A Scintillating Fibre Tracker for the LHCb Upgrade

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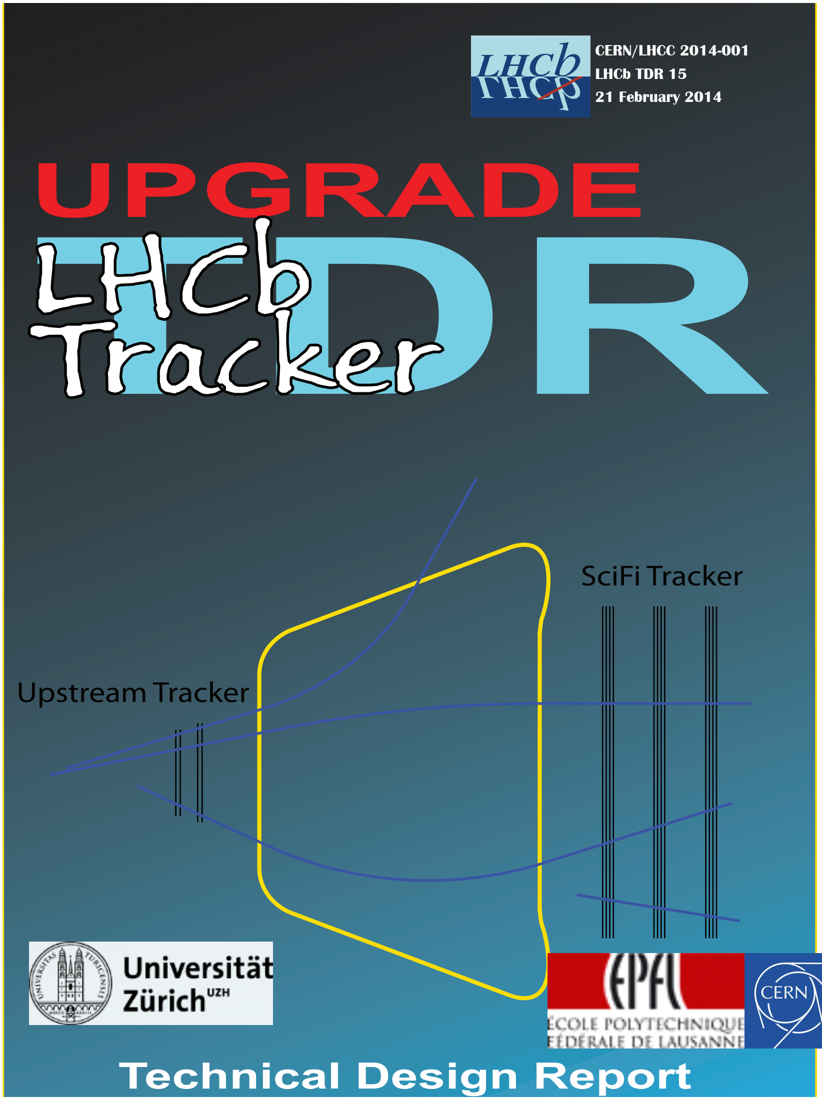
Overview

- Introduction to LHCb.
- Upgrade of LHCb:
  - Motivation.
  - Scintillating Fibre Tracker.
  - Schedule.
- Conclusions.

- More information in:
  - CERN-LHCC-2014-001
  - LHCb TDR 15

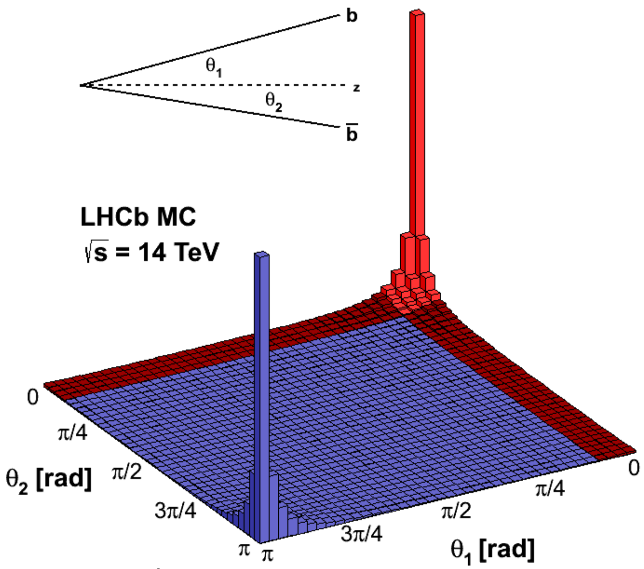


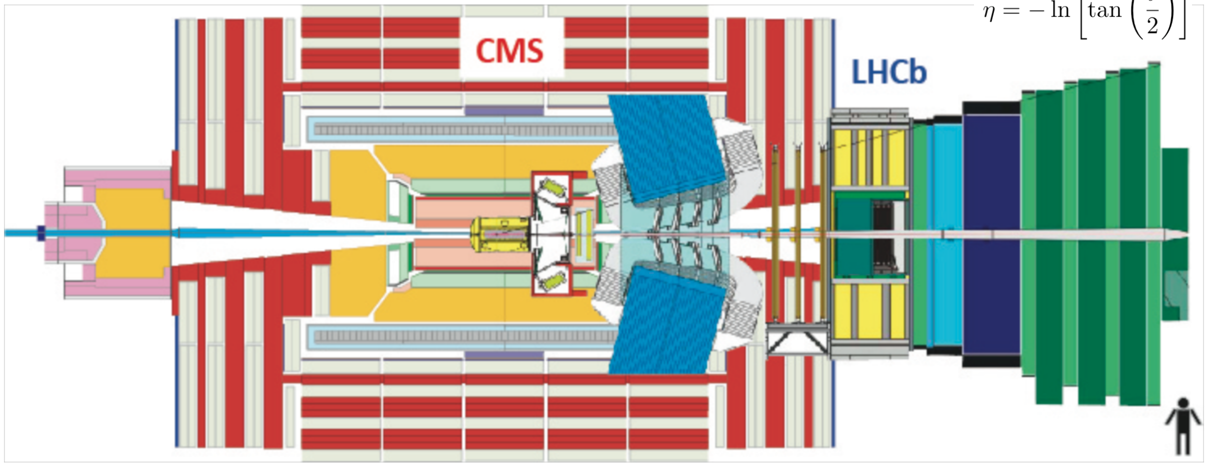
LHCb

- Dedicated heavy flavour experiment at LHC.
  - Measure CP-violation in *b*- and *c*- sector.
  - Study rare *b*- and *c*- hadron decays.
- ***Indirect searches for New Physics.***
- Forward production of *b*-pairs with low angle.
  - 27% of *b*-pairs in LHCb acceptance @ √s=7 TeV.
  - Single-arm forward spectrometer.
- Over 190 physics papers published.

$2 < \eta < 5$

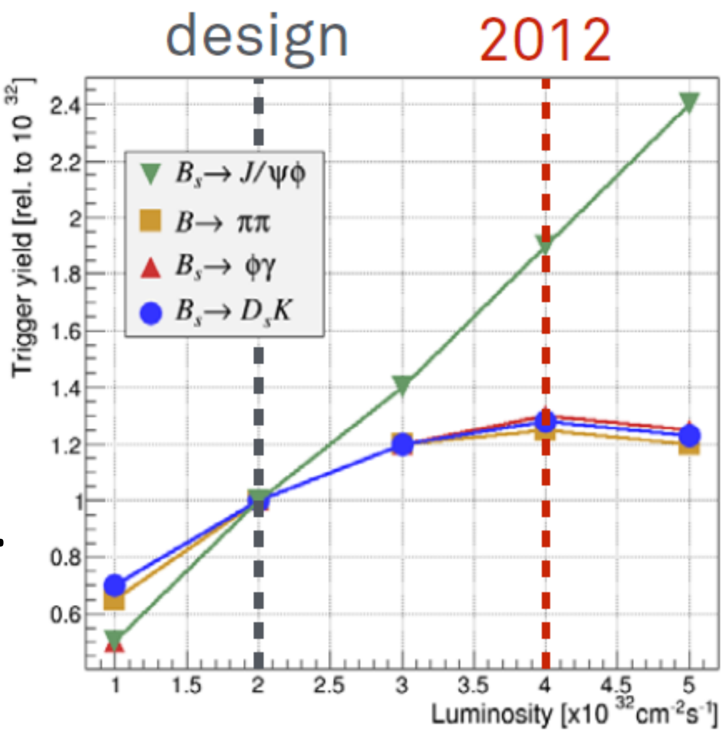
$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$





Why upgrade?

- No evidence for New Physics in LHC Run 1.
  - Look for deviations from Standard Model.
  - Most measurements still limited by statistics.
- Limited by Level-0 hardware trigger.
  - Maximum rate is 1.1 MHz.
- Increase luminosity:
  - Already ran well above design.
  - Trigger yield saturates.
  - No real gain in statistics.
- Higher occupancy.
  - Degraded detector performance.
  - Radiation damage of detectors.



LHCb Upgrade

- Remove Level-0 hardware trigger.
  - Read out every bunch crossing (40 MHz).
  - Full software trigger for every 25 ns bunch crossing.
  - Replace all front-end electronics.
    - Replace also detectors with embedded read-out.
- Run at higher instantaneous luminosities.
  - Instantaneous luminosity = 2×10^{33} $cm^{-2}s^{-1}$.
  - # visible interactions / crossing = 5.2
  - Higher occupancy.
    - Redesign several sub-detectors.
- Install during LHC Long Shutdown 2.
- Collect integrated luminosity = 50 fb^{-1}.

