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COMETA

Di-Higgs physics in CMS (and the Baltics)

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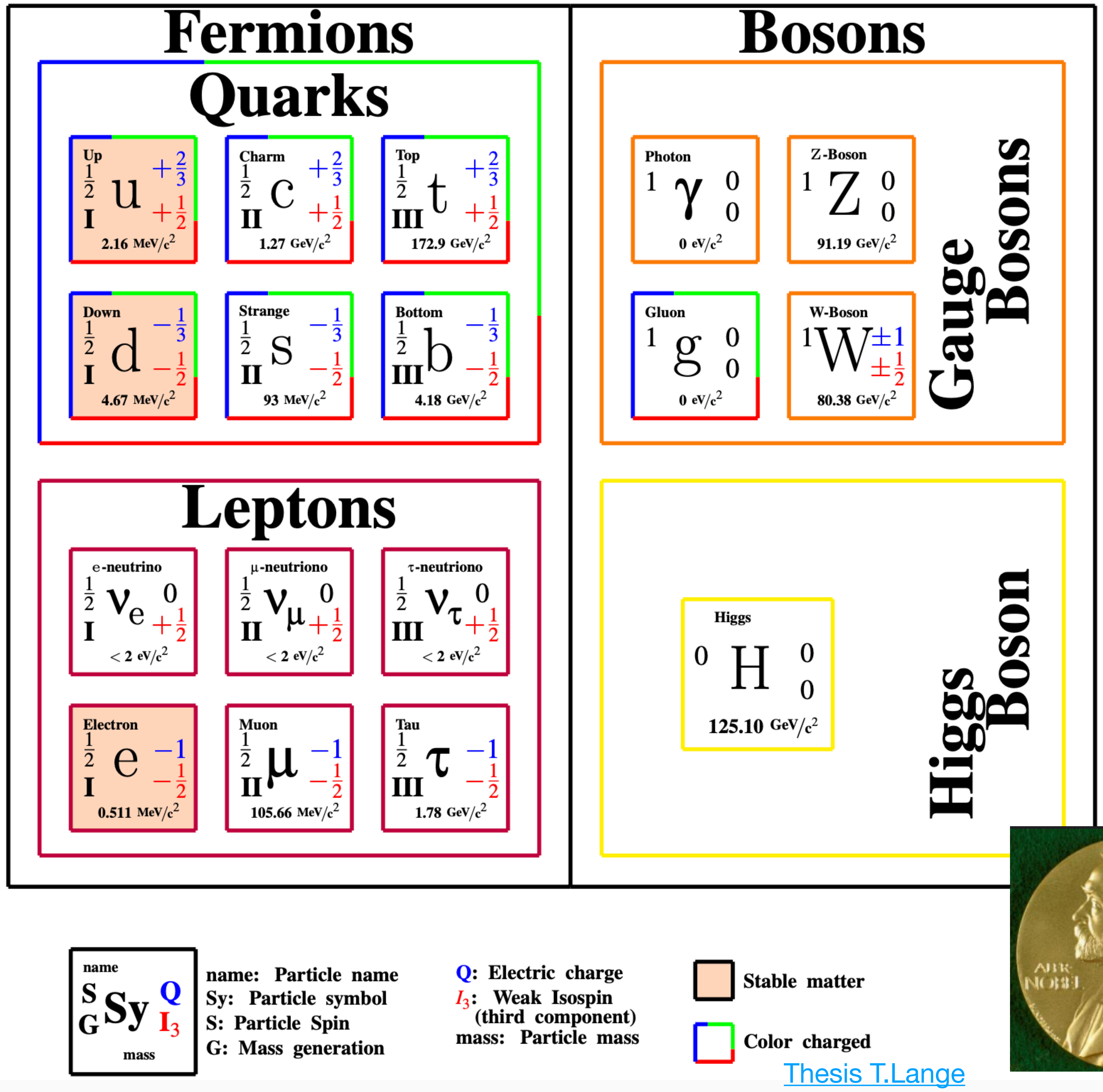
RVTT3 & TK202 “Fundamental Universe”

Introduction - Why do we need the Higgs?

- The Standard model of particle physics (SM) describes our universe in the most fundamental way
- Describes almost everything we observed almost perfect
- Relies on the Higgs mechanism for self consistency, the simples way to give particles mass
- Envisioned ~60 years before the discovery of the associated boson in 2012 by CMS and ATLAS
- Important enough to yield a Nobel Prize only 2 years later



Thesis T.Lange

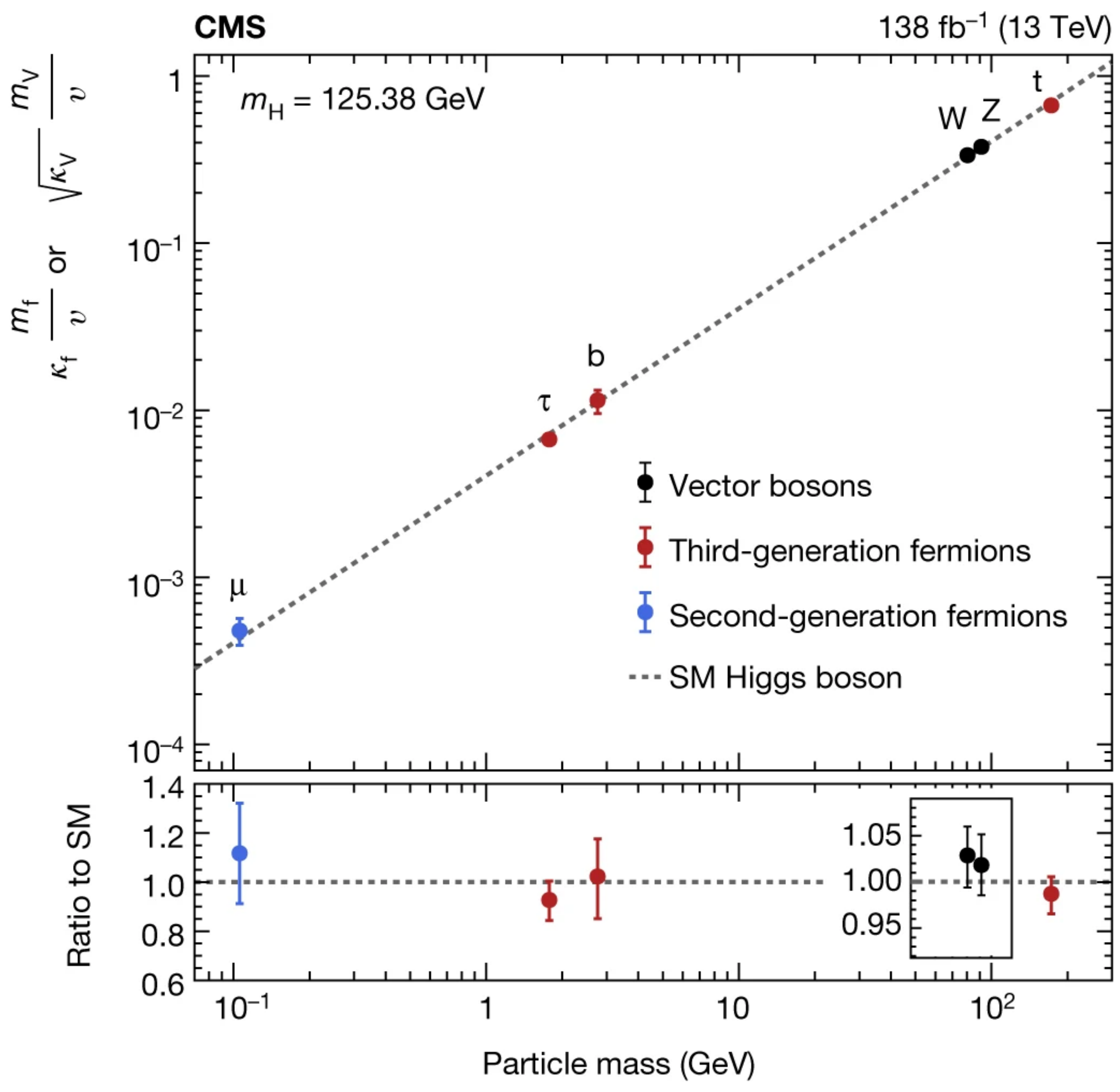
Introduction - What do we know?
(And what not?)

- Since 2012 we measured many Higgs boson properties: Its mass, the couplings to many SM particles, its spin and CP properties, many differential cross sections… all in agreement with the SM

- But: As we are seeing in many presentations today, we know the SM is wrong! So, where is the new physics?

- The Higgs sector still has a few corners to explore -> Higgs boson self coupling and multi Higgs production

Nature volume 607, pages 60–68 (2022)



The Higgs boson self coupling

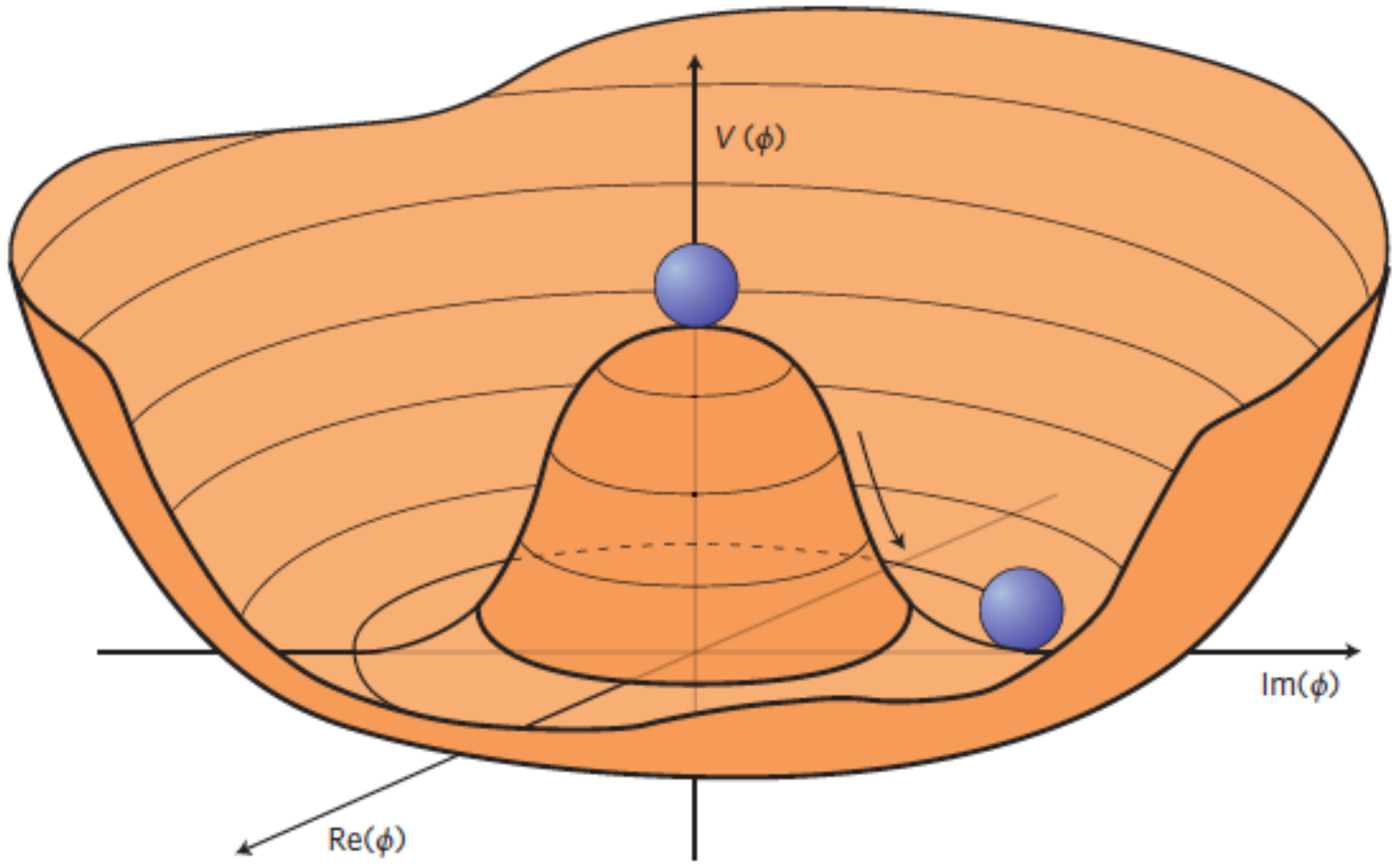
- Higgs mechanism enters SM with the Higgs boson potential

- Adds mass term for the Higgs boson and a trilinear (quartic) self coupling proportional to λ

- → Self coupling directly connected to the shape of the potential, (meta) stability of the universe and a crucial parameter of the SM

$$\mathcal{L}_{SM} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi) + \mathcal{L}_{rest}$$

doi:10.1142/9789814733519_0014

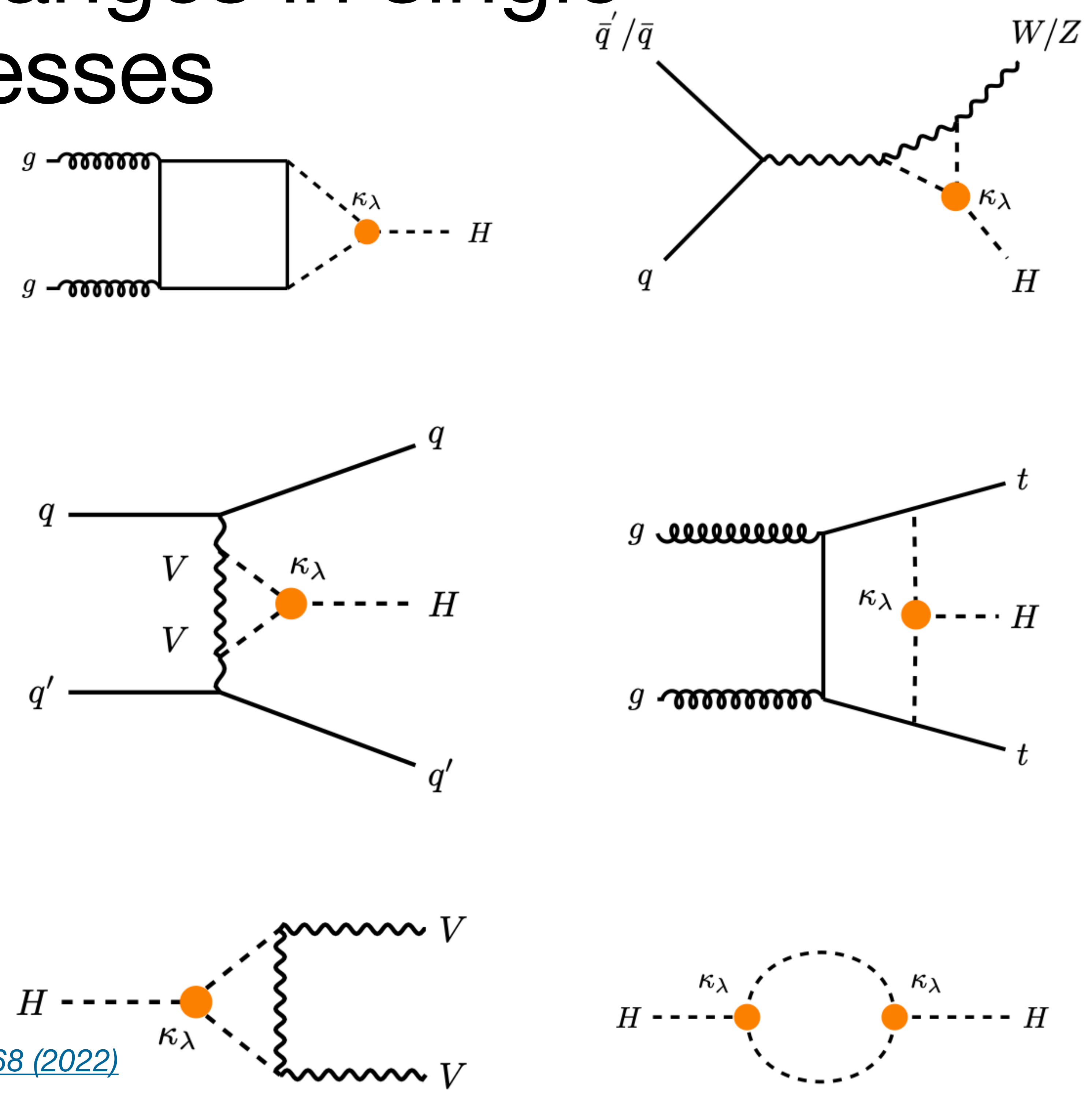


$$V(\phi) = \mu^2 \phi\phi^\dagger - \lambda(\phi\phi^\dagger)^2$$

$$\lambda_{SM} = \frac{m_H^2}{\nu^2};\ \nu = 246\,\text{GeV};\ m_H = 125\,\text{GeV}$$

How do we measure the self coupling?

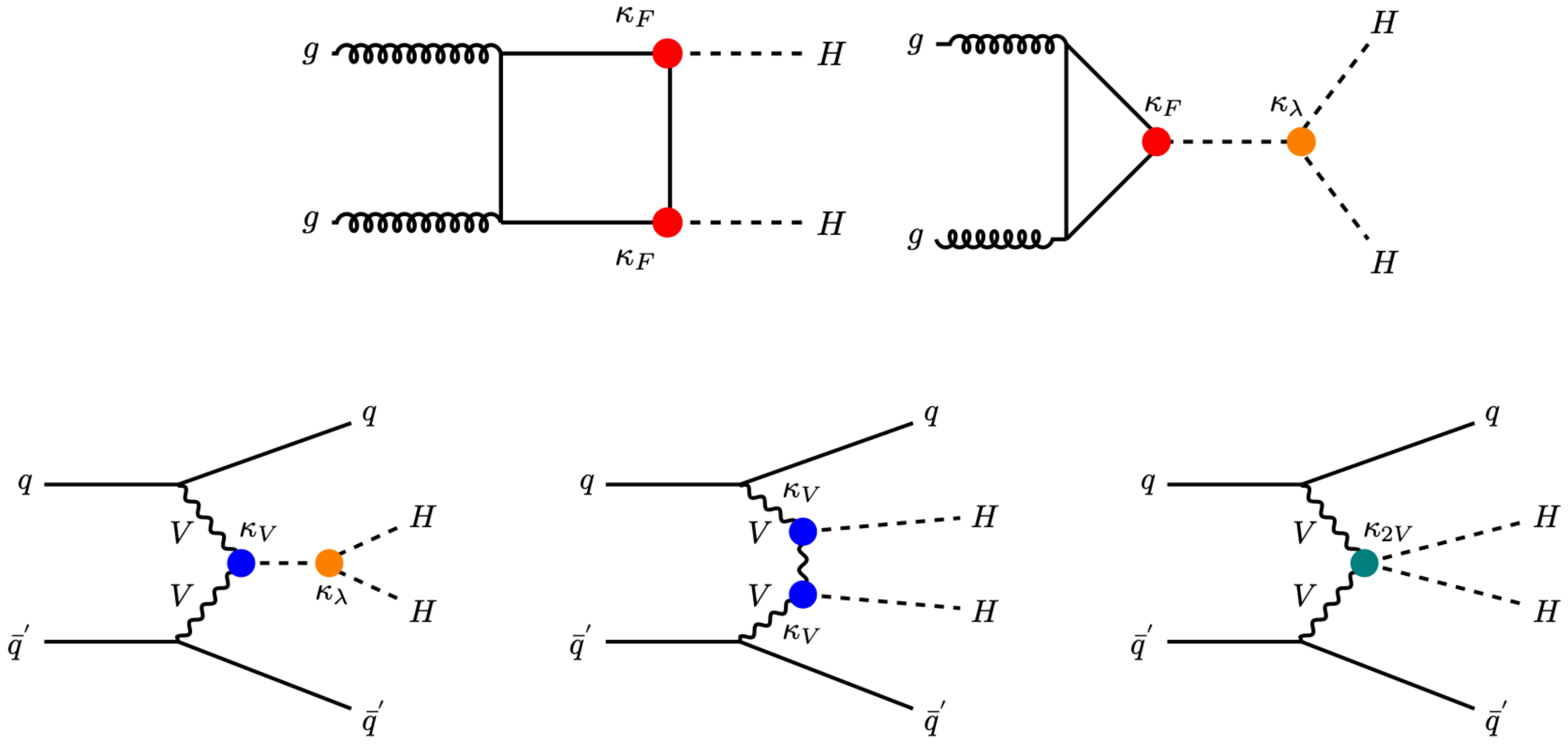
Indirect: Changes in single Higgs processes



[Nature volume 607, pages 60–68 (2022)](#)

Only indirect, small, gradual changes…

Direct: Searching for Higgs boson Pairs



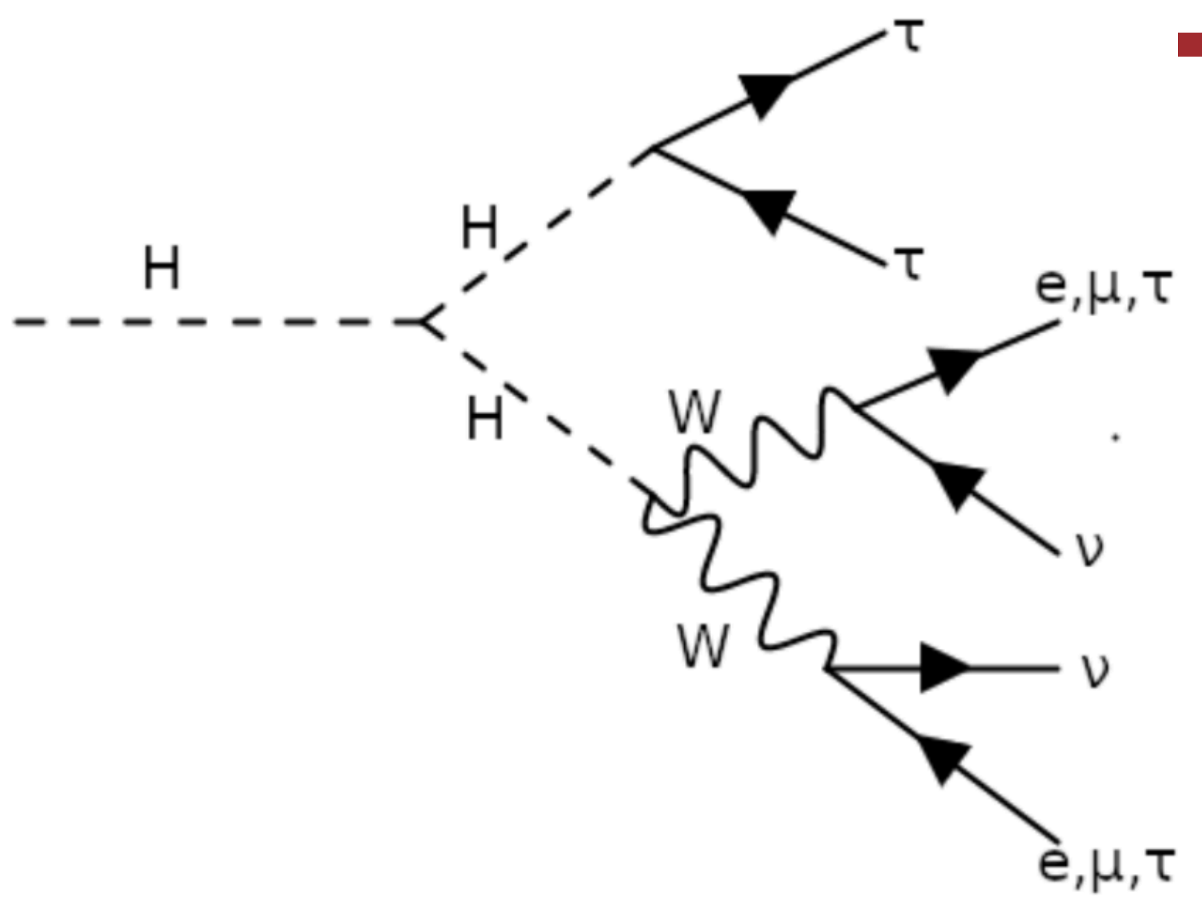
[Nature volume 607, pages 60–68 (2022)](#)

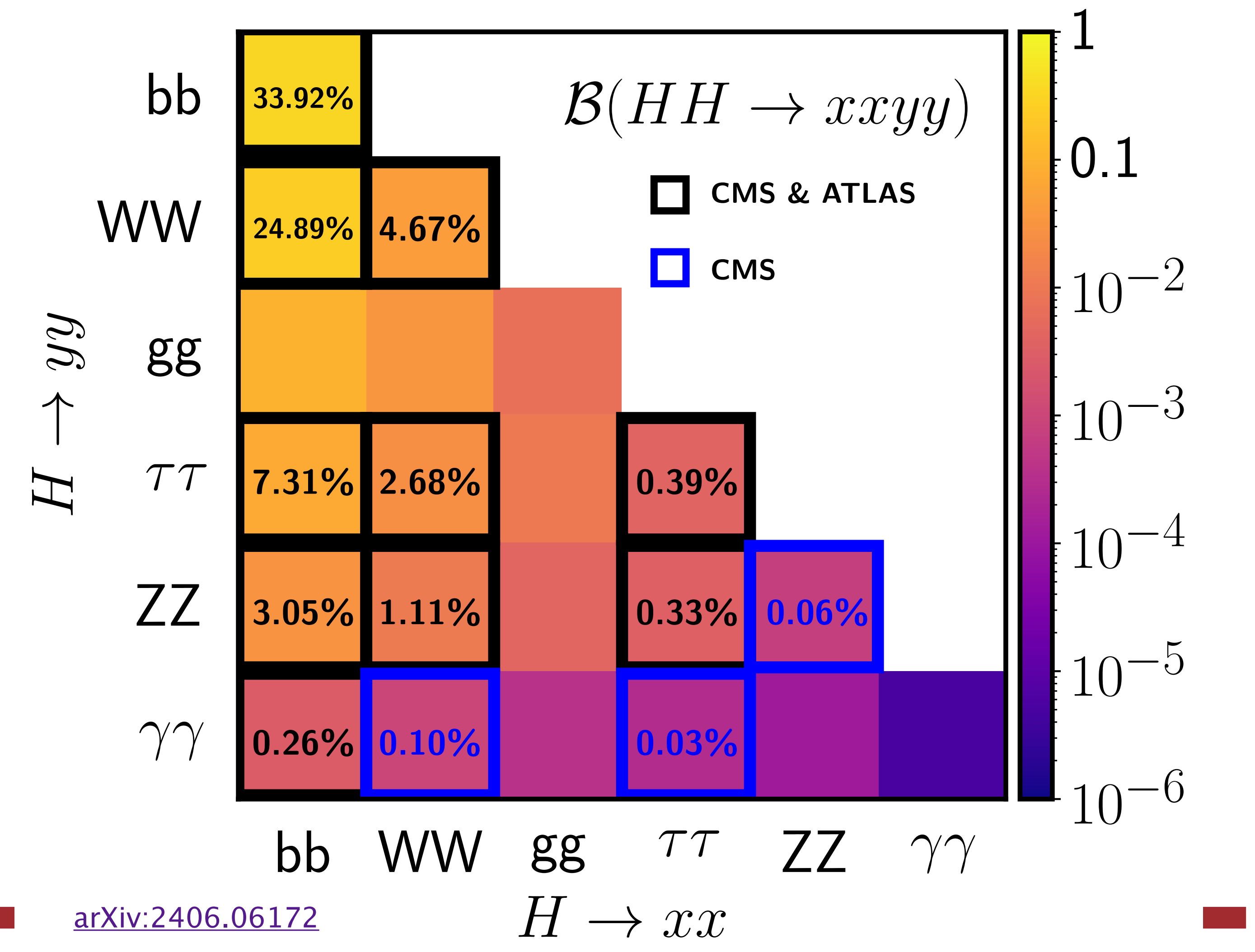
2000 times rarer than single Higgs…

If it's so rare, then how?

- Very rare but also very unique! Usually many final state objects that are useful to suppress backgrounds!
- Can be searched for in boosted states where background is also low
- Where this doesn't help, new analysis techniques, lots of machine learning and dedicated taggers
- Last but not least, we are by now looking at almost all accessible final states!

Example: HH -> Multilepton



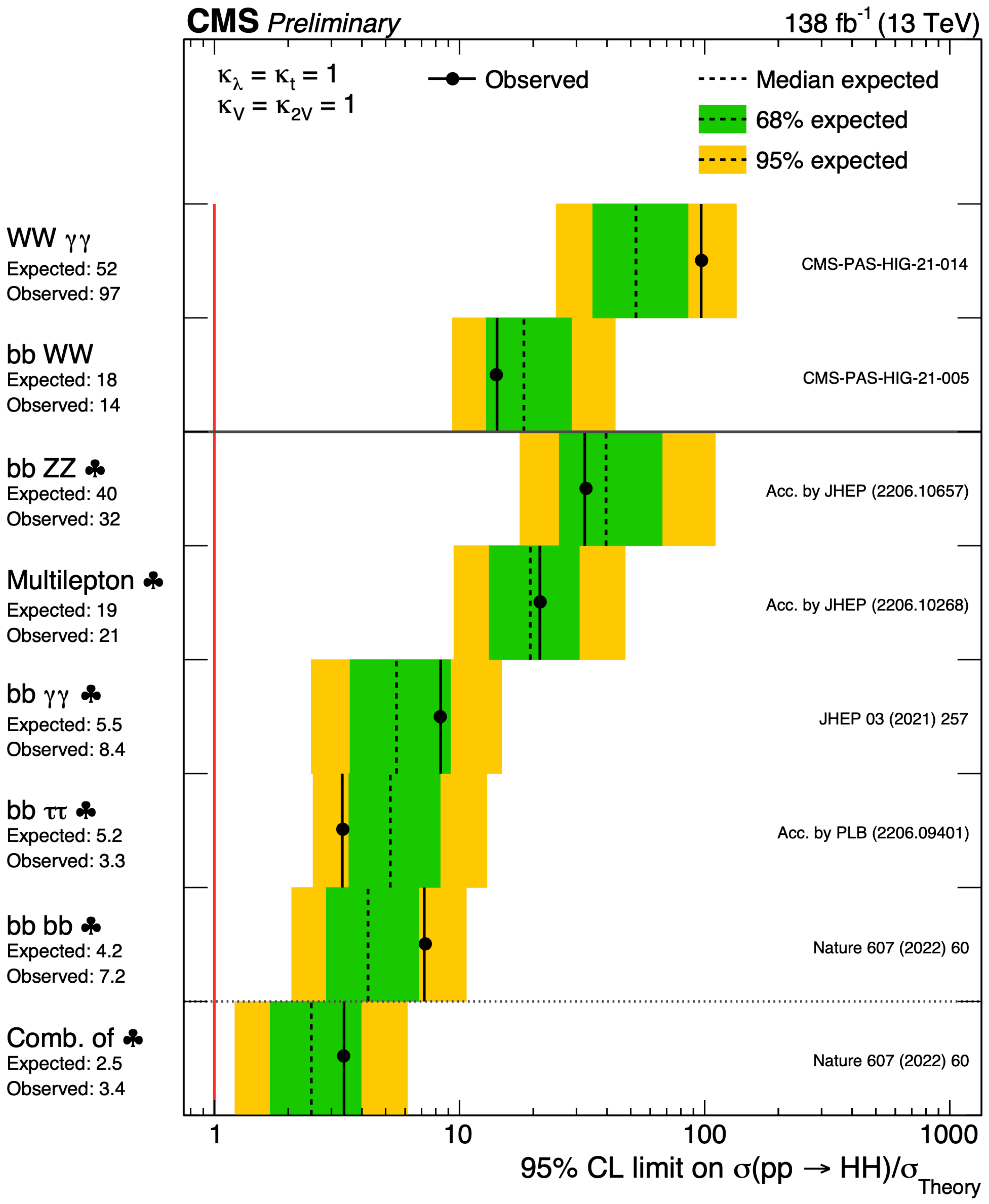


arXiv:2406.06172

What did we learn so far?

- Still far from a (precision) measurement, but..
- Approaching SM sensitivity, currently excluding HH production above about three times the SM rate
- Improvement of factor 5 since early Run 2 despite only a factor 2 expected from the additional data
- We also have ATLAS and a new dataset from Run3…
- Self coupling constraint: $-1.24 \times \lambda_{SM} < \lambda < 6.49 \times \lambda_{SM}$, can we exclude 0?

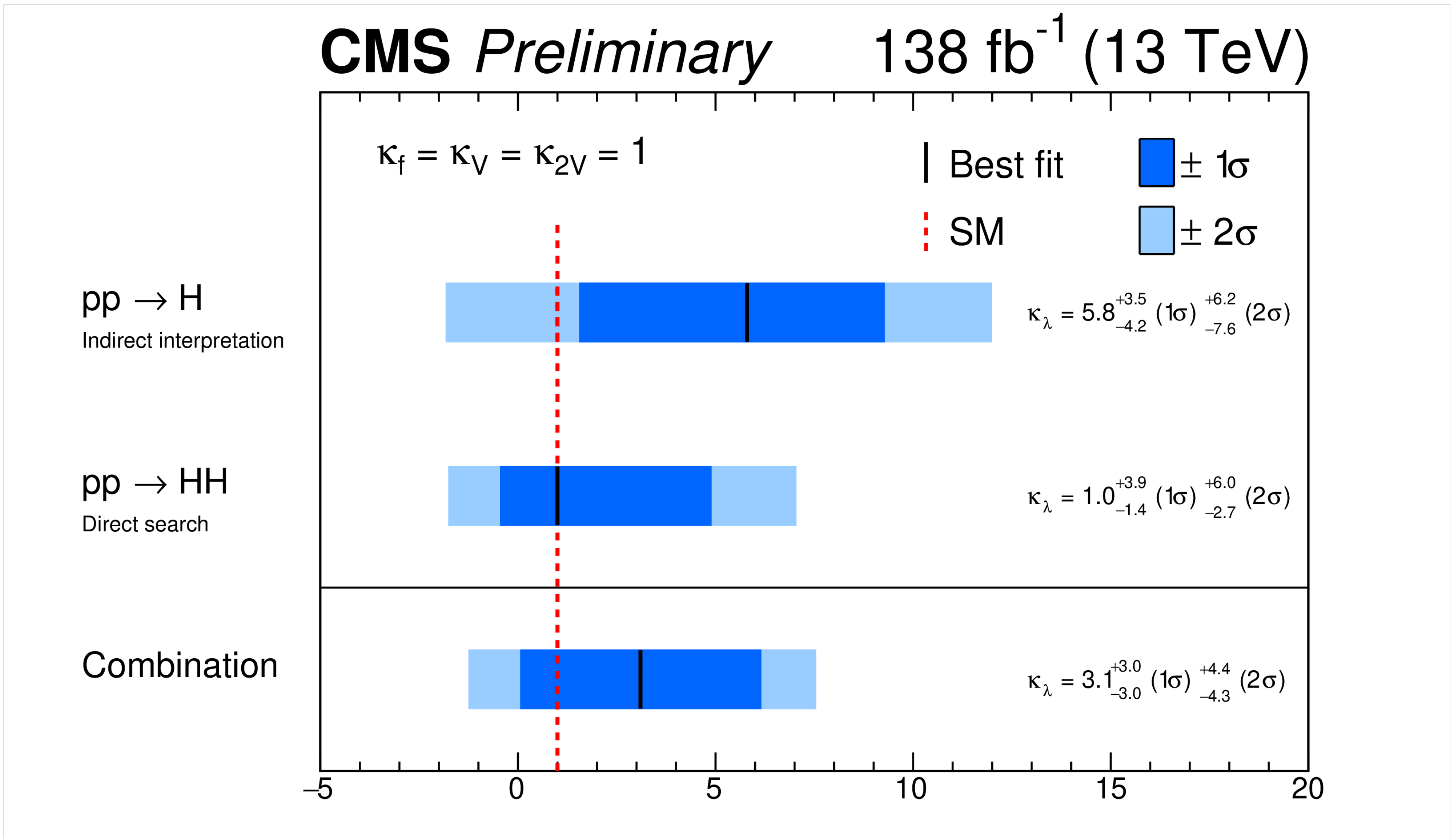
CMS HIG PAG



$+ \tau\tau\gamma\gamma + VHH \rightarrow bb + bbWW^*(boosted) + \ldots.$

What about single Higgs?

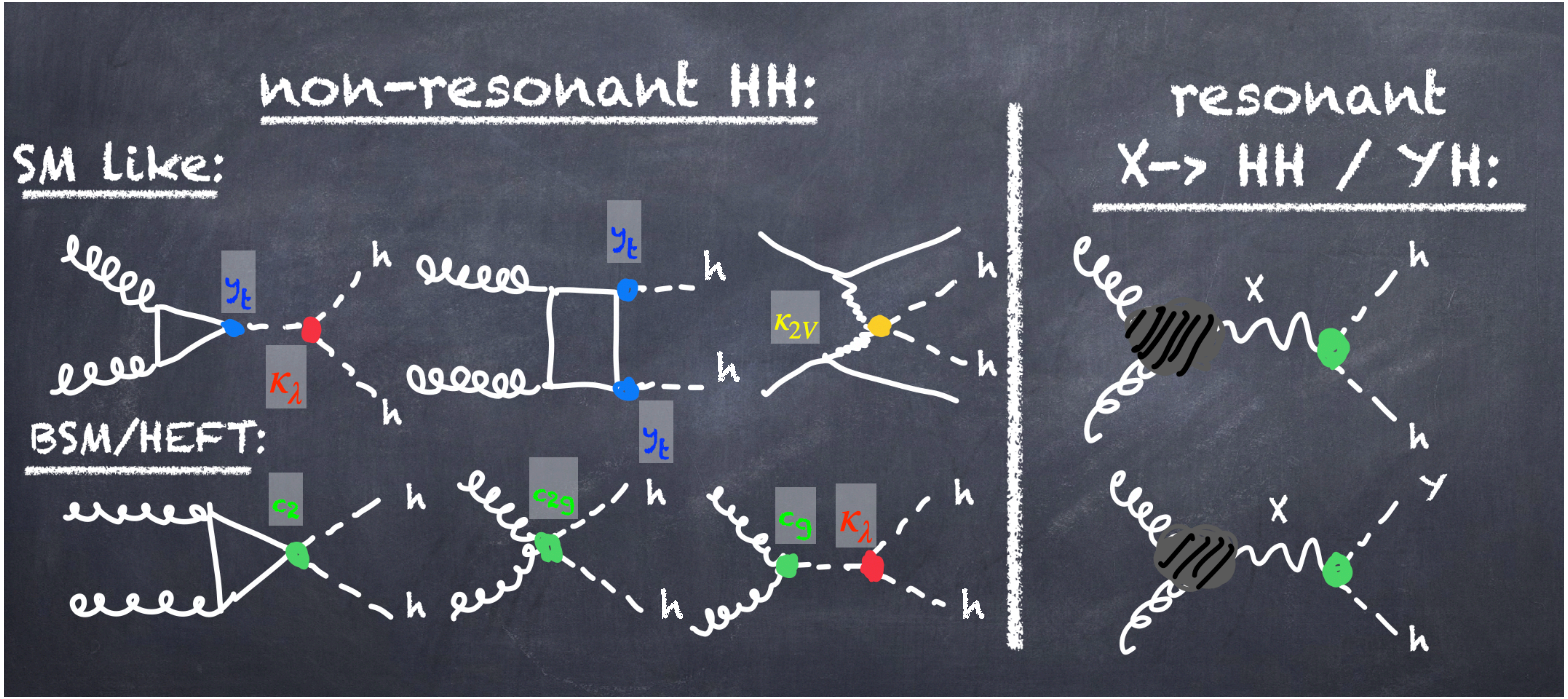
- We also can add constraints from single Higgs!
- More importantly however, we can use it for more models independent interpretations
- New physics likely not restricted to one deviation
- Single Higgs allows us to make conclusions without fixing other Higgs boson couplings to their SM values



CMS-PAS-HIG-23-006 (additional material)

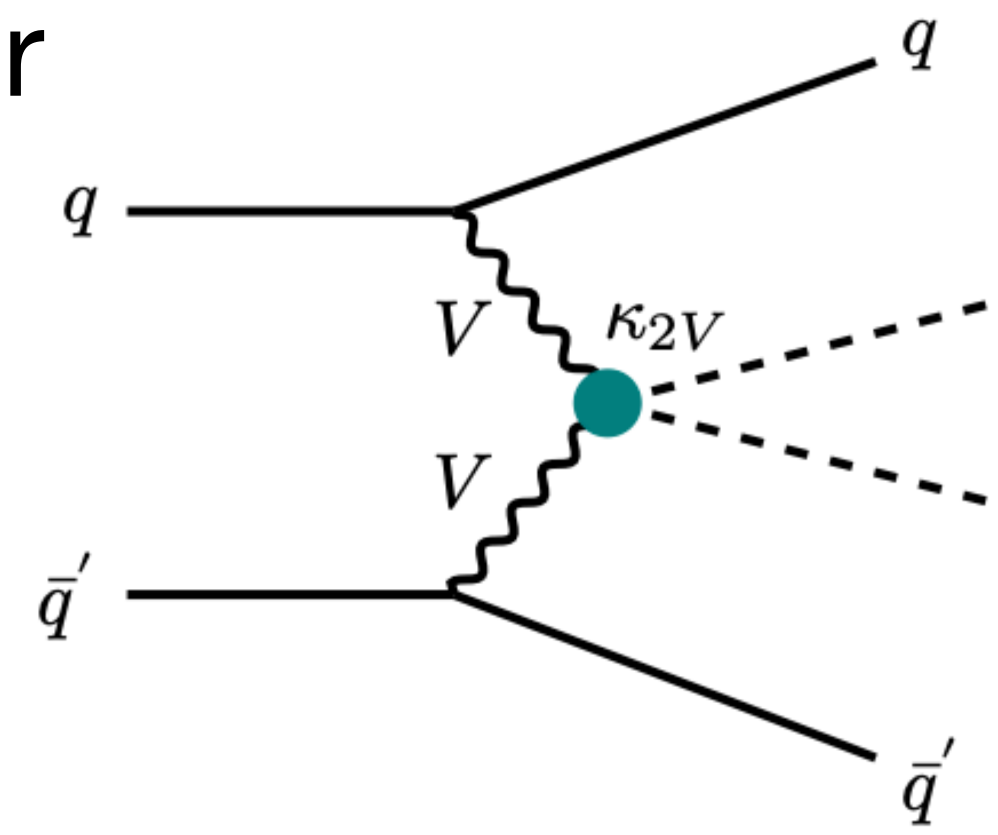
Hypothesis	Best fit κ_λ value $\pm 1\sigma$ Expected	Best fit κ_λ value $\pm 1\sigma$ Observed	2σ interval Expected	2σ interval Observed
Other couplings fixed to the SM prediction	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, 7.7]$	$[-1.2, 7.5]$
Floating ($\kappa_V, \kappa_{2V}, \kappa_f$)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, 7.8]$	$[-1.7, 7.7]$
Floating ($\kappa_V, \kappa_t, \kappa_b, \kappa_\tau$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, 7.7]$	$[-1.4, 7.8]$
Floating ($\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, 7.8]$	$[-1.4, 7.8]$

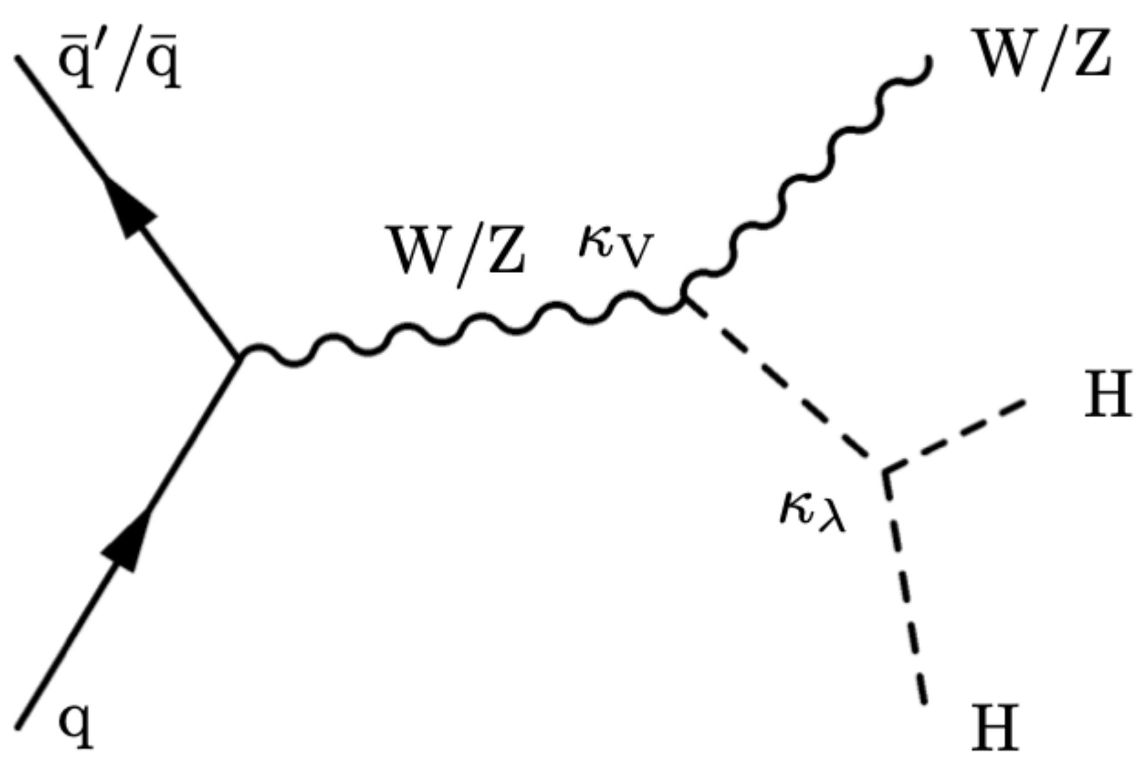
Is that everything? No!

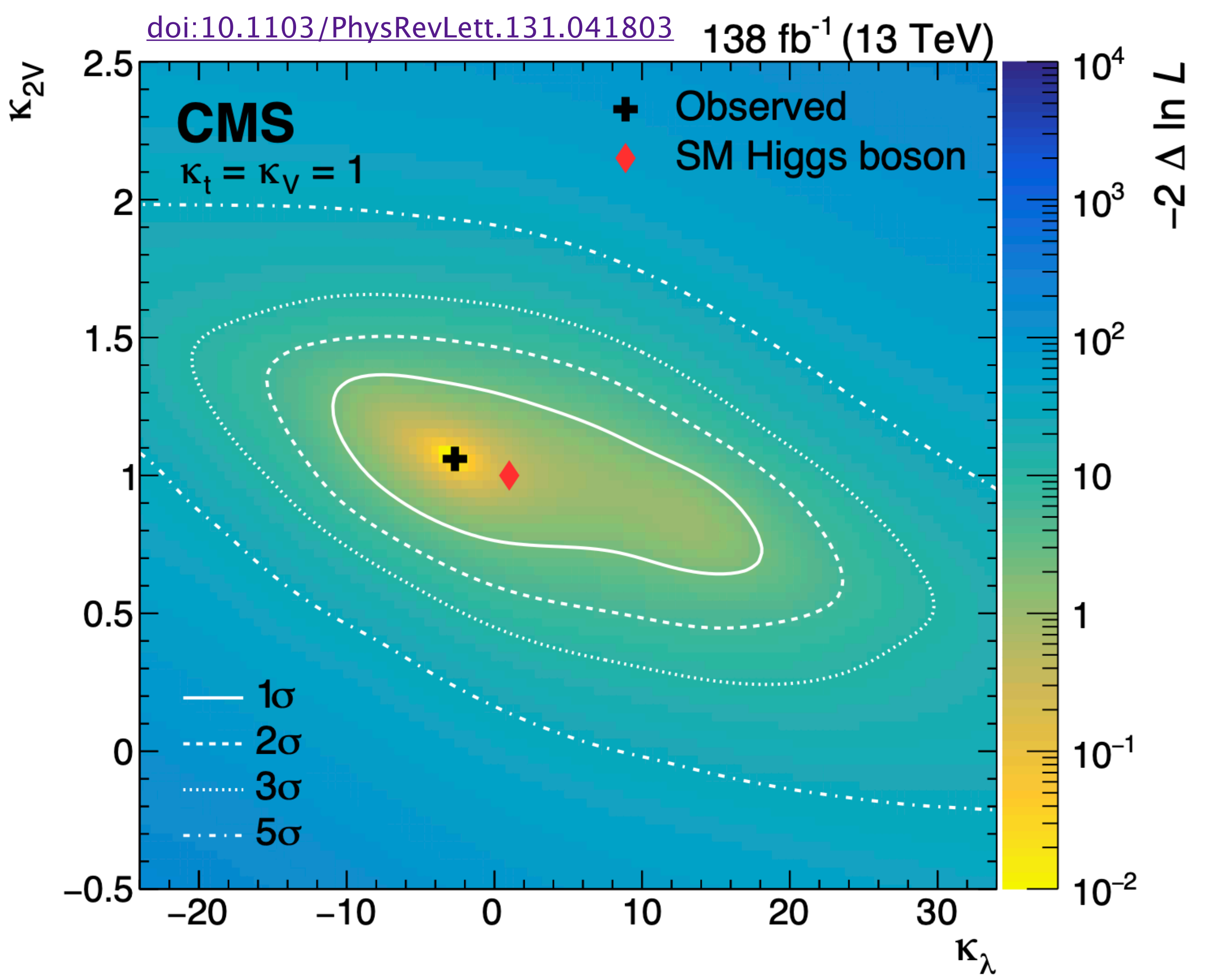


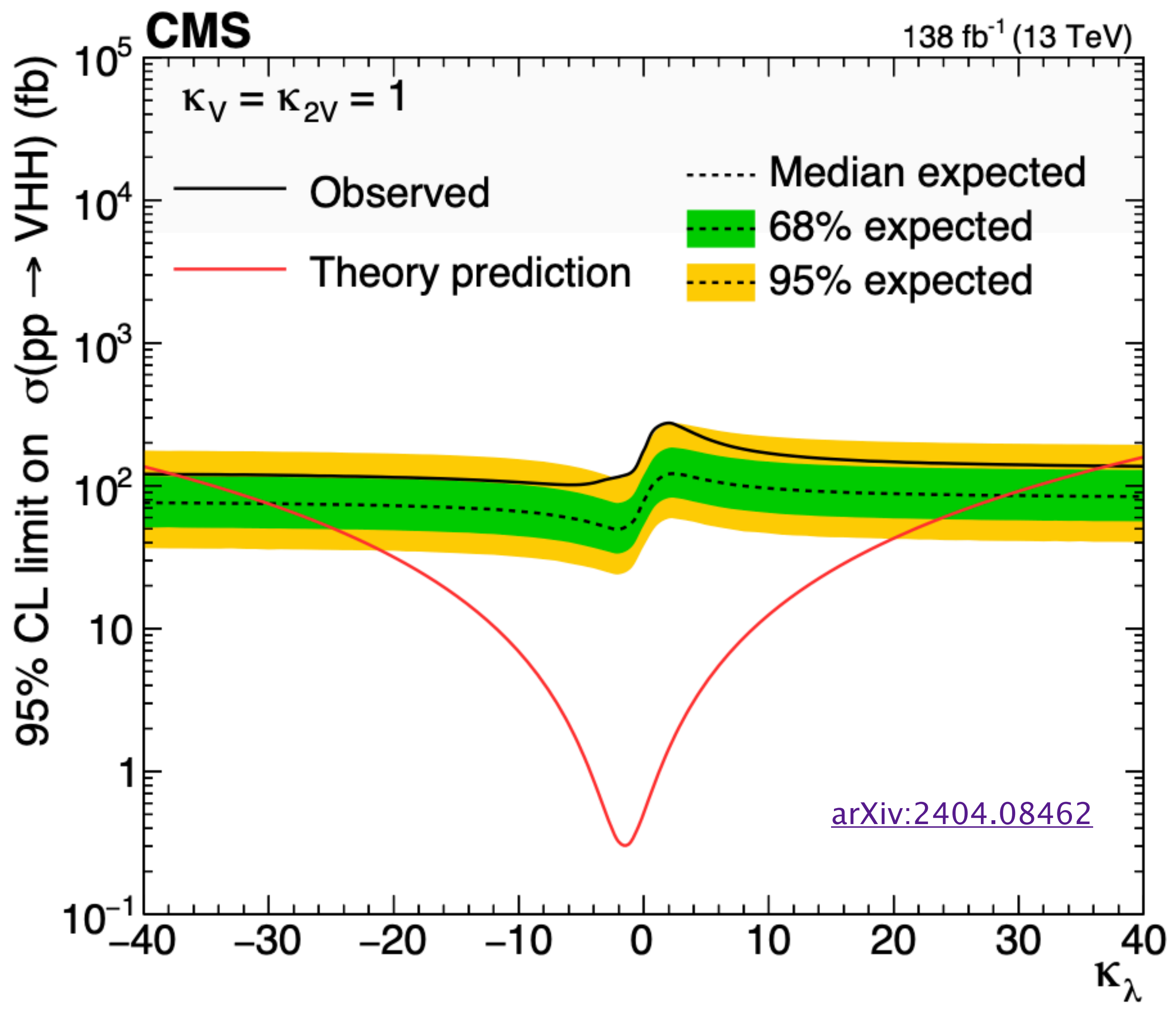
Subdominant production modes!

- Similar to single Higgs, we can look for subdominant production modes
- qqHH / VHH about 5-20 times rarer than ggHH
- Constraints on SM rates very loose
- But, another unmeasured SM coupling is involved: C2V
- Now already excluded to be <0 at 6+ σ...



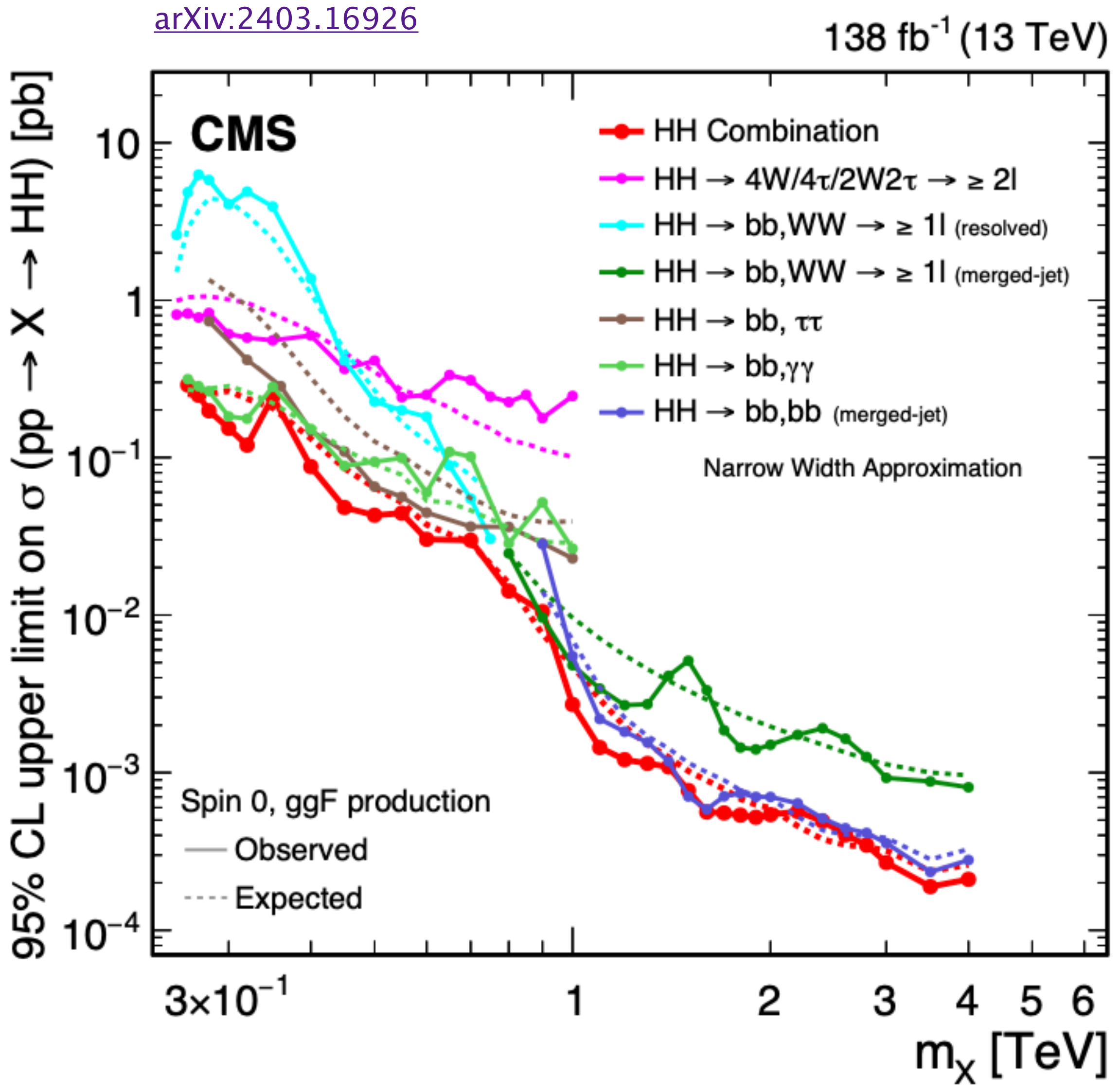


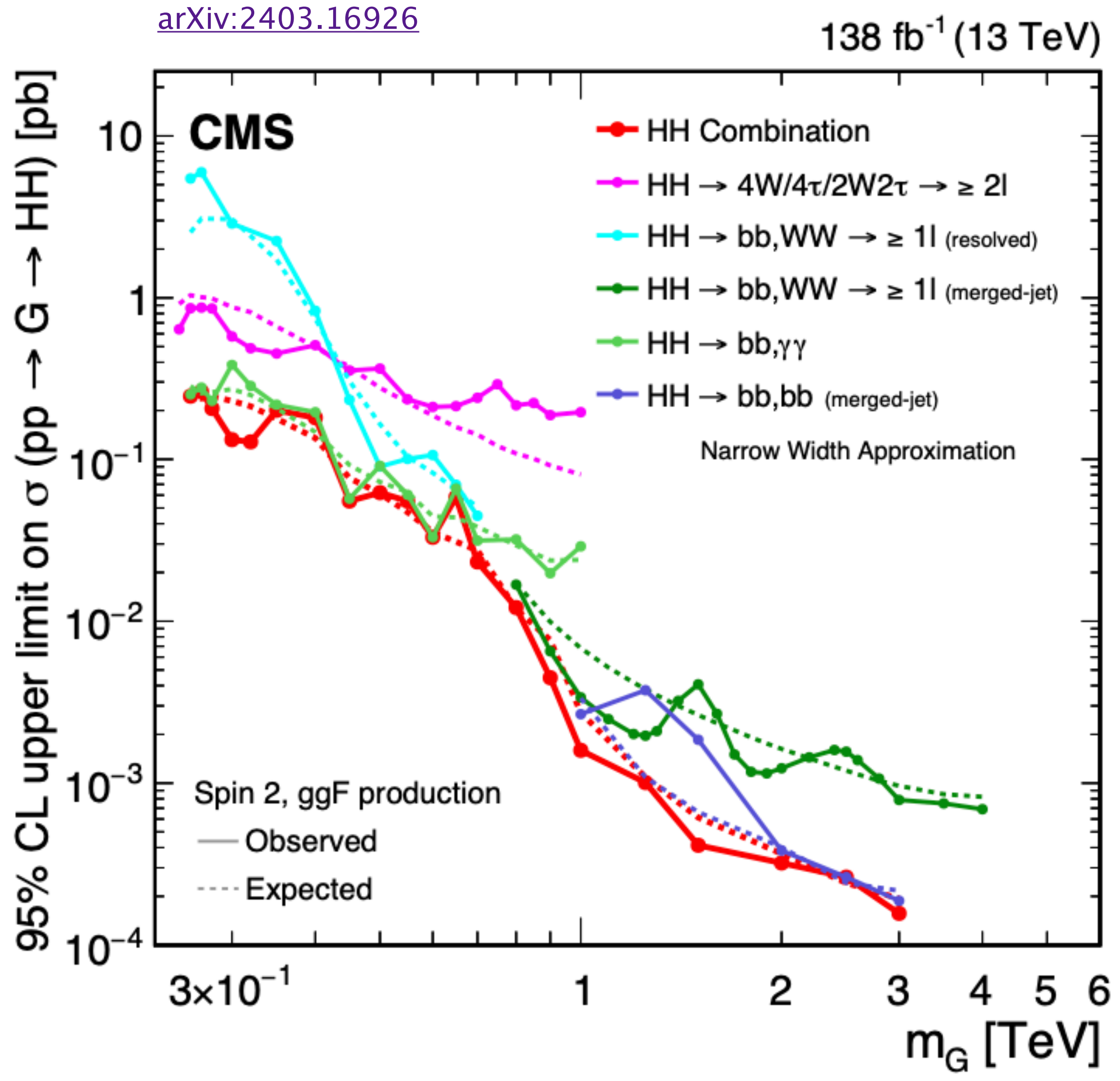


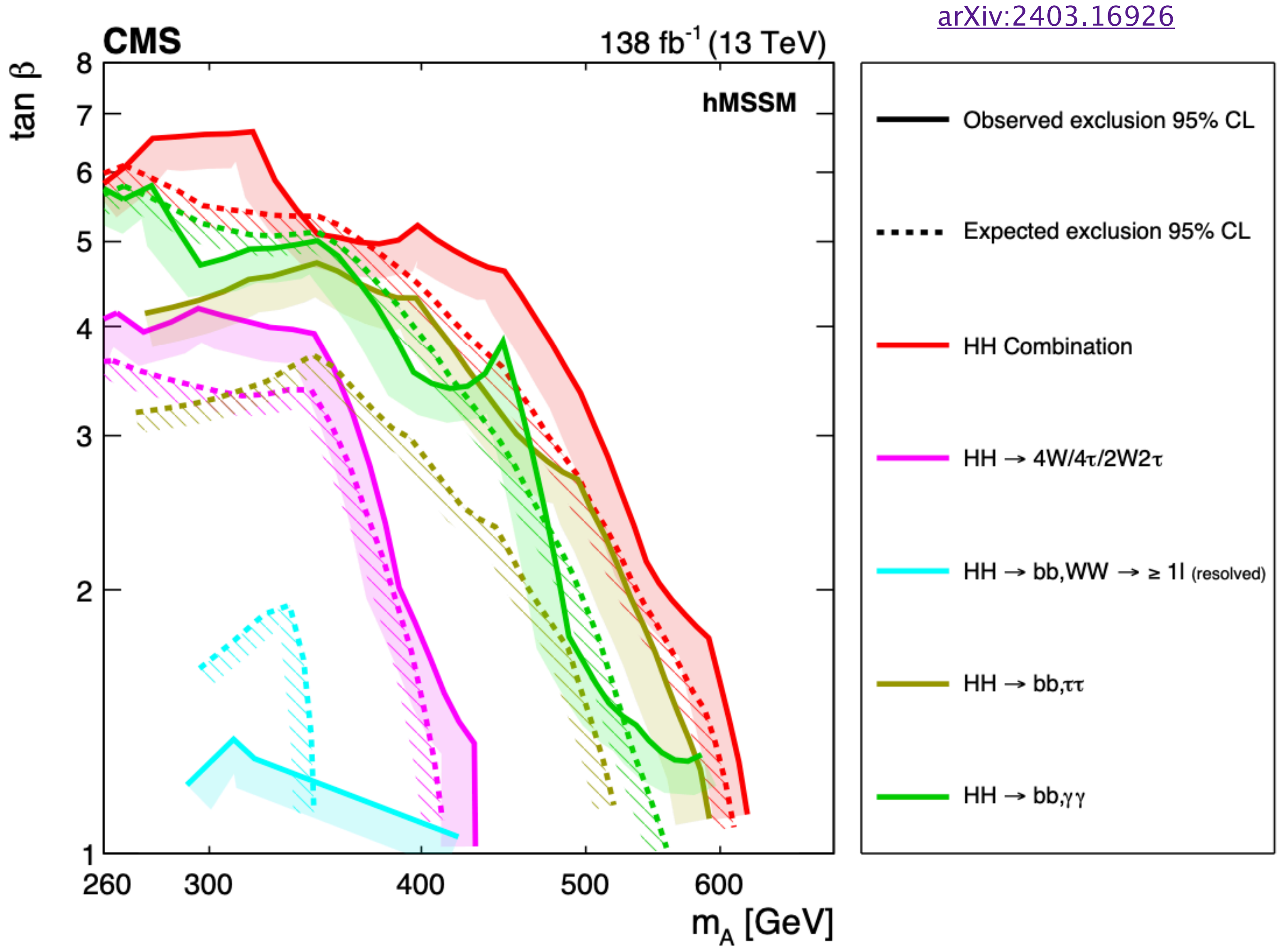


Resonant production! (And Reinterpretations)

- Resonant production has been tested for masses up to 4 TeV and two spin hypothesis
- Also similar X->Y/H production is being studied
- Recently a combination was released, also including many interpretations in UV complete models such as extended Higgs sectors or extra dimensions

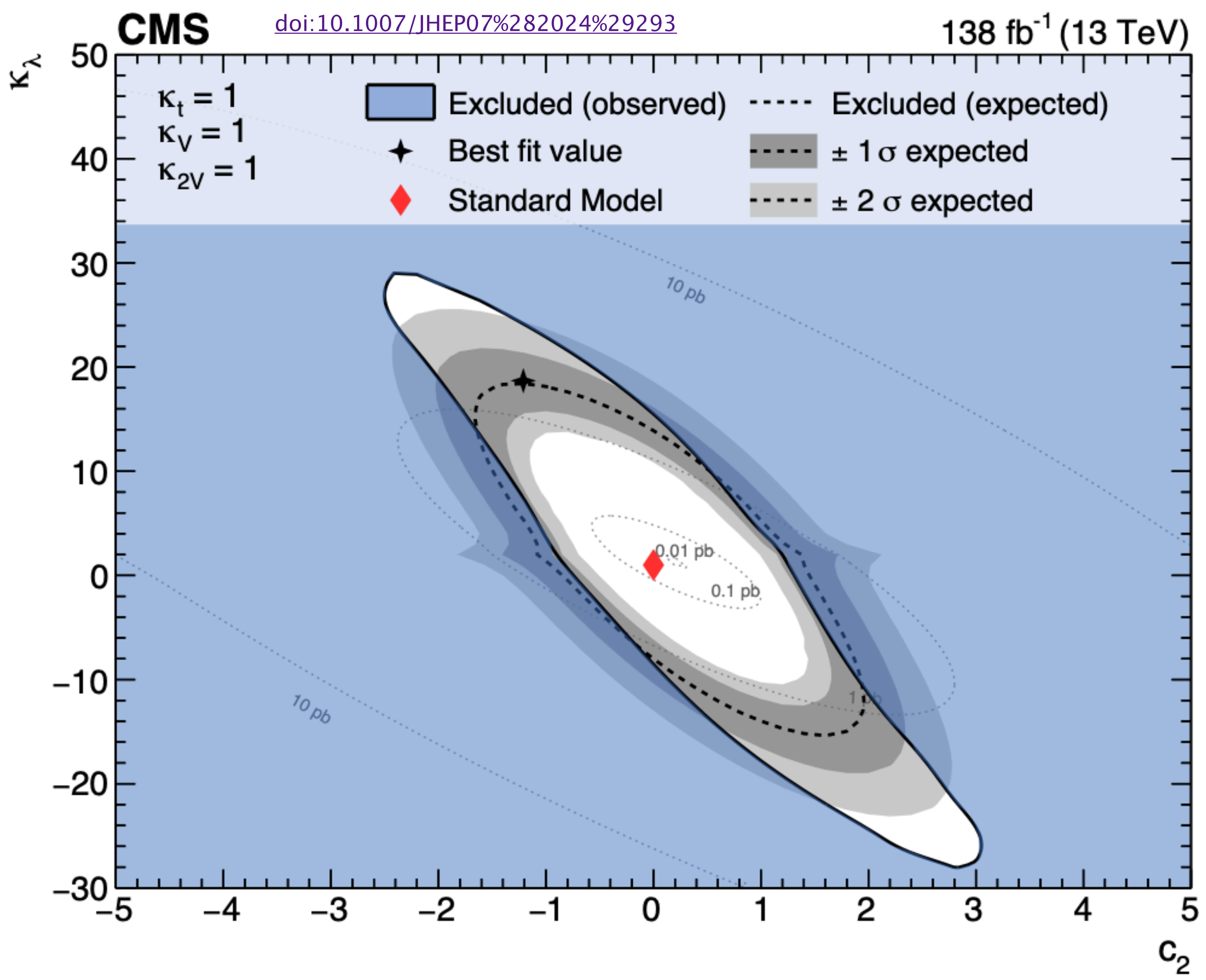


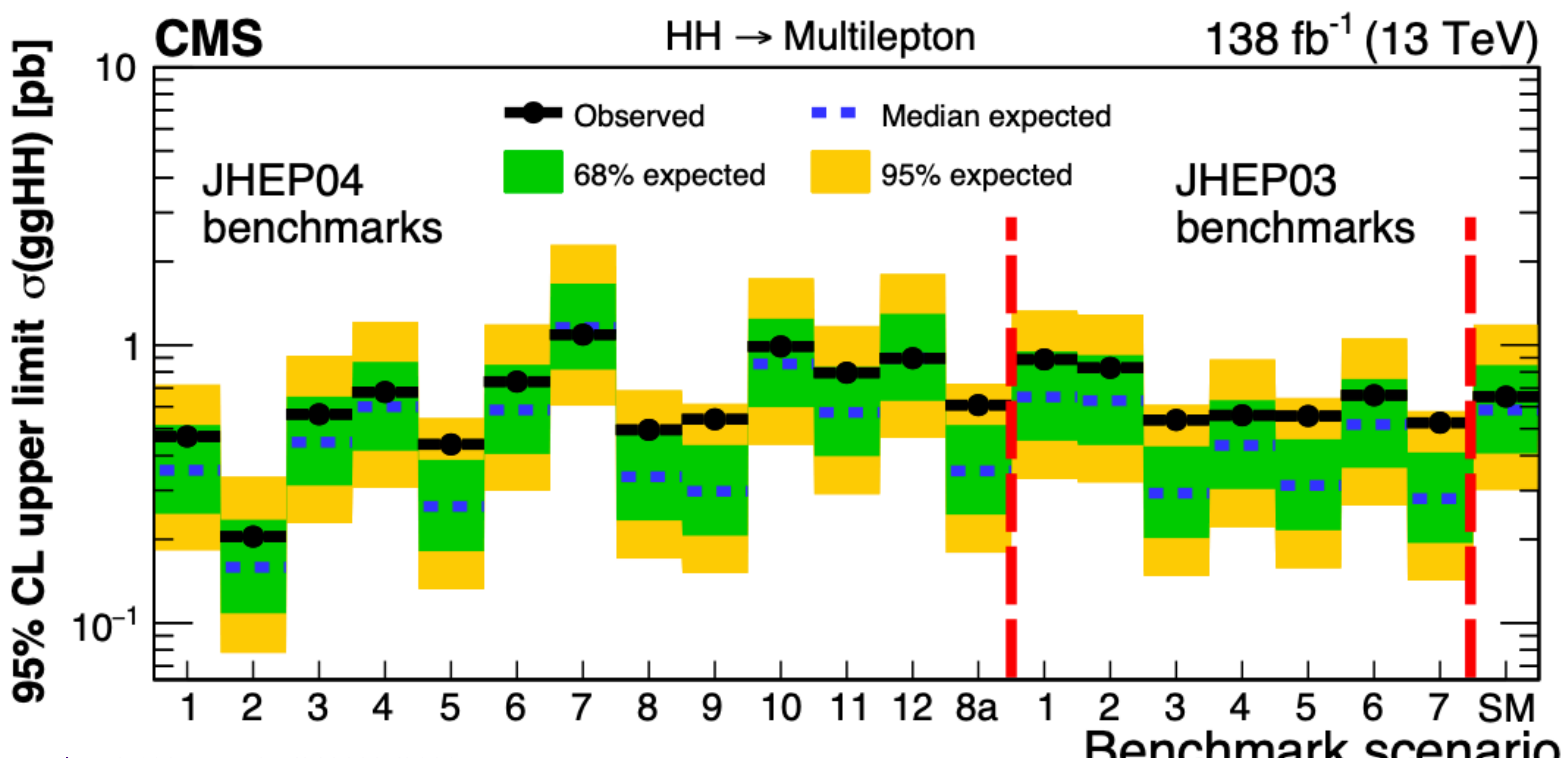




EFT!

- Mostly studied in HEFT so far (for CMS)
- Results in several benchmark scenarios [1,2,3] and a variety of parameter scans
- Stay tuned for more updates in the future!





doi:10.1007/JHEP07%282023%29095

The Baltic footprint…

Past: KBFI in Tallinn

- HH→Multilepton Run2 (SM, EFT and resonant) [link]
- HH->bbWW Run2 (SM, EFT and resonant) [link]
- HH non-resonant Nature combination [link]
- H+HH combination [link]
- HH/YH resonant combination and reinterpretation [link]
- CMS internally driving new interpretations/HH coordinator

Future: KBFI and now also RTU!

- Run3 bbtt - see Normans talk
- Run3 WWZZ (completely new!) - see Antras talk
- More, but still CMS internal projects ;)

Summary and outlook

- The Di-Higgs sector gives inside into many SM and BSM scenarios, most importantly some of the still missing SM constants!
- Processes extremely rare, but signatures quite unique, together with incredible advances in analysis techniques good progress was made during LHC Run2
- Run3 is upcoming, more results, more precision and more interpretations! One of the most thought after topics in HEP right now
- Baltics strongly involved and expanding!
- Stay tuned!