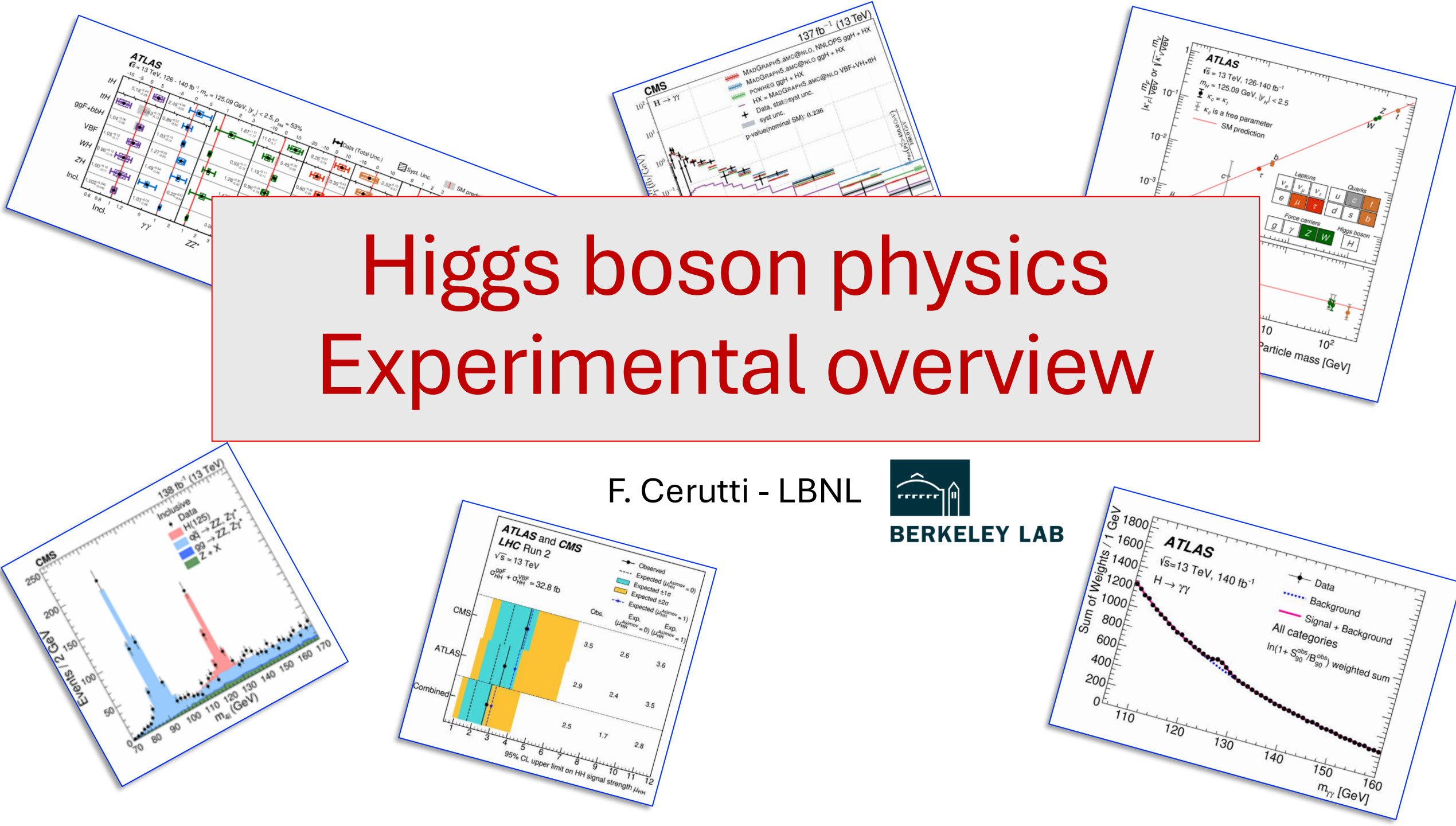


Higgs boson physics Experimental overview

F. Cerutti - LBNL



BERKELEY LAB



Disclaimer

- I'll try to focus on the **main experimental achievements giving you the overall picture**, I **cannot cover analysis details**: a single LHC analysis could cover a one-hour seminar (to get more info you can read the cited papers)
- I have a deeper knowledge of **ATLAS** techniques so in some cases I refer them, though I tried to cover both experiments (**ATLAS** + **CMS**) in terms of results
- I rely on the other excellent lectures to cover:
 - **Higgs theory**: Marco Bonetti
 - **Higgs at Future Colliders**: Christophe Grojean
 - **Modern technique in Higgs analysis**: Sergio Sanchez Cruz
 - **Statistical techniques in Higgs boson analysis**: Hongtao Yang

Outline

- Lecture 1:
 - Short introduction
 - Pre LHC era
 - The discovery at the LHC
 - Higgs boson production and decay at the LHC
 - Mass and spin measurements
 - Cross-section measurements (focusing on principles and combinations)
- Lecture 2:
 - Rare Higgs boson decays: $H \rightarrow \mu\mu$ and “invisible”
 - Higgs boson pair production
 - Higgs boson total width from off-shell measurements
 - Interpretation of the results:
 - The κ framework
 - The EFT approach (if time allows it)
 - CP studies in HVV and Hff interactions (if time allows it)
 - Prospects at HL-LHC (if time allows it)

Useful Reviews:

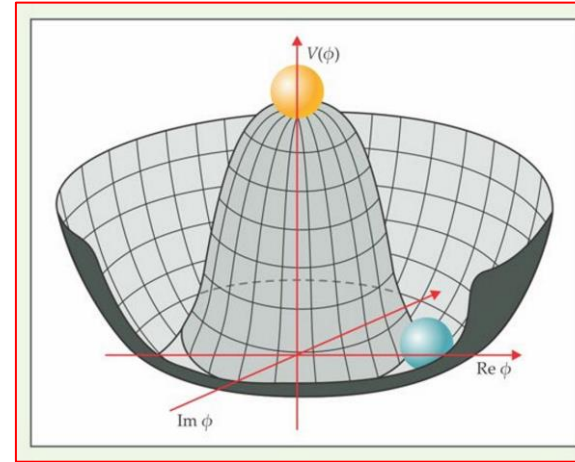
- [A historical profile of the **Higgs boson**](#) J. Ellis, M. K. Gaillard, D. V. Nanopoulos
- [The **Higgs boson** implications and prospects for future discoveries](#) S. Bass, A De Roeck, M. Kado
- [The profile of the **Higgs boson**: status and prospects](#) K Jakobs and G. Zanderighi
- [**Higgs Boson Couplings: Present and Future**](#). F. Cerutti and R.Salerno
- [PDG review on **Higgs Boson** physics](#)

Short Introduction

The Higgs boson and BEH mechanism

- **SM** is a quantum field theory that describes interactions between elementary particles arising from **local gauge symmetries**: $SU(3)_{\text{QCD}} \times SU(2)_L \times U(1)_Y$
- Gauge invariance **forbids masses** for EW bosons and chiral fermion: **Brout-Englert-Higgs** mechanism generates masses via **spontaneous symmetry breaking**: $SU(2)_L \times U(1)_Y$ symmetry broken to $U(1)_{\text{em}}$ via the **vacuum expectation value** of the Higgs field v
- **SSB**: Symmetry “**restored**” at **high energy**: SM remains well behaved (**renormalizable**) and **predictive theory** → **TESTABLE**
- The **BEH** mechanism links elementary **particle masses** to their **interaction strengths** with the **Higgs boson**: **key feature experimentally testable**

$$SU(3)_{\text{QCD}} \times SU(2)_L \times U(1)_Y$$



$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \bar{\psi}_i \gamma_5 \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$v = \sqrt{\frac{-\mu^2}{\lambda}}$$

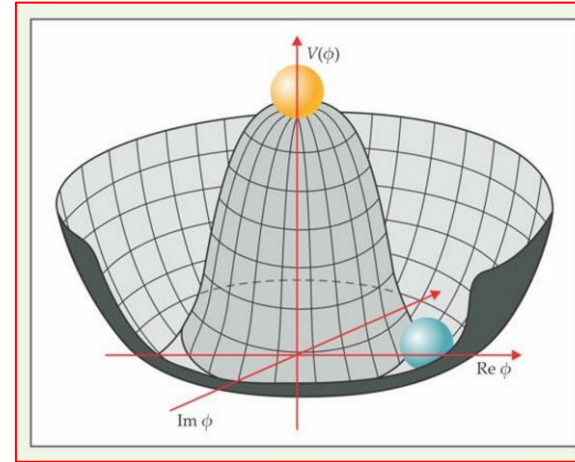
$$m_W^2 = \frac{g^2 v^2}{4}, \quad m_Z^2 = \frac{(g'^2 + g^2) v^2}{4}$$

$$\mathcal{L}_{\text{Yukawa}} = -\hat{Y}_{d_{ij}} \bar{q}_{L_i} \Phi d_{R_j} - \hat{Y}_{u_{ij}} \bar{q}_{L_i} \tilde{\Phi} u_{R_j} - \hat{Y}_{l_{ij}} \bar{l}_{L_i} \Phi e_{R_j} + h.c.$$

The Higgs boson and BEH mechanism

- The SM has many “free” parameters: 15 of the 19 fundamental SM parameters (ignoring 7 related to neutrinos) are related to Higgs boson interactions (9 F masses + 4 flavor CKM, 2 Higgs sector mass and VEV)
- Despite passing many experimental tests, the SM is thought to be the low energy approximation of a more complete UV theory: smallness of Higgs boson mass (hierarchy problem), smallness of ν masses, indications from cosmology (dark matter if not of gravitational origin, inflation, Q-gravity) and more generally the abundance of free parameters ...
- A thorough experimental test of the SM Higgs boson sector is of paramount importance: the (HL-)LHC is an ideal machine to do that

$$SU(3)_{\text{QCD}} \times SU(2)_L \times U(1)_Y$$



$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

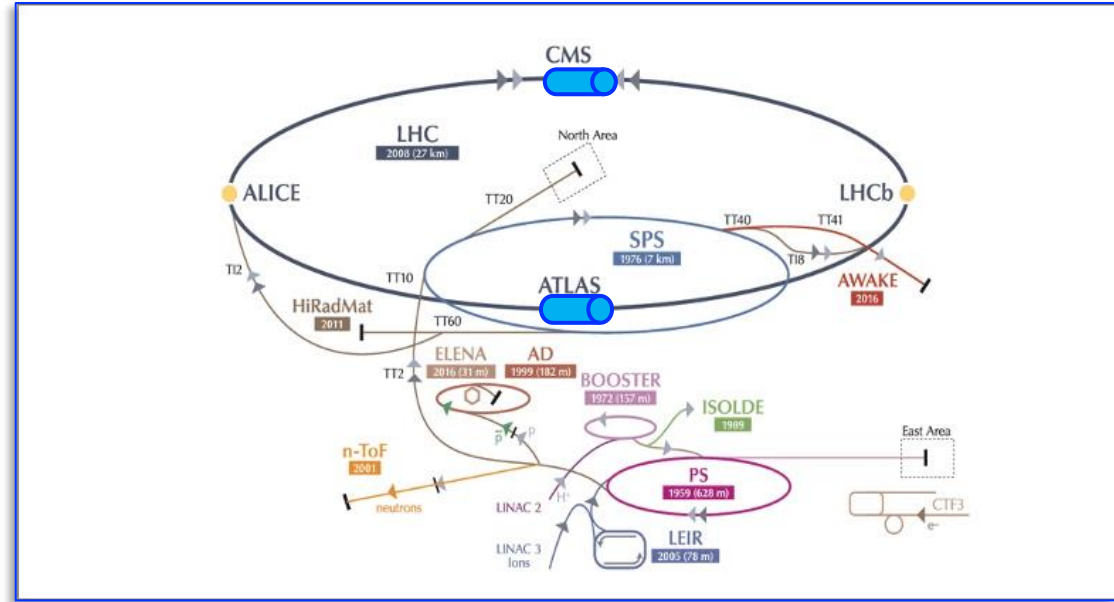
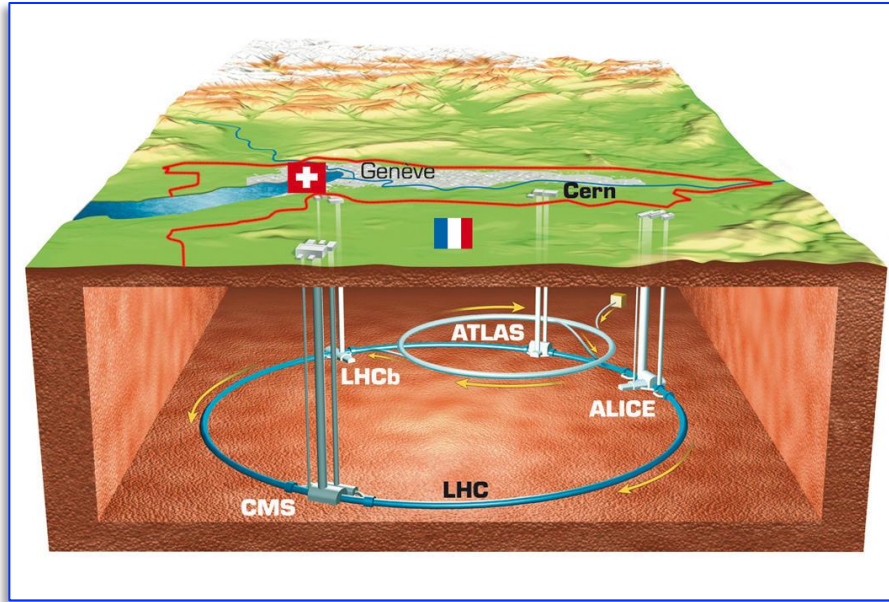
$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi \\ & + \bar{\chi}_i \gamma_{ij} \chi_j \phi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

$$v = \sqrt{\frac{-\mu^2}{\lambda}}$$

$$m_W^2 = \frac{g^2 v^2}{4}, \quad m_Z^2 = \frac{(g'^2 + g^2) v^2}{4}$$

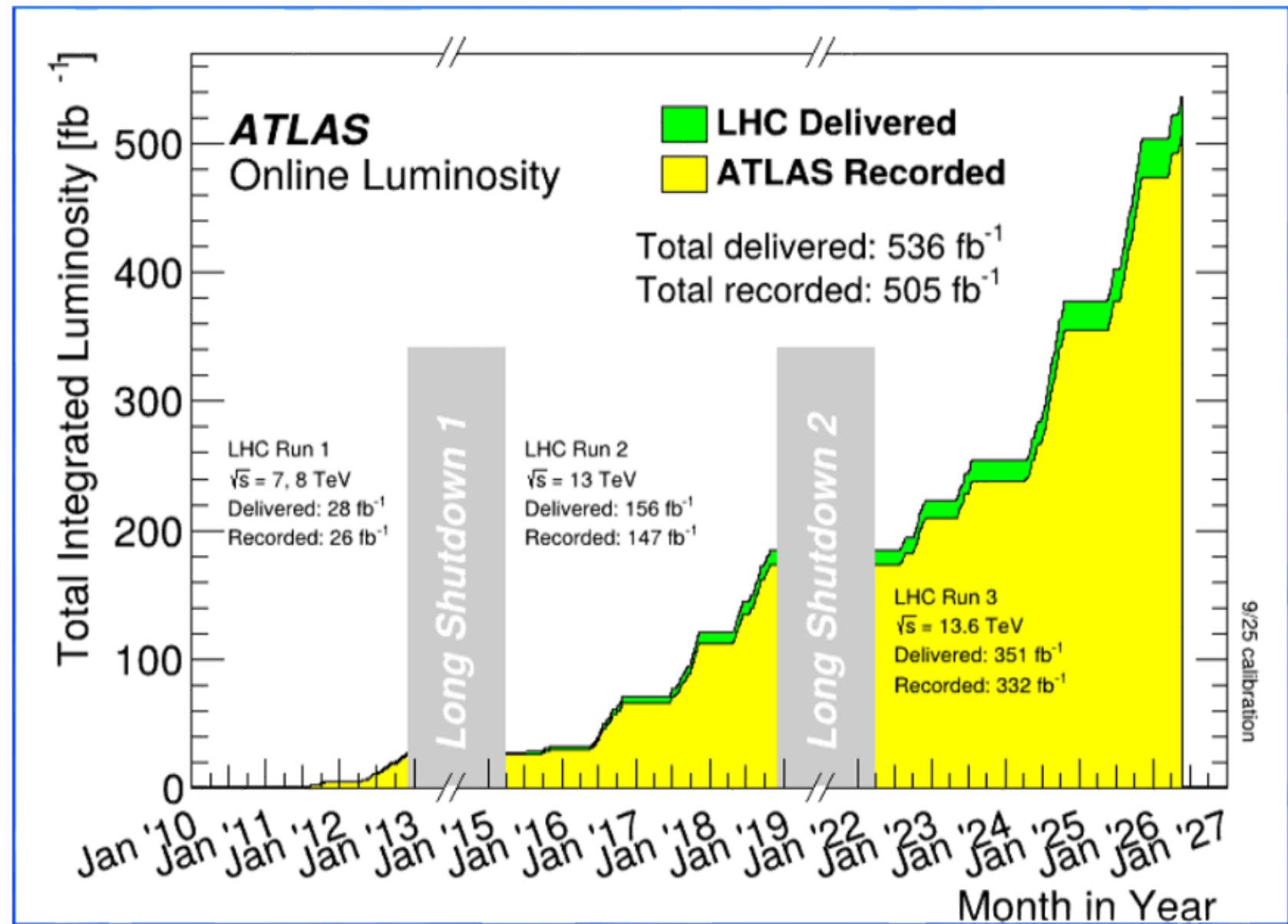
$$\mathcal{L}_{\text{Yukawa}} = -\hat{Y}_{d_{ij}} \bar{q}_{L_i} \Phi d_{R_j} - \hat{Y}_{u_{ij}} \bar{q}_{L_i} \tilde{\Phi} u_{R_j} - \hat{Y}_{l_{ij}} \bar{l}_{L_i} \Phi e_{R_j} + h.c.$$

The Large Hadron Collider



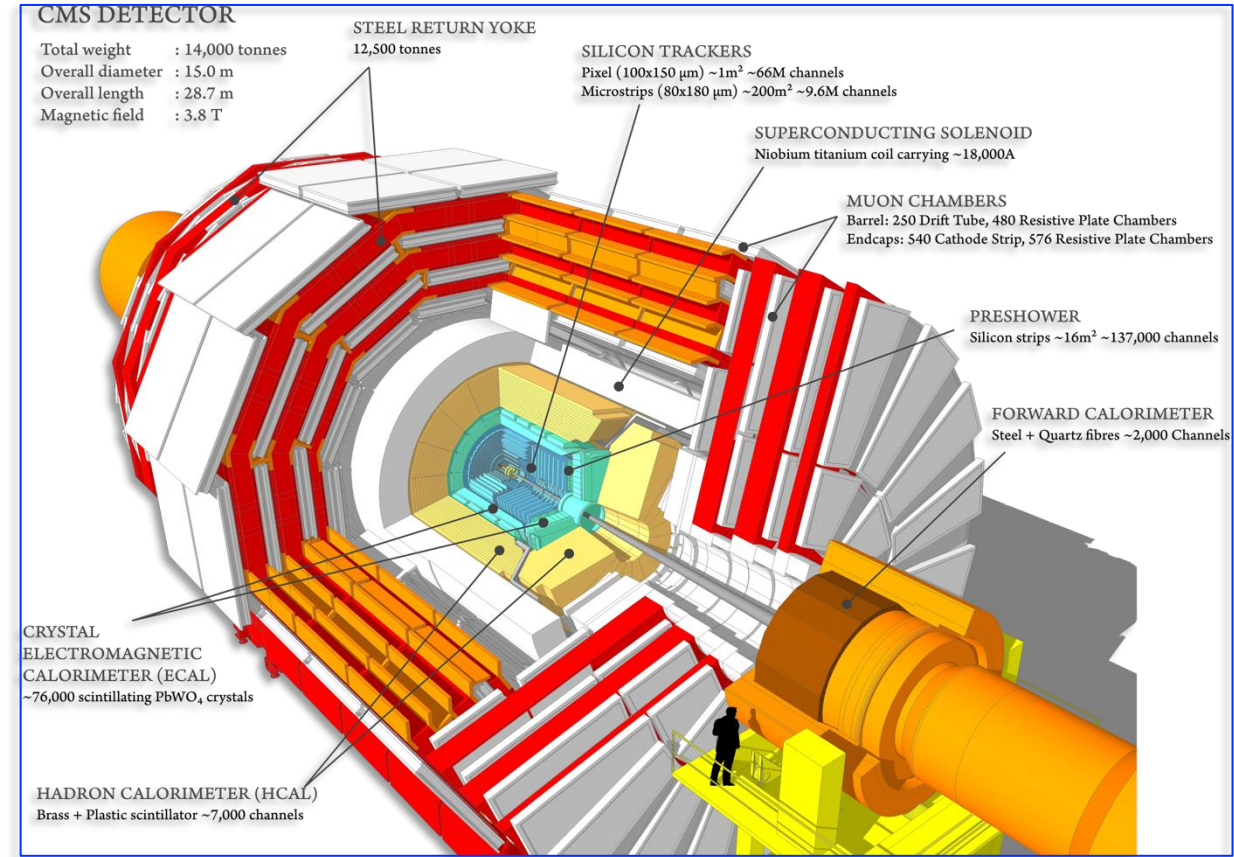
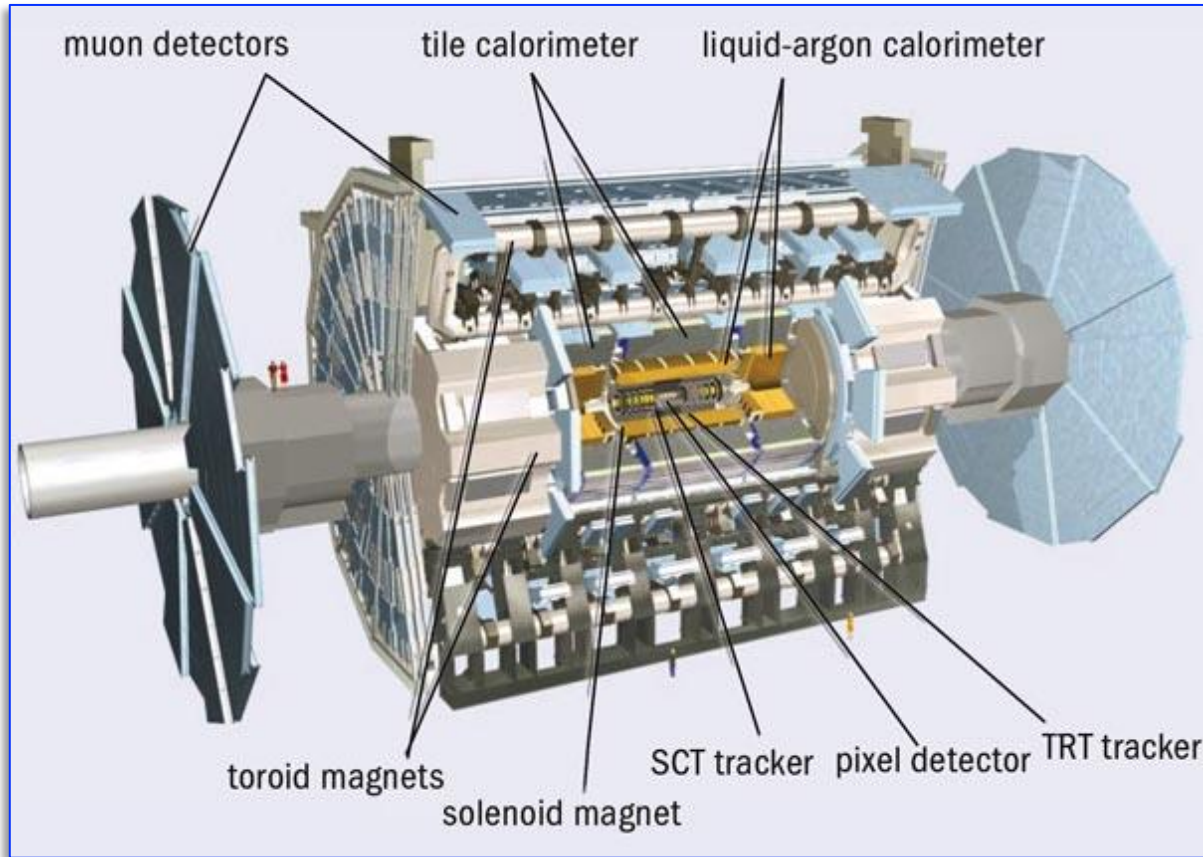
- The **LHC ring (27km)** collides protons at a centre-of-mass energy (up to) **13.6 TeV**, **~3000 bunches** each containing **$\sim 1.6 \times 10^{11}$** protons
- Collision rate **$\sim 40\text{MHz}$** (30 MHz of filled bunches)
- Instantaneous Luminosity achieved at LHC **$\sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$**
- **4 Experiments** of which **2** are general purpose experiments playing a leading role in Higgs boson physics: **ATLAS** and **CMS**

The LHC



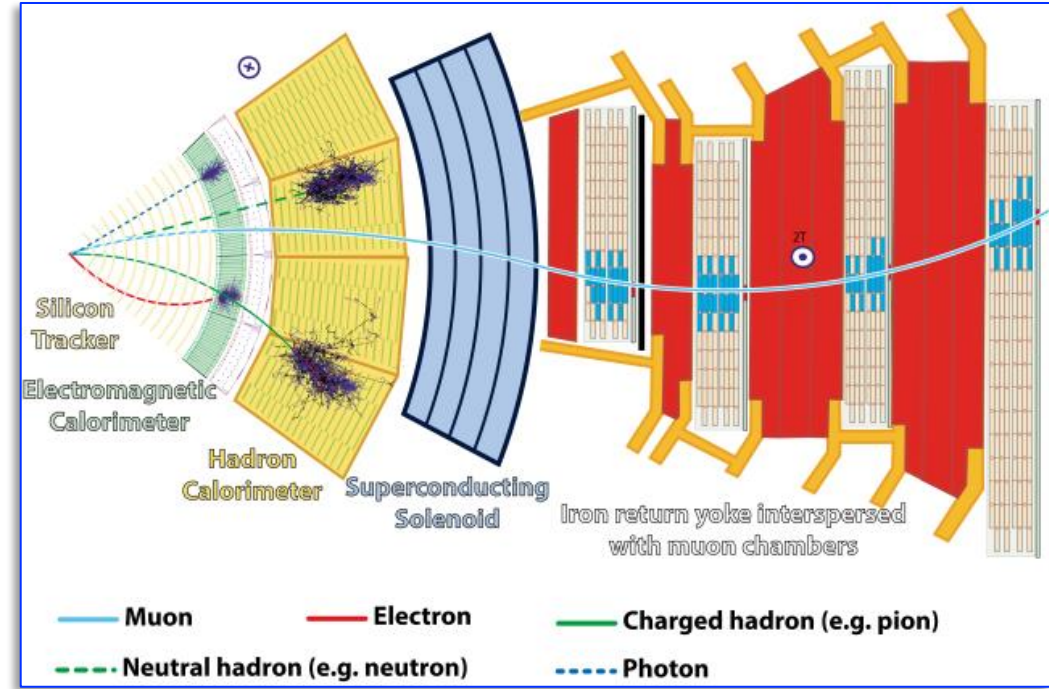
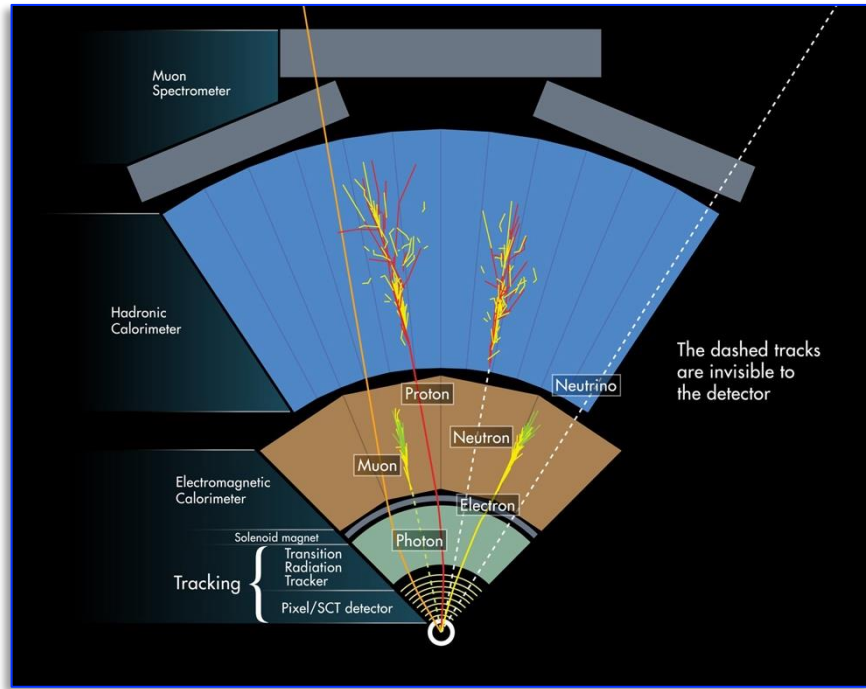
LHC delivered luminosity from 2011 to 2026 at different E_{CM}
Total $\sim 0.5 \text{ ab}^{-1}$ per experiment (1/6 of total HL-LHC goal)

ATLAS and CMS detectors



- **ATLAS** and **CMS** are two general purpose detectors at the LHC. They have similar structure with some differences that make them complementary

ATLAS and CMS detectors

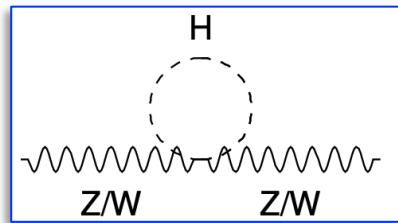


- Inner Tracker for charged particles immersed in a solenoidal magnetic field: ($\sim 2\text{T}$ ATLAS and $\sim 4\text{T}$ CMS) charge, momentum, impact parameters, decay vertices
- Electromagnetic calorimeter: identify and measure electron and γ energies (including pointing capabilities)
- Hadronic calorimeter: measure energy of “stable” hadrons: π , K, n, K_L^0 , p, etc.
- Muon detector: identify and measure momentum of $\mu^\pm$ s
- Trigger system: use all detector elements to select “interesting” events to be recorded, two-level structure:
 - L1: hardware-based (muon detectors and calorimeters) $40\text{ MHz} \rightarrow \sim 100\text{kHz}$
 - HLT: software-based (all detectors) $\sim 100\text{kHz} \rightarrow \sim 10\text{-}15\text{kHz}$

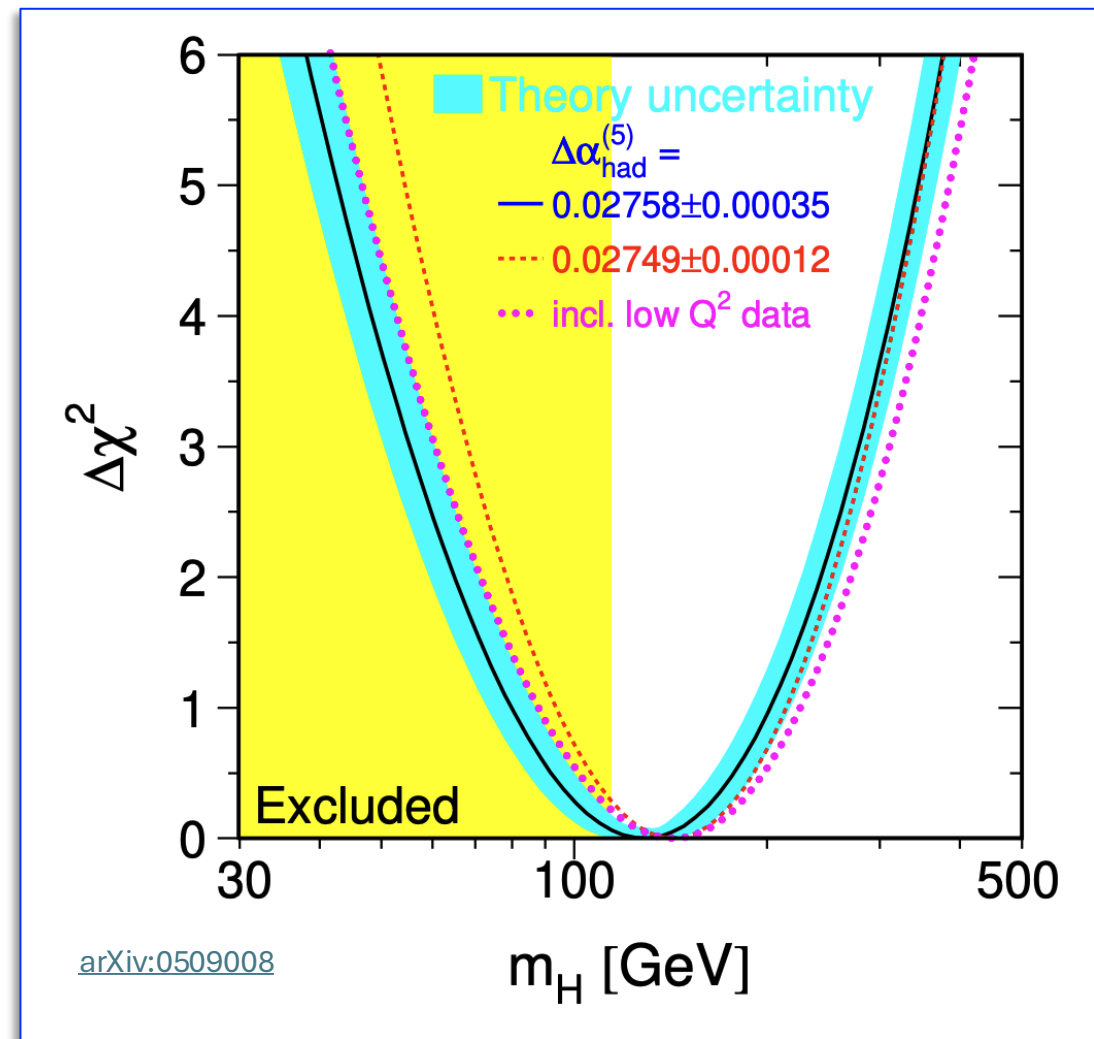
Pre LHC era...

Pre LHC era: LEP

- Higgs boson **direct** searches at LEP
 - $e^+e^- \rightarrow ZH \rightarrow jjbb, \nu\nu bb, \ell\ell bb$
 $m_H > 114 \text{ GeV @95\% CL}$
- Indirect** constraint from EW observables
LEP+SLC (ALEPH+DELPHI+L3+OPAL+SLD)



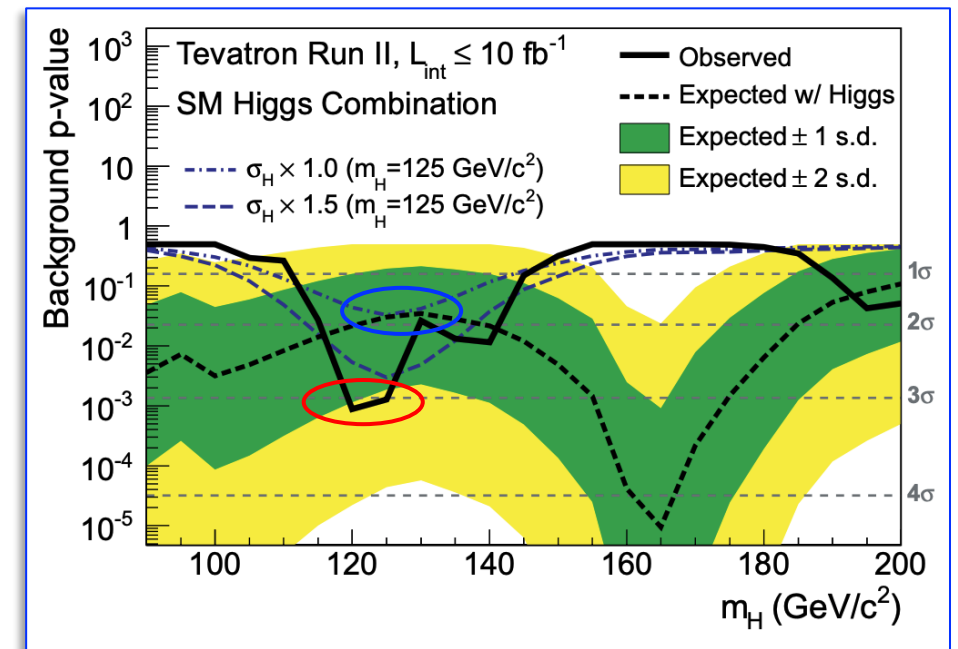
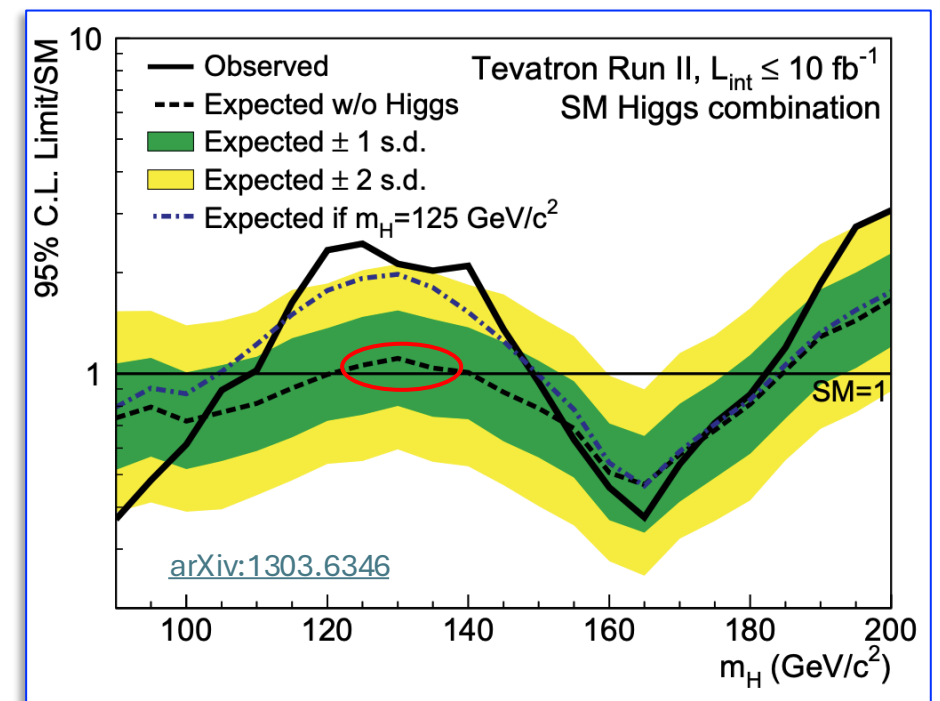
- Radiative corrections sensitive to Higgs boson mass $\sim \log(m_H^2 / M_Z^2)$
 $m_H = 129^{+74}_{-49} \text{ GeV (68\%CL)}$
 $m_H < 287 \text{ GeV @95\% CL}$



$$114 < m_H < 287 \text{ GeV @95\% CL}$$

Pre-LHC era: Tevatron

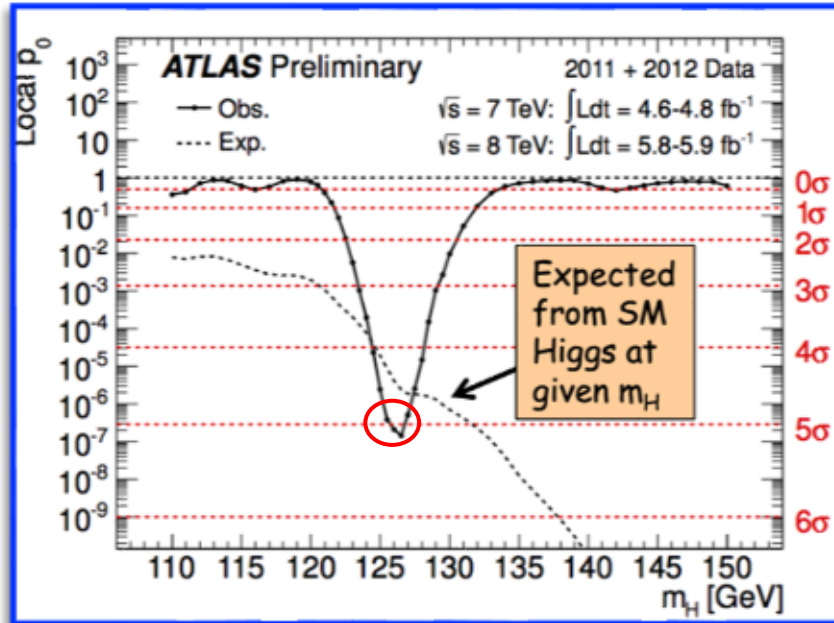
- Higgs boson direct searches at Tevatron:
 - $\sim 10\text{fb}^{-1}$ of p-pbar collisions
 - Main search channels around 125 GeV :
 $VH \rightarrow bb$ and $H \rightarrow WW^*$
- Expected to **exclude SM-like Higgs boson** over a large range of possible masses ($\sim 90\text{-}180$ GeV), though sensitivity **slightly below 2σ** in **$120\text{-}140$ GeV** mass range
- Achieved **$\sim 3\sigma$** evidence (expected **SM $M_H = 125$ GeV $\rightarrow 1.9\sigma$**) in **2013** in the range **$m_H \sim 120\text{-}130$ GeV BUT** this was **after Higgs boson discovery** at the **LHC**



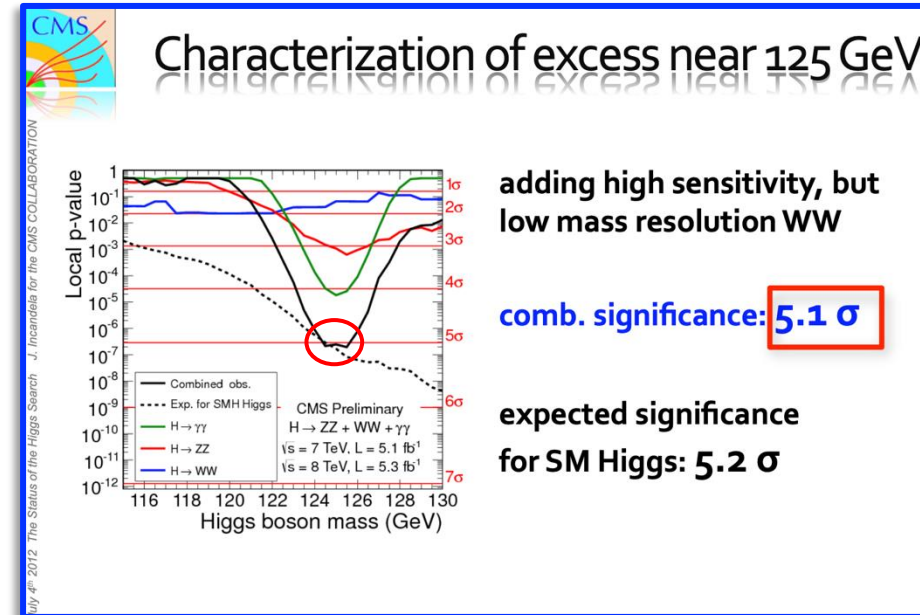
The Higgs boson discovery in 2012

The Higgs boson discovery at LHC

F. Gianotti - ATLAS

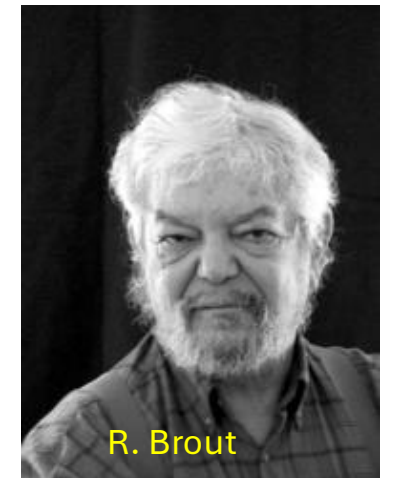
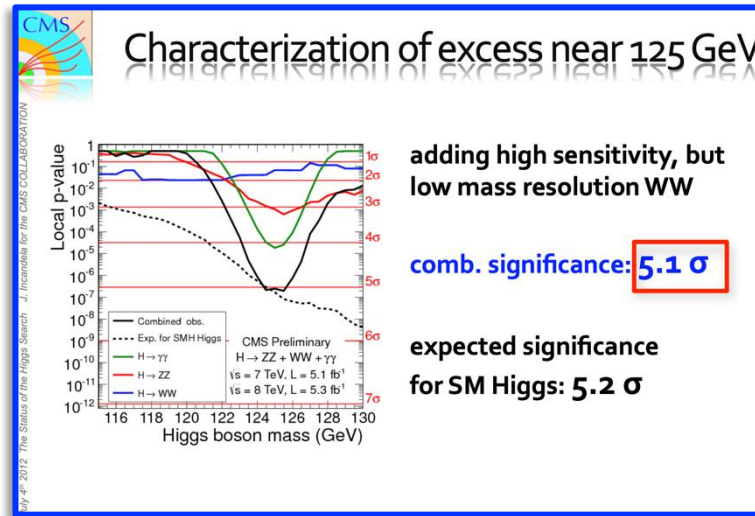
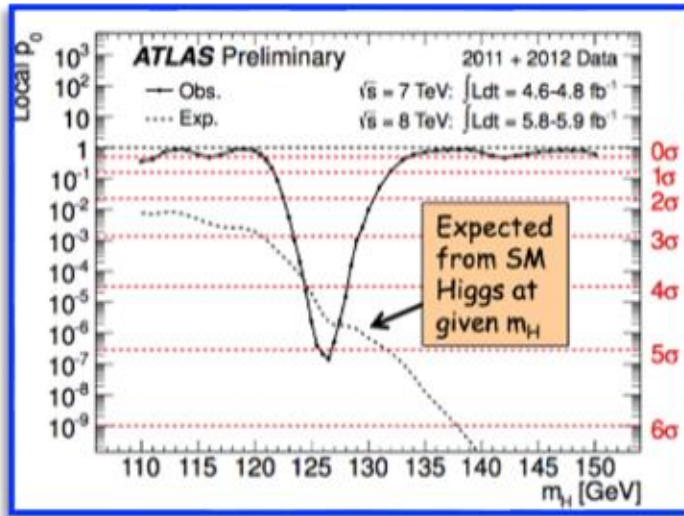


