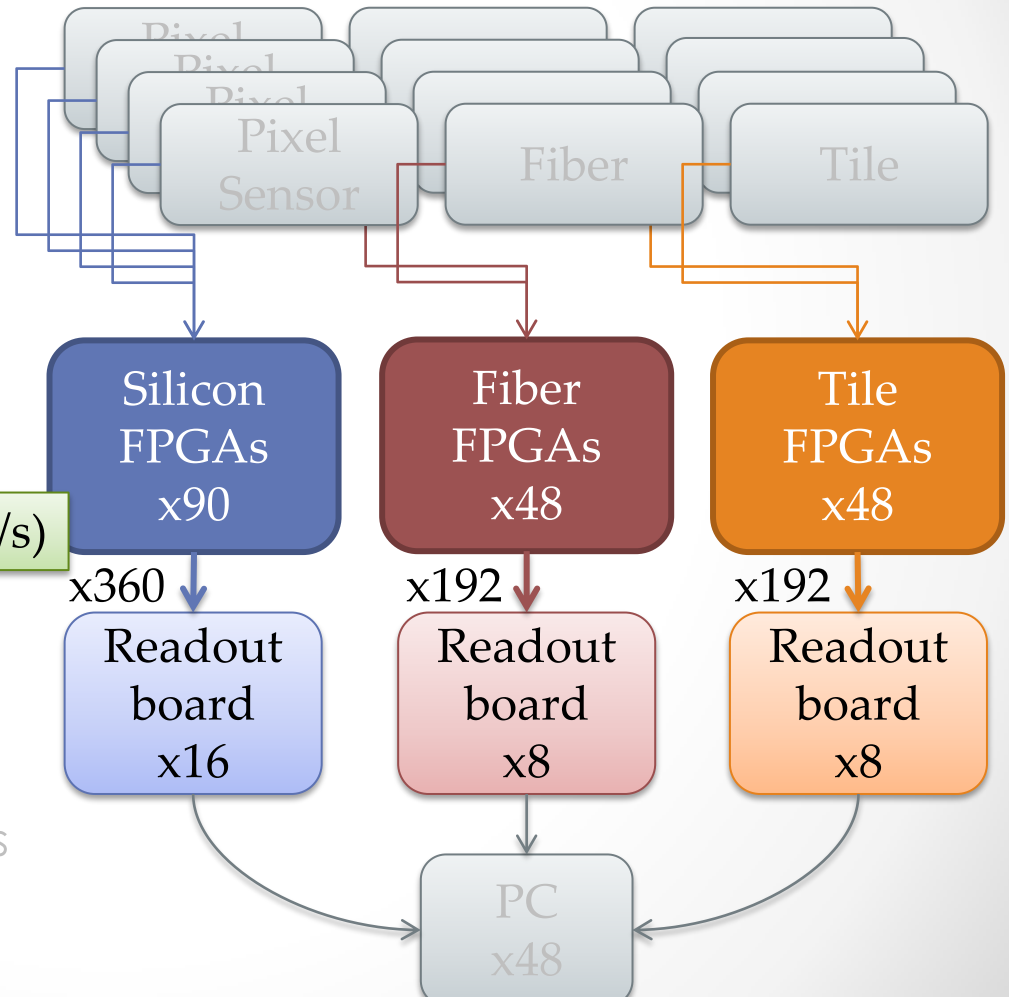
O(4Tbit/s)



