Measurement of $H \rightarrow ZZ^{*} \rightarrow 4l$ and $H \rightarrow \mu\mu$ using the ATLAS detector at the LHC

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Outline

- Why do we study the Higgs boson and its rare decays?
- How the Higgs fits into the Standard Model
- How we study Higgs decays at the LHC
- Two key Higgs decay channels:
    - H → ZZ* → 4 leptons (clean and precise)
    - H → μμ (rare but important)
- What we've learned and what's next

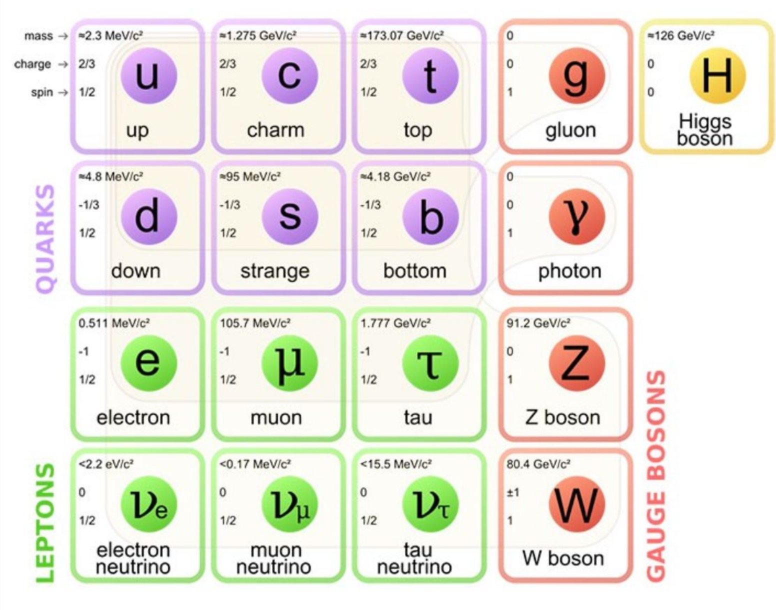
The Standard Model (SM)

- The Standard Model explains the fundamental particles and forces of the universe - the “laws” of Nature.
- It includes:
    - Matter particles: electrons, quarks, neutrinos, etc
    - Force carriers: photons (electromagnetic), W/Z bosons (weak force), gluons (strong force carriers)

- The Higgs field gives the fundamental particles their mass.
    - An excitation of the Higgs field manifests as particle: **the Higgs boson!**

- But there are still big mysteries not explained by the SM
    - What is dark matter?
    - Why do neutrinos have mass?
    - How does gravity fit in?

The Standard Model of particle physics



Through careful studies of the Higgs boson, we hope to find clues to answer these questions!

The Higgs Boson:
A Cornerstone of the Standard Model

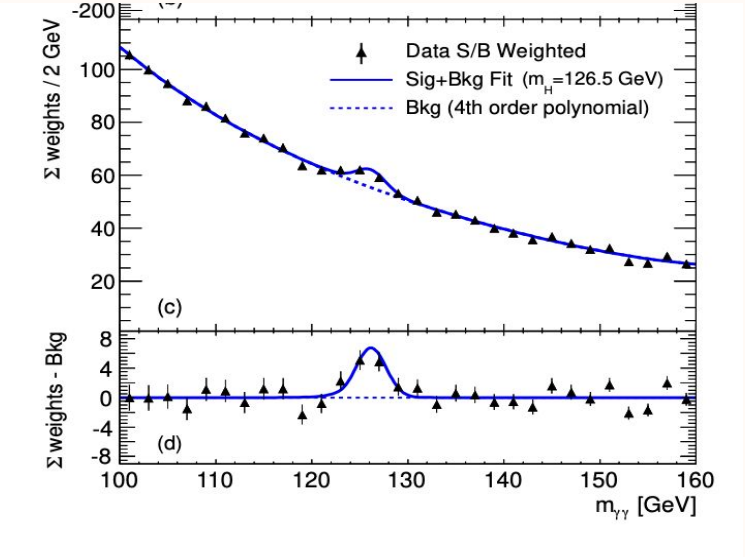
- **Discovered in 2012** by ATLAS & CMS at the LHC — confirms the Higgs mechanism that gives mass to fundamental particles.

- **Mass ~125 GeV**, extremely narrow width (~4 MeV) which is too small to measure directly with current detectors

- **Can decay** in different ways:
  - To force carriers (Z, W, photons)
  - To matter particles like muons and quarks

- Still unknown:
  - Does it interact with itself?
  - Are there other Higgs-like particles?
  - Could it decay into dark particles?

H → γγ



Yukawa coupling

- The Yukawa coupling quantifies the coupling between a given particle and the Higgs field
- The Yukawa coupling is directly proportional to the mass of the particle
- The stronger a particle couples to the Higgs field, the more it interacts with the Higgs boson
- In other words:
  More mass → stronger coupling → more interactions
    - Hence $H \to \mu\mu$ very rare (μ has small mass!)
    - Want to verify that also μ follows the expected trend: coupling proportional to mass

The particle with greatest mass is the **top quark**, having about the same weight as an atom of gold.

It is **60 billion times** larger than the electron neutrino, the smallest known particle.

Like the other large particles, the **Z boson** lasts an infinitesimally small time before decaying away into smaller particles.

The **W boson** particle is essential for weak nuclear reactions. Without it, the sun would not shine.

