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7th Annual Workshop

2-4 December 2013

Karlsruhe

The LHCb Detector Upgrade

Blake Leverington
Heidelberg University
On behalf of the LHCb Upgrade Group

Topics:
- Electroweak Phenomena and QCD
- Heavy Flavour Physics
- Searches for Higgs and Phenomena beyond the Standard Model
- Detector Technologies

Outline

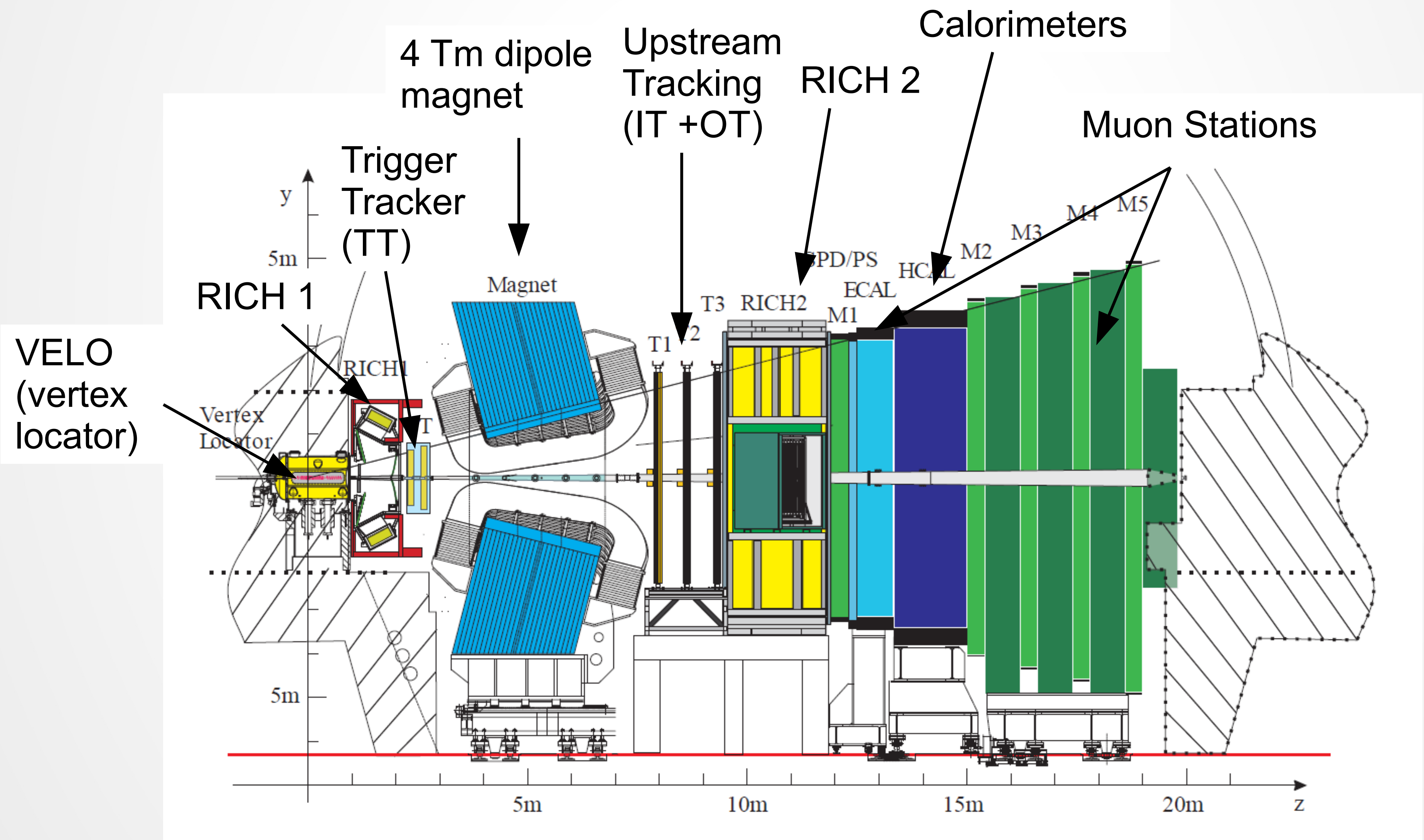
- The LHCb Detector Upgrade [15']
- The Scintillating Fibre Tracker [15'] (Where Germany contributes most)

LHCb Schedule

- 2013-2014: 1st LHC long shutdown:
  - LHCb maintenance
  - Submission of LHCb subsystems TDRs to LHCC
- 2015-2017:
  - LHCb data taking @ 13-14 TeV and 25ns bunch spacing
  - New hardware construction
- 2018/2019: LS2 (2nd LHC long shutdown)
  - Installation and commissioning of the upgraded detector
- After 2019:
  - LHCb data taking @ 14 TeV, 25ns, with L=1-2x10^33cm–2s–1

The Current LHCb detector

- Single-arm forward spectrometer designed to search new physics through measuring CP violation and rare decays of heavy flavor mesons



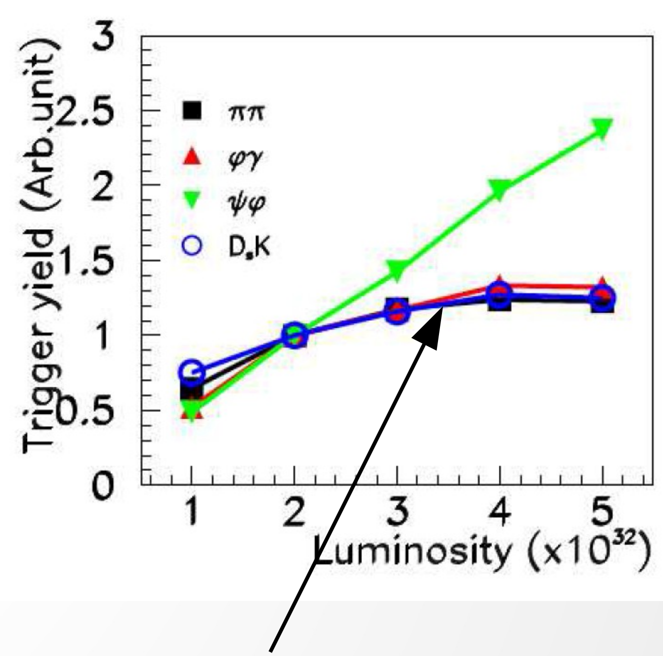
Current LHCb

- Physic motivation:
  - Core flavour physics program to search for rare decays, such as $\mathbf{B^0_s \to \mu\mu}$ (Beyond the SM searches)
  - Evidence of matter-antimatter asymmetries in charm sector and B^0_s decays
  - Search for CP violation in charm sector
  - Constraints on gamma(~4º) of the Unitarity Triangle

- Total data: 0.3 fb^{-1} (2010) + 1 fb^{-1} (2011) + 2fb^{-1} (2012) + 4-6 fb^{-1} (2015-17)
- Maximum Int. Luminosity of 4 x $10^{32} cm^{-2} s^{-1}$ (twice the design value)
- L0 hardware trigger with cuts on E_T and P_T in muon and calorimeters
- 1 MHz readout rate

Higher Luminosity in LHCb

- Physics:
  - Improved statistics would reduce uncertainties in some channels near to SM predictions (i.e. $B^0_s \rightarrow \mu\mu$ = 0.19; Theory = 0.3)
  - Improved sensitivities on β (0.8º → 0.3º) and γ (4 → 1º) in Unitarity Triangle
  - the sample sizes in most exclusive B and D final states will be far larger than those that will be collected elsewhere, for example at the upgraded e+e-B factories. The LHCb upgrade will have no serious competition in its study of B0s decays and CP violation. Also, charmed with charged tracks.
- It has been shown the detector could run up to a luminosity of 10^{33} $cm^{-2}s^{-1}$, but...
  - L0 hardware cut requires ever increasing E_T for hadrons, muons, eletrons and photons
  - high efficiencies on dimuon events, but removes larger fraction of hadronics decays and B meson mass (signal)
- LHCb-PUB-2013-015 "Updated sensitivity projections for the LHCb Upgrade"



Saturation with L0-hardware trigger

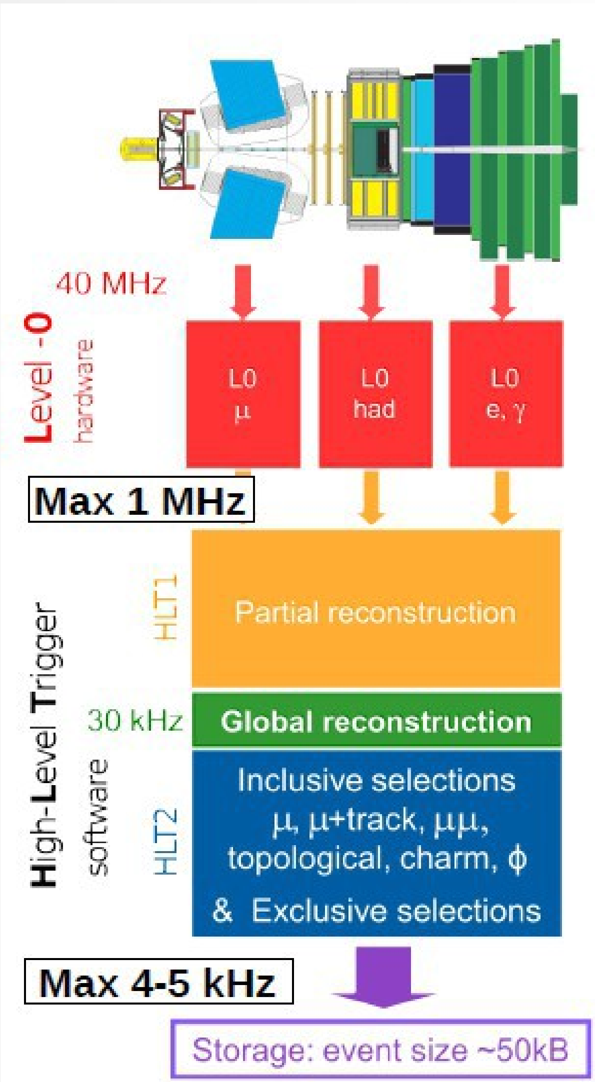
LHCb Upgrade

- Remove the L0-hardware trigger, replace with flexible software trigger and analyse each event in a trigger system
  - Needs a fast tracking system for fast pattern recognition
  - the yield of hadronic B decays increases by up to a factor of 7-10 for the same LHC machine run-time. > factor 20 for heavy-flavour decays to hadronic final states
- Upgrade all the front-end readout electronics from 1MHz to 40 MHz
- Increased luminosity of 2 x 10^{33} $cm^{-2}s^{-1}$ (not tied to LHC luminosity upgrade)
- ~5 fb^{-1} / year after the upgrade in LS2(2018-19), 50 fb^{-1} total

