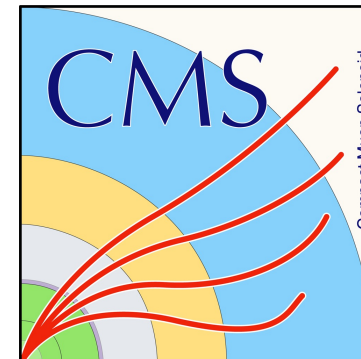# Review on Higgs boson production cross sections & couplings
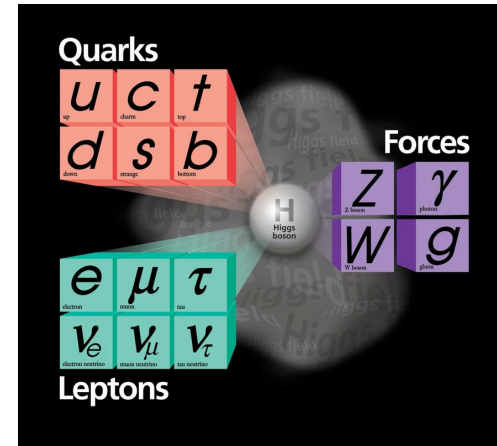
Mingshui Chen (IHEP Beijing)

On behalf of ATLAS and CMS Collaborations

Outline

- **Introduction**

- **Higgs production cross sections**

- **Higgs couplings**

- **Prospects @ HL-LHC**

- **Summary**

Disclaimer: only a few selected recent updates among all results from ATLAS and CMS

The Higgs Boson

- **The Higgs boson, discovered in 2012 by ATLAS and CMS, "completes" the Standard Model of particle physics**
    - **It's the quantum of the Higgs field , whose spontaneous symmetry breaking is responsible for generating particle masses**
- **The SM model still does not explain many of the phenomena of our physical universe**
    - **Neutrino masses, baryon asymmetry of the universe, dark matter .....**
- **The discovery of the Higgs boson opens a new window for us to understand the universe**
    - **First fundamental scalar particle (also the only one in SM) found so far**
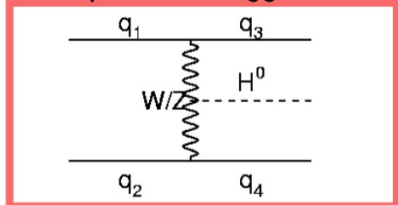   - **Looking for deviations from the SM predictions by studying its properties......**

~88%

~7%

~4%

~1%

σ=49 pb / 6.9M Higgs in 140fb⁻¹
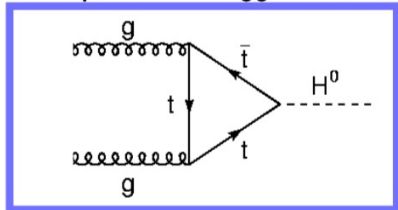
σ=3.8 pb / 520k Higgs in 140fb⁻¹

σ=2.3 pb / 320k Higgs in 140fb⁻¹
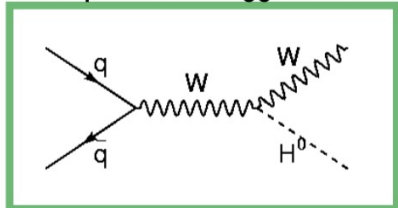
σ=0.5 pb / 70k Higgs in 140fb⁻¹

$\sqrt{s}$= 13 TeV
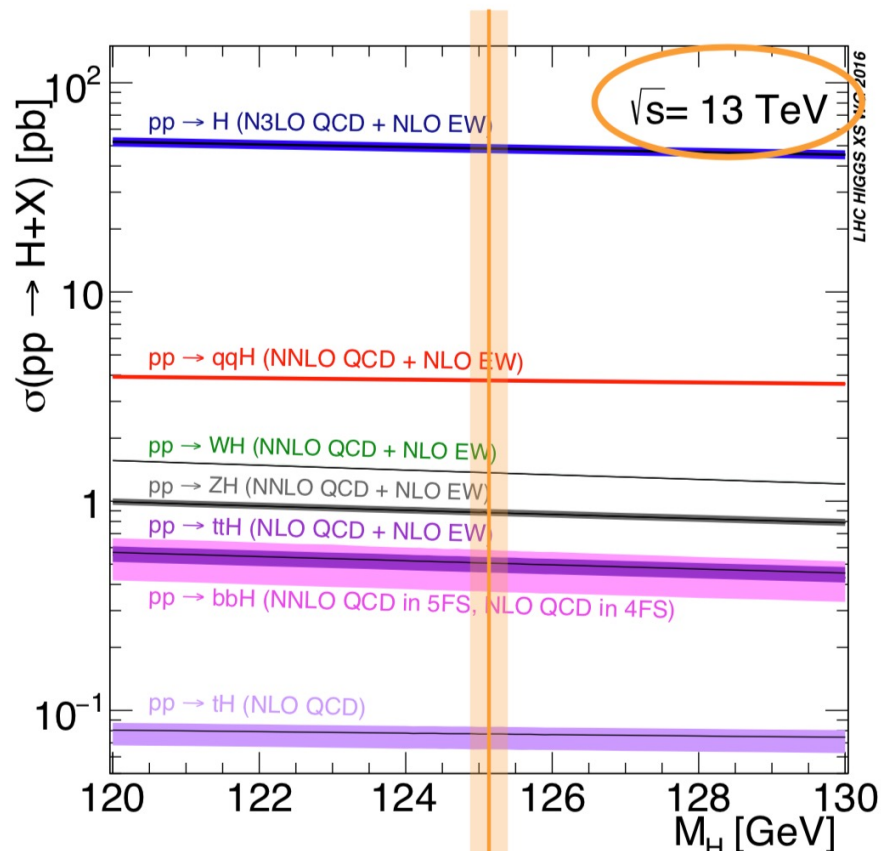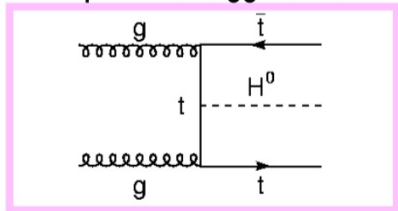
125.09 ± 0.24 GeV
LHC Run1 measurement
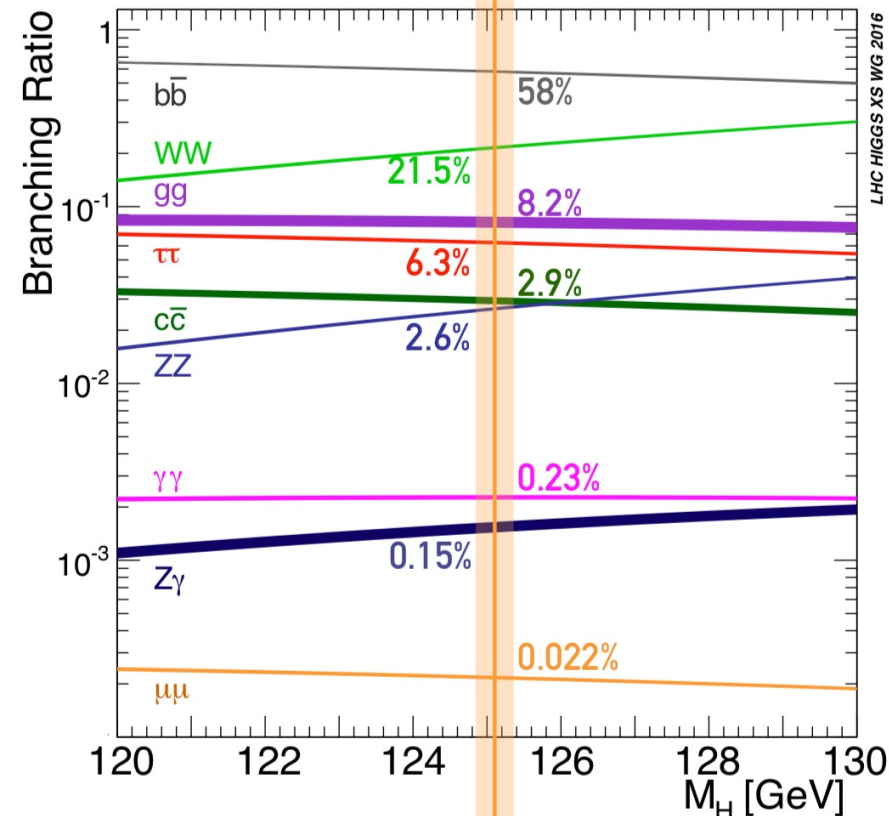
125.09 ± 0.24 GeV
LHC Run1 measurement

Thanks to its mass ~ 125 GeV, the Higgs physics program at LHC is very rich.
All the main production and decay modes are under scrutiny by ATLAS and CMS.

Where do we stand ?

CMS Integrated Luminosity Delivered, pp

Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC

- 2010, 7 TeV, 45.0 pb⁻¹
- 2011, 7 TeV, 6.1 fb⁻¹
- 2012, 8 TeV, 23.3 fb⁻¹
- 2015, 13 TeV, 4.2 fb⁻¹
- 2016, 13 TeV, 41.0 fb⁻¹
- 2017, 13 TeV, 49.8 fb⁻¹
- 2018, 13 TeV, 67.9 fb⁻¹

ATLAS Online, 13 TeV $\int Ldt = 146.9\ fb^{-1}$

- 2015: $\langle\mu\rangle$ = 13.4
- 2016: $\langle\mu\rangle$ = 25.1
- 2017: $\langle\mu\rangle$ = 37.8
- 2018: $\langle\mu\rangle$ = 36.1
- Total: $\langle\mu\rangle$ = 33.7

Run II Mean Pileup
34 interactions/Xing

A Z->$\mu\mu$ event with 28 vertices
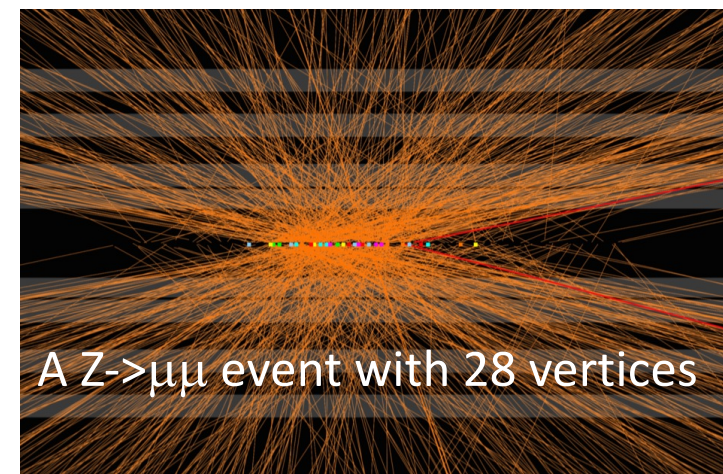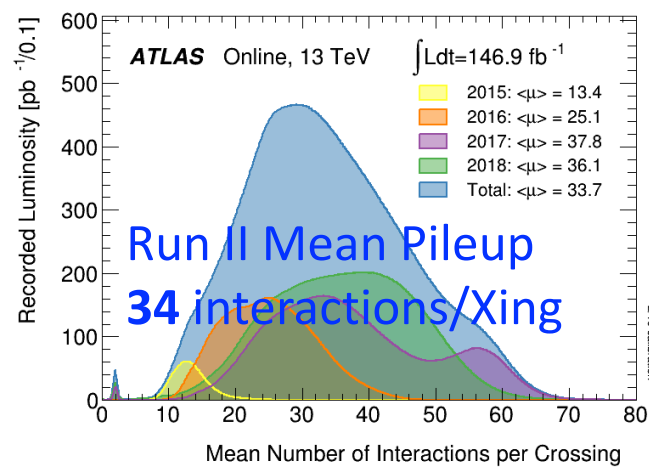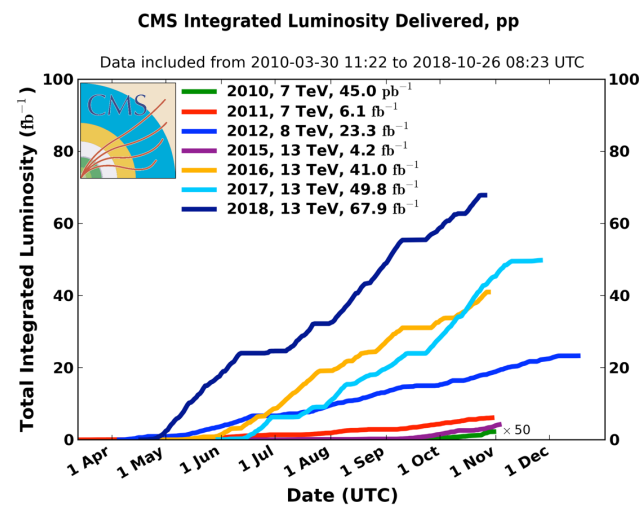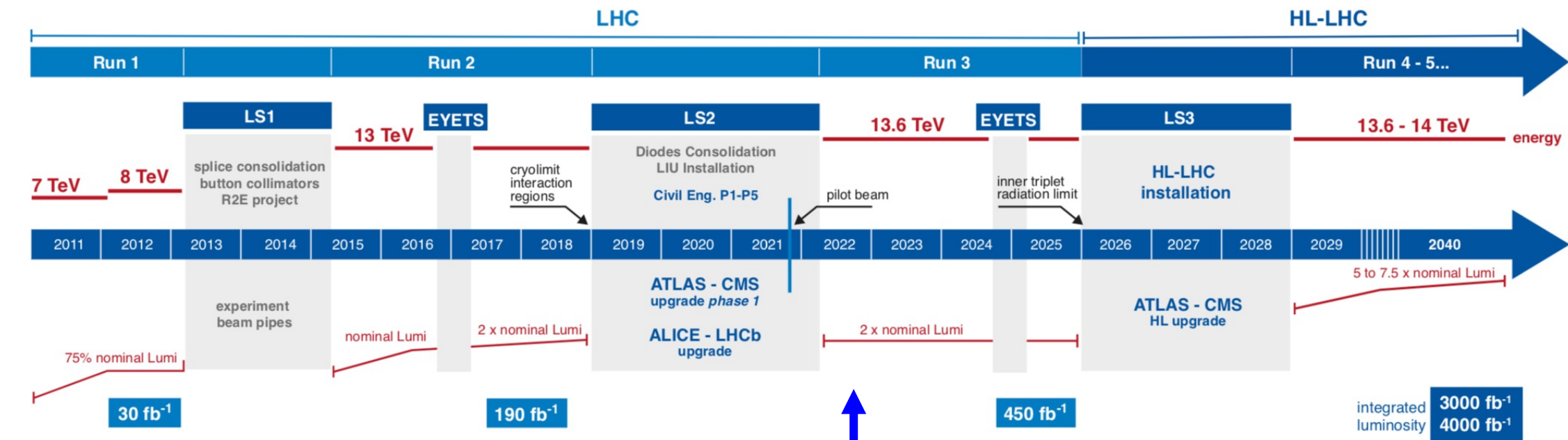
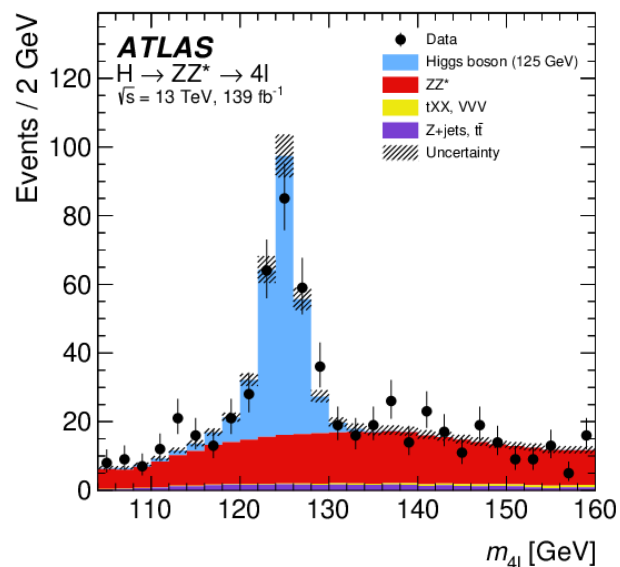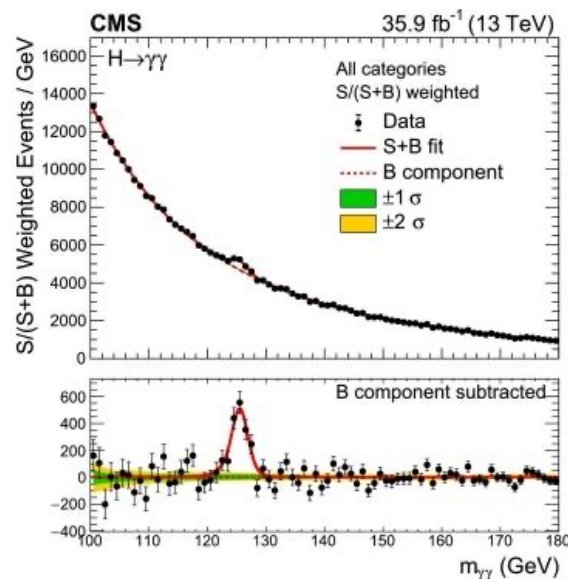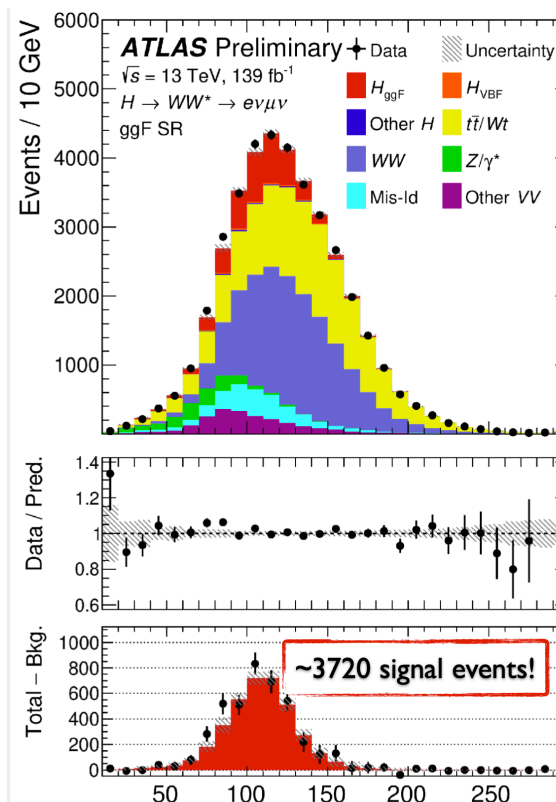# Higgs decays to bosons

