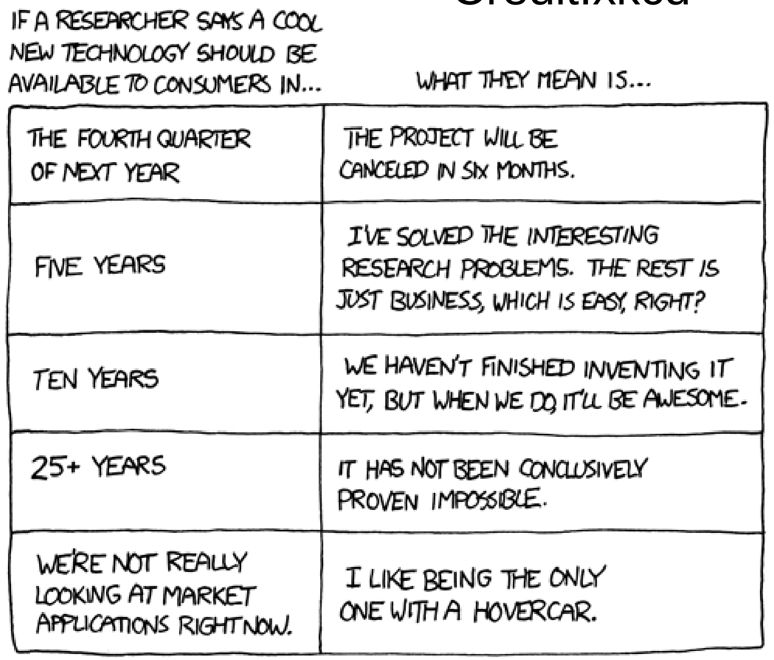
ECFA Detector R&D Roadmap:
Detector R&D for the HL-LHC (post LS3)

Credit:xkcd



19th February 2021

Chris Parkes

On behalf of ATLAS, CMS & LHCb

With thanks to:

Frank Hartmann (CMS), Francesco Lanni (ATLAS)

HL-LHC: an amazing opportunity

- The LHC has completed the first of three decades of operations
  - ~4000 papers. Higgs > 10k citations, Pentaquark > 1k.
- Upgrade I all expts currently under installation during LS2

- ATLAS, CMS Upgrade II for HL-LHC construction commencing for installation during LS3
- HL-LHC enlarge data sets by order of magnitude
- Our ability to exploit the HL-LHC is **limited by our detector technology**: spatial & time resolution, radiation hardness, cost
- Standard requirement: 25ns signal collection

HL-LHC Timelines

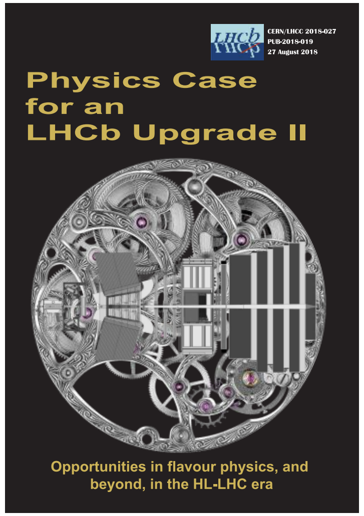
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

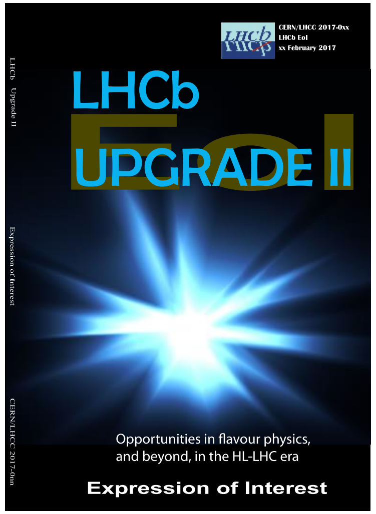
- HL-LHC will run from 2025-~ 2040
- Current schedule has shutdowns in 2031 (LS4) & 2035 (LS5)
  – In addition to end of year stops
- Detector construction typically 5+ years before shutdown for installation
  – R&D for LS4 (LS5) projects over next five (ten) years

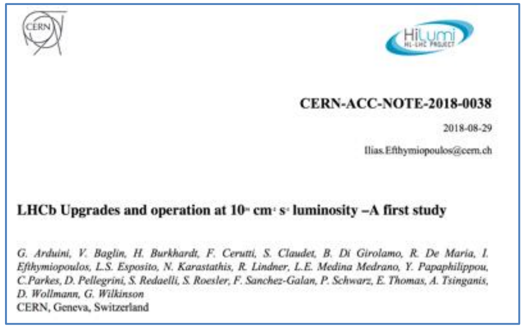
HL-LHC (post LS3) Projects

LHCb Upgrade II

- Major Upgrade of LHCb for HL-LHC era in LS4
  - – Preparatory work / consolidation in LS3
  - – Strong support in European strategy
  - – EOI & Physics Case approved by LHCC/RB
  - – 2021: Framework TDR, CDR of HL-LHC







