The Scintillating Fibre Tracker for the LHCb Upgrade

DESY
Joint Instrumentation Seminar

Presented by

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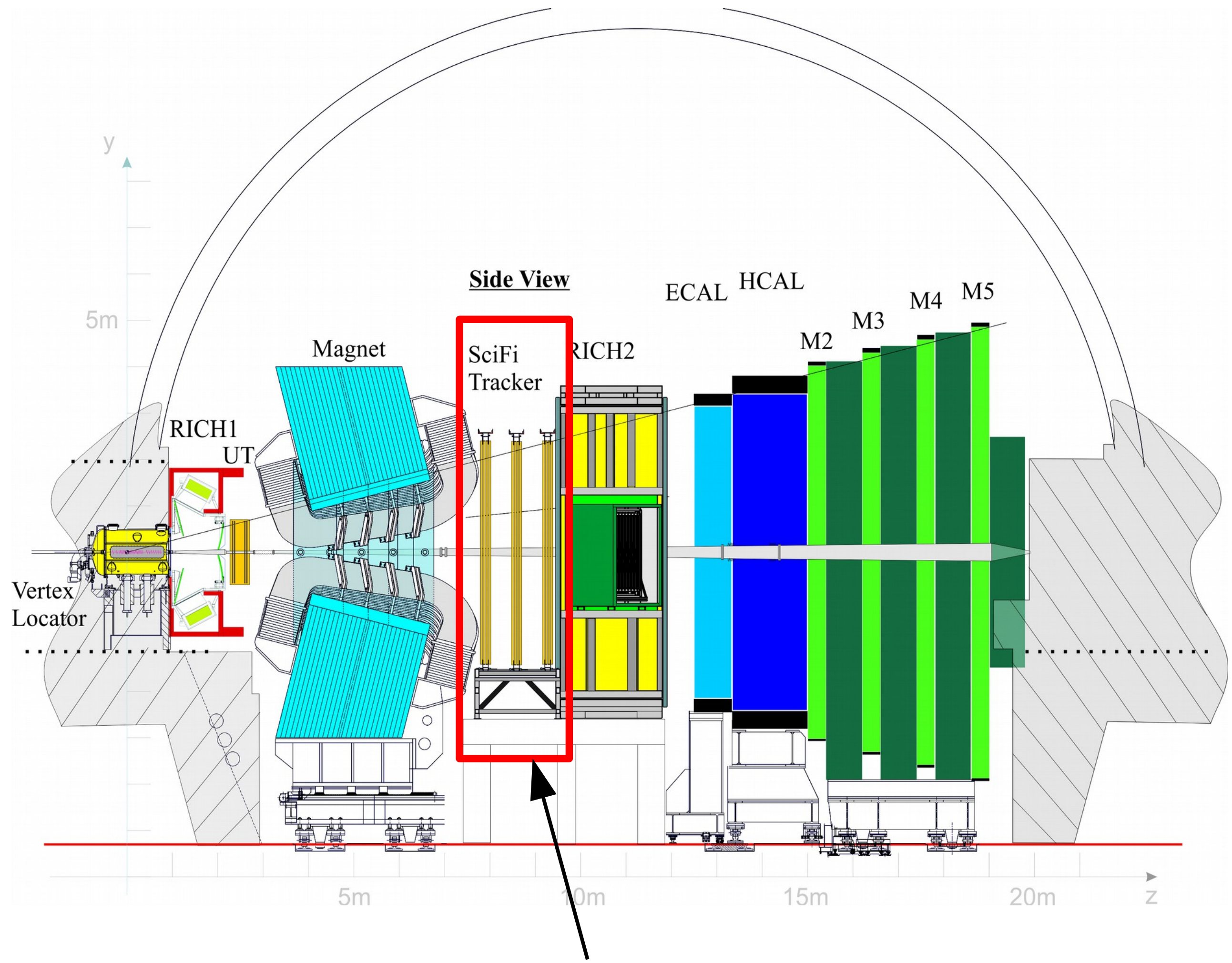
on behalf of the LHCb SciFi Tracker group

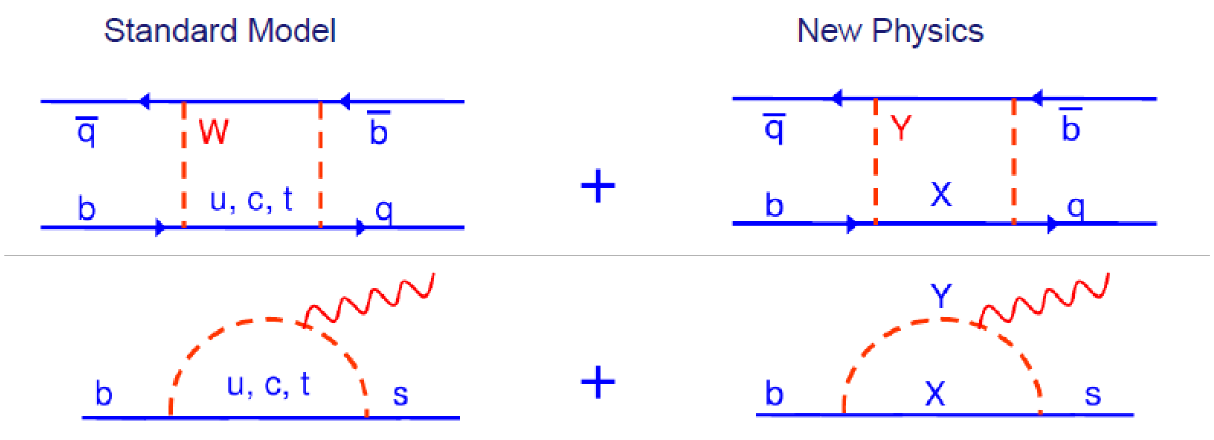
Outline

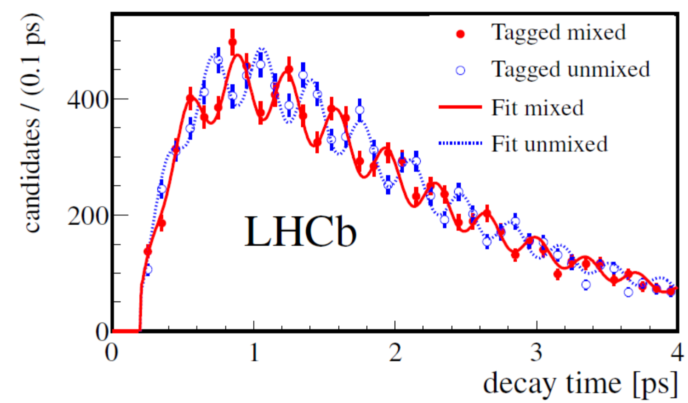
- LHCb and the Upgrade overview
- The SciFi Tracker
  - Detector basics
  - Challenges



The LHCb detector

- Built for indirect searches for new physics via precision measurements of quantum loop induced processes in the b- and c-quark systems
    - Rare decays
    - Particle/anti-particle asymmetry

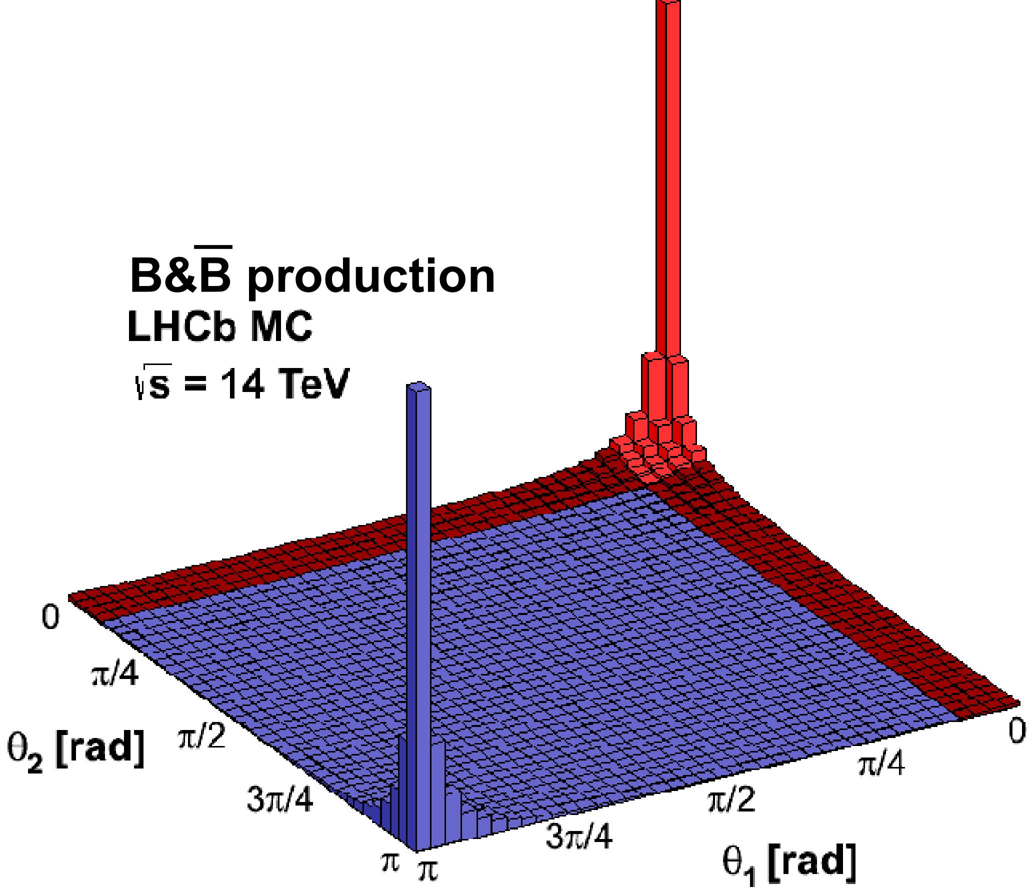


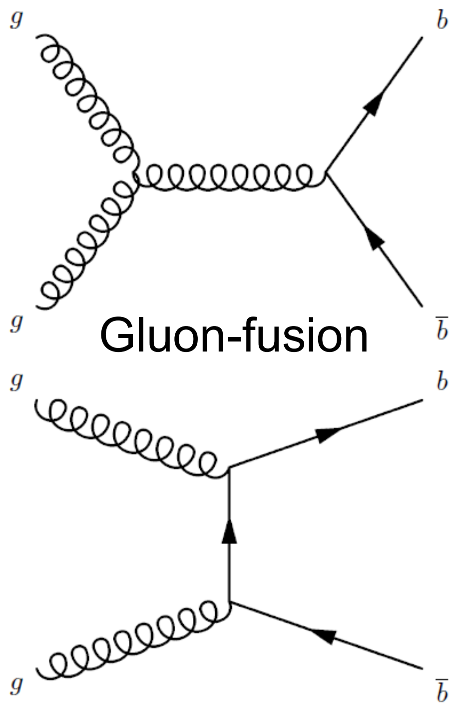


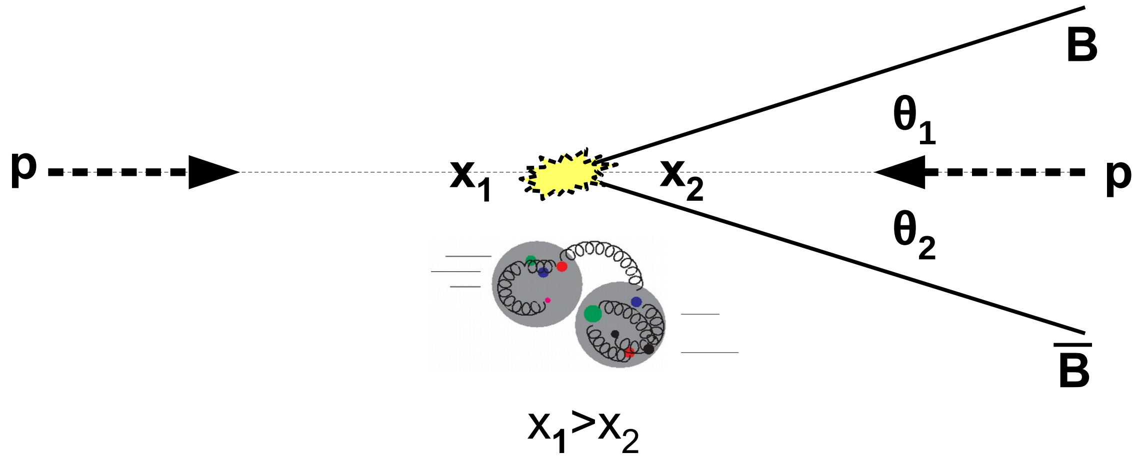
Theoretical predictions

Deviations from predictions

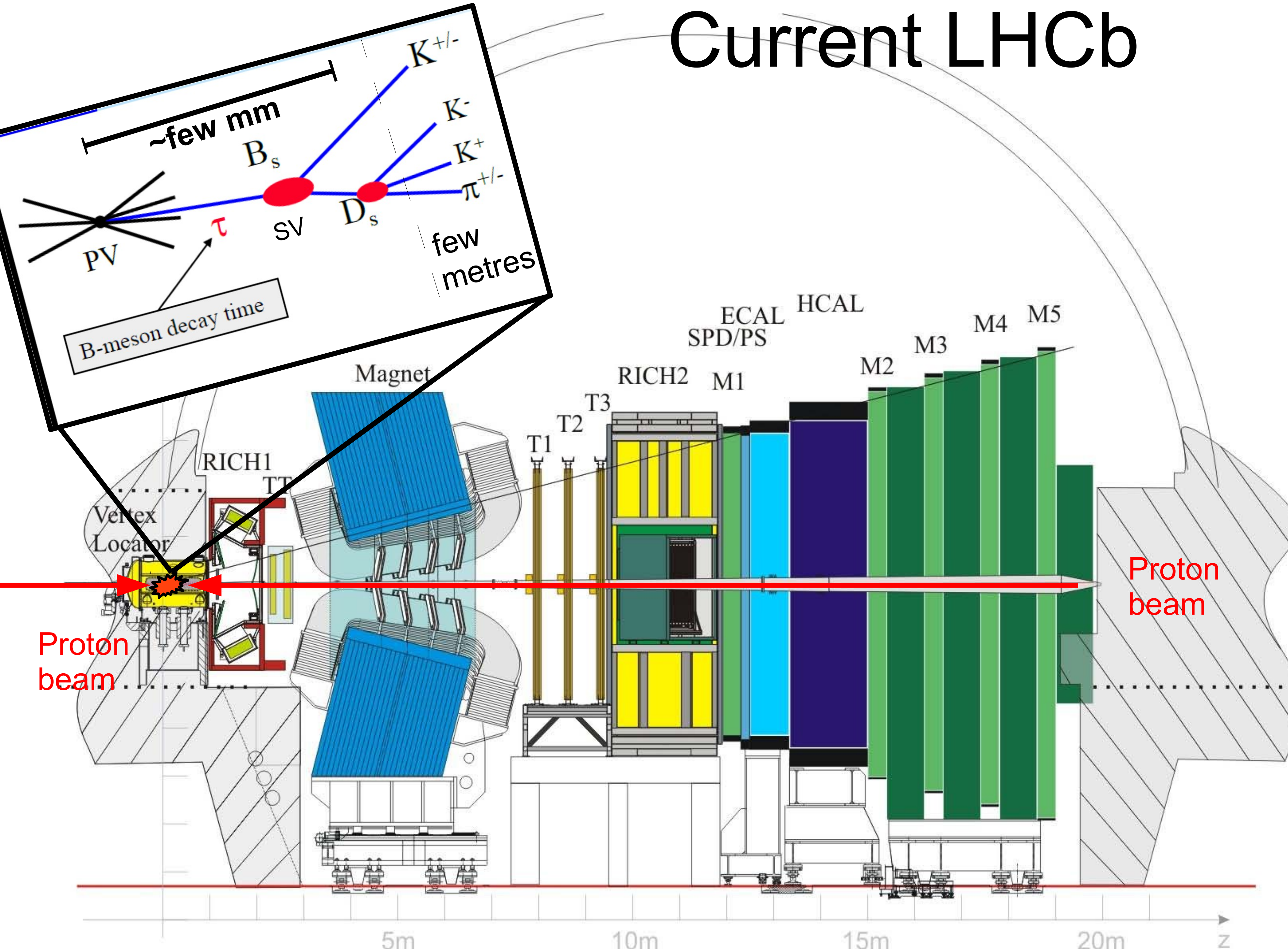
b-mesons are produced in the forward direction at the LHC



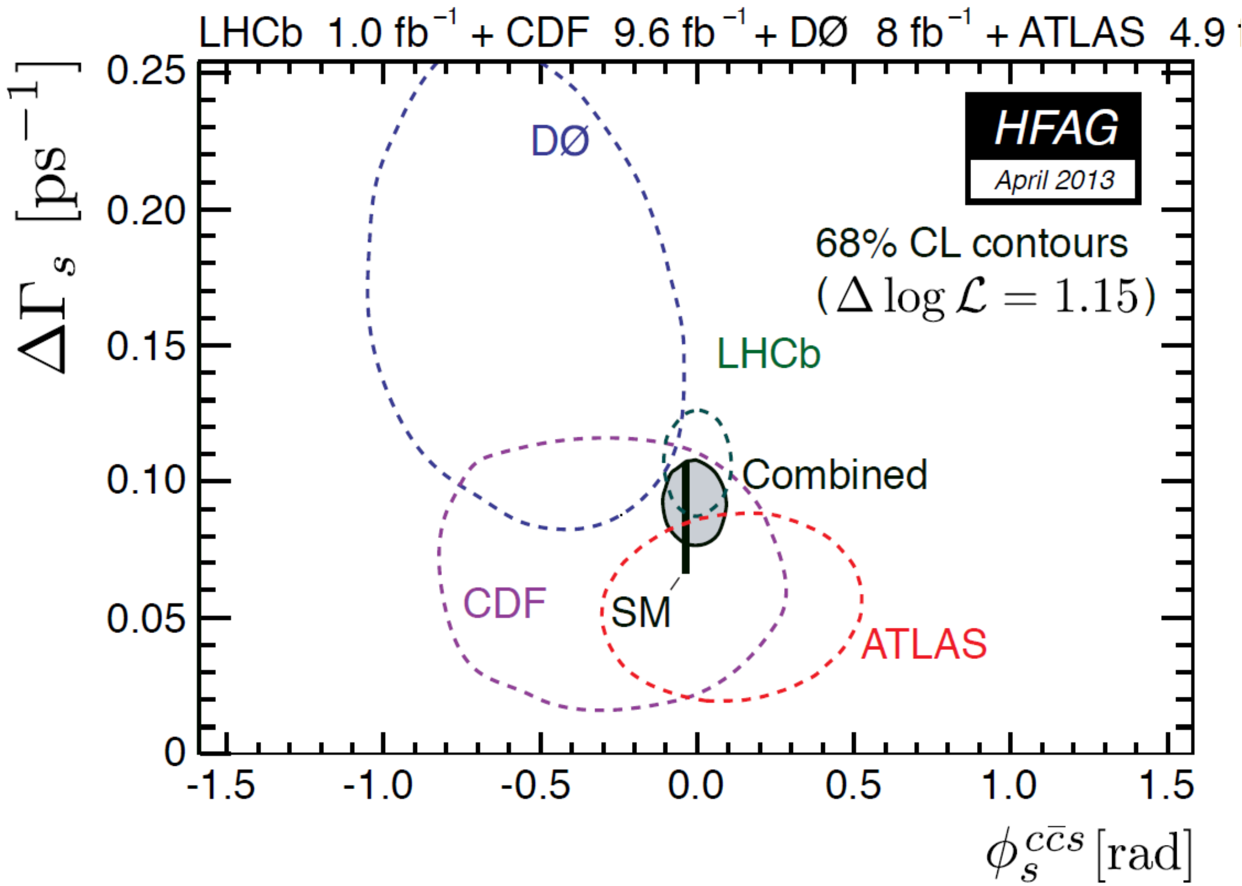




Current LHCb



- LHCb is running at twice its design value (~2×10^{12} $b\bar{b}$/year), 180+ papers published

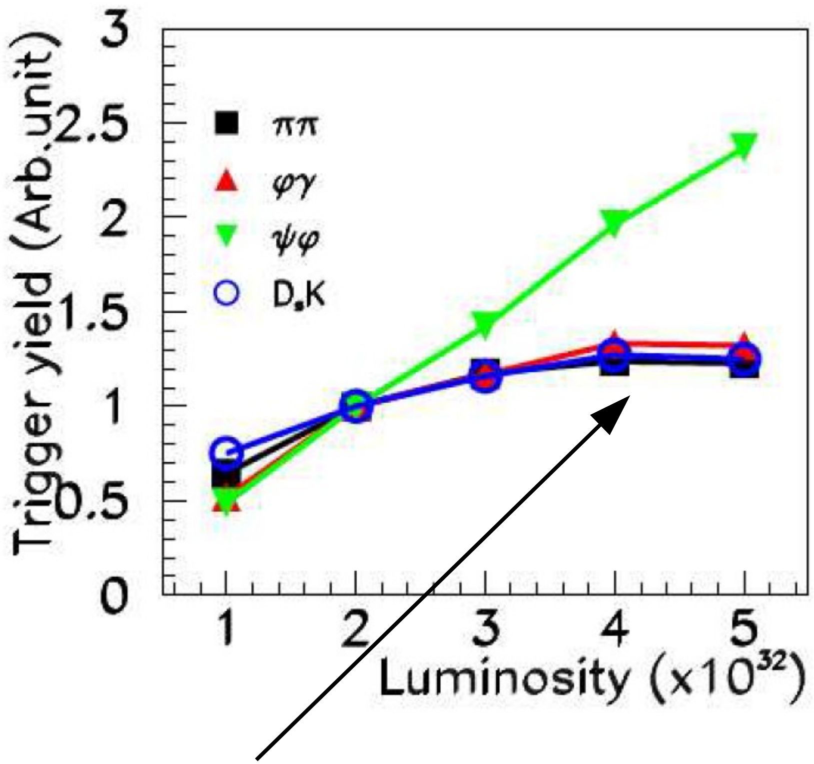


- Almost every physics measurement in LHCb is limited by statistical uncertainties, not systematic

→ We need more data!!

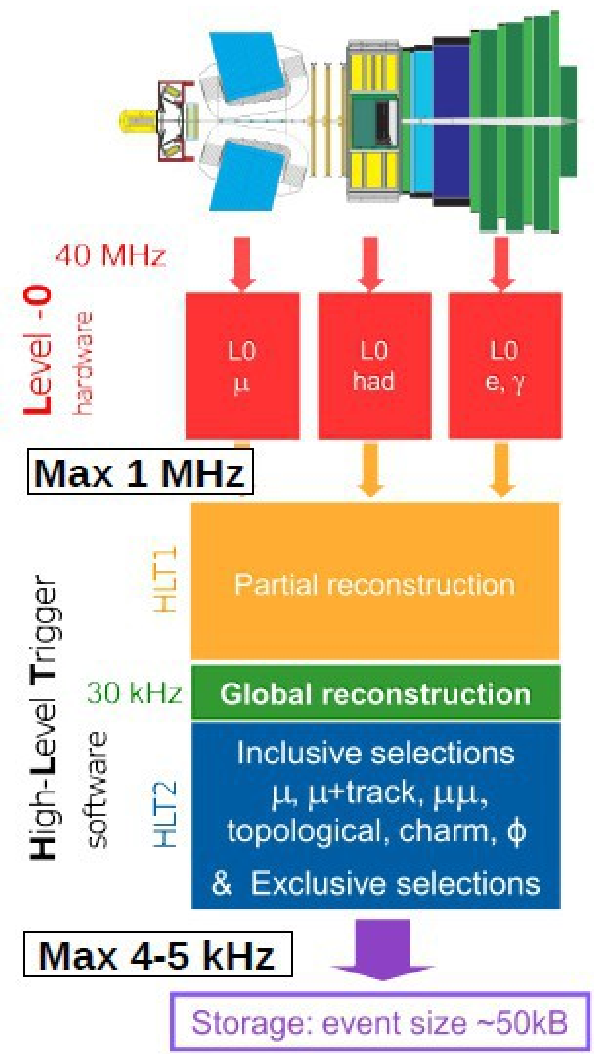
Limitations

- LHCb collision rate is tuned to manage data rate (can be increased), but...
- Statistics are limited by the 1MHz hardware trigger rate and then detector occupancy

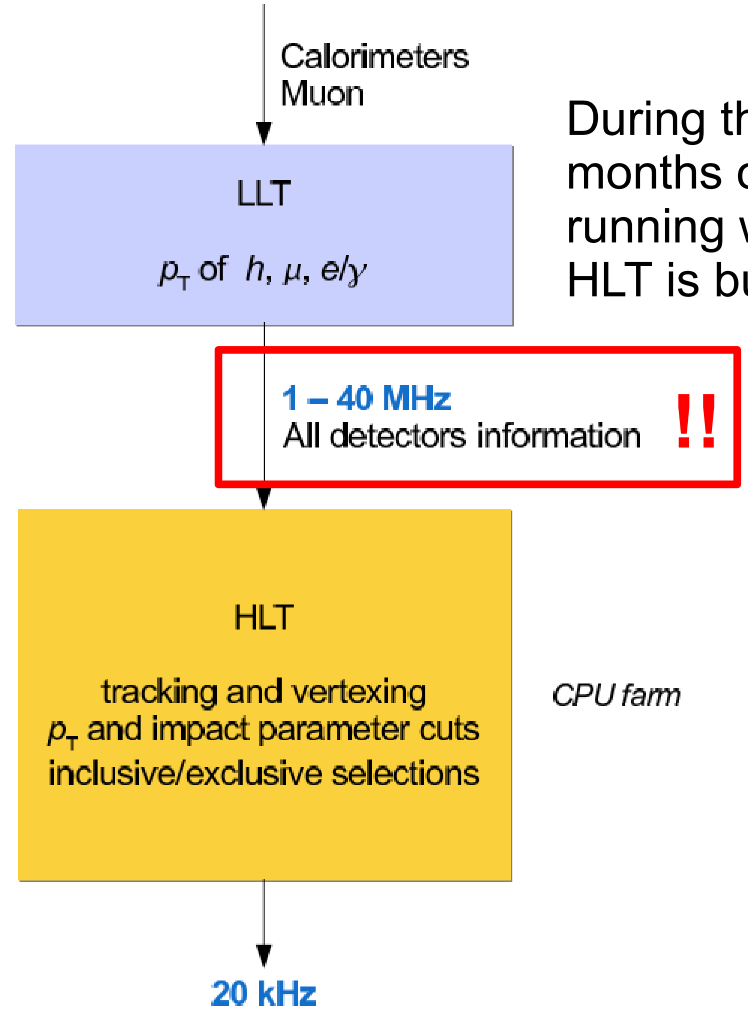


Saturation of hadronic modes with L0-hardware trigger

Current Trigger Scheme



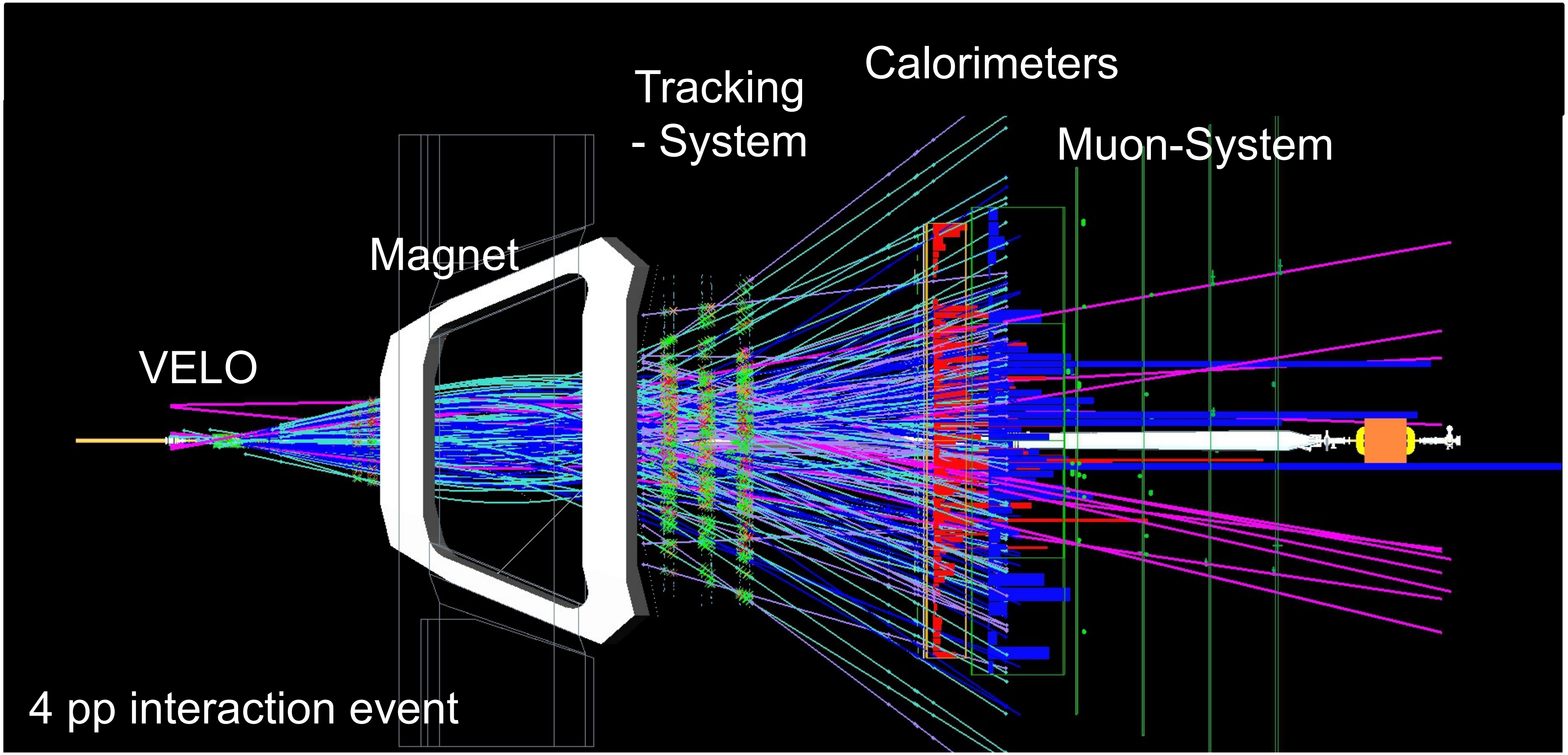
Upgrade Trigger Scheme



During the first months of low L running while HLT is built up.

10 Gbits/s to the farm
- Event selection in the farm

Detector Occupancy and Efficiency



<u>Current visible pp interactions/event</u>:

Poisson distribution with $\mu \approx 2$;
Upgrade is at $\mu \approx 5$

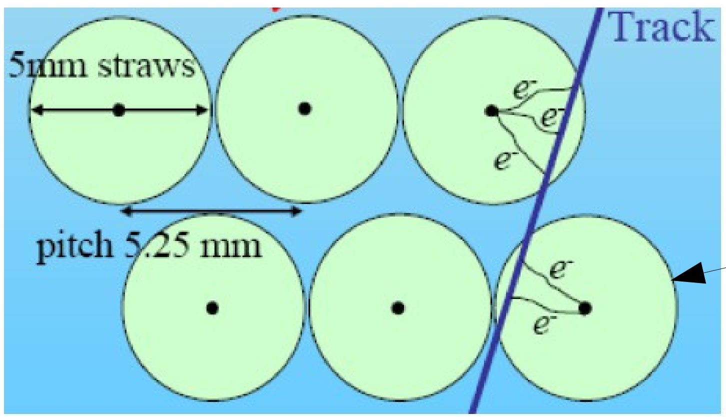
72 tracks, on average for a B-Bbar event;
180 in upgrade

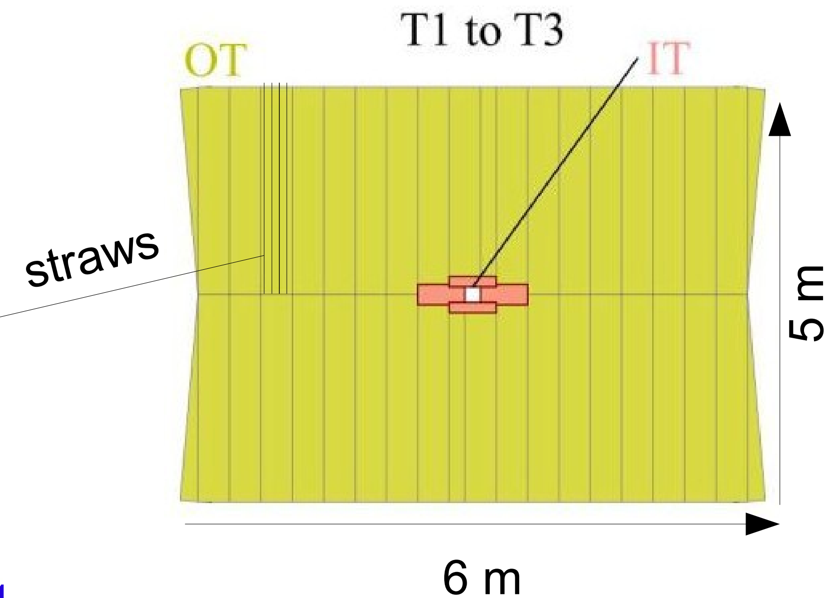
→ We need a high hit detection efficiency (98+%)

Detector Occupancy and Efficiency

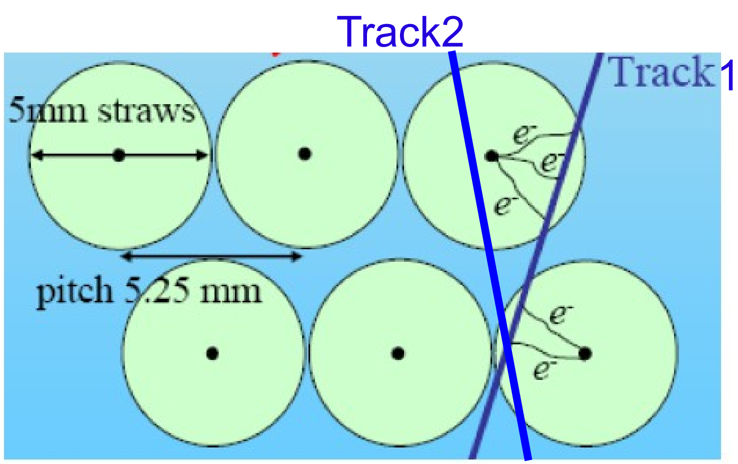
Outer Tracker = 5 mm straw gas drift tubes (2.5m long)
• Detector is insensitive to multiple tracks per tube (35ns drift time)

Good!!





BAD!!

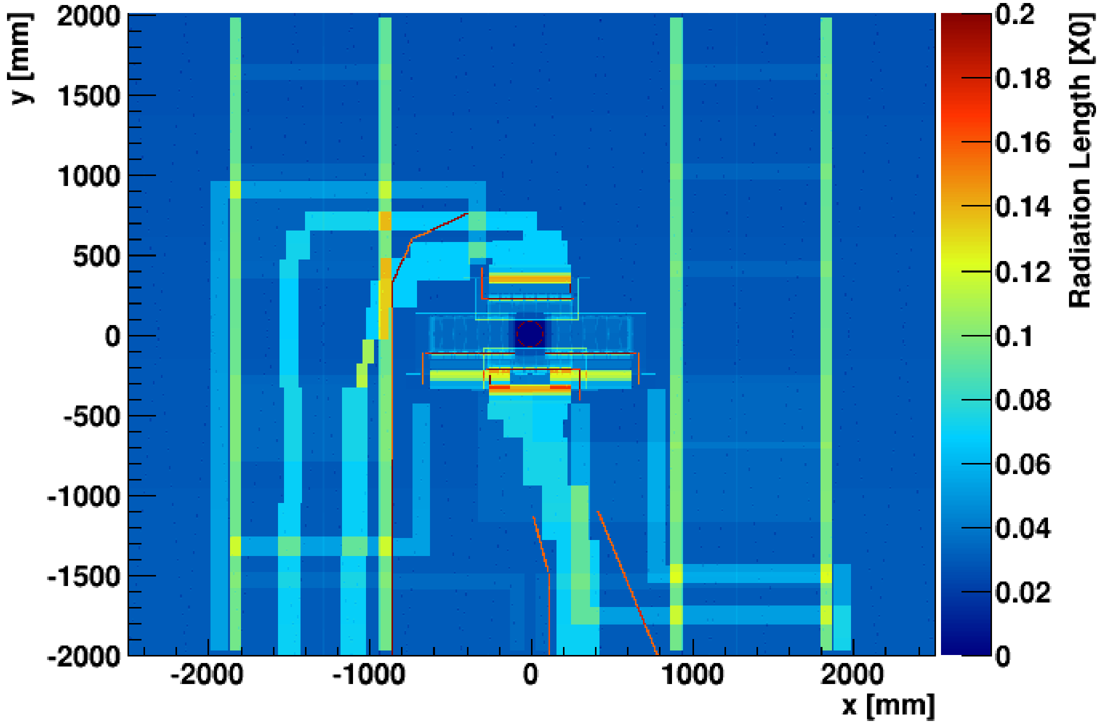


Outer Tracker tracking efficiency decreases above 25% occupancy → 40% expected in the upgrade

Beam bunch spacing will be 25ns in 2015+

Material Budget

- Material in T1



Particles averaged over eta and phi see 17.5% of X0 over 3 stations

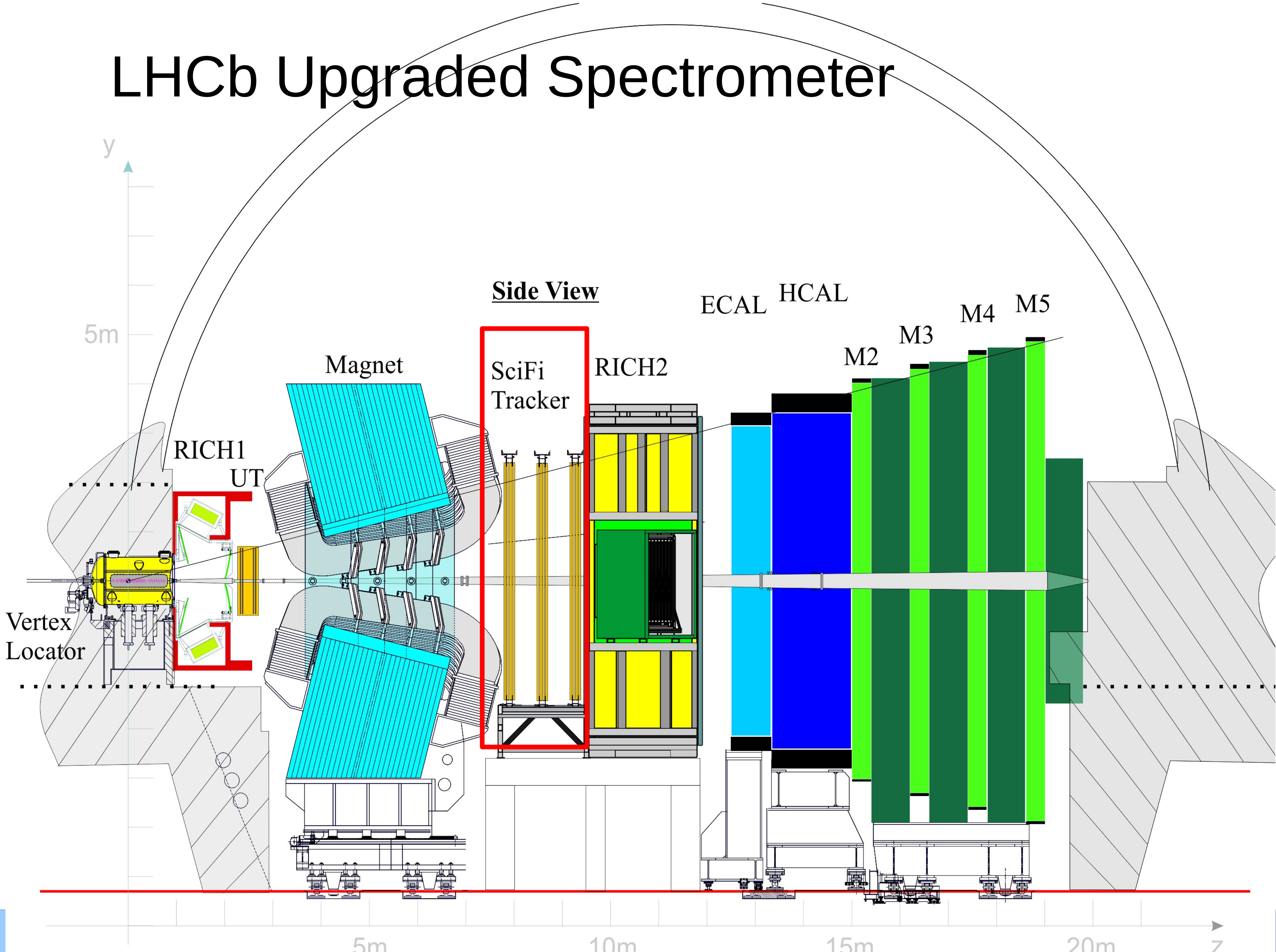
The other Upgrade detectors

- **VeLo → VeLoPix** @ 40MHz
  - 55 x 55 um^2 pixels; a full 3D pattern recognition in HLT.
- **TT → UT** (tracker) @ 40MHz
  - silicon strip detectors (X-U-V-X) at 5º ; Improved small angle acceptance, less material (<4.5% X_0) .
- **RICH/PID** Upgrade
  - integrated HPD+FEE(pixel @ 1 MHz) → MA-PMT @ 40MHz
  - Remove the aerogel from RICH-1; only C4F10; RICH-2 stays as CF4.
- **Calorimeter** electronics → 40 MHz
  - Scintillating Pad Detector (SPD) and the Preshower (PRS), lead absorber will be removed. Lose some e/gamma PID power
- **Muon Stations**: Front-end is already 40MHz to L0 trigger; switch to LLT;
  - Remove M1

