Preparation toward HL-LHC

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What physics do you order for TeV scale?

$m_H = 125.20 \pm 0.11\ \mathrm{GeV}$ (PDG)

$\delta m_H^2 = \kappa \Lambda^2$ with κ typically in the range of 10^{-2} (arXiv:0801.2562)

"Natural" expectation:
Quantum correction δm_H^2 is not too large compared to physical m_H^2

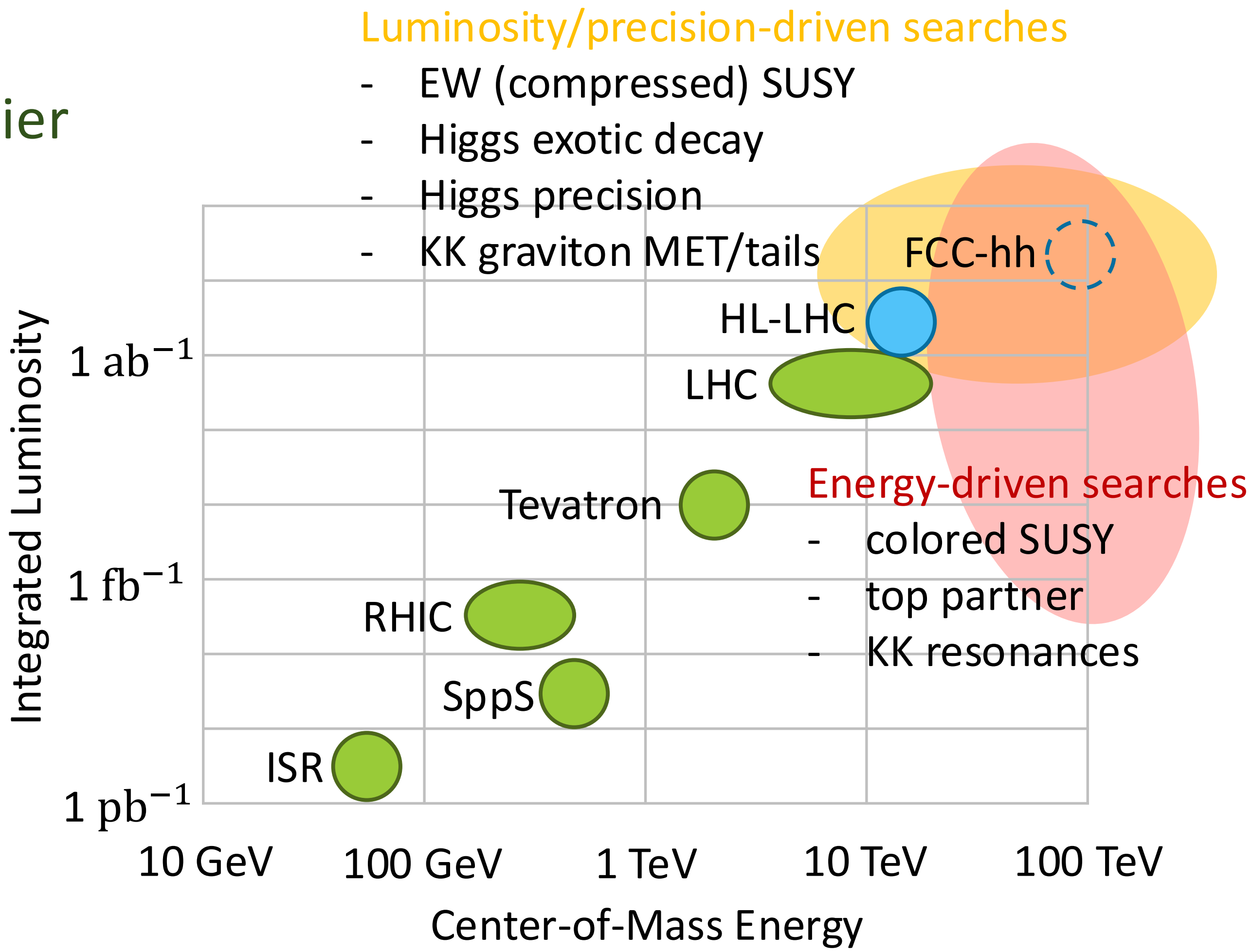
- Implying BSM physics at the TeV scale controls m_H sensitivity to high scales
  - Low-energy SUSY?
  - Composite/Little/Twin Higgs?
  - Warped/Large extra dimension?
  - Relaxion with cosmological dynamics?
  - … Or give up naturalness and consider anthropic selection?

Tested at Collider (Low-energy SUSY, Composite/Little/Twin Higgs, Warped/Large extra dimension)

Colliders to probe TeV physics

- Hadron Colliders lead the energy frontier
  - Synchrotron-radiation less limiting
- Current Frontier: LHC
  - Direct searches set multi-TeV limits
  - Remaining targets: rare and non-standard signatures
  - Need statistics to control backgrounds and systematics

