Combination of Higgs couplings at CMS

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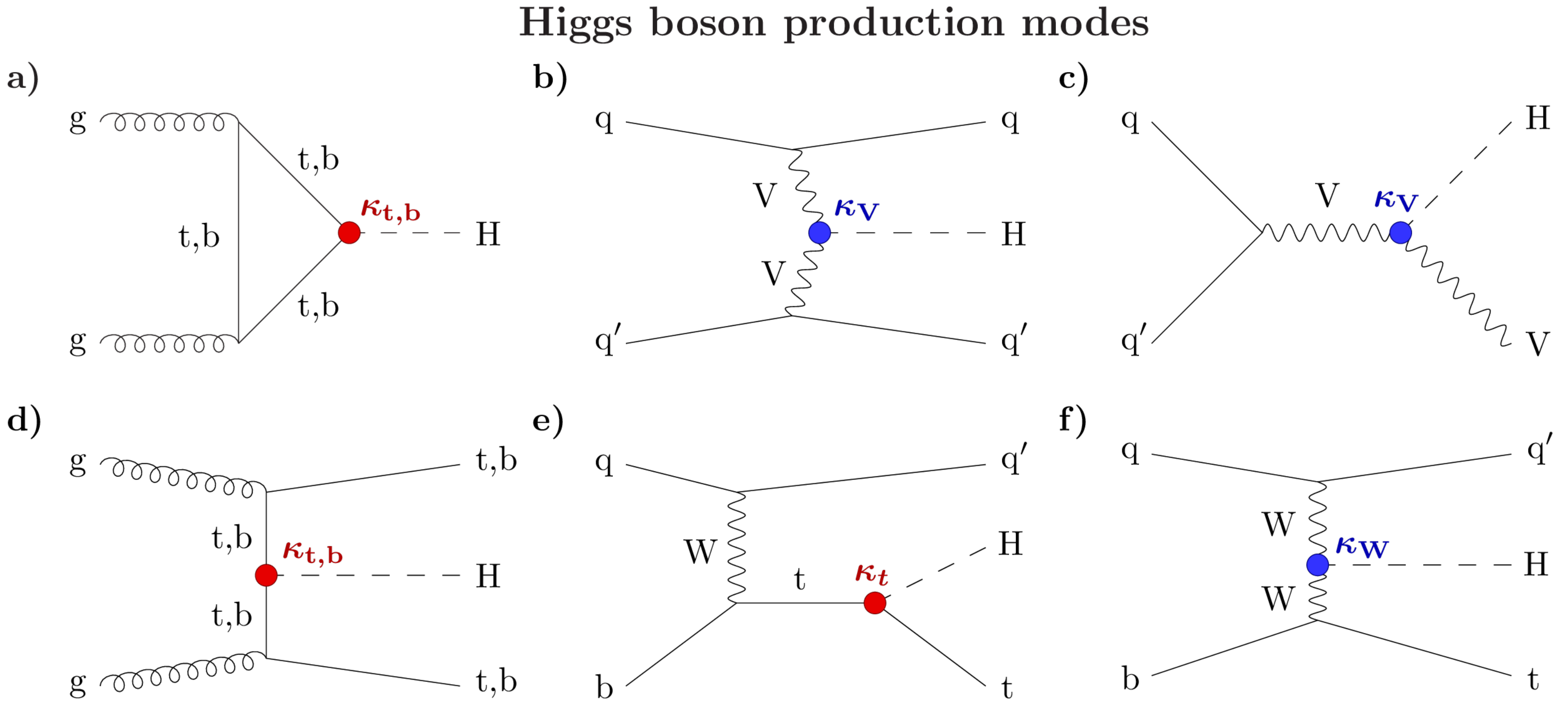
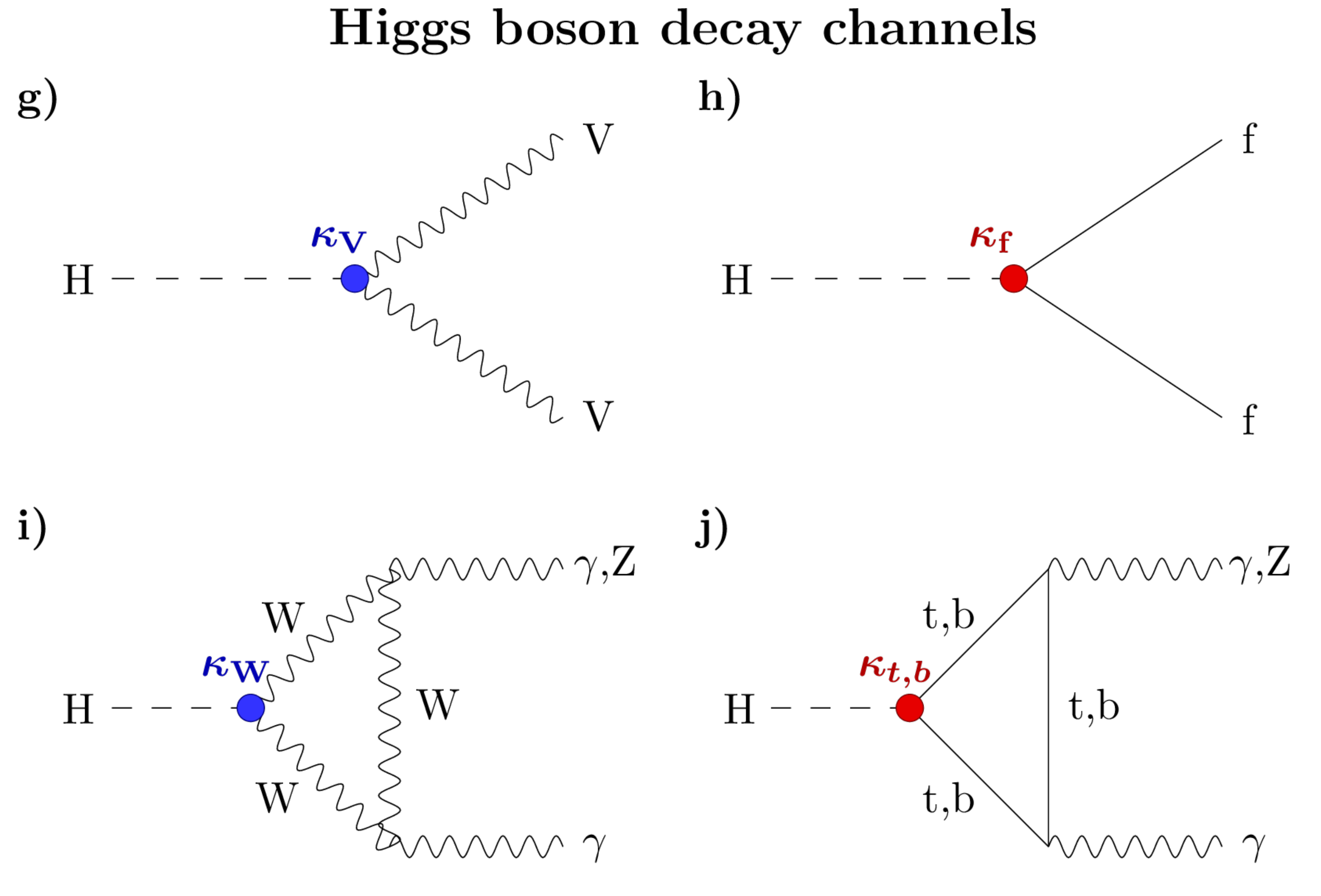
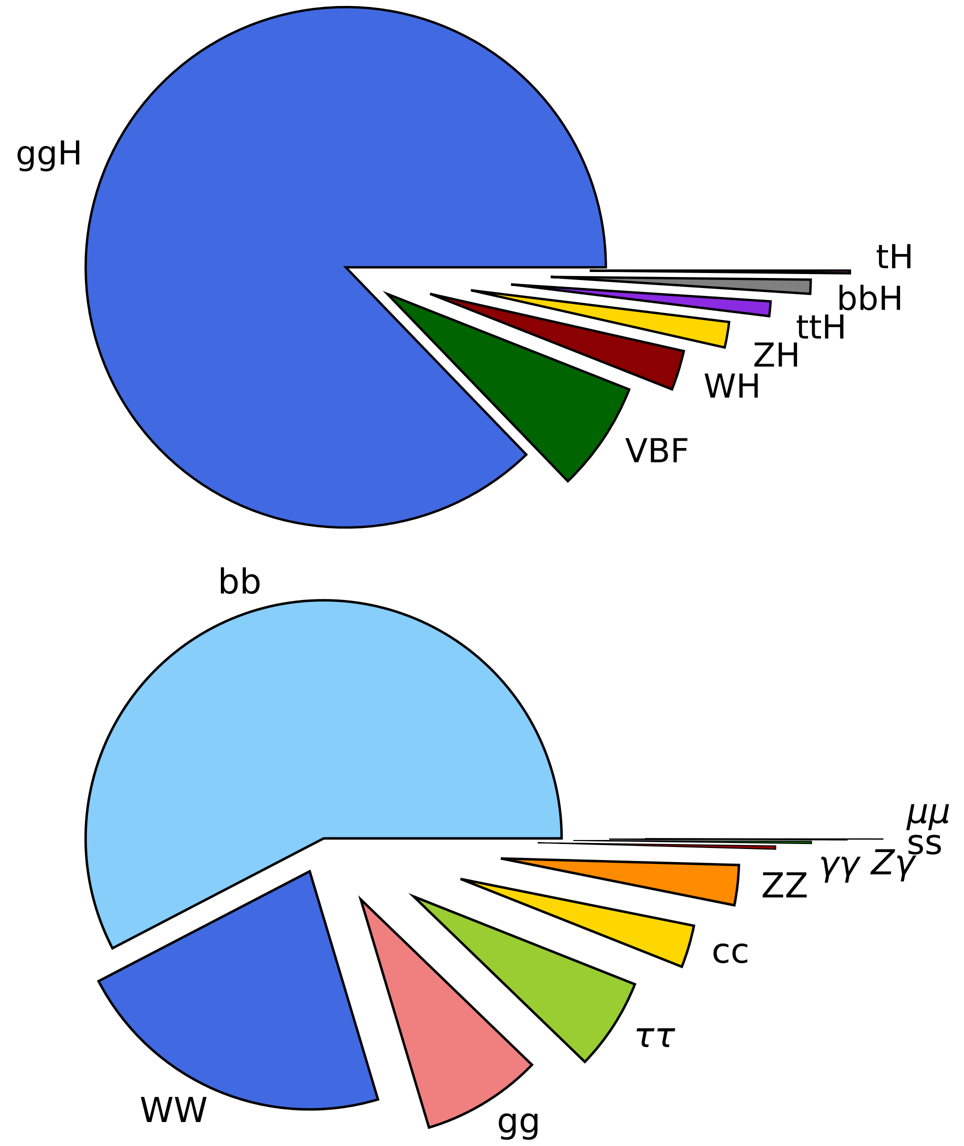
What are we looking for (h125)

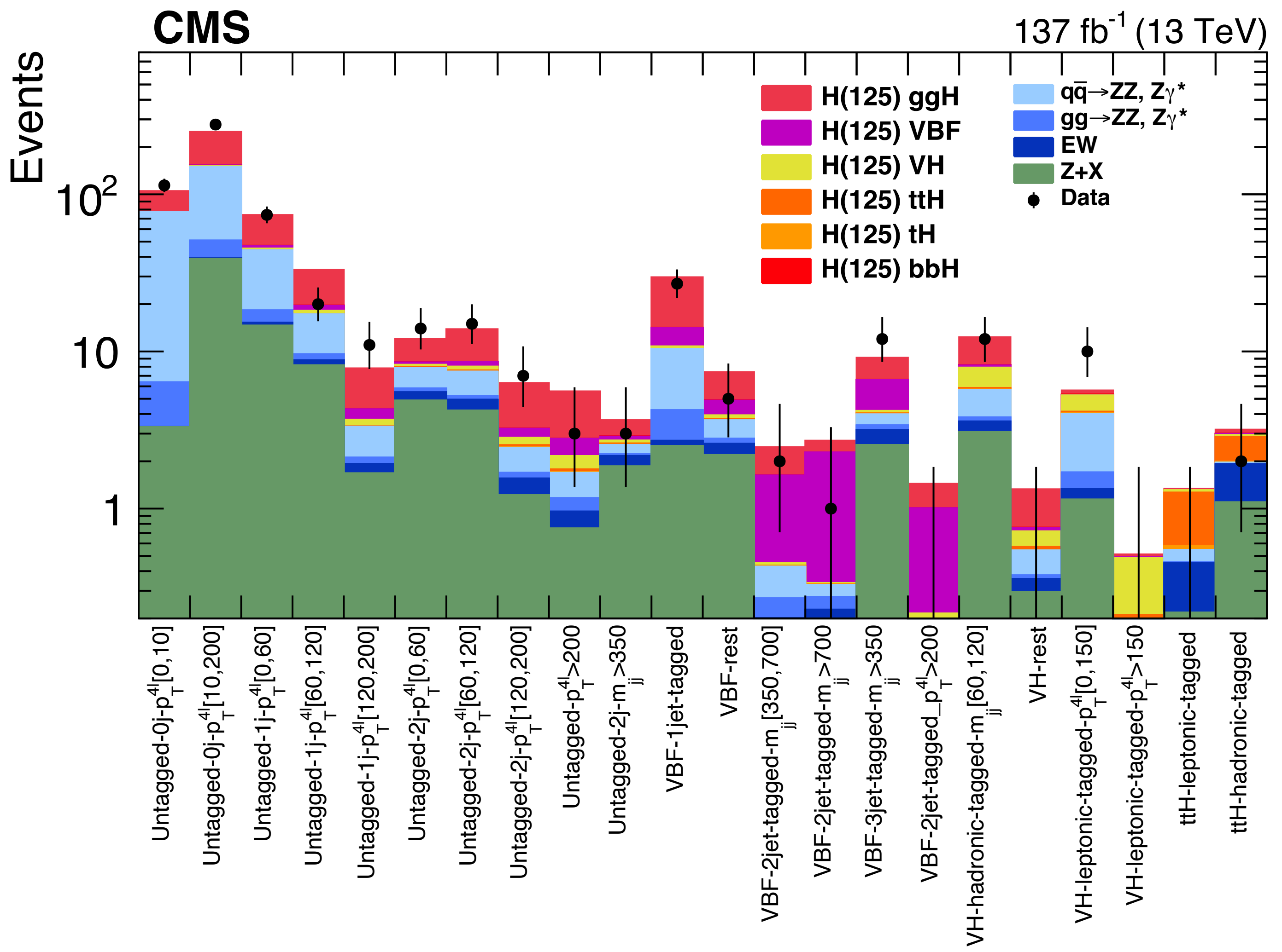






Higgs width is narrow: we can disentangle production and decay.

- 6 accessible production modes (ggH, VBF, WH, ZH, ttH, tH) X 7 decay (ZZ, WW, bb, ττ, γγ, γZ, μμ) → 42 possible combinations!



Basic strategy: separate analyses decay-wise, create a lot of categories and extract the different production modes. Then combine everything

What is a “combination”?

Easy to reinterpret

Need exp. knowledge

Simple: weighted average

- Can be done in a few moments with pen-and-paper
- Usually gets the right ball-park
- Neglects correlations between parameters

Not too simple: average + correlation matrix

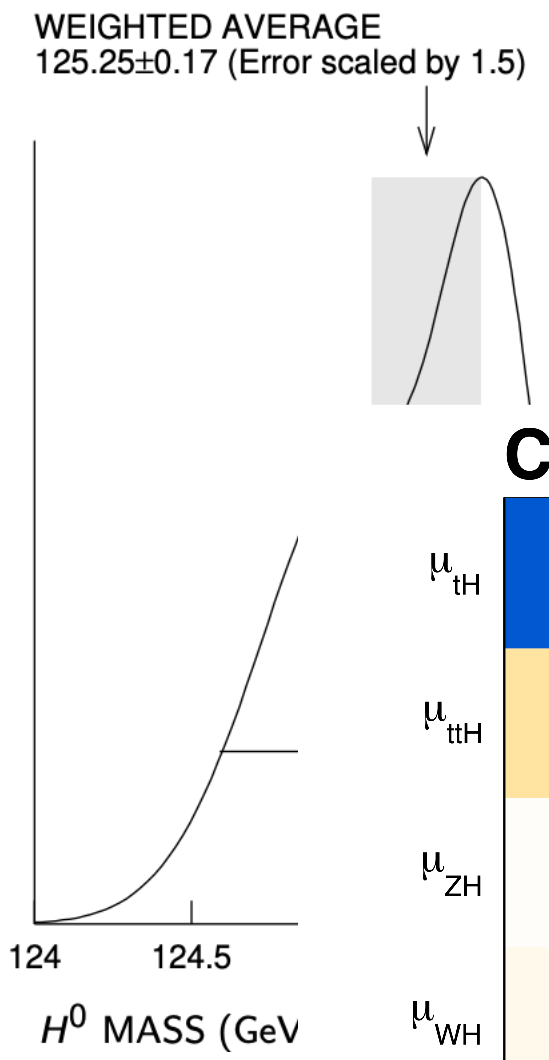
- Takes into account correlations between uncertainties, but neglects more subtle effects