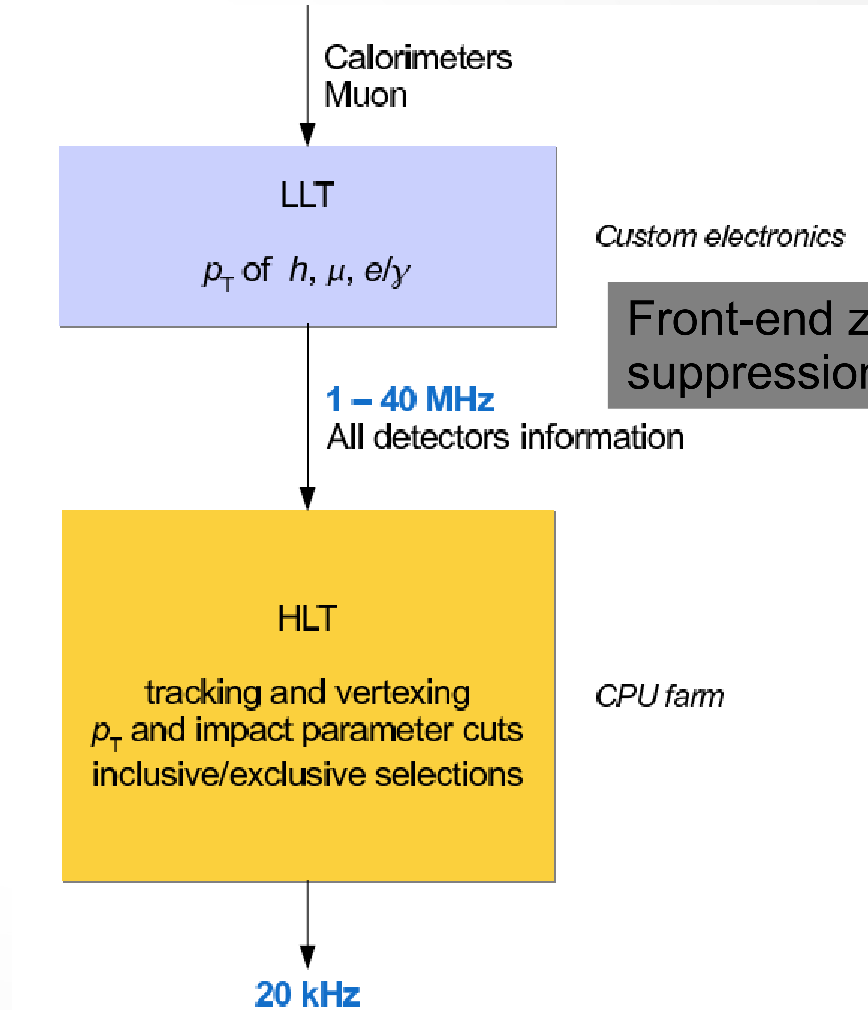
- Detectors will require upgrades to improve tracking and sustain the increased luminosity...
- A full description of the LHCb Upgrade plans can be found in the Letter of Intent (LoI) (CERN-LHCC-2011-001) and the Framework-TDR (CERN-LHCC-2012-007); all TDRs will be submitted from Nov. 2013 to March 2014

Trigger Upgrade

Current Trigger Scheme



Upgrade Trigger Scheme



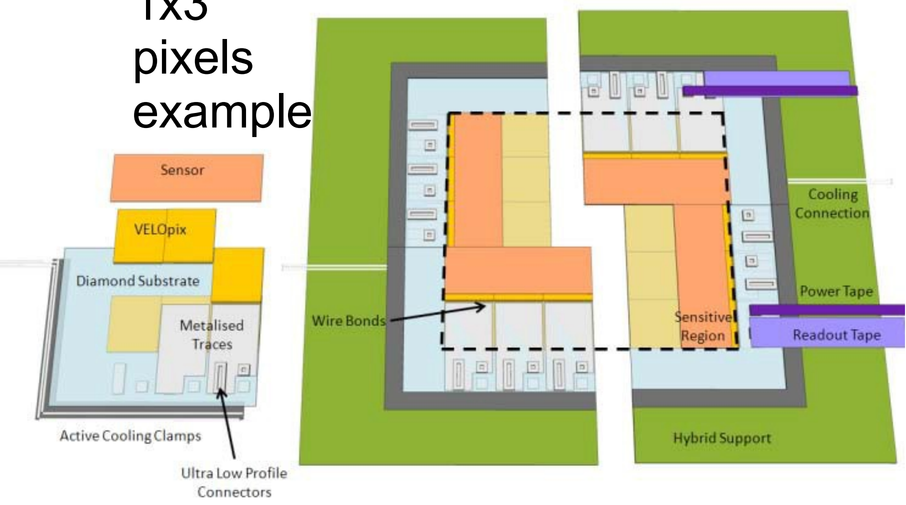
Front-end zero-suppression

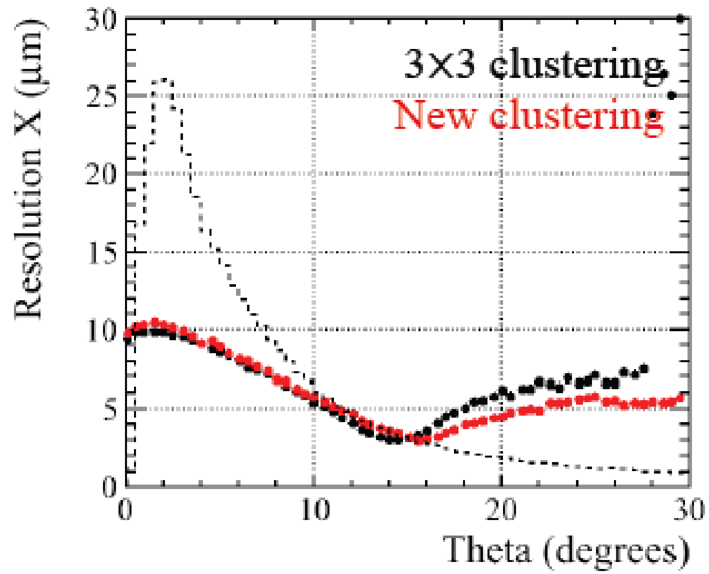
10 Gbits/s to the farm
- Event selection in the farm

VELO Upgrade

- VeLo → VeLoPix @ 40MHz
- Decay vertex (impact parameter resolution) improvement
- Must open and close precisely around beampipe
- Based on TimePix3 prototype
  - 130 nm CMOS, 8 metal layers, 170 M transistors
- Binary or ToT readout (being decided)
  - Simplicity vs flexibility
- 2 x 4 super pixels likely, 55 x 55 um^2 pixels
- 200 um thickness for sensor and ASIC
- CO_2 micro-channel cooling (development)
- Thinning of the RF foil
- Improving clusterisation algorithms; The VELO reconstruction is fast enough to allow a full 3D pattern recognition in HLT
- Focusing on the D in R&D; TDR submitted in Nov 2013

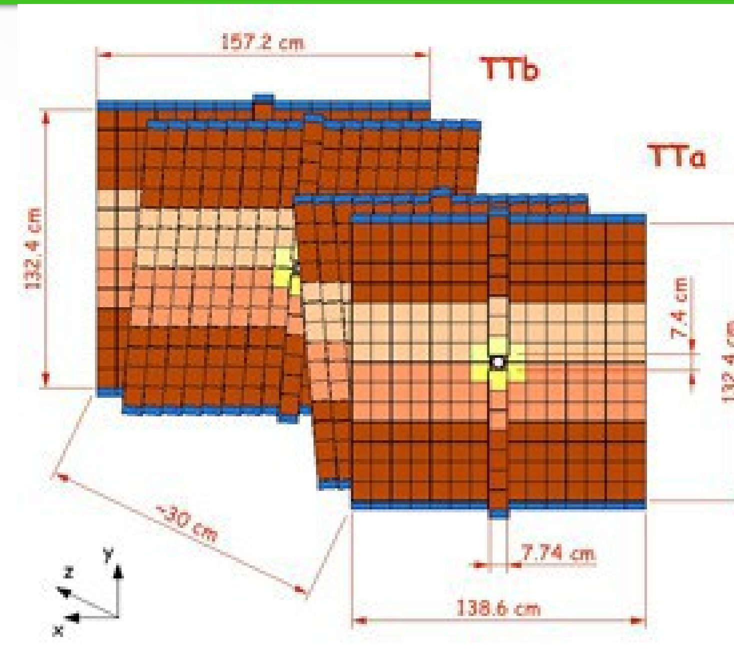
1x3 pixels example

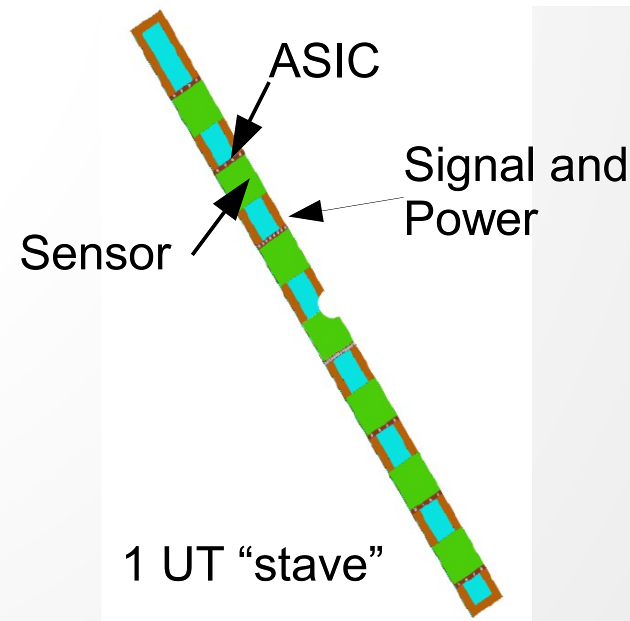




TT Upgrade

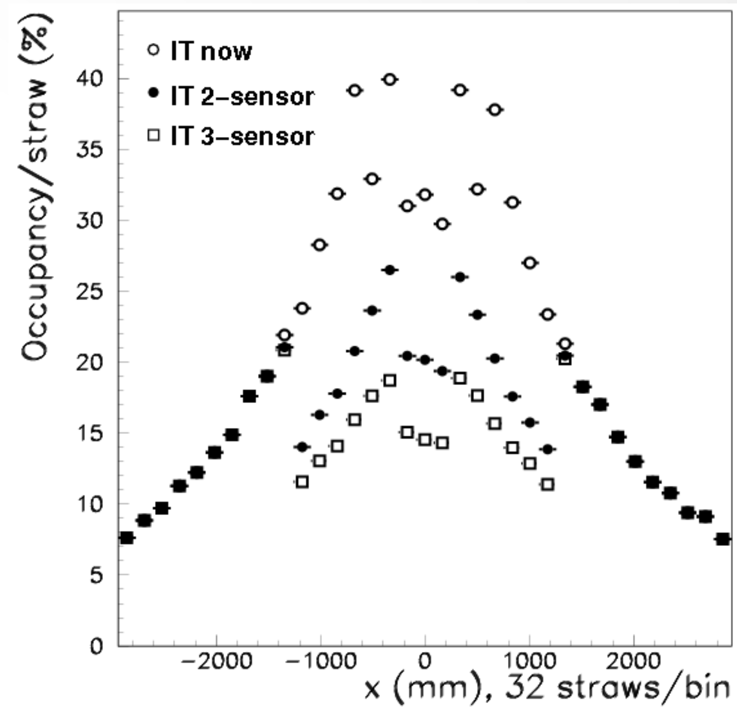
- TT Upgrade = UT (tracker) @ 40MHz
- 4 planes of silicon strip detectors (X-U-V-X) at 5^0
- Improved small angle acceptance, better segmentation, less material (<4.5% X_0)
- Cooled to -5C
- Must be able to open away from the beam pipe during “bake out”

