Rare Higgs Decays from ATLAS Experiment

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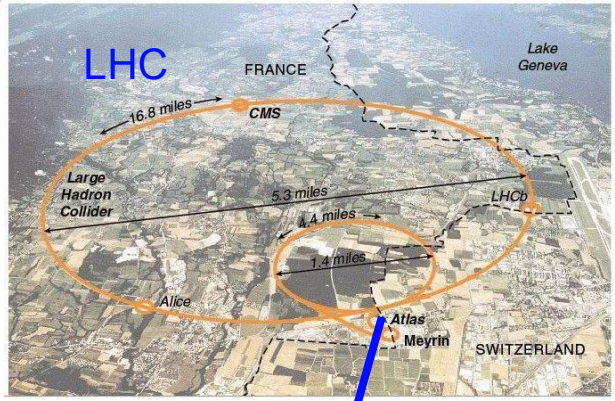
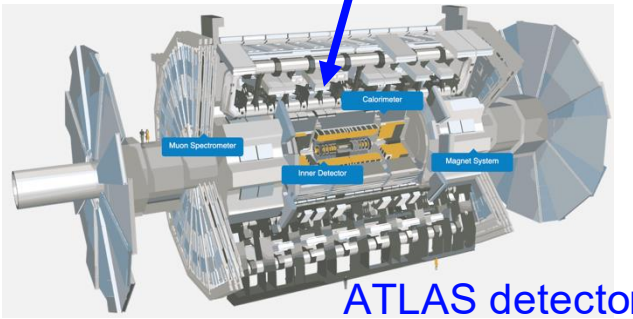
TeV物理前沿专题研讨会暨第31届LHC Mini-Workshop
2025年10月10日-12日

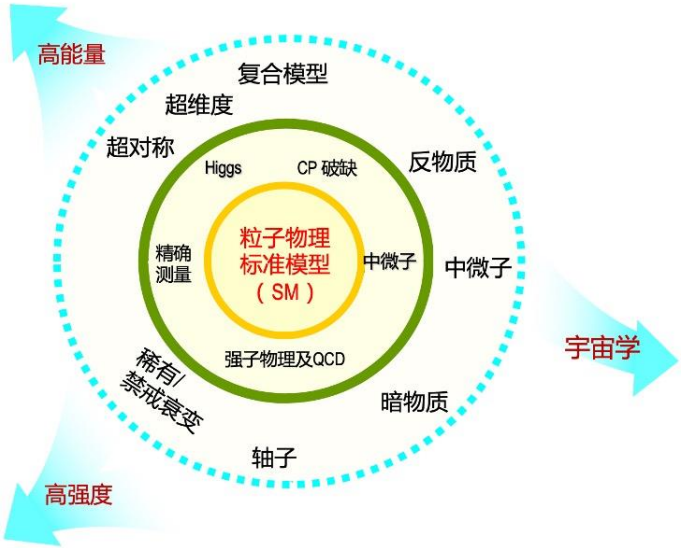
LHC and ATLAS Experiment





ATLAS detector

- High energy frontier: LHC experiments
- Higgs physics is one of the primary goals at the LHC



ATLAS collaboration: ~5000 people, around 200 institutes from >40 countries

Higgs Discovery in 2012

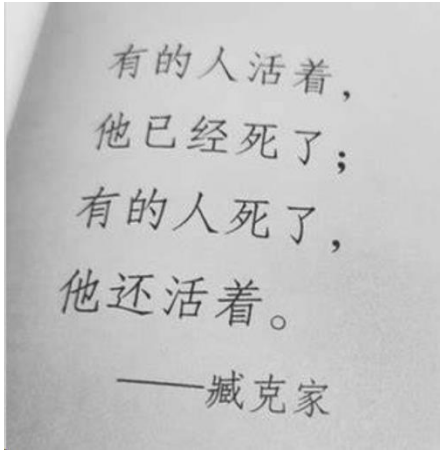
Peter left, but “Higgs” is there..

Statement on the death of Professor Peter Higgs

It has been confirmed that Professor Peter Higgs has died at the age of 94. He passed away peacefully at home on Monday 8 April following a short illness.

Professor Peter Higgs following confirmation of the existence of Higgs Boson particle in 2012.