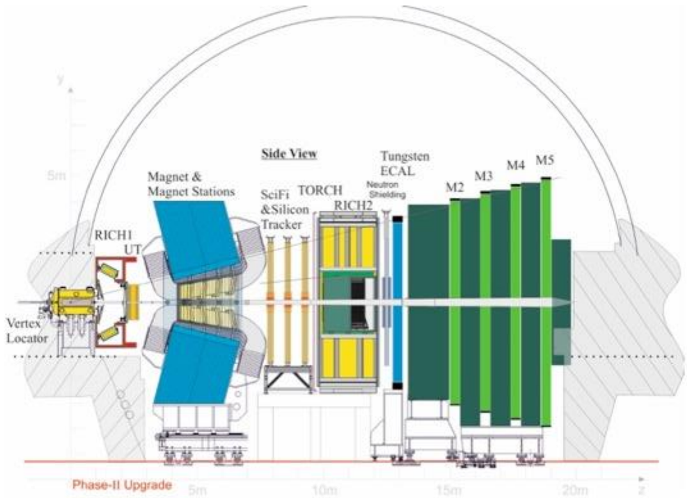
CERN-ACC-NOTE-2018-0038

2018-08-29

Ilias.Efthymiopoulos@cern.ch

LHCb Upgrades and operation at 10[illegible] cm[illegible] s[illegible] luminosity –A first study

G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland



Beyond Flavour

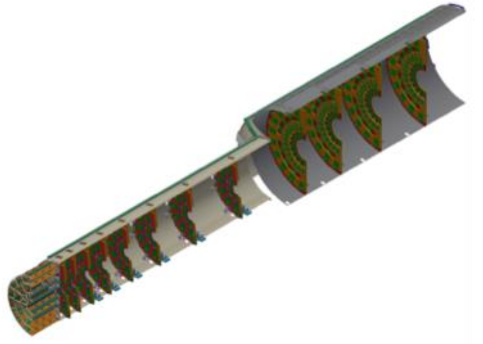
Topic	Comment
Spectroscopy	Enormous yields in gold-plated final states
	e.g. 4M $\Lambda_b^0 \to J\psi p K^-$ decays ('pentaquark' mode)
Higgs	Measure Higgs-charm Yukawa within factor 2 to 3 of SM value
$\sin^2\theta_W$	Uncertainty $< 10^{-4}$, better than LEP/SLD
Proton structure	Precision probes at extremely low and high Bjorken-x values,
	with $Q^2 > 10^5\,\mathrm{GeV}^2$
Hidden sector	Sensitivity to most of relevant parameter space for dark-photon models

HL-LHC (post LS3) Projects

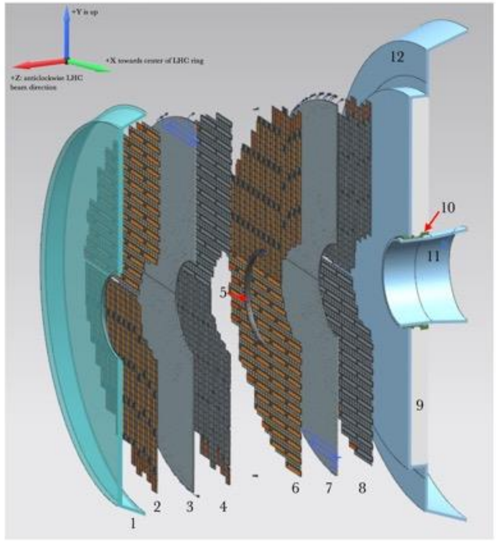
CMS in LS5

- LS3 Upgrade, almost fully lasting until LHC end
  - main upgrades large, not accessible/replaceable after LS3 (e.g. Outer Tracker, HGCAL)
- One exchange of the inner layer/rings of the pixel detector
- Maybe exchange inner rings of End-cap Timing Layer
- No agreed plan on future upgrades but some ideas where could profit from advancements in technology **– mainly in forward**

