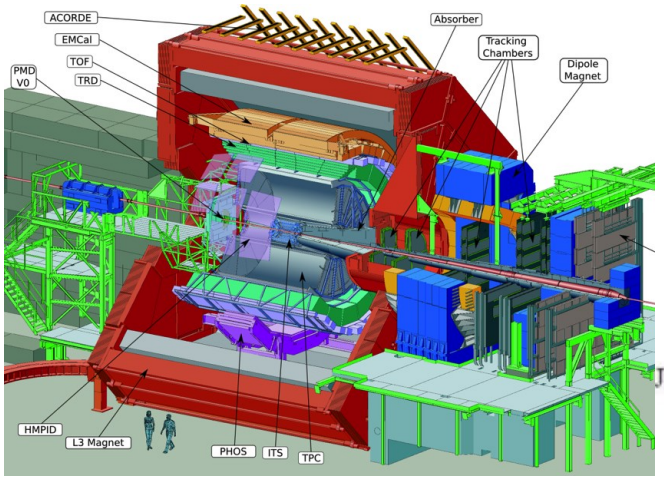
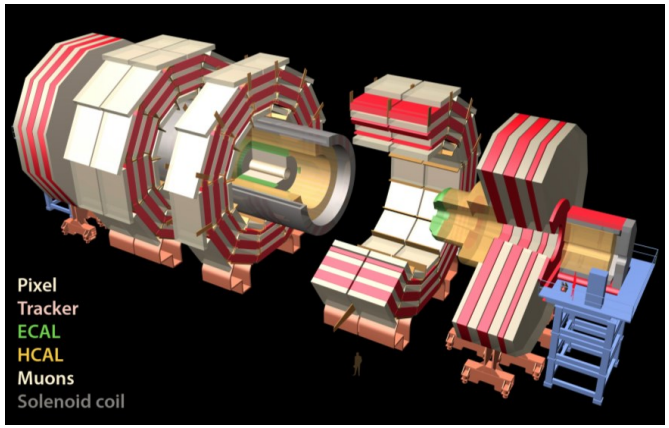
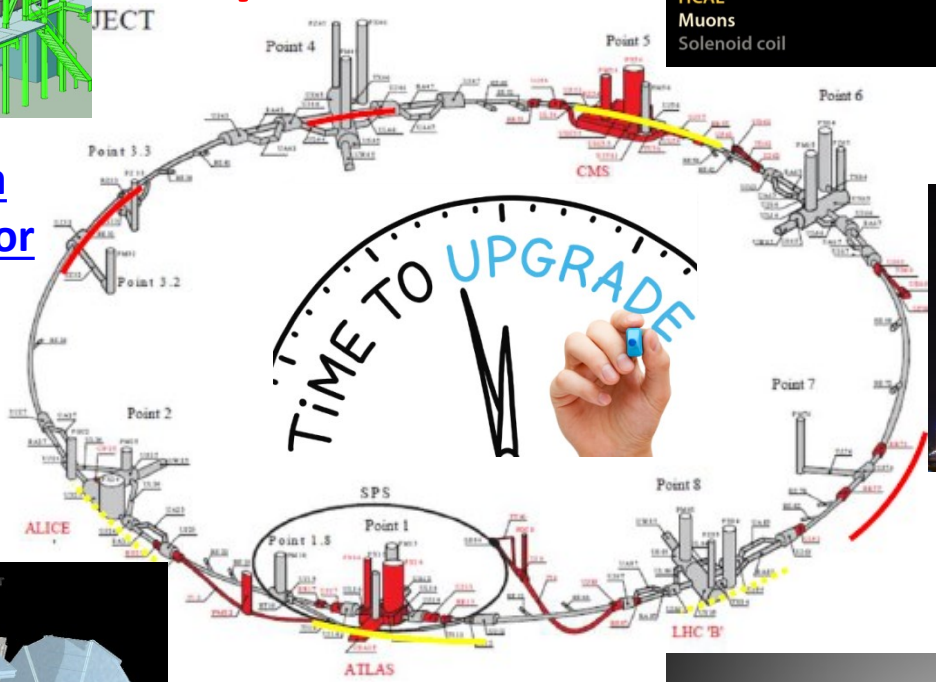
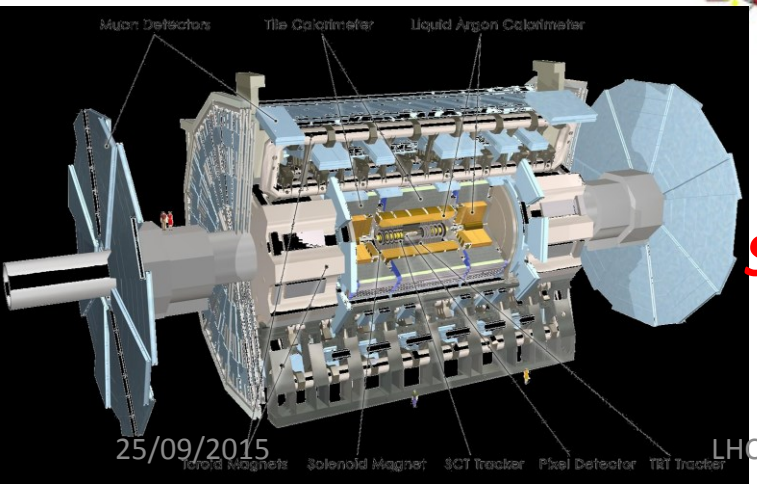


LHC Upgrades Accelerator & Experiments

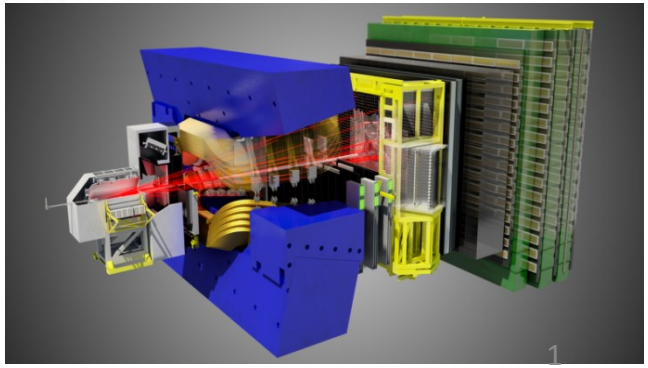


10th Hiroshima Symposium Application of Semiconductor Tracking Detectors, Xi'an, China

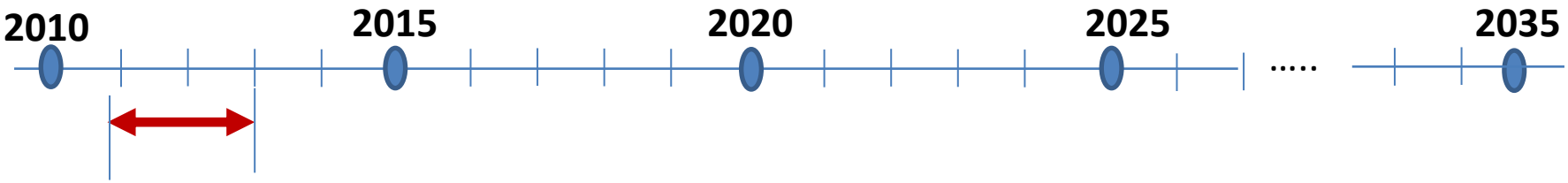




Steve McMahon
RAL/Oxford
UK



Timeline to Upgrades



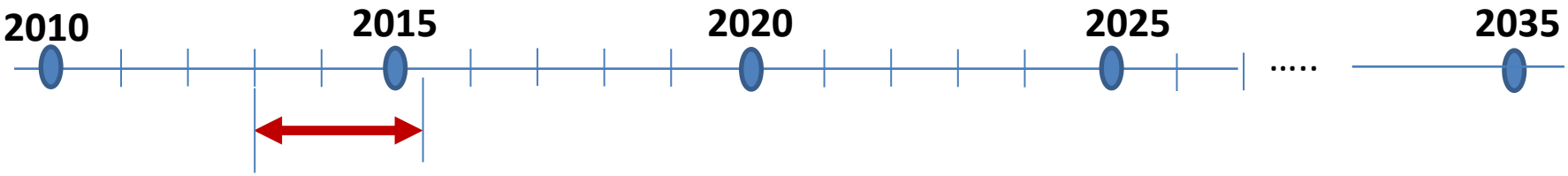
LHC-Run-1 : *History*

proton-proton (p-p) centre-of-mass energy 7 - 8 TeV
Bunch spacing 50ns *(some tests at 25ns, mainly used for scrubbing)*
Number of p-p interactions per beam crossing : Pile-up :<μ> 20-30
Maximum instantaneous luminosity 6-7 x 10^{33} cm^2s^{-1}
Integrated luminosity for **G**eneral **P**urpose **D**etectors (ATLAS and CMS) ~30fb^{-1}
LHCb p-p : collect around 3.36fb^{-1}
ATLAS-CMS-ALICE: (pb-pb) : 0.15 nb^{-1}
All experiments p-Pb 30nb^{-1}

High Luminosity LHC plan beyond 2015, updated according to the CERN MTP for 2016-2020, CERN Council June 2015
These slides rely heavily on presentations made at the two ECFA workshops in 2013 and 2014.

Start of year

Timeline to Upgrades



LHC-Long-Shutdown-1 (LS1 or Phase-0)

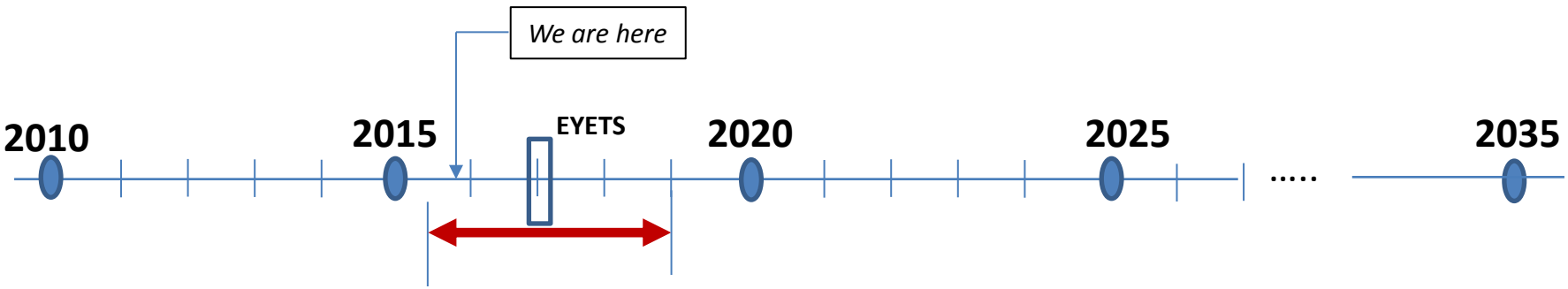
LHC

Consolidation of the LHC – splice repairs, Improved collimation, R2E project … see next slide.

ALICE, ATLAS, CMS, LHCb

Different levels of upgrade discussed in the slides

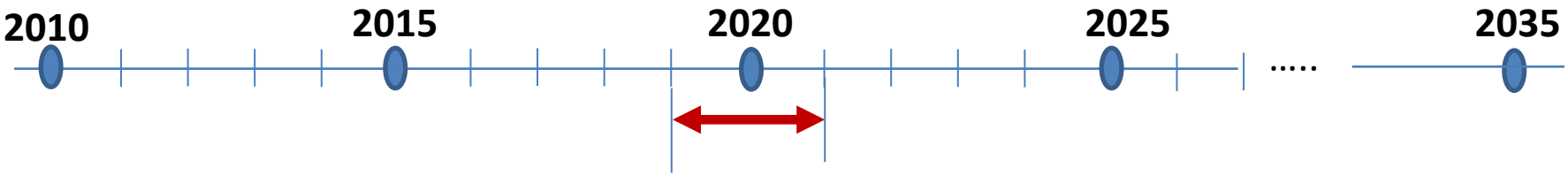
Timeline to Upgrades



LHC-Run-2 : *The Present*

proton-proton centre-of-mass energy 13-14 TeV, bunch spacing reduced to 25ns, 2808 bunches
Maximum instantaneous luminosity 1-2 x 10^{34} cm^2s^{-1}
Number of p-p interactions per beam crossing : Pile-up : $<\mu>$ 25-50
Integrated luminosity for GPD's (ATLAS and CMS) 150fb^{-1} at end of run.
Extended Year End Technical Stop (EYETS) **16-17** CMS install new pixel detector
LHCb p-p : collect around 7fb^{-1}
ATLAS-CMS-ALICE: (pb-pb) : 1 nb^{-1}
All experiments p-Pb ~100nb^{-1}

Timeline to Upgrades



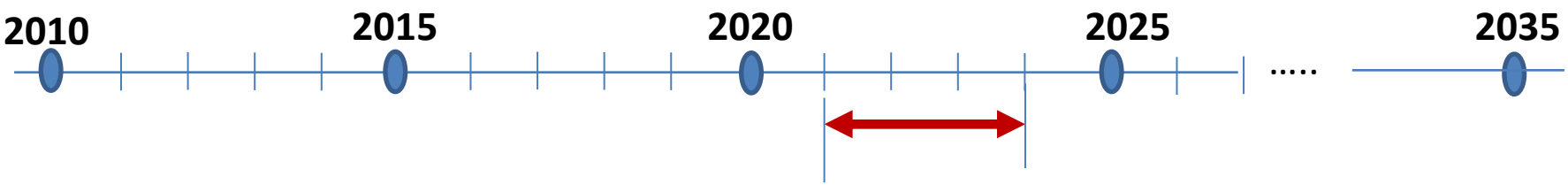
LHC-Long-Shutdown-2 (LS2 or Phase-1)

LHC

Injector upgrade Linac-4 , cryogenics at point-4, Civil engineering at P1-P5
A new SPS injection kicker system with a 50ns rise time
Collimators with dispersion suppression regions close to experimental points to avoid quenches and excessive radiation load.

ALICE, ATLAS, CMS and LHCb all have upgrades *(see slides below)*
For ALICE and LHCb these are the Major upgrades

Timeline to Upgrades

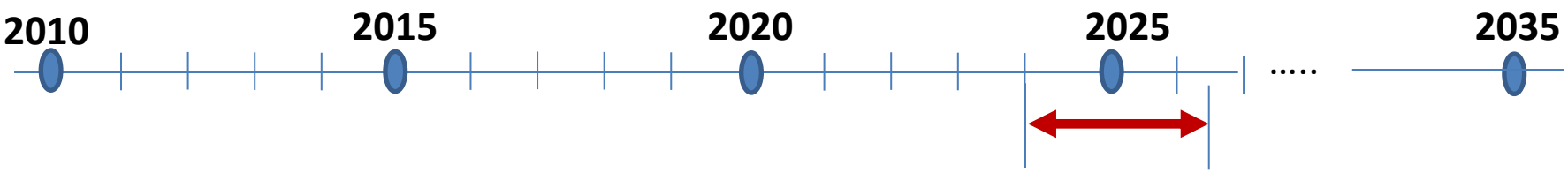


LHC-Run-3

proton-proton centre-of-mass energy 14 TeV at bunch spacing 25ns
Maximum instantaneous luminosity ~≥ 2 x 10^{34} cm^2s^{-1}
Integrated luminosity for GPD's (ATLAS and CMS) 300fb^{-1}
Heavy Ion luminosity goes from 1 x 10^{27} cm^2s^{-1} to ~7 x 10^{27} cm^2s^{-1}
LHCb p-p : 2020to end of program aim to collect around 50fb^{-1}

This marks the end of phase I

Timeline to Upgrades

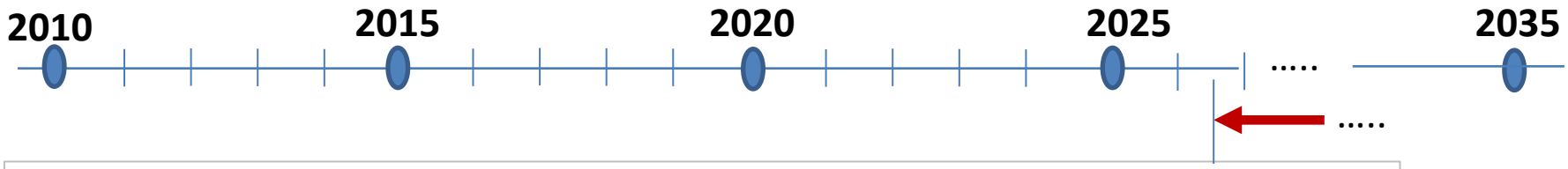


LHC-Long Shutdown 3 (LS3 or Phase-2)

LHC, ATLAS & CMS

All have major upgrades (details in the slides below)
30 months in total.
ATLAS and CMS upgrades cost ~270MCHF.

Timeline to Upgrades

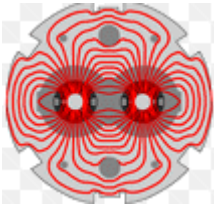


HL-LHC-Run-4 and beyond ...*The Future*

proton-proton centre-of-mass energy 14 TeV, bunch spacing 25ns
Maximum available instantaneous luminosity ~2.0 x 10^{35} cm^2s^{-1}
Use levelled instantaneous luminosity up to a peak of 7.5 x 10^{34} cm^2s^{-1}
Number of p-p interactions per beam crossing : $<\mu>$ 200
Integrated luminosity for GPD's (ATLAS and CMS) **3,000fb^{-1}**, (300$fb^{-1}yr^{-1}$)
ATLAS-CMS-ALICE: (pb-pb) : 10 nb^{-1}

After Run-3 : Getting to HL-LHC

from 300fb^{-1} to 3,000fb^{-1} (300fb^{-1}yr^{-1})



Number of bunches
50ns - 25ns

Number of particles per bunch

$$L = \gamma \left(\frac{f_{rev}}{4\pi}\right) \frac{n_b \,.\, N_b^{\,2}}{e_n \,.\, \beta^*} F(\phi, \beta^*, \varepsilon, \sigma_s)$$

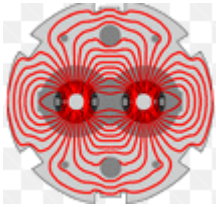
emittance

Beta-Star

Geometric Factor

- maximize bunch intensities → Improve upgrade accelerator complex
- minimize beam size (constant beam power) → Focusing quadrupoles at Interaction points
- maximize number of bunches (beam power) → 25ns operation
- minimize the beam emittance
- compensate for geometric factors → Crab cavities
- Improve machine 'up-time' → Minimize unscheduled aborts

Getting to the HL-LHC luminosity



Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)
Beam energy in collision [TeV]	7	**7**
N_b	1.15E+11	**2.2E+11**
n_b	2808	**2748**[1]
Number of collisions at IP1 and IP5	2808	**2736**
beam current [A]	0.58	**1.09**
x-ing angle [μrad]	285	**590**
beam separation [σ]	9.4	**12.5**
β^* [m]	0.55	**0.15**
ε_n [μm]	3.75	**2.50**
ε_L [eVs]	2.50	**2.50**
Geometric loss factor R0 without crab-cavity	0.836	**0.305**
Geometric loss factor R1 with crab-cavity	(0.981)	**0.829**
beam-beam / IP without Crab Cavity	3.1E-03	**3.3E-03**
beam-beam / IP with Crab cavity	3.8E-03	**1.1E-02**
Peak Luminosity without crab-cavity [cm^{-2} s^{-1}]	1.00E+34	**7.18E+34**
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}]	(1.18E+34)	**19.54E+34**
Events / crossing without levelling w/o crab-cavity	27	**198**
Levelled Luminosity [cm^{-2} s^{-1}]	-	**5.00E+34**
Events / crossing (with levelling and crab-cavities for HL-LHC)	27	**138**
Peak line density of pile up event [evt/mm] (max over stable beam)	0.21	**1.25**
Levelling time [h] (assuming no emittance growth)	-	**8.3**