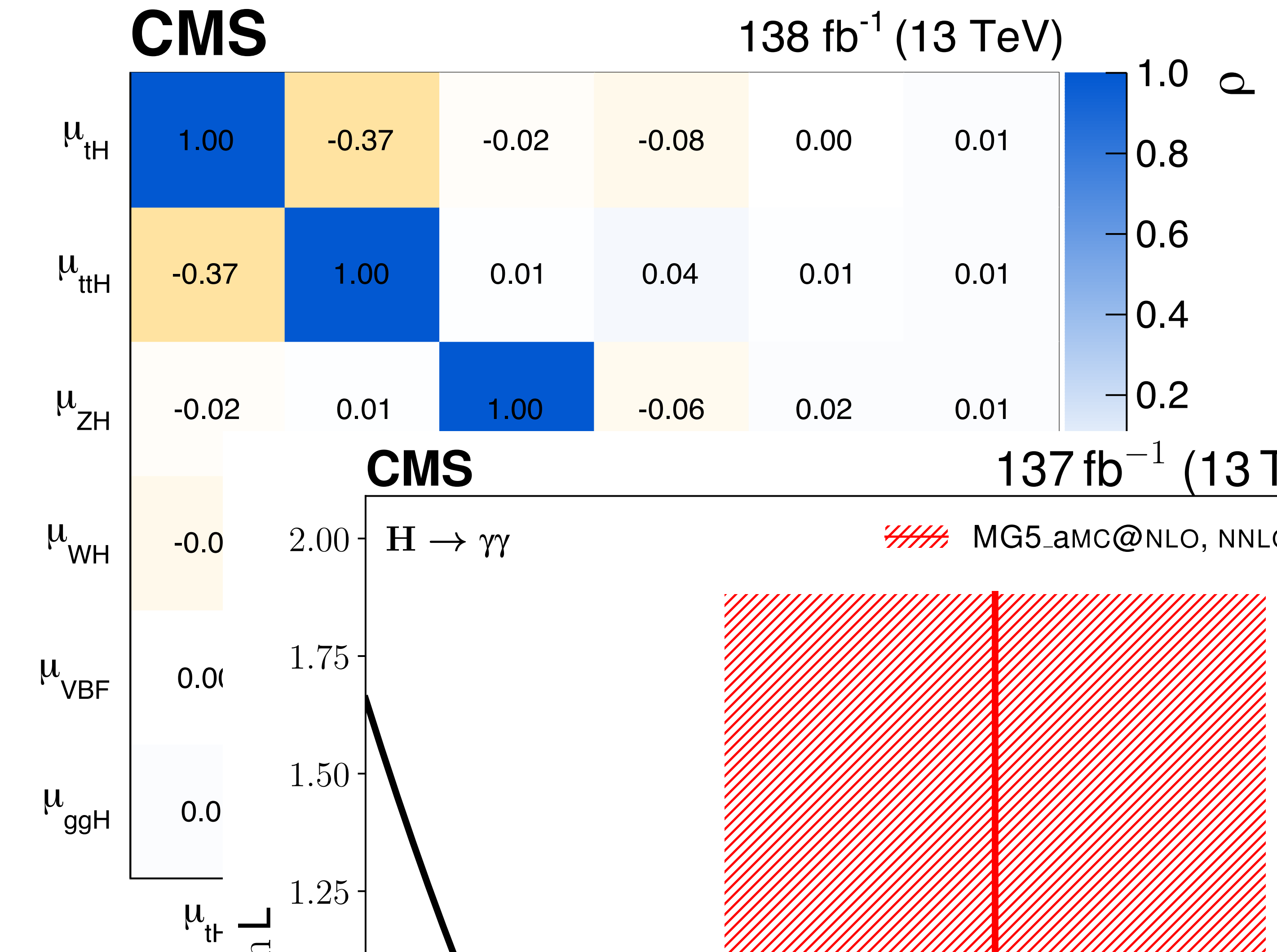
Complex: likelihood based.

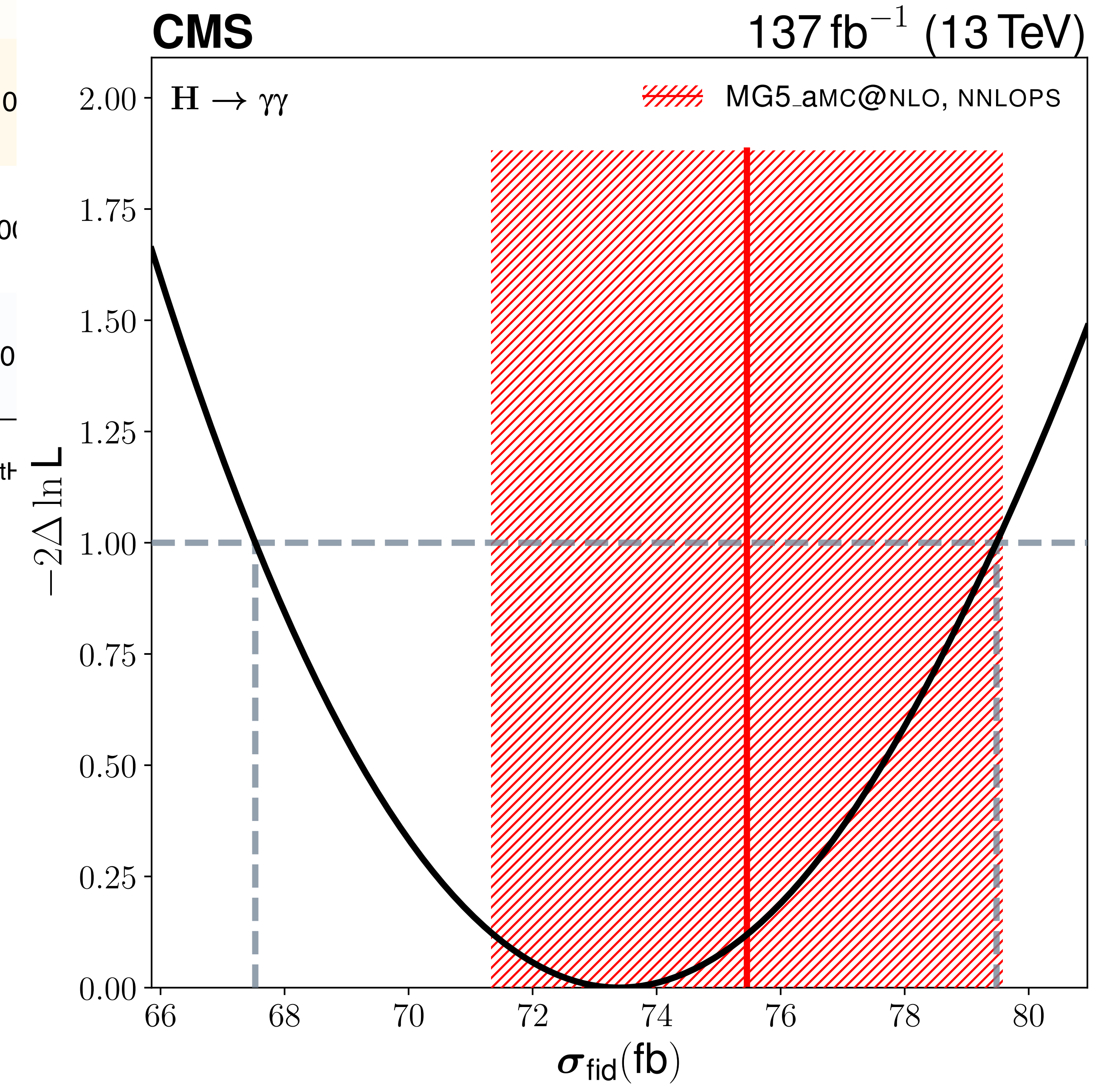
- Exploits the likelihood information to properly represents the physics model behind. ML algorithms can be developed to assist in this effort for example for CMS/ATLAS combinations

Full combination

- All relations between parameters are taken into account (this talk)

