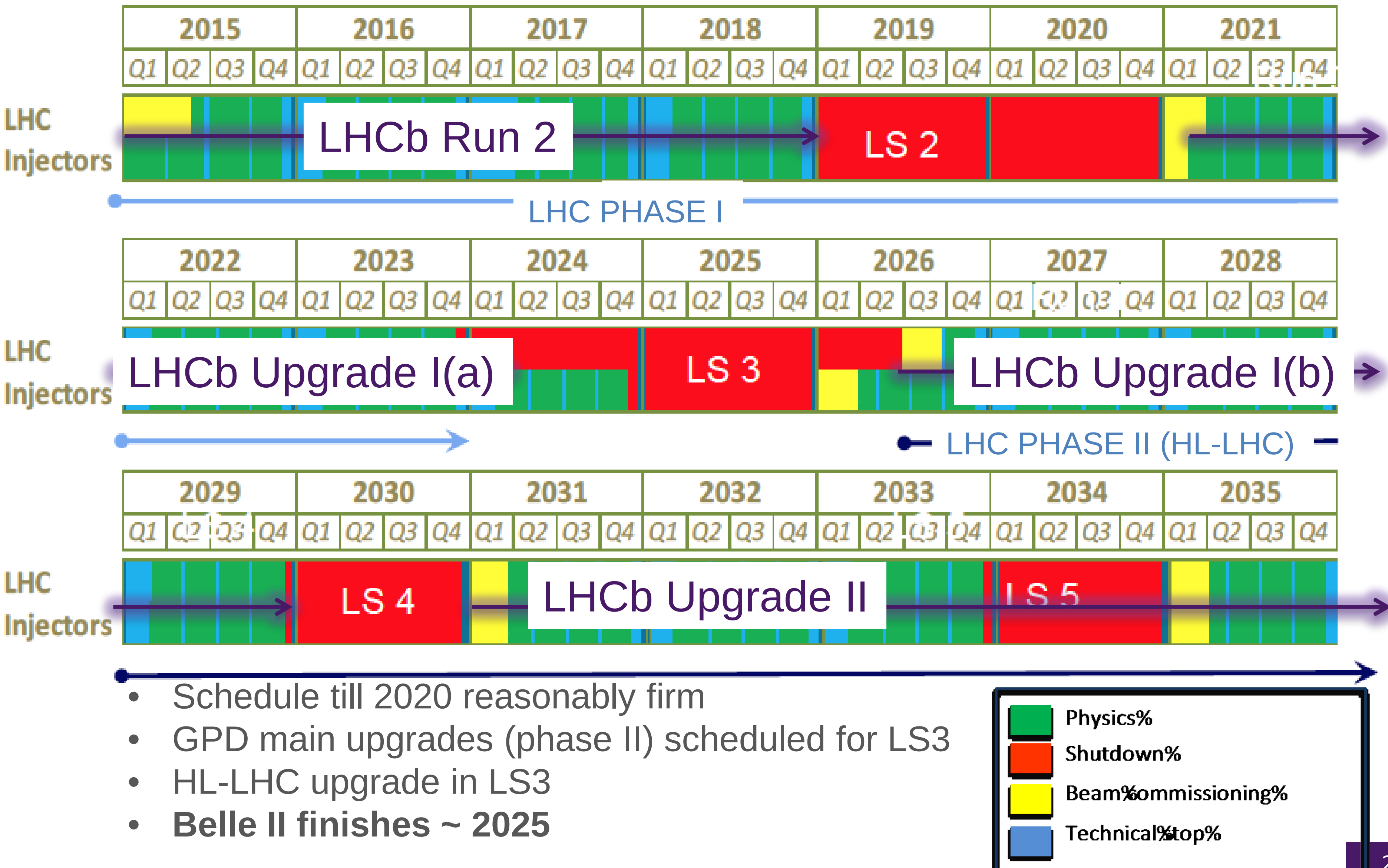
Phase II – Tracking:
What is the light at the end of the LHC tunnel ?

A very short introduction

Slides by Chris Parkes

LHC Schedule & LHCb



- Schedule till 2020 reasonably firm
- GPD main upgrades (phase II) scheduled for LS3
- HL-LHC upgrade in LS3
- **Belle II finishes ~ 2025**

Tracking Environment during phase II

- Instantaneous Luminosity $L=2x10^{34}$ cm^{-2} s^{-1}
- Average number of visible interactions per bx $\mu=50$
- Charged particles inside acceptance 1500-3500
- Challenges:
  - matching of upstream and downstream tracks.
  - SciFi has no y-segmentation.
  - Fraction of ghosts in the SciFi rises rapidly
  - Occupancy
  - Matching ghosts (rise linearly with #PV)

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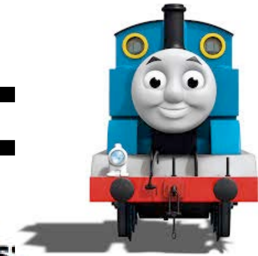
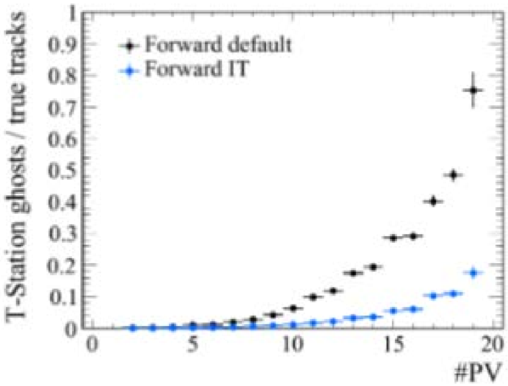
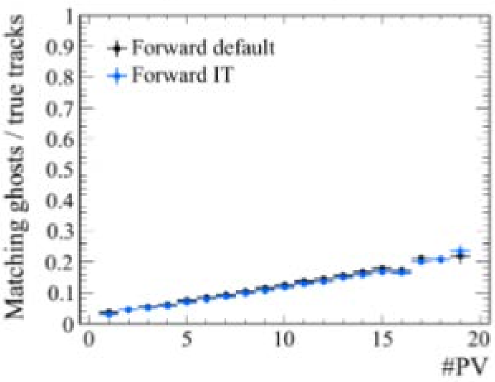


T-Station Ghosts:
wrong SciFi Hits



Matching Ghosts:
wrong matching to VELO



See Thomas Nikodem presentation at October TTFU

- Can we design a detector system to perform flavour physics in this environment ?
  - We don’t know yet.
  - EoI Identifies challenges and potential solutions

Phase I(b) – Consolidate & Enhance

- LS3: 2½ year shutdown in the middle of LHCb Upgrade I operations
  - Utilise this to consolidate upgrade experiment
    - Phase I(b), same luminosity
  - Enhance physics programme
    - Pathways to Phase II
  - Financial/ personnel resources limited

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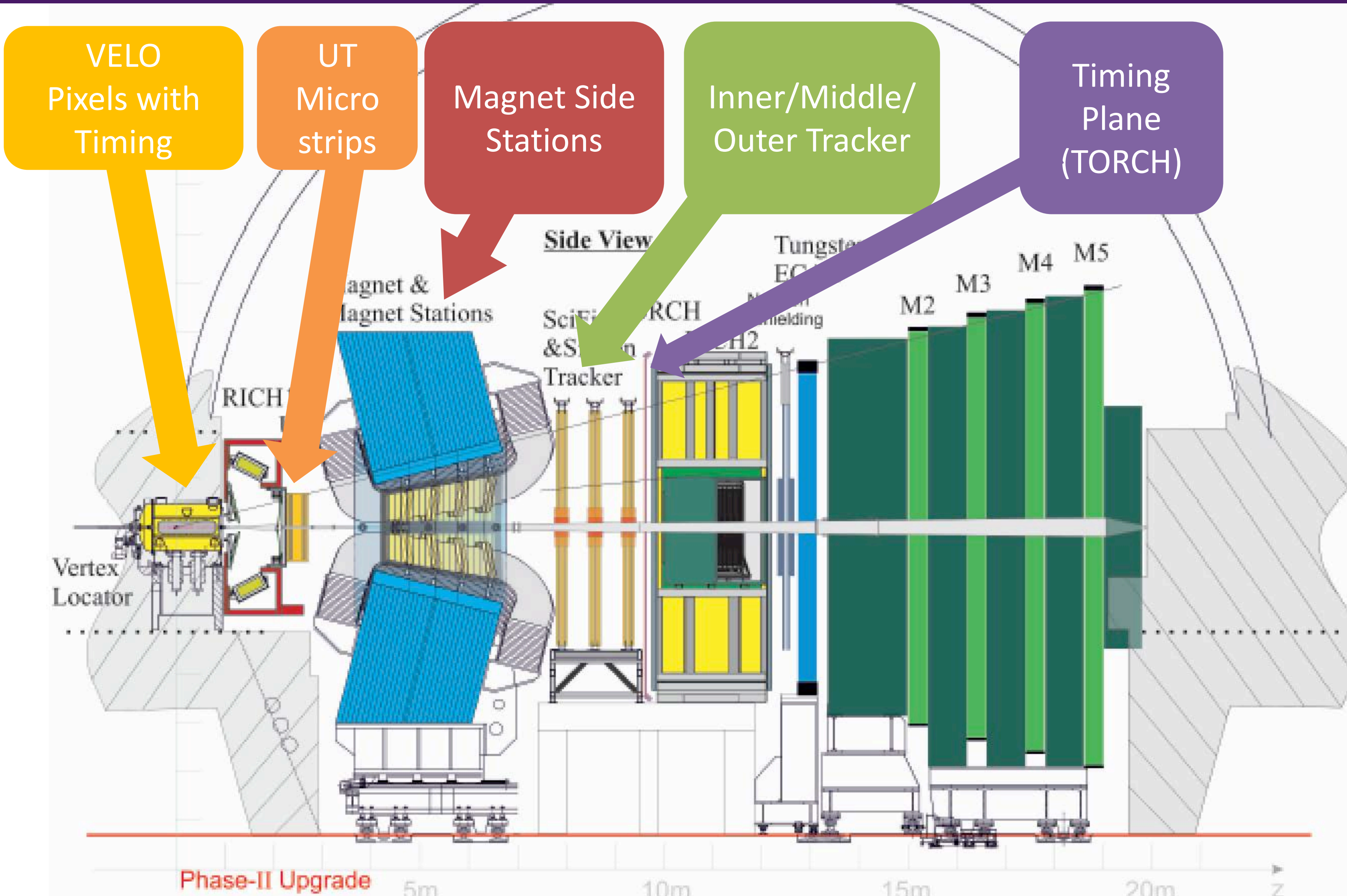
Same timescale:

ATLAS EXPERIMENT Upgrade Phase II

CMS Upgrade Phase II

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Phase-II Detector

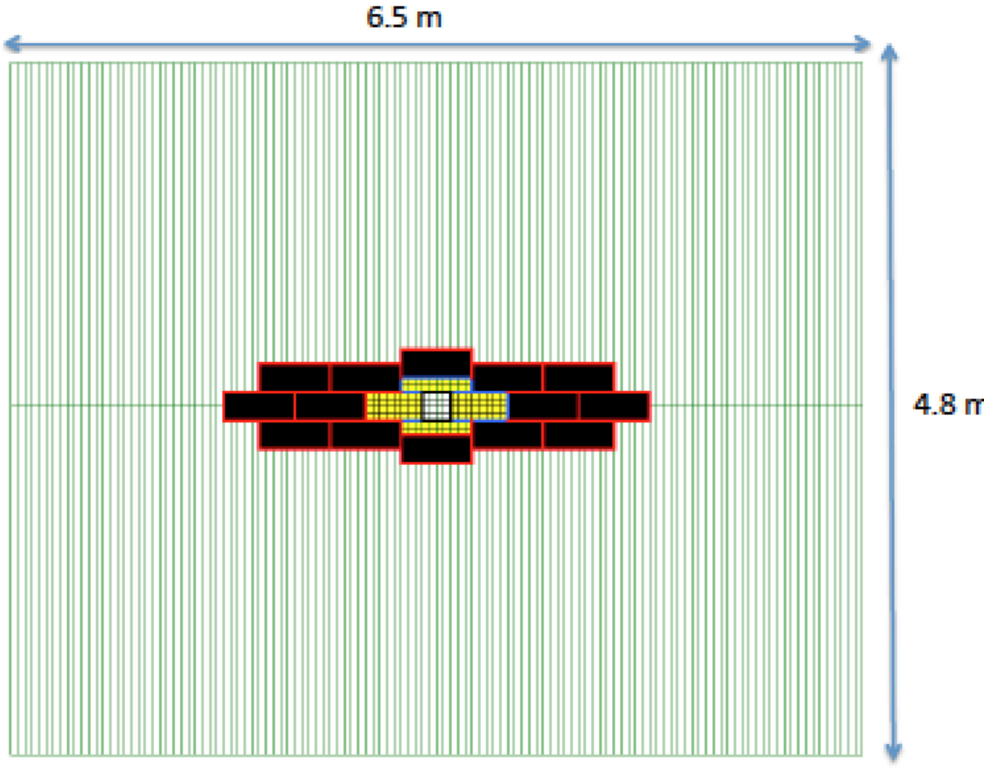


Tracking Evolution: Inner/Middle/Outer

	outer dimension	surface (12 layers)	installation
beamhole	$\varnothing$ 0.23 m		
IT	1.2×0.4 m^2	3.4 m^2	LS3
MT	3.2×0.8 m^2	16.9 m^2	LS4
SciFi, OT	6.3×5.0 m^2	380 m^2	LS2, LS4

- Large area tracker (360m^2)
- Cover area at affordable cost

- High y granularity in inner
  - Short Si strips (few cm)
- Medium y lengths in middle
  - Longer Si strips (10 cm)
- No y granularity in outer
  - Scintillating Fibres



