Christoph Englert (Glasgow or Manchester depending on when you'll catch me here)

To precision frontiers with newish ideas?

based on [Anisha, Arco, Di Noi, CE, Mühlleitner, 2506.18555]
[Anisha, Biermann, CE, Mühlleitner, 2510.xxxxx]

5th Asian-European Institutes Workshop

29/09/25

hep-ph – quo vadis?

- fair to say that we don’t understand the mechanism behind the weak scale…

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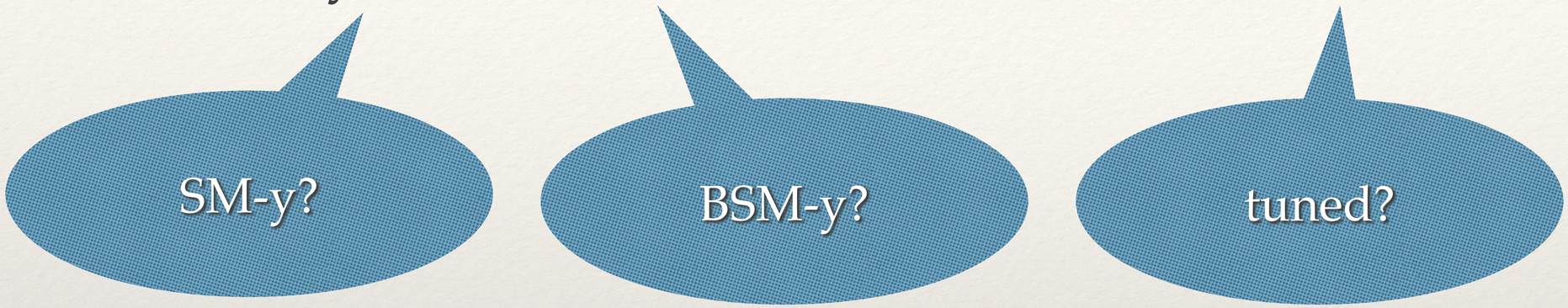

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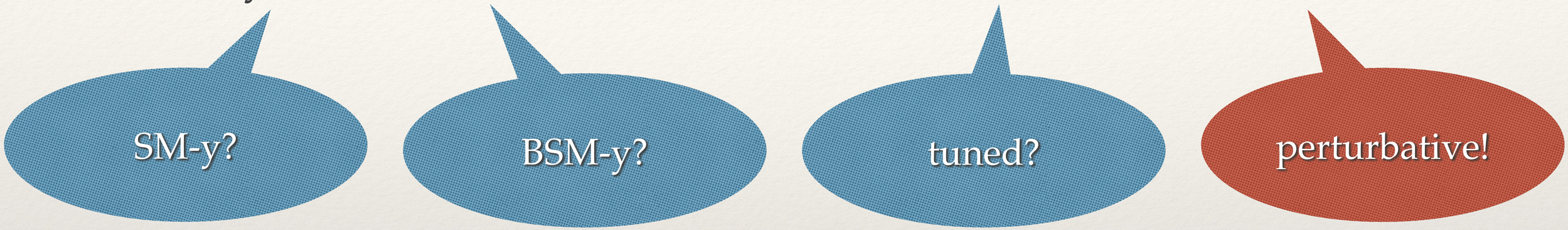