J. Incandela - CMS

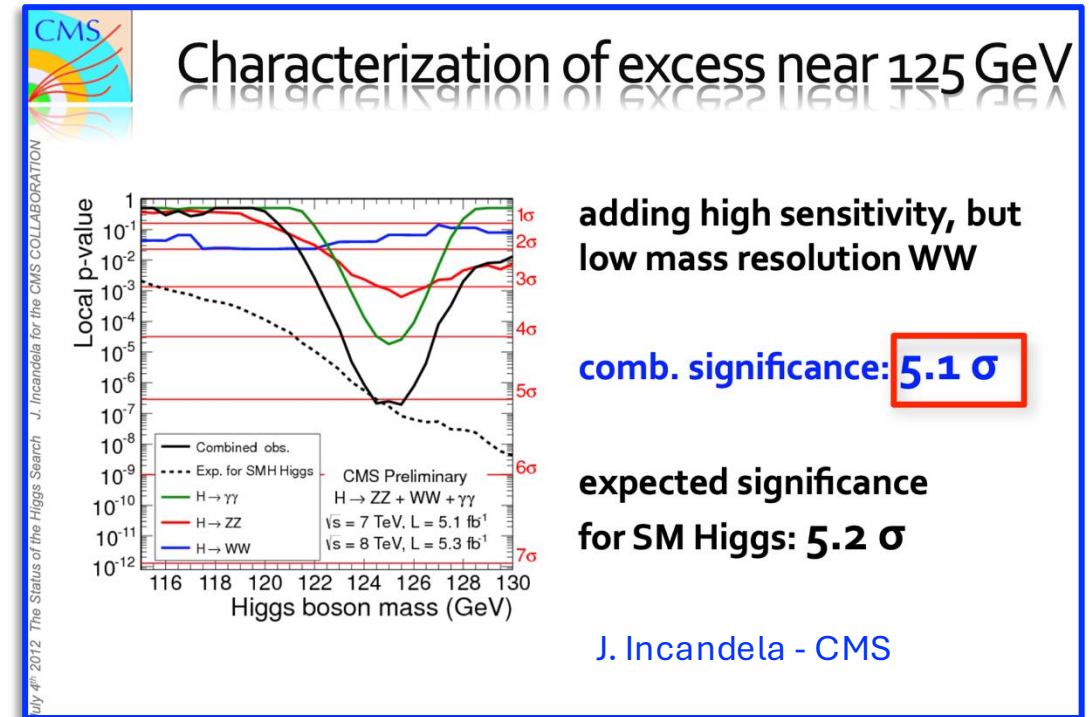
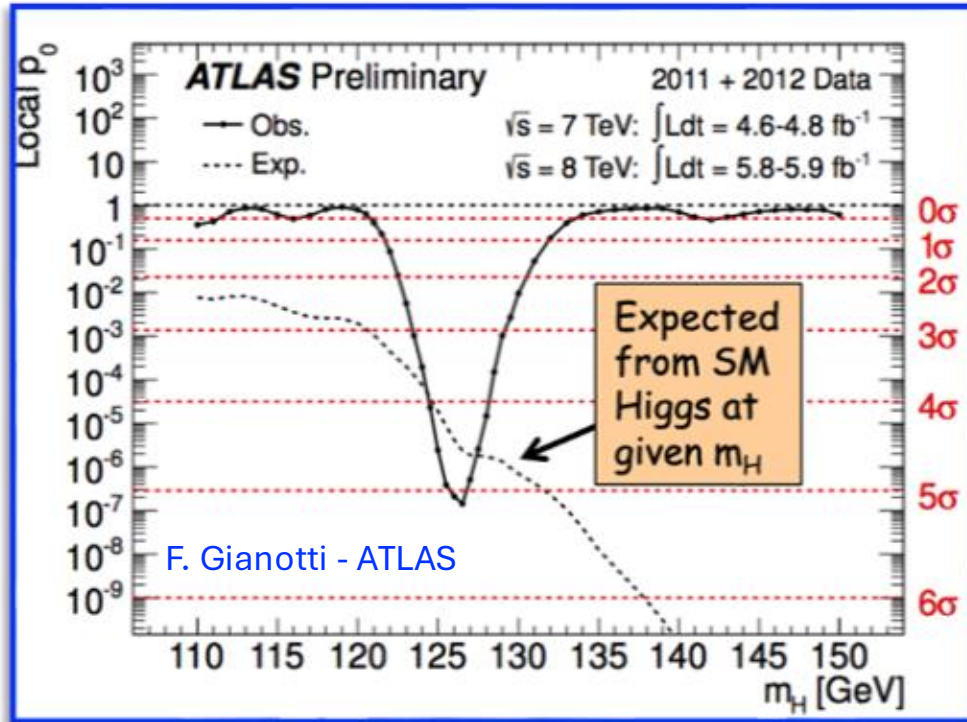


- On 4 July 2012 the discovery of a *new boson* was announced in a joint ATLAS+CMS special seminar at CERN: [Agenda with video](#)
- Driving channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\text{-leptons}$ (lepton = e or μ), though also other decay channels were shown ($H \rightarrow WW^*$, $\tau\tau$)

The Higgs boson discovery at LHC



The Higgs boson discovery at LHC



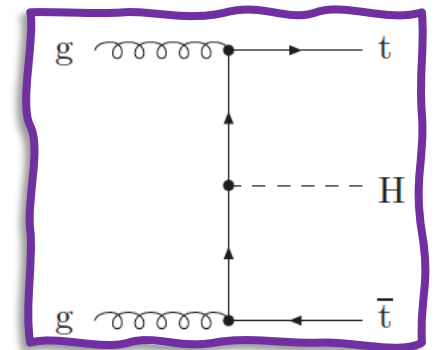
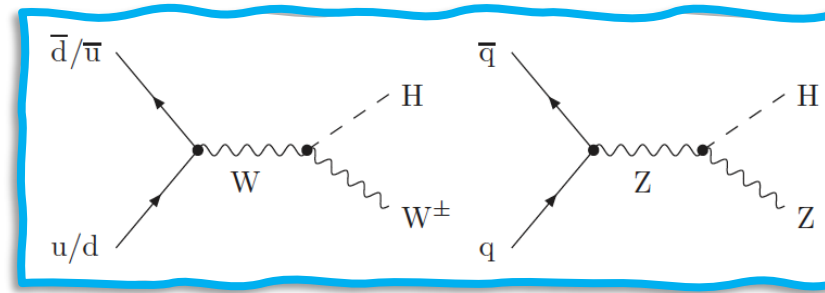
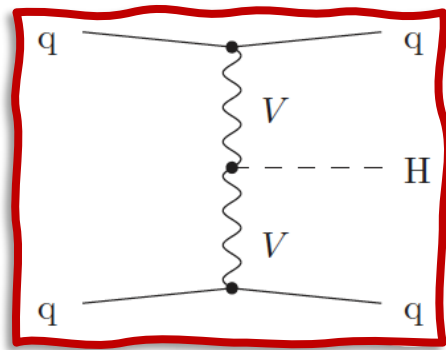
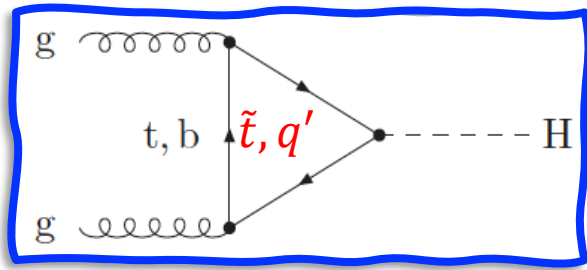
- Mass around **125 GeV** (uncertainty $\sim 600 \text{ MeV}$),
- Signal strength (commonly used for Higgs boson results) $\mu == \sigma_i / \sigma_{\text{SM}}$
 - **ATLAS** $\mu = 1.2 \pm 0.3$
 - **CMS** $\mu = 0.8 \pm 0.2$
- Decay into two on-shell γ **excluded spin 1** resonance by **Landau-Yang theorem**

Find the “teacher”: drink of your choice offered to the first student who will find me in this picture!

- $H \rightarrow \gamma\gamma$ Overview
- Main analysis is a Multi-Variate-Analysis (MVA)
 - MVAs for photon ID and event classification
 - Fit mass distribution in 4 event classes based on a diphoton MVA output + 2 di-jet categories
 - Improvement in expected limit –15% over cut-based analysis
 - Cross-checked with an alternative background model extraction:
 - Fit output of a 2nd MVA combining diphoton MVA and $m_{\gamma\gamma}$ using data in mass sidebands to construct the background model
 - Also cross-checked with a cut based analysis
 - Simple and robust
 - Cut based photon ID and event classification
 - Fit data mass distribution in 2 rapidity x 2 shower shape $\Rightarrow$ 4 categories with different Signal over Background (S/B) + 2 di-jet categories
 - Published for 2011 data
 - Phys Lett. B710 (2012) 403–425 arXiv:1202.3487

The SM Higgs boson at the LHC

Higgs boson production at the LHC



All updated Higgs boson σ and BR: [LHCHSWG](#)

Cross-section in pb (10^{-36} cm^2) at 13.6 TeV $m_H=125.09 \text{ GeV}$						
ggF	VBF	WH	ZH	ttH	Total	HH
51.66	4.109	1.464	0.947	0.592	59.45 +/- 4.5%	0.0377

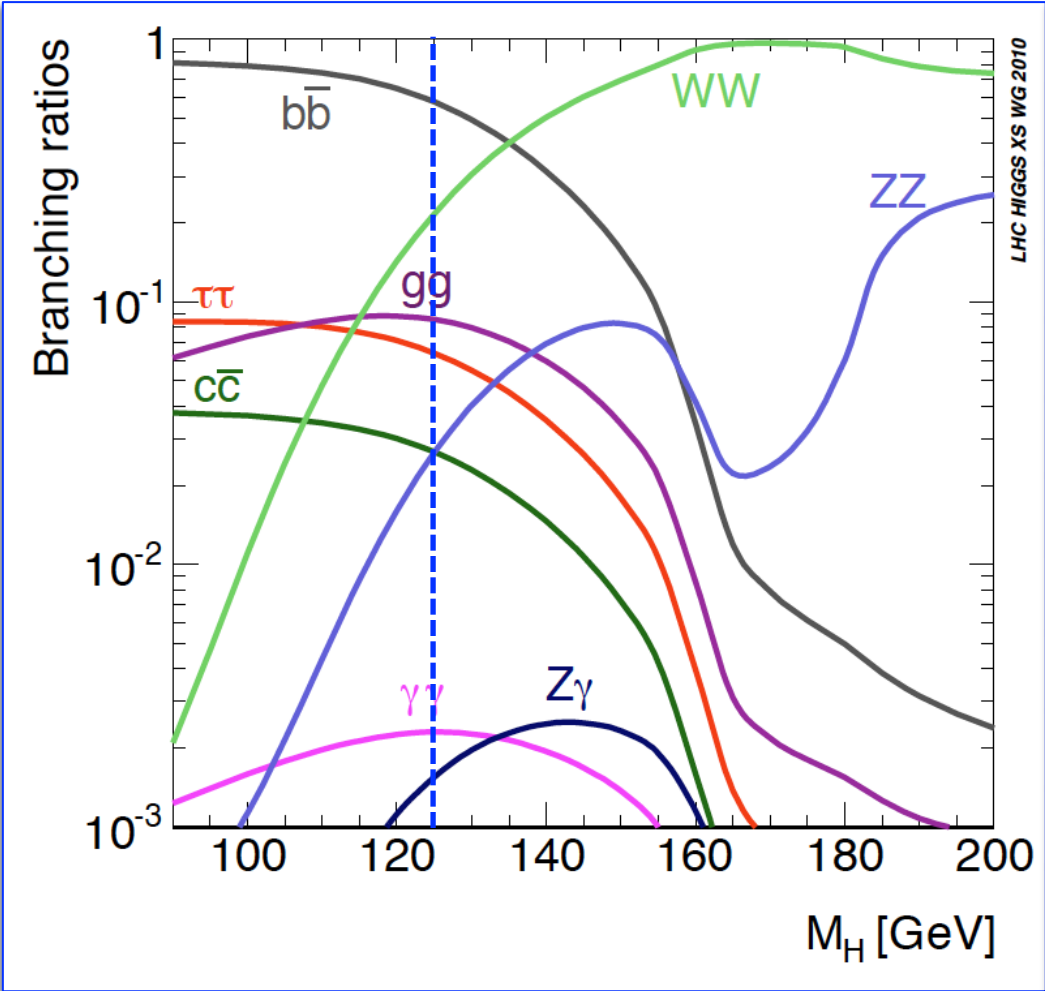
5 main production modes: ggF (loop-induced process), VBF, WH, ZH, ttH

Very rare HH process sensitive to Higgs boson self coupling (Lecture 2)

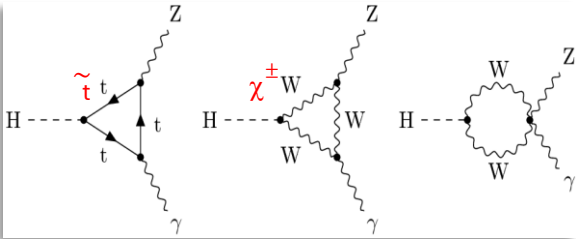
Total >25M Higgs bosons/experiment produced at the LHC

H Production rate at Run 3 peak luminosity $\sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (20 nb $^{-1} \text{ s}^{-1}$) $\sim 1 \text{ Hz}$

Higgs boson decay



Decay Mode	BR value %
$b\bar{b}$	58.1%
$\tau\tau$	6.3%
$\mu\mu$	0.022%
$c\bar{c}$	2.9%
WW^*	21.5%
ZZ^*	2.6%
gg	8.2%
$\gamma\gamma$	0.23%
$Z\gamma$	0.15%
$ZZ^* \rightarrow 4l \ (l=e,\mu)$	0.0125%
$WW^* \rightarrow \nu\bar{\nu} \ (l=e,\mu)$	1.06%



Many decay modes accessible for $m_H \sim 125$ GeV

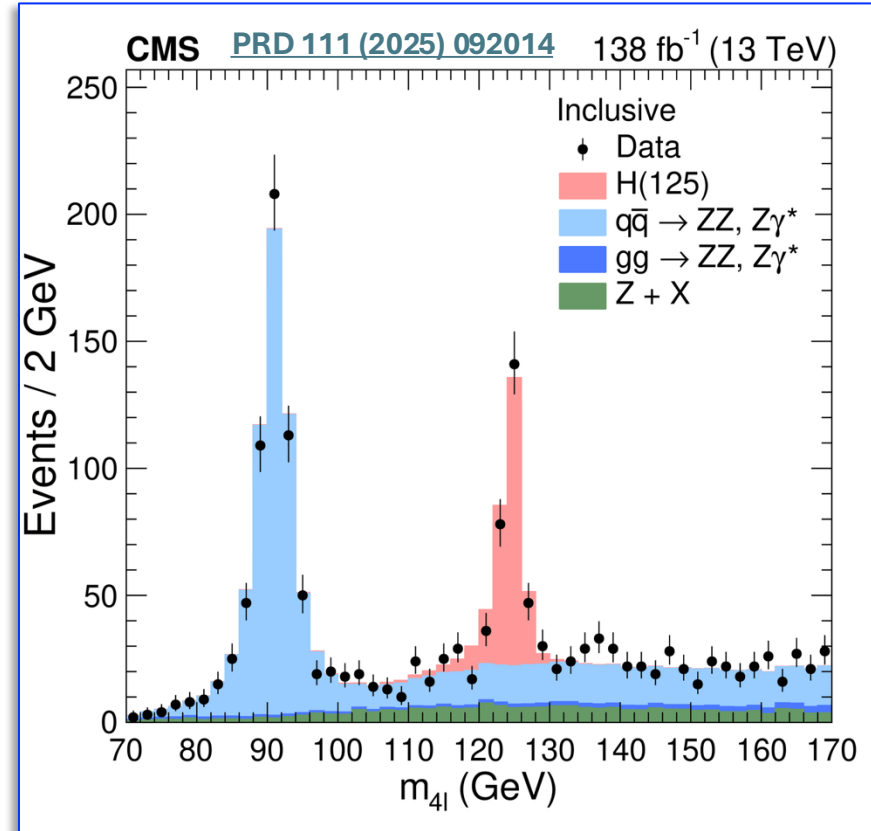
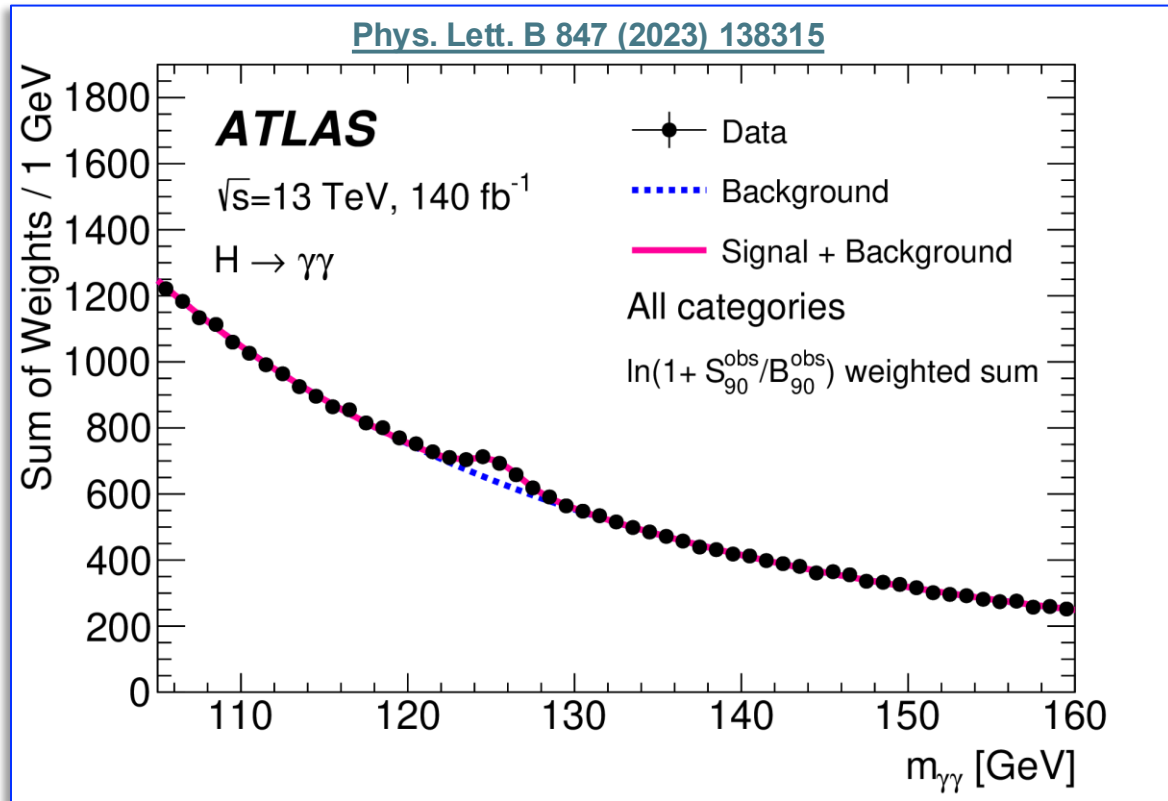
Total width $\Gamma_H = 4.1$ MeV ($\pm 1.4\%$), not **directly** accessible at the LHC

Loop-induced decays sensitive to **BSM**

1st and **2nd** generation **fermions** accessible

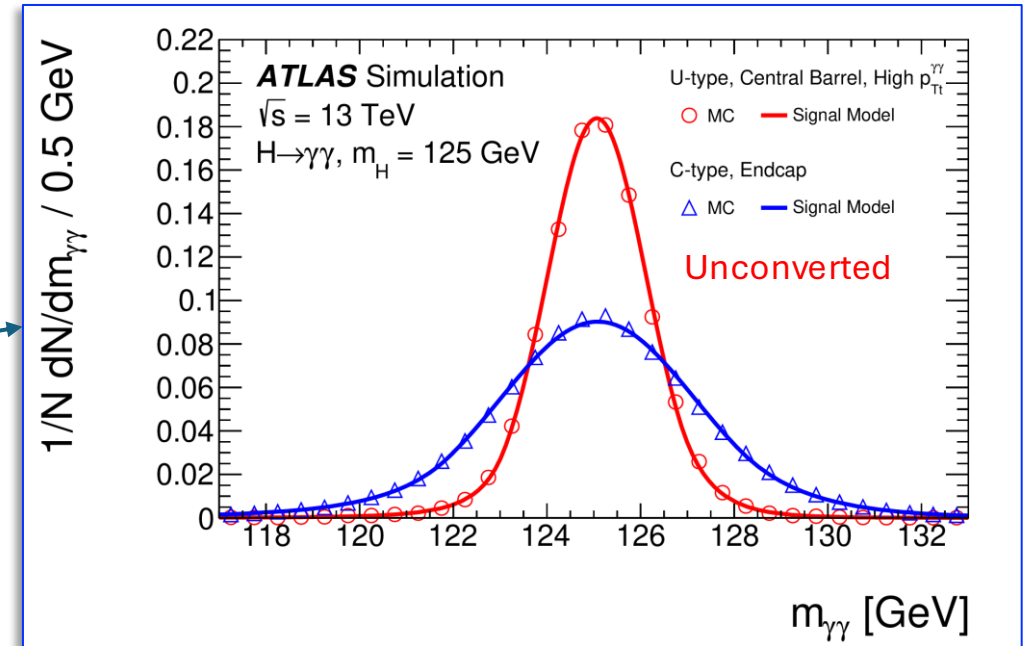
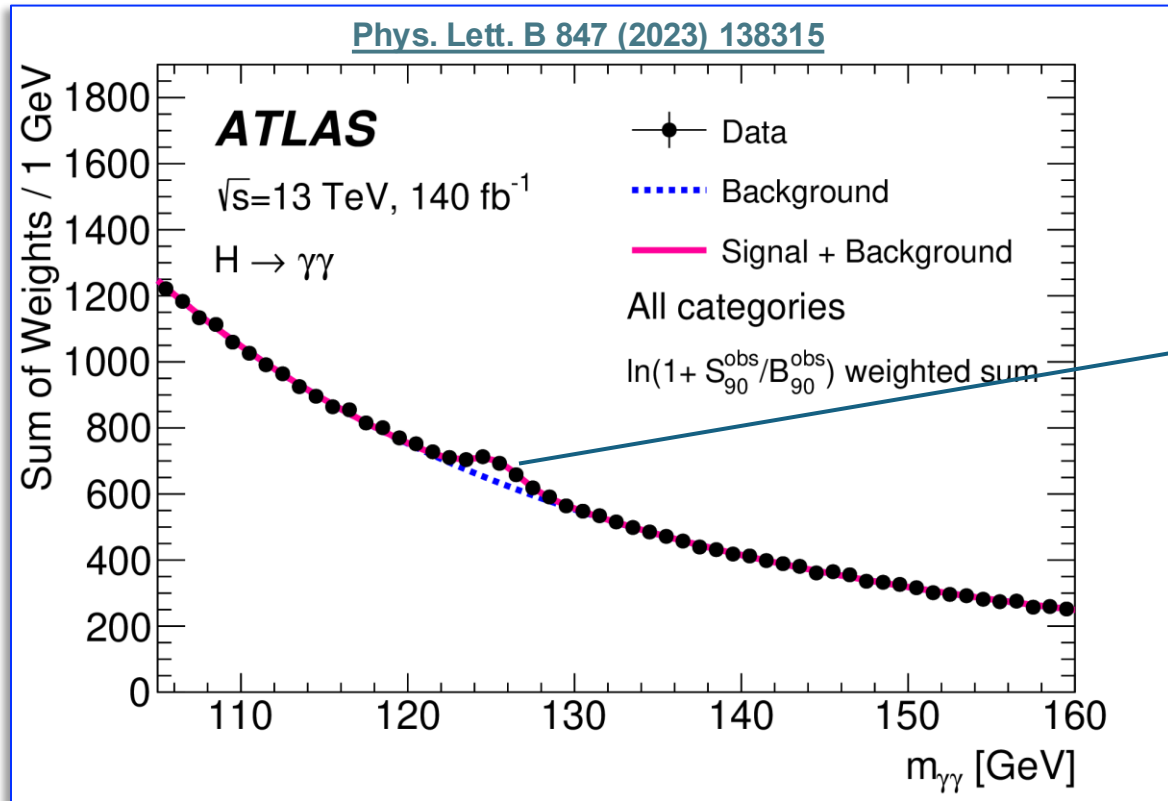
Higgs boson Mass and Spin

Mass measurement



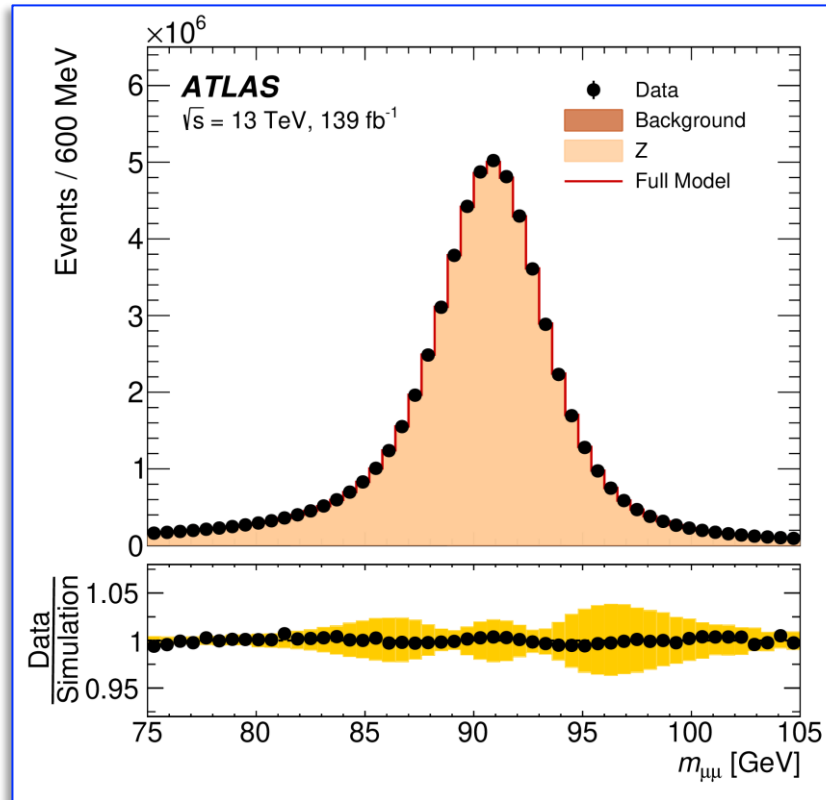
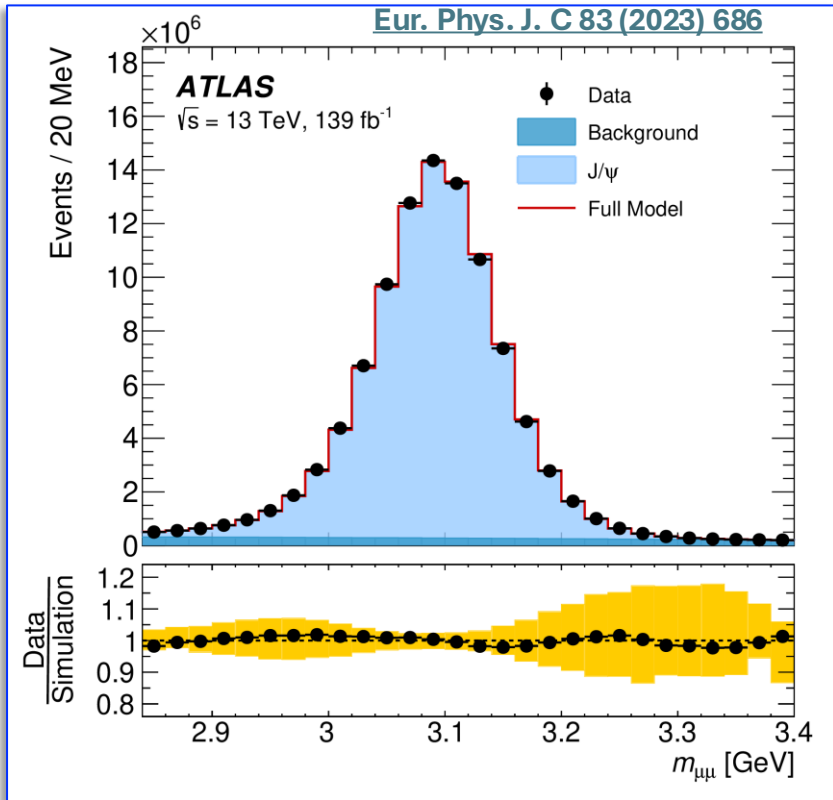
- Before the Higgs boson discovery, 1 fundamental SM parameter was missing: m_H
- Measurement performed from a fit to the invariant mass spectra of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ decays
- In four-lepton channel the precision is dominated by final states containing muons, mass constraint applied to the lepton-pair compatible with the on-shell Z decay

Mass measurement

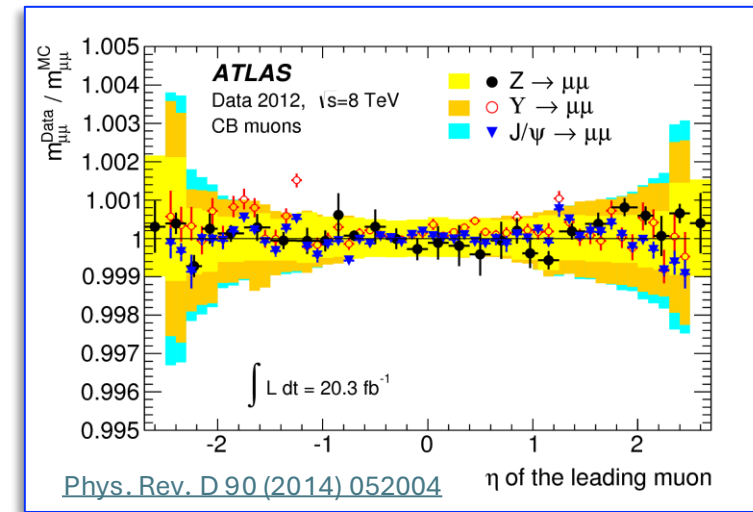


- Measurement performed from a fit to the invariant mass spectra of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ decays
 - Signal: double-sided crystal ball (Gaussian core + power-law tails)
 - Background analytic function fit to data ($\gamma\gamma$) or MC template ($ZZ^* \rightarrow 4l$)
 - Use categories to enhance S/B and select region with better mass resolution

Mass measurement: μ P scale calibration

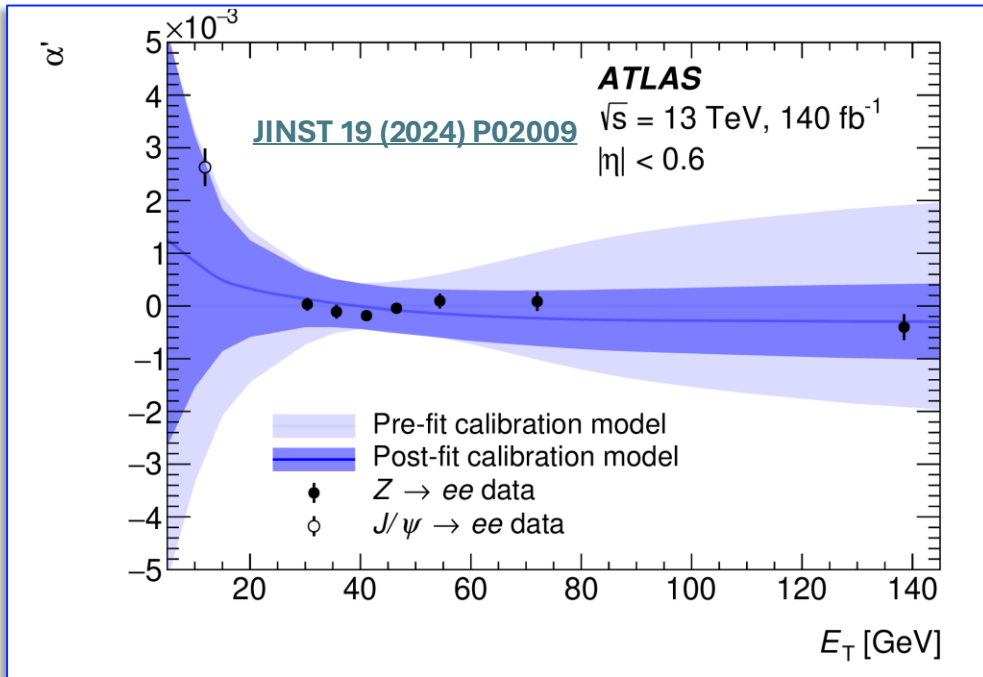


Achieved precision on the μ momentum scale
 $\sim 0.05\text{-}0.15\%$



- Muon momentum scale calibrated mainly from $Z \rightarrow \mu\mu$ events Z mass known at $\sim 20 \text{ ppm}$ (2 MeV / 91 GeV from LEP) and $J/\Psi \rightarrow \mu\mu$, $Y \rightarrow \mu\mu$
- Parameterize $M_{\mu\mu}$ as a function of several corrections to make data and MC mass scales coincide charge dependent corrections (“sagitta” biases only to data) $\propto qxp^2$, linear corrections $\propto p$ (magnetic field) and constant offset (energy loss, typically negligible)

Mass measurement: γ E scale calibration

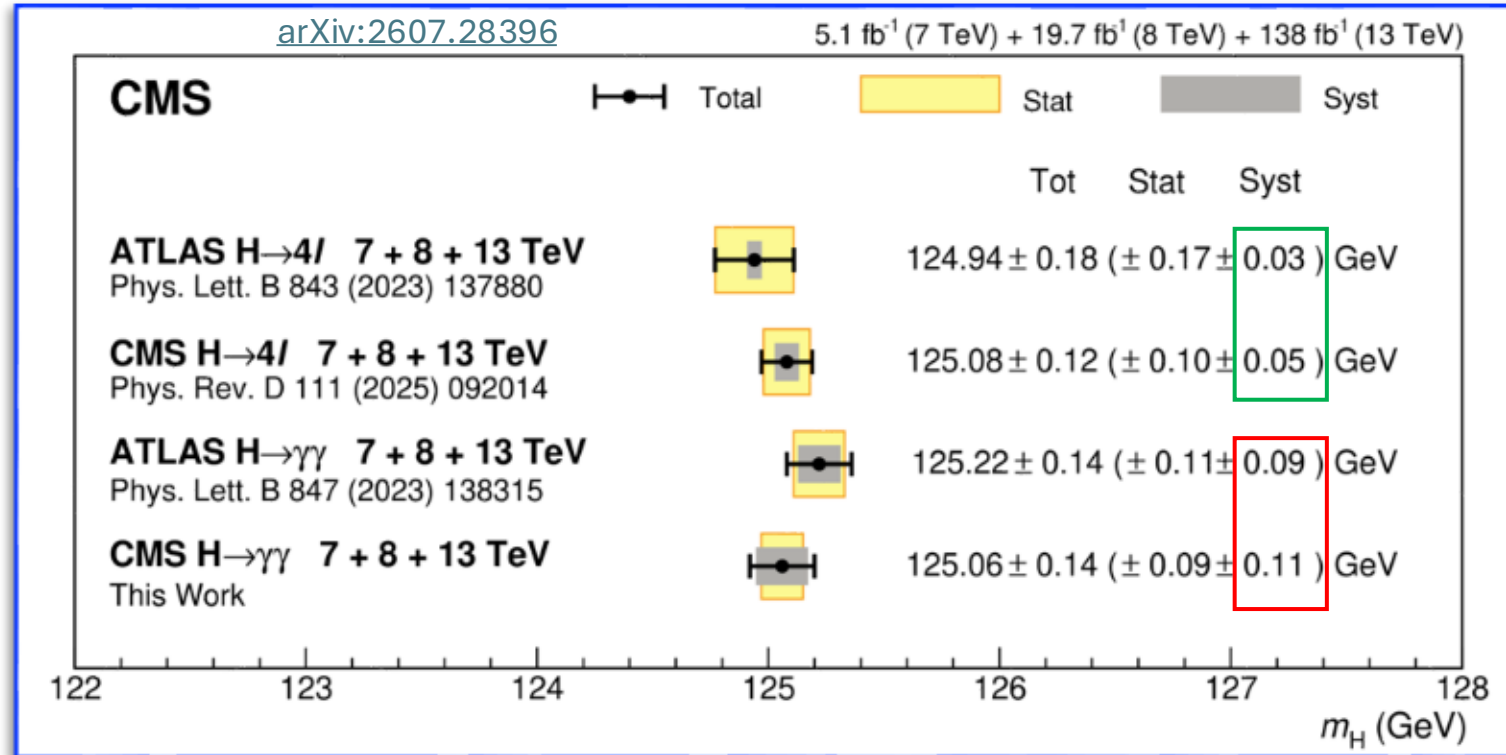


Systematic category	Photon energy scale uncertainty $\times 10^3$			
	$ \eta < 1.37$		$1.52 < \eta < 2.37$	
	Unconverted	Converted	Unconverted	Converted
$Z \rightarrow ee$ calib.	0.49	0.49	1.10	1.10
Cell energy non-linearity	0.99	0.31	1.22	0.35
Layer (presampler, E1/E2, scintillator) calibration	0.83	0.08	3.09	0.71
ID material	0.31	0.20	1.21	0.86
Other material	0.91	0.07	1.39	0.12
Conversion reconstruction	0.06	1.40	0.59	1.04
Lateral shower shape modelling	0.31	0.68	2.51	0.82
Total	1.71	1.68	4.72	2.09

Achieved precision on the γ energy scale $\sim 60 \text{ GeV} \sim 0.2\%$

- Difficult to calibrate photon energy scale at the LHC: need to extrapolate electrons from Z decay to higher energy photons $\rightarrow$ dedicated calibration for Higgs boson mass measurement considering energy and pseudo-rapidity dependence using “standard candles” Z and $J/\psi \rightarrow e^+e^-$

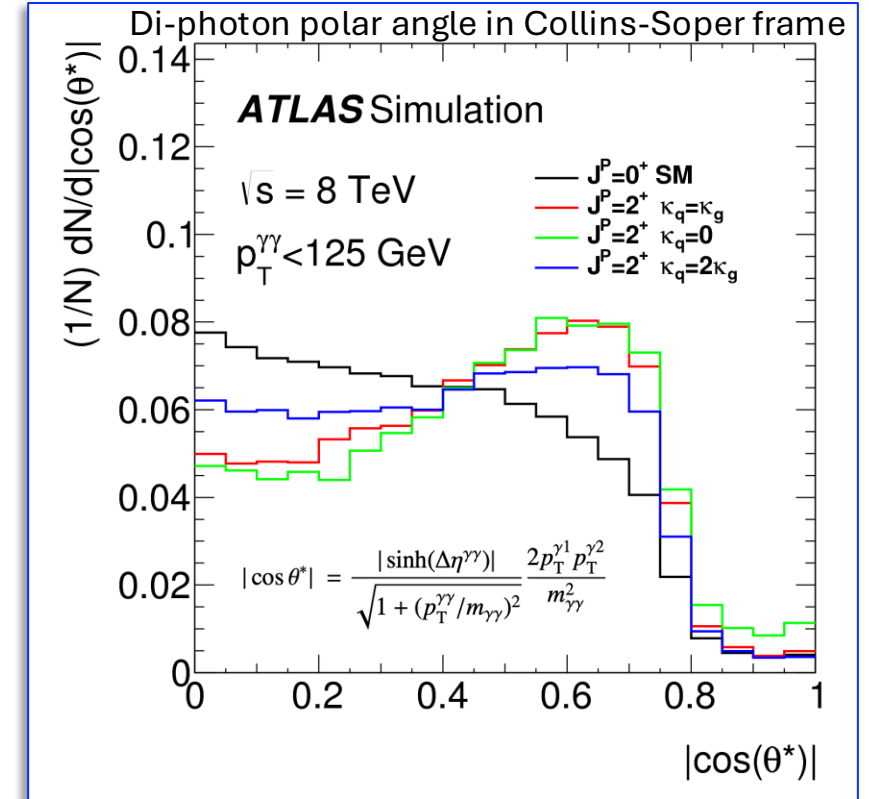
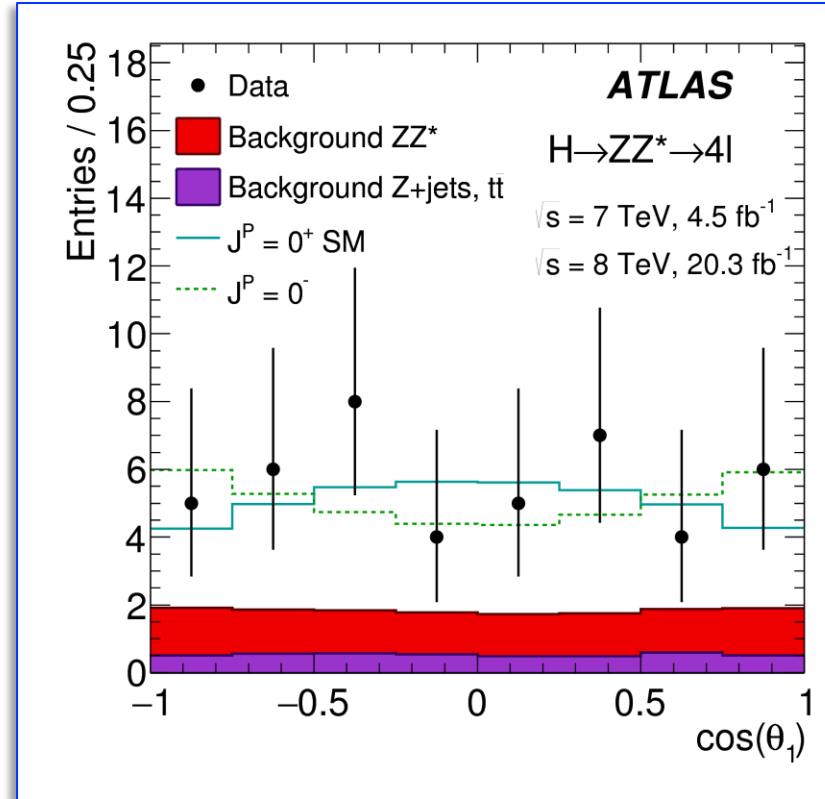
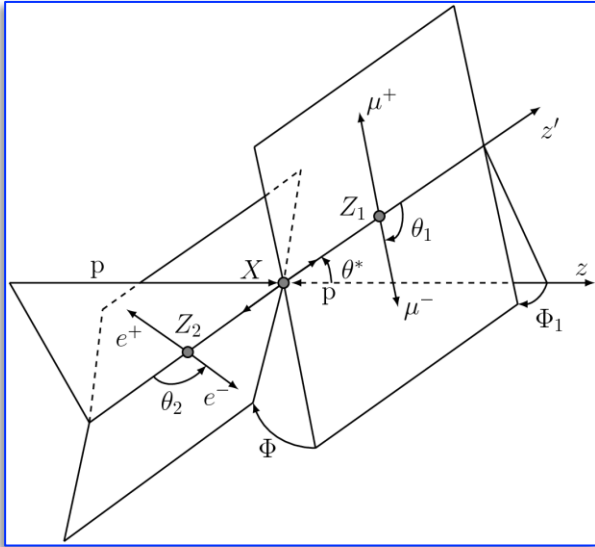
Mass measurement



- Main limiting factors: small statistics for $H \rightarrow ZZ^* \rightarrow 4l$ (BR~0.0125%)
- Calibration of the μ momentum scale easier: large Z and $J/\psi \rightarrow \mu^+\mu^-$ samples available
- Expected precision legacy Run 2 ATLAS+CMS combination ~70 MeV (~0.6 per mill)
- Most sensitive observable is $BR(H \rightarrow ZZ^*)$ $\delta m_H \sim 100$ MeV $\rightarrow \delta BR/BR \sim 0.9\%$

Spin determination

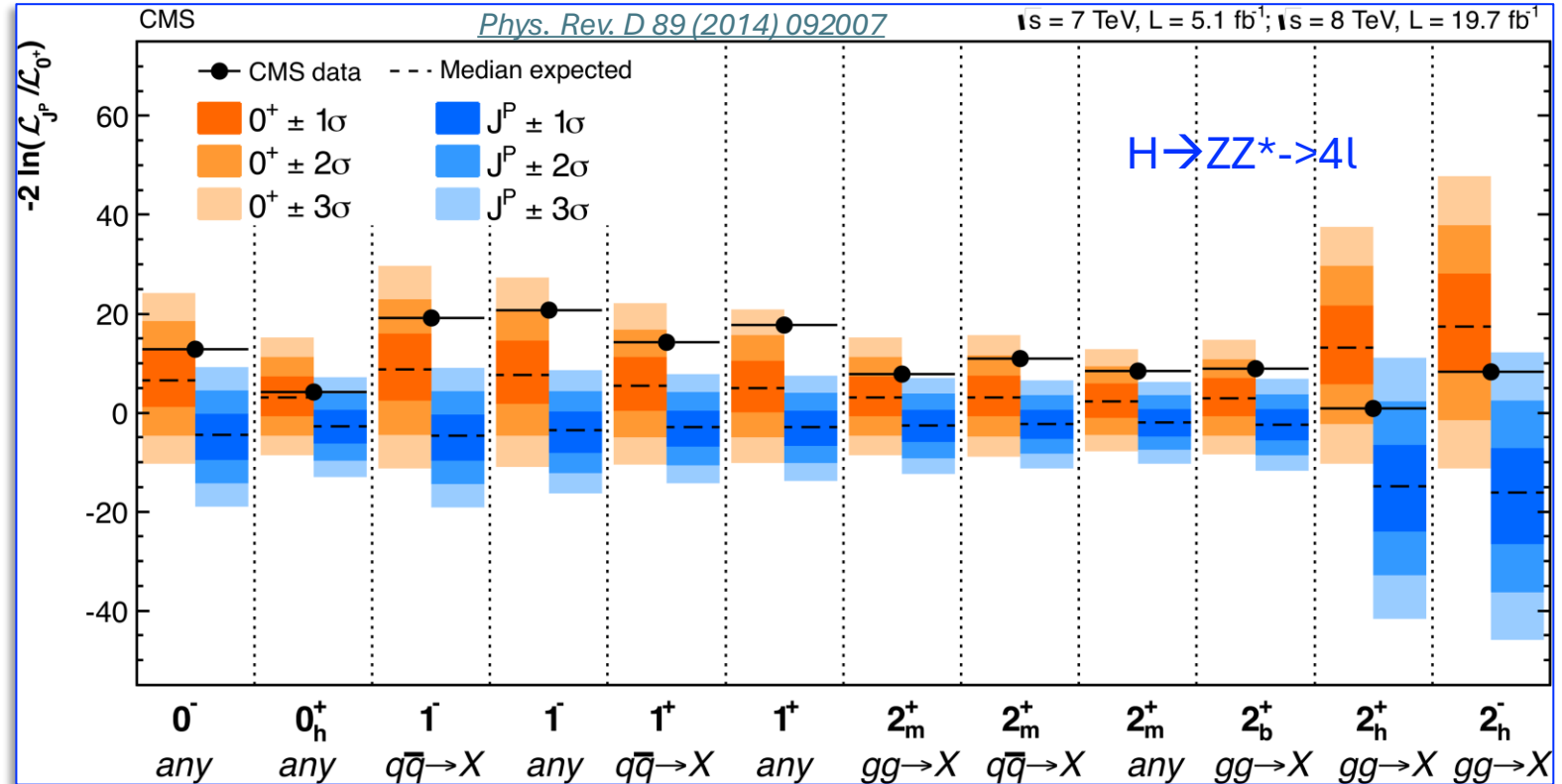
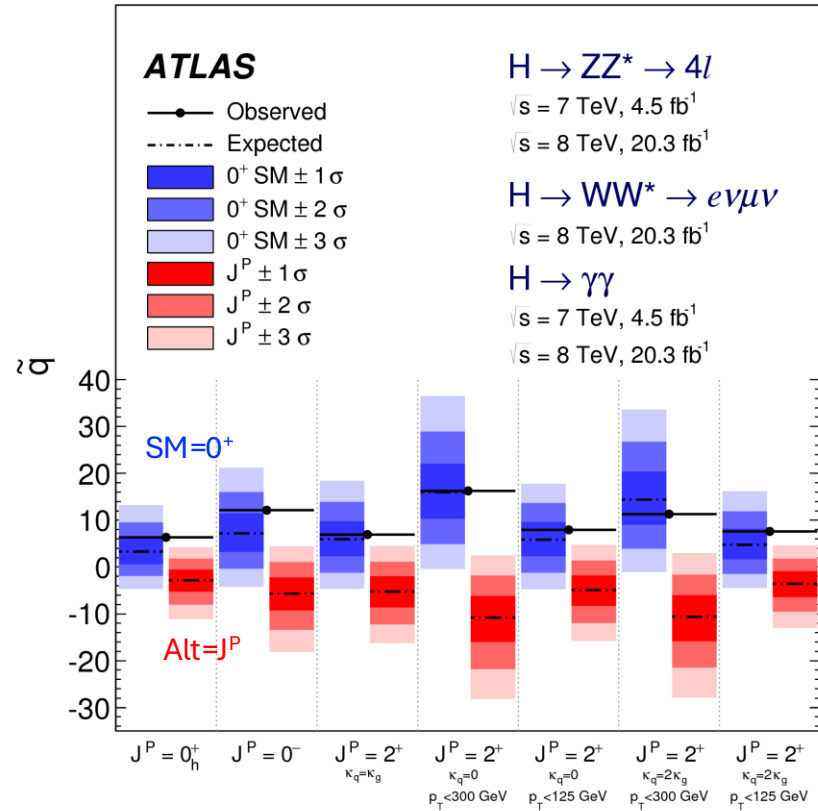
Eur. Phys. J. C 75 (2015) 476