The now famous **Higgs boson** is part of the Higgs field, which interacts with almost all particles in the universe to give them mass.* In general, the more a particle interacts with the Higgs field, the more mass it has.

*except neutrinos

Almost identical in size, the proton and neutron are the only particles shown here which are composites, consisting of even smaller particles: up quarks and down quarks.

symmetrymagazine.org

The Large Hadron Collider & The ATLAS experiment

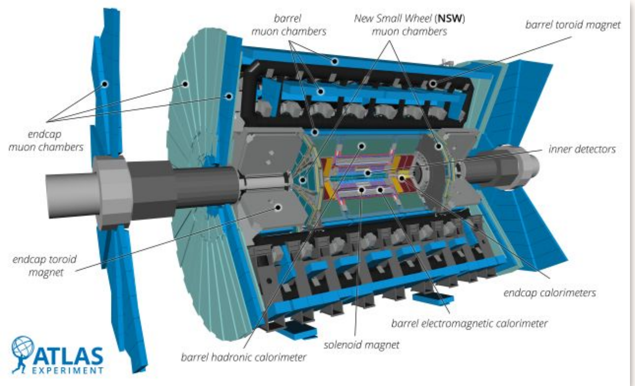
- **The LHC** at CERN (Geneva) is the world's most powerful particle collider:
    - 27 km ring, ~100 m underground
    - Collides protons at √s = 13.6 TeV (Run 3)
- **Recreates the extreme** conditions of the early universe
    - Only machine powerful enough to produce Higgs bosons

- **ATLAS** is one of two general-purpose detectors at the LHC (alongside CMS), designed to measure a wide range of processes (from Higgs bosons to dark matter candidates)

- **Layered detector system** enables full event reconstruction:
    - **Inner Detector** – precise tracking of charged particles
    - **Calorimeters** – measure energy of electrons, photons, and hadrons
    - **Muon Spectrometer** – identifies and measures muons

https://cds.cern.ch/record/2253966

https://atlas.cern/Resources/Schematics



Analyses Overview

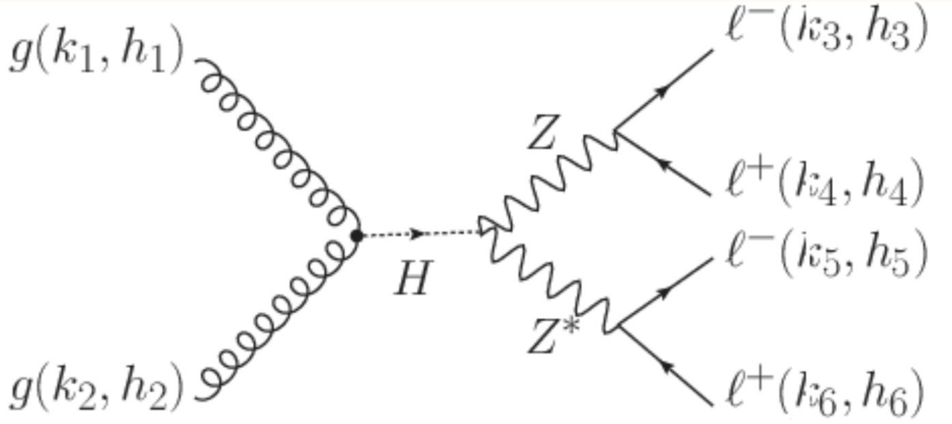
- **Two Higgs decay modes will be presented:**
  - **The golden channel H → ZZ* → 4ℓ**: clean and precise
  - **H → μμ**: very rare, but key for testing Higgs interactions with lighter particles (first test of Higgs boson interaction to second-generation fermions).

- What we do:
  - Select events with Higgs-like signatures
  - Group events by production mode
  - Use statistical models to extract signal from background

The golden decay channel

$H \rightarrow ZZ^* \rightarrow 4\ell$

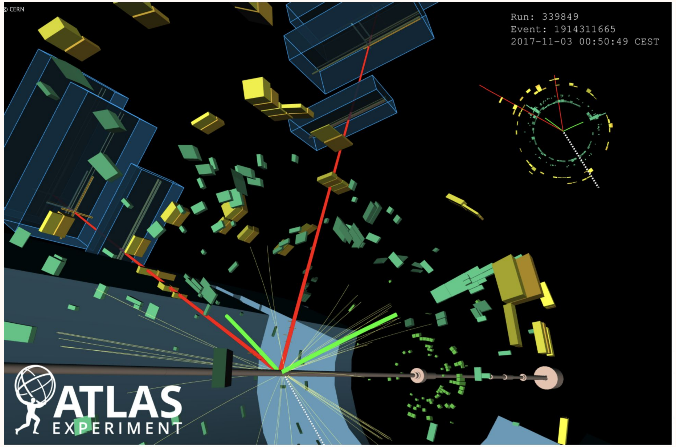
https://cds.cern.ch/record/2748809/plots?ln=en



Dataset & Event Selection

- We use proton-proton collision data taken in 2015-2018 (Run 2) and 2022-2024 (Run 3) totaling nearly 200 fb^{-1}.
- Events must contain exactly four high-quality leptons (electrons or muons).
- Each lepton must be energetic, isolated, and come from the same collision point (vertex).
- We form lepton pairs to reconstruct two Z bosons — one close to the known Z mass (~91 GeV).
- If multiple combinations exist, we choose the best one based on particle type and momentum resolution.