  → <u>High-Luminosity LHC</u>



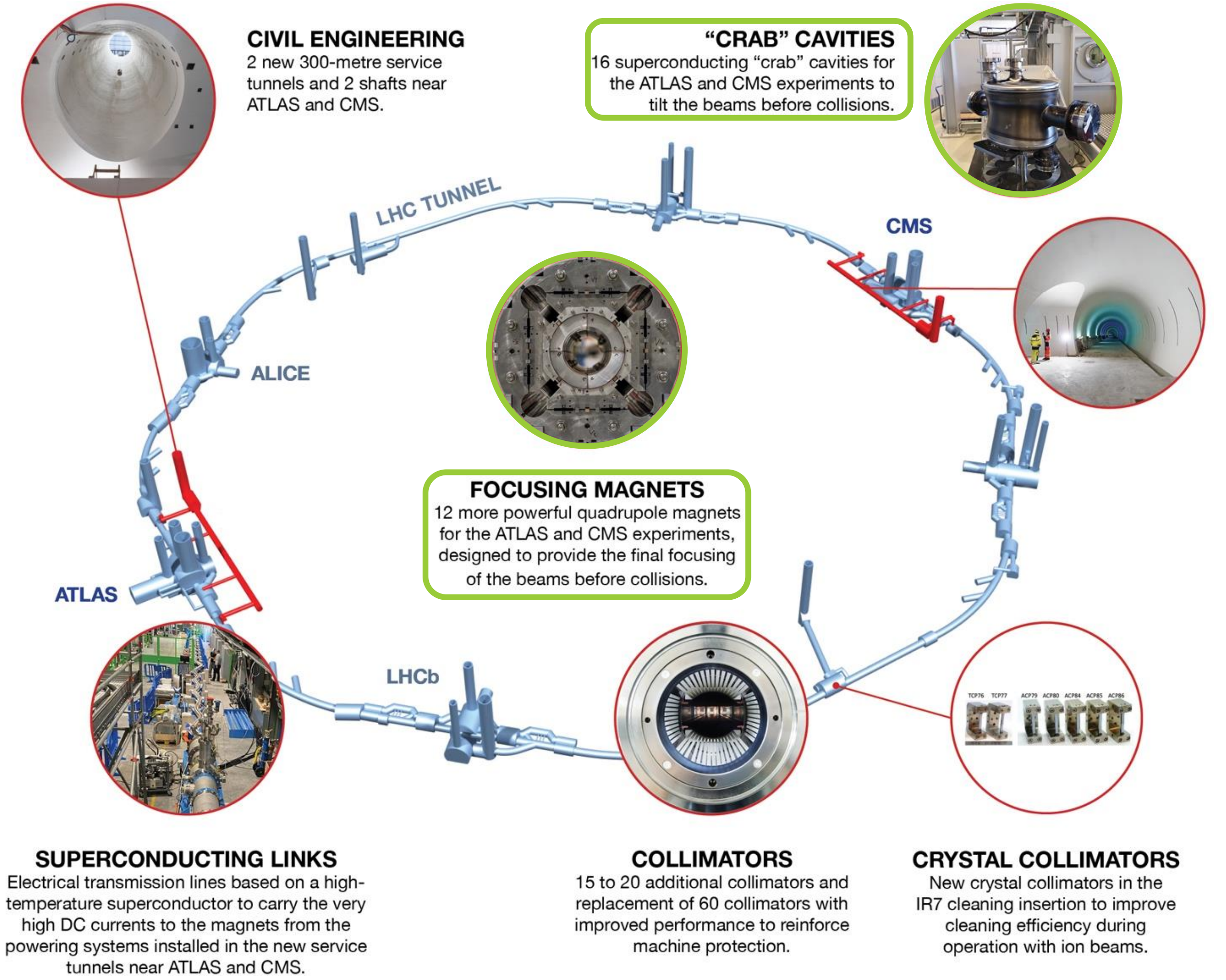
High-Luminosity LHC

	Run 1-3 Achieved	Run 4-5 Nominal (Ultimate)
Virtual Luminosity $[10^{34}\ \mathrm{cm^{-2}s^{-1}}]$	**3.1**	**17**
No. of bunches	2556	2748
Particles per bunch N_b $[10^{11}]$	**1.8**	**2.2**
Normalized emittance ϵ_n $[\mu\mathrm{m}]$	2.0	2.5
Minimum β^* [cm]	**30**	**15** (10)
Geom. half xing angle $\theta_c/2$ $[\mu\mathrm{rad}]$	160	250
Eff. half xing angle $(\theta_c/2)_{\mathrm{eff}}$ $[\mu\mathrm{rad}]$	**160**	**$\sim$0**
Levelled Luminosity $[10^{34}\ \mathrm{cm^{-2}s^{-1}}]$	**2.3**	**5.0** (7.5)
Average pileup $\langle\mu\rangle$	64	140 (200)
Leveling Time [h]	**7**	**7.5** (3.5)
Collision Energy	7-13.6	14

- LHC Upgrade
  - $\times$ 5 virtual luminosity
  - Longer leveling time with higher levelled luminosity
- Key Components
  - Injector for N_b
    - Completed, operated from Run3
  - Final Focus Magnet for β^*
  - Crab Cavity for $(\theta_c/2)_{\mathrm{eff}}$

arXiv:2505.03535v1

Upgrade in the LHC ring

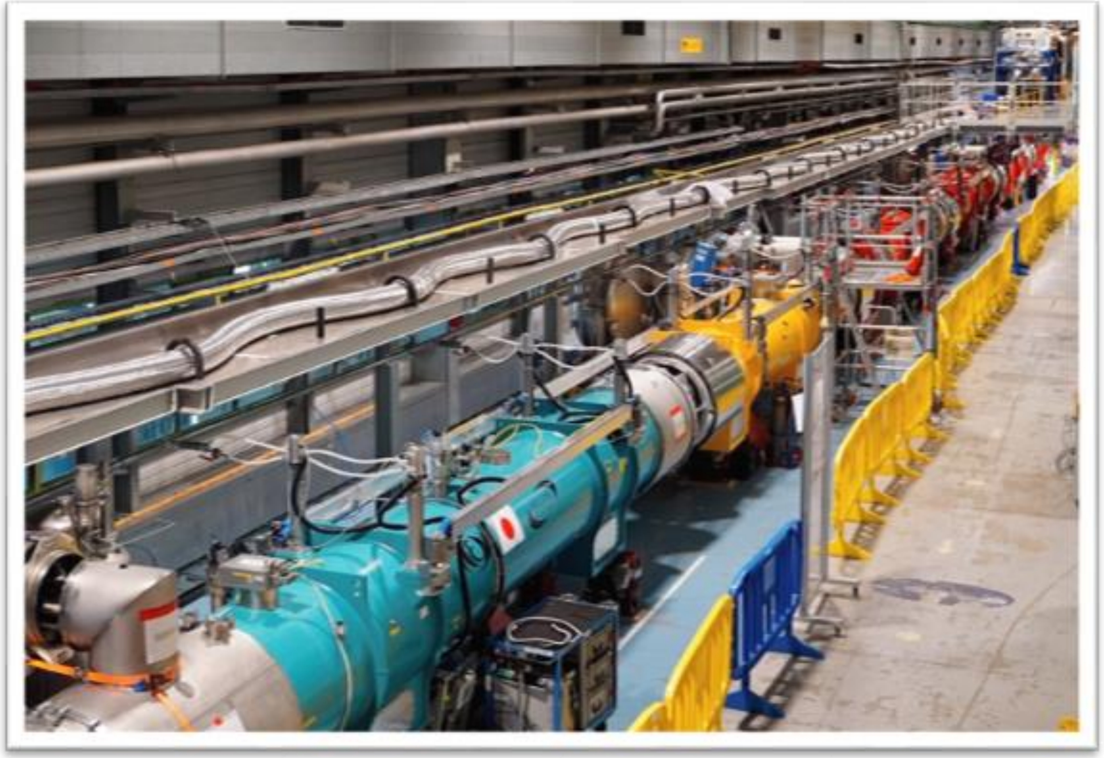


CDS

Final Focusing System

- Final Focus: Inner Triplet
  - Nb_3Sn quadruples
    - Higher J_c and B_{c2} at high field than NbTi
  - High gradient enabling $\beta^* = 15\ \mathrm{cm}$
  - Large aperture for higher N_b
- Separation Dipole
  - At small β^*, $\beta(s)$ rises quickly away from the IP
  - Early beam separation after the IP to accommodate large beam size
- IT String
  - Integrated test bench for cryogenic + powering + protection