The SciFi tracker(s) in Run 3, 4, 5, …

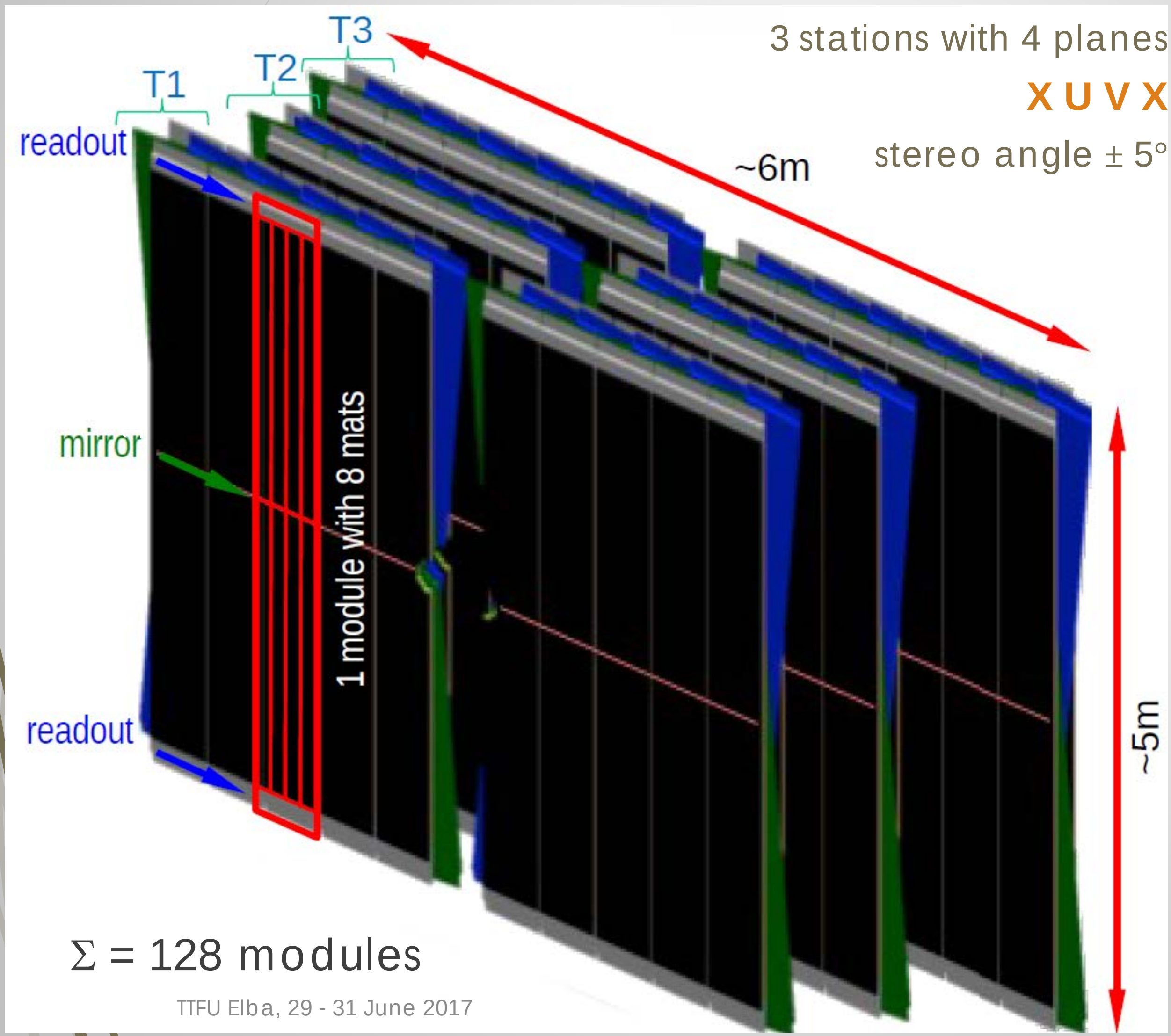
phases Ia Ib II

C. Joram for the LHCb SciFi team

TTFU Elba
29-31 May 2017

Run 3 (2021 – 2023)

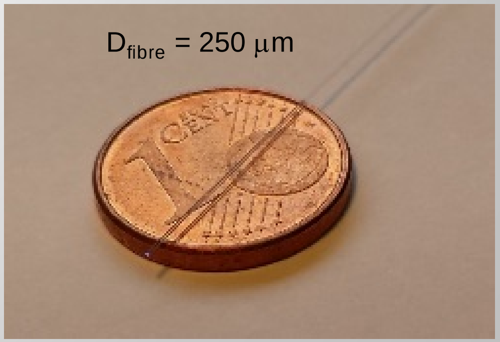
Design, challenges and status of the SciFi Tracker



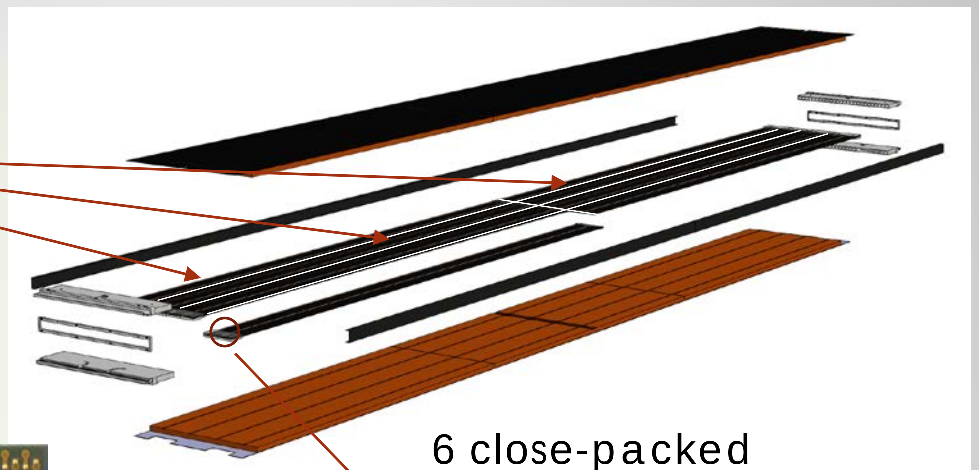
80 μm resolution over a total active surface of ~ 340 m²

12% X_0 total

~ 11’000 km of fibres

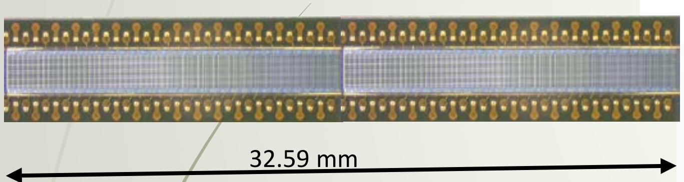


1 module (0.5 x 5 m^2)

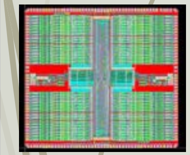


= 8 fibre mats

= 2 x 16 SiPM

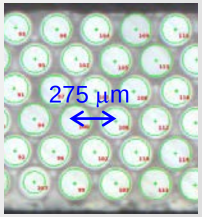


= 2 x 32 Pacific ASICs

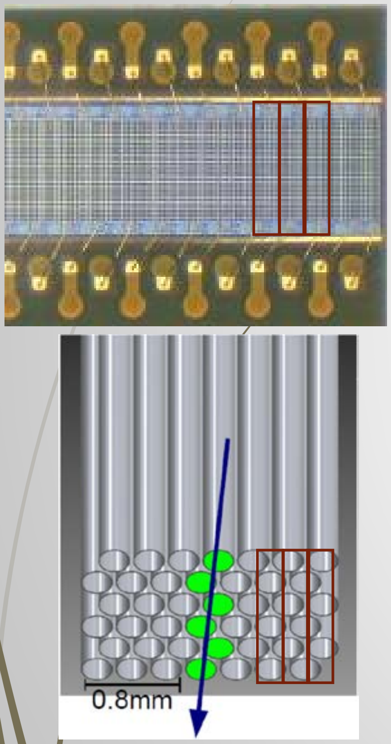


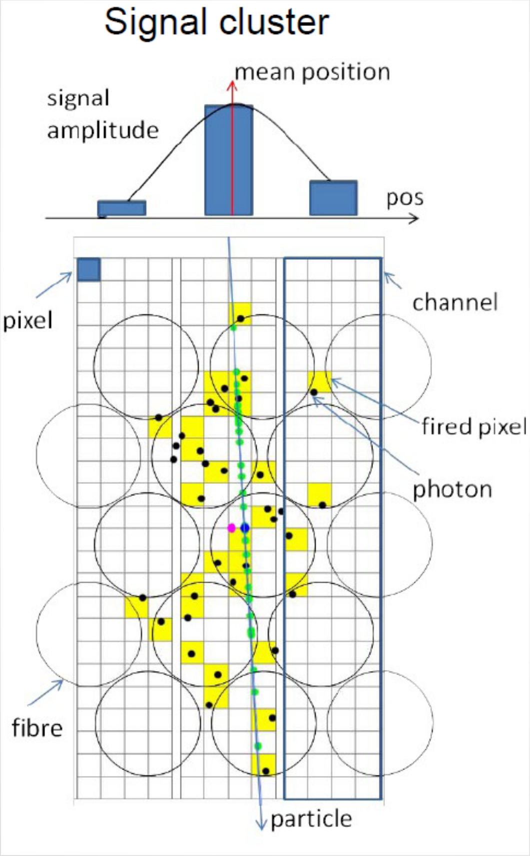
= 2 Cold Boxes

6 close-packed fibre layers

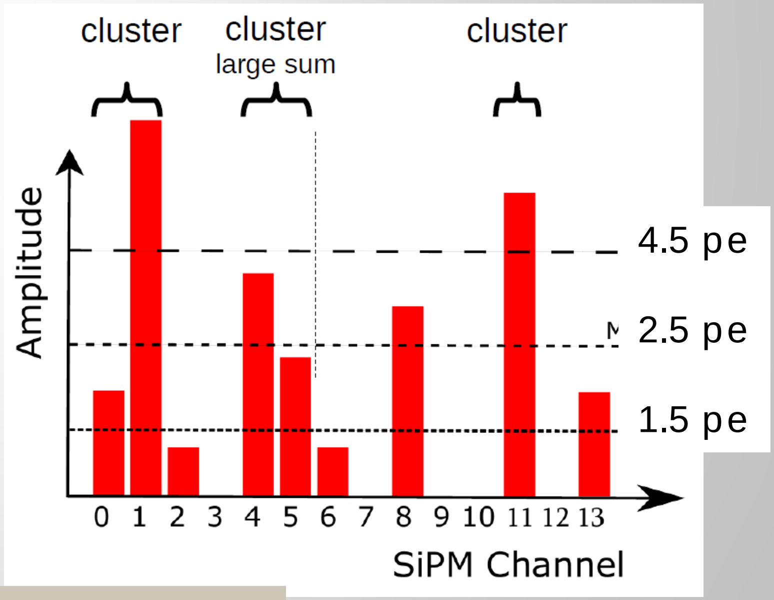


How to form signal clusters? How to suppress noise ?





Full analog readout not affordable (bandwidth) → Binary readout (2 bits) with 3 programmable thresholds



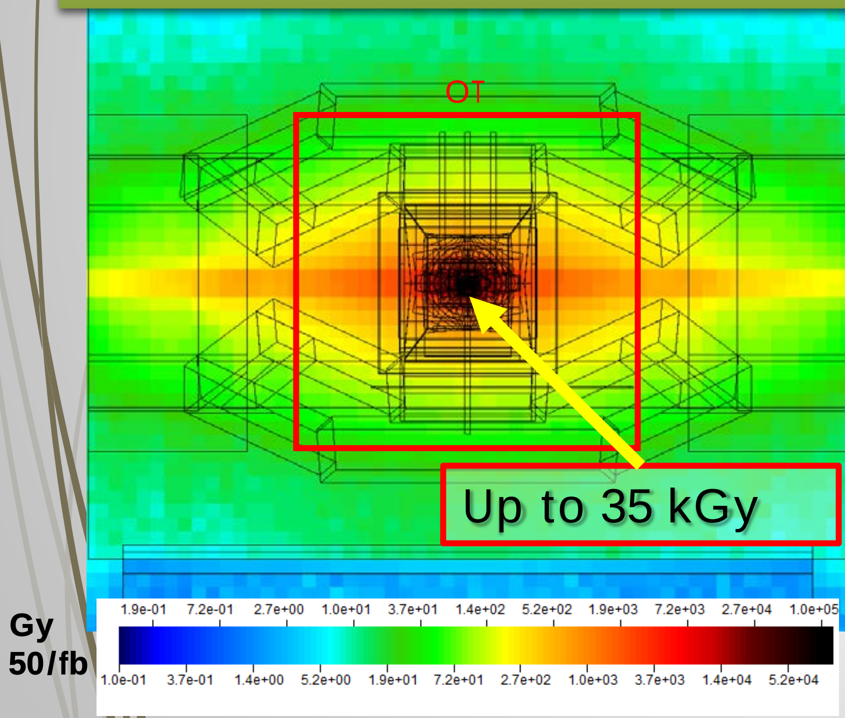
SiPM dark noise consists primarily of single pe signals. Beware of SiPM cross-talk, after-pulses, noise pile-up. They can make noise look like signal.

