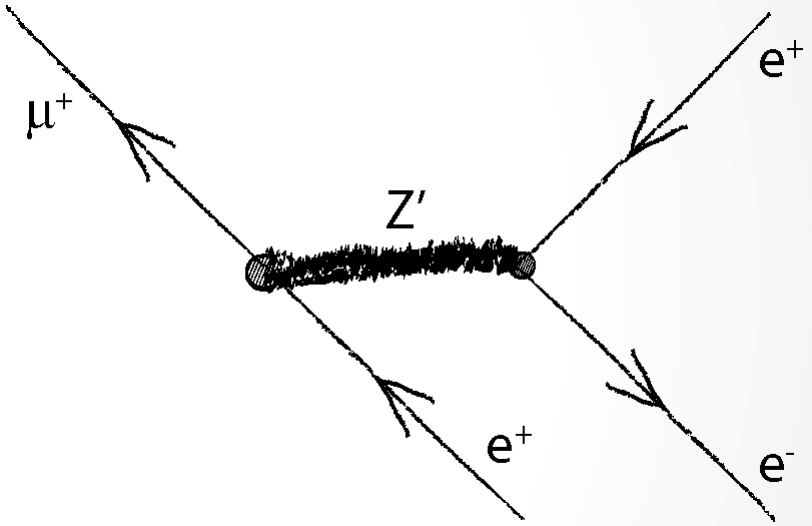
The trigger-less TBit/s readout for the Mu3e experiment

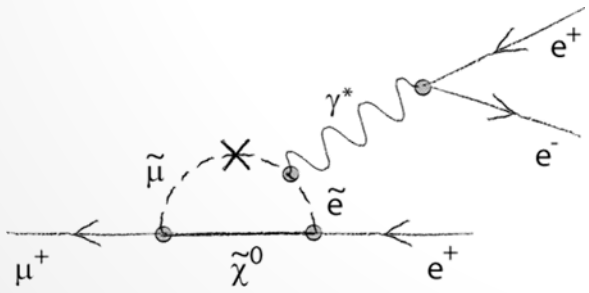
Dirk Wiedner

On behalf of the Mu3e collaboration

The Mu3e Signal

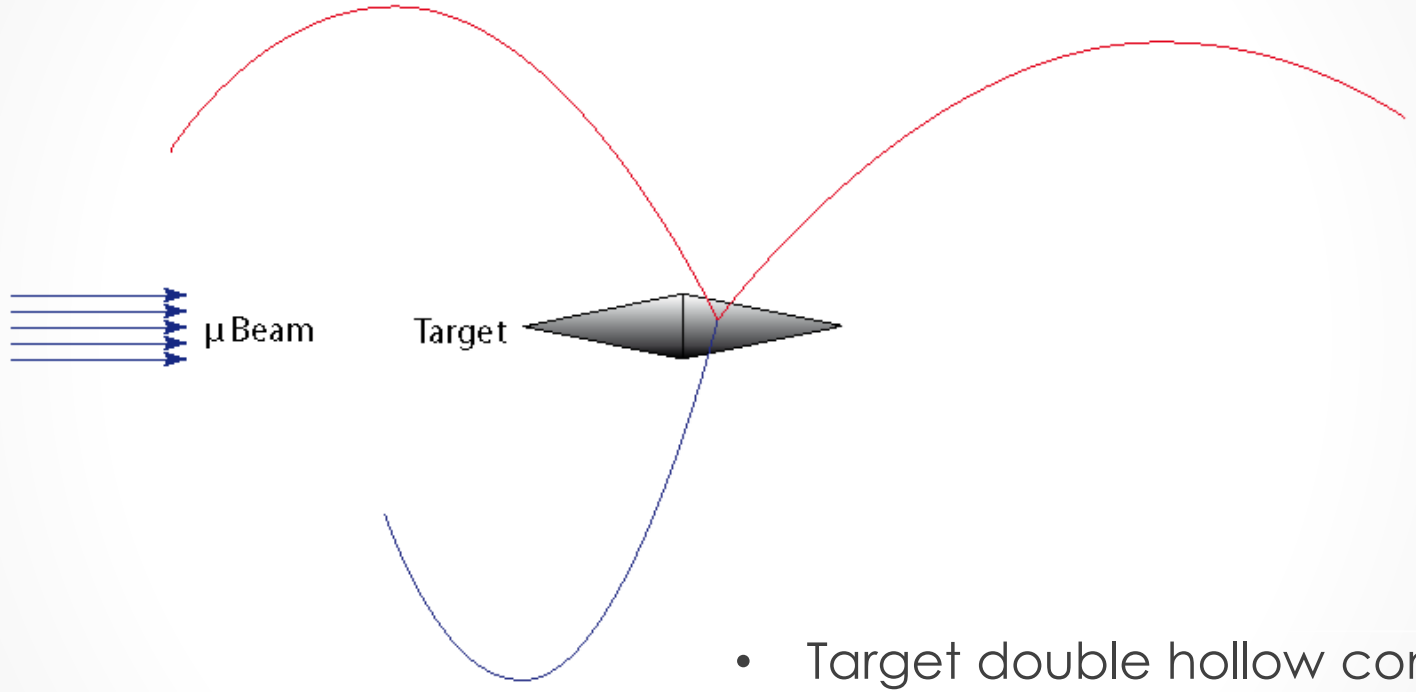
- μ→eee rare in SM
- Enhanced in:
  - Super-symmetry
  - Grand unified models
  - Left-right symmetric models
  - Extended Higgs sector
  - Large extra dimensions





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

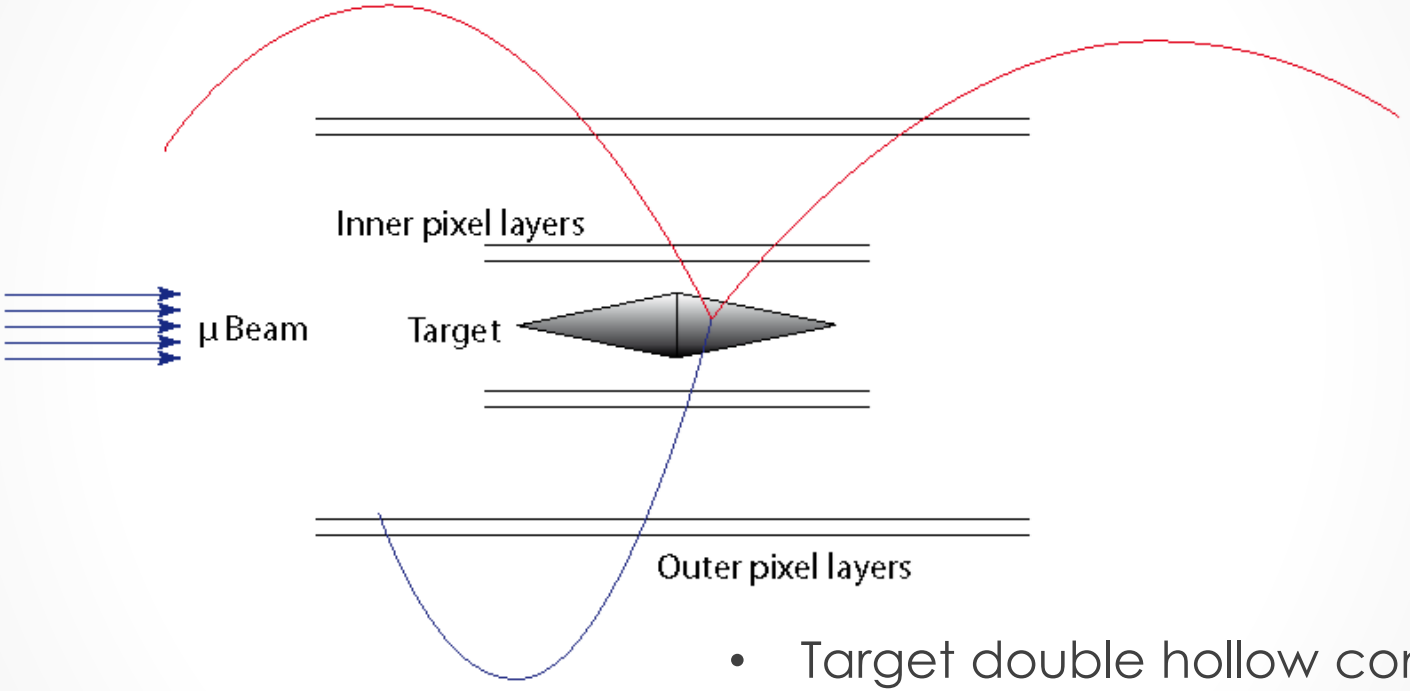
The Mu3e Experiment



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

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

The Mu3e Experiment



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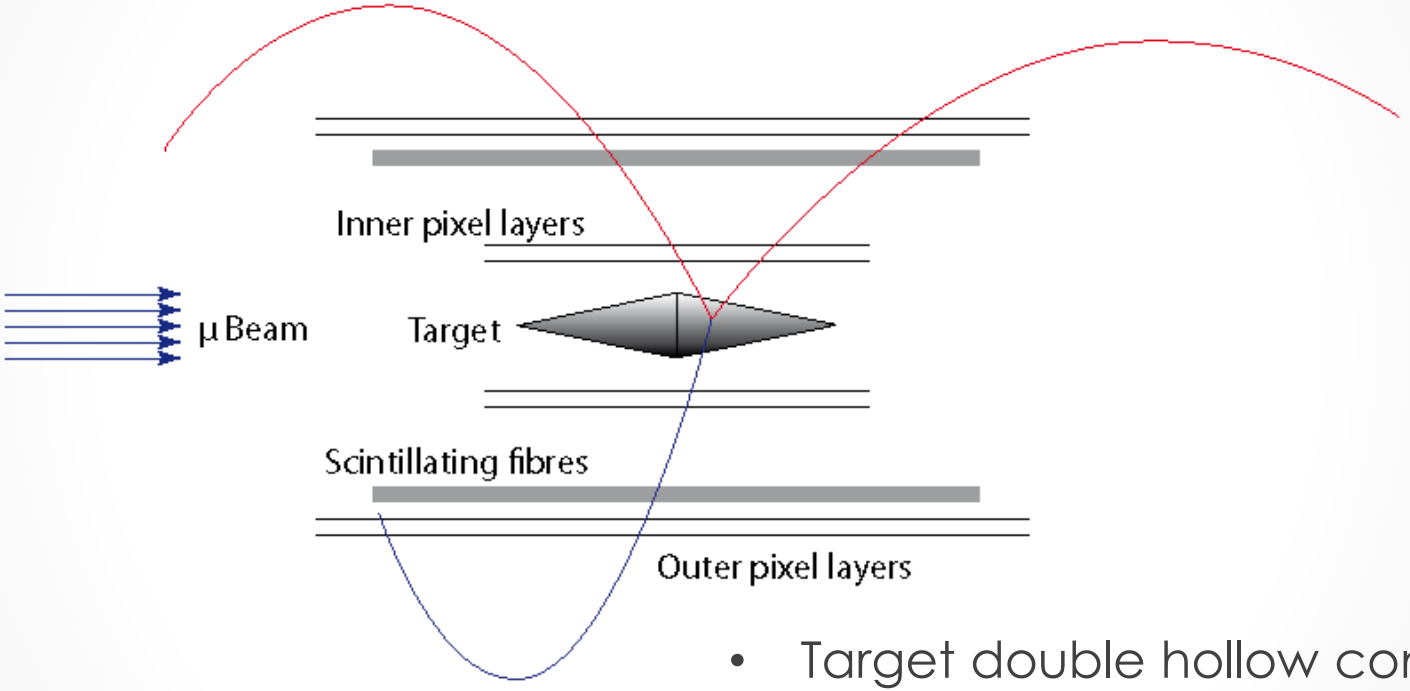

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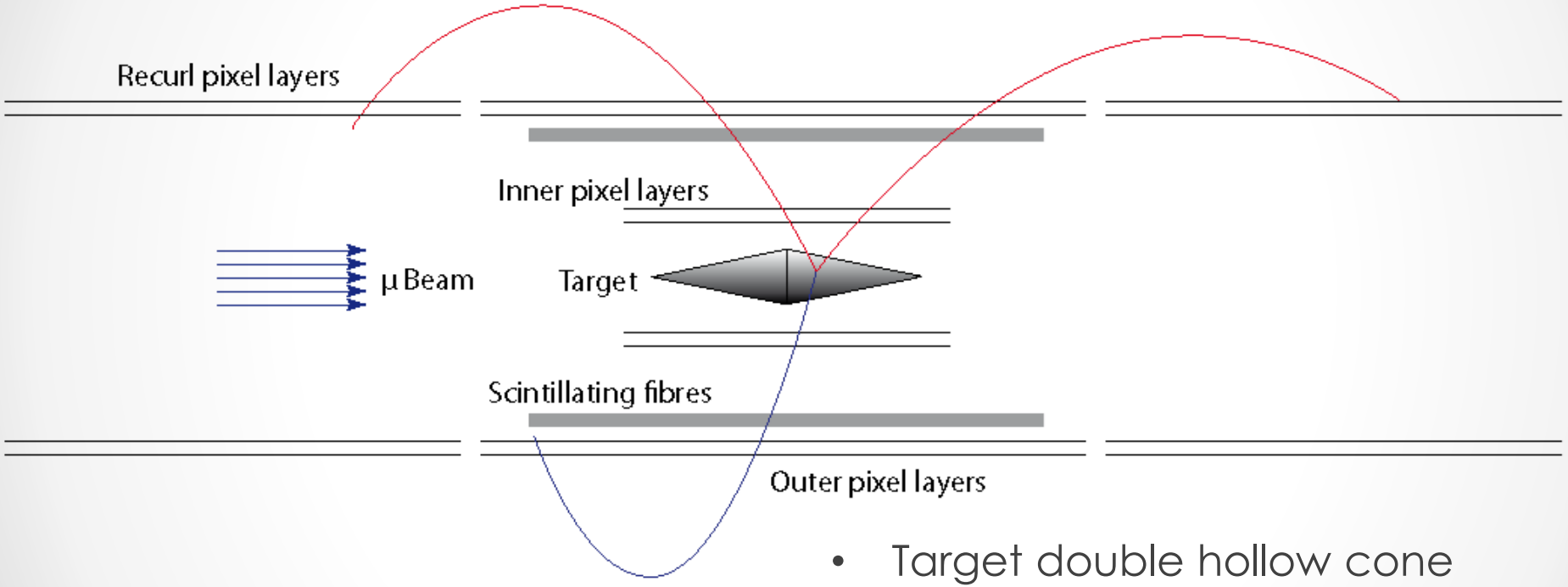