IT String



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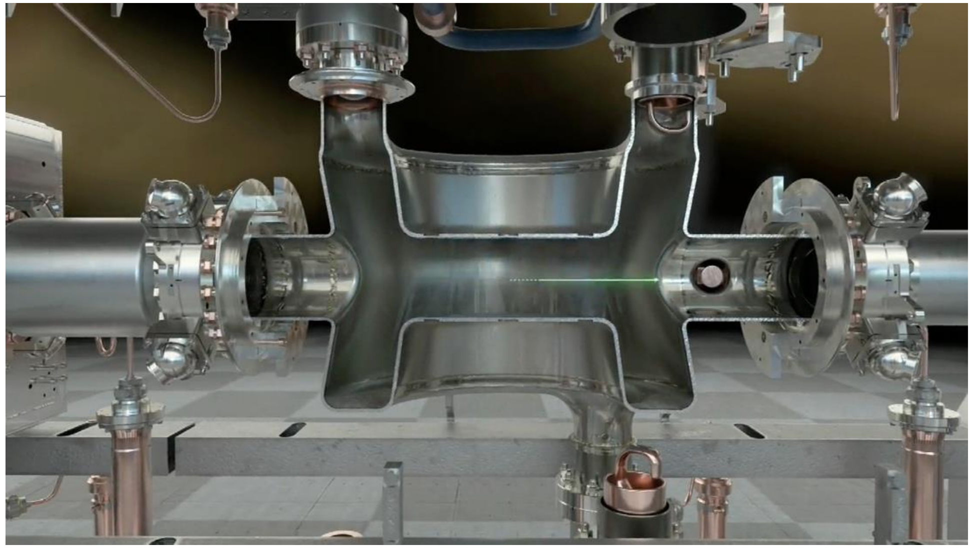
Crab Cavity

- IP with large crossing angle
  - Small β^* requires large crossing angle
    - To reduce long-range beam-beam effect
  - But it reduces geometric overlap



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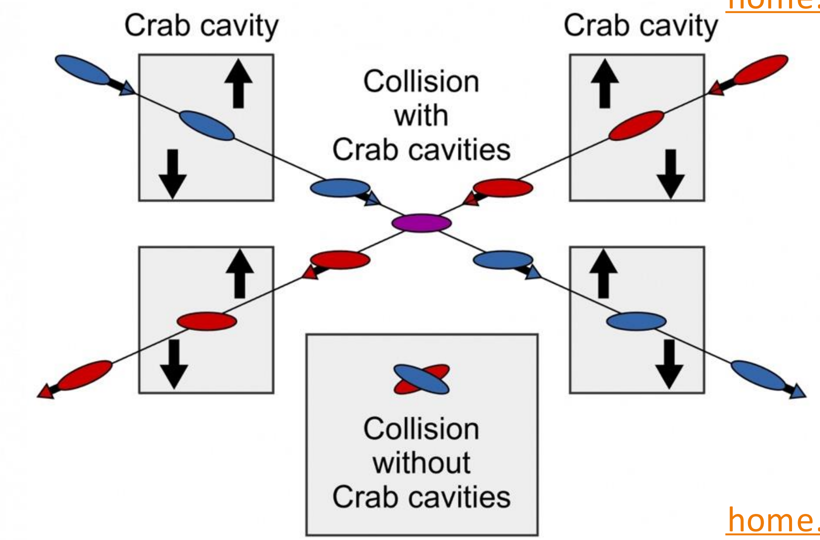
- Crab cavity
  - Transverse RF kick tilts bunches (head-tail)
    - vertical kick for vertical crossing at IP1 (ATLAS)
  - Restores geometric overlap
    - up to $\sim 3\times$ in the ideal case



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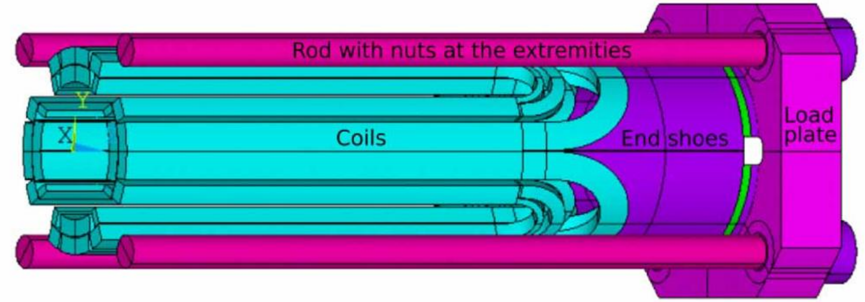
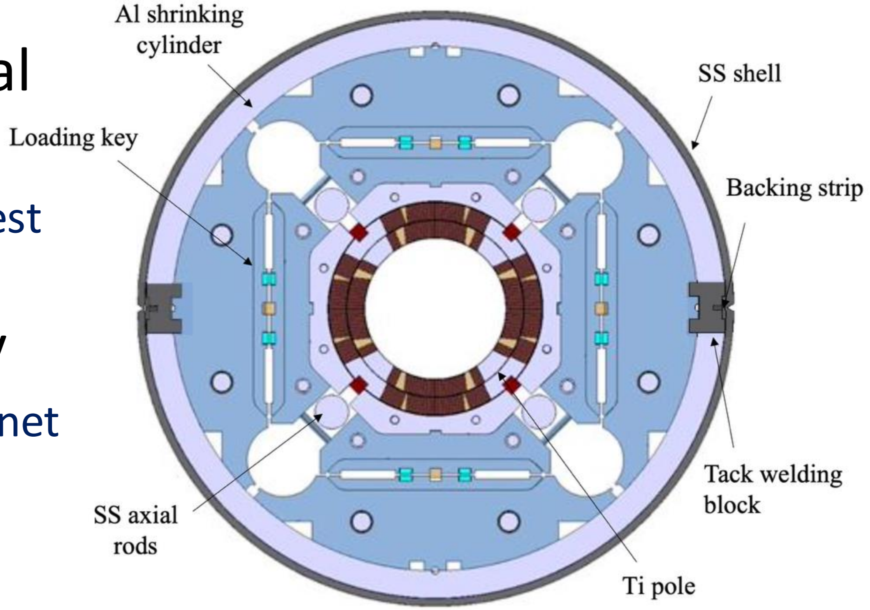
Challenges in Production

