The LHCb Scintillating Fibre Tracker

B. Leverington, on behalf of the SciFi Tracker Collaboration

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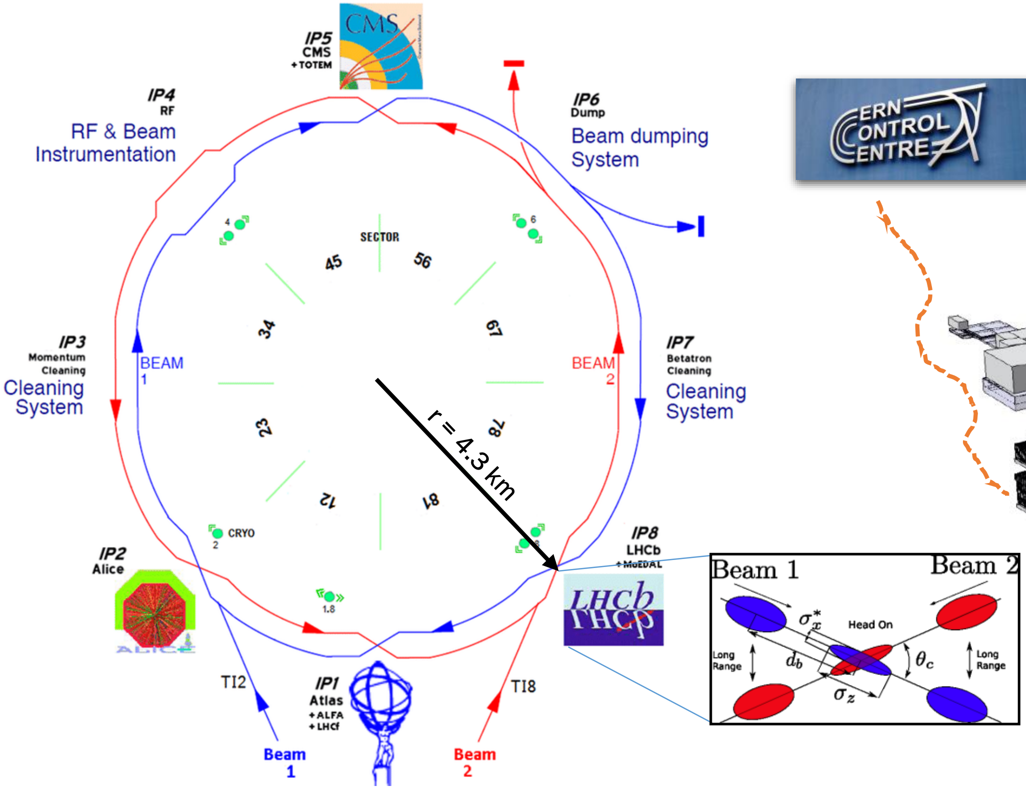
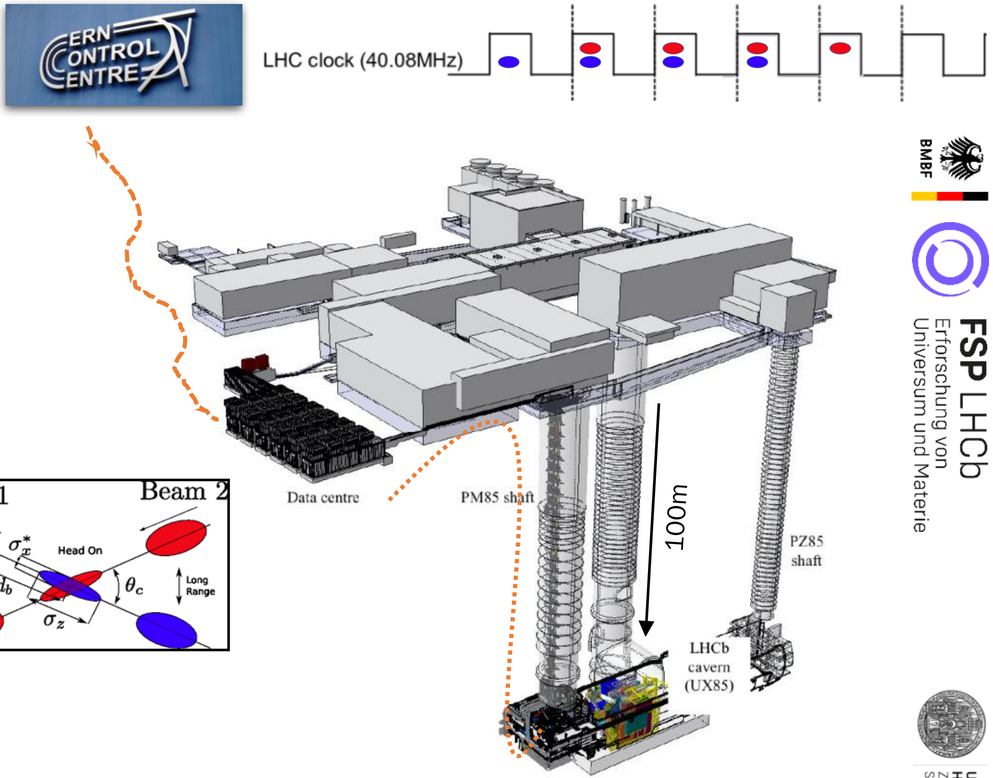
BMBF

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

LHCb at the LHC





LHCb: Upgrade 1

Performance of the LHCb Upgrade I in Run3
F. Oliva - LHCb collaboration at BEAUTY2023

A single-arm forward spectrometer, completed in April 2022

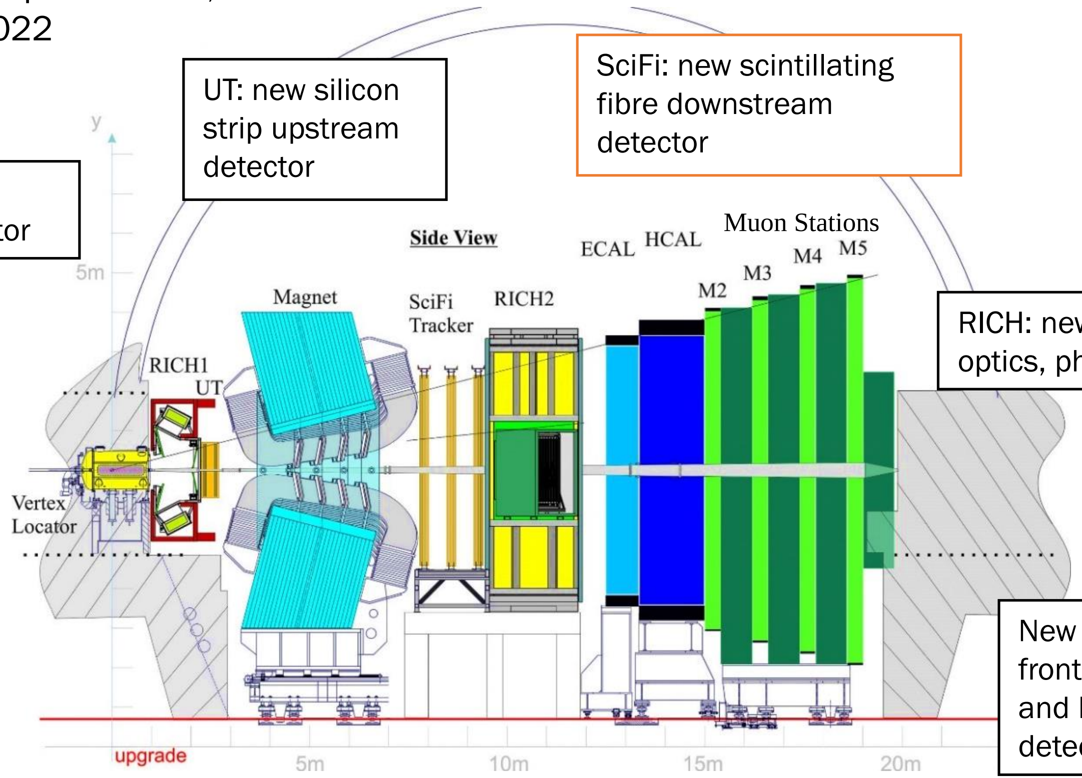
UT: new silicon strip upstream detector

SciFi: new scintillating fibre downstream detector

VELO: new pixel detector

Remove L0 Trigger → Full 30 MHz Software trigger in GPU(HLT1) & CPU(HLT2)

RICH: new mechanics, optics, photodetectors



Increased pileup: from ~1 in Run 1 & 2 to ~5 in Run 3 & 4 (2022-2032)

New 40 MHz frontend electronics and DAQ for all sub-detectors

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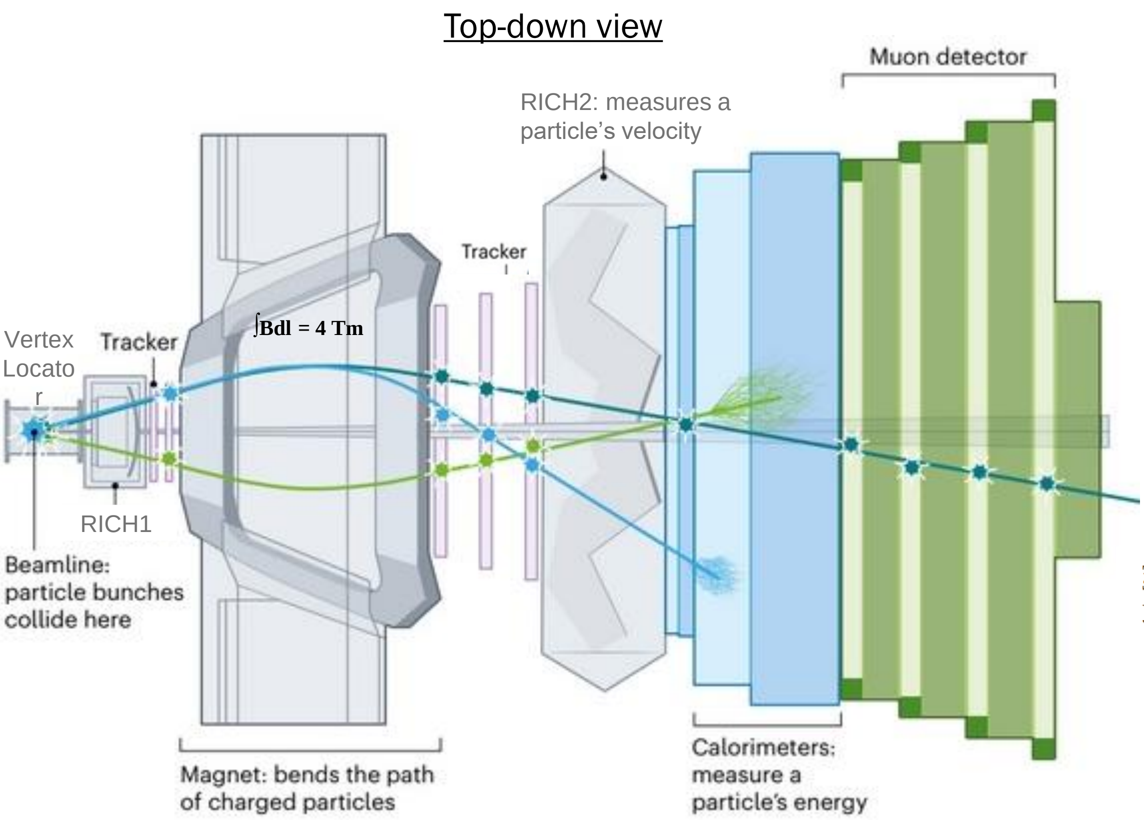
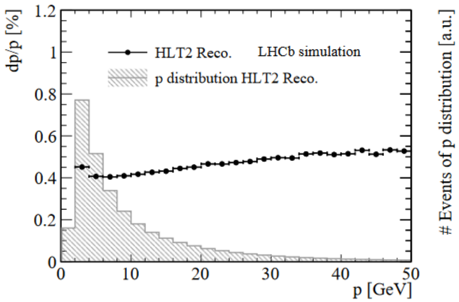
LHCb Tracking



The tracking system provides a measurement of the momentum, p, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c.

https://arxiv.org/pdf/2305.10515.pdf



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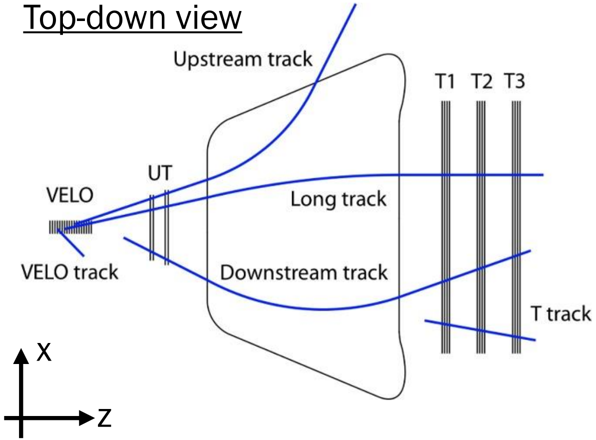
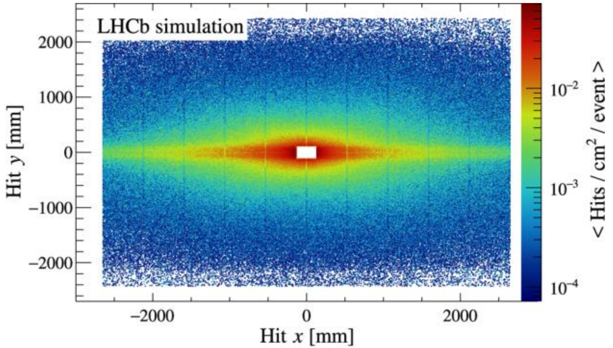
A bit more on Tracking

Top-down view



Event average hit density in a single layer of the SciFi. The hole in the middle corresponds to the beam hole.



