THE UNIVERSITY of EDINBURGH

Higgs physics at ATLAS (& CMS): highlights & prospects

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Higgs Maxwell Workshop 2023

Outline

Status:

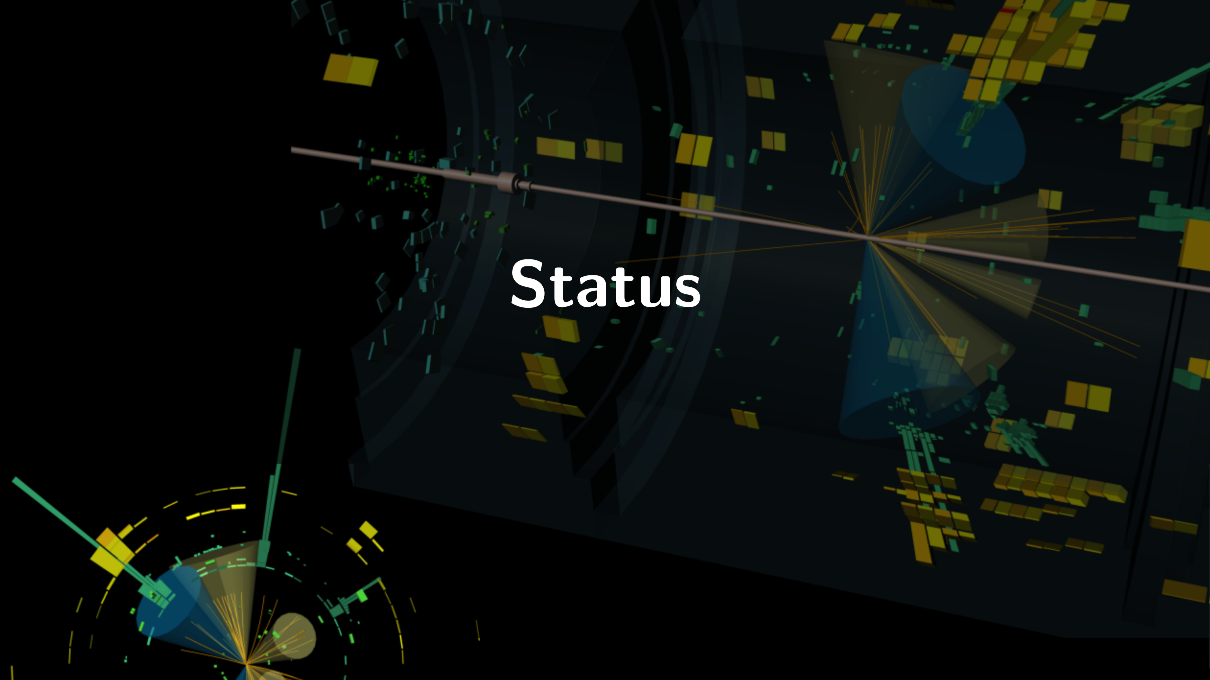
- mass
- couplings
  - 2nd generation
- Higgs width

Prospects:

- mass
- couplings
  - 2nd generation
- Higgs potential

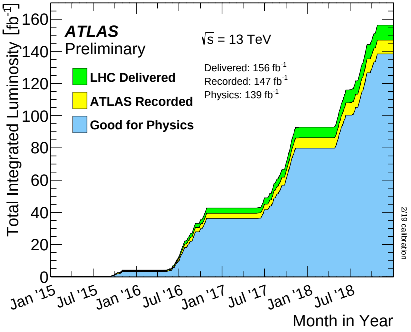
Image credits: Nature Picture Library and The Nobel Foundation, S. Jardeback (artist), L. Engblom(reproduction).

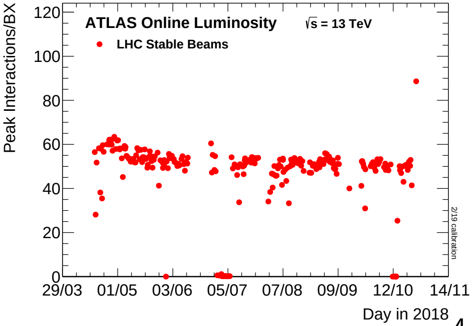
Status



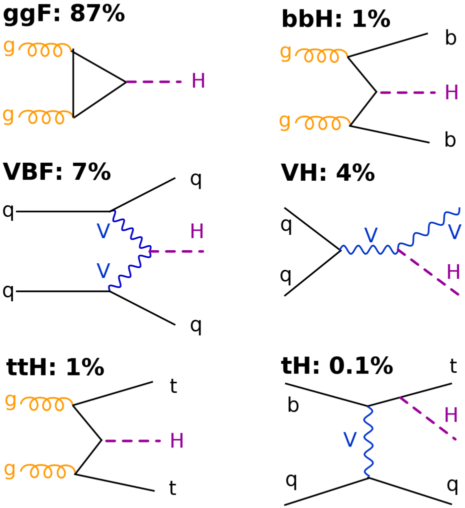
ATLAS: data-taking

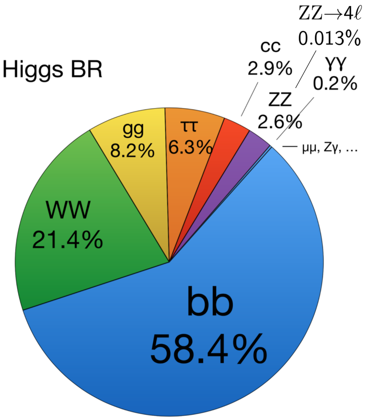
- Run3 ongoing: 2022-2025.
- Data for today's results: **Run2**, $\sqrt{s} = 13\ \mathrm{TeV}$.
- About x2 LHC design instantaneous luminosity & pile-up.
- Data-taking efficiency: 94%, data quality fraction: 95%
  $\Rightarrow$ **139 fb^{-1} of data**.