- Inner Triplets production
  - Challenge: Handling of Nb_3Sn
    - Especially for 7.2 m-long accelerator-quality magnets
  - Conductor limitation in early production
    - Target: nominal 16.23 kA + 300A mergin at 1.9 K/4.5 K
  - Cause: local I_c degradation due to mechanical overstress and frictional constraints
    - Even small conductor damage becomes visible at 4.5 K test (limited temperature margin)
  - Mitigated by improving tooling and assembly
    - Reduced mechanical coupling between SS shell and magnet
    - Optimized assembly to avoid overstress during loading
    - Reduced friction during reaction heat treatment



E. Takala et al., 2021

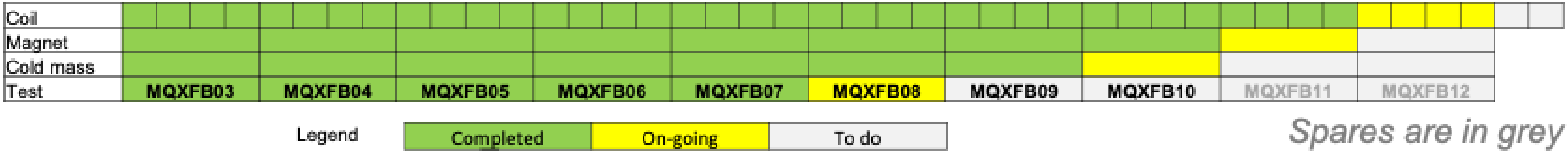


S. I. Bermudez et al., 2025

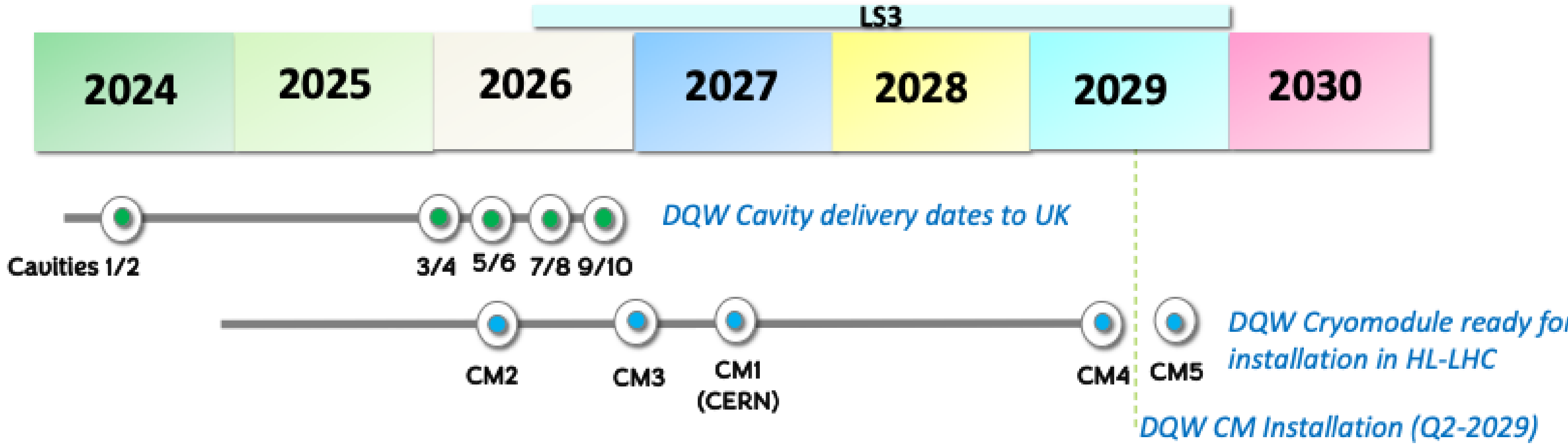
Production Progress

◆ Engaging in Series Production for all components

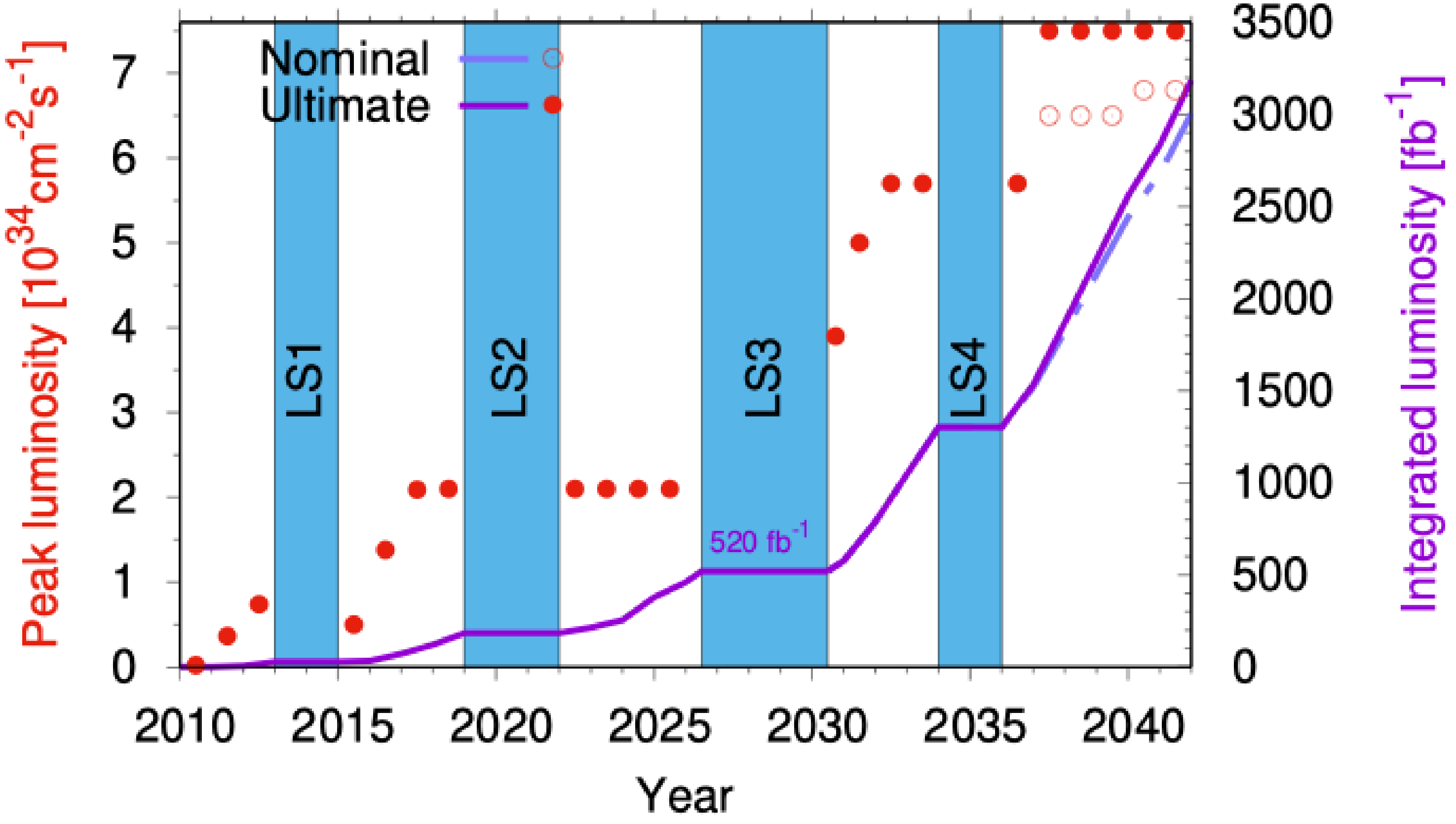
- Inner Triplets (as of Oct. 2025) S. I. Bermudez, 15th HL-LHC Collaboration Meeting