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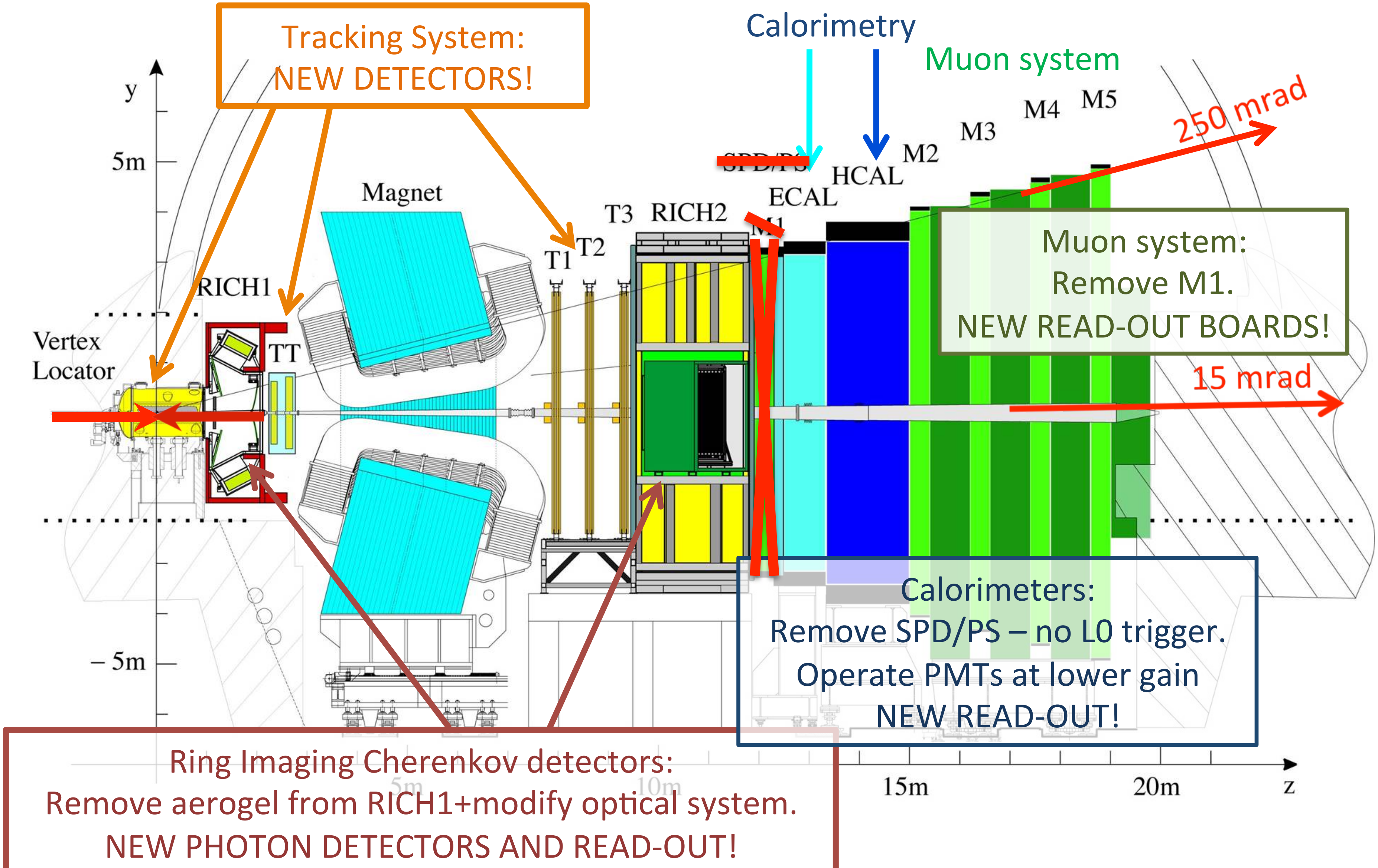
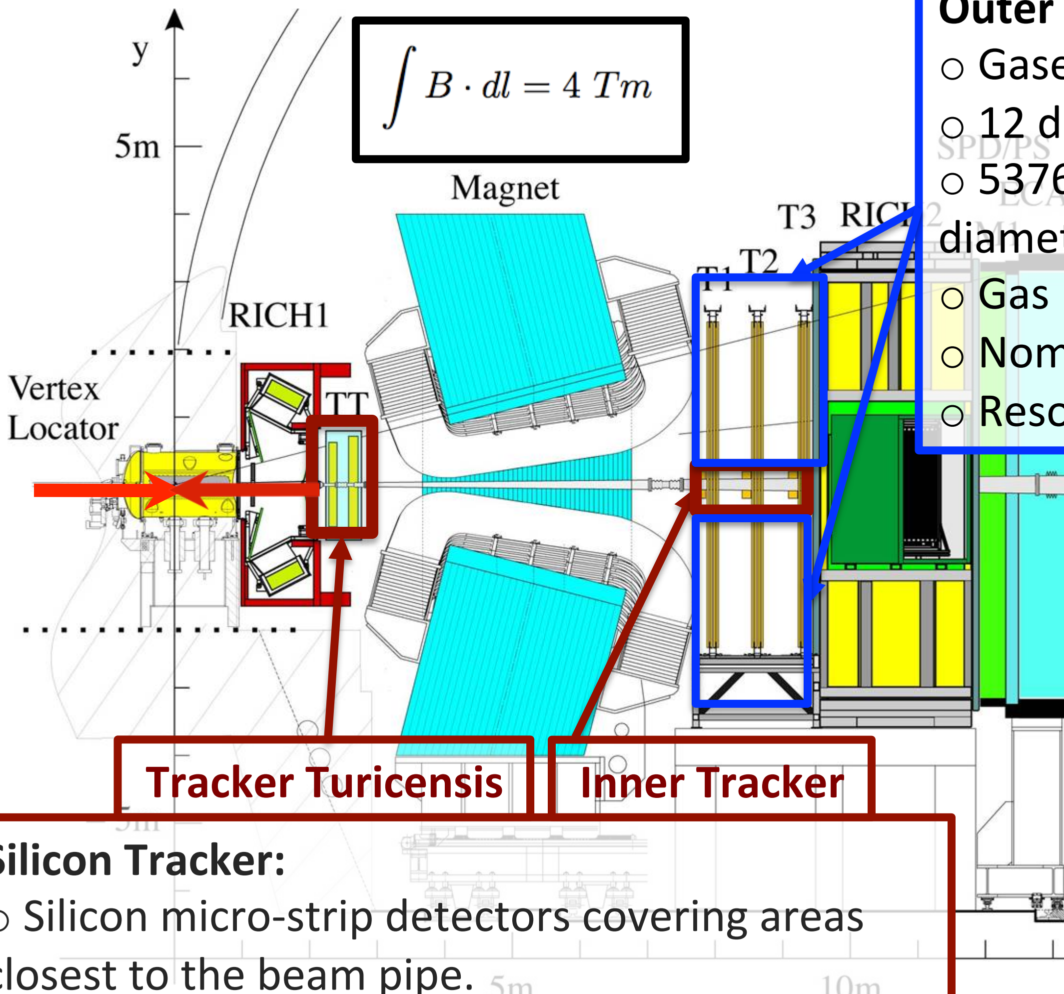
Upgraded LHCb detector

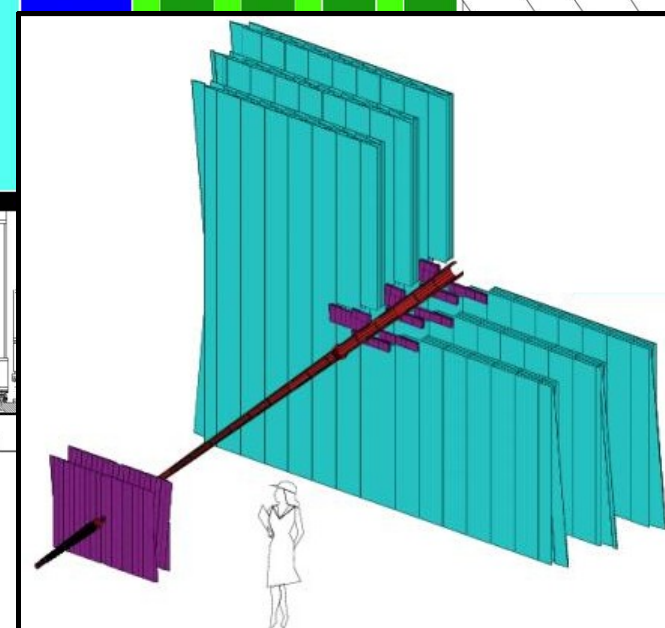


Current Tracker



Outer Tracker:

- Gaseous straw tube detector.
- 12 detection layers (~ 6 x 5 m^2).
- 53760 straw tubes (2.4 m long, 4.9 mm diameter).
- Gas mixture: $Ar/CO_2/O_2$ (70%/28.5%/1.5%).
- Nominal operating voltage is 1550 V.
- Resolution ≈ 200 µm.



Silicon Tracker:

- Silicon micro-strip detectors covering areas closest to the beam pipe.
- Pitch: 183 µm (TT), 198 µm (IT).
- Thickness: 500 µm (TT), 320/410 µm (IT).
- Strips up to 37 cm long.
- Resolution ≈ 50 µm.

swiss made

Scintillating Fibre Tracker

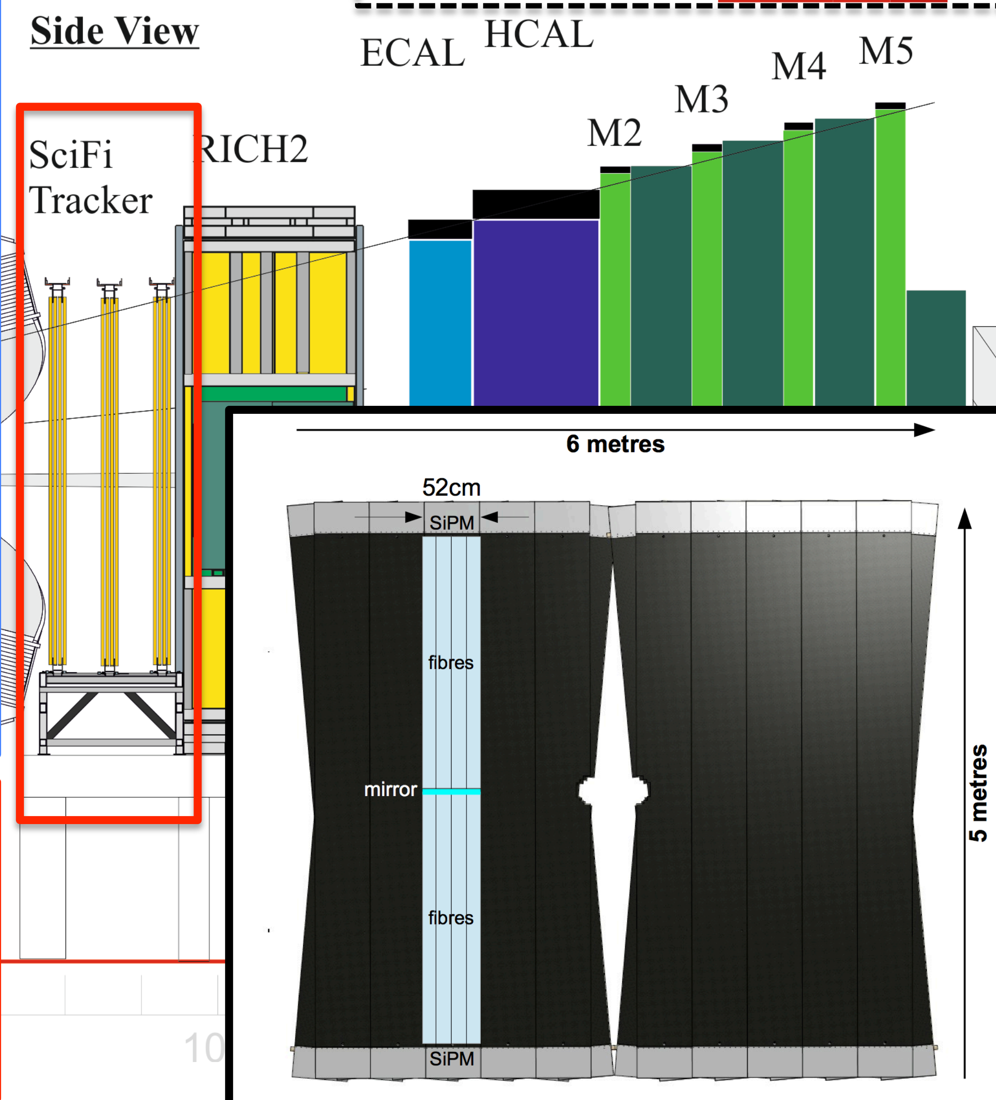
20 institutes in:

Design:

- Replace IT+OT with single technology.
  - Occupancy too high in OT.
  - Embedded 1 MHz read-out.
- Scintillating fibres.
  - 2.5 m long, 250 μm diameter.
  - Mirrored at one end.
  - (*x*, *u*, *v*, *x*) × 3 stations.
  - 5 or 6 layers of fibres in module..
- Read out by Silicon Photomultipliers.
  - Inside light-tight read-out box.
  - Cooled to –40°C.
- New ASIC for read-out (PACIFIC).
  - Three hardware thresholds (2-bit).

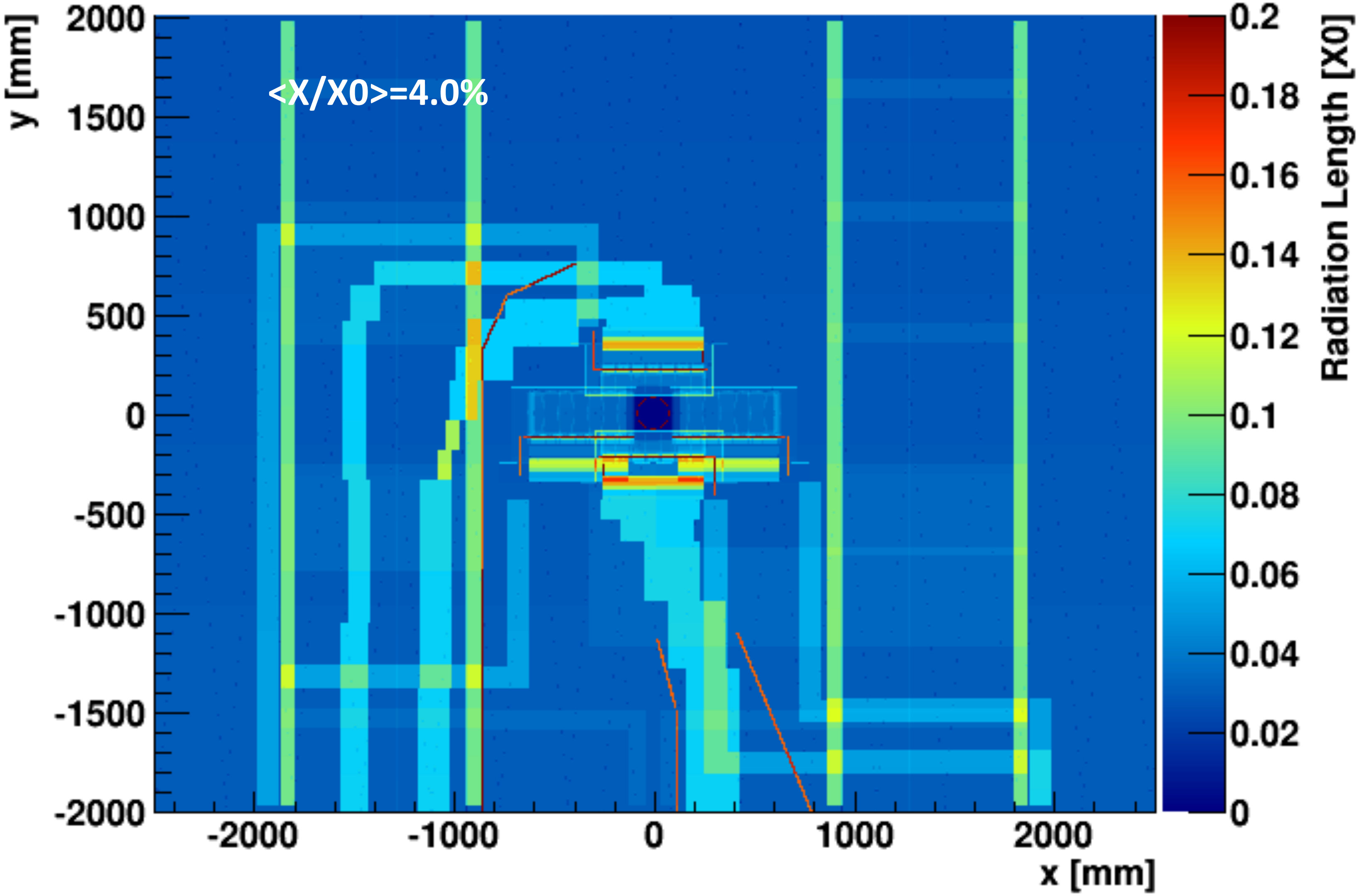
Challenges:

- Mechanical design.
- Radiation hardness of fibres & SiPMs.
- Light yield.
- Timescale.