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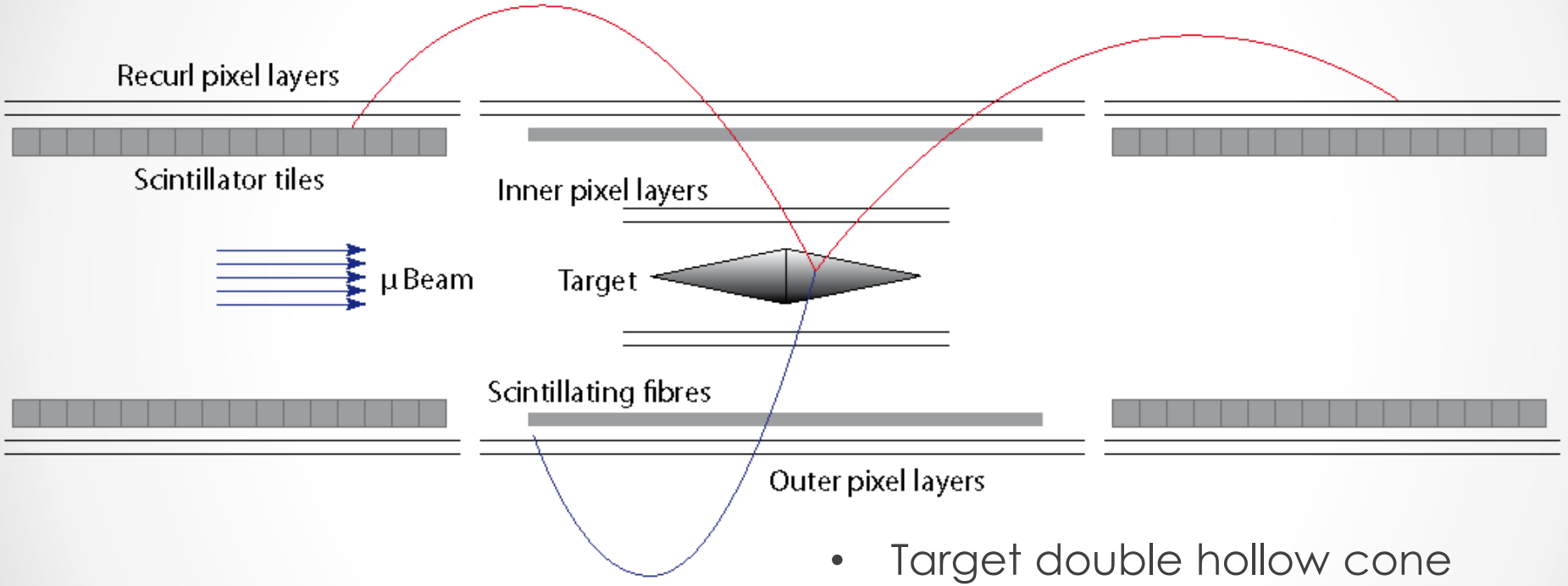

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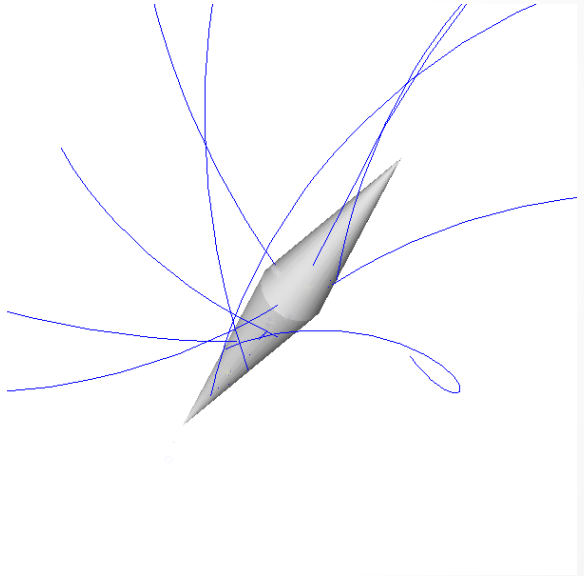
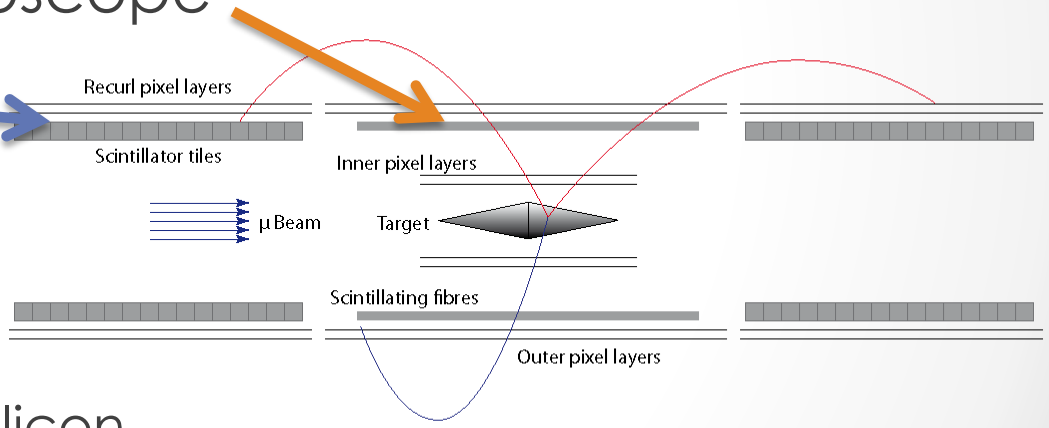
Readout Requirements

- 2.5 GHz muon decays
- 50 ns readout frames (pixel)
- O(5000) pixel chips
- O(7000) scintillating fibers
- O(7000) timing tiles
- Online filtering



Timing Detectors

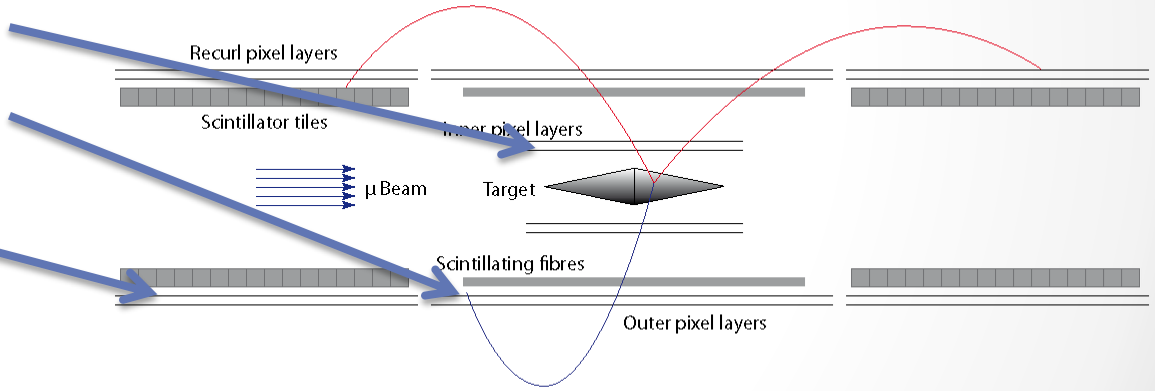
- Scintillating fiber hodoscope
- Timing tiles
- On detector zero-suppression
- Poster Session:
  - STiC - A Mixed Mode Silicon-Photomultiplier Readout ASIC for Time-of-Flight Applications (Tobias Harion)



O(7000) fibers
O(7000) tiles

Silicon Pixel Detector

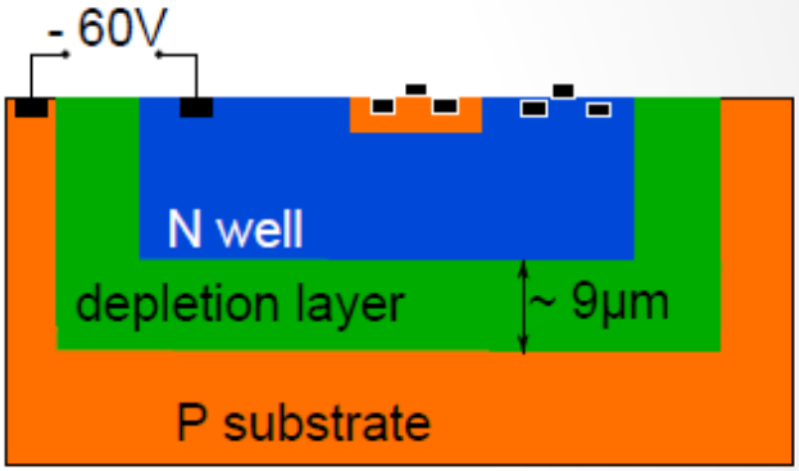
- Inner double layer
- Outer double layer
- Re-curl layers
  - Both sides (x2)
- Sensor size
  - 1x2 cm^2 inner layers
  - 2x2 cm^2 outer layers



180 inner sensors
4680 outer sensors

HV-MAPS

- **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
- HV-CMOS technology
- Reversely biased ~60V
  - Charge collection via drift
    - ➢ Fast O(100 ns)
  - Thinning to < 50 µm possible



by Ivan Peric

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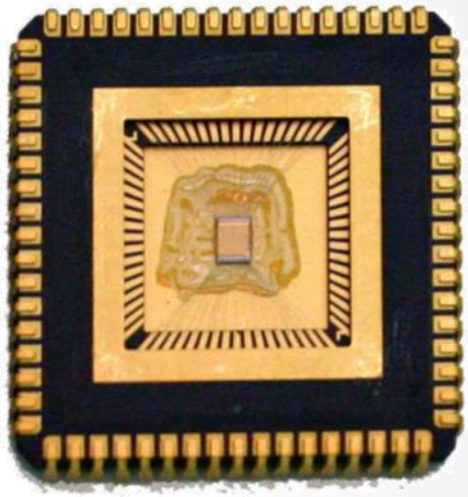

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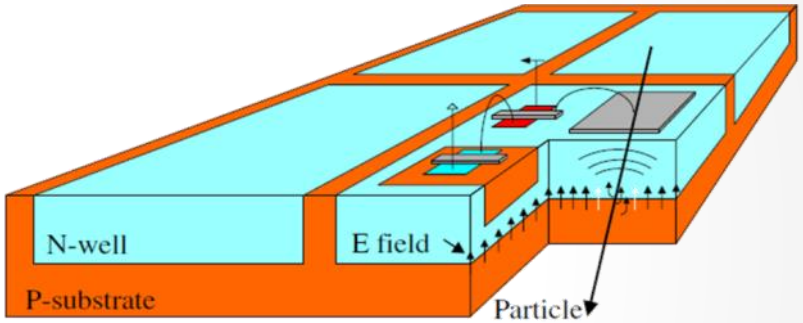
  - **Zero suppression**
  - **800Mbit/s serial LVDS outputs**



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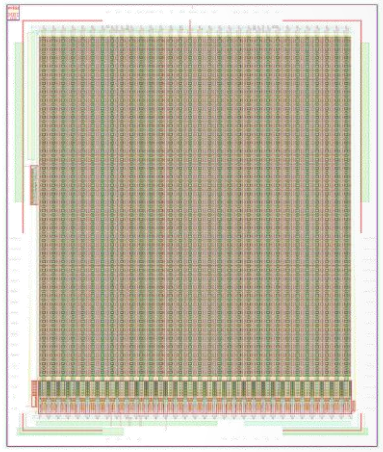

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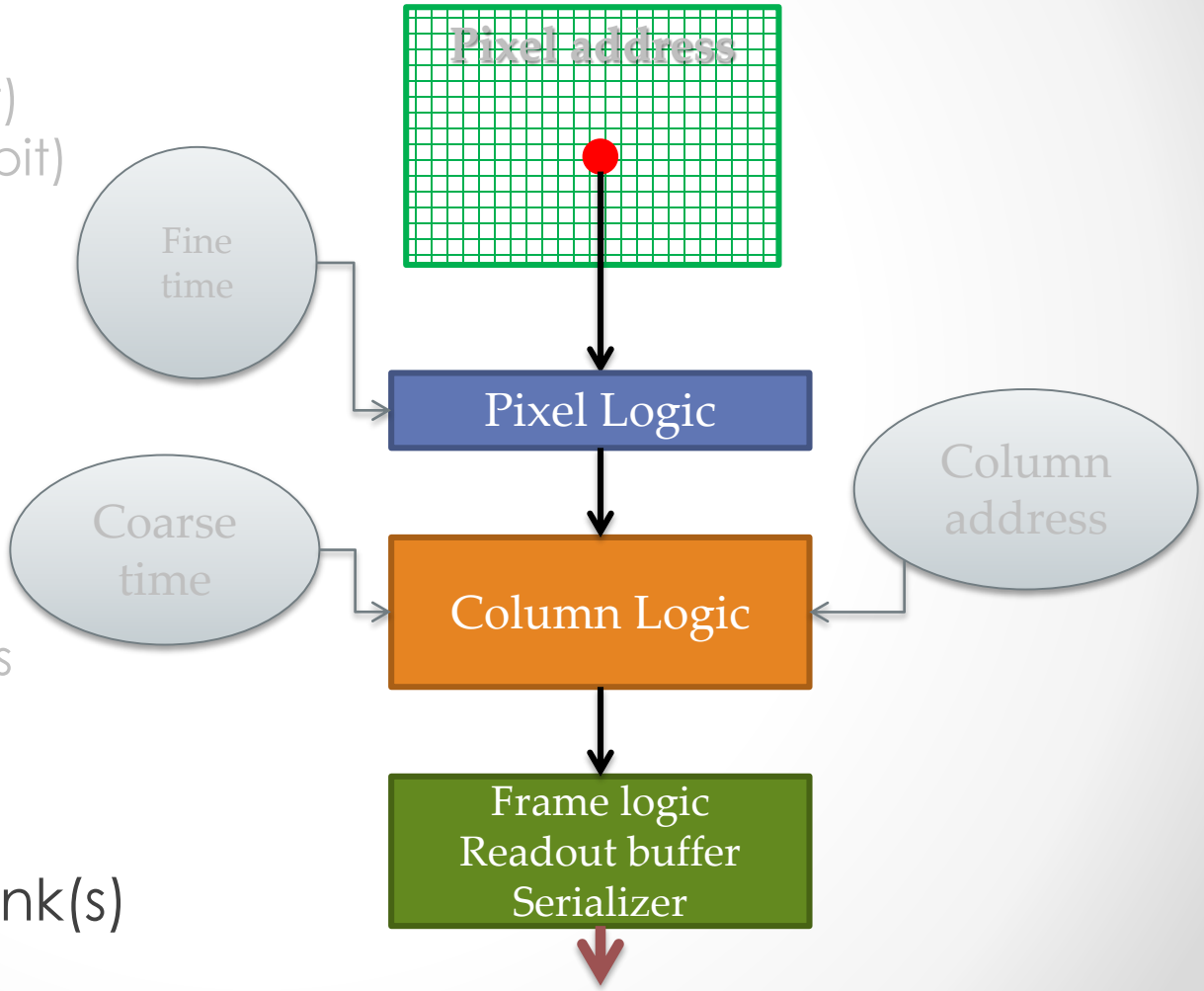
Pixel Readout Scheme

