Highlights of LHC, ATLAS, CMS and LHCb upgrades

Séminaire thématique GT01: « Physique des particules »

12 - 13 Mars 2020, IP2I Lyon

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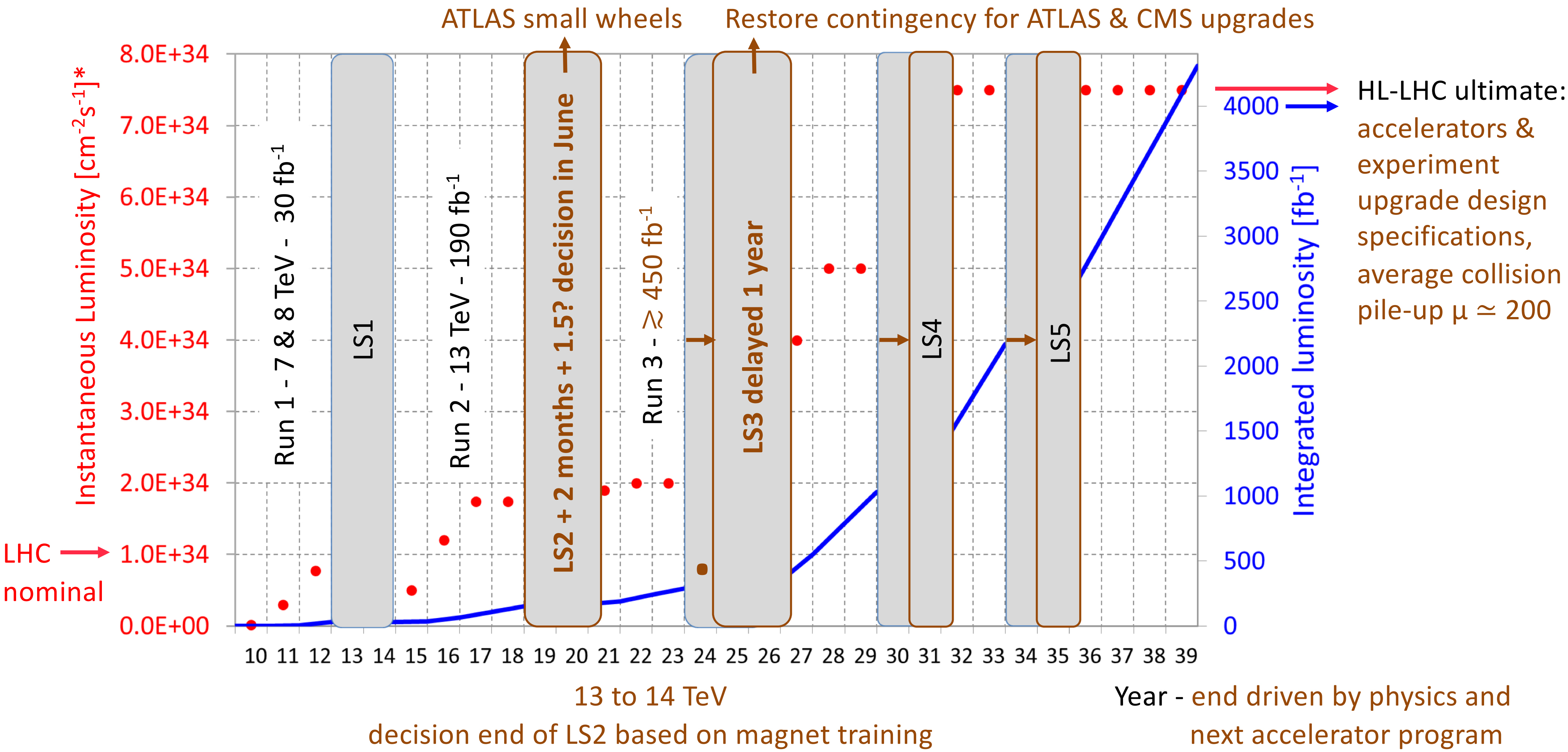
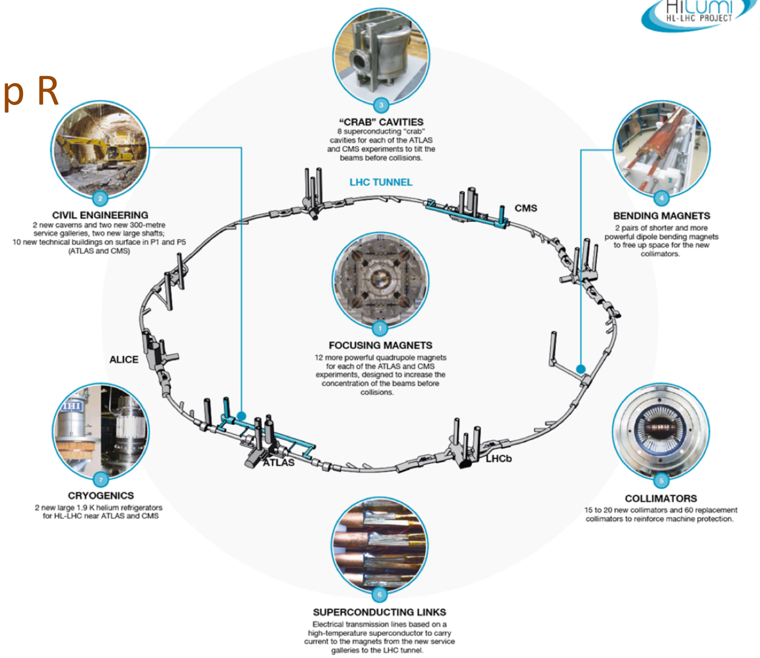
LHC luminosity planning (ATLAS & CMS): Dec. 2019 update



** Luminosity leveling since 2017 - accelerator performance exceeds ability of experiments to cope with collision pile-up average $\mu \simeq 40$ up to 60 in Run 2*

HL-LHC Upgrades: $L_{peak} = [n_b N_b^2 f_{rev} / 4\pi\beta^*\varepsilon_n] \times R \simeq 1.5 \times 10^{35}$ (Hz/cm²)*

- During LS2
  - LHC Injection Upgrade (LIU): increase intensity (N_b x 2) & brightness (Nb/ε_n), reliability and availability
    - Linac 2 @ 50 MeV → Linac 4 @ 160 MeV with H^- acceleration
    - PSB 1.4 → 2 GeV, H^- charge injection exchange to p
    - SPS new 200 MHz RF power system
  - First 4 x 5.5 m Nb/Sn magnets (dipoles) at 11 T (gain space for beam loss collimation)
  - Civil engineering**: pits and service caverns for new super conducting links toward magnets
- During LS3
  - Interaction Point upgrades**: increase beam focus β* & tune overlap R
    - 100 magnets of 11 types in matching region around IPs: focusing
      - New quadrupoles triplets: 12 Nb/Sn magnets at 12 T
    - "Crab" Cavities : tilt beams for luminosity levelling at 7.5 x 10^{34} Hz/cm²
      - 4 cavities on each side of IPs
    - New collimators for machine protection
      - ½ replaced with new material (60) and 15 to 20 new ones



* *Before levelling*
** *At ATLAS and CMS*

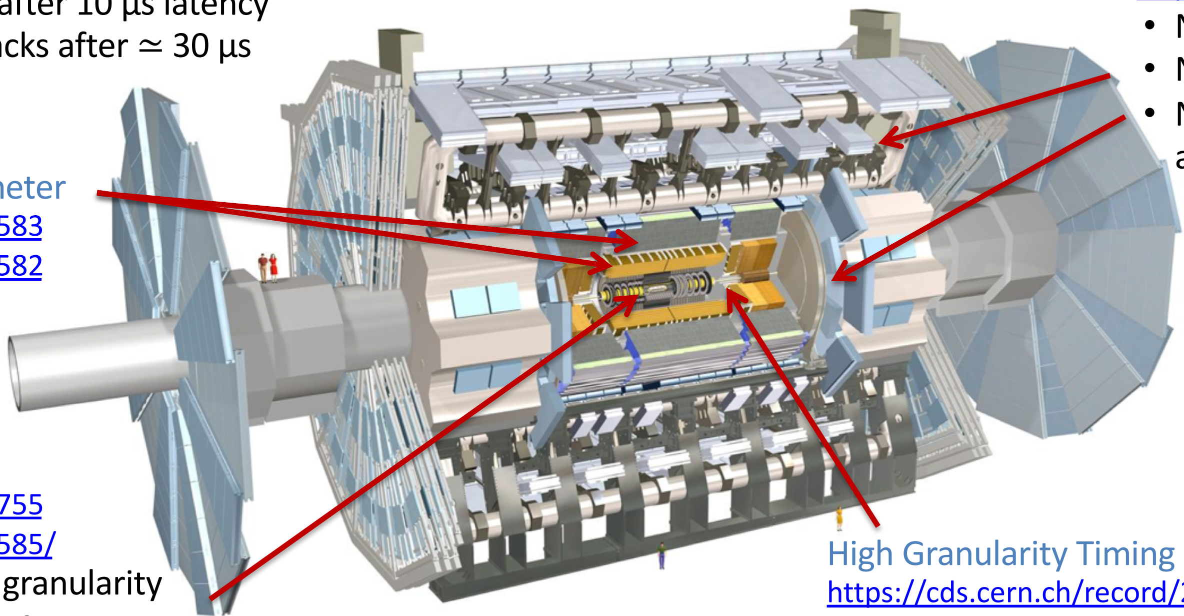
L. Rossi: https://indico.cern.ch/event/806637/timetable/?view=standard

ATLAS Upgrades - rates, radiation tolerance & pile-up

Trigger/HLT/DAQ https://cds.cern.ch/record/2285584
- Tracker readout at 1 MHz after 10 µs latency
- HLT input 400 kHz with tracks after ≃ 30 µs
- HLT output 10 kHz

Liquid Argon and Tile calorimeter
https://cds.cern.ch/record/2285583
https://cds.cern.ch/record/2285582
- New electronics increased granularity at 40 MHz (partly in LS2)

New Tracker
https://cds.cern.ch/record/2257755
https://cds.cern.ch/record/2285585/
- Si-Strip & Pixels increased granularity
- Extended coverage to η ≃ 4



Muon systems
https://cds.cern.ch/record/2285580
- New electronics
- New inner barrel chambers
- New Small Wheels during LS2 and EYETS 21-22

High Granularity Timing Detector (TDR in preparation)
https://cds.cern.ch/record/2623663
- Low Gain Avalanche Diodes 2.4 ≲ η ≲ 4

- Pixel: Module production (IJCLab, IRFU, LPNHE), integration of ladders (CPPM, LAPP, LPSC)
- LAr calorimeter: FE and calibration ASIC (OMEGA), FE ASIC and board tests (IJCLab), calibration board (LAPP), BE boards and firmware (CPPM, LAPP)
- Tile Calorimeter: Production of FE ASIC, HV for PMTs and laser monitoring (LPC)
- High Granularity Timing Detector: ASIC FE (OMEGA), Test ASIC and Hybrids (IJCLab, OMEGA, LPC), beam test with sensors (IJClab, LPNHE), module assembly (LPNHE, IJClab), cooling and mechanical structure (IJCLab)
- New Small Wheels: Production of 32 chambers (half and the largest - 2m) (IRFU)

CMS Upgrades - rates, radiation tolerance & pile-up

L1-Trigger/HLT/DAQ (L1 TDR Q1 2020, HLT/DAQ TDR Q2 2021)
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