Event display of a $H\to ZZ^{*}\to 2\mu 2e$ candidate



- Background : other processes that look like Higgs decays

- Most common: regular production of Z bosons decaying to four leptons

- Others:
  - fake leptons (other particles misidentified as muons/electrons) from unrelated particles or rare processes.

- We estimate background directly from data to reduce simulation bias

- Then we look for a bump in the mass spectrum from the Higgs

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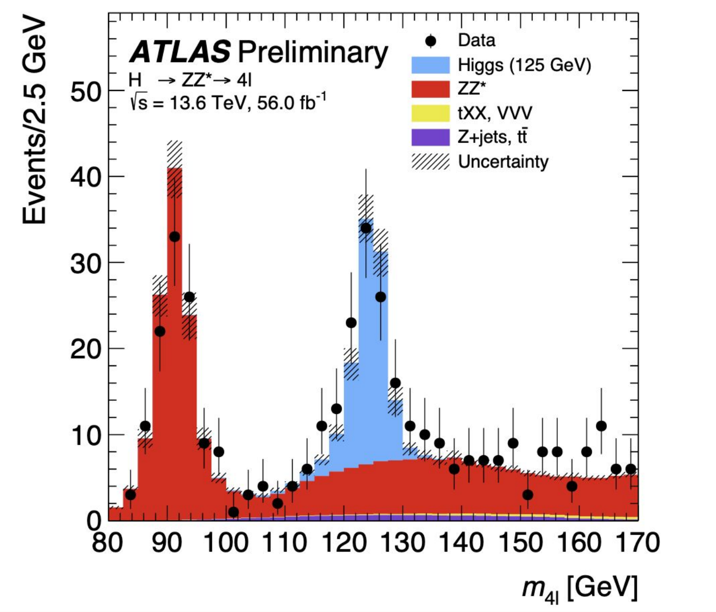

Additional Information:
Jiayi Chen

Cross sections

- We measure the cross section which is the combination of
  - how often Higgs bosons are produced in collisions (the production cross section), and
  - how likely they are to decay into four leptons (the branching ratio).
- We study the total rate (**inclusive),** and how it varies with key properties (**differential**).
- These measurements are done within a well-defined detector region (**fiducial** phase space).
- We explore how the Higgs behaves as a function of:
  - Its momentum ($\mathbf{p_T}$)
  - Direction (rapidity **y**)
  - **Jet activity** and Z boson **masses**

- These results allow precise comparisons with theory and help us look for deviations from the Standard Model.

Cross section: Results

Inclusive & Fiducial cross sections

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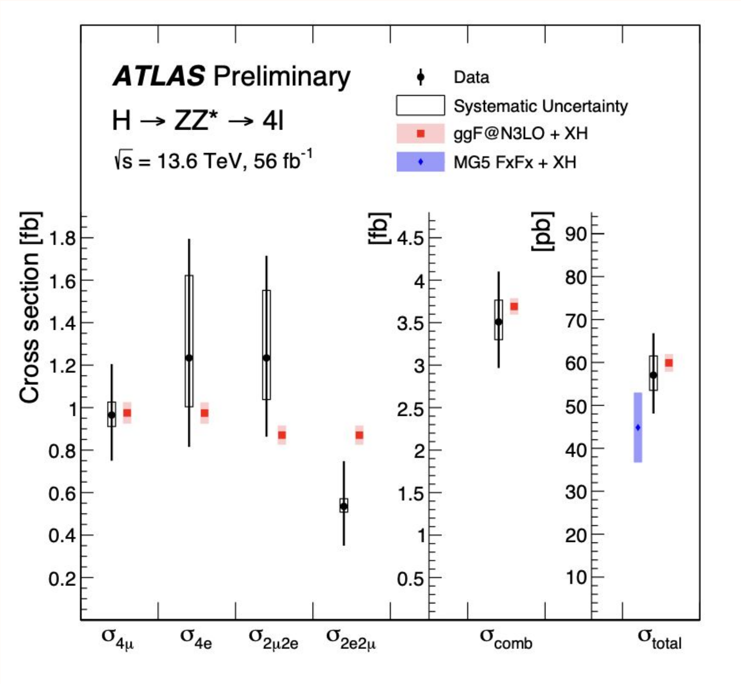
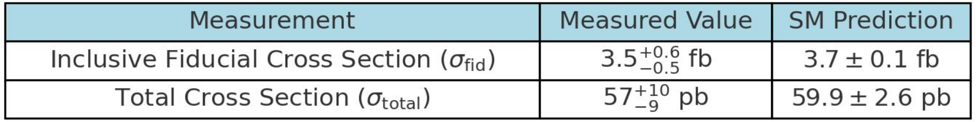




Measurement	Measured Value	SM Prediction
Inclusive Fiducial Cross Section (σ_{fid})	$3.5^{+0.6}_{-0.5}$ fb	3.7 ± 0.1 fb
Total Cross Section (σ_{total})	57^{+10}_{-9} pb	59.9 ± 2.6 pb

- Results agree with Standard Model predictions.
- Electron-based final states have larger uncertainties.

