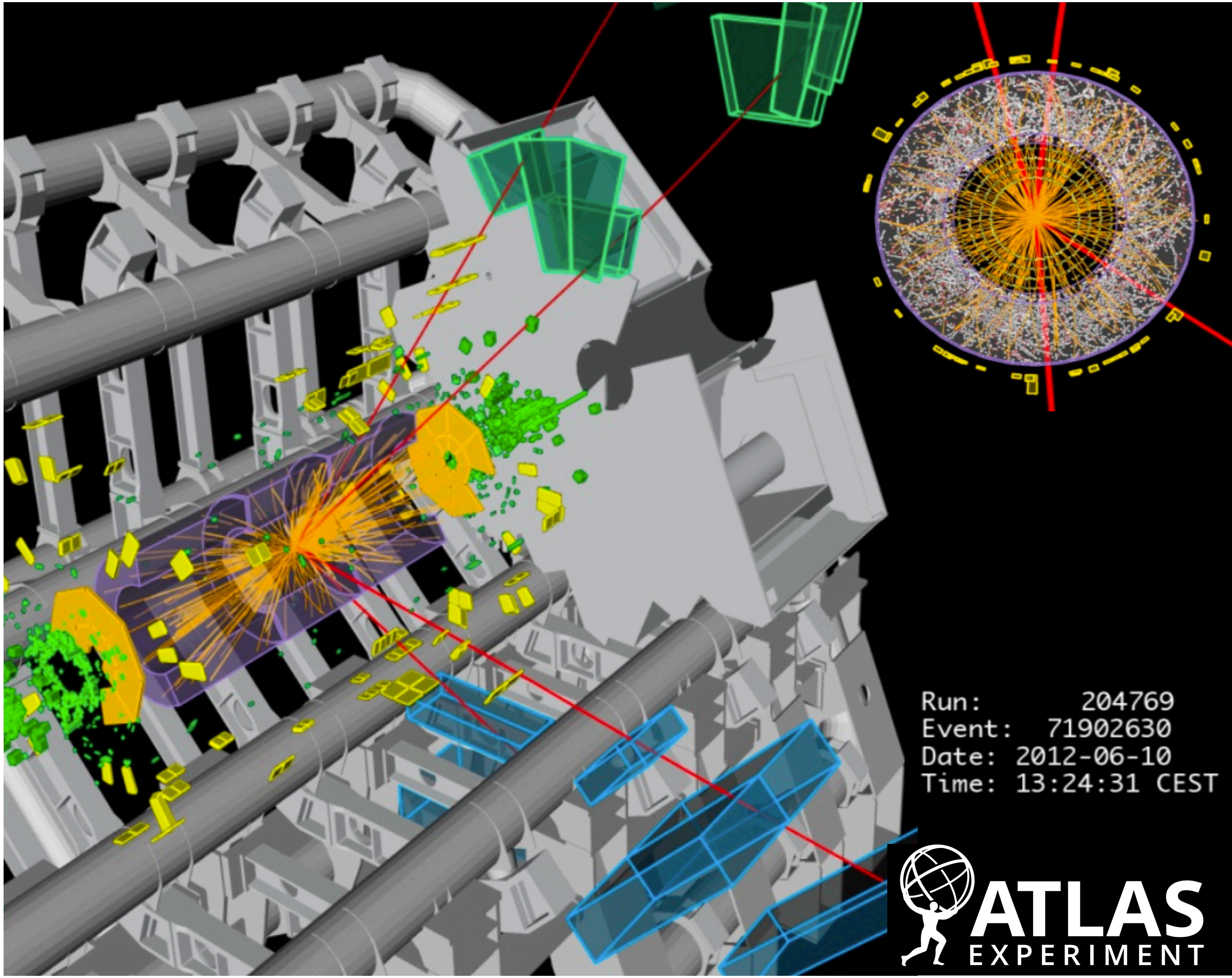
Higgs results and prospects from ATLAS

Jiayi Chen
on behalf of the ATLAS collaboration



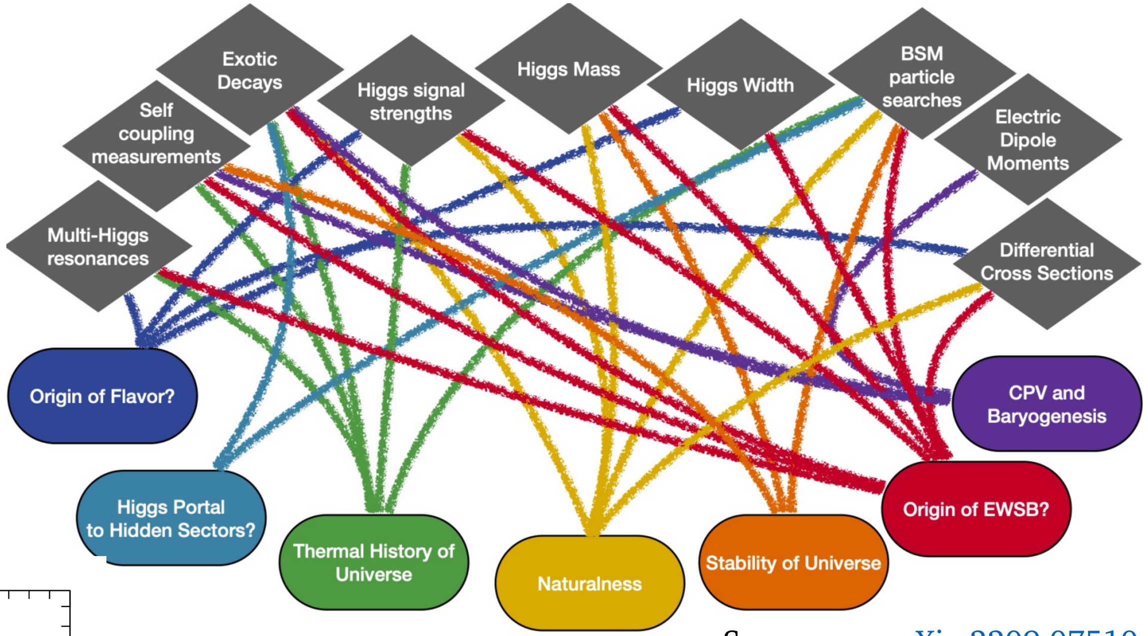
LISHEP 2023
International School on High Energy Physics

SFU SIMON FRASER UNIVERSITY

ATLAS EXPERIMENT

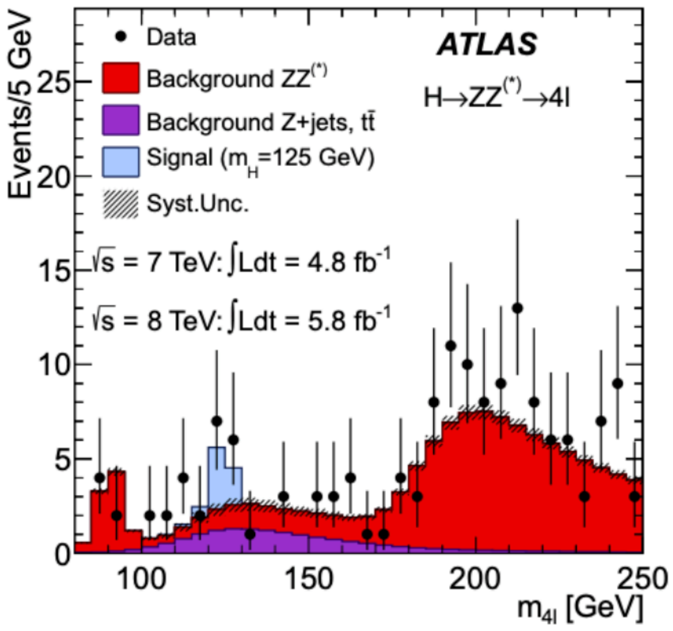
Introduction

- 10 years after the discovery, the Higgs boson remains at the core of the LHC program
- Many unexplained physics phenomenon call for the precise determination of the Higgs boson nature

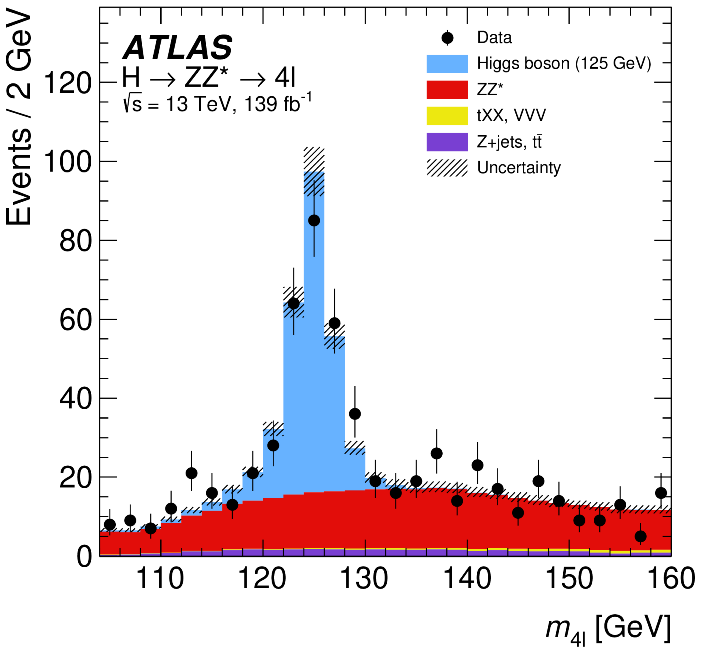


Snowmass arXiv:2209.07510

Phys. Lett. B 716 (2012)



arXiv:2207.00320 (2022)
- covered by this talk



- All results covered in this talk uses the ATLAS data collected in Run-2 between 2015-2018, corresponding to an integrated luminosity of 139 fb^{-1}
- During Run-2, expected amount of Higgs boson events is ~30 times larger than at the time of its discovery

Overview of ATLAS Higgs results and prospects

Precise coupling measurements to unveil new physics signature for interpretation

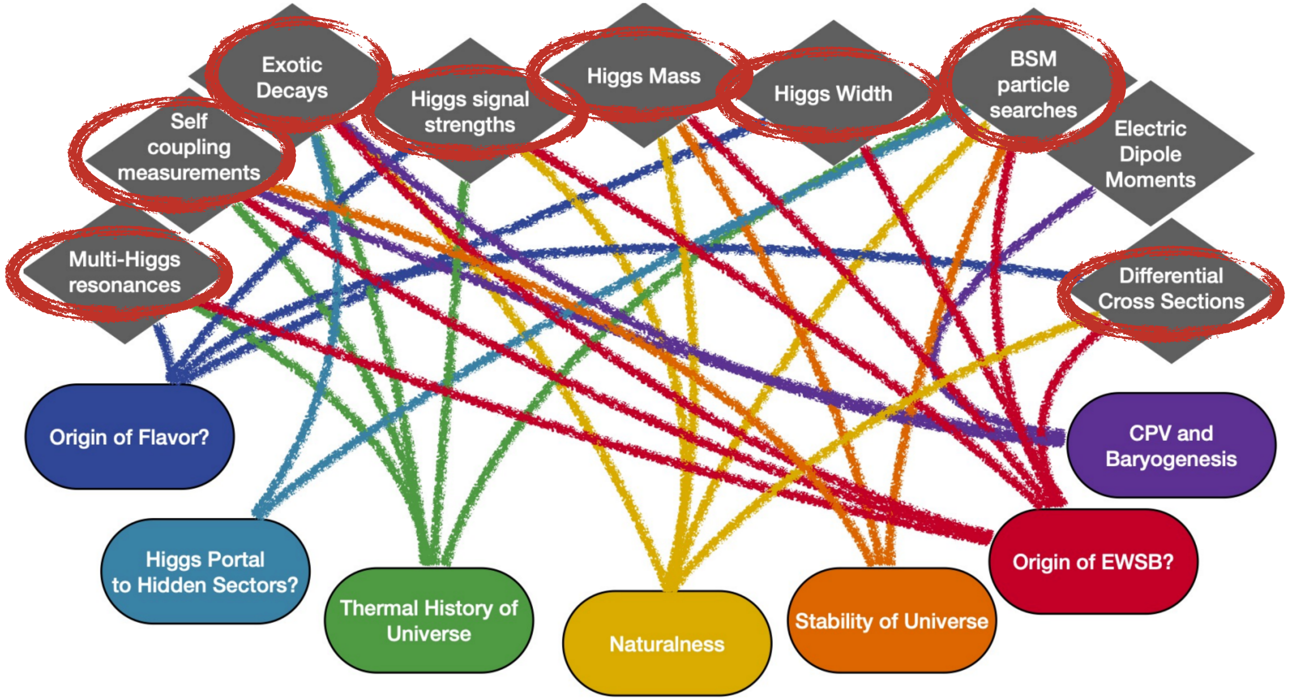
- Combined *coupling* measurements [Nature 607 (2022)]
- Combined $H \to 4l$ and $H \to \gamma\gamma$ differential cross-section measurement [arXiv:2207.08615]
- Invisible decays of the Higgs boson [arXiv:2301.10731]

Important input parameters for MC simulations

- Higgs boson *mass* measurement with $H \to 4l$ [arXiv:2207.00320]
- Constrain Higgs boson *width* with off-shell Higgs boson production [ATLAS-CONF-2022-068]

Higgs self-coupling and HL-LHC prospect:

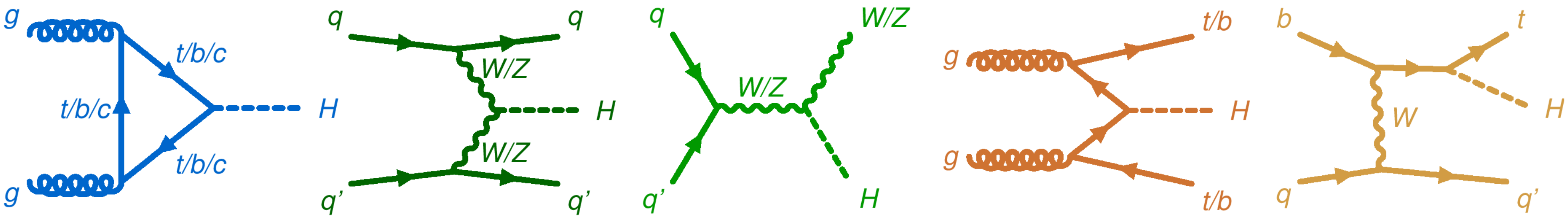
- Constrain self-coupling from single- and double-Higgs production [arXiv:2211.01216]
- di-Higgs [ATL-PHYS-PUB-2022-053]



Combined Higgs coupling measurement (I)

[Nature 607 (2022)]

- This analysis combines mutually exclusive measurements of Higgs boson production and decay modes



Dominant production modes at $\sqrt{s} = 13$ TeV:

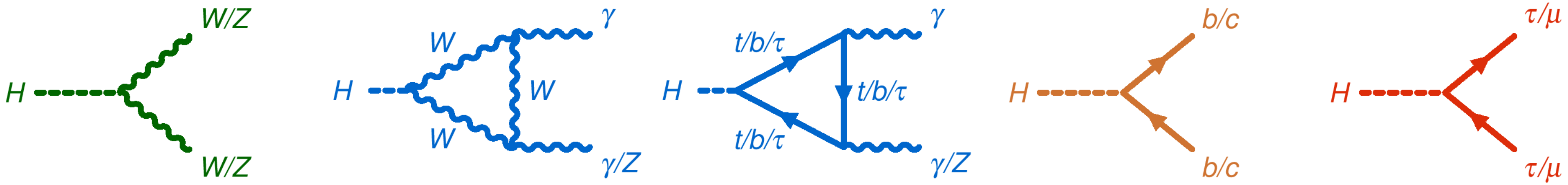
gluon-gluon fusion (ggF): 87%

vector boson fusion (VBF): 7%

in-association with weak boson (VH): 4%

in-association with t/b-quark pair ($t\bar{t}H/b\bar{b}H$): 1%

in-association with single top (tH): 0.05%



Decay channels branching ratio at $m_H = 125$ GeV:

$H \to WW$: 22%
$H \to ZZ$: 3%

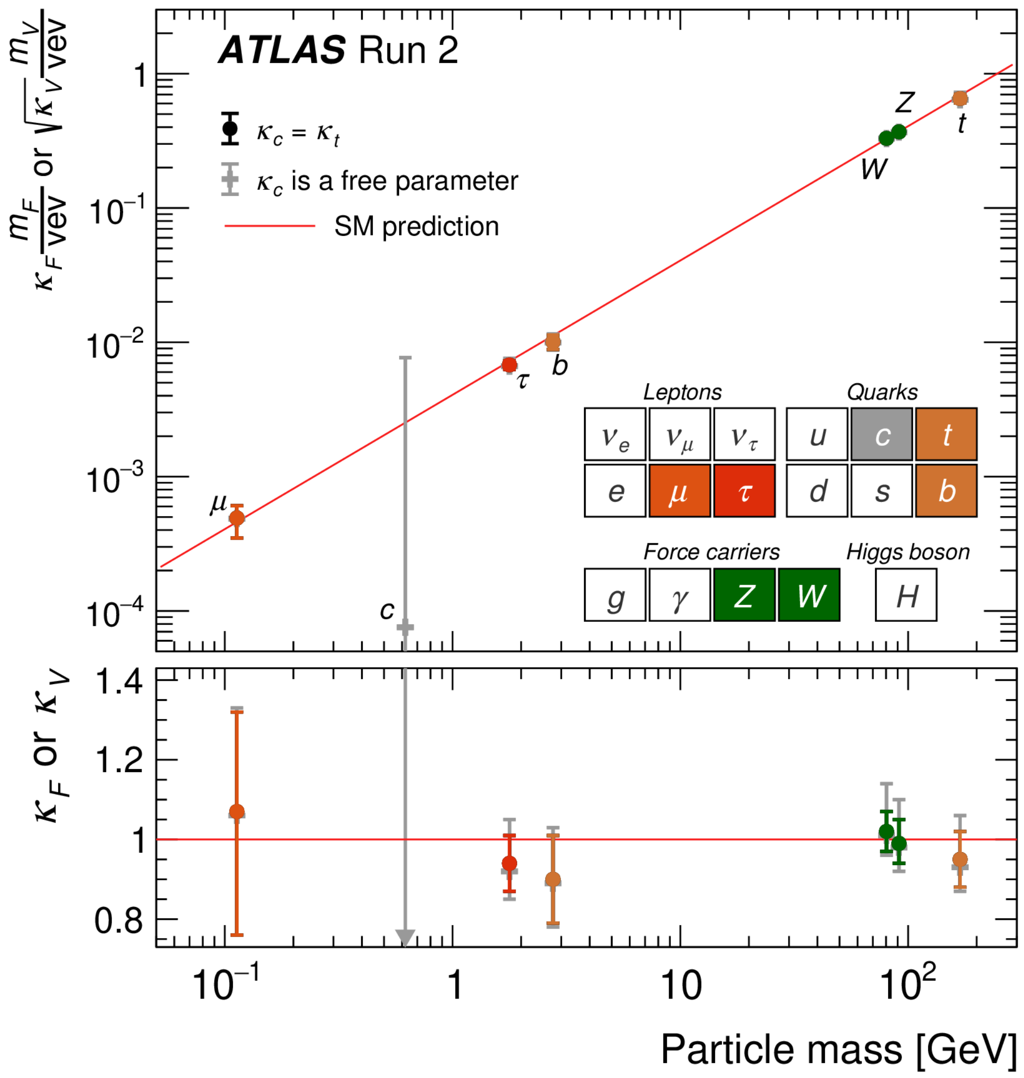
$H \to \gamma\gamma$: 0.2%
$H \to Z\gamma$: 0.2%

$H \to bb$: 58%
$H \to cc$: 3%

$H \to \tau\tau$: 6%
$H \to \mu\mu$: 0.02%

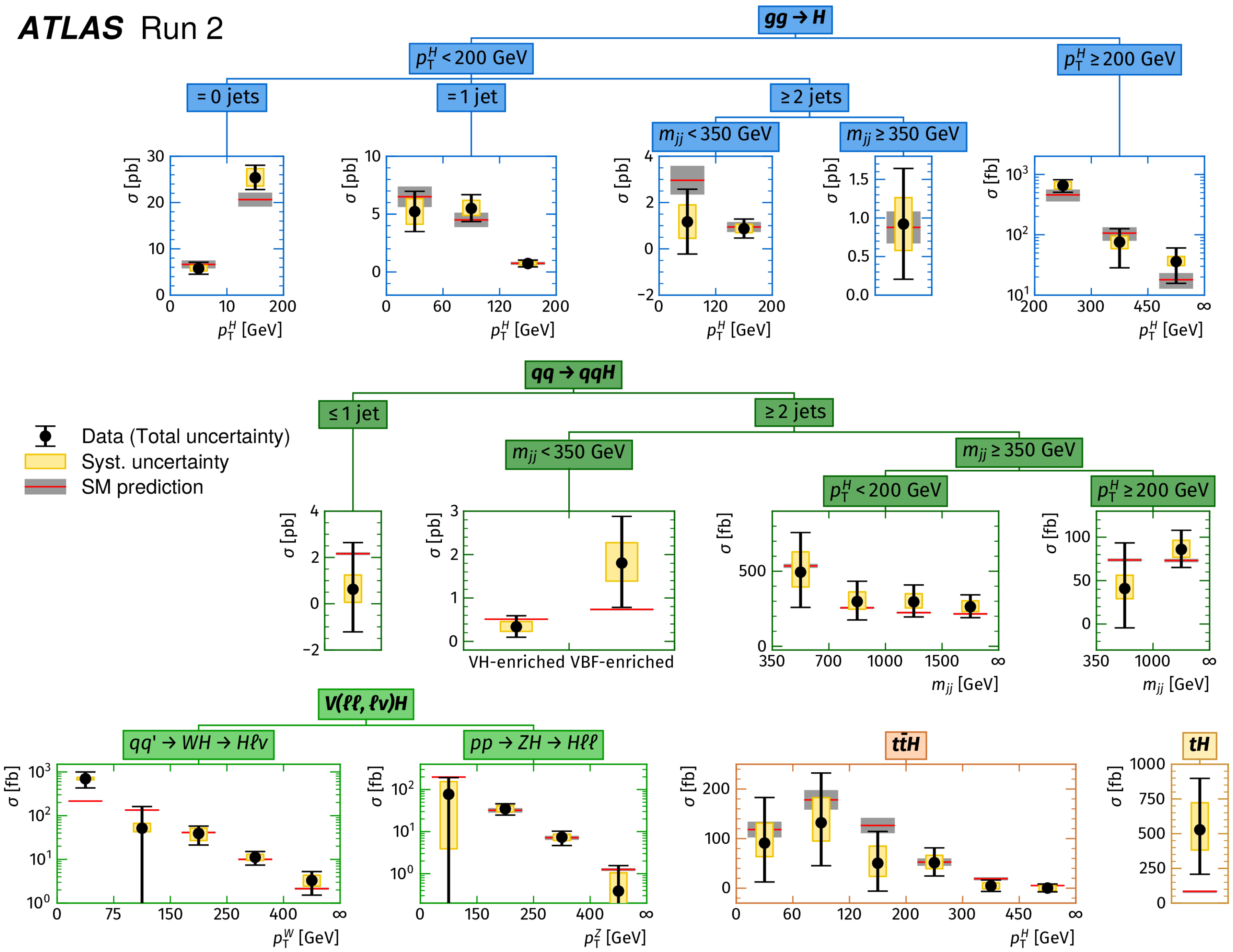
- Signal-strength modifier $\mu_{if} = (\sigma_i/\sigma_i^{\mathrm{SM}}) \times (B_f/B_f^{\mathrm{SM}})$ for a specific production process i and decay mode f
- Observed global signal strength $\mu = \mu_{if}$:

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$$



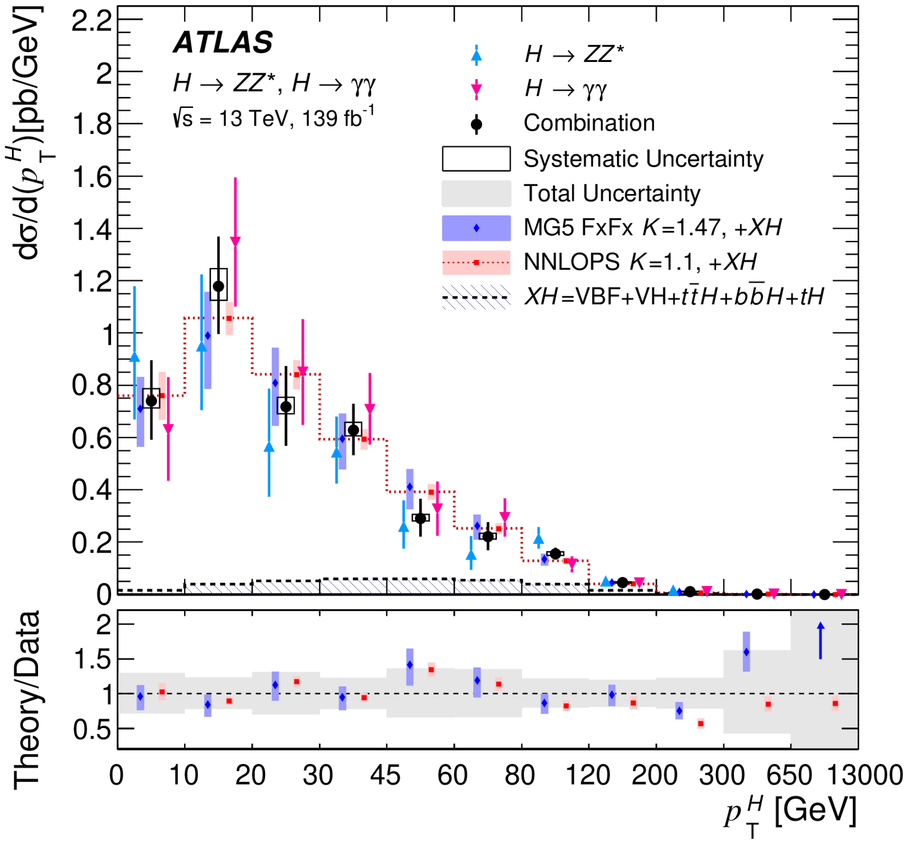
- The κ-framework introduces coupling modifiers for the Higgs coupling with the fermions (κ_f) and bosons (κ_V)
- Coupling measurement with precision 7-12% (5%) for fermions (vector bosons) (κ_c is unconstrained at the moment)

- STXS framework partitions Higgs production phase space into several regions to
  - avoid large theory uncertainties
  - provide BSM sensitivity
- STXS measurement can be interpreted with the Effective Field Theory framework, e.g.
  - four-lepton EFT interpretation [Eur. Phys. J. C 80 (2020)]
  - Higgs coupling combination and interpretation [ATLAS-CONF-2020-053]

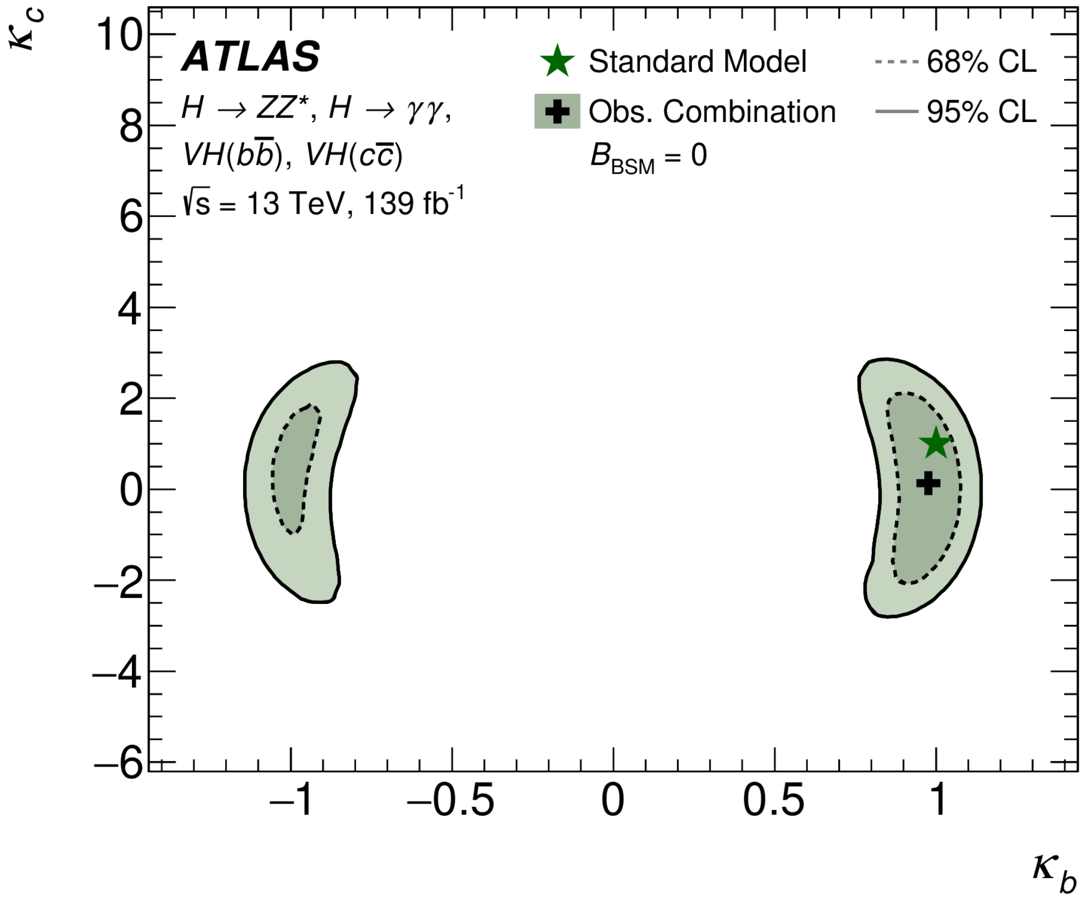


Combined differential cross-section measurement and interpretation [arXiv:2207.08615]

- Combined $H \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ analysis measures cross-section differentially as functions of various Higgs boson kinematic variables
- Each channel measures cross-sections in defined fiducial volume and extrapolates measurements to the full phase space using acceptance corrections



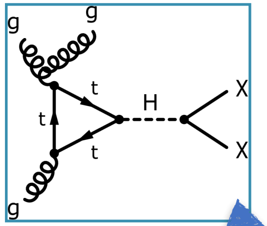
- Sensitivity on c-quark coupling modifier (κ_c) from p_T^H spectrum is driven by b/c-quark contribution to loop induced ggF and quark-initiated Higgs production modes
- Combining with the constraints from VH(bb) and VH(cc) production - κ_b and κ_c sensitivity through decay - provides the best constraint on κ_c

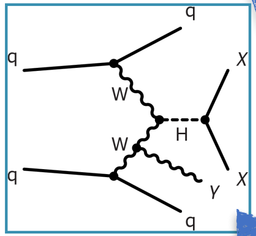


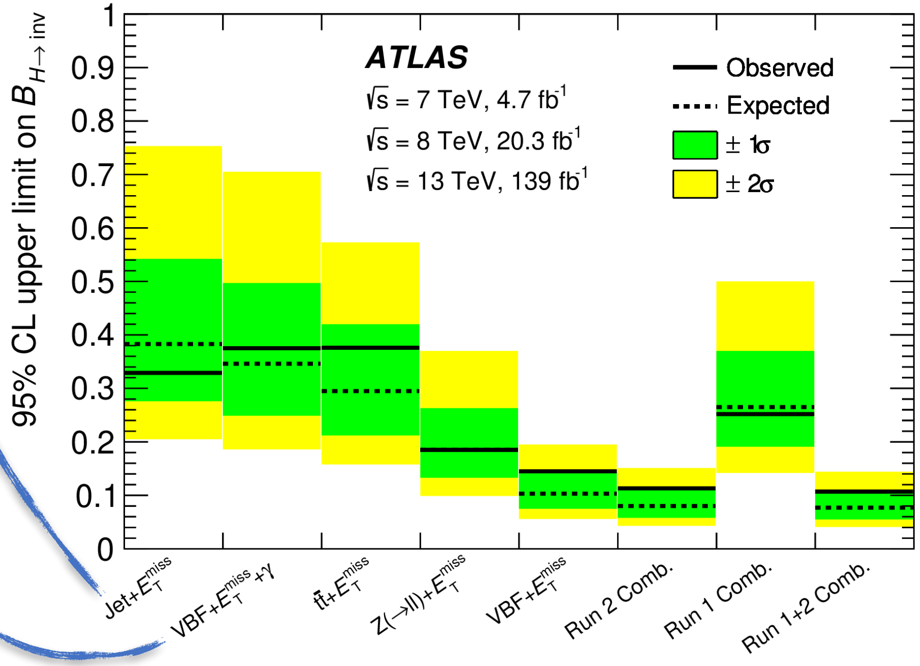
Higgs to invisible combination

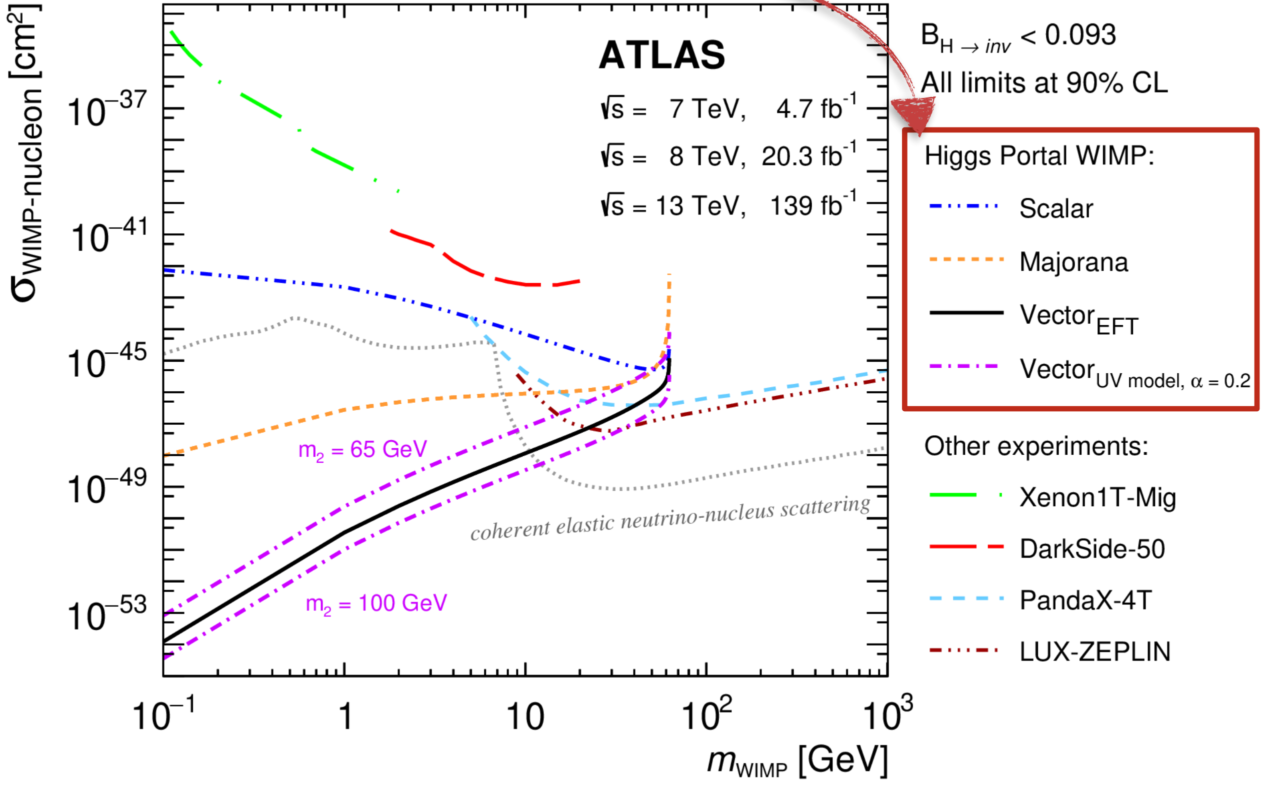
[arXiv:2301.10731]

- Higgs invisible decay BR would be larger than SM prediction ($H \to ZZ \to 4\nu$, ~0.1%), if the Higgs boson can decay to dark matter particles
- 5 production modes are studied separately and in combination
- Run1+2 combination measures BR=0.04±0.04; puts 95% C.L. upper limits at 0.107
- Spin independent elastic scattering cross-section of dark matter and nucleon limits converted from BR limits complement direct dark matter searches
- Several weakly interacting massive particle (WIMP) hypotheses are tested





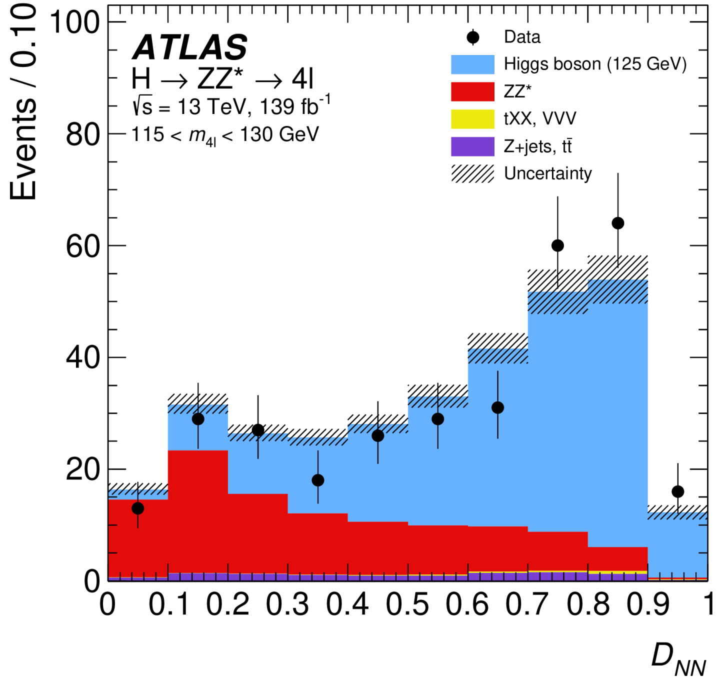


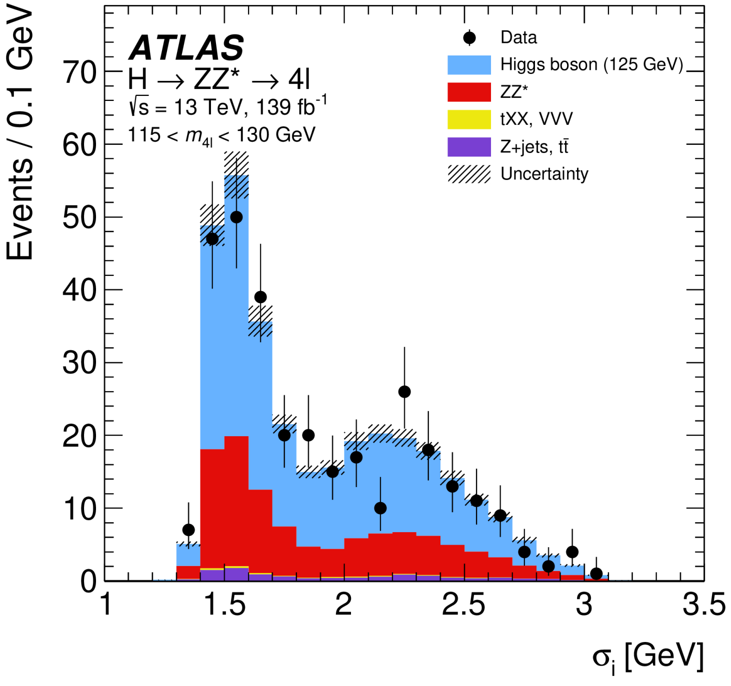


Higgs boson mass measurement in the $H \to ZZ^* \to 4l$ channel

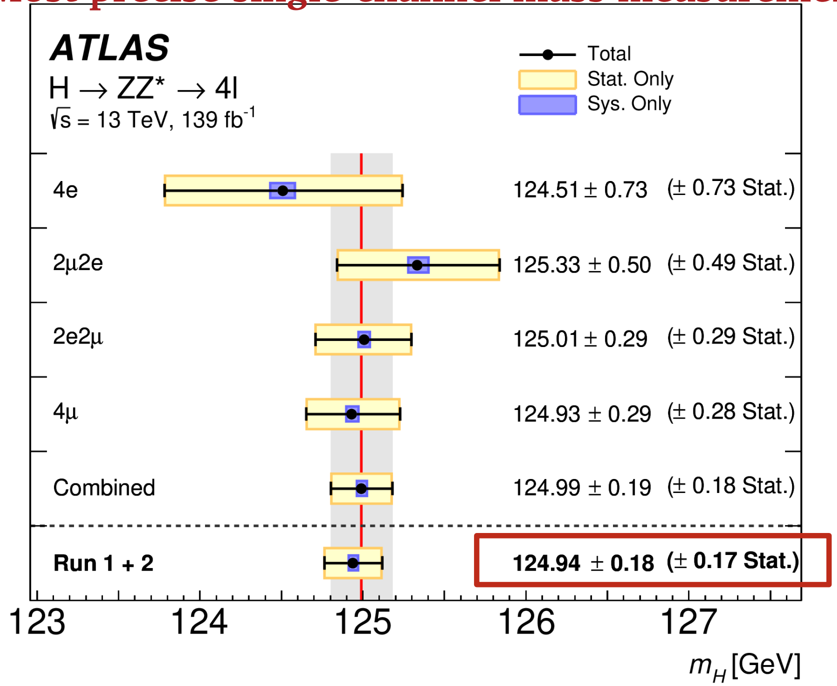
[arXiv:2207.00320]

- Mass of the Higgs boson (m_H) is not predicted by theory
- The four-lepton channel allows to perform very precise measurements of the Higgs mass thanks to the fully leptonic final states and with very good resolution.
- Discriminant variables and techniques:
  - m_{4l}: resolution improved by ~17% with a Z-boson mass constraint fit to the leading lepton pairs
  - Signal-background deep neural network (DNN) discriminant: signal events in the training contains samples with different Higgs masses to reduce dependency on m_H; DNN improves measurement precision by 2%
  - Event-level m_{4l} resolution (σ_i): estimated using a quantile regression neutral network (QRNN); help to extract mass information from events that are not in the "good" detector region; reduces total expected uncertainty by 1%





Most precise single-channel mass measurement



Higgs boson decay width measurement (I)

[ATLAS-CONF-2022-068]

- Higgs width is predicted to be 4.1 MeV - too small comparing to detector resolution of LHC experiments
- Instead, the ratio of on-shell and off-shell Higgs production probes the Higgs width (unique to $H \to VV$):

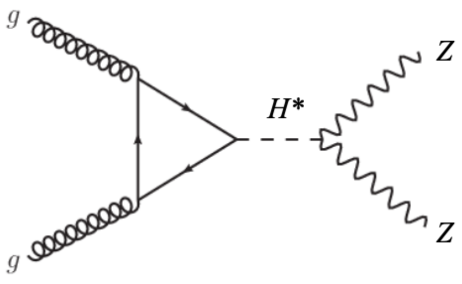
$$\sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m^2_{ZZ}}$$

$$\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

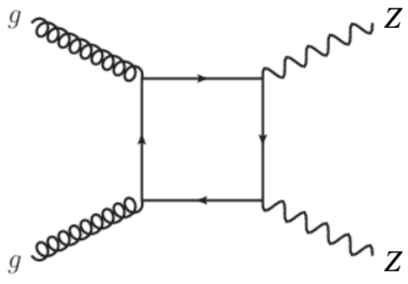
From on-shell Higgs measurement in the $4l$ channel

- Analysis considers ggF and electroweak (EW=VBF+VH) production modes and $H^* \to ZZ \to 4l/2l2\nu$ final states
  - The interference ($\boldsymbol{I}$) between the off-shell signal ($\boldsymbol{S}$) and the $gg/qq \to ZZ$ continuum background ($\boldsymbol{B}$) is negative
  - The size of the deficit in $gg/qq \to ZZ$ depends on the off-shell signal strength ($\mu_{\text{off-shell}}$):

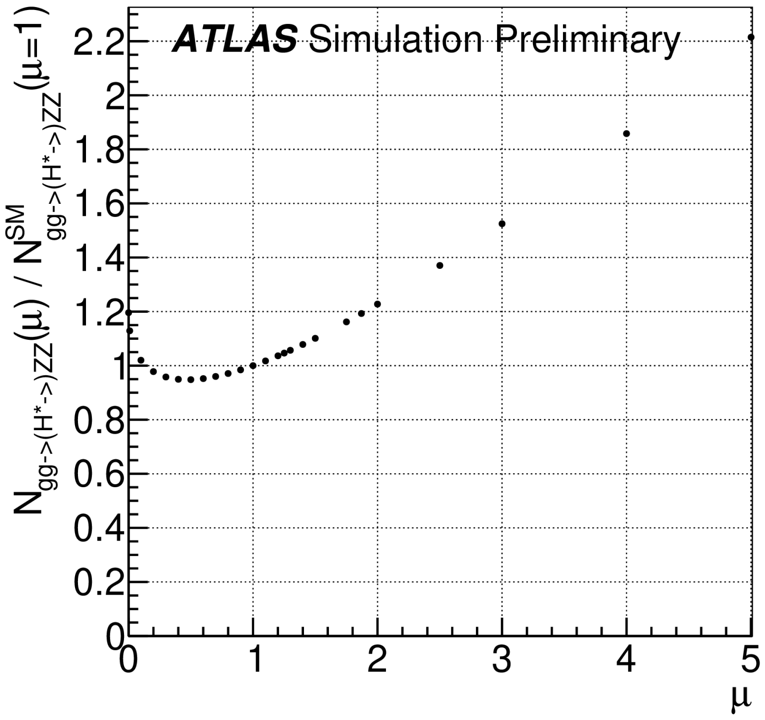
$$N = \mu_{\text{off-shell}} \cdot S + \sqrt{\mu_{\text{off-shell}}} \cdot I + B \quad (I < 0)$$



ggF off-shell signal



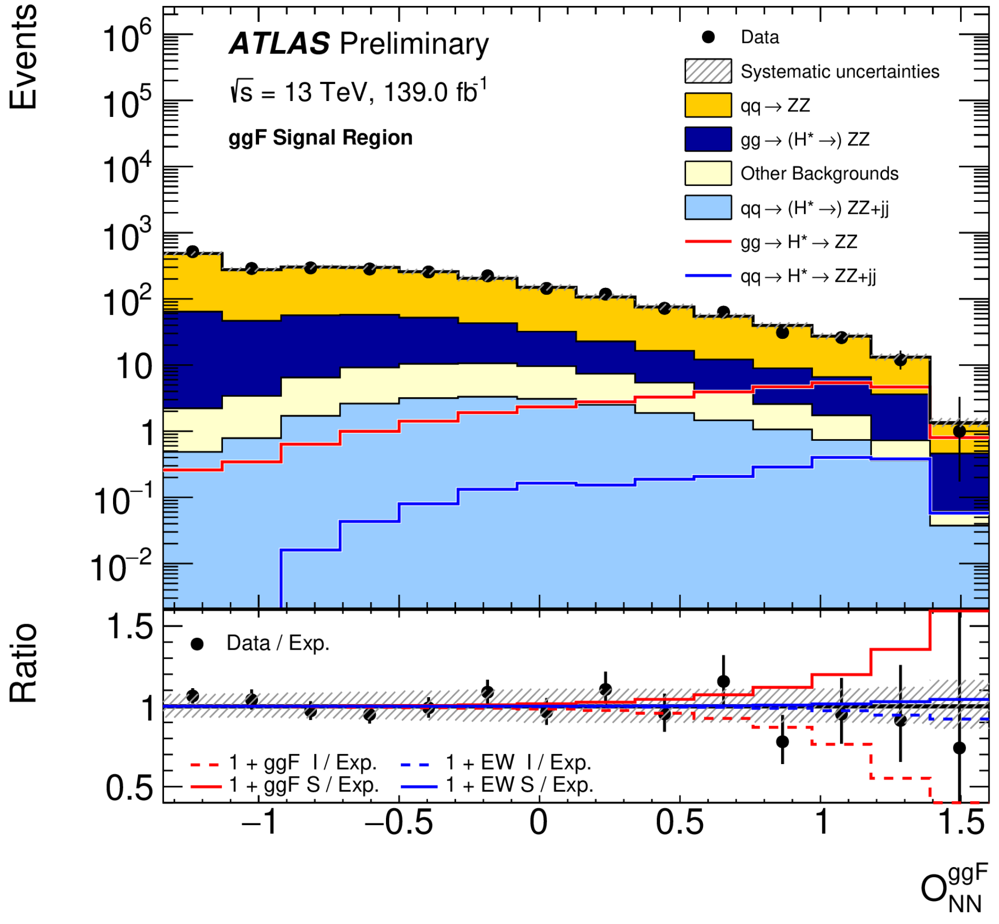
ggZZ background

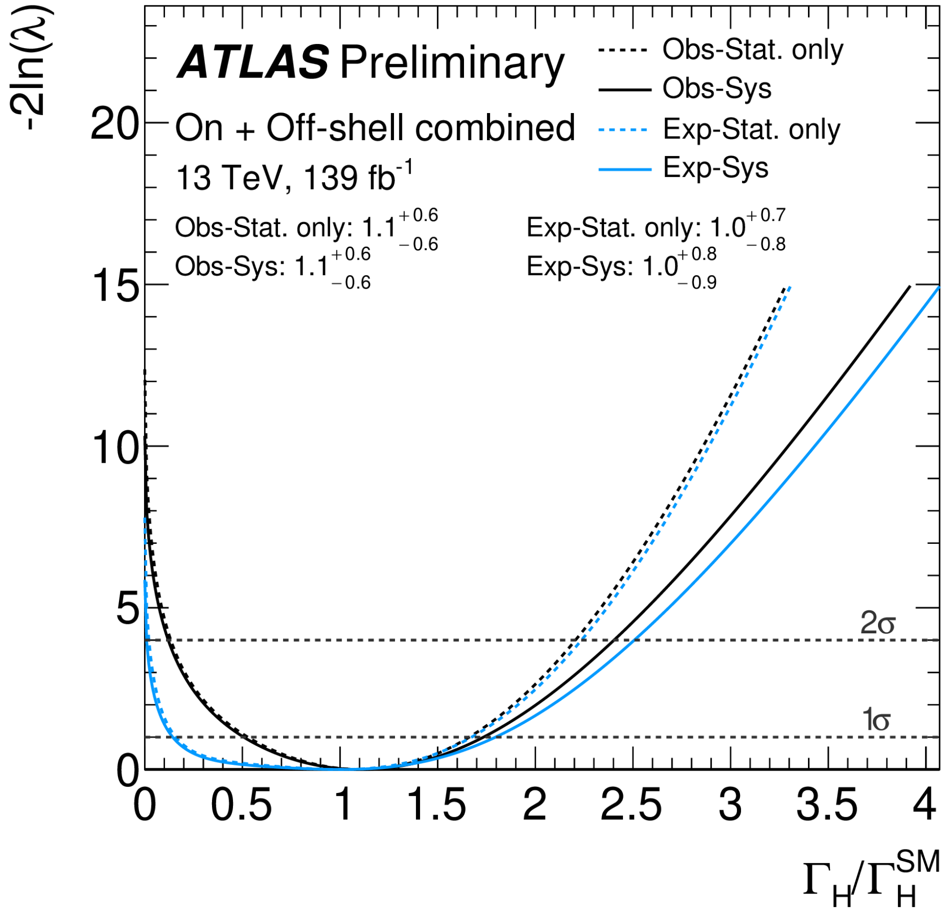


Higgs boson decay width measurement (II)

[ATLAS-CONF-2022-068]

- $ZZ \to 4l$ channel uses neural networks trained with kinematic variables and matrix-element discriminants
- $ZZ \to 2l2\nu$ channel uses the transverse mass of the ZZ system
- The off-shell/on-shell coupling strength ratio, measures the total Higgs boson width of: $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV
  - on-shell analysis: [Eur. Phys. J. C 80 (2020)]



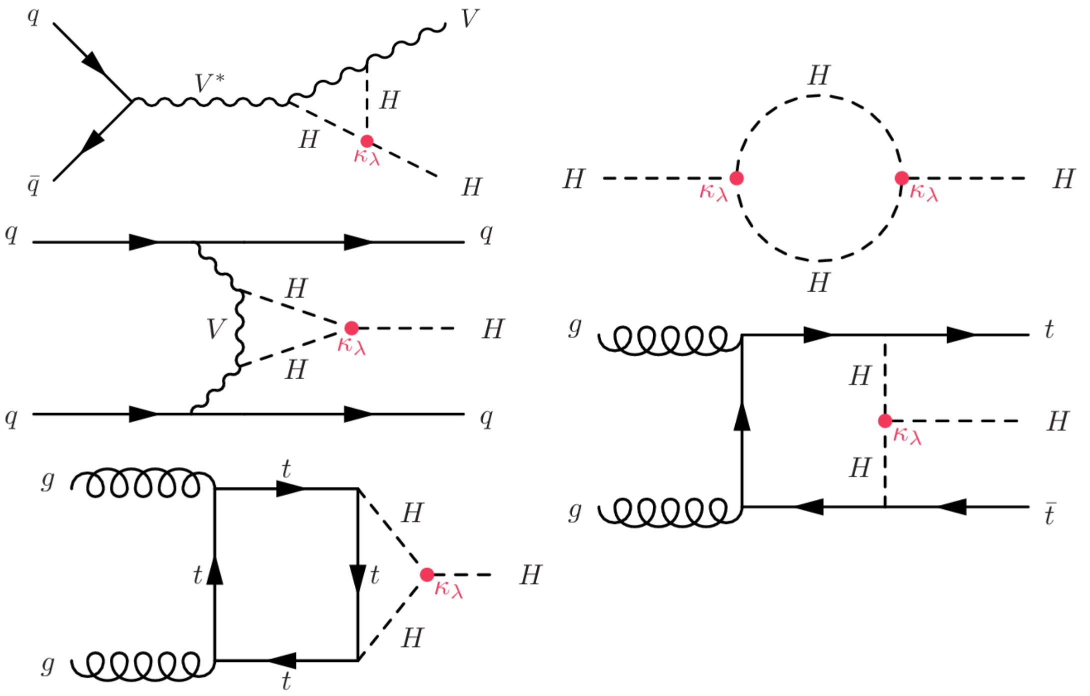


Combined single- and double-Higgs to constrain self-coupling

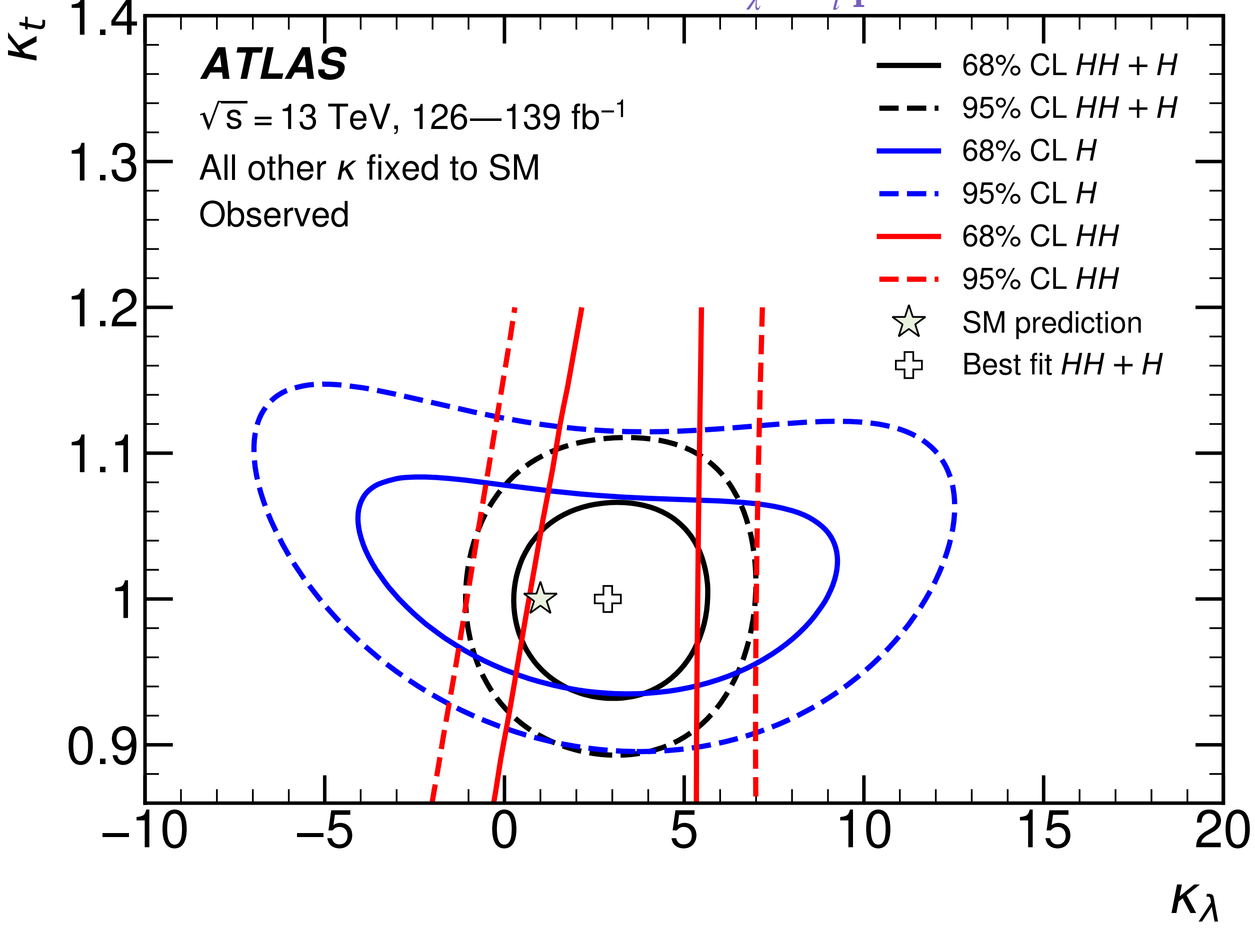
[arXiv:2211.01216]

- Expected di-Higgs production cross-section is ∼1000 times smaller than single-Higgs production
- Higgs self-coupling (coupling modifier κ_λ) can be probed not only directly via di-Higgs production but also indirectly via **NLO EW corrections on single-Higgs** (taken from combined Higgs coupling measurement)
- Tight **constraint on κ_t** mainly comes from single-Higgs analysis

One-loop κ_λ dependent diagrams of single-Higgs production

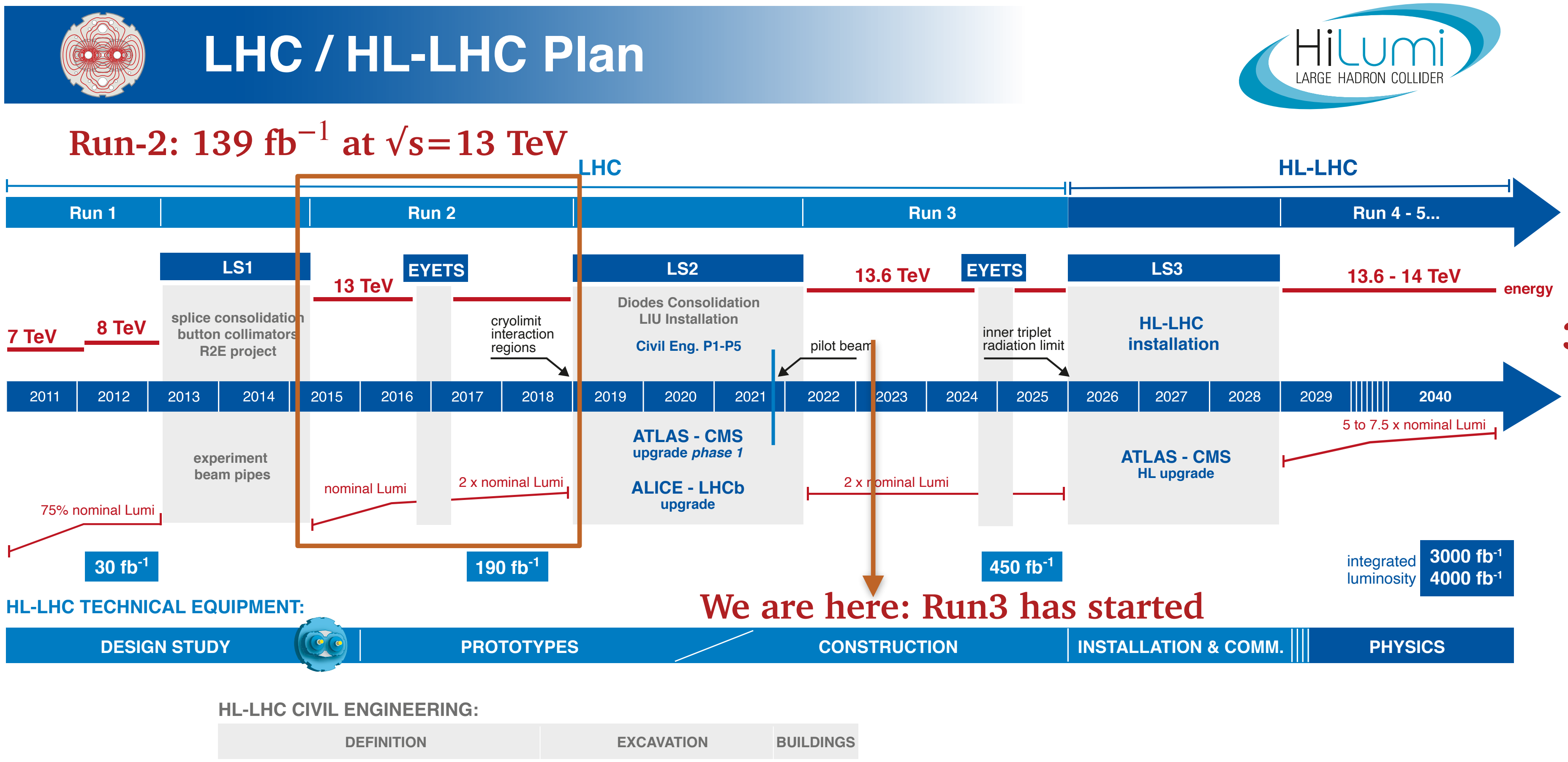


Constraints in the $\kappa_\lambda - \kappa_t$ plane



Higgs prospect at the HL-LHC

Run-2: 139 fb^{-1} at $\sqrt{s}$=13 TeV

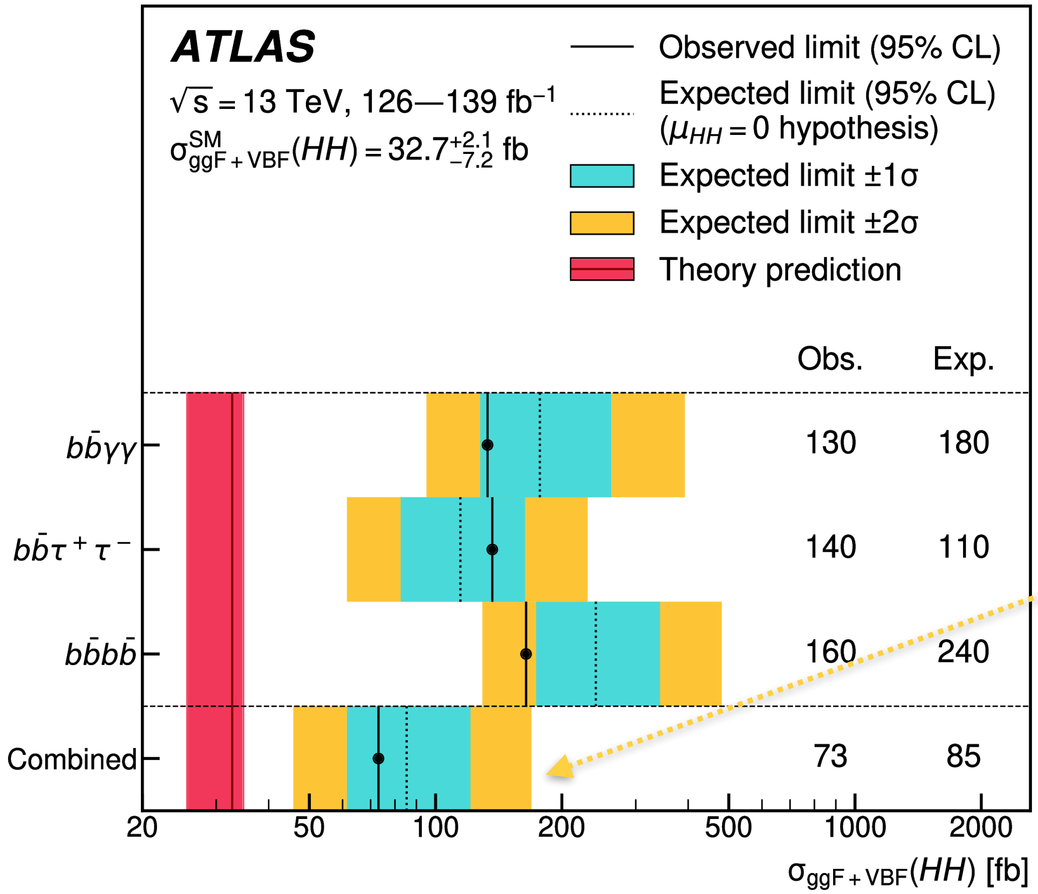


*HL-LHC prospect to be shown corresponds to the expected dataset of 3000 fb^{-1} of *pp* collisions at $\sqrt{s} = 14$ TeV

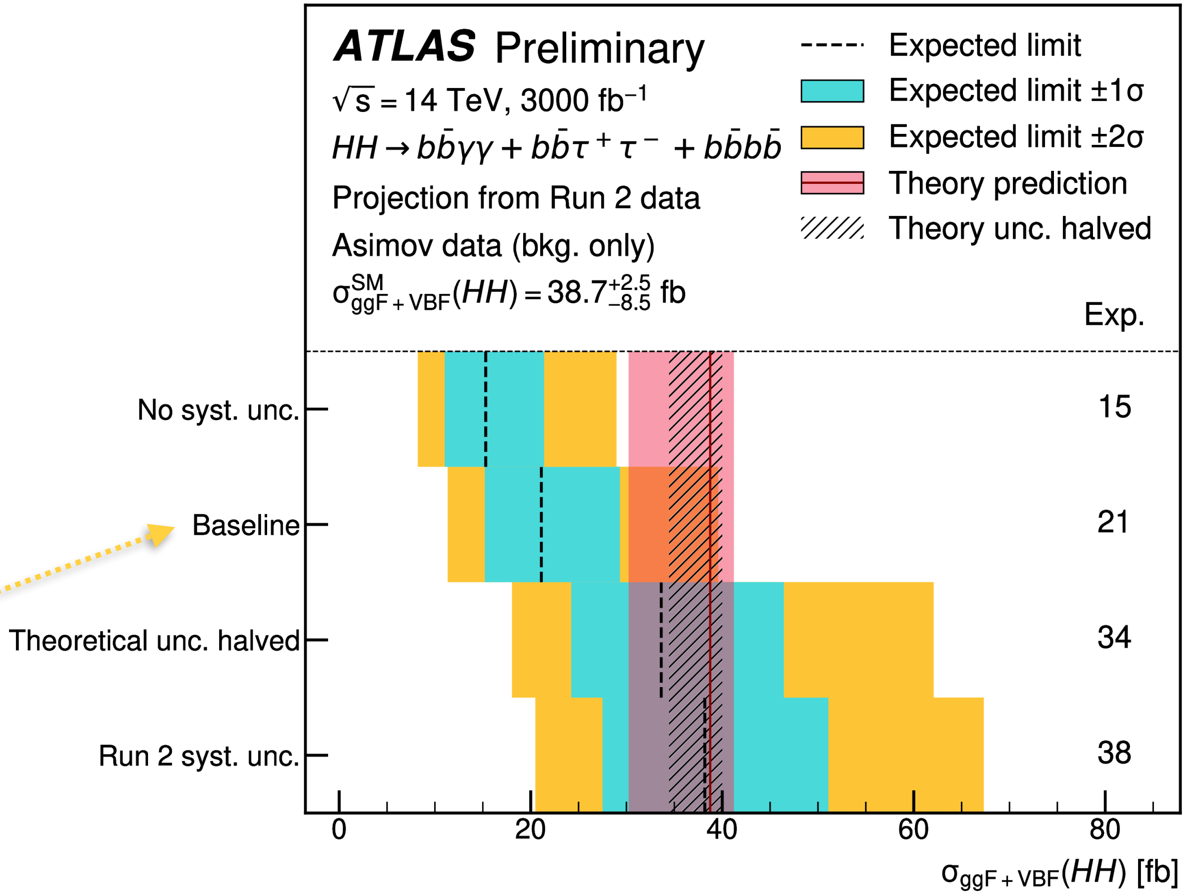
- Two main strategies for ATLAS projections:
  - Extrapolation based on Run-2 results
    - Benefit from well-studied systematics models developed for Run-2 analyses
  - Parametric simulations based on detailed simulations of the upgraded detectors under HL-LHC conditions

Prospect - di-Higgs (I)

- Expected significance is at 3.4σ assuming SM self-coupling strength and a scaled-down systematic uncertainty (baseline scenario)
- Cross-section limits (assuming no di-Higgs production) extrapolated from Run-2 analysis on the di-Higgs production cross section "touches" theoretical prediction



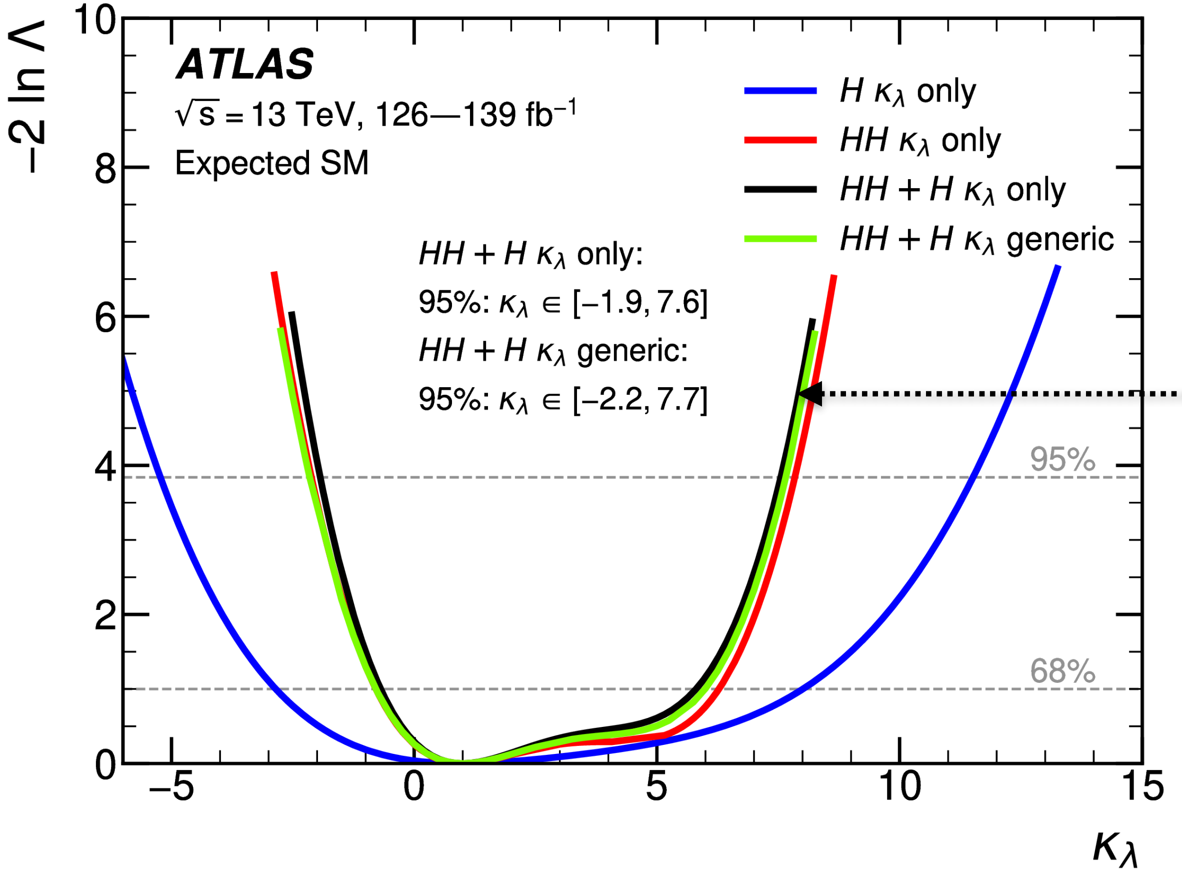
Run2: [arXiv:2211.01216]



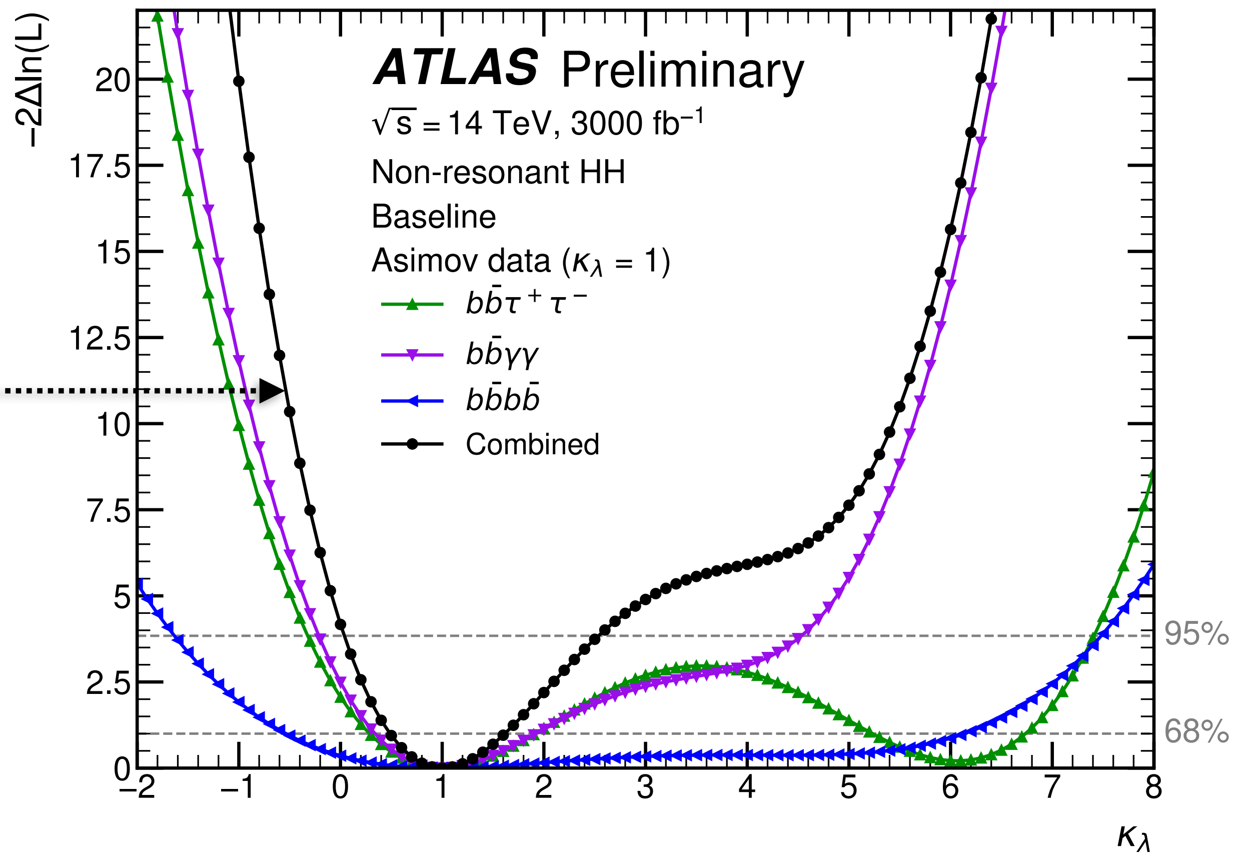
HL-LHC projection [ATL-PHYS-PUB-2022-053]

Prospect - di-Higgs (II)

- Expected self-coupling modifier 95% C.L. constraint:
  - Single- and di-Higgs current combination: [-1.9, 7.6] vs HL-LHC projection: [0.0, 2.5]



Run2: [arXiv:2211.01216]



HL-LHC projection [ATL-PHYS-PUB-2022-053]

Summary and outlook

- The ATLAS Higgs group is examining the particle from many distinct perspectives
  - Precise measurements on Higgs cross-sections in both individual production/decay channels as well as their combinations help to probe anomalous couplings induced by BSM physics (e.g. κ-framework)
  - Novel techniques in the Higgs measurement, such as machine learning, achieve resolution beyond pure detector sensitivity
- More Run-2 results are to appear soon; early Run-3 analyses are launching
- Data to be collected during HL-LHC has prospective potential to make new observations, including di-Higgs at a statistical evidence 3σ, projected from Run-2 analysis strategy, upgraded detectors with state-of-the-art technologies, and improved systematic uncertainties
- Finally, a combination with CMS results foresees a significance at 5σ level [CERN Yellow Report]

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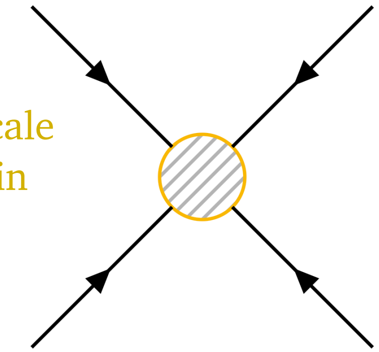
Viewed at current energy scale (going higher and higher in precision)



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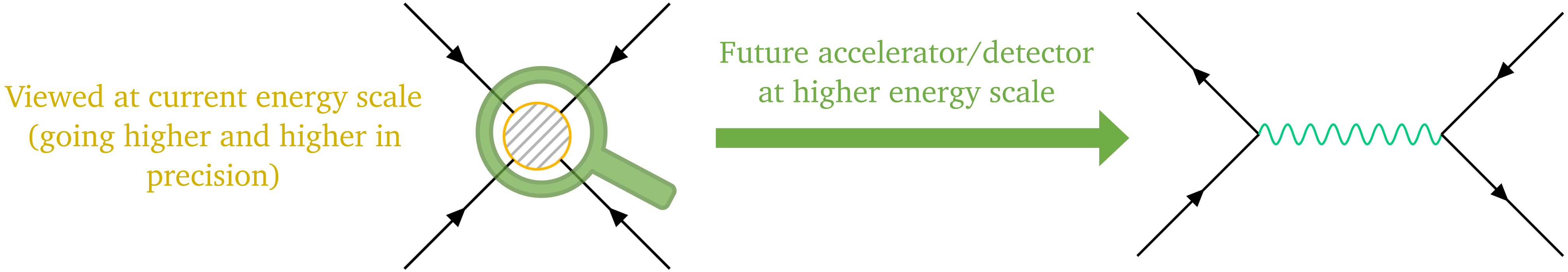
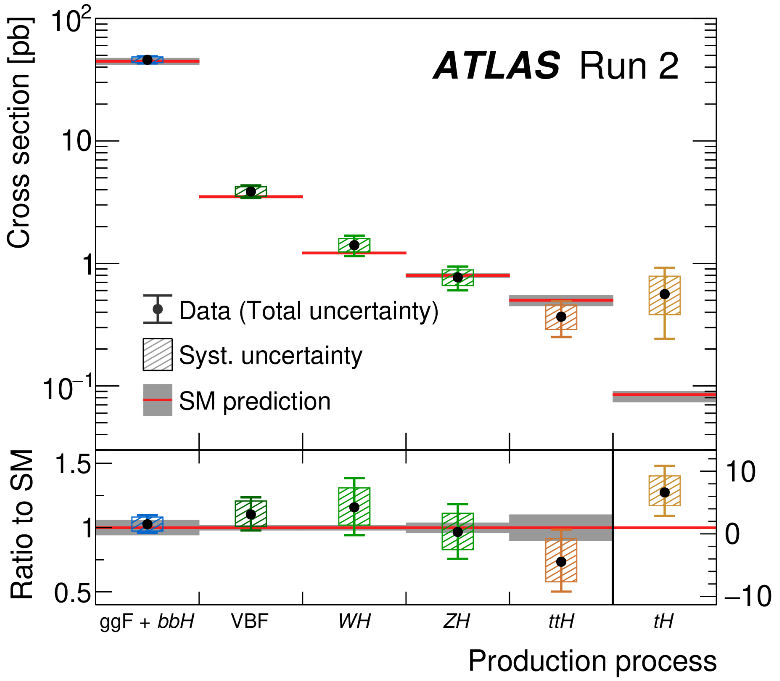


Backup

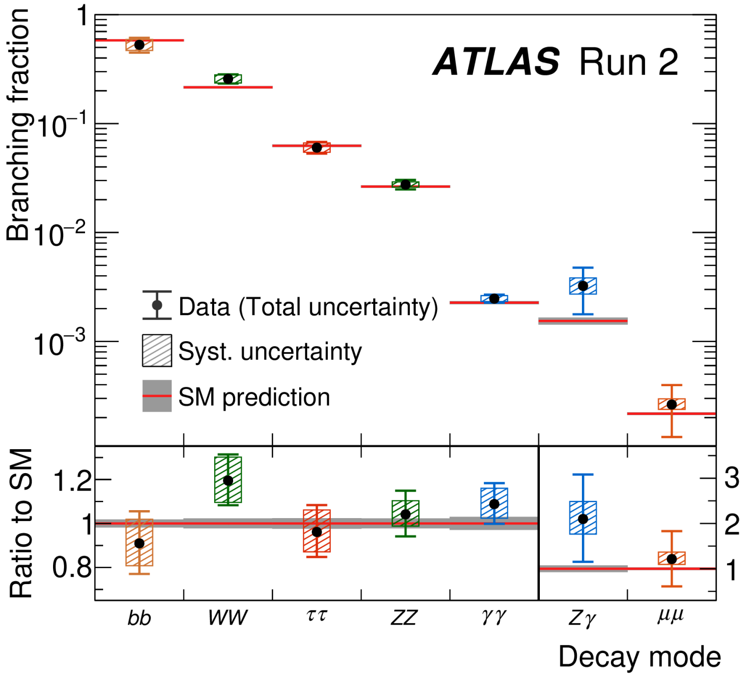
Combined Higgs coupling measurement

[Nature 607 (2022)]

- ggF and VBF: precision at 7% and 12%
- Productions (significance) that were not observed in Run1:
  - *WH* (5.8σ); *ZH* (5.0σ)
  - *ttH* and *tH* (6.4σ)
- Separating *ttH* and *tH* leads to *tH* upper limit at 15 times the SM value



- $\gamma\gamma, ZZ, WW, \tau\tau$: precision at 10-12%
- Decay (significance) that were not observed in Run1:
  - *bb* (7.0σ)
  - $Z\gamma(2.3\sigma)$; $\mu\mu(2.0\sigma)$