- The **spin** (=0) of the Higgs boson was established shortly after its discovery using the kinematic properties of its decay into $ZZ^* \rightarrow 4l$, $WW^* \rightarrow l\nu l\nu$ and $\gamma\gamma$ final states
- HVV interactions used to test **SM** (0^+) vs several **alternative spin^{CP}** hypotheses

Spin determination

Eur. Phys. J. C 75 (2015) 476



Spin=0 of the Higgs boson **established**; the tested Spin 1 and 2 benchmark models excluded at >95% CL using LHC Run 1 data (~25fb⁻¹)

Pure CP-odd interactions (0⁻) between Higgs boson and vector bosons also excluded >95%CL

Production x decay measurements

Cross-section measurements at the LHC

- The core of the LHC Higgs program consists of measuring cross-sections for different decay modes:

$$N_{\text{Signal}}(i \rightarrow H \rightarrow f) = \underbrace{[\sigma(i \rightarrow H \rightarrow f)]}_{\text{Physics compared with SM}} \times \underbrace{[\text{Acceptance} \times \text{Efficiency}]}_{\text{Reconstructed in the detector (MC)}} \times \underbrace{\text{Luminosity}}_{\text{Machine performance}}$$

$$\sigma(i \rightarrow H \rightarrow f) \sim \sigma_i \times \frac{\Gamma_f}{\Gamma_H} = N_{\text{signal}}(i \rightarrow H \rightarrow f) / [A \times \text{Eff} \times L]$$

- From data we extract N_s using discriminating variables to disentangle signal processes from background events
- Since we cannot measure directly Γ_H , we always measure the product $\sigma \times \text{BR}$ of a given production for a specific decay: need assumptions to extract information on Higgs couplings from our measurements
- Categorize events to target different production modes, kinematic phase space, decay properties, etc.
- Two main complementary approaches:
 - Fiducial cross-section
 - Cross sections targeting production modes and Simplified Template Cross Sections (STXS)

Observed production and decay modes

Production mode	Status today
ggF	Observed Run 1
VBF	Observed Run 1
VH	Observed Run 2
ttH	Observed Run 2
tH	Not observed yet
HH	Not observed yet

Decay mode	Status today
$\gamma\gamma$	Observed Run 1
ZZ^*	Observed Run 1
WW^*	Observed Run 1
bb	Observed Run 2
$\tau\tau$	Observed Run 1
$Z\gamma$	Evidence Run 2/3
$\mu\mu$	Evidence Run 2/3
cc	Not observed yet

- Current situation in terms of “**observed**” (>5 σ **significance** relative to its absence)
production and **decay** modes:

Fiducial Cross-sections

Fiducial cross-sections

- Match (as much as possible) the **measured phase space** with the **acceptance** of the **detector** to reduce (almost eliminate) **model dependence** of the measurement
- Particularly suited when the **final state is fully reconstructed** (e.g., $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$)
- The measured yields are corrected for **detector effects** (P/E resolution, efficiency) and **out-of-acceptance contributions** $\rightarrow$ unfolding procedure
- These measurements can be **directly compared** with **theory predictions** at *particle* level
- They can also be “**binned**” in specific kinematic variables (e.g., Higgs **pT**, **pseudo-rapidity**, **number of accompanying jets**, etc.)
- **Disadvantages:**
 - Typically, **inclusive in production mode** (dominated by ggF)
 - Some final states have large “**detector and acceptance**” corrections so **model dependence** is reintroduced as a systematic uncertainty of the unfolding

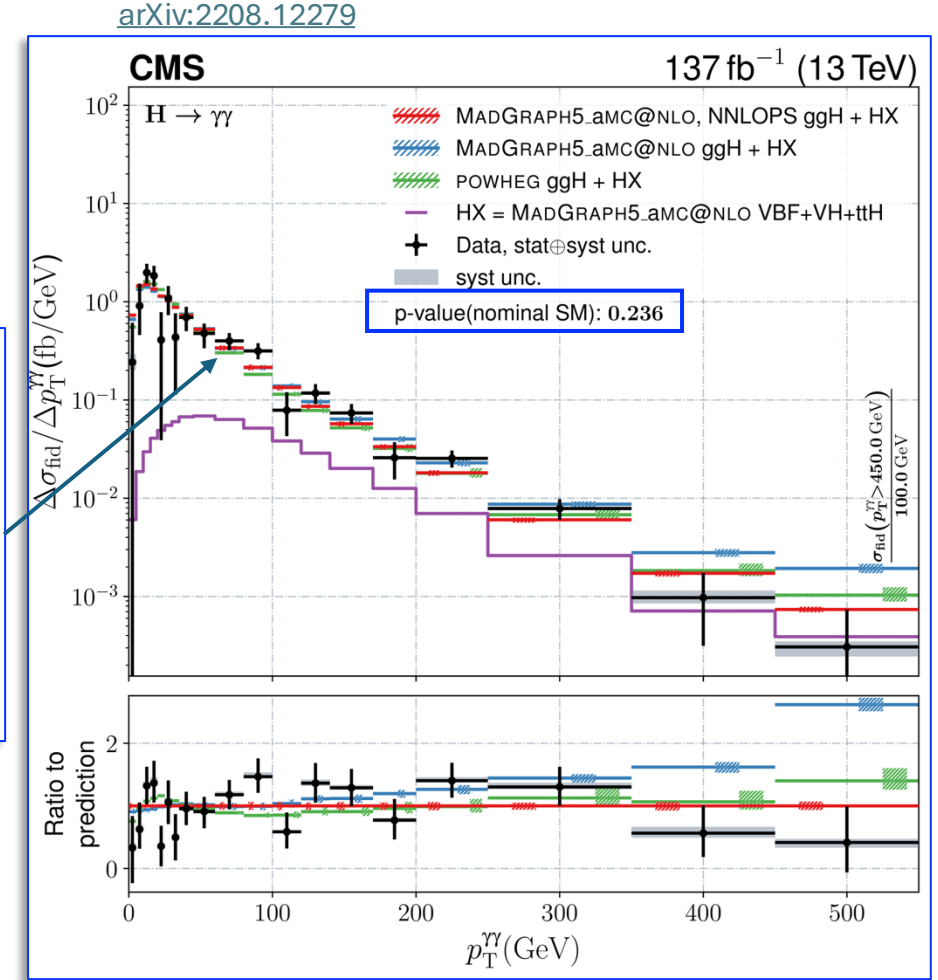
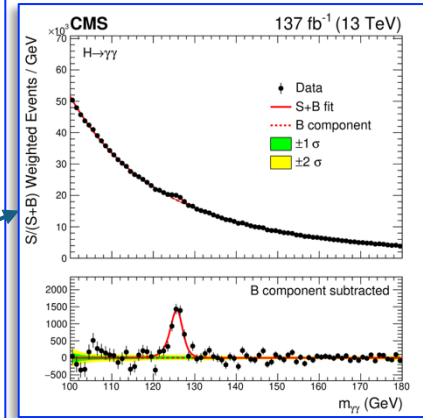
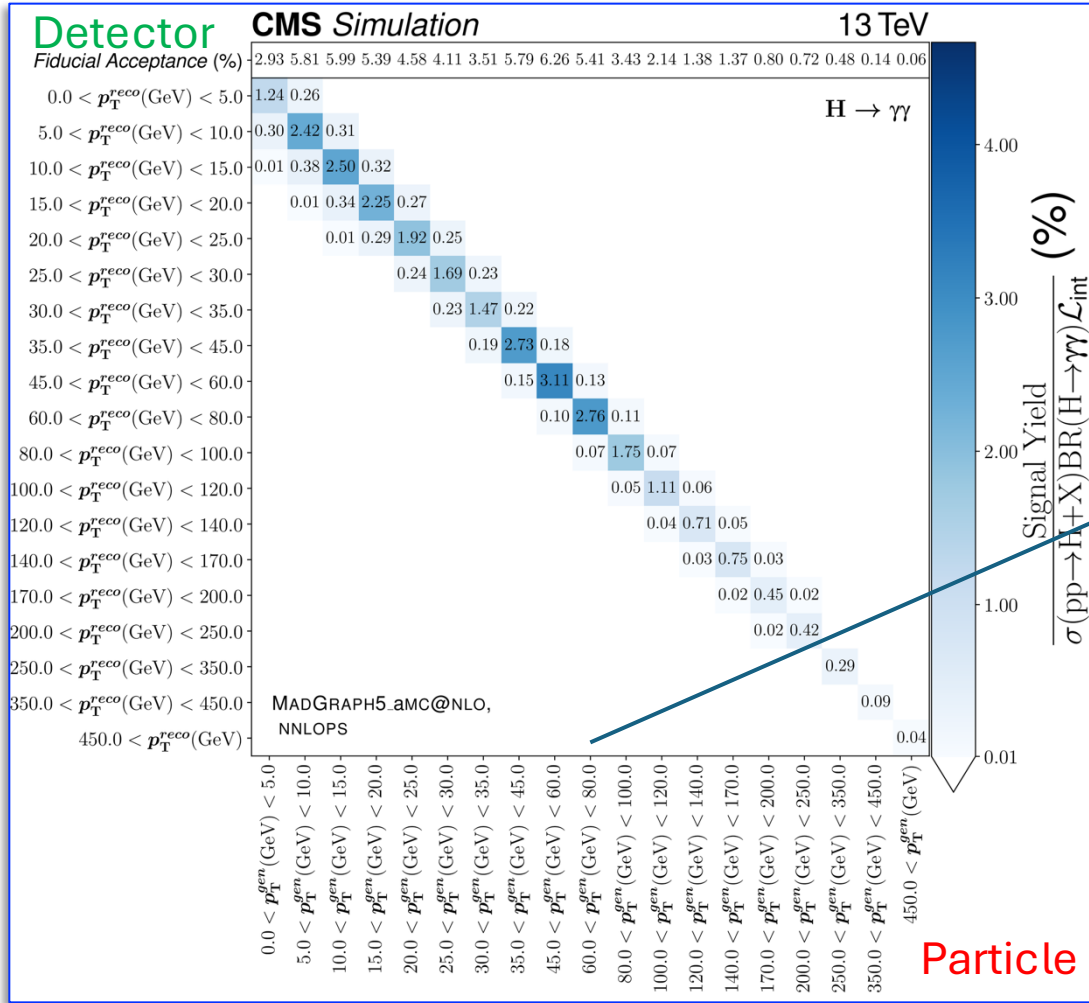
Fiducial cross sections

[JHEP 08 \(2022\) 027](#)

Object	particle-level	detector-level
Photons	$E_T > 0.35/0.25 \times m_{\gamma\gamma}$ $ \eta \in [0, 1.37] \cup [1.52, 2.37]$ $E_T^{\text{iso}}(\Delta R < 0.2, p_T > 1 \text{ GeV, charged}) < 0.05 E_T$	$\leftarrow$ same $\leftarrow$ same <i>tight identification (shower shapes)</i> $E_T^{\text{iso, track}}(\Delta R < 0.2, p_T > 1 \text{ GeV}) < 0.05 E_T$ $E_T^{\text{iso, calo}}(\Delta R < 0.2) < 0.065 E_T$
Leptons	dressed with photons in $\Delta R < 0.1$ $p_T > 15 \text{ GeV}$ $e: \eta \in [0, 1.37] \cup [1.52, 2.47]$ $\mu: \eta \in [0, 2.7]$	$ z_0 \sin \theta < 0.5 \text{ mm} \wedge d_0/\sigma(d_0) < 5(e)/3(\mu)$ $\leftarrow$ same $\leftarrow$ same $\leftarrow$ same <i>medium identification requirements</i> calorimeter and track-based isolation
Jets	anti- k_t $R = 0.4$ (excluding $\nu, \ell, X \leftarrow H$) $p_T > 30 \text{ GeV}$ $ y < 4.4$	anti- k_t $R = 0.4$ particle-flow $\leftarrow$ same $\leftarrow$ same tight-JVT for jets with $ \eta < 2.5$ and $p_T < 60 \text{ GeV}$
b -jets	jets with $ \eta < 2.5$ and b -hadron of $p_T > 5 \text{ GeV}$ within $\Delta R < 0.4$	jets passing the DL1r b -tagging at 70% efficiency
E_T^{miss}	$\sum p_T$ of neutrinos not from hadrons	$-\sum p_T$ of selected γ, ℓ , jets + soft tracks from primary vertex

- Example of *fiducial* vs *detector* for $H \rightarrow \gamma\gamma$ from ATLAS: Minimize extrapolation

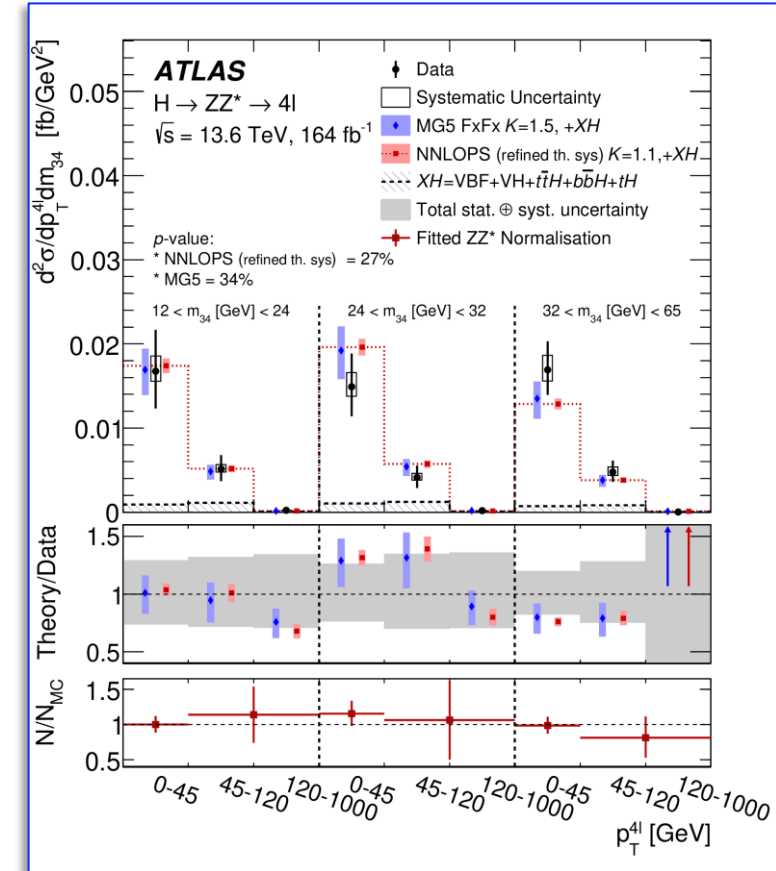
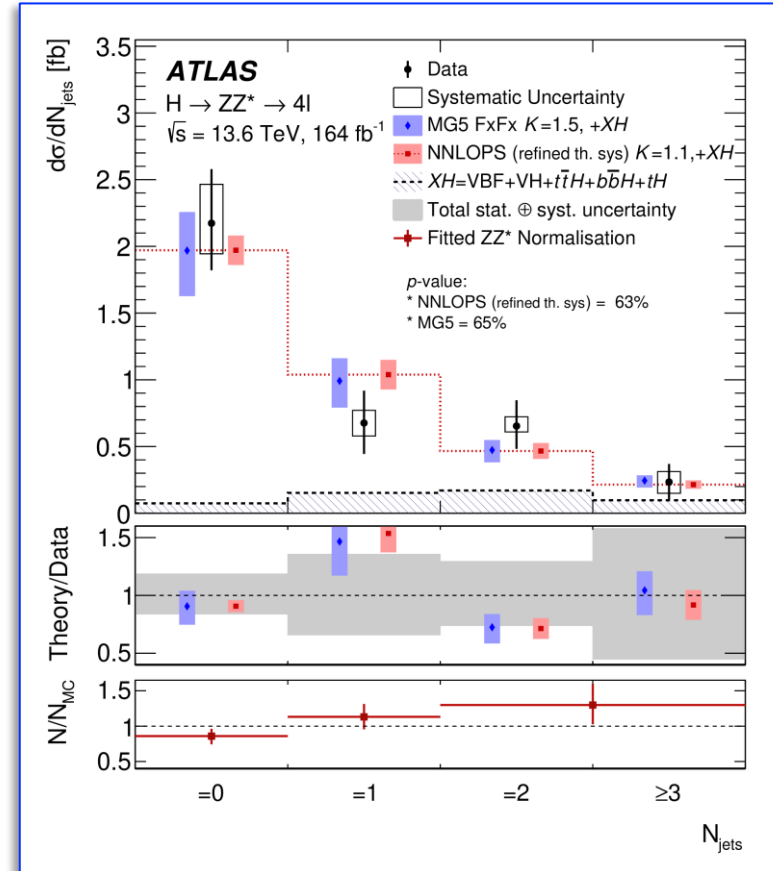
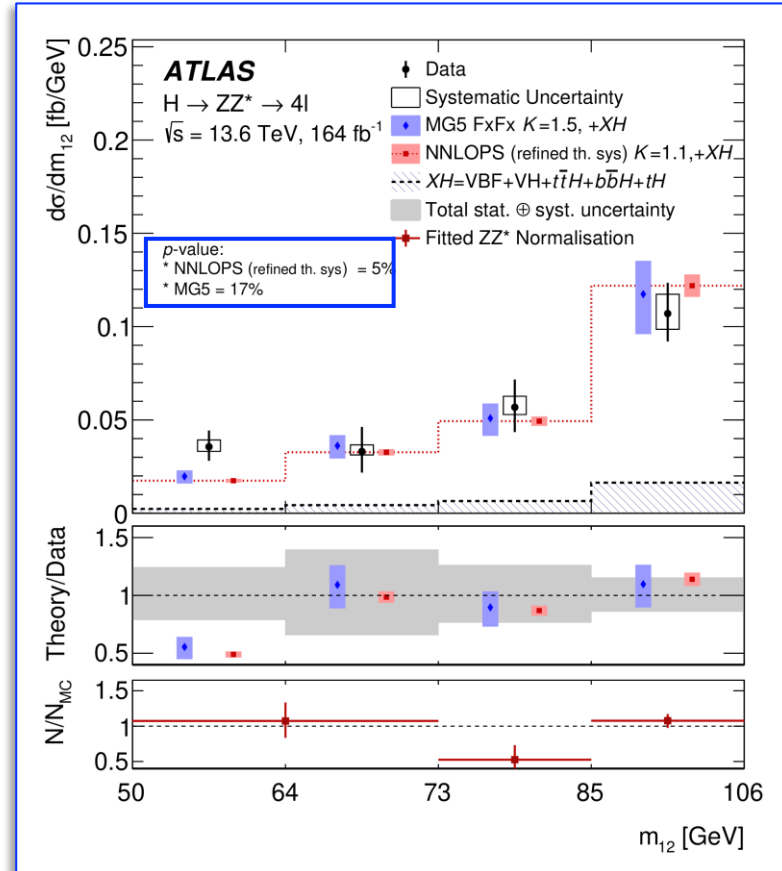
Fiducial cross sections $H \rightarrow \gamma\gamma$



- Split events into $p_T(\gamma\gamma)$ bins and extract σ correcting for detector effects

Differential fiducial cross-sections: $H \rightarrow 4\text{-leptons}$

arXiv:2605.19016



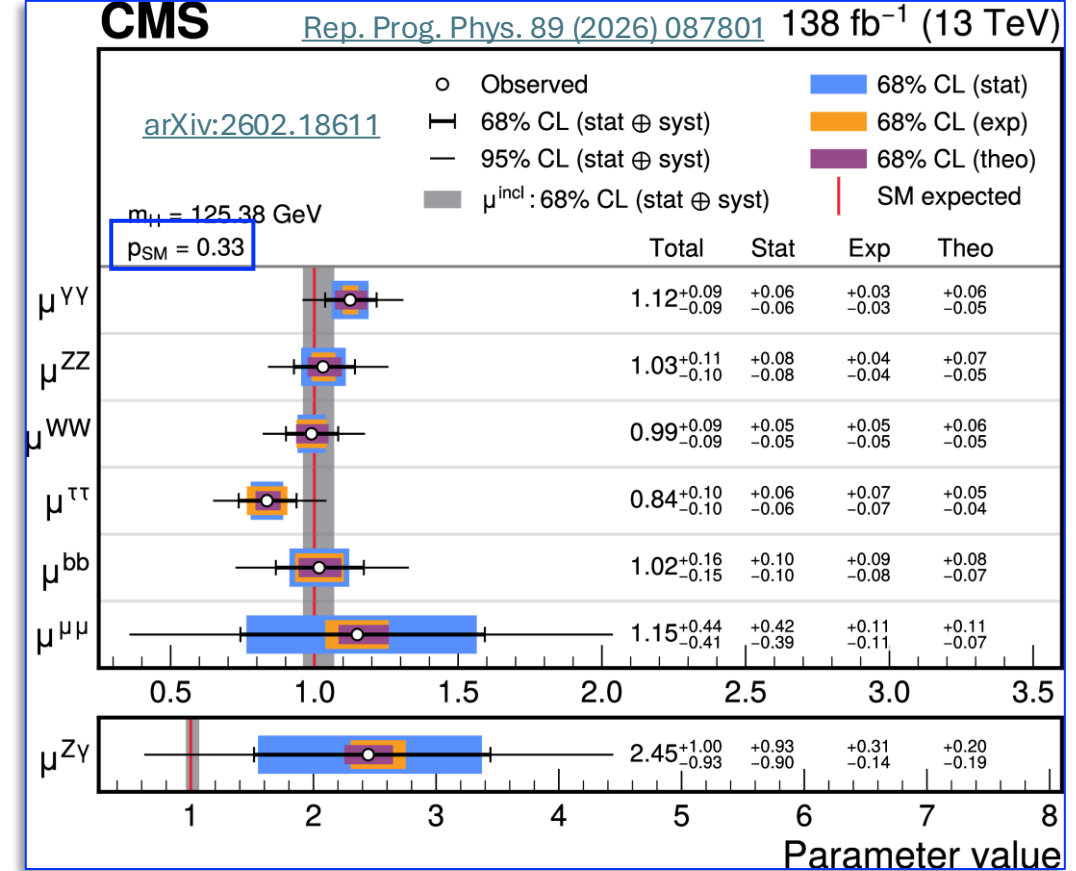
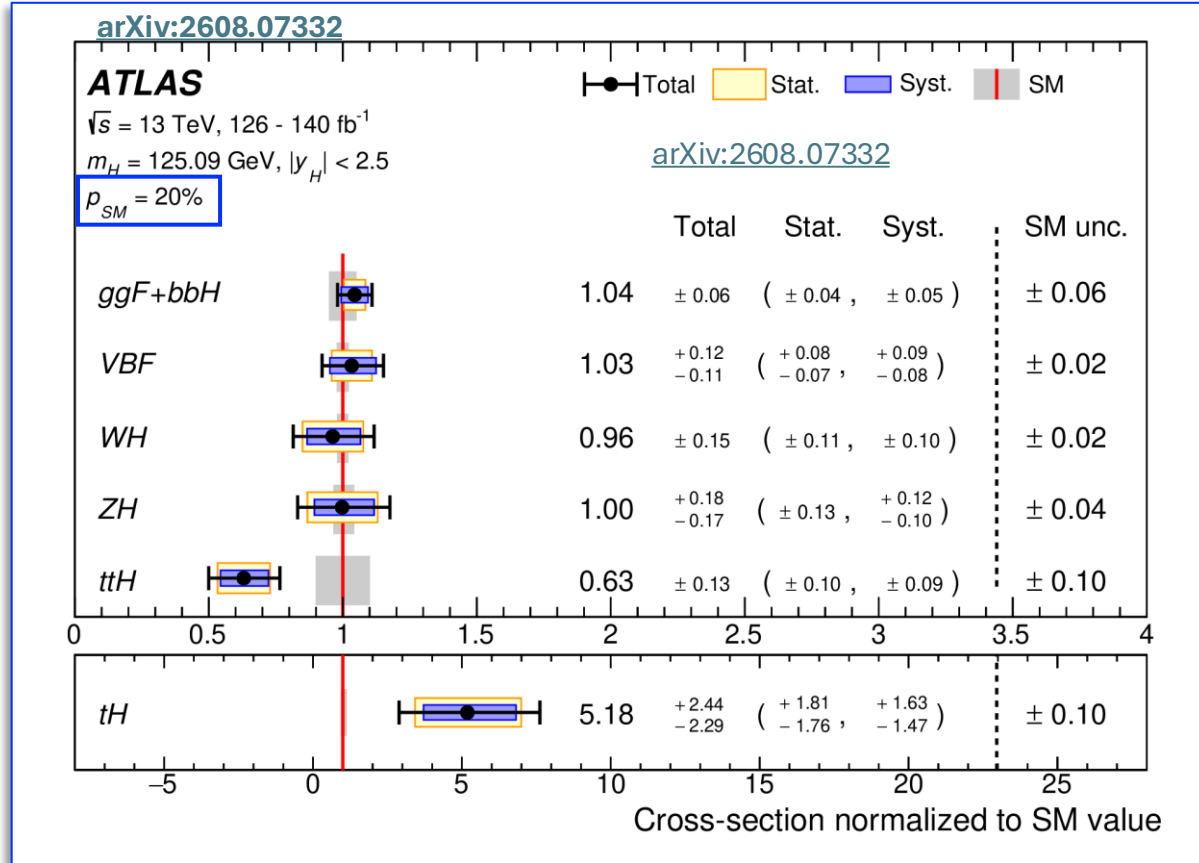
- Detailed study of kinematic properties, p -values for agreement with *state-of-the-art* SM predictions reported: no significant deviations found up to now

Cross-section per
production mode and STXS

Measurement of the cross-sections per production mode

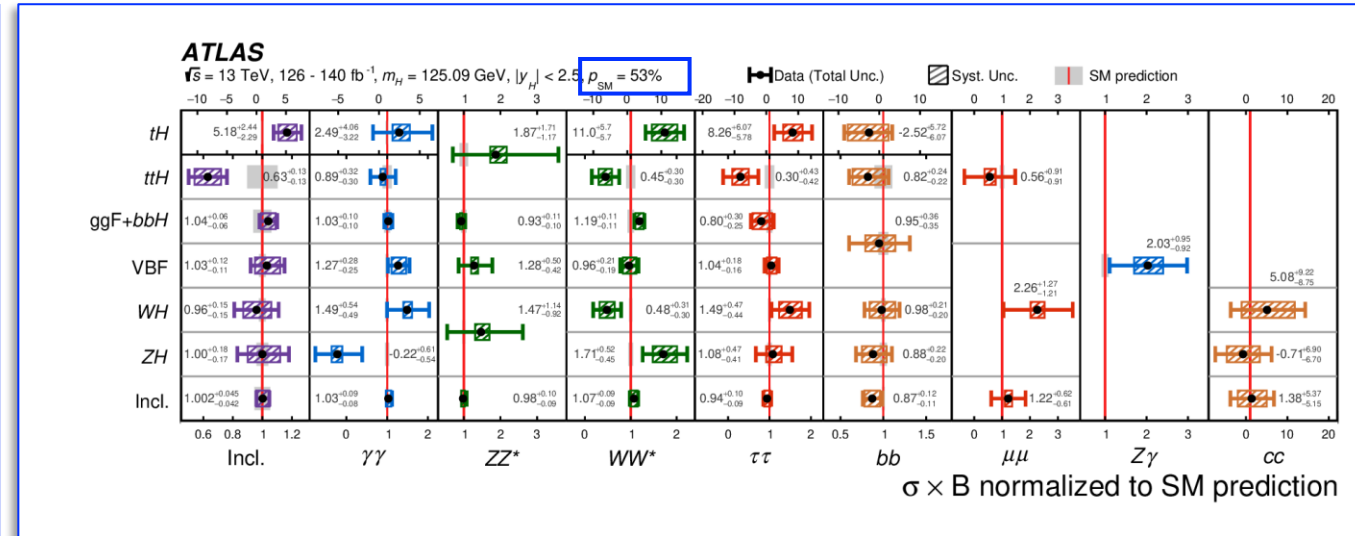
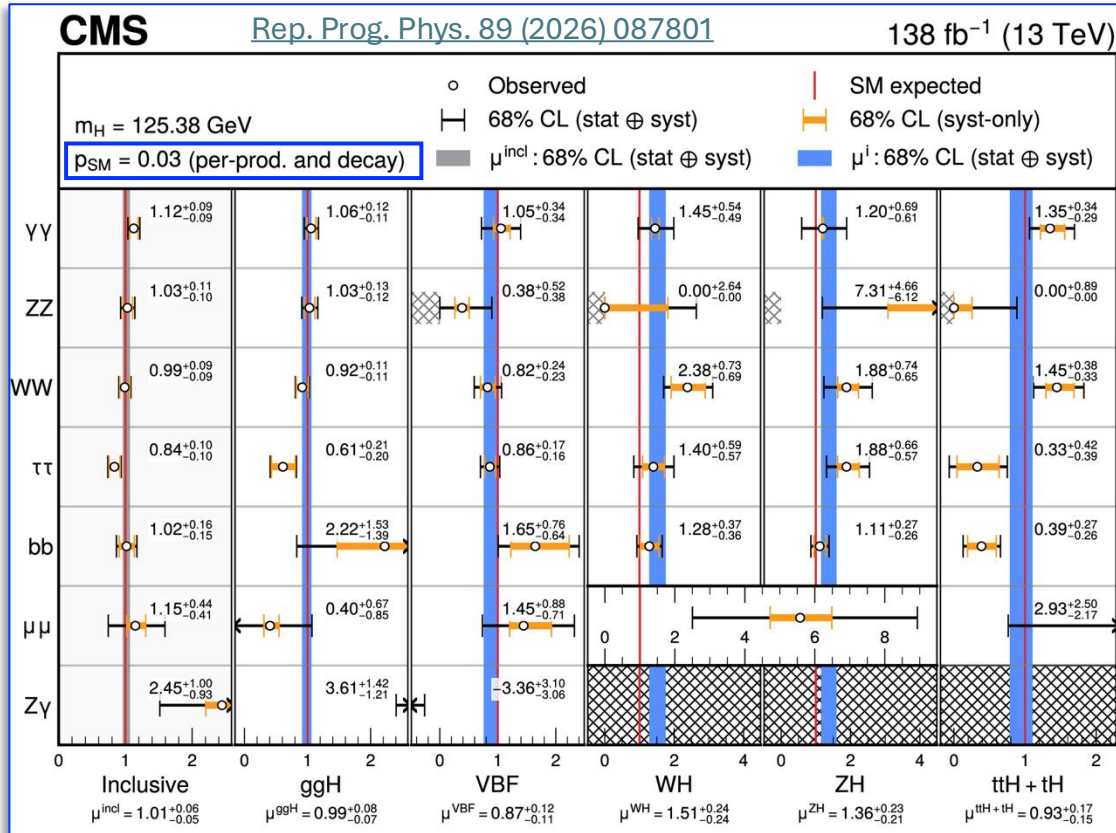
- The richness of **production modes** available at LHC makes it particularly interesting to measure them individually:
 - **ggF**: loop-induced, hence **sensitive to BSM physics**. The SM prediction is very challenging, but theory uncertainty today reduced to about **5%** (N3LO in QCD x NLO EW)
 - **VBF**: test of **V-H** interaction, can be predicted with good accuracy (**~2%**). Can be used to test **V-H CP interaction**
 - **ZH/WH**: sensitive to **V-H interaction**. Used to observe **H→bb** thanks to leptonic Z and W decays
 - **ttH**: directly sensitive to **top Yukawa coupling** (in natural unit of order 1!), can be used to test **CP nature** of top-Higgs interaction
 - **tH**: Sensitive to **relative sign** of **top-H** vs **W-H couplings** and **top-H CP**

Cross-sections per production and decay



- Several measurements can be combined to extract more *inclusive* information
- For this kind of interpretation some assumptions are always needed:
 - Combine **production modes** (assume **SM BR**)
 - Combine **BR** (assume **SM production modes**)

Cross-sections per production and decay



p -values SM computed using the global Likelihood:

$$\chi^2(N_{dof}) = [-2NLL(\text{all } \mu \text{ float})] - [-2NLL(\text{all } \mu=1)]$$

N-dof = number of independent POI's in the fit

Use asymptotic approximation ($-2NLL \sim \chi^2$)

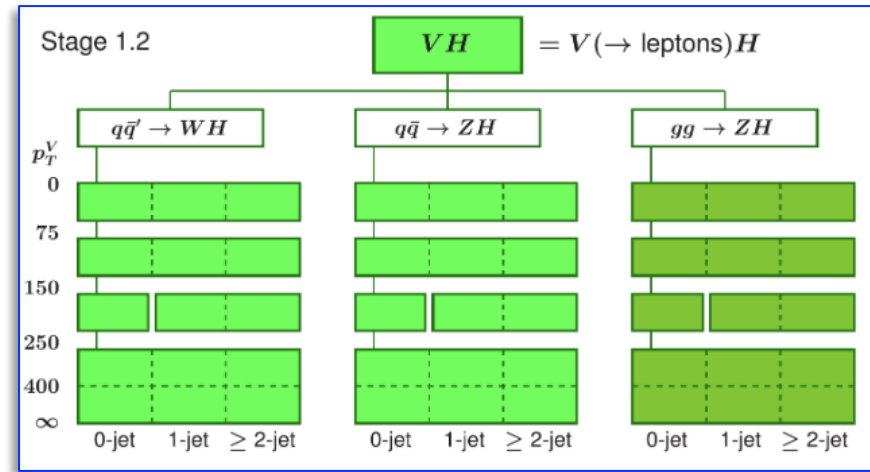
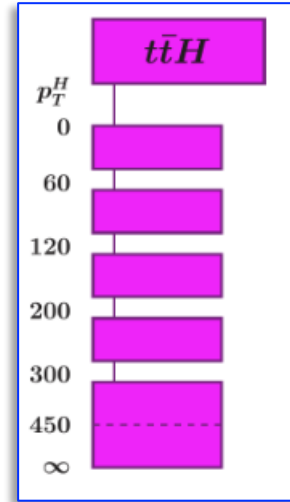
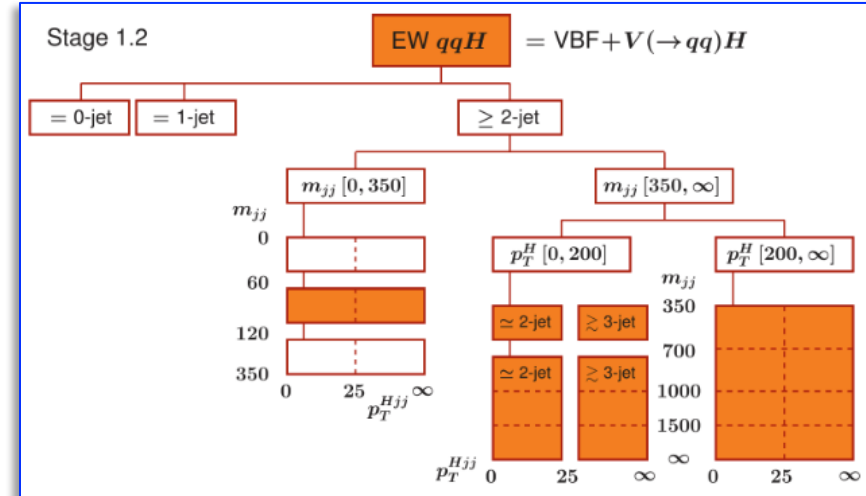
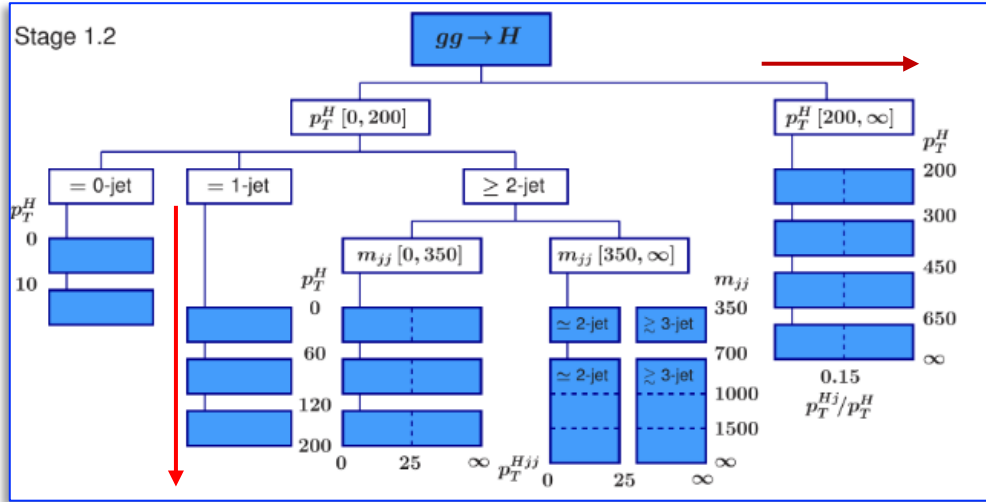
See Hongtao Yang lecture

- The full grid of measurements [production x decay] (signal strength $\mu = \sigma / \sigma_{SM}$)
- Legacy Run 2 results do not show significant deviations from SM (all p -values > 3%)

The STXS approach

- The **SM Higgs boson** is a **scalar** with a **narrow width**; the **production** and **decay factorize** to very good approximation in the narrow-width approximation. We can measure properties of the production processes combining different decay channels with mild model assumptions
- The basic idea is to target measurements of the **different production modes** in **kinematic regions** that are **particularly sensitive to BSM effects**: (e.g., high- p_{TH}):
Simplified Template Cross-Section (STXS) approach
- The granularity of the region splits (bins) is a compromise between **maximal BSM sensitivity** and **available experimental precision**:
 - Proposed by the **LHC Higgs cross section WG** (see [NOTE](#))
 - Several "**stages**" implemented: **1.1** used in **Run 1**, **1.2** in **Run 2** and **1.3** in **Run 3**
- Better treatment of **theory uncertainties**: distinguish uncertainties on **total cross-sections** from **migrations** between kinematic regions

STXS phase-space definition

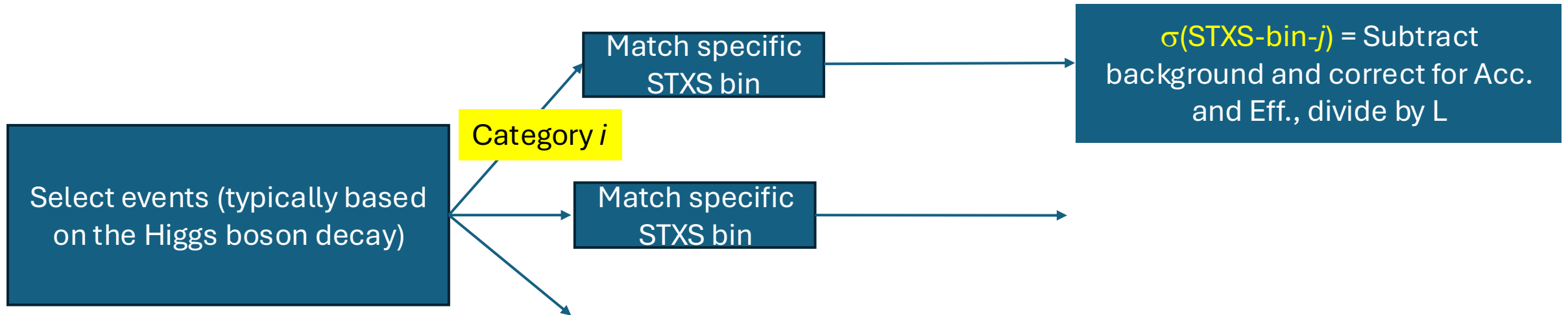


Info at: [LHCHWGFiducialAndSTXS](#)

Increasing **BSM** sensitivity

This is the [Stage 1.2](#) used by ATLAS and CMS in [Run 2](#) (1.3 proposed for Run 3)

Strategy



- Define **categories i** using final state objects: Higgs boson **decay products + accompanying jets**: optimized to disentangle the different “**STXS regions**” j
- Typically use an **MVA approach** to get optimal $i \rightarrow j$ **match** for signal events and to improve **signal-to-background** ratio

Example Measurements in the $\gamma\gamma$ final state

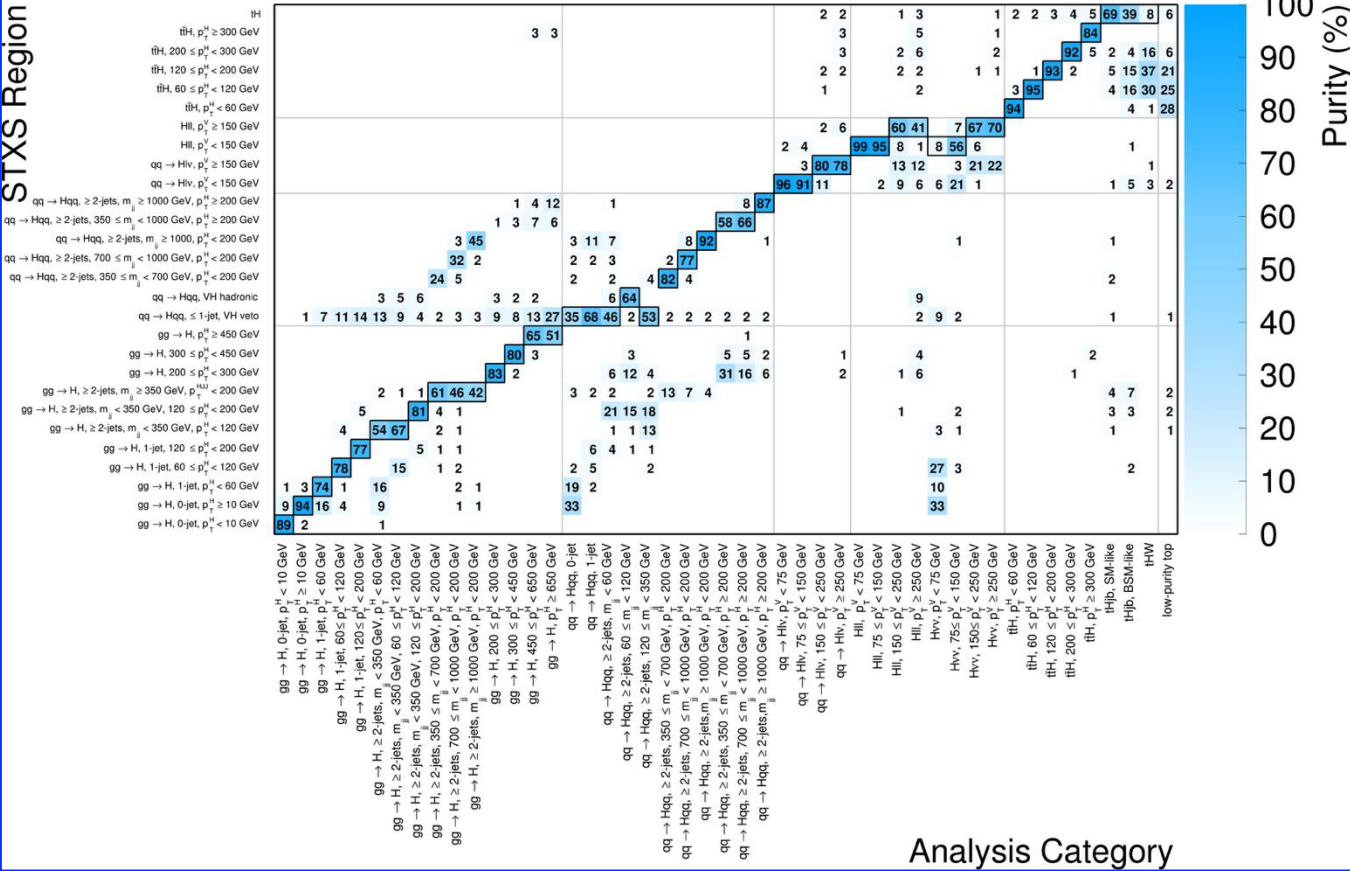
- This channel is particularly powerful:
 - Reasonable BR ($\sim 0.23\%$)
 - Fully reconstructed final state
 - Signal extracted with an analytic fit to the $\gamma\gamma$ invariant mass
 - Continuum background with a smoothly falling spectrum, signal peak with mass resolution $\sim 1.5\text{-}2\%$
- Different techniques adopted by the two experiments to assess the background-modeling systematic uncertainty:
 - CMS: *discrete profiling* of the background functions (chosen among a few families)
 - ATLAS: the "*spurious signals*" method performs an S+B fit to the background-only templates (no signal present) $\rightarrow$ fitted signal is considered as a background systematic uncertainty