A. Build track segment (T-Track) (stand-alone or matched)
   1. First build candidates in the bending plane (x, z) from 0° x-layers
   2. The track pattern in the non-bending plane (y) is formed by matching the seed track with hits from ±5° *u*- / *v*-layers.

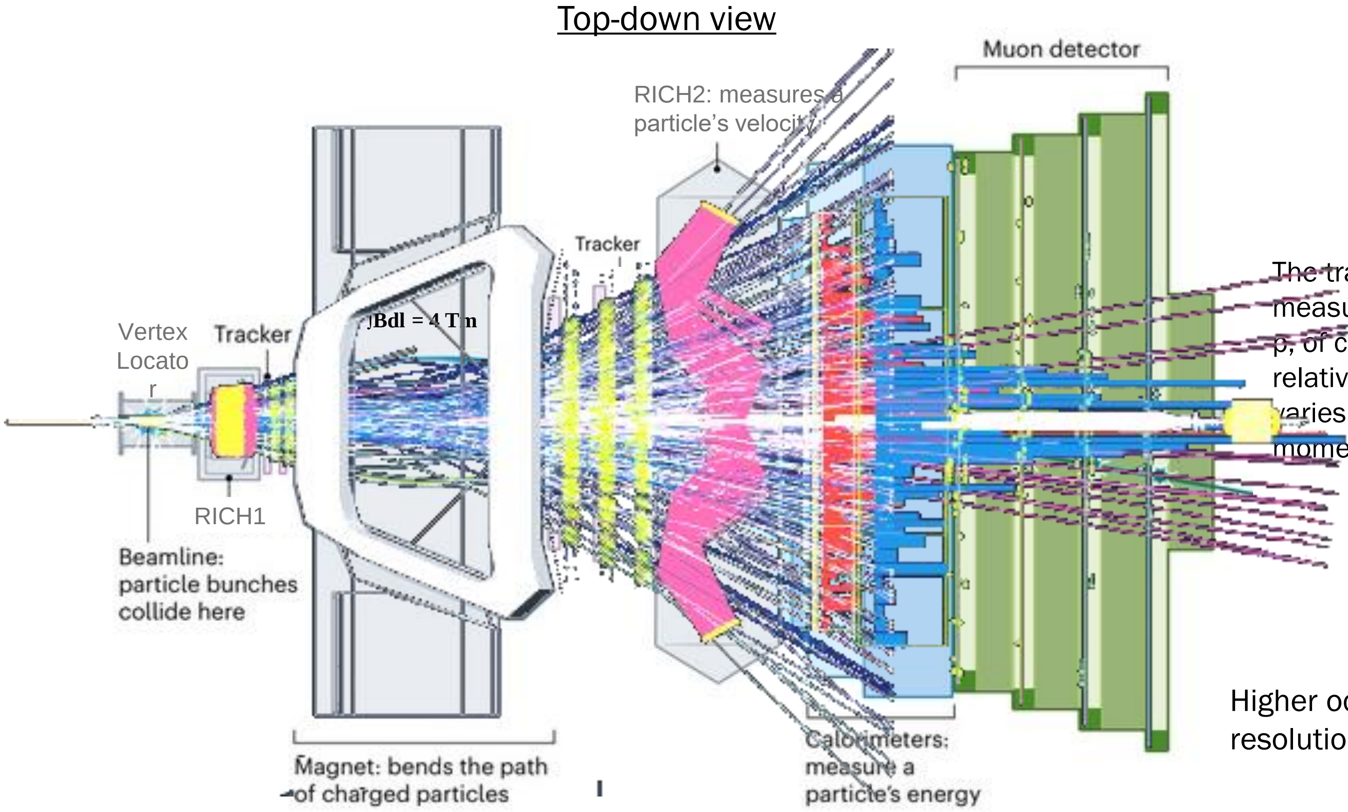
B. Match VELO, UT, T-Track and determine χ^2/ndf as track quality
   → Achieve high efficiency with low fake-track rates

Hybrid seeding: A standalone track reconstruction algorithm for scintillating fibre tracker at LHCb ☆

S. Aiola [d 1], Y. Amhis [b], P. Billoir [a], B. Kishor Jashal [c], L. Henry [c d 1], A. Oyanguren Campos [c], C. Marin Benito [b 2], F. Polci [a], R. Quagliani [a 3], M. Schiller [e], M. Wang [f]

https://doi.org/10.1016/j.cpc.2020.107713

LHCb Tracking



The tracking system provides a measurement of the momentum, p, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c.

Higher occupancies can degrade the resolution.

Downstream Tracking Detector Requirements

arXiv > hep-ex > arXiv:2305.10515

High Energy Physics - Experiment

[Submitted on 17 May 2023]

The LHCb upgrade I

https://arxiv.org/pdf/2305.10515.pdf

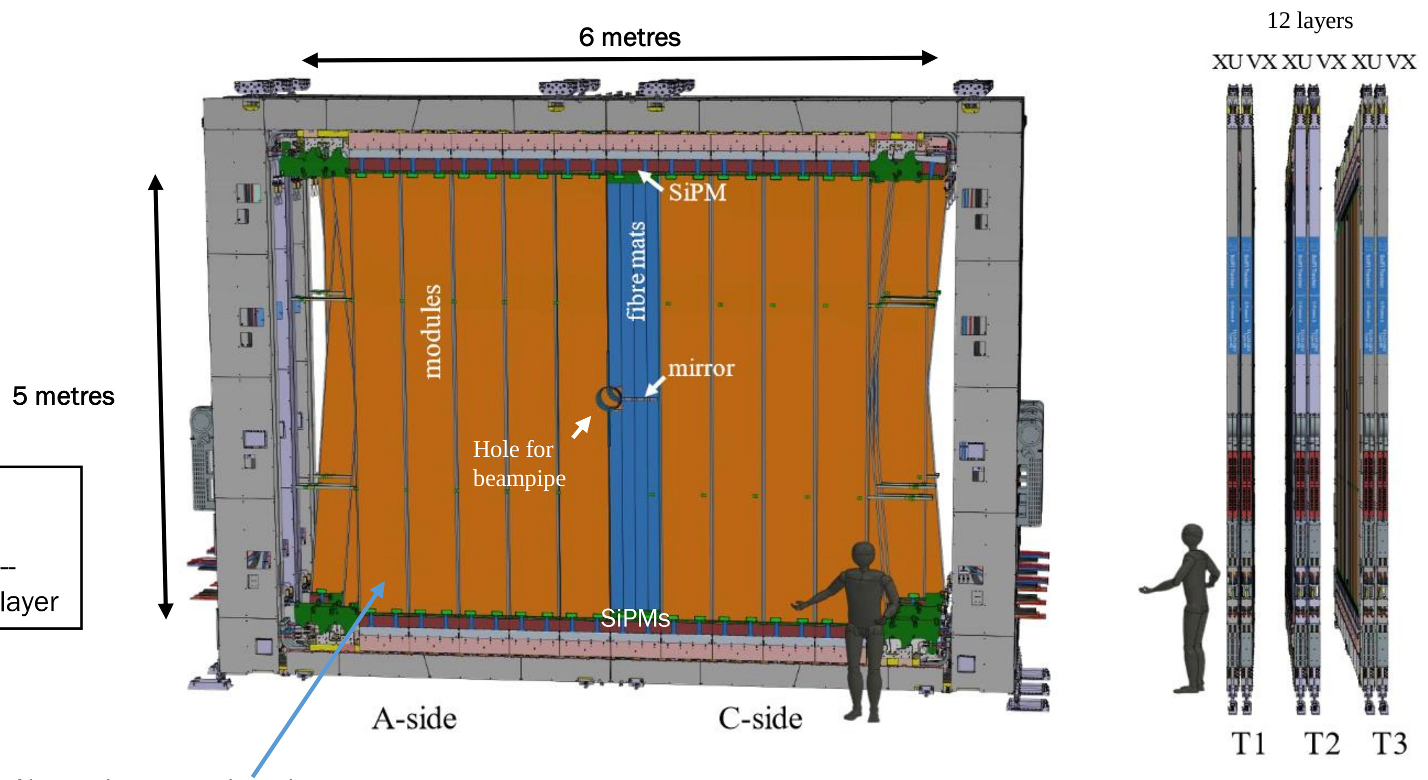
6.1.1 Detector requirements

The design of the tracker must take into account the following requirements:

- Performance: the tracker should provide a single hit position resolution of better than 100 µm in the magnet bending plane and a single hit reconstruction efficiency better than 99%.
- Rigidity: the mechanical stability of the detector must guarantee that the positions of the detector elements are stable within a precision of 50 (300) µm in x (z); the detector elements should also be straight along their length within 50 µm.
- Material budget: to limit further multiple scattering and secondary particle production, each of the 12 layers should not introduce more than 1% of a radiation length.
- Radiation hardness: the tracker should operate at the desired performance over the lifetime of the experiment, where $50\,\mathrm{fb}^{-1}$ of integrated luminosity is expected to be collected.
- Granularity: the tracker must have an occupancy low enough so that the hit efficiency is not impacted with an instantaneous luminosity of $2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [74, 75].

A tracker design based on scintillating fibre (SciFi) technology with SiPM readout was chosen to fulfil these requirements.

The SciFi Tracker

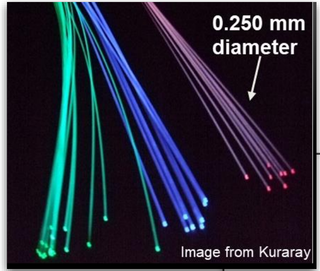


Fibres = 0.4% X0
Other = 0.6% X0
———————————
Total = 1% X0 per layer

Nomex honeycomb and
carbon fibre panels

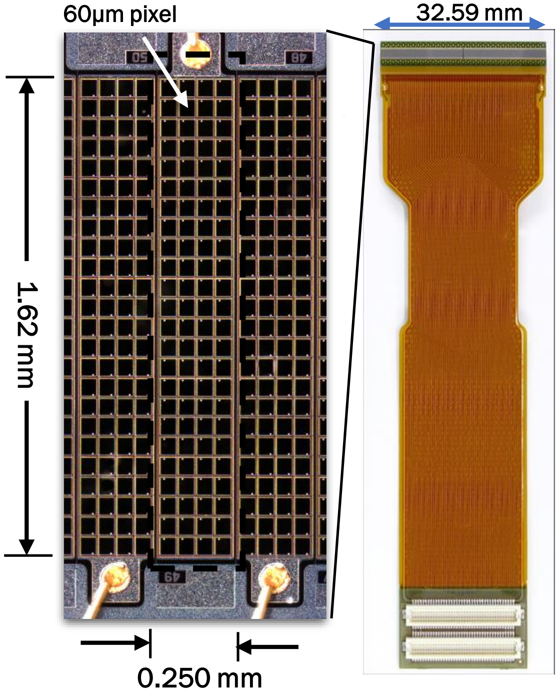
Front and side views of the 3D model of the SciFi Tracker detector.

SciFi Basics



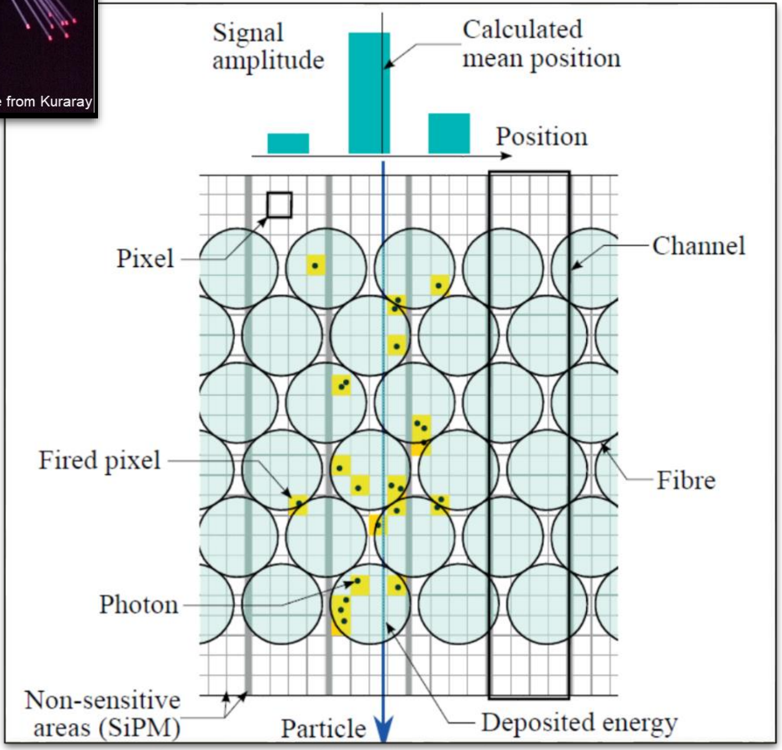
SCSF-78MJ fibres from Kuraray.
(fast 2.8 ns decay time)

