
SM Physics Measurements at the LHC

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Introduction

- ATLAS and CMS have a broad and ambitious physics programme
 - determine fundamental parameters of the SM with high precision
 - measure rare SM processes for the first time in a hadron collider
 - direct and indirect searches for new physics
 - probe for new particles and interactions at the multiple-TeV scale
- Precision measurements of SM processes
 - Higgs boson - also see talk by Arun Nayak
 - Top quark - see talk by Saranya Ghosh
 - Vector bosons - see talk by Saranya Ghosh
 - QCD physics - see talks by Manas Maity, Sanmay Ganguly
 - B Physics

The ATLAS & CMS Detectors

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

SILICON TRACKER
Pixels ($100 \times 150 \mu\text{m}^2$)
~1m² ~66M channels
Microstrips (80-180 μm)
~200m² ~9.6M channels

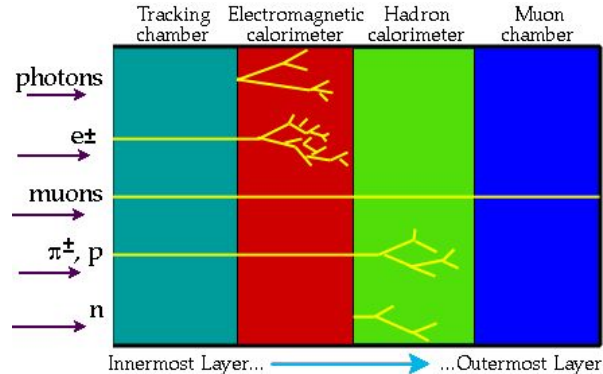
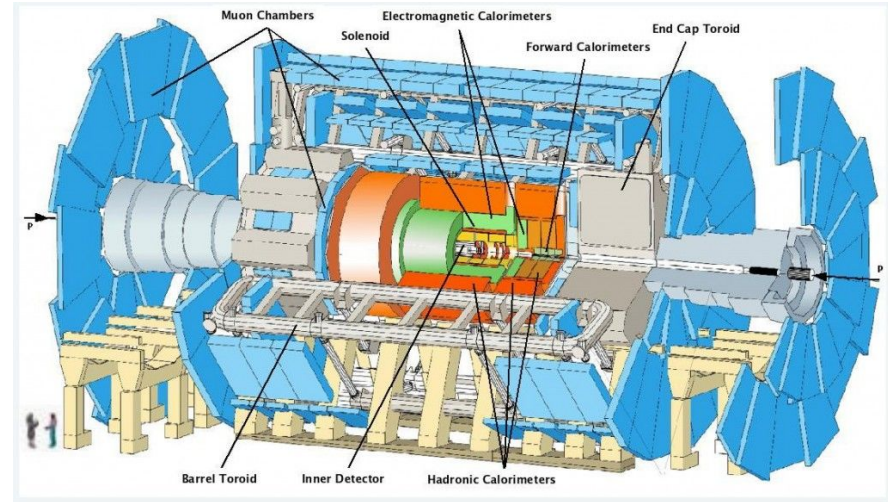
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



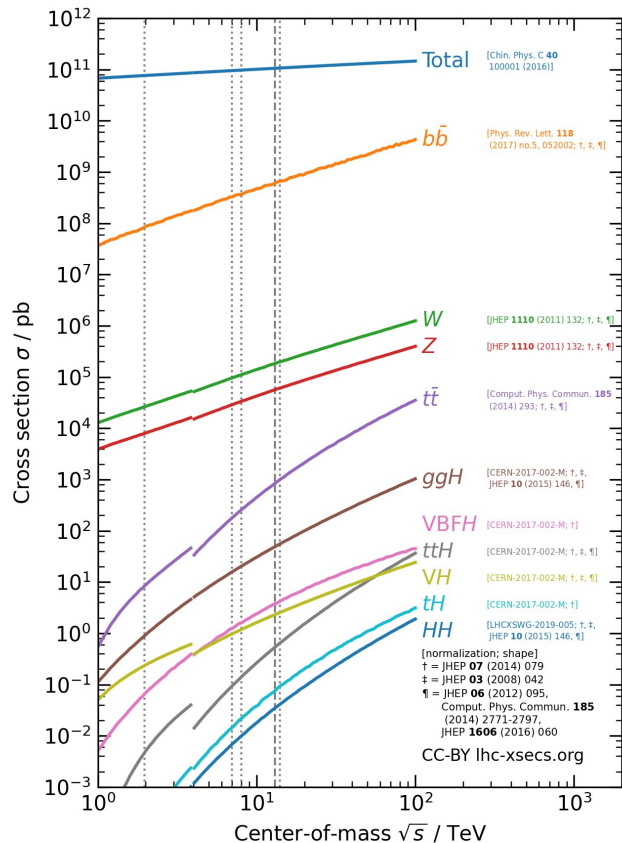
Number of readout channels in CMS

- Silicon tracker > 135M
- Electromagnetic Calorimeter > 75k
- Hadron Calorimeter ~20k
- Muon Spectrometer > 200k

Event Size: ~2 MB

pp Collision Rate at the LHC

<https://lhc-xsecs.org>



← Total Collision Rate: ~2.5 GHz

← B quark rate ~ 10 MHz

← W boson rate - ~ 4 KHz

← Higgs boson rate - 1 Hz

keep rare physics

- The CMS/ATLAS detector produces ~ 100 TB/s
- The experiments must selectively read out detector data using a real-time data selection system known as the “trigger”
 - select the collisions you want most (rare processes)
 - data you did not record are lost forever

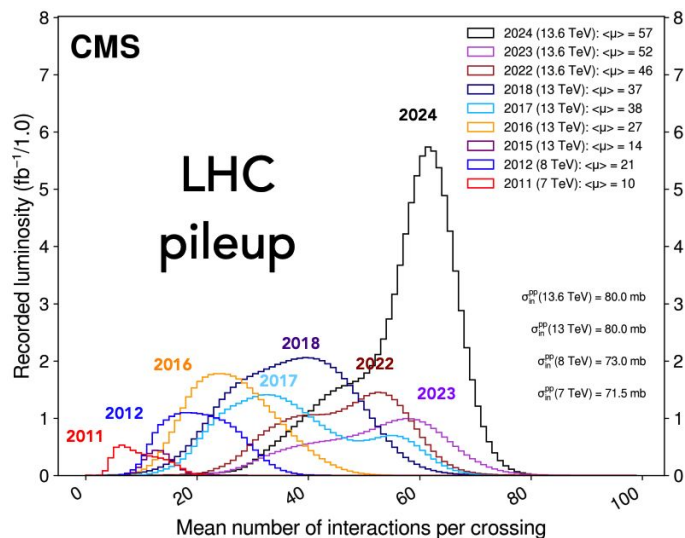
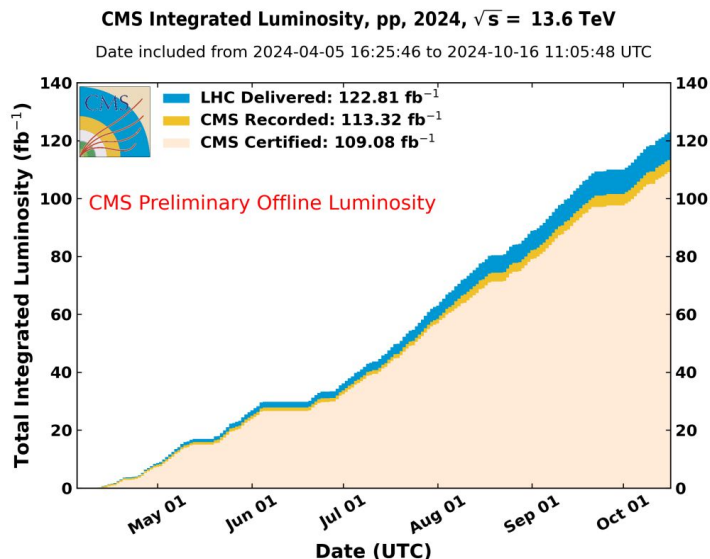
2024 pp Data Taking - what a year!

Integrated luminosity

- delivered: 122.8 fb^{-1}
- recorded: 113.3 fb^{-1} (92.3%)
- certified for physics: 109.1 fb^{-1} (96.3%)

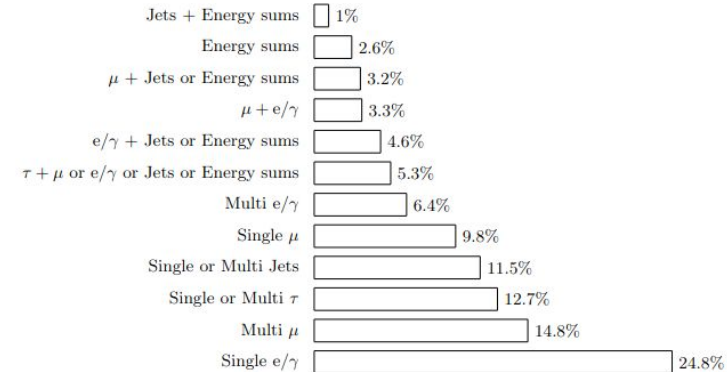
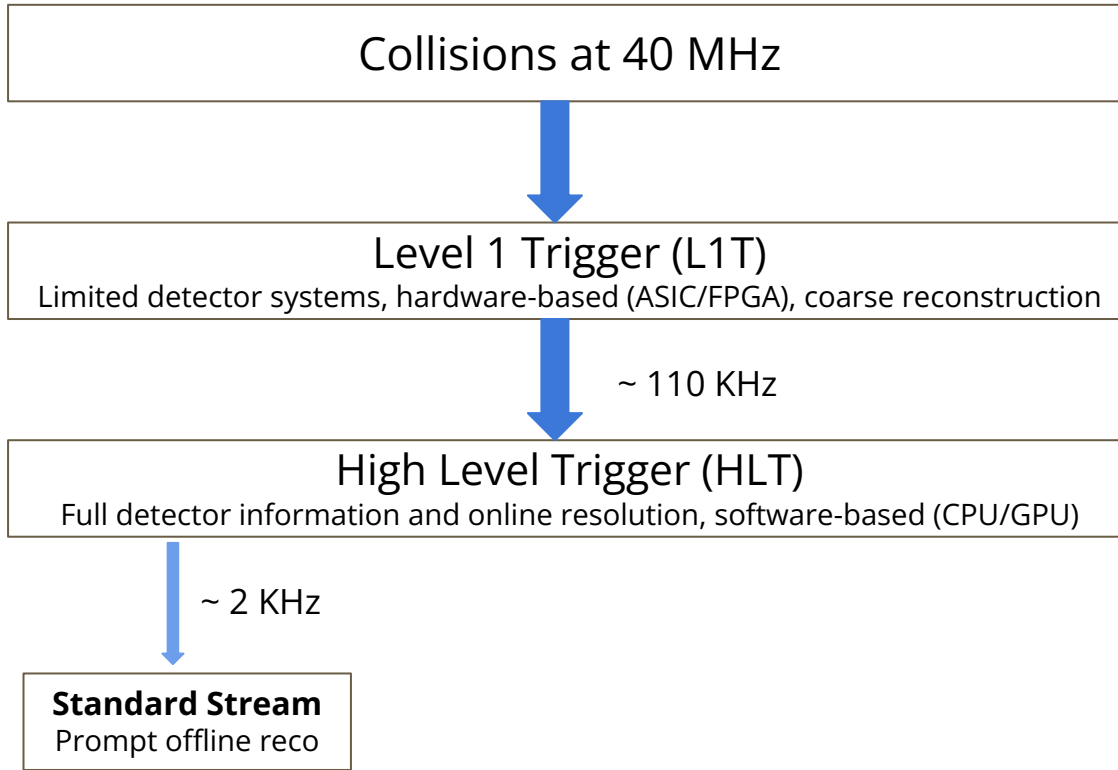
Pileup (PU) levelled at 62-64 during the year:

- 105-115 kHz of L1 trigger rate
- 3-6% downtime
- Mitigation measures to control dead time caused by ECAL noise evolution
 - Minimal effect on physics performance and uniformity



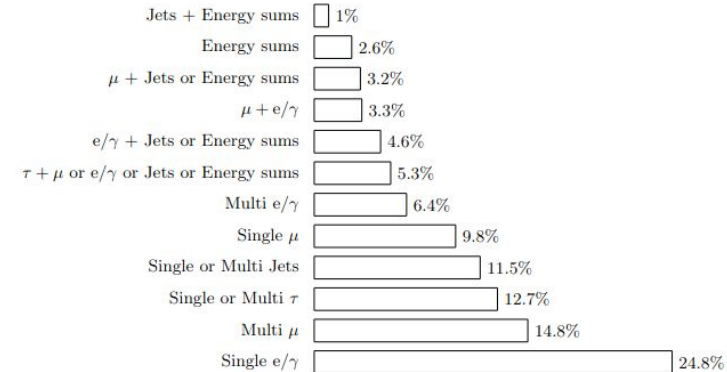
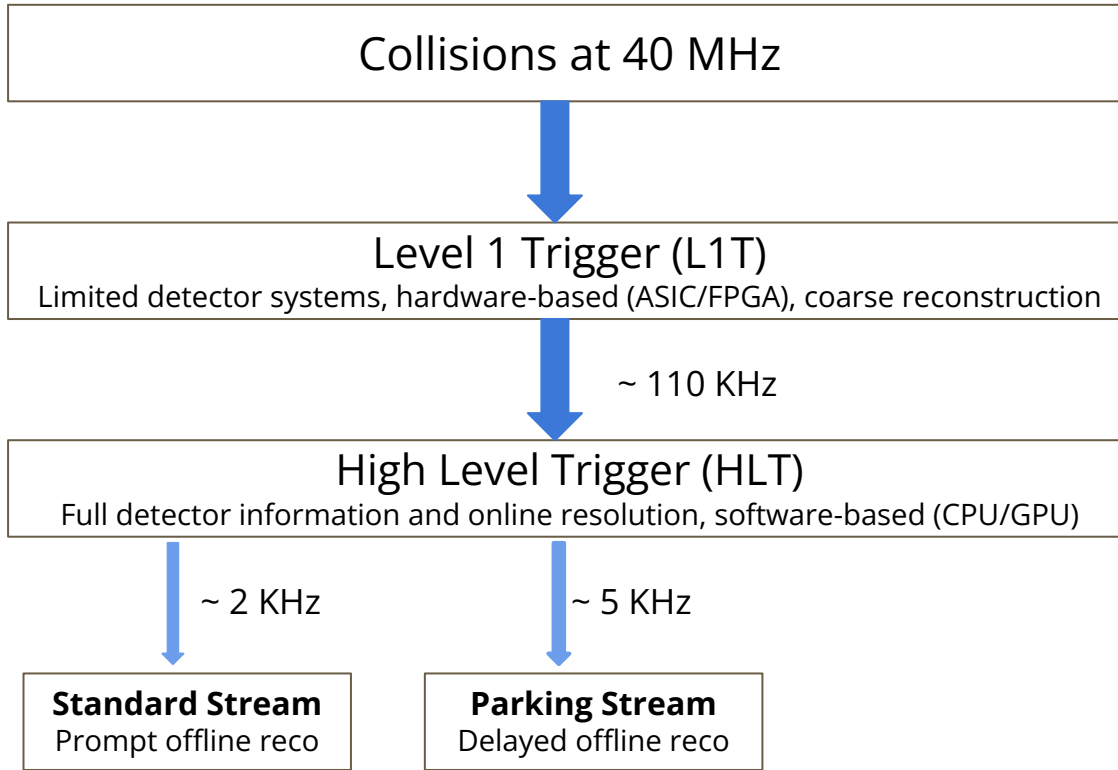
Overview of CMS Trigger System

