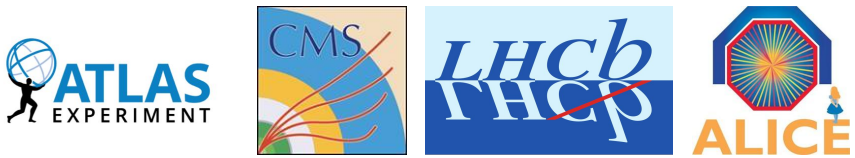
LHC Upgrades and HL-LHC physics prospects

Gerhard Brandt[1] on behalf of the **ATLAS**, **CMS**, **LHC*b*** and **ALICE** Collaborations
[1] Bergische Universität Wuppertal



35th Rencontres de Blois
20-25 October 2024, Blois, Centre-Val de Loire France

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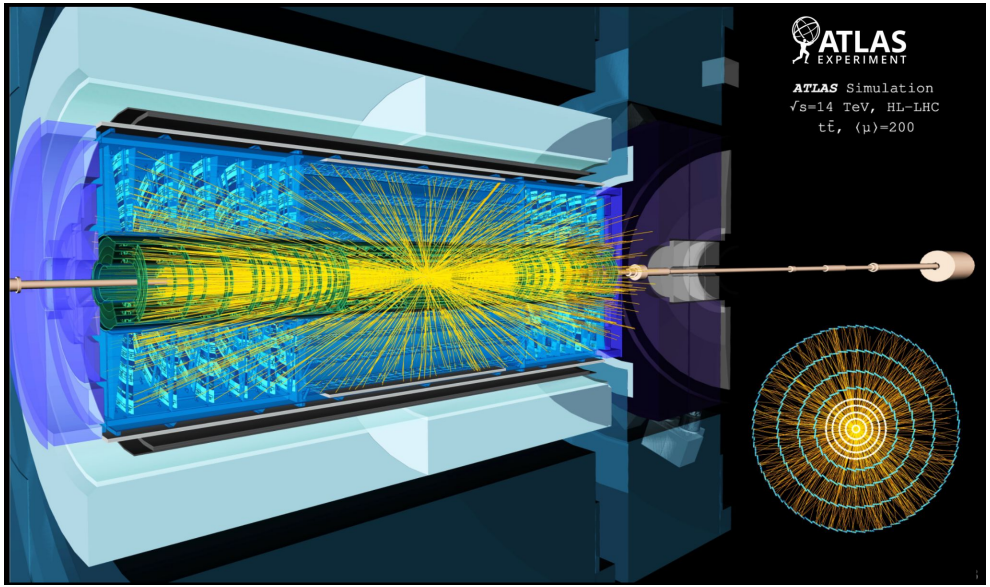
Overview

- HL-LHC Plans
- ATLAS and CMS Detector Upgrades
- HL-LHC Physics Prospects
  - Precision SM Physics
  - Higgs sector
  - SUSY and other BSM
- Proposed LHCb Upgrade II
  - Flavour Physics Prospects
- Proposed ALICE 3 Upgrade
  - QGP Physics Prospects

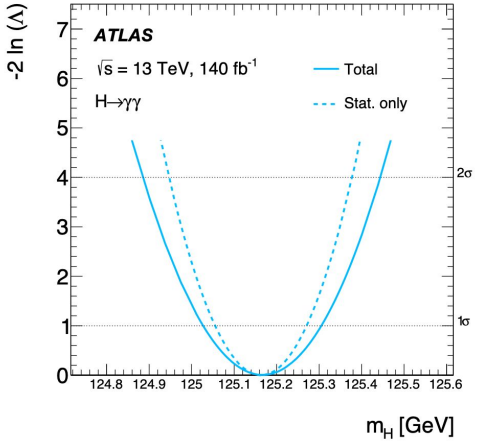


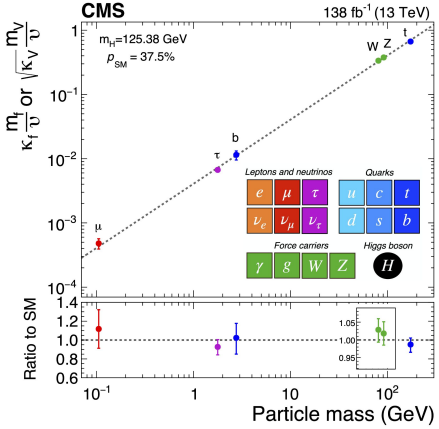
simulated $t\bar{t}$ event at HL-LHC with 200 events pile-up

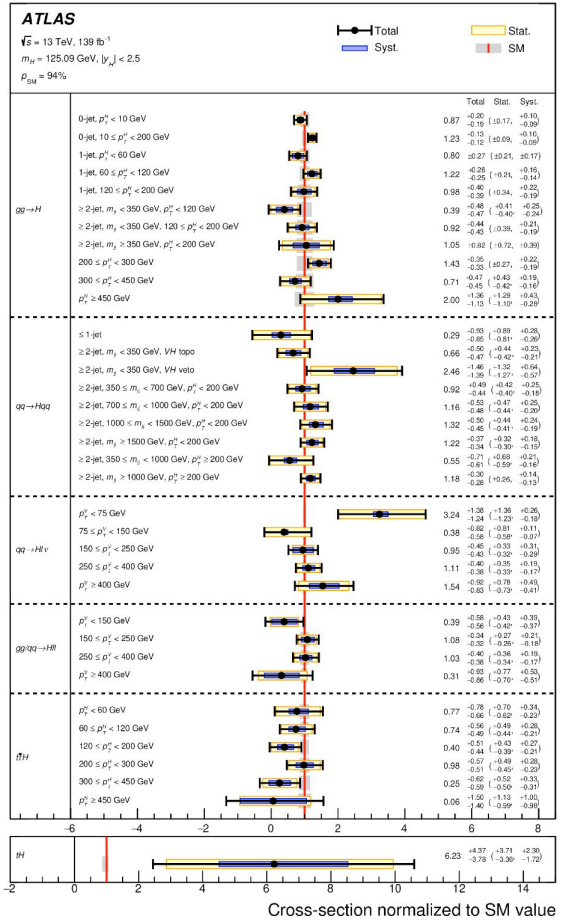
LHC Recap

- 12 years since Higgs discovery were huge Success for Standard Model
- Just to highlight Higgs Sector …
  - 0.09% precision on m_H (=125.11± 0.11 GeV) Phys. Rev. Lett. 131, 251802
  - Couplings measured precisely to
    - 5% (bosons)
    - 10%(3rd gen. fermions)
  - Huge progress in searches for coupling to 2nd generation fermions and for di-Higgs production

→ *see talk by H. Arnold yesterday*



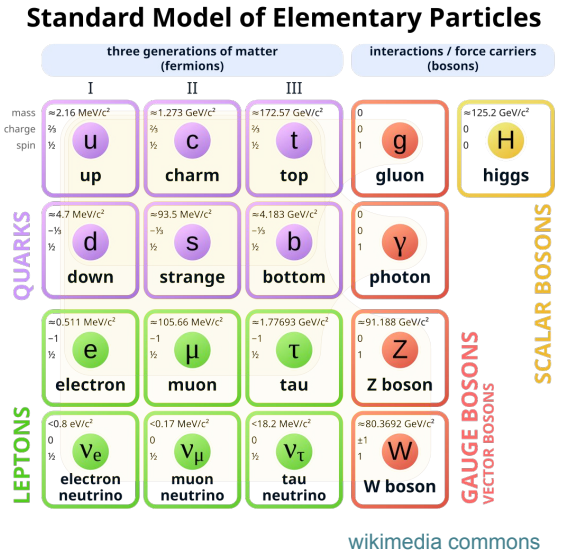




However Many Questions Remain

- Standard Model incomplete description of Nature
- Fundamental questions remain that **must** be addressed:
  - Origin of electroweak scale and electroweak phase transition?
  - Higgs boson non-natural? Composite?
    Part of an extended scalar sector?
  - Flavor puzzle: Origin of fermion generations, masses, mixings?
  - Matter - antimatter asymmetry (CP violation)?
  - Nature of dark matter?
  - What is the quark-gluon plasma (QGP) formation mechanism and its properties?
- Those questions can be addressed at the High-Luminosity LHC (HL-LHC)