Silicon Photomultipliers (SiPM) from Hamamtsu

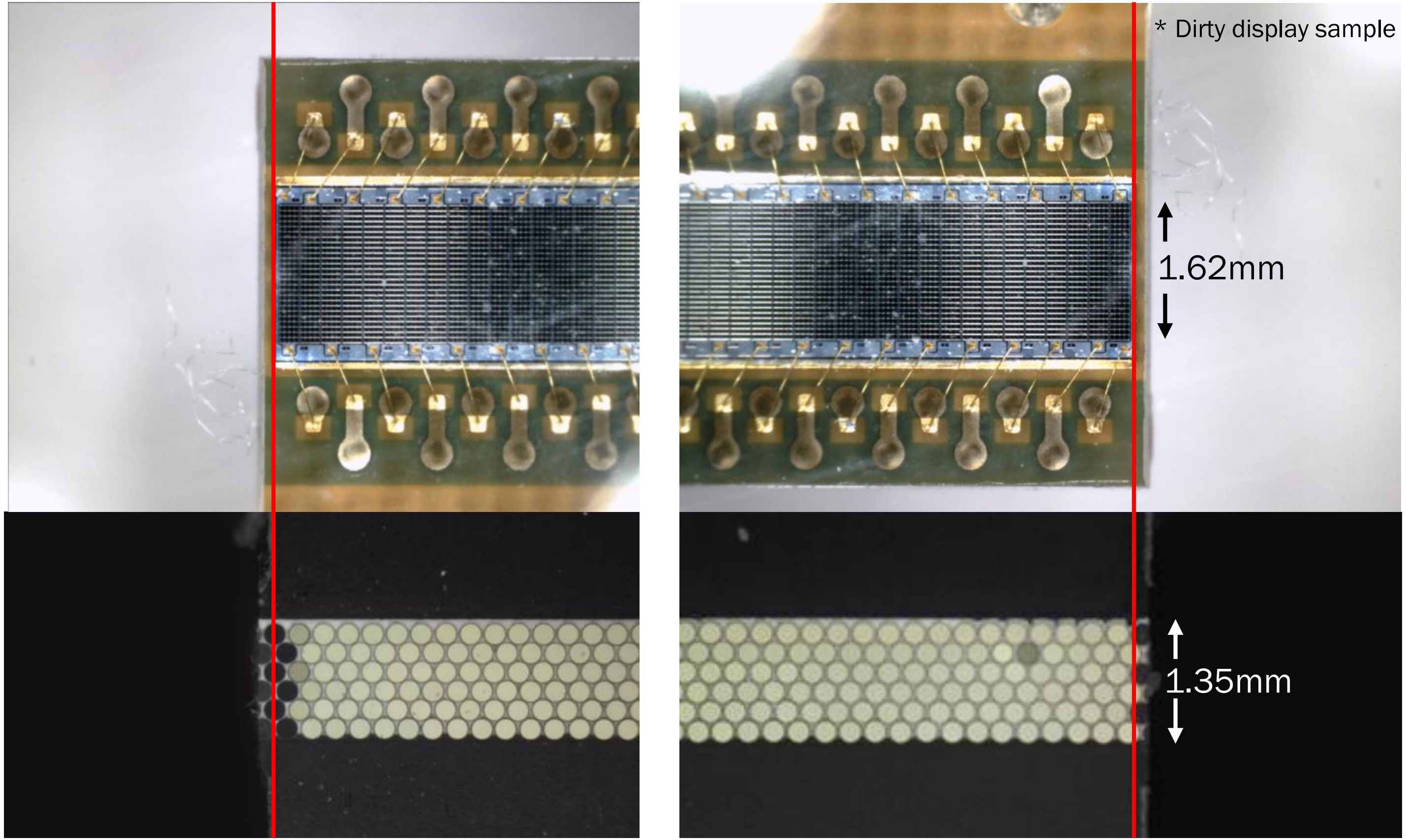


2 x 64 channel arrays

We need 4096!

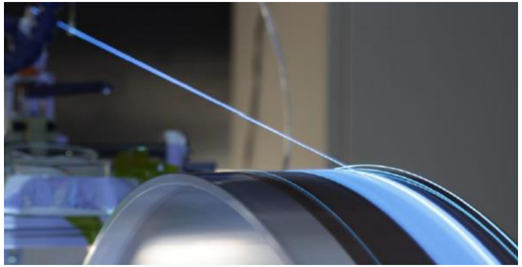


(a parallel array of Avalanche Photodiodes in Geiger-Mode)

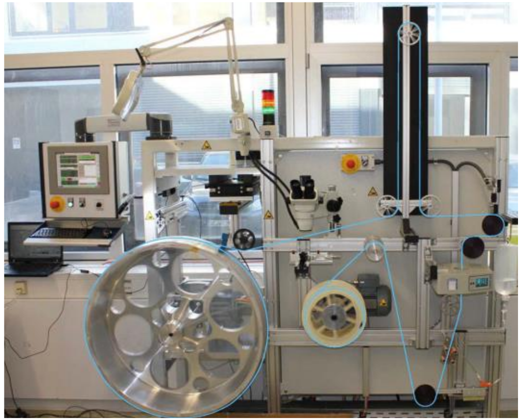


Photos of fibre mats and SiPMs approximately to scale

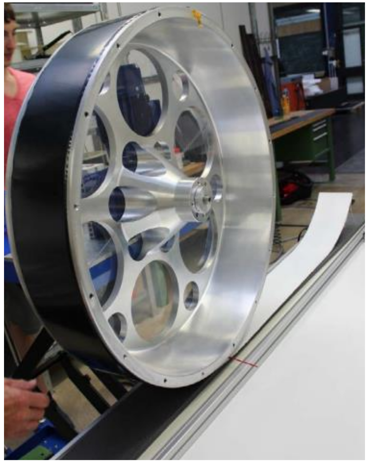
Fibre Mats



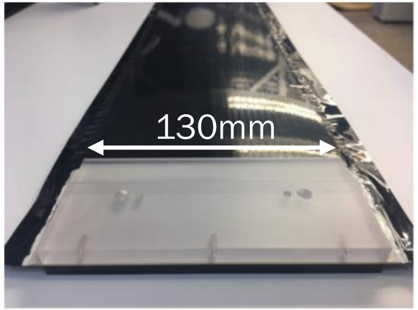
1. 11,000km Fibre has been pre-inspected before winding (not shown here).



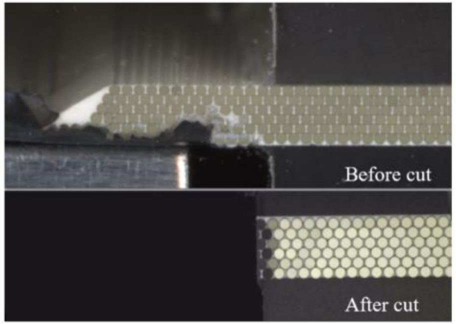
2. The winding machine controls the tensions and looks for jumps.



3. A grooved winding wheel. TiO2 loaded epoxy.



4. Black Kapton foil. PC endpiece for SiPM alignment.



5. Optical milling of ends and sides cut for packing in the module.

Ionising Radiation Damage (Fibres)

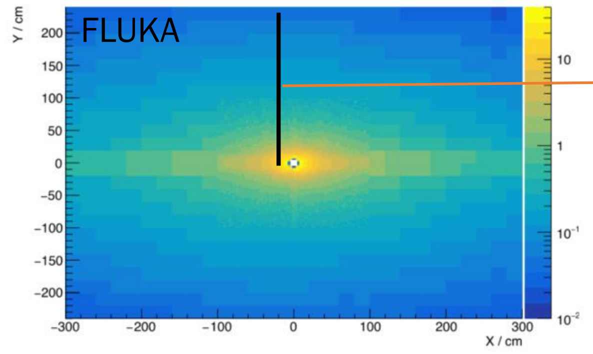
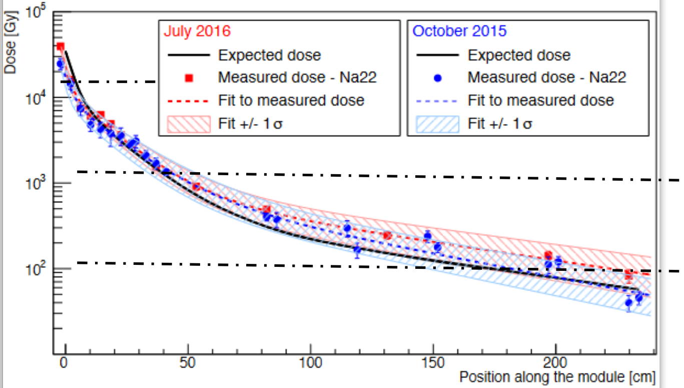


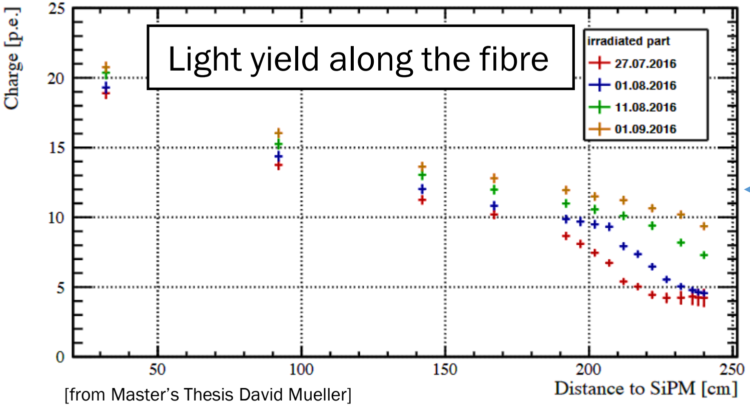
Figure 43: Map of the total expected ionising dose in kGy for an integrated luminosity of 50 fb^{-1} at the T1 station of the SciFi Tracker from FLUKA simulations of the LHCb detector.

35 kGy peak near the beampipe

Dose profile of the most irradiated fibre. Irradiated at IRRAD (CERN PS)



[from Master's Thesis David Mueller, Uni Heidelberg.]



[from Master's Thesis David Mueller]

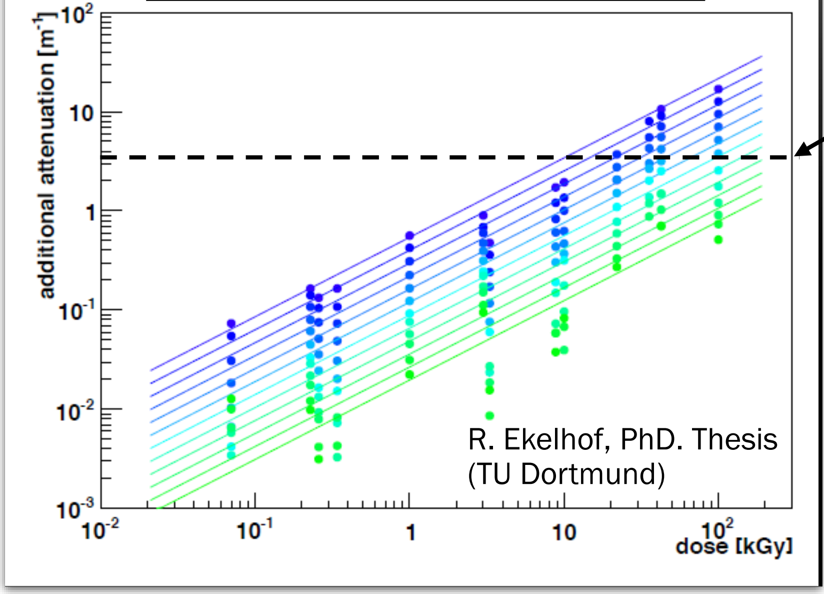
Annealing with a time constant of 12 days with 35% permanent loss at the mirror with LHCb dose distribution.

We will measure this again directly in the LS3 shutdown (2026-2028).

Ionising Radiation Damage (Fibres)

- Formation of radicals produces absorption/scattering centres
- Strong wavelength dependence (greener is better)
- Annealing over time with air exposure observed
- Difficult to study equivalent dose rate effects as in experiment
  - Evidence of oxygen effects
  - Slight aging even without radiation (~1% loss in attenuation length/year)

A collection of data from multiple irradiation campaigns

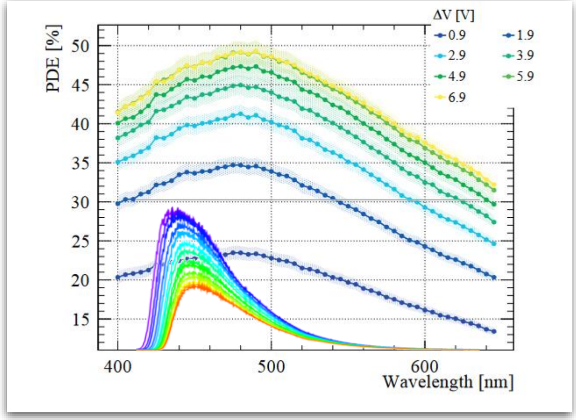


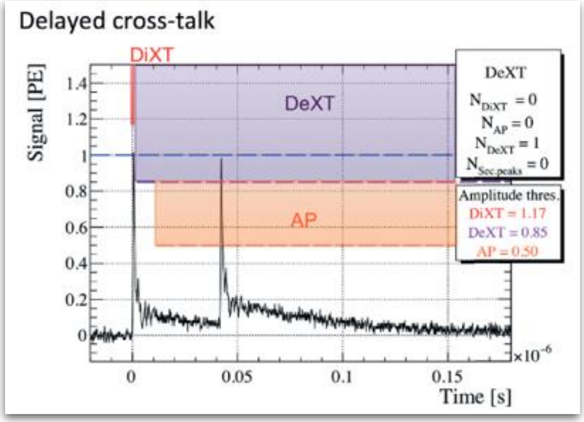
Attenuation of unirradiated fibre

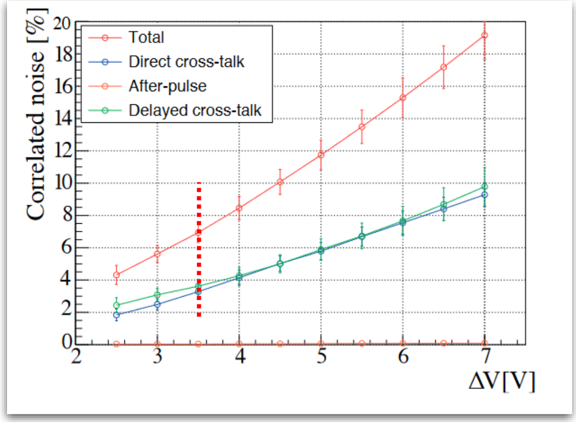
SiPMs

- The performance of SiPMs greatly improved during the development of SciFi
  - First arrays in 2011 had 30% PDE, >20% crosstalk at ΔV = 1.3V over breakdown.
  - Hamamatsu S13552-H2017 for LHCb SciFi (installed) had ~43% PDE, 8% crosstalk at ΔV = 3.5V
    - Pixel Trenches
    - Gain of >1E6 e- / ΔV
    - Optimised shape (fast initial peak)

PDE vs Wavelength. Fibre spectra overlaid.