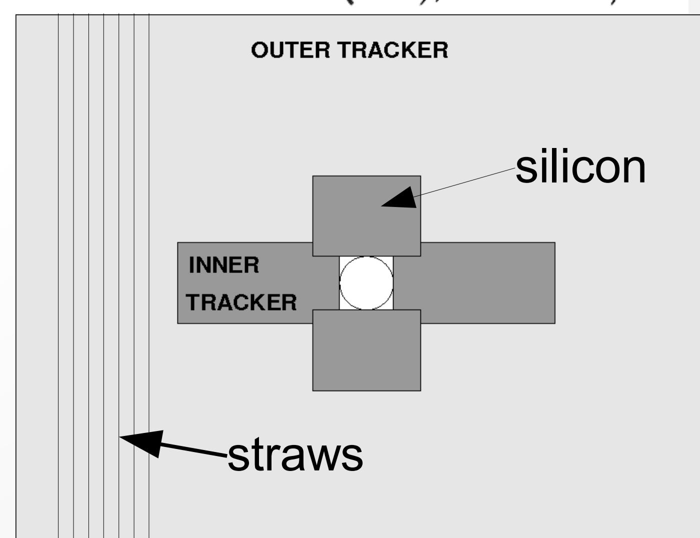




Outer (Inner) Tracker Upgrade

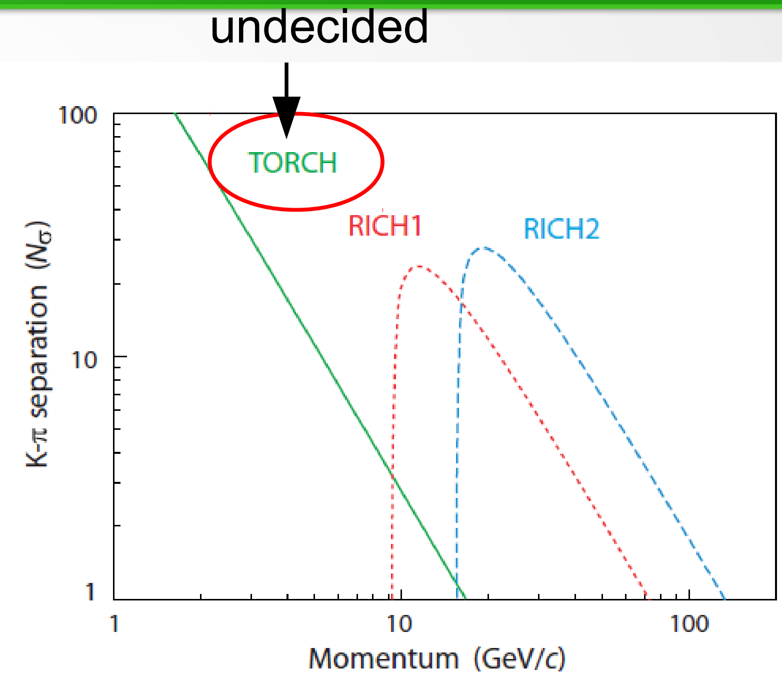
- Replace with 40MHz front-end electronics
- Occupancy in the OT becomes too large due to secondaries from the IT structure (40% with current IT at 2x10^32cm-2s-1)
  - OT is 5mm straw drift tubes
  - OT can handle ~25%
- Either replace make the new IT larger (4x area) and reduce the OT (rebuild 96 5m straw modules)
- Reduce the IT detector material (lots of cables and cooling infrastructure in the acceptance)
- <u>OR</u> Replace (mostly) everything with scintillating fibres! See Part 2.

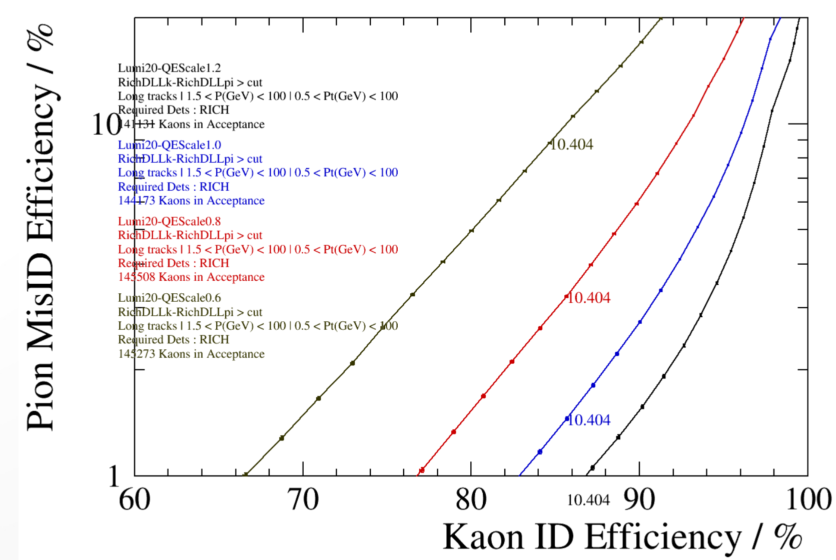




RICH / PID Upgrade

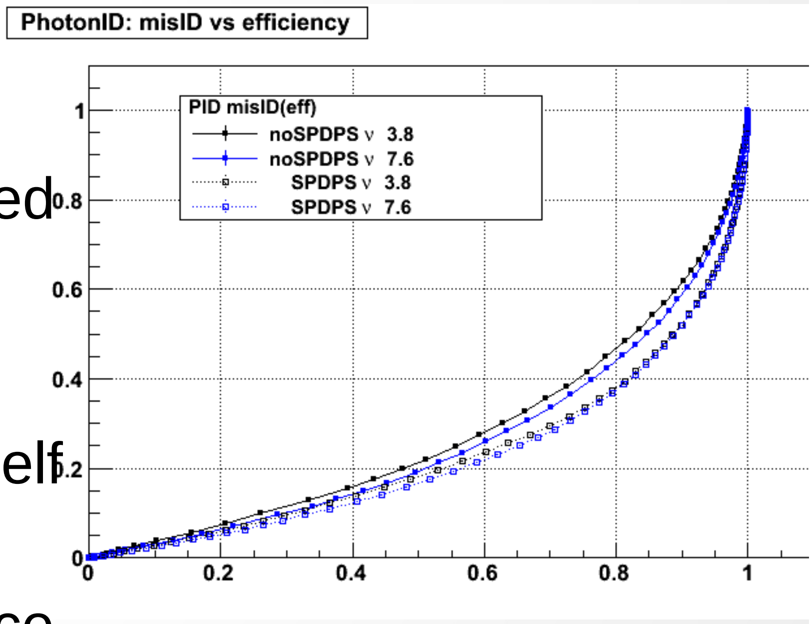
- Current HPD(pixel) and readout electronics are integrated (@ 1 MHz)
  - Upgrade: replace all with 3700 MA-PMT @ 40MHz; similar granularity
  - New mechanical housing
- Remove the aerogel from RICH-1 due to occupancy (sacrifice low momentum resolution); only C4F10
  - RICH-2 stays as CF4
- Radiation damage degrades gain of MA-PMT but gain plateaus eventually
- Optimizing PMT placement and optics
- TDR submitted in November 2013





Calorimeters

- Only need to replace the electronics @ 40 MHz
- PMT gain reduced to allow acceptable anode gain during high luminosity running
- Front-end electronics must have 5x higher gain (analog noise issues)
- Scintillating Pad Detector (SPD) and the Preshower (PRS), lead absorber will be removed
  - some loss in particle identification performance at low pT,
  - improved energy resolution in the ECAL itself
  - calorimeter calibration will be more straightforward without the SPD/PRS in place.
- Central cells replaced in LS3 due to radiation damage

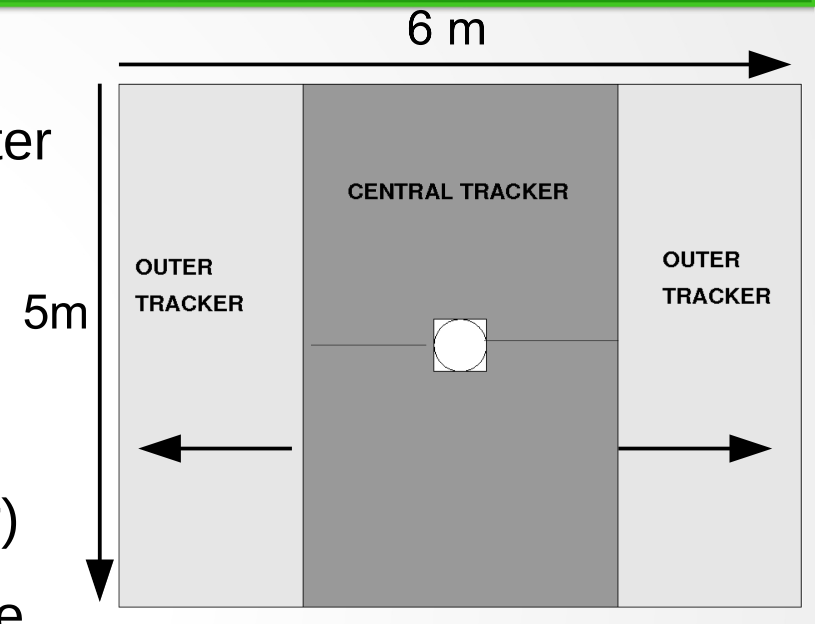


Muons

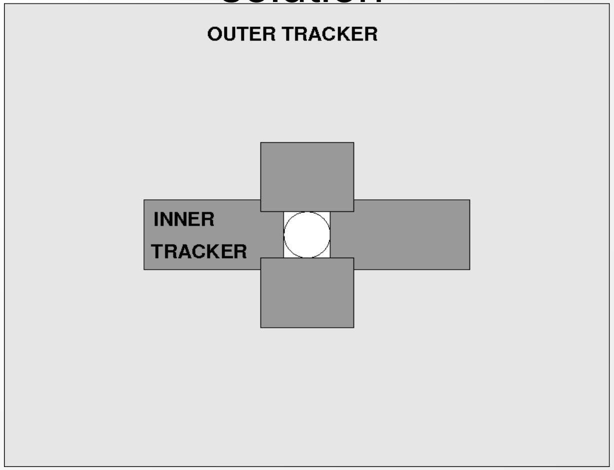
- Front-end is already 40MHz to L0 trigger; switch to LLT
- Remove M1 station (M2-5 remain); won't contribute
- studies with real data indicate that the measured particle rates in the muon system scale linearly with luminosity and agree well with simulation (see previous trigger yield plot pg. 5)
- Minimal changes to detector (maybe shield M2 more)
- Aging studies
- TDR submitted in November 2013 (planned)
- Phase 2 (> LS2): new high readout granularity detectors for high-luminosity regions

Part 2: The SciFi Tracker

- Replace the Inner Tracker and (most of) the Outer Tracker with a scintillating fibre (SciFi) based tracker
- Same X-U-V-X layer scheme; 12 layers total divided in 3 stations
- Reduced material budget (1 SciFi <= 1 OT layer)
- 65 um X-position resolution over the whole plane (OT = ~200um, IT~ 50um)
- Requires developing a new technology (no one has built a fibre tracker this large in this environment)
  - **Not an off-the-shelf technology**
- ~30% more expensive to replace to whole OT



Large IT becomes backup solution



The SciFi Tracker

<u>Participating groups:</u>

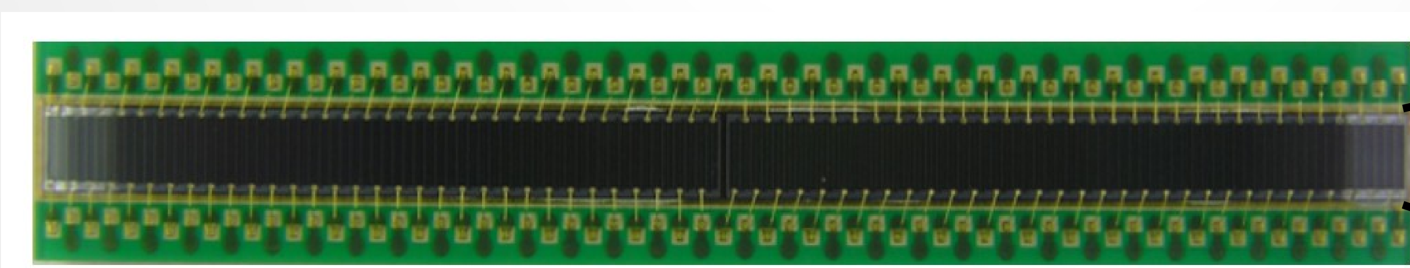
- Brasil (CBPF) [electronics test benches]
- France (Clermont-Ferrand, LAL, LPNHE) [electronics, simulation]
- **Germany (Dortmund, Heidelberg, Aachen*, Rostock*)**
  - **Active detector development and construction (SciFi panels)**
  - **simulation**
- Netherland (Nikhef) [design, test benches, SciFi panel construction, simulation]
- Russia (PNPI, ITEP, …) [cooling, fibres, panels]
- Spain (Barcelona) [electronics]
- Switzerland (CERN, EPFL) [cooling, electronics, fibres, simulation]
- UK (Imperial College) [engineering]

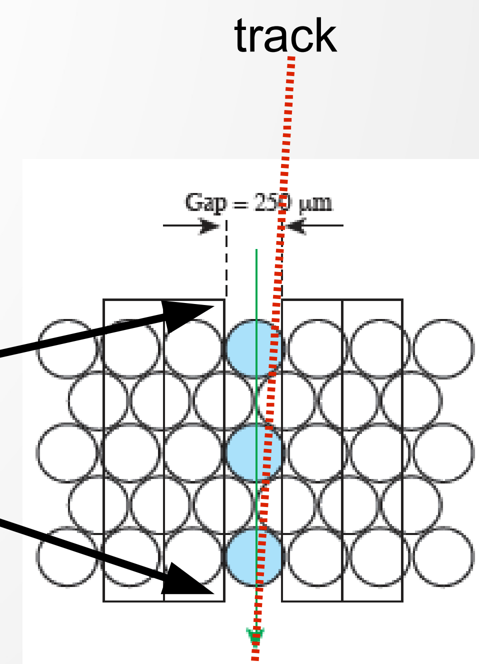
- TDR to be submitted in March 2014

What is a SciFi detector?

