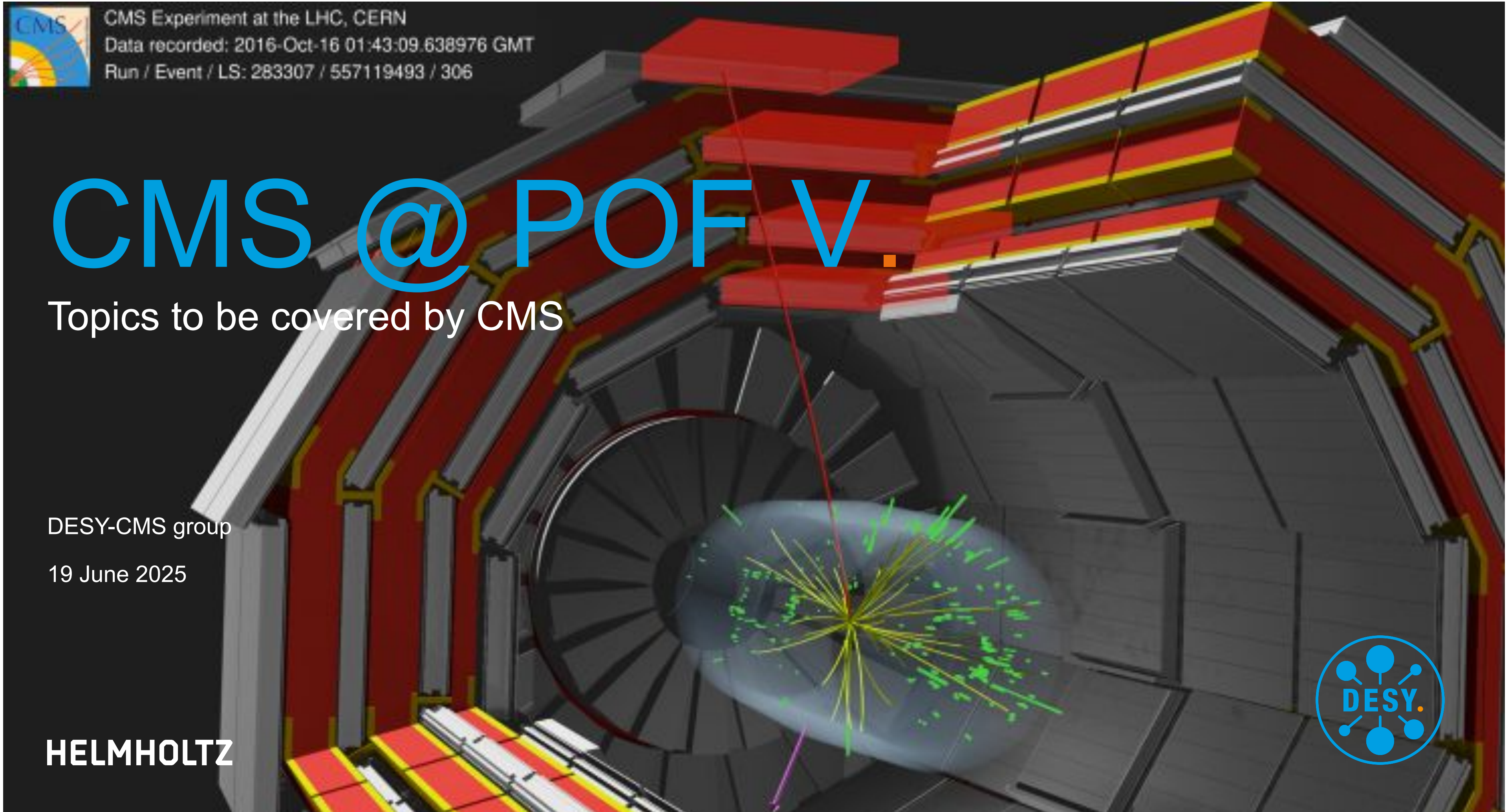


CMS @ POF V.

Topics to be covered by CMS

DESY-CMS group

19 June 2025

HELMHOLTZ

CMS and ATLAS @ DESY: synergy and complementarity

DESY groups are almost the largest groups in their experiments

- Both groups are key players in the construction of the most complex upgrade detectors:
  Tracker endcaps (shared clean rooms and infrastructure), and HGCAL in CMS
- Profit from complementarity in data analysis, exchange with each other and theory (combinations, etc)

DESY-CMS group:

- Contribution to 10-15% of all CMS papers (342 papers so far in PoF IV)
- Important contributions to education: 42 PhD thesis so far in PoF IV (+9 BSc and 7 MSc theses)
- Leadership in the experiment on all levels, including Physics Coordination and Collaboration Board Chair

Moving from this comfortable position into PoF V:

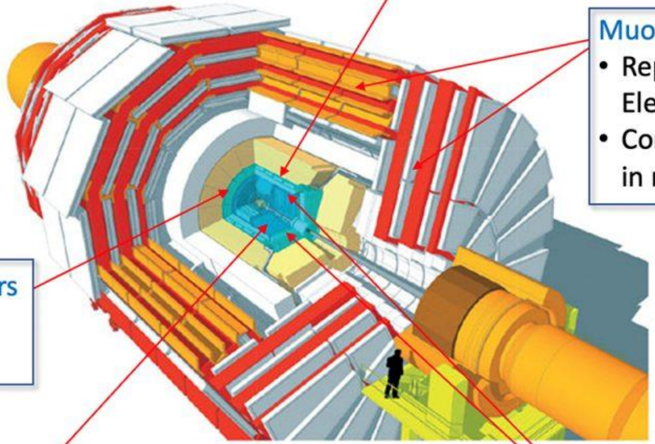
- **Following the comments from the reviewers:**
  - Ensure that the future overall program portfolio remains clearly focused on the science objectives of MU and is overall scoped to ensure delivery within available resources.
  - Ensure the tremendous and sustained investment in the hardware contributions to the experimental program continue to translate into leadership in the scientific exploitation of the projects.

CMS at HL-LHC

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 $1.5<\eta<2.4$



DESY!

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 $\eta=4$

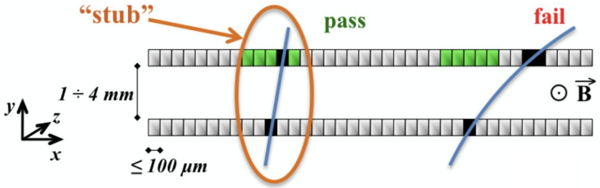
DESY!

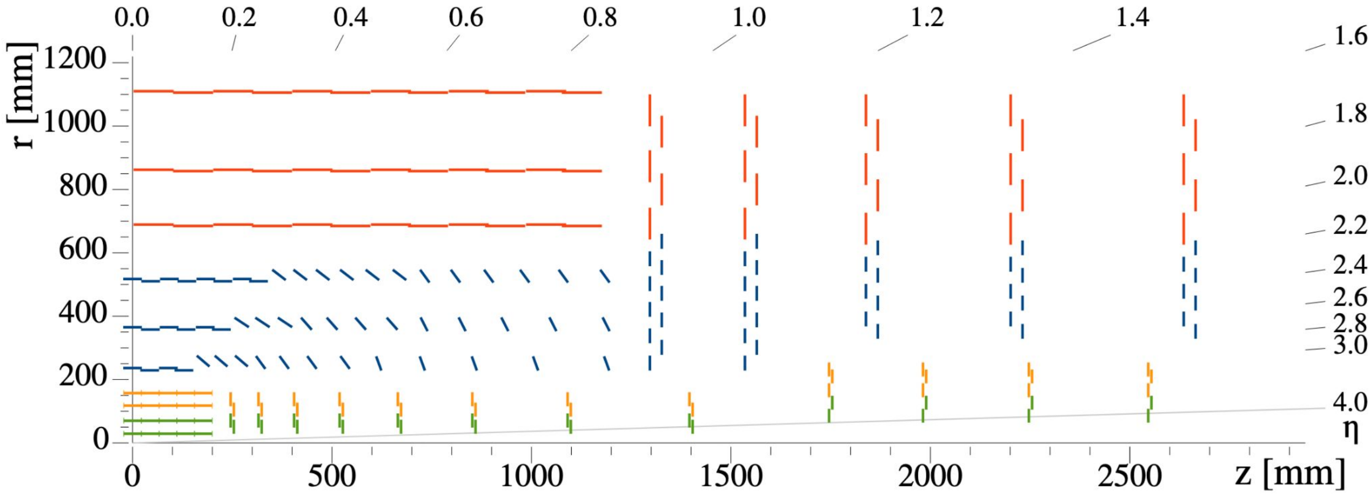
New Precision Timing Detector
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

Upgrade project: Tracker endcap

Highlighted features

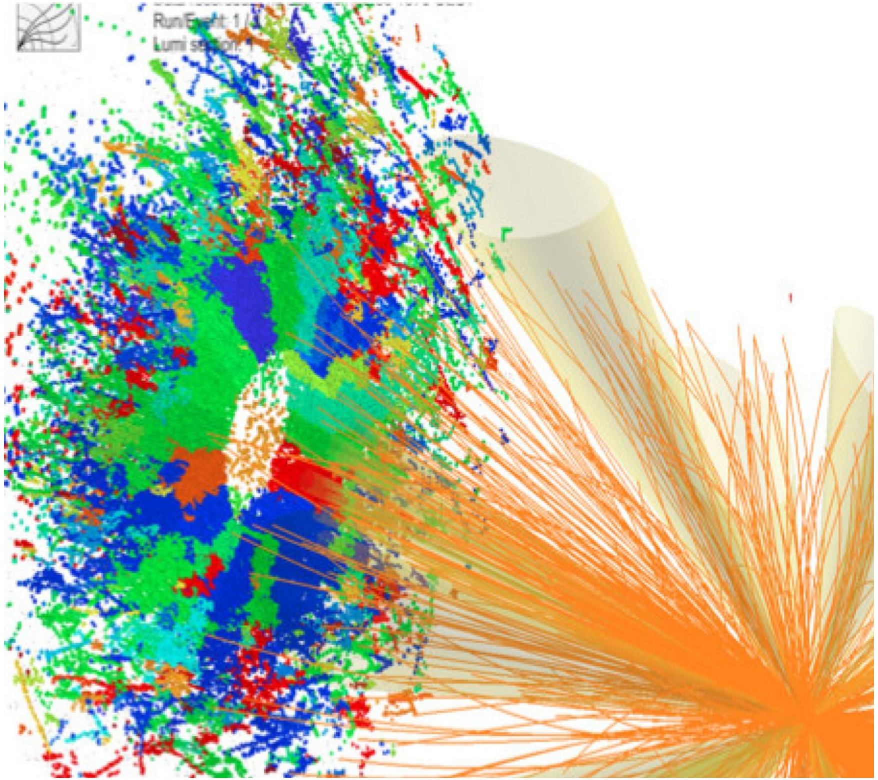
- Extended tracking to the forward region → better access to VBF measurements
- Increased granularity → cope with the dense environment at HL-LHC
- Increased radiation tolerance → cope with the harsh environment at HL-LHC
- Track trigger → data reduction at trigger readout by factor 10-20





Upgrade project: HGCAL

Highlighted features



- First particle flow calorimeter at a hadron collider, first precise 5-D calorimeter with the timing information
- First machine-learning calorimeter!
- HGCAL is key to improving high profile physics topics at HL-LHC that we are interested in:
  - HH, H signatures, VBF, tau signatures, vector-boson scattering
  - Pileup improvement
  - Forward flavour-tagging.
  - This means more precise measurements but also improves sensitivity BSM searches meaning more exotic signatures and specific searches with HGCAL
- HGCAL creates links to other institutes in Germany

Tracker and HGCAL during next PoF round - getting it to work

<u>Make most of experience of construction at DESY</u>

- Commissioning (2027-2029) and early data taking (2029-2030)
- Initial calibrations (2029-2030) profit from testbeam experience
- Initial performance papers (2030-2032) profit from production experience
  - Perfect opportunity for young people to “touch the detector” and become real experimentalists

<u>Profit of those ML papers being written in our groups</u>

- Let’s show that it works in real life!
- Reconstruction and low-level expertise at DESY (alignment, particle flow, …)
- Be the first/leading to put this in HL-LHC physics analyses

Data analysis - Higgs

Challenges, scientific goals and strategic relevance, also in relation with research policy objectives and in the context of international developments.

Which scientific challenges are addressed?

- Investigating the shape of the Brout-Englert-Higgs potential, search for first-order phase transition (FOPT) and CP violation
- Search for resonant production of Higgs boson pairs, extended Higgs sectors, warped extra dimensions

Which analyses are planned?

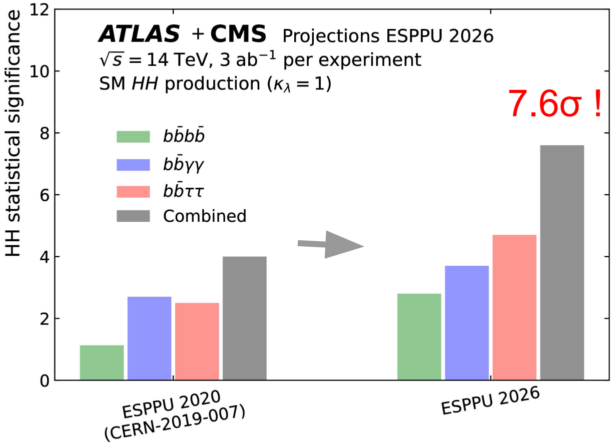
- Measuring resonant and non-resonant HH production in the H(bb)H(bb) and H(bb)H(ττ) channels
- Search for CP violation in H→ττ decay: sensitive probe of the model of electroweak baryogenesis
- Search for additional Higgs bosons in bb and ττ channels

Do they profit from our new detectors?

- Advanced triggering (track trigger, HGCAL…) and identification
- Improved b-tagging and τ reconstruction -> next slide
- Analyses are statistics-limited -> full benefit from luminosity upgrade
- High granularity imaging calorimetry: a more efficient reconstruction of neutral pions - essential for identification of τ decay modes in the CP H→ττ analysis

Data analysis - Higgs

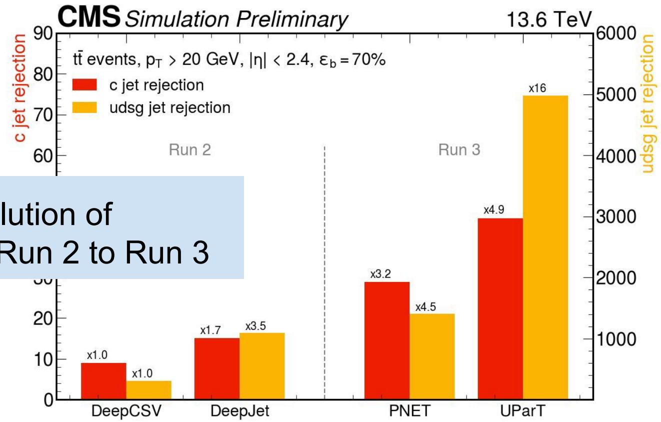
Some performance plots for di-Higgs



Significant improvements in b-tagging and tau-tagging (both ML!) recently, expecting MUCH better performance for HH

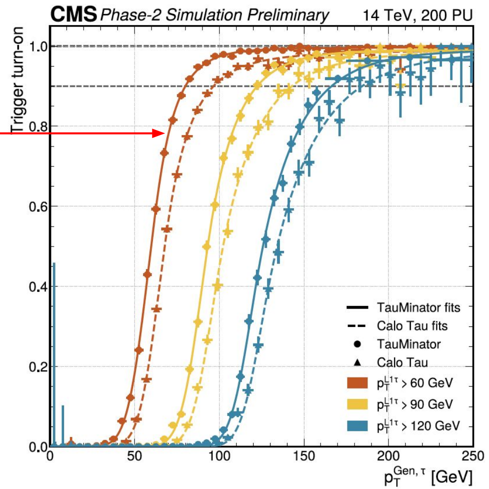
5σ discovery already with 2 ab^{-1} (S2)

Combined significance at 3 ab^{-1}: 7.6σ (S3)



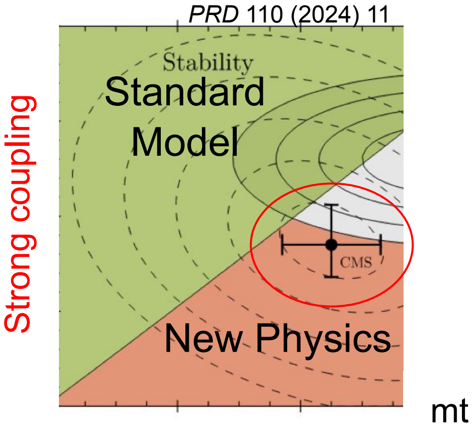
Example of evolution of b-tagging from Run 2 to Run 3

At HL-LHC, new algorithm for taus at L1 and using HGCAL + ML allowing lower thresholds in p_T, keeping 20-30% lower rate for taus and di-taus

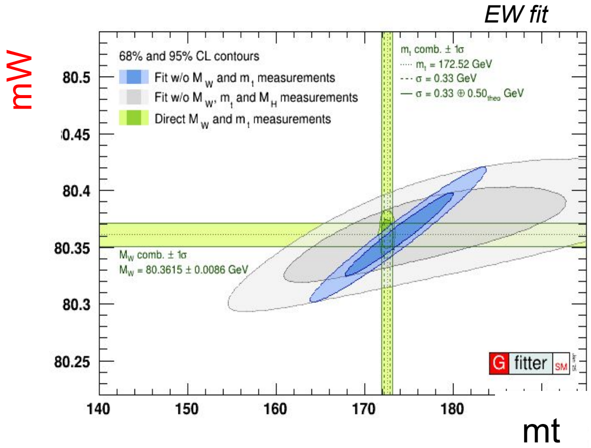


Data analysis - Standard Model Physics

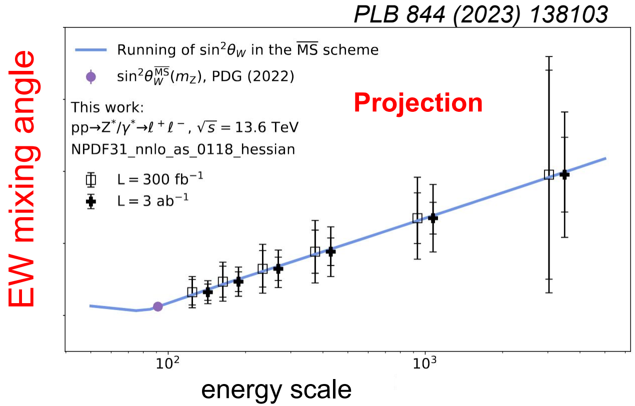
Fundamental particle masses and interaction strengths: match recent boost in theory (N2/N3LO) by precision in experimental measurements, explore new paradigms in probing New Physics



Improve by factor of 2!



Reach better accuracy



First measurement

- **Strong coupling, electroweak mixing angle and their running**
- **Impact of heavy-quark mass effects on extraction of mW, strong coupling, parton distributions**
- **Considering correlations of SM parameters and PDFs in global SMEFT interpretation** [proof of principle papers]

Data analysis - Standard Model Physics

Which analyses are planned and profit from detector upgrade in HL-LHC era?

- Z boson production at large invariant di-lepton masses, extraction of the electroweak mixing angle and its running
  - **New tracker:** improved hit resolution for high-pT tracks, extension of rapidities will enable phase-space coverage unaccessible before in CMS
  - **HGCAL**: pileup mitigation in the forward region
  - **luminosity upgrade:** population of high-mass di-lepton range

- Running of strong coupling via Energy Correlators in track-based jets with a novel unbinned unfolding method
  - **New tracker:** tracking at the trigger level enables precise high-pt jet reconstruction
  - **HGCAL**: granularity, radiation hardness, and extended coverage will be instrumental for jet physics reducing energy resolution and enabling measurements in the forward direction

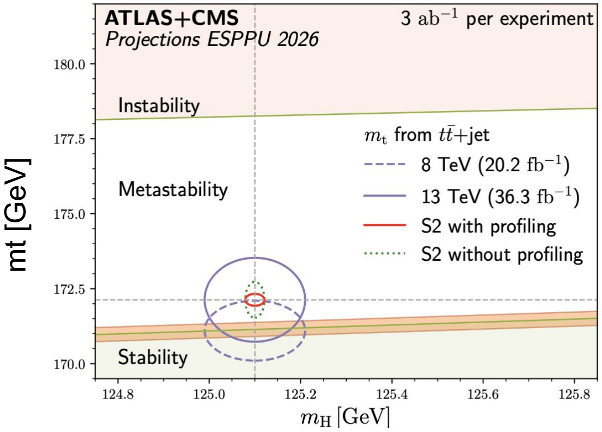
- c/b and c/b+V cross sections, fractions, extraction of mc and mb. Reduction of related uncertainties in mW and mZ, contributions to c and b Higgs Yukawa couplings.
  - **MTD timing detectors: improved PID**

- Global SM and SM+EFT interpretation of electroweak boson, jets, and top quark production in terms of PDFs, SM parameters and EFT coefficients. Collaboration with the theory group of DESY, University of Hamburg, and beyond

Data analysis - top quark physics

Understanding the top quark as a quantum state: from non-relativistic to highly-boosted regime – ultimate stress test of the SM and window to BSM physics

arXiv:2504.00672

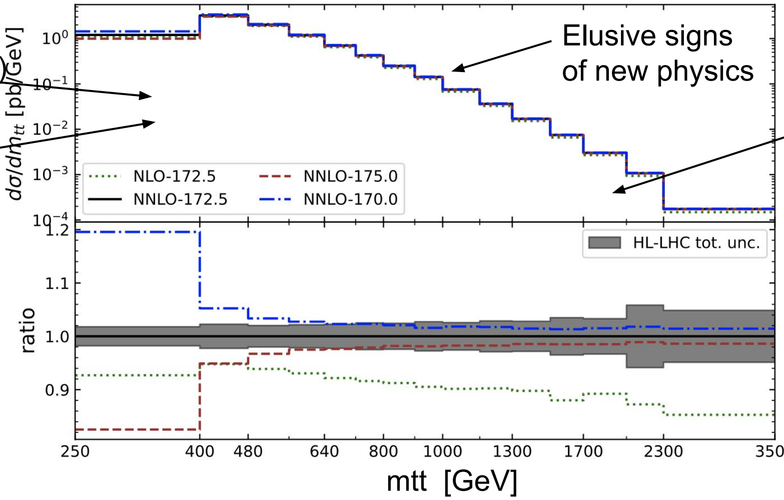


End HL-LHC mt precision ~ 200 MeV

Probe tt bound-state structures (toponium?)

Sensitive to top mass

arXiv:2407.16061



Elusive signs of new physics

Sensitive to mt from boosted top jets

Scientific challenges for Run3 and HL-LHC:

- Top quark mass at highest precision: test of stability of the Universe and window to new physics
- Explore BSM signatures through tt structures and stress-test of SM predictions
- Precision top Yukawa and EW couplings through top-associated processes

Data analysis - top quark physics

Which analyses are planned and profit from detector upgrade in HL-LHC?

- Multidifferential tt cross sections in extreme phase space regions, use for SM parameter extraction, anomaly detection and BSM interpretation (target: < 2% precision)
- Full characterization of mtt spectrum to stress-test the SM: extract top mass, explore tt binding effects, probe toponium dynamics, search for BSM signatures by distinguishing tt resonances from peak-dip structures (eg. Heavy Higgs, CP-violation in Heavy Higgs, axion) (target: top mass precision << 1 GeV)
- Top couplings from differential measurements: top-Higgs and b-Higgs from top+H(bb), focus on CP properties; EW couplings to Z, W, γ via top+vector boson (target: leave statistical limitations)
- Global SM and SM+EFT interpretation together with SM and Higgs

→ Analyses profit from improved track reconstruction (higher granularity/resolution), more precise b-/c-tagging; extended pseudorapidity coverage, improved jet energy resolution; increased statistics in remote phase space regions

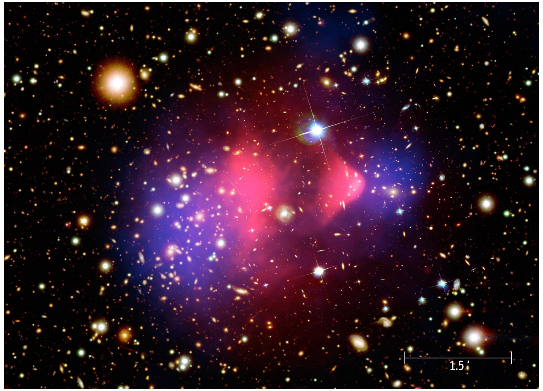
Strategic contributions to pave the way:

- Collaboration with theory groups from DESY, UHH, Aachen, and others for theory prescriptions and data interpretations
- Improved analysis strategies and use of novel ML techniques (eg. unbinned unfolding, tt kinematic reconstruction)
- Contributions to detector calibration tools and Monte Carlo simulations

Data analysis – searches

Strategy

- **Motivation stems on fundamental questions**
  - Dark matter and axions
  - Hierarchy problem
  - Extended Higgs sector
  - Testing a theory that addresses all these questions at once
- **There must be new physics - the question is whether we can see it at the LHC**

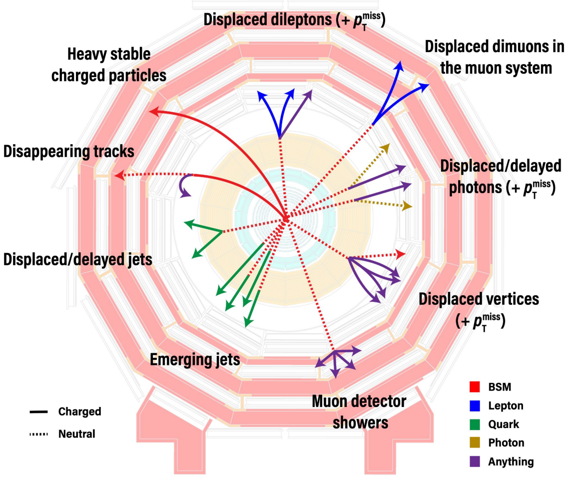


- **Focus: signatures that only now first have sensitivity in LHC Run 3 and HL-LHC Run 4**
  - Newly enabled by detector upgrades (in particular tracker, HGCAL, and trigger)
  - Newly enabled by better tools (machine learning)
  - Newly enabled by larger dataset (rare processes)
  - New physics in our Higgs, SM, Top precision measurements
    (e.g. BSM in HH and top+DM/axions, tt invariant mass spectrum CP violation at threshold)
- Local expertise in the *theory group* and complementary to *axion on-site experiments*
- *Novel* searches are all about detailed understanding the (standard model and instrumental) background
  - Engagement in chain from **commissioning, low-level reconstruction/calibration** to analysis is vital to success

Data analysis – searches

Signatures

New physics with long-lived particles (incl τ leptons, jets, leptons)



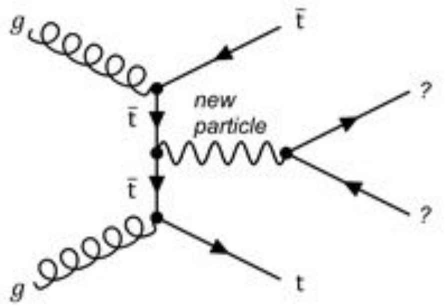
New L1 triggers (HGCAL)

τ-reco (Tracker)

New physics in (multi)top final states

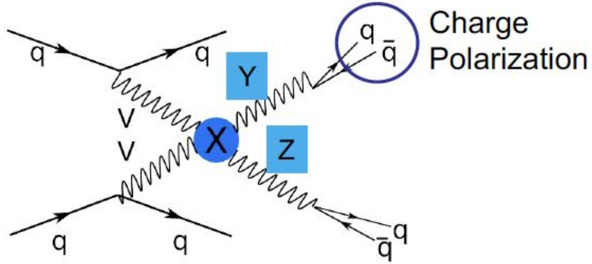
(full range: single top+X through tttt(+X?) signatures)

b-tagging (Tracker)



VBF-produced new physics

Jet-substructure (Tracker)



VBF/forward jets (HGCAL/Tracker)

Machine learning for

- Object identification
- Background prediction
- Event classification

This broad strategy is sensitive to many BSM scenarios and ready for (positive) surprises at HL-LHC

Backup material

Upgrade project: Tracker endcap

Milestones

- Work at DESY finishes at the end of 2027 with the transport of the last Double-Disk to CERN
- Assembly, integration and testing of the end caps finishes Q3/2028

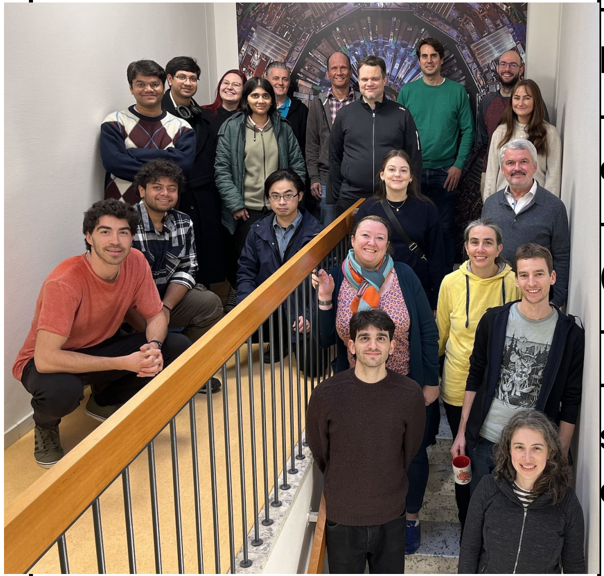
Top 5 Milestones

First Double-Disk fully integrated, shipped to and tested at CERN	01.10.2026
Dee production finished	01.12.2026
Module production finished	01.11.2027
Last Double-Disk fully integrated, shipped to and tested at CERN	01.01.2028
End caps integrated, tested and installed in BTST	01.07.2028

CMS-HGCAL now at DESY

<u>hardware</u>

- wrapping of scintillators
- construction of boards and modules
- production quality control chain
- testing of SiPms
- test stand with cosmic muons
- test beams



<u>software</u>

- simulation of test stand and test beams (CMSSW)
- geometrical mapping of readout channels (CMSSW)
- scintillator raw data readout (CMSSW)
- particle flow L2 group convener
- machine learning for particle simulation and reconstruction in calorimeters

Data analysis – searches (input from IMP)

Challenges, scientific goals and strategic relevance, also in relation with research policy objectives and in the context of international developments.

Which scientific challenges are addressed?

Dark matter, hierarchy problem and finetuning of the Higgs mass + testing a theory that addresses all these questions at once

Which analyses are planned?

Search for SUSY in prompt and long-lived final states with tau leptons, possible revisit of searches with top quarks

Do they profit from our new detectors?

Advanced triggering and reconstruction/identification of τ leptons

Searches will likely be combined with the different SM analyses where applicable

Data analysis – searches (input from AH)

Challenges, scientific goals and strategic relevance, also in relation with research policy objectives and in the context of international developments.

Which scientific challenges are addressed?

- Hierarchy problem
- Understanding of Higgs sector

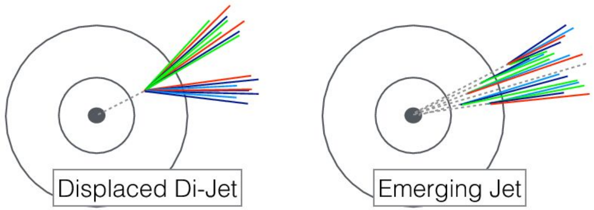
Which analyses are planned?

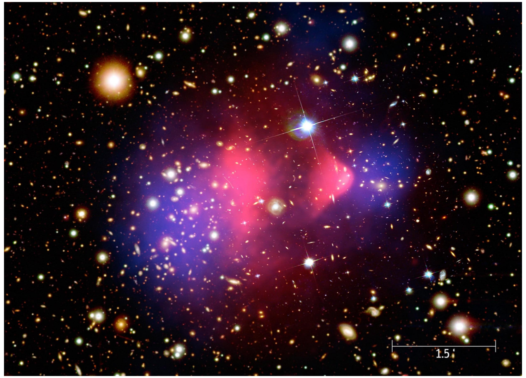
- VBF-produced resonances (scalars, vectors) in final states: qqWW, qqWZ, qqZZ, qqWH, qqZH, qqHH
- Resonances in multi-top final states: ttX->4t, tX->3t

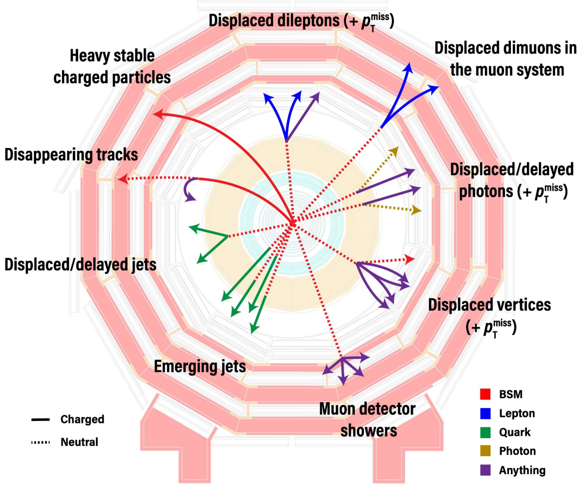
Do they profit from our new detectors?

- HGCAL enables quark/gluon/pileup-jet separation to identify VBF jets, surpassing Run3 performance despite more pileup
- Tracker with finer granularity improves jet substructure identification of W/Z/H/top jets despite more pileup, for final states with high-pT W/Z/H/tops
- HGCAL enables reconstruction of relatively low-momentum forward jets, improved capability to reconstruct final states with multiple tops

Dark QCD possible figures







Data analysis – Search for Dark QCD (from JA)

Which scientific challenges are addressed?

Despite the strong astrophysical and cosmological evidence that **dark matter** exists, its **source is still unknown**

- Since WIMP dark matter has not yet been found, more complicated dark sectors may be needed
- Nonminimal dark sectors may include multiple new particles and potentially new interactions decoupled from the SM
- **Dark QCD** is an example of such a complicated dark sector, with an additional broken U'(1) gauge group
- In dark QCD, the dark photon can communicate with SM via kinetic mixing
- **Rich phenomenology** available: dijets, multijets, semivisible jets, emerging jets, etc.

Which analyses are planned?

New search for **emerging jets in dark QCD**

Do they profit from our new detectors?

Look for emerging jets in the new HGCAL

- Design a **new L1 trigger for nonpointing jets in the HGCAL**, based on proof-of-concept paper

Can develop a suite of L1 triggers for other nonpointing objects in the HGCAL

- Also given the rich phenomenology of dark QCD, can target a variety of different signatures
- Potential for a suite of analyses

Backup

Data analysis - top

At the crossroads of precision and discovery: top quark physics at the energy frontier

Which scientific challenges are addressed?

- Top quark mass at highest precision: test of stability of the Universe and window to new physics
- Understanding the top quark as a quantum state: from non-relativistic to highly-boosted regime
- Characterization of top quark electroweak and Yukawa couplings at the highest precision
- Exploring BSM signatures through tt structures and stress-test of SM predictions

Data analysis - top

At the crossroads of precision and discovery: top quark physics at the energy frontier

Which analyses are planned?

- Full analysis of tt multidifferential cross sections using advanced ML tools to unfold simultaneously the complete kinematic picture of tt production and decay, stress-testing the SM and enabling global fits of SM parameters and EFT constraints
- Complete characterization of the tt invariant mass (mtt) spectrum:
  - Precision SM tests: extract top quark mass, stress-test QCD, constrain EFT
  - Explore tt binding effects: probe non-relativistic threshold behaviour, search for different toponium states
  - BSM signatures: resolve resonances (toponium) and distinguish them from peak-dip structures (Heavy Higgs, CP-violation in Heavy Higgs, axion)
- Boosted top quark jets: Lund jet plane to study the full radiation pattern of boosted tops and measure dead cone effect; top quark mass from energy correlators with unbinned ML unfolding
- High precision top couplings through differential measurements, constraints on anomalous couplings and EFT interpretations, search for new particles produced in association with top quarks, top quark quantum state:
  - EW couplings to Z, W, γ via top+vector boson production
  - top-Higgs, b-Higgs Yukawa couplings via top+H(bb) production; measure tt+heavy flavour production to test QCD modelling and constrain heavy flavour structures in EFT
  - Search for Dark Matter in tt+DM, t+DM production to complement DM mediator searches in mtt
  - Search for toponium in $\gamma\gamma$ final states

Data analysis - top

At the crossroads of precision and discovery: top quark physics at the energy frontier

Do they profit from the new detectors?

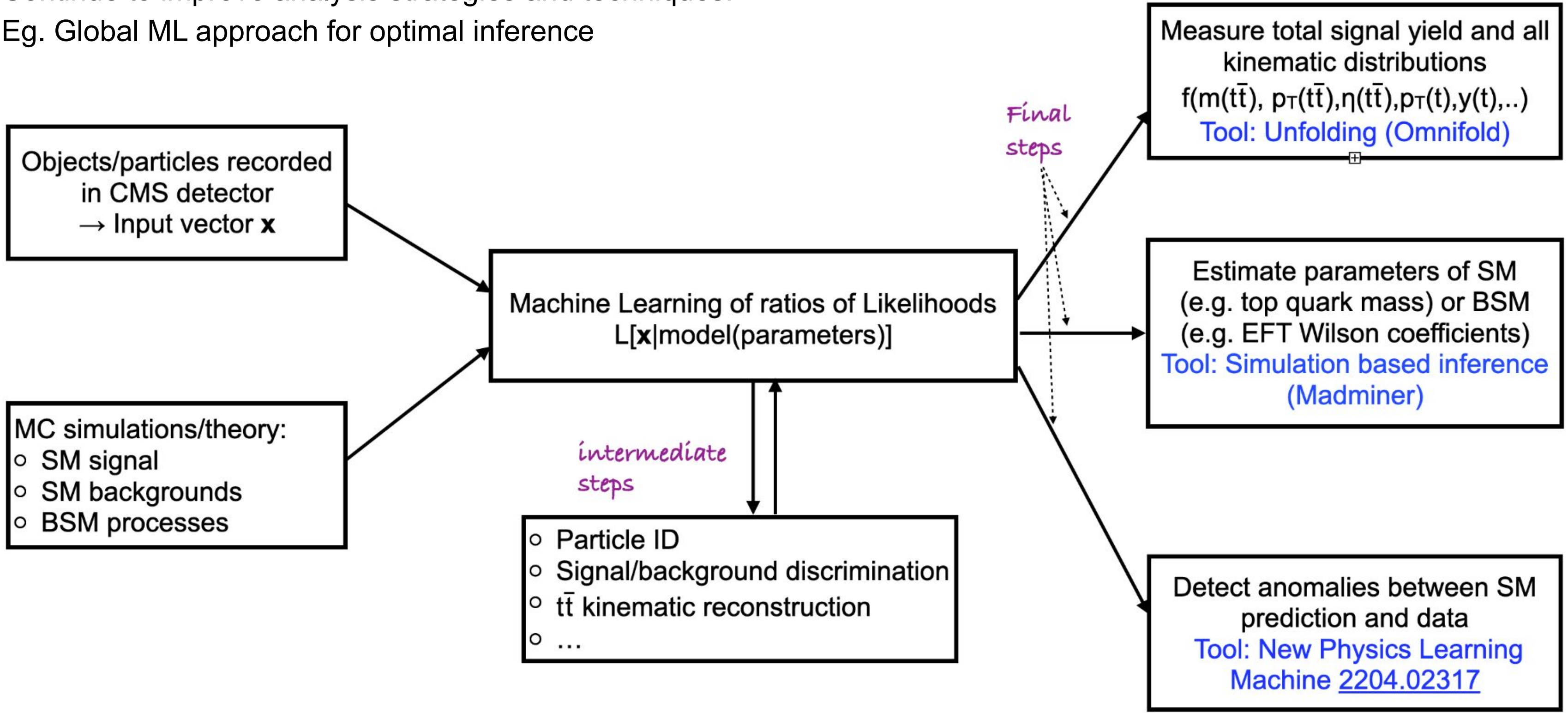
- **Tracker**: improved track reconstruction (higher granularity/resolution) crucial low and high-pT jet/lepton reconstruction and for more precise b-/c-tagging; extended pseudorapidity coverage
- **Calorimeters (HGCAL)**: better granularity, forward coverage, and pileup mitigation; improve jet energy resolution and photon identification
- **Timing**: improved particle ID and jet substructure from better pileup mitigation
- **Luminosity**: Higher statistics overcome previous limitations in rare final states and remote phase space regions

Data analysis - top

At the crossroads of precision and discovery: top quark physics at the energy frontier

Continue to improve analysis strategies and techniques:

Eg. Global ML approach for optimal inference



Data analysis - SM

Standard Model at ultimate precision as a probe for new physics: particle masses, couplings and their scale dependence

Which scientific challenges are addressed?

- Investigation of heavy quark mass effects and fragmentation and their impact on precision measurements of electroweak boson masses, strong coupling and nucleon structure (PDFs)
- Considering correlations of SM parameters and PDFs in the global interpretation in terms of SM and new physics.
- Precise determination of strong coupling and its running from observables with reduced sensitivity to nonperturbative effects

Data analysis - SM

Which analyses are planned ?

- Measurement of **neutral current Drell-Yan** production at large invariant di-lepton masses, extraction of the electroweak mixing angle and the first demonstration of its energy scale dependence (running) at LHC energies, using full Run3 and first HL-LHC data. Cooperation with theory for the electroweak schemes.

- Measurement of **Energy Correlators** and extraction of alpha_s and its running by probing regimes from confinement to asymptotic freedom with a novel unbinned unfolding method (development in cooperation with TOP group). First measurement with full Run3 data, and first HL-LHC data. Cooperation with theory for NNLO+N3LL calculations.

- Measurement of cross sections for **charm and beauty production** (inclusive and associated with electroweak bosons) in the full LHC phase space, and measurements of the related nonuniversal production fractions. Extraction of mc and mb using full Run1, Run2 and Run3 data and first HL-LHC data. Reduction of related uncertainties on the determinations of mW and mZ, and contributions to the determination of c and b Higgs Yukawa couplings. Collaboration with the theory group of University of Hamburg.

- **Global SM and SM+EFT** interpretation of electroweak boson, jet, and top quark production in terms of PDFs, SM parameters (masses and couplings) and constraints on the scale for new physics. Collaboration with the theory group of DESY and University of Hamburg.

Data analysis - SM

Do they profit from our new detectors?

- **silicon tracker upgrade:** improved hit resolution relevant for high-pT tracks, improvement of jet-core tracking (cluster merging) for track-based measurements like energy correlators, high-pt track selection at the trigger level enables precision in particular high-pt jet and leptons reconstruction. Extension of the tracker to rapidities up to 3.8 will enable phase space coverage for charm and beauty quarks to regions unaccessible before in CMS

- **calorimeter upgrade:** granularity, radiation hardness, and extended coverage of HGCAL will be instrumental for jet physics concerning the energy resolution and acceptance in forward direction; while top-quark and electroweak measurements will profit from pileup mitigation in forward region

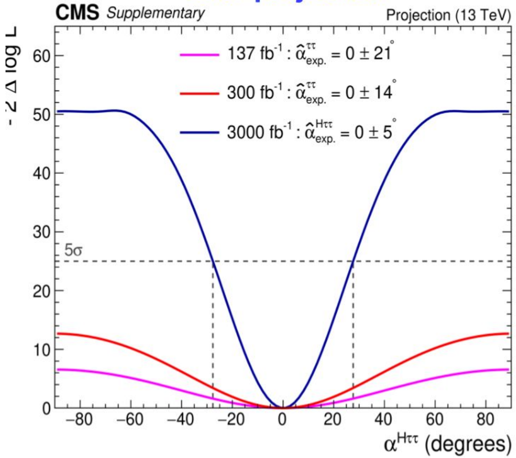
- **timing detectors:** MTD will reduce combinatorial backgrounds in high-pileup environments and measures time of flight, which leads to strong improvements in particle ID for protons, kaons and pions especially at intermediate momenta, enhancing the capabilities for charm and beauty measurements in hadronic final states. Pileup mitigation at high pT will reduce background effects in jet substructure measurements and track-based measurements.

- **luminosity upgrade:** the increased statistics and data taking capabilities will contribute to improve measurement precision in phase space regions and/or for final states that were so far statistically limited.

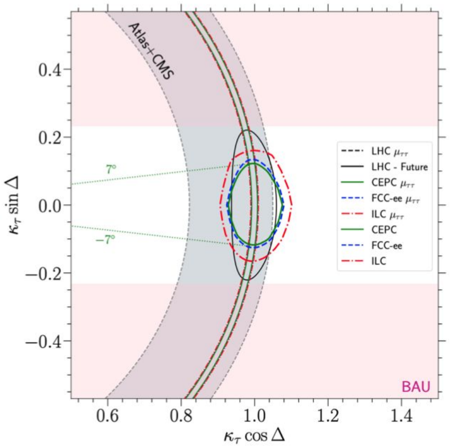
Data analysis - Higgs

CP violation measurement: projection of sensitivity

CMS projection



Phys. Rev. D 103, 095027 (2021)



with additional LHC data and assuming the same analysis techniques, precision of better than 10° in CP-mixing angle is plausible

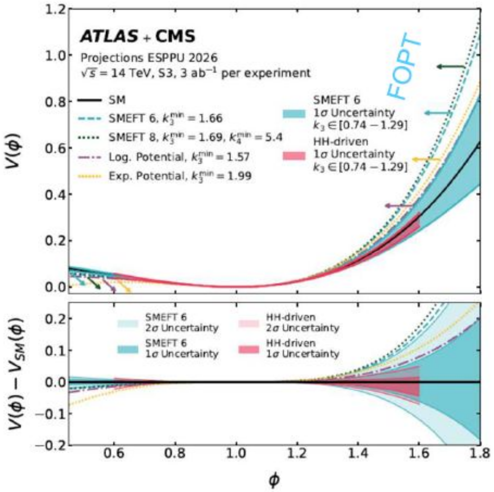
→ good target for future analysis with Run 3 and HL-LHC data

→ sensitive probe of the lepton flavored electroweak baryogenesis models (see for example Phys. Rev. D 103, 095027 (2021), arXiv:1206.2942 and Phys. Rev. D 96, 115034 (2017))

Data analysis- Higgs

Shape of the BEH potential + 1st-order phase transition

- Four non-SM BEH potential shapes studied in context of SM effective field theory
  - predict strong 1st-order phase transition in early universe (→ baryogenesis) for sufficiently large values of κ_3 and κ_4
  - not realized in the SM
- At 3 ab^{-1} and assuming the SM, ATLAS+CMS combination should be able to exclude as good as all possible strong-FOPT scenarios across the four alternative hypotheses
- Important measurement for understanding the origin of the universe



FOPT excluded!