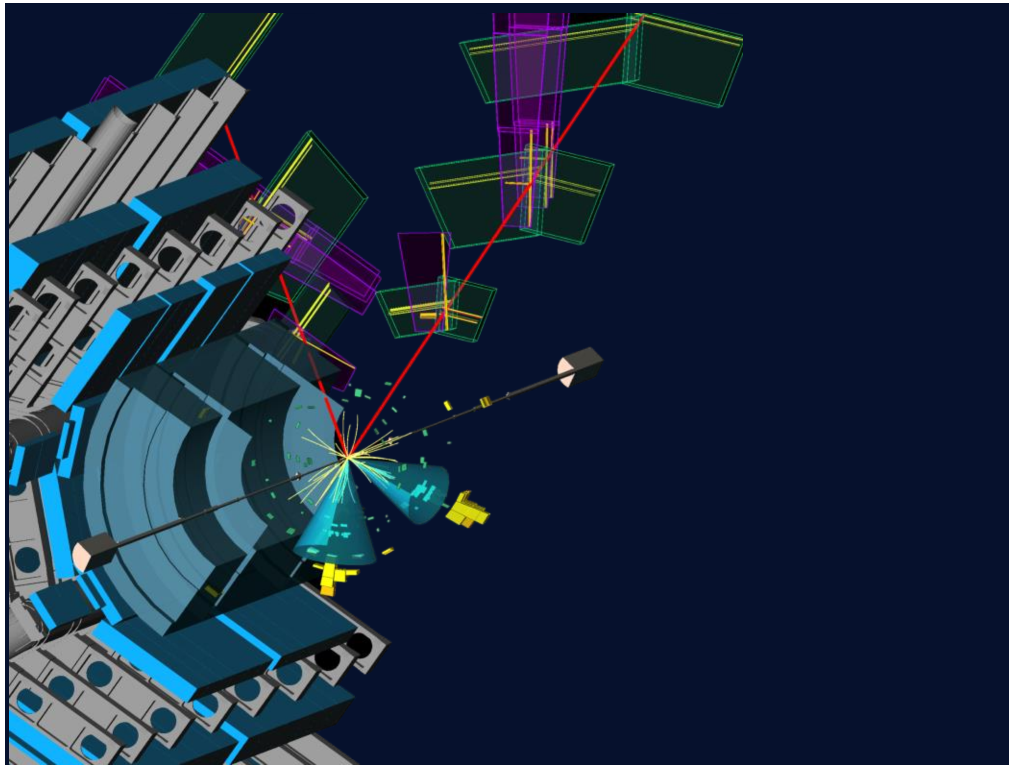
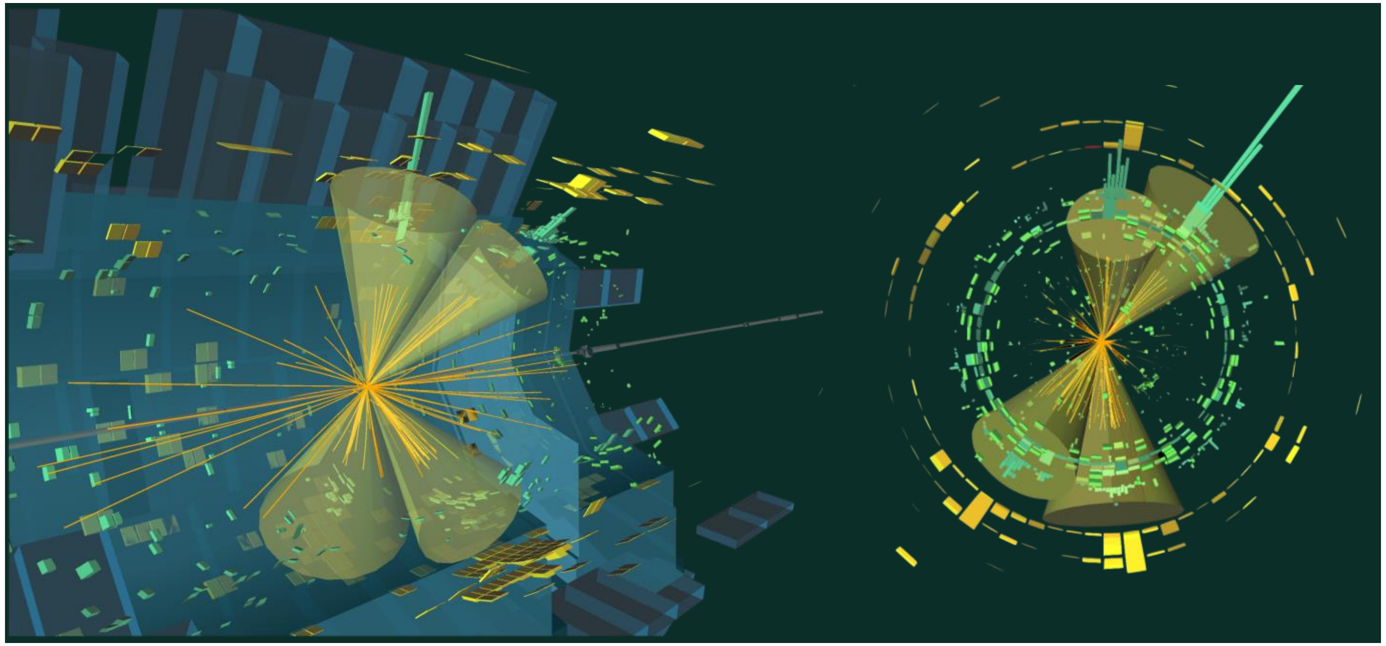




Mapping out the Higgs Boson: Highlights from the LHC Experiments

Elisabeth Schopf

DPG Frühjahrstagung, Göttingen, 02/04/2025

Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

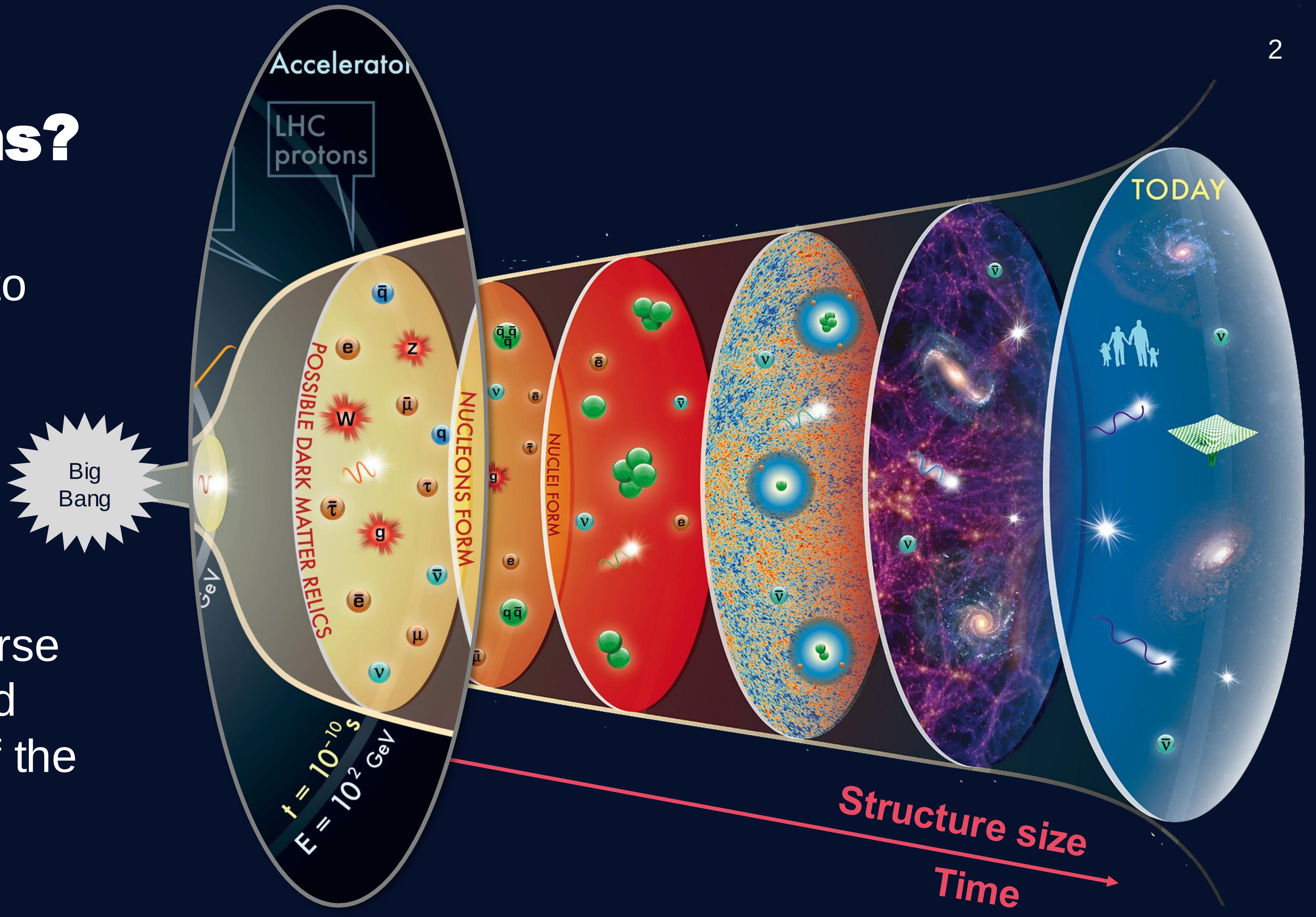
Bundesministerium für Bildung und Forschung

FSP ATLAS Erforschung von Universum und Materie

Why study Higgs bosons?

A look back in time to very early universe

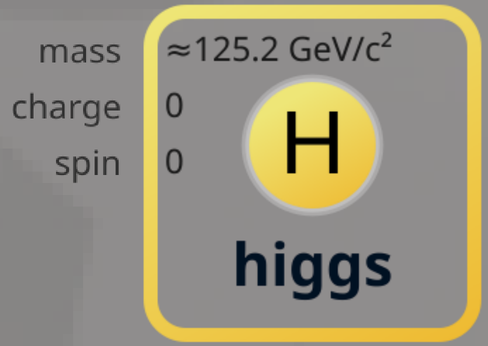
Study of early universe matter formation and long term stability of the universe



Higgs Field & Higgs Boson

A unique field & particle in the Standard Model of Particle Physics

Higgs field present everywhere in the universe



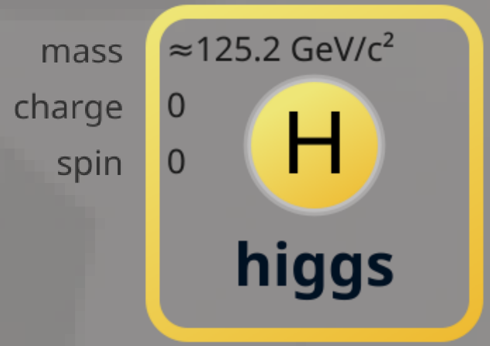
Self-excitation of the field
→ **Higgs boson**

Higgs Field & Higgs Boson

A unique field & particle in the Standard Model of Particle Physics

What are the properties of the Higgs boson?