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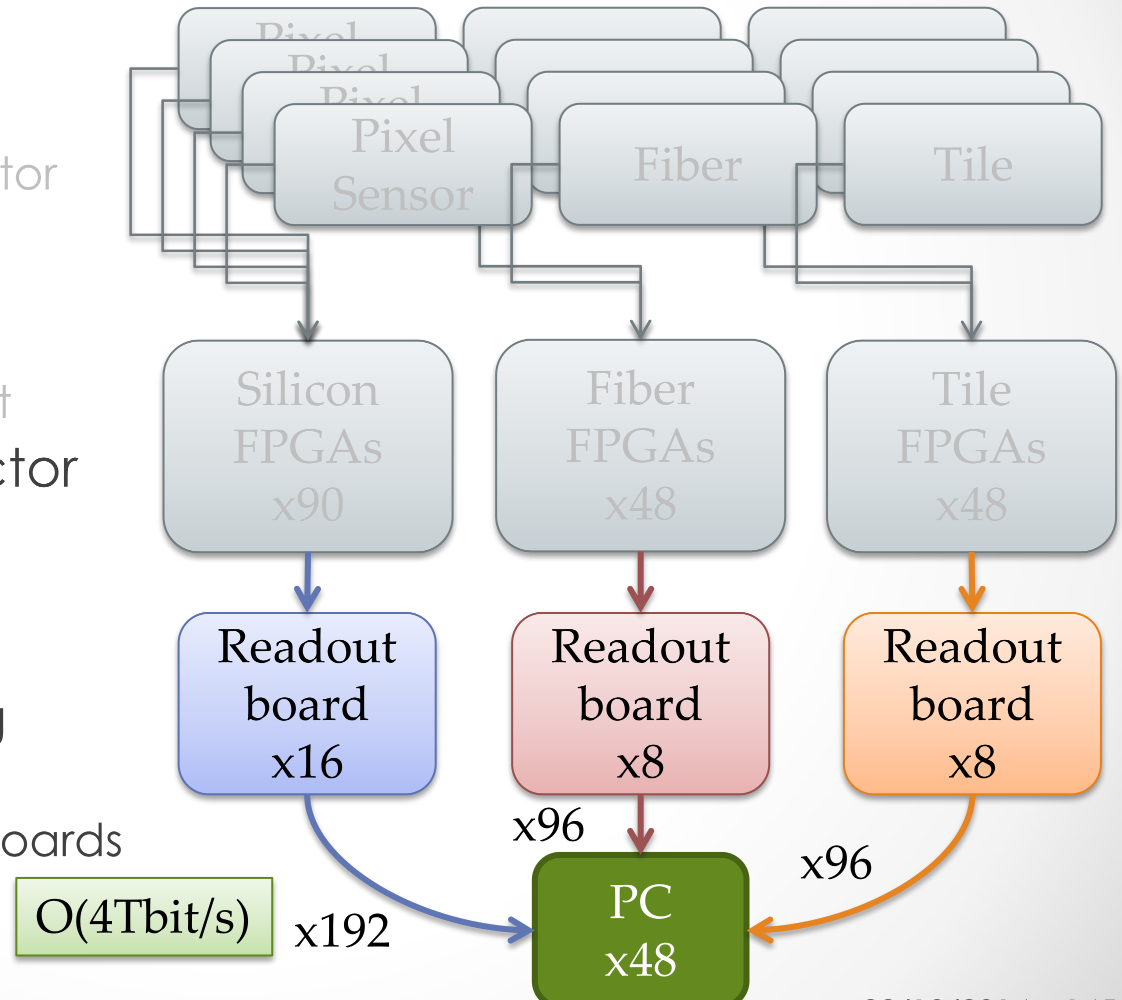

GPU-PC

- 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

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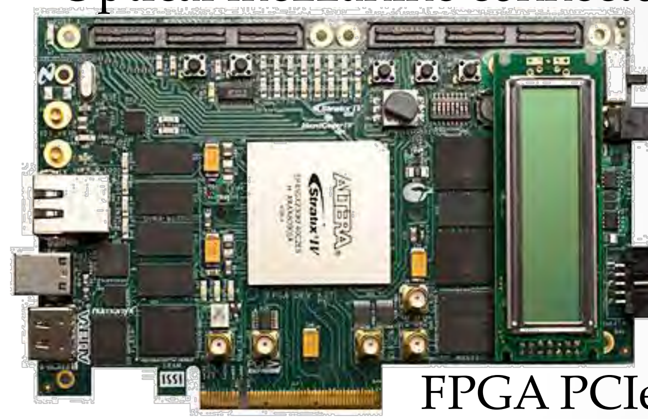
Optical mezzanine connectors



