ATLAS, CMS, LHCb Prospects for the High-Luminosity LHC Era

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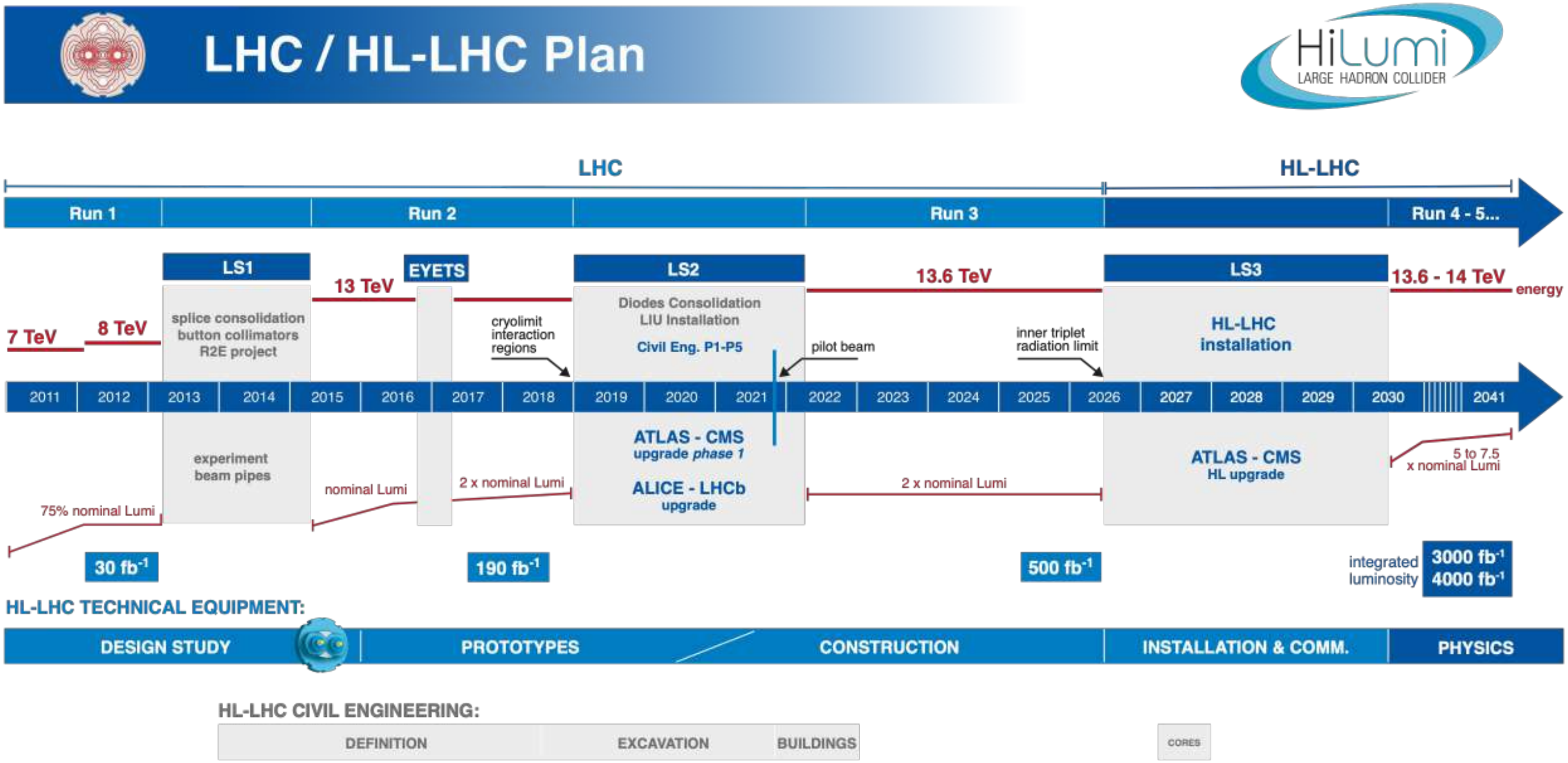
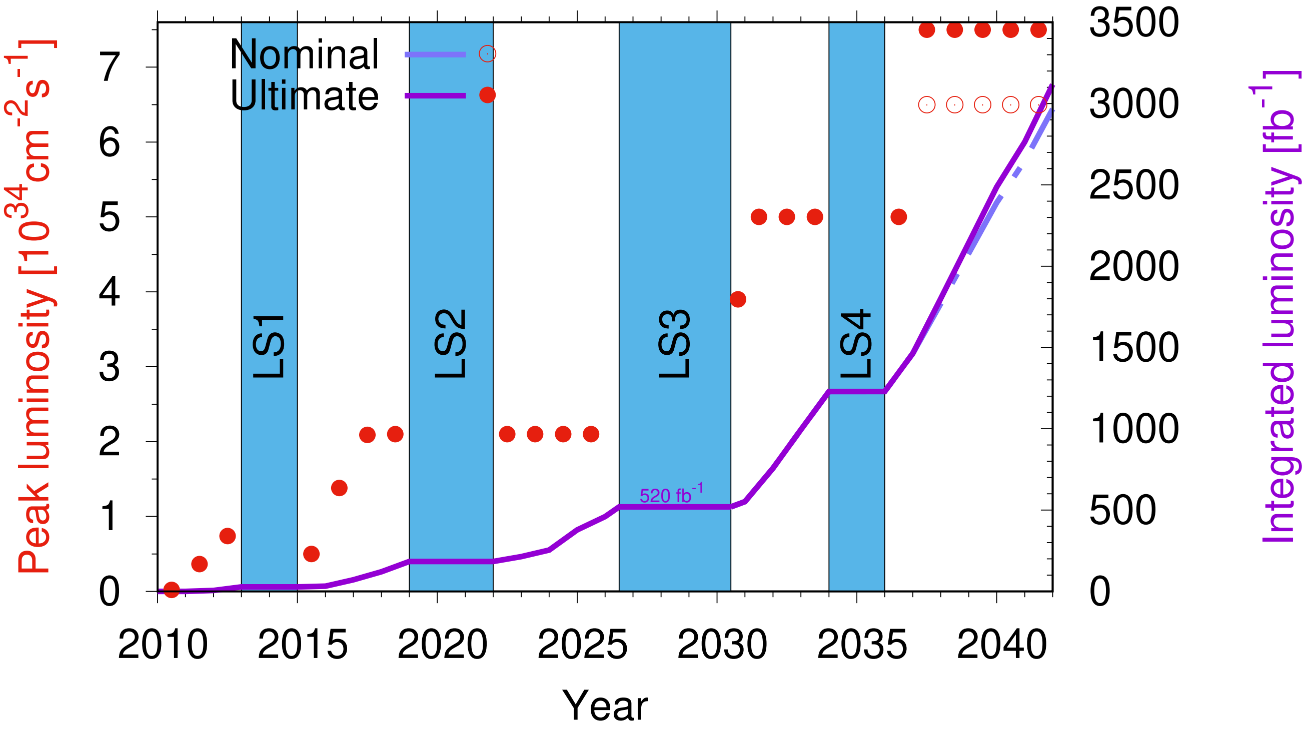
FOR THE ATLAS, CMS AND LHCB COLLABORATIONS

SPRACE-Unesp

The High-Luminosity LHC



HL-LHC Luminosity for ATLAS and CMS



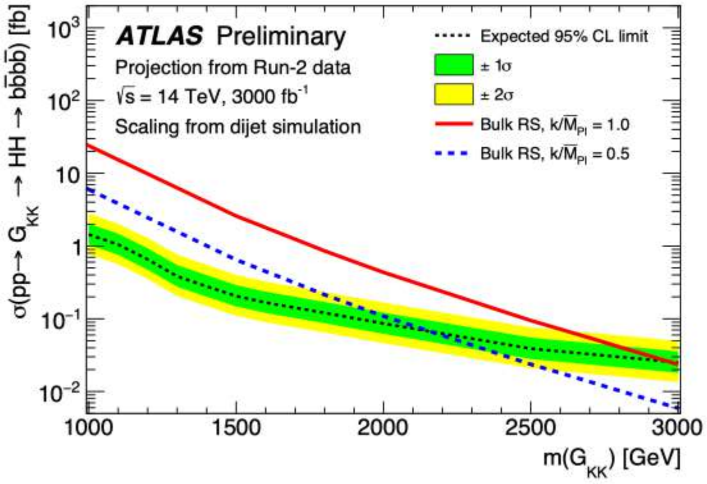
ATLAS/CMS Expectations for the HL-LHC

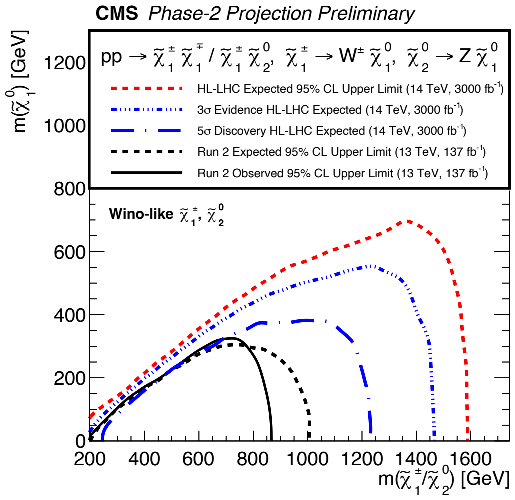
Current limits on BSM

⟶ a rare process

even with 3000 fb^{-1}

- ❑ Full luminosity needed for evidence of new physics





Important role for

precision physics

- ❑ Precise measurements of SM parameters
- ❑ Searches for rare ⟶SM processes (*e.g.* H ⟶ μμ, HH)

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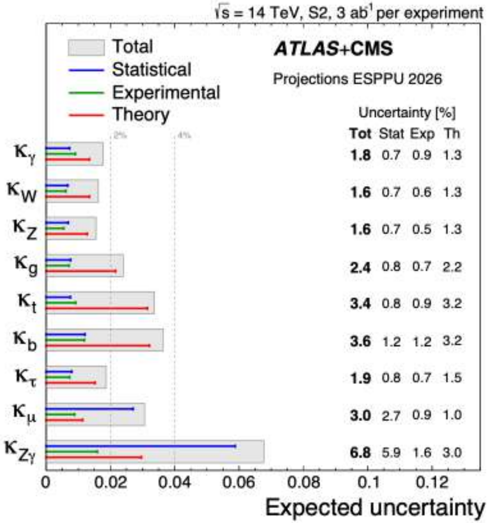
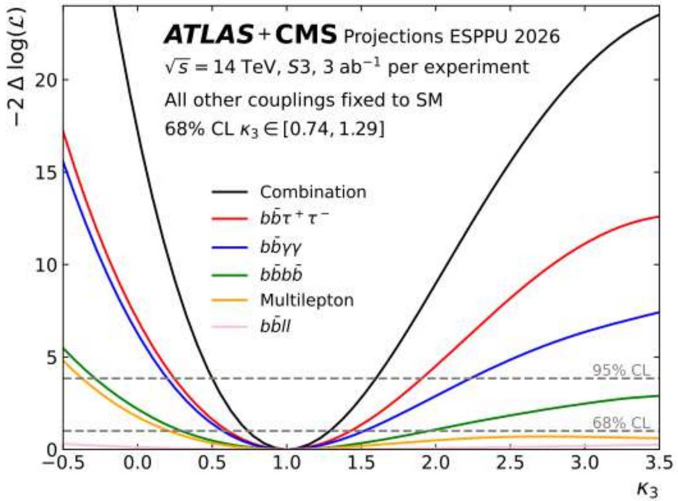




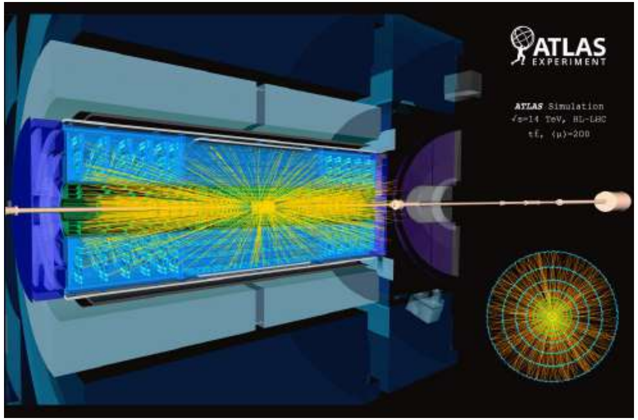
ATLAS/CMS in the High-Luminosity LHC Era

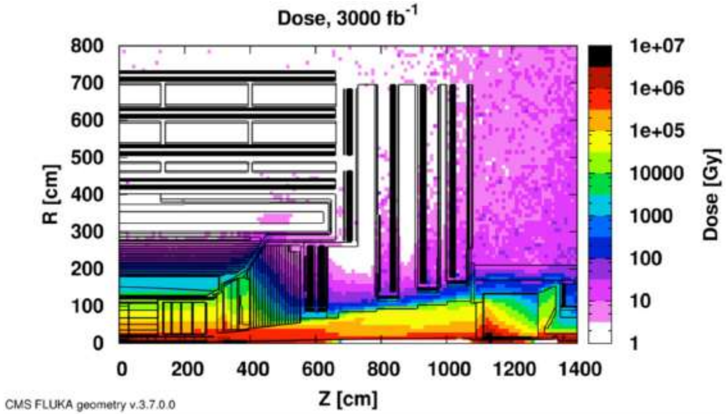
Goal

- Extend the physics programme to the 3000 fb^{-1} integrated luminosity target
- Keep the detector performance
  - Efficiency
  - Resolution
  - Background rejection