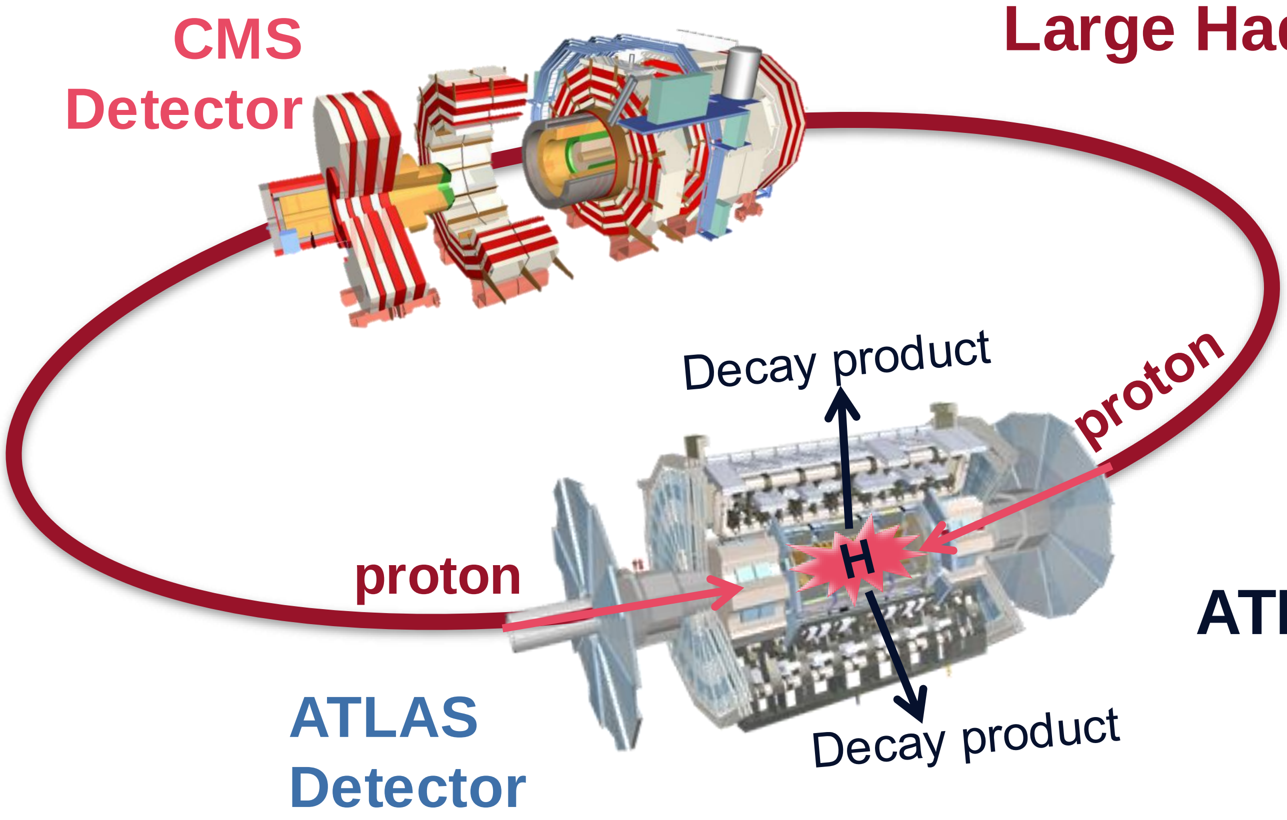
How does the Higgs boson interact with SM particles?



How does the Higgs boson interact with itself?

Does the Higgs boson interact with yet unknown particles?

Our Tools to Study Higgs Bosons



Large Hadron Collider proton-proton collisions

2015-2018: collisions at $\sqrt{s}$=13 TeV ("Run 2")
since 2022: collisions at $\sqrt{s}$=13.6 TeV ("Run 3")

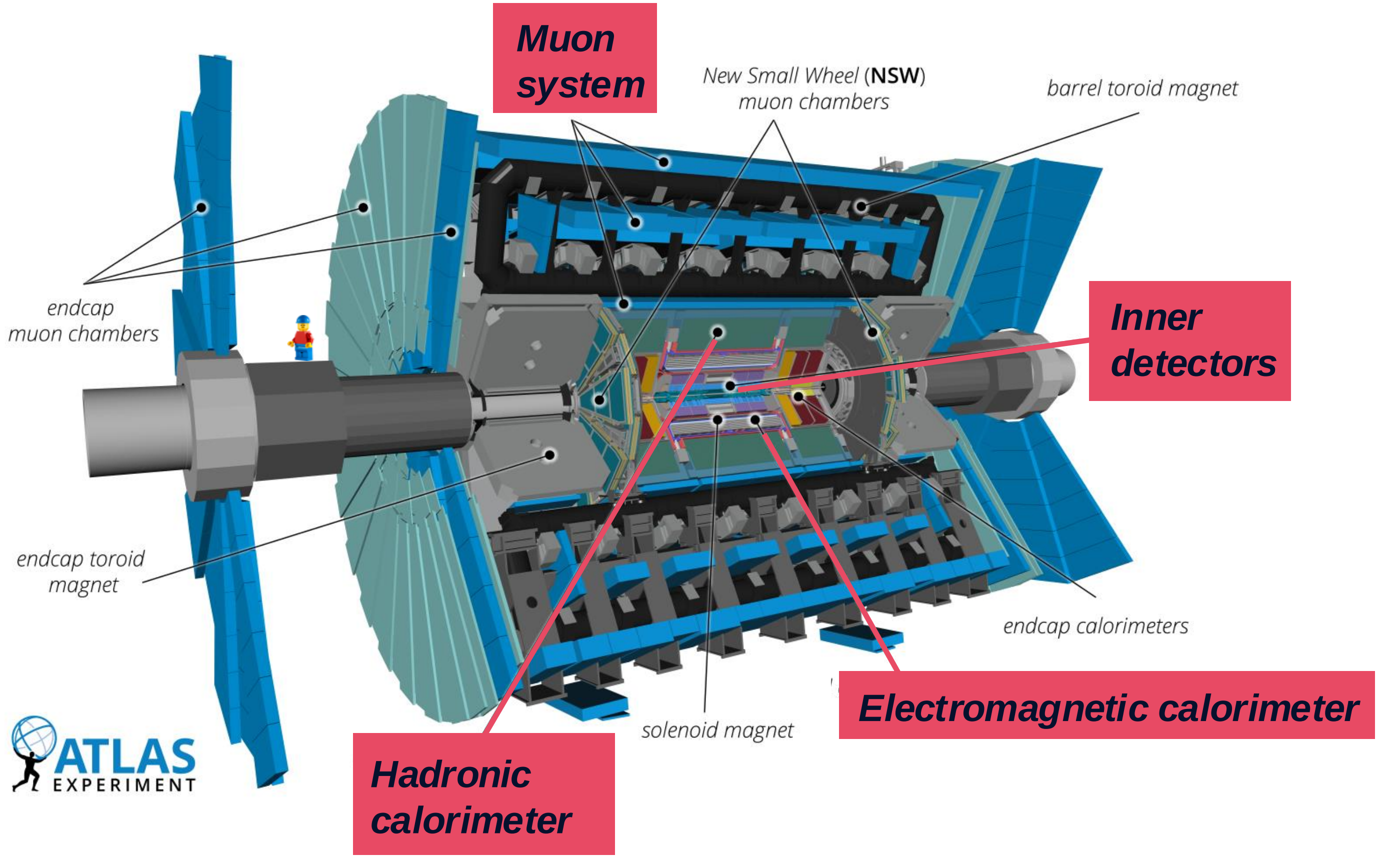
~1 in 10^9 collisions produce Higgs boson

ATLAS and CMS: multi-purpose detectors

Both experiments collected massive datasets that contain **~10^8** (SM) **Higgs bosons**

- **Today: size of Run-2 dataset ≈ size of Run-3 dataset** (1.5 more years of Run 3 to come)

Higgs Detection Machines
Example: ATLAS



Inner detectors: high precision tracking (trajectories + momentum) and vertexing

EM calorimeter: electron and photon energy measurements

Hadronic calorimeter: hadron energy measurements, esp. “jet” reconstruction

Muon system: muon tracking and identification

*similar layout and detection layers in CMS

Higgs Boson Property Measurements

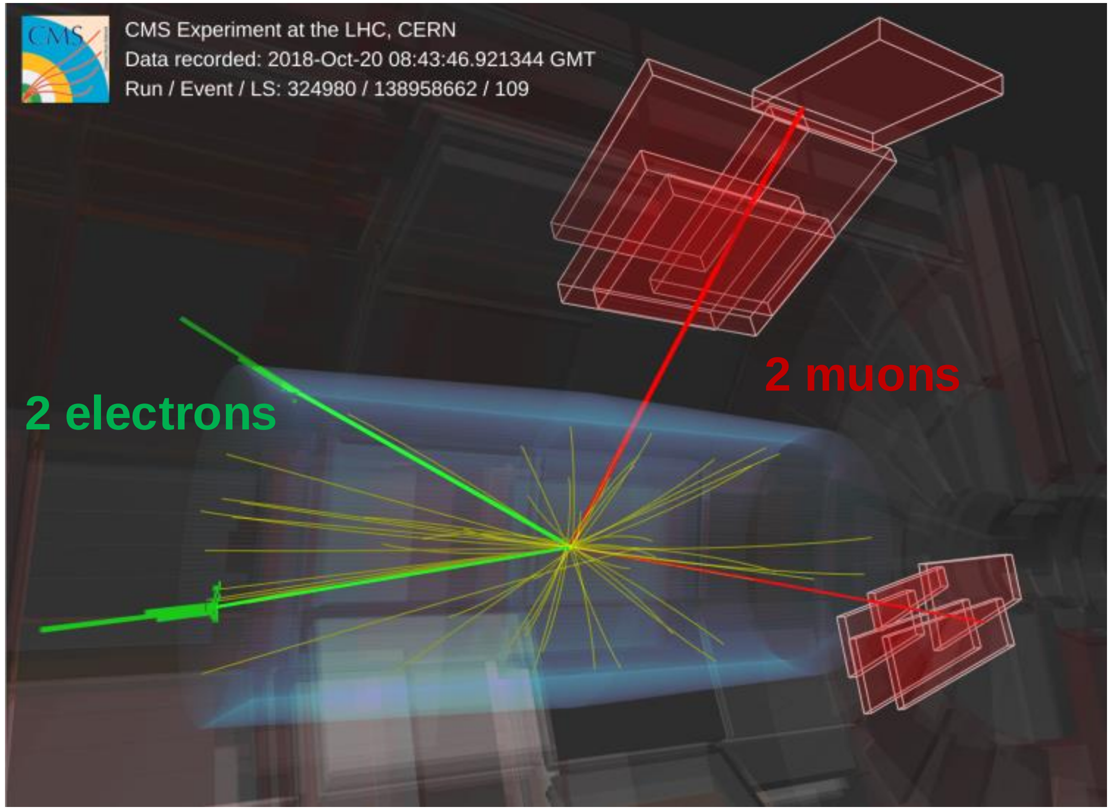
Charge-parity (CP) properties: CP-odd excluded, odd-even mixing angle compatible with SM expectation of 0 with tight constraints