Golden channels

- $BR_{SM}(H \to \gamma\gamma) \approx 0.23\%$
- narrow mass peak over smooth backgrounds

- $BR_{SM}(H \to ZZ \to 4l) \approx 1.3 \times 10^{-4}$
- high S/B ratio, clean and narrow mass peak

H→WW→lνlν

- Large $BR_{SM}(H \to WW^*) \approx 22\%$
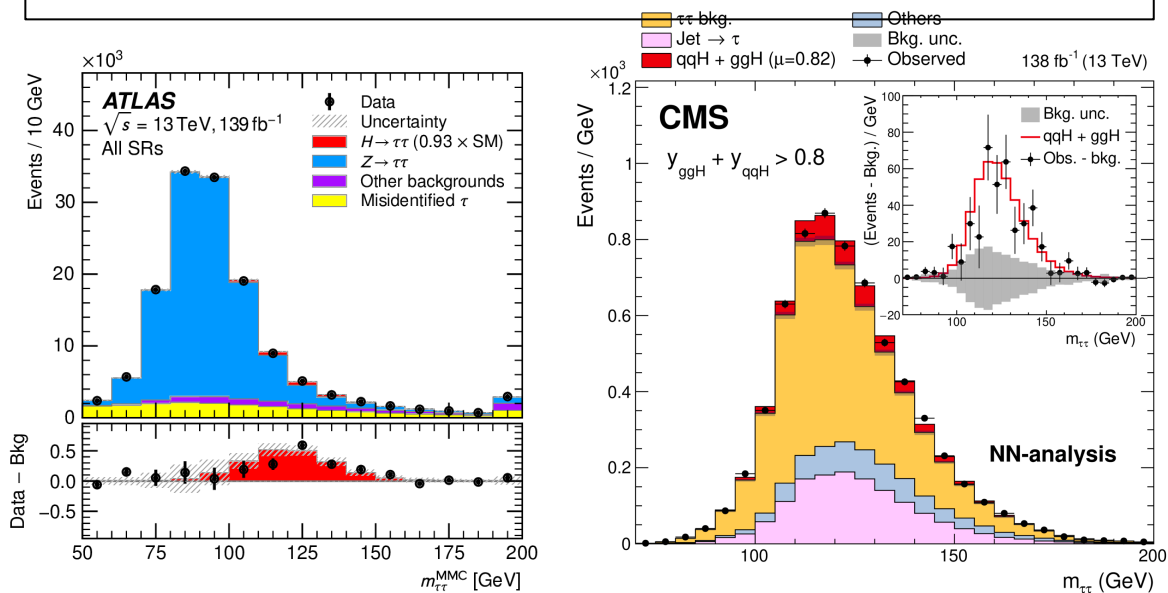- but missing a final state (ν)
- and difficult backgrounds...

H → Zγ

- loop induced process
- $BR_{SM}(H \to Z\gamma) \approx 0.16\%$
- leptonic decay searched

Many precision measurements
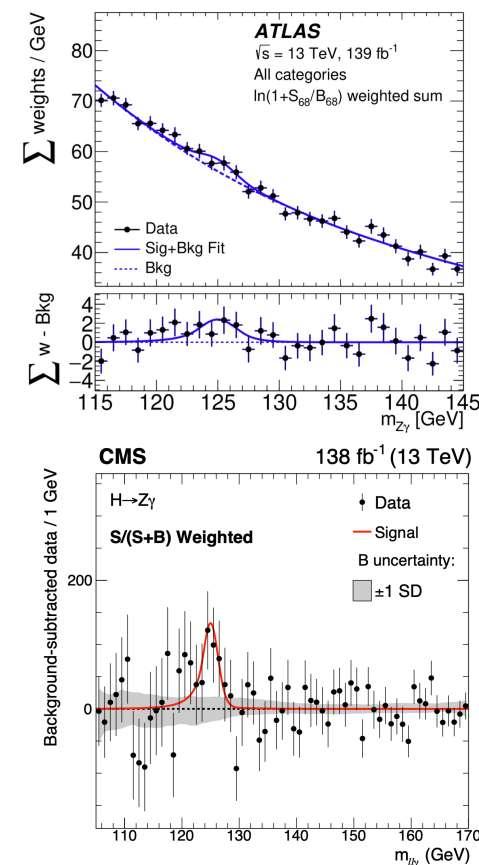
Higgs decays to third generation fermions

H → ττ

- Strongest coupling to leptons
- $BR_{SM}(H \to \tau\tau) \approx 6.3\%$
- Exploit all production modes
- Established with a significance >5σ

H → bb

- Difficult channel despite largest BR (58%) due to large bkg
- VH most sensitive but ggF, VBF and ttH play a role
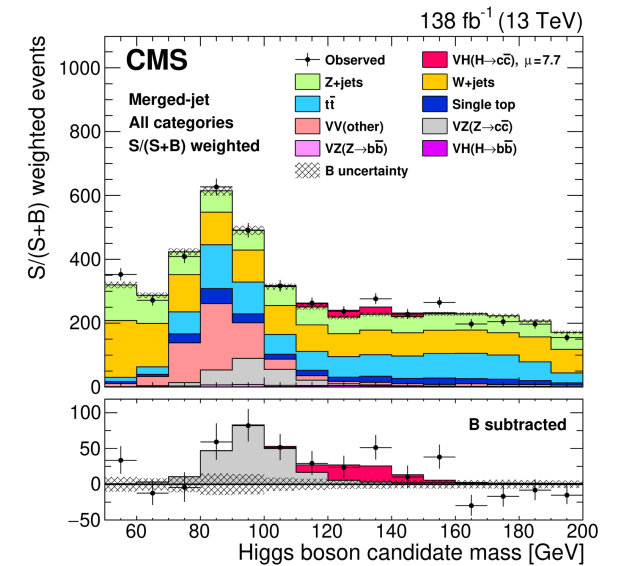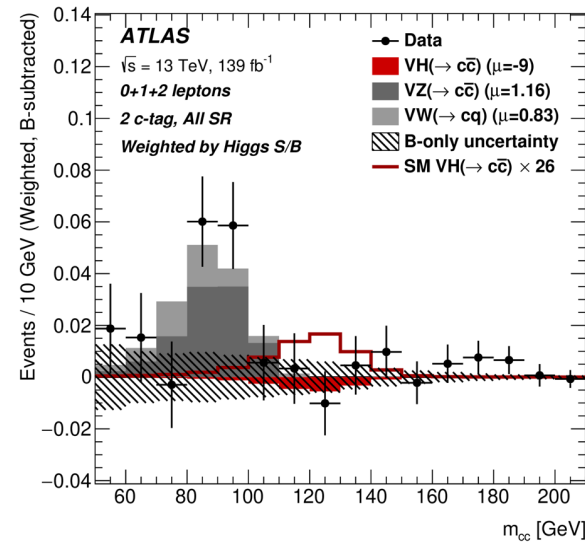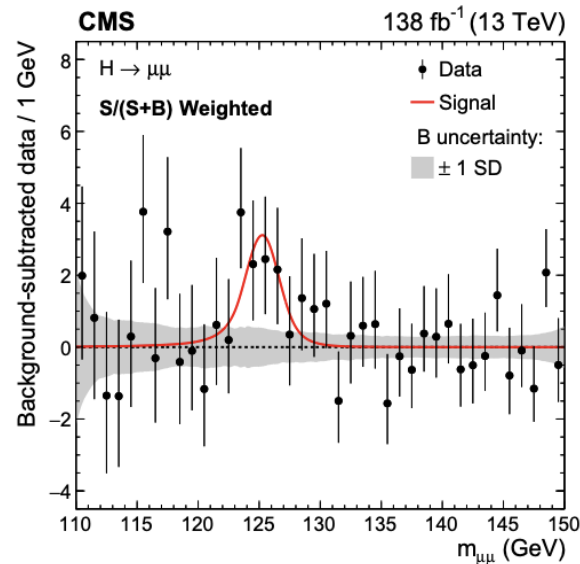- Established with a significance >5σ
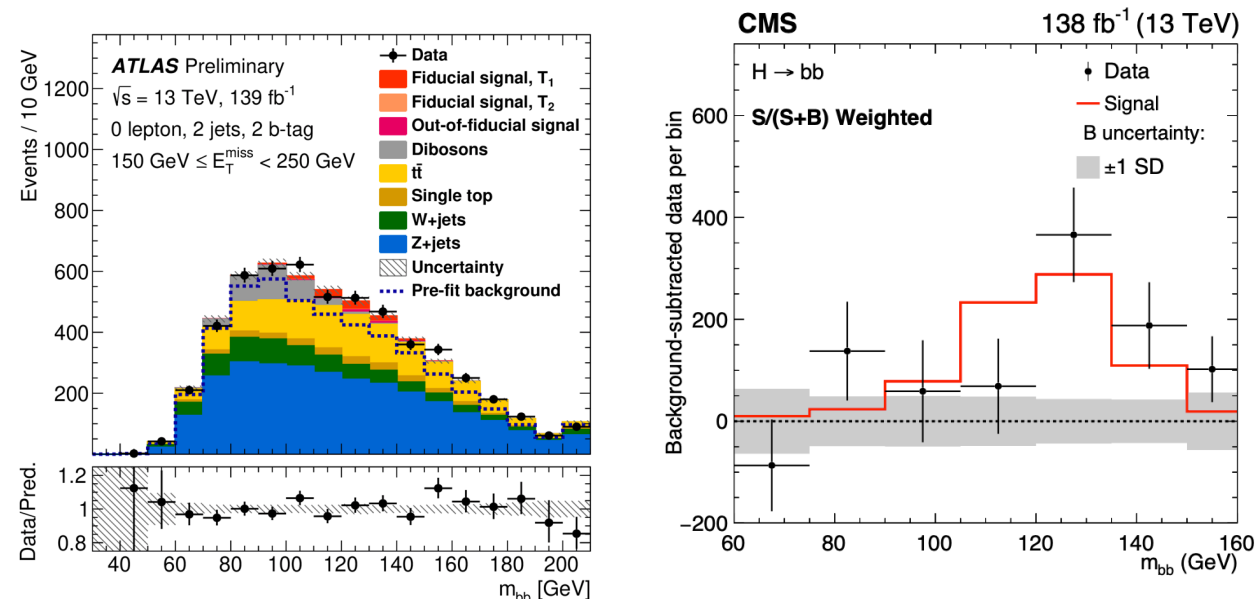
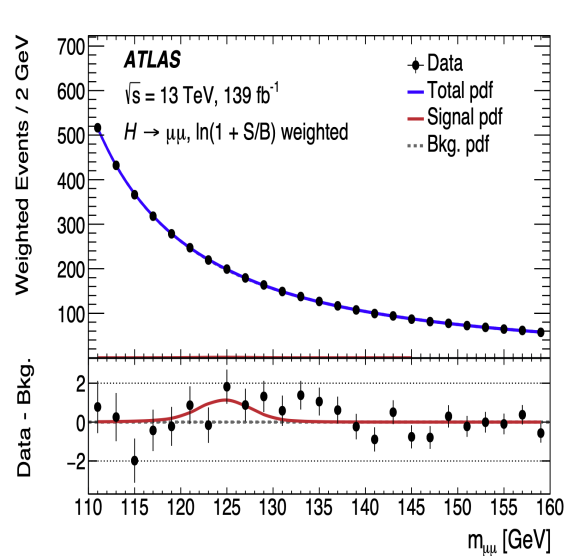# Higgs decays to second generation fermions

H→ μμ

- Very small signal: B(H →μμ) ≈ 2.2×10^{-4}
- Exploit all production modes
- Evidence-level measurement at the LHC (3.0σ observed)

H→ cc

- B(H→cc) ≈ 2.8×10^{-2}
- c quarks harder to identify than muons
- Exploit associated production VH
- Sensitivity to H→cc < 10×SM

Full view of the Higgs boson from combination

- Individual analyses study **specific** Higgs boson characteristics
  ➔ need to **combine** them to get a **full view** of the Higgs boson

- Targeted signatures **included in combined measurements**:

Most of the main production x decay channels included

Note: some additional channels not yet included in combined measurements

Rare decay modes starting to feature in combined measurements

Searches for invisible H decays (for coupling strengths)