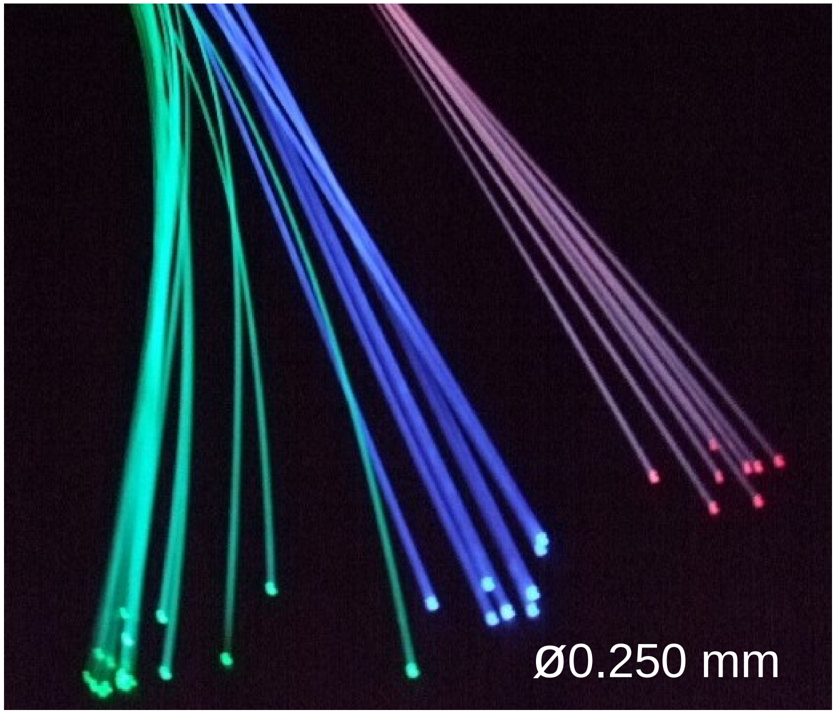
Upgrade summary

- Replace 1 MHz hardware trigger → 40MHz software trigger, all front-end electronics to 40 MHz
- Visible interactions per bunch crossing increase to mu = 2.5 – 5 (from 1.8)
- Expected **annual** physics yields increase (with respect to 2011)
  - 14 Tev cross section (x2), trigger rate (≥ x4), luminosity (≥ x2.5)
    - **x10** in muonic channels
    - more than **x20** in hadronic channels
- 10 times smaller uncertainties after 10 years

LHCb Upgraded Spectrometer

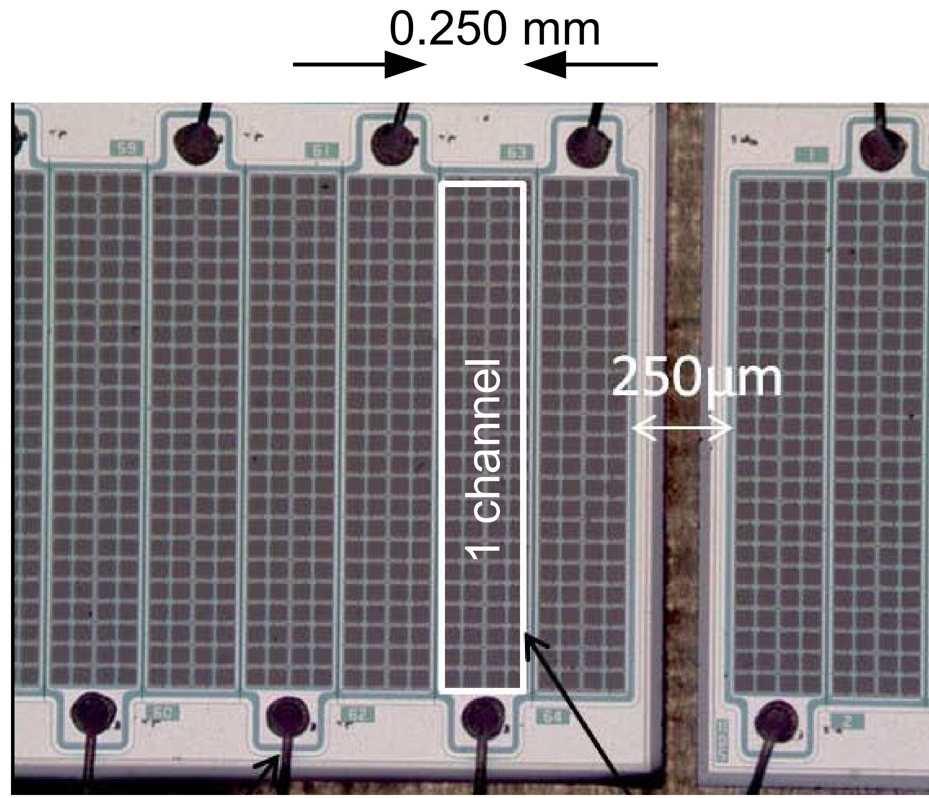


The SciFi Tracker



Scintillating fibres

- fast scintillation decay time (2.8ns)
- good light yield and attenuation length



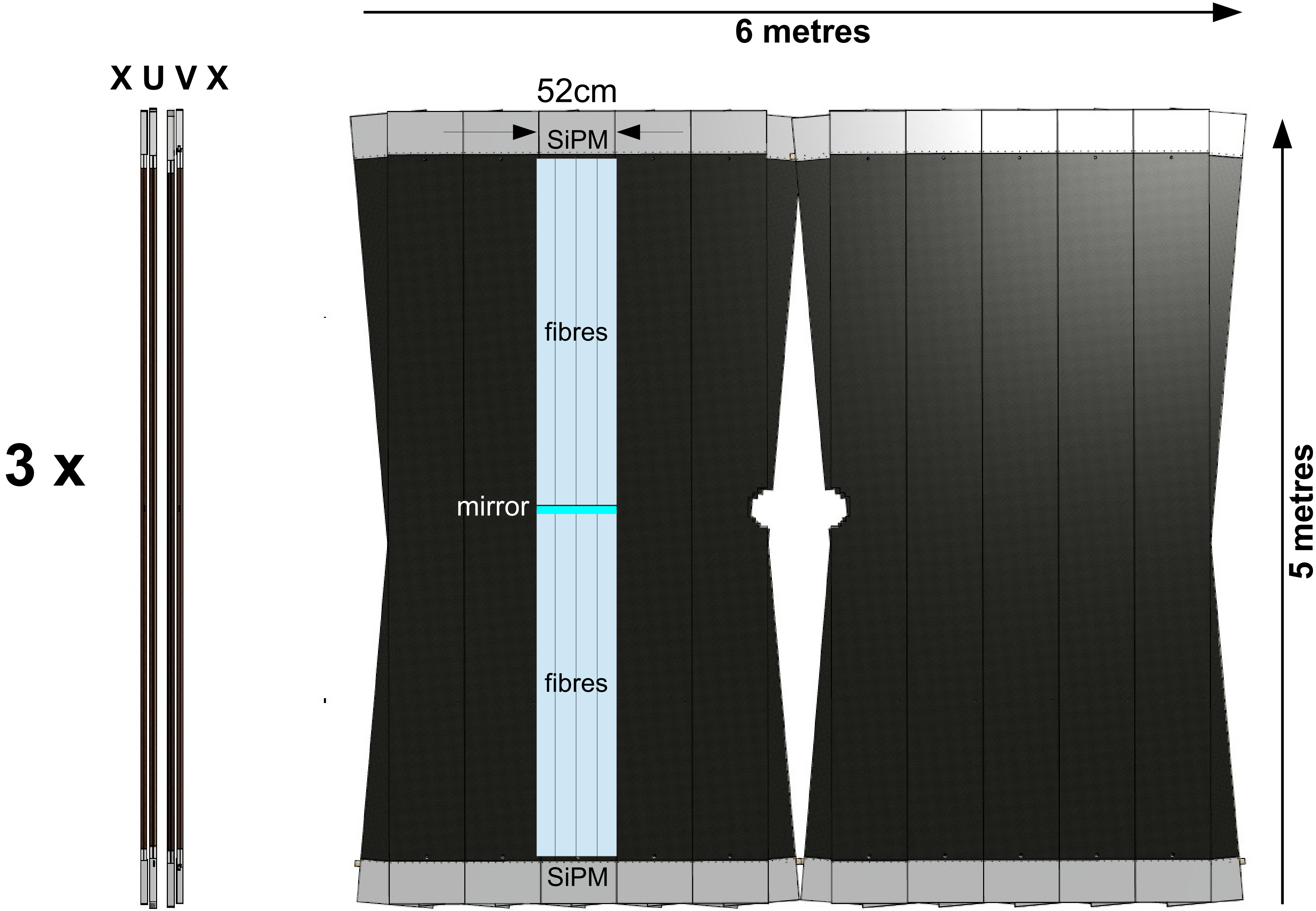
An array of pixelated silicon photomultipliers

- fast signals
- high photon detection efficiency (40+%)
- compact channel size

SciFi Collaboration

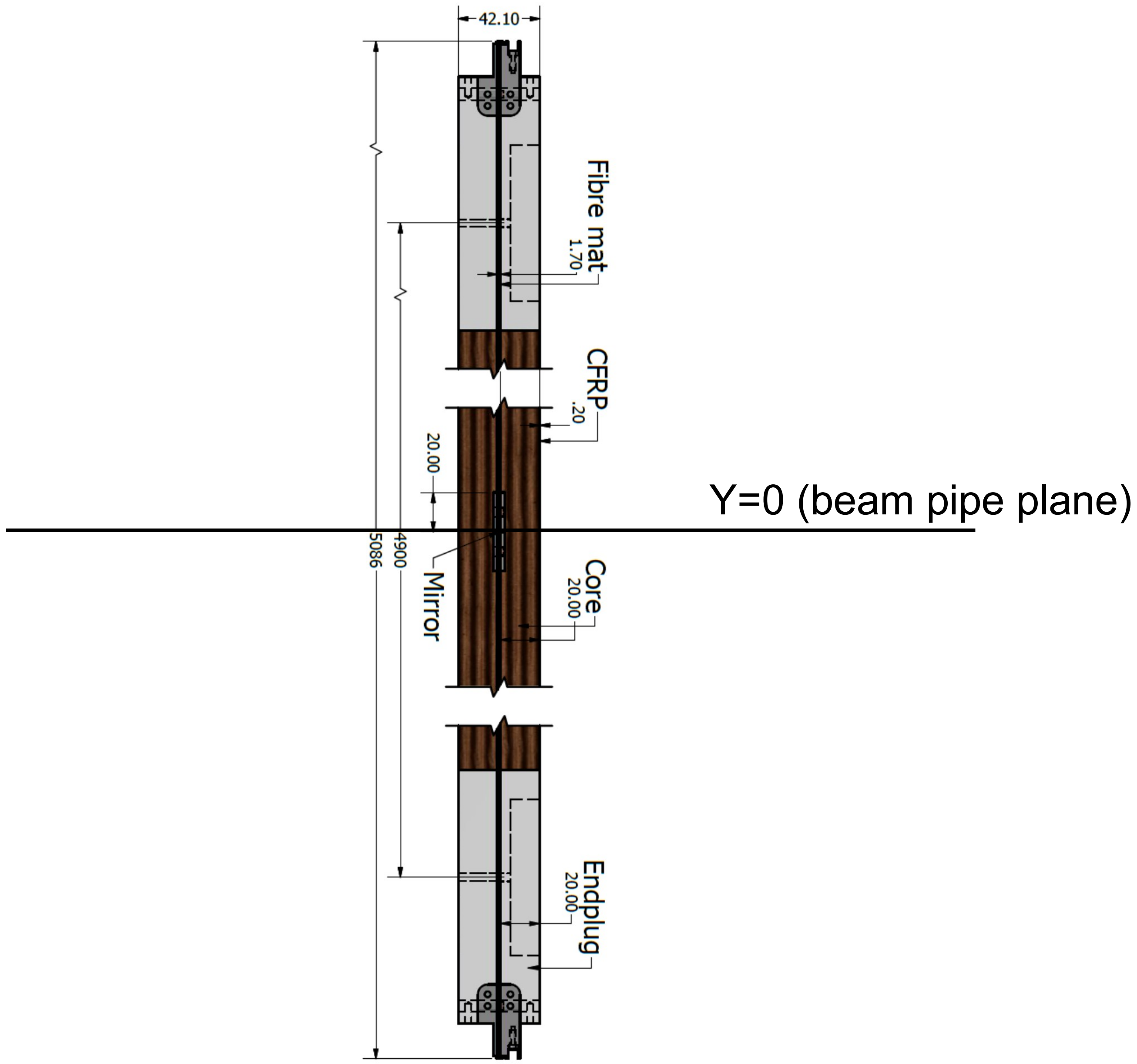
- 20 Institutions, 10 countries

Task(s)		Institute(s)
Detector	SiPM assembly	EPFL
	SiPM QA	CERN, EPFL, NCBJ
	Fibre QA	CERN, NCBJ, RWTH, TUD, HD
	Fibre mat production	Russia, RWTH, TUD, HD
	Panel & module construction	Russia, RWTH, TUD, HD
	Read-out box	CERN, EPFL, LPC, NIKHEF, RWTH
	Module testing (including electronics)	CBPF, NIKHEF
Electronics	PACIFIC ASIC	UB, IFC, LPC, NIKHEF, HD
	Front-end boards	EPFL, LPC, NIKHEF, RWTH, HD
	Tell40 board software	LPNHE, TUD
Infrastructure	Frames	CERN, EPFL, NIKHEF
	Cooling	CERN, RWTH



6 metres
X U V X
52cm
SiPM
fibres
3 x
mirror
fibres
SiPM
5 metres

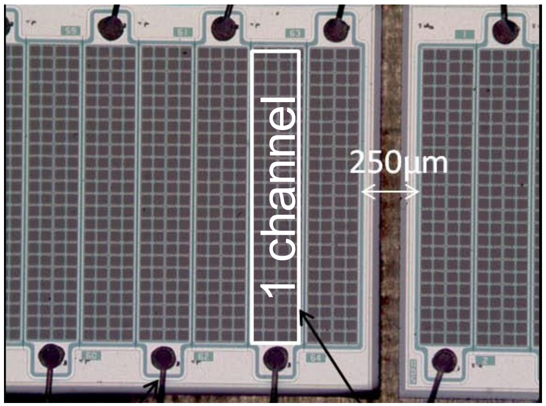
Modules



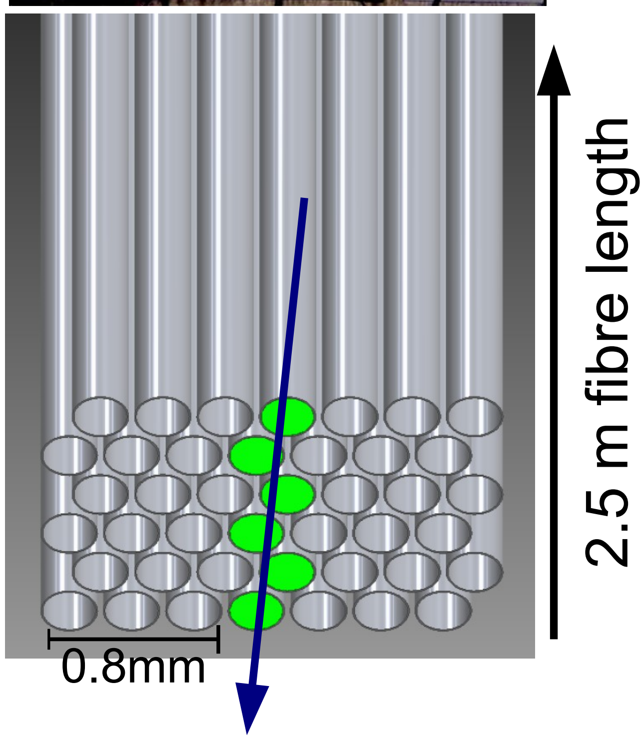
42.10
Fibre mat
1.70
CFRP
.20
20.00
Y=0 (beam pipe plane)
5086
4900
Mirror
Core
20.00
Endplug
20.00

Basic principle

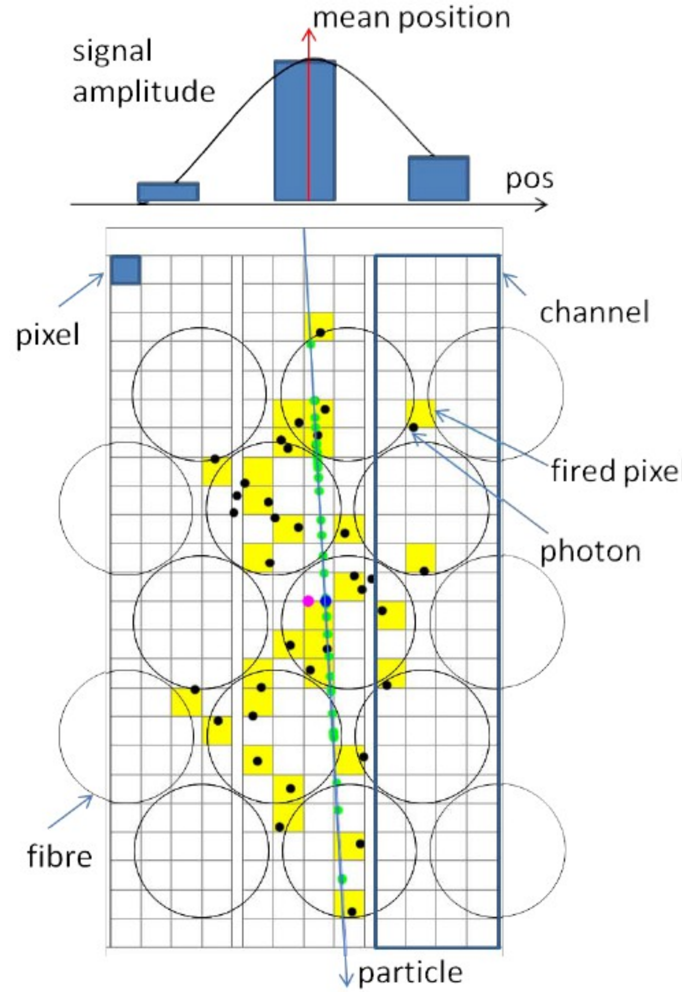
SiPM array



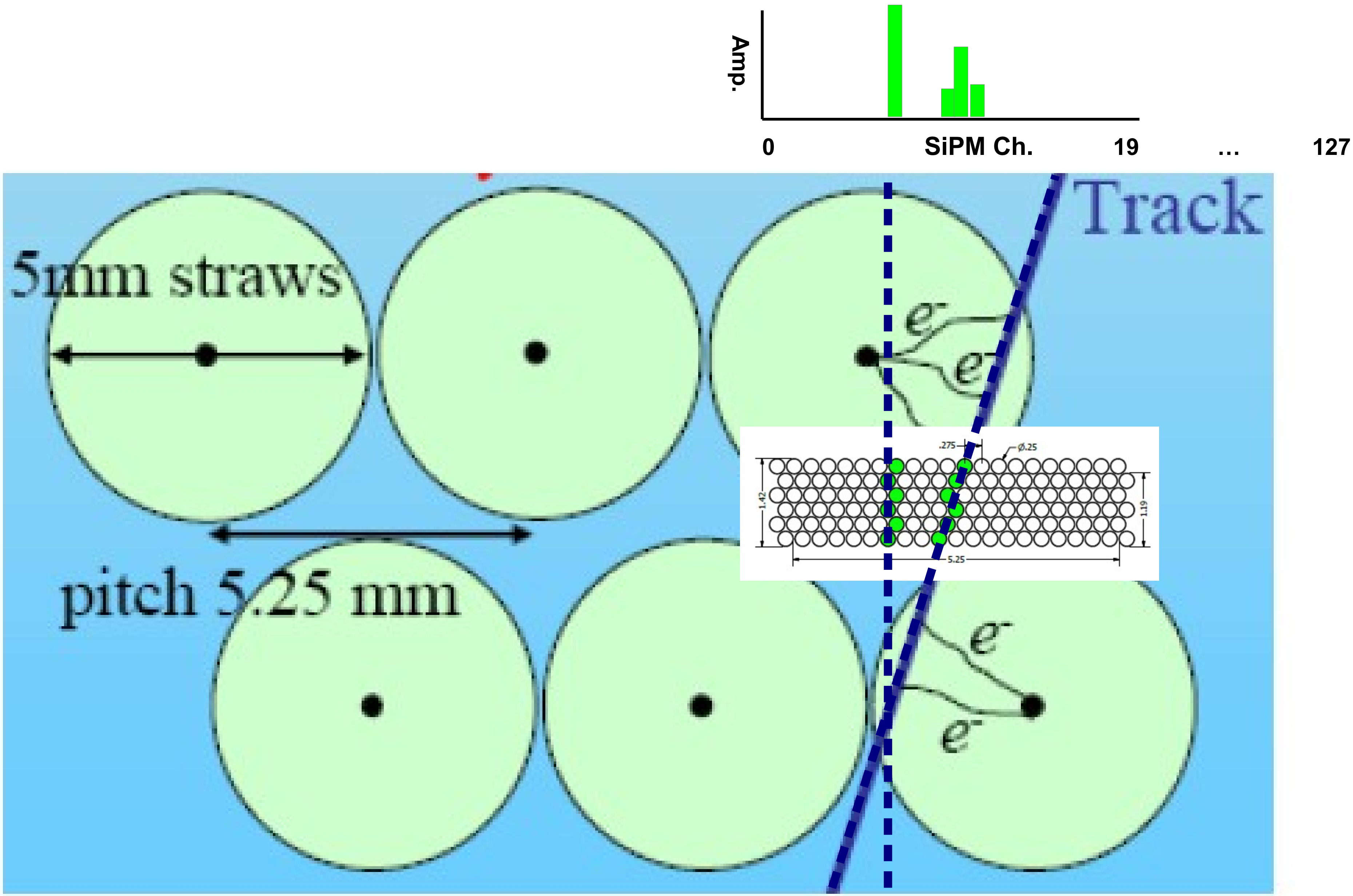
Scintillating Fibres (0.250mm diameter)



