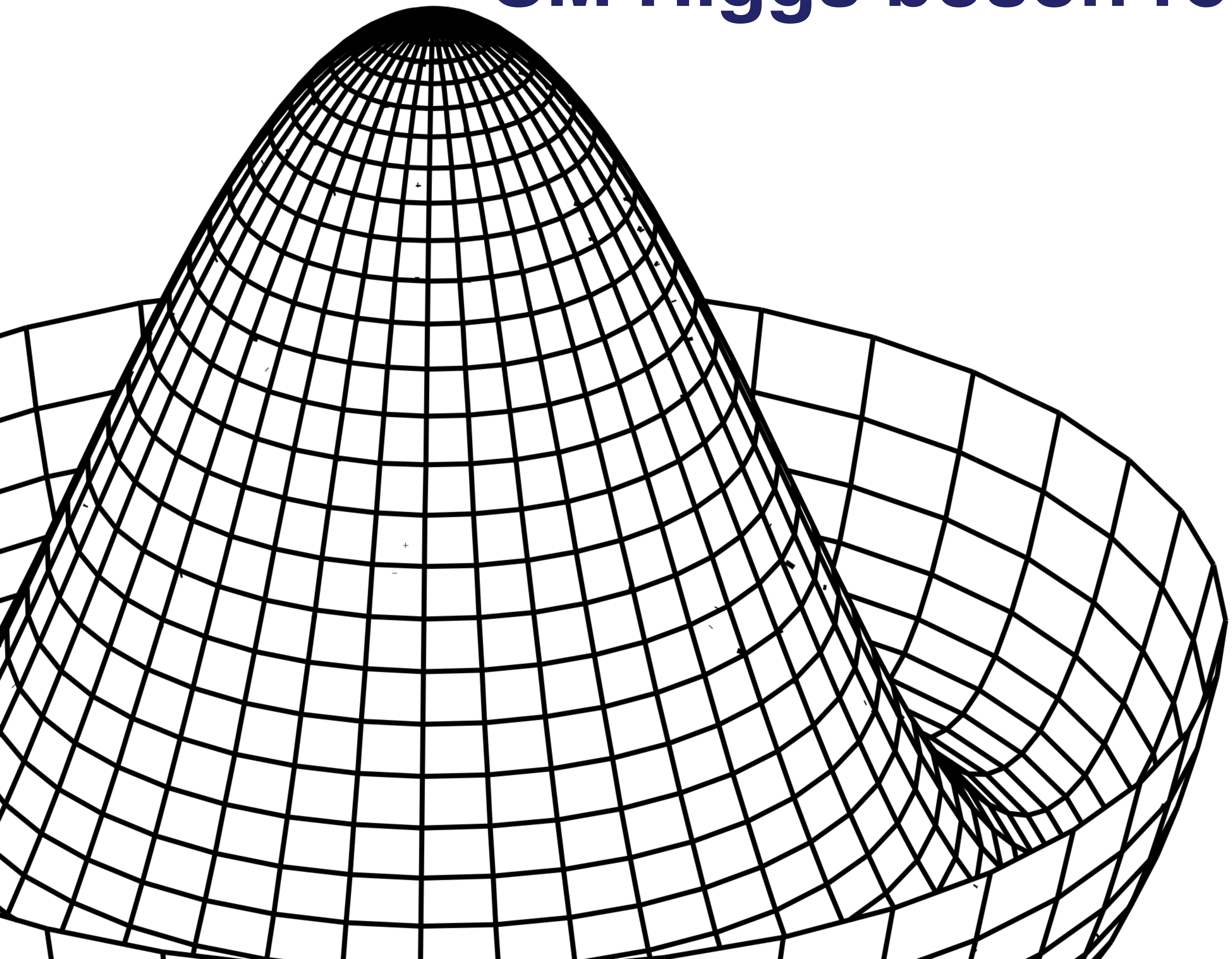
SM Higgs boson results from CMS



Roberto Salerno

CERN · cnrs IN2P3 · LLR · École Polytechnique IP Paris

The primary target of the Higgs boson physics

Determination of the Higgs boson properties and their connection with ElectroWeak Symmetry Breaking

The primary target of the Higgs boson physics

Determination of the Higgs boson properties and their connection with ElectroWeak Symmetry Breaking

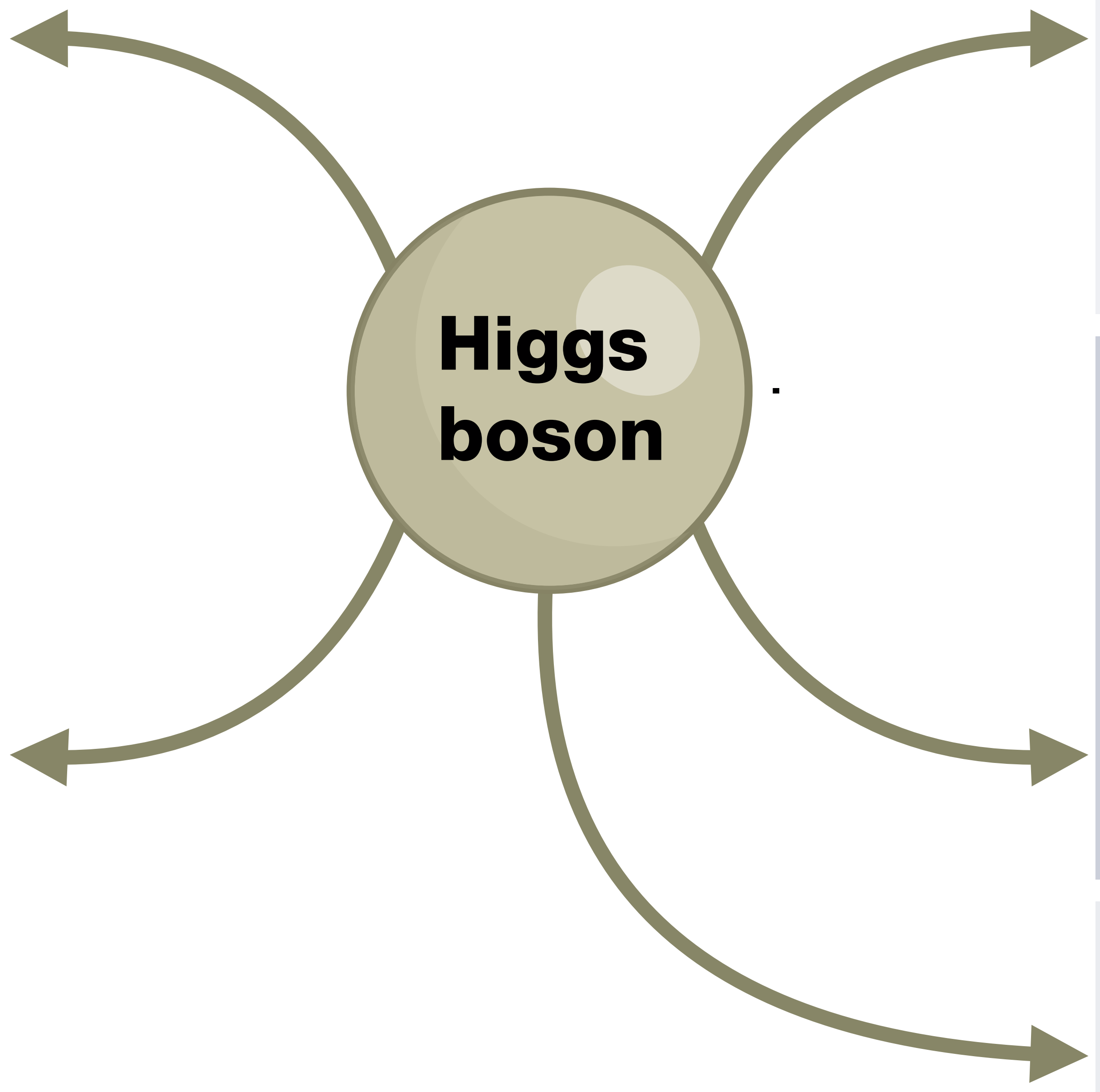
More profound questions could be asked

Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the *W* and *Z* bosons?

Why is there more matter than antimatter in the Universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?



What is dark matter?

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+ \tau^-$)?

What is the origin of the early Universe inflation?

- Any imprint in cosmological observations?

G. P. Salam, L. Wang, G. Zanderighi : Nature 607, 41-47 (2022)

The Higgs boson mass : "is not" vs. "is"

✔ The Higgs boson mass **is not** a prediction of the theory but the Higgs boson mass **is** free input parameter of the theory

✔ The Higgs boson mass measurement **is not** a test of the SM but the Higgs boson mass **is** an important[1)] ingredient in SM predictions of many "m_H-dependent" SM observables:

- **Higgs boson observables : couplings, branching ratios, width**
- **Electroweak observables : mass of the W boson, mass of the top quark, effective weak mixing angle, ...**

✔ The Higgs boson mass value **is** connected to the Fermi and the Planck scales and ultimately with the vacuum stability

1) I would argue that is the most important

m_H and effects on EWK observables

Approximated parametrisation for the mass of W boson (m_W) :

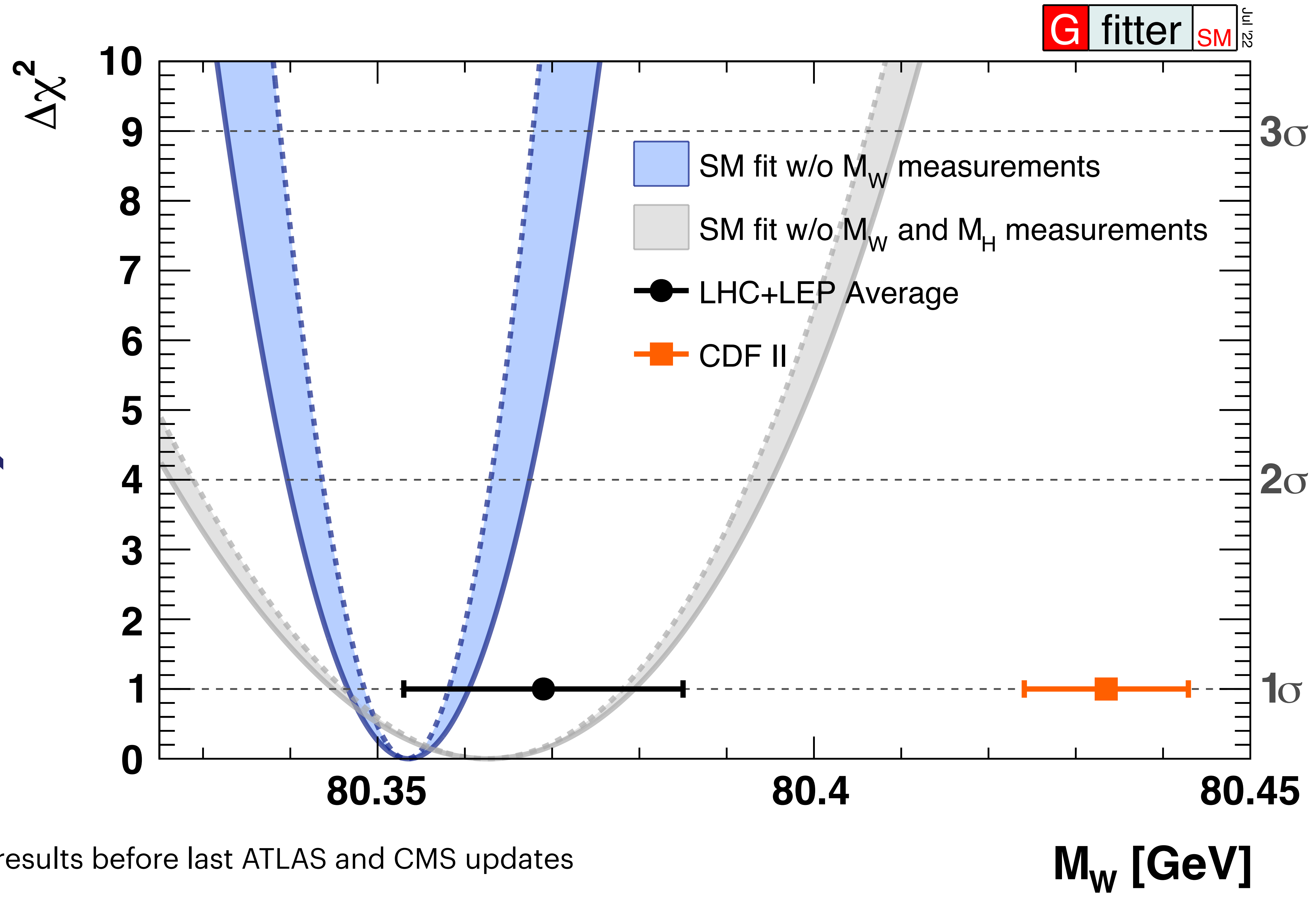
$$M_W = M_W^0 - c_1\,dH - c_2\,dH^2 + c_3\,dH^4 + c_4(dh-1) - c_5\,d\alpha + c_6\,dt - c_7\,dt^2 - c_8\,dH\,dt + c_9\,dh\,dt - c_{10}\,d\alpha_s + c_{11}\,dZ,$$

Significant one loop corrections growing like the logarithm of m_H.

where

$$dH = \ln\left(\frac{M_H}{100\ \text{GeV}}\right), \quad dh = \left(\frac{M_H}{100\ \text{GeV}}\right)^2, \quad dt = \left(\frac{m_t}{174.3\ \text{GeV}}\right)^2 - 1,$$

$$dZ = \frac{M_Z}{91.1875\ \text{GeV}} - 1, \quad d\alpha = \frac{\Delta\alpha}{0.05907} - 1, \quad d\alpha_s = \frac{\alpha_s(M_Z)}{0.119} - 1,$$



LHC experimental results before last ATLAS and CMS updates

m_H and effects on EWK observables

Approximated parametrisation for the mass of W boson (m_W) :

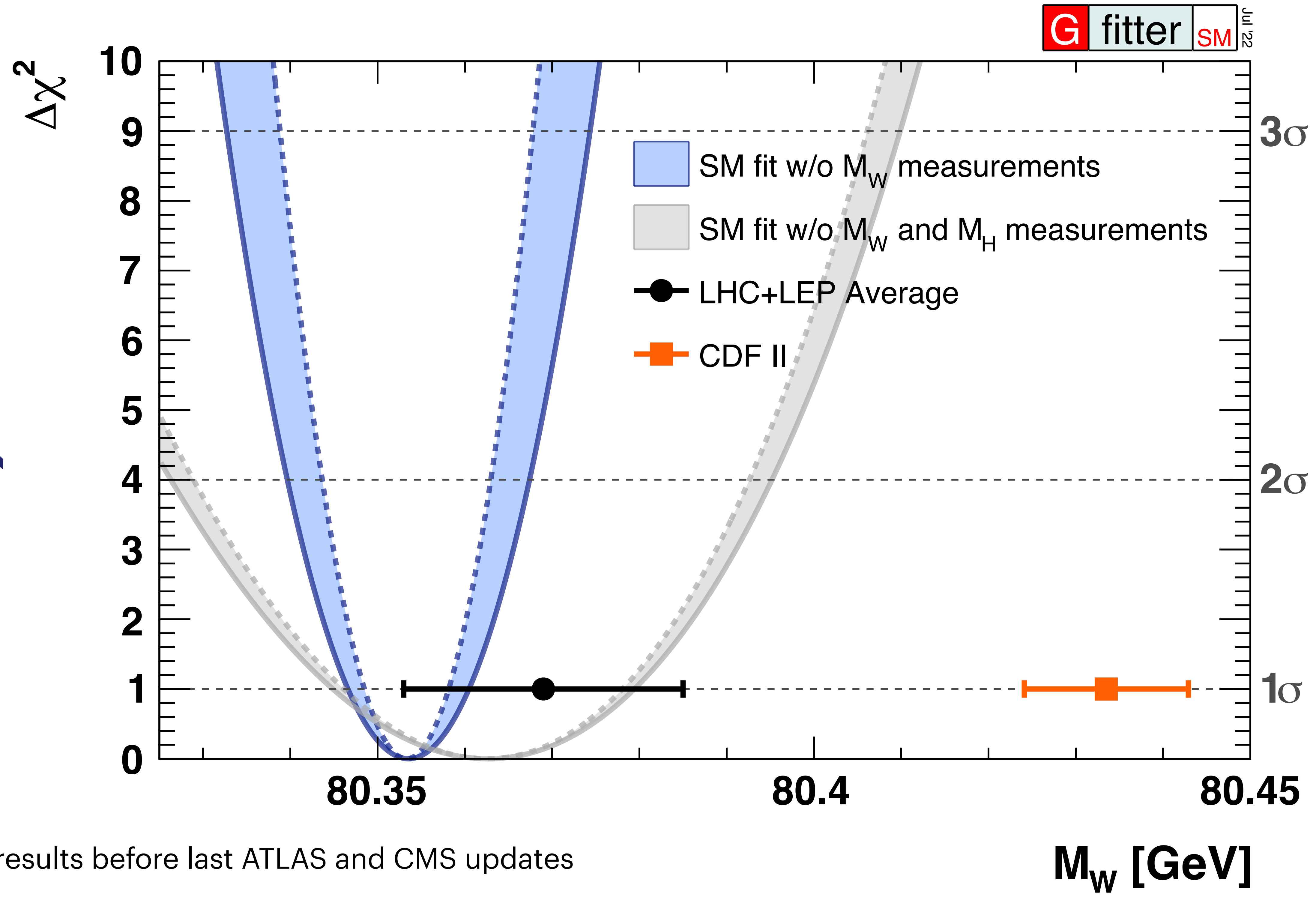
$$M_W = M_W^0 - c_1\,\mathrm{dH} - c_2\,\mathrm{dH}^2 + c_3\,\mathrm{dH}^4 + c_4(\mathrm{dh}-1) - c_5\,\mathrm{d}\alpha + c_6\,\mathrm{dt} - c_7\,\mathrm{dt}^2 - c_8\,\mathrm{dH}\,\mathrm{dt} + c_9\,\mathrm{dh}\,\mathrm{dt} - c_{10}\,\mathrm{d}\alpha_s + c_{11}\,\mathrm{dZ},$$