1.9^2

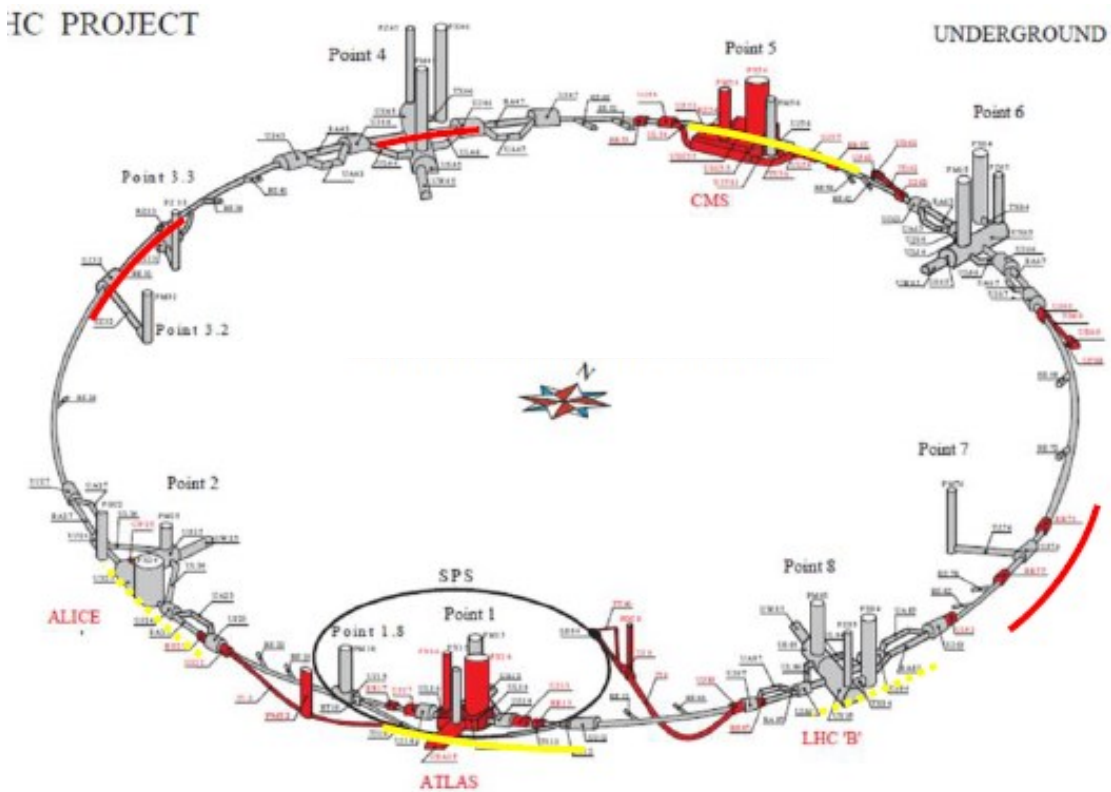
3.6

1.5

Factors ~20

Without upgrading machine (using continuous evolution) luminosity limited to 1,000fb^{-1}

The HL-LHC Project



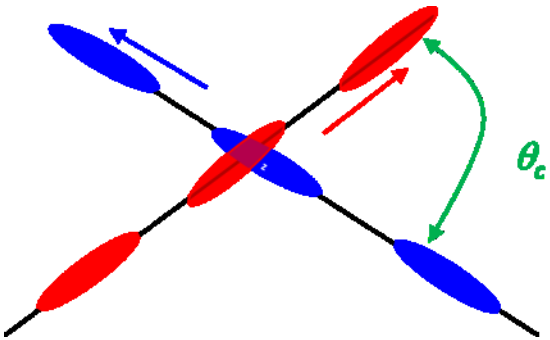
- New IR-quads Nb_3Sn (inner triplets-focussing)
- New 11 T Nb_3Sn (short) dipoles (allow collimation)
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

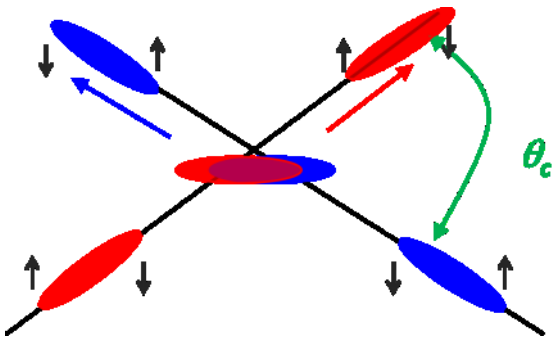
Crab Cavities, compensation

Aim: reduce the effect of the finite crossing angle

Without crabbing

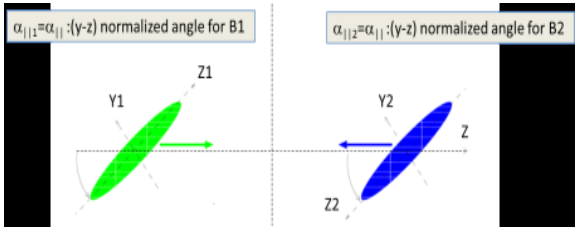


Without crabbing

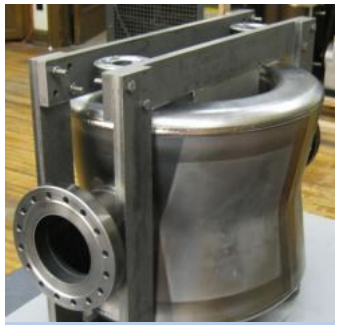


RF-Dipole Nb prototype

New crossing strategy under study mitigate the pile-up density: some new of the new schemes have interesting potential as “crab-kissing”

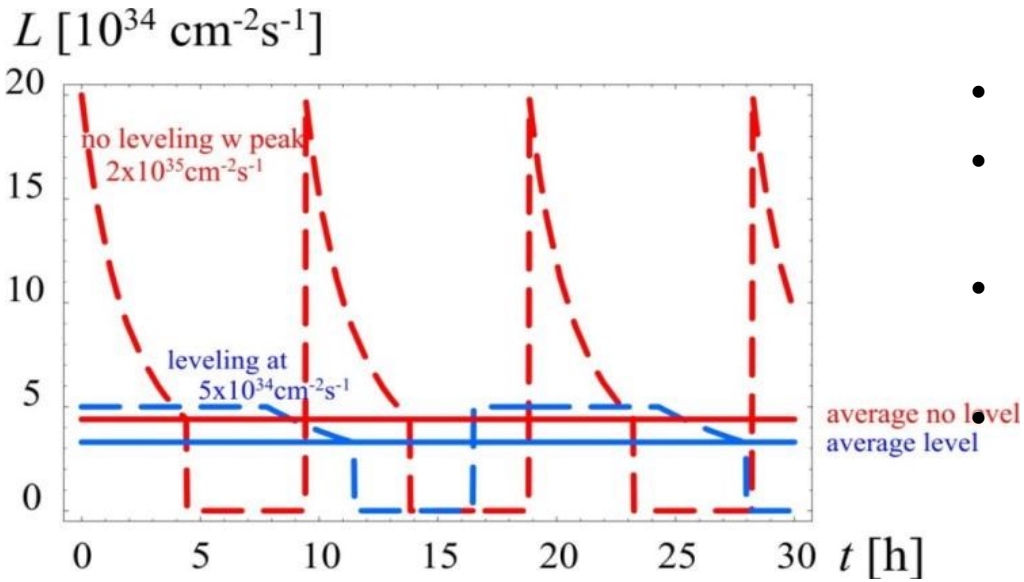


- 3 proto types available
- Cavity tests are on-going
- Test with beam in SPS foreseen in 2015-2016
- Beam test in LHC foreseen in 2017

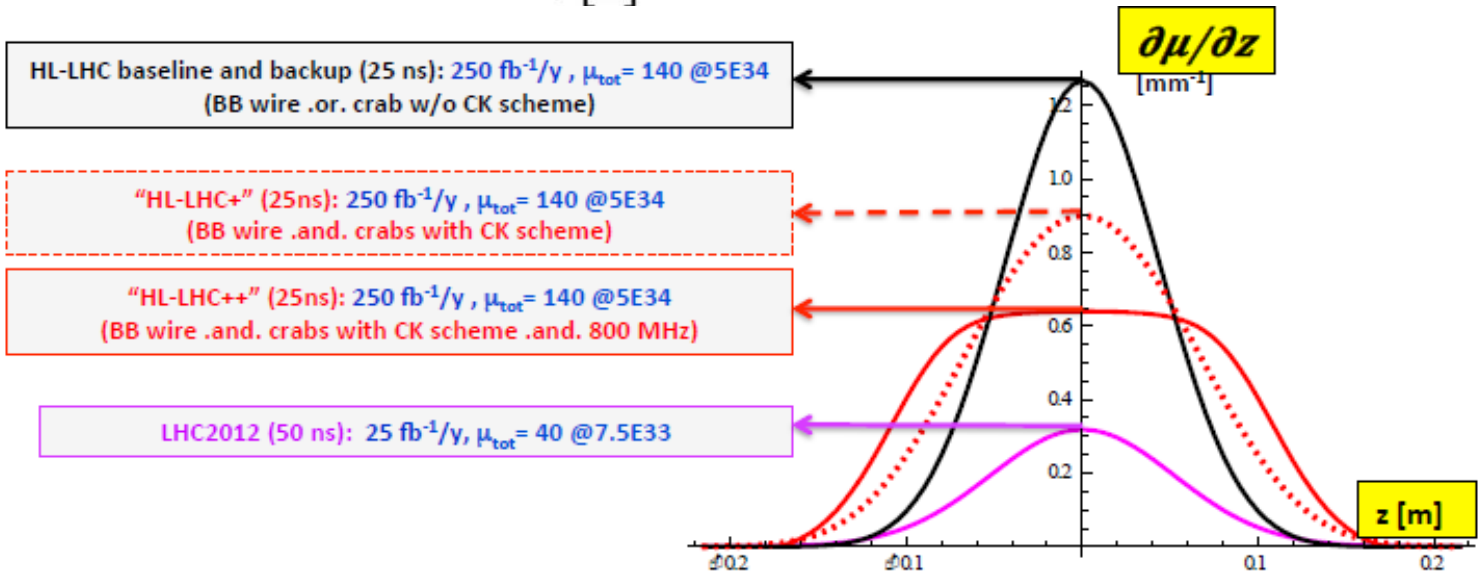


DQWR prototype
17-Jan-2013

Luminosity Levelling at HL-LHC

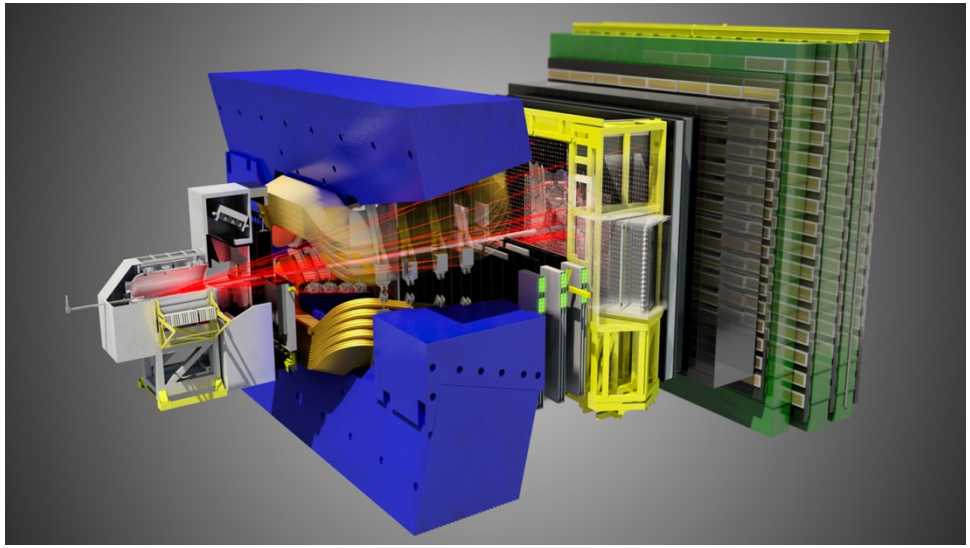


- High peak luminosity … not that useful
- Levelling minimizes pile-up in experiments and provide "constant" luminosity
- Schemes to minimize pile-up density in Z.
  - Crab Kissing
- Obtain about 3 - 4 fb^{-1}/day (40% stable beams)



The LHCb Upgrade Program

LHCb Phase 1

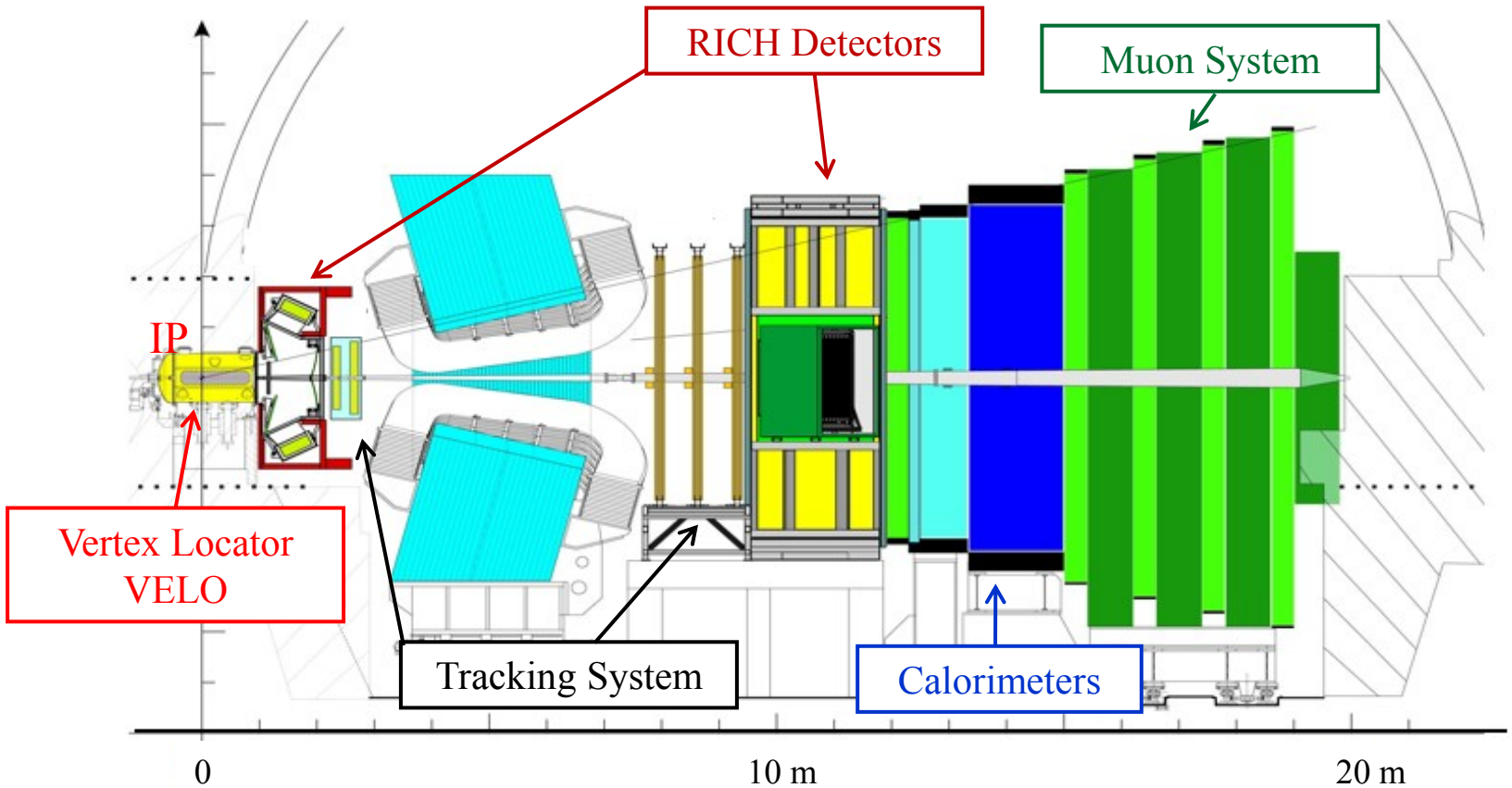


LHCb Overview

- High-precision b-physics experiment devoted to and the search for new physics.
  - Studying
    - CP violation and rare decays in the b and c-quark sector
    - Search for deviations from the SM due to new particles in loop diagrams
    - Maintaining sensitivity to new physics above the TeV scale
- **Run-1**
  - Excellent performance of all sub-detectors
  - running at levelled luminosity of ~4 x 10^{32} $cm^{-2}s^{-1}$, pile-up <μ> ~1
  - first level hardware trigger running at ~1 MHz
  - Trigger by looking for displaced vertices
  - Record data at ~3-5 kHz
- **LS2 and beyond**
  - increase luminosity to a levelled 2 x 10^{33} $cm^{-2}s^{-1}$, pile-up <μ> ~5
  - Now send data to fully flexible & efficient software trigger farm at 40MHz
  - 20kHz to storage
  - Plan to integrate ≥50 fb^{-1} of data over 10 years.
  - Installation takes about 18 months

LHCb full readout at 40 MHz

- Upgrade all of the sub-systems to 40 MHz Front-End readout
- Replace complete sub-systems with embedded legacy electronics
- Redesign sub-systems to increased occupancies and maintain excellent performance at the higher rates



LHCb : Vertex Locater upgrade

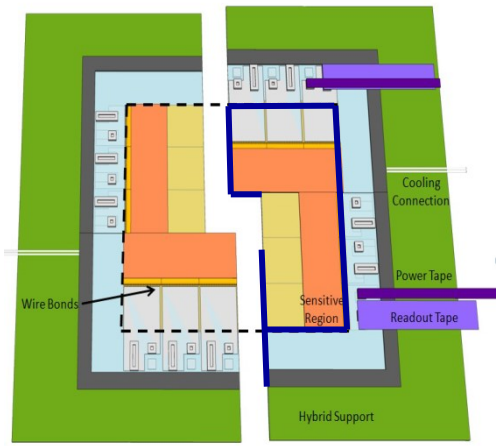
See talk by Xabier Cid Vidal

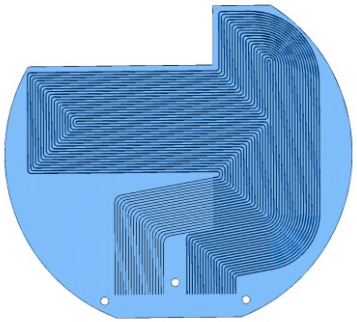
The Challenges:

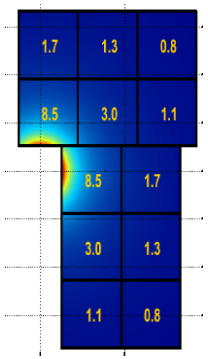
- withstand increased, non-uniform, radiation up to 8 x 10^{15} $n_{eq}cm^{-2}$
- high data volume at 40 MHz
- Increased acceptance
- Reduce the inactive material
- Move first layer closer to the beam 5.5mm → 3.5mm

Design and Technology Choices:

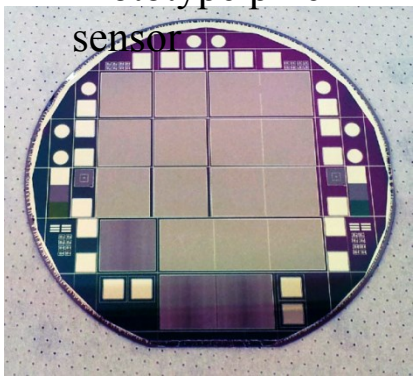
- 55x55 μm^2 pixel sensors
- 40 MHz VELOPIX (130 nm technology to sustain ~400 Mrad) (VELOPIX which is an evolution of the TIMEPIX)
- Thickness of foil between primary and secondary vacua from 300μm to 150μm
- Micro channel CO_2 cooling



