Detector R&D for the High Luminosity LHC

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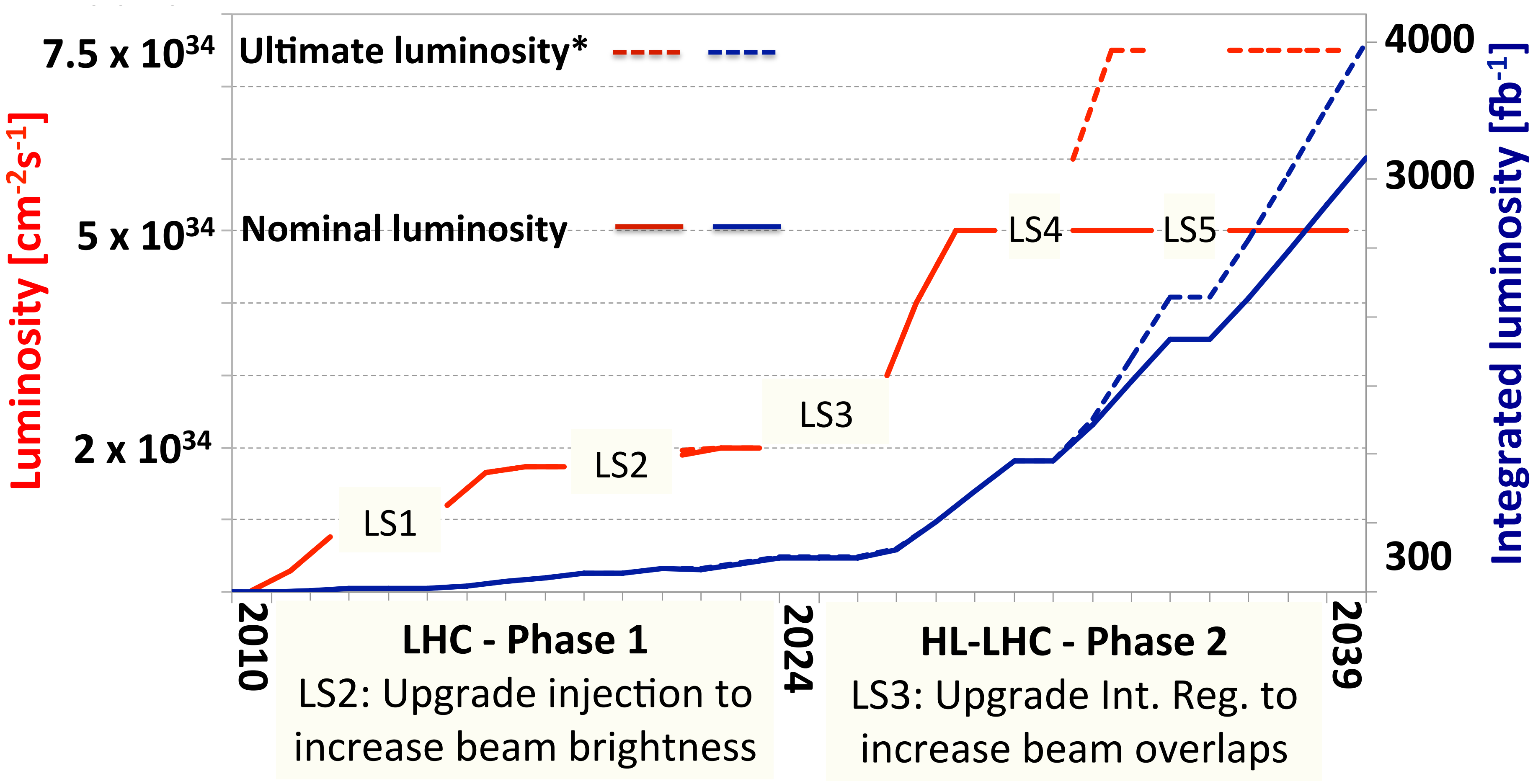
Overview of the LHC upgrade program, high luminosity challenges to the experiments and upgrade designs, major R&D examples

New schedule for Long Shutdowns and Accelerator perspective for luminosity



* “Ultimate luminosity” is a design specification - effective integrated luminosity is not limited by instantaneous luminosity - potentially 30% more fb^{-1}/year

Main considerations for detector upgrades

Much higher rates → new readout electronics - digitization and data compression on detector - full data transfer to the control room at 40 MHz crossing frequency (as much as possible)

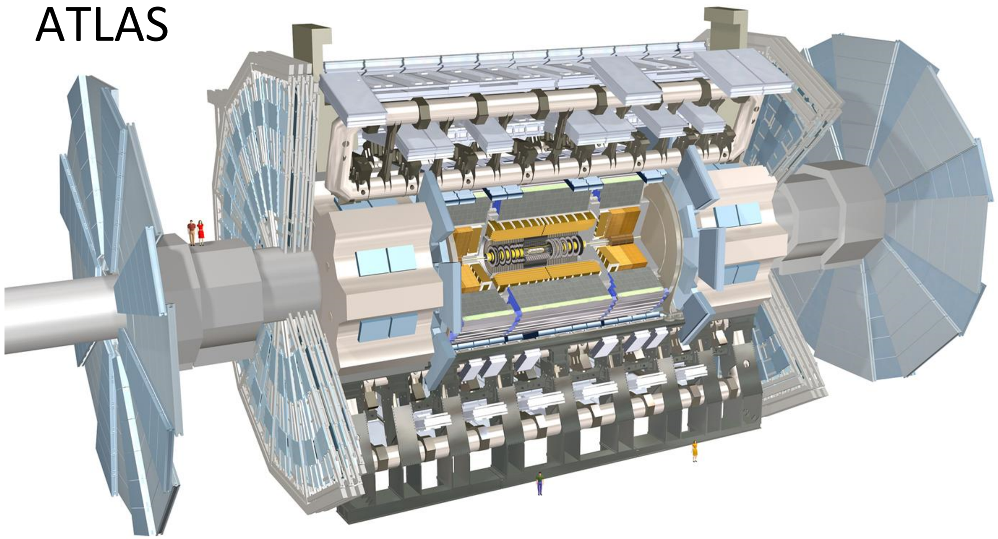
Much more complex events (collision Pile-Up) → increased granularity to maintain hardware Trigger acceptance (low energy thresholds), and online and offline object reconstruction performance

Much higher radiation doses and longer operation time → careful evaluation of radiation tolerance and longevity of detectors - new technologies

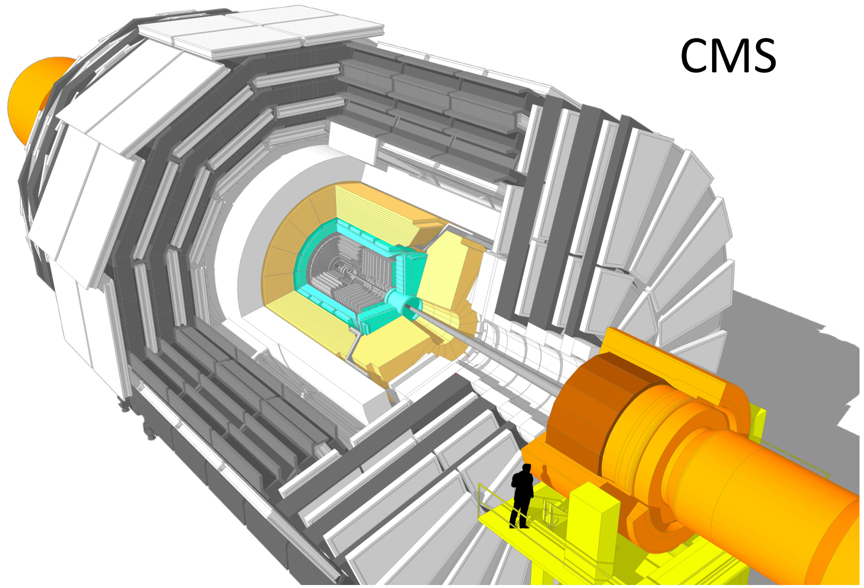
ATLAS and CMS upgrade in Phase-I (LS1 to LS2) to prepare for twice more peak luminosity than in original design

- Add one measurement in Pixel detectors closer to the collision point to preserve track finding efficiency and improve resolution
- Increase calorimeter granularity in Trigger to preserves thresholds
- Complete muon systems in End-Caps to preserve Trigger coverage
- Increase bandwidth and processing power in Trigger/DAQ

ATLAS



CMS

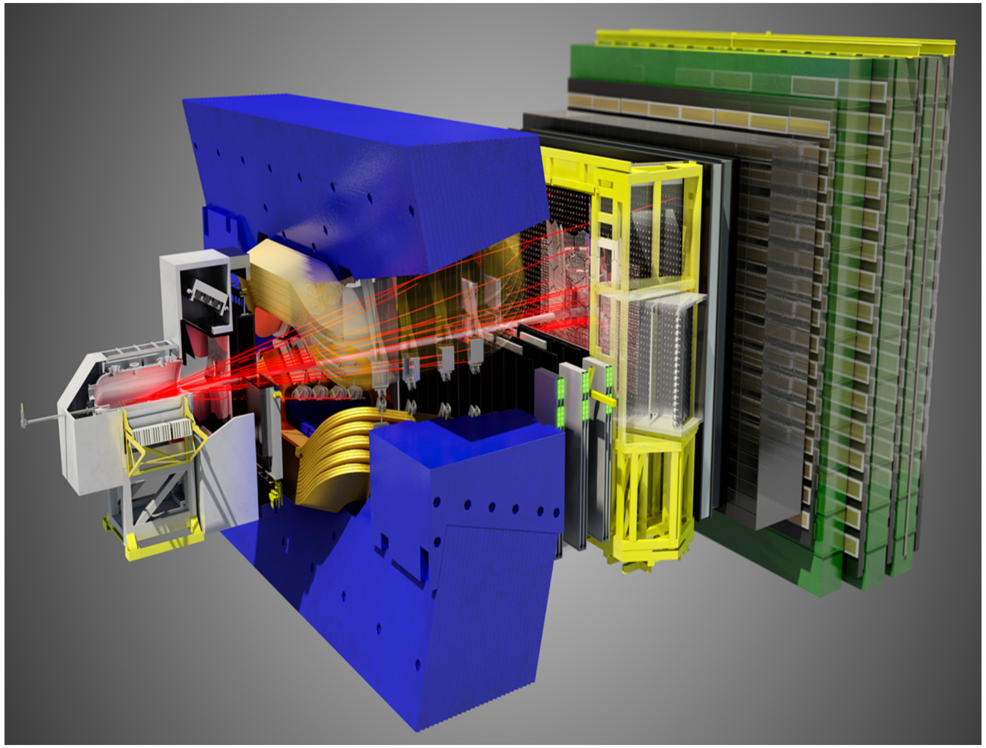


LHCb will upgrade already in LS2 and collect 50 fb-1 at 2 x 10^{33} cm-^{2} s-^{1} in runs 3 and 4

Software trigger operating at 40 MHz for 20 kHz of p-p events registered
→ Trigger/DAQ throughput at 4 TB/s (≃ ATLAS/CMS at HL-LHC)

New electronics for all detectors and other major innovations:

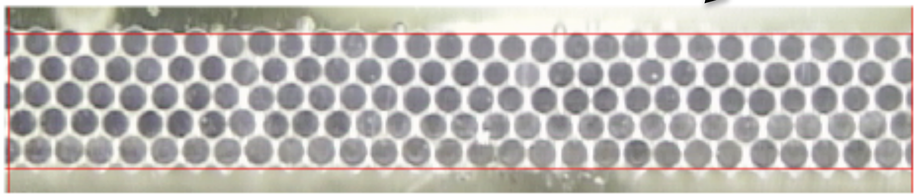
- New Vertex Locator with pixels at 5.1 mm from beam - 55 x 55 μm^2 pixels - fluence of 8 x 10^{15} n_{eq}/cm^2 - 2 Tbit/s data rate - light mechanics with micro-channels cooling
- Tracking with scintillating fibers (10000 km) and cooled SiPMs (-40◦)