Mass: ~125 GeV → on next slides

Mass Measurements

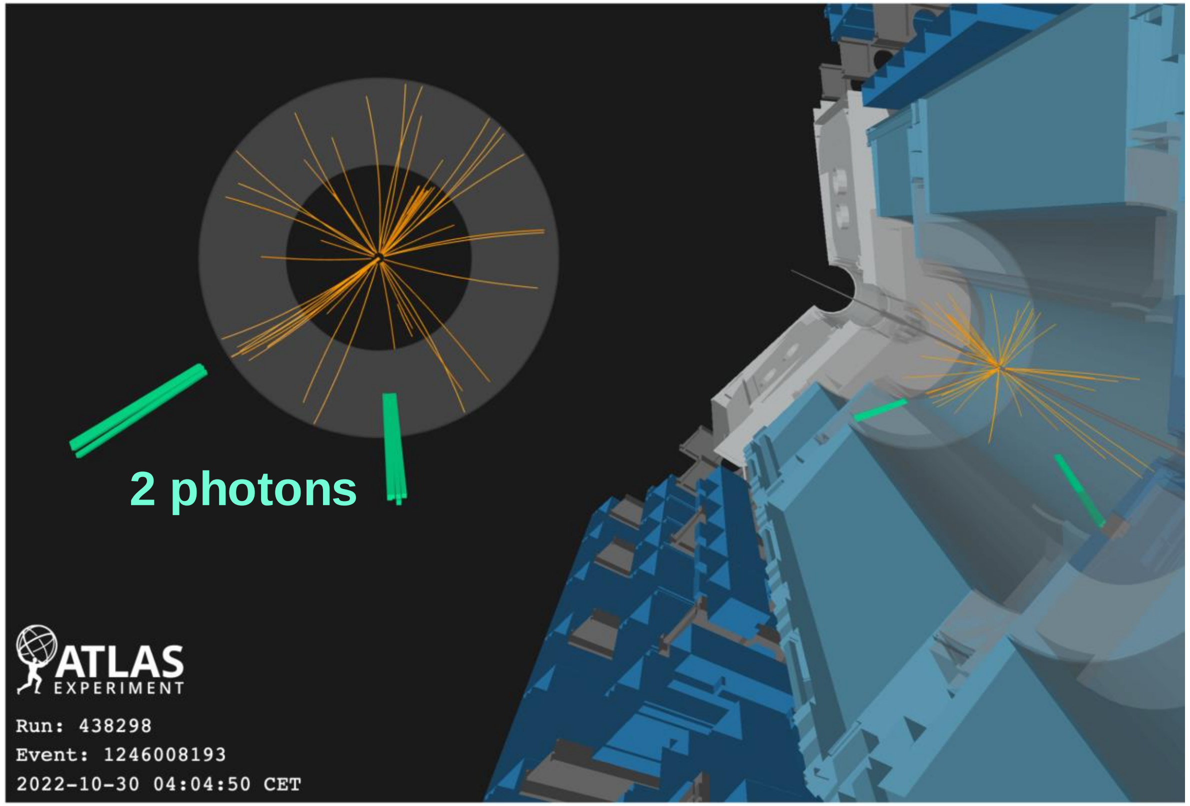
Full Higgs candidate reconstruction in H→ZZ→4e/4μ/2e2μ and H→$\gamma\gamma$

Mass of the Higgs boson is a free parameter in the Standard Model



H→ZZ candidate

CMS-PHO-EVENTS-2024-036

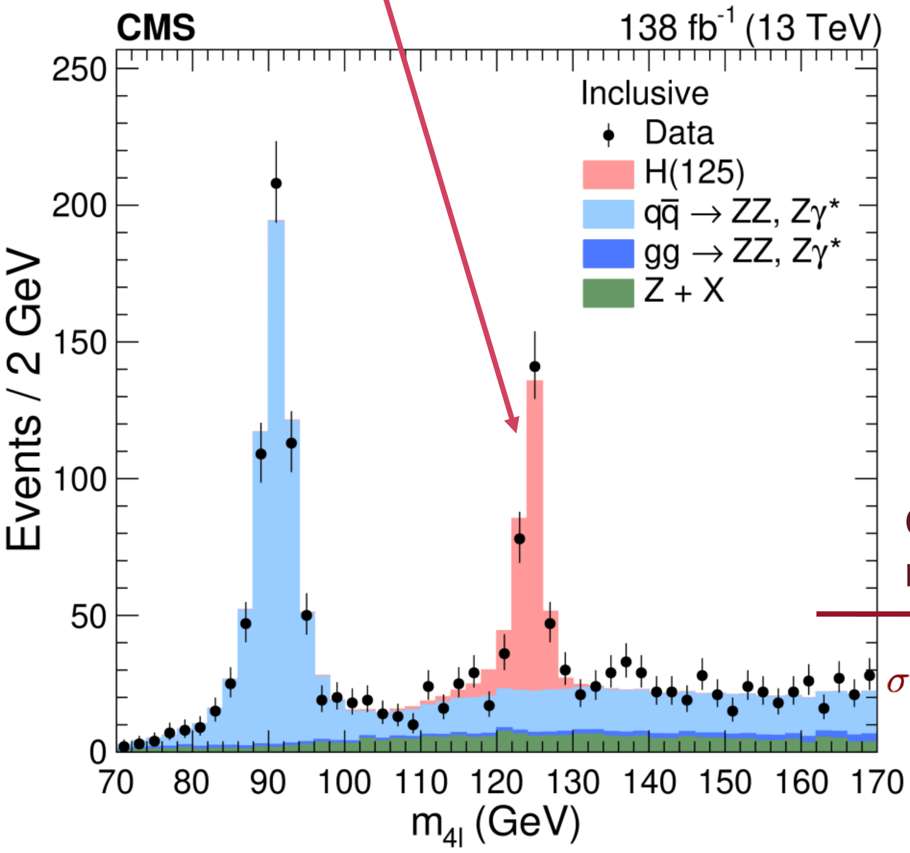


HIGG-2022-12

H→$\gamma\gamma$ candidate

Simultaneous Higgs Mass and Width Extraction in H→ZZ→4e/4μ/2e2μ

(on-shell) Higgs resonance $\sigma \propto \frac{N_{obs}^{on\text{-}shell}}{N_{SM}}$



Off-shell regime

$\sigma \propto \frac{N_{obs}^{on\text{-}shell}}{N_{SM}} \Gamma_H$

Mass from resonance: **125.04 ± 0.12 GeV**
- Improved muon track reconstruction
- Improved event categorisation

Width simultaneously extracted from on- and off-shell regimes
- Reduced assumptions on Higgs-boson couplings

	Limit 68% CL	95% CL
Γ on-shell	< 50 MeV	< 330 MeV
Γ on+off-shell	$2.9^{+2.3}_{-1.7}$ MeV	$0.3 < \Gamma < 7.9$ MeV
Γ combination	**$3.0^{+2.0}_{-1.5}$ MeV**	$0.6 < \Gamma < 7.3$ MeV

arXiv:2409.13663

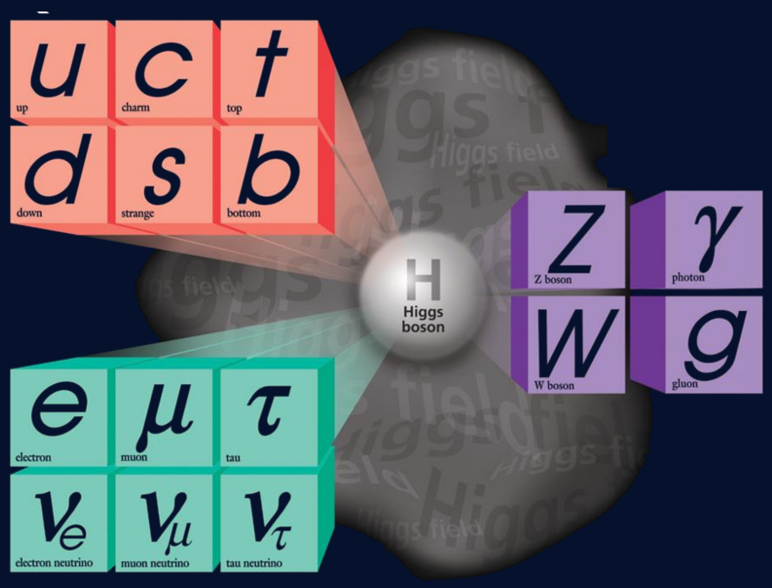
SM expectation (m_H=125 GeV): Γ_H = 4.1 MeV

ATLAS Run-2 mass measurement: 125.17 ± 0.14 GeV (Phys. Lett. B 847 (2023) 138315)

Higgs Boson Production & Couplings

All massive particles interact with the Higgs boson and the **interaction strength is proportional to the particle's mass**

Fermion mass terms added ad-hoc to SM



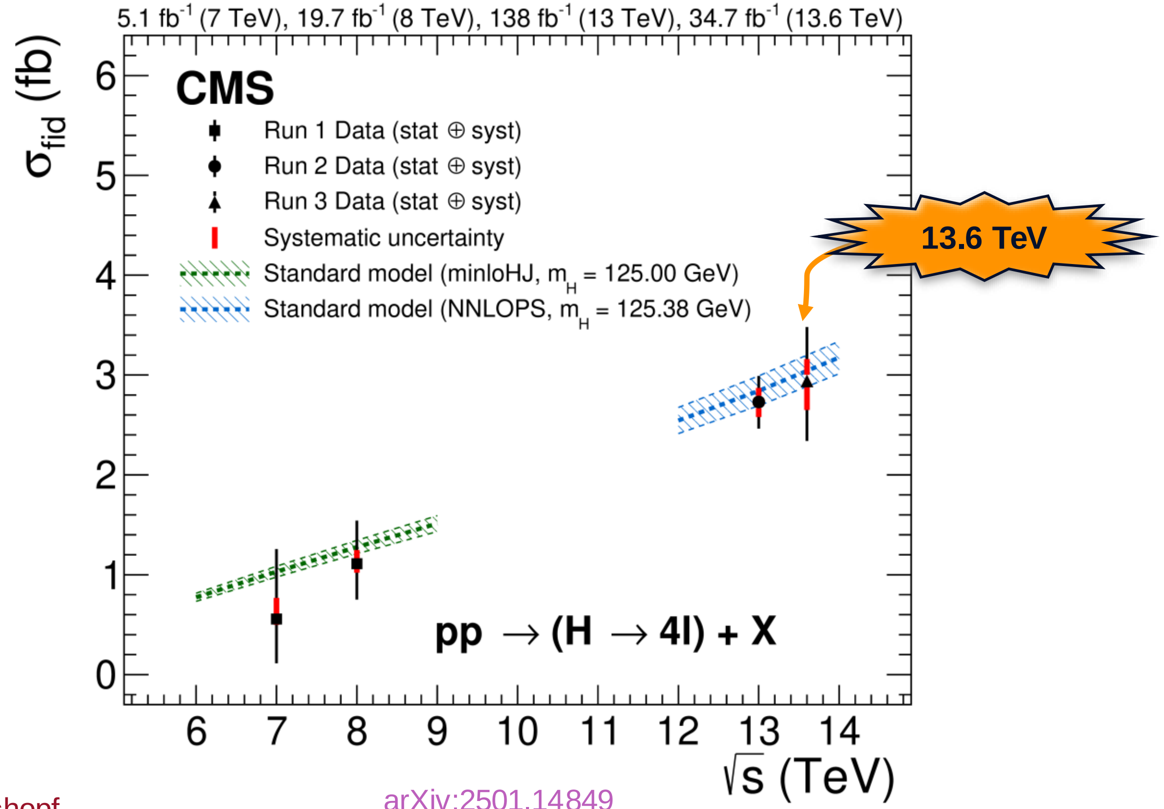
W and Z boson mass terms arise naturally through Higgs mechanism

Higgs Boson Production & Couplings

Knowledge of Higgs boson mass fixes predictions for SM Higgs-boson decay rates and production cross-sections

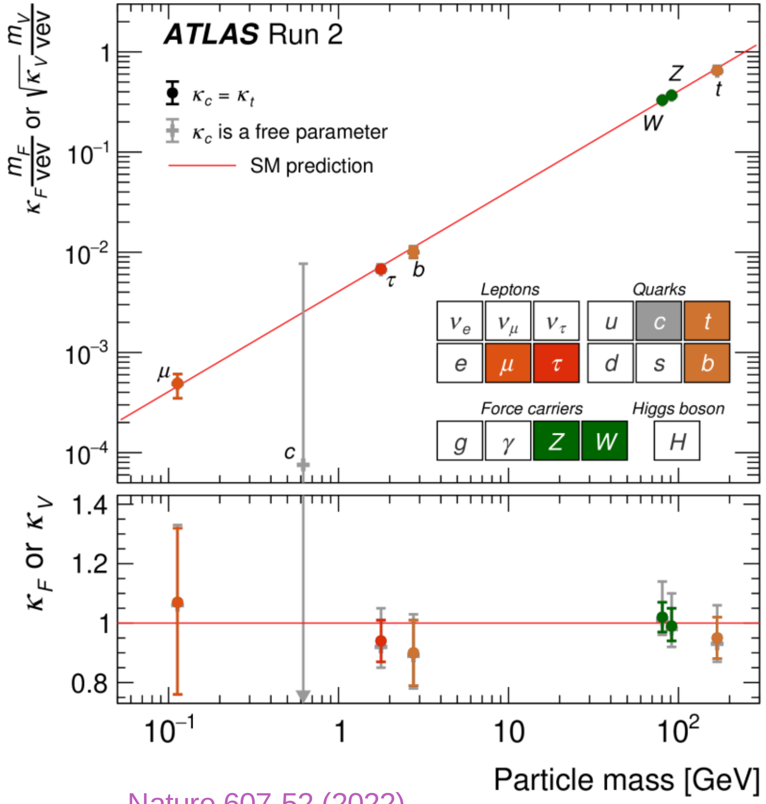
→ Deviations from SM expectations would be hints for new physics