Run 3&4 (2021 – 2029, 50/fb)

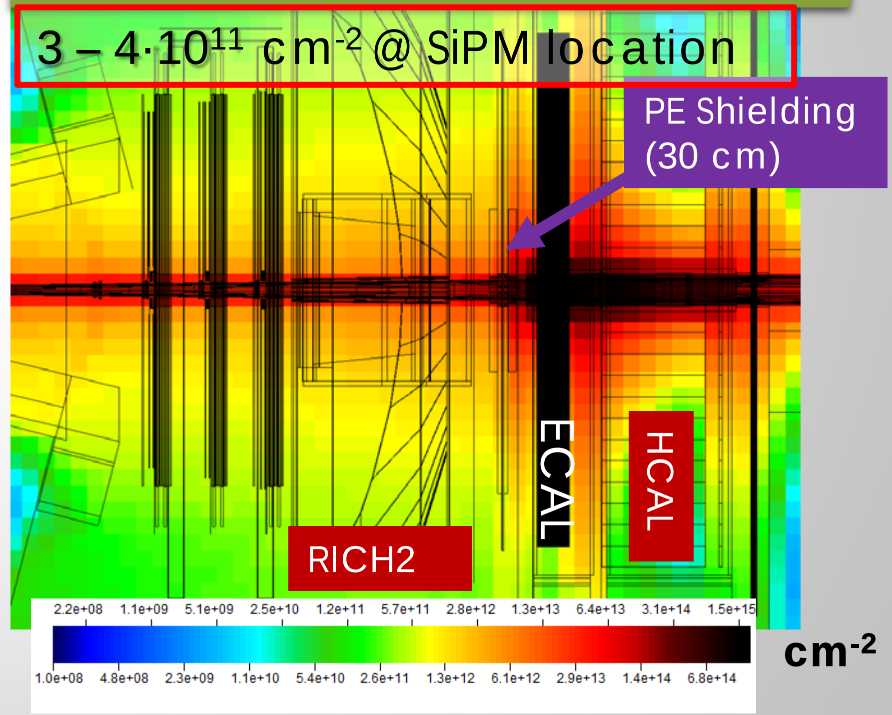
The main challenges

- **Ionising dose** → loss of fibre transparency → loss of signal → loss of efficiency
- **n-fluence** → increasing dark count rate (DCR) in SiPM → signal-like noise clusters → ghosts

Dose [Gy], 50 fb^{-1}. 84mb, z = [780, 800] cm



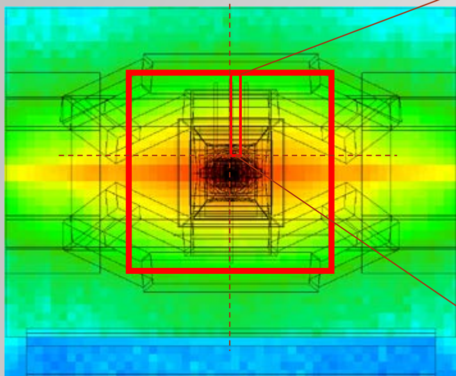
N fluence, x=[0, 20] cm



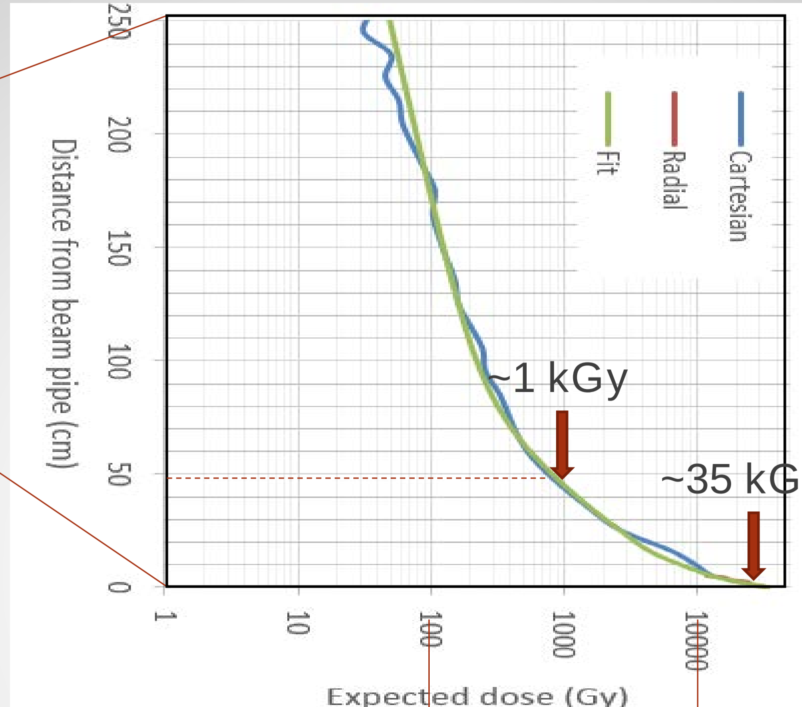
Fluka
M. Karacson

Ionising Dose

SiPM position



Fluka
M. Karacson



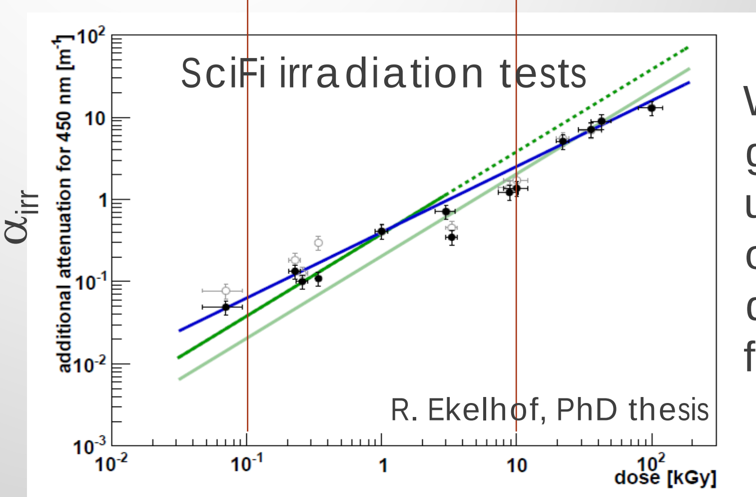
beampipe level

Attenuation length Λ

Attenuation factor $\alpha = 1/\Lambda$

$\alpha = \alpha_0 + \alpha_{irr}$

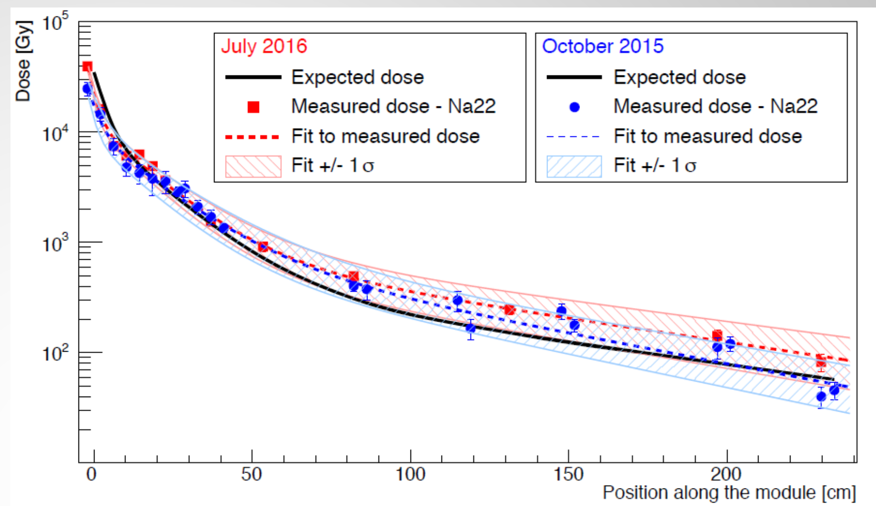
$\alpha_{irr} \sim k \cdot D$



We achieved a good understanding of radiation damage over full dose range.

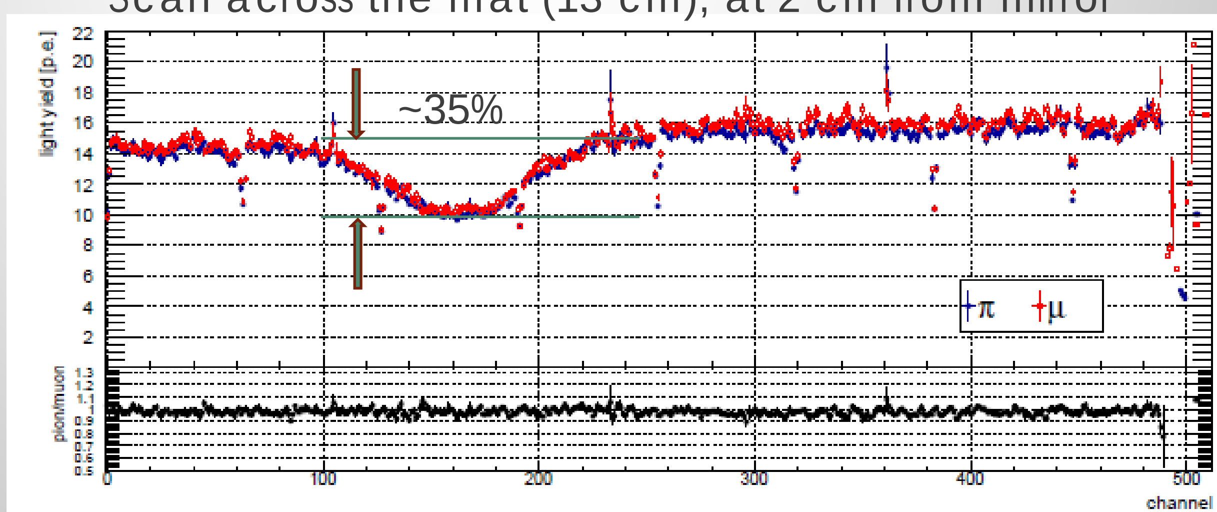
The (almost*) ultimate irradiation test

We irradiated two mirrored SciFi mats in the PS Irrad facility at CERN to the expected steep dose profile.
Only a **25 mm wide band** along the mat was irradiated.



The **expected signal loss** at the mirror end of the mat was 40%.
We found ~35%.

Scan across the mat (13 cm), at 2 cm from mirror



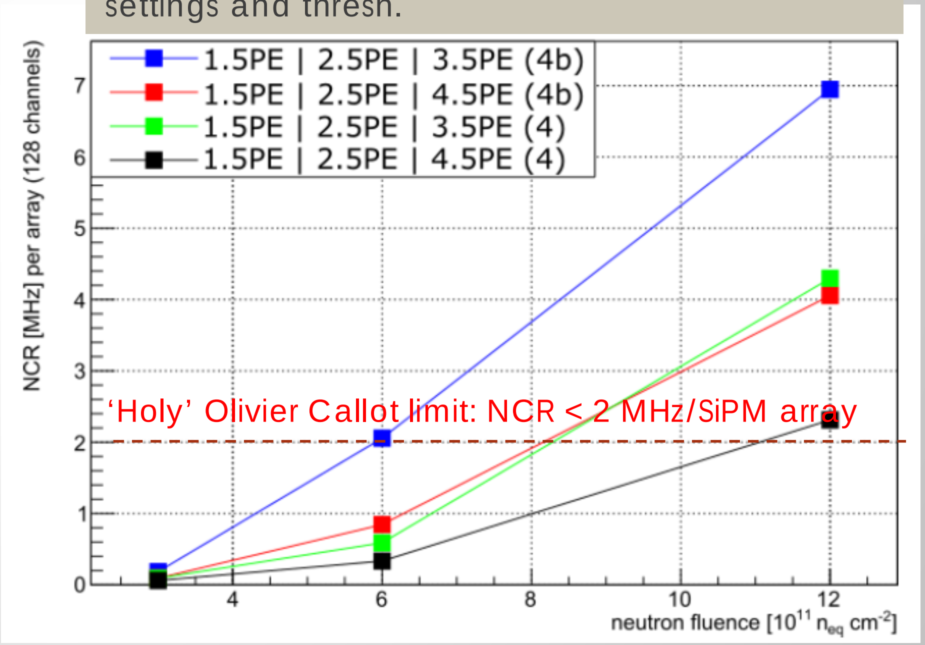
10 pe is already less than what you want for optimum hit efficiency.

* the ultimate test would be to irradiate at the correct (non-accelerated) dose rate, which would have taken 5 years. However, we have so far no strong indications that rate matters a lot. Tests ongoing!

Neutron fluence

- As in every Si device, neutrons damage the Si lattice. In a SiPM the main effect is the increase of the dark count rate DCR ~ k · F_n
- Gain and PDE are practically unaffected, however DCR just goes through the roof. 50 fb^{-1}, $4 \cdot 10^{11}$ n/cm^2 → **hundreds of MHz per SiPM channel** (at RT)
- Problem: noise hits have same amplitude as 1 pe signal hits. They can combine/pile up to signal-like clusters.
- **Solutions:**
  - **Cooling:** Every 10 K reduction halves DCR. T = -40°C gives a factor 64 (2^6) reduction.
  - **Clustering.** Noise hits don't form clusters, except accidentally!
  - **Optimise SiPM** for low cross-talk and after pulses.
  - Use preamp with **short shaping** time.
  - **Neutron shielding**.

Noise cluster rate (NCR) for different Pacific settings and thresh.



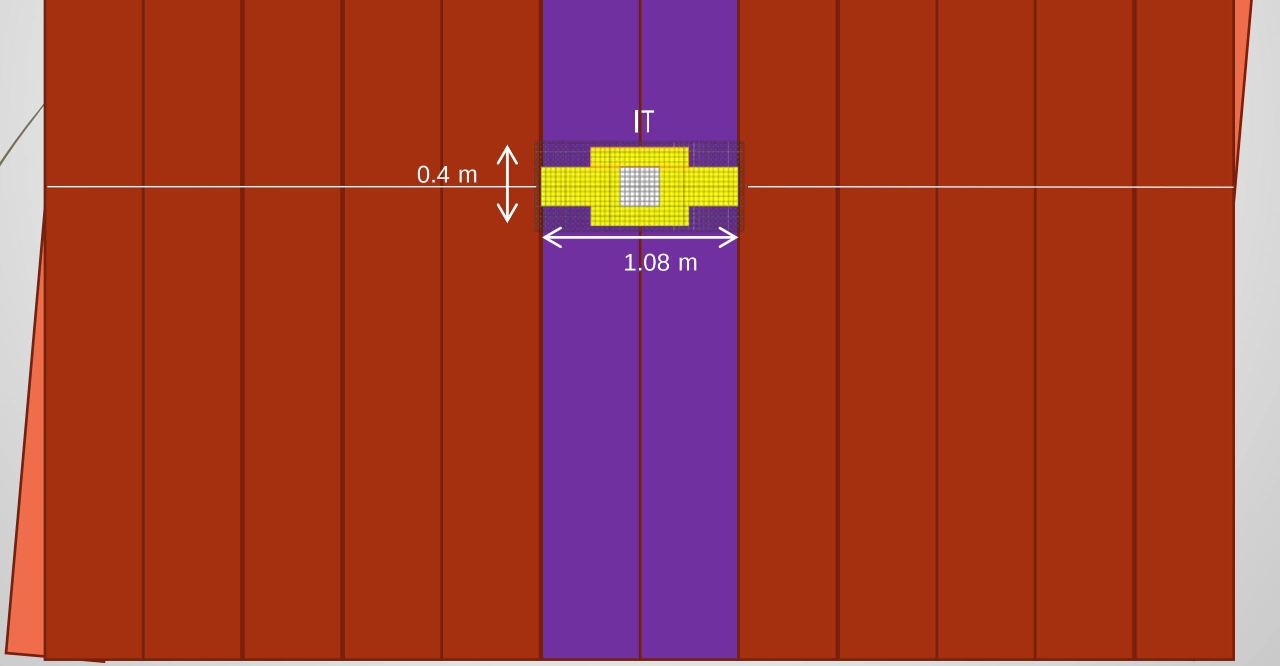
NCR shall be less than half of the smallest Signal CR
- SCR > 4 MHz/SiPM array
- NCR < 2 MHz/SiPM array