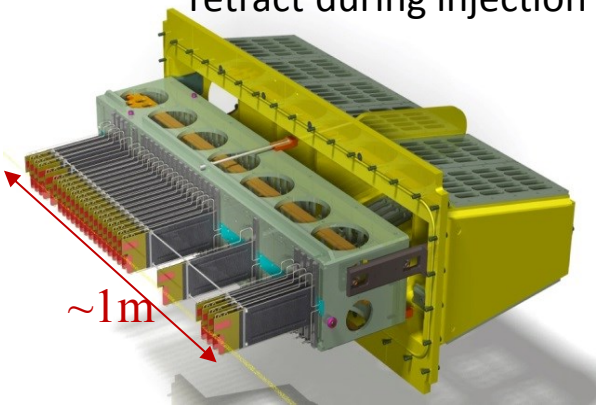




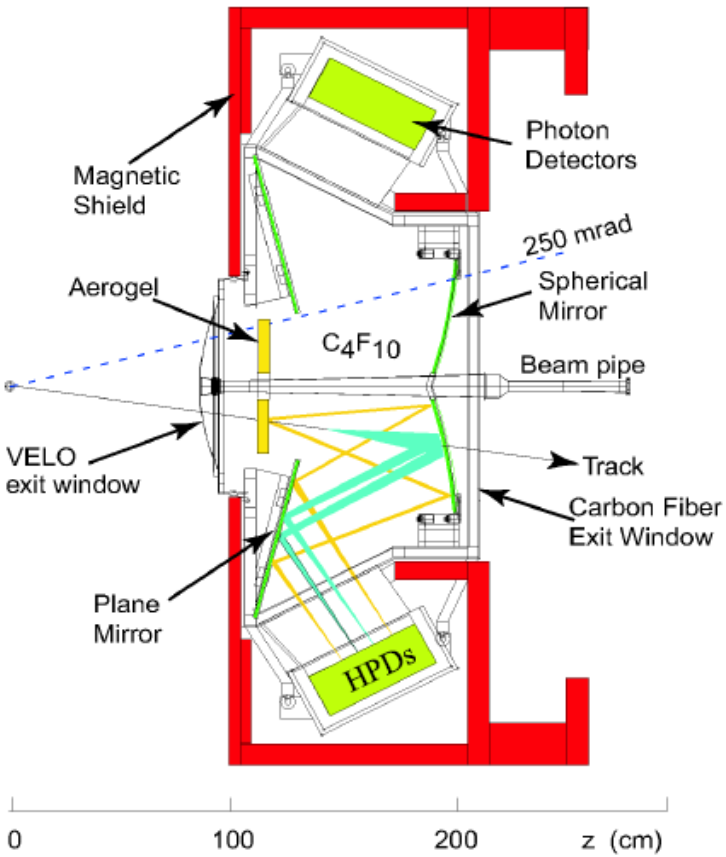
Prototype pixel sensor

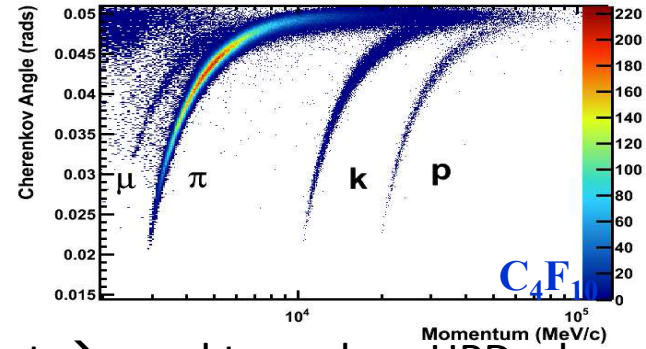


retract during injection



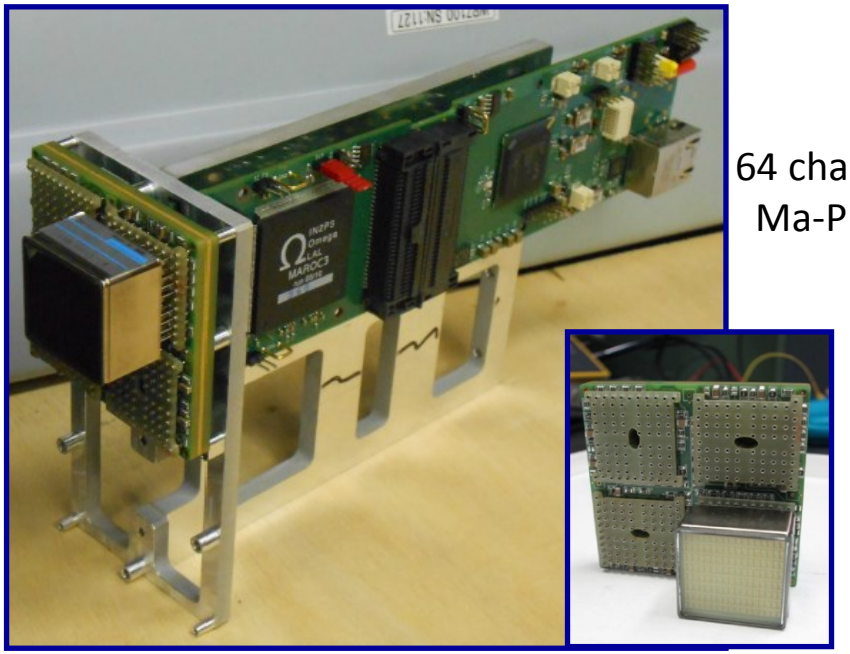
RICH Upgrade





40 MHz readout → need to replace HPDs due to embedded FE (1MHz limitation)

- Change to 64 channel Multi-Anode PMTs
- 40 MHz Front-End



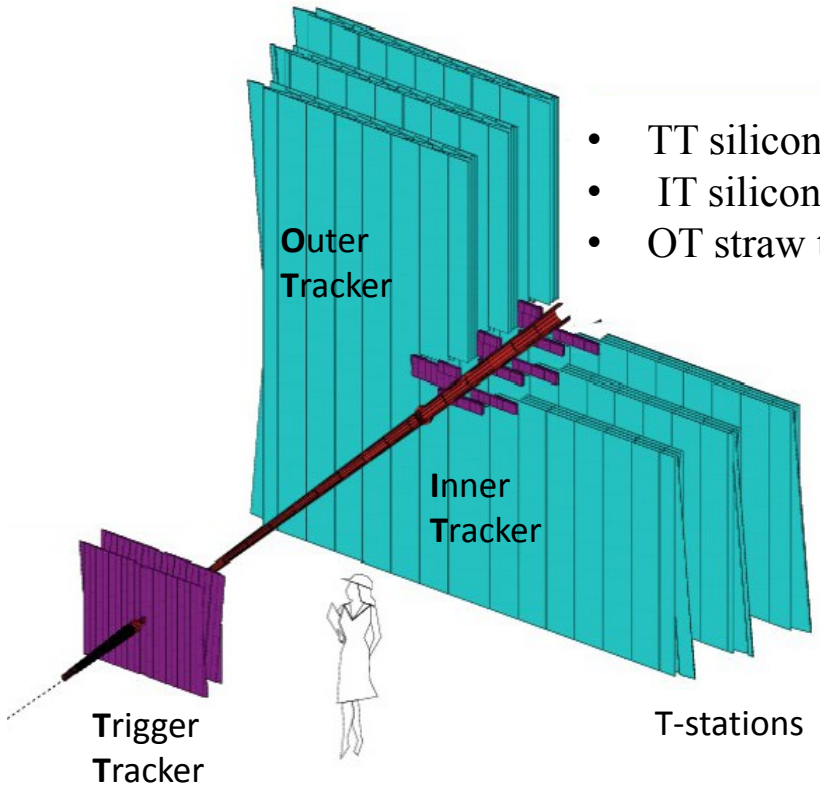
64 channel Ma-PMT

New photo-detector readout module

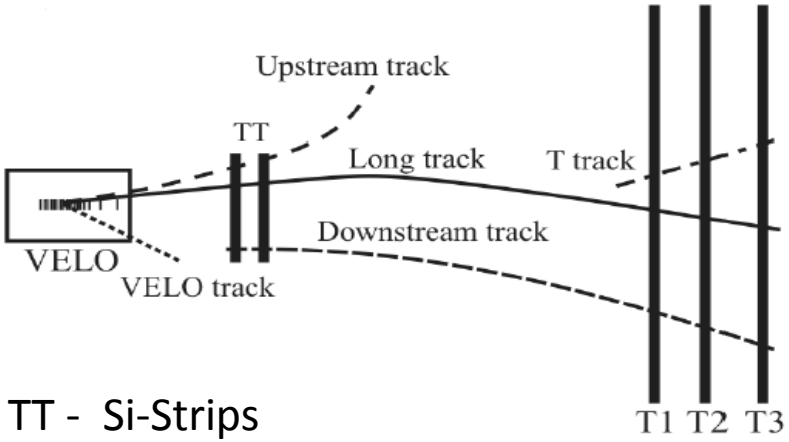
- Adapting to higher occupancy
  - Remove aerogel radiator
  - modify optics of RICH1 to spread out Cherenkov rings (optimise gas enclosure without modifying B-shield)

Tracking System Upgrade

- Excellent mass resolution
- Very low background

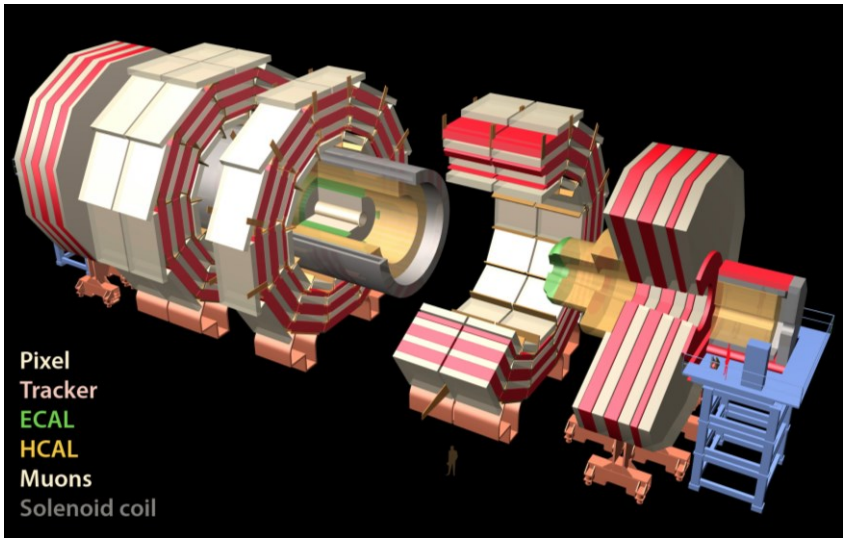


- TT silicon
- IT silicon
- OT straw tubes

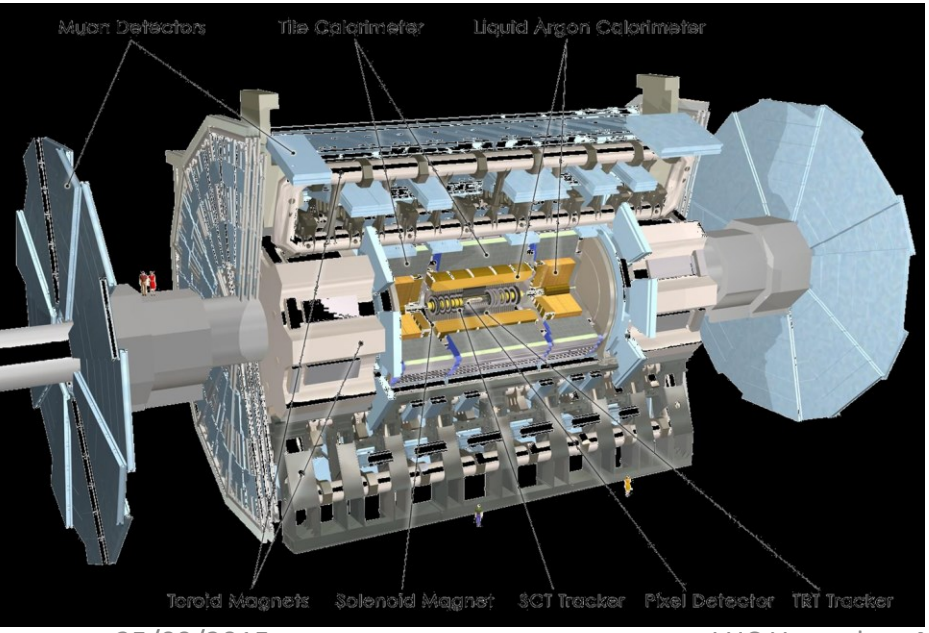


- TT - Si-Strips
  - p-in-n change to n-in-p
  - 5cm to 10cm long silicon strips
  - 180 → 90 µm pitch
  - ATLAS IBL like structures (Ca foam)
- Ti Stations
  - Fibre Tracker away from beam
  - Scintillating fibres MAT
  - Si-PM array to read out
  - Excellent position resolution
  - Cooling challenges (-40°C)

See talks by Mark Tobin, Olaf Steinkamp



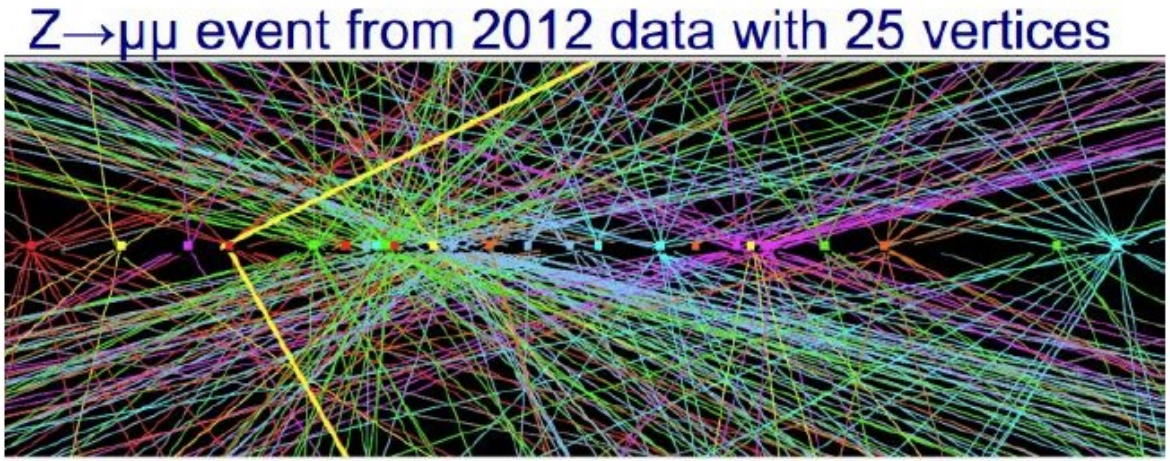
ATLAS and CMS

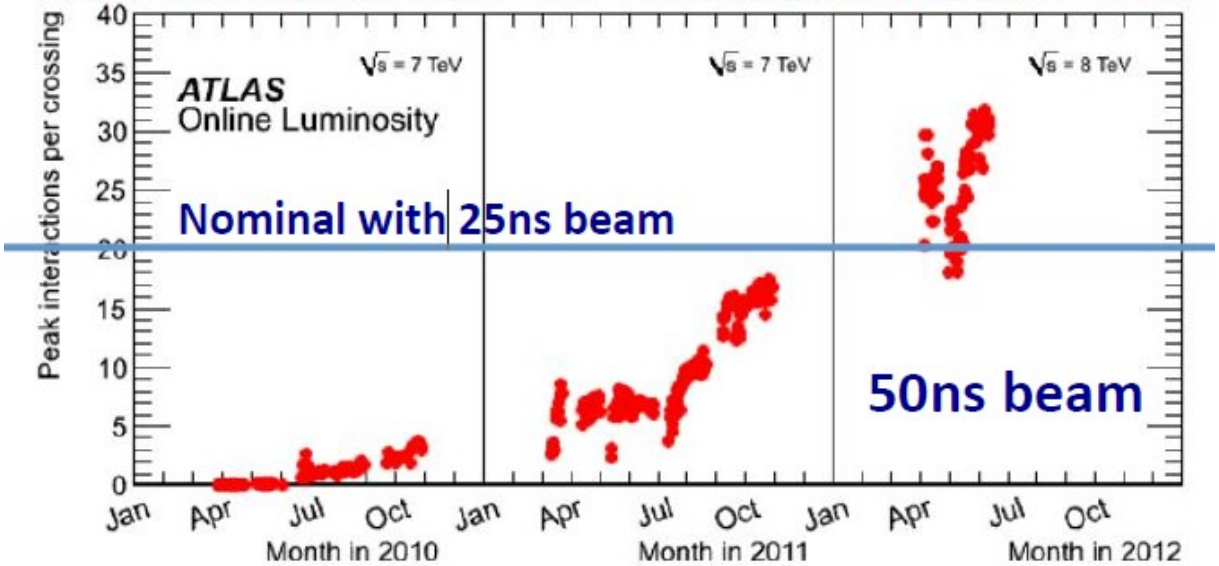


ATLAS and CMS Upgrades

- **Technical/Design issues/choices that apply to both experiments**
  - High radiation field within the detector (operation, installation and maintenance)
  - Radiation tolerant sensors for the pixel and strip detectors up to $2x10^{16}$ $n_{eq}cm^{-2}$
  - Radiation tolerant, low power, small feature size ASIC developments
  - Radiation tolerant powering schemes for High and Low Voltage (Serial Power or POL DC-DC)
  - Radiation tolerant high-bandwidth and optical data transmission (GBT, VL projects…)
  - High density, high reliability, low cost interconnects
  - Efficient trigger selection and getting from 40,000kHz to ~1,000kHz to 10kHz (incl Track Tigger)
  - Fast processors for track-triggers
  - Light mechanical structures, detector assemblies
  - Radiation tolerant crystals, photo-detectors and fibres for calorimeters
  - Radiation hard High rate gas chambers
  - Possibility of using high precision timing in calorimeter pre-sampling
  - Handling BIG DATA
  - …

Pile up in the GPD's

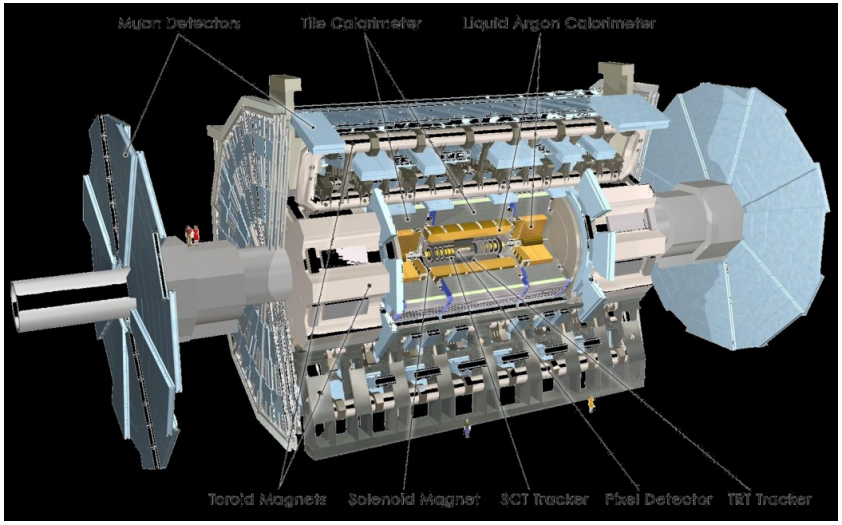




ATLAS and CMS Upgrades

- Performance Issues
  - Performance of detectors must not be significantly degraded in the presence of highest pile-up
  - Extensions of the rapidity coverage of all detectors towards $|\eta| = 4$
  - The possibility of using fast timing signals in the calorimeters to mitigate the effects of pile-up
  - Keeping the thresholds of trigger objects down while respecting the available bandwidth limitations
  - Using tracking in the earliest stages of triggering.
  - ….