STXS $H \rightarrow \gamma\gamma$

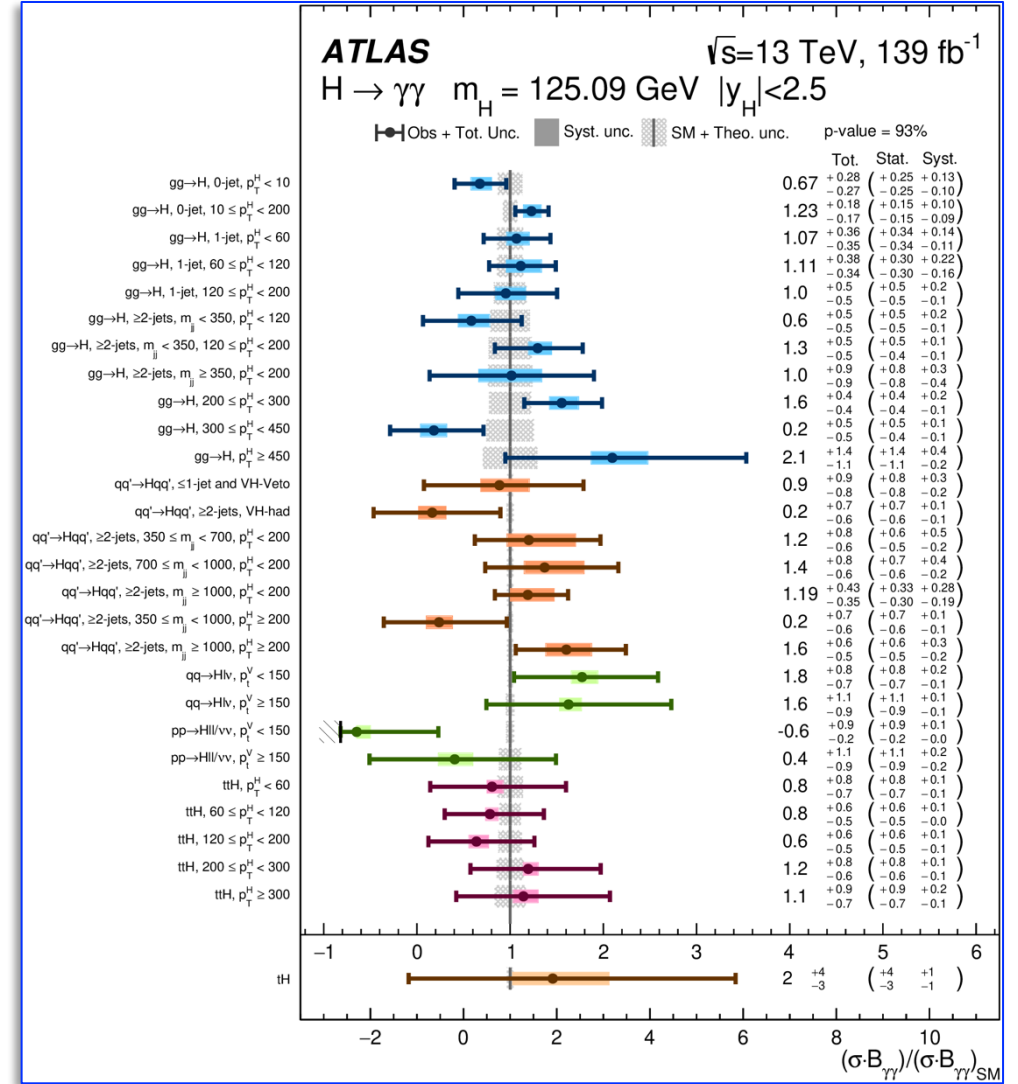
JHEP 07 (2023) 088

ATLAS Simulation 139 fb⁻¹ $H \rightarrow \gamma\gamma$, $\sqrt{s}=13$ TeV

STXS Region

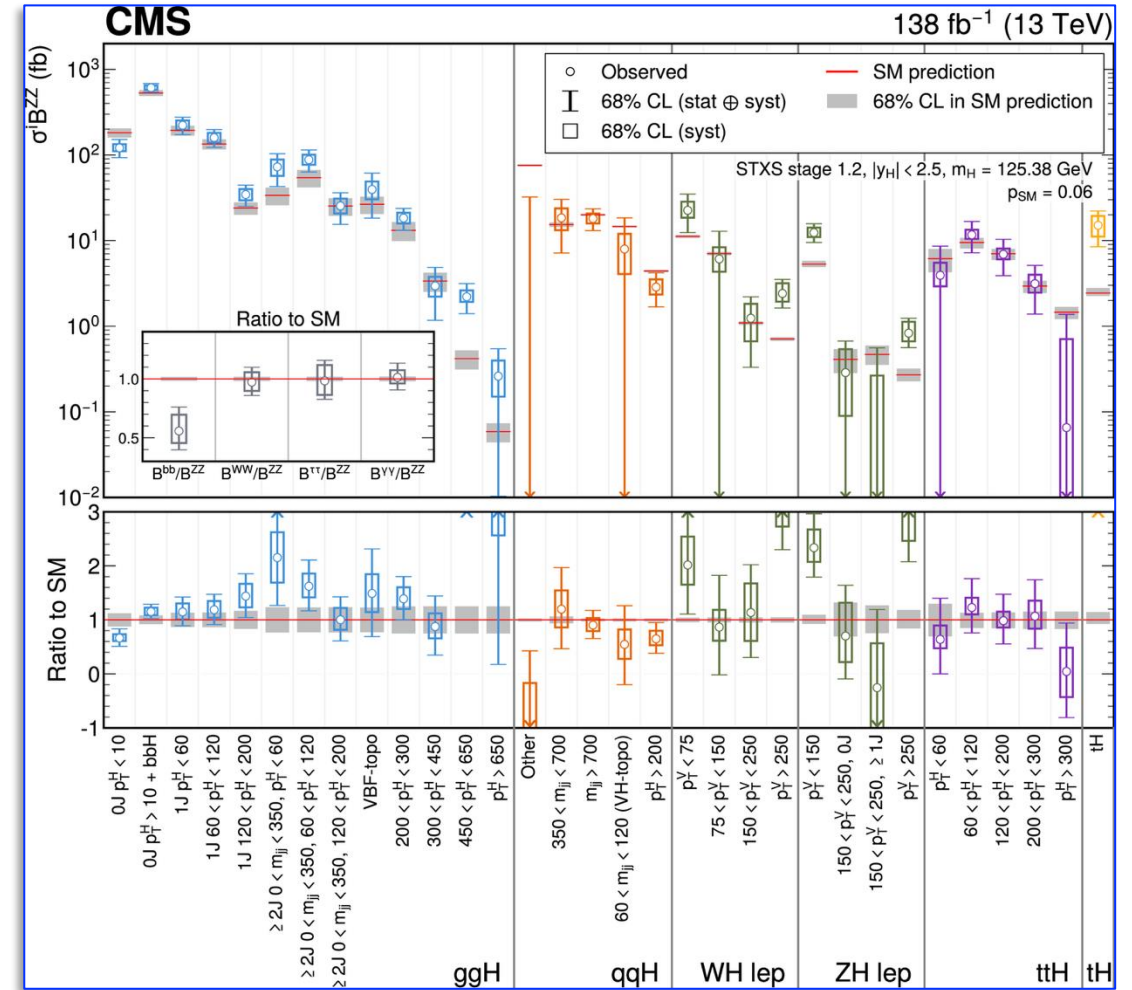
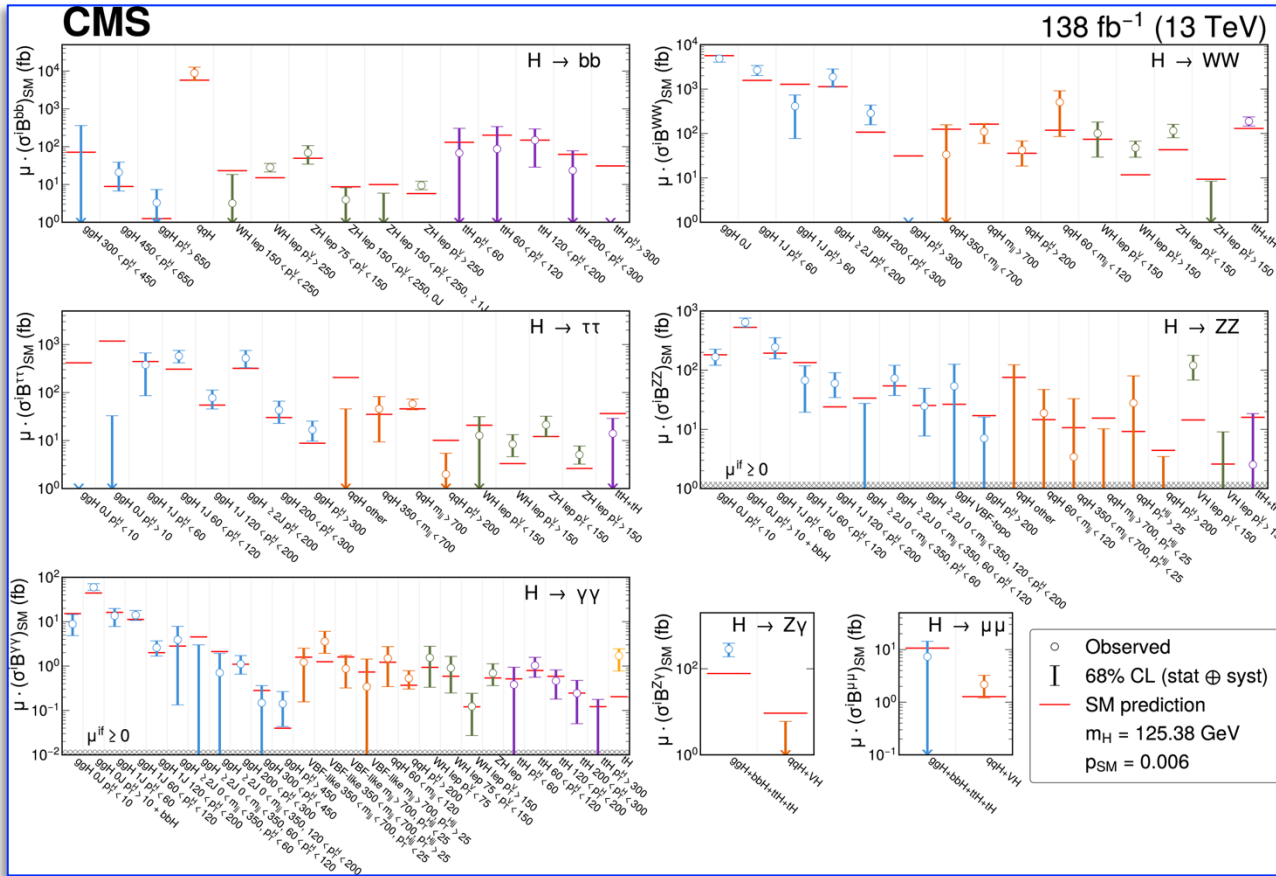


- Analyses designed to match the measured regions with STXS bins



STXS channels combination

arxiv:2602.18611



- Different decay channels can be combined, normalize to $\text{BR}(H \rightarrow ZZ^*)$ to reduce model dependence

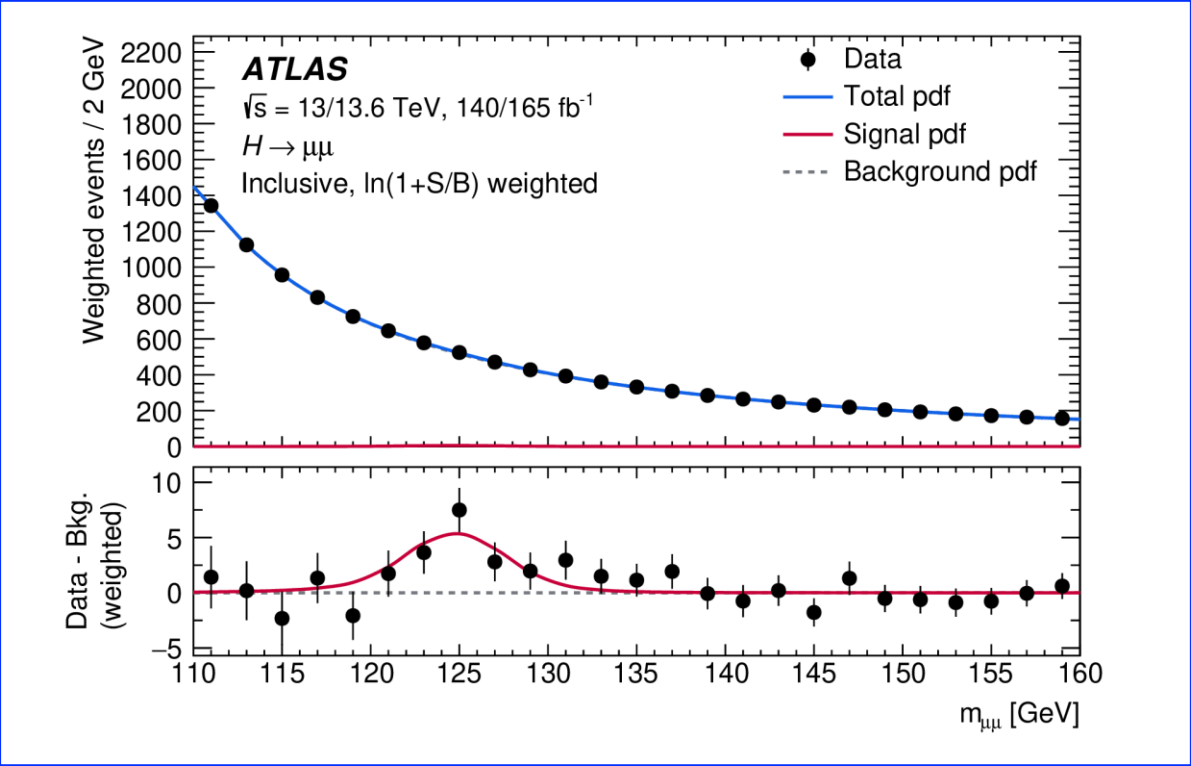
Questions?

Lecture 2

Search for $H \rightarrow \mu\mu$ and
invisible decays

2nd-generation fermion $H \rightarrow \mu\mu$

Phys. Rev. Lett. 135 (2025) 231802

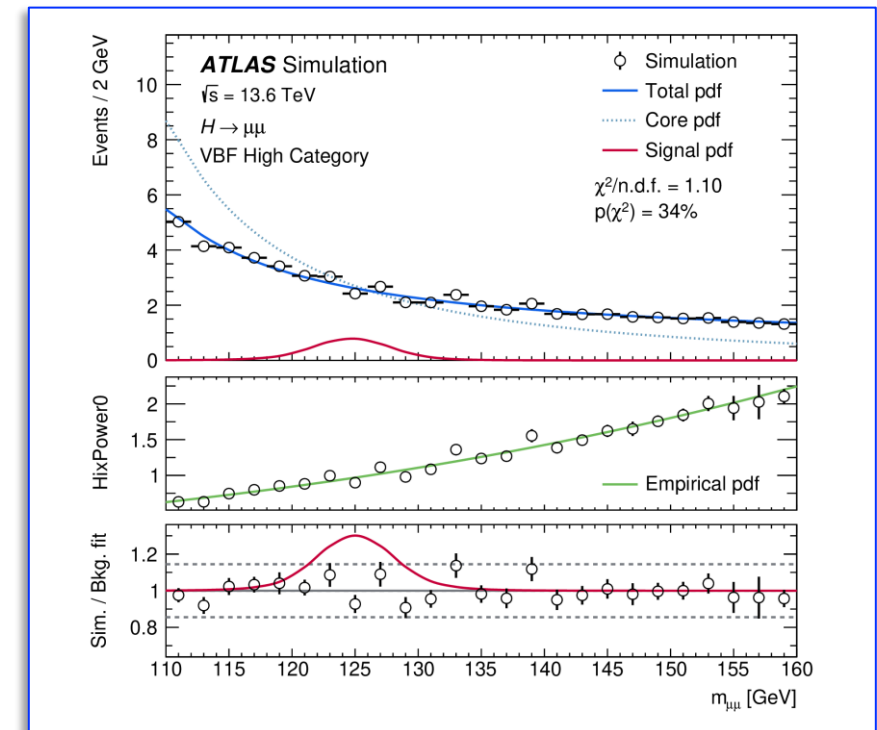
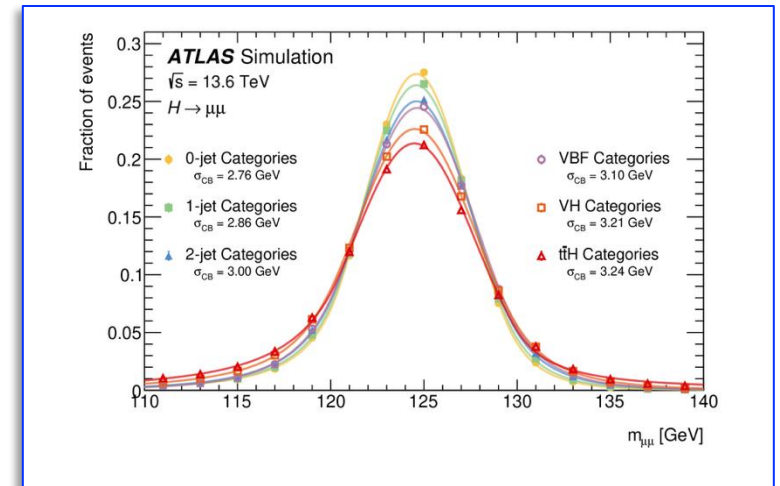


Category	Data	S	B	$S/\sqrt{B}$	$S/B [\%]$
$t\bar{t}H$ -High	12	1.9 ± 0.7	15.5 ± 2.3	0.49	12.5
$t\bar{t}H$ -Medium	117	3.9 ± 1.4	115 ± 7	0.36	3.4
VH4L	11	0.78 ± 0.29	12.2 ± 1.8	0.22	6.4
VH3L-High	25	1.4 ± 0.5	17.4 ± 2.9	0.33	8.0
VH3L-Medium	143	3.7 ± 1.4	136 ± 10	0.31	2.7
VH2L-High	19	1.0 ± 0.4	18.3 ± 2.9	0.23	5.3
VH2L-Medium	30	0.38 ± 0.14	31.7 ± 3.1	0.07	1.2
VBF High	9	4.3 ± 1.6	10.5 ± 1.8	1.34	41.2
VBF Medium	28	5.3 ± 2.0	25.8 ± 2.7	1.04	20.5
VBF Low	69	7.2 ± 2.7	62 ± 4	0.91	11.6
VBF Very Low	217	11 ± 4	225 ± 8	0.76	5.1
2-jet High	1 399	31 ± 12	$1 367 \pm 25$	0.84	2.3
2-jet Medium	5 657	69 ± 26	$5 560 \pm 50$	0.92	1.2
2-jet Low	17 684	110 ± 40	$17 300 \pm 70$	0.87	0.7
2-jet Very Low	35 147	110 ± 40	$35 160 \pm 140$	0.59	0.3
1-jet High	708	17 ± 6	710 ± 16	0.65	2.4
1-jet Medium	7 166	80 ± 30	$7 140 \pm 70$	0.95	1.1
1-jet Low	31 761	180 ± 70	$31 510 \pm 120$	1.00	0.6
1-jet Very Low	73 578	200 ± 80	$73 330 \pm 200$	0.75	0.3
0-jet High	19 445	120 ± 50	$19 260 \pm 90$	0.89	0.6
0-jet Medium	50 742	200 ± 80	$50 830 \pm 190$	0.90	0.4
0-jet Low	94 032	240 ± 90	$93 770 \pm 210$	0.78	0.3
0-jet Very Low	136 762	170 ± 60	$136 510 \pm 290$	0.47	0.1

- Best chance to test coupling to 2nd-generation fermions
- Signal extracted from analytic $S+B$ fit to invariant mass distribution
- Similar strategy to $H \rightarrow \gamma\gamma$ BUT: BR and S/B (DY lepton pair-production) 1 order of magnitude smaller ($\sim 10^{-3}$): B modeling is crucial
- Categorize events to enhance S/B based on production mode and kinematics, while exploiting categories with better mass resolution

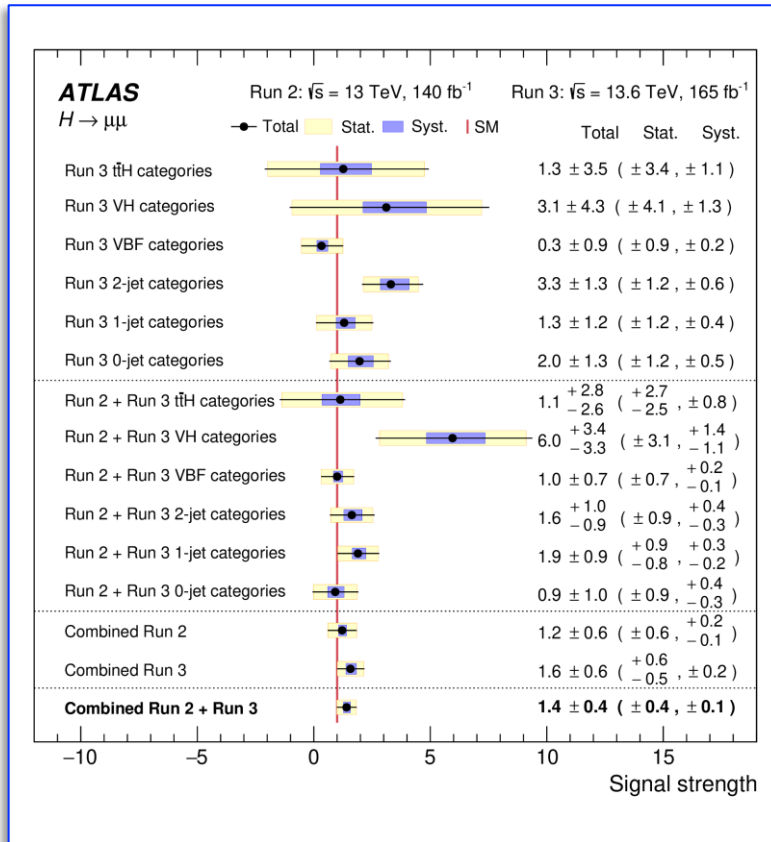
$H \rightarrow \mu\mu$ example: ATLAS analysis

- Signal extracted via an **analytical fit** to $m_{\mu\mu}$ spectra
- Signal modeling: **Double-Sided crystal ball** from calibrated MC
- Bkg. Modeling: based on **Core** x **Empirical** analytic function
 - **Core** DY same for all categories (no free DOF)
 - **Empirical**: flexible enough to adapt to mass distortions caused by selection, between **1 and 4 free shape parameters** depending on category plus **normalization** extracted from fit to data
- Choice of the bkg. function:
 - Required **good quality fit** on: MC, data SB: $\text{prob}(\chi^2) > 1\%$ for all samples/categories
 - **Spurious Signals**: defined as signal yields obtained from a fit to the background-only MC spectra $\rightarrow$ require to be below **20% stat. uncertainty**
 - Choose the functions with **smaller DOF** that passes the criteria described above (see next slide for list of functions)
- **Background modeling uncertainty** from the **Spurious Signals** measured in each category
- **CMS** uses a similar approach based on “core-PDF method” and “discrete profiling”

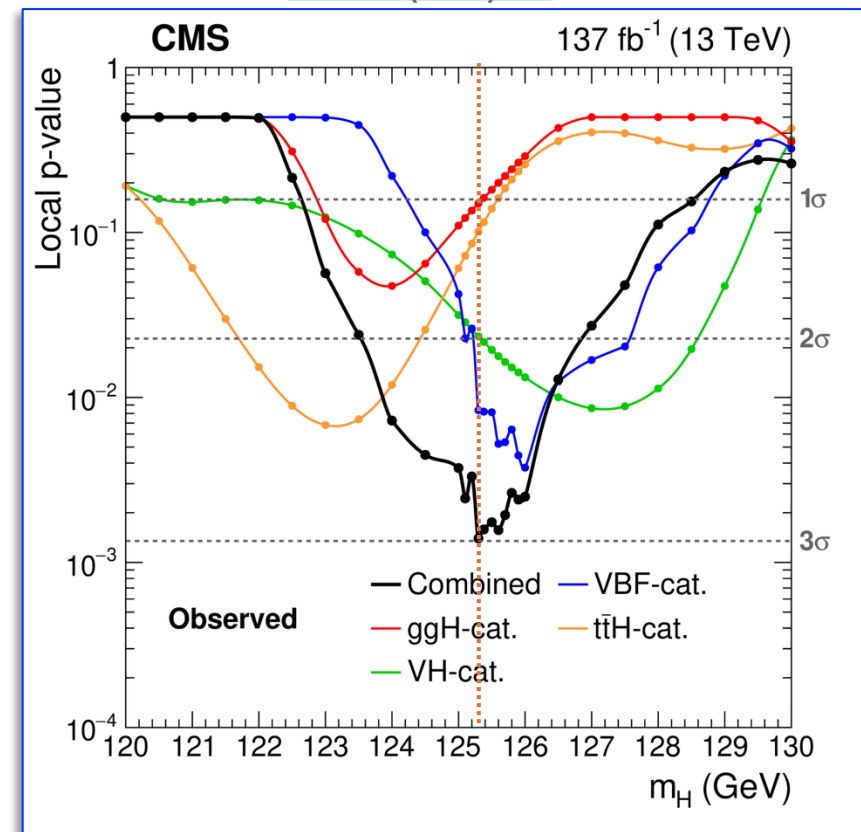


$H \rightarrow \mu\mu$ most recent results

Phys. Rev. Lett. 135 (2025) 231802

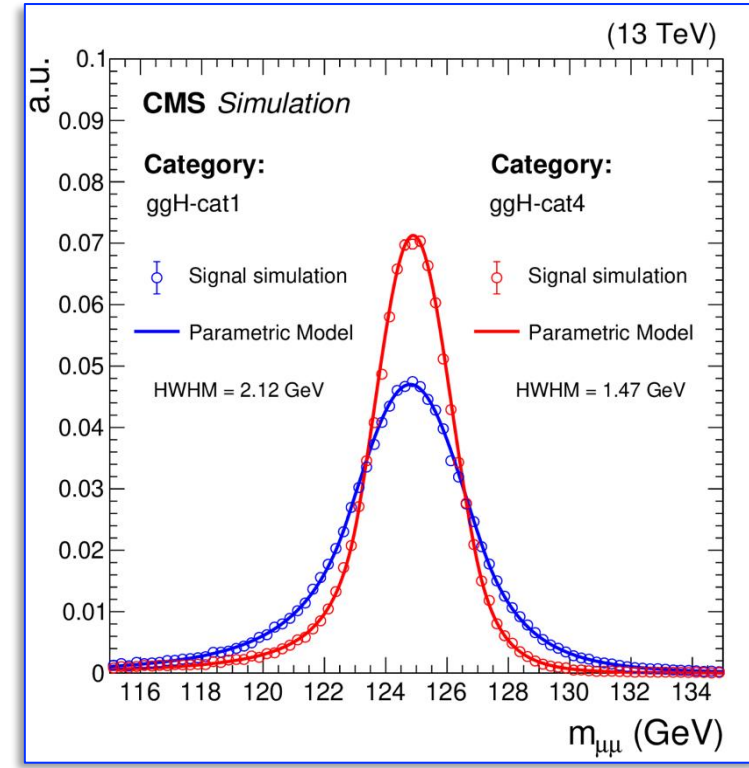
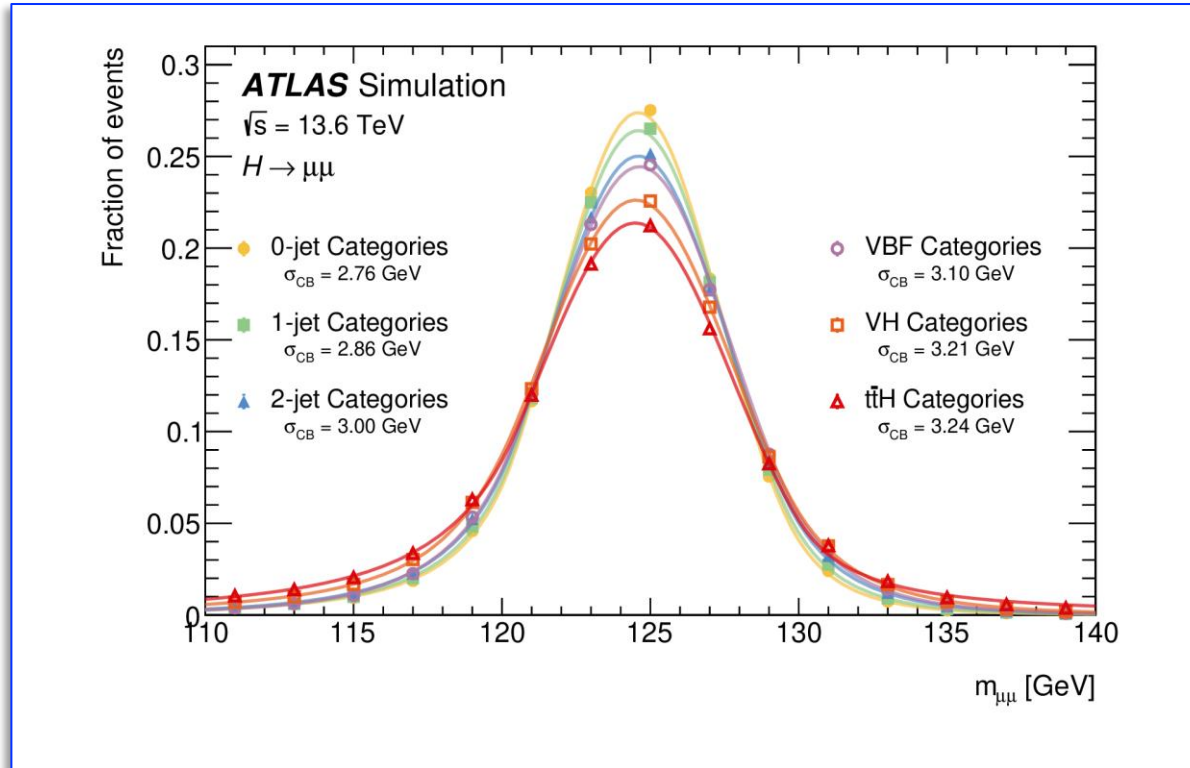


JHEP 01 (2021) 148



- Both **ATLAS** and **CMS** reached **>3 σ evidence** for this process (expected **SM** sensitivity ~ 2.5 for both, see next slide)
- Measured signal strengths μ compatible with **unity (SM)**: **1.4 ± 0.4 ATLAS** and **1.2 ± 0.4 CMS**
- A future **ATLAS+CMS** combination including **Run 3 + Run 2** data should lead to an **observation** if **SM is correct**

$H \rightarrow \mu\mu$ Comparison ATLAS vs CMS



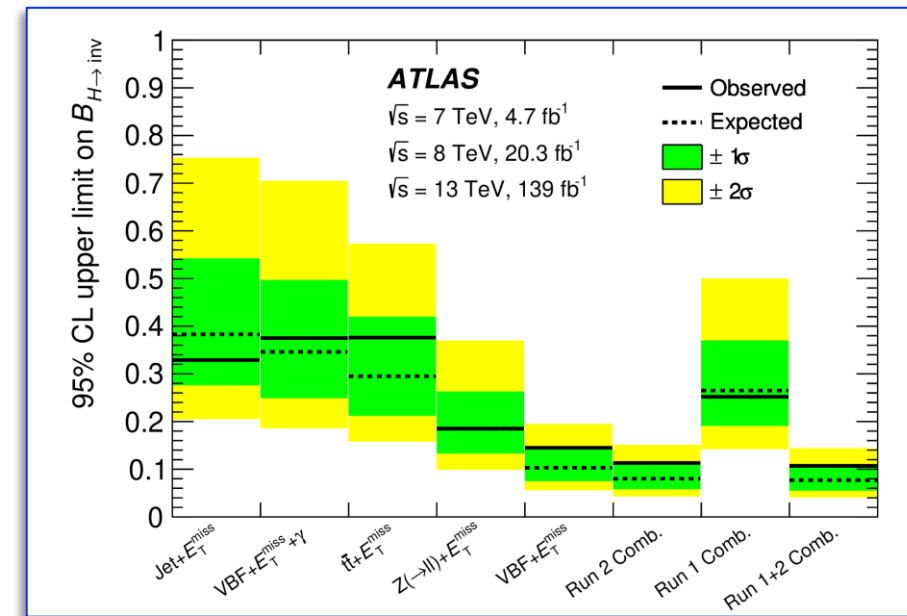
- Muons from H decays are moderate $P_T \sim 40$ -100 GeV and central: **mass resolution** for **best** category:
 - CMS $\sim$ **1.2 GeV**
 - ATLAS $\sim$ **2.6 GeV**
- The main reason is that CMS solenoidal field ~ 2 stronger than ATLAS
- Sensitivity $\sim S/\sqrt{B}$ in $\pm 2\sigma(m_{\mu\mu})$ range $\rightarrow$ about **40% more sensitivity** for CMS

Higgs to “invisible” decay

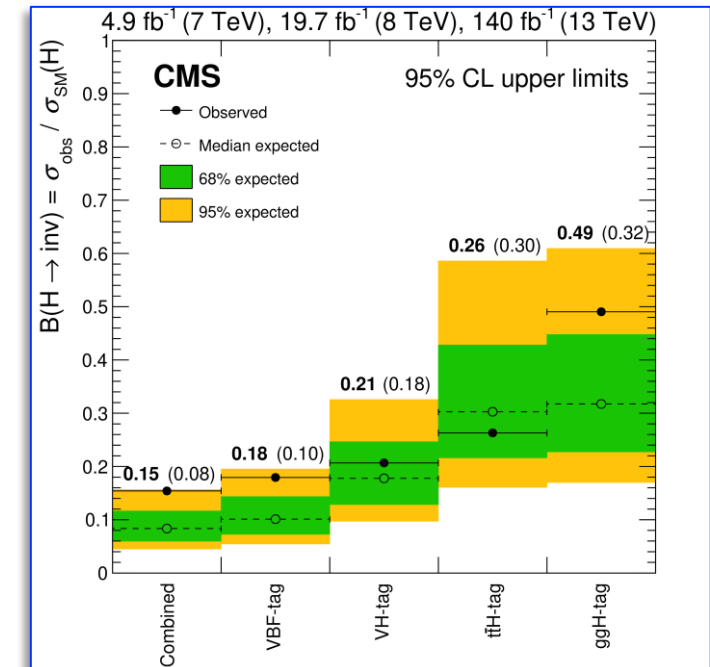
- The **irreducible** SM invisible decay is $BR(H \rightarrow ZZ^* \rightarrow 4\nu) \sim 0.1\%$, well below current experimental sensitivity $\rightarrow$ an **observation** at the LHC would imply **BSM physics**
- Search for decays to **weakly interacting neutral particles** that are **invisible** to the LHC detectors (e.g., $H \rightarrow \chi^0 \chi^0$ Neutralino Dark matter candidate)
- Need additional **objects** to **trigger** and **select** the event, typically use associated production:
 - $ggF + \text{high } p_T \text{ jet}$, VBF , $Z(l\bar{l})H$, $t\bar{t}H$, ...
- Presence of **invisible decay** detected indirectly via **missing transverse energy**: contrary to e^+e^- colliders, at LHC the p_z of the primary collision is not known in the LAB frame (spread of longitudinal momenta of proton constituents), momentum balance only in the **transverse plane** (p_T spread of proton constituents negligible relative to experimental sensitivity)
- In case of the discovery of a signal, will need a study of σ for **different signatures** to interpret it as Higgs **invisible** decay
- Current $BR(H \rightarrow \text{inv})$ upper limits @95% CL:

<11% ATLAS, **<15% CMS**

Phys. Lett. B 842 (2023) 137963



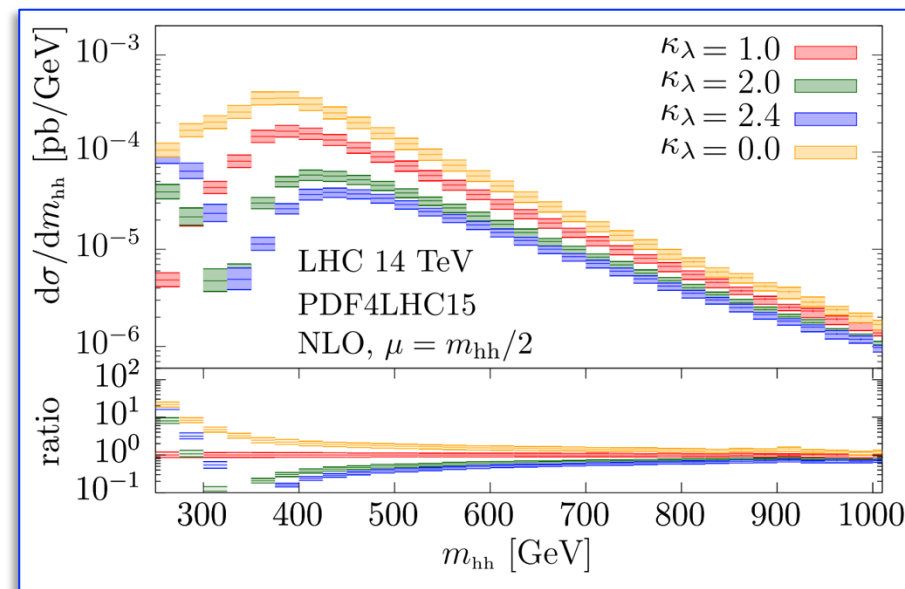
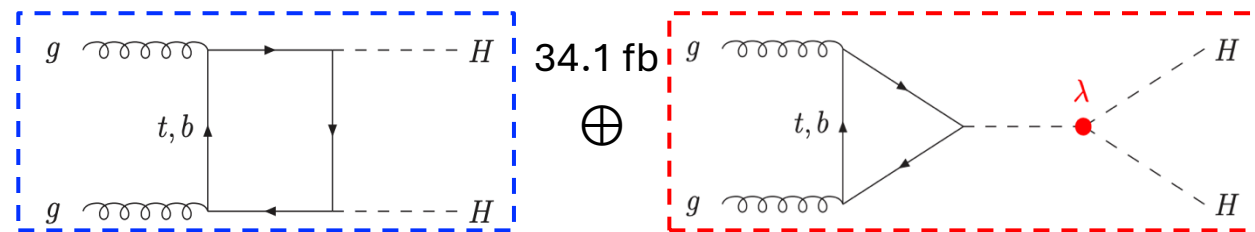
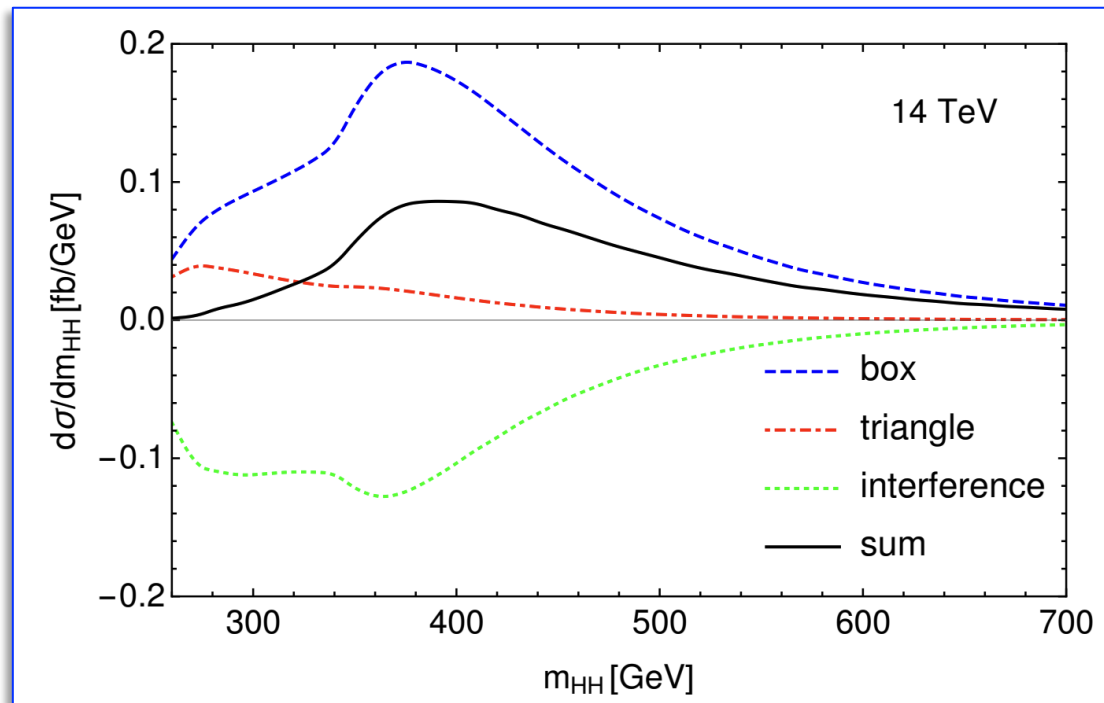
Eur. Phys. J. C 83 (2023) 933



Higgs boson pair-production

Search for HH production

LHCHWG di-Higgs white paper

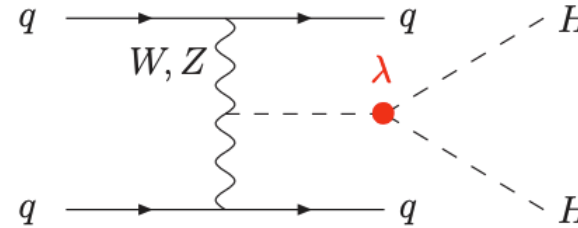
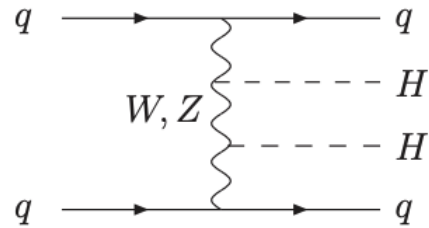


- **Extremely rare** but also **extremely important** process: it probes the Higgs boson **self-coupling**, determined in the **SM** by the parameter $\lambda = \left(\frac{m_h^2}{2 v^2}\right) = \frac{(m_H^2 G_F)}{\sqrt{2}}$
- Main production mechanisms **ggFHH** ($\sigma=34.1\text{fb}$ at **13.6 TeV**) characterized by **negative interference** between **box-** and **self-interacting** diagrams
- If λ different from **SM**, **total yield** and **kinematic** (e.g., M_{HH}) are both affected

Search for Higgs –pair production

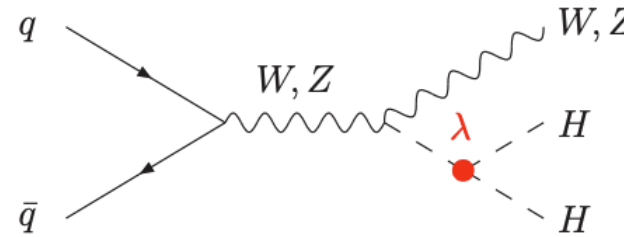
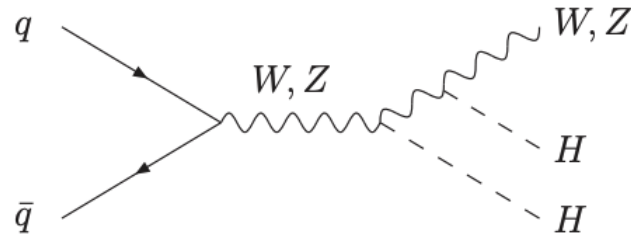
[LHCHWG di-Higgs white paper](#)

VBFHH



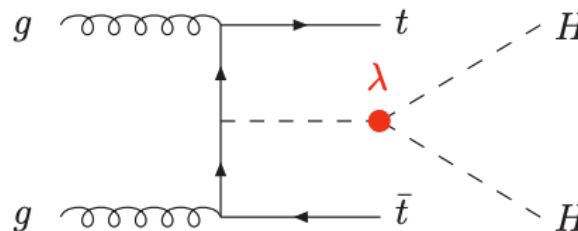
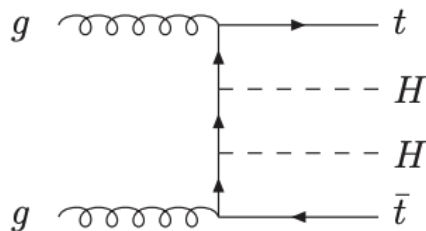
~ 1.9 fb

VHH



~ 1.0 fb

ttHH



~ 0.9 fb

- Other production mechanisms are VBFHH, VHH, ttHH with smaller cross-sections

HH measurements at the LHC

- Given the smallness of the **cross-section**, the strategy is to cover **as many** final states **as possible**