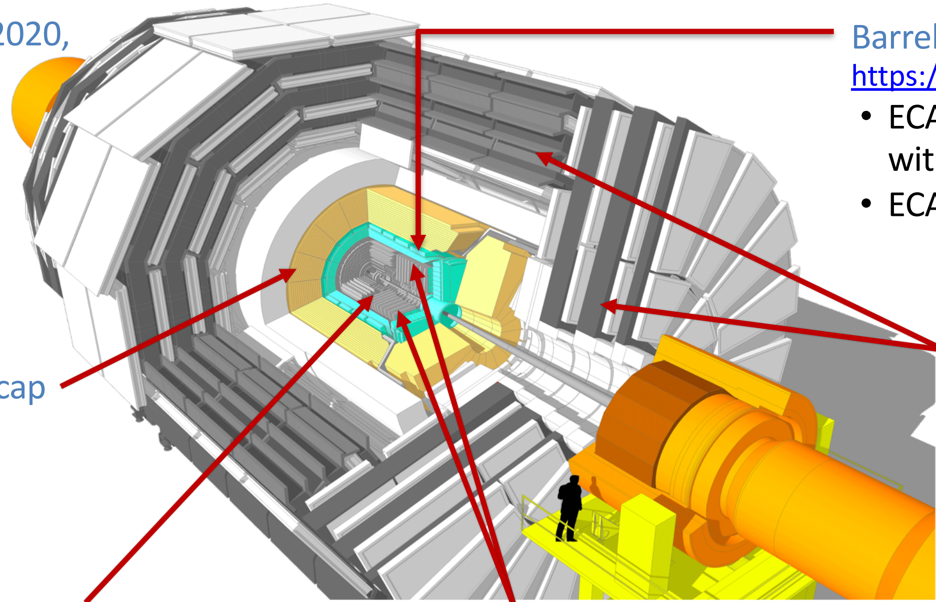
- Tracks in L1-Trigger at 40 MHz
- PFlow-like, 750 kHz output
- HLT output 7.5 kHz

High Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb-W/SS

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

- Si-Strip & Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$c



MIP Timing Detector
https://cds.cern.ch/record/2296612

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

Barrel Calorimeters
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC link -board
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Beam Radiation Instr. and Luminosity, Common Systems and Infrastructure
https://cds.cern.ch/record/002706512
Precision Proton Spectrometer
EoI in preparation

- IPHC: assembly of outer barrel ladders and production of support wheel, DAQ system for outer and inner tracker, system test CYRCé beam line
- IP2I: production of endcaps support dees, integration 1/2 of short dees, FE concentrator ASIC TSMC 65 nm, RPC PCB & FE readout boards
- LLR: production of HGC cassette plates, system/beam tests, trigger system firmware and software
- OMEGA: HGCROC Frontend ASIC in TSMC 130 nm, Muon RPC PETIROC ASIC in AMS 350 nm
- IRFU: TDC, PLL of HGCROC, ECAL analog FE ASIC 130 nm, clock distribution for timing (MTD fanout ASIC TSMC 130nm , ECAL, HGC), ECAL laser monitoring

LHCb Upgrades - rates, radiation tolerance & pile-up

LS2 upgrade: L = 2 x 10^{33} Hz/cm^2 ($\mu \simeq 5$) - 50 fb^{-1} integrated by LS4 upgrade*: L = 2 x 10^{34} Hz/cm^2 ($\mu \simeq 50$) toward 300 fb^{-1}

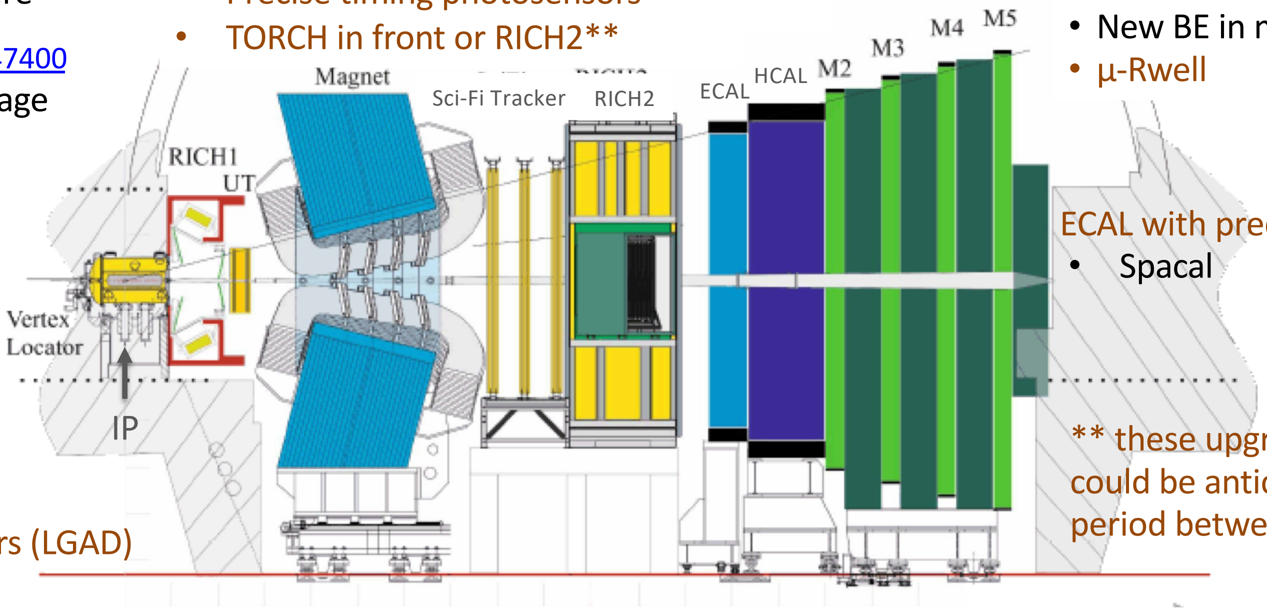
HLT/DAQ https://cds.cern.ch/record/1701361
- Software event selection
- DAQ output 20 kHz
- New readout boards everywhere

Tracker https://cds.cern.ch/record/1647400
- UT Si-strip, granularity & coverage
- T Scintillating Fiber + SiPMs
- Magnet low p_T stations

Smog
https://cds.cern.ch/record/2673690
- Fixed gas target
- Running in // with collider mode

Vertex
https://cds.cern.ch/record/1624070
- New Si-pixel system
- MAPs* and precise timing layers (LGAD)

PID https://cds.cern.ch/record/1624074
- New photosensors in both RICH
- Modified optics in RICH1
- Precise timing photosensors
- TORCH in front or RICH2**



Calorimeter and Muon system
https://cds.cern.ch/record/1333091
https://cds.cern.ch/record/1443882
- New FE & BE in calorimeter
- New BE in muon stations
- µ-Rwell

ECAL with precise timing**
- Spacal

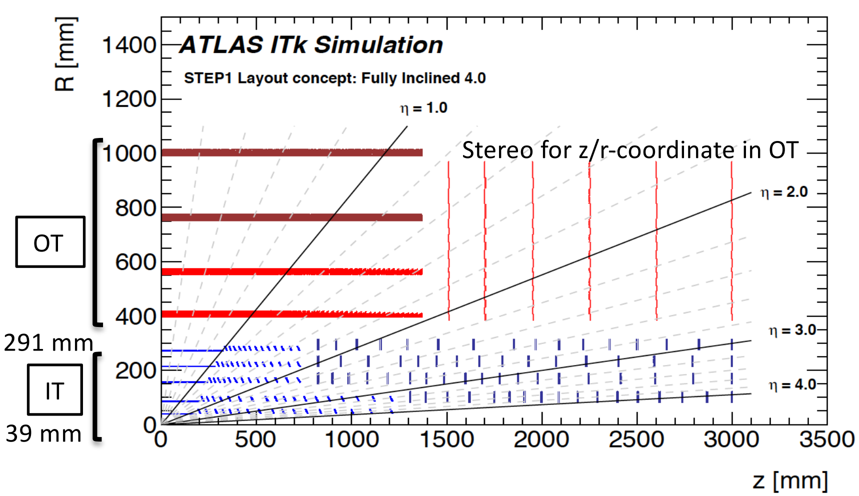
** these upgrades or parts could be anticipated to the period between LS3 and LS4

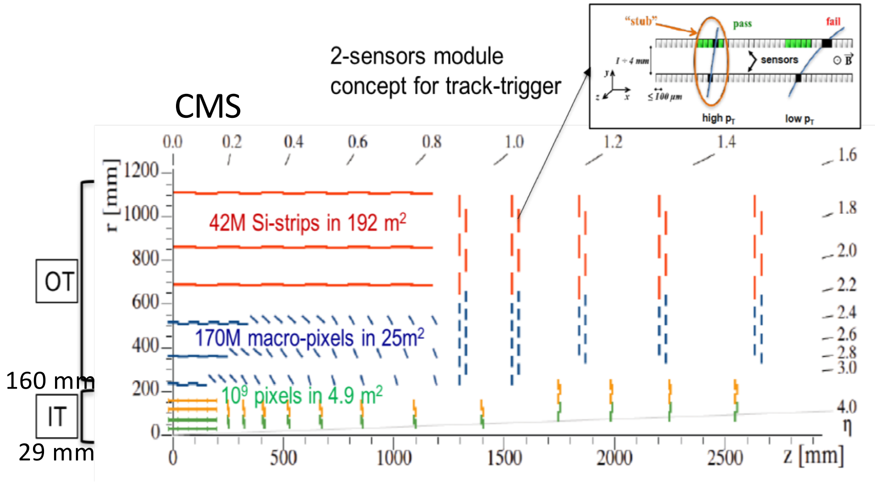
- Calorimeters: FE boards and controllers (IJCLab), microcode (firmware) of readout boards (LAPP), removal of SPS/PS, mechanics to replace inner calo. modules
- Scintillating Fibers Tracker: FE ASIC and boards (LPC), microcode (firmware) of readout boards (LPNHE), integration and cooling of boards (LPC)
- DAQ system: readout boards (CPPM), microcode (firmware) and framework developments (LAPP, CPPM), Real Time Analyses system (LPNHE)

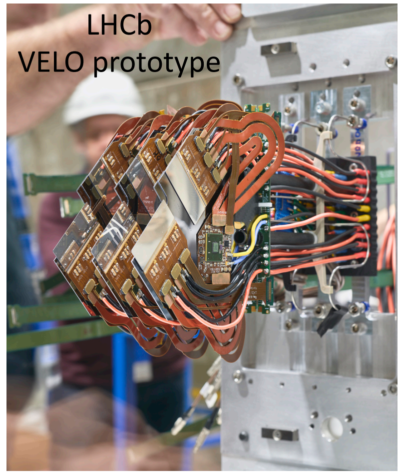
** Physics case https://cds.cern.ch/record/2320509 reviewed by LHCC and CERN RB recommendation for framework TDR in 2021 and approval process*

New paradigms: tracking systems

- New technologies
  - Si-sensors: n-in-p (all exp.) & 3D inner pixel layer (ATLAS-CMS), thinner, granularity x 4 to 6
  - Front-End ASIC: TSMC 65 nm (Pixels, data transmission) increase radiation tolerance and lower power consumption
  - Material budget: light materials, CO_2 cooling, micro-channel in LHCb, DC/DC powering (CMS tracker weight ≃ 1/2)
  - LHCb outer tracker: Scintillating fibers, with SiPM photosensors at -40°
- Design optimizations
  - ATLAS: all Si-tracker with 5 barrel pixel layers
  - CMS: concept for readout of tracks with $p_T \gtrsim 2$ GeV at 40 MHz for L1 trigger
  - ATLAS and CMS: less layer inclined geometries in transition regions, pixel coverage extension to η ≃ 4
  - LHCb: VELO with pixel sensors very similar to ATLAS and CMS already in LS2 - at 4.5 mm from beam in vacuum