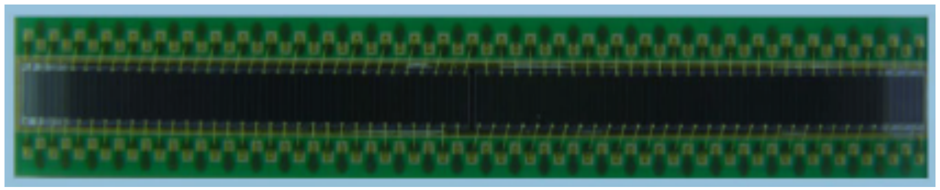
LHCb Scintillating Fiber Tracker R&D

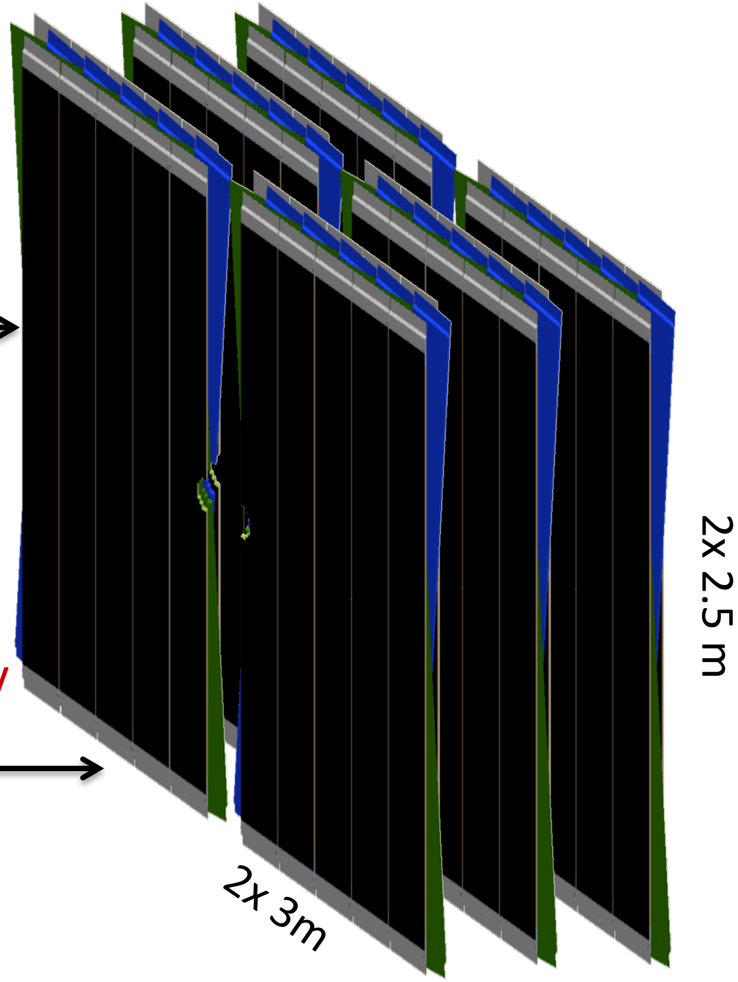
3 stations, each 2.5% X/X0 - 4 plans (X-U-V-X) with ± 5◦ stereo angle - 50-75 µm resolution

- 3 M fibers Φ 250 µm x 2.5 m (10 000 km)
  → Development for 3 Mrad in inner region
  → High precision assembly of fiber mats



- Readout with 128 SiPM array 250 µm pitch
  → -40◦C cooling to sustain $1.2 \cdot 10^{12}$ neq. /cm2
  → Work to improve Photo-Detection Efficiency



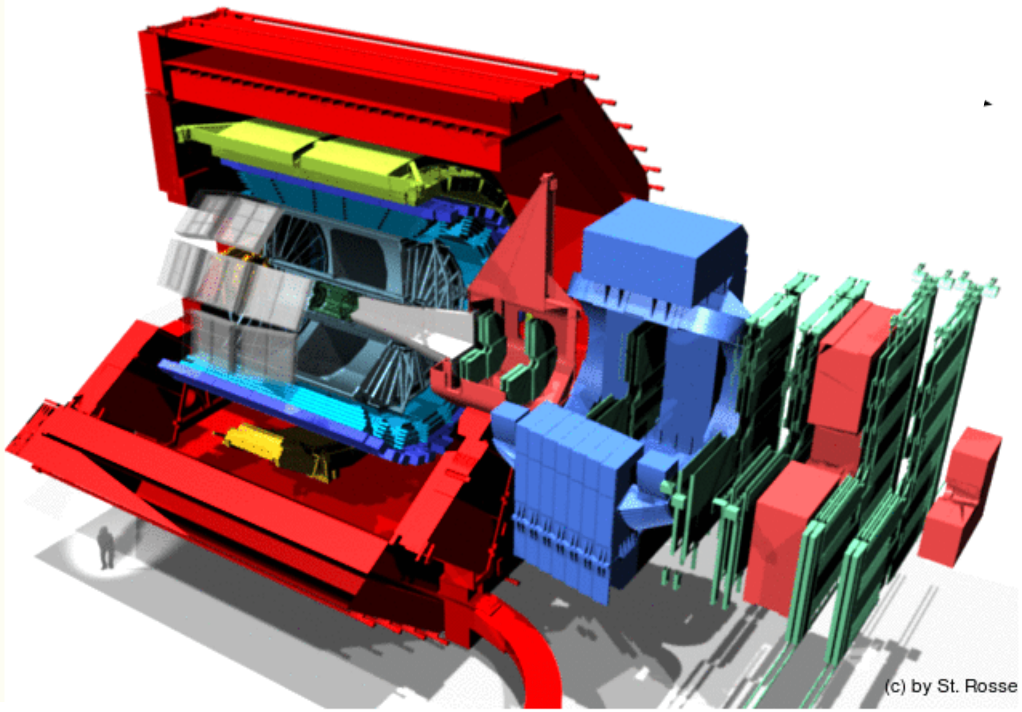


ALICE will upgrade already in LS2 to integrate ~ 10 nb^{-1} at 6 x 10^{27} $cm^{-2}s^{-1}$ in runs 3 and 4

Register all Pb-Pb collisions ≃ 50 kHz → Fast online calibration and reconstruction with FPGAs and GPUs for data compression, from 1 TBps to 50 GBps storage (storage ≃ ATLAS/CMS at HL-LHC)

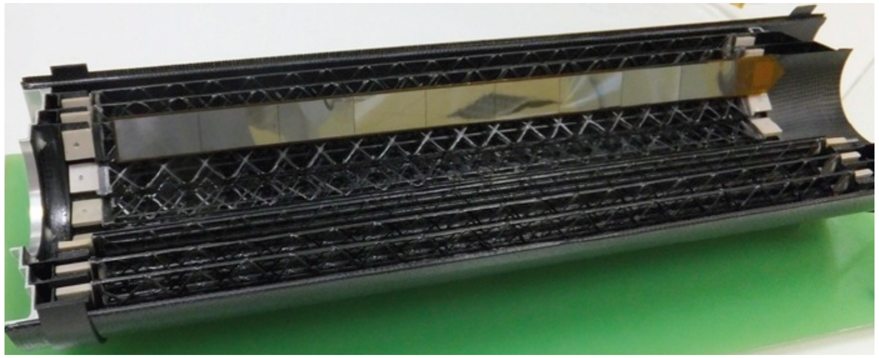
New electronics for all detectors and other major innovations:

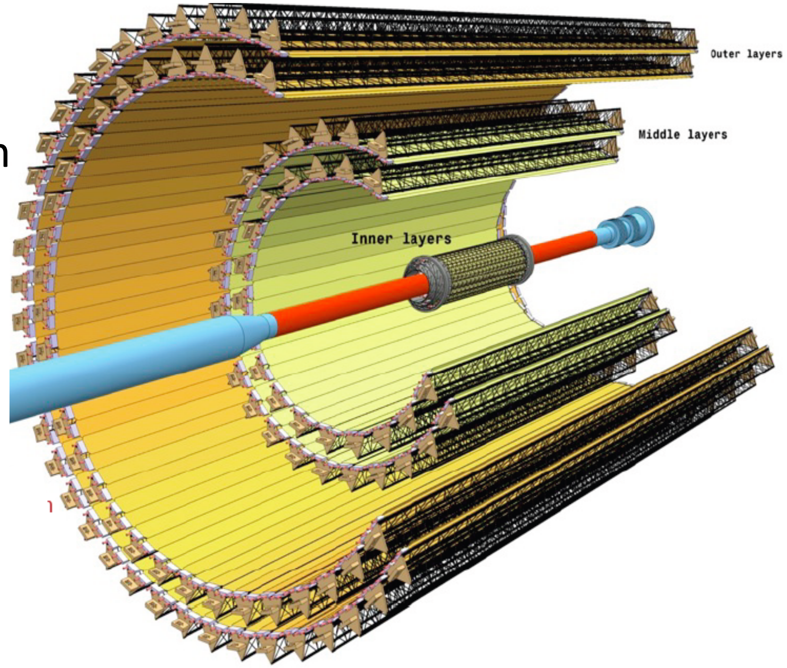
- New Internal Tracker System using Monolithic Active Pixels - 12.5 Gpix. 30 x 30 μm^2 - ultra-light mechanics
- Use Micro-Pattern Gas Detectors for TPC readout (GEM and/or Micro-Megas)
- Trigger timing ≃ 20 ps resolution quartz Cerenkov with MCP-PMT



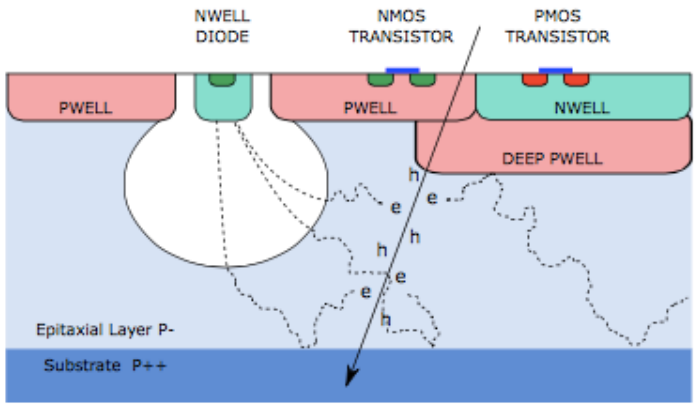
ALICE Inner Tracker System R&D

- Ultra light system to improve IP resolution by a factor ≃ 3
  - 7 layers of Monolithic Active Pixels
    ≃ $10 m^2$ with 12.5 Gpix
    - 3 inner layer each 0.3% X/X0 from 20 to 40 mm
    - 4 outer layers of 1% X/X0 up to 400 mm





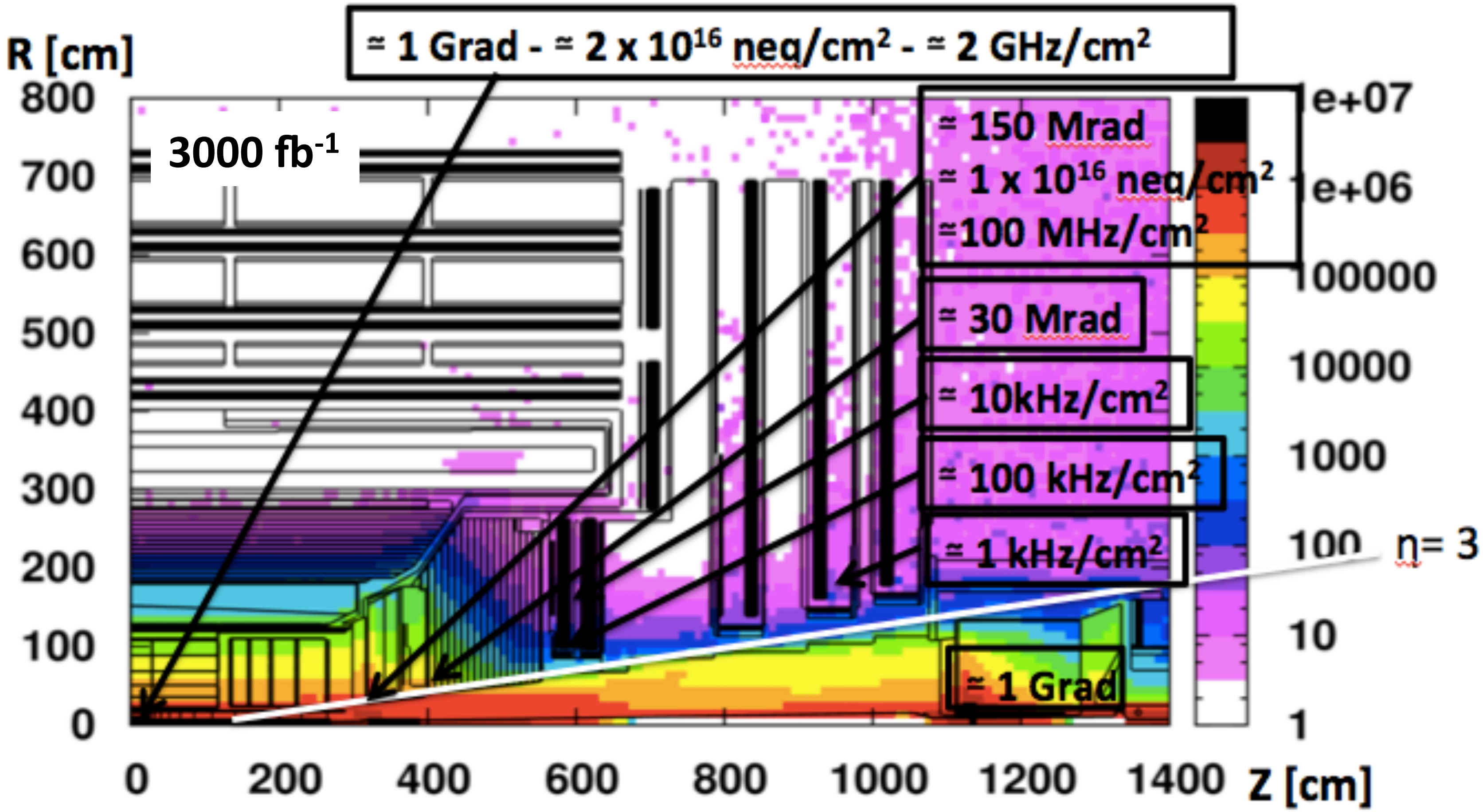
- MAPs Technology
  - Tower Jazz Technology (0.18 μm)
  - Thin sensors ≃ 50 μm
  - Pixels ≃ 30 x 30 μm^2
  - Radiation tolerance 10^{13} neq/cm^2
  - Binary readout