Higgs Production and Decay

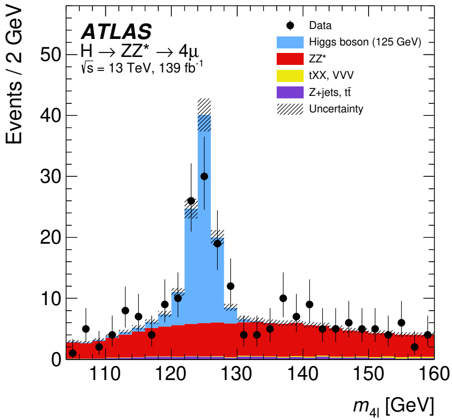




Mass

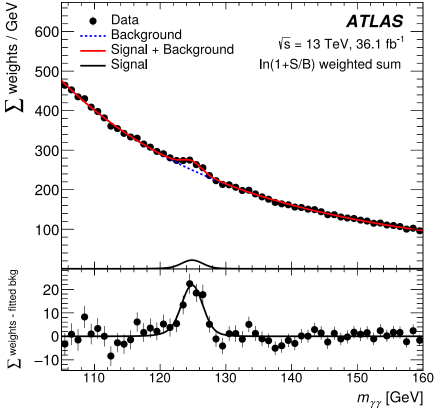
$H \to ZZ^* \to 4\ell$

124.99 ± 0.18 stat. $\pm\, 0.04$ syst. GeV



$H \to \gamma\gamma$ (36 fb^{-1})

124.93 ± 0.21 stat. $\pm\, 0.34$ syst. GeV

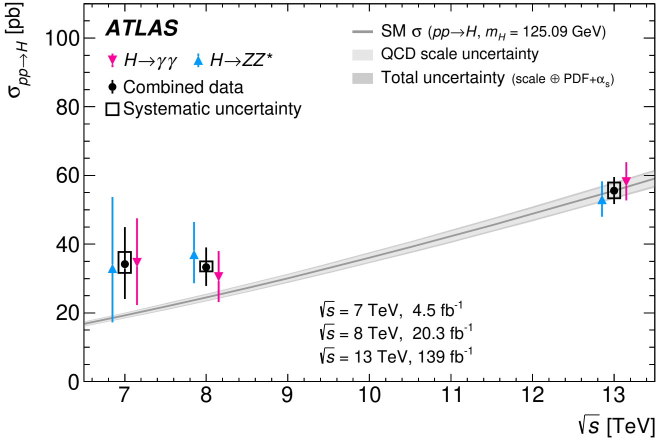


Sources: arXiv:2207.00320, Phys. Lett. B 784 (2018) 345.

Cross-section

$$\mathrm{SM}: \sigma(pp \to H, \sqrt{s} = 13\ \mathrm{TeV}) = 55.6 \pm 2.5\ \mathrm{pb}$$

$$\mathrm{ATLAS}: \sigma(pp \to H, \sqrt{s} = 13\ \mathrm{TeV}) = 55.5^{+4.0}_{-3.8}\ \mathrm{pb}\,(\pm 3.2(\mathrm{stat.})\ {}^{+2.4}_{-2.2}(\mathrm{sys.}))$$



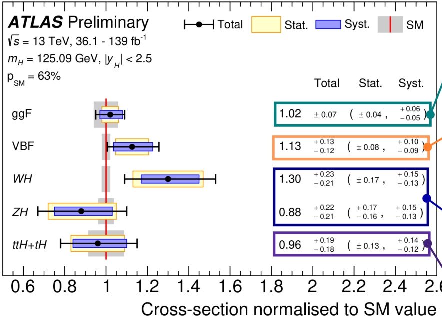
Source: arXiv:2207.08615.

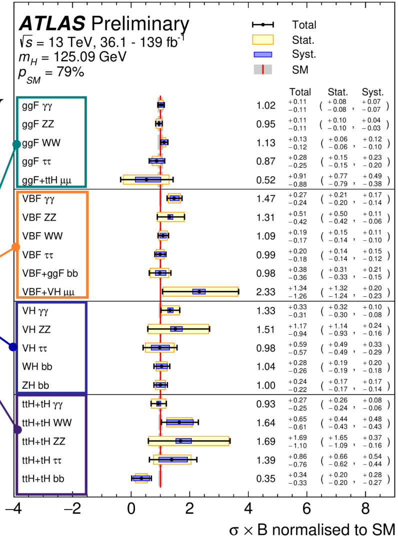
Higgs: combination

Total signal strength:

$$\mu = 1.06 \pm 0.06\,;$$

$$0.03\ \text{stat.} \oplus 0.03\,\text{exp.} \oplus 0.04\,\text{theory}$$





Source: ATLAS-CONF-2021-053

Higgs couplings interpretation

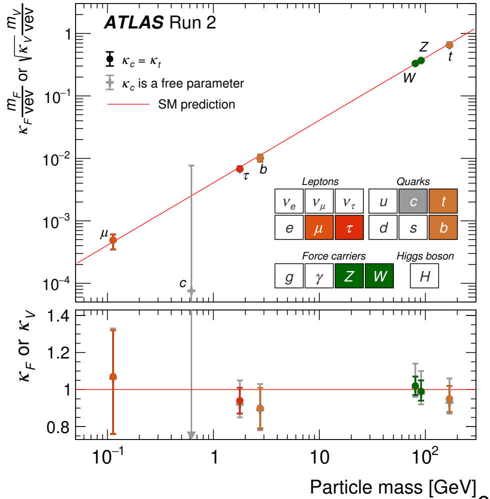
SMEFT, 2HDM & **κ-framework:**

Couplings:

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \text{ or } \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

Width:

$$\kappa_{\mathrm{H}}^2(\kappa, B_{\mathrm{i.}}, B_{\mathrm{u.}}) = \frac{\sum_j B_j^{\mathrm{SM}} \kappa_j^2}{1 - B_{\mathrm{i.}} - B_{\mathrm{u.}}}$$



Source: Nature 607 52-59 (2022)

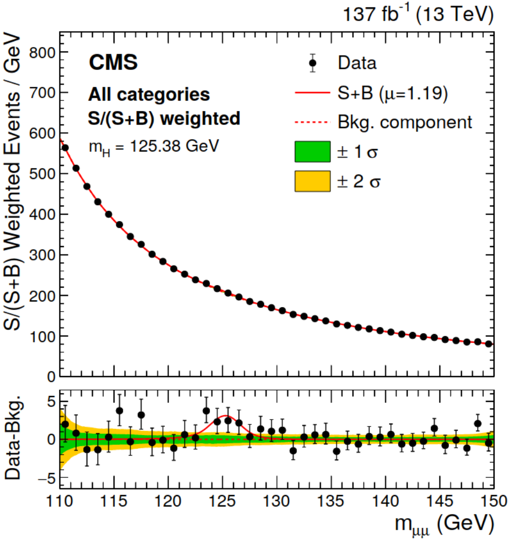
Higgs-muon coupling

Challenges:

- Low $\mathrm{BR}(\mathrm{H} \to \mu\mu) \sim 0.022\%$.
- Very low S/B ratio.
- Requirement:
  stringent constraint on background.

Run2 results:

- CMS: 3.0σ (2.5 expected),
  $\mu = 1.19 \pm 0.43$
- ATLAS: 2.0σ (1.7 expected),
  $\mu = 1.2 \pm 0.6$

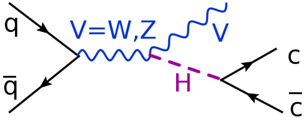


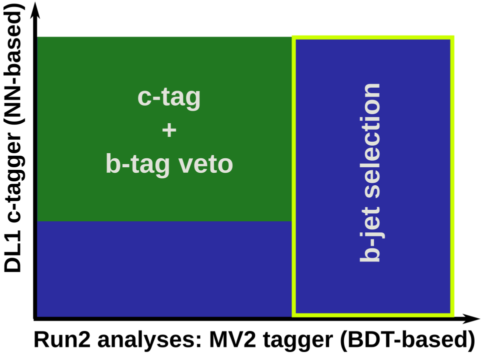
Sources: JHEP01 (2021) 148, Phys. Lett. B 812 (2021) 135980.

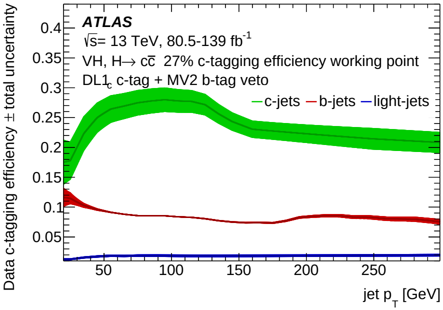
Higgs-charm coupling

Challenges in addition to $\mathrm{VH,H} \to \mathrm{b\bar{b}}$:

- $\mathrm{BR(H \to c\bar{c})}$=2.9% << $\mathrm{BR(H \to b\bar{b})}$.
- Tagging charm jets. Efficiency(tag+veto): c-jet:27%, b-jet:8%, light: 1.6%



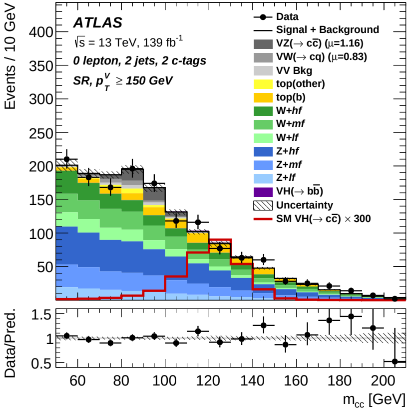


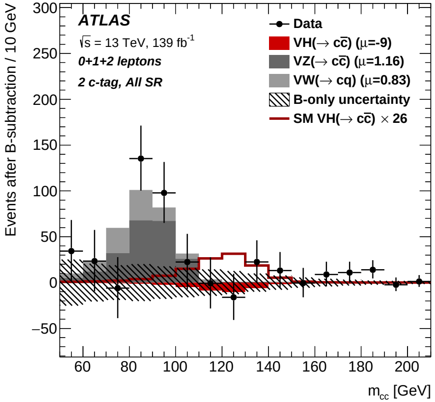


Source: arXiv:2201.11428

Higgs-charm coupling: analysis

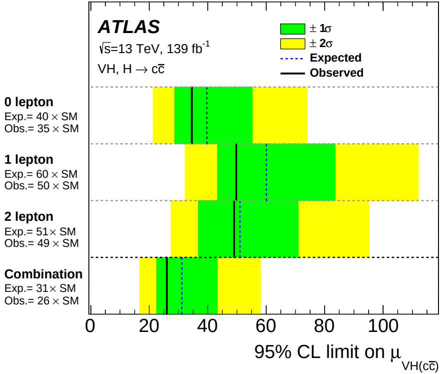
- SR-s: N(ℓ), N(c-tags), Njet, $\mathrm{p_T}$(V).
- Control regions: large $\Delta R(\mathrm{jet1}, \mathrm{jet2})$
- Simultaneous fit of VV and VH.

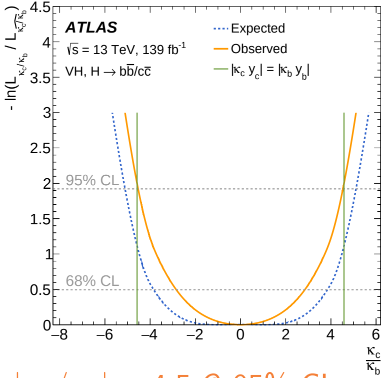




Source: arXiv:2201.11428

Higgs-charm coupling





- $|\kappa_c| < 8.5$ @ 95% CL

- $|\kappa_c/\kappa_b| < 4.5$ @ 95% CL.
- $m_b/m_c = 4.578 \pm 0.008$
- Higgs-charm coupling $<$ Higgs-bottom coupling.

Source: arXiv:2201.11428

Higgs width

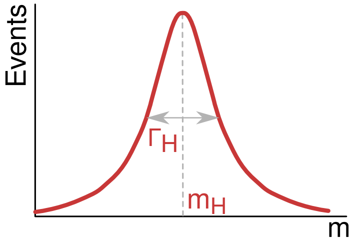
Source: Nature Picture Library, Bod an Deamhain, Cairngorms

Why Measure the Higgs Width?

1) Key properties of a fundamental particle: mass (m) and lifetime (τ).
   Higgs boson: $\Delta \mathrm{m_H}/\mathrm{m_H}$: $\sim$ 2‰, τ_H: not measured yet!
   Measurement of the Higgs width (Γ_H) would determine lifetime: $\tau_\mathrm{H} = \hbar/\Gamma_\mathrm{H}$.

   Width of a resonance:

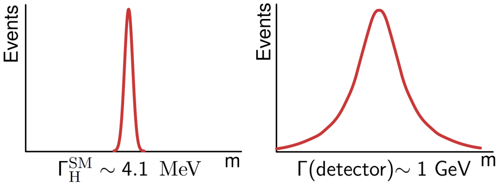
   - Heisenberg's uncertainty:
     $\Delta \mathrm{E} \Delta \mathrm{t} \geq \hbar/2$
   - Einstein's relativity: $\mathrm{E} \sim \mathrm{mc}^2$

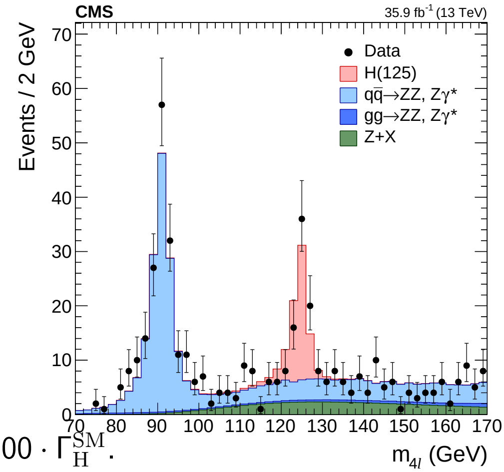


2) Higgs couplings (c) are extracted from cross-sections: $\sigma \propto c_f^2 \,/\, \Gamma_\mathrm{H}$.
   Γ_H: needed to reliably extract all Higgs couplings.

Higgs Width: the Challenge

- Higgs boson is predicted to be very narrow: $\Gamma_{\mathrm{H}}^{\mathrm{SM}} \sim 4.1\ \mathrm{MeV}$.
- Detector resolution: O(GeV).





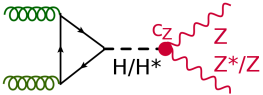
- Line-shape measurement [1]: $\Gamma_{\mathrm{H}} \lesssim 300 \cdot \Gamma_{\mathrm{H}}^{\mathrm{SM}}$.

How could we probe the width @ the LHC?

Figure [1]: CMS collaboration, JHEP **11** (2017) 047.

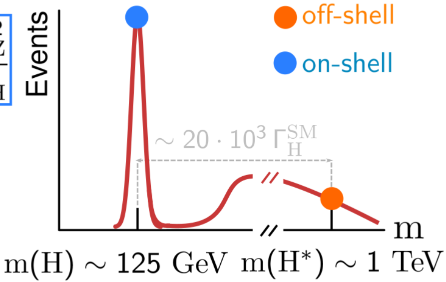
Off-shell production

$$\frac{d\sigma_{gg\to H\to ZZ}}{dM_{4\ell}^2} \propto \frac{c_g^2 \cdot c_Z^2}{(M_{4\ell}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$



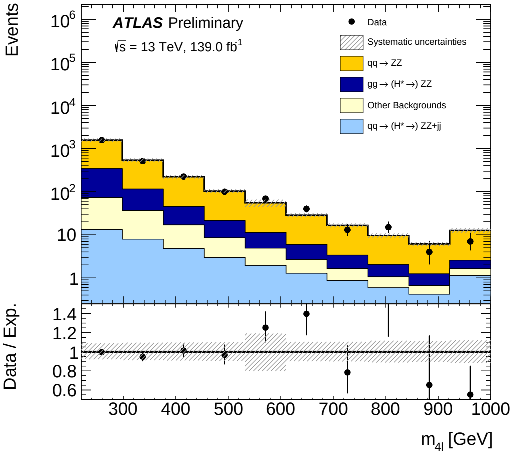
$$\boxed{\sigma_{gg\to H\to ZZ}^{off-shell} \propto \frac{c_g^2 \cdot c_Z^2}{M_{4\ell} - m_H}} \quad \boxed{\sigma_{gg\to H\to ZZ}^{on-shell} \propto \frac{c_g^2 \cdot c_Z^2}{m_H\Gamma_H}}$$

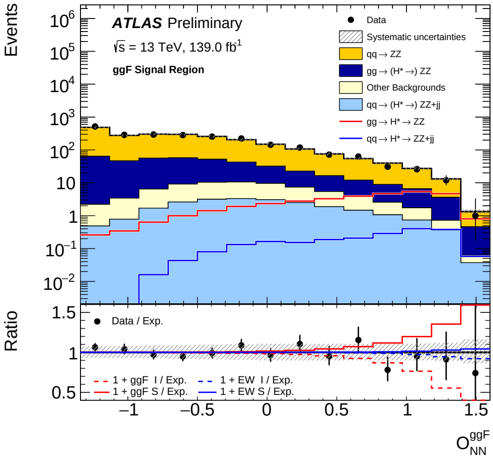
$$\frac{\sigma^{off-shell}}{\sigma^{on-shell}} \propto \Gamma_H$$



Off-shell production @ ATLAS

- $m_{4\ell}$ fit for SM off-shell production (left) & ML discriminant (right)

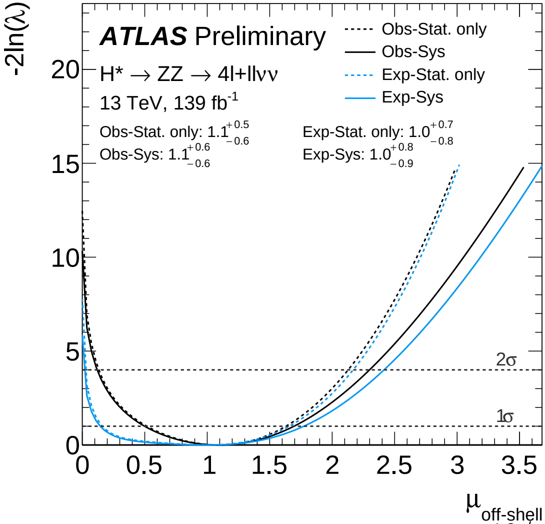




Source: ATLAS-CONF-2022-068

Off-shell signal strength

- 6 signal regions
- $\mu_{\text{off-shelll}} = 0$ excluded at 3.2 (2.4) σ obs. (exp). $\Rightarrow$ evidence for off-shell production.
- Best-fit: $\mu_{\text{off-shelll}} = 1.1^{+0.6}_{-0.6}$



Source: ATLAS-CONF-2022-068, first evidence for off-shell production by CMS in Nature Physics 18 (2022).

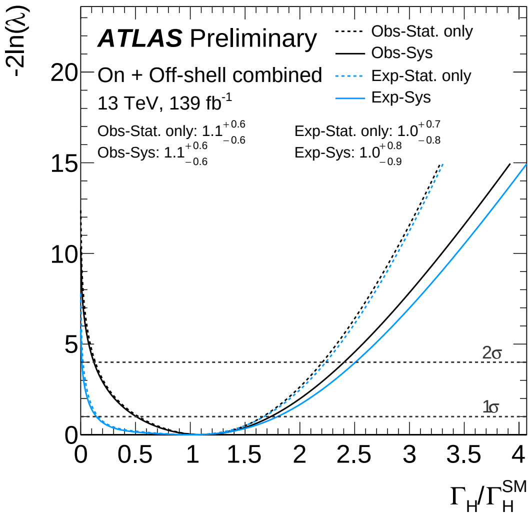
Interpretation in terms of Γ_{H}

- Reminder:

$$\frac{\sigma^{\mathrm{off-shell}}}{\sigma^{\mathrm{on-shell}}} \propto \Gamma_{\mathrm{H}}$$

- $\Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}^{\mathrm{SM}} = 1.1^{+0.6}_{-0.6}$

- $\Gamma_{\mathrm{H}} = 4.6^{+2.6}_{-2.5}\ \mathrm{MeV}$



Source: ATLAS-CONF-2022-068, $\Gamma_{\mathrm{H}} = 3.2^{+2.4}_{-1.7}$ MeV reached by CMS, Nature Physics 18 (2022).

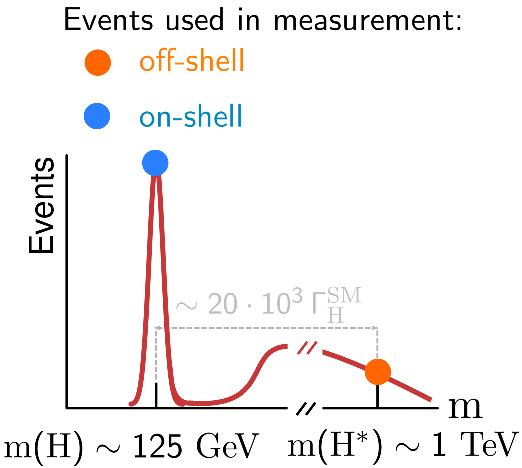
Interpretation: Caveat

- Γ_{H} extracted from:

$$\frac{\sigma^{\mathrm{off-shell}}}{\sigma^{\mathrm{on-shell}}} \propto \Gamma_{\mathrm{H}}$$

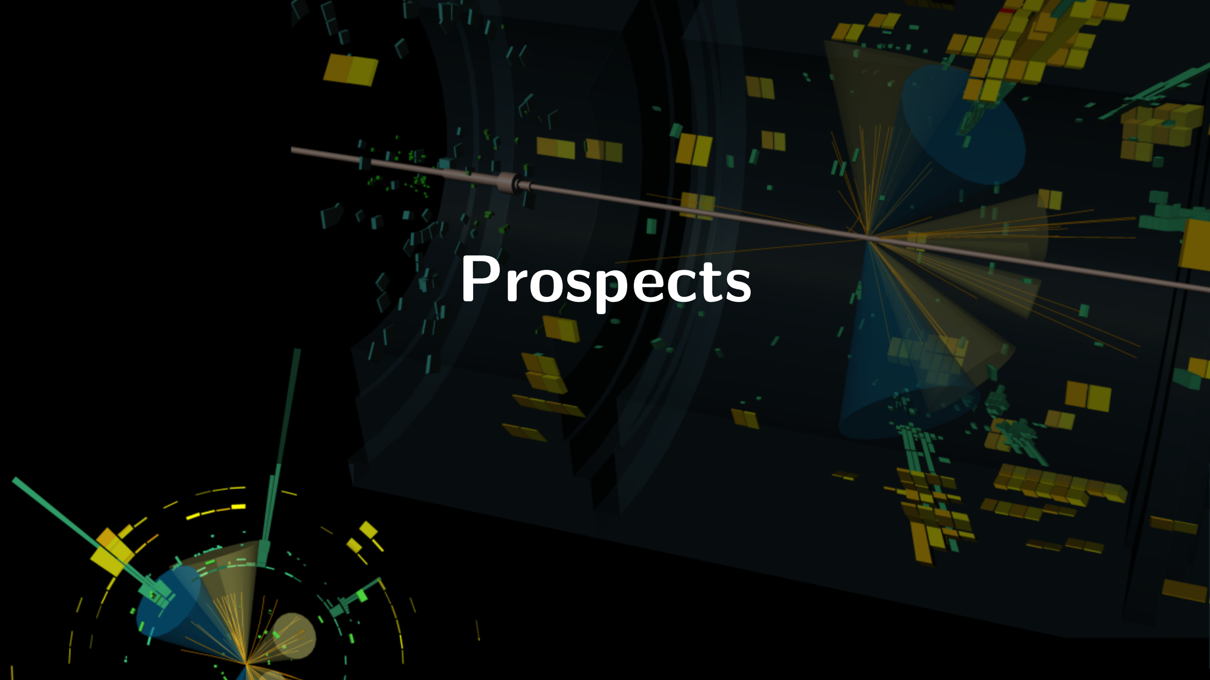
- Assumption: $\mu_{\mathrm{off-shell}}/\mu_{\mathrm{on-shell}} = 1.$

- Generally not valid in presence of BSM physics [1].



[1] C. Englert, Y. Soreq, M. Spannowsky JHEP **05** (2015) 145.

Prospects



LHC Schedule

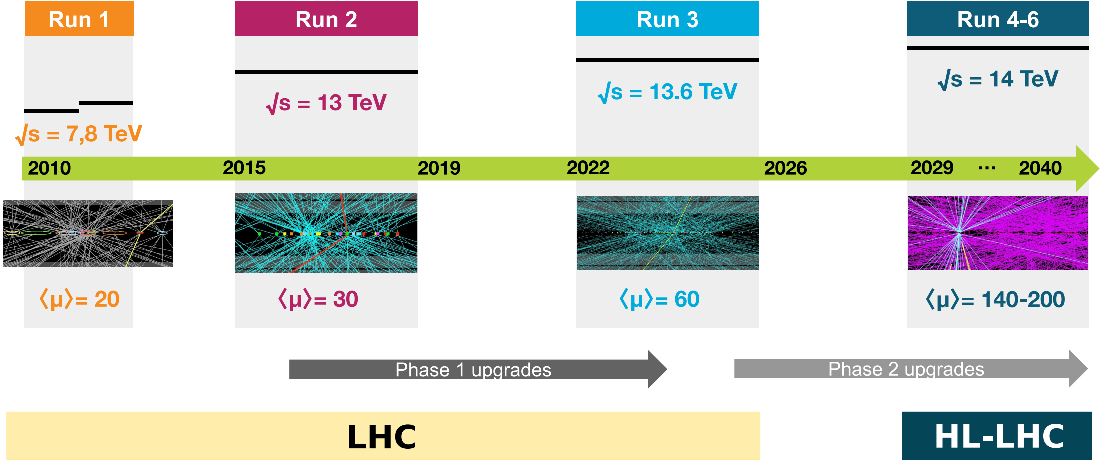
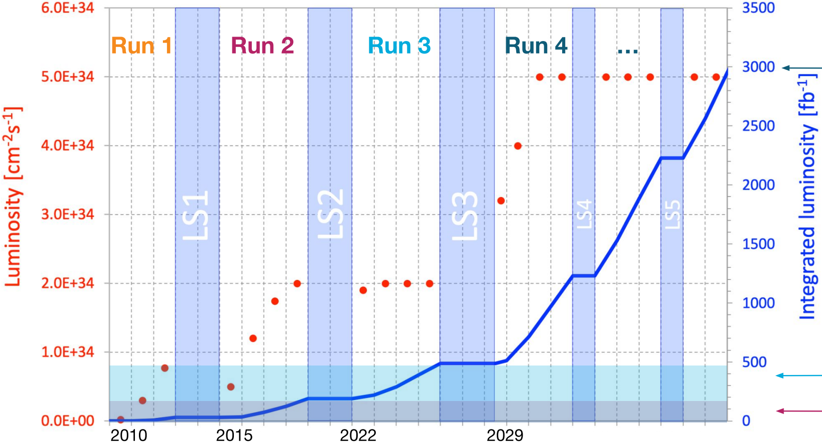


Image credit: L. Brost's talk @ Higgs2022

Proton-proton dataset



Total HL-LHC dataset ($3000\ fb^{-1}$)

Run 3: ~10% of total dataset collected

Run 2: ~5% of total dataset collected

↑ Higgs discovery

↑ Start of HL-LHC operations

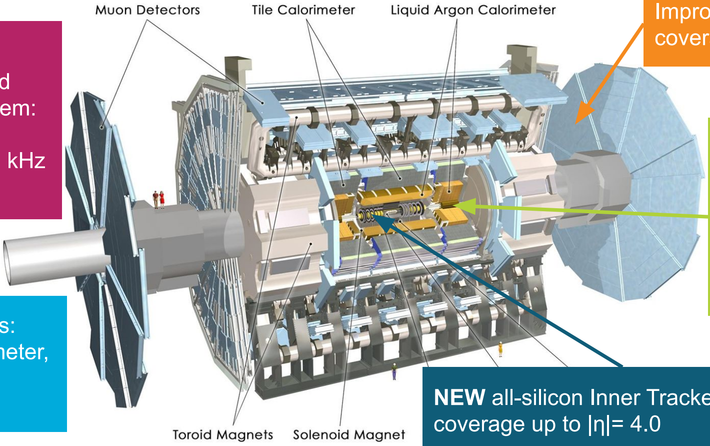
Image credits: https://lhc-commissioning.web.cern.ch & L. Brost's talk @ Higgs2022

ATLAS Phase-II upgrade

Upgraded Trigger and Data Acquisition system:

- L0 rate: 1 MHz
- Event Filter: 10 kHz

Upgraded electronics:
Liquid Argon Calorimeter,
Tile Calorimeter,
Muon system



Improved muon coverage and trigger

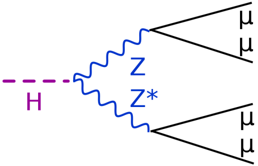
NEW endcap high - granularity timing detector

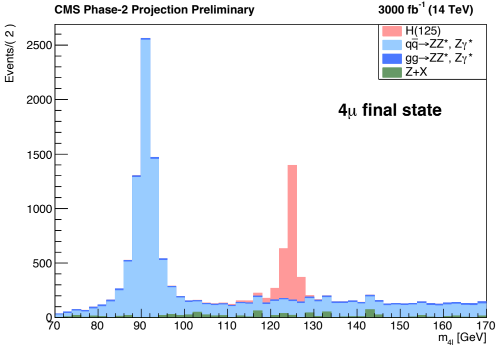
NEW all-silicon Inner Tracker, coverage up to $|\eta|= 4.0$

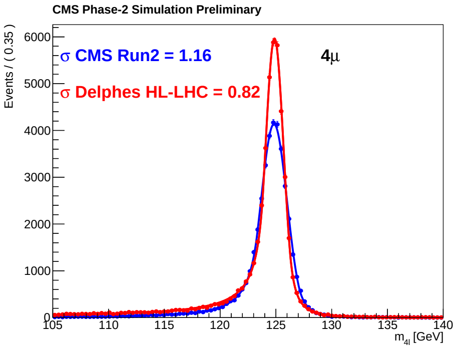
Annotation credits: L. Brost's talk @ Higgs2022

Higgs Mass @ HL-LHC

$m_{4\ell}$ expected uncertainty (MeV)	inclusive	4μ	4e	$2e2\mu$	$2\mu 2e$
Total	26	30	105	60	67
Syst impact	16	11	64	31	32
Stat only	22	28	83	51	59







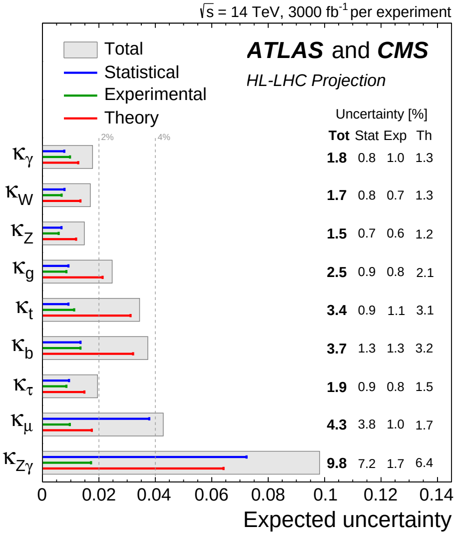
Source: CMS-FTR-21-007

Higgs couplings @ HL-LHC

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \text{ or } \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

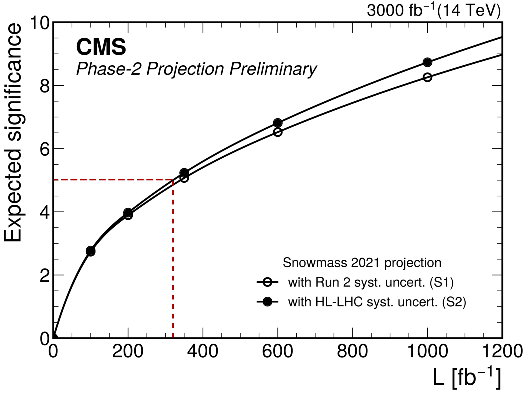
Uncertainty:

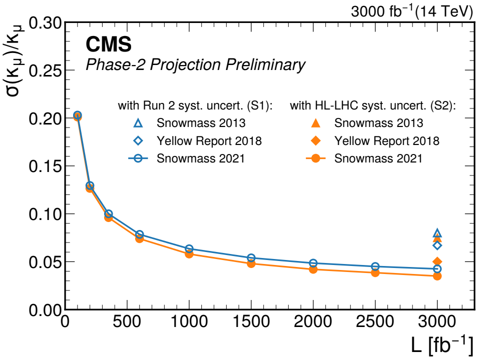
- **Gauge boson couplings: 1.5% - 2.5%**
- **3rd gen fermions: 2% - 4%**
- **Dominated by theory uncertainty.**
  - Assumption: 1/2 Run2 uncertainty.
  - How will we achieve this 1/2?



Higgs-muon coupling @ HL-LHC

- $\mathrm{H}\rightarrow$ observation feasible with $\sim 300\ \mathrm{fb}^{-1}$ of data
- By end of HL-LHC: $\Delta\kappa_\mu/\kappa_\mu \sim 3\%$

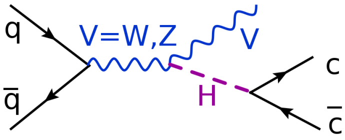


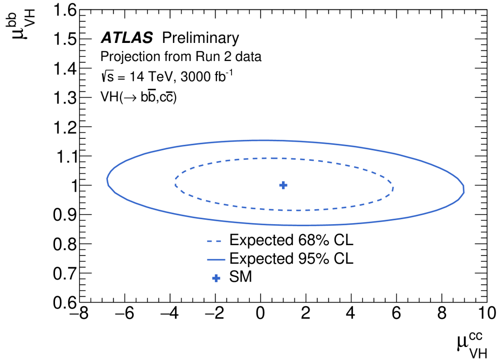


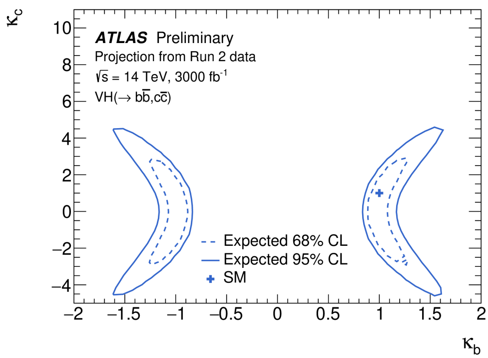
Source: CMS-FTR-21-006. Note: the projection uses HL-LHC detector resolution.

Higgs-charm coupling @ HL-LHC

- **ATLAS:** $|\kappa_c| < 3$
- **CMS:** $\mu_{\mathrm{VH,H}\to c\bar{c}} = 1.0 \pm 0.6\ \text{stat.} \pm 0.5\ \text{syst.}$



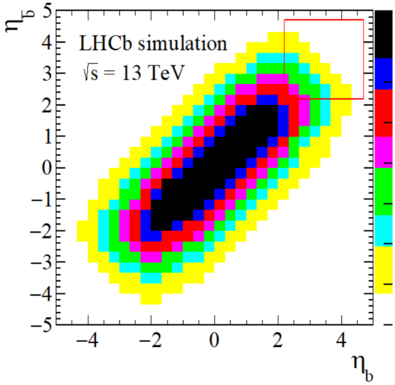


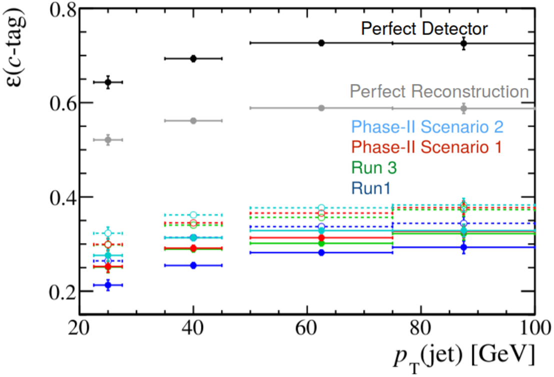


Source: Snowmass White Paper: ATL-PHYS-PUB-2022-018. Constraints from differential x-section measurements not yet part of projections!

Higgs-charm coupling @ LHCb

- Run1: $|\kappa_c| < 80$, 2 fb^{-1} of data
- HL-LHC: $|\kappa_c| < 2-3$, 300 fb^{-1} of data





Sources: LHCb-CONF-2016-006,LHCC-G-171, CERN-LPCC-2018-04

The Higgs Potential

Credit: The Nobel Foundation
Susanne Jardeback (artist)
Lovisa Engblom(reproduction)

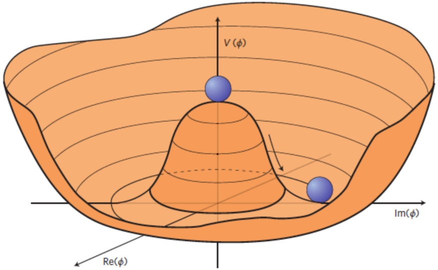
Higgs potential

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

$$\mathrm{SM}: \lambda_3 = \lambda_4 = \lambda^{\mathrm{SM}} = m_H^2/(2v^2)$$

$$\mathrm{Define}: \kappa_\lambda = \lambda_3/\lambda_3^{\mathrm{SM}}$$

No sensitivity to λ_4 @ LHC

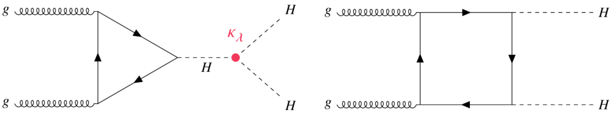


Probe κ_λ: HH production.

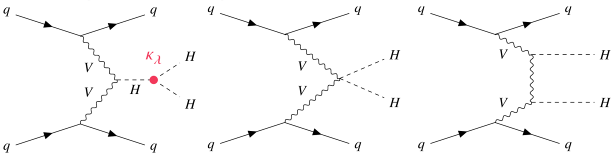
HH production

HH production cross-sections and event shapes sensitive to κ_λ.

$$\sigma_{ggF}(pp \to HH) = 31.05 \text{ fb} @ \sqrt{s} = 13 \text{ TeV}$$



$$\sigma_{VBF}(pp \to HH) = 1.73 \text{ fb} @ \sqrt{s} = 13 \text{ TeV}$$



HH branching ratios:

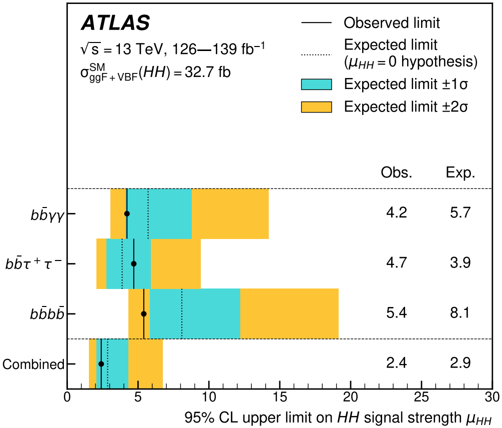
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Image credit: Katherine Laney

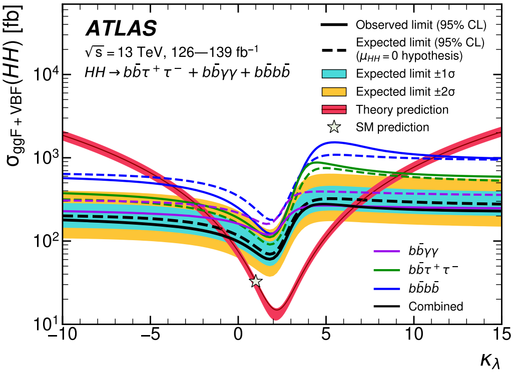
HH production @ LHC

Signal strength:

$$\sigma(pp \to HH)/\sigma(pp \to HH)^{\mathrm{SM}}$$



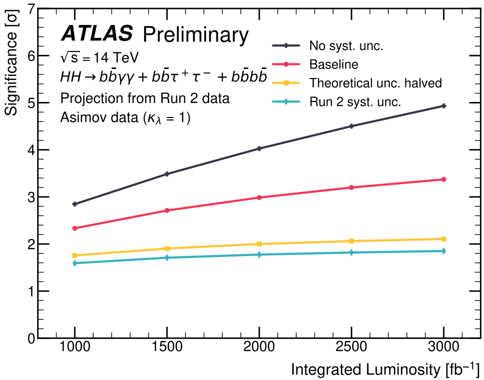
κ_λ interpretation, accounting for cross-section, event shape, and acceptance $\times$ efficiency effects.