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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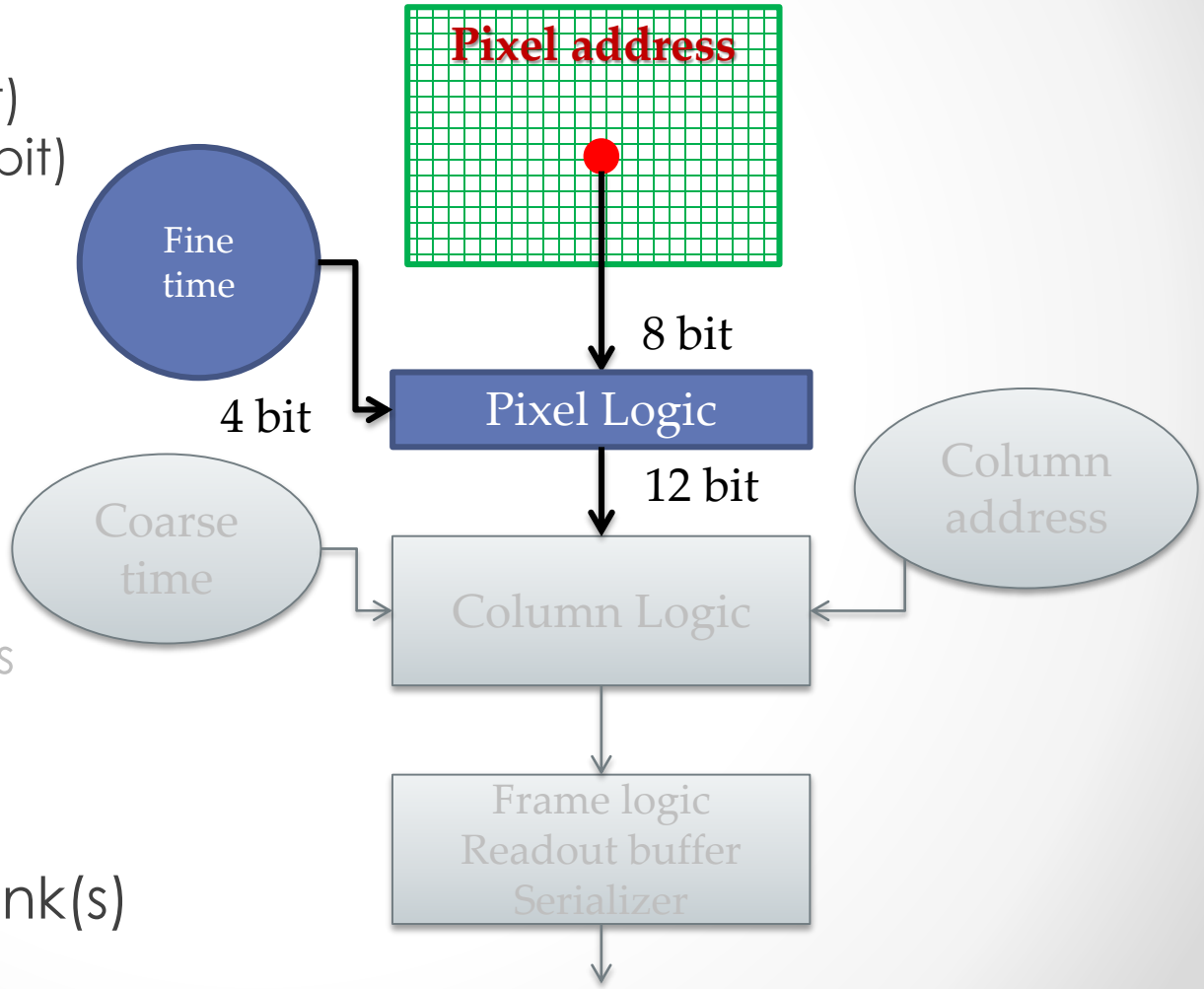

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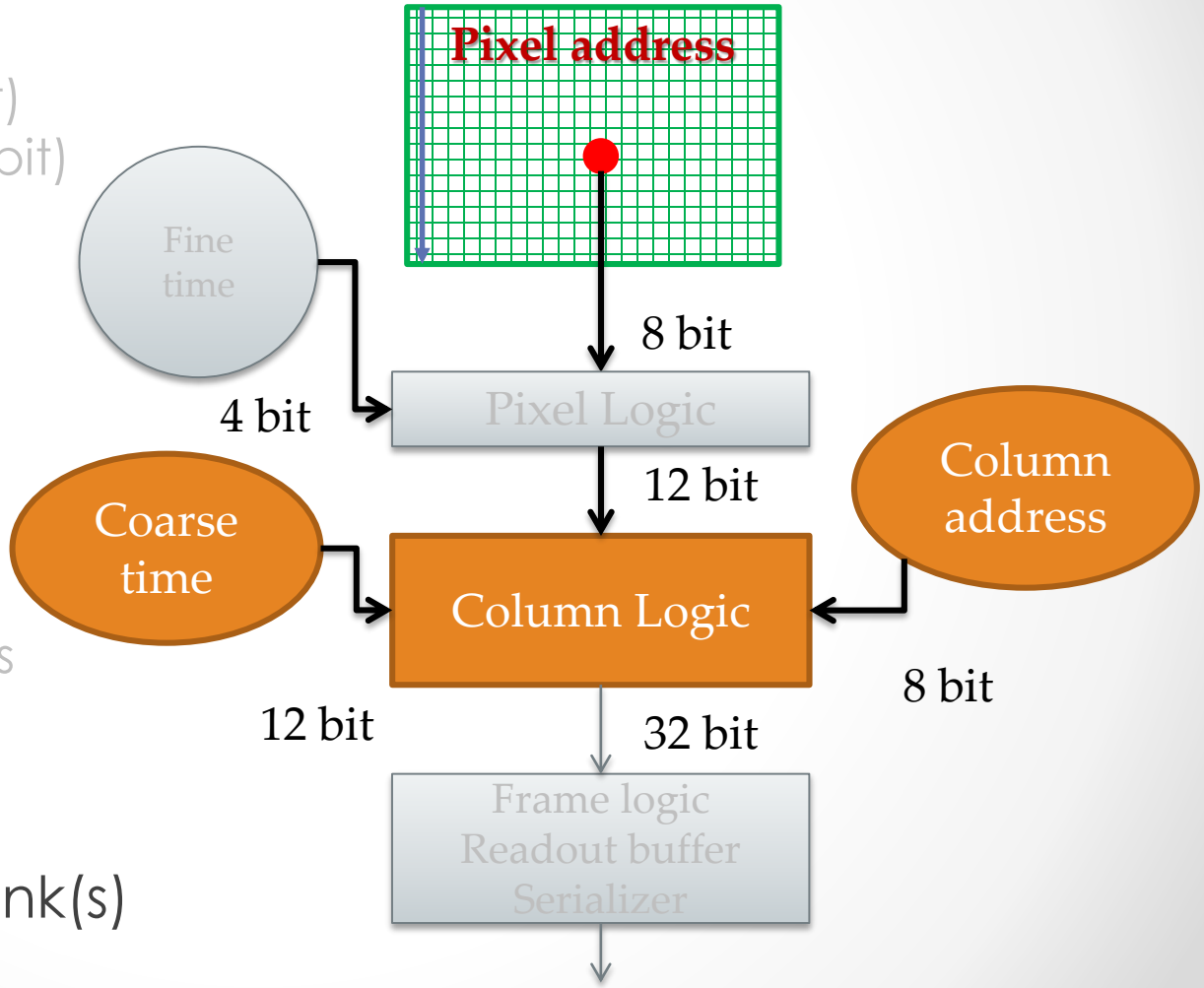

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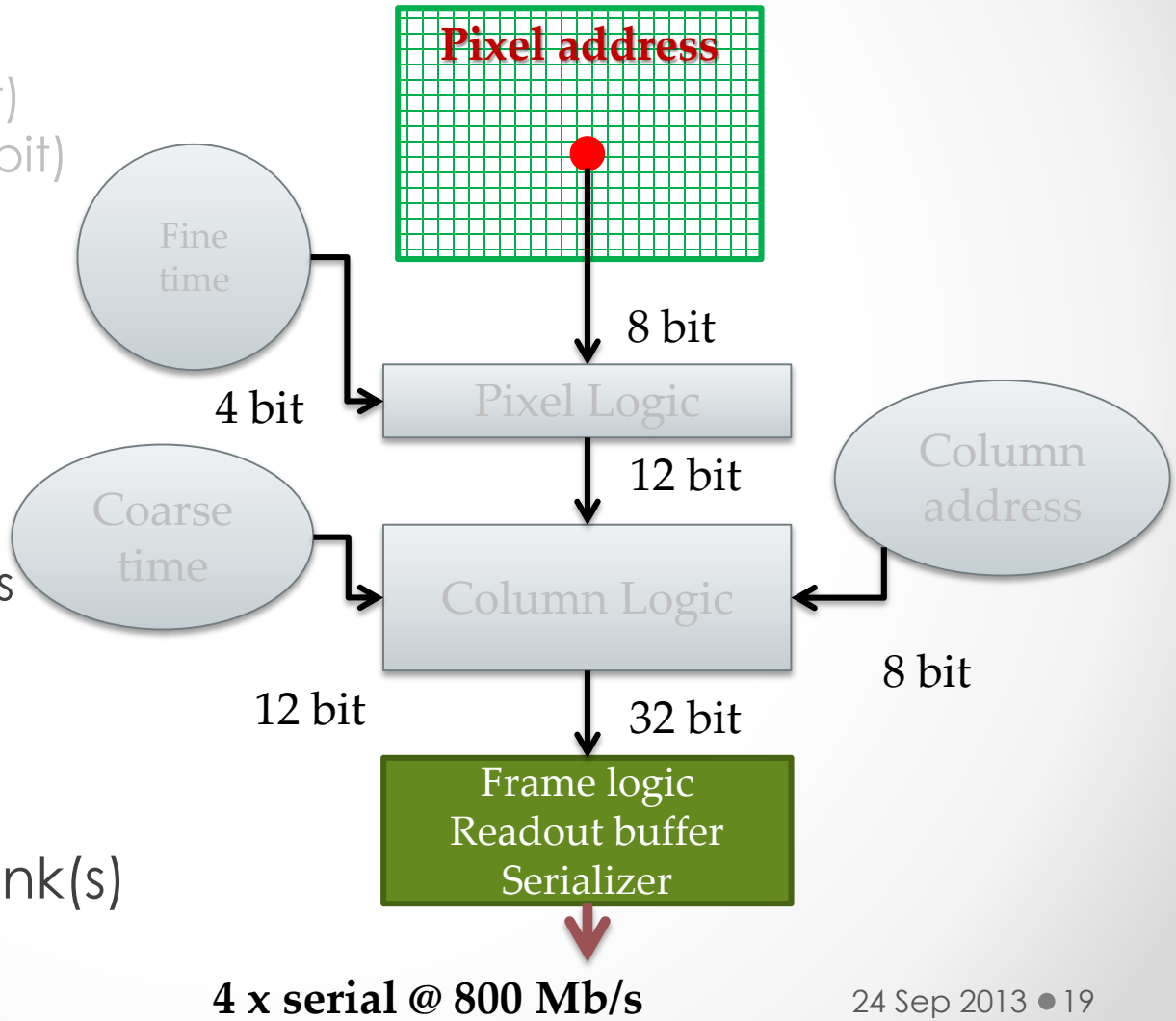
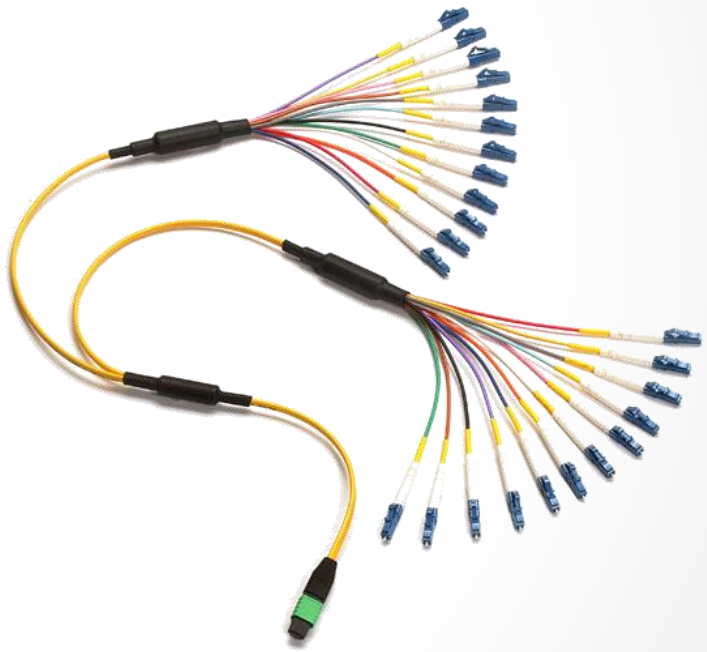