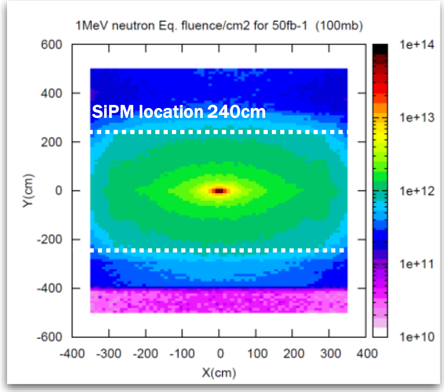




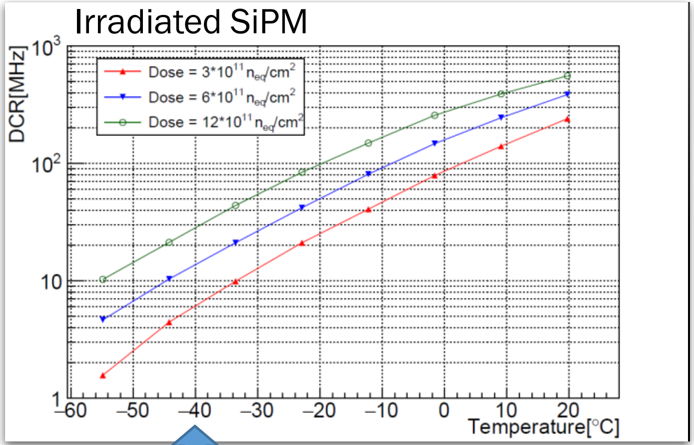
Plots from Thesis A. Kuonen, EPFL

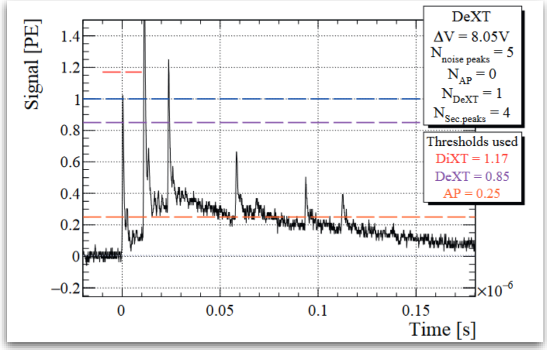
Non-Ionising Radiation Damage (SiPMs)

- Non-Ionising Energy Loss (NIEL) causes damage to the silicon structure
  - Allows thermal excitations to cross the bandgap more easily (dark avalanches!)
  - Cooling helps reduce the effect
  - Borated polyethylene shielding (2x reduction) before the ECAL
- 1 photoelectron uncorrelated signals
  - Pixel-cross talk produces **7% 2p.e. Signal, 0.49% 3 p.e. signals, etc…**
  - Eventual overlap at high rates.
  - Annealing (~30% recovery)



Fluka simulation



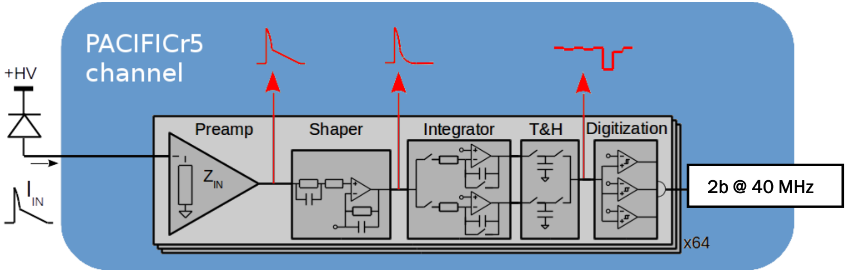


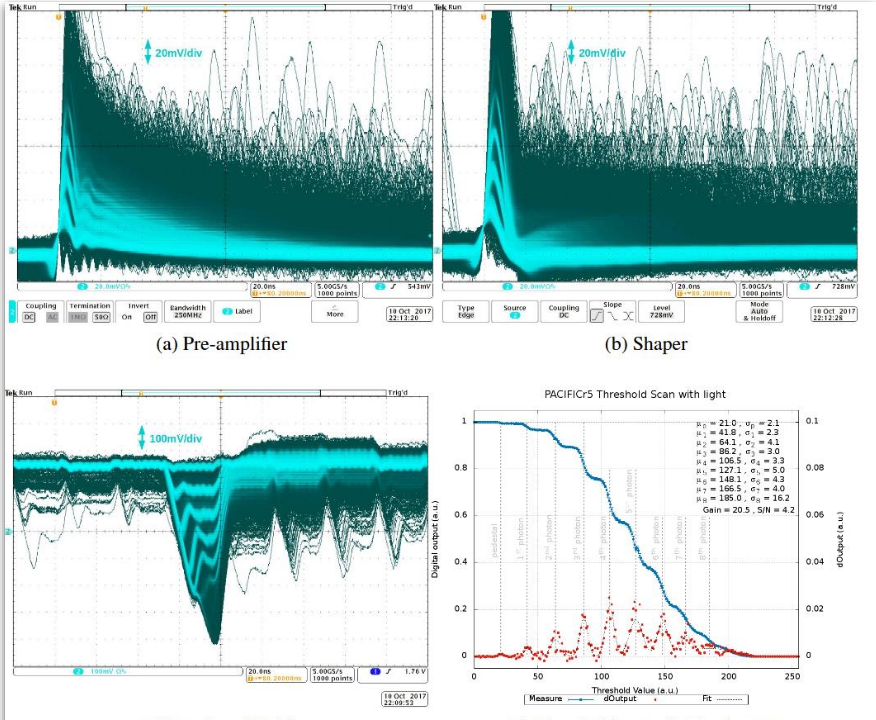
Pulse waveform classified as delayed cross-talk with additional secondary pulses recorded at high ΔV (H2017 at ΔV = 8.0 V)

SciFi Operation Point = -40°C
→ DCR = 14 MHz of single p.e. noise at EOL

READOUT ASIC: the PACIFIC

- Fast (10ns) shaping to reduce spill over
- Double integrators to avoid dead time
    - Alternates BX
    - Integrate signal charge over the crossing
- 2-bits /channel from 3 hysteresis comparators
    - Optimal thresholds are (1.5,2.5,4.5) p.e. for SciFi





(a) Pre-amplifier (b) Shaper (c) Track and Hold (d) Threshold scan digitized output

Modules and SiPM Cooling

A single phase cooling fluid at -50C is used.

- started with Novec 649 (GWP = 1, forms acids with water)
- Currently using C6F14 (GWP ~ 10,000, standard at CERN)
- Will switch to Novec 7100 (GWP = 300, no acid)
- PFAS-ban by EU means 3M stopping production of Novec. Requesting derogation for CERN.

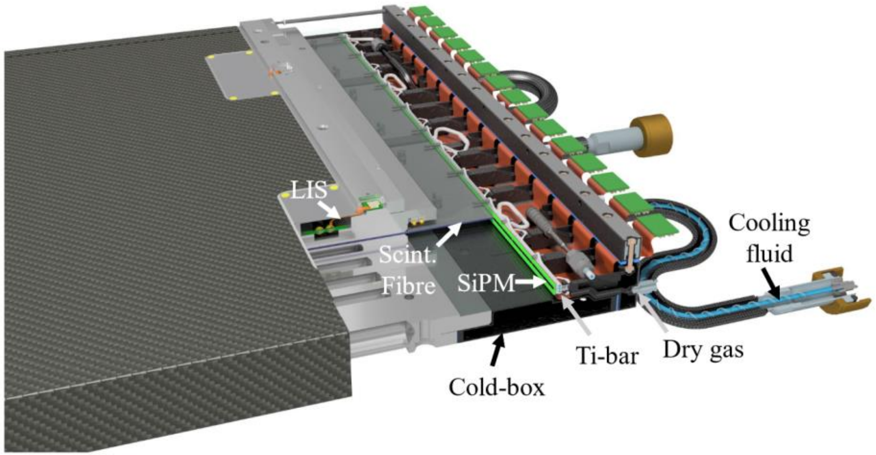
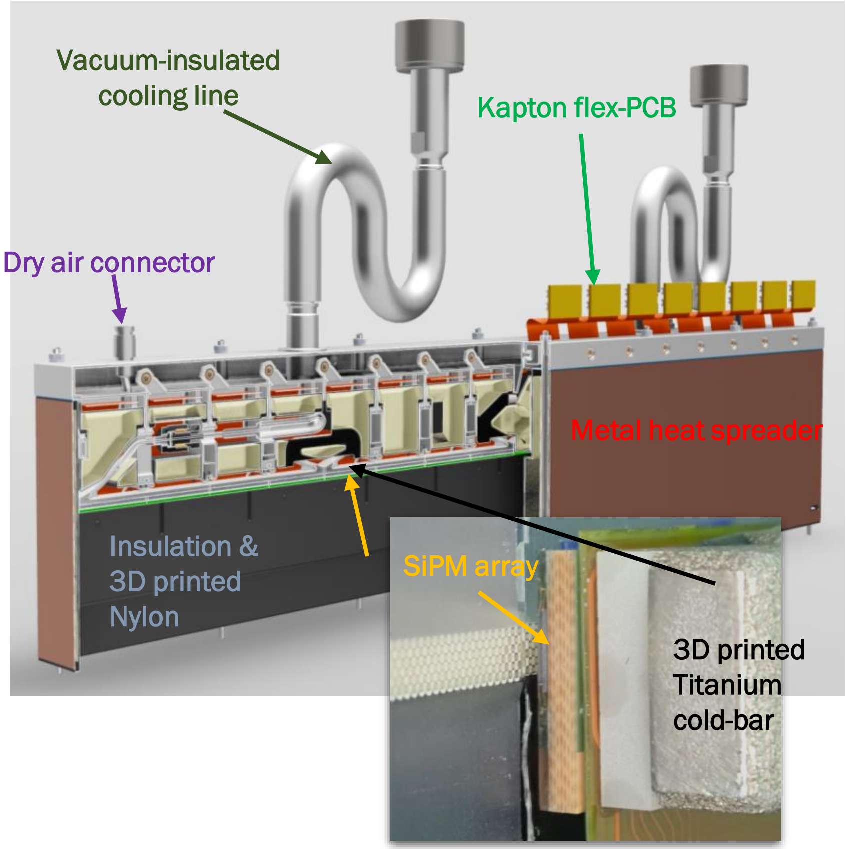
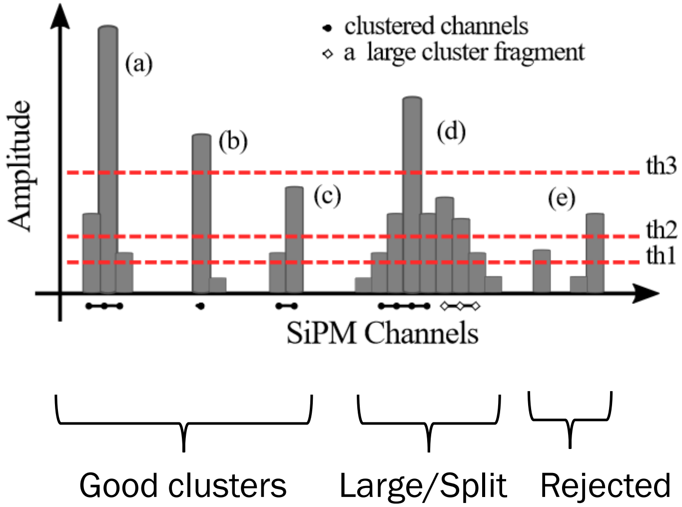


Figure 53: A cutaway view of the cold-box fixed to the fibre module.