Inner Tracker



Endcap Timing Layer



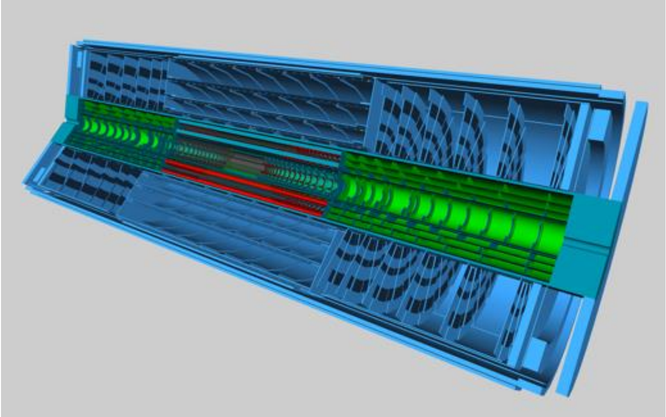
HL-LHC (post LS3) Projects

ATLAS in LS4/LS5

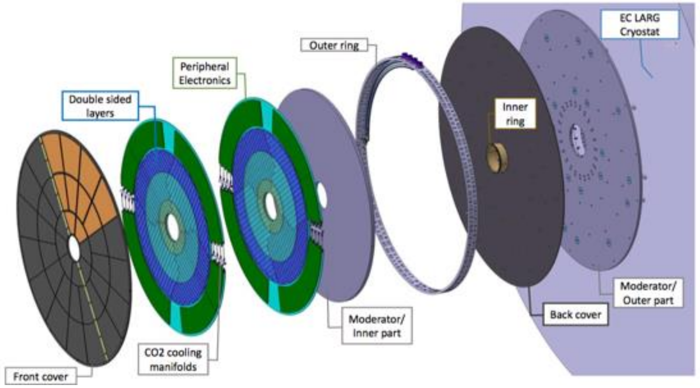
- The HL-LHC upgrade full installation of upgraded detectors and electronics in LS3
- Future Partial replacement:
  - Inner Tracker Pixel (ITk-Pixel)
  - High Granularity Timing Detector (HGTD)

- Technology advance may provide opportunities for possible evolution of the trigger system

ITk



HGTD



Pursuing HL-LHC R&D while working on other projects

- LHC experiments happy to collaborate on R&D across projects
  - prohibit simultaneous physics research on more than one LHC experiment (ensuring scientific independence)
  - Many engineering and technical staff in multiple experiments
  - All have Technical Associate Memberships that allows work on detector projects (while pursuing physics on other experiments)
- Future accelerator based projects
  - Strong encouragement from LHC spokes for pursuing R&D in collaboration with LHC experiments - identify synergies and avoid duplication in R&D
  - LHC will trial technology for future projects and much R&D can likely use these projects as the starting point for plans
- CERN R&D Programmes (RD50, RD51, RD53+…) play an important role in common R&D

TF1: Gaseous Detectors (& Large Scale Tracking)

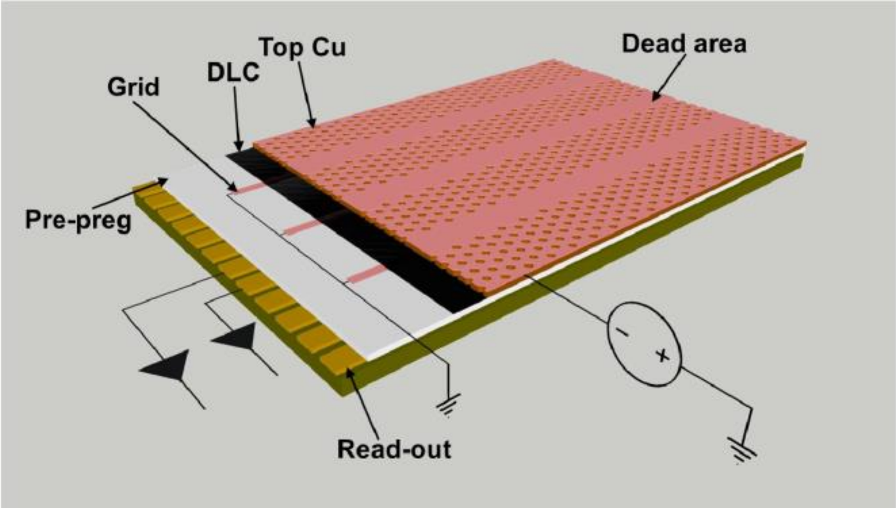
LHCb Upgrade II : Muon system

- Requirements

-Rates up to several MHz/cm^2 in the inner regions

-Efficiency > 95% within 25 ns

-Stability up to 6 C/cm^2 accumulated charge in 10 years of operation



- R&D on μ-RWELL

- Single-amplification stage, spark-protected resistive MPGD based on a breakthrough technology suitable for large area planar tracking devices
- The detector is being characterized: gas gain ~ 10^4, rate capability ~10 MHz/cm^2 , efficiency ~97%

- A design for the high rate has been found which is suitable for a simple industrialisation process

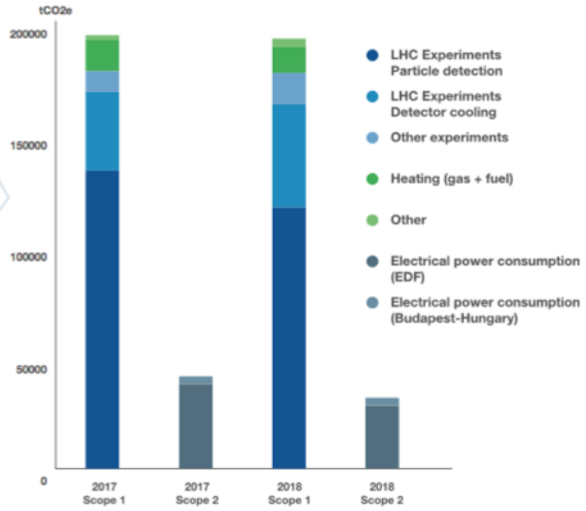
TF1: Gaseous Detectors (& Large Scale Tracking)