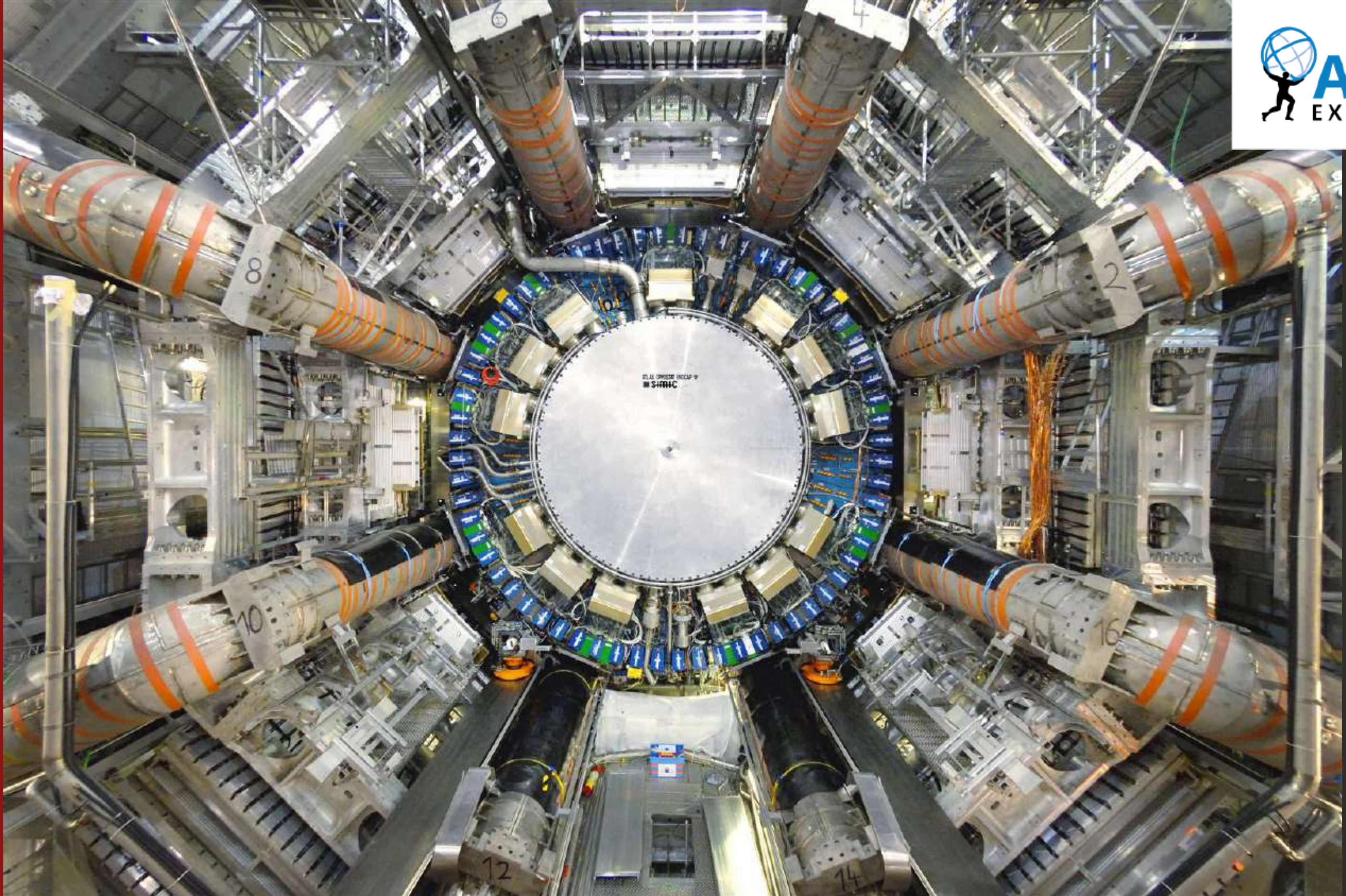
Obstacles

- High instantaneous luminosity (pileup)
  - Improved granularity and timing information
- High integrated luminosity (radiation)
  - Replacement of most affected subsystems
- Huge amount of data (computing and storage)
  - Overhauled Trigger and DAQ systems

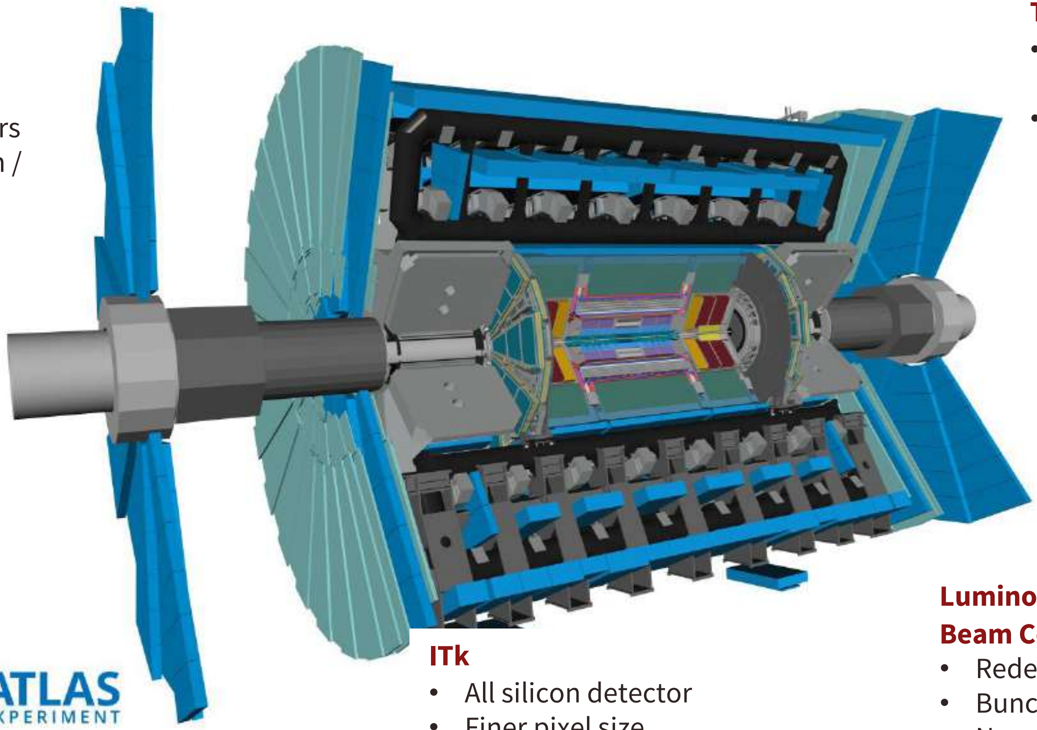




ATLAS EXPERIMENT



ATLAS Upgrade Overview



Muon Spectrometer
- Inner barrel region with new RPC and sMDT detectors
- Improve trigger momentum / efficiency, reduce fakes
- Increased forward (TGC) coverage

LAr and Tile Calorimeter
- Electronics upgrades
- 40 MHz continuous readout with finer segmentation to trigger

ITk
- All silicon detector
- Finer pixel size
- 5 pixel layers + 4 strip layers
- Coverage up to $|\eta| = 4$

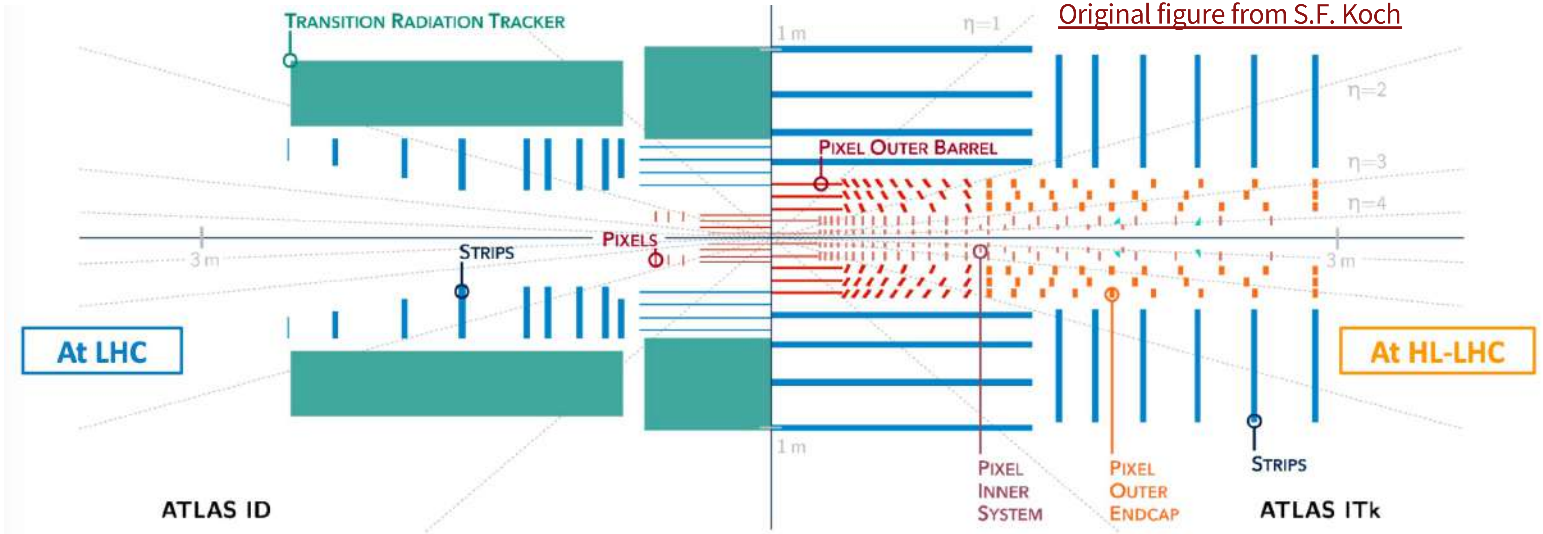
Trigger and Data Acquisition
- First level trigger with 1 MHz output (x10 current)
- High Level Trigger 10 kHz output (x3 current)

HGTD
- 30-50 ps time resolution
- $2.4 < |\eta| < 4$
- Pileup suppression and per-bunch luminosity measurement

Luminosity Detectors and Beam Conditions Monitors
- Redesigned LUCID
- Bunch-by-bunch lumi from HGTD
- New 3D-diamond-based beam conditions monitor
- New pixel luminosity ring

ITk – A New Tracking Detector

Original figure from S.F. Koch



ITk will be full silicon detector with extended coverage up to |η| = 4.0

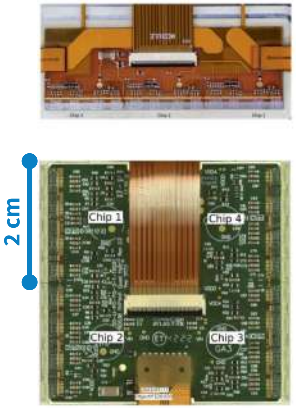
Pixel layers (Current ⟶ ITk)

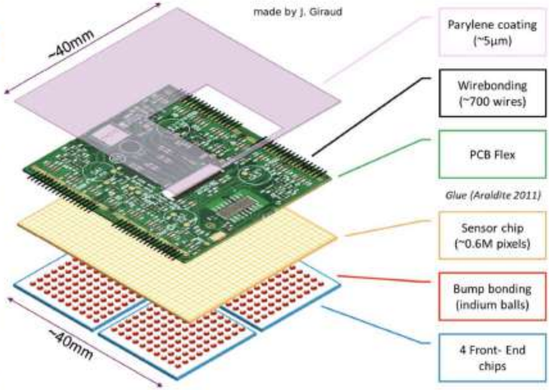
- ~2k modules ⟶ ~9k modules
- 90M channels ⟶ 5G channels
- 1.7 m^2 ⟶ 13 m^2

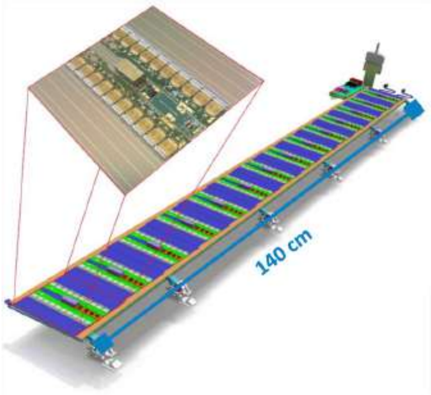
Strip layers (Current ⟶ ITk)

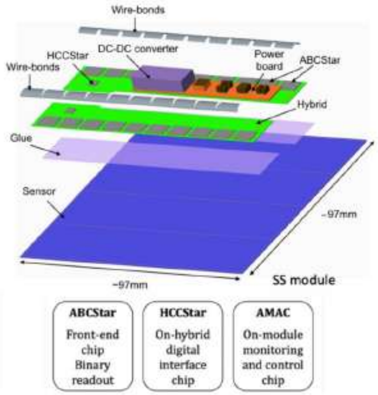
- ~4k modules ⟶ ~18k modules,
- 6M channels ⟶ 60M channels,
- 61 m^2 ⟶ 165 m^2

ITk – Modules

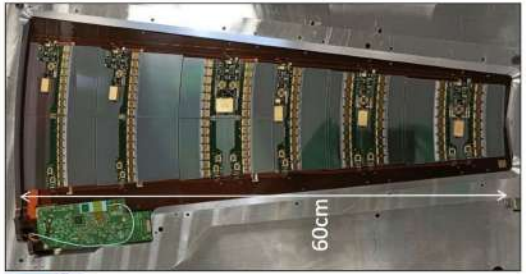


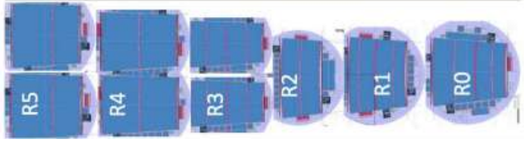






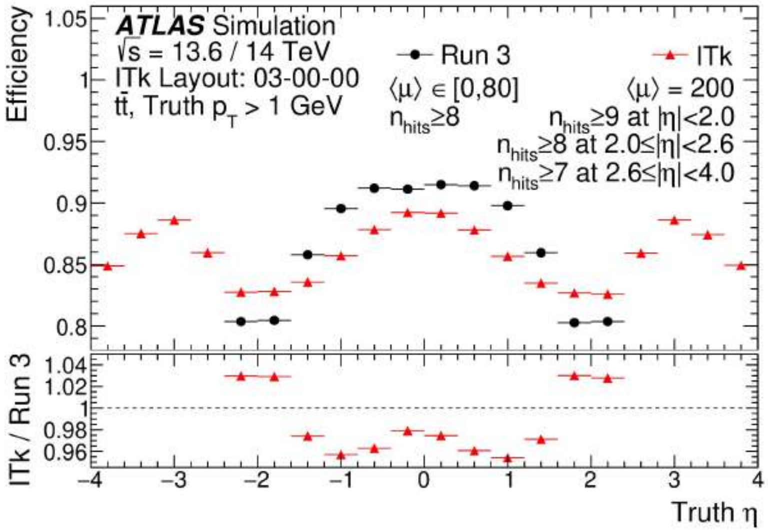
System	Layer	Region	Sensor / Pixel pitch	Module type	Design fluence [neq/cm²] (SF incl., 4000 fb⁻¹)
		ITk Pixel Detector			
Inner system (replaceable ~2000 fb⁻¹)	L0	Innermost barrel + rings 396 triplets	3D 25×100 µm² (barrel) 3D 50×50 µm² (rings)	Triplet (3 chips/mod)	1.7×10^{16} Simulated (no SF): 9.2×10^{15} at 2000 fb⁻¹
	L1	Inner barrel + rings 1160 quad modules	50×50 µm² Planar n-in-p, 100 µm bulk	Quad (4 chips/mod)	
Outer system	L2-L4	Outer barrel (3 layers) + inclined rings + endcap 7106 quad modules	50×50 µm² Planar n-in-p, 150 µm bulk	Quad (4 chips/mod)	5×10^{15} Simulated: 2.3×10^{15} barrel 3.1×10^{15} endcap
		ITk Strip Detector			
Barrel	L0-L1	392 staves, 28 mod/stave	75.5 µm pitch, strip 24.1 mm, 320 µm n-in-p Si	Short Strip (SS)	$\leq1.6\times10^{15}$ Max across strip system SF = 1.5 included
	L2-L3		75.5 µm pitch, strip 48.3 mm, 320 µm n-in-p Si	Long Strip (LS)	
Endcap	R0-R5	6 disks/side , 32 petals/disk, 12 mod/petal	70-80 µm pitch, strip 15-60 mm, 320 µm n-in-p Si	Petal (R0-R5)	