Production cross-section vs collision energy



arXiv:2501.14849

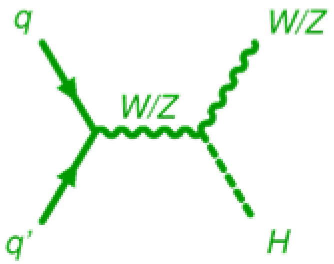
Coupling strength vs particle mass

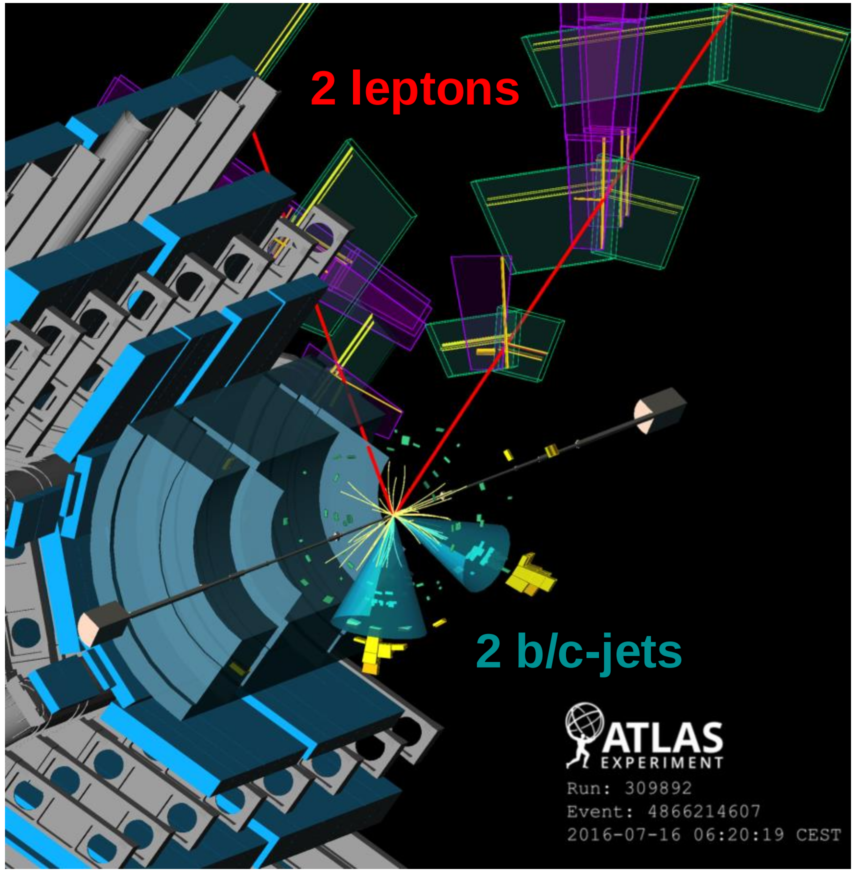


Nature 607 52 (2022)

arXiv:2410.19611

Higgs Boson Couplings to Bottom and Charm Quarks



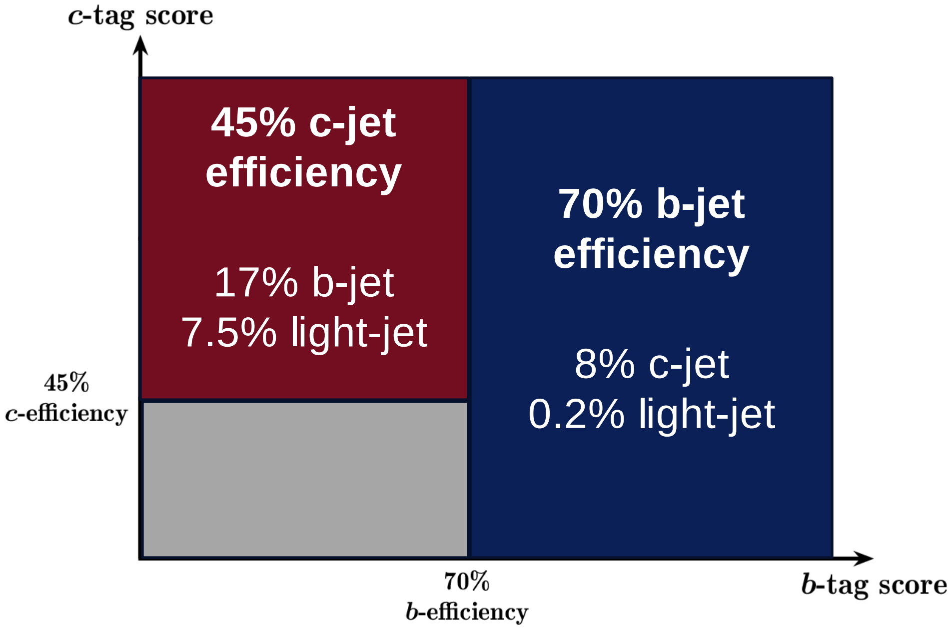


HIGG-2021-12

Studied in V(→leptons)H(→bb/cc) channel

First simultaneous extraction of H→bb and H→cc

- Optimised and fully orthogonal b/c-jet identification scheme
- Extended usage of machine learning
- Improved control regions to provide auxiliary measurements of background processes



b/c-jet identification scheme and identification efficiencies

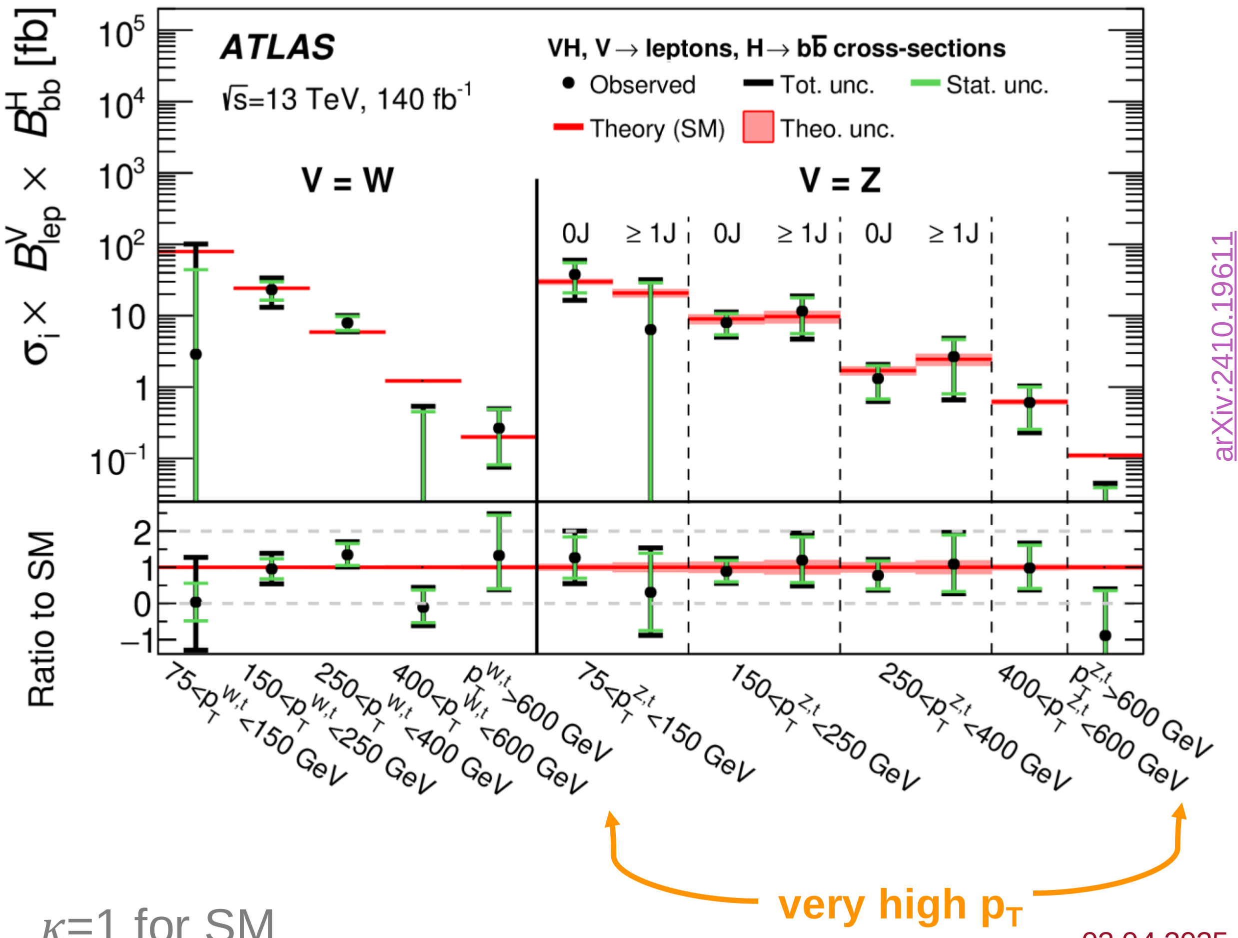
VH Cross-Section Measurement & Limit on Higgs-Charm Couplings

WH and ZH measurements reached ~**20% precision**

Observed (expected) 95% CL
Limit on μ_{VH}^{cc} < 11.5 (10.6) x SM
Coupling strength modifier κ_c**<4.2**

Higgs-model independent combined H→bb and H→cc result: **Higgs-charm coupling is weaker than Higgs-bottom coupling** at ~3σ level

WH and ZH cross-section measurement vs transverse momentum and jet multiplicity

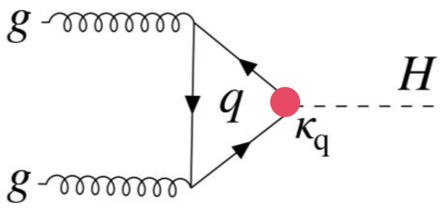


arXiv:2410.19611

μ = signal strength = N_{obs}/N_{exp} κ=1 for SM

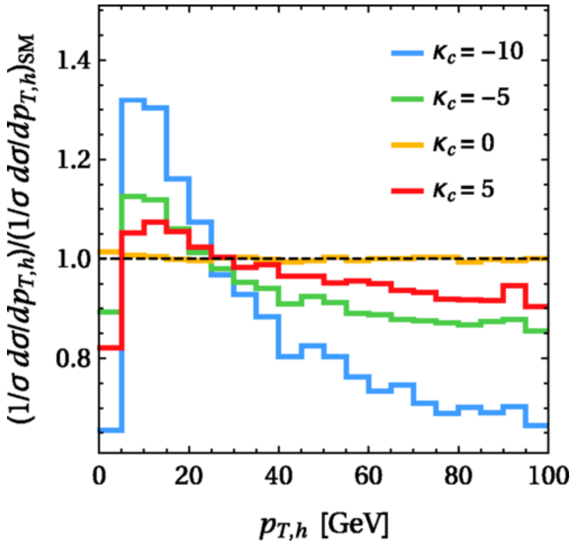
"Alternative" Ways to Assess Couplings to First and Second Generation Quarks

Differential cross-section measurement in H → 4 leptons



Transverse momentum spectrum sensitive to enhancements of Higgs-quark couplings
→ **Parametrisation of differential cross-section in terms of quark-coupling modifiers**

Higgs p_T spectrum for different κ_c scenarios



Phys. Rev. Lett. 118, 121801

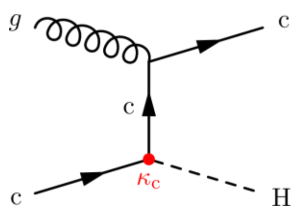
All κ extracted simultaneously

95% CL limit
-2400 < κ_u < 2400
-1000 < κ_d < 1000
-46 < κ_s < 44
-4.0 < κ_c < 3.4

Assume κ_b=1 and κ_t=1 (SM)

arXiv:2502.05665

What about H+c production?