CMS: RPC, ATLAS: RPC/NSW, LHCb: RICH, μ-RWELL

- New gas mixture with lower environment impact
- Recuperation systems
- Detectors
  - RPCs, GEMs, MWPCs…
  - RICH Radiators: C_4F_{10}
- Cooling Systems
  - Move to NOVEC, CO_2

https://e-publishing.cern.ch/index.php/CERN_Environment_Report/index

GROUP	GASES	tCO_2e 2017	tCO_2e 2018
PFC	CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_6F_{14}	61 984	69 611
HFC	CHF_3 (HFC-23), $C_2H_2F_4$ (HFC-134a), HFC-404a, HFC-407c, HFC-410a, HFC R-422D, HFC-507	106 812	96 624
	SF_6	10 192	13 087
	CO_2	14 612	12 778
TOTAL SCOPE 1		193 600	192 100

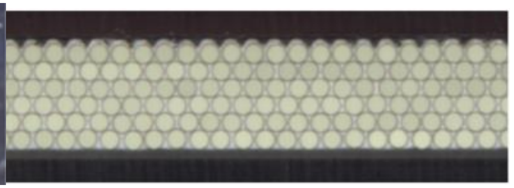


Source: CERN Environment Report 2017-18

TF1: Gaseous Detectors (& Large Scale Tracking)

LHCb Upgrade II : Tracking System

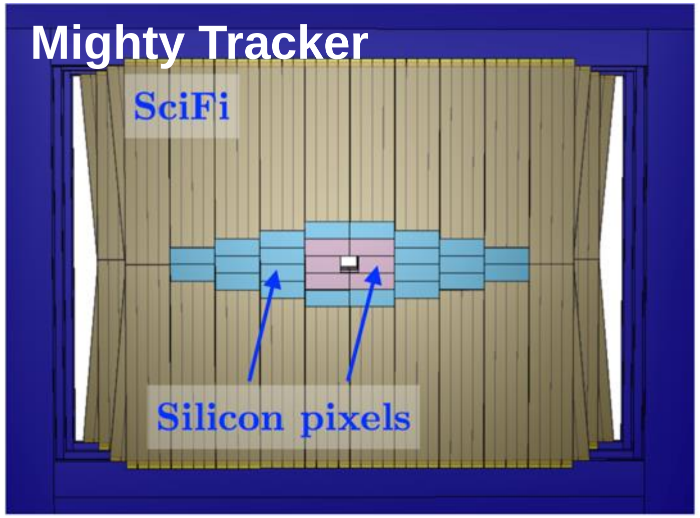
- Requirements:
  - large scale, low cost: $30m^2$ per layer, 12 layers
  - 70μm resolution in bending plane
- R&D:
- **Scintillating Fibre tracker**.
  - Radiation hard NOL fibres. > 35kGy
  - Cryogenic operation SiPMs.
  - SiPMs reduce active area, micro-lenses.
  - Time resolution to provide y-segmentation ?
- **Gaseous Solutions ?** No R&D currently

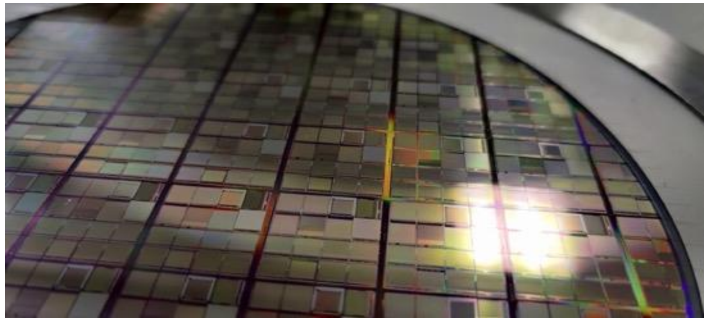


TF3: Solid State Detectors

LHCb Upgrade II : Tracking System

- System before magnet (UT), inside SciFi (MT)
- Requirements:
  – Si Area for LS4 (with aim small scale in LS3)
    - UT Si – 6m^2 . MT Si - 20m^2
  – Pixel size e.g. 50x150,100x300μm^2
  – Radiation e.g. 5x10^{13}-5x10^{14} 1MeV n_{eq}/cm^2
  – Precision timing ?





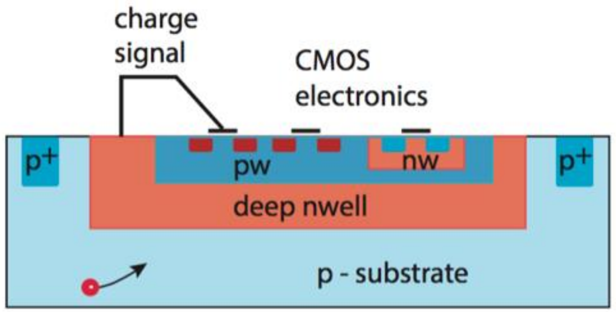
- R&D: MAPS. **First large-scale rad-hard CMOS detector at LHC**
  – MightyPix based on MuPix/ATLASPix HV-CMOS
  – Other solutions ? Synergy EP R&D , future accelerators ?