Trigger is Physics



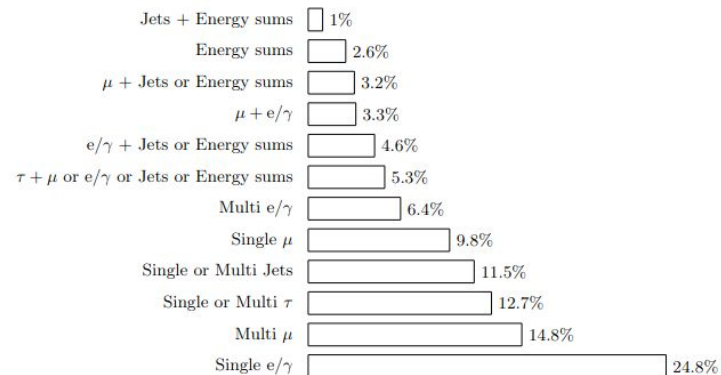
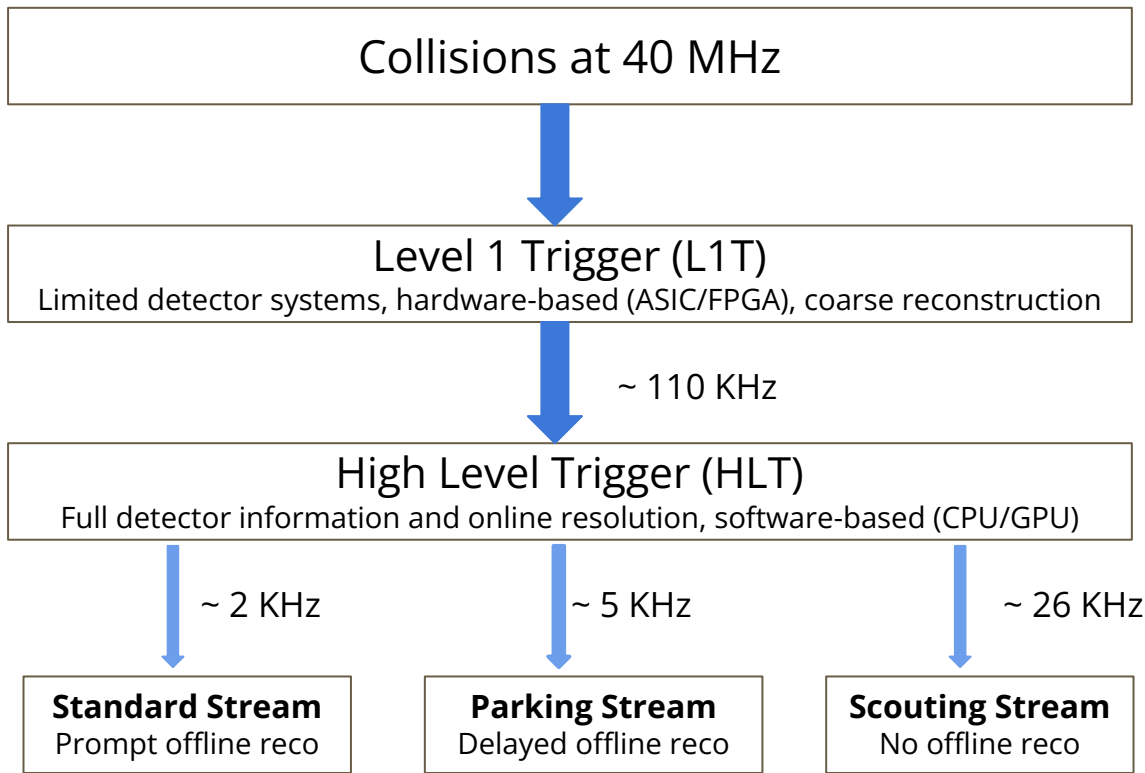
Overview of CMS Trigger System

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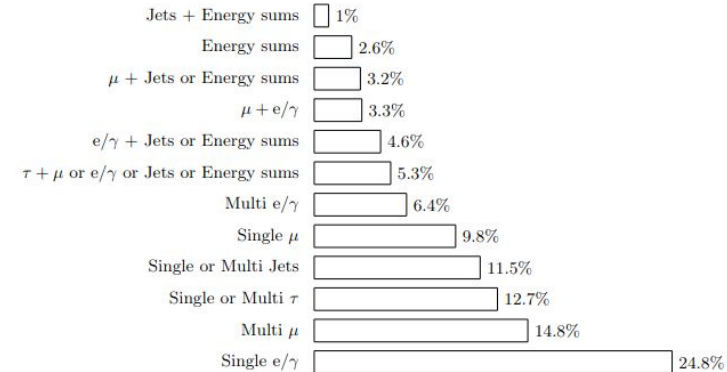
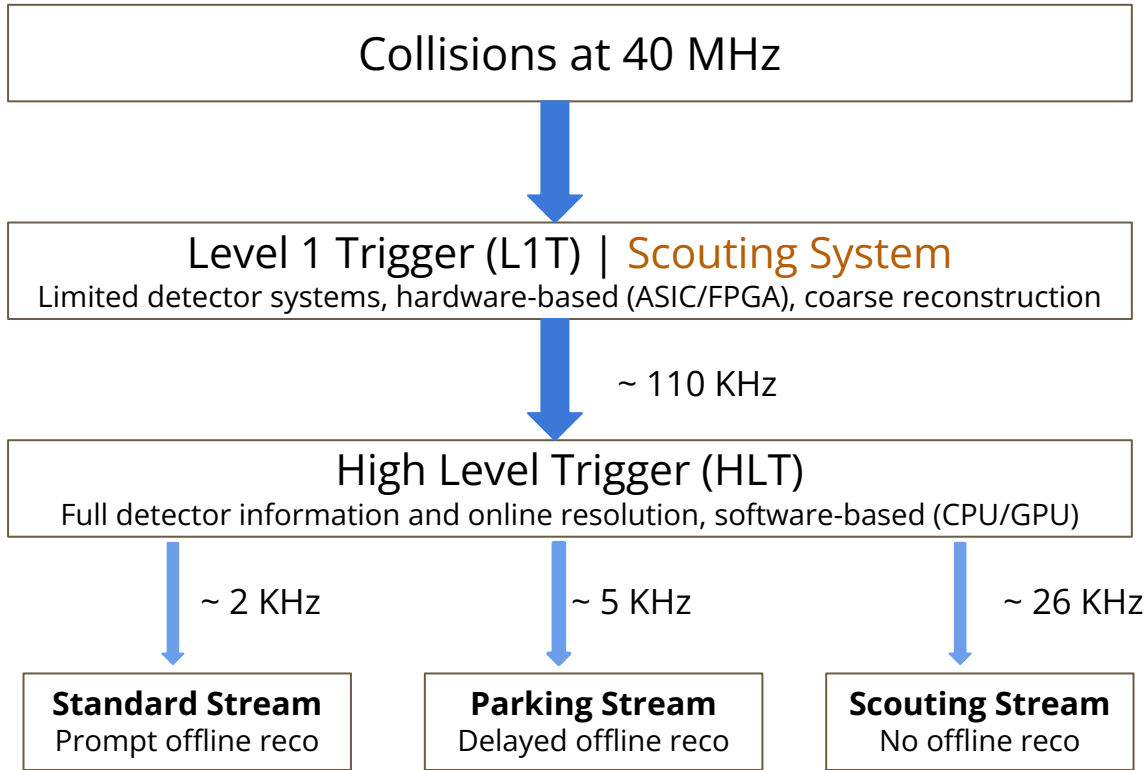
Overview of CMS Trigger System

Trigger is Physics



Overview of CMS Trigger System

Trigger is Physics



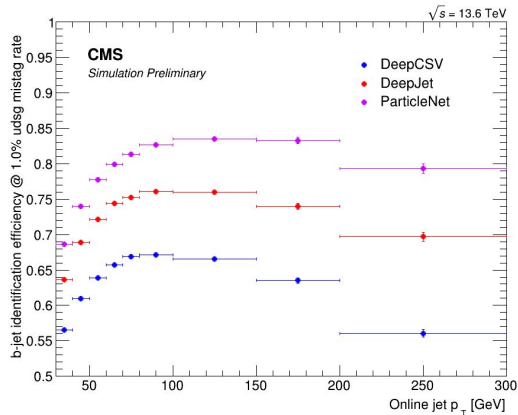
CMS Trigger System Improvement in Run3 (2024)

Stable operations and good performance for both L1 trigger and HLT throughout 2024

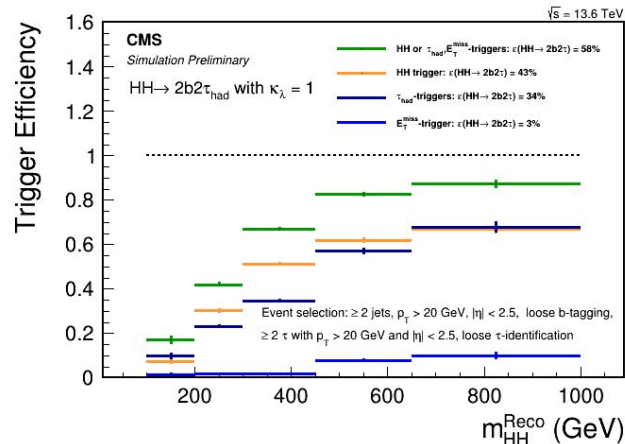
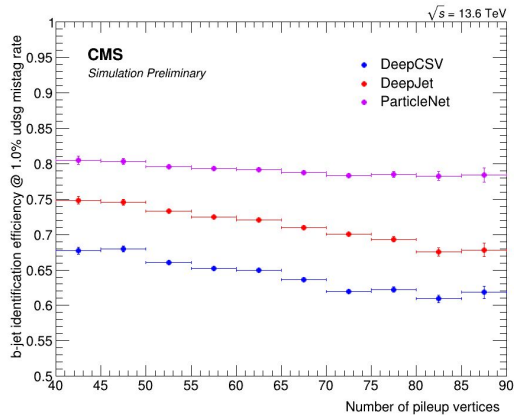
- Several new triggers added in 2024
 - New neural network based anomaly detection triggers (AXOL1TL and CICADA)
 - Low p_T single muon triggers in barrel (extremely valuable for CMS B-physics program)
 - Low p_T lepton + jet cross-triggers
- Improvements in the HLT reconstruction, and extended event content for HLT scouting
- Heterogeneous (CPU+GPU) reconstruction software used at HLT ported to Alpaka portability library

Improvement in CMS Trigger System - HH Triggers

- The Higgs self coupling is a key parameter of the Higgs potential
 - The dominant decay mode of the Higgs boson is $H \rightarrow b\bar{b}$
- New b-tagging algorithm based on graph net (ParticleNet) implemented @ HLT
 - 10% improvement over DeepJet (Run 2) across the entire p_T range and stable vs pileup
 - Lower L1 trigger requirement on the event energy scale ($HT \geq 280$ GeV vs 360 in Run 2)



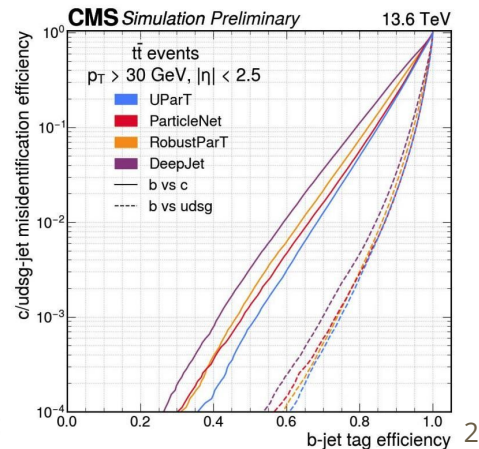
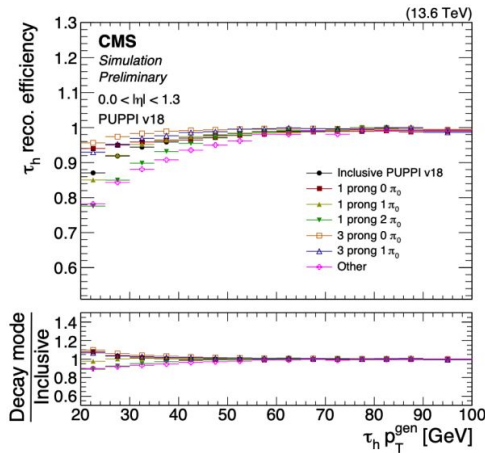
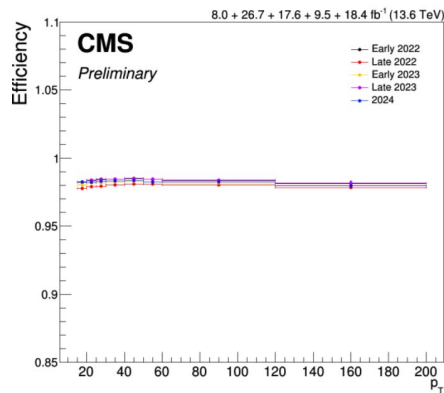
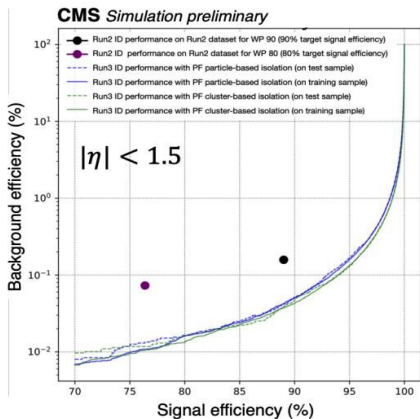
CMS DP-2023/021