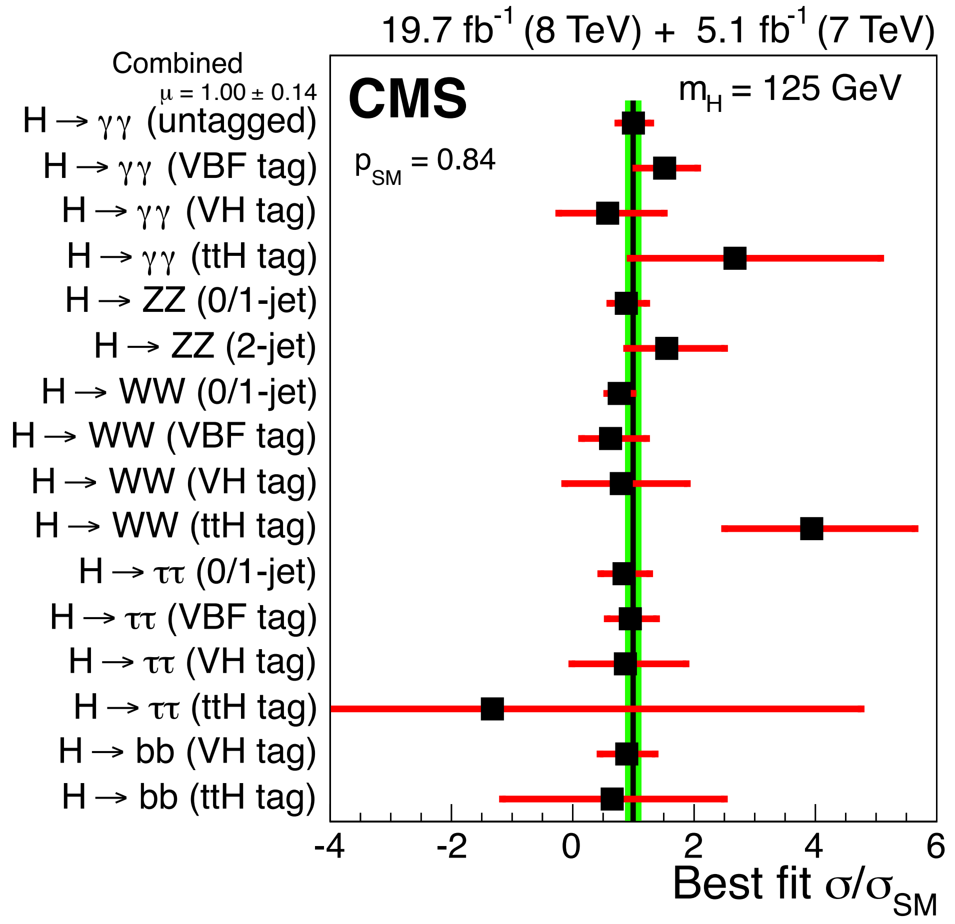






Increasing complexity

CMS has developed a set of roofit based suite of tools called combine (also available outside CMS) to ease combination efforts and ensure consistency across analyses.

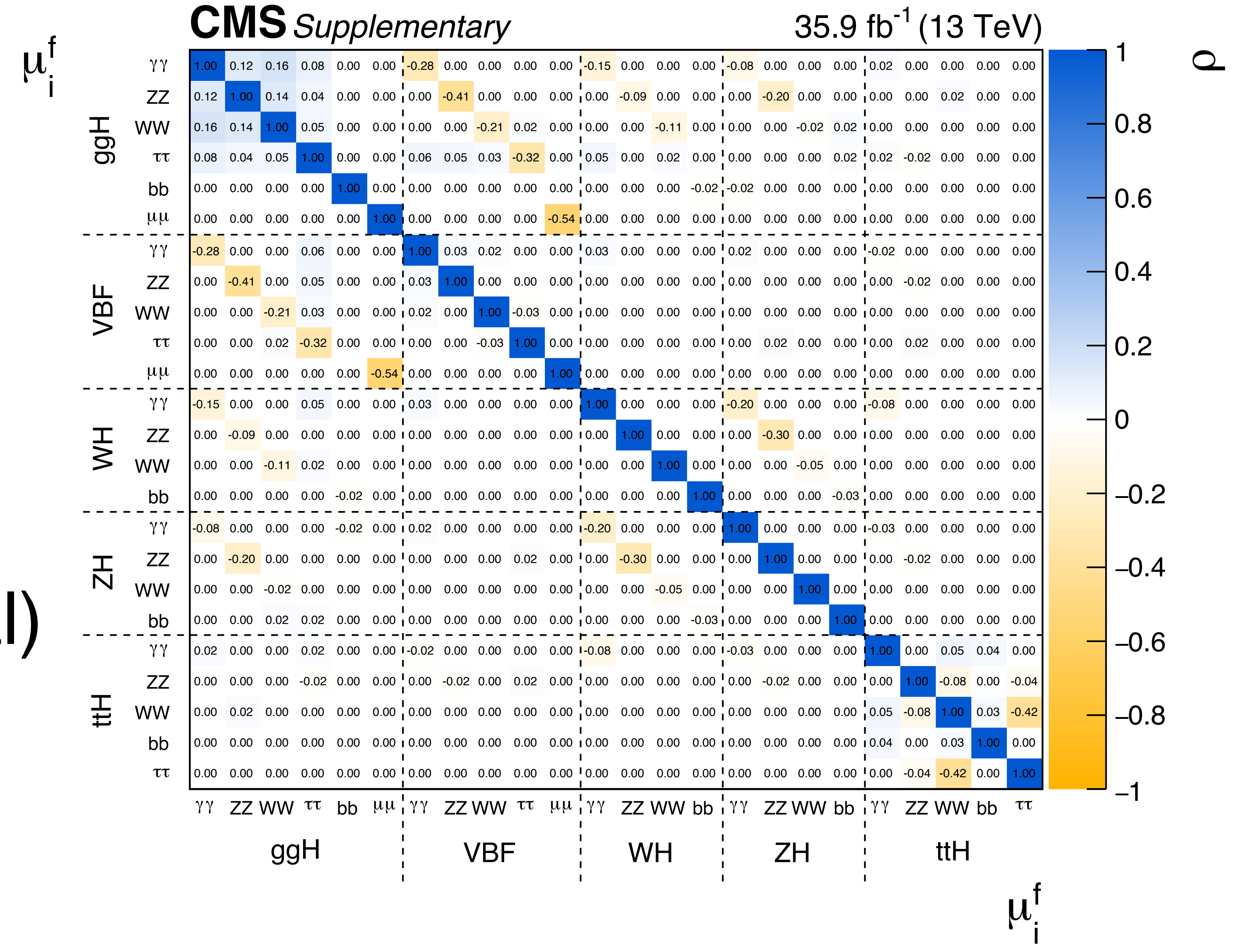


2012: Run 1 combination (Eur. Phys. J. C 75 (2015) 212)

- 216 (sub-)categories, 2500 nuisance parameters, 6+1 dimensions fit

2017: Run2 combination (Eur. Phys. J. C 79 (2019) 421)

- 265 Event categories, 5500+ nuisance parameters, 24 dimensions fit (in the most complex model)
- Runs in a bit more then 24 hours



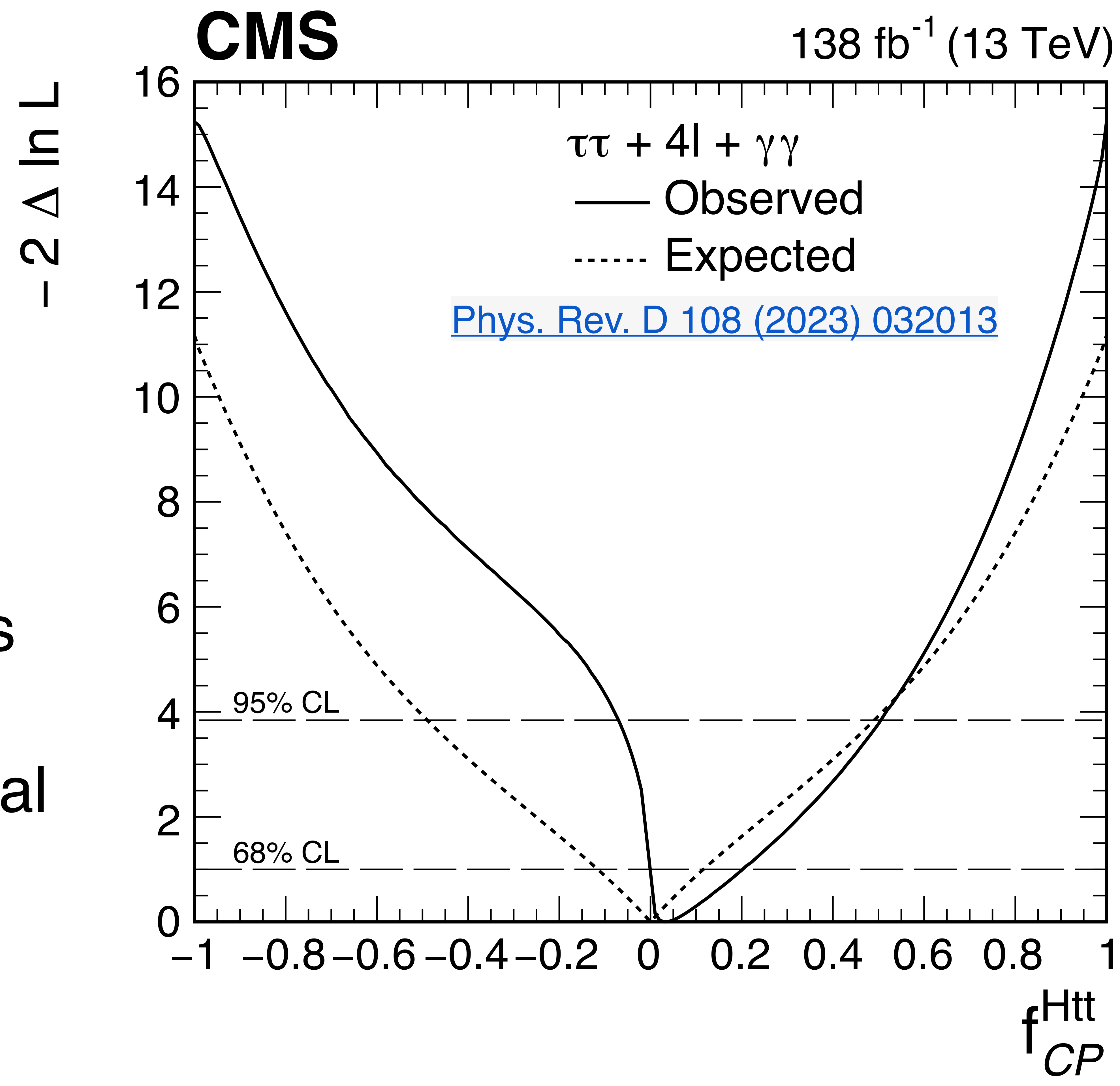
2022: 10-years since the discover (Nature 607 (2022) 60-68)