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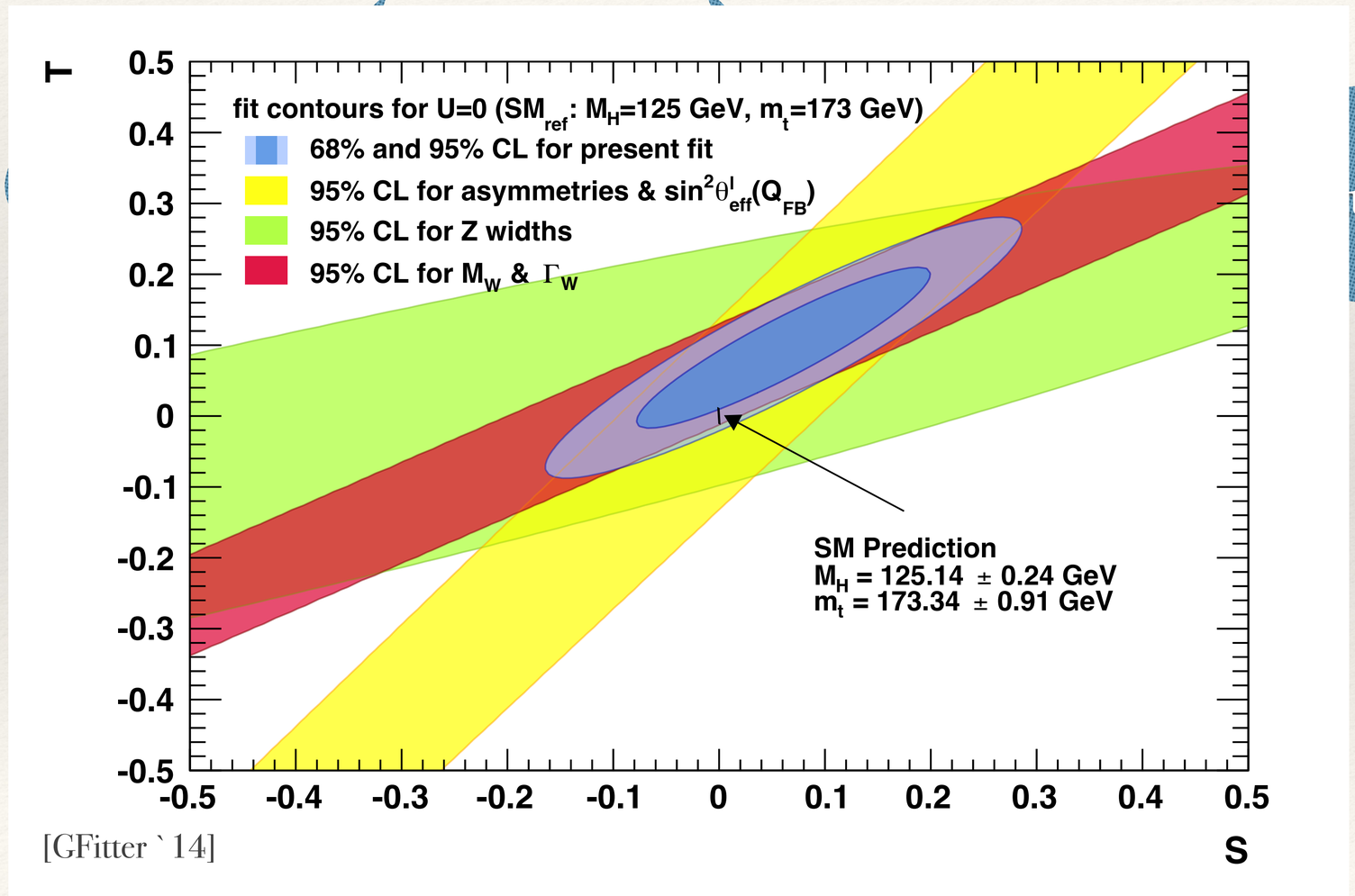
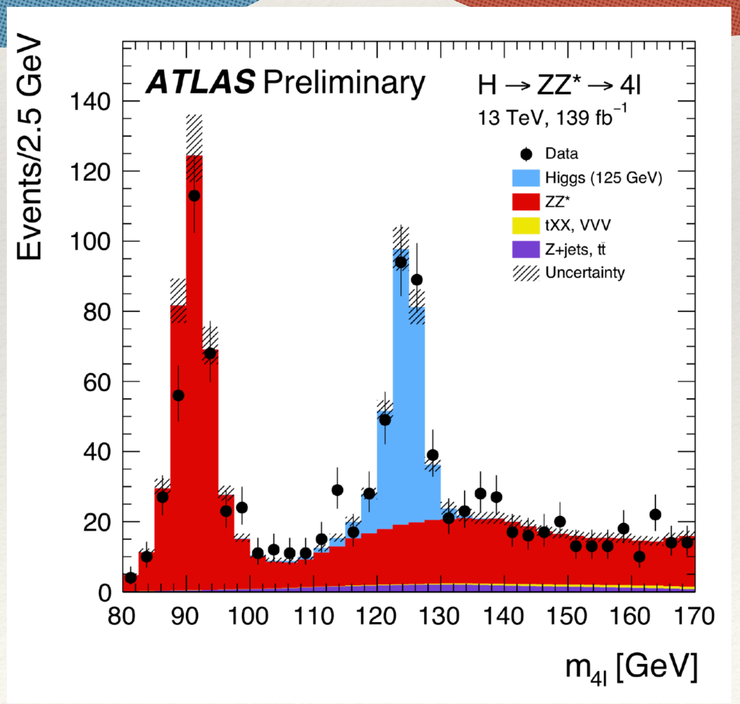


[GFitter `14]

uned?

perturbative!



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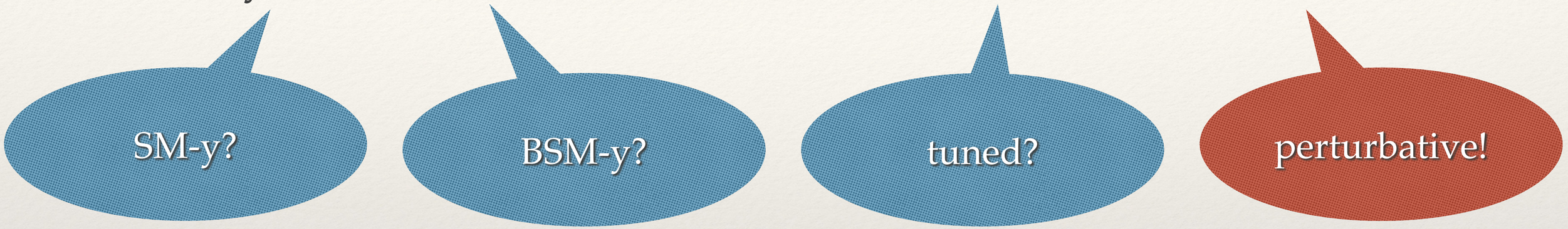
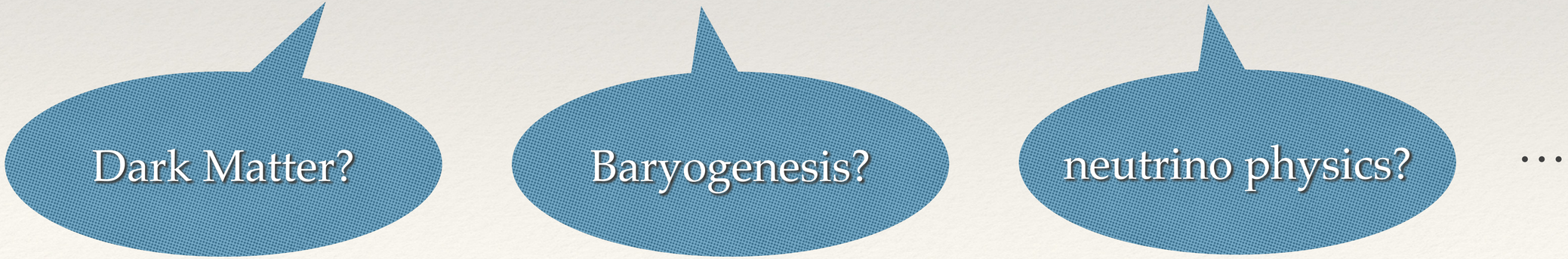