- Based on PEBS balloon experiment 80cm modules
- A SciFi module consists of 2.5 m long ribbons (5-6 layers) of 0.250 mm diameter scintillating optical fibres (SciFi) with a silicon photomultiplier (SiPM) array readout (40 MHz).

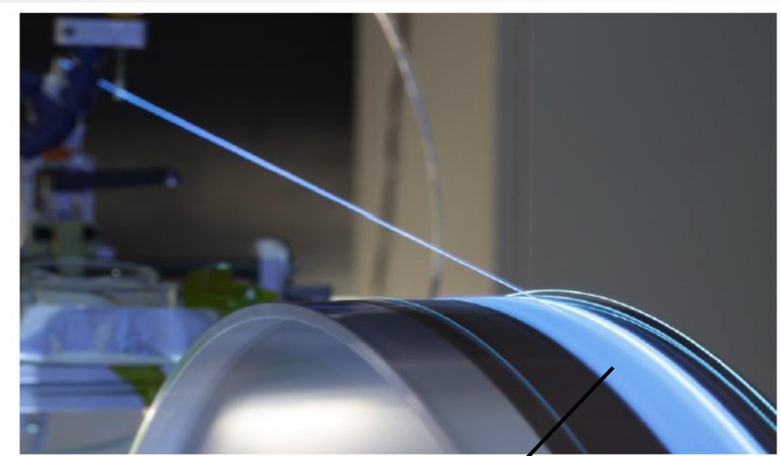
- A full SciFi = A single technology to operate; little performance difference
- Uniform material budget (similar to OT) over the acceptance
- Fibres act as active material and signal transport
- Fine channel granularity of 250 μm (low occ.)
- x-position resolution of 50 – 75 μm