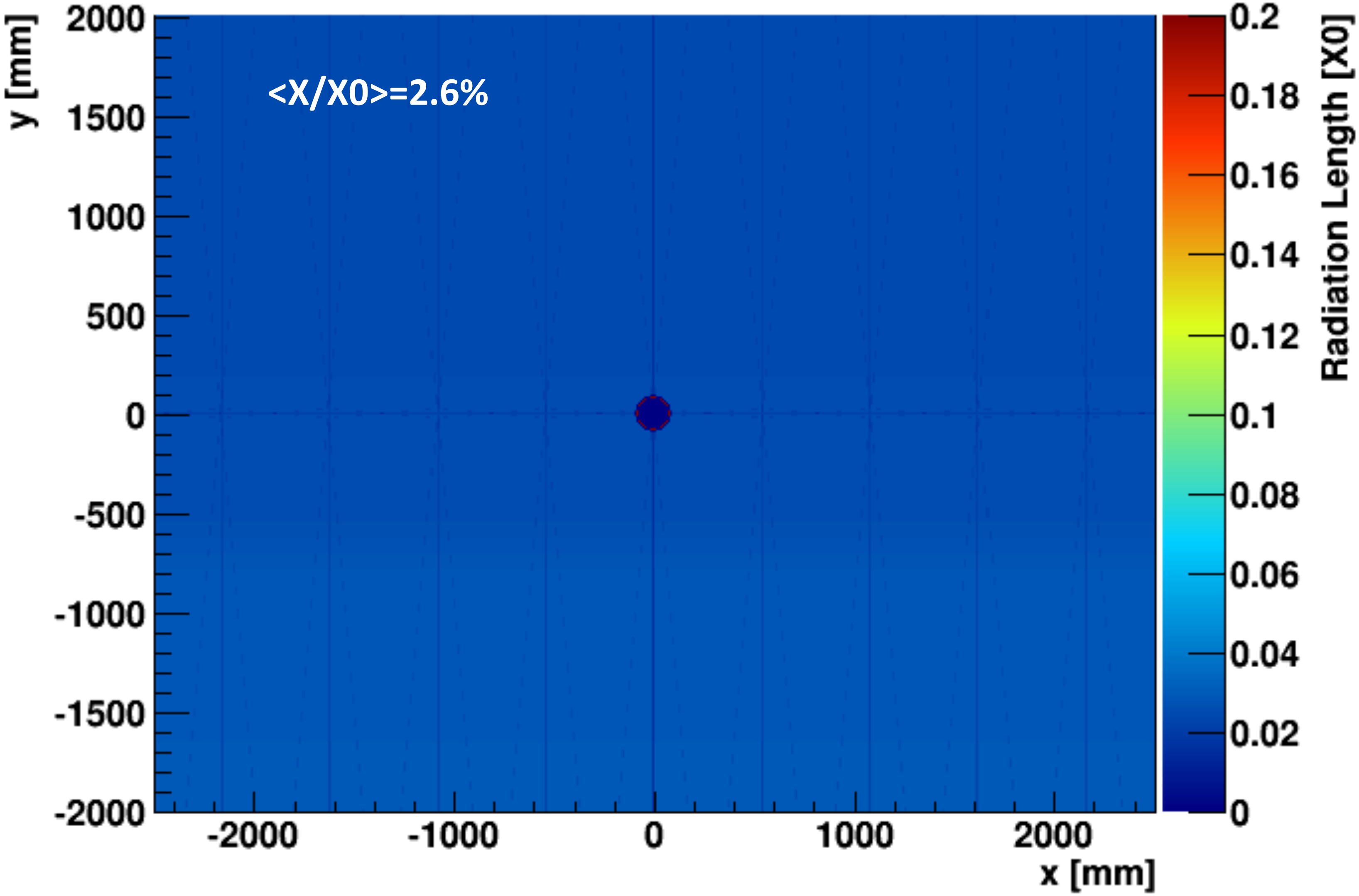
Material in first tracking station

IT+OT

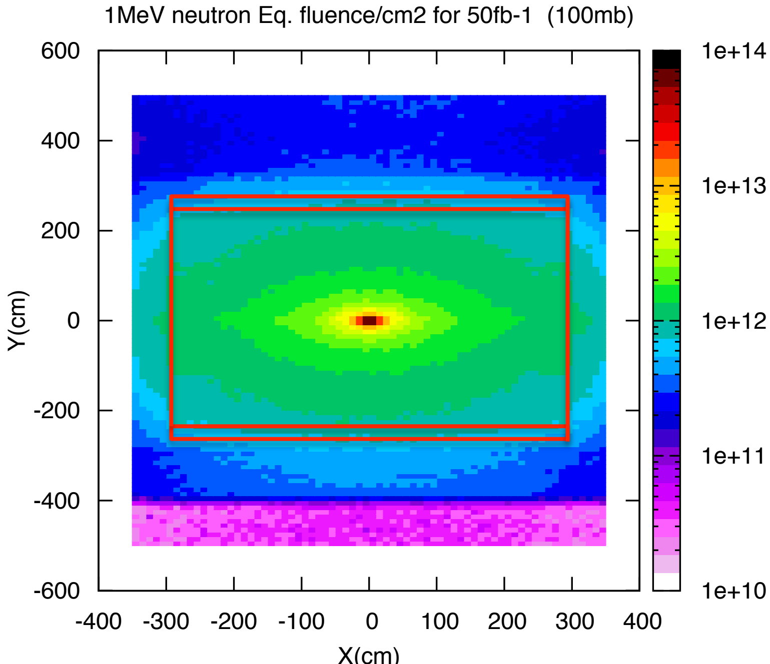


Material in first tracking station

SciFi Tracker



Radiation environment



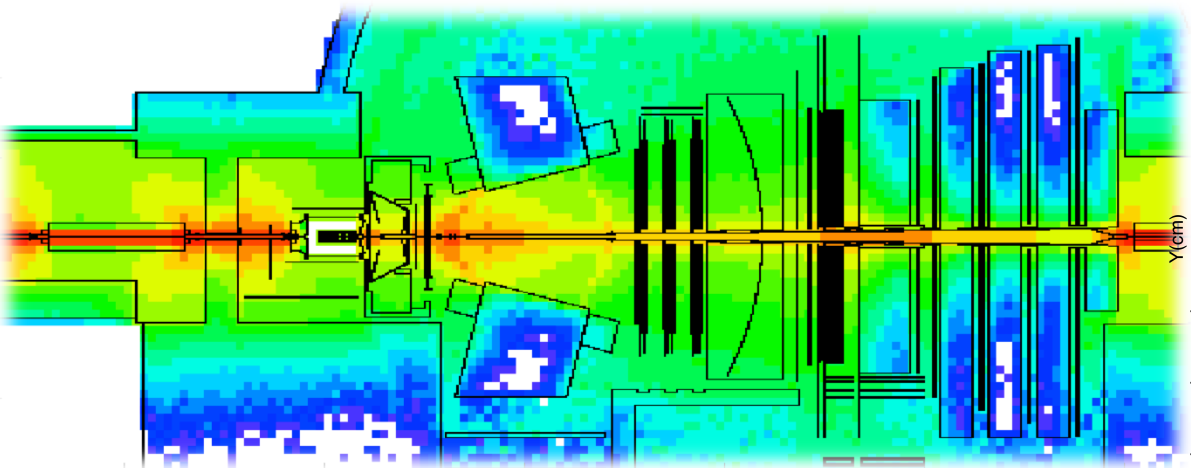
NIEL (neutrons):

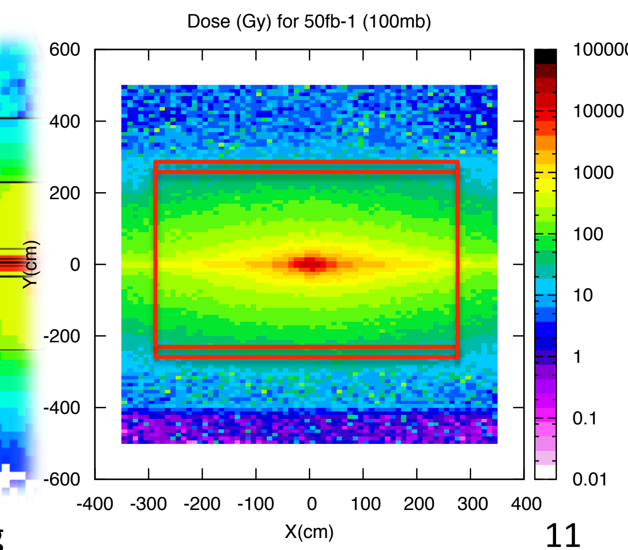
- SiPMs at ±250 cm
  - 9.5×10^{11} n_{eq} / cm^2 (T1).
  - 13×10^{11} n_{eq} / cm^2 (T3).
- Shielding of SiPMs.
  - 6×10^{11} n_{eq} / cm^2.

Ionising dose:

- 35 – 25 kGy (fibres).
- 40 – 80 Gy (SiPMs).