Current status of SciFi project

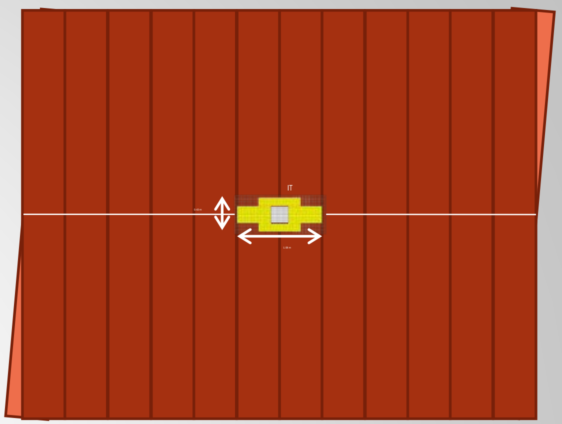
	R&D	proto	pre-series	series	On schedule	
Fibres				55%	☑	
Mats				25%	☑	catching up
Modules				15%	☑	catching up
SiPM					☑	
Flex cable					☑	tight
Cold box					☑	
Pacific ASIC					☑	tight
FEE					☑	tight
C-frames					☑	

A possible upgrade during LS3 (2024/25)

- **Replace** 2 inner SciFi modules by slightly (10 – 20 cm) shorter modules → 24 new modules in total ~ 2000 km of fibres.
- **Add** a Si Inner Tracker: 1.08 x 0.4 m^2



Upgrade during LS3 (2024/25)

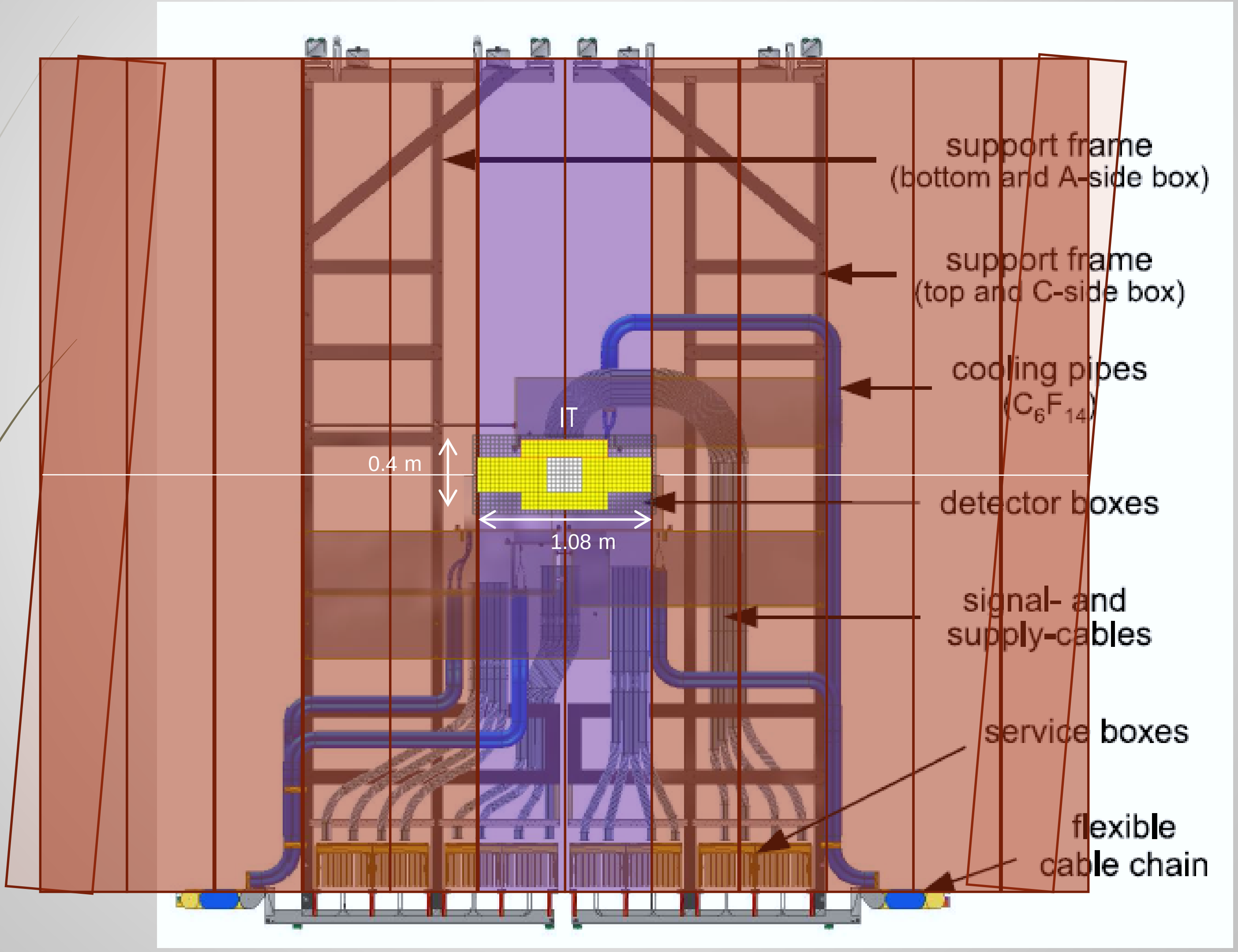


- What do we gain (from a SciFi POV)?
  - Fresh non-damaged modules, possibly with better fibres (see below) → initially optimum hit efficiency
  - We would profit from a higher (y) IT → larger SciFi cut-out in order to reduce the damage of the fibres (see below)
- What do we loose?
  - Add non-uniformly distributed material, up to 30% X_0. One may consider to use SciFi modules as IT supports?
- Other issues ?
  - Space (in z)

A possible upgrade during LS3 (2024/25)

- In reality it may more look like this ?

Up to 30% X_0 extra material, non-uniformly distributed

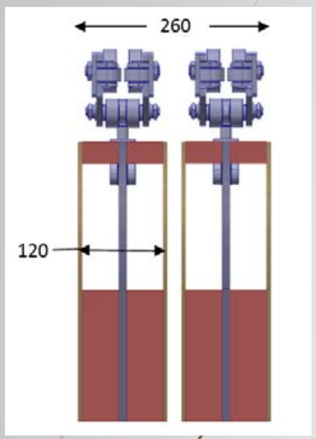


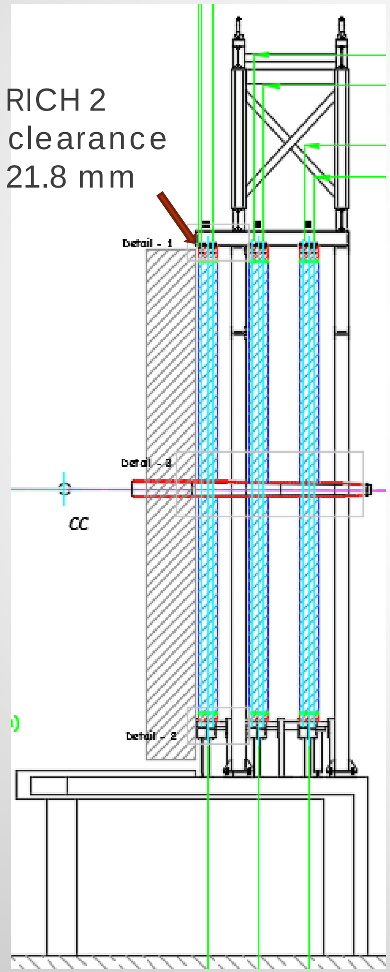
Upgrade during LS3 (2024/25)

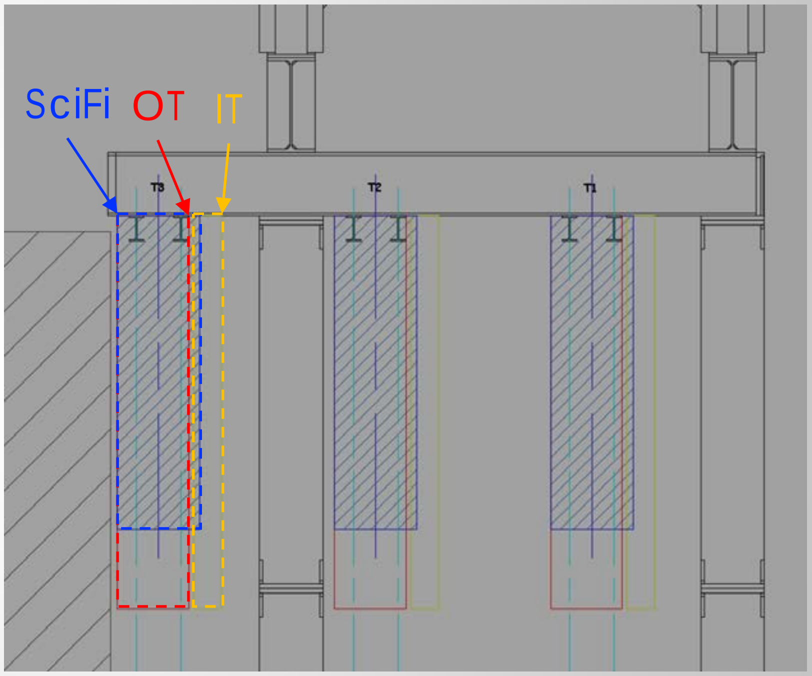
- Envelope issues …

1 SciFi station = 4 (XUVX) modules

A. Saputi
https://edms.cern.ch/document/1792415/1

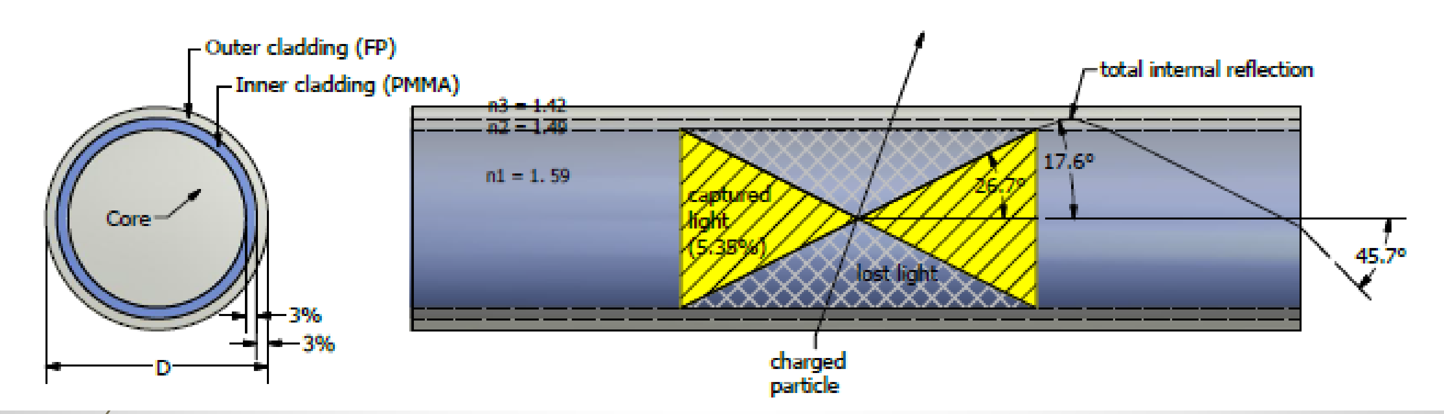






SciFi uses the full OT envelope and penetrates 20 mm into the current IT envelope

Can we hope for better fibres?
The NOL dream (saga)

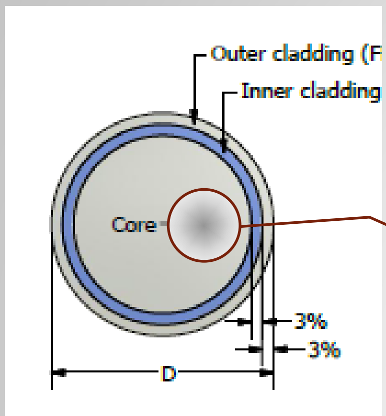


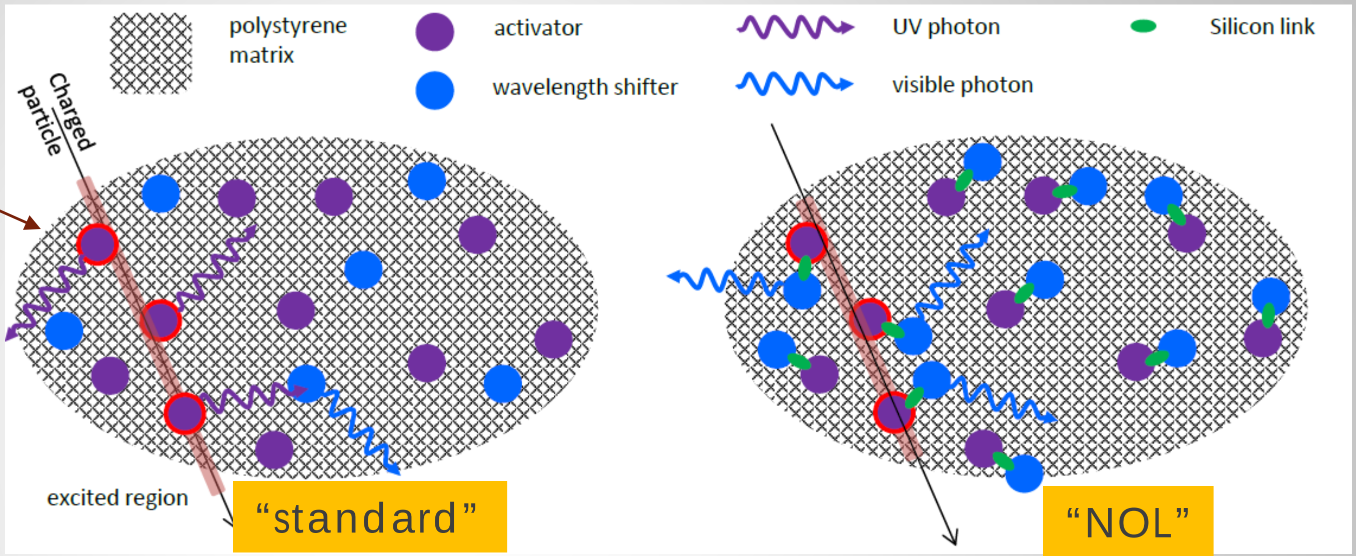
- **What limits the light output of a scintillating fibre ?**
  - dE/dx → god-given
  - Construction, i.e. double cladded. There seems to be no suitable plastic material with n<1.42
  - Activation and wavelength conversion → idea of NOL fibres

The NOL dream (saga)

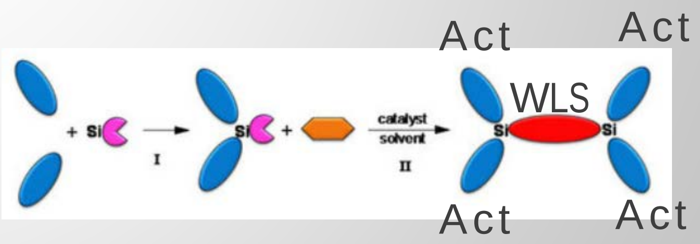
S.A. Ponomarenko et al., Nature Sci. Rep. 2014, 4, 6549

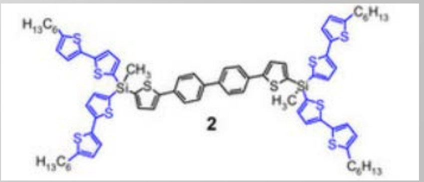
- Nanostructured Organo-Silicon Luminophores





- Chemically couple activator and wavelength shifting molecules to 1 complex.
- Fast and efficient (non radiative) energy transfer → higher light yield.