- …and no emerging evidence of it being connected to more profound physics



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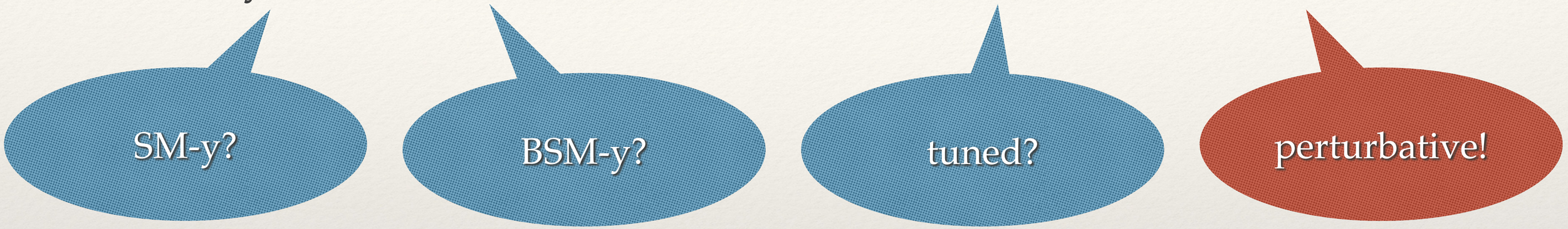

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LHC outcome so far

- a Higgs boson, highly aligned with the SM hypothesis
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… how can this be?

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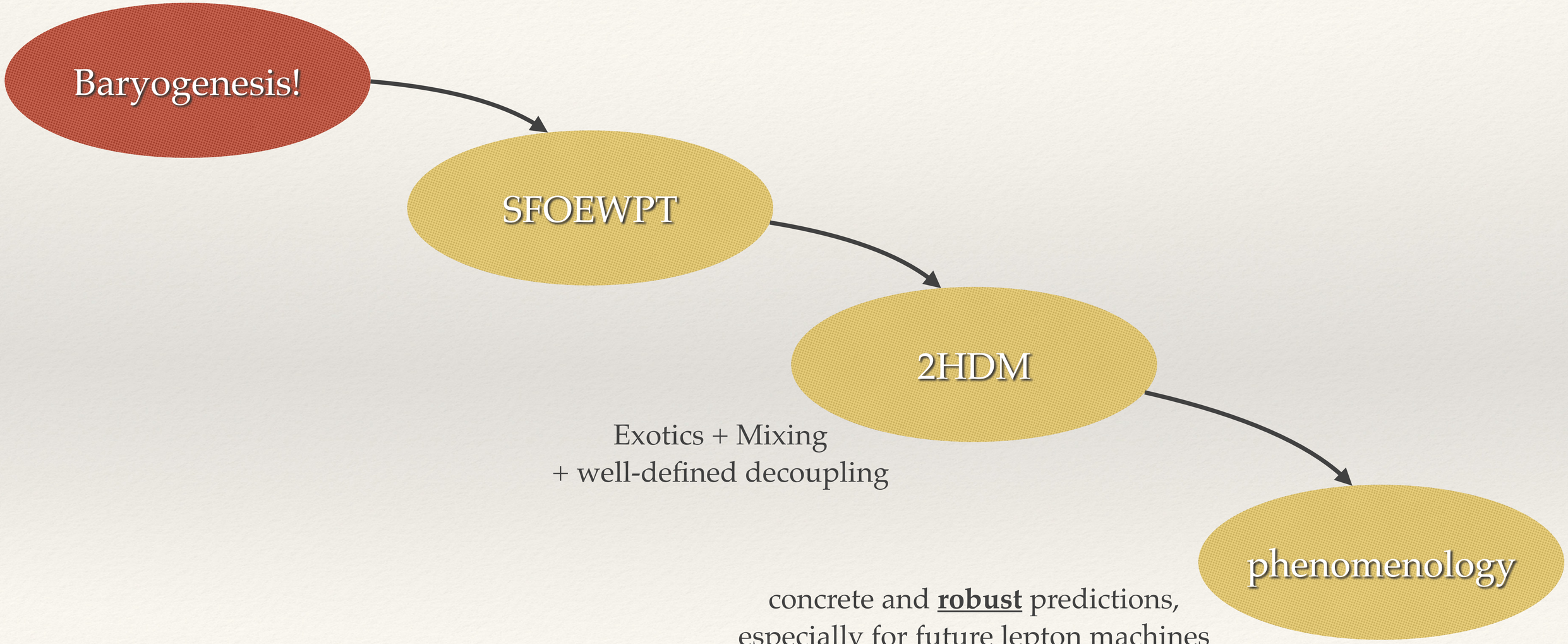
… how can this be?