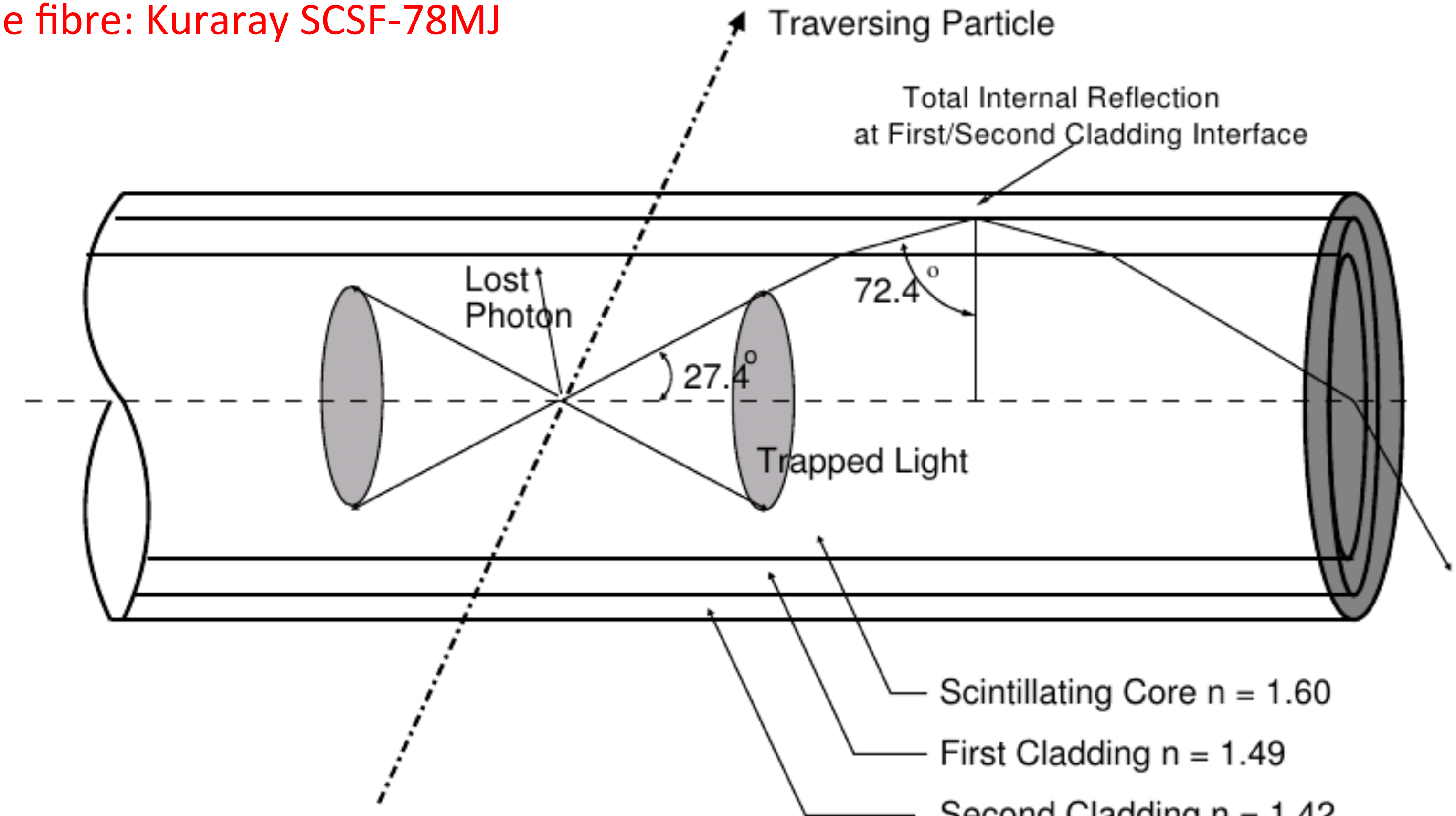
FLUKA simulation of LHCb





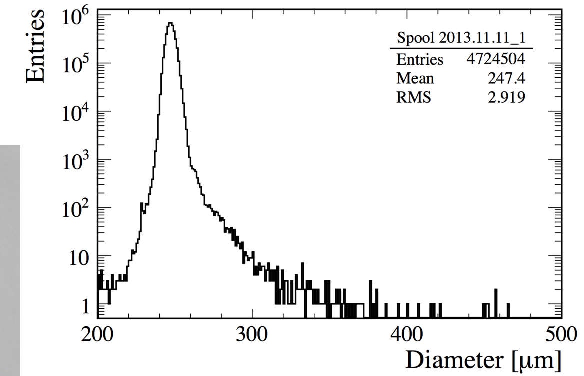
Scintillating fibres

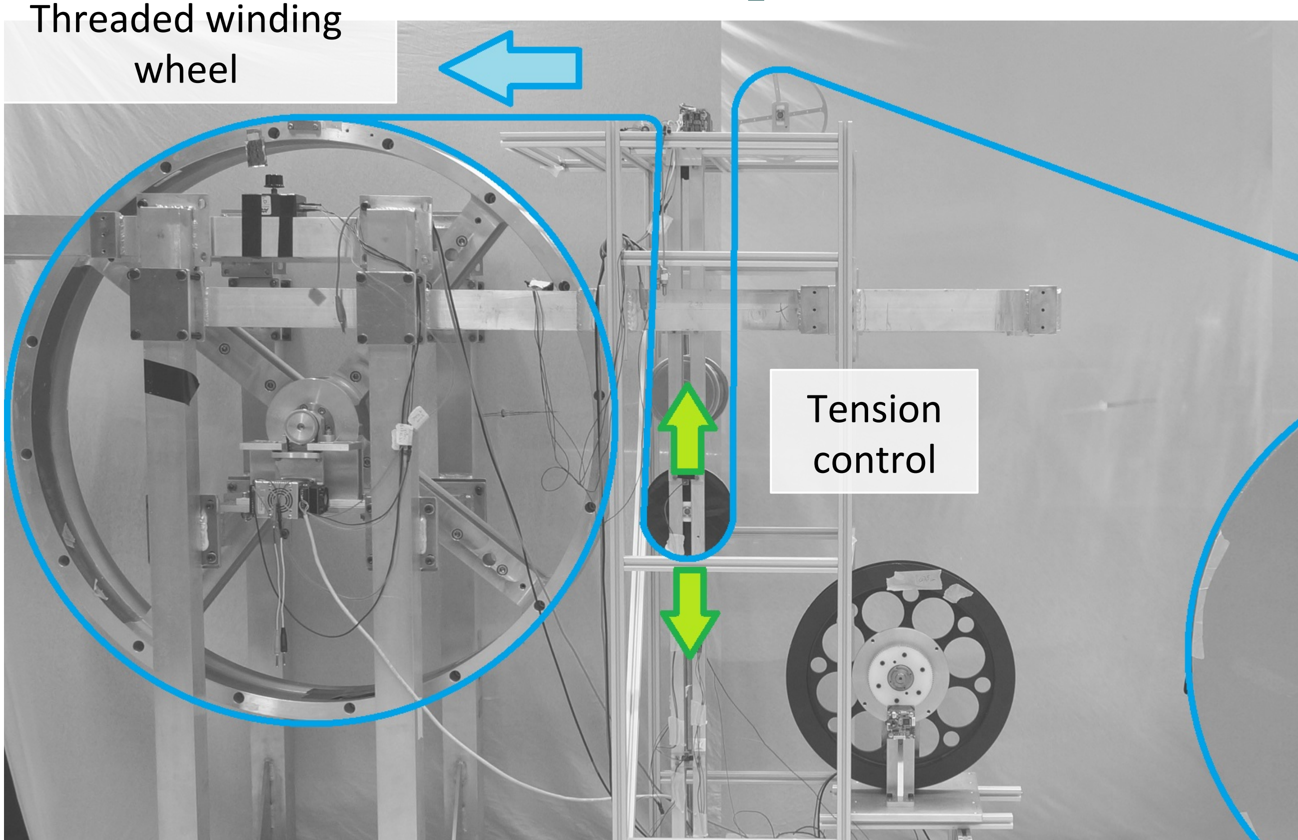
Baseline fibre: Kuraray SCSF-78MJ

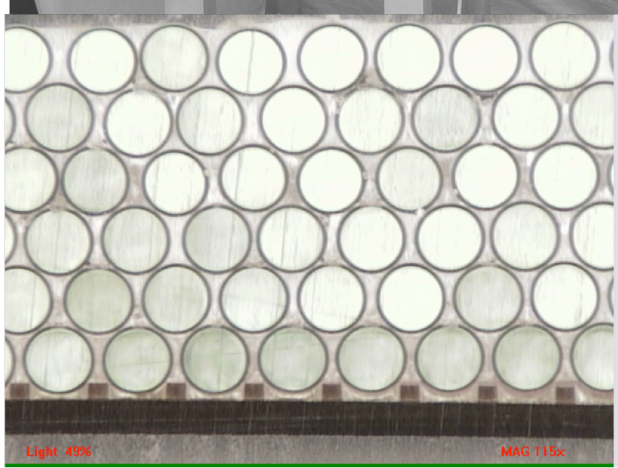


- Polystyrene core with two wavelength shifting dyes.
- Around 300 photon / MIP.
- Only a few photons after 2.5 m.

Fibre mat production

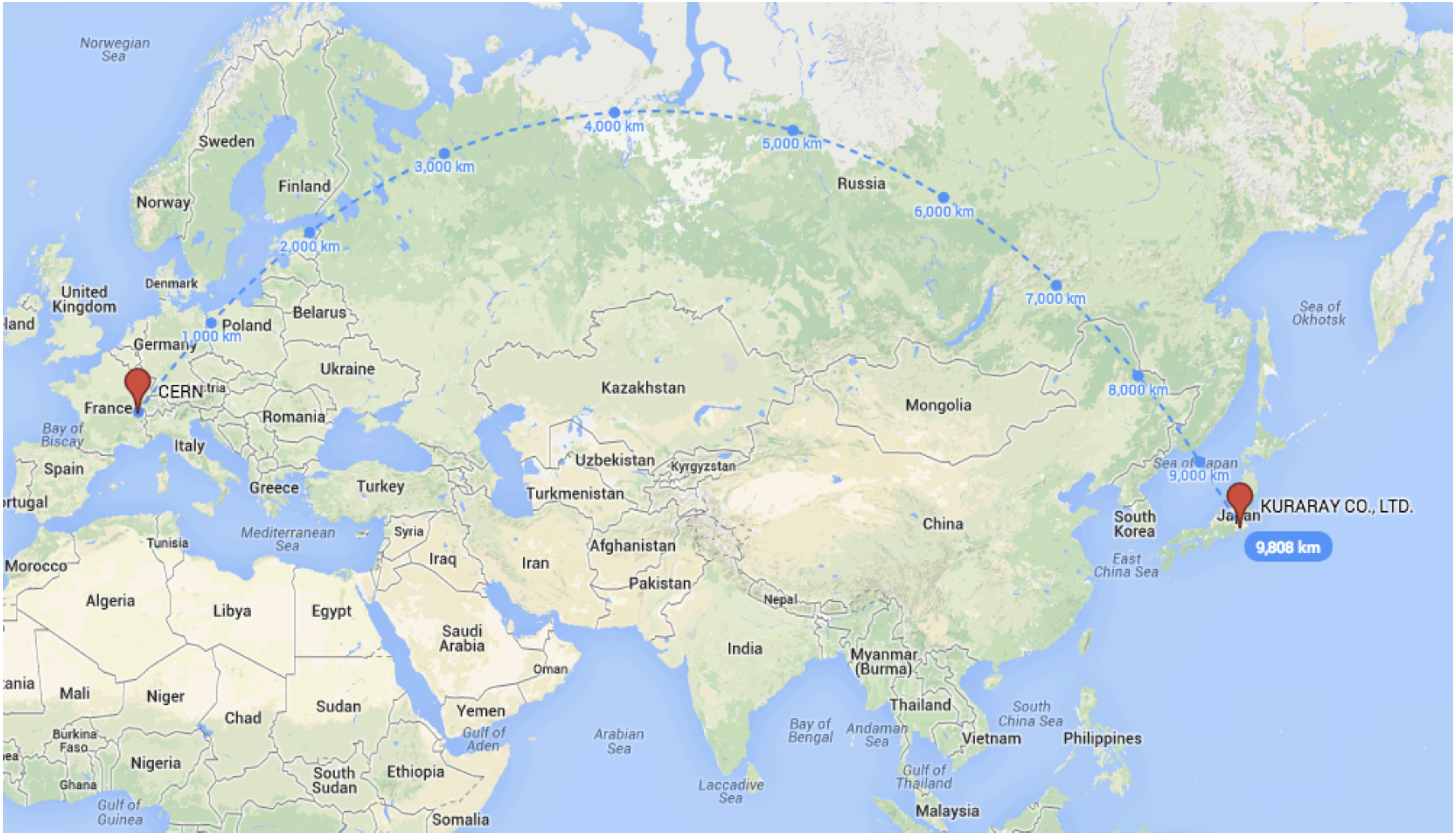






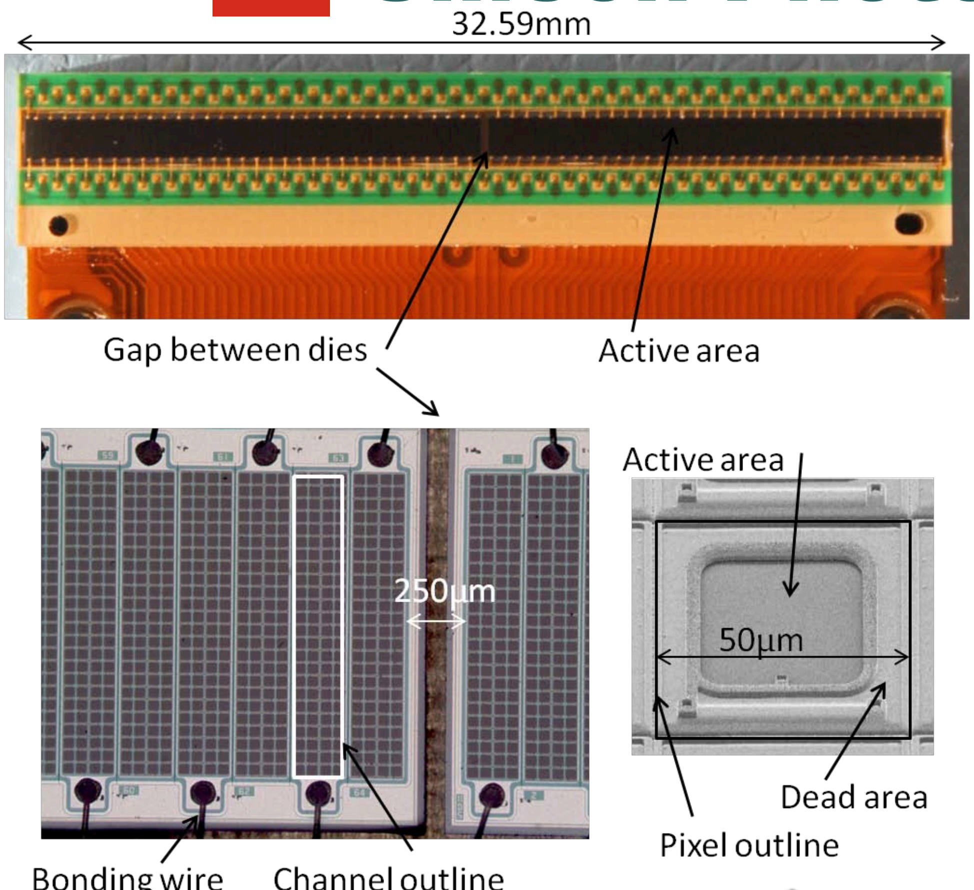
- Fibre diameter measured before winding.
- Glue injected after winding.
- Mat is cut to correct dimensions.
- Require 8 km to produce mat with 6 layers.
- Around 10,000 km needed for full detector.