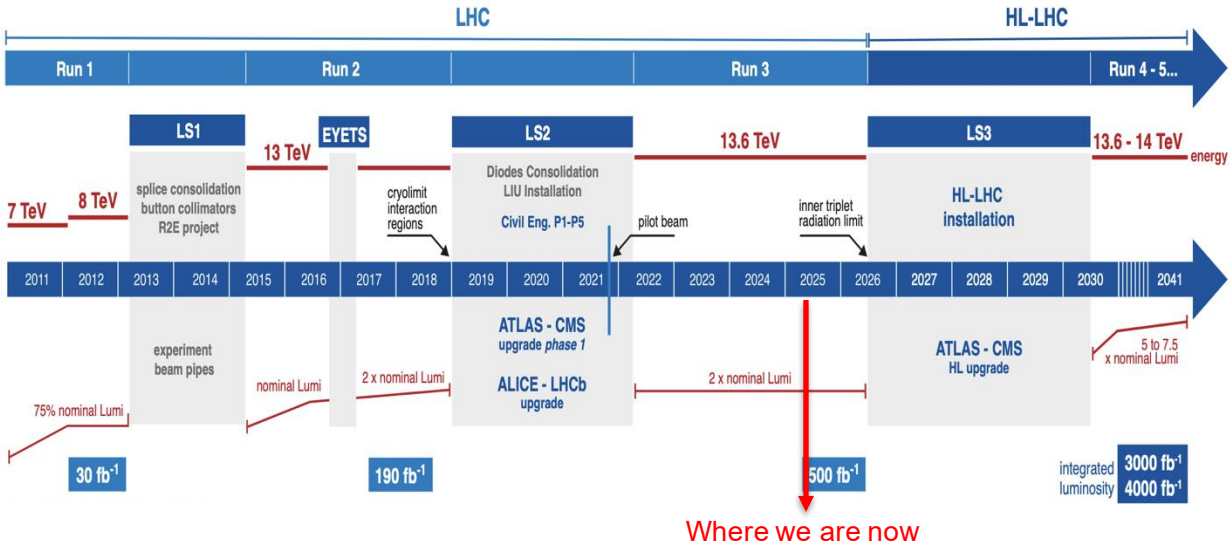
Higgs studies are crucial to be continued…

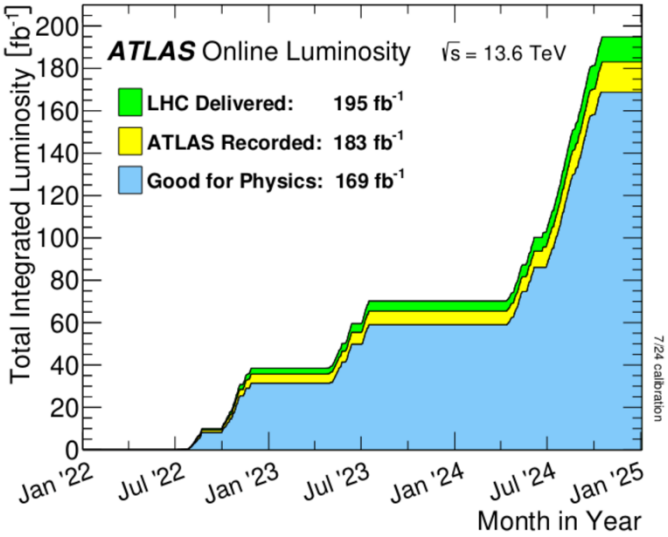


Open Questions about the Higgs

- Are the properties and couplings of the Higgs consistent with the SM prediction?
- What are its mass, width, rate, etc?
- How to access the structure of the Higgs potential?
- Can we probe the rare Higgs boson decays? ⟶ What I will cover today
- …

Run-2 and Run-3 Datasets

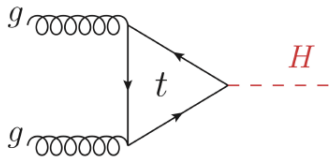




- During Run-2, 140 fb^{-1} (13 TeV) data collected for physics
- From 2022-2024 (partial Run-3), ~165 fb^{-1} (13.6 TeV) data for physics

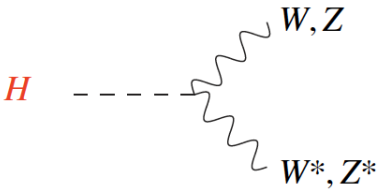
Higgs Production and Decay at LHC

ggF



Gluon fusion process

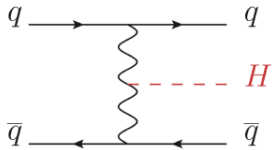
~8 M events produced



$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$

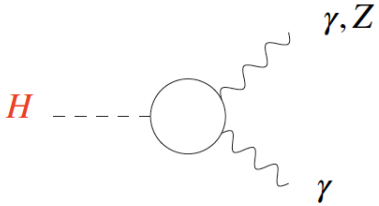
VBF



Vector Boson Fusion

Two forward jets and a large rapidity gap

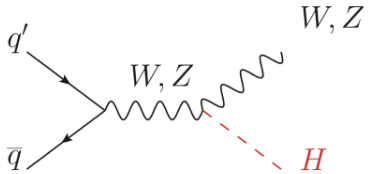
~600 k events produced



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$

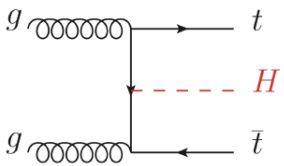
VH



W and Z Associated Production

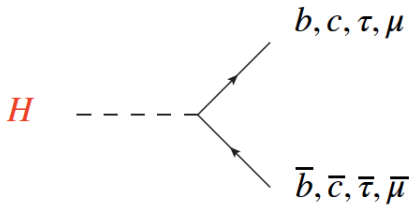
~400 k events produced

ttH



Top Assoc. Prod.