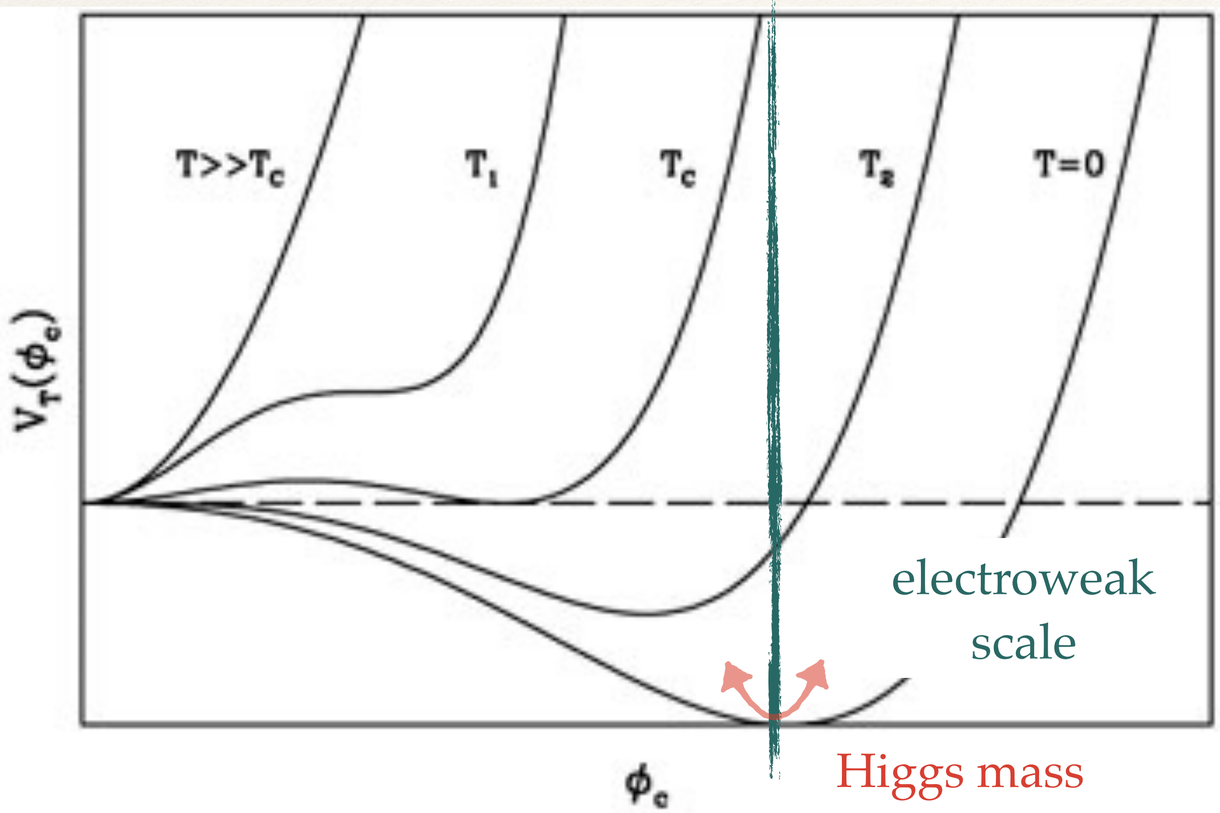
- (current) model-independent EFT approaches provide little insight here
  - no flavour
  - no baryon number violation
  - little CP
  - unrealistic sensitivity expectation scaling
- still useful as an approach/tool, and intelligent people can hold two naively contracting ideas in their mind simultaneously….

‘Strawman’ scenarios



2HDM address SFOEWPT

- standard approaches using effective potentials at finite temperature



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

many publicly available codes / approaches

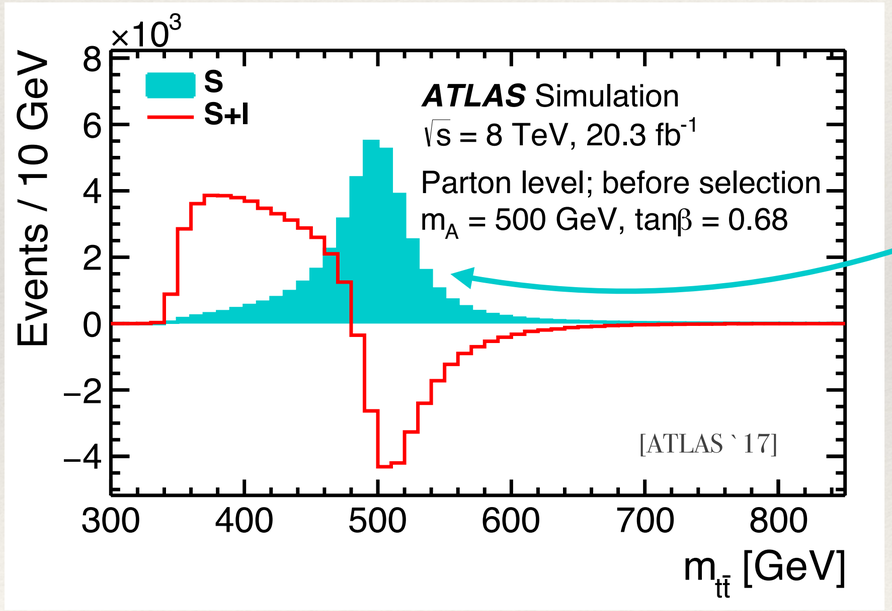
[BSMPT]
[CosmoTransition]
...
[Ramsay-Musolf et al. `24]
[Niemi et al. `24]

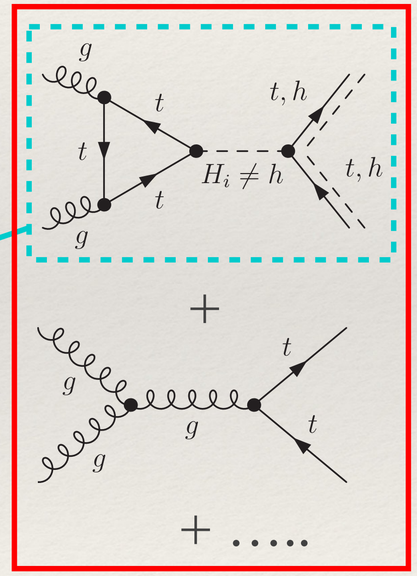
Upshot: New states need to be light.

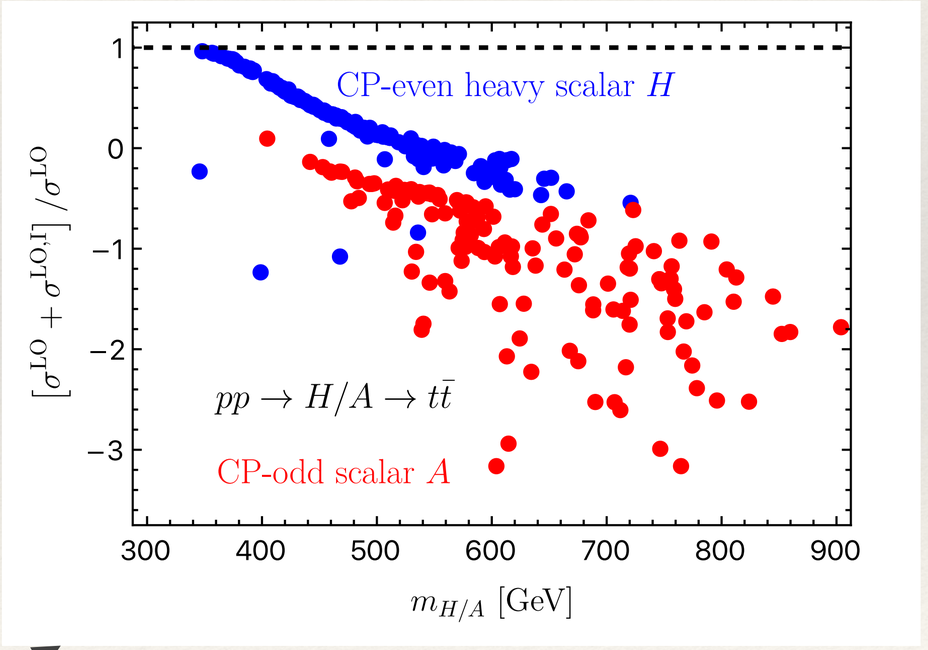
Where are the exotics?

- large accidental destructive interference effects for top-philic BSM [Gaemers, Hoogeveen `84] [Dicus et al. `94] ...