10,000 km (ish)

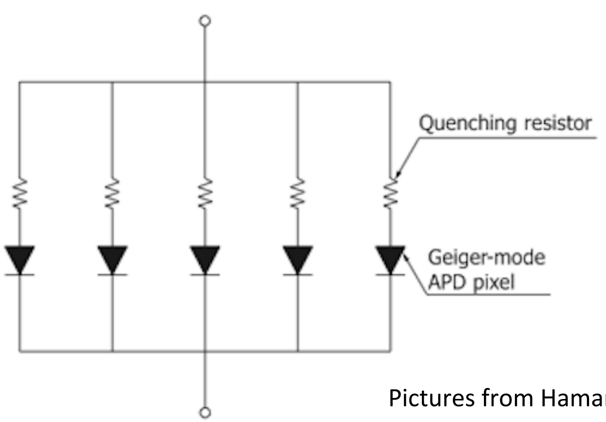


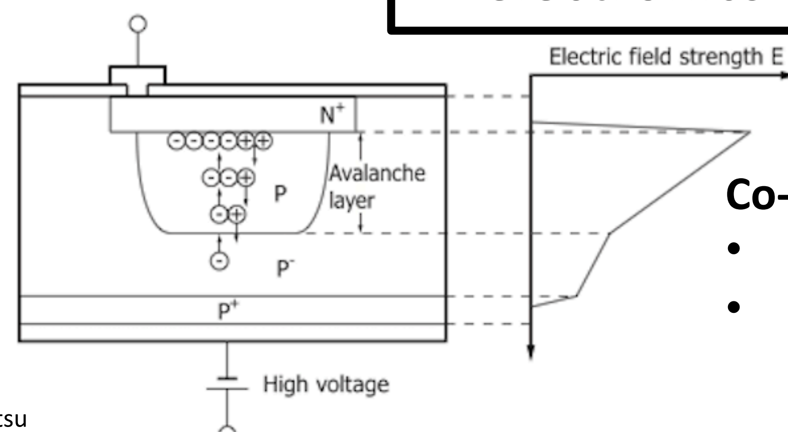
CERN
KURARAY CO., LTD.
1,000 km
2,000 km
3,000 km
4,000 km
5,000 km
6,000 km
7,000 km
8,000 km
9,000 km
9,808 km

Silicon Photomultipliers



- Avalanche photo-diode operated in Geiger mode.
- ~ 100 pixels connected in parallel /channel.
- 128 channels / array.
- Channel width: 250 µm.
- 147m instrumented:
  - 590k channels.
  - 4608 SiPMs.
- Connected to read-out electronics via flex PCB.





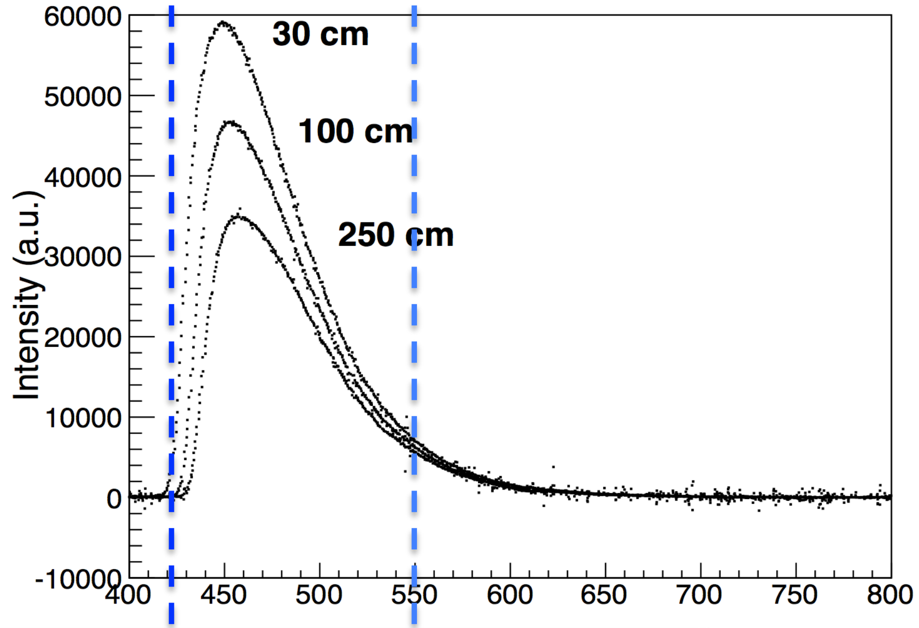
Pictures from Hamamatsu

Co-development with:
- Hamamatsu (Japan).
- KETEK (Germany).

Signal

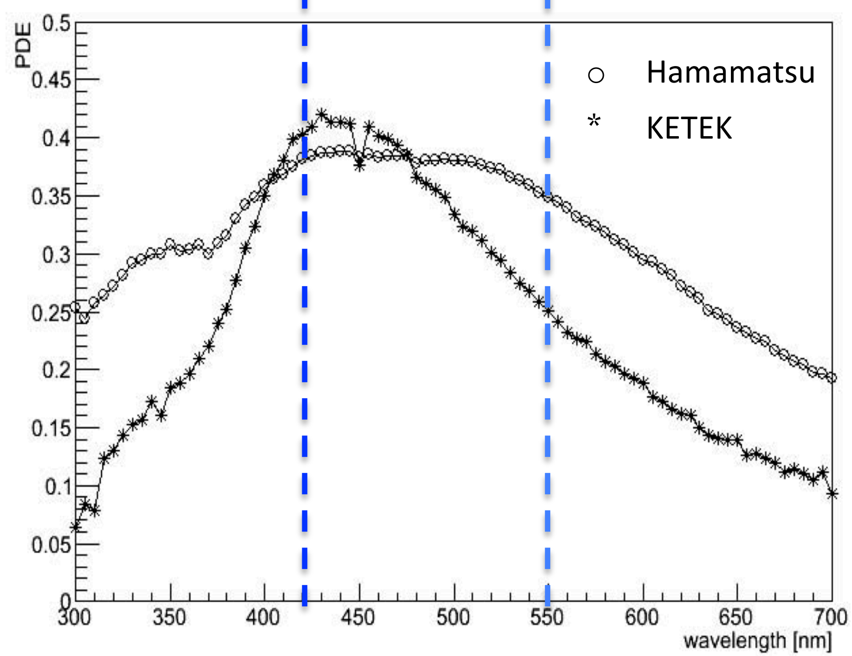
Fibres:

- Emission spectra.
- Measured at different distances from detector.

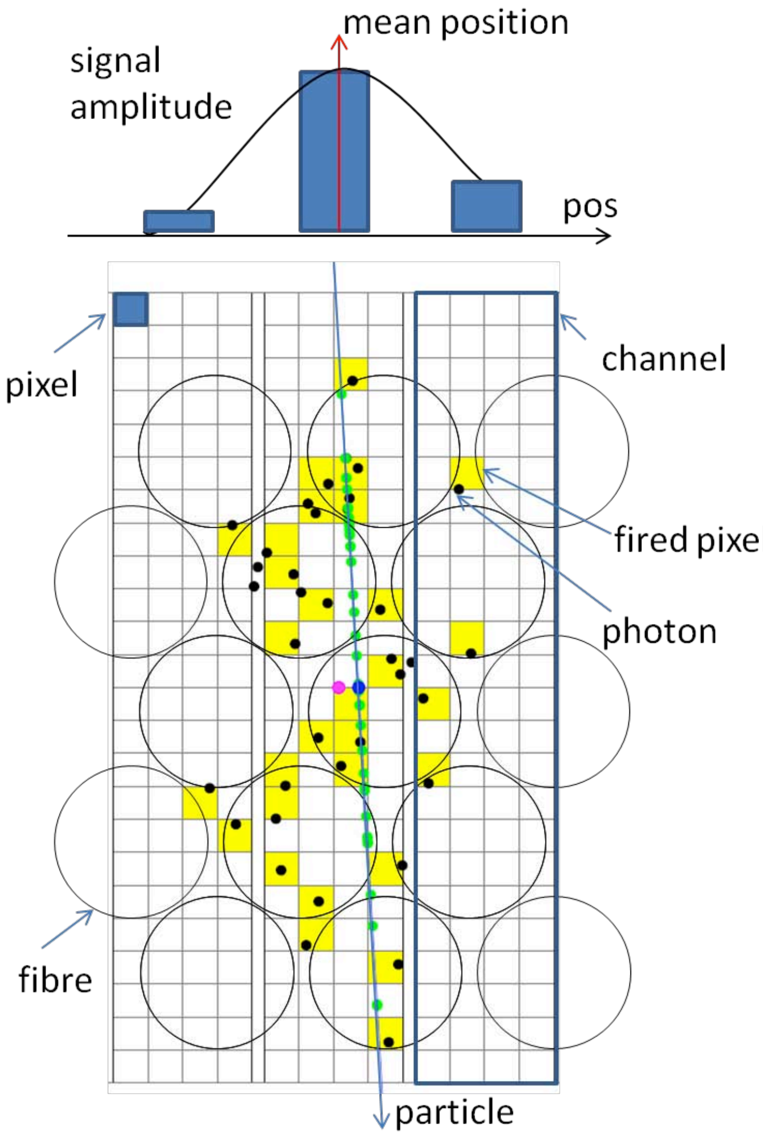


SiPMs:

- PDE = QE × GF
  - PDE: Photon detection efficiency.
  - QE: Quantum Efficiency.
  - GF: Geometrical factor.
- Single channel.
- 50 µm pixels.



Light yield



- Pixels fired (pixels fired).
- Photon exit point.
- Channel pitch < fibre pitch.

SiPMs:

- Dark noise increases with neutron radiation.
- Cooling and annealing.