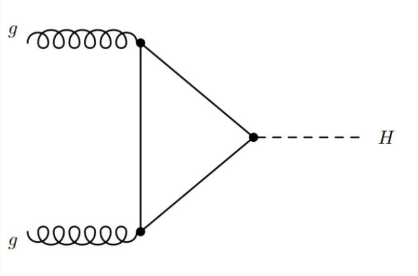
Production mechanisms

- The **production cross section** quantifies the probability of a Higgs boson being produced via a specific mechanism
  - Different production mechanisms create different experimental signatures
  - They allow us to test **Higgs couplings** to other particles and explore how the Higgs behaves in various environments.

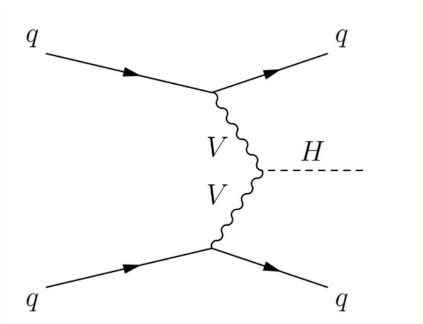
Main production modes:

- **Gluon Fusion (ggF)** – Most common (~90%)
  Gluons interact via a top-quark loop to produce a Higgs.
- **Vector Boson Fusion (VBF)** – Quarks emit W/Z bosons, which fuse into a Higgs.
  Characterized by two forward jets.
- **Associated Production (VH)** – Higgs produced with a W or Z boson.
  Useful for leptonic decays.
- **Top-Associated (ttH)** – Higgs produced with a top–antitop pair.
  Rare but gives direct access to the top–Higgs coupling.

VBF



ggF



Production cross sections

- Events are classified based on jet multiplicity, lepton count, and kinematic variables (e.g., dilepton mass, transverse momentum).
- These categories enhance sensitivity to different Higgs production modes — for example:
  - **VBF-enriched**: Two forward jets with a large rapidity gap
  - **VH-enriched**: Presence of additional leptons or missing energy from vector boson decays
- Machine learning models (neural networks) are trained to distinguish between production modes beyond cut-based categorization.
- Inputs include:
  - **Jet and lepton multiplicities**
  - **Lepton kinematics**: pT, η invariant mass
  - **Event topology**: angular separations, missing transverse energy, dijet invariant mass
- These models exploit subtle correlations in the event structure that are difficult to capture with traditional techniques.

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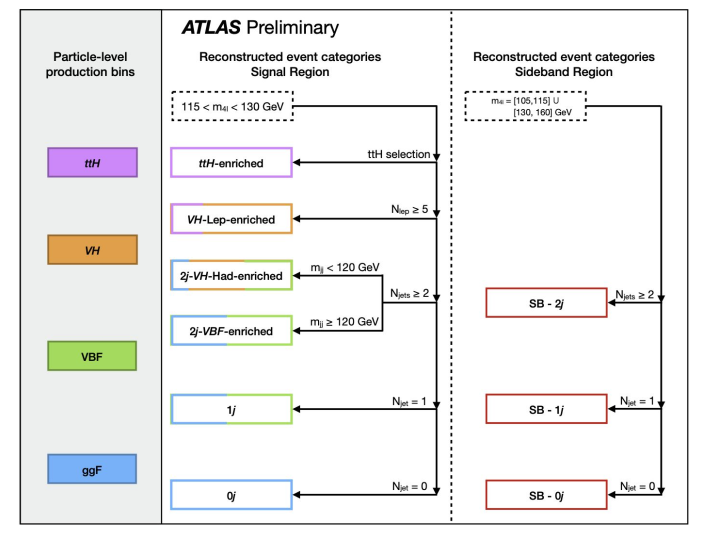

Production cross sections: Results

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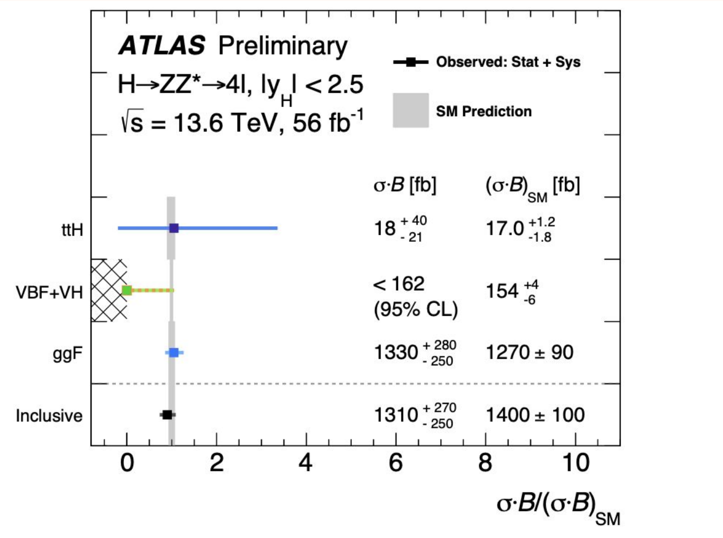
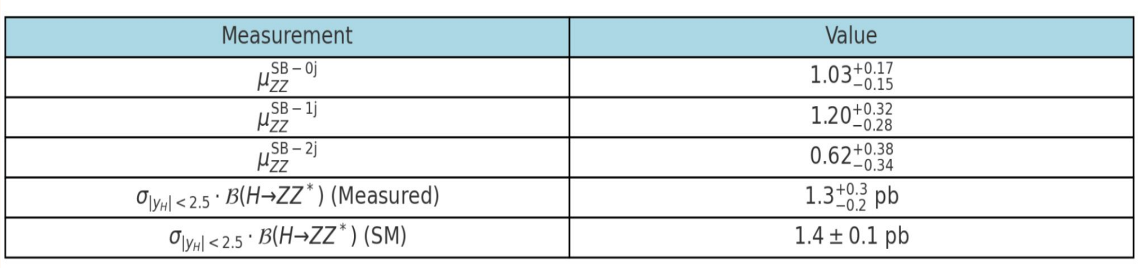




