Overview of Higgs boson results

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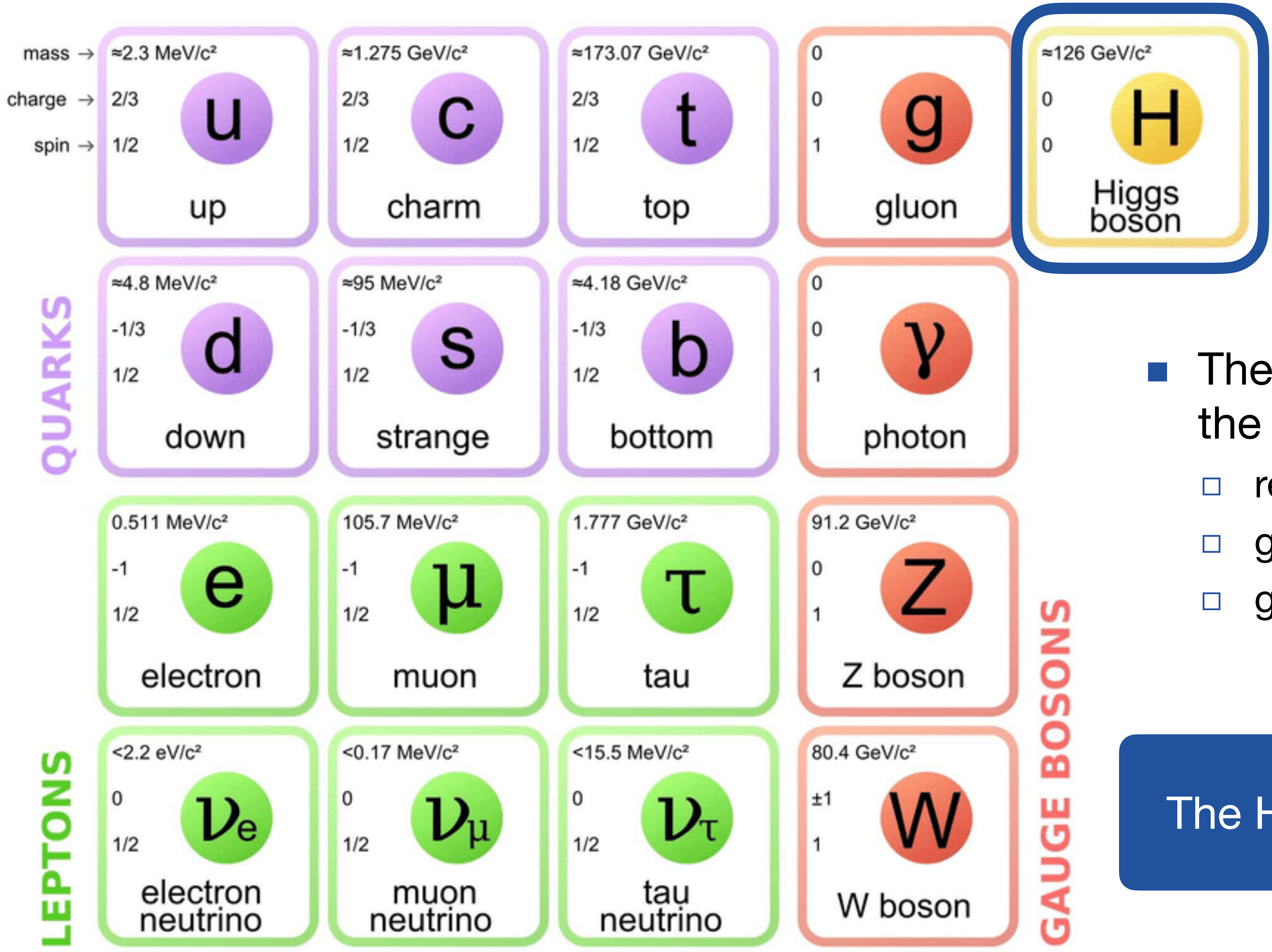
The Standard Model

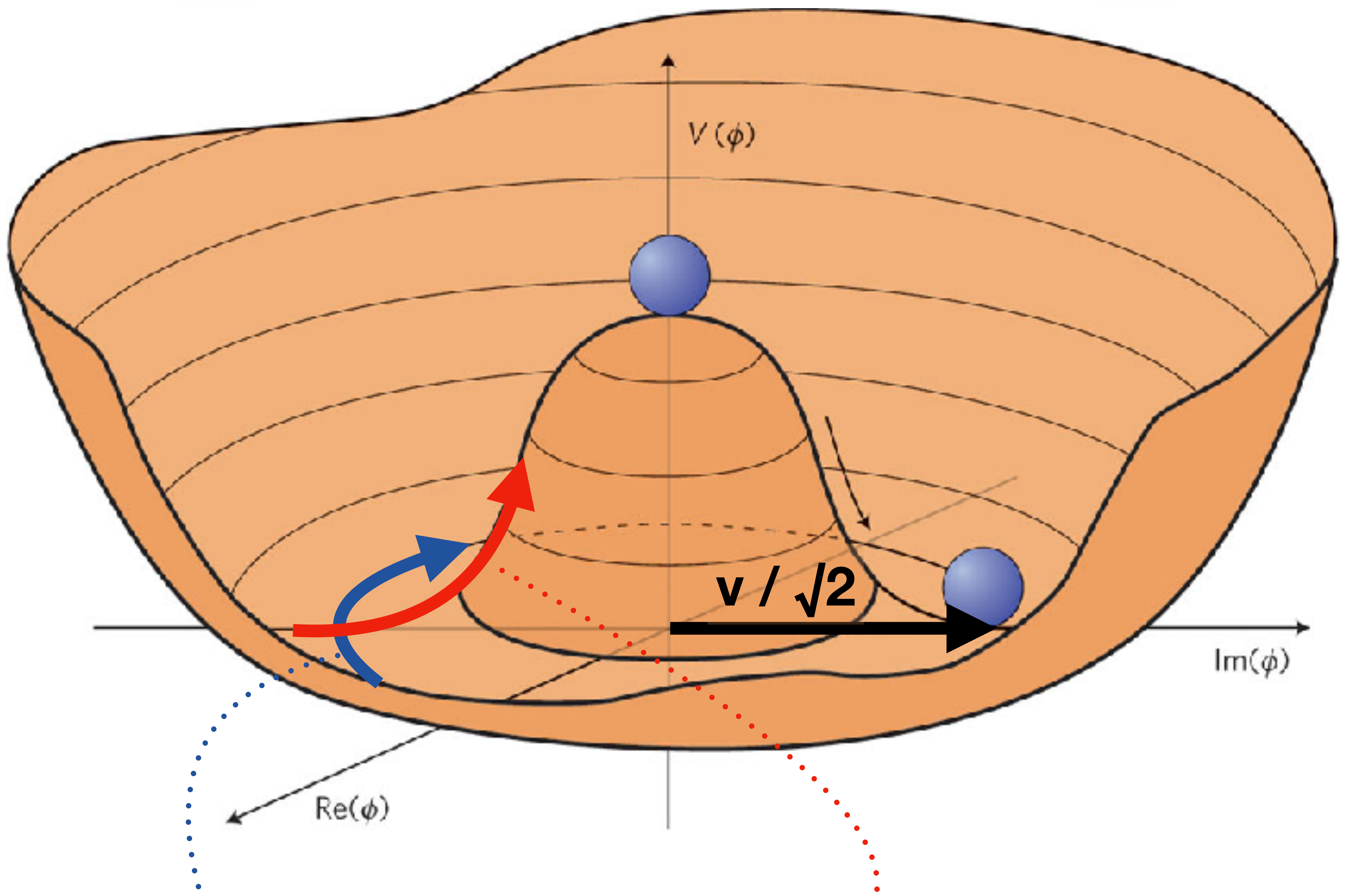


- The Higgs field is a necessary element of the SM
  - regularises the theory at the TeV scale
  - gives mass to all fermions
  - gives mass to W and Z bosons

The Higgs field is the cornerstone of the SM

The scalar sector of the standard model

$$V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$



Additional d.o.f.
⟹ **W and Z polarisation**

Quantum of the field
⟹ **Higgs boson**

$$m_H^2 = 2\lambda v^2 = 2\mu^2$$

- **Gauge sector:** electroweak and strong interactions explained with local gauge symmetries : SU(3) × SU(2) × U(1)
- **Scalar sector:** complex scalar doublet of fields subject to potential with VEV ≠ 0
- Spontaneous electroweak symmetry breaking : **Brout-Englert-Higgs mechanism**
  - 3 of the 4 components of ϕ become the W and Z masses
  - the remaining component is the **Higgs field**
  - fermion masses via Yukawa interactions

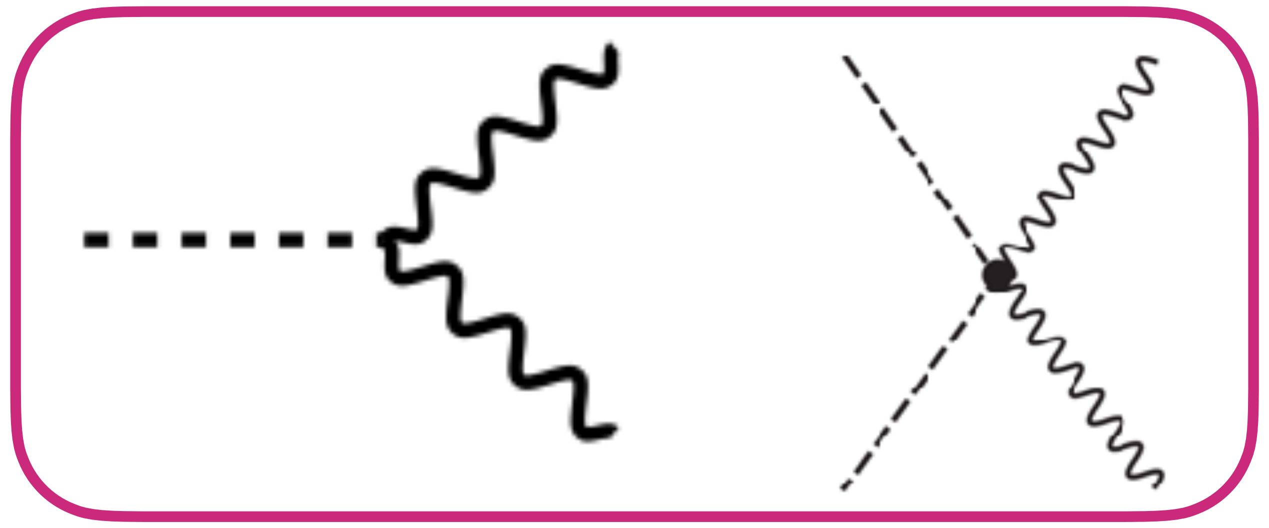
A unique type of mechanism in HEP

Higgs boson interactions

Higgs field
$m_H^2 = 2\lambda v^2 \rightarrow \lambda \approx 0.13$
since m_H ~ 125 GeV (Higgs obs.)
and v ~ 246 GeV (from G_F)

$$\mathcal{L}_{\mathrm{BEH}} = \frac{1}{2}\partial^\mu H \partial_\mu H - \frac{1}{2}\left(2\lambda v^2\right) H^2$$
$$+ \left[\left(\frac{gv}{2}\right)^2 W^{\mu+} W^-_\mu + \frac{1}{2}\frac{(g^2+g'^2)v^2}{4} Z^\mu Z_\mu\right]\left(1+\frac{H}{v}\right)^2$$
$$+ \lambda v H^3 + \frac{\lambda}{4} H^4 - \frac{\lambda}{4} v^4$$

Mass of W / Z
HWW, HZZ interactions,
strength $\propto m_V^2$

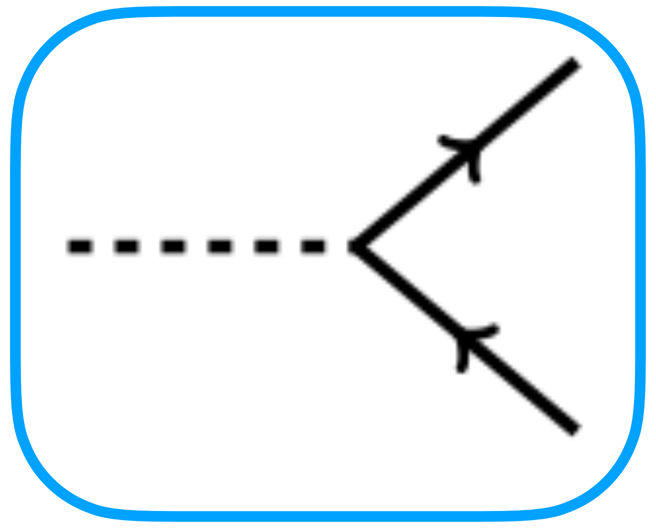


Cosmological constant. Note that this is 54 orders of magnitude larger than the upper bound from observations

Higgs boson self-interactions

$$\mathcal{L}_{\mathrm{Yukawa}} = -\sum_f m_f (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)\left(1+\frac{H}{v}\right)$$

Fermion masses
Hff interaction with strength $\propto m_f$

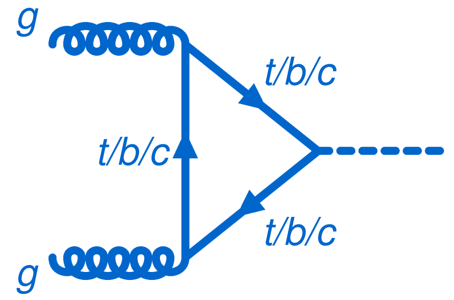


We need a precise measurement of all these interactions to characterise the Higgs boson

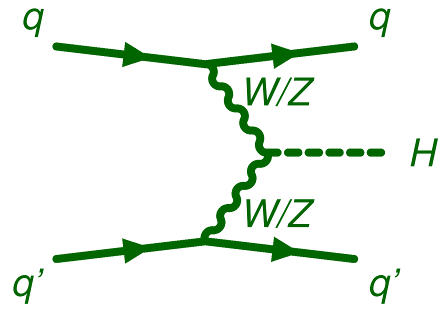
Higgs boson phenomenology

Smaller cross section

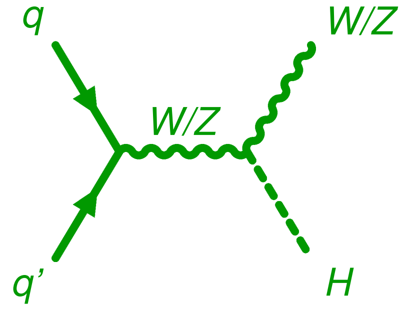
ggF
49 pb (86%)



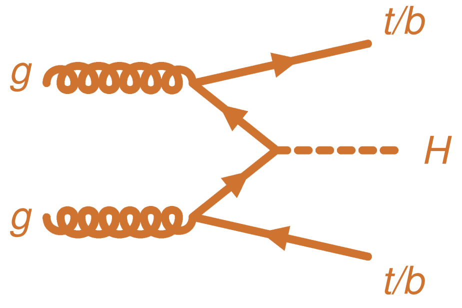
VBF
3.8 pb (6.5%)



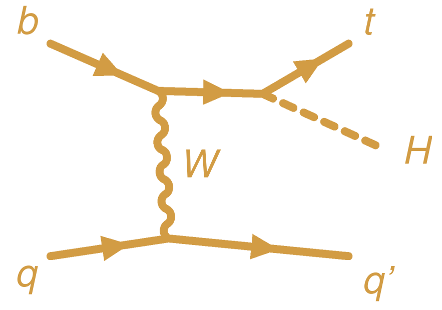
VH
2.3 pb (4%)



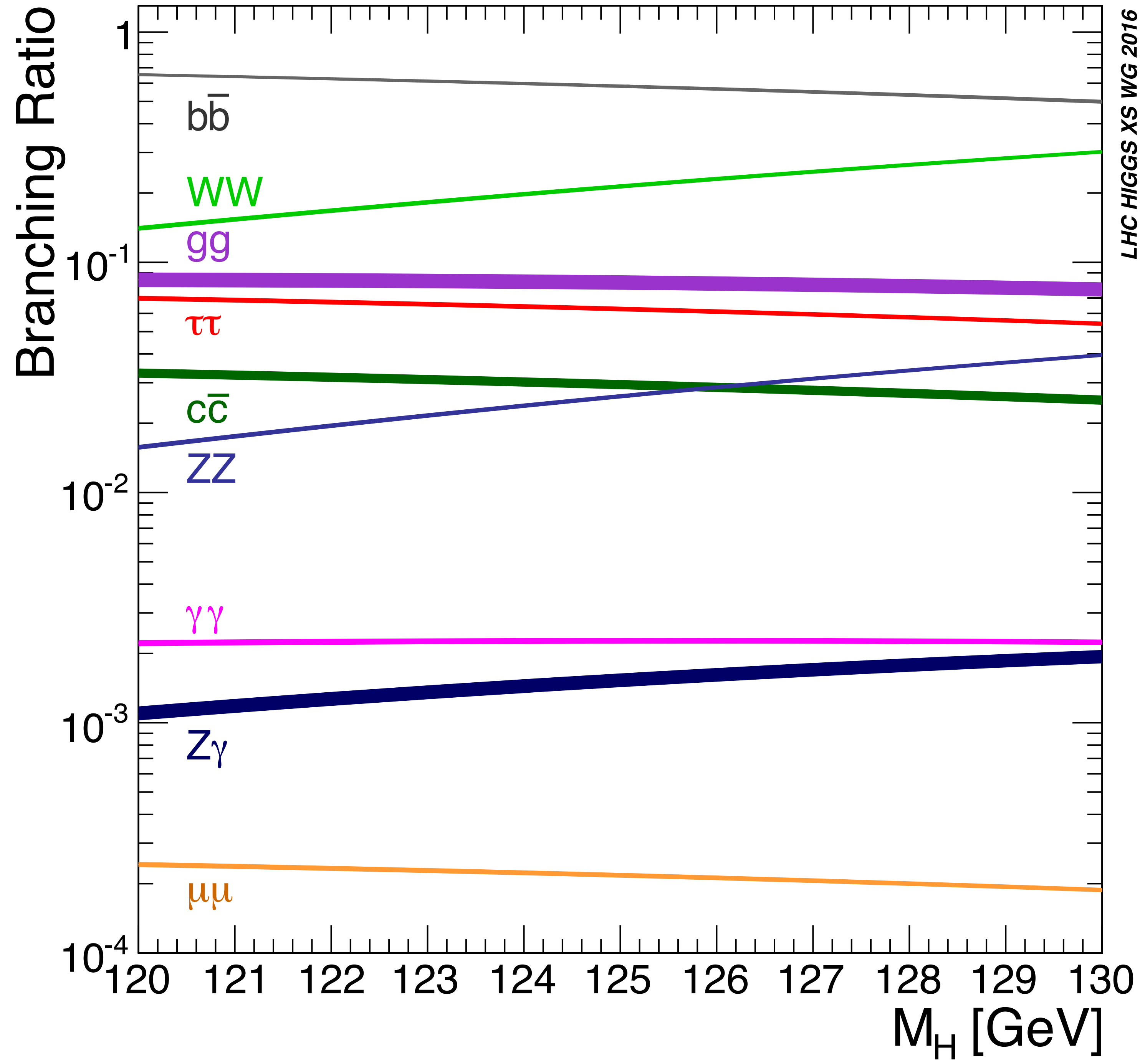
ttH
0.5 pb (1%)

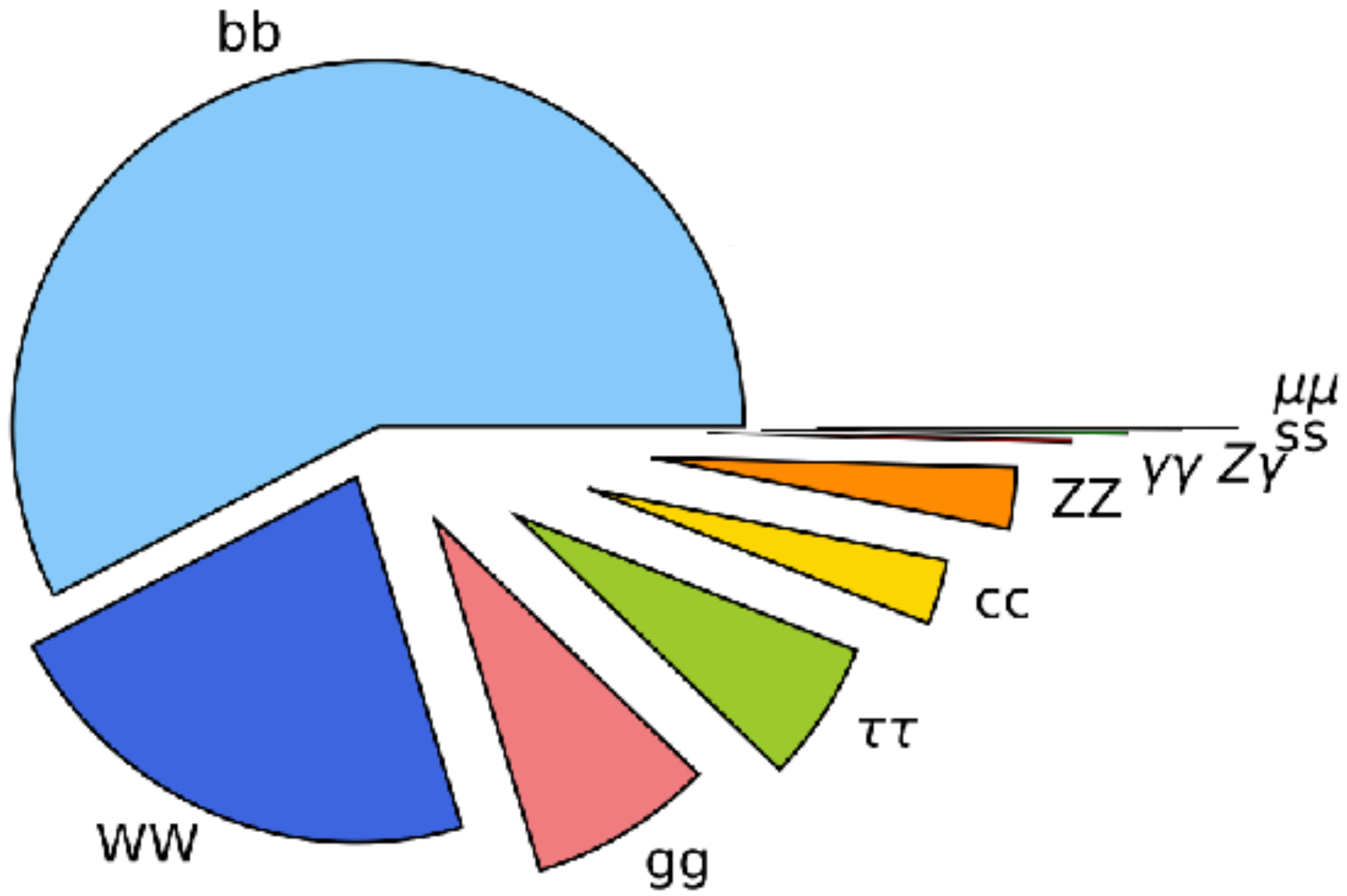


tH
0.5 pb (1%)



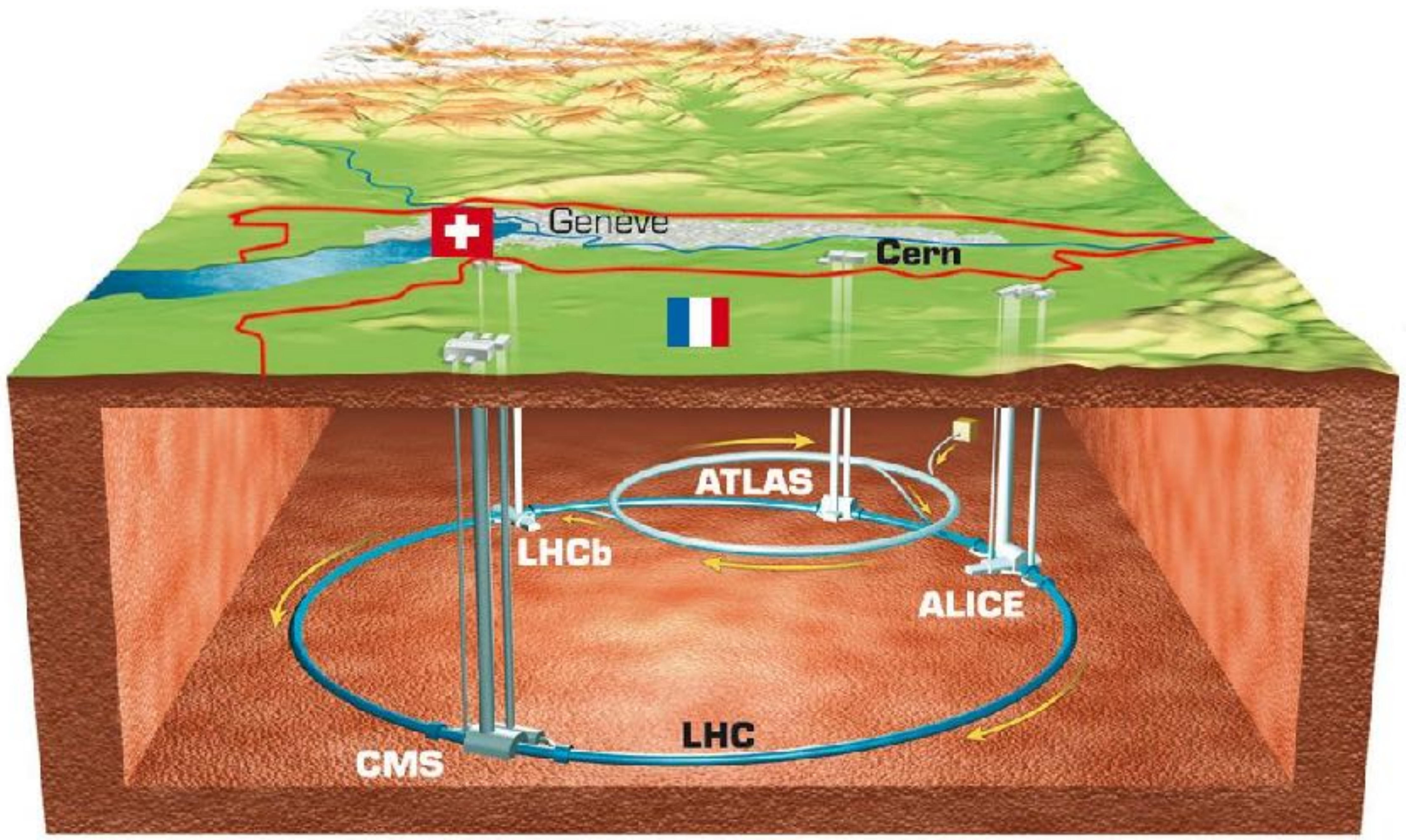
Production mode
xs @ 13 TeV (% of total)

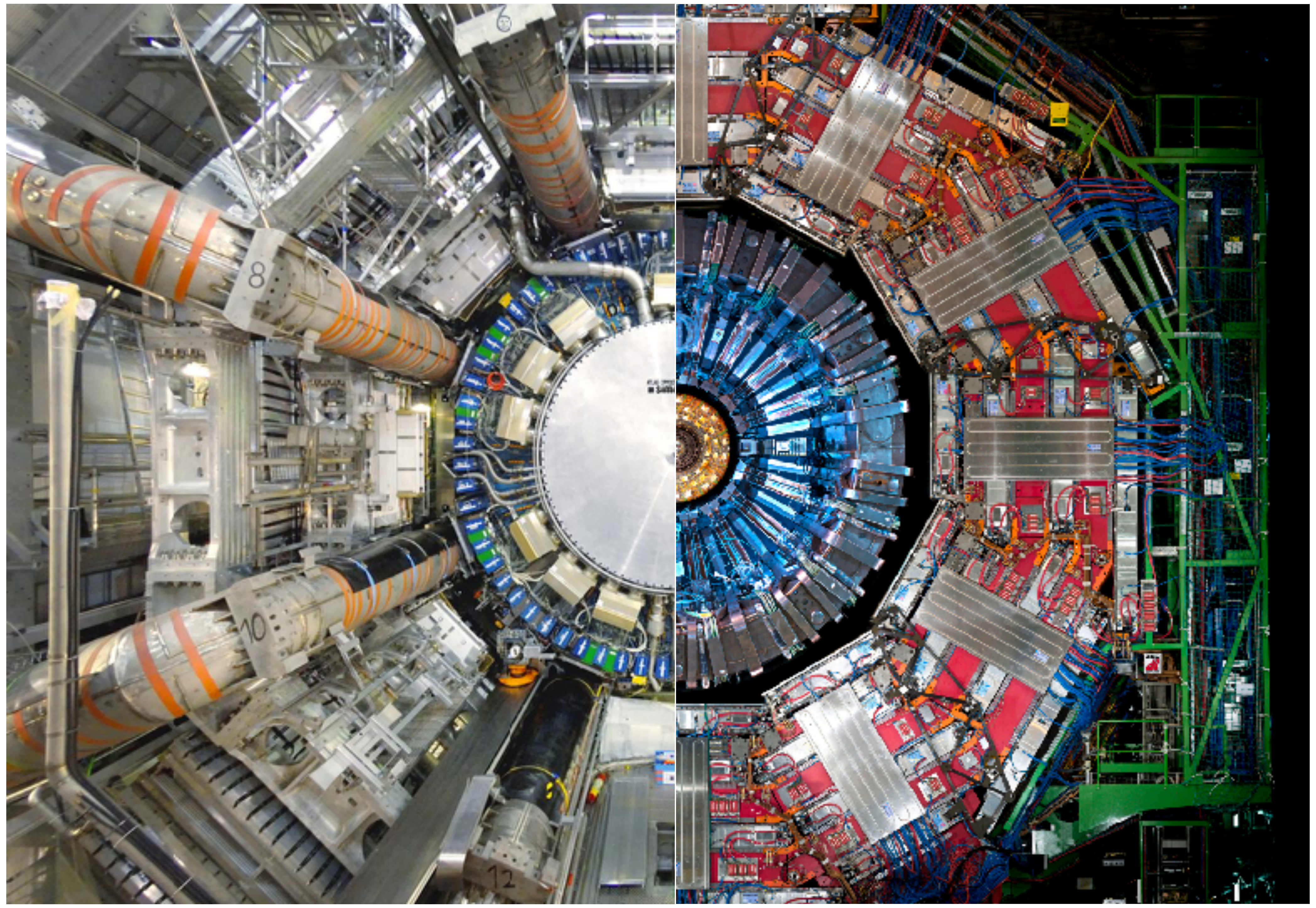




We can access a variety of production and decay modes spanning few orders of magnitude

LHC and the ATLAS and CMS experiments

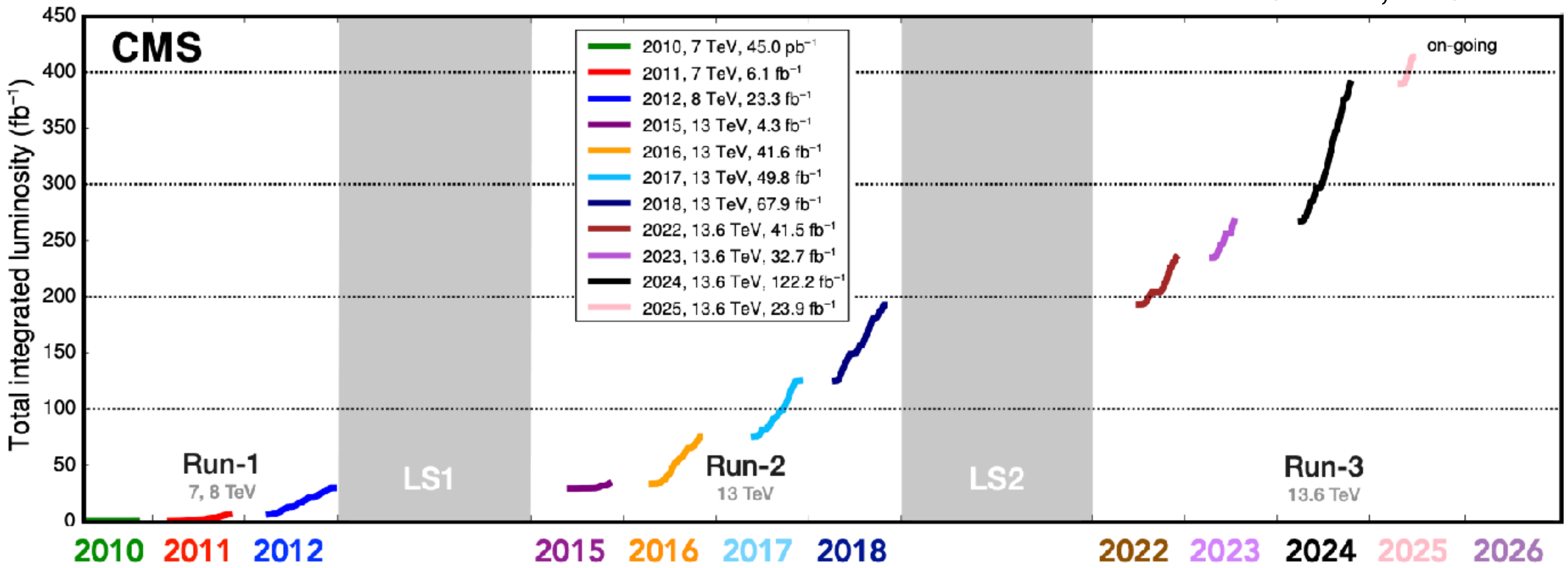




- The CERN LHC is designed to deliver pp collisions at $\sqrt{s}$ = 14 TeV and $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- ATLAS and CMS are the two general purpose, nearly hermetic detectors, designed to trigger, identify and measure the particles produced in collisions occurring every 25 ns

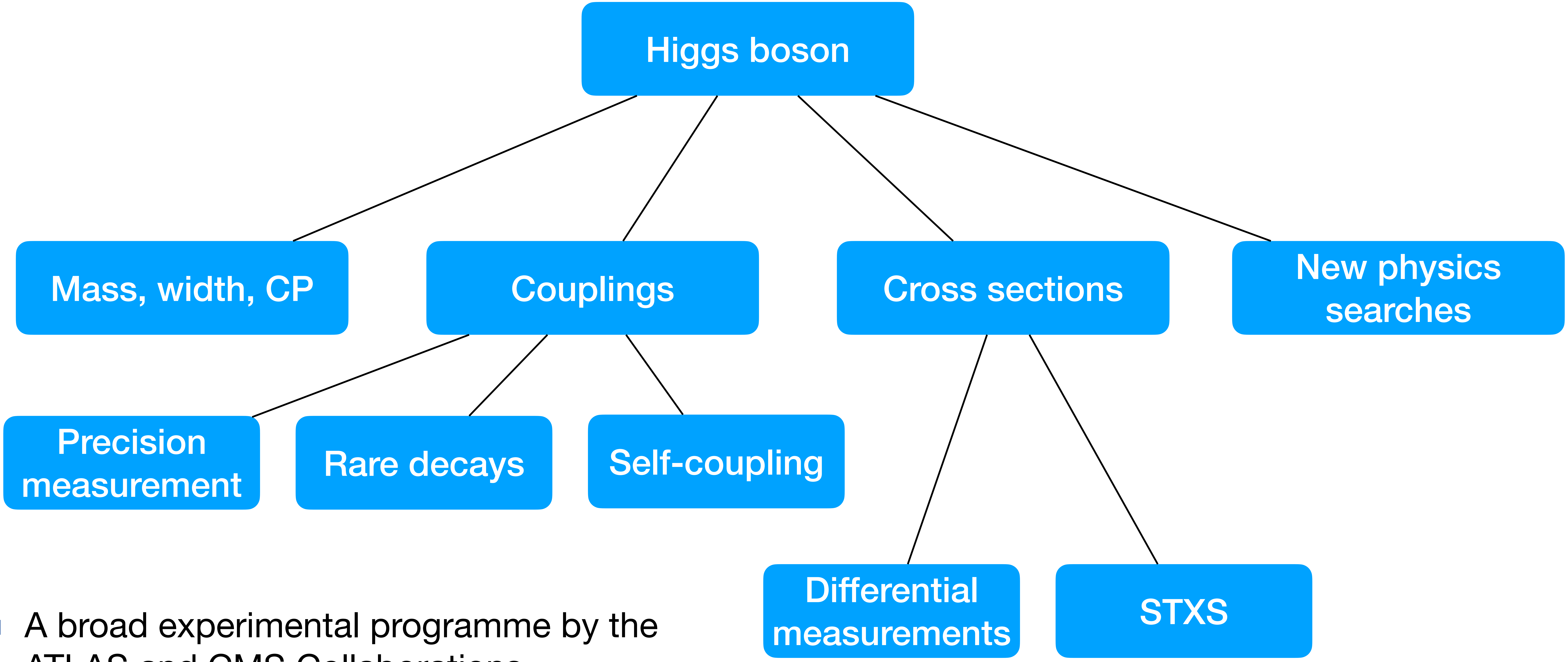
LHC operations

R. Salerno, EPS 2025



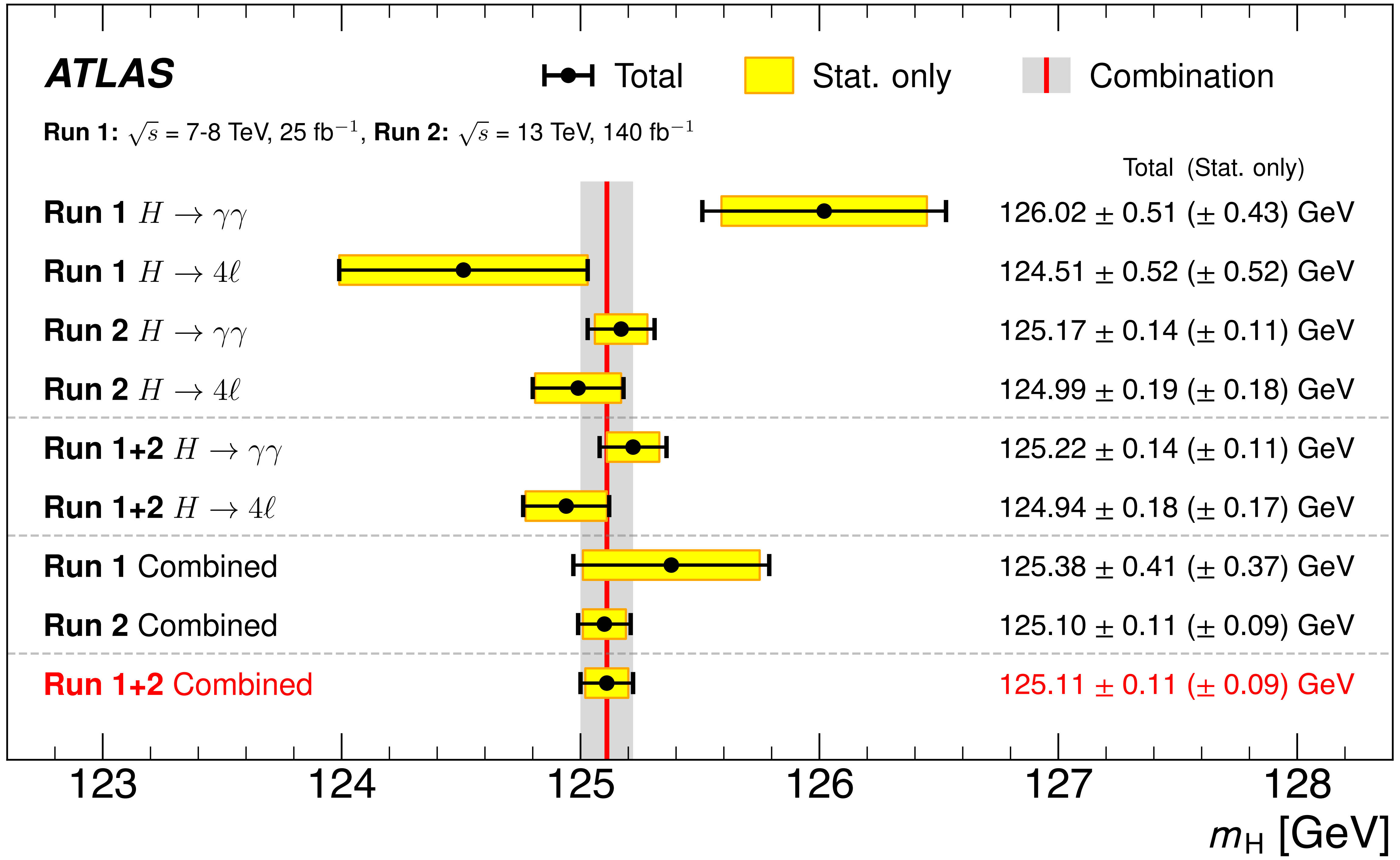
	Higgs boson discovery	Observation of main production and decay modes	Precise Higgs boson characterization
Cumulative nr of Higgs bosons produced in each exp.	*~650 k*	*~8.5 millions*	*~29 millions*

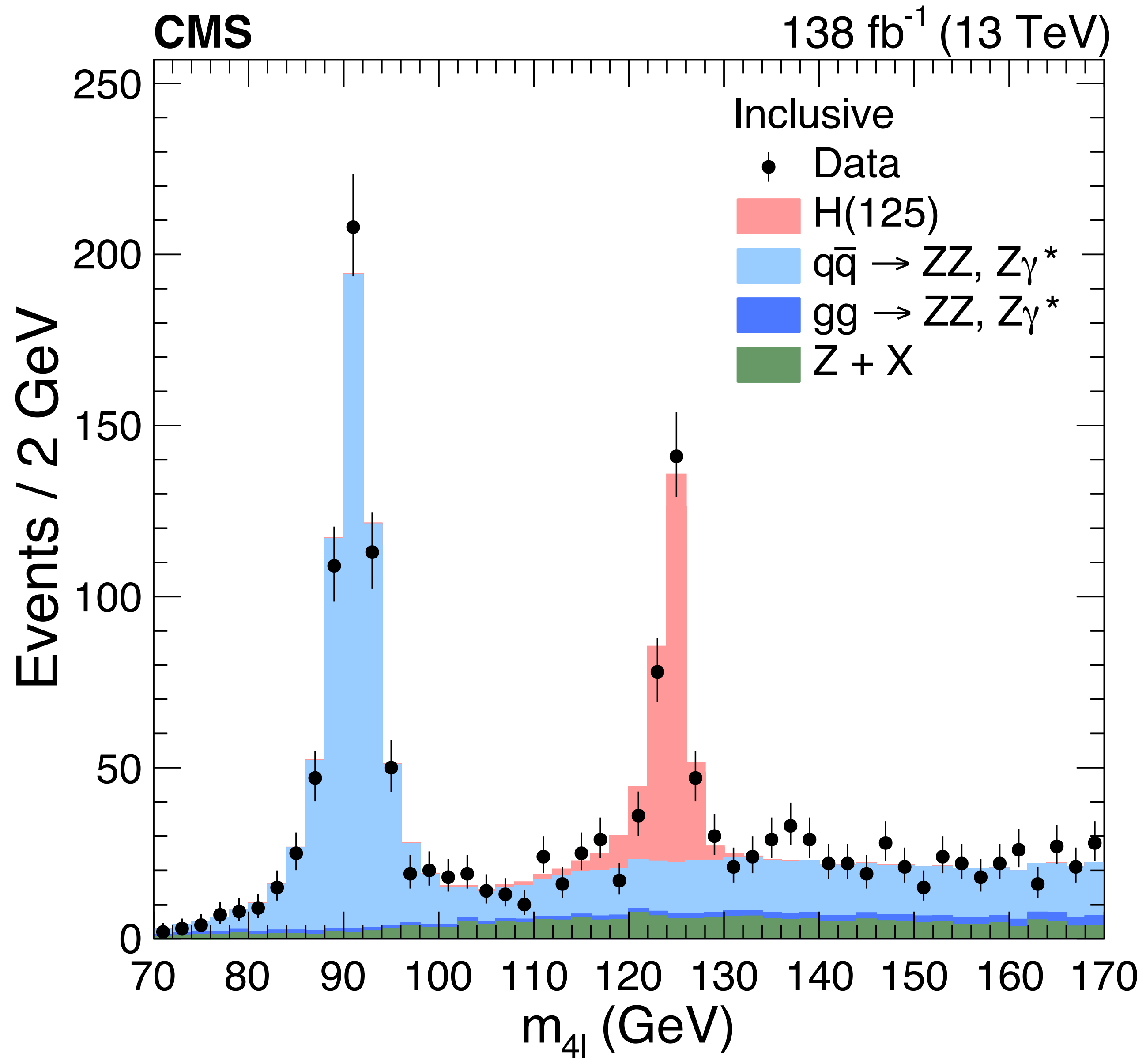
Characterising the Higgs boson

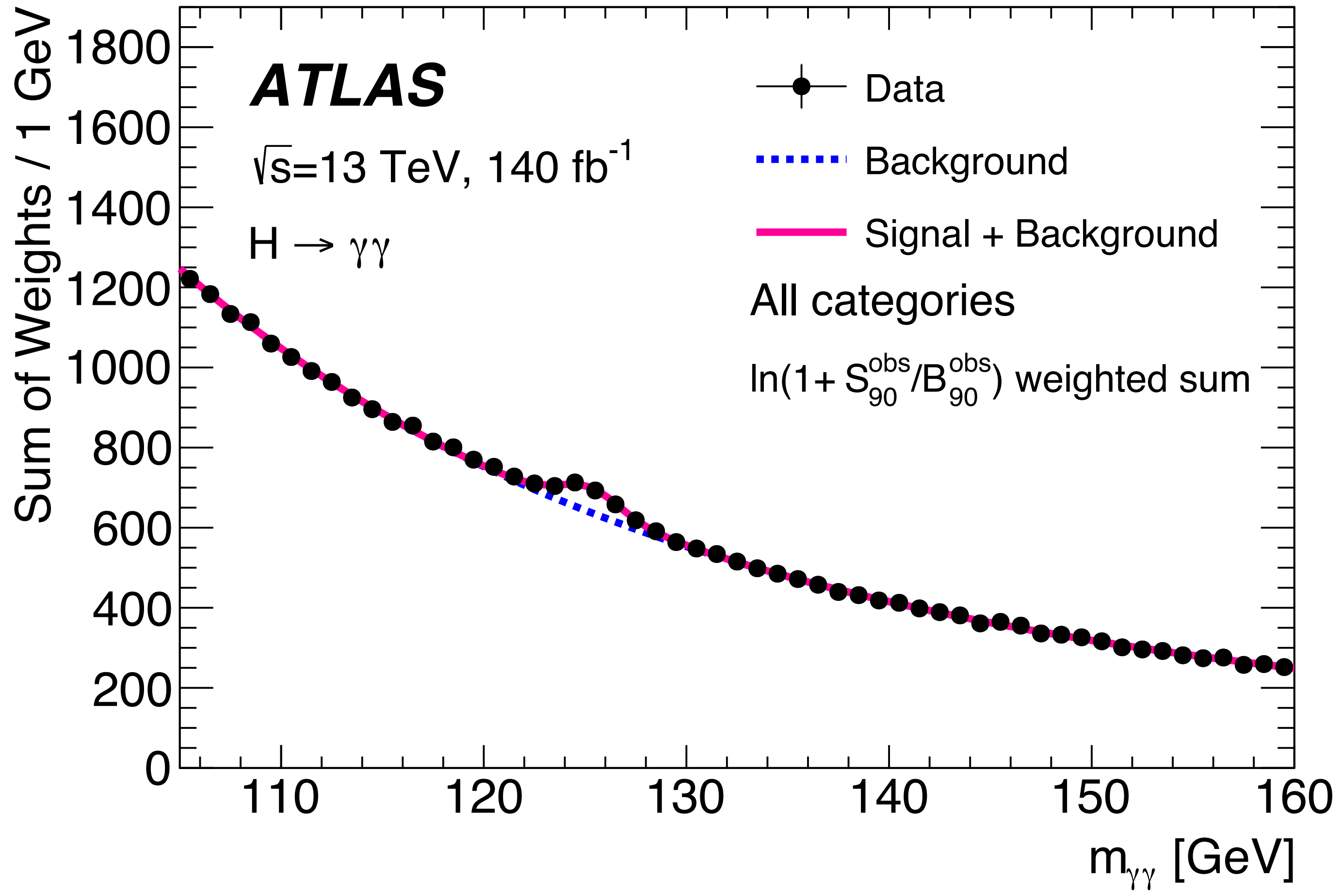


- A broad experimental programme by the ATLAS and CMS Collaborations

Mass measurement





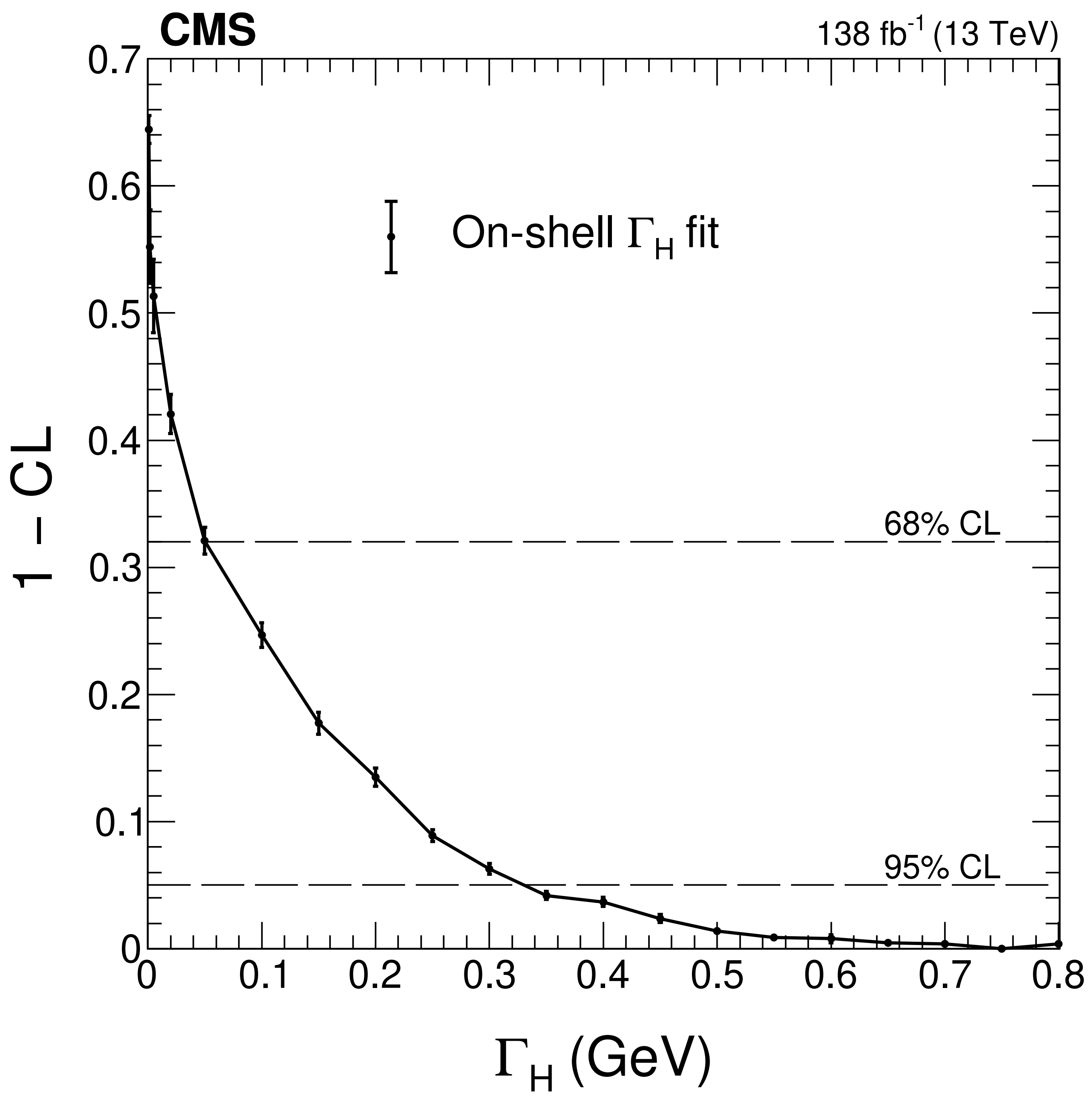


- High resolution H→ZZ→4ℓ and H→γγ channels
- Relies on the excellent detector performance in lepton/photon energy scale determination and calibration

Higgs mass measured with a precision below 1 per mille

Higgs boson width

Lineshape fit from H→ZZ→4ℓ



Γ_SM (H) = 4.07 MeV

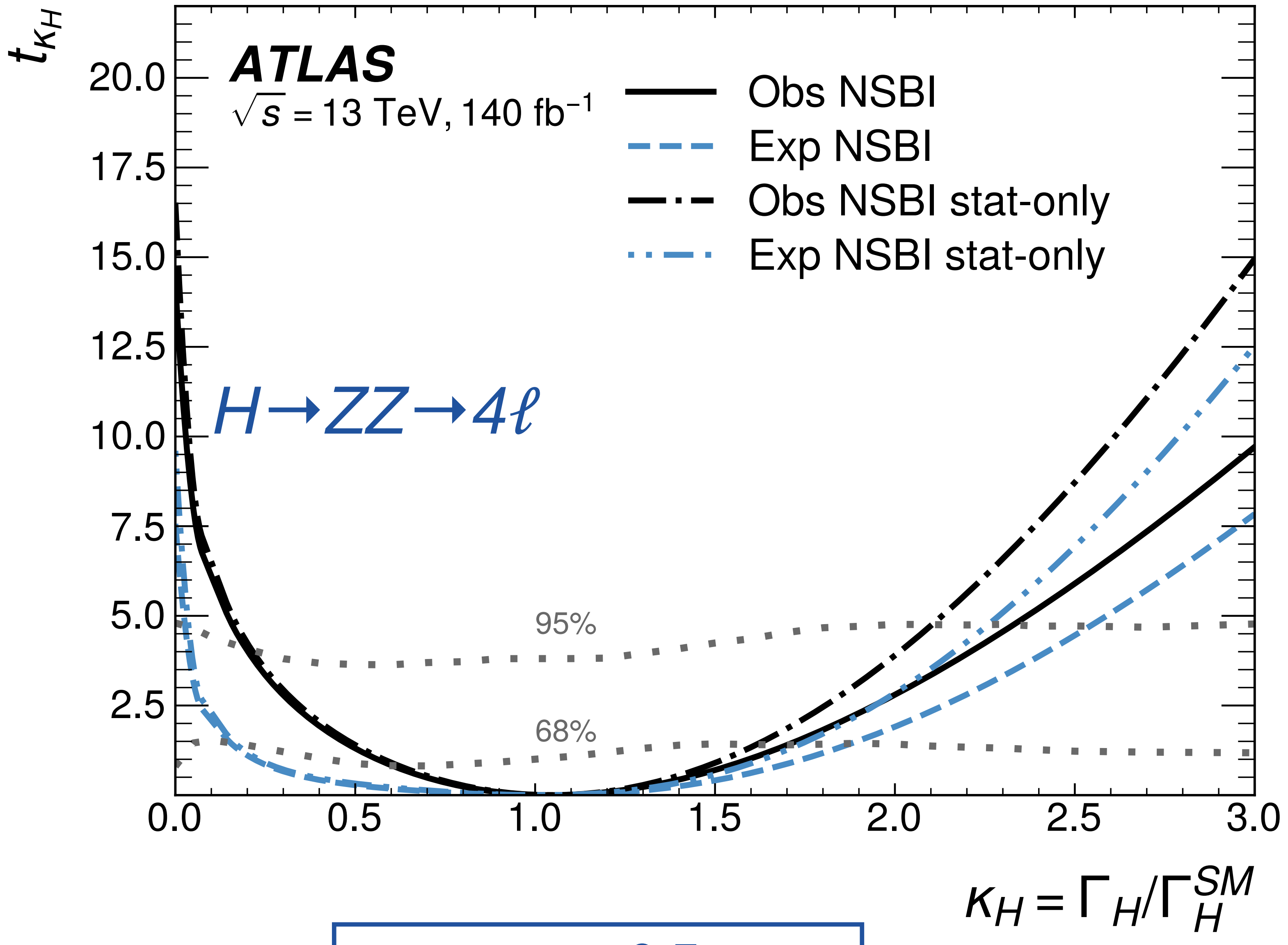
Direct determination from resonance lineshape is limited by detector resolution

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

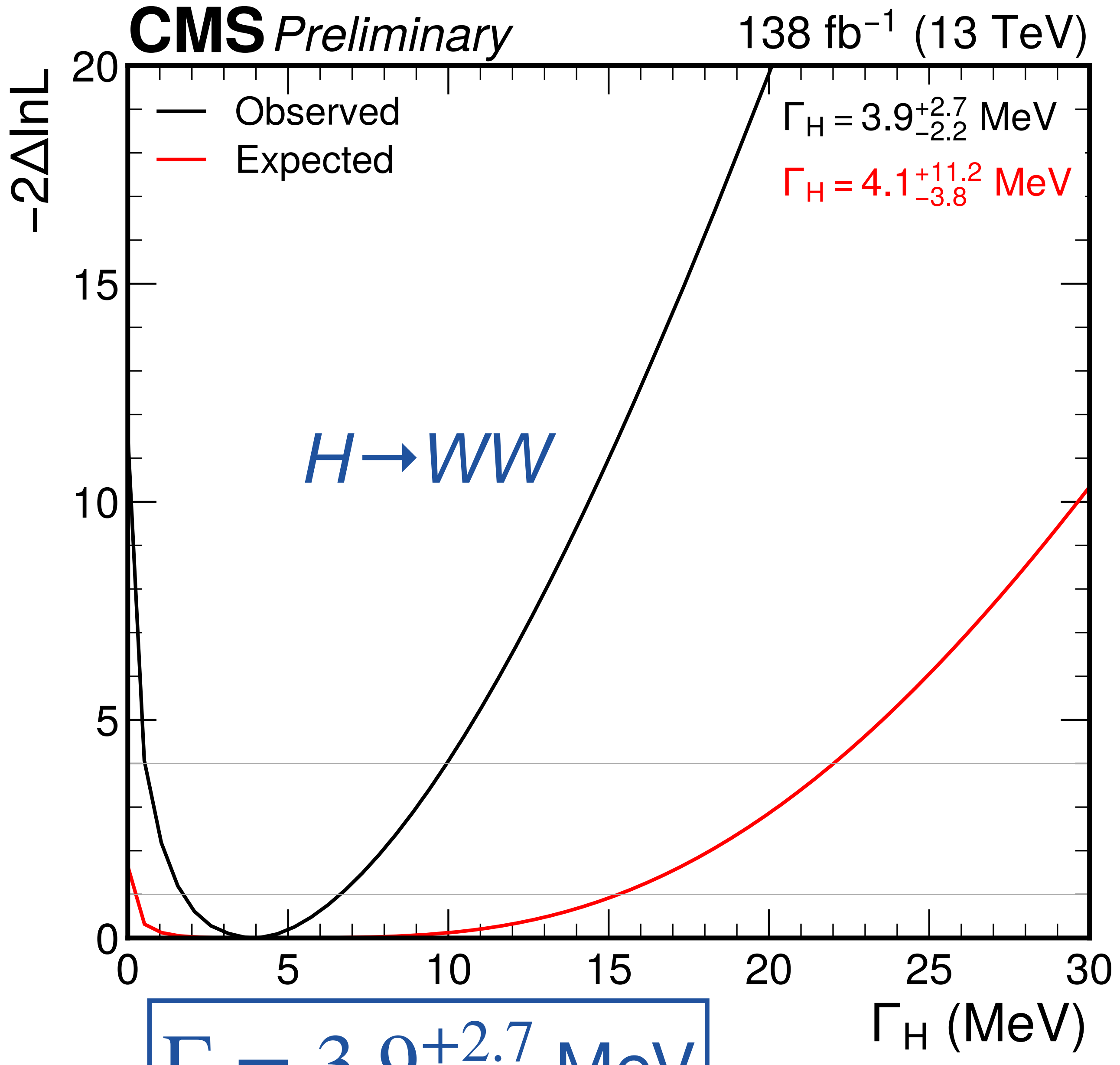
$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$

Determination from off-shell vs on-shell production possible with much larger precision

Done in H→ZZ→4ℓ, H→WW and in ttH/tttt combination (off-shell ttH(tt))*



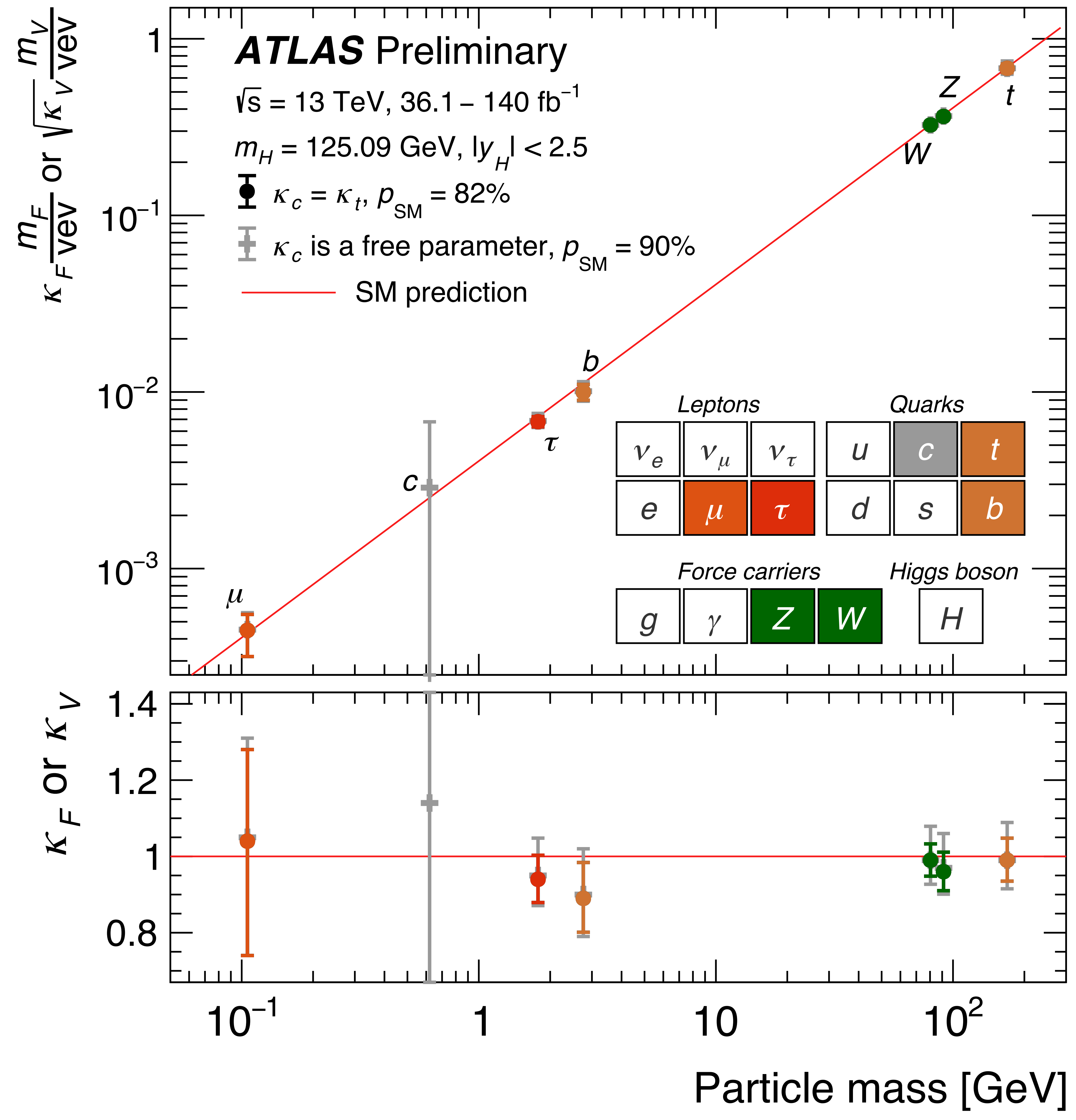
$\Gamma = 4.3^{+2.7}_{-1.9}$ MeV



$\Gamma = 3.9^{+2.7}_{-2.2}$ MeV

Higgs width measured with ~50% precision

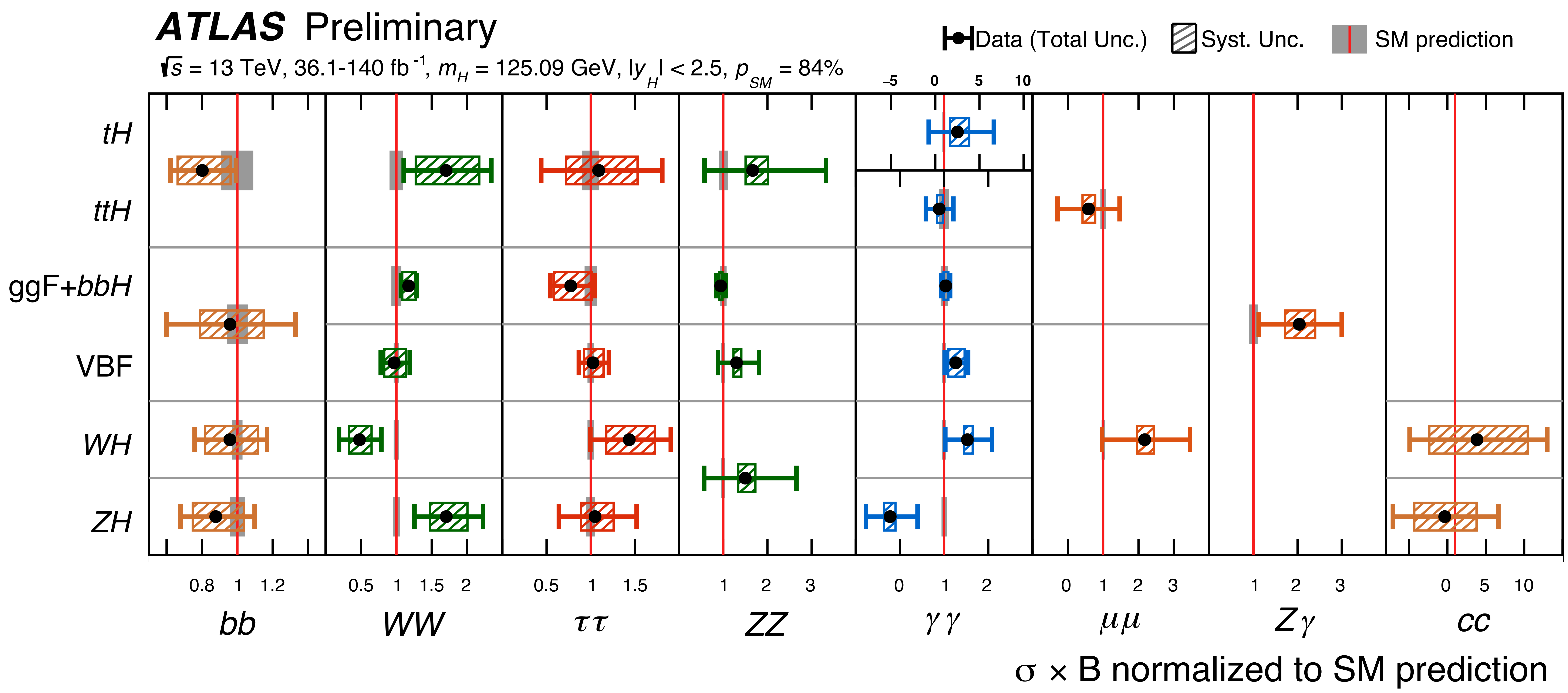
Higgs boson in action



- Couplings to weak bosons and 3rd generation firmly established
  - test EWSB
  - test Yukawa interactions
- Starting to approach the second generation

We have established the quantum-relativistic nature of the mass of fundamental particles

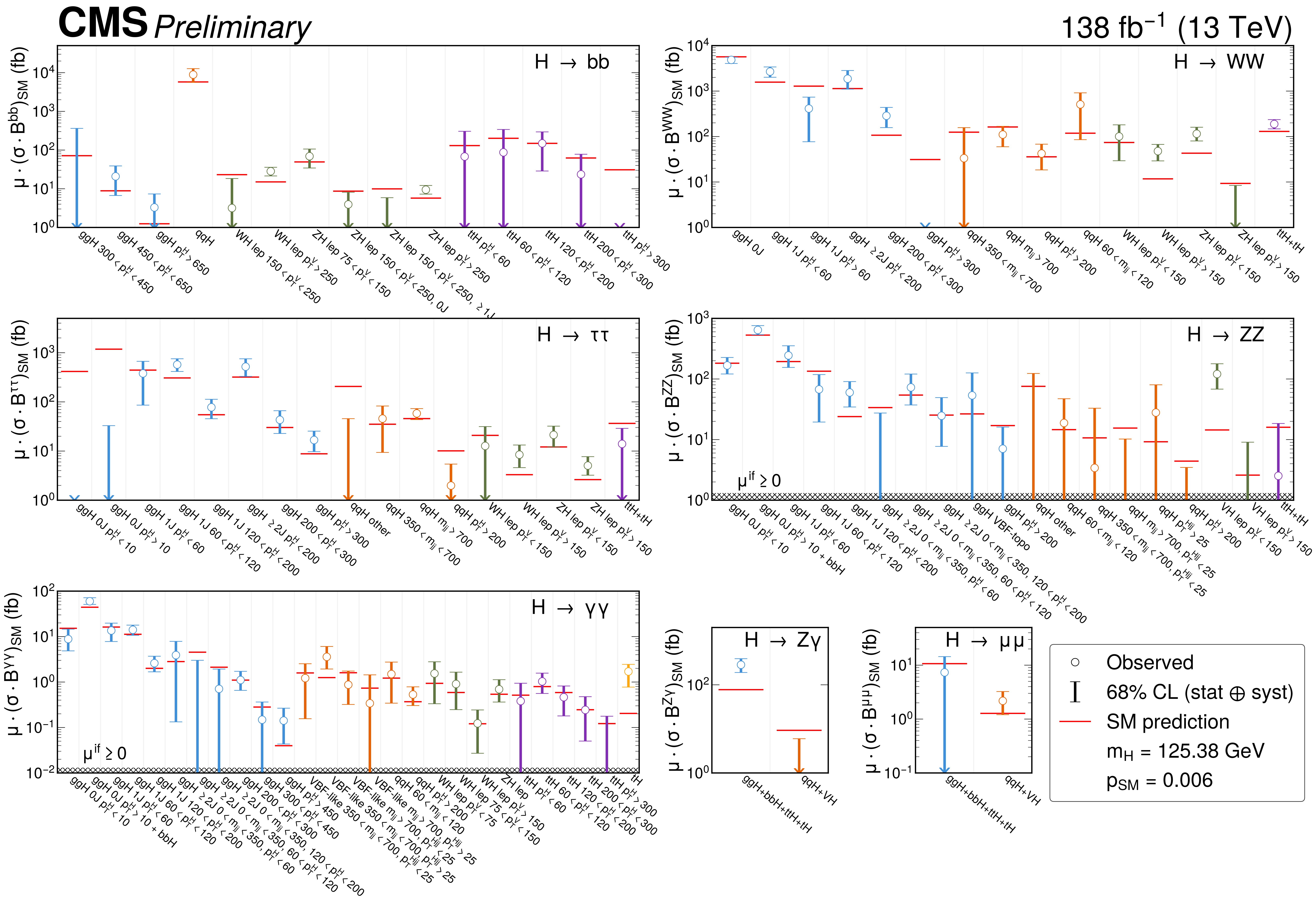
Completely charting production and decay …



- Charting individual production and decay modes
- All measurements in agreement with the SM

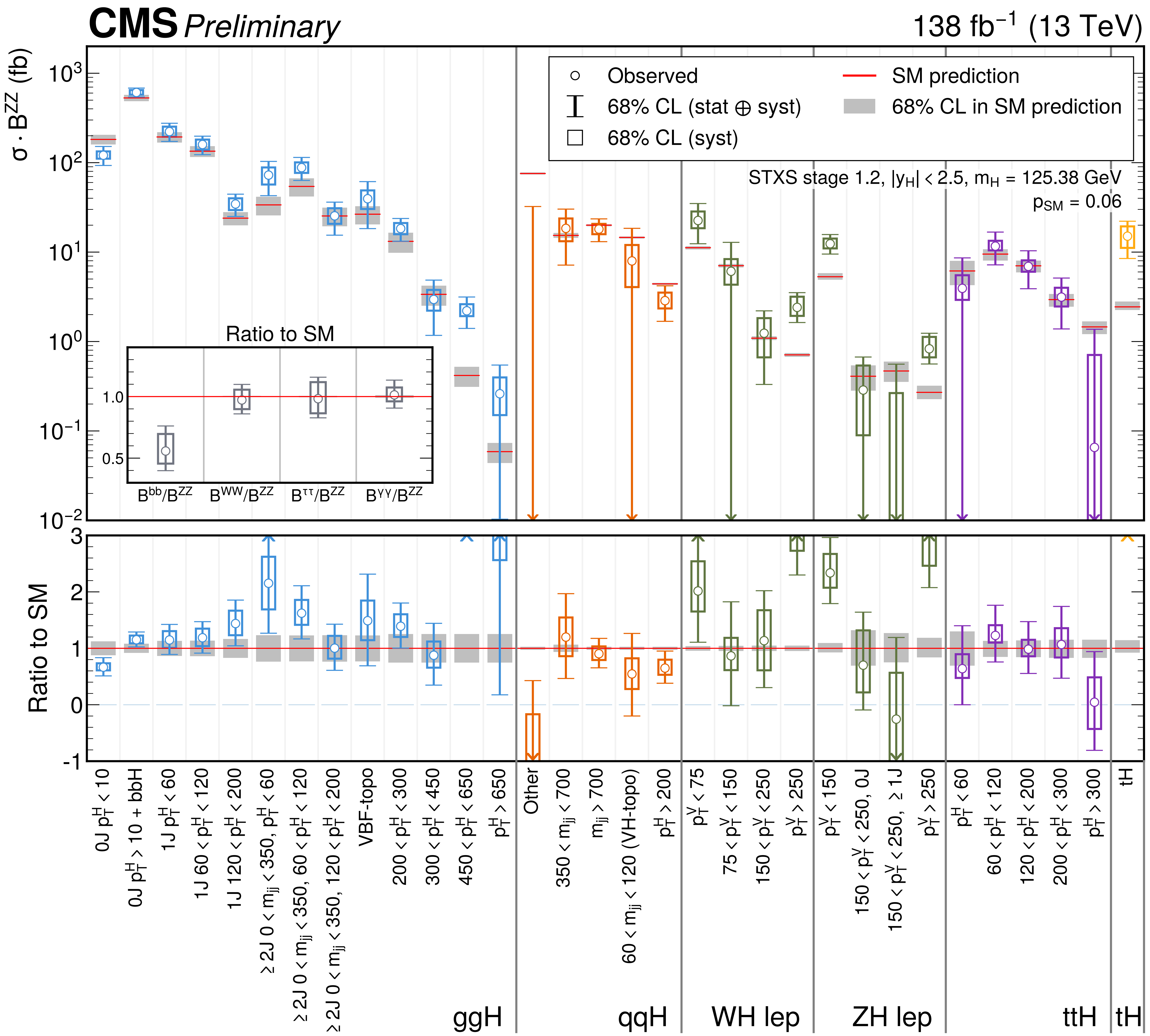
… to an amazing level of granularity

- Further splitting the different production and decay modes by the kinematics
- 97 different signal strengths measured!



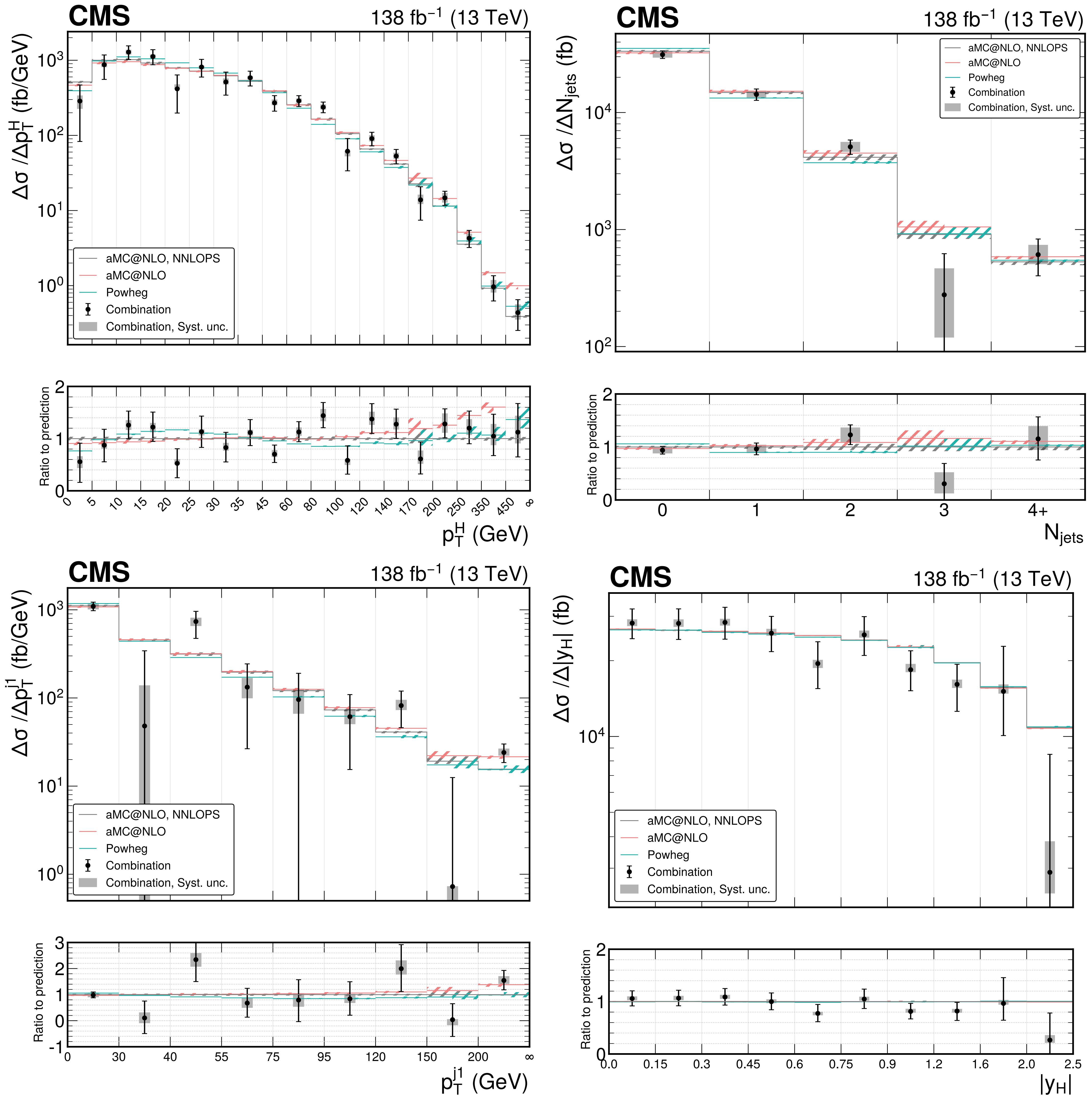
Simplified template cross sections

- Detector response and reconstruction different depending on the decay channels → difficult to simultaneously exploit (requires unfolding, some incompletely reconstructed final states, ..)
- Use Simplified Template Cross Sections (STXS) as cross section in specific regions of the production phase space



Precise combined characterization of the Higgs boson over a broad kinematic regime

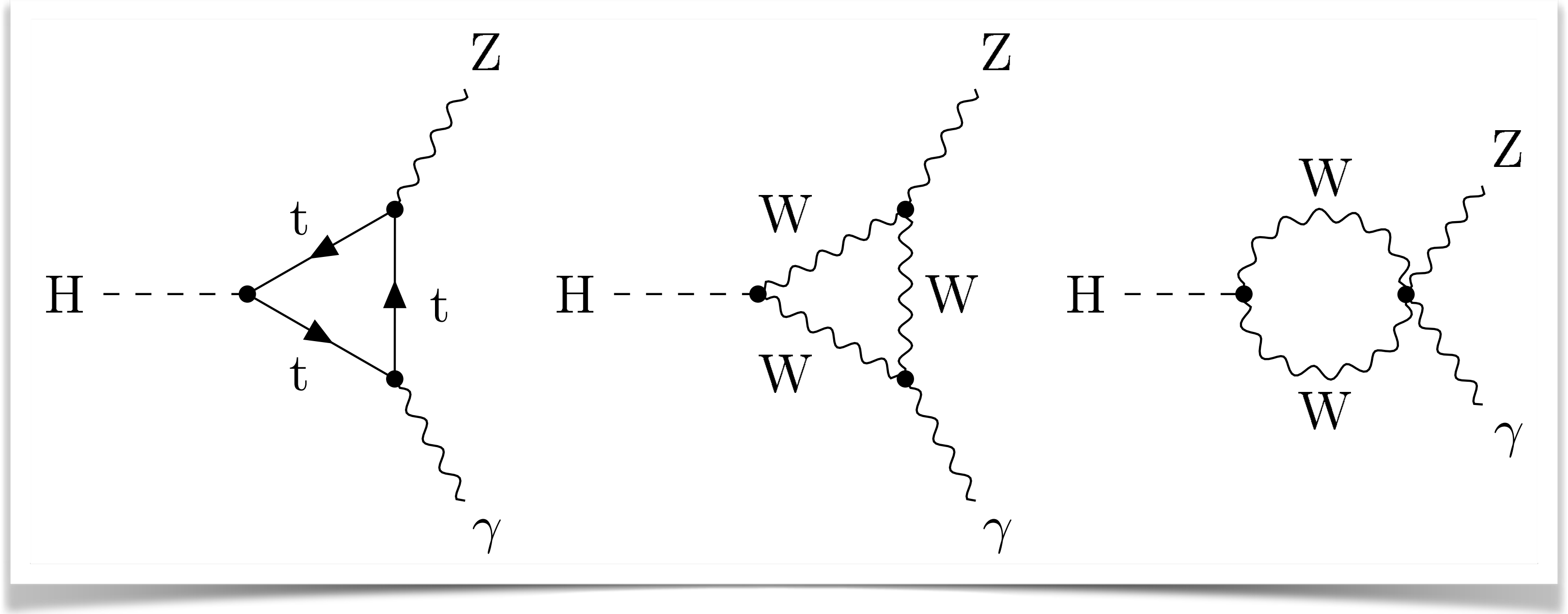
Differential measurements

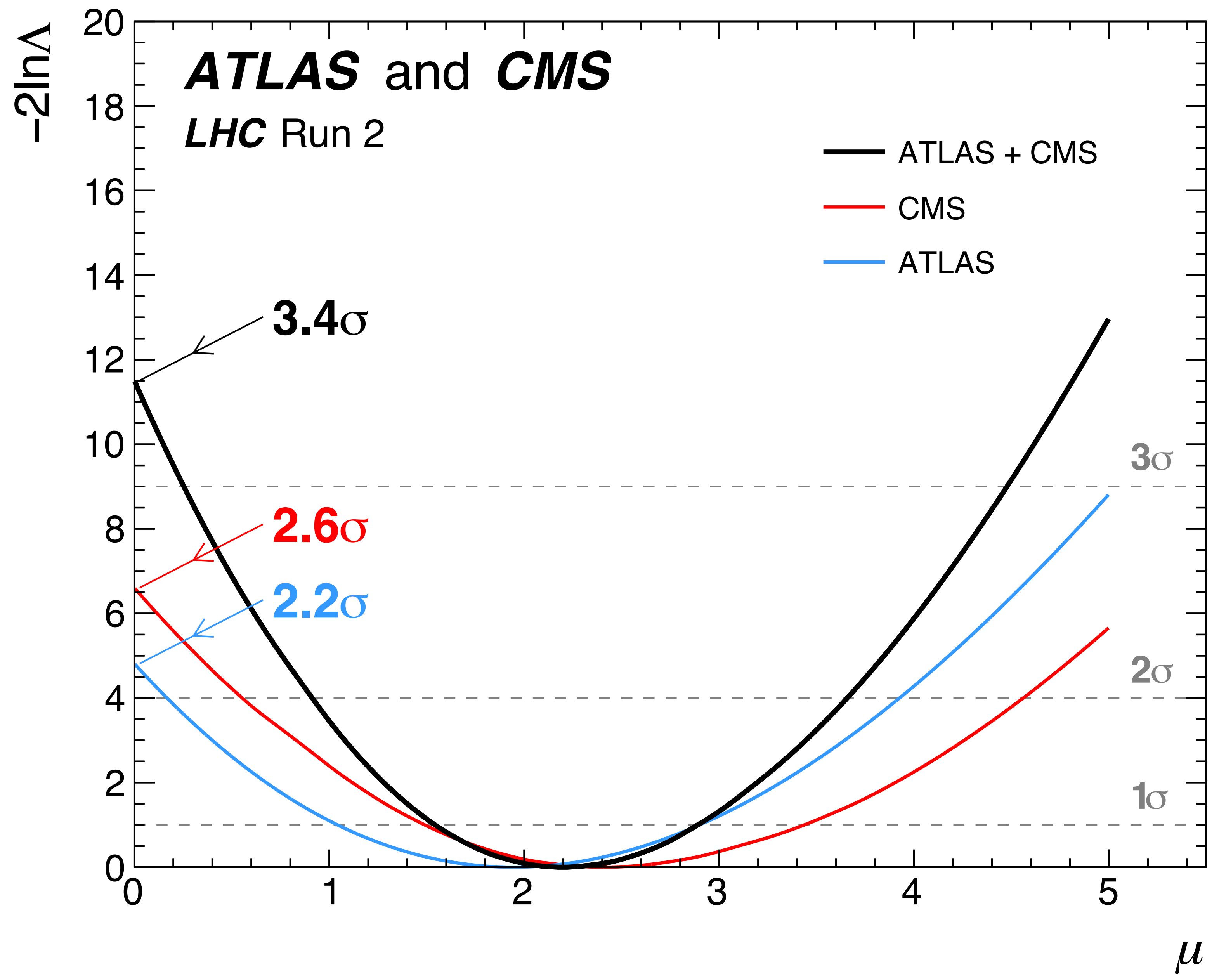


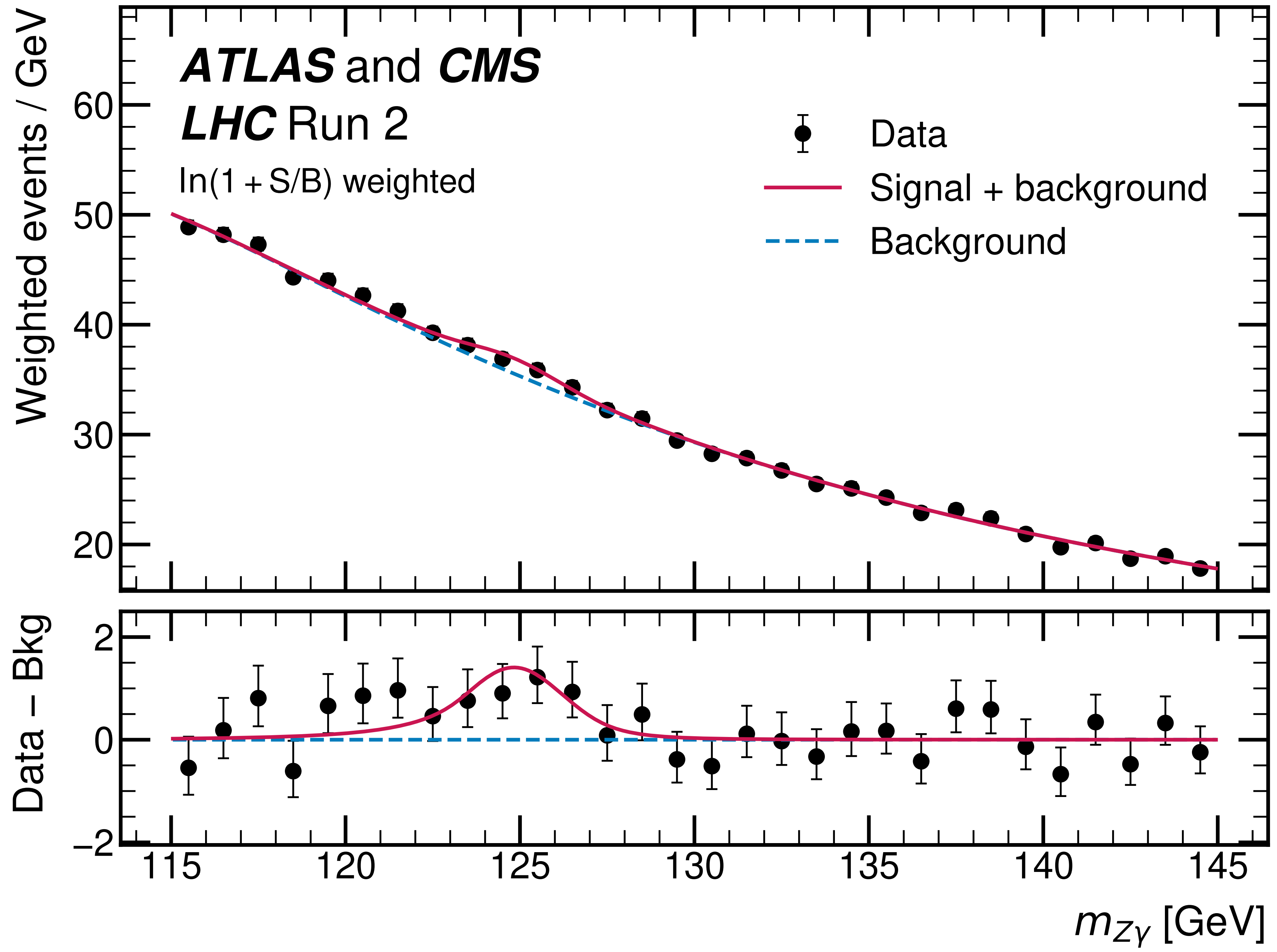
- Unfolded differential cross sections are also measured as function of several kinematic variables
- Combination of several decay channels ($\gamma\gamma$, ZZ, boosted $\tau\tau$) to optimally cover the whole phase space

Rare decays : H→Zɣ

- Extremely rare loop-induced process : BR = 1.5 × 10^{-3} in the SM
  - plus $Z \to ee/\mu\mu$ BR for the experimentally accessible final state
- 3.4 σ evidence from ATLAS+CMS combination
- Excess with respect to the SM : 1.9 σ deviation
  - tension reduced in new ATLAS Run 2 + Run 3 analysis (2.5 σ standalone significance)

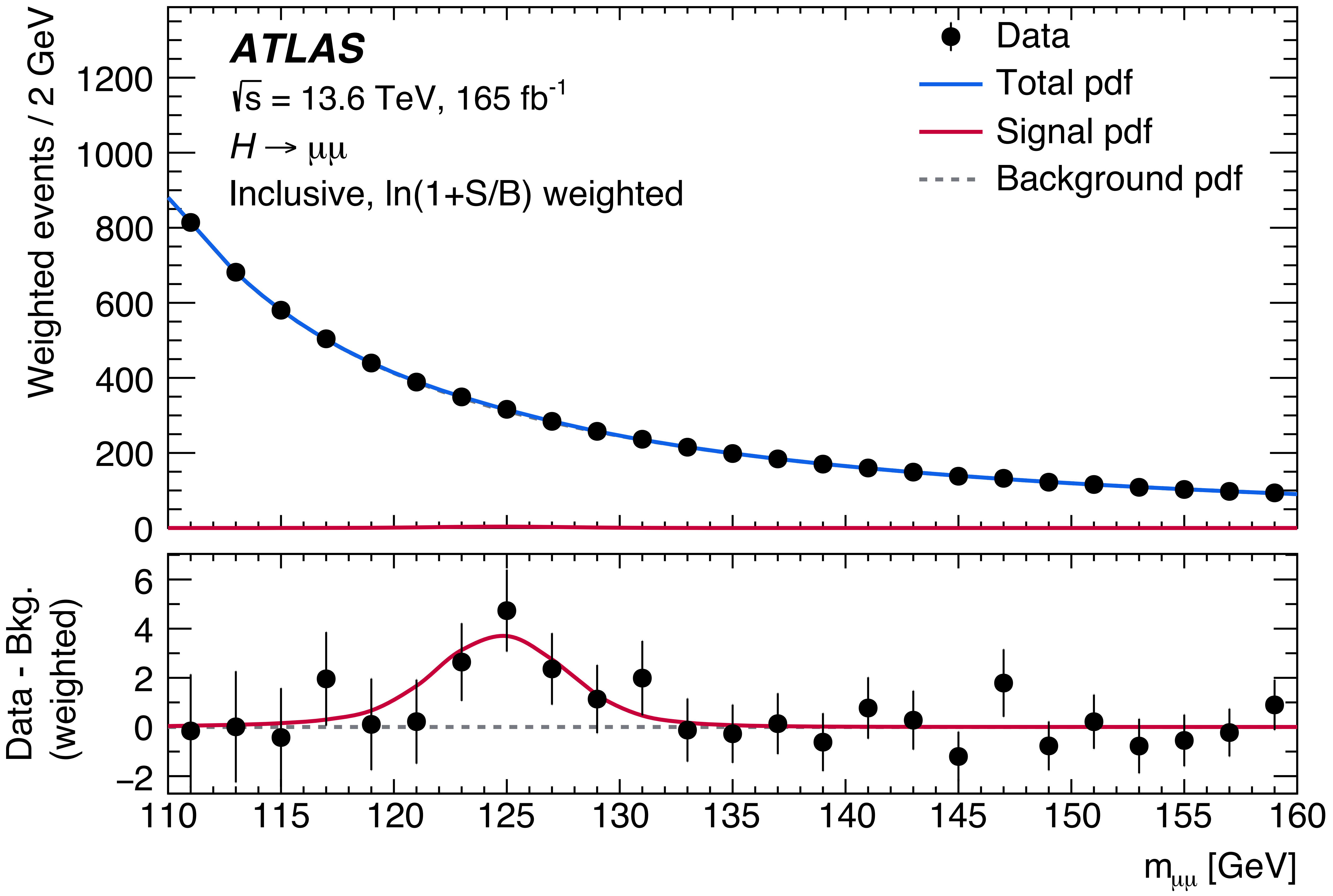


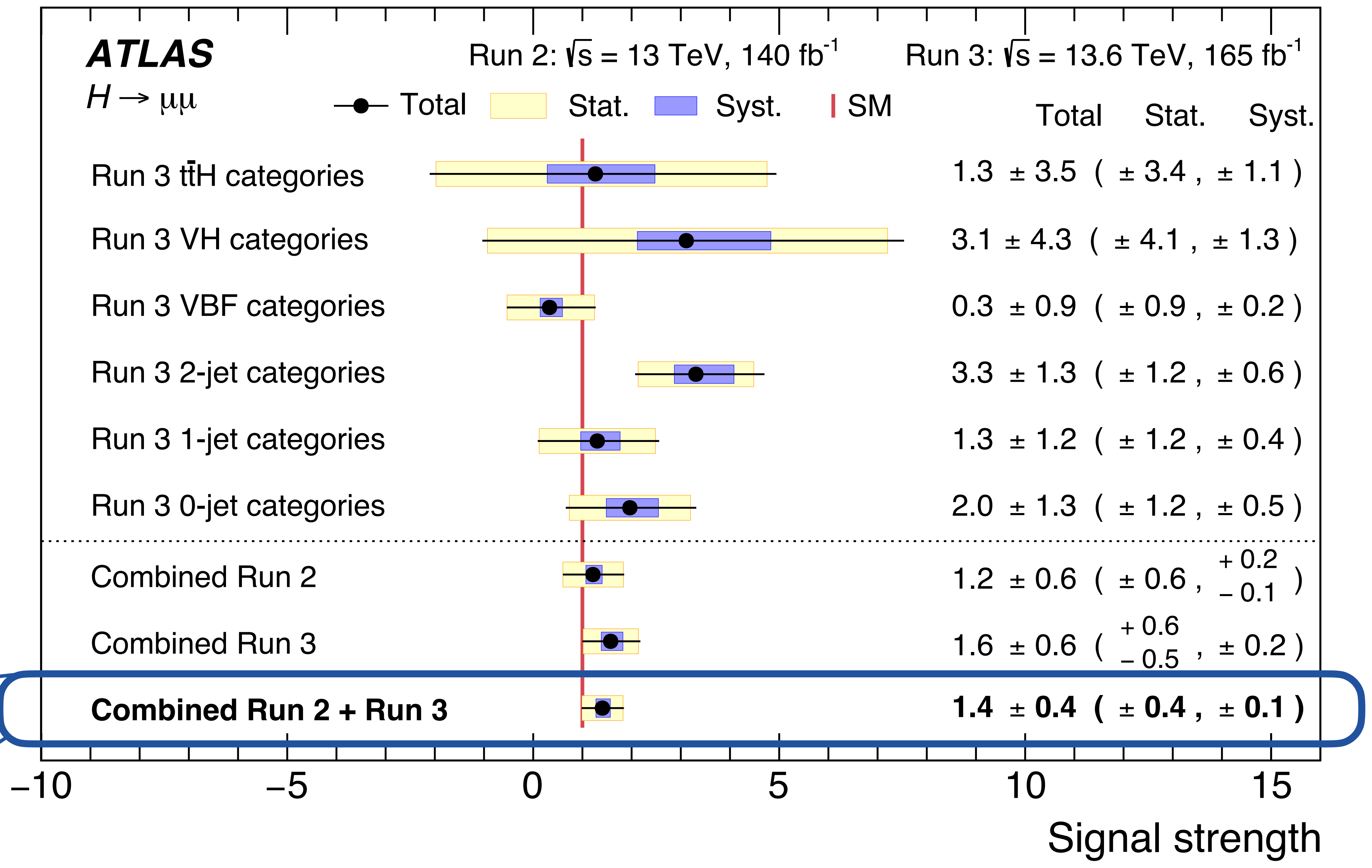




The second generation : H → μμ

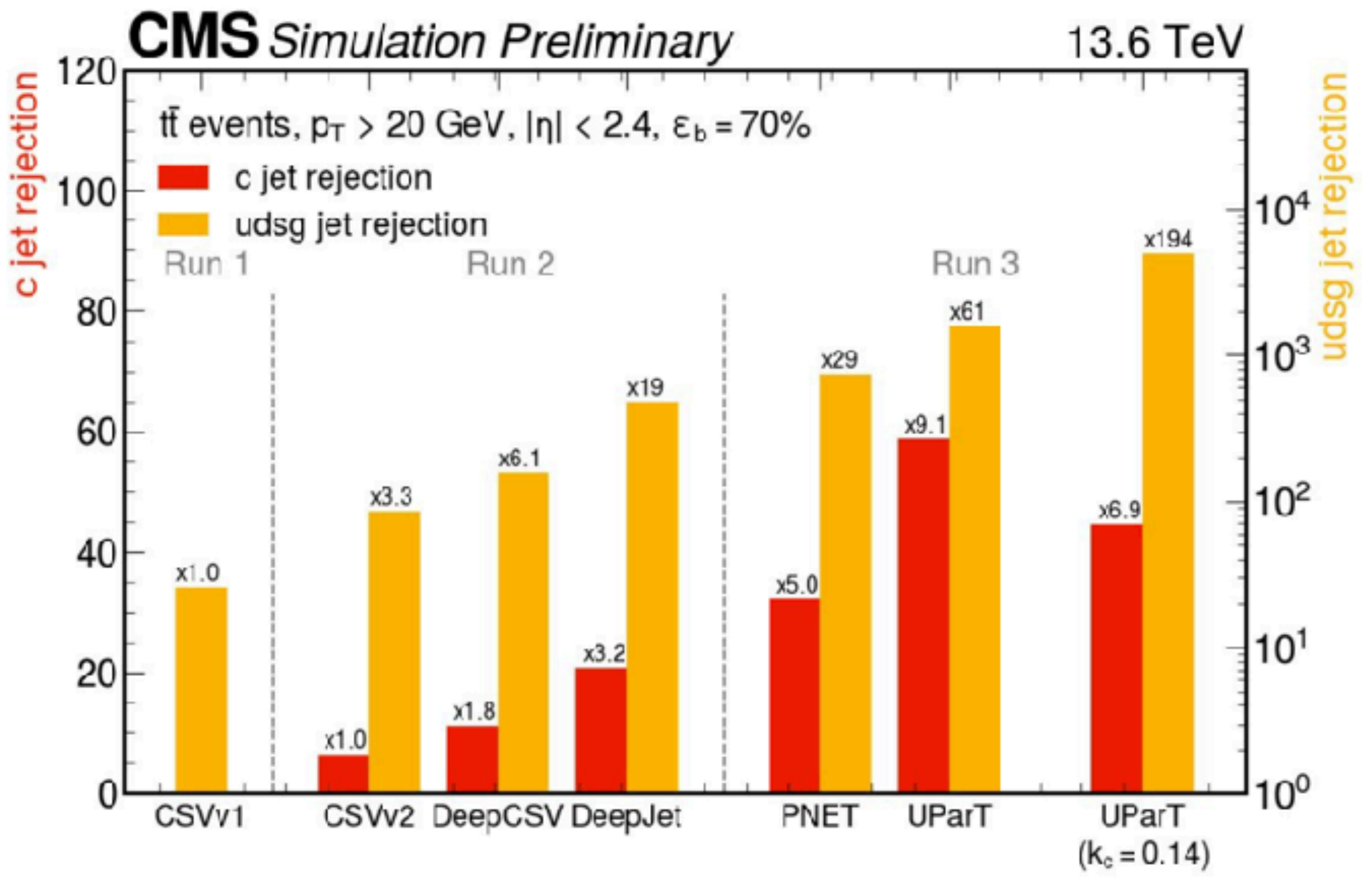
- Extremely rare BR ($H \to \mu\mu$) ~2×10^{-4}
- Irreducible Drell-Yan background
- Keys are excellent bkg description, mass resolution, extensive categorization

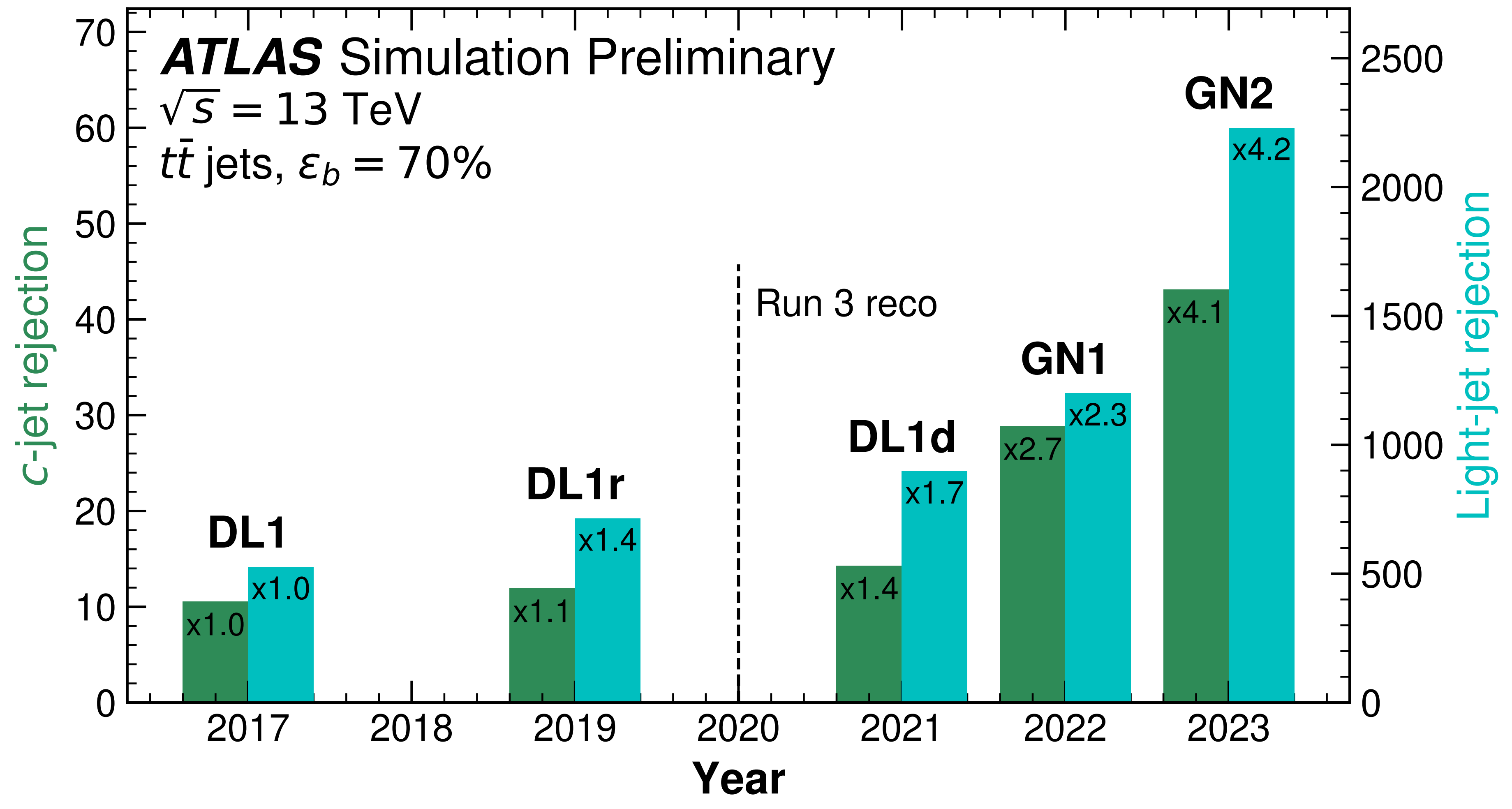




Evidence by both ATLAS (Run 2 + Run 3) and CMS (Run 2)

Intermezzo : ML usage for particle physics



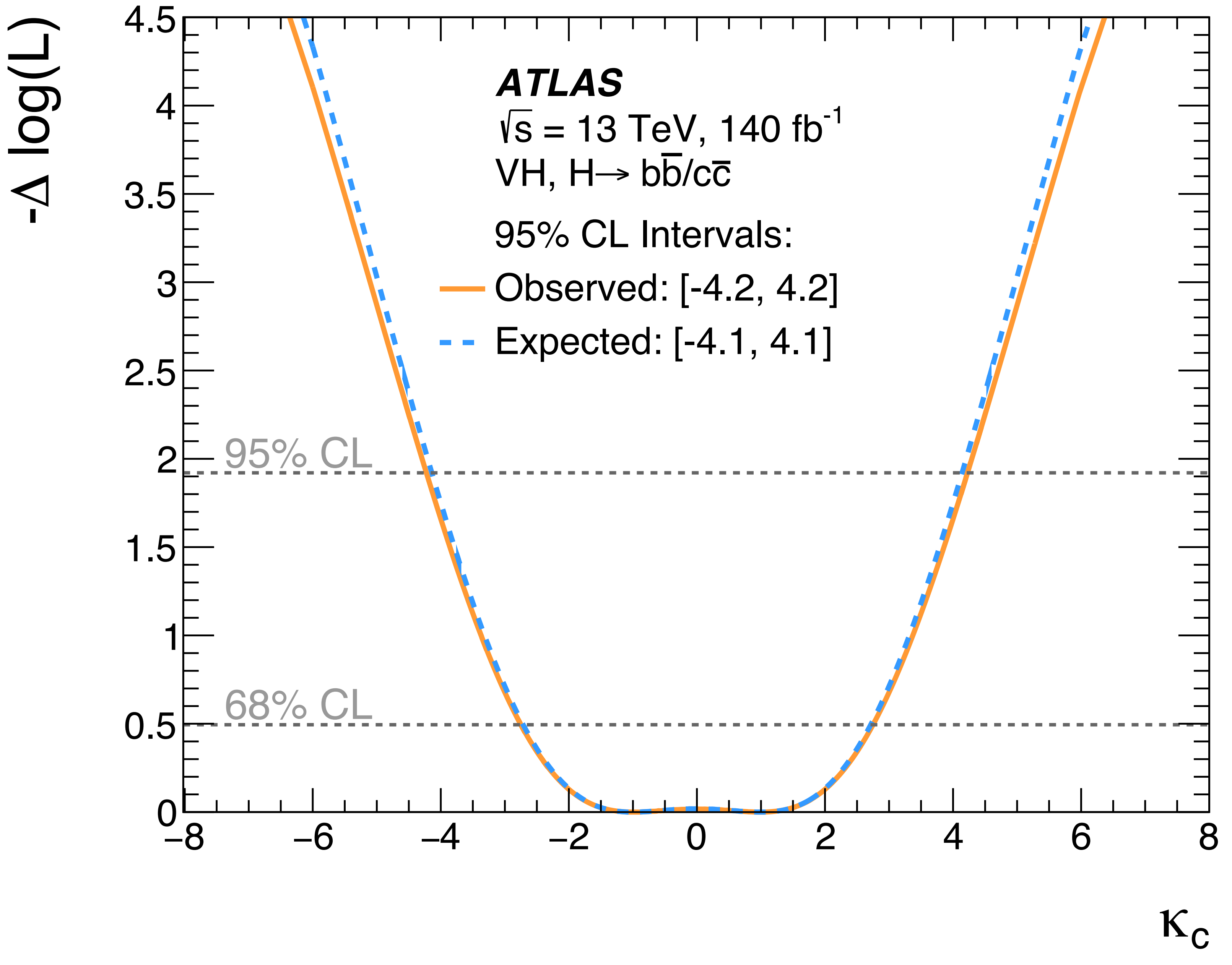


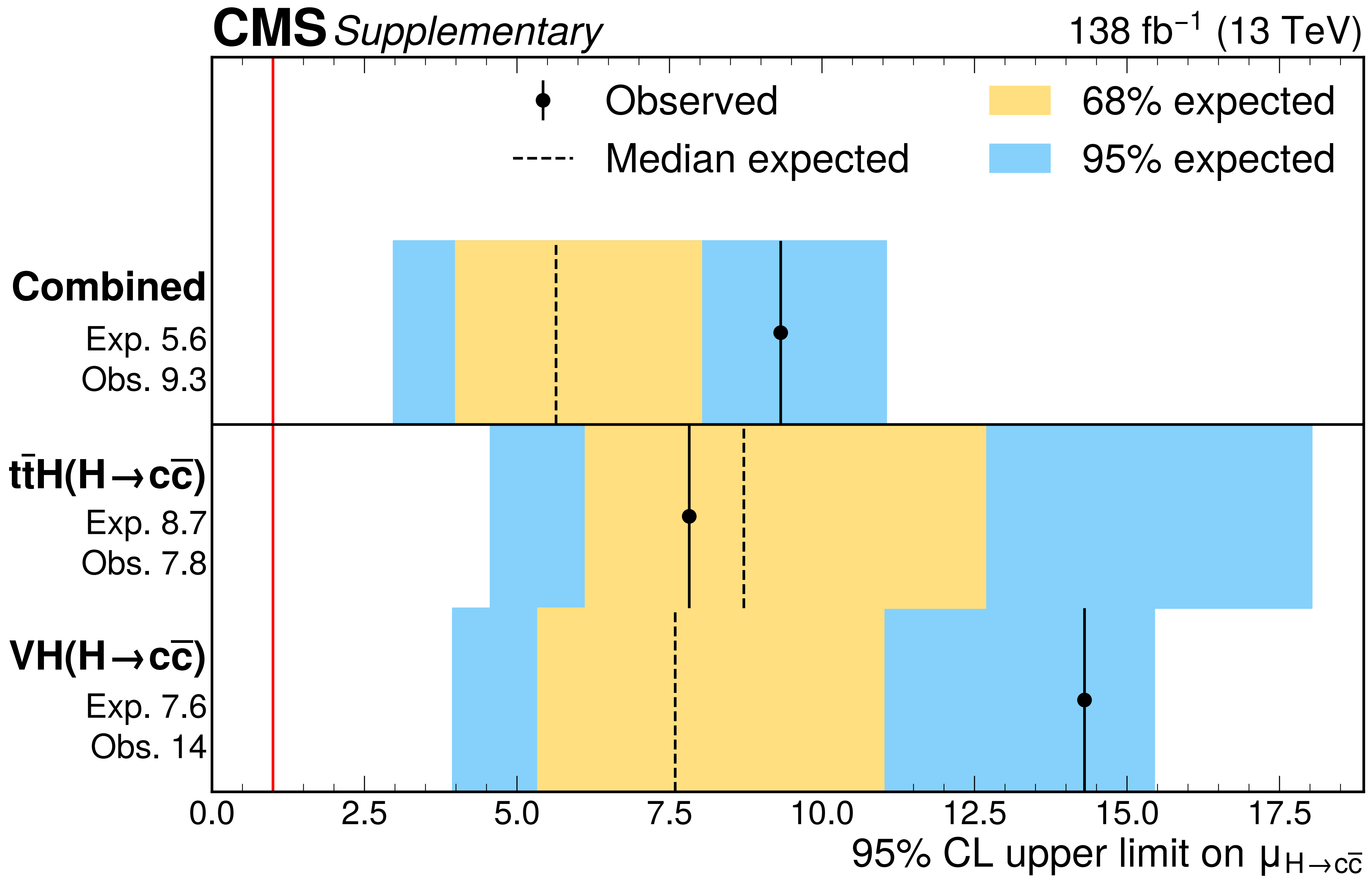
- Modern machine learning techniques are rapidly and extensively being deployed at all levels of the analysis chains
  - object identification
  - calibration
  - signal and background separation
  - bkg estimation
  - …
- Same trend in both experiments, often a key driver in the improvement of the sensitivity of the results

Extensive application of ML is drastically improving the sensitivity of the results

The second generation : H→cc

- Extremely challenging process : rare (BR ~2.9%) and high contamination from QCD processes : highly performant charm flavour taggging is key
- Highest sensitivity VH production (trigger and reject backgrounds from V) and recently ttH





Run 2 sensitivity around 5-10 × SM

Value of the charm coupling $|\kappa_c| < 4.2$

The self-coupling

$$V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

EWSB

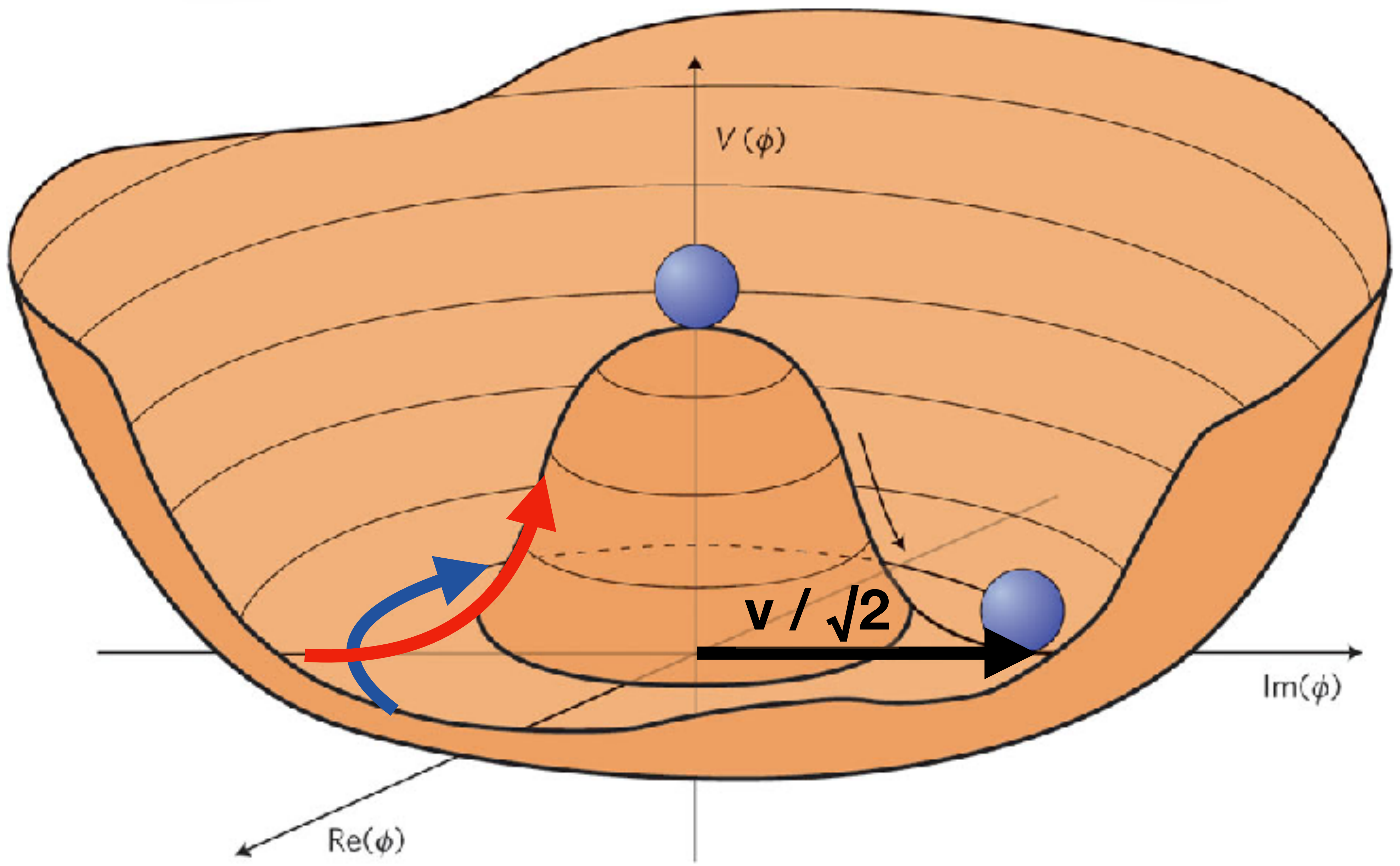
$$V(H) = \frac{1}{2}m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4}\lambda_{\mathrm{HHHH}} H^4 - \frac{\lambda}{4}v^4$$

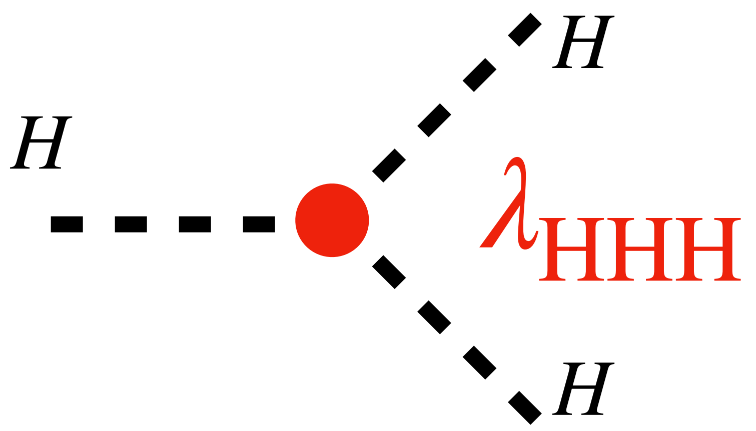
Higgs boson mass

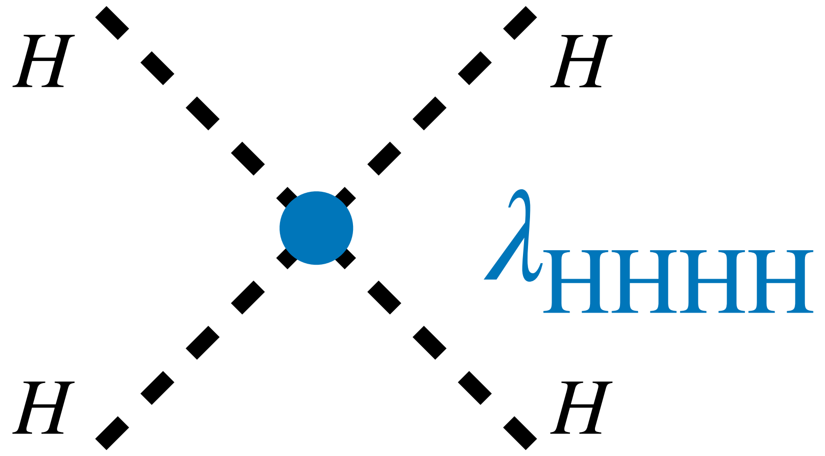
Vacuum energy density

Cubic self-coupling

Quartic self-coupling







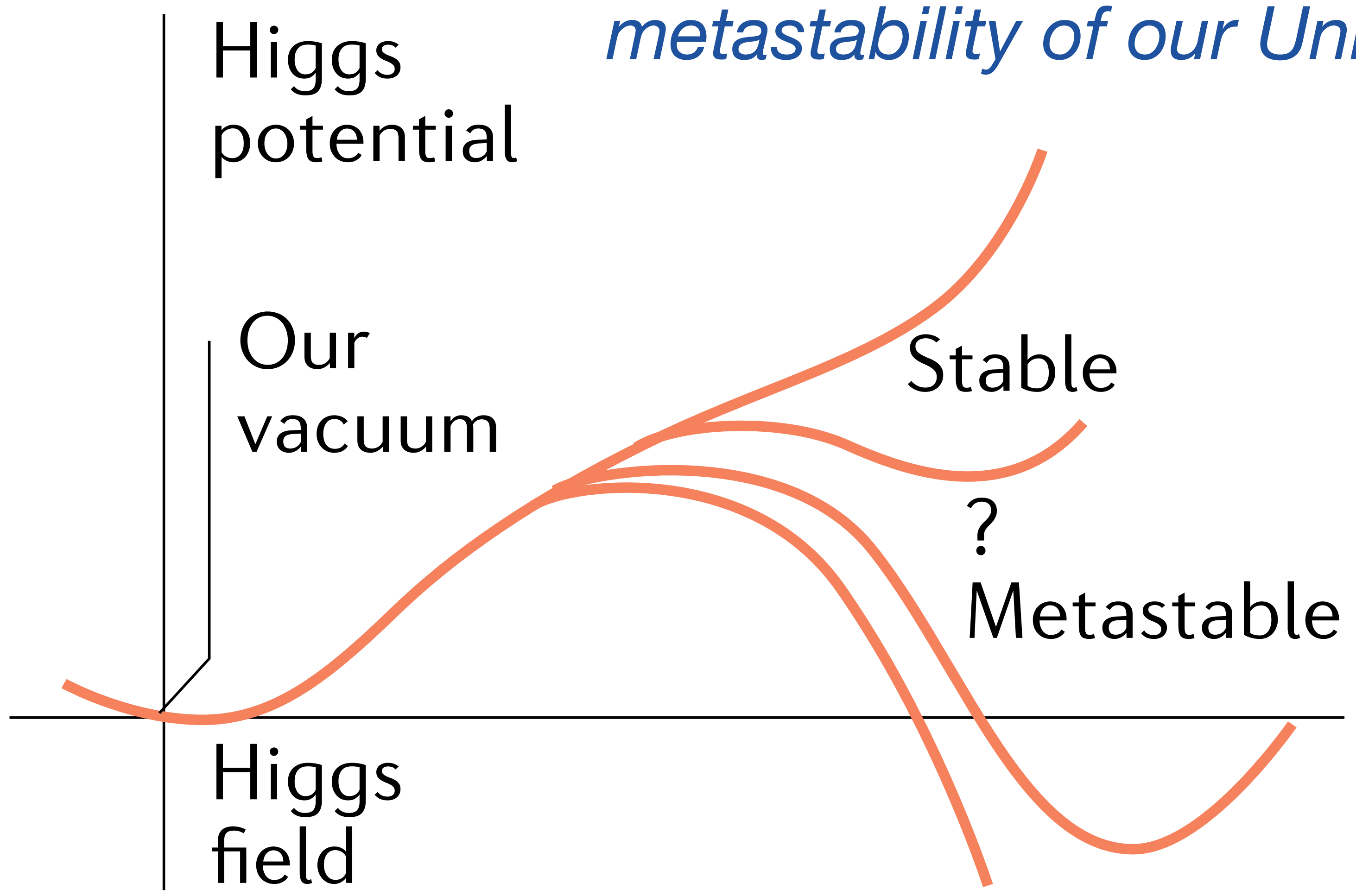
$$\lambda_{\mathrm{HHH}} = \lambda_{\mathrm{HHHH}} = \lambda = \frac{m_{\mathrm{H}}^2}{2v^2} \approx 0.13$$

The self-coupling is directly connected to the shape of the scalar potential

Why is it important?

The shape of the scalar potential connects to many open questions of particle physics and cosmology

The evolution of the self-coupling with the energy scale may imply a metastability of our Universe



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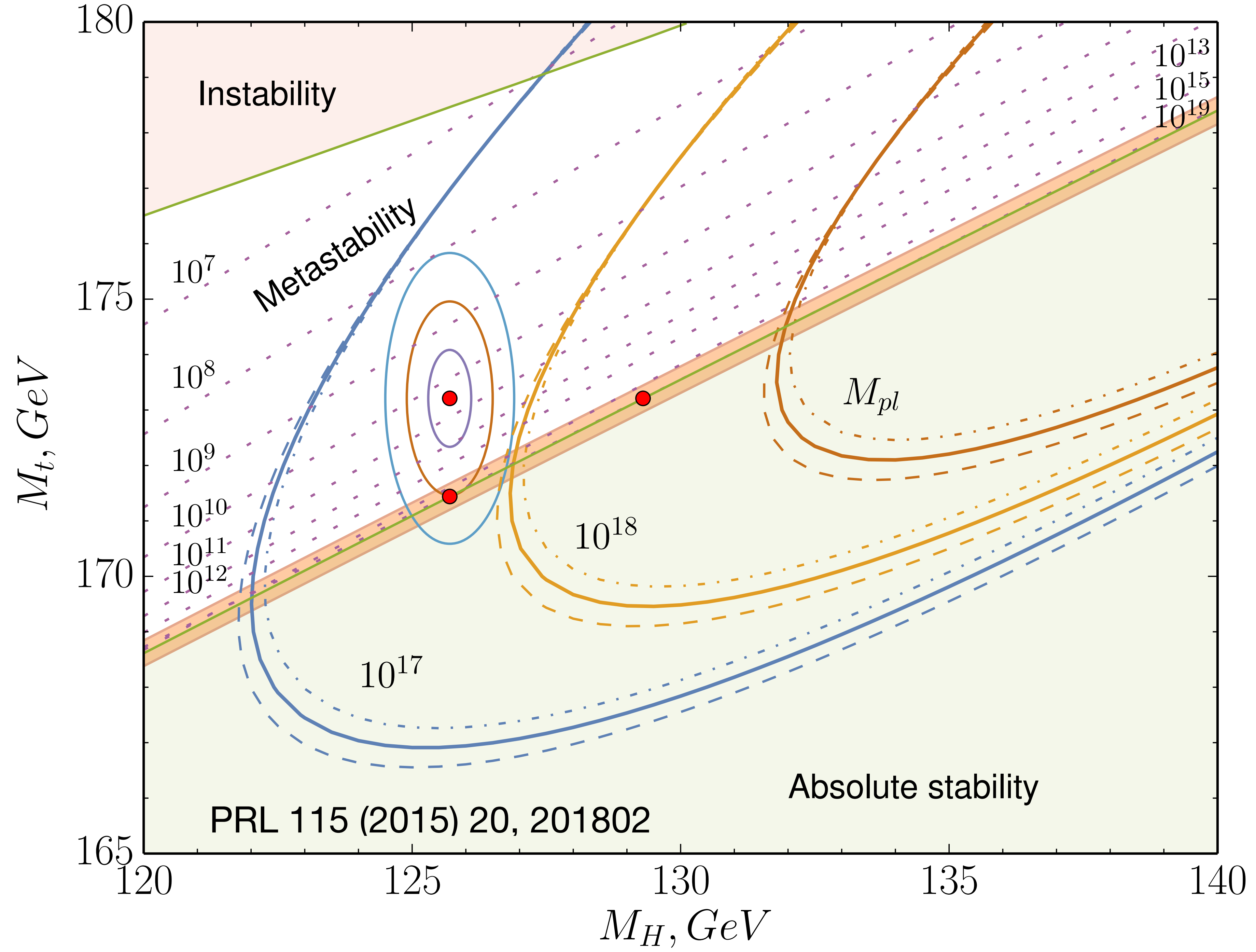
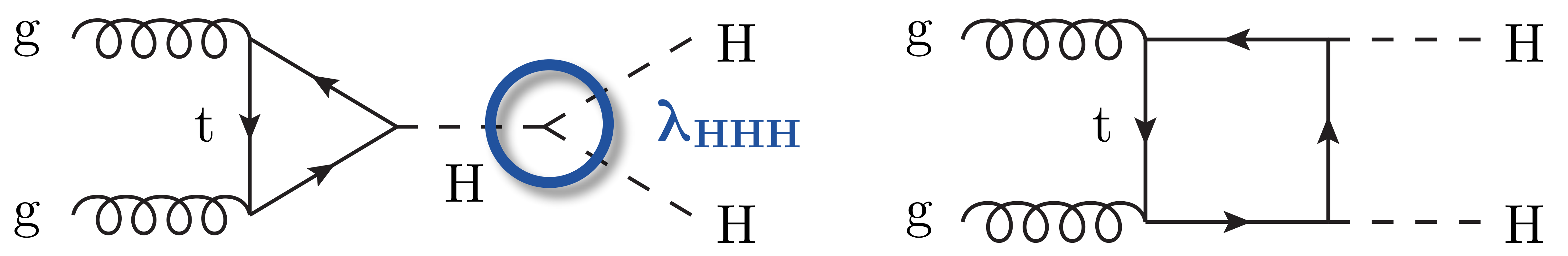


λ

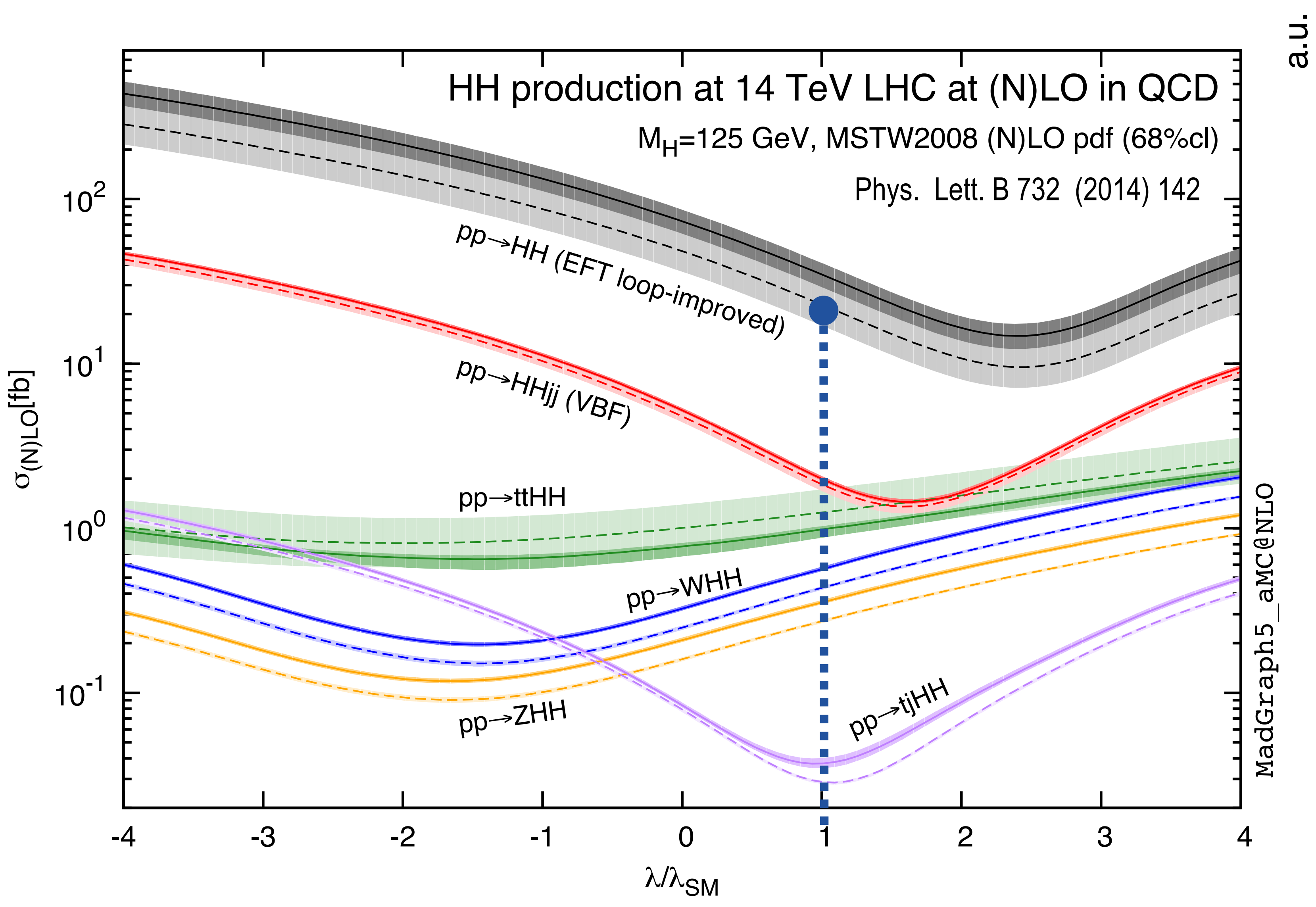
- Metastability or the Universe
- EWSB phase transition and link to baryogenesis
- Cosmological constant

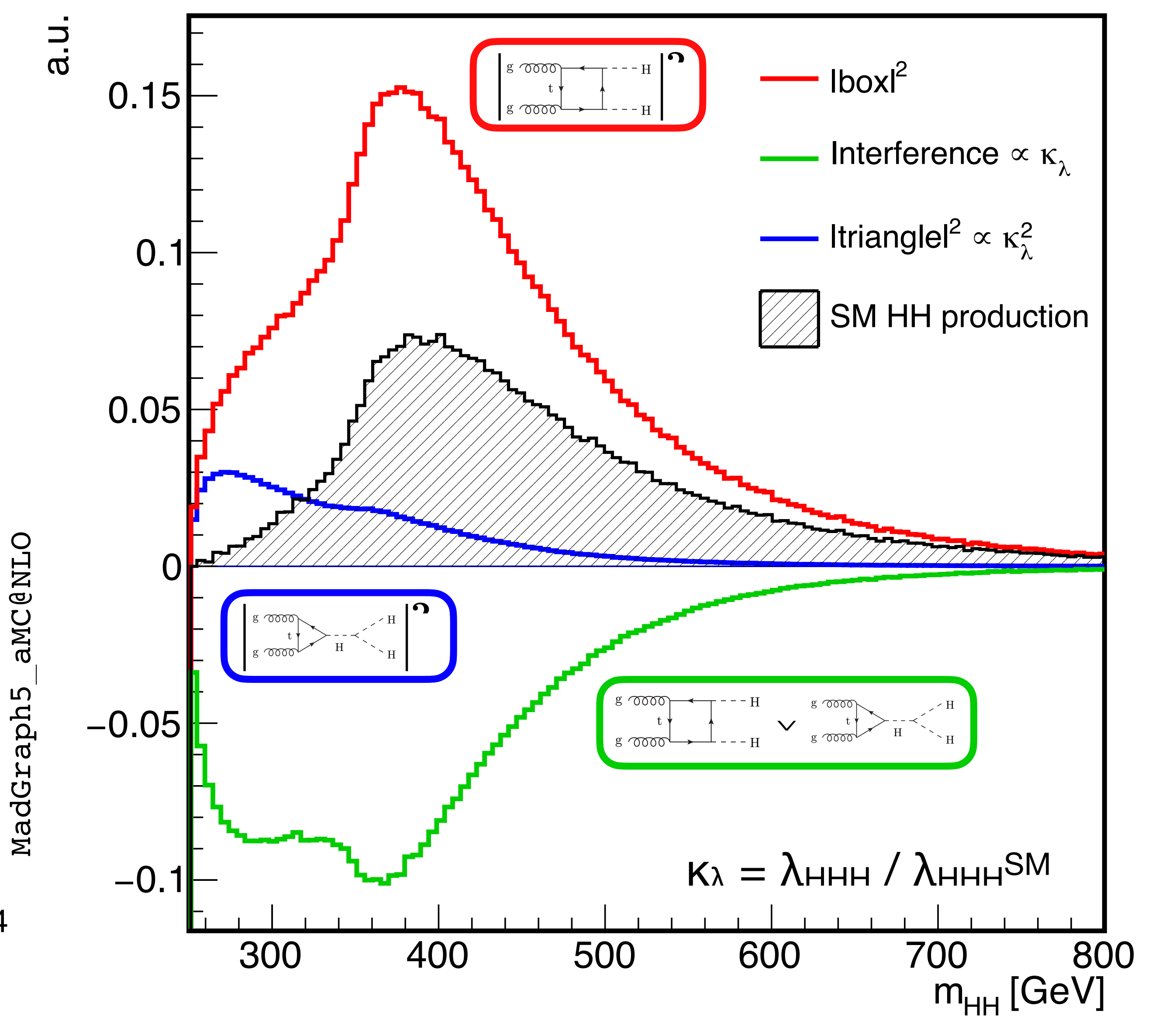
HH searches



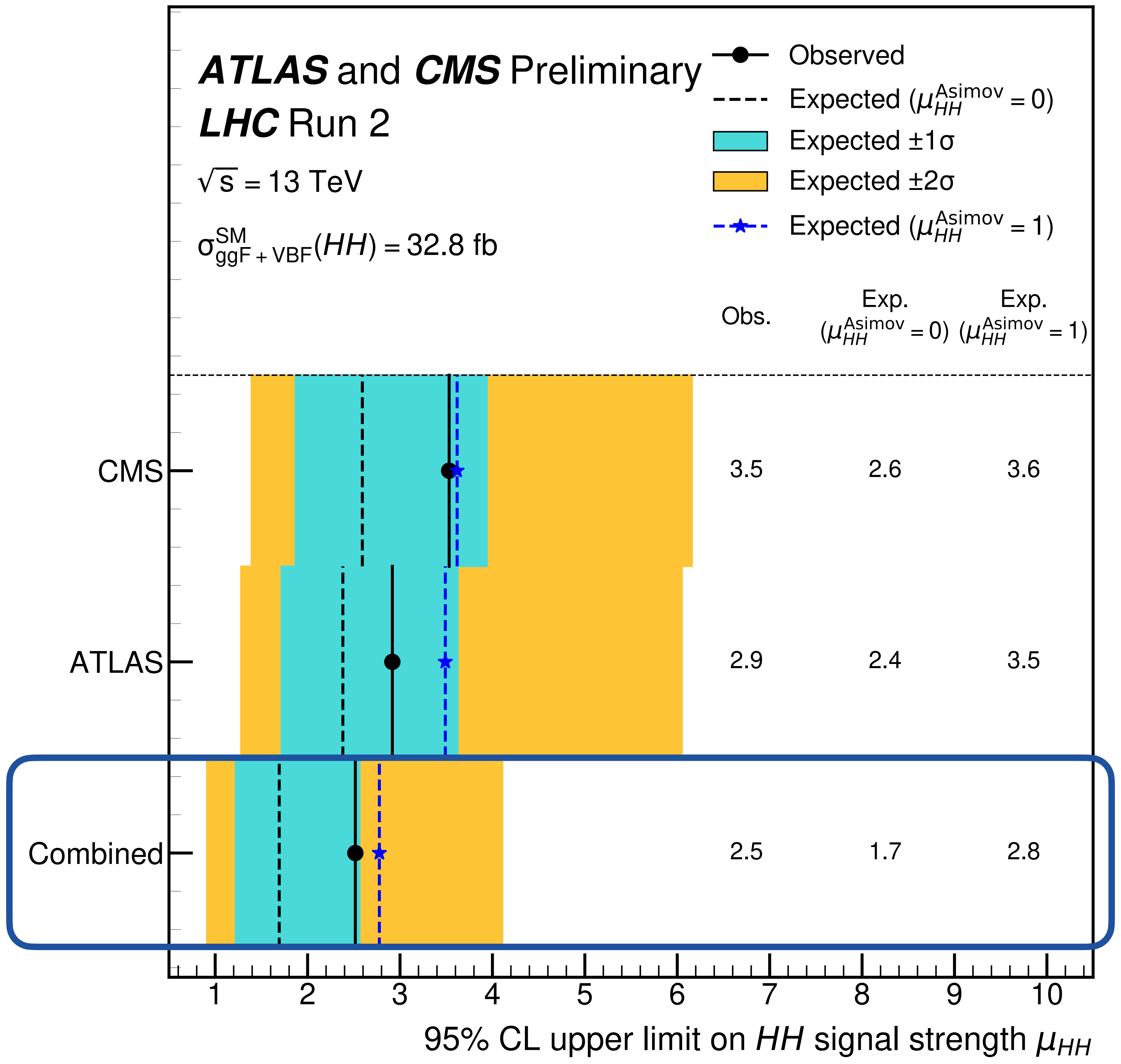
$$\sigma_{HH}^{SM} = 30.77\ (34.13)\ ^{+6.4\%}_{-23.1\%}\ \text{at}\ 13\ (13.6)\ \text{TeV}$$

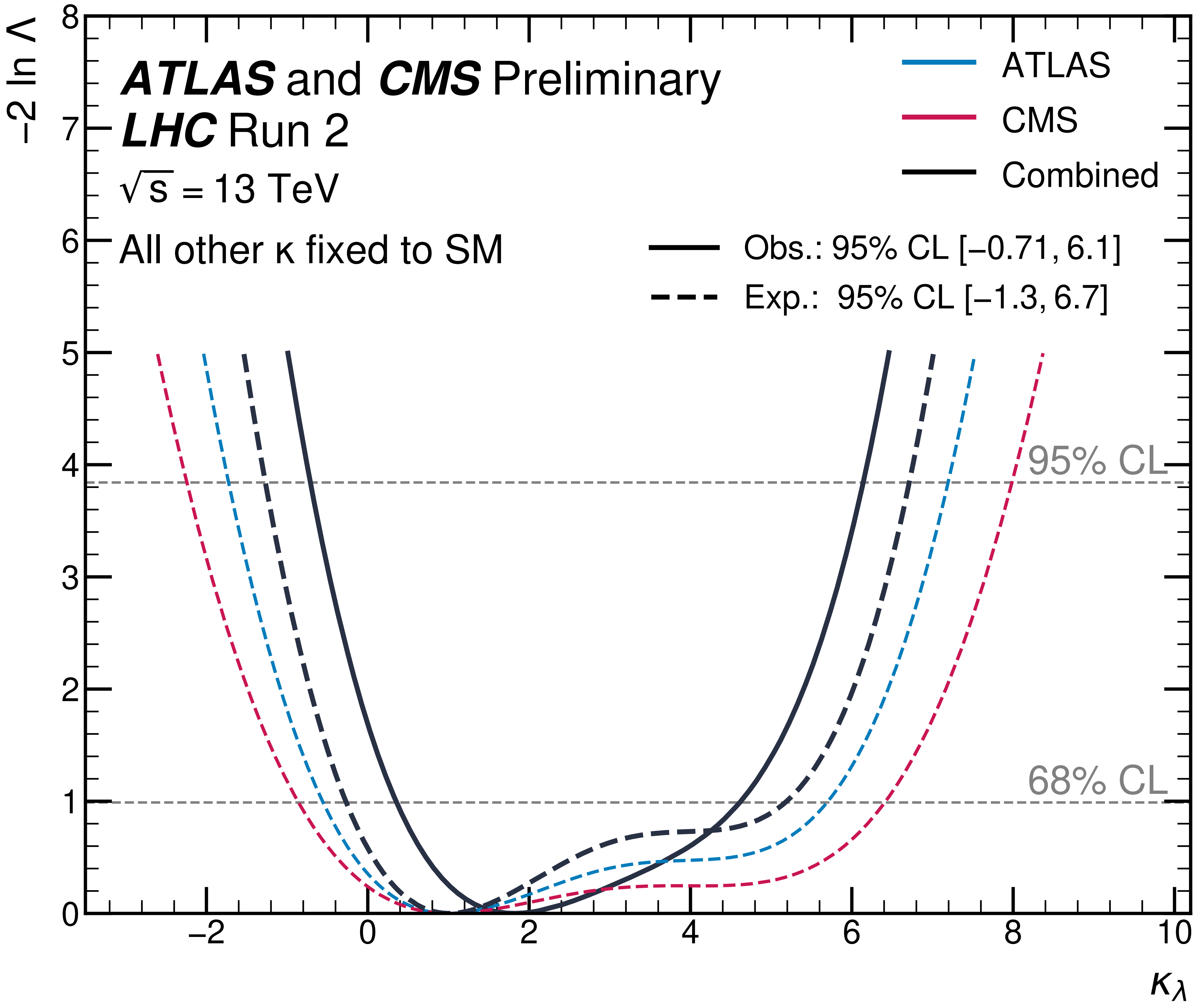
- Direct access to λ_{HHH} via HH production in a variety of final states
- Interference effects : signal distributions have a strong dependence on λ
- Extremely rare process (~1/1000 wrt single Higgs cross section)
  - studied via the combination of several HH decay channels (bbbb, bb$\tau\tau$, bb$\gamma\gamma$, bbWW, multilepton final states)





HH results





- ATLAS + CMS Run 2 combination achieves 2.5 × the SM
- Evidence for HH at the Run 3 is possible!