Signal cluster

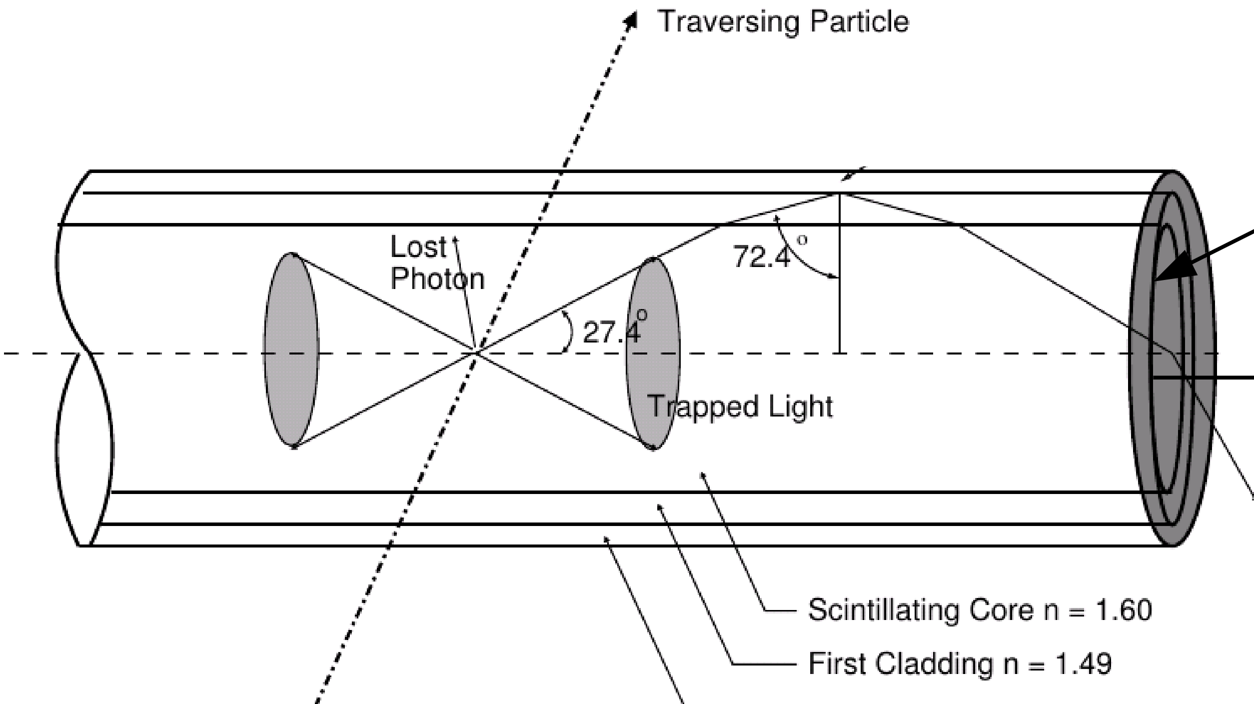


Typically one observes 15-20 photoelectrons for 5 layers of fibre



Amp.
0
SiPM Ch.
19
…
127
Track
5mm straws
pitch 5.25 mm
e-
e-
e-
e-
.275
Ø.25
1.42
1.19
5.25

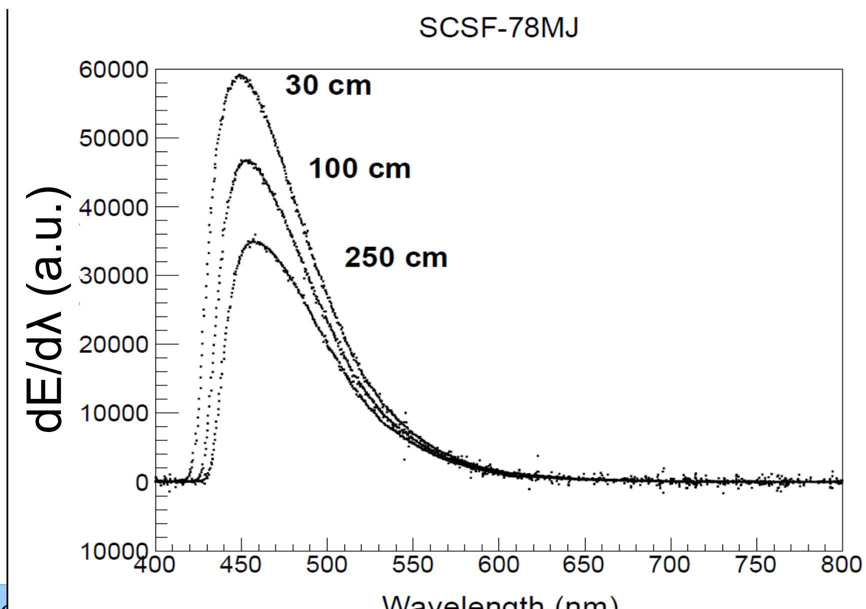
Scintillating Fibres

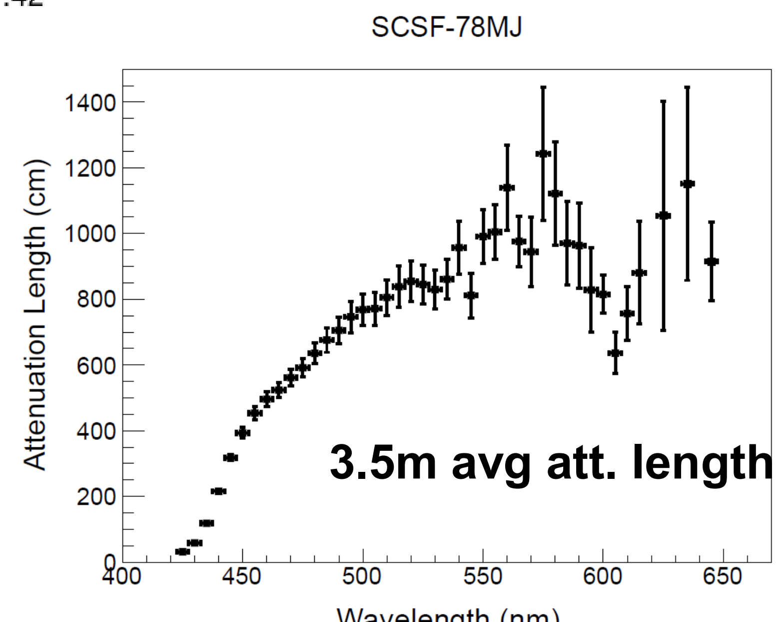


(scintillator)
Polystyrene core with 2 dyes

Only a few photons after 2.5m

300 photons per MIP produced
(only 5% captured)

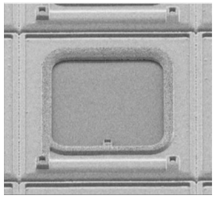




SiPMs

- The SiPM pixel is a photo-diode (reverse-biased, above breakdown Geiger mode)
- a single free electron/hole-pair can trigger an avalanche of electrons
- 10^6—10^7 gain
- 20-50% photon detection efficiency

Each pixel



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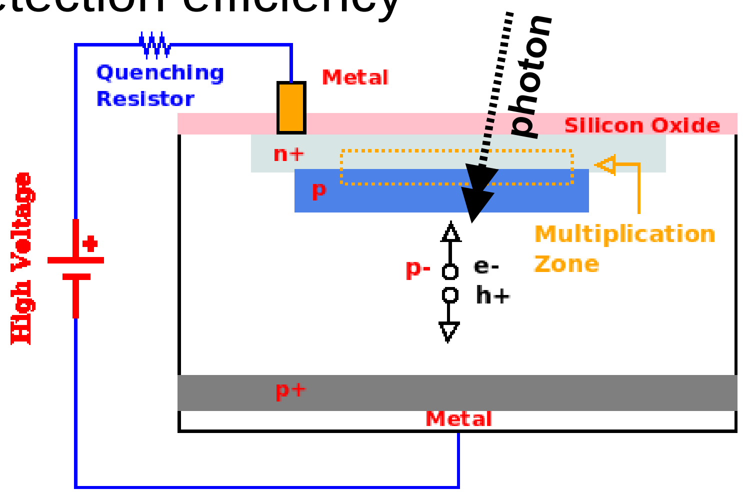
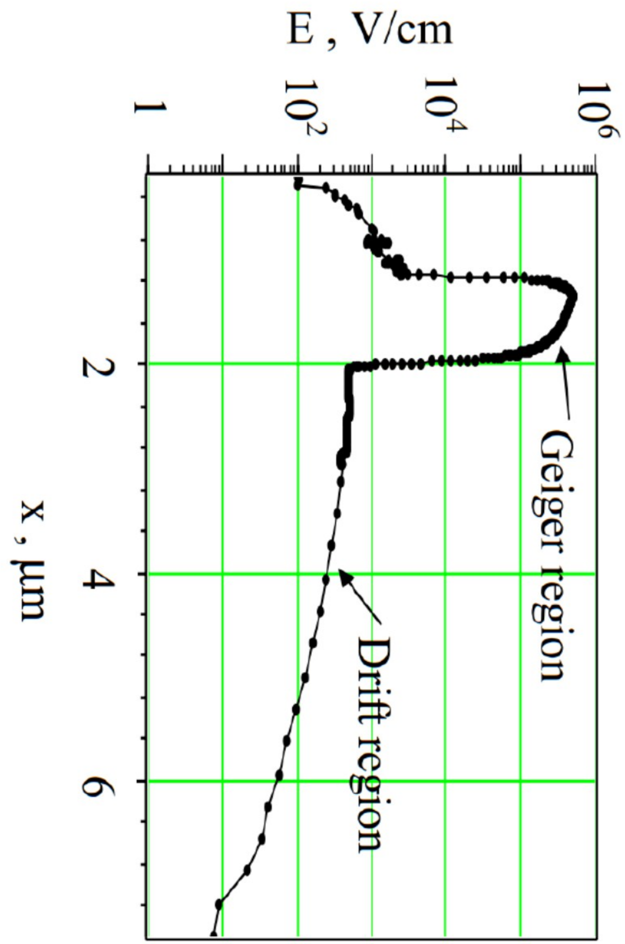
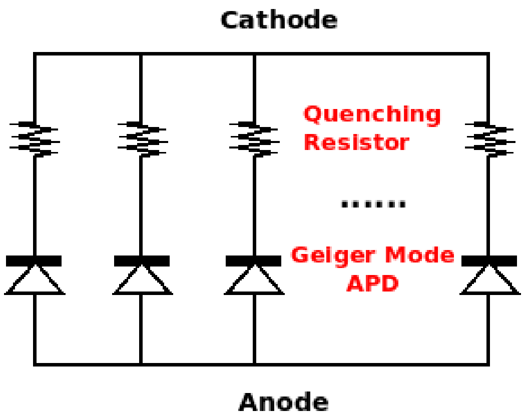




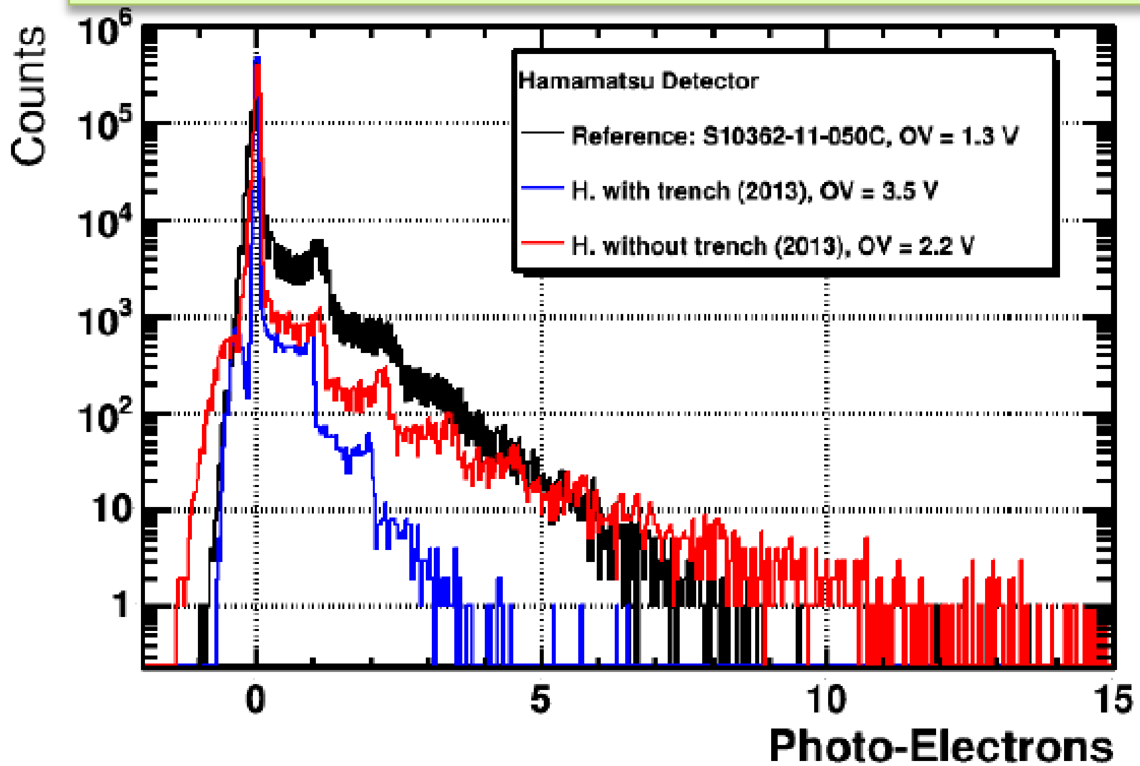
= 100s pixels in parallel



SiPM dark noise

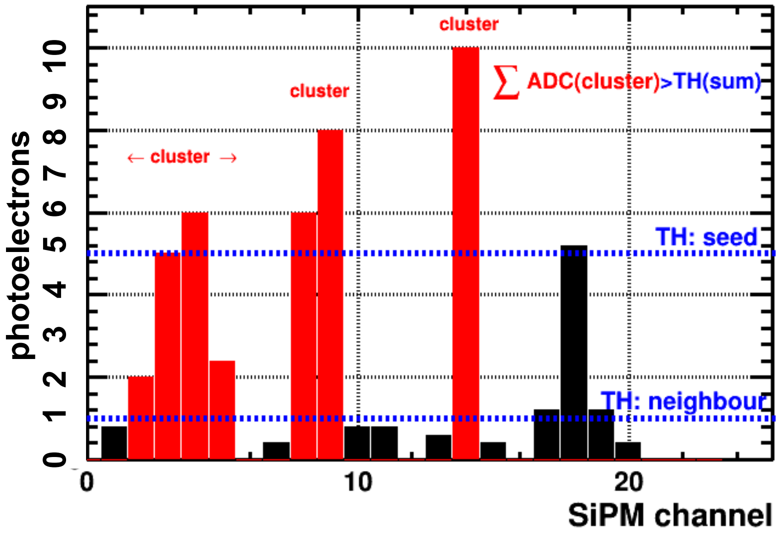
Unirradiated SiPMs produce about 100 kHz of >0.5 photoelectron signals per mm^2 at room temperature from thermal excitations and pixel crosstalk.

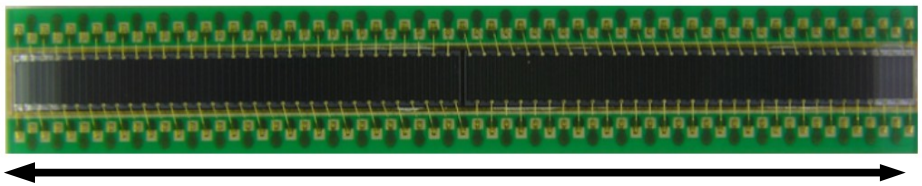
Hamamatsu, 50um pixel, standard (ref.), with trench (2013), without trench (2013), at typical over-voltage, recorded with VATA64.



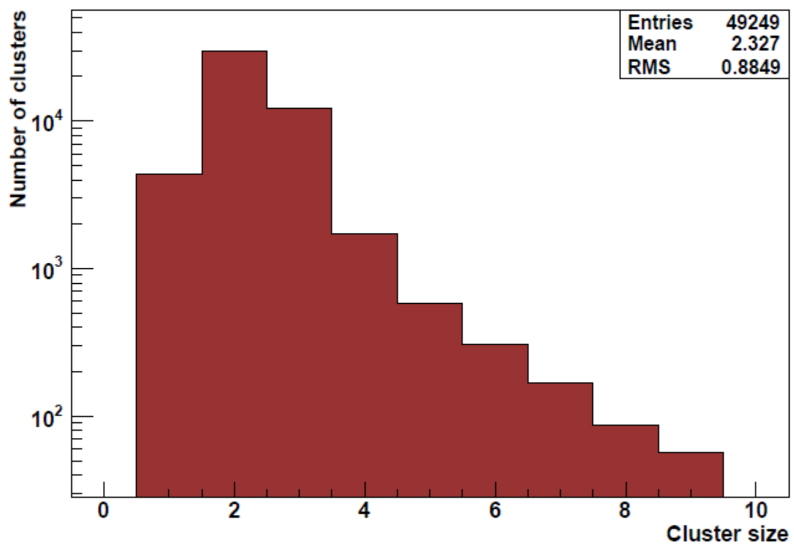
Plot from G. Haefeli (EPFL), presented at TIPP 2014

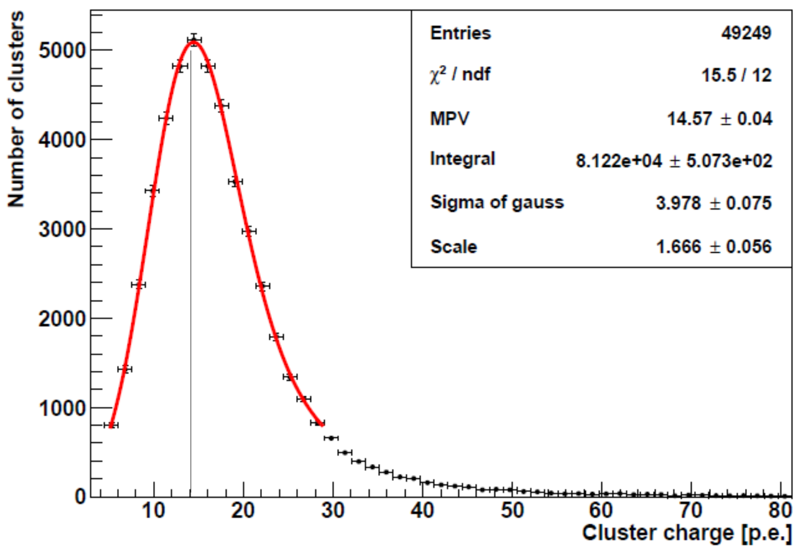
Clustering algorithm





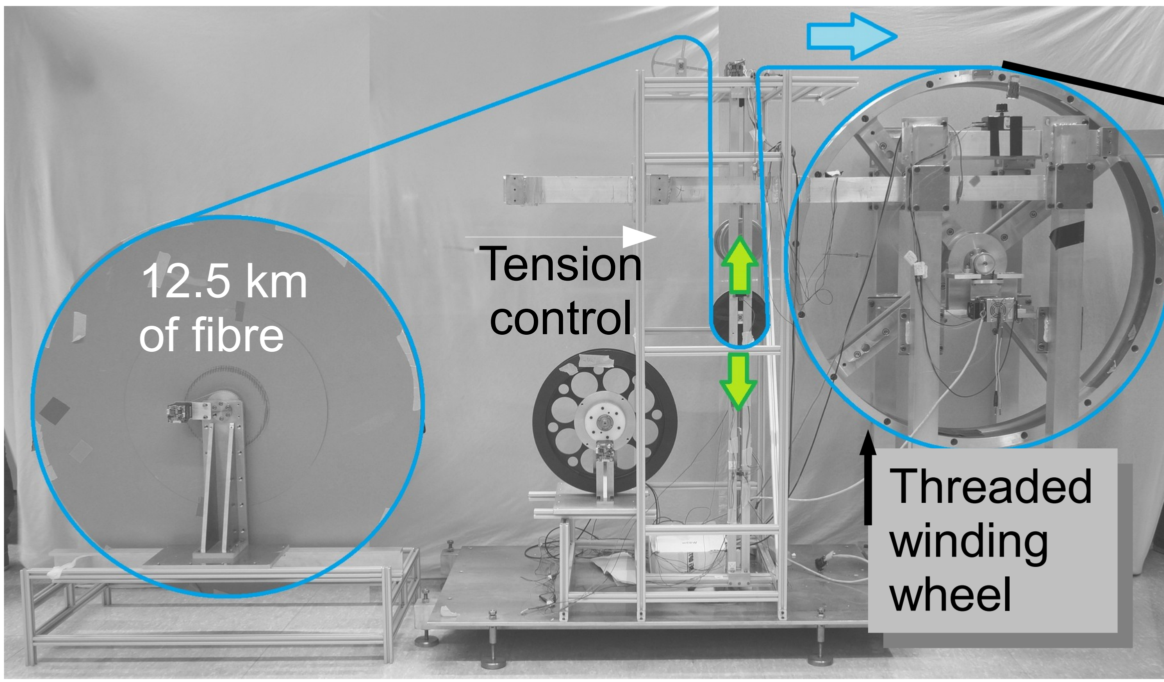
Apply clustering and threshold cuts to reject dark noise clusters in the front-end electronics

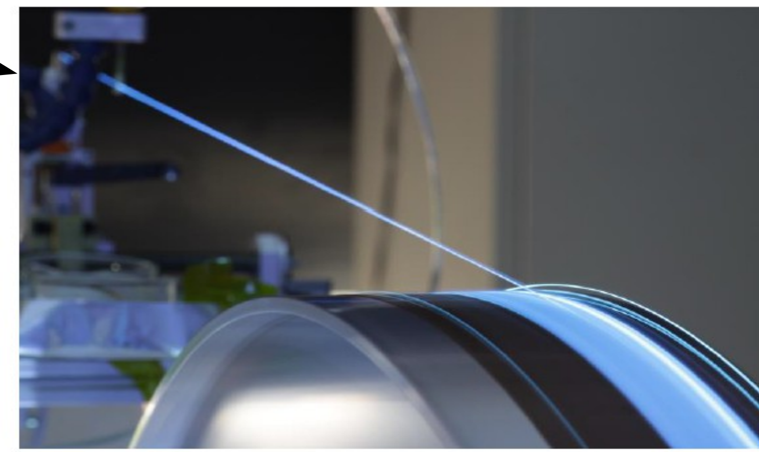


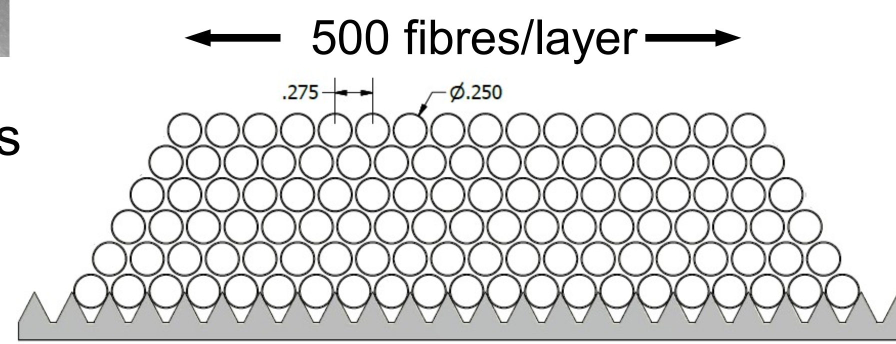


Fibre Mats

Fibre mats are produced from winding a single fibre onto a threaded wheel.