Answers require upgrades to collider and experiments



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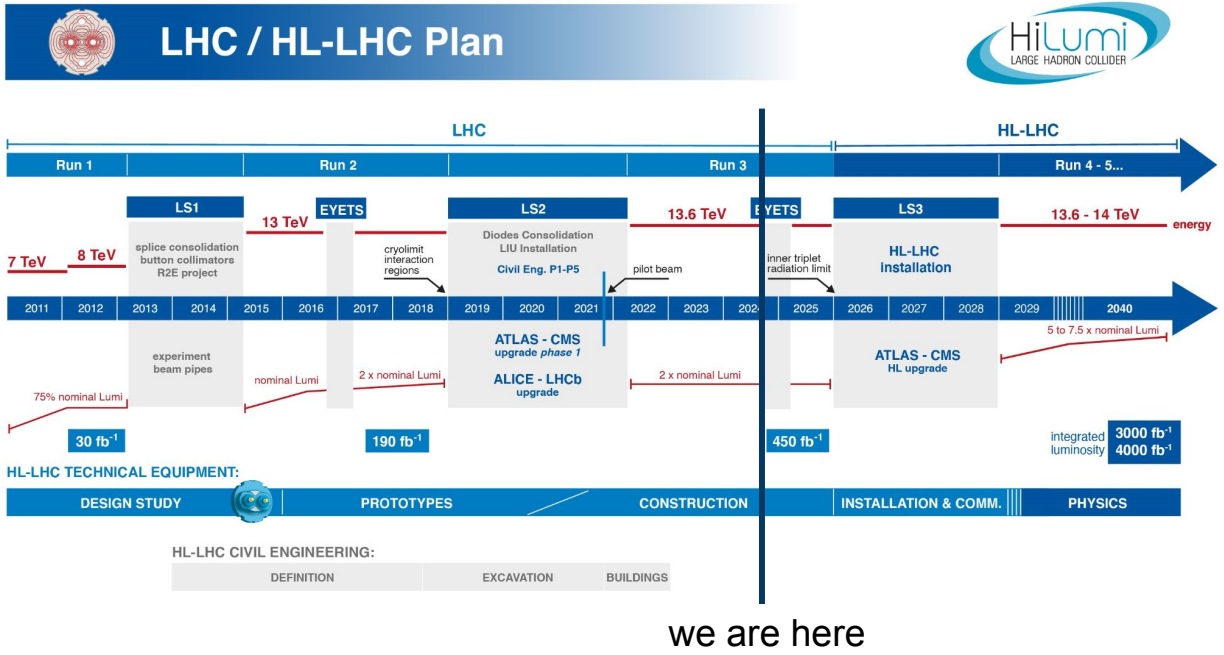
LHC to HL-LHC

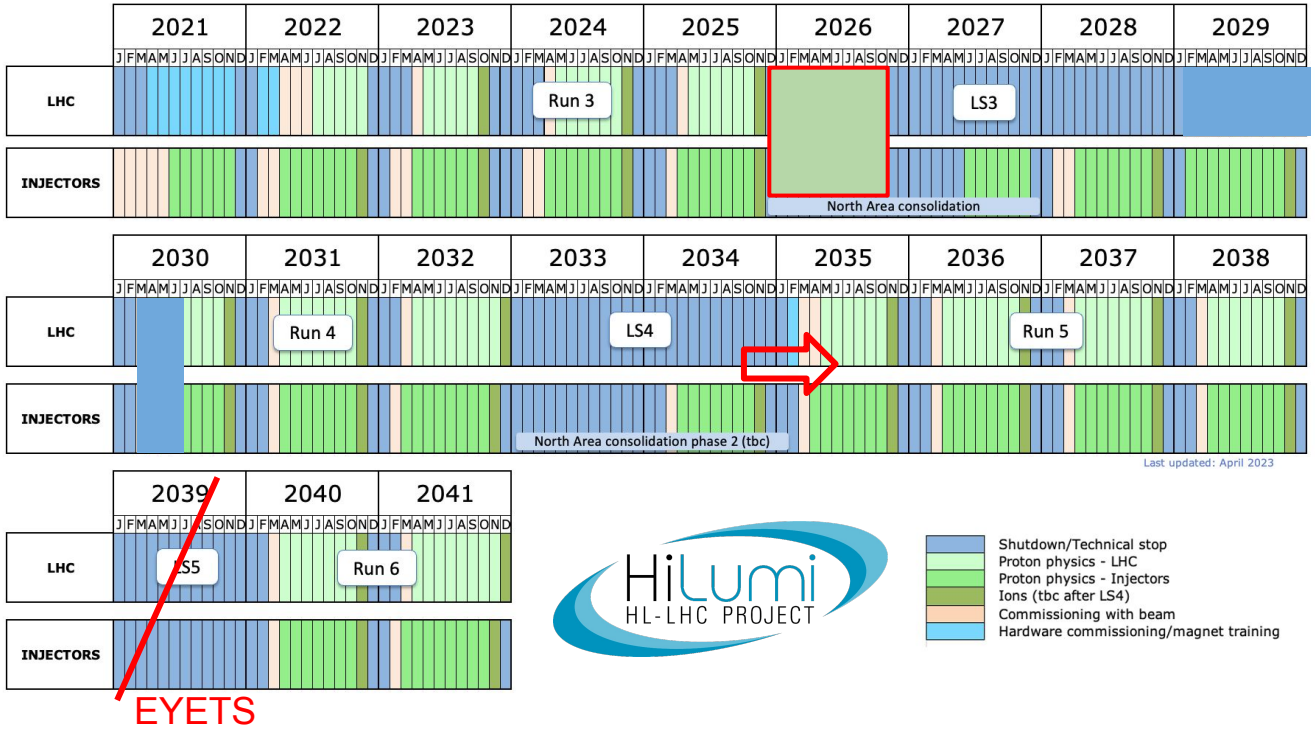
- 350 fb^{-1} already collected at LHC
- LHC delivering *pp* at 13.6 TeV center-of-mass energy
- Nominal Luminosity $L_{nom} = 10^{34}\ cm^{-2}s^{-1}$
- 500 fb^{-1} within reach for Run-3
- 8 years since HL-LHC approval
- 4.5 years remain until the end of LS3



we are here

Updated HL-LHC Schedule

- Delays in upgrades have pushed back original schedule
- Series production for HL-LHC accelerator upgrades now well underway
- Run-3 planned into 2026
- LS4 moved by 1 year
- LS5 replaced by EYETS



HL-LHC Planned Specs

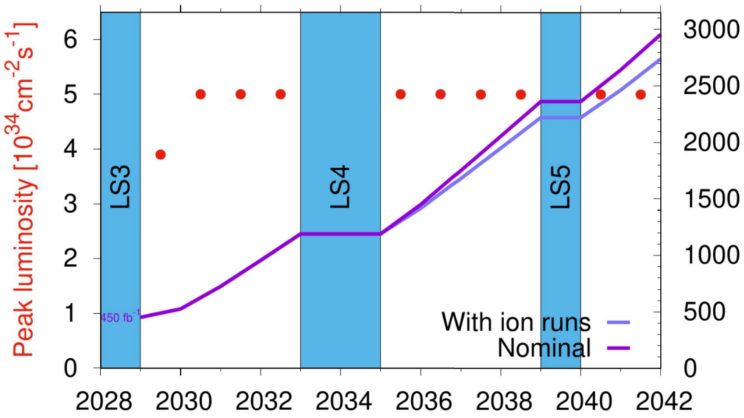
- Operation scenarios for
  total int. luminosity of up to 4000 fb^{-1}
  in around 10-12 years (ca. 10x LHC)
  (~250 fb^{-1} / year)