Fibres:

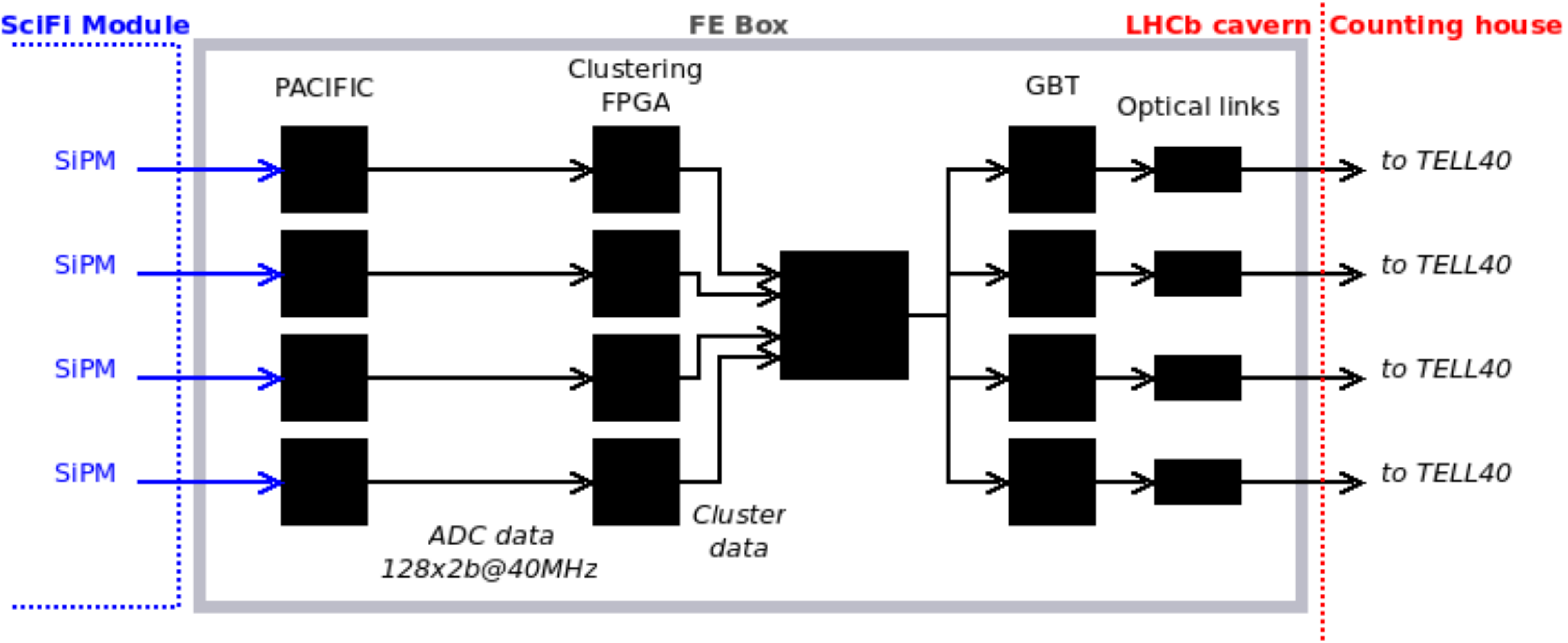
- Darken after irradiation.
- Six layers of fibres.

Expected signal:

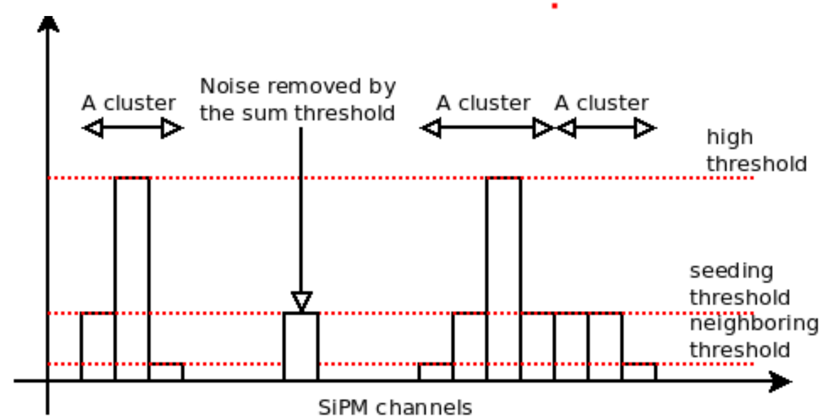
- ~ 12 – 16 photo-electrons after irradiation.

See talk of Zhirui Xu for more (actual) details.

Electronics



- Trigger-less read-out.
  - Zero-suppression in front-ends.
- Development of custom ASIC.
  - Called PACIFIC (128 channels).
  - Three hardware thresholds = 2-bit.
- Use FPGA for clustering.
  - Sum threshold.



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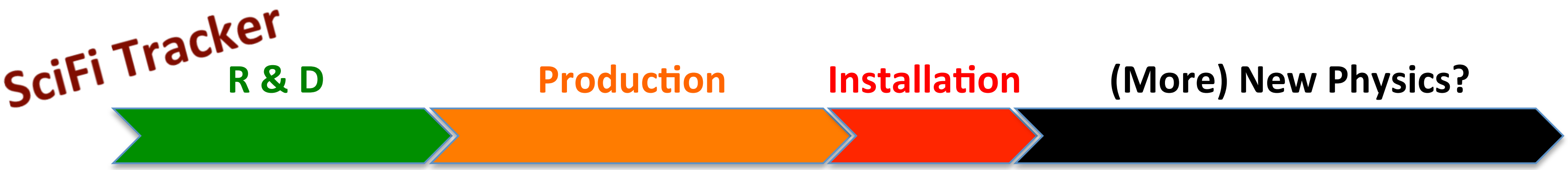
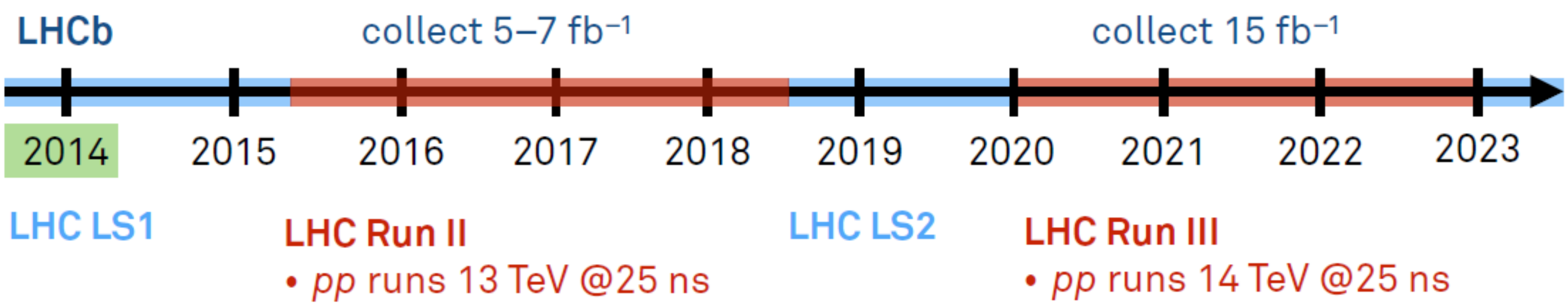
Schedule / timeline





LHC LS3
HL-LHC

- Installation during LS2.
- Collect 50 fb^{-1} after upgrade.

Conclusions

- Remove Level-0 hardware trigger.
  - Trigger-less read-out system.
  - Full software trigger for every bunch crossing.
- Instantaneous luminosities up to 2×10^{33} $cm^{-2}s^{-1}$.
  - Redesign detector to cope with higher occupancies.
  - Collect integrated luminosity = 50 fb^{-1}.
- New tracking system with scintillating fibres.
  - Long fibres read out with SiPMs.
  - TDR approved by CERN Research Board.
  - Installation in 2018/2019.
  - Ready for data taking in 2020!

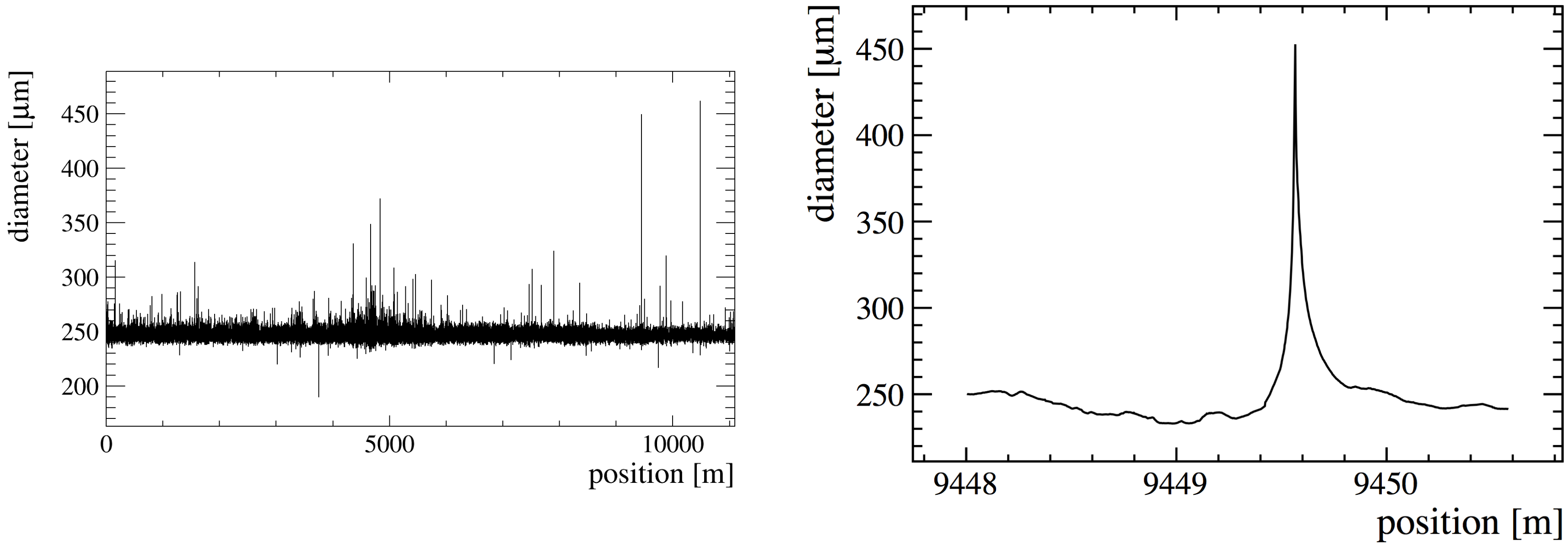
Merci à tous!
Merci vielmal!
Grazie mille!
Grazia fitg!*

* Thanks to Arno Gadola for pointing out "Grazcha fich" was wrong! engraziel fetg!

More?

BACK UP

Fibre diameter



- Measure diameter every 3 mm with laser micrometer.
- Once per km, diameter goes above limit (300 µm).
- Manually remove during winding process.

Light yield

- 3 m long SCSF-78 fibres irradiated at CERN PS (24 GeV protons).

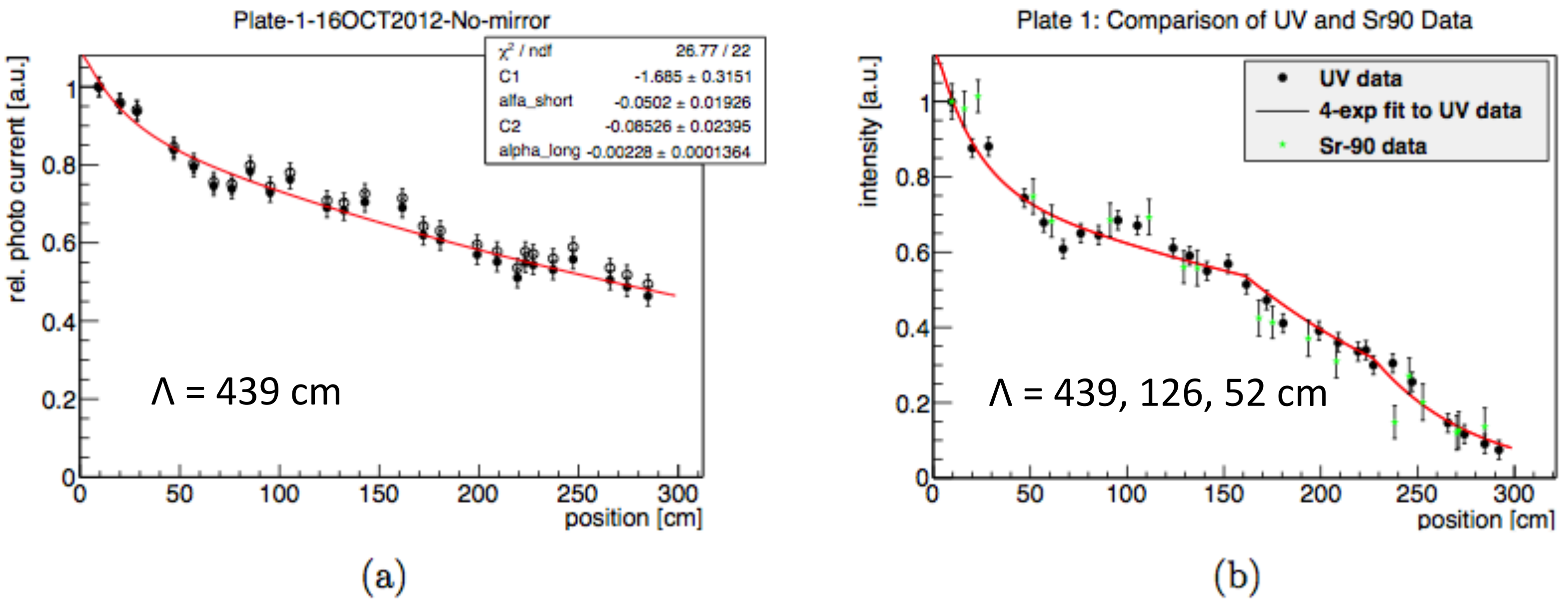
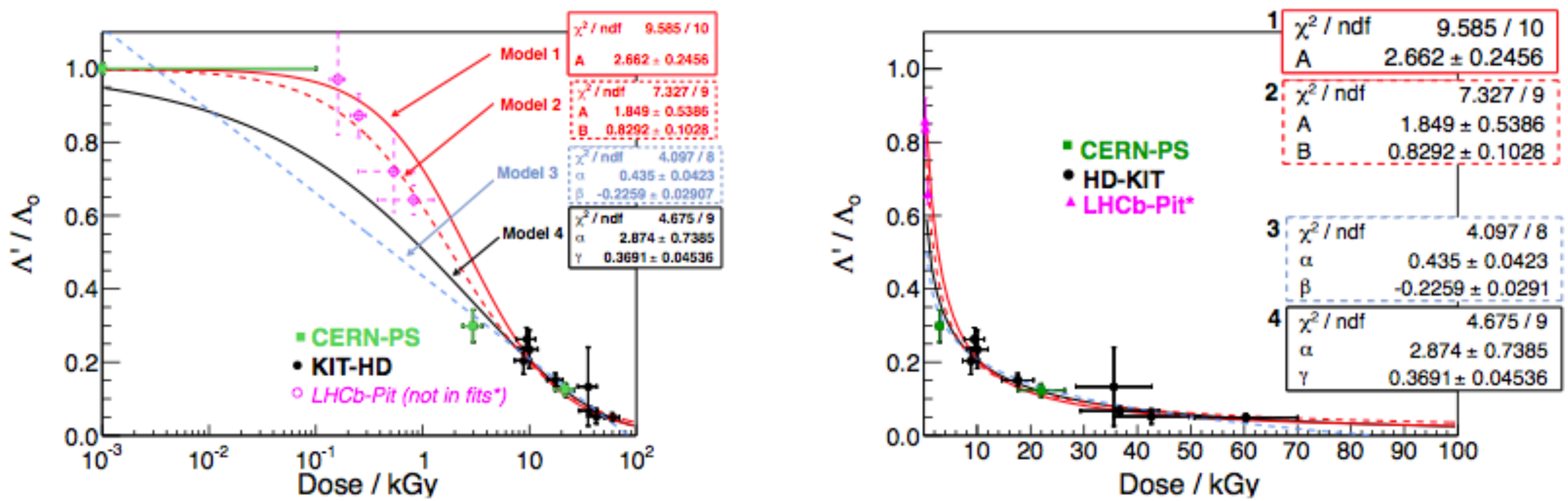