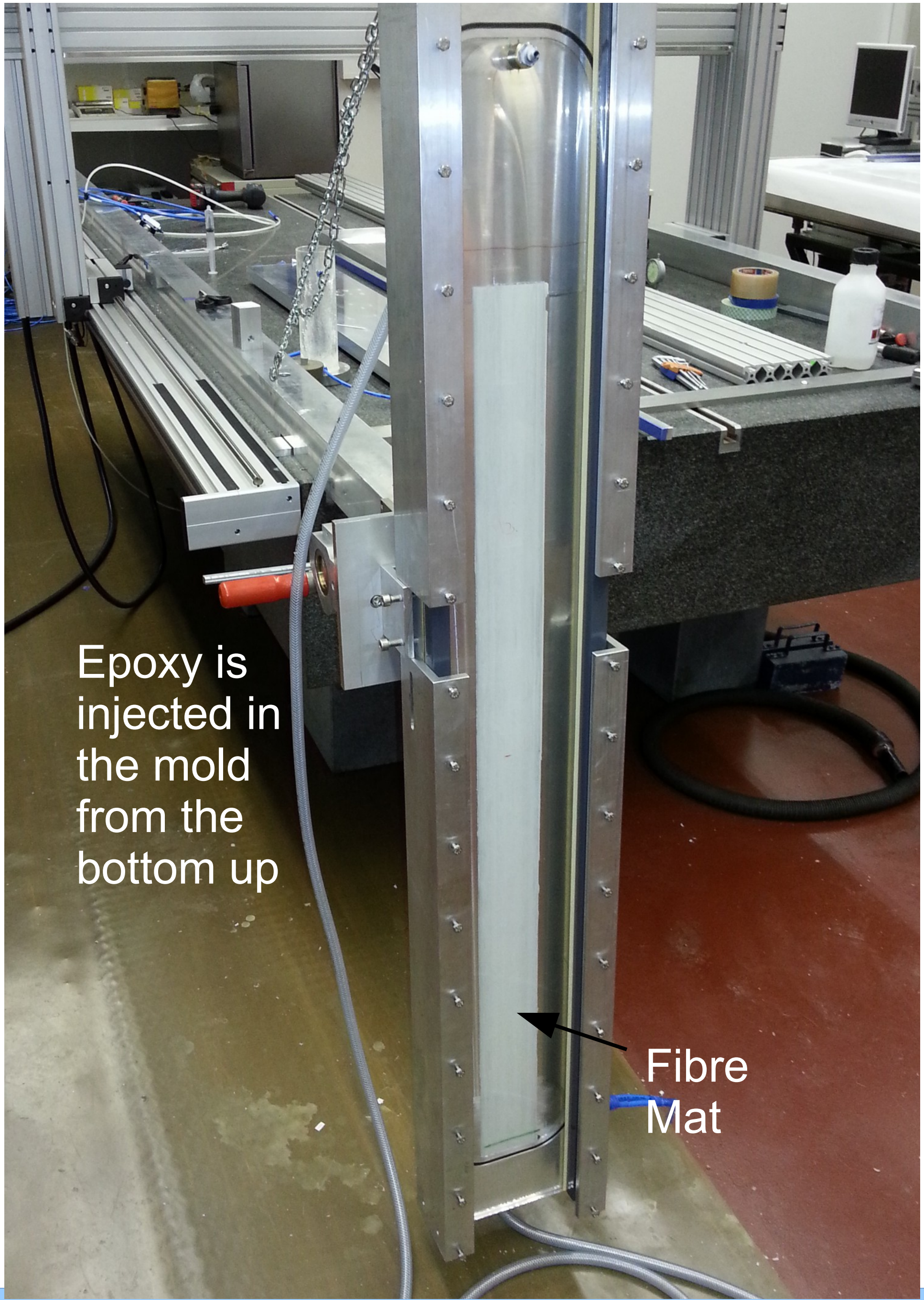




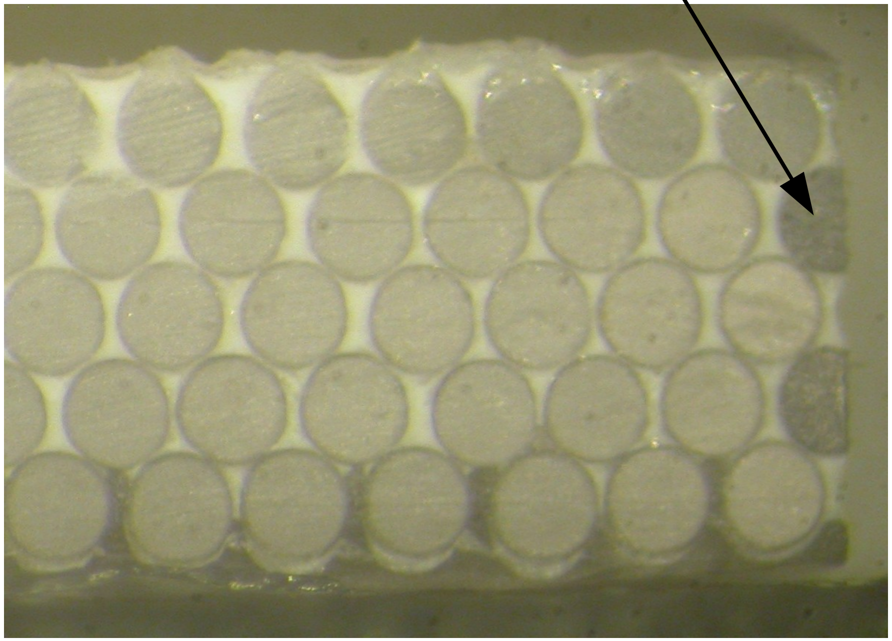


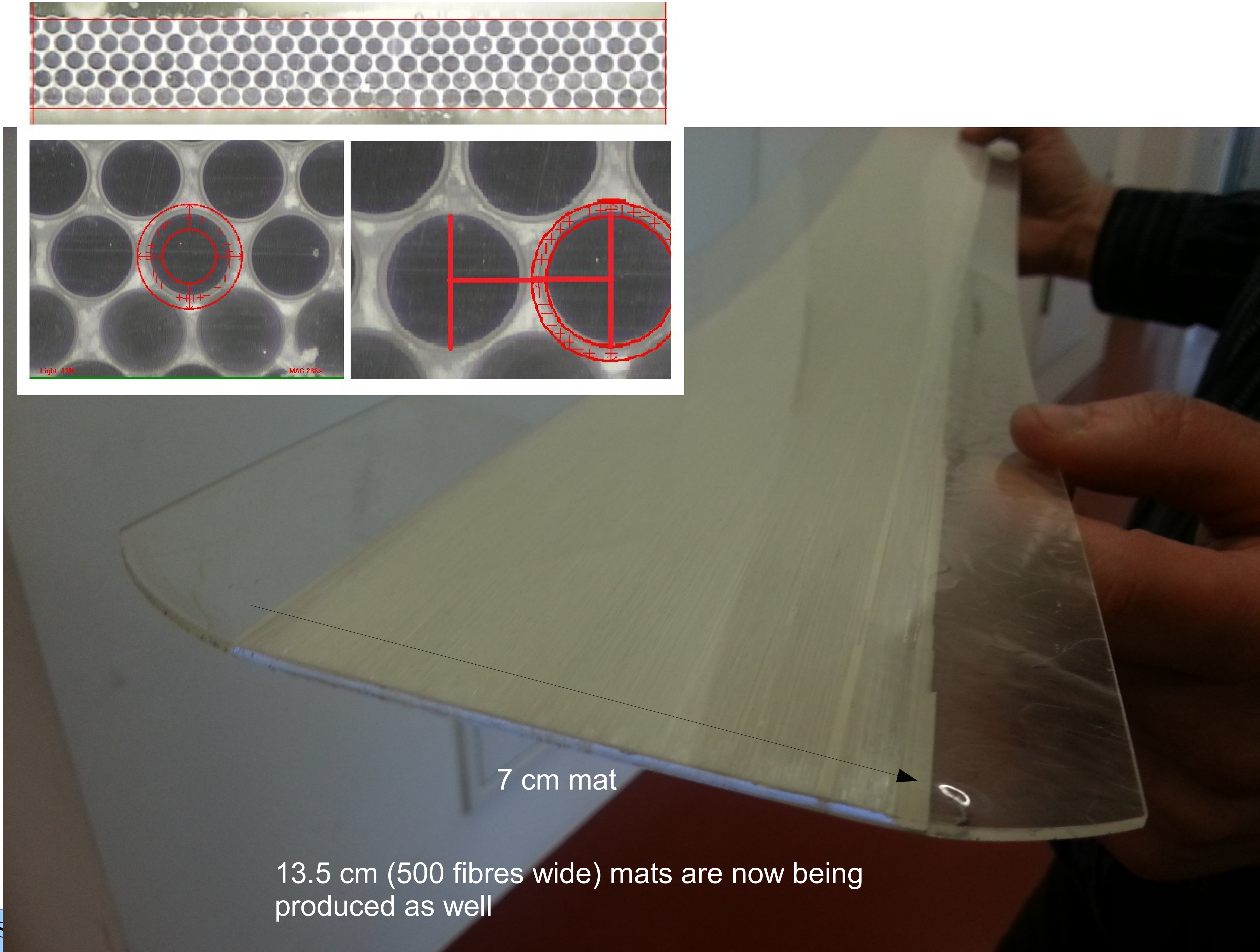
- Need about 8km of fibre for one mat of 6 layers 2.5 metres long
- 10,000 km of fibre in total ...

Fibre Mats



Cutting will create dead fibres on the edges



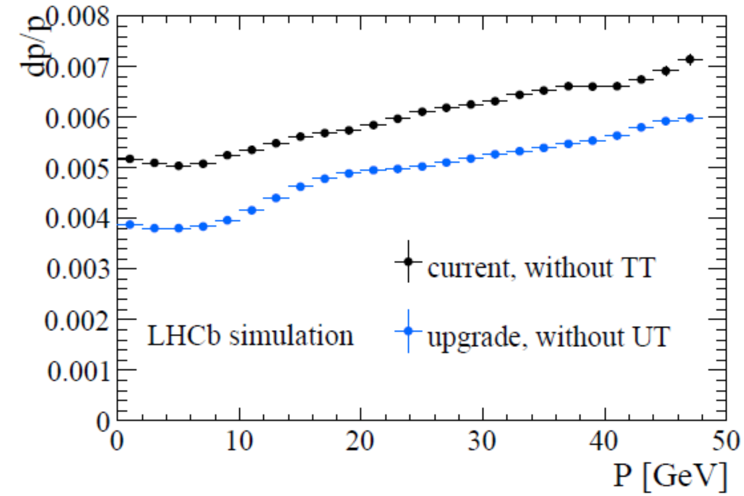


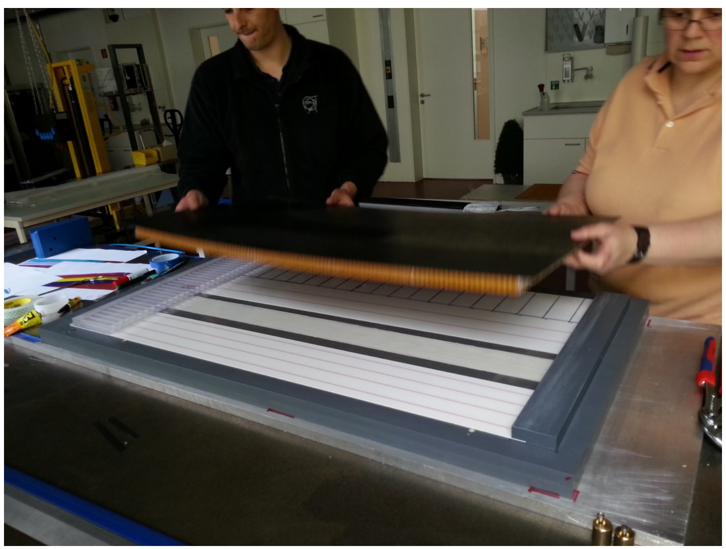
13.5 cm (500 fibres wide) mats are now being produced as well

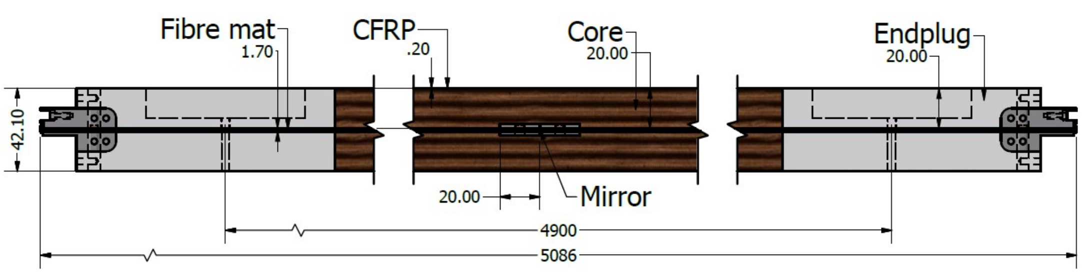
Challenges: Detector design

- Stability and alignment of the detector must be ~100μm
- Must be <1% of a radiation length per detector layer (4mm equiv. of plastic)

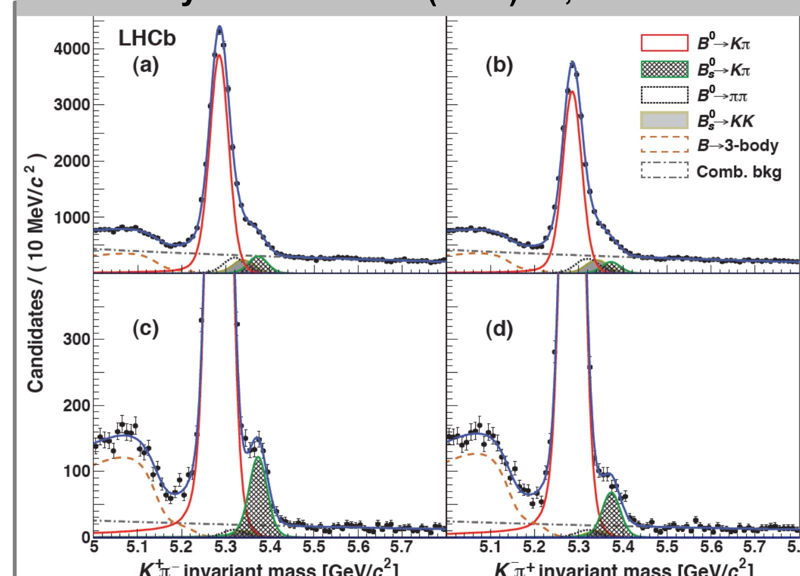
Less material + stable detector = improved momentum resolution = better mass resolution



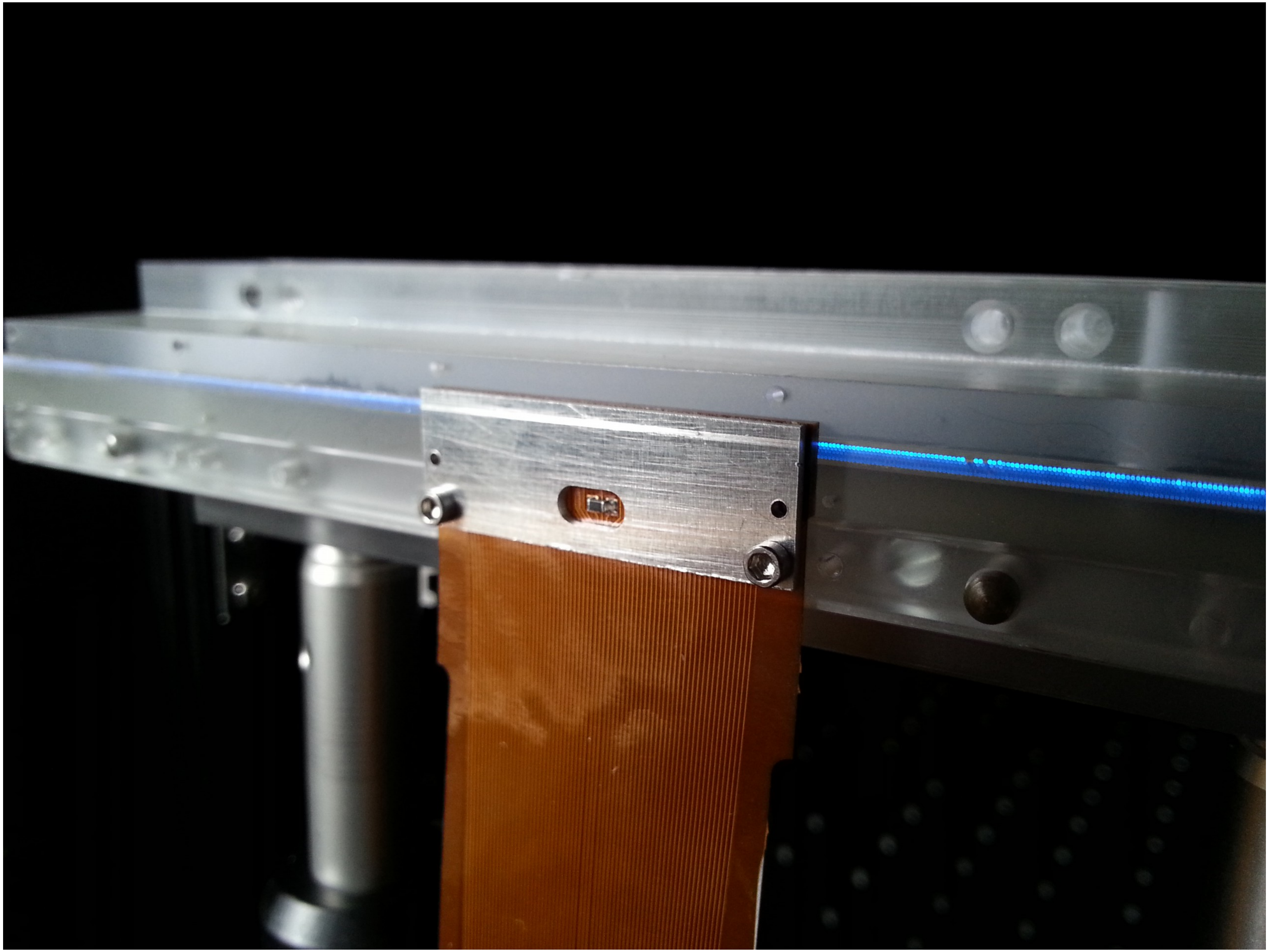




Phys.Rev.Lett. 110 (2013) 22, 221601

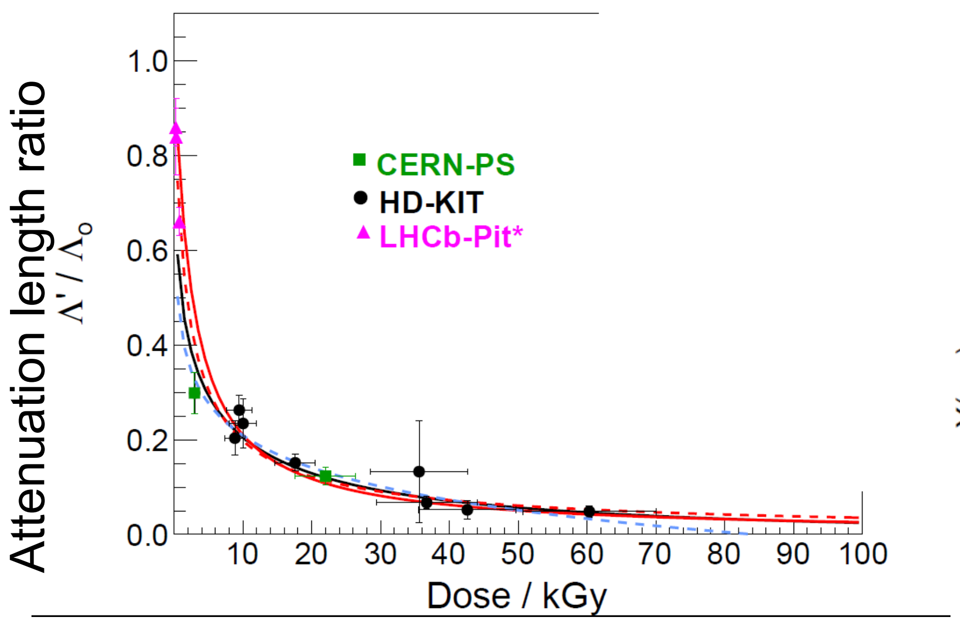


Prototypes and Test-beam in October 2014! :)