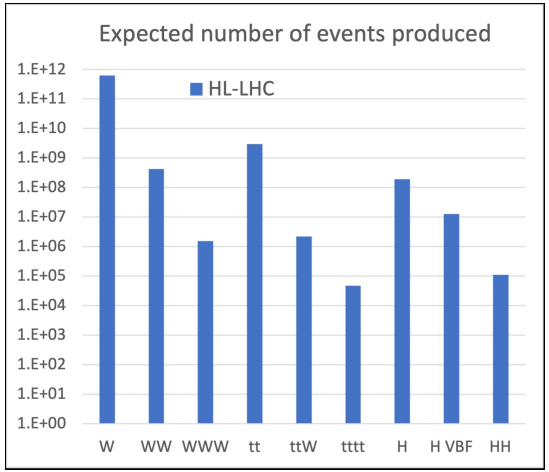
- "Nominal" scenario
  - Luminosity 5 x 10^{34} $cm^{-2}s^{-1}$
  - Events/crossing ~130

- "Ultimate"scenario
  - Luminosity 7.5 x 10^{34} $cm^{-2}s^{-1}$
  - Events/crossing ~200

- Operation with levelled luminosity
- Higher rates ad higher radiation doses a challenge for machine and experiments

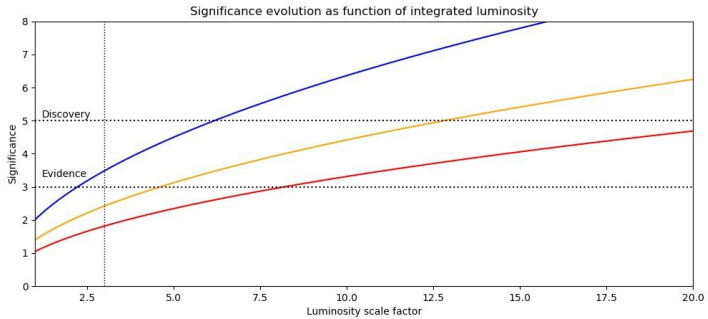
→ Factory for access to huge numbers of Higgs bosons, other heavy particles and rare processes



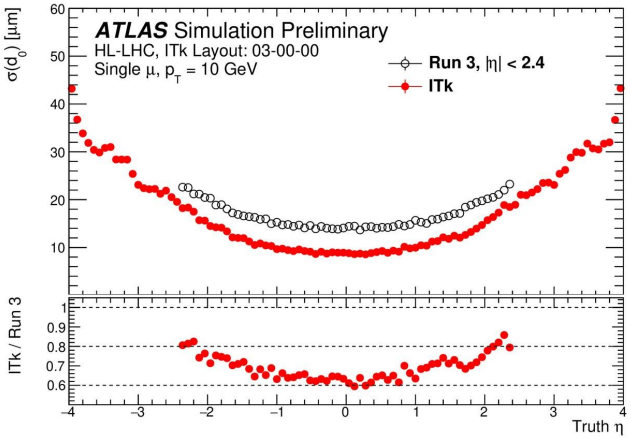


Why do we need Detector Upgrades

- Survive higher radiation doses and see through more pile-up
- Higher Data Volume Handling
  - Expect ~10x integrated lumi at HL-LHC compared to LHC
- However in spite of huge number of particles produced significance increase by luminosity scaling alone is *relatively slow*
- Detector and software upgrades should allow **much better sensitivity**
  - Extended Physics Reach e.g. via increased solid angle
  - Enhanced Precision eg. via improved vertexing



Cowan et al.
Eur.Phys. J.C. (2011) 71

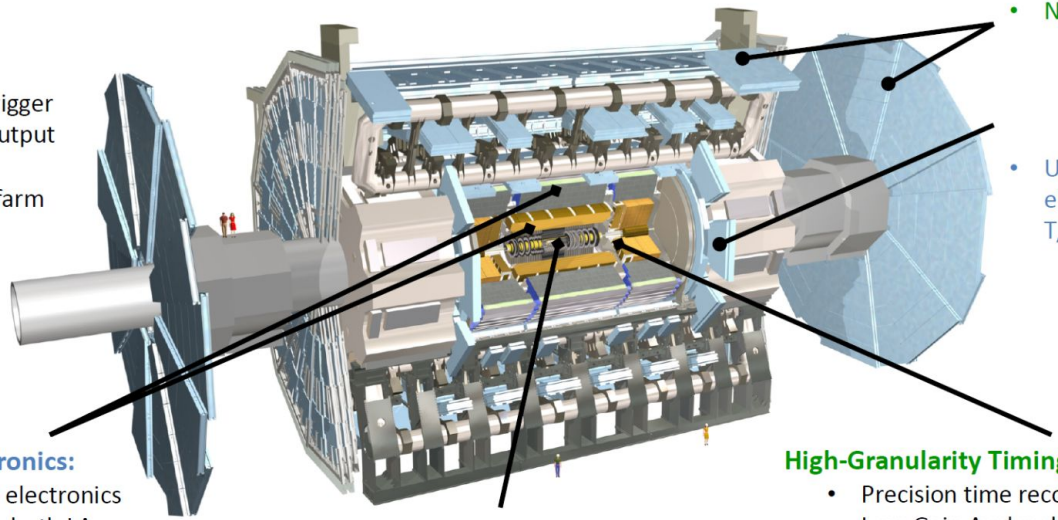


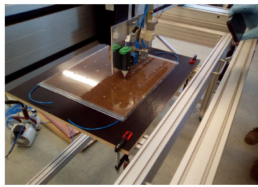
ATLAS Phase II Detector Upgrades for HL-LHC

New and improved detectors:

Trigger and DAQ Upgrade:
- Single-level trigger with 1 MHz output (x10 current)
- Faster event farm

Muon Chambers:
- New Inner-Barrel chambers
  - Improved trigger efficiency and momentum resolution
  - Reduced fake rate
- Upgrade of the detector electronics for the new T/DAQ





Calorimeter Electronics:
- On-detector electronics upgrades for both LAr and Tile Calorimaters

→ 40MHz readout for triggering

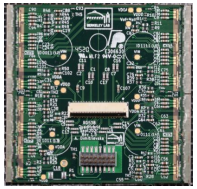
Inner Tracker (ITk):
- Replacement for Inner Detector
- All-silicon, 9 layers up to $|\eta|=4$
- Less material, finer segmentation → improved vertexing, tracking, b-tagging

High-Granularity Timing Detector:
- Precision time reconstruction (30ps) with Low-Gain Avalanche Detectors (LGADs)
- Improved pile-up rejection in the forward region
- Also bunch-by-bunch luminosity

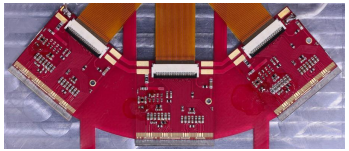
J. Pater, ICHEP 2024

ATLAS Phase-II Inner Tracker

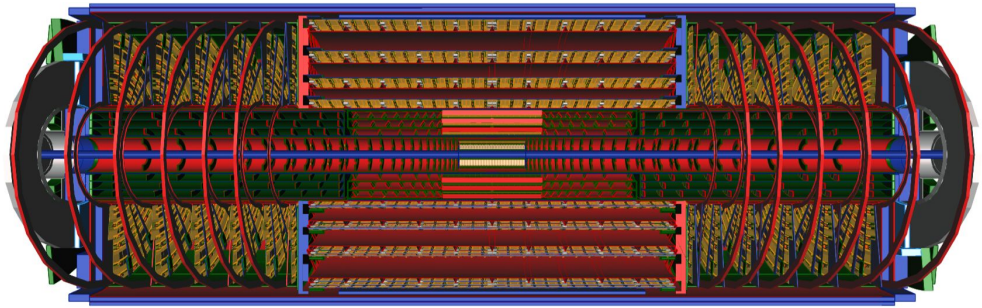
- Complete replacement of the current Inner Detector tracking system
  - All-silicon
    - 168 m^2 of strips (~18000 modules)
    - 13 m^2 of pixels (~10000 hybrid Si modules)
  - Radiation hard design:
    up to 10^{16} n_{eq}/cm^2 on innermost layers
- Improved performance:
  - Increased coverage
    $|\eta| < 2.5 \rightarrow |\eta| < 4.0$
  - > 9 space points per track
  - Reduced material budget
    - Pixel: Serial powering with up to 14 modules in chain
  - Finer segmentation
- Many parts currently in production