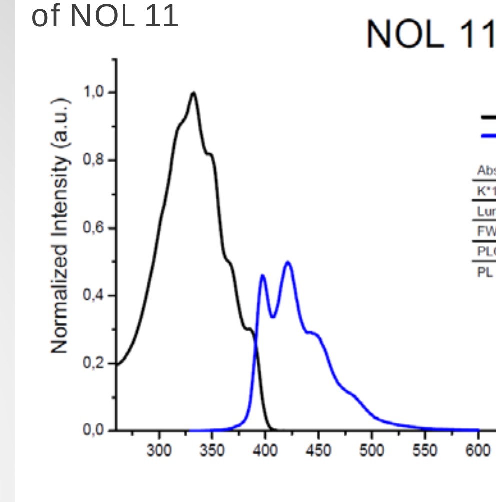


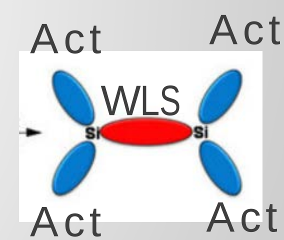


The NOL dream (saga)

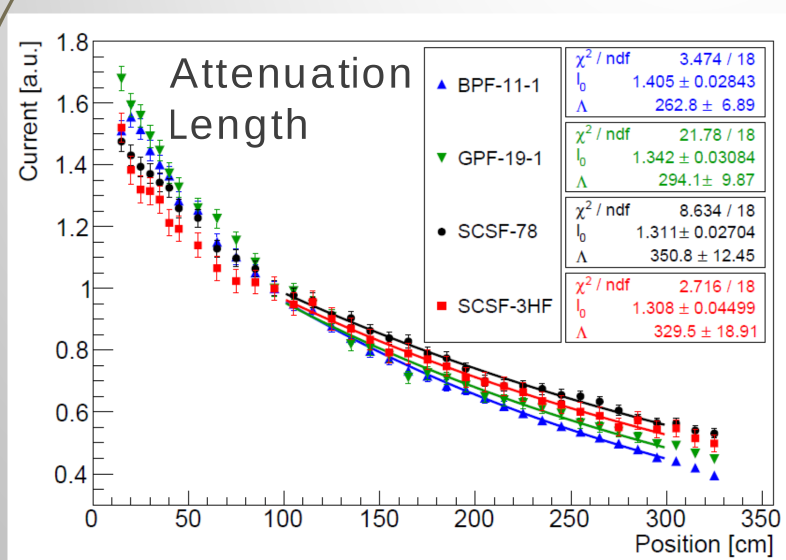
- The fibre geometry poses some problems to NOLs:
  - For efficient transfer PS → Act, $[C_{Act}]$ should be ~1-2 %
  - As WLS have often a non-complete Stokes shift, they partly re-absorb their own light. → [WLS] < 1000 ppm, otherwise the attenuation length drops too much.
  - NOLs have a [Act]/[WLS] ratio of 4/1 or 6/1 → Pure NOLs do not work in a fibre. We need to add some non-NOL Activator.

Absorption and emission spectra of NOL 11





- What have we (Kuraray, CERN, Rus. Acad. Sci) achieved, after 8 iterations?



Best blue NOL

Best green NOL

Best blue standard

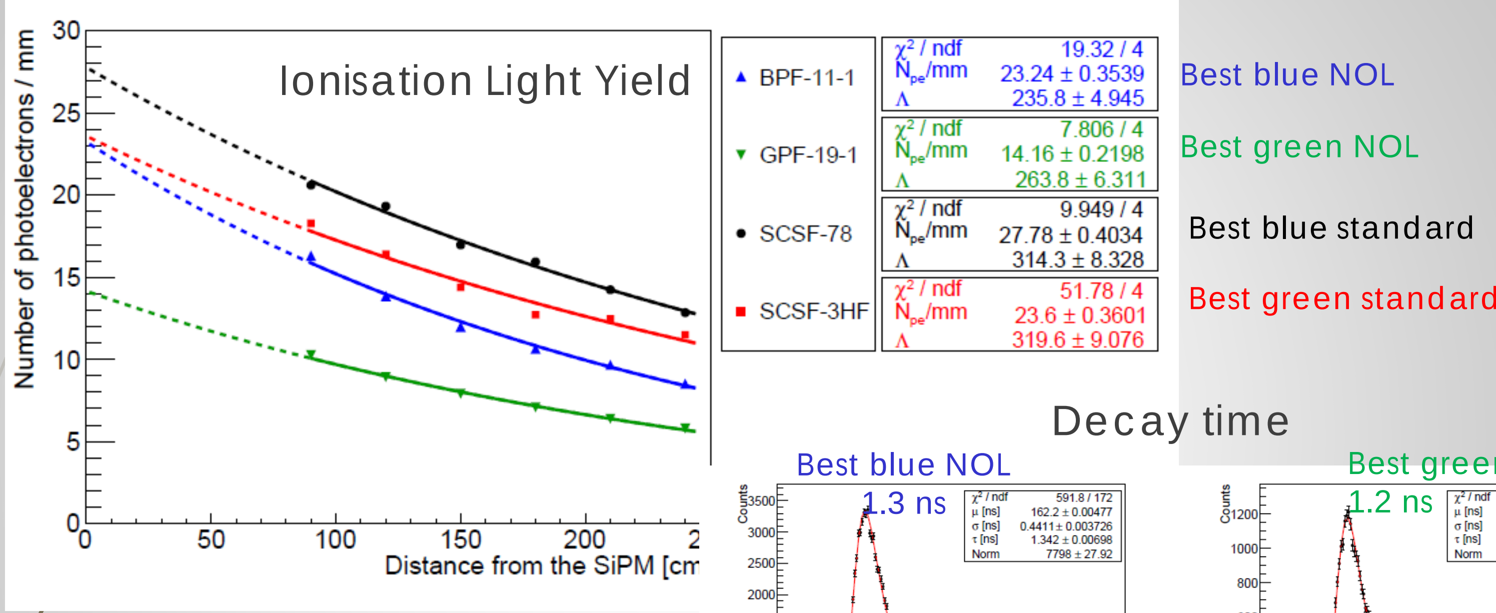
Best green standard

Oleg Borshchev et al., 2017 JINST 052P 0317 (just out)

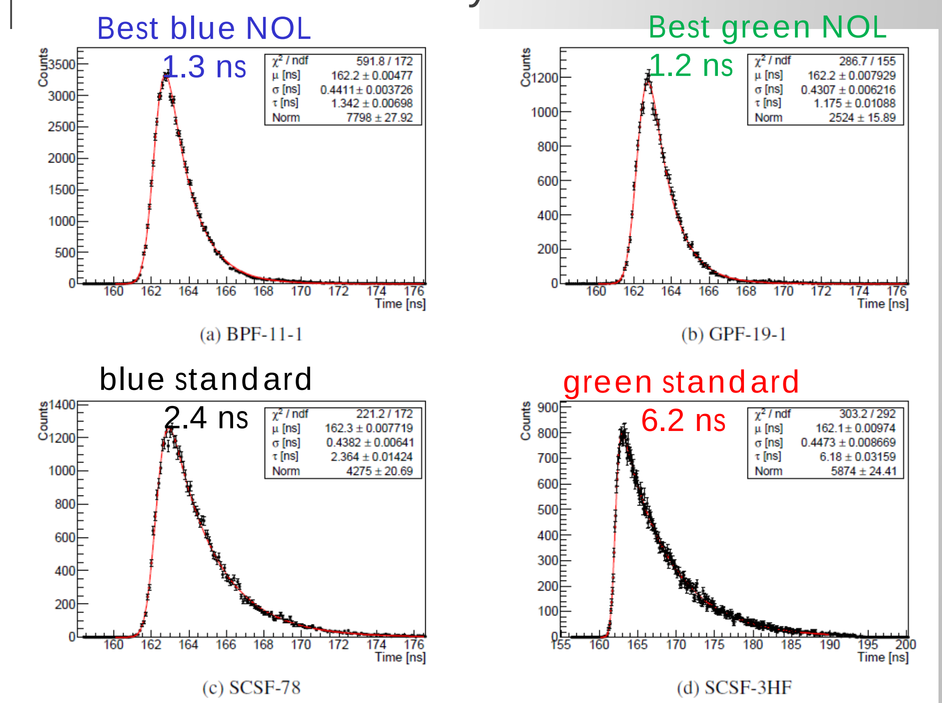
The NOL dream (saga)

Oleg Borshchev et al., 2017 JINST 052P 0317 (just out)

- What have we achieved ?



Decay time

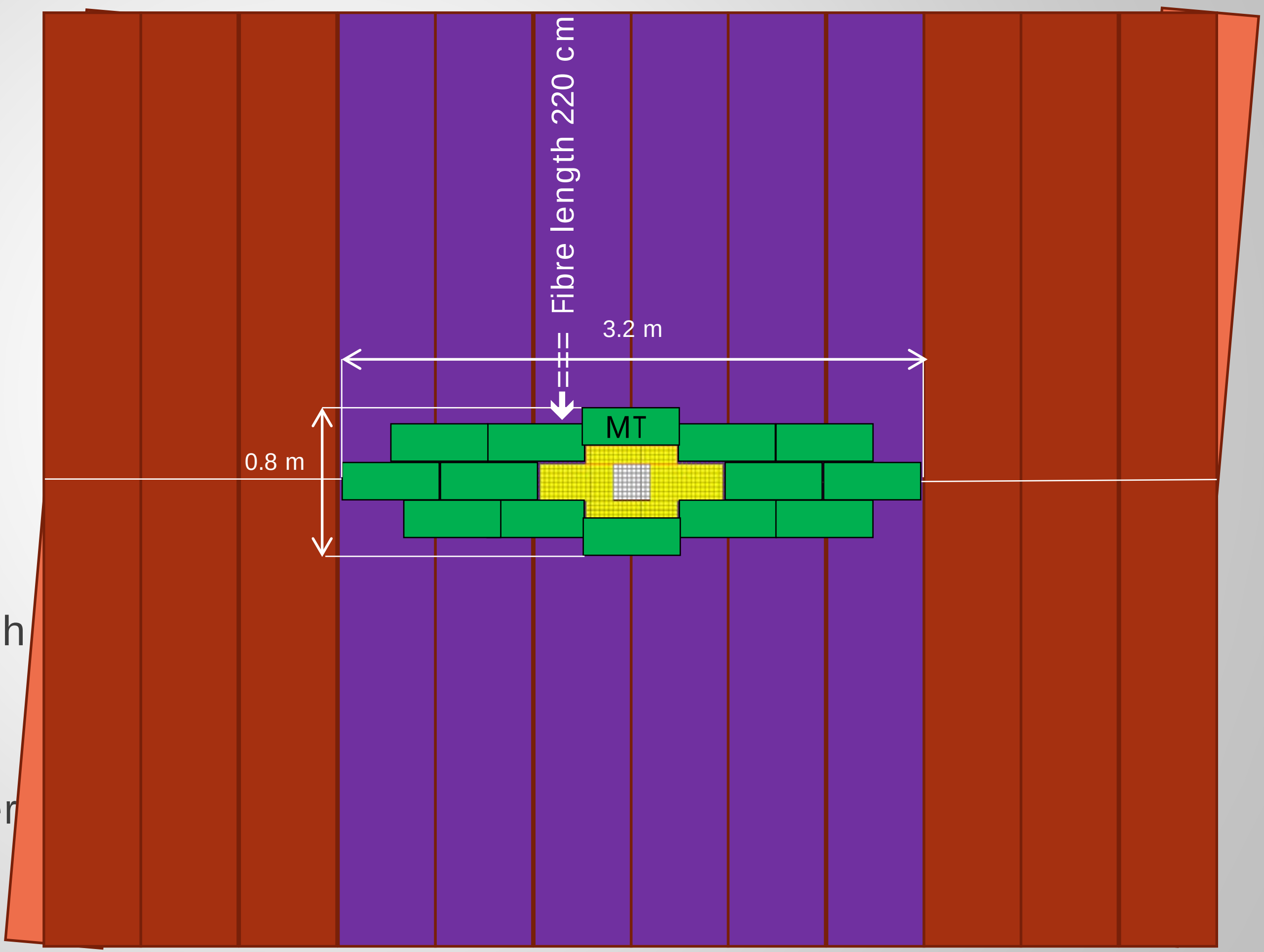


- NOLs are faster than standard fibres, but still have deficits in terms of att.length and light yield.
- Self absorption seems to be a key issue.
- We have ideas how to continue, but it's too late for the current SciFi.