A. de Wit, Higgs@10

3

Signal strengths & cross sections

**Inclusive cross-section：
first quantity to measure
when establishing a channel**

Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}\cdot}$$

Scaling of generic i → H → f process

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$
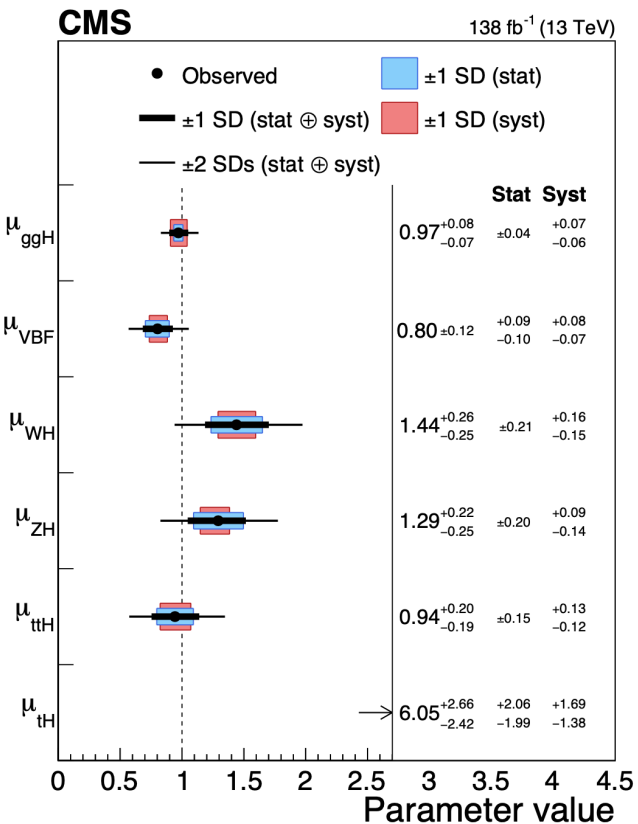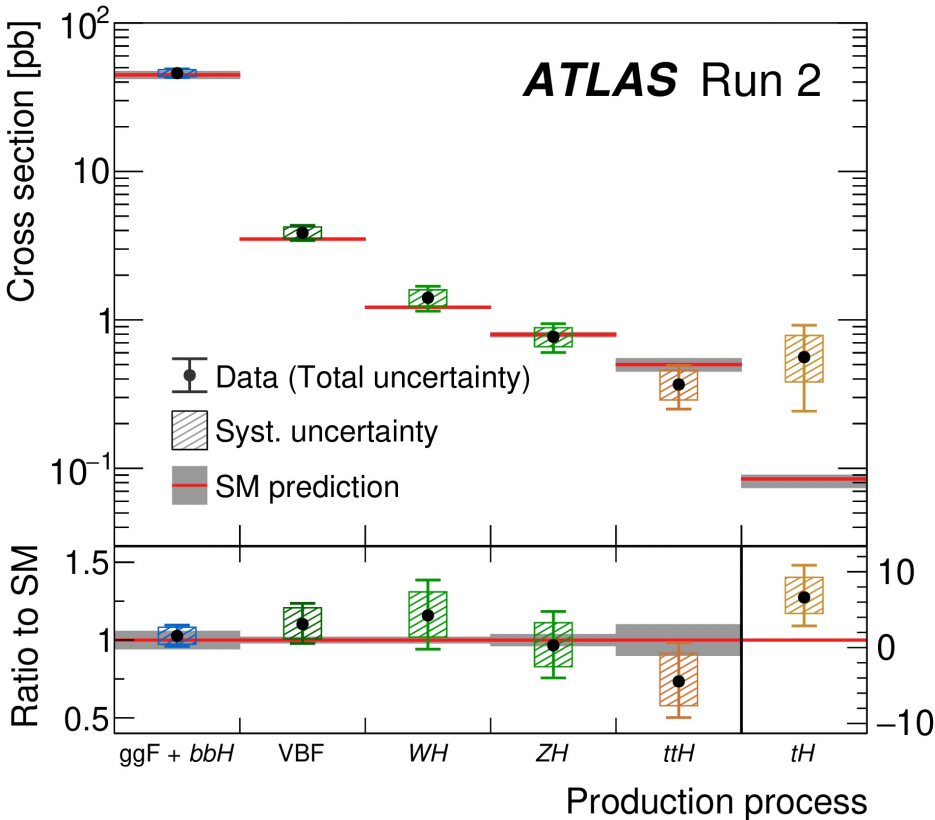
gluon-gluon fusion precision better than 10%!
10-20% precision on other major production modes
Starting to probe rare production modes (e.g. tH)

Signal strengths & cross sections

**Inclusive cross-section：
first quantity to measure
when establishing a channel**

Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}_{\mathrm{SM}}^f.}$$

Scaling of generic i → H → f process

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$
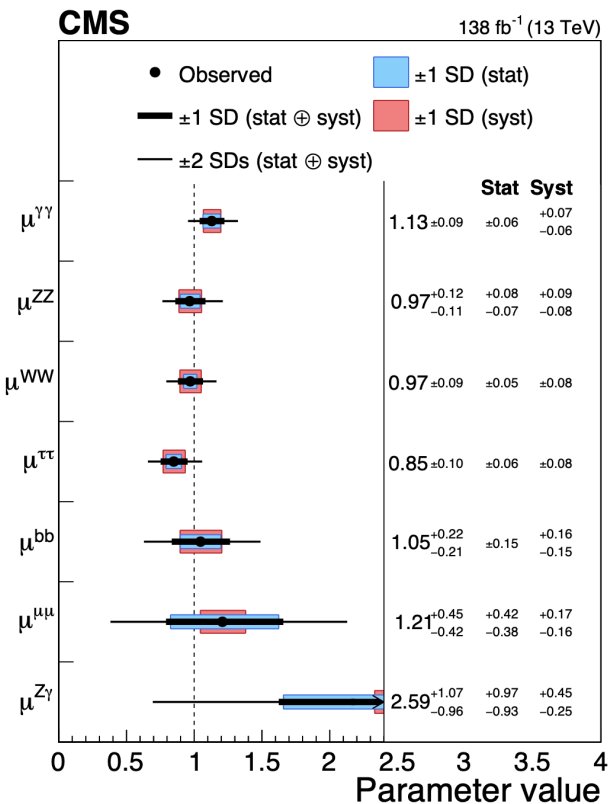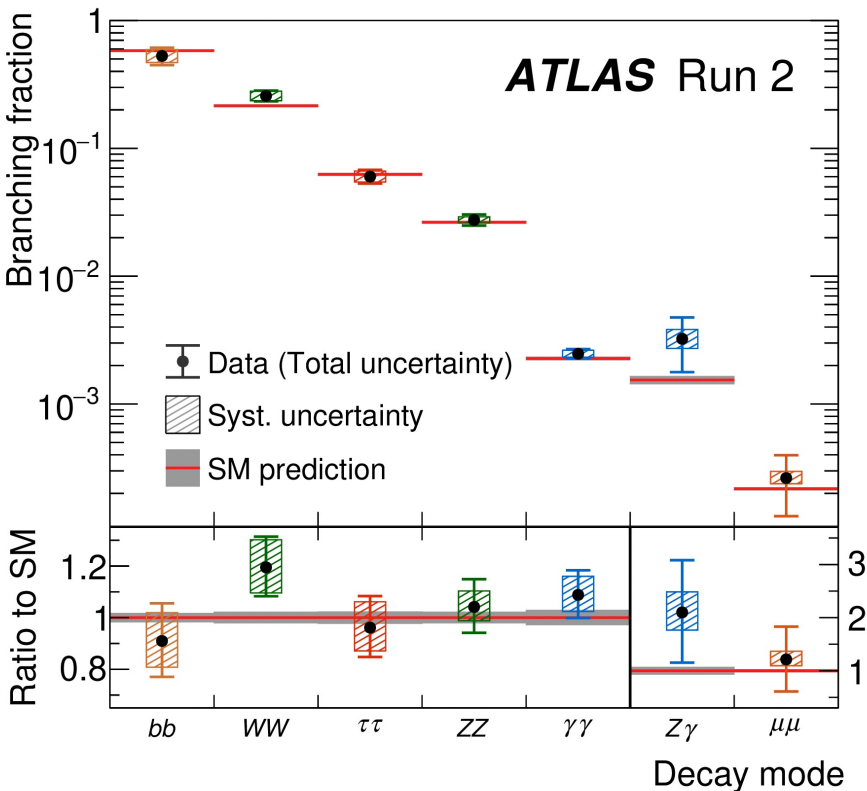
Precision on bosonic decays, decays to tau leptons: ~10%
Uncertainties on rare decay BRs (μμ, Zγ) still sizeable

Signal strengths & cross sections

Inclusive cross-section：
first quantity to measure
when establishing a channel

Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \qquad \mu^f = \frac{\text{BR}^f}{\text{BR}_{\text{SM}}^f}.$$

Scaling of generic i → H → f process

$$\mu_i^f \equiv \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i \cdot \text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

Global signal strength scaling all channels

CMS μ = 1.002 $\pm$ **0.057** = 1.002 $\pm$ **0.036** (theo) $\pm$ 0.033 (syst) $\pm$ 0.029 (stat)

ATLAS μ = 1.05 $\pm$ **0.06** = 1.05 $\pm$ **0.04** (theo) $\pm$ 0.03 (syst) $\pm$ 0.03 (stat)

Improvement in relative precision:
14% (Run 1) ➔ 6% (Run 2)
Theory uncertainty:
7% (Run 1) ➔ 4% (Run 2)

Simplified template cross sections

Split production modes finer in specific final states, p_T^H, or m_{jj} and measure the cross section for each 'production bin'

- **Maximise sensitivity to isolate BSM effects while reducing theory dependence**
- **Exploit many variables simultaneously**
- **Inclusive over the Higgs decays - easier combination of the many channels explored**
- **Cross-sections in mutually exclusive regions of phase space (separated into production modes)**
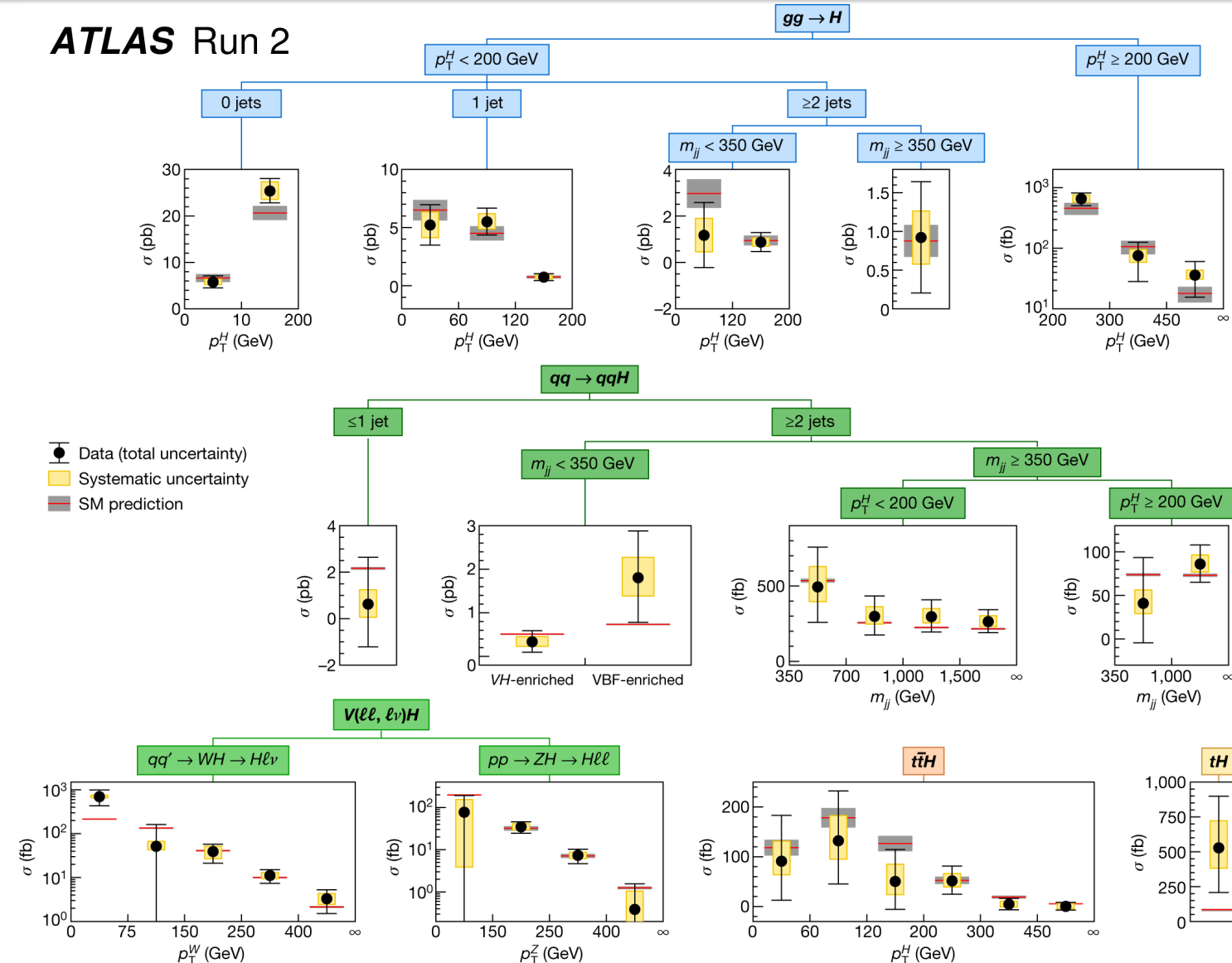
Differential (fiducial) cross sections

Generally with fiducial selection for the decay

- **Measure the rate of Higgs boson production in a certain region(s) of phase space, e.g. in different regions of Higgs boson pT , rapidity, and Njets, pTjet1, mjj, Δφjj, …**

- **Compare with various predictions**
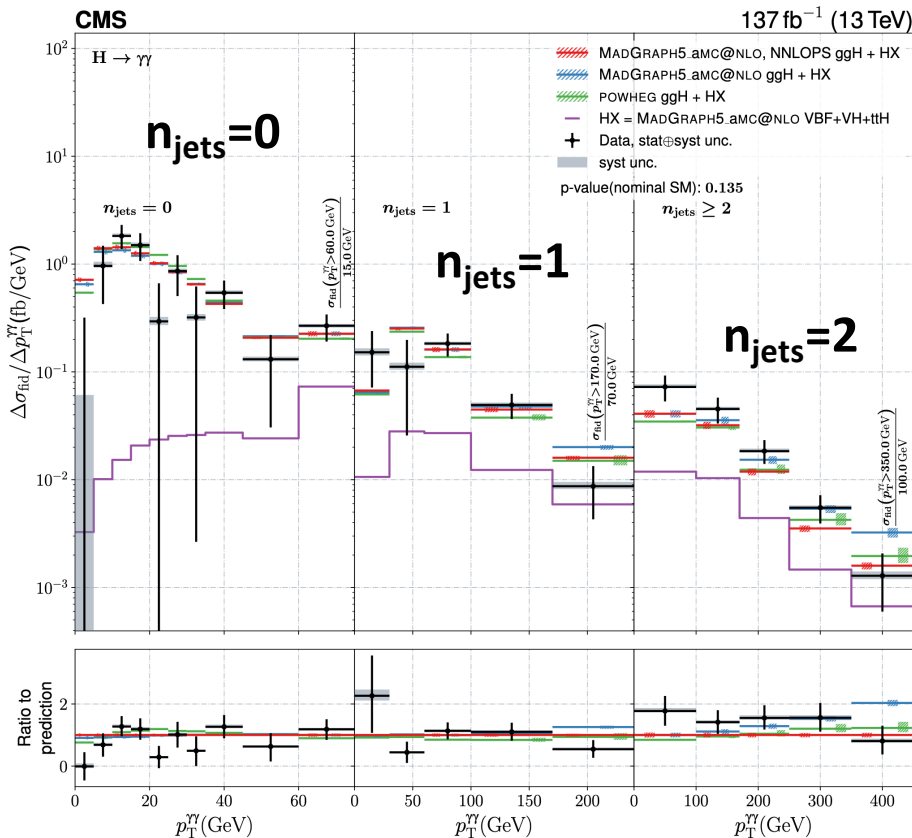
p_T, n_{jets}
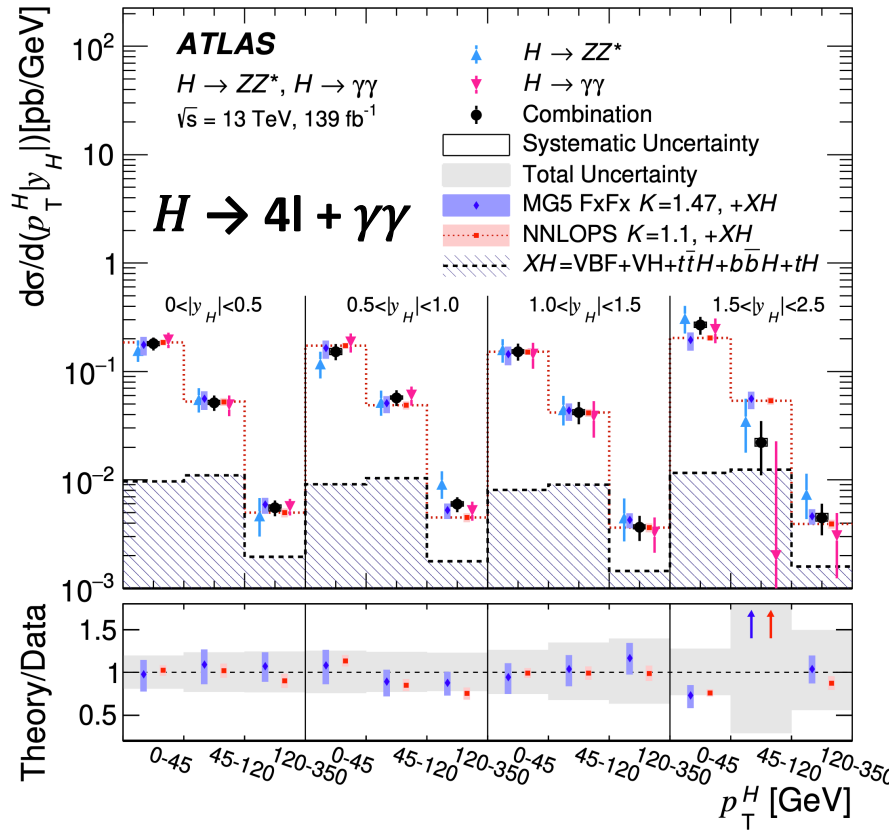
p_T, y