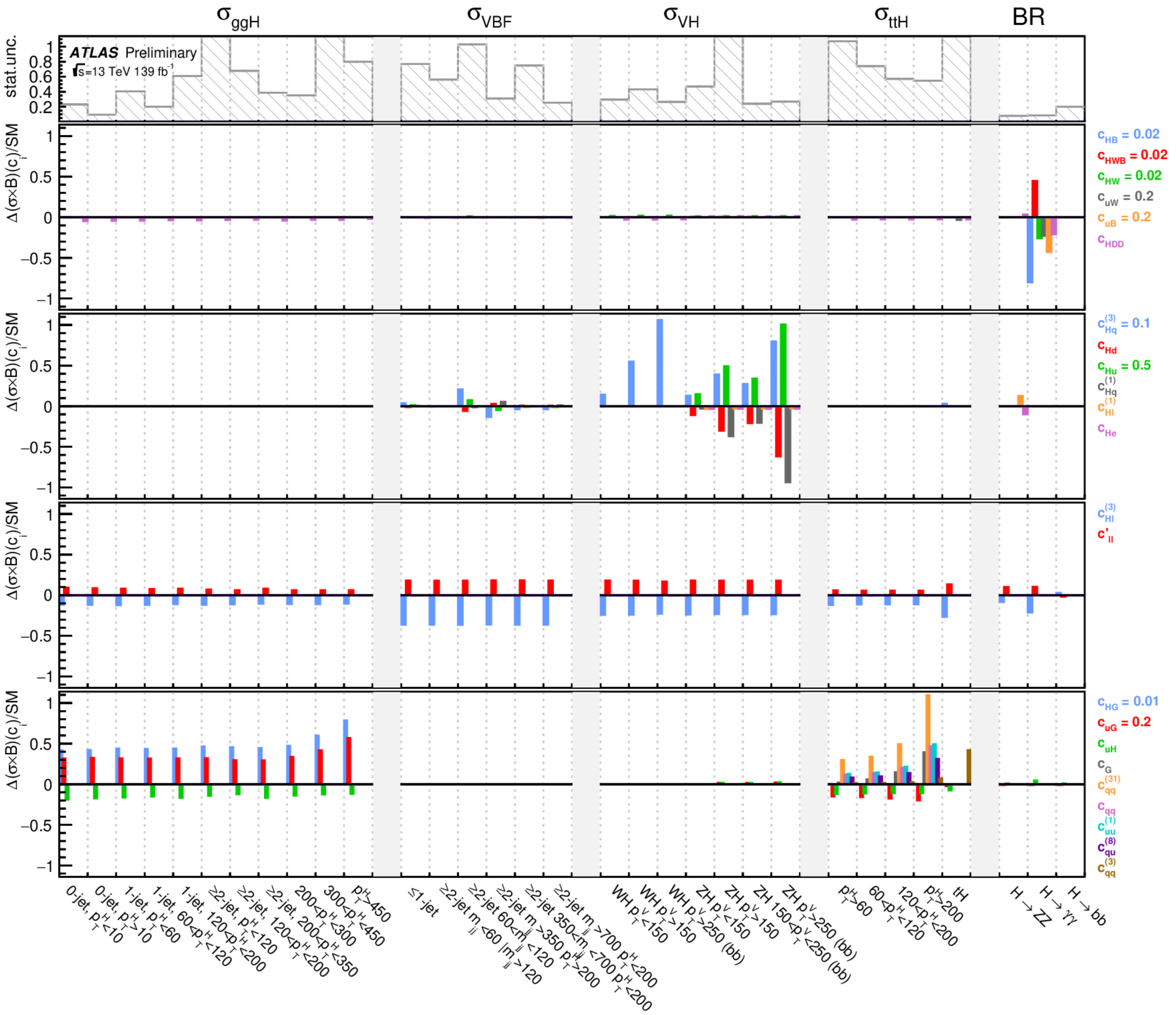


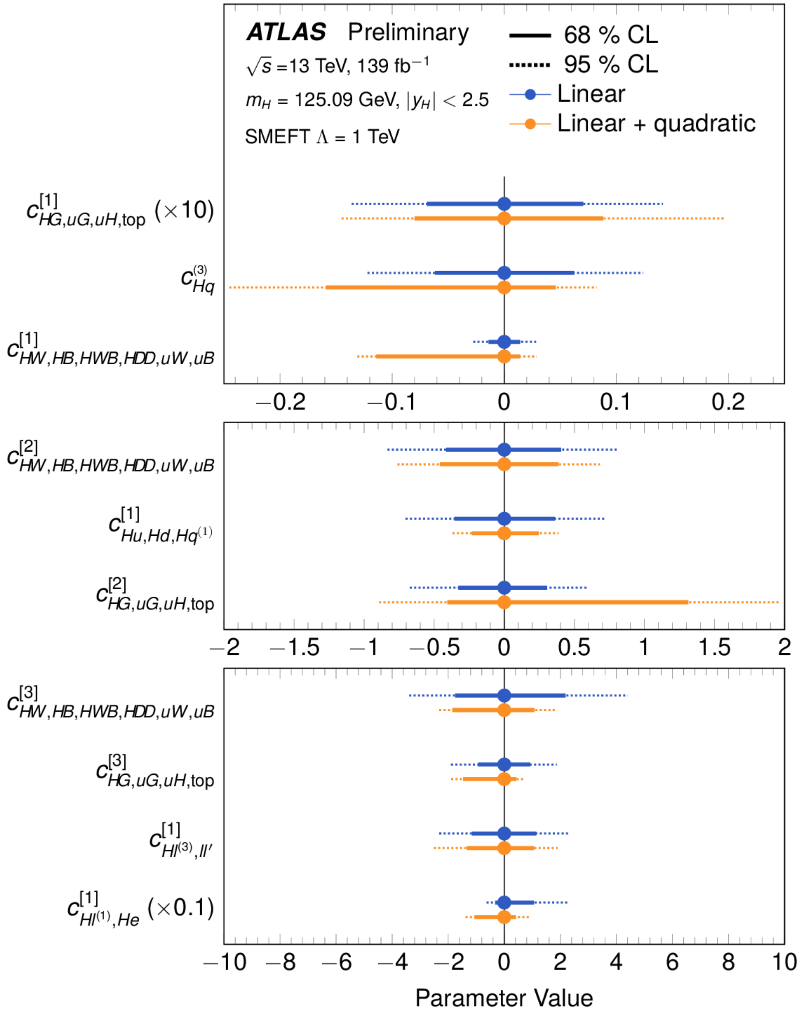
*When measuring **production** signal strengths, **decays** are assumed SM-like and vice-versa

Combined Higgs coupling measurement interpretation

- [ATLAS-CONF-2020-053]

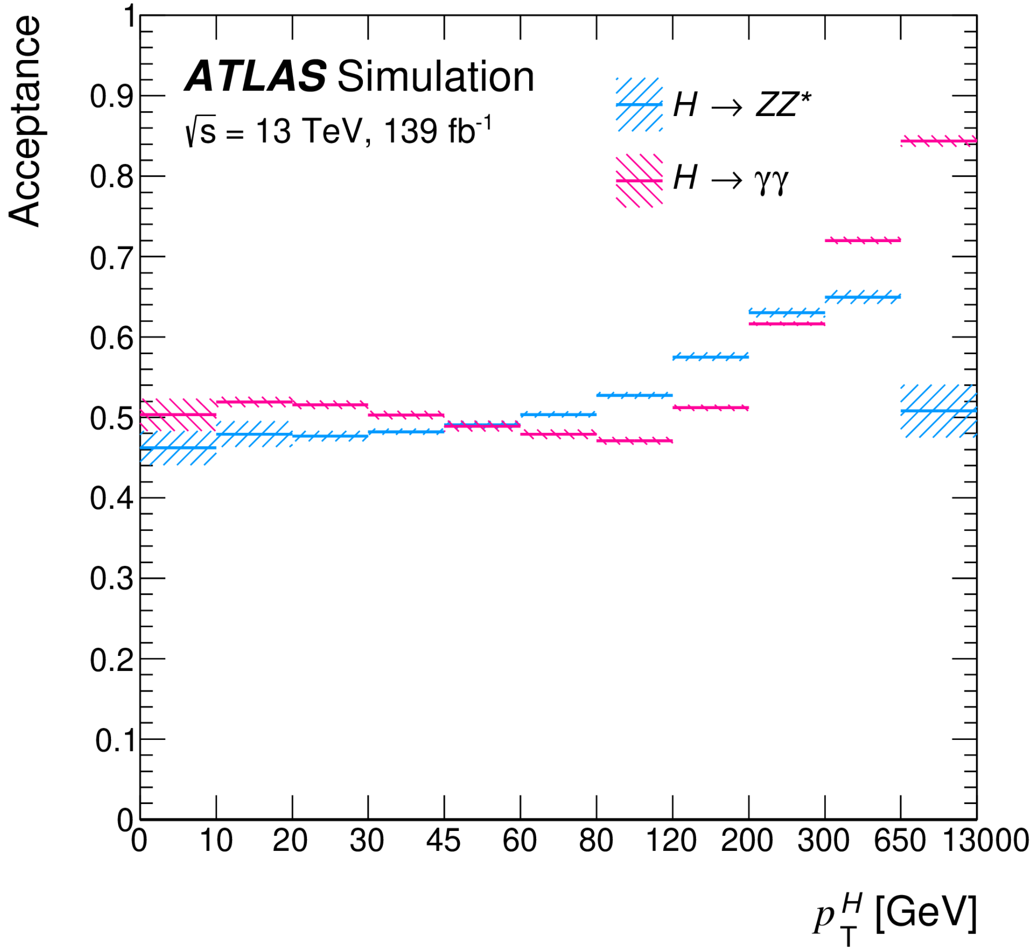
$$\sim \frac{c}{\Lambda^2}\mathcal{O}_{\text{dim-6}}$$



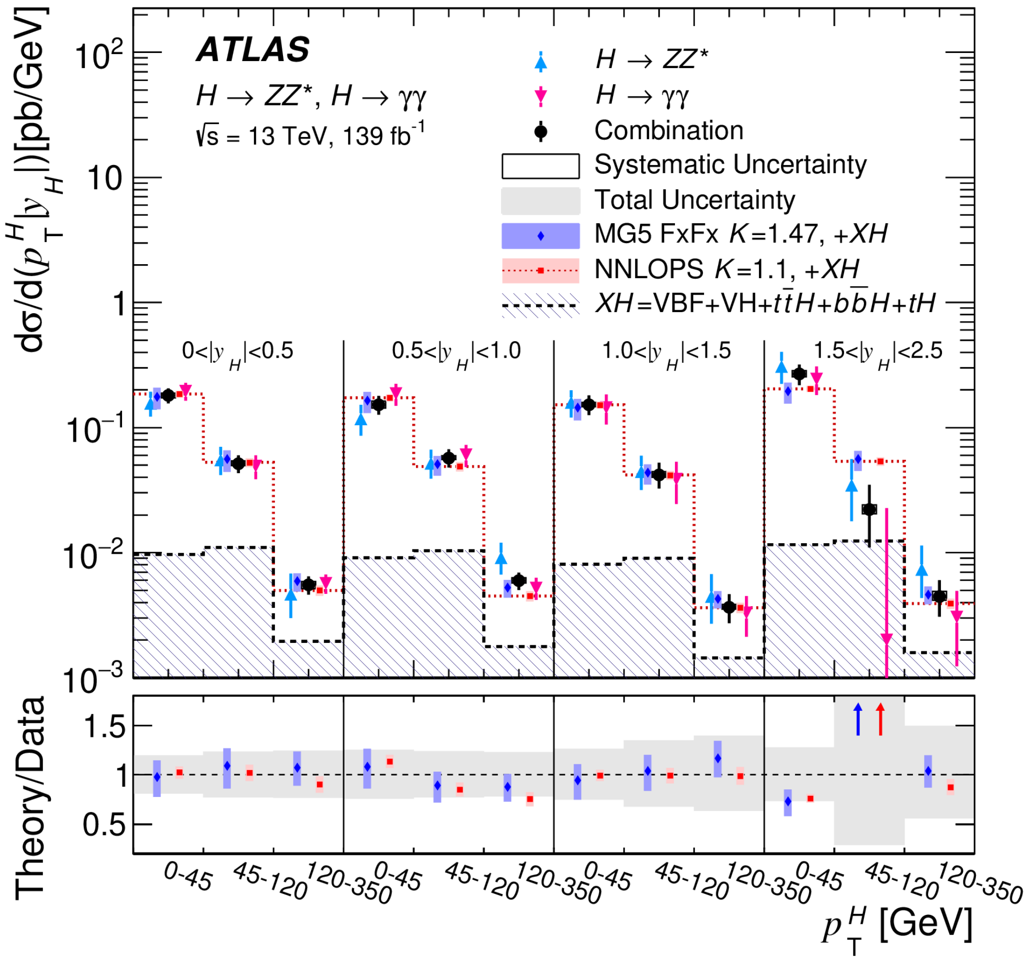


Combined differential cross-section measurement and interpretation [arXiv:2207.08615]

- Acceptance correction



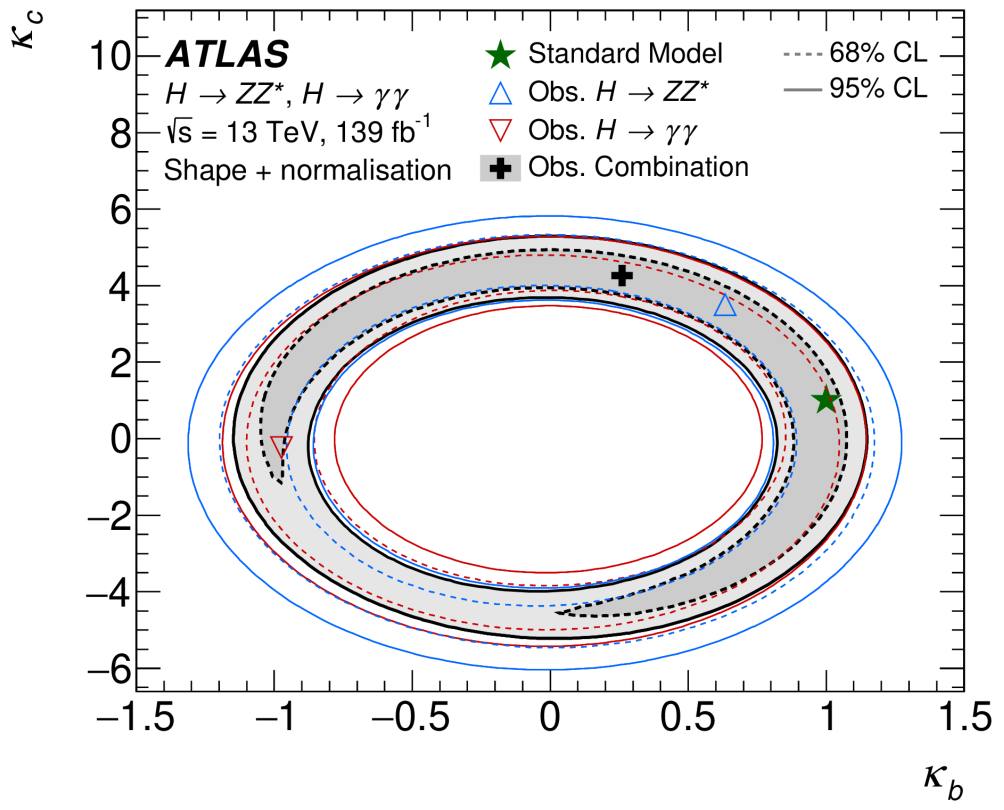
- 2-dimensional differential cross-section measurement