ATLAS & CMS Phase-II: radiation & particle rate challenge

Substantial effort to simulate irradiations and damage in current detectors

→ Both experiments replace Trackers
→ CMS replaces End-Cap calorimeters
→ ATLAS investigates replacement of LAr Forward Calorimeter (FCAL)



CMS example of dose map (left scale in Gray) 5 10^{34} $cm^{-2}s^{-1}$ assumption for rates

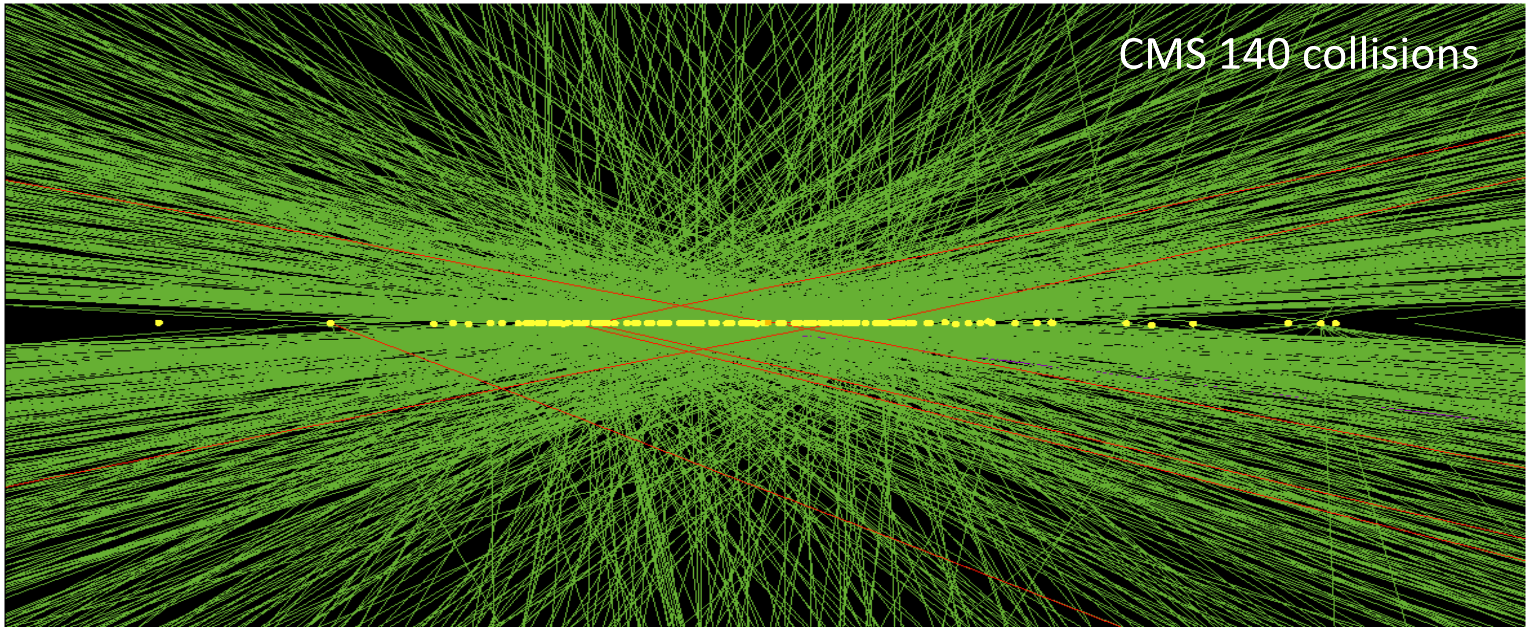
ATLAS & CMS Phase-II: Pile-Up challenge

Mean number of p-p collisions (PU) will reach ≃ 140 and 200 at luminosities respectively leveled at 5 and 7.5 x 10^{34} $cm^2 s^{-1}$

→ Tracking system is crucial to identify vertex of hard scatter of interest and associate proper charged tracks

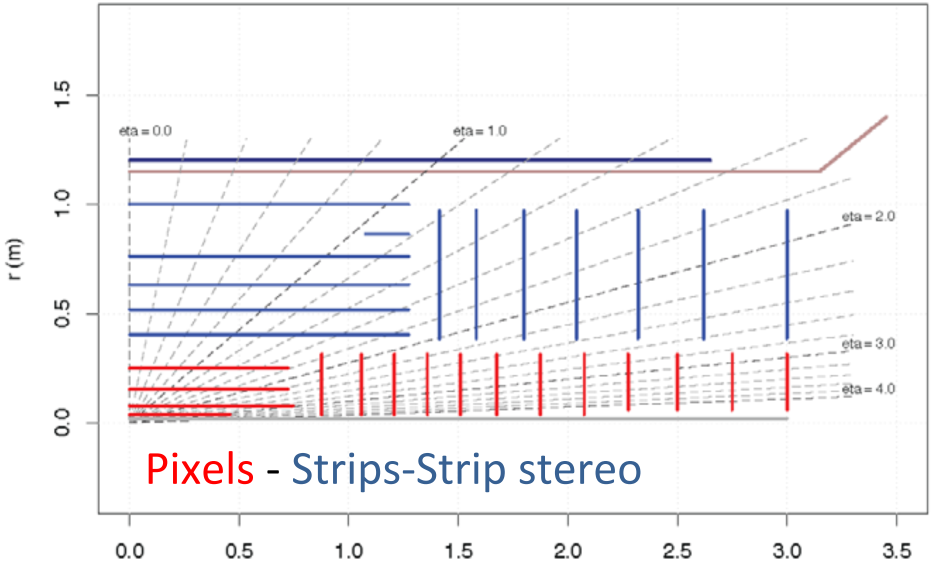
→ Out Of Time PU from signal developments ≳ 25 ns crossing interval, typically calorimeters, needs to be mitigated with proper pulse shaping/sampling

→ Complexity of events also imposes severe constraints on software and computing

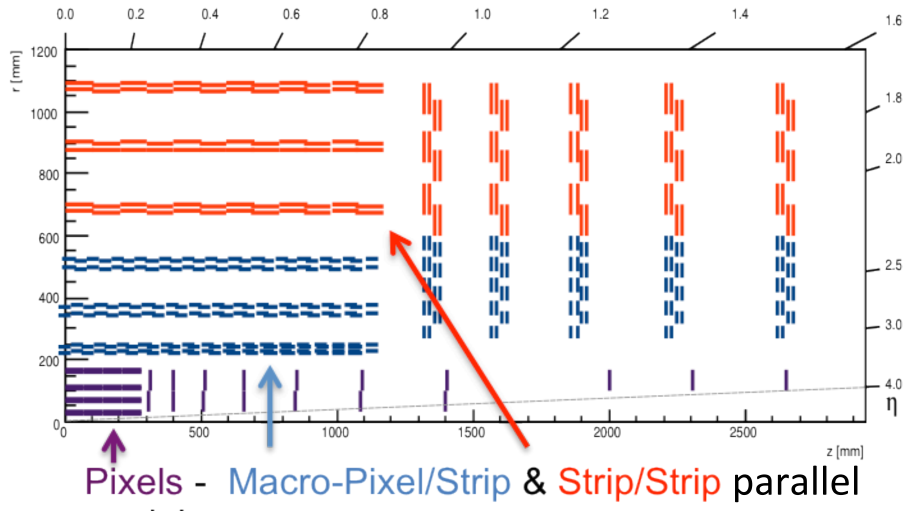


ATLAS and CMS Silicon Tracker main features

ATLAS



CMS



- High granularity (≃ 4 to 6 x present Trackers):
  - Pixel sizes in range ≃ 50 x 50 - 25 x 100 μm^2 - first layer(s) replaceable
  - Strip pitch ~ 75 to 90 μm and length ~ 2.5 to 5 cm length
  - Imposes lower power consumption for front-end electronics
- Lightness, an opportunity to improve resolution & reduce γ-conversions:
  - Design, new materials - new cooling (CO_2) - DC/DC, serial powering

ATLAS and CMS Silicon Tracker main features

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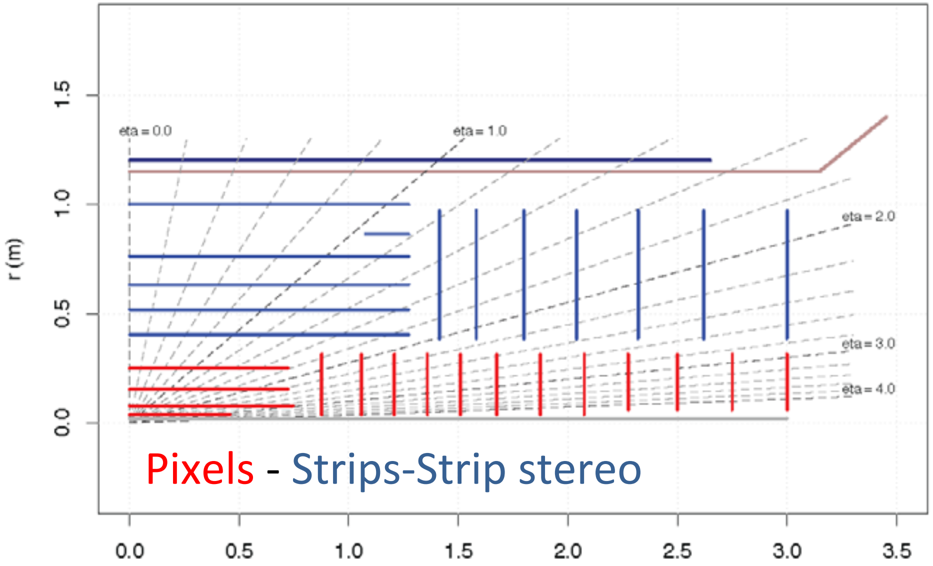
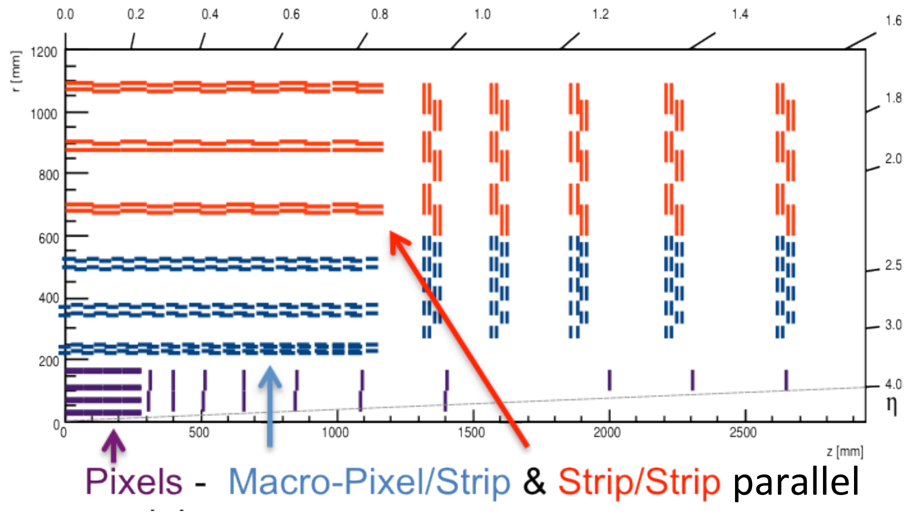