Coupling measurements (κ framework)

- $\sigma(ii \to H)$ and $\mathcal{B}(H \to ff)$ are proportional to the square of effective Higgs boson couplings to the corresponding particle

- To test SM deviations, modified couplings are defined, denoted by scale factors κ

- The coupling modifier framework parametrizes production and decay modes inclusively

resolve loops   effective couplings κ
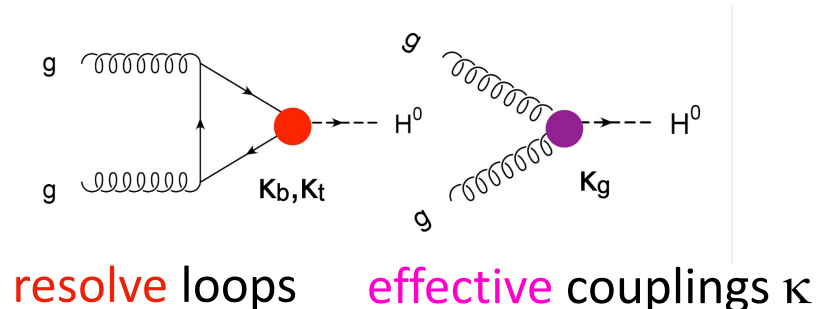
Couplings, κ

Parameters scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \qquad \kappa_j^2 = \Gamma_j / \Gamma_j^{\mathrm{SM}}$$

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{\mathrm{H}}},$$

Total width determined as

$$\Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

Where

$$\kappa_H^2 = \sum_j \mathrm{BR}_{\mathrm{SM}}^j \kappa_j^2$$

Couplings to vector bosons and fermions

- **Scale all vector boson couplings with κ_V, all fermion couplings with κ_f**
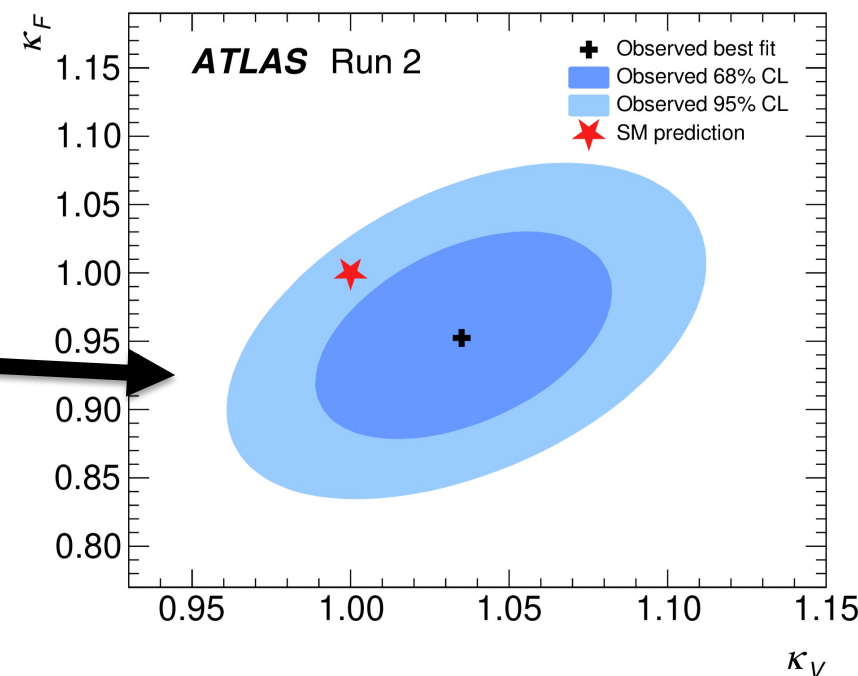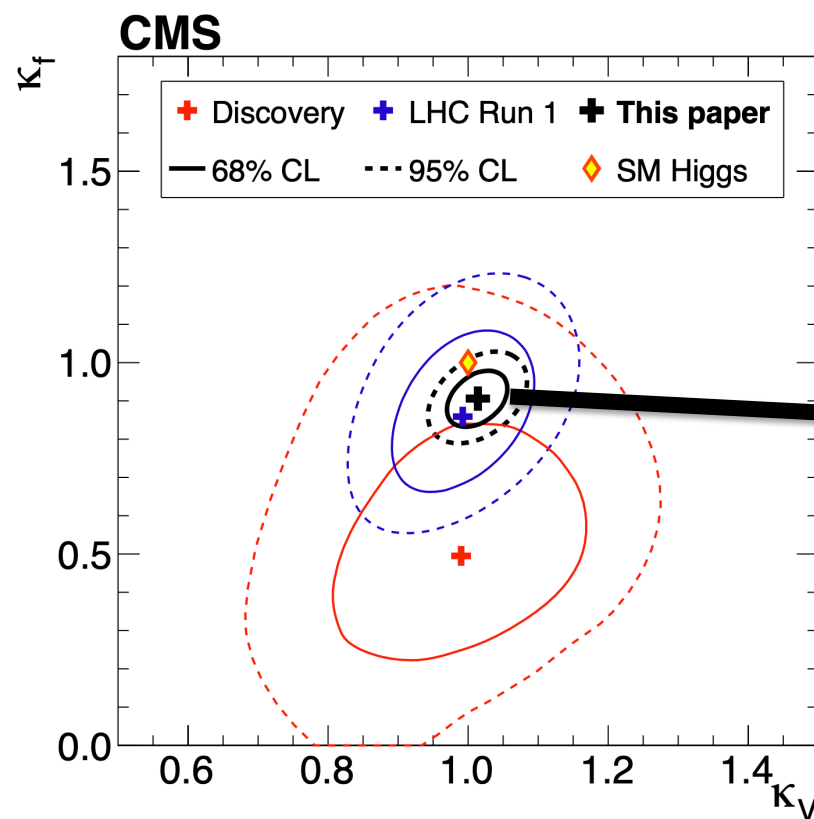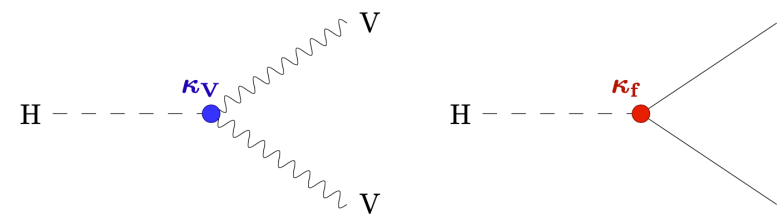
- **Notice improvement with time, from discovery to run 1 to run 2**

Couplings vs. mass

- **Reduced coupling modifiers vs particle mass**

- **Follows pattern expected in SM**

- **The Higgs boson couples with the particle mass!**
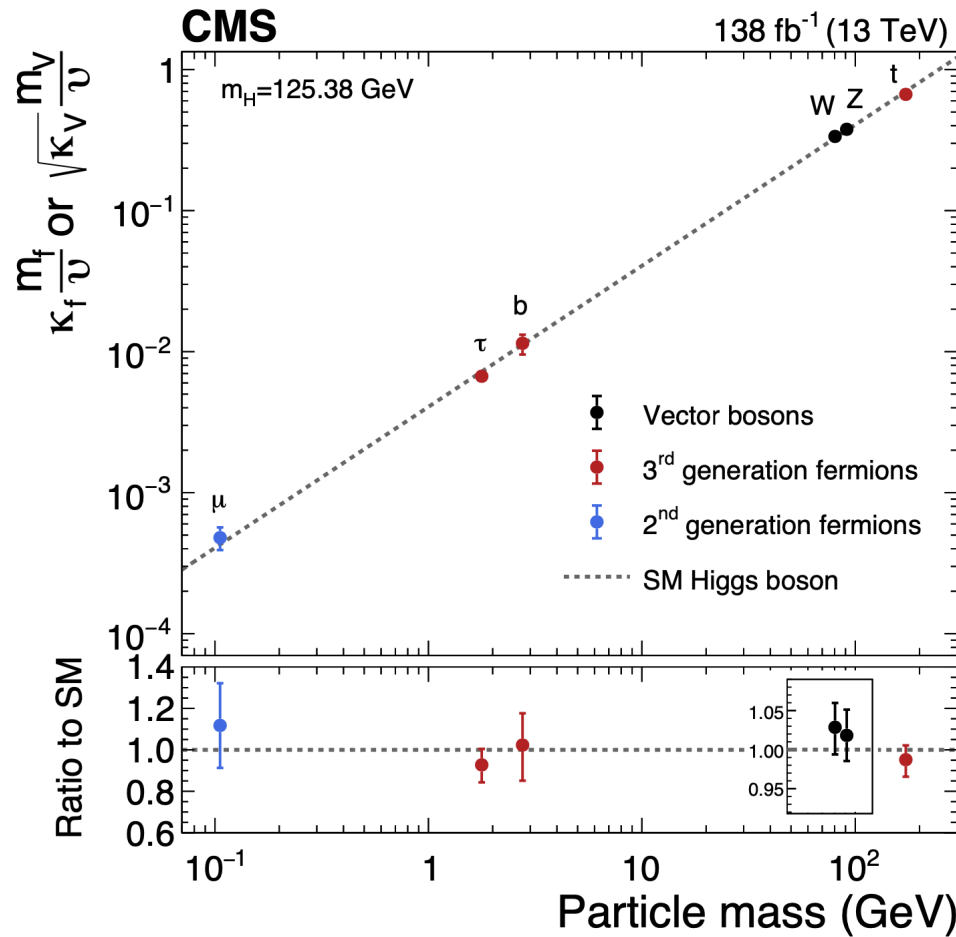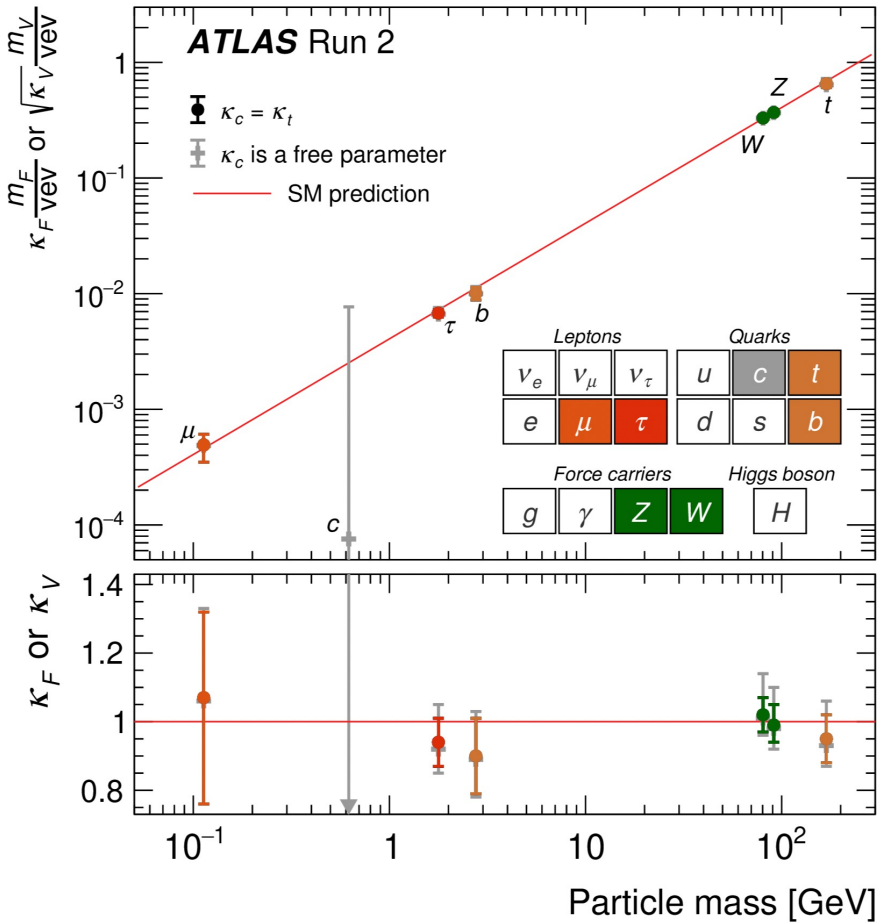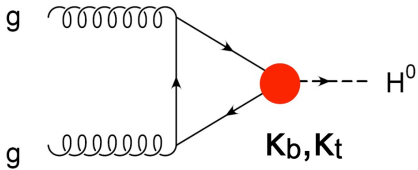
Couplings to BSM

- **Strongest constraints on effective coupling modifiers for $H\gamma\gamma$, Hgg : O(5%)**