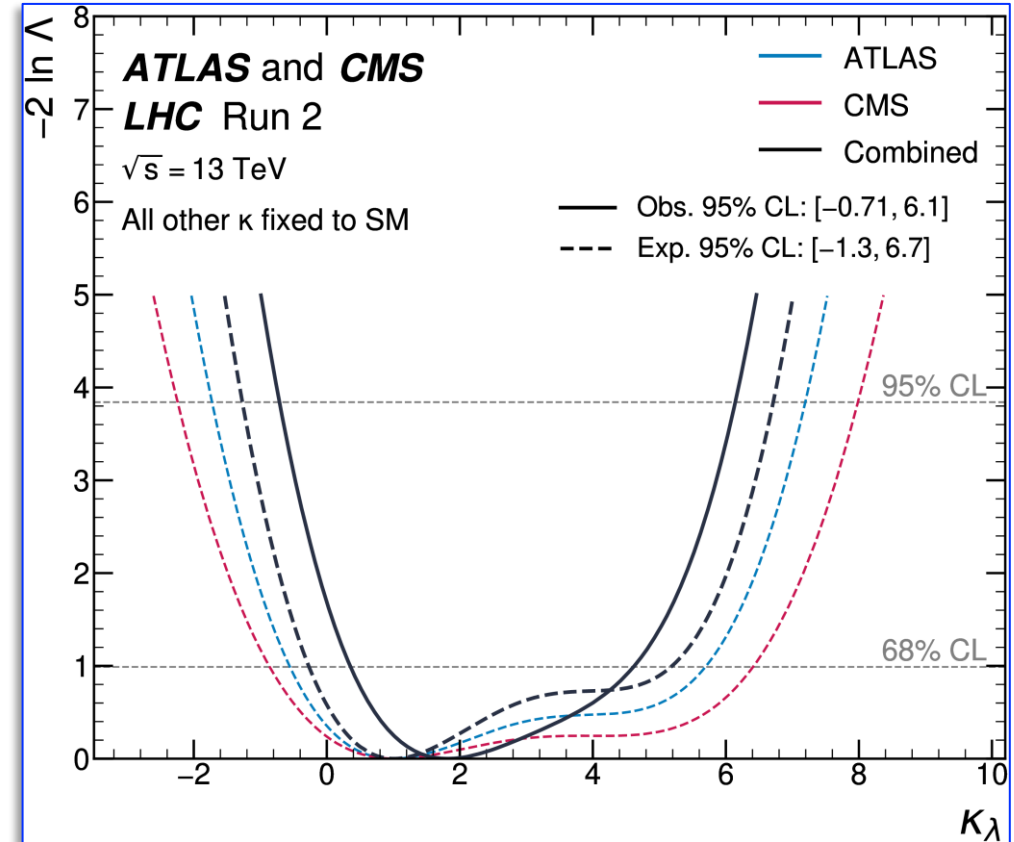
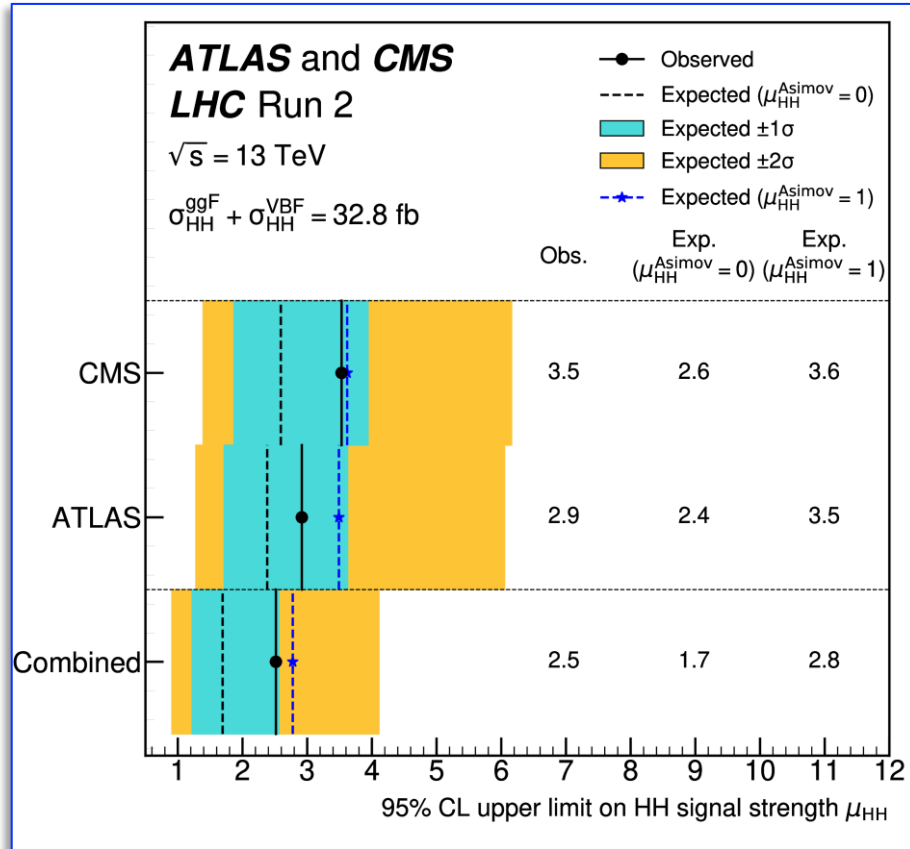
Most relevant channels at the LHC are:

- $HH \rightarrow b\bar{b}\gamma\gamma$
 - Small BR ($\sim 0.3\%$)
 - Favorable S/B
 - The non-resonant background can be determined in situ (fit to $m_{\gamma\gamma}$)
- $HH \rightarrow b\bar{b}\tau\tau$
 - Larger BR (7.3%)
 - Intermediate S/B
 - Need advanced techniques to keep B under control (good B modeling for irreducible B and data-driven techniques for reducible B)
- $HH \rightarrow b\bar{b}b\bar{b}$
 - Largest BR ($\sim 34\%$)
 - Very small S/B ($\sim 10^{-5}$ after simple preselection)
 - Dominant B is $pp \rightarrow b\bar{b}b\bar{b}$ multijet production, no reliable simulation, need to fully rely on data-driven techniques

	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%

HH measurements at the LHC

arxiv:2602.23991 Accepted by PRL

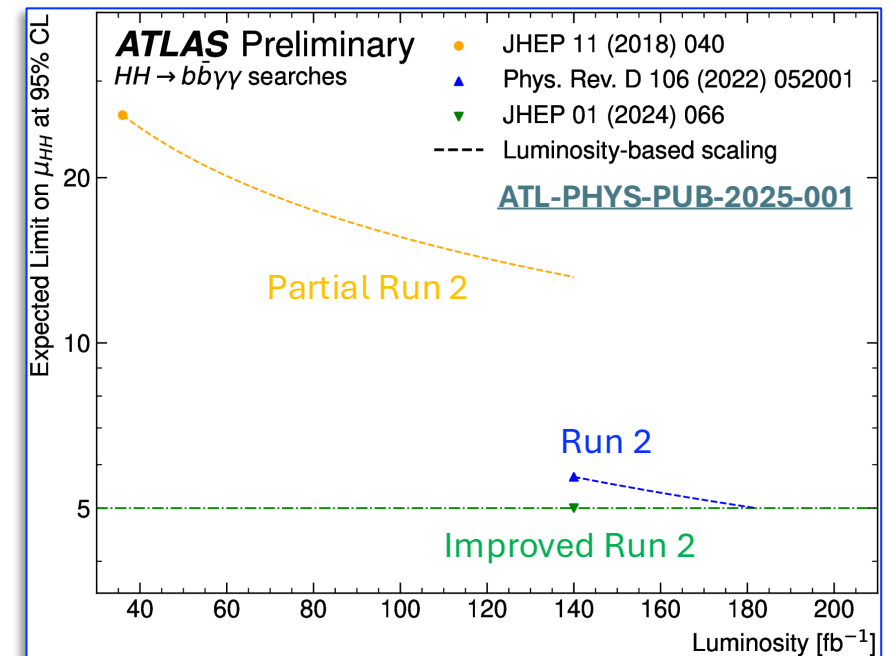
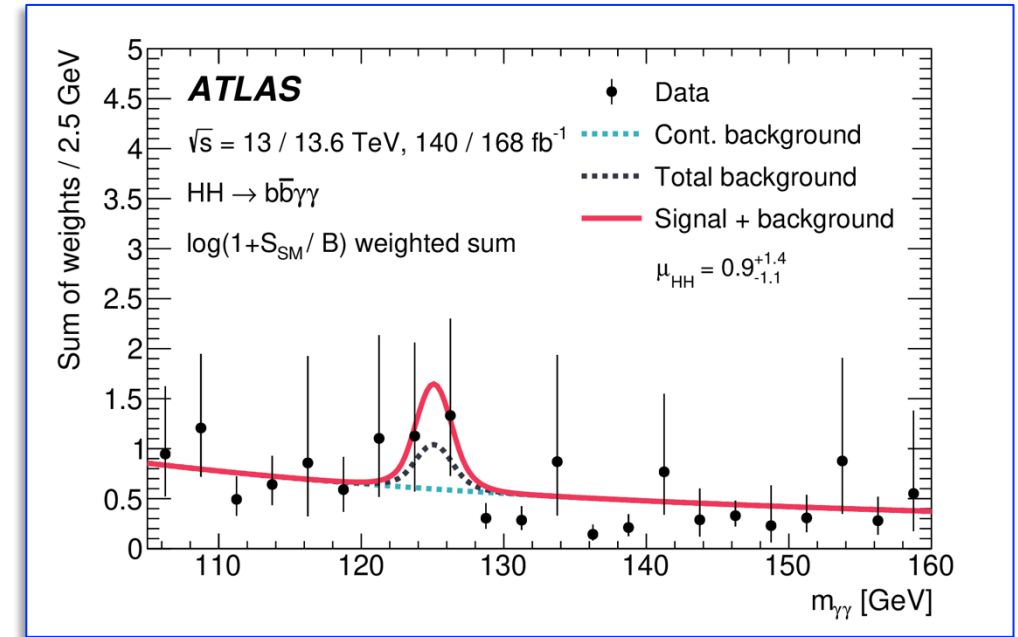


- Legacy Run 2 combination from ATLAS and CMS:
- $\mu_{HH} (\sigma_{HH}/\sigma_{SM}) = 0.8^{+0.9}_{-0.7}$ observed significance 1.1σ (expected SM 1.3σ)
- Limit on $\kappa_\lambda (\lambda/\lambda_{SM})$ @95% CL excluded outside the range $[-0.71, 6.1]$

HH in $b\bar{b}\gamma\gamma$ Run 3

- LHC experiments are investing a lot of **hard work** and **ingenuity** to improve the **HH** search
- Measurement combining **Run 2** + **Run 3** $\rightarrow$ Total **308 fb⁻¹**
- Improvements** on **HH sensitivity** relative to **Run 2 analysis**:
 - Additional data: **50%**
 - New flavor tag algorithm **GN2**: **20%**
 - Analysis preoptimization: **10%**
 - m_{bb} kinematic fit : **5%**
- Signal extracted by a fit to $m_{\gamma\gamma}$ in **7 BDT categories**
 - Observed $\mu_{HH} = 0.9^{+1.4}_{-1.1}$
 - 0.8 σ** significance (**1.0 expected**)
 - $\mu_{HH} < 3.7$ @95% CL
- Every update, the **analysis improvements** surpass the simple $1/\sqrt{L}$ extrapolation (analysis limited by data sample size)

Phys. Lett. B 876 (2026) 140280

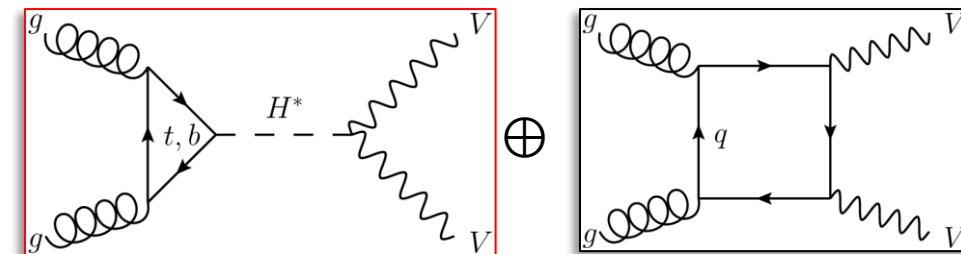


Higgs boson width from off-shell measurement

Γ_H from off-shell Higgs production

Kauer - Passarino
Caola - Melnikov

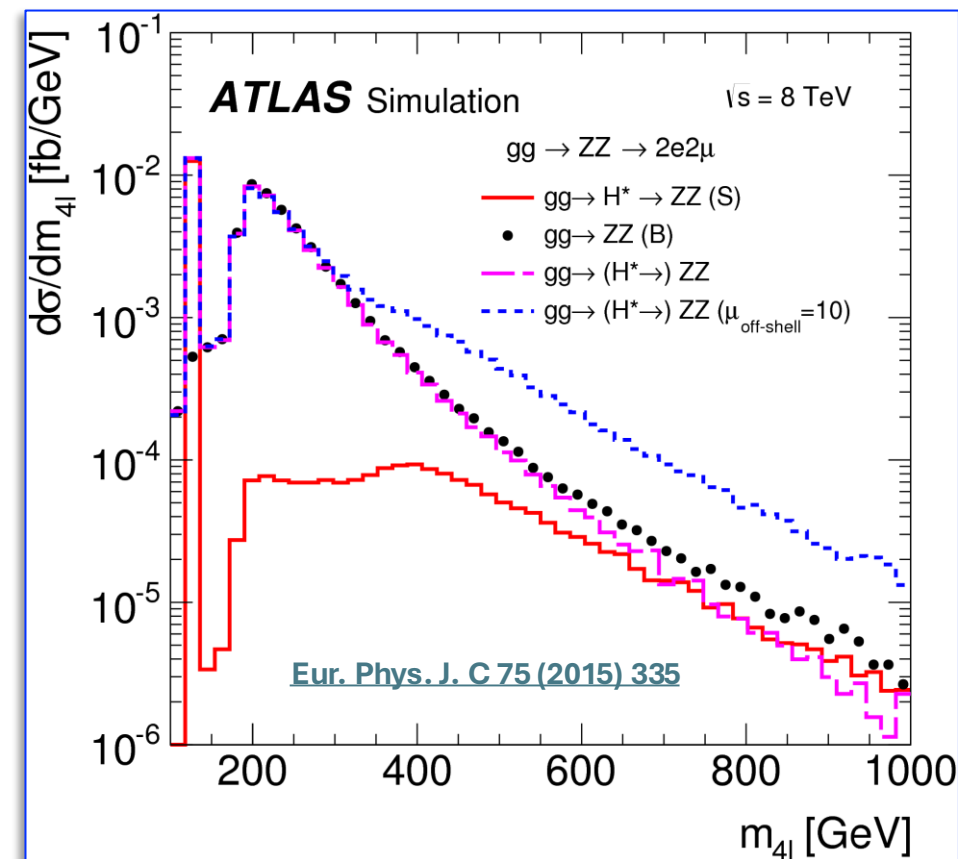
- Due to large couplings to top, W and Z bosons, the SM predicts a sizeable ggF **off-shell H** cross-section, $\sim 10\%$ the **on-shell** one in **VV** final state (enhancements above VV and tt thresholds)
- The **off-shell** contribution is independent of Γ_H



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})}{\sigma_{\text{off-shell, SM}}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})} = \kappa_{g, \text{off-shell}}^2(\hat{s}) \cdot \kappa_{V, \text{off-shell}}^2(\hat{s})$$

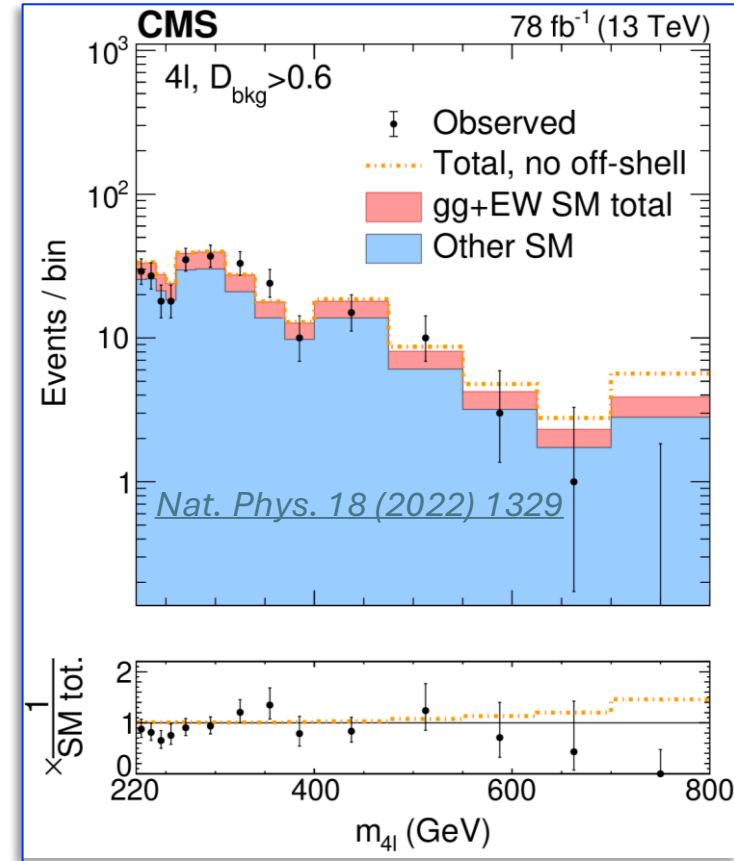
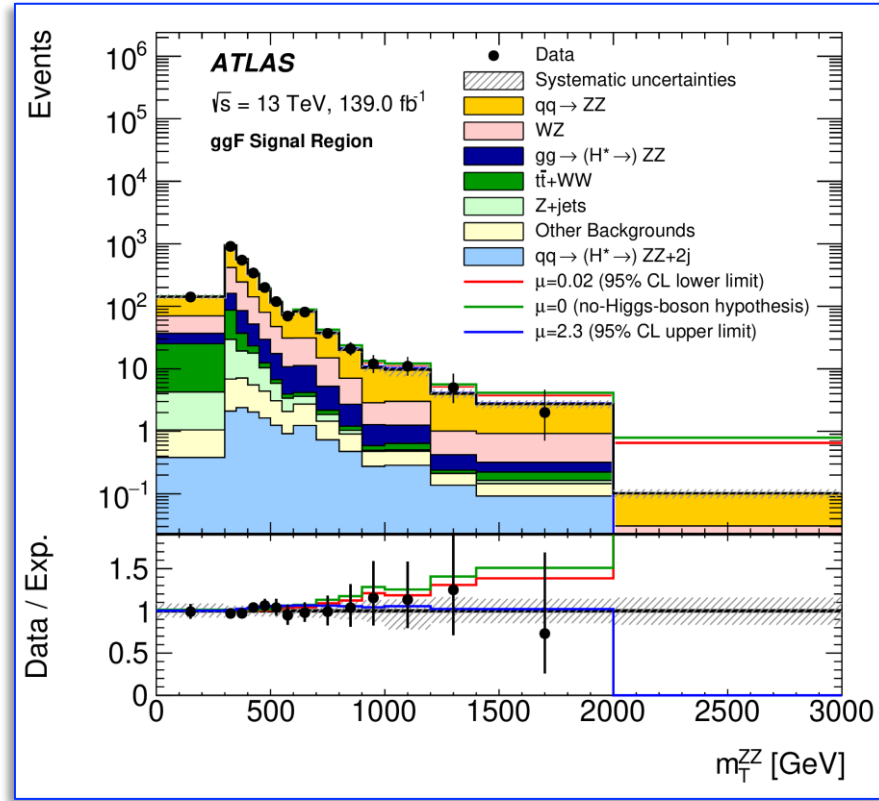
$$\mu_{\text{on-shell}} \equiv \frac{\sigma_{\text{on-shell}}^{gg \rightarrow H \rightarrow VV}}{\sigma_{\text{on-shell, SM}}^{gg \rightarrow H \rightarrow VV}} = \frac{\kappa_{g, \text{on-shell}}^2 \cdot \kappa_{V, \text{on-shell}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

- Assuming κ are the same **on-** and **off-shell** one can constrain Γ_H using the ratio of the two measurements
- In the SM there is a **destructive interference** between the H^* and the **box** contributions
- Channels used to measure **off-shell** productions are $ZZ^* \rightarrow 4l$, $ZZ^* \rightarrow 2l2\nu$ (the most sensitive) and $VW^* \rightarrow l\nu l\nu$ - most sensitive region is at **very high** m_{VV} - major background is $qq \rightarrow VV$



Γ_H from off-shell Higgs production

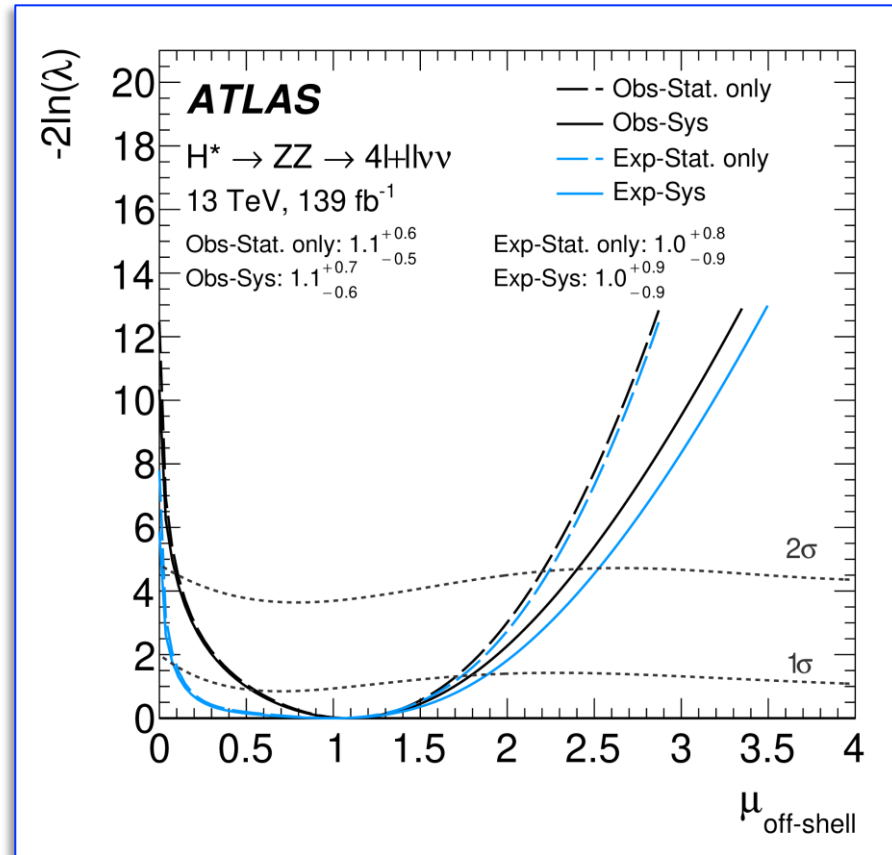
Phys. Lett. B 846 (2023) 138223



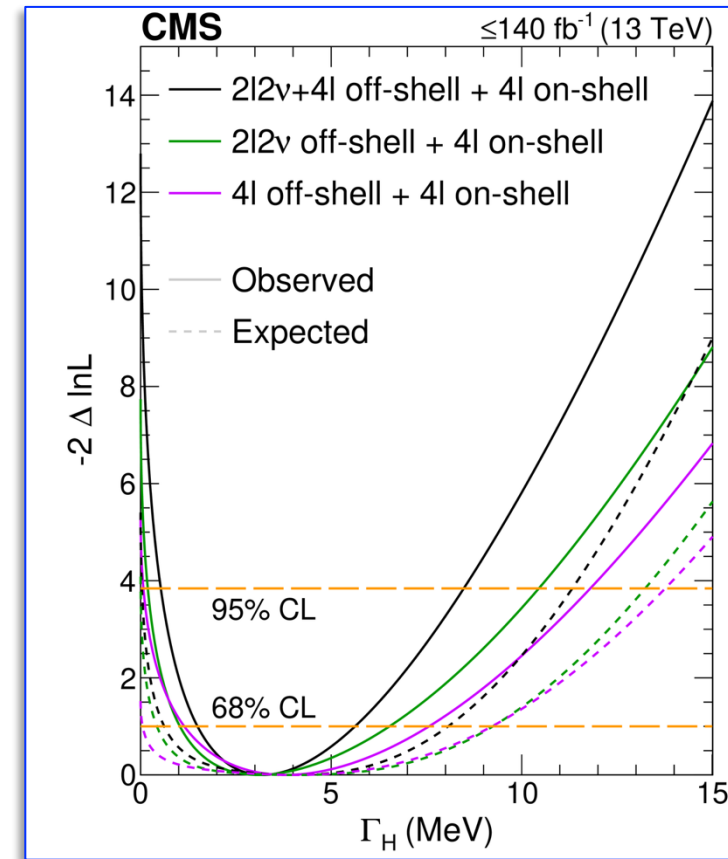
- $ZZ^* \rightarrow 4l$ full kinematic reconstruction of the final state, use of **MVA** (NN for ATLAS) to enhance sensitivity, absence of H^* contribution, limiting factor is the low available statistics
- $ZZ^* \rightarrow 2l2\nu$ larger BR ($Z \rightarrow ll \sim 6.6\%$, $Z \rightarrow \nu\nu \sim 20\%$) but more **challenging experimentally** ($\nu\nu = \text{MET}$)
- $\mu_{\text{off-shell}} = 0$ will **increase the yields** (because of **destructive** interference)

Γ_H from off-shell Higgs production

Phys. Lett. B 846 (2023) 138223



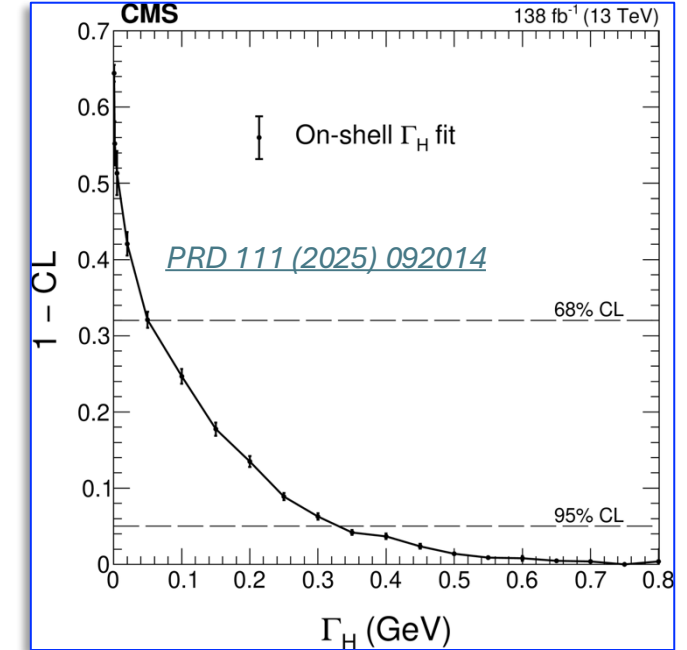
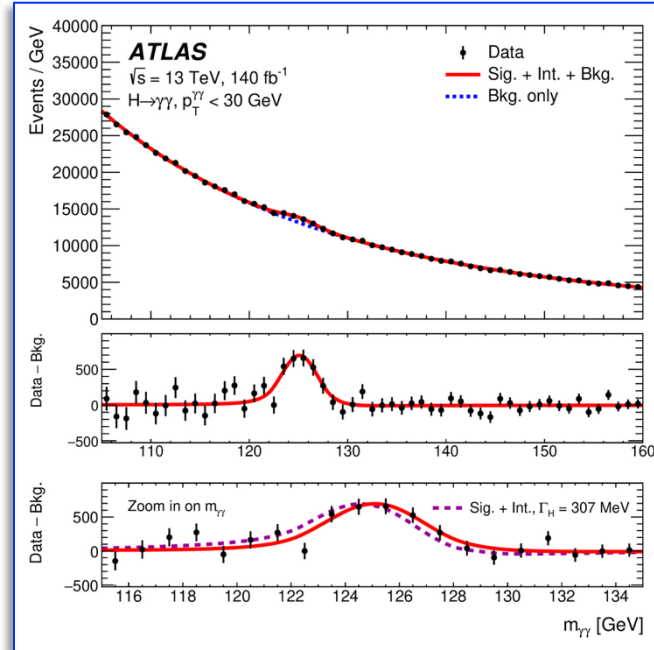
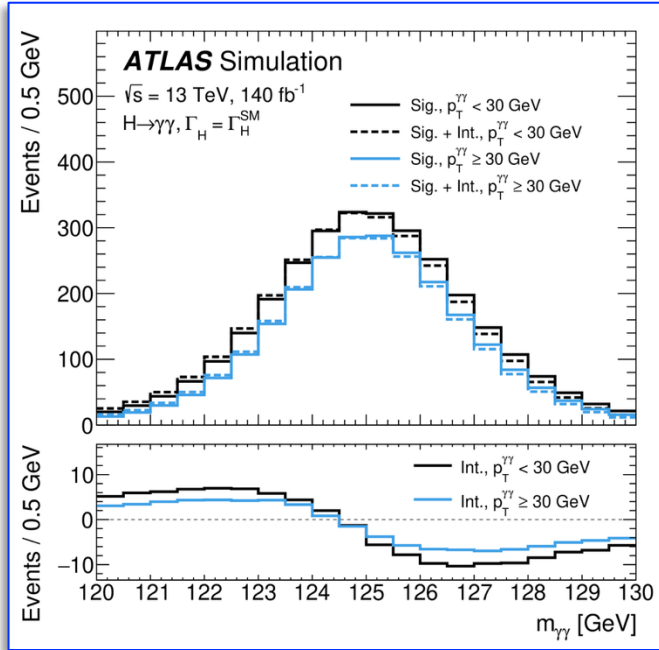
Nat. Phys. 18 (2022) 1329



- Channels used to measure **off-shell** production are $ZZ^* \rightarrow 4l$, $ZZ^* \rightarrow 2l2v$ (most sensitive) and $WW^* \rightarrow l\nu l\nu$
- Both **ATLAS** and **CMS** achieved **evidence** ($>3\sigma$) for **H off-shell** production
- Extracted Γ_H by combining **off-shell** + **on-shell** measurements:

$$\text{CMS } \Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV} \quad - \quad \text{ATLAS } \Gamma_H = 3.6^{+2.1}_{-1.6} \text{ MeV} \quad (\text{arXiv:2608.07332}) \quad - \quad \text{SM } \Gamma_H = 4.1 \text{ MeV}$$

Other methods to infer Γ_H



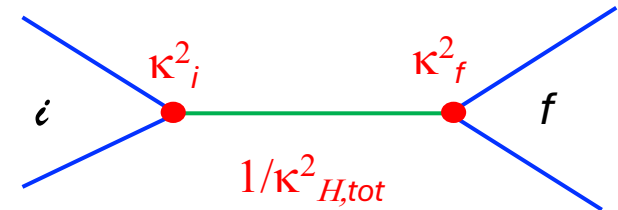
- There are other methods used at the LHC to constrain Γ_H :
 - Interference between $gg \rightarrow \gamma\gamma$ and $gg \rightarrow H \rightarrow \gamma\gamma$ on-shell: affects the mass shape, but the effect is small relative to experimental precision:
 - ATLAS ([arXiv:2609.19948](#)): $\Gamma_H < 307 \text{ MeV}$ (258 MeV) @95% CL dominated by modeling and photon energy scale uncert.
 - CMS ([arXiv:2609.01385](#)): $\Gamma_H < 92 \text{ MeV}$ (138 MeV) @95% CL
 - Direct study of $H \rightarrow 4l$ on-shell mass spectrum (CMS) $\Gamma_H < 330 \text{ MeV}$ @95% CL
- They are complementary to the off-shell method (less model dependent)

Measurements interpretation: the κ -framework

“Coupling” inference in the κ formalism

- Measuring the *couplings* of the Higgs boson is a strong test of the **BEH mechanism**: interaction strength $\longleftrightarrow$ particle mass
- A simple, leading-order inspired approach to extract coupling information is the so-called κ -framework
- It assumes the **narrow-width approximation** (allowing production and decay to factorize) and **tensor structure** of couplings as in **SM** (CP-even scalar)
- We **cannot directly measure** the **total width Γ_H** , so we have a degeneracy when linking our measurements $\sigma_i \times BR_f$ to the *i* and *f* couplings
- **SM** passes the test if κ is compatible with 1

$$\sigma_i \times BR(H \rightarrow f) = \frac{\kappa_i^2 \kappa_f^2}{\kappa_{H,tot}^2} \times \sigma_{i,SM} \times \frac{\Gamma_f}{\Gamma_{SM}}$$



“Coupling” inference in the κ formalism

- It can provide a **meaningful test** of **specific sectors** of the **SM** allowing the **combination** of different measurements: easy interpretation in terms of **Higgs-SM-Particle couplings**
- Easy way to **benchmark performance** between **different experiments** and between **different colliders** (see C. Grojeans lecture)
- **Limitations** of κ formalism:
 - Having a κ significantly different from unity does not provide information on the **BSM theory** that caused that since this model **is not a computable extension of the SM**
 - In addition, it is mainly sensitive to **inclusive effects**, and it does not catch the **possible kinematic dependence of BSM physics** (e.g., BSM effects that modify the high transverse-momentum regime of Higgs boson production)

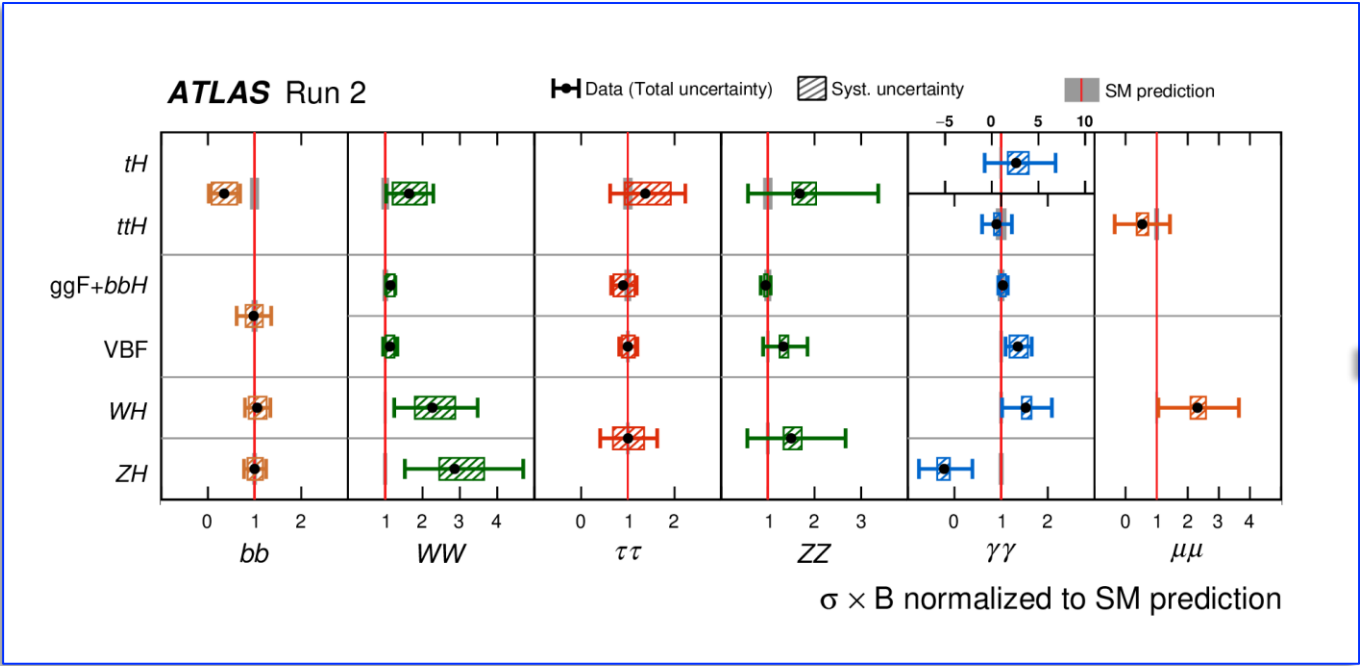
κ formalism

- Particularly interesting are the interactions that are **loop-level** in the SM (**absent at tree level**)
 - $ggF, H \rightarrow \gamma\gamma, Z\gamma$
 - Comparing **resolved** vs **effective** parameterizations can reveal BSM effects
- Processes that involve **interference** provide information on the **relative sign (phase)** of couplings (e.g. $H \rightarrow \gamma\gamma \rightarrow \text{top-W}$)
- Total width can be modified by adding **invisible** and/or **undetectable BRs** (e.g., $H \rightarrow qq$ at LHC)
- Need **additional assumptions** to constrain the Γ_H in the fit:
 - No BSM contributions to Higgs boson decay
 - $\kappa_V < 1$ motivated by 2HDMs and some other BSM models
 - Use off-shell measurement (constrain Γ_H)
 - + Use invisible decay constraints: Constrain **BR_{inv}** and **BR_{undet}**
- Best sensitivity by **combining** all measurements

Production	Loops	Main interference	Effective modifier	Resolved modifier	From <u>LHCHWG YR4</u>
$\sigma(gg \rightarrow H)$	✓	t - b	κ_g^2	$1.040 \kappa_t^2 + 0.002 \kappa_b^2 - 0.038 \kappa_t \kappa_b - 0.005 \kappa_t \kappa_c$	
$\sigma(qq' \rightarrow qq' H)$	-	-	-	$0.733 \kappa_W^2 + 0.267 \kappa_Z^2$	
$\sigma(qqZH)$	-	-	-	κ_Z^2	
$\sigma(ggZH)$	✓	t - Z	$\kappa_{(ggZH)}$	$2.456 \kappa_Z^2 + 0.456 \kappa_t^2 - 1.903 \kappa_Z \kappa_t$ $- 0.011 \kappa_Z \kappa_b + 0.003 \kappa_t \kappa_b$	
$\sigma(WH)$	-	-	-	κ_W^2	
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2	
$\sigma(tHW)$	-	t - W	-	$2.909 \kappa_t^2 + 2.310 \kappa_W^2 - 4.220 \kappa_t \kappa_W$	
$\sigma(tHq)$	-	t - W	-	$2.633 \kappa_t^2 + 3.578 \kappa_W^2 - 5.211 \kappa_t \kappa_W$	
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2	
Partial decay width					
Γ^{bb}	-	-	-	κ_b^2	
Γ^{WW}	-	-	-	κ_W^2	
Γ^{gg}	✓	t - b	κ_g^2	$1.111 \kappa_t^2 + 0.012 \kappa_b^2 - 0.1 \kappa_t \kappa_b$	
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2	
Γ^{ZZ}	-	-	-	κ_Z^2	
Γ^{cc}	-	-	-	$\kappa_c^2 (= \kappa_t^2)$	
$\Gamma^{\gamma\gamma}$	✓	t - W	κ_γ^2	$1.589 \kappa_W^2 + 0.072 \kappa_t^2 - 0.674 \kappa_W \kappa_t$ $+ 0.009 \kappa_W \kappa_\tau + 0.008 \kappa_W \kappa_b$ $- 0.002 \kappa_t \kappa_b - 0.002 \kappa_t \kappa_\tau$	
$\Gamma^{Z\gamma}$	✓	t - W	$\kappa_{(Z\gamma)}^2$	$1.118 \kappa_W^2 - 0.125 \kappa_W \kappa_t + 0.004 \kappa_t^2 + 0.003 \kappa_W \kappa_b$	
Γ^{ss}	-	-	-	$\kappa_s^2 (= \kappa_b^2)$	
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2	
Total width ($BR_{\text{inv.}} = BR_{\text{undet.}} = 0$)					
Γ_H	✓	-	κ_H^2	$0.581 \kappa_b^2 + 0.215 \kappa_W^2 + 0.082 \kappa_g^2$ $+ 0.063 \kappa_\tau^2 + 0.026 \kappa_Z^2 + 0.029 \kappa_c^2$ $+ 0.0023 \kappa_\gamma^2 + 0.0015 \kappa_{(Z\gamma)}^2$ $+ 0.0004 \kappa_s^2 + 0.00022 \kappa_\mu^2$	

“Coupling” inference: κ formalism

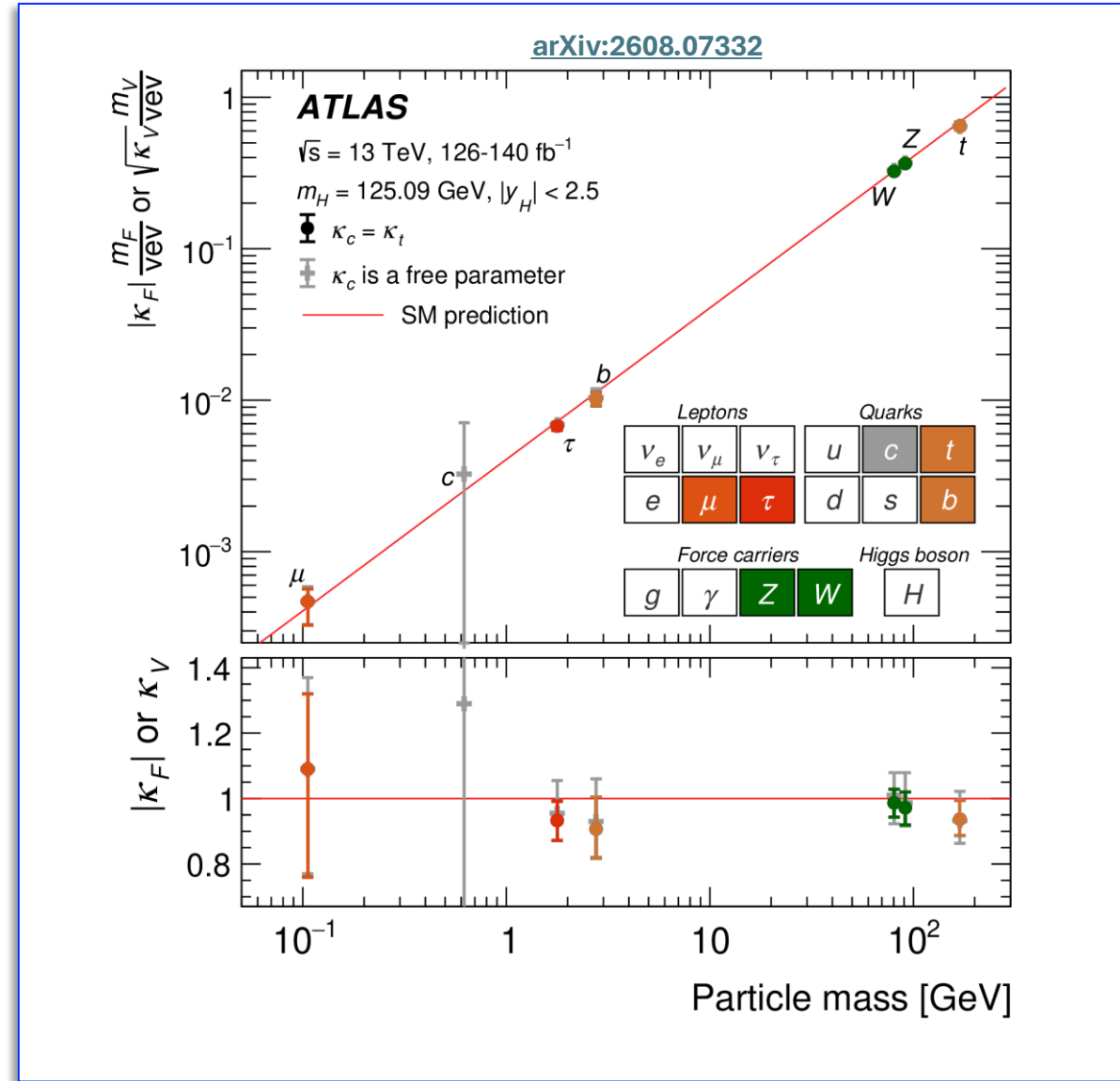
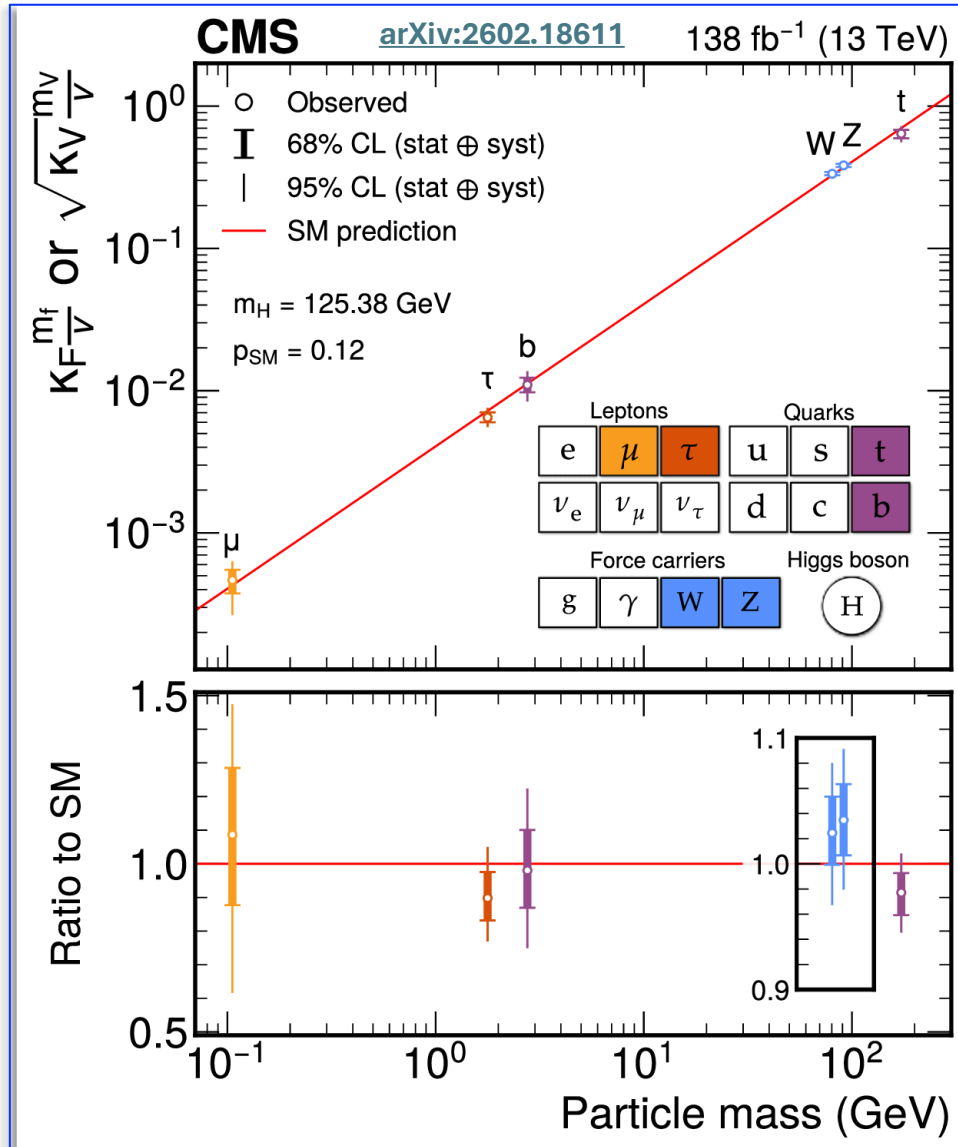
Nature 607 52 (2022)



	(a) $B_{inv.} = B_u = 0$	(b) $B_{inv.}$ free, $B_u \geq 0, \kappa_{W,Z} \leq 1$
κ_Z	$0.99^{+0.06}_{-0.06}$	$0.98^{+0.02}_{-0.05}$
κ_W	$1.05^{+0.06}_{-0.06}$	$1.00_{-0.02}$
κ_t	$0.94^{+0.11}_{-0.11}$	$0.94^{+0.11}_{-0.11}$
κ_b	$0.89^{+0.11}_{-0.11}$	$0.82^{+0.09}_{-0.08}$
κ_τ	$0.93^{+0.07}_{-0.07}$	$0.91^{+0.07}_{-0.06}$
κ_μ	$1.06^{+0.25}_{-0.30}$	$1.04^{+0.23}_{-0.30}$
κ_g	$0.95^{+0.07}_{-0.07}$	$0.94^{+0.07}_{-0.06}$
κ_γ	$1.01^{+0.06}_{-0.06}$	$0.98^{+0.05}_{-0.05}$
$\kappa_{Z\gamma}$	$1.38^{+0.31}_{-0.37}$	$1.35^{+0.29}_{-0.36}$
$B_{inv.}$	-	< 0.13
$B_u.$	-	< 0.12

- Fit $\sigma \times B$ in different final states – Can compute compatibility with SM (all κ 's =1) p-value 61%