- Crab Cavity (DQW, as of Oct. 2025) O. Capatina, 15th HL-LHC Collaboration Meeting



Operation Plan



M. Zerlauth, Lepton-Photon 2025

- Operation plan
  - Resume physics run in Aug. 2030 after LS3
  - Run 4: 3.5 years
  - LS4: 2 years
  - Run 5: 6 years
  - Finish at 2041
    - …then next collider project?
  - Total target: 3 ab^{-1} (incl. current LHC)

(as of Nov. 2024)

Upgrade of Experiments

- Experiments will fully leverage 3 ab^{-1} data
  - Keep physics performance with $\langle\mu\rangle = 140(200)$ @40 MHz
- Pure and fast trigger decision
  - L0/L1 accept 1 MHz/750 kHz within latency of 10 us/12.5 us
- Large-bandwidth data readout
  - Throughput = L0/L1 accept × Event size
- Granular and rad-hard detector
  - Improve trigger purity, but increase event size

Trigger nomenclature

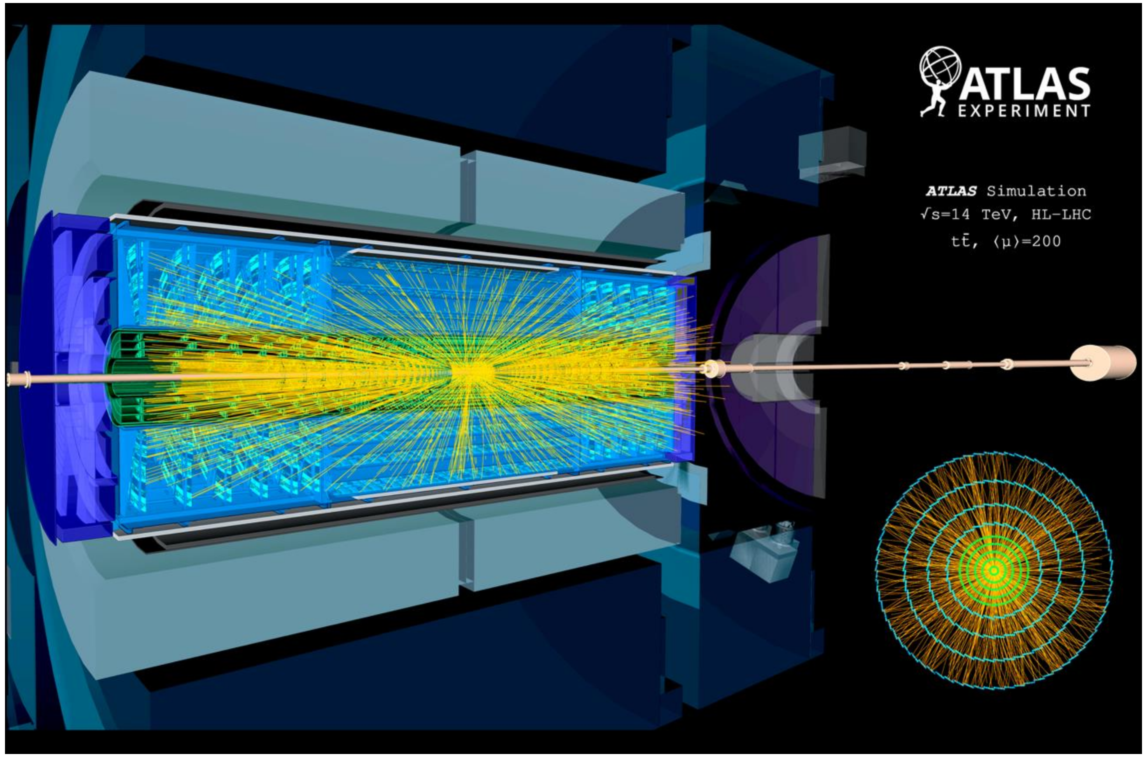
	ATLAS	CMS
HW trigger	L0	L1
SW trigger	EF	HLT