Figure 3.13: Relative light yield with UV excitation as function of the excitation distance of the scintillating fibres before and after irradiation. (a) Before irradiation. Open symbols: As measured with the PIN diode. Full symbols: Scaled to the spectral response of a KETEK SiPM detector. (b) After irradiation: Relative light yields resulting from UV excitation and exposure to electrons from the Sr-90 source.

Radiation damage



(a) Logarithmic x-axis (b) Linear x-axis

Figure 3.16: The combined attenuation length data shown with statistical errors versus dose from three fibre irradiation studies and fits to 4 models. Model 1 assumes a linear damage with dose effect ($\Lambda'(D)/\Lambda_0 = 1/(1+(D/A))$). Model 2 assumes a power law function ($\Lambda'(D)/\Lambda_0 = 1/(1+(D/A)^B)$). Model 3 is the logarithmic function $\Lambda'(D)/\Lambda_0 = \alpha + \beta Log(D)$. Model 4 has an exponential-like behaviour ($\Lambda'(Dose)/\Lambda_0 = exp((D/\alpha)^\gamma)$). The LHCb-Pit data are not yet included in these fits as they likely have much larger systematic errors that are currently being determined.

Dark noise

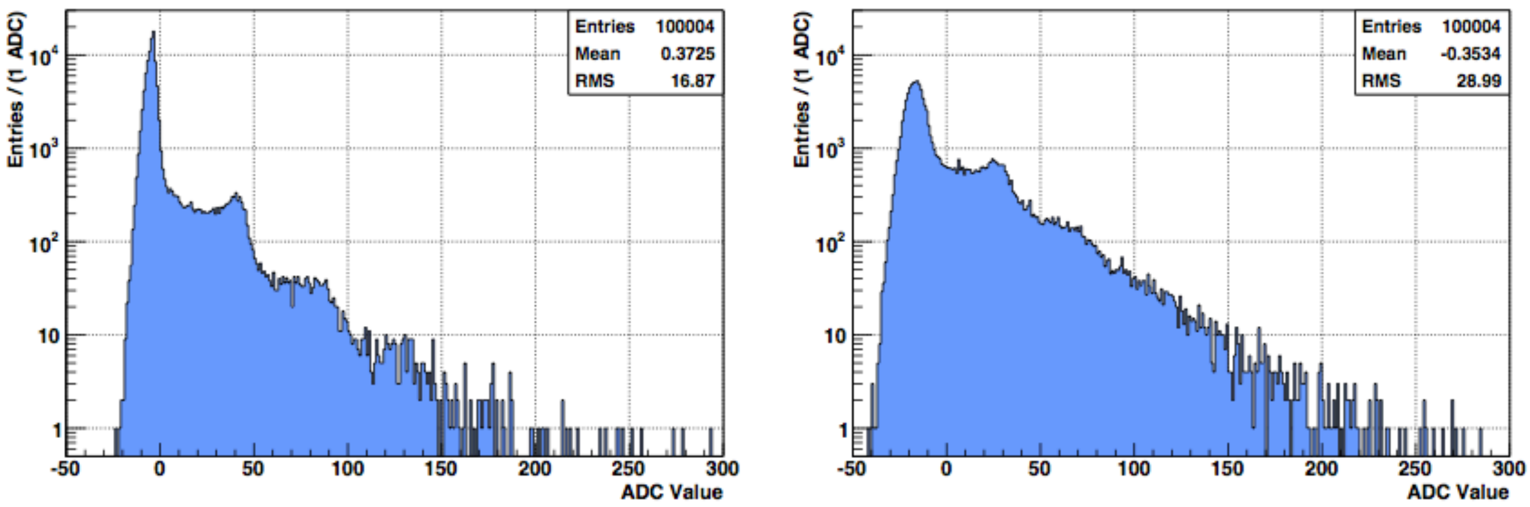


Figure 3.22: Left: Measured dark noise amplitude for a non-irradiated standard technology Hamamatsu detector at nominal operation voltage and 25°C. Note the exponential decrease of the probability of large amplitude events. The relative intensity of the second and third peak, corresponds to the sum of the cross-talk and after-pulse probability of the SiPM. The probability of two random noise pulses is very small in a non-irradiated detector. Right: Measured dark noise amplitude of the same detector at nominal operation voltage and −60°C after irradiation to $2 \times 10^{11}\ \mathrm{n_{eq}/cm^2}$. The relative intensity of the second and third peak is almost unchanged which confirms that the cross-talk is not changed due to irradiation. However, a small change can be explained by the fact that, at this DCR, random pulses can overlap in time. The ratio between pedestal and one photon noise is reduced in this case to about 10.

Dark current

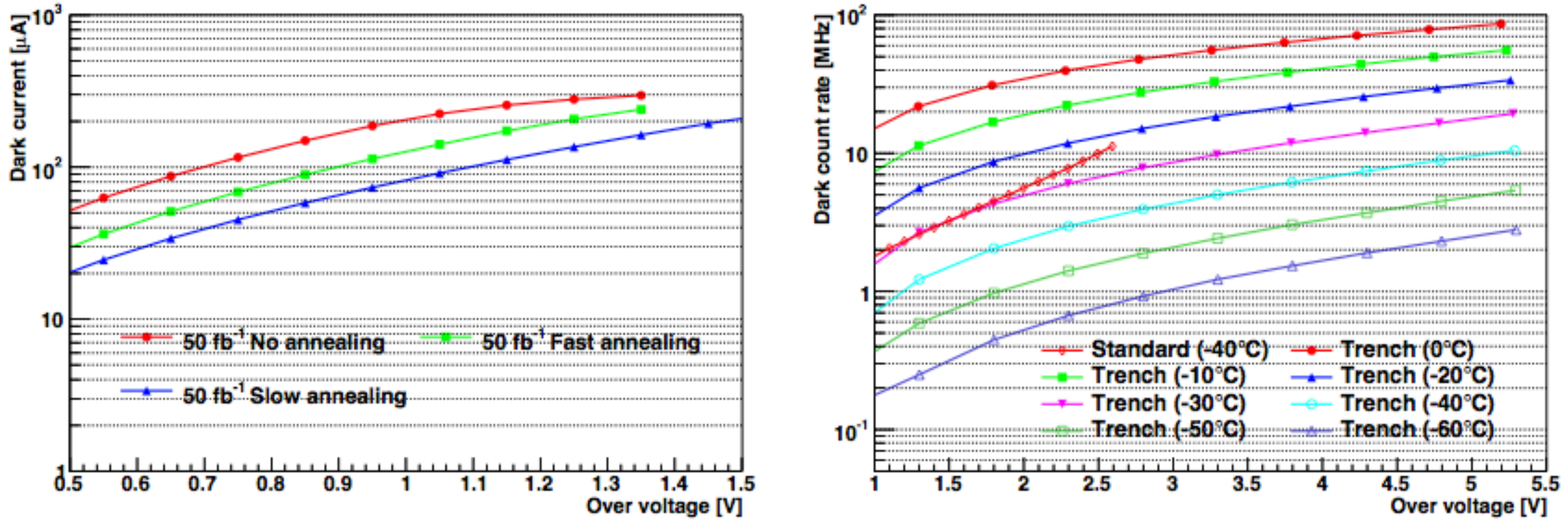


Figure 3.24: Left: Hamamatsu with trench, dark current as a function of over-voltage for different annealing scenarios. The dark current is decreased by a factor 2.5 after one week of annealing at 40°C. Right: Two types of detectors irradiated to an equivalent fluence of 25 fb^{-1}. Here the DCR can be compared for the standard Hamamatsu at 1.3 V at -40°C and the trenched detectors at different temperatures. The desired operation point for the trenched technology is 3.5 V in order to reach a high PDE. The DCR changes by a factor of two every 10°C over a large temperature range. The expected DCR at -40°C is 5 MHz at the desired operation point. The DCR for an irradiated detector is expected to double after an integrated luminosity of 50 fb^{-1}. All plots are given for fully annealed detectors after slow annealing during one week at 40°C.

Eur. Phys. J. C(2013) 73:2373

Physics reach!

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_sK)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

LHC Page1 Fill: 3021 E: 4000 GeV t(SB): 09:27:32 02-09-12 18:36:25

PROTON PHYSICS: STABLE BEAMS

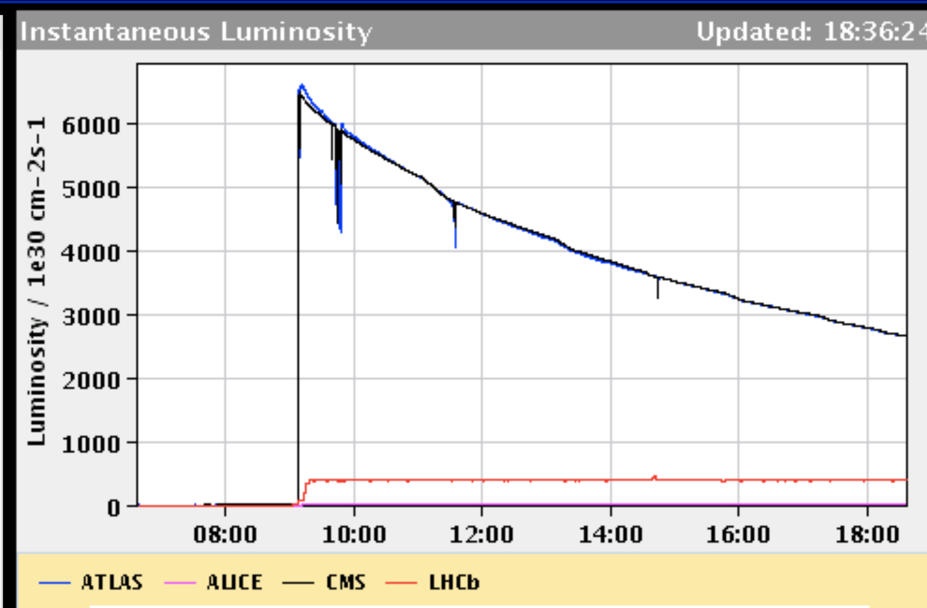
Energy:	4000 GeV	I(B1):	1.55e+14	I(B2):	1.56e+14

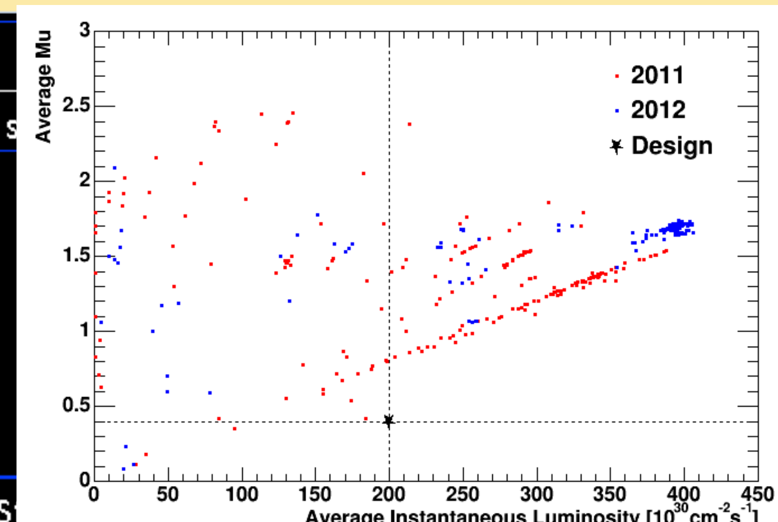
Design:

- $\sqrt{s}$ = 14 TeV
- 2622 bunches, 25 ns spacing.
- L = $2*10^{32}$ $cm^{-2}s^{-1}$.
- Average number of visible pp interactions / bunch crossing (μ) = 0.4.

