MANCHESTER
1824
The University of Manchester

Christoph Englert

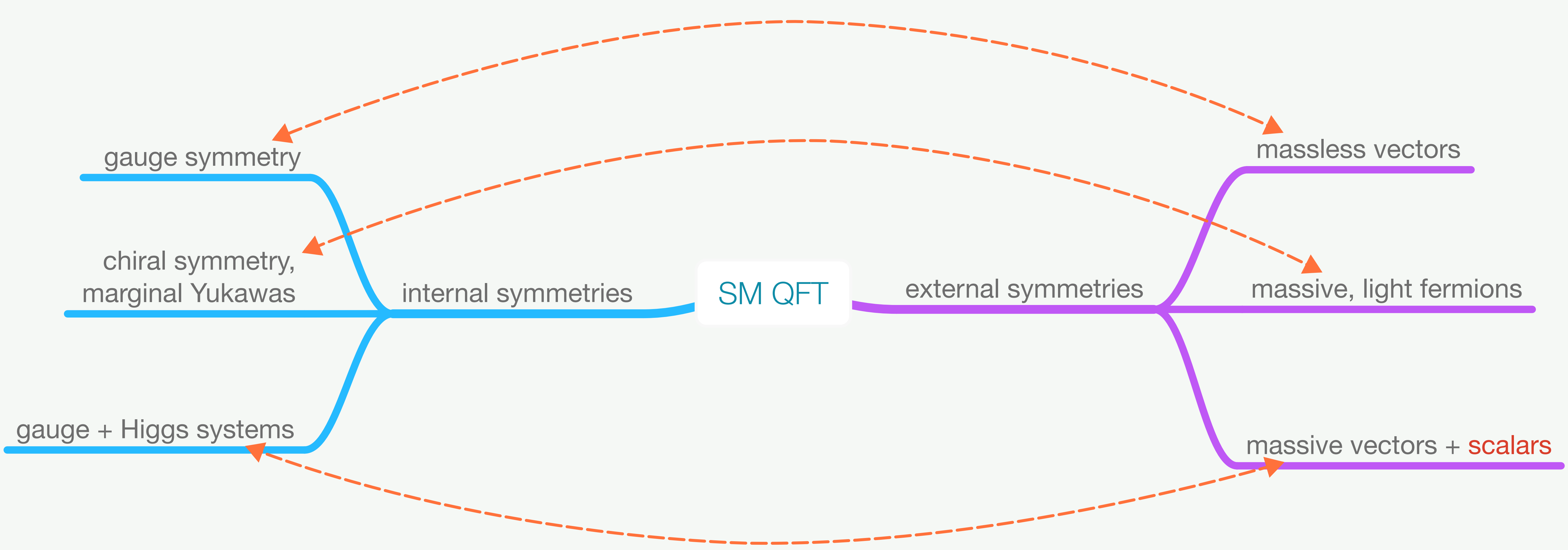
Towards BSM with weak scale physics

Particle Physics Department

Seminar, RAL

22/07/26

What is the nature of the TeV scale?

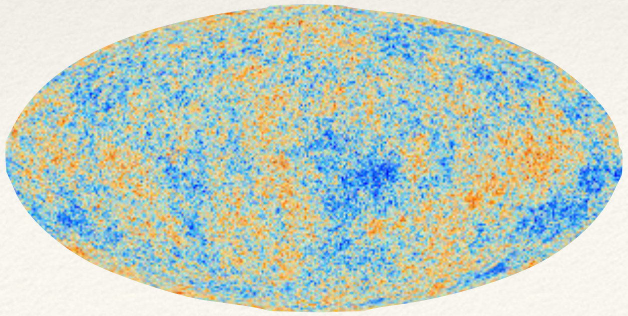


The SM is extremely restrictive - by accident….

e.g. [Sakharov ` 67]

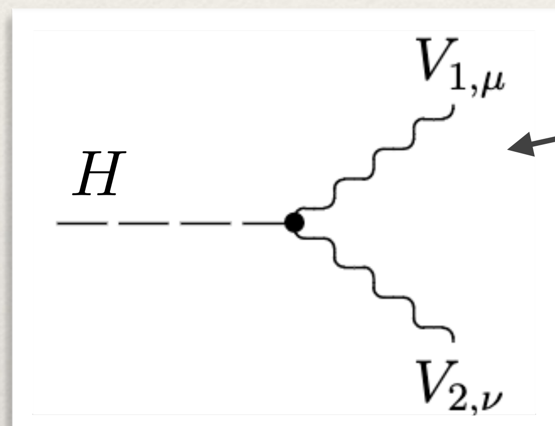
- baryon-number conservation, CP, custodial isospin, …
- *trouble in theory land*: strong CP, Higgs naturalness, …

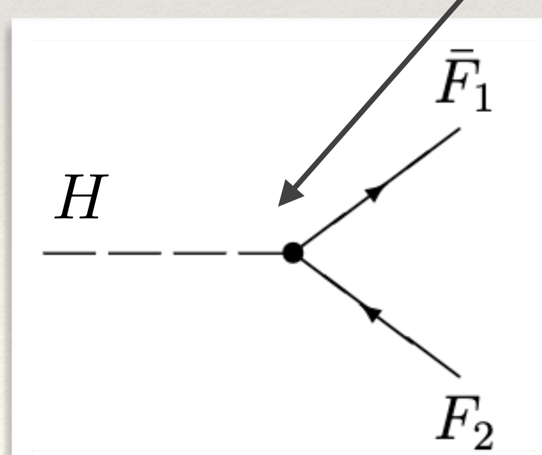
\+

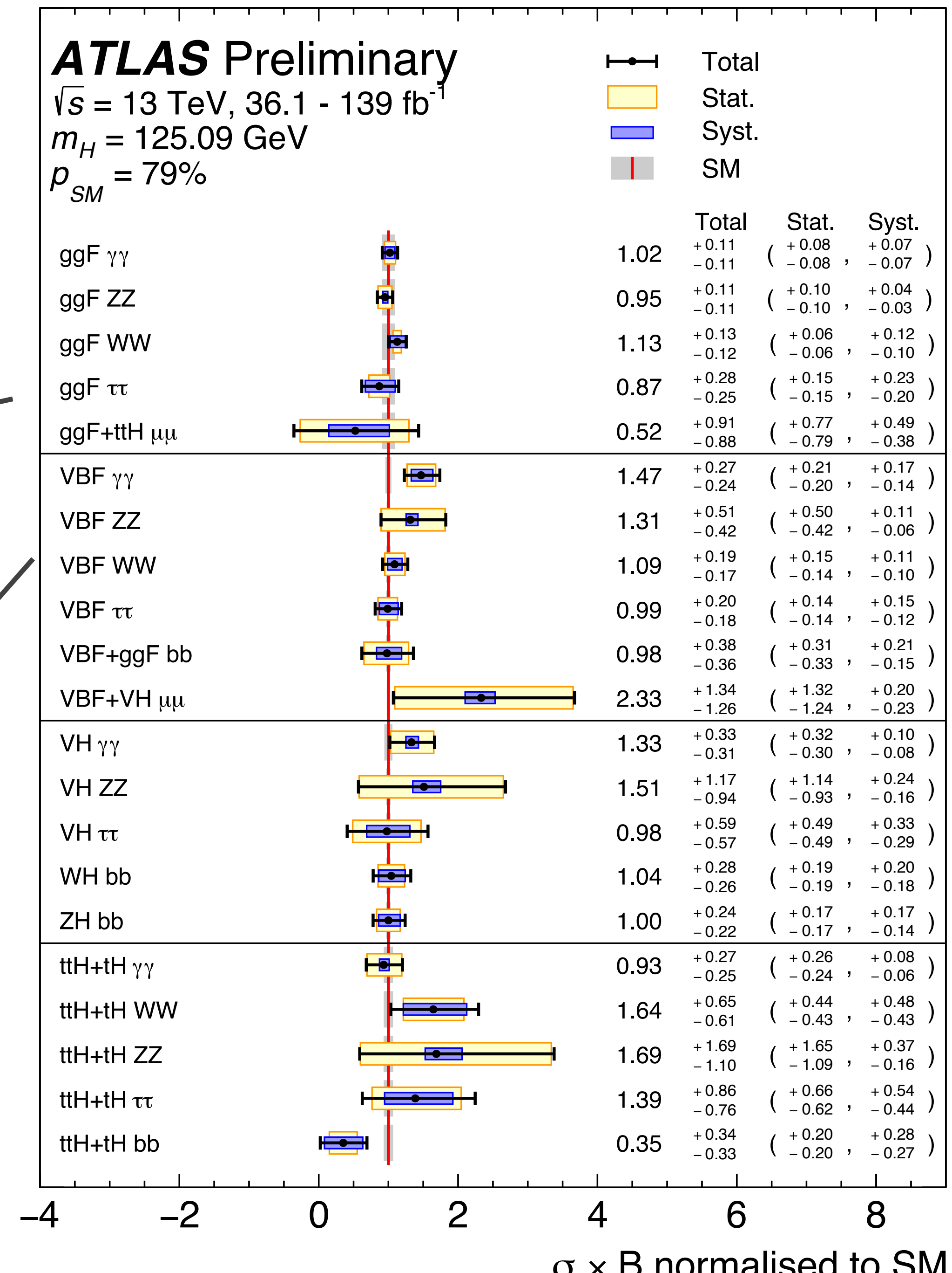


What is the nature of the TeV scale?

- somehow SM correlations are (un)expectedly accurate…







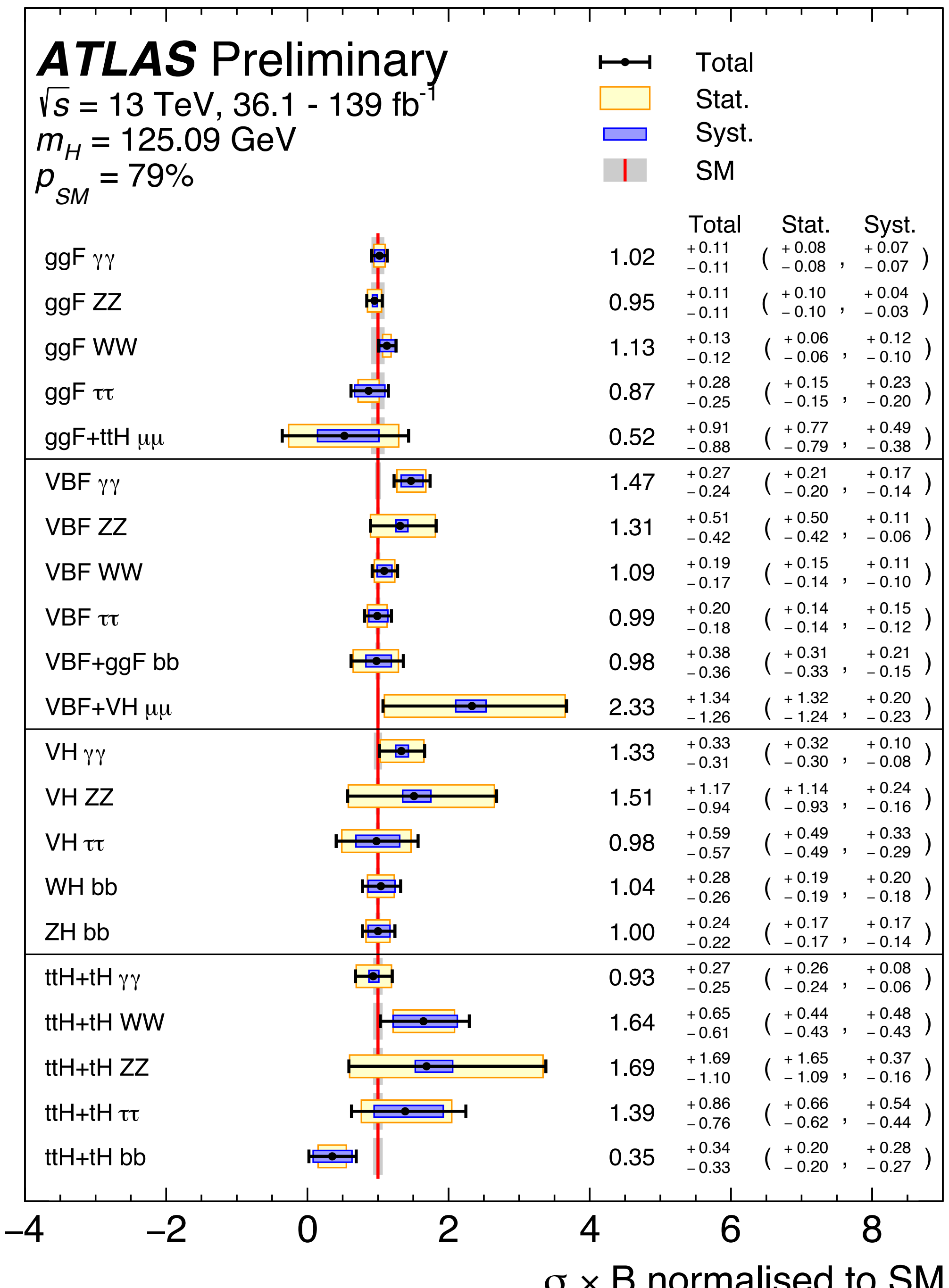
e.g. [ATLAS `21]

What is the nature of the TeV scale?

- somehow SM correlations are (un)expectedly accurate…

*What are the possibilities?**

- *our data are not accurate (yet)*
- *we are looking in the wrong place*
- *particle physics does not have answers*



e.g. [ATLAS `21]

* *mostly TeV scale collider phenomena today*

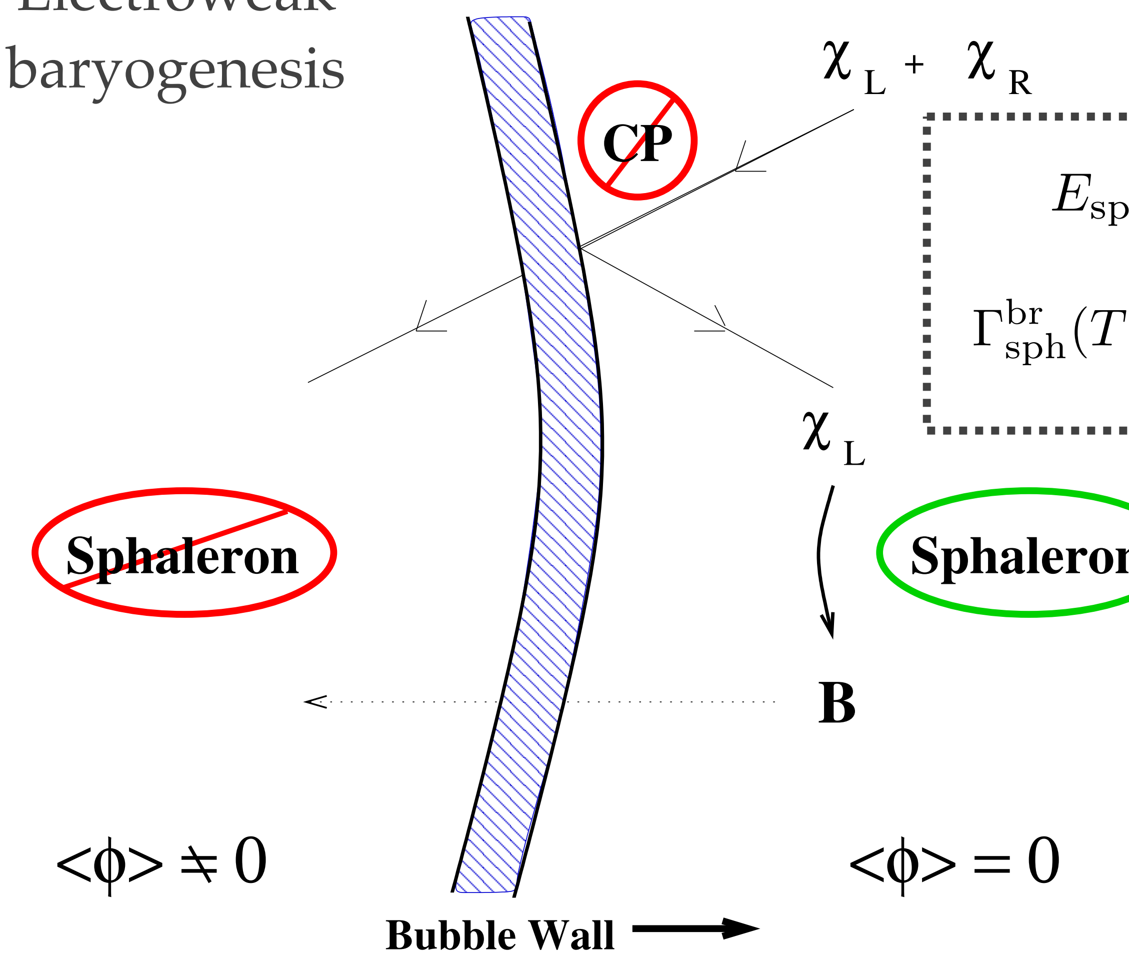
Higgs coupling deviations @ HL-LHC?

- perturbativity has been a huge success story !
- trust it one more time ? (then there are many options…)

Baryogenesis!

Sakharov Conditions	SM?
1.) Baryon number violation	✓
2.) C and CP violation	✗
3.) departure from equilibrium	✗

Electroweak baryogenesis



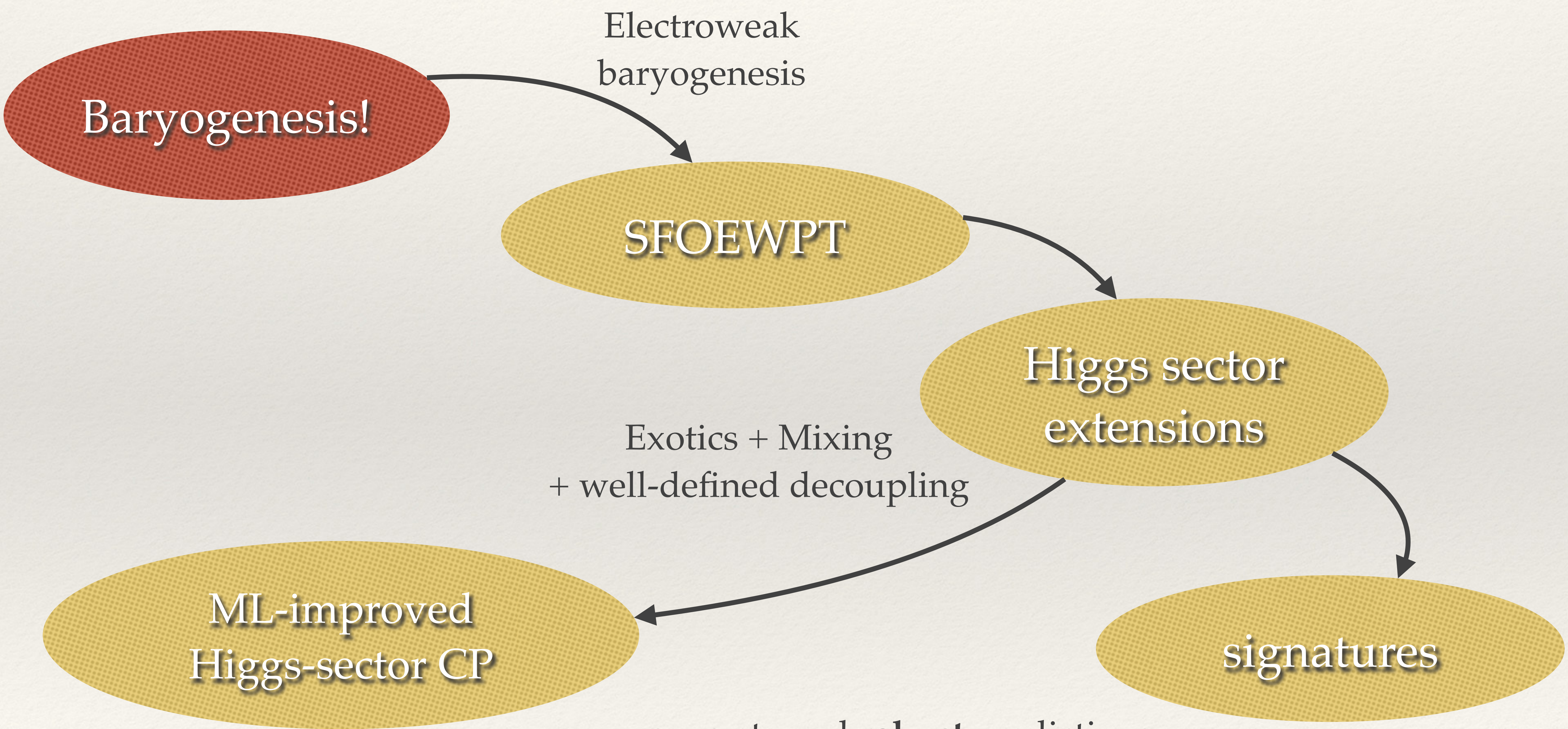
$$E_{\rm sph}(T) \sim \frac{4\pi\, v(T)}{g}$$

$$\Gamma^{\rm br}_{\rm sph}(T) \sim \exp\left[-\frac{E_{\rm sph}(T)}{T}\right]$$

e.g. [Morrissey, Ramsey-Musolf ` 12]

Higgs coupling deviations @ HL-LHC?

- perturbativity has been a huge success story !
- trust it one more time ? (then there are many options…)

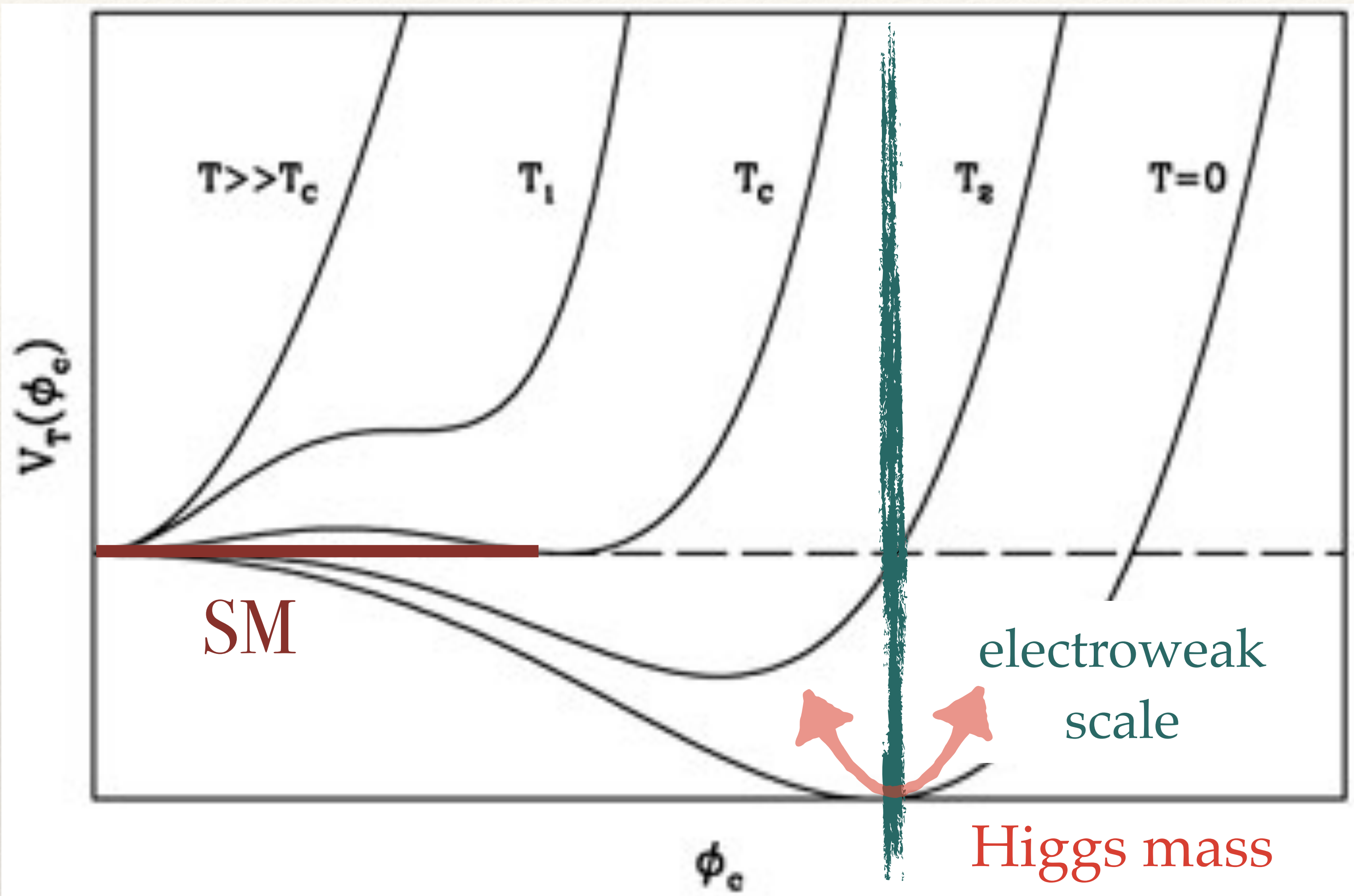


e.g. [Atwal, Burridge, Costa, et al. `25]

concrete and **robust** predictions,
especially for future lepton machines

Higgs coupling deviations @ HL-LHC?

- standard approaches using effective potentials at finite temperature



"strong enough" for

$$\xi_p \equiv \frac{v_p(T_p)}{T_p} > 1$$

many publicly available codes/approaches

[BSMPT]
[CosmoTransition]
...

- *LHC data tells us that we are SM-aligned*
- *SFOEWPT tells us that new physics has large impact*

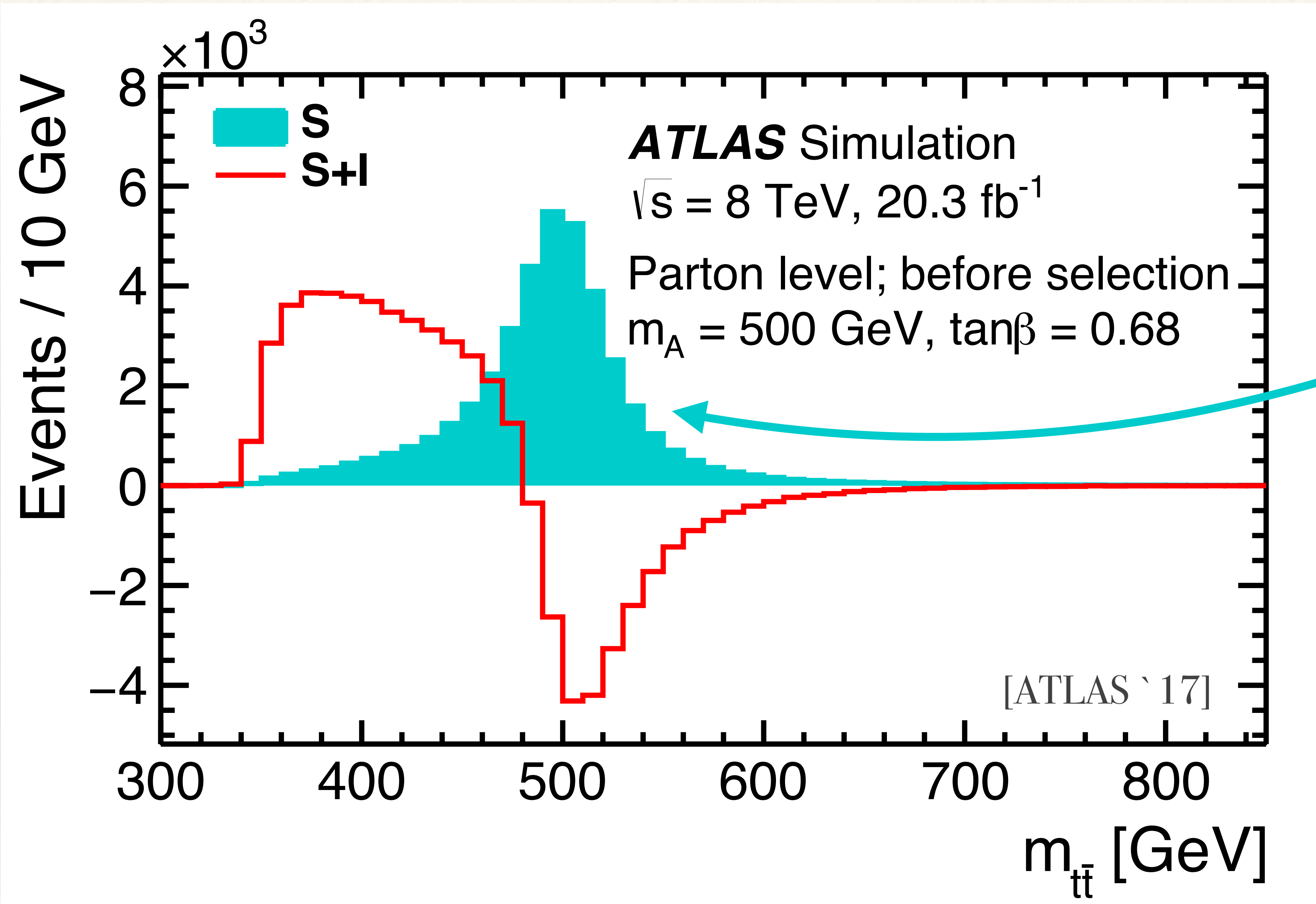
Upshot: New states need to be light.

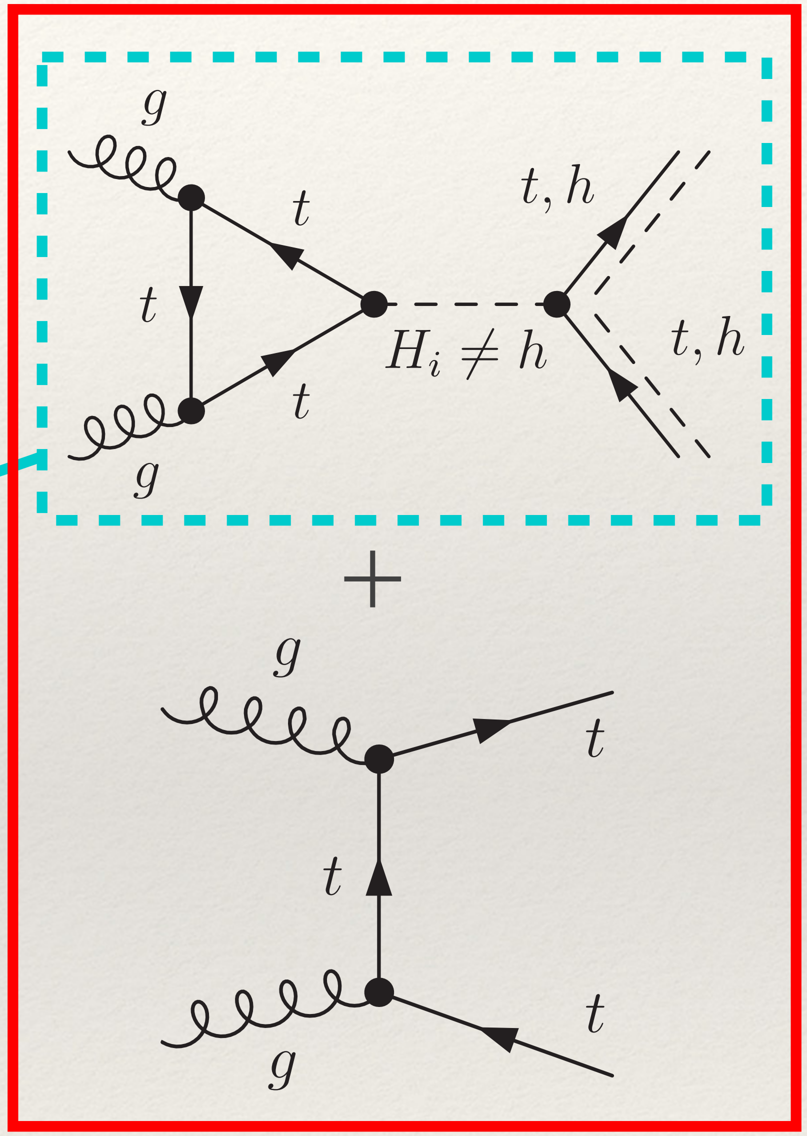
caveat: non-perturbative BSM effects
[Biermann, Chakrabortty, CE `26]

Where are these exotic states?

- large interference effects of Higgs "signal" with QCD background

[Gaemers, Hoogeveen `84]

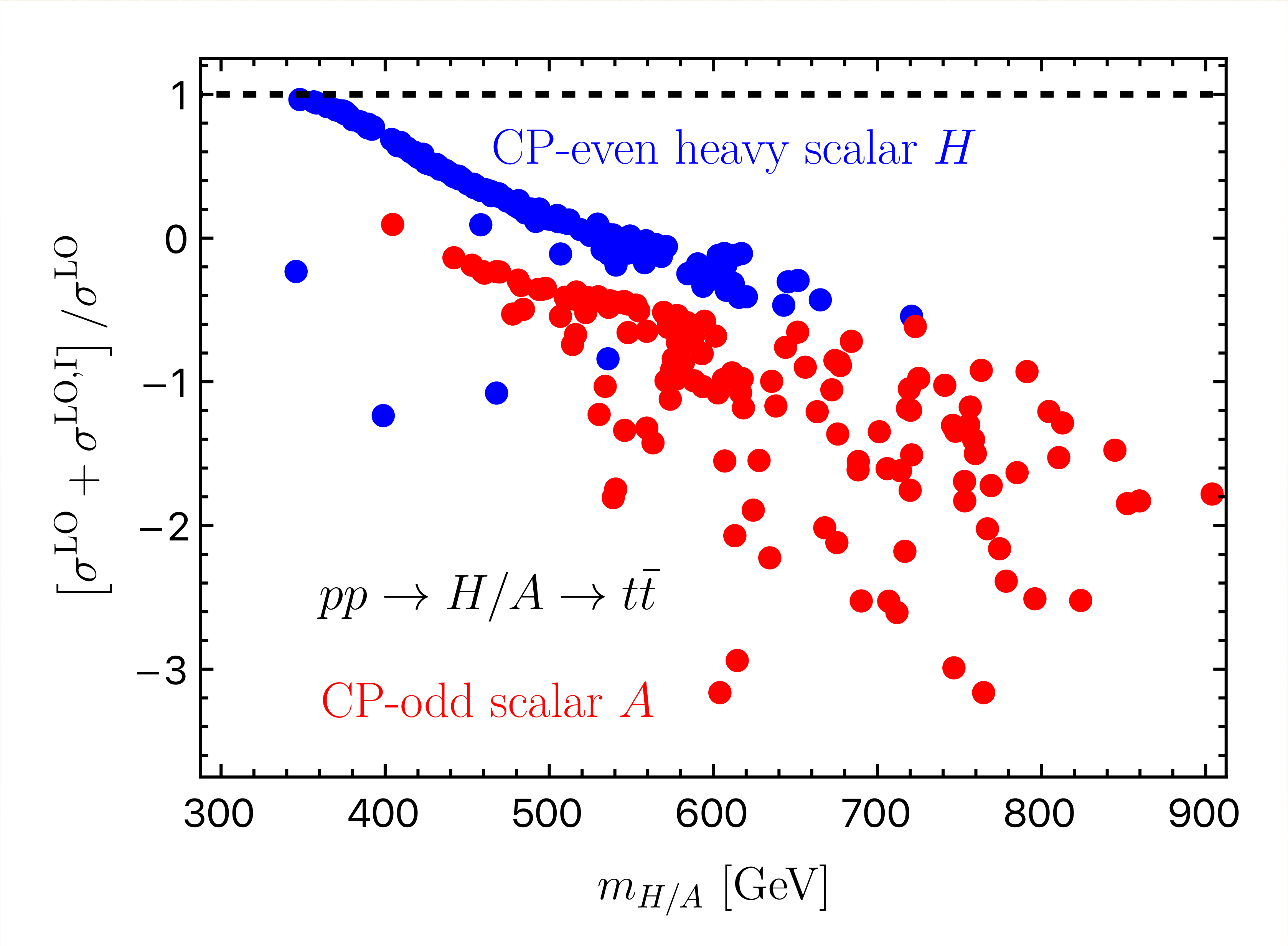




- top resonance searches in Higgs sector extensions with narrow width approximation inadequate!

Where are these exotic states?

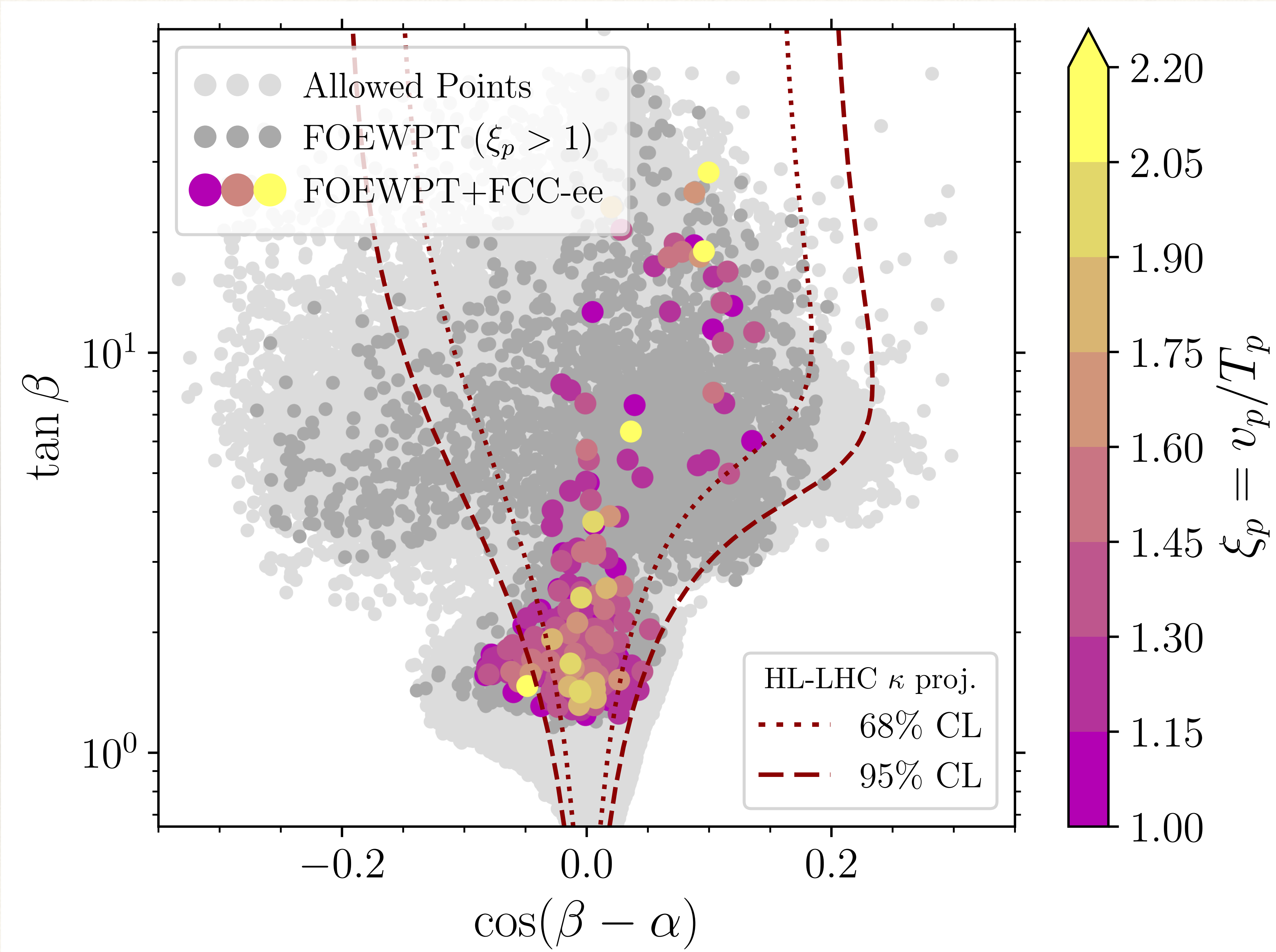
- for instance 2HDM + current Higgs signal coupling fits [Anisha et al. `25]



- large modifications of on-shell pheno - *there is a chance to miss this*

back to 2HDM: Higgs signal strength sensitivity ?

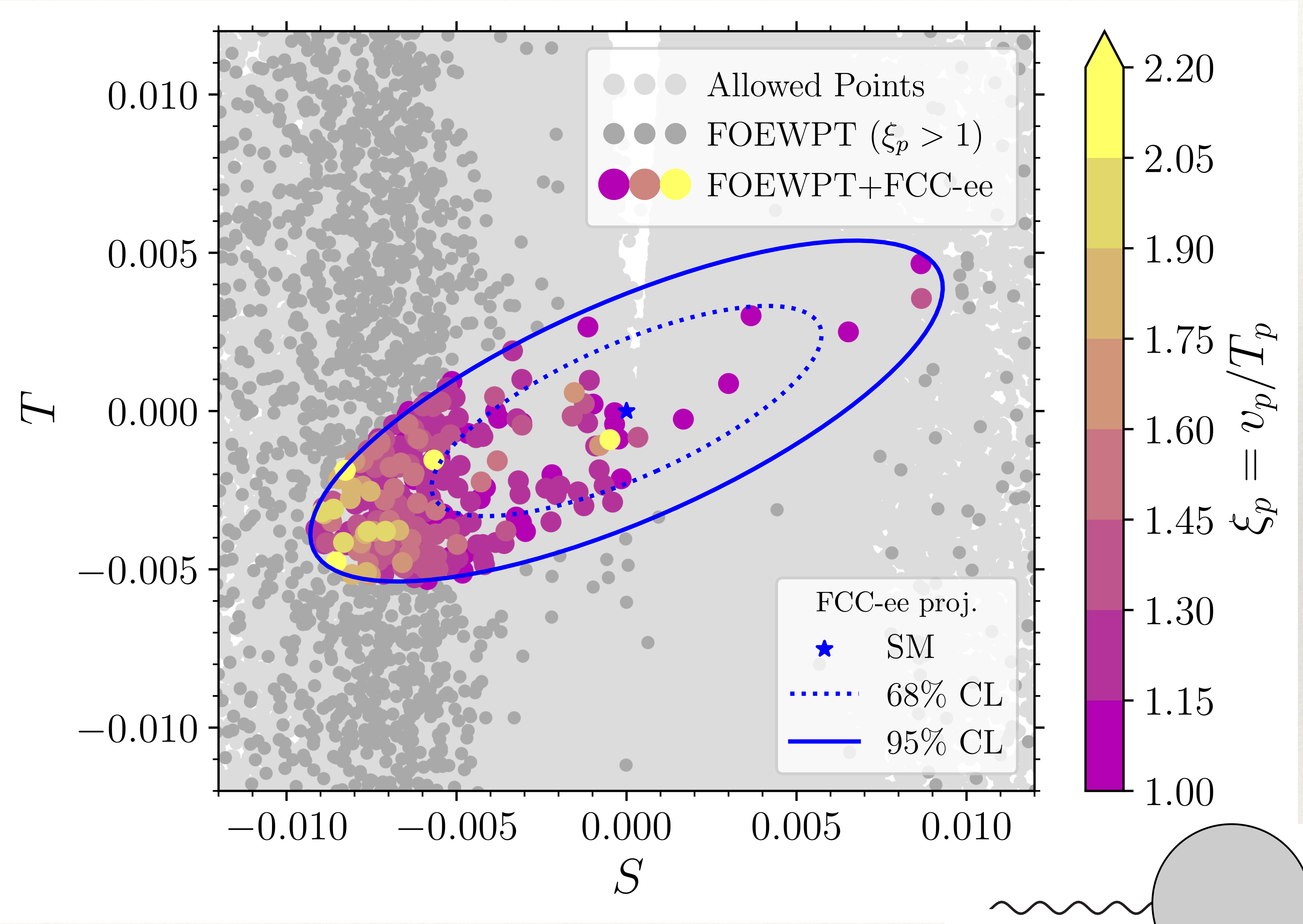
- for instance 2HDM + current Higgs signal coupling fits [Anisha et al. `25]

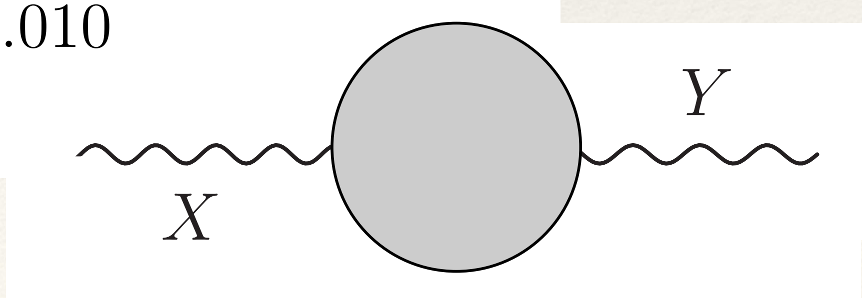


HL-LHC Higgs couplings

Higgs signal strength sensitivity ?

- for instance 2HDM + current Higgs signal coupling fits [Anisha et al. `25]

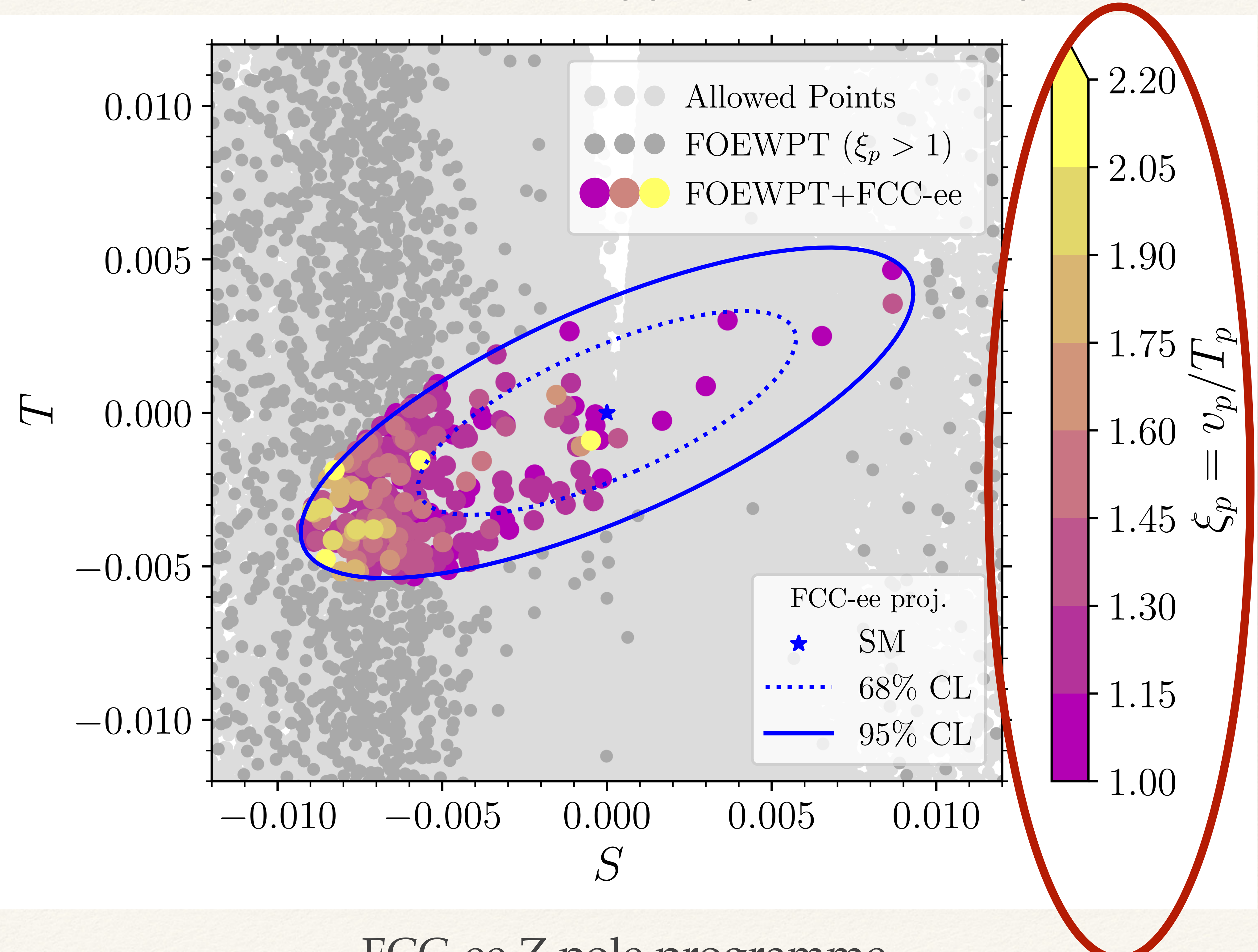




FCC-ee Z pole programme

Higgs signal strength sensitivity ?

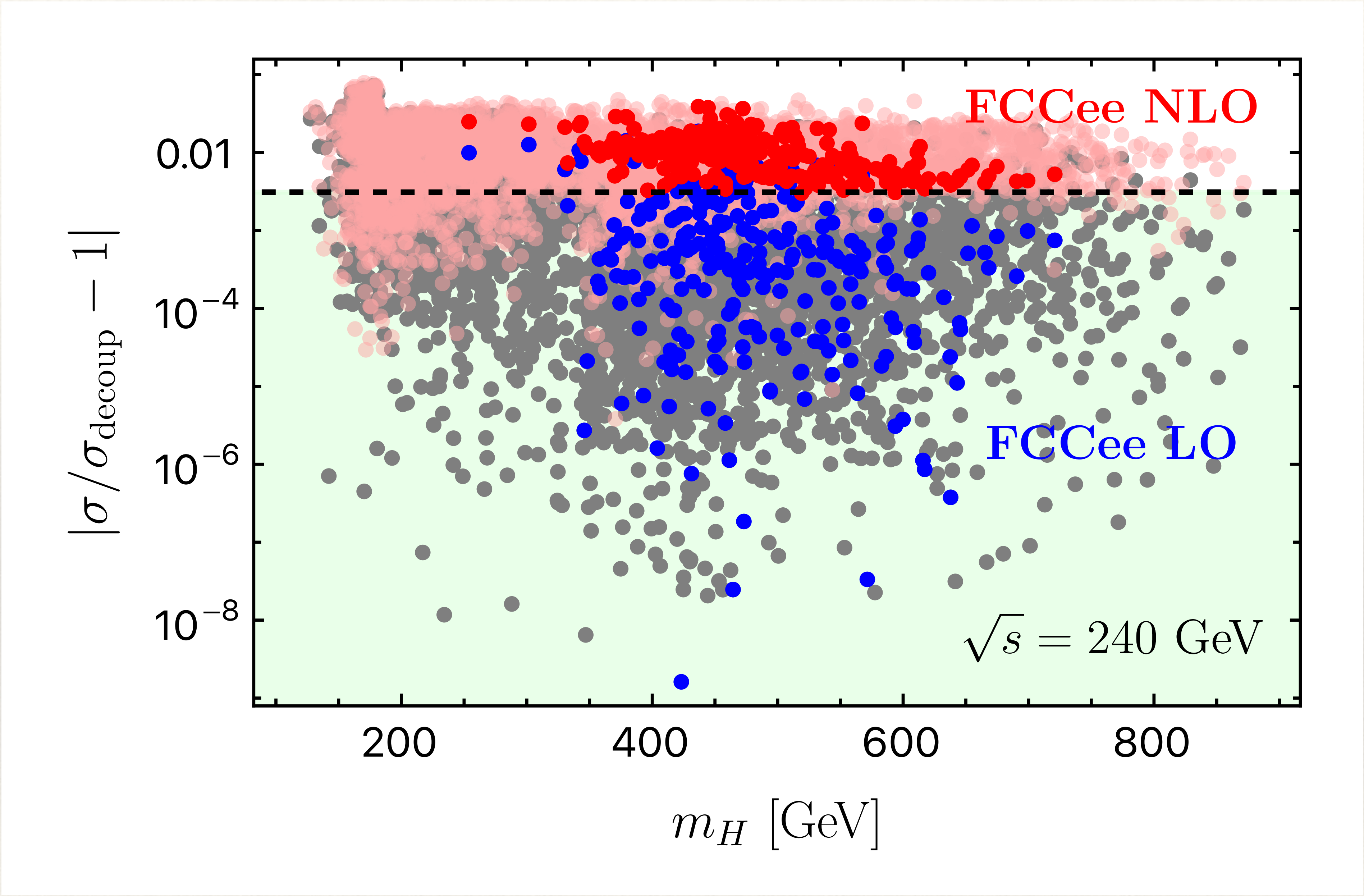
- for instance 2HDM + current Higgs signal coupling fits [Anisha et al. `25]

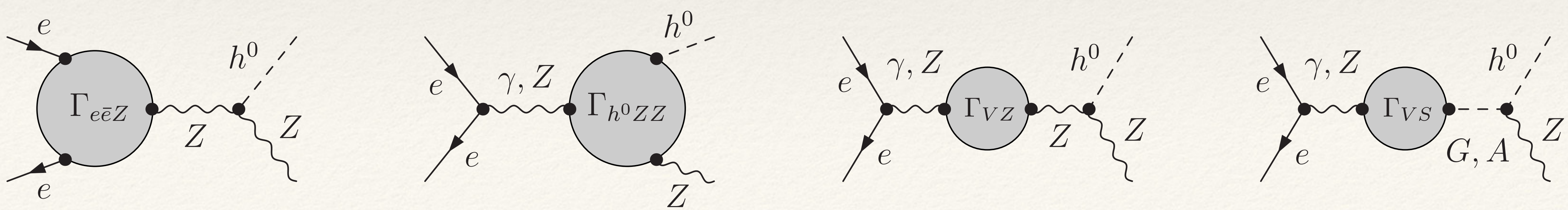


FCC-ee Z pole programme

Higgs signal strength sensitivity ?

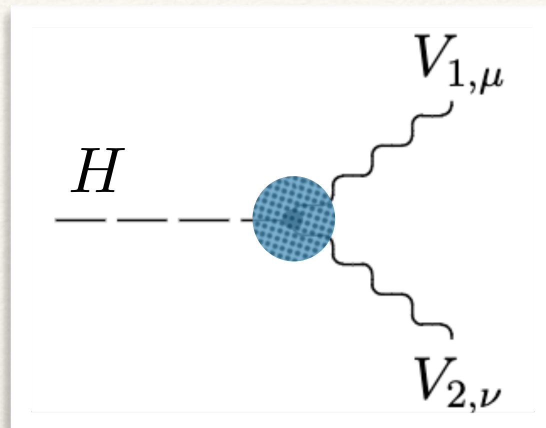
- but alignment without decoupling cannot hide forever ! [Anisha et al. `25]

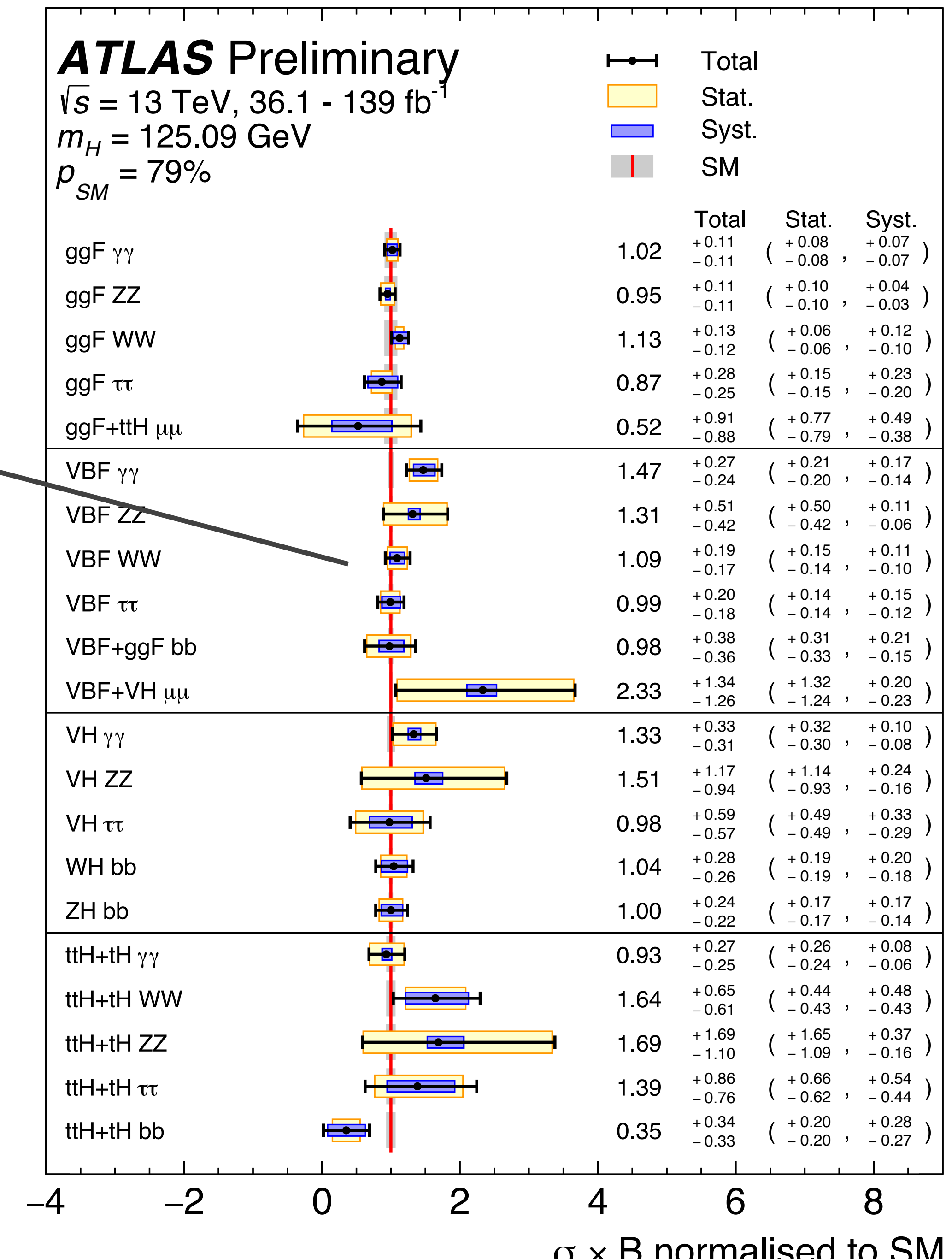




No reason to be so pessimistic….

HL-LHC could reveal %-level coupling deviations



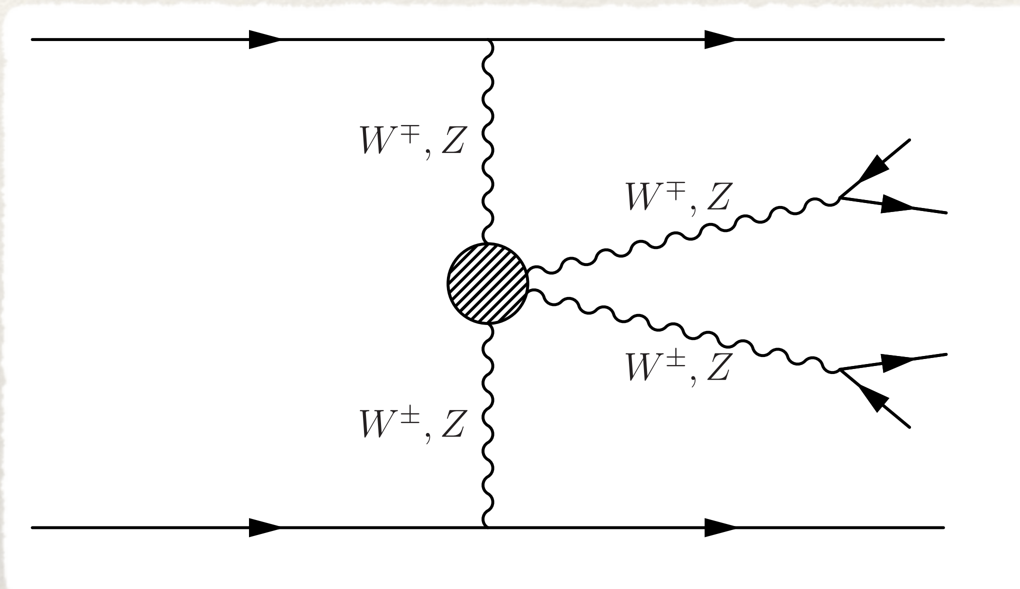


e.g. [ATLAS `21]

…back in business big time!

No reason to be so pessimistic….

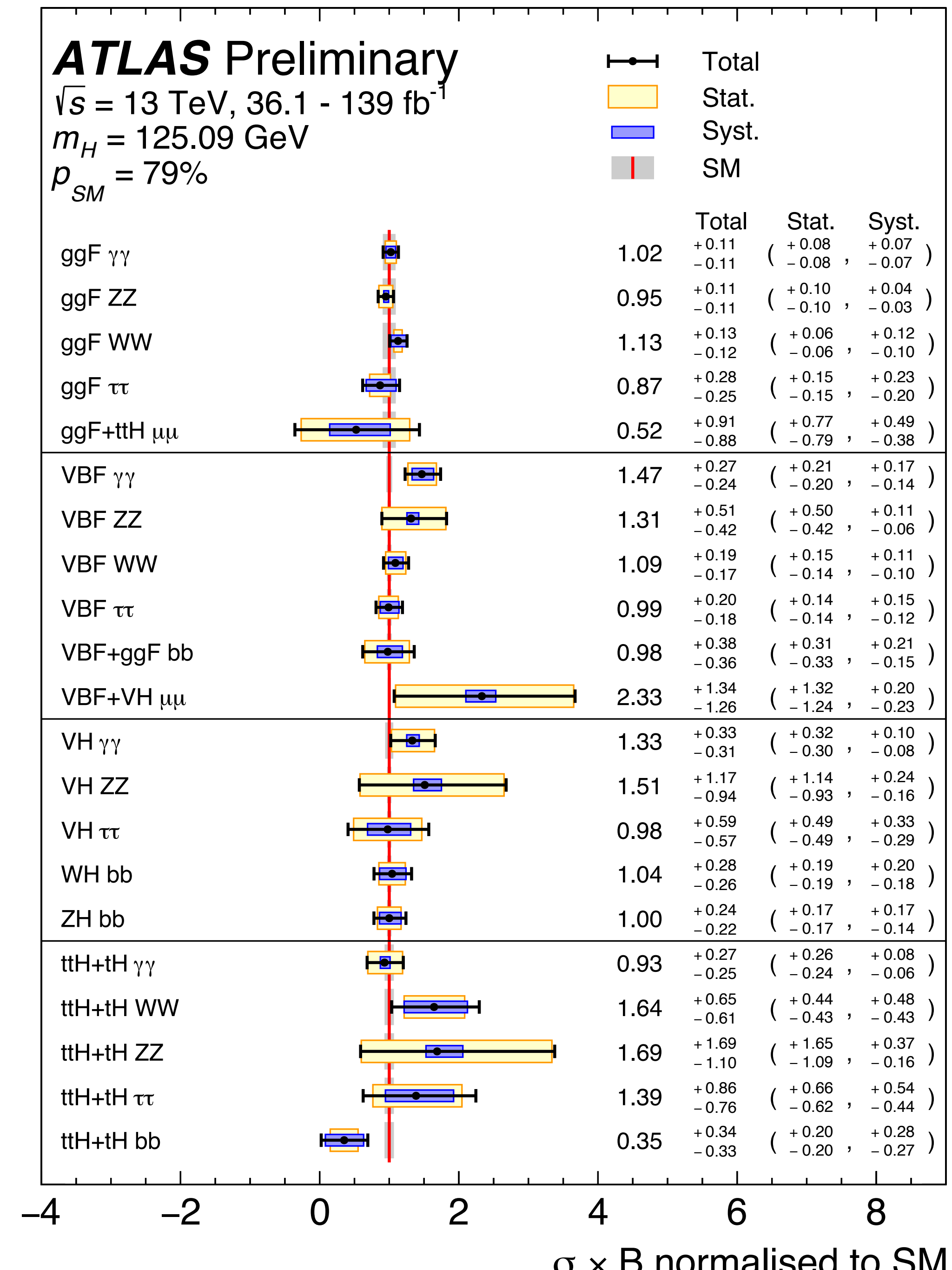
HL-LHC could reveal %-level coupling deviations



…back in business big time!

Any coupling modification away from the SM:

- Unitarity violation induces a new particle scale correlated with size of deviation
- Which (WBF) collider concept prepares us best ?



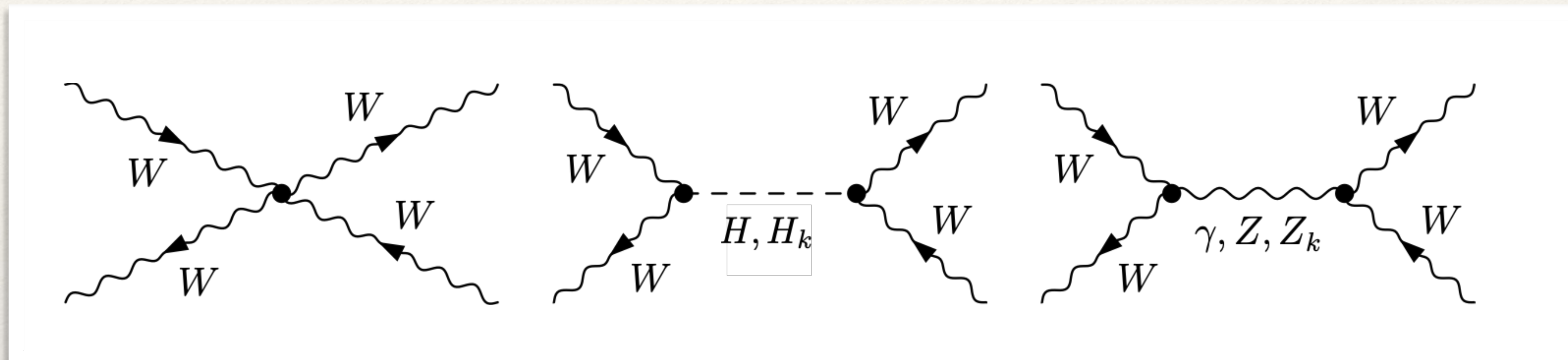
e.g. [ATLAS `21]

Unitarity for discovery

- Unitarity restoration is only efficient with scalar and vector resonances

  sum rules for longitudinal vector boson scattering

[Weinberg `67]...
...[Alboteanu et al. `08]
[Birkedal, Matchev, Perelstein `04]
[CE, Harris, Spannowsky, Takeuchi `15]



prediction

$$g_{WWWW} = g^2_{WW\gamma} + \sum_k g^2_{WWZ_k}\,,$$

$$4m^2_W g_{WWWW} = \sum_k 3m^2_{Z_k} g^2_{WWZ_k} + \sum_k g^2_{WWH_k}$$

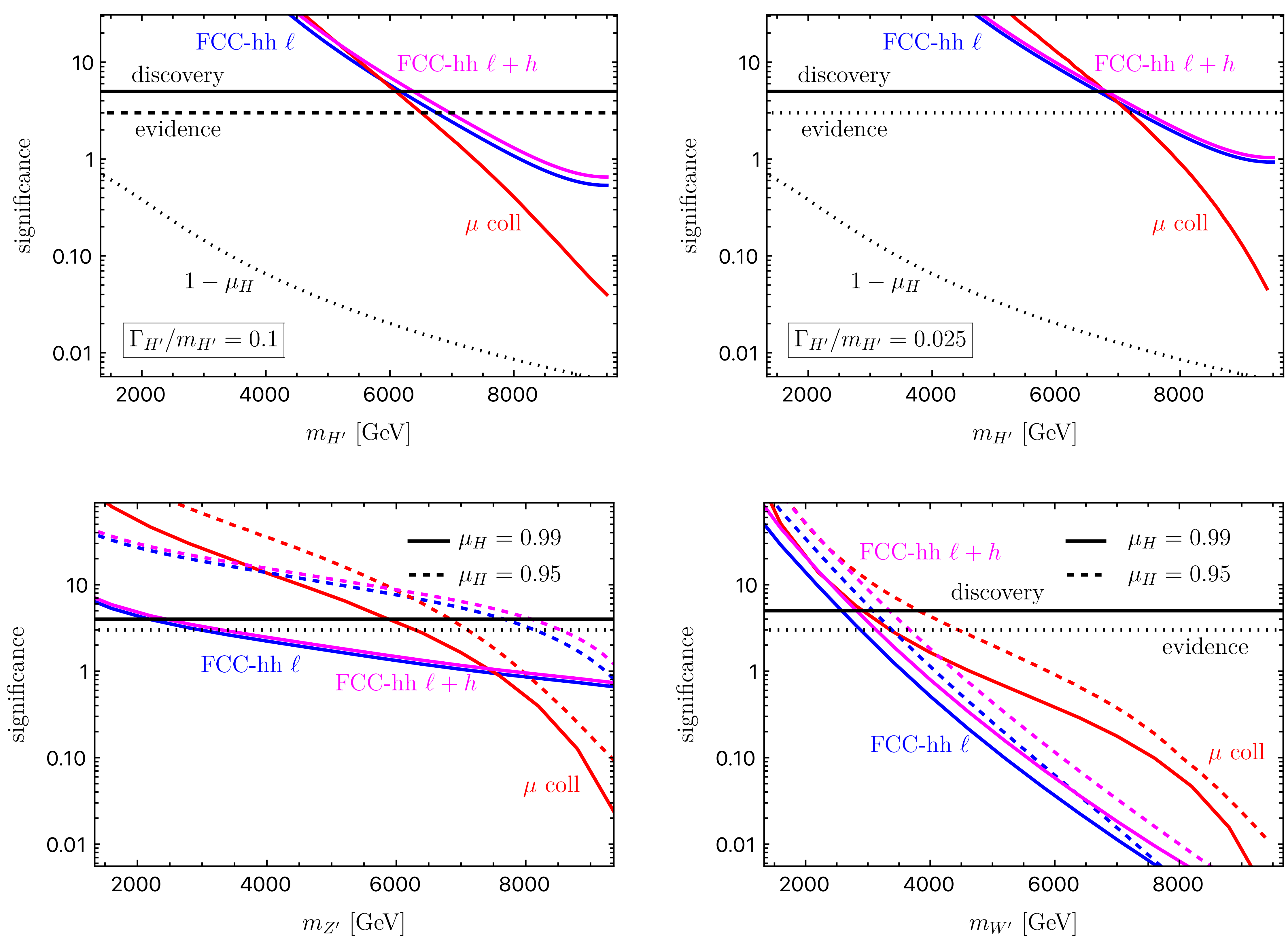
Higgs coupling deviation

pheno determined by unitarity,
gauge symmetry, and convergence

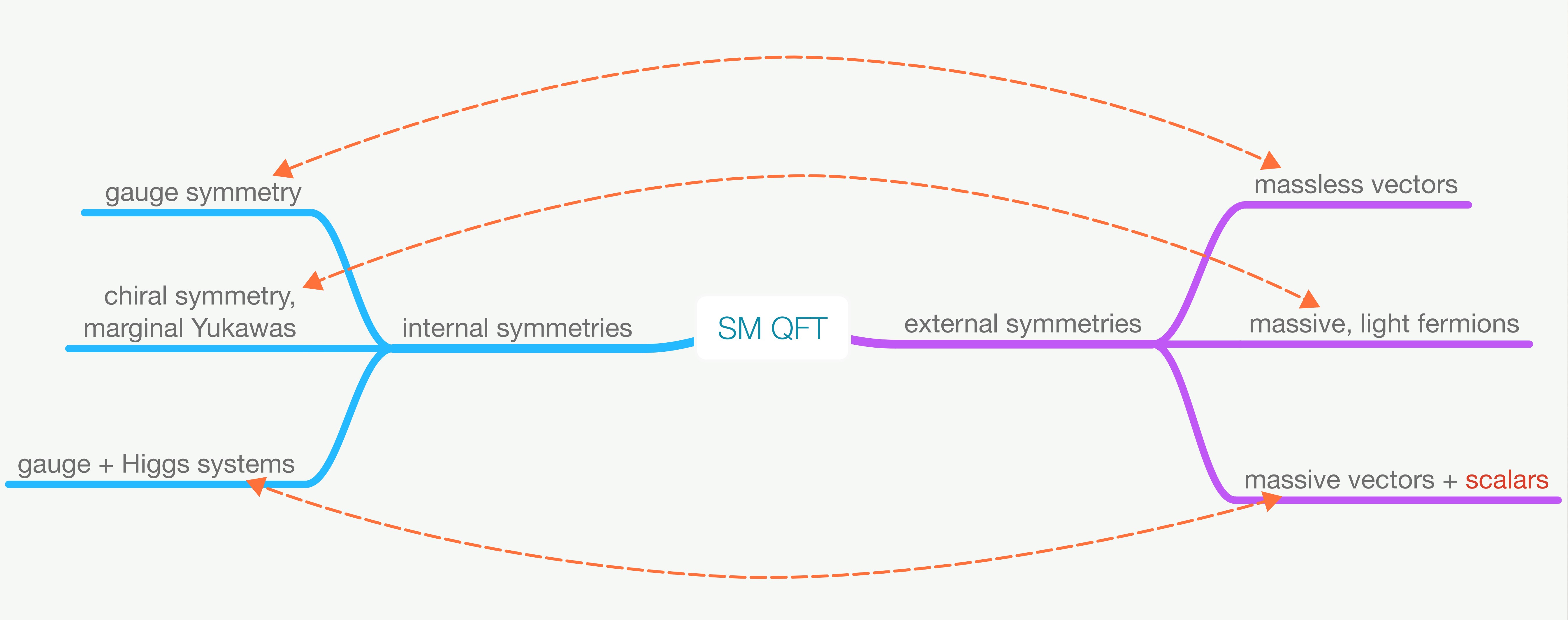
prediction

Unitarity for discovery

[CE, Naskar, Pilkington, Spannowsky `26]

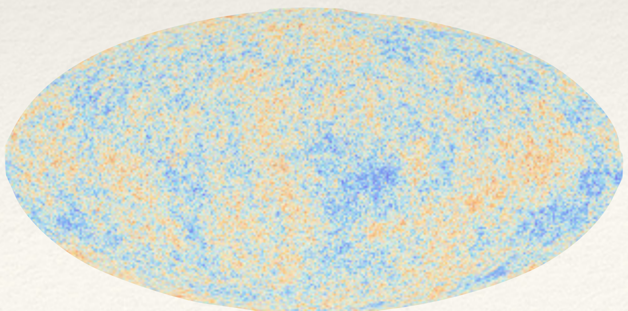


What is the nature of the TeV scale?



The SM is extremely restrictive - by accident….

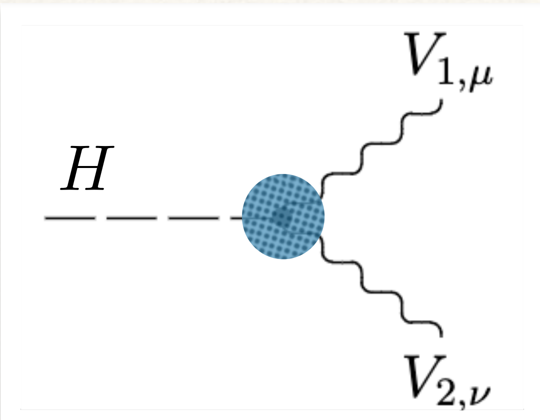
- baryon-number conservation, CP, custodial isospin, …
- fine tuning: strong CP, Higgs naturalness, …

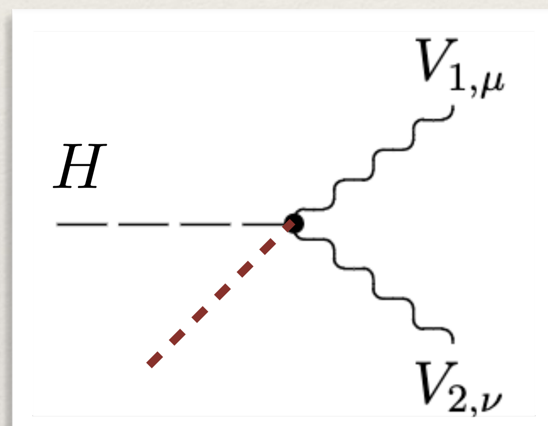
+ 

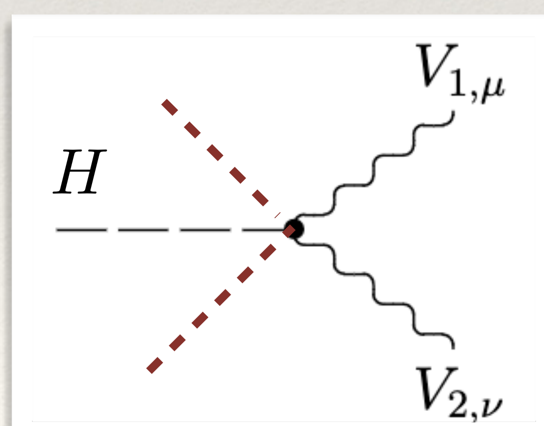
- **SM correlations to restrictive for new physics ?**

No reason to be so pessimistic….

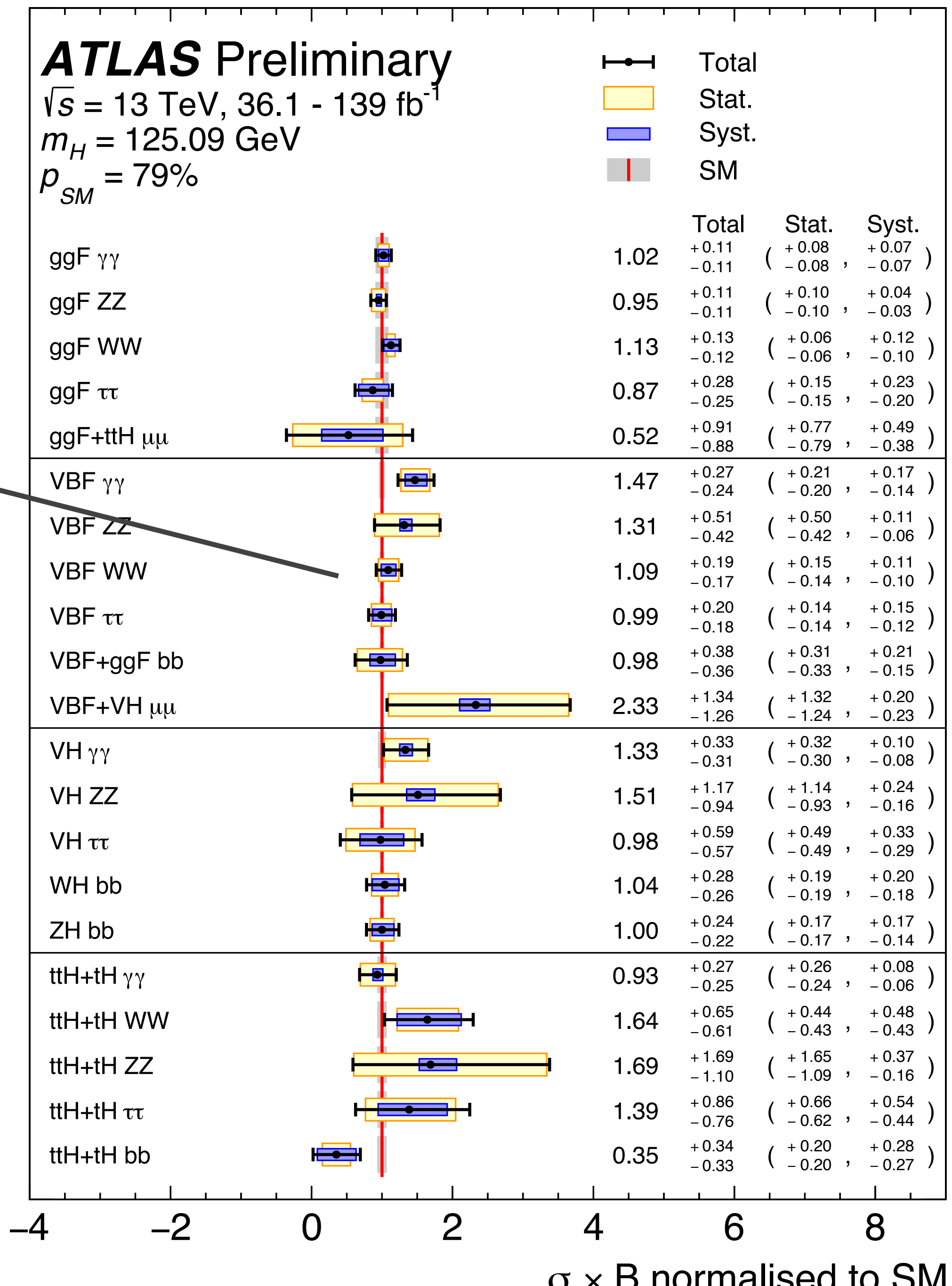
HL-LHC could reveal %-level coupling deviations



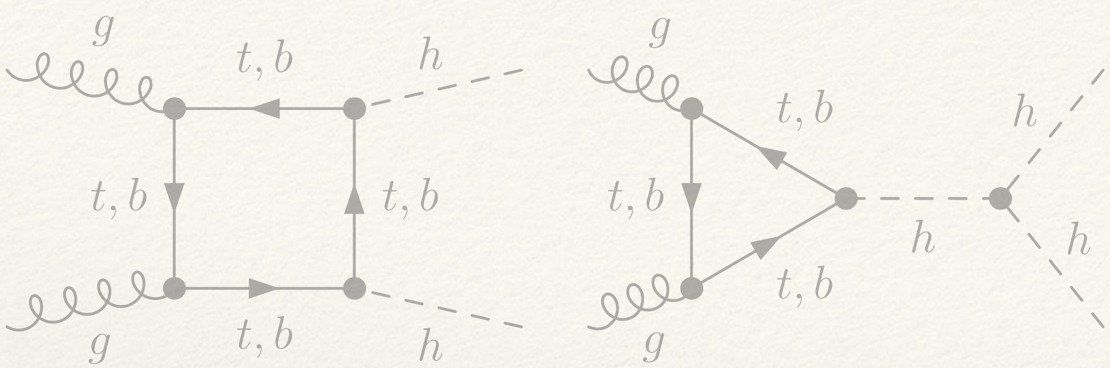




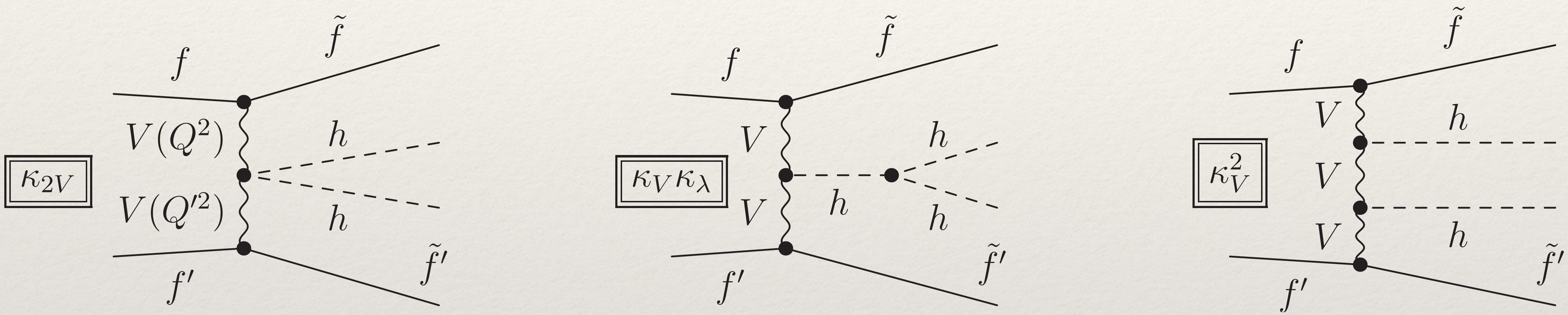
??



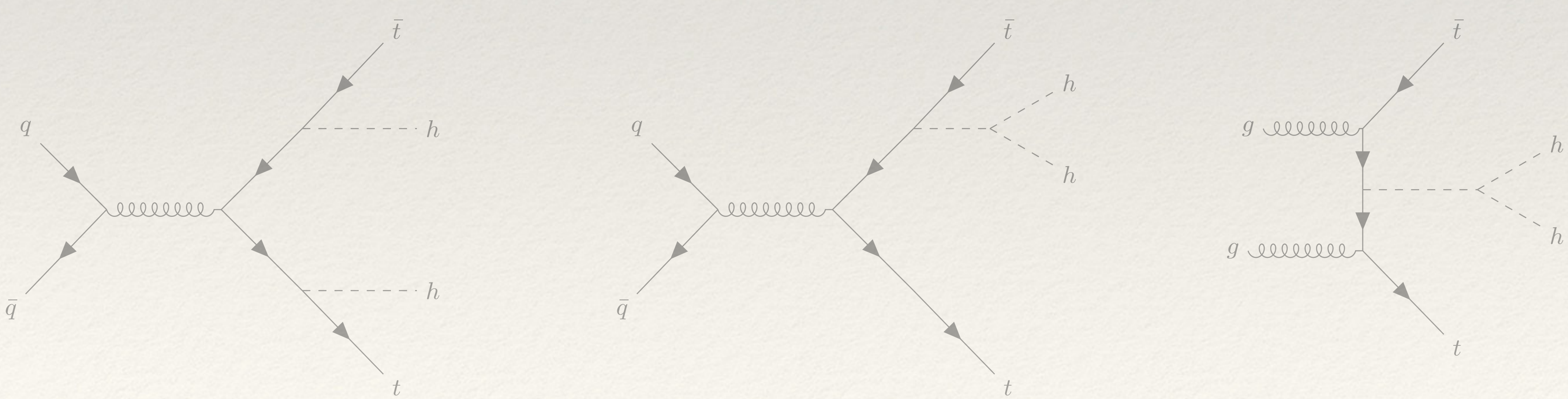
e.g. [ATLAS `21]



GF Higgs pair production ~30 fb

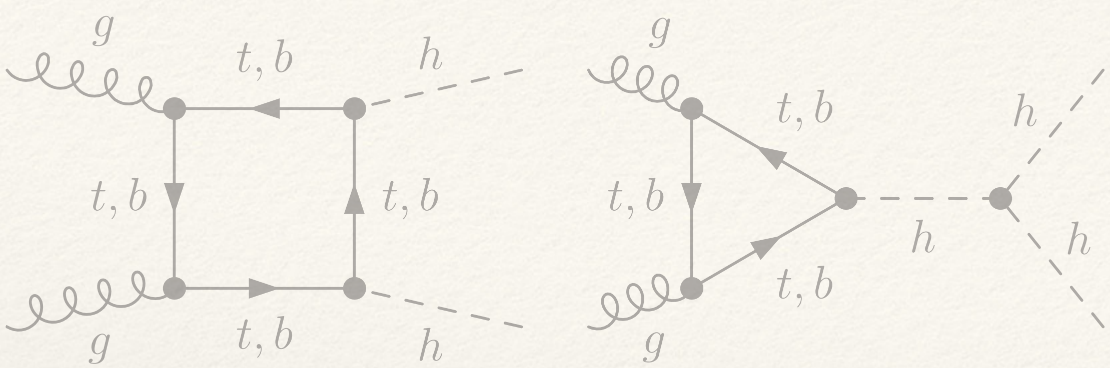


WBF Higgs pair production ~1 fb

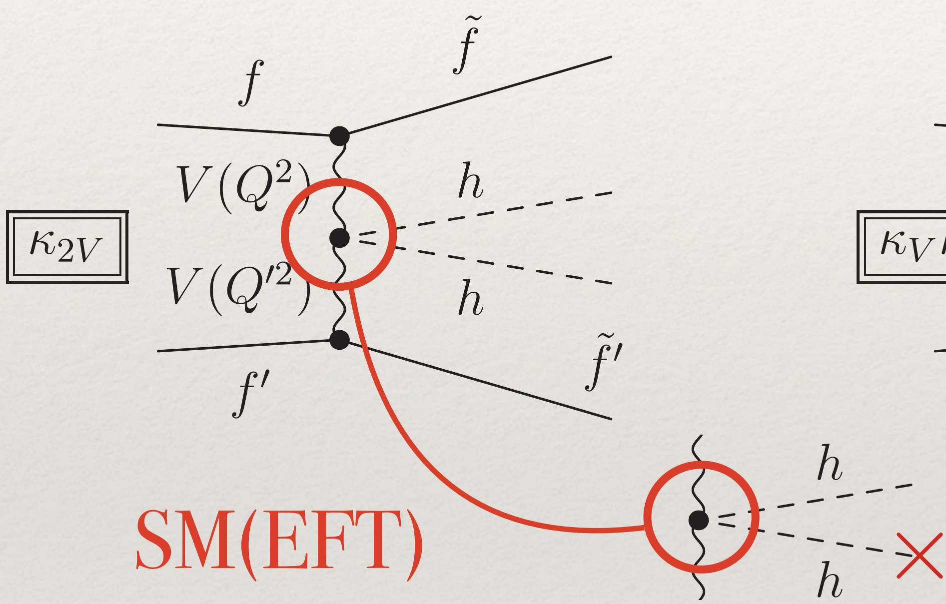


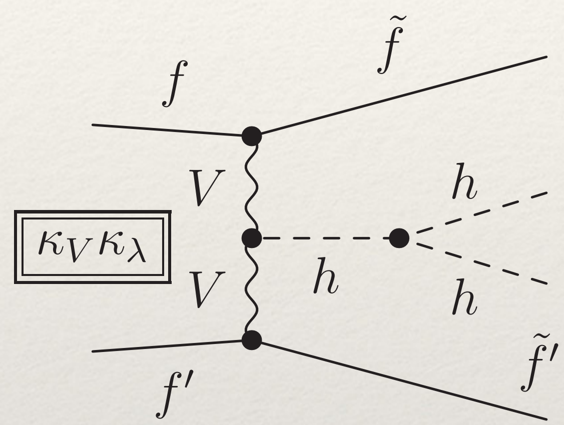
top-associated Higgs pair production ≲1 fb

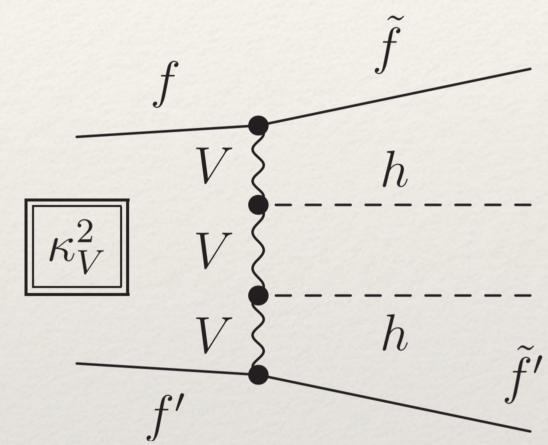
collider probes



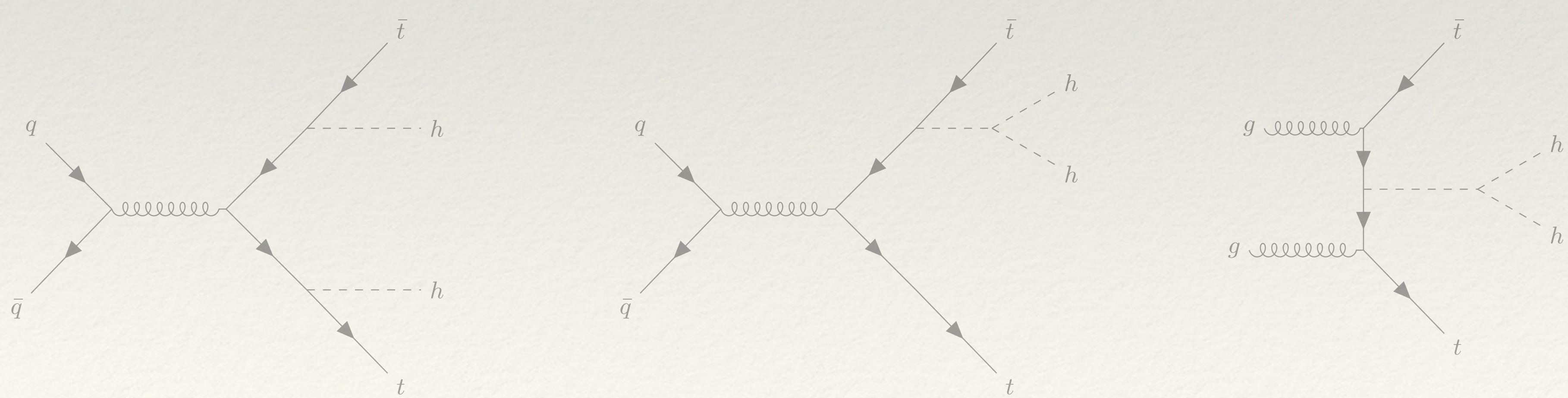
GF Higgs pair production ~30 fb





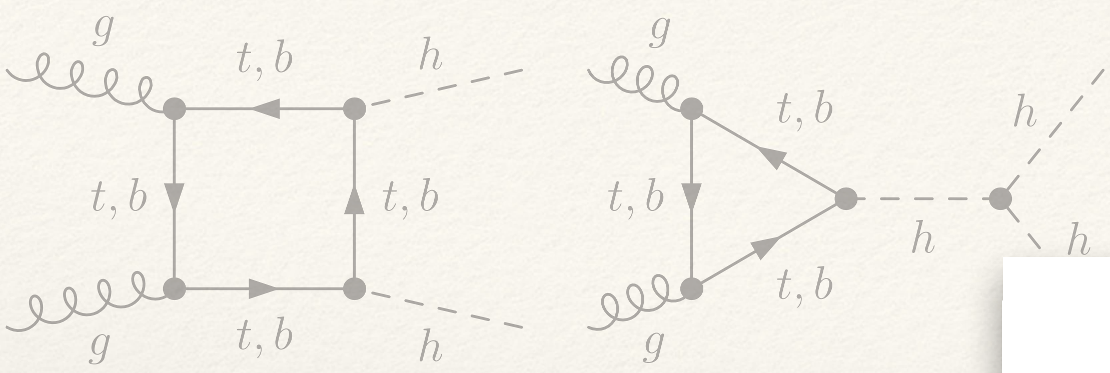


WBF Higgs pair production ~1 fb

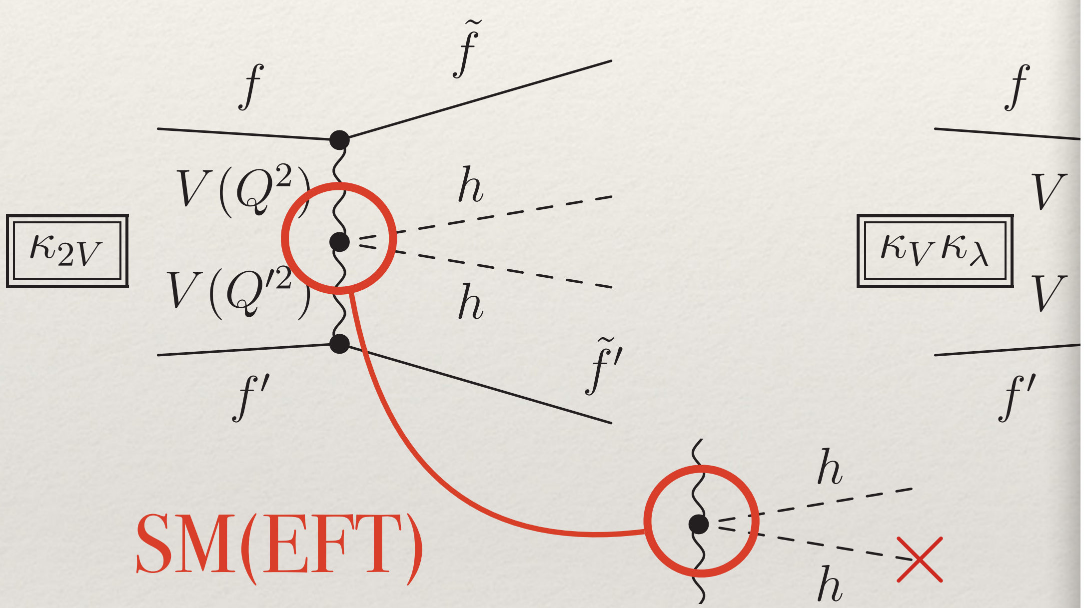


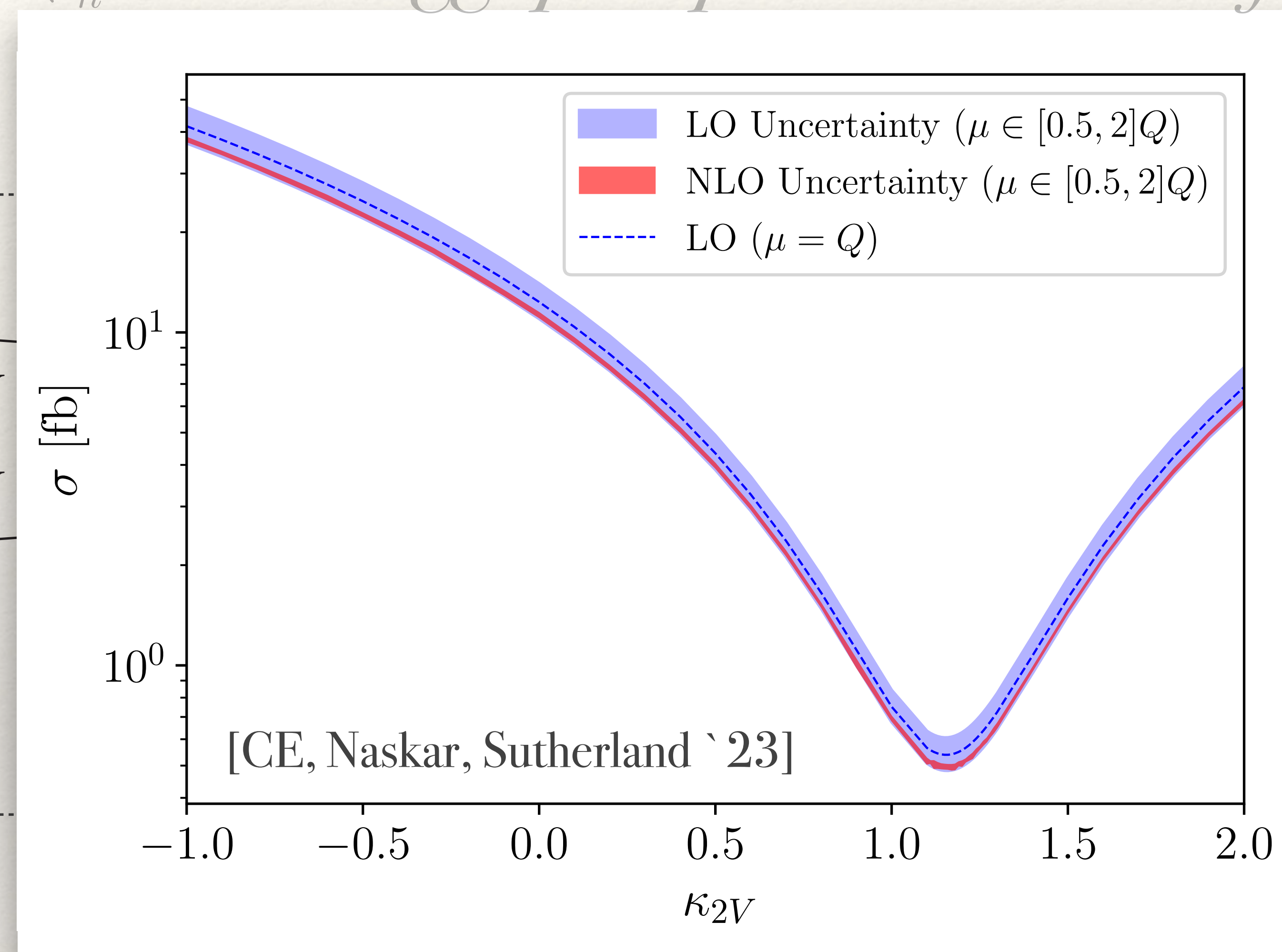
top-associated Higgs pair production ≲1 fb

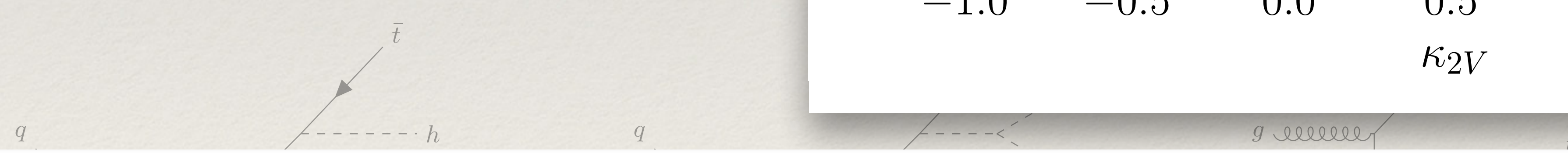
collider probes



GF Higgs pair production ~30 fb







$$\kappa_\lambda \in [-3.5, 11.3]\,, \qquad \kappa_{2V} \in [0.0, 2.1]$$

e.g. [ATLAS + CE `23]

What do these mean if SM(EFT) can't accommodate them?

gauge-Higgs quartics are dangerous…

SMEFT

singlet mixing

$\kappa_V = \cos\alpha$

$\kappa_{2V} = \cos^2\alpha$

$$H_1 = \cos\chi\, H_s + \sin\chi\, H_h$$
$$H_2 = -\sin\chi\, H_s + \cos\chi\, H_h$$

- high scale unitarity requirements

$$\frac{m_W^2}{s}\mathcal{A}(W_L h \to W_L h) \sim \frac{m_W}{\sqrt{s}}\mathcal{A}(W_T h \to W_L h) \sim \kappa_{2V} - \kappa_V^2$$

SMEFT

- high scale unitarity requirements

singlet mixing

$$\kappa_V = \cos\alpha$$
$$\kappa_{2V} = \cos^2\alpha$$

$$H_1 = \cos\chi\, H_s + \sin\chi\, H_h$$
$$H_2 = -\sin\chi\, H_s + \cos\chi\, H_h$$

$$\frac{m_W^2}{s}\mathcal{A}(W_L h \to W_L h) \sim \frac{m_W}{\sqrt{s}}\mathcal{A}(W_T h \to W_L h) \sim \kappa_{2V} - \kappa_V^2$$

"Physics must not depend on coordinate choices"

linked to sectional curvature of EWSB manifold

[Alonso et al. `16]

[Alonso, CE, Naskar, Rahaman et al. `25]

- Goldstone-equivalence: relation probes scalar EWSB manifold

SMEFT

- high scale unitarity requirements

singlet mixing

$$\kappa_V = \cos\alpha$$
$$\kappa_{2V} = \cos^2\alpha$$

$$H_1 = \cos\chi\, H_s + \sin\chi\, H_h$$
$$H_2 = -\sin\chi\, H_s + \cos\chi\, H_h$$

$$\frac{m_W^2}{s}\mathcal{A}(W_L h \to W_L h) \sim \frac{m_W}{\sqrt{s}}\mathcal{A}(W_T h \to W_L h) \sim \kappa_{2V} - \kappa_V^2$$

"Physics must not depend on coordinate choices"

linked to sectional curvature of EWSB manifold

[Alonso et al. `16]

[Alonso, CE, Naskar, Rahaman et al. `25]

- Goldstone-equivalence: relation probes scalar EWSB manifold

compact groups

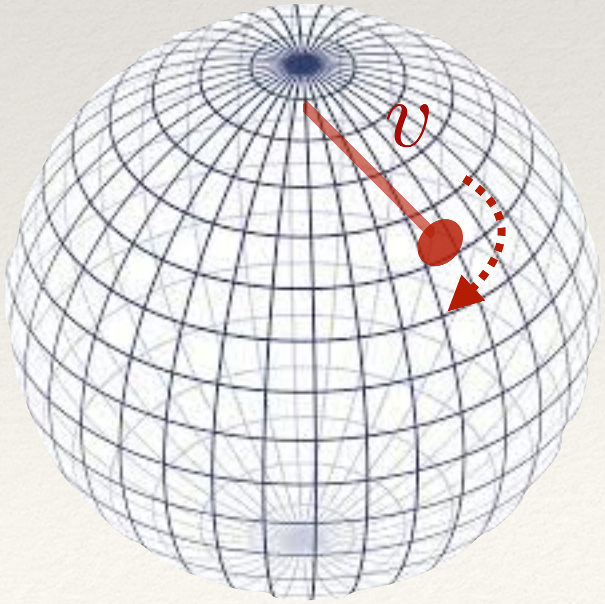
$$1 - \kappa_V^2 \geq 0\,,$$
$$\kappa_V^2 - \kappa_{2V} \geq 0\,.$$

[Alonso et al. `16]

MCHM

SO(5)/SO(4) ~ S^4

$$\kappa_V = \sqrt{1-\xi}\,,$$
$$\kappa_{2V} = 1 - 2\xi\,,$$



Scattering = Curvature

SMEFT

- high scale unitarity requirements

singlet mixing

$$\kappa_V = \cos\alpha$$
$$\kappa_{2V} = \cos^2\alpha$$

$$H_1 = \cos\chi\, H_s + \sin\chi\, H_h$$
$$H_2 = -\sin\chi\, H_s + \cos\chi\, H_h$$

$$\frac{m_W^2}{s}\mathcal{A}(W_L h \to W_L h) \sim \frac{m_W}{\sqrt{s}}\mathcal{A}(W_T h \to W_L h) \sim \kappa_{2V} - \kappa_V^2$$

"Physics must not depend on coordinate choices"

linked t… EWSB manifold

single Higgs is not enough to resolve*

$\cos 2\alpha \neq \cos\alpha$

[Alonso et al. `16]

…, CE, Naskar, Rahaman et al. `25]

- Goldstone-equivalence: relation pro… scalar EWSB manifold

compact groups

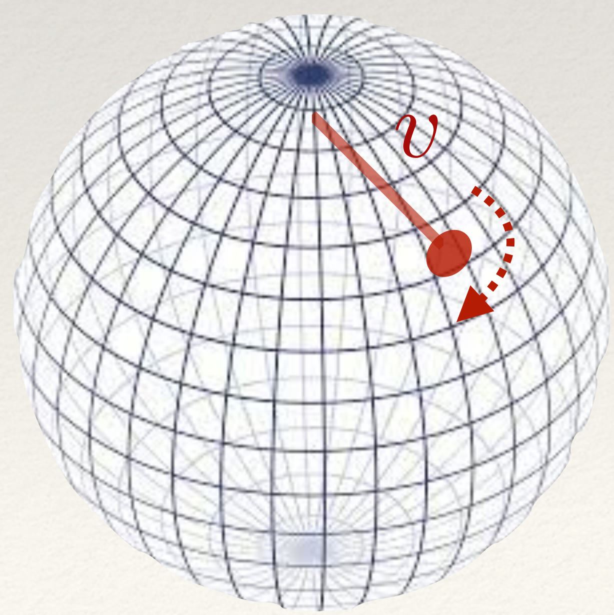
$$1 - \kappa_V^2 \geq 0\,,$$
$$\kappa_V^2 - \kappa_{2V} \geq 0\,.$$

[Alonso et al. `16]

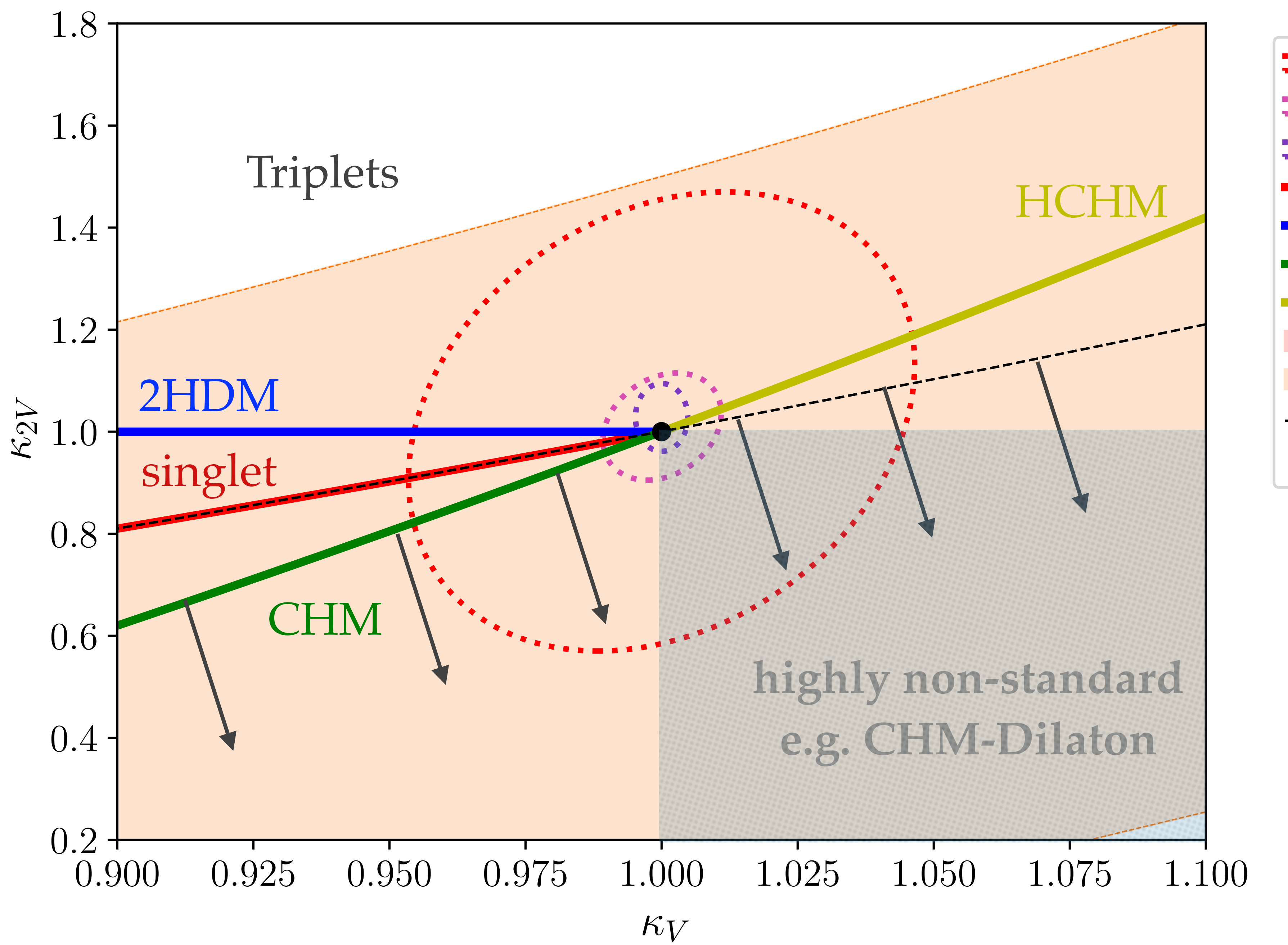
MCHM

SO(5)/SO(4) ~ S^4

$$\kappa_V = \sqrt{1-\xi}\,,$$
$$\kappa_{2V} = 1 - 2\xi\,,$$



charting phenomenological possibilities



[CE, Naskar, Sutherland `23]

- radiative correcitions possible using "HEFT"
    - *lots of interesting physics/technical advantages*
    - *indirect sensitivity at precision ee machines*

[Buchala et al. `17]
[Herrero, Morales `21]
[Anisha et al. `22]
[Alminawi, Brivio, Davighi `23, `26]
…

Summary

- no new physics so far, but LHC has a lot of headroom for sensitivity
- clear BSM opportunities for HL-LHC and beyond FCC-ee/muCol/…
- holistically-informed & directed effort for discovery-led physics

  model-(in)dependent techniqes, ML, ….
- only limited insights into the electroweak scale (& flavour!) so far
  - …we could be in for a surprise!
  - direct relevance for other phenomenological arenas

BSM momentum dependencies…

(non-)perturbative electroweak symmetry breaking

relation with electroweak baryogenesis, cosmology…