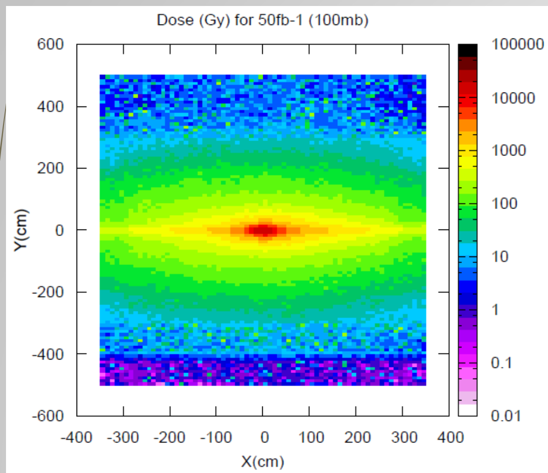
And another upgrade during LS4 (2030)

(1 year only)

- Replace 6 inner SciFi modules by (10 – 40 cm) shorter modules → 72 new modules in total ~ 6000 km of fibres
- Replace <u>all</u> SiPMs.
- Add a **Si Middle Tracker**: 3.2 x 0.8 m^2
- Total Si surface: O(20) m^2 (12 planes needed?)
- Can IT stay or does it need to be remade, too ?
- Let's hope that enough space can be found under the bridge!
- We need to find clever ways to share space and mechanics/ services



Expected radiation damage to fibres



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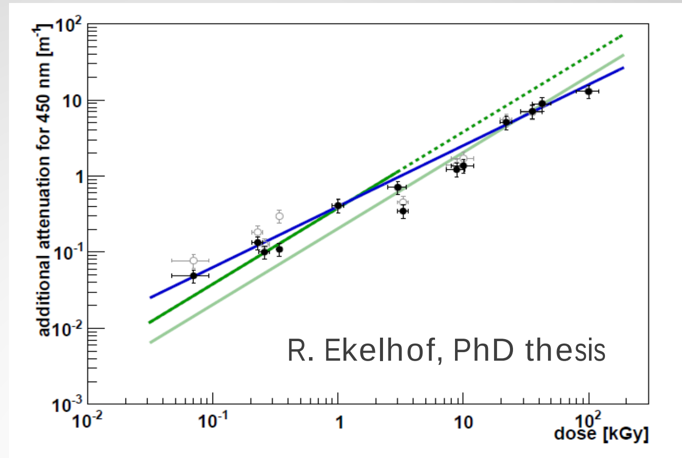

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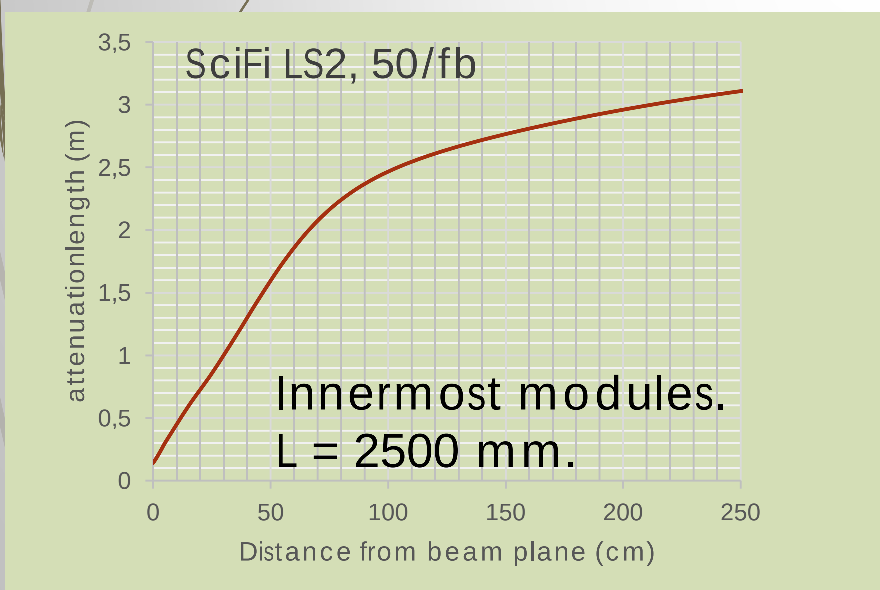
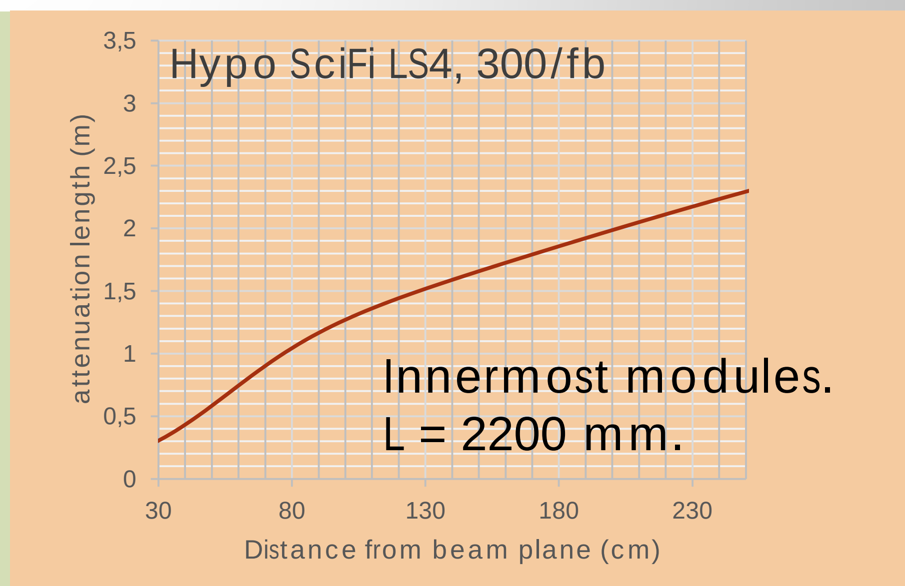
Quick spread sheet calculations
➔ **Estimates!**

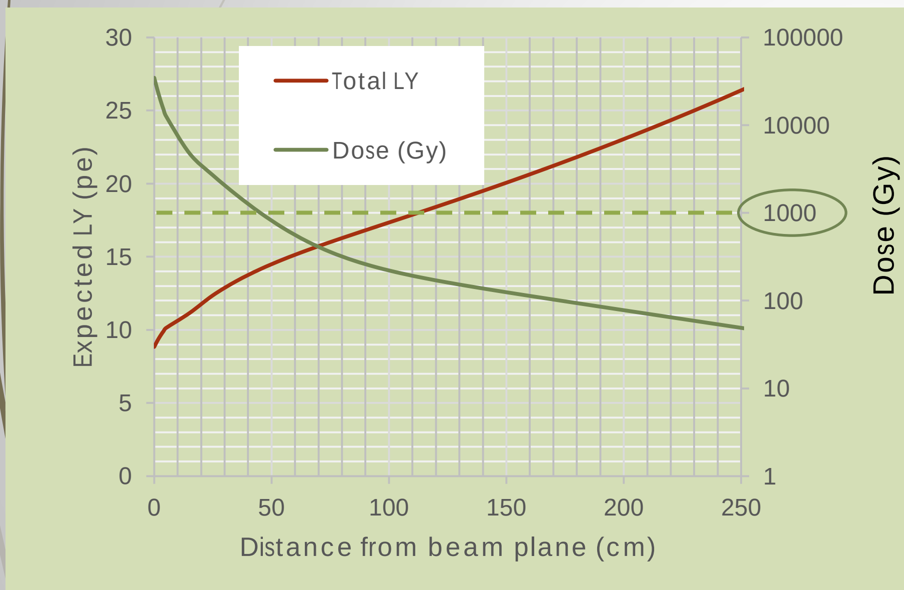




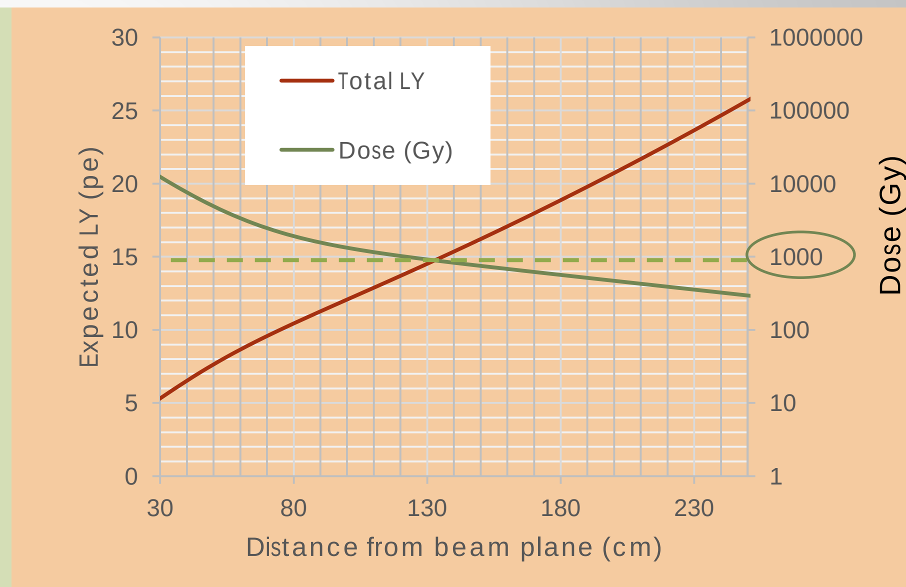
Can such a SciFi stand 300 fb^{-1} ?

- Calculate light yield, by integrating the attenuation along the fibres. Assume same SiPM, electronics etc.

Current SciFi (LS2), 50/fb



Hypo SciFi (LS4), 300 /fb



For D_{max} = 35 kGy (50 fb^{-1}) we get ~ 10 pe. In agreement with lab and test beam measurements

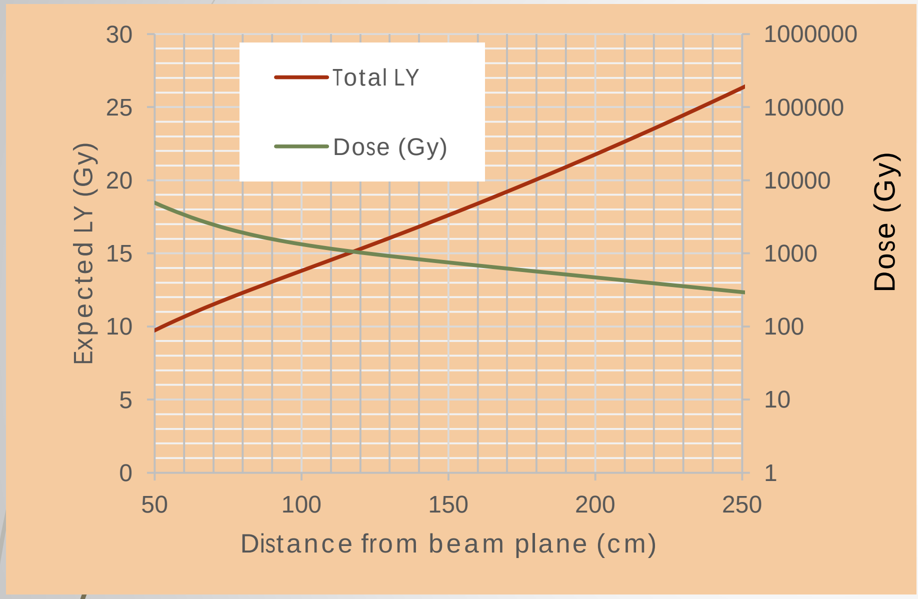
For D_{max} = 10 kGy (300 fb^{-1}) we get only ~5 pe. The light passes larger distances in heavily damaged fibre.

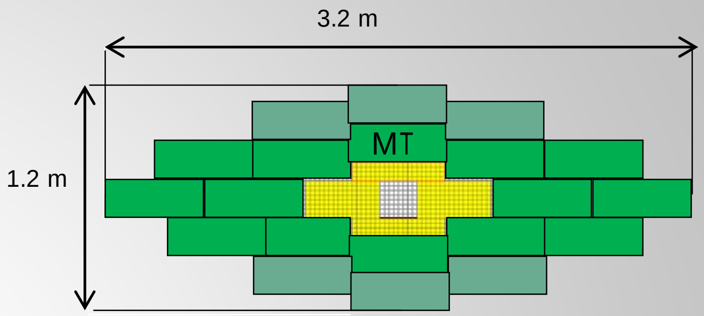
Insufficient for high efficiency!

What about a more SciFi-friendly MT ?

- Allows to shorten innermost fibres to 200 cm.

Opti-Hypo SciFi (LS4), 300 /fb





Adding 6 Si panels

Fibres may just survive 300 /fb!
Performance comparable to current SciFi.

Where may we still gain some margin ?

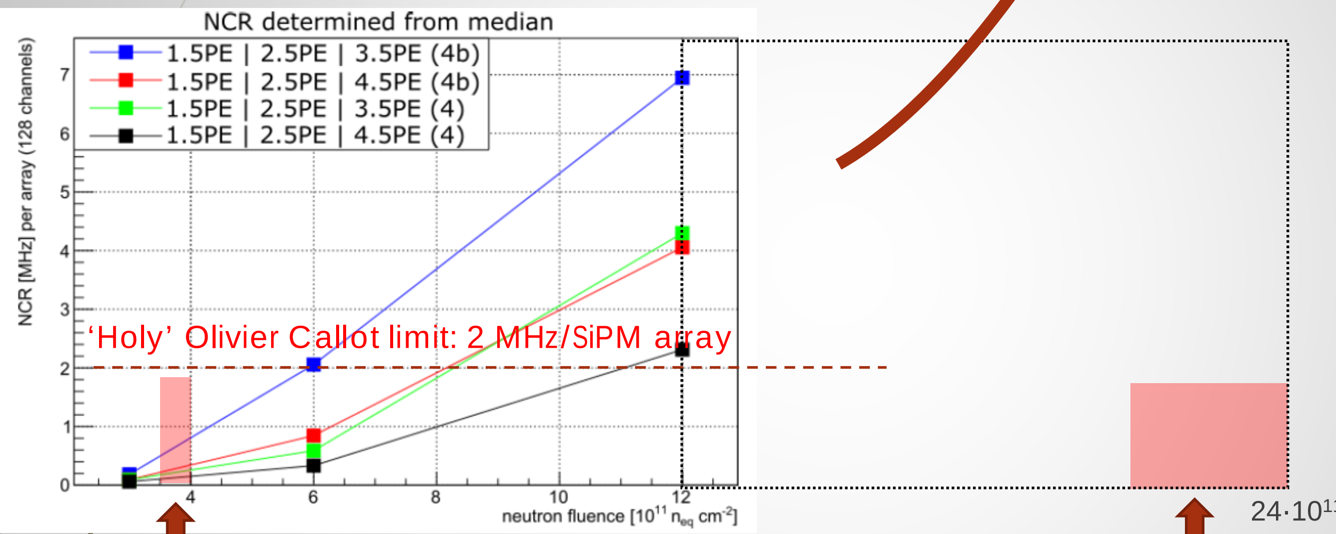
- More fibre layers, e.g. 8 instead of 6 per mat → money
- Better fibres (in ~8 years from now)
- Better SiPMs → higher PDE ?

Expected radiation damage to SiPMs

Exploding noise cluster rate !!!

Reminder: DCR = k· $F_n \sim \int L dt$

Noise cluster rate (for different Pacific settings and thresh.)



Currently we are here!

300 /fb would bring us here !

There may be a bit of margin in the current SciFi. Let's try to keep it.

Question: can we raise the Callot limit of 2 MHz if the SCR rises, too?
→ SiPM DCR, data bandwidth, #of GBT links ?? ?

Expected radiation damage to SiPMs

- What are the knobs we can turn ?
  - T_{SiPM} **Every 10K halves DCR**

    Is it realistic to operate SiPMs at -50 or -60°C ? It is at least very challenging! Issues: Insulation of cold box. Significantly more complex (and expensive) chiller. Cascaded chillers?
  - **n-Shielding**

    30 cm of PE (as foreseen for the current SciFi) should reduce F_n by ~3. There is hardly any space for local shielding of the SiPMs.
  - **Optimisation of SiPMs**

    Even lower cross talk, optimisation of SiPM design (E-field geometry)
  - **FE-Electronics**

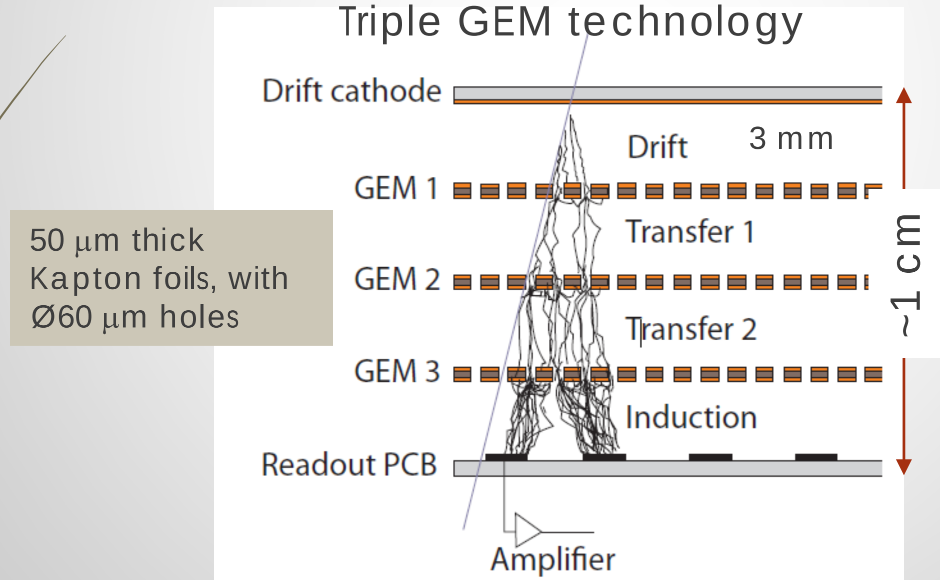
    Perhaps (!) one could still gain a bit by further shortening the time constant of the shaper. It's already very fast (5 ns FWHM).

→ It's <u>not completely hopeless</u> to gain a factor 2-4 in the DCR, but it requires VERY substantial efforts. <u>Essentially we build a new detector!</u>
New SiPMs, new cold boxes, new cooling system, new FE-ASICs.
We are talking about a O(10) million investment.

Alternatives to a SciFi tracker?

- **Silicon micro strips** over the full surface (300 m^2) are not affordable and would probably be an overkill.
- **Micro Pattern Gas Detectors** (GEM, Micromegas, ...) as alternatives ?

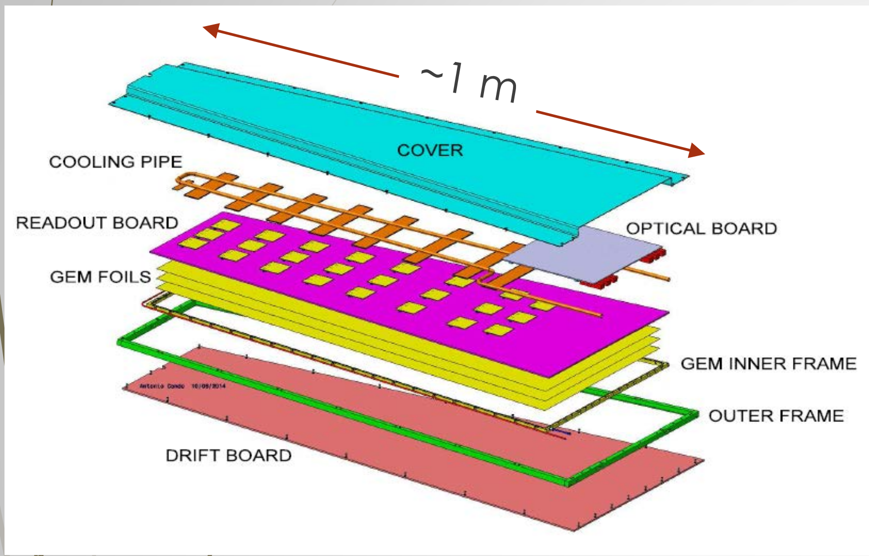
Let's have a brief look at the CMS Muon Endcap upgrade **CMS-TDR-013**

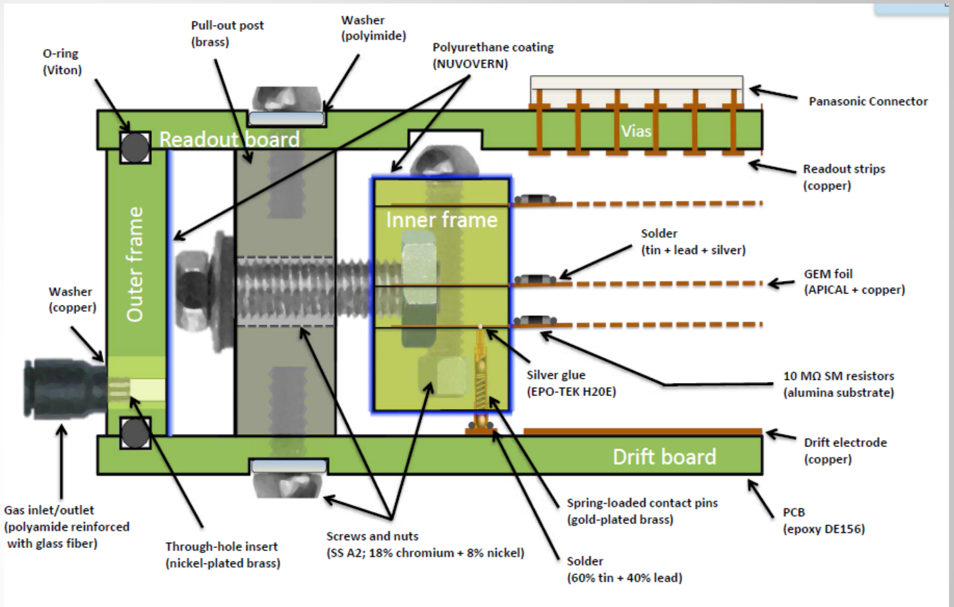


Ar/CO_2 (70/30), gas gain up to ~10000

Alternatives to a SciFi tracker?

CMS-TDR-013



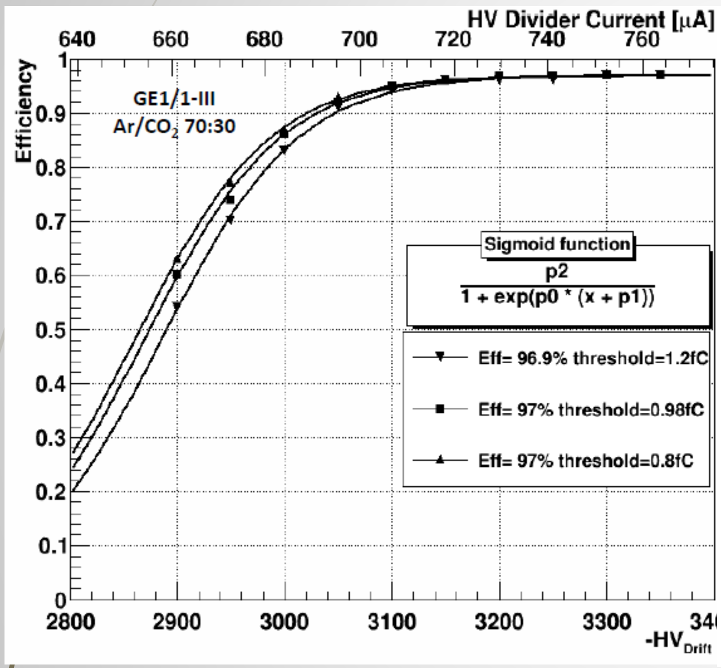


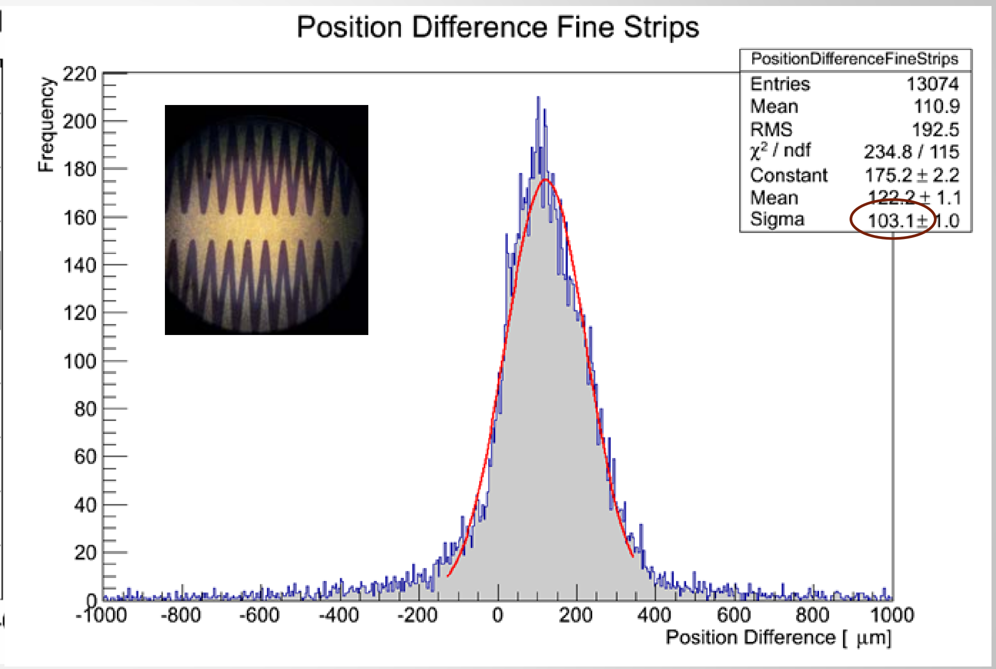
- Readout board can be freely segmented (2D).
- Detectors have an inactive edge region → Need to foresee overlap

- Some thick and heavy frames are unavoidable.
- The material distribution of the major part of the chamber is **relatively** light and uniform: (7 mm PCB ~ 5% X_0).

→ 6(12) layers = 30(60)% X_0

CMS 3-GEM performance

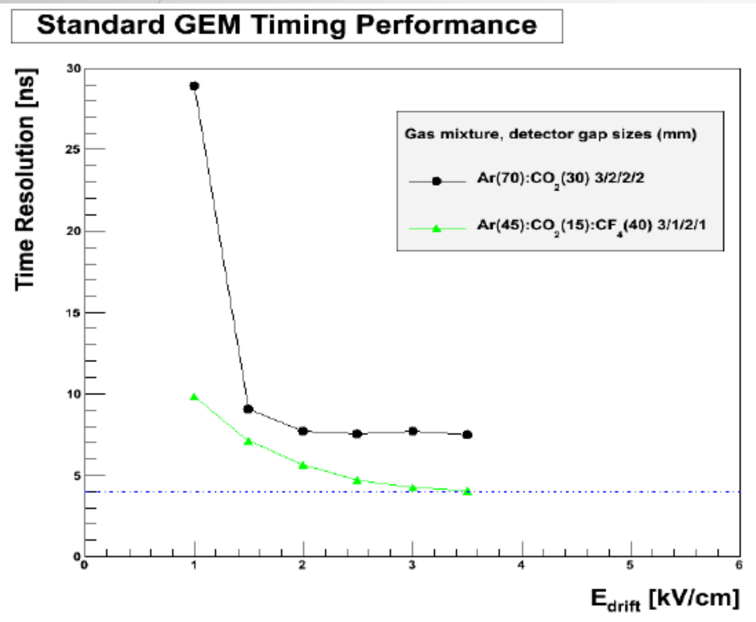




Hit efficiency up to 98%. 100% hard to achieve with a 3 mm drift gas gap.

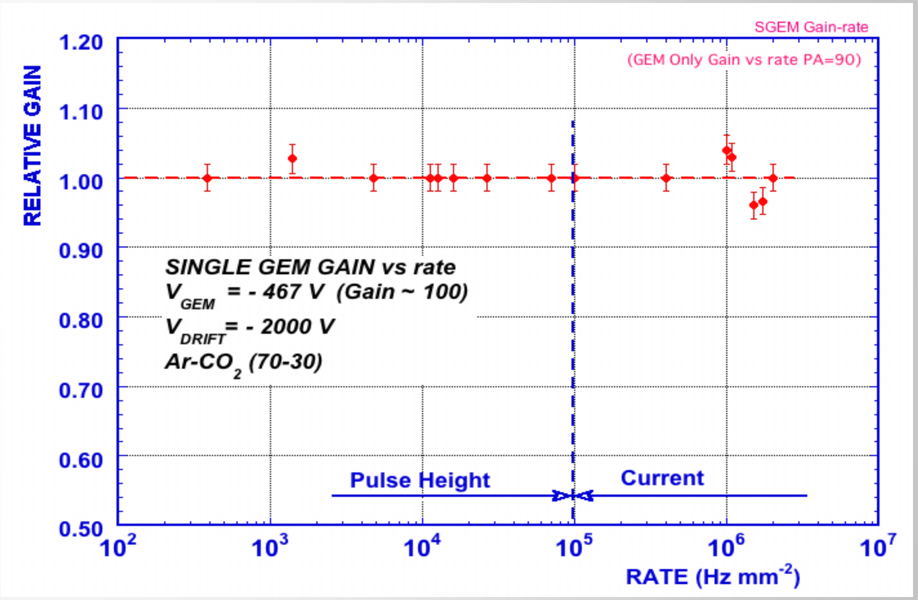
Depending on RO geometry and electronics, values << 100 μm are achievable

CMS 3-GEM performance



97% of hits fall in correct 25 ns bin

Rate capability (not from CMS!)



Guirl, L. et al. (2002) Nucl. Instr. and Meth. A 478, 263.