~80 k evts produced



$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

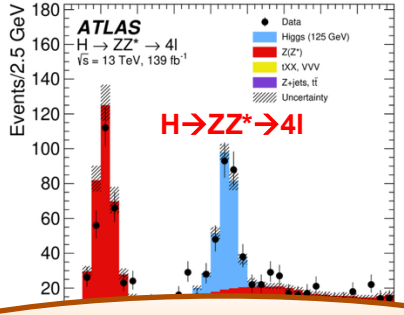
$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

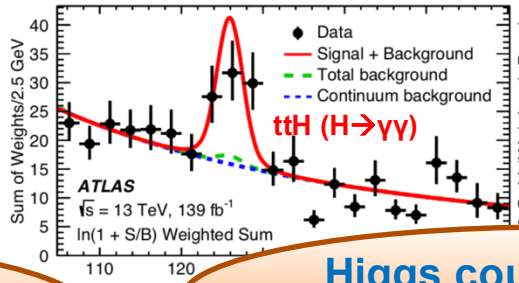
Outline of My Talk Today

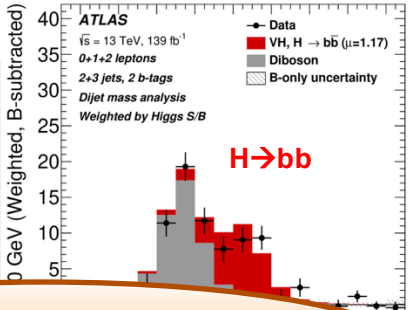
- H→μμ, H→cc and H→ee: Yukawa coupling to 2nd and 1st generation fermions
- H→Zγ and H→$\gamma^*\gamma$→llγ: decay via loops, sensitive to BSM physics

Disclaimer: due to time constraint, the selected topics are likely towards my personal taste, apologize for this!

Higgs Couplings to Massive Particles (>5σ)