TF3: Solid State Detectors

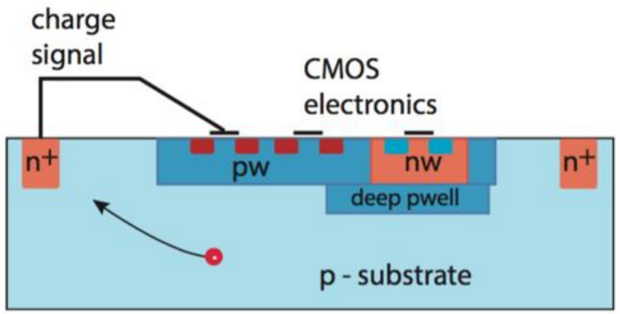
ATLAS in LS4/LS5

- Replace inner two pixel layers ~1500 fb^{-1}
  - 3D pixel sensors: neutron fluence
  - CMOS Front-end ASICs: total ionizing dose
  - Add timing information 10-50ps ?
- Radiation hard MAPS
  - ITk-Pixel Inner System, minimize material
- Replace inner HGTD ring every 1000 fb^{-1}, middle ring 2000 fb^{-1}
  - degrade below 4 fC threshold for neutron fluence > 2.5×10^{15} 1 MeV-Si n/cm^2

MAPs alternatives studied for Upgrade II but not yet sufficiently mature



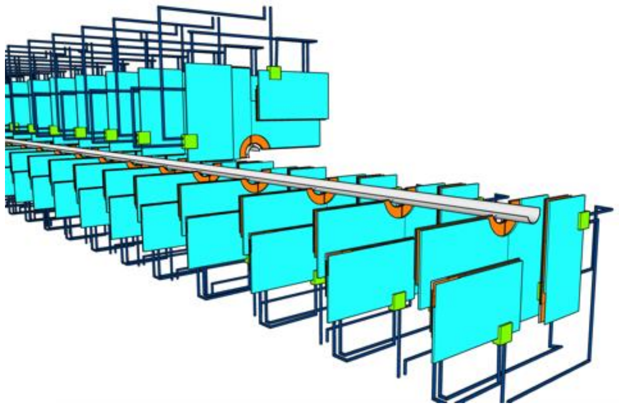
(a) Large fill-factor

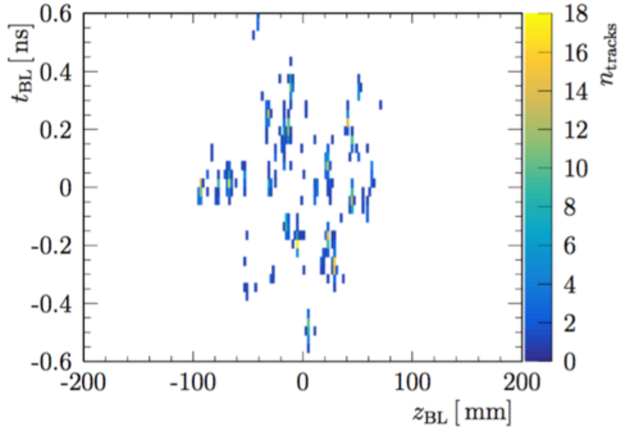


(b) Small fill-factor

TF3: Solid State Detectors

LHCb Upgrade II : Vertex Detector (VELO)





- Requirements
  - Small scale: 52 modules U1
  - Pixel size: <=55x55μm
  - Timing: < 50ps per hit
  - Extreme Radiation: $6x10^{16}$ 1MeV n_{eq}/cm^2 at 5mm from beam
  - Max Chip Data rate: 250Gbps
- R&D: Hybrid Pixel Detectors
- Sensors: Thin Planar – small signals. Low Gain Avalanche Diodes – isolation, radiation. 3D - Dead areas (CMS interest also). Prototypes of all.
- Chips: TimePix4, TIMESPOT. Cooling: below CO_2 ?

TF3: Solid State Detectors

CMS in LS5: Pixel Upgrade & Inner Rings

- Planar sensors with **smaller** pixel and correspondingly thinner
- Corresponding very fine pitch bump bonding (hybridisation)

CMS in LS4/5: Additional Pixel Disk in Forward ?

- Or other additions on high precision timing
  - understanding/improvement on rad tolerance, smaller cells and higher fill factor

CMS – other items

- Radiation hard SiPMs – a key technology
- Thermo-Electrical Coolers – cool SiPMs or other applications

TF4: Photon Detectors & Particle ID

LHCb Upgrade II : RICH

- Aim: ~0.2 mrad single photon angular resolution
  - 50ps time resolution
  - 20-40 Cherenkov photon hits
  - Wide momentum coverage between 10 to 200 GeV/c
- Requirements: composite optics
  - – novel opto-electronic chain (with ps-time resolution, 2-bits logic and a ns-gated latching scheme)
  - – green-extended (cooled) photodetectors.
- R&D: Cooling and cryogenics;
  - – New cost-effective optical and radiator materials;
  - – Rad-hard photodetectors;
  - – Rad-hard low-consumption ps-resolution high-granularity front-end electronics.

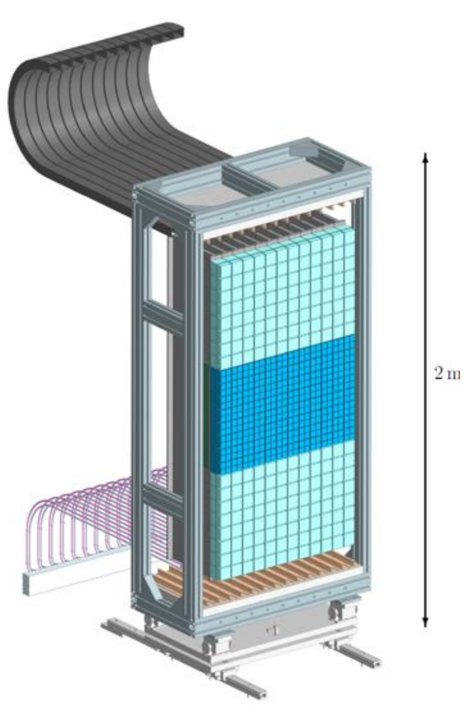
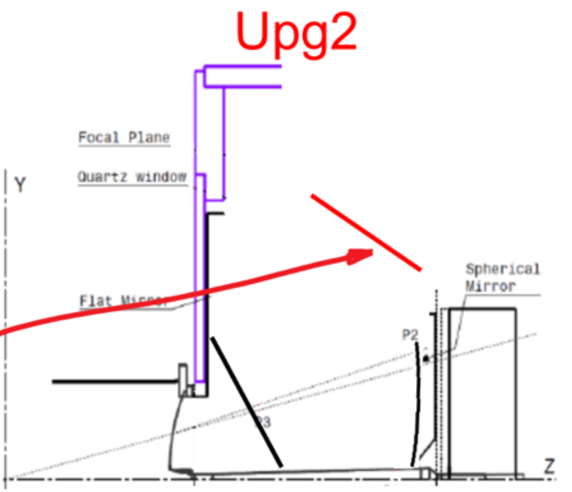


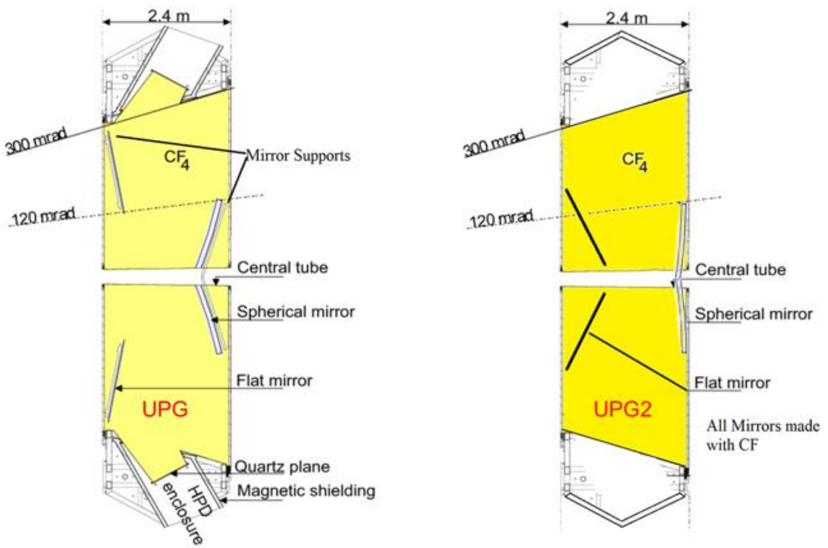
Figure 4: A CAD representation of the photodetector array.

Lumi = 10^{34} cm^{-2} s^{-1}; Occupancy < 30%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	60 - 40
Single Photon Errors [mrad]	
Chromatic	0.24
Pixel	0.15
Emission Point	0.1
Track resolution	?
Overall	0.3

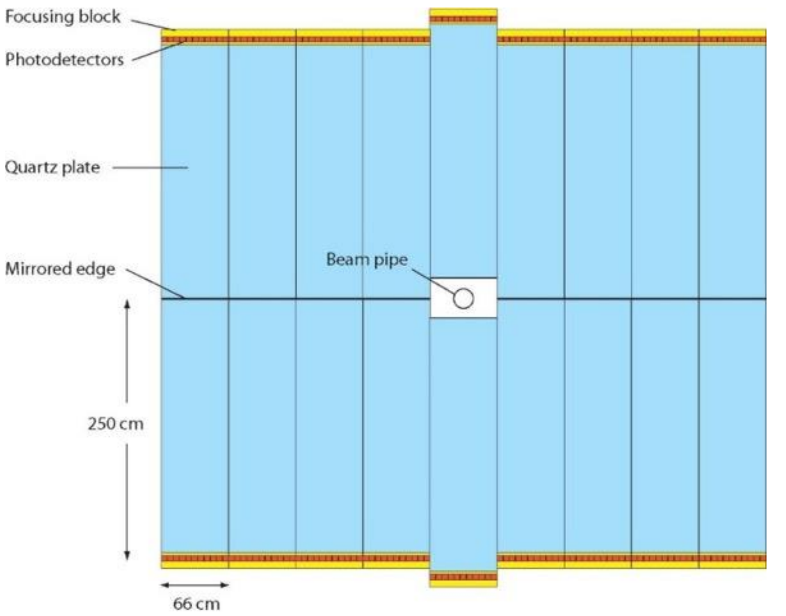


Reduce chromatic by choosing a photodetector with a “green-shifted” QE curve (and filter the shorter wavelengths)

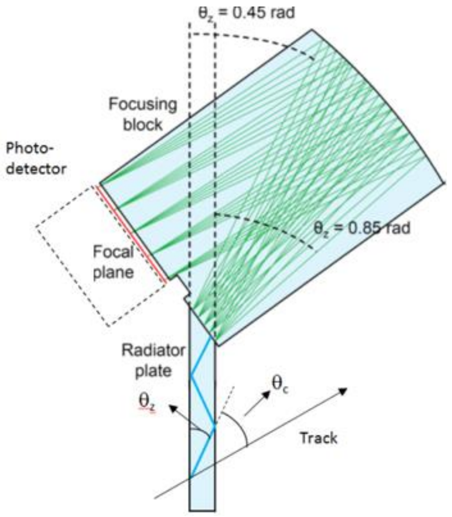


TF4: Photon Detectors & Particle ID

LHCb Upgrade II : TORCH ToF



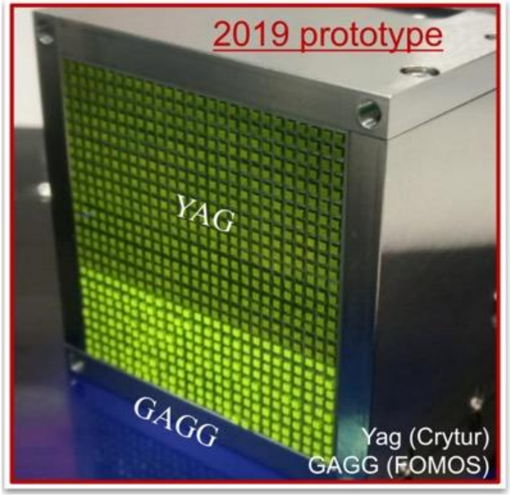
- Timing information and precise photon reconstruction
  achieve a ToF resolution ~15 ps per track.
- Requirements:
  - 30m^2 of 1cm thick quartz with surface roughness ~1nm
  - MCP photon detectors with ~20 ps intrinsic resolution
  - Fast front-end ASICs with compatible timing resolution
- R&D:
  - Cheaper large-area quartz production and polishing
  - MCPs with high granularity (128x128 pixels over 2” active square area) withstanding integrated currents >100 Ccm^{-2}
  - High resolution amp/discriminator/TDC readout chips with high channel count

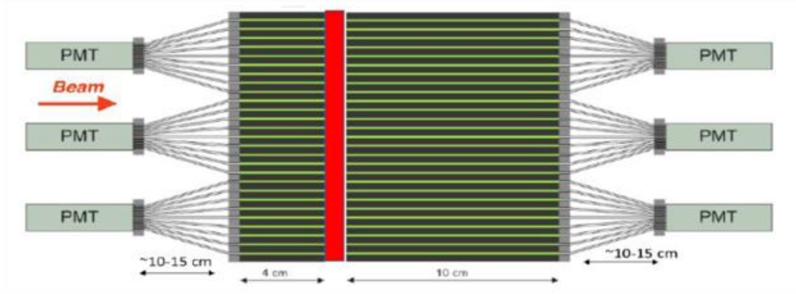


TF6: Calorimetry

LHCb Upgrade II : Electromagnetic Calorimetry

- Increased interest in ECAL: LFU, electrons, π^0, radiative decays
- Requirements:
  - Radiation regions: 1MGy, 200kGy, < 10kGy
  - Energy Resolution: $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
  - Timing capabilities: O(10)ps for pile-up mitigation
- R&D: SPACAL, Shashlik with timing
  - Crystal Scintillator, Tungsten absorber
  - Polystyrene fibres, Lead absorber
- Timing Layer
  - i-MCP layer for 10-20ps, Si layer ?



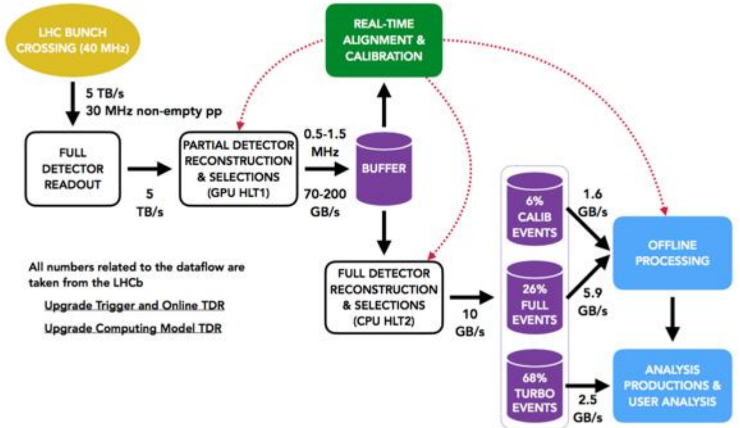


TF7: Electronics & On-detector Processing

ATLAS/ CMS / LHCb

- ASIC feature size CMOS e.g. 28 nm
- CERN support for chips important
- Next-generation rad hard data optical links
  - Low power,low-mass, towards 100 Gbps?
  - with silicon photonics ?
- DC-DC converters – higher input V?
- Processing Both **ON** and **OFF** detector
- Innovative algorithms for real-time trigger applications in **heterogeneous** architectures
  - GPUs, IPUs, TPUs, FPGAs
- data-centre / commodity / cloud technologies for Online processing?