Measurement	Value
μ_{ZZ}^{SB-0j}	$1.03^{+0.17}_{-0.15}$
μ_{ZZ}^{SB-1j}	$1.20^{+0.32}_{-0.28}$
μ_{ZZ}^{SB-2j}	$0.62^{+0.38}_{-0.34}$
$\sigma_{\|y_H\|<2.5} \cdot \mathcal{B}(H\to ZZ^*)$ (Measured)	$1.3^{+0.3}_{-0.2}$ pb
$\sigma_{\|y_H\|<2.5} \cdot \mathcal{B}(H\to ZZ^*)$ (SM)	1.4 ± 0.1 pb

- We perform a simultaneous fit across all categories (0j, 1j, 2j, VBF, VH, ttH...) to disentangle the contributions from different Higgs production modes.
- Each category targets a specific production signature, increasing our sensitivity to rare modes like VBF or ttH.
- The signal strengths (μ) — ratios of measured to predicted yields — are consistent with the SM across all jet multiplicities.
- The measured cross section in the fiducial region is in excellent agreement with the SM prediction:
    - This agreement strengthens confidence in the Higgs boson’s behavior as predicted by the Standard Model.

Systematic Uncertainties

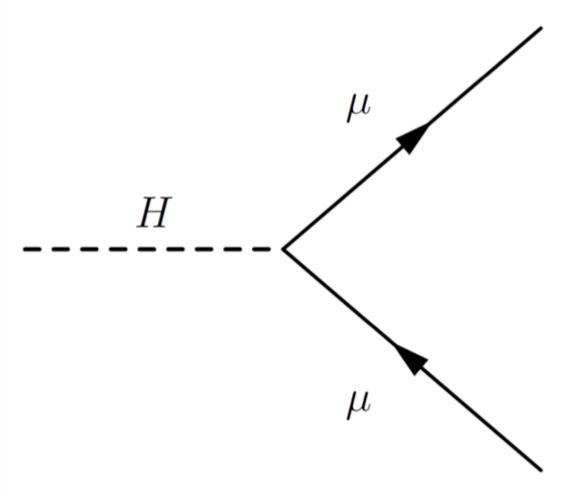
- Systematic uncertainties reflect imperfect knowledge of the experiment and theory.
- Key sources include:
  - Detector performance (e.g., how well we measure leptons)
  - Background modeling and event selection
  - Theoretical predictions (e.g., cross sections, parton distributions)
  - Total luminosity of the dataset

- These uncertainties are included in the statistical model and affect both yield and the shape of the distributions.

- In H → 4ℓ, lepton calibration and background modeling (especially from non-resonant ZZ production) are among the dominant sources, and can impact the signal strength and mass shape.

$H \rightarrow \mu\mu$

https://cds.cern.ch/record/2748292/plots?ln=en



H->μμ: Motivation

- The Higgs → μμ decay is extremely rare — expected in only 1 in 5,000 Higgs decays.
- Measuring it tests whether the Higgs gives mass to second-generation fermions (like muons).
- This is the **first time** we can directly probe the **Higgs–μ** coupling.
- It provides a complementary test to decays into heavy particles (like Z bosons or top quarks).
- Detecting the signal requires excellent mass resolution and advanced analysis techniques.

Analysis Strategy & Event categorisation

- Boost sensitivity by dividing events into **20 distinct categories.**
- Categories are optimized for different **Higgs production modes**:
  - **Gluon Fusion (ggF)** – most common
  - **Vector Boson Fusion (VBF)** – features forward jets
  - **Associated Production (VH, ttH)** – includes leptons, b-jets
- **Each category is defined by**:
  - **Jet activity** (jet multiplicity, dijet invariant mass)
  - **Muon geometry** (central vs forward muons)
  - **Event topology** (e.g. VBF-like structure)
- Improves **signal-to-background ratio**
- Allows targeted fits in regions with **different backgrounds and resolutions**
- **Advanced techniques** (e.g. machine learning) further refine separation.

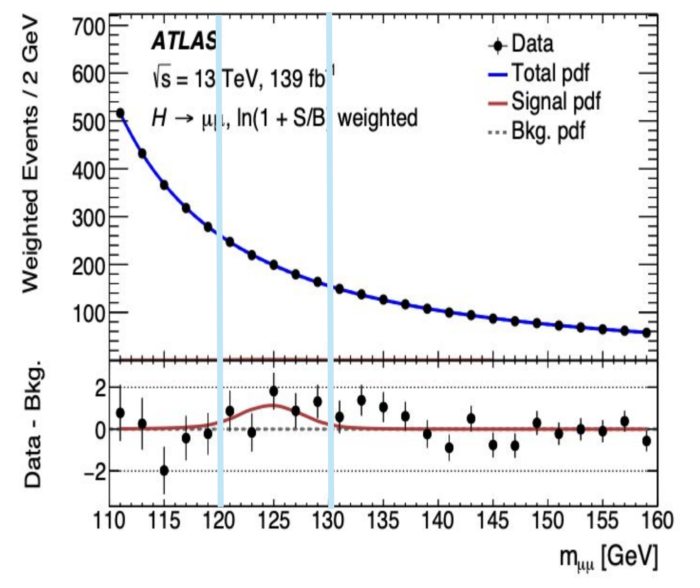
Systematic Uncertainties

- Systematics affect both the **signal yield** and **mass shape**, and are included in the fit as extra uncertainty terms
- **Experimental:**
  - Muon momentum scale/resolution
  - Trigger, reconstruction efficiency
  - Jet-related uncertainties (for VH/ttH)