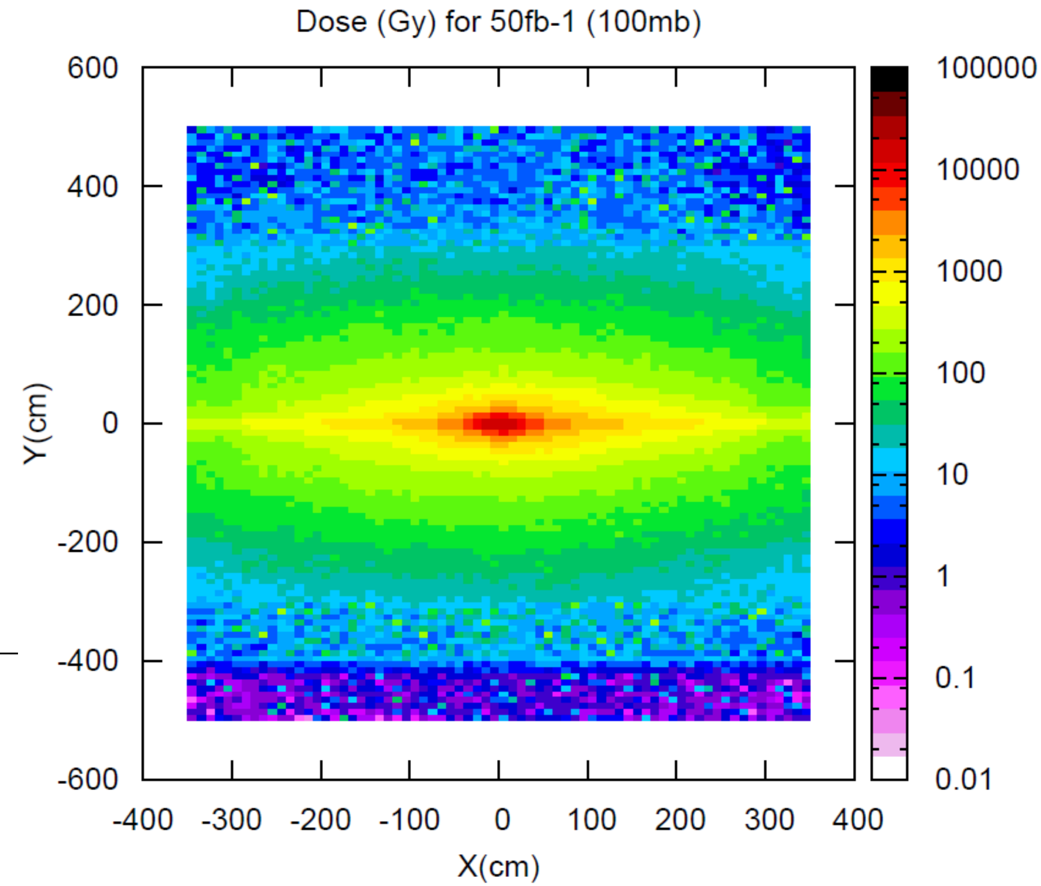
Challenges: Fibre irradiation

- The scintillating fibres darken with radiation (up to 35 kGy expected near the beam pipe over the upgrade lifetime)



Expect a 40% loss in signal near the beam pipe after 10 years

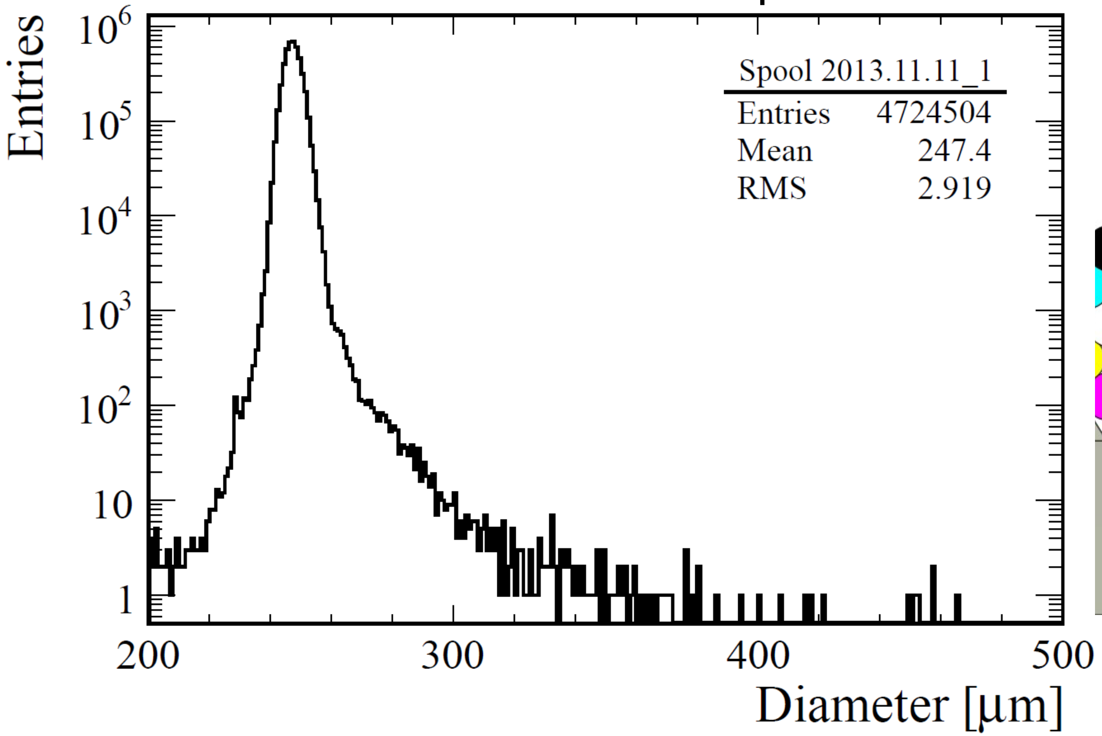
Expected ionizing dose for LHCb Upgrade



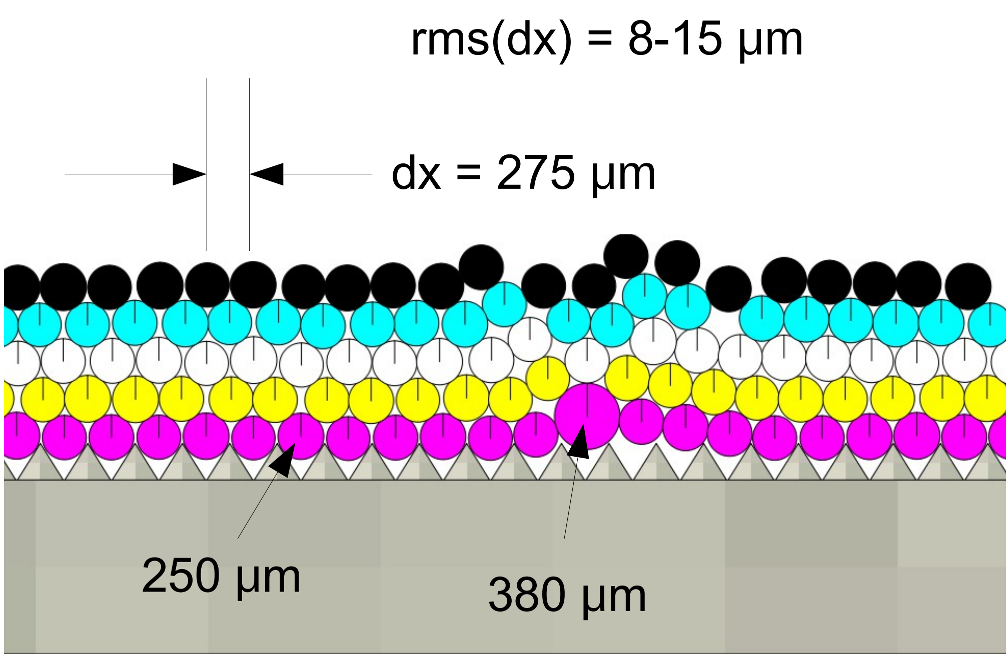
Challenges: Fibre bumps

- Defects of the fibre can be created during the extrusion process making "blobs"

Fibre diameter over one spool



For a good mat
rms(dx) = 8-15 μm



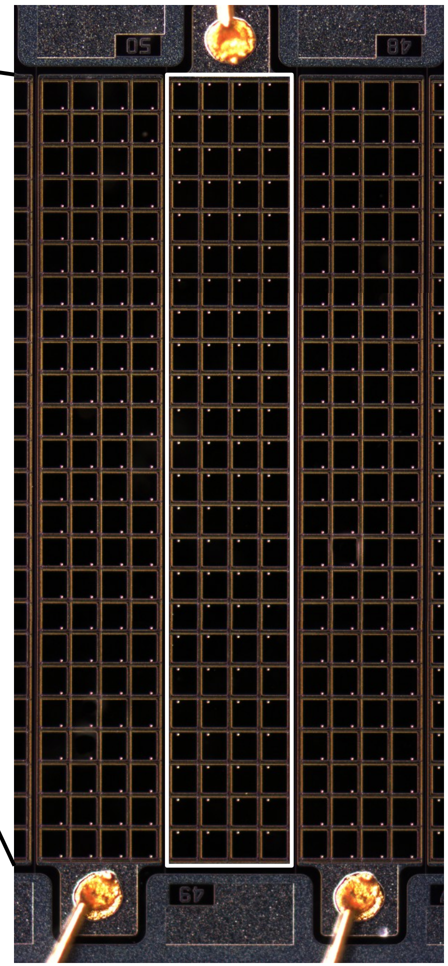
Challenges: SiPM array development

128 channels = 32.59 mm

1 channel

0.25mm x 1.52mm

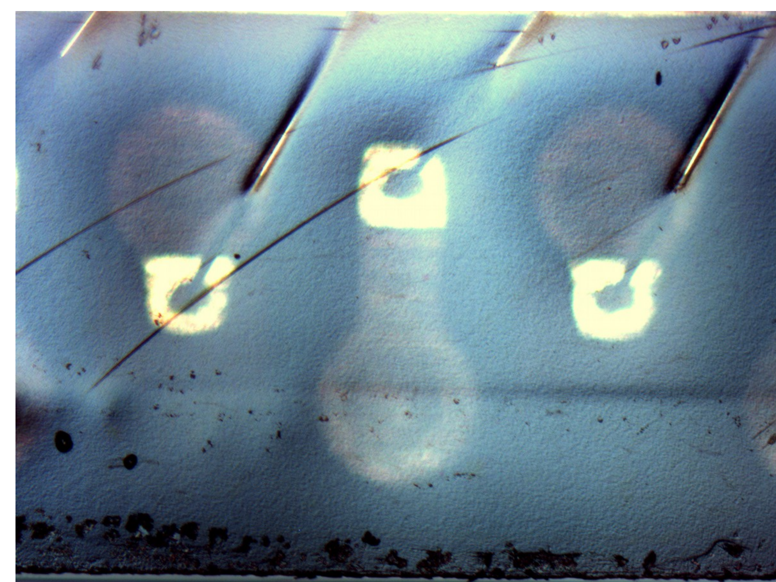
4 x 24 pixels (~50 micron)



Issues with packaging:

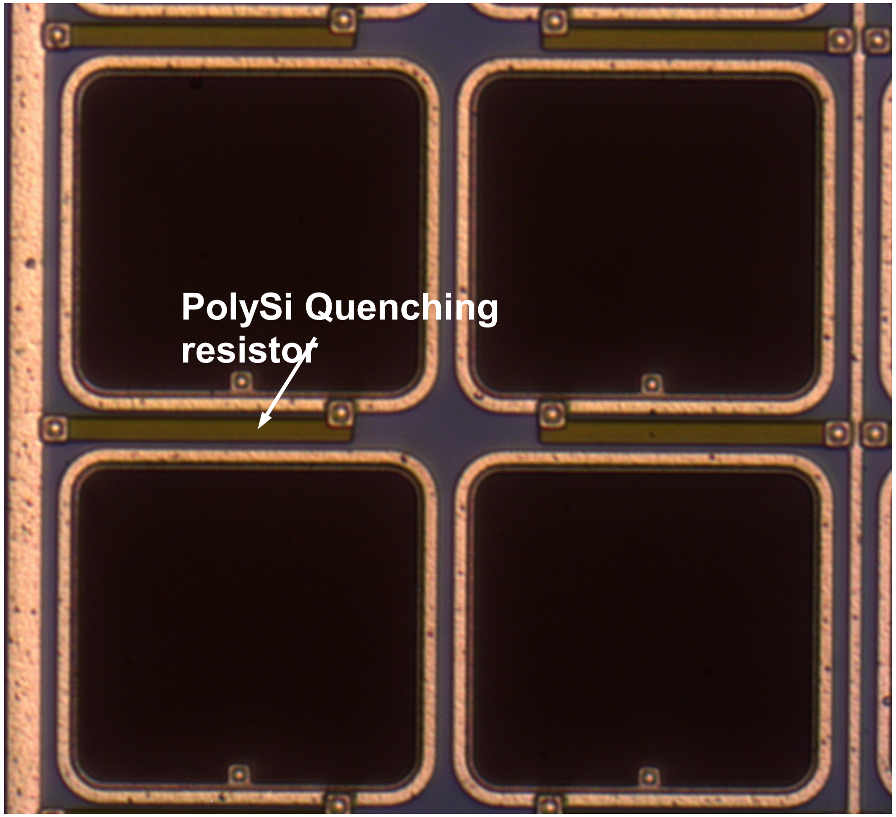
-dead channels
-exposed bondwires

A fix is promised from the companies....



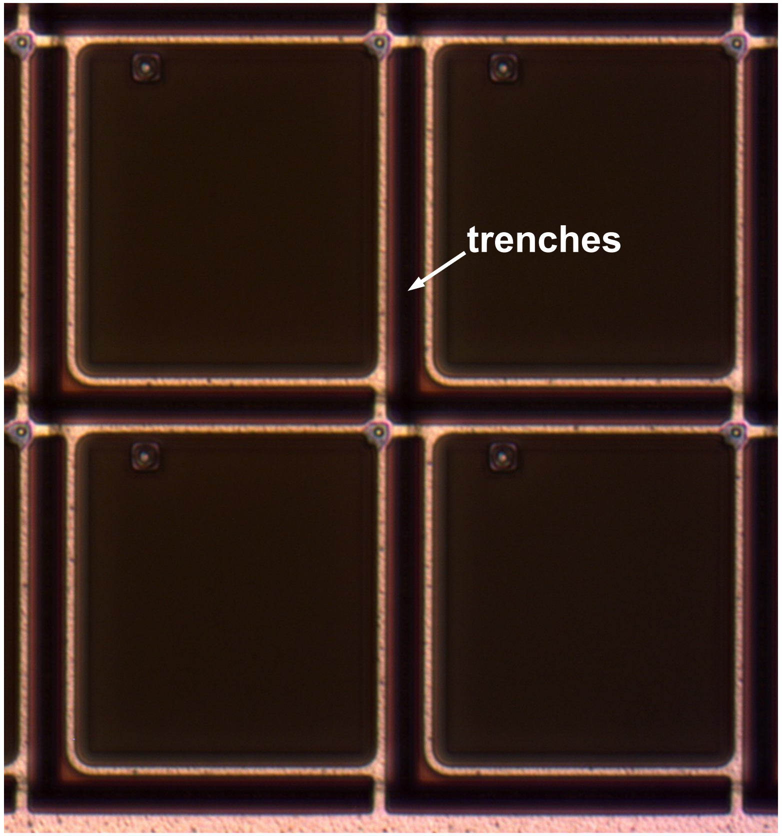
Old Hamamatsu arrays (~2010)

Operating voltage = ~72 V
Overvoltage = ~1 V
Crosstalk = 21%

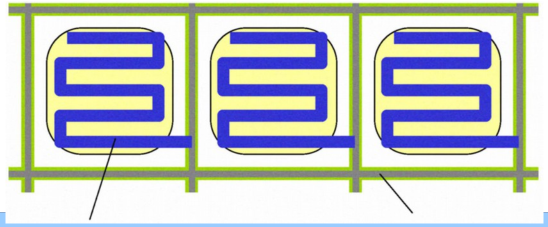


New Hamamatsu arrays (2014)

Operating voltage = ~52 V
overvoltage = ~2.5 V
Crosstalk = ~5%

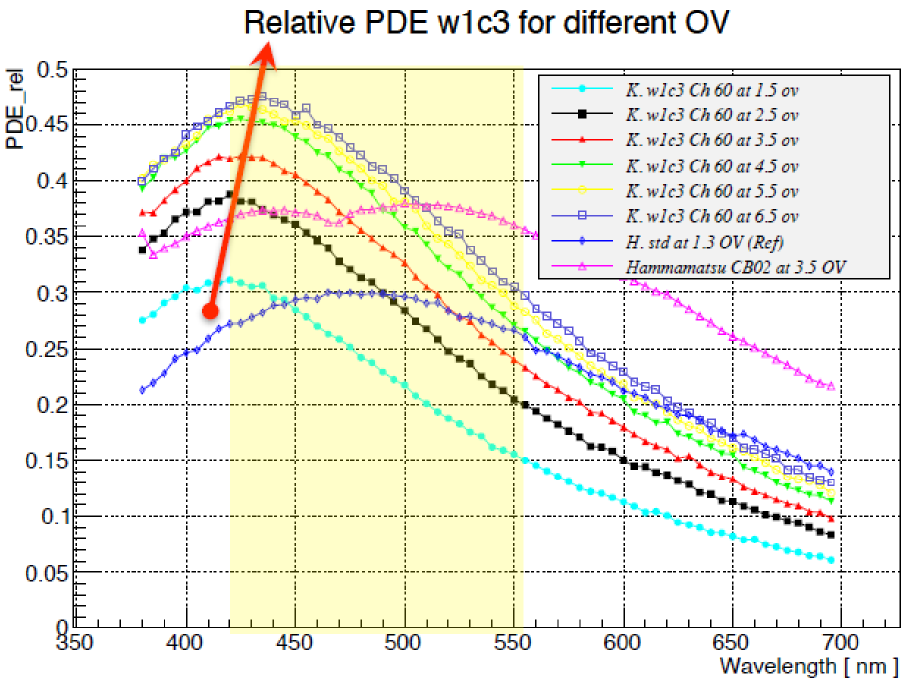


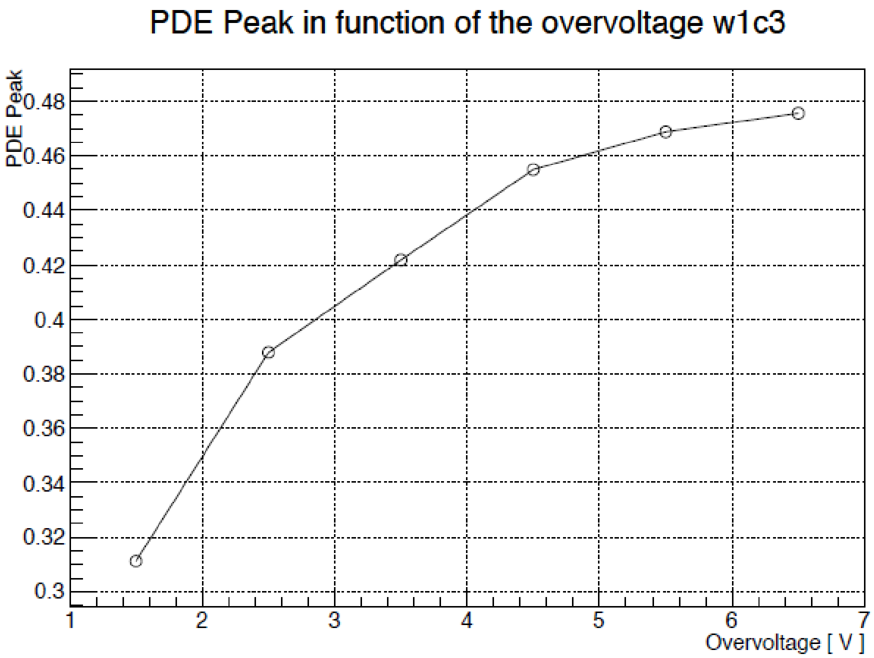
Thin metal film quenching resistor = higher PDE, lower TCR



(photon detection efficiency)

PDE Hamamatsu and Ketek





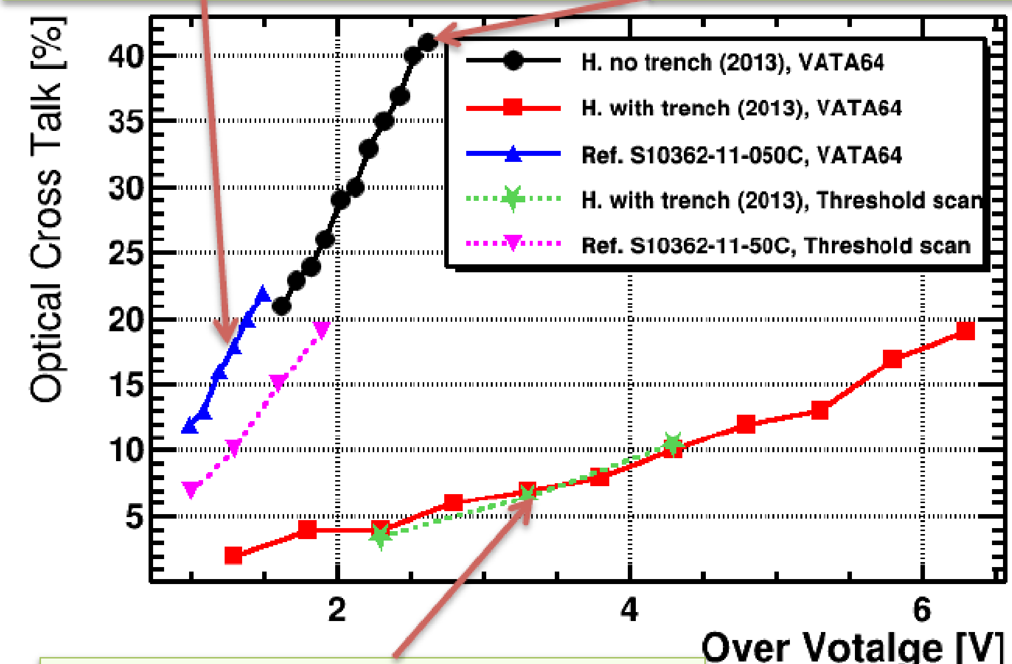
Plots from G. Haefeli, presented at TIPP 2014

(pixel)

X-talk Hamamatsu and Ketek

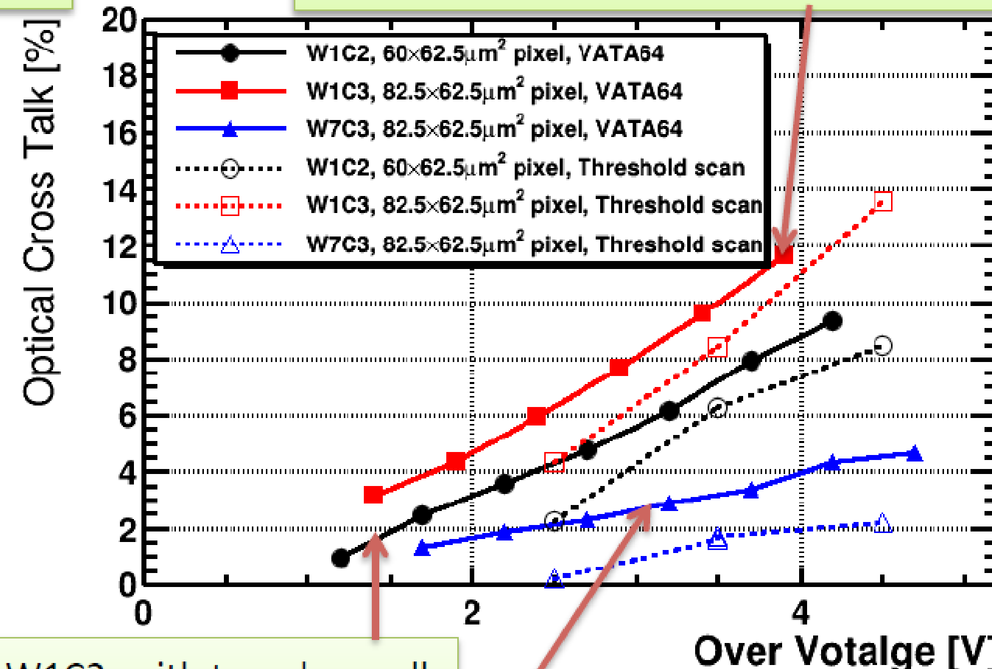
Difference due to after-pulsing (1.3V over-voltage) (17% vs 10%)

No trench, extremely high x-talk



With trench, low after-pulsing, 7% x-talk at 3.5V over-voltage

W1C3, with trench, large pixels (3.5V over-voltage) (10% vs 8%)



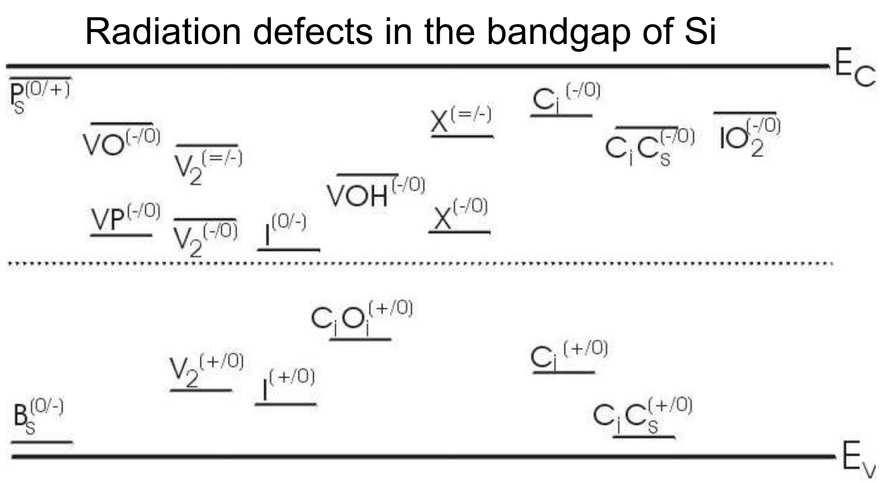
W1C2, with trench, small pixels (3.5V over-voltage) (8% vs 7%)

W7C3, double trench, large pixels (3.5V over-voltage) (3% vs 2%)

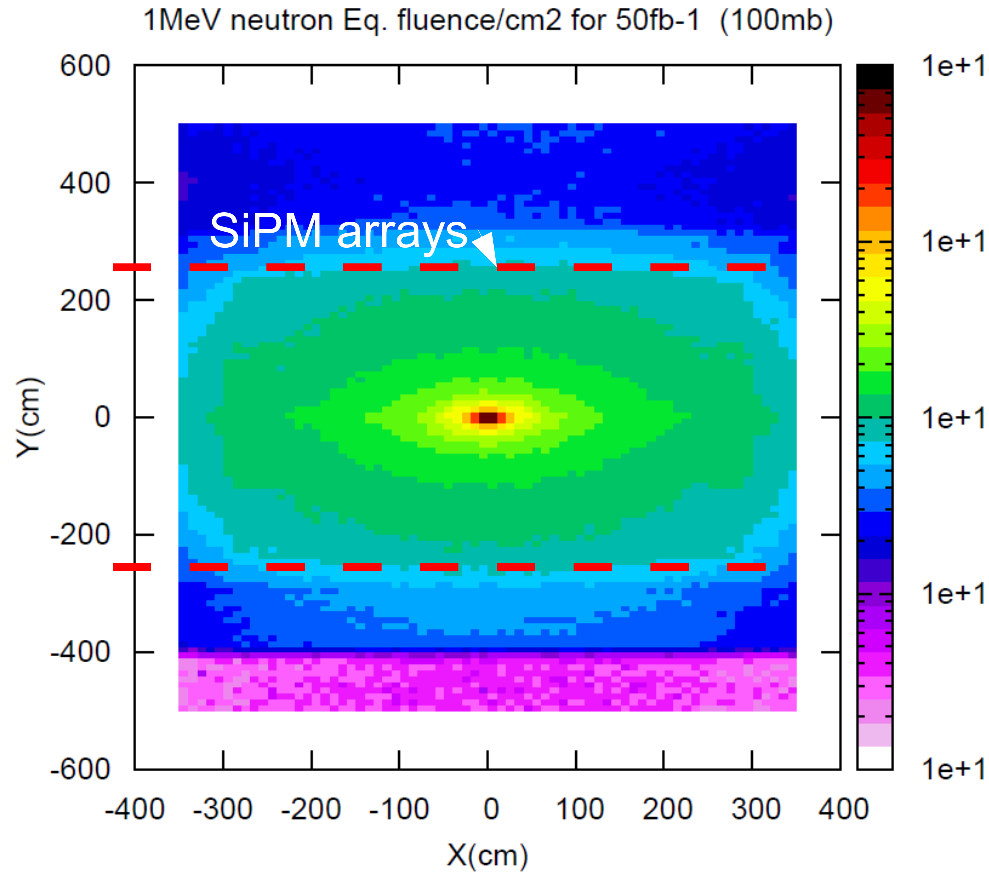
Plots from G. Haefeli (EPFL), presented at TIPP 2014

Challenge: Radiation damage to SiPMs

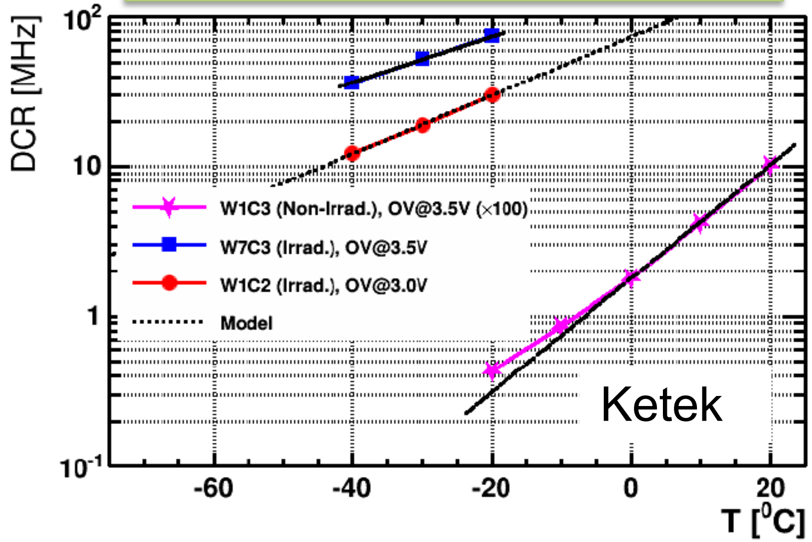
- SiPMs create single photo-electron signals from thermal electrons, cross-talk between pixels makes 1 photo-electron look like 2+



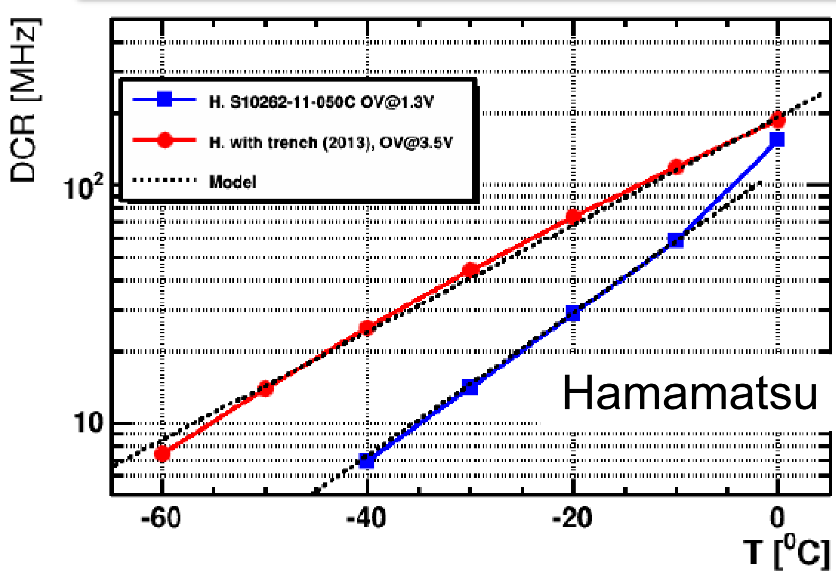
Interstitials(I-) and vacancies (V+)



1/3mm^2 , 2×10^{11} n_{eqv}/cm^2 fluence at different temperatures

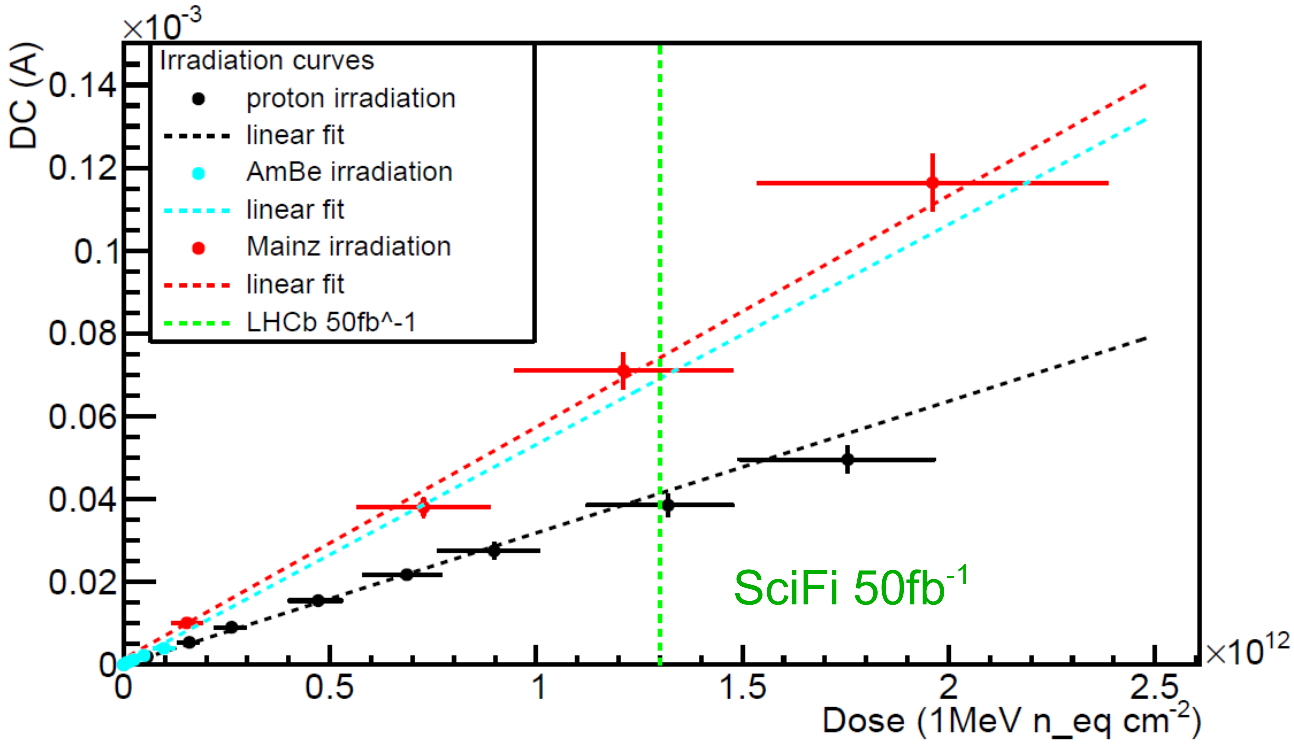


1mm^2 single channel, 3.1×10^{11} n_{eqv}/cm^2 fluence at different temperatures



- We expect 1.3 x 10^{12} n_{eq}/cm^2
- Requires cooling to -40C
- So far, Ketek shows 2-3 times worse noise due to irradiation compared to Hamamatsu

For a Hamamatsu S12571-50C 1mm^2 SiPM (@-30C, no trenches)

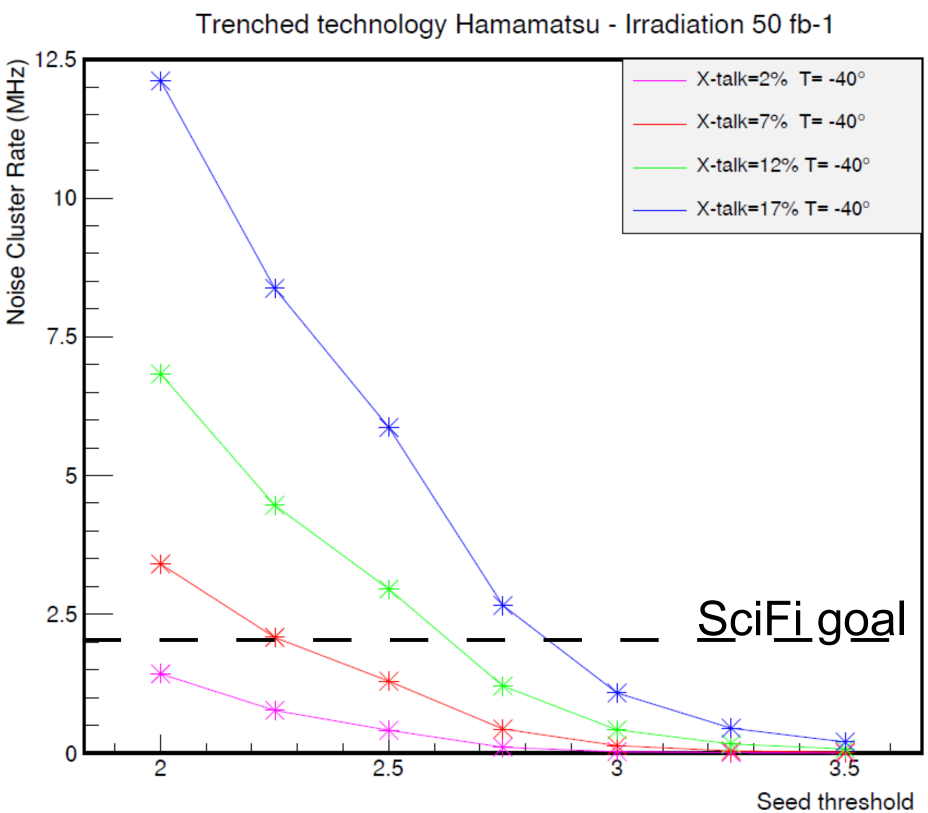


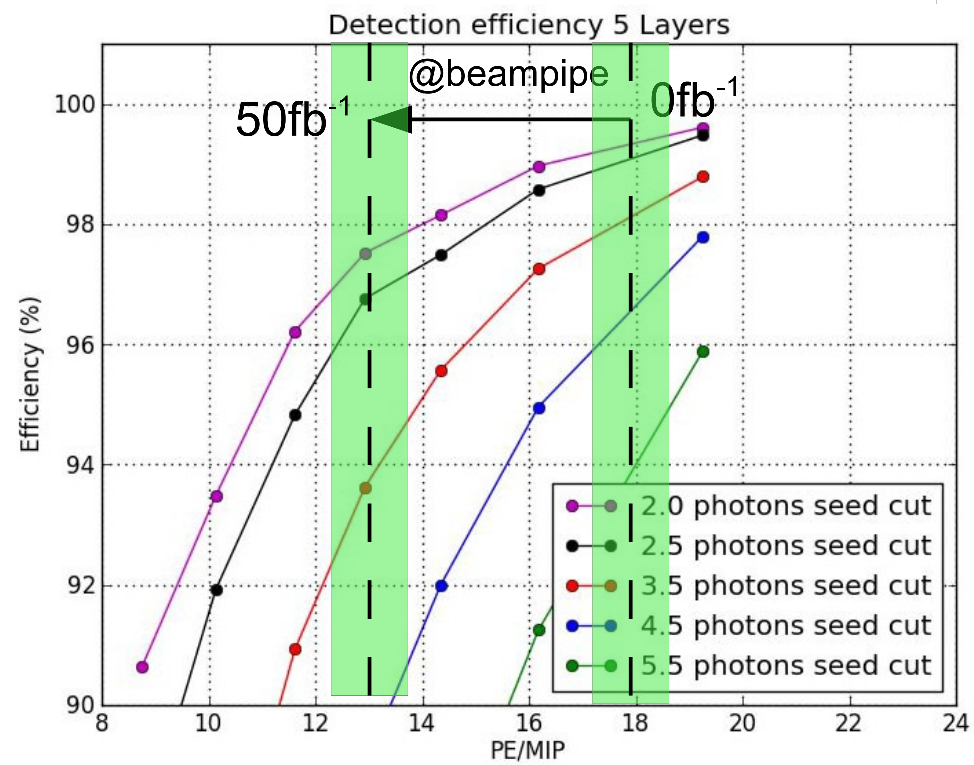
Expect about **20 MHz** of >0.5 p.e. noise per channel after 1.3 x 10^{12} n_{eq}/cm^2

Need to have **clusters** per 128ch array less than 2 MHz for efficient tracking = no crosstalk!!