CMS DP-2023/050

CMS Physics Object Performance in Run3

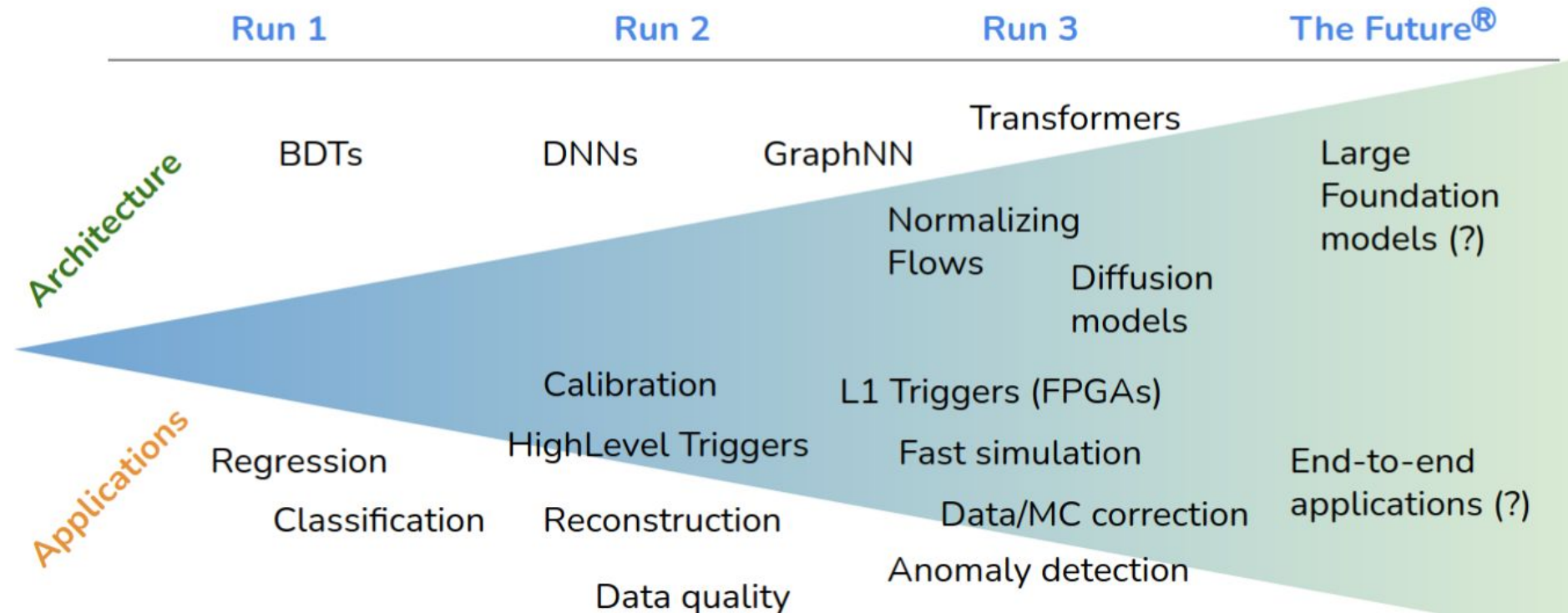
- Require deep understanding of the detector performance and high-performant object ID to carry out high-precision measurements and BSM searches
- A lot of effort is put into improving understanding of detector and development of reconstruction/identification algorithms
 - Stable physics performance of electrons, photons, muons, taus, jets
- Improvements in jet tagging performance using machine learning
 - latest algorithms using graph-nets and transformers
 - extended to multiple kinds of jets (also τ_h)



Machine Learning in HEP

Fourth Pillar of LHC

ML is everywhere (L1, HLT, Reconstruction, Fast Simulation, Analysis) in HEP today



Higgs Physics

Status of Higgs boson Physics

- All the main production modes have been observed with a 5σ significance
- Production modes ggH and VBF probed at $\sim 10\%$ level
- ggH measurements are limited by systematic uncertainties
- Measuring inclusive signal strengths gives us an overall characterisation of the SM

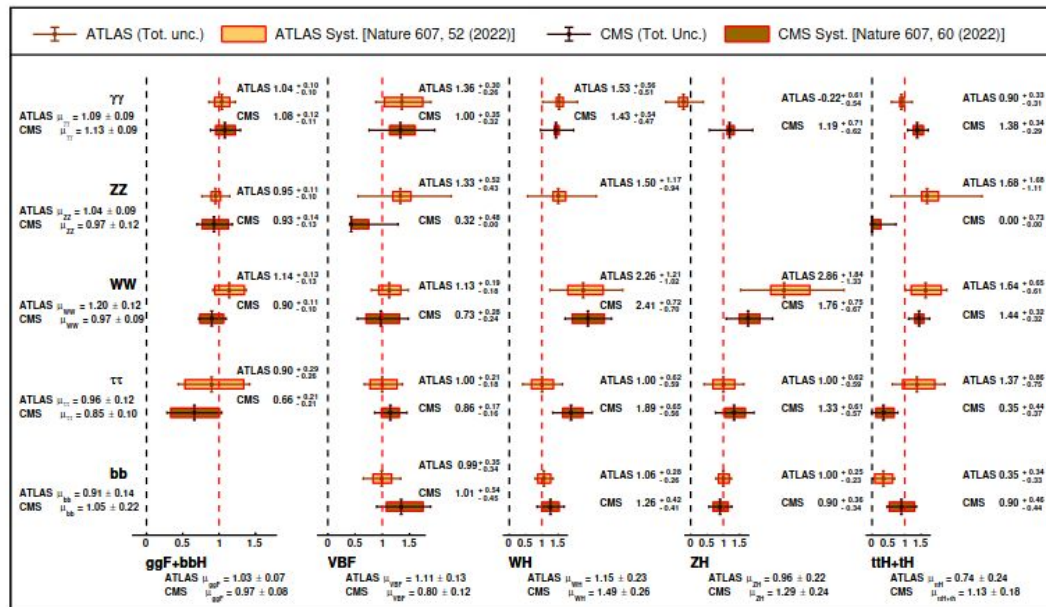
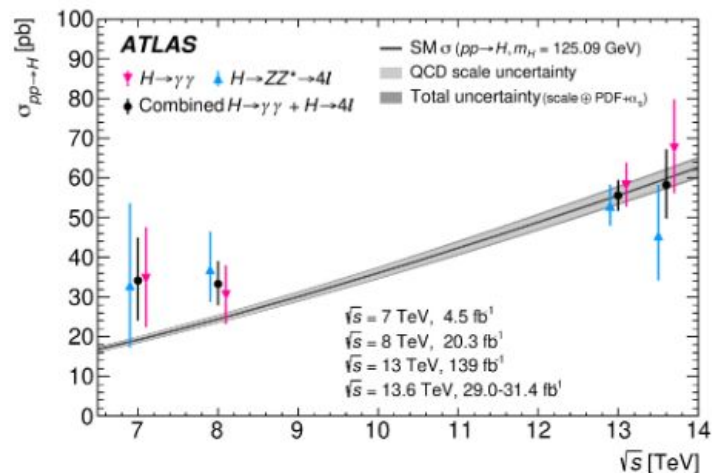
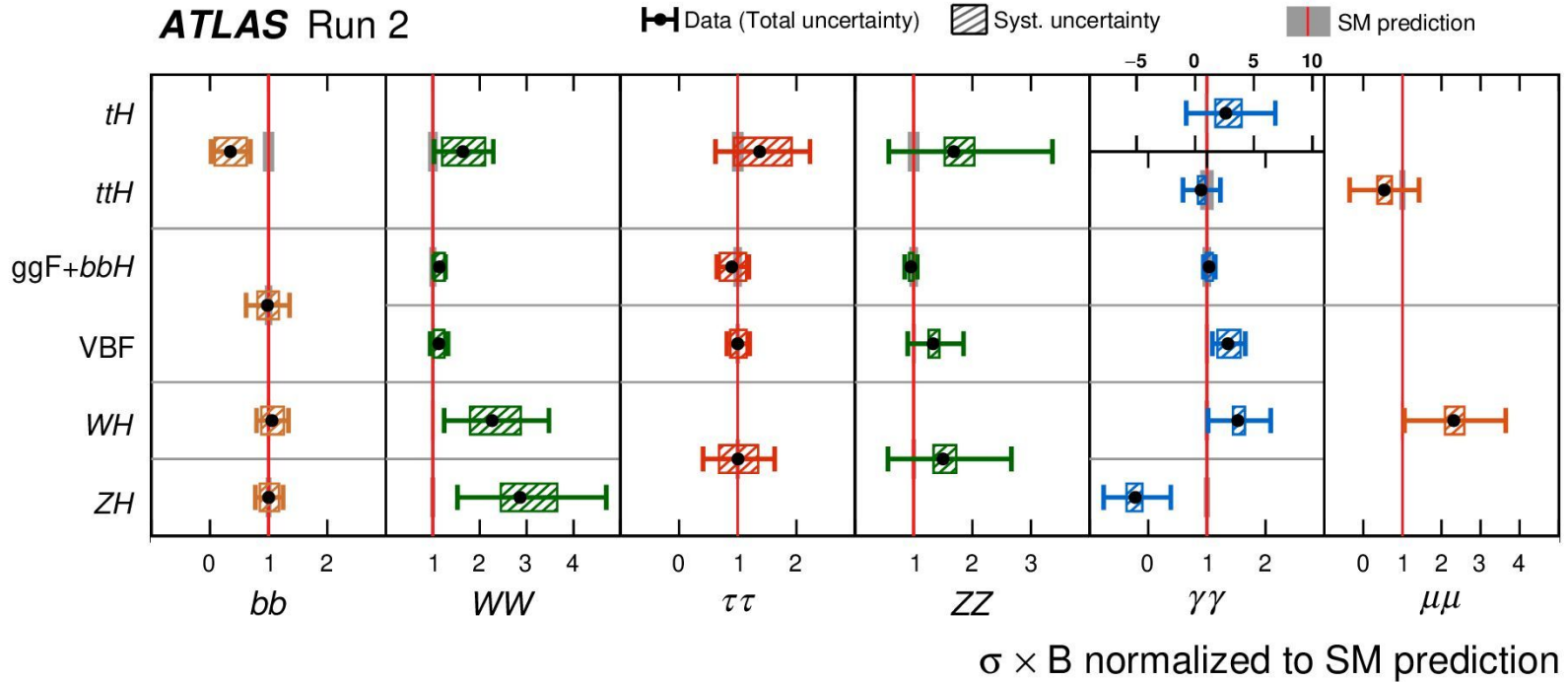


Figure 11.3: Combined measurements by ATLAS [183] and CMS [184] of the products $\sigma \cdot \text{BR}$, normalised to the SM predictions, for the five main production and five main decay modes.

<https://pdg.lbl.gov/2023/reviews/rpp2023-rev-higgs-boson.pdf>

SM is stronger than ever!

Higgs boson coupling modifiers

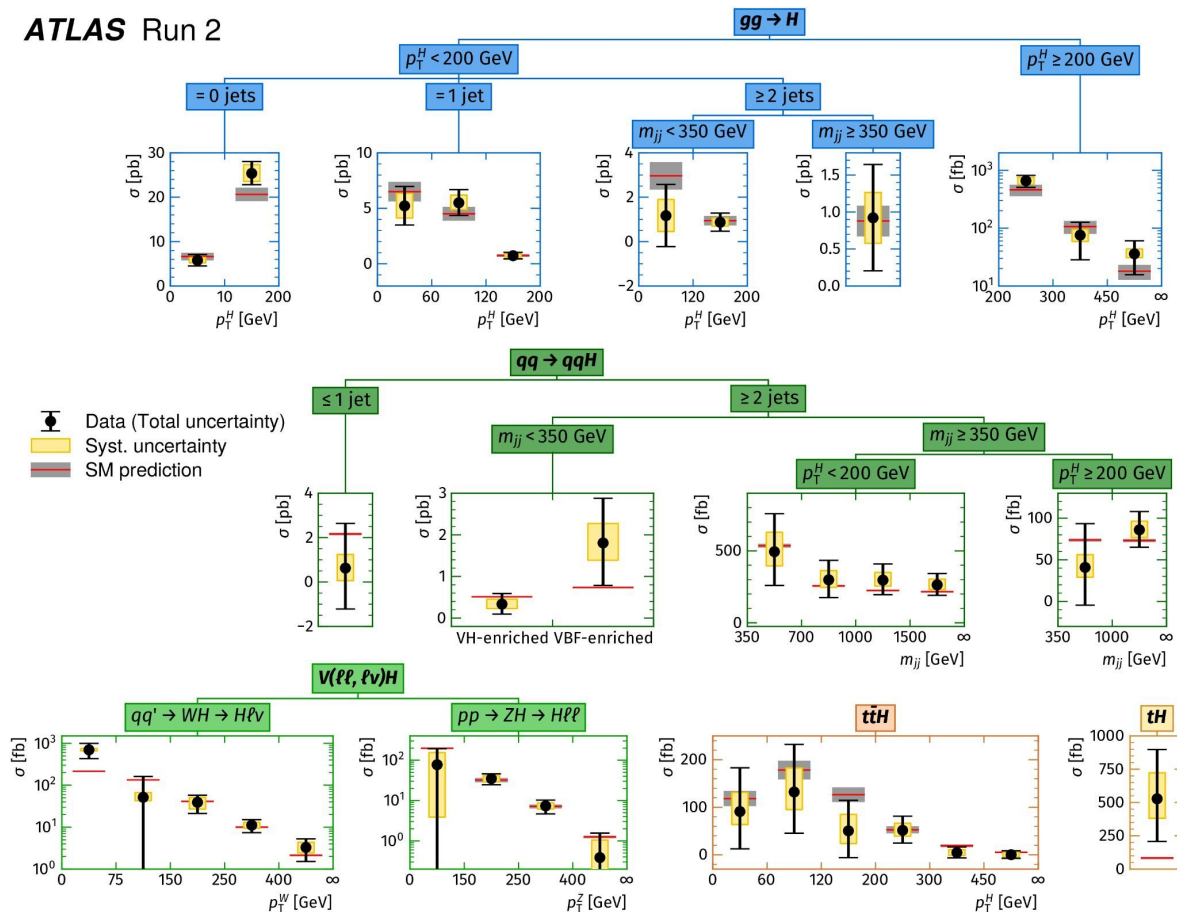


No deviations from SM predictions observed

Cross Section Measurements in Kinematic bins

- With ever-growing statistics, time to shift focus towards
 - measurements at high p_T which are sensitive to new physics
 - observables that are CP-sensitive

ATLAS Run 2

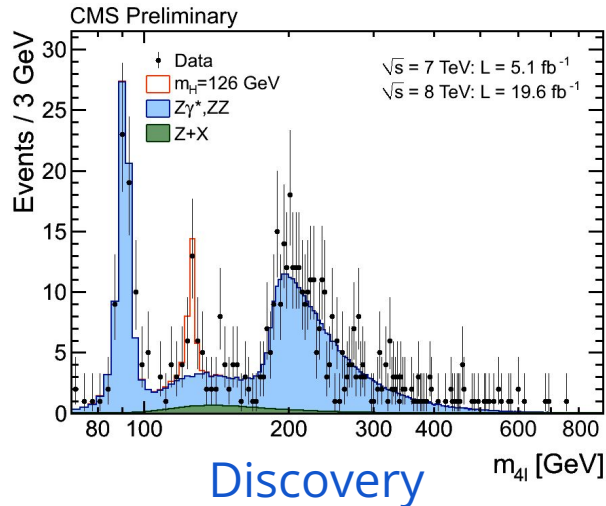


Nature 607, 52 (2022)

Higgs boson - From Discovery to Precision



Run 1

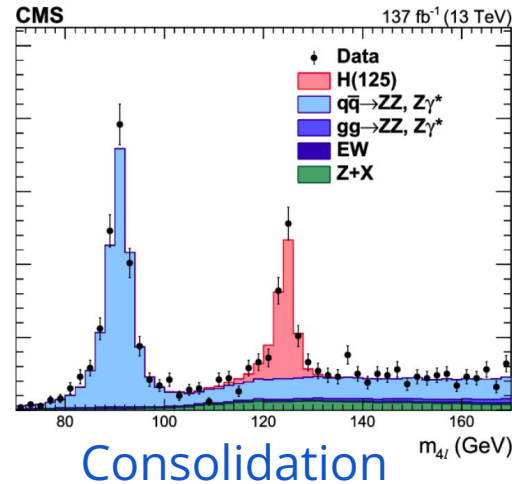
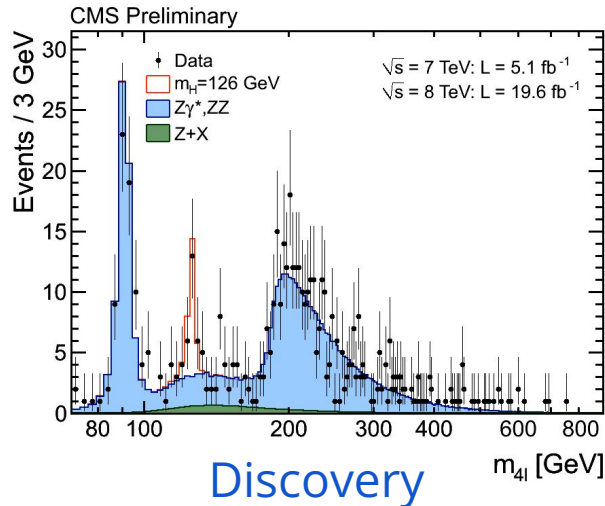