- 900 Event categories, STXS1.2 POI +EFT and anomalous couplings.
- ~4K nuisance parameters + MC statistical uncertainties (8000+ NP in total)
- 16GB+ to build the likelihood model, 10GB+ to perform the fit
- Runs in 24-48 hours!
- We had to use loss-y strategies to constraint the model complexity

Dedicated combinations

Using common tools, definitions, and conventions allows to "quickly" perform dedicated combinations targeting specific measurements, for example:

- Mass Involving high-resolution channels (and also the ATLAS experiment) → Savvas' talk
- Discoveries: performed between ATLAS and CMS when there's a chance of a new discovery. H discovery, Zγ evidence → Tina's talk
- HH is a very rare process. Combinations (within and across experiments) to enhance sensitivity → Jona's talk
- Higgs-top coupling is obtained from a combination of several channels → Philip's talk
- HZZ-H$\tau\tau$-H$\gamma\gamma$ performed a joint combination to measure anomalous Higgs couplings and CP violation in the Higgs sector → Angela's talk



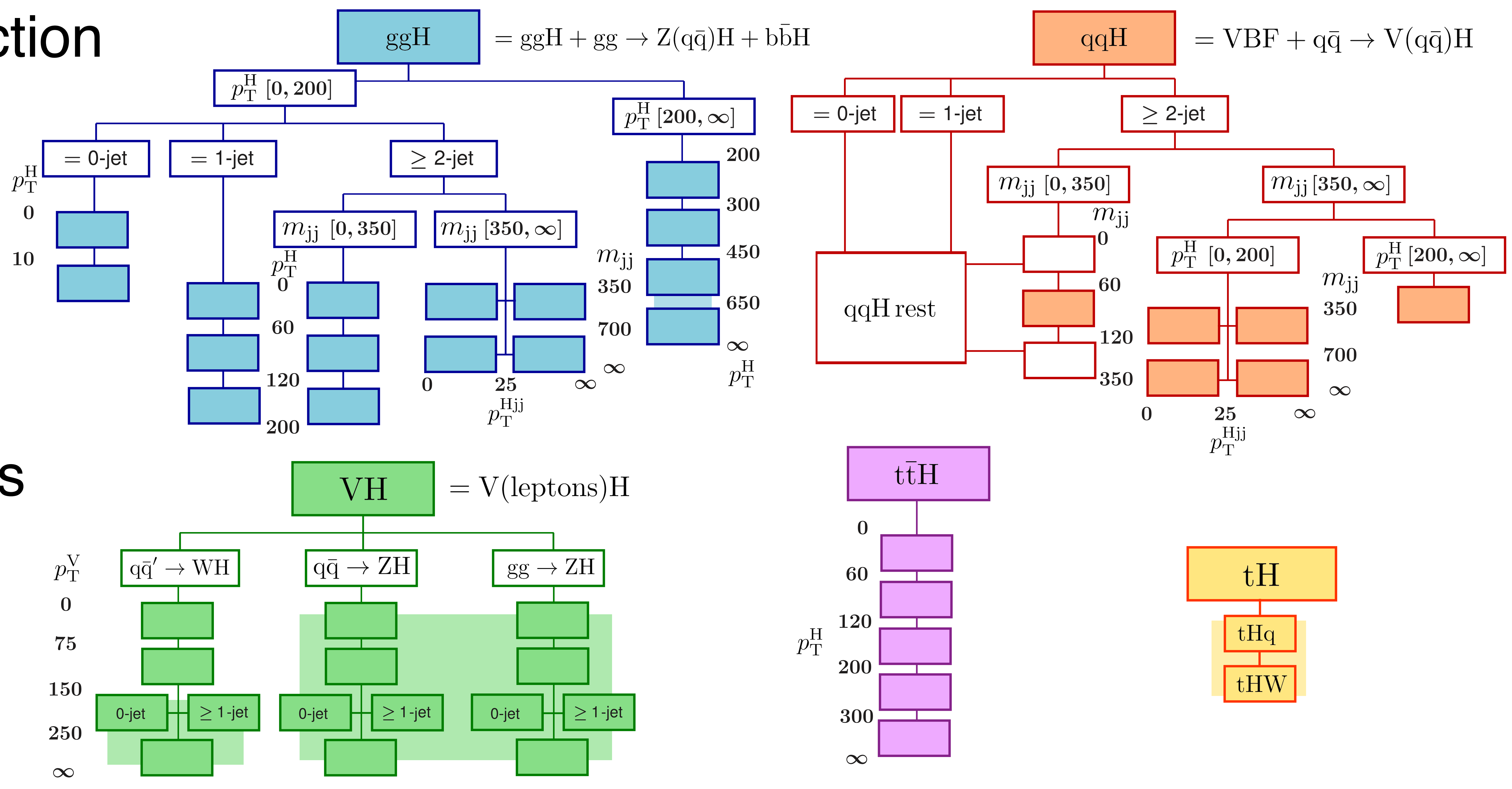
Measuring the Higgs couplings

At first, signal strengths μ (ratio of observed cross-section to SM predictions)

- Good to verify H(125) properties and check compatibility with SM

Second step, couplings via K-framework:

- Disentangles production and decay mechanisms.
- Effective coupling modifiers for processes with loops (k_g, k_γ, k_H…)



Couplings, κ

Parameters scale cross sections and partial widths relative to SM

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

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

Total width determined as

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

Where

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

Now, Simplified templates cross section

- Target maximum sensitivity, while keeping theoretical dependence as small as possible
- Cross section split by production mode and divided in exclusive regions of phase space (bins)
- Inclusive in Higgs decay
- Can be done in all decay modes
- Explicitly designed for combinations