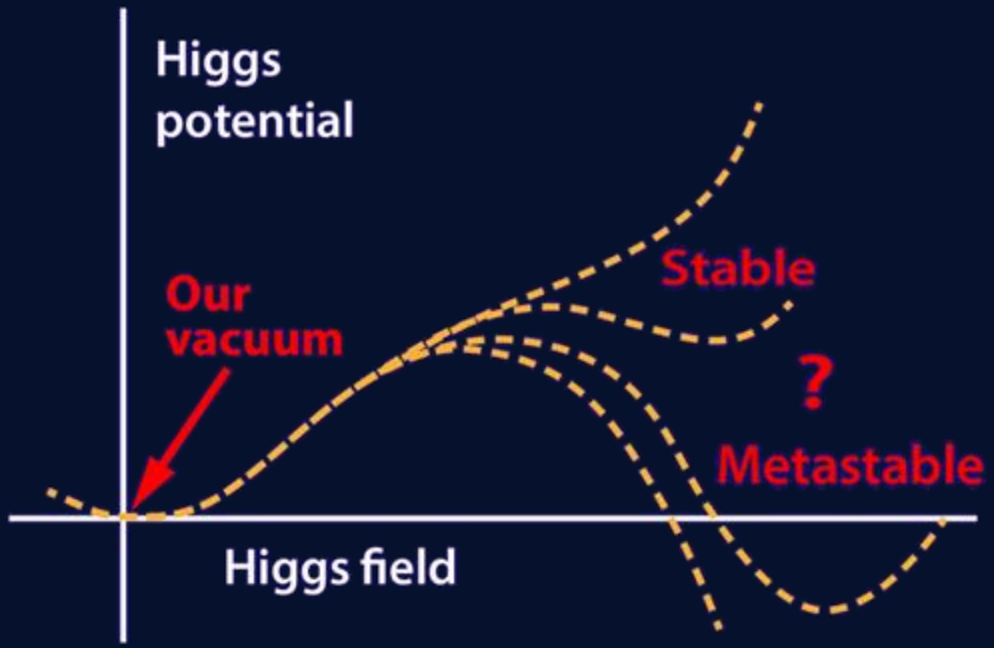


H($\gamma\gamma$)+c search: **κ_c<38.1 (72.5)** obs. (exp.) 95% CL limits

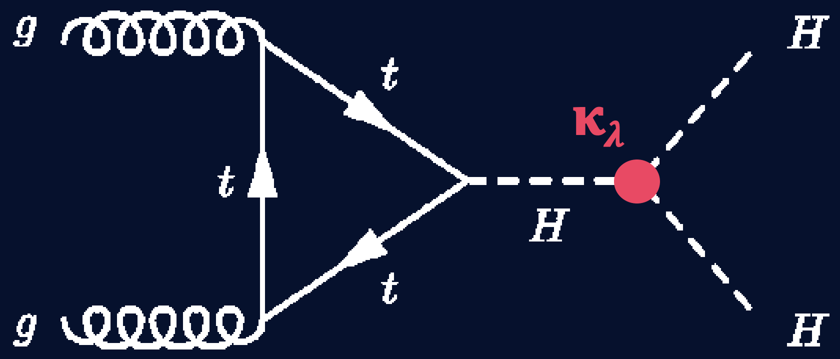
arXiv:2503.08797

κ=1 for SM

Higgs-Boson Pair Production



APS/ A. Stonebraker



Direct access to **Higgs self-coupling** strength (λ), which probes **shape of Higgs potential**

(SM) Di-Higgs Combination

(SM) Di-Higgs production has tiny cross-section → Run 2+3:
~10,000 di-Higgs events collected

Optimising searches for signal acceptance

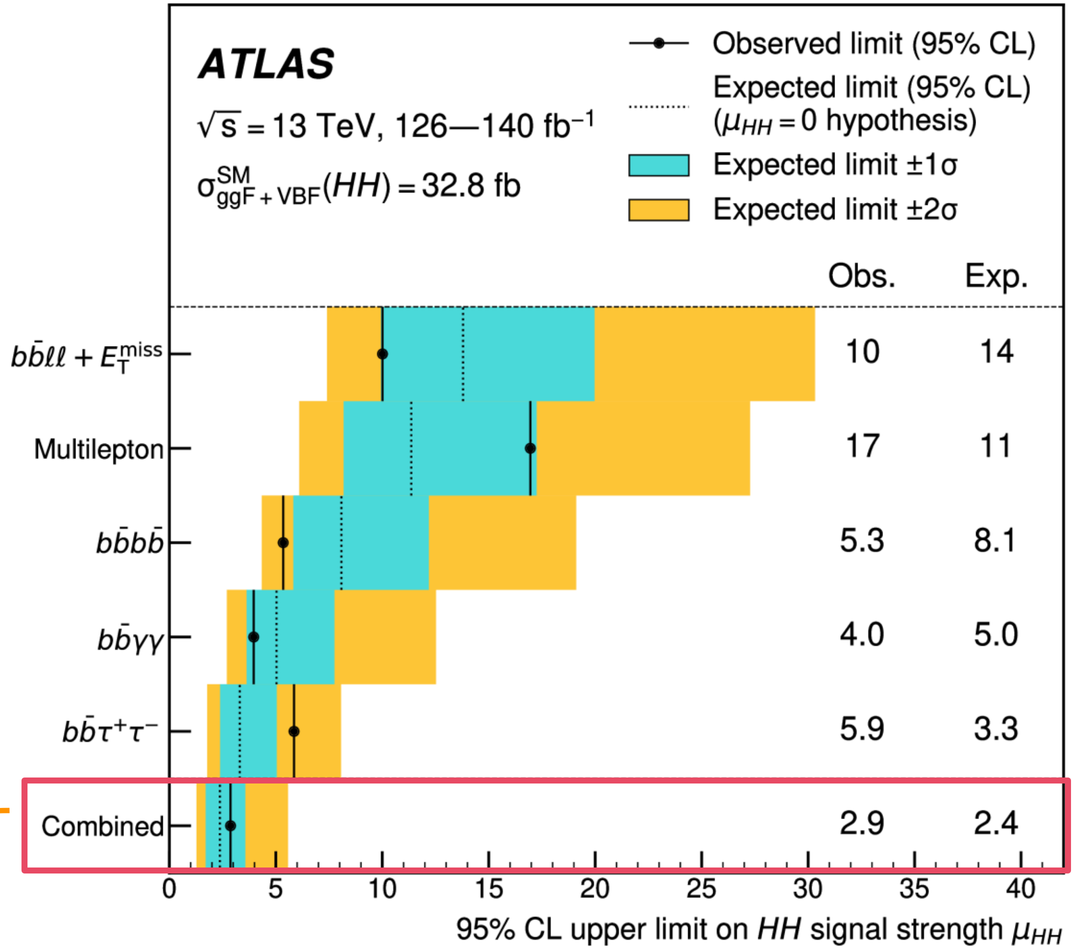
- New/improved triggers
- Machine learning for background rejection

Pushing closer and closer to SM precision

Di-Higgs branching ratios

Higgs 2 decay \ Higgs 1 decay	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%

K. Leney



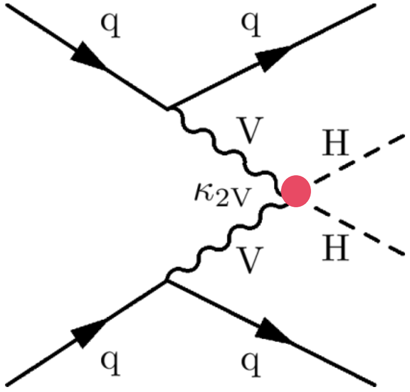
$-1.2<\kappa_\lambda<7.2$

Phys. Rev. Lett. 133 (2024) 101801

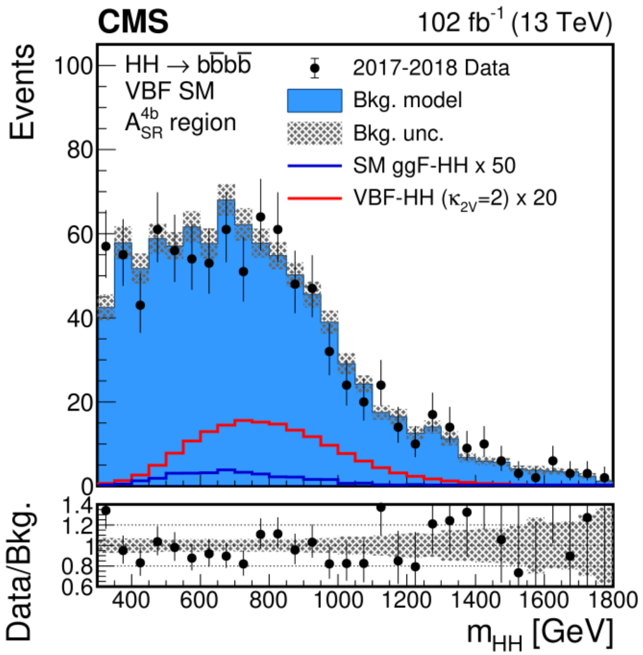
κ=1 for SM

Di-Higgs Beyond Higgs-Self Coupling

Access VVHH-vertex in VBF HH production

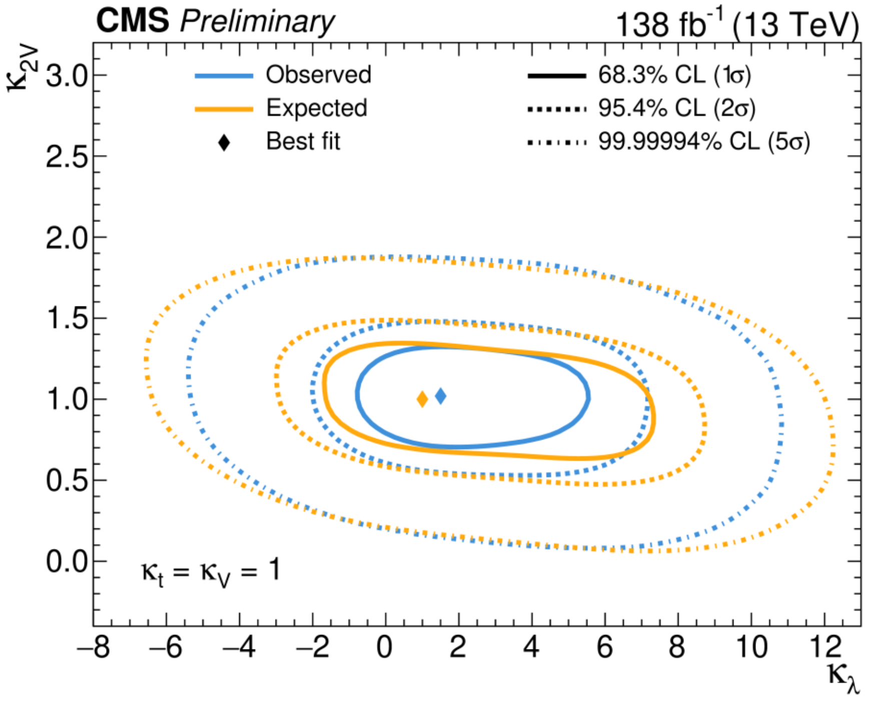


m_{4b} spectrum in VBF HH→4b search



Phys. Rev. Lett. 129 (2022) 081802

Combination of Di-Higgs searches:
$0.62<\kappa_{2V}<1.42$ (95% CL limit)