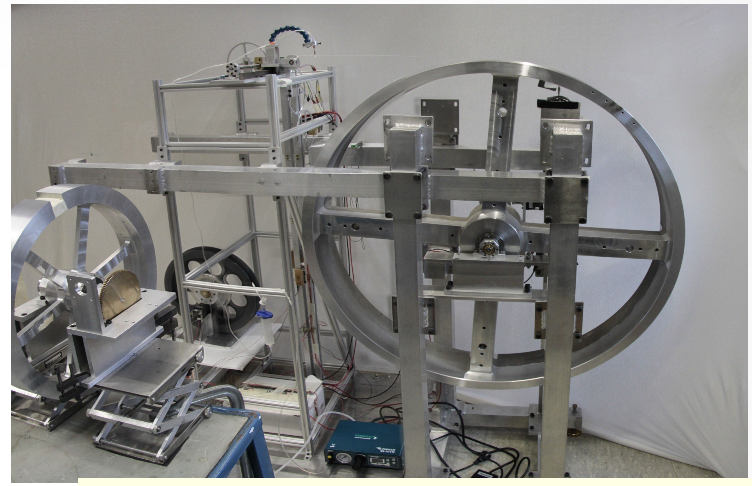




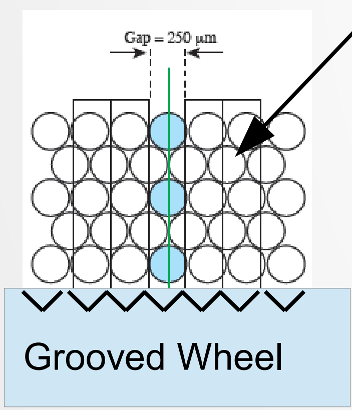
128 x 0.250 mm SiPM channels

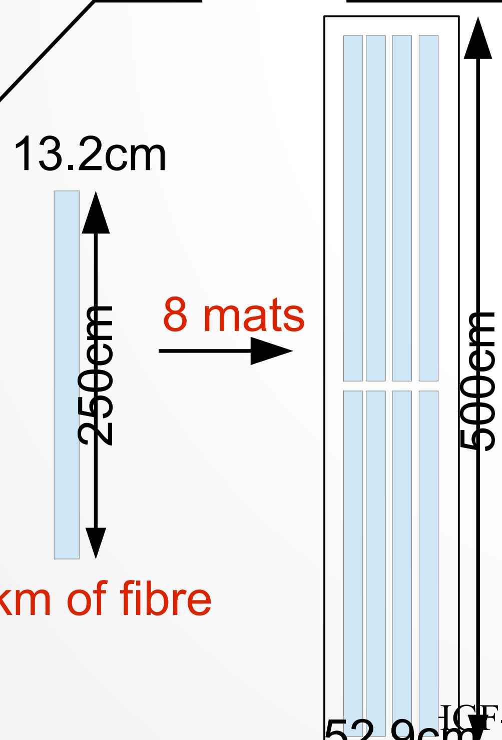
Building a module





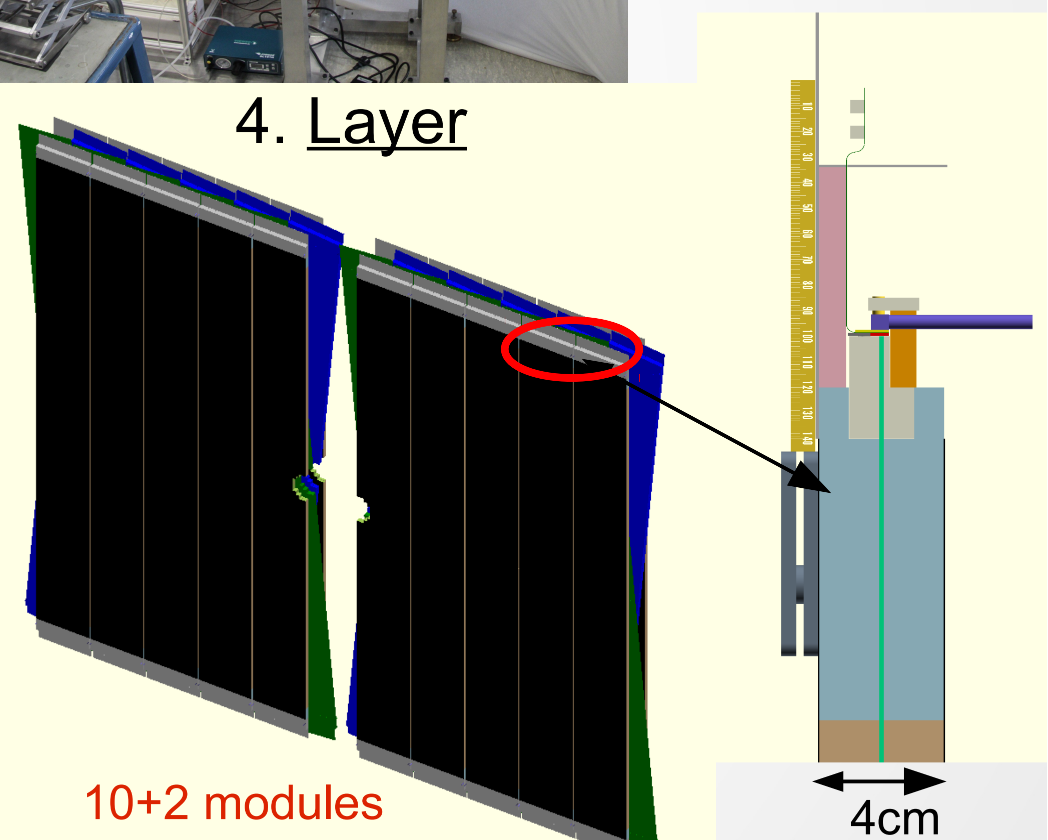
1.Winding 2. Mat 3.Module





6.6 km of fibre

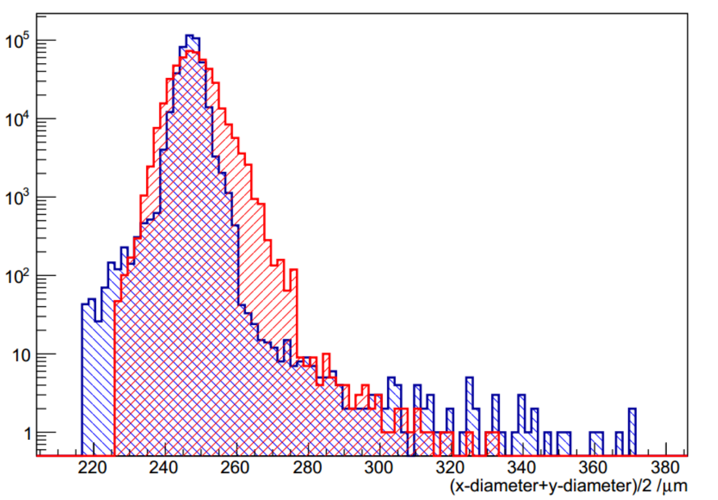
4. Layer

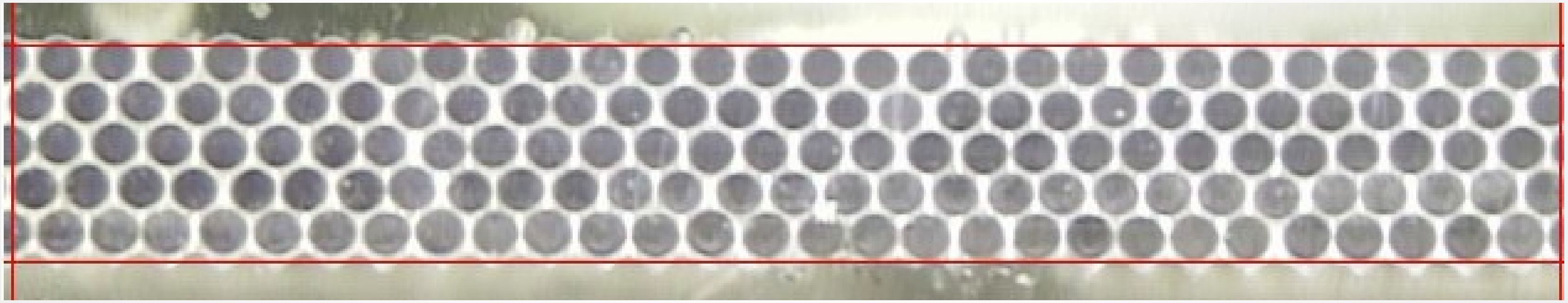


~8-10 x 10^6 m of good fibre for 3 stations

Fibre Mat Quality

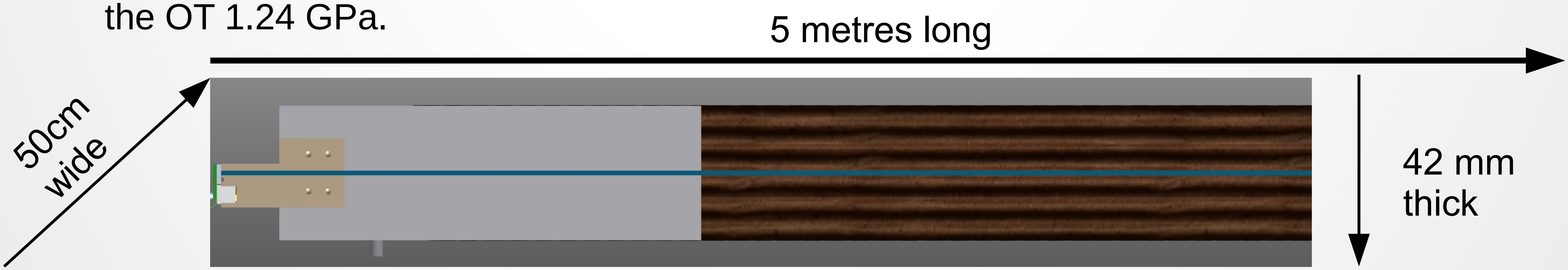
- A lot of fibre winding work by Dortmund and Aachen
- 250um fibres tend to have >280micron blobs (1/km) a few cm long
  - 1 layer = ~1.3km of fibre
  - Impacts ribbon/mat packing and alignment, causes “jumps”
- RMS of typical fibre spacing increases from 8um in the 1st layer up to 16 um in the 5th





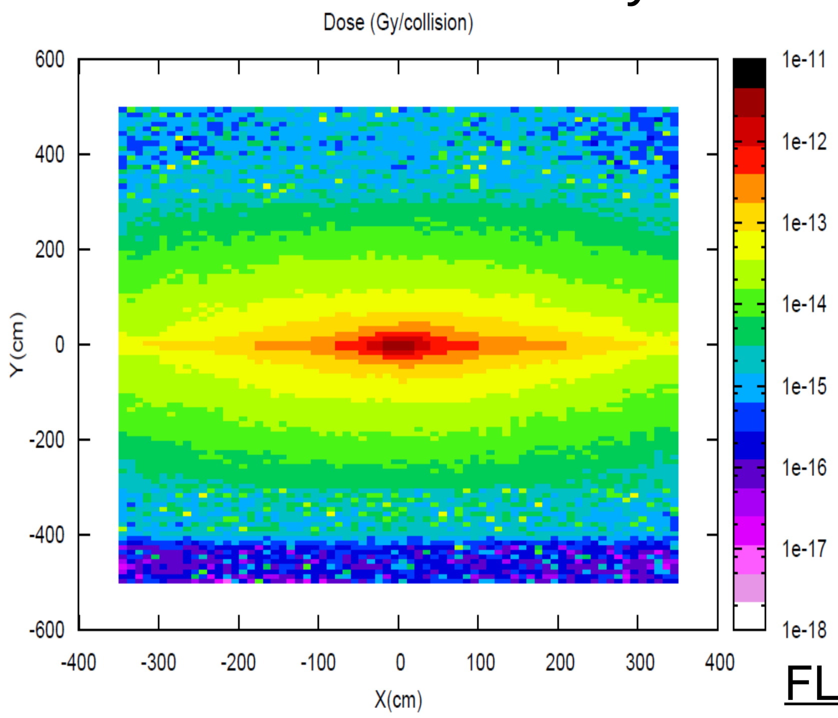
Panel construction: HD, DO, AC

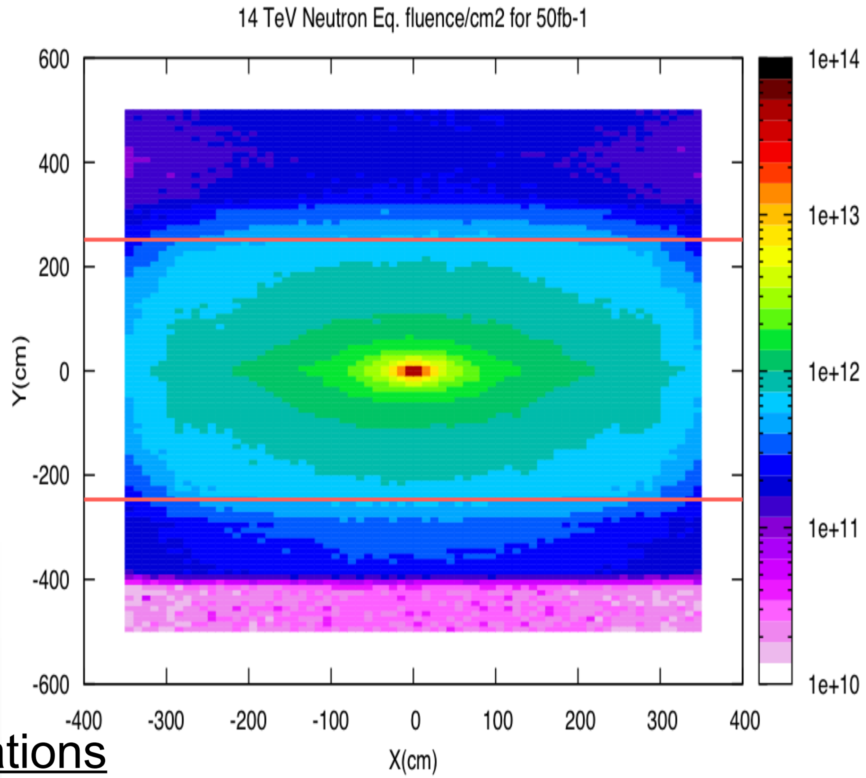
- The fibre mats are quite brittle and delicate
- Require “casting” in epoxy to produce a flat, protected surface
- A parallel cut better than 150 micron over 2.5 meter defines the edges of the mat
- Finished detector panel must be rigid and flat
  - X-position better than 75 micron; Z-position better than 300 micron from early simulations
- Sandwich the module between 2 x 2cm of honeycomb and carbonfibre skins
- A template aligns 8 fibre mats to the panels and defines the flatness of the panel
- Less material: Prototype panel has 3.18 kg/m^2 compared to the OT 3.92 kg/m^2, no IT
- Stiffer: Improved Young's modulus of the prototype panel = 1.73 GPa compared to the OT 1.24 GPa.



Radiation Viability

- Viability assessment in February 2013. (Referee's report: https://twiki.cern.ch/twiki/pub/LHCb/UpgradeSciFiTracker/SciFiViability_RefereeReport.pdf)
- One of the first questions: Are the scintillating fibres and SiPMs radiation hard enough for the upgrade?
- Maximum ionizing dose of ~35 kGy near the beam pipe in the SciFi after 50fb^{-1} (FLUKA)
- Neutrons: ~10^{12}n/cm^2 at y=±2.5m



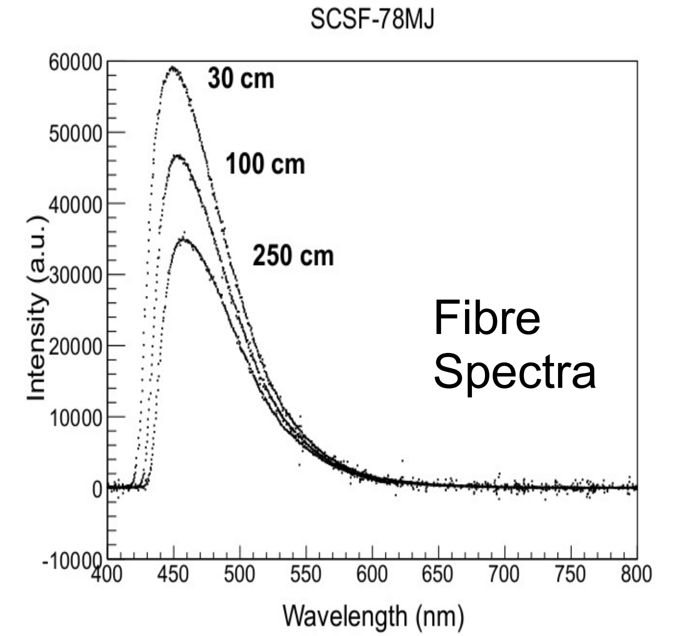


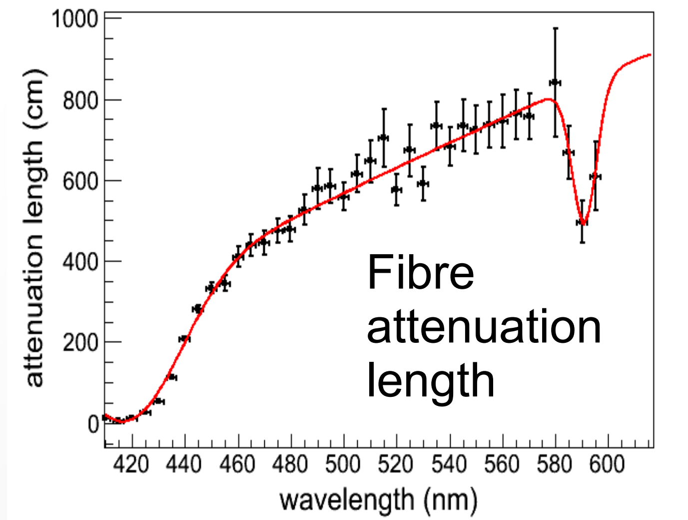
FLUKA Simulations

Fibre Basics

SiPM PDE

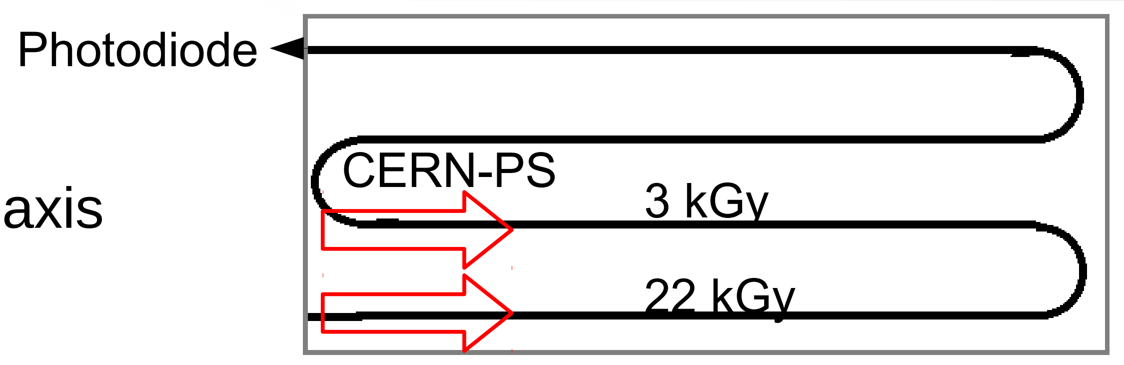
- Two main suppliers: Kuraray and Saint-Gobain(Bicron)
  - Kuraray has historically better quality
- Basic properties (Kuraray SCSF-78MJ):
  - Best properties available on the market
  - Wavelength spectra matches photodetectors well
  - Fast decay time of 2.3 ns; ~6ns/m propagation time
  - Bulk attenuation length > 2.5m
  - Scintillating dyes shown to be radiation hard
  - light yield is "sufficient", 1600 photons/mm/MIP, Double clad (5.3% capture), expect >10 p.e.
- Known issues:
  - The polystyrene core of the fibre darkens with radiation damage (transmission loss); conflicting literature
  - The diameter of 0.25mm fibres shows "blobs" of diameters > 0.3mm