Planar Pixel Quad Modules in Barrel Region



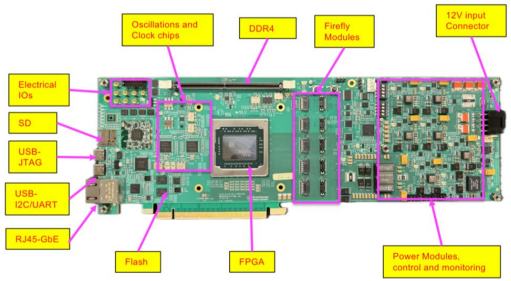
Pixel Ring Triplet Module



ATLAS Phase II TDAQ and HGTD Upgrades

Trigger and DAQ Upgrades

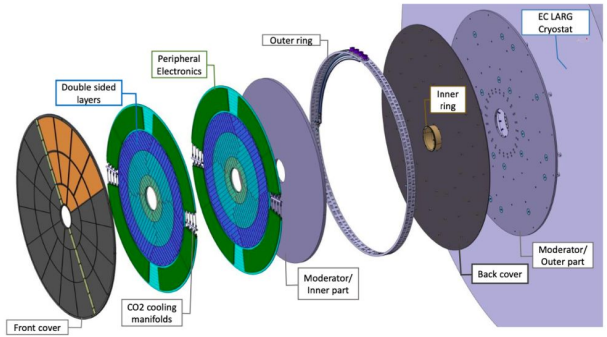
- Move to 1MHz single-level L0 HW trigger w. full event building for all systems
- SW-based Event Filter (HLT) at 10 kHz using ML and NN on GPUs
- All frontend electronics linked via custom FPGA based FELIX readout to DAQ



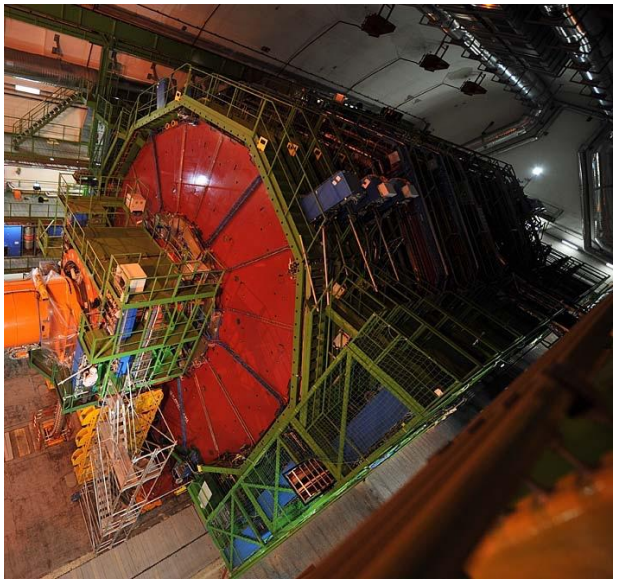
FELIX Custom readout Board

High-Granularity Timing Detector (HGTD)

- New Low-gain Avalanche Detector (LGAD) arrays
- Disentangle pileup in fwd region with timing information
- Precision luminosity bunch-by-bunch measurements (together with BCM' and LUCID3)

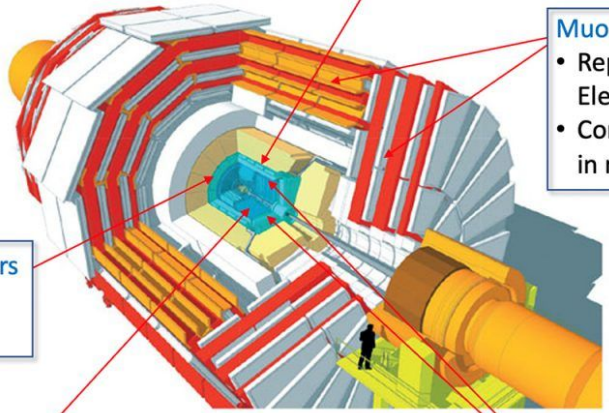


CMS Detector Upgrades



Trigger/HLT/DAQ
- Track information in L1-Trigger
- L1-Trigger: 12.5 μs latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)



Muon Systems
- Replace DT & CSC FE/BE Electronics
- Complete Muon coverage in region $1.5<\eta<2.4$

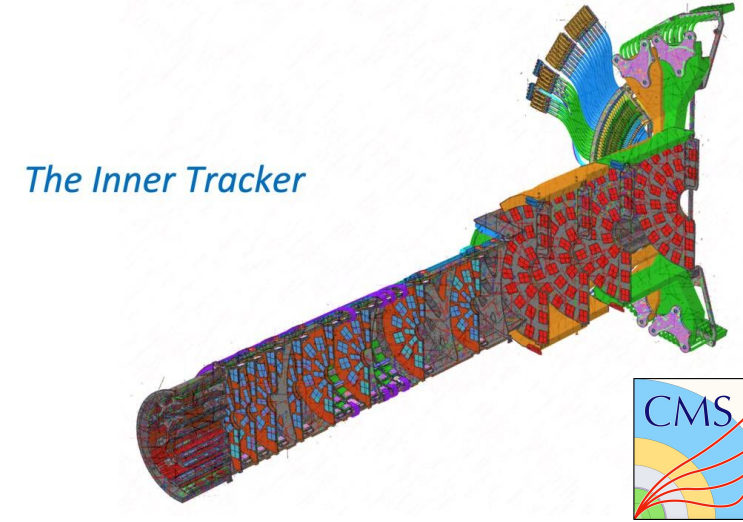
New Endcap Calorimeters
- High granularity
- 3D capable

New Tracker
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (p_T>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to η=4

New Precision Timing Detector
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

CMS Tracker Upgrade

- Key features of the new Phase 2 Tracker
  - Extended tracking acceptance up to |η| = 4
  - Increased granularity
  - Radiation tolerance up to 10^{16} 1 MeV n_{eq}
  - Expected rate 3 GHz/cm^2 innermost pixel layer
  - Material budget reduced by factor 2
  - Improved performance
- Inner Tracker
  - 5 m^2 of silicon + 2G readout channels
  - 65nm ROC chip only active element on modules
- Outer Tracker
  - Microstrips + macropixels
  - Tilted barrel geometry for better triggering and reduced number of modules
  - **190 m^2** of silicon
  - 213M readout channels

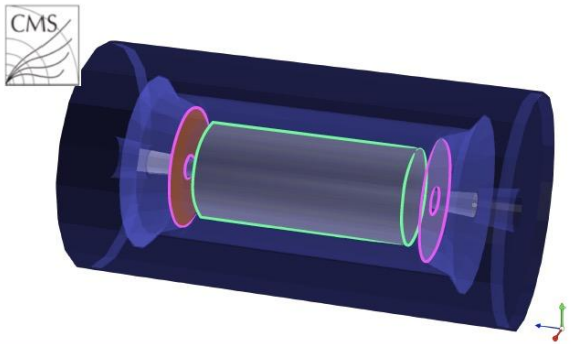


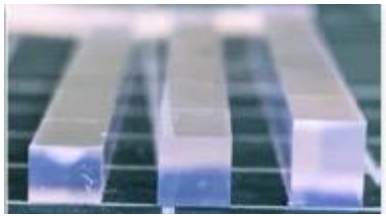
Outer Tracker
Tilted barrel geometry

CMS Timing and Muon Upgrades

New Timing Detector MTD to measure the MIP

- Thin layers (ETL, BTL) between tracker and calorimeters
- Hermetic coverage for |η| <3
- Time resolution of 30-50 ps to MIPs

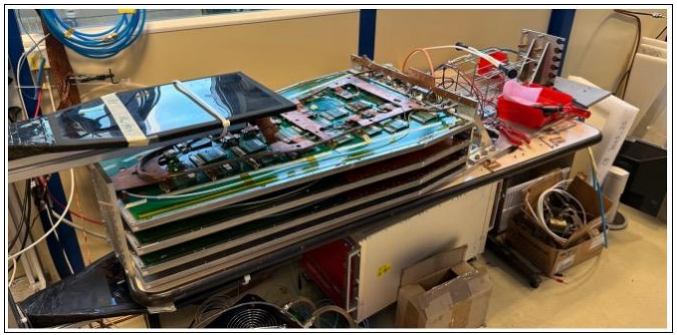




38 m^2 of LYSO Crystals in Barrel Timing Layer

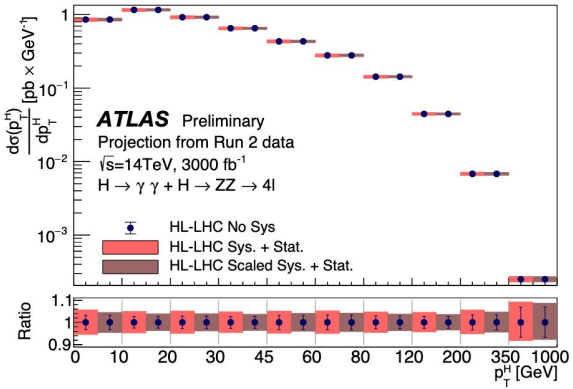
New Muon detectors

- Restore redundancy and extend the muon coverage up to |η| < 2.8
- Improve Trigger efficiency without increasing the trigger rate
- Improve Muon reconstruction

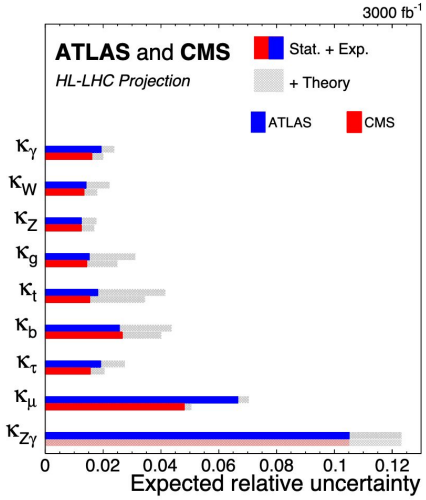


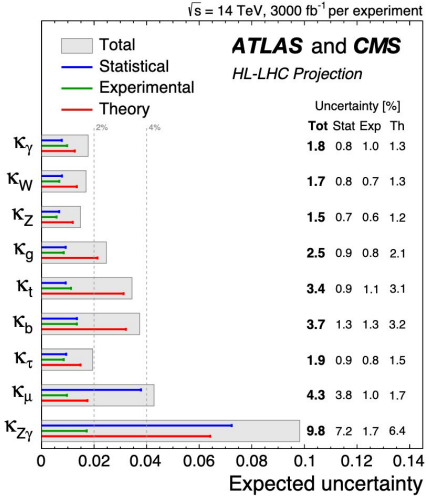
Key Reports with Upgrade Physics Projections

- CERN Yellow Report [CERN-2019-007]
- European Strategy Update [CERN-ESU-2019]
- Snowmass White Paper [ATL-PHYS-PUB-2022-018]



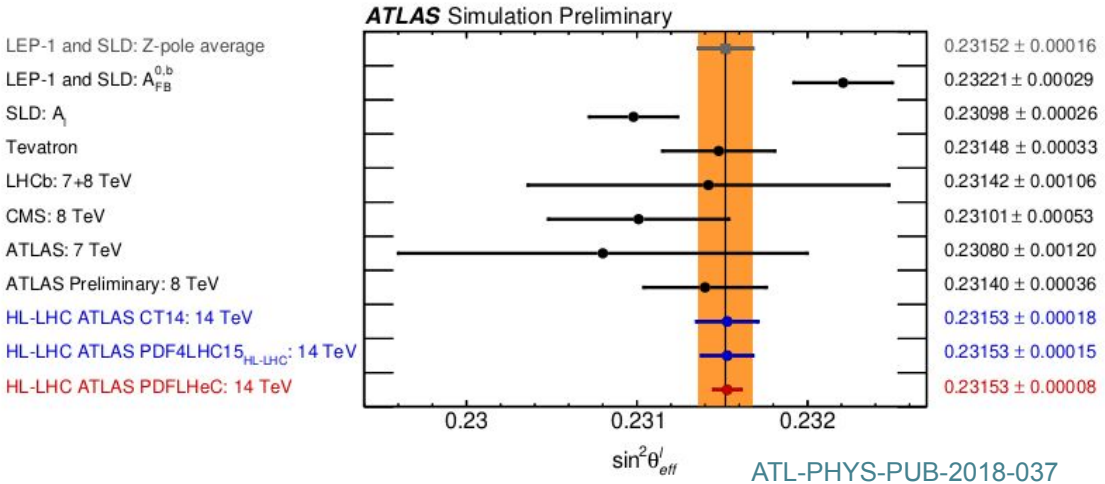
- Most projections from 2018
- Improved techniques should allow to do better now
- Novel reconstruction techniques being developed for tracking, hard jets / multi hard-scatter vertexing
- Novel analysis techniques employing ML / (G)NN techniques





Standard Model Projections Example

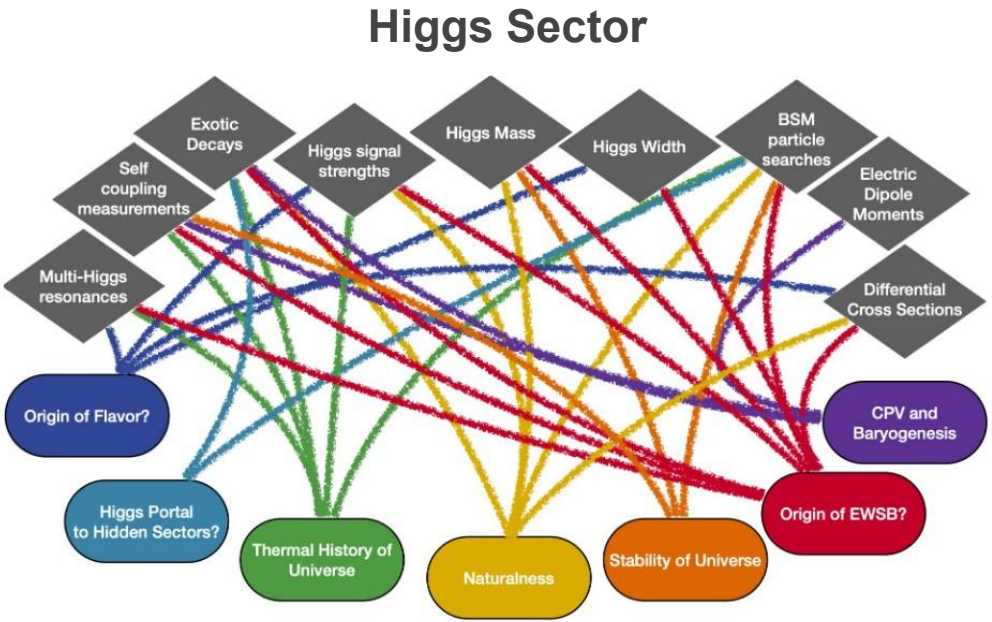
- EW mixing angle using forward-backward asymmetry in DY dileptons
- Benefit from statistics and improved fwd electron reconstruction
- Should settle LEP-1 SLD discrepancy



ATL-PHYS-PUB-2018-037

Higgs Sector at HL-LHC

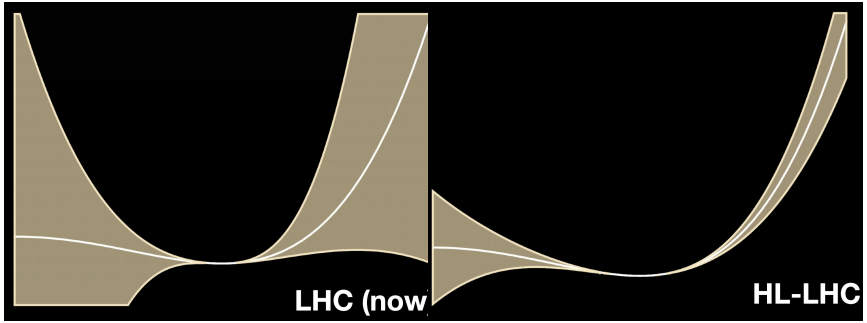
- Higgs Boson: Last remaining puzzle piece of SM
- Much better insight at HL-LHC compared to LHC
- Higgs Sector potential gateway to new physics



Open Questions in Standard Model → New Physics?

Snowmass 2021 Report ArXiv:2209.07510

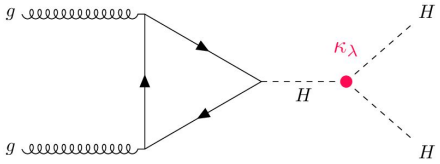
Higgs Potential and Higgs Self Coupling

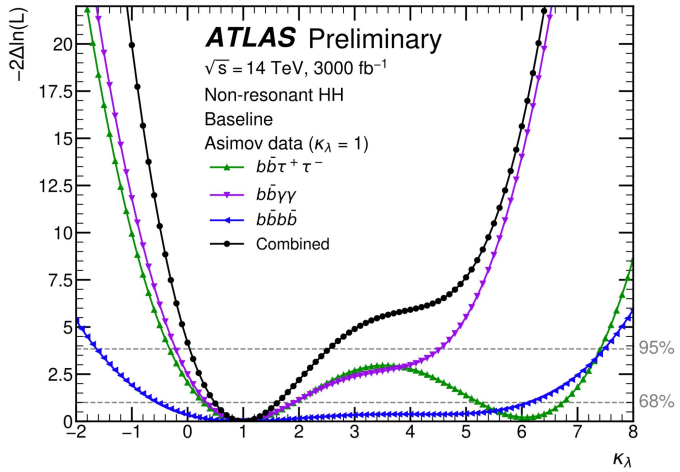


- Measurement of Higgs potential science driver for HL-LHC
- Largely unconstrained so far
- Shape of potential
  - Key to understand EW phase transition in early universe
  - Determines vacuum stability

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4}H^4$$

- Higgs self coupling: *H* pair production gives tri-linear coupling
- Single Higgs production sensitive to coupling via higher order corrections





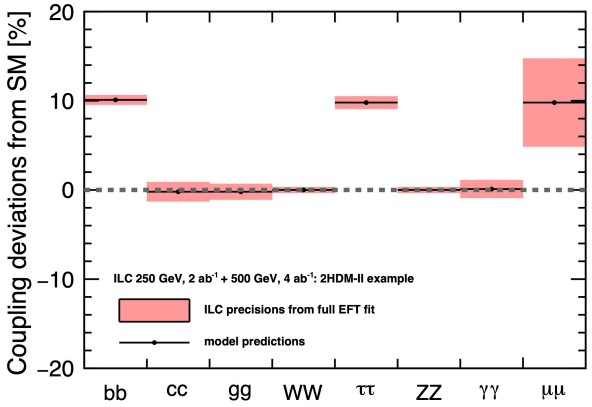
ATL-PHYS-PUB-2022-053

Higgs Couplings Sensitivity to BSM

- Higgs coupling deviations depend on BSM scenario
- High p_T region of Higgs diff. cross section sensitive to BSM

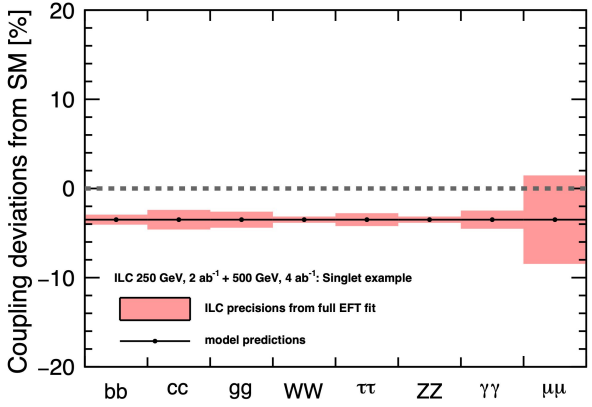
2HDM Type-II

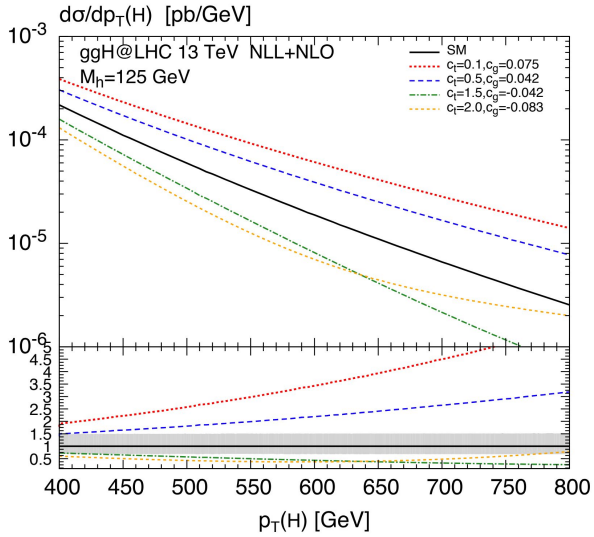
$m_A = 600$ GeV, $\tan\beta = 7$



Extra Higgs singlet

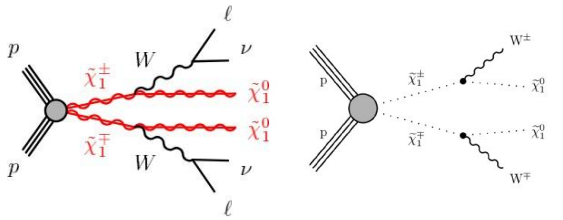
$m_X = 2.8$ TeV, max allowed mixing

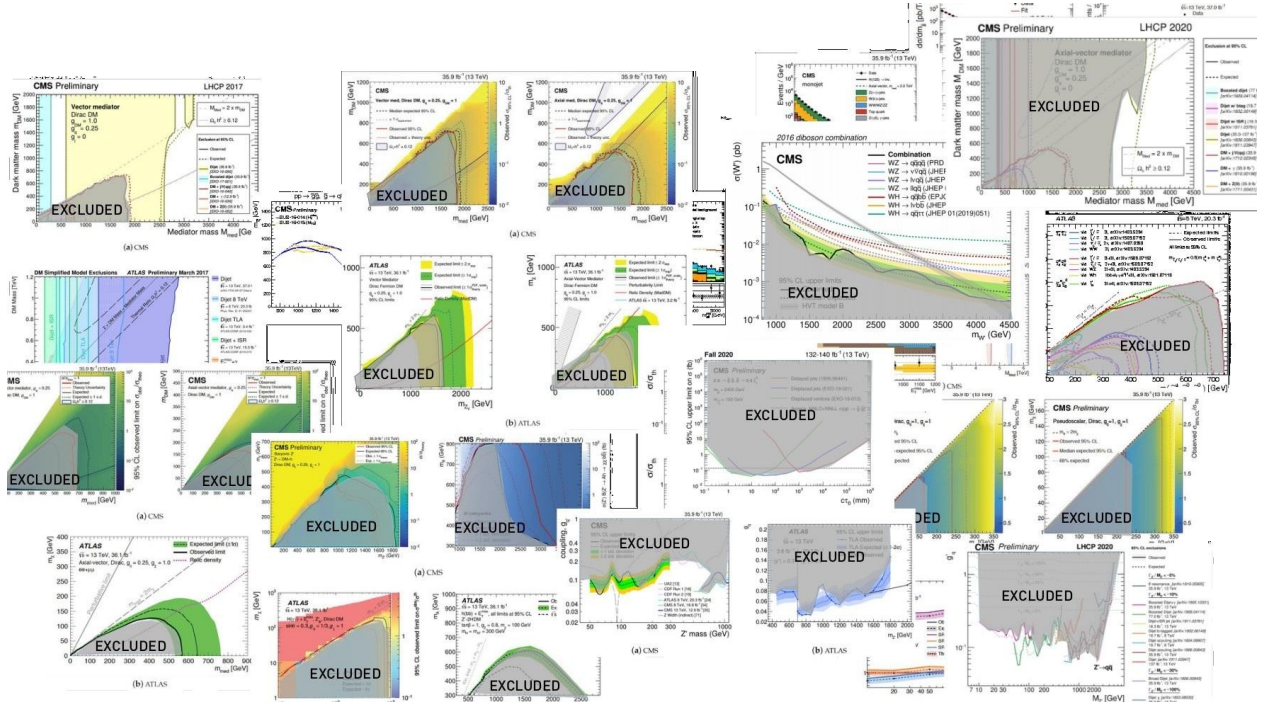




What happened to SUSY?

- If it exists, it's hiding very well…
- HL-LHC still has sensitivity in very specific scenarios
- eg. very specific chargino or stau pair production scenarios

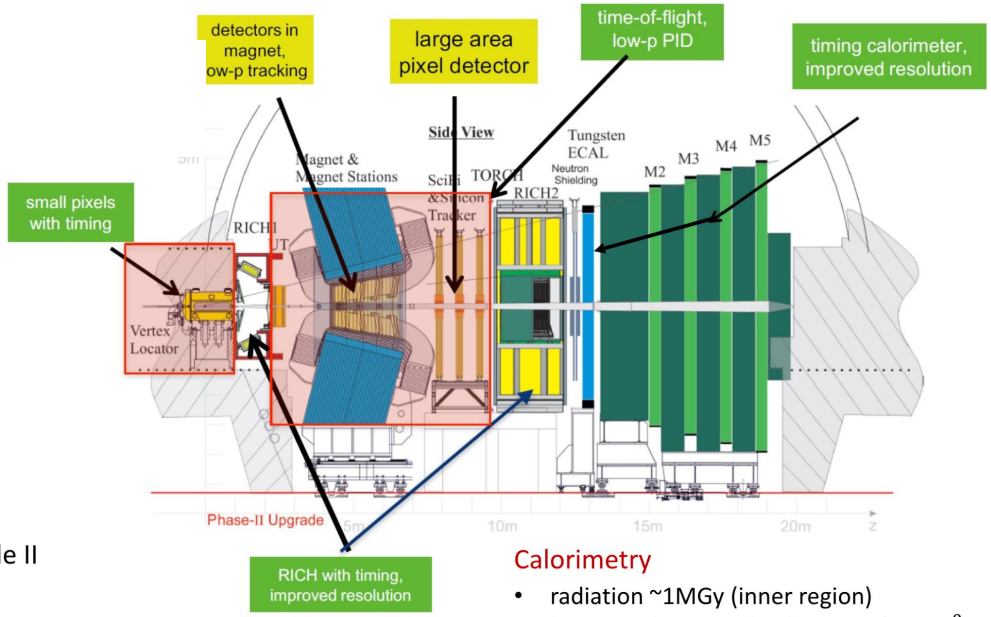




adapted from Thea Aarrestad, CERN-70 symposium, Bergen 13/9-24

Proposed LHCb Upgrade II

- Flavor physics programmes by all LHC experiments, but LHCb is dedicated detector
- New Trackers **VELO II** , **UP** and **Mighty Tracker**, Magnet Stations with scintillators proposed
- New PID system with **RICH 1 & 2**, **TORCH**
  - Improved em. Calorimeter **PicoCAL**
    - higher resolution
    - added timing information
  - Upgraded Muon detectors μ**RWELL**, **MWPC**
- "Triggerless" - record everything
- Goal to put stringent test on CKM paradigm with 300 fb^{-1} 300 fb^{-1} of *pp* collisions in Run 5 & 6
- Scoping document submitted, TDRs planned
  CERN-LHCC-2024-010



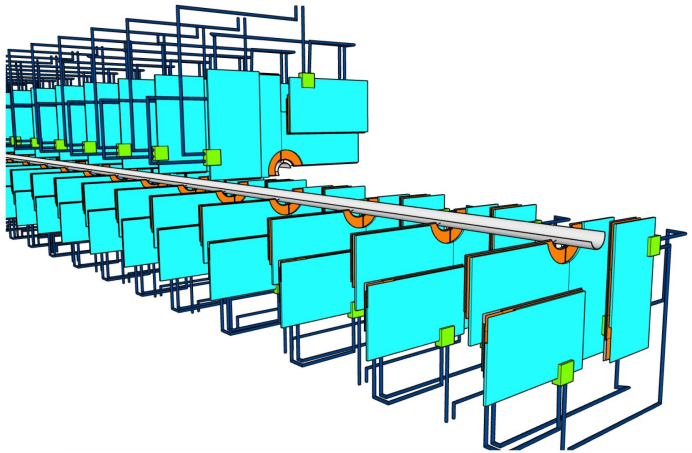
e II

Calorimetry

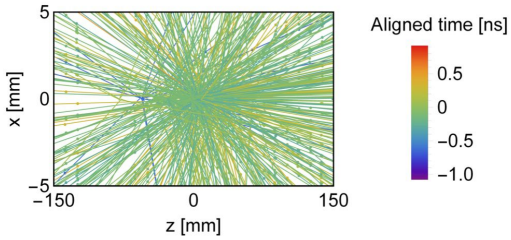
- radiation ~1MGy (inner region)
- large combinatoric background from π^0

Proposed LHCb VELO II Vertex Locator

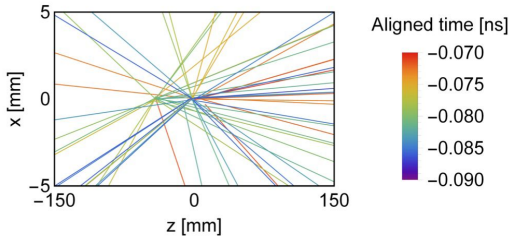
- 20ps/track time resolution
- ASIC bandwidth > 250 Gb/s
- 6x radiation hardness w.r.t. VELO



without 20 ps timing



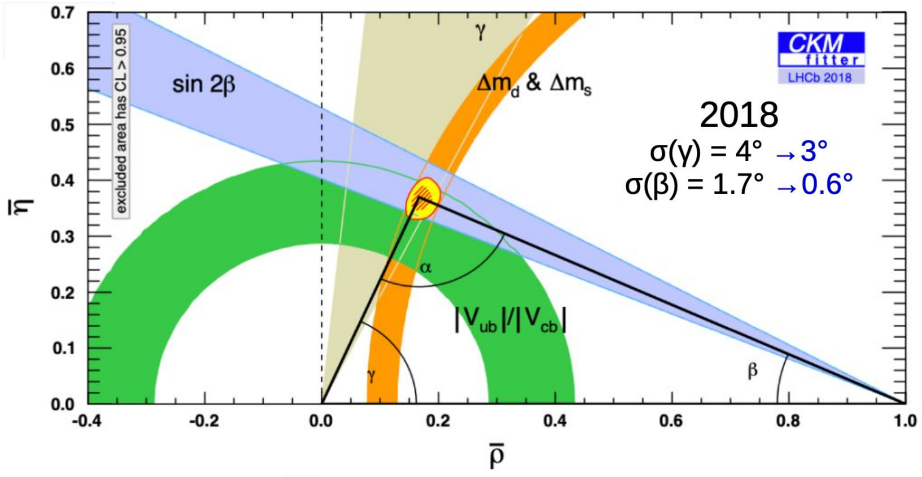
with 20 ps timing

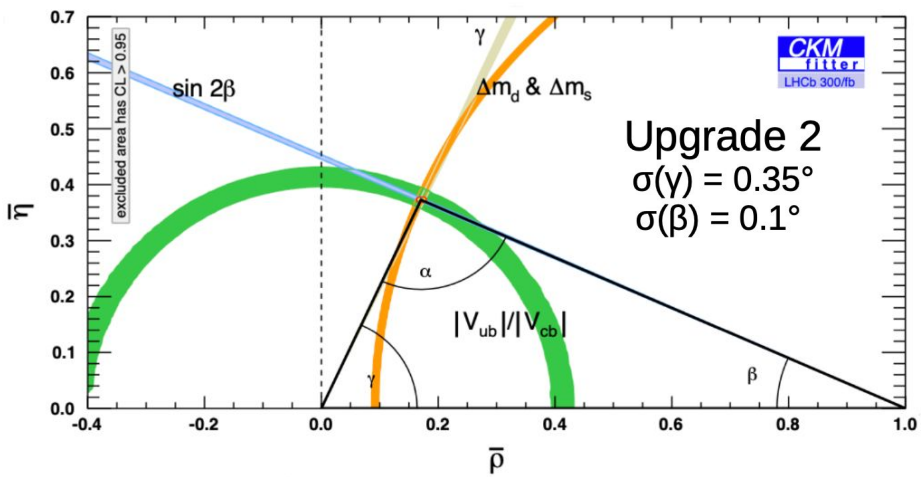


- Same or better performance compared to LHCb but at HL-LHC conditions (7x pile-up)

Flavor Physics at the HL-LHC

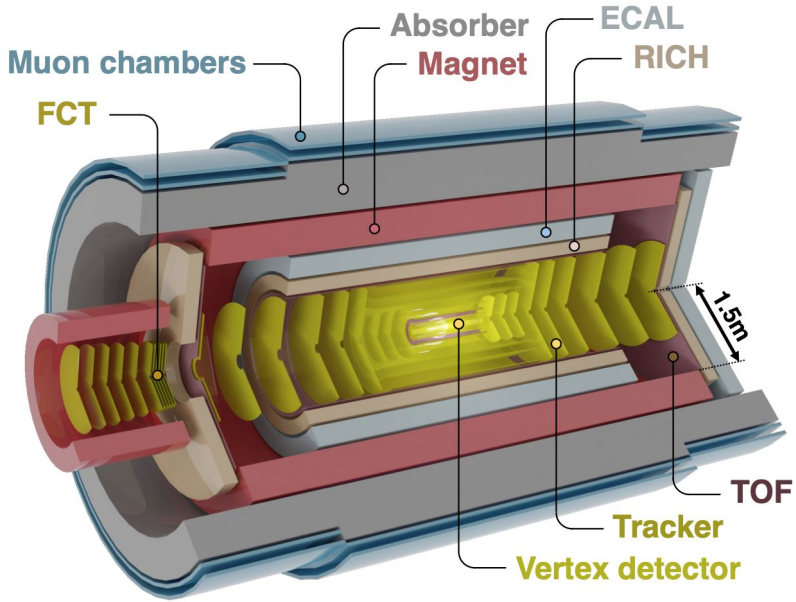
- LHCb has outperformed expected Run 2 sensitivities for both β and γ
- Reasons for LHCb Upgrade II: Are there additional sources of CP violation? Does lepton universality hold? → input to many BSM Searches
- Plan to make the most precise measurement of all 5 key CP violation parameters (β, γ, ϕ_s, A^s_{sl}, A^d_{sl}) in the *B* system
- Also physics programme for CPV in charm, RH currents, QCD spectroscopy, fixed target, …





Proposed ALICE 3 Upgrade

- Upgrades for Run 4:
  - New bending vertex detector ITS3
  - FoCal
- Upgrades for Run 5 & 6:
  - New detector with better pointing resolution, tracking and PID
  - η coverage 4x larger than ALICE
- Goal to collect 35 nb^{-1} of *Pb+Pb* collisions

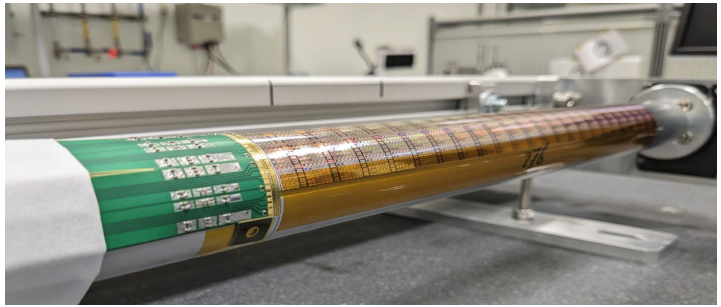


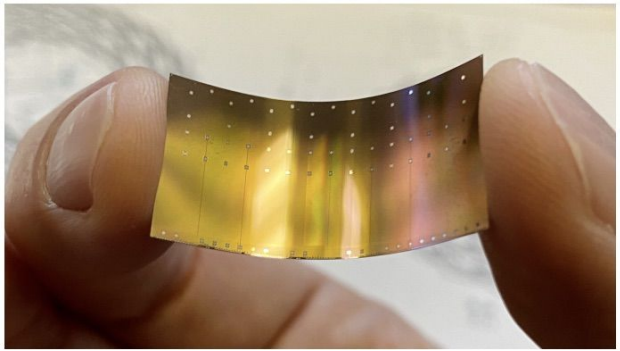
ALICE 3 Letter of Intent
https://arxiv.org/abs/2211.02491

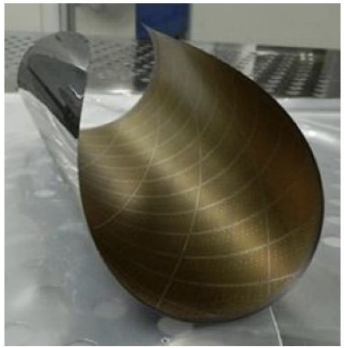
ALICE 3 ITS3 Vertex Detector R&D

TDR https://cds.cern.ch/record/2890181

- Ultra-thin bending silicon pixel sensor
- Material budget only 0.05%X/layer
- Demonstrated with 12 inch wafers
- Bent to cylinder around carbon foam
- Physics analysis improvements
  - Focal, prompt photons
  - Excellent $\pi^0\gamma$ separation
  - Can probe QCD at extremely low momentum fractions
  - Secondary vertex resolution (*b*,*c*)

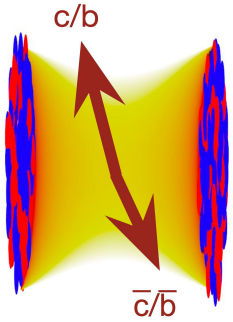


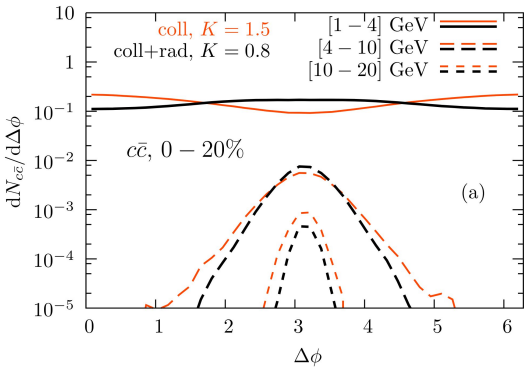


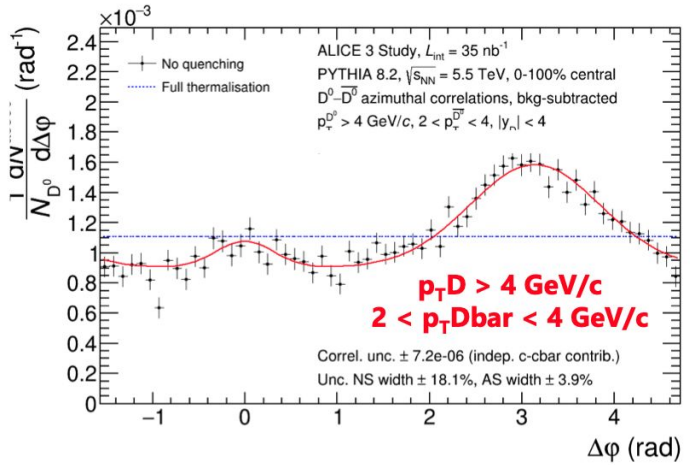


Physics of the Quark Gluon Plasma at the HL-LHC

- How do properties of hadrons and the quark-gluon plasma arise from QCD?
- Study formation and properties of QGP in *Pb+Pb* collisions
- Heavy-quark correlations
  - What drives system toward thermal equilibrium?
  - Azimuthal (de)correlation between and from produced back-to-back provides direct access to interactions with QGP
  - Complementary to flow measurements
  - Requires large statistics of high-purity D mesons w/ larger η coverage due to significant broadening at low pT
- First differential measurements of e^+e^- emission to probe QGP temperature as a function of time
  - Requires very light and precise tracker







Summary

- HL-LHC will address key questions/puzzles of particle physics w/ multi-facetted program
- Only tip of the iceberg of total effort going into upgrades for HL-LHC could be shown here
- Only glimpse of the full HL-LHC program could be shown here
- Full exploitation of HL-LHC is key
  - **Last hadron collider for decades!**
  - Many years before other opportunity to directly probe Higgs potential or access rare (exotic?) Higgs decay
  - 100x more Higgs bosons than at e^+e^- colliders

The particle physics iceberg