Conclusions

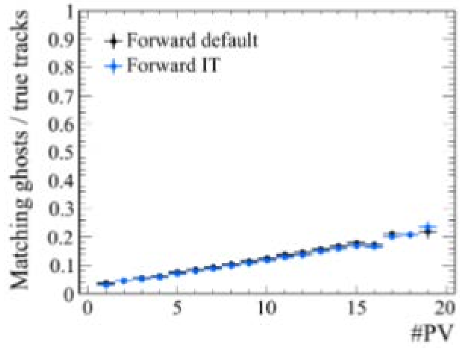
- The phase **Ib** upgrade (LS3) **looks relatively minor** to the SciFi, however entails quite some cost - O(1M) - and effort (1 year).
- The manpower situation would allow to produce the 24 special modules only after the installation of the current SciFi (2021/22).
- It would be nice if a new IT could extend a bit further than just ±20 cm in y to mitigate radiation damage of the fibre ends.
- The phase **II** upgrade (LS4) is **a real challenge** for the SciFi technology. The dose at y ~ 30 cm is too high for the fibres. We can probably survive 300/fb at 40-50 cm from the beam.
- The neutron fluence will **torture the SiPMs to/beyond their limits**. The operation in terms of DCR, NCR, SCR needs further studies. Going colder than -40C is difficult.
- **Micro Pattern Gas Detectors** have lots of attractive features and further matured over the last 10 years. However their higher material budget and non-uniform distribution may be a too high price to pay.

BACK-UP SLIDES

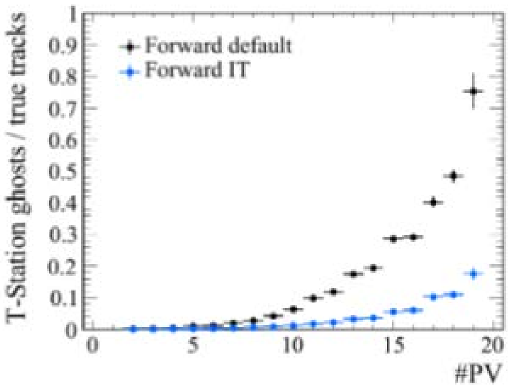
Tracking

- Challenges:
  - Track Segment Matching
    - Matching of upstream & downstream
  - Occupancy
    - Finer segmentation
- Opportunities:
  - Low momentum tracking

Matching Ghosts:
wrong matching to VELO

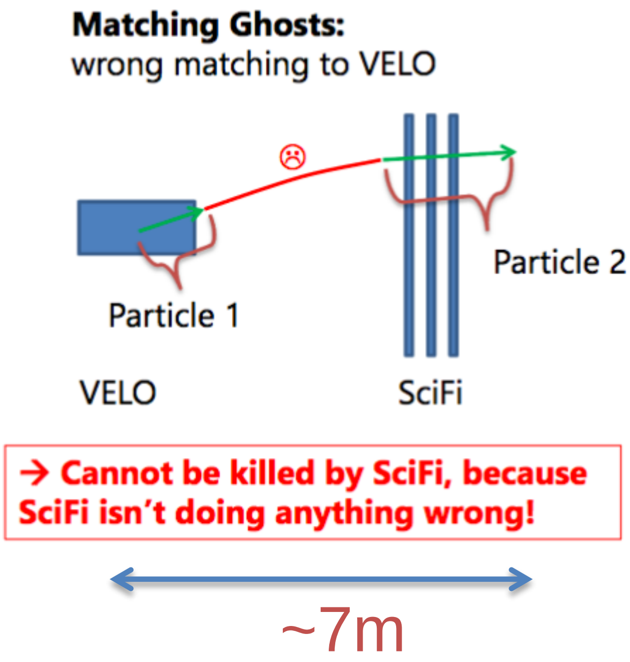


T-Station Ghosts:
wrong SciFi Hits



See Thomas Nikodem presentation at October TTFU

UT

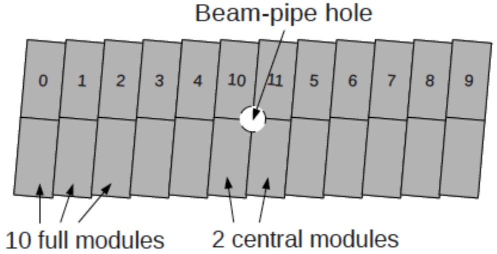


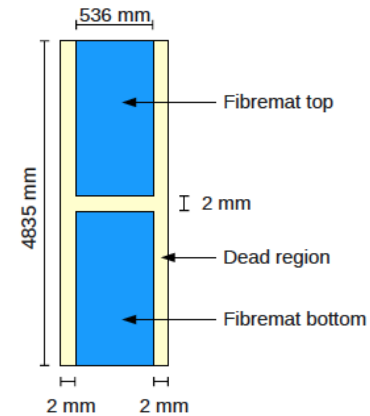
- UT provides space-points for matching VELO and downstream tracking
- Do we need additional stations in magnet region for Phase II ?

- Occupancies & radiation levels achievable in silicon
- Designs and technologies as for IT

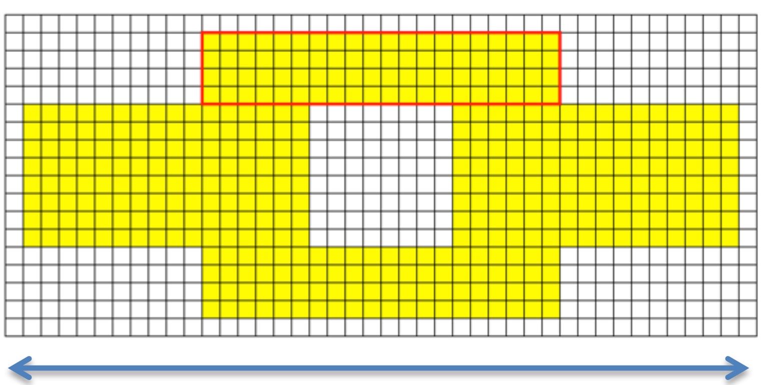
IT/MT/OT

- LS3 – Phase Ib
  - Install IT
  - **Modify** Sci-Fi - two modules per layer for LS3
- LS4 – Phase II
  - Install MT
  - **New** SciFi for LS4
    - Radiation tolerance of fibres and SiPMs?
    - Cooling (-50C), additional shielding, technology improvements



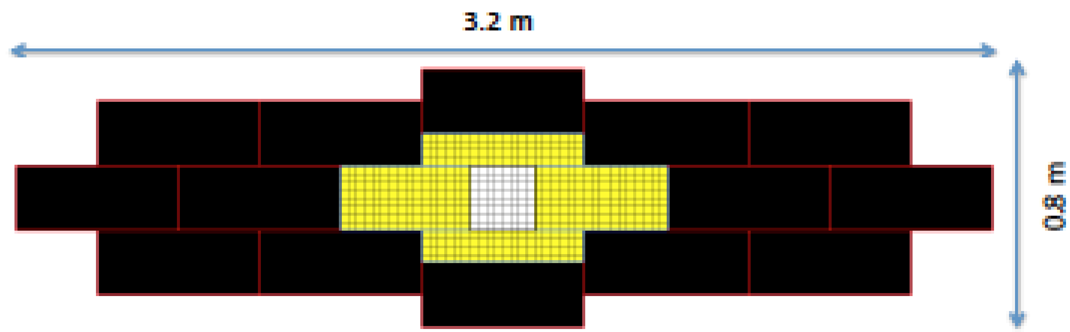


IT



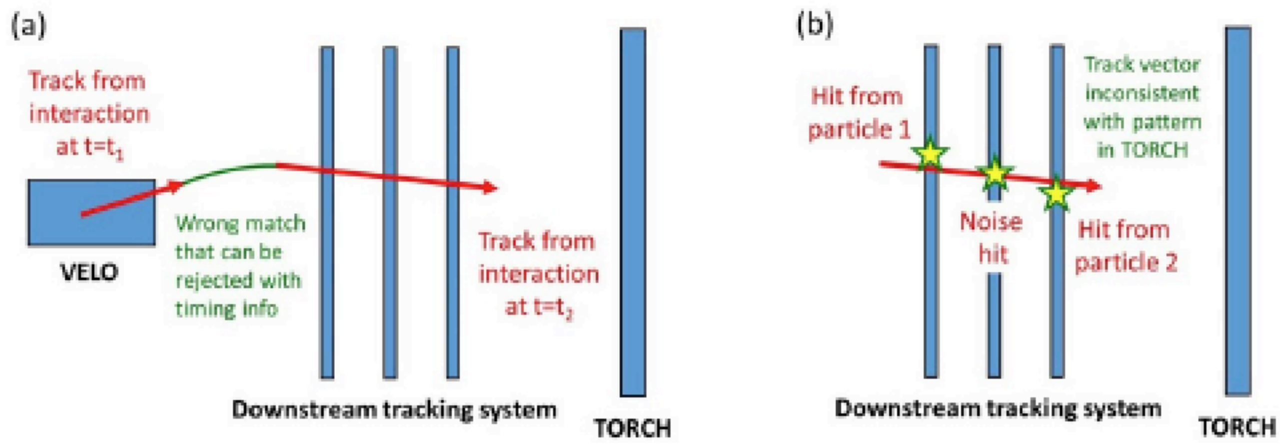
1.08m

IT+ MT



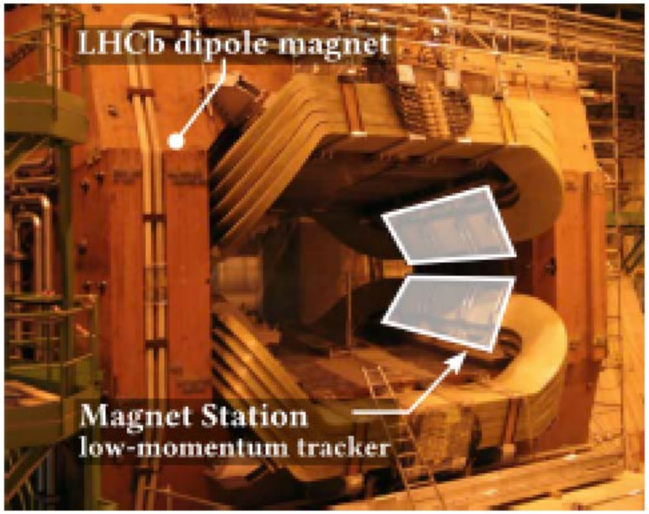
MT Area = 16.9 m² (for 12 layers) composed of 14 lots of
IT Area = 3.4 m² (for 12 layers)

Matching: Timing Planes in Tracking



- Distance from VELO to main Tracker is ~ 7m
  - Intermediate station before magnet
- VELO will add timing
- Is timing needed in tracker region also to obtain correct matching of track stubs in Phase II?
  - TORCH would be a candidate technology

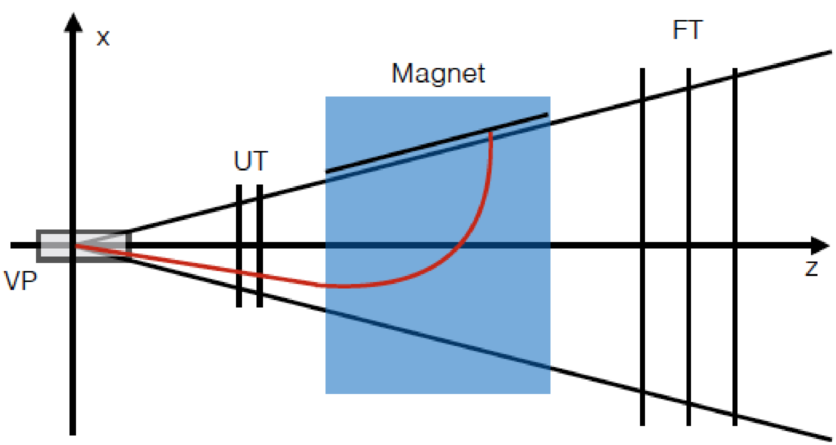
Phase 1(b)+II – Magnet Side Stations

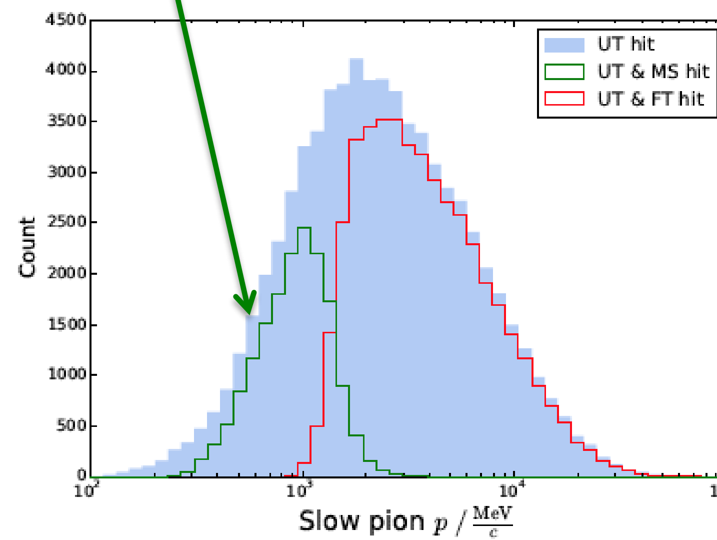


- Improve tracking acceptance for low momentum particles
  - Install tracking stations on the dipole magnet internal sides

Many physics gains

e.g. $D^{*+} \rightarrow D\,\pi_s^{+}$, 40% extra slow pions





- Candidate technology is SciFi / scint. bars +SiPMs outside acceptance

See Marc Olivier Bettler presentation at October TTFU

Detector System Summary

Detector	LS3	Phase-II
VELO	Deployment of prototype modules	New detector with fast timing
Tracking	Insert Silicon IT, modify SciFi; install MS	Silicon UT and IT, SciFi OT
RICH	New photodetectors for selected regions; use of timing information	New optics; full replacement of photodetectors
TORCH	Installation	Higher granularity photodetectors
CALO	Tungsten sampling modules installed in inner region	New modules in middle and outer regions
Muon	Replace HCAL with iron shielding; installation of high-rate chambers	Complete chamber installation
Trigger and data processing	Adiabatic software improvements; review of offline processing; installation of downstream track-finding processor	Expansion/replacement of links, readout boards and servers and servers

- We will not be able to afford all items in LS3 column for LS3
- Prioritisation required but not in EoI

Tracking: Final Points

- EoI - challenges and plausible solutions for Phase-II
  - Exploit LS3 - IT & magnet side stations

- **4D**: Timing likely to play a key role
- Downstream tracking mixed technology solution (**Si +SciFi**)
- Potential to **improve** capabilities (low momentum tracking

- In all areas R&D projects are identified in “Next Steps” section of EoI

- First cost estimates of systems given in October TTFU – not in EoI

- We need a comprehensive optimisation of the tracking system for Phase-II
  - Particularly to understand the matching issues