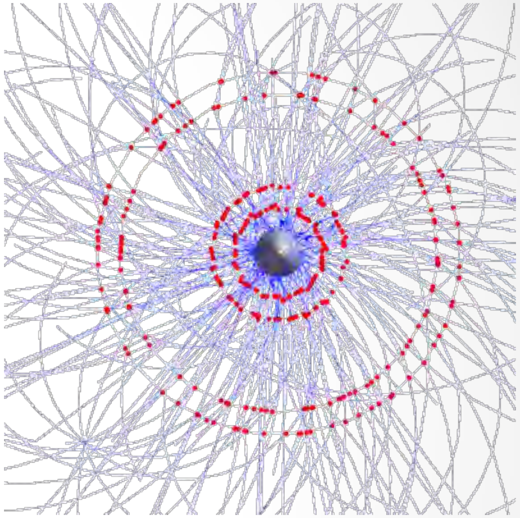
FPGA PCIe board

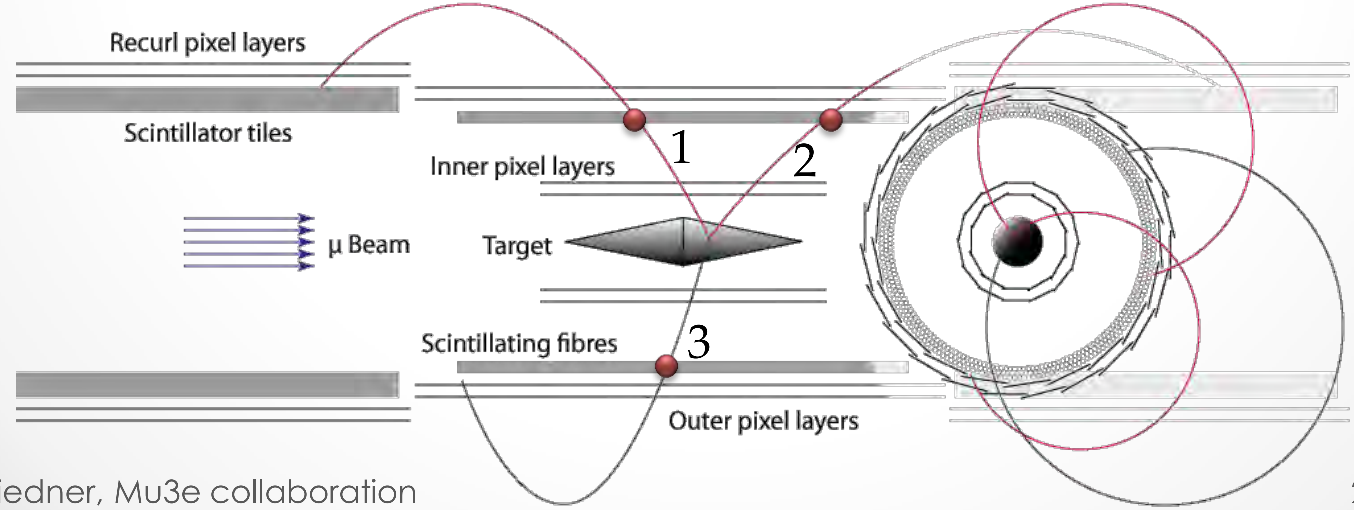
GPU computer

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