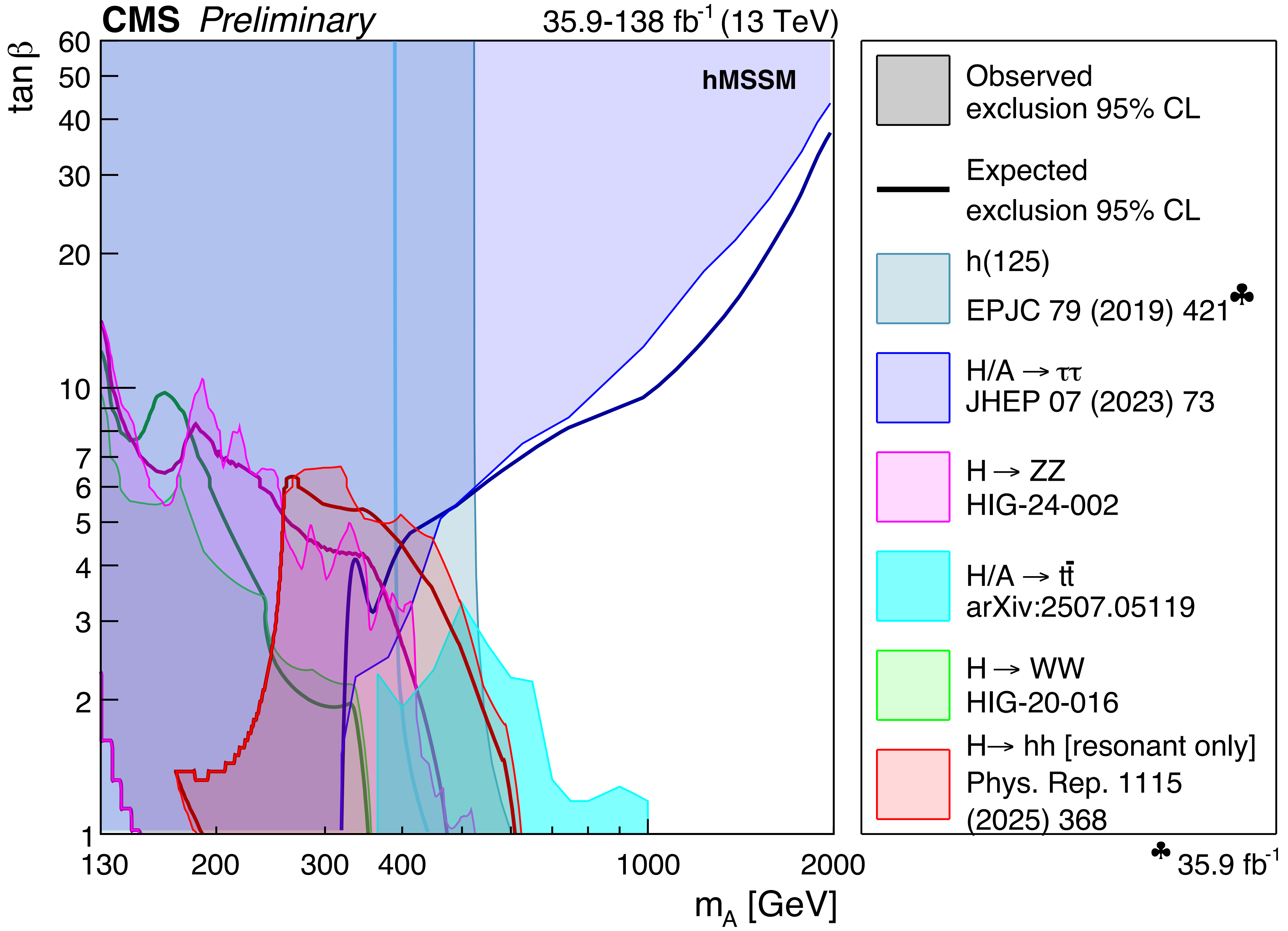
HH will be one of the key parts of the LHC Run 3 physics programme

Higgs boson for new physics searches

Direct searches

Specific UV-complete models

- Direct search for extended scalar sectors or new particles that couple with the Higgs boson

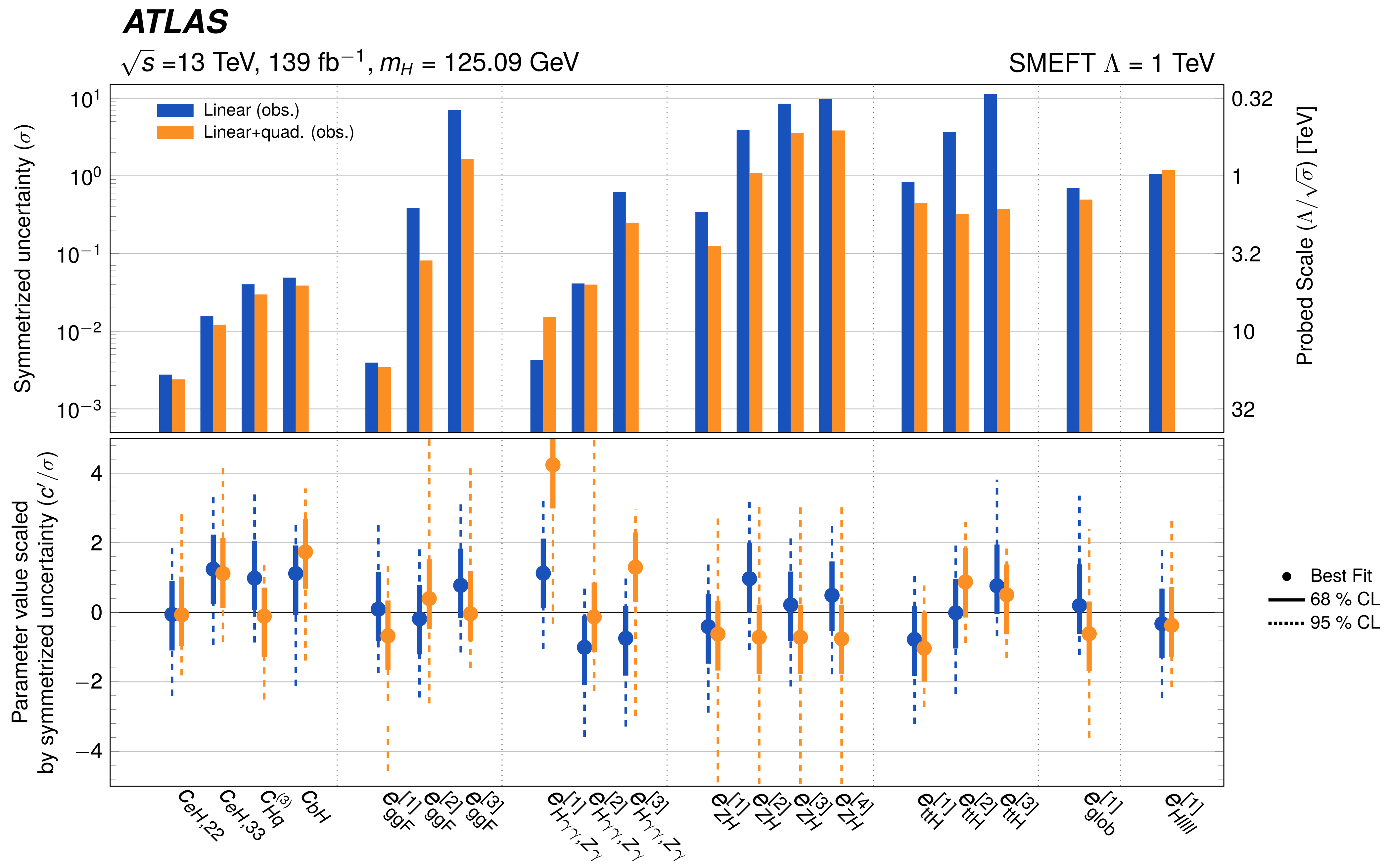


EFT

Low-energy expansion if theory scale beyond direct LHC access

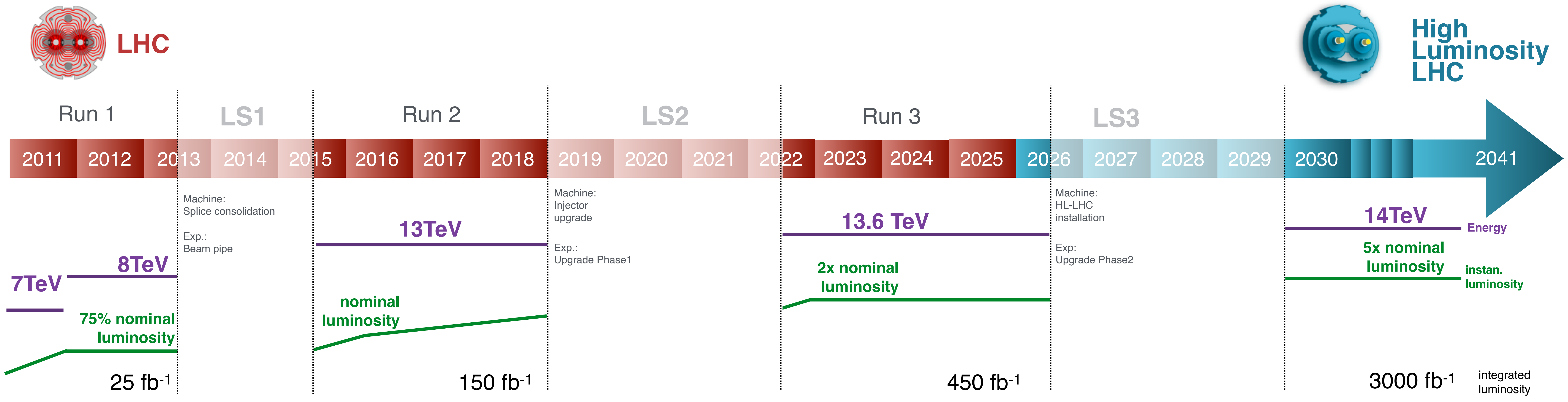
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \cdots$$

- SM Lagrangian expanded with dim-6 operators
  - 2499 operators! Symmetries + eigenvector combinatons



The Higgs boson is a powerful and versatile probe for new physics

High-Luminosity LHC

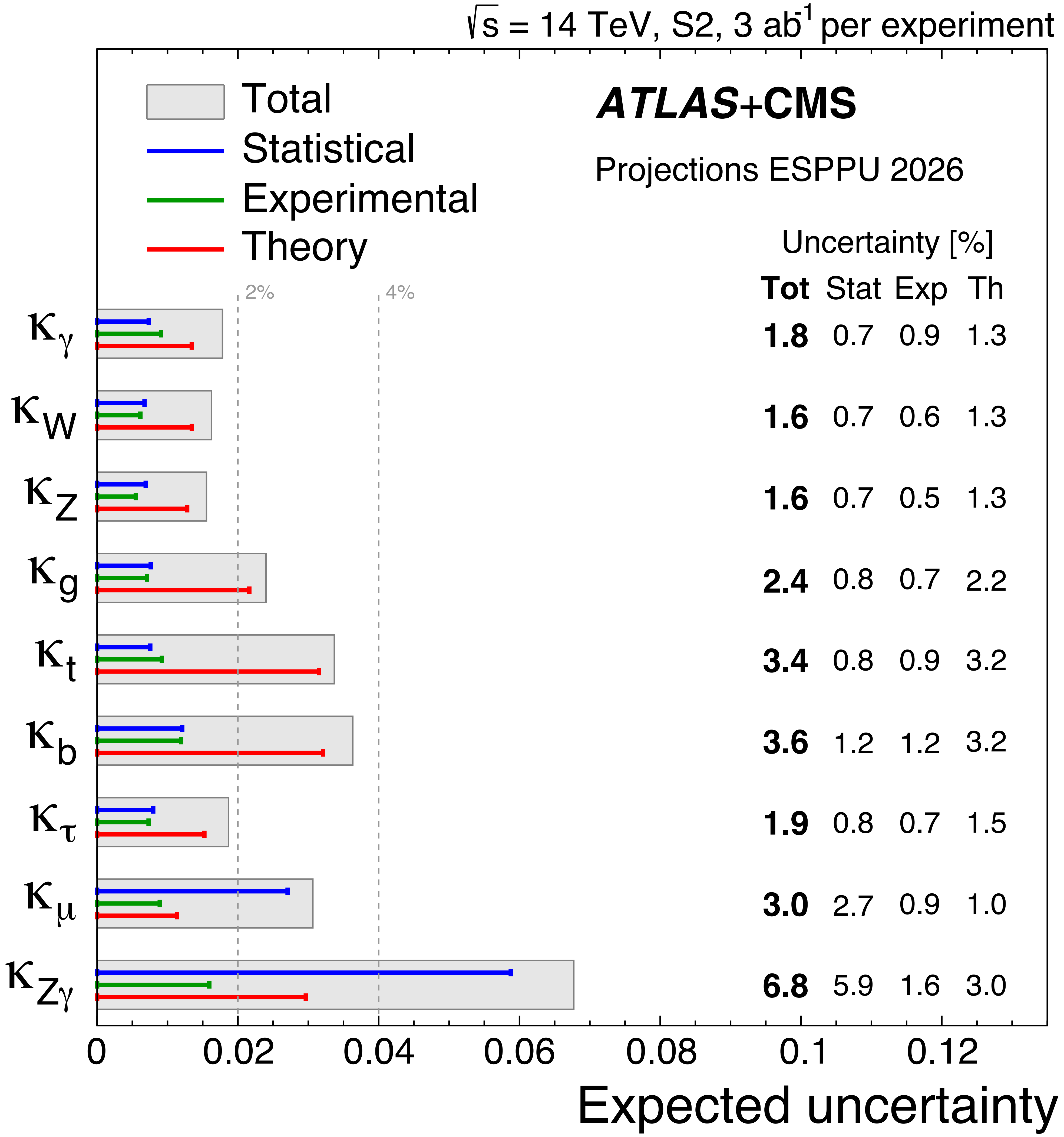


- Upgrade of the LHC planned to start after the LS3
  - expect first beams in 2030
- Increase of the instantaneous luminosity by ~5 w.r.t. design values
- **3 ab^{-1} during a decade of operations**
- A very challenging programme of upgrades of ATLAS and CMS is ongoing
  - new trackers, timing information, upgraded barrel electronics, new endcap calorimeter (CMS), upgraded trigger systems

Unique possibility for high precision Higgs physics

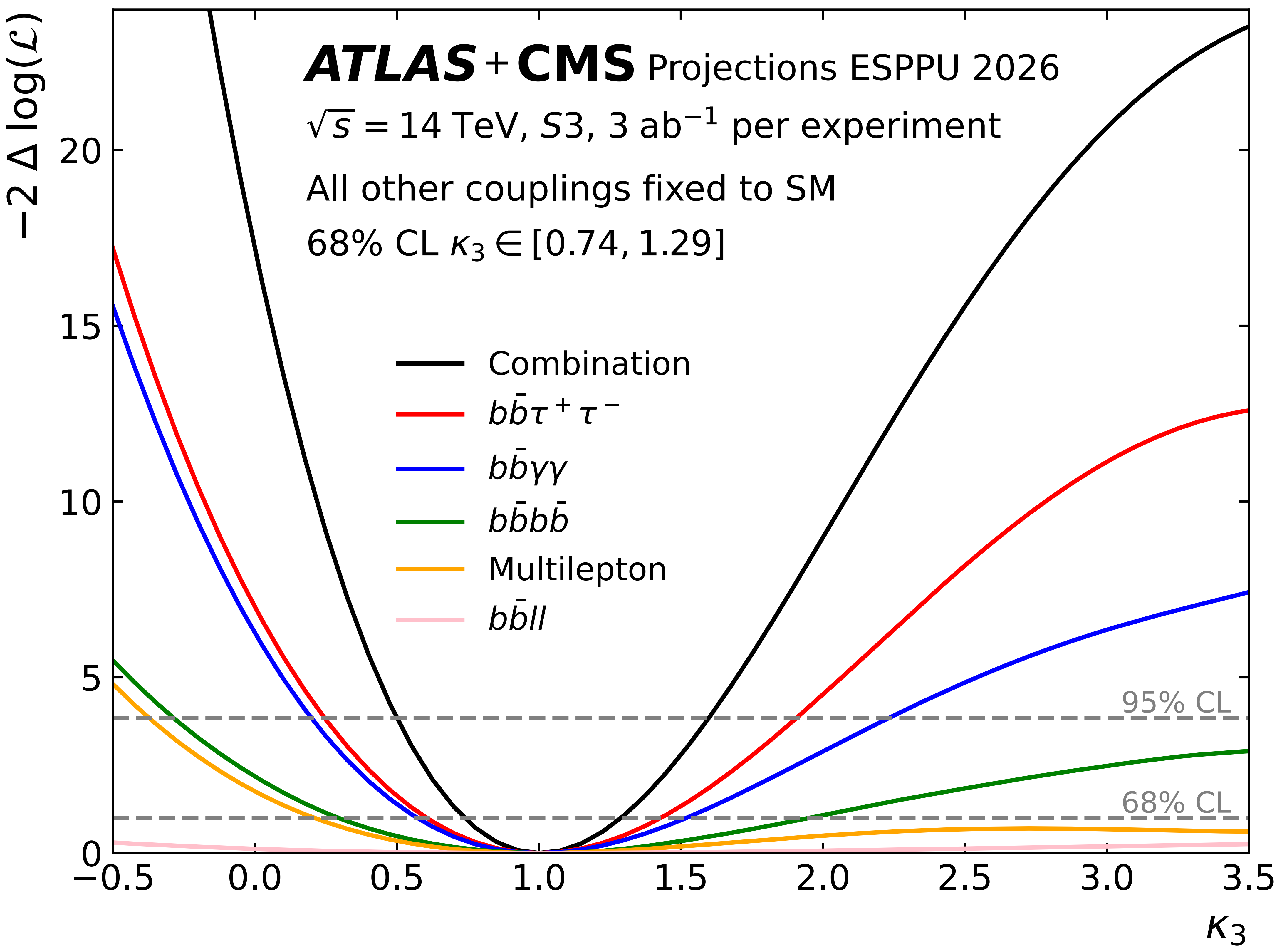
The success of the HL-LHC physics programme depends crucially on the success of the upgrade projects

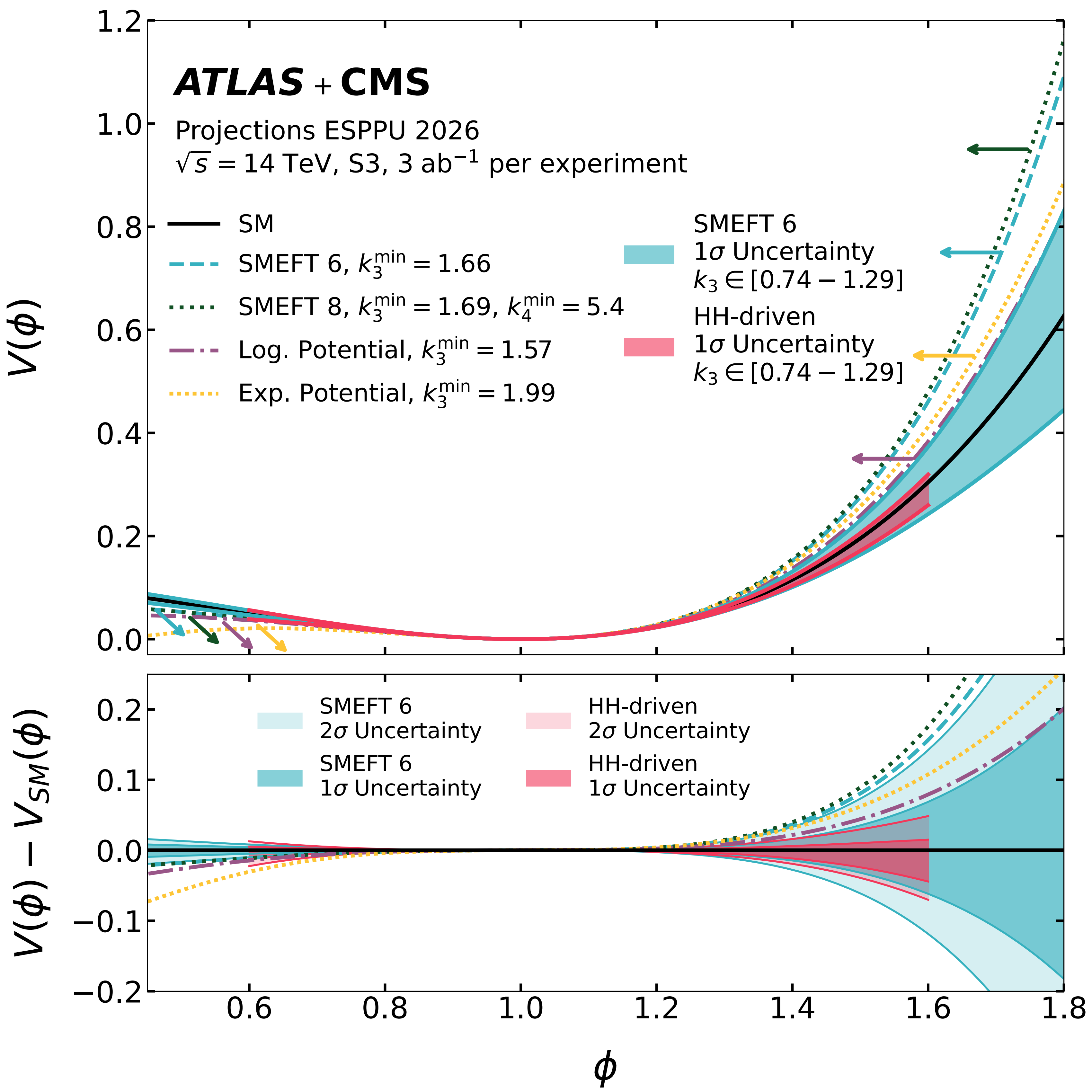
Prospects for HL-LHC : Higgs boson couplings



- Projections of current experimental analyses extrapolated at 3000 fb-1
  - consider reduction in most experimental uncertainties
  - consider 50% reduction in theoretical uncertainties
- Most couplings will be constrained at the level of 2-4%
  - for the H→cc coupling, expect to be sensitive to values 1.5 times the SM prediction
- Dominated by theory uncertainties in most measurements
  - challenges ahead for the whole HEP community to optimally exploit the HL-LHC data aset

Prospects for HL-LHC : HH production





- Expect 7.6σ significance for SM HH production (ATLAS+CMS)
- Expect -26%/ +29% precision on the self-coupling

Direct access to the shape of the Higgs potential

Conclusions

- The Higgs boson is the cornerstone of the SM, and its study is at the center of the ATLAS and CMS programmes
- Impressive advancement with the Run 2 and early Run 3 data sets
  - precise determination of properties and couplings
  - rare decays
  - differential cross sections and STXS
  - self-coupling via HH
- With the Run 3 ending in 2026, we will have an unprecedented data set to achieve the most precise results
  - $H \to \mu\mu$, single-experiment $H \to Z\gamma$ evidence, possibly combined ATLAS + CMS HH evidence
  - progress is much faster than anticipated!
- Ultimate precision at the HL-LHC
  - 2-4%-level determination of most couplings
  - Sensitive to κ_c = 1.5
  - Single-experiment observation of HH and ~30% uncertainty on λ