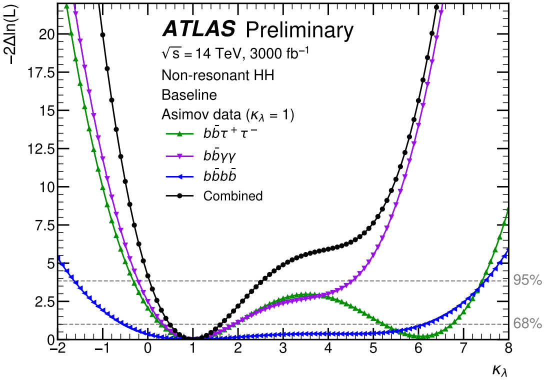


Source: arXiv:2211.01216

Higgs potential @ HL-LHC

- Observation?
- HH signal strength: 22% stat. and $^{33\%}_{-30\%}$ stat. $\oplus$ syst.
- κ_λ 1-σ interval: [0.7,1.4] stat. and [0.5,1.6] stat. $\oplus$ syst.





Source: ATL-PHYS-PUB-2022-053

Take-aways

Higgs width:

- Key for knowledge of all Higgs couplings.
- Off-shell production: $\Delta\Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}^{\mathrm{SM}} \sim 60\%$.
- Caveat: assumptions about BSM.

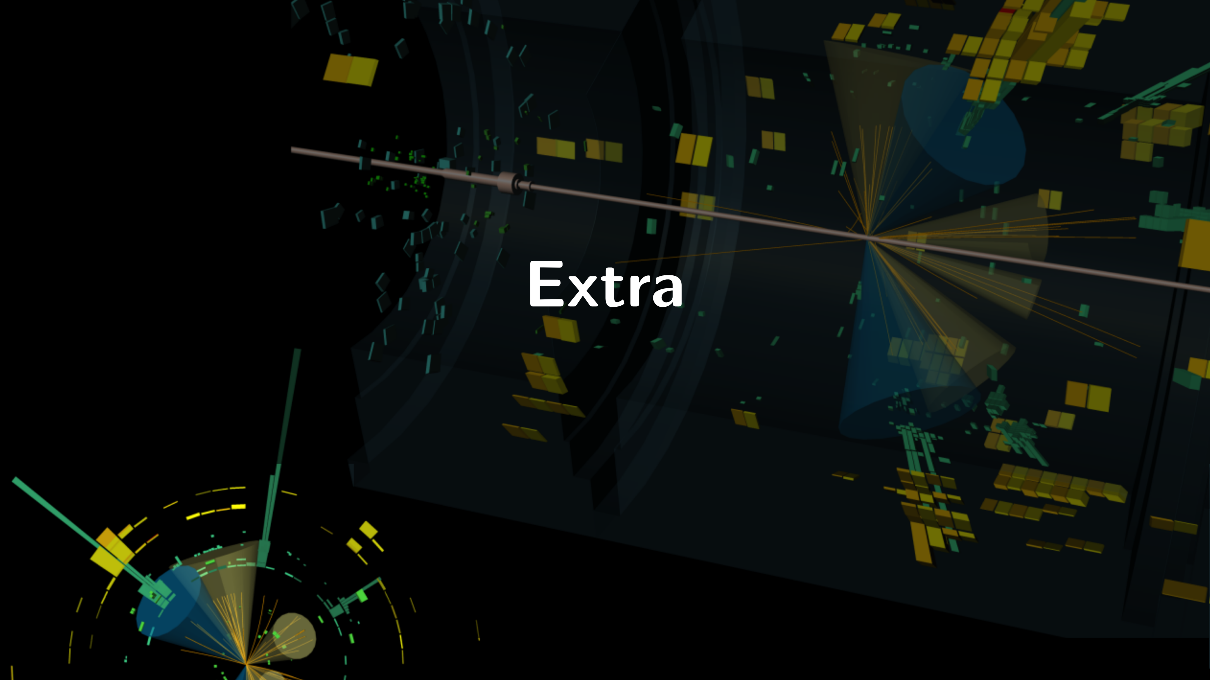
Higgs potential:

- Main probe: HH production.
- HH @ HL-LHC: close to observation.
- HH: an incomplete probe; no λ_4.

Future colliders: key for both areas.

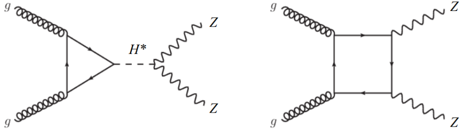
Image credits: Nature Picture Library and The Nobel Foundation, S. Jardeback (artist), L. Engblom(reproduction).

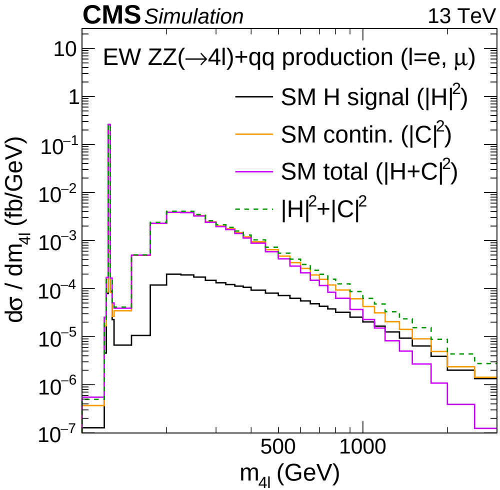
Extra



Off-shell production

- Interference in $H^* \to ZZ$ events:

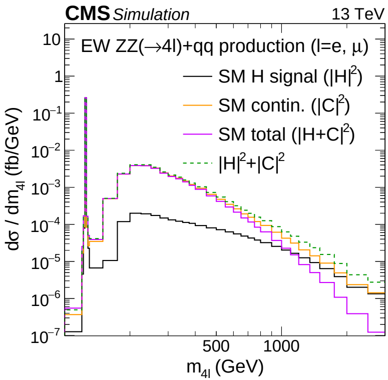


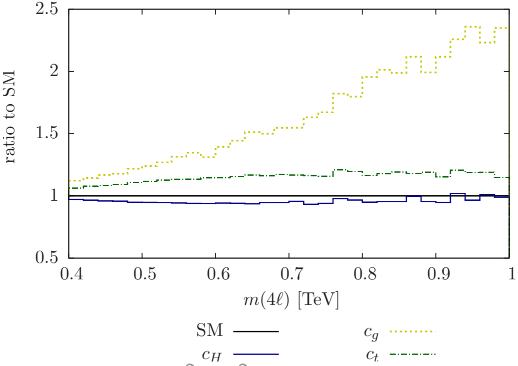


- SM: deficit of events at high $m_{4\ell}$ wrt non-resonant background.

Figure: CMS, Nature Physics 18 (2022)

Interpretation: Caveat





$$\mathcal{L}_{\text{SILH}} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} + \dots$$

Model-independent measurement of $\Gamma_{\rm H}$: key task for future colliders.

Figures: CMS, Nat. Phys. (2022), C. Englert et. al, JHEP **05** (2015) 145.