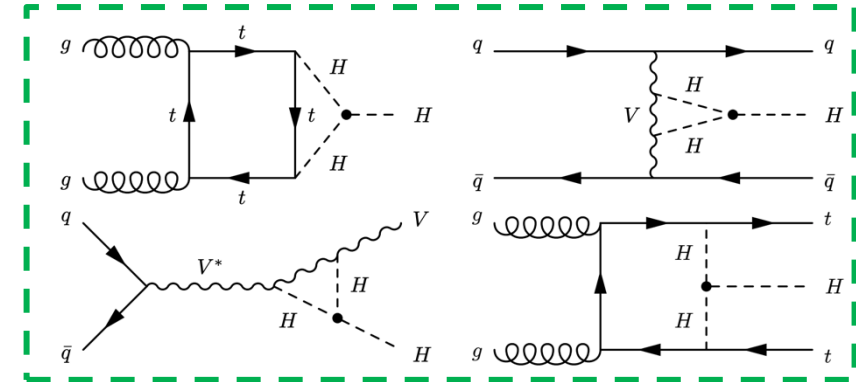
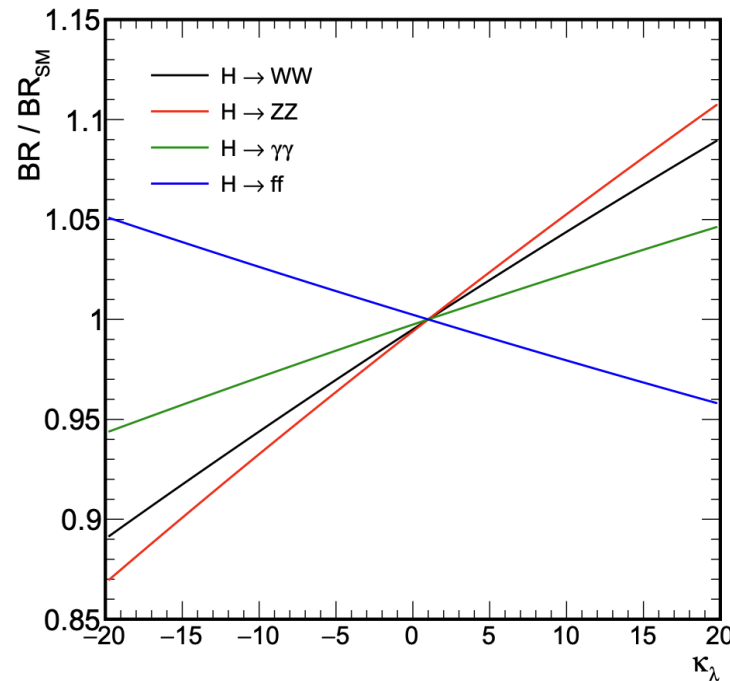
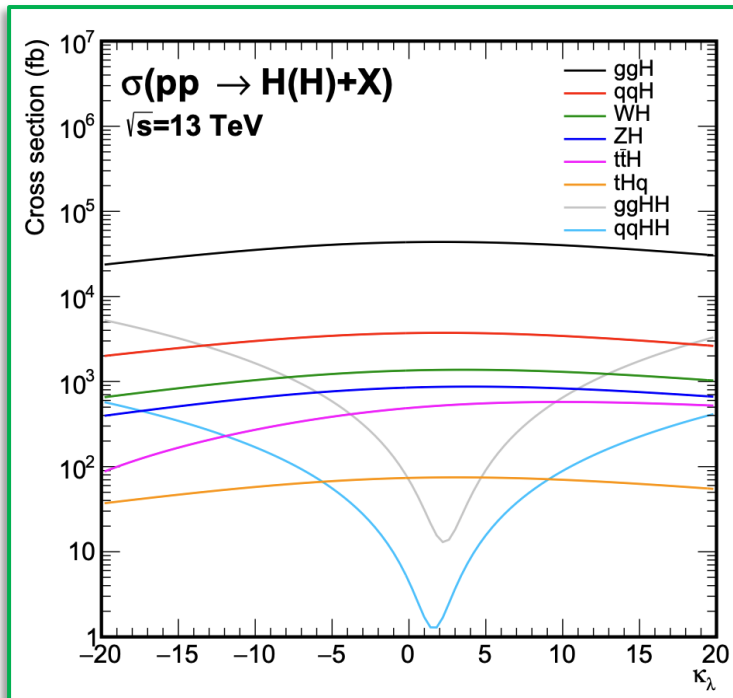
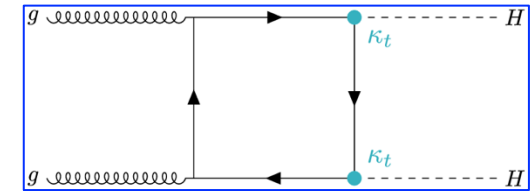
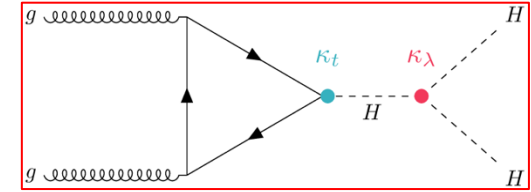
“Coupling” inference: BEH mechanism at work



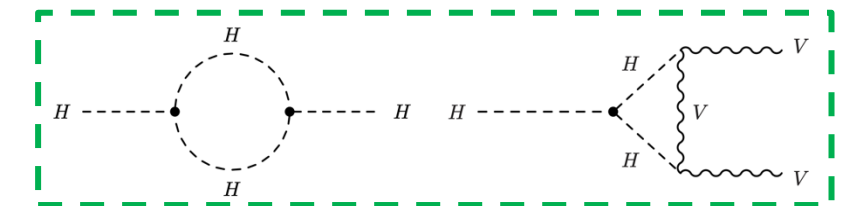
- Scale κ by fermions or vector boson masses m_f/v or $(m_V/v)^2$ to explicitly show expected mass dependence

“Coupling” inference: combination single-H and HH

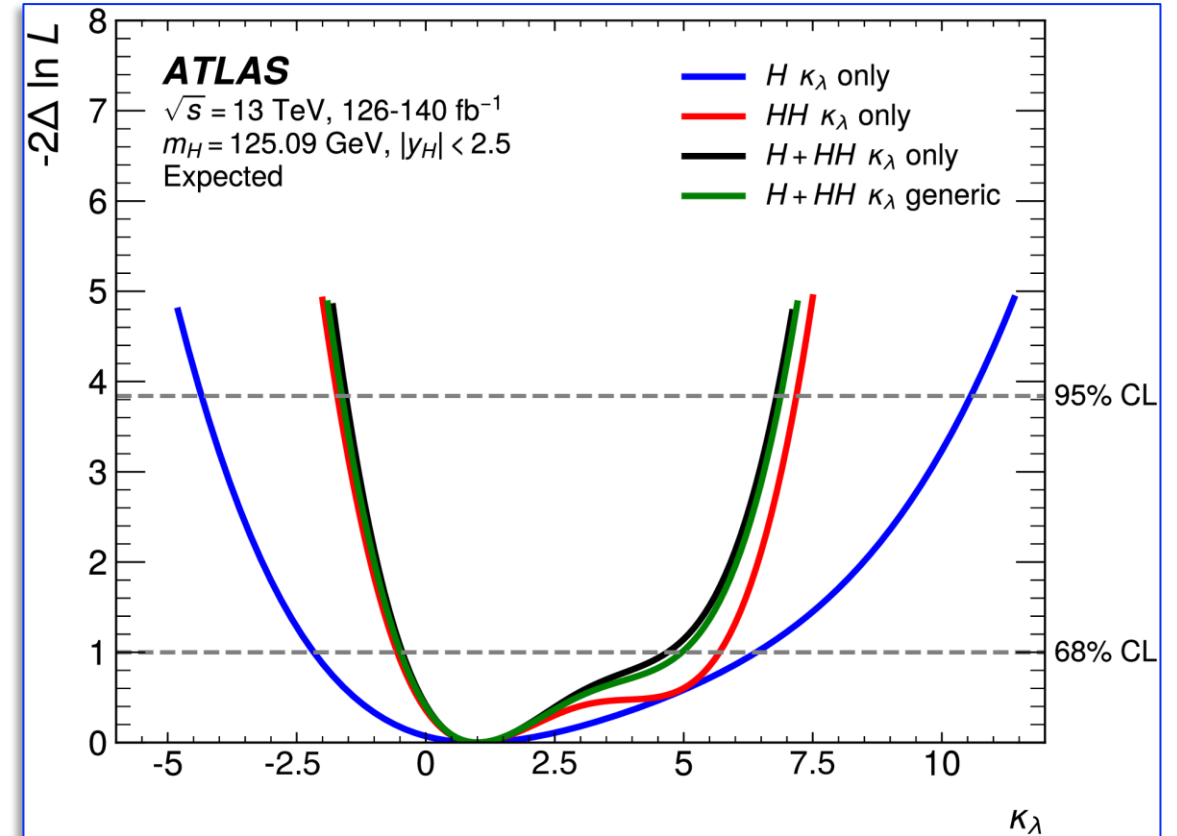
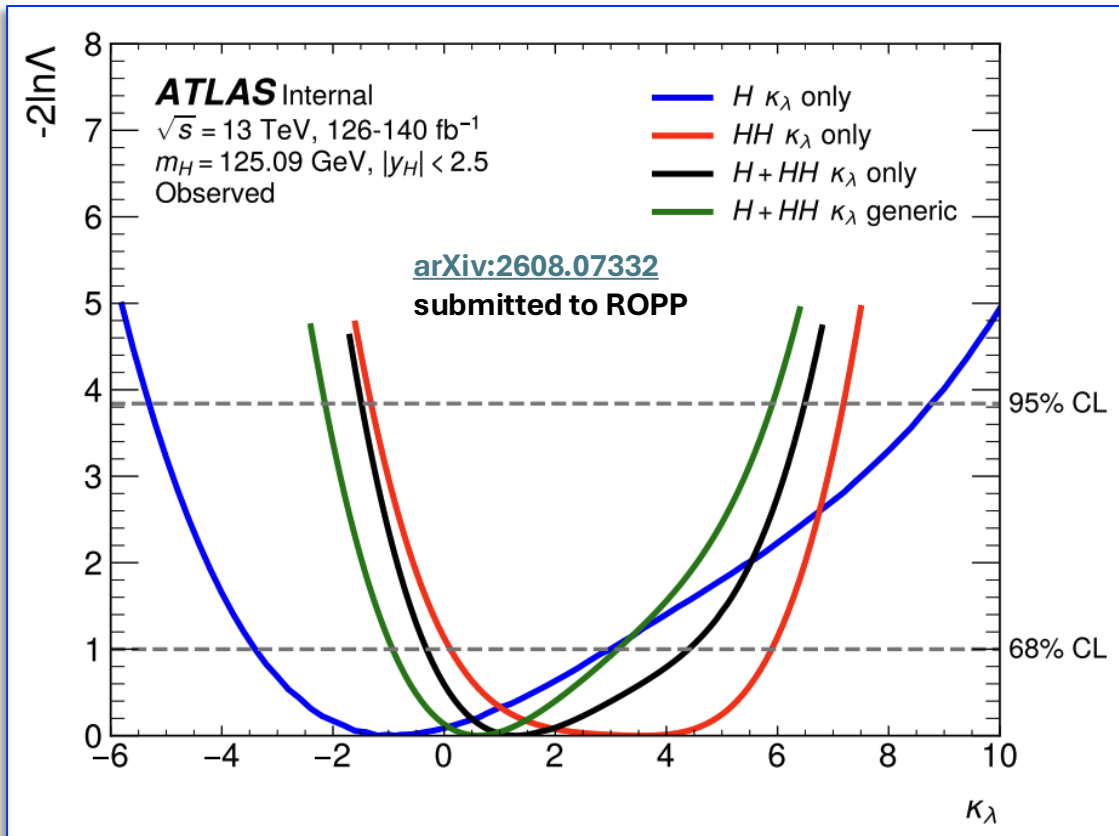
- The $ggHH$ process is sensitive to combinations of κ_λ and κ_t
- But single-H production (and decay) is also sensitive to the Higgs boson **self-coupling** via **EW corrections** (in SM $\sim 1\text{-}2\%$)
- It is possible to perform a “consistent” κ parameterization of all H and HH measurements including
 - Increasing sensitivity to κ_λ
 - Relaxing assumptions on **other couplings**



LHCHWG-2022-002



“Coupling” inference: combination single-H and HH



- ATLAS legacy Run 2 couplings combination uses all H (STXS) and HH measurements
- Fit with only κ_λ floating (others fixed) but also with κ_τ κ_t κ_b and κ_V floating (generic)
- First scenario $\kappa_\lambda = 1.3^{+3.10}_{-1.62}$
- Similar constraints on κ_λ also in the “generic” scenario

Measurements interpretations: Effective Field Theory

SMEFT:

Standard Model
Effective Field Theory



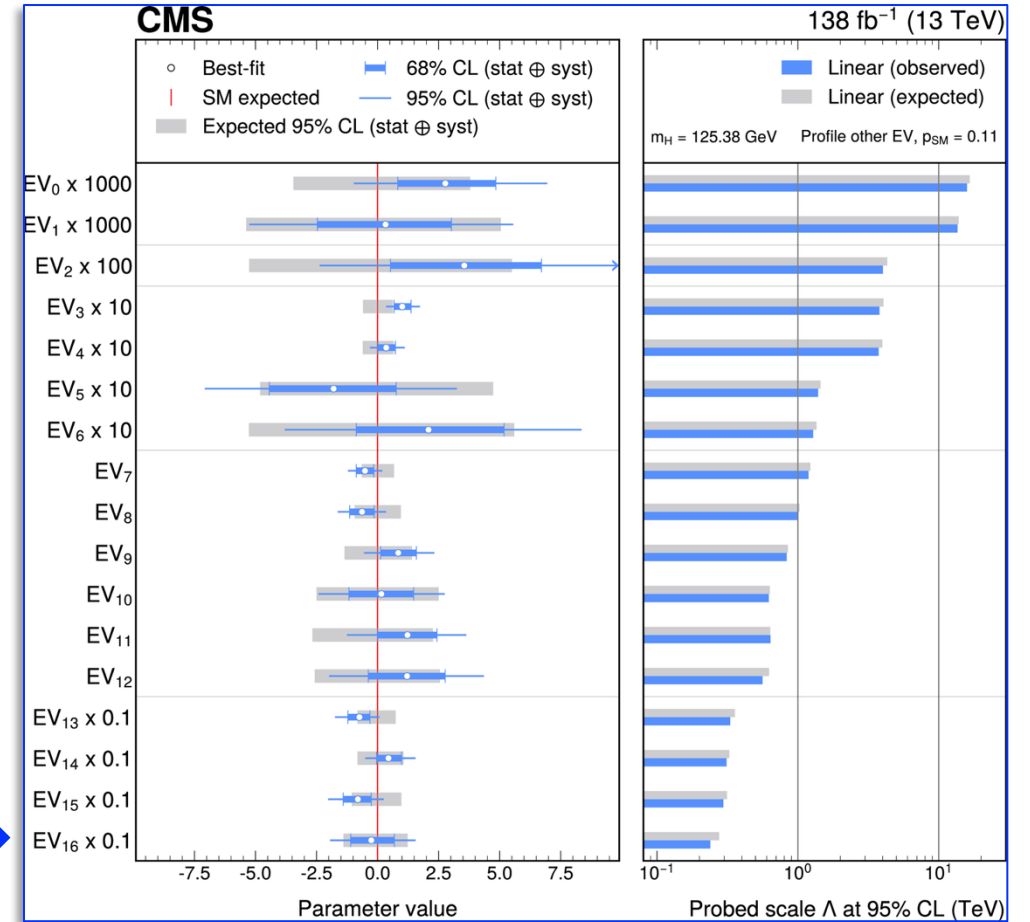
The EFT approach

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

- Under the assumption $\Lambda_{BSM} \gg E_{LHC}$, we can extend the SM Lagrangian with *effective* terms based on SM particle fields, respecting basic symmetries (Poincaré invariance, Gauge symmetries), this approach is like the *Fermi theory* describing *weak interactions* at $E \ll M_W$
- Series expansion in terms of $1/\Lambda$, dimension d means term of order $1/\Lambda^{(d-4)}$
- The $d=5$ (e.g., Weinberg operator) violates L-number (can provide ν masses)
- In general, consider first terms of $d=6$
- **Pros:**
 - Provides a more general and formally correct approach
 - Can catch BSM impact on kinematics (e.g. distortions of the spectra at high energies)
 - Suitable to combine measurements of different physics processes (EW precision, top, Higgs, ...)
- **Cons:**
 - If kept general there are 2499 independent $d=6$ operators (B and L conserving, 3 fermion families), many of them have degenerate impact on measurable observables
- Nice description of *EFT for Higgs* in: [LHCHSWG Yellow Report 4](#)

Interpretation	n_{POI}	$H \rightarrow \gamma\gamma$, STXS	$H \rightarrow ZZ \rightarrow 4\ell$, STXS	$H \rightarrow WW \rightarrow \ell\nu\ell\nu$, STXS	$H \rightarrow \tau\tau$, STXS	$H \rightarrow \tau\tau$, incl.	$H \rightarrow bb$ boosted, STXS	$H \rightarrow bb$ boosted, incl.	VBF ($H \rightarrow bb$), incl.	VH ($H \rightarrow bb$), STXS	$t(t)H$ ($H \rightarrow bb$), STXS	$t(t)H$ ($H \rightarrow bb$), incl.	$t(t)H$ ($H \rightarrow \text{leptons}$), STXS	$H \rightarrow \mu\mu$, incl.	$H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$, incl.	$H \rightarrow \text{inv}$, incl.	Off-shell $H \rightarrow ZZ \rightarrow 4\ell$	Suppl. Mat.
Signal strength (inclusive)	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Signal strength (production)	6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Signal strength (decay)	7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Signal strength (production-times-decay)	31	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Cross section (STXS stage 0)	7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Cross section (STXS stage 1.2)	32	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Cross section with branching fraction ratios (STXS stage 0)	13	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Cross section with branching fraction ratios (STXS stage 1.2)	36	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Signal strength (STXS stage 0)	7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Signal strength (STXS stage 1.2)	32	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Signal strength with branching fraction ratios (STXS stage 0)	13	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Signal strength with branching fraction ratios (STXS stage 1.2)	36	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Signal strength with STXS times branching fraction	97	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Resolved coupling modifiers	6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Effective coupling modifiers ($\mathcal{B}_{\text{BSM}} = 0$)	9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Effective coupling modifiers ($\mathcal{B}_{\text{inv}}, \mathcal{B}_{\text{undet.}}$ floating)	11	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Off-shell coupling model ($\mathcal{B}_{\text{inv}}, \mathcal{B}_{\text{undet.}}$ floating)	11	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Ratios of coupling modifiers	8	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Ratios of coupling modifiers, symmetry of fermion couplings	3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Higgs self-coupling, κ_λ (κ_V and κ_F fixed)	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Higgs self-coupling, κ_λ (κ_V and κ_F floating)	3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Higgs self-coupling, κ_λ -vs- κ_V (2D)	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Higgs self-coupling, κ_λ -vs- κ_F (2D)	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
UV-complete extensions to SM (2HDM and hMSSM)	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
SMEFT, one-POI-at-a-time, linear	1 (x43)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
SMEFT, one-POI-at-a-time, lin+quad	1 (x43)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
SMEFT, multiple POIs (PCA), linear	17	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		

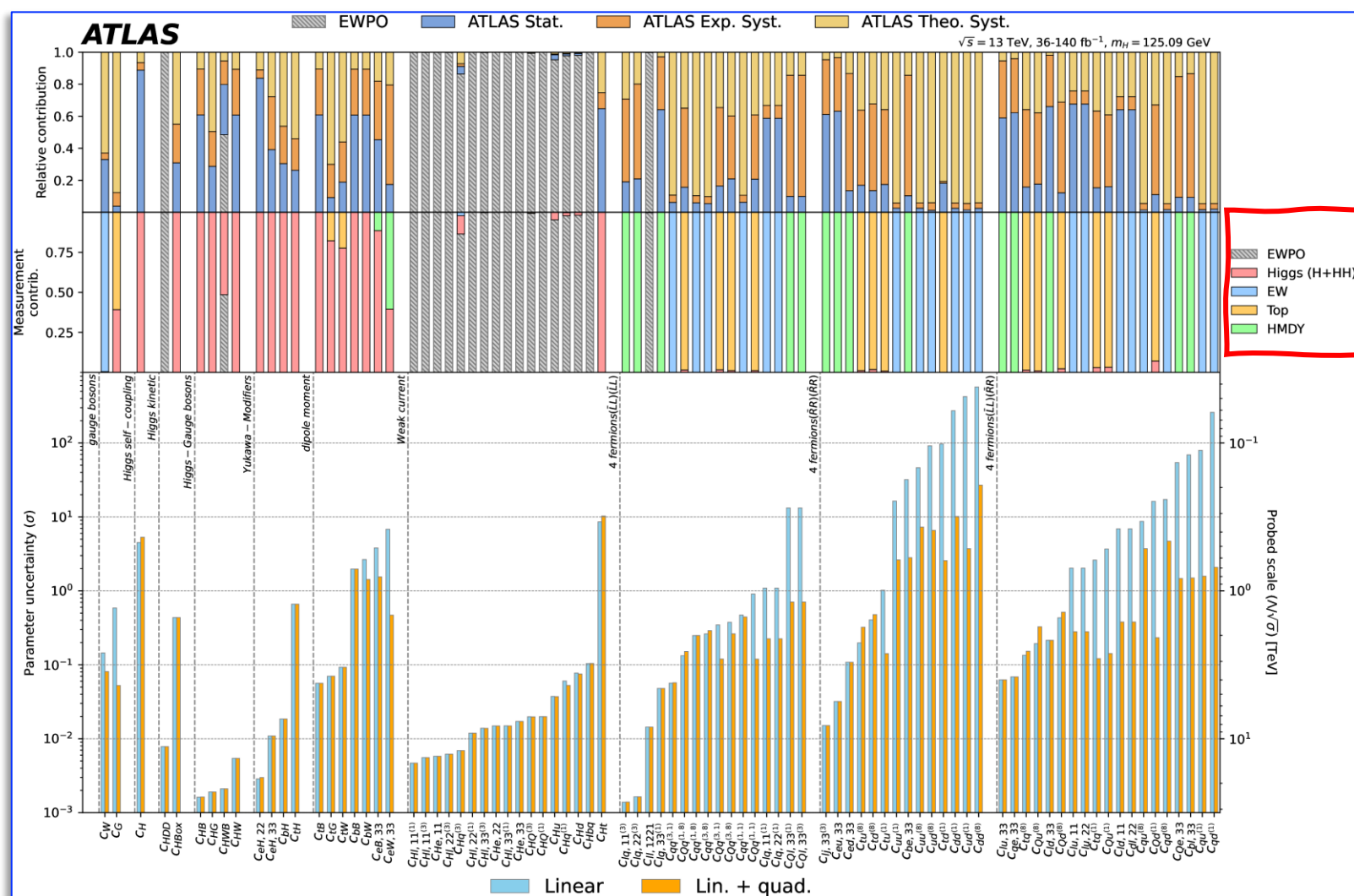
The EFT approach



- The extraction of the EFT (Wilson) coefficients is done via a fit to experimental observables (STXS, σ inclusive, fiducial, etc.)
- For $d=6$ the measured σ can be written as: $\sigma_{\text{tot}} = \sigma_{\text{SM}} + \sigma_{\text{interf.}}(c_i/\Lambda^2) + \sigma_{\text{BSM}}(c_i^2/\Lambda^4)$ (the last term is same order in $1/\Lambda$ as $d=8$ interference)
- To resolve degeneracy, constrain linear combinations of EFT operators to which experimental observables provide sensitivity: EigenValues

The EFT global fit

JHEP 07 (2026) 238



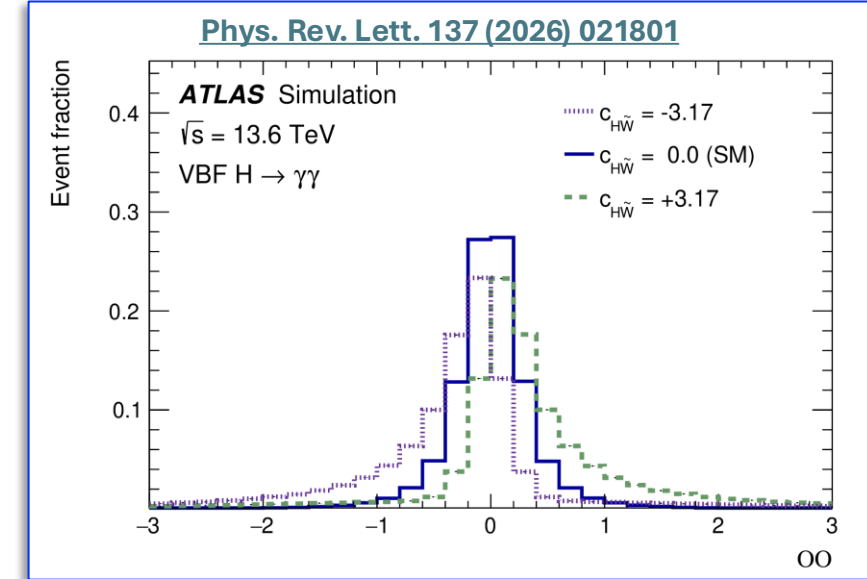
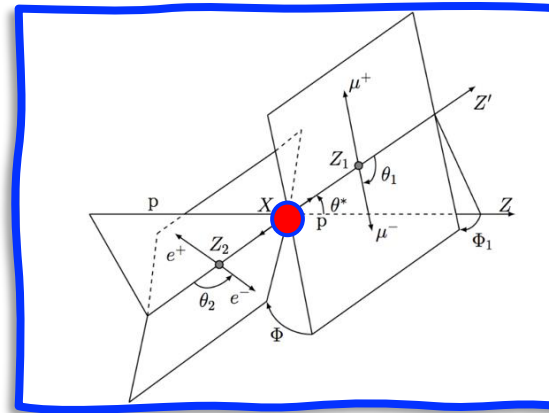
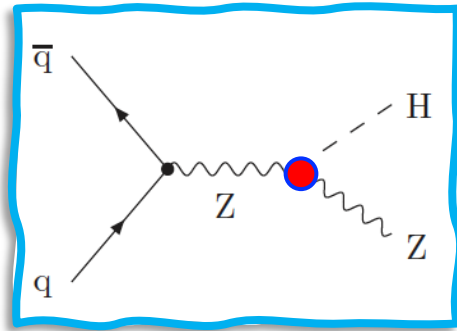
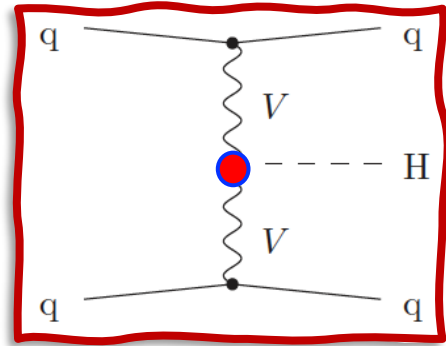
- The final goal is to include **all available measurements**: ATLAS study from H, HH, top, VV, High mass DY, EW precision observables to get sensitivity to more operators: up to **86 operators** (Warsaw basis) constrained **one at a time**
- Also **simultaneous** fit of **47 operators** in a new parameter basis obtained with **linear combinations** of O to which experimental results are sensitive (Principal Component Analysis applied to covariant matrix of all coefficients), in backup
- **Mind the overlap**: some processes can enter as **background** in some measurements and **signal** in others (e.g., VV in Higgs to WW* and ZZ*), important to implement **data-driven background scaling**

Search for CP Violation in the Higgs boson interactions

Higgs CP interactions

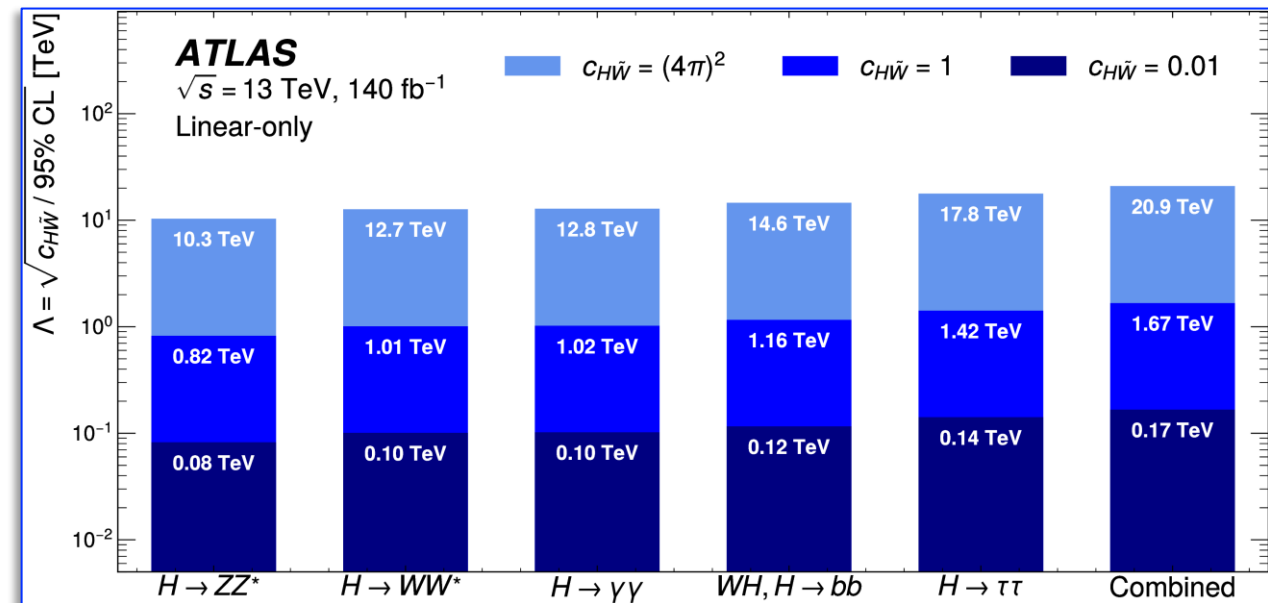
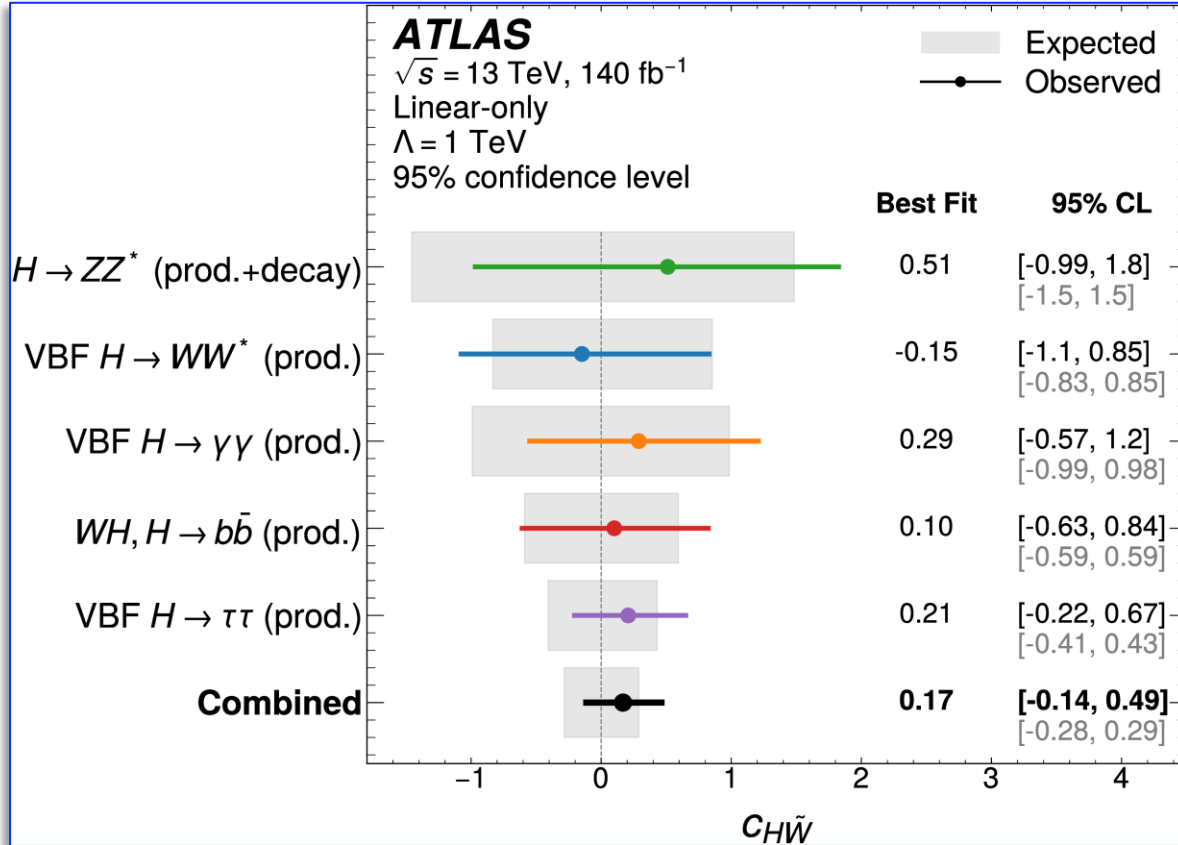
- The SM Higgs boson is CP-even, and its leading interactions are also CP-even (CKM-induced CP-violating effects in Higgs interactions are tiny)
- Higgs boson field has been established to have spin 0, however CP-odd contributions to its interactions are still possible and subject to studies
- HV interactions:
 - Use VBF and VH associated production using accompanying jets
 - Use kinematics in the decay $H \rightarrow VV^*$ (and $H \rightarrow \gamma\gamma$)
 - Usually CP-odd interactions parameterized using EFT approach only appearing at $d=6$ so expected to be suppressed by $(E/\Lambda)^2$ (at least)
- HF interactions:
 - Can be described phenomenologically described with $d=4$ operators
 - $H \rightarrow \tau\tau$ using measurement of the tau's polarizations
 - $t\bar{t}H$ kinematic to study H-top

CP interactions: H-V



- Kinematics of jets coming from accompanying quarks of **VBF** and **VH** systems are sensitive to **CP-odd interactions**: three possible **CP-odd** operators $C_{H\tilde{W}}$, $C_{H\tilde{W}B}$ and $C_{H\tilde{B}}$
- For decays **$H \rightarrow WW^*$** and **$H \rightarrow ZZ^*$** final-state kinematics sensitive to **CP-odd** interactions
- Define **CP-odd** observables that have the property **$CP(\theta) = -\theta$** , CP invariance implies **$\langle \theta \rangle = 0$** over the full phase space
- Frequently used are the **Optimal Observables** defined as **$OO = 2RE(\mathcal{M}_{SM}\mathcal{M}_{CP-odd}^*)/|\mathcal{M}_{SM}|^2$**
- They can be defined using **production** and/or **decay particles**

CP interactions: H-V



[Phys. Rev. Lett. 137 \(2026\) 021801](#)

- Recent result from **ATLAS** combining several measurements (this case only considers the **SM + interference** terms “linear only”)
- Interesting to convert **C** into a BSM scale Λ (assumption on possible coupling): for large values of the coupling, testing scale Λ up to **21 TeV**, but for weak coupling (0.01) range is **~outside EFT validity** ($\Lambda \sim E$)

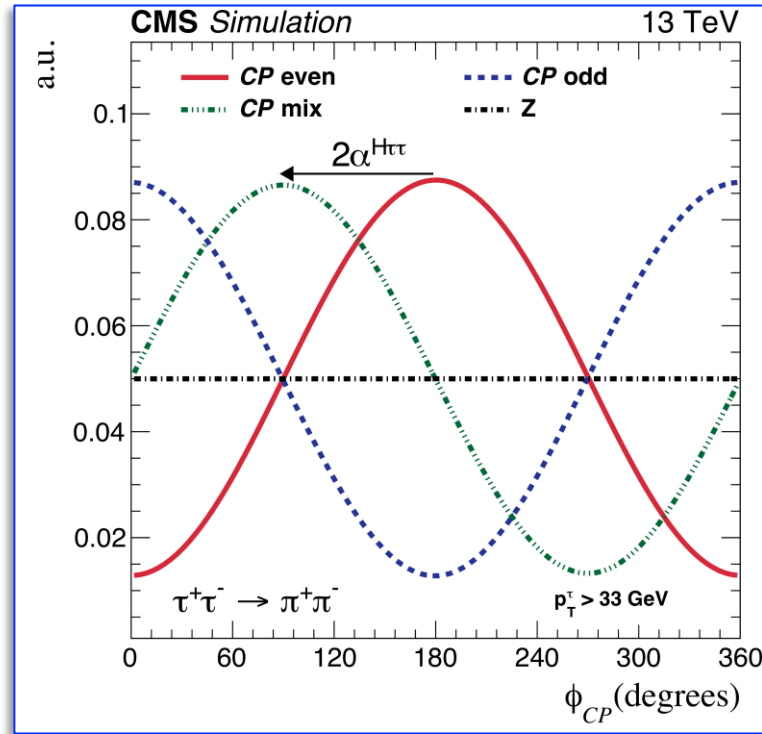
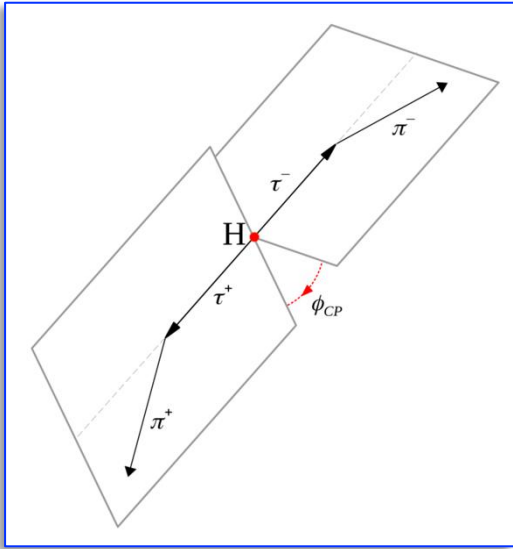
CP interactions H-Fermion

$$\mathcal{L} \propto \lambda_f (\kappa_f H \bar{\psi}_f \psi_f + i \tilde{\kappa}_f H \bar{\psi}_f \gamma_5 \psi_f)$$

Mixing angle $\tan(\alpha_f) = \tilde{\kappa}_f / \kappa_f$

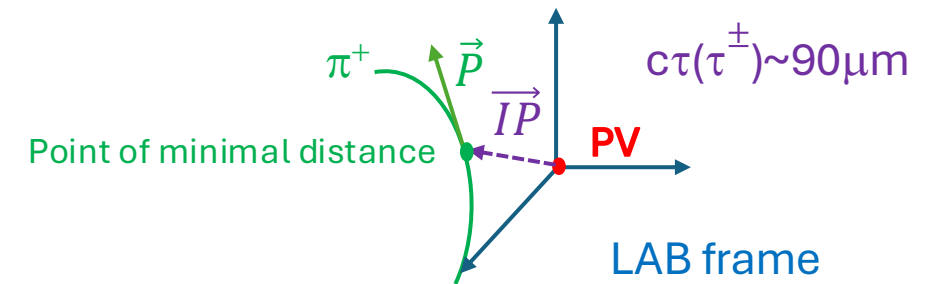
- Particularly interesting to study CP in H-Fermion $\rightarrow$ Unlike H-V interactions (CP-odd operators only possible at $d=6$ suppressed by $1/\Lambda^2$), for Fermions $d=4$ CP-odd terms are possible, SM corresponds to $\alpha_f=0$ and $\kappa_f=1$ – Pure CP-odd $\alpha_f=90^\circ$
- Possible in $H \rightarrow \tau\tau$ decays and $t\bar{t}H/tH$ production

CP interactions H- τ lepton



JHEP 06 (2022) 012

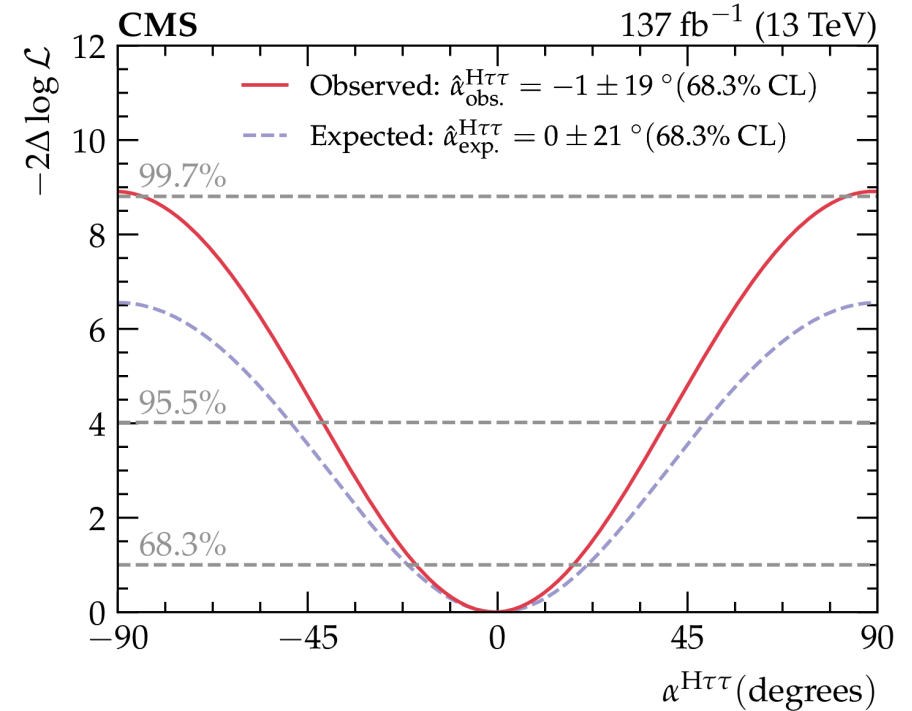
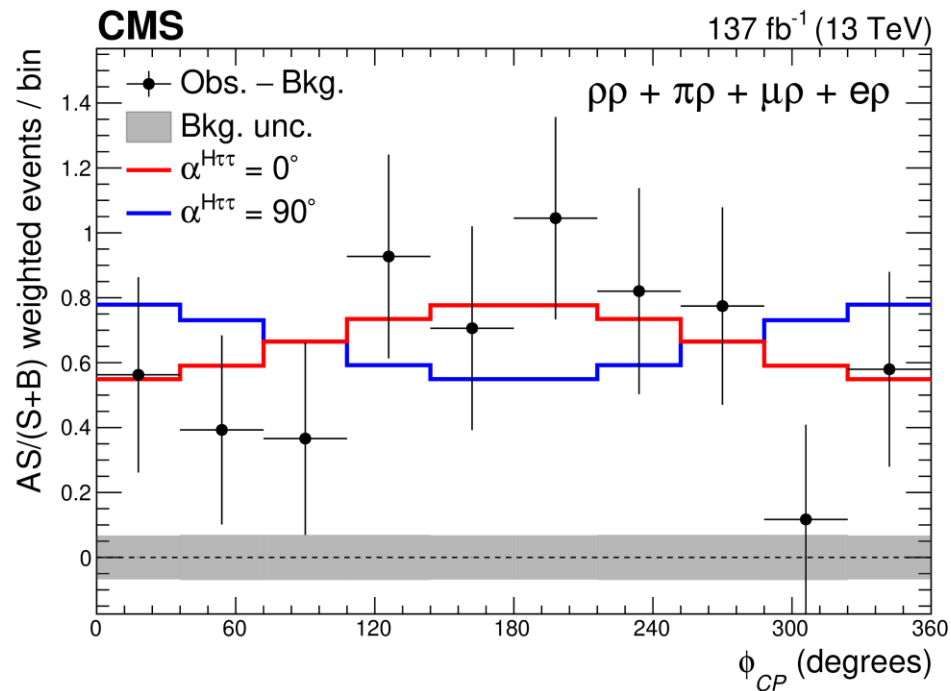
$$\frac{d\Gamma}{d\phi_{CP}}(H \rightarrow \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$



- Angle between the τ -lepton decay planes in the Higgs rest frame is sensitive to CP mixing angle α
- ϕ_{CP} is the angle between the τ leptons decay planes in the H rest frame
- Functions $b(E)$ encode the correlation between decay particles' energy and tau polarization (chiral structure of Weak interactions), different for $\tau \rightarrow \text{lep}, \pi, \rho(\pi^+\pi^0)$ and $a_1(\pi^+\pi^-\pi^+, \pi^+\pi^0\pi^0) + \nu$ decays
- 4 different methods employed to reconstruct ϕ_{CP} depending on the τ decay products. For example, for $\tau \rightarrow \pi^+\nu$ use the *impact-parameter method*: plane defined by the π direction and its impact parameter vector

CP interactions H- τ lepton

JHEP 06 (2022) 012



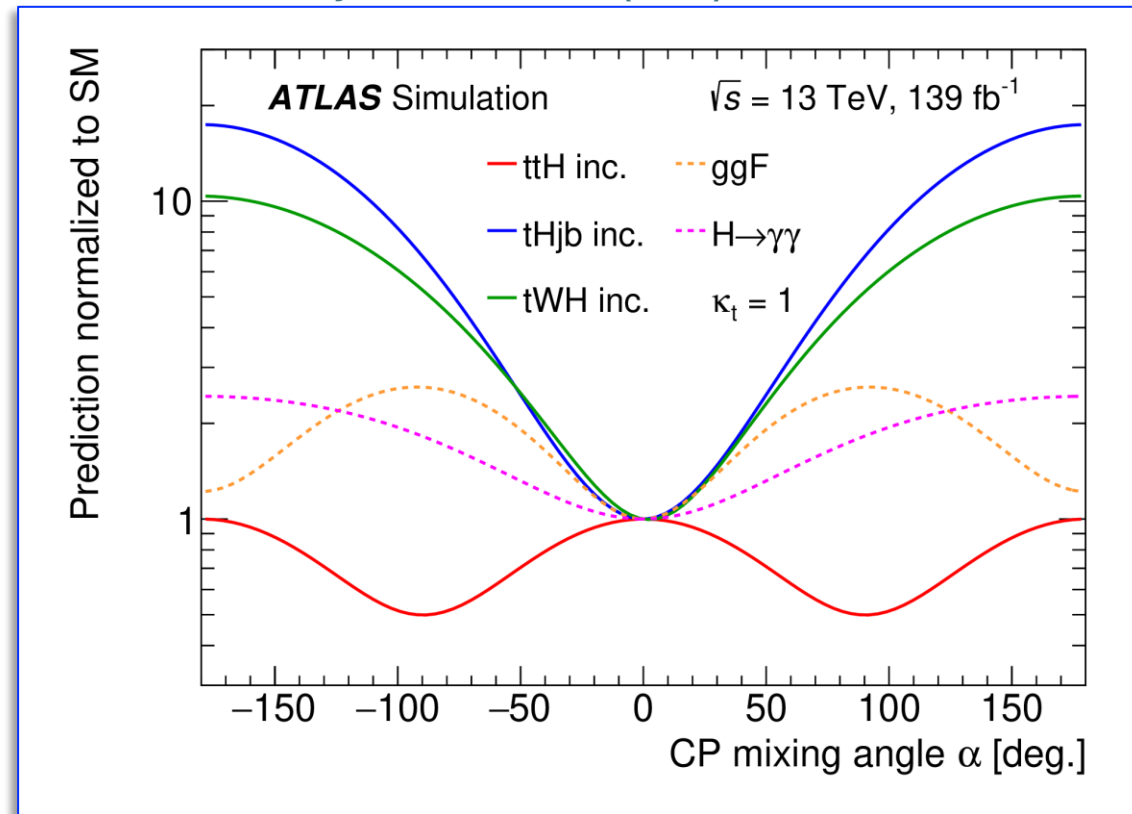
- Several $\tau\tau$ decay channels combined
- Measured CP angle $\alpha^{\tau\tau} = -1 \pm 19^\circ$, recently updated in [arXiv:2606.03510](https://arxiv.org/abs/2606.03510) to $\alpha^{\tau\tau} = 7 \pm 16^\circ$
- Full CP-odd interaction excluded at ~ 3 standard deviations (CL 99.7%)
- For HL-LHC projected precision $\alpha^{\tau\tau} \sim \pm 3^\circ$