- **Also presents constraints with invisible and undetected branching ratios result from combination of all channels, 95% CL UL:**
  - **B_{inv} < 0.13 (ATLAS)**
  - **B_{undet} < 0.12 (ATLAS) (assuming κ_W,κ_Z ≤1)**
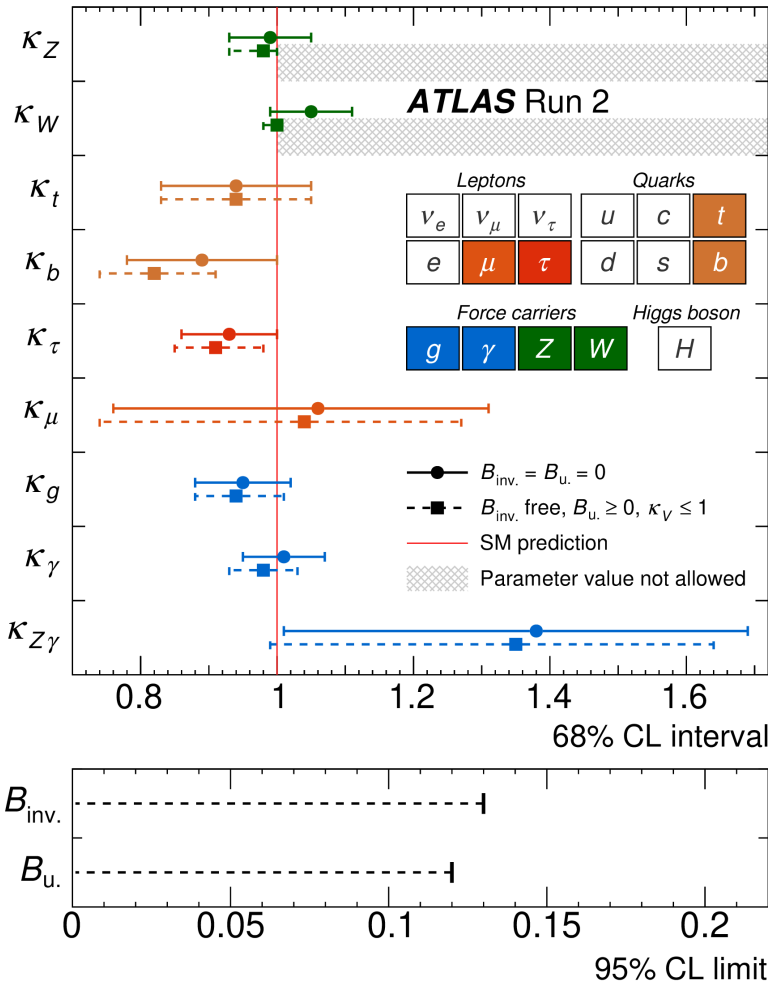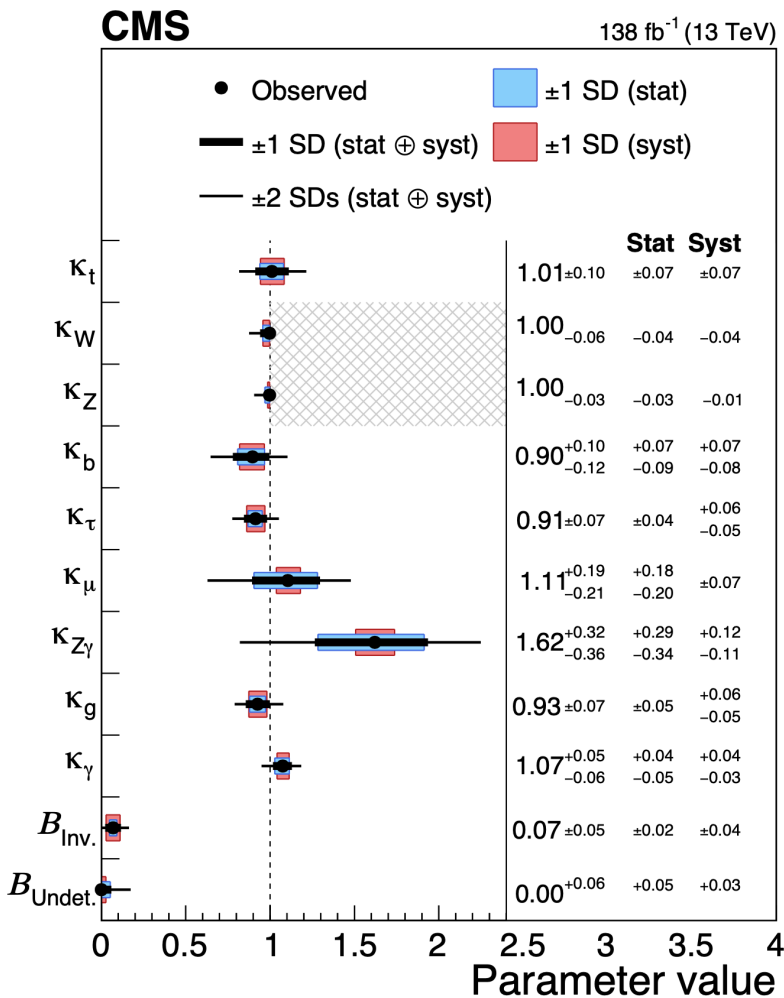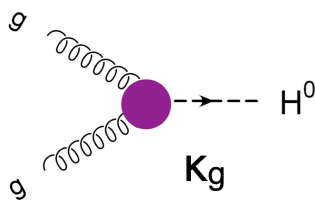
Higgs self-coupling
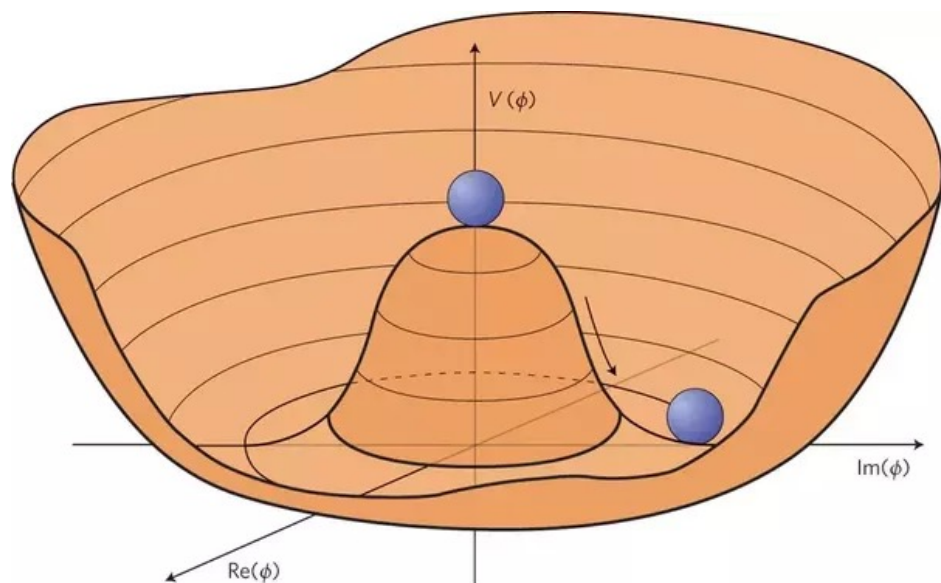
$$V(h) \simeq \frac{1}{2} m_H^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots$$

λ_{HHH}

λ_{HHHH}
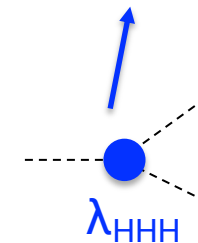
Directly measure λ$_{HHH}$
via HH production
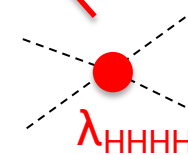
Out of reach for HL-LHC...
... probably...

Higgs boson pair (HH) production allows to probe directly the Higgs boson self-interaction and, ultimately, the shape of the Higgs potential.

HH production at the LHC

Cross-section ~1000x smaller than single Higgs

gluon-fusion
$\sigma_{ggF}(pp \to HH) = 31.05$ fb
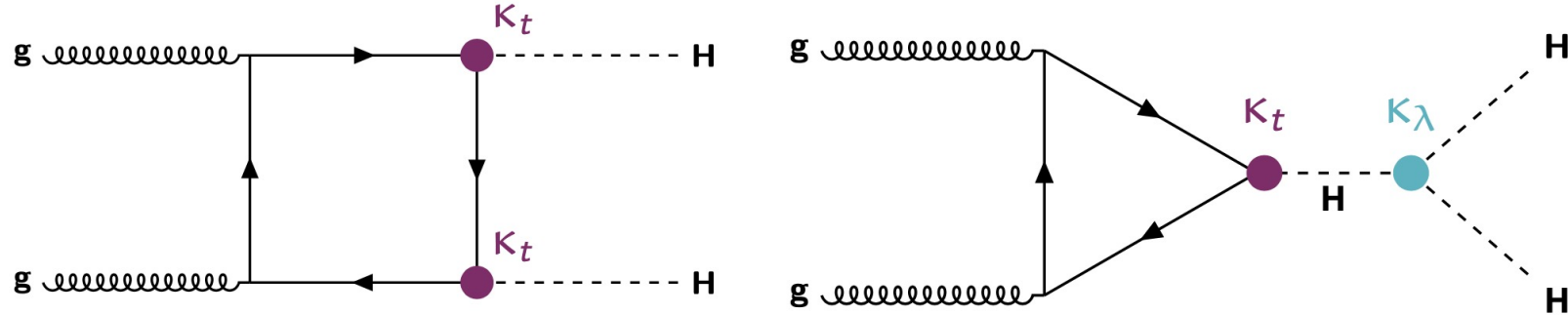
VBF
$\sigma_{VBF}(pp \to HH) = 1.726$ fb
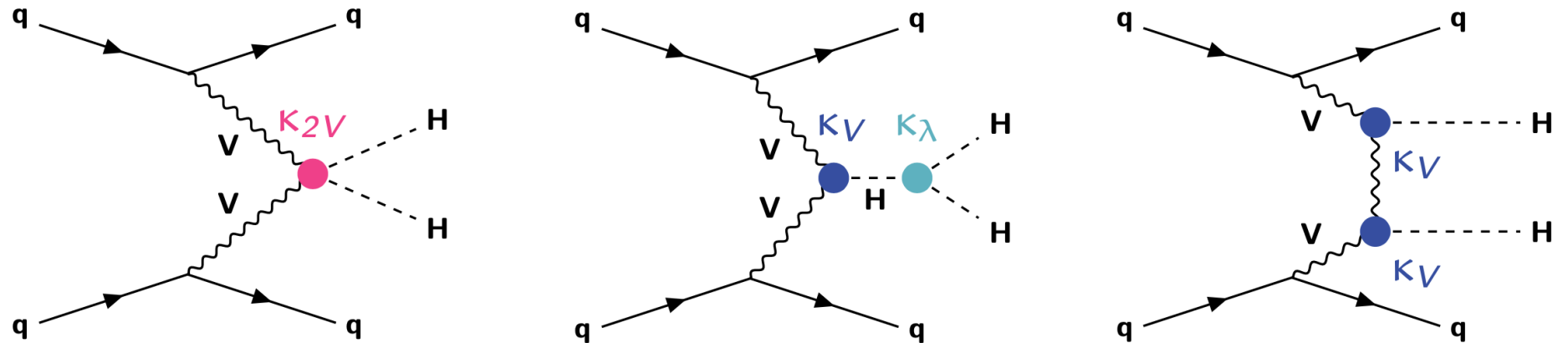
HH mass distr. and cross sections dependence on κ_λ

Cross-section and shape of m_{HH} distribution changes with the self-coupling strength κ_λ (= λ/λ_{SM})

Destructive interference between the 'triangle' and `box' diagrams
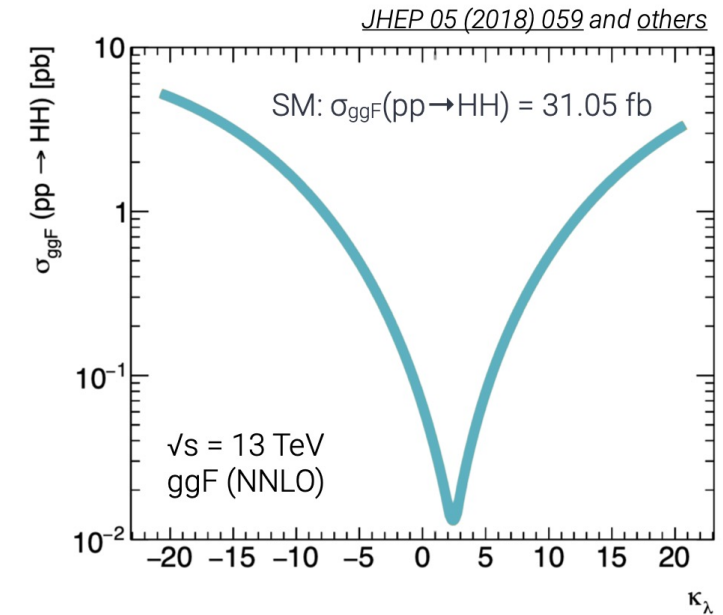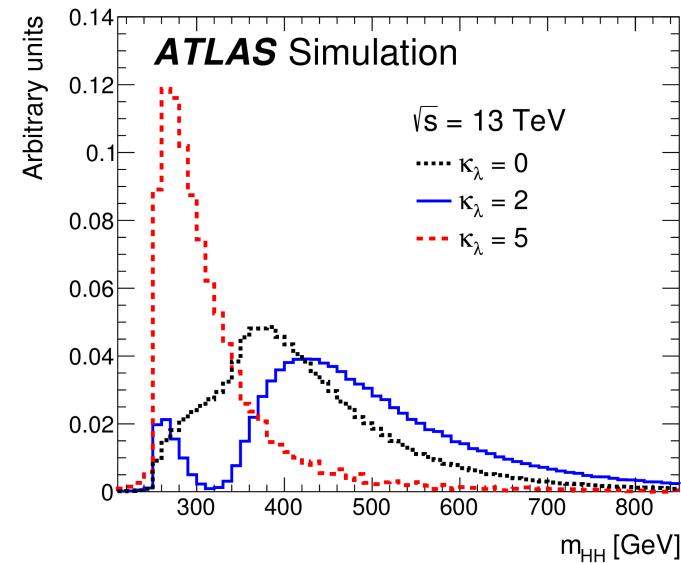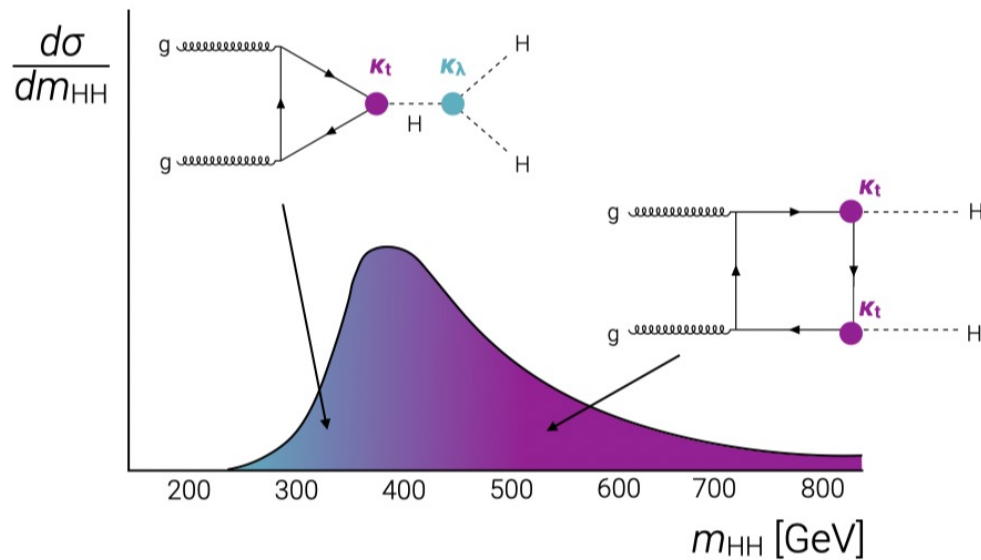
HH decays and search channels

	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 by Katharine Leney

All channels have trade-offs between branching ratio vs final state, each with specific experimental challenges and sensitivity reach

No single "golden" channel.