Reality (2011+2012):

- $\sqrt{s}$=7 TeV / 8 TeV
- ≈1300 bunches, 50 ns spacing.
- L ≈ $2\text{-}4*10^{32}$ $cm^{-2}s^{-1}$.
- Higher pile-up.
  - <μ> ≈ 1.4 / 1.7
- Luminosity levelling.
- Exceeding design by factor two





AFS: 50ns_1374_1368_0_1262_144bpi12inj

Trigger in 2012

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

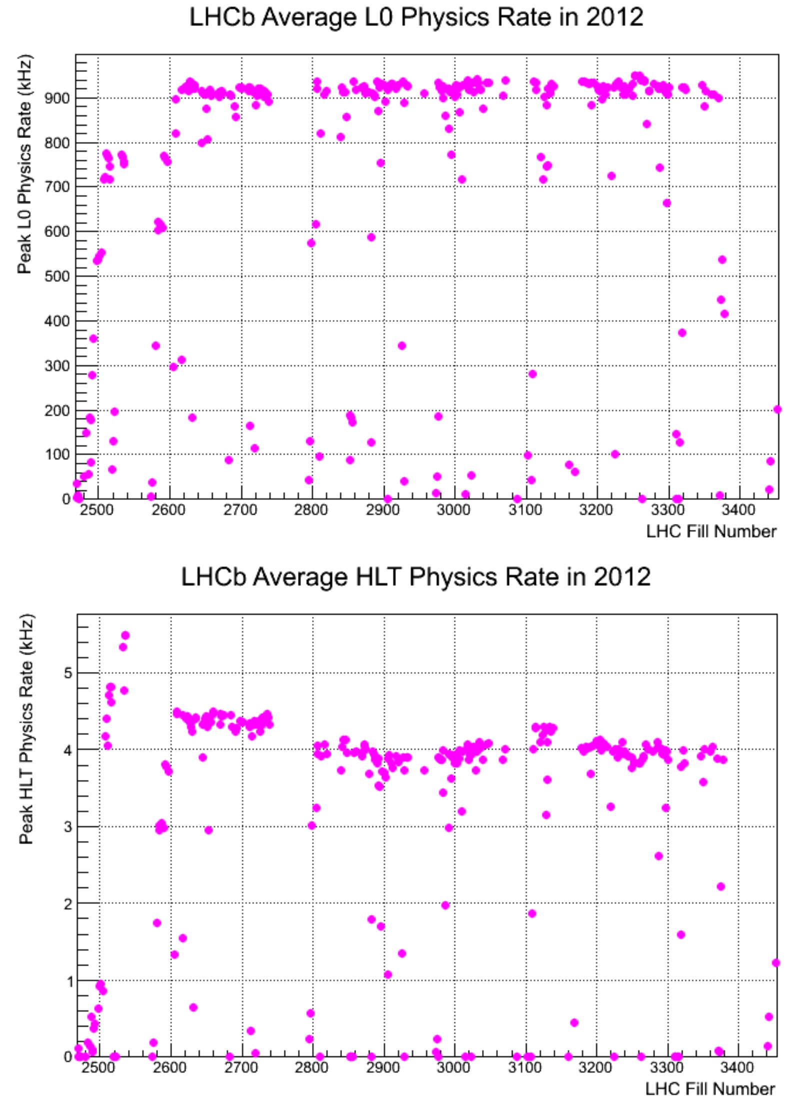
450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

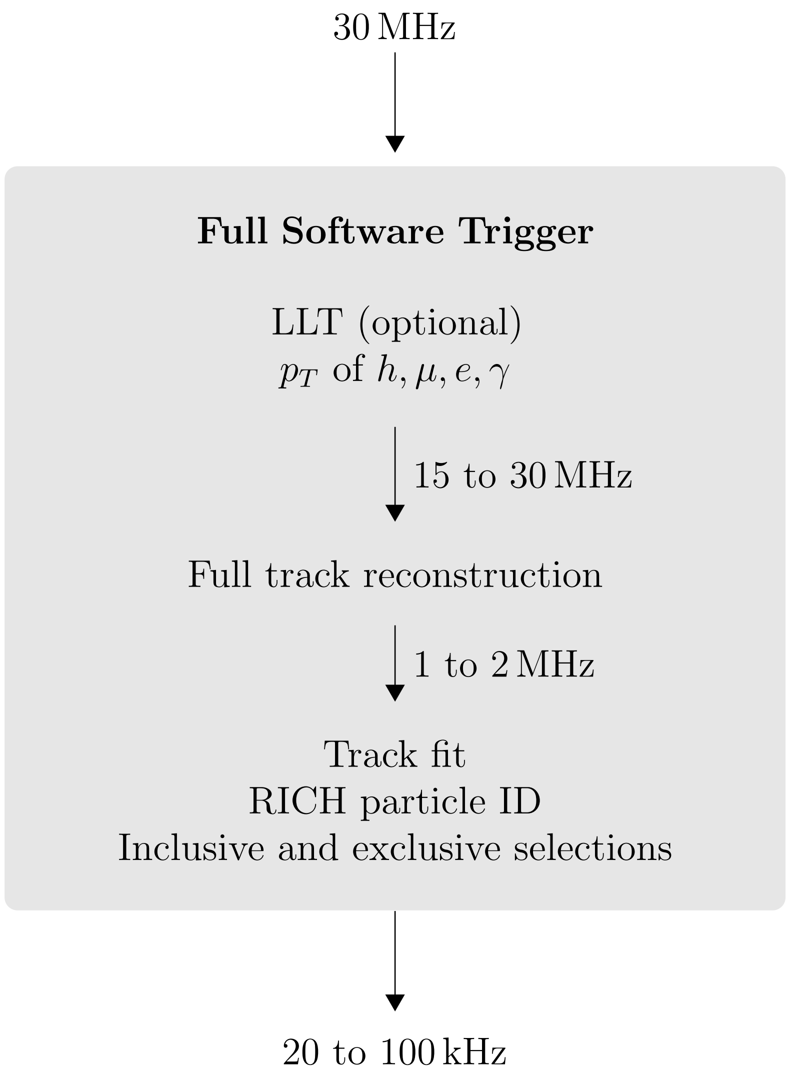
2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon



Hardware Trigger @ ≈ 1 MHz

Software Trigger @ ≈ 5 kHz

Upgrade Trigger



- Trigger-less read-out.
- Zero suppression in front-ends.
- Full detector data to Full Software Trigger.
- Inelastic collision rate is 30 MHz.

- Low level trigger as throttle.
- Partial information from muon system and calorimeters.

- Full event reconstruction.
- Run-by-run detector calibration.

- Perform simplified Kalman track fit.
- Add RICH information.
- Inclusive and exclusive selections.

- 2 – 10 GBytes/s to storage.

Reconstruction sequence

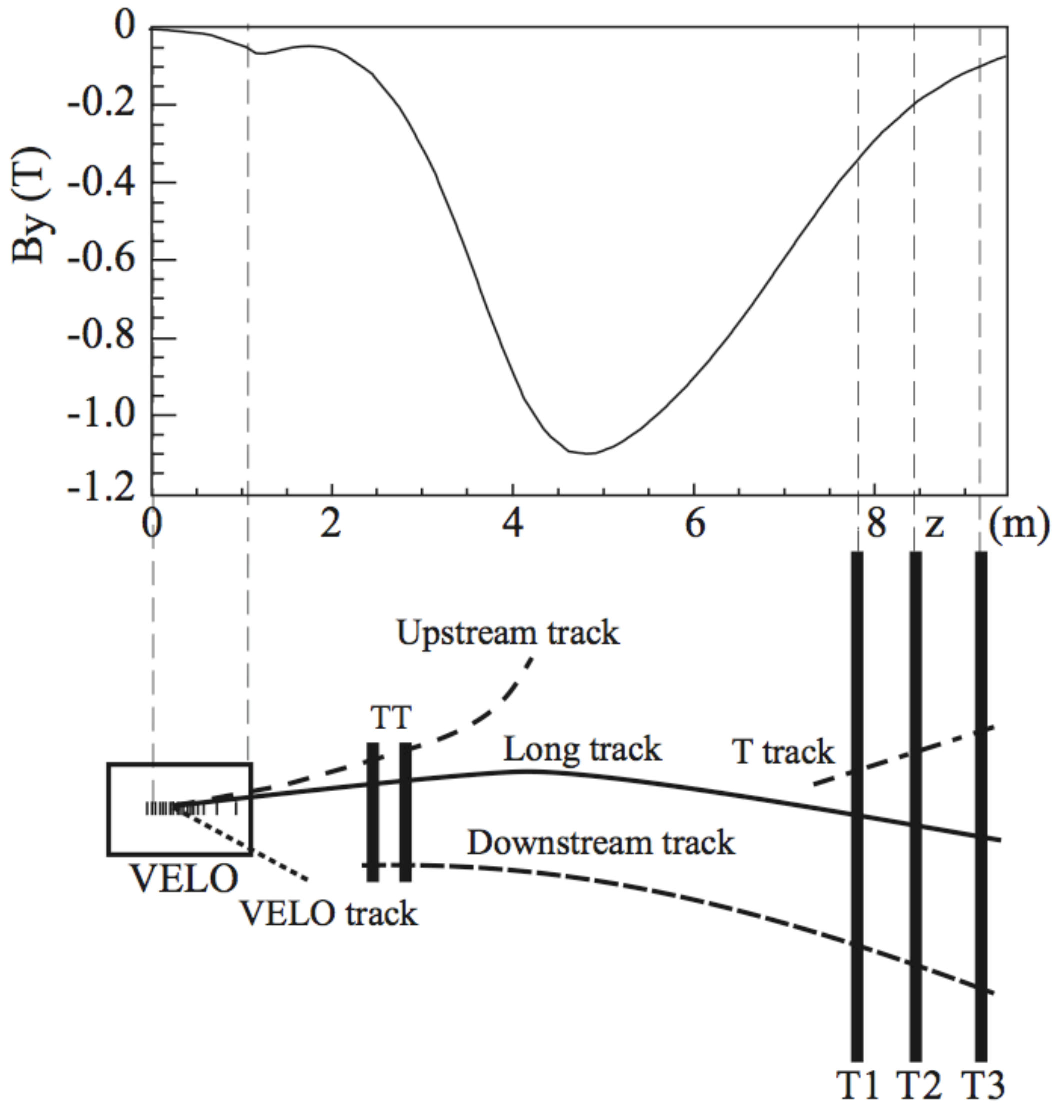
Offline

- VELO tracking
- VELO-UT
- Forward reco $p_T > 70$ MeV/c
- PV finding
- Full Kalman Fit
- RICH PID

Upgrade HLT

- VELO tracking
- VELO-UT $p_T > 200$ MeV/c
- Forward reco $p_T > 500$ MeV/c
- PV finding
- Trigger cuts to reduce rate to 1 MHz
- Muon ID
- Simplified Kalman Fit
- Online RICH PID

Track types



By (T)
0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
2
4
6
8
z (m)
Upstream track
TT
Long track
T track
VELO
VELO track
Downstream track
T1 T2 T3

Read-out architecture

- Trigger-less read-out.
- Zero suppression in front-ends.
- Hardware LLT kept as back-up.