Significant one loop corrections growing like the logarithm of m_H.

where

$$\mathrm{dH} = \ln\left(\frac{M_H}{100\ \mathrm{GeV}}\right), \quad \mathrm{dh} = \left(\frac{M_H}{100\ \mathrm{GeV}}\right)^2, \quad \mathrm{dt} = \left(\frac{m_t}{174.3\ \mathrm{GeV}}\right)^2 - 1,$$

$$\mathrm{dZ} = \frac{M_Z}{91.1875\ \mathrm{GeV}} - 1, \quad \mathrm{d}\alpha = \frac{\Delta\alpha}{0.05907} - 1, \quad \mathrm{d}\alpha_s = \frac{\alpha_s(M_Z)}{0.119} - 1,$$



LHC experimental results before last ATLAS and CMS updates

Intermezzo

You will know everything about the new results from CMS on M_W (**the most precise at LHC!**) in David Walter's talk this week

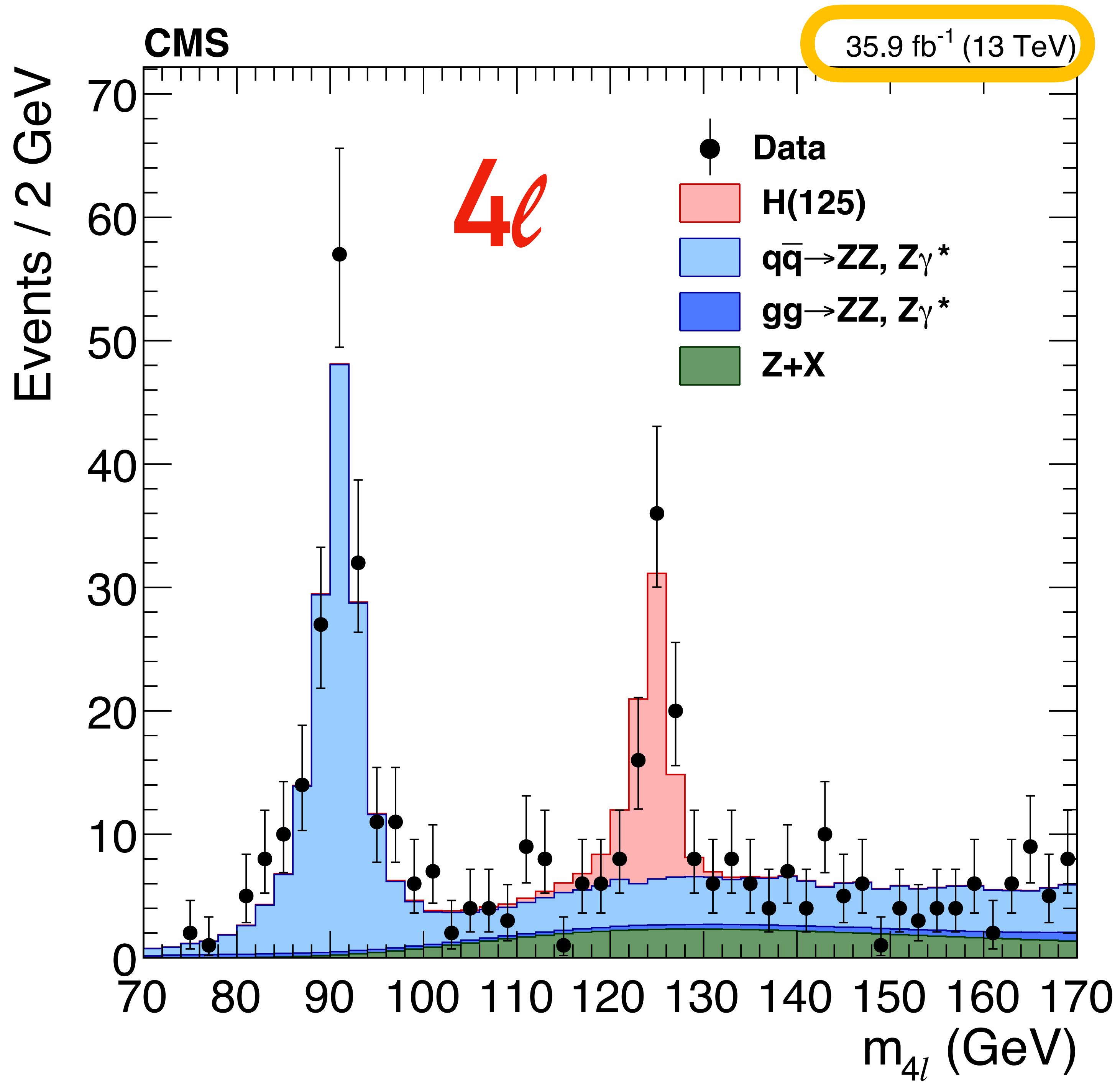
The Higgs boson mass measurement

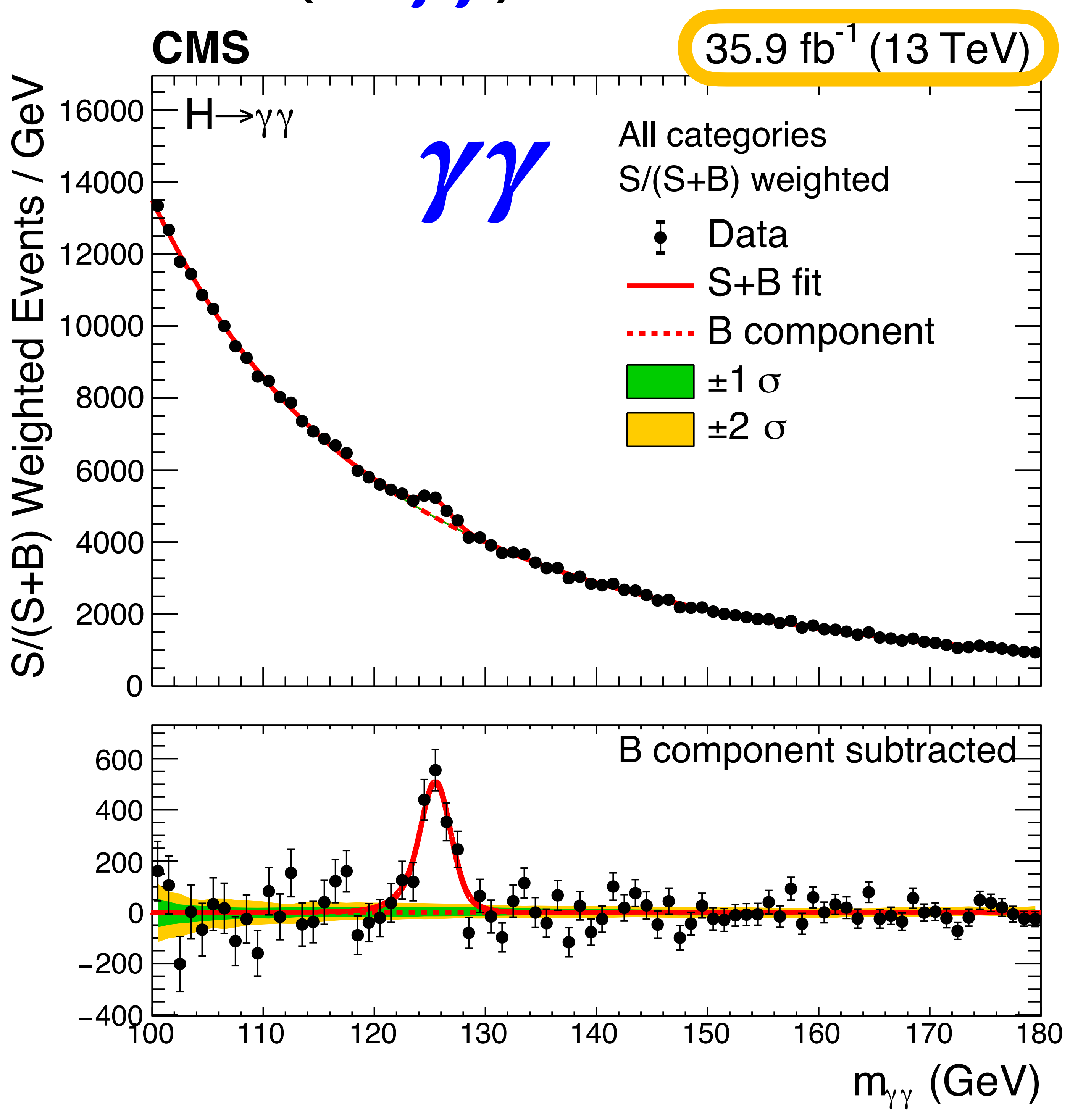
PLB 805 (2020) 135425

The concept oversimplified

"Mass Peaks"

using high resolution channels (4ℓ+$\gamma\gamma$)





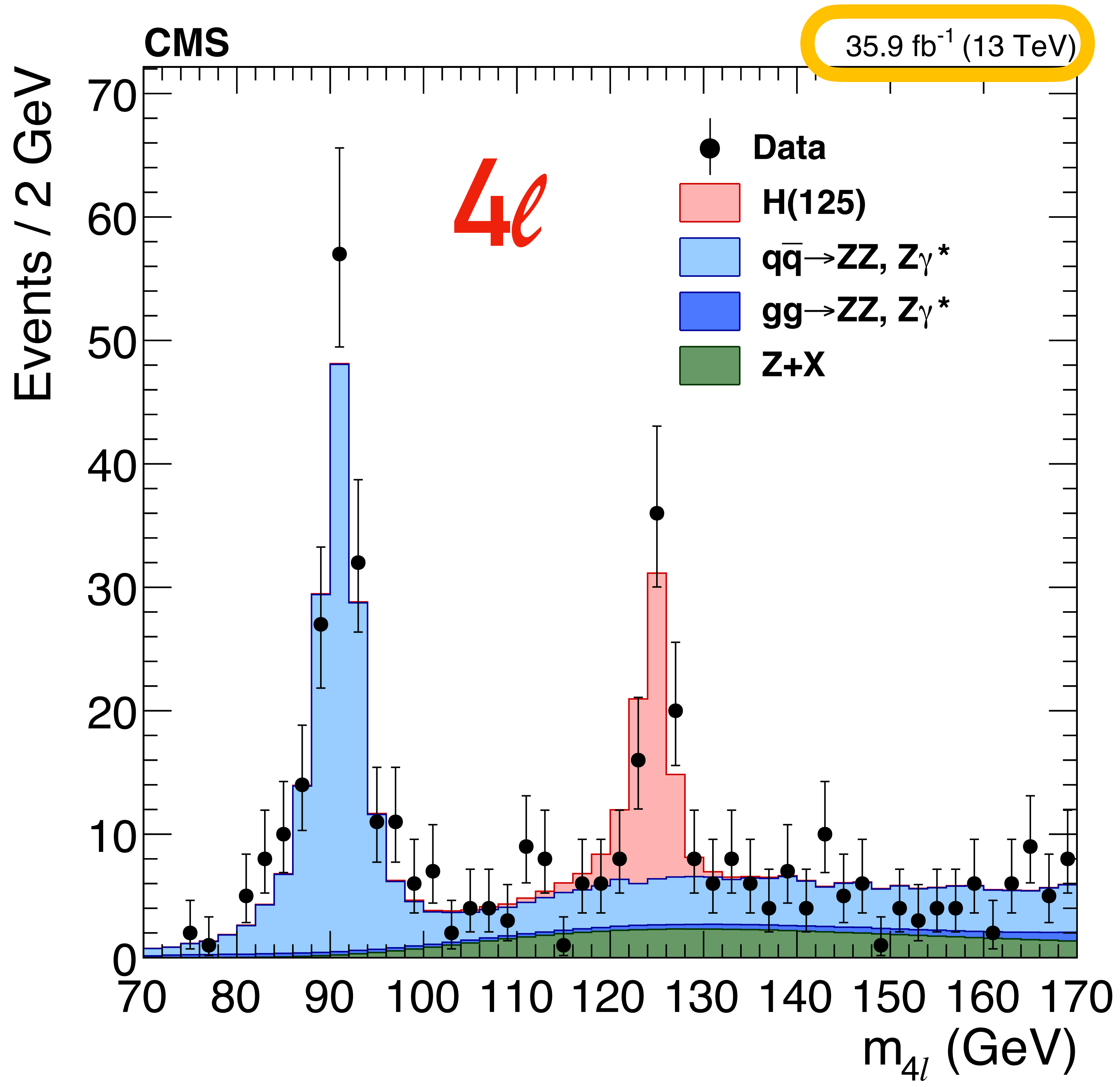
The Higgs boson mass measurement

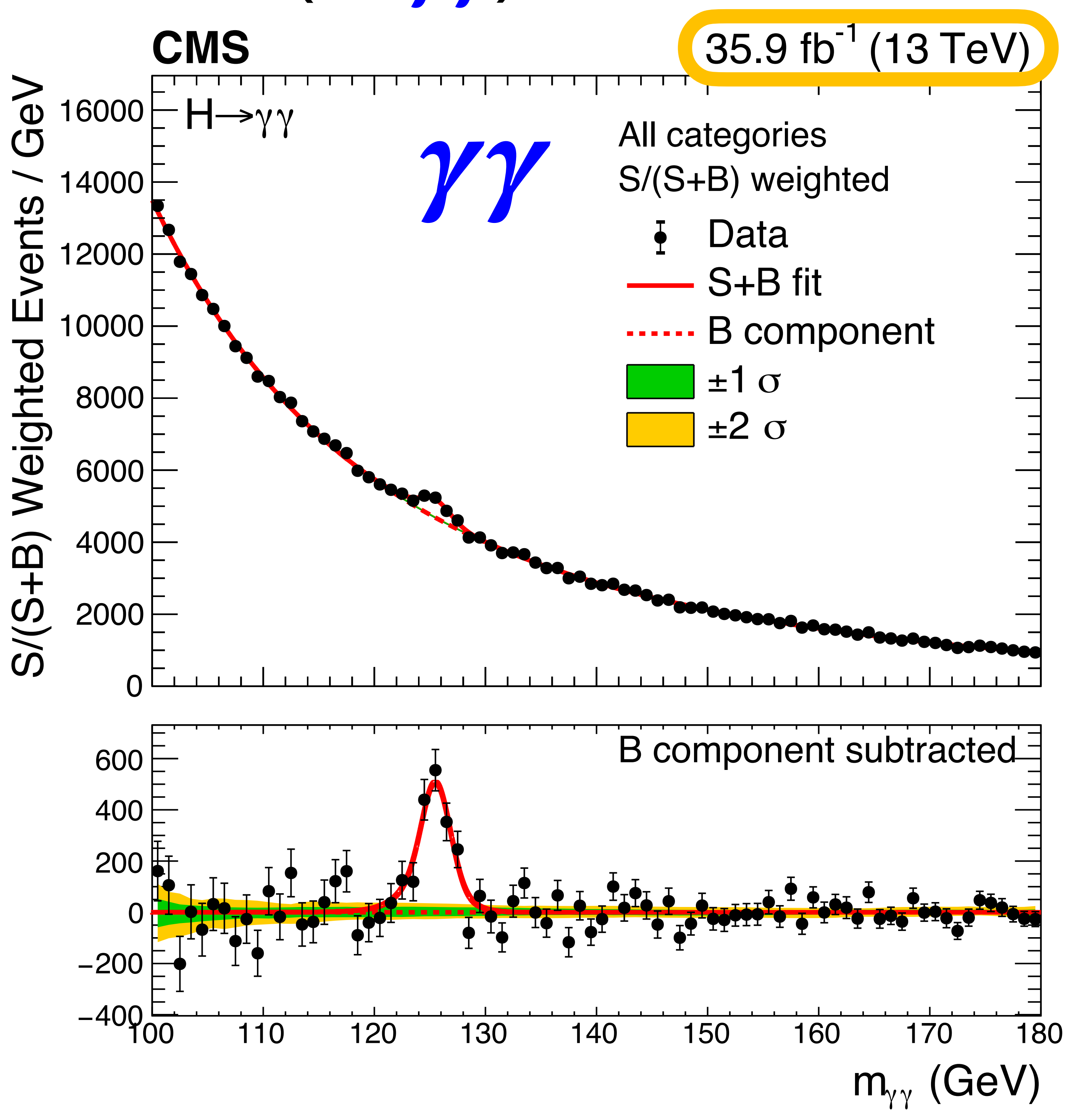
PLB 805 (2020) 135425

The concept oversimplified

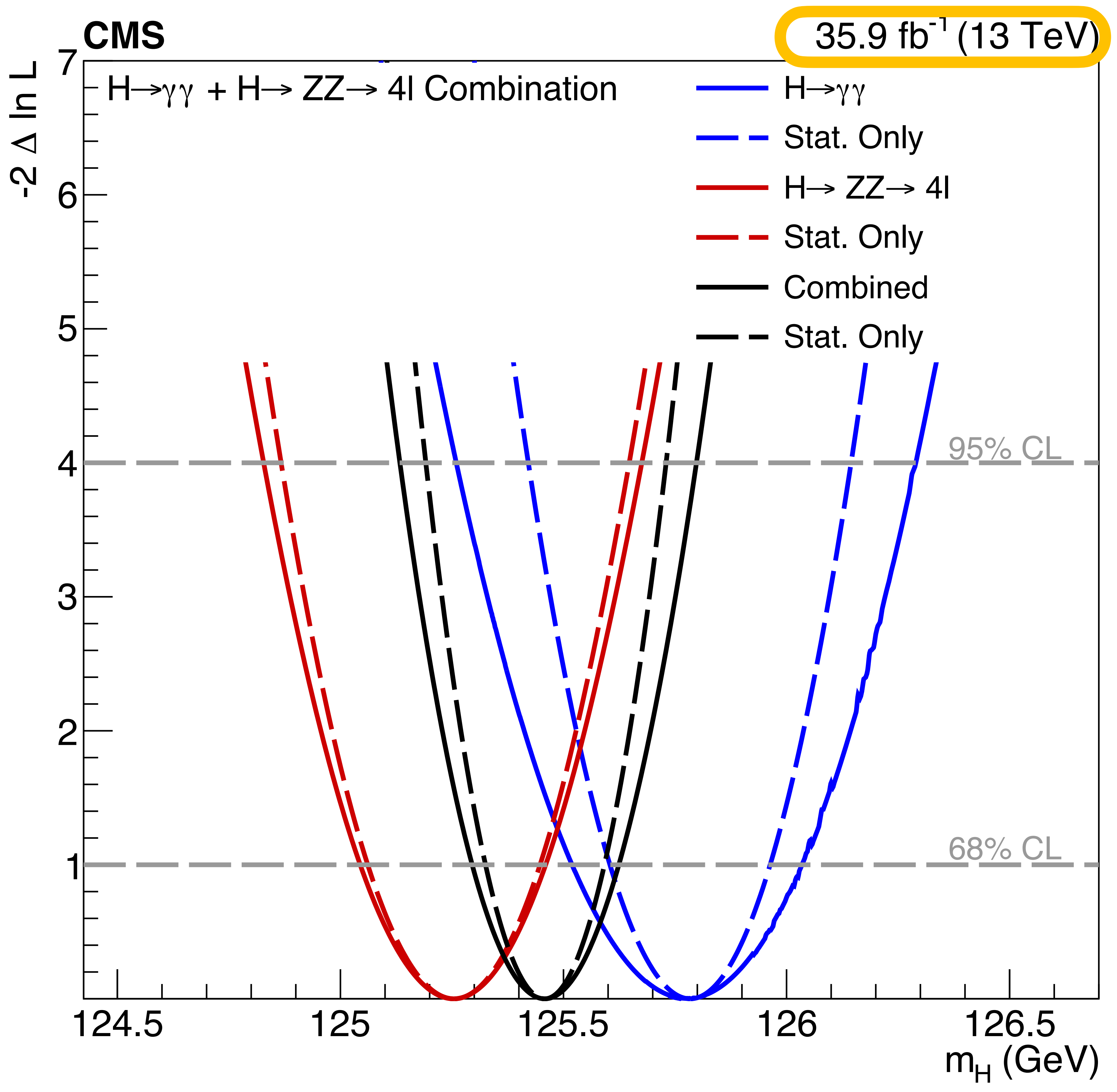
"Mass Peaks"

using high resolution channels ($4\ell+\gamma\gamma$)





m_H a single POI when in the **combination**

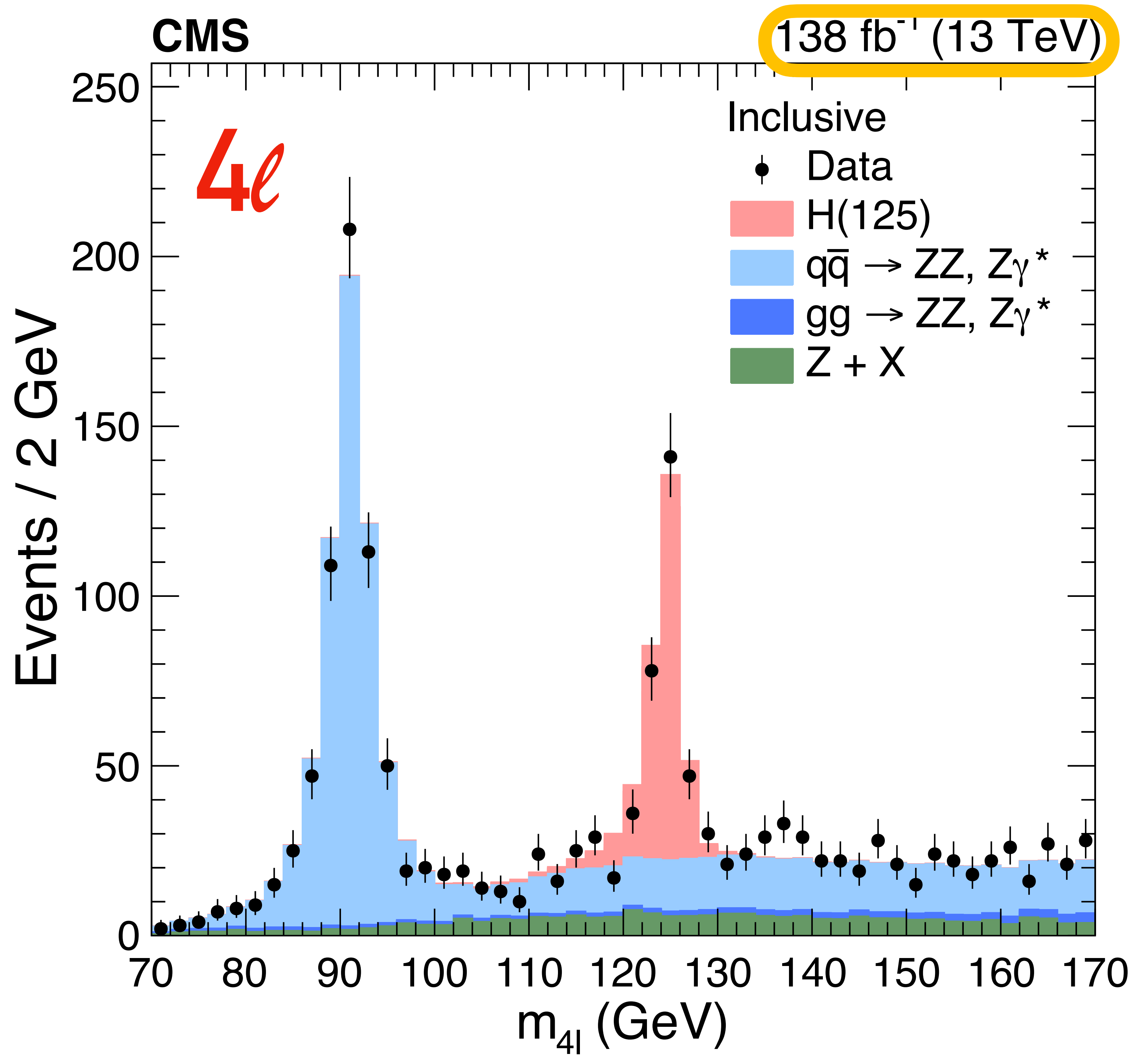


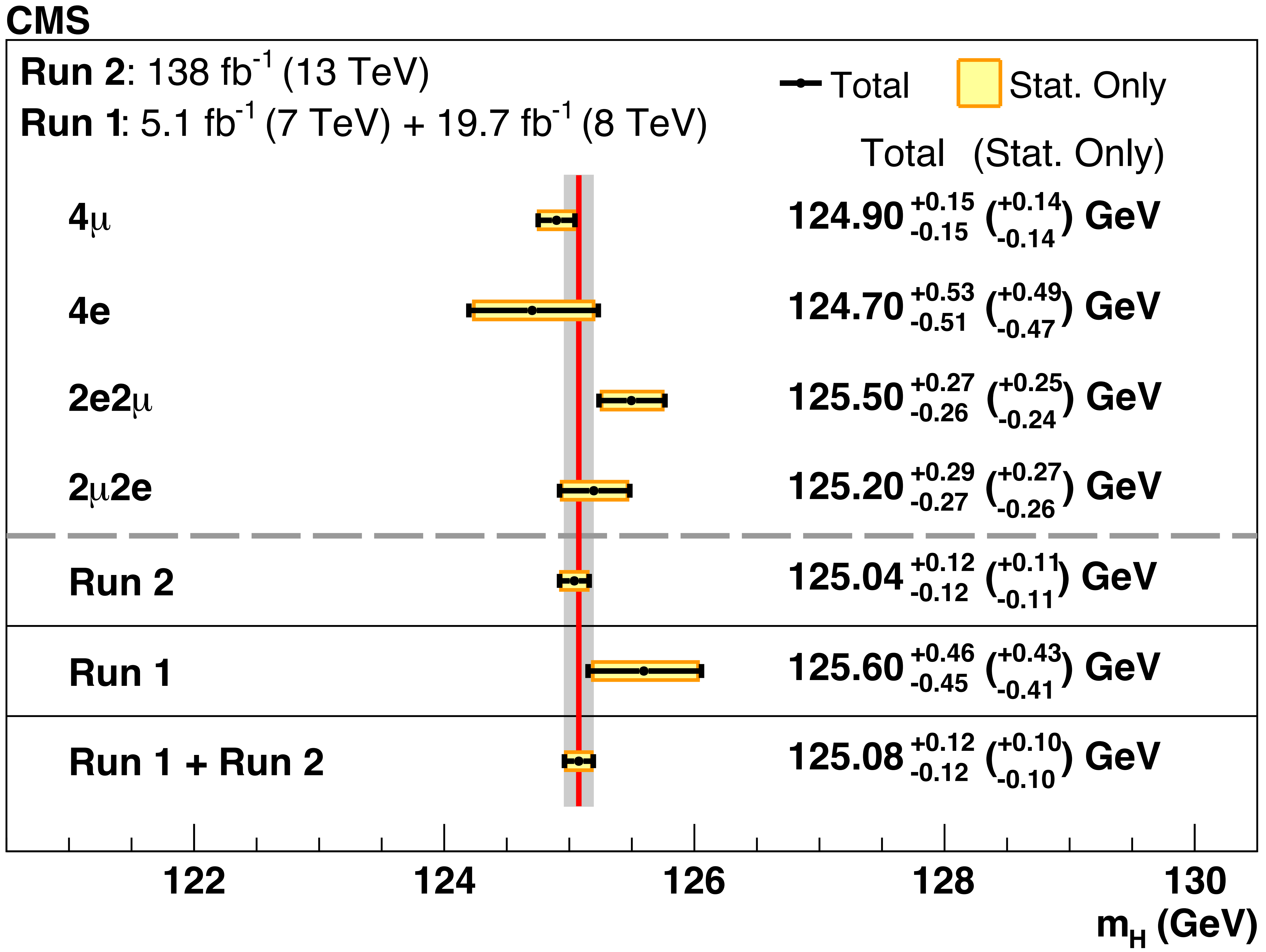
Precision 140 MeV (0.11%)

The Higgs boson mass measurement

arXiv:2409.13663 submitted to PRD

4ℓ Run2 results, **best single channel** measurement at LHC !





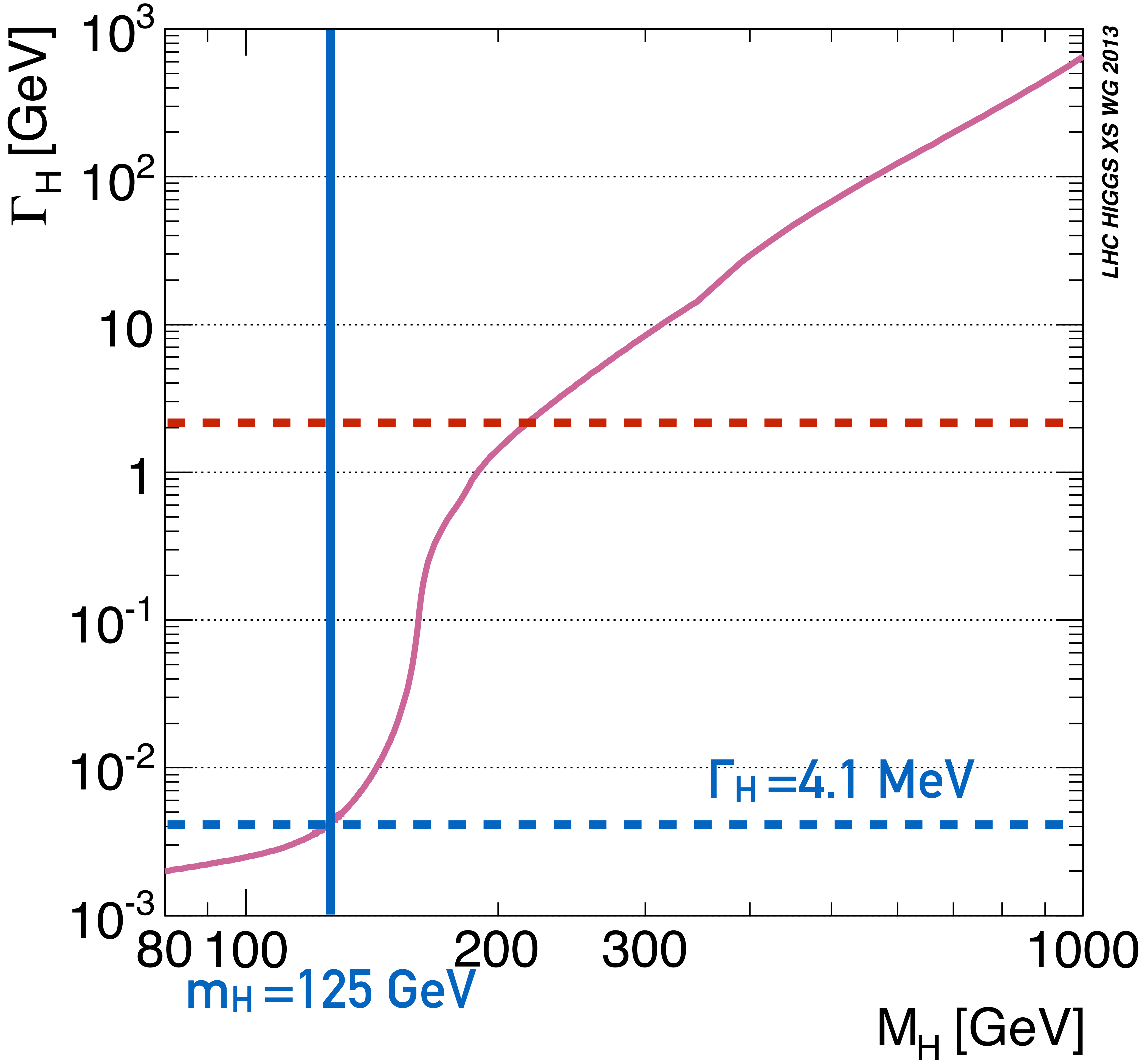
Expecting to go below 30 MeV at HL-LHC

Improvements due to: x20 more luminosity, the new tracker with less material, the stability of the HGCal, the improvements to the barrel calorimeters, and the pileup suppression provided by the new MTD.

Precision 120 MeV (0.09%)

Precision fully driven by statistics.

Higgs boson width



A crucial parameter for BSM searches, in SM $c\tau_H = 48$ fm, small width $\Gamma_H = 4.1$ MeV

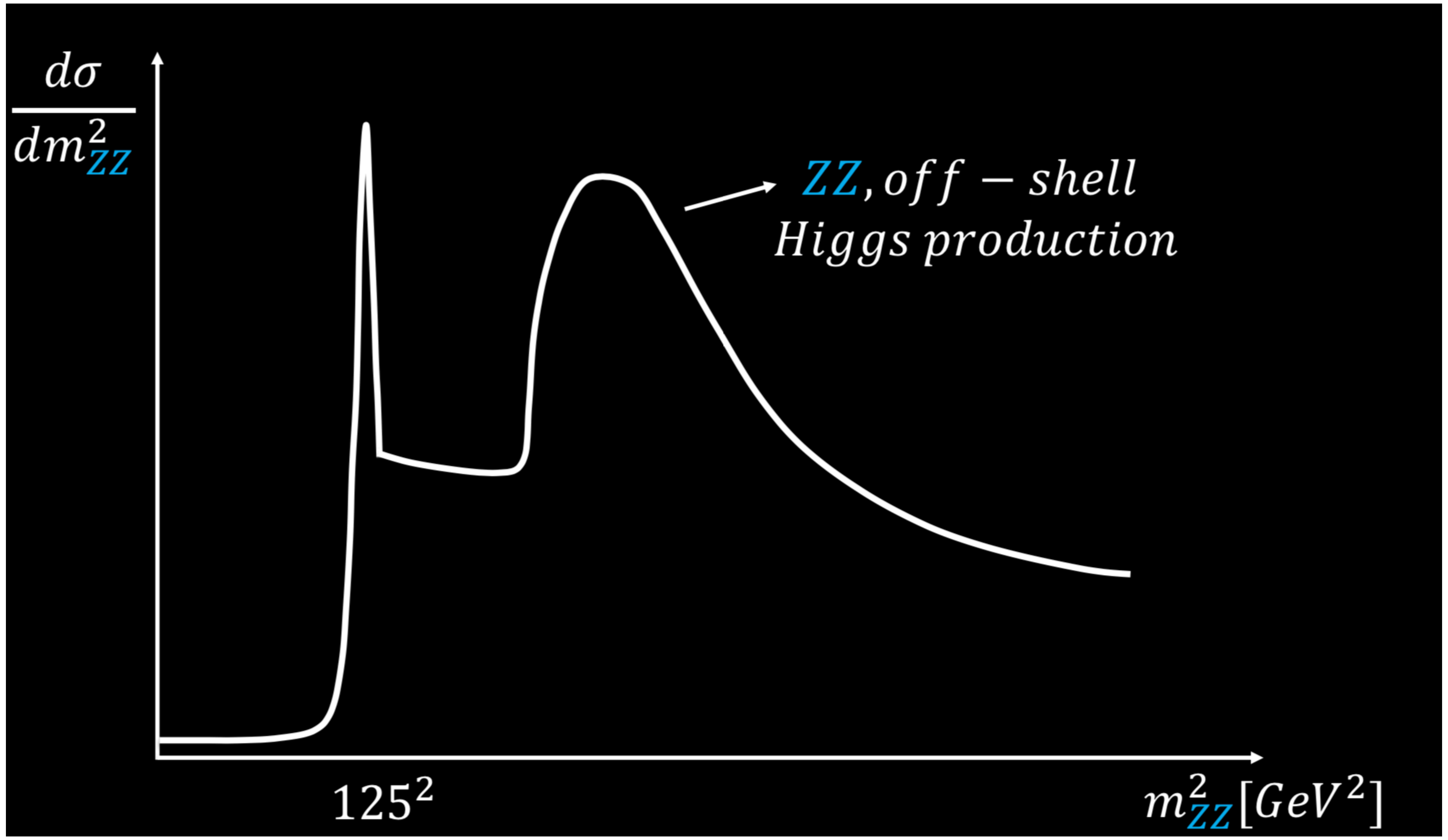
We have long experience with heavy EW bosons (W and Z). However, their width is $\Gamma_H \sim 2$ GeV !

The direct measurements it is extremely hard! In addition, the total width is the sum of all the partial widths, on the contrary of LEP, at LHC only σxBR can be measured.

From off-shell production

Idea

Indirect measurement



The fixed-width Breit-Wigner scheme is generally good in describe the inclusive differential ($d\sigma/dm^2$) Higgs boson production

... but ...

... as soon as we restrict to VV decay channel there is a large off-shell contribution above the VV threshold (high Higgs virtuality), it means that two q^2 propagators compensate and the cross section is enhanced.

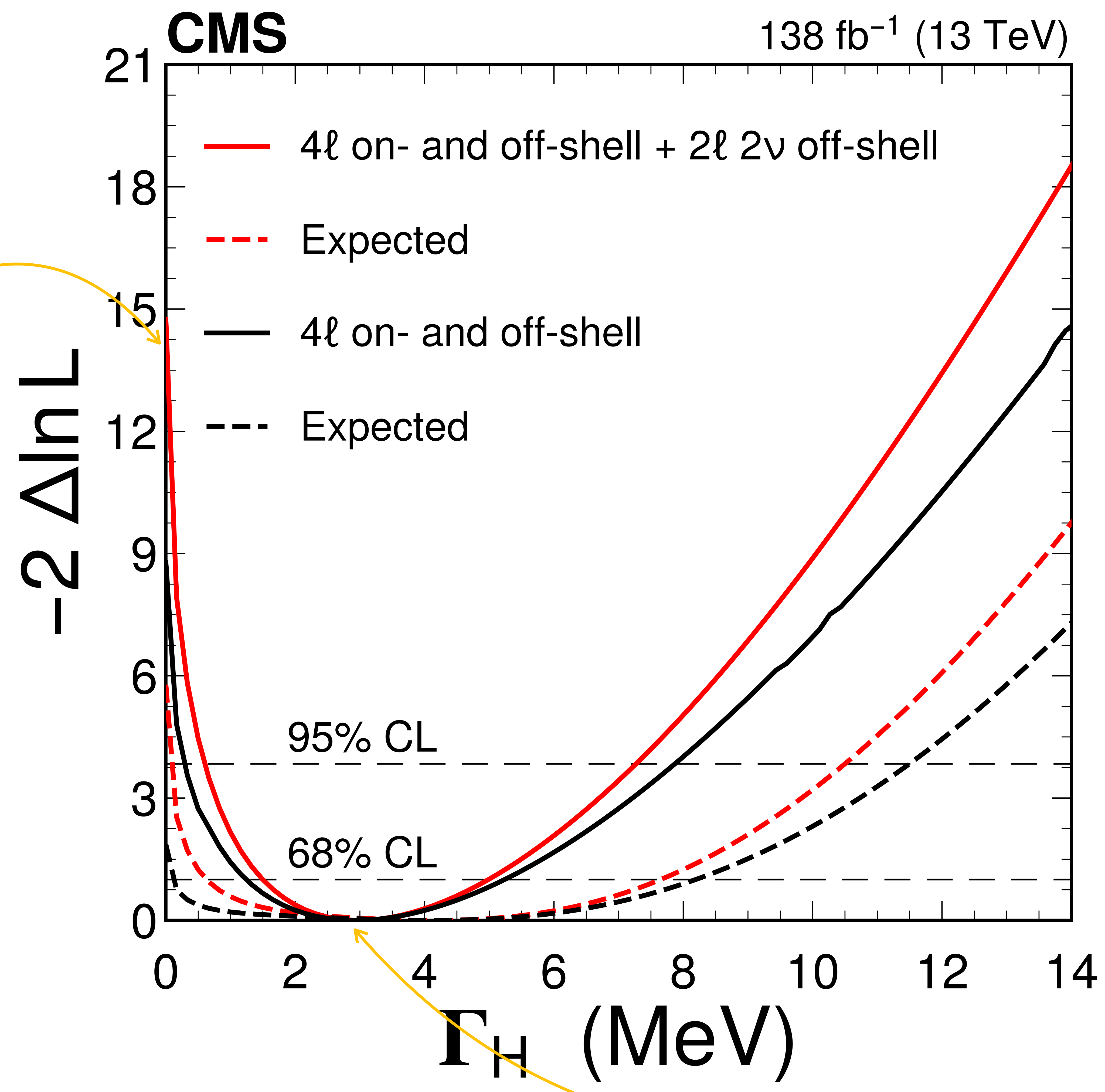
$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \dfrac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \dfrac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}}$$

Higgs boson width measurement

arXiv:2409.13663
submitted to PRD

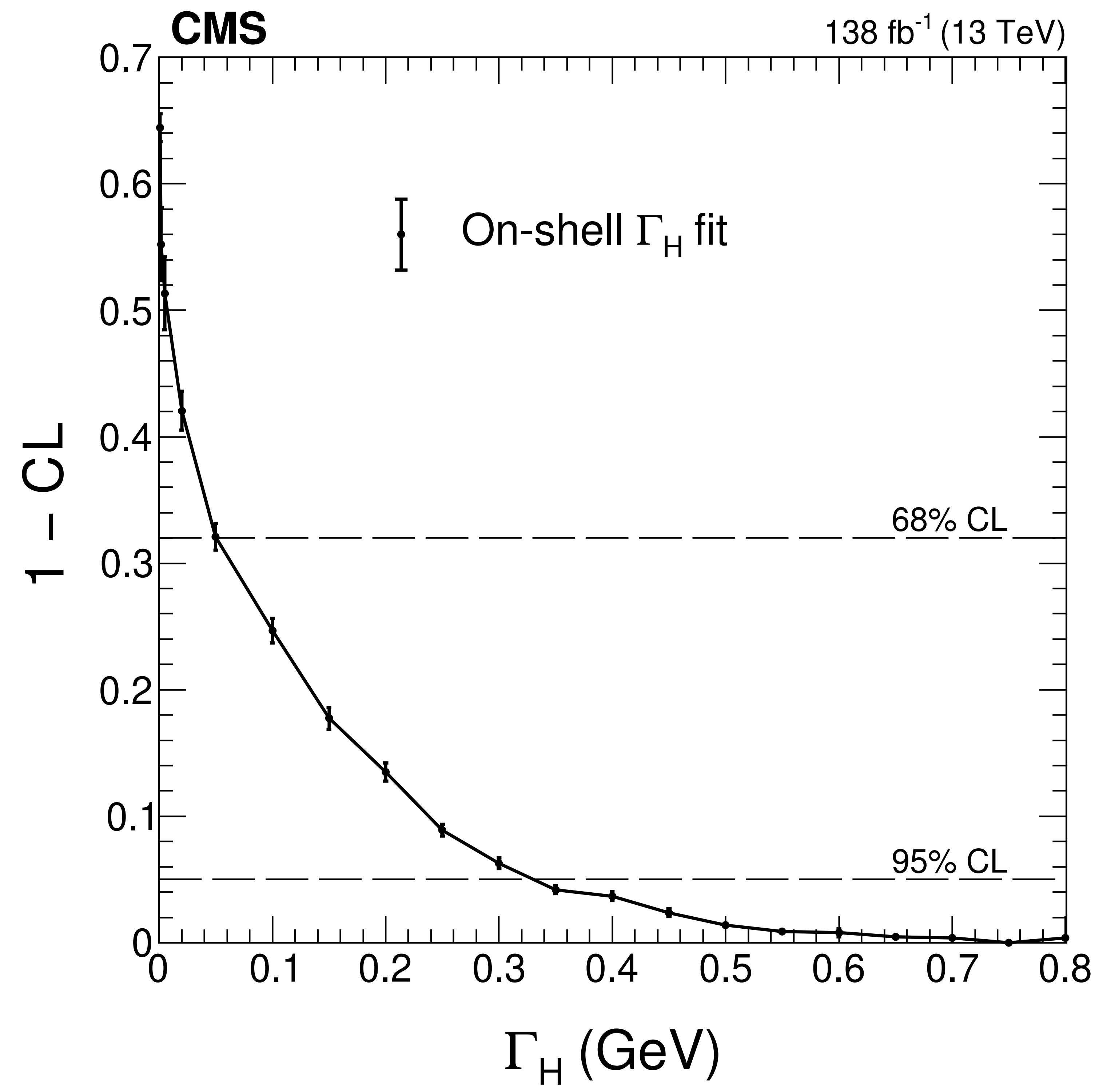
Off-shell

no off-shell H production excluded at **3.8σ**



Measured Higgs boson width of **$\Gamma_H = 3.0^{+2.0}_{-1.7}$ MeV**

On-shell



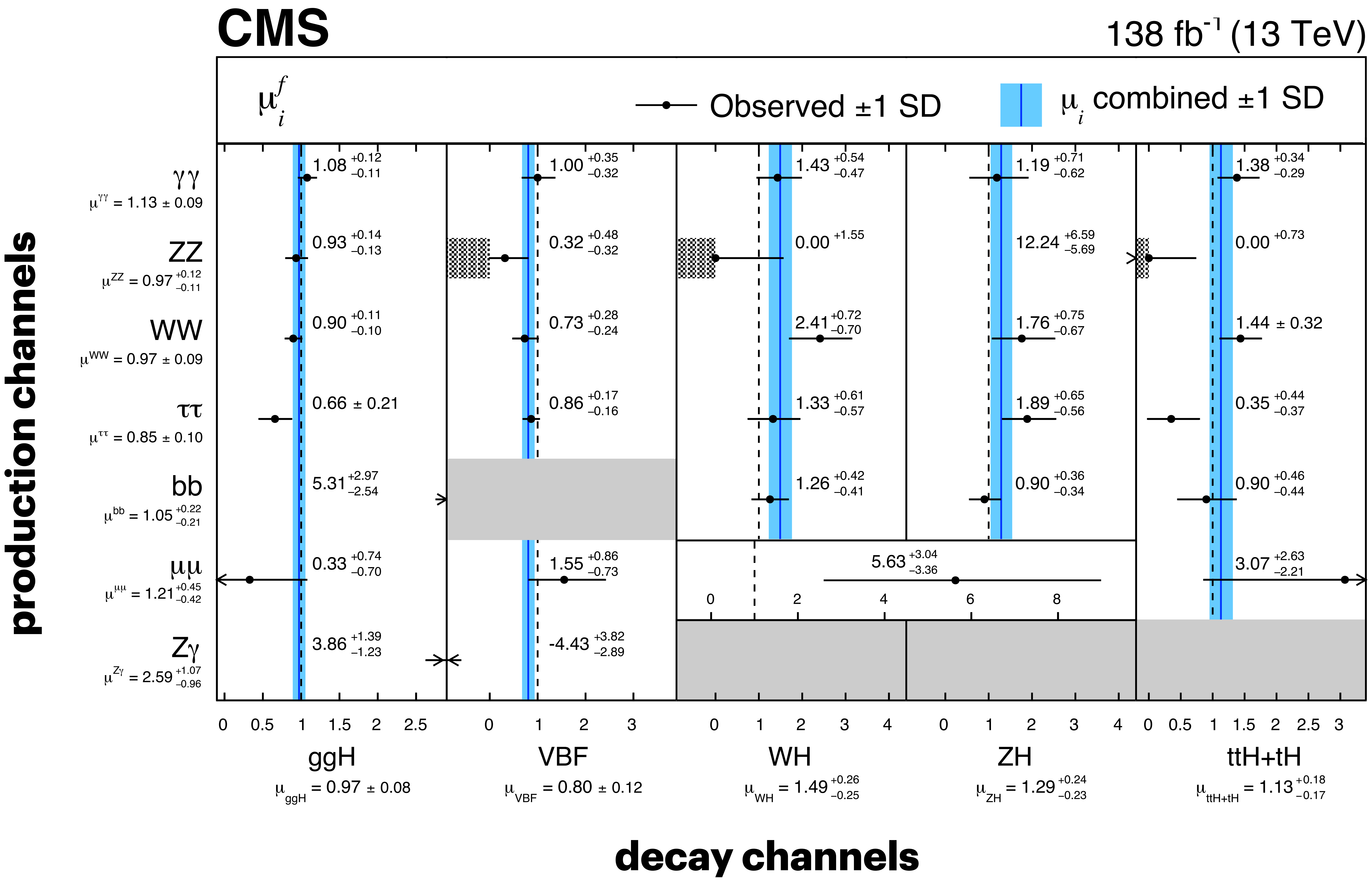
UL @95% CL on **Γ_H< 330 MeV**

UL @68% CL on **Γ_H< 60 MeV**

Higgs boson couplings

Nature 607 (2022) 60

Many signal strength modifiers[1] measured



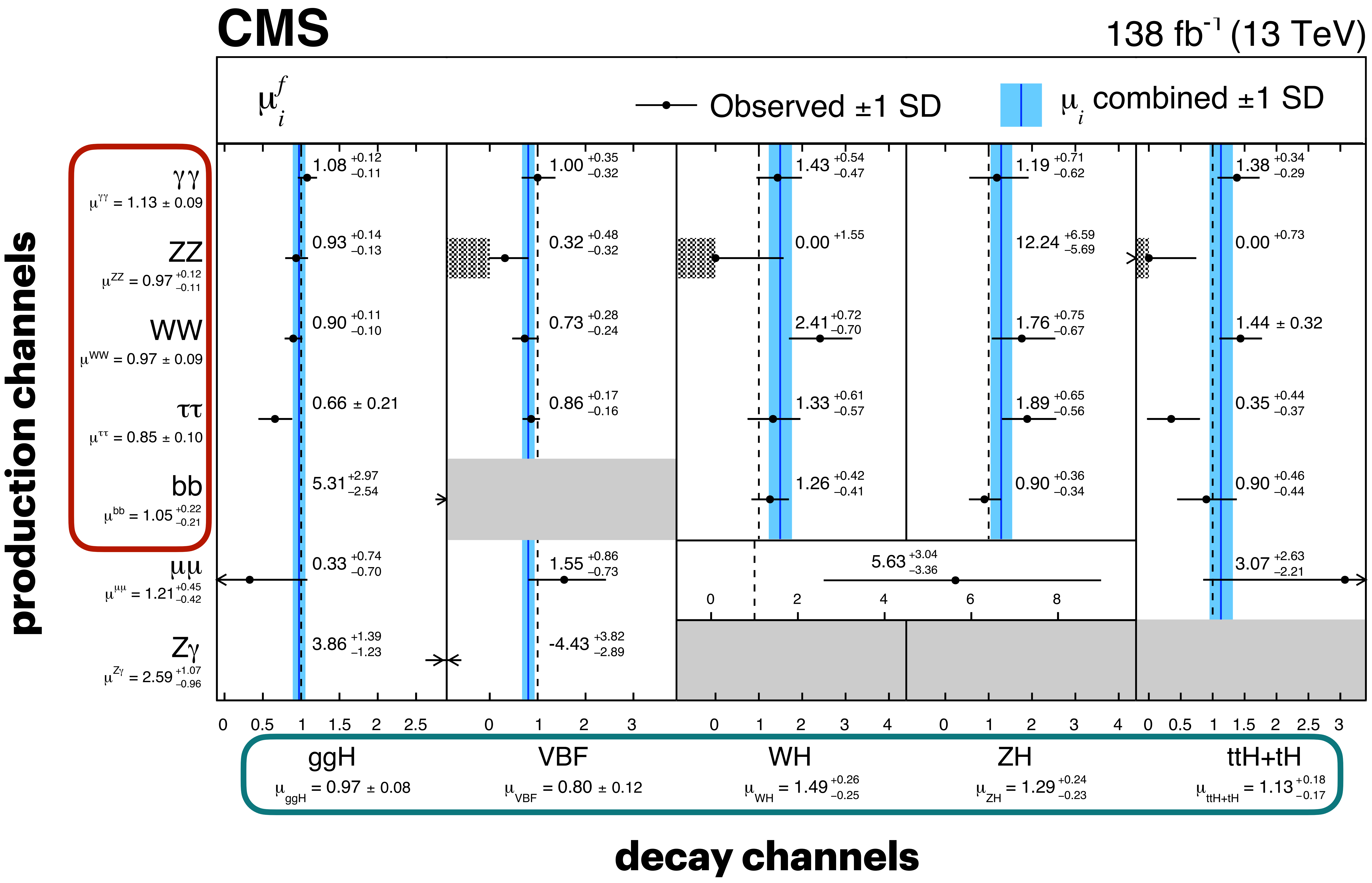
1) μ scale cross sections and branching fractions relative to the SM

Higgs boson couplings

Nature 607 (2022) 60

Many signal strength modifiers[1)] measured

5 main production channels and **5 main** decay channels are observed



1) μ scale cross sections and branching fractions relative to the SM

Higgs boson couplings vs. mass

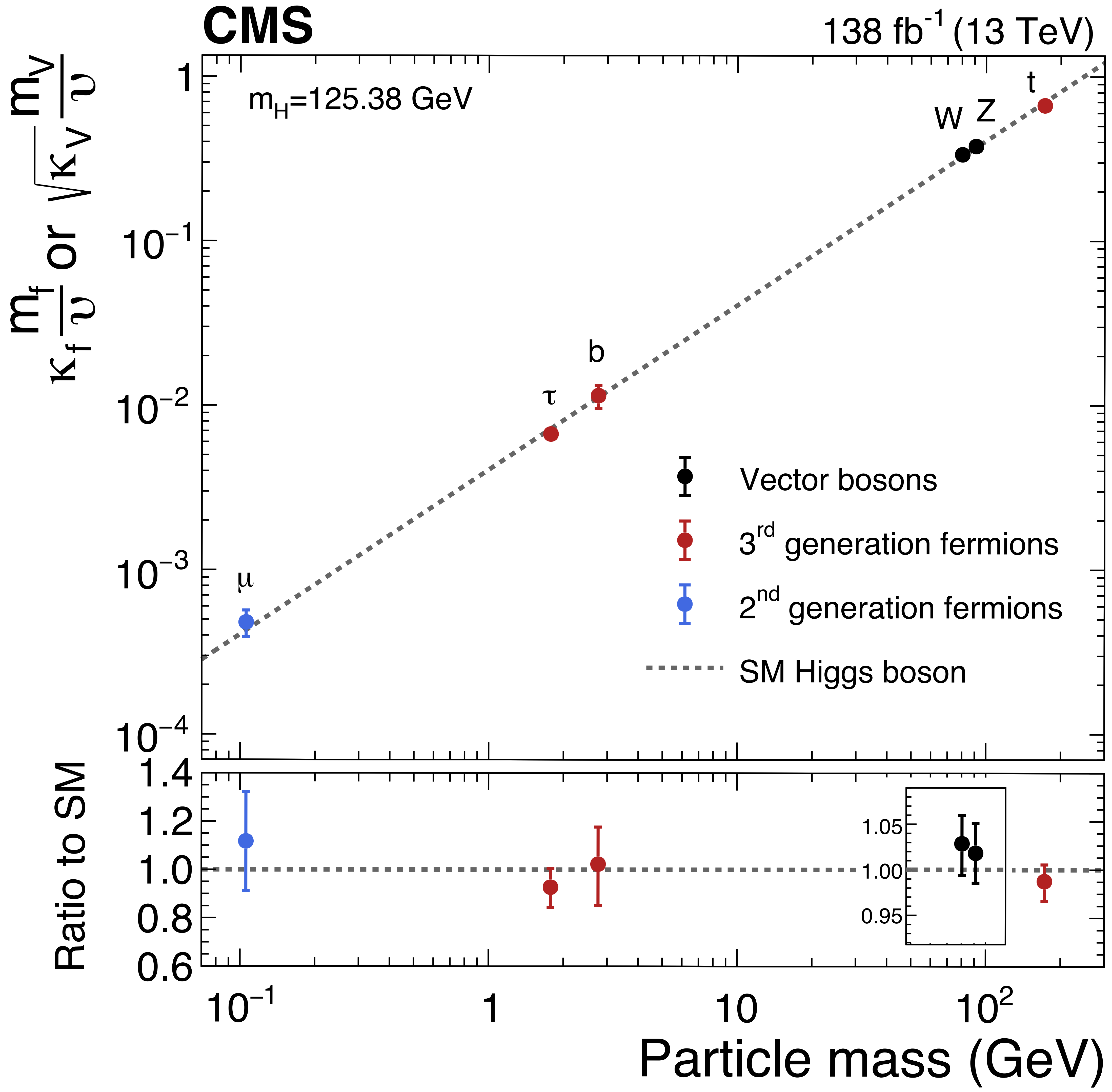
Nature 607 (2022) 60

Remarkable agreement with the predictions of the BEH mechanism over 3 orders of magnitude of mass!

~5% precision on k_V

Observation (>5σ) of coupling with 3rd gen.

Evidence (>3σ) of coupling with 2nd gen.



Coupling modifier k_j : parameterisation of inclusive production and decay rates
e.g. $k_j^2 = \sigma/\sigma_{SM}$

Higgs boson couplings vs. mass

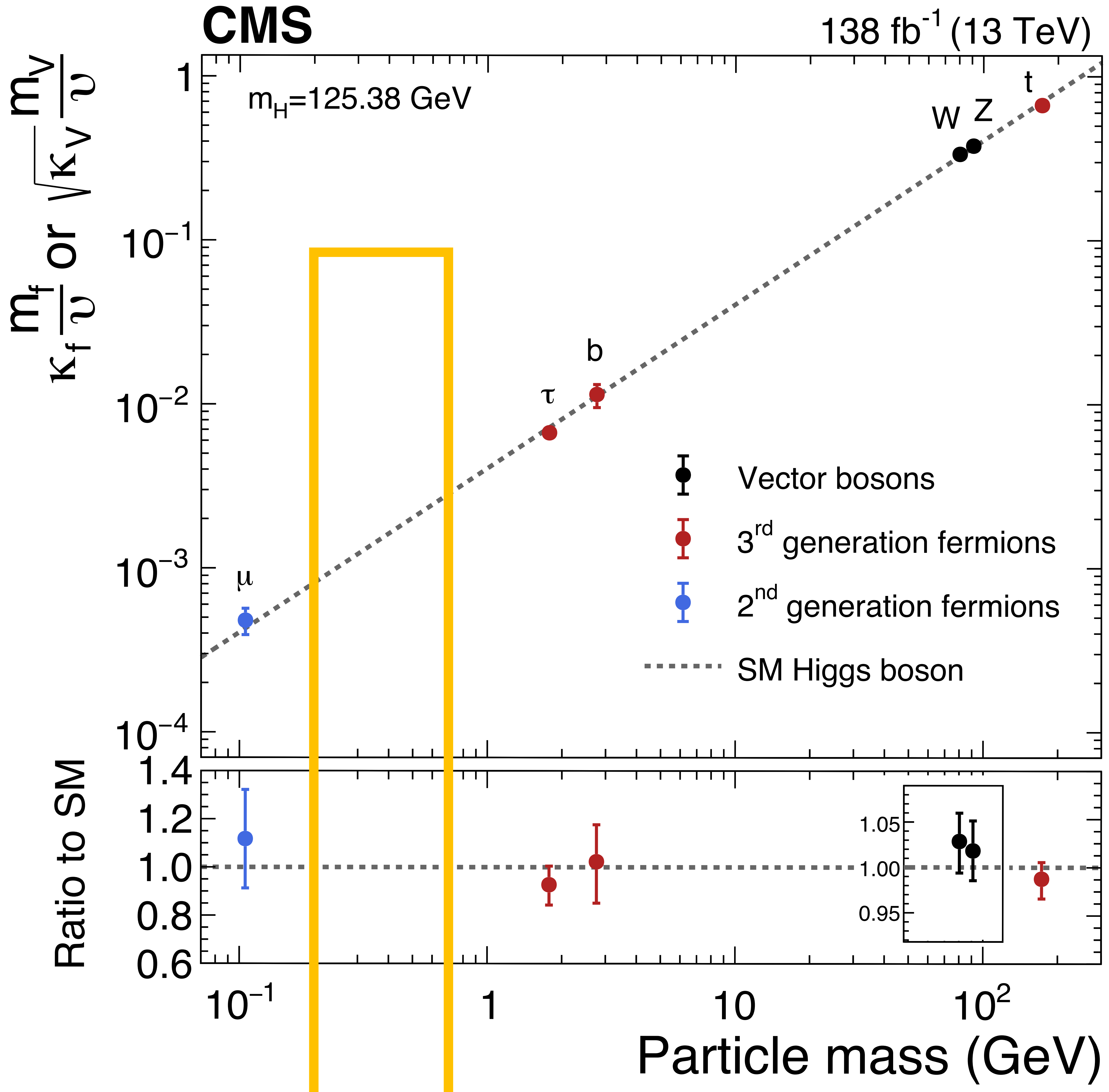
Nature 607 (2022) 60

Remarkable agreement with the predictions of the BEH mechanism over 3 orders of magnitude of mass!

~5% precision on k_V

Observation (>5σ) of coupling with 3rd gen.

Evidence (>3σ) of coupling with 2nd gen.



...and Higgs-charm coupling ?

Coupling modifier k_j : parameterisation of inclusive production and decay rates
e.g. $k_j^2 = \sigma/\sigma_{SM}$

H→cc̄ decay

[PRL 131 (2023) 041801]

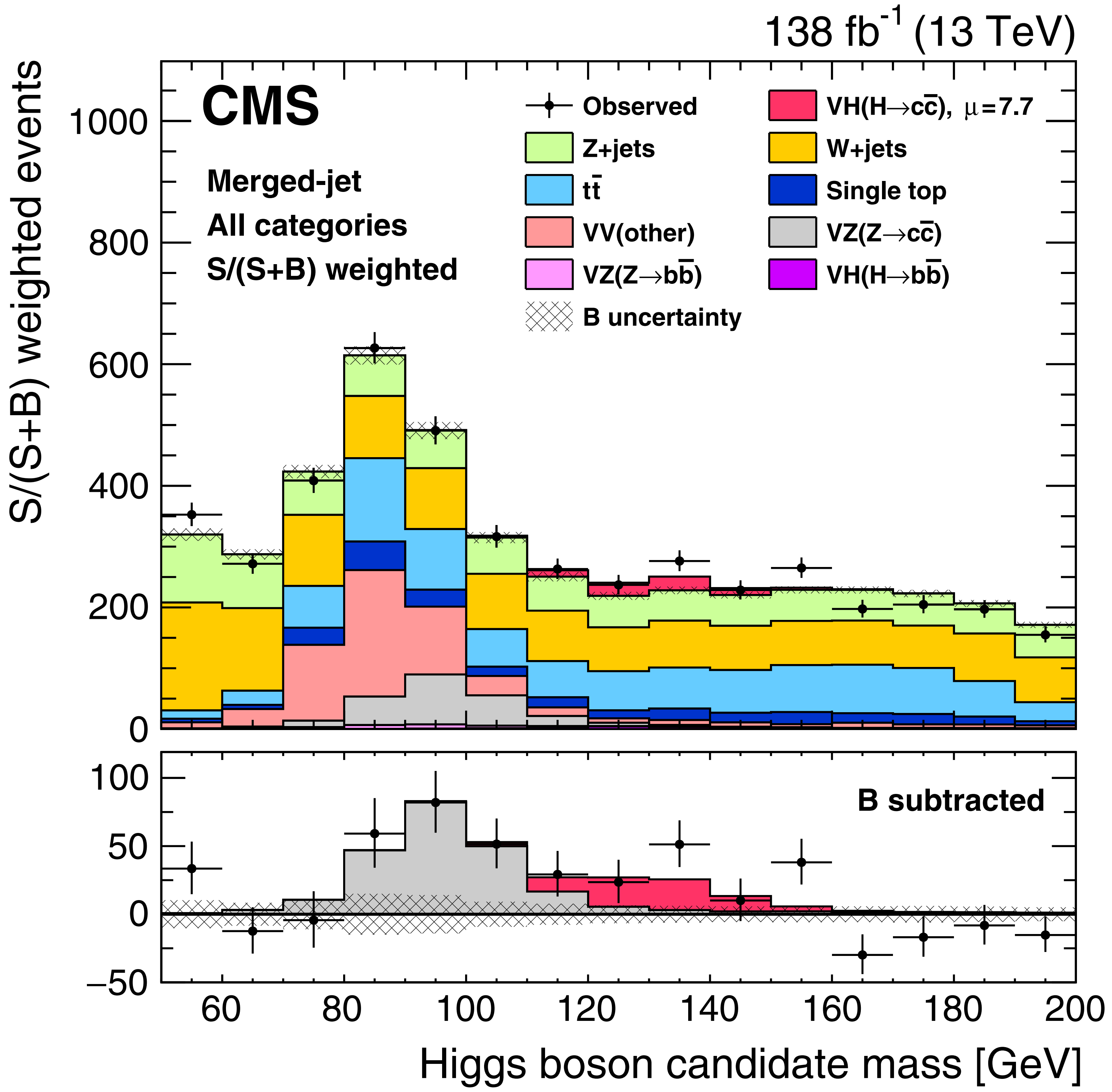
The main channel to probe Higgs- charm coupling (BR in SM: 2.8%)

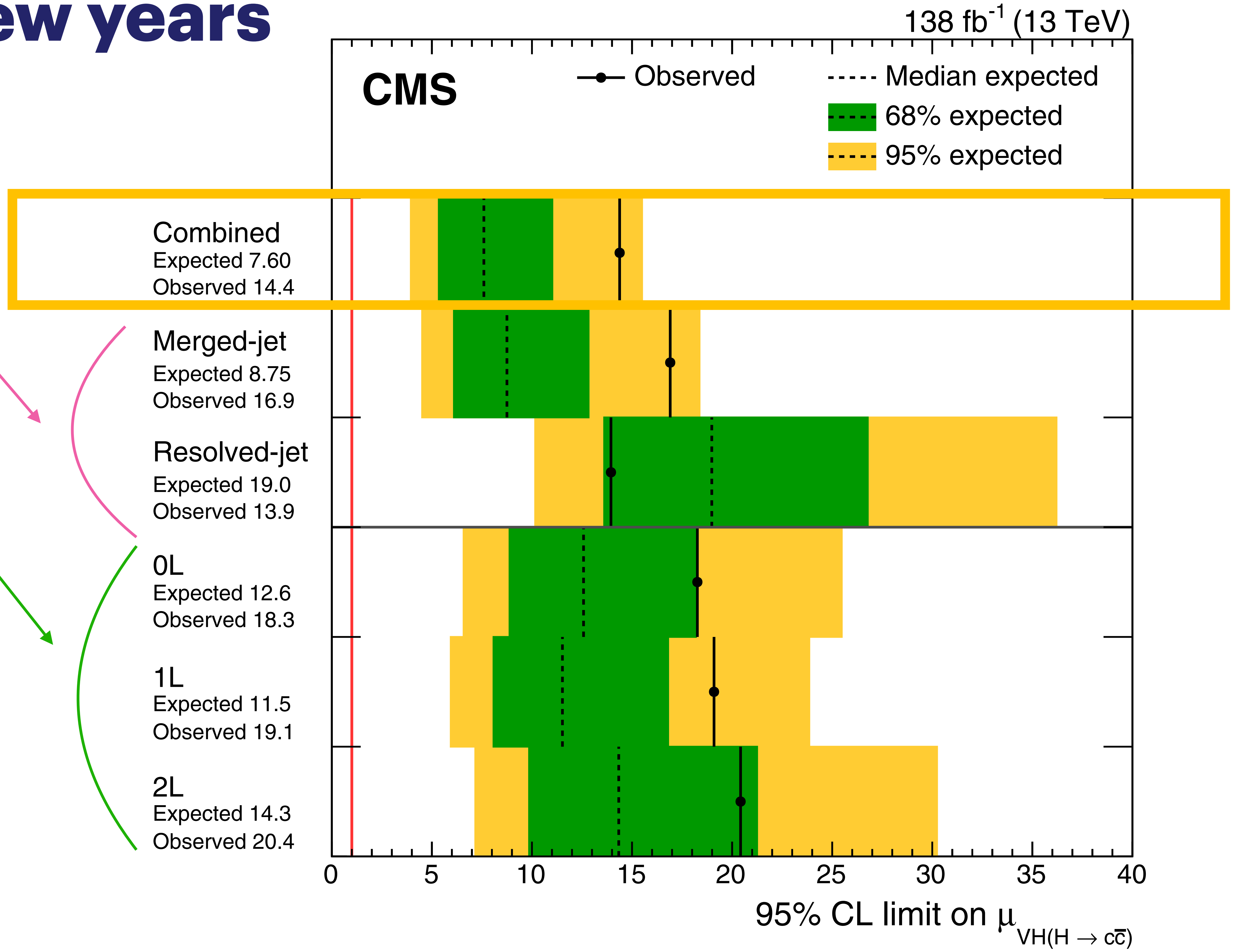
VH(cc) : great improvements in the last few years

Tag leptonically decaying W/Z boson

Combine both resolved and boosted analyses

Novel deep-learning (Graph Neural Network based) for charm tagging





The observed (expected) 95% CL interval is

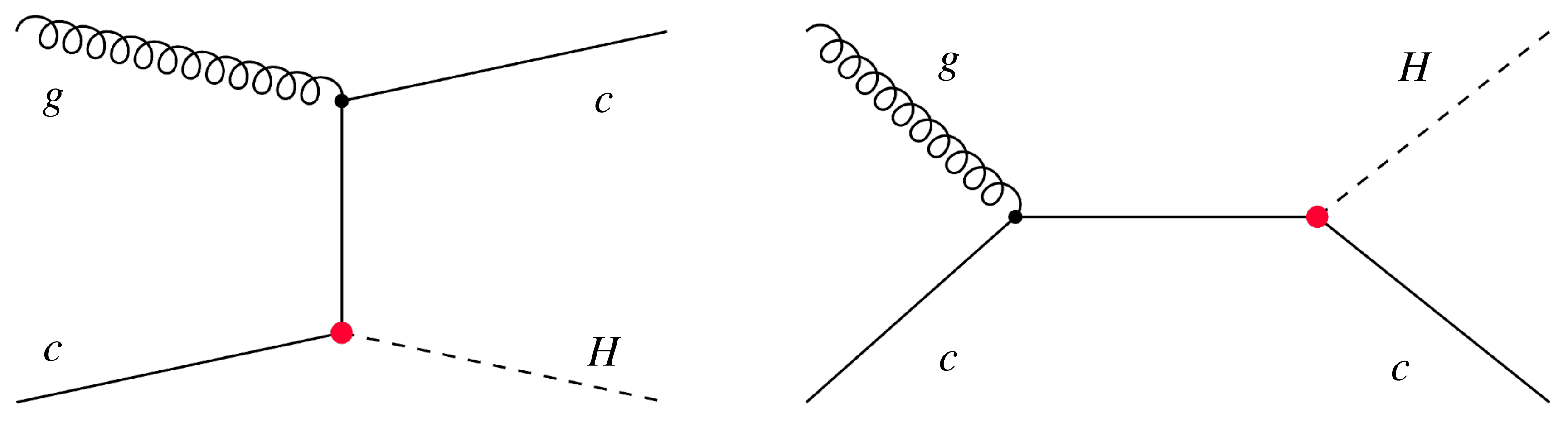
$1.1 < k_c < 5.5$ ($|k_c| < 3.4$)

H→cc̄ decay

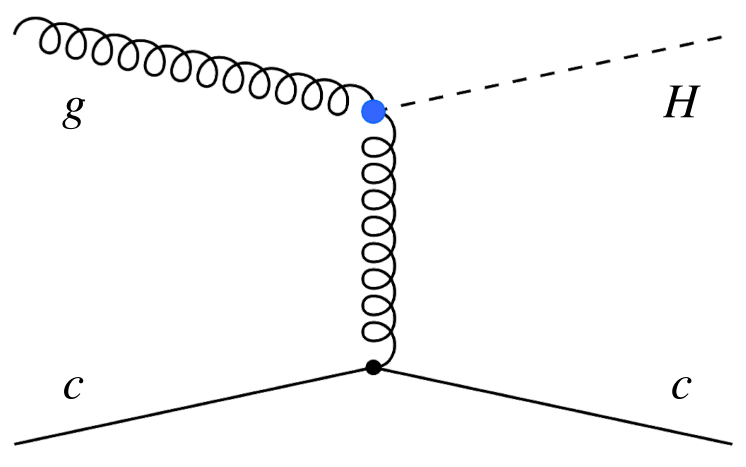
CMS-PAS-HIG-23-010

The main channel to probe Higgs coupling to c quarks (BR in SM: 2.8%)

Probe y_c in the production side with associated production



cH signal



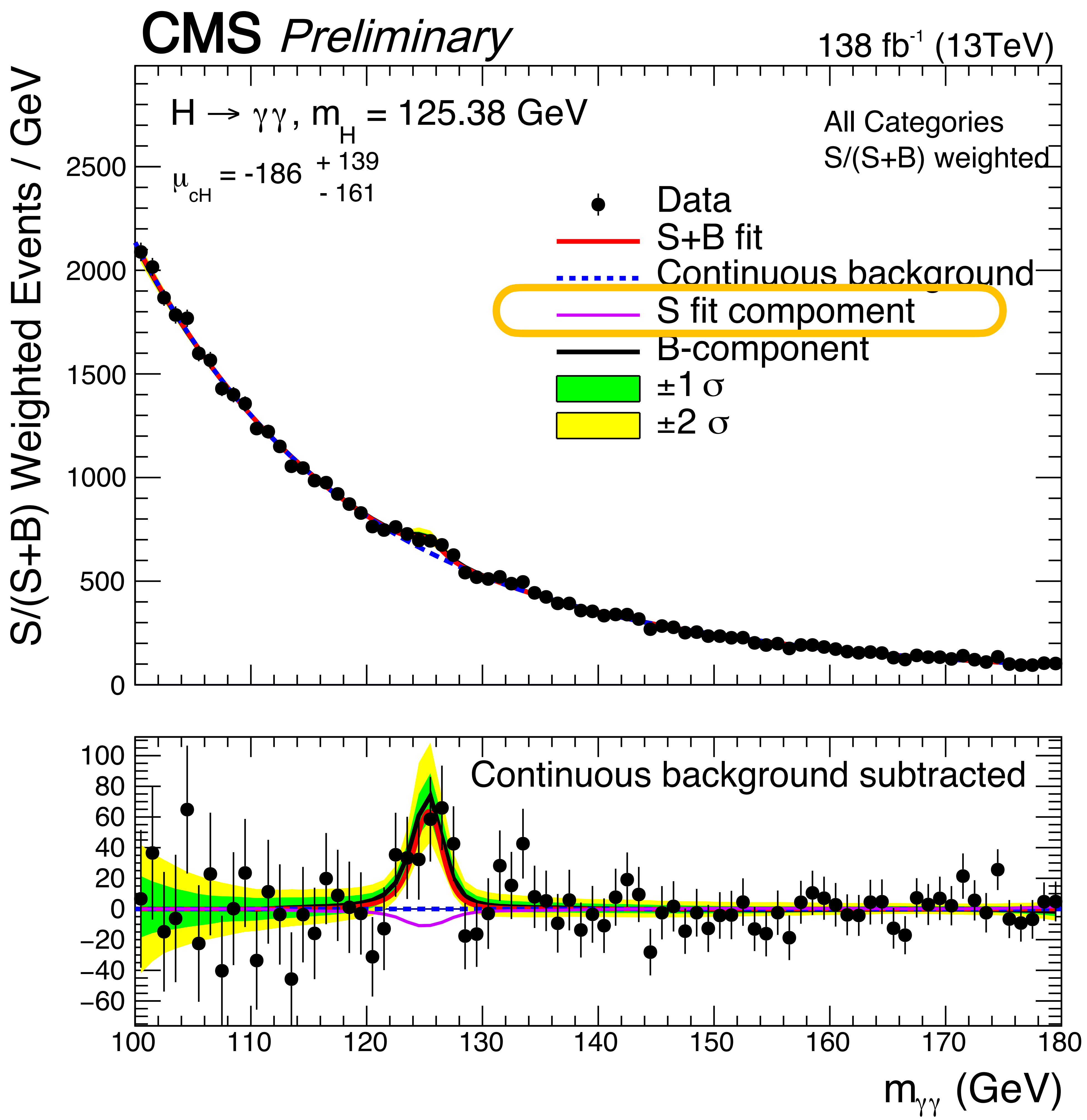
Resonant background

The sensitivity of this analysis is dominated by the statistical uncertainty of data

Theoretical uncertainties on cH signal	38%
Theoretical uncertainties on resonant background	59%
Experimental uncertainties on yields	27%
Experimental uncertainties on mass shapes	negligible
Luminosity uncertainties	negligible

The observed (expected) 95% CL interval is

$$|k_c| < 38.8 \ (|k_c| < 72.5)$$

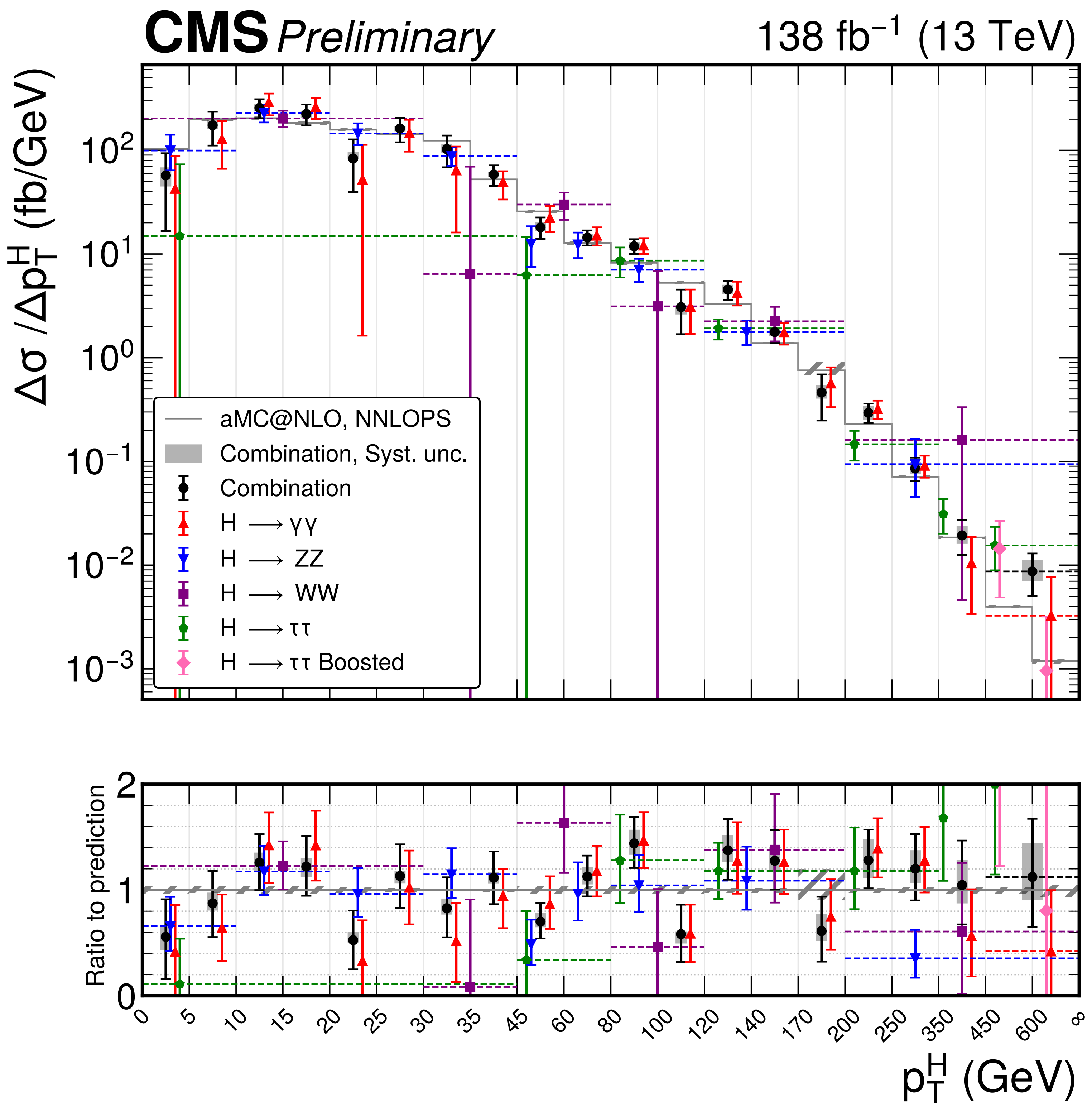


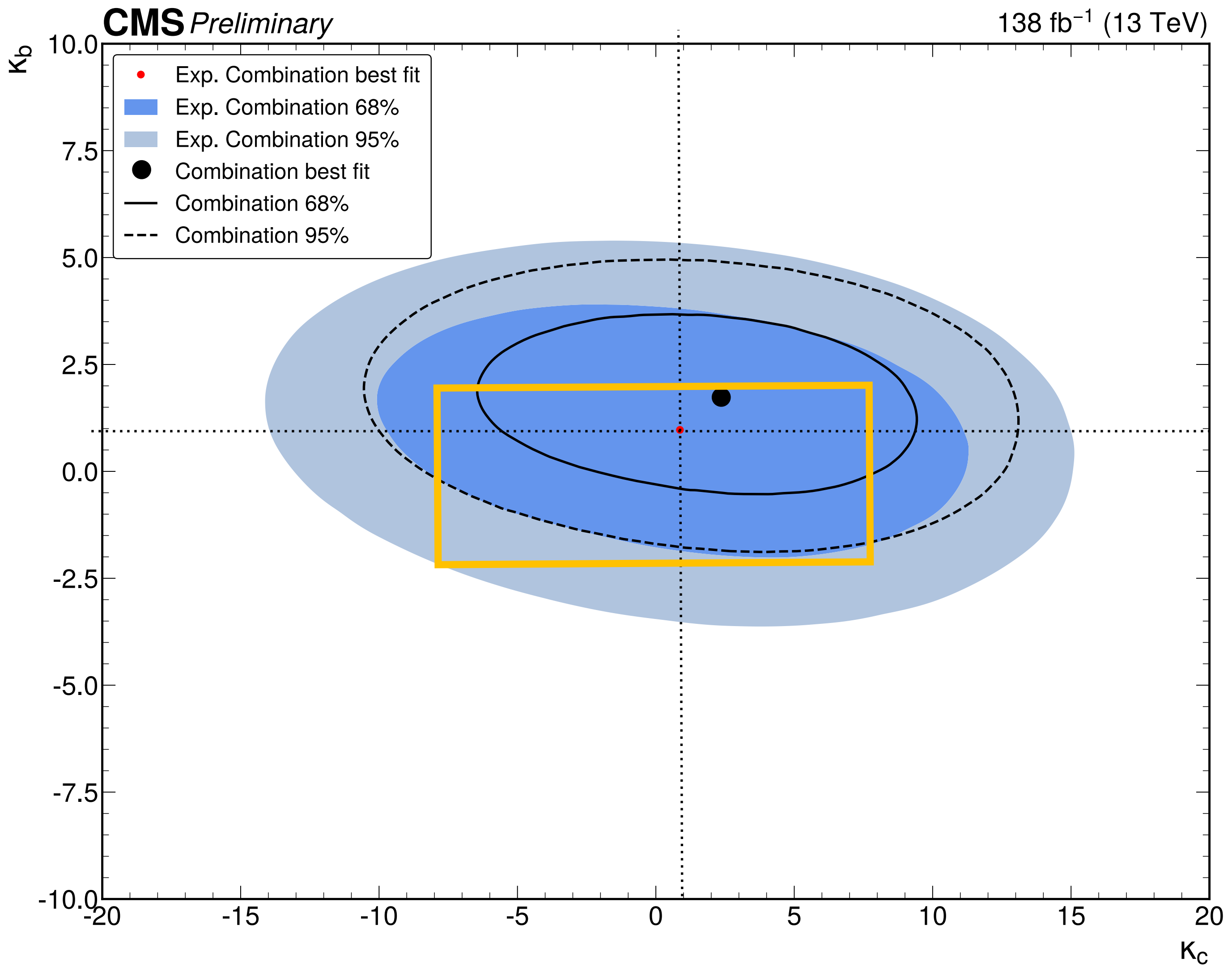
Couplings from Higgs p_T *Combination*

CMS-PAS-HIG-23-013

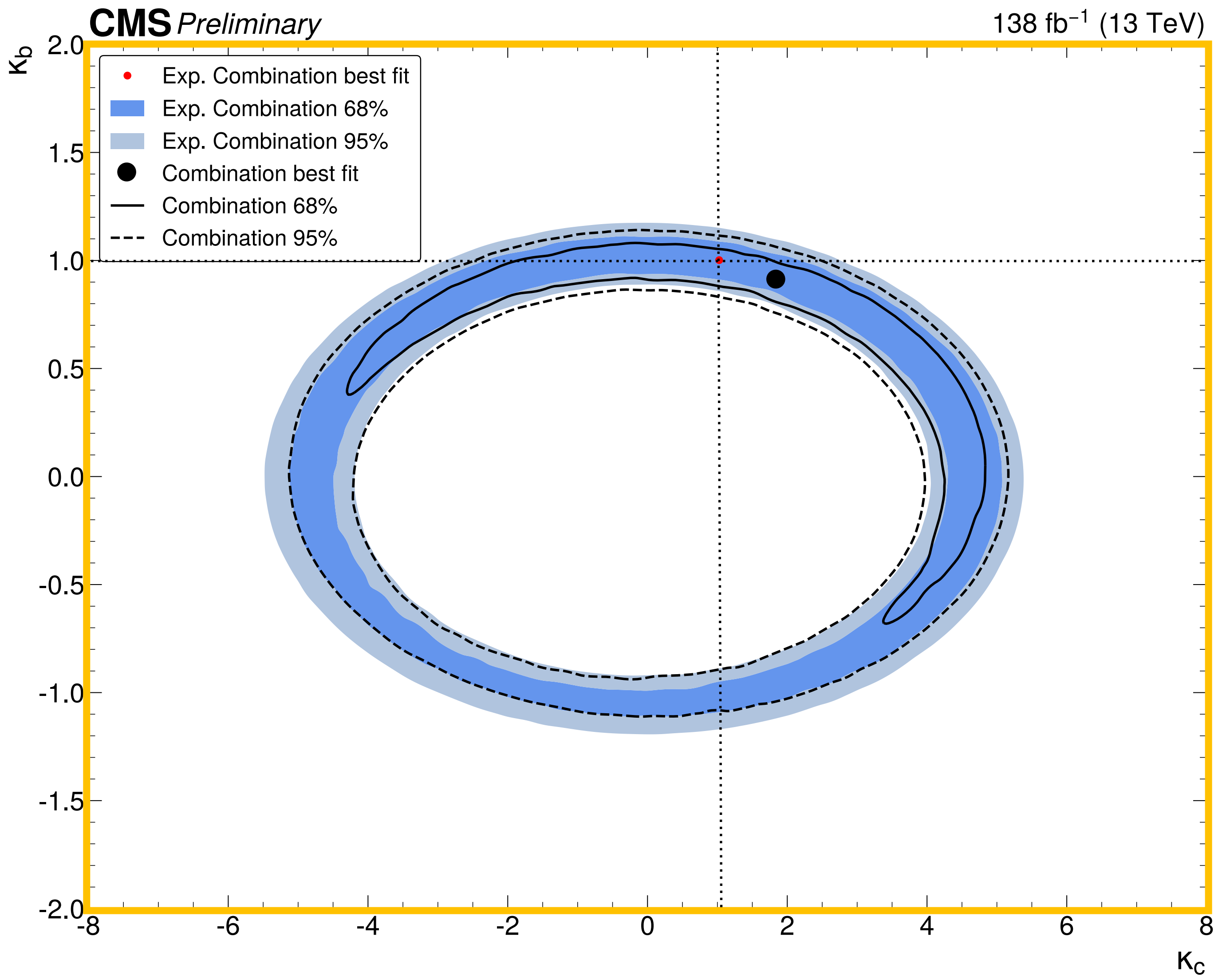
Combining 5 different analyses, differential measurements are obtained in finer bins, and with less model-dependence.

Interpreted in terms of b- and c-quark couplings considering only the p_T shape (weaker) or also the branching ratios (stronger)





no dependence on the BRs



assuming a coupling dependence of the BRs

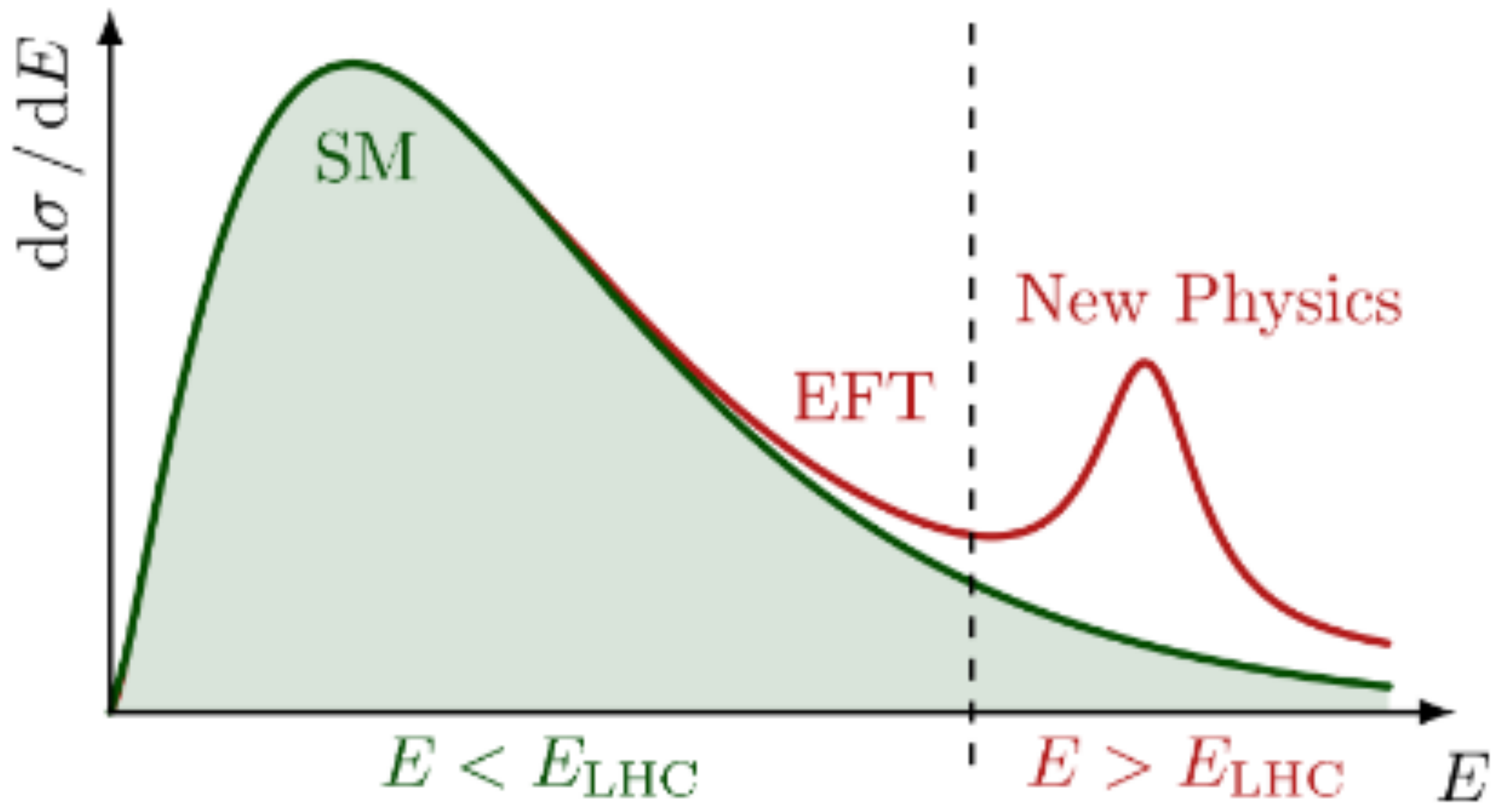
Not only ....

EFT interpretation

Assume that the New Physics that could be observed via a **new resonance** that will not be in the kinematical reach of LHC ($E>E_{LHC}$)
Low-energy effects of New Physics can modify the interactions of the Higgs bosons via modifications of the SM processes

New Physics is parametrised via additional effective couplings

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d,j} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_j^{(d)}$$

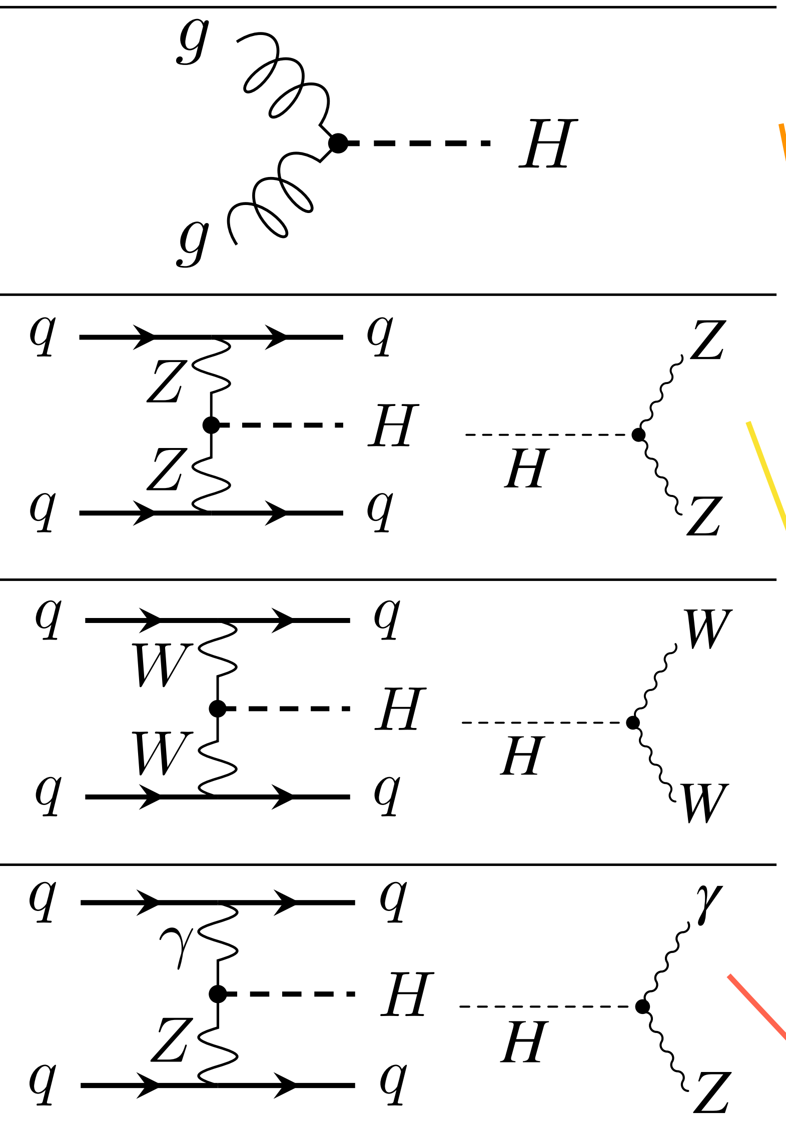


EFT interpretation from Higgs p_T

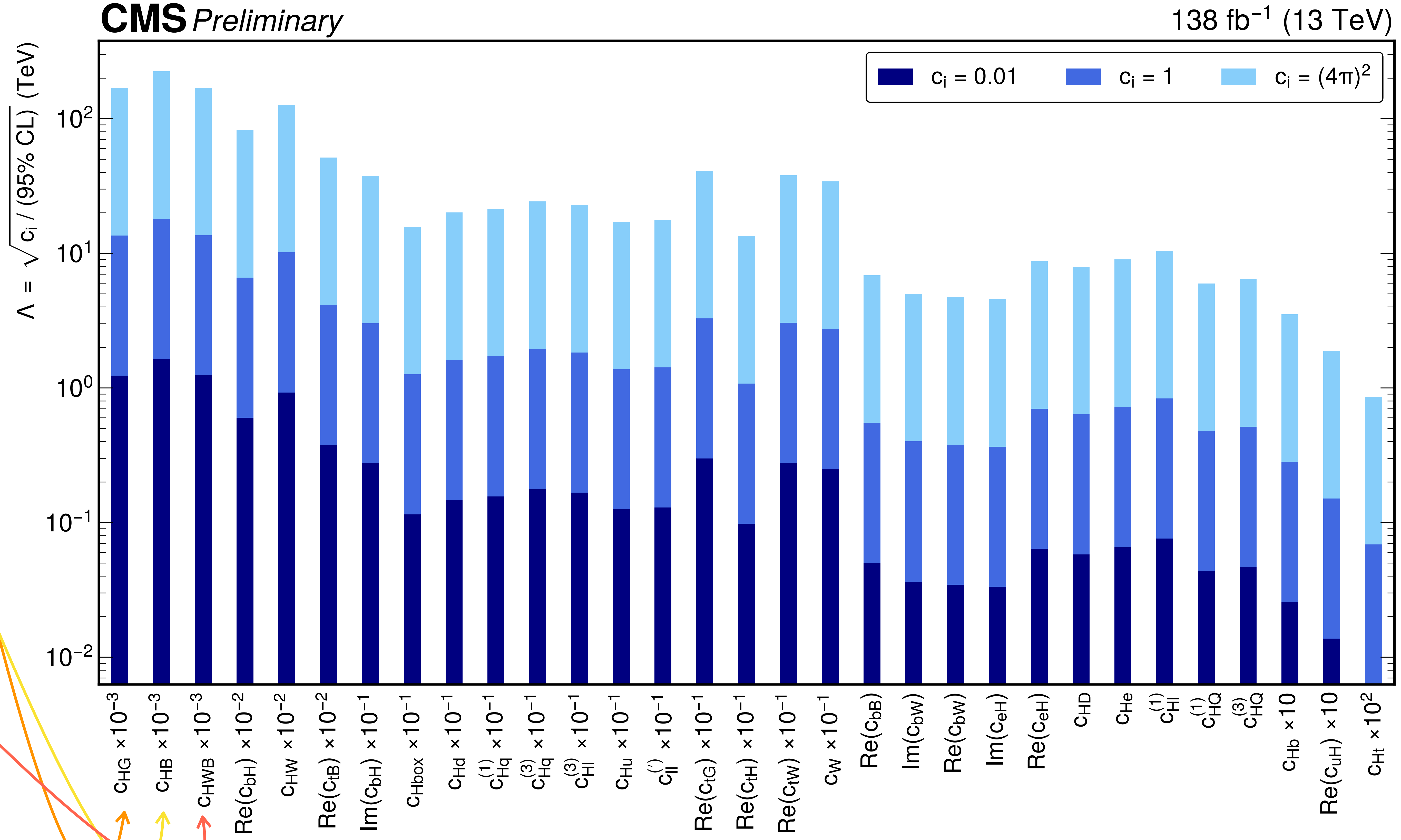
CMS-PAS-HIG-23-013

- 2D constraints for pairs of CP-even and CP-odd operators
- Limits for each Wilson coefficient interpreted in term of a coupling and an energy scale
- Probe energy scales up to 100 TeV depending on the Wilson coefficient and the assumed coupling

Operator	Wilson coefficient	Example process
$H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$	c_{HG}	
$H^\dagger H \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$	$\tilde{c}_{HG}$	
$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	c_{HB}	
$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\tilde{c}_{HB}$	
$H^\dagger H W^i_{\mu\nu} W^{i\mu\nu}$	c_{HW}	
$H^\dagger H \tilde{W}^i_{\mu\nu} W^{i\mu\nu}$	$\tilde{c}_{HW}$	
$H^\dagger \sigma^i H W^i_{\mu\nu} B^{i\mu\nu}$	c_{HWB}	
$H^\dagger \sigma^i H \tilde{W}^i_{\mu\nu} B^{i\mu\nu}$	$\tilde{c}_{HWB}$	



Operators and relative Wilson coefficients that provided larger constrains



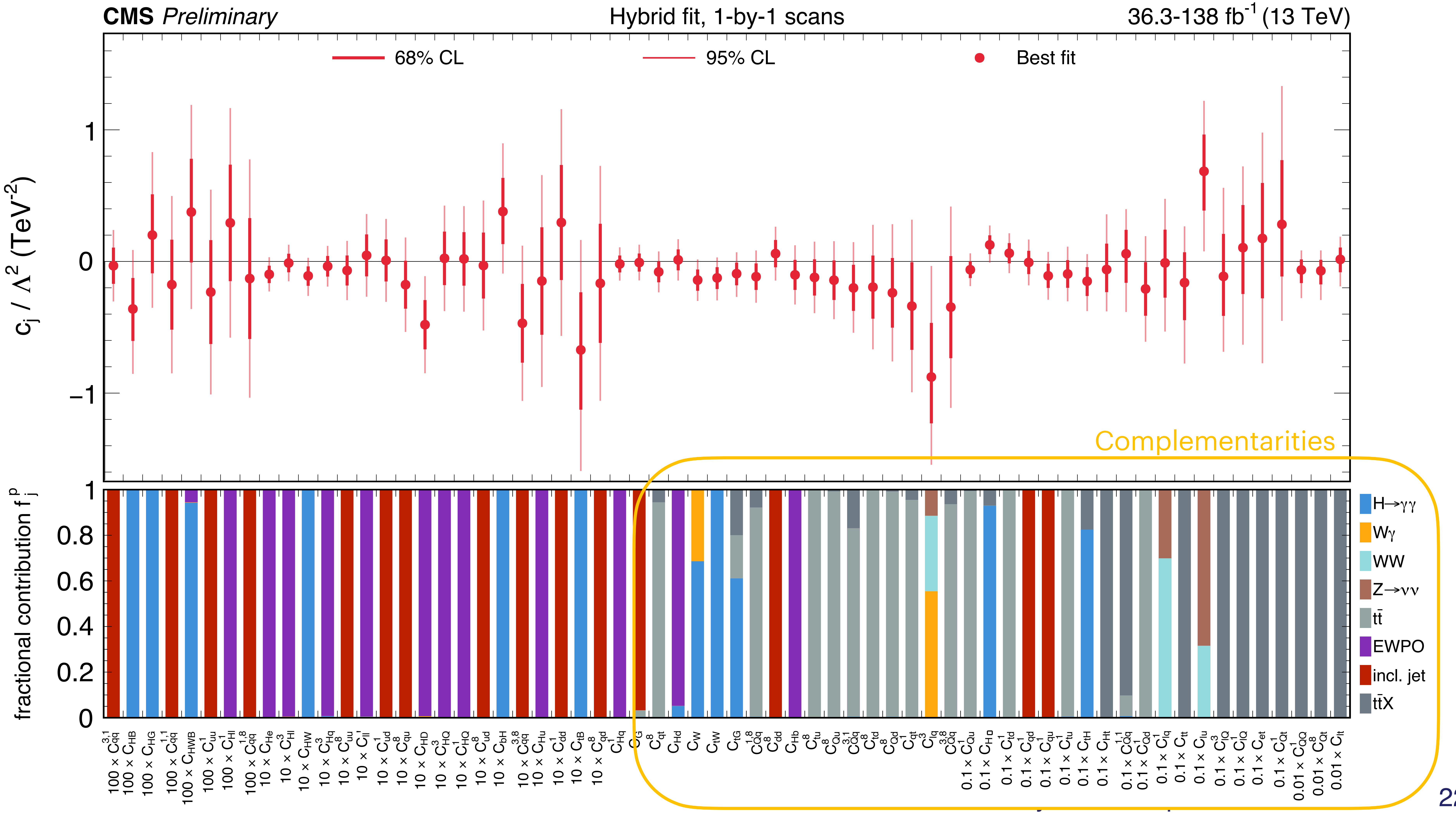
General EFT interpretation

CMS-PAS-SPM-24-003

It requires simultaneous constraints from a global set of measurements.

$H\to\gamma\gamma$, tt , ttX, WW, Wγ, $Z\to\nu\nu$, and inclusive jet production are used. In addition the electroweak precision observables (EWPO) at LEP and SLC are also included

Individual constraints on 64 WCs and constraints on 42 linear combinations of WCs, are obtained.

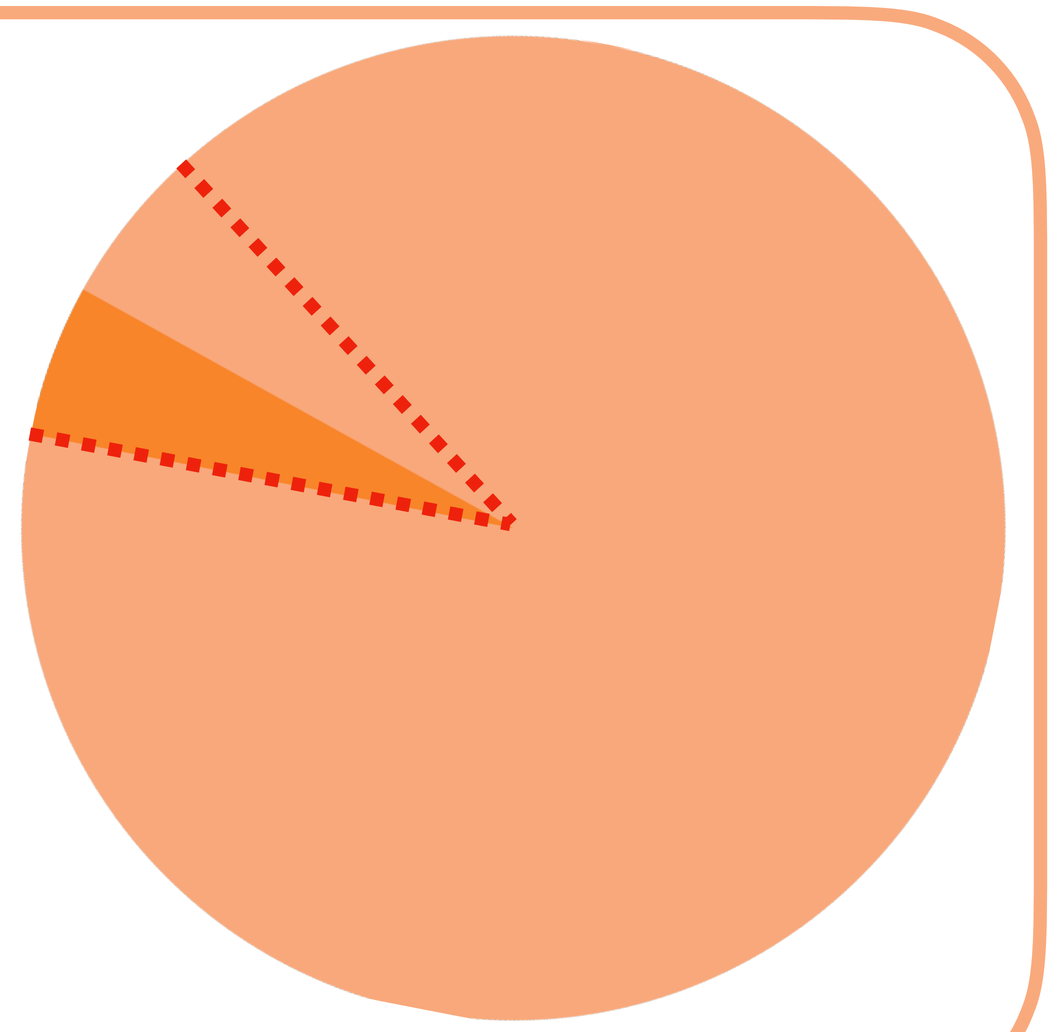


CMS Run 3 results

We have them, they are great … but … you will see later this week

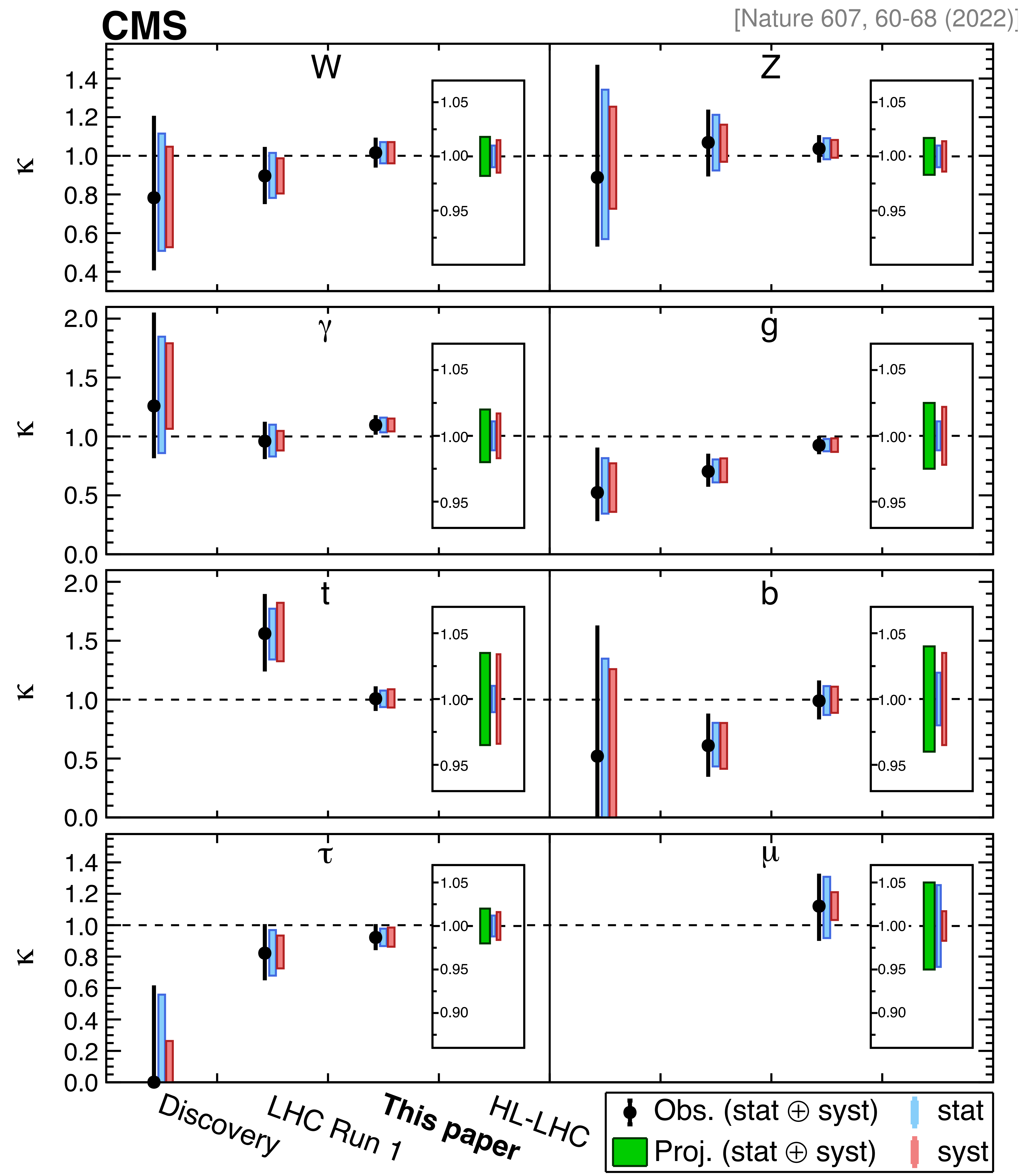
Projections of H couplings

We have collected **10%** and have analyzed **only 5%** of the expected final LHC + HL-LHC integrated luminosity,
yet we have already achieved magnificent results

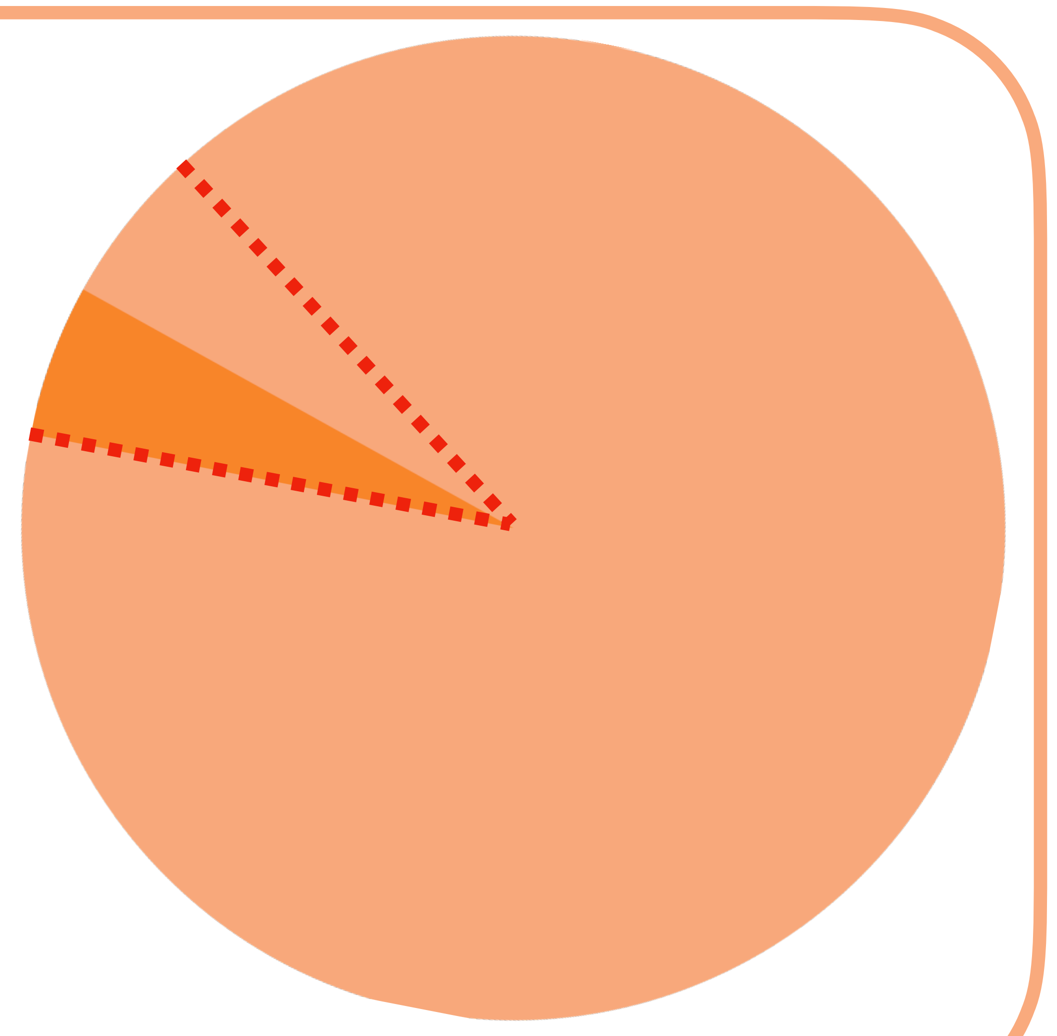


Projections of H couplings

Nature 607 (2022) 60



We have collected **10%** and have analyzed **only 5%** of the expected final LHC + HL-LHC integrated luminosity,
yet we have already achieved magnificent results



hopes & wishes

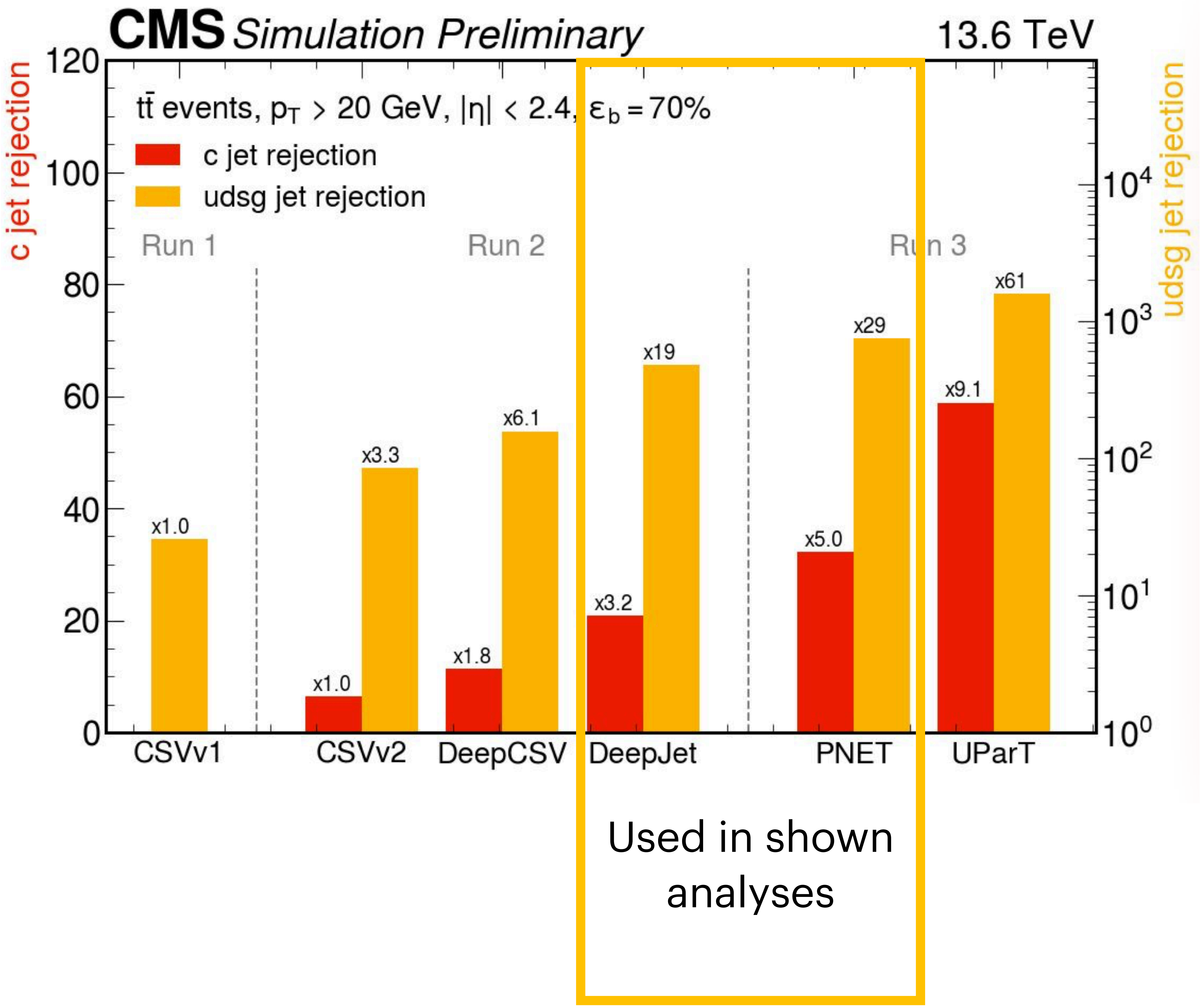
High Luminosity LHC

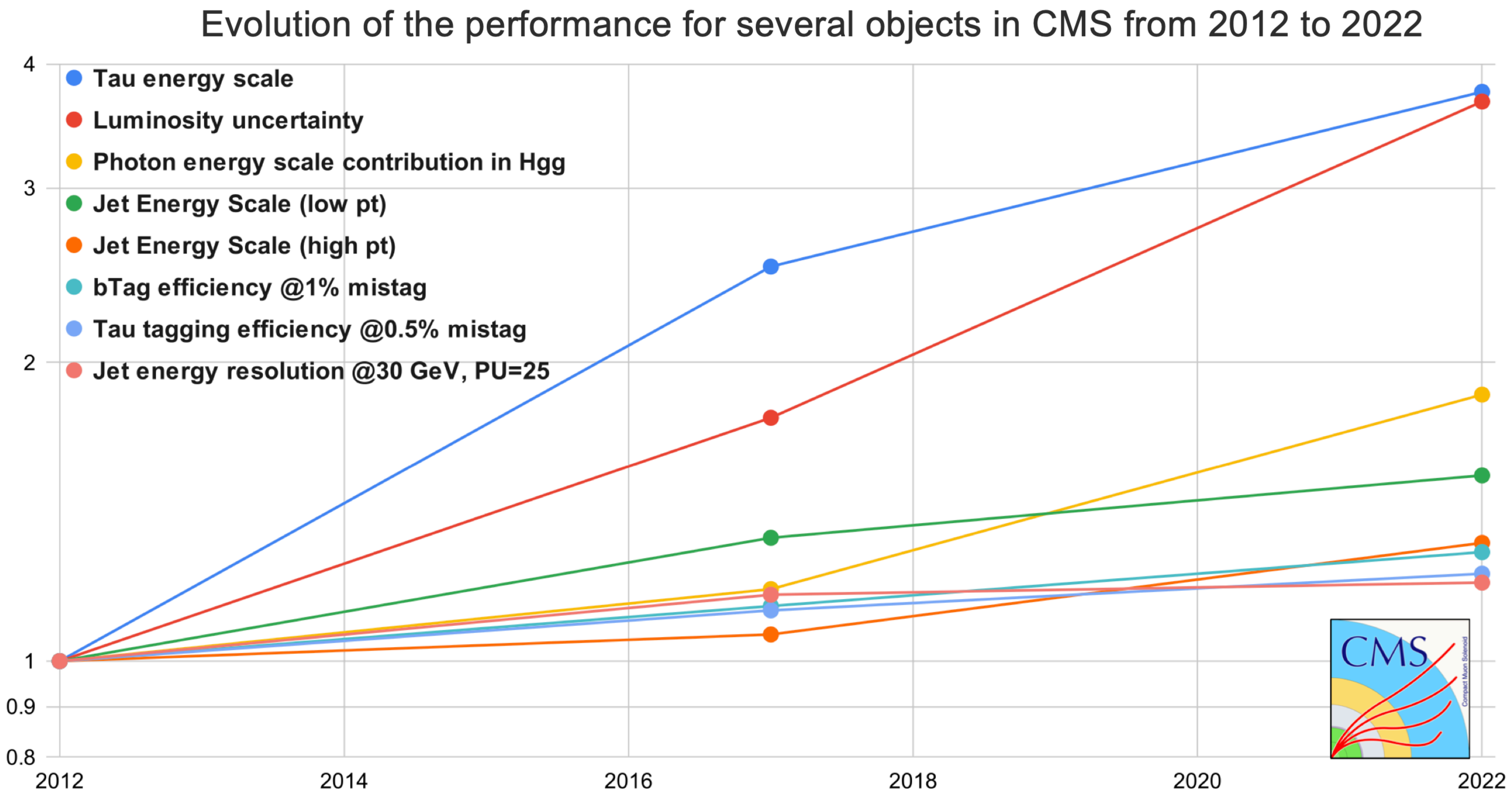
Many beyond SM scenarios predict only %-level deviations from SM !

→ Harsher experimental conditions require upgrades of our detectors

Looking ahead

Since Run 1, there have been significant improvements on all fronts, some further enhanced by the use of deep learning algorithms. As a result, event reconstruction has become much more accurate, enabling improvements wrt past projections.





F. Gianotti's talk at ICHEP 2022

Closing remarks

We face a period of unprecedented possibilities in particle physics.

With the Higgs boson discovery **new conceptual questions are defined.**
A fundamental scalar? A self-interacting particle? …

Additionally other **major discoveries** have occurred at the LHC so far:

- The observation of the Higgs boson Yukawa coupling with the 3rd family of fermions
- The establishment of three as the total number of fermion families.
- The non-observation of SUSY (e.g a model that could solve Hierarchy, Unification, and Dark Matter problems in one go)

The future will be all profoundly interesting, whether or not the results will be in agreement with SM predictions and Higgs boson physics will provide a reach set of results