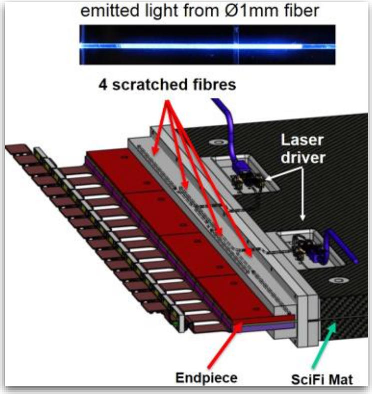
Clustering on FPGA

- Separate signal and noise
  - Zero-suppression (2x bandwidth reduction)
  - Cluster bandwidth is limited to DAQ (10 per data link, 16 per link for nearest to beampipe)
- Some-what radiation tolerant IGLOO2 FPGA provides the clusterization algorithm
  - Loses programmability early (but still works)
- also prepares the data for the backend
  - 20 Tb/s to the backend (4096 data links)
  - ~40% of LHCb data links

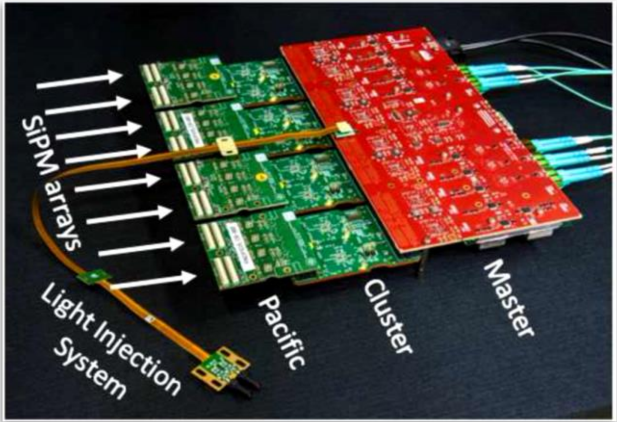


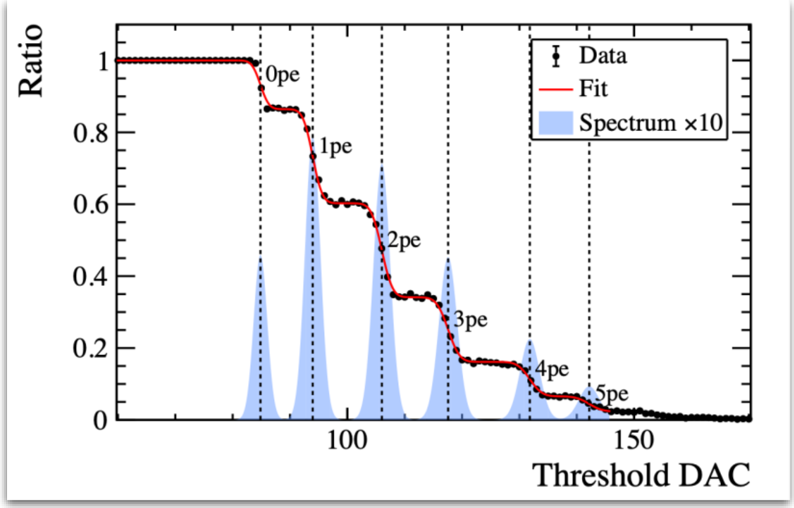
Commissioning and Calibration

- Timing of all the digital clocks needs adjusting
- To accurately set the thresholds one needs to calibrate:
  - gain due to possible variations in temperature and bias voltage (SiPM)
  - pedestal position (PACIFIC)
  - DAC vs signal amplitude (PACIFIC)



VCSL driven by GBTx and controlled by Front-end

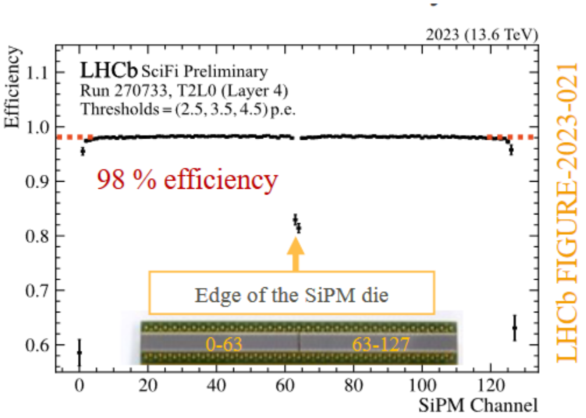




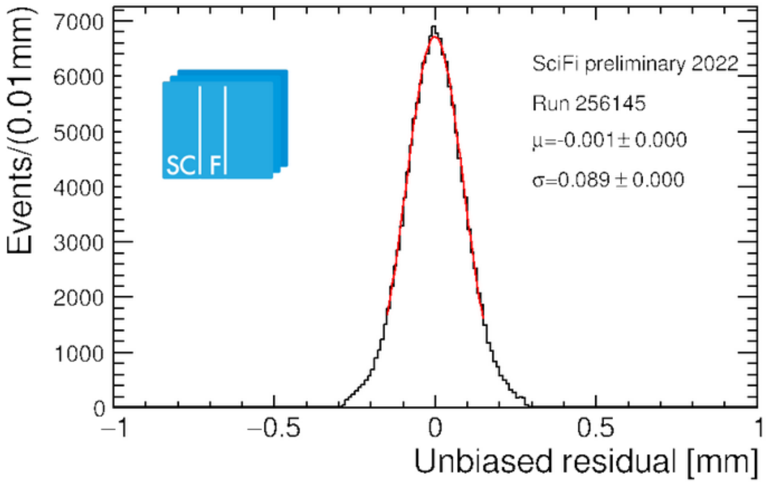
Tracker Performance 2022/2023

SciFi:

- 98 % hit efficiency
- close to design goal of 99 %



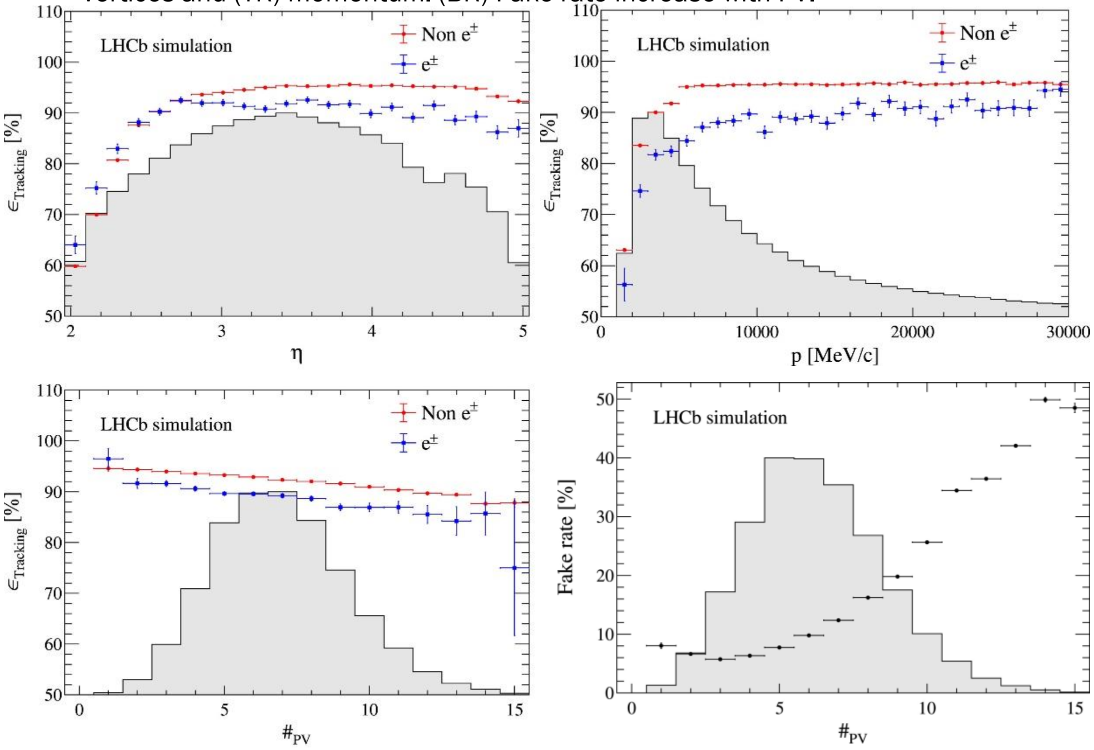
Single Hit Resolution



Tracking performance

- efficiency is close to or larger than 90% for all types of tracks that are relevant to LHCb physics analyses
- Efficiency saturates at around 95% for non-electron, high-momentum tracks, and decreases slightly with increasing number of primary vertices.
    - Long-tracks with p>5GeV with VELO typically more efficient
- almost half of the tracks originate from secondary interactions with the detector

seeding efficiencies with respect to (TL) pseudorapidity, (BL) the number of primary vertices and (TR) momentum. (BR) Fake rate increase with PV.



Figures from https://doi.org/10.1016/j.cpc.2020.107713

2019 - 2022

Paella after completing the first C-frame

Checking Front-end electronics currents.

Installing bias cables.

Assembling C-Frame mechanics.

Connecting SiPMs.

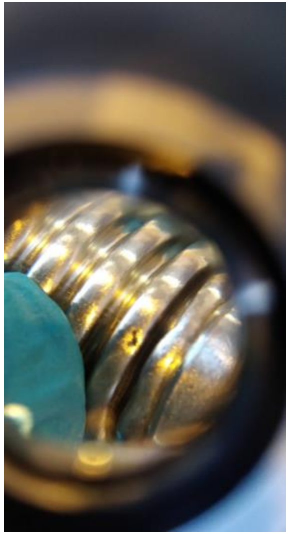
2019 - 2022

Replacing a defective cooling and vacuum manifold.

Preparing Front-end electronics.

Testing installation of the mechanics.

Connecting cooling lines.



Vacuum bellow with a pin-hole.

Inspecting and cleaning optical fibres

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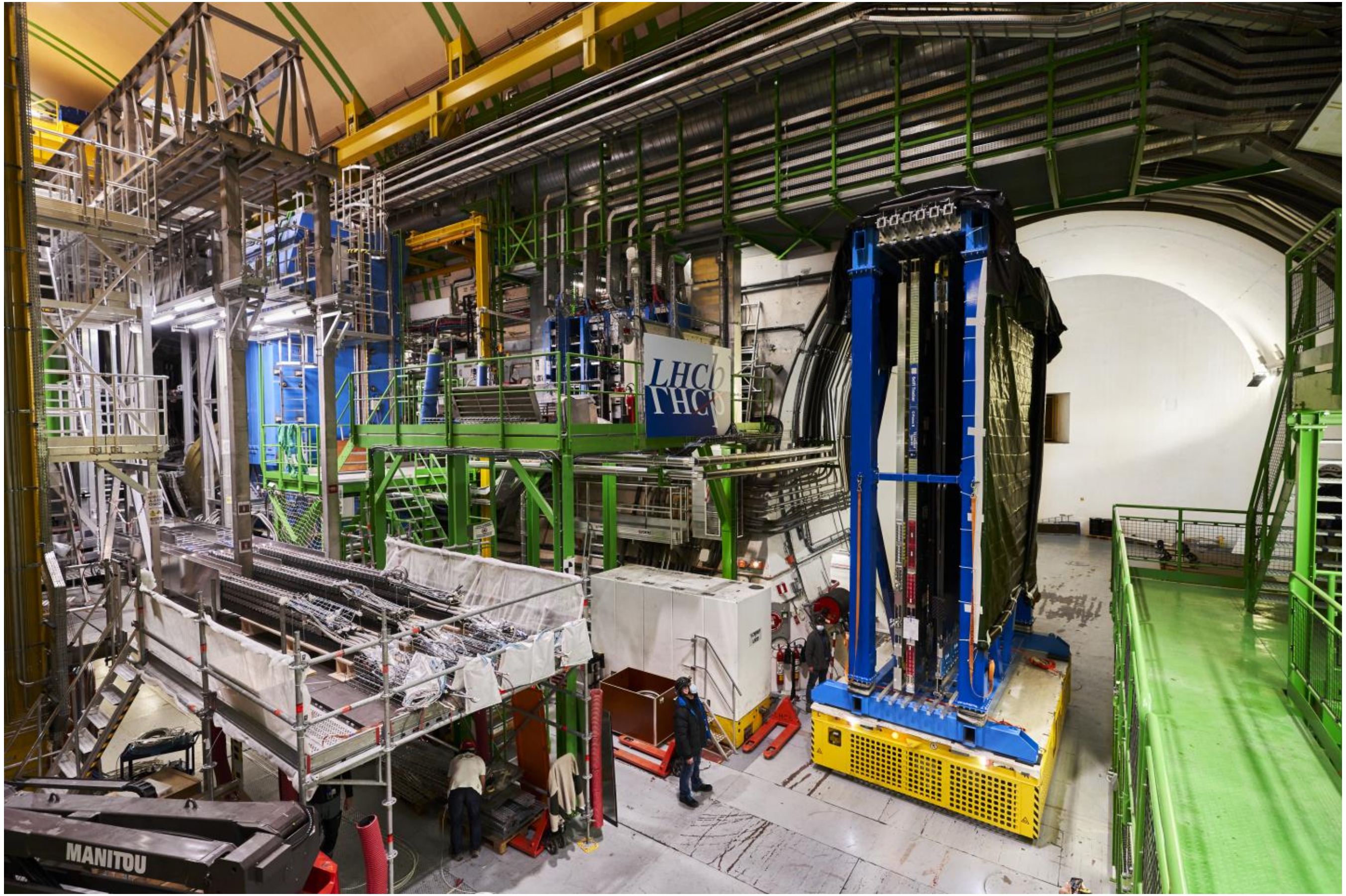
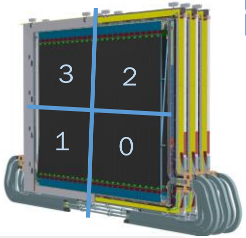
Transportation of C-Frames from the Assembly Hall to the Cavern. July 2021

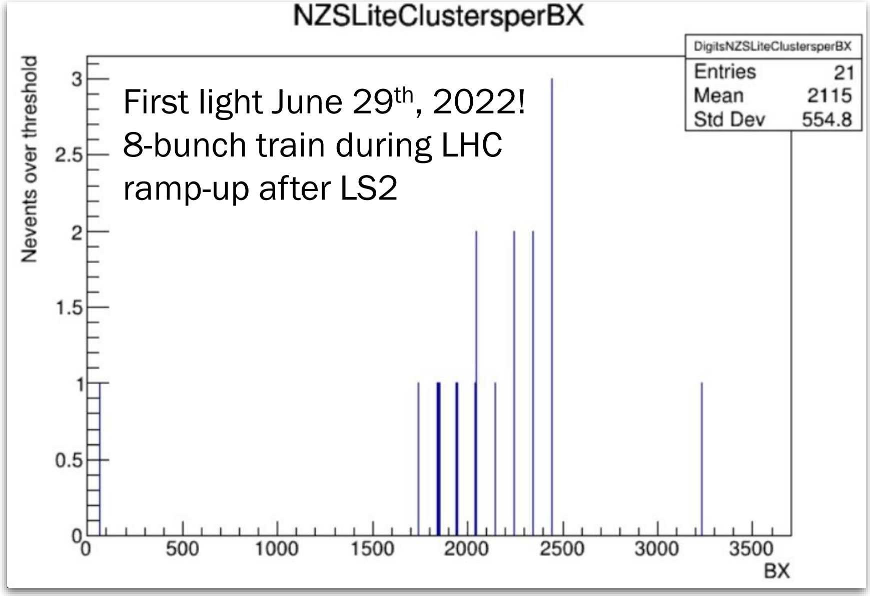


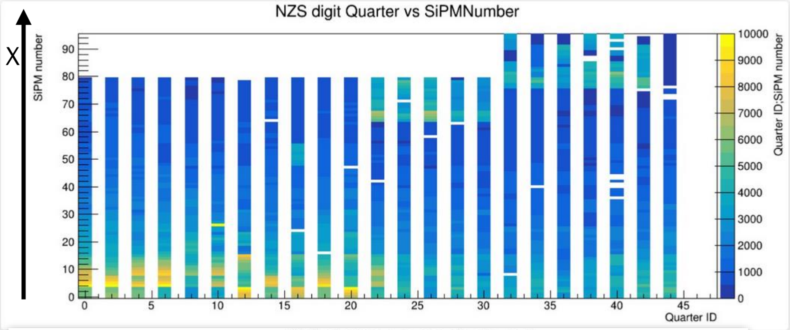
Unser Baustelle.