LHCb Upgrade II: Trigger & DAQ system



- GPU based real-time HLT1 reconstruction and triggering In LHCb Upgrade I
- U2 foresees 5x data throughput

TF8: Integration

LHCb Upgrade II – but many points in common

- mechanical challenges for inner trackers
  - support structures: lightweight material in the acceptance with stringent stability and radiation tolerance requirements.
- original solutions for neutron shielding for critical components
  - SiPMs
- Robotics and remote intervention ?
  - VELO module replacement
  - Central part of the Calorimeter
- In General, R&D should also be carried

on the radiation tolerances of the material used

  - glue, rubber, support structure...

Nuclear power plant robot

TF9: Training

- "Learning by Doing"
  - The HL-LHC experiments will be the foremost particle physics research environment for the next 20 years
  - As such they provide the primary training environment for our community
- Provides both opportunities (R&D & operations) & responsibilities
  - Responsibility to be involved in training activities
  - Collaborations have surprisingly little centralized formal training activities for organizations of our size but numerous strong supporting activities
- Balance between internationalisation & reducing travel
  - Equal access, CO_2 footprint

Summary: Detector R&D for the HL-LHC

- Our ability to exploit HL-LHC limited by our detector technology
  - Timing at < 50ps; radiation hardness; low-cost, high granularity
- HL-LHC timescales
  - LS4/LS5: R&D period next five (ten) years
    - LHCb Upgrade II, larger scale than previous versions
    - ATLAS/CMS by LS5 inner pixels, timing dets
- HL-LHC provides the proving ground for the technologies of the future, collaborate on R&D

References

LHCb Upgrade II

- Expression of Interest: CERN-LHCC-2017-003

http://cdsweb.cern.ch/record/2244311?ln=en

- Physics Case: CERN-LHCC-2018-027

http://cdsweb.cern.ch/record/2636441?ln=en

- Contact: Matteo Palutan
  - U2 Planning group chair & Deputy Spokes

ATLAS Post-LS3 Upgrades

- Contact: Francesco Lanni

No post-LS3 references yet. Systems for partial replacement

- High-Granularity Timing Detector. ATLAS-TDR-031

https://cds.cern.ch/record/2719855?ln=en

- Inner Tracker Pixel Detector. ATLAS-TDR-030

https://cds.cern.ch/record/2285585?ln=en

CMS Post-LS3 Upgrades

- Contact: Frank Hartmann

No post-LS3 references yet. Systems for partial replacement

- Inner Tracker for Upgrade II. CMS-TDR-014

https://cds.cern.ch/record/2272264

- Endcap Timing Layer for Upgrade II. CMS-TDR-020

https://cds.cern.ch/record/2667167?ln=en

LHCb Muon μ-RWELL

- *G. Bencivenni et al., 2015_JINST_10_10_P02008*
- *G. Bencivenni et al., 2019_JINST_14_P05014*

LHCb Large Scale Tracker References

- Upgrade I SciFi TDR: **http://cdsweb.cern.ch/record/1647400?ln=en**.

- LHCb Original straw tubes: **http://cdsweb.cern.ch/record/519146?ln=en**

- Fred Blanc. Upgrade II presentation. Scintillating fibres and depleted silicon sensors for the LHCb Mighty Tracker. FCC Workshop.
  https://indico.cern.ch/event/932973/contributions/4041318/attachments/2141574/3609095/20201112_LHCbMightyTracker_FCCWorkshop.pdf

LHCb CMOS based Tracker

- Upgrade I UT TDR: **http://cdsweb.cern.ch/record/1647400?ln=en**.

- Mighty Tracker Design studies. Internal Note. LHCb-INT-2019-007
  – Available to potential collaborators. Contact: Chris Parkes
- HV-CMOS chip spec. LHCb-INT-2020-016
  – Available to potential collaborators. Contact: Chris Parkes

- Fred Blanc. Upgrade II presentation. Scintillating fibres and depleted silicon sensors for the LHCb Mighty Tracker. FCC Workshop. https://indico.cern.ch/event/932973/contributions/4041318/attachments/2141574/3609095/20201112_LHCbMightyTracker_FCCWorkshop.pdf

LHCb VELO Upgrade II

- Upgrade I VELO TDR:
- http://cdsweb.cern.ch/record/1624070?ln=en

- VELO U2 Design studies. Internal note in preparation
  - Contact: Paula Collins

LHCb Particle Identification

- Upgrade I RICH Systems TDR

http://cdsweb.cern.ch/record/1624074?ln=en

  – Contact: Carmelo D'ambrosio

- TORCH LHCb Public note. LHCb-PUB-2020-006

http://cdsweb.cern.ch/record/2729016?ln=en

  – Contact: Neville Harnew