HH decays and search channels
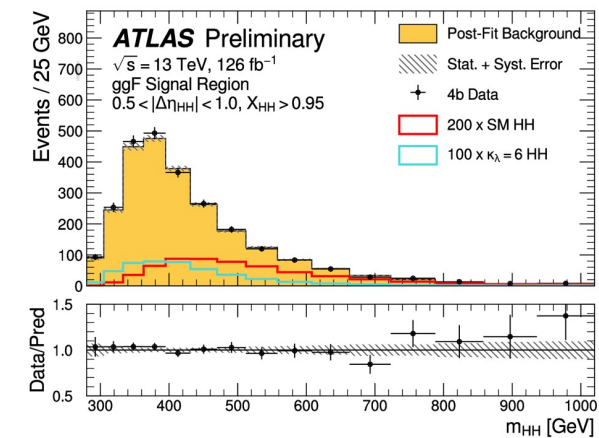
bbbb – resolved topology
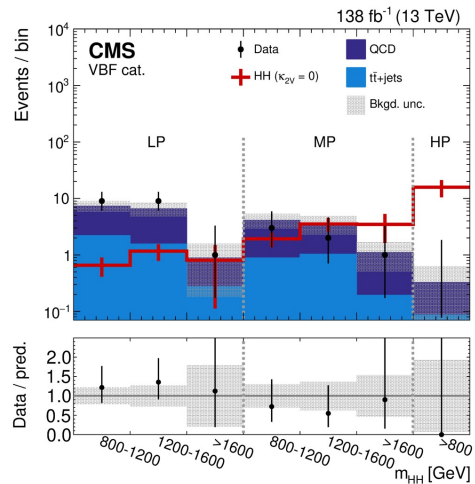
bbbb – merged topology

bbττ

bbττ

bbγγ

bbγγ

bbWW(lνlν)

bbZZ(4l)

Obs. (exp.) 95% CL combined limit: 2.4 (2.9) × SM prediction.
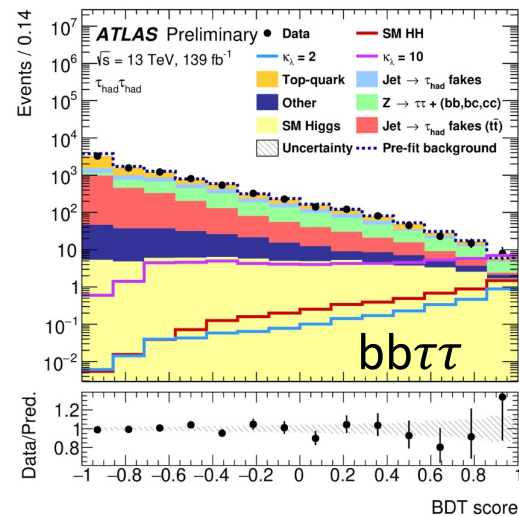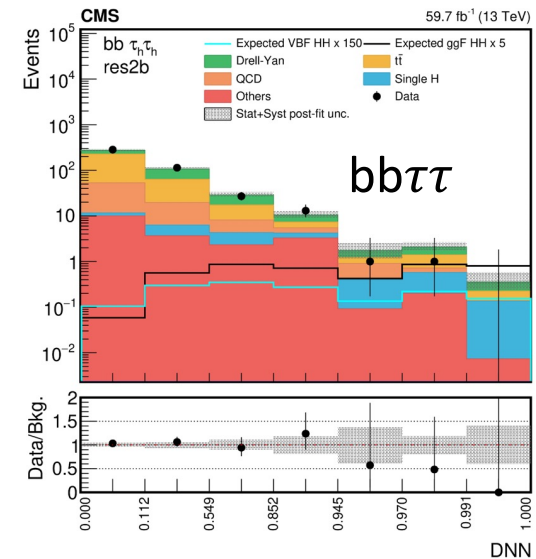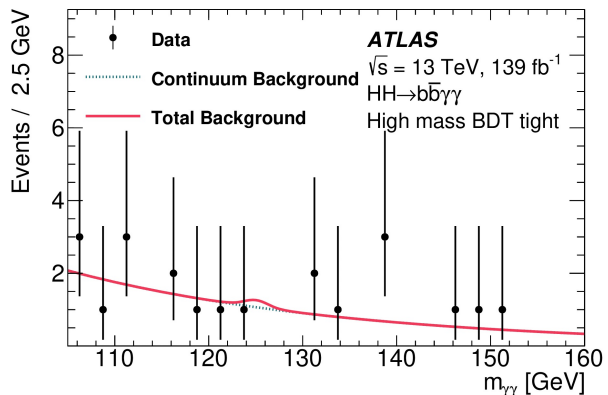
Obs. (exp.) 95% CL combined limit: 3.4 (2.5) × SM prediction.
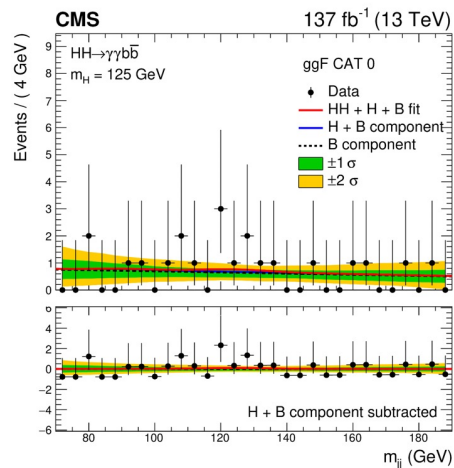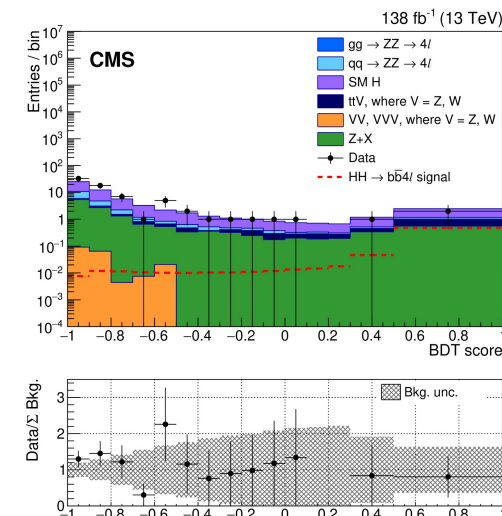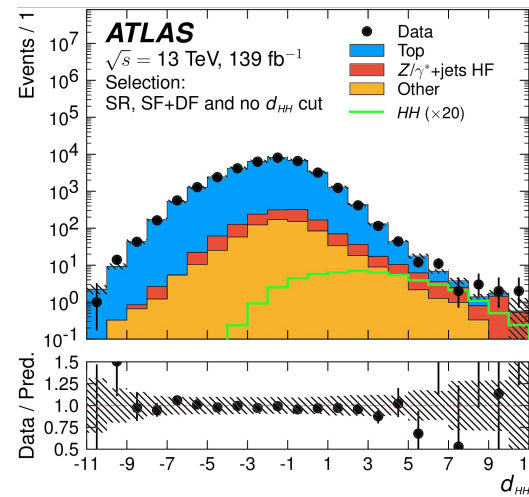
HH combination: limits on self-coupling

ATLAS and CMS 95% CL limits on σ_{HH} vs κ (all other κ's at 1):
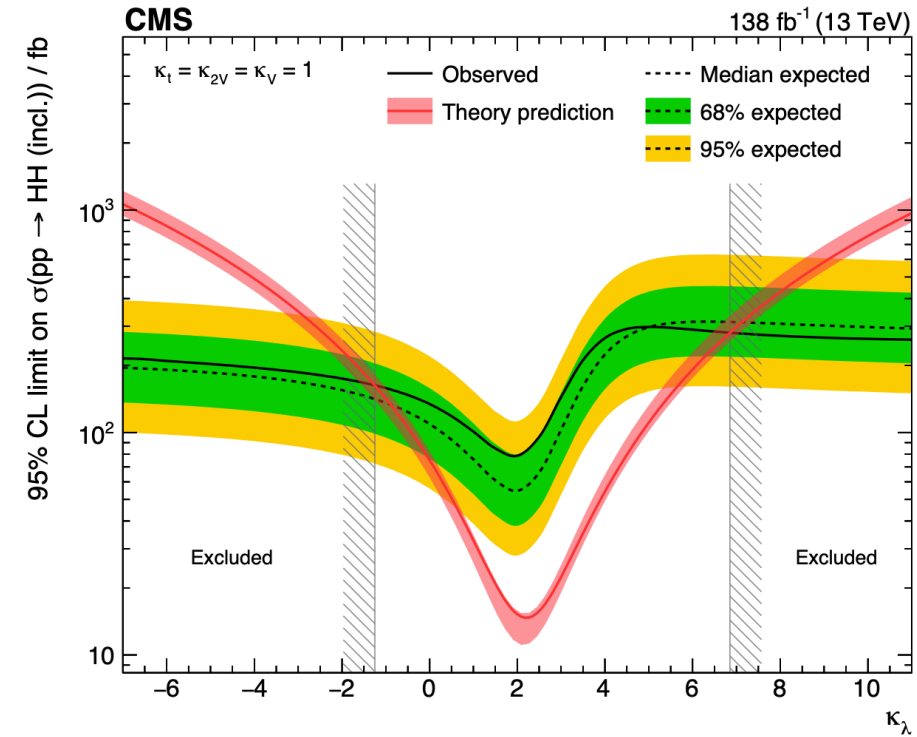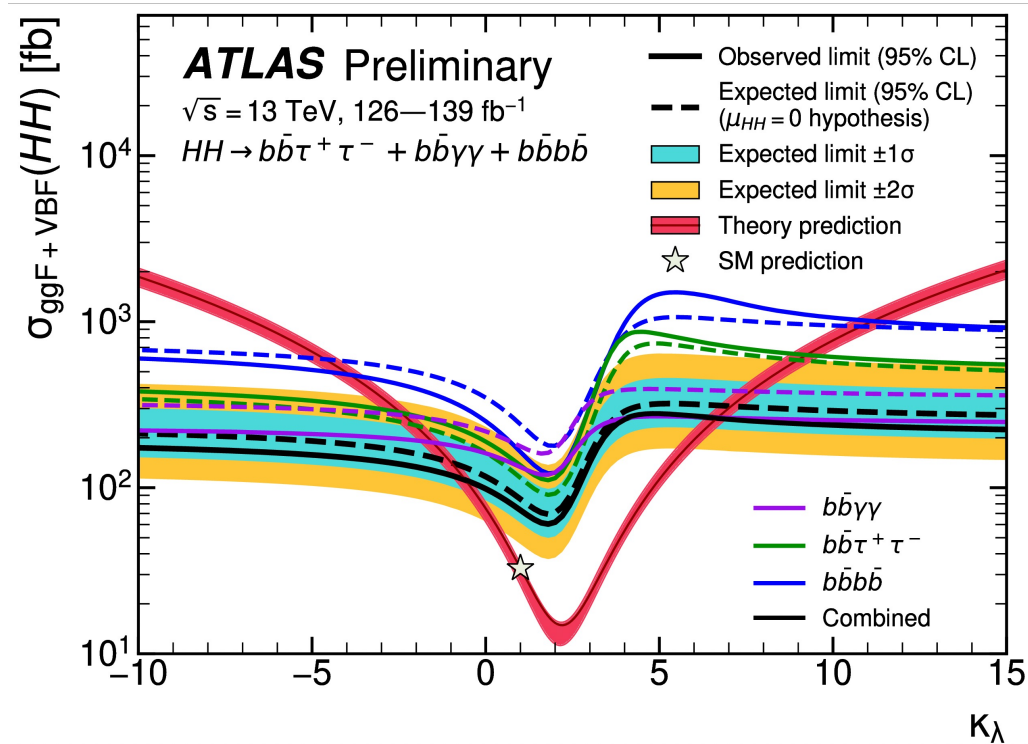
Probe self-coupling through single-H

Single Higgs boson processes do not depend on κ_λ at LO.

However, NLO electroweak loops allow κ_λ to affect single Higgs boson production and decay modes.

LHCHWG-2022-002
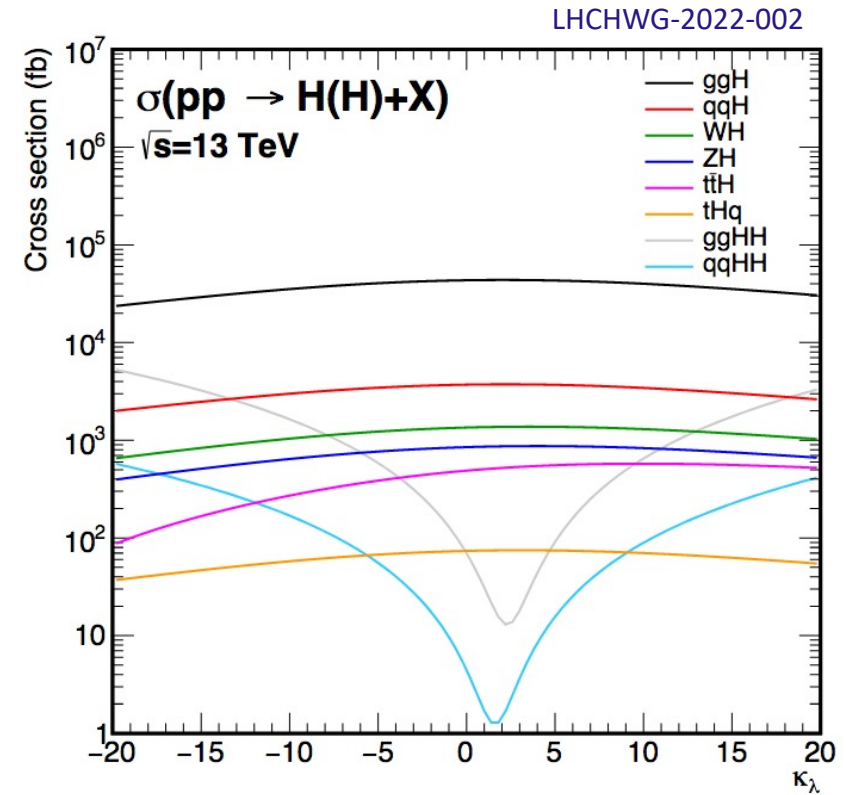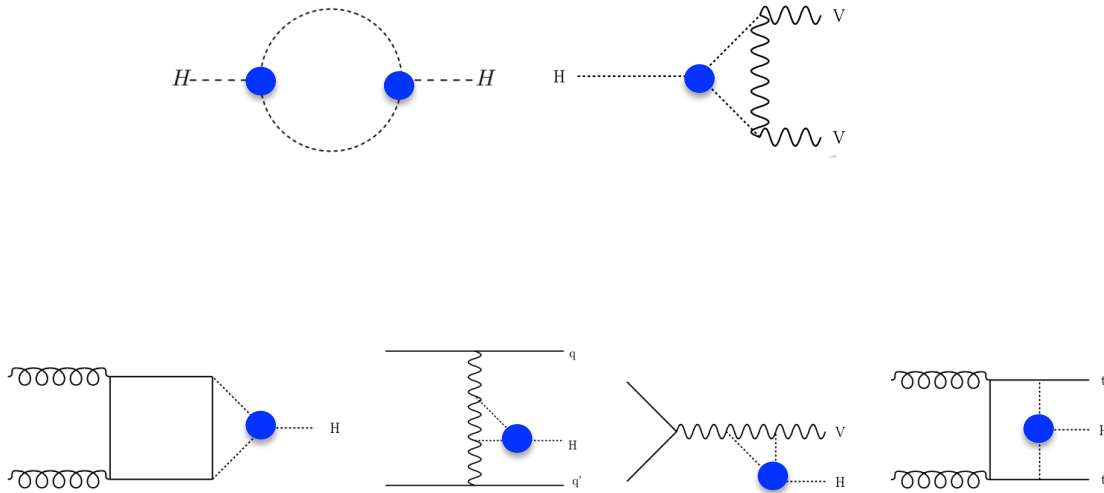
HH+H: constraints on κ_λ : ATLAS

Constraints on κ_λ via a scan of the negative-logarithm of the profile likelihood, for various fit configurations:

- **HH searches only, single-H measurements only, or their combinations.**
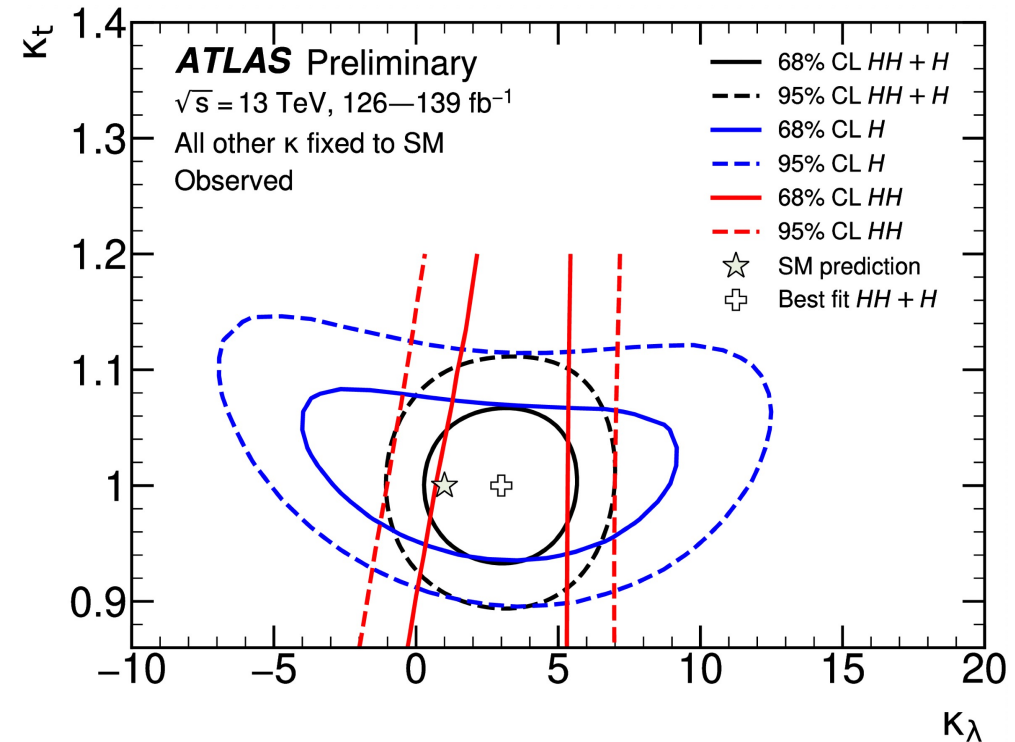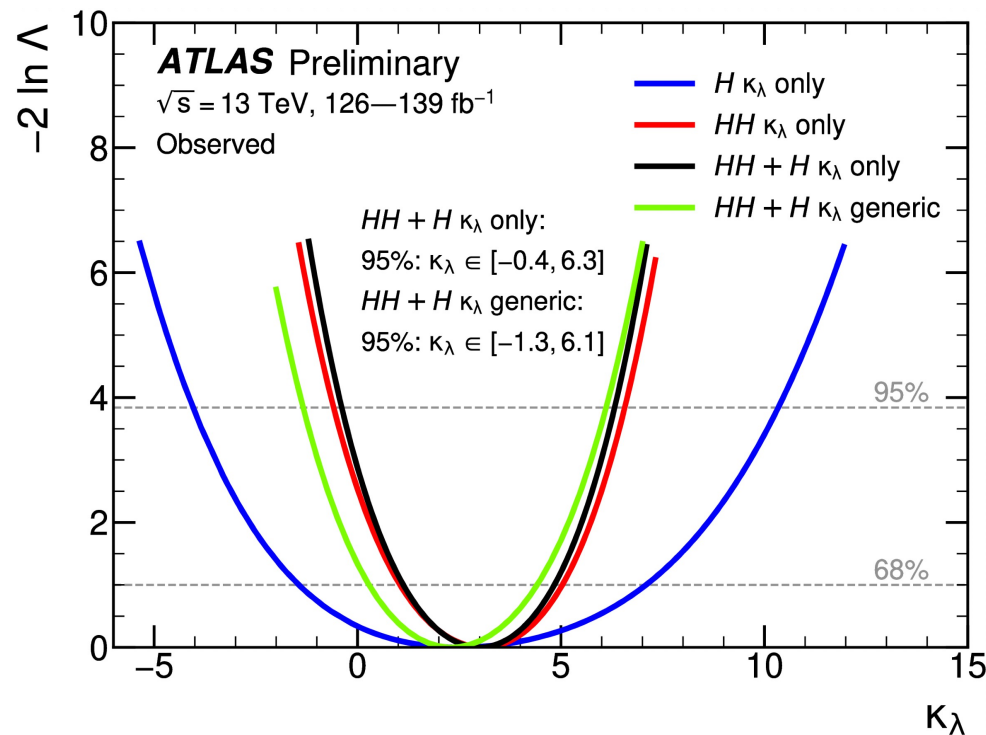
Summary of ATLAS HH+H combined results:

Profile κ_λ only: $-0.4 < \kappa_\lambda < 6.3$ (95% CL).

Profile κ_λ, κ_t, κ_V, κ_b, κ_τ: $-1.3 < \kappa_\lambda < 6.1$ (95% CL).

HH+H: constraints on κ_λ : CMS

Constraints on κ_λ via a scan of the negative-logarithm of the profile likelihood, for various fit configurations:

• **HH searches only, single-H measurements only, or their combinations.**

Summary of CMS single-H and HH results (profile κ_λ only):

Single-H: $-3.6 < \kappa_\lambda < 12.6$ (95% CL).

HH: $-1.3 < \kappa_\lambda < 6.4$ (95% CL).

Towards HL-LHC
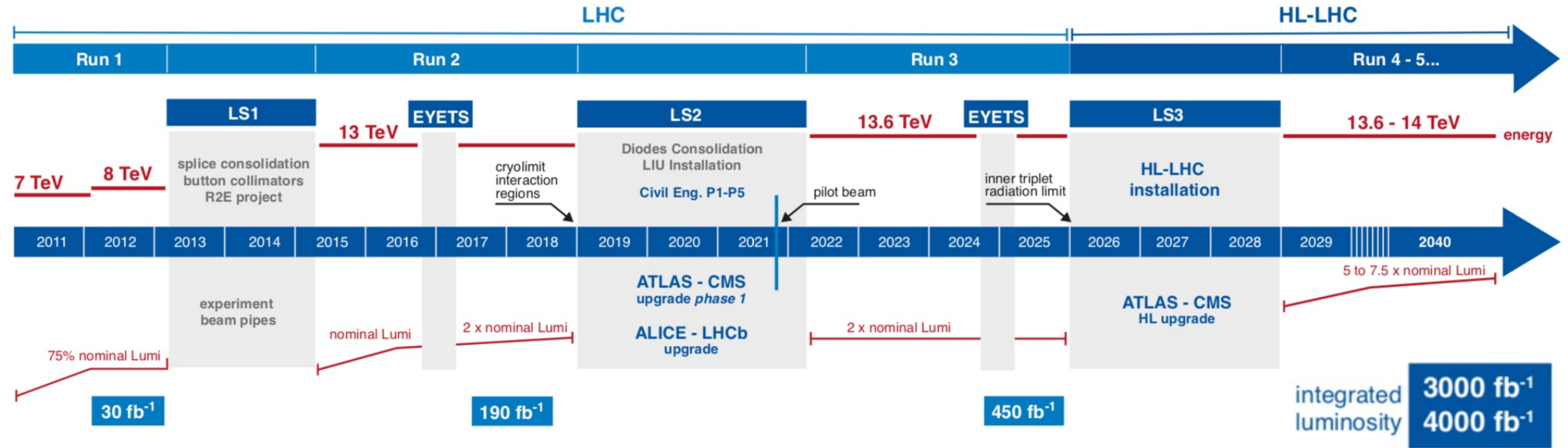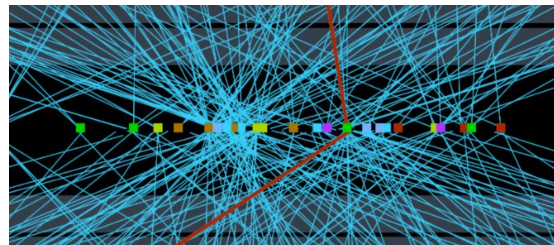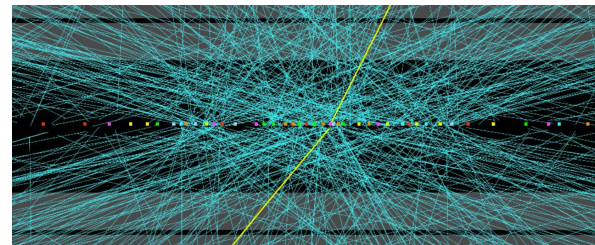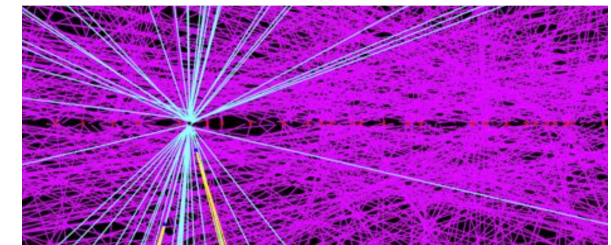
Mean Pileup will increase from ~30@Run2 to ~200@HL-LHC

Experiment Upgrades for the HL-LHC

ATLAS Detector Upgrade

Muon Detectors   Tile Calorimeter   Liquid Argon Calorimeter

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 $|\eta| = 4.0$

Toroid Magnets   Solenoid Magnet

Elizabeth Brost - Higgs@10 Symposium - July 4th, 2022   8

CMS Detector Upgrade

Upgraded Trigger and Data Acquisition system:
- Add tracks at L1 (1 MHz)
- High Level Trigger output 7.5 kHz

Electronics upgrade: barrel calorimeters and muon system
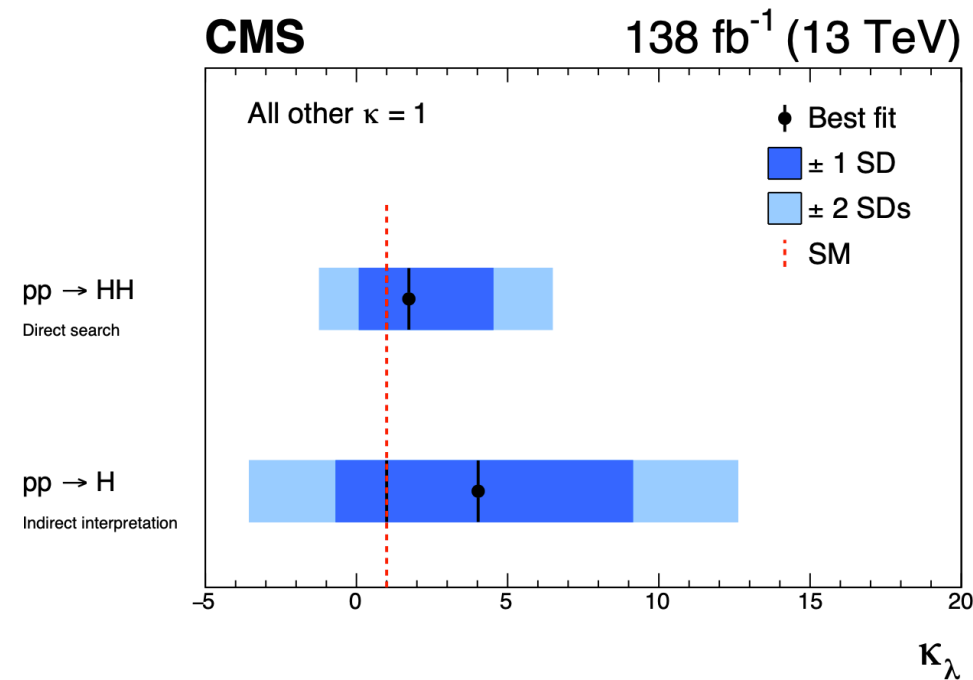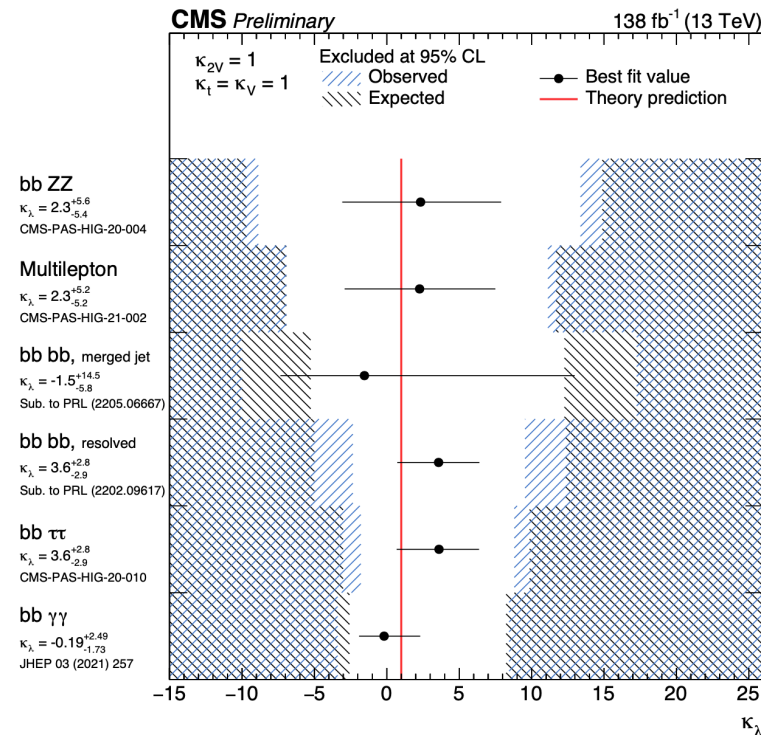
Extended muon coverage to $|\eta| \sim 2.8$

NEW MIP timing detector with 30 - 50 ps time resolution

NEW High-granularity calorimeter endcap

NEW Inner Tracker, coverage up to $|\eta| = 4$, reduced material

Elizabeth Brost - Higgs@10 Symposium - July 4th, 2022   9

The harsh conditions at the HL-LHC will challenge the experiments in all areas, and will require improvements to:

- Detectors themselves
- Trigger menu and hardware

- Event reconstruction
- Software & computing
- Physics analysis techniques

The Higgs boson at HL-LHC

A substantial amount of parameter space to be covered

- **Higgs couplings move into precision regime**
  - most dominated by theory uncertainties
  - **~2-4 % precision of Higgs couplings to W/Z, γ/g, 3rd gen. fermions, muon**
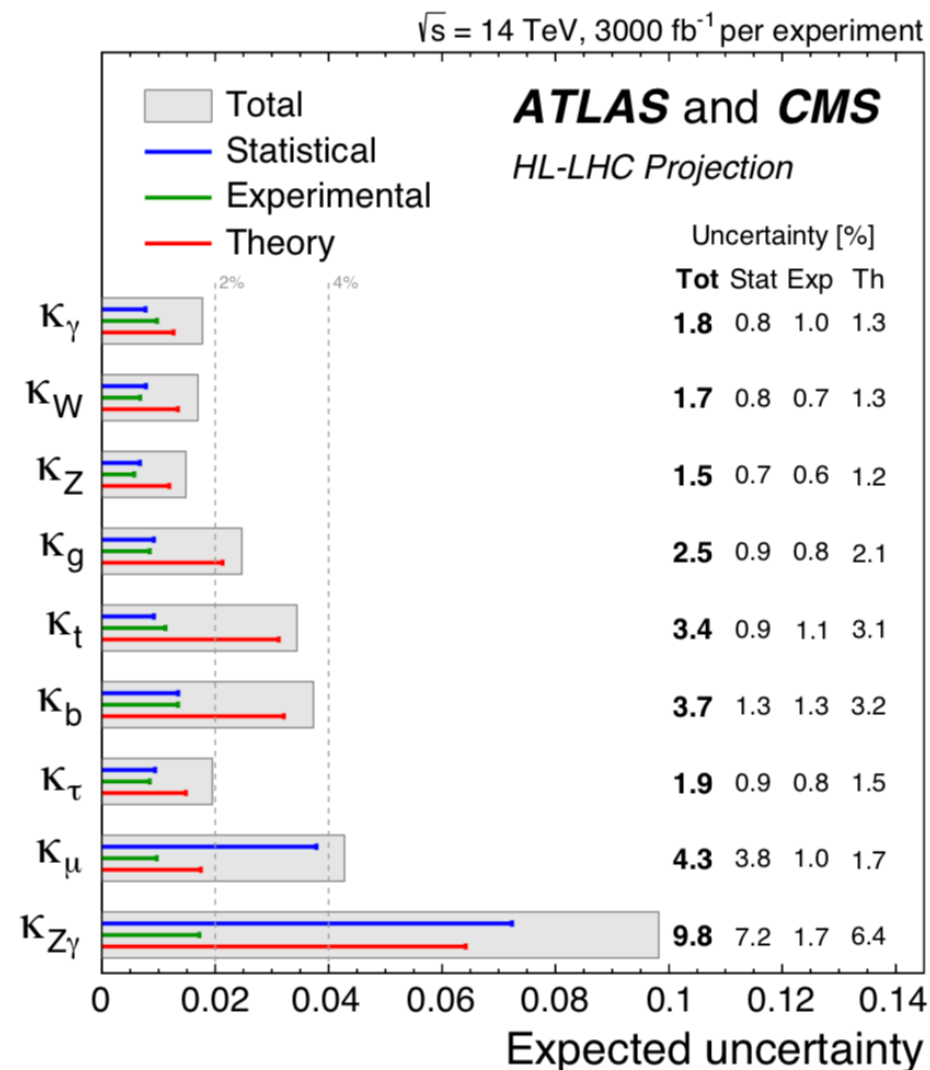
Higgs couplings to muon/charm@ HL-LHC
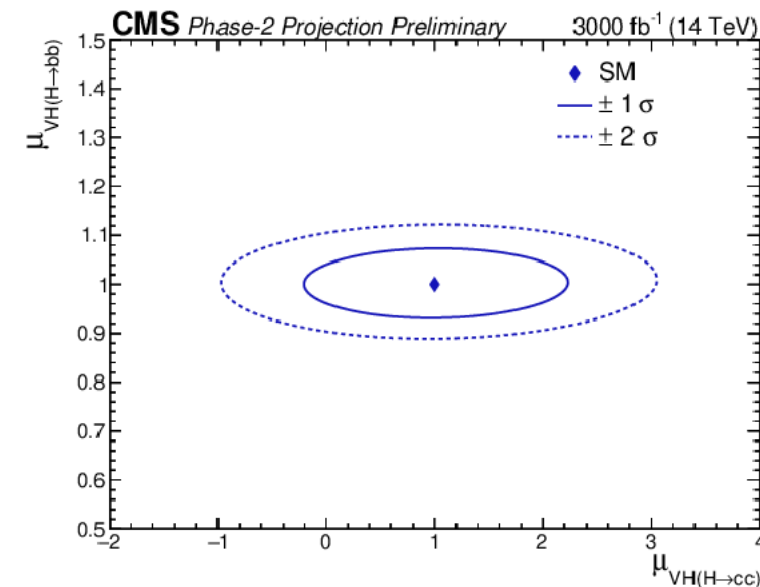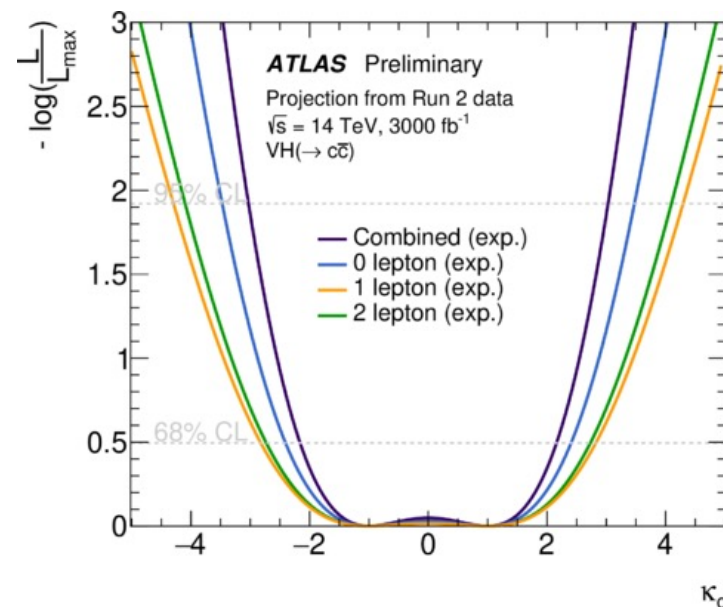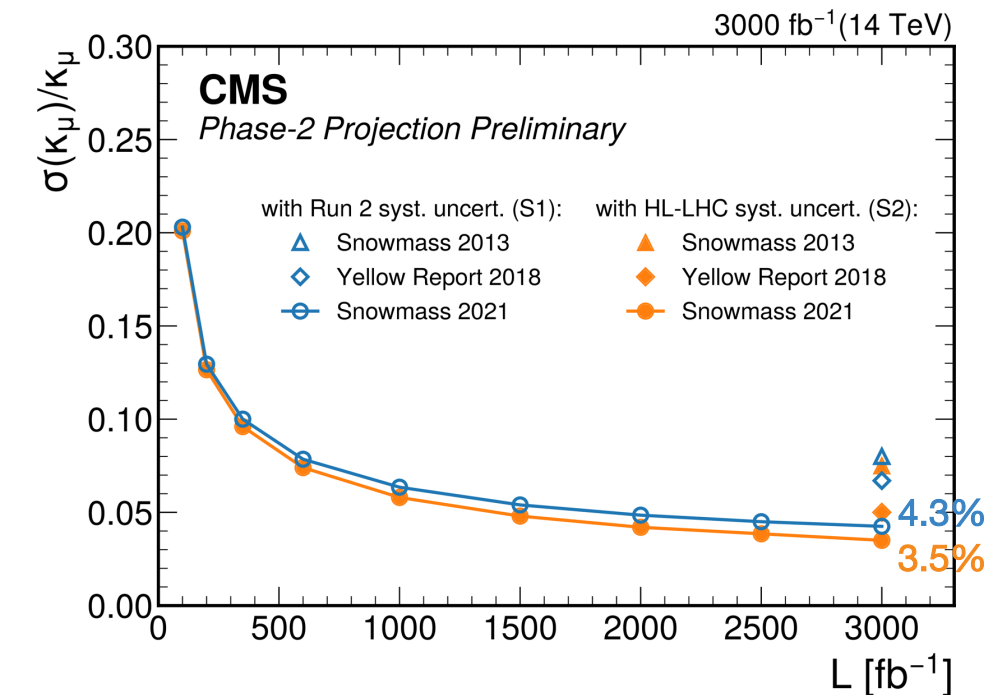
- CMS new **H → μμ** projection based on the Run 2 3σ evidence analysis
- Estimate increases in signal and background yields due to new detectors (larger muon η acceptance)
- Improvement over previous projection: ~ 30%

- Use VH production mode to probe **H(cc)** couplings
- Observation of Higgs coupling to charm will be difficult to achieve at the HL-LHC - new analysis techniques, such as the use of multivariate techniques and jet substructure variables, are making great progress in the right direction

HH @ HL-LHC
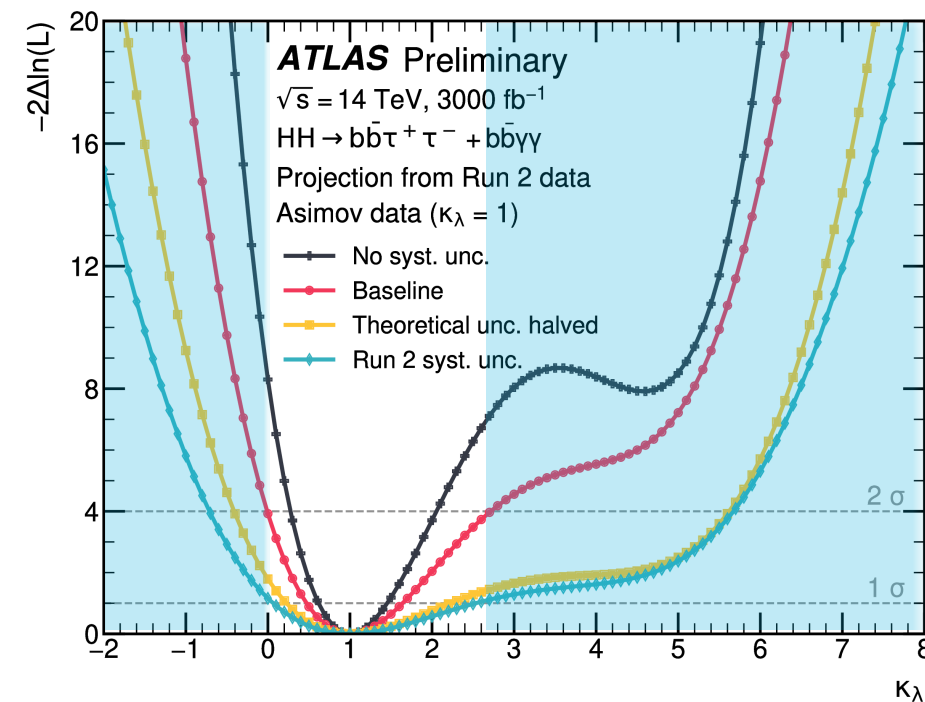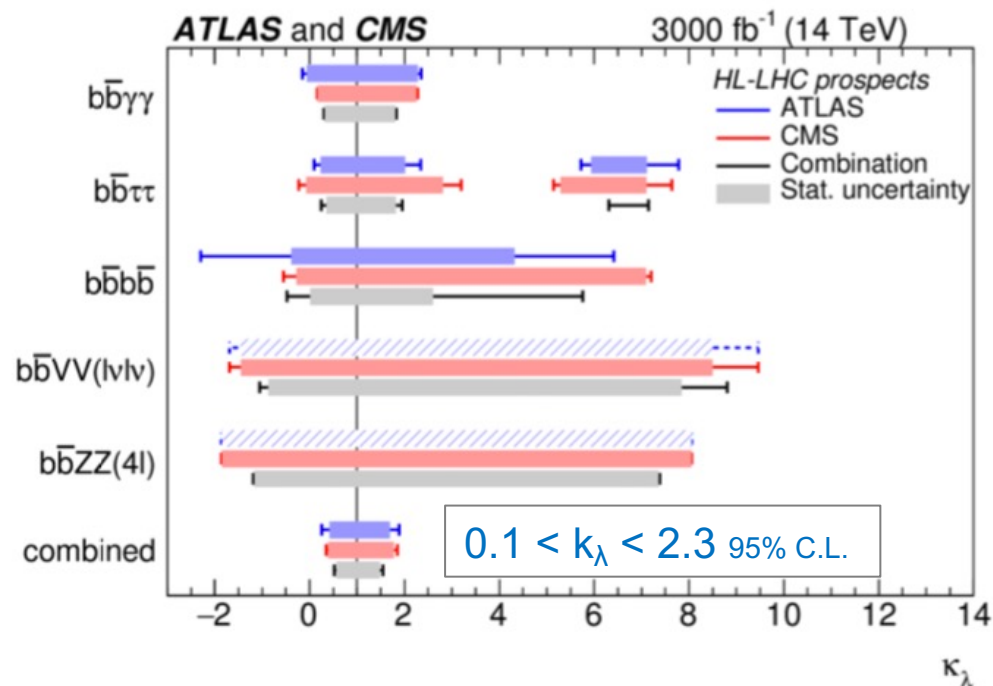
European Strategy (2019) :
- Combination of 5 HH channels, many based on partial Run 2 analysis strategy
- 50% precision on self-coupling
- **4σ SM HH significance** (ATLAS+CMS)

Snowmass update (2022) :
- ATLAS γγbb+bbττ combination: 3.2σ
- CMS updated γγbb results, added γγWW, γγττ, ttHH(bbbb)
- **5σ SM HH significance** from back-of-the-envelope combination
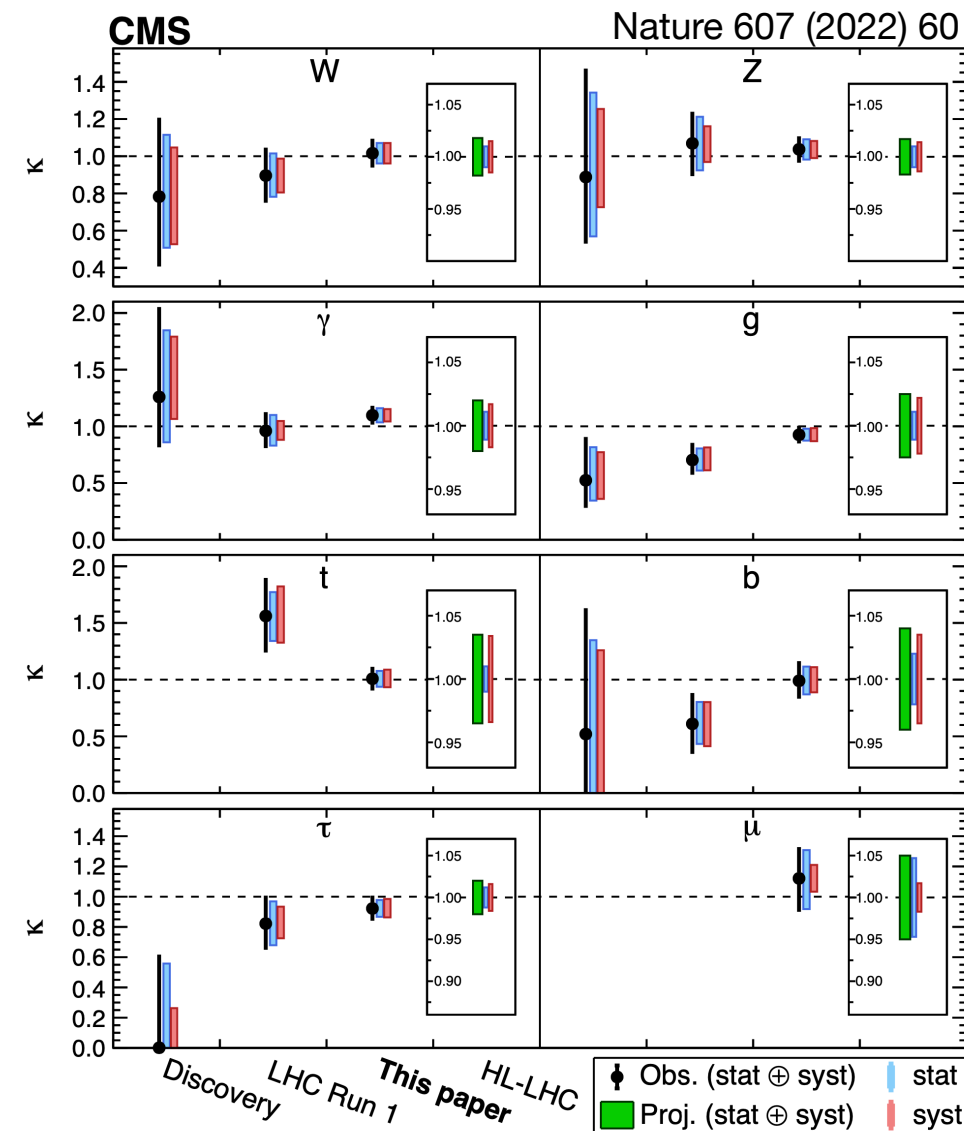
Summary

- **The Higgs measurements have entered a precision era at LHC**

- **Many exciting results from ATLAS and CMS to understand Higgs boson properties**

- **No new physics yet, but great precision already being achieved**

  - **Run2 dataset is only <5% of the final HL-LHC integrate luminosity**

- **Stay tuned for more exciting results as we enter the LHC Run 3 era!**

CMS — Nature 607 (2022) 60

Thanks for your attention

More references at

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults