Upgrade Programs of the LHC Experiments

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7th HL-LHC Collaboration Meeting - 13-16 November 2017, CIEMAT, Madrid

Major upgrade of all 4 LHC Experiments

- Replace detectors which reach end of their lifetime
- Replace old outdated electronics
- ALICE and LHCb: Improve experiments to collect much larger statistics by increased data rate capability
- ATLAS and CMS: Upgrade experiments to maintain similar performance as the current experiments at HL-LHC conditions

  Cope with high radiation doses, increased pile-up, and challenging trigger rates

  - Target integrated luminosity 3000 fb^{-1}
  - Nominal peak luminosity $5x10^{34} \rightarrow$ 140 pile-up
  - Ultimate peak luminosity $7x10^{34} \rightarrow$ 200 pile-up

  Moderate improvements due to extended coverage

Upgrade in several phases

- Continuous upgrades ongoing, e.g. computing, trigger electronics outside cavern
- Upgrades during YETS and EYETS
- Phase I upgrades during LS2

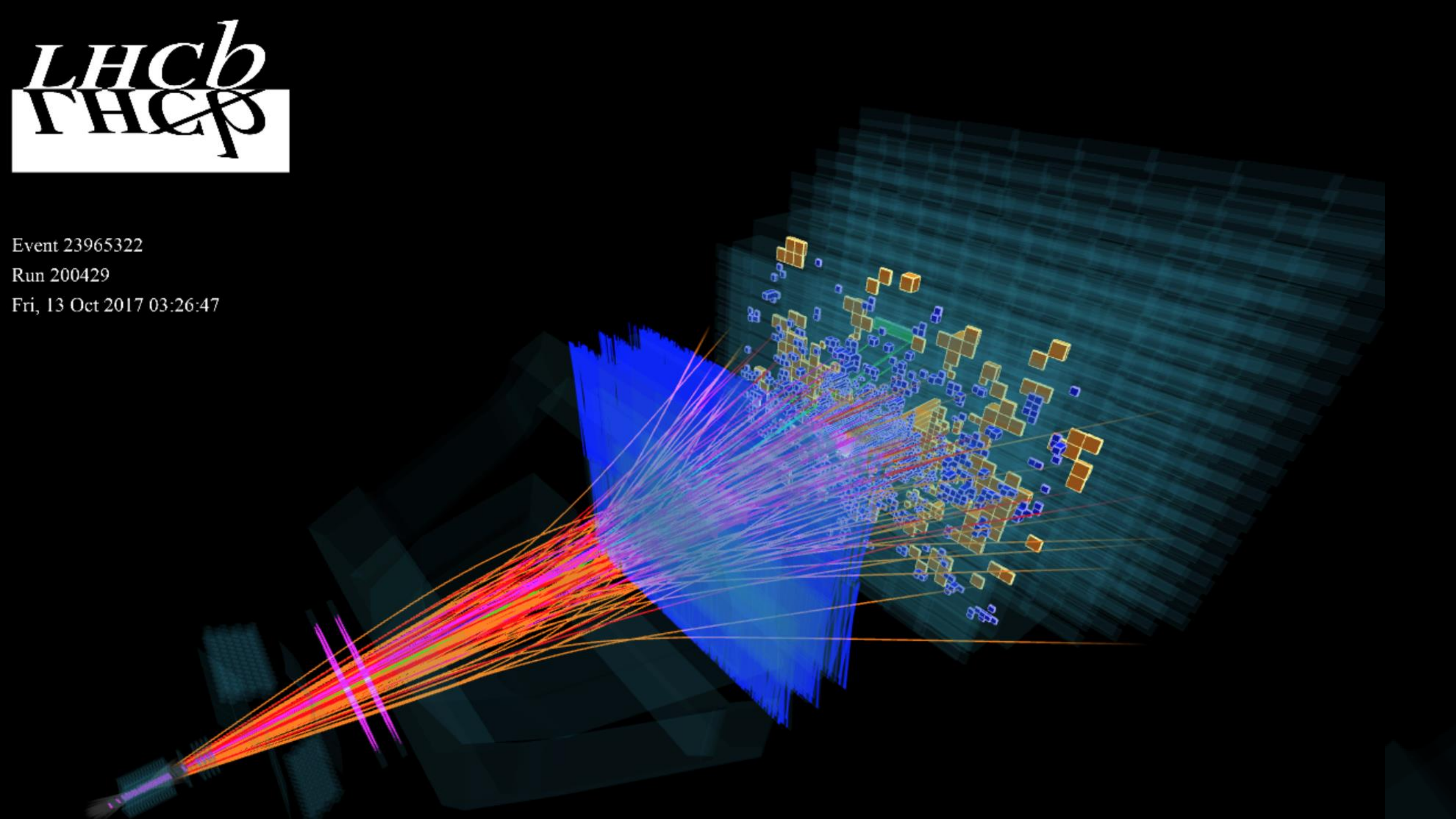
  Major upgrades for LHCb and ALICE, first upgrades in ATLAS and CMS already in preparation for HL-LHC

  Phase I projects approved, funded, and under construction
- Phase II upgrades during LS3

  Major upgrades in ATLAS and CMS

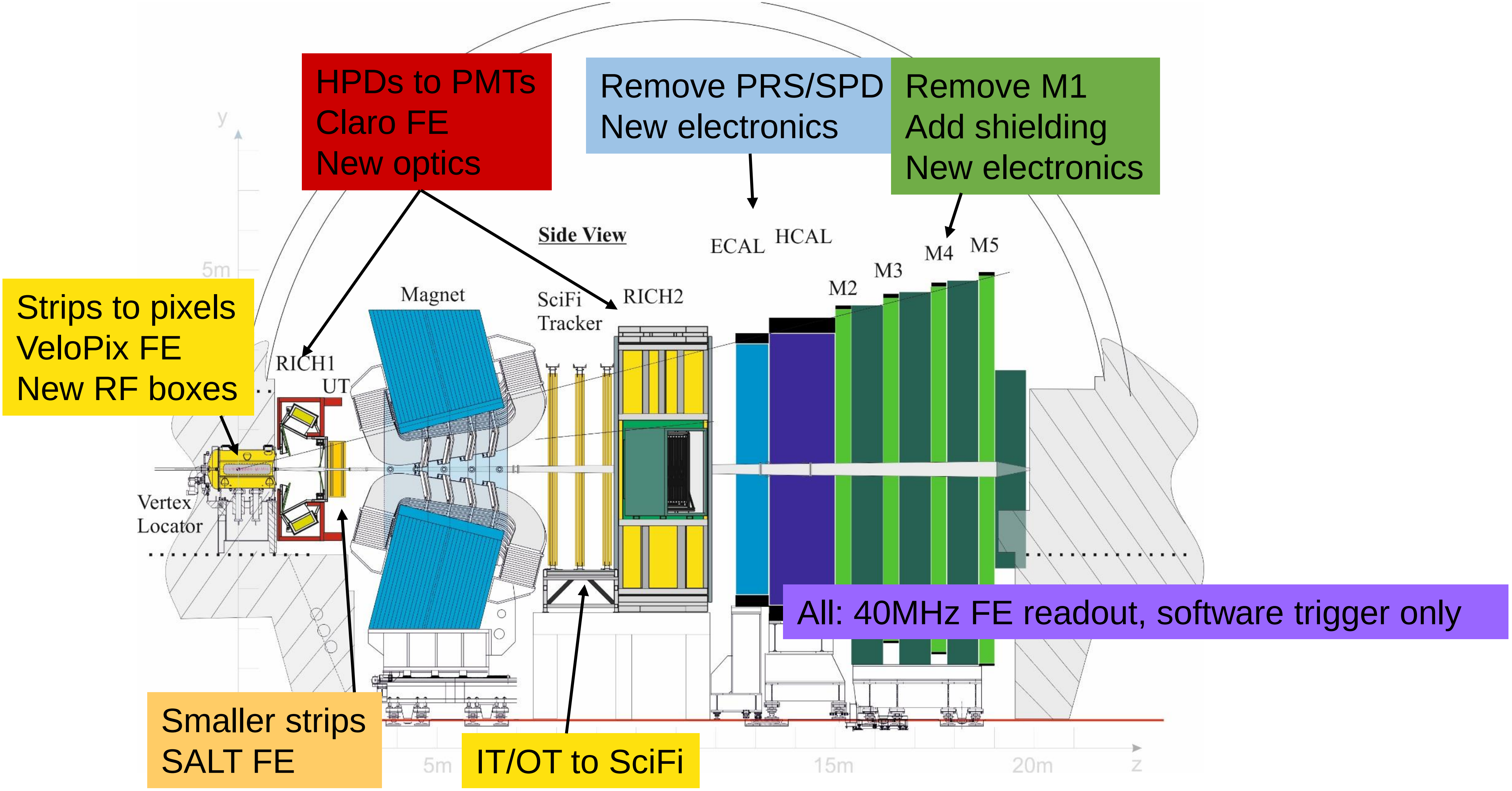
  Approval process ongoing:

  - Step1 (Sept. 2015): Approval of preliminary design for the complete set of Phase-II upgrades
    - Scoping document Including scoping options
    - Reasonable matching of cost to funding availability
  - Step2 (now): Approval of baseline design, cost and schedule, TDRs submission and scrutiny by LHCC and UCG (Upgrade Cost Group)
  - Step3 (2018 and beyond): Approval for construction following Engineering Design Review


LHCb
Event 23965322
Run 200429
Fri, 13 Oct 2017 03:26:47

LHCb LS2 upgrade

Goal: Raise operational luminosity by factor five to 2 x 10^{33} $cm^{-2}s^{-1}$



Status of LHCb upgrades

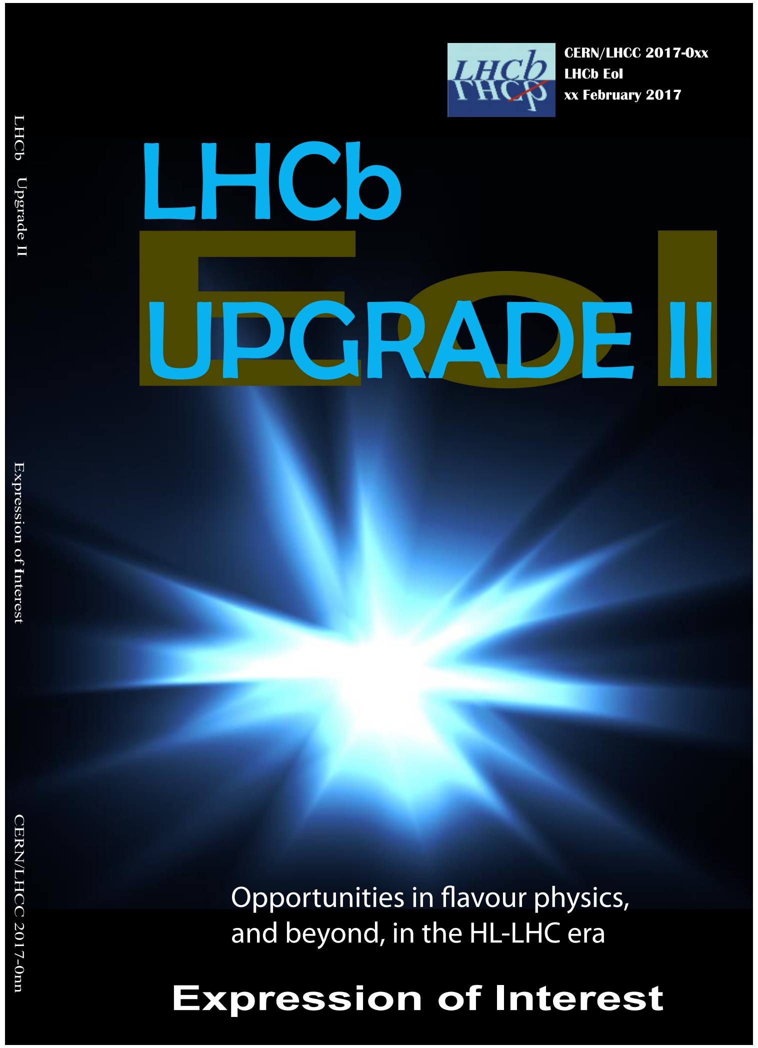
- VELO ready to start producing pre-series modules
  - Just chose among three beautiful solutions the CO_2 cooling substrate technology: Si µchannel (other 2: Ti 3D printed, ceramic with embedded SS capillaries)
  - Two full size RF boxes in hand: 1st being etched down to 0.15mm, 2nd machined down to 0.25mm thickness
  - Velopix v2 pre-series wafers at CERN
- SciFi tracker production at full speed
  - Fibre: 9600km received and tested (out of 11000 km), 760 of 1200 mats made
  - 500 preseries SiPM tested/validated
  - PACIFIC chip ready for production
- UT approaching first populated stave production:
  - Type-A sensors (the bulk) ready for ordering, others will follow soon
  - SALT 128ch chip v2 back from foundry, under test soon
  - Flex cables being ordered
- RICH in production:
  - PMTs flowing in: 1000 of 3500 received
  - Full CLARO chip production received
- CALO, MUON: on track

LHCb LS4 upgrade, in the pipeline

LHCb have issued an Expression of Interest in a second Upgrade, a HL-LHC era flavour physics experiment

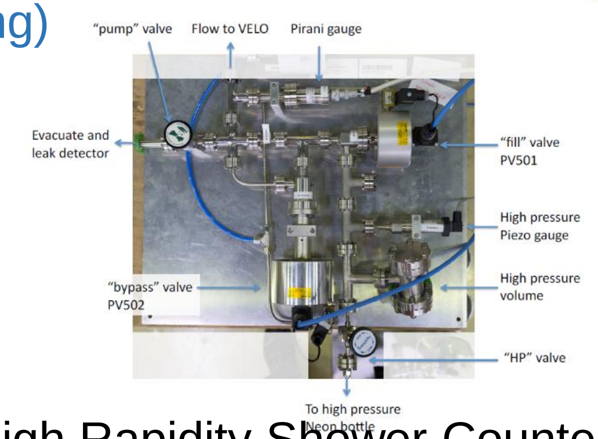
- Data taking for after LS4
- Luminosity 1-2 x10^{34} cm^{-2} s^{-1}
- Collect ~ 50 fb^{-1} / year, > 300 fb^{-1} total

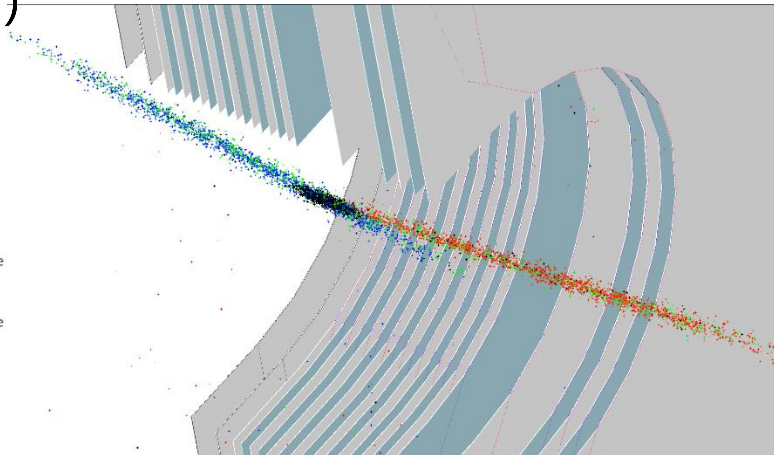
- Presented to LHCC and encouraged to continue to a physics case document and proceed with discussions with LHC
- Preliminary discussions with HL-LHC reported in EoI and are promising



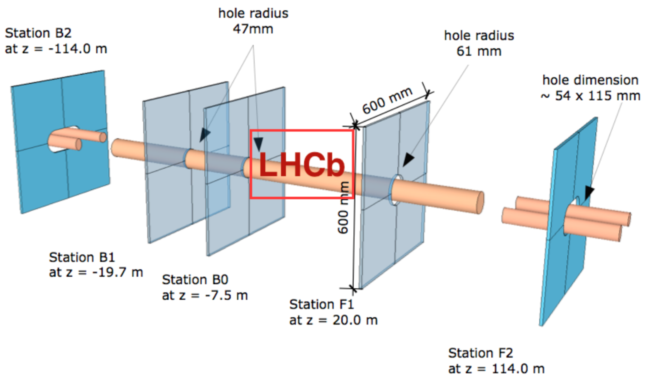
Current LHCb Forward-Physics

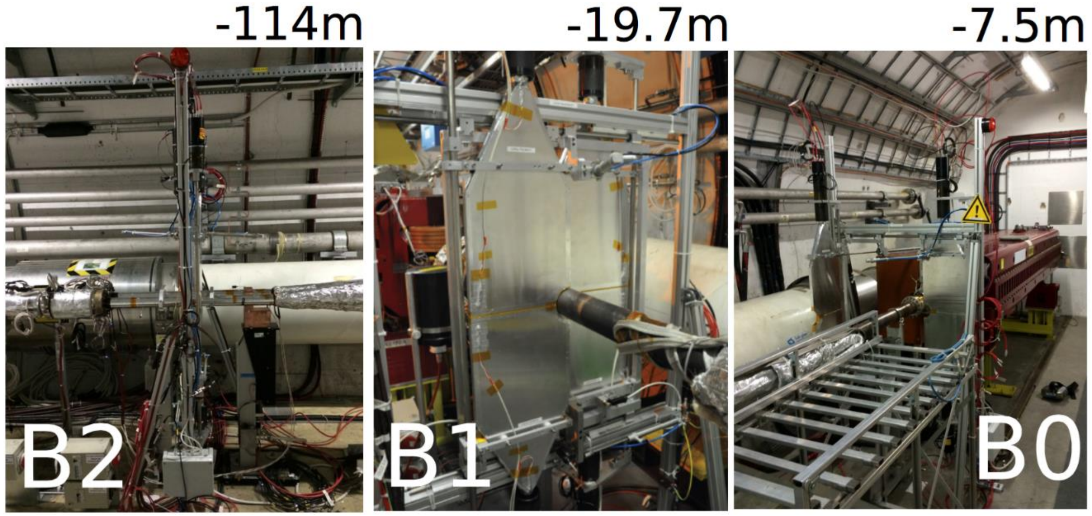
- SMOG: gas injection into VELO, gaseous unpolarised target (He, Ne, Ar)
  - Luminosity calibration (beam-gas imaging)
  - Ghost charge measurements
  - Beam size/emittance measurements
  - **Fixed-target physics**





- Forward Detectors in the tunnel: Herschel (High Rapidity Shower Counters for LHCb) **C**entral **E**xclusive **P**roduction physics and beyond





HERSCHEL will run until LS2 and probably at the start up phase after LS2.

Considered future projects - Ideas

- Since beginning 2017 LHCb is **considering** a few new fixed-target physics proposals in the frame of a **Fixed Target Panel (FITPAN).**
- These ideas are also discussed in **Physics Beyond Collider (PBC)** forum.
- **Nothing approved / decided => in evaluation phase!**

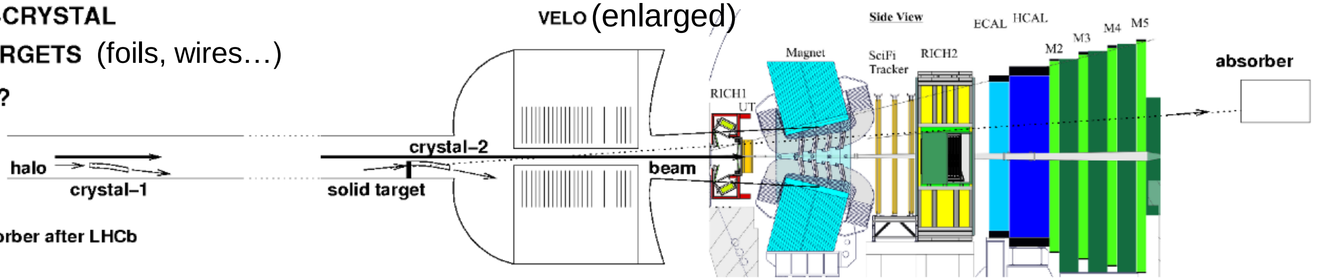
Polarization precession in crystal-2
=> bayron MDMs, EDMs

QCD (ion) physics

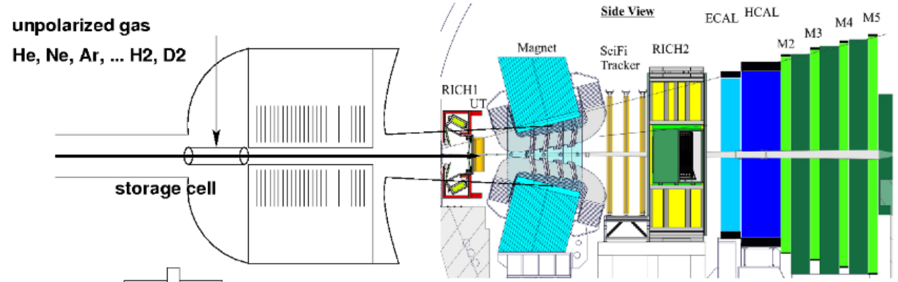
QCD spin physics

DOUBLE–CRYSTAL SOLID TARGETS (foils, wires…)
after LS2 ?

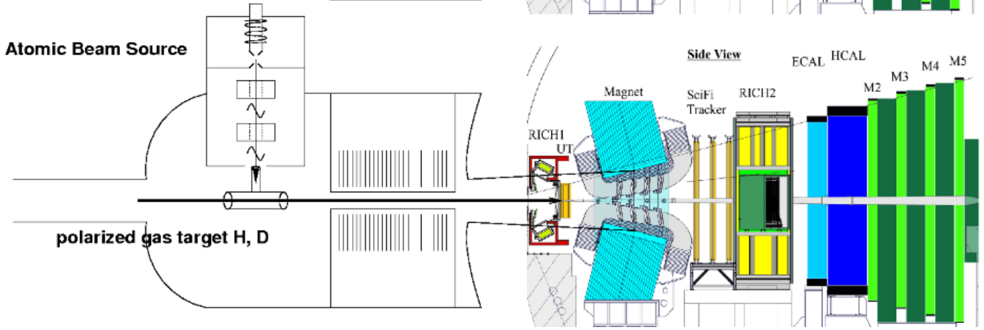
requires absorber after LHCb



SMOG++ (SMOG2) with a storage cell in LS2 ?