- **Theoretical:**
  - Higgs production modeling
  - Parton shower and PDFs
  - Signal lineshape choice

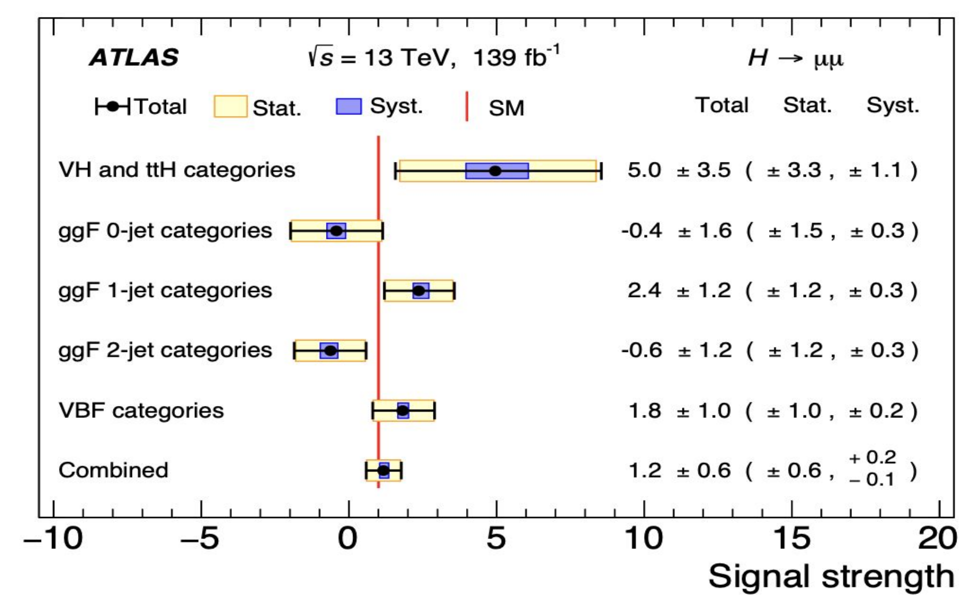
Signal modelling & background

arXiv:2007.07830v2



- We model the observed dimuon mass spectrum using:
  Total Model = μ × Signal(μμ) + Background(μμ)
- The **signal** appears as a narrow peak around **125 GeV**, modeled using a **Gaussian** or **Crystal Ball** function based on **simulation**.
- The **background** is a smooth, decreasing distribution — typically described by an **exponential** or **polynomial**.
  Importantly, we do not take this shape from simulation.
- Instead, we determine the background shape by fitting **data outside the signal region**, known as **sidebands**:
  - Sidebands: [110–120 GeV] and [130–160 GeV]
  - These regions are assumed to be **signal-free**, so the background shape is derived directly from **real data**.

Fit Results per category



arXiv:2007.07830v2

- We extract the **signal strength μ** from a simultaneous fit across all categories.
- Each production mode (ggF, VBF, VH, ttH) contributes differently to sensitivity.
- Signal strengths are compatible with the Standard Model (μ = 1).
  - Largest deviation seen in VH/ttH category (not statistically significant).

Combined result & Outlook

- The **combined fit** shows an excess at **$\mu = 1.2 \pm 0.6$**, corresponding to a **2.0σ** significance.
- Not enough for a discovery, requires **5σ** to confirm a signal.
- The **HL-LHC** will provide enough data (~3000 fb^{-1}) to reach discovery potential for $H \to \mu\mu$.

Summary

What We’ve Measured

H → ZZ → 4ℓ

- We precisely measured the Higgs decay to four leptons.
    - Mass, width, signal strength (μ), and production rate (cross-section)

H → μμ

- First evidence for the Higgs decaying to muons
    - Signal strength: μ = 1.2 ± 0.6 (**consistent** with SM expectations)
    - Significance: 2.0σ (**not a discovery yet,** but promising)
- Confirms the Higgs interacts with second-generation fermions

Still missing

- Higgs → μμ not yet observed at the 5σ (discovery) level
  - But it's a key test of how the Higgs gives mass to light matter
- No anomalies seen in H → ZZ*
  - Decay patterns match Standard Model predictions
- No significant signs of new physics (yet)

Next Steps

- Run 3 and HL-LHC will deliver much more data
  - Improved precision for Higgs → μμ and rare decays
  - First opportunities for precision Higgs self-coupling studies
- Upgraded analysis techniques
  - Better multivariate (ML) tools
- Combining results with CMS will be essential
  - It increases our statistical power