Working Points for Data Flow

	ATLAS	CMS
Bunch crossing	40 MHz	
Event size @$\langle\mu\rangle = 200$	4.6 MB	7.4 MB
L0/L1 accept	1 MHz	750 kHz
EF/HLT input	4.6 TB/s	5.5 TB/s
EF/HLT output	10 kHz	7.5 kHz
Tier-0 transient storage	50 GB/s	54 GB/s

Trigger and DAQ

- Trigger upgrade: coping with high $\langle \mu \rangle$
  - Fake forward muon
    - Additional MPGD precesion layers
  - Calorimeter shower overlap
    - 3D shower readout with increased granularity
  - Fast track finding
    - Increased granularity with all-silicon tracker
  - + Electronics upgrades / Global trigger
- DAQ upgrade: scalable networking
  - FPGA-based I/O bridges optical links from detectors to standard networks
    - ATLAS: Front-end Link Exchange (FELIX)
    - CMS: DAQ and Timing Hub (DTH)



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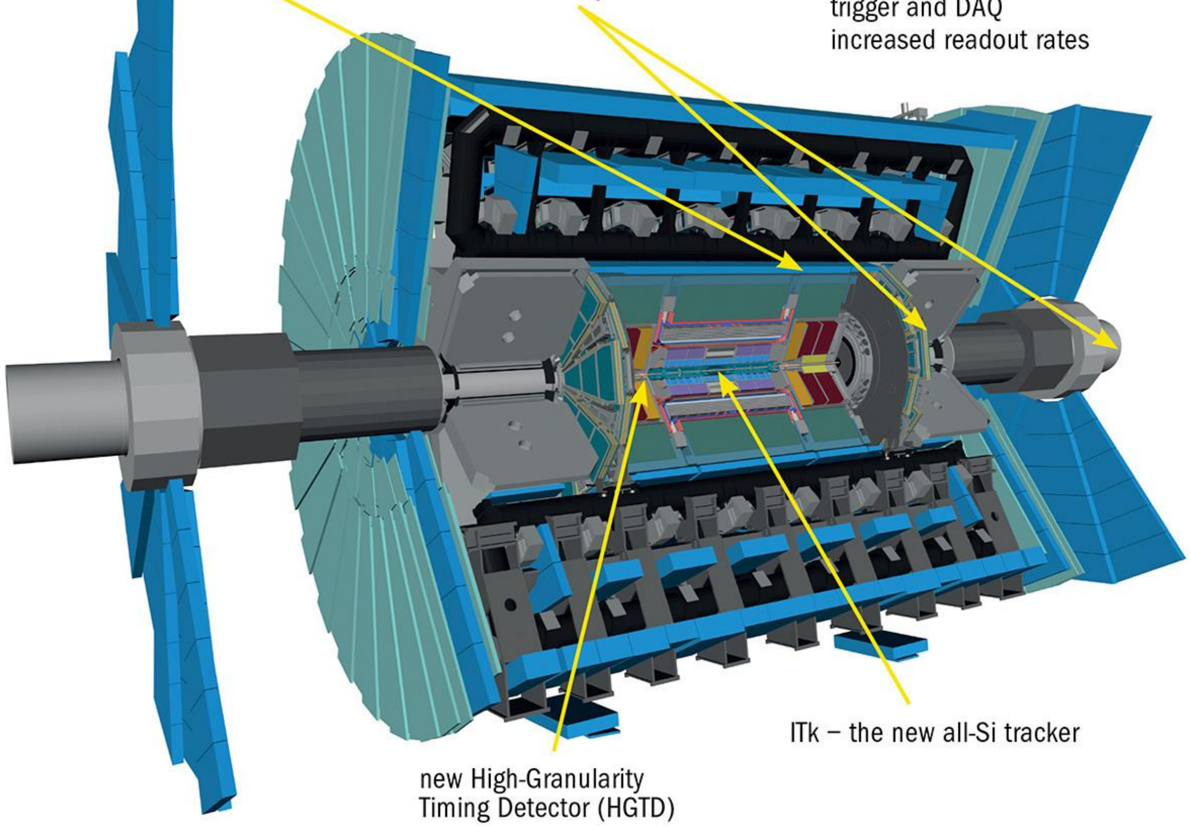
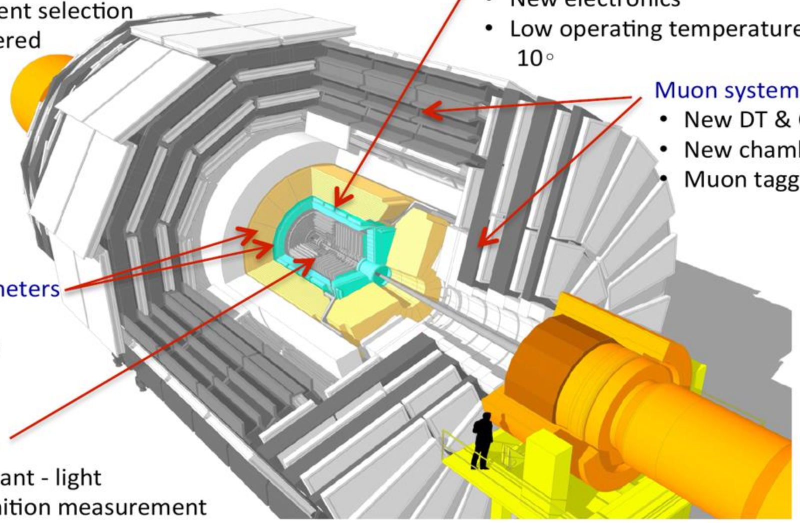
Detector upgrades during LS3