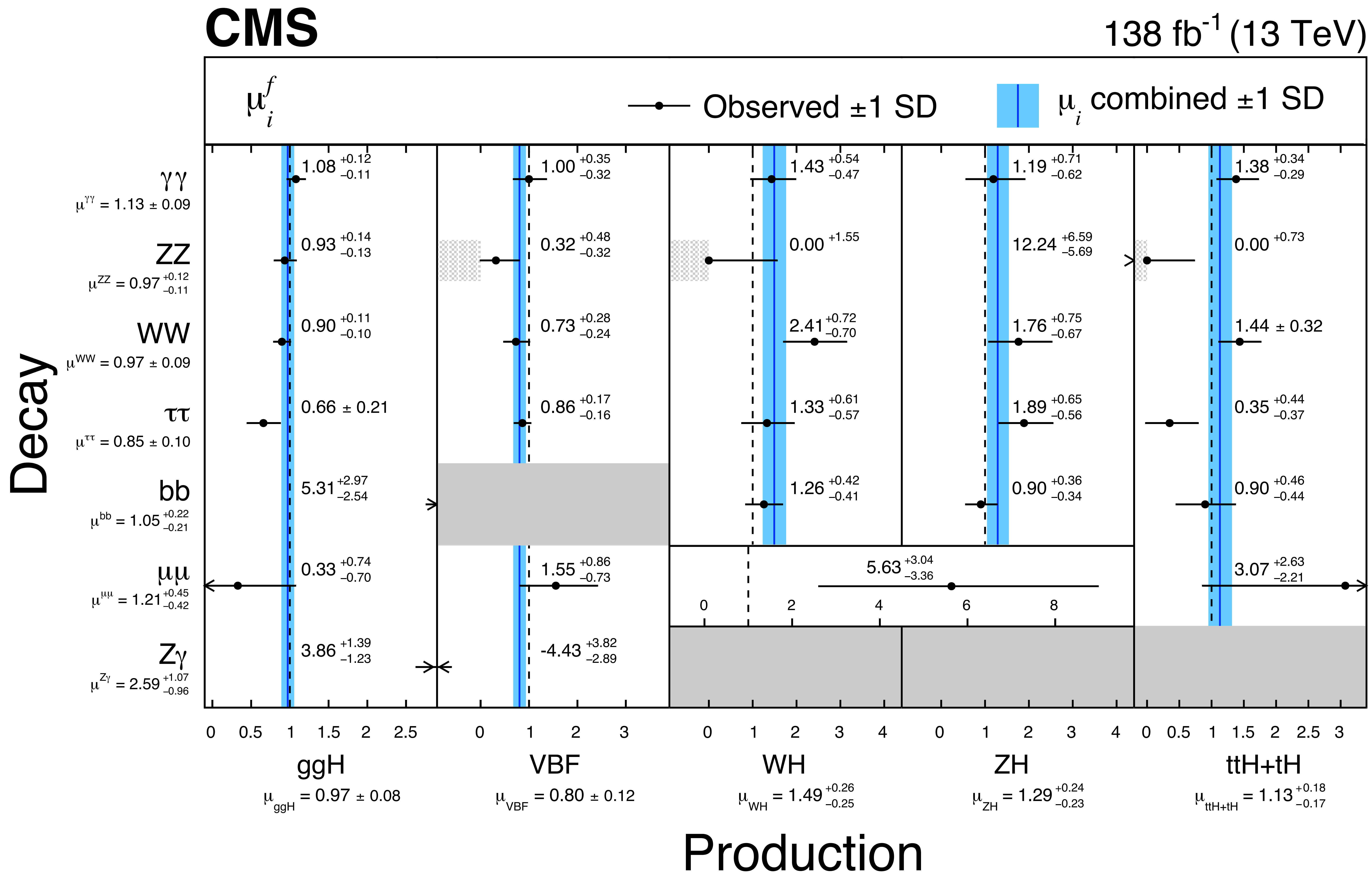
Putting all together: signal strengths

CMS combination matrix

Most results are in good agreement with expectations

Few discrepancies in channels with limited statistical precision

μ=1.002±0.057



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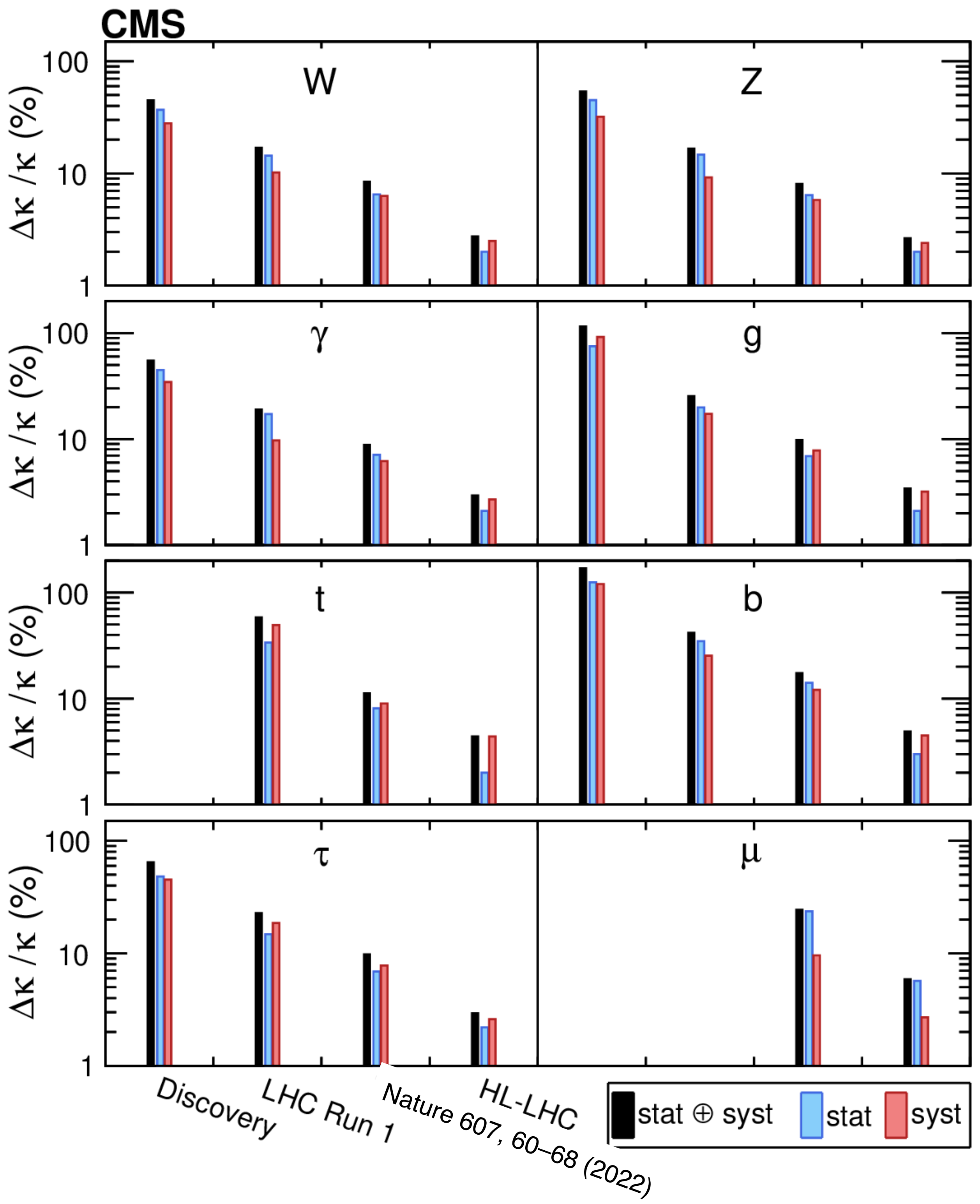
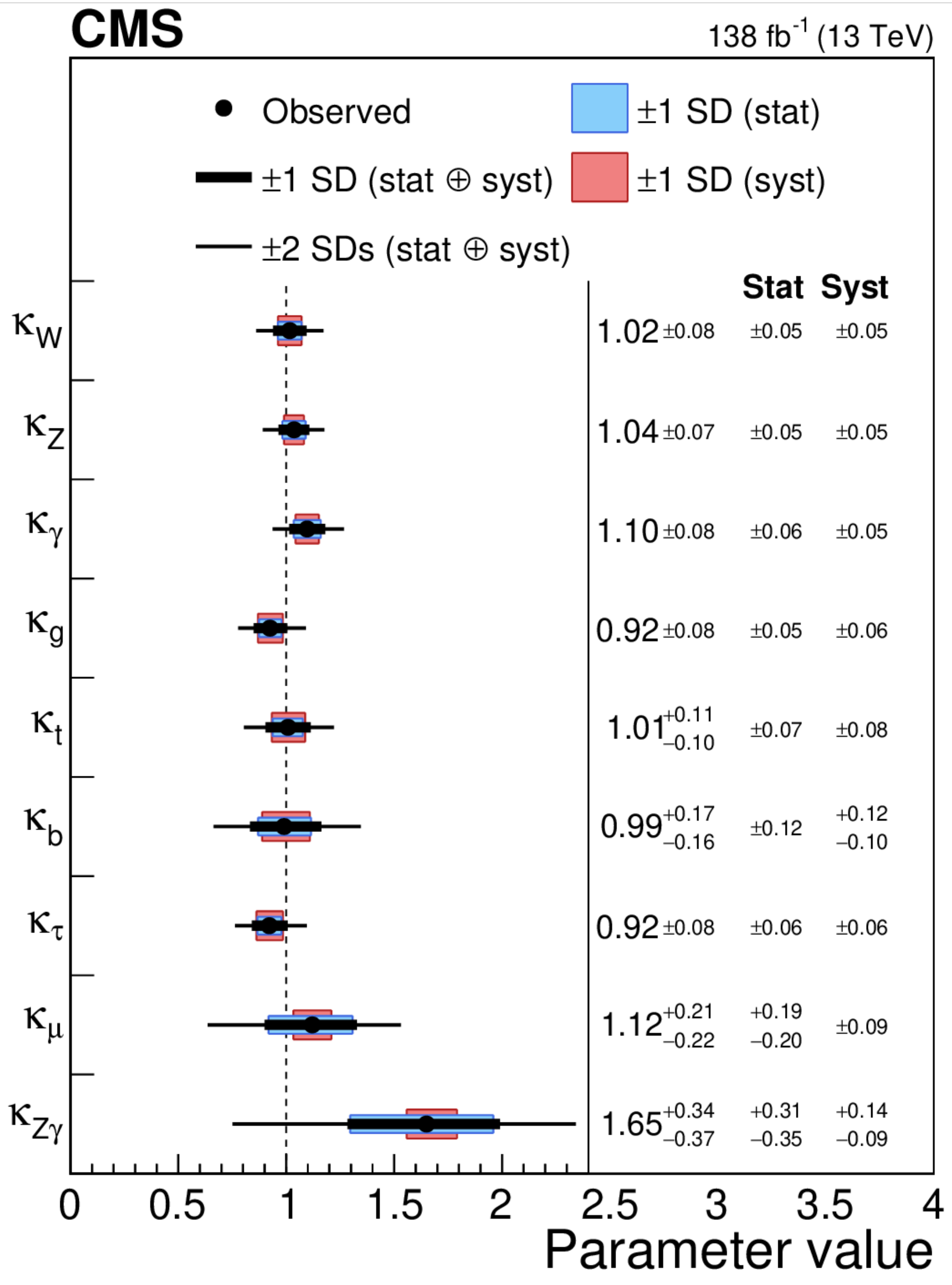
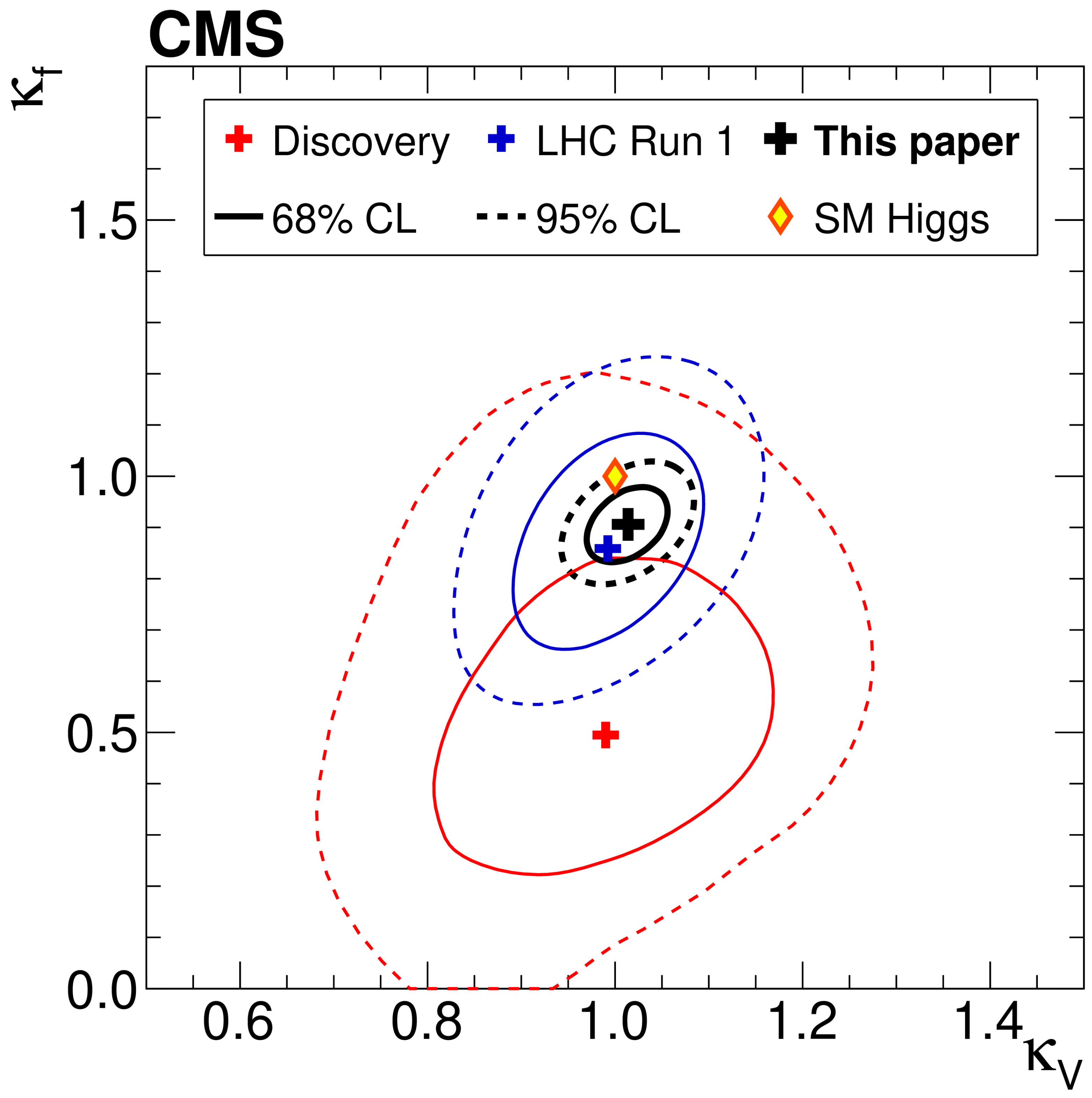
Putting all together: couplings