Data Link Scheme

From detector slices
to time slices

Link Overview

- 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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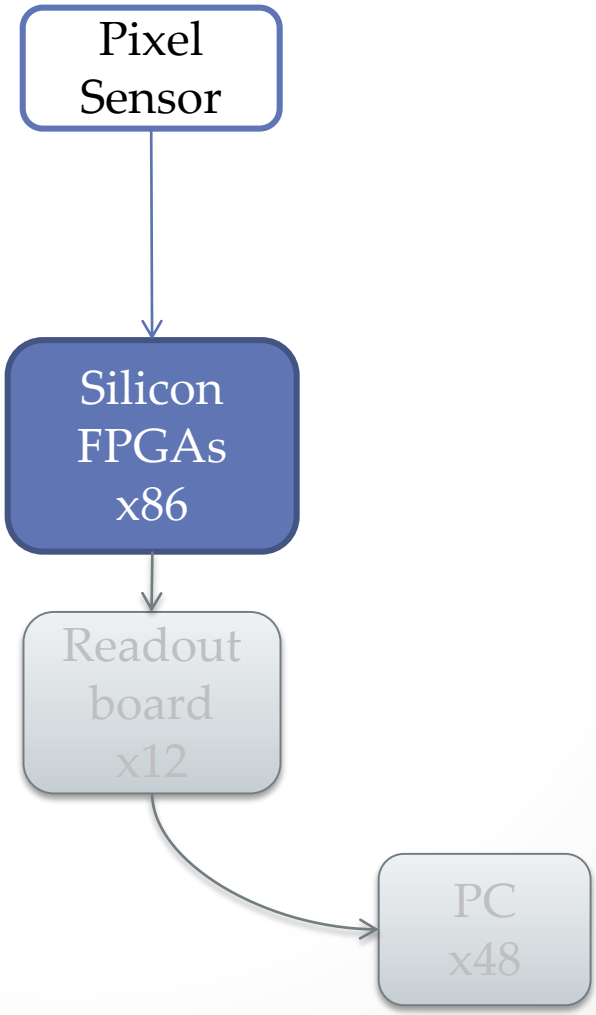

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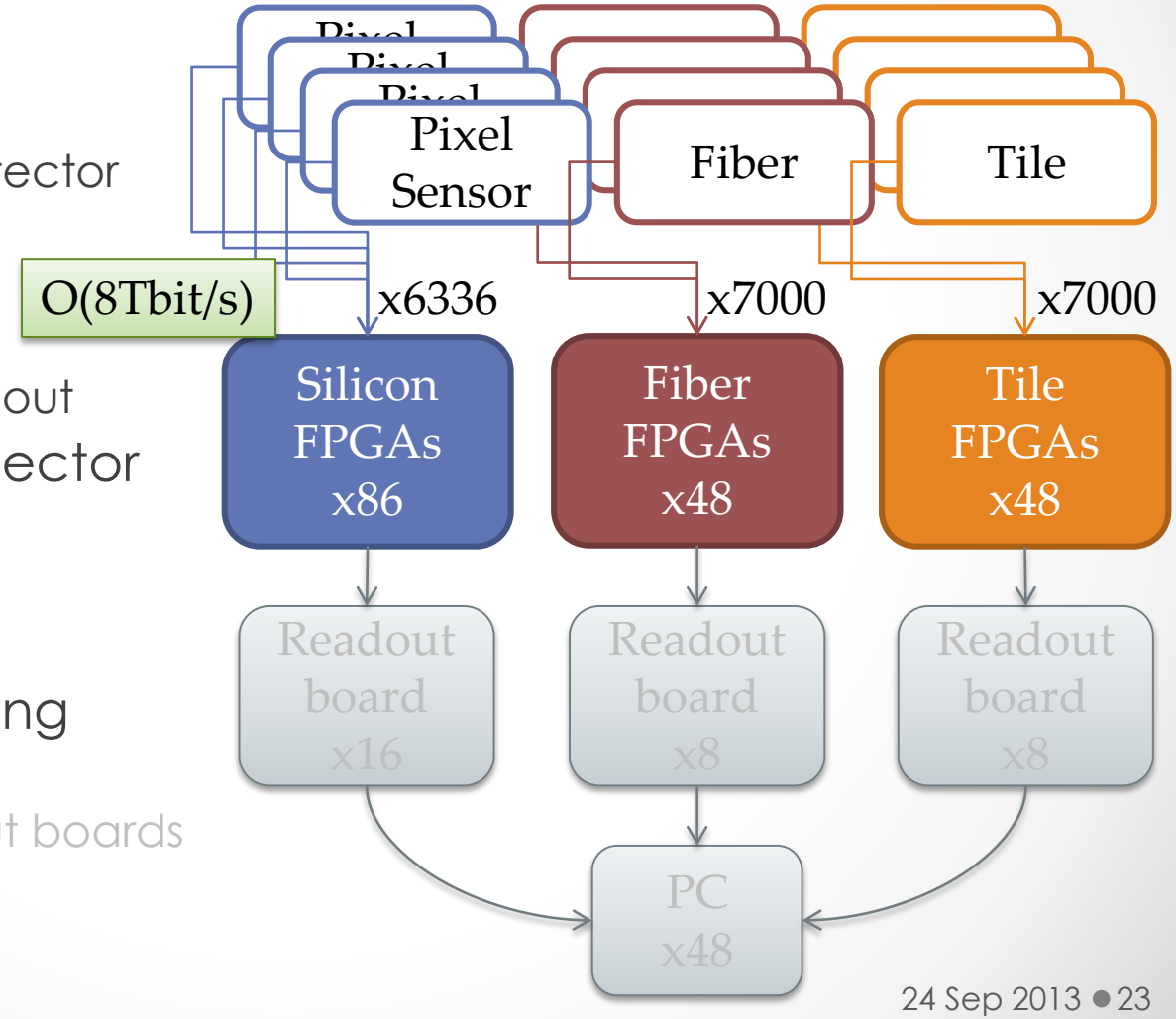

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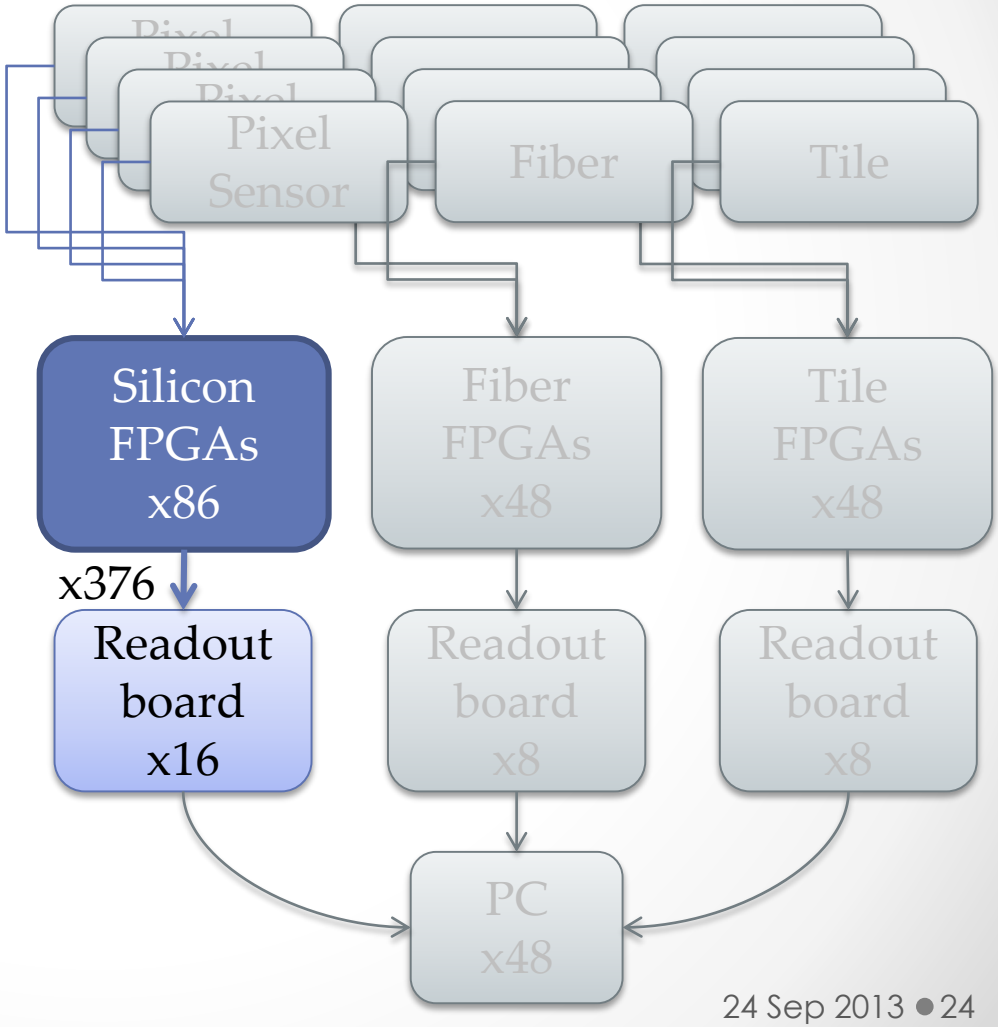

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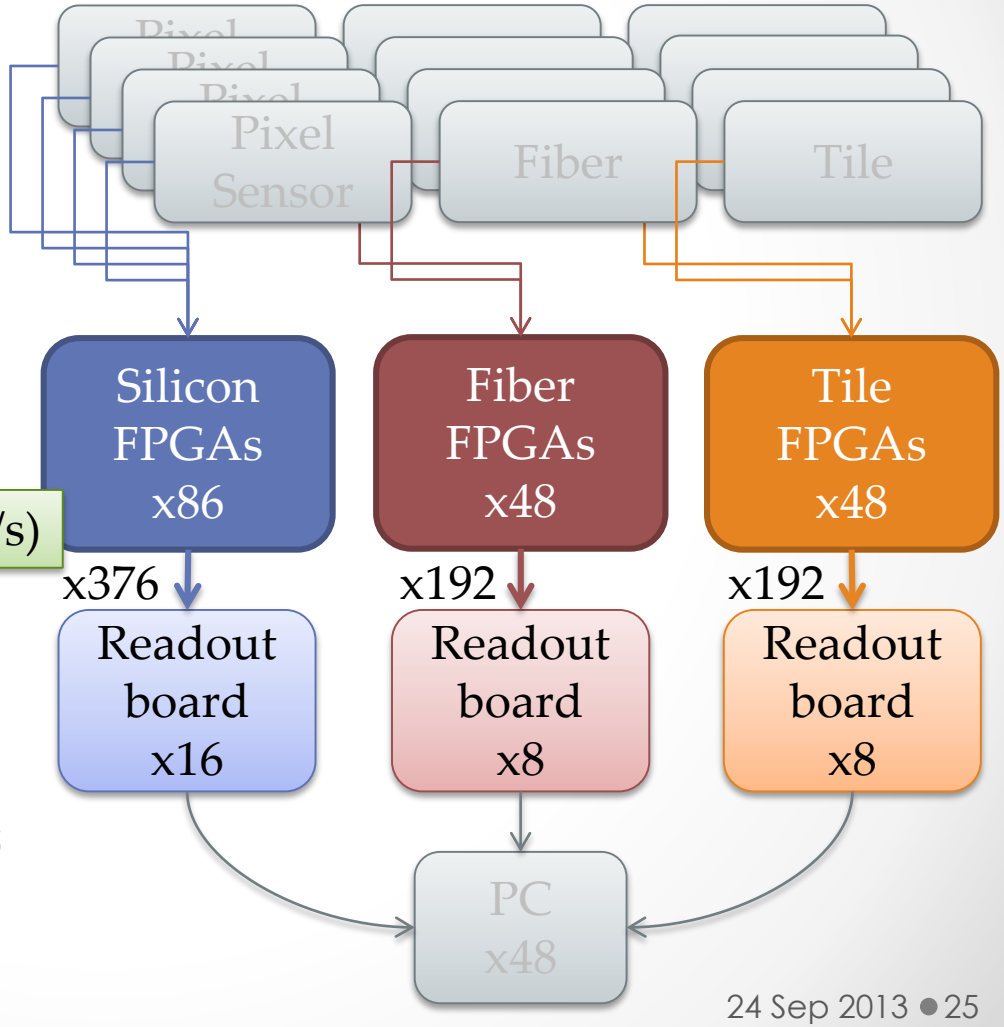