→ exp. systematics: conceivable that this is not *yet* accessible at the LHC



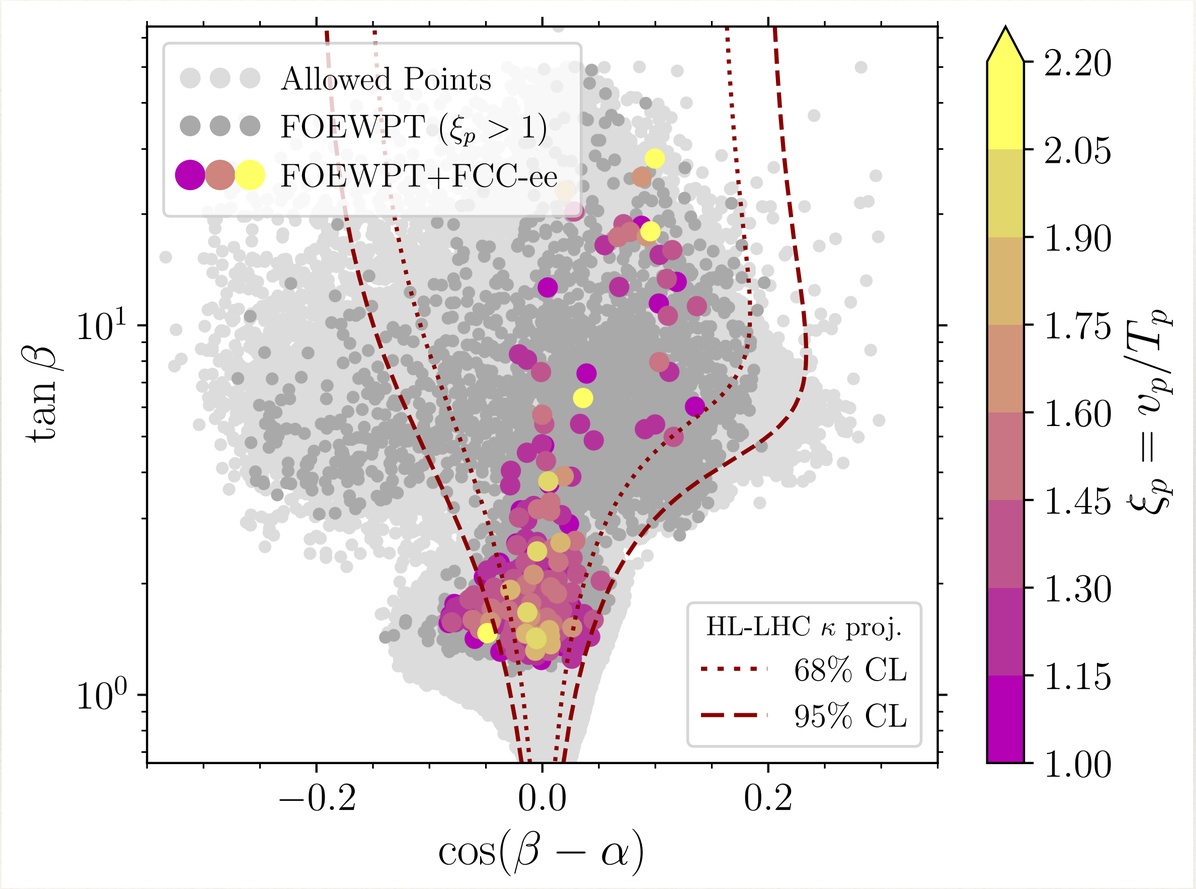




SFOEWPT-enriched scan

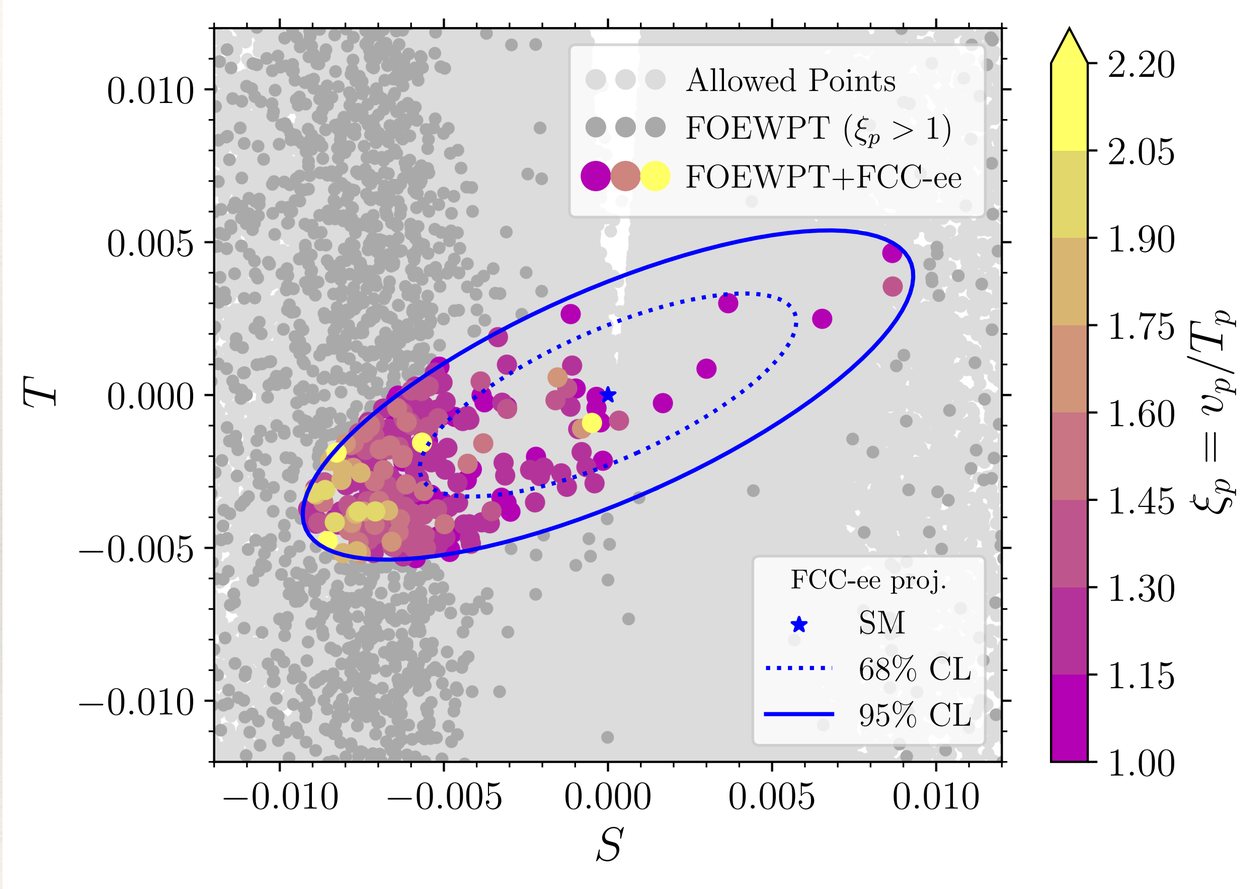
Higgs precision beyond the LHC?

[Anisha et al. `25]