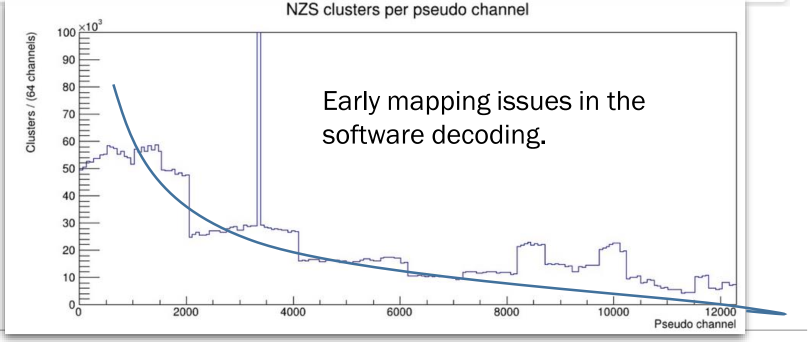
First collisions seen in SciFi June 29th, 2022



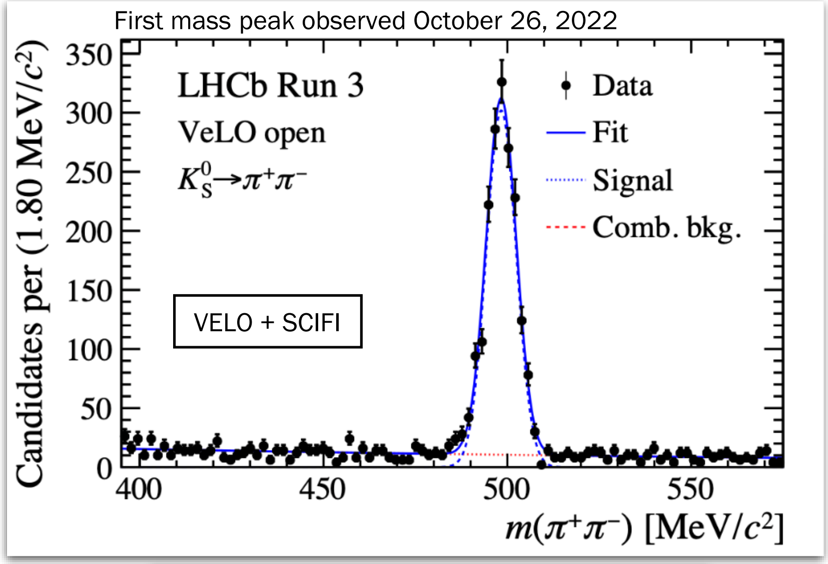
- 450 GeV beams, Quarters 0 & 2 only
- “Some” debugging and development still to do
  - Timing & Fast Commands (TFC) and Slow-control (ECS) were also new systems



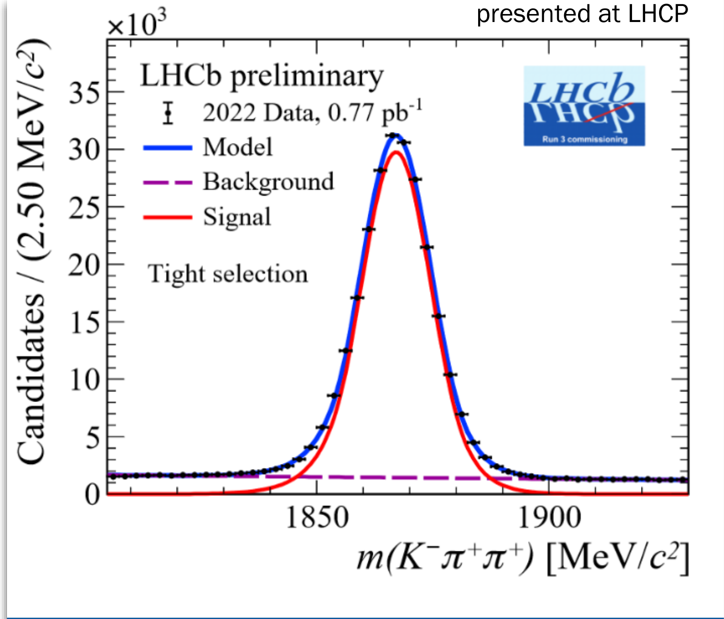




2022 Results



LHCb-FIGURE-2023-013
presented at LHCP



The invariant mass distribution of $K^-\pi^+\pi^+$ from $D^+ \to K^-\pi^+\pi^+$ decays, selected without (left) and with (right) requirement of \texttt{HTL1TrackMVA} or \texttt{HLT1TwoTrackMVA} lines being triggered by the D^+ candidates. The dots with error bars are real data, the blue line represents for the total fit model, the red line is for the signal, and the dashed purple line for the combinatorial background. The signal yields are 503923 ± 1871 and 234295 ± 571 for the cases without and with the HLT1 trigger requirement, respectively.

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2023

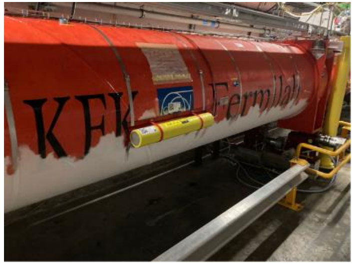
Solved some significant bugs during 2023, also some problems persisted

- VELO suffered a deformation of the RF foil (failure in pressure relief safety system while under atmosphere end of 2022)
- Couldn't run in a closed position during 2023

- **99% of SciFi was operational.**
  - **Some final tuning to achieve last 1-2% of hit efficiency needed**

Ready for pp-collissions in July but

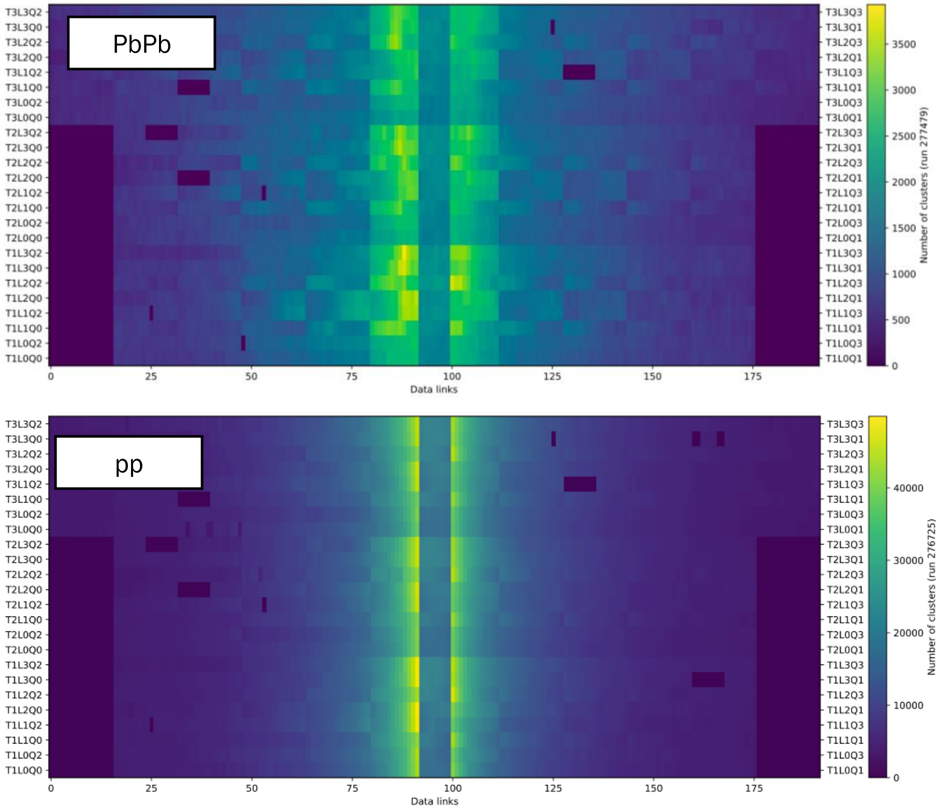
- Some LHC inefficiency due to vacuum failures



A frosty triplet after a vacuum leak following a quench during a storm.

- Mostly Heavy-ion data in 2023

2D occupancy plots of the SciFi Tracker

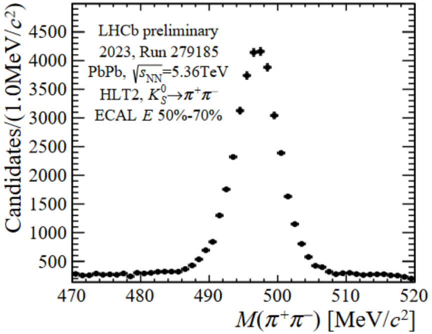


Some first ion plots from 2023

First invariant mass spectra and performance figures of the 2023 ion run

https://cds.cern.ch/record/2883088

Data corresponds to lead-lead (PbPb) and lead-argon (PbAr) collisions at √sNN = 5.36 TeV and √sNN = 70.9 GeV , respectively.



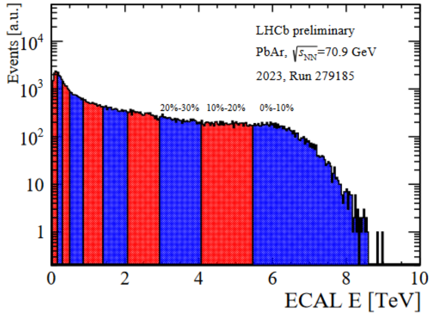


Figure 4: Distribution of the total energy collected in the ECAL for PbAr collision events divided in event activity classes.

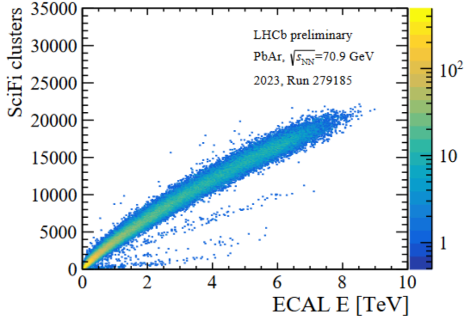


Figure 5: Correlation between the total energy collected in the ECAL and the number of clusters

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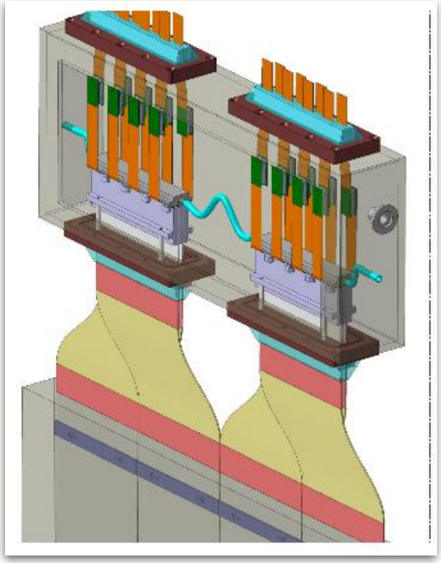
Towards Upgrade 2

- Inner region replaced with HV-CMOS pixels
- Cryogenic cooled SiPMs
  - 2% crosstalk
  - >50% PDE (higher overvoltage operation)
  - Microlenses to recover light; could reduce pixel size
  - Would allow for less fibre or more radiation (lower thresholds)
- Investigating new scintillator
  - Now included in ECFA DRD4 collaboration
  - SCSF-78MJ is 25 year old tech
  - Investigating new fast green scintillator (<4ns)



Laterally-flexible fibre mat with feed-through into a vacuum box for LHCb Upgrade 2, which may use cryogenically cooled SiPMs. [Source: Guido Haefeli EPFL]