Impressive improvement on Higgs couplings determination over the years

couplings to boson and 3rd generation particles are now known at ~10% level, with no significant deviations from the SM predictions

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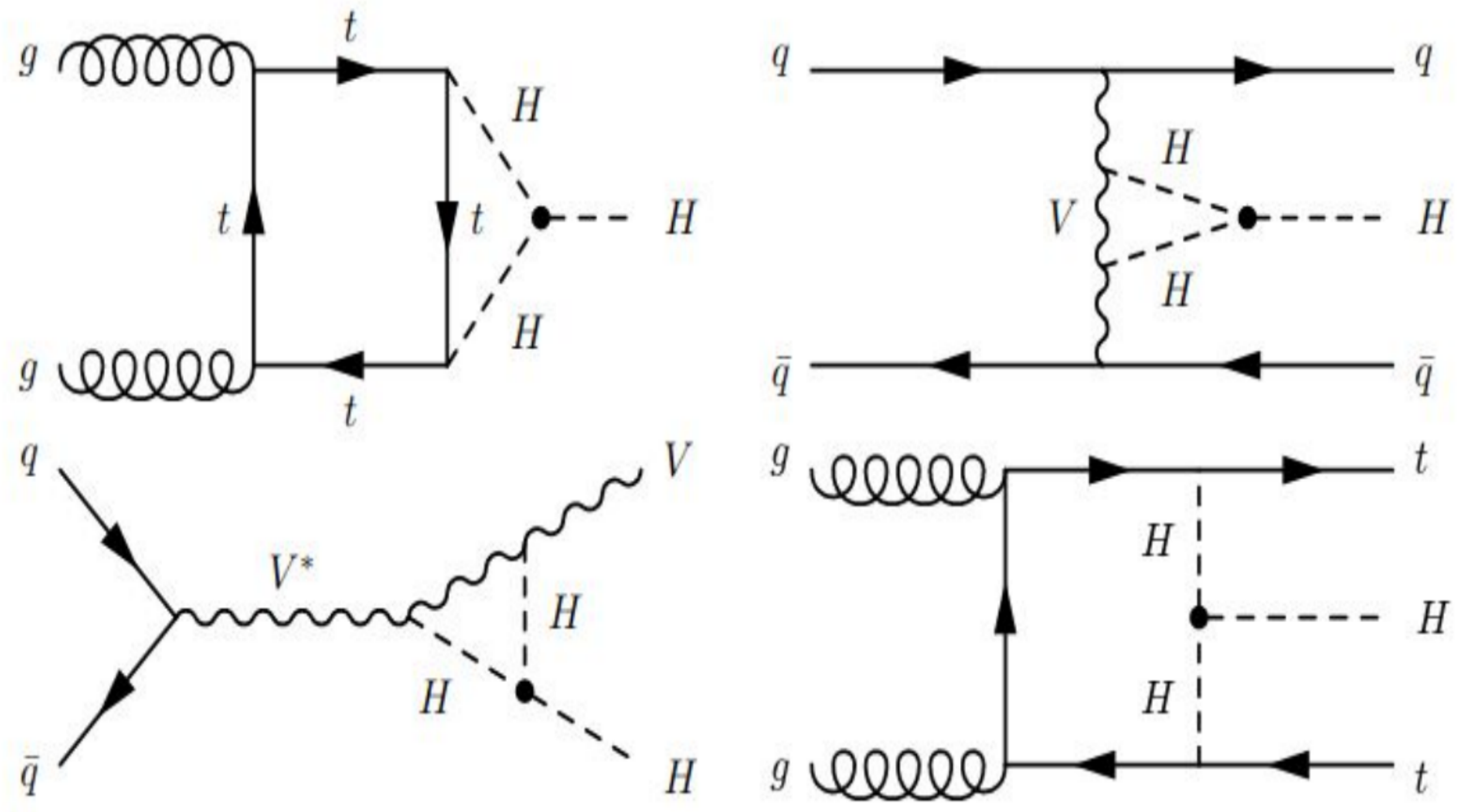
Higgs self-coupling