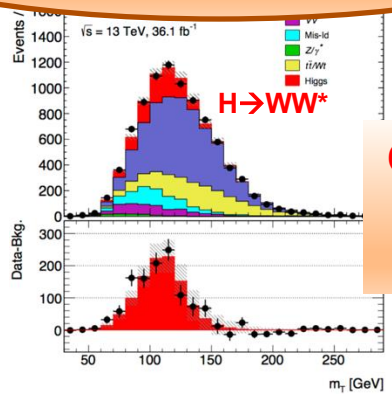




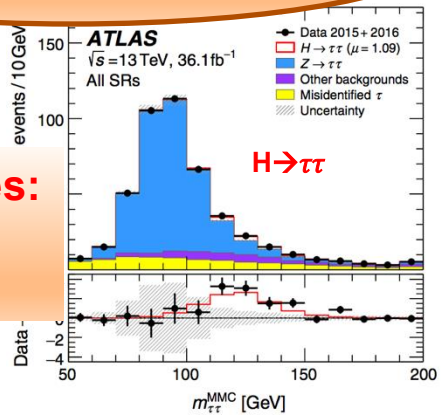


Higgs coupling to massive gauge bosons

Higgs couplings to the 3rd generation fermions

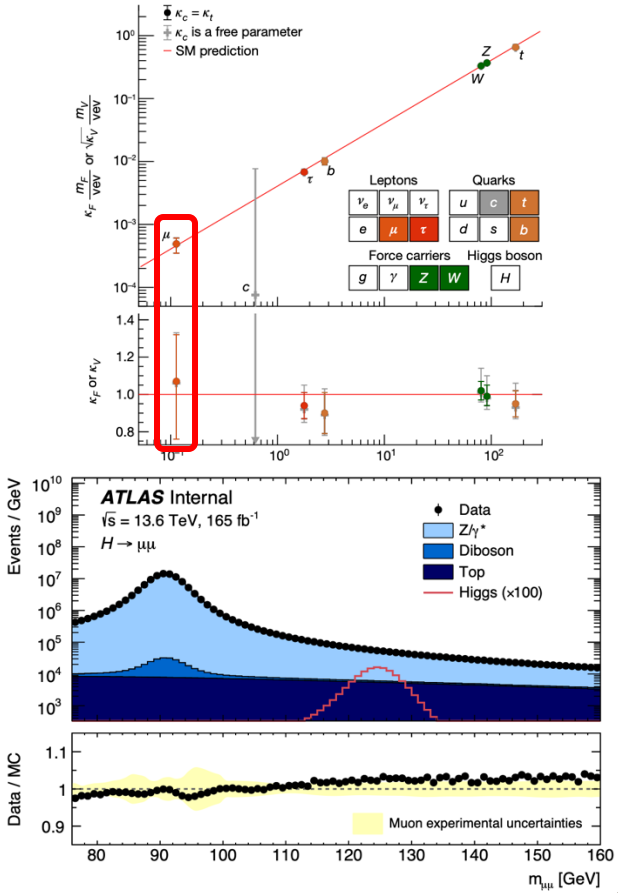


One of the next big milestones: Higgs couplings to the 2nd generation fermions



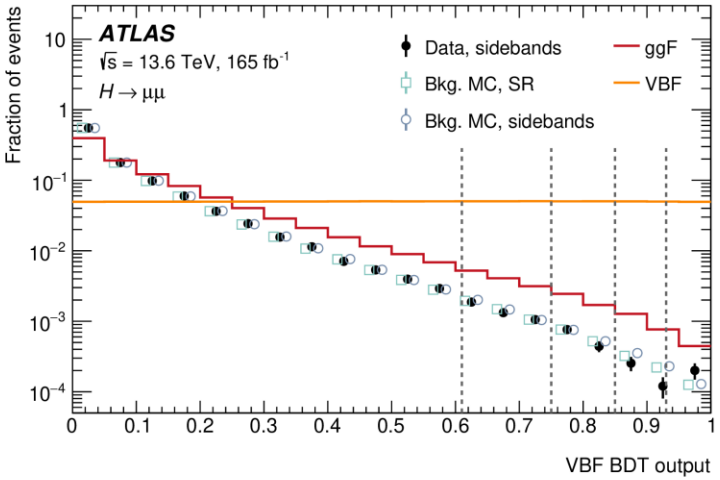
H→μμ: Physics Motivation

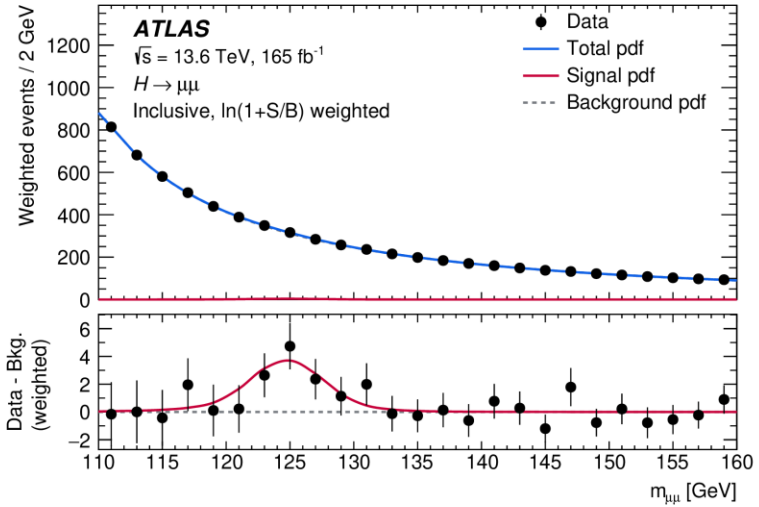
- H→μμ: most promising channel to explore Yukawa coupling to 2nd generation fermions
- Major challenge: low BR and large irreducible bkg. from Drell-Yan, S/B at ~0.1%
- Run-2 analysis: obs. (exp.) significance is 2.0σ (1.7σ)
- Latest analysis based on partial Run-3 (165 fb^{-1}) combining with full Run-2 (140 fb^{-1}) analysis



H→μμ: Analysis Strategy

- Signatures: 2 isolated muons with opposite charge
- MVA-based categorization driven by four major Higgs production modes
- Signal extraction: analytic function fit to $m_{\mu\mu}$ spectra (110-160 GeV)





H→μμ: Results

New!

- Run-3 data only: obs. (exp.) significance is 2.8σ (1.8σ), μ = 1.6 ± 0.6
- Run-2 and Run-3: obs. (exp.) significance is 3.4σ (2.5σ), μ = 1.4 ± 0.4
- First evidence of Higgs boson Yukawa coupling to 2nd generation fermions at the ATLAS experiment!
- Paper accepted by PRL, selected as Editors' Suggestion (arXiv:2507.03595)

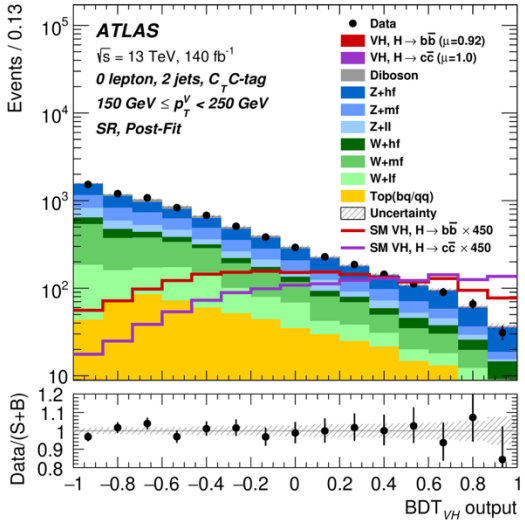
HIGGS AND ELECTROWEAK | NEWS

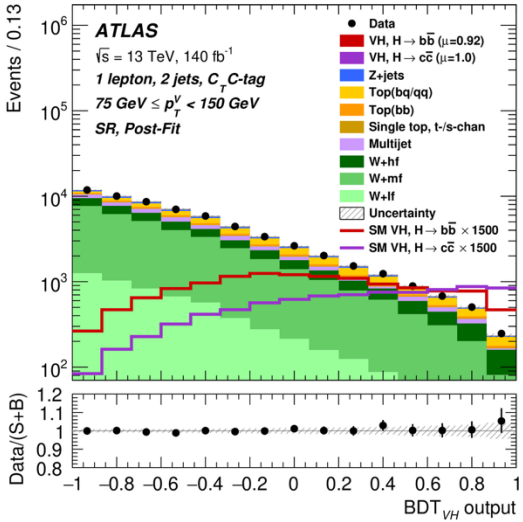
Mapping rare Higgs-boson decays

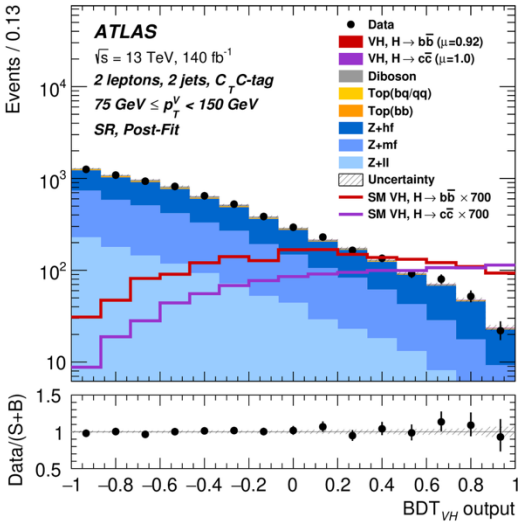
9 September 2025

H→cc: VH Analyses

- Direct probe of Higgs Yukawa coupling to the charm quark
- Hadronic signature at a hadron collider: need additional objects to trigger on and enhance S/B ratio
- Target leptonic decay of VH, major bkg.: W/Z+heavy-flavor, ttbar
- Used novel c-tagging techniques, BDT used to separate sig. from bkg.

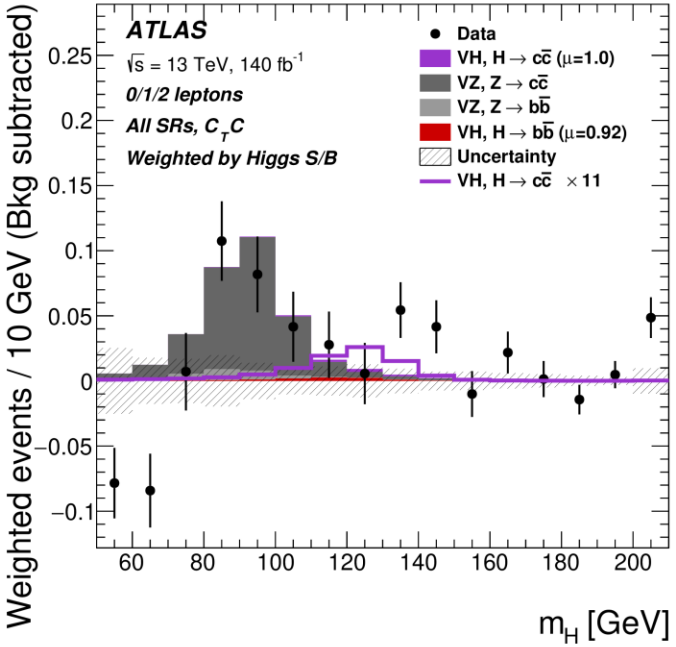






H→cc: Results

JHEP 04(2025) 075

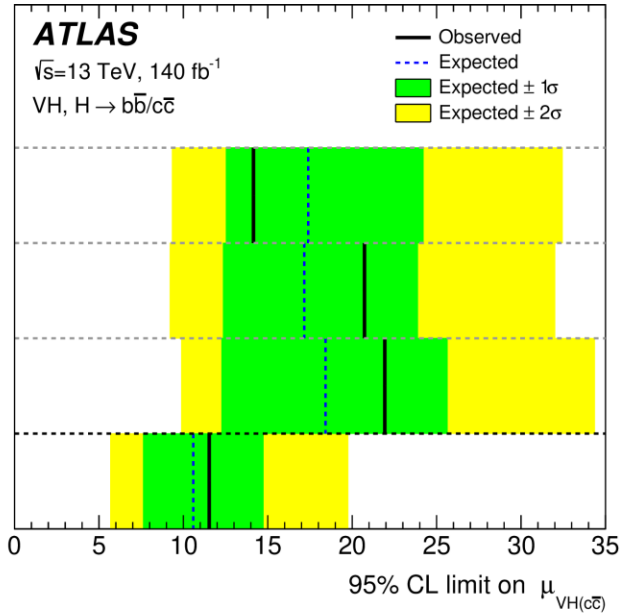


0 lepton
Exp.= 17× SM
Obs.= 14× SM

1 lepton
Exp.= 17× SM
Obs.= 21× SM

2 lepton
Exp.= 18× SM
Obs.= 22× SM

Combination
Exp.= 11× SM
Obs.= 12× SM



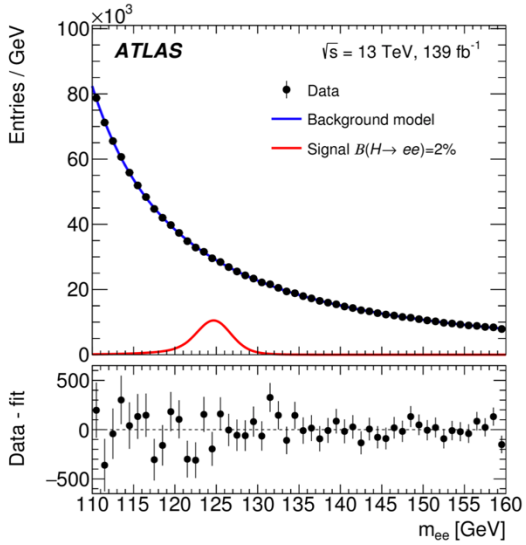
- Measured signal strength = $1.0^{+5.4}_{-5.2}$ for VH(→cc) process
- Obs. (exp.) upper limit is 11.5 (10.6) × σ_{SM}

H→ee

PLB 801 (2020) 135148

- Yukawa coupling to the 1st generation fermions, very low BR: ~5×10^{-9}
- Categorization optimized for ggF and VBF production modes
- A simultaneous fit to m_{ee} spectra across the categories with analytic functions

Category	S	B	S/B	Data
Central Low $p_{\mathrm{T}}^{\ell\ell}$	230	39200	0.0057	39872
Forward Low $p_{\mathrm{T}}^{\ell\ell}$	390	98500	0.0039	100844
Central Medium $p_{\mathrm{T}}^{\ell\ell}$	420	30700	0.014	31182
Forward Medium $p_{\mathrm{T}}^{\ell\ell}$	710	74900	0.0095	76477
Central High $p_{\mathrm{T}}^{\ell\ell}$	380	13400	0.028	13625
Forward High $p_{\mathrm{T}}^{\ell\ell}$	590	29900	0.020	30164
VBF	120	2530	0.049	2561



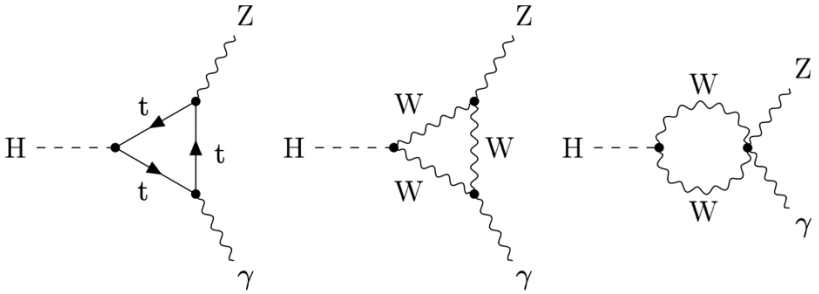
Obs.(exp.) limit on BR: 3.6×10^{-4} (3.5×10^{-4})

H→Zγ

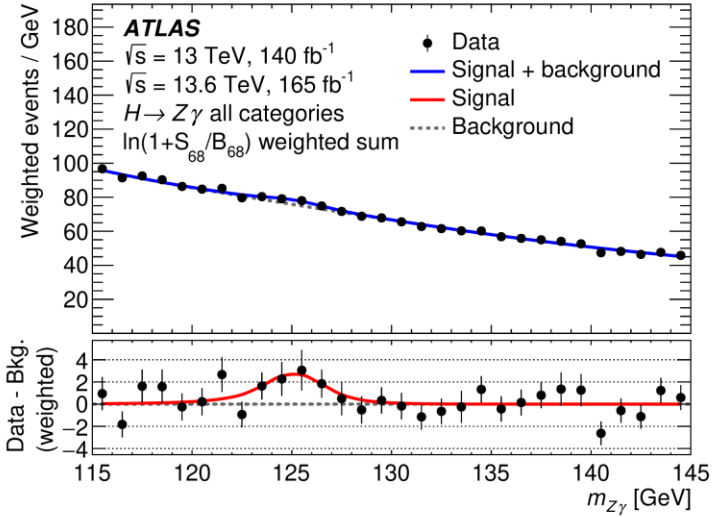
arXiv:2507.12598

New!

- In SM, BR is 1.54×10^{-3}, sensitive to BSM physics entering loop corrections; signal signature: Z→ee/μμ + 1 photon
- Selected events categorized to exploit four major production modes
- Simultaneous fit to $m_{ll\gamma}$ spectra across the categories to extract signal
- Partial Run-3 (165 fb^{-1}) combining with full Run-2 (140 fb^{-1}) analysis



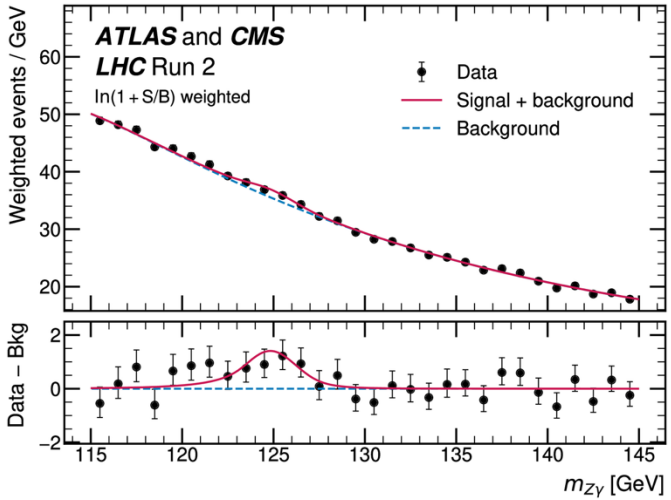
Obs.(exp.) significance: 2.5 (1.9)σ by combining Run-2 and Run-3 data

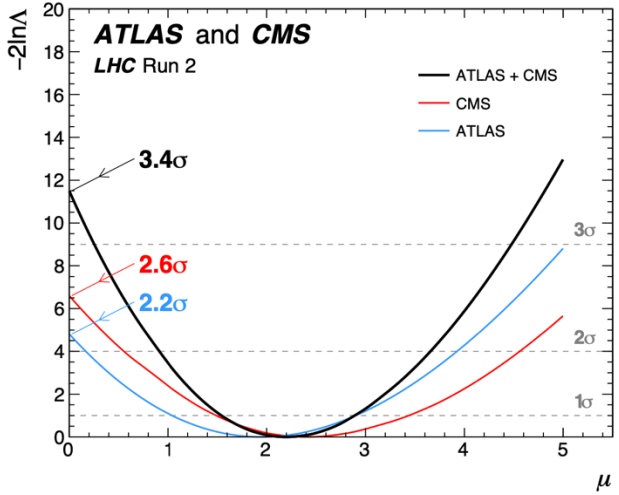


H→Zγ: Run-2 ATLAS+CMS Combination

PRL 132 (2024) 021803

- Performed statistical combination between the two experiments
- Uncertainties are treated uncorrelated except for sys. associated with the missing high order of ggF XS and H→Zγ BR predictions
- Obs.(exp.) significance: 3.4σ (1.6σ), first evidence for this process



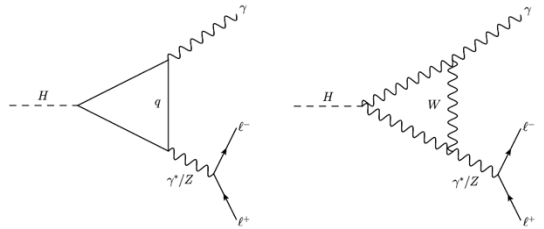


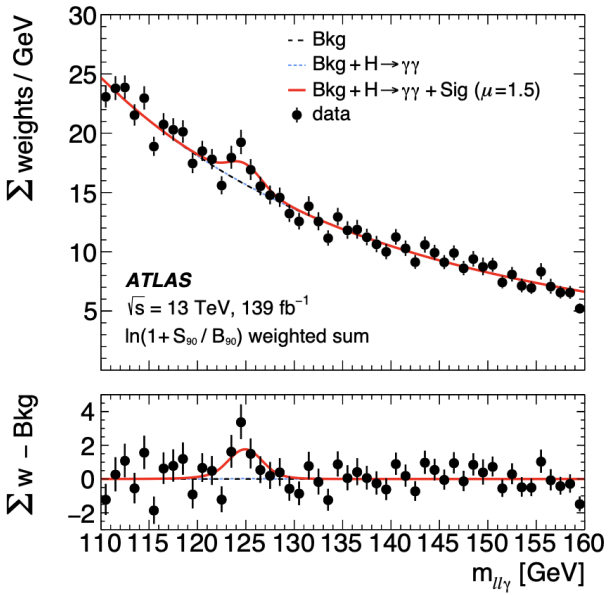
H→γ*γ→llγ

PLB 819 (2021) 136412

- Sensitive to new physics as well as CP-violation effect in the Higgs sector
- m_{ll} < 30 GeV, orthogonal to H→Zγ phase space
- Dedicated electron ID for collimated signatures
- Three channel: μμγ, eeγ merged, eeγ resolved
- Categories based on lepton flavor and topologies
- Analytic function fit to the $m_{ll\gamma}$ spectra

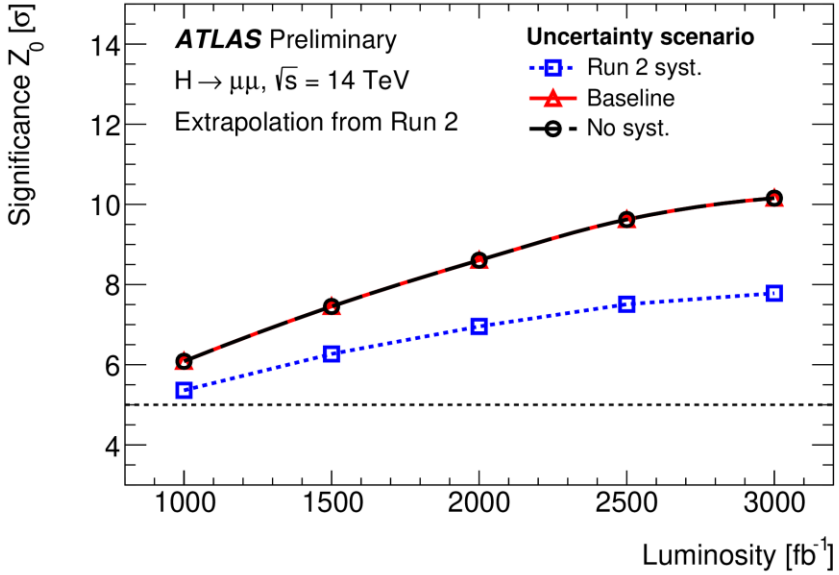
The measured μ = 1.5 ± 0.5
Obs.(exp.) significance: 3.2 (2.1)σ, evidence of this rare decay

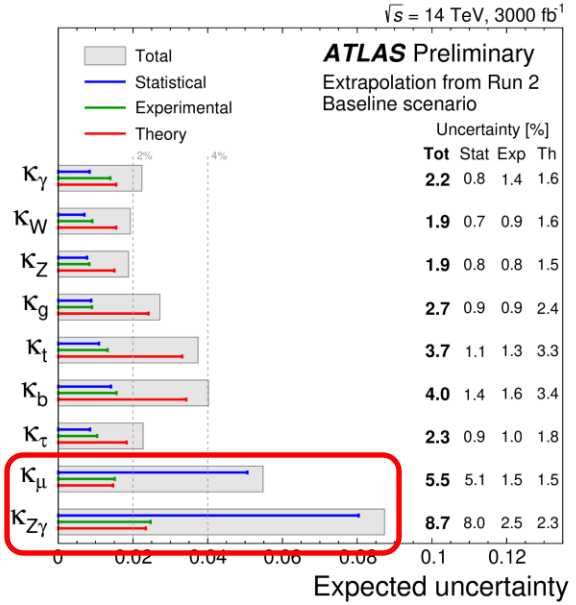




HL-LHC Projection for H→μμ and H→Zγ

ATL-PHYS-PUB-2025-014



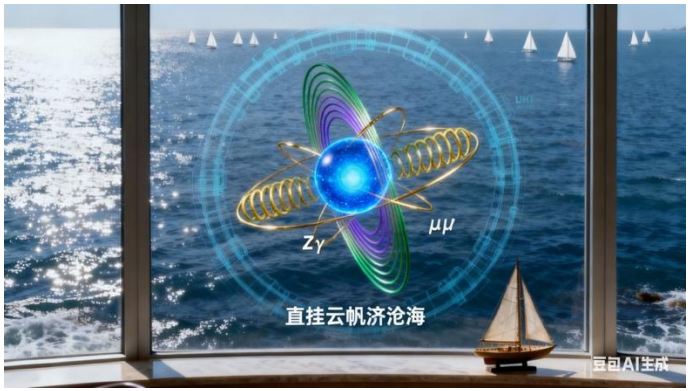


Projection performed based on Run-2 analysis strategy

Precision for κ_μ and $\kappa_{Z\gamma}$ can reach better than 10% with 3000 fb^{-1} data

Summary

- Presented the studies for Higgs boson rare decays at the ATLAS experiment based on Run-2 (plus partial Run-3) data
  - First evidence of Higgs Yukawa coupling to 2nd generation fermions (H→μμ) at ATLAS
  - Latest results for H→Zγ shown as well
- Full Run-3 and future HL-LHC datasets provide more room for exploring the Higgs boson rare decays (e.g. confirm the Yukawa coupling to muons by >5σ) !



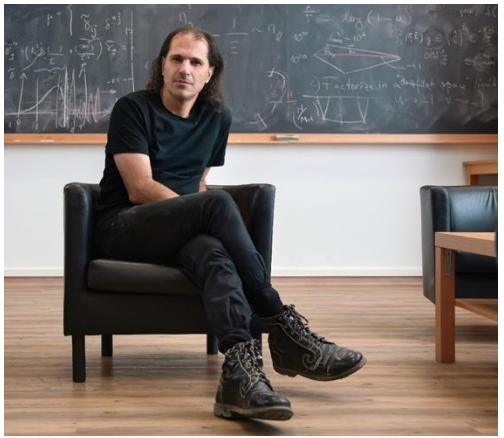
It Is Not the End…

Higgs is Really New Physics!

* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum

PUT IT UNDER MICROSCOPE

STUDY IT TO DEATH



From Nima Arkani-Hamed