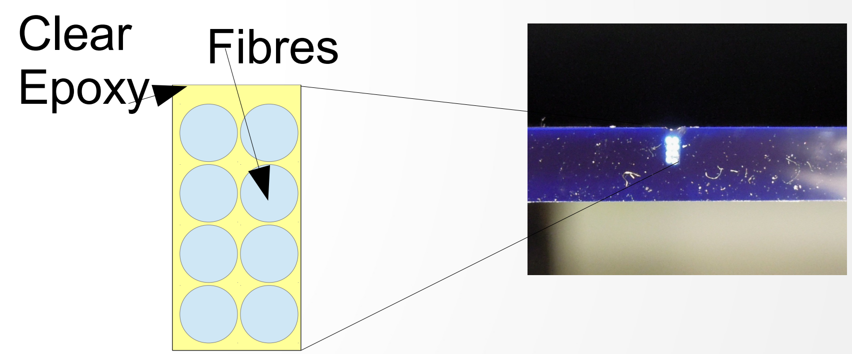


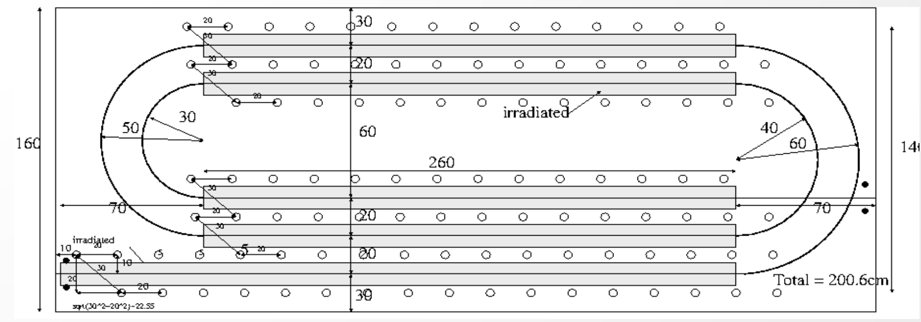


Fibre Radiation Studies

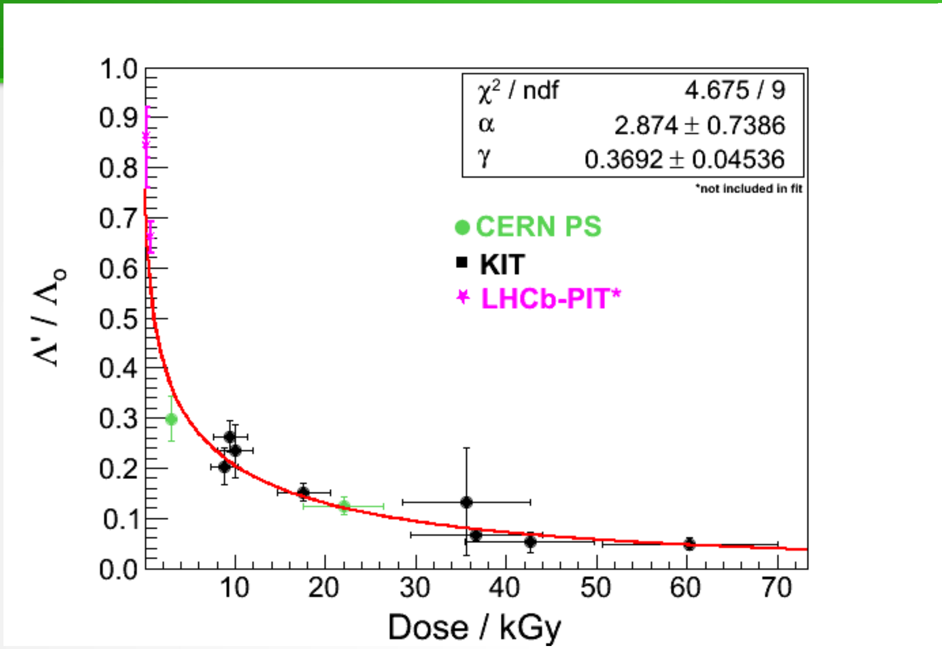
- CERN-PS with 24 GeV protons
  - 8 fibres 2.94m long
  - 22 kGy and 3 kGy doses
  - Proton beam parallel to fibre axis
  - UV LED and Sr-90 sources
- At KIT with 23 MeV protons
  - 6 fibres 1.94m long;
  - 5 x 6 fibres 0.4m long
  - 9 kGy up to 63 kGy
  - Protons perpendicular to fibre axis
  - UV LED source
- *Insitu* in LHCb pit (0.1 to 1 kGy)
  - larger uncertainties in results
  - Results are comparable

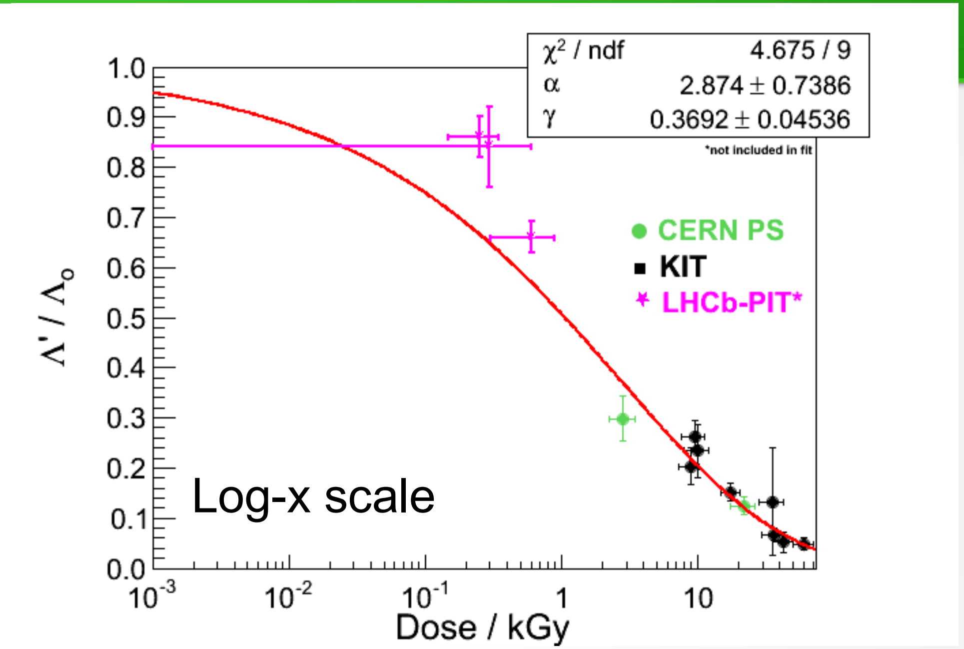




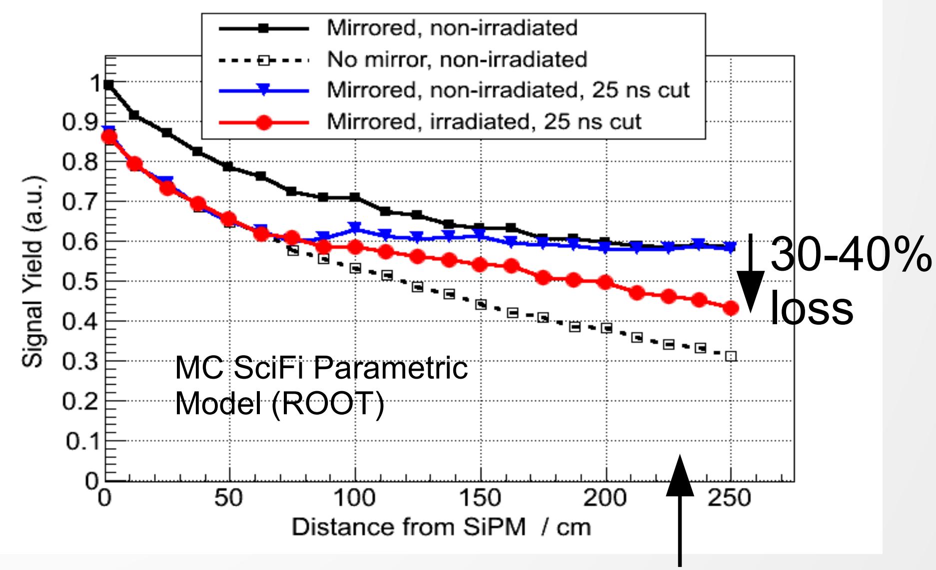


Fibre radiation studies





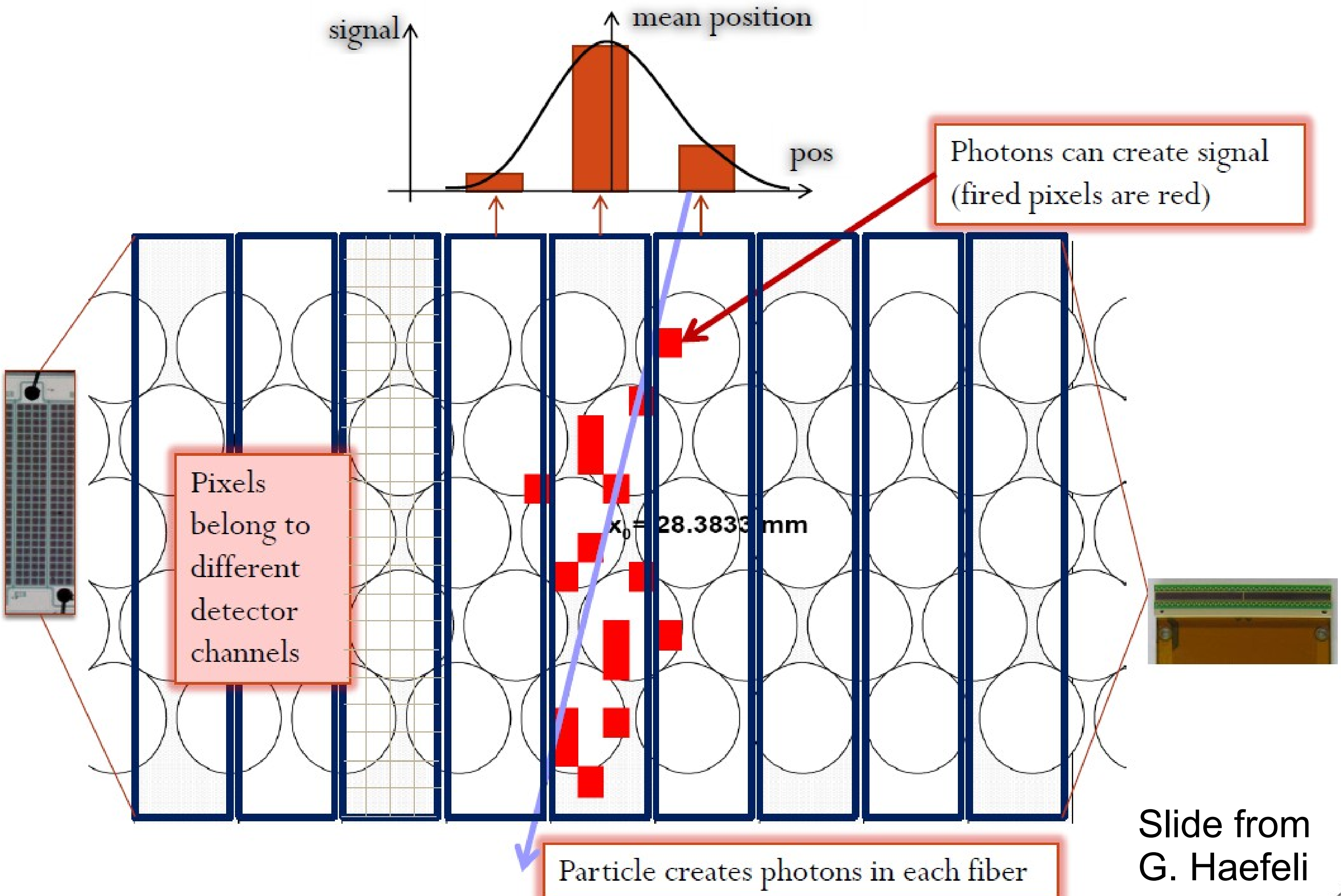
- Rapid loss of transmission at low doses
- Expect 30-40% loss in signal amplitude from the most damaged regions
- A shift in the wavelength spectrum peak to a higher value
- Annealing observed in KIT measurements, but not CERN-PS