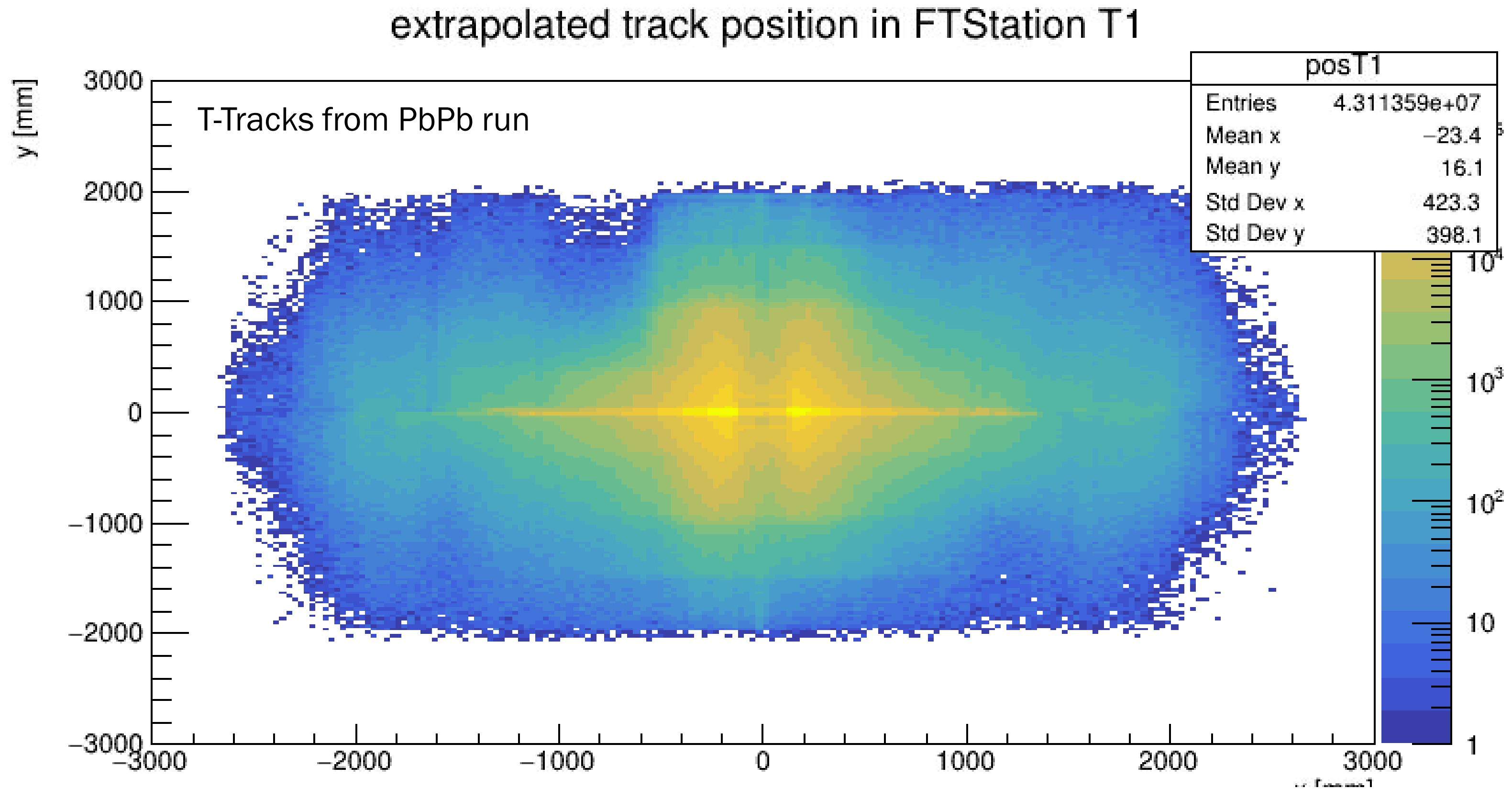
Conclusion

- A Scintillating Fibre Tracker can provide good tracking in a hadronic environment
  - We would require more cooling for SiPMs and more light from the fibres to tolerate a large dose of radiation without replacement

- It is cost effective compared to silicon, but it depends on your requirements


Thank you for listening.

- Backup Slides



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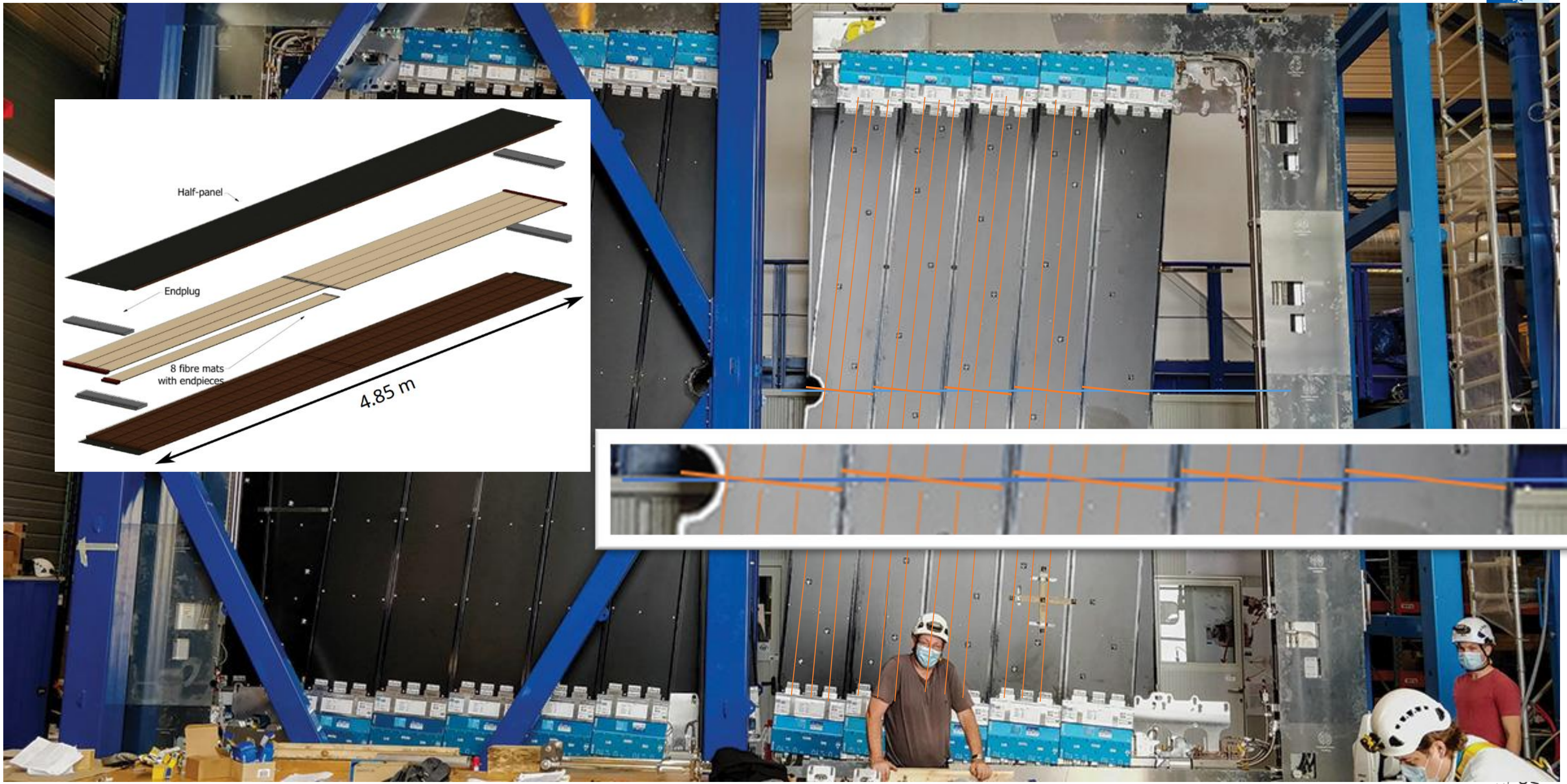

Half-panel
Endplug
8 fibre mats
with endpieces
4.85 m

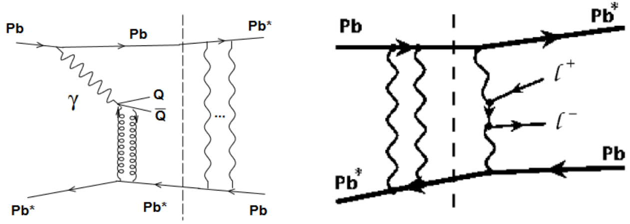


Figure 36. The leading order diagrams for Υ (left) and lepton pair [123] (right) production in γA and $\gamma\gamma$ processes accompanied by Coulomb excitation in ultraperipheral Pb+Pb collisions.

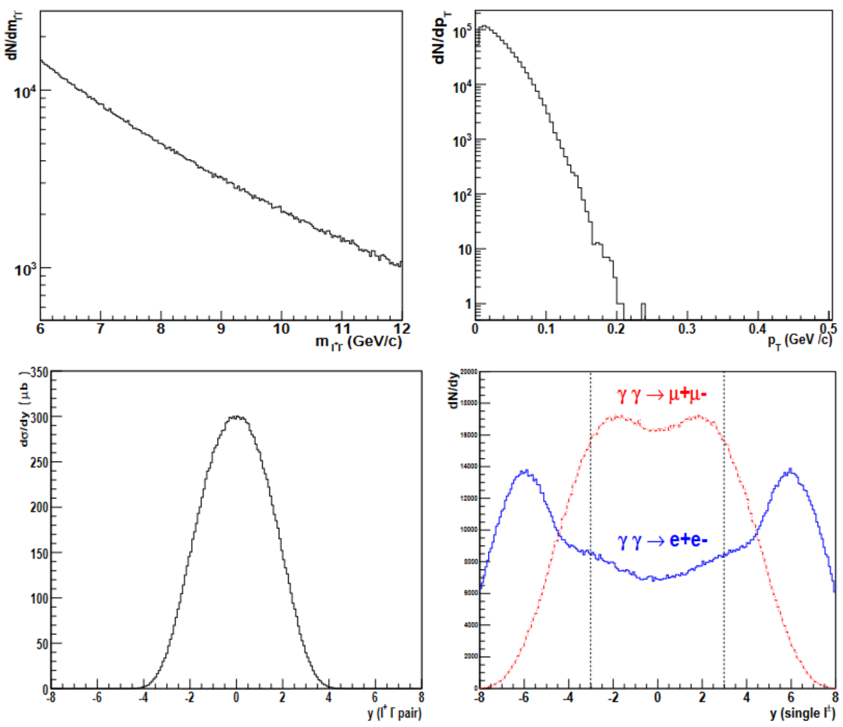


Figure 39. The STARLIGHT dilepton $(e^{\pm}, \mu^{\pm})$ invariant mass (top left), pair p_T (top right), pair rapidity (bottom left) and single lepton rapidity (bottom right) distributions in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV [132]. The single muon (dashed) and electron (solid) rapidity distributions are shown separately in the bottom right plot. The vertical dashed lines indicate the CMS acceptance.

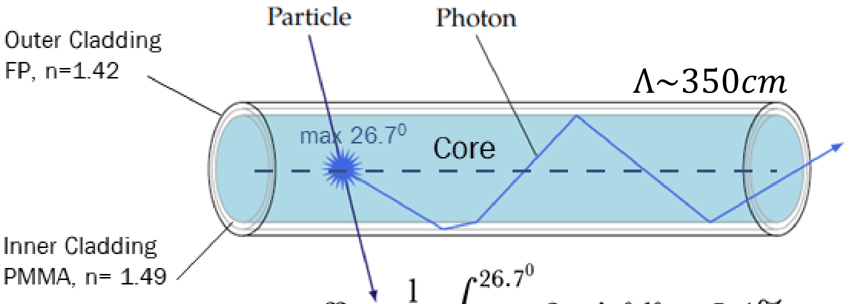
Table 3.1: This matrix summarizes the high level performance of the di
of this matrix can be obtained through the Yellow Report Detector Wo

η	Nomenclature	Tracking					
		Resolution	Relative Momentun	Allowed X/X_0	Minimum-p_T (MeV/c)	Transverse Pointing Res.	Longitudinal Pointing Res
< -4.6	Low-Q2 tagger						
-4.6 to -4.0							
-4.0 to -3.5							
-3.5 to -3.0	Backward Detector		$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$	~5% or less	150-300		
-3.0 to -2.5							
-2.5 to -2.0			$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$				
-2.0 to -1.5						$dca(xy) \sim 40/p_T$ μm ⊕ 10 μm	$dca(z) \sim 100/$ μm ⊕ 20 μm
-1.5 to -1.0							
-1.0 to -0.5	Barrel		$\sigma_p/p \sim 0.02\% \times p \oplus 5\%$		400	$dca(xy) \sim 30/p_T$ μm ⊕ 5 μm	$dca(z) \sim 30/p_T$ μm ⊕ 5 μm
-0.5 to 0.0							
0.0 to 0.5							
0.5 to 1.0							
1.0 to 1.5	Forward Detectors		$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$		150-300	$dca(xy) \sim 40/p_T$ μm ⊕ 10 μm	$dca(z) \sim 100/$ μm ⊕ 20 μm
1.5 to 2.0							
2.0 to 2.5							
2.5 to 3.0			$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$				
3.0 to 3.5							
3.5 to 4.0	Instrumentation to separate charged particles from photons						Re
4.0 to 4.5							
> 4.6	Proton Spectrometer						
	Zero Degree Neutral Detection						

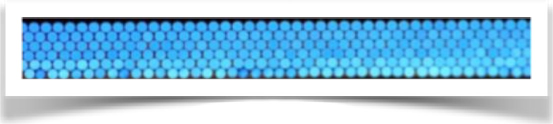
- The components of an EIC detector will have moderate occupancy as the event multiplicities are low. However, specific components close to the beam-line might see higher occupancies depending on the machine background level.
- Compared to LHC detectors, the various subsystems of an EIC detector have moderate radiation hardness requirements.
- Excellent momentum resolution in the central detector ($\sigma_{p_T}/p_T(\%) = 0.05 p_T \otimes 0.5$).
- Good momentum resolution in the backward region with low multiple-scattering terms ($\sigma_{p_T}/p_T(\%) \approx 0.1 p_T \otimes 0.5$).
- Good momentum resolution at forward rapidities ($\sigma_{p_T}/p_T(\%) \approx 0.1 p_T \otimes (1-2)$).
- Good impact parameter resolution for heavy flavor measurements ($\sigma_{xy} \sim 20/p_T \otimes 5\ \mu m$).
- Good electromagnetic calorimeter resolution in the central detector ($\sigma(E)/E \approx 10\%/\sqrt{E} \otimes (1-3)\%$ at midrapidity).
- Excellent electromagnetic calorimeter resolution at backward rapidities ($\sigma(E)/E \approx 2\%/\sqrt{E} \otimes (1-3)\%$).