POLARIZED TARGETS
after Run3 ?
requires moving back by 1–2m MBXW

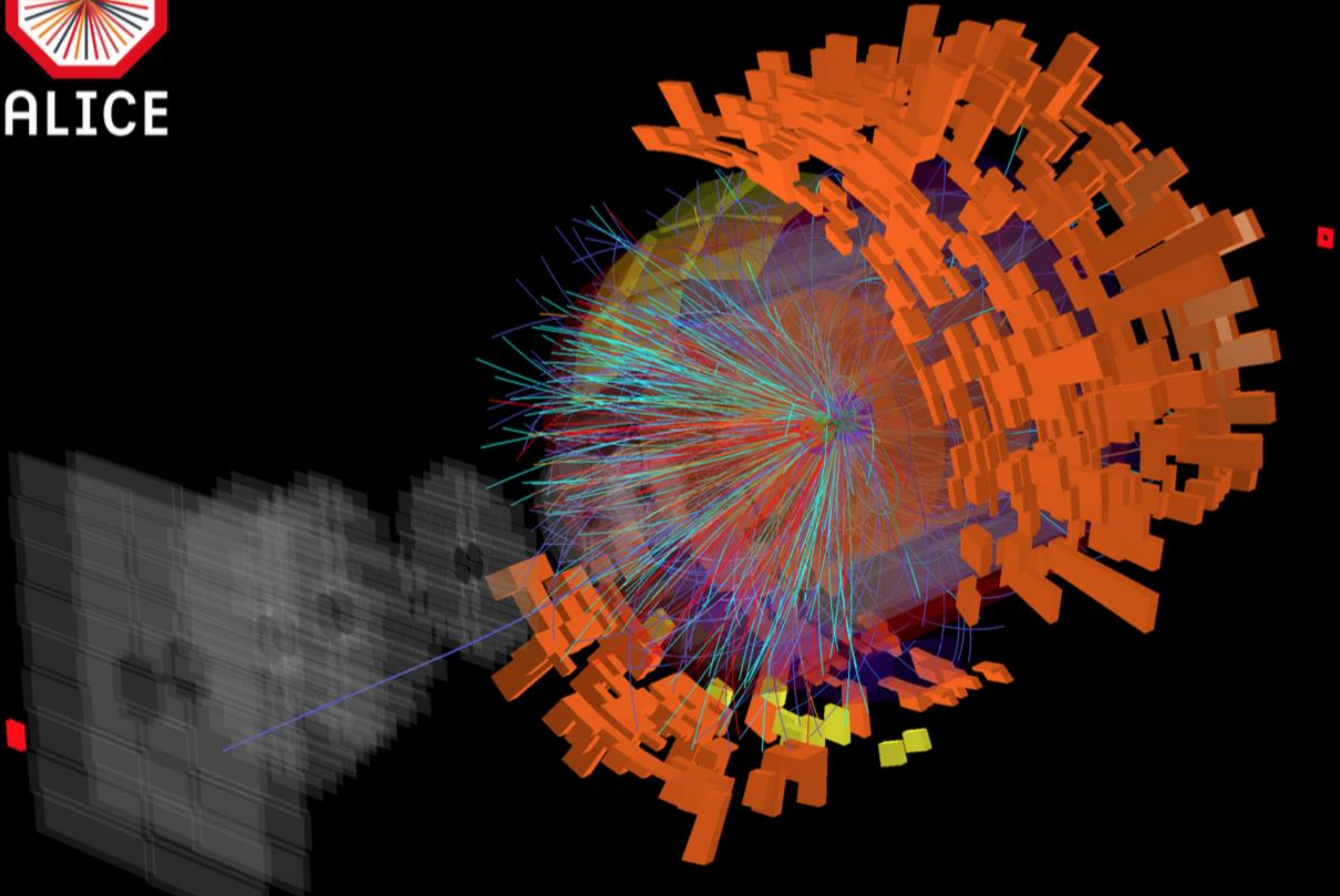


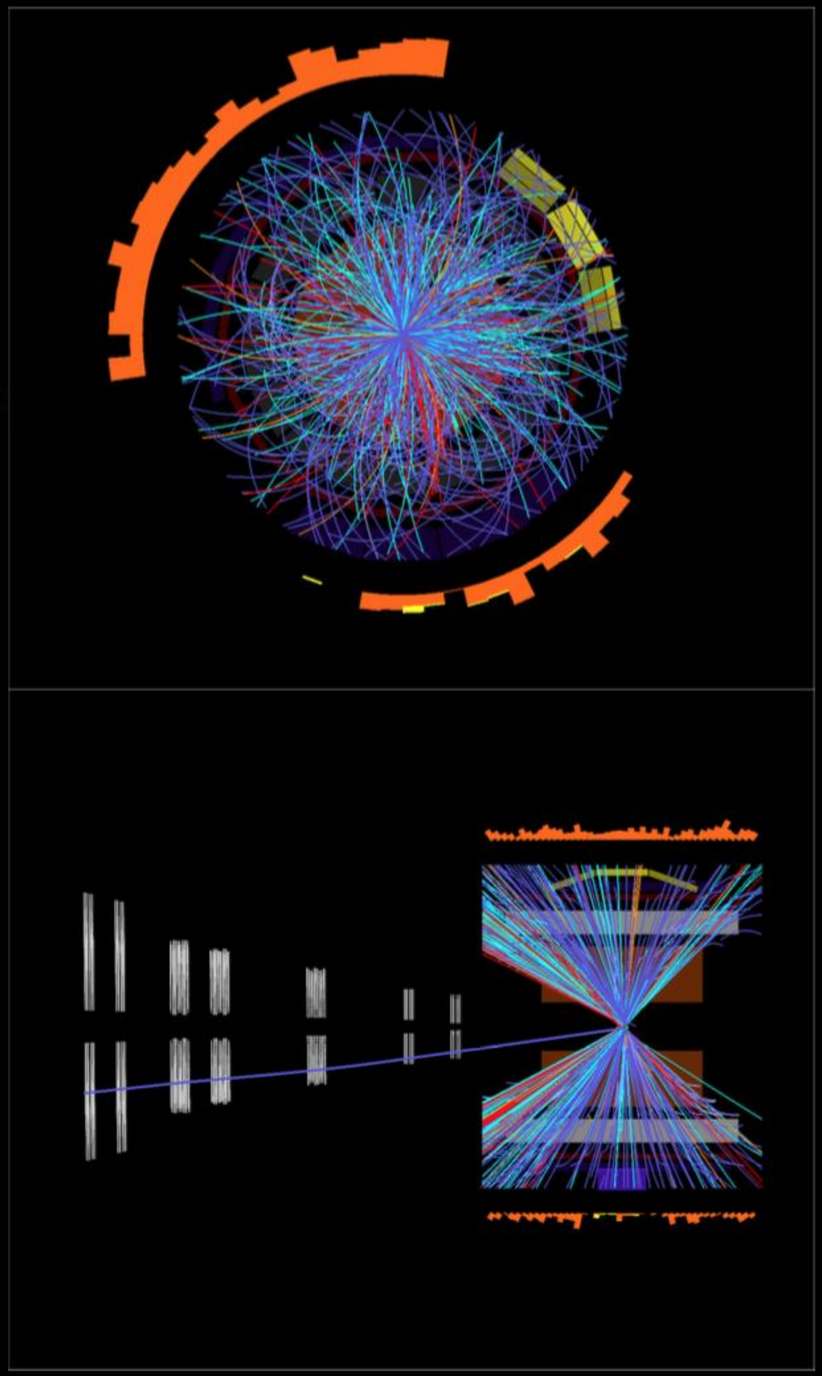
Impact

- Machine elements must adapt to slow LHCb evolution
  - Must **maintain possibility to flip regularly B field, up to highest luminosity**
    - **Rotate beam screen of inner triplet**
  - Shielding, protection of inner triplets to cope with increasing lumi ?
  - Compensator magnet to be moved by few m ?
  - Additional absorber (crystal-extracted beam) ?

- Vacuum system must also evolve with it
  - Separation valve just before VELO
  - Crystals, movable devices ?
  - Storage cell SMOG2, adapt vacuum system ?
  - Polarized target, new pumping system, coatings, … ?

Tight collaboration with TE-VSC





Xe-Xe

Run:280235

Timestamp:2017-10-12 21:56:43(UTC)

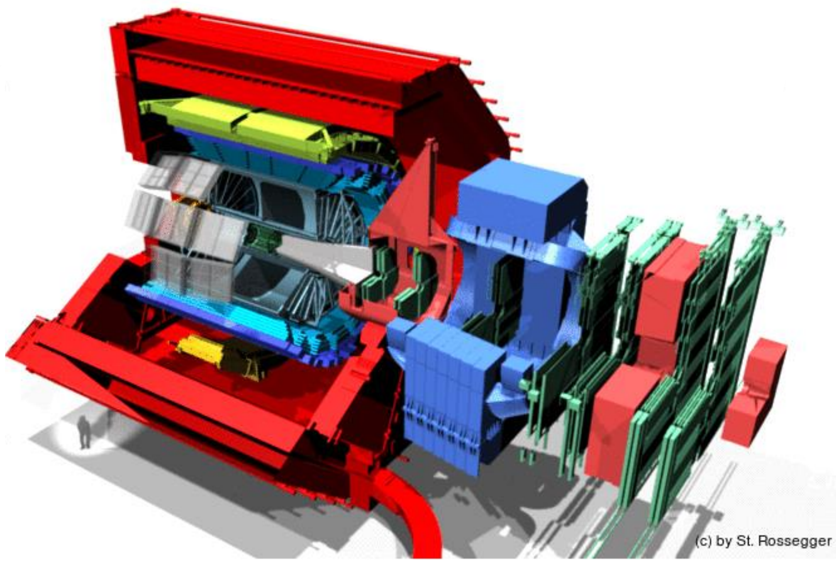
Colliding system:Xe-Xe

Energy: 5.44 TeV

The ALICE upgrade

Goal:

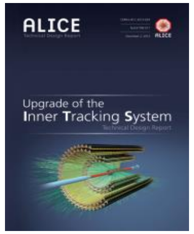
- High precision measurements of rare probes at low $p_{T,}$ which cannot be selected with a trigger. Target a recorded Pb-Pb luminosity $\geq 10\ nb^{-1}$ ➡ 8×10^{10} events to gain a factor 100 in statistics over the Run1+Run2 programme and
- Significant improvement of vertexing and tracking capabilities



Detector:

- Read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6x10^{27}\ cm^{-1}s^{-1}$) upon a minimum bias trigger
- Perform online data reduction based on reconstruction of clusters and tracks
- Improve vertexing and tracking at low p_T ➔ New Inner Tracking System (ITS)

The ALICE Upgrade, 5 TDRs



- Silicon Inner Tracking System (ITS) upgrade

- Time Projection Chamber (TPC) readout chamber upgrade

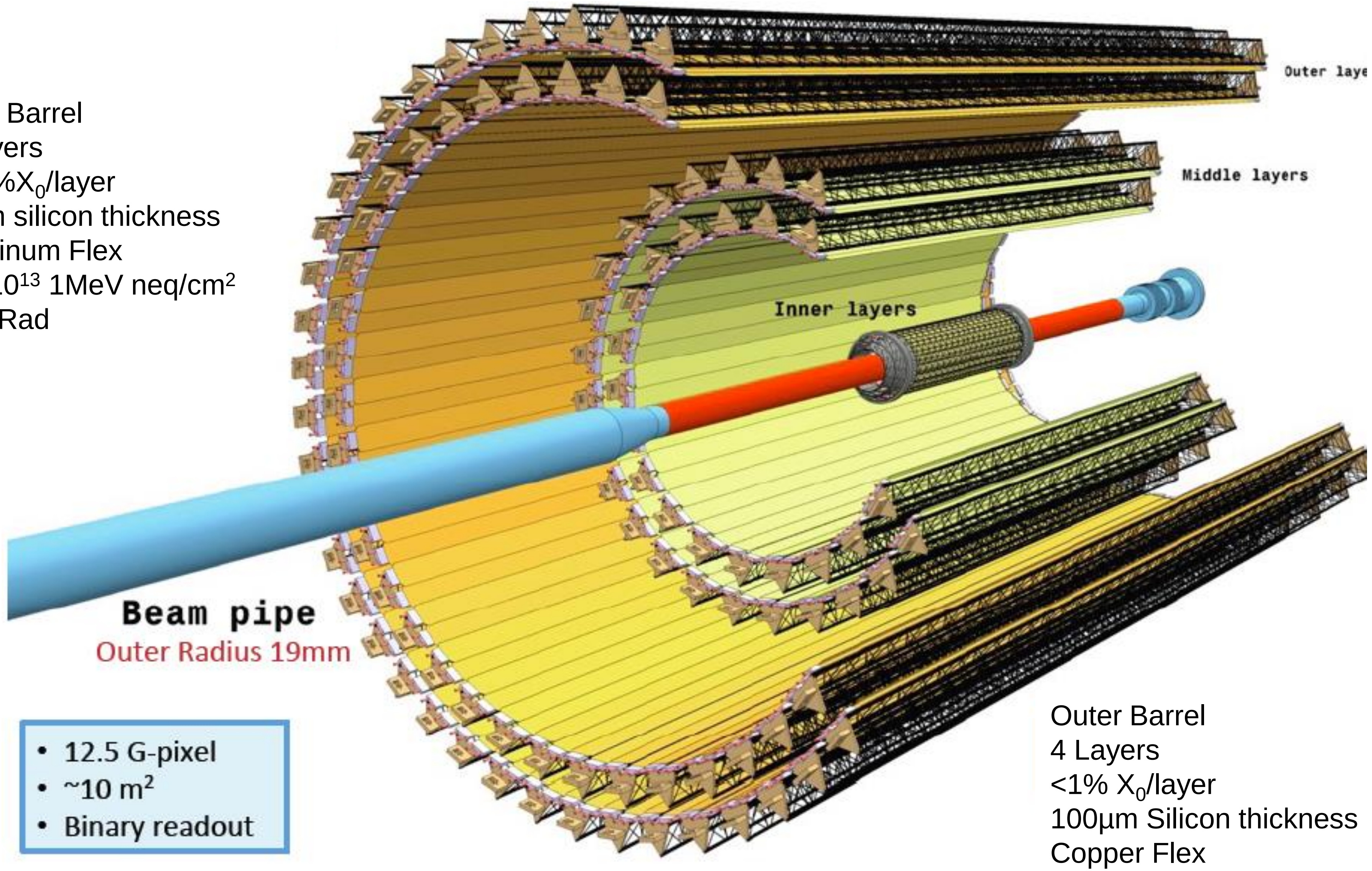
- Muon Forward Tracker (MFT)

- Upgraded readout for all detectors to cope with the higher rate (SAMPA, CRU)
  Upgraded Central Trigger Processor
  Upgraded Fast Interaction Trigger (FIT) based on Quartz+MCP & Scintillator
  New Radiation requirements

- Upgraded Online-Offline (O2) system to handle the continuous readout at 50kHz PbPb collisions and reconstruction

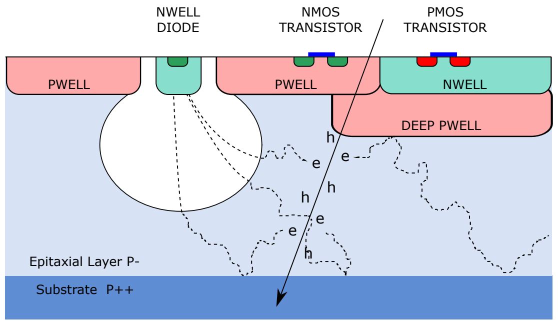
7 Layers of Monolithic Active Pixel Layers

Inner Barrel
3 Layers
<0.3%X_0/layer
50µm silicon thickness
Aluminum Flex
1.7×10^{13} 1MeV neq/cm^2
2.7MRad



- 12.5 G-pixel
- ~10 m^2
- Binary readout

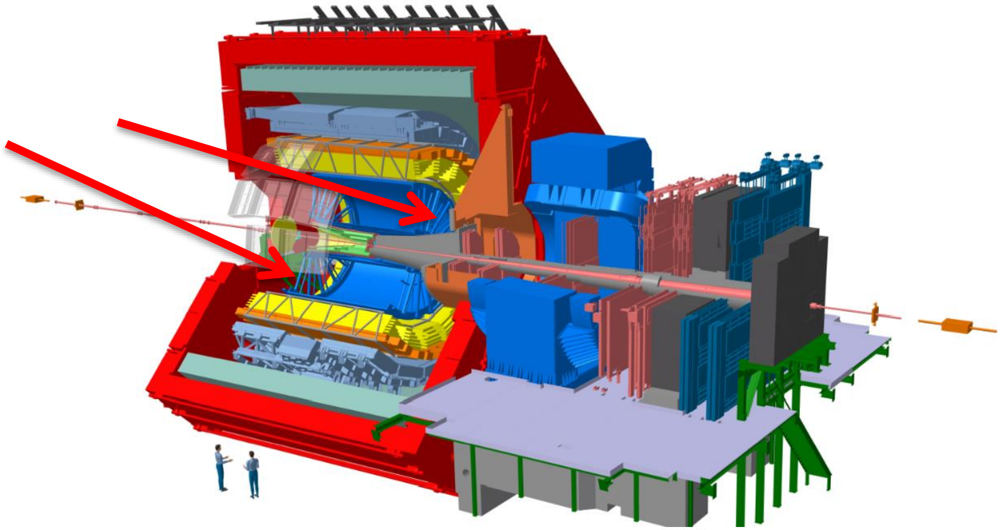
ALPIDE: CMOS Pixel Sensor using TowerJazz 0.18mm CMOS Imaging Process

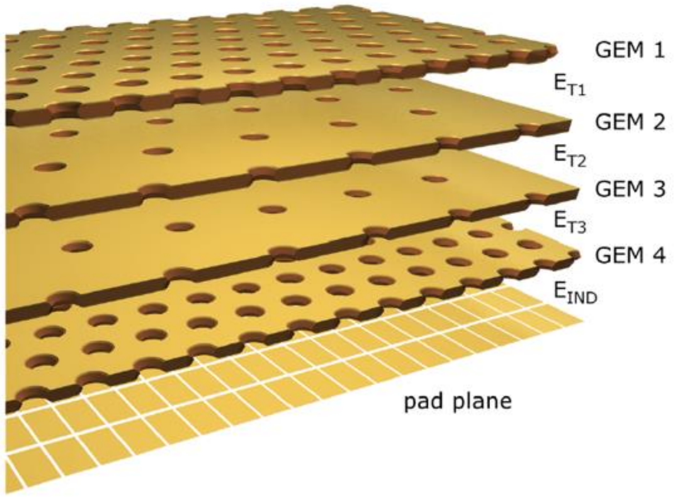


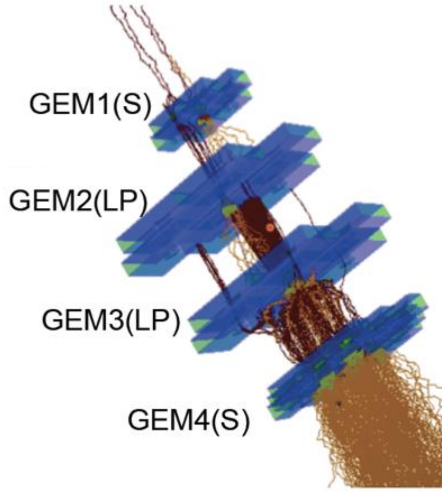
Outer Barrel
4 Layers
<1% X_0/layer
100µm Silicon thickness
Copper Flex
10^{12} 1MeV neq/cm^2, 100kRad

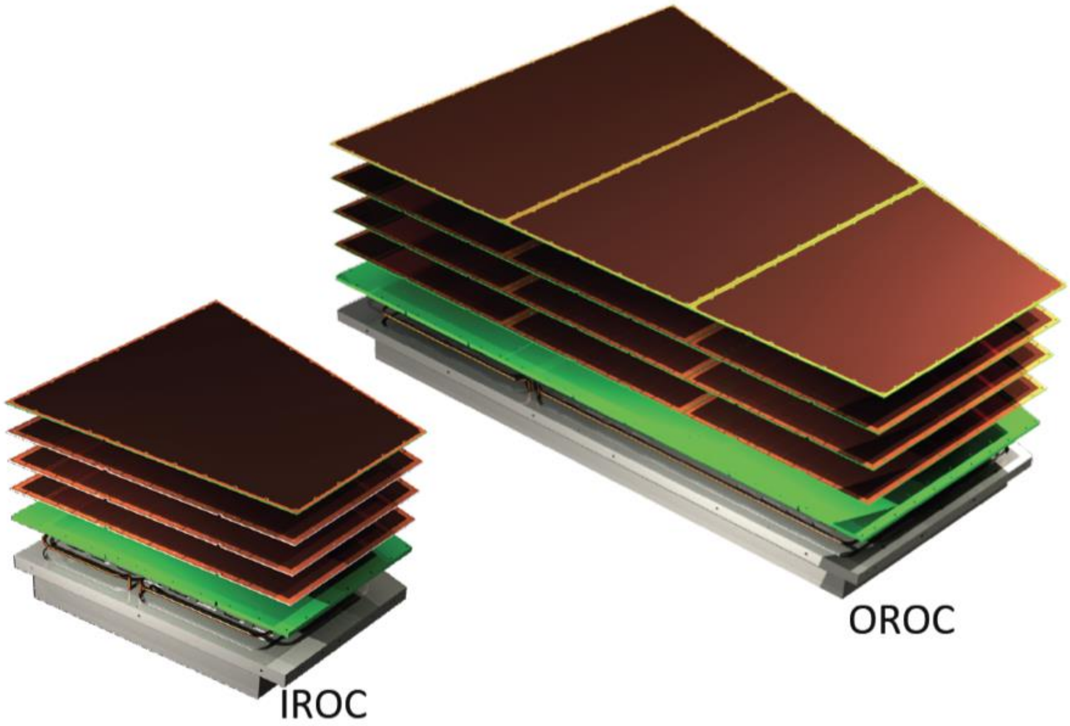
TPC Upgrade

Exchange wire chamber readout by 4 GEM setup









- Large-size single-mask foils from CERN PCB workshop
- 1 stack in IROC, 3 stacks in OROC

Production has started.

O^2 System

Requirements

1. LHC min bias Pb-Pb at 50 kHz
   ~100 x more data than during Run 1
2. Rare physics processes with very small signal over background ratio
3. Triggering techniques very inefficient if not impossible
4. 50 kHz > TPC inherent rate
   Support for continuous read-out

New computing system

➔ Read-out the data of all interactions

➔ Compress these data intelligently by online reconstruction

➔ One common online-offline computing system: O^2

Unmodified raw data of all interactions shipped from detector to online farm in triggerless continuous mode

⇩ HI run 3.4 TByte/s

Baseline correction and zero suppression
Data volume reduction by zero cluster finder.
No event discarded.
Average compression factor 6.6

⇩ 500 GByte/s

Data volume reduction by online tracking.
Only reconstructed data to data storage.
Average compression factor 5

⇩ 100 GByte/s

Data Storage
1 year of compressed data

120 GB/s ⇩ ⇧

Tier 0, Tiers 1 and Analysis Facilities

200 GB/s ⇩ 20 GB/s

Asynchronous (hours) event reconstruction wi[th] final calibration

Detector Electronics
9000 GBTs links

⇩

270 First-Level Processors
Hw acc: FPGAs

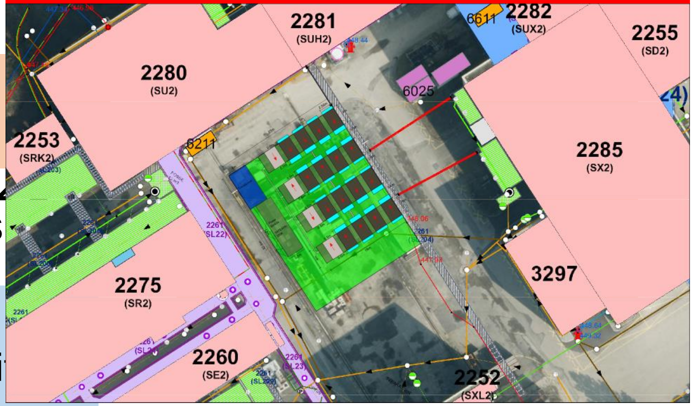
⇩

Switching Network

⇩

1500 Event Processing

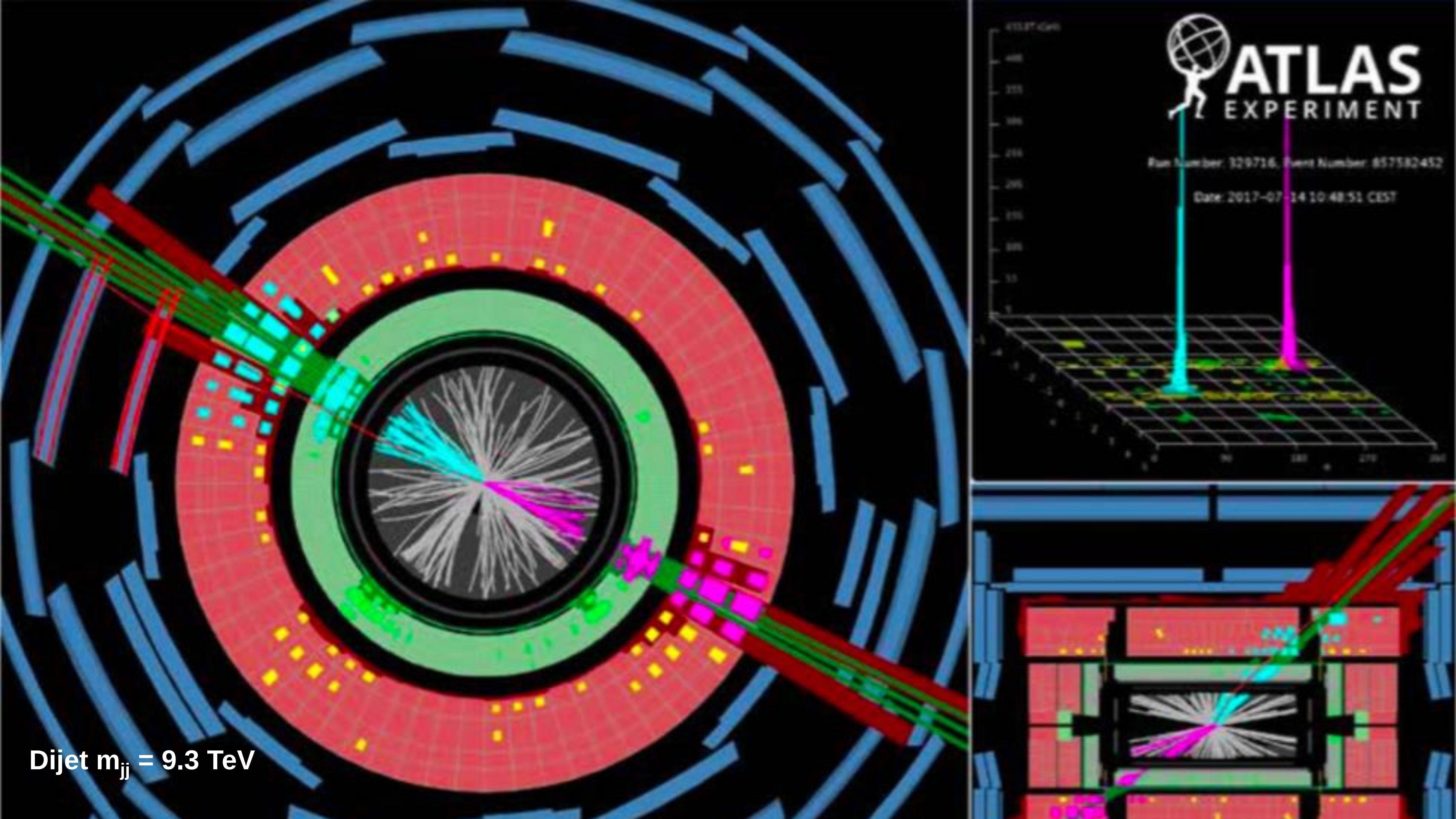
4 container at P2
Capacity of 2300 units
2 MW cooling



And beyond….

ALICE approved physics programme until Run 4 (included)

Possible installations in LS3 and LS4 are currently discussed internally

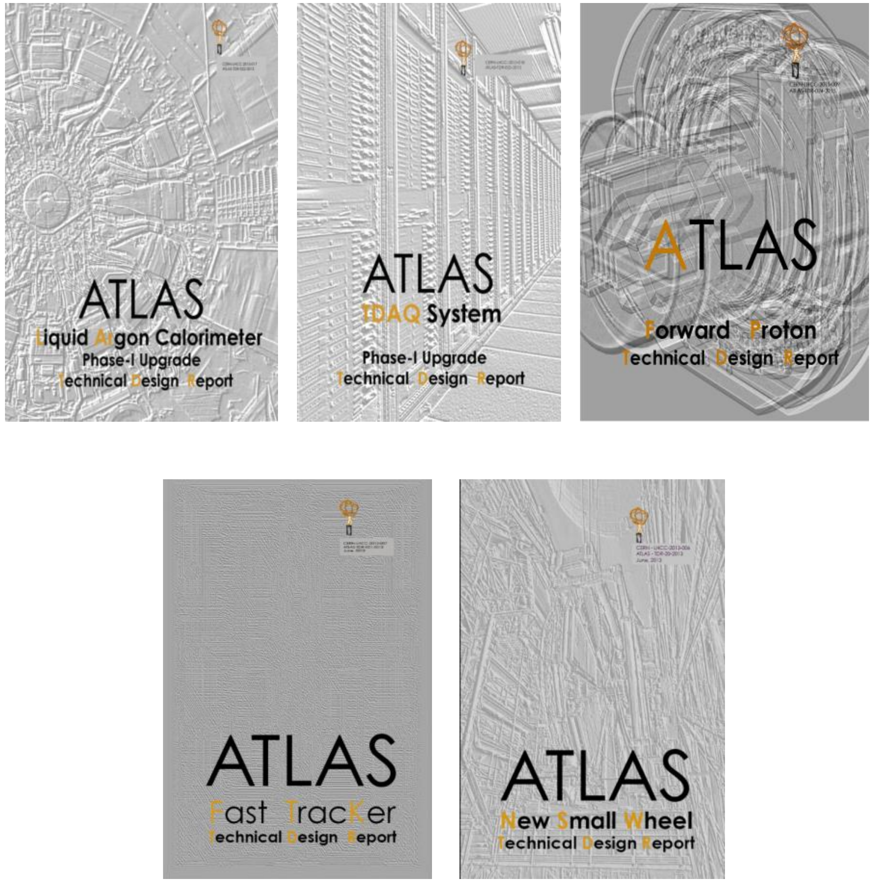


Dijet m_{jj} = 9.3 TeV

ATLAS Phase 1 Upgrades

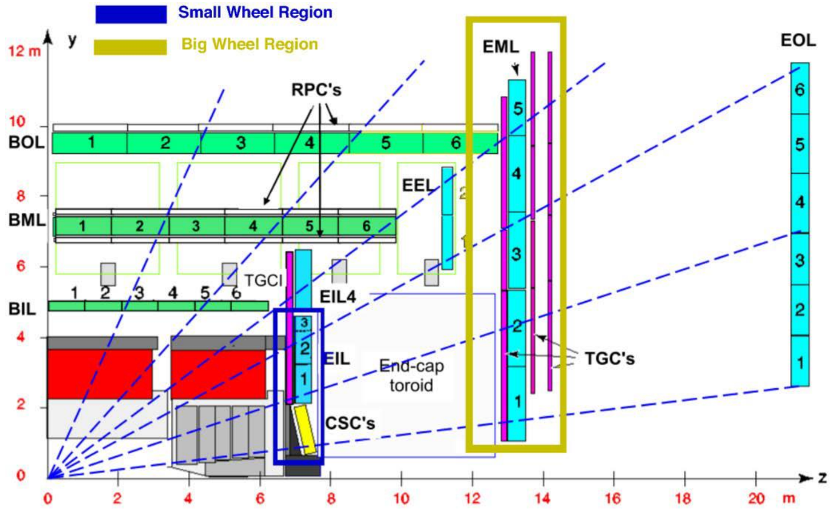
The ATLAS Phase I upgrade consists of five main projects:

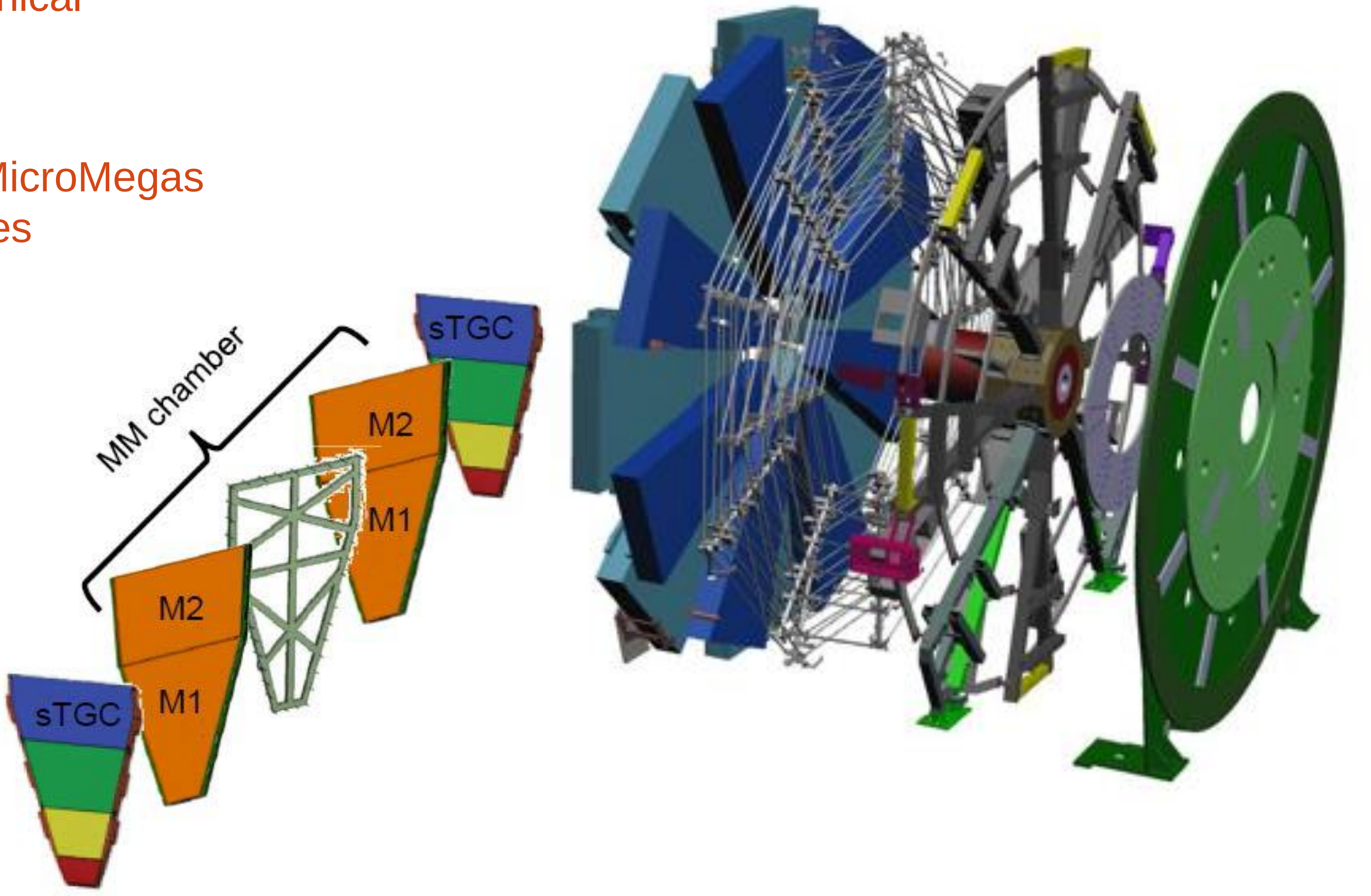
- The New Small Wheel (NSW)
  Improve end cap muon trigger sharpness and detector rate capability
- The LAr Upgrade
  New electronics to enlarge granularity in L1 trigger. Control electron and photon trigger rates through use of shower shapes at trigger level – under production
- FastTracKer (FTK)
  New logic based on Associated Memory Provide Fast Tracking information at the input of HLT - in installation and commissioning phase
- TDAQ phase I upgrade
  Improve L1 trigger hardware for calorimeters and muons, and upgrade DAQ hardware – expect completion Q1 2018
- AFP (ATLAS Forward Proton)
  Installed in YETS 2016&2017. Produce a new physics object for ATLAS physics: 2 forward protons - DONE



The New Small Wheel (NSW)

- Mechanics:
  Construction of New JD and mechanical Structure (10 m diameter,~100 t)
- Detectors:
  16x2 Sectors each consisting of 2 MicroMegas chambers (MM) and 2 sTGC Wedges
- Electronics:
  4 Different ASICs + 5 elx cards
  sTGC Pad Trigger and Router
  Trigger Processor





Status of the New Small Wheel Project

- Mechanical structure well advanced
  - First new JD assembled at CERN and second to be assembled by the end of October
  - NSW Aluminium structure and Cylindrical Hub will arrive at the end of the year
  - Copper disks for the Hub will arrive by end of March
- Micromegas production starting in each production sites (PRR passed by all production sites except Dubna)
  - Readout PCB production OK in both industries (ELVIA and ELTOS)
  - Tight schedule
- sTGC production starting in Chile, Canada and Israel, Protvino will join later due to missing raw material, PRR for Protvino at the end of the month
  - PCB production improved in Trilabs (new manpower hired and new Pressing machine under commissioning)
  - New parallel line of production by Israeli and Italian firms activated
  - Tight schedule
- Pre series of the four ASICs has been launched last week
  - Read out Boards still not finalized due to noise problems to be solved
  - Very tight schedule

Overall schedule: the installation of both wheels in LS2 is feasible if there are no further delays in any part of the production

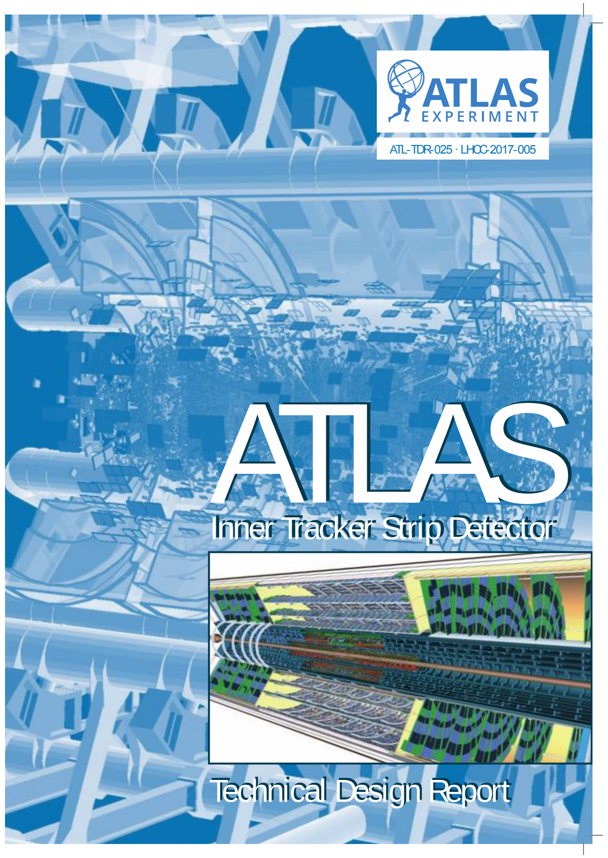
ATLAS Phase 2 Upgrades

6 TDRs in preparation or already delivered:

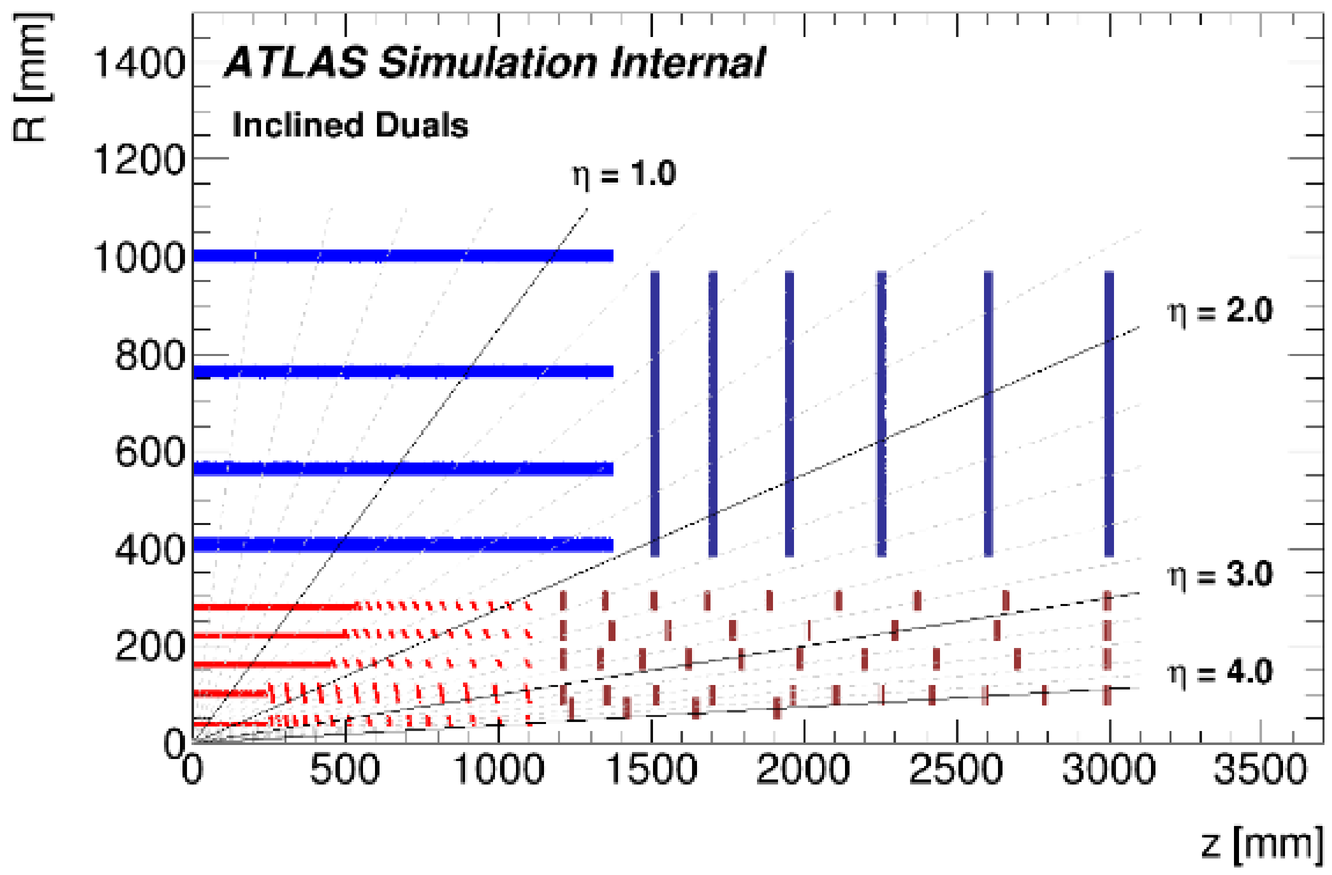
- Inner Tracker (ITK) strip delivered last year and approved
- Muon (delivered in July, approval under LHCC discussion) Replace MDT front-end electronics, add RPC chambers on innermost layers
- LAr Phase 2 (delivered under LHCC discussion) Complete replacement of front-end (on-detector) and back-end (off-detector) electronics, 40 MHz streaming
- Tile Calorimeter (delivered, under LHCC discussion) Complete replacement of on- and off-detector electronics, 40 MHz streaming
- ITK pixel and TDAQ to be delivered before the end of the year

Under discussion in the collaboration:

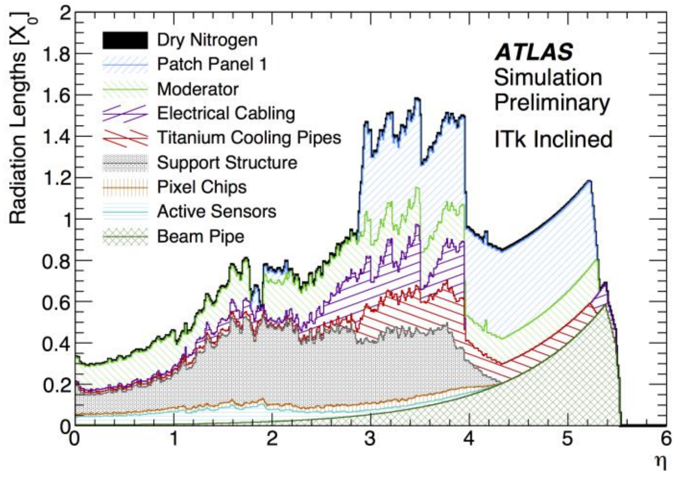
- Highly segmented Timing Detector, “Thin” high-precision timing layer (O 50ps) in the forward region ($2.4 < \eta < 4.0$), LGAD Silicon sensors, use space of MBTS (MinBiasTrigger Scintillators), installation in LS3, area also easily accessible during YETS, if detector made in two halves.



ITK: All Silicon Tracker

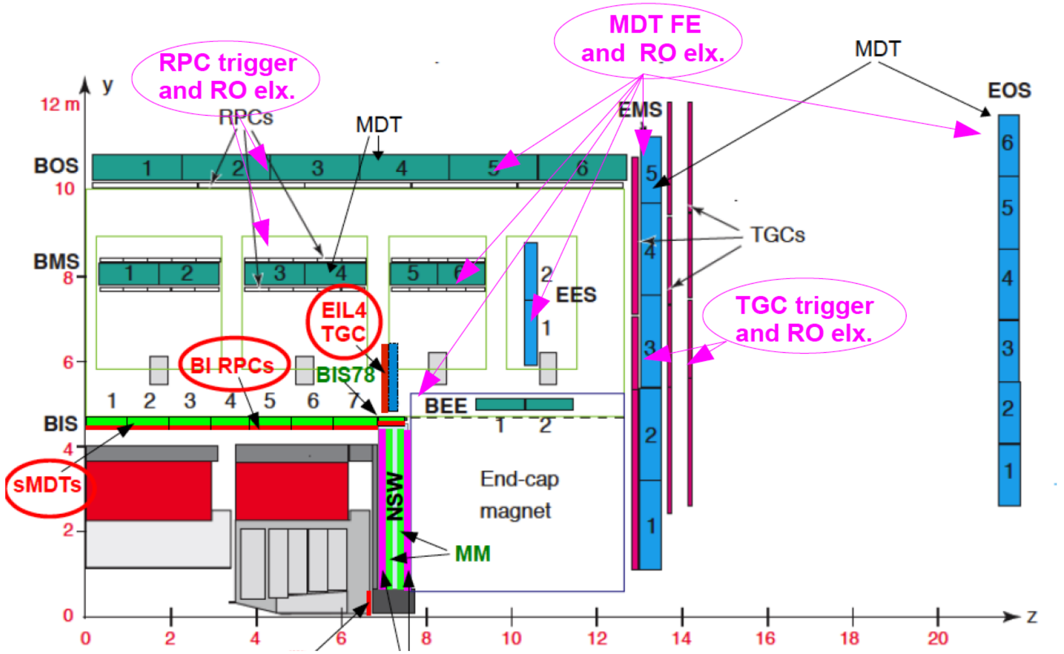


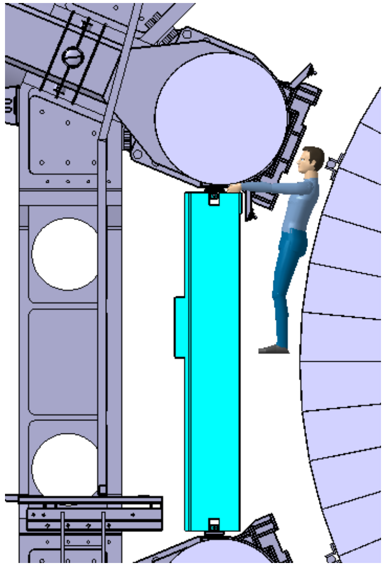
- Extend tracking to η=4, 165 m^2 of silicon, 5 Pixel layers, 4 strip layers, 6 discs
- Inclined geometry in the pixel barrel
- Read out at 1 MHz at a pile-up of 200 and L=7.5x10^{34}cm^{-2}s^{-1}
- Careful study to minimize material budget in particular on services
- Plan to replace the 2 inner Pixel layers after 2000 fb^{-1}



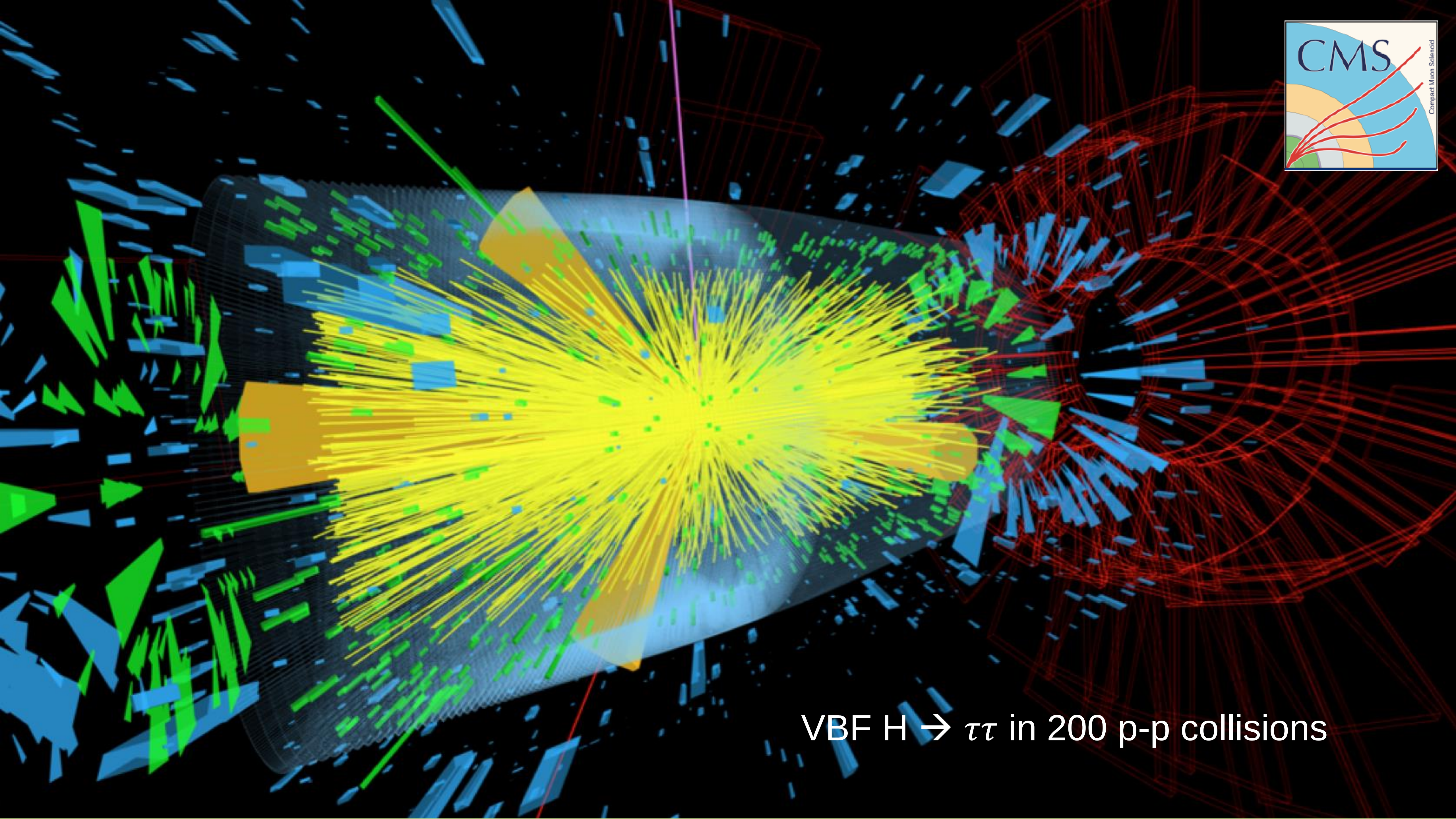
Muon Phase 2 upgrades

- Assume that it is possible to change all of the MDT electronics on the innermost barrel layer of the muon system. This eliminates any artificial limits on the L1 trigger rate and L1 latency arising from the legacy electronics;
- Replacing MDT electronics on all BI chambers allows making more significant changes. In particular, it provides the possibility to add RPCs on the innermost layer (current system has 3 doublets of RPCs, two on BM and one on BO). It also allows the use of an RPC-seeded MDT trigger in L0 => sharper P_T thresholds.
- These upgrades will require very substantial work inside ATLAS!





Replacement of the MDT front-end electronics with extremely difficult access



VBF H → $\tau\tau$ in 200 p-p collisions

CMS phase 1 upgrades

- Main activities planned for YETS 2017/18
  - Hadron Endcap upgrade: HPDs → SiPMs – preparations continuing; final review in November
  - Infrastructure (second bridge crane in experimental cavern, Yoke4+ pushback system
  - Extract pixel detector for urgent diagnostics (reduce 2017 run by one week)

- Main activities planned for LS2
  - Hadron Barrel upgrade: replacement of HPDs with SiPMs
    Plus potentially HE upgrade, depending on outcome of review
  - CSC Phase-2 front-end electronics upgrade in inner ring (stations 1, 2, 3 ,4)
  - Installation of muon GE1/1 GEM chambers
  - Installation of Phase-2 beampipe (→ requires extraction of pixel detector)
  - Refurbishment of pixel detector
    Replacement of layer 1 modules (new readout chip, new TBM) under discussion
    Repair of non-working power and readout groups
  - Refurbishment of Pixel Luminosity Telescope & Beam Condition Monitoring systems

CMS Phase-2 upgrades

L1-Trigger/HLT/DAQ

- Track information in trigger at 40 MHz
- 12.5 μs latency
- HLT input/output 750 kHz/7.5 kHz

Barrel EM calorimeter

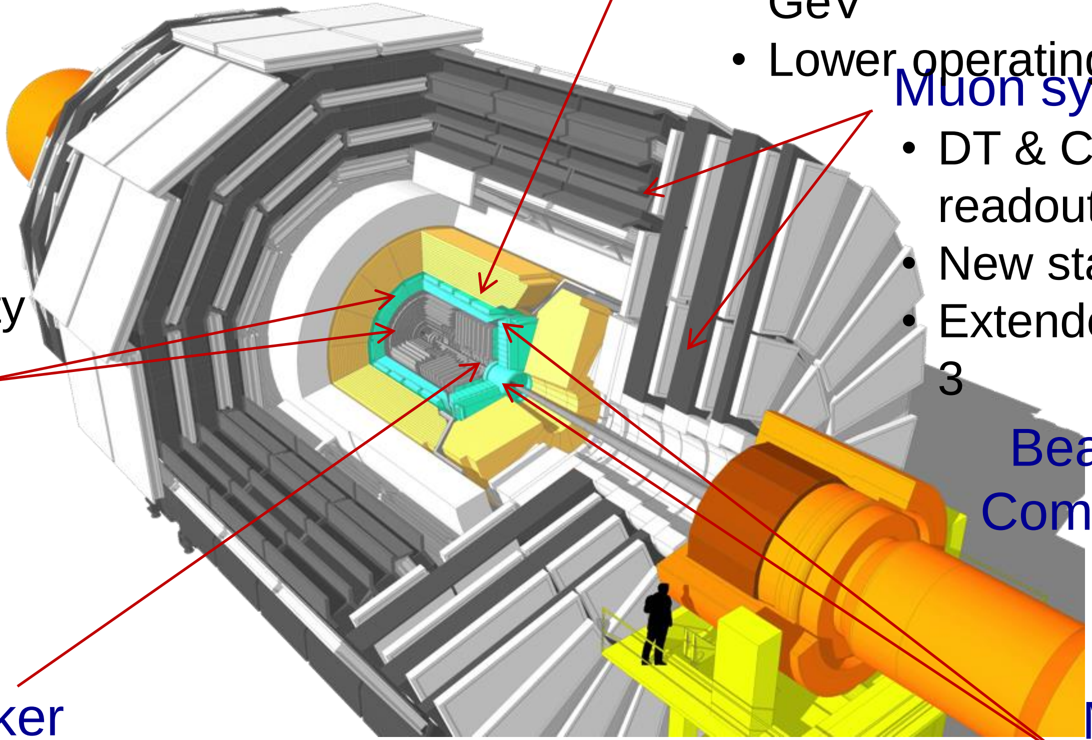
- New FE/BE electronics for full granularity readout at 40 MHz, ≃ 30 ps e/γ-shower resolution at 30 GeV
- Lower operating temperature (9∘)

Muon systems

- DT & CSC FE/BE new readout
- New stations 1.6 < η < 2.4
- Extended coverage to η ≃ 3

New Endcap Calorimeters

- Rad. tolerant - high granularity transverse and longitudinal
- 4D shower measurement including precise timing



Beam Rad. Inst. and Luminosity
Common systems and infrastructure

New Tracker

- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout (strips) for L1-trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector (≃ 30 ps)

- Barrel layer: Crystal + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

CMS Phase-2 upgrade approval process

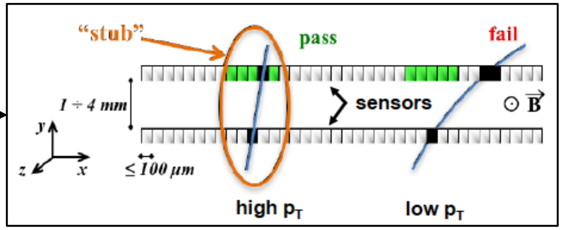
- Tracker TDR review
  - LHCC approval: "The Tracker Upgrade Project pushes tracker designs into a new paradigm with a scope that is justified in terms of technical realization as well as physics performance. The design is bold, but no technical showstoppers have been identified"
  - UCG now reviewing management, resource, schedule and risks
- Muon and Barrel Calorimeters TDRs submitted to LHCC Sep. 12
  - Reviews are on-going
- Trigger and DAQ Interim TDRs submitted to LHCC Sep.12
  - Design, R&D status and plans, cost estimate and schedule, TDRs in 2020 and 2021
  - Reviews are ongoing
- Calorimeter Endcap TDR
  - Submission to LHCC Nov. 27
- MIP Timing Detector Technical Proposal
  - Conceptual design, R&D status and plans, initial cost estimate and planning
  - Submission to LHCC Nov. 27

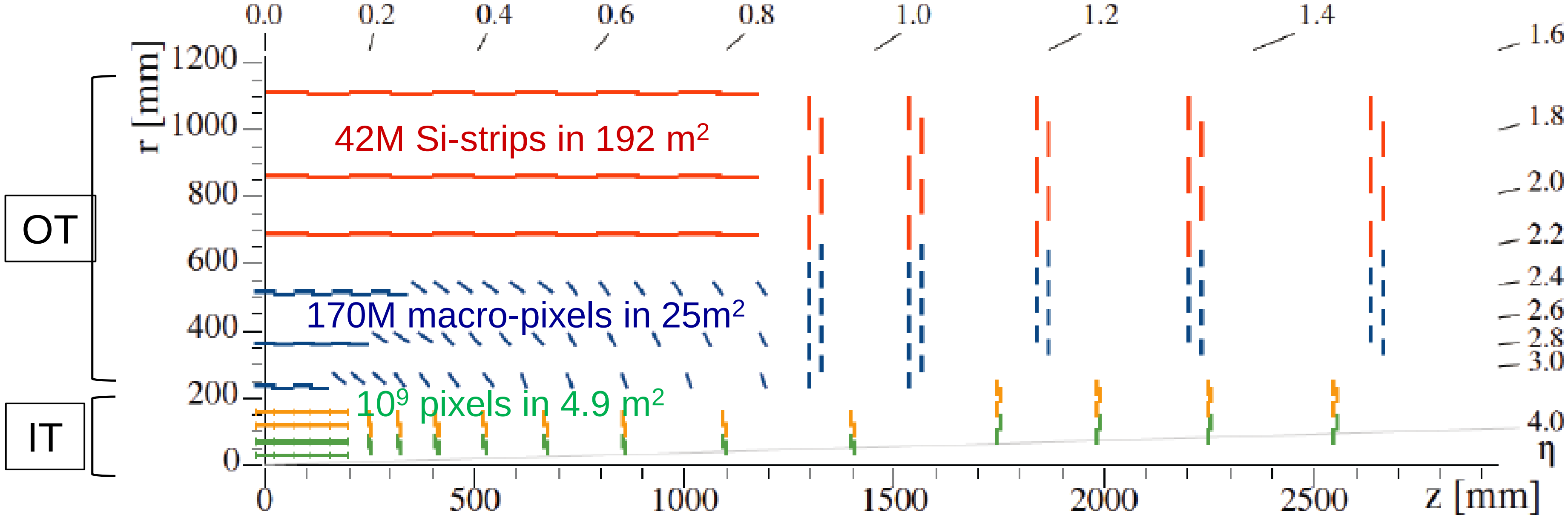
➢ Target for all projects to be approved to proceed to next step by Apr. 2018 RRB

CMS Phase-2 Tracker

Outer Tracker designed for 40 MHz L1-trigger capability
Tracking in L1-Trigger

- Special module concept in outer tracker to measure track transverse momentum within layers
- Macro-pixels in 3 inner layers to measure vertex origin, with tilted modules for efficiency





Inner Tracker designed for track impact parameter precision, up to $\eta \simeq 3.8$

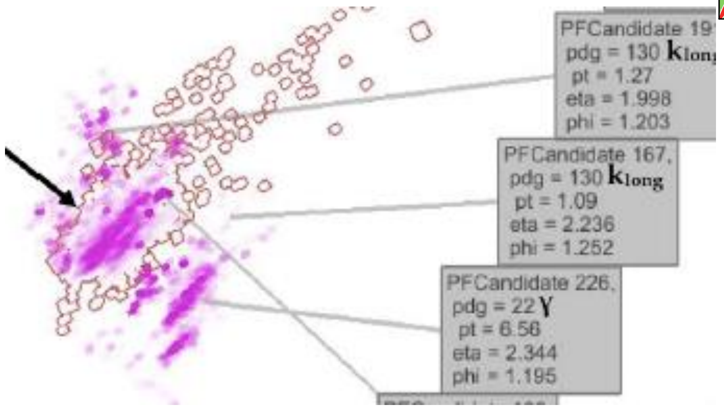
- Small pixel size 25 x 100 µm² or 50 x 50 µm²

CMS Phase-2 Calorimeter Endcap

Designed for 4D (x-y-z-t) measurement of shower energies

Shower X-ray view weighted by pulse height

- Multiple core showers clearly visible
- σ_t ~ 20 ps for ~ 5/20 MIPs (300/120µm sensors)

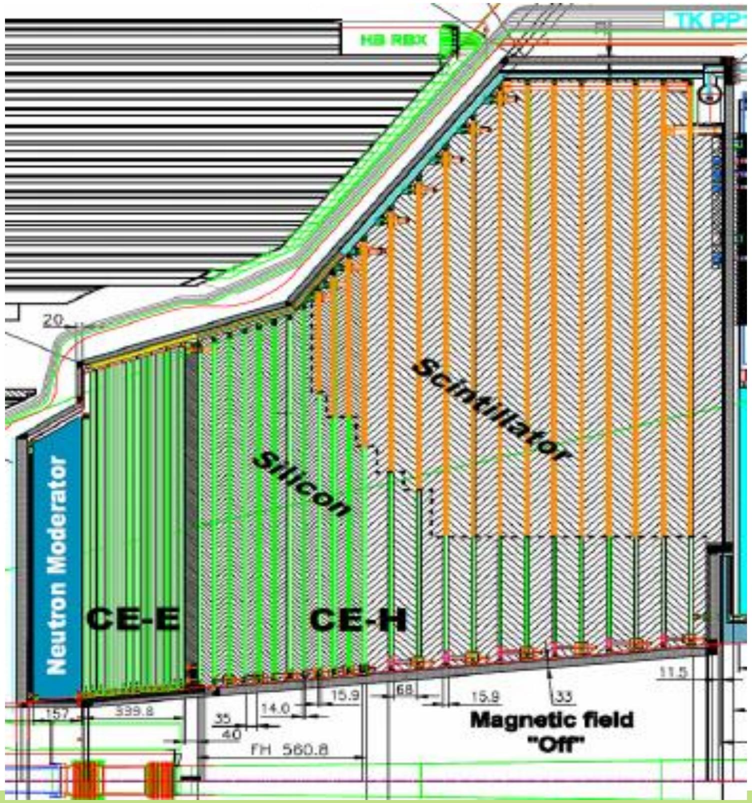


Calorimeter Endcap Electromagnetic (CE-E)

- 28 layers of Silicon sensors in W/Pb absorber (25 X_0 - 1.7d λ)

Calorimeter Endcap Hadronic (CE-H)

- 24 layers: 8 silicon + 16 silicon (high η) scint (low η) in stainless steel absorber (9 λ)



Key parameters:

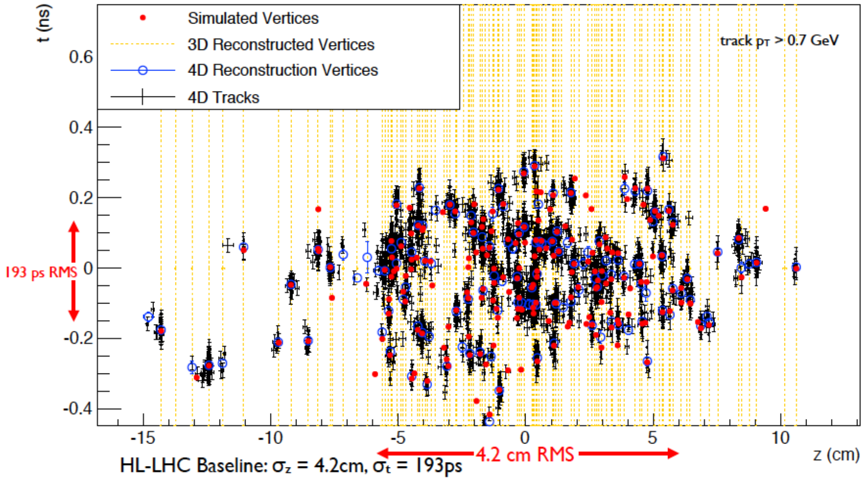
- 600 m^2 of hexagonal 8” silicon sensors
- 6M ch, 0.5 or 1 cm^2 cell-size
- 25’000 modules (8” sensors)
- 520m^2 of SiPM on tile plastic scintillator
- ~400k ch, 2x2cm^2 -> 5x5cm^2 tiles
- Total weight 253 t
- Total power at end of life 160~180 kW @-30^{o}C

CMS Phase-2 MIP-Timing Detector

Designed for 4D event reconstruction (x-y-z-t)

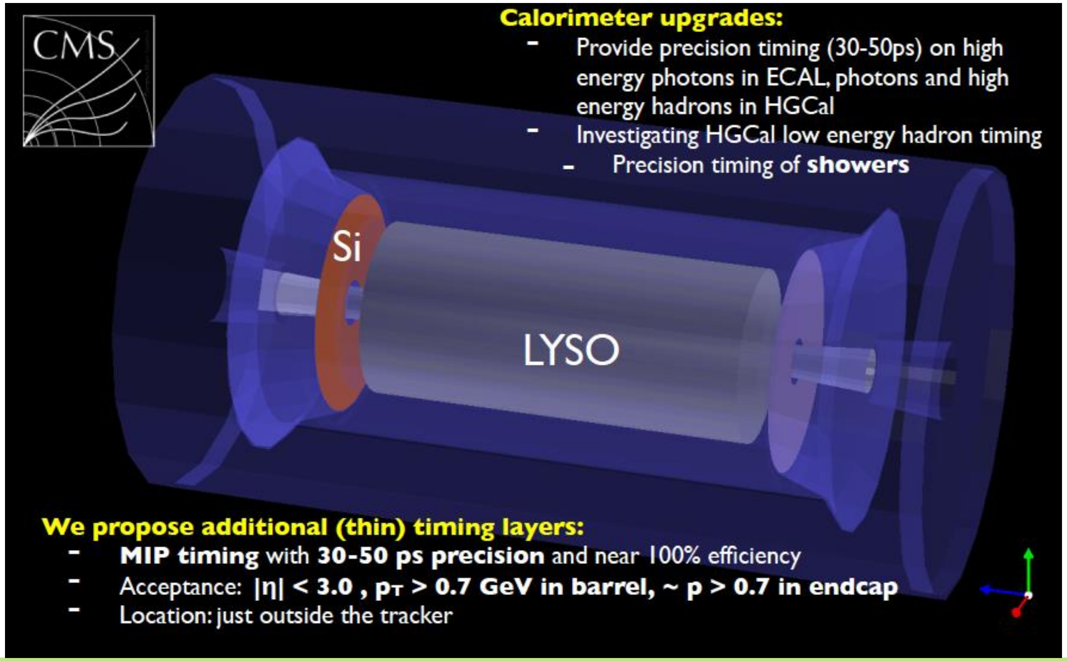
MIP ToF measurement with ≃ 30 ps precision

- ➢ 15% merged vertices reduced to ≃ 1.5% at 200 PU
- ➢ Recover low pileup track purity of hard scatter vertices



Coverage up to η ≃ 3, P_t > 0.7 GeV (barrel), P > 0.7 GeV (endcap)

- ➢ Barrel Timing Layer installed in Tracker support tube
  - 250k Lyso crystals 1.2x1.2 cm^2 + 4x4 mm^2 SiPMs
- ➢ Endcap Timing Layer installed in front of Calorimeter Endcap
  - 2600 Low Gain Avalanche Diode Si-sensors, 4 x 10 cm^2 with 1 x 3 mm^2 pixels



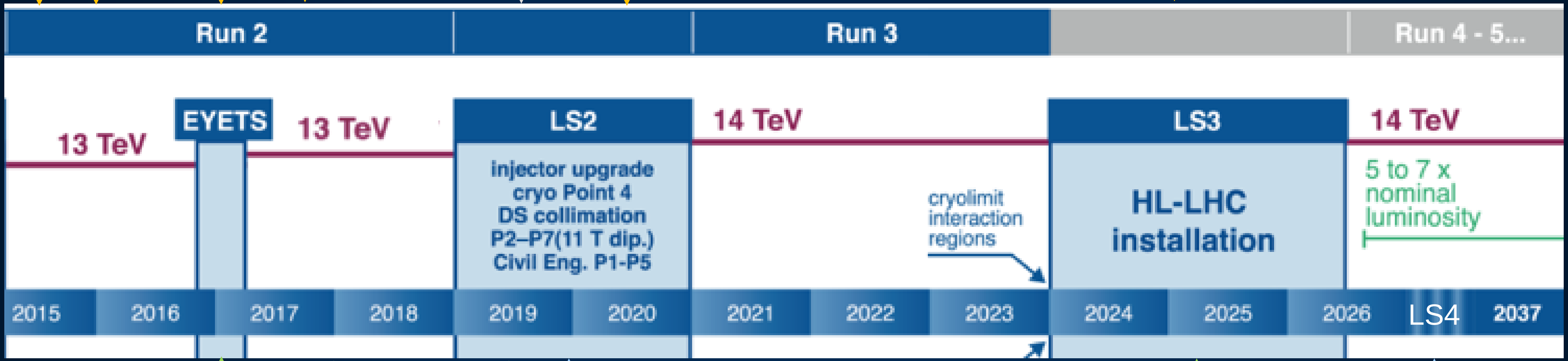
Summary

- Massive improvement program ongoing for all experiments (about O(½) the costs of the original experiments)
- Construction and preparation for LS2 (phase 1) ongoing, tight schedule for some projects, some concerns exist
- Approval process for upgrades during LS3 (phase 2) has started, funding discussions make good progress, aim to have ~90% achieved in April 2018
- First discussion on possible LHCb upgrade during LS4

Detector upgrades - Overview

ALICE ITS, TPC, MFT, SAMPA, FIT, O2

ATLAS AFP AFP BMG FTK NSW, LAr ITK, MUON, LAr, TileCalo, Timing?



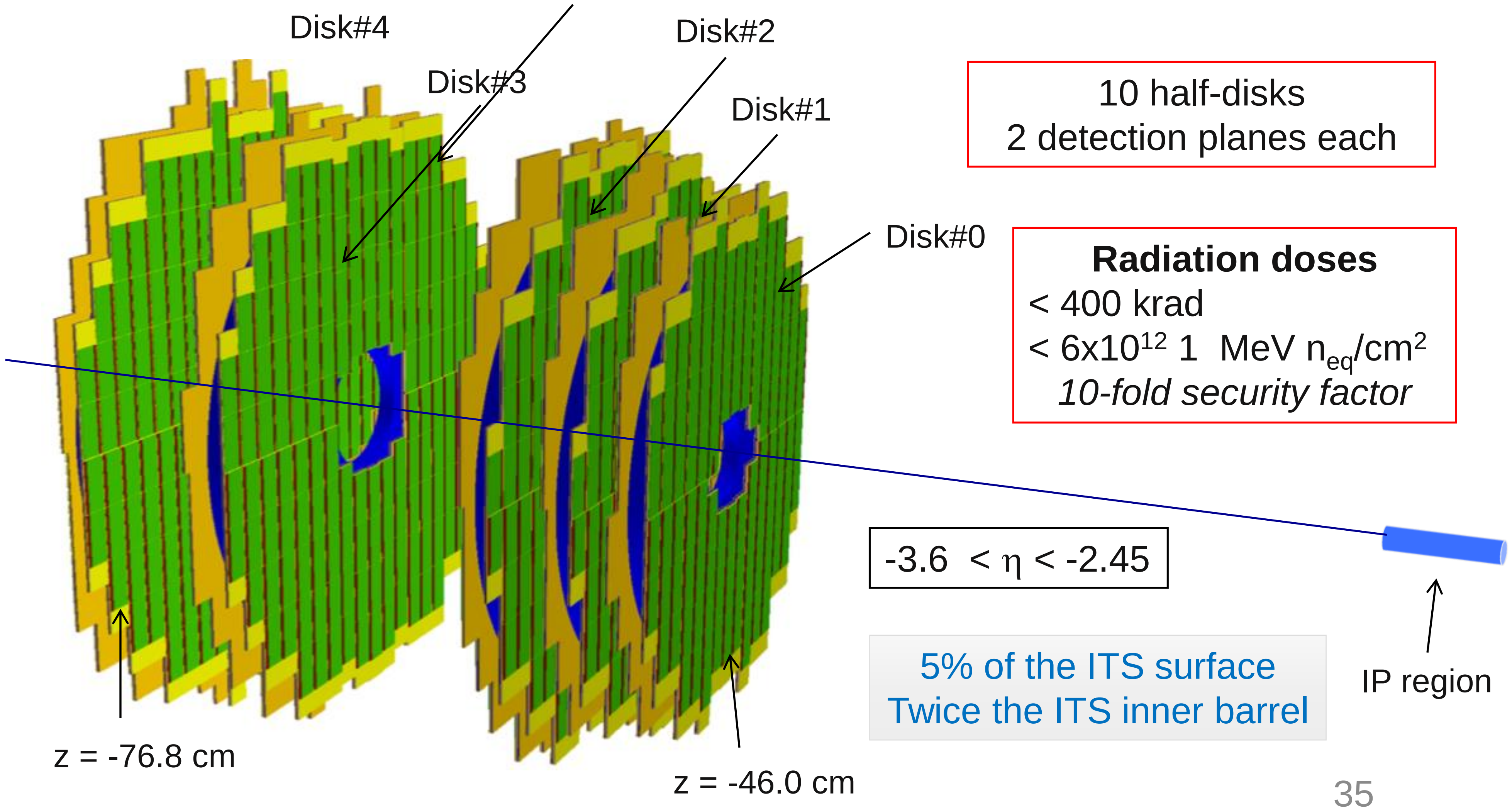
CMS Pixel Hadron Endcap Hadron Barrel, GE1/1 GEM, Refurbish Pixel Tracker, HGC, Muon, Barrel EM, TDAQ, MIP Timing?

LHCb VELO, SciFi, UT, RICH, CALO, Muon *VELO, UT, Magnet, I-M-OT, RICH, TORCH, ECAL Muon*

CERN

Muon Forward Tracker

920 silicon pixel sensors (0.4 m^2) in 280 ladders of 2 to 5 sensors each – using the ALPIDE chip



10 half-disks
2 detection planes each

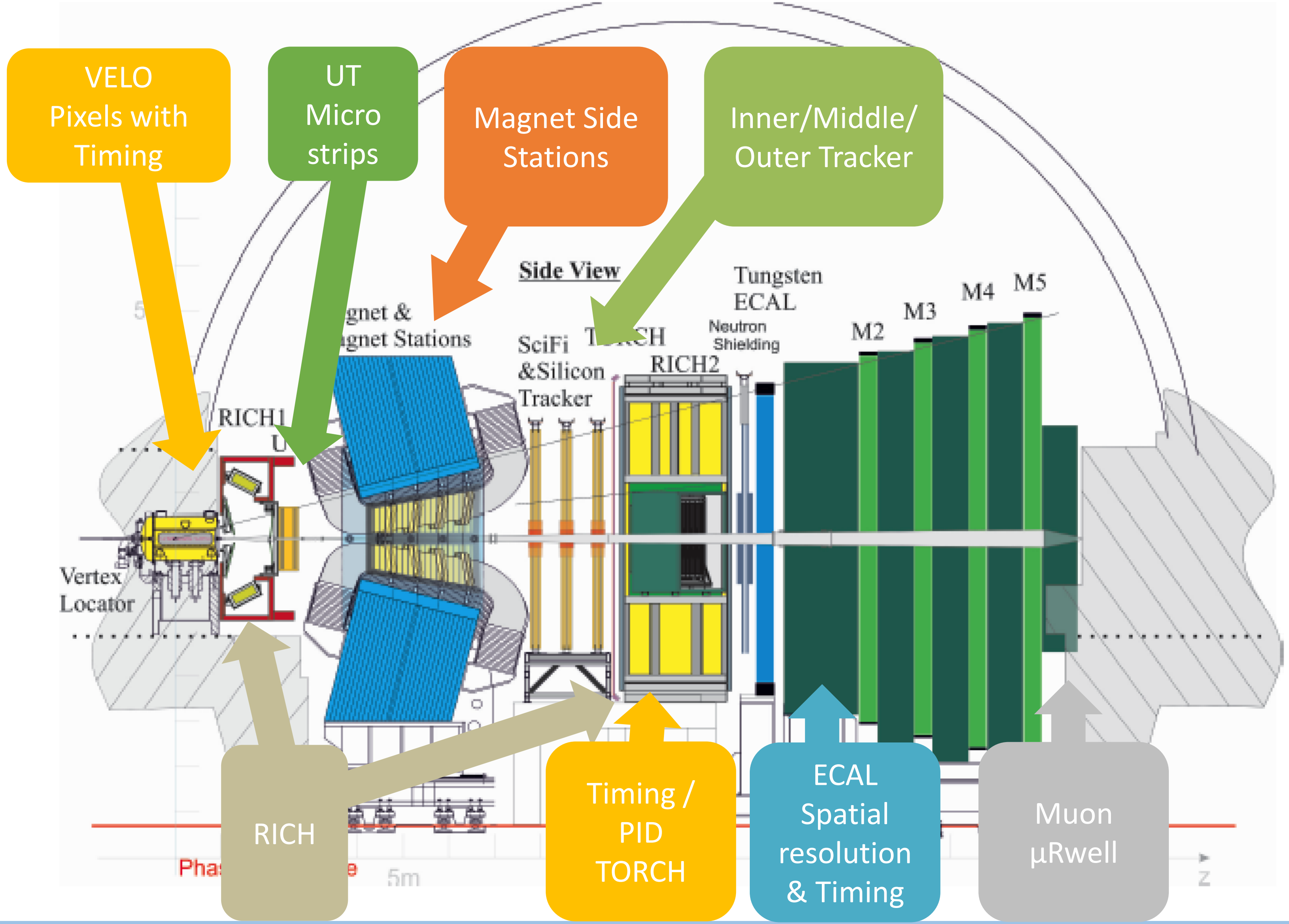
Radiation doses
< 400 krad
< $6x10^{12}$ 1 MeV n_{eq}/cm^2
10-fold security factor

$-3.6 < \eta < -2.45$

5% of the ITS surface
Twice the ITS inner barrel

35

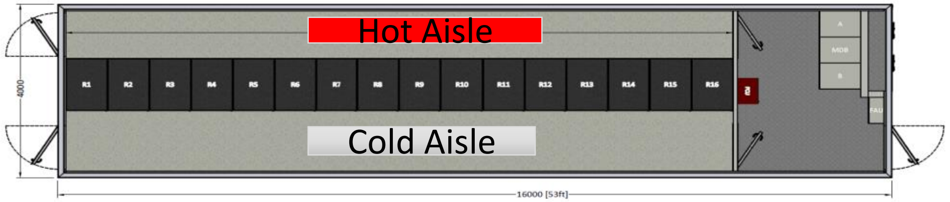
LS4 upgrade

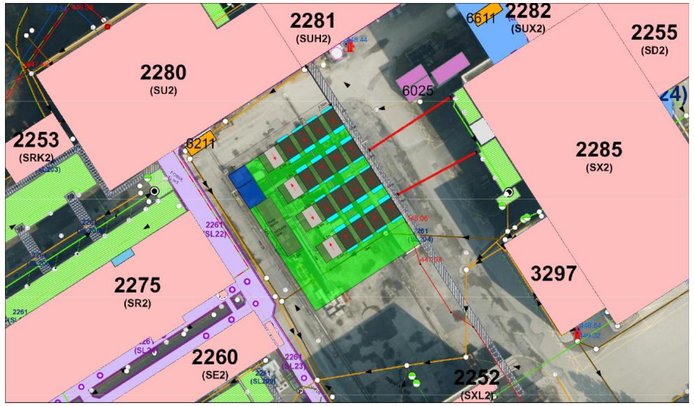


VELO
Pixels with
Timing
UT
Micro
strips
Magnet Side
Stations
Inner/Middle/
Outer Tracker
Side View
Tungsten
ECAL
Neutron
Shielding
M2
M3
M4
M5
SciFi
&Silicon
Tracker
RICH2
RICH1
Vertex
Locator
RICH
Timing /
PID
TORCH
ECAL
Spatial
resolution
& Timing
Muon
µRwell
5m

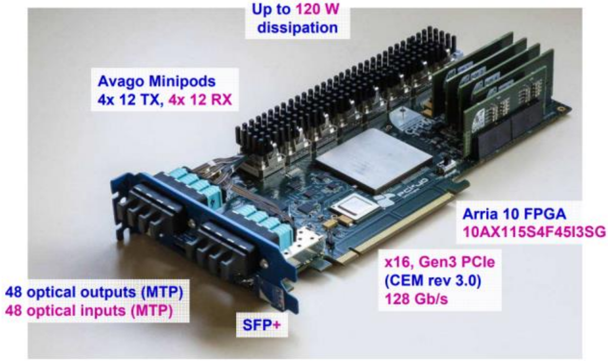
O² achievements and plans

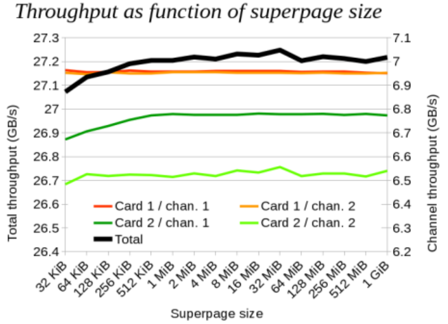
- Tender for the procurement of computer containers - Complet
  - Sep 17 : approved by the FC (Procurement procedure with LHCb)
  - Capacity of 2300 U and 2 MW cooling in 4 containers (Indirect free air with adiabatic cooling)
  - → Oct 17 – Jun 18: infrastructure preparation at P2
  - → February and May 2018: factory acceptance tests
  - → Sep 18 : installation of first container at P2





- Detector read-out
  - Sep 17: detector read-out with final read-out electronics (same hardware as LHCb)
  - Successful test performed with the ITS electronics
  - In progress with the TPC front-end card
  - → 2018: CRU production (Elec. Coord.)
  - → Feb 18: TPC Inner RO Chamber test
  - → Apr 18: TPC sector test in clean room
  - → Sep 18: ITS commissioning in Hall 167
  - → 2019: fibres installation at P2
  - → 2020: detectors commissioning at P2





CMS Phase-2 Muon upgrades

Designed for L1-Trigger, displaced vertices, long-lived particles, increased acceptance

DT, RPC and endcap CSC chambers readout electronics

- Comply with L1-Trigger latency and accept rate, improved spatial/time resolution

GEM stations in endcap

- Reduce L1-trigger rates, enable trigger for displaced vertices, ME0 extend to $\eta \simeq 3.8$
  - 3 GEM foils design

iRPCs in endcaps

- Improve robustness and acceptance in cracks
  - 1.4 mm thinner gap and electrodes, r-measurement through readout at both strip-ends