ATLAS Phase 0



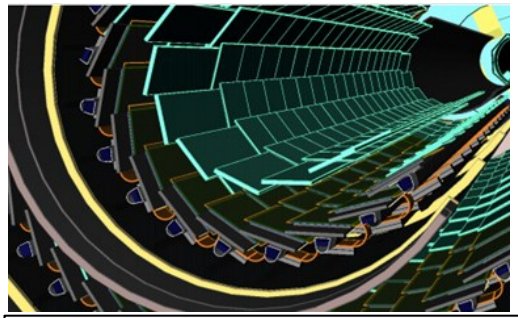
Points to draw your attention to..
EM Calorimeter in central region is LAr
Had-Calorimeter Scintillator
Forward Calorimeter LAr

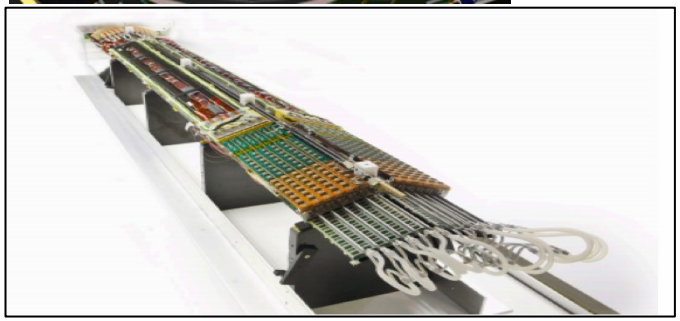
ATLAS Phase-0 upgrades

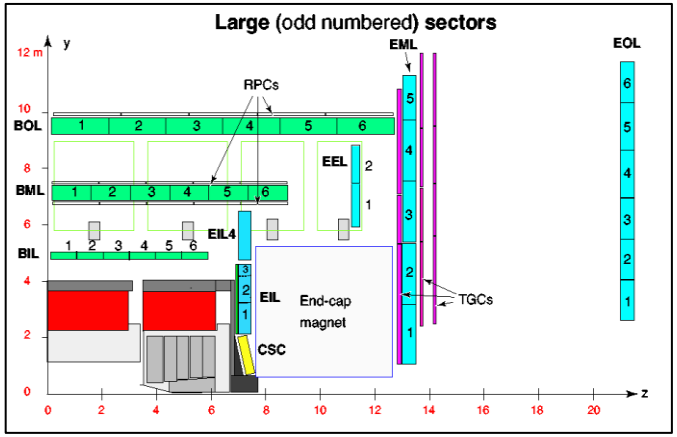
- Insertable B-Layer to 4 layer Pixel

  See talk by Malte Backhaus

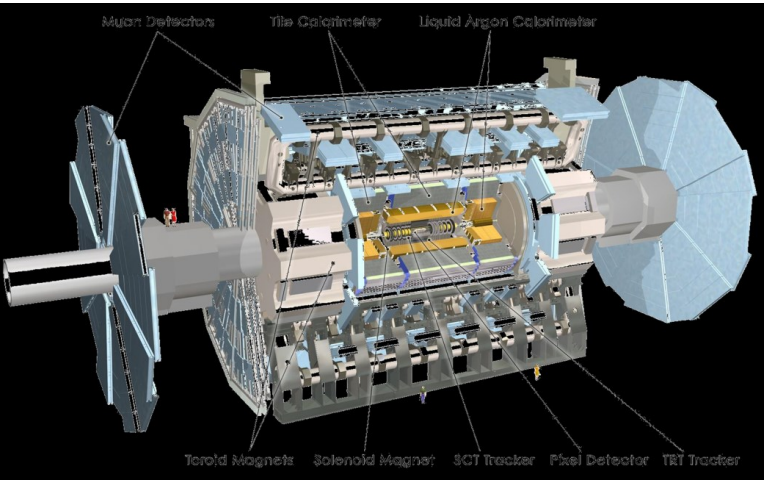
  – Add additional measurement/layer point close to I.P.
  – Better impact parameter resolution
  – Installation IBL in spring 2014
  – Important ingredient for low mass, rad-hard
  – construction: 2x2 cm FE-I4 Pixel Chip, 130 nm CMOS
  – Will stay up-to Phase-II
- Pixel Detector
  – new service panels – recover non-functional channels, better access, increased bandwidth
- Pixel + SCT Detectors
  – New thermoshipon cooling system
- Muon spectrometer
  – Install Muon End-cap Extension (EE) chambers to improve coverage at 1.0 < |n| < 1.3





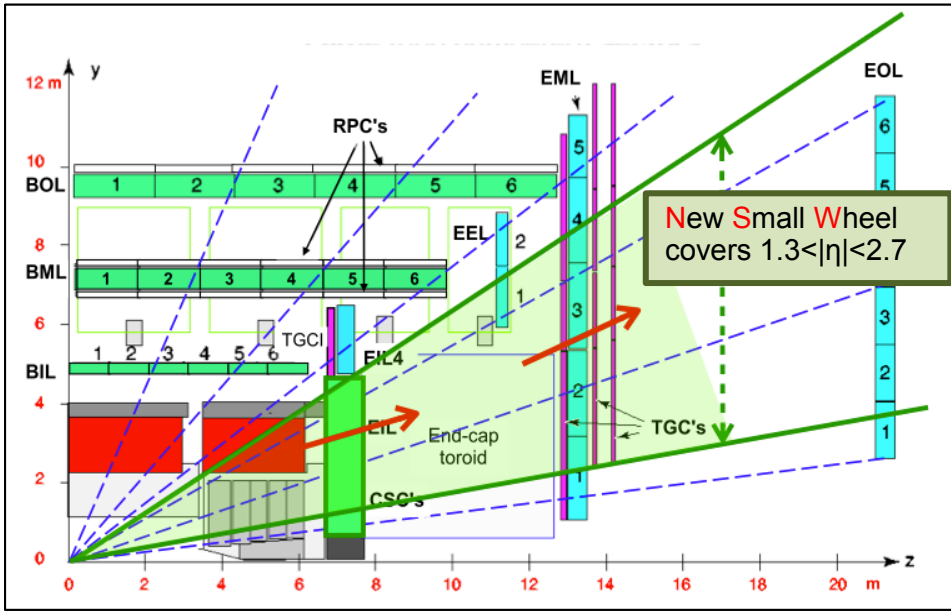


ATLAS Phase 1



Phase 1: New Small Wheel

- Replace existing Small Wheels with New Small Wheels
  - Cover the region in rapidity between 1.3 and 2.7
  - improved tracking and trigger capabilities
  - position resolution < 100 µm
  - IP-pointing segment in NSW with σ_θ~ 1 mrad
  - Meets Phase-II requirements
    - compatible with <µ>=200
    - Luminosities up to L~7x10^{34} cm^{-2}s^{-1}
  - Technology: Micro-Megas and s-TGC's
- Large reduction of muon L1 trigger rate
  - Especially in forward direction which is dominated by fakes
  - Coincidences with outer layers of Tile Calorimeter removes peak of muon fakes



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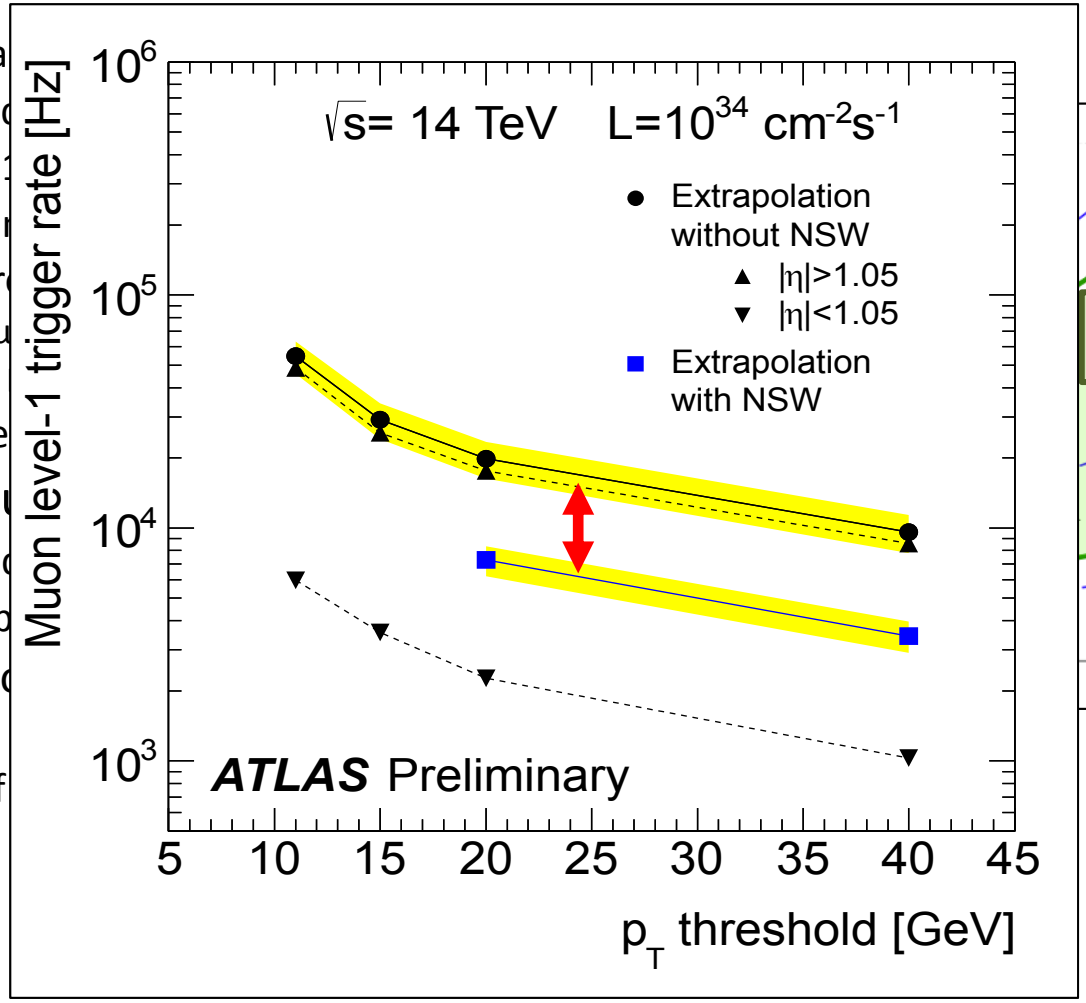
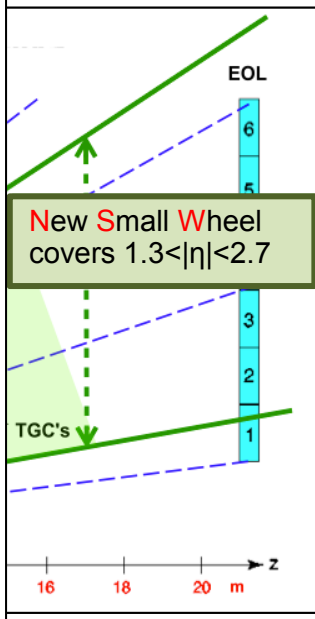


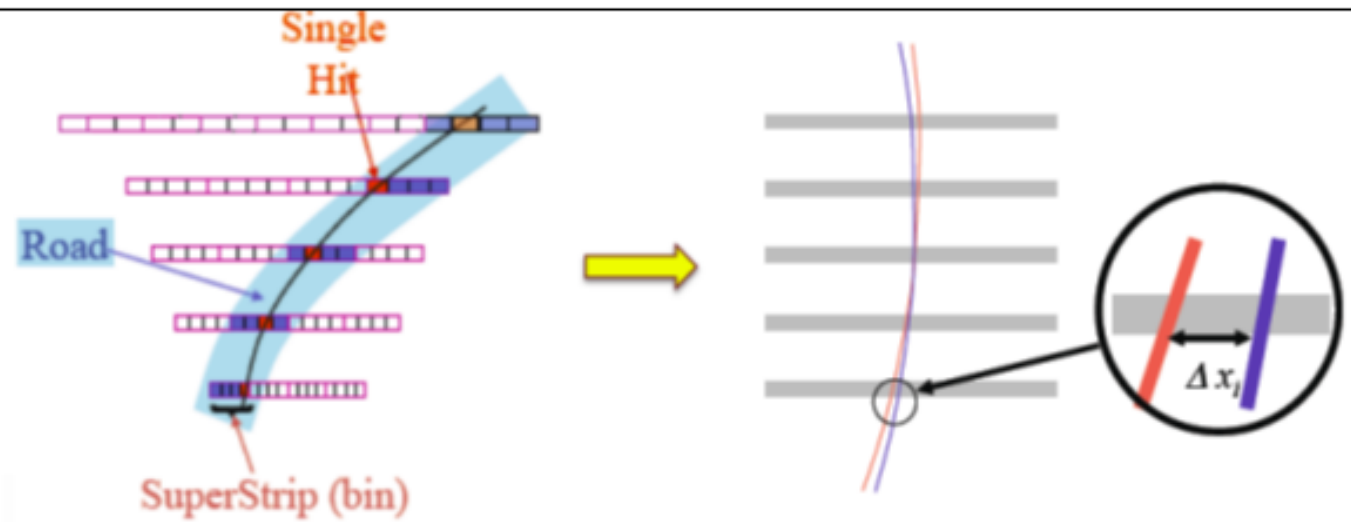


Fast TracK Trigger (FTK)

- Dedicated, hardware-based track finder
  - Runs after L1, on duplicated Si-detector read-out links (strip and pixel)
  - Provides tracking input for L2 for the full event, fast customized electronics
  - Finds and fits tracks (~ 25 µs) in the ID silicon layers at an "offline precision"
  - Processing performed in two steps

1. hit pattern matching to pre-stored patterns (coarse)

2. subsequent linear fitting in FPGAs (precise)



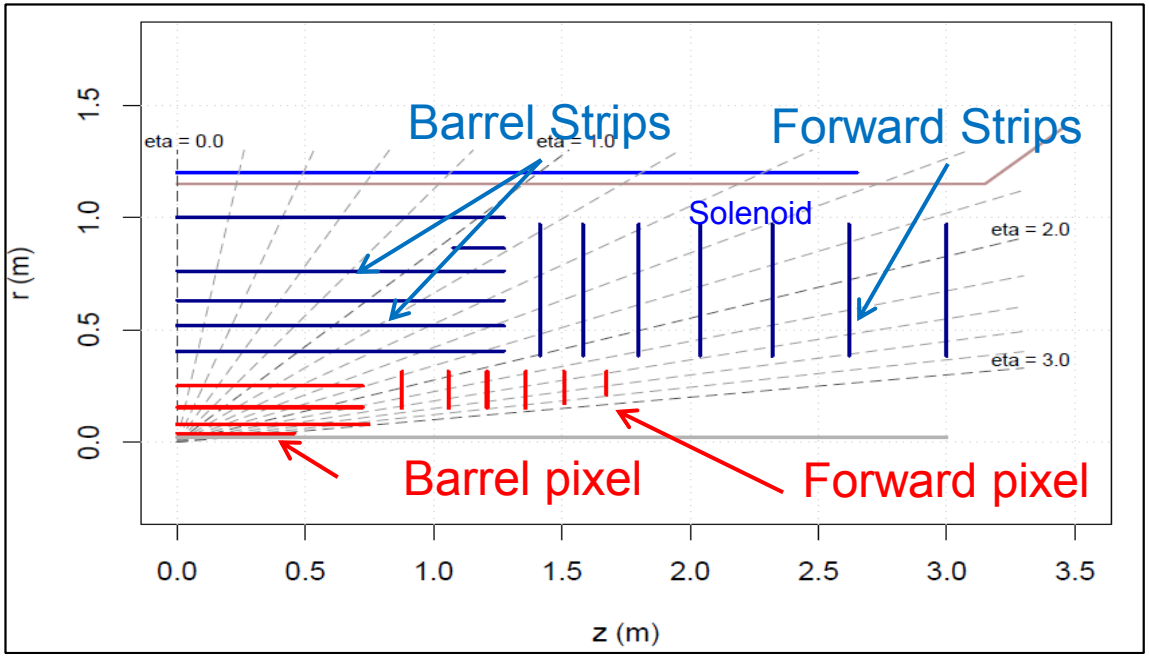
Associative memory Chip

ATLAS Phase 2

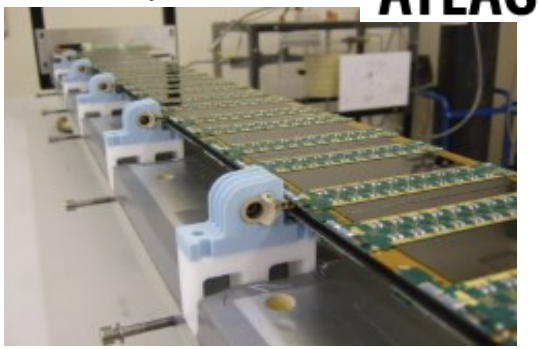
New Tracking detector

- Current Inner Detector (ID)
  - Designed to operate for 10 years at $L=1x10^{34}$ $cm^{-2}s^{-1}$ with <μ>=23, @25ns, L1=100kHz
- Limiting factors at HL-LHC
  - Bandwidth saturation (Pixels, SCT)
  - Occupancy limits (TRT, SCT)
  - Radiation damage (Pixels (SCT) designed for 400 (700) fb^{-1})

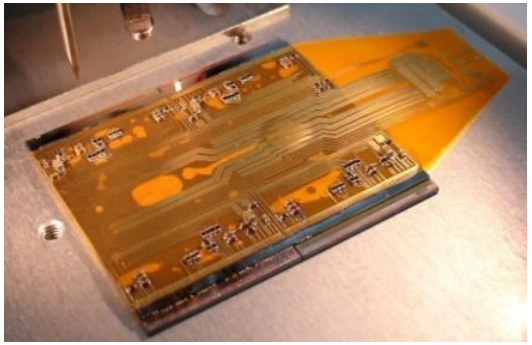
LoI layout new (all Si) ATLAS Inner Tracker for HL-LHC



Microstrip Stave Proto



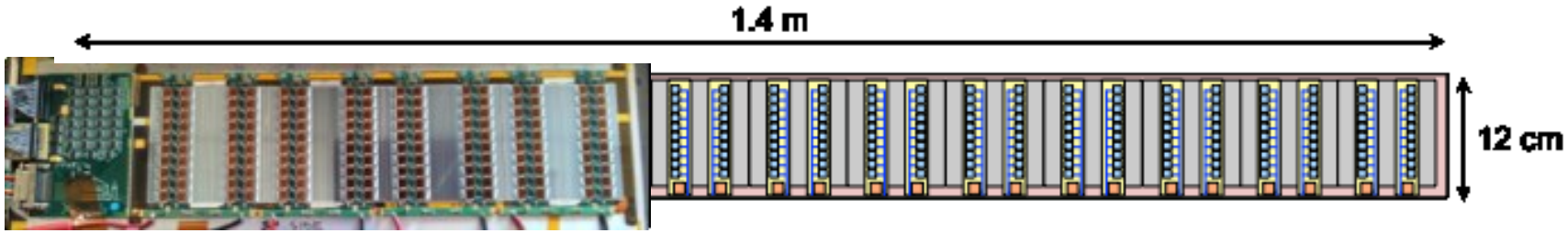
Quad Pixel Module Prototype



New 130nm prototype strip ASICs in design

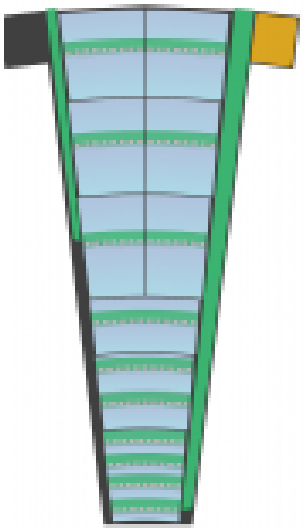
- incorporates L0/L1 logic
- Able to read out at 1Mhz L0

ATLAS Silicon Strip Tracker

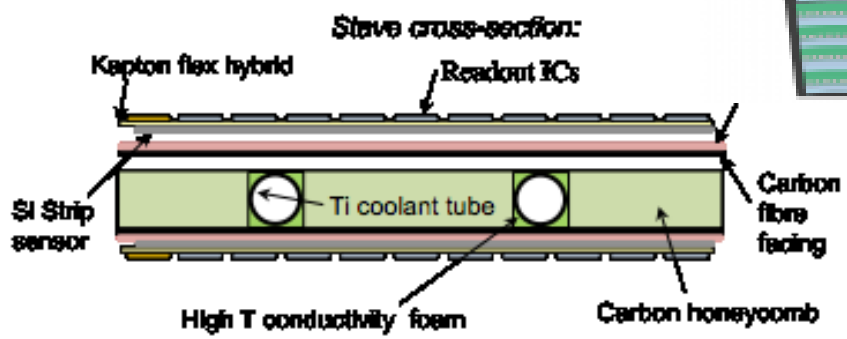


See talks by Barl Hommels , Kazuhiko Hara, Vitaliy Fadeyev, Marcela Mikestikova, Ricardo Mori

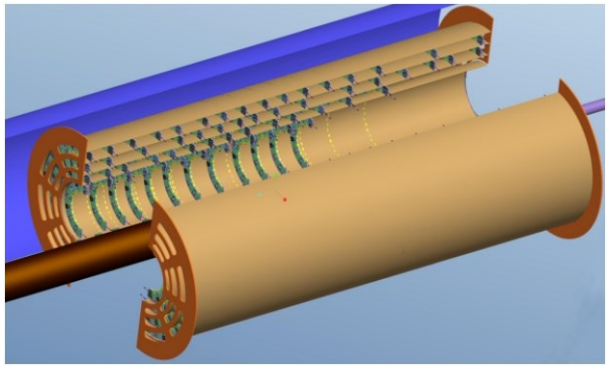
- Outer tracker is a silicon strip detector with n-in-p sensors
- Double-sided layers with implemented stereo angle (40mrad)
  - Short (23.8 mm) & long strips (47.8 mm) 74.5 µm pitch in barrel
  - End-Cap with radial strips of different pitch (6 different module)
- Stave/petal one object; top and bottom side read out separately

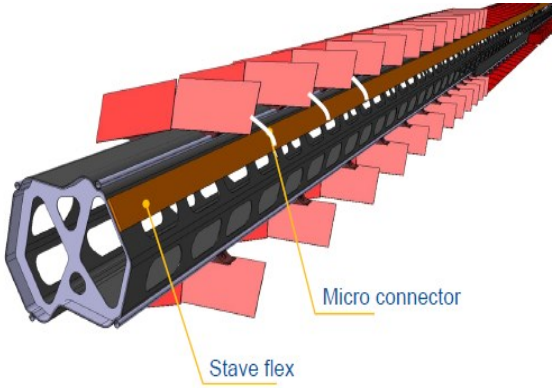


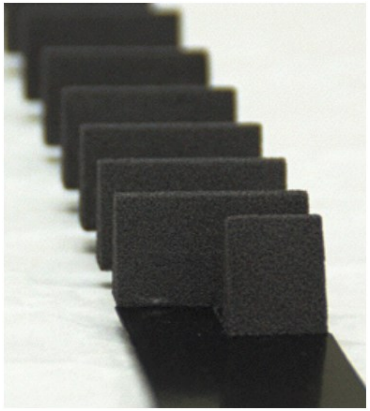
- Silicon Modules directly glued to a car[illegible] fibre plate with embedded cooling.
- Services integrated into face sheet including power control and data transmission.



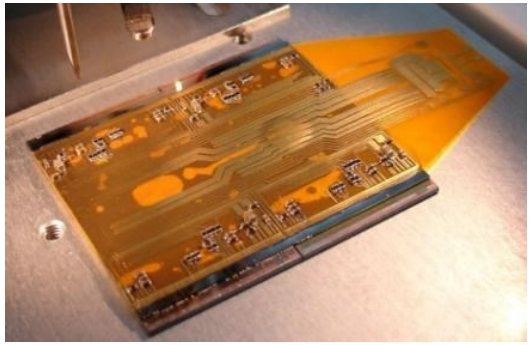
ATLAS Pixel Tracker







- Module development well advanced
- Final Layout and mechanical design still under active review
- Inner and Outer Cylinders for Barrel region (*inner cylinders are replaceable*)
  - Not necessarily the same technology in inner and outer barrels
- HV/HR CMOS "smart" sensors are still an attractive option for the outer layers

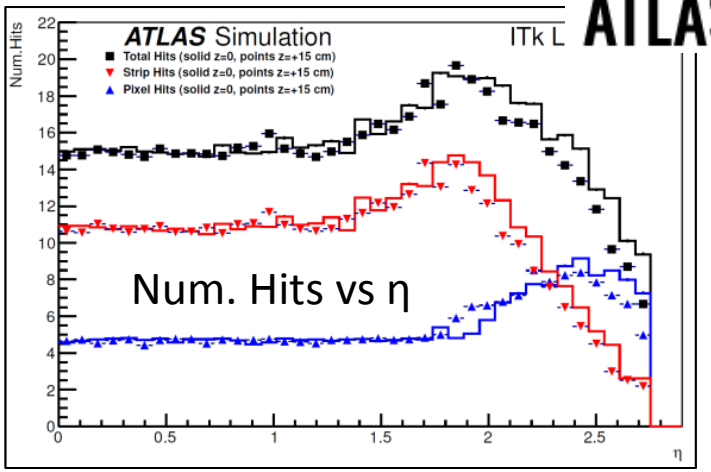


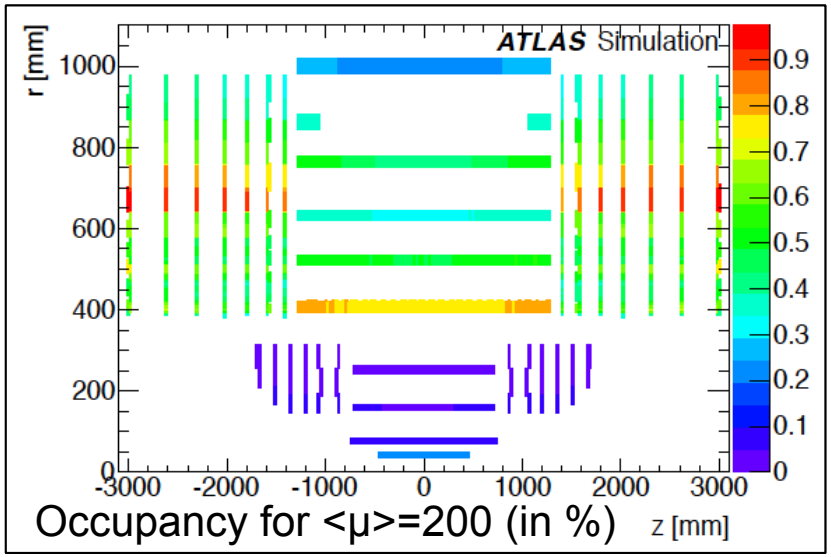
Quad Pixel Module Prototype

See talks (x 6) by Branislav Ristic, Toko Hirono Anna Macchiolo, Nobu Unno, Giovanni Calderini, Simon Viel

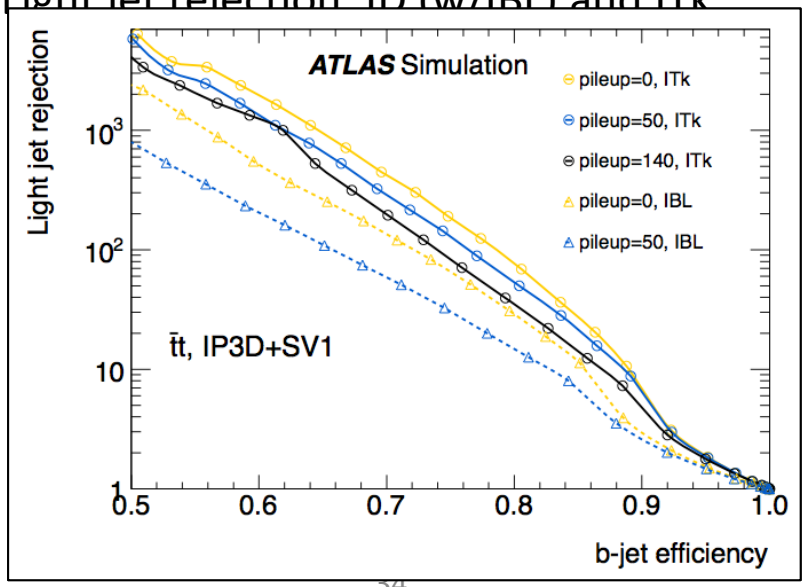
New Tracking detector cont.

- Studies with LOI layout
  - Robust tracking
  - Low Occupancy <1 % for <μ>=200
  - Reduced material wrt current ID
  - Comparable / better tracking performance at <μ>=200 as current ID at <μ>=0
  - Latency margins
- Solid baseline design
  - **Now working on optimisation, final Q1 2016**
  - **Will include a rapidity extension**





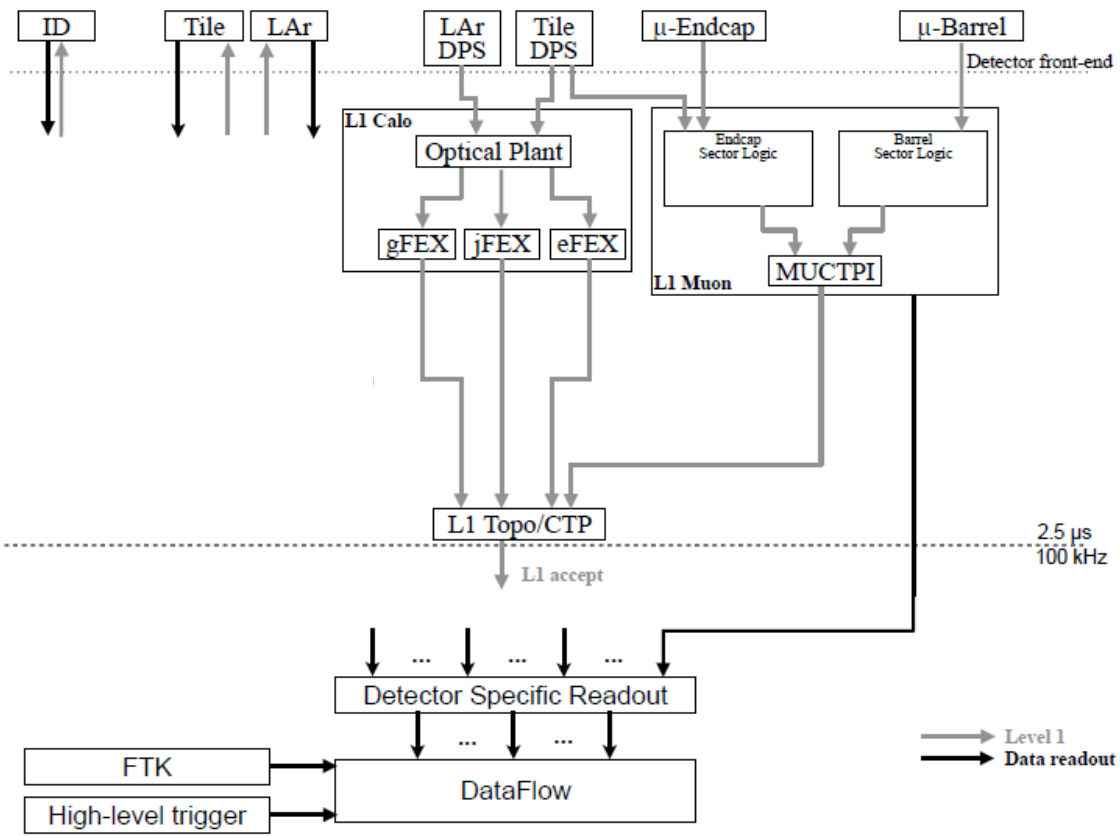
Light jet rejection, ID (w/IBL) and ITk



Trigger system architecture

- New design for Phase II
  - 2-level system, Phase-I L1 becomes Phase-II L0, new L1 includes tracking
  - Requires changes to detector FE electronics feeding trigger system
  - Level-0: Rate ~ 1,000 kHz, Lat. ~10 μs : Muon + Calorimeter
  - Level-1: Rate ~400 kHz, Lat. ~30 μs: Muon + Calorimeter + Tracks

End of Run-3



Trigger system architecture

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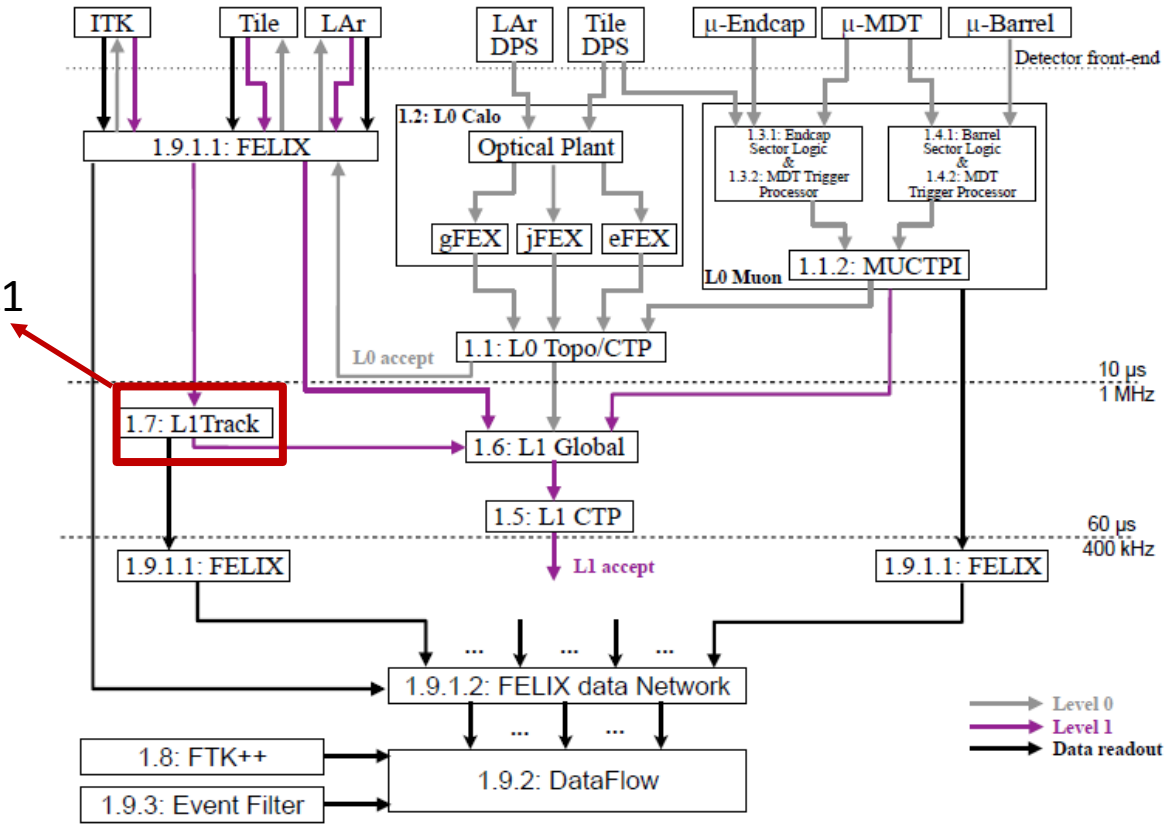
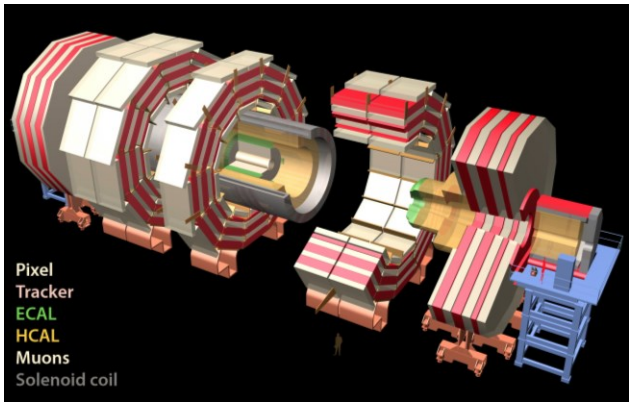
  - Level-1: Rate ~400 kHz, Lat. ~30 μs: Muon + Calorimeter + Tracks

Start of Run-4

Track Trigger at Level-1 (L1)

- Move part of High Level Trigger reconstruction into L1
- Goal: keep thresholds on p_T of triggering leptons and L1 trigger rates low

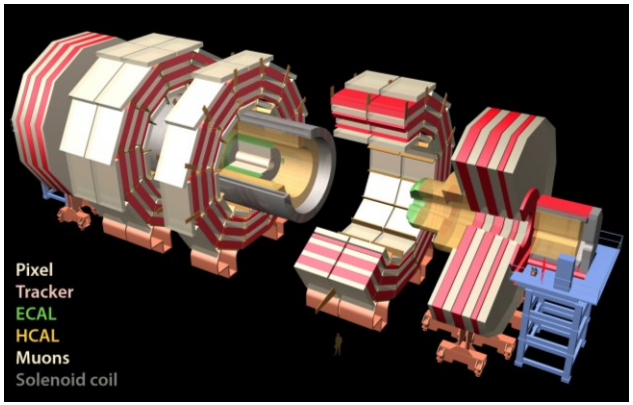




CMS Phase 0

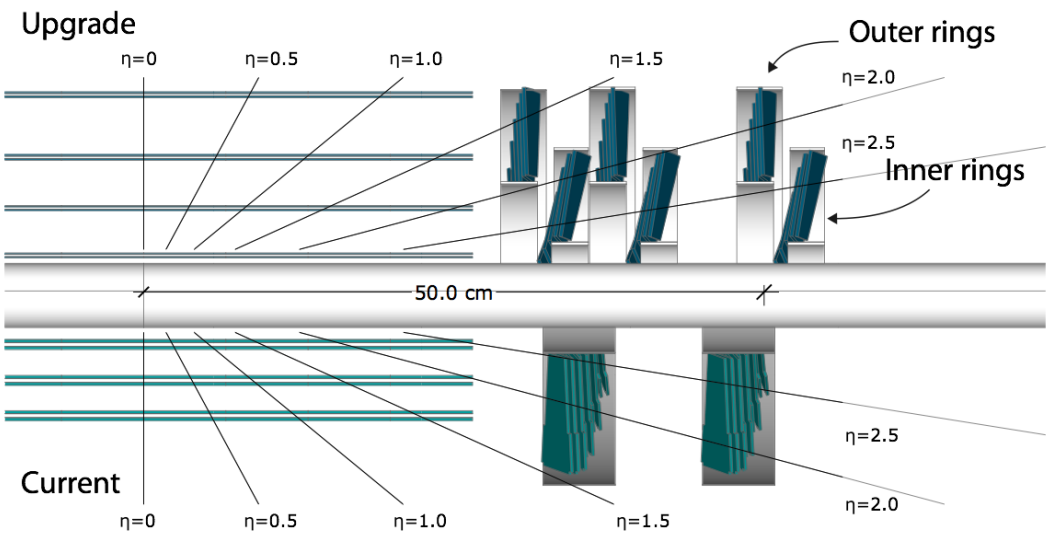
CMS Phase-0 upgrades

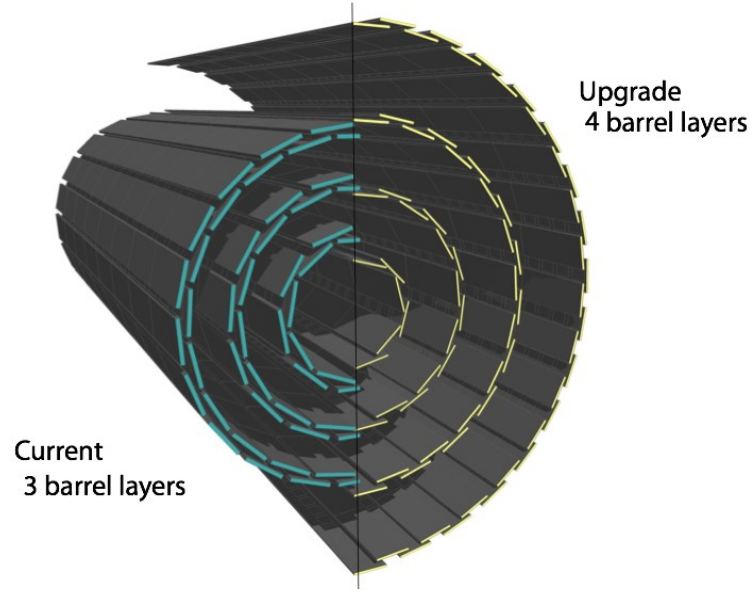
- Completion/consolidation of the detector for $1x10^{34}cm^{-2}s^{-1}$
  - Muon end-cap system
    - ME1/1 electronics (un-ganging), ME4/2 complete stations & shielding
  - Si Tracker
    - Prepare for cold operation (-20°C coolant)
- Issues identified during Run 1
  - HF photo-detectors
    - Reduce beam-related background
  - HO photo-detectors
    - replaced with Silicon Photo-Multipliers (Si-PM)
- Preparatory work for Phase 1 Upgrades
    - New beam pipe and “pilot blade” installation for the Pixel Upgrade
    - New HF backend electronics - ahead of HCAL frontend upgrade
    - Splitting for L1-Trigger inputs to allow commissioning new trigger in parallel with operating present trigger



CMS Phase 1

Phase 1 – Pixel Detector





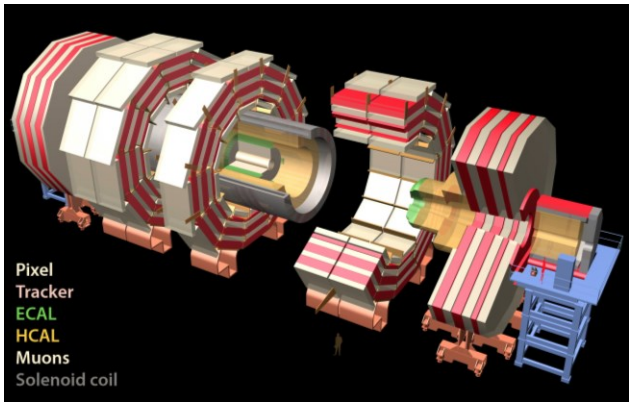
- 4 layers central and 3 disks forward
  - 1 more space point, closer to beam at 3cm
  - Improved track resolution and efficiency
  - Tolerate up to 100 PU and survive to 500 fb^{-1}, with exchange of innermost layer

See talk by Simon Spannagel

- New readout chip
  - Recovers inefficiency at high rate and Pile-up

Ready to install EYETS 2016-2017
Runs to 2023

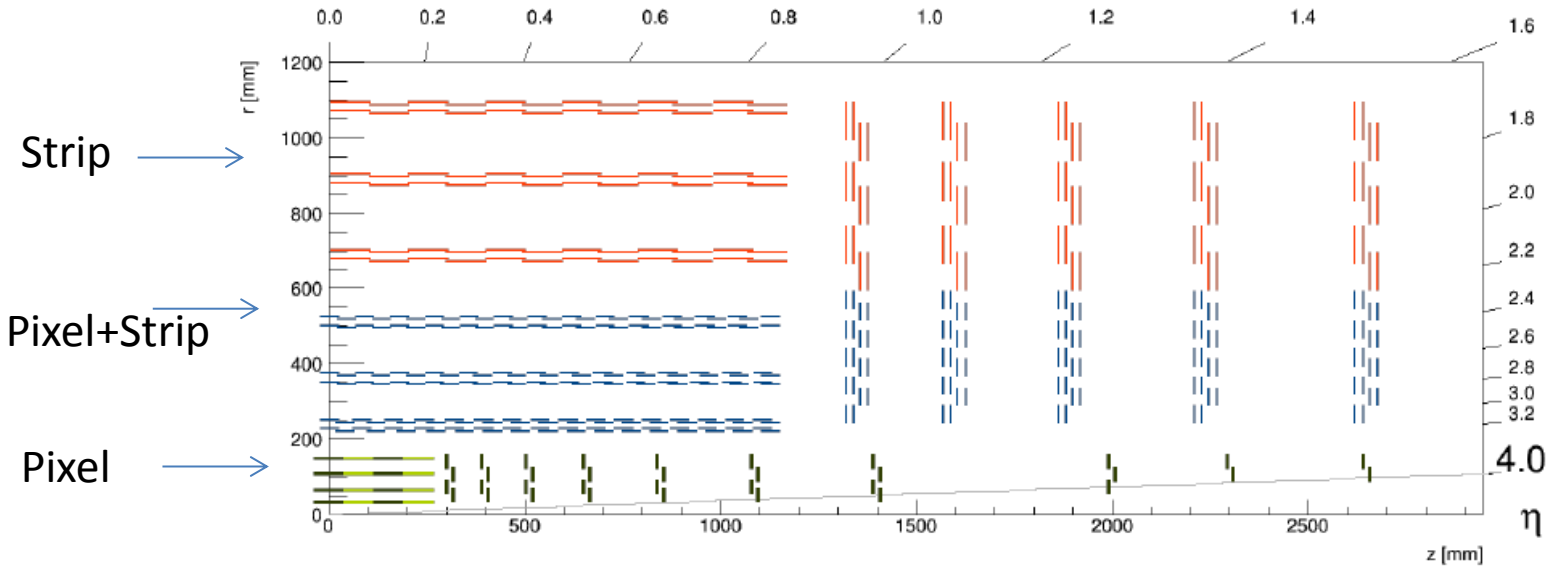
- Less material
  - CO2 cooling, new cabling and powering scheme (DC-DC)



CMS Phase 2

Phase 2 Tracker: Conceptual design

- Outer tracker
  - High granularity for efficient track reconstruction beyond 140 PU
  - Two sensor "P_T modules" to provide trigger information at 40 MHz for tracks with Pt≥2GeV
  - Improved material budget

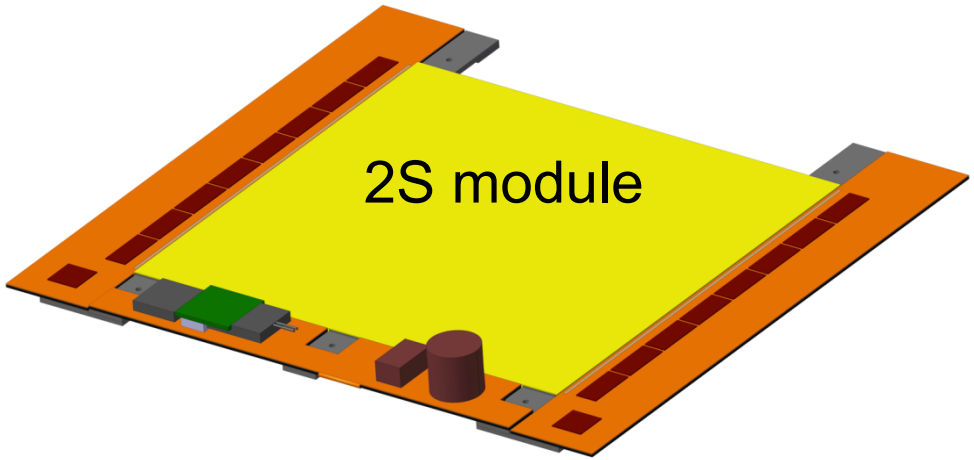


- Pixel detector

See talks by Thomas Bergauer,

  - Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to |η|= 4
  - Thin sensors 100 µm; smaller pixels 30 x 100 µm

CMS Outer Tracker



2S Strip Sensor modules

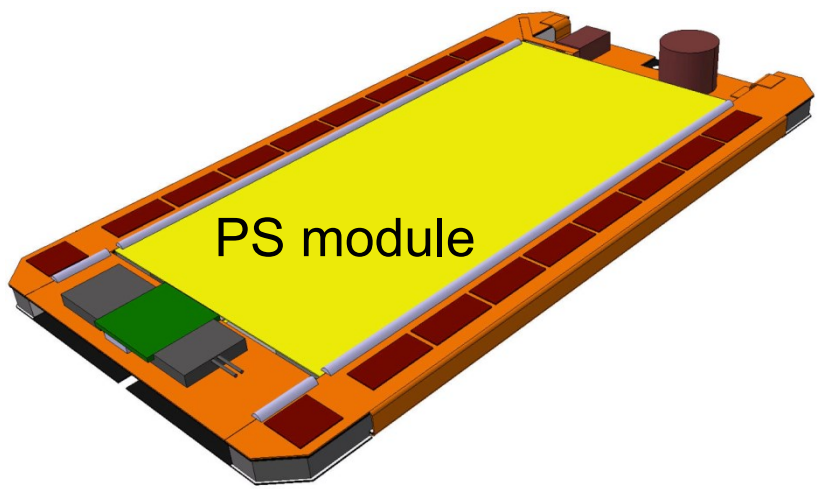
3 layers at R>60cm

2 x 1016 strips : 5cm x 90μm

Power ~ 5W

90cm^2 active area

Spacing 1.8mm and 4.0mm



PS Pixel + Strip Sensor modules

2 layers at R>20cm

2 x 960 strips : 2.5cm x 100μm

32 x 960 pixels : 1.5mm x 100μm

Power ~ 7W

45cm^2 active area

Spacing 1.6mm, 2.6mm and 4.0mm

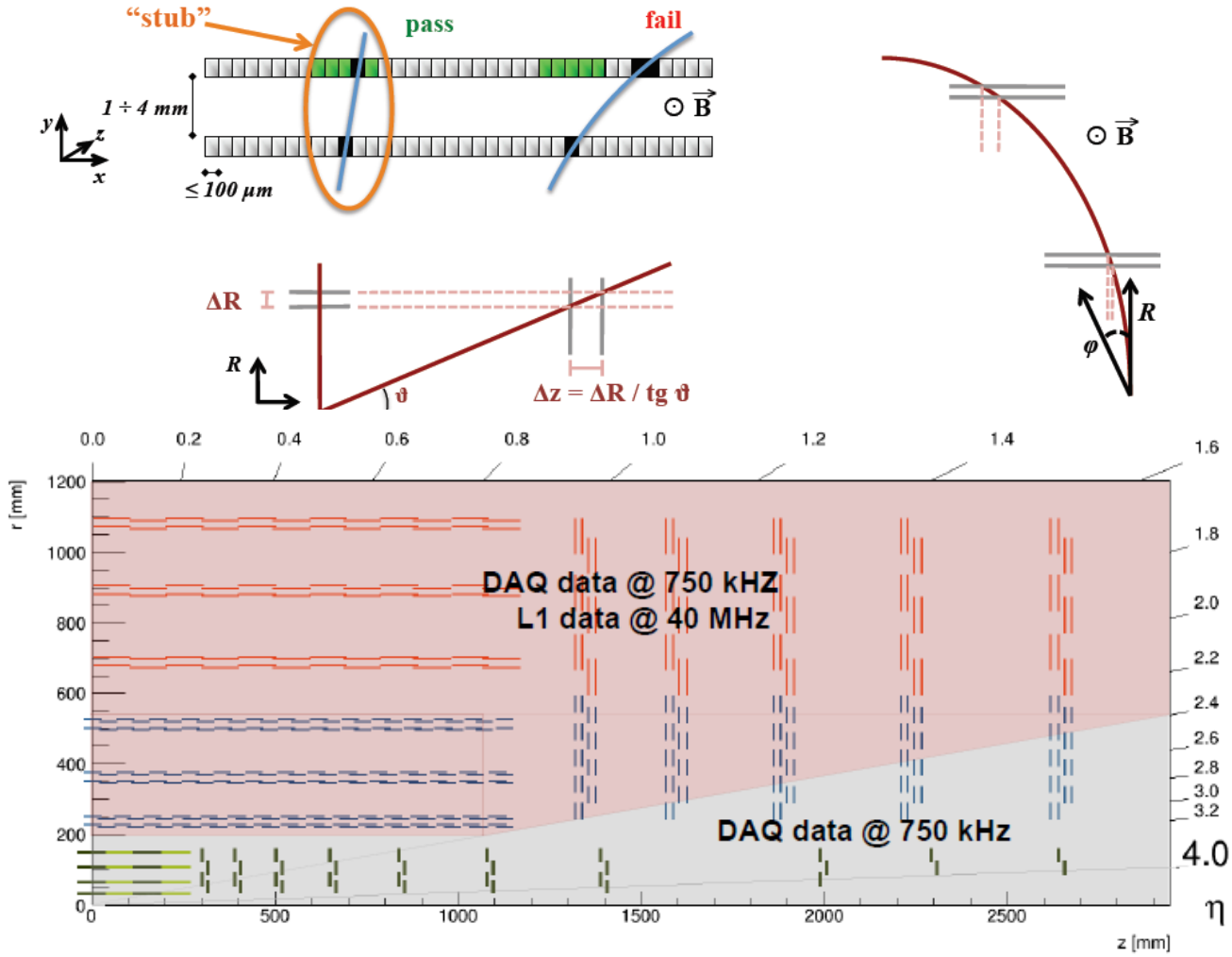
Operates at ~-20^{c}C, set point -30^{c}C

Modules discriminate low-p_T tracks in the FE electronics. data for track reconstruction at L1

Hybrid is key element: Wire-bonds from the sensors to the hybrid connect two sides

Overall 216 m^2 with 47 M strips, 215M long pixels

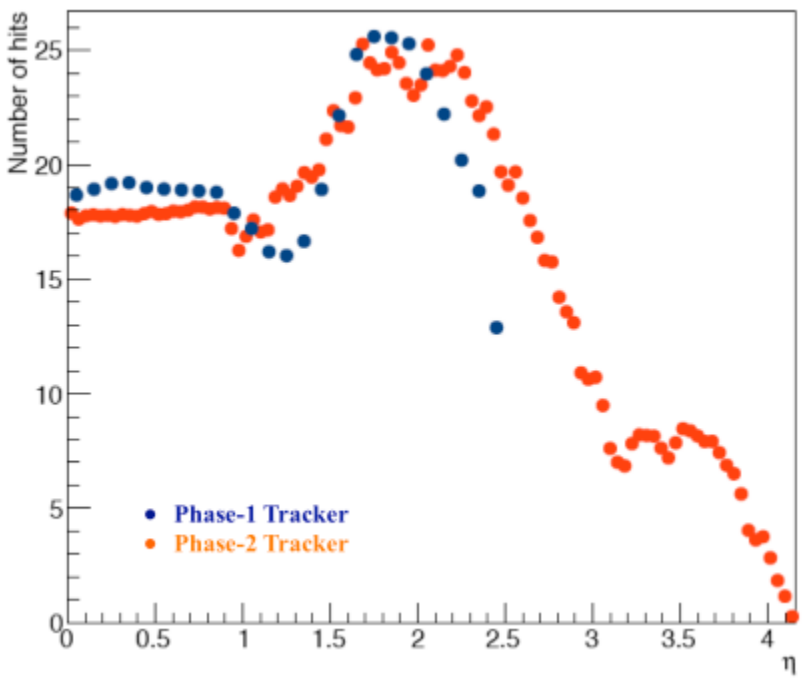
Triggering Using Outer Tracker

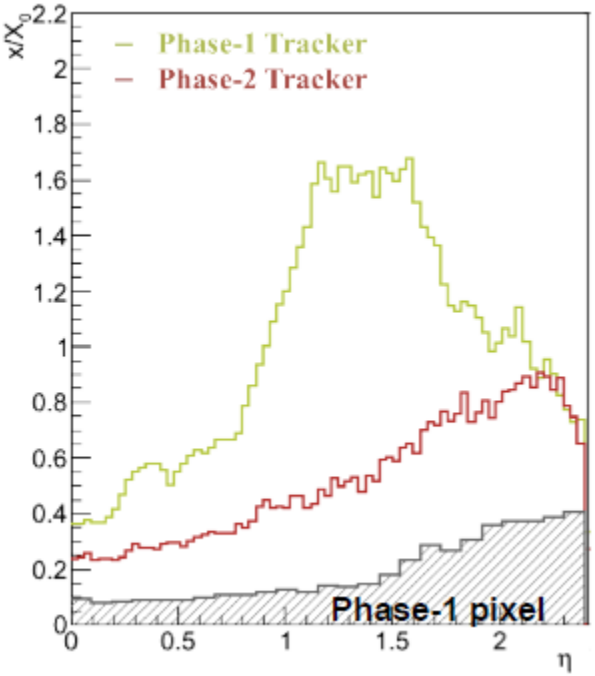


Two sensor "Pt-modules" to provide trigger information at 40 MHz for tracks with Pt≥2GeV

L1 tracking acceptance is limited to $|\eta| < 2.5$

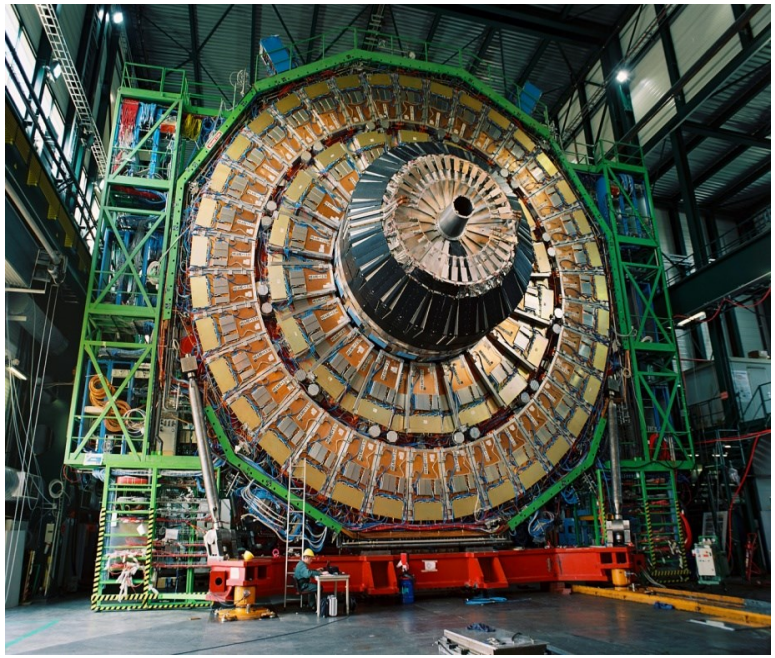
CMS Tracker : Hits and Material

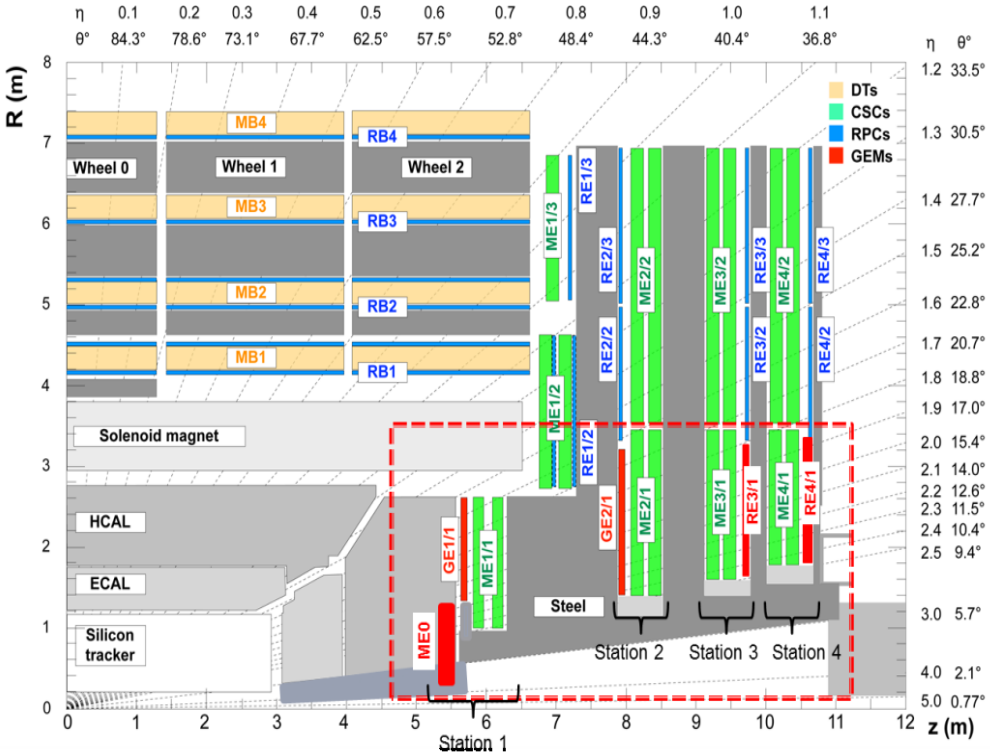




CMS Muon System

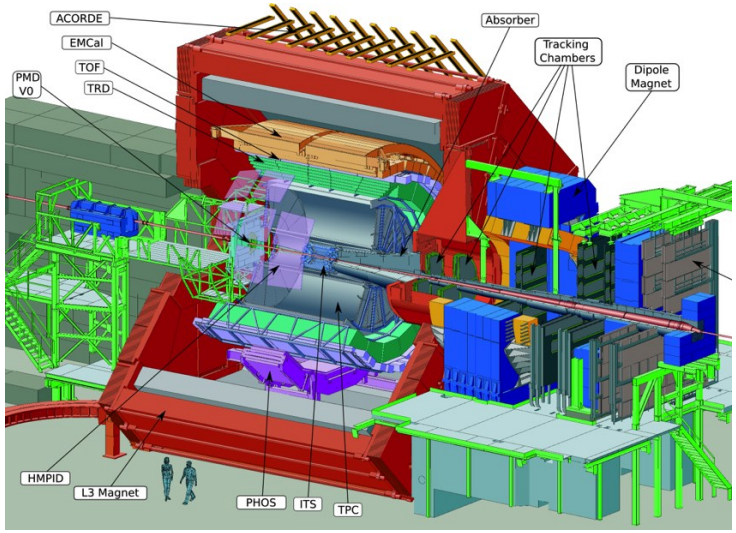
- Investigating increase of the muon coverage beyond $|\eta| < 2.4$ with GEM tagging station (ME0) coupled with extended pixel (depending on HE upgrade)
- Concept under study to complete muon stations at $1.6 < |\eta| < 2.4$
  - GEM in 2 first stations (Pt resolution)
  - Glass-RPC in 2 last stations (timing resolution to reduce background)