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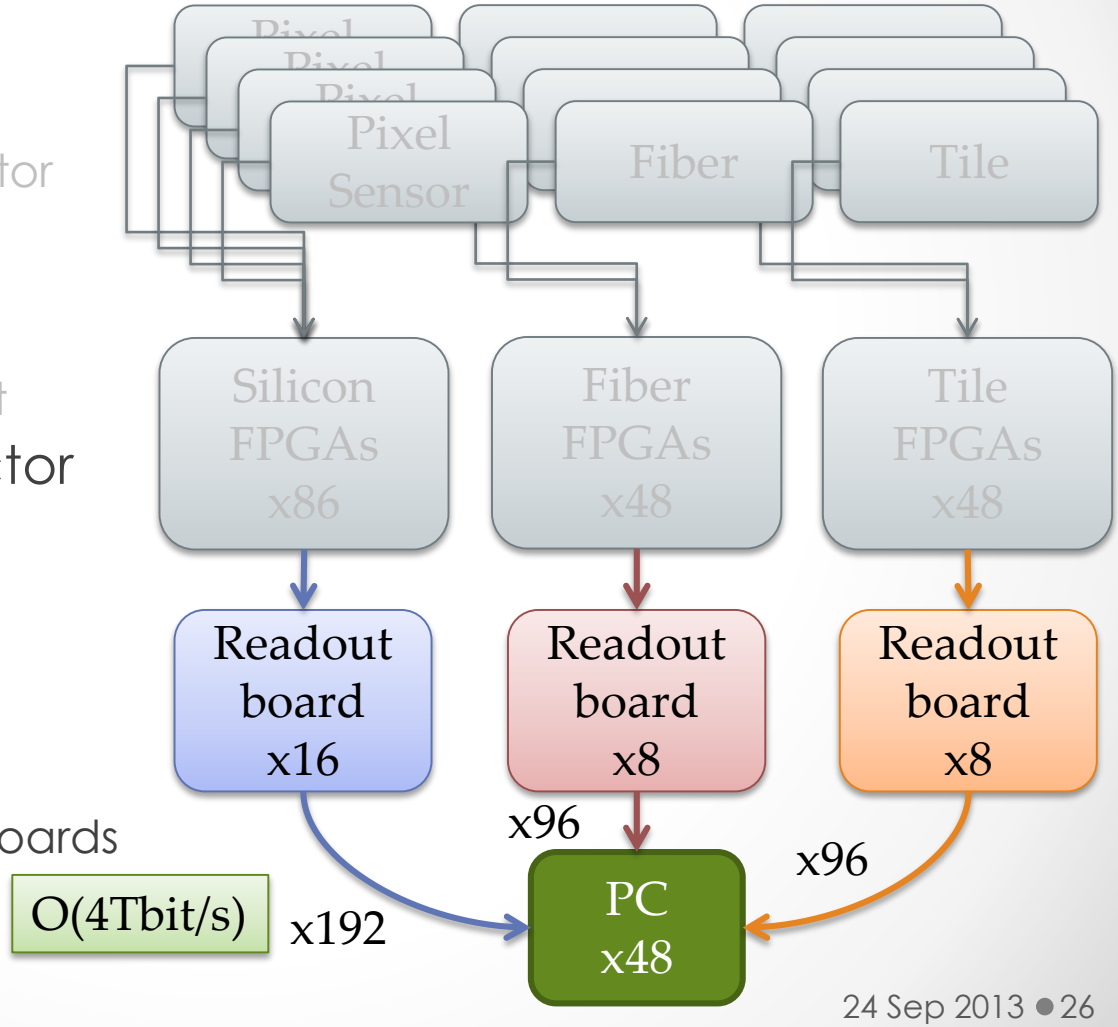
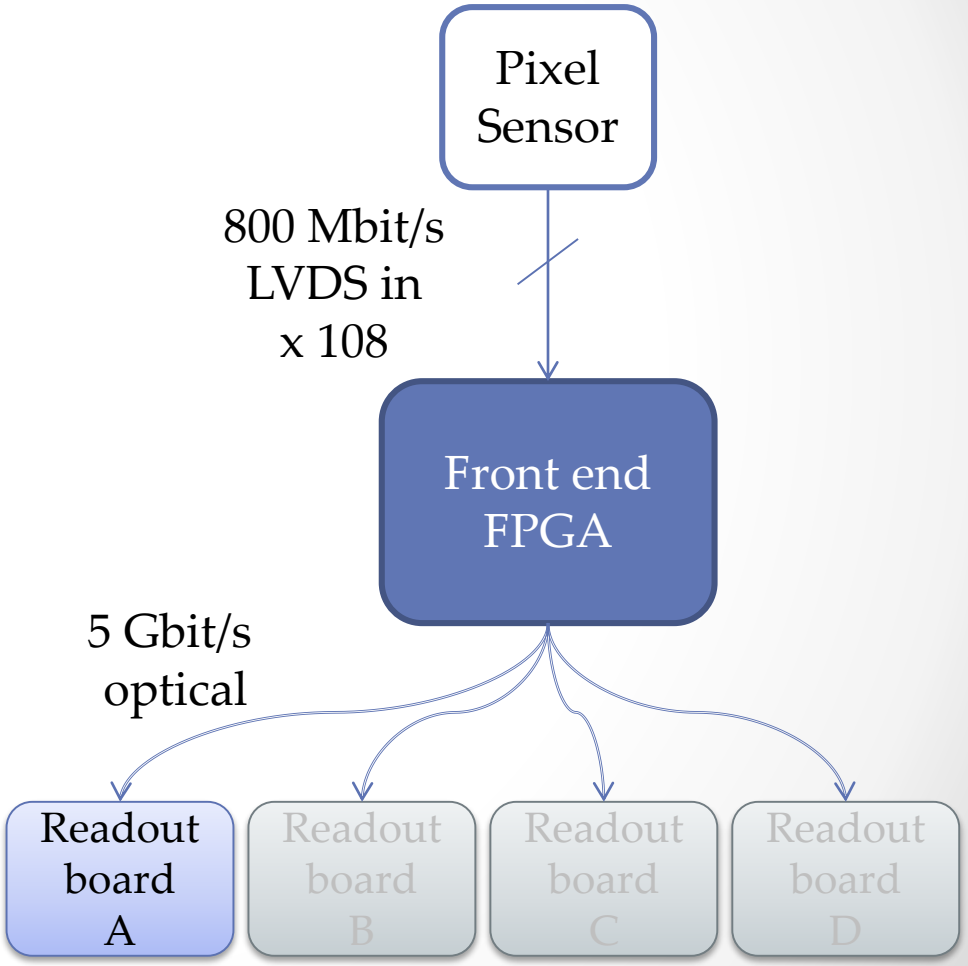


Front End FPGAs

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



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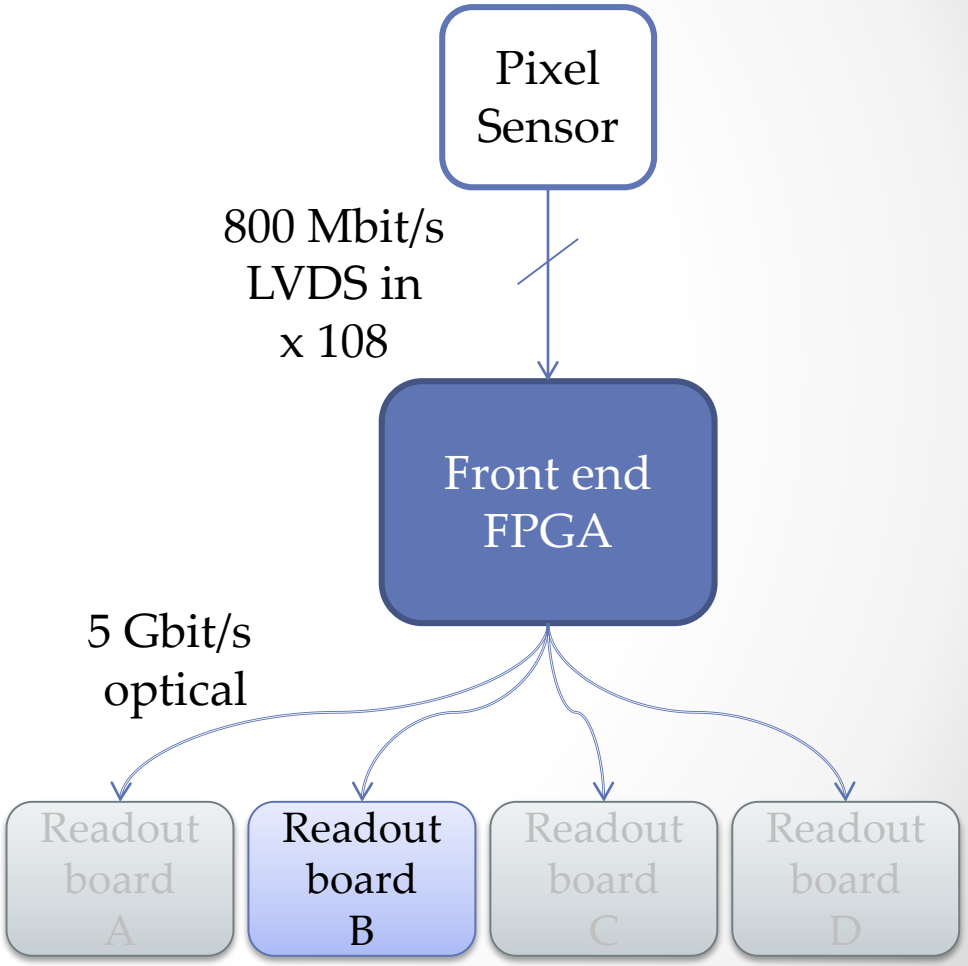

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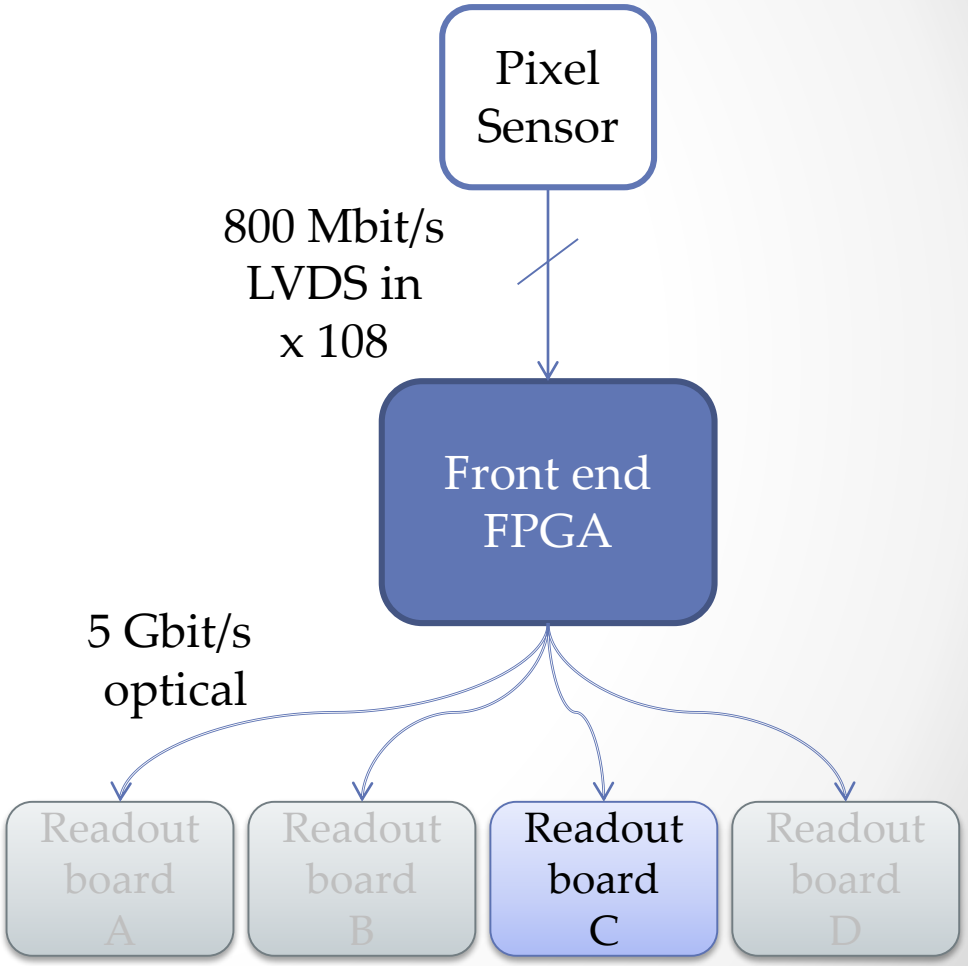

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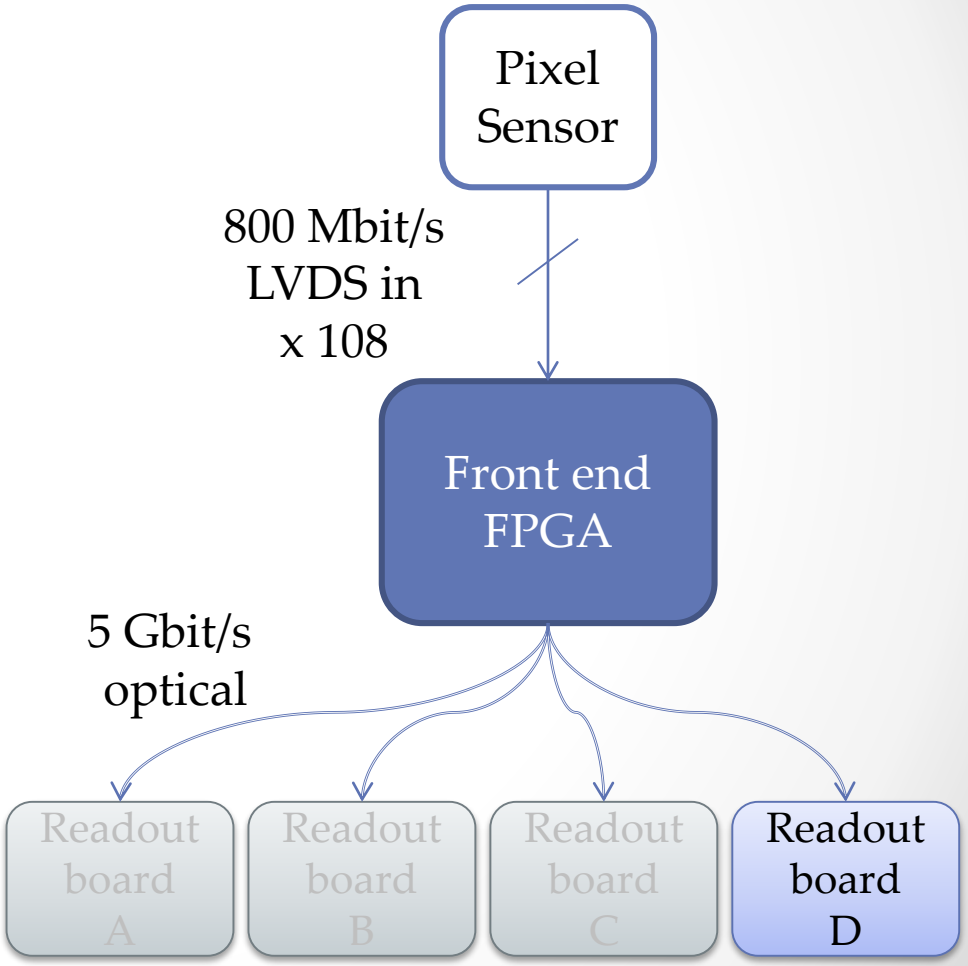
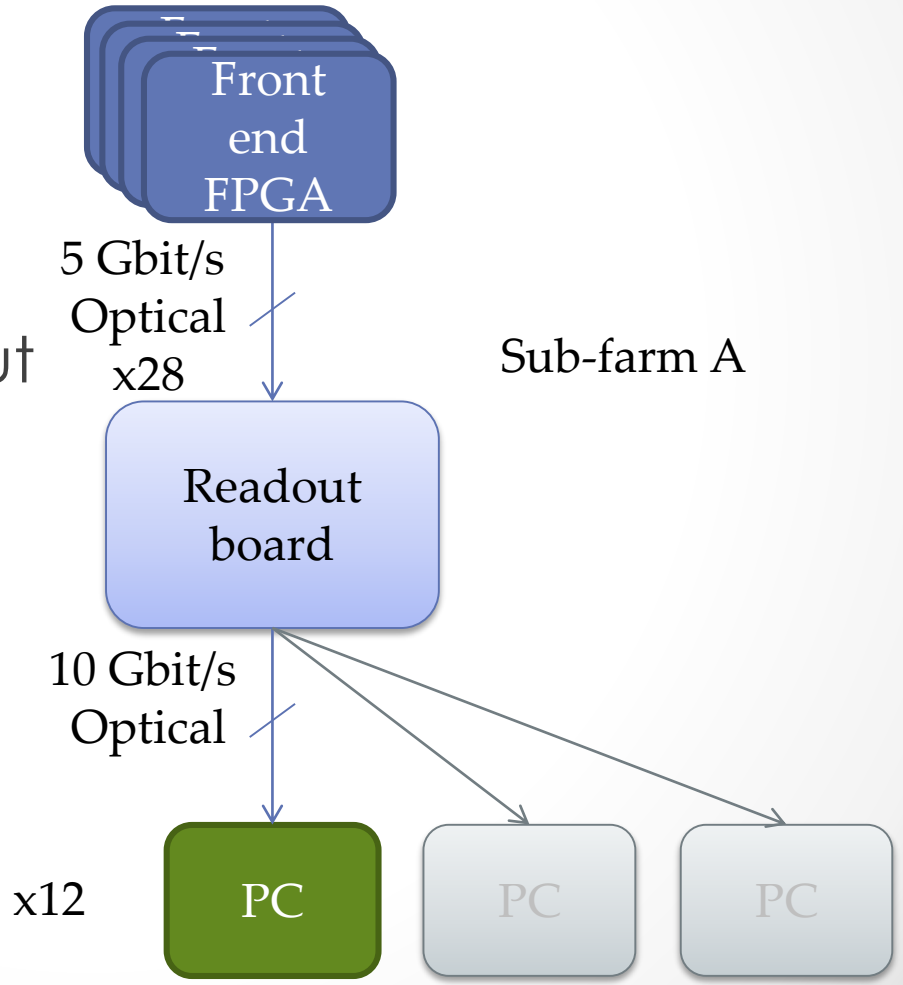


