EFT ON THE EW SECTOR

Based on 'Production of two, three, and four Higgs bosons: where SMEFT and HEFT depart'

arXiv: 2311.04280

(Rafael L. Delgado, RGA , Javier Martínez-Martín, Alexandre Salas-Bernárdez , Juan J. Sanz-Cillero)

PART I: OPEN QUESTIONS

Why new physics? We've all seen the list

- What is dark matter? What is dark energy?
- Why is the top quark so much heavier than the W boson?
- Why is the weak force so much weaker than the strong force?
- Where does CP violation come from?
- What is the source of the matter-antimatter asymmetry in the universe?
- What is the shape of the Higgs potential?
- What about neutrino masses?

We have the SM, but…

The SM doesn't answer any of these questions

Together, the LHC and future colliders can yield new insights

I will focus on e^+e^- colliders

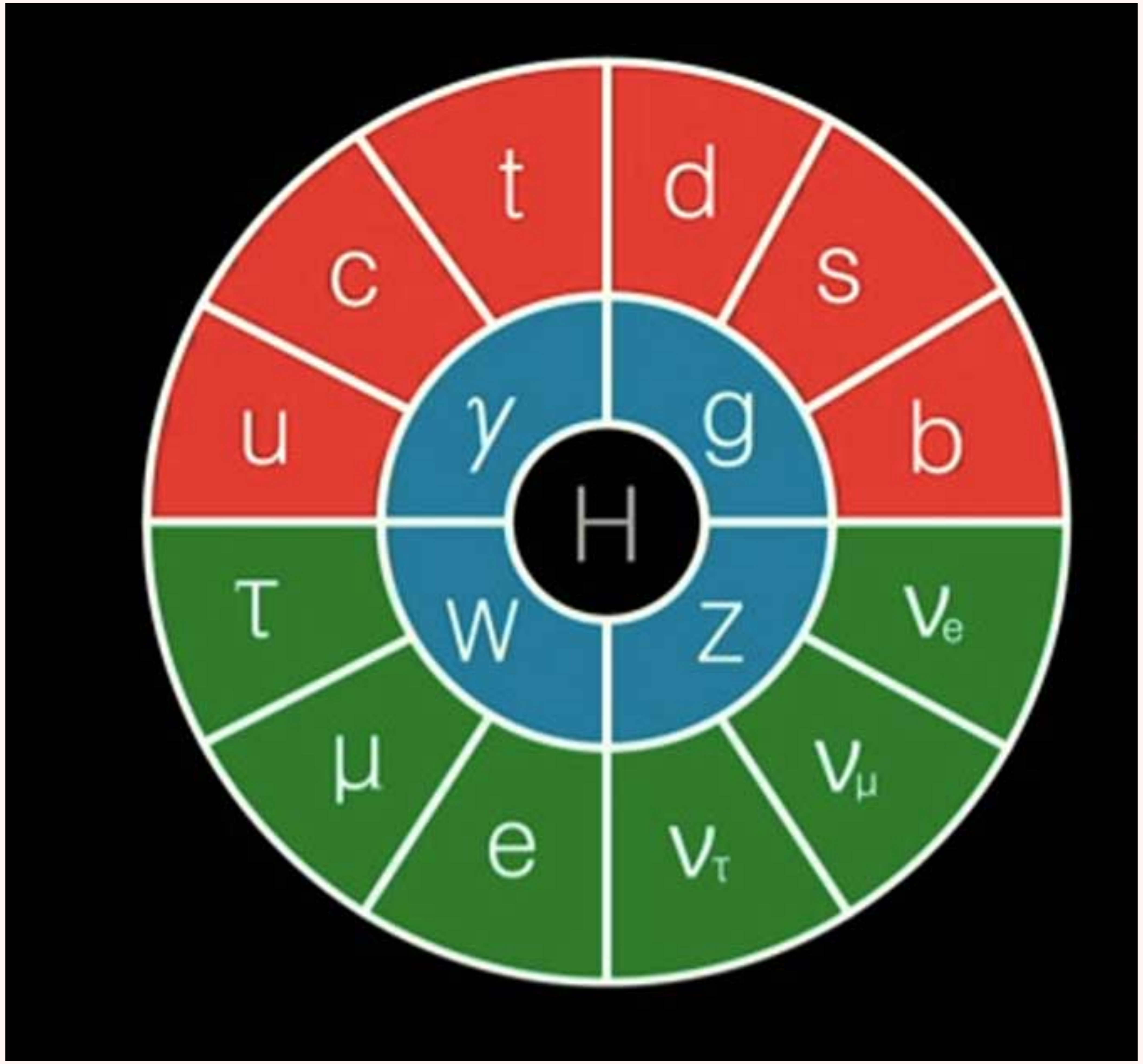
New physics is needed, but we don't know where

- **Here we will focus on the following questions:**

  1. **What is the shape of the Higgs potential**

  2. **Why is the weak force so much weaker than the strong force**

  3. **What is the origin of EWSB?**



PART II: WHAT WE KNOW

- **The Higgs sector (as seen from the SM)**

$$\mathscr{L}_H = (D_\mu \Phi)^\dagger (D_\mu \Phi) - V$$

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

- **If we assume a doublet shape, λ_3 and λ_4 will be related, and so will eventually any λ_5, λ_6**
- **Same goes for hv and hvv**
- **If the Higgs is NOT a doublet, we will need to measure the λ_i independently to parametrise the potential and the hv^n to decipher the EWSB mechanism**

If we assume EWSB and V are SM-like (implying new physics is weakly coupled), we can write down the SMEFT Lagrangian:

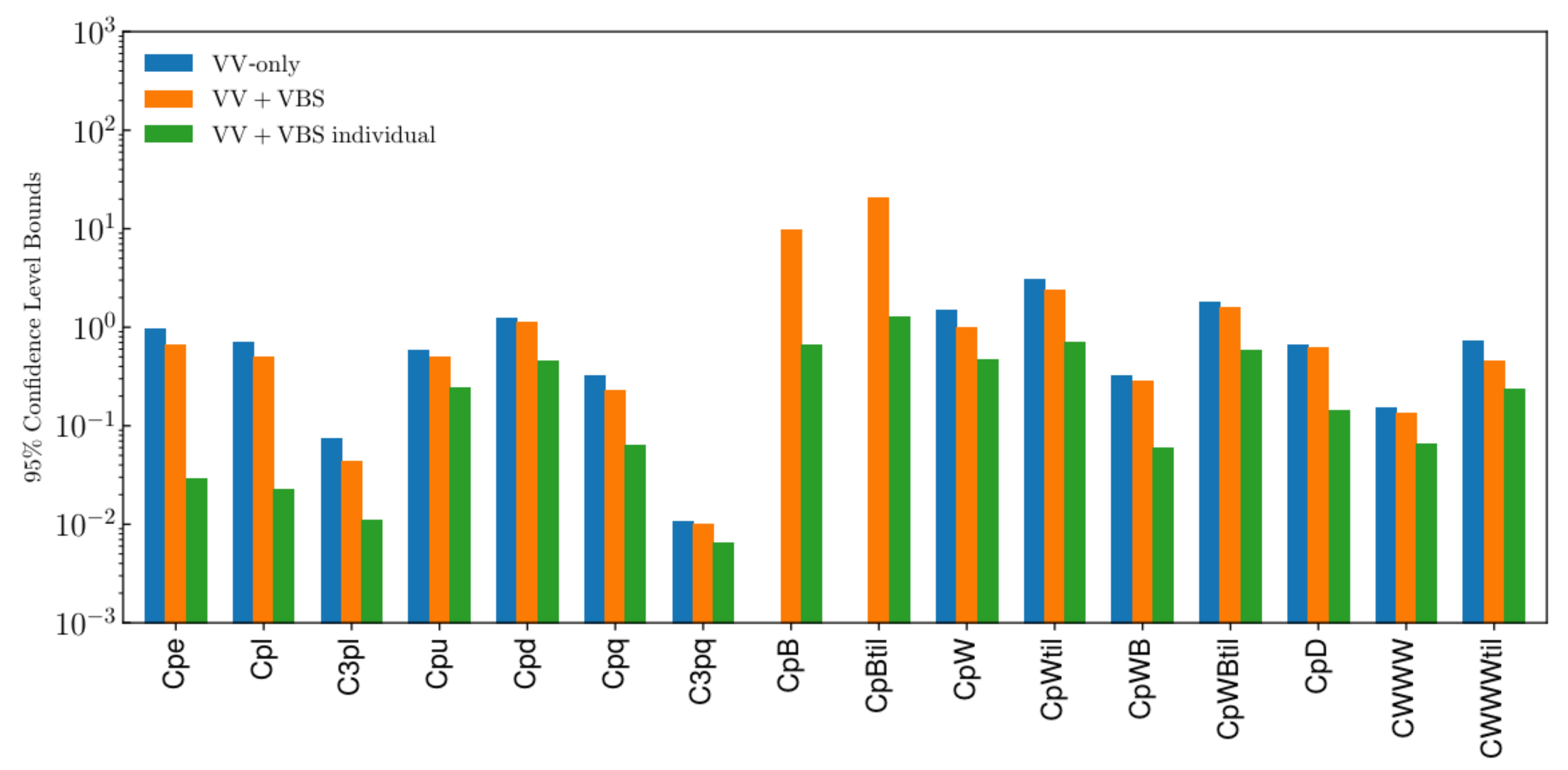
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + c_1 \frac{\mathcal{O}_1^{(6)}}{\Lambda^2} + c_2 \frac{\mathcal{O}_2^{(6)}}{\Lambda^2} + \ldots + c_3 \frac{\mathcal{O}_3^{(8)}}{\Lambda^4} + c_4 \frac{\mathcal{O}_1^{(8)}}{\Lambda^4} + \ldots$$

See talk by J. Rojo

SMEFT

- **Dim-6 analyses of the EW sector**
  - **In 2020 with 52 data points in VV and 18 in VBS, we found no big deviation from the SM**
- **Natural next steps:**
  - **update the fit with 2023 data**
  - **add dim-8 operators**

https://arxiv.org/abs/2101.03180



PART III: WHAT WE DON'T KNOW

“THE HIGGS IS A DOUBLET UNDER SU(2)”.... LET’S START BY VALIDATING THIS STATEMENT

Measuring the H couplings to multiple vector bosons can also be a smoking gun for new physics

hZZ vs Higgs self-coupling

$$\frac{1}{\Lambda^2}(H^\dagger \partial H)^2 \qquad \frac{1}{\Lambda^2}(H^\dagger H)^3$$

δ_{Zh}

Modify H-Z coupling $\Rightarrow \delta_{Zh}$

Modify Higgs self-coupling $\Rightarrow \delta_{\lambda_3}$

However, $\delta_{Zh} \propto g_z$, while δ_{λ_3} is not related to $\lambda_{3,\mathrm{SM}}$

With some tuning, one can find models in which $\delta_{\lambda_3} > \delta_{Zh}$

HEFT VS SMEFT

SMEFT Lagrangian: $\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + c_1 \frac{\mathcal{O}_1^{(6)}}{\Lambda^2} + c_2 \frac{\mathcal{O}_2^{(6)}}{\Lambda^2} + \ldots + c_3 \frac{\mathcal{O}_3^{(8)}}{\Lambda^4} + c_4 \frac{\mathcal{O}_1^{(8)}}{\Lambda^4} + \ldots$

HEFT Lagrangian:

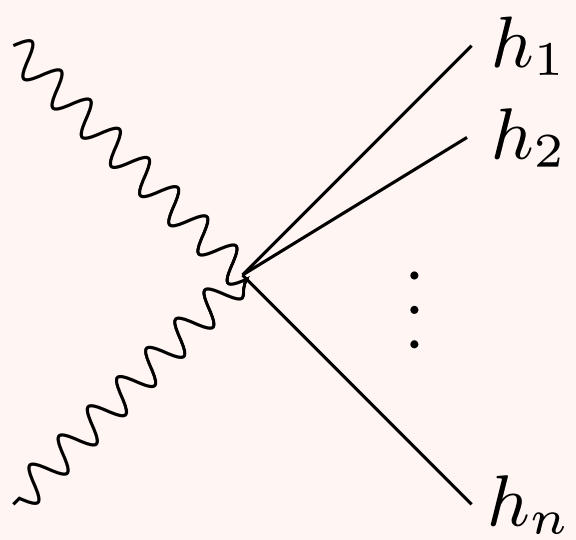
$$\mathscr{L}_{HEFT} = \frac{1}{2}\partial_\mu h\, \partial^\mu h + \left(1 + a_1 \frac{h}{v} + a_2 \left(\frac{h}{v}\right)^2 + a_3 \left(\frac{h}{v}\right)^3 + \ldots + a_n \left(\frac{h}{v}\right)^n \right) \partial_\mu w^+ \partial^\mu w^- + \ldots$$

$\mathcal{F}(h)$ *Flare Function*

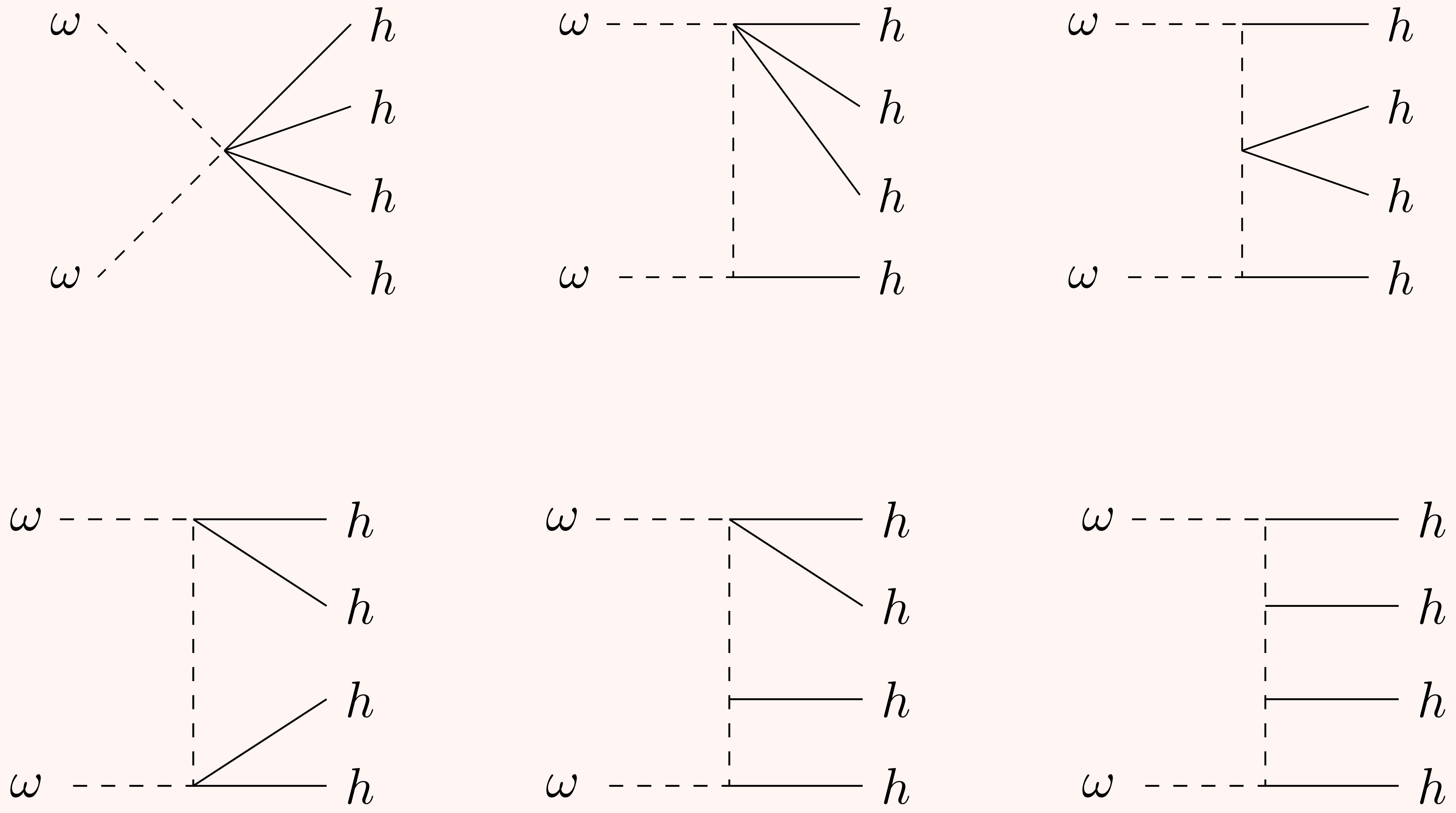
See Duarte Fontes' talk on HEFT

LOOK AT WW TO NH

- **We use the Equivalence Theorem (collisions at several TeV, Higgs is "massless")**

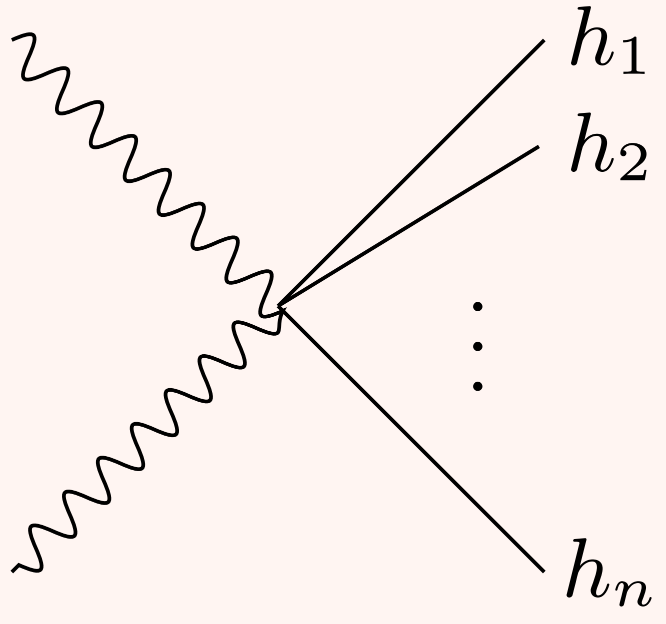


$$= -\frac{n! a_n}{2v^n} s$$



LOOK AT WW TO NH

- **We use the EqTh (collisions at several TeV)**
- **We are not looking at a global fit, but at interesting pseudo observables**
- **Whereas in SMEFT, corrections to processes with n higgsses are suppressed by increasing factors of Lambda, in HEFT this is not necessarily the case (smoking gun!)**
- **BSM scenarios often predict large nH Xsecs**



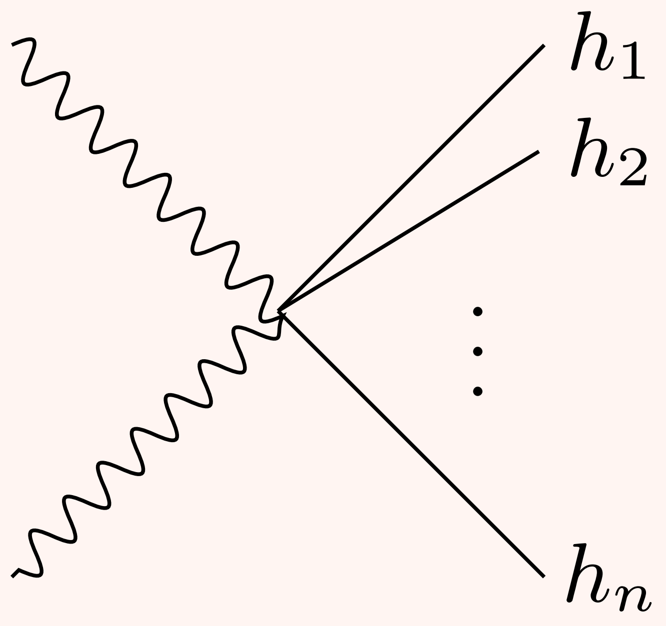
$$= -\frac{n!a_n}{2v^n}\, s$$

$$\sigma_{\omega\omega\to 2h} = \frac{8\pi^3\,\hat{a}_2^2}{s}\left(\frac{s}{16\pi^2 v^2}\right)^2$$

$$\sigma_{\omega\omega\to 3h} = \frac{12\pi^3\,\hat{a}_3^2}{s}\left(\frac{s}{16\pi^2 v^2}\right)^3$$

SMEFT exclusion plot, 2311.04280

LOOK AT WW TO NH



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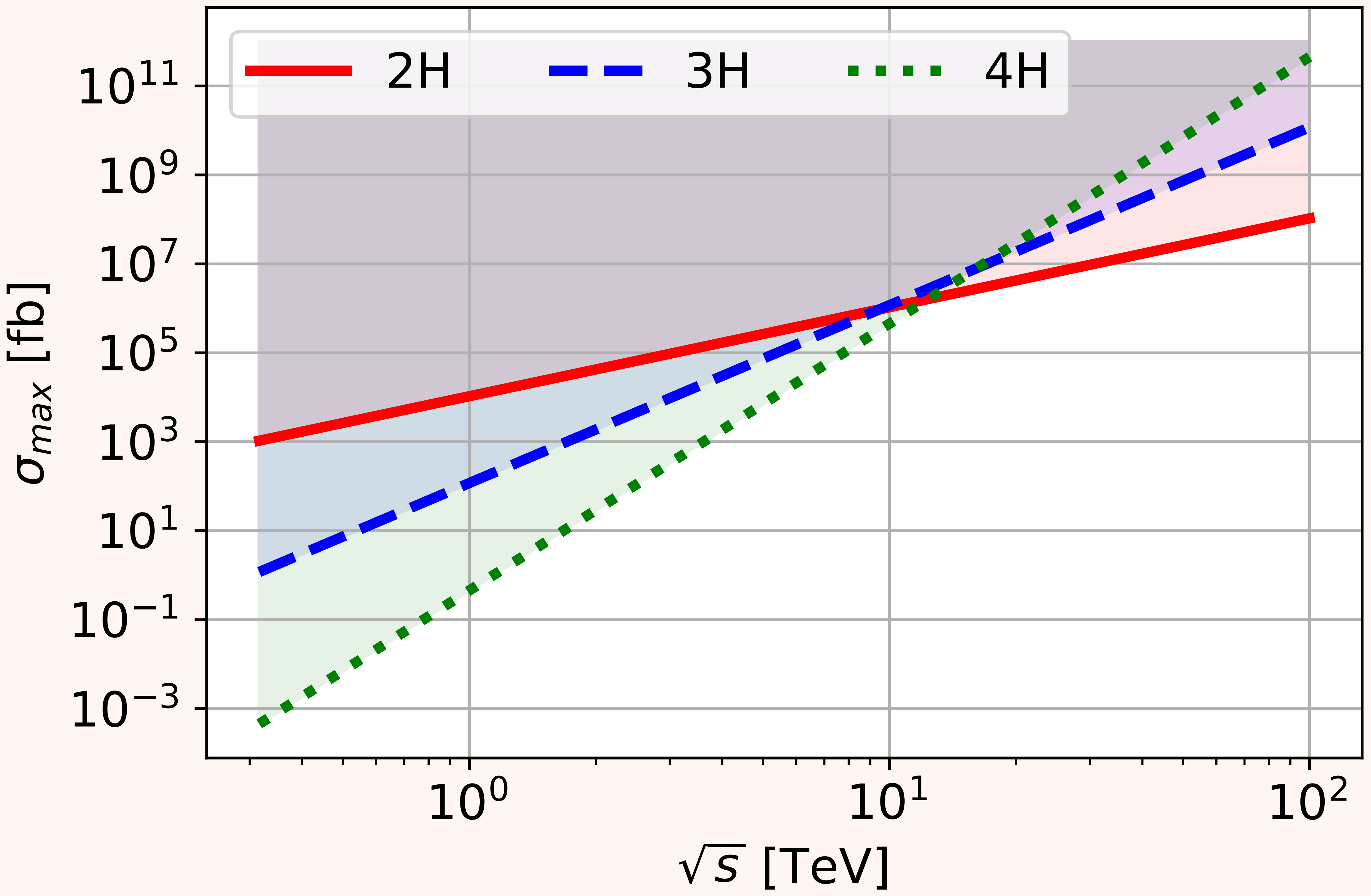
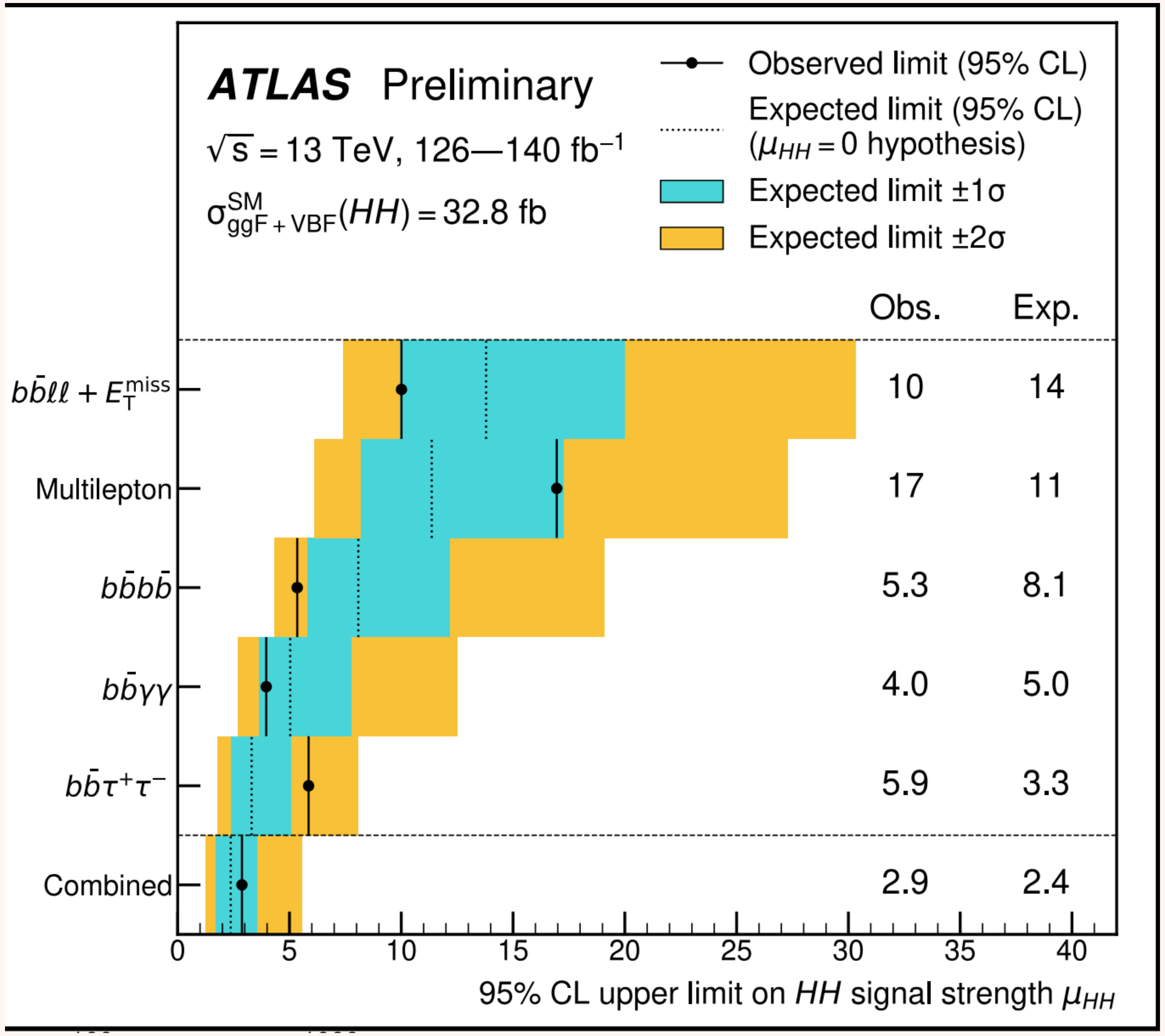
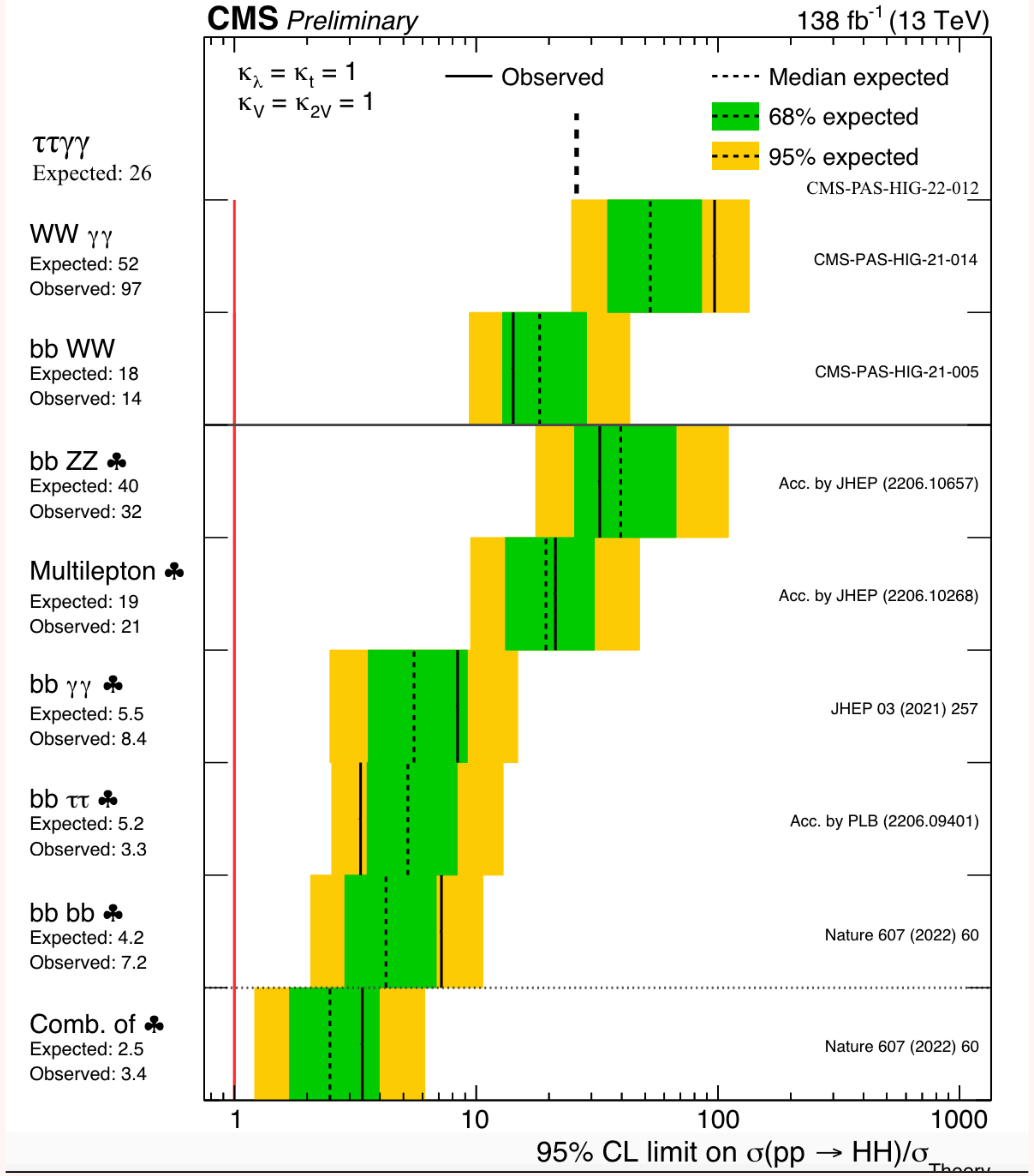


SMEFT exclusion plot, 2311.04280

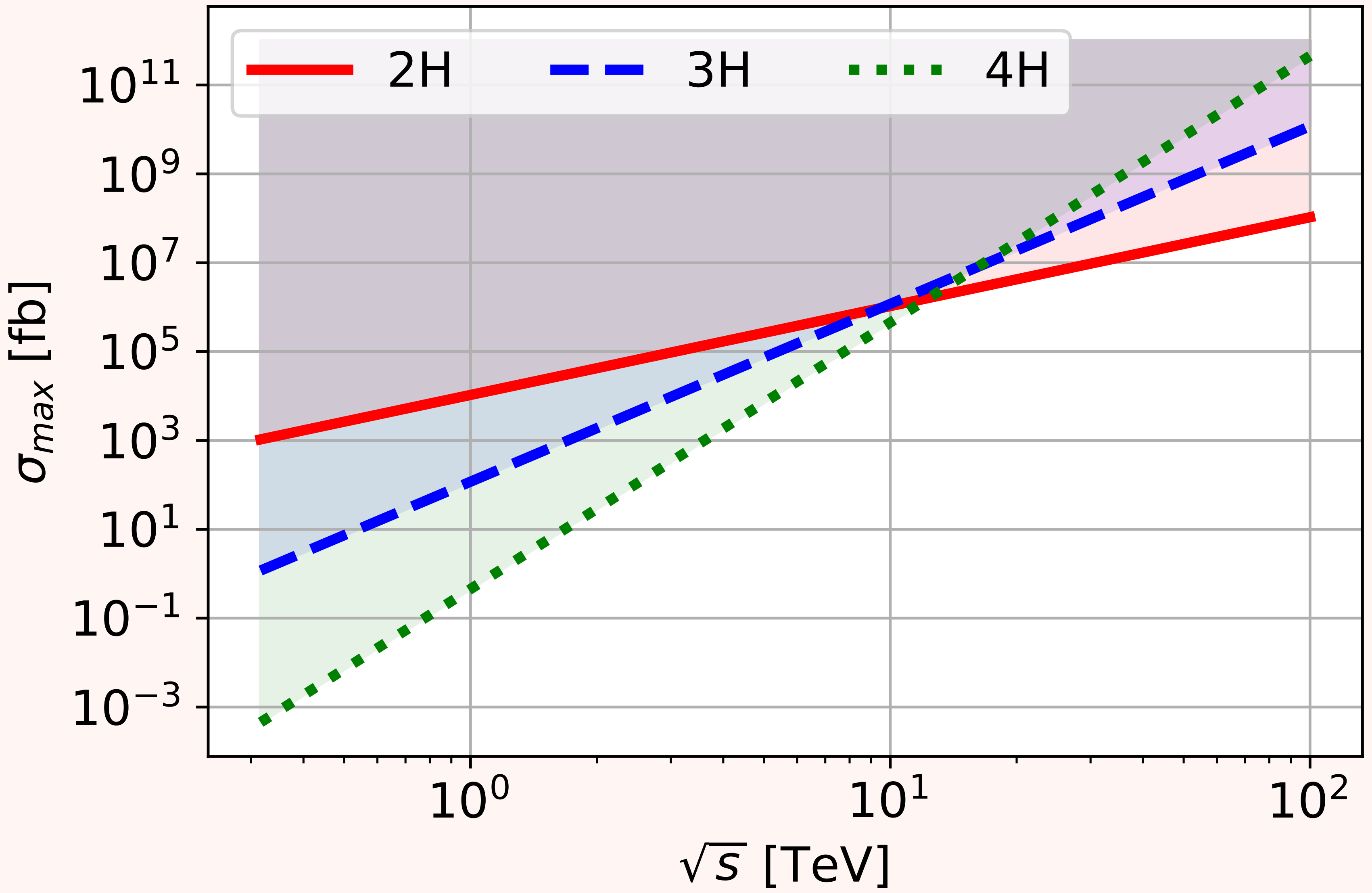
WW TO NH

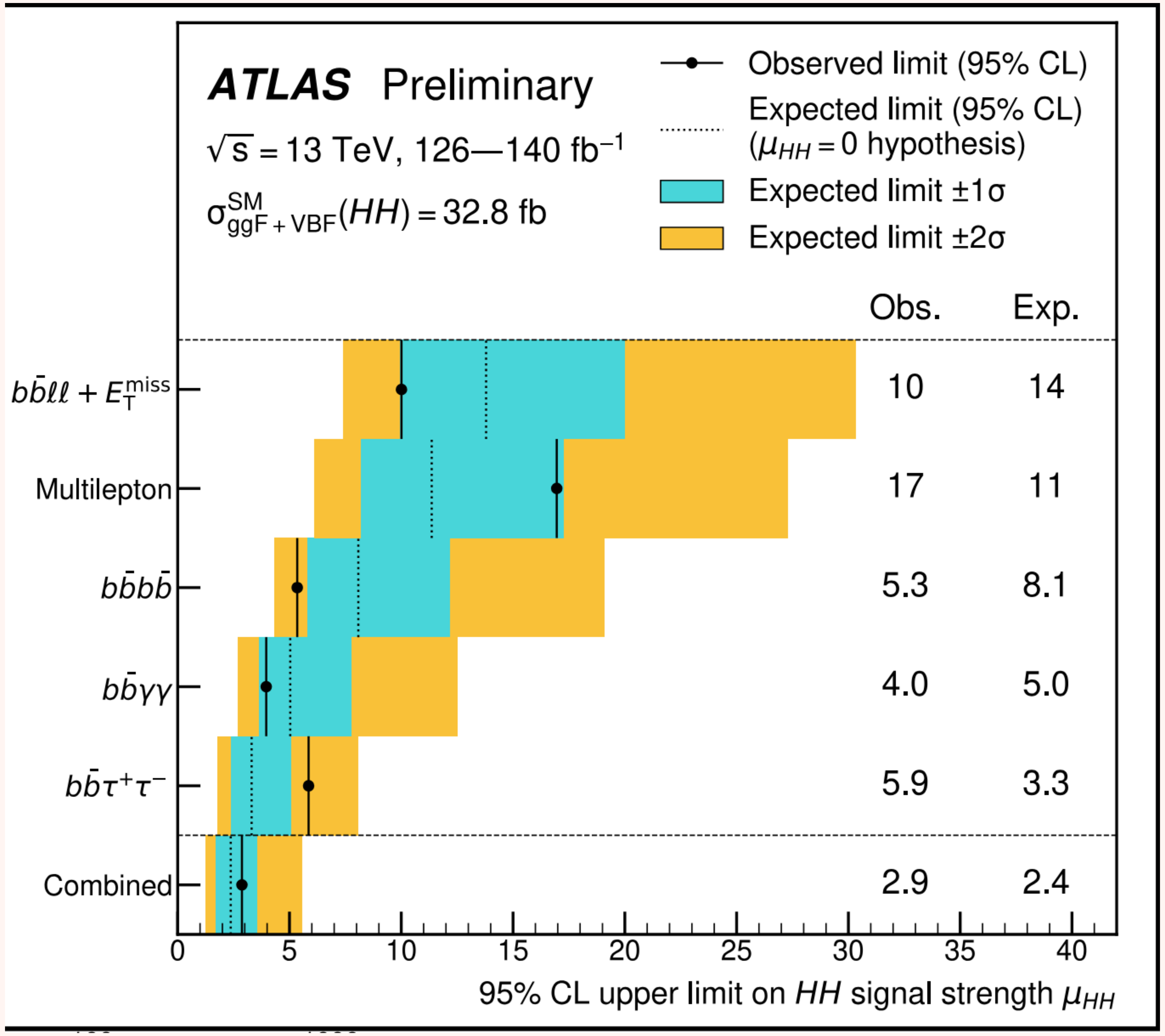

ATLAS Preliminary
√s = 13 TeV, 126—140 fb⁻¹
σ SM ggF + VBF (HH) = 32.8 fb
Observed limit (95% CL)
Expected limit (95% CL) (μHH = 0 hypothesis)
Expected limit ±1σ
Expected limit ±2σ
Obs.
Exp.
bb̄ℓℓ + E miss T
10
14
Multilepton
17
11
bb̄bb̄
5.3
8.1
bb̄γγ
4.0
5.0
bb̄τ⁺τ⁻
5.9
3.3
Combined
2.9
2.4
0
5
10
15
20
25
30
35
40
95% CL upper limit on HH signal strength μHH


CMS Preliminary
138 fb⁻¹ (13 TeV)
κλ = κt = 1
κV = κ2V = 1
Observed
Median expected
68% expected
95% expected
ττγγ
Expected: 26
CMS-PAS-HIG-22-012
WW γγ
Expected: 52
Observed: 97
CMS-PAS-HIG-21-014
bb WW
Expected: 18
Observed: 14
CMS-PAS-HIG-21-005
bb ZZ ♣
Expected: 40
Observed: 32
Acc. by JHEP (2206.10657)
Multilepton ♣
Expected: 19
Observed: 21
Acc. by JHEP (2206.10268)
bb γγ ♣
Expected: 5.5
Observed: 8.4
JHEP 03 (2021) 257
bb ττ ♣
Expected: 5.2
Observed: 3.3
Acc. by PLB (2206.09401)
bb bb ♣
Expected: 4.2
Observed: 7.2
Nature 607 (2022) 60
Comb. of ♣
Expected: 2.5
Observed: 3.4
Nature 607 (2022) 60
1
10
100
1000
95% CL limit on σ(pp → HH)/σTheory

WW TO NH

- **We don't need a precision mesaurement. If we observe an excess in the pp to HH production with respect to the SM, we can rule the SMEFT and assume more complex scenarios**
- **This would then be confirmed by a 3H production measurement**





PART IV: MAP THE HEFT TO SMEFT

WW TO NH

- **By comparing the Lagrangians term-by-term we can map the HEFT to the SMEFT**

$$
\begin{aligned}
a_1/2 &= a = 1 + \frac{d}{2} + \frac{d^2}{2}\left(\frac{3}{4} + \rho\right) + \mathcal{O}\left(d^3\right) ,\\
a_2 &= b = 1 + 2d + 3d^2\left(1+\rho\right) + \mathcal{O}\left(d^3\right) ,\\
a_3 &= \frac{4}{3}d + d^2\left(\frac{14}{3} + 4\rho\right) + \mathcal{O}\left(d^3\right) ,\\
a_4 &= \frac{1}{3}d + d^2\left(\frac{11}{3} + 3\rho\right) + \mathcal{O}\left(d^3\right) ,\\
a_5 &= d^2\left(\frac{22}{15} + \frac{6}{5}\rho\right) + \mathcal{O}\left(d^3\right) ,\\
a_6 &= d^2\left(\frac{11}{45} + \frac{1}{5}\rho\right) + \mathcal{O}\left(d^3\right) ,
\end{aligned}
$$

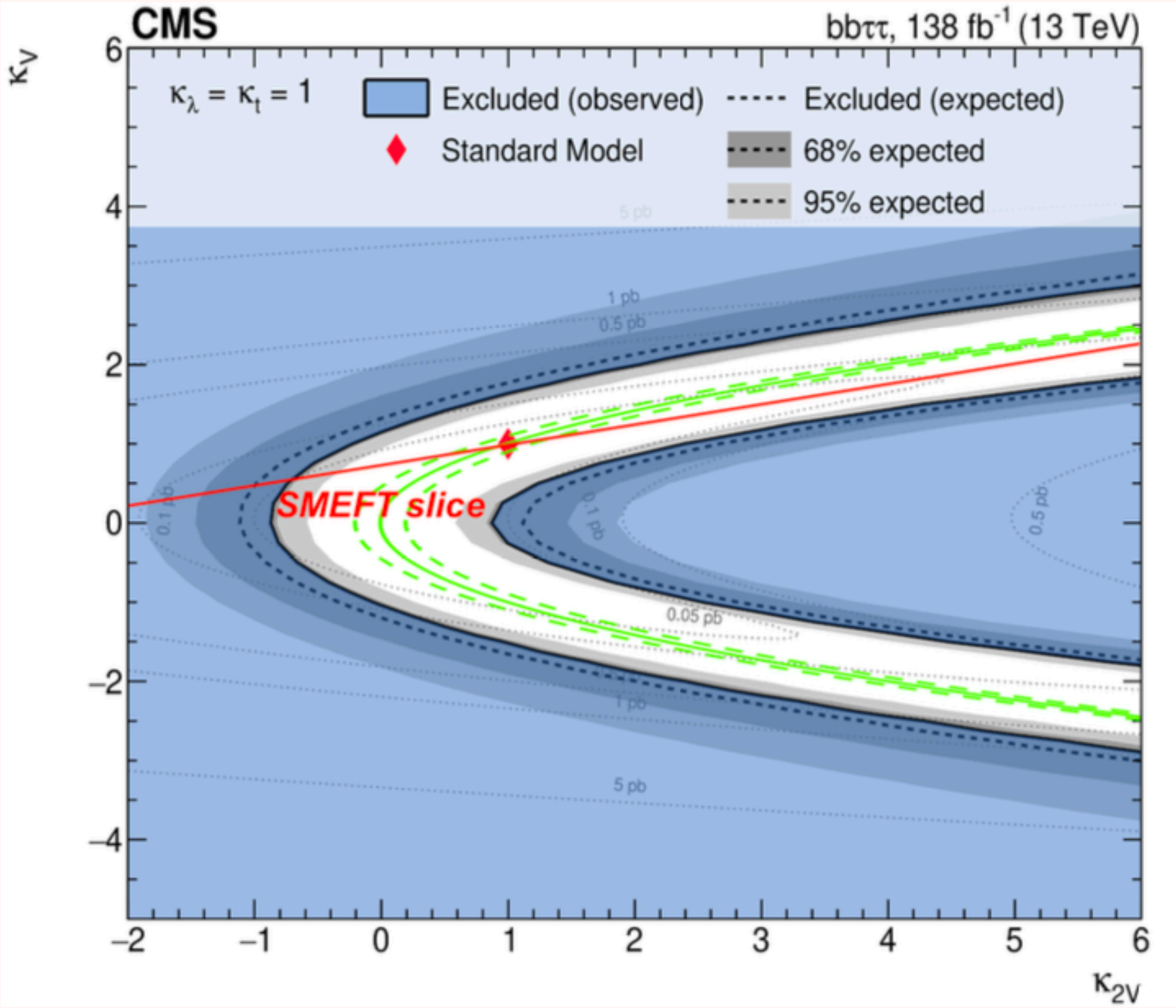
$$
\begin{aligned}
\sigma^{\mathrm{EFT-max}}_{\omega\omega\to hh} &= \frac{\epsilon^2}{8\pi s} ,\\
\sigma^{\mathrm{EFT-max}}_{\omega\omega\to 3h} &= \left(\frac{v^2}{16\pi^2 s}\right)\frac{4\epsilon^4}{3\pi s}\left(1+\rho_{\max}\right)^2 ,\\
\sigma^{\mathrm{EFT-max}}_{\omega\omega\to 4h} &= \left(\frac{1}{16\pi^2}\right)^2\frac{\epsilon^4}{18\pi s}\left((1+\rho_{\max})^2 + 2(1+\rho_{\max})\chi_1 + \chi_2\right)
\end{aligned}
$$

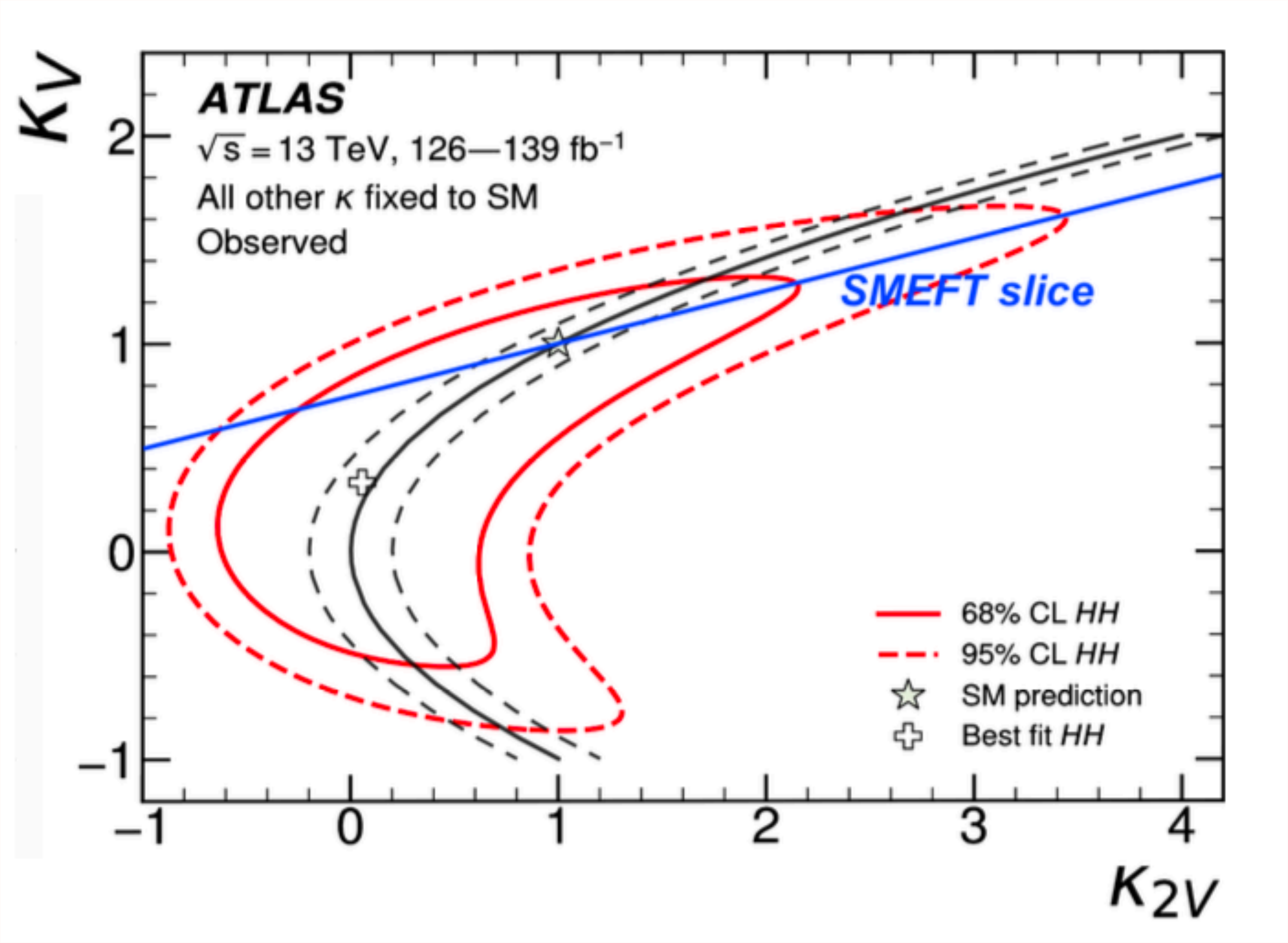
$$
d = \frac{2v^2 c^{(6)}_{H\Box}}{\Lambda^2} , \qquad \rho = \frac{c^{(8)}_{H\Box}}{2(c^{(6)}_{H\Box})^2}
$$

See more details in https://arxiv.org/abs/2204.01763 and https://arxiv.org/abs/2207.09848

WW TO NH

- **What else can we do? Look at the available κ_v and κ_{2v} measurements. Another way of "ruling out " the SMEFT**

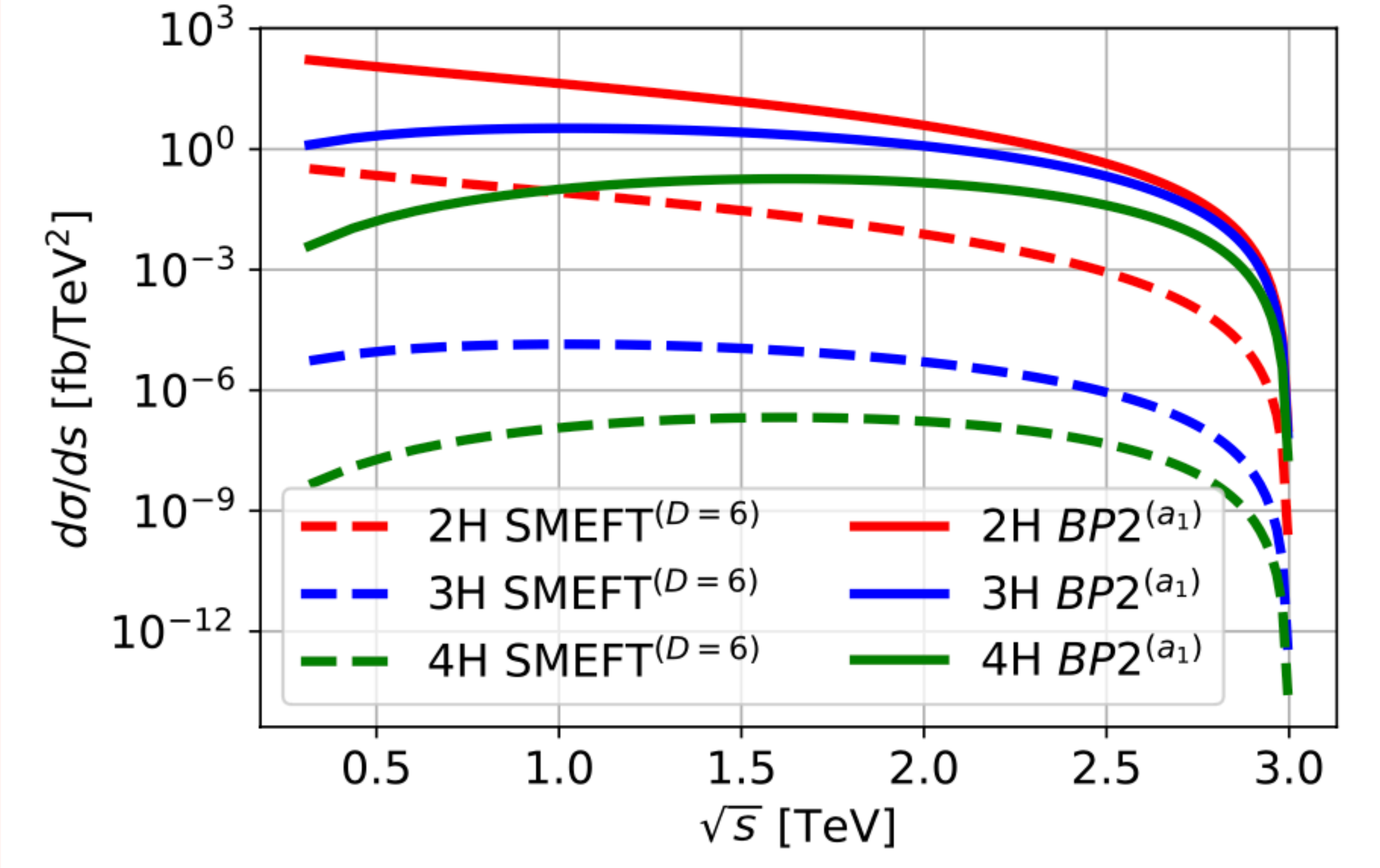


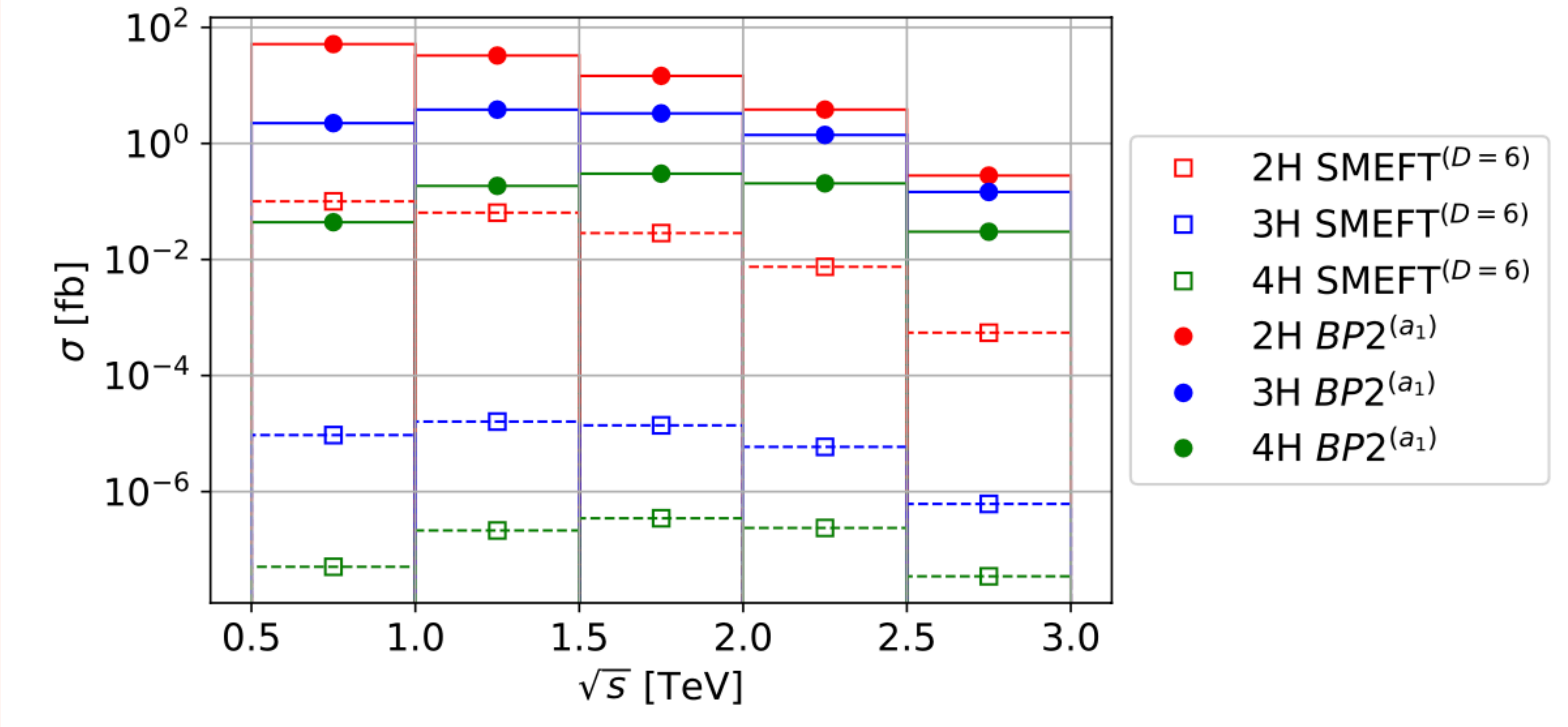


A theory is only a proper theory if it can be falsified….

WW TO NH AT CLIC

- **Going a bit more *pheno-ish*, we use the EWA approximation to predict cross sections at an ee collider (CLIC) at 3 TeV**





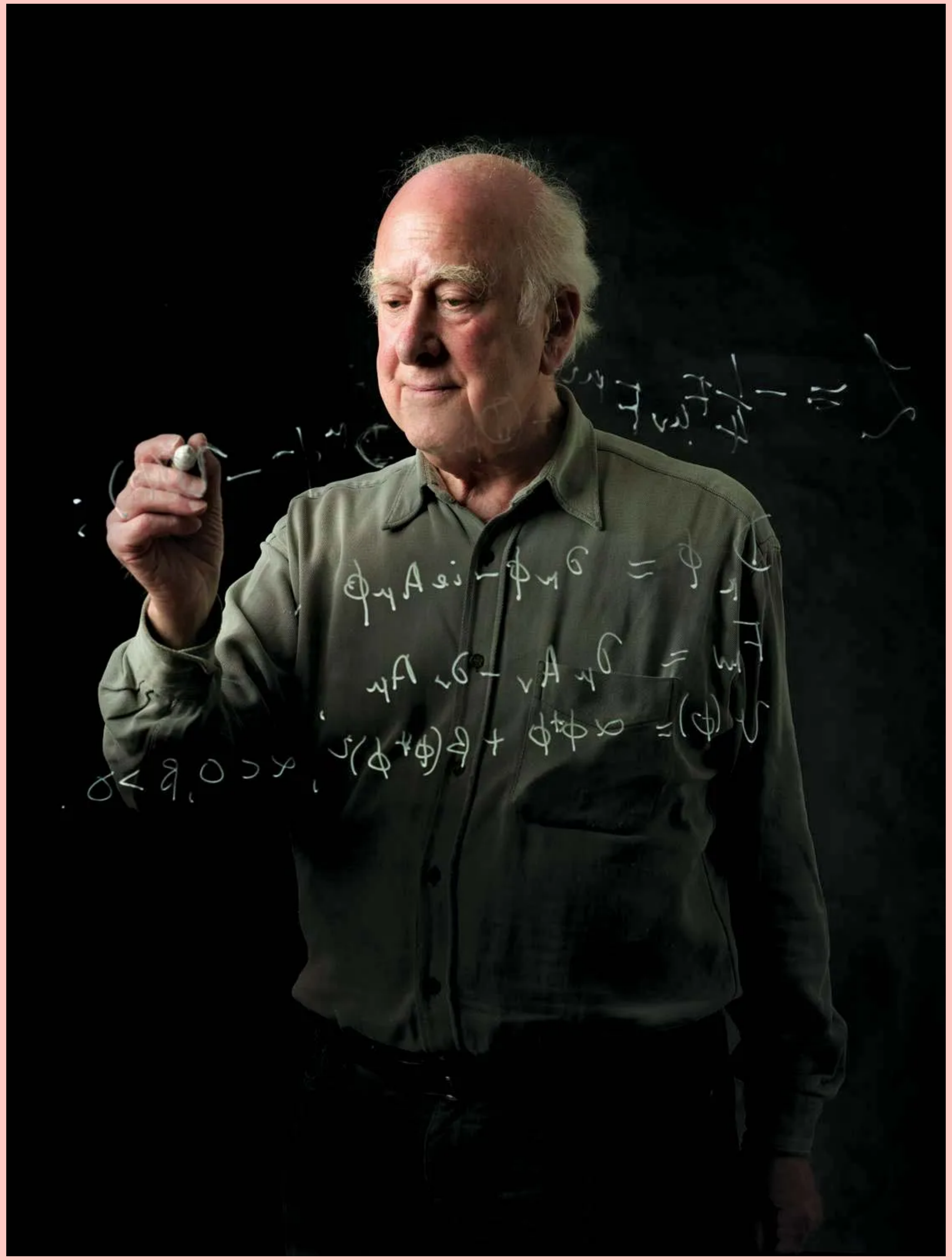
CONCLUSIONS

What can we do until HL-LHC

- Plenty of new HH results, always sharper
- We don't need a precision measurement to rule-out or confirm new physics, we can look at (the lack of) a small excess in HH as a smoking gun
- SMEFT fits of Run-2 are giving tighter and tighter constraints on the dim-6 Wilson coefficients. Time to consider broader EFTs
- (That is no problem, since we can map them back and forth)
- Next step: full phenomenological study to reproduce the ATLAS and CMS yields for HH production, and the HHH projections

THANK YOU!

And many thanks, Peter!



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