Higgs boson - From Discovery to Precision

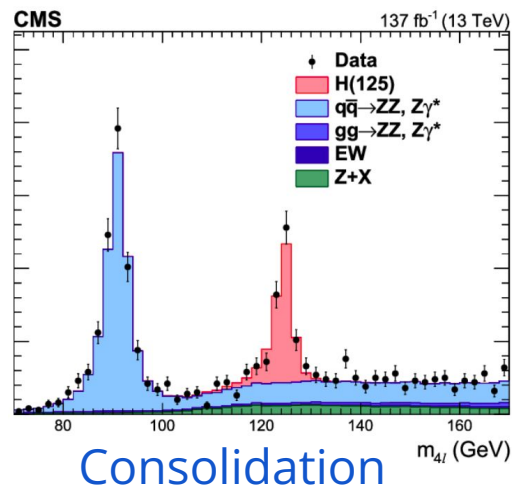
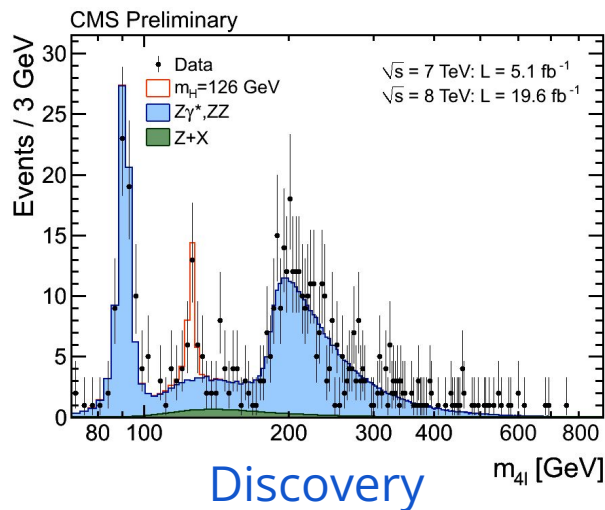
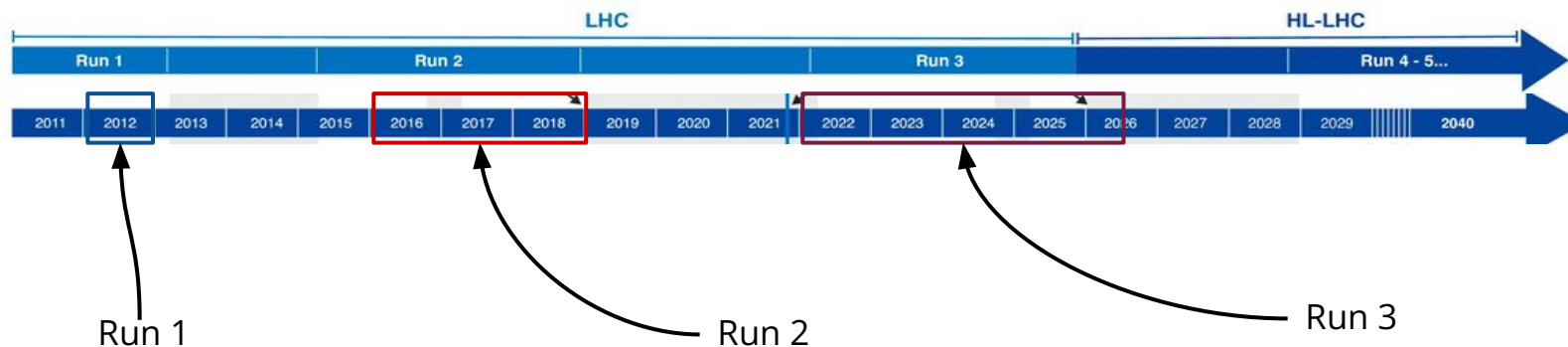


Run 1

Run 2



Higgs boson - From Discovery to Precision



- $\sqrt{s} = 13.6$ TeV
- Int. Lumi ~ 350 fb $^{-1}$
- Access to rare decays of Higgs boson
- Improved analysis techniques
- Stringent tests of SM

Precision Era

Rare Higgs Physics

Rare Higgs Physics

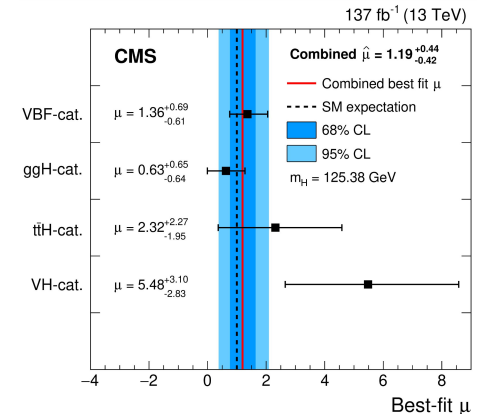
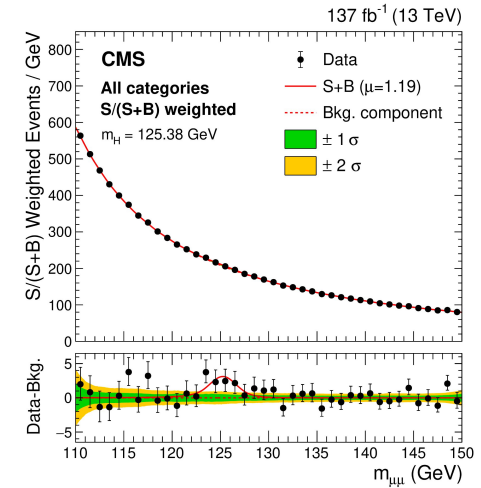
- Access to rare channels possible, but experimentally challenging
 - small number of signal events
 - techniques to reduce relatively large backgrounds while retaining high signal efficiency
- ATLAS and CMS have results on
 - $H \rightarrow \mu\mu$
 - $V + H (\rightarrow cc)$
 - $H (\rightarrow \gamma\gamma) + c$
 - $H \rightarrow Z + \gamma$
 - $H \rightarrow J/\psi / \psi(2S) + \gamma$
 - $H \rightarrow \rho / \varphi / K^{*0} + \gamma$



- main production modes considered
- Final state with two muons
 - good signal resolution
 - small branching ratio ($\sim 2.2 \times 10^{-4}$)
- Categorisation based on the Higgs production modes
- ML techniques used to discriminate signal and background events
- Large irreducible bkg from DY process ($Z \rightarrow \mu\mu$)
- Simultaneous binned-likelihood fit to obtain

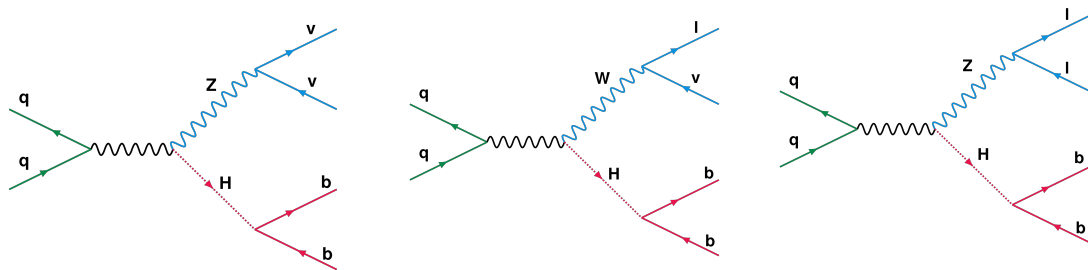
$$\mu = 1.19^{+0.41}_{-0.40}(\text{stat})^{+0.17}_{-0.16}(\text{syst})$$

- Obs (exp) significance 3 (2.5) σ
- upper limits on BR of $1.9 \times \text{SM}$ @ 95% CL



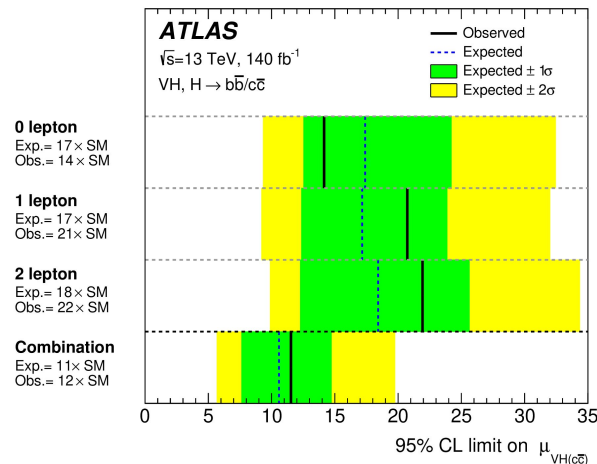
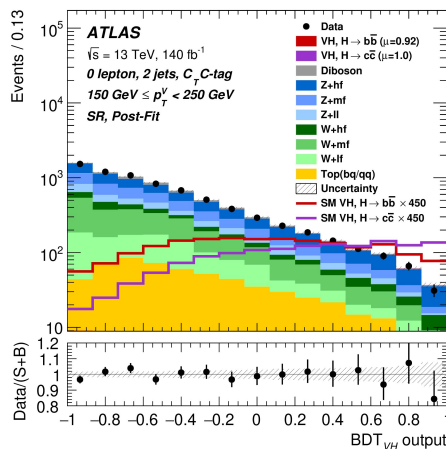
VH($\rightarrow c\bar{c}$)

- Small $B(H \rightarrow c\bar{c}) \sim 3\%$ $\rightarrow$ analysis targeting the $V(\text{lep})H$ production
- Simultaneous study of the $VH(b\bar{b})$ and $VH(c\bar{c})$ final states



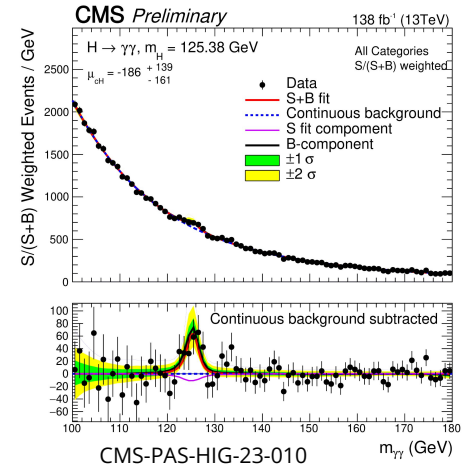
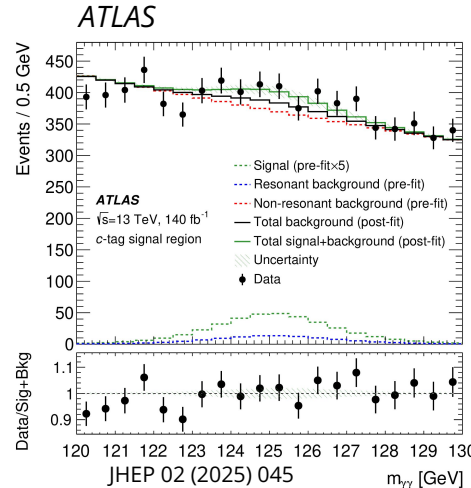
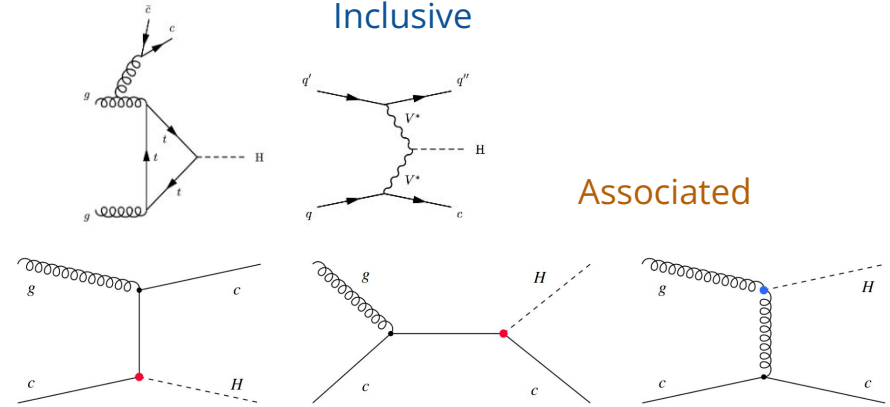
Observed (expected) upper limits
on μ_{VH}^{cc} of 11 (10) $\times$ SM @ 95% CL

- Categorisation based on flavour categories, # leptons, # add. jets, p_T of the vector boson
- Major backgrounds from Z + jets, W + jets and top
 - shape from MC, normalisation from the control regions
- MVA techniques to discriminate VH signal and bkg events



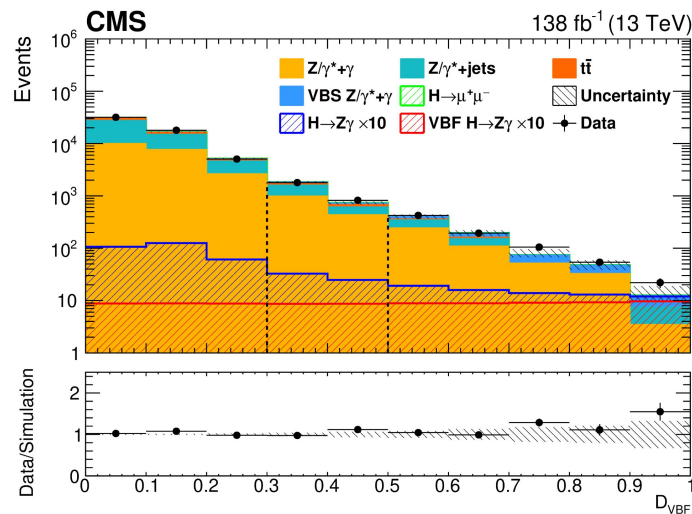
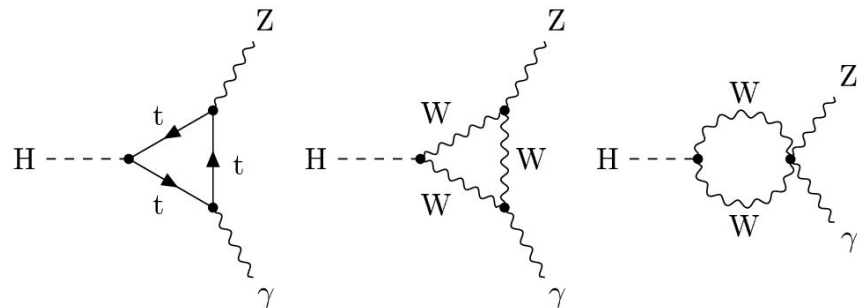
$H(\rightarrow \gamma\gamma) + c$

