

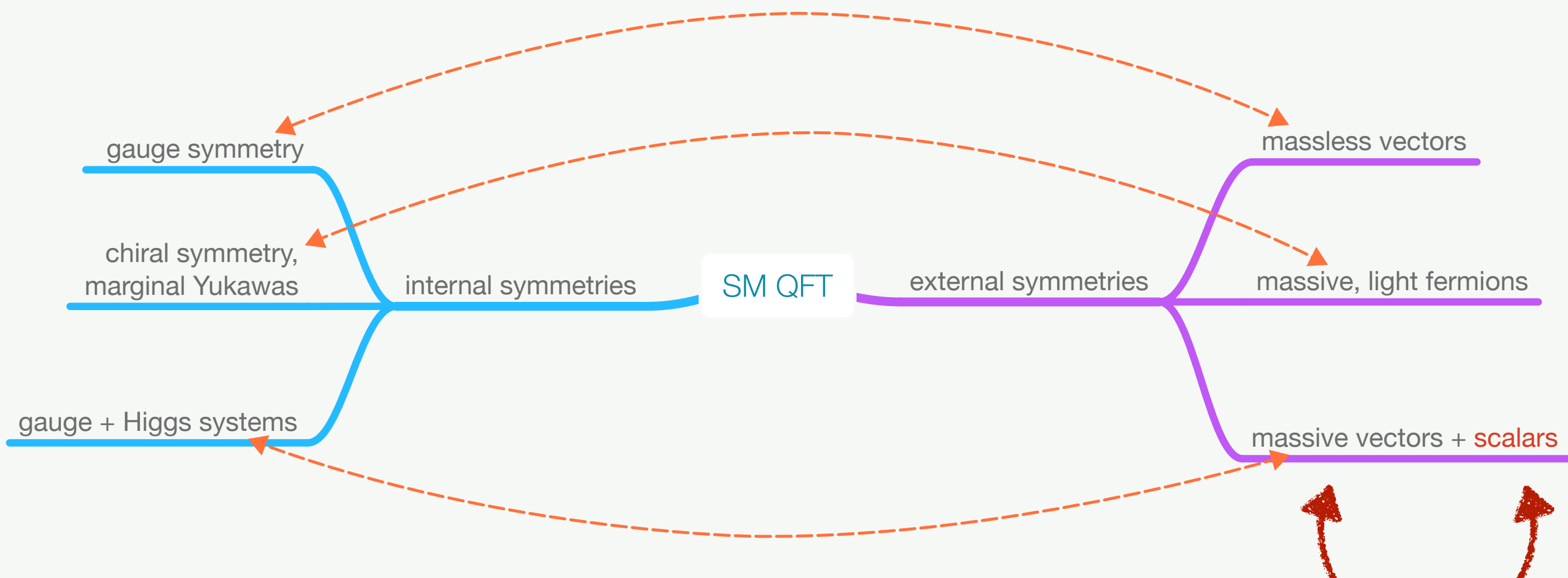
Christoph Englert

Towards BSM with weak scale physics

Warwick

05/02/26

What is the nature of the TeV scale?

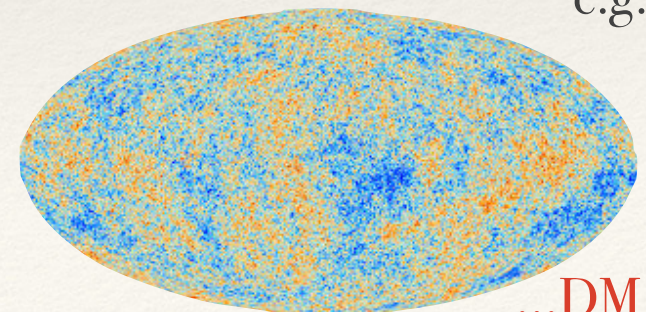


The SM is extremely restrictive - by accident....

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

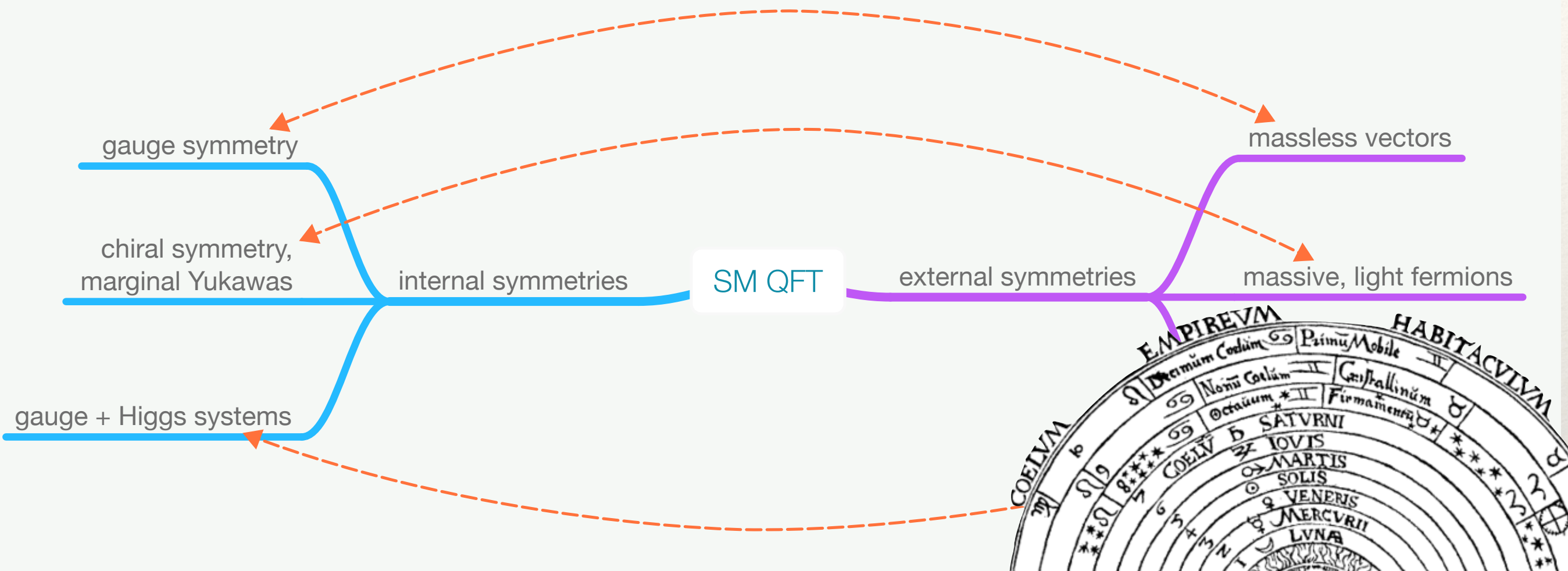
e.g. [Sakharov '67]

+



...DM, inflation...

What is the nature of the TeV scale?



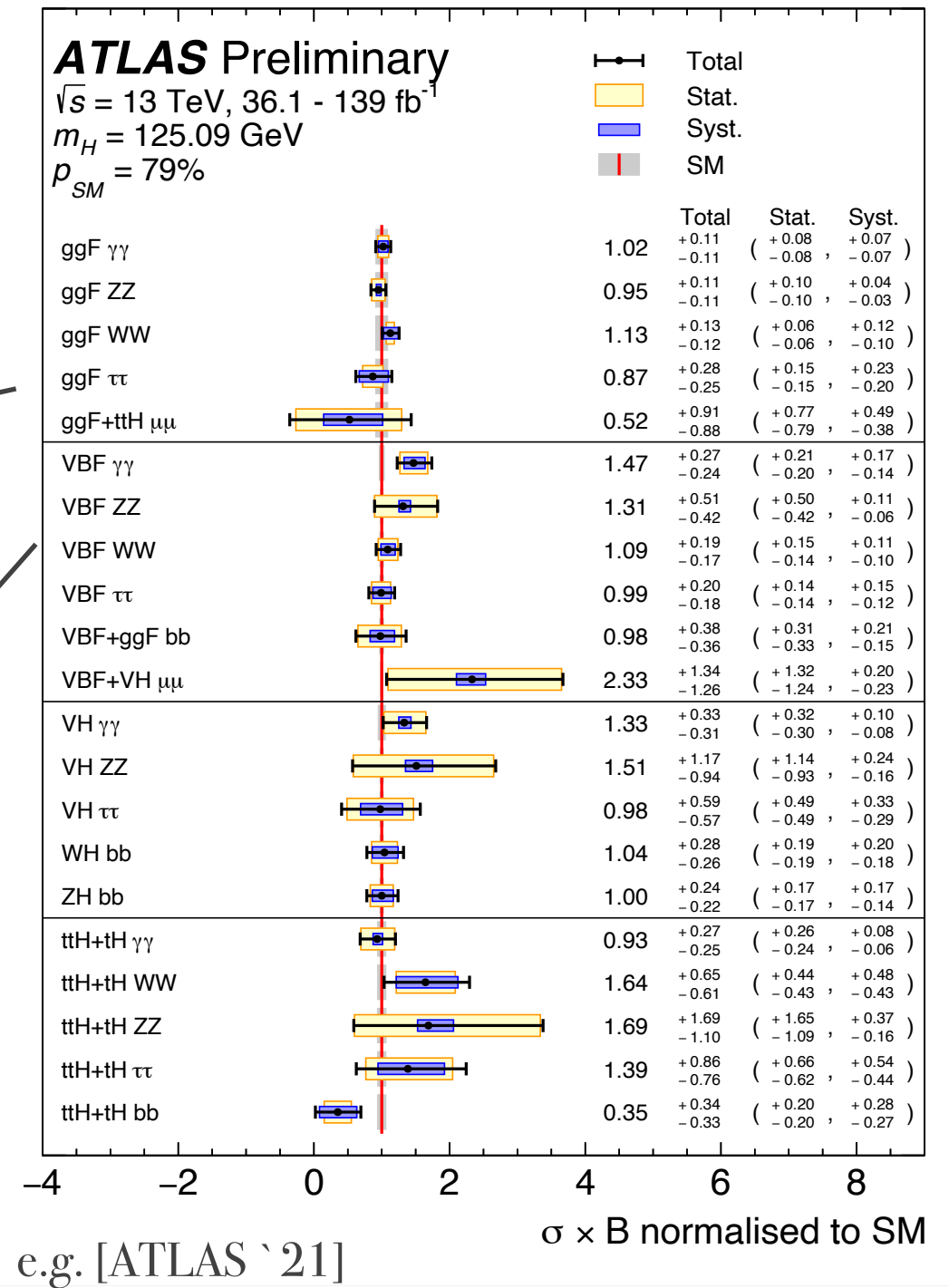
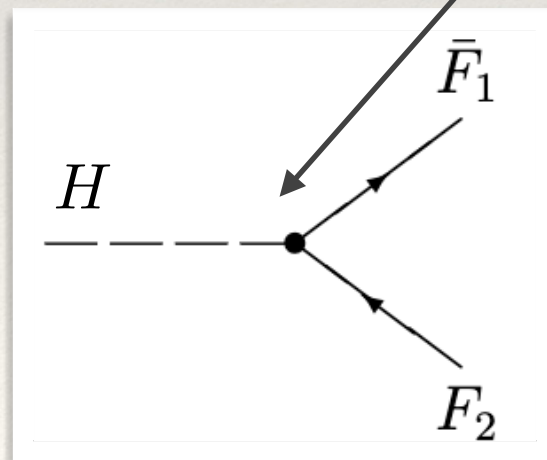
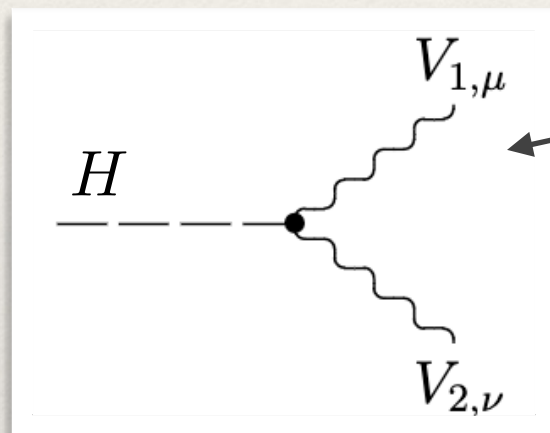
The SM is extremely restrictive

- ▶ baryon-number conservation, CP, custodial isospin
- ▶ fine tuning: strong CP, Higgs naturalness, ...
- ▶ SM correlations too restrictive for new physics ?



What is the nature of the TeV scale?

- somehow SM correlations are (un)expectedly accurate...

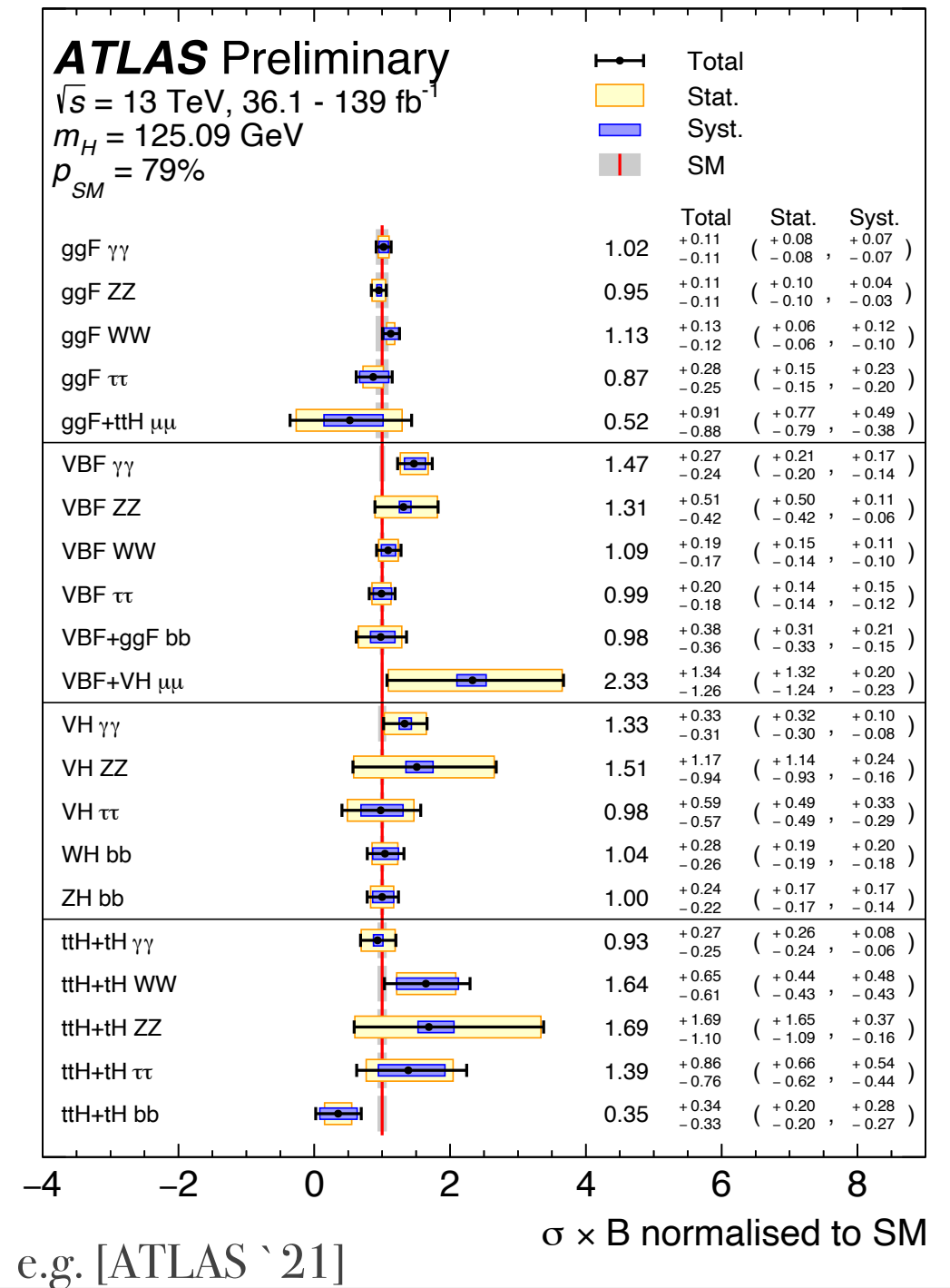


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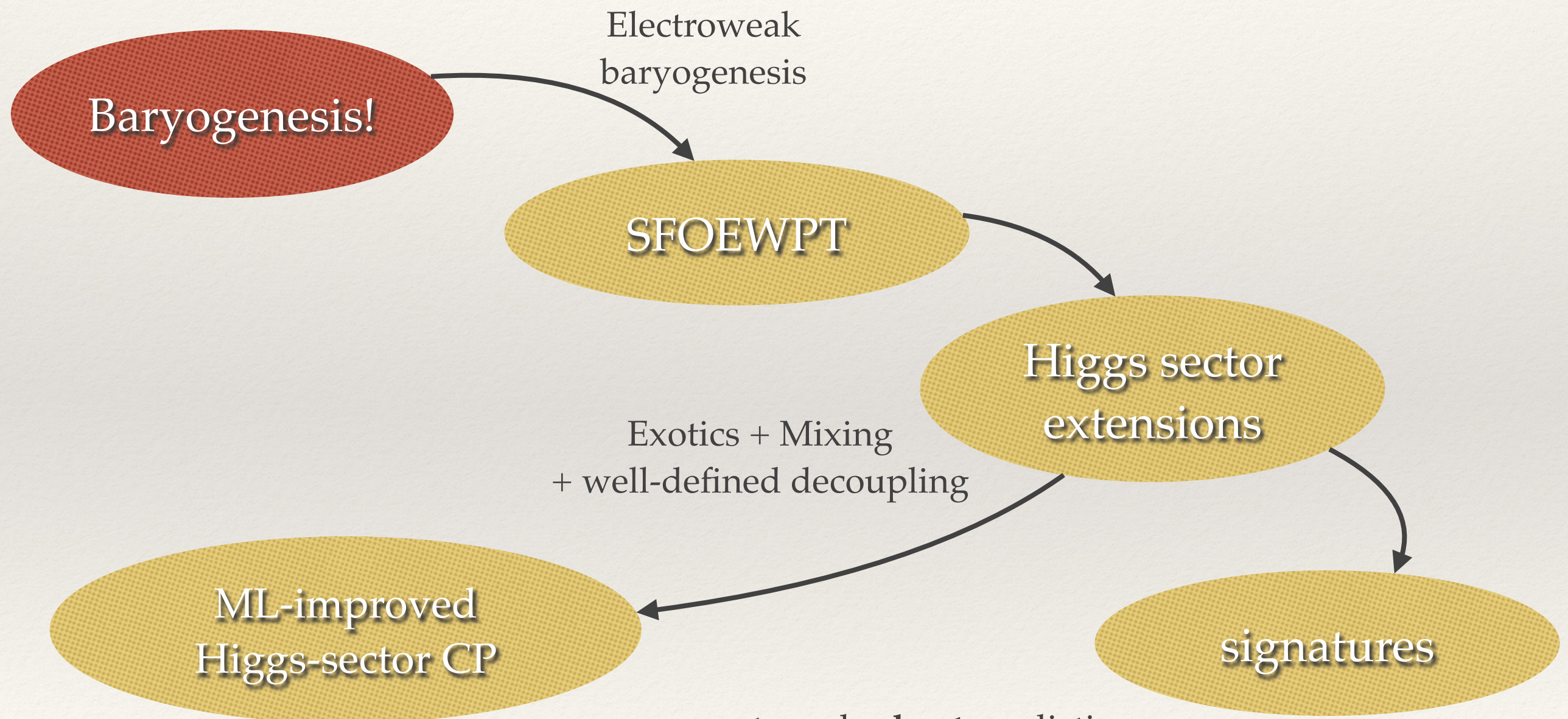
What are the possibilities?

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



Higgs coupling deviations @ HL-LHC?

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

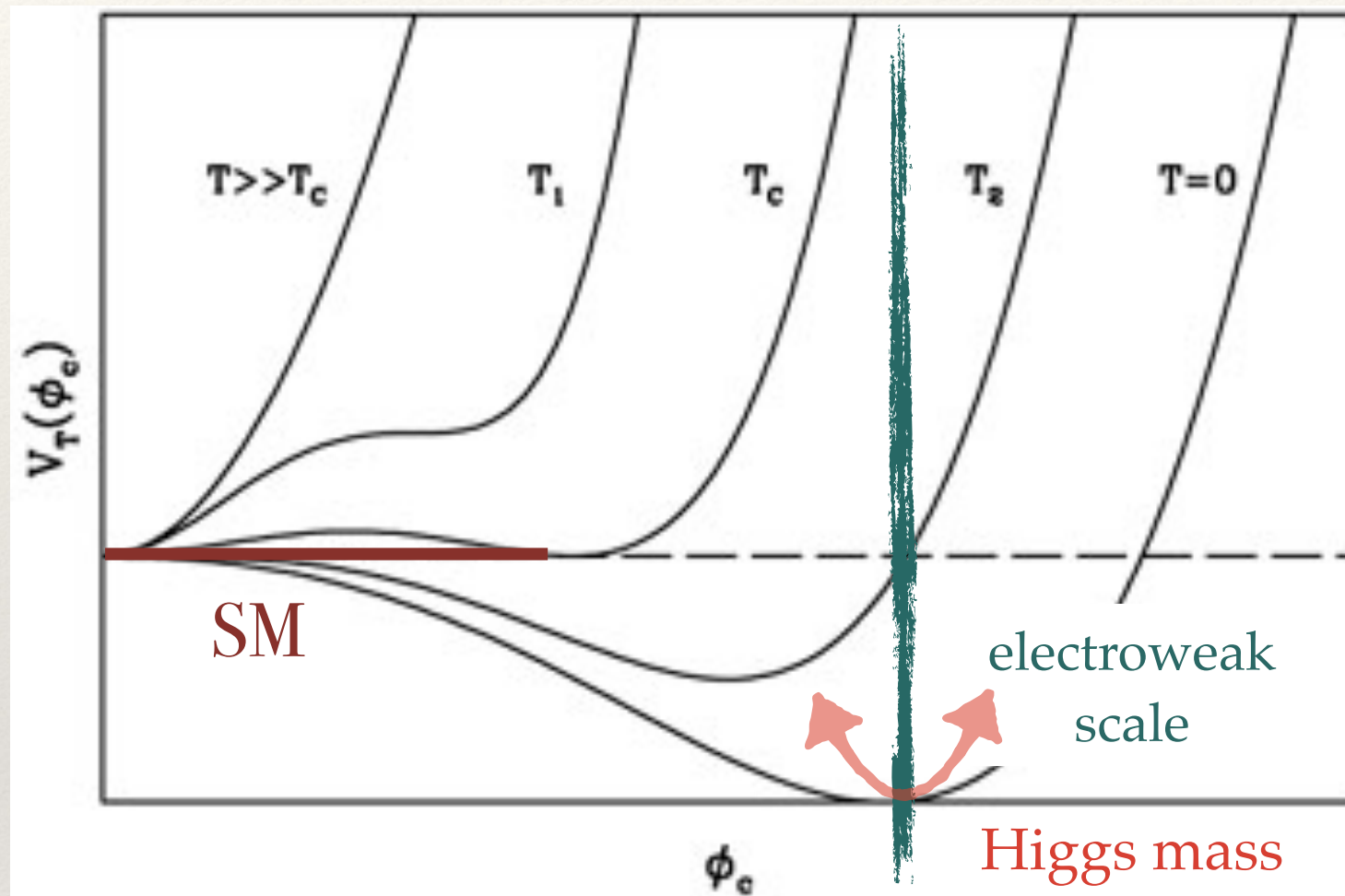


e.g. [Atwal, Burrridge, Costa, et al. '25]

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*

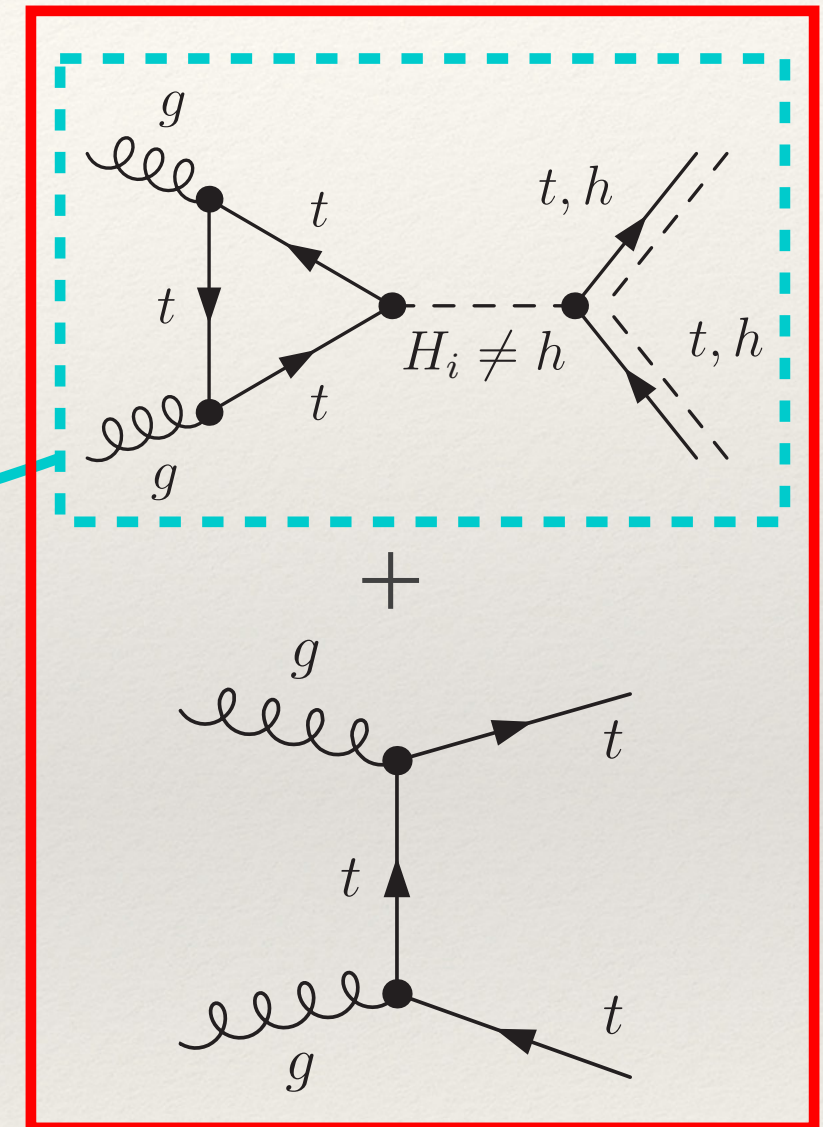
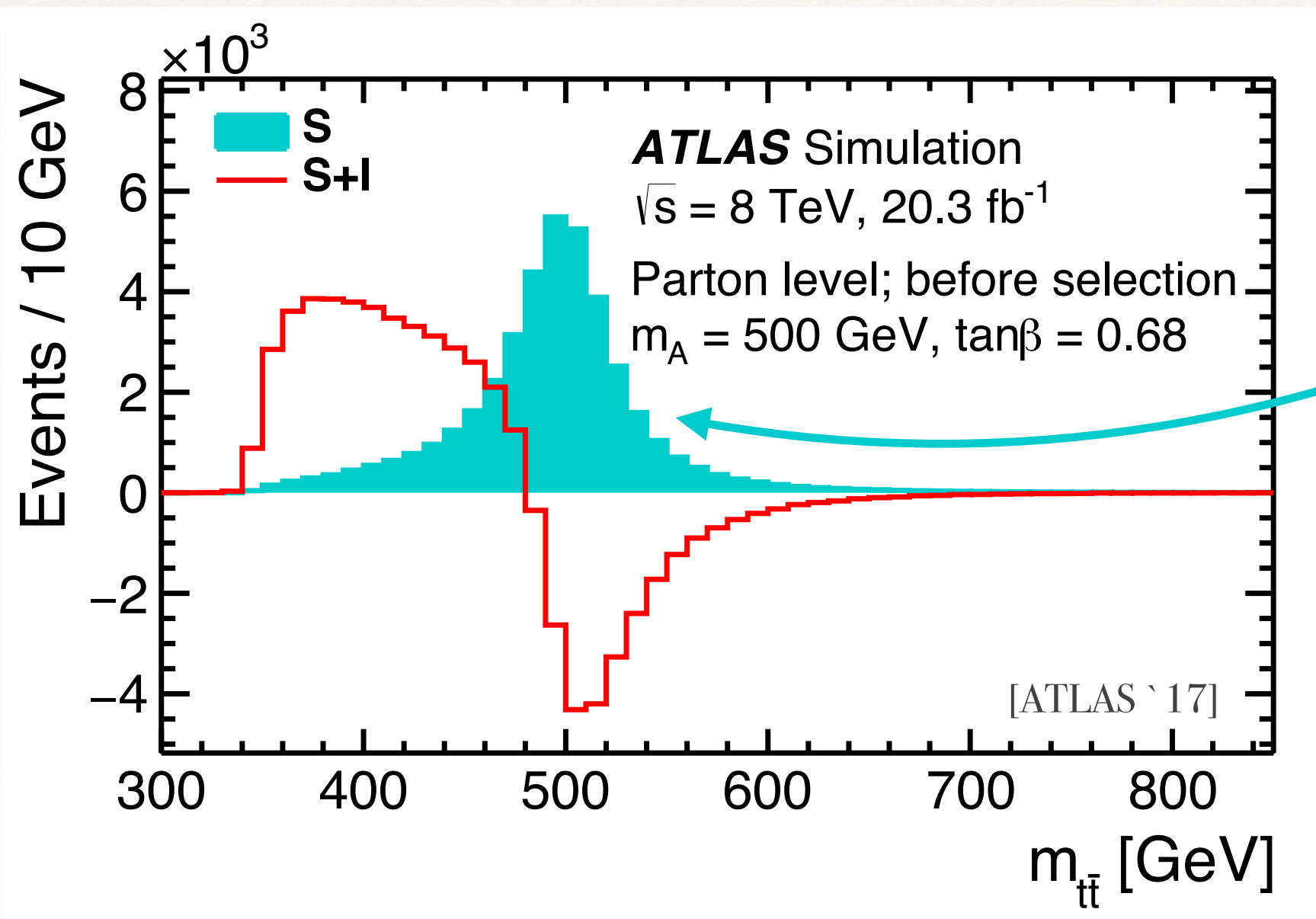
caveat: non-perturbative BSM effects
[Biermann, Chakraborty, CE, in prep.]

Upshot: New states need to be light.

Where are these exotic states?

- large interference effects of Higgs “signal” with QCD background

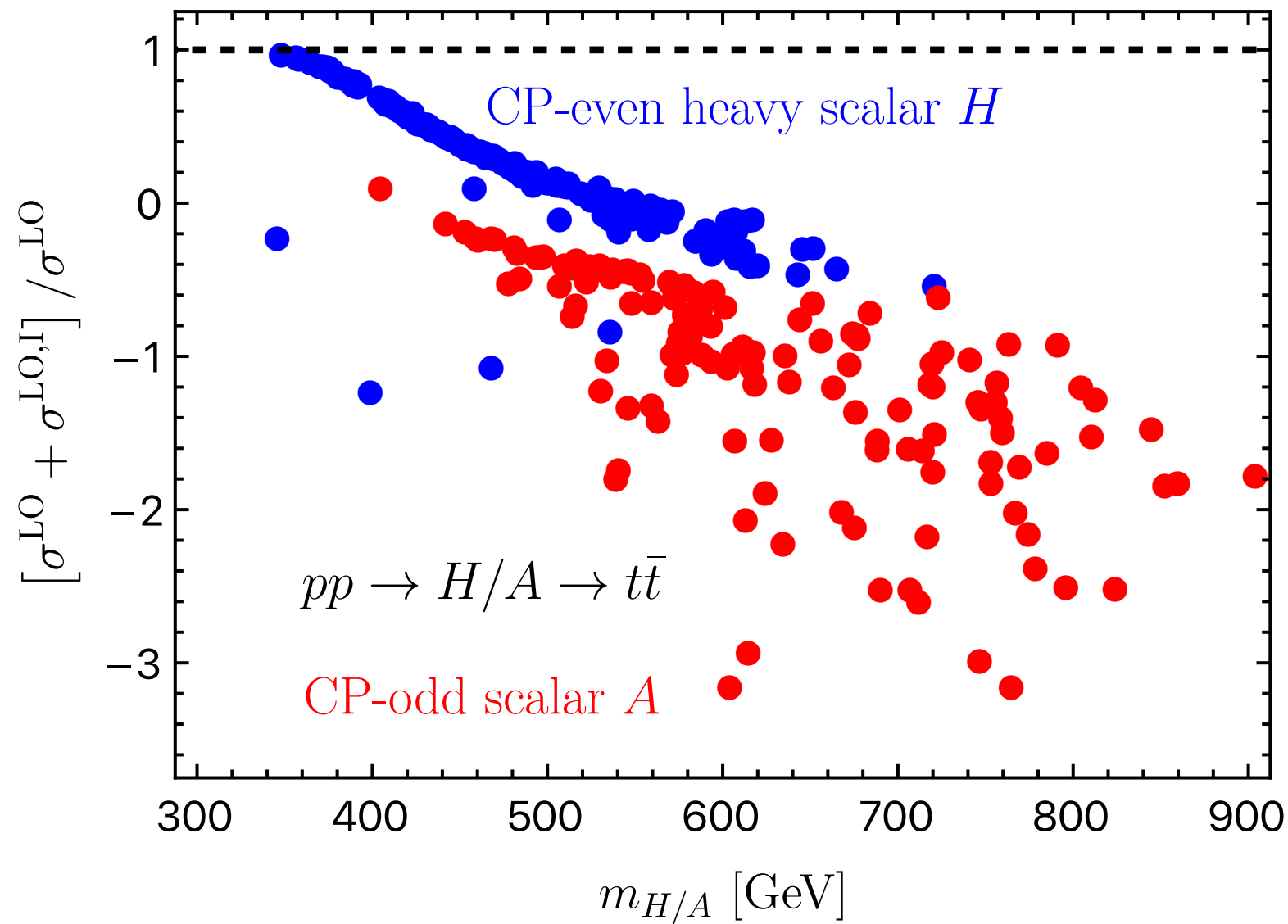
[Gaemers, Hoogeveen '84]



- 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]



	Channel	Experiment	SM	Pull
R_K	$\bar{B}^0 \rightarrow D^+ K^-$	$0.058^{+0.004}_{-0.004}$	$0.082^{+0.002}_{-0.001}$	$\approx 5.6 \sigma$
$R_{s\pi}$	$\bar{B}_s \rightarrow D_s^+ \pi^-$	0.71 ± 0.06	$1.06^{+0.04}_{-0.03}$	$\approx 5 \sigma$
R_{K^*}	$\bar{B}^0 \rightarrow D^+ K^{*-}$	0.136 ± 0.023	$0.14^{+0.01}_{-0.01}$	$\approx 0.16 \sigma$
R_K^*	$\bar{B}^0 \rightarrow D^{*+} K^-$	0.064 ± 0.003	$0.076^{+0.002}_{-0.001}$	$\approx 3.6 \sigma$
$R_{s\pi}^*$	$\bar{B}_s \rightarrow D^{*+} \pi^-$	$0.52^{+0.18}_{-0.16}$	$1.05^{+0.04}_{-0.03}$	$\approx 3.1 \sigma$

dijet resonances

[Bordone, Greljo, Marzocca '21]

proto 2HDM for B^0 under pressure!

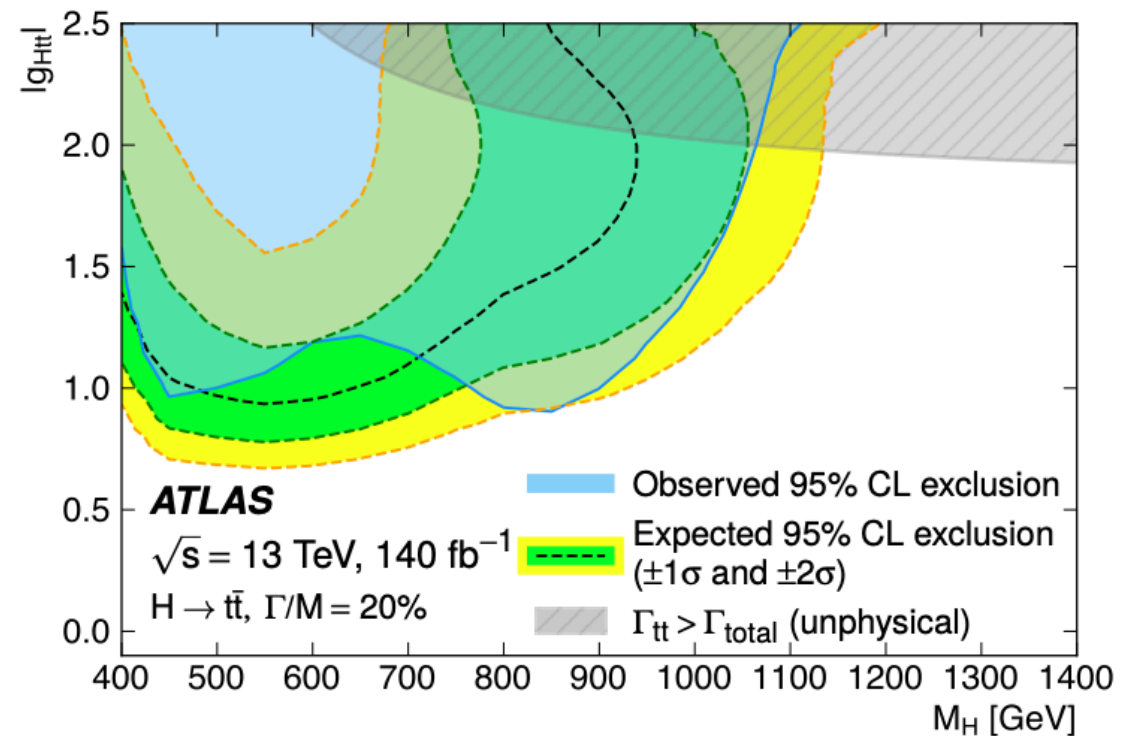
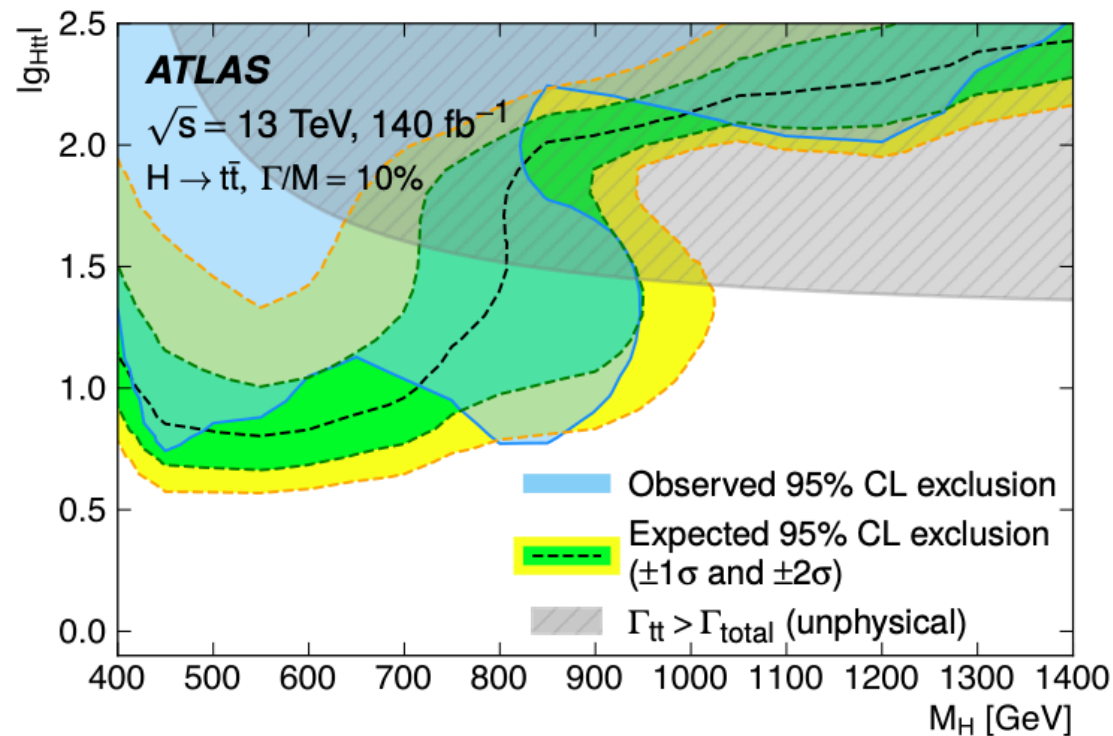
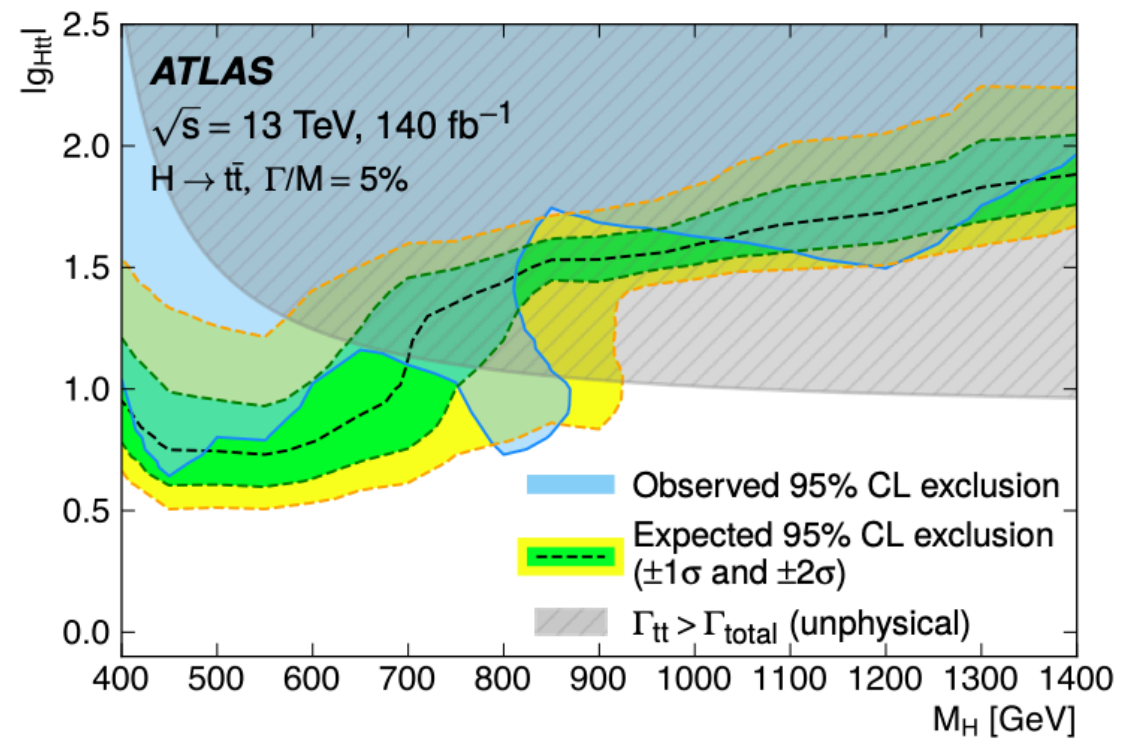
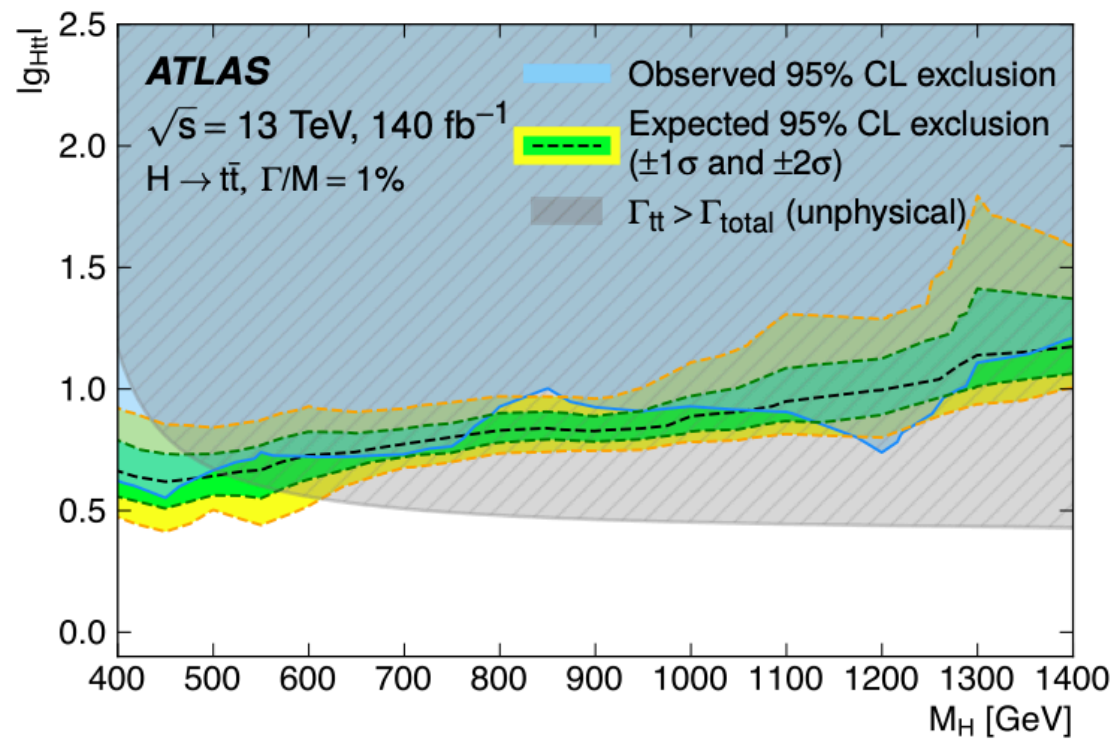
- large modifications of on-shell pheno - *there is a chance to miss this*

maybe not
e.g. QCD rules vs FQCD

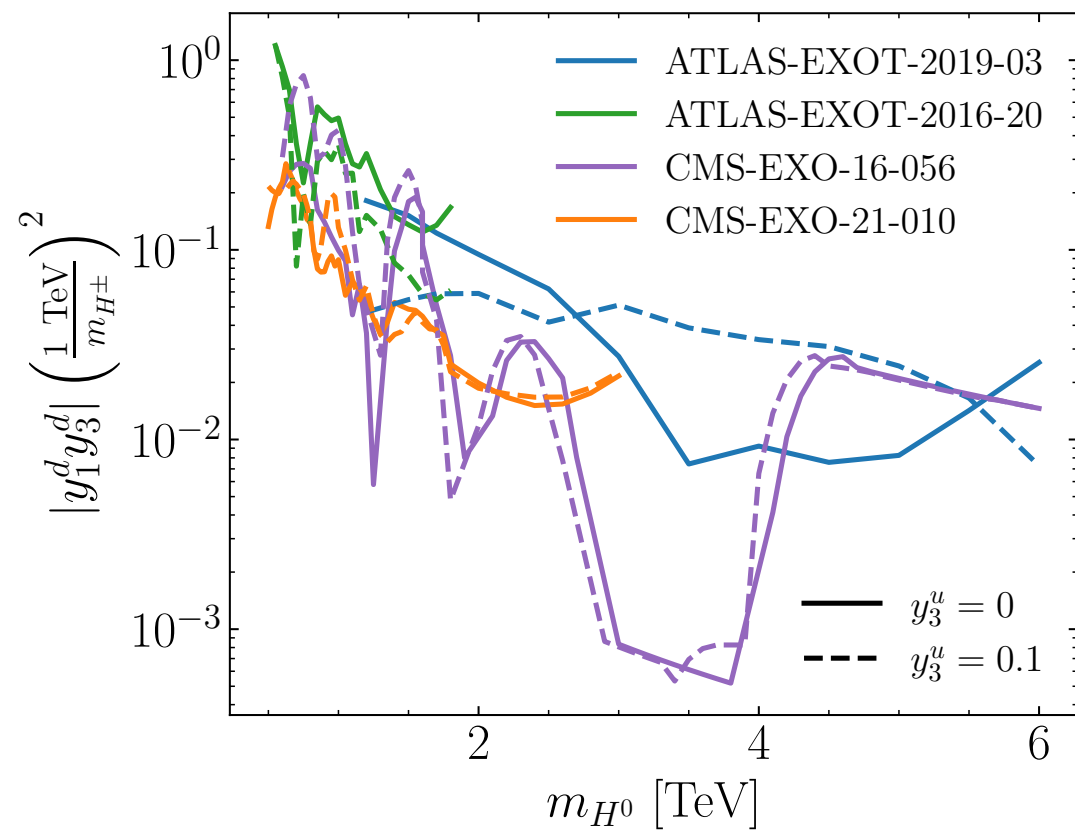
potential link with flavour anomalies?

perhaps (still) yes?
[Araz, CE, Kirk et al. in prep.]

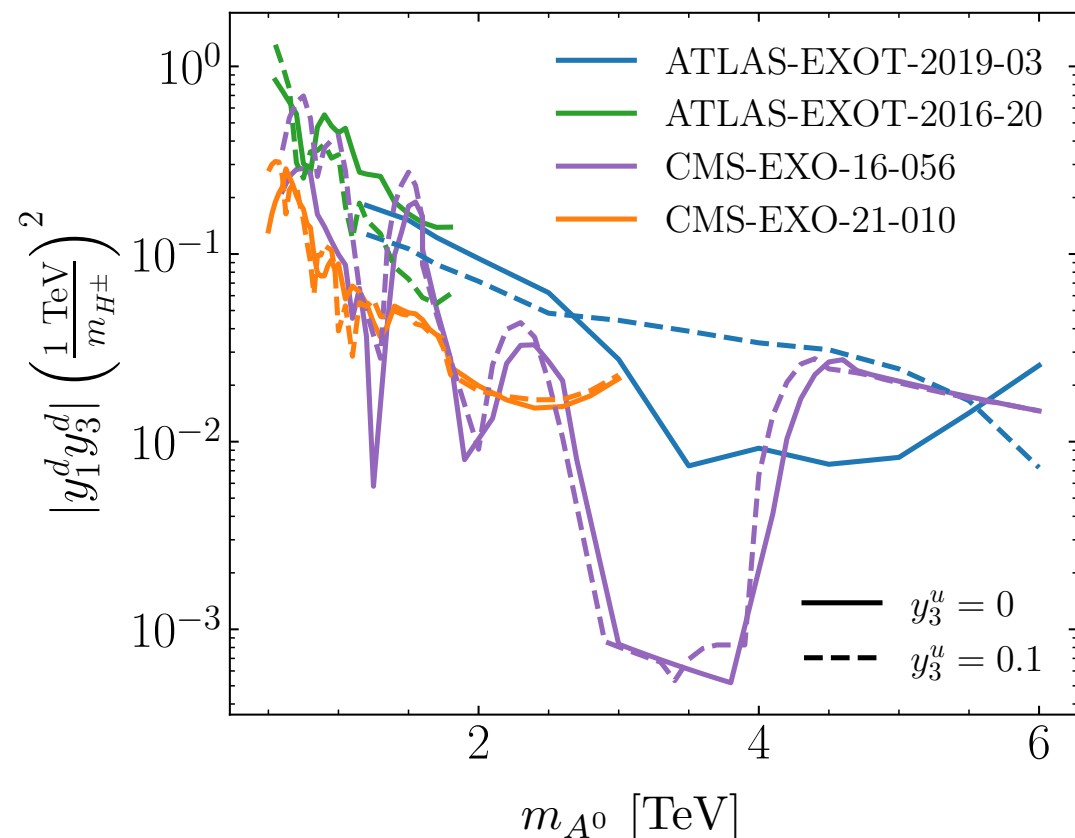
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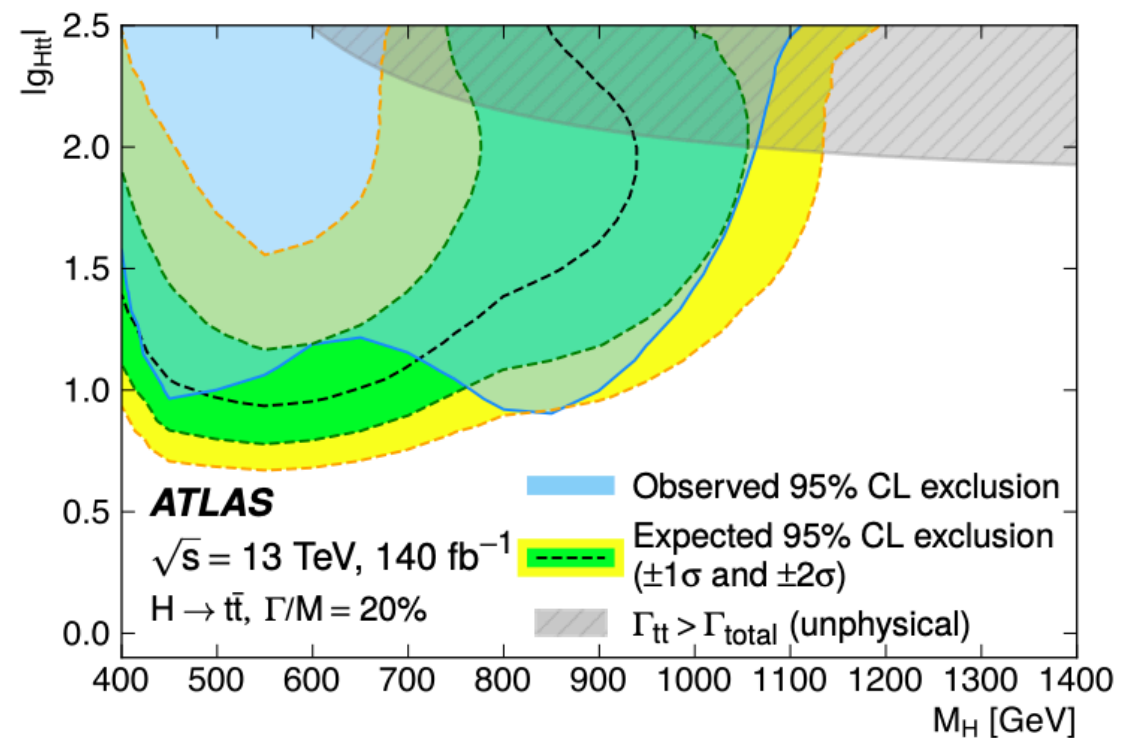
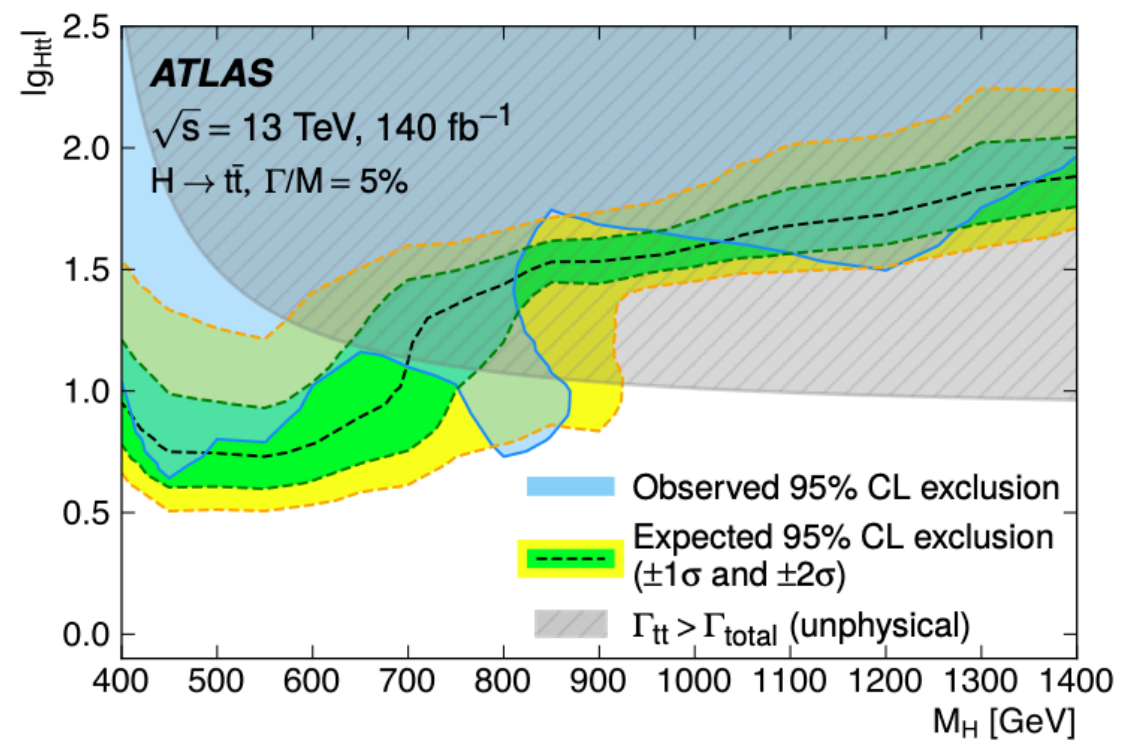
Where are these exotic states?



top-philic generalisation hidden in data!



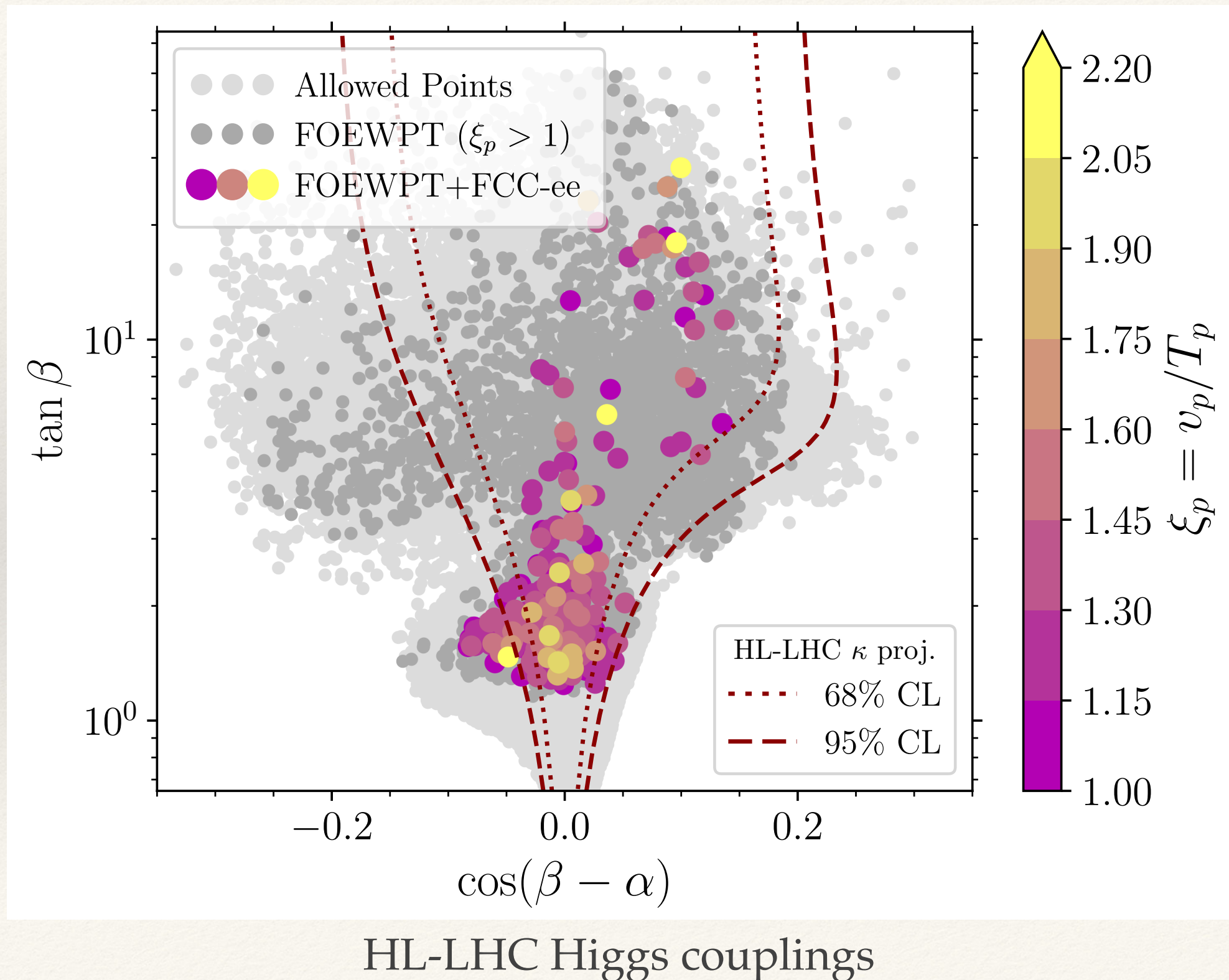
[Araz, CE, Kirk et al. in prep.]



back to 2HDM: Higgs signal strength sensitivity ?

- for instance 2HDM + current Higgs signal coupling fits

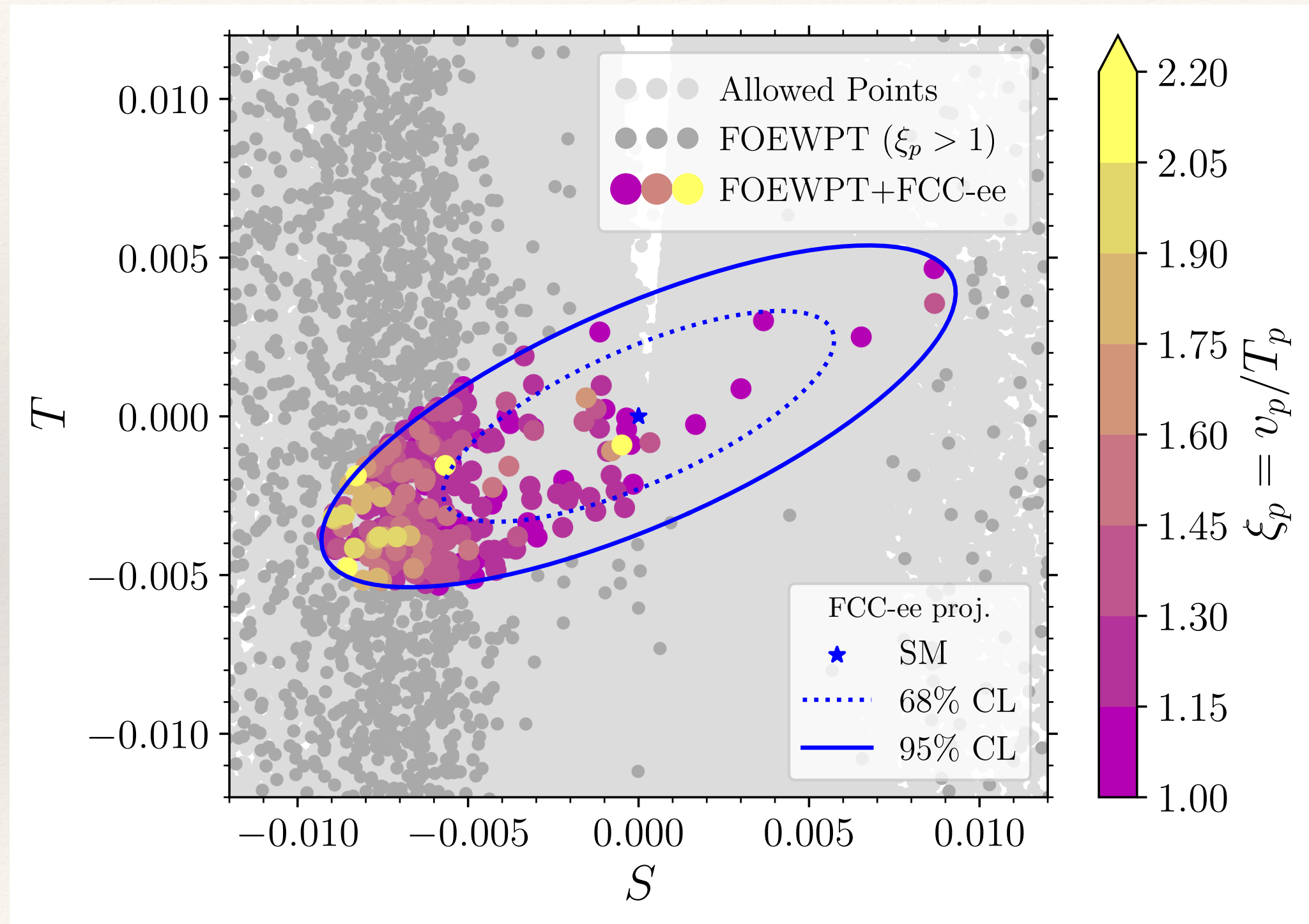
[Anisha et al. '25]



Higgs signal strength sensitivity ?

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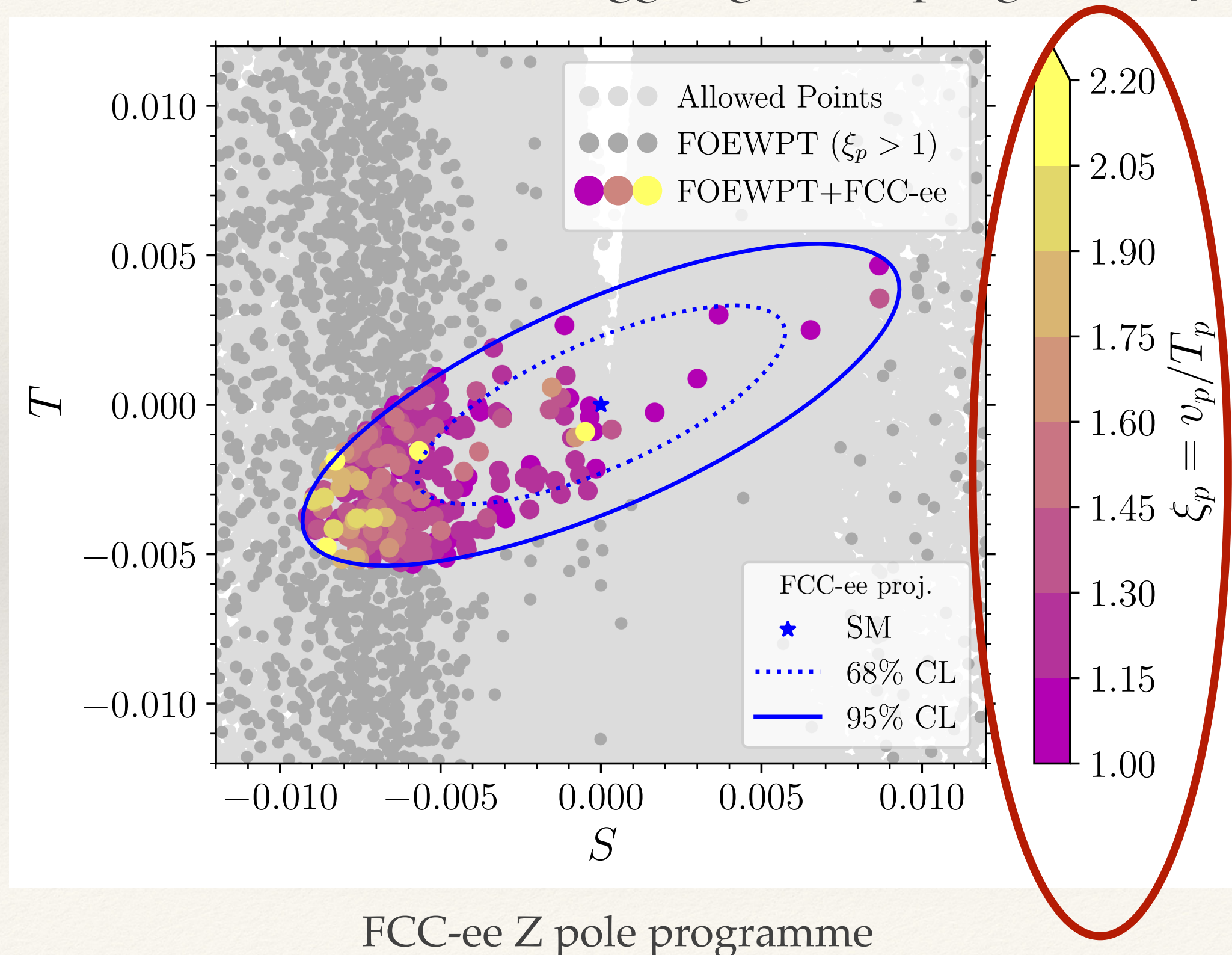


FCC-ee Z pole programme

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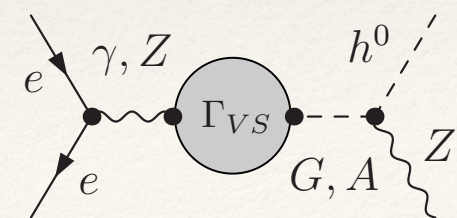
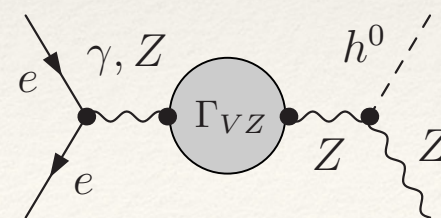
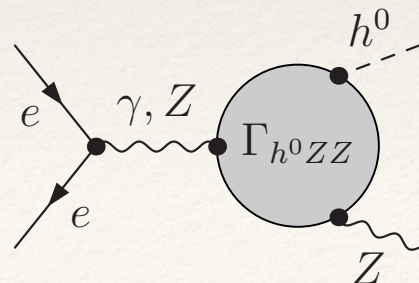
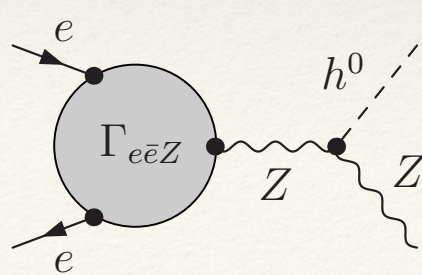
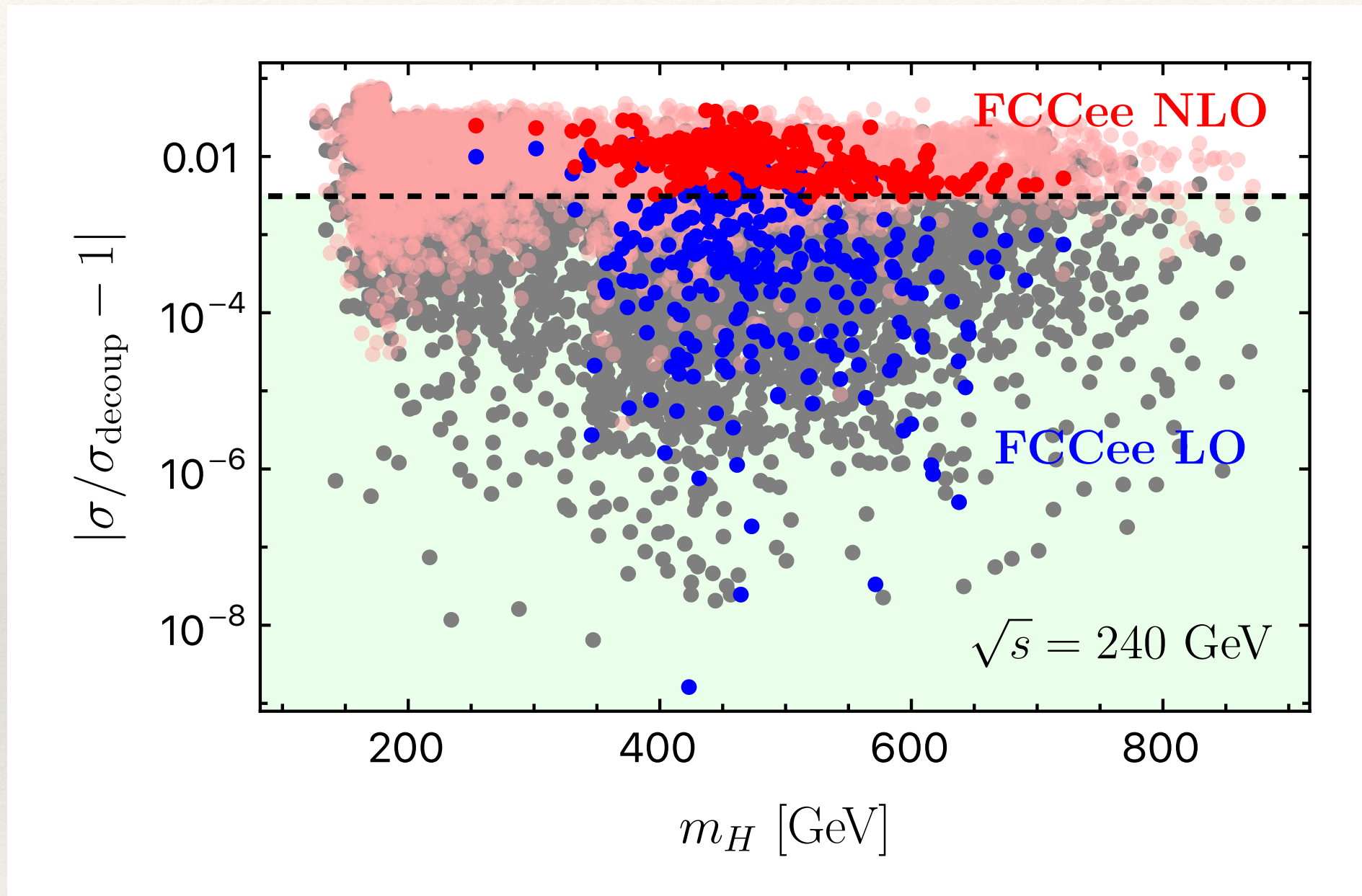
[Anisha et al. '25]



Higgs signal strength sensitivity ?

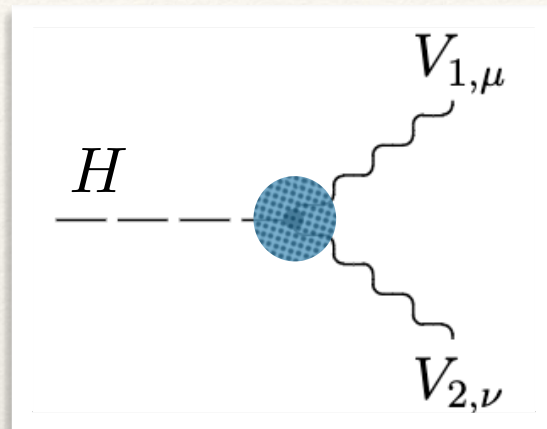
- but alignment without decoupling cannot hide forever !

[Anisha et al. '25]

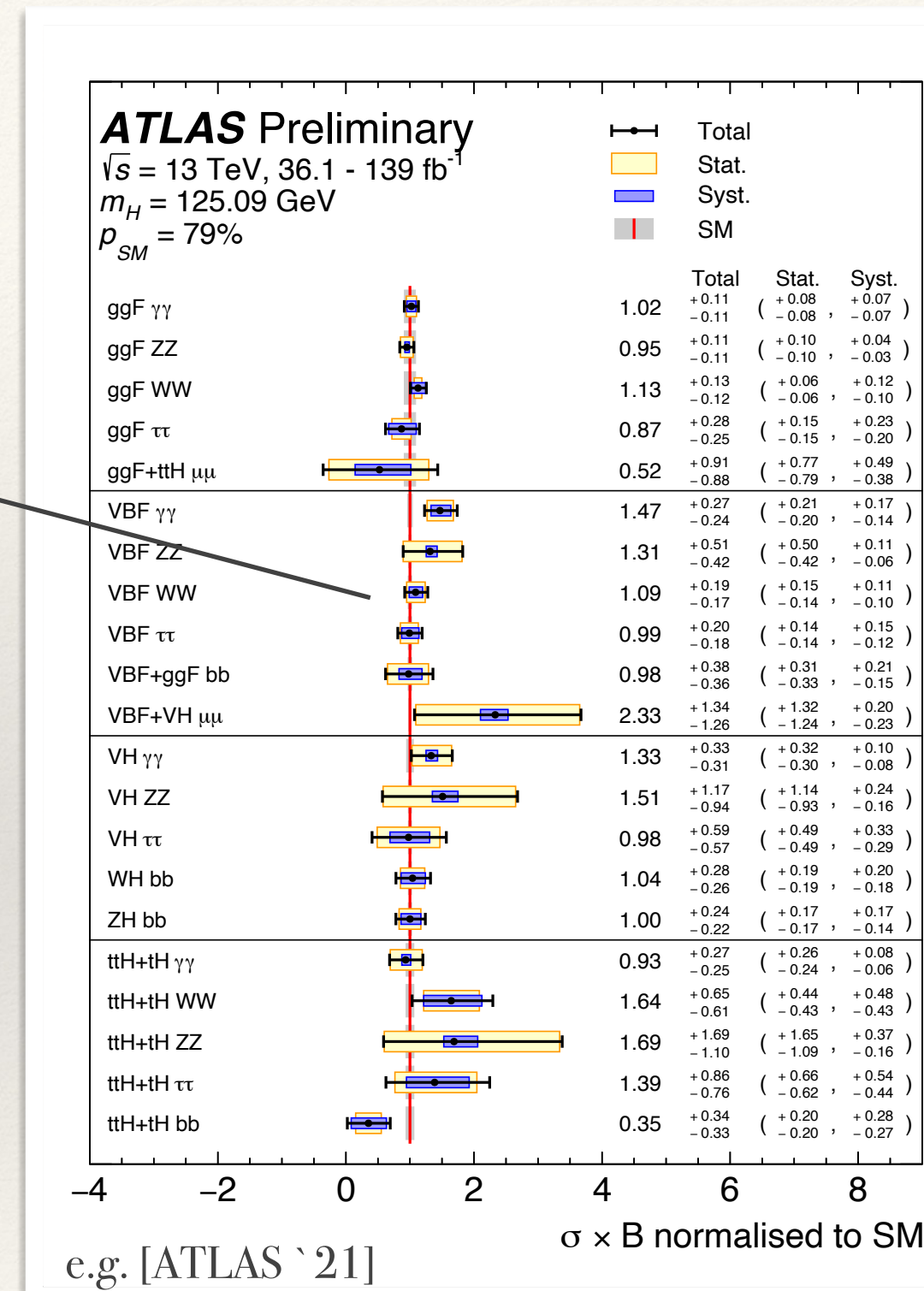


No reason to be so pessimistic....

HL-LHC could reveal %-level coupling deviations

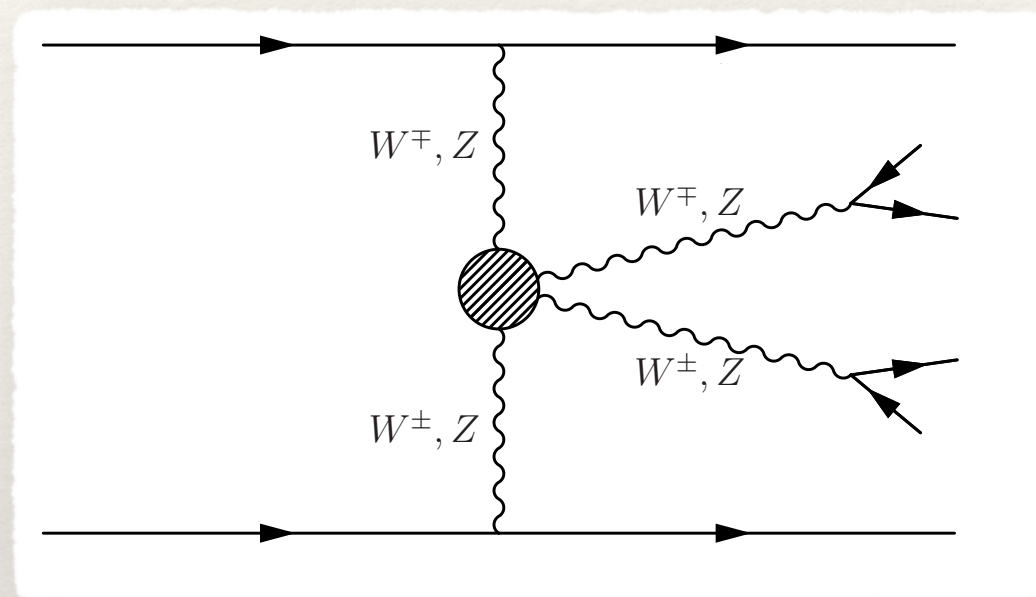


...back in business big time!



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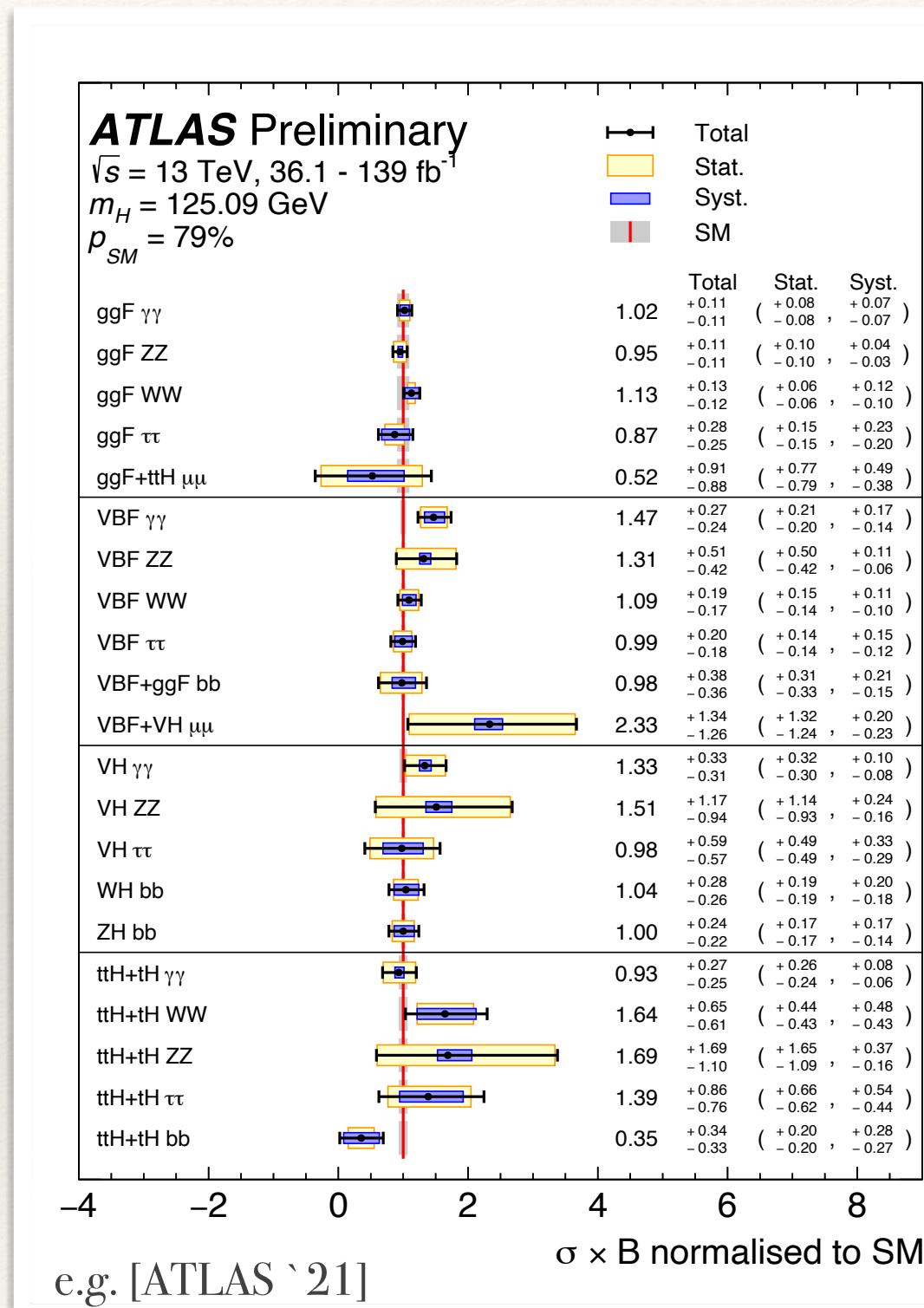


...back in business big time!

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 ?



Unitarity for discovery

- Unitarity restoration is only efficient with scalar and vector resonances

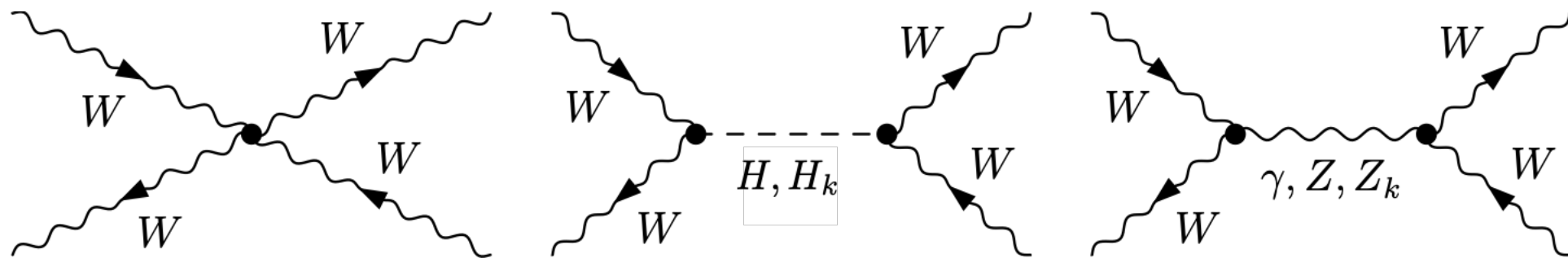
sum rules for longitudinal vector boson scattering

[Weinberg '67]...

...[Alboteanu et al. '08]

[Birkedal, Matchev, Perelstein '04]

[CE, Harris, Spannowsky, Takeuchi '15]



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

$$4m_W^2 g_{WWWW} = \sum_k 3m_{Z_k}^2 g_{WWZ_k}^2 + \sum_k g_{WWH_k}^2$$

prediction

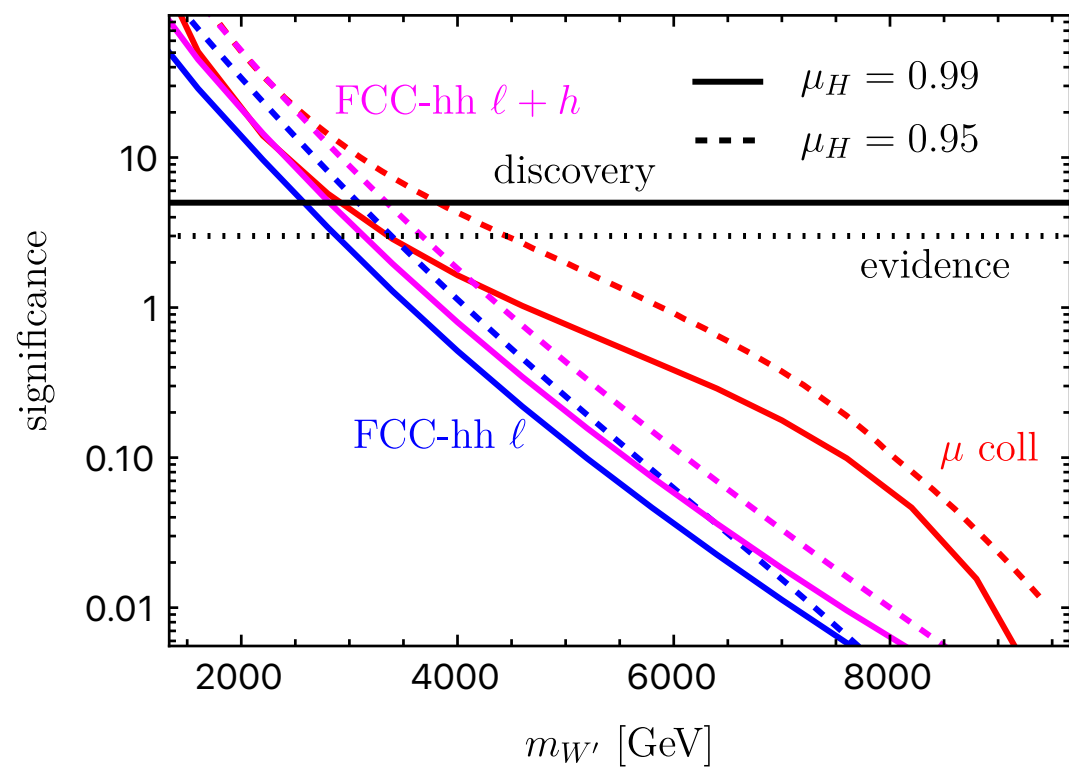
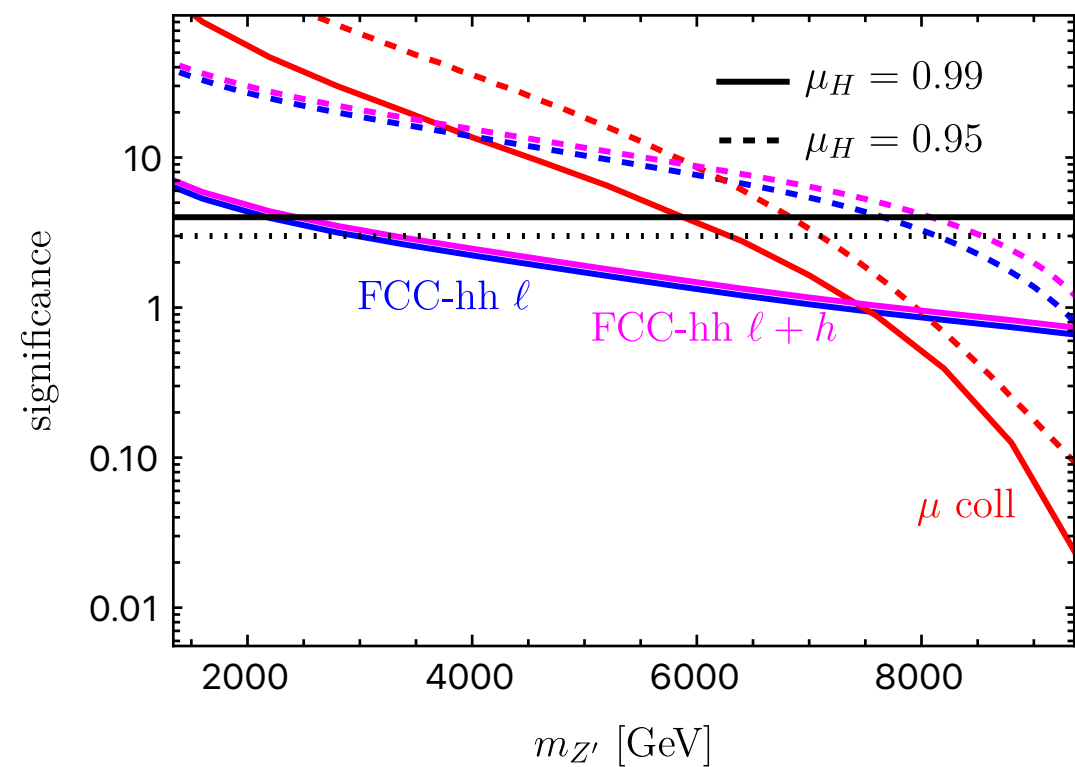
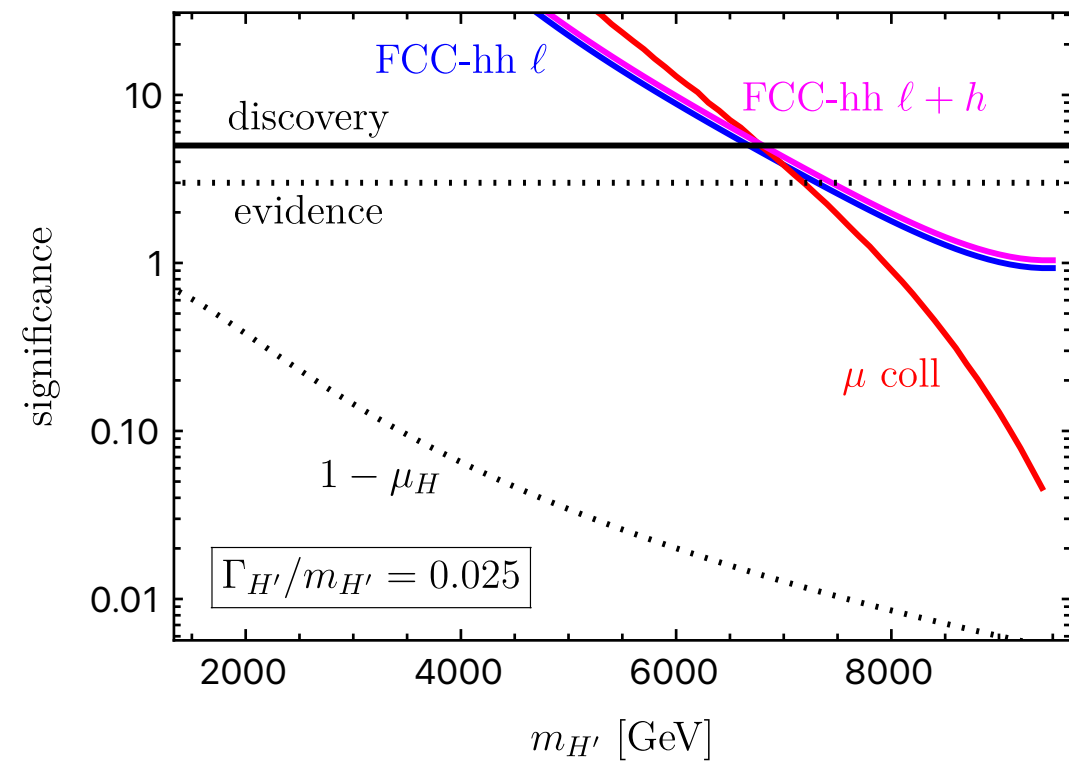
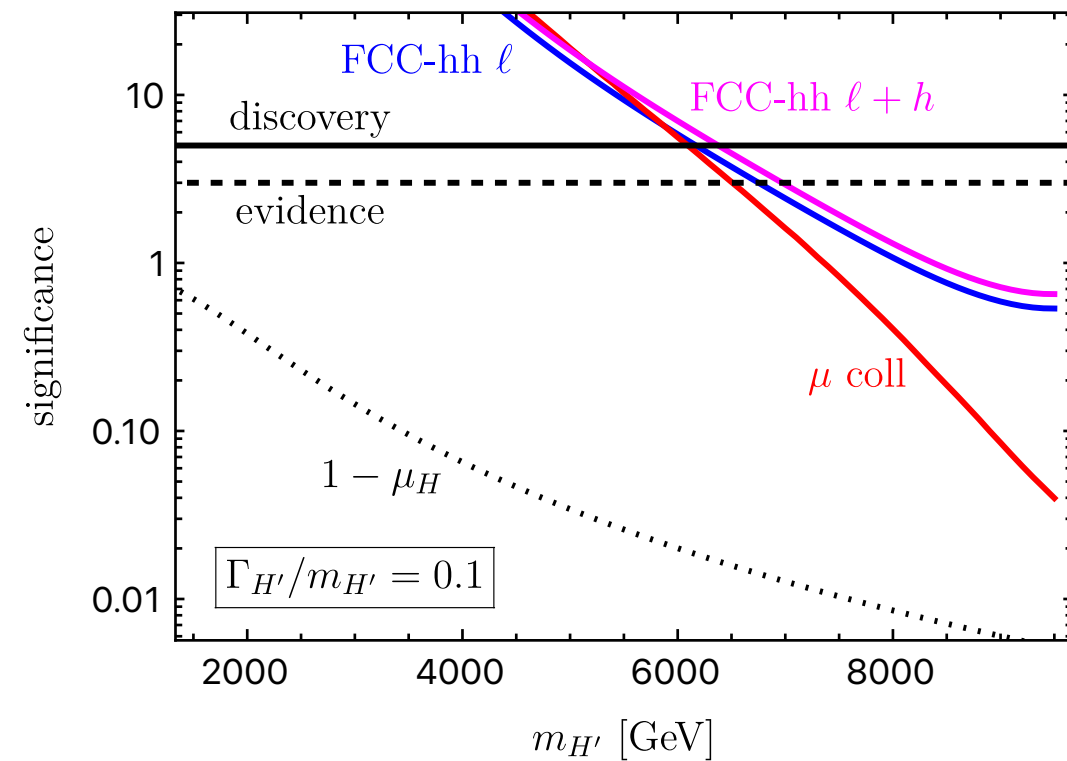
Higgs deviation

pheno determined by unitarity,
gauge symmetry, and convergence

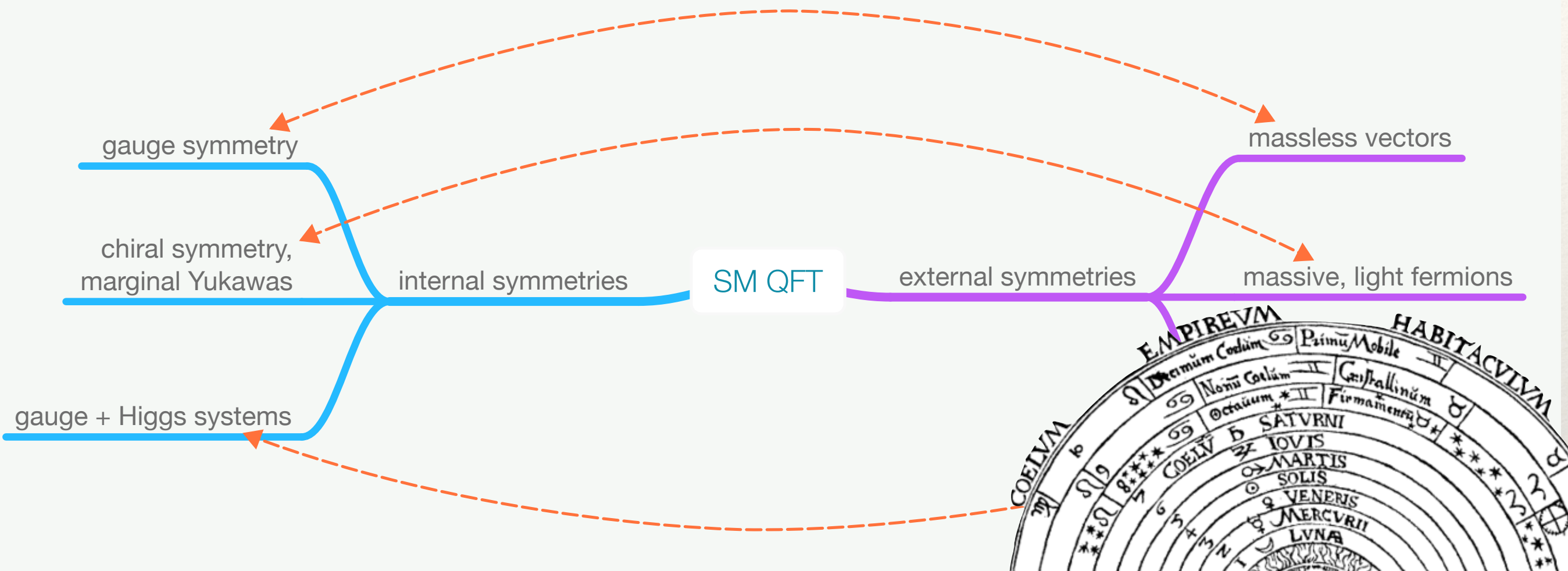
prediction

Unitarity for discovery

[CE, Naskar, Pilkington, Spannowsky '26]



What is the nature of the TeV scale?



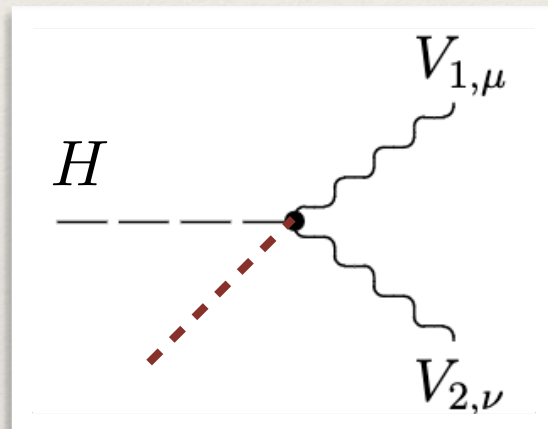
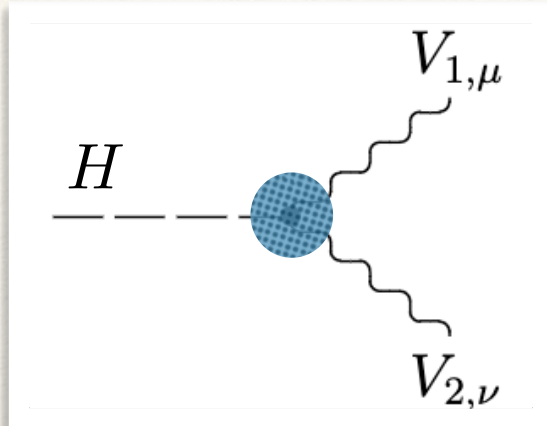
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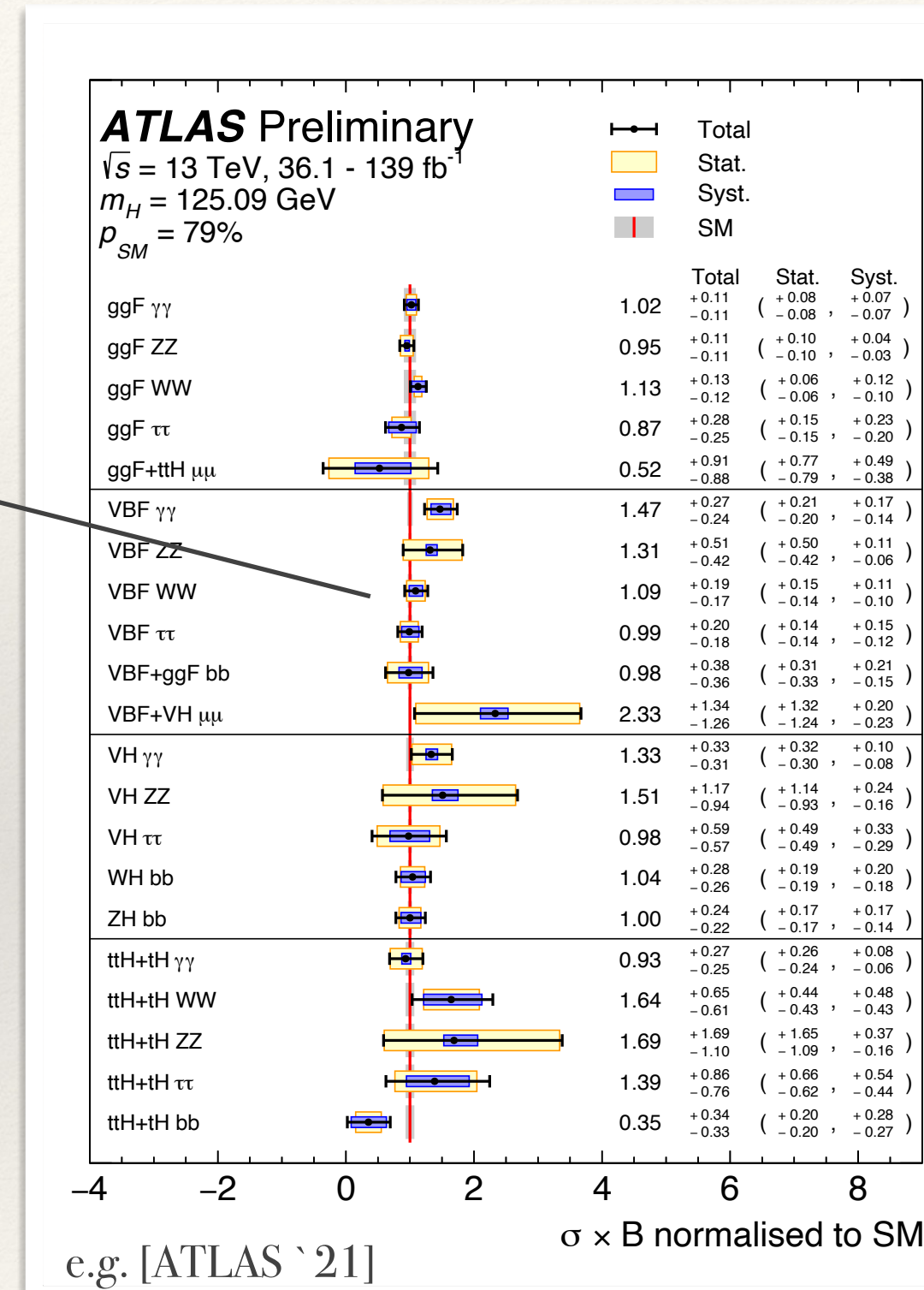
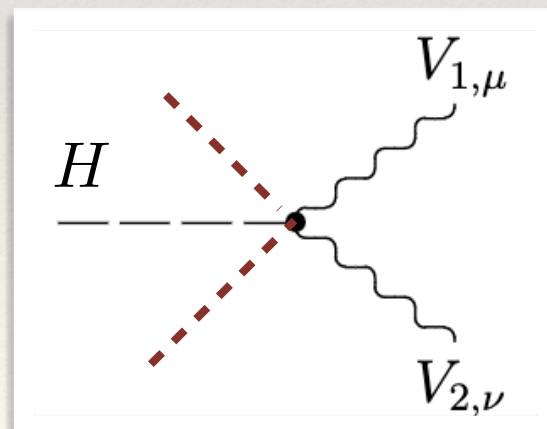


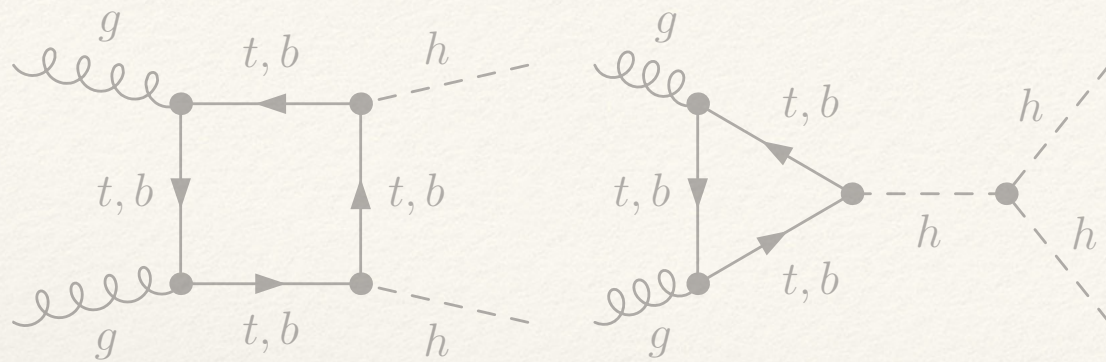
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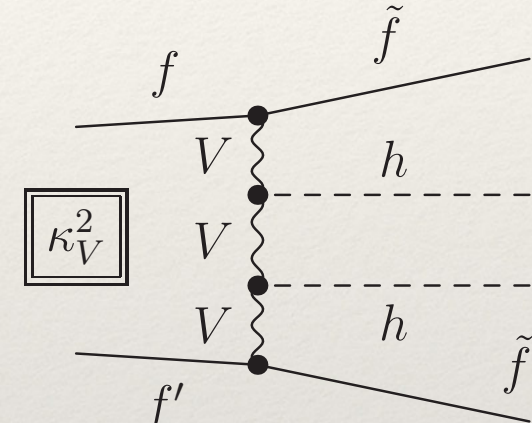
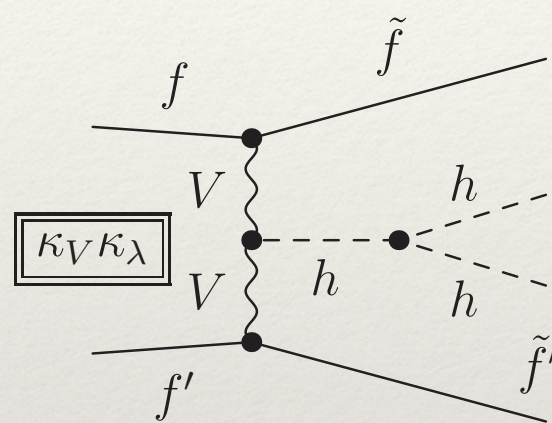
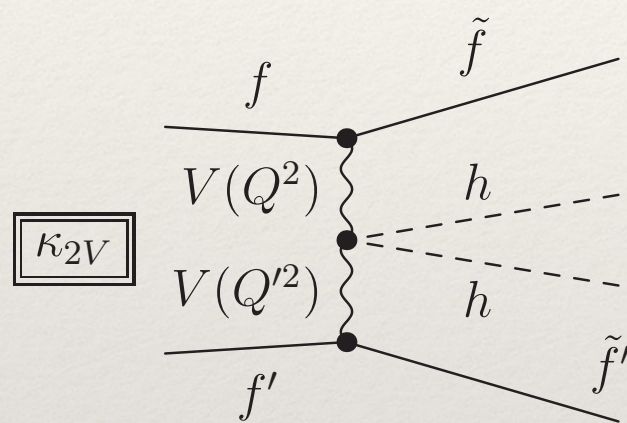


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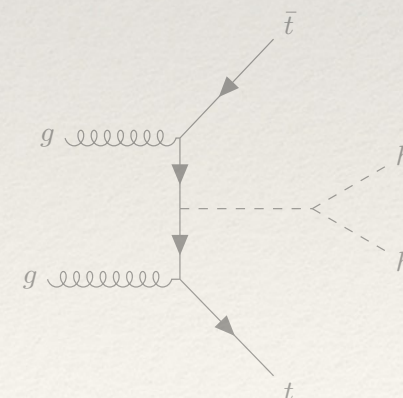
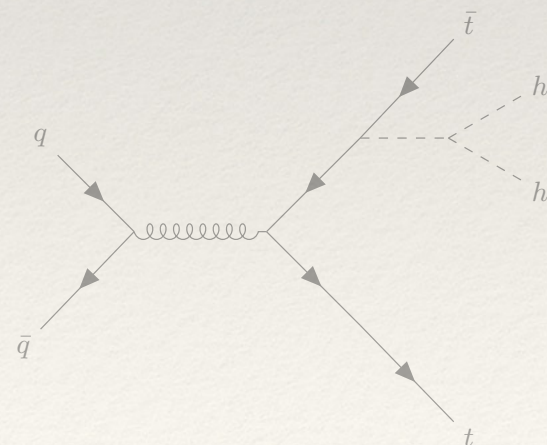
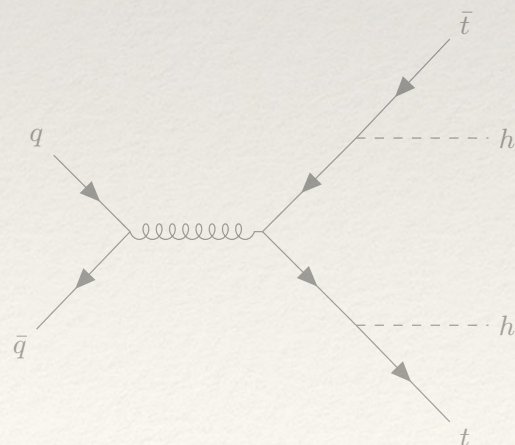




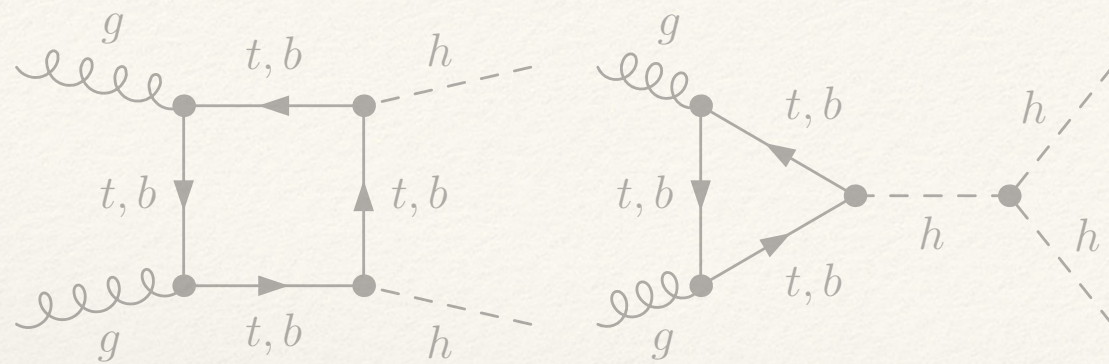
GF Higgs pair production $\sim 30 \text{ fb}$



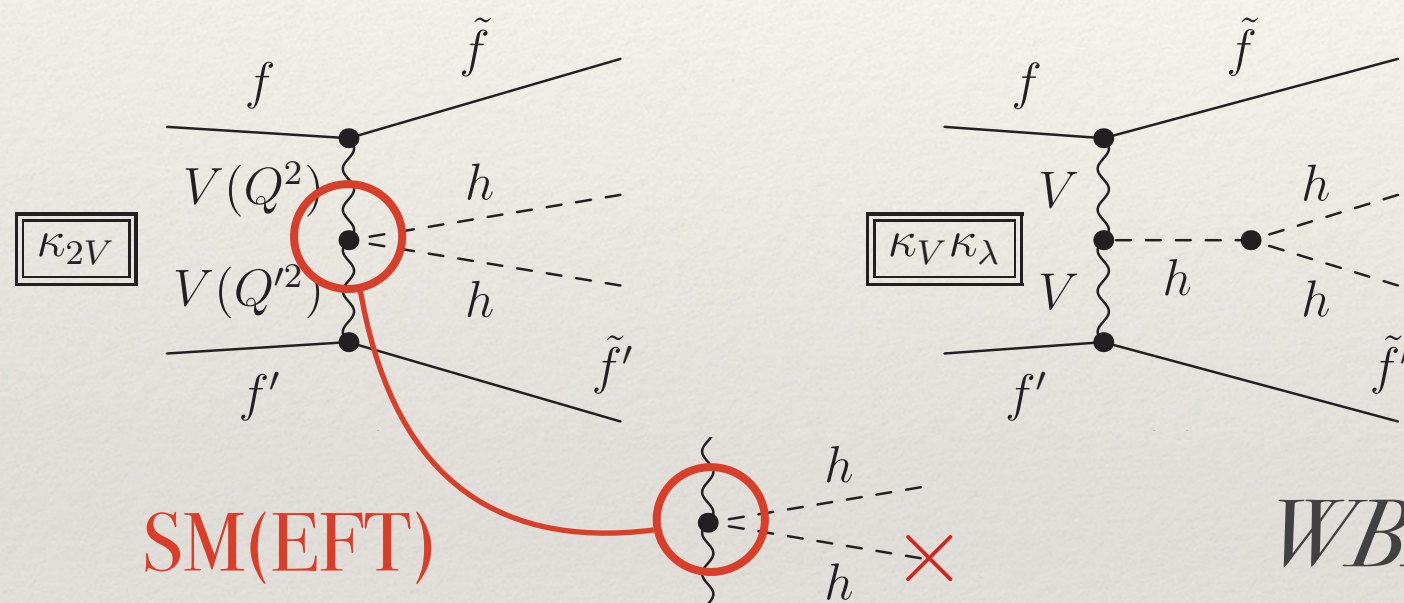
WBF Higgs pair production $\sim 1 \text{ fb}$



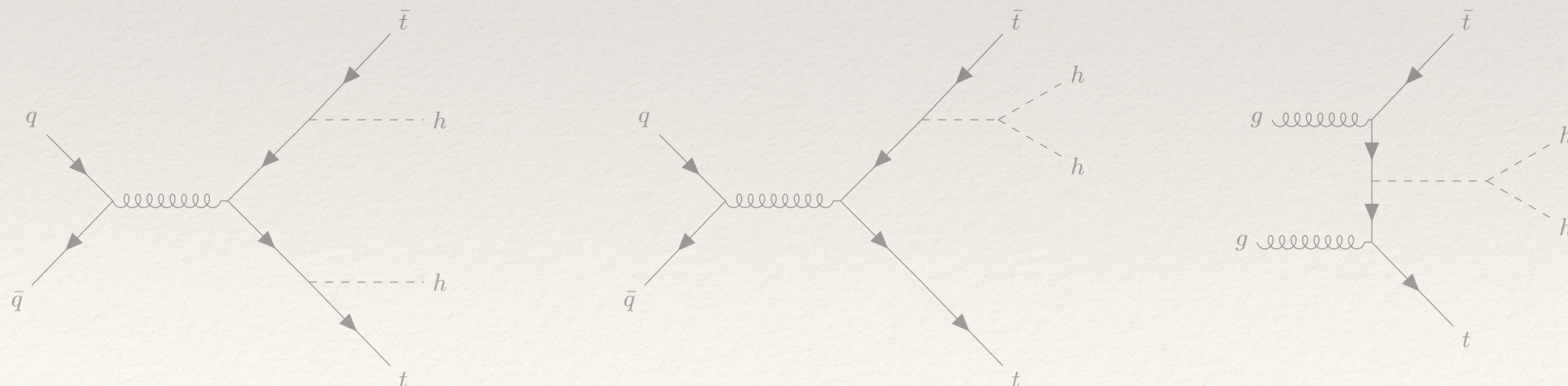
top-associated Higgs pair production $\approx 1 \text{ fb}$



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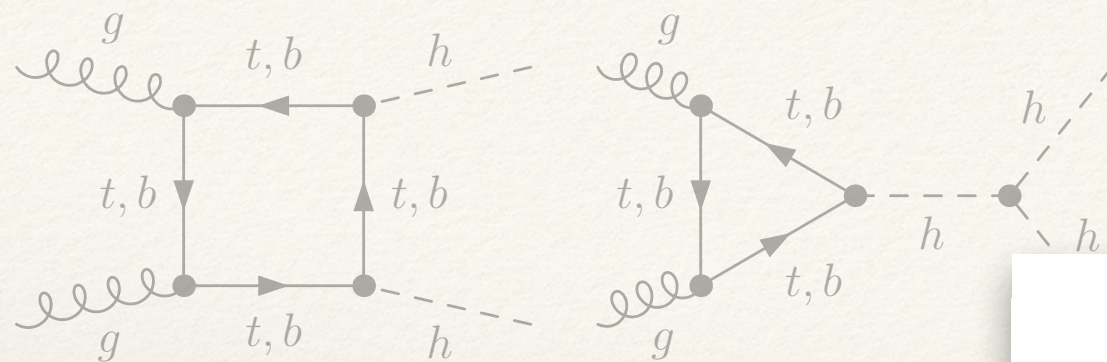


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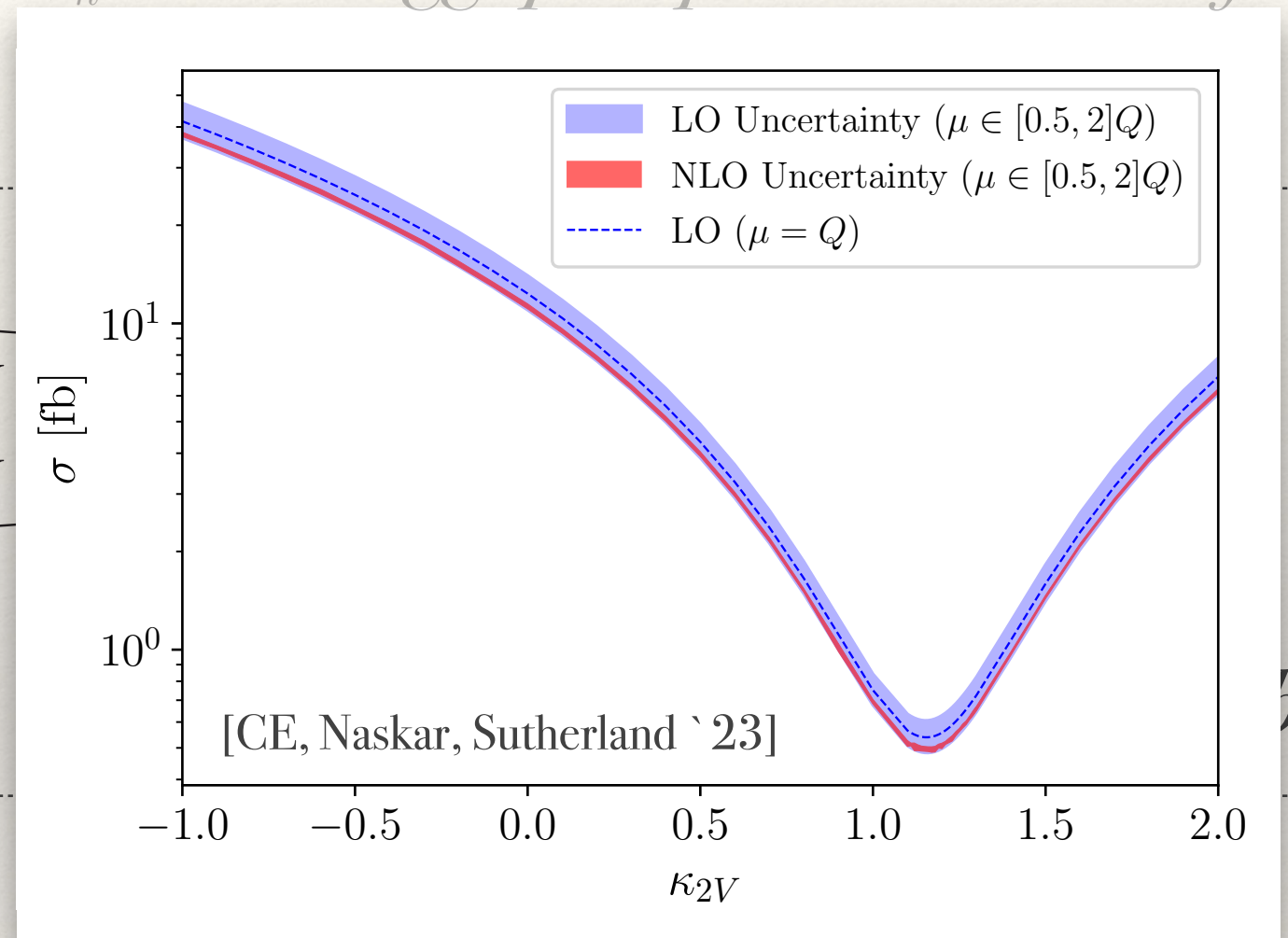
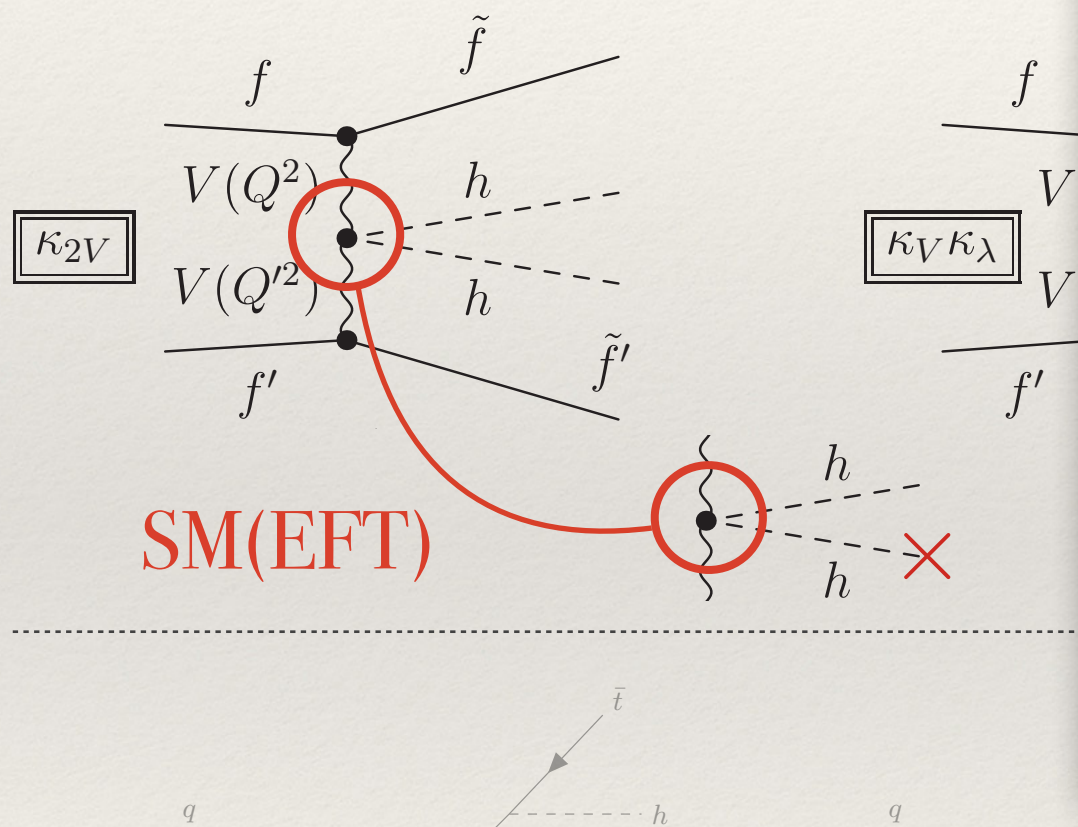


top-associated Higgs pair production $\approx 1 \text{ fb}$

collider probes



GF Higgs pair production ~ 30 fb



$$\kappa_\lambda \in [-3.5, 11.3], \quad \kappa_{2V} \in [0.0, 2.1] \quad \text{e.g. [ATLAS + CE '23]}$$

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

gauge-Higgs quartics are dangerous...

- ▶ high scale unitarity requirements

singlet mixing

$$\kappa_V = \cos \alpha$$

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

SMEFT

$$H_1 = \cos \chi H_s + \sin \chi H_h$$

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

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

Scattering = Curvature

- high scale unitarity requirements

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“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

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compact groups

$$1 - \kappa_V^2 \geq 0,$$

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

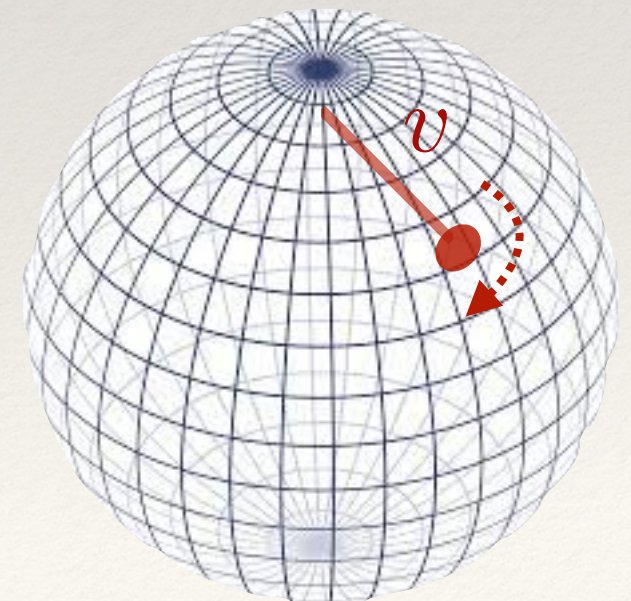
[Alonso et al. `16]

MCHM

$$SO(5)/SO(4) \sim S^4$$

$$\kappa_V = \sqrt{1 - \xi},$$

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



Scattering = Curvature

- high scale unitarity requirements

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

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SMEFT

$$H_1 = \cos \chi H_s + \sin \chi H_h$$

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“Physics must not depend on coordinate choices”

linked to

single Higgs is not enough to resolve*
 $\cos 2\alpha \neq \cos \alpha$

EWBS manifold

[Alonso et al. '16]

, CE, Naskar, Rahaman et al. '25]

- Goldstone-equivalence: relation between scalar EWSB manifold

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$$1 - \kappa_V^2 \geq 0,$$

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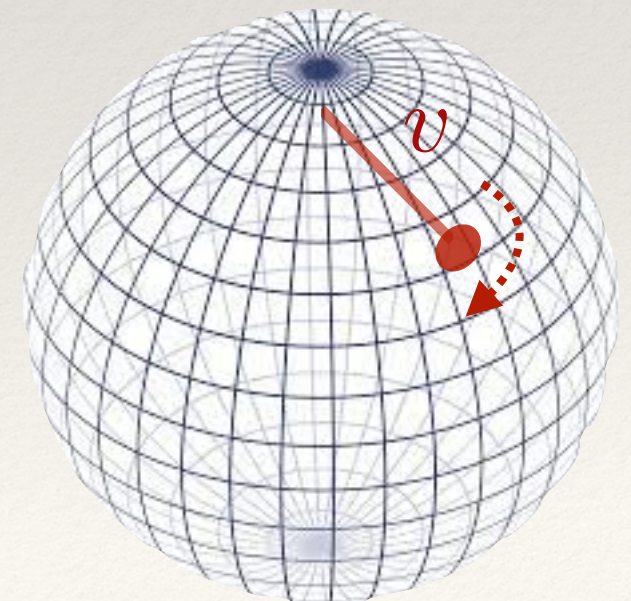
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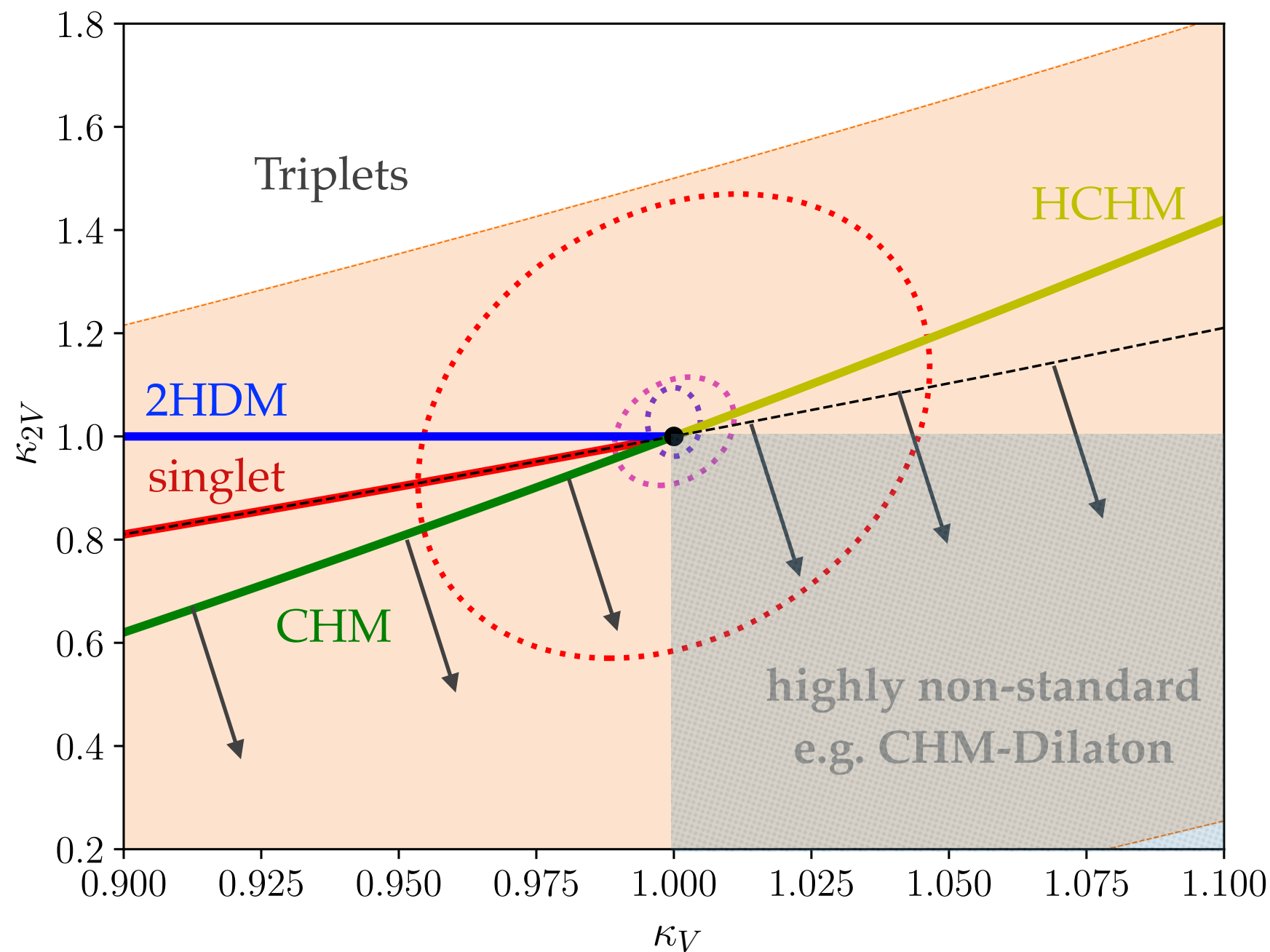
$$SO(5)/SO(4) \sim S^4$$

$$\kappa_V = \sqrt{1 - \xi},$$

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



charting phenomenological possibilities



[CE, Naskar, Sutherland '23]

generalising to existing problems: strongly-interacting DM

$$\mathcal{L}^{\text{EFT}} = \mathcal{L}_{\text{SM}} - \Phi^\dagger \Phi \left(\frac{\eta_S}{2} S^2 + \frac{\eta_{KS}}{\Lambda^2} \partial_\mu S \partial^\mu S + \dots \right).$$

- ▶ this Lagrangian is unique at dimension-6, tree-level and intact $\mathbb{Z}_2$
[Song et al. '23, '23]

- ▶ microscopically motivated in Composite Dark Matter theories
[Frigerio et al. '12] [Marzocca et al '14] [Carmona et al. '15]...

cusps vs core

missing
satellites

.....

- ▶ such a theory is immediately constructed by SM + dark QCD
 $\text{SU}(3)^2/\text{SU}(3)$

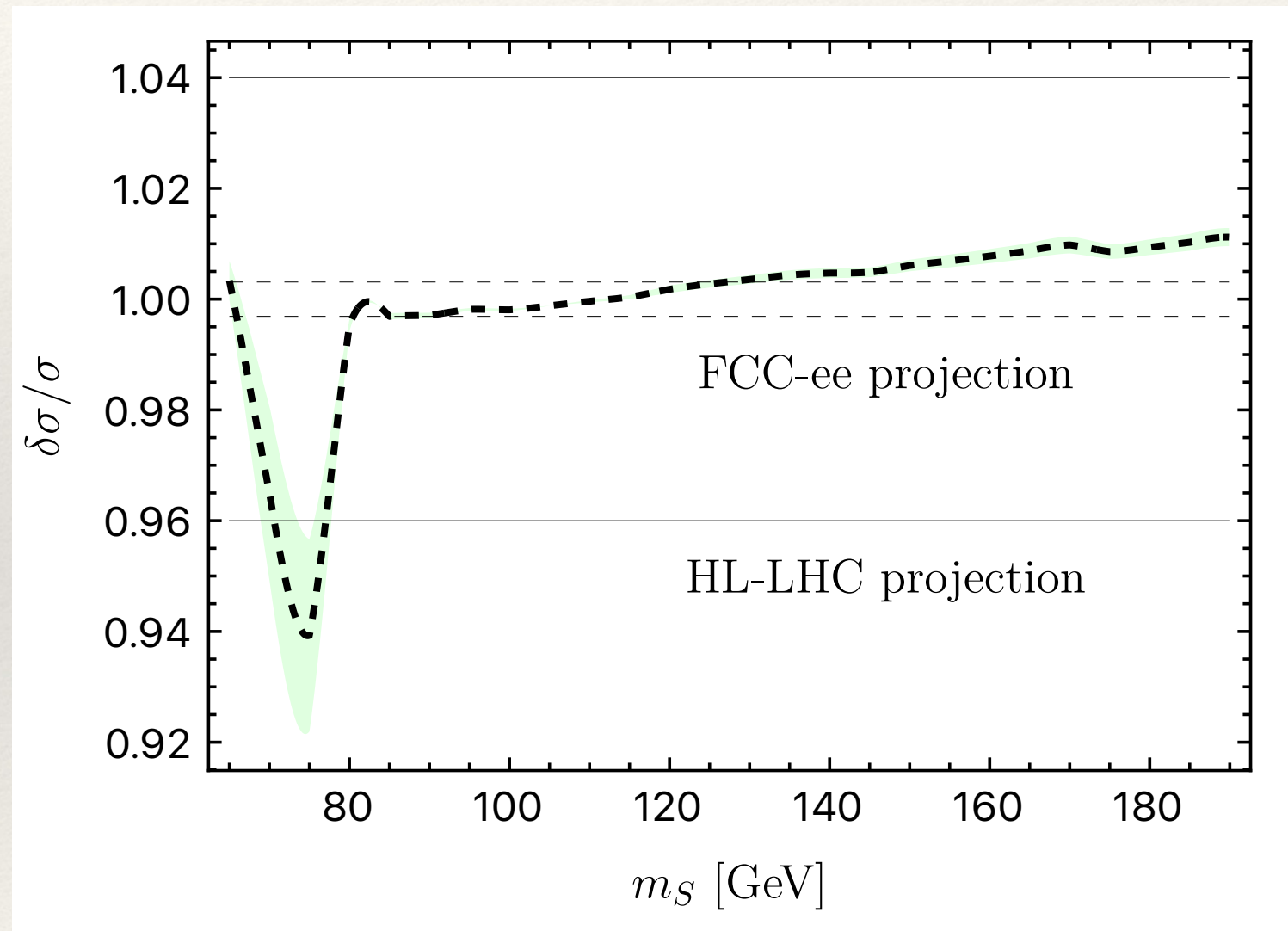
$$\mathcal{L}^{\text{EFT}} = \mathcal{L}_{\text{SM}} - \Phi^\dagger \Phi \left(\frac{f^2}{4\Lambda_1^2} \text{Tr}[M(\xi + \xi^\dagger)] + \frac{f^2}{4\Lambda_2^2} \text{Tr}(\partial_\mu \xi^\dagger \partial^\mu \xi) + \dots \right).$$

- ▶ at a technical level transparent treatment in (Higgs) EFT!

resurrecting the Higgs portal

- ▶ can satisfy direct detection and relic abundance simultaneously
- ▶ need carefully arranging parameters, especially for light states

$$m_S = 55 \text{ GeV}, \quad \eta_{KS} = -0.3, \\ \eta_S = 0.003, \quad (\text{BR}(\text{inv}) = 1.9\%)$$

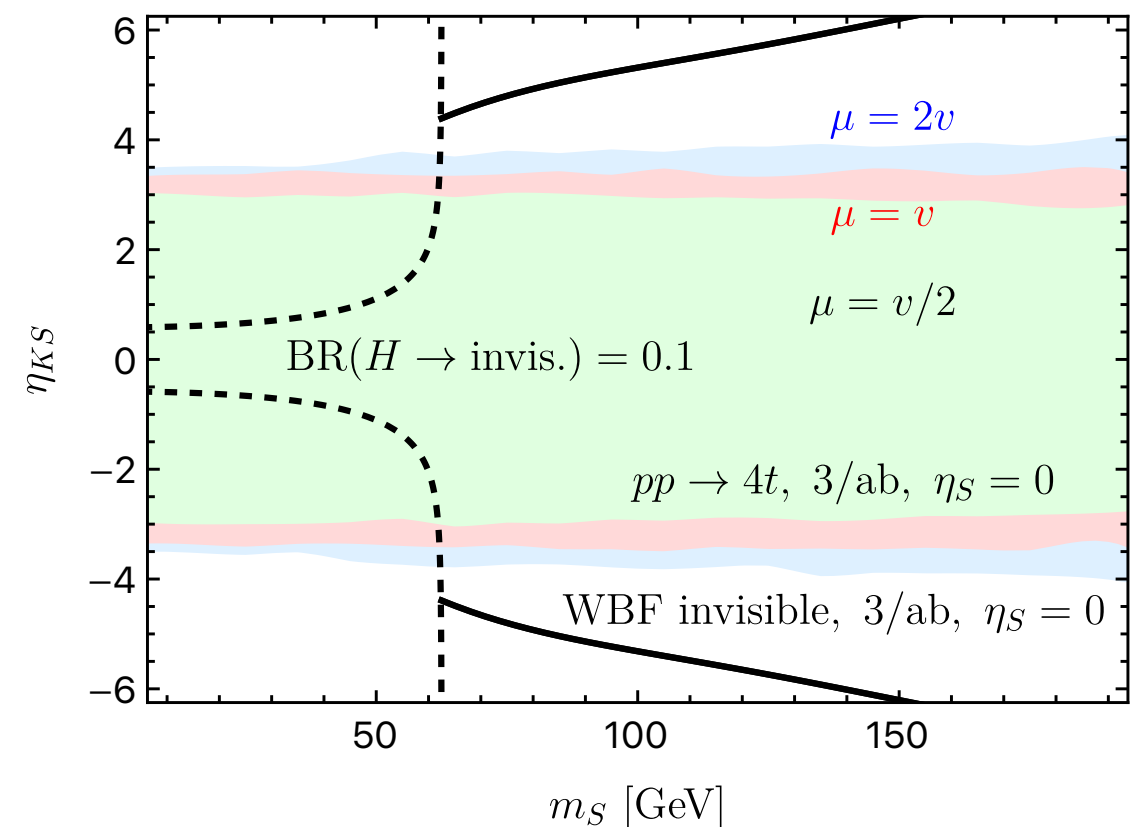
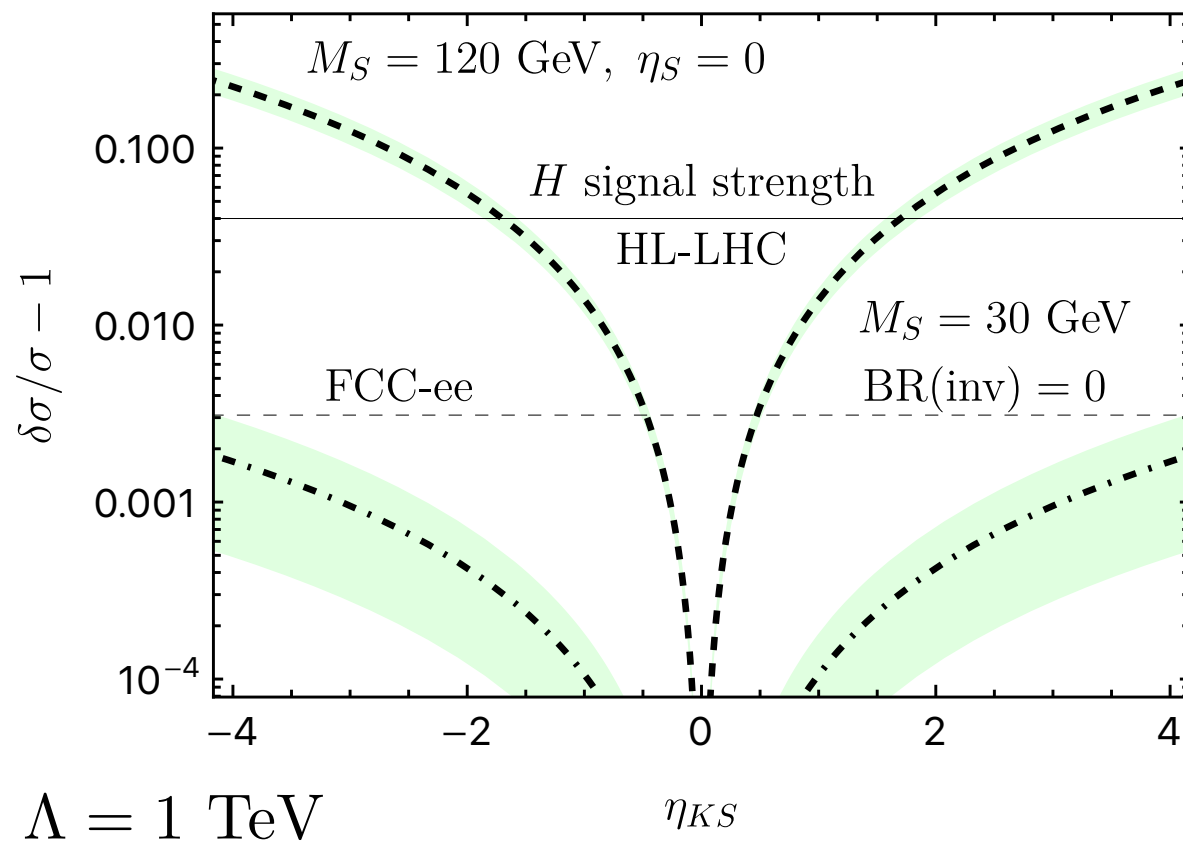


- ▶ **experimentally constrainable over a wide range of parameters**

- relax Higgs signal strength constraints for

$$\Gamma(H \rightarrow SS) = \frac{1}{32\pi} \sqrt{1 - \frac{4m_S^2}{m_H^2}} \frac{v^2}{m_H} \left(\eta_S + \eta_{KS} \frac{2m_S^2 - m_H^2}{\Lambda^2} \right)^2.$$

- sensitivity in Higgs propagation & couplings: $-\cdots\text{---}\overset{H}{\circ}\text{---}\cdots\text{---}\overset{H}{\circ}\text{---}$



universal Higgs coupling modifications

Higgs propagation in 4 top production

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 techniques, 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
& dark matter

(non-)perturbative
electroweak symmetry breaking

relation with electroweak
baryogenesis, cosmology...