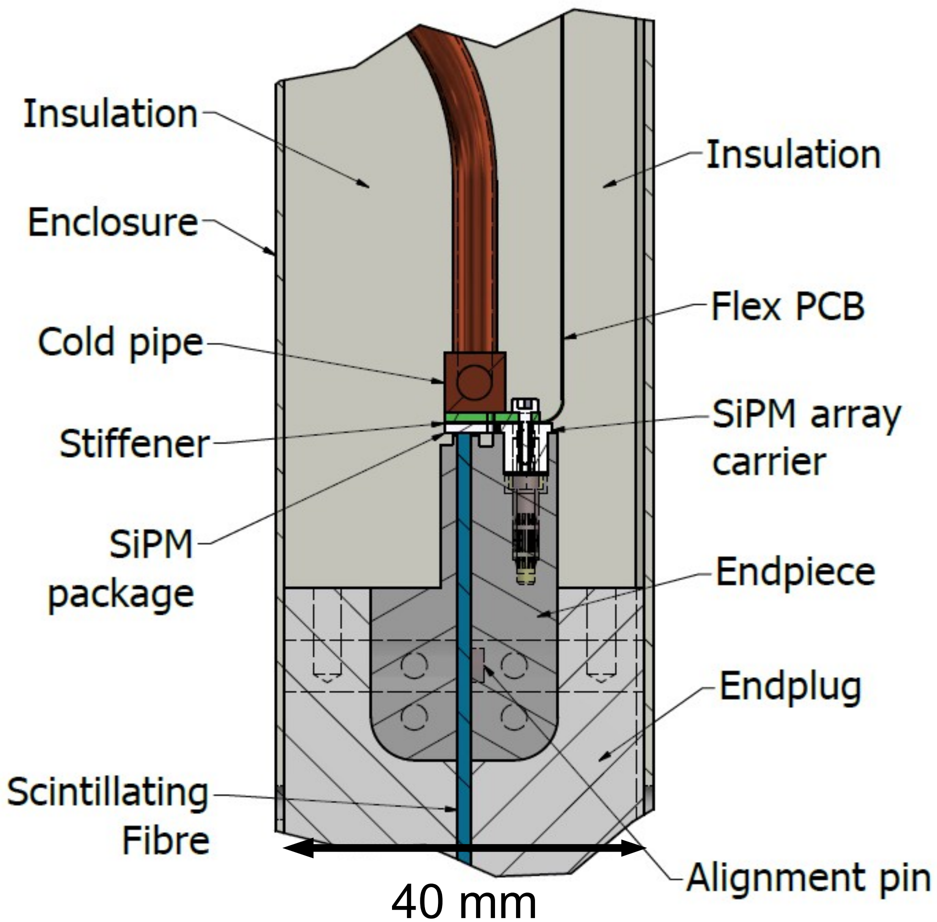
Thermal annealing @ +40C is planned during week long stops.

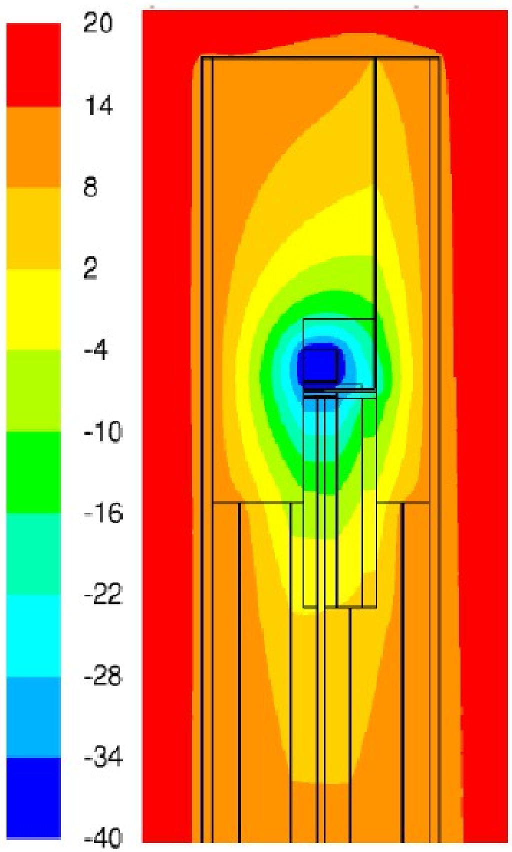
- We want a higher threshold to exclude noise contributions but a low threshold to retain signal, resolution and hit efficiency
- Excessive noise clusters will degrade tracking





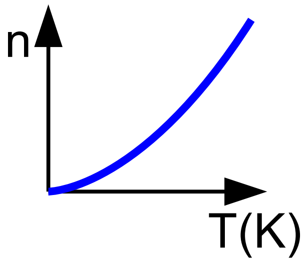
Challenges: Cooling





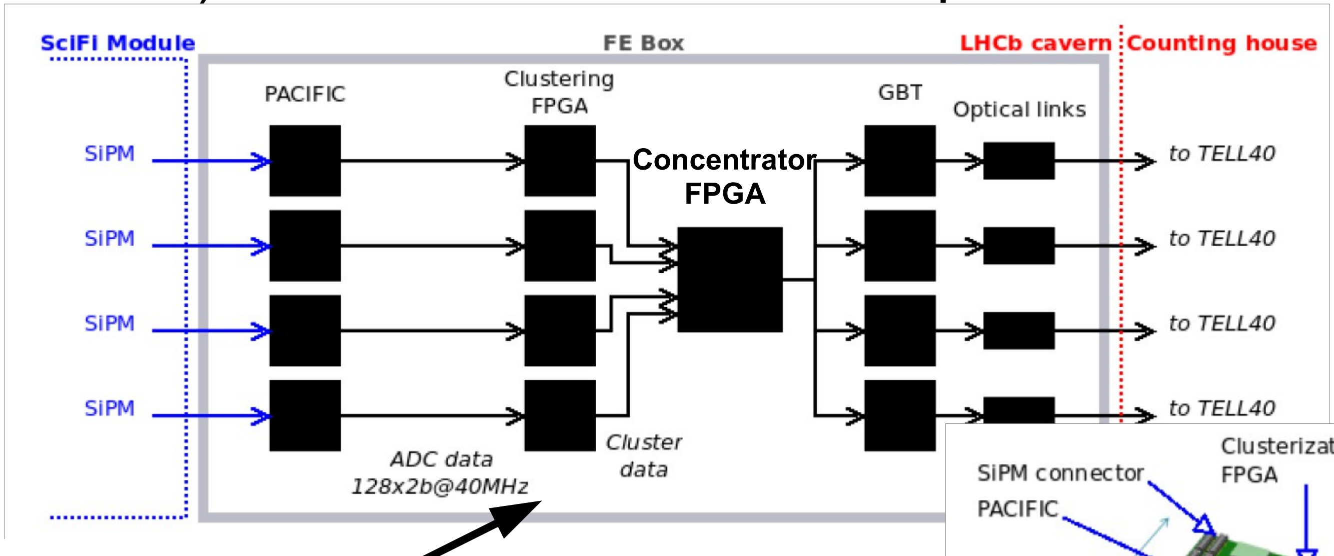
- Acceptable cluster rates require -40C cooling and +40C annealing

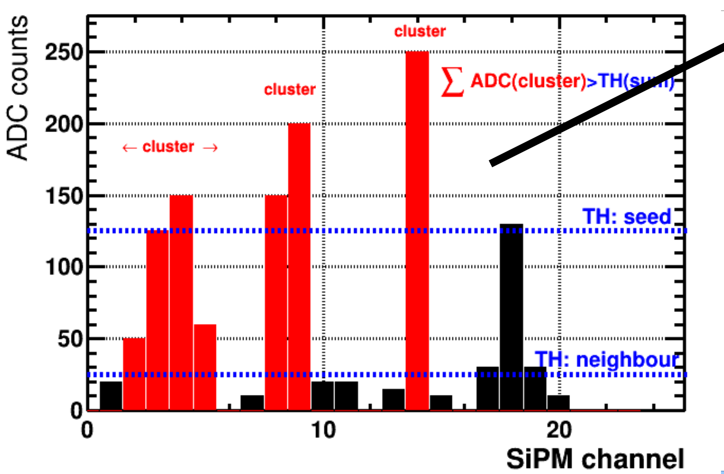
$$dark\,noise \propto T^2 \exp\left(\frac{-E_g}{2k_B T}\right)$$

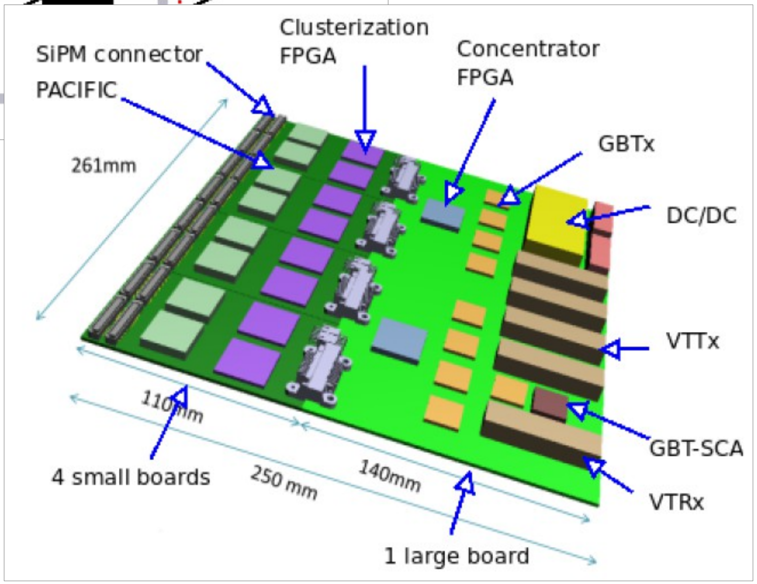


Challenges: Electronics

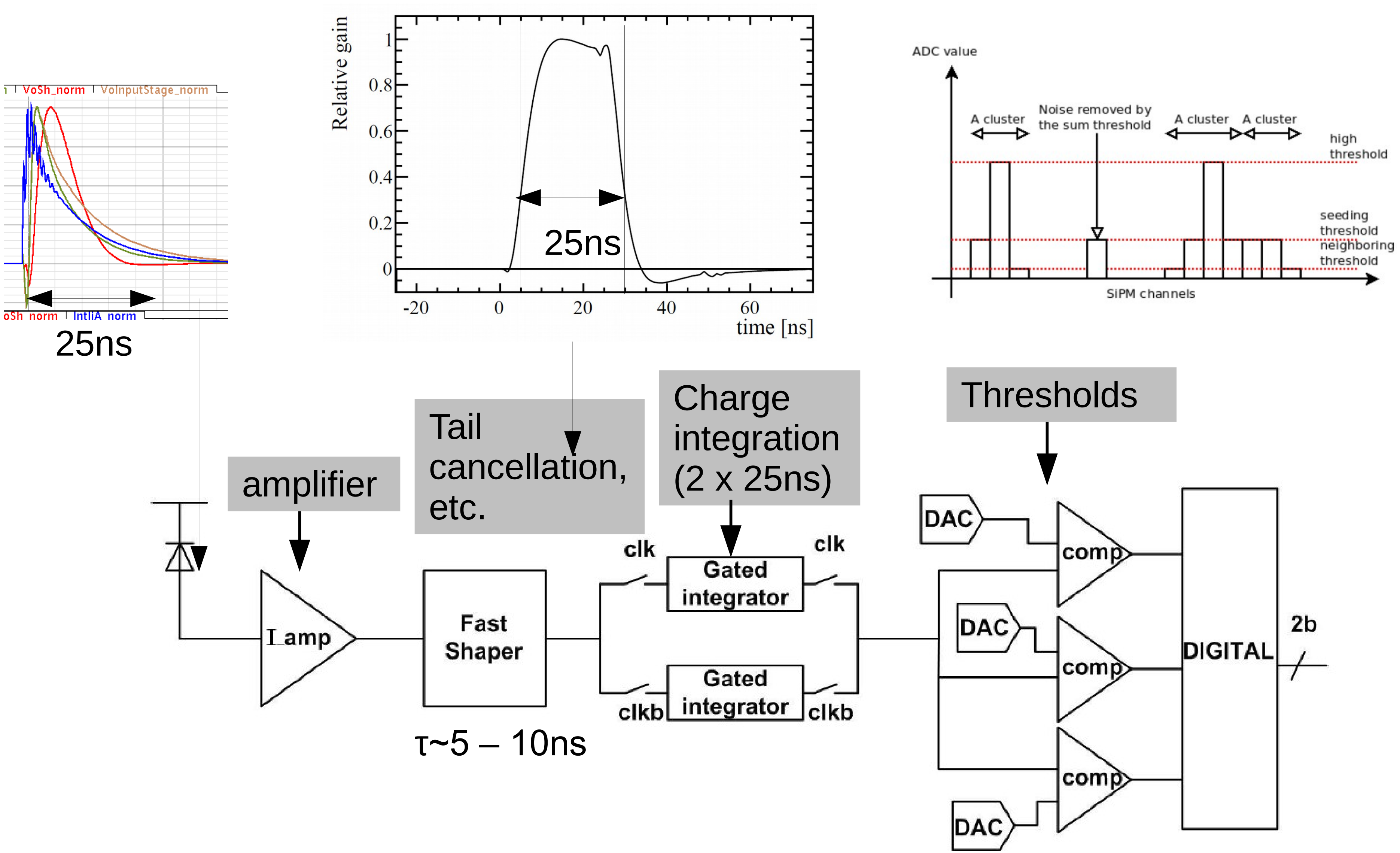
- Digitizes the 560,000 SiPM signals and forms the clusters and hit positions
- ASIC (PACIFIC) and front-end board development



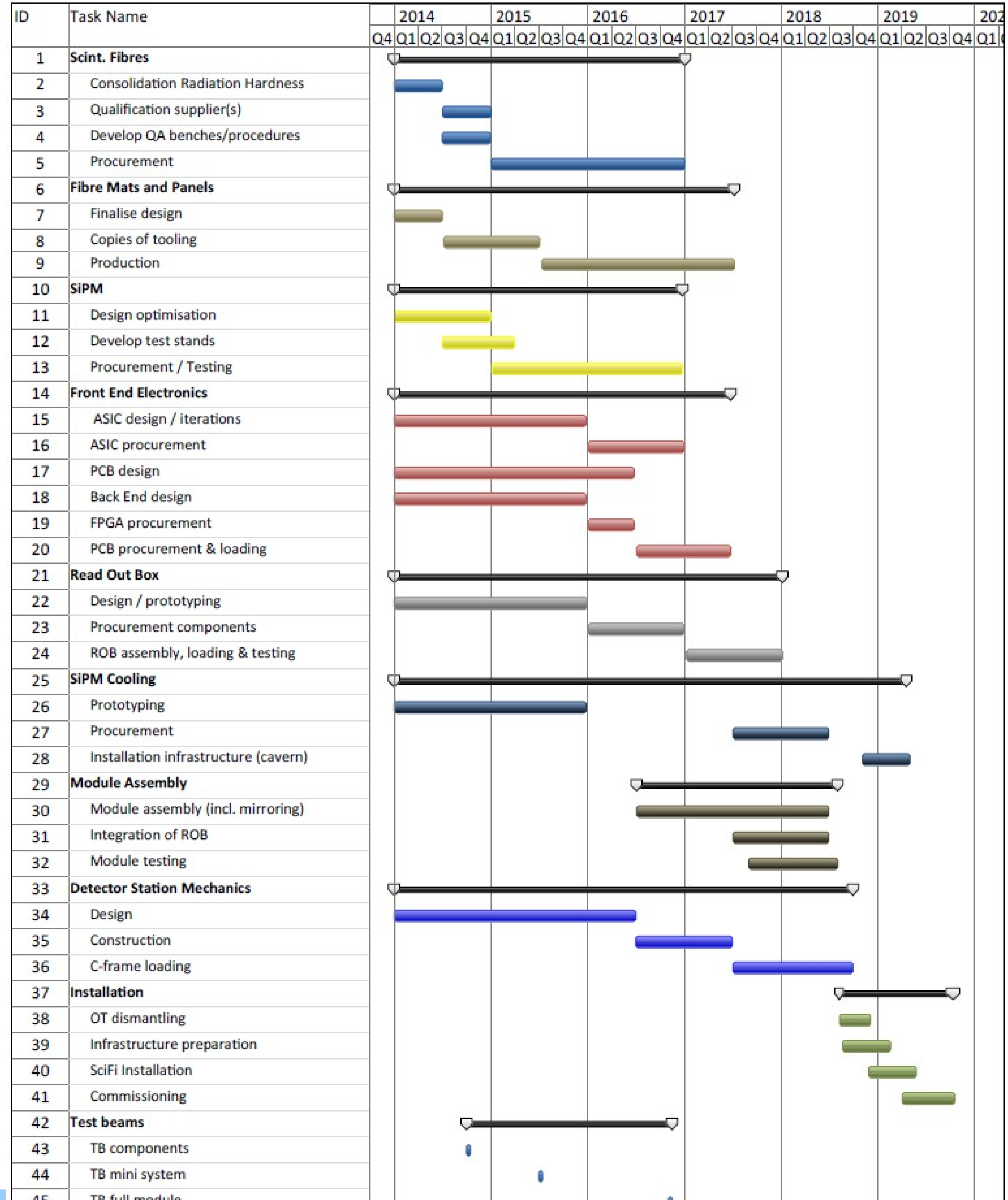




The PACIFIC


VoSh_norm
VoInputStage_norm
oSh_norm
IntlA_norm
25ns
Relative gain
1
0.8
0.6
0.4
0.2
0
-20
0
20
40
60
time [ns]
25ns
ADC value
A cluster
Noise removed by the sum threshold
A cluster
A cluster
high threshold
seeding threshold
neighboring threshold
SiPM channels
amplifier
Tail cancellation, etc.
Charge integration (2 x 25ns)
Thresholds
I_amp
Fast Shaper
τ~5 – 10ns
clk
clk
Gated integrator
Gated integrator
clkb
clkb
DAC
DAC
DAC
comp
comp
comp
DIGITAL
2b

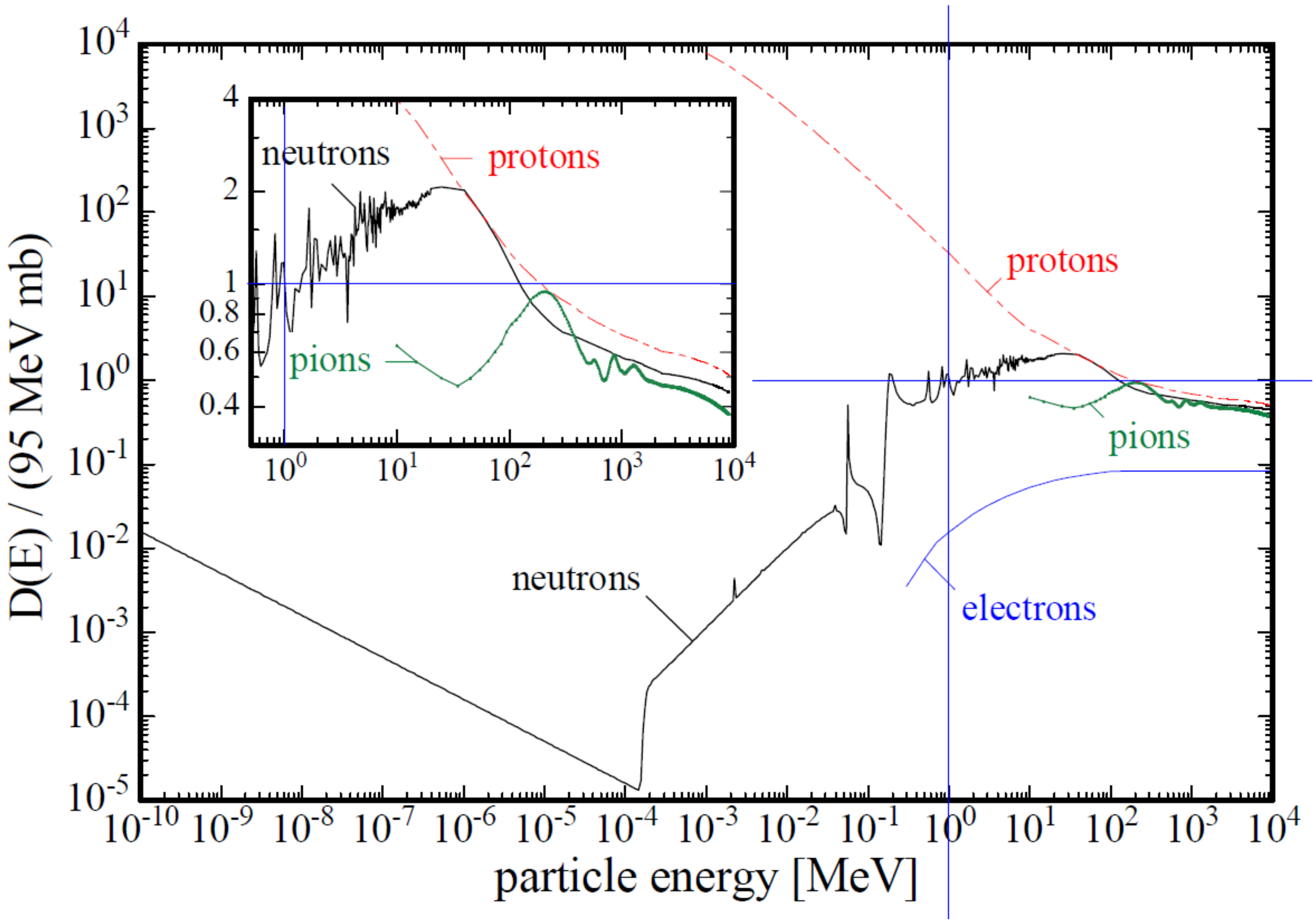
- Research is finished.
- Engineering has started.
- SiPM improvements under development yet.
- PACIFIC-2 (8ch at the foundry now)
- Everything must be working and in the LHCb pit mid-2018.



Summary

- The order of magnitude increases in precision will allow new physics searches down to Standard Model theoretical uncertainties
- The SciFi tracker is crucial to scope with the upgrade requirements
- SciFi collaboration with 10 countries in 20 institutions
- Begin construction in end of 2015; Ready for installation in 2018

backup



D(E) / (95 MeV mb)
particle energy [MeV]
neutrons
protons
pions
electrons