- Search for the $pp \rightarrow H + c$ production
 - Probe of the coupling of the Higgs boson to charm quarks via the $g + c \rightarrow H + c$ process
 - Large bkg contribution
 - use clean $H \rightarrow \gamma\gamma$ decay
- Final state with two photons and one jet
 - ATLAS: the jet can be either a c-tagged jet or non c-tagged jet
 - CMS: jet is a c-tagged jet
- ATLAS: inclusive $H+c$ production
 - $\sigma(H + c) = 5.2 \pm 3.0$ pb
 - Obs (exp) limits $\sigma(H + c) < 10.4$ (8.6) pb @ 95%CL
- CMS: associated production $c+H$ to study k_c
 - Obs (exp) $\mu_{cH} < 243$ (355)
 - Obs (exp) limits $|k_c| < 38.1$ (72.5) @ 95%CL



$$H \rightarrow Z + \gamma$$

- Rare $H \rightarrow Z\gamma$ decay via loop diagrams $\rightarrow$ sensitive to new physics
 - $\text{Br}(H \rightarrow Z\gamma) = 1.54 \times 10^{-3}$
- Final state with one photon and two same flavor opposite charge leptons ($l = e, \mu$)
- Additional requirements depending on the target production mode
- Major backgrounds: Drell-Yan with ISR photon or Drell-Yan with jets
- Analysis categories to target the different H production modes
 - In some categories, BDT score used to define analysis regions with different S/B
- Signal and background modelled with analytical functions
 - Signal modelled from Crystal ball and Gaussian function
 - Bkg modelled using exponential, power law functions, Laurent series and Bernstein polynomial

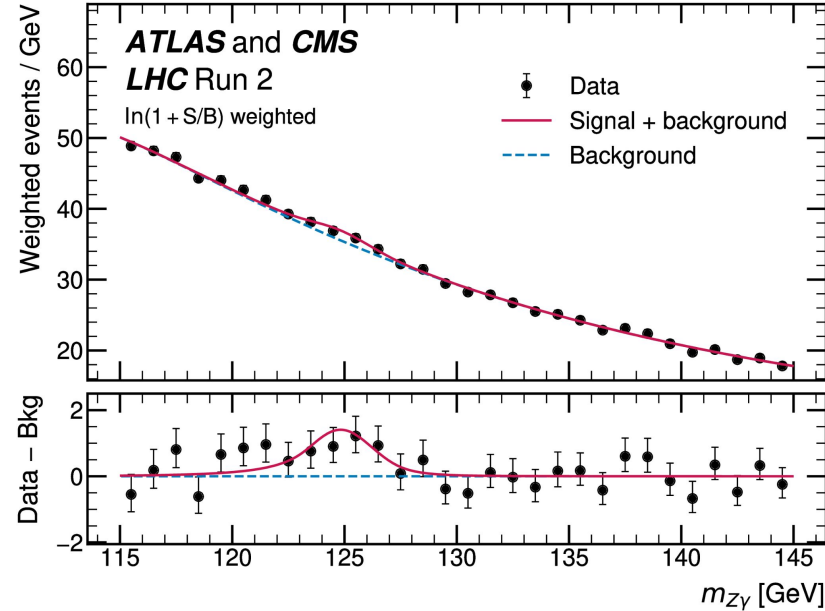
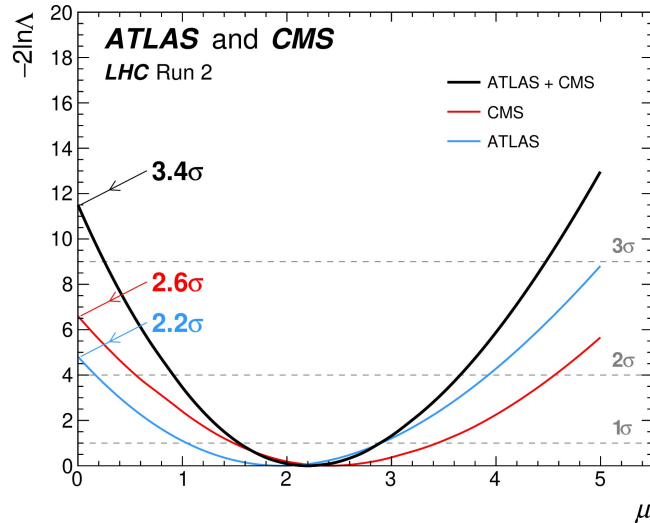


$H \rightarrow Z + \gamma$

- Binned-maximum likelihood fit to all $m_{Z\gamma}$ distributions

$$\mu = 2.2 \pm 0.6 \text{ (stat)}^{+0.3}_{-0.2} \text{ (syst)}$$

- Obs (exp) significance of 3.4 (1.6) σ

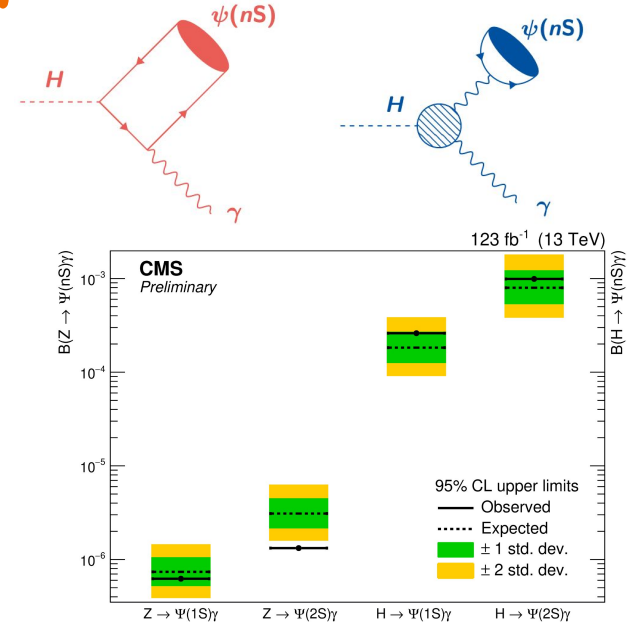


- Measured $\text{Br}(H \rightarrow Z\gamma) = (3.4 \pm 1.1) \times 10^{-3}$
- Measurement agrees with the expectations from SM prediction within 1.9 σ

$H \rightarrow J/\psi / \psi(2S) + \gamma$

- $H \rightarrow J/\psi / \psi(2S) + \gamma$ allows to access the c-quark Yukawa coupling
 - radiative decays helps to suppress multi-jet background
- Interference between the direct and indirect contributions
 - direct amplitude sensitive to c-quark Yukawa coupling
 - indirect contribution mimics $H \rightarrow \gamma\gamma$ with one photon fragmenting into quark-antiquark pair and forming the meson
- SM branching fraction predictions
 - $\text{Br}(H \rightarrow J/\psi + \gamma) = (2.95 \pm 0.17) \times 10^{-6}$
 - $\text{Br}(H \rightarrow \psi(2S) + \gamma) = (1.03 \pm 0.06) \times 10^{-6}$
- $J/\psi / \psi(2S) \rightarrow \mu\mu$ decays considered in the analysis
 - final state with two muons and one isolated photon
- Analysis exploring also the Z boson decays (expected $\text{Br} \sim 10^{-8}$)
- Signal strength interpreted with the k-framework to derive constraints on $H \rightarrow c\bar{c}$ coupling
 - $\mu(H \rightarrow J/\psi + \gamma) / \mu(H \rightarrow \gamma\gamma) \sim k_c / k_\gamma$
 - Obs (exp) constraint @ 95% CL: $-157 < k_c / k_\gamma < 199$ ($-121 < k_c / k_\gamma < 161$)
- CMS results on branching ratio limits and k_c / k_γ constraints comparable to those of ATLAS (Eur. Phys. J. C 83 (2023) 781)

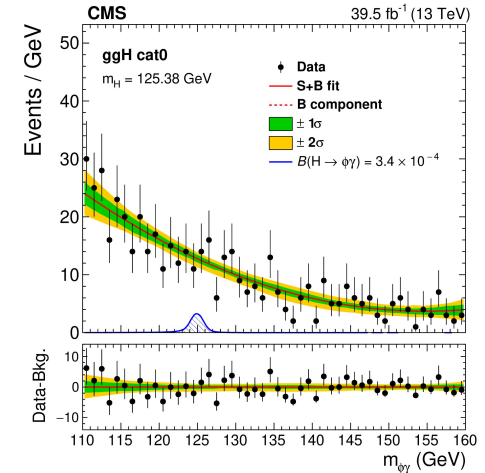
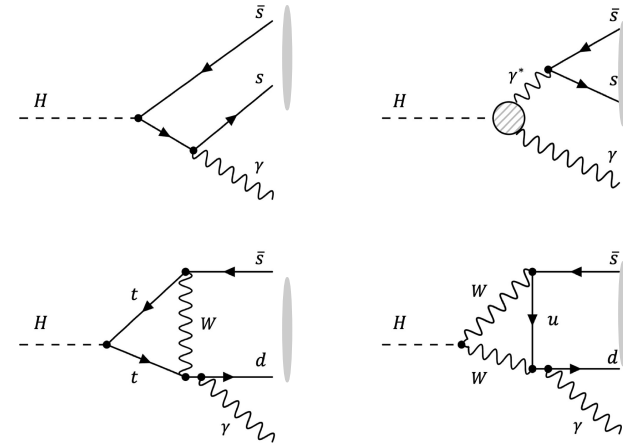
CMS-PAS-SMP-22-012



95% CL upper limit (obs.) on branching fraction	
$H \rightarrow J/\psi \gamma$	2.6×10^{-4}
$H \rightarrow \psi(2S) \gamma$	9.9×10^{-4}
$Z \rightarrow J/\psi \gamma$	0.6×10^{-6}
$Z \rightarrow \psi(2S) \gamma$	1.3×10^{-6}

$H \rightarrow \rho / \phi / K^{*0} + \gamma$

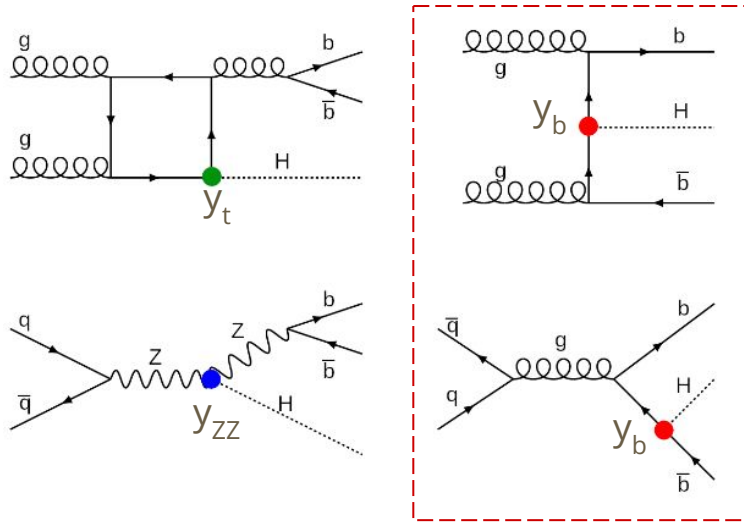
- $H \rightarrow \rho / \phi + \gamma$: study the Higgs coupling to light-quarks (u, d, s)
 - main contribution from diagram with Higgs to di-photon, with one off-shell photon
- $H \rightarrow K^{*0} + \gamma$: probe the flavour changing neutral current
- Higgs boson branching
 - $\text{Br}(H \rightarrow \rho + \gamma) = (1.68 \pm 0.08) \times 10^{-5}$
 - $\text{Br}(H \rightarrow \phi + \gamma) = (2.31 \pm 0.11) \times 10^{-6}$
 - $\text{Br}(H \rightarrow K^{*0} + \gamma) \sim 10^{-19}$
- Analysis of ggF, VBF, VH production modes
- Final state with one photon + 2 tracks to identify the meson decays into K or π
- Main background from γ +jets and multi-jet processes
- No excess over the bkg expectations
- Upper limits @ 95% CL on the branching ratios



	Expected	Observed
$\mathcal{B}(H \rightarrow \rho + \gamma)$	5.7×10^{-4}	3.74×10^{-4}
$\mathcal{B}(H \rightarrow \phi + \gamma)$	2.9×10^{-4}	2.97×10^{-4}
$\mathcal{B}(H \rightarrow K^{*0} + \gamma)$	1.7×10^{-4}	1.71×10^{-4}

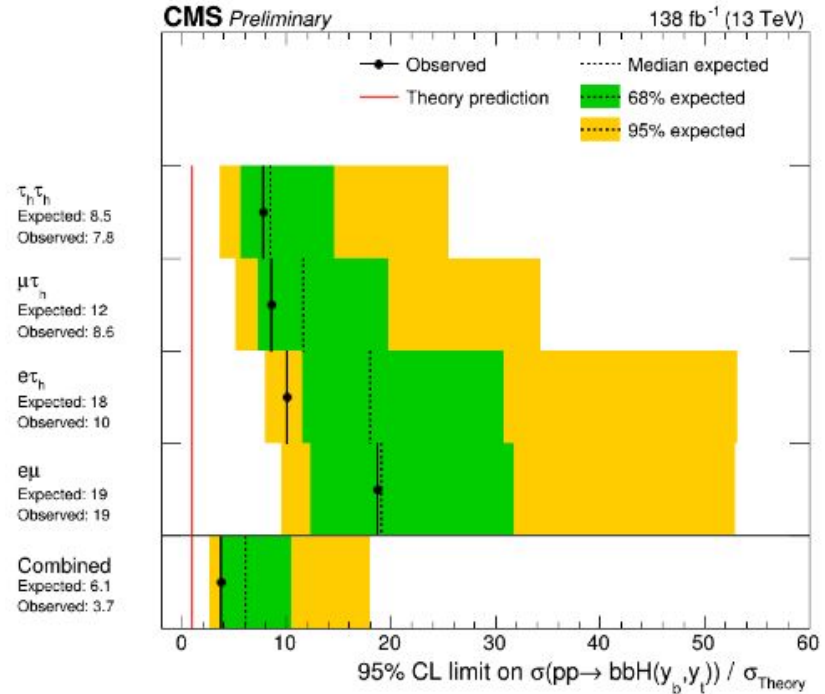
bbH Associated Production

- Direct probe of Higgs couplings to the bottom quark (y_b) in production



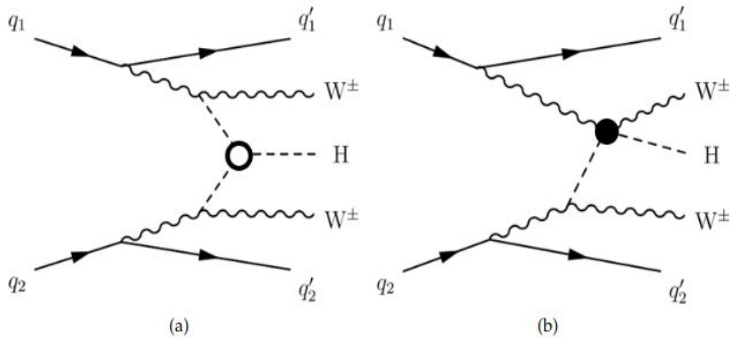
$H \rightarrow \tau\tau / W^+W^- \rightarrow e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$ considered