FLUKA rad. dose map folded in

Detector signal overview

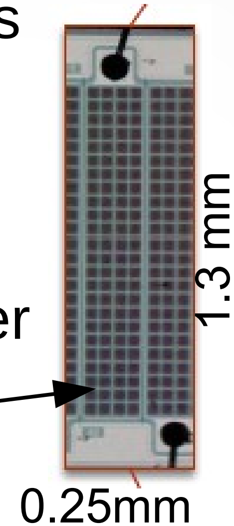
Average cluster size = 2
60% have 2 channels

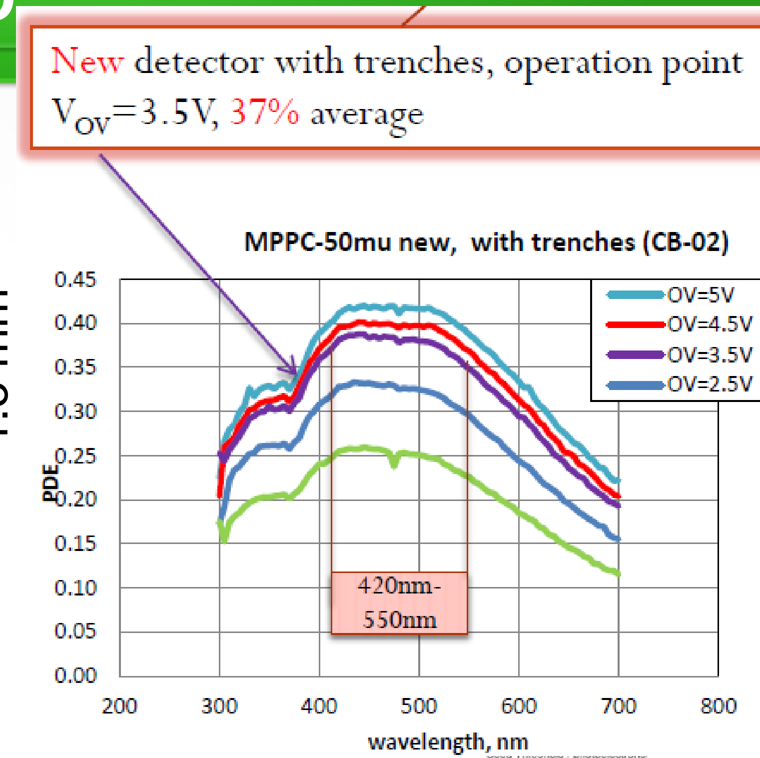


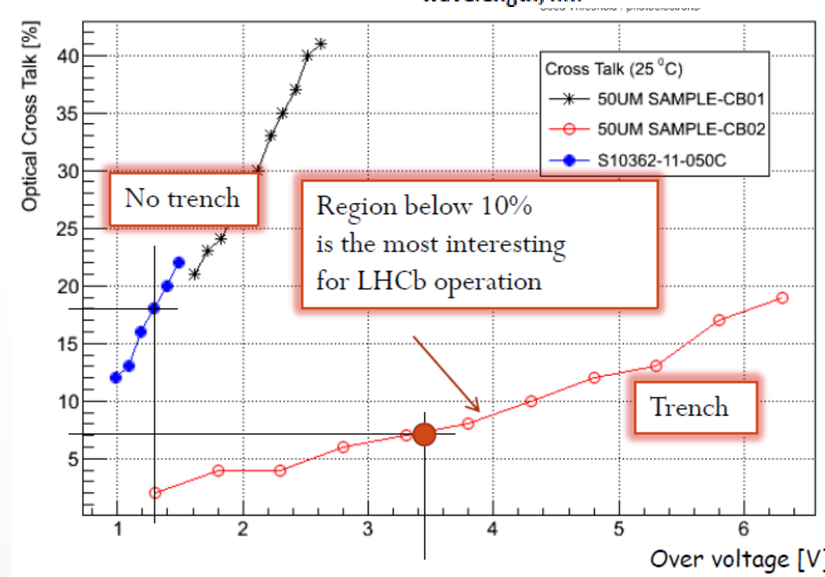
Slide from G. Haefeli

SiPMs and Signals

- Ribbons produce ~11.3 photoelectrons with current SiPM technology (when mirrored at 80%); 30% PDE, 18% crosstalk
- Crosstalk and thermal noise are a killer
  - Pixel crosstalk will create clusters above 2 pe threshold
  - Radiation damage will increase single p.e. thermal noise
- Working with two companies, Hamamatsu and KETEK (Munich, DE) to develop better SiPMs
- Simulation exists which models noise, crosstalk, gain and radiation effects
- 4608 128-channel SiPM arrays

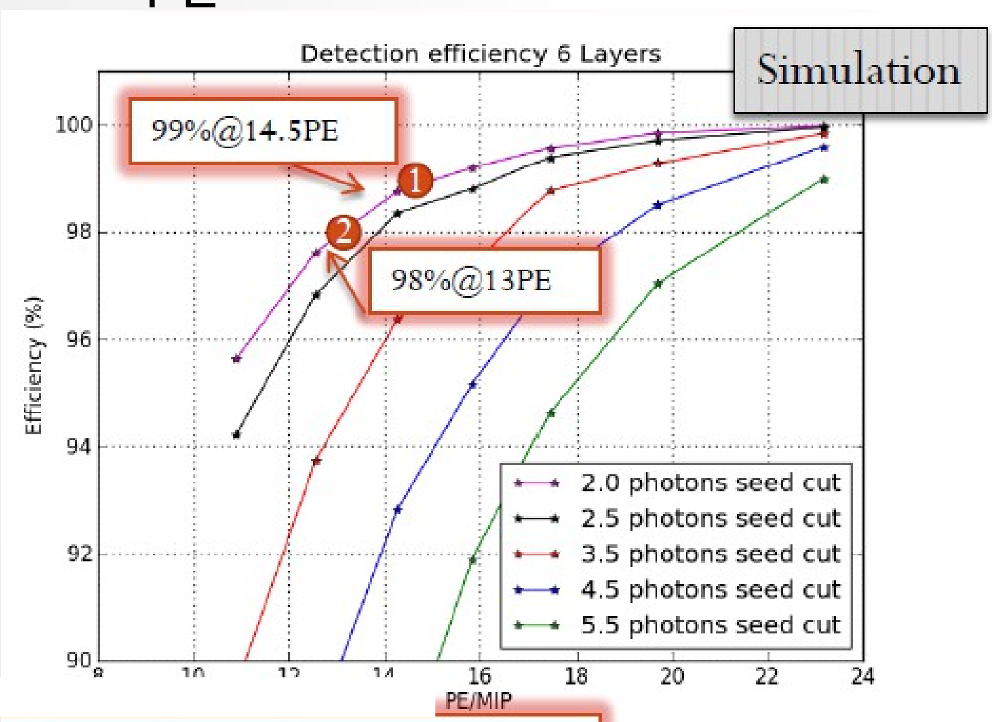


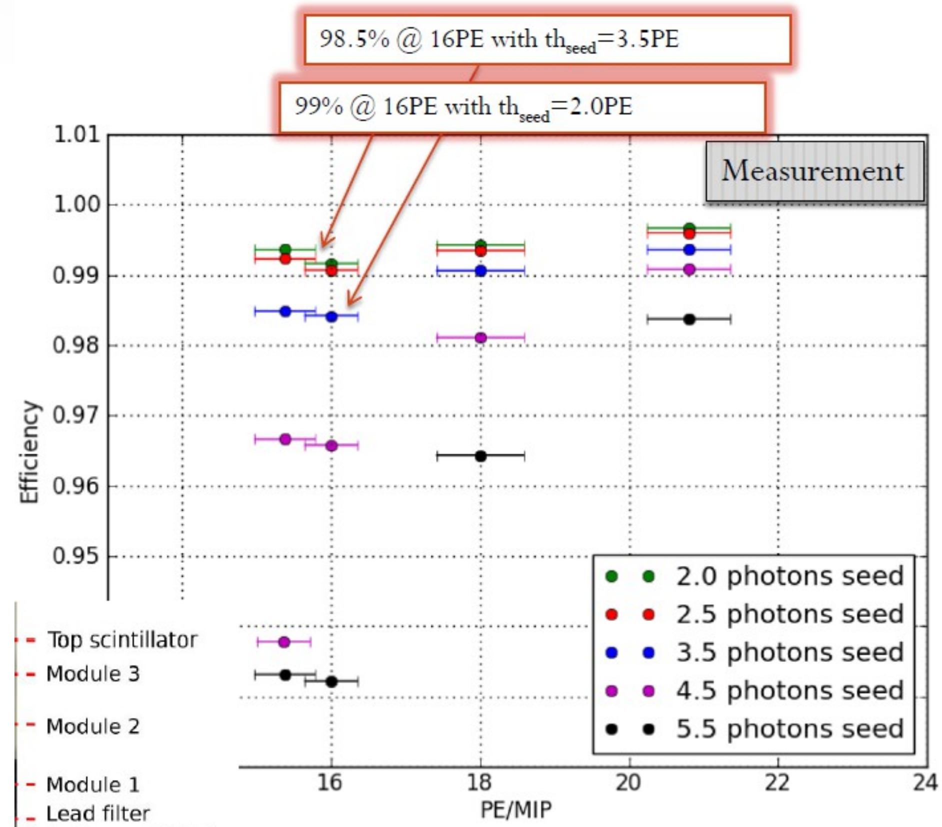




Hit Detection Efficiency

- Expected signal after irradiation
  - 5 layers = 10.8 PE
  - 6 layers = 13 PE
- 5 layer fibre mats = 99% at 16PE, 95.5% at 10.8 PE
- 6 layer = 99% @ 14.5PE, 98% at 13 PE