Readout Board

- 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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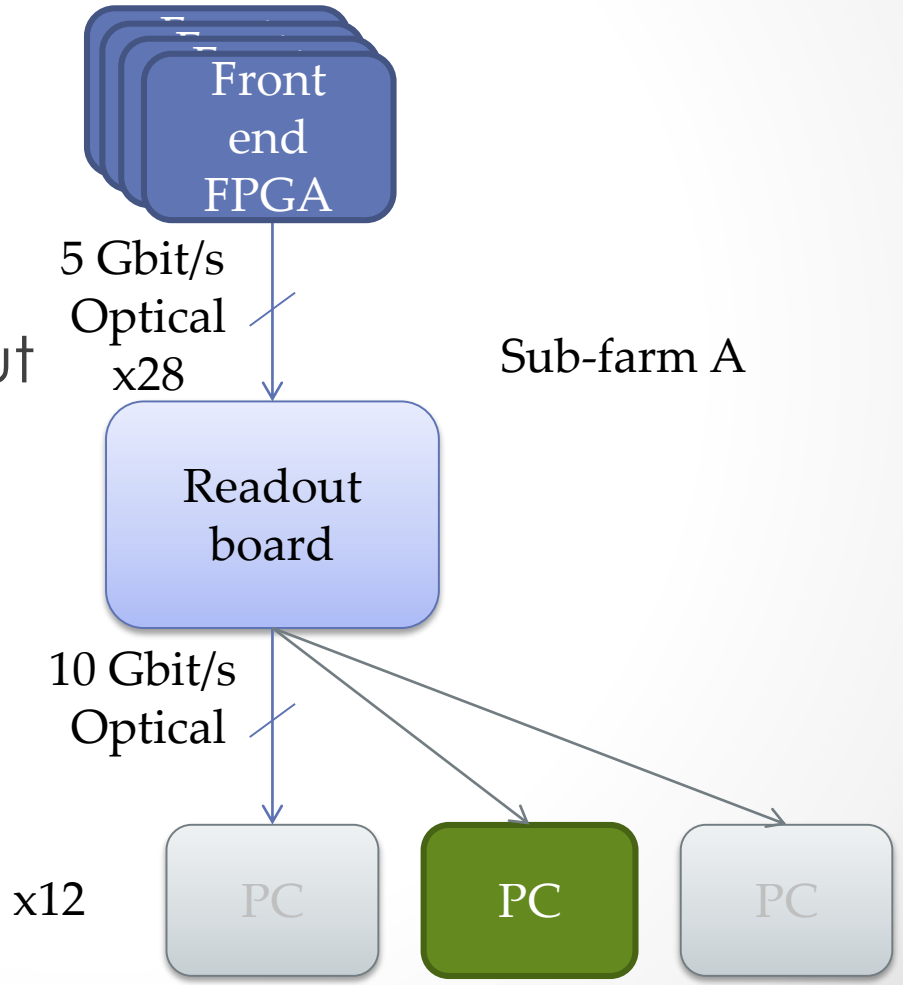

GPU-PC

- 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

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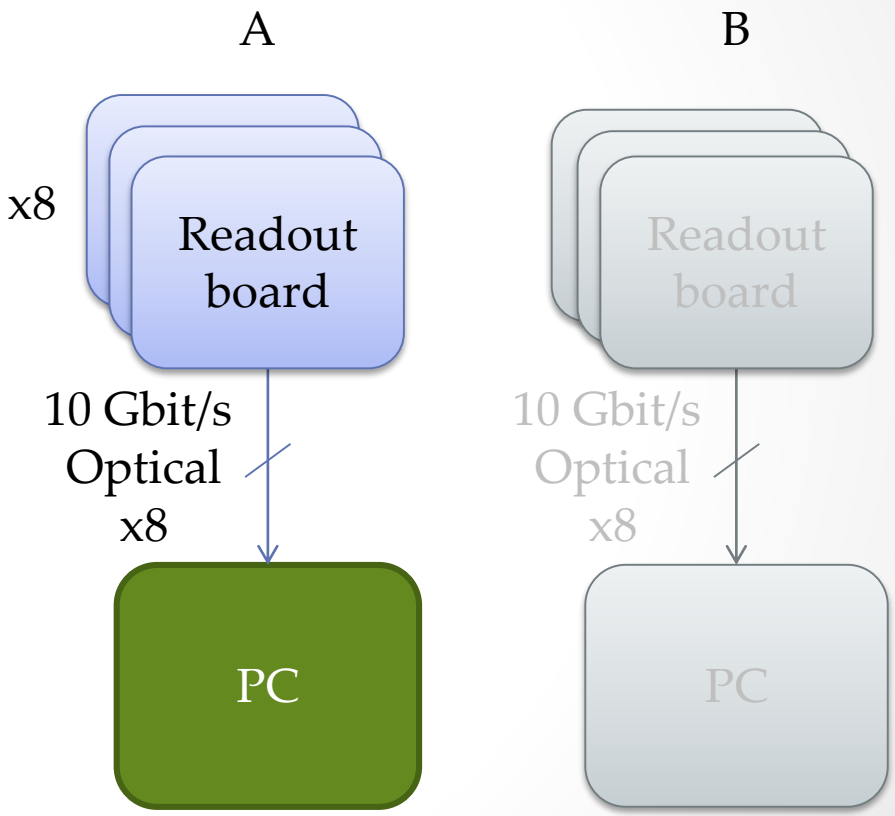
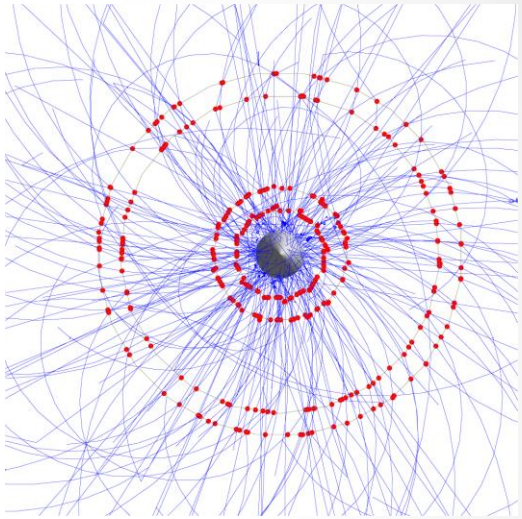
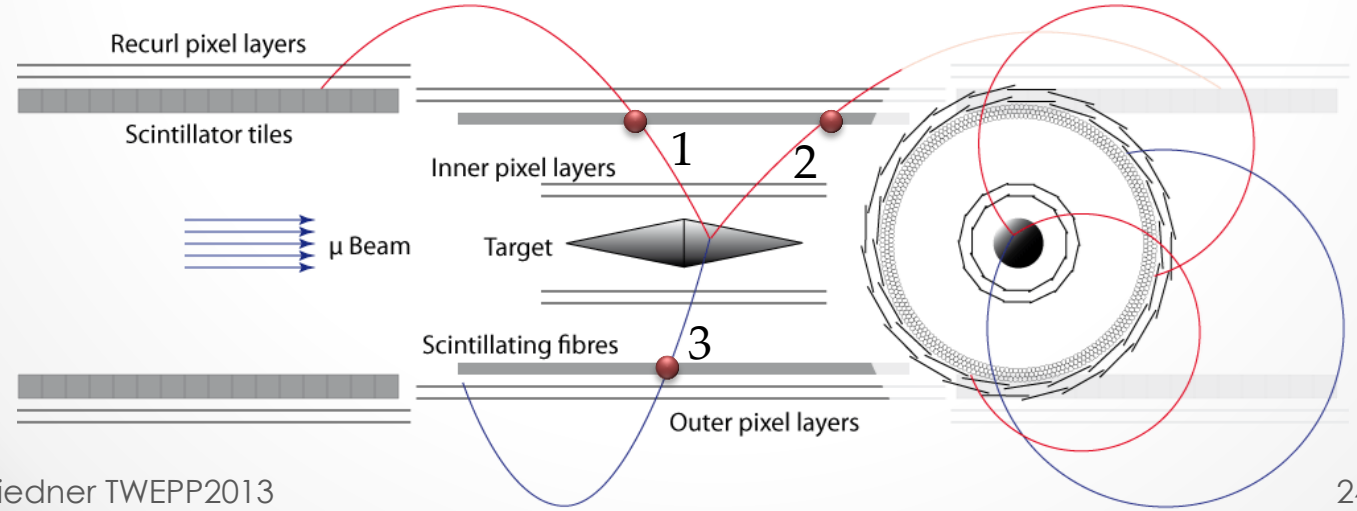


Timing Filter

- 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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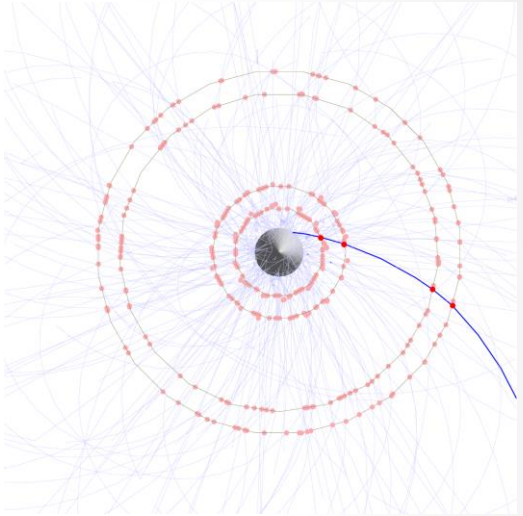
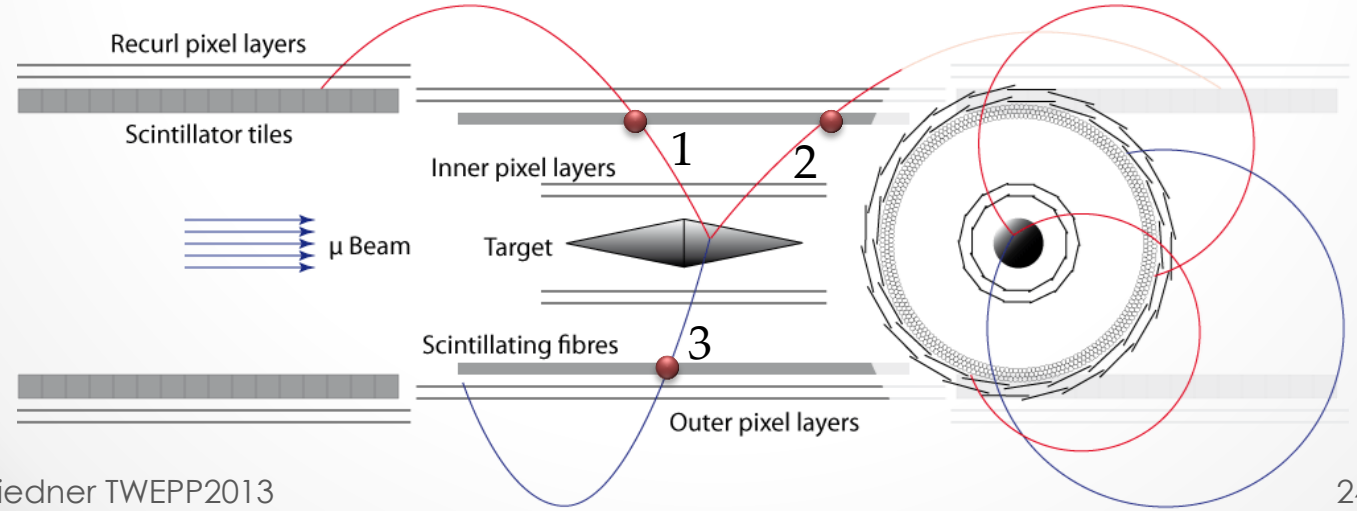
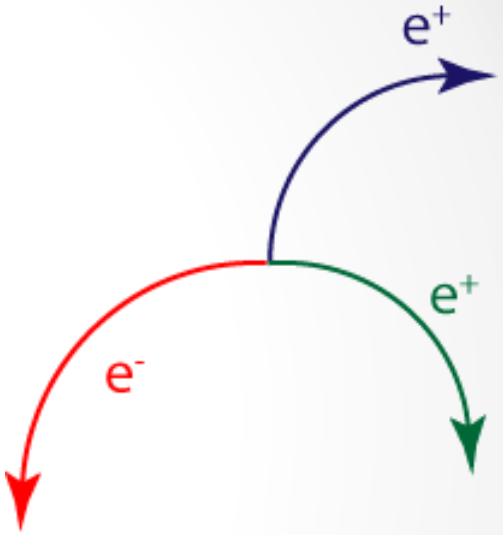
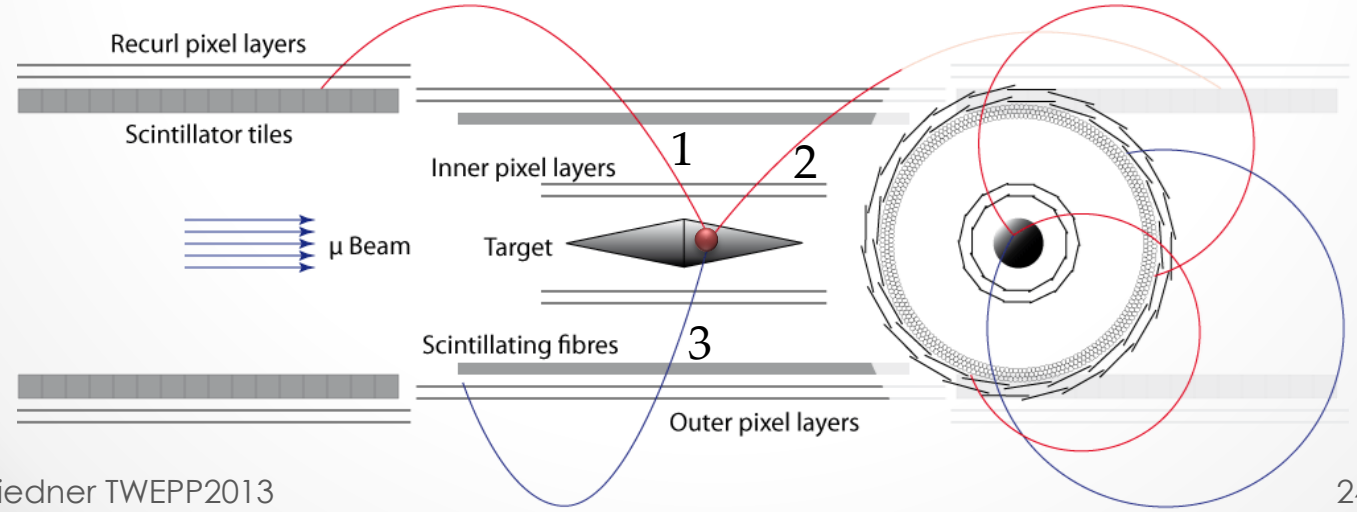




Vertex Filter

- 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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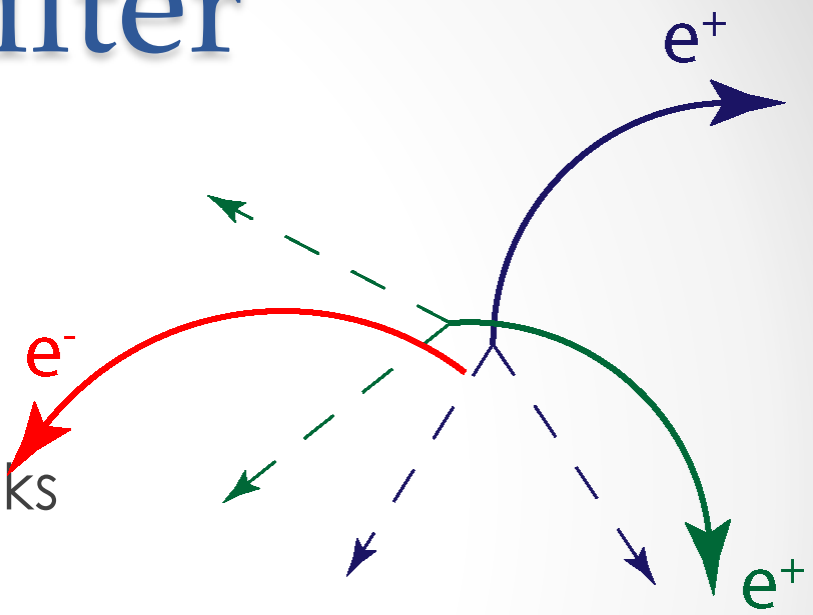
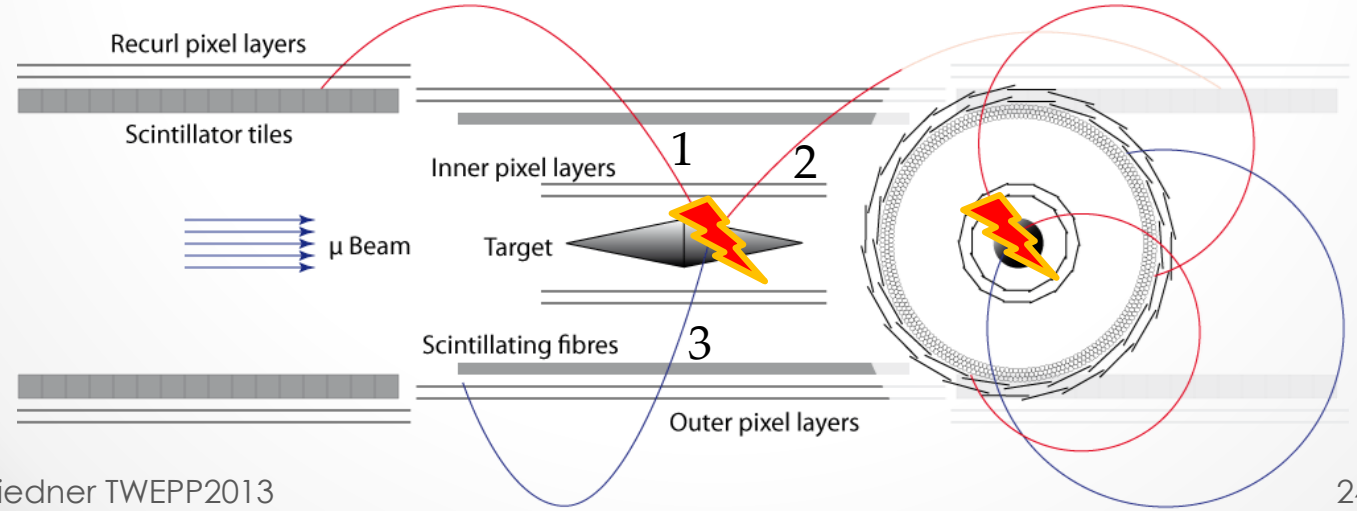
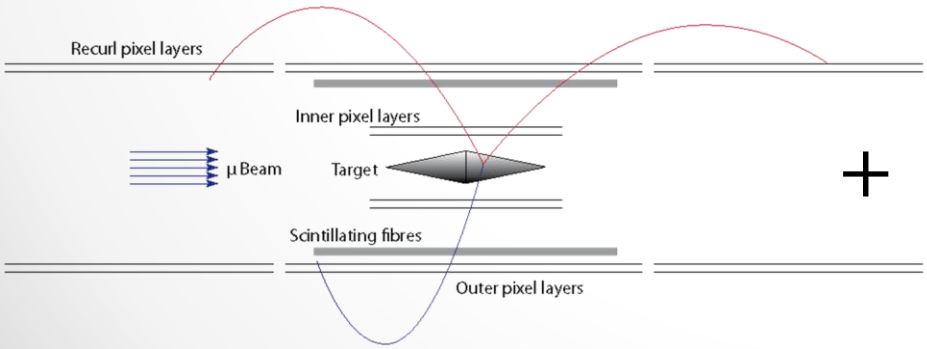
- Reject data without three tracks
  - … inside area interval on target





Summary

- Mu3e has 280M pixels @ >10^9 muons/s
- >1 Tbit/s data
- 0-suppressed serial data from active pixel sensors
- Switched optical network
- GPU filter farm with optical inputs



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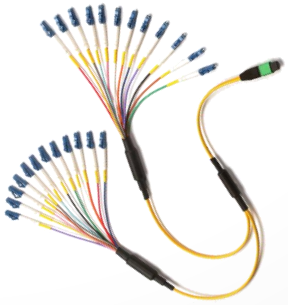

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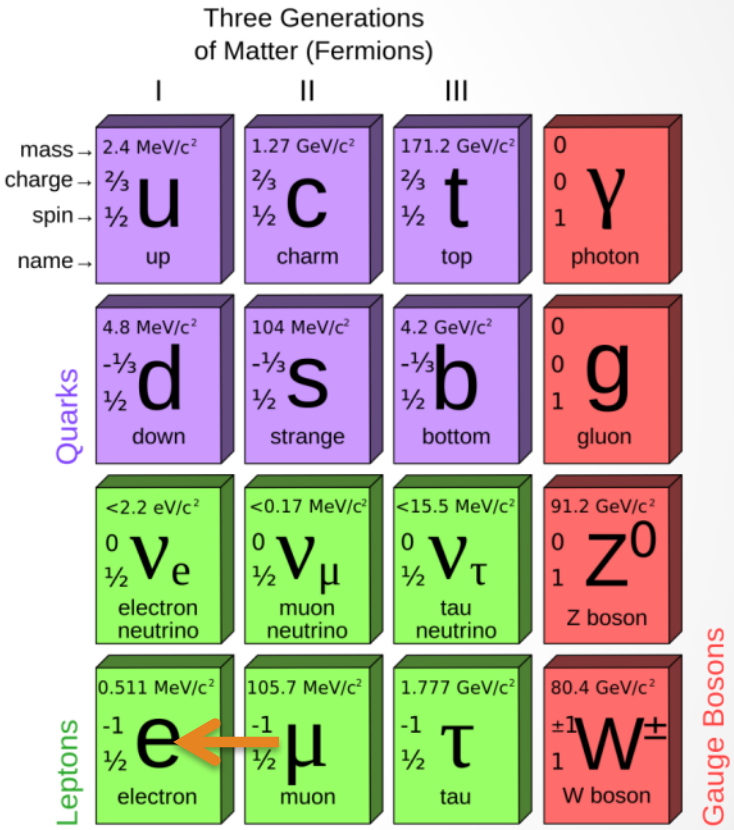
Backup Slides

Physics Motivation

Lepton flavor violation?

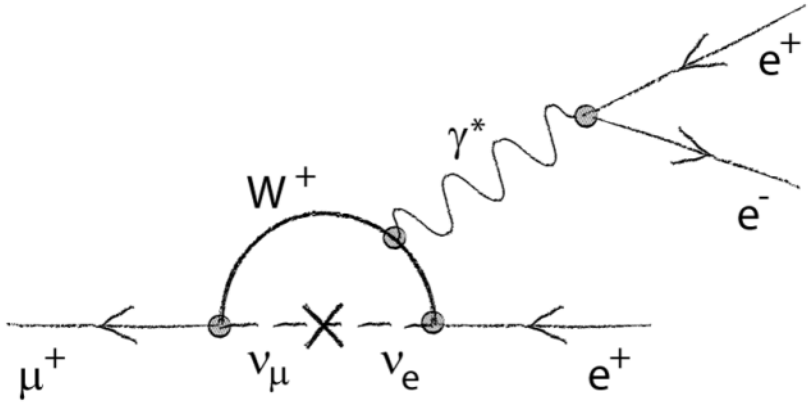


Standard model:

- No lepton flavor violation

Physics Motivation

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

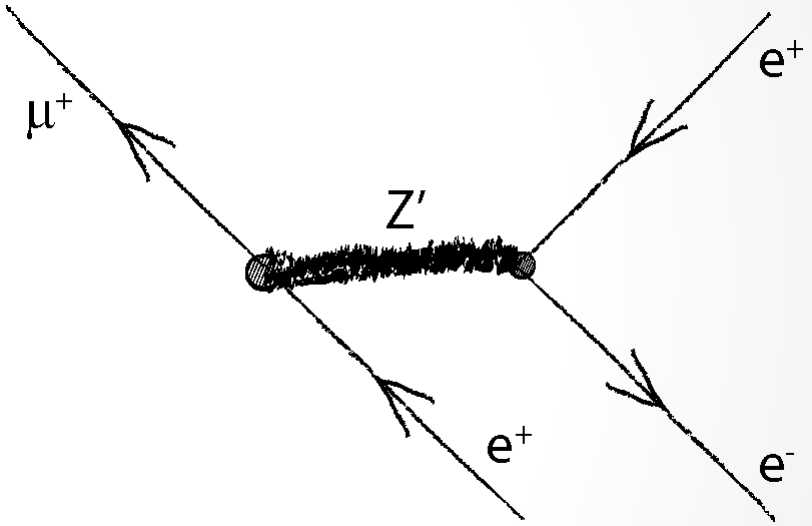


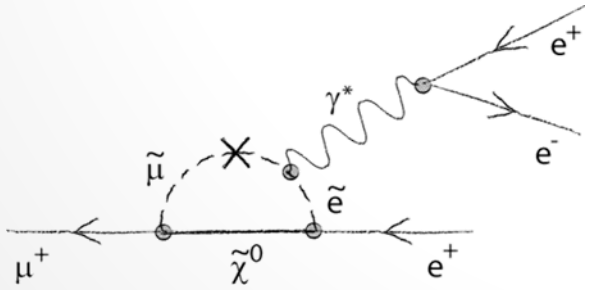
Standard model:

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

The Mu3e Signal

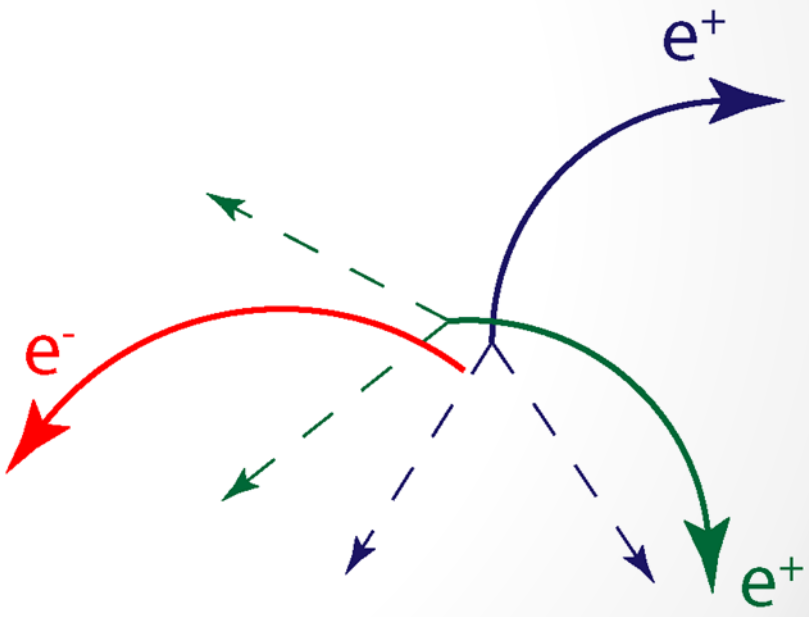
- μ→eee rare in SM
- Enhanced in:
  - Super-symmetry
  - Grand unified models
  - Left-right symmetric models
  - Extended Higgs sector
  - Large extra dimensions





The Mu3e Background

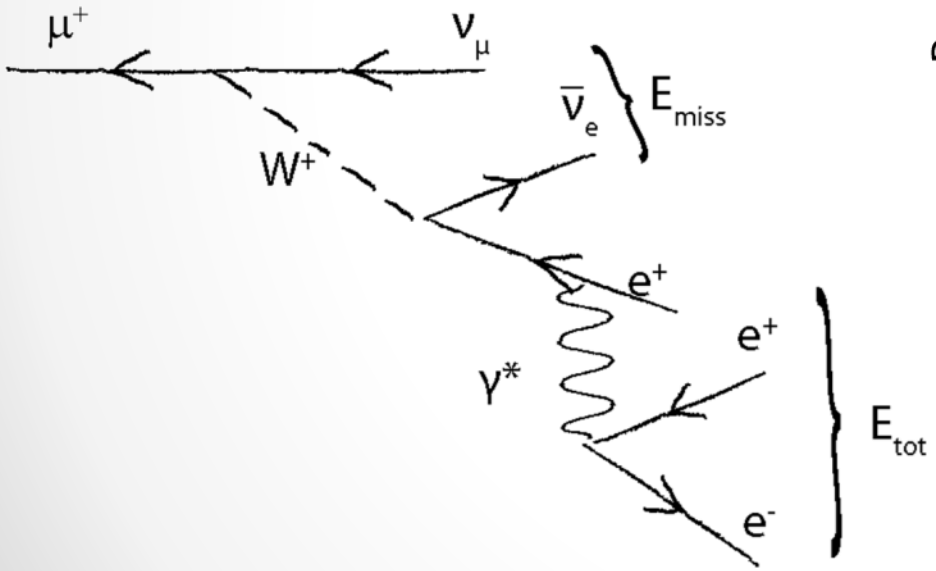
- Combinatorial background
  - $\mu^+ \rightarrow e^+\nu\nu$ & $\mu^+ \rightarrow e^+\nu\nu$ & e^+e^-
  - many possible combinations

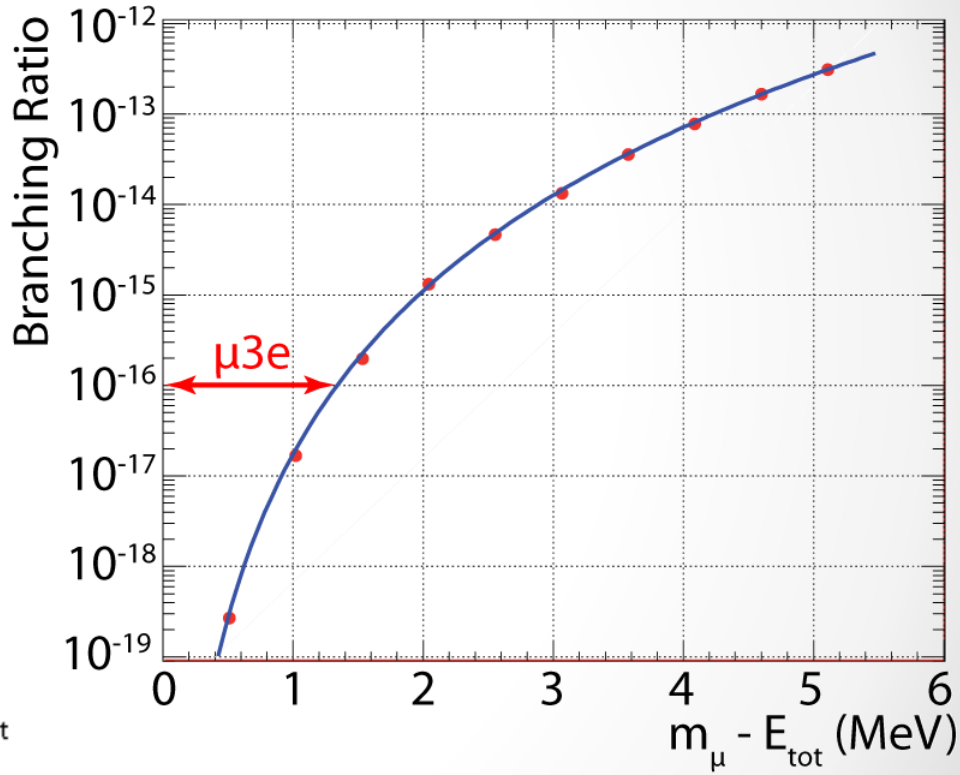


- ➢ Good time and
- ➢ Good vertex resolution required

The Mu3e Background

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

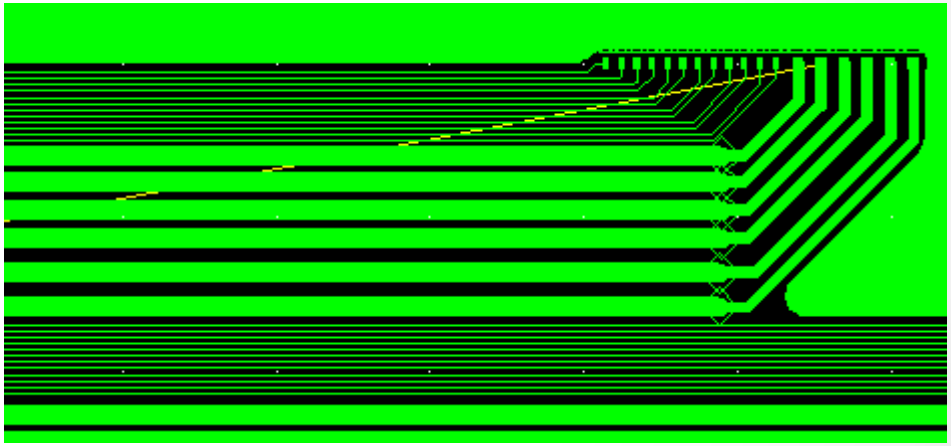




(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

Pixel Sensor Links

- Vertex Sensor chips
  - 180 chips
  - 4 LVDS links
  - 800 Mbit/s per link
- Central Silicon Tracker
  - 936 chips
  - 2 LVDS links
  - 800 Mbit/s
- Recurl stations
  - 3744 chips
  - 1 LVDS link
  - 400 Mbit/s



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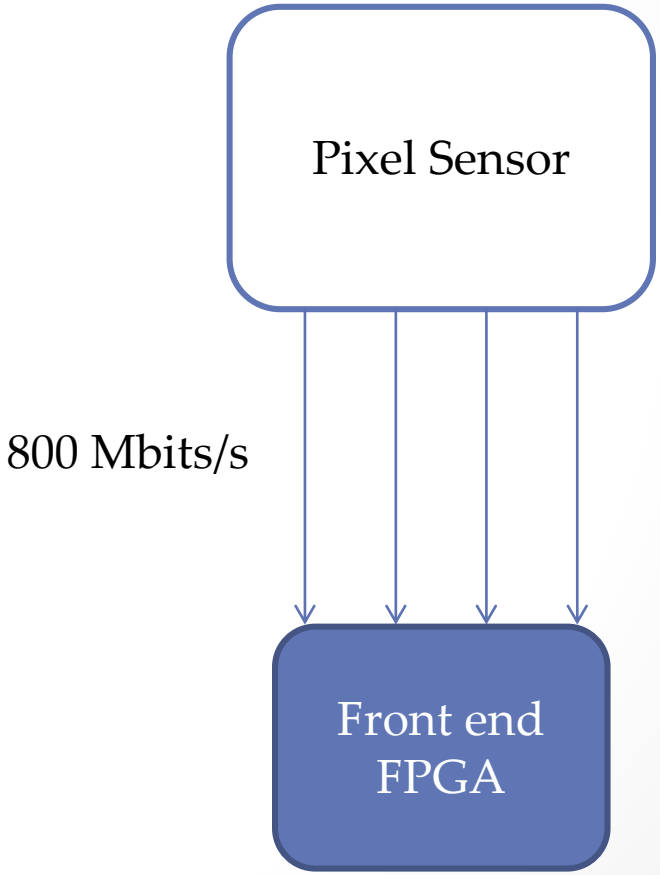


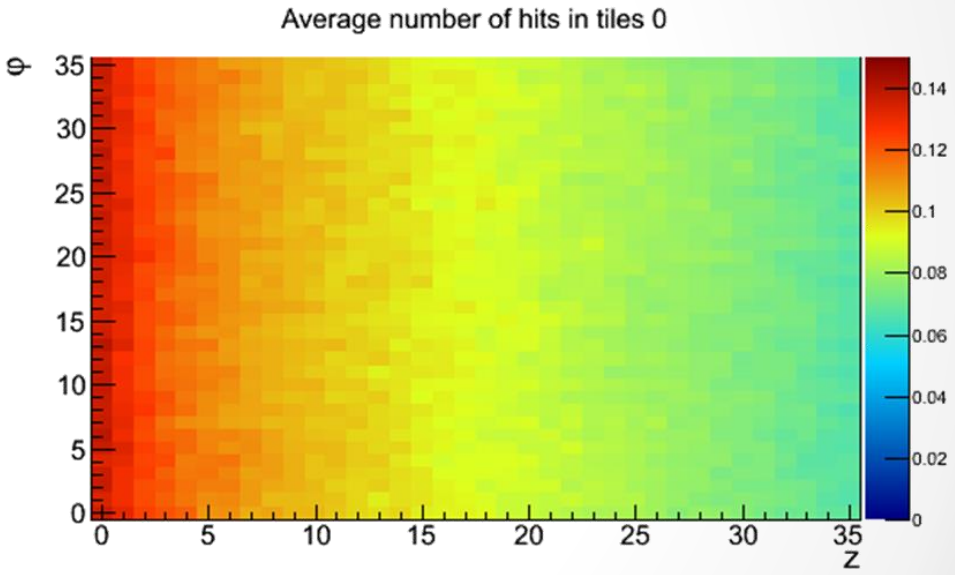
Front End FPGAs

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

Optical transceiver FE board

Average Occupancies

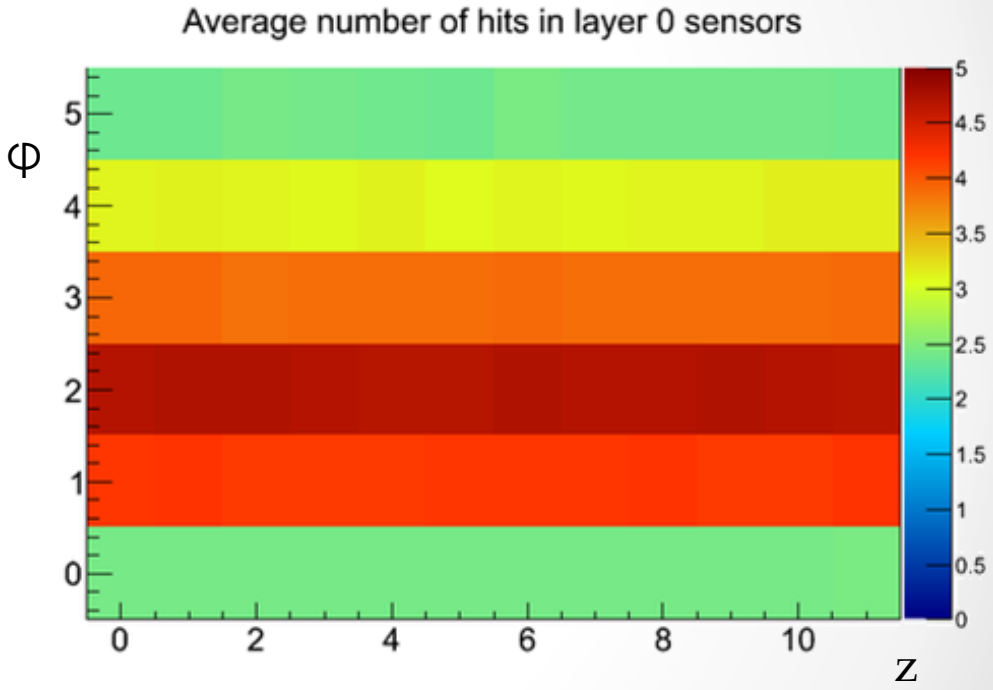
- All numbers per frame of 50 ns
- Vertex detector
  - 2 hits per sensor
- Central silicon tracker
  - 0.6 hits per sensor
- Recurl stations
  - 0.13 hit per sensor
- Fiber hodoscope
  - 0.16 hits per fiber
- Timing tiles
  - 0.09 hits per tile



Tile occupancies

Maximum Occupancies

- All numbers per frame of 50 ns
- Vertex detector
  - 5 hits per sensor
- Central silicon tracker
  - 2 hits per sensor
- Recurl stations
  - 1 hit per sensor
- Fiber hodoscope
  - 0.24 hits per fiber
- Timing tiles
  - 0.14 hits per tile



Vertex occupancies