- obs (exp) upper limits ~ 3.7 (6.1) x SM expectation



HWW production through VBS CMS PAS HIG-24-001

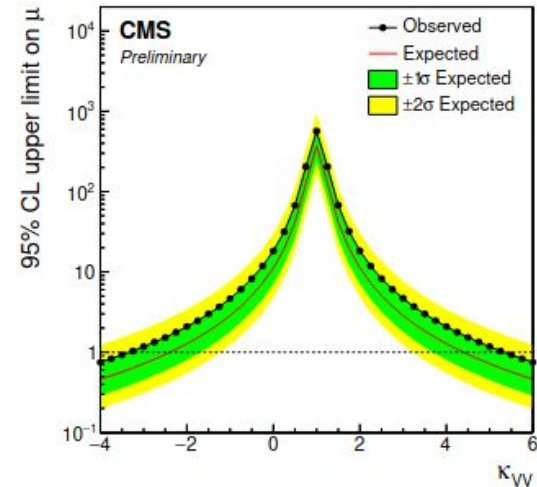
- HWW production through vector boson scattering is sensitive to k_λ and k_{WW}
- Goal is to constrain k_{WW}



Final state

- two same signed leptons (e, μ or τ) from W bosons
- two merged jets consistent with $H \rightarrow b\bar{b}$
- a pair of forward-backward jets

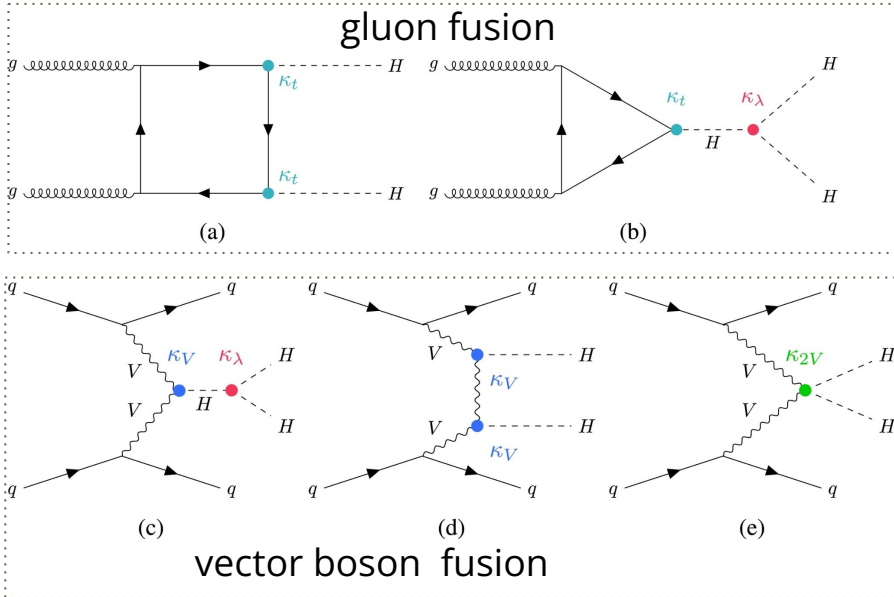
- fit data with different k_{WW} hypotheses to obtain the upper limit 95% CL on the signal strength (μ) as a function of k_{WW}
 - allowed range k_{WW} found from the intersections with the line $\mu = 1$
- The observed (expected) 95% CL constrained interval for κ_{WW} is $[-3.3, 5.3]$ ($[-2.4, 4.4]$).



Higgs Pair Production

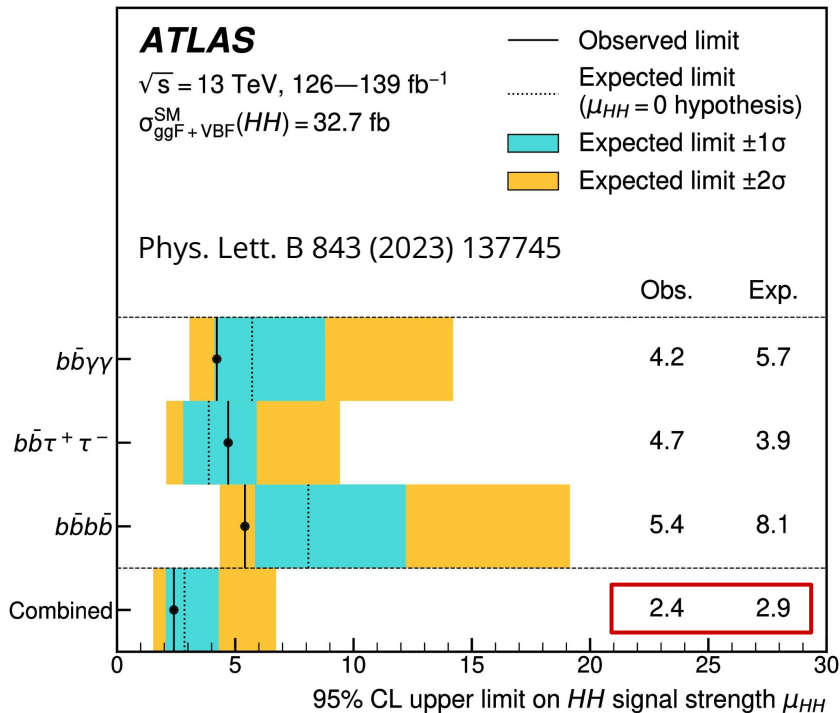
Non-resonant Higgs boson Pair Production

- Total HH production cross section is about 1000 x smaller than single-H
- Higgs boson pair production is sensitive to self-interaction strength λ
- Cross-section for each mode can be precisely parameterized as a function of $k_\lambda = \lambda/\lambda_{\text{SM}}$

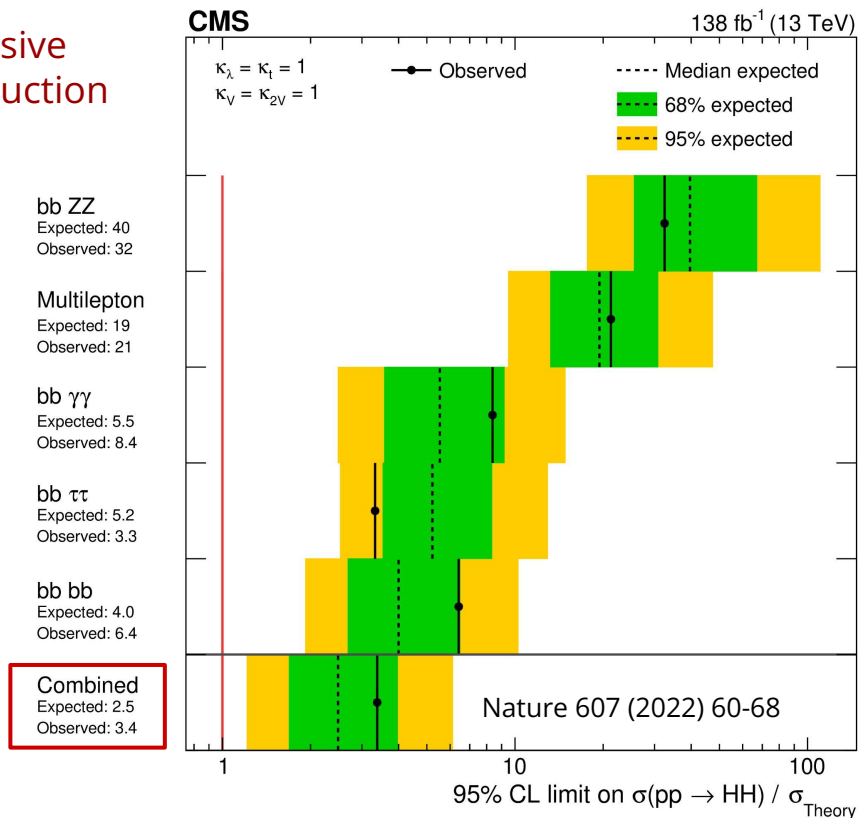


	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

Searches for Non-resonant Higgs boson Pair Production



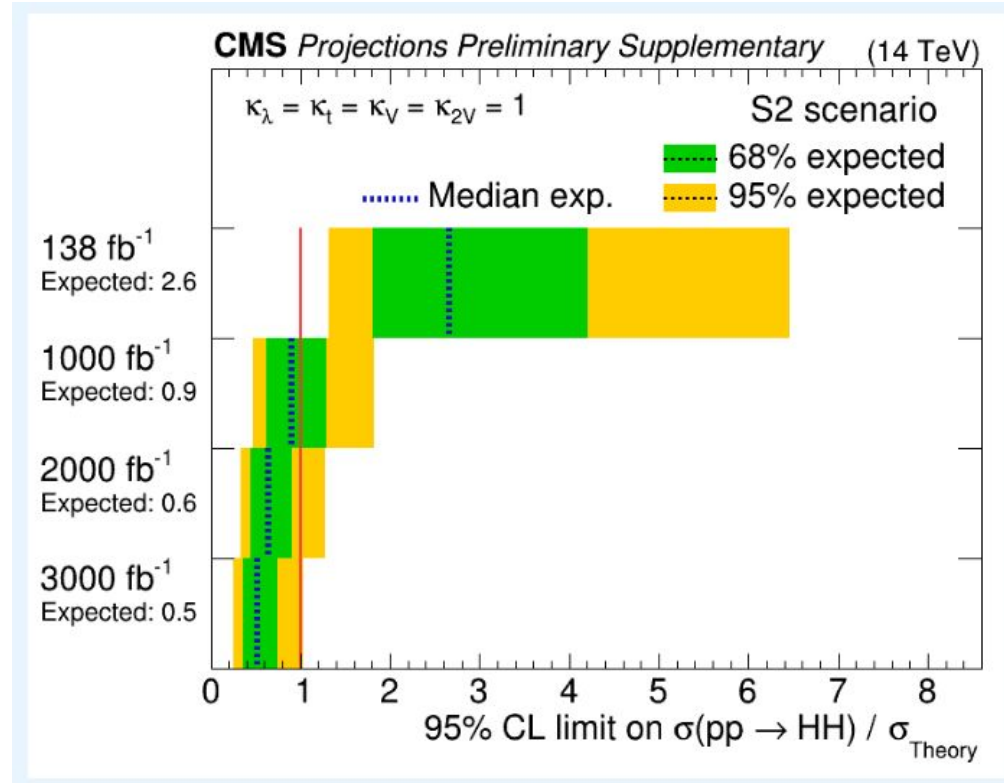
Inclusive
production



- Similar sensitivity for ATLAS and CMS
- Results **still** statistically limited
- background modelling and theoretical uncertainties on σ_{ggHH} play important role

Higgs boson Pair Production - Projections to HL-LHC

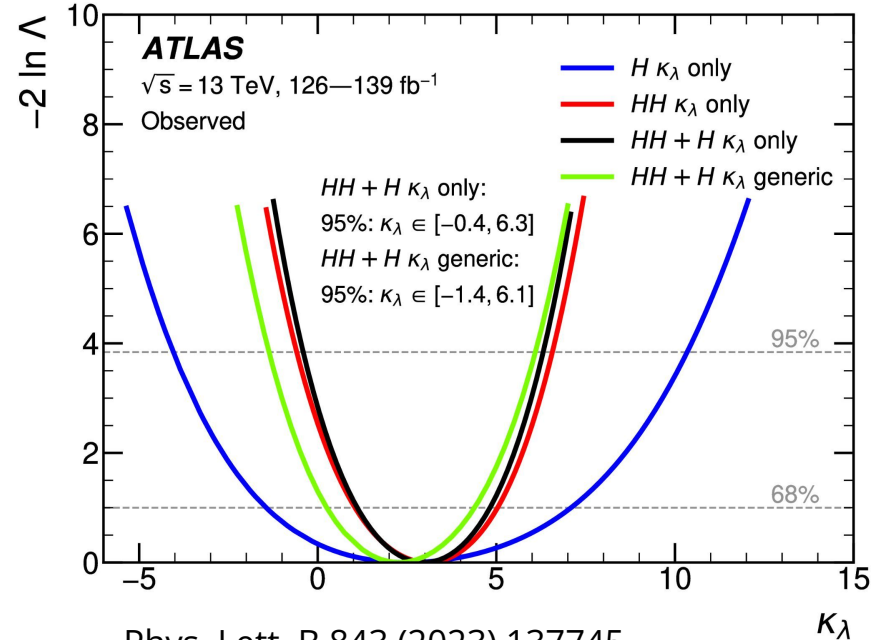
- Projection study performed for: $bbbb$, $bb\tau\tau$, $bby\gamma$, $bbWW$, and Multilepton
- Run-2 results projected up to the full HL-LHC dataset (3000 fb^{-1})
- Efficiency of physics object reco, id, misid and resolution are assumed to be same as Run 2
- Systematic uncertainty (S2) : stat. unc. reduced with luminosity, theory unc. halved, MC stat. removed
- Lumi scenarios: 1000, 2000, 3000 fb^{-1}
- Sensitivity is sufficient to establish HH existence
- Results conservative and do not include improvement achieved in Run-3
- Combination with ATLAS results will enhance the sensitivity further



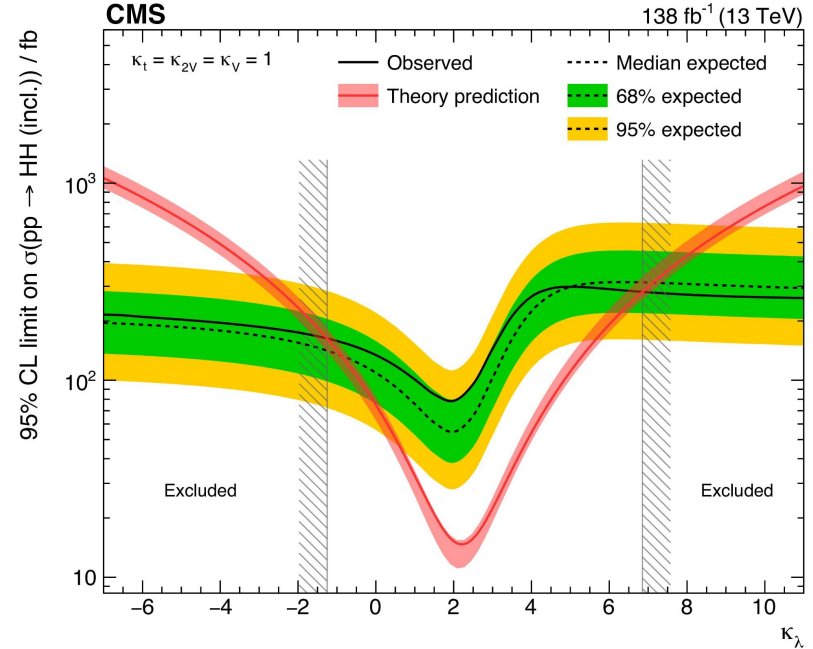
Higgs boson Self Interaction Strength (κ_λ)