CMS-PAS-HIG-20-011

Di-Higgs analyses also set:

- Limits on anomalous (Di)Higgs couplings
- Limits on heavy resonances (e.g. X→HH, XH production)

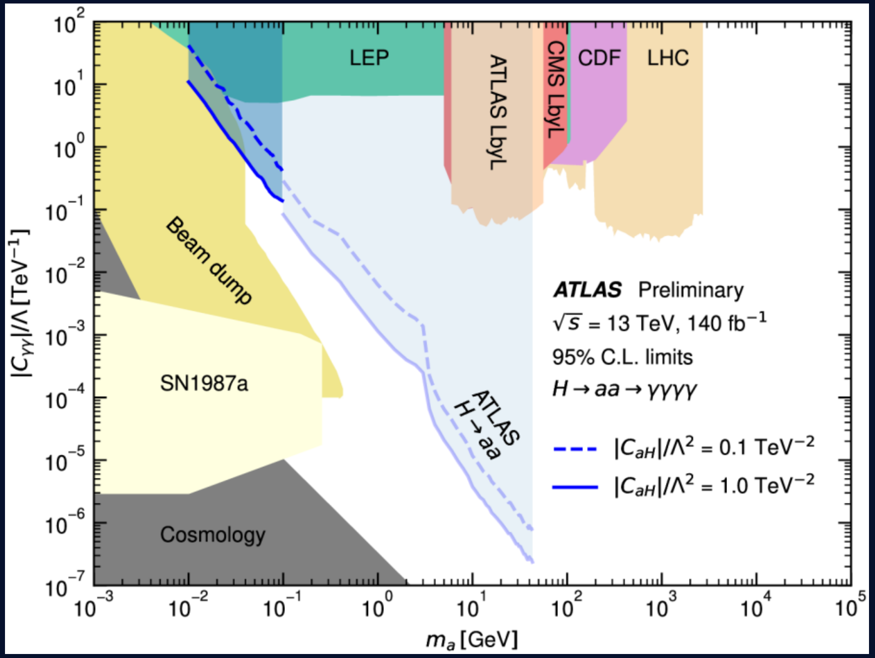
κ=1 for SM

Searches for Beyond Standard Model Physics in the Higgs Sector

Plethora of new physics scenarios:

- Additional Higgs bosons
  - Additional heavy Higgs bosons
  - Additional light Higgs bosons
  - Additional charged Higgs bosons
- Exotic Higgs boson decays
  - Decays to unknown particles
  - Lepton-flavour violating decays
- Heavy Resonances decaying to Higgs bosons
- …

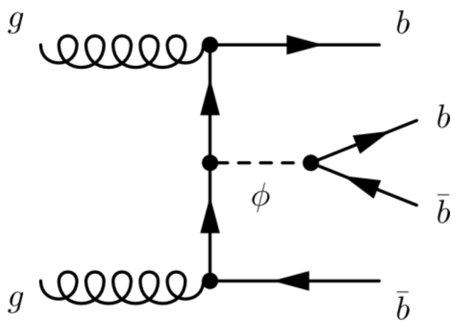
Long lived axion searches



ATL-PHYS-PUB-2025-007

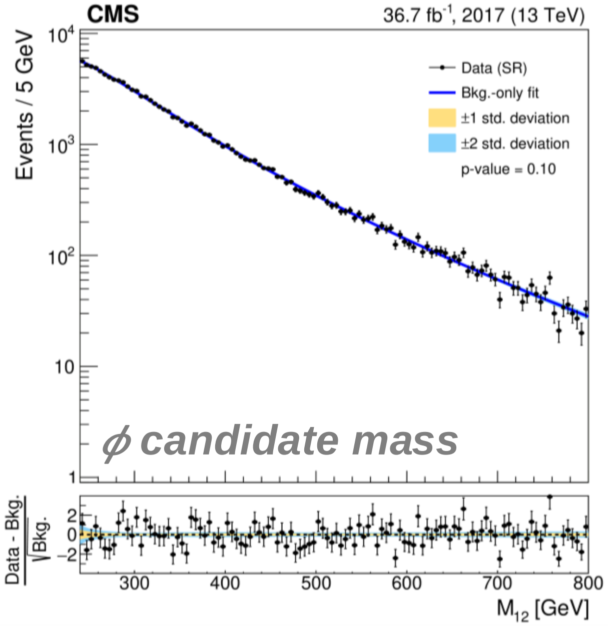
Extended Higgs Sectors

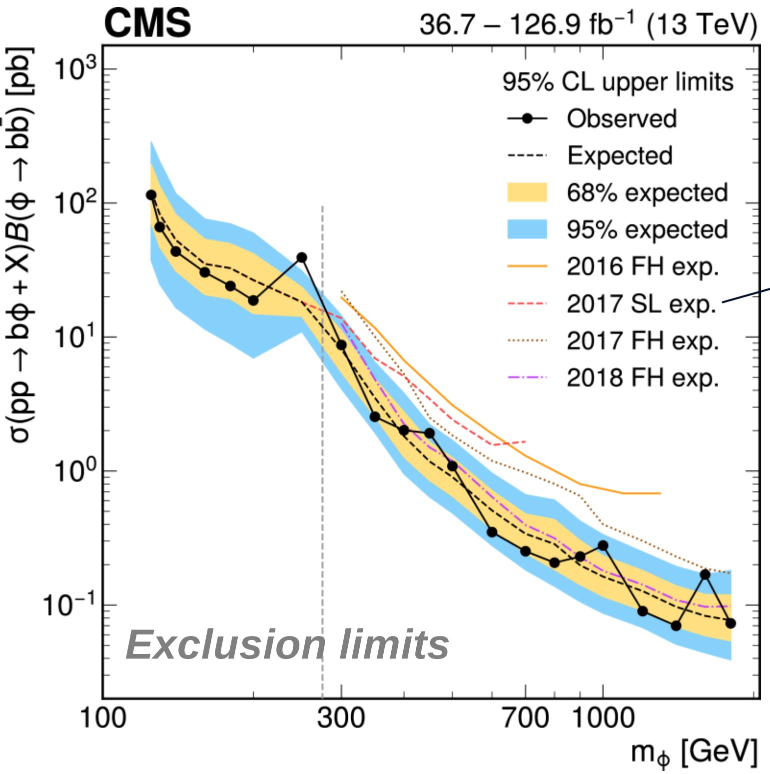
Search for additional (neutral) Higgs bosons $\phi \rightarrow bb$

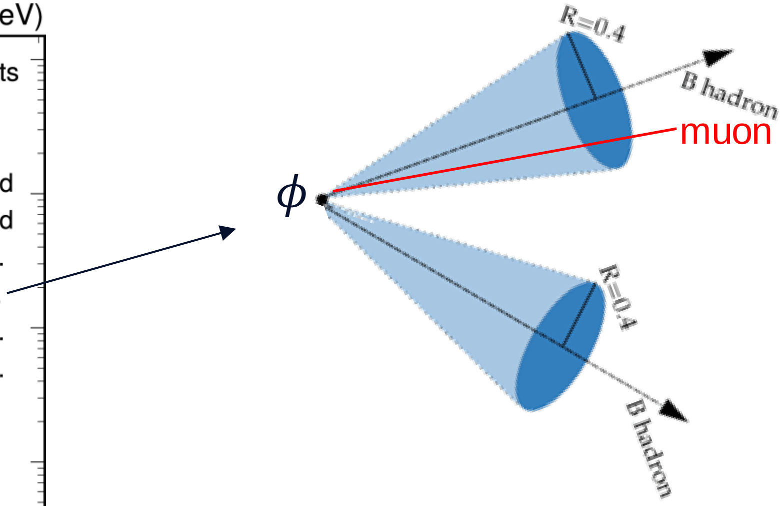


ϕ candidate reconstructed from two highest p_T b-jets

To extend reach at low p_T: overcome trigger limitations by looking for b-jets containing semi-leptonic decays

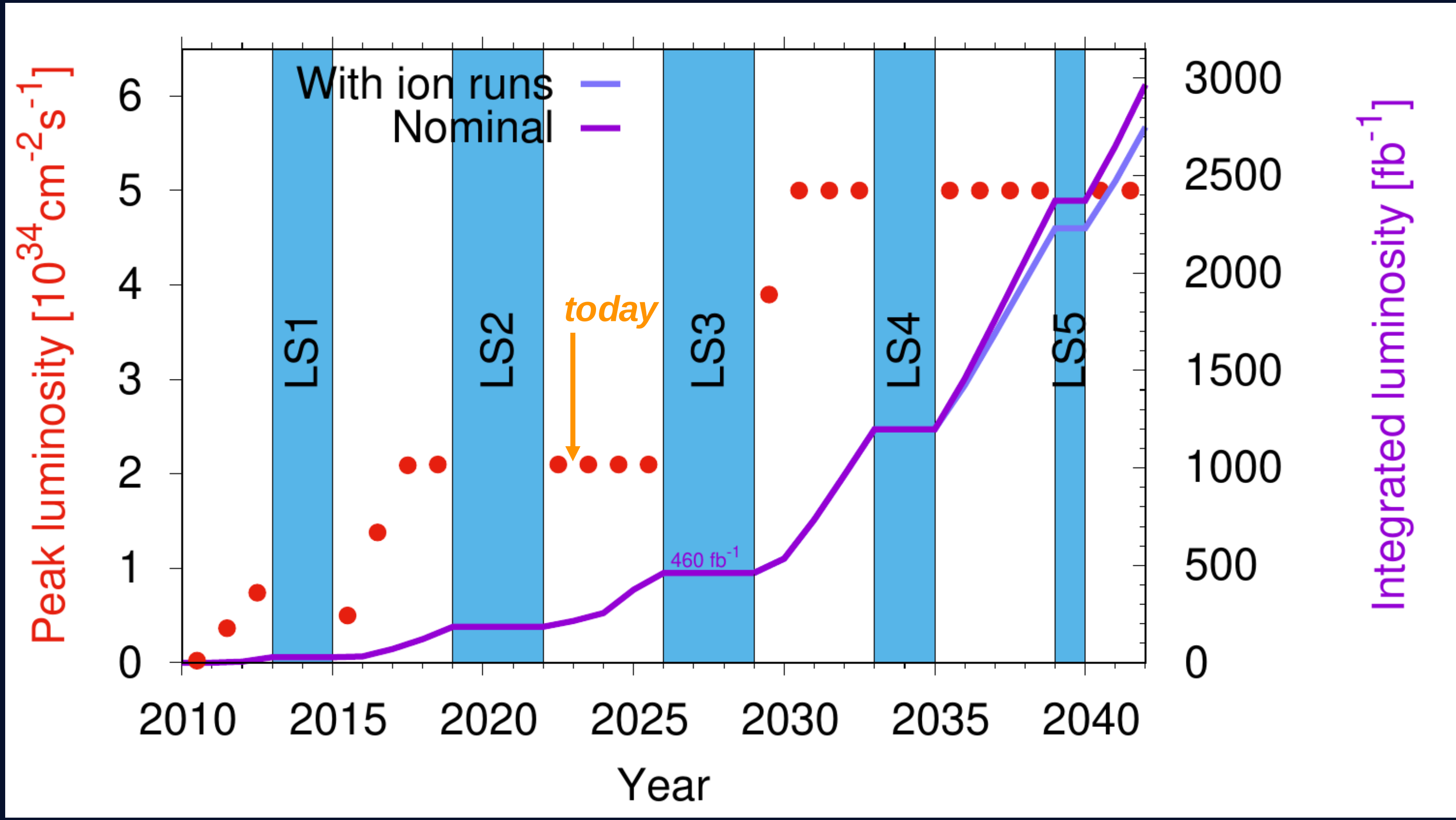






arXiv:2502.06568

A Look Into the Future: High-Luminosity LHC



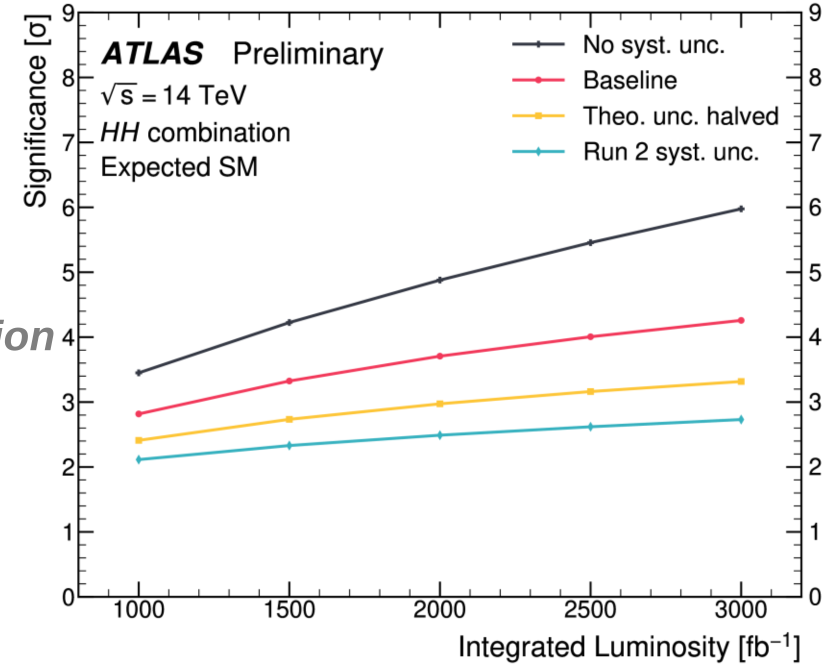
LHC long term schedule

Projected Experimental Precision

Selected Higgs boson measurements

Di-Higgs Measurements

Projected HH significance for different projection scenarios



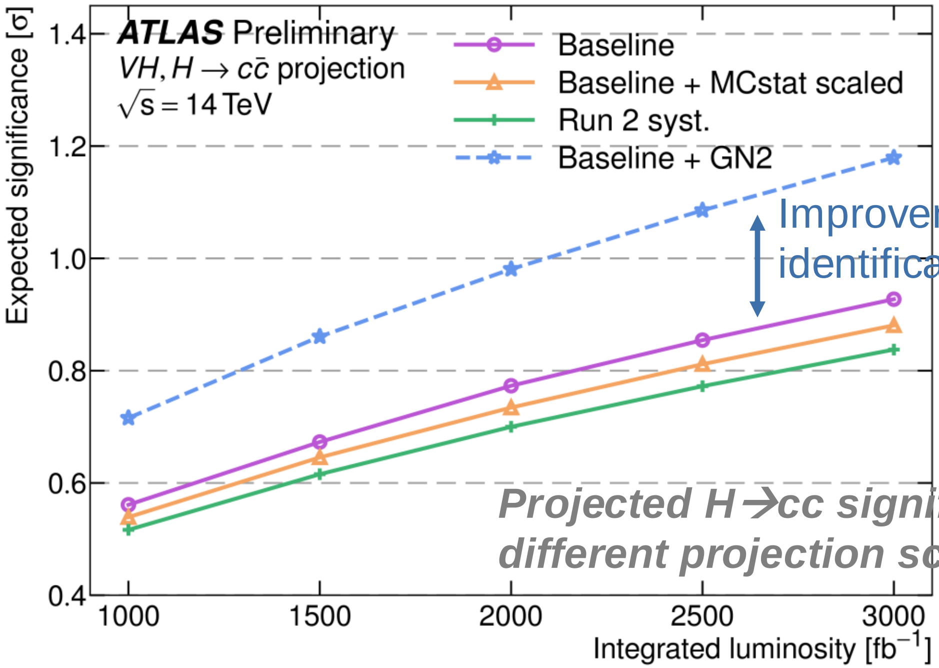
Observation in reach

Projected Higgs-self coupling result: $\kappa_\lambda = 1.0^{+0.48}_{-0.15}$

ATL-PHYS-PUB-2025-006

Higgs decays to charm quarks

Extrapolation of VH,H→cc search



Expected sensitivity heavily influenced by improvements in measurement techniques

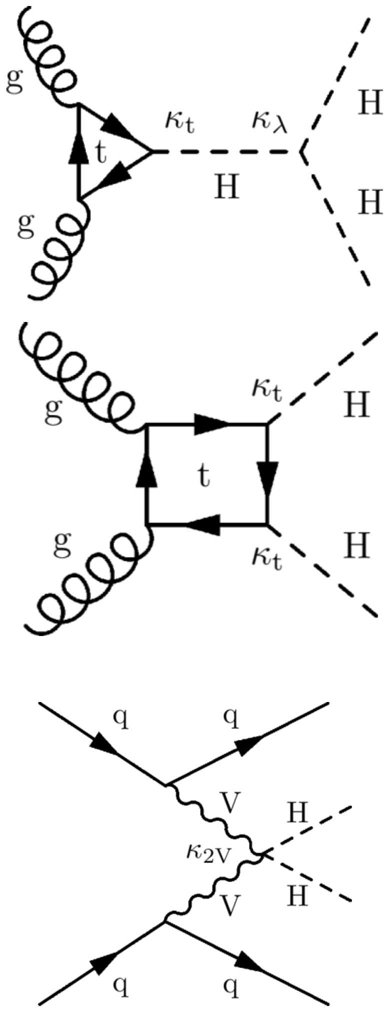
ATL-PHYS-PUB-2025-012

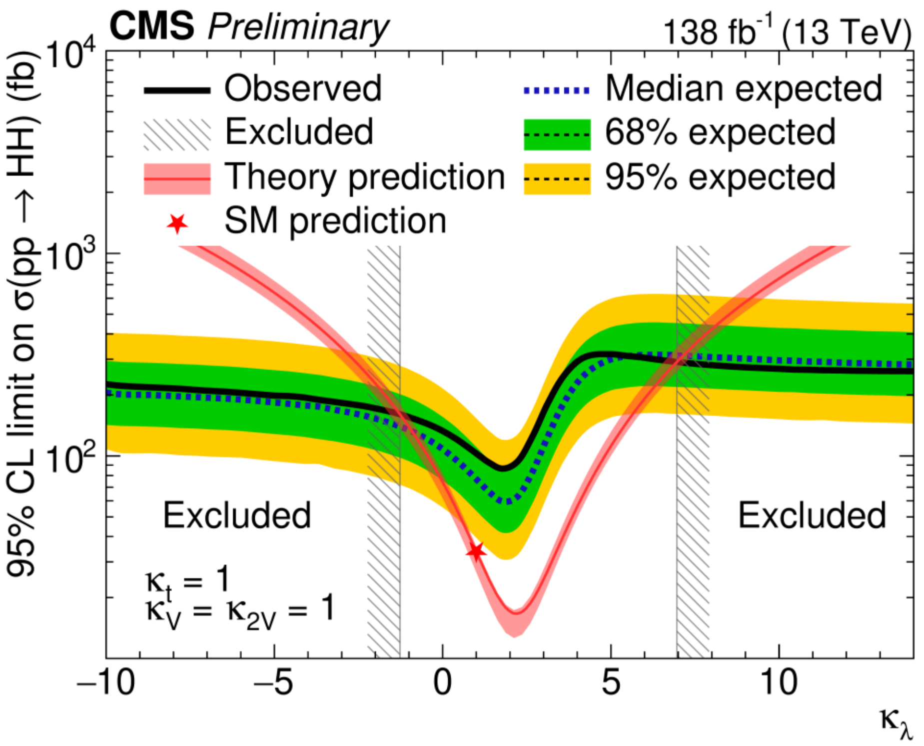
Summary & Outlook

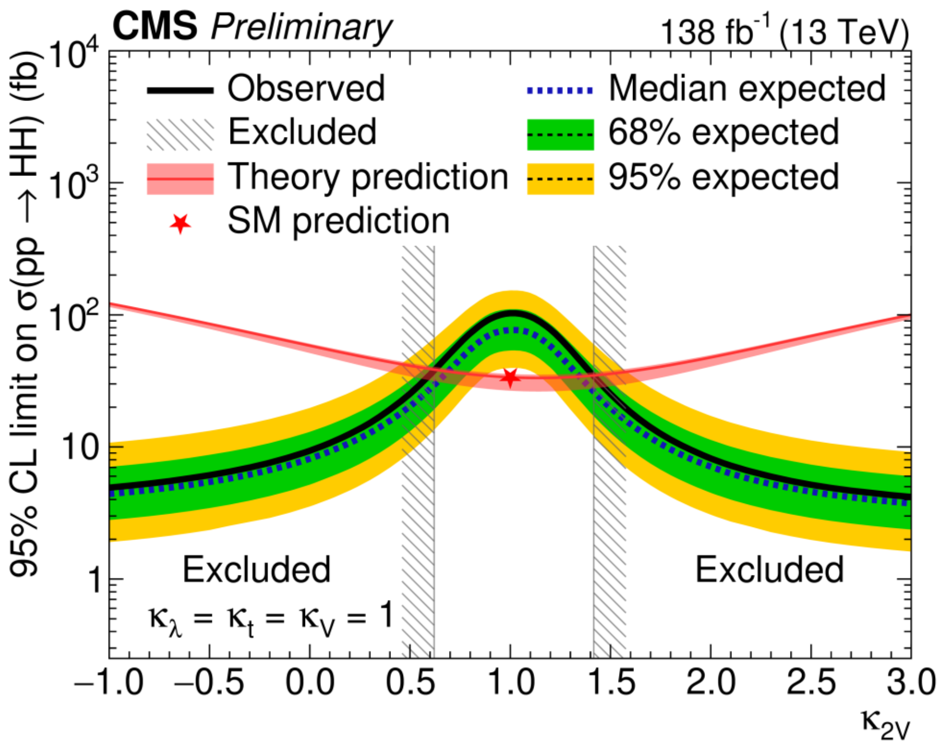
- Plethora of measurements and searches in Higgs sector
  - Much more than I could cover today!
- Many Higgs coupling measurements reach precision measurement status
  - Expanding searches for rare production and decay modes
- Di-Higgs measurements pushing towards SM precision
- Breadth of new physics scenarios probed
- Data sets expanding fast (LHC Run 3) and will reach new heights at HL-LHC

Additional Material

κ_λ and κ_{2V} Limits from Di-Higgs Combinations

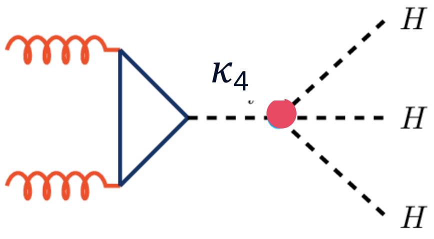


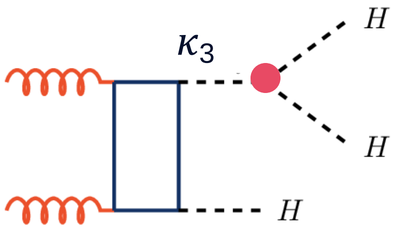




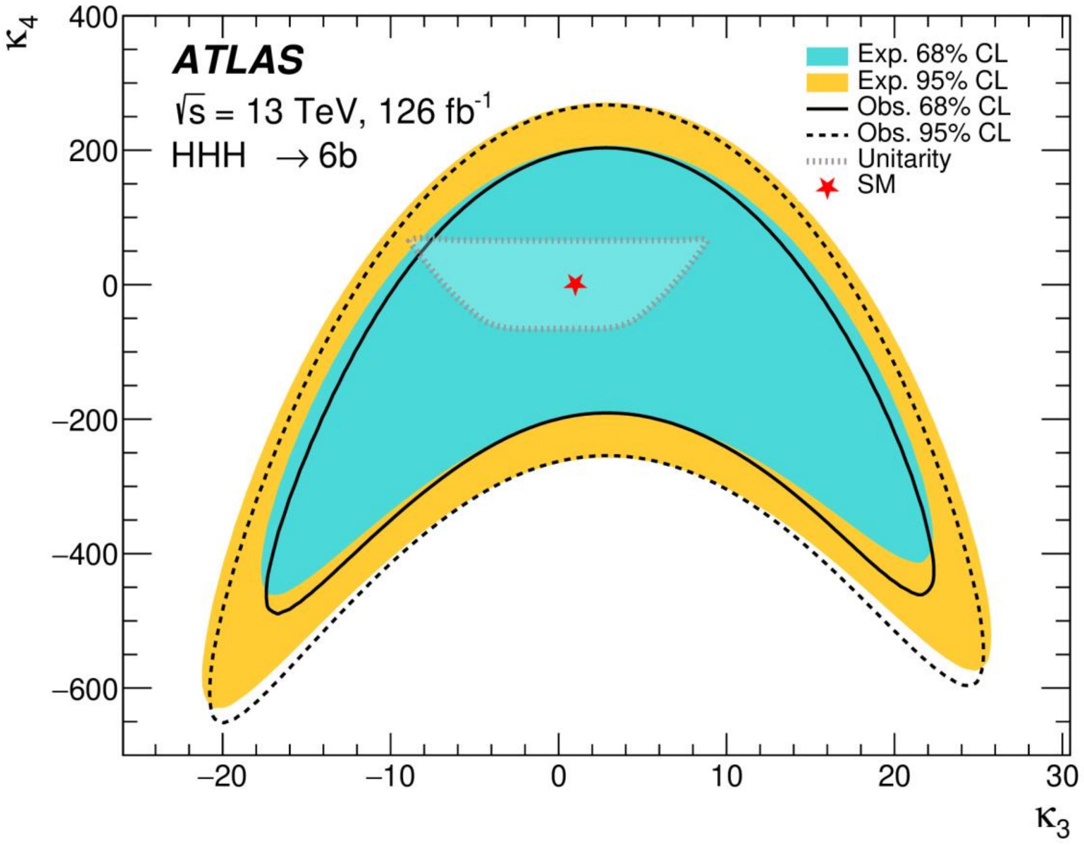
CMS-PAS-HIG-20-011

Quartic Higgs-self coupling in HHH→6b



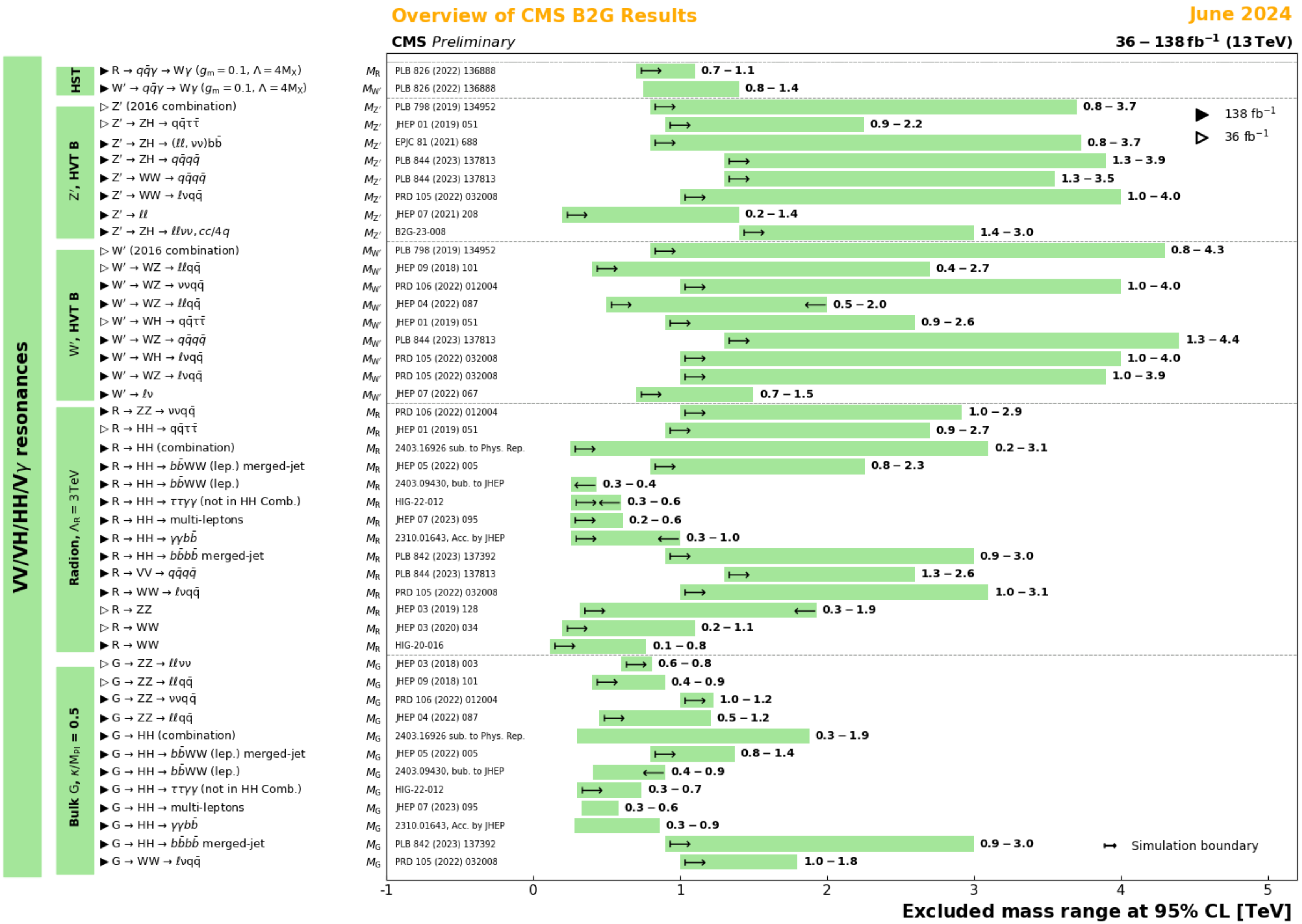


Simultaneous constraint on Higgs triple- and quartic-couplings



[Phys. Rev. D 111 (2025) 032006]

Overview of Heavy Resonance Searches



CMS B2G Summary plots (June 2024)

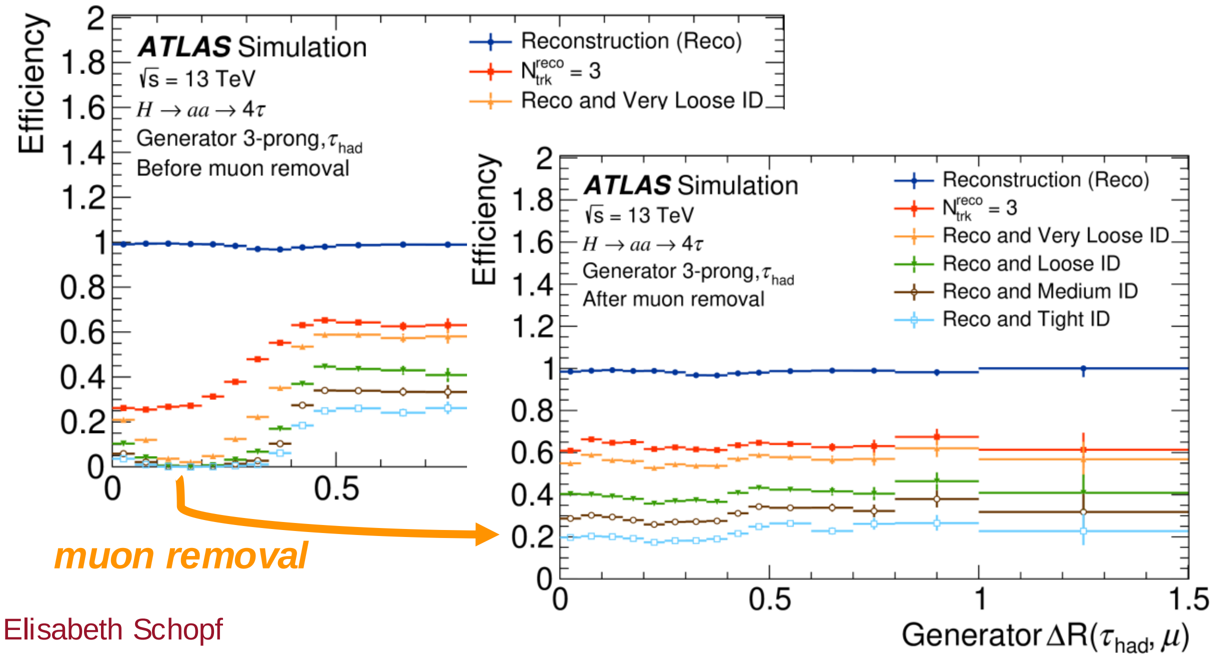
Exotic Higgs Boson Decays

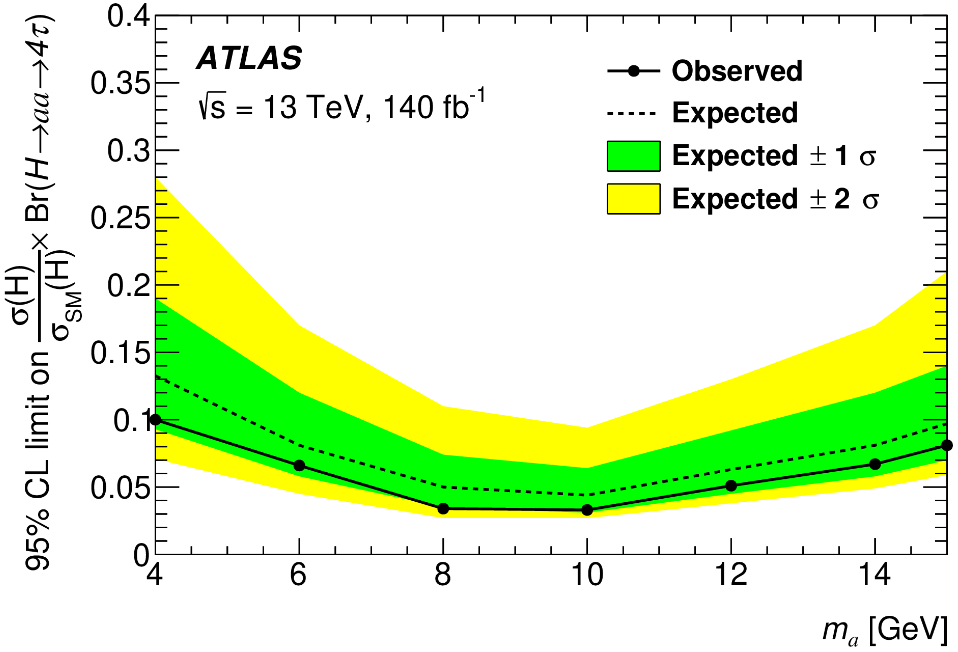
Search for low-mass scalars *a: H→aa→4τ* (m_H=125 GeV)

Probing very low masses 4 GeV < m_a < 15 GeV
→ ***a***-boson has high transverse momentum → **τ**-decay products overlap
Targeted decays: one **τ** decays via muons, one **τ** decays via hadrons

Muons close to hadronically decaying **τ**-lepton (**τ**$_{had}$) removed from reconstructed **τ**$_{had}$ candidate to then use standard **τ**$_{had}$ identification techniques

***τ**$_{had}$ identification efficiency*





arXiv:2503.05463