ATLAS



atlas.cern

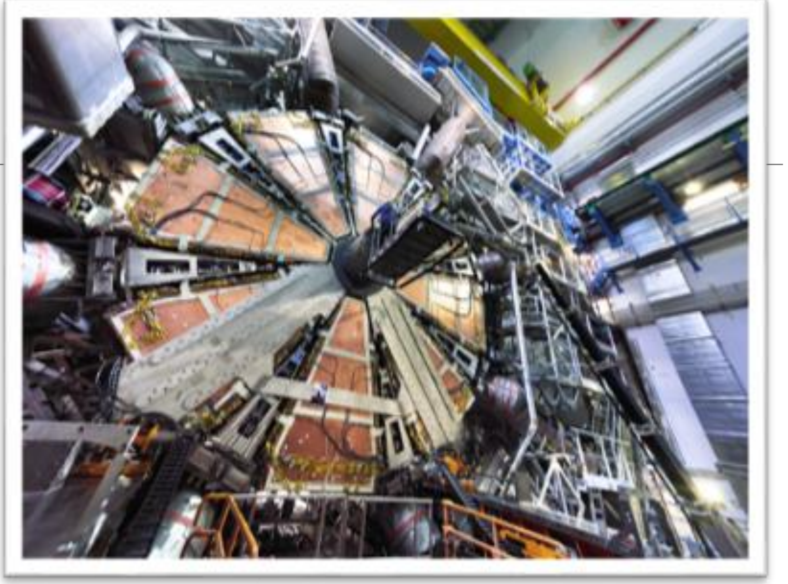
CMS



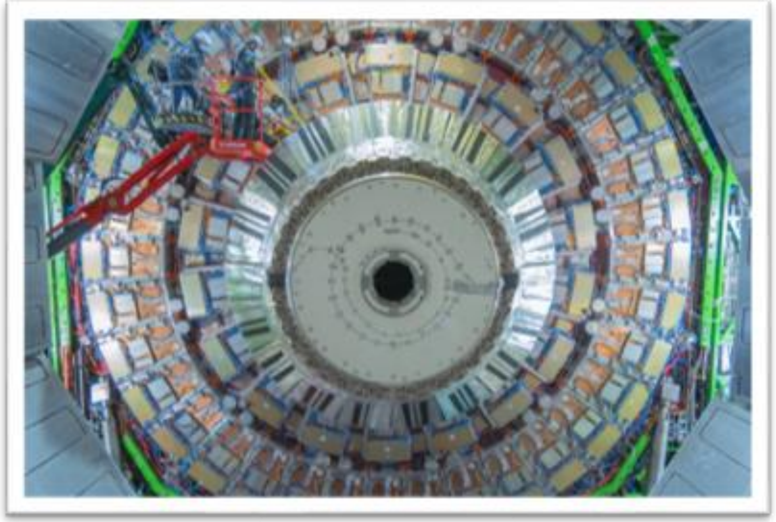
https://indico.cern.ch/event/647676/contributions/2721136/

Muon System

- Fake (forward) muon increases at high $\langle\mu\rangle$
  - Punch-through, shower, non-prompt,…
- ATLAS
  - New Small Wheel (from Run3)
    - Micromegas (focusing on precision)
    - short-strip TGC for fast trigger response
  - Upgrade part of TGC/RPC/MDT
    - integrate MDT p_{T} information in trigger
  - Electronics upgrades
- CMS
  - GEM (partially from Run3)
    - Gas Electron Multiplier (focusing on rate capability)
  - improved RPC
  - Electronics upgrades



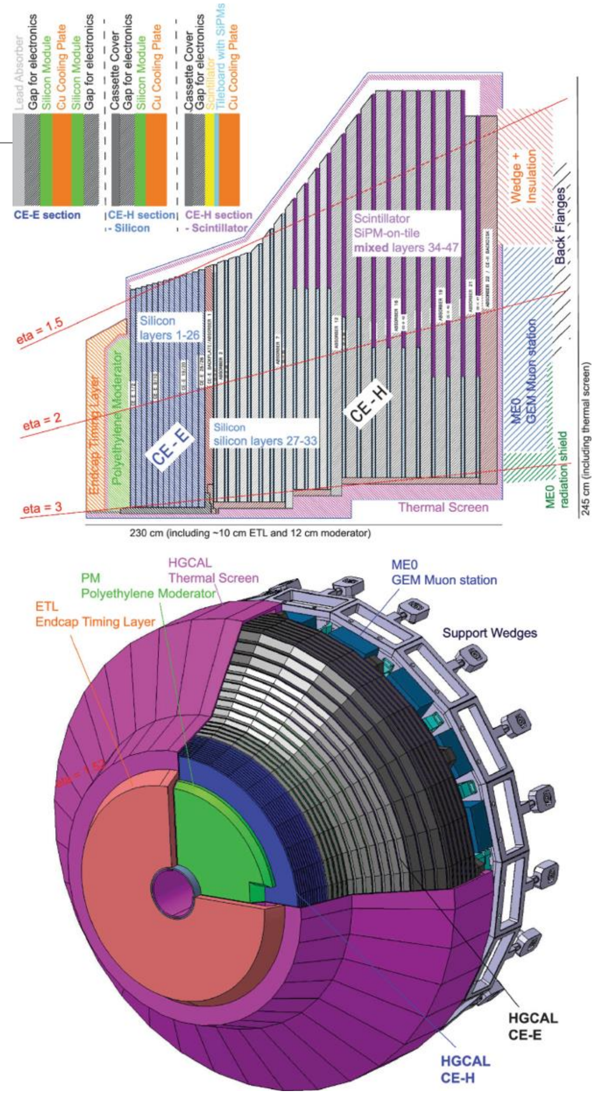
L. Martellini, 2024



GEM (home.cern)

Calorimeter

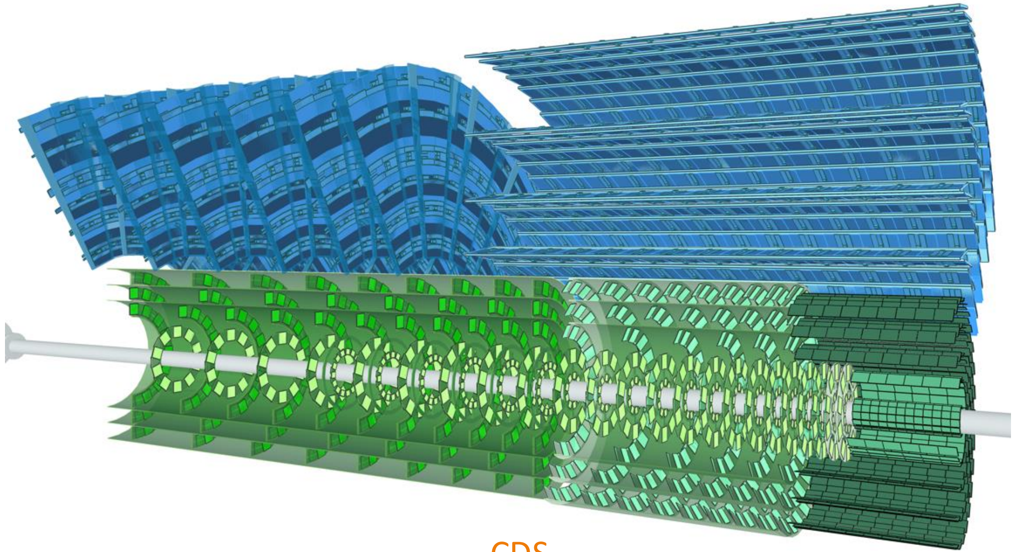
- Overlap of calorimeter shower
  - Overlapped shower cause longer tail in cluster energy → nonlinearly increases fake trigger
- ATLAS
  - Electronics upgrades in LAr/Tile
    - 40 MHz digitization of LAr cells with full granularity
      - Additional L0 inputs complementing super cells
    - 40 MHz digitization of Tile PMT
- CMS
  - High Granularity Calorimeter (HGCAL)
    - $0.5\ \mathrm{cm}^2$ "imaging" calorimeter with rad-hard and 3D readout
    - Electro-magnetic: 26 Si layers with lead, copper, tungsten absorber
    - Hadron: 21 Si/Scint. layers with stainless steel absorber