ATLAS observed (expected) at 95% CL:
 $-0.4 (-1.9) < \kappa_\lambda < 6.3 (7.6)$

CMS observed: $-1.24 < \kappa_\lambda < 6.49$



Phys. Lett. B 843 (2023) 137745

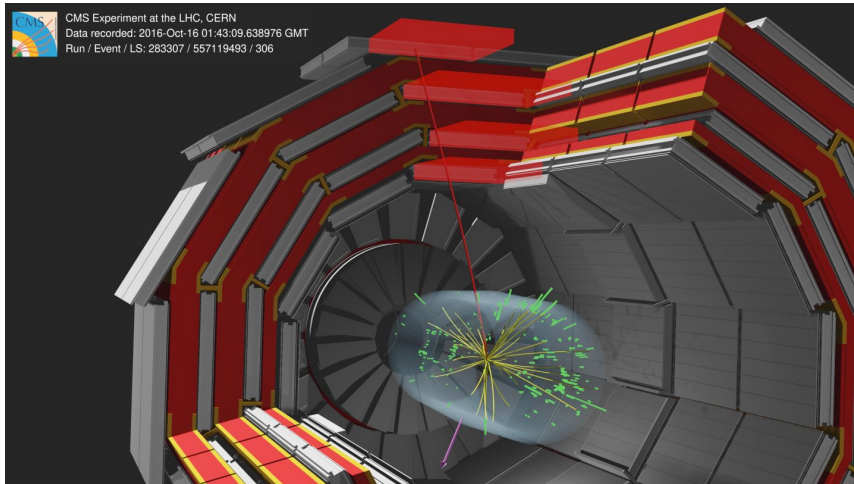


Nature 607 (2022) 60-68

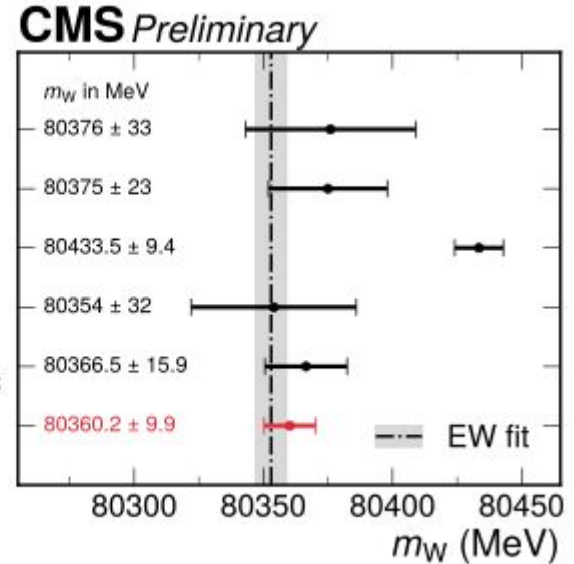
Precision Tests of SM

W Mass Measurement

The eagerly awaited result is the most precise measurement of the W mass made at the LHC so far



LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arxiv:2403.15085, subm. to EPJC
CMS
This Work



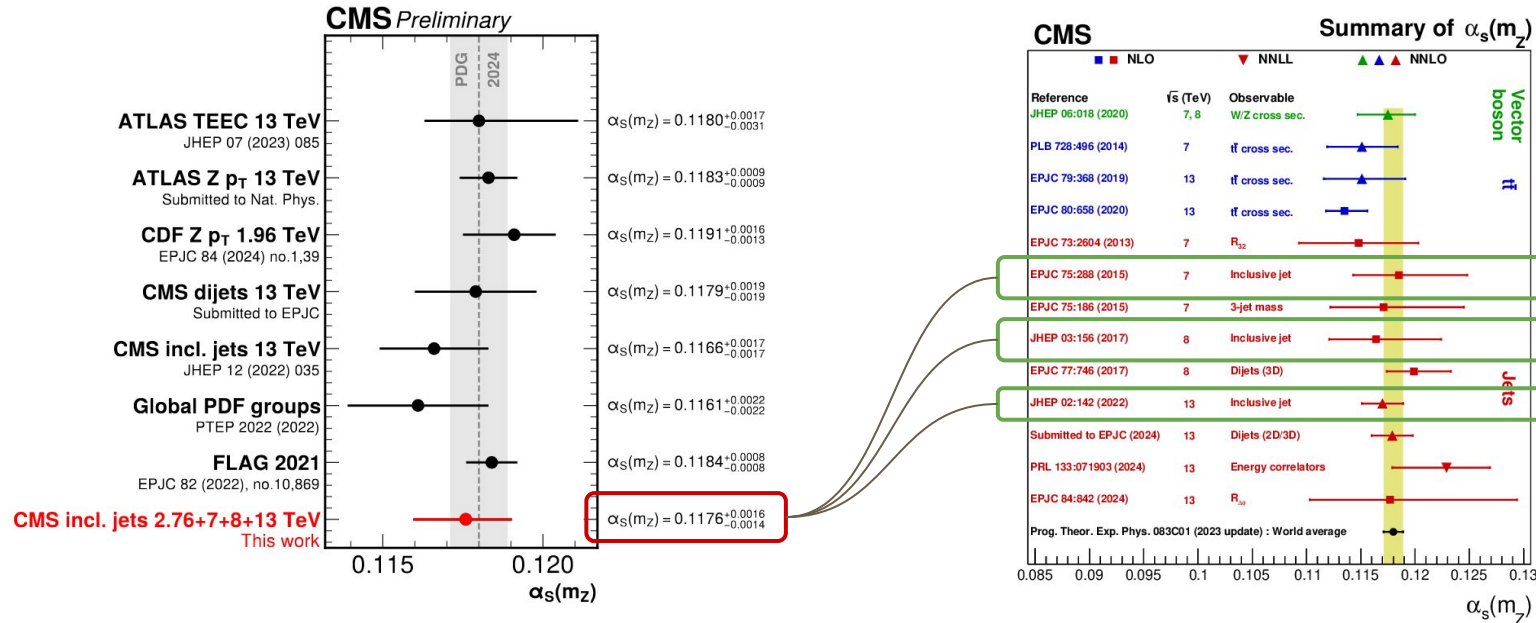
Results in line with the Standard Model prediction

α_s Measurements from Jets

CMS-PAS-SMP-24-007

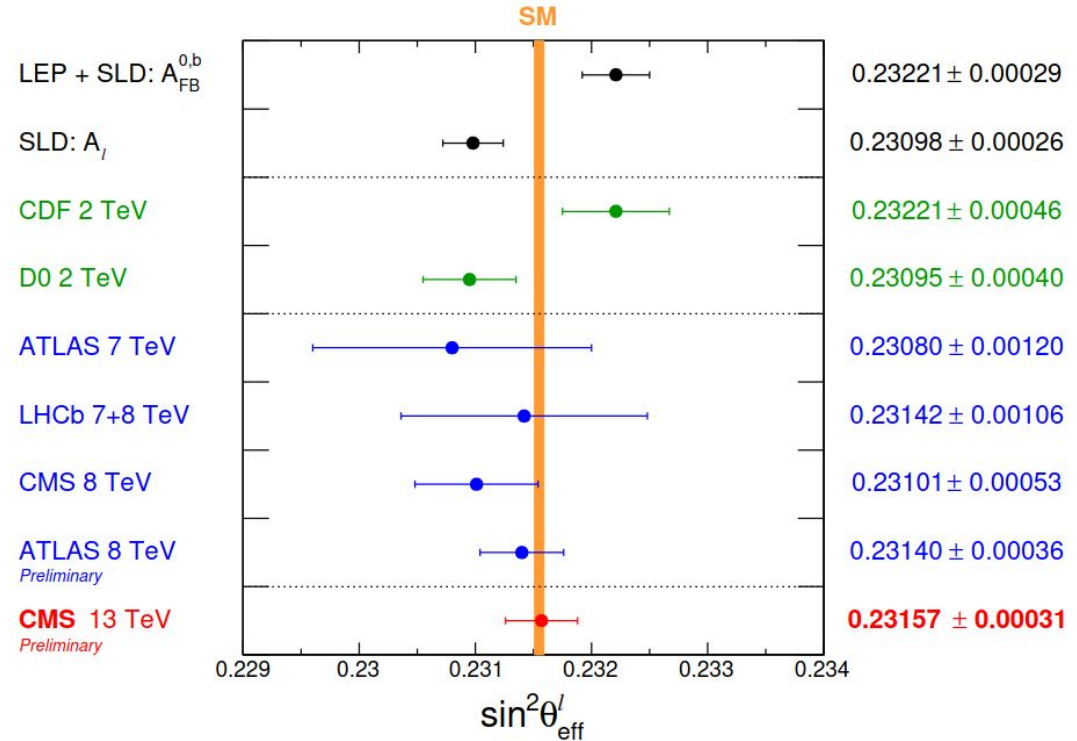
- analysis at next-to-next-to-leading order (NNLO) accuracy in QCD
- double-differential cross section measurements of inclusive jet production at centre-of-mass energies of 2.76, 7, 8, and 13 TeV
- simultaneous determination of $\alpha_s(m_Z)$ together with the proton PDF

Most precise measurement of α_s from jet cross sections



Measurement of $\sin^2\theta_{\text{eff}}^l$

- Measurement of forward-backward asymmetry in the Drell-Yan production and the effective leptonic electroweak mixing angle (θ_{eff}^l), a key parameter of the SM at $\sqrt{s} = 13$ TeV with 137 fb^{-1}
 - uses both dimuon and dielectron events
 - performed as a function of the dilepton's mass and rapidity

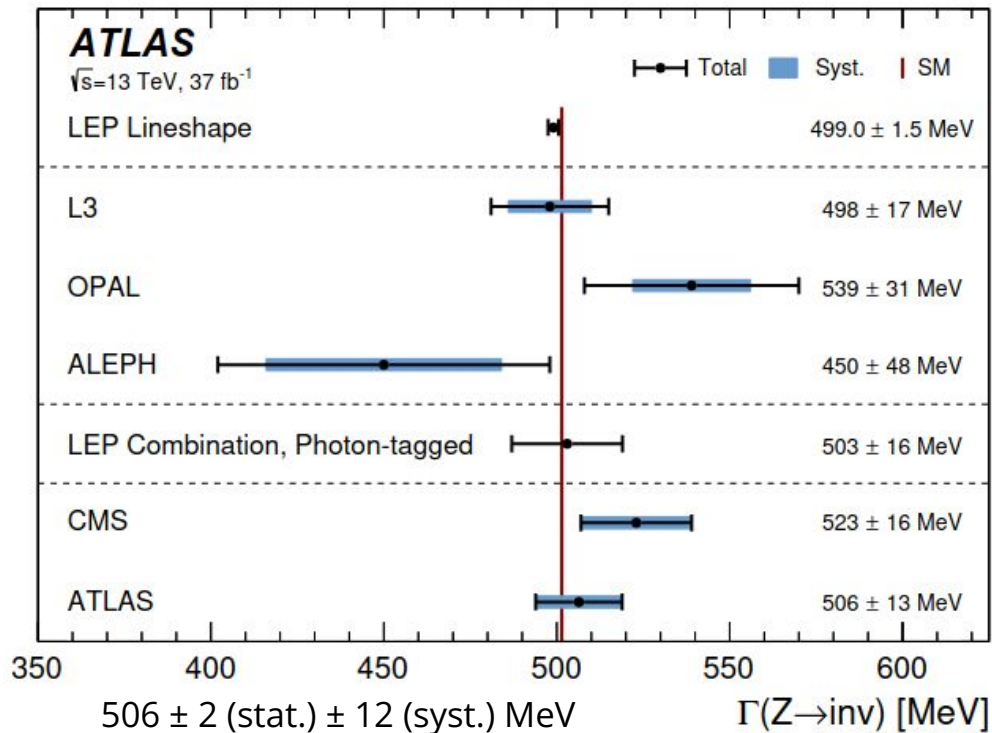


$\sin^2\theta_{\text{eff}}^l = 0.23157 \pm 0.00010 \text{ (stat)} \pm 0.00015 \text{ (syst)} \pm 0.00009 \text{ (theo)} \pm 0.00027 \text{ (PDF)}$

Most precise $\sin^2\theta_{\text{eff}}^l$ measurement at a hadron collider, as precise as the results obtained at LEP and SLD

Z boson invisible width

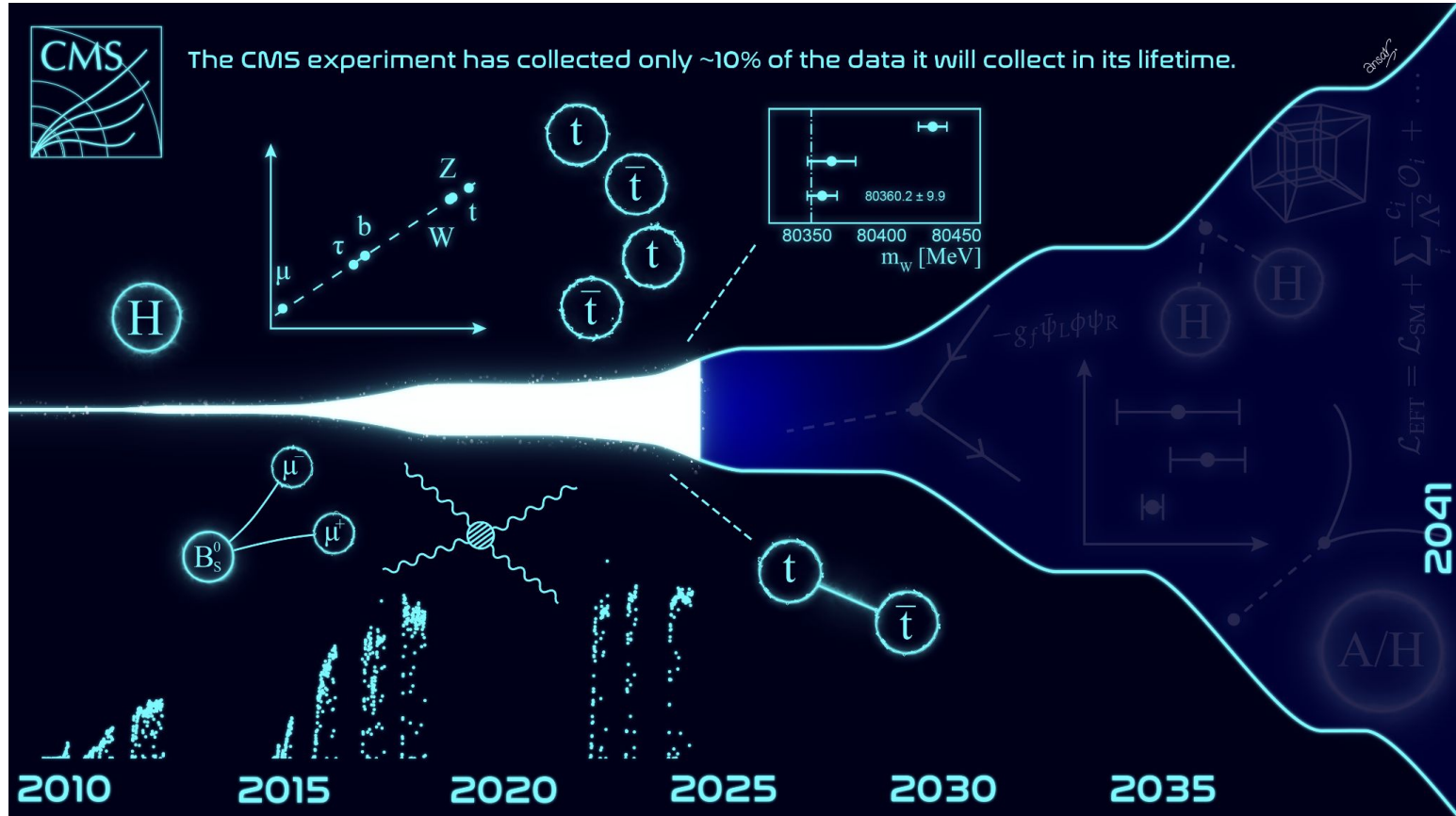
A measurement using events with jets and missing transverse momentum