Thank you

Back up

K- framework

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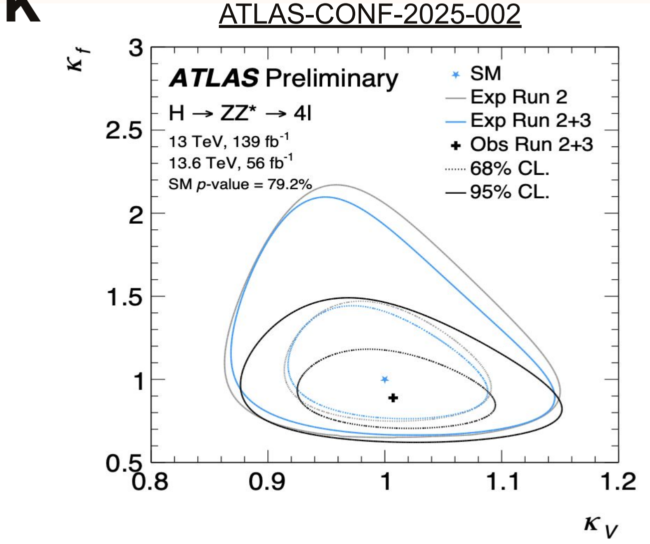

- The κ-framework tests how strongly the Higgs couples to other particles.
  - κ = 1 means the strength matches the Standard Model prediction.
    - κ_V: Higgs coupling to vector bosons (W, Z)
    - κ_f : Higgs coupling to fermions (quarks, leptons)
  - If κ differs from 1, it could indicate new physics.
- We fit the data to extract the best values of κ_V and κ_f, using all decay and production channels.
- Couplings re consistent with the Standard Model within uncertainties

Effective Field Theory (EFT) Interpretation of Higgs Couplings

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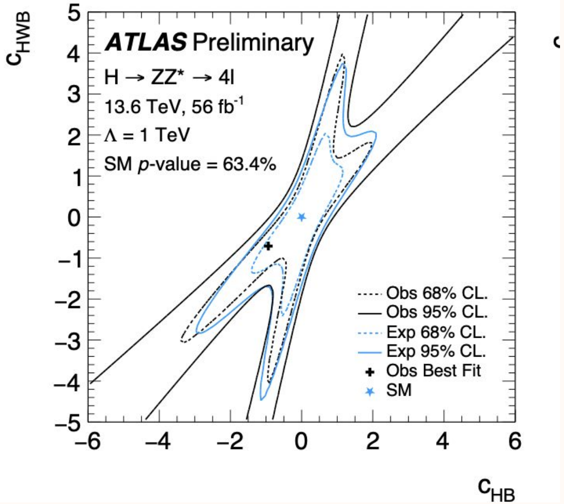

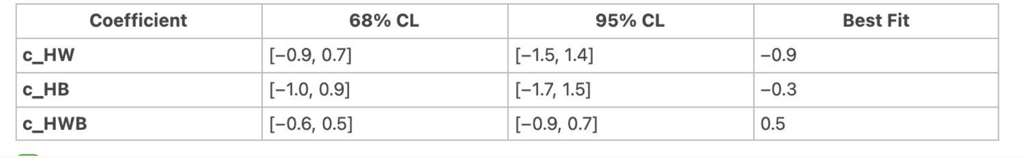

Coefficient	68% CL	95% CL	Best Fit
c_HW	[−0.9, 0.7]	[−1.5, 1.4]	−0.9
c_HB	[−1.0, 0.9]	[−1.7, 1.5]	−0.3
c_HWB	[−0.6, 0.5]	[−0.9, 0.7]	0.5

- EFT allows us to test for subtle effects of new physics that may not appear directly.
    - It adds extra terms (“operators”) to the Standard Model equations.
- Each operator has a “Wilson coefficient” — a number that tells us how strong the new effect is.
    - If all coefficients are zero, we recover the Standard Model.
- All fitted values are consistent with the Standard Model (i.e., zero).
    - No significant signs of new physics, but we set limits on possible deviations.

Fiducial/rapidity restricted/total cross section

- **Fiducial** = what we measure **directly** in the detector
- **Rapidity-restricted inclusive**: broader but still partially model-independent
- **Total**: covers everything but needs full extrapolation using acceptance + BR.

$$\sigma_{\mathrm{tot}}^{H} = \frac{\sigma_{\mathrm{fid}}^{4\ell}}{A \cdot \mathcal{B}(H \to ZZ^{*}) \cdot \mathcal{B}(ZZ^{*} \to 4\ell)}$$

- **Fiducial cross section in bin j** is extracted by fitting m4ℓ distributions across reconstruction bins i, accounting for detector effects and acceptance.

$$N_i(m_{4\ell}) = \sum_j \sigma_j^{\mathrm{fid}} \cdot P_i(m_{4\ell}) \cdot r_{ij} \cdot (1 + f_i^{\mathrm{nonfid}}) \cdot \mathcal{L} + N_i^{\mathrm{bkg}}(m_{4\ell})$$

$\sigma_j^{\mathrm{fid}} = \sigma_j \cdot a_j \cdot B$
$P_i^{(m4\ell)}$: signal shape in bin i
r_{ij}: detector response matrix
f_i^{nonfid}: fiducial leakage
$a_{j:}$ acceptance, B: branching ratio, L: integrated luminosity

Acceptance

$$A = \frac{N_{\text{fid}}^{\text{truth}}}{N_{\text{total}}^{\text{truth}}}$$

- The fraction of signal events that fall within the **fiducial phase space** at **particle level** (truth, stable leptons only).
- **Generate signal MC** (e.g., Powheg+Pythia, ggF+VBF+VH+ttH).
- At **truth level**, apply fiducial cuts to stable leptons:
  - 4 isolated leptons (electrons or muons),
  - pTℓ1>20 pTℓ2>15, pTℓ3>10>10 GeV, pTℓ4>7 GeV
  - ∣ηℓ∣<2.5
  - On-shell Z: ∣m12−mZ∣<15 GeeV
  - Off-shell Z: m34>12 GeV,
  - 105<m4ℓ<160.