The ALICE Upgrade Program

ALICE Phase 1



ALICE Overview

- Major upgrade of ALICE detector to process Pb-Pb collisions at high rates and improve vertex reconstruction capabilities at low transverse momentum capabilities (rare probes).
- Read out all Pb-Pb interactions at a maximum rate of 50kHz ($L > 6x10^{27}$ $cm^{-1}s^{-1}$), with a minimum bias trigger (currently limited to 0.5kHz)
- Online data reduction based on reconstruction of clusters and tracks
- Aim to record $10nb^{-1}$ of Pb-Pb and > $50nb^{-1}$ of p-Pb (factor 100 in statistics to 2018)

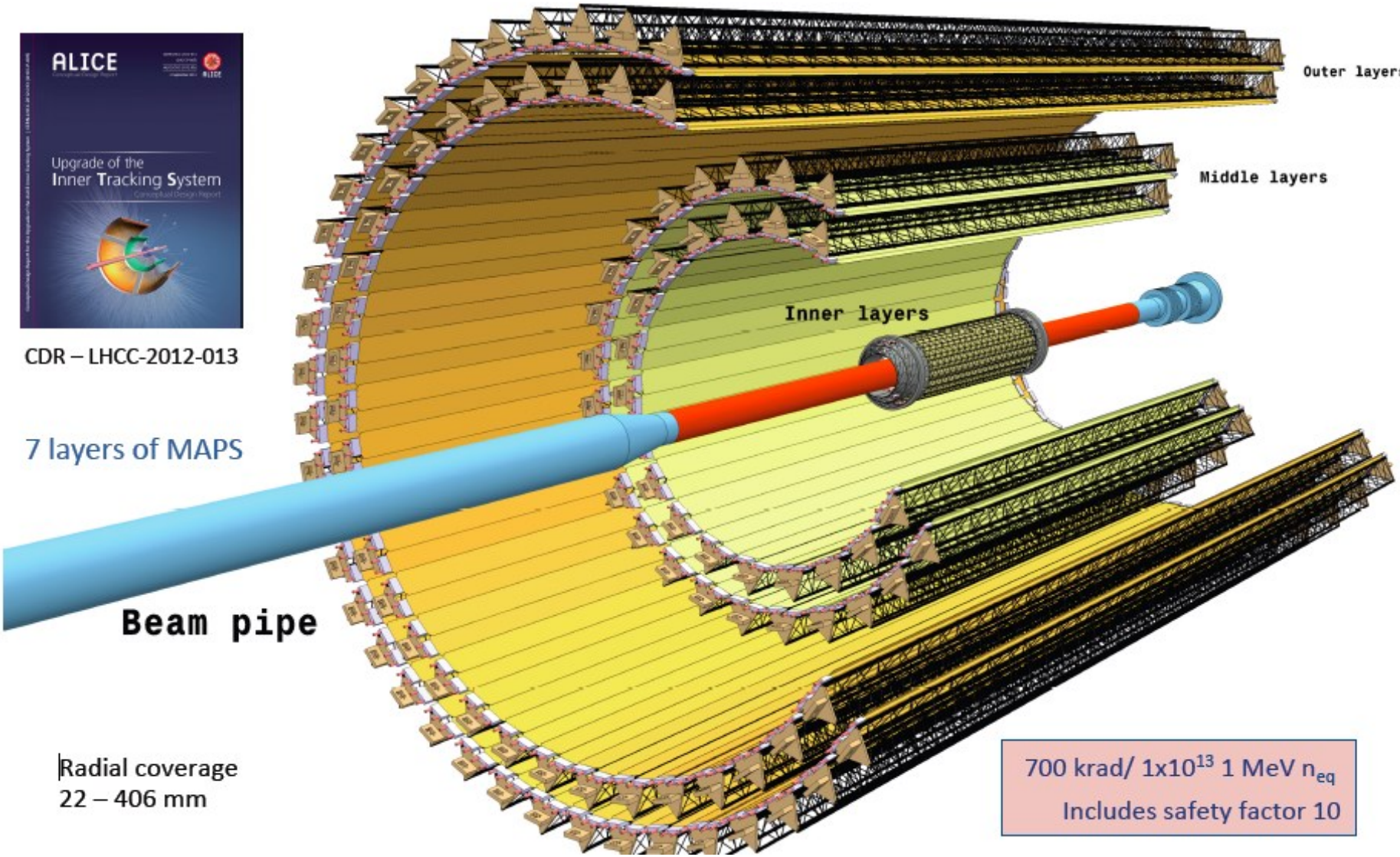
- **Key elements of the upgrade programme are:**
  - New Inner Tracking System - ITS (7 layers, ~$11m^2$)
    - Built on the experience from STAR vertex detector *See talk by Giacomo Contin*
  - Replace TPC endplates with new electronics for continuous readout
  - New 5-plane muon silicon telescope in forward region in front of hadron absorber in the acceptance of the muon Spectrometer
  - Readout rate upgrade of all other ALICE sub-detectors to 50kHz
  - All data written to tape, processed (reconstructed) data

ALICE ITS

Replaces existing detector

CDR – LHCC-2012-013

7 layers of MAPS

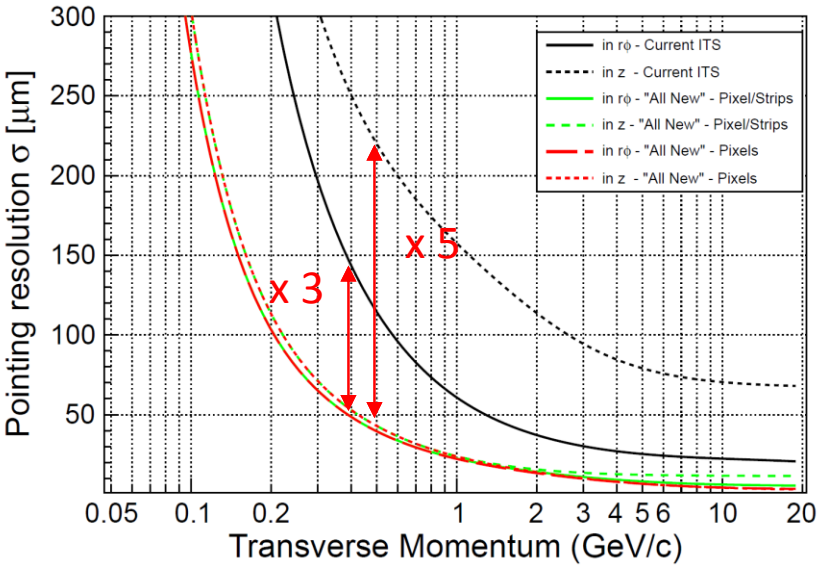


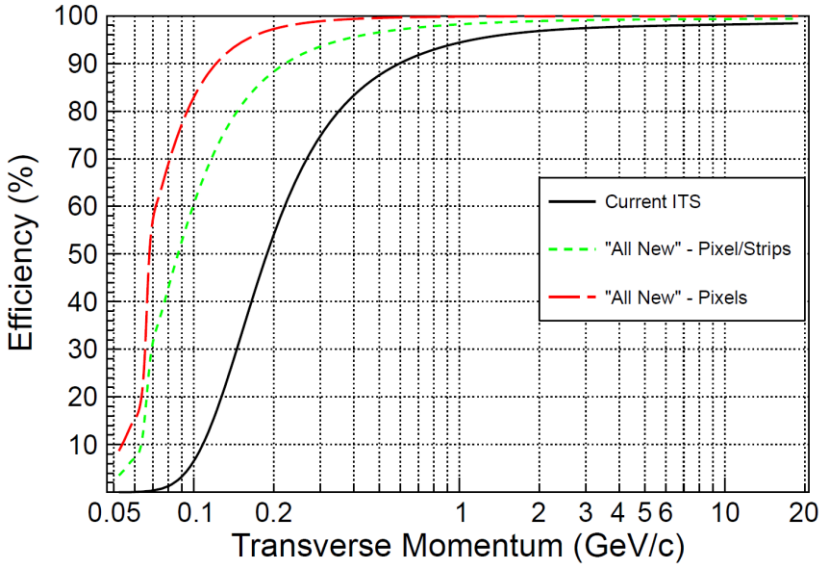
Radial coverage
22 – 406 mm

700 krad/ $1x10^{13}$ 1 MeV n_{eq}
Includes safety factor 10

ALICE ITS

- Impact parameter resolution Improved by a factor of about 3
- Get closer to Impact Point 39mm → 22mm (1 MRad and 10^{13} n cm^{-1})
- Material budget at inner layers: X/X_0 : ~1.14% → ~ 0.3%
- Reduce pixel size : 50μm x 425μm → 20μm x 20μm (50μm thick)
- Number of layers 6 → 7 (25Gpixels of MAPS at 50kHz)

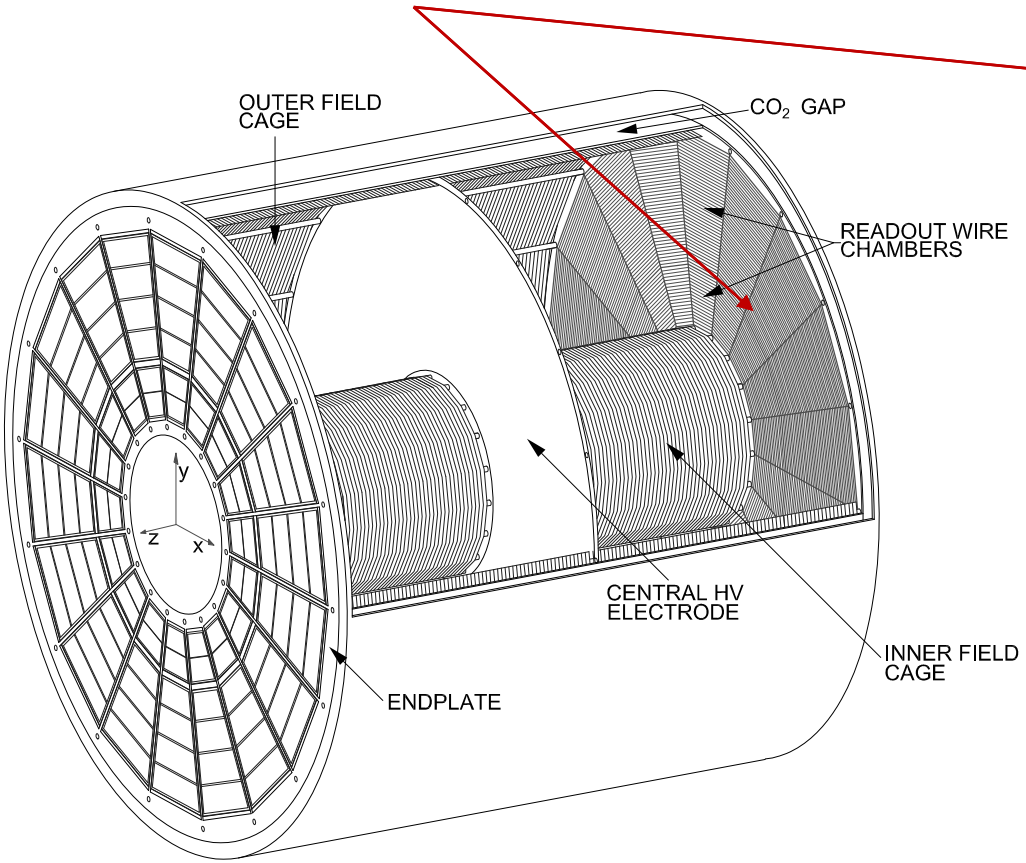


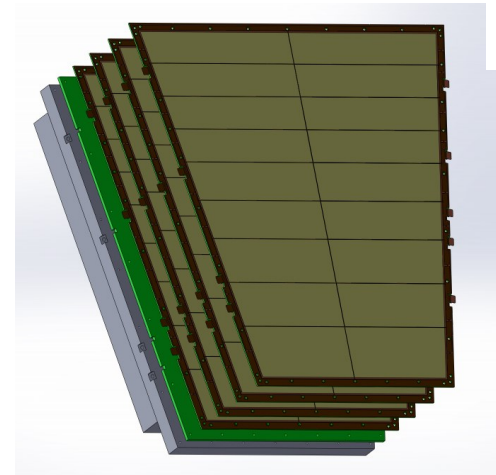


Readout of Pb-Pb interactions at > 50 kHz and pp interactions at ~ 1 MHz
Resolutions: $\sigma_{r\phi}$ = 4 μm, σ_z = 4 μm for all layers.

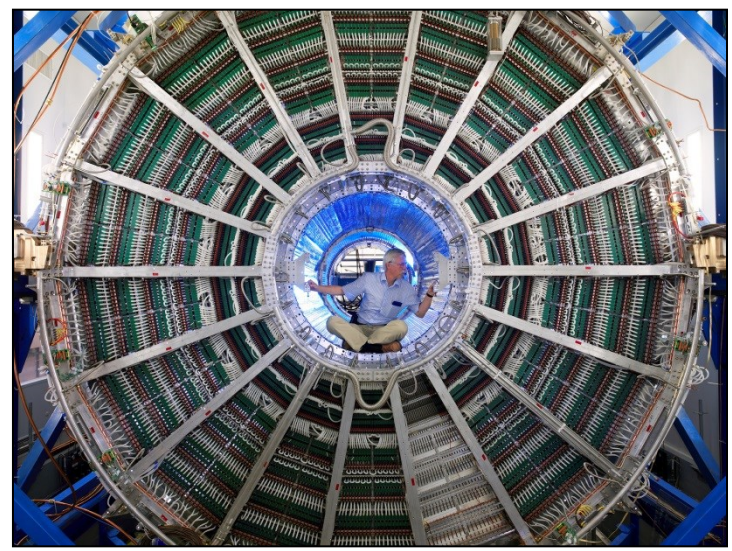
ALICE TPC

Replace wire chambers with quadruple-GEM chambers





Exploded view of a GEM IROC



Increase rate limitation from 3.5kHz to 50kHz

Gas Electron Multiplier gain ~2k

Conclusions

- The next 20 years will include a very exciting program of measurements at the highest energy frontier the HLHC.
- The LHC will go from 300 fb^{-1} at the end of phase I to 3000 fb^{-1} at the end of phase II and will be a unique facility for particle physics.
- The physics program will certainly include precise measurements of Higgs properties and the search of new particles.
- All four experiments have exciting and vigorous upgrade programs. These are challenging technically and are leading us to push our undersanding and developments to the limits.

Comprehensive summaries available on INDICO of ECFA HL-LHC Workshop in Aix-les-Bains. A lot of slides from there.
See also CMS technical proposal **CERN-LHCC-2015-10 - ISBN 978-92-9083-417-5**

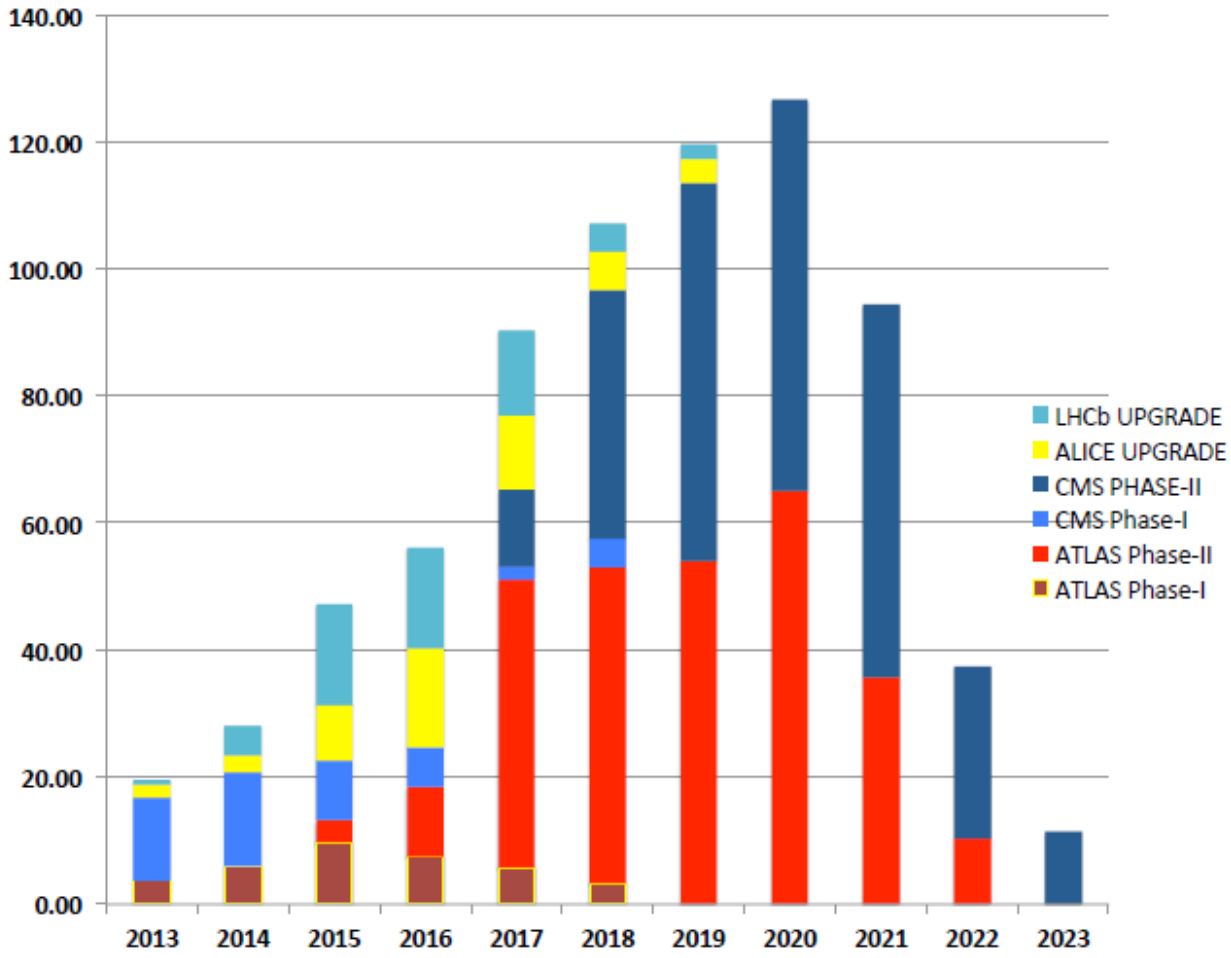
Back Up Slides

This means I could not fit in these slides for lack of time.

Less relevant for this Symposium

Please look at these at your leisure

Cost per year of upgrades



The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

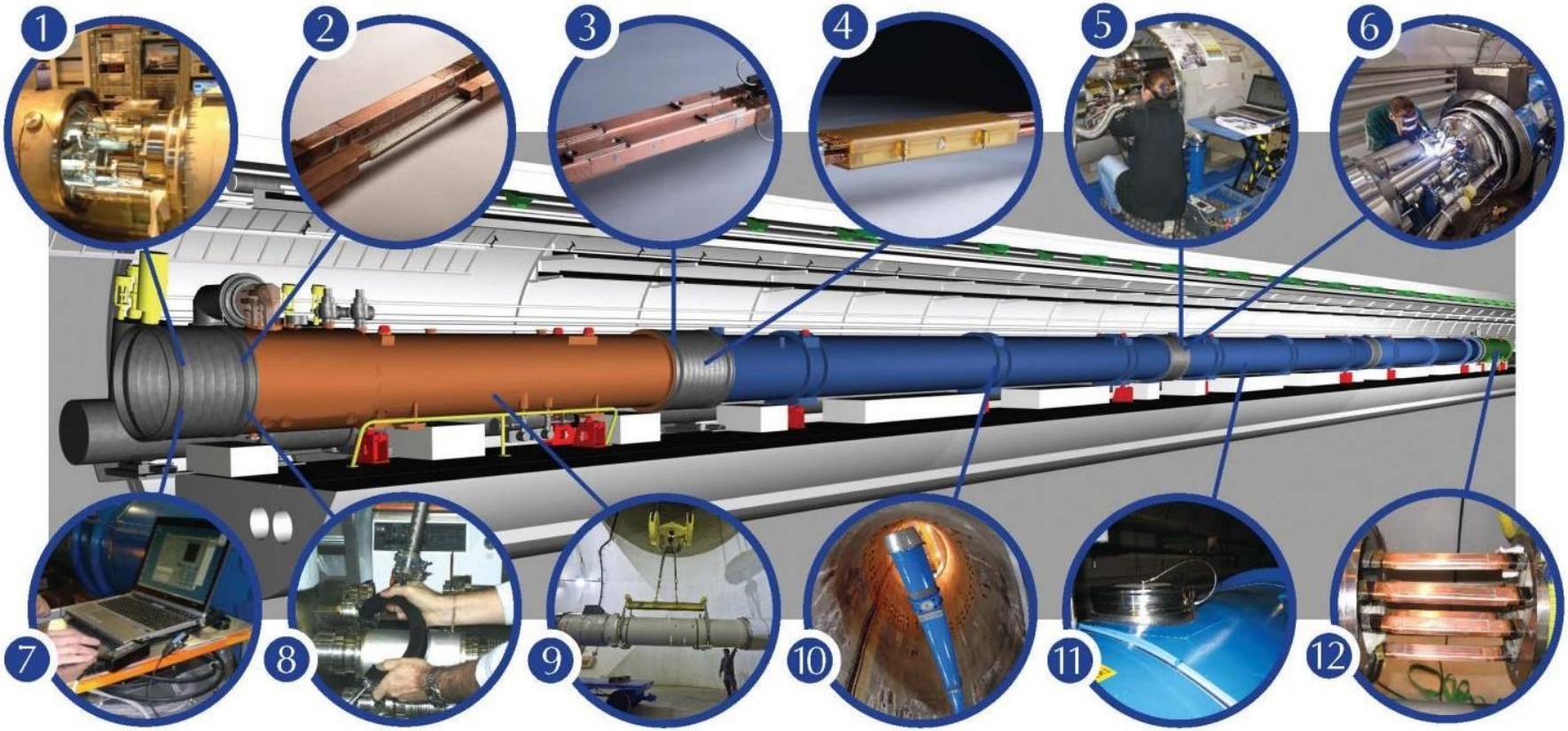
Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

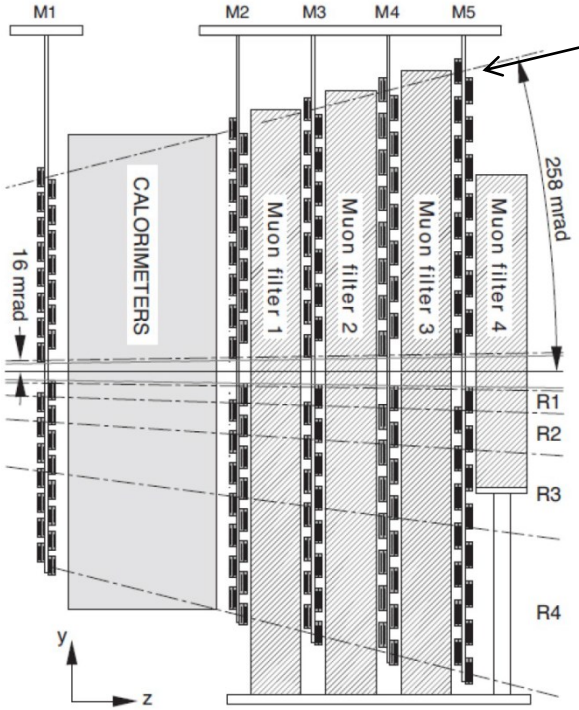
4 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

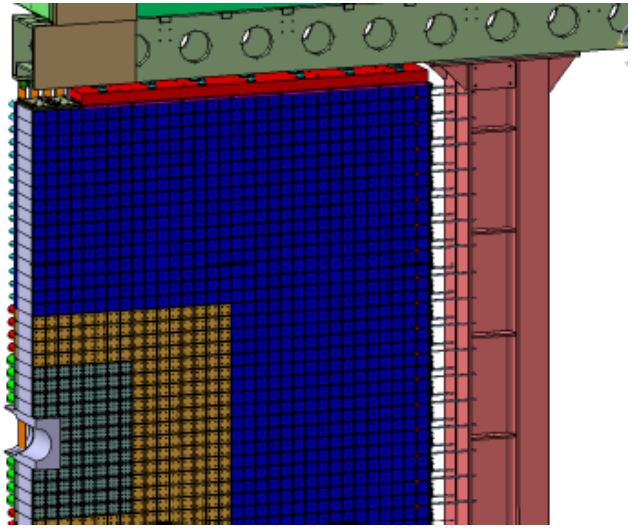
Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

Calorimeter and Muon Upgrades



- Remove station M1 due to too high occupancies
- keep on-detector electronics already at 40 MHz readout
- new off-detector electronics readout
- production of spare MWPC for installation in LS3 in hottest regions

Inner ECAL modules around beam-pipe replaced



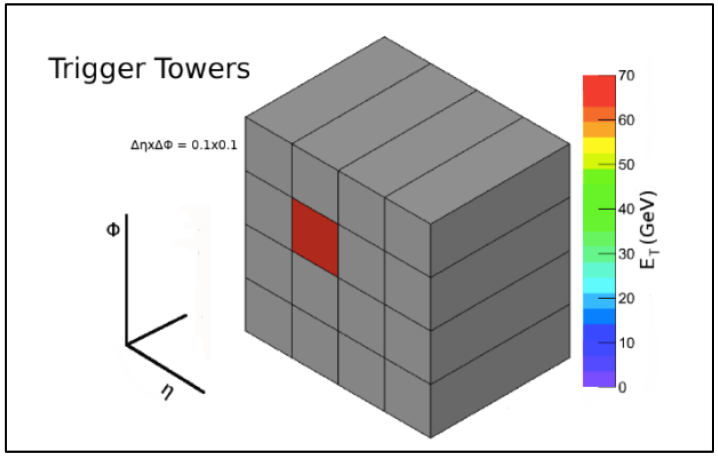
Radiation damage and occupancies

- Calorimeter stays
- Pre-shower and SPD removed
- HCAL modules ok up to ~50 fb^{-1}
- irradiation tests show that ECAL modules resist up to ~20 fb^{-1} → LS3

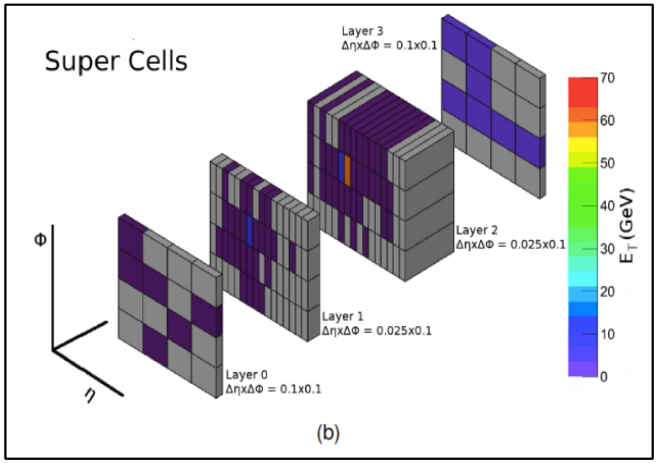
Level-1 calorimeter trigger

Trigger Towers $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

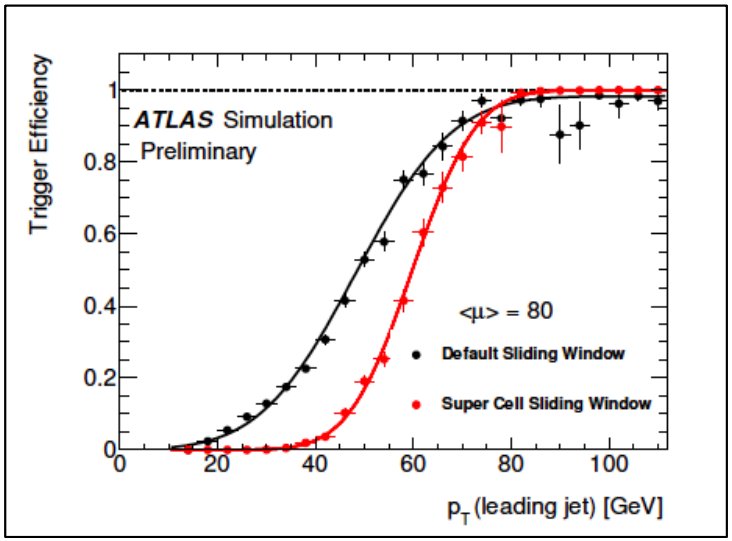
- Used to calculate core energy, isolation



Better granularity, energy resolution same threshold at acceptable rates

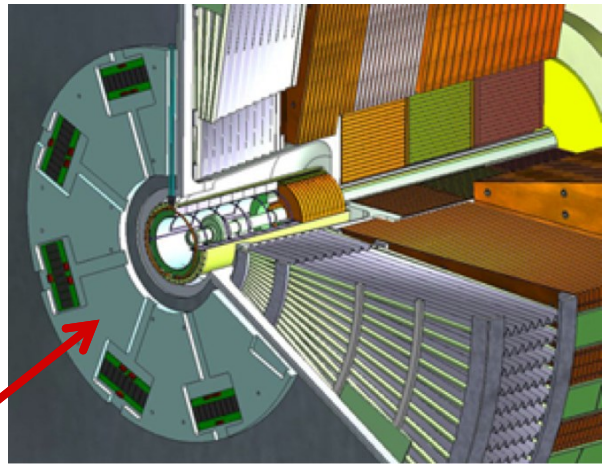


Without the upgrade Run-1 trigger menu at L_{inst}=3 x 10^{34} $cm^{-2}s^{-1}$ the total rate for EM triggers would be **270 kHz** (Total L1 bandwidth is 100kHz)



Calorimeter electronics

- Tile Calorimeters
  - No changes required to the detector
  - Full replacement of electronics (FE and BE)
    - New read-out architecture: Full digitisation of data at 40MHz and transmission to off-detector system
- LAr Calorimeter
  - Replace FE and BE electronics
    - Aging, radiation limits
    - 40 MHz digitisation, inputs to L0/L1
    - Natural evolution of Phase-I trigger boards
  - Replace Forward calorimeter (FCal) if required
    - Install new sFCAL in cryostat or miniFCAL in front of cryostat if significant degradation in current FCAL

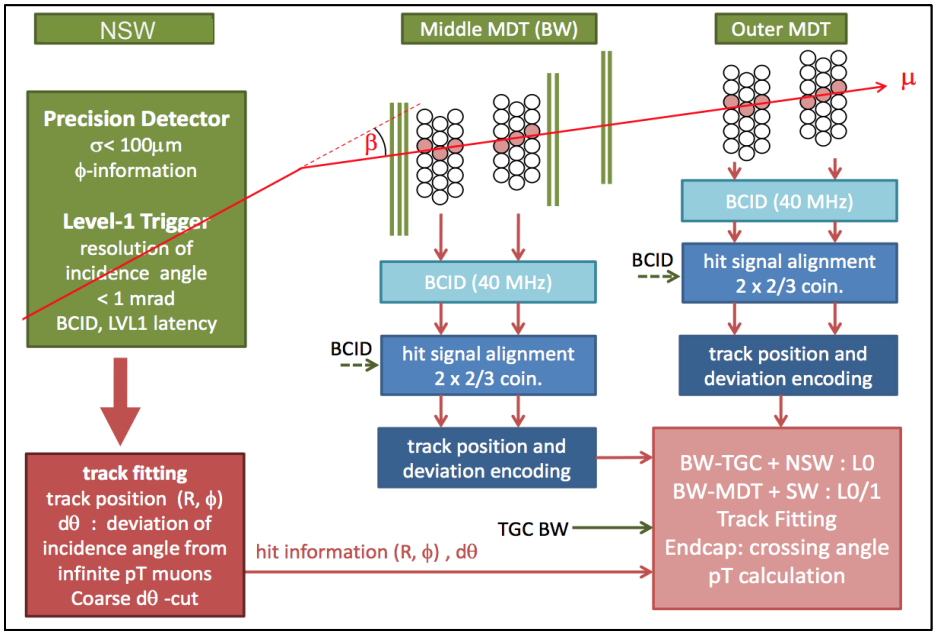


Muon system upgrade

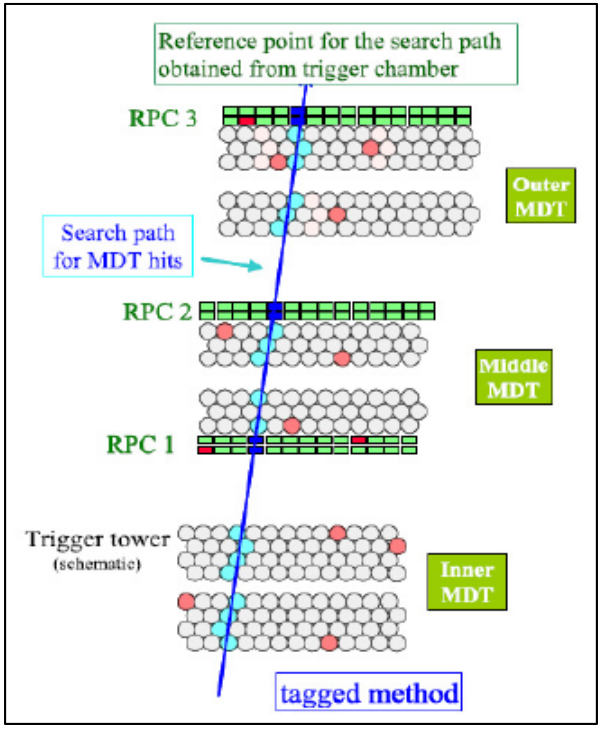
Upgrade FE electronics

- accommodate L0/L1 scheme parameters

- Improve L1 p_T resolution
  - Use MDT information possibly seeded by trigger chambers ROIs (RPC/TGC)
  - Another option: add higher precision RPC layer at inner MDT station



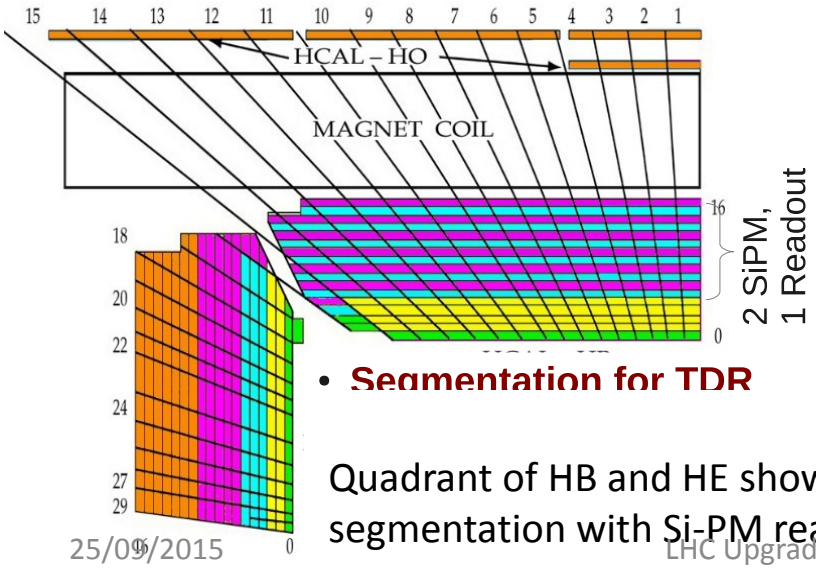
Match angle measurement in end-cap MDTs to precision measurement in NSW



RoI of high-p_T track used in a search road for MDT hits of the candidate track

Phase 1 – HCAL

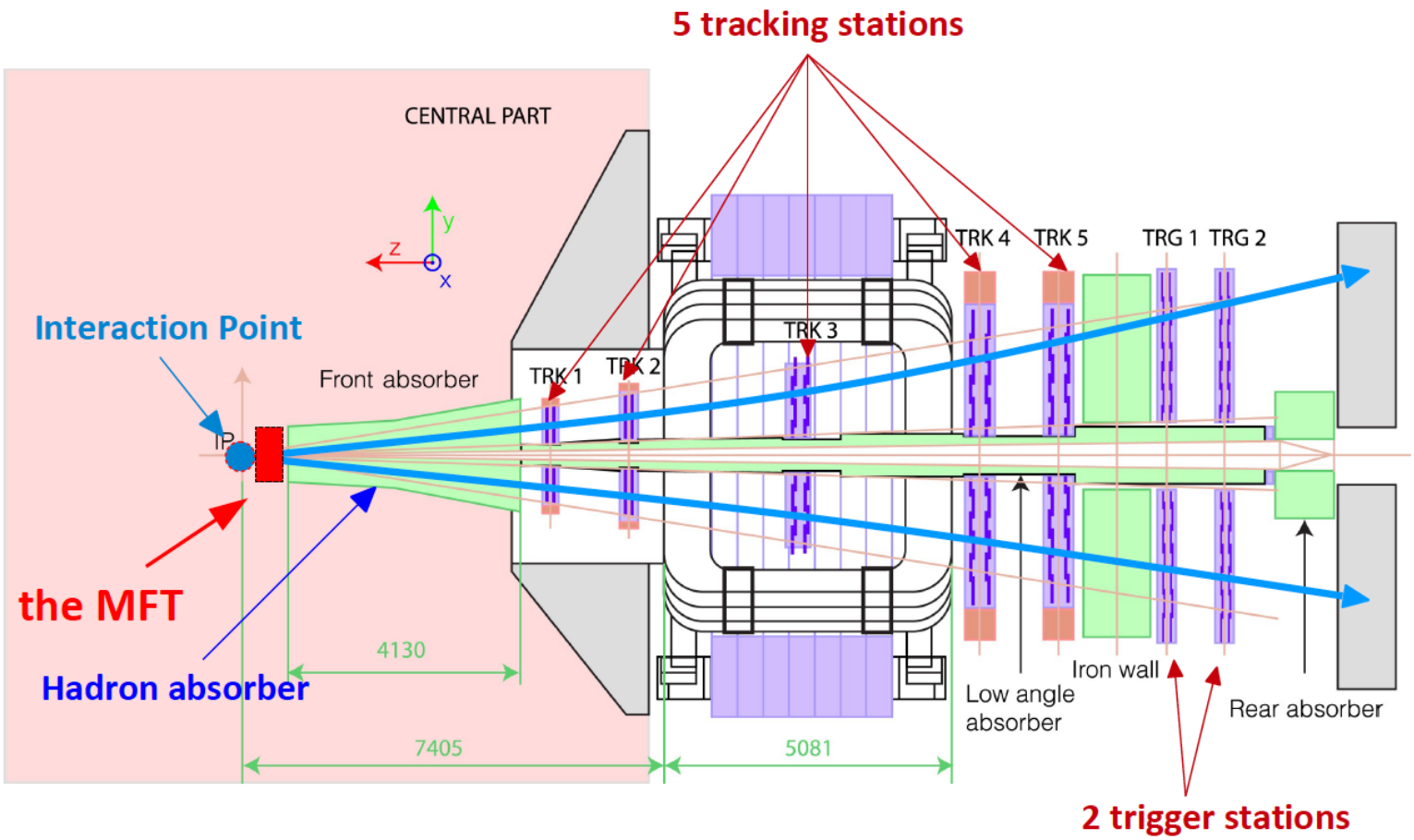
- New readout chip (QIE10) with TDC
  - Timing: improved rejection of beam-related backgrounds, particularly HF
- **Replace HPDs in HB and HE with SiPMs**
  - Small radiation tolerant package, stable in magnetic field
  - PDE improved x3, lower noise
  - Allows depth segmentation for improved measurement of hadronic cluster rejection of backgrounds, and re-weighting for radiation damage



- **Segmentation for TDR**

Quadrant of HB and HE showing depth segmentation with Si-PM readout

MFT and muon spectrometer



Silicon pixel tracker in the acceptance of the Muon Spectrometer placed between the Interaction Point and the Hadron Absorber to track back to the IP (also MAPS)