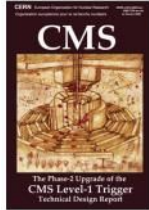
- The ratio of $Z \rightarrow \text{inv}$ to $Z \rightarrow \ell\ell$ events, where inv refers to non-detected particles and ℓ is either an electron or a muon, is measured and corrected for detector effects
- Events with at least one energetic central jet with $p_T \geq 110$ GeV are selected for both the $Z \rightarrow \text{inv}$ and $Z \rightarrow \ell\ell$ final states to obtain a similar phase space in the ratio
- The single most precise recoil-based measurement
- The result is in agreement with the most precise determination from LEP and the Standard Model prediction based on three neutrino generations

Before I close

Summary



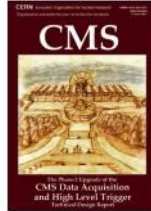
CMS Phase-2 Detector Upgrade



L1-Trigger

<https://cds.cern.ch/record/2714892>

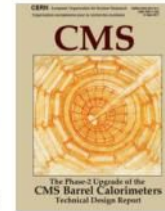
- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

<https://cds.cern.ch/record/2759072>

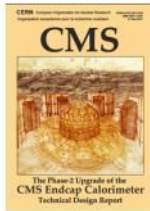
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output



Barrel Calorimeters

<https://cds.cern.ch/record/2283187>

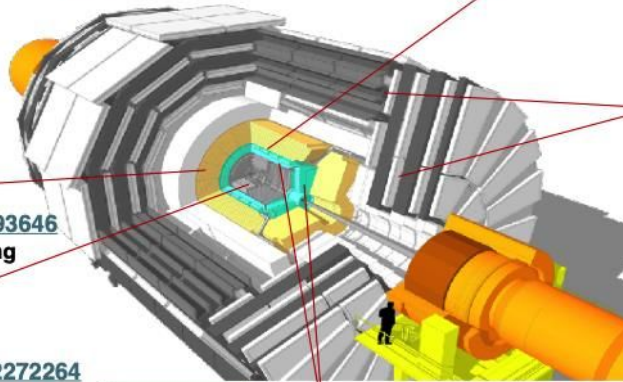
- ECAL crystal granularity readout at 40 MHz
- with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Calorimeter Endcap

<https://cds.cern.ch/record/2293646>

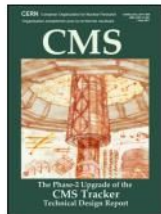
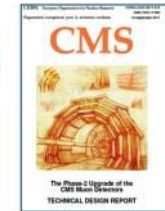
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Muon systems

<https://cds.cern.ch/record/2283189>

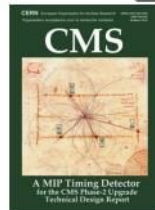
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta = 3$



Tracker

<https://cds.cern.ch/record/2272264>

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$



MIP Timing Detector

<https://cds.cern.ch/record/2667167>

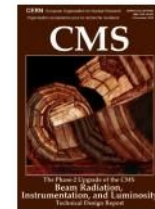
Precision timing with:

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

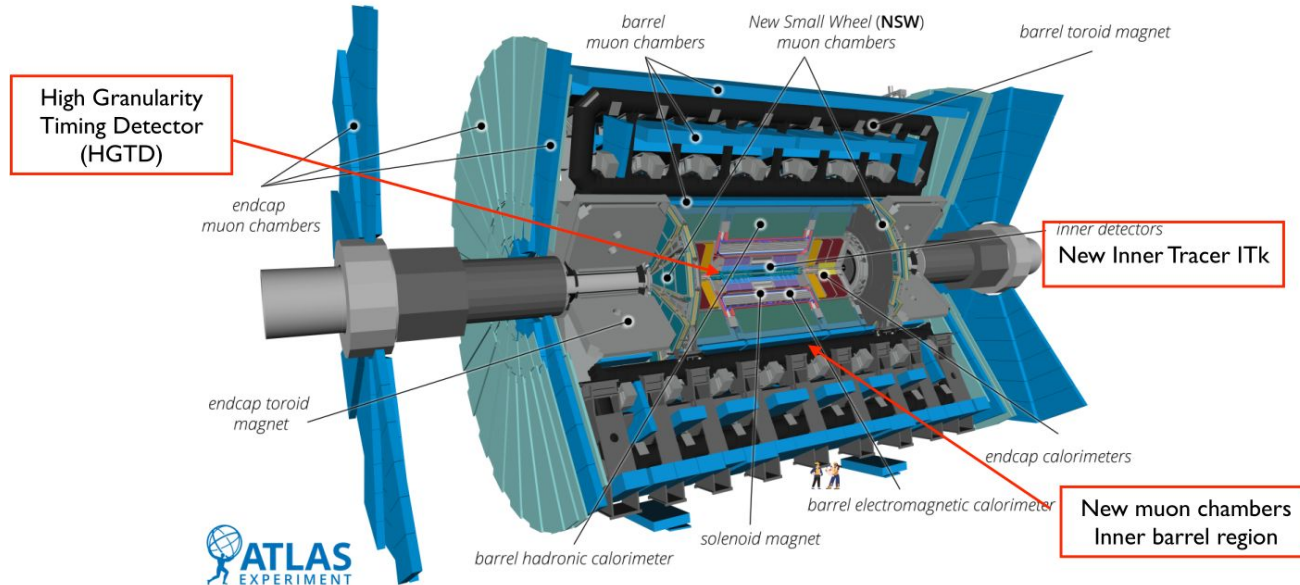
Beam Radiation Instr. and Luminosity

<http://cds.cern.ch/record/2759074>

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

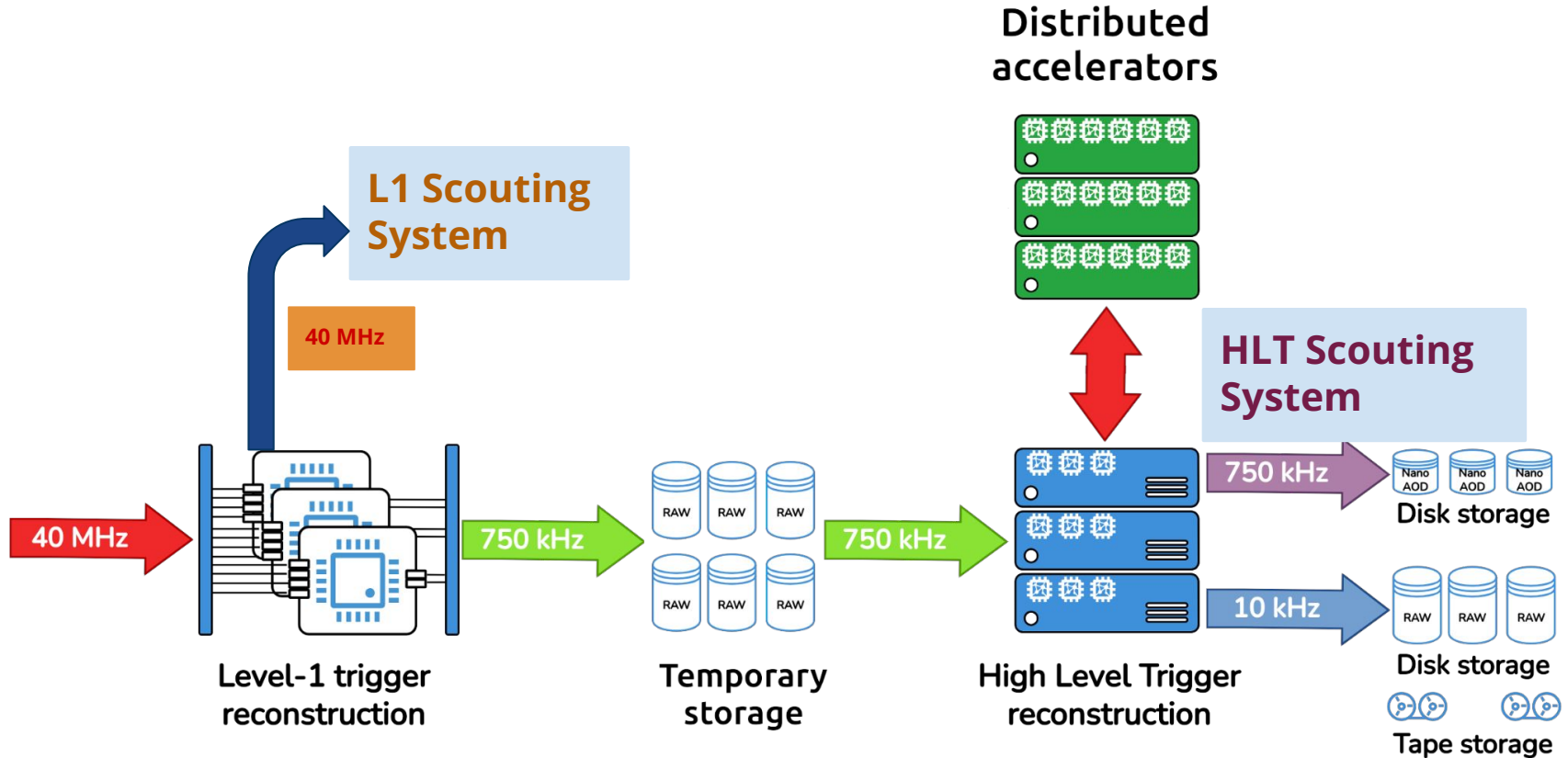


ATLAS Phase-2 Detector Upgrade



- Additional smaller upgrades (Luminosity detectors aiming for 1% precision, HL-LHC ZDC)
- All around electronics upgrades (Muon, Tile, LAr) for better rad-tolerant and trigger compatibility
- Upgraded trigger and DAQ system
 - New L0 (100 kHz $\rightarrow$ 1 MHz), improved HLT trigger, full-scan tracking @ 150kHz

CMS Phase-2 Trigger System

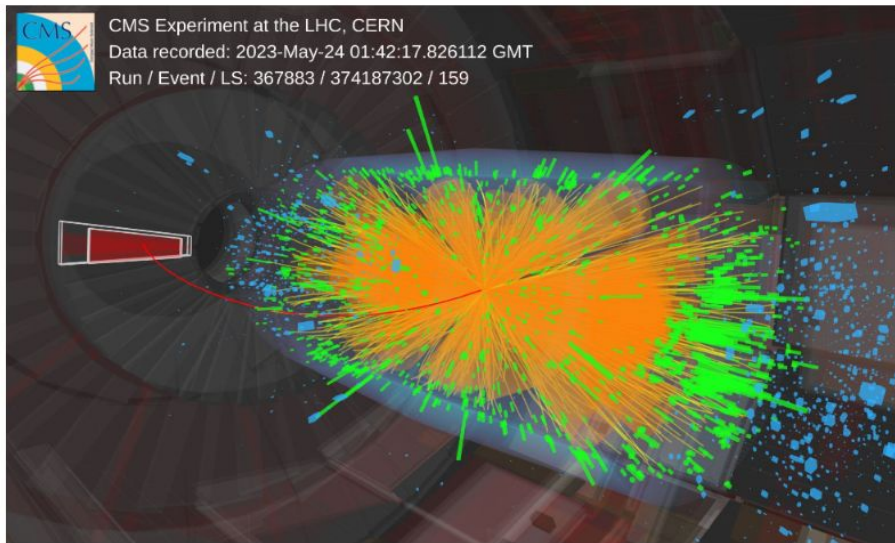


Backup Slides

ML based L1 Trigger (AXOL1TL)

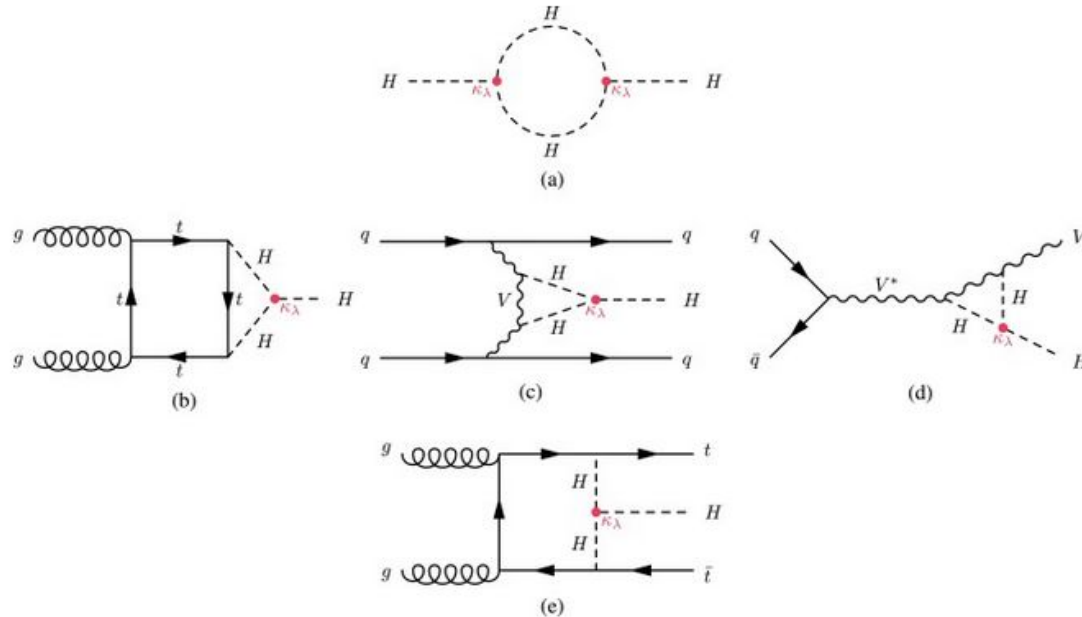
Anomaly eXtraction Online Level-1 Trigger aLgorithm (AXOL1TL)

- ML-based trigger algorithm, selects anomalous events in real-time
 - signal agnostic approach means sensitivity to wide variety of signals
 - trained on ZeroBias data to detect data outliers
- Kinematic variables from Level-1 global trigger system are the inputs for AXOL1TL



Event display of the highest anomaly score event that is not selected by the normal L1T menu, from Ephemeral Zero Bias 2023 Run 367883

One loop λ_{HHH} dependent diagrams



[Download: Download high-res image \(185KB\)](#)

[Download: Download full-size image](#)

Fig. 2. Examples of one-loop λ_{HHH} -dependent diagrams for (a) the Higgs boson self-energy, and for single-Higgs production in the (b) ggF, (c) VBF, (d) VH, and (e) $t\bar{t}H$ modes. The self-coupling vertex is indicated by the filled circle.

Simplified template cross section (STXS)

- Split production mode cross-sections into various phase-space regions, which are chosen according to sensitivity to beyond Standard Model effects, avoidance of large theory uncertainties, matching to experimental selections
- For each STXS region, use the SM predicted signal templates to fit data

