BEYOND THE PURE HIGGS SELF-COUPLINGS – HEFT, SMEFT

Based on 'Production of two, three, and four Higgs bosons: where SMEFT and HEFT depart', 'Distinguishing electroweak EFTs with ww to nh' etc.

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

https://inspirehep.net/literature/2720159

https://inspirehep.net/literature/2154526

PART I: OPEN QUESTIONS

WHY NEW PHYSICS?

We have the SM, but… it doesn't answer all the questions

What is Dark Matter? Dark energy?

Baryon asymmetry, CP-violation, neutrino masses….

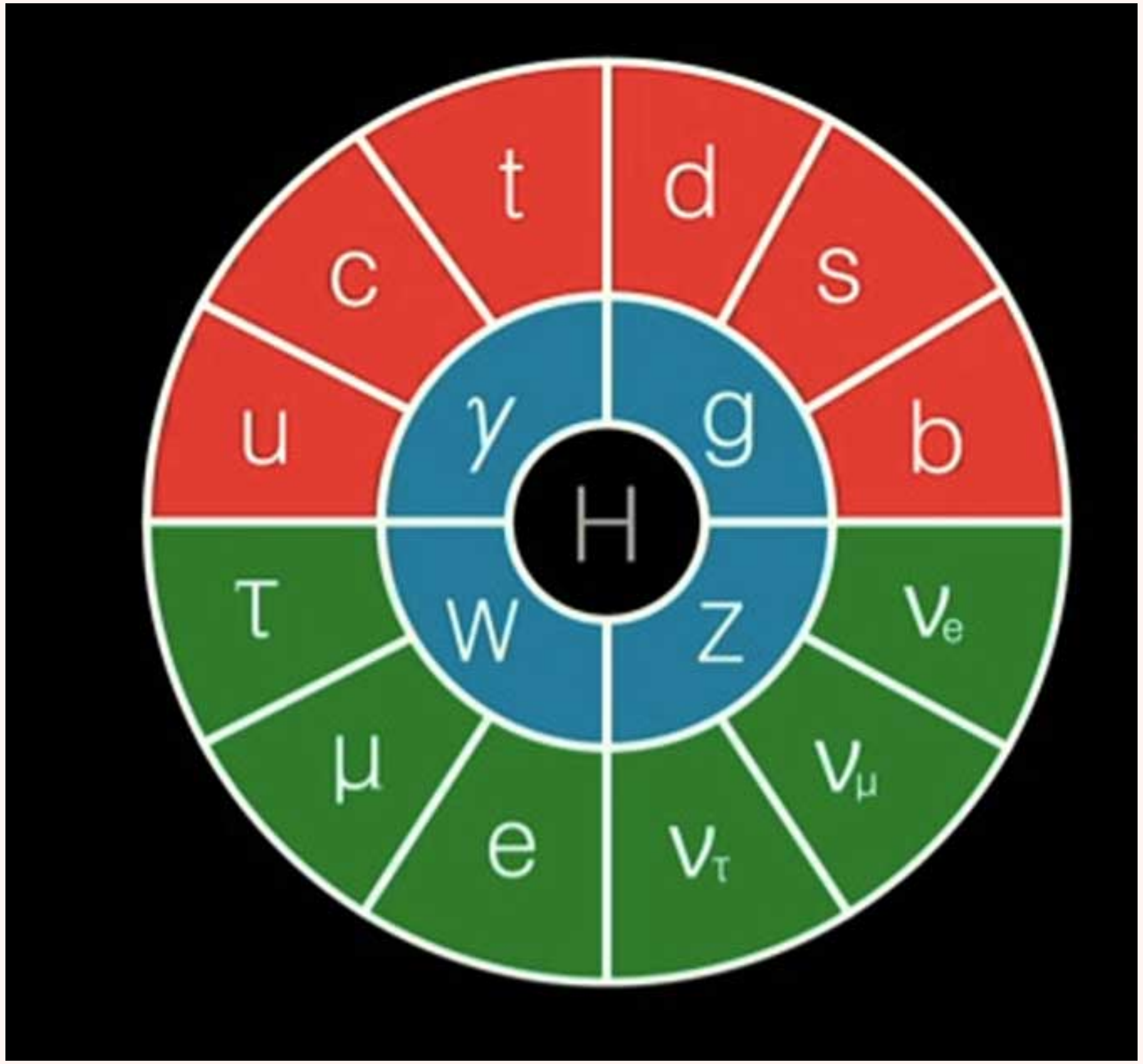
New physics is somewhere, we just don't know where

- **I 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:

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

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

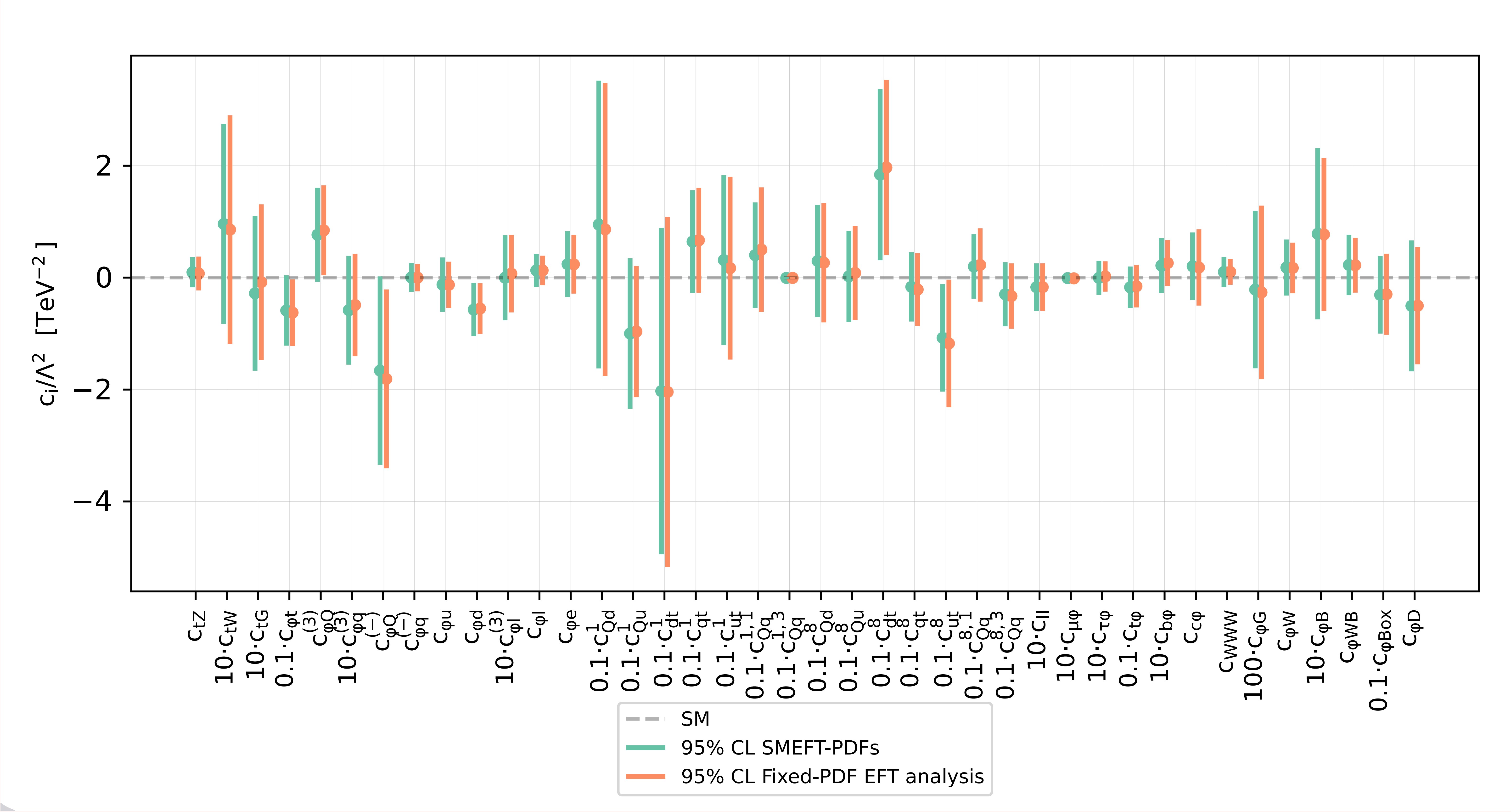
$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

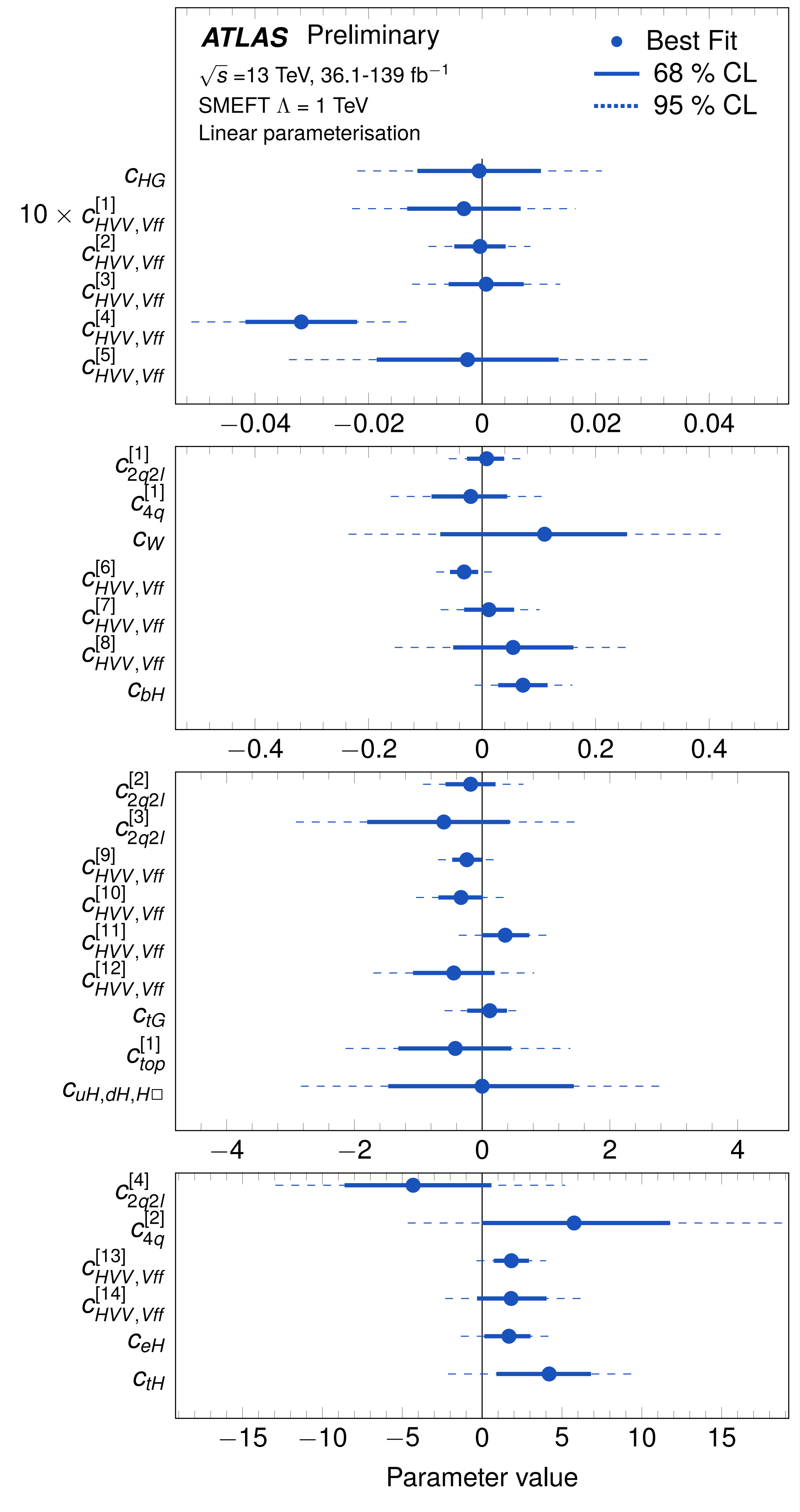
$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Dimension 6 SMEFT basis

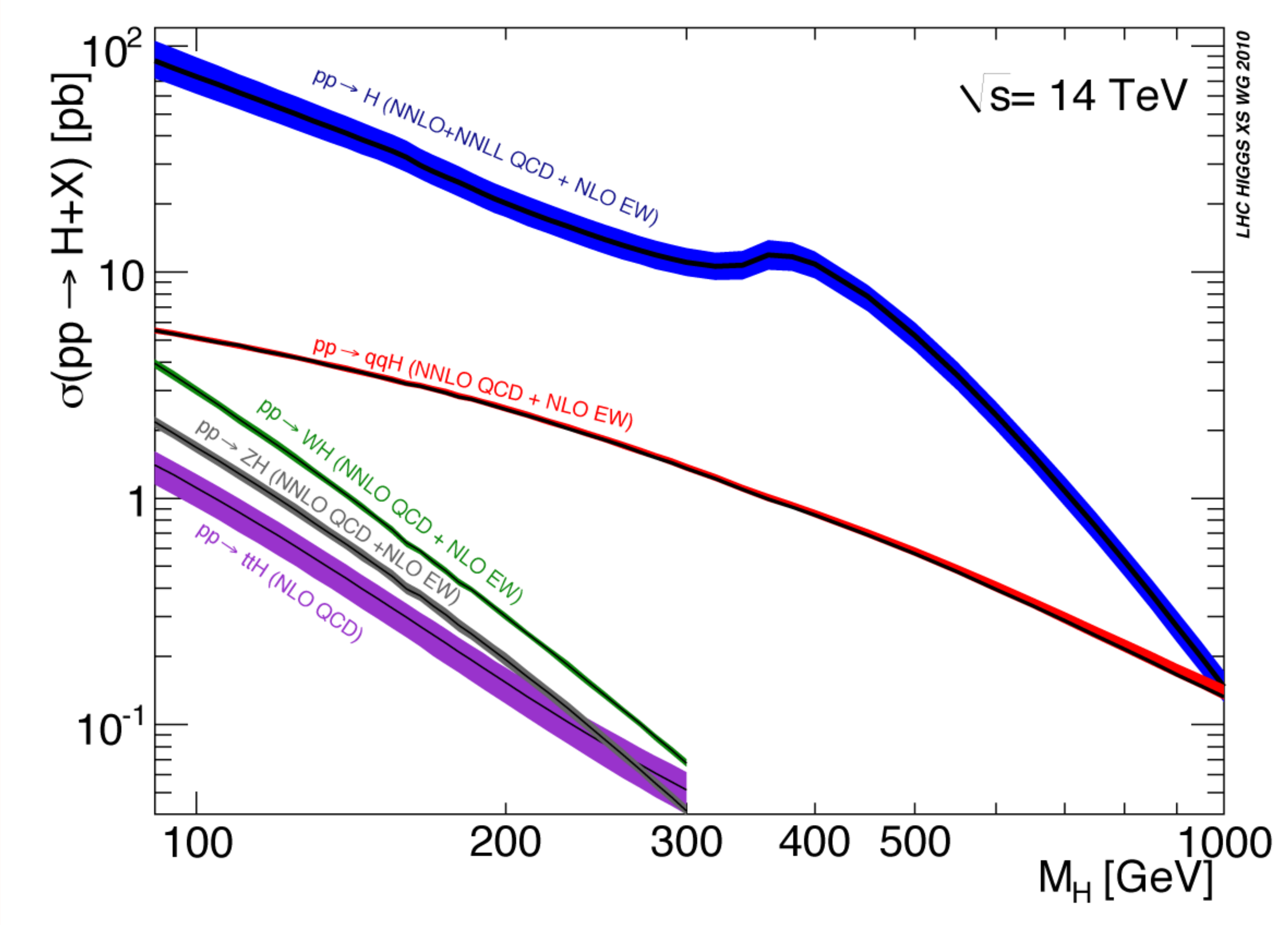
SCENARIO: ALL SMEFT COEFFICIENTS BOUND TO ~ ZERO

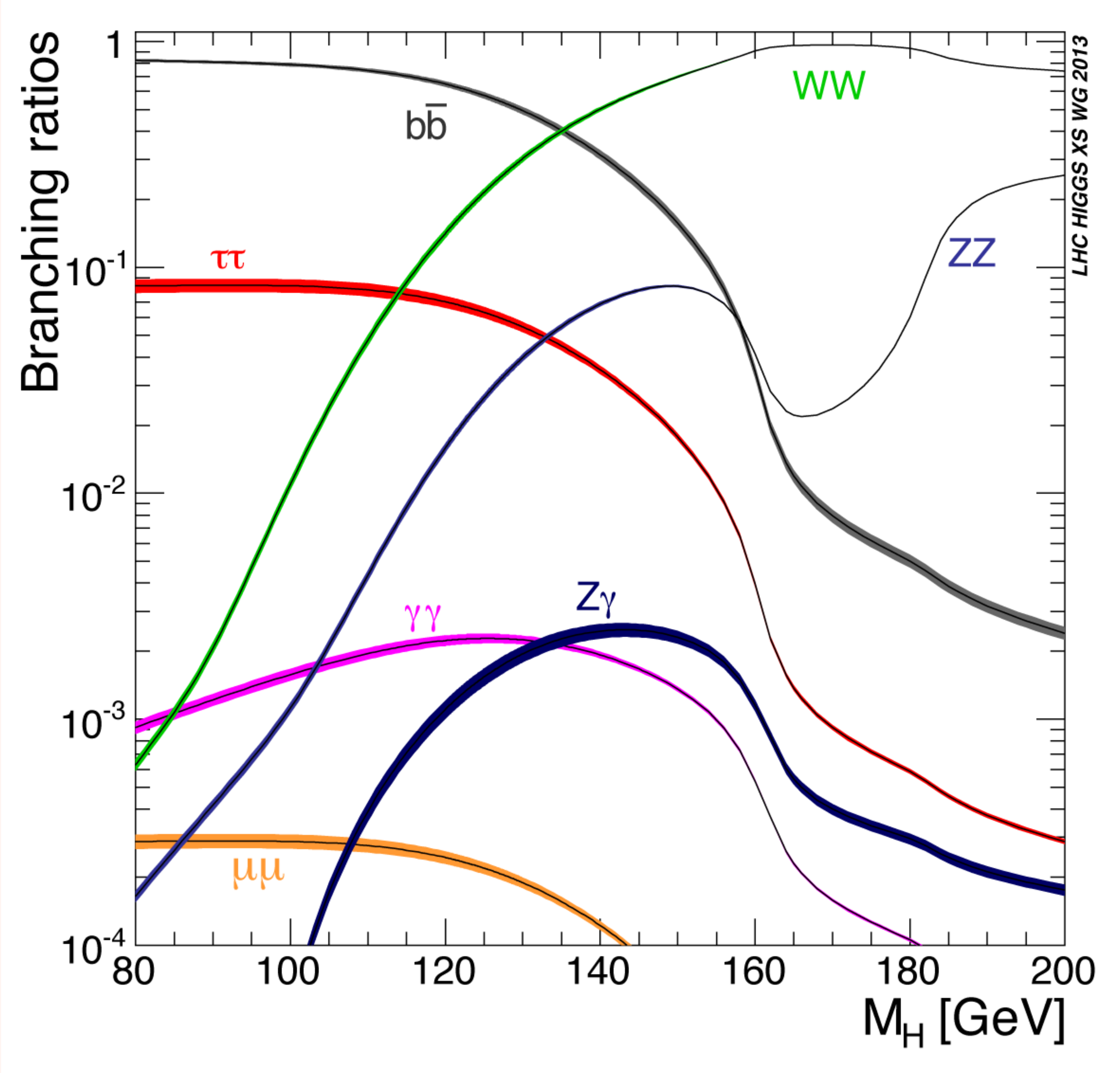




SCENARIO: ALL SMEFT COEFFICIENTS BOUND TO ~ ZERO

We might have to revisit our assumptions: what if the Higgs is not in a doublet? What if the NWA is hiding new physics effects?





PART III: WHAT WE DON'T KNOW

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

Two ways we can stress test the doublet through the couplings:

Measuring the H couplings to multiple vector bosons or the H coupling to itself

hZZ vs Higgs self-coupling

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

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 $\delta_{\lambda_3} > \delta_{Zh}$

Lian Tao Wang, LHCP 2024

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:

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

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

HEFT VS SMEFT

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

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

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

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

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$6: \psi^2 X H + \mathrm{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
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Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
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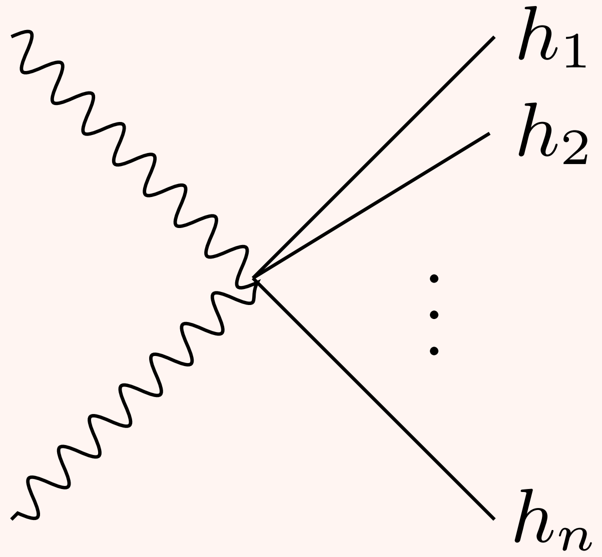
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

The "naive" class 3 operators might contain much more information than we are extracting

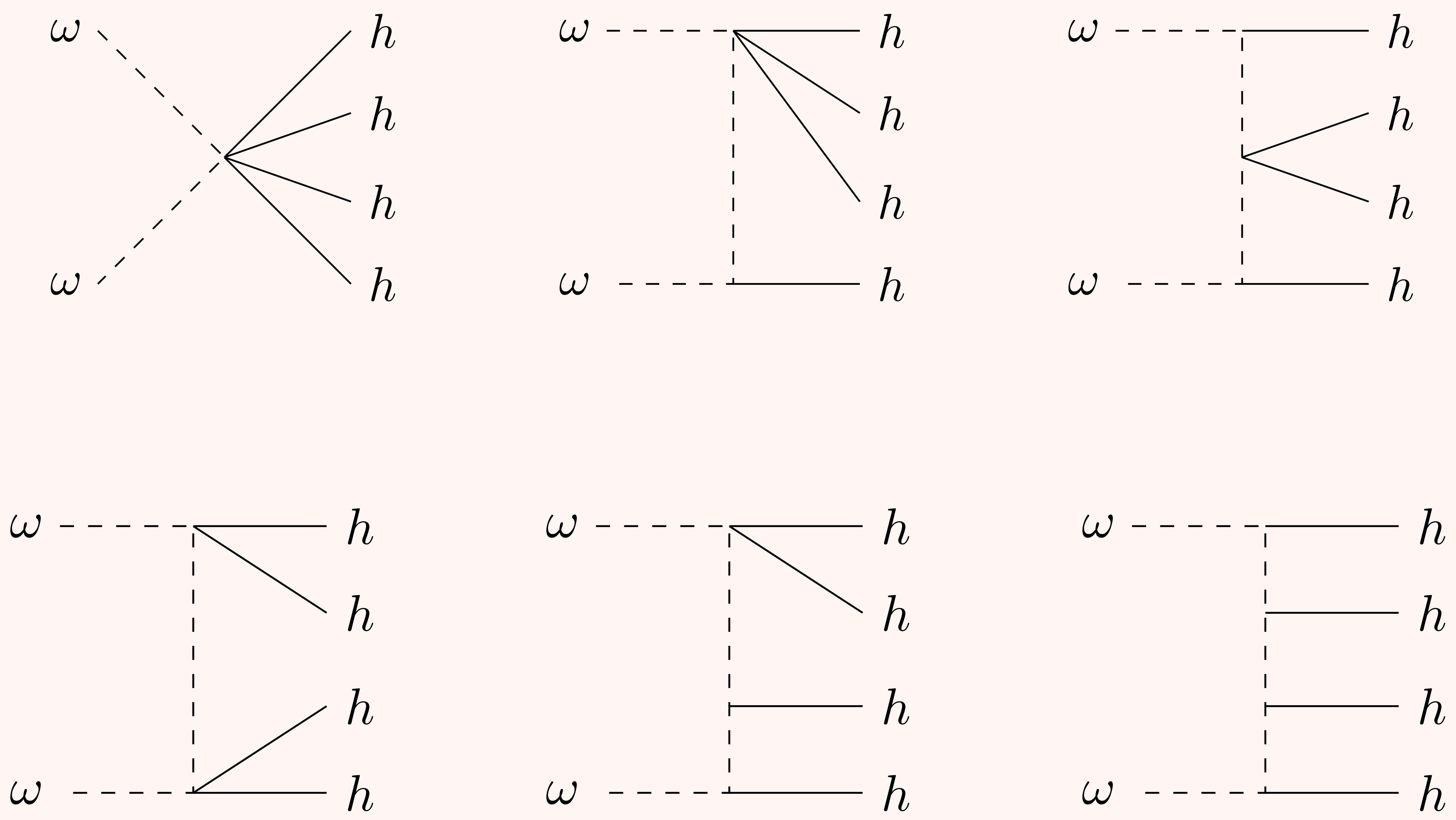
Dimension 6 SMEFT basis

LOOK AT WW TO NH

- **We use the Equivalence Theorem (collisions at several TeV, Higgs is “massless”, gauge bosons are goldstone)**



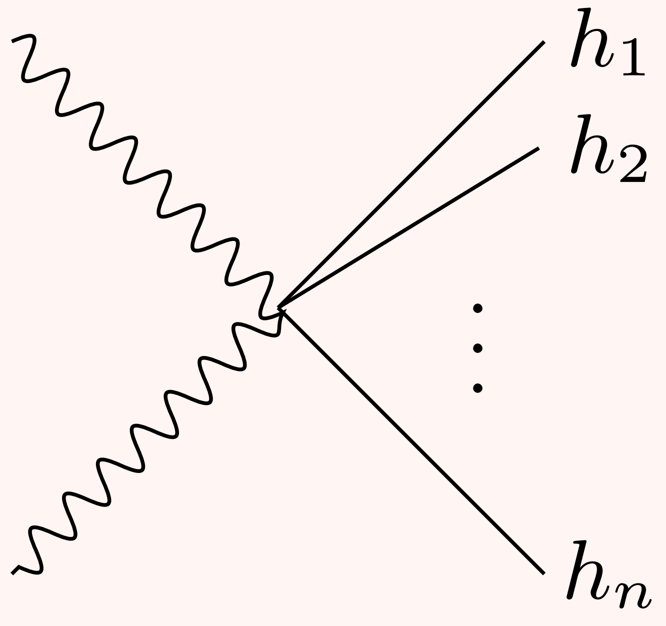
$$= -\frac{n! a_n}{2v^n}\, s$$



SMEFT exclusion plot, 2311.04280

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 higgses are suppressed by increasing factors of Lambda, in HEFT this is not necessarily the case (smoking gun!)
- BSM scenarios often predict large nH Xsecs



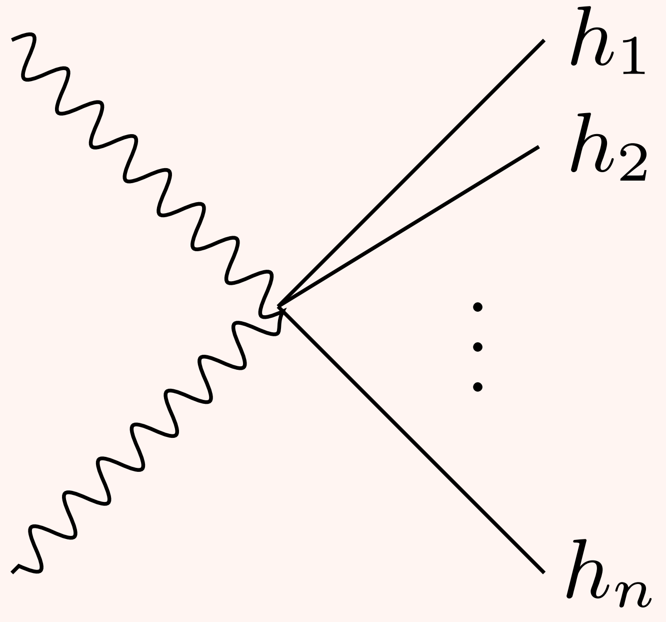
$$= -\frac{n! a_n}{2v^n} s$$

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

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

SMEFT exclusion plot, 2311.04280

LOOK AT WW TO NH



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

- **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!)**
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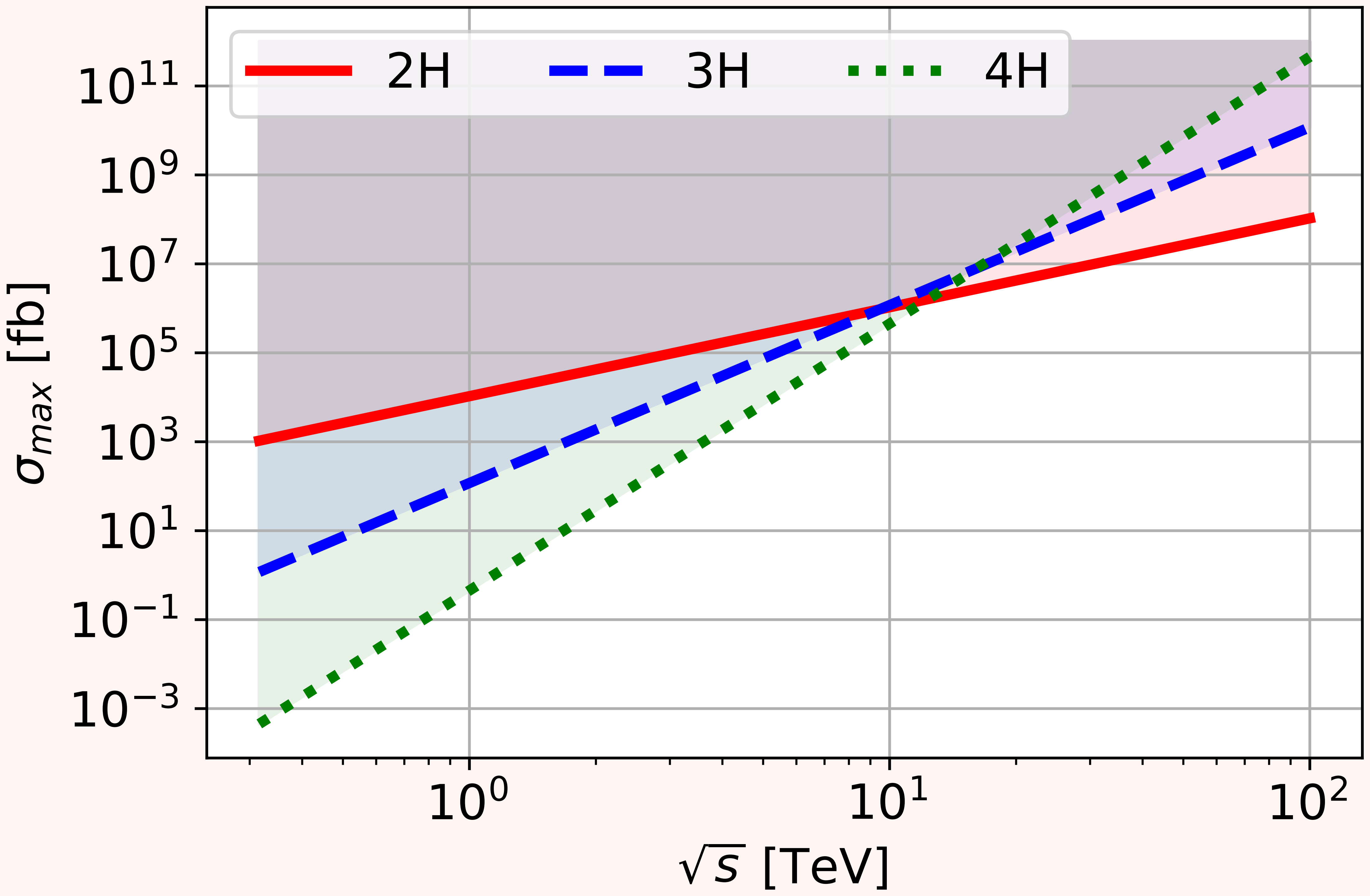
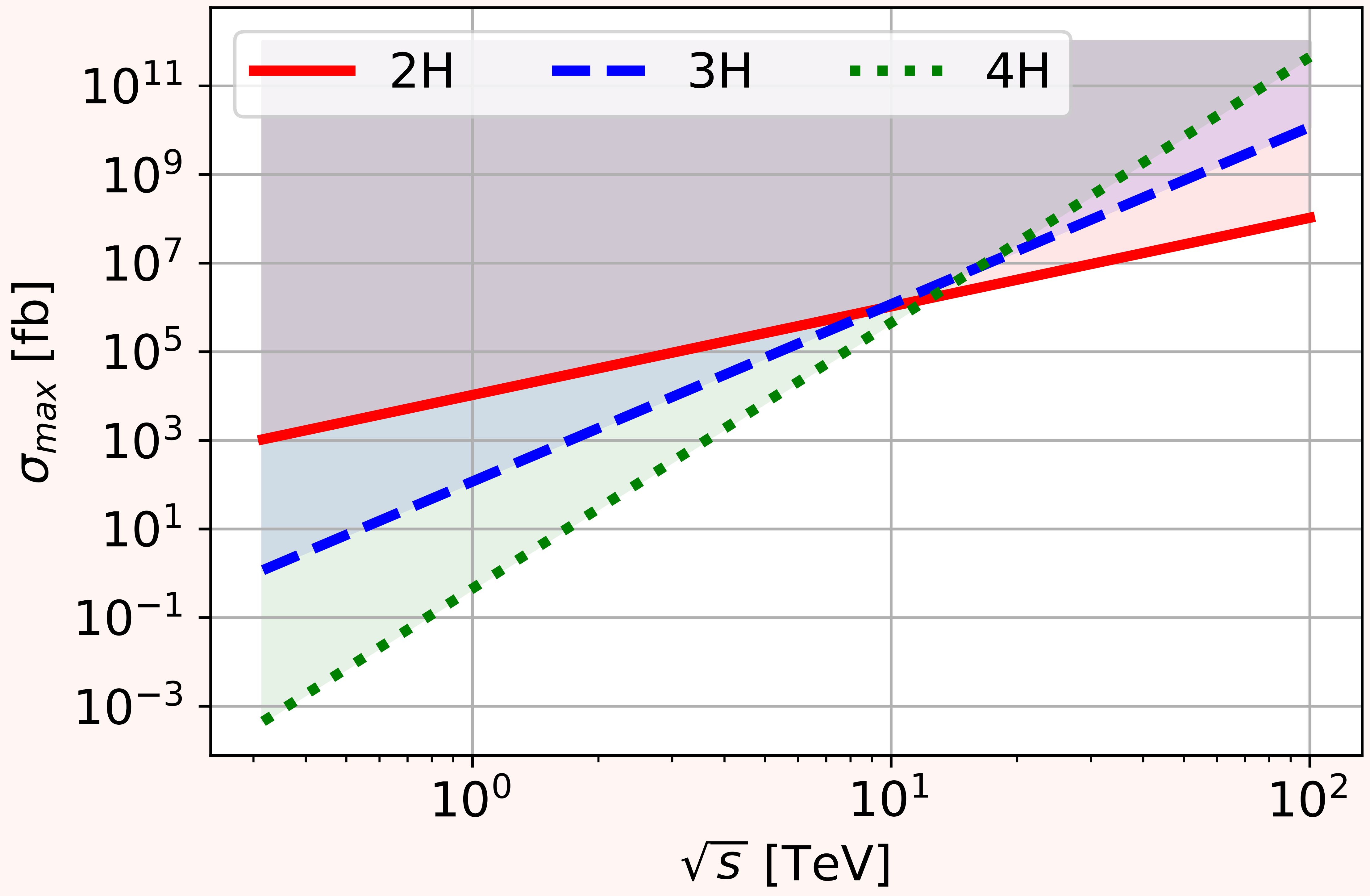


SMEFT exclusion plot, 2311.04280

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
- Of course loads of caveats…. Mainly: Measurements are mainly GGF whereas we focus on VBF



PART IV: MAP THE HEFT TO SMEFT

HEFT VS SMEFT

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

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

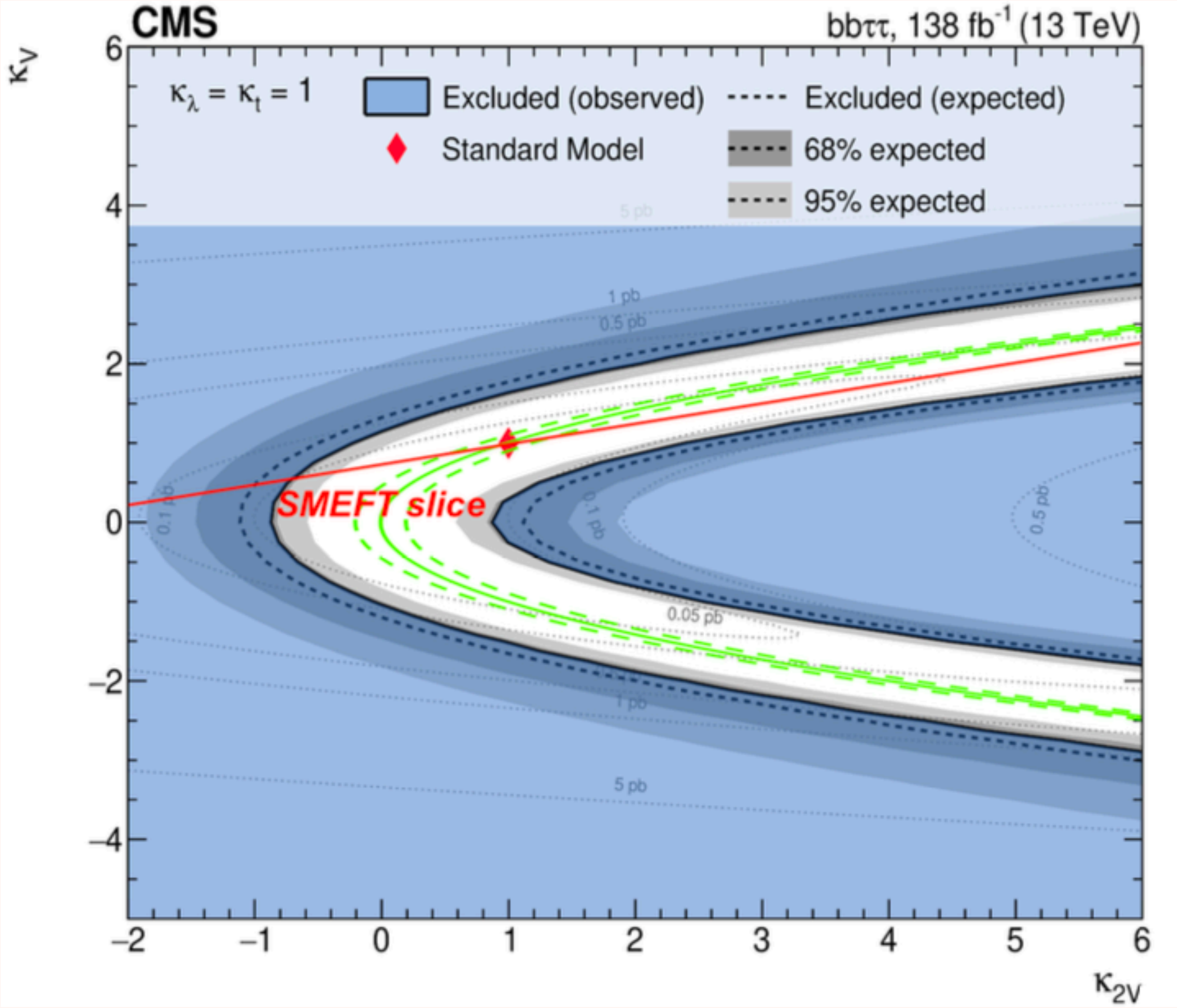
$$
\begin{aligned}
\sigma^{\mathrm{EFT-max}}_{\omega\omega\to hh} &= \frac{\epsilon^2}{8\pi s} , \\
\sigma^{\mathrm{EFT-max}}_{\omega\omega\to 3h} &= \left(\frac{v^2}{16\pi^2\, s}\right)\frac{4\epsilon^4}{3\pi s}\left(1 + \rho_{\mathrm{max}}\right)^2 , \\
\sigma^{\mathrm{EFT-max}}_{\omega\omega\to 4h}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

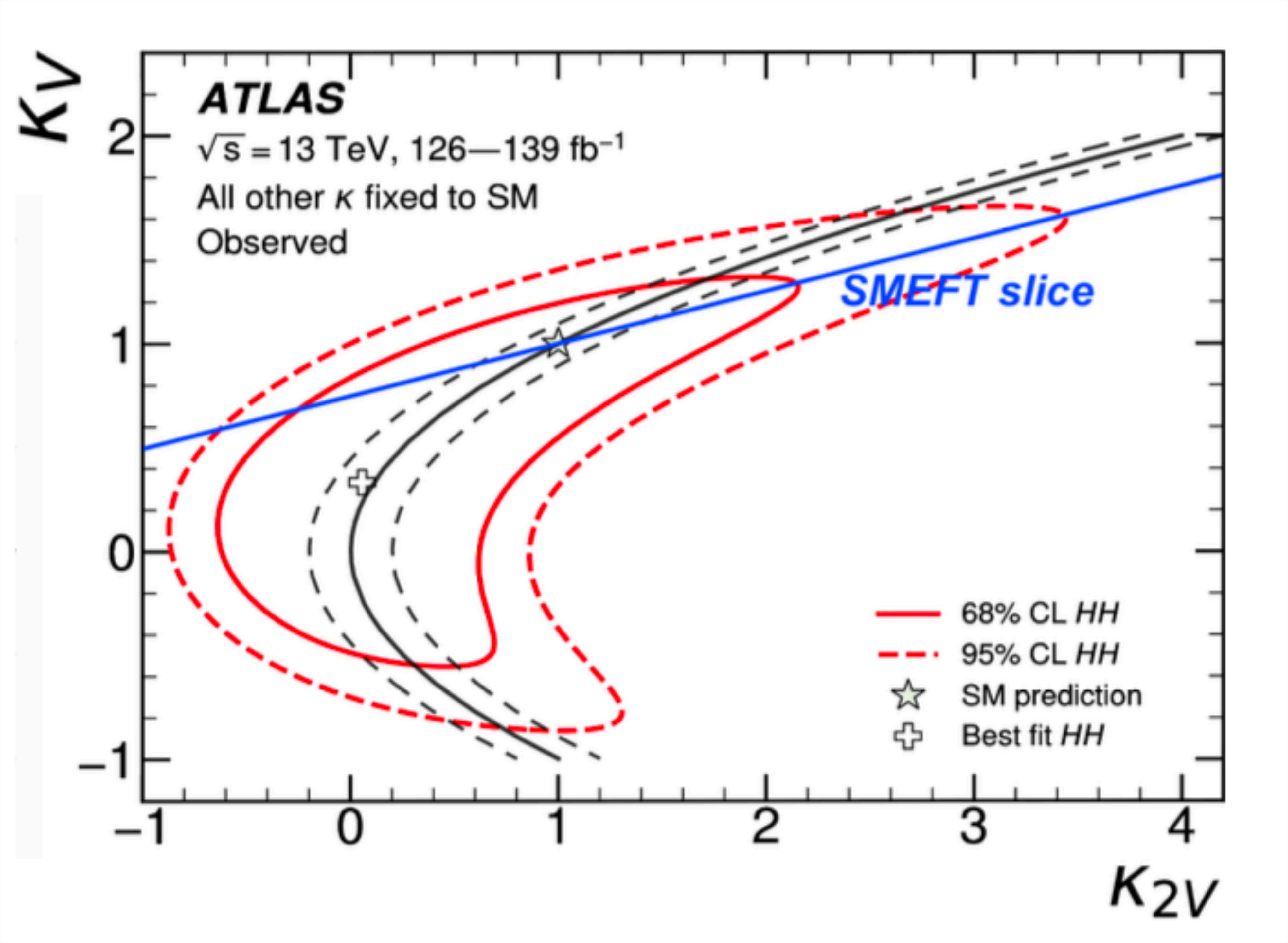
$$
d = \frac{2v^2 c^{(6)}_{H\Box}}{\Lambda^2} , \qquad \rho = \frac{c^{(8)}_{H\Box}}{2(c^{(6)}_{H\Box})^2}
$$

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**





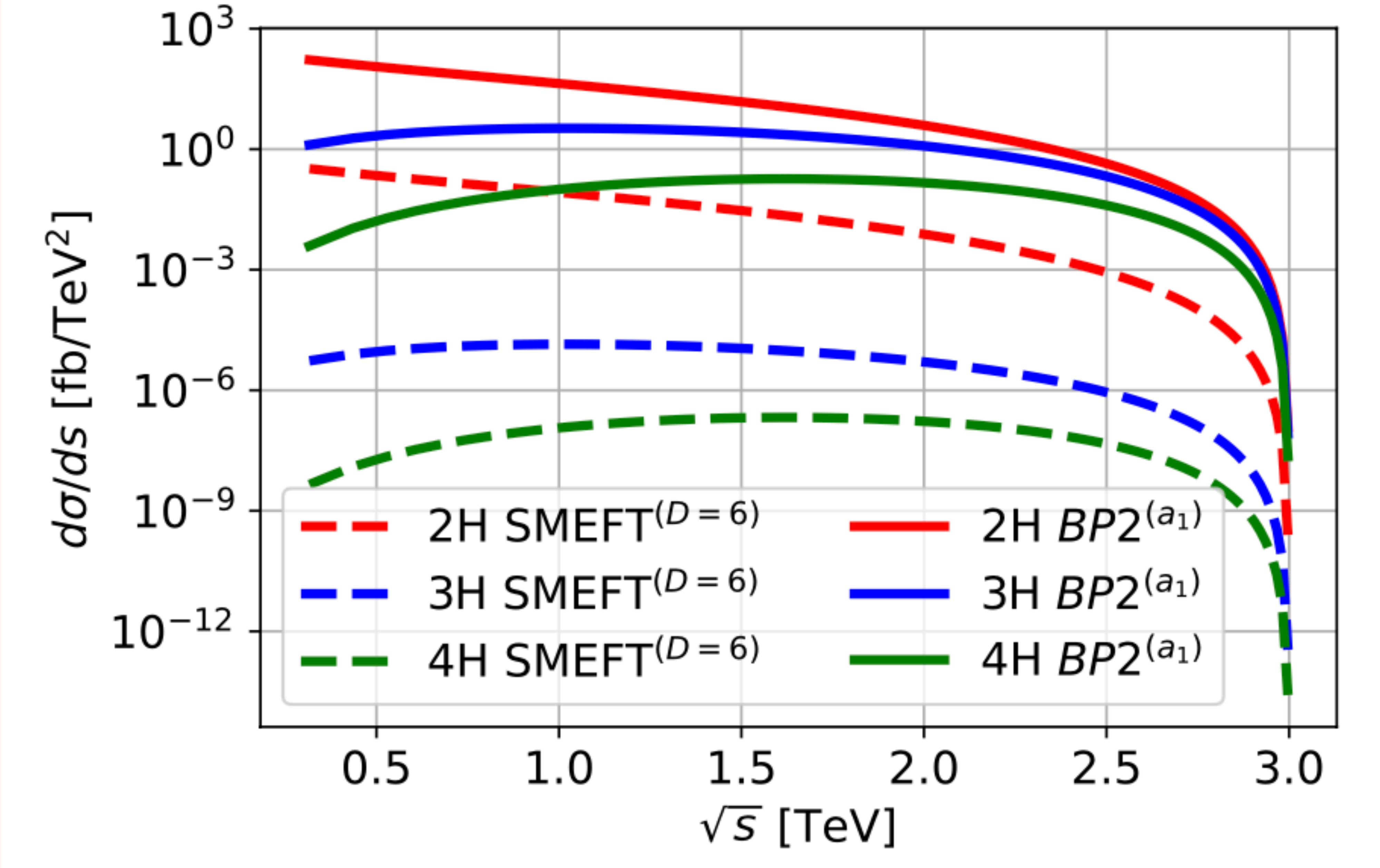
A theory is only a proper theory if it can be falsified....

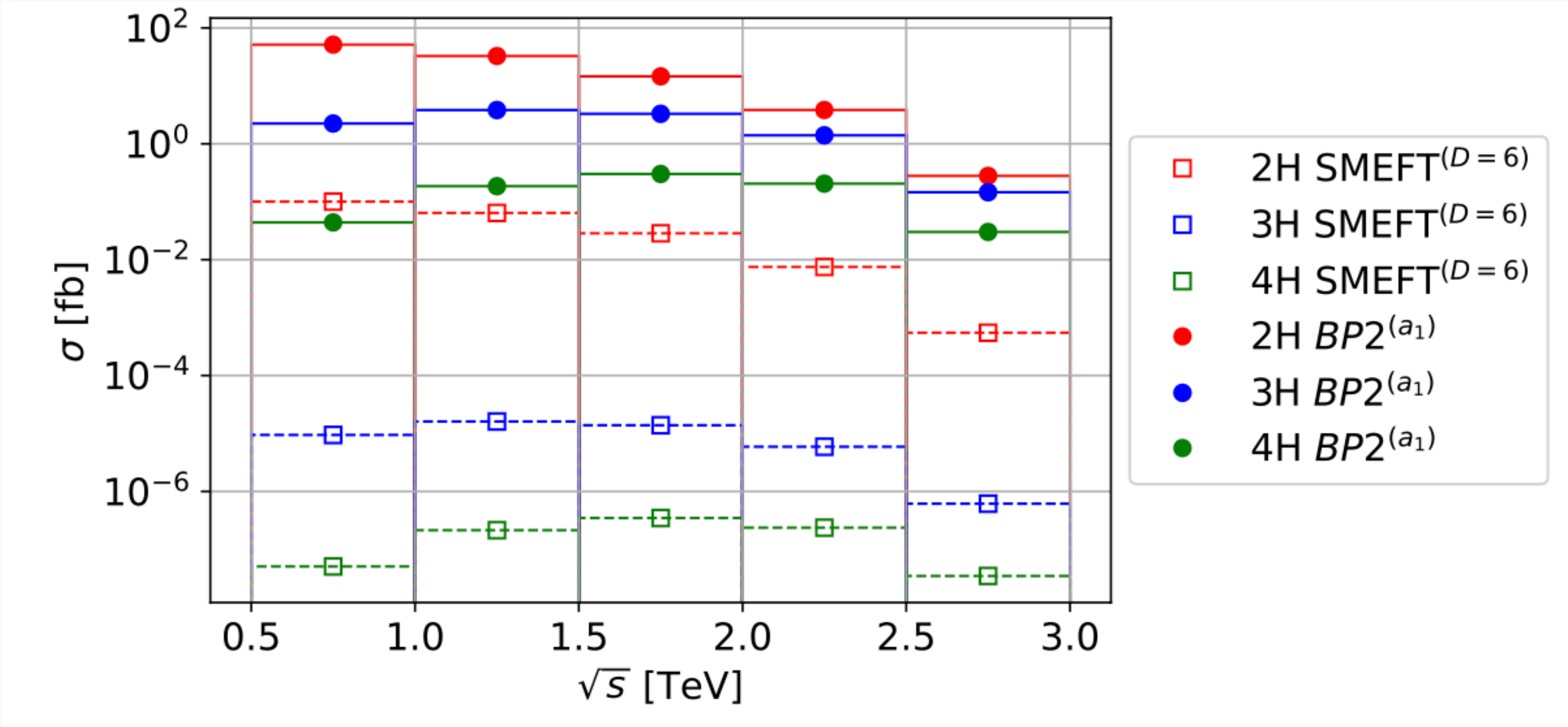
To be updated after this conference!

PART V: NEXT STEPS

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**



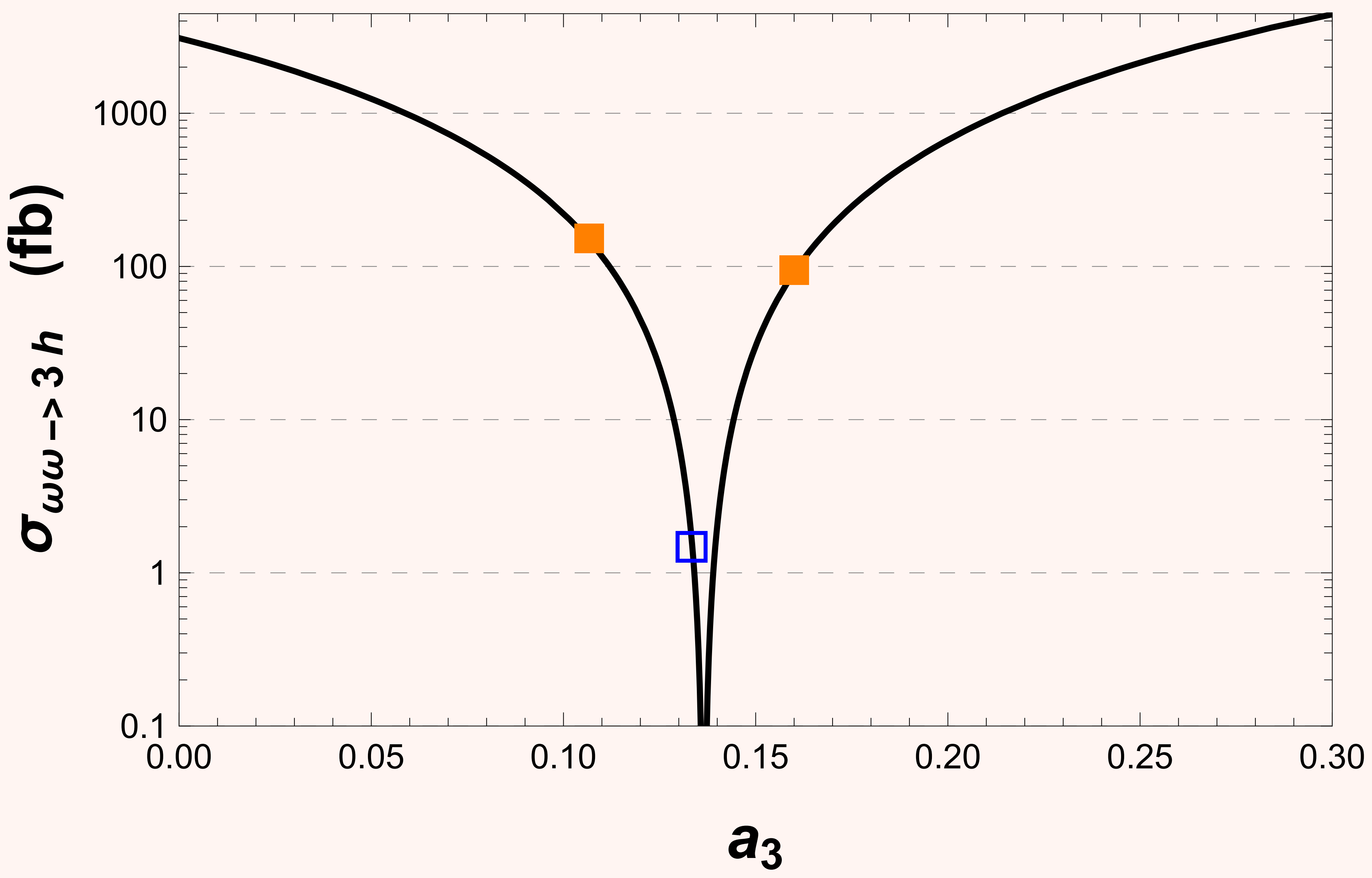


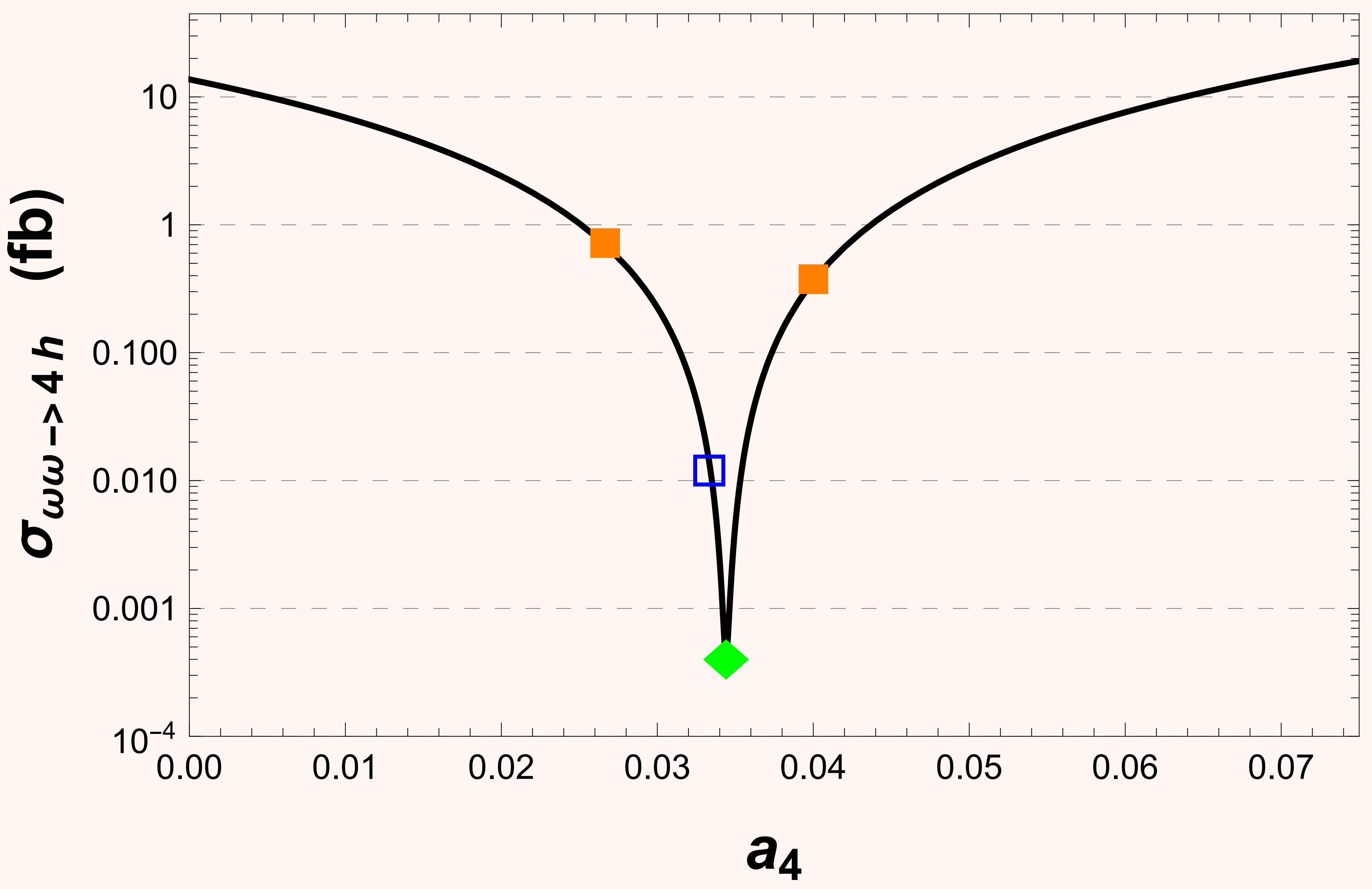
WISHLIST (PART 1: DIRECT SEARCH)

- The aim is to produce precise predictions for LHC, HL-LHC and future colliders: Need a realistic set of Monte Carlo events
  - Challenges:

1. HEFT is not SMEFT -> intrinsically different field structure. Creating a UFO model is not trivial
2. We are focusing only on the EW sector. There are two options for the LHC simulation:
   - Full simulation with proton PDFs and EFT only in the EW sector
   - Use of effective W approximation (Vs as parsons)
3. Last but not least: we would want to drop the equivalence theorem

WISHLIST (PART 2: INDIRECT SEARCH)





The blue box is the SMEFT-compatible value, any small deviation from that (orange box, 20%) changes the XS significantly

CONCLUSIONS

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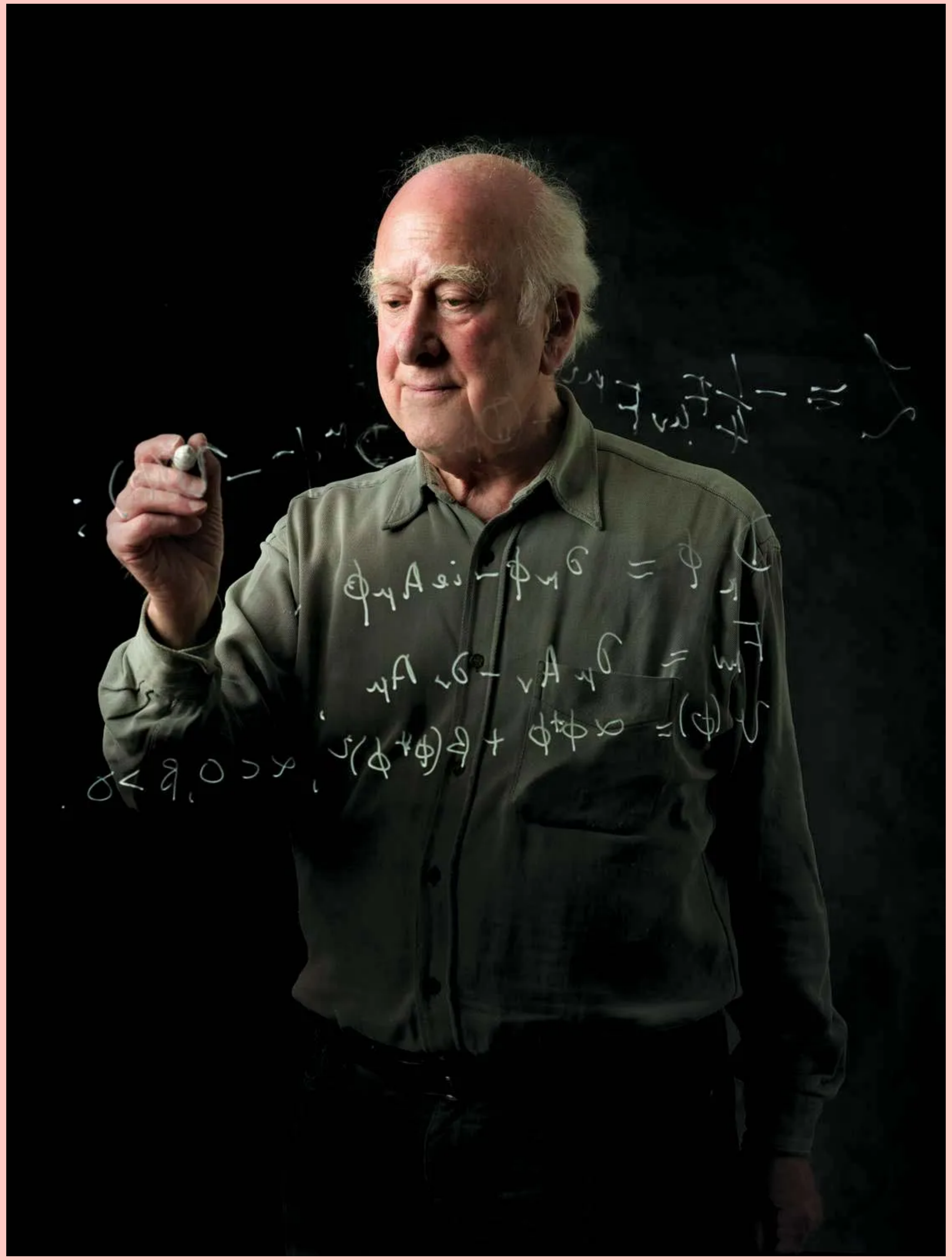
What can we do until HL-LHC

- 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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