HL-LHC Higgs couplings

vs



FCC-ee Z pole programme

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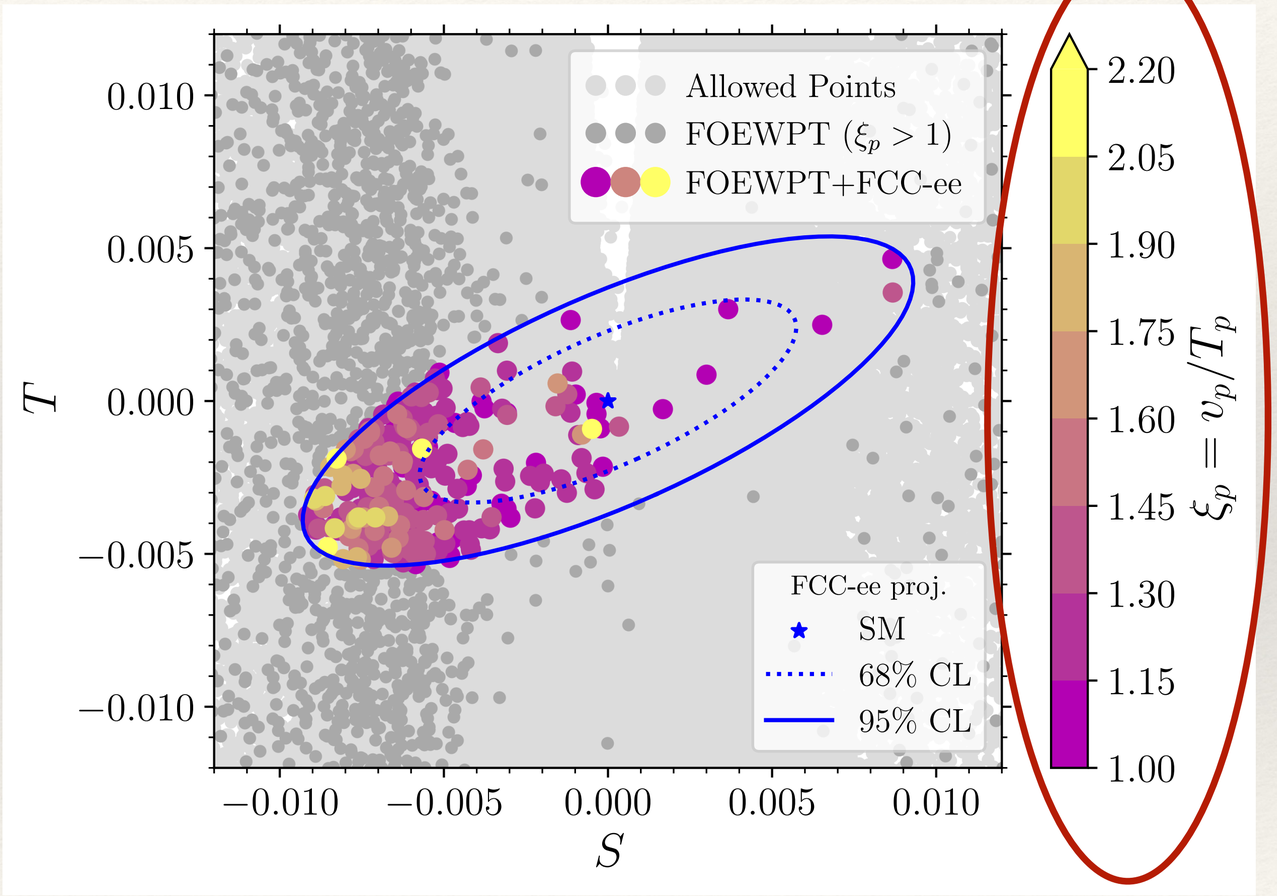
Consistency with SM Higgs in the gauge sector after HL-LHC + Z pole