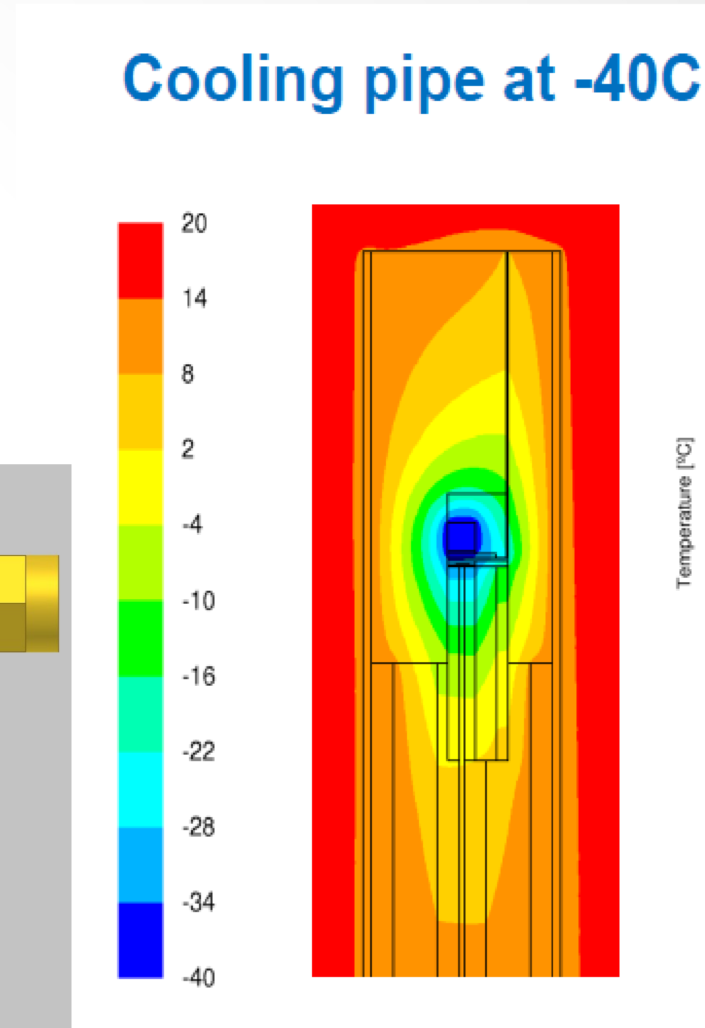


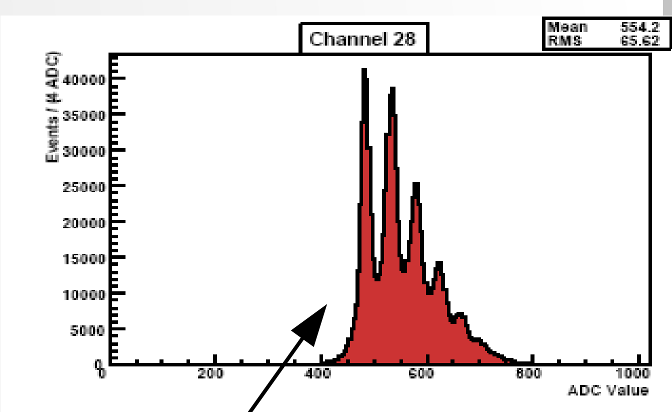


Non-irradiated fibre mats and SiPM measurement

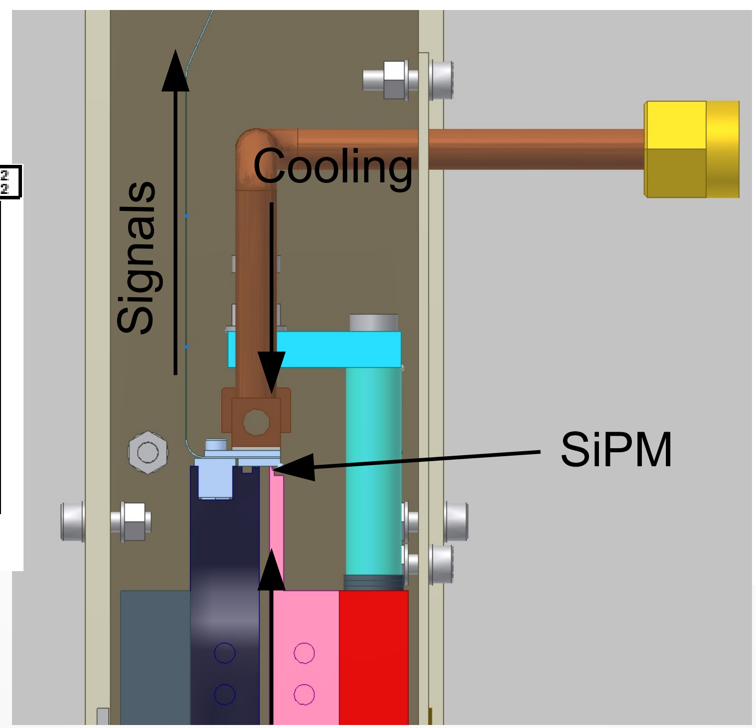
Cooling

- To achieve low enough noise rates, the SiPMs must be cooled to -40C → -50C
- Baseline solution is single-phase liquid cooling; heat load is not a problem
- Problems with condensation and frost, 144m of detectors to cool





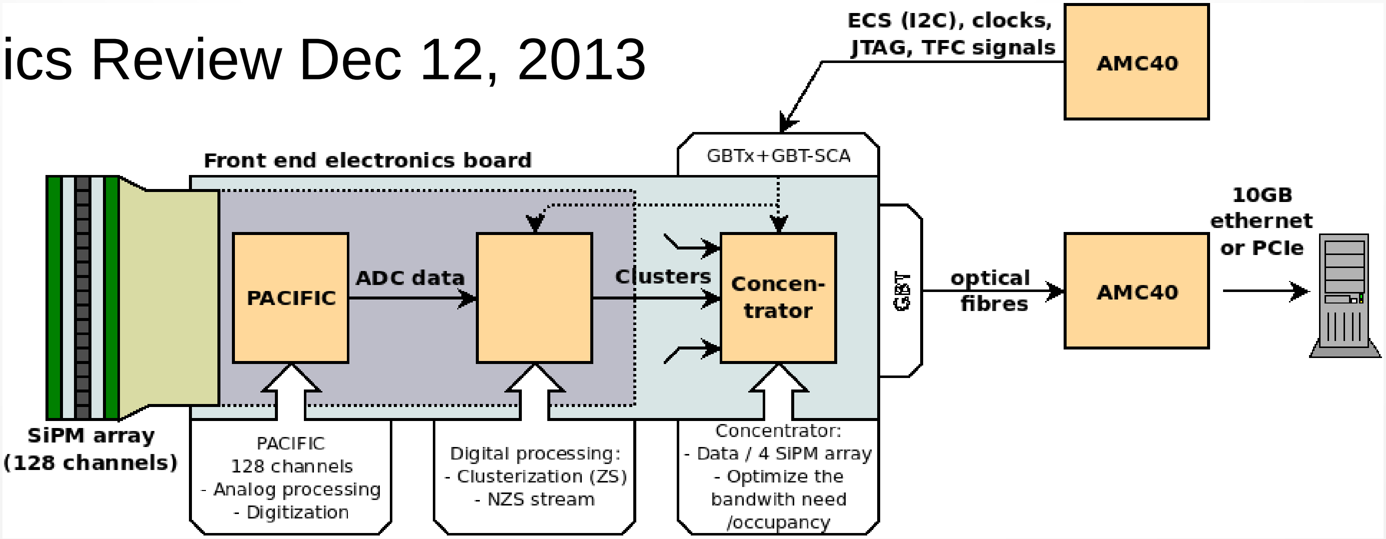
Irradiated SiPM noise at -40C



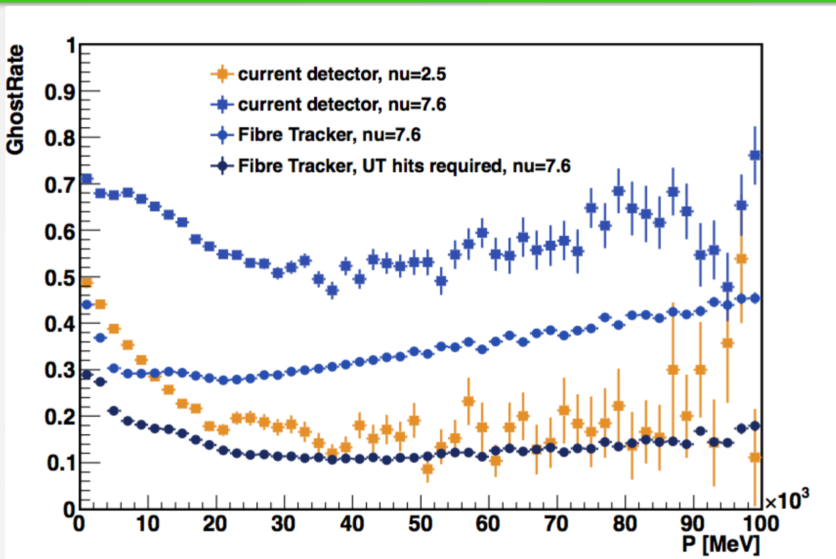
Fibres

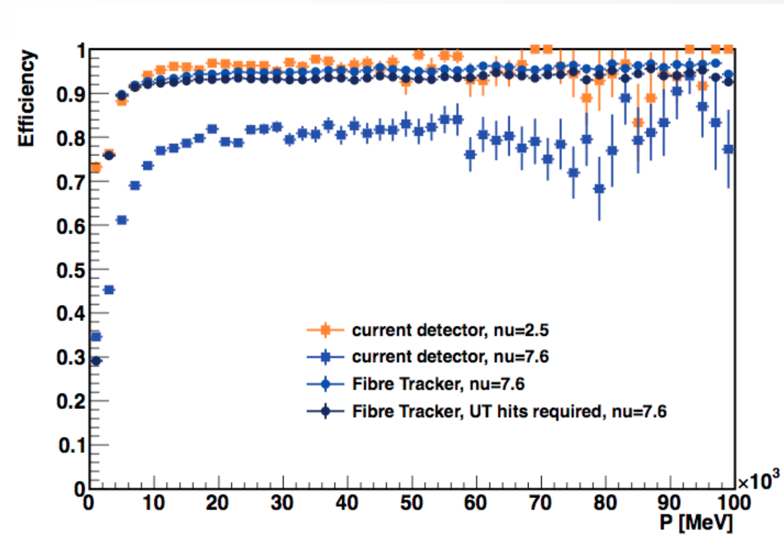
Readout Electronics

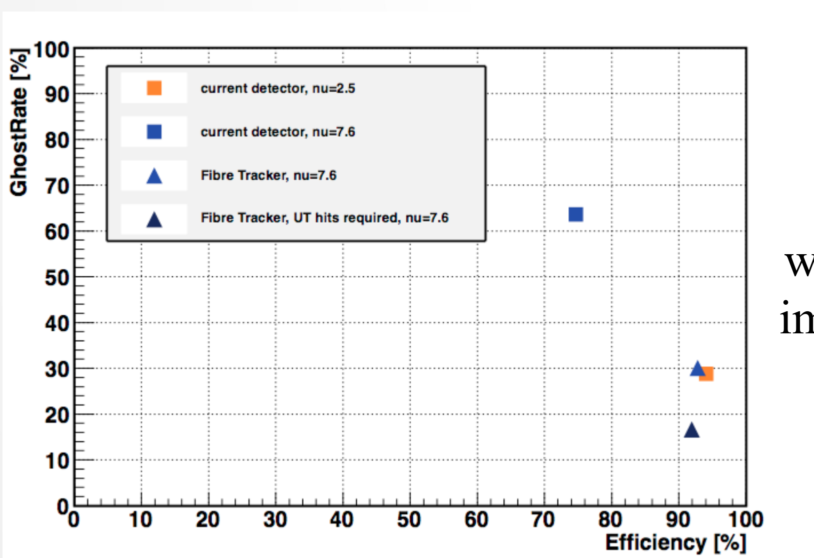
- 128 channel PACIFIC ASIC preamplifier and shaper (~10ns shaping time) for the analog processing and digitization
- FPGA for clusterisation and zero suppresion
- 590k channels
- Maximum mean occupancy/SiPM array(128ch) at L=2 x $10^{33}cm^{-2}s^{-1}$: 2.5 clusters
- Compute the particle hit position on the FE board (no ADC data in the Zero-Suppressed stream)
- Electronics Review Dec 12, 2013



Tracking Simulation







Comparison of the current detector with the Upgrade detector show **significant** improvements in the tracking efficiency and and the ghost rate reduction.

Performances remain good when running at $2 \times 10^{33}\ cm^{-2}\ s^{-1}$

Slide from Y.Amhis

Conclusion

- The Upgraded detectors of the LHCb will provide for a significant reduction in measurement uncertainties in the physics program
- The new precision will allow for the boundaries of BSM physics to be constrained further in rare decay searches
- There are still challenges to be met in the design and construction of the tracking detectors, but solutions are foreseen
- Germany will play a leading role in the SciFi tracker for the LHCb upgrade