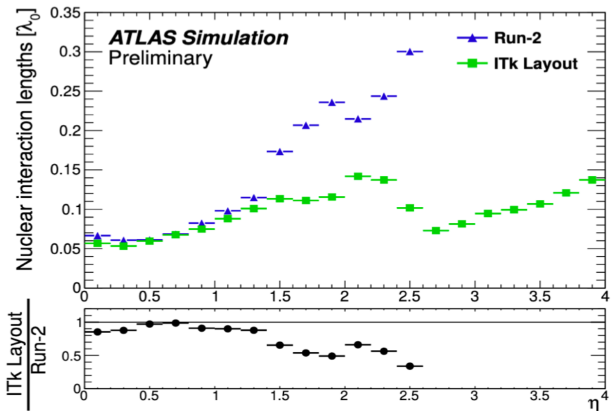


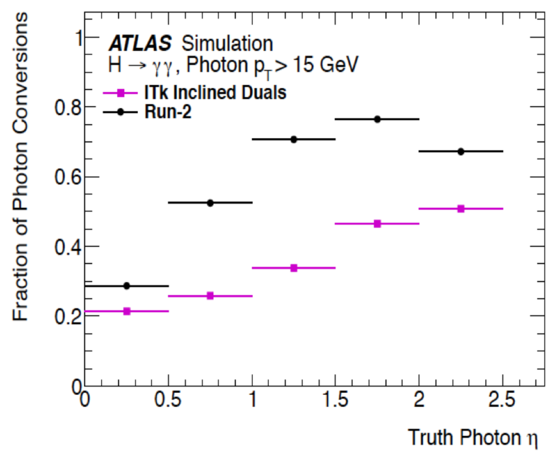


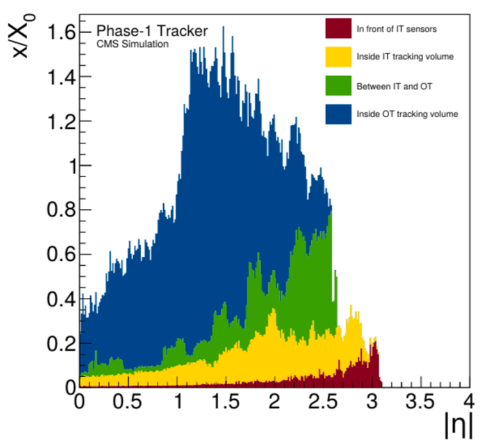


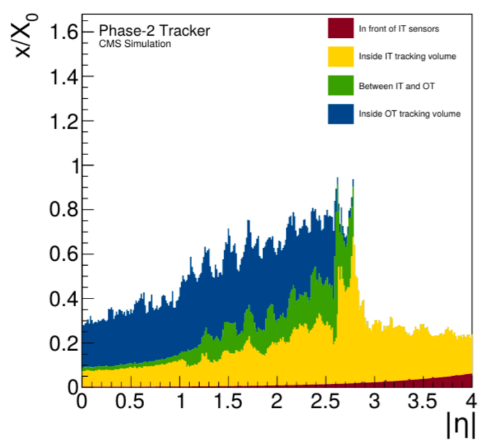
New paradigms: tracking systems

Radiation and Interaction length improvements

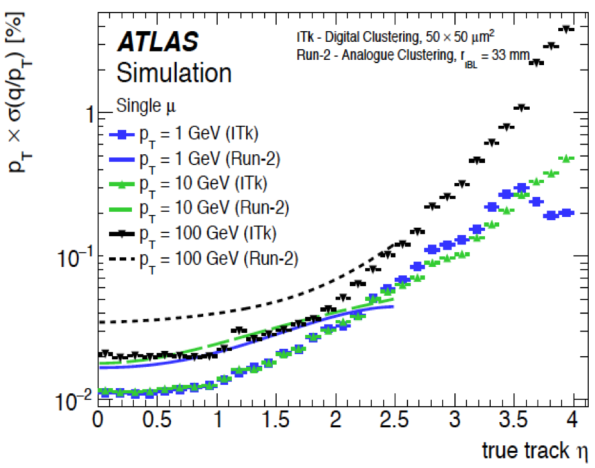


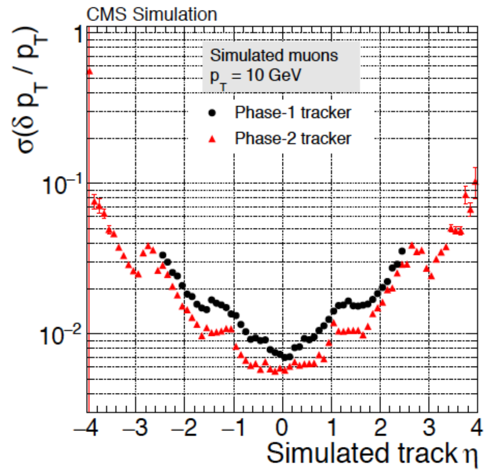


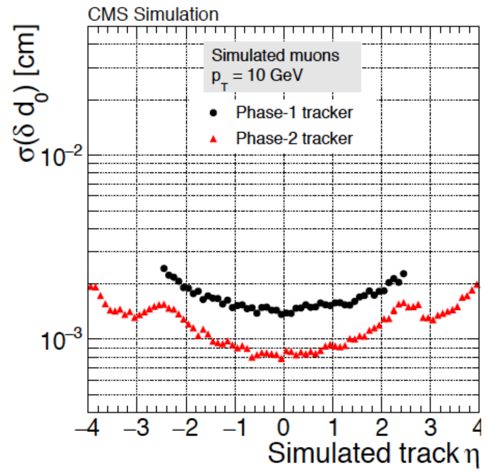


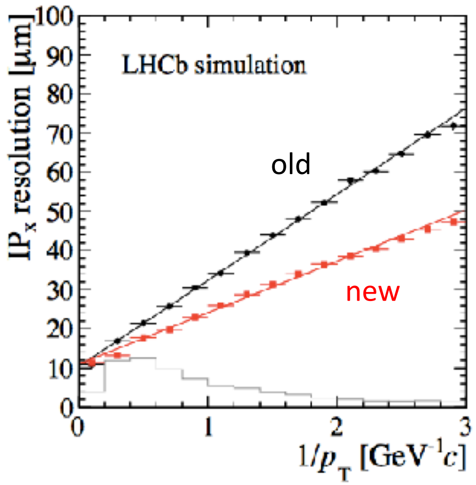


Momentum and Impact Parameter improvements





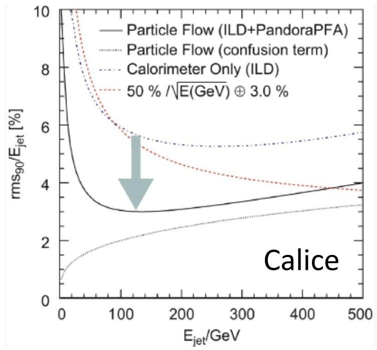


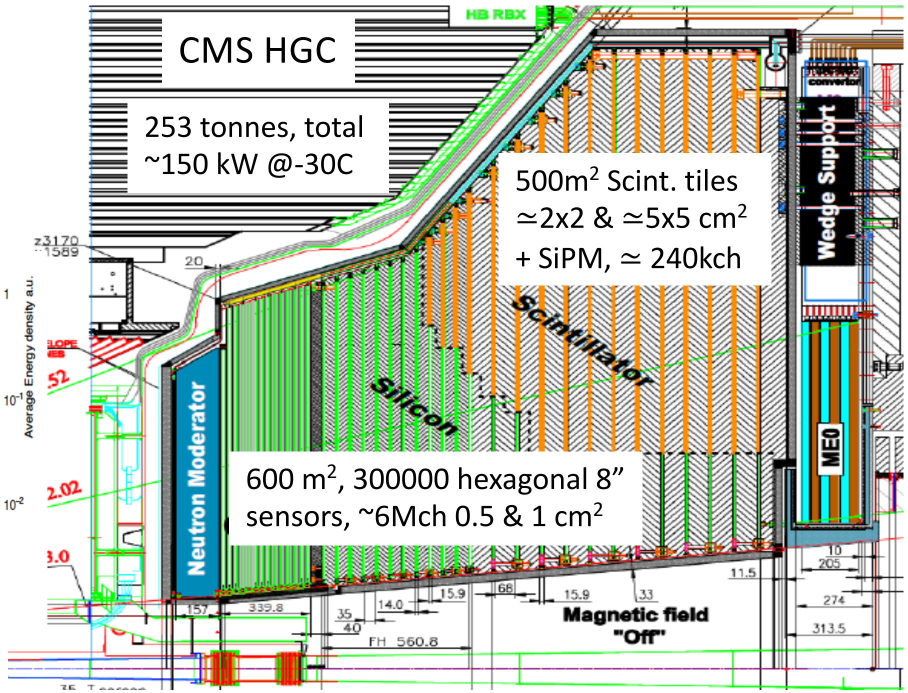


New paradigms: High Granularity Calorimeter in CMS endcaps

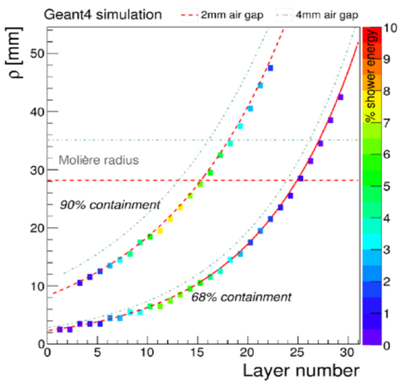
CALICE + PFlow concept used for pile-up mitigation in e/γ/τ/Jet ID and in HT and MET*

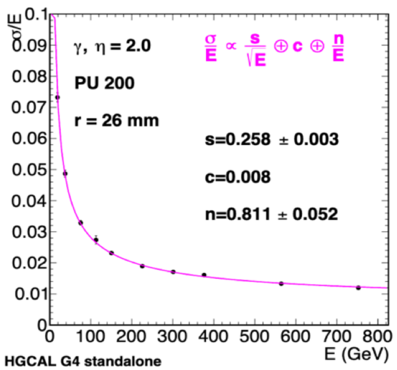
- Design optimization
  - Electromagnetic (CE-E) 28 layers Si-sensors with W/Pb absorber (26 X_0 - 1.7 λ)
  - Hadronic (CE-H) 22 layers: 8 Si and 14 mixed Si/Scintillating tuiles + SiPMs in Stainless Steel absorber (9 λ)
- Technologies
  - First use of 8” Si-sensors (n-in-p)
  - SiPM photosensors for direct scintillator tile readout
  - Very complex readout ASIC with 50 ps time precision
  - Engineering challenges compactness, cooling, weight…