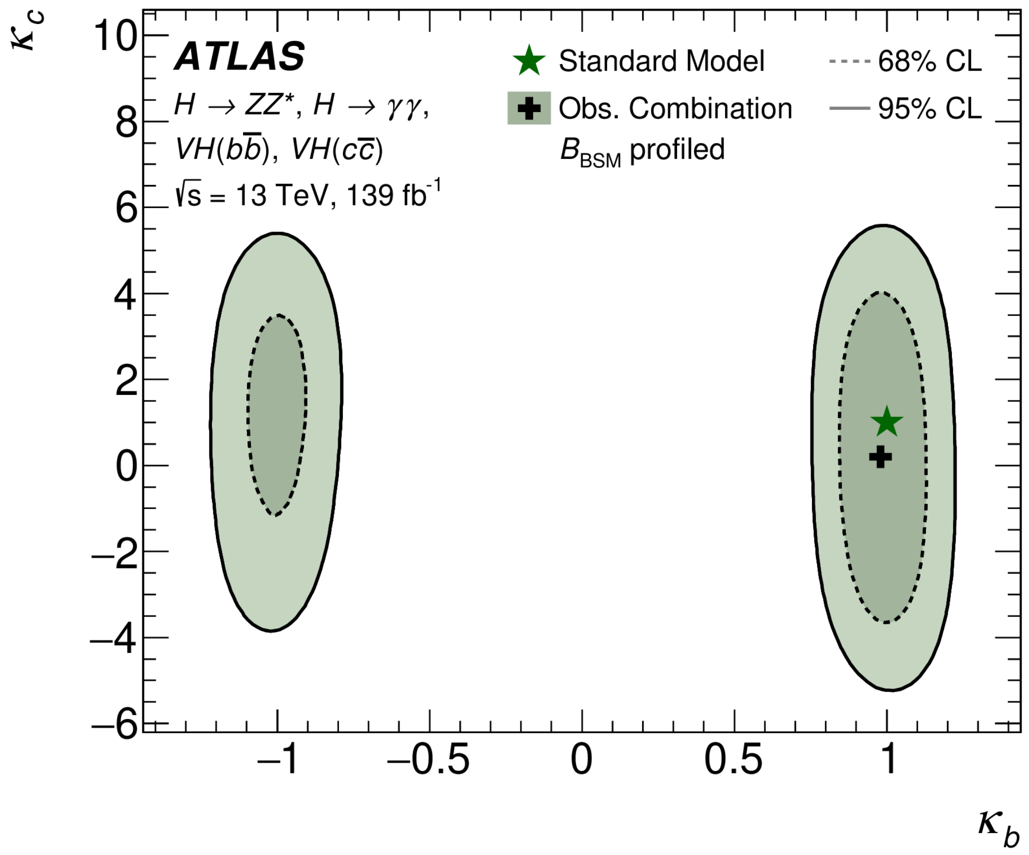


Combined differential cross-section measurement and interpretation [arXiv:2207.08615]

- Combine this indirect constraint from pTH spectrum with the direct constraints from VH(bb) and VH(cc) production - sensitive to κ_b and κ_c through the decay
- Higgs width parametrized with B_{BSM} - branching ratio to BSM particles

$$\Gamma_{\mathrm{BSM}} = \bar{\Gamma} \times B_{\mathrm{BSM}} = \Gamma_{\mathrm{SM}} \frac{B_{\mathrm{BSM}}}{1-B_{\mathrm{BSM}}}$$



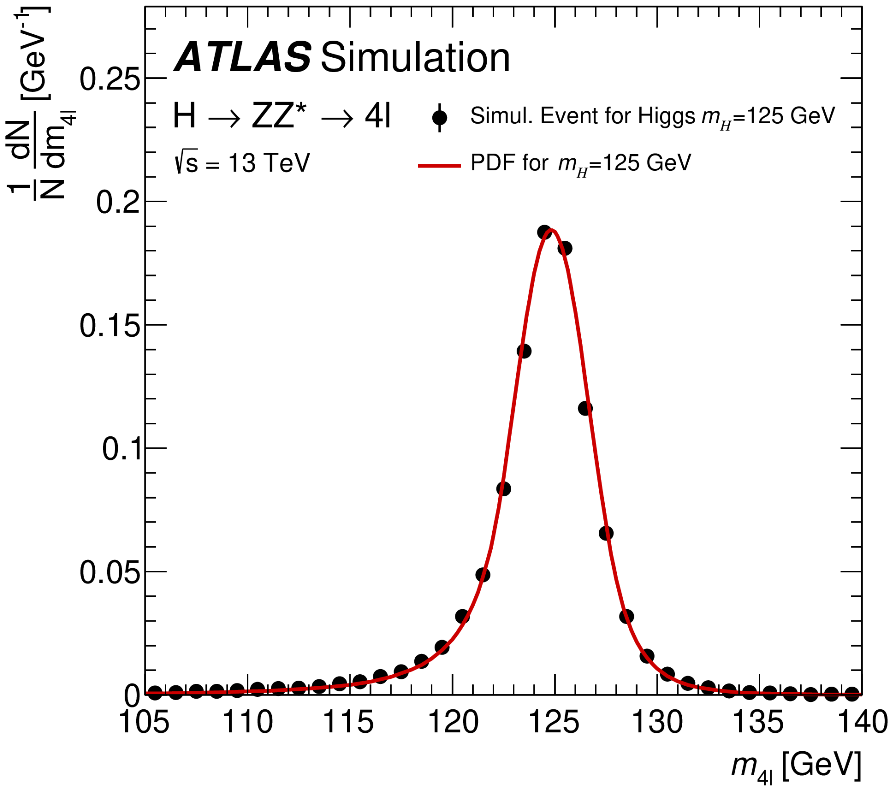


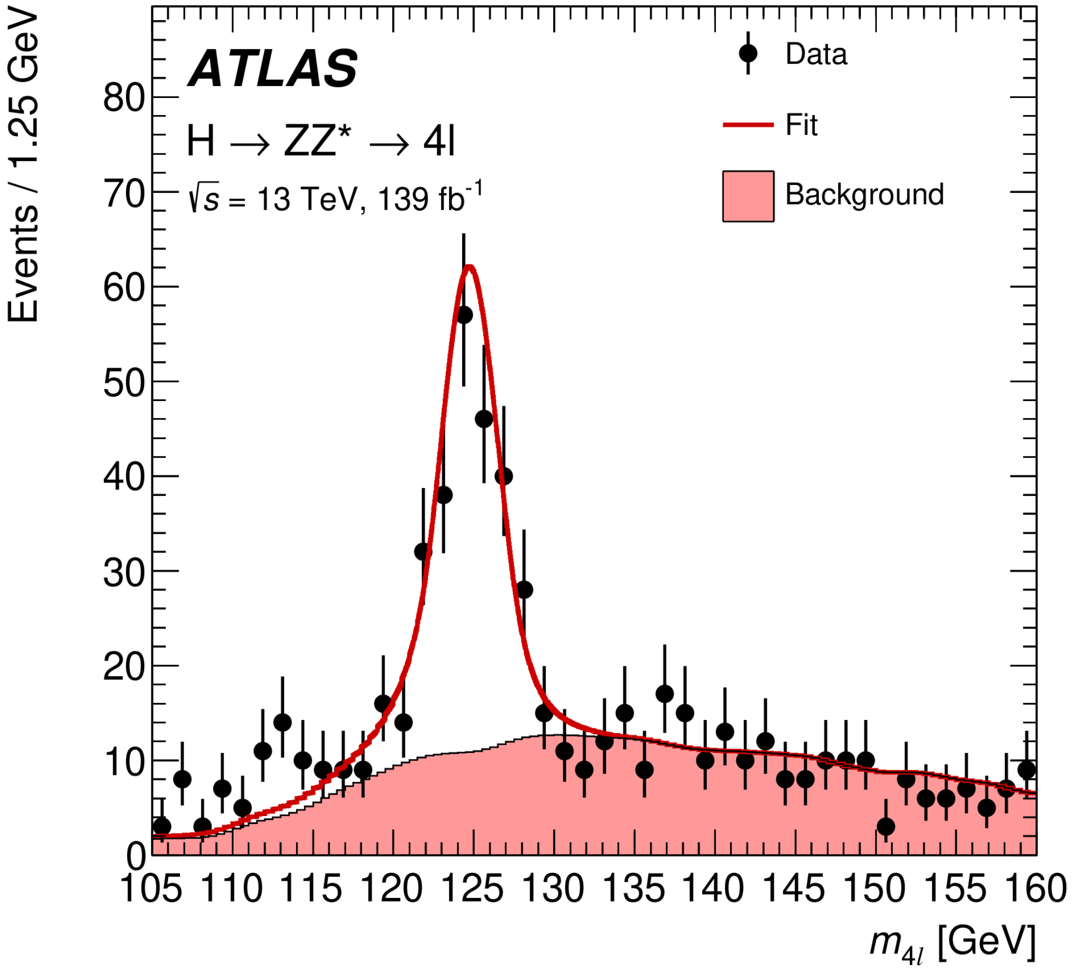
Higgs boson mass measurement in the $H \to ZZ^* \to 4l$ channel

[arXiv:2207.00320]

The signal probability density function is modelled as

$$\mathcal{P}(m_{4\ell}, D_{NN}, \sigma_i | m_H) = \mathcal{P}(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} | \sigma_i, m_H) \cdot \mathcal{P}(\sigma_i | m_H)$$
$$\simeq \mathcal{P}(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} | m_H),$$





ATLAS HL-LHC Projection

- CERN Yellow Report from European Strategy for Particle Physics (2019):
- Snowmass White Paper (2022)
- Two main strategies for ATLAS projections:
  - Extrapolation based on Run-2 results
    - Benefit from well-studied systematics models developed for Run-2 analyses
  - Parametric simulations based on detailed simulations of the upgraded detectors under HL-LHC conditions

- Higgs boson mass measurement projections based on the Run-1 $H \to ZZ^* \to 4l$ results

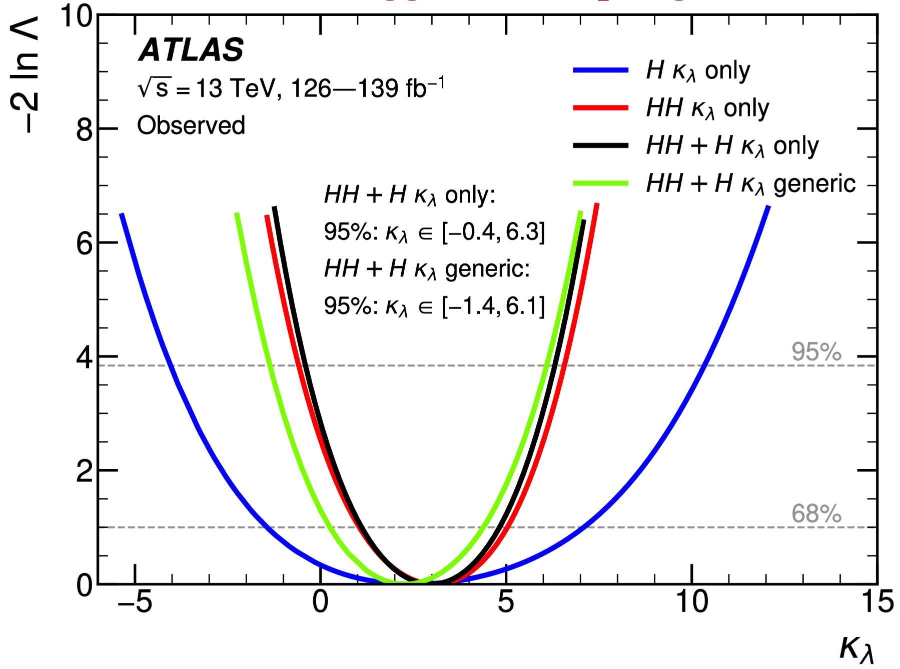
	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14

Combined single- and double-Higgs to constrain self-coupling

[arXiv:2211.01216]

- Expected di-Higgs production cross-section is ~1000 times smaller than single-Higgs production
- Higgs self-coupling (coupling modifier κ_λ) can be probed not only directly via di-Higgs production but also indirectly via **NLO EW corrections on single-Higgs** (taken from combined Higgs coupling measurement)
- **κ_λ constraint** driven by di-Higgs channel (marginal contribution from single-Higgs ~5%)

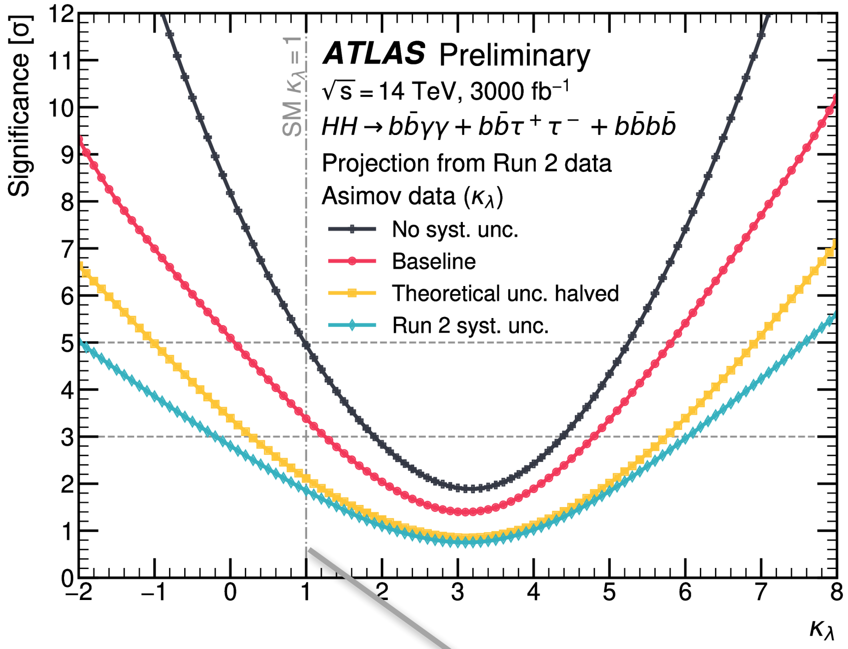
Combination provides most constraints results on Higgs self-coupling to-date



Prospect - self-coupling

[ATL-PHYS-PUB-2022-053]

- Expected significance is at 3.4σ assume SM self-coupling strength



Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

*Baseline scenario: HL-LHC with systematic uncertainties scaled down

Prospect - single-Higgs coupling

[ATL-PHYS-PUB-2018-054]

- HL-LHC prospect single-Higgs results are extrapolated from the Run-2 dataset

- S1: Run-2;
- S2: HL-LHC