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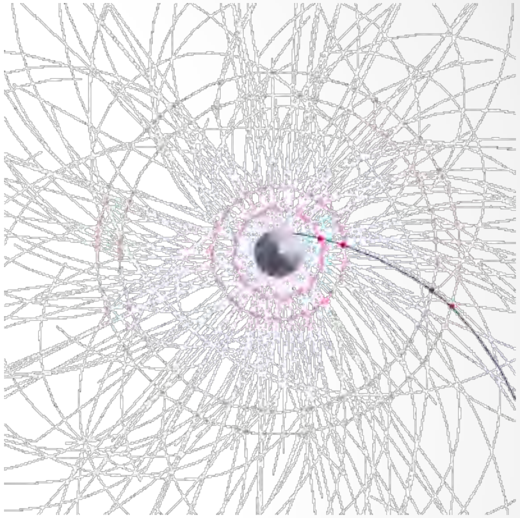
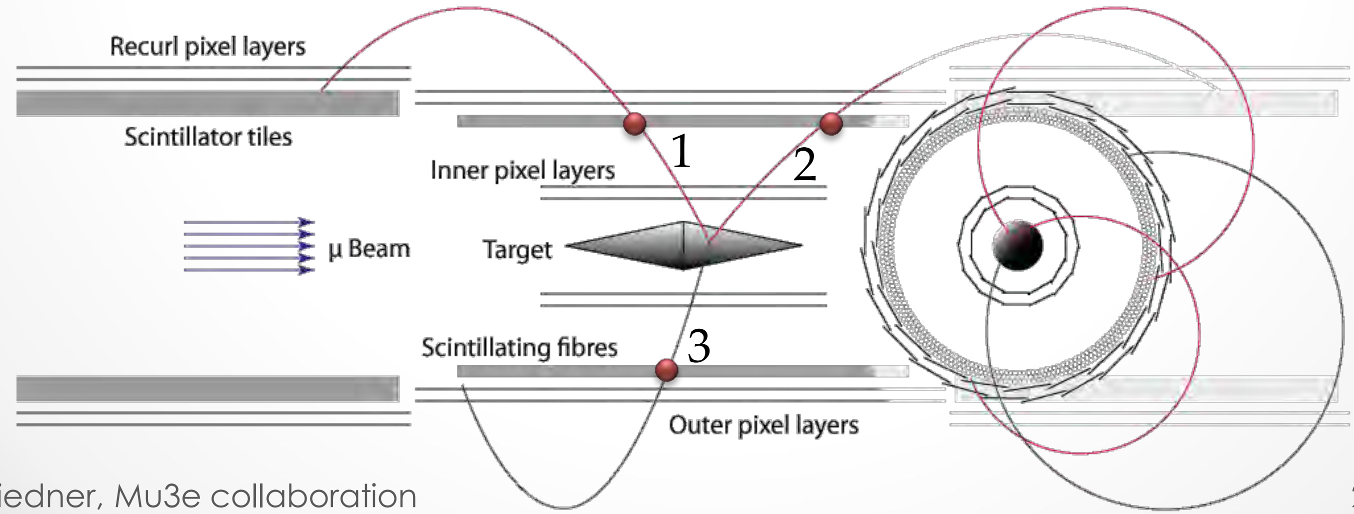
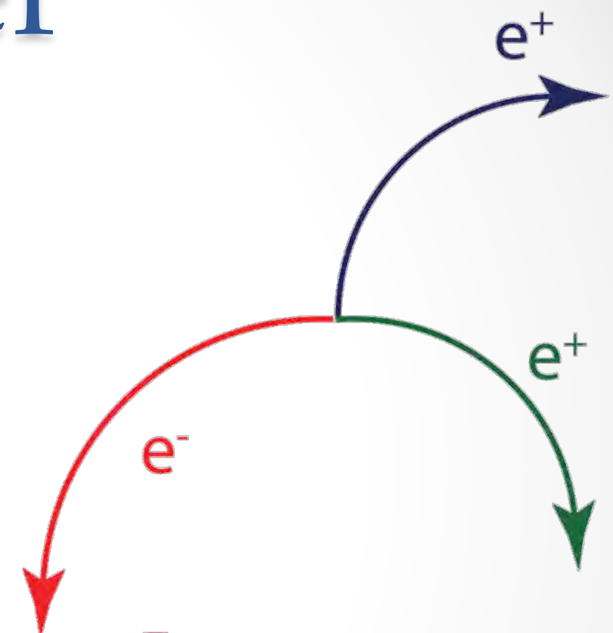
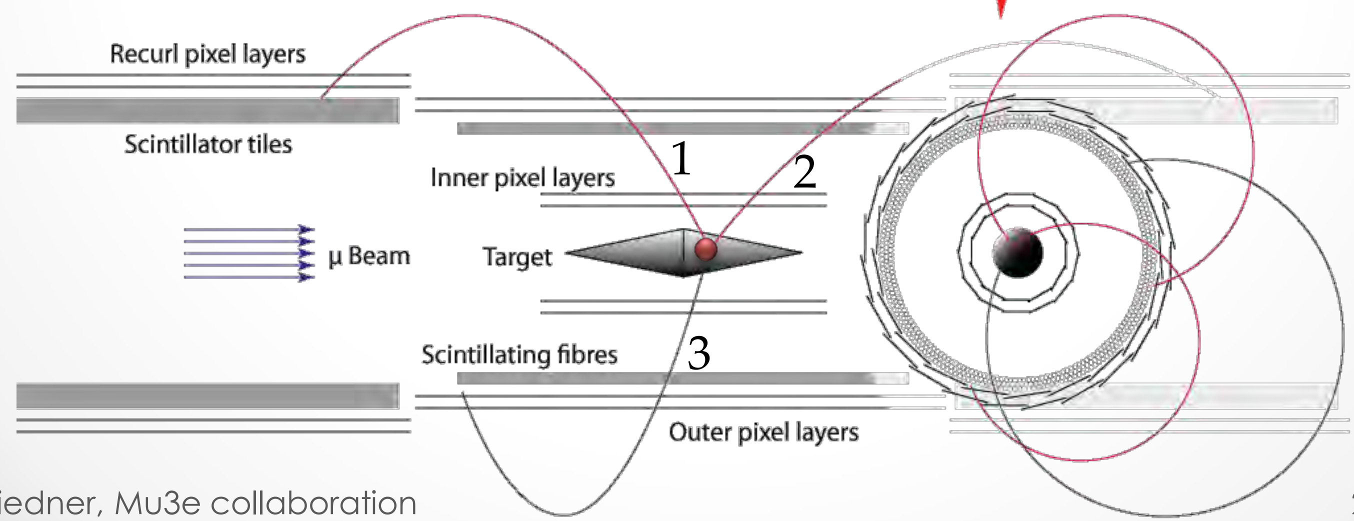