CP interactions H-top quark

- The study of the **ttH** and **tH** processes is sensitive to the **CP structure** of top-Higgs interaction
- A pure **CP-odd** term with the same Yukawa coupling strength as in the SM would significantly alter **ttH**, **tH** production rates (and also **ggF** and **H→γγ**)
- Very stringent constraints on the CP-odd coupling can also be derived from the EDM, but they assume **SM-like interactions** between the Higgs boson and the **1st-generation fermions**
- It is also interesting to study CP-odd terms being **agnostic on production yields** and **interactions with other SM particles** relying mainly on the final state kinematics

$$\mathcal{L} = - \frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t [\cos(\alpha) + i \sin(\alpha) \gamma_5] \psi_t \right\} H$$

[Phys. Rev. Lett. 125 \(2020\) 061802](#)

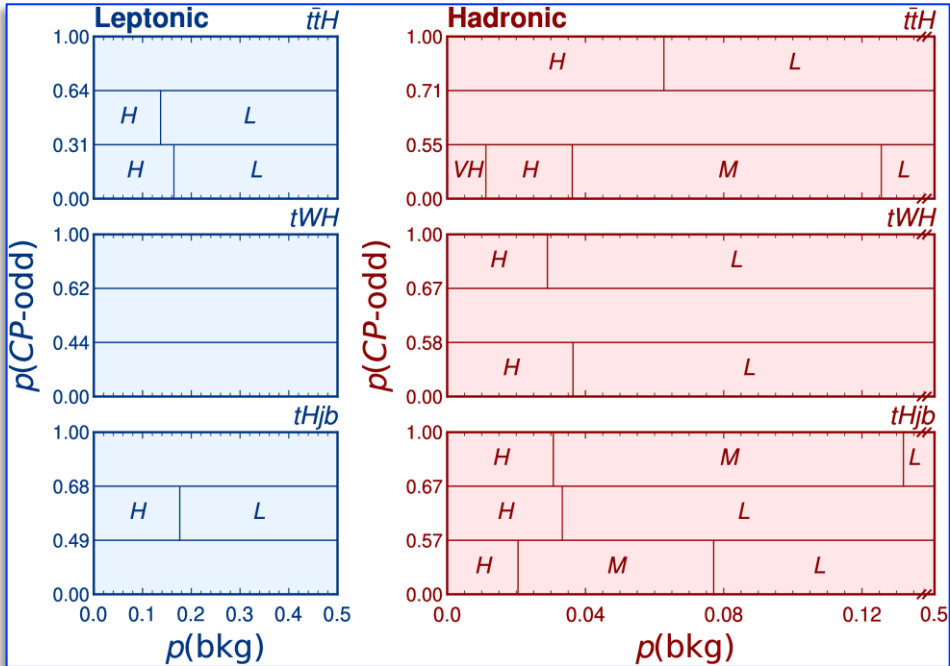
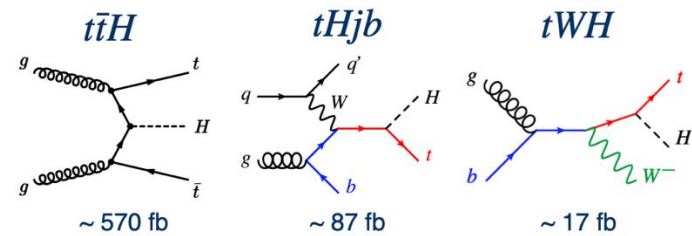


CP interactions H-top quark

- A nice example is from the $t\bar{t}H/tH$ with $H \rightarrow \gamma\gamma$ from ATLAS using Run 3 data
- Four-stage categorization strategy based on Graph Neural Networks (GNN)
 - 1) Leptonic vs hadronic top decays $\rightarrow$ 2 categories
 - 2) GNN to classify $t\bar{t}H$, tHb , tHW $\rightarrow$ 3 categories
 - 3) GNN to classify CP-even vs CP-odd
 - 4) GNN to classify Higgs signals from bkg.
- This results in 32 categories
- In each category, fit to $m_{\gamma\gamma}$ to extract $t\bar{t}H$, tH signal yields and α

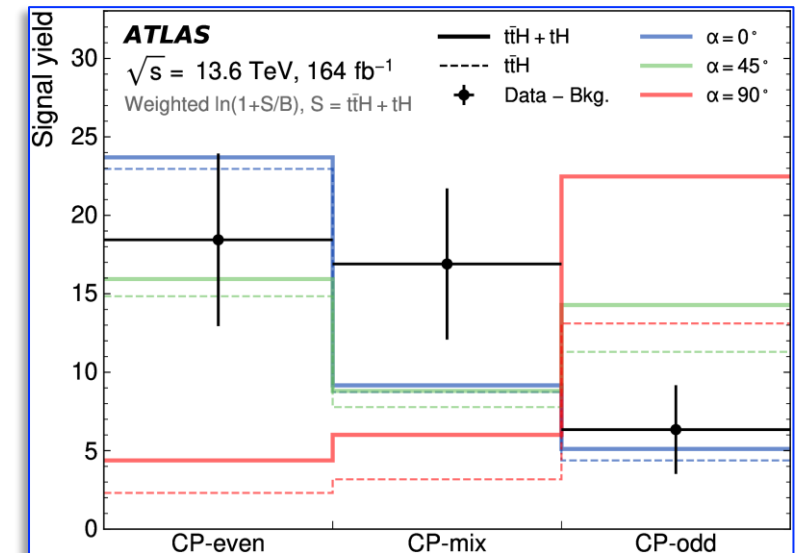
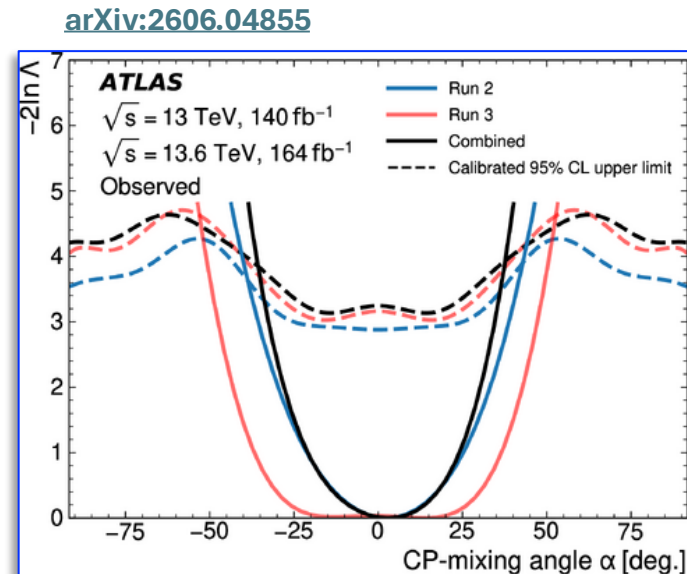
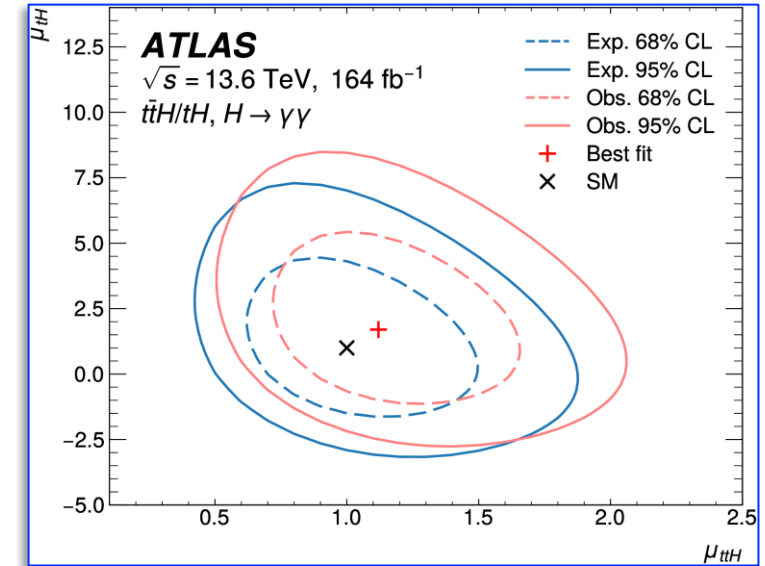
GNN inputs

Feature	Jet	μ	e	γ	E_T^{miss}
Kinematic	p_T	p_T	p_T	$p_T/m_{\gamma\gamma}$	p_T
	η	η	η	η	0
	ϕ	ϕ	ϕ	ϕ	ϕ
	$p_T \times \cosh \eta$	$p_T \times \cosh \eta$	$p_T \times \cosh \eta$	$p_T/m_{\gamma\gamma} \times \cosh \eta$	p_T
b-tagging	PCBT bin	0	0	0	0
Charge	0	± 1	± 1	0	0
Node Type	0	1	2	3	4



CP interactions H-top quark

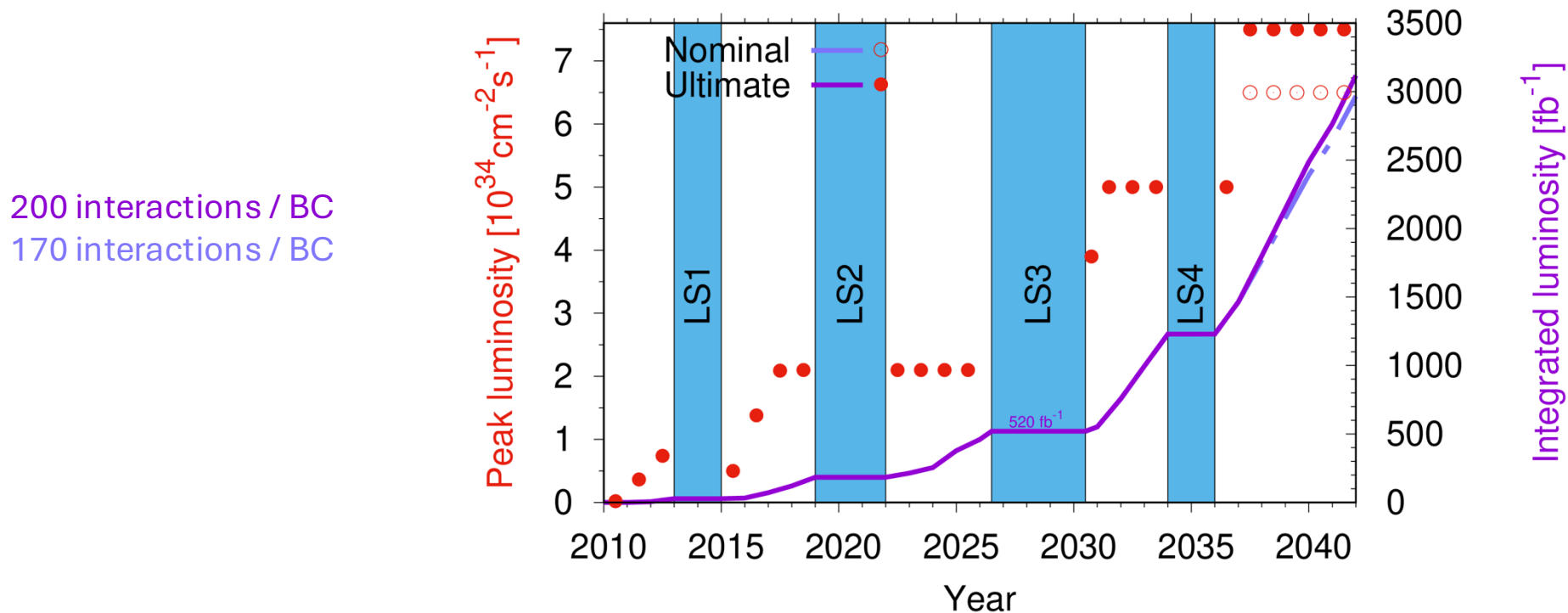
- Simultaneous measurements of $t\bar{t}H$ and tH signal strengths
- Constraints on α agnostic on production rates ($t\bar{t}H$ and tH signal strengths “profiled”):
 - $|\alpha| < 38^\circ$ @95% CL



The High Luminosity LHC

The Phase II upgrade program

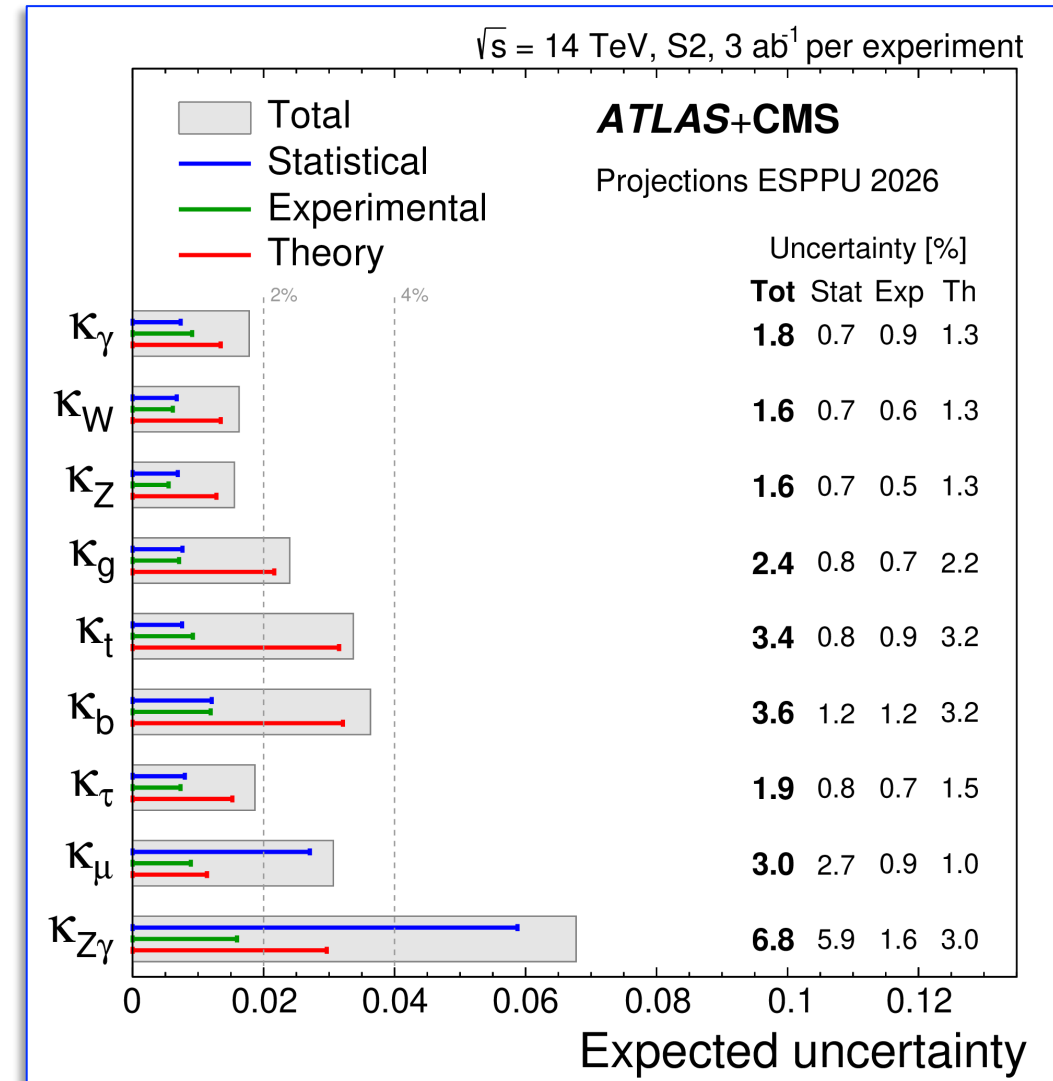
- ATLAS and CMS are working on an ambitious **Phase II upgrade** aimed at maintaining the detector performance, and in some cases **improving** it, in the harsh high-luminosity LHC running conditions
- Designed to cope with up to **200 interactions per bunch crossing** to reach **3 ab⁻¹** *good for physics*



The ultimate HL-LHC precision

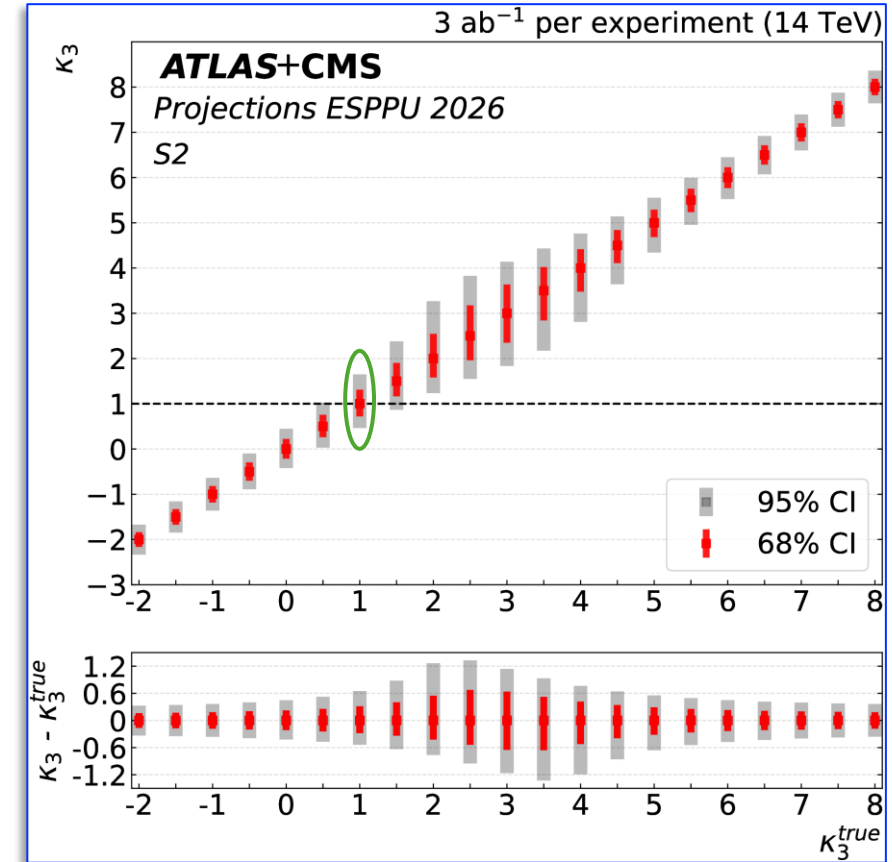
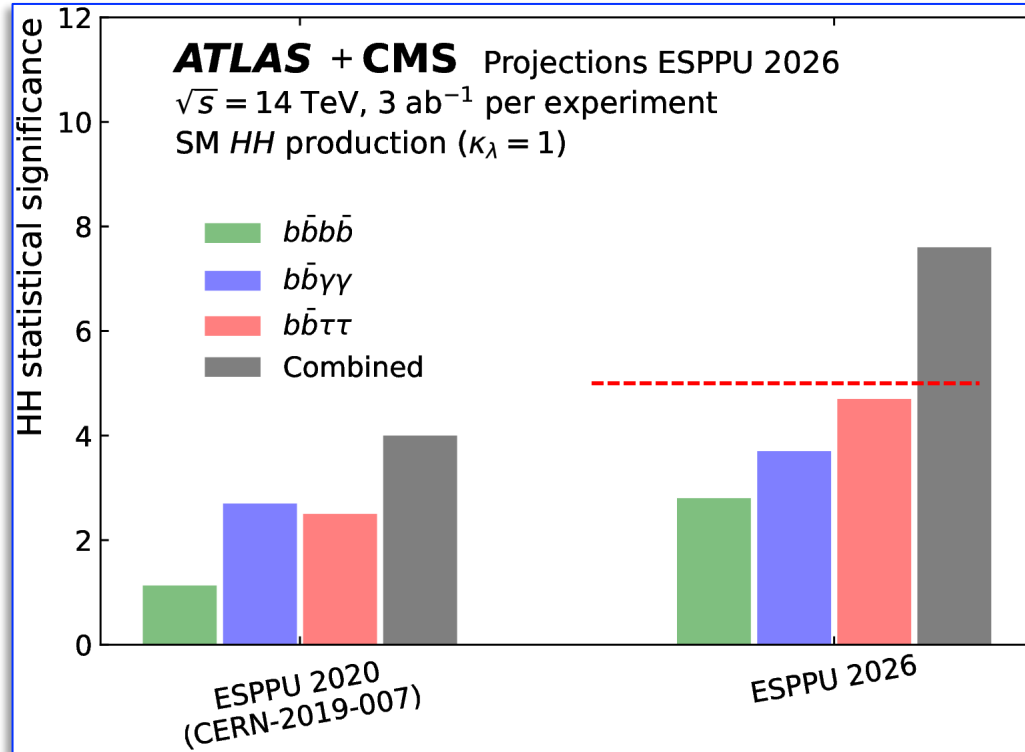
- Precision on **coupling modifiers κ** :
 - **$\sim 1.6\text{--}3.0\%$** precision assuming no BSM contribution to Higgs boson width (using ratio of couplings we can relax this assumption with similar performance)
 - **Statistical** uncertainties **$\sim 0.7\text{--}1.2\%$**
 - **Experimental** uncertainties comparable to stat. ones (most of them scale as $1/\sqrt{L}$)
 - **Theory-prediction uncertainties** are an important limiting component for several coupling modifiers: in this plot **a factor 2** improvement relative to current precision is assumed
 - Very challenging for **ggF** (dominant production) that is already computed at **N^3LO** in QCD perturbative order

ATL-PHYS-PUB-2025-018/CMS-HIG-25-002



HH and Higgs self-coupling at HL-LHC ...

ATL-PHYS-PUB-2025-018/CMS-HIG-25-002



One of the **main physics goals** of the **HL-LHC program** is the **observation** of the **HH process** and the measurement of the **Higgs boson self-coupling** with a **30%** precision → we will need **3ab^{-1} good for physics** per experiment to achieve it

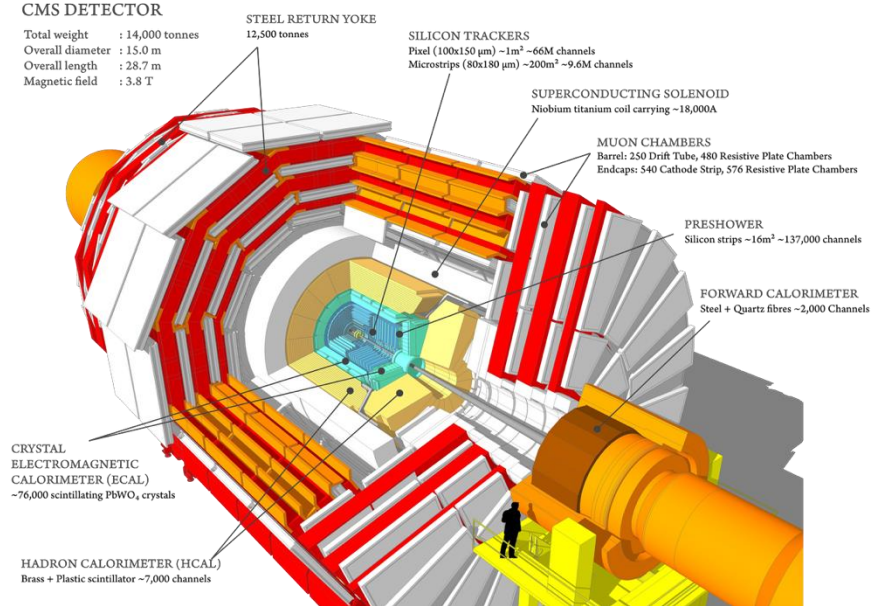
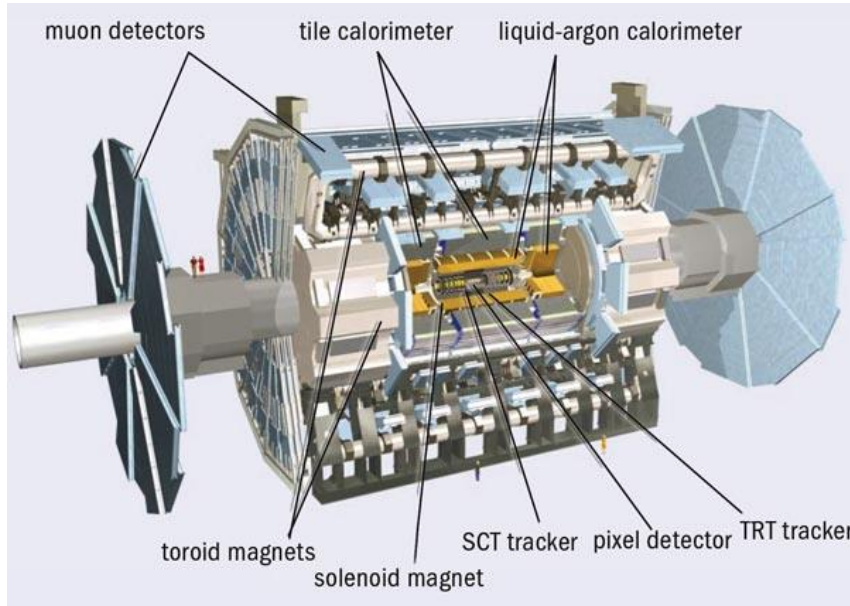
Summary

- There is a **before** and an **after** in **Higgs boson physics**: **4 July 2012** marked the beginning of an extremely challenging and interesting era focused on the measurements of the properties of the Higgs boson
- Very rich **LHC experimental program**: fiducial cross-sections, STXS, rare decays, HH, CP properties, extreme kinematic regime, ... I tried to give you a quick, partial (and biased) overview
- Improvements in **experimental techniques** and in **physics-object reconstruction** (mainly based on ML but not only) are having a **huge impact** on the sensitivity of the experimental studies: precision **improving more than $1/\sqrt{L}$** !
- The **HL-LHC** (adding ~ 5 times today's data) will challenge the **SM** in the **Higgs boson sector** at the **10^{-2} level** and will hopefully allow us to shed more light on the **Higgs boson potential**
- The future **looks bright for young** and **brilliant HEP physicists** ... I look forward to seeing **how you will benefit** from the great opportunities offered by the current experimental programme!

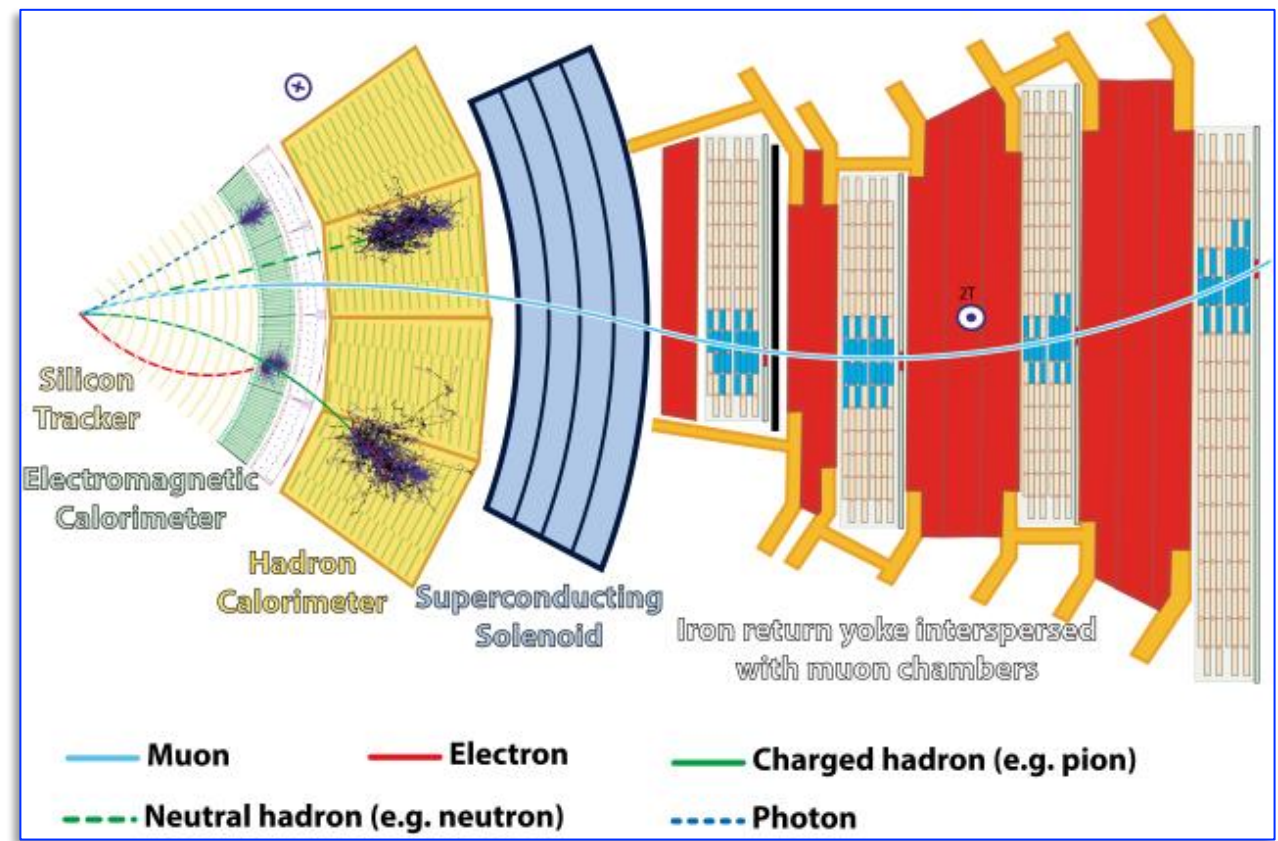
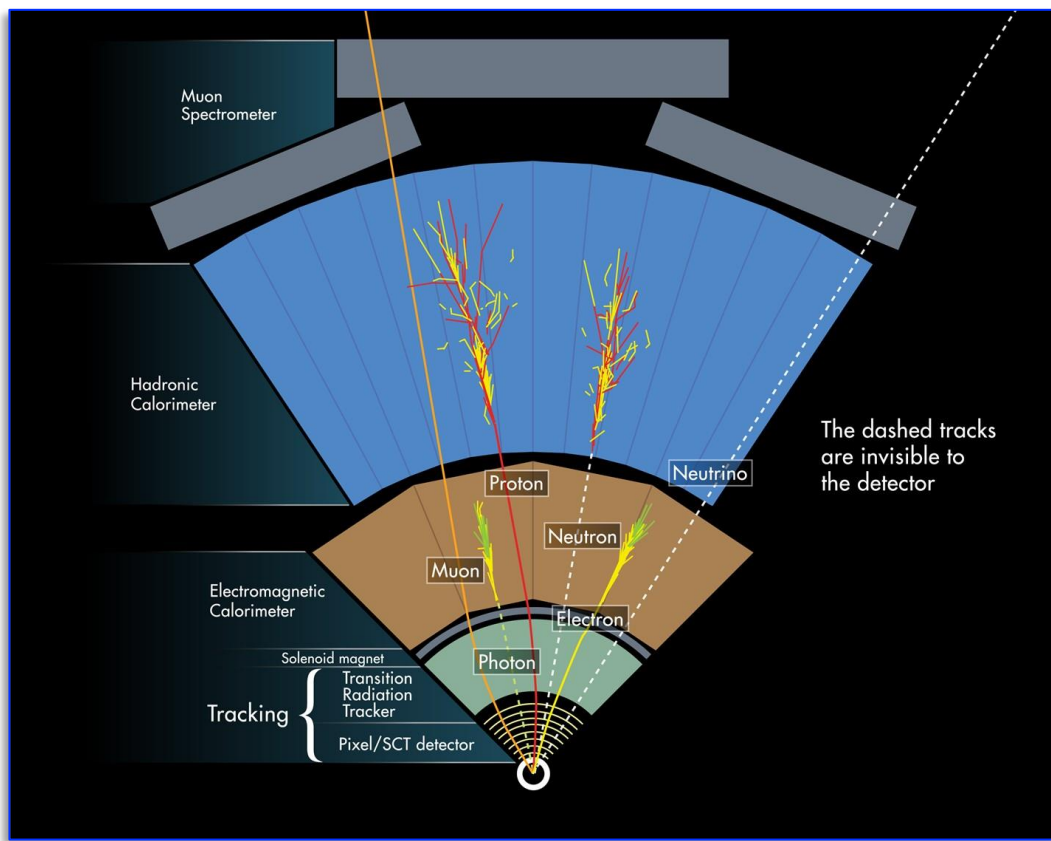
Questions?

Backup

ATLAS and CMS detectors



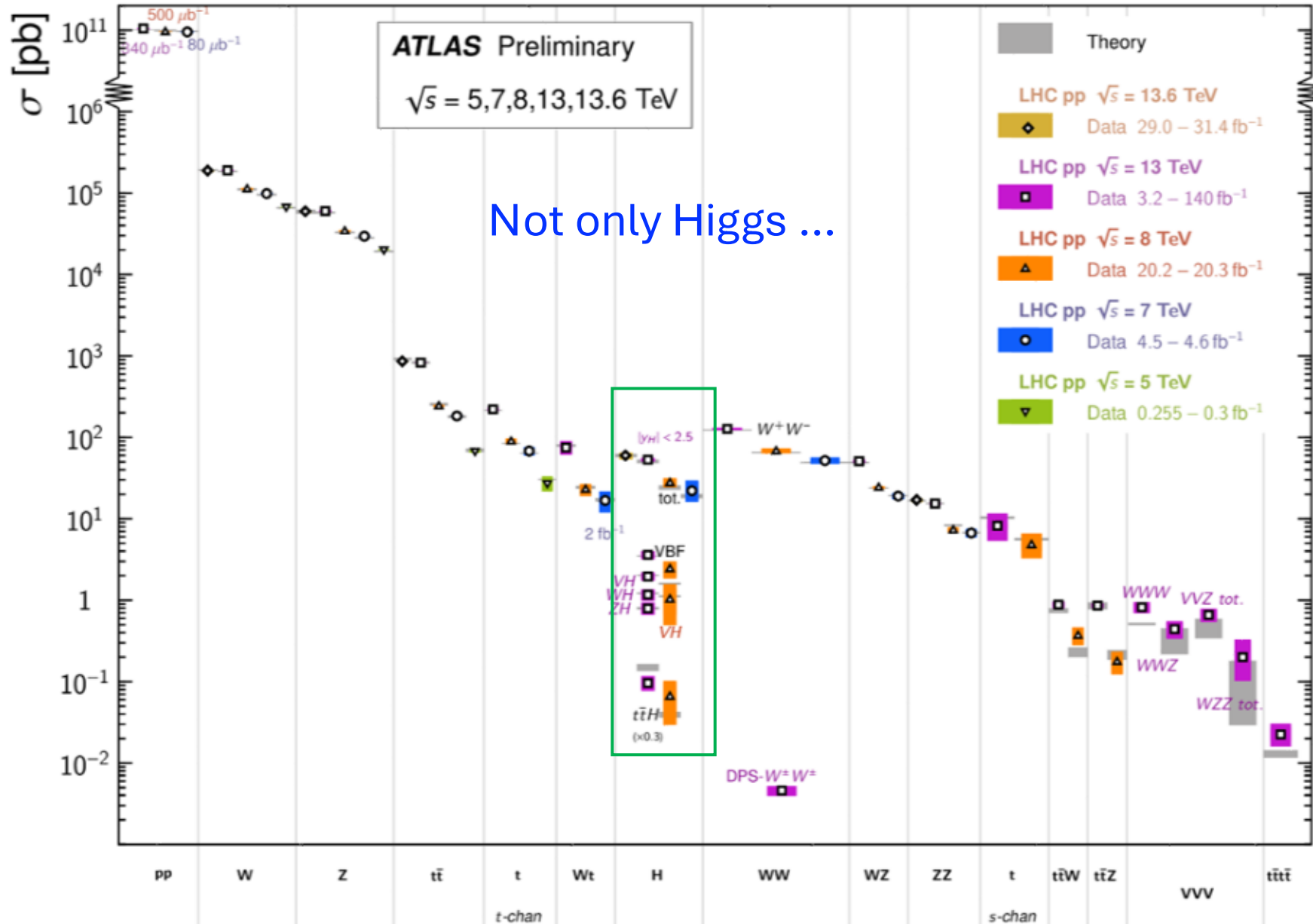
- Inner Tracker for charged particles immersed in a solenoidal magnetic field: (~2T ATLAS and 4T CMS) charge, momentum, impact parameters, decay vertices
- Electromagnetic calorimeter: identify and measure electron and γ energies
- Hadronic calorimeter: measure energy of “stable” hadrons: π , K, n, K⁰, p, etc.
- Muon detector: identify and measure momentum of μ
- Trigger system: use all detector elements to select “interesting” events to be recorded, 2 level structure:
 - L1 (hardware-based) 40 MHz $\rightarrow$ ~100kHz
 - HLT (software-based) ~100KHz $\rightarrow$ ~10-15kHz



- They measure the particles produced in the pp LHC interactions:
 - Identify: e , μ , τ , γ , non-interacting particles (ν) via missing transverse energy, clusters of particles (jets) including their “flavor”
 - Measure their energy, momentum, charge, lifetime (via impact parameters and decay vertices)

Standard Model Production Cross Section Measurements

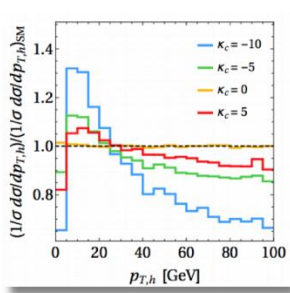
Status: July 2026



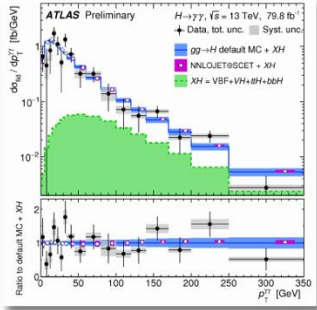
- Large **variety of SM processes** with measured σ 's spanning over **13 orders of magnitude**
 - pp-QCD $\sim 100 \text{ mb}$
 - $V \sim 200\text{-}60 \text{ nb}$
 - $t\bar{t} \sim 1 \text{ nb}$
 - $VV \sim 100\text{-}20 \text{ pb}$
 - $H \sim 60 \text{ pb}$
 - 4-top $\sim 15 \text{ fb}$
- Production rates at $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ($20 \text{ nb}^{-1} \text{ s}^{-1}$)
 - $V \sim 4\text{-}1.2 \text{ KHz}$
 - $t\bar{t} \sim 20 \text{ Hz}$
 - $VV \sim 2\text{-}0.4 \text{ Hz}$
 - $H \sim 1 \text{ Hz}$
- LHC was a “**factory**” for many SM processes
- At the **HL-LHC** these rates will increase by about a factor of **3**

Pt-Higgs measurement

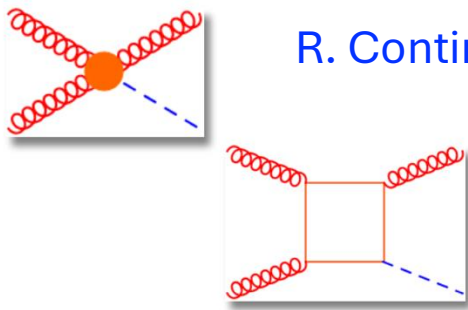
$p_{t,H}$: a major probe for Higgs physics



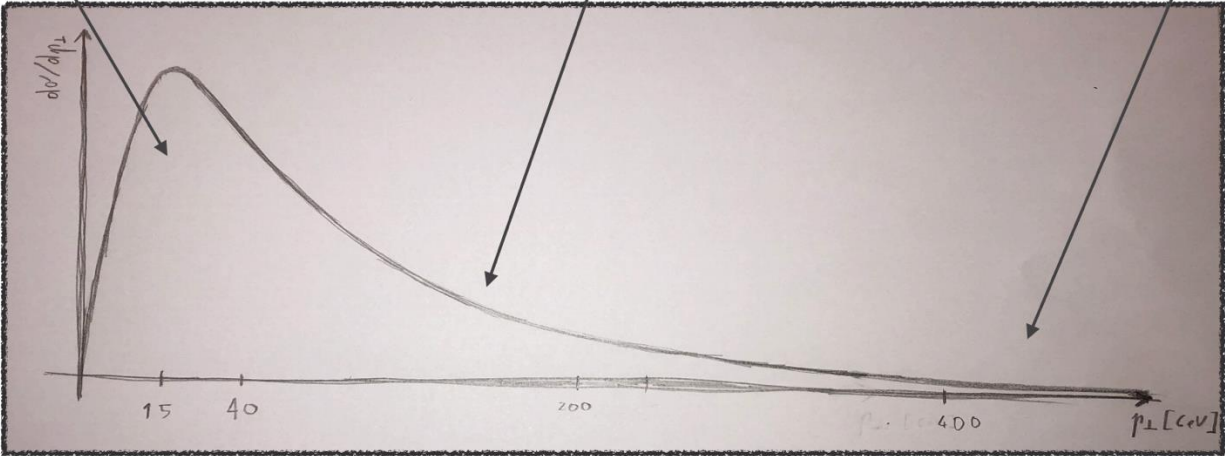
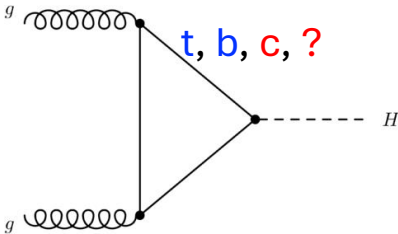
Low p_t
Light Yukawas...



Bulk of the distribution
Highest precision



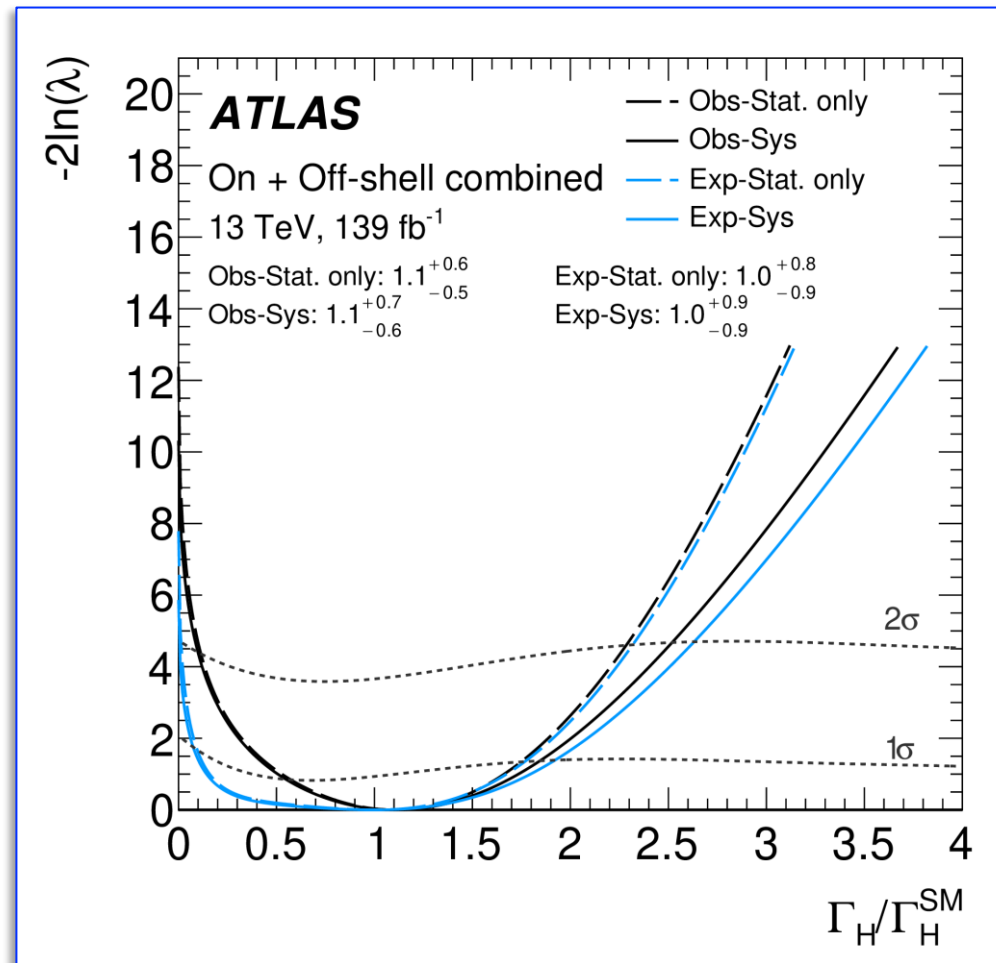
Boosted
ggH vs ttH, EFT...



- Higgs Pt spectrum dominated by **gluon fusion production (ggF)** - not true at **very high Pt**
- Full range sensitive to several **BSM effects**:
 - Higgs **couplings** to **charm, bottom, top, BSM Top partners** ([A.Banfi, A.Martin, V.Sanz '13](#)) , **EFT operators**, ...