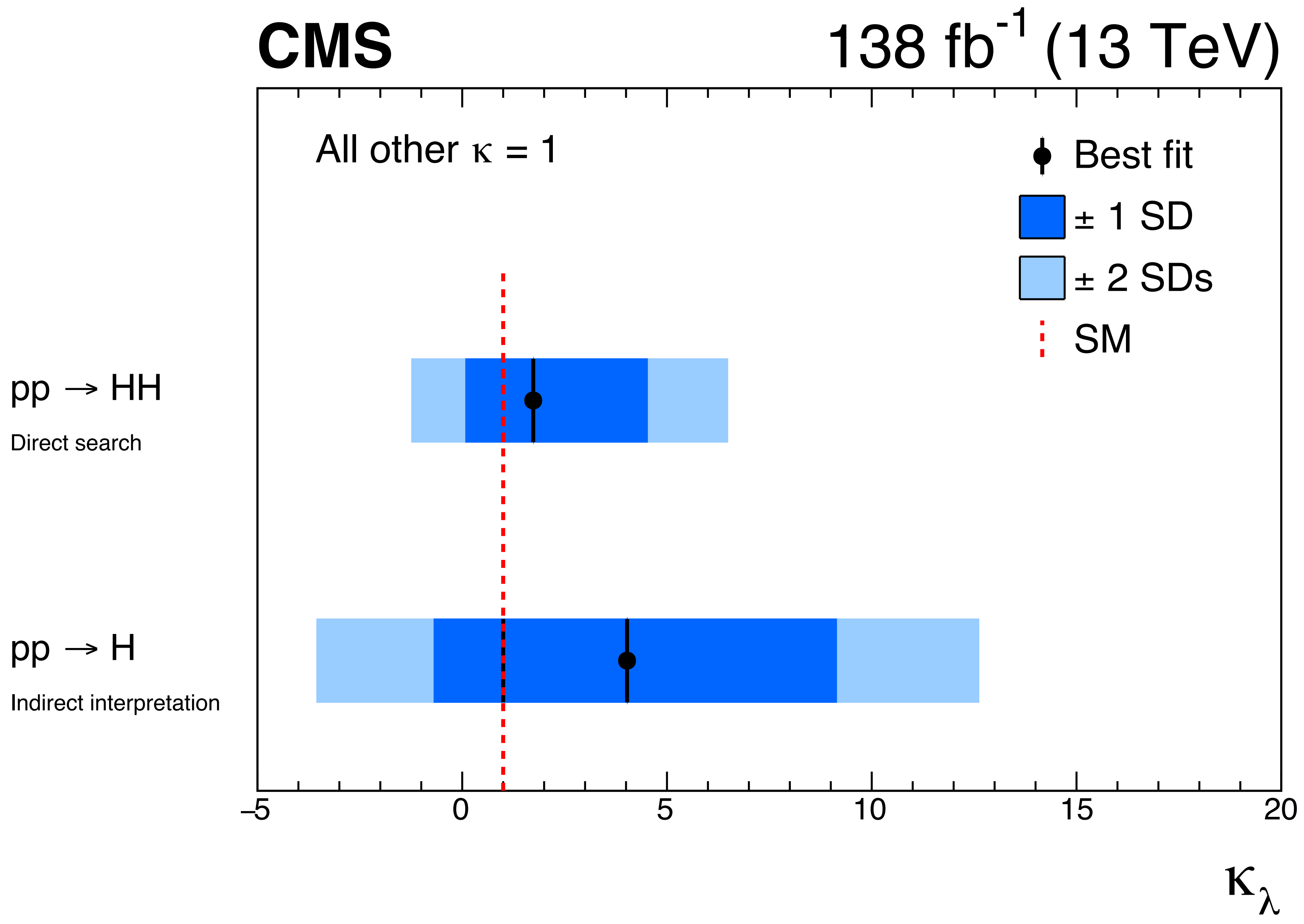


The Higgs self-coupling affects the Higgs propagator and enters single Higgs production via loops

Combining several channels together, it is possible to extract limits on the Higgs trilinear coupling k_λ (indirect measurement)

Single and double Higgs production are not meant to be a separate effort though!

By combining the direct and indirect measurement it is possible to profit from the **higher precision** of the direct measurement and at the same time **remove degeneracy** due to the assumptions on the SM couplings

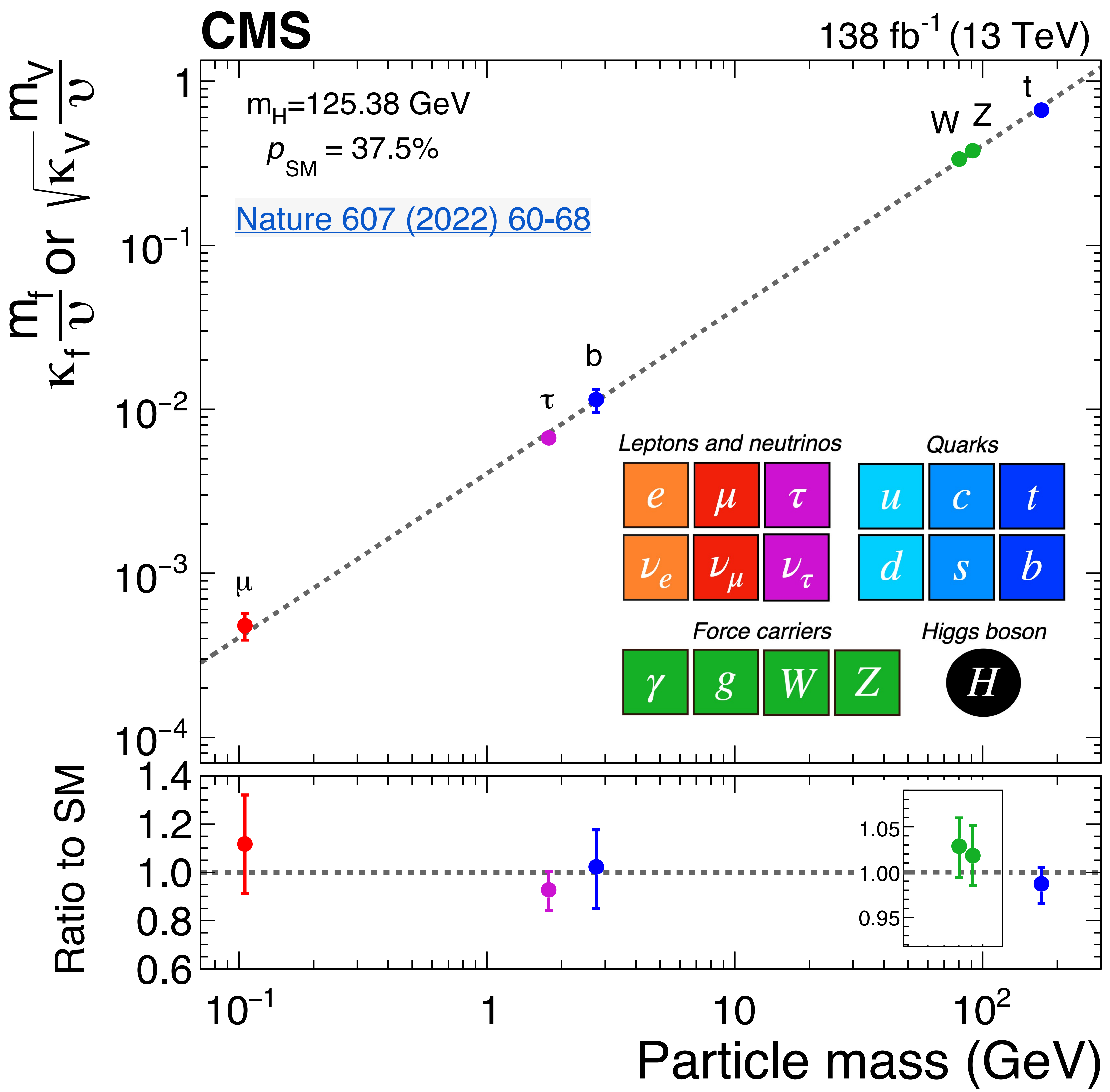


See Jona’s talk for more details

The SM, 10+ years after the Higgs discovery

The Higgs sector of the standard model, tested across 3 orders of magnitude in particles masses shows an amazing agreement with the theoretical predictions for the scaling of the couplings.

We are starting to probe the 2nd generation!



Conclusions

To have a consistent summary of our knowledge of the Higgs sector, combinations of the different results are needed

Huge efforts, requiring coordination, expertise, computing power and patience
- Not to mention cross-experiment combinations!

Beyond full global combination, other efforts targeting more specific aspects of the SM profit from the expertise obtained in Higgs combination (and the combine tool):
- HVV anomalous couplings, HH combinations, H-top coupling,…

Combinations have become more complex and more flexible, allowing to test several representations at once (EFT, STXS, k, signal strengths, …).

The overall agreement with the SM is extremely good.