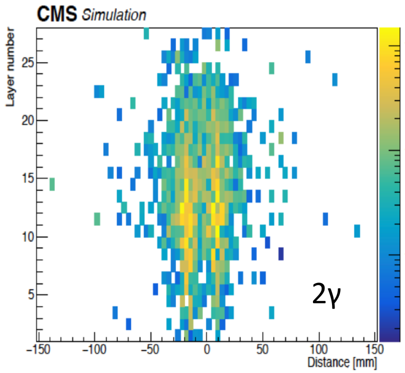




Silicium - scintillateur + SiPMs limit defined by radiation tolerance

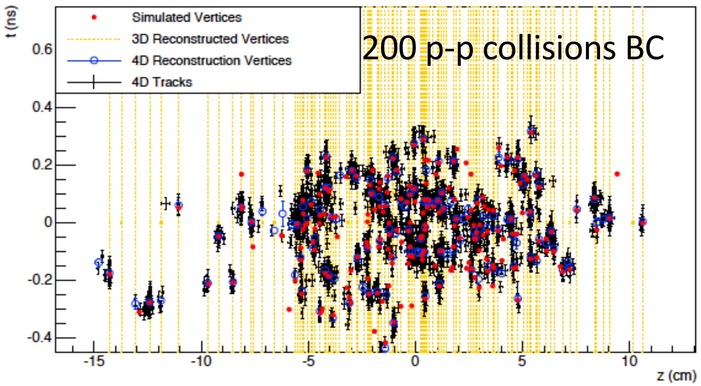


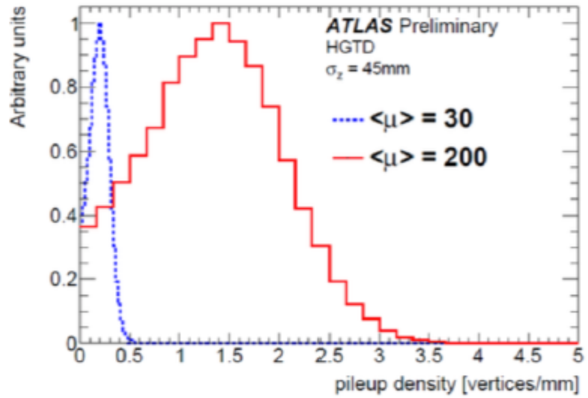


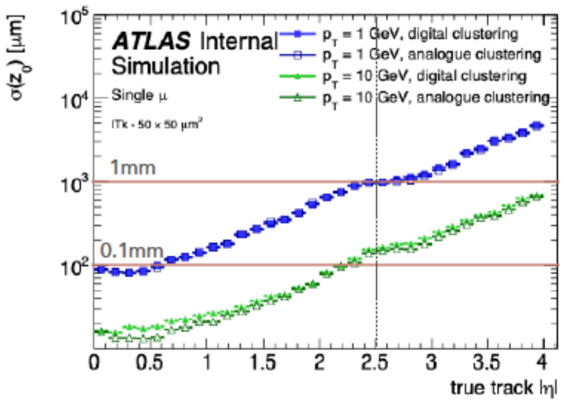


** Also allows energy compensation for hadron energy resolution*

New paradigms: precise ToF MIP





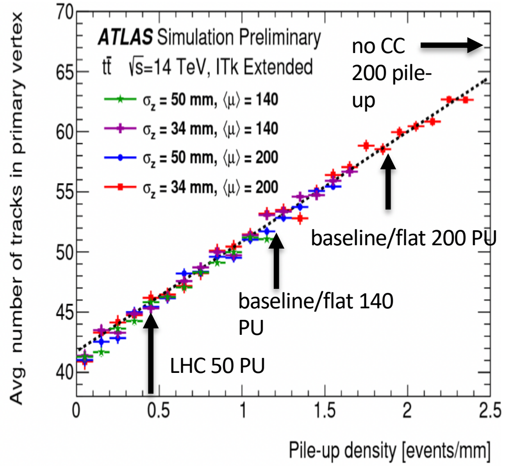


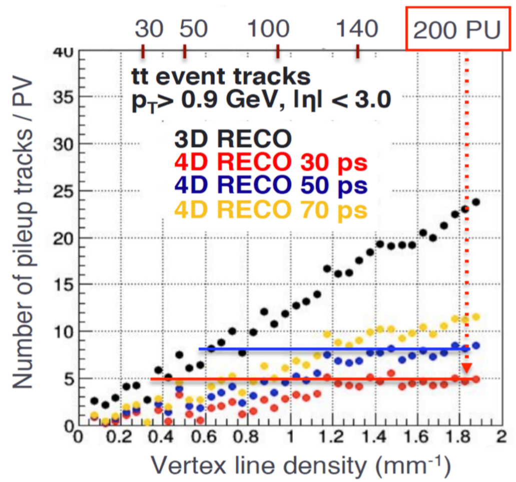
MIP precise Time of Flight to recover track purity in hard collision vertices to fully profit from luminosity potential*

improves all object reconstruction, particularly beneficial to reject fake jets in forward region and to improve missing transverse energy resolution

- ATLAS HGTD in more critical region $2.4 < \eta < 4.0$
- CMS hermetic up to $\eta = 3$

≃ 20% to 40% luminosity gain in barrel - forward



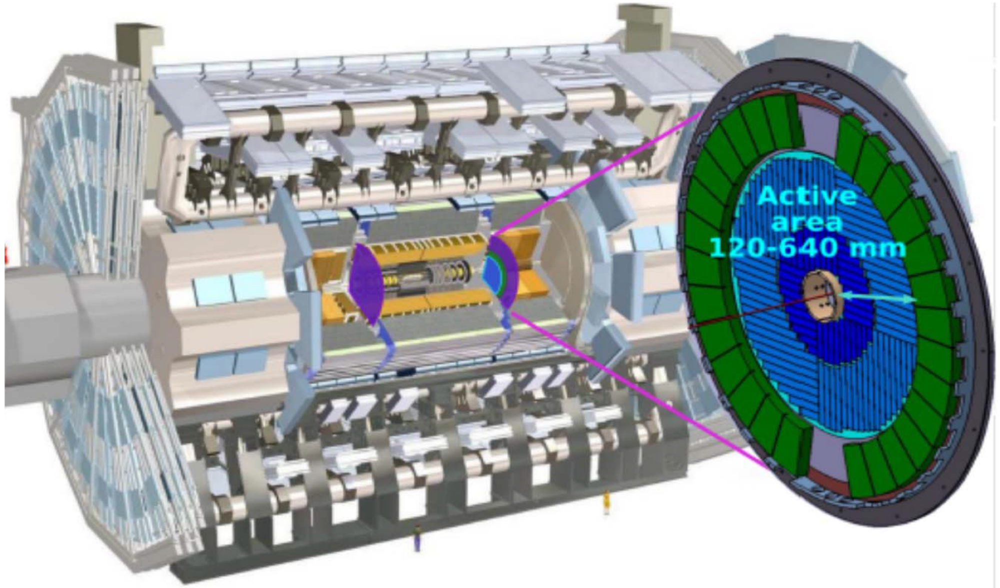


** Luminosity levelling is tunable*

New paradigms: precise ToF MIP

30 (40) ps time resolution before (after) irradiation in ATLAS and CMS
New technologies LYSO crystals and Low Gain Avalanche Diodes*, ASICs(clock distribution) resolutions ≃ 20(10) ps

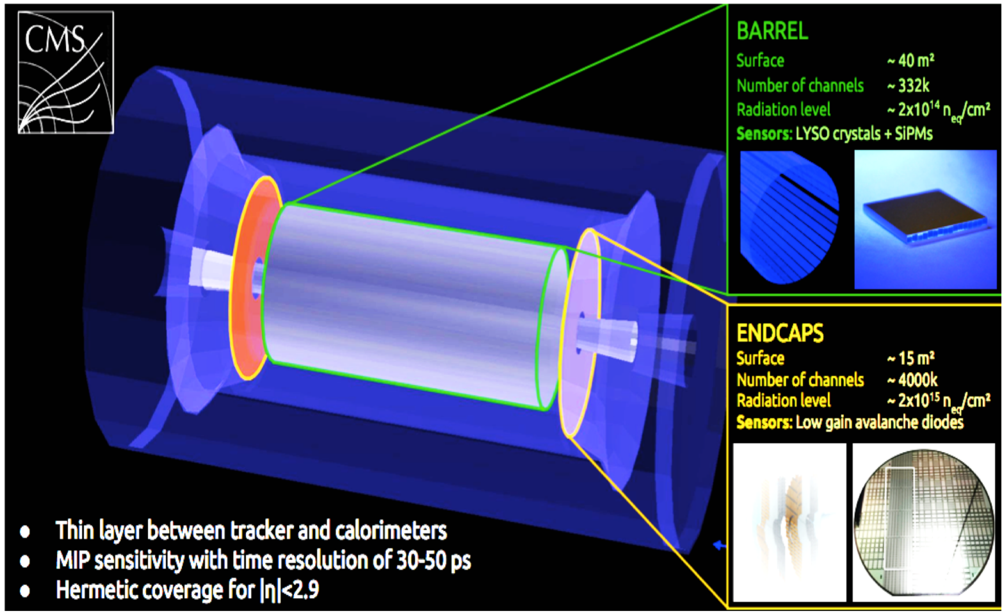
ATLAS High Granularity Timing Detector



Two double sided layers (75 mm) covering $2.4 < \eta < 4.0$

- 2(3) hits per track for R >(<) 30 cm
- LGADs 15 x15 array of 1.3 x 1.3 mm^2 pixels
- 6.3 m^2, 3.54 Mch

CMS MIP Timing Detector**



Barrel layer in Tracker volume (28 mm)

- Lyso crystal bars 56 x 3 x3 mm^2, ≃ 350 kchannels, 40 m^2
- Readout at both ends with 2 SiPM 3 x 3 mm^2,

Endcap 2 layers in front of Calo. Endcap (42 mm)

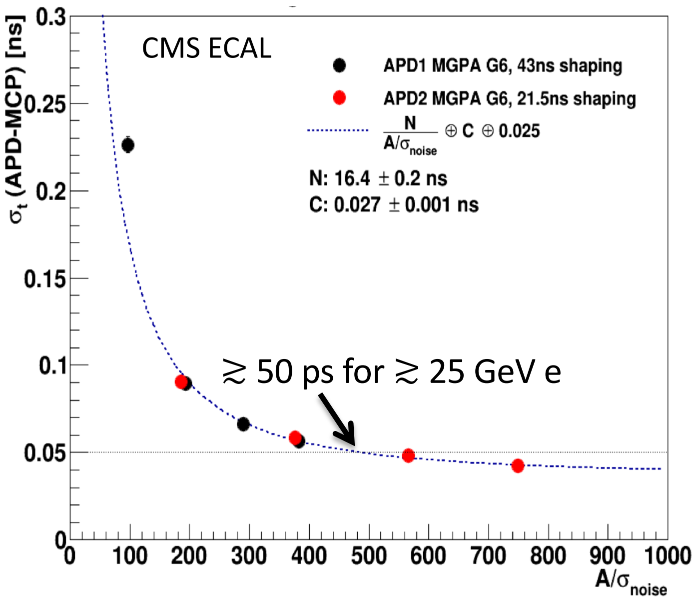
- LGAD 1.3 x 1,3 mm^2 pads, ≃ 4 Mch, 12 m^2

** Also foreseen for LHCb tracking upgrade in LS4, ** provides good ID for low momentum range π/K/p*

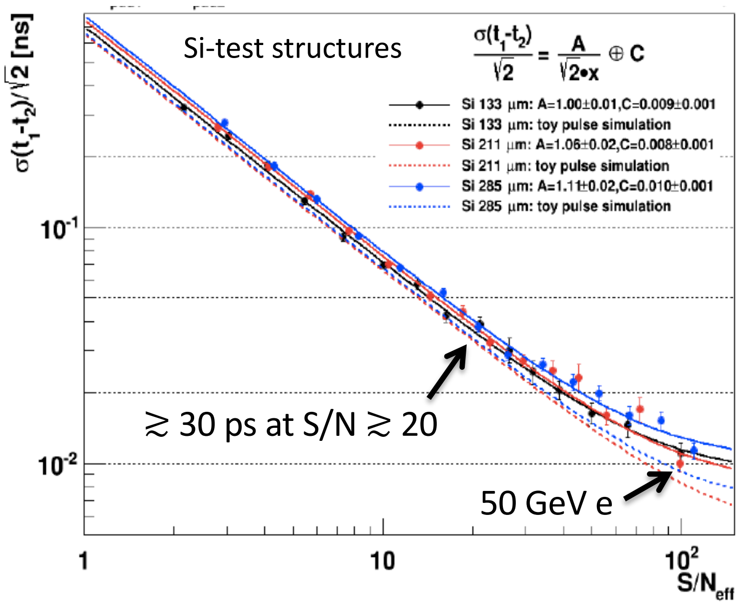
New paradigms: precision ToF showers

Exploit fast signal development in regular Silicon-sensors & Scintillating devices together high S/N in calorimeter showers to further mitigate pile-up effects for neutrals (γ and h_0)

25 ns peaking time and 160 MHz sampling of CMS ECAL FE ASIC provides 30 ps resolution for γ of 30 GeV



50 ps time resolution of CMS HGC FE ASIC provides 30 ps resolution for e/γ of few GeV in Si-sensors multiple layers



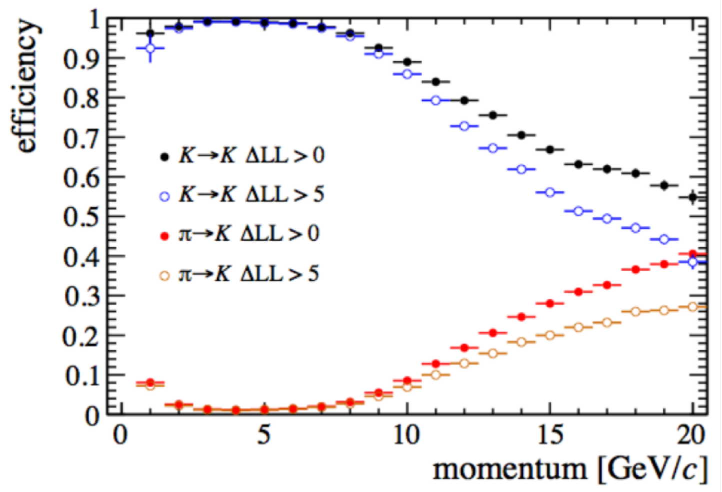
LHCb foresees precise ToF in scintillating device ECAL upgrade in LS4

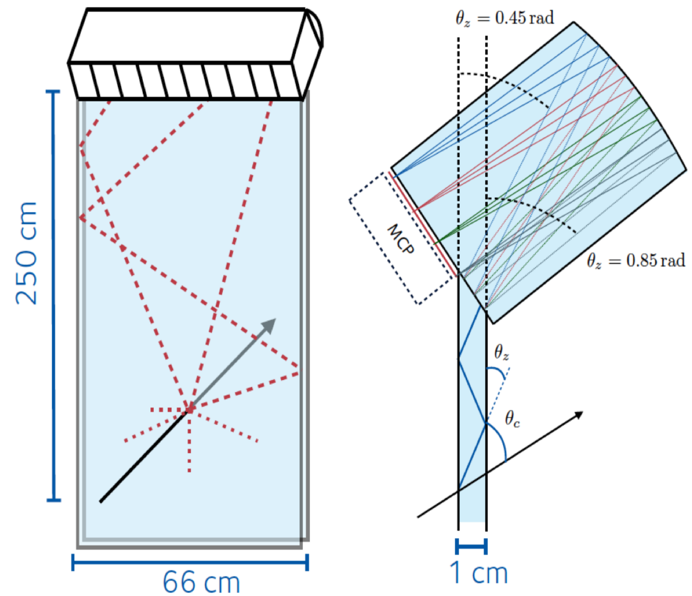
New paradigms: precision ToF of Cerenkov light for PID

Time of Reflected Cerenkov Light Rich (TORCH) for LHCb upgrade in LS4 for low momentum ID*

Wall of 18 elements in front of RICH2

- Quartz bar radiator and focusing on MCP-PMT
  - Target id in the range 2 -10 GeV combining Cherenkov angle and TOF measurements with σ(ToF) ≃ 15 ps, (≃ 70 ps SPTR & ≃ 30 γ/track)
  - MCP demonstrated to achieve ≃ 35 ps
  - TORCH ½ full size prototype tested in 5-8 Gev π/p beam achieved SPTR of ≃ 90 ps

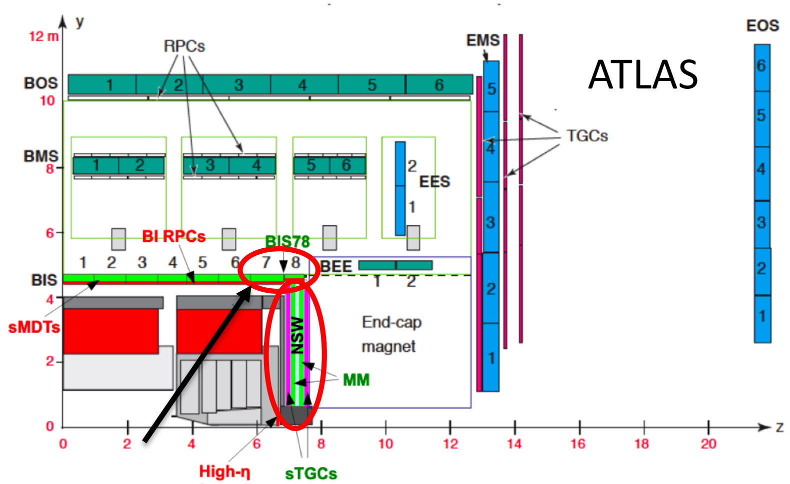


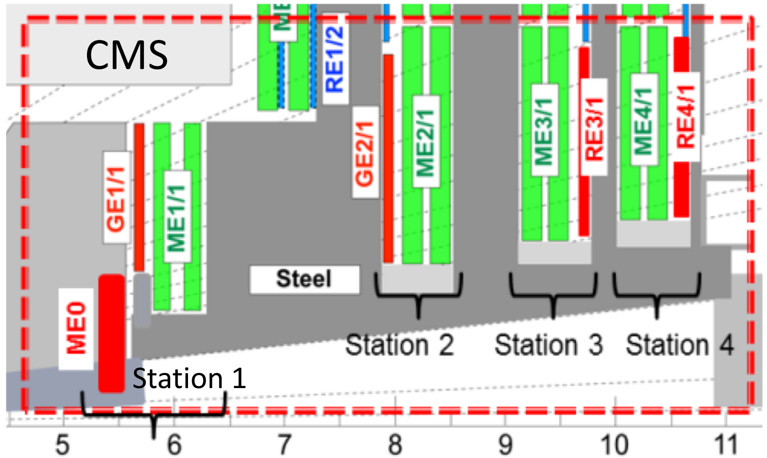


** A similar concept w/o expansion volume (ToP) in Belle-II*

New paradigms: muon systems

Enhancement of forward region for rates and trigger issues, including capability to for LLPs displaced or late vertices (DT and RPC resolution improved to respectively 4 - 2 ns in CMS)





- Small Wheels
  - Small Thin Gap (2.8 mm) Chambers, shorter strips 2 cm to 3.2 mm, 3 mm pitch, $\sigma \simeq 50$ µm, up to 2 x 1.2 m^2
  - Resistive strip Micro-Megas (0.5 mm pitch), $\sigma \simeq 80$ µm, largest module 2 x 2.3 m^2 made of 5 PCBs, Ar:CO2 (93:7)
- Small Monitoring Drift Tubes
  - Reduced Φ 30 mm (200 Hz/cm^2) to 15 mm (2 kHz/cm^2), wires 50 µm, $\sigma \simeq 100$ µm, L = 1.6 m, Ar:CO2(93:7)

- New GEM stations and extended coverage to $\eta \simeq 3$
  - Triple GEM design, H = 1.8 m x W = 1.2 m wedges with 4 foils, PCB radial strips, pitch 0.7 mm to 1.6 mm, $\sigma \simeq 200$ to 450 µm
  - Single mask foil photolithography, stretching mechanism
  - Up to > 1 MHz/cm^2, time resolution O(10ns),
- New multigap RPC stations
  - Low-ρ Bakelite 1-3 10^6 Ω.cm, thin gap & electrode 2 → 1.4 mm, Φ pitch 1.3° to 1.2°, up to few kHz/cm^2, $\sigma \simeq 0.3(2)$ cm ⊥(//)
  - FE 2 strip-ends readout with 100 ps for r(η)-coordinate
  - Track time resolution $\simeq 2$ ns

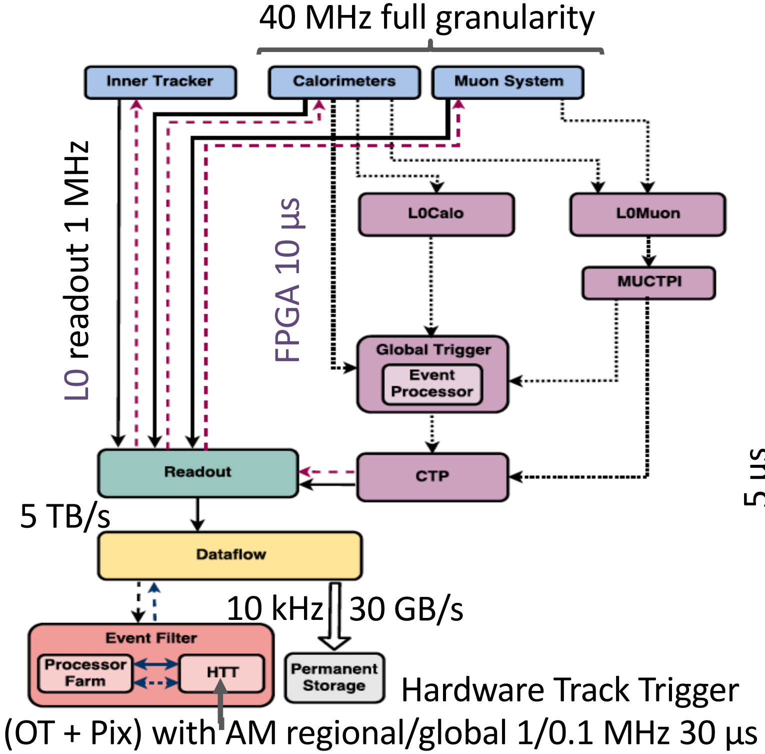
New paradigms: Trigger and DAQ

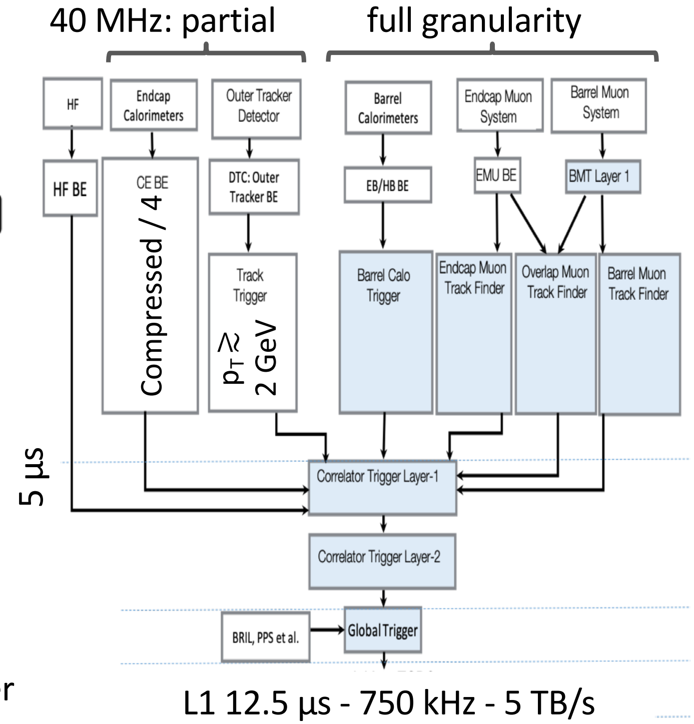
- Technologies:
  - Generic boards to ease DAQ integration, use interposers to adapt FPGA grade for cost(CPU vs #links (up to 28 Gb/s))
  - New firmware programming technique (High Level Synthesis), sophisticated algorithms ≃ HLT
  - Use of GPUs at computing level

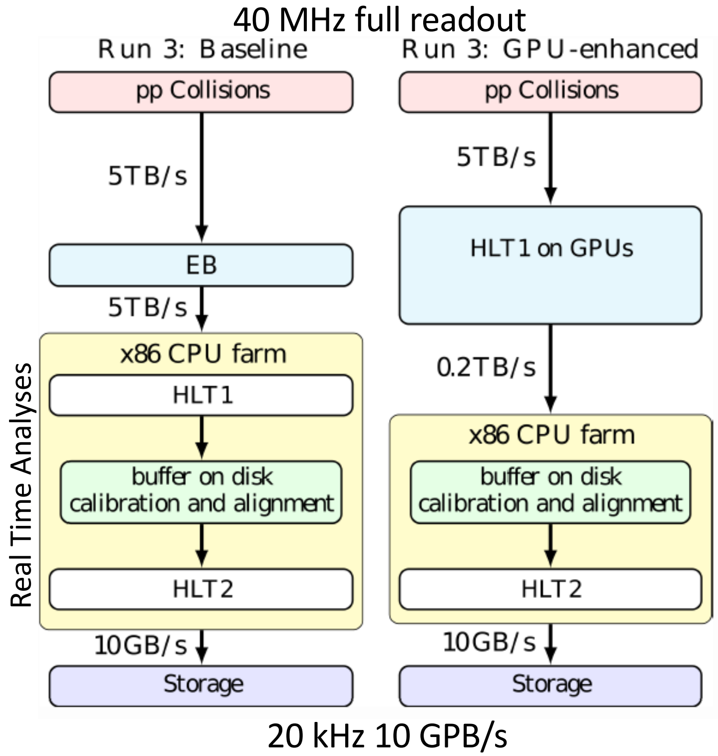
ATLAS: baseline below, hardware compatible with L0 at 4 MHz for partial tracker RoI readout and L1 at 1 MHz with HTT

CMS: L1 at 750 kHz with FPGAs, HLT heterogenous processing GPU/CPU with output 7.5 kHz 60 GB/s

LHCb: Software trigger only at new computing center two levels GPU option for L1, full reconstruction at L2





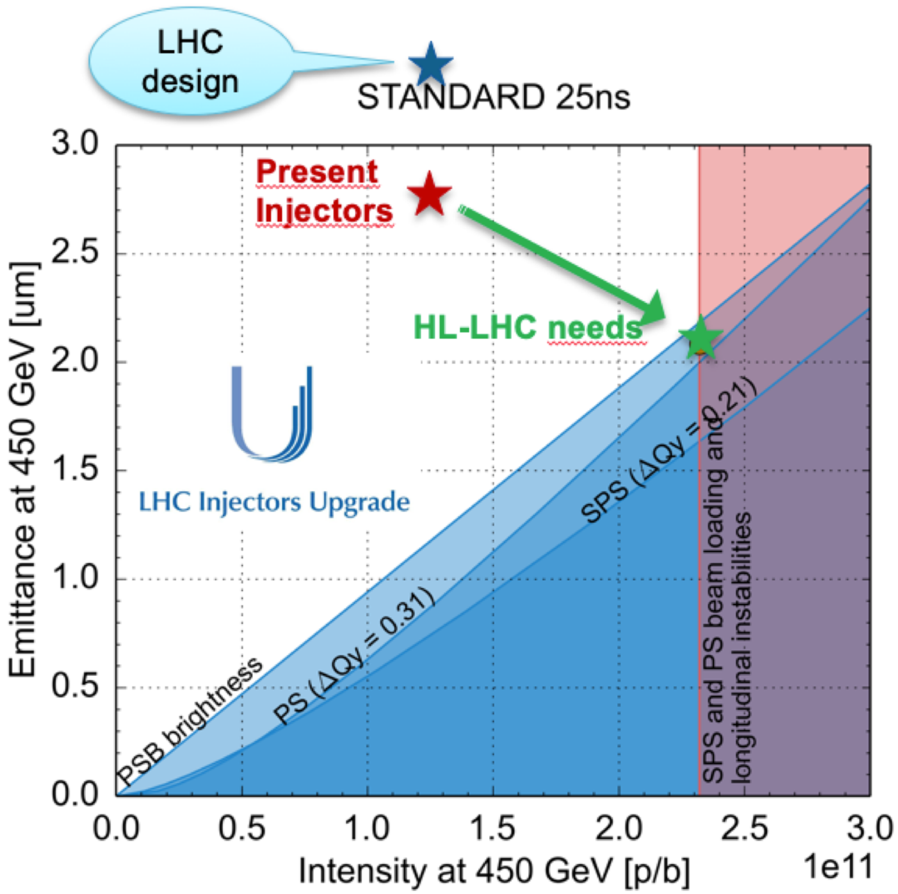


Outlook

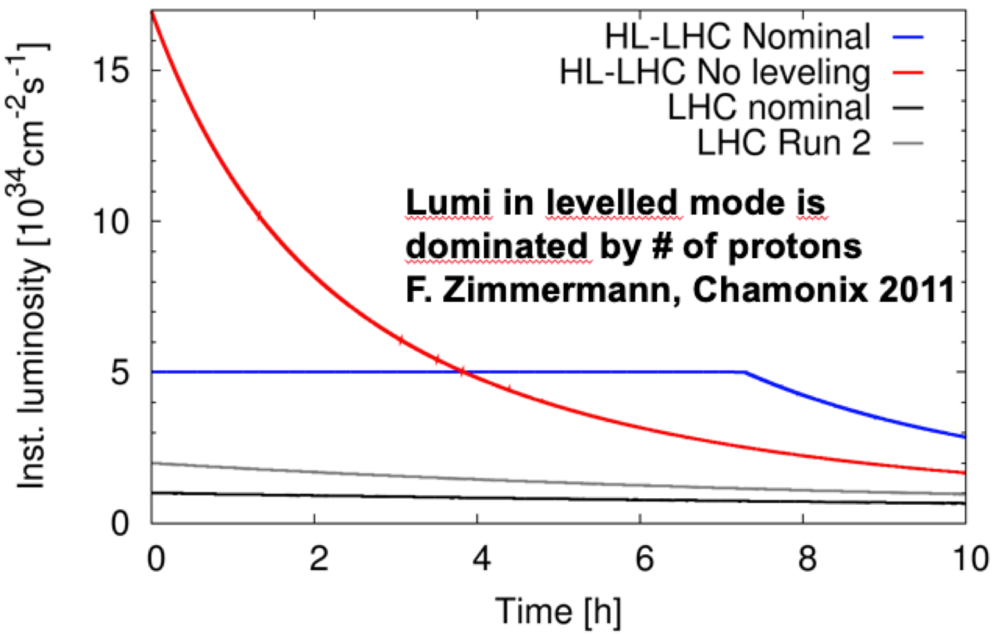
- To keep-up with the HL-LHC luminosity capability and the radiation conditions is a challenge for detectors
  - Several new techniques implemented in Phase-2 upgrades but we are not in a performance asymptote
- LHCb upgrades in LS2 already implement some features of ATLAS and CMS Phase-2 - could also be a playfield for future detectors with LS4 upgrade
- ATLAS and CMS designs are mostly completed and we are soon entering production stage for Phase-2 upgrades
  - Lot of work in parallel to Run-3 with still a tight schedule
  - As well to prepare full exploitation of new features in event reconstruction and selection adjusted to physics goals (eg establish sensitivity to pile-up - make best use of luminosity levelling)

Additional information

LIU (Intensity) and Levelling mode



Reducing heat load on the IT triplet (quench and cooling limits)
Limiting pile up in the detectors



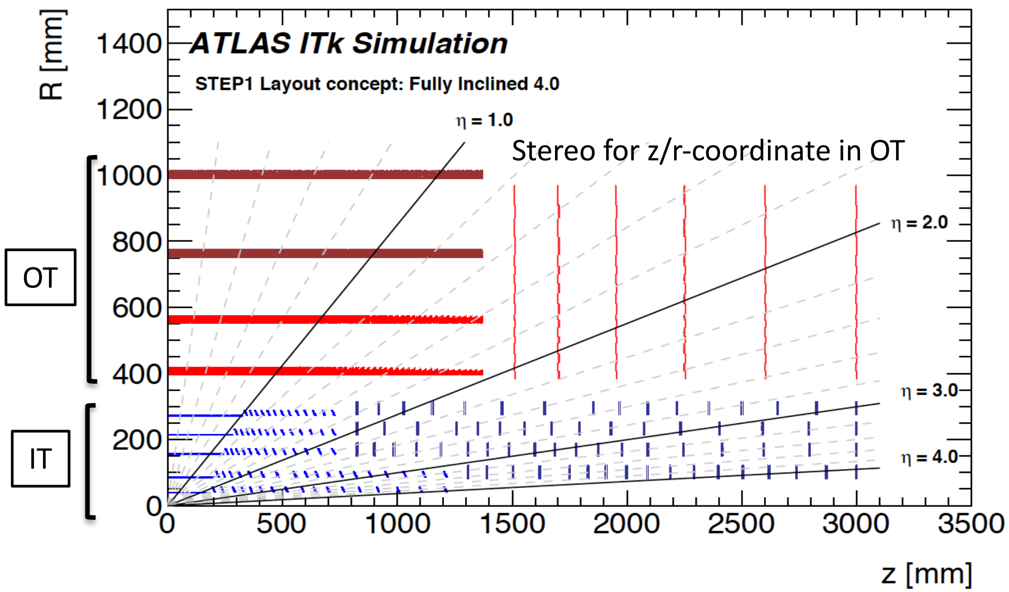
HL-LHC parameters

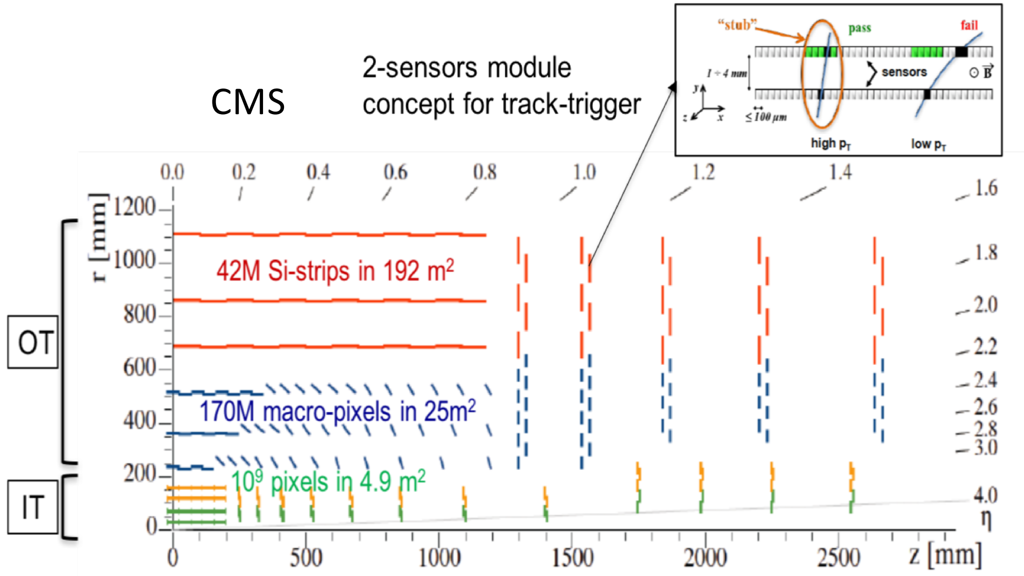
Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)	HL-LHC 8b+4e [10]
Beam energy in collision [TeV]	7	7	7
N_b	1.15E+11	2.2E+11	2.2E+11
n_b [12]	2808	2760	1972
Beam current [A]	0.58	1.1	0.79
Half Crossing angle [μrad]	142.5	250	235 [9]
Minimum β^* [m]	0.55	0.15	0.15
ε_n [μm]	3.75	2.50	2.20
Total loss factor R0 without crab-cavity	0.836	0.342	0.342
Total loss factor R1 with crab-cavity	-	0.716	0.749
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2} s^{-1}$]	-	1.70E+35	1.44E+35
Levelled Luminosity [$cm^{-2} s^{-1}$]	-	5.0E+34 [4]	3.82E+34
Events / crossing (with leveling and crab-cavities for HL-LHC) [7]	27	131	140
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.28	1.3
Leveling time [h] (assuming no emittance growth) [7]	-	7.3	7.1

Back-up for e-cloud

ATLAS and CMS Phase-2 Silicon Trackers

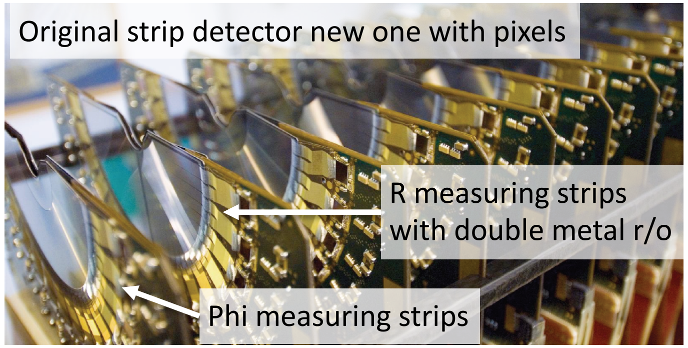
ATLAS has a 5 layers pixel detector while CMS has a design for tracks in hardware trigger at 40 MHz
pixel coverage is extended from $\eta \simeq 2.4$ to $\eta \simeq 4$





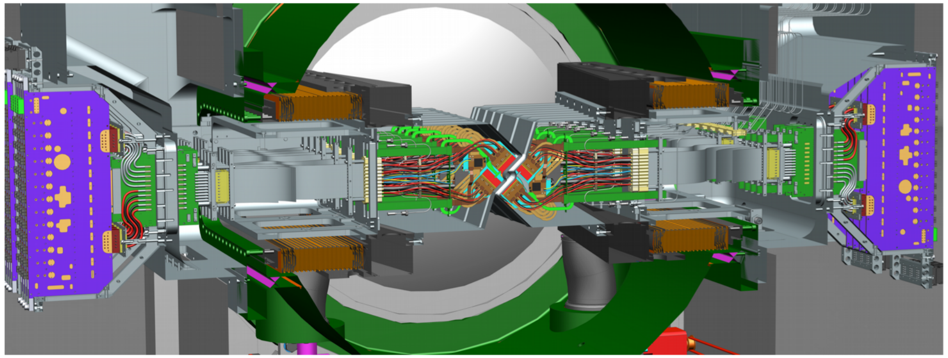
- High granularity ($\simeq$ 4 to 6 x present trackers) to maintain low occupancy
  - Pixel sizes in range $\simeq$ 50 x 50 or 25 x 100 μm^2 - first layer(s) replaceable
  - Strip pitch ~ 75 to 90 µm and length ~ 2.5 to 5 cm length
- Light (1/2 current weight) to reduced multiple scattering, interactions, e-bremsstrahlung and γ-conversions)
  - Design, new materials - new cooling (CO_2) - DC/DC, serial powering
- n-in-p and 3D sensors, radiation tolerance up to NIEL $\simeq 2 \times 10^{16}$ 1 MeV neq/cm^2 and TID of 1 GRad

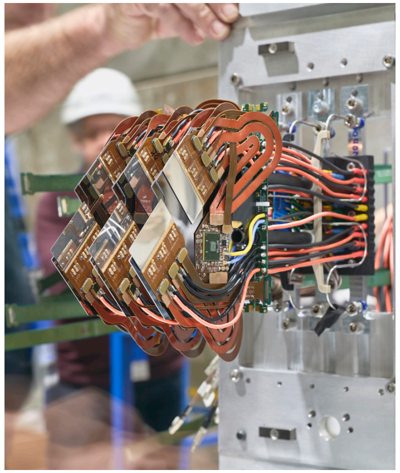
LHCb Vertex (pixel) Locator

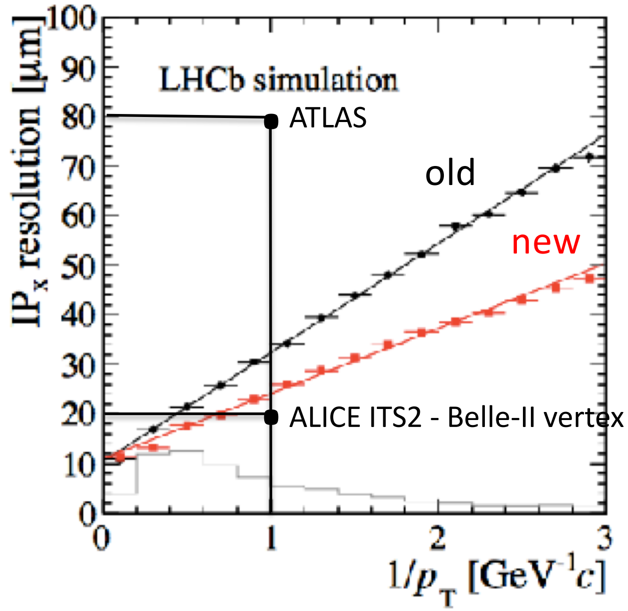


LHCb VELO upgrade for installation during 2020

- 12 disks of 4 modules, inner radius ≃ 4.5 mm
- Planar n-in-p sensors fully depleted up to ≃ kV
- 200 µm thick, 55 x 55 µm^2 pixels, ≃ 10 µm hit resolution
- 120 x 120 µm^2 micro cooling-channel etched in sensor substrate
  - ≃ 1.5% X/X_0 per disk
- Radiation tolerance ≃ 10^{15} 1 MeV neq/cm^2 (T ≃ -20°)



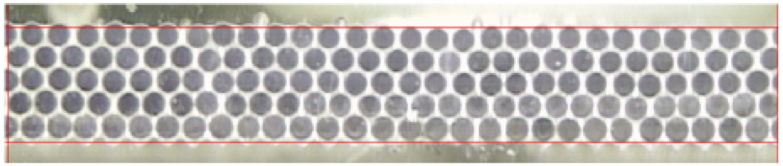


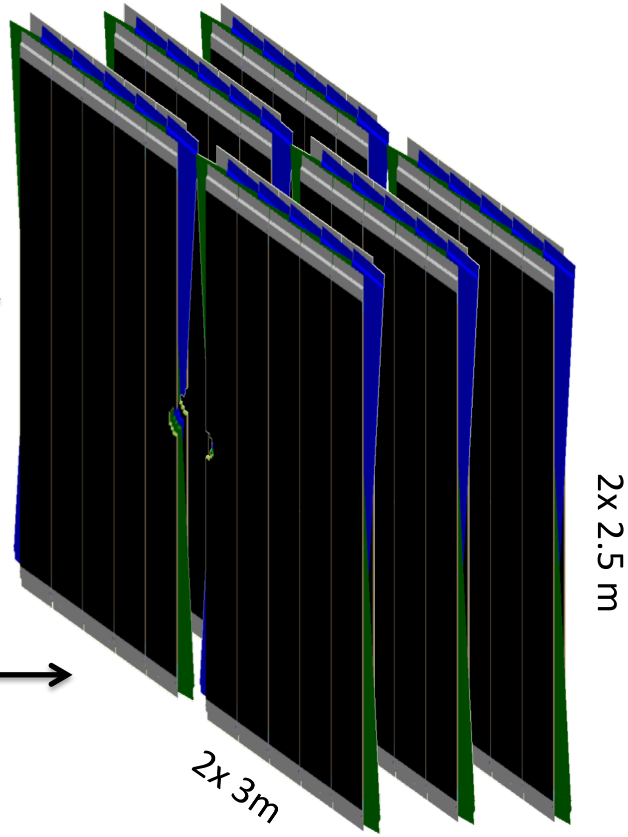


LHCb scintillating Fiber Tracker

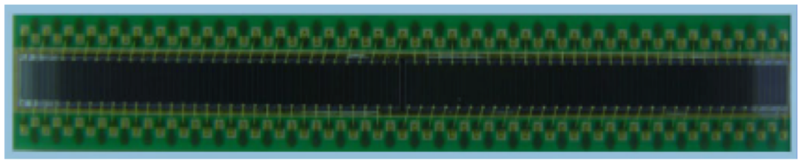
3 stations, each 2.5% X/X0 - 4 plans (X-U-V-X) with ± 5∘ stereo angle - 50-75 µm resolution

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

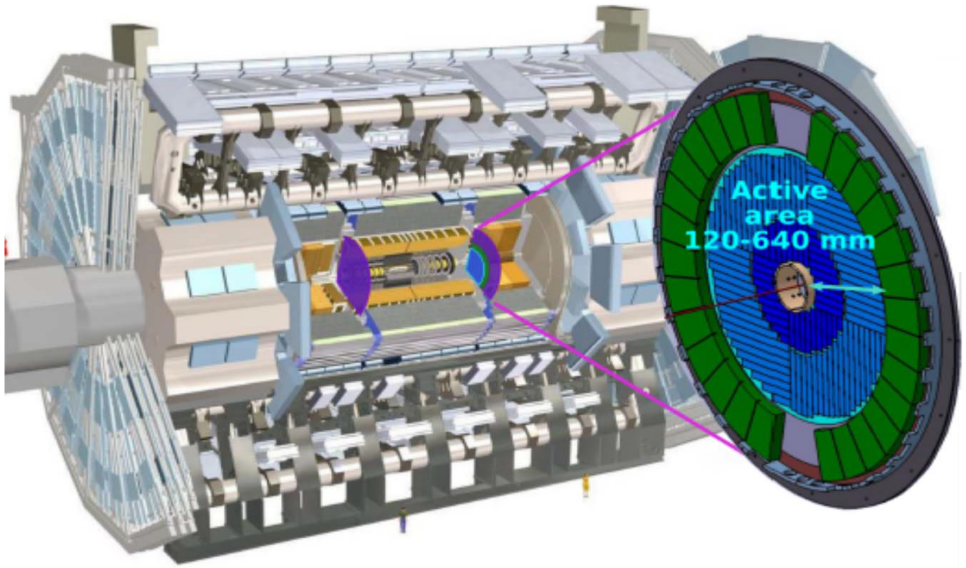




- Readout with 128 SiPM array 250 µm pitch
  - 40°C cooling to sustain $1.2 \cdot 10^{12}$ neq. /cm2



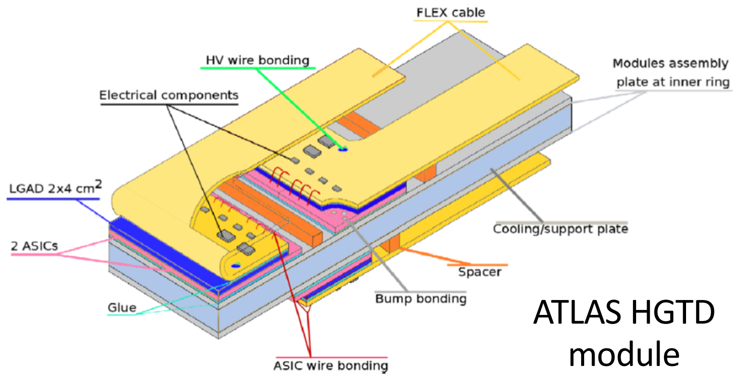
ATLAS High Granularity Timing Detector



Pad size	1x1 mm^2
Detector capacitance	2pF
Total dose in the electronics	500- 600 MRad
Neutron dose in the electronics (n/cm^2)	5 10^{15}
Total power available per area	100 mW/cm^2
Collected charge (1 MIP) for a LGAD gain of 10	4.6fC
Noise from Landau fluctuations	25ps
(preamplifer+discri)	
iome walk contribution	< 10 ps
TDC binning	20 ps
TDC range	1.2ns up to 3ns
Dynamic range wo/wi PreShower	20/600 MIPs

Two double sided layers 2.4 < η < 4 in front of Calorimeter endcap (r_{active} = 12 - 64 cm), z < 75 mm

- 2(3) hits per track for R >(<) 30 cm
  - 30 ps resolution per track after irradiation
- LGADs 1.3 x 1.3 mm^2 pads, 6.3 m^2, 3.54 Mch
- Fluence and TID 4000 fb^{-1}
  - up to 4 x 10^{15} 1 MeV neq/cm^2 and 400 MRad
- Operation at -30°
- Inner ring replaceable



ATLAS HGTD module

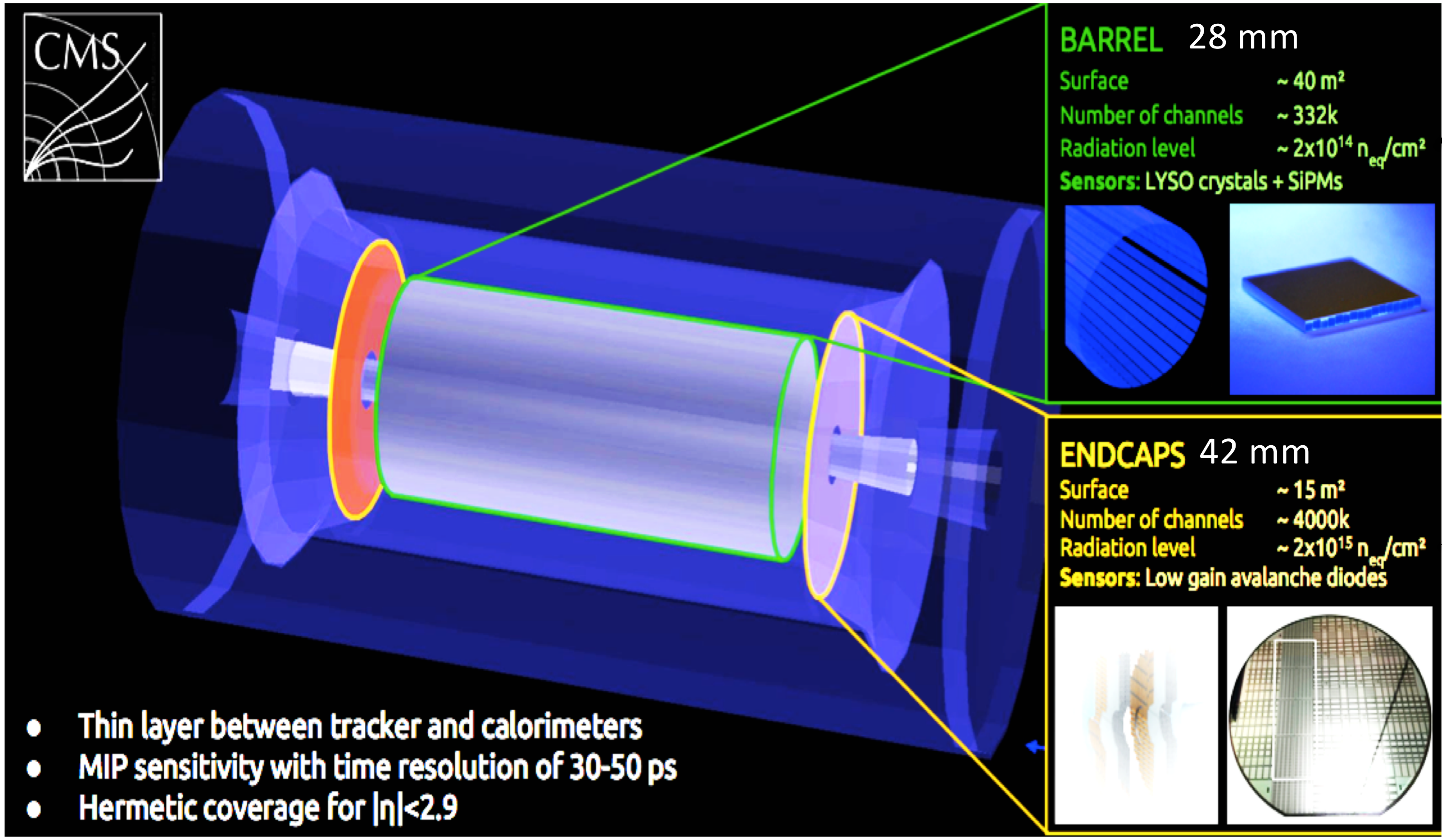
CMS Mip Timing Detector

Barrel layer (28 mm) in Tracker volume

- Lyso bars 56 mm x 3 x 3 mm^2, readout both ends with 2 SiPM 3 x 3 mm^2, 30(40) ps before(after) irradiation

Endcap 2 layers (42 mm each) in front of Calo. Endcap (42 mm), $1.6 < \eta < 3$

- LGAD 1.3 x 1.3 mm^2 pads, 30(40) ps per track before(after) irradiation



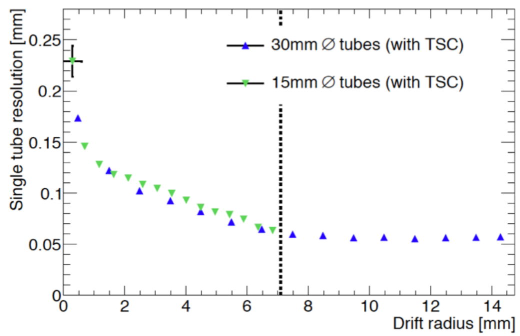
For 3000 fb^{-1}
TID = 2.5 MRad

For 3000 fb^{-1}
TID = 70 MRad

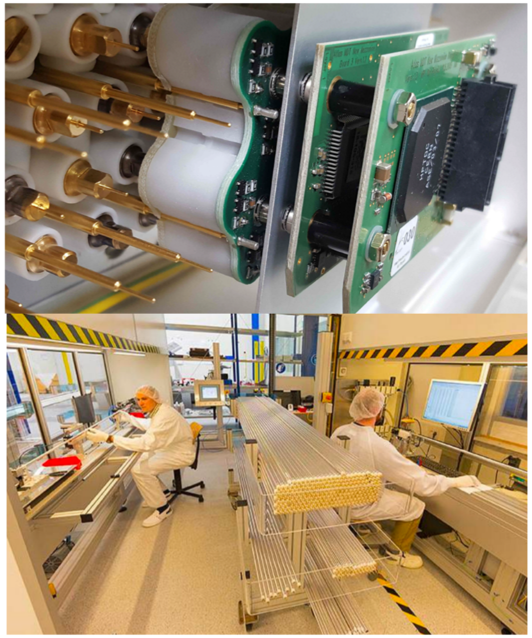
ATLAS muon system upgrades

- Small Wheels
  - Small Thin Gap (2.8 mm) Chambers, shorter strips 2 cm to 3.2 mm, 3 mm pitch, $\sigma \simeq 50$ µm, up to 2 x 1.2 m^2, CO_2:n-pentane (55:45)
  - Resistive strip Micro-Megas (0.5 mm pitch), $\sigma \simeq 80$ µm per layer, largest module 2 x 2.3 m^2 made of 5 PCBs, Ar:CO2 (93:7)
- Small Monitoring Drift Tubes
  - Reduced Φ 30 mm (200 Hz/cm^2) to 15 mm (2 kHz/cm^2), wires 50 µm, $\sigma \simeq 100$ µm, L = 1.6 m, Ar:CO2(93:7)

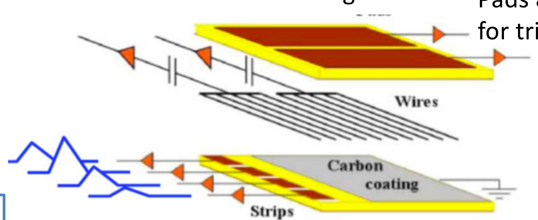
MDT/sMDT resolution

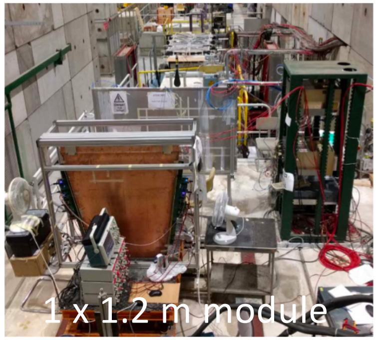


sMDT

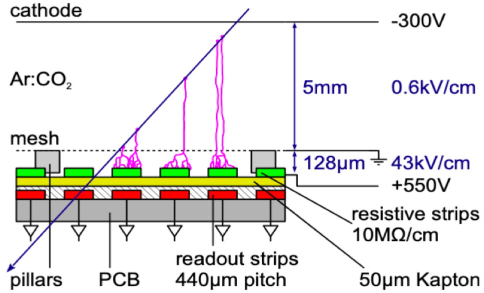


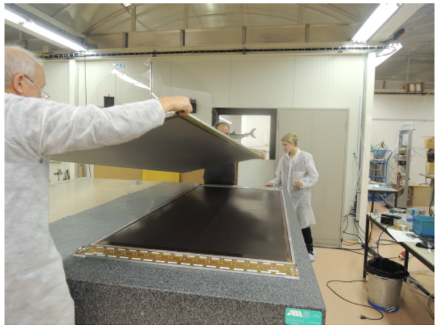
sTGC





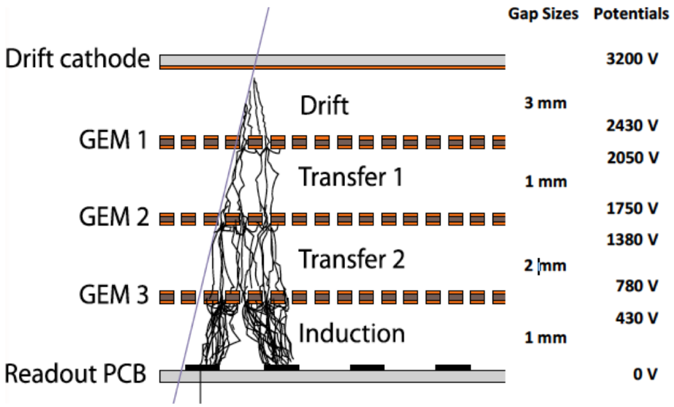
MicroMegas

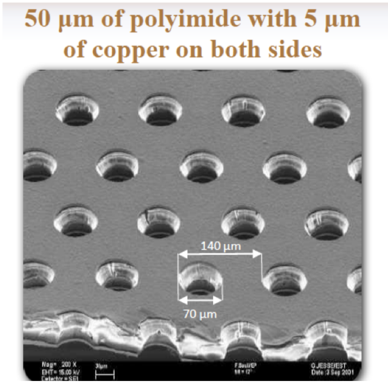




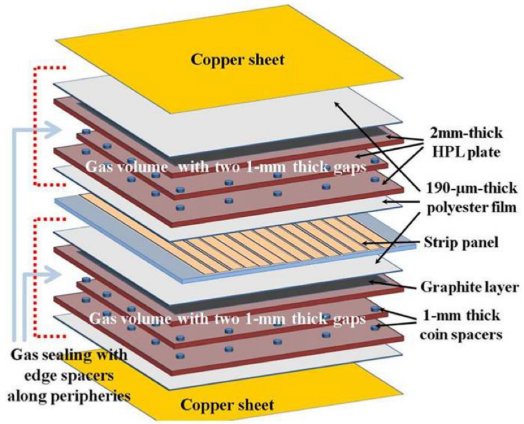
CMS muon systems upgrades

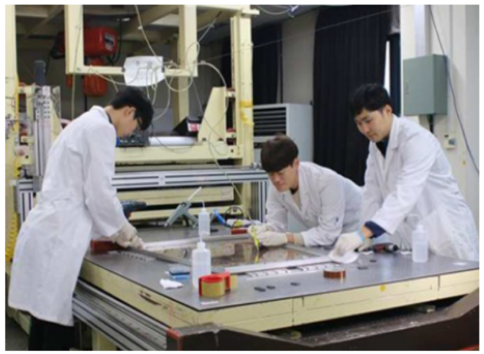
- New GEM stations
  - Triple GEM design, H = 1.8 m x W = 1.2 m wedges in 4 modules largest foil size so far (0.5 x 1.2 m^2)
  - Improved fabrication single mask foil photolithography, foil stretching mechanism
  - PCB with radial strips, pitch from 0.7 mm to 1.6 mm, $\sigma \simeq$ 200 to 450 µm
  - Rate capability up to > 1 MHz/cm^2, time resolution O(10ns),
- New multigap RPC stations
  - Low resistivity Bakelite 1 to 3 10^6 Ω.cm, thinner gap and electrodes 2 mm to 1.4 mm,
  - Φ pitch 1.3° to 1.2°, rate capability few kHz/cm^2, $\sigma \simeq$ 0.3(2) cm ⊥ (//) to strips
  - Front-end electronics with 2 ns time resolution, 2 strip-ends readout for r(η)-coordinate





GEM





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