Inference of Γ_H from off-shell Higgs production

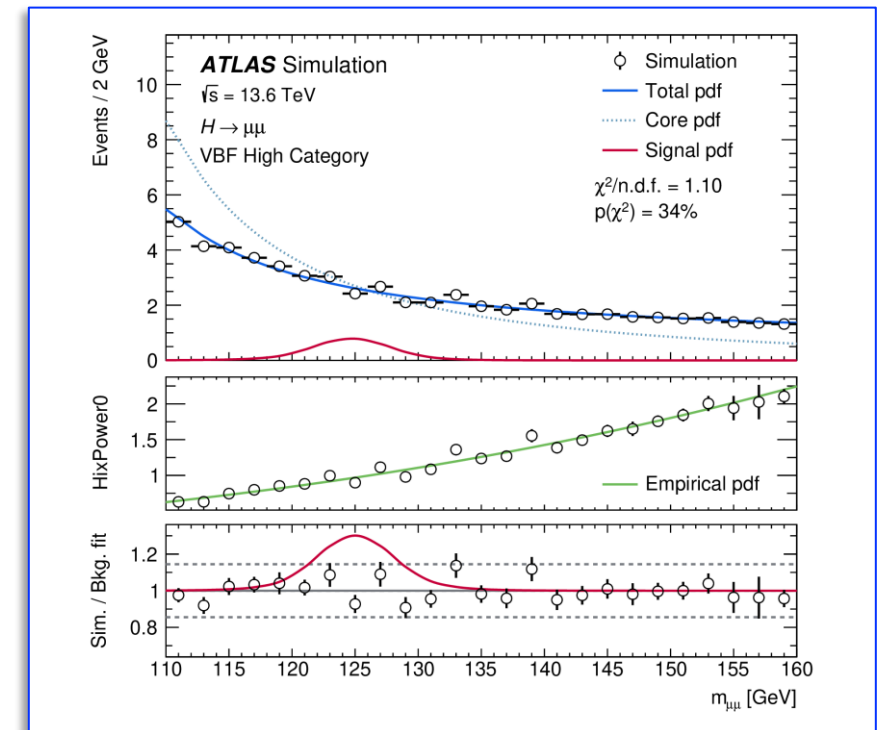
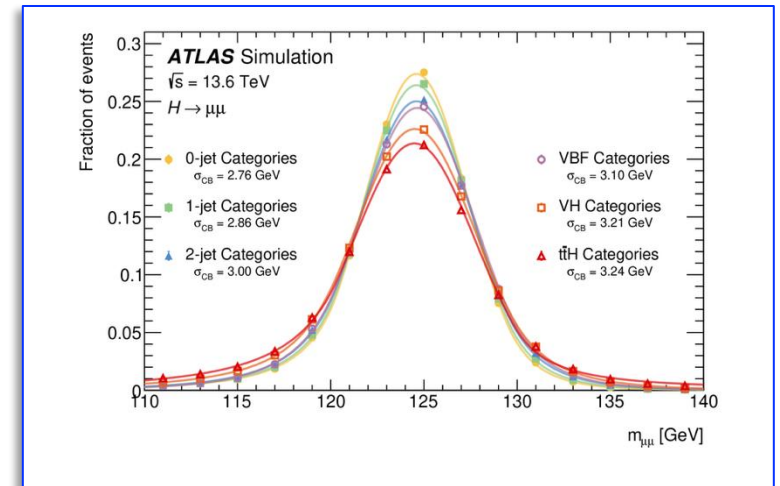
Process	Uncertainty	Final State	Value (%)
ggF Signal Region			
$qq \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	4–40
$qq \rightarrow ZZ + 2j$	QCD Scale	4ℓ	21–28
$qq \rightarrow ZZ + 2j$	QCD Scale	$2\ell 2\nu$	22–37
$qq \rightarrow ZZ + 2j$	Parton Shower	$2\ell 2\nu$	1–67
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	$2\ell 2\nu$	8–45
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	Parton Shower	$2\ell 2\nu$	6–43
$WZ + 0j$	QCD Scale	$2\ell 2\nu$	1–54
1-jet Signal Region			
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow H^* \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	13–18
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$qq \rightarrow ZZ$ (EW)	QCD Scale	$2\ell 2\nu$	7–18
2-jet Signal Region			
$qq \rightarrow ZZ + 2j$	QCD Scale	4ℓ	18–26
$qq \rightarrow ZZ + 2j$	QCD Scale	$2\ell 2\nu$	8–32
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	20–22
$qq \rightarrow ZZ$ Control Regions			
$qq \rightarrow ZZ + 2j$	QCD Scale	4ℓ	26
Three-lepton Control Regions			
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	28



- Measurement is still **statistically limited**, but **systematic uncertainties** start to play a significant role, dominated by **modeling uncertainties** on the **signal** ($gg \rightarrow (H^*) \rightarrow VV$) and **background** ($qq \rightarrow VV$) processes

$H \rightarrow \mu\mu$ example ATLAS analysis

- Signal extracted via an **analytical fit** to $m_{\mu\mu}$ spectra
- Signal modeling: **Double-Sided crystal ball**
- Bkg. Modeling: based on **Core** x **Empirical** analytic fit or spectra
 - **Core** DY same for all categories (no free DOF)
 - **Empirical**: flexible enough to adapt to mass distortions caused by selection, between 1 and 4 shape DOF depending on category (plus normalization)
- Choice of the bkg. function:
 - Required **good quality fit** on: MC, data SB: $\text{prob}(\chi^2) > 1\%$ for all samples/categories
 - **Spurious Signals**: defined as signal yields obtained from a fit to the background-only MC spectra $\rightarrow$ require to be below **20% stat. uncertainty**
 - Choose the functions with **smaller number of DOF** that passe the criteria described above (see next slide for list of functions)
- **Background modeling uncertainty** from the **Spurious Signals** measured in each category
- **CMS** use a similar approach based on “core-PDF method” and “discrete profiling”



$H \rightarrow \mu\mu$ example ATLAS analysis

- Choice of the bkg. function:
 - Required **good quality fit** on: MC, data SB: $\text{prob}(\chi^2) > 1\%$ for all samples/categories
 - Spurious Signals**: defined as signal yields obtained from a fit to the background-only MC spectra $\rightarrow$ require to be below **20% stat. uncertainty**
 - Chose the functions with **smaller DOF** that passes the criteria described above (see next slide for list of functions)
- Background modeling uncertainty: the **Spurious Signals** measured in each category

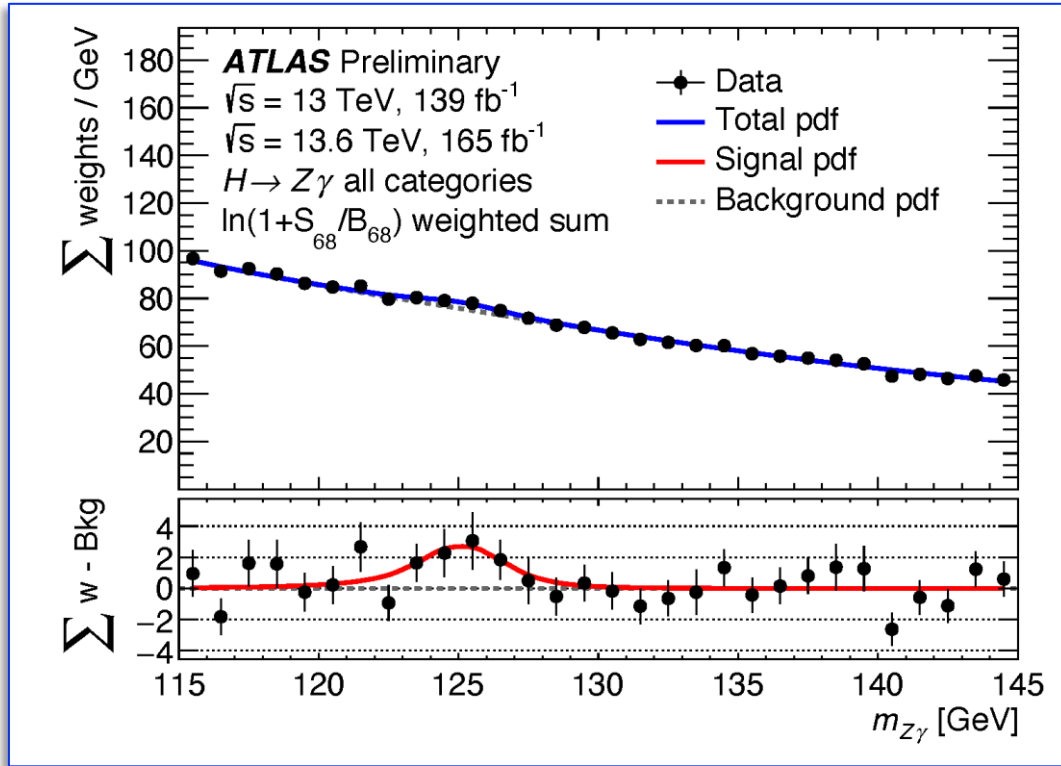
Uncertainty source	$\Delta\mu$	
Statistical uncertainty	-0.40	+0.41
Systematic uncertainty	-0.12	+0.15
Spurious signal	-0.09	+0.09
Theory	-0.07	+0.10
Luminosity	-0.02	+0.04
Muon	-0.02	+0.04
Jets, flavor tagging	-0.01	+0.01
Other	-0.02	+0.03
Total	-0.42	+0.43

Function	Expression
PowerN	$m_{\mu\mu}^{(a_0 + a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \dots + a_N m_{\mu\mu}^N)}$
EpolyN	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \dots + a_N m_{\mu\mu}^N)$

Category	Empirical Function
$t\bar{t}H$ -High	Power0
$t\bar{t}H$ -Medium	Epoly2
VH4L	Power0
VH3L-High	Epoly2
VH3L-Medium	Epoly4
VH2L-High	Epoly2
VH2L-Medium	Power0
VBF High	Power0
VBF Medium	Power0
VBF Low	Epoly1
VBF Very Low	Power0
2-jet High	Epoly2
2-jet Medium	Power1
2-jet Low	Power0
2-jet Very Low	Power1
1-jet High	Power0
1-jet Medium	Epoly3
1-jet Low	Power1
1-jet Very Low	Power1
0-jet High	Power0
0-jet Medium	Epoly3
0-jet Low	Power1
0-jet Very Low	Epoly3

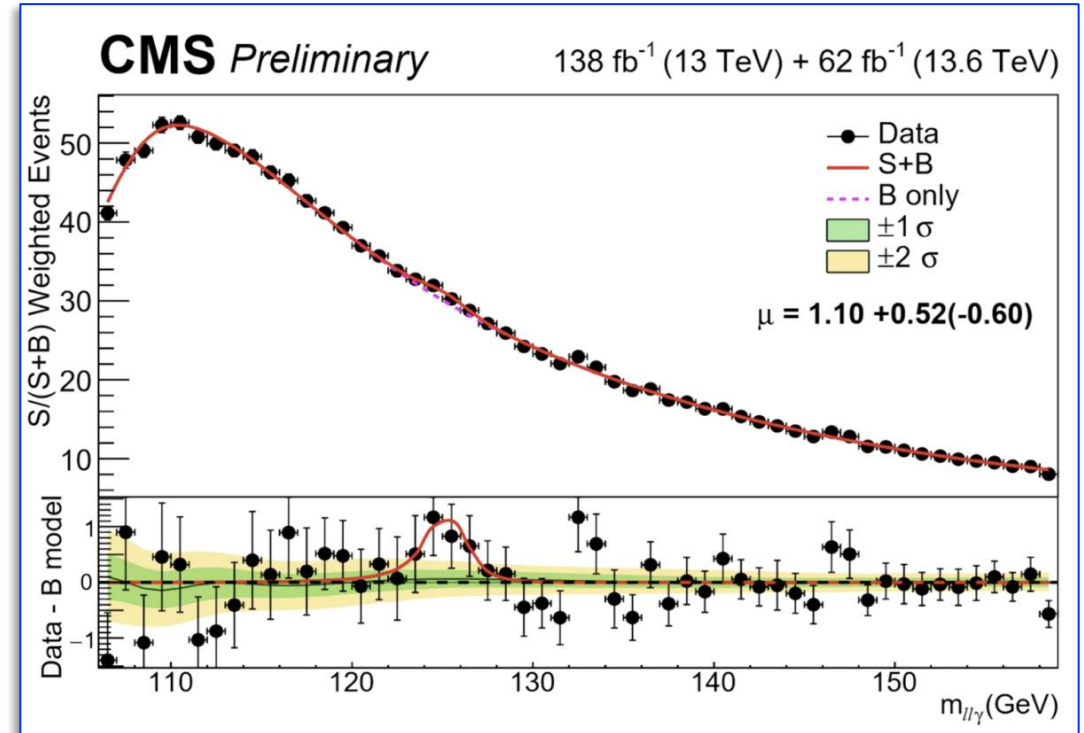
$H \rightarrow Z\gamma$

Phys. Lett. B 876 (2026) 140313



Run2+Run3: $\mu = 1.3^{+0.6}_{-0.5}$ significance 2.5σ (exp. SM 1.9σ)

CMS-PAS-HIG-25-010

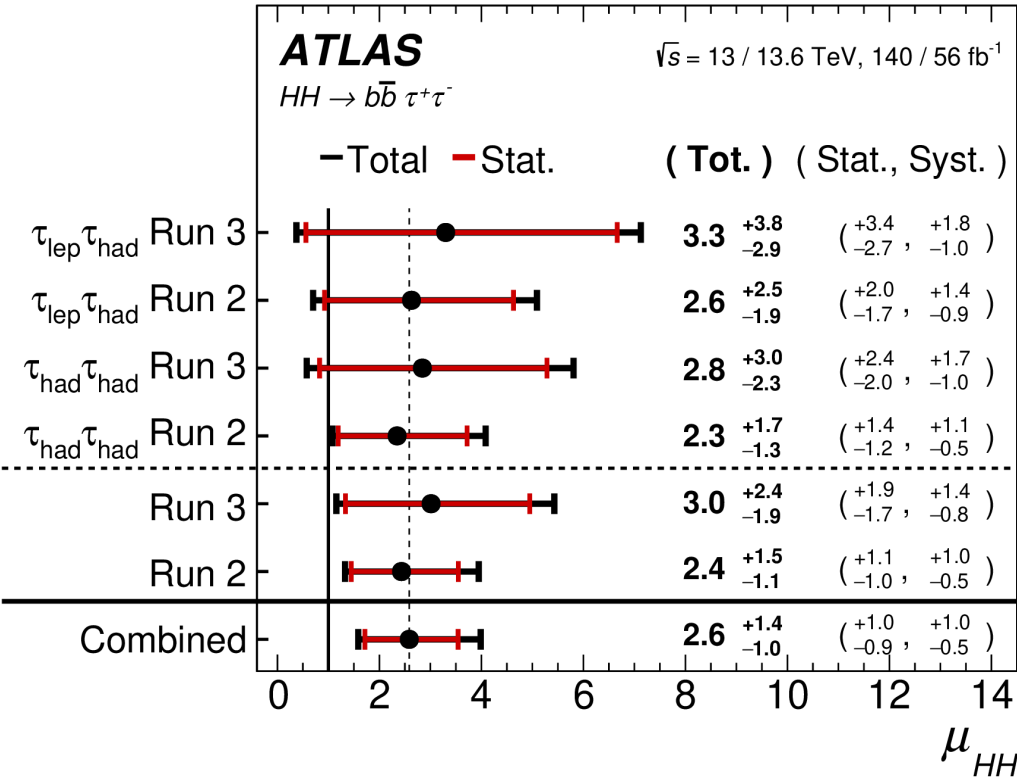
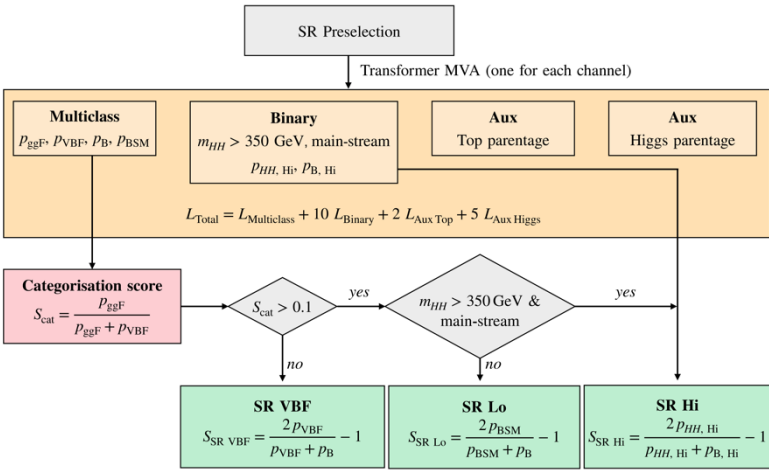


Run2+Run3: $\mu = 1.10^{+0.52}_{-0.61}$ significance 1.9σ (exp. SM 2.3σ)

- Select $Z \rightarrow ll$ decays, fit to $m_{ll\gamma}$, Categorization to enhance S/B
- Evidence (3σ) achieved combining Run 2 ATLAS+CMS with slight excess in μ not confirmed in Run 3

HH in $bb\tau\tau$ Run 3

- Analysis released for ICHEP 2026 combining improved Run 2 analysis with Run 3 (2022-2023) data
- Expected sensitivity to μ_{HH} improved by **~50%** relative to previous results:
 - **~15%** from an improved Transformer-based approach
 - **~10%** improved flavor tag GN2
 - **~10%** improved selection
 - **~15%** adding Run 3 data
- Measured $\mu_{HH} = 2.6^{+1.4}_{-1.0}$
- Observed (expected) significance **2.6 (1.2) σ**



“Coupling” inference: combination single-H and HH

- ATLAS legacy Run 2 couplings combination uses all H (STXS) and HH measurements

Analysis	Prod. modes	$\mathcal{L}$ [fb ⁻¹]	Ref.	Comparison with Ref. [3]	Measurements		
					Incl.	κ	STXS
$H \rightarrow ZZ^* \rightarrow 4\ell$	All	140	[73]	Unchanged	✓	✓	✓
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	ggF, VBF	140	[74]	Updated	✓	✓	✓
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu, \ell\nu jj$	VH	140	[75]	Full Run 2	✓	✓	✓
$H \rightarrow \gamma\gamma$	All	140	[76]	Unchanged	✓	✓	✓
$H \rightarrow Z\gamma$	All	140	[70]	Unchanged	✓	✓	
$H \rightarrow \tau\tau$	All, except $(V \rightarrow \text{leptons})H$	140	[77]	Updated	✓	✓	✓
$H \rightarrow \tau\tau$	$(V \rightarrow \text{leptons})H$	140	[72]	New	✓	✓	
$H \rightarrow \mu\mu$	All	140	[71]	Unchanged	✓	✓	
$H \rightarrow bb$	VBF	126	[5]	Unchanged	✓	✓	✓
$H \rightarrow bb, cc$	$(V \rightarrow \text{leptons})H$	140	[78]	Updated	✓	✓	✓
$H \rightarrow bb$ (high p_T^H)	All	136	[69]	Unchanged			✓
$H \rightarrow \text{multileptons}$	ttH	140	[79]	Full Run 2	✓	✓	✓
$H \rightarrow bb$	ttH	140	[80]	Updated	✓	✓	✓
$H \rightarrow bb$	tH	140	[81]	Updated	✓	✓	✓
$H \rightarrow \text{invisible}$	VBF	140	[65]	Unchanged		✓	
$H \rightarrow \text{invisible}$	VBF + γ	140	[68]	New		✓	
$H \rightarrow \text{invisible}$	$(V \rightarrow \text{leptons})H$	140	[66]	Unchanged		✓	
$H \rightarrow \text{invisible}$	ttH	140	[67]	New		✓	
$H^{(*)} \rightarrow ZZ^{(*)}$	ggF, VBF	140	[63]	Updated		✓	
$H^{(*)} \rightarrow WW^{(*)}$	ggF, VBF	140	[64]	New		✓	
$HH \rightarrow bbbb$	ggF, VBF	126	[6]	New		✓	
$HH \rightarrow bbbb$ (high p_T^H)	VBF	140	[82]	New		✓	
$HH \rightarrow bb\tau\tau$	ggF, VBF	140	[83]	New		✓	
$HH \rightarrow bb\gamma\gamma$	ggF, VBF	140	[84]	New		✓	
$HH \rightarrow bb\ell\ell + E_T^{\text{miss}}$	ggF, VBF	140	[85]	New		✓	
$HH \rightarrow \text{multileptons}$	ggF, VBF	140	[86]	New		✓	

“Coupling” inference: ratios of couplings λ

General parameterization allowing all gauge and third generation fermion couplings to float allowing for invisible or undetectable widths

Free parameters: $\kappa_{gZ}(= \kappa_g \cdot \kappa_Z / \kappa_H)$, $\lambda_{\gamma Z}(= \kappa_\gamma / \kappa_Z)$, $\lambda_{WZ}(= \kappa_W / \kappa_Z)$, $\lambda_{bZ}(= \kappa_b / \kappa_Z)$, $\lambda_{\tau Z}(= \kappa_\tau / \kappa_Z)$, $\lambda_{Zg}(= \kappa_Z / \kappa_g)$, $\lambda_{tg}(= \kappa_t / \kappa_g)$.

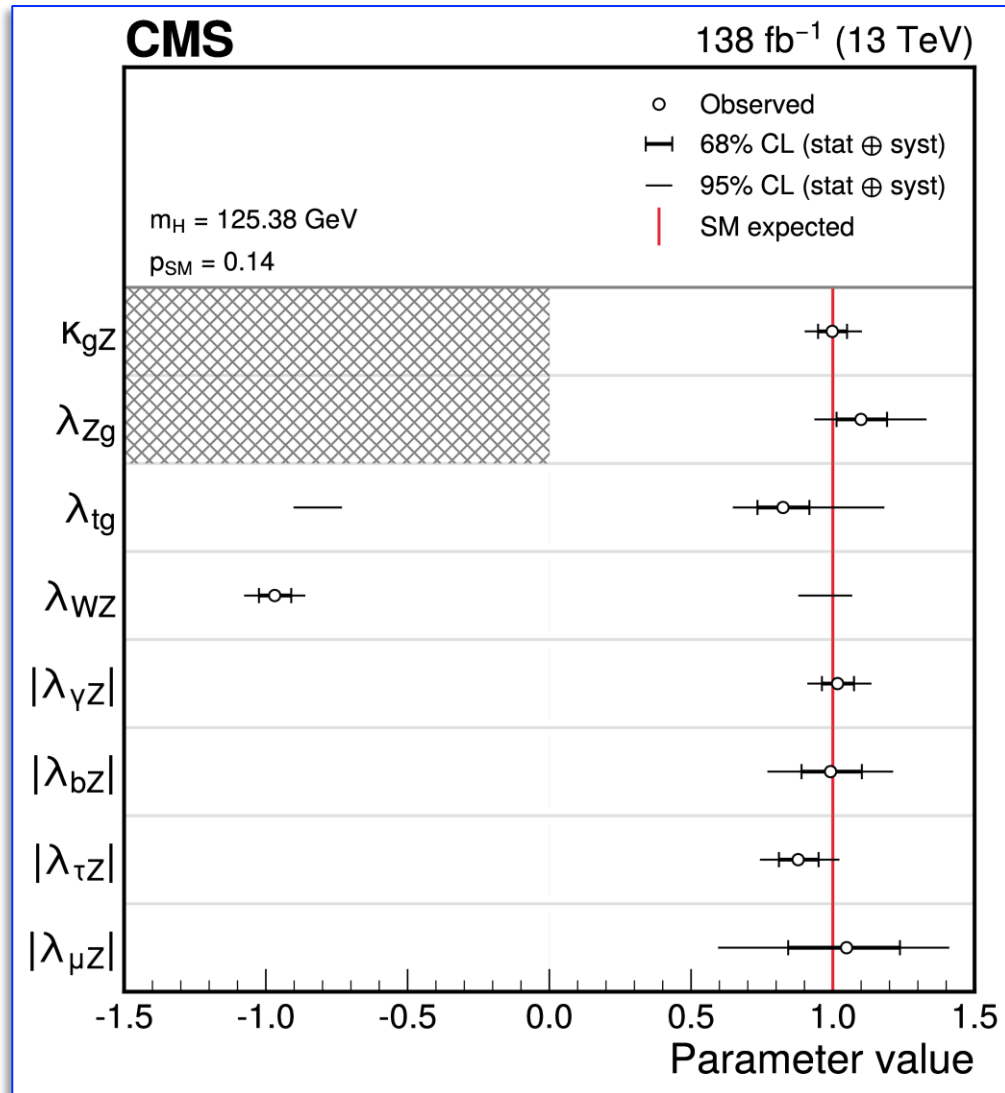
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\kappa_{gZ}^2 \cdot \lambda_{\gamma Z}^2$	κ_{gZ}^2	$\kappa_{gZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{gZ}^2 \cdot \lambda_{bZ}^2$	$\kappa_{gZ}^2 \cdot \lambda_{\tau Z}^2$
ttH	$\kappa_{gZ}^2 \lambda_{tg}^2 \cdot \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \lambda_{tg}^2$	$\kappa_{gZ}^2 \lambda_{tg}^2 \cdot \lambda_{WZ}^2$	$\kappa_{gZ}^2 \lambda_{tg}^2 \cdot \lambda_{bZ}^2$	$\kappa_{gZ}^2 \lambda_{tg}^2 \cdot \lambda_{\tau Z}^2$
VBF	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) \cdot \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ})$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) \cdot \lambda_{WZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) \cdot \lambda_{bZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) \cdot \lambda_{\tau Z}^2$
WH	$\kappa_{gZ}^2 \lambda_{Zg}^2 \lambda_{WZ}^2 \cdot \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \lambda_{WZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \lambda_{WZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \lambda_{WZ}^2 \cdot \lambda_{bZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \lambda_{WZ}^2 \cdot \lambda_{\tau Z}^2$
ZH	$\kappa_{gZ}^2 \lambda_{Zg}^2 \cdot \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \cdot \lambda_{WZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \cdot \lambda_{bZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \cdot \lambda_{\tau Z}^2$

$\kappa_i^2 = \Gamma_{ii} / \Gamma_{ii}^{SM}$

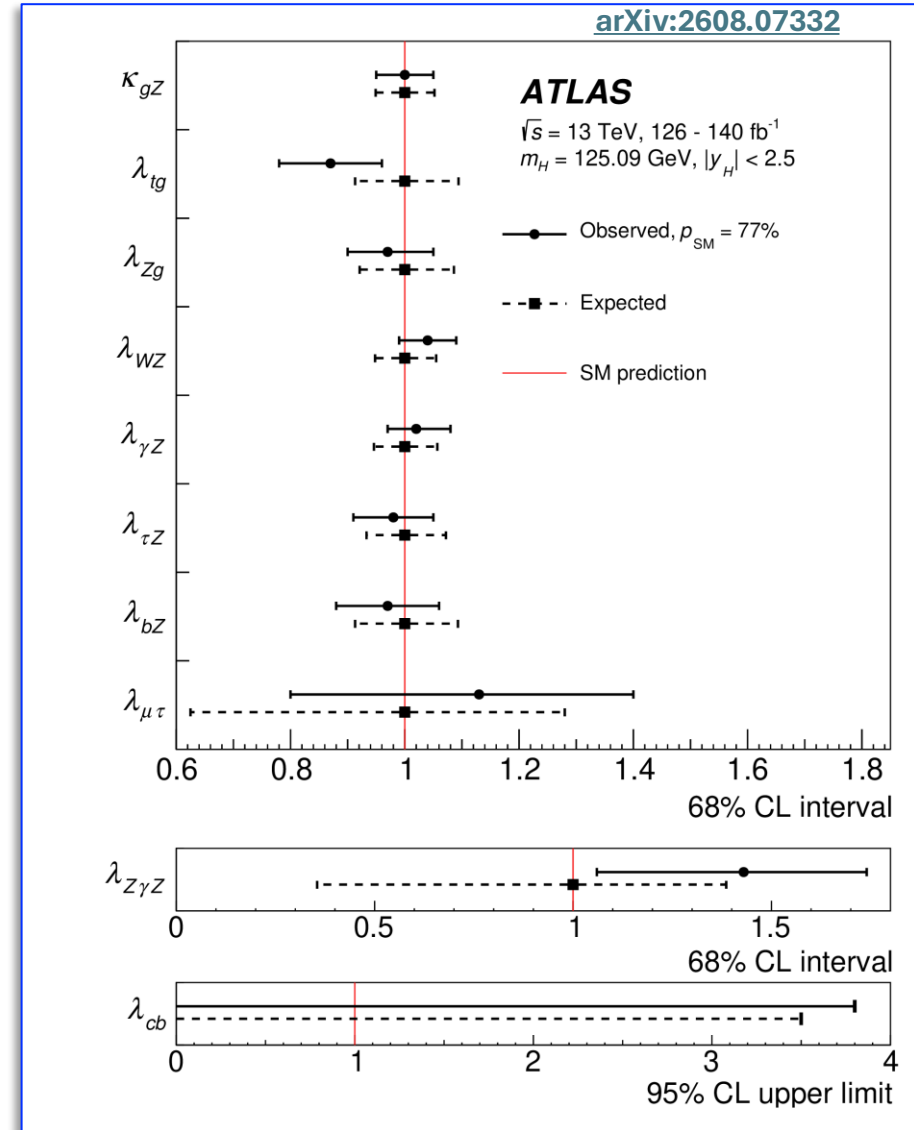
- A parameterization that does not require assumptions on Γ_H is based on the coupling ratios + global scale factor for a specific $i \rightarrow H \rightarrow f$ process: $\sigma[ggF(H \rightarrow ZZ^*)] = \kappa_{gZ} \times \sigma[ggF(H \rightarrow ZZ^*)]_{SM}$
- All production processes $i \rightarrow H \rightarrow f$ expressed as a product of $\kappa_{gZ} \times [\lambda_{ig} \times \lambda_{fZ}]$
 - **Pros**: no assumptions on Γ_H
 - **Cons**: all scales as the measured $\sigma[ggF(H \rightarrow ZZ^*)] / \sigma[ggF(H \rightarrow ZZ^*)]_{SM}$

“Coupling” inference: ratios of couplings

Rep. Prog. Phys. 89 (2026) 087801



arXiv:2608.07332



- Run 2 legacy results: CMS p -value SM 14% and ATLAS p -value SM 77%

EFT d=6 operators bosons

[arXiv:1610.07922](https://arxiv.org/abs/1610.07922)

Table 97: Bosonic $D=6$ operators in the SILH basis.

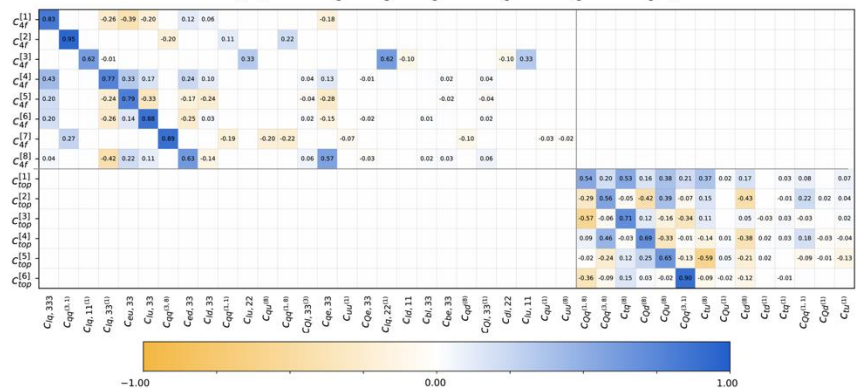
Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2} \left[\partial_\mu (H^\dagger H) \right]^2$		
O_T	$\frac{1}{2v^2} \left(H^\dagger \overleftrightarrow{D}_\mu H \right)^2$		
O_6	$-\frac{\lambda}{v^2} (H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H G_{\mu\nu}^a G_{\mu\nu}^a$	$\tilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H \tilde{G}_{\mu\nu}^a G_{\mu\nu}^a$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B_{\mu\nu}$	$\tilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H \tilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2} \left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H \right) D_\nu W_{\mu\nu}^i$		
O_B	$\frac{ig'}{2m_W^2} \left(H^\dagger \overleftrightarrow{D}_\mu H \right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2} \left(D_\mu H^\dagger \sigma^i D_\nu H \right) W_{\mu\nu}^i$	$\tilde{O}_{HW}$	$\frac{ig}{m_W^2} \left(D_\mu H^\dagger \sigma^i D_\nu H \right) \tilde{W}_{\mu\nu}^i$
O_{HB}	$\frac{ig'}{m_W^2} \left(D_\mu H^\dagger D_\nu H \right) B_{\mu\nu}$	$\tilde{O}_{HB}$	$\frac{ig}{m_W^2} \left(D_\mu H^\dagger D_\nu H \right) \tilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W_{\mu\nu}^i D_\rho W_{\rho\nu}^i$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G_{\mu\nu}^a D_\rho G_{\rho\nu}^a$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W_{\mu\nu}^i W_{\nu\rho}^j W_{\rho\mu}^k$	$\tilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \tilde{W}_{\mu\nu}^i W_{\nu\rho}^j W_{\rho\mu}^k$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G_{\mu\nu}^a G_{\nu\rho}^b G_{\rho\mu}^c$	$\tilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \tilde{G}_{\mu\nu}^a G_{\nu\rho}^b G_{\rho\mu}^c$

Warsaw basis

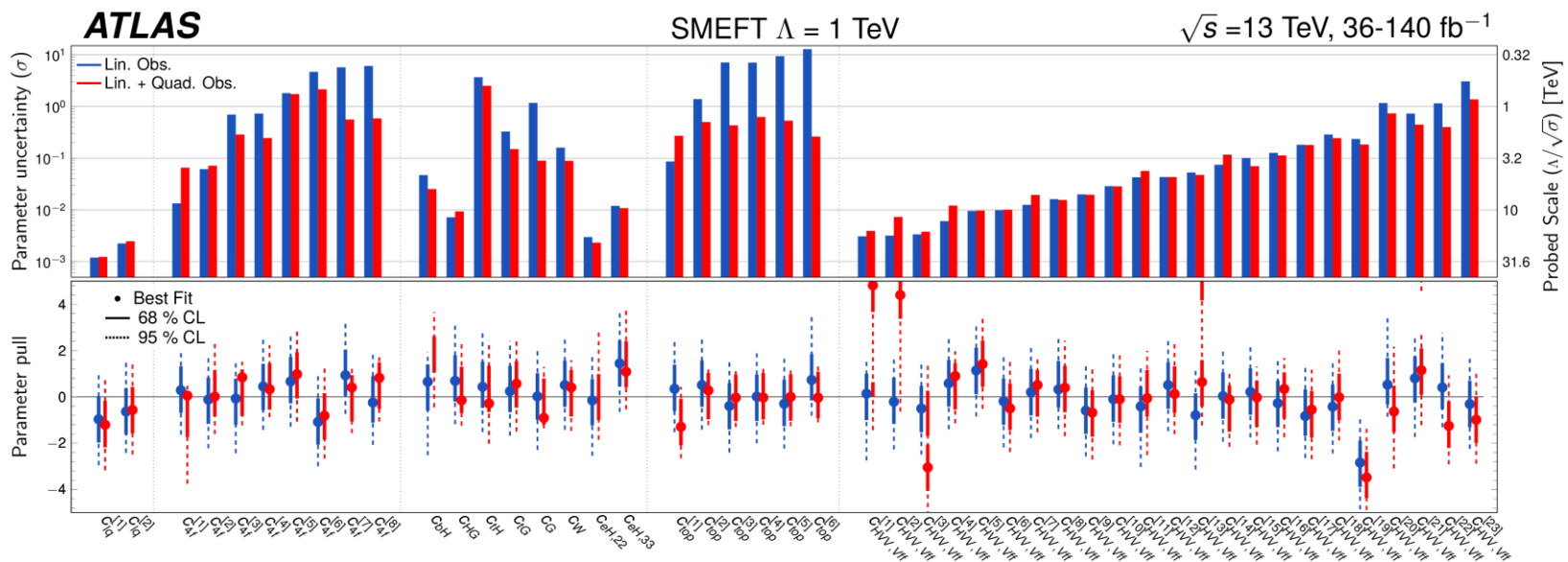
$$\mathcal{O}_{HW} = (H^\dagger H) W_{\mu\nu}^I \tilde{W}^{I\mu\nu}$$

$$\mathcal{O}_{HB} = (H^\dagger H) B_{\mu\nu} \tilde{B}^{\mu\nu}$$

$$\mathcal{O}_{H\tilde{W}B} = (H^\dagger \tau^I H) W_{\mu\nu}^I \tilde{B}^{\mu\nu}$$

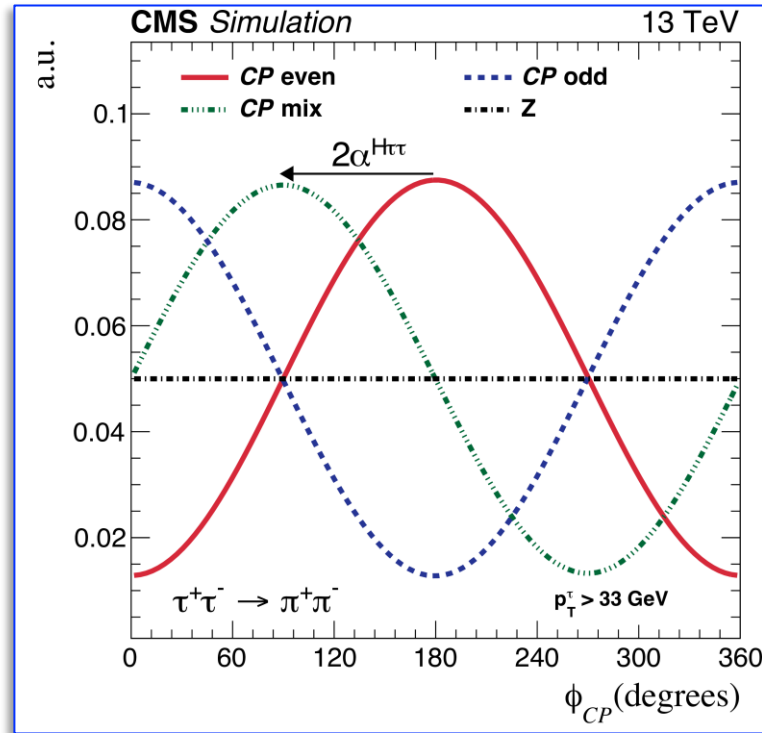
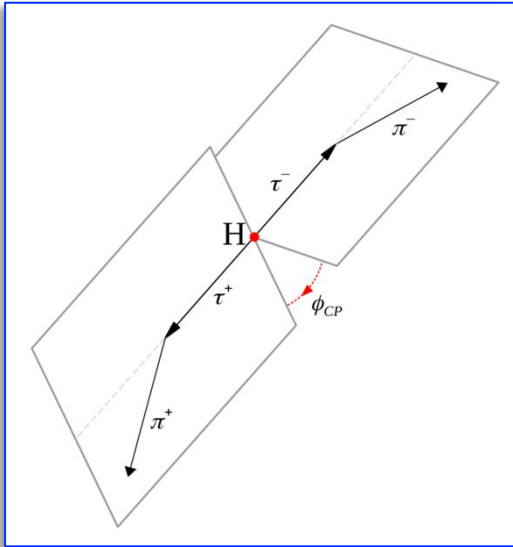


EFT global fit from ATLAS



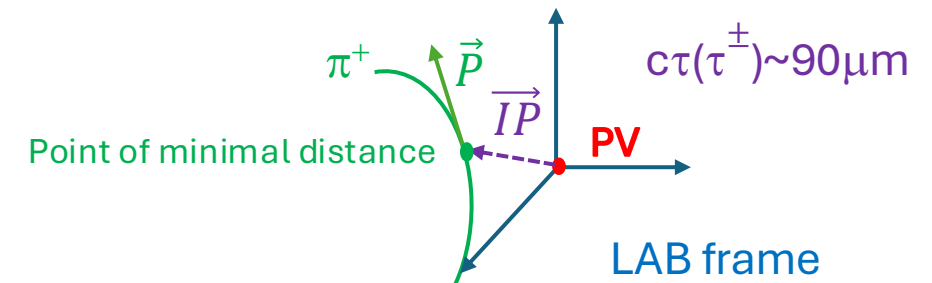
Simultaneous fit to **47 coefficients** after choosing the new “fit” basis defined in the left figure

CP interactions H- τ lepton



JHEP 06 (2022) 012

$$\frac{d\Gamma}{d\phi_{CP}}(H \rightarrow \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$



- 4 different methods employed to reconstruct ϕ_{CP} depending on the τ decay products.
- For example, for $\tau \rightarrow \pi^+\nu$ use the *impact-parameter method*: plane defined by the π direction and its impact parameter vector
- Approximate the Higgs rest frame using the 0-momentum frame (ZMF) of the charged decay products, both vectors boosted in this frame and used to build the two planes and their angle

CMS upgrade for HL-LHC

9

Tracker

- Enhanced radiation tolerance
- Increased granularity
- Extended coverage to $|\eta| \sim 4$
- Designed for tracking in L1T

MIP timing detector (MTD)

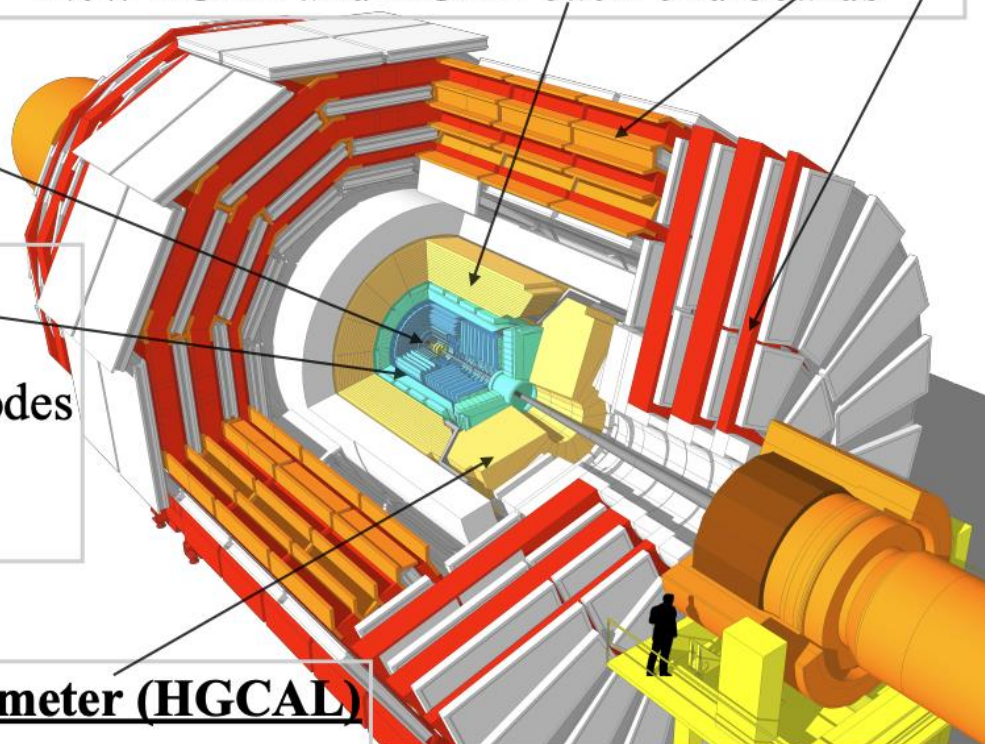
- Barrel: LYSO crystals + SiPMs
- Endcap: Low-gain avalanche diodes
- 30 ps timing resolution
- Full coverage to $|\eta| \sim 3$

High-Granularity Endcap Calorimeter (HGCAL)

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

Barrel Calorimeter

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- New ECAL and HCAL back-end boards



Beam Radiation Instrumentation and Luminosity (BRIL)

- Target 1% offline (2% online) luminosity uncertainty

Muon system

- New Drift Tubes (DTs) & Cathode Strip Chambers (CSCs) FE/BE readout
- New Resistive Plate Chambers (RPCs) BE electronics
- New Gas Electron Multipliers (GEMs) & iRPCs
- Extended coverage to $|\eta| \sim 3$

Level 1 Trigger

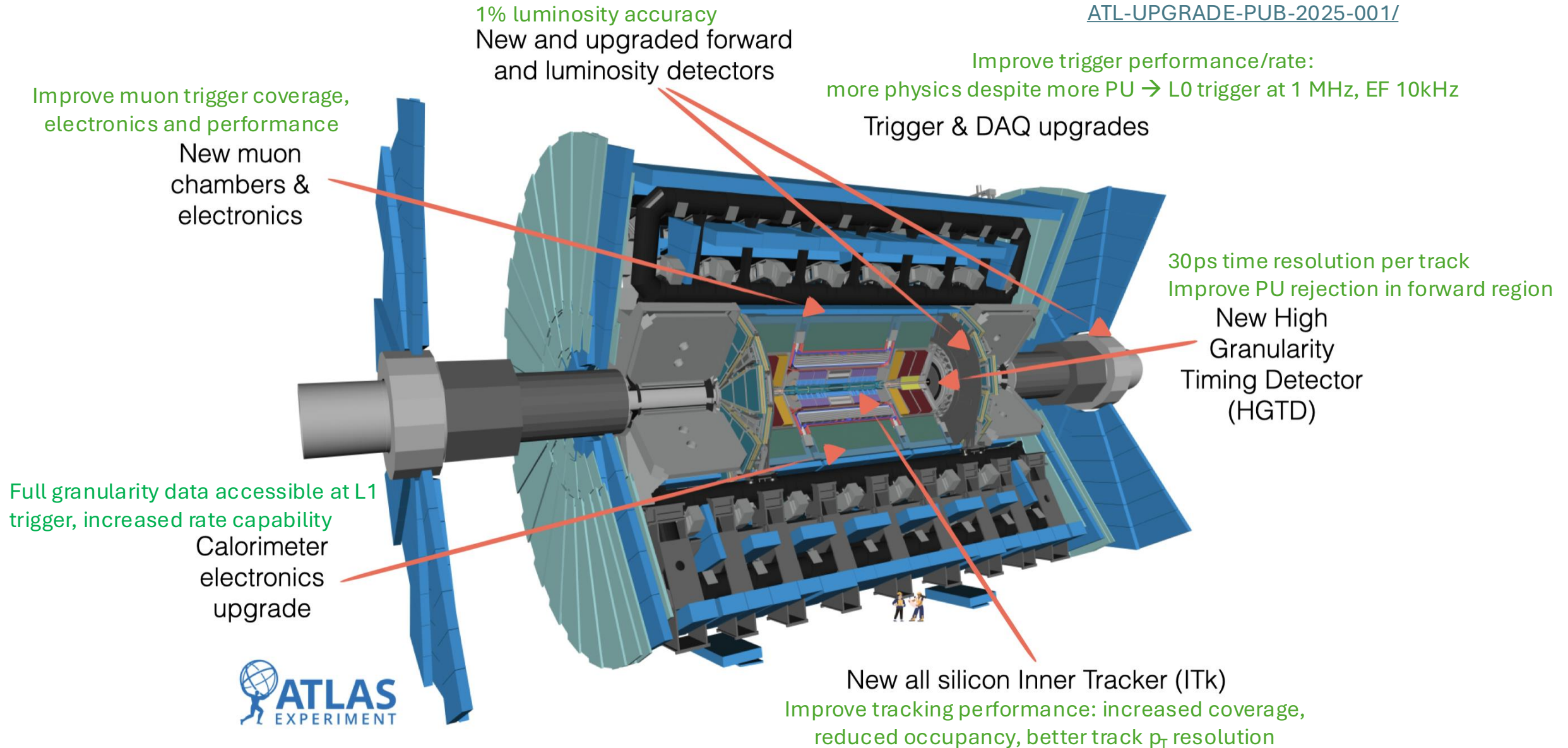
- New track trigger at 40 MHz
- Particle flow selection
- 750 kHz L1 output
- 40 MHz data scouting
- L1T latency: 12.5 μ s

DAQ & High Level Trigger (HLT)

- Full optical readout
- Heterogeneous architecture
- 60 TB/s event throughput
- 7.5 kHz HLT output

The Phase II upgrade program

[ATL-UPGRADE-PUB-2025-001/](#)



	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%