alignment without decoupling



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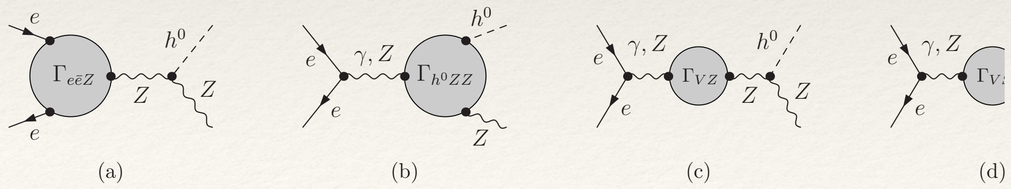
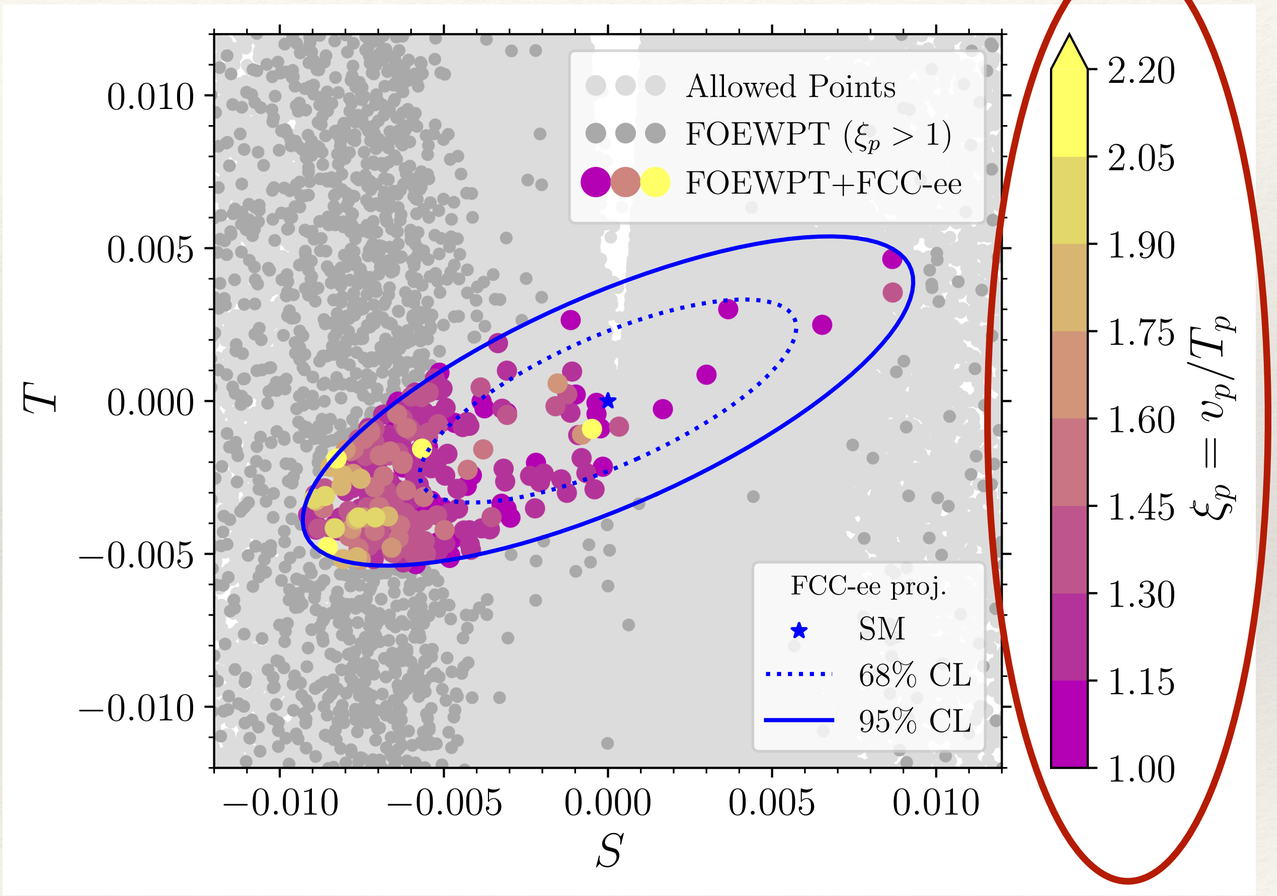
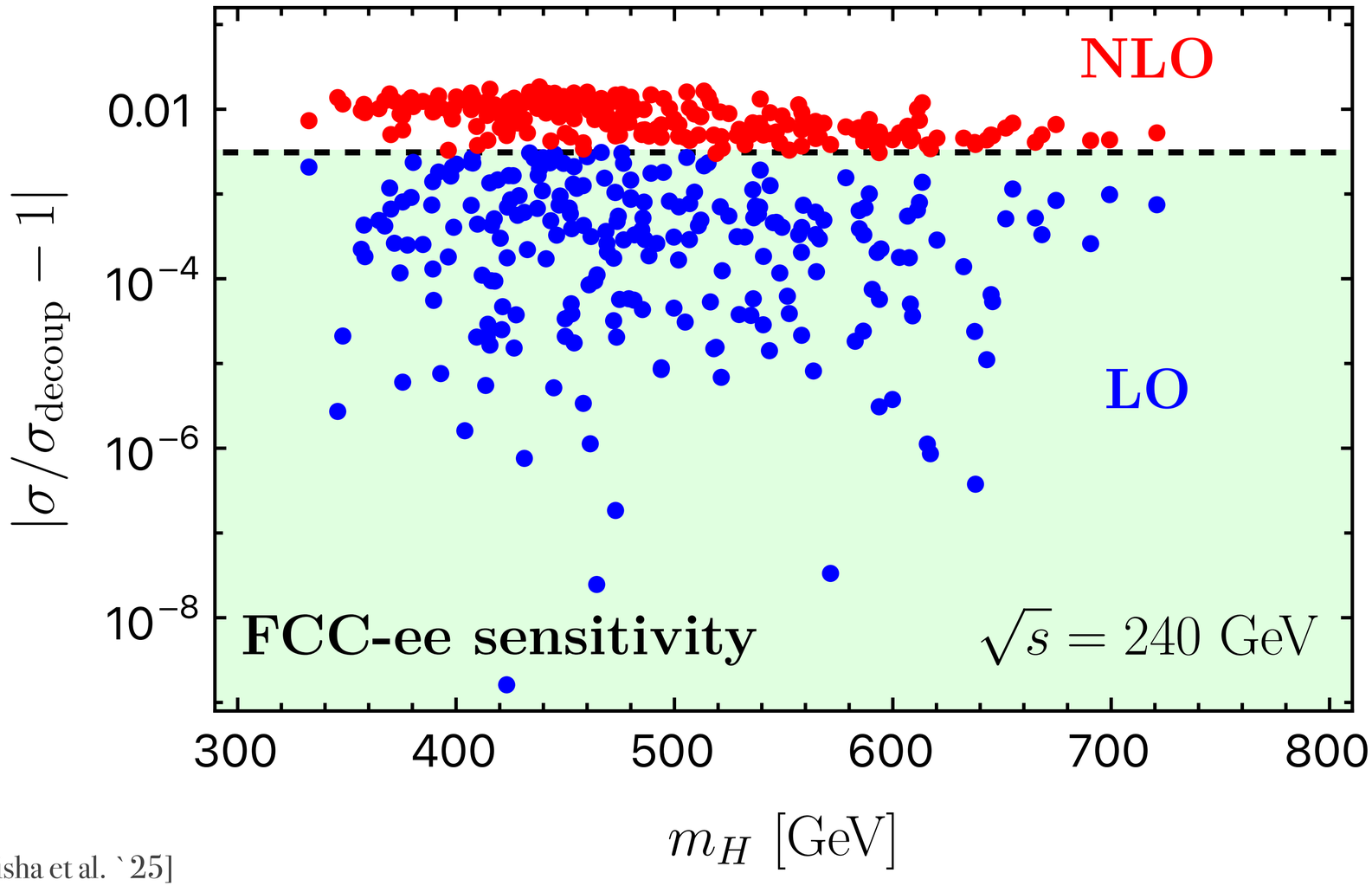
Will a Higgs run discover new physics?





Most likely yes.



projected CEPC/FCC-ee sensitivity ~0.3%

[Anisha et al. `25]

Higgs precision!

'SMness' of HL-LHC