Vertex Filter

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





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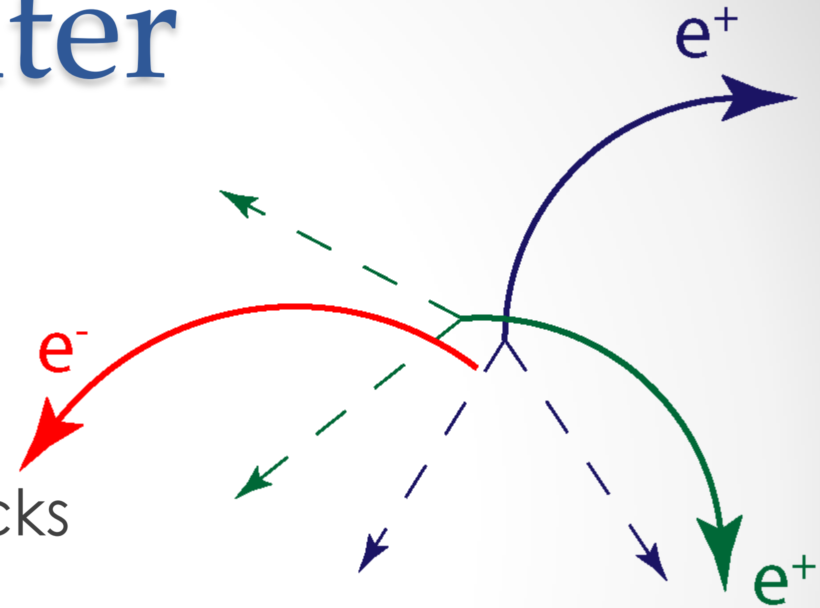

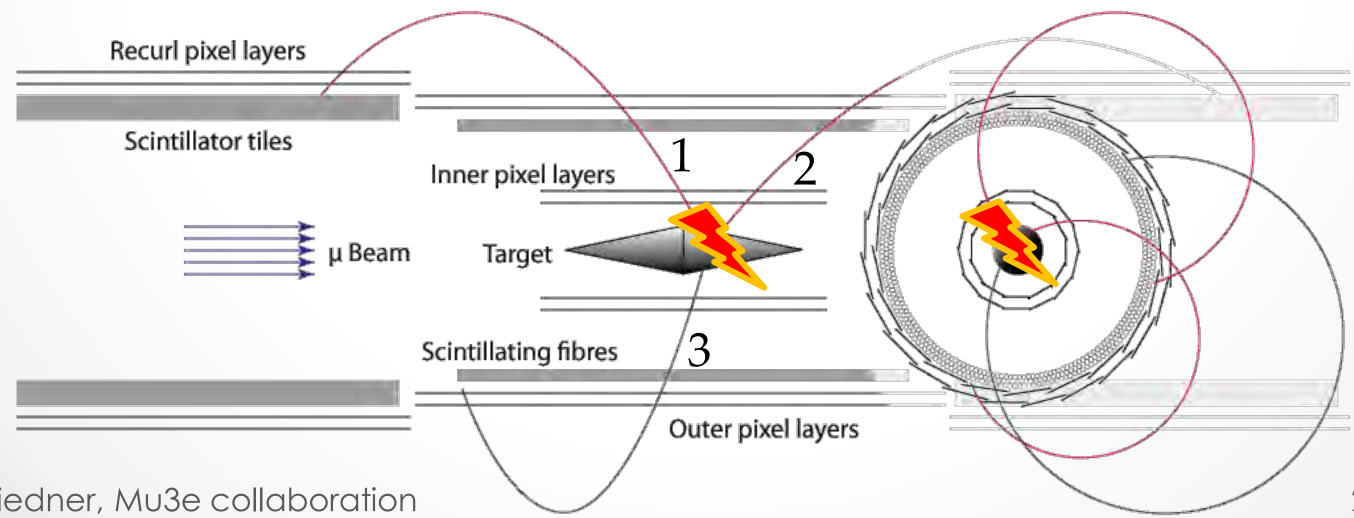

Schedule

- **2012 Letter of intent** to PSI, tracker prototype, research proposal
- **2013/14** Detector **R&D**
- **2015** Detector **construction**
- **2016** Installation and **commissioning** at PSI
- **2017** Data taking at up to a few **10^8 μ/s**
- **2018+** Construction of **new beam-line** at PSI
- **2019++** Data taking at up to **$2 \cdot 10^9$ μ/s**