Double-clad round fibres: Kuraray SCSF-78MJ

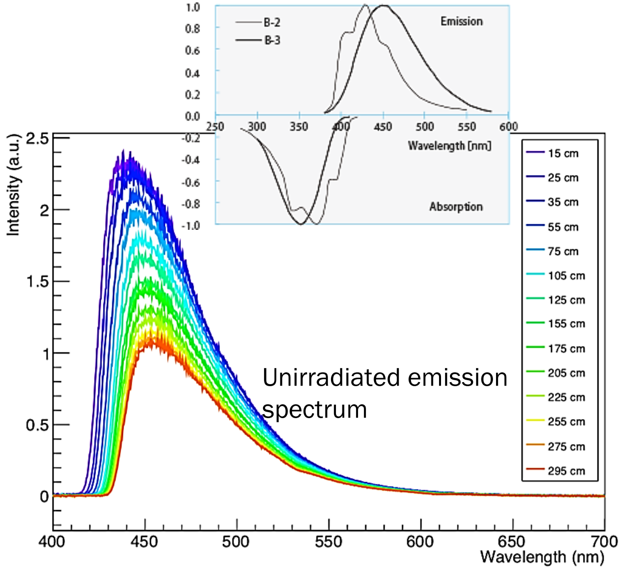
- Polystyrene core with activator (PTP) and wavelength shifter (TPB)
- dE/dx(MIP)= 2 MeV/cm, dN/dE = 8000 γ MeV^{-1}

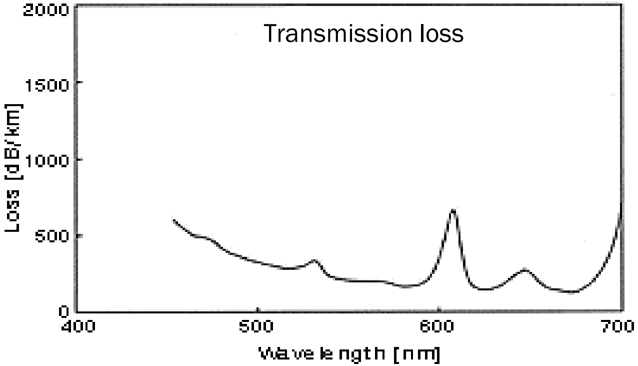


$$\text{trap eff} \sim \frac{1}{4\pi}\int_0^{26.7^0} 2\pi sin\theta d\theta = 5.4\%$$

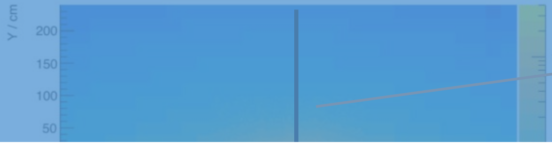


$$N_{obs.} = \frac{dE}{dx}\Delta x \frac{dN}{dE}\eta_{trap}\eta_{detector}(e^{-l/\Lambda} + \eta_{mirror}e^{-(2L-l)/\Lambda})$$

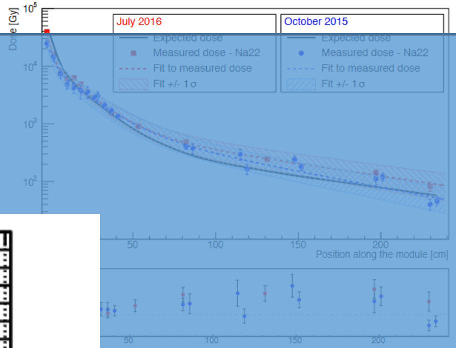




Ionising Radiation Damage (Fibres)



35 kGy peak
near the



Dose profile of the most irradiated fibre

l expected irradiation dose of both test modules irradiated
as function of the module position. Position 0cm (left side)
o the mirror side. The black line indicates the expected
he red (July 2016), respectively blue (October 2015) points
measurements of the dose. The shaded areas are showing
ope. The plot on the bottom shows additionally the ratio
nd targeted dose. [35]

[from Master's Thesis David Mueller, Uni Heidelberg.]

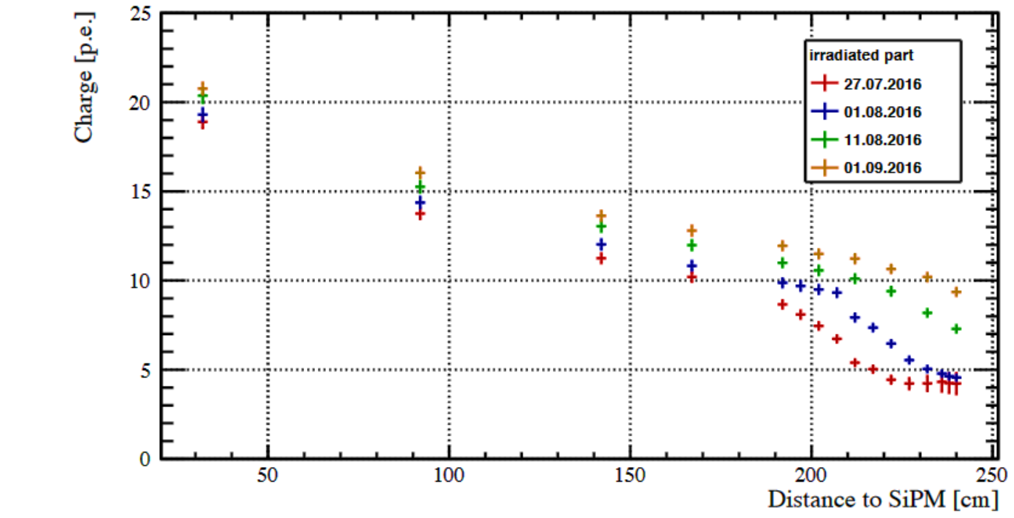


Figure 5.9: Evolution of the mean light yield in the irradiated part along the fibre mat over time. In the the high irradiated part near the mirror the annealing is most intense. Also the limitation due to the cluster algorithm limits the first two measurement runs (*red* and *blue*) near the mirror.

Annealing with a time constant of 12 days with 35% permanent loss at the mirror with LHCb dose distribution.

We will measure this again directly in the LS3 shutdown (2026-2028).

Annealing of Fibre Irradiation

Irradiated Fibre section

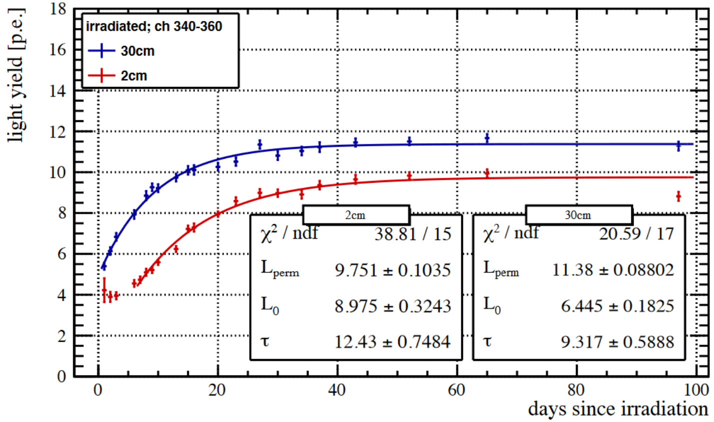


Figure 5.10: Time evolution of the mean light yield at the centre of the irradiated region (channel 340-360) at positions 2 cm (*red*) and 30 cm (*blue*) in front of the mirror. The lines are the fit of an exponential function. The fit parameters (L_{perm}, L_0, τ) are given in the boxes.

Non-Irradiated Fibre section

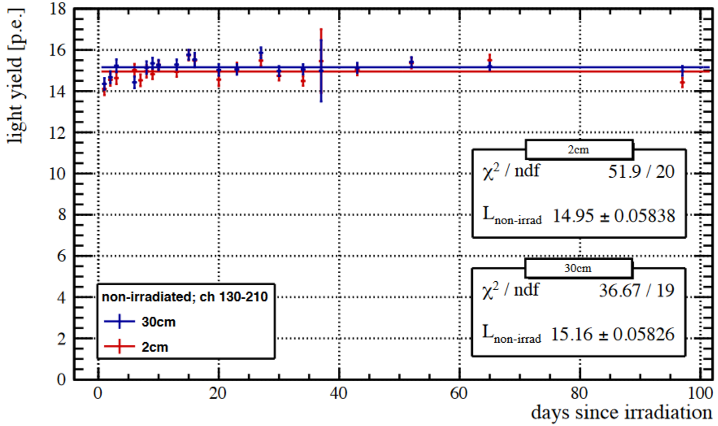


Figure 5.11: Averaged mean light yield of the non-irradiated part (Channel 130-210) monitored over time. The light yield measurement is also slightly dependent on the temperature. A linear fit is performed to average the light yield. Both positions see about 15 photoelectrons.

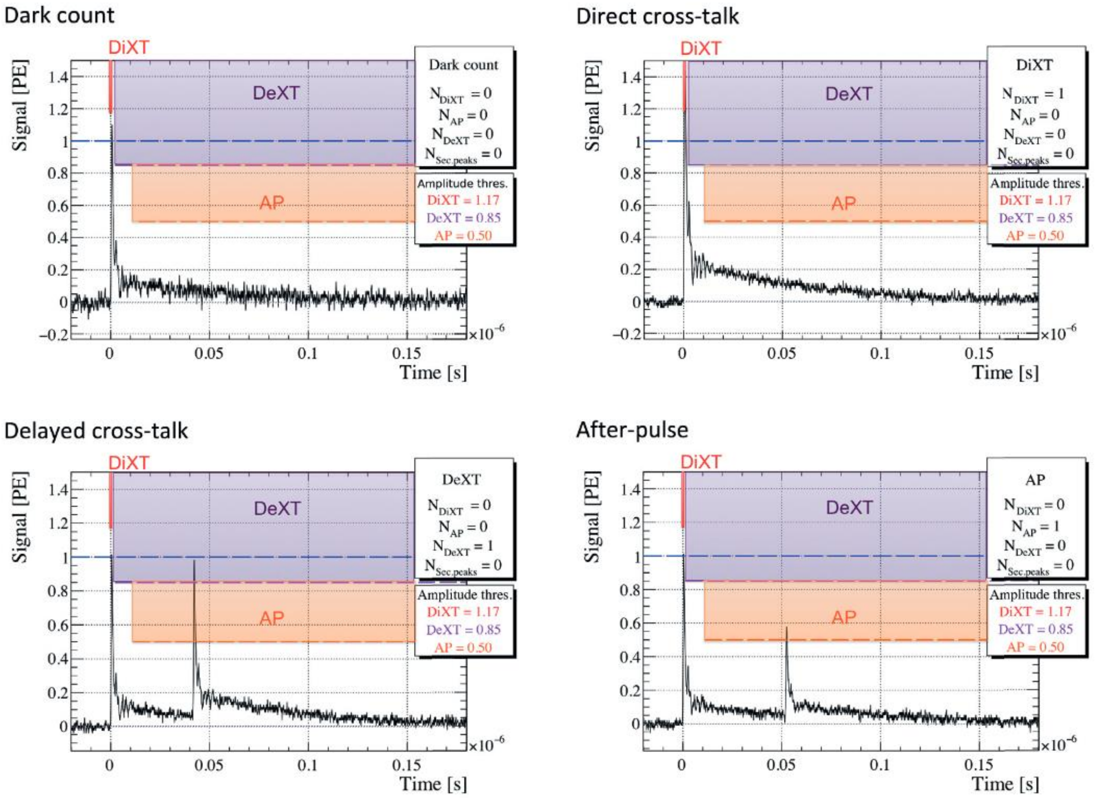
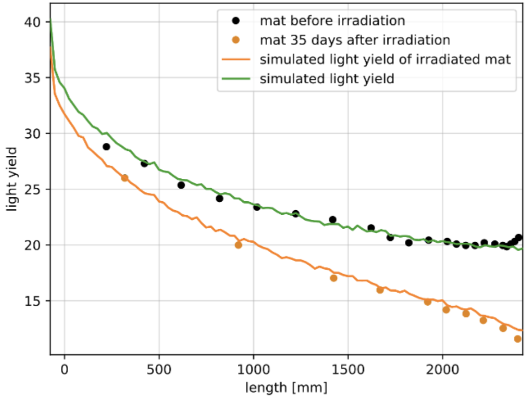


Figure 6.4: Example of peak categorisations with dark count (top left), DiXT (top right), DeXT (bottom left) and AP (bottom right).

Cluster Light Yield → Hit Efficiency

Model from 2019 includes improved fibres and sipms



Worst case irradiation model

Figure 14: Measured light yield of a mat before (dark blue) and after irradiation (light blue) compared to simulations. Simulations are scaled to point A of the measured light yield before irradiation (2230 mm away from the SiPM) [15].

http://cds.cern.ch/record/2673602/files/LHCb-PUB-2019-007.pdf