HGCAL (F. Hartmann, 2024)

Silicon trackers

- High $\langle\mu\rangle$ explodes hit combination in track finding
  - Computationally expensive
- All-silicon tracker (pixel inner + strip outer) with higher granularity and improved radiation tolerance
  - ATLAS: ITk Pixel + Strip
  - CMS: Inner + Outer Tracker
  - Suppress hit occupancy at 1% level
  - Extended forward coverage to |η| < 4.0
  - Material reduction to protect momentum resolution
    - services routing, CO_2 evaporative cooling, and lightweight supports
- L1 Track Trigger in CMS
  - p_T module provide "stub" for high- p_T tracks
  - offload burden from HLT track finding



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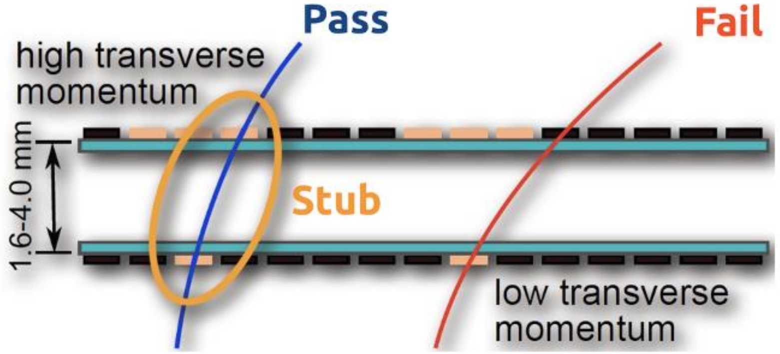
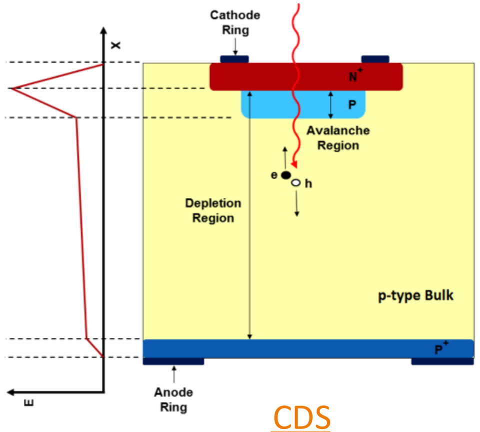


A. Purohit, EPS-HEP 2025

Timing detectors

- Add granularity in another dimension: time
  - 30–40 ps timing to charged particles to separate pileup interactions
- ATLAS: HGTD (High-Granularity Timing Detector)
  - Forward timing layer in front of the LAr endcap calorimeters
    - Coverage: $2.4 < |\eta| < 4.0$
  - LGAD-based high-granularity sensor planes



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- CMS: MTD (MIP Timing Detector)
  - A hermetic timing system covering both barrel and endcap region
    - BTL (Barrel Timing Layer): at the Tracker–ECAL interface
    - ETL (Endcap Timing Layer): endcap disks (forward timing)
    - Coverage: BTL: $|\eta| < 1.45$, ETL: $1.6 < |\eta| < 3.0$
  - BTL: L(Y)SO crystals + SiPM, ETL: LGAD

Production Challenges

- Powering of silicon trackers
  - Many channels, large power consumption, but far from the power source
- Strips: On-detector DC-DC converter
  - Send power with high voltage to reduce cable loss
  - Regulate voltage near-detector
    - ATLAS: on detector, CMS: on service hybrid
  - DC-DC converter development is challenging
    - Study ongoing to understand power-up instability in repetition test at cold temperature with radiation damage

https://power-distribution.web.cern.ch/modules/

- Pixels: Serial Powering
  - Implement Shunt-LDO in module to work correctly with serial powering
    - DC-DC converter is not sutiable due to harsh radiation and limited space
  - Most strict requirement in QC as a bad SLDO module breaks the whole SP chain
    - E.g., severe damage to the FE during bump-bonding could cause short and SLDO failure

Summary

- Both accelerator and detector productions are cutting edge
  - Discovered new issues and measures in early production phase

- We have now transitioned to production phase
  - We are working hard to close a few remaining issues

- We will keep production moving forward to achieve the timely delivery!

Thank you!

ITk Outer Shell

Xmas card design
by Katarina Anthony

Backup

Completed and operational for Run3
Linac 4 replaced Linac 2 (2020)
Beam commissioning (2021)
Providing 160 MeV H^{-} beam to PSB
Space-charge limitations reduced by higher energy
Injection losses reduced by charge-exchange injection
Improved PSB-PS-SPS chain
High-intensity beam commissioning
Tested whole chain including SPS (2025)
Planning 2026 one-month commissioning at the run end

LHC Injector Upgrade

- Completed and operational for Run3
  - Linac 4 replaced Linac 2 (2020)
    - Beam commissioning (2021)
  - Providing 160 MeV H^{-} beam to PSB
    - Space-charge limitations reduced by higher energy
    - Injection losses reduced by charge-exchange injection
  - Improved PSB-PS-SPS chain
- High-intensity beam commissioning
  - Tested whole chain including SPS (2025)
  - Planning 2026 one-month commissioning at the run end

Final-stage Π-mode RF cavities in Linac 4

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