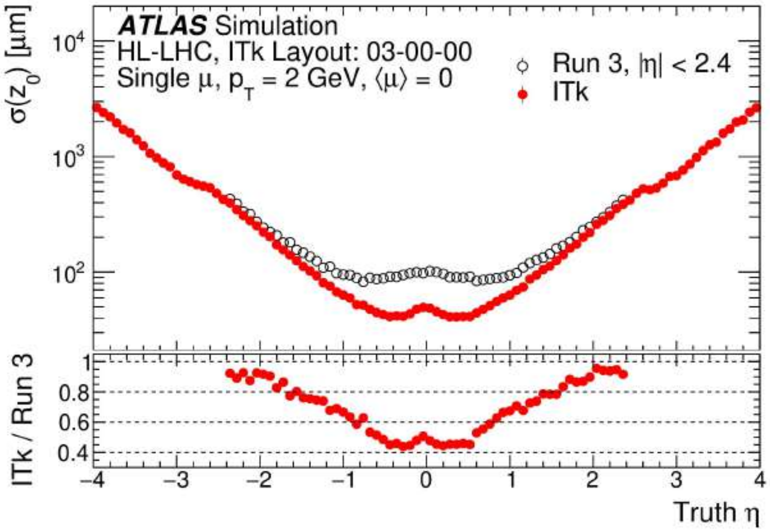




ATL-ITK-PROC-2024-018

ITk – Expected Performance





Tracking efficiency performance remains similar to that achieved in much milder pile-up conditions

Tracking acceptance is extended further into the forward region

Significant improvement in the track parameter resolution thanks to the finer sensor pitch

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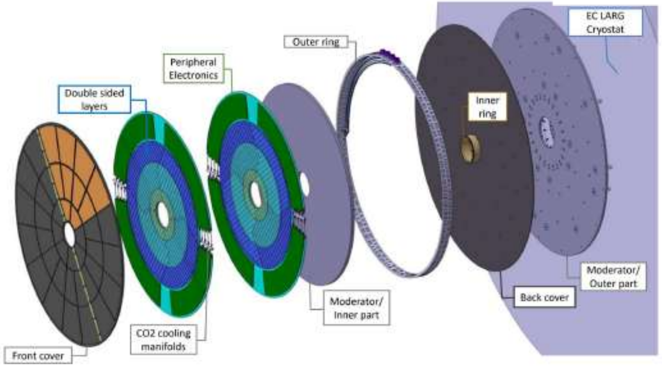
High Granularity Timing Detector (HGTD)

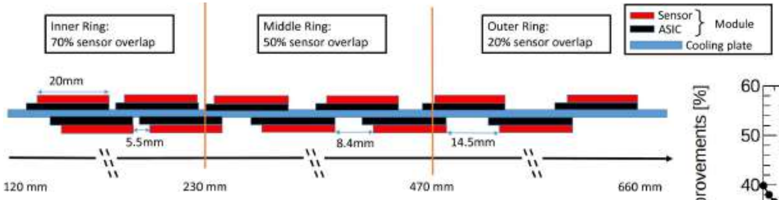
HGTD is designed to provide precise timing:

- 30 – 50 ps/track up to a fluence 2.5 x 10^{15} n_{eq}/cm^2
- Bunch-by-bunch luminosity measurement



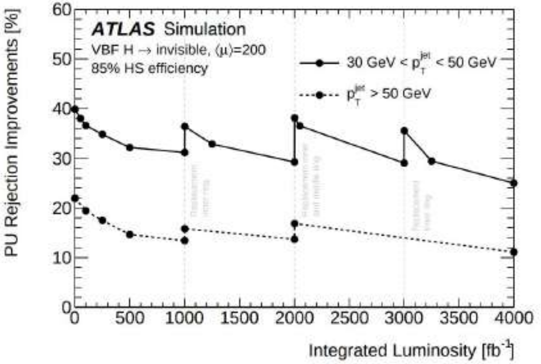
Two double-sided disk per endcap at ±3.5 m from the interaction point and 2.4 < |η| < 4

Radius: 120 mm < r < 640 mm

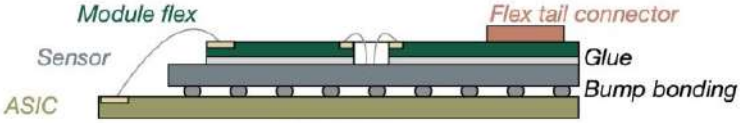


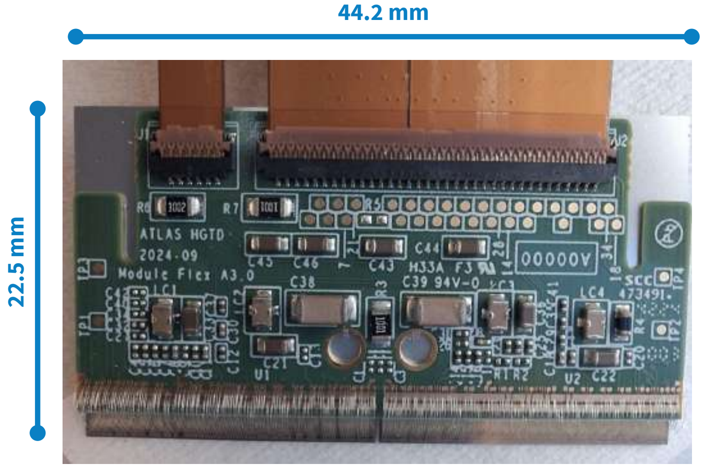
Total thickness of HGTD: 7.5 cm + 5cm moderator

- Massive engineering challenge



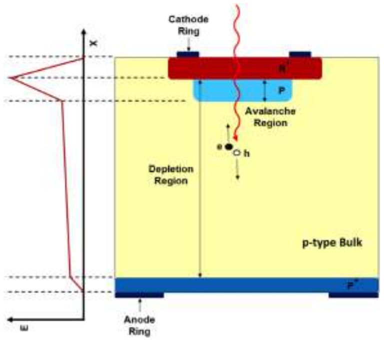
HGTD – Modules

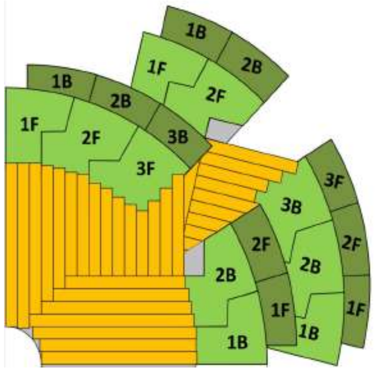




8032 modules

- 2 LGAD Sensors (50 µm active thickness): 2 cm x 2 cm 15x15 pads of 1.3x1.3 mm^2
- 2 ALTIROC ASICs 15x15 channels
- Module flex PCB

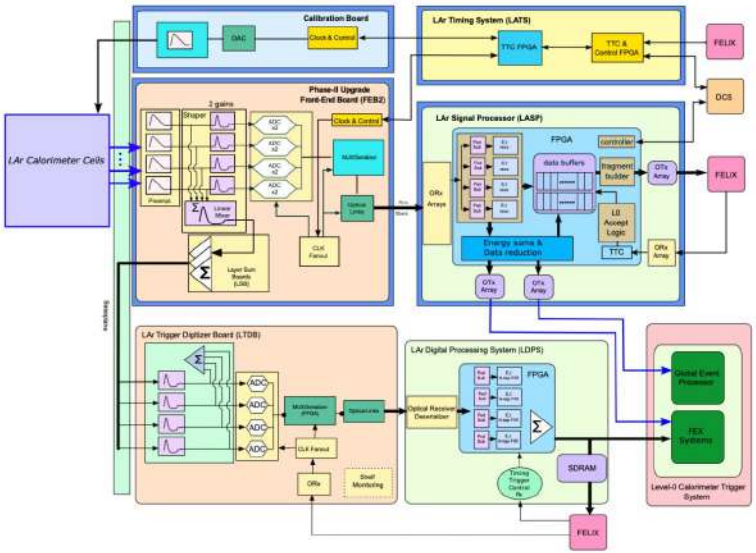




Liquid Argon (LAr) Calorimeter

The LAr calorimeters remains unchanged,
but the readout electronics will be replaced.

New electronic boards designed to digitize and
transmit all data off-detector at 40 MHz for processing.



Board	Count	Function
FEB2 Front-End Board 2	1524	Amplify, shape, digitize and transmit analog signals off-detector at 40 MHz
Calibration board	122	Inject known calibration pulses to calibrate the readout chain
LATS Timing & Control	30	Distribute clocks and control signals to all front-end boards (high fanout)
LASP Digital Processor	278	Energy and timing processing at 40 MHz for DAQ and Trigger (2 large FPGAs/board)

Tile Calorimeter

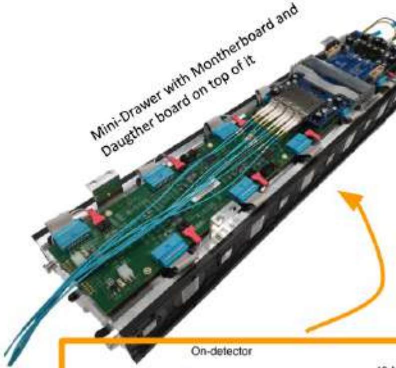
Full replacement of readout electronics to readout of full granularity at 40 MHz for trigger signal

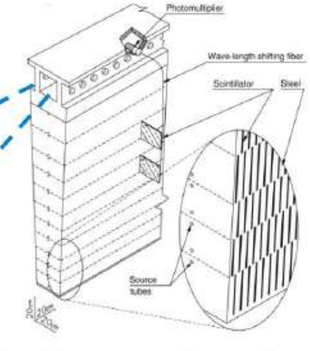
On-detector electronics

- About 10% PMTs will be exchanged
- New mechanical structure (Mini-Drawers) to ease maintenance
  - FE board (FENICS) shape and amplify PMT signals (x2 gains)
  - Main Boards digitises the signal, communicates between FENICS and Daughterboard
  - Daughter Boards: serialise digital data and send to off detector

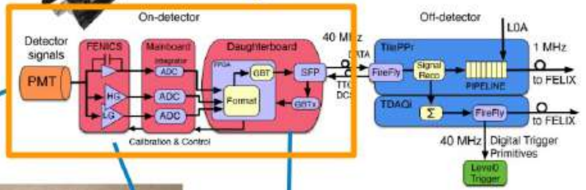
Off-detector electronics

- Pre-processor (Ppr) boards compute energy deposits, provide data to Trigger and DAQ





Tile Calorimeter wedge module



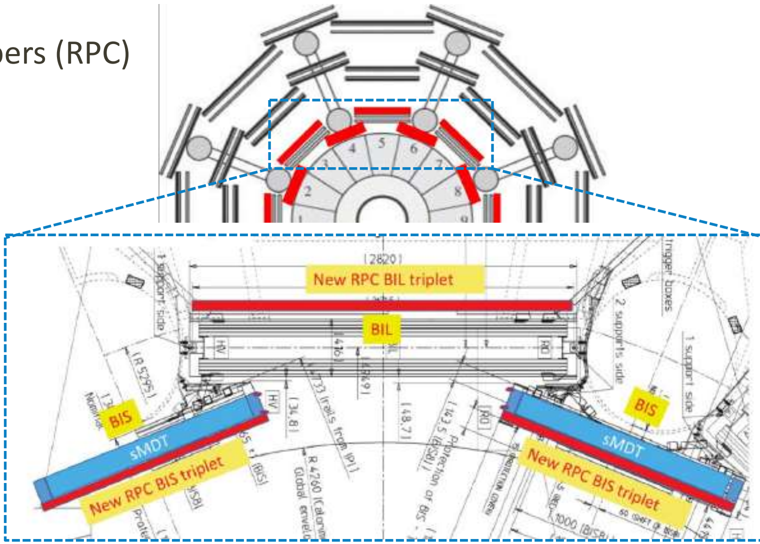
PMT and FENICS card

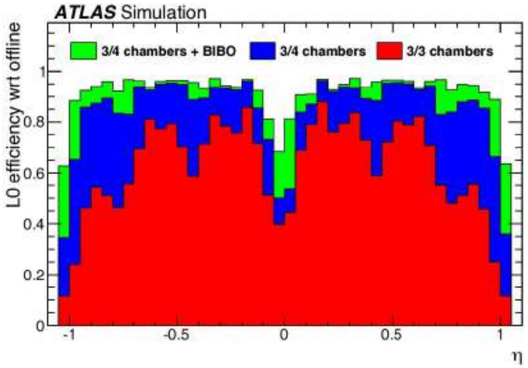
Daughter Board v6.4

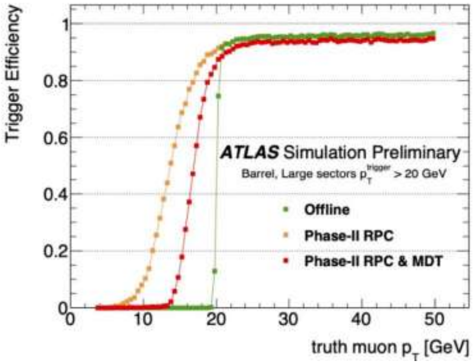
Muon System

Several projects aiming mostly to improve trigger efficiency

- ❑ Installation of small-diameter Monitored Drift Tubes (MDTs) (from 30 to 15 mm)
  - Gain of space allow to insert additional Resistive Plate Chambers (RPC)
  - MDT information will be included in the Level-0 muon trigger
  - New triplet RPC with 1 mm gas gap singlet (BIL 130 +BIS 96)
- ❑ Replacement of Thin Gap Chambers (TGCs) doublets with triplet chambers in the barrel–endcap transition region
- ❑ Most of the readout electronics will be exchanged to cope with new TDAQ requirements







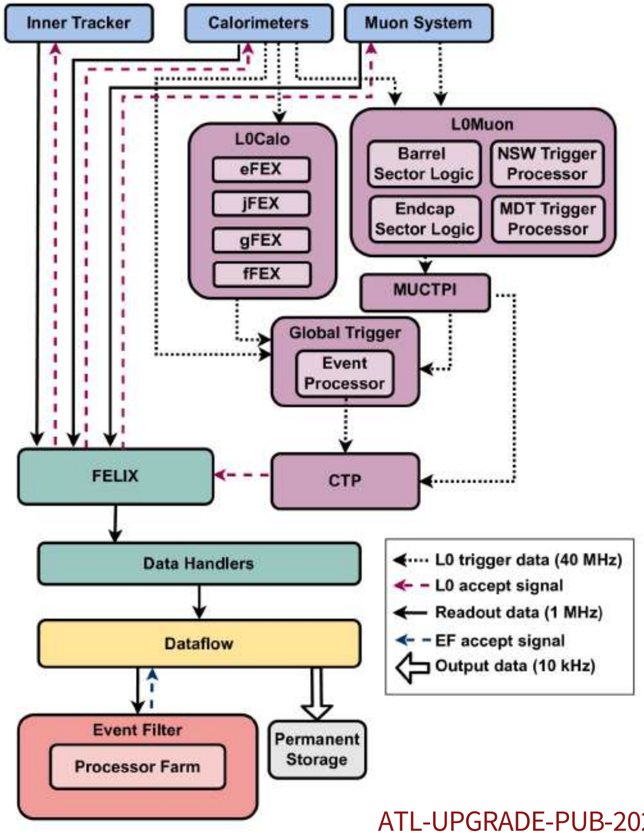
New RPC increase barrel trigger acceptance from ~78% to ~96%

The inclusion of MDT improves the trigger turn-on curve

TDAQ Upgrade

ATLAS TDAQ system is composed of two systems:

- Level 0 Trigger system
  - Based on calorimeters and muon system signals, send trigger to all sub-detectors
  - 40 MHz input and 1 MHz output (Run 3: ~100 kHz)
- Event Filter
  - Based on all sub-detector signals, filter event to be recorded into permanent storage
  - 1 MHz input and 10 kHz output (Run 3: 3 kHz)



ATL-UPGRADE-PUB-2025-001

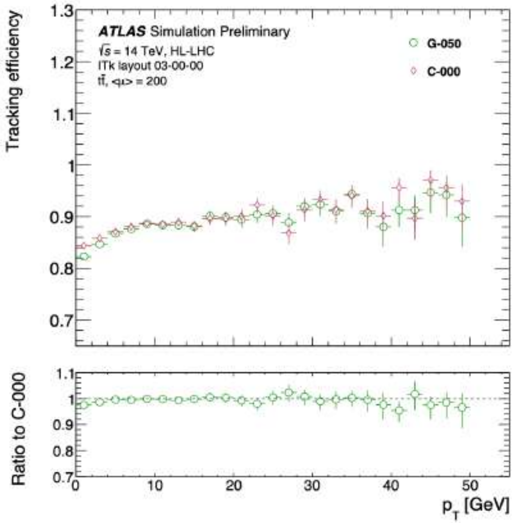
Event Filter Upgrade

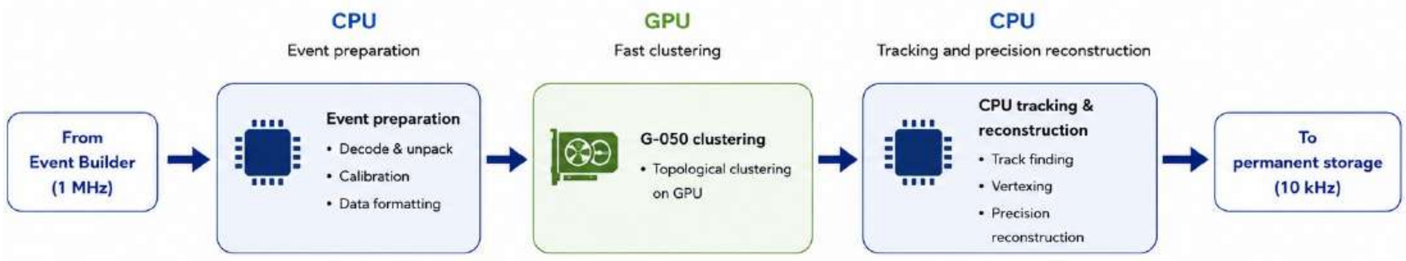
Second-stage event selection processing farm for event reconstruction

Heterogeneous CPU/GPU architecture adopted for HL-LHC

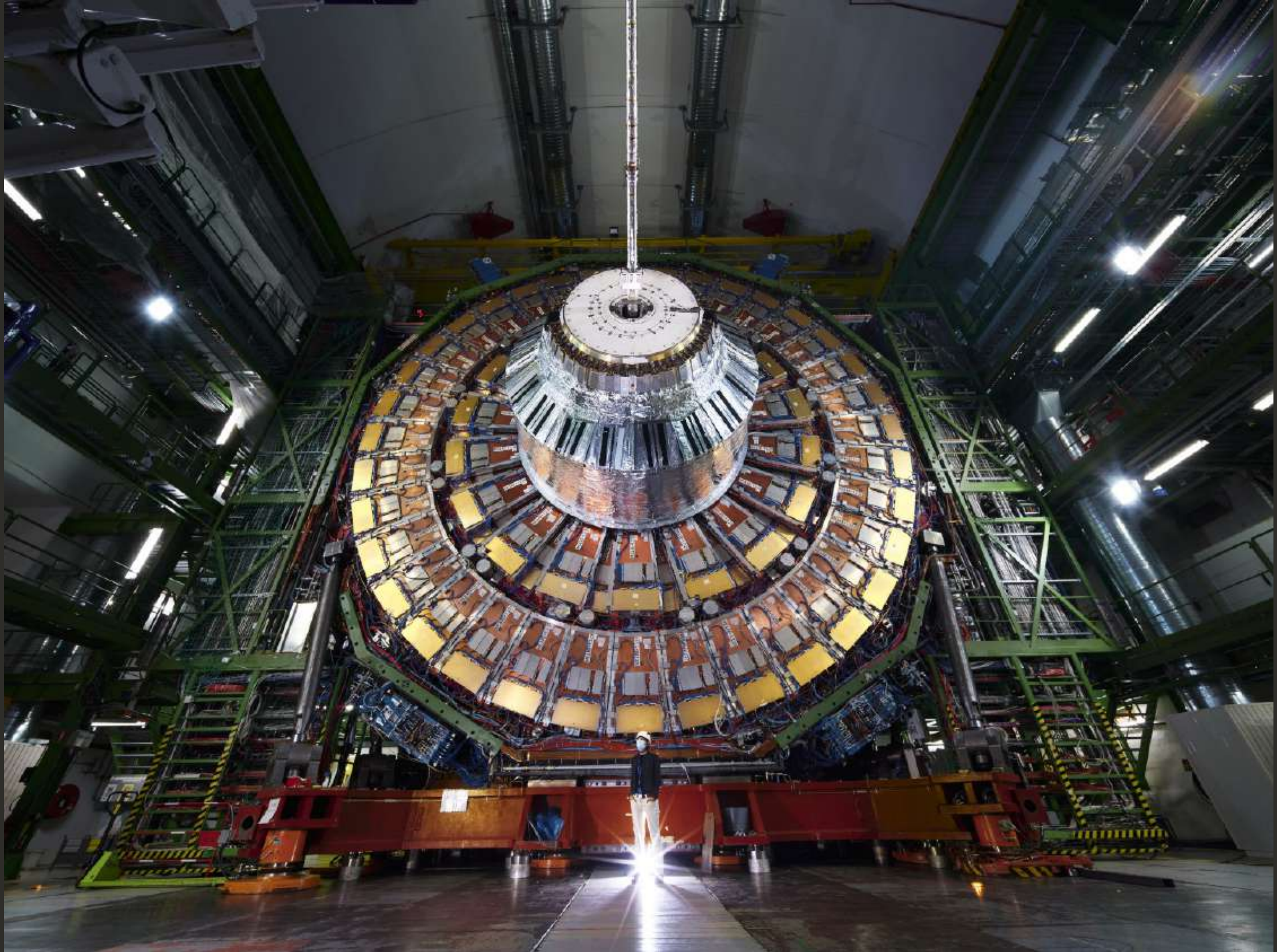
GPU-accelerated tracking efficiency comparable to offline reconstruction

GPU-accelerated tracking achieves < 100 ms / event

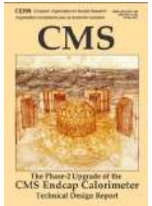




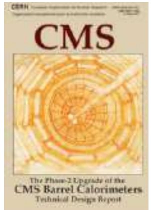
CMS



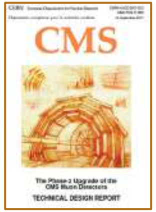
CMS Phase-2 Upgrade Overview



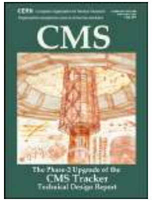
Endcap Calorimeter
- 3D showers + precise timing
- Si, Scint+SiPM in Pb/W-SS



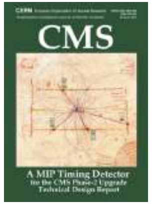
Barrel Calorimeters
- ECAL readout at 40 MHz w/ precise timing at 30 GeV
- ECAL/HCAL new back-end boards



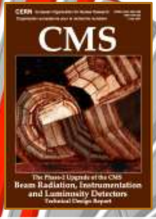
Muon Systems
- DT/CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended to $\eta \simeq 3$



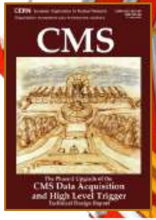
Tracker
- Si-Strip/Pixels increased granularity
- Tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

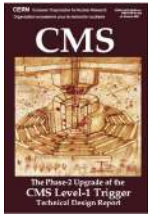


MIP Timing Detector
- Precision timing with:
- - Barrel layer: Crystals + SiPMs
- - Endcap layer: Low Gain Avalanche Diodes



Beam Rad. Instr. and Lumi
- Beam abort and timing
- Beam-induced background
- Bunch-by-bunch luminosity
- Radiation monitoring

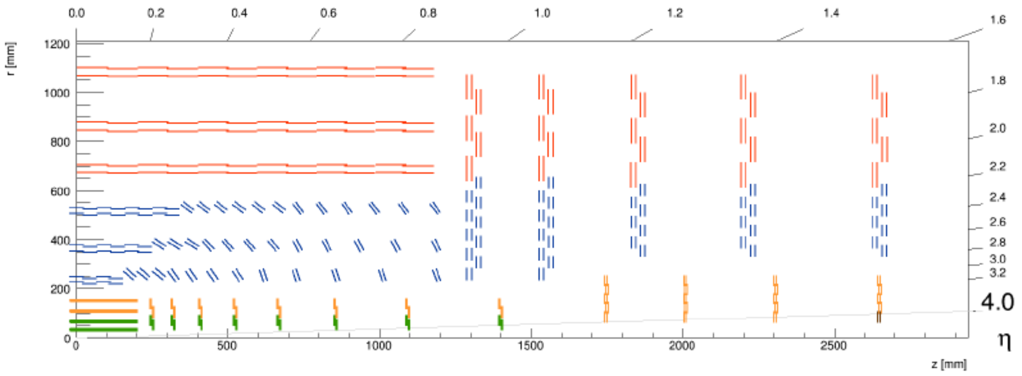


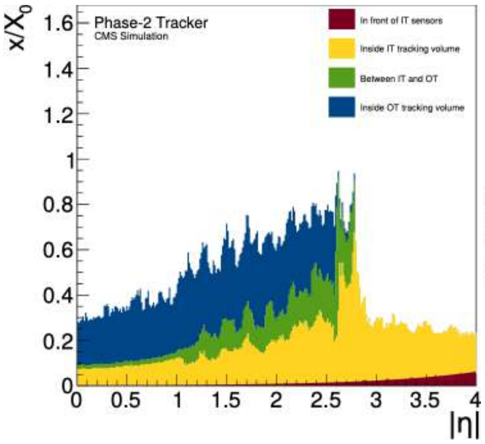


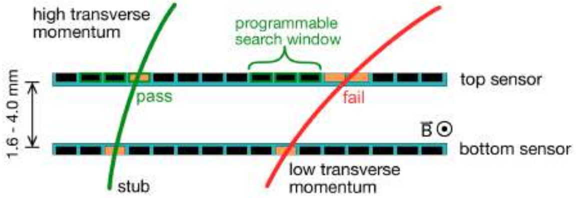
L1-Trigger
- Tracks in L1-Trigger at 40 MHz
- PFlow selection
- 750 kHz L1

DAQ and High-Level Trigger
- Full optical readout
- Event network 60 Tb/s
- Heterogeneous architecture
- 7.5 kHz HLT

Phase-2 CMS Tracker







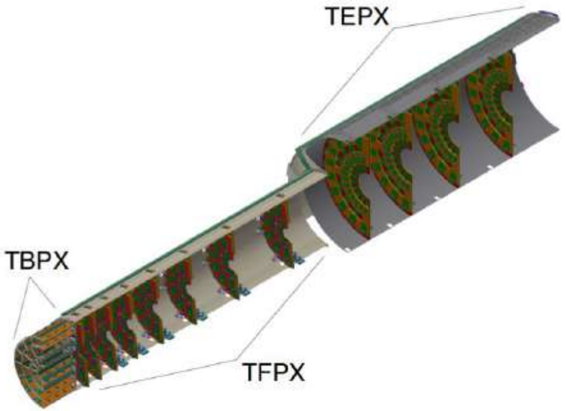
Requirements

- Radiation resistance
  - Max fluence up to O(10^{16}) n_{eq}/cm^2
- Increased granularity
  - ~1200 tracks / unit of η
- Reduced material
  - Preserve calorimetric resolution
- Contribution to the L1 trigger
  - Outer Tracker: p_T modules ⟶ stubs compatible with tracks p_T > 2 GeV
- Extended acceptance: |η| < 4.0

Phase-2 Tracker Geometry and Parameters

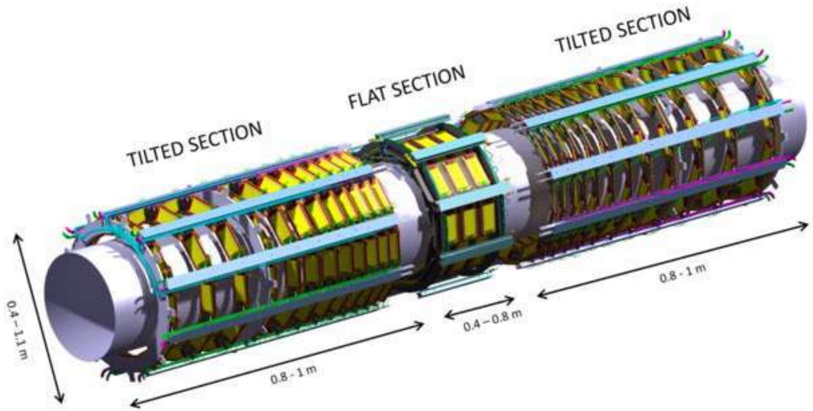
Inner Tracker

- 4 barrel layers,
- 8 small disks, 4 large discs per side
- Pixel size: 25 x 100 μm^2
- 2 x 10^9 channels



Outer Tracker

- 6 barrel layers
- 5 discs per side
- 9.5 million channels
- 44M strips + 174M macropixels



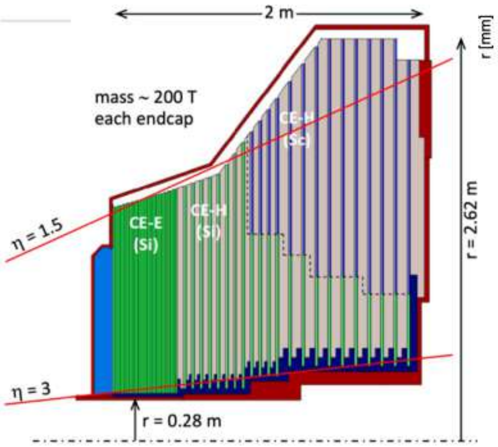
High-Granularity Calorimeter (HGCAL)

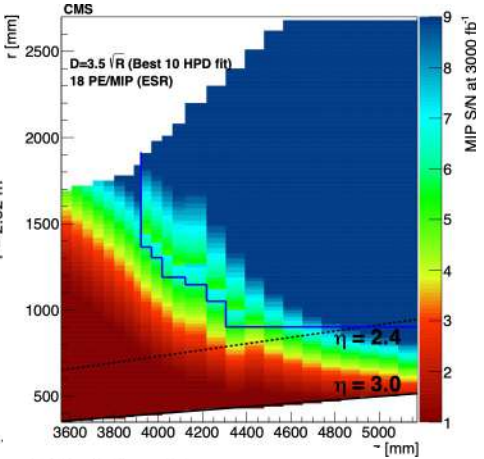
Requirements

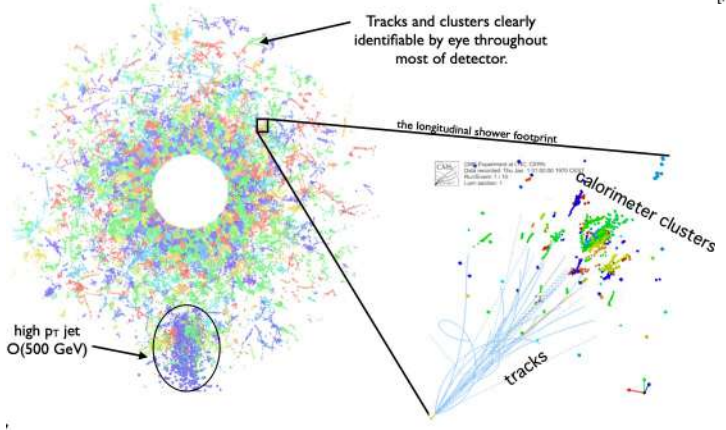
- ❑ Radiation tolerance
- ❑ Dense calorimeter
  - ▪ Shower lateral compactness
- ❑ Fine lateral/longitudinal granularity
- ❑ Precision time measurement of the showers
  - ▪ Resolution: 20 ps / channel
- ❑ Contribution to the L1 trigger

Sections

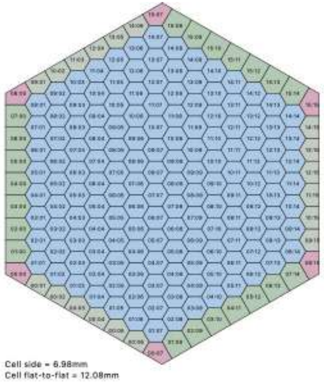
- ❑ Electromagnetic calorimeter (CE-E)
  - ▪ Si, Cu & CuW & Pb absorbers,
  - ▪ 26 layers, 27.7 X_0 and ~1.5 λ
- ❑ Hadronic calorimeter (CE-H)
  - ▪ Si & Scintillator, stainless steel & Cu absorbers
  - ▪ 21 (8+13) layers, ~8.5 λ



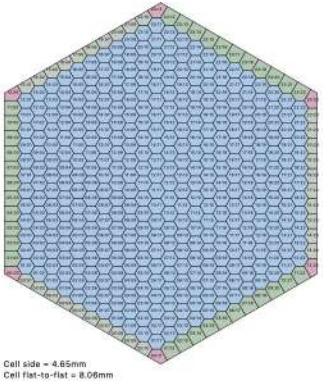




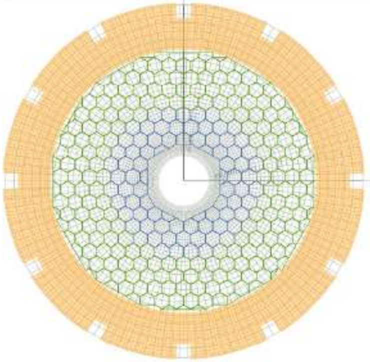
HGCAL Geometry and Parameters



(a) Low density Silicon sensors



(b) High density Silicon sensors



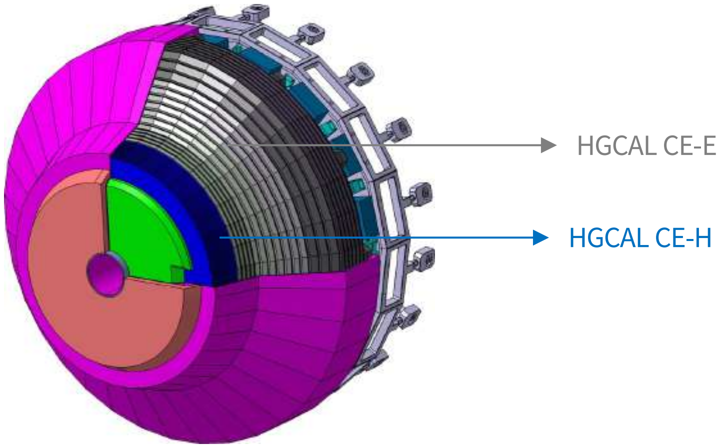
(c) Layout of a layer(38) with silicon and scintillator sensors

Sensors

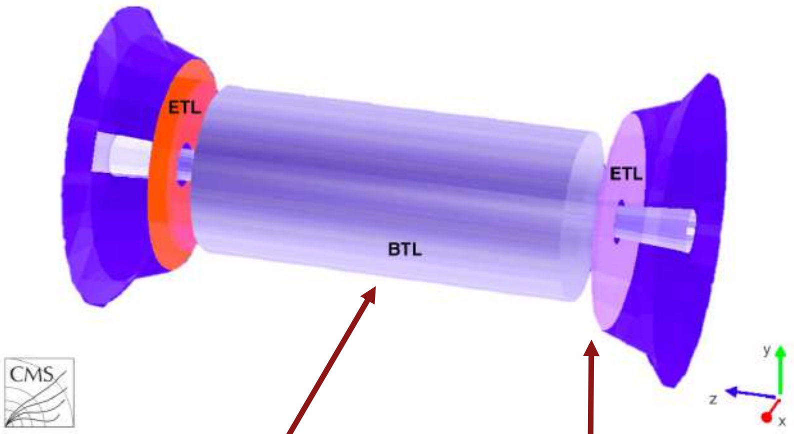
- ❑ Silicon (120/200/300 μm)
  - Total 620 m^2
  - $0.5 – 1.0\ cm^2 \Rightarrow 6M$ channels
- ❑ Plastic scintillators with SiPM readout
  - Total 400 m^2
  - $4 – 30\ cm^2 \Rightarrow 240k$ channels

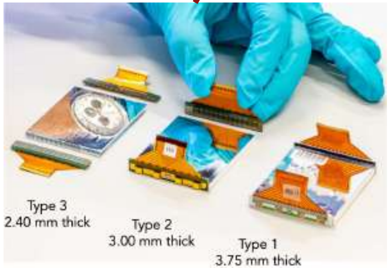
Intrinsic timing capabilities

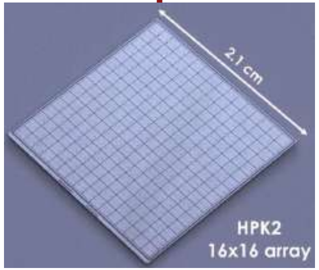
- ❑ ~25 ps resolution



Phase-2 MIP Timing Detector (MTD)







Measure the production time of minimum ionizing particles

- Longitudinal spread of bunches
- Interactions in a bunch crossing spread with rms ~200 ps

Motivations

- Pileup mitigation
- Searches for beyond the standard model
  - Delayed particles
  - Time-of-flight of heavy stable charged particles (HSCPs)
- Particle identification

	Barrel Timing Layer (BTL)	Endcap Timing Layer (ETL)
Technology	LYSO crystal bars (with SiPM readout)	LGADs
Coverage in $\lvert\eta\rvert$	< 1.45	1.6-3.0
Surface area (m^2)	~38	~14
No. channels	332k	~8.5M
Fluence at 4 ab^{-1} (n_{eq}/cm^2)	2×10^{14}	2×10^{15} max

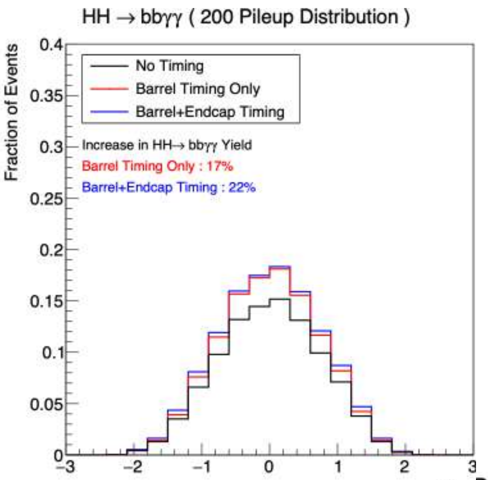
MTD Performance

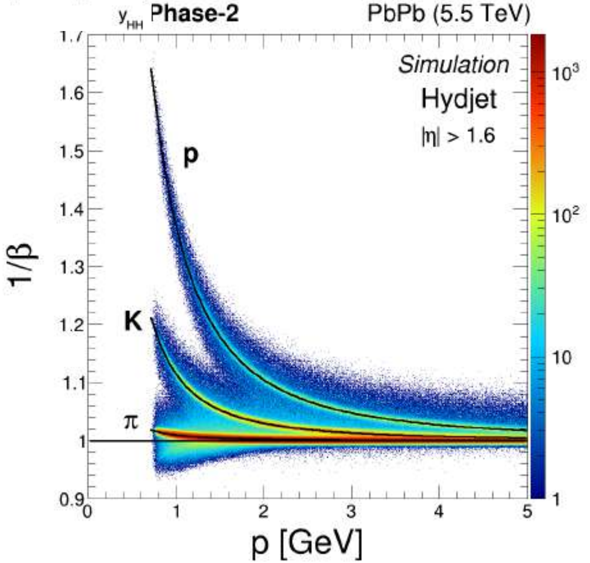
Timing resolution

- 30 – 60 ps in the barrel
- 35 ps per track in the endcap

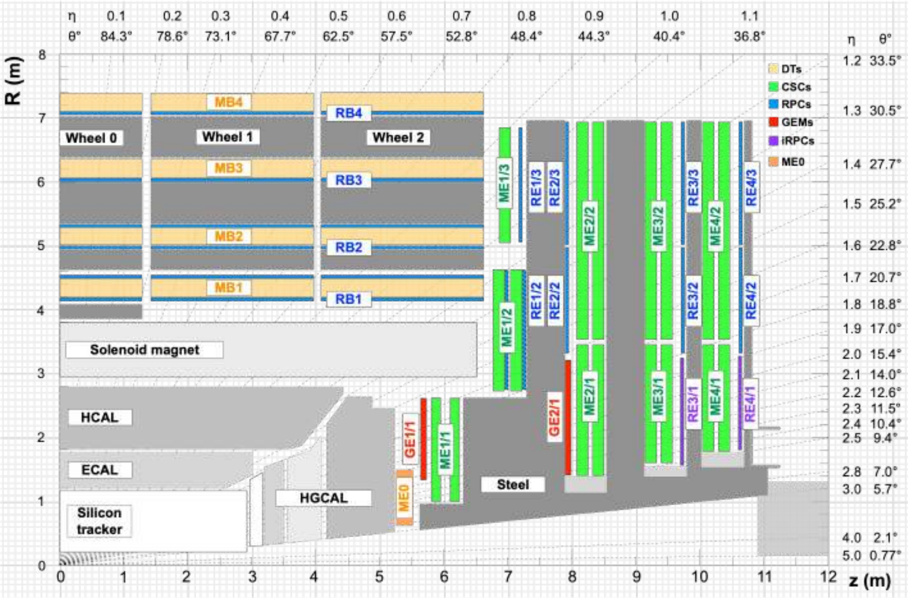
Impact on physics

- 10 – 12% improvement in p_T^{miss} resolution
  - H ⟶ ττ, BSM searches
- HH production: +20% signal yield
- PID for heavy ion physics





Phase-2 Muon Detector



Existing DT, CSC, and RPC detectors

- Upgraded electronics for HL-LHC conditions

Enhanced forward muons

- iRPC: RE3/1 and RE4/1
  - Short electrode recovery
  - Reduced total charge discharge
- GEM detectors: GE1/1 (already in) and GE2/1
  - Improved L1 μ trigger in endcap
- ME0 detector
  - Muon coverage to |η| = 2.8:

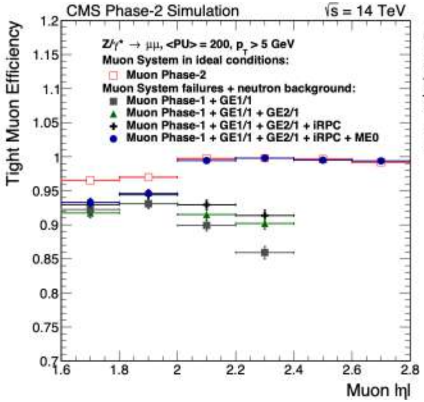
Phase-2 Muon Performance

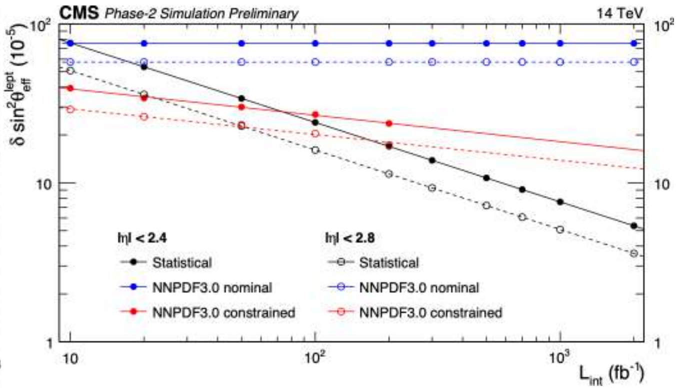
Muon trigger & reconstruction

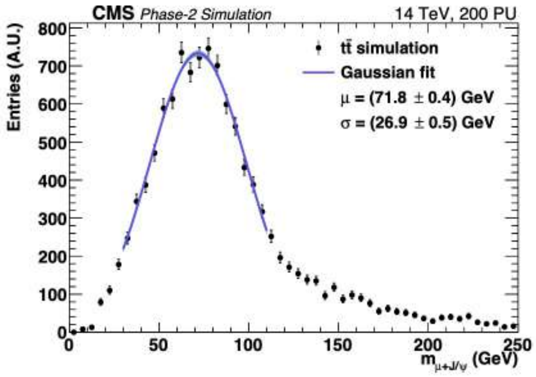
- Increased trigger efficiency
- Lower trigger rate
- Extended pseudorapidity range
- Improved redundancy

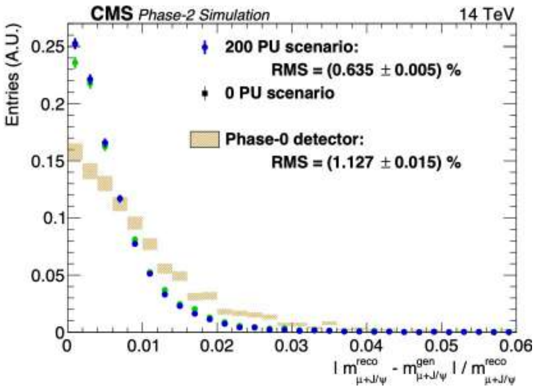
Physics improvements

- 7% increase in
  H ZZ ⟶ 4μ signal strength
- Improved weak angle measurement
- Top quark mass in
  t ⟶ J/ψ (μμ)μ + X decays









Phase-2 Level-1 Trigger

Key parameters

- Rate: 100 kHz ⟶ 750 kHz
- Latency: 3.8 μs ⟶ 12.5 μs

Inputs calorimeters, muon system and outer tracker

Charged particle track reconstruction

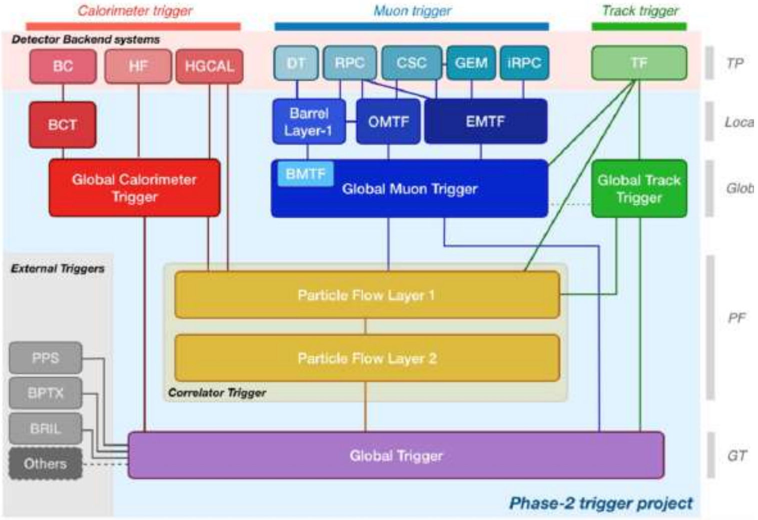
- Stubs from Outer Tracker
- Hybrid tracklet+KF track finder
- Extended L1 tracking for displaced trajectories

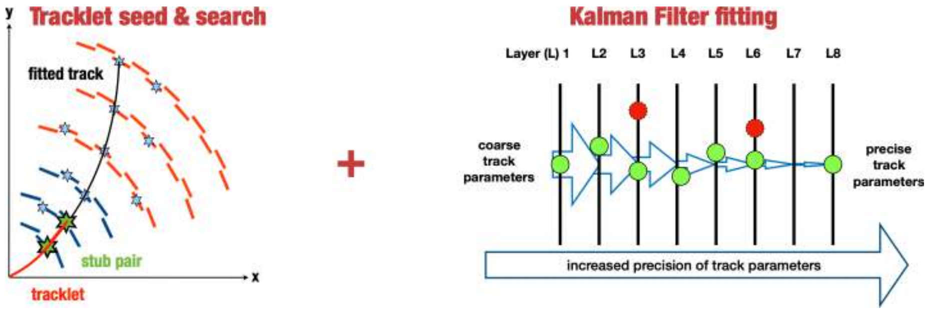
Correlator layer for sophisticated algorithms

- Particle-flow and machine learning
- Machine learning

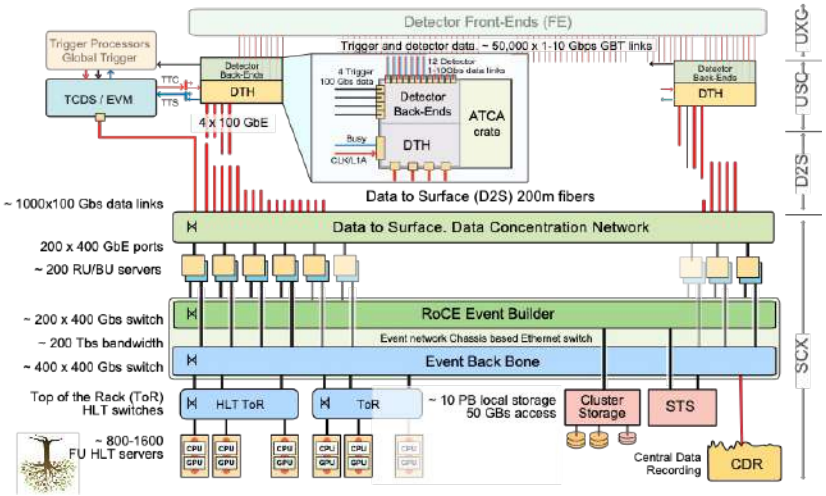
40 MHz Scouting

- Intermediate L1T data streams
- Diagnostics, monitoring and physics





Phase-2 DAQ and HLT



CMS detector	LHC	HL-LHC	
	Phase-1	Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size at HLT input	2.0 MB	6.1 MB	8.4 MB
Event Network throughput	1.6 Tb/s	24 Tb/s	51 Tb/s
Event Network buffer (60 s)	12 TB	182 TB	379 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power	0.7 MHS06	17 MHS06	37 MHS06
Event Size at HLT output	1.4 MB	4.3 MB	5.9 MB
Storage throughput	2 GB/s	24 GB/s	51 GB/s
Storage throughput (Heavy-Ion)	12 GB/s	51 GB/s	51 GB/s
Storage capacity needed (1 day)	0.2 PB	1.6 PB	3.3 PB

Key parameters

- 50,000 high-speed front-end optical links
- Up to 60 Tb/s data rate
- Total event size 7—10 MB

Highlights

- Unified detector readout
  - ATCA form-factor for detector backend
- Dual-function board DTH-400
  - DAQ data aggregation
  - Timing and Trigger Control and Distribution
- Event Network
  - RDMA over Converged Ethernet
- Heterogeneous HLT nodes
  - GPU-equipped servers
  - HLT code port – building upon successful Run-3 experience


LHCb
YCMM01
UX85

LHCb Upgrades Overview

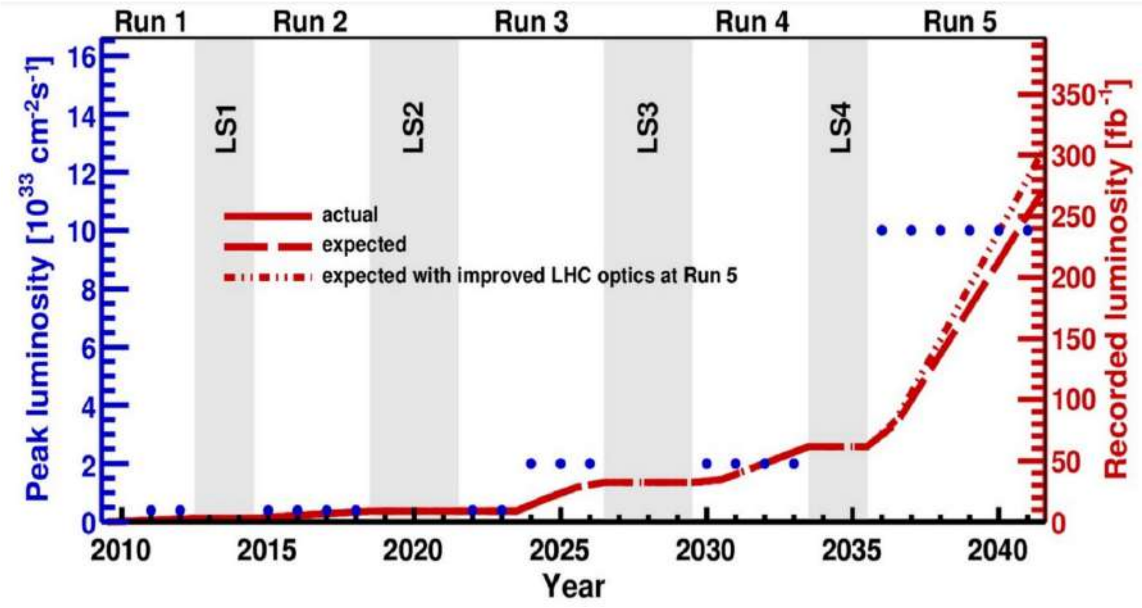
Upgrade I (U1) started in LS2

- ❑ $\mathcal{L}_{max}$ ~$2x10^{33}$ $cm^{-2}s^{-1}$
- ❑ $\mathcal{L}_{int}$ ~50 fb^{-1}

Some smaller detector consolidation and enhancements in LS3 (2026)

Upgrade II (U2) starts in LS4

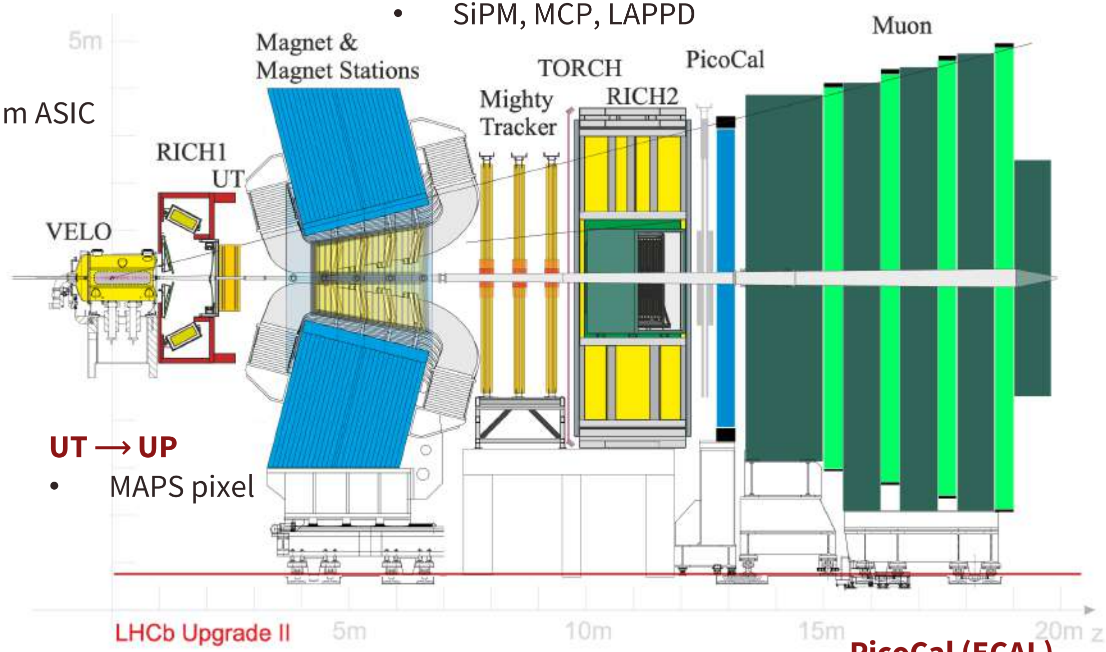
- ❑ $\mathcal{L}_{max}$~$1x10^{34}$ $cm^{-2}s^{-1}$
- ❑ $\mathcal{L}_{int}$~250 - 300 fb^{-1}



LHCb Upgrade II Overview

RICH1, RICH2
- Reduced pixel size
- Add timing information
- SiPM, MCP, LAPPD

VELO ⟶ TV
- 3D Si Pixel, 28 nm ASIC
- Timing ~50 ps
- New RF-foil



Muon Detector
- New MPGD (inner)
- Keep MWPC (outer)

UT ⟶ UP
- MAPS pixel

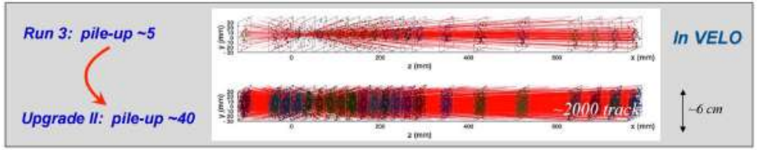
Mighty Tracker (MT)
- MAPS pixel (inner)
- SciFi (outer)

PicoCal (ECAL)
- Timing, longitudinal segmentation
- SPACAL with radiation hard crystals
- Shashlik technology for outer region

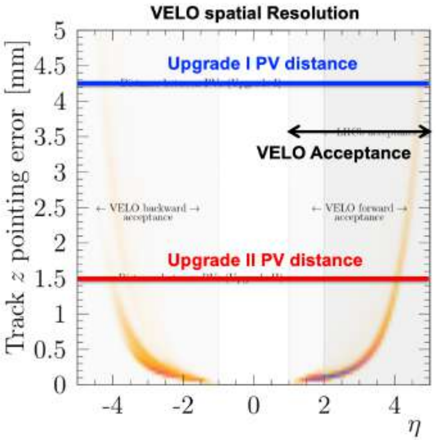
Detector With Timing Information

In Upgrade II

- $\mathcal{L}_{max}$~1.0 x 10^{34} $cm^{-2}s^{-1}$
- $\mathcal{L}_{int}$ ~250 – 300 fb^{-1}
- ~40 visible interactions/bunch crossing



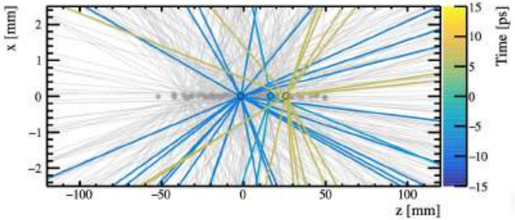
High pile-up induces PV spatial separation of the same order as VELO resolution ⟶ PV unresolvable

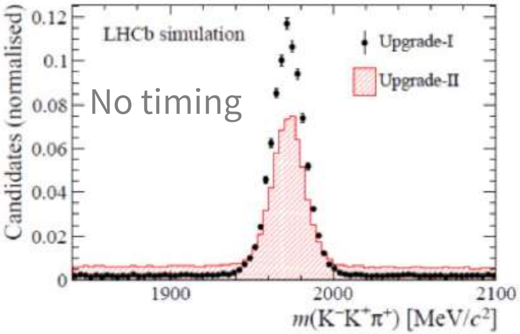


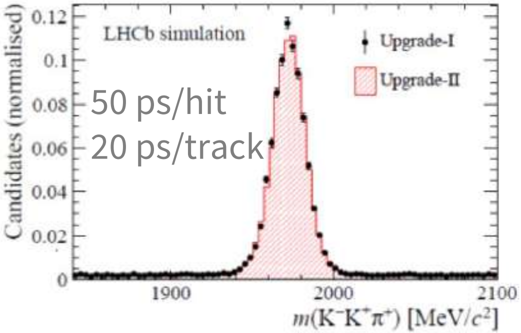
Ensure trigger efficiency at high pileup condition

LHCC-2021-012

VELO: 4D detector with timing



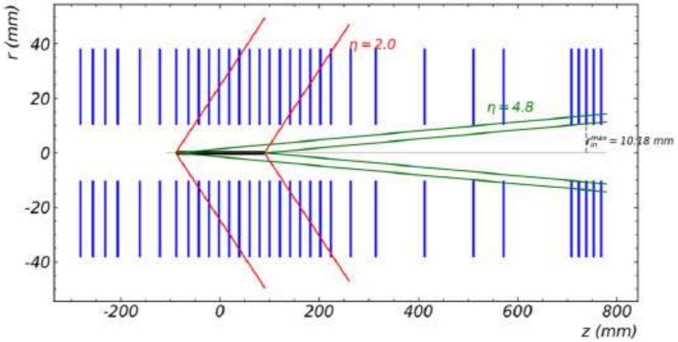


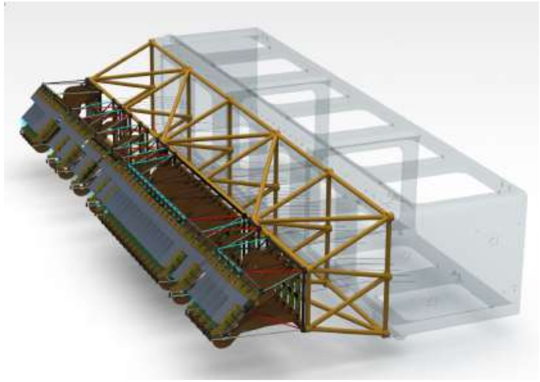


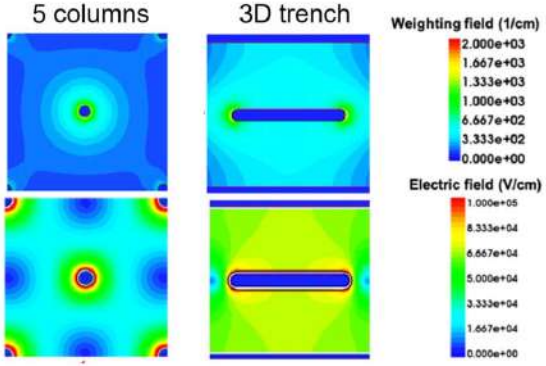
σ_t(Track)=20 ps restores the performance to U1 level

Vertex Locator With Timing (TV)

LHCC-2021-012







Baseline: 32 stations

Sensor: 3D silicon sensor

- Radiation tolerance, max ~6 x 10^{16} neq/cm2
- Trench vs column

ASIC (28nm technology):

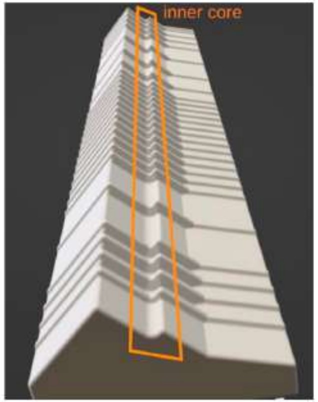
- Requirement < 30 ps
- Picopix (50 μm pixel pitch); Ignite (45 μm pixel pitch)

Module cooling

- Coolant: CO_2 or Krypton
- Substrates: silicon, ceramics, metal 3D printing

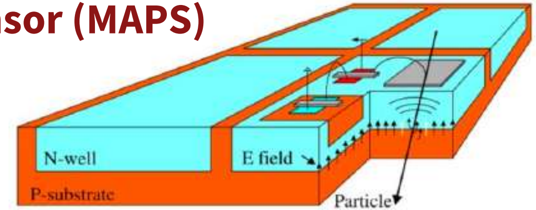
RF shield: 50 μm Al + 20 μm carbon fiber

Minimizing the material (substrate & RF shield) crucial for σ_{IP} improvement



MAPS Technology For Tracker

Monolithic Active Pixel Sensor (MAPS)



Parameter	Key Specification	
	MT-Pixel	UP
Pixel size, square rectangular	$\leq 100\times200\ \mu m^2$	$\leq 85\times85\ \mu m^2$ $\leq 50\times200\ \mu m^2$
Max hit rate	34 MHz /cm^2	150 MHz /cm^2
In-time efficiency	> 99% within 25 ns	
Rad-hard (NIEL) (TID)	$3\times10^{14}\ n_{eq}/cm^2$ 40 Mrad	$3\times10^{15}\ n_{eq}/cm^2$ 240 Mrad
Power consumption	$\leq$ 150 mW/cm^2	$\leq$ 200 mW/cm^2

MightyPix2

MightyPix (AMS 180 nm)

- MightyPix1/TSI-180, $\sigma_t \sim 3$ ns
- LF-MightyPix uses LF-150, power ~200 mW/cm^2

RadPix (LF 150 nm)

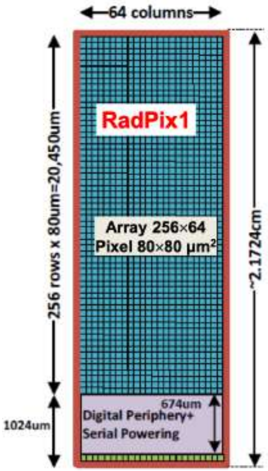
- LFMonoPix, 99% efficiency after $10^{15}\ n_{eq}/cm^2$

COFFEE (55 nm)

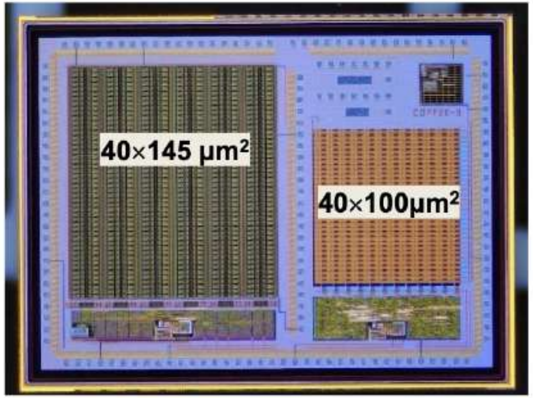
- COFFEE3 responds to laser and radiation source, digital functions validated

MANTA (TPSCo 65 nm)

- Based on SPARC for ALICE



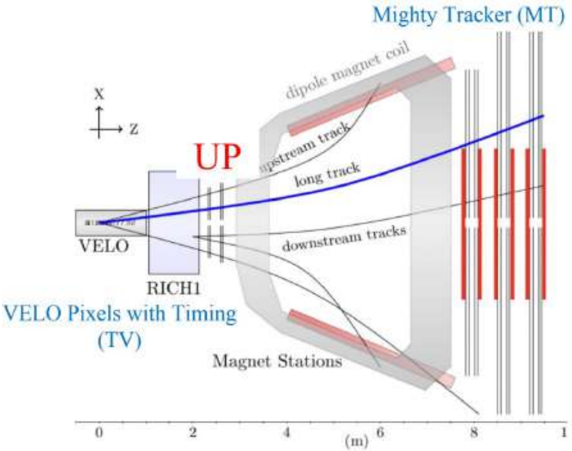
COFFEE 3

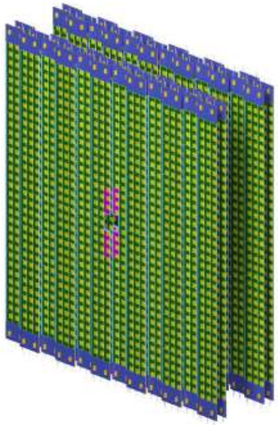


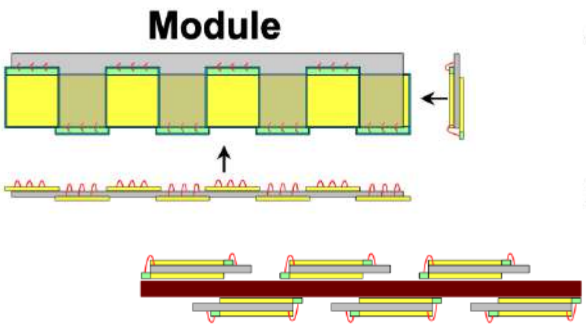
Upstream Pixel (UP) Detector

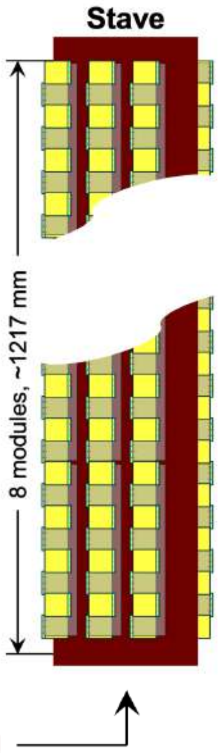
UP: a key role in LHCb tracking system

- Four layers based on MAPS, total active area ~7m^2
- Module/stave designs being finalized
- Readout electronics at the end of staves

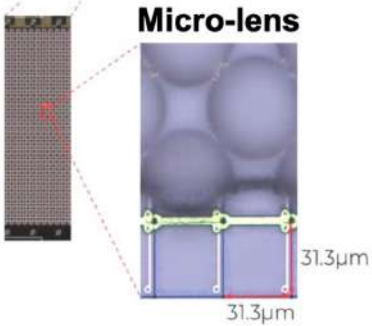


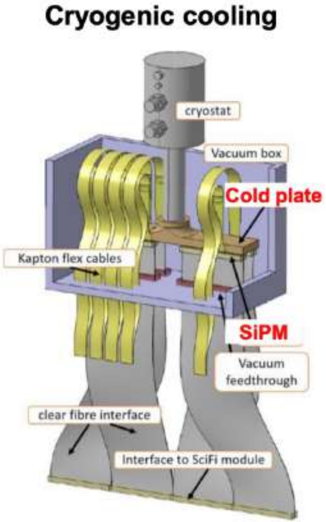






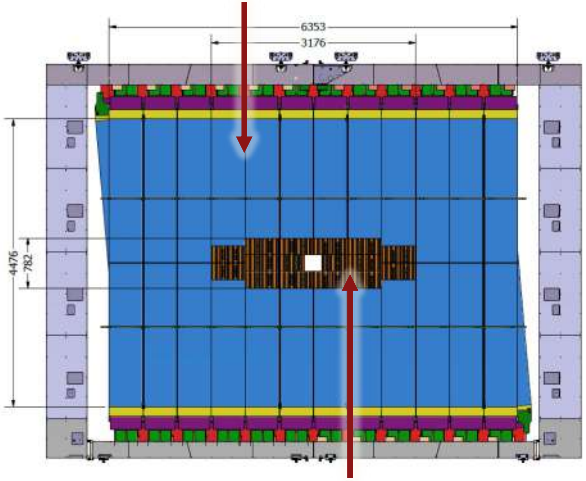
SciFi and Mighty Tracker (MT)

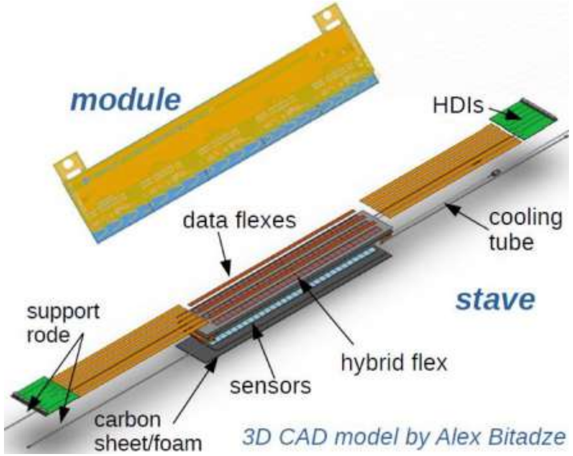




Use SciFi technology where rates allow

- Outer region further from beam
- Micro-lens on SiPM to enhance light collection
- Cryogenic cooling for SiPM: -40º C ⇒ ~100K





LHCC-2024-010
LHCC-2021-021

HV-CMOS MAPS detector

- 6 layers, total active area ~13 m^2
- Pixel size ~84 x 84 μm^2

RICH Detectors with Improved Timing

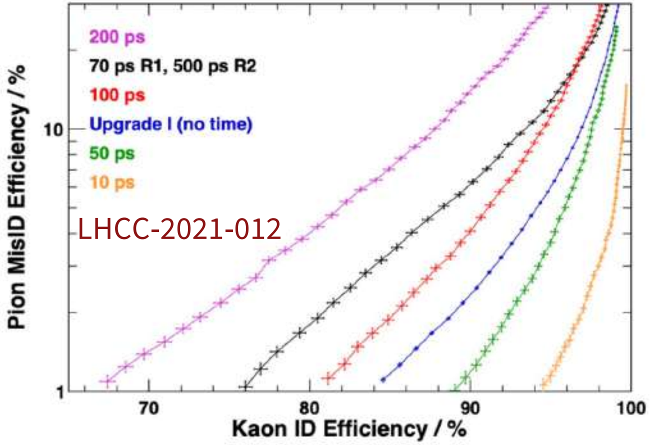
RICH 1&2 will maintain same geometry, reduce pixel size

Photon detector options: SiPM, MCP, LAPPD.

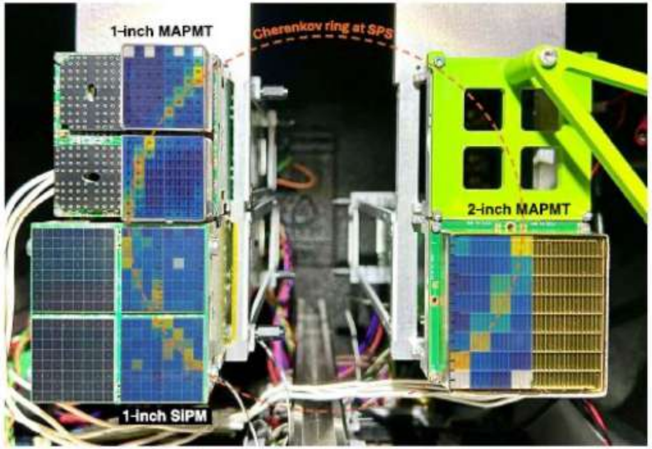
- MAPMT may be backup for low occupancy area

Time-stamping each photon with high precision, which is crucial to PID performance

FastRICH has 25 ps time-stamping and digital output compatible with lpGBT



JINST 21 (2026) 03, C03008



Upgrade	Photon Detector	FE ASIC	Time Resolution	TimeStamp Precision
I	MAPMT	CLARO	~ 150 ps	3.125 ns
I.b*	MAPMT	FastRICH	~ 150 ps	25 ps
II	SiPM, MCP LAPPD	FastRICH	< 100 ps	25 ps

* LS3 consolidation

5D Calorimetry with Precision Timing

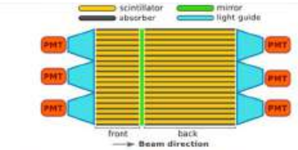
Preserve calorimeter performance at high luminosity

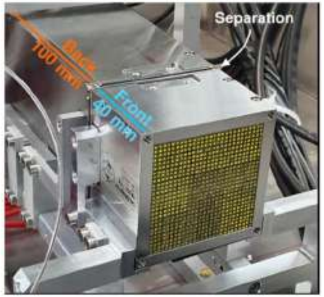
Re-organize ECAL zones to follow radiation & occupancy map

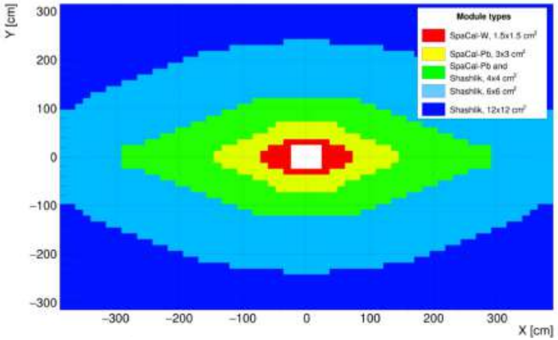
Baseline: combination of technologies for different regions starting from inner-most

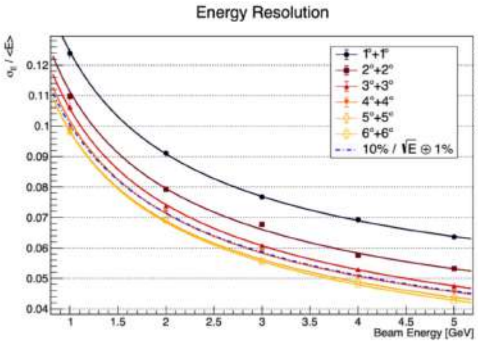
- ❑ SpaCal-W/ GAGG fibers
- ❑ SpaCal-Pb / Plastic fibers
- ❑ Shashlik / WLS fibers

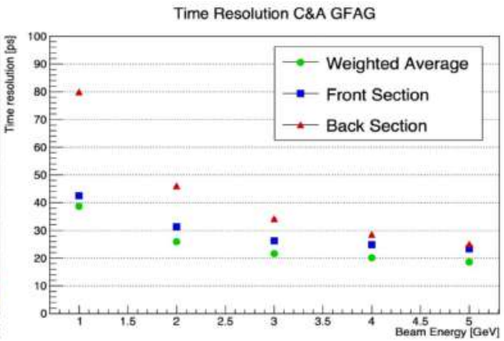
Cell size [cm²]	Module type	Modules	Cells
1.5 × 1.5	SpaCal-W with GAGG fibers	40	5120
3 × 3	SpaCal-Pb with plastic fibers	136	4352
4 × 4	SpaCal-Pb with plastic fibers	272	4896
	Shashlik with WLS fibers	176	3168
6 × 6	Shashlik with WLS fibers	448	3584
	Shashlik with new tiles and WLS fibers	896	7168
12 × 12	Shashlik with WLS fibers	1344	2688
Sum		3312	30976





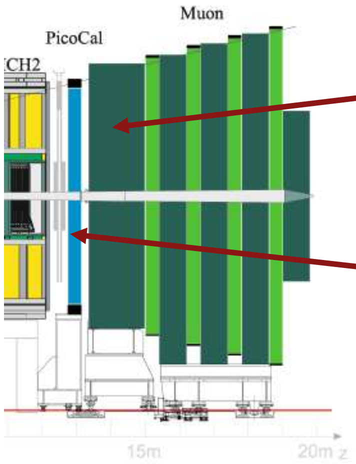






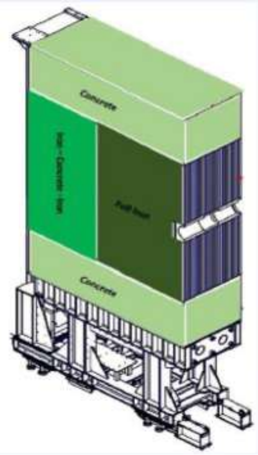
NIMA 1045, 167629 (2022)

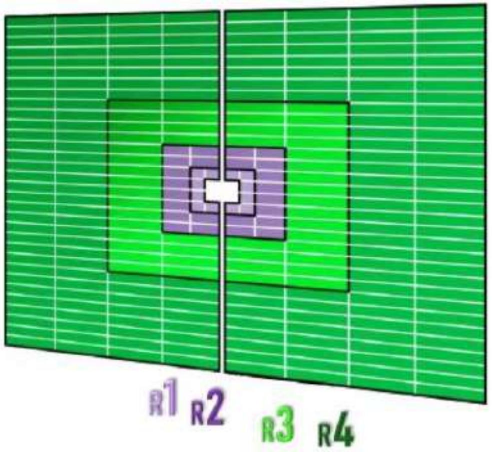
Muon Detector



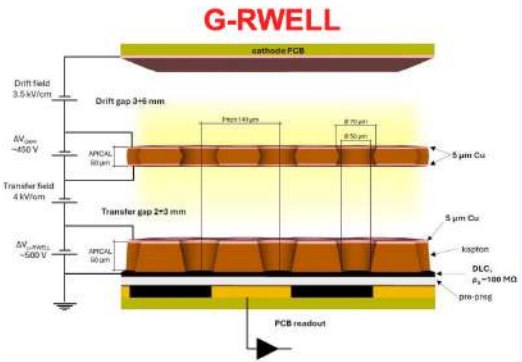
HCAL replaced with iron/concrete shield

Shielding to protect electronics against slow neutrons





- Novel G-RWELL for inner-most region (R1, R2)
- Reuse existing MWPC in outer region (R3, R4)
- New readout scheme in all regions, for background reduction and a new front-end electronics
- Additional shielding ($4\ \lambda_I \longrightarrow 10\ \lambda_I$) to be installed in front of Muon Detector



Online and Offline

Novel trigger system for Upgrade I

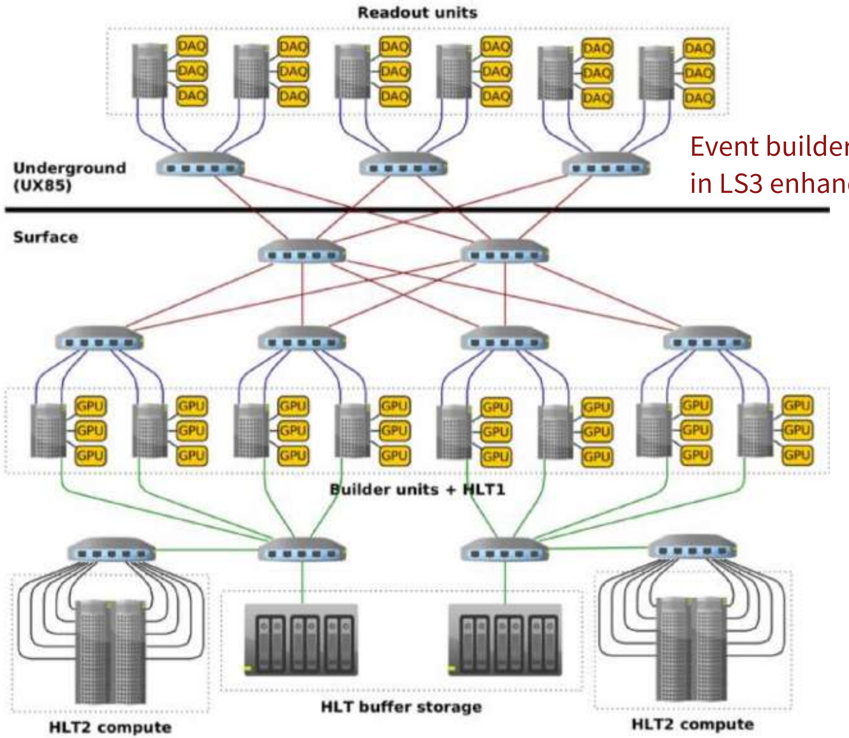
- ❑ Fully software trigger
- ❑ HLT1 based on GPUs, HLT2 on CPUs

Similar concept planned for Upgrade II

- ❑ Expected data throughput for real time analysis is ~200 Tb/s
- ❑ Further exploitation of hybrid architectures: CPU, GPU, FPGA …

Offline computing requirements are significant

- ❑ Software R&D match requirement to prospective resources
- ❑ Issues in Run 5 similar to ATLAS & CMS Run 4
- ❑ Coordination with WLCG and the HEP Software Foundation on mitigation



Event builders in UX85 in LS3 enhancement

Upgrade II – Expected Physics Results

Experiment Assumed data sample	ATLAS 20.3-99.7 fb^{-1}	CMS 116-140 fb^{-1}	LHCb 2-9 fb^{-1}	Belle II 364-1075 fb^{-1}
CKM angles				
β	—	—	0.57° [15]	1.2° [16]
α	—	—	—	6.6° [17]
γ	—	—	2.8° [18]	13° [17]
ϕ_s [mrad]	42 [19]	23 [20]	20 [21]	—
***CP* violation in loop-dominated decays**				
$S(B^0 \to \eta' K^0_S)$	—	—	—	0.087 [17]
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	—	—	69 [22]	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	—	—	130 [23]	—
***CP* violation in $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mixing**				
a^s_{sl} [10^{-4}]	—	—	33 [24]	—
a^d_{sl} [10^{-4}]	—	—	36 [25]	40 [26]
***CP* violation in the charm sector**				
ΔA_{CP} [10^{-5}]	—	—	29 [27]	630 [16]
$A_{CP}(D^{+,0} \to \pi^{+,0}\pi^0)$ [10^{-5}]	—	—	900 [28], —	870, 750
$A_\Gamma(KK, \pi\pi)$ [10^{-5}]	—	—	11 [29]	—
$\Delta x(D^0 \to K^0_S\pi^+\pi^-)$ [10^{-5}]	—	—	18 [30]	140 [31]
Semileptonic *B* decays				
$\lvert V_{ub}\rvert$	—	—	6% [32]	6.3% [33]
$\lvert V_{cb}\rvert$	—	—	—	1.7% [34]
$R(D)$, $R(D^*)$	—	—	14% [35], 6% [36]	12%, 7% [17]
Leptonic *B* decays				
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ [10^{-9}]	$^{+0.8}_{-0.7}$ [37]	0.45 [38]	0.48 [39]	—
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ [10^{-10}]	$< 2.1^*$ [37]	< 1.5 [38]	0.79 [39]	—
$\tau_{\text{eff}}(B^0_s \to \mu^+\mu^-)$ [ps]	$^{+0.45}_{-0.18}$ [40]	0.23 [38]	0.29 [39]	—
$S(B^0_s \to \mu^+\mu^-)$	—	—	—	—
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	—	—	—	34% [17]
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	—	—	—	41% [17]
Flavour-changing neutral current $b \to s\ell\ell$ decays				
$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$ [10^{-3}] †	390 [41]	100 [42]	111 [43]	—
$\mathcal{B}(B^{+,0} \to K^{+,*0}\nu\overline{\nu})$	—	—	—	57%, 110% [17]
$\mathcal{B}(B^{+,0} \to K^{+,*0}\tau^+\tau^-)$ [10^{-4}]	—	—	—	< 10, < 18 [44]
Flavour-changing neutral current $b \to s\gamma$ decays				
$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,\text{GeV})$	—	—	—	$(16-18)\%$ [17]
$S(B^0 \to K^0_S\pi^0\gamma)$	—	—	—	0.27 [45]
$S(B^0_s \to \phi\gamma)$	—	—	0.32 [46]	—
$A^{(2)}_T(B^0 \to K^{*0}e^+e^-;\text{very low } q^2)$	—	—	0.10 [47]	0.76 [48]
$\alpha_\gamma(\Lambda^0_b \to \Lambda^0\gamma)$	—	—	0.26 [49]	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \to \mu^+\gamma)$ [10^{-8}]	—	—	—	< 7.5 [16]
$\mathcal{B}(\tau^+ \to \mu^+\mu^+\mu^-)$ [10^{-8}]	< 37.6 [50]	< 2.9 [51]	< 4.6 [52]	< 1.8 [53]

arxiv:2503.23087

Upgrade II will fully realize the flavour physics potential of the HL-LHC

Further pursue a broad physics programme

- Spectroscopy
- High precision EW and Higgs
- Dark sector
- Exotic searches
- Heavy ions and fixed target

Success of the physics programme relies on

- HL-LHC providing LHCb ~50 fb^{-1}/year during Run 5
- A detector with similar or better performance as the present one for Upgrade I

Conclusions

The high-luminosity configuration paves the way for the full exploitation of the LHC.

- Complete the cycle LEP ⟶ LEP2 ⟶ LHC ⟶ HL-LHC

Full luminosity needed for the most extensive searches and most precise measurements.

- Elucidation of the EWSB and of the Higgs boson characteristics
- Completion of the LHC flavour programme

The HL-LHC conditions will be the harshest to date.

- Event rate, pileup, radiation

The Upgrade projects will allow us to profit from the HL-LHC era.

- Keep (and improve) the high performance delivered by all detectors

Thanks!

References

- High Luminosity LHC Technical Design Report: https://cds.cern.ch/record/2284929

- Report on the Physics at the HL-LHC and Perspectives for the HE-LHC https://arxiv.org/abs/1902.10229

- Highlights of the HL-LHC physics projections by ATLAS and CMS https://arxiv.org/abs/2504.00672

References for the Experiments

- ATLAS
  - Letter of Intent for the Phase-II Upgrade of ATLAS
  - ATLAS Phase-II Upgrade Scoping Document
  - Technical Design Reports:
    - Inner Tracker Pixels and Strips, Liquid Argon and Tile Calorimeters, Muon Spectrometer
    - High Granularity Timing Detector
    - Trigger and DAQ + Event Filter Tracking Amendment
- CMS
  - Technical proposal for the Phase-II Upgrade of CMS
  - CMS Phase II Upgrade Scope Document
  - Technical Design Reports:
    - Tracker, Barrel and Endcap (HGCAL) Calorimeters, Muon Detectors
    - MIP Timing Detector
    - Level-1 Trigger, DAQ and High Level Trigger
    - Beam Radiation, Instrumentation and Luminosity
- LHCb
  - Framework TDR for the LHCb Upgrade II
  - LHCb Upgrade II Scoping Document

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