Count:

- Nfidtruth: events that pass cuts,
- Ntotaltruth: all generated events.

Typical value: A≈0.45 for H→ZZ∗→4ℓ in Run2

Differential cross sections

- The Higgs boson transverse momentum, pT4ℓ
  - provides a test of **perturbative QCD calculations** and is sensitive to the structure of Higgs boson interactions.
- The rapidity of the Higgs boson, y4ℓ, is:
  - sensitive to the parton distribution functions **(PDFs**) of the colliding protons, and
  - influenced by QCD radiative corrections.
- The jet multiplicity, Njets, is:
  - sensitive to different Higgs boson **production mechanism**s, and
  - provides sensitivity to the theoretical modeling of high-pTpT quark and gluon emission.
- The invariant mass of the sub-leading lepton pair, **m34,** is:
  - sensitive to **higher-order electroweak corrections to** the Higgs boson decay, and
  - probes potential beyond-the-Standard-Model (BSM) contributions in the HZZ interaction vertex.

pT4l

- **Initial-State Radiation (ISR)**:
  - Gluons can radiate additional gluons before Higgs production.
  - This radiation imparts transverse momentum to the Higgs → pT4ℓ>0.
  - Dominates the **low-pTpT** region; requires resummation techniques in theory predictions.
- **Multiple QCD Emissions**:
  - Higher-order corrections (NLO, NNLO) introduce multiple partons in the final state.
  - These emissions modify the momentum balance, affecting **medium to high pTpT** regions.
  - Captured via parton showers and matrix-element corrections in simulations.
- **Recoil Against Jets**:
  - When the Higgs is produced with one or more jets (e.g. H+jets), it recoils against them.
  - Jet activity drives the Higgs to higher pTpT, especially important in the **high-pT** tail.
  - This region is sensitive to modeling uncertainties and potential BSM effects.

Rapidity

- **Rapidity** is a measure of a particle's motion along the **beam (longitudinal) direction** in a way that's especially useful in **high-energy collisions**.
- The **rapidity y** is defined as:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

    - E is the energy of the particle,
    - Pz is the momentum along the beam axis
- Differences in rapidity are **Lorentz-invariant** under boosts along the beam direction — ideal for collider physics.
- At high energies (when particle mass ≪ momentum), **rapidity ≈ pseudorapidity**, which is directly measurable from the detector.

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right)$$

    - θ is the **polar angle** between the particle's momentum and the beam axis.
- **In the context of Higgs physics:**
    - The Higgs boson rapidity y4ℓ tells us how far **forward or backward** the Higgs is produced in the detector.
    - It provides information about the **initial parton momentum fractions** (from the PDFs of the protons).

y4l

- **Rapidity y4ℓ** describes the Higgs boson’s motion along the beam axis (longitudinal boost).
- It depends on the momentum fractions x1 and x2 of the colliding partons → directly probes the **parton distribution functions (PDFs)**.
- Particularly sensitive to the **gluon PDF** in the dominant gluon-fusion production mode.
- **QCD radiative corrections** can modify the rapidity distribution, especially through initial-state radiation and higher-order effects.

Njets

- **Sensitive to Production Modes**:
  - Different Higgs production mechanisms (e.g. gluon fusion, vector boson fusion, associated production) produce different **numbers of jets** in the final state.
- **Probes QCD Radiation**:
  - The number of jets reflects the amount of **initial-state QCD radiation**, especially at high transverse momentum.
- **Discriminates Theory Models**:
  - Jet multiplicity tests the **theoretical modeling** of parton showers and higher-order QCD corrections.
- **Enables BSM Searches**:
  - Deviations in the jet spectrum could indicate **new physics**, such as anomalous couplings or heavy particles radiating extra jets.

m34

- **Defined as** the invariant mass of the subleading lepton pair in H→ZZ∗→4ℓ decays.
- **Sensitive to Electroweak Corrections**:
  - Accurate predictions of the m34m34 shape require inclusion of **higher-order electroweak (EW) corrections**, such as loop diagrams involving W, Z, and top quarks.
  - These corrections affect the **lineshape** of the off-shell Z∗Z∗, especially at low m34m34.
  - Incomplete modeling of EW corrections can lead to **mismatches between theory and data** in this region.

- **Probes New Physics in the HZZ Vertex**:
  - Anomalous couplings or BSM effects can distort the m34 distribution
  - If there are **anomalous couplings** (e.g., from dimension-6 EFT operators) that modify the HZZHZZ vertex, these can change the **momentum dependence** of the Higgs-to-ZZ interaction.
  - This would manifest as a **distortion in the m34m34 distribution**, particularly in the **low-mass tail**.
- **Tests Spin and CP Properties**:
  - Combined with angles, helps verify the **scalar nature of the Higgs**.