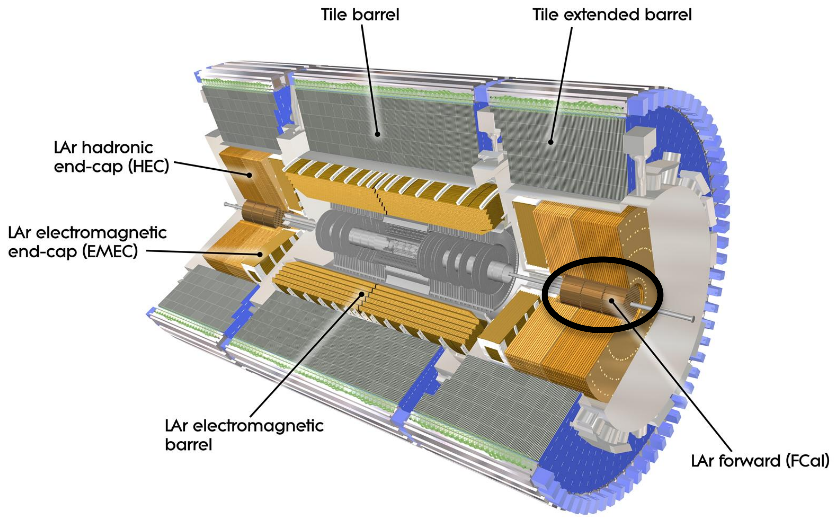
CMS



- Implementation of tracking information in hardware trigger
  - Improves lepton energy assignment and isolation, allows association to vertex for PU rejection in multiple object triggers - condition to maintain low energy Trigger thresholds - different concepts in ATLAS and CMS
- Extension of coverage from η ≃ 2.4 to η ≃ 4
  - Better matching with calorimeter coverage to improve Jet ID and MET tails and resolution, crucial for VBF and VBS jet tagging

ATLAS Calorimeter upgrades main features

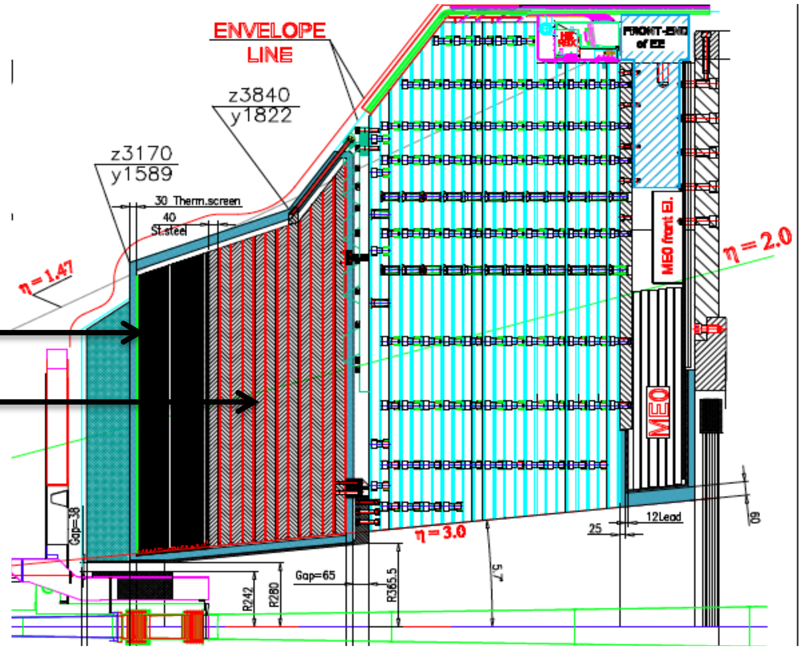
- ATLAS LAr calorimeters & Scint. Tile
  need new readout electronics - full granularity at hardware Trigger
- Forward CALorimeter ($3 \lesssim \eta \lesssim 5$)
  Ion space charge effect (due to peak luminosity) is investigated - option to replace with sFCAL - lower gap ≃ 100 μm and x 2 better segmentation in η & Φ, or add mini-FCAL in front of current FCAL
- Thin High Granularity Si/W(Cu) Calo.
  ($2.5 \lesssim \eta \lesssim 4$) is being investigated to further mitigate PU, particularly through precise timing measurement ($\lesssim$ 50 ps)

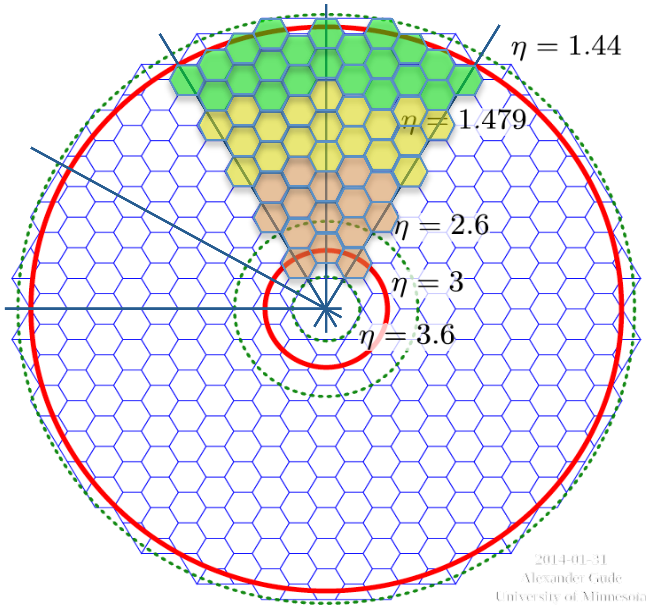


CMS Calorimeter upgrades main features

- **Barrel EM Calorimeter**
  need new readout - full granularity at hardware Trigger and lower T ≃ 8◦C
- **New High Granularity Calorimeter with 4D shower measurement**
  - Electromagnetic 28 layers of Si-W/Cu
  - Front Hadronic 12 layers of Si/Brass

  → R&D synergies with Tracker





Hexagonal sensors - 3 active thicknesses depending on radius 100/200/300 μm - 0.5 - 1 cm^2 pads for 100 - 200/300 μm

EE: 380 m^2 - 4.3 Mch - 13.9k modules

FG: 209 m^2 - 1.8 Mch - 7.6k modules

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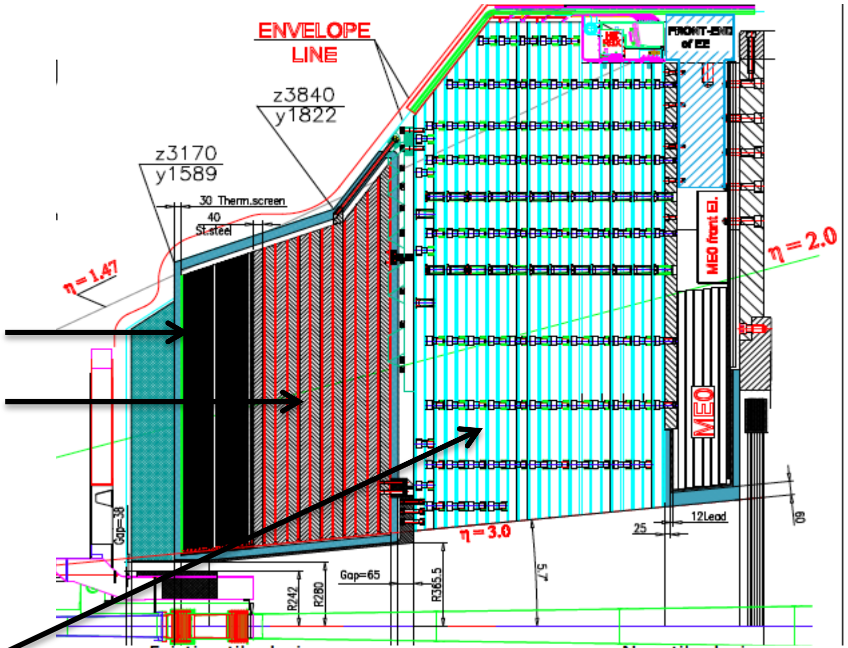
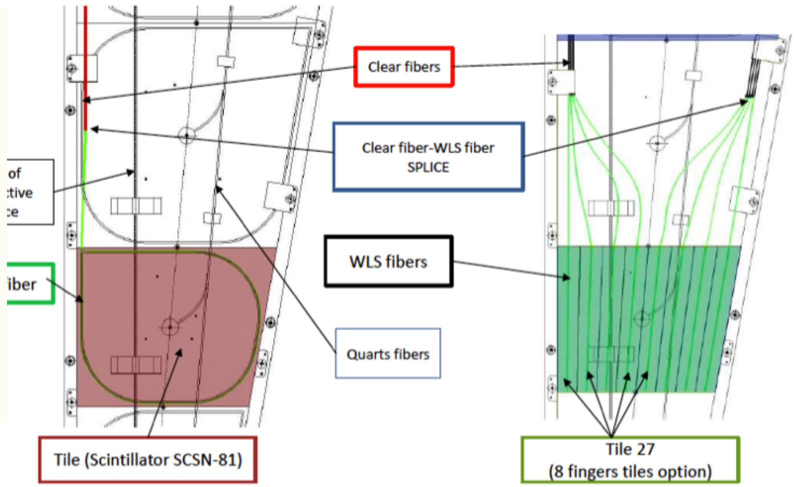


- Back Hadronic Scintillator tiles/Brass
  - Doubled transverse granularity - 2 depths

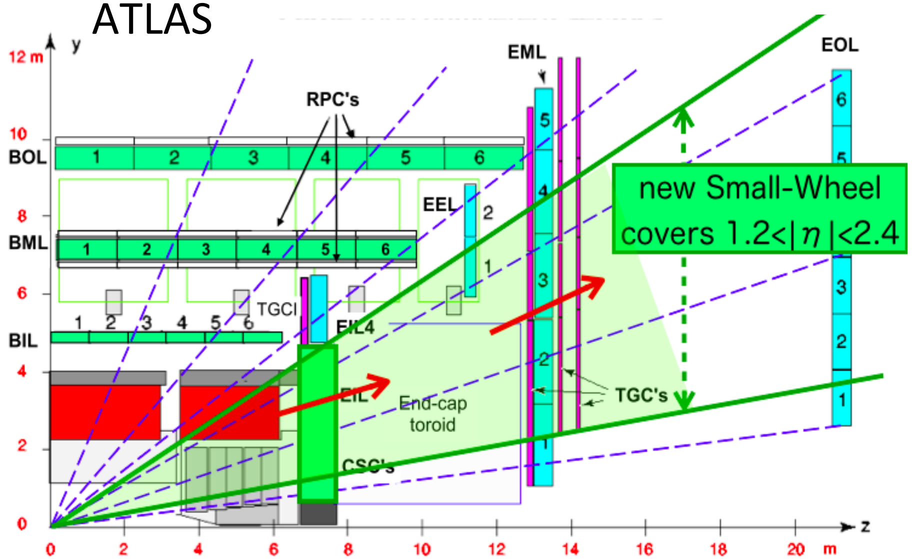
  → R&D to sustain 5 Mrad
  - Finger concept reduce light path to WLS
  - Doubly-doped plastic scintillator
    x 2 light collection after irradiation



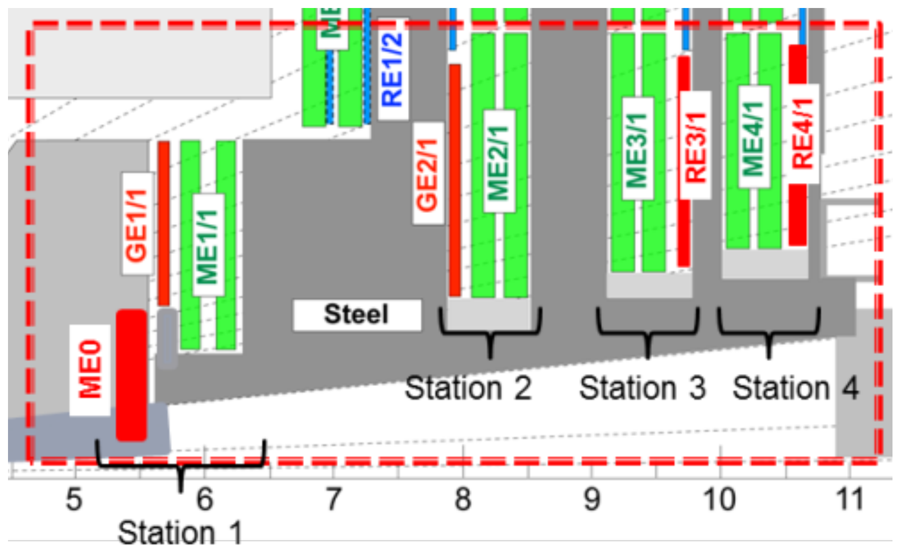
ATLAS and CMS Muon upgrades main features

- Muon systems are expected to sustain 3000 fb^{-1} → several tests in preparation at GIF++ to confirm and particularly for R&D in compliant "green" gas mixtures
- Higher rates → increase granularity and also replace readout electronics to comply with Trigger specifications
- Extended coverage for μ-tagging to η ≲ 4 (in conjunction with Tracker extension)
- Technologies are mature enough to install during LS2 with already substantial benefit to maintain Trigger acceptance during Run 3

ATLAS



CMS



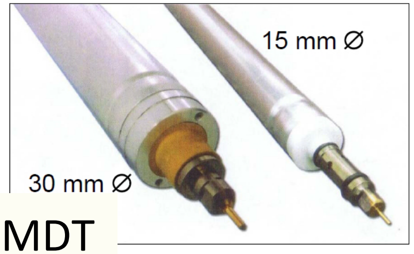
ATLAS and CMS Muon upgrades main features

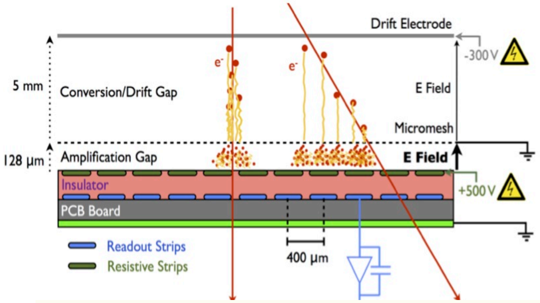
ATLAS technologies

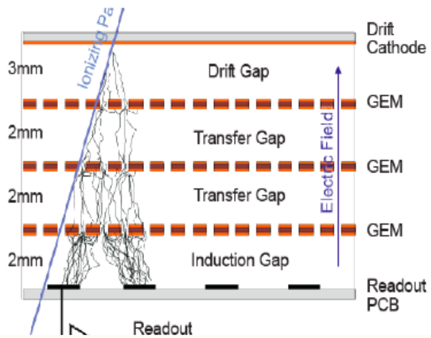
- **New Small Wheels**
  small Thin Gap Chambers - shorter strips 2 cm → 3.2 mm (3mm pitch), thinner gap and Micro-Megas (0.5 mm pitch)
- **And small Monitoring Drift Tubes**
  reduced diameter 30 mm & 200 Hz/cm^2 → 15 mm & 2 kHz/cm^2

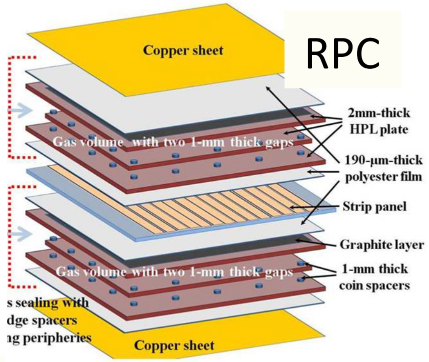
CMS technologies

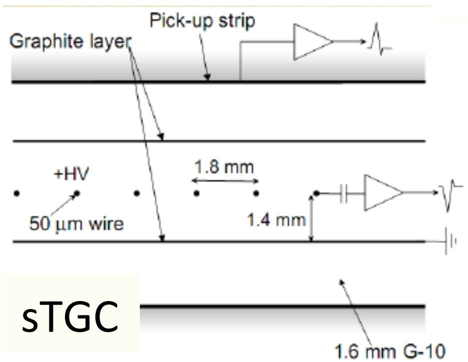
- **Triple GEM** 140 micron pitch, single mask and new assembly technique
- **iRPC's** for few kHz/cm^2 - low resistivity Bakelite or Glass - multi-gap/thinner gap and electrodes - higher gain in Front-End electronics - good time resolution depending on number of gaps ≈ 100 ps



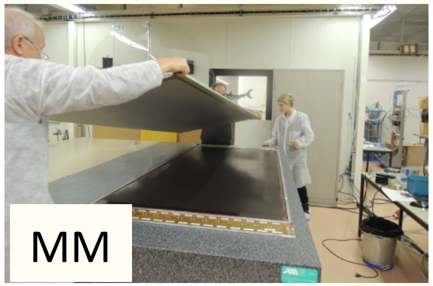


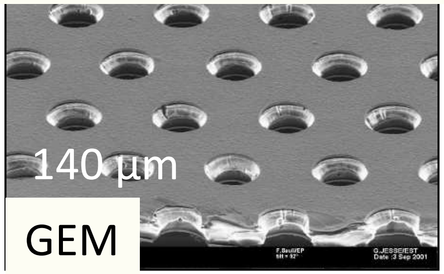


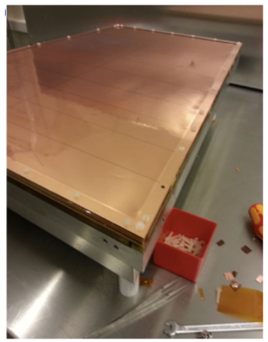




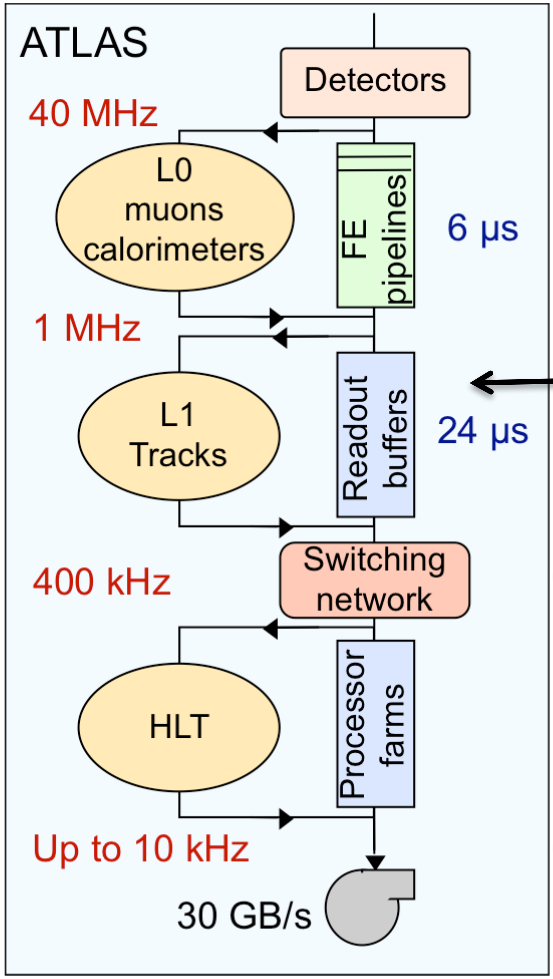
Micro Pattern Gas Detector (MM & GEMs) RD51







ATLAS and CMS Trigger upgrades

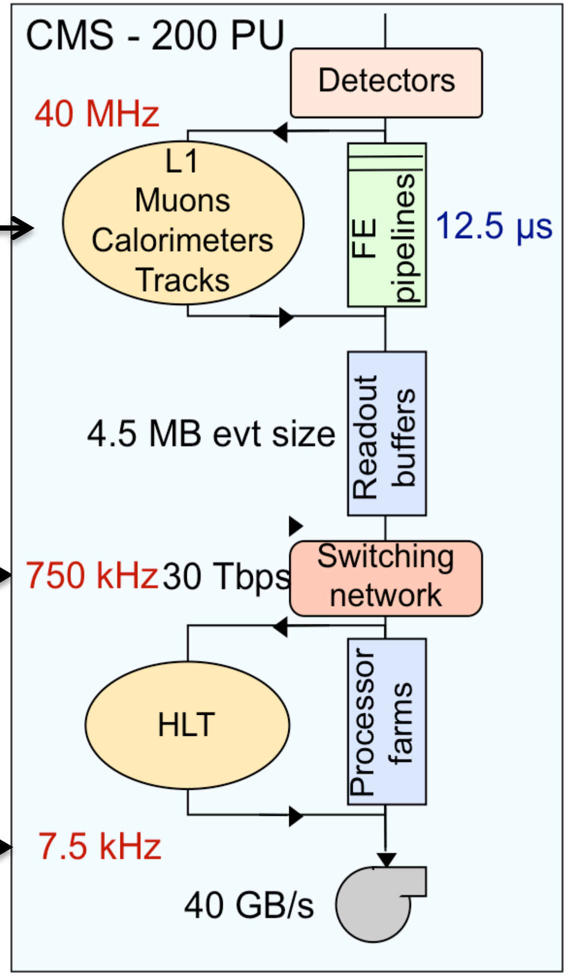


CMS reconstructs tracks with $P_t \gtrsim 2$ GeV at 40 MHz

ATLAS reconstructs tracks with $P_t \gtrsim 1$ GeV at 1 MHz in Muons & Calor. Reg. of Inter.

Full Tracker data readout (currently 100 kHz)

High Level Trigger output (registered events)



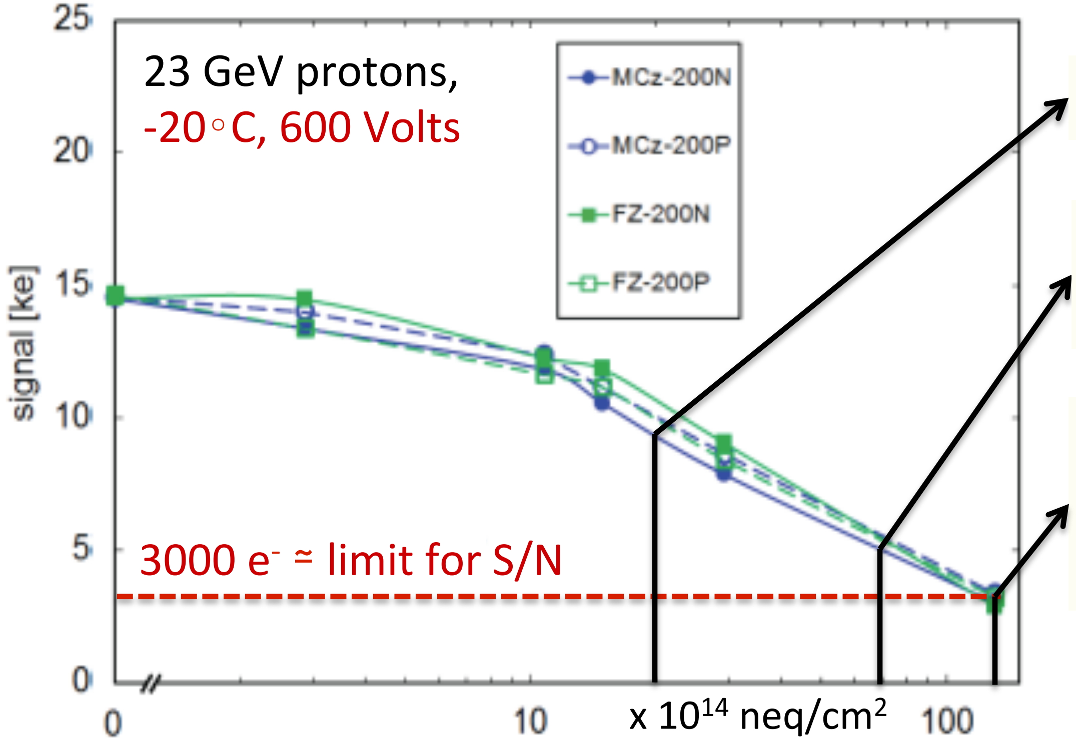
R&D on Associative Memories for track reconstruction - High processing power FPGA and bandwidth boards - High bandwidth back plan crates xTCA

Silicon sensors R&D - RD50

Higher radiation tolerance with shorter charge collection path

→ Larger collection efficiency, at low voltage and low leakage current

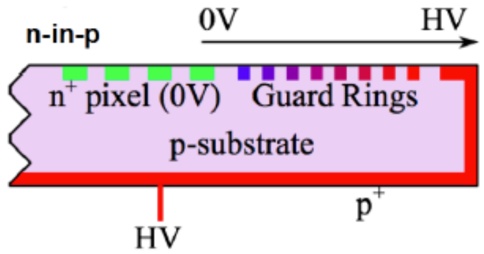
→ Improved bulk material for limited annealing effects



≃ 4000 fb^{-1} at 20 cm 1st strip layer

≃ 4000 fb^{-1} at 7 cm 2nd pixel layer and also ≃ LHCb pixels

≃ 3000 fb^{-1} at 3 cm 1st pixel layer
≃ 5000 fb^{-1} Si/W calorimeter η ≃ 3
confirmed with neutron irradiation



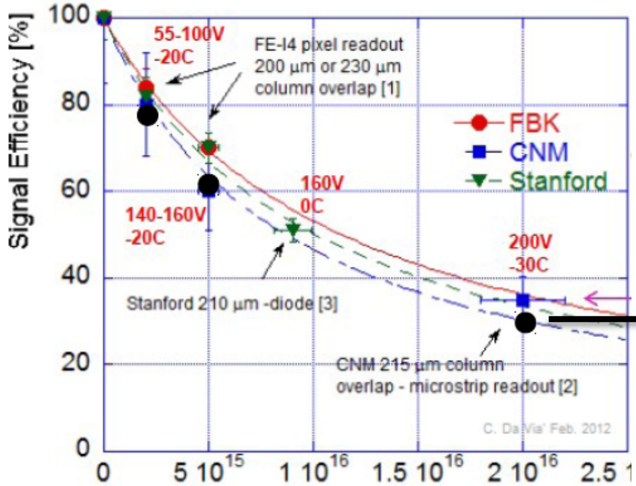
All strip Tracker and CMS Si/W calorimeter:

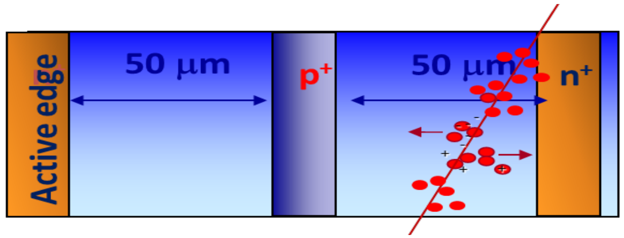
- n-in-p technology selected - qualifying vendors for final specifications: physically thin versus deep diffusion
  - Float Zone versus Magnetic Czochralski material, wafer size 6” or 8”…

→ ≃ 1000 m^2 of Silicon sensors (including CMS Si/W calorimeter)

Silicon sensors R&D - RD50

For fluence at 2 x 10^{16} neq/cm^2 in 1st pixel layer, or up to 10^{17} neq/cm^2 in Si/W calorimeter at η ≃ 4 the 3D sensors technology is an alternative



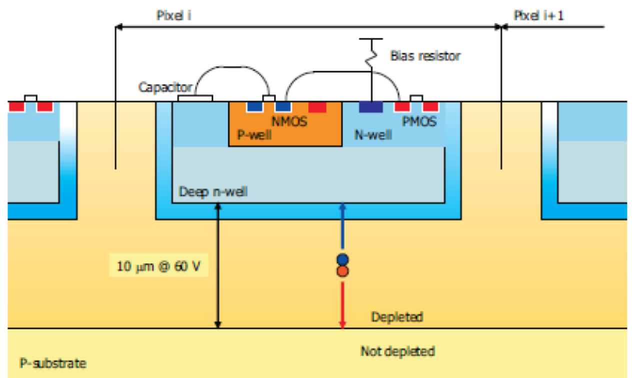


6000 e$^-$ after 2 x 10^{16} neq/cm^2 at -30◦C

HR/HV CMOS R&D - RD50

R&D in radiation tolerant High Resistivity/High Voltage (HR/HV) CMOS

Electronics in deep n-well collection electrode to allow depletion voltage (≃ 100 V) - promising results on charge collection efficiency up to 10^{15} neq/cm^2 - several technical developments still needed on tight time scale for HL-LHC



Front End ASICs R&D

- Several (≃20) ASIC chips of increased complexity developed for the 4 experiments in different technologies - already many prototypes
- R&D focuses on new TSMC technology 130 nm and 65 nm to validate rad. tol. & develop common IP blocks - also connected development of Trough Silicon Via and DC/DC and serial powering techniques

RD53 ATLAS/CMS Pixel ASIC
TSMC 65 nm

- Smaller Pixel size
- Larger chips (≳ 2 x 2 cm^2)
- Hit rates up ≃ 2-3 GHz/cm^2
- Rad. Tol. up to 1 Grad, 10^{16} n/cm^2
- High trigger rate and latency up to 1 MHz and ≳ 10 μs
- Low power budget ≲ 1 W/cm^2
- Low noise ≃ 1000 e^-

CMS HGCal FE ASIC
TSMC 130 nm

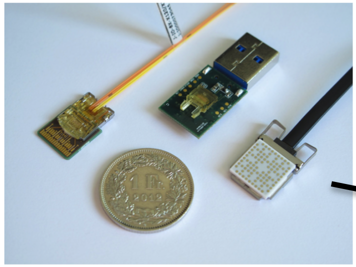
- Shaping ≃ 15 ns - noise ≃ 2000 e^- (after 3000 fb^{-1})
- Low power ≲ 10 mW/ch
- Dynamic range 10 pC - 10 bit ADC ≤ 100 fC and Time over Threshold (ToT) ≥ 80 fC
- Channel calibration better than 1%
- ToT time resolution ≃ 50 ps

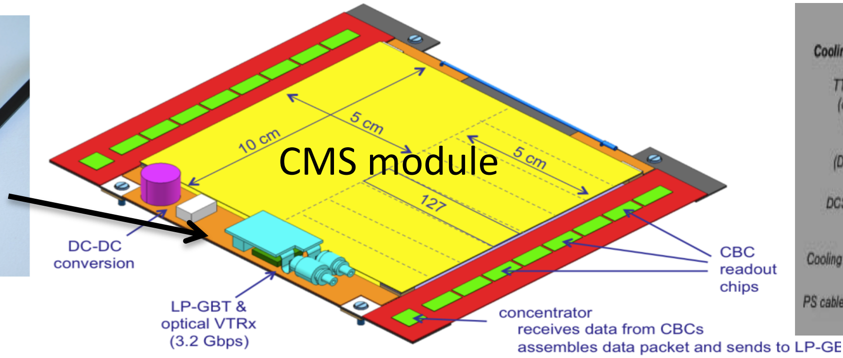
RD53 has developed layout rules to ensure radiation tolerance at 500 Mrad in 65 nm TSMC, more work is needed for 1 Grad (1^{st} pixel layer) where behavior may depend on operation history (bias, temperature) and annealing

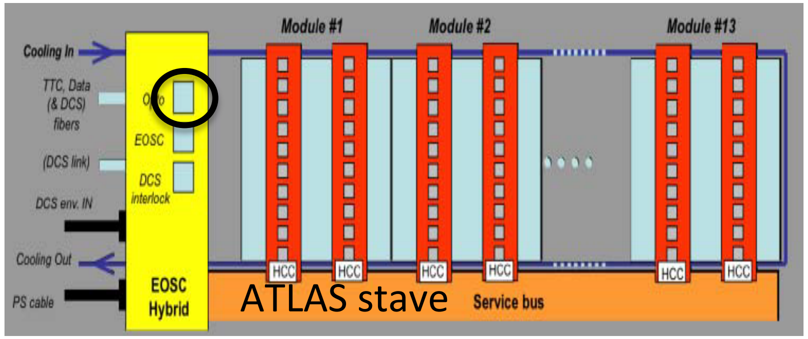
Data transfer R&D

All experiments (det.) use the GigBitTranciever (GBT) & Versatile Link developed through CERN

→ R&D for low power GBT ASIC (≃ 0.5 W) in 65 nm technology with 10 Gb/s data transmission, particularly important for tracker where BW needs are high due to new Trigger capability and higher Trigger rates







Radiation hardness of the Versatile Link is insufficient for inner pixels

→ Crucial R&D on very light high BW electrical link before OL transfer (twinax cable)

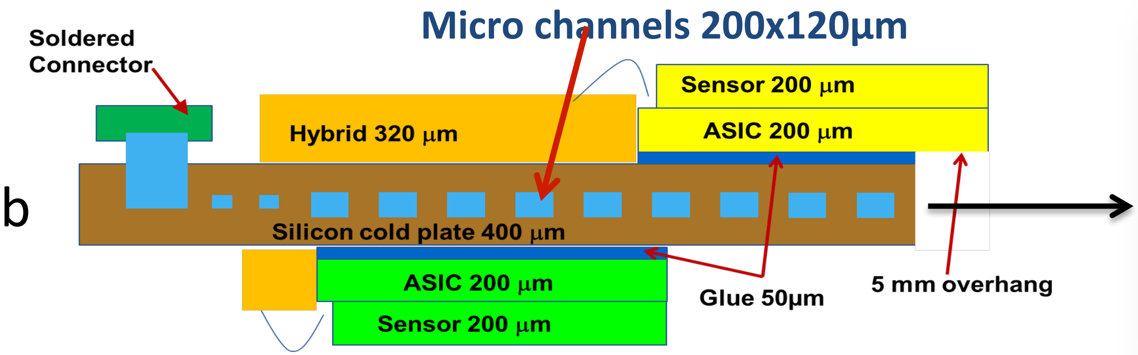
Cooling system R&D

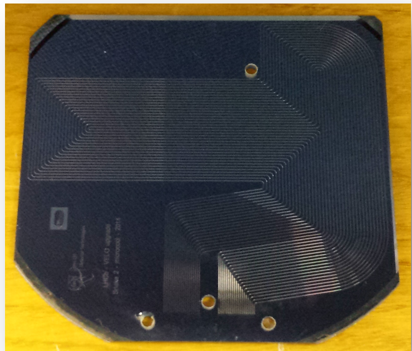
Lower temperature needed to mitigate radiation damage in silicon devices and also need of light cooling and "greener" systems

→ Two-Phase CO_2 cooling in ALTLAS/CMS/LHCb - R&D effort federated by CERN - standard systems & common prototypes in perspective of ≃ 50 kW and ≃ -35° plants

Micro-channel cooling presents further advantages in material reduction & thermal expansion matching - LHCb (VELO) are leading R&D

LHCb



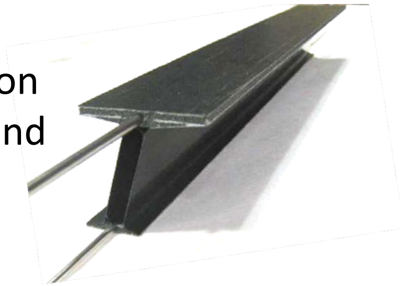


Mechanical structures R&D

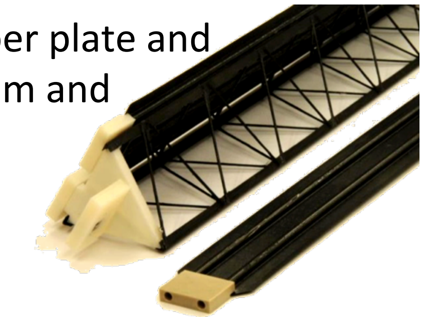
Light mechanical structure are crucial in Tracker for resolution and to minimize secondary interaction and photon conversions

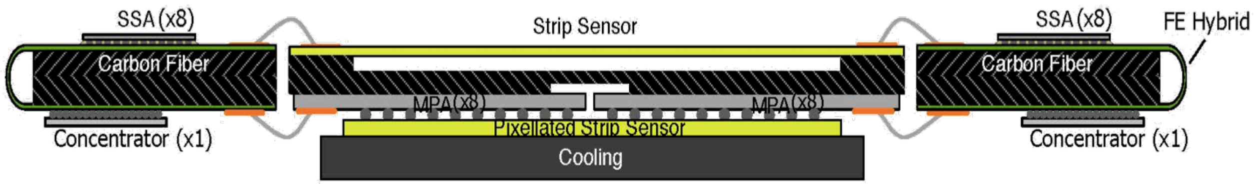
→ Several new materials or techniques (3D printing) investigated in all aspects including radiation tolerance

ATLAS pixels carbon fiber plate foam and Titanium pipes

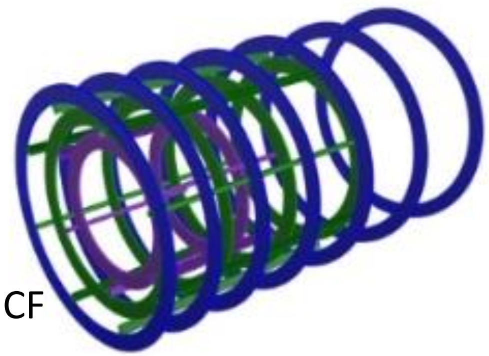


ALICE ITS carbon fiber plate and support, carbon foam and polyimide pipes





CMS PS-module AlCF frame



Atlas barrel mechanics in CF

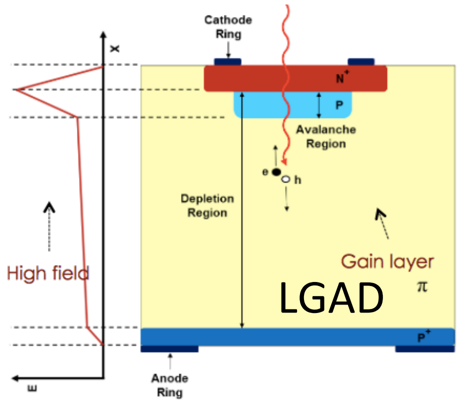
QA, assembly procedures, integration and environmental aspects need to be addressed at an early stage to keep system simple and reliable

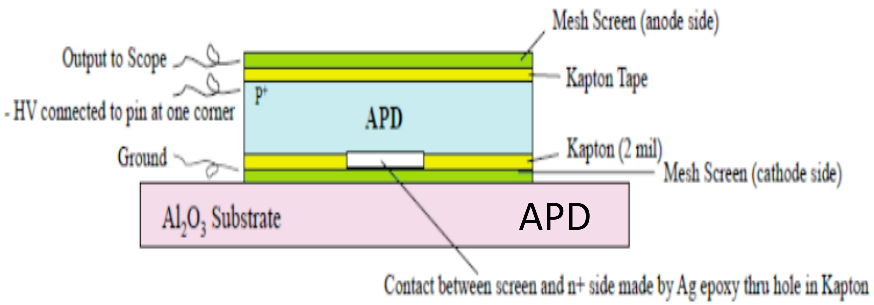
Precise Timing devices R&D

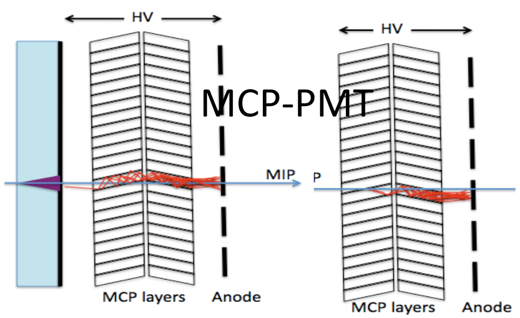
Precise timing measurements to further mitigate PU effects is investigated by ATLAS and CMS , particularly for neutral energy measured in forward calorimeters

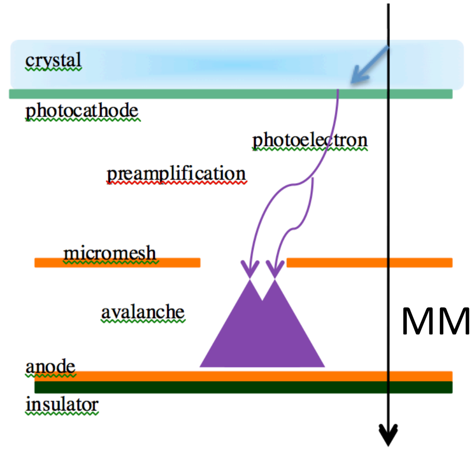
→ Nominal collision time rms is ≃ 160 ps - a time resolution of ≲ 50 ps would allow to reduce PU to an effective value similar to Phase-I

- Several concepts and technologies investigated
  - Using shower max in calorimeter - specific layer in front part of calorimeter - Pre-shower
  - MCP-PMT - Ultra Fast Silicon Detector (LGAD) - High Gain APDs - Micro-Megas
- Clock distribution also a challenge for precision/stability









Online - Offline - Computing R&D

CPU need for online/offline reconstruction and analyses is expected to be roughly 30/80 times larger than for Run 2 at 140 PU

→ Anticipating x 8 gain at constant resources (25%/year improvement) another factor of ≃ 4/10 gain (online/offline) would be needed at 140 PU

R&D focuses on:

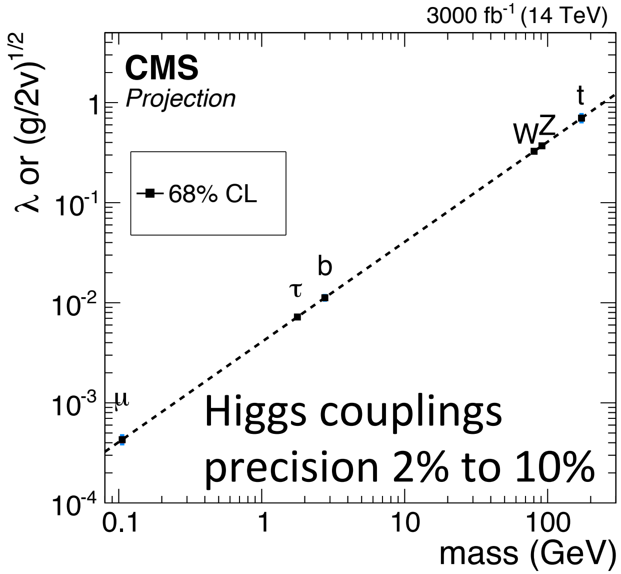
- Low power ARM processors, high performance GPU systems…
  → Develop multi-threaded code - data oriented for memory usage
- More broadly distributed resources to access opportunistic computing
  → Develop portable kernels of reconstruction and simulation code
  → Use cloud provisioning tools
- More efficient use of storage and data distribution
  → Develop dynamic data placement to use remote services through Content Delivery Network techniques

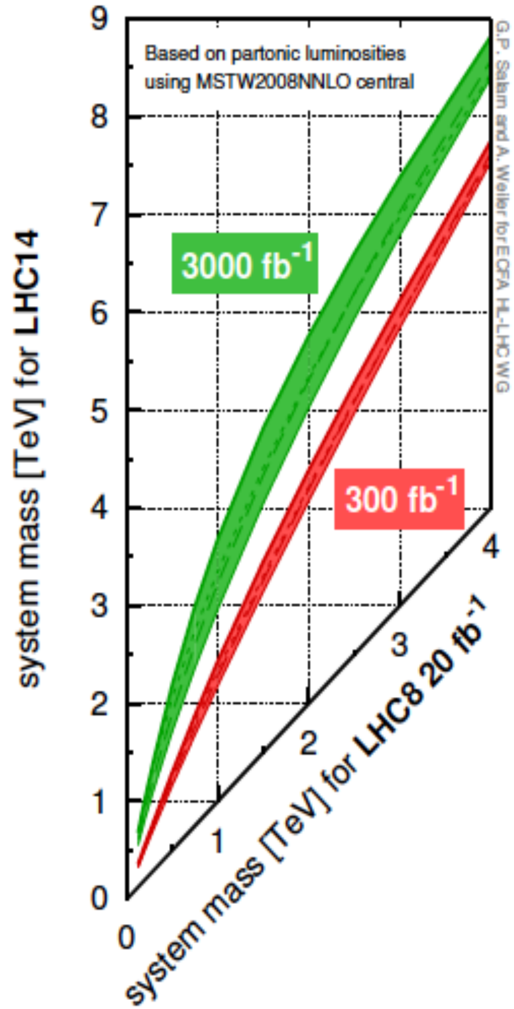
Concluding remarks

The LHC at 300 fb^{-1} and then at 3000 fb^{-1} is the unique facility for indirect and direct search of New Physics in the next decades:

- Higgs coupling precision - rare processes: H to μμ, Zγ - HH - VV scattering – FCNC - B_s/B_d to μμ …
- Discovery in Run 2/3 ?
- Extended phase space & mass reach coverage

→ It is important to support ATLAS and CMS upgrade design optimizations with full simulation of physics benchmarks





ATLAS projection	gluino mass	squark mass	stop mass	sbottom mass	χ_1^+ mass WZ mode	χ_1^+ mass WH mode
Run 3 300 fb^{-1}	2.0 TeV	2.6 TeV	1.0 TeV	1.1 TeV	560 GeV	None
HL-LHC 3000 fb^{-1}	2.4 TeV	3.1 TeV	1.2 TeV	1.3 TeV	820 GeV	650 GeV

Concluding remarks

- Experiments are preparing upgrades already since several years
- Many progress have been made in developing new techniques to meet the High Luminosity challenges, nevertheless we still have a lot of work ahead of us on a tight and busy time scale
- Upgrades must be cost-effective, but to ensure success they need to preserve: margins in performance, flexibility with respect to operating conditions, and safety with redundant systems
- Upgrades need our attention for a bright future at the HL-LHC

Additional information

HL-LHC upgrades general documentation

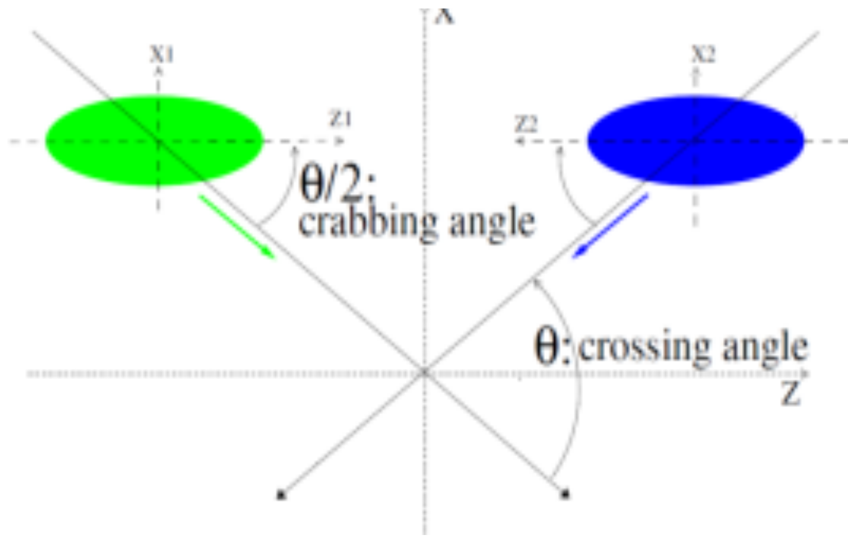
ECFA HL-LHC Experiments Workshops in 2013 and 2014

→ physics goals and performance reach - accelerator upgrades and experiment interface - experiments upgrade scope, conceptual design & technology R&D

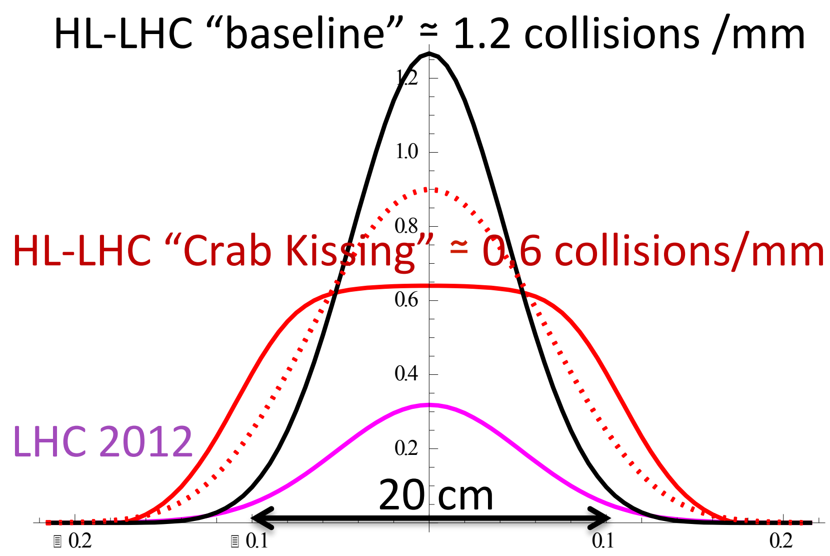
- Indico Agendas:
  - https://indico.cern.ch/event/252045/
  - https://indico.cern.ch/event/315626/
- ECFA reports
  - https://cds.cern.ch/record/1631032
  - https://cds.cern.ch/record/1983664?ln=fr

Accelerator Upgrades for HL-LHC

- Well defined baseline:
  - 1200 m of new magnets around the interaction region to improve the beam focus (β* ≃ 10-15 cm) and tune it along the fill to level the luminosity profile
  - Crab Cavities to limit collision density along beam (compensate crossing angle)
- And options:
  - Wire Compensation technique to mitigate long range beam-beam interactions
  - Crab Cavities transverse (kissing) scheme to further lower collision density if beneficial to experiments



Beam Crossings with CRAB cavities

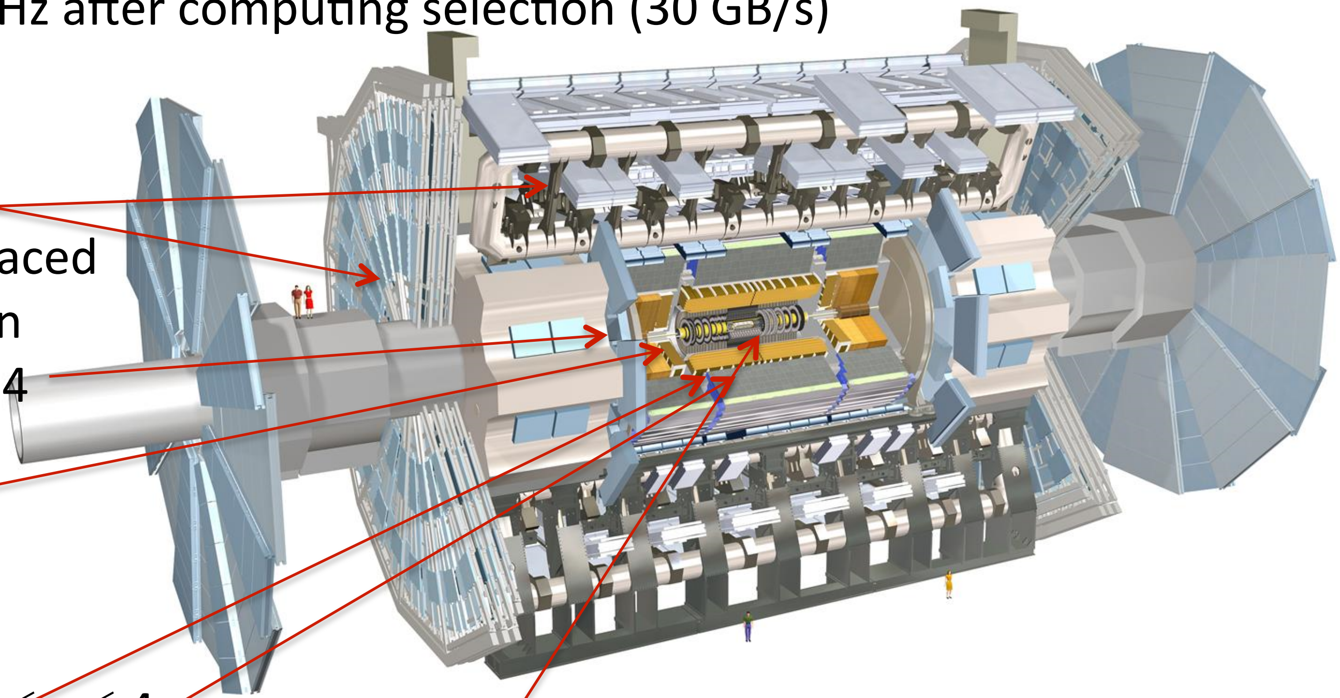


Vertex density vs z at 5 x 10^{34} Hz/cm^2

ATLAS upgrades for Phase 2

Trigger/DAQ
- 1 MHz Tracker readout in Region of Interest after 6 μs latency
- Full read-out at ≃ 400 kHz after ≃ 30 μs latency
- Register up to ≃ 10 kHz after computing selection (30 GB/s)

Muon systems
- New electronics
- Some chambers replaced to improve resolution
- Muon tagging to η ≃ 4



Forward calorimeter
- New sFCAL with x 4 granularity
- 4D Si/W to cover 2.4 ≲ η ≲ 4

Liquid Argon and Tile calorimeter
- New electronics

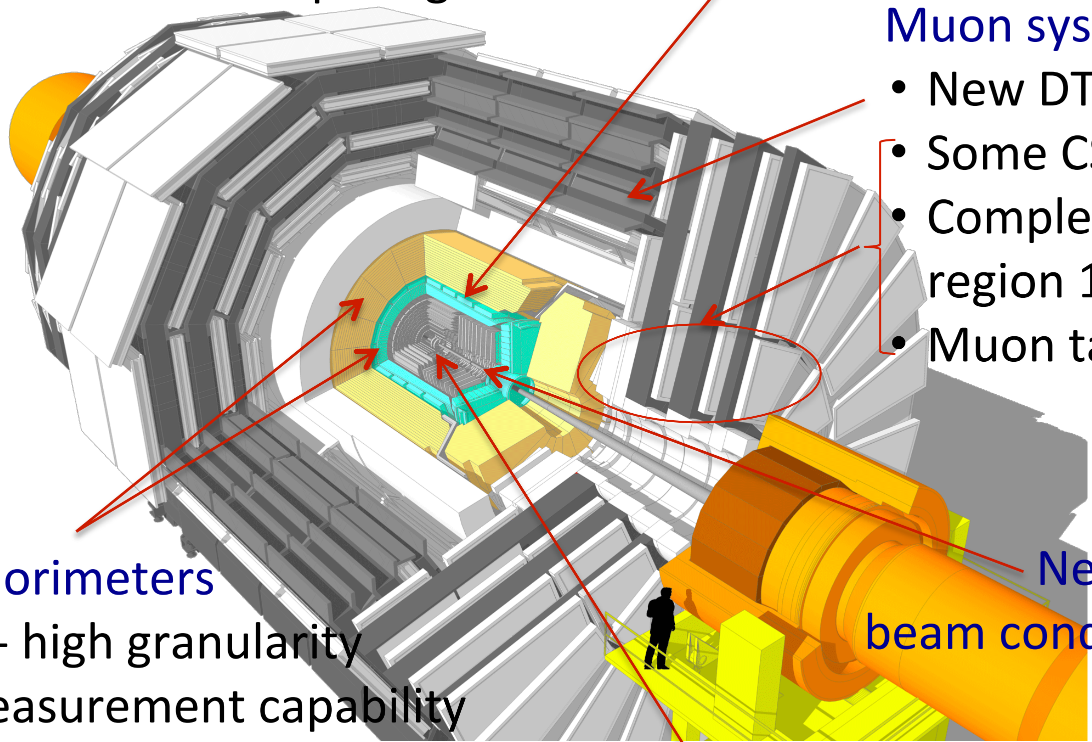
New Tracker
- Rad. tolerant, high granularity and light
- Extend coverage to η ≃ 4

CMS upgrades for Phase-II

Trigger/DAQ
- Implement track information at 40 MHz
- Full readout at $\simeq$ 750 kHz after 12.5 µs
- Register $\simeq$ 7.5 kHz after computing selection (40 GB/s)

Barrel Electromagnetic calorimeter
- New electronics
- Lower operating temperature (8°)

Muon systems
- New DT electronics
- Some CSC electronics
- Complete RPC coverage in region $1.5 \lesssim \eta \lesssim 2.4$
- Muon tagging $2.4 \lesssim \eta \lesssim 3$



New Endcap Calorimeters
- Rad. tolerant - high granularity
- 4D shower measurement capability (including precise timing $\lesssim$ 50 ps) with Si/W and Si/Brass sections

New Luminosity and beam conditions monitoring

New Tracker
- Rad. tolerant, high granularity and light
- 40 MHz selective readout for hardware trigger
- Extend coverage to $\eta \simeq 3.8$

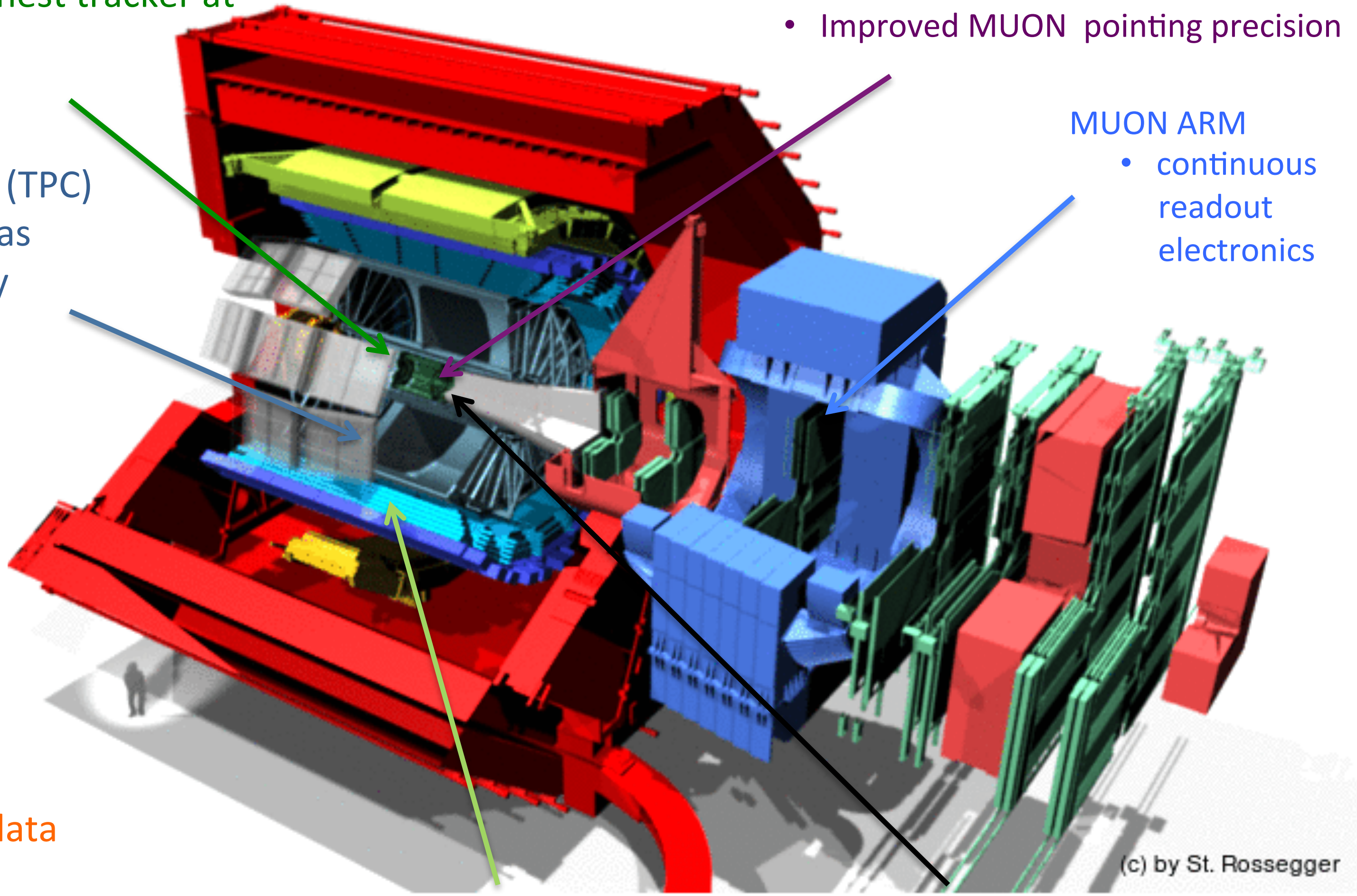
ALICE upgrades in LS2

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- New Micropattern gas detector technology
- continuous readout



New Central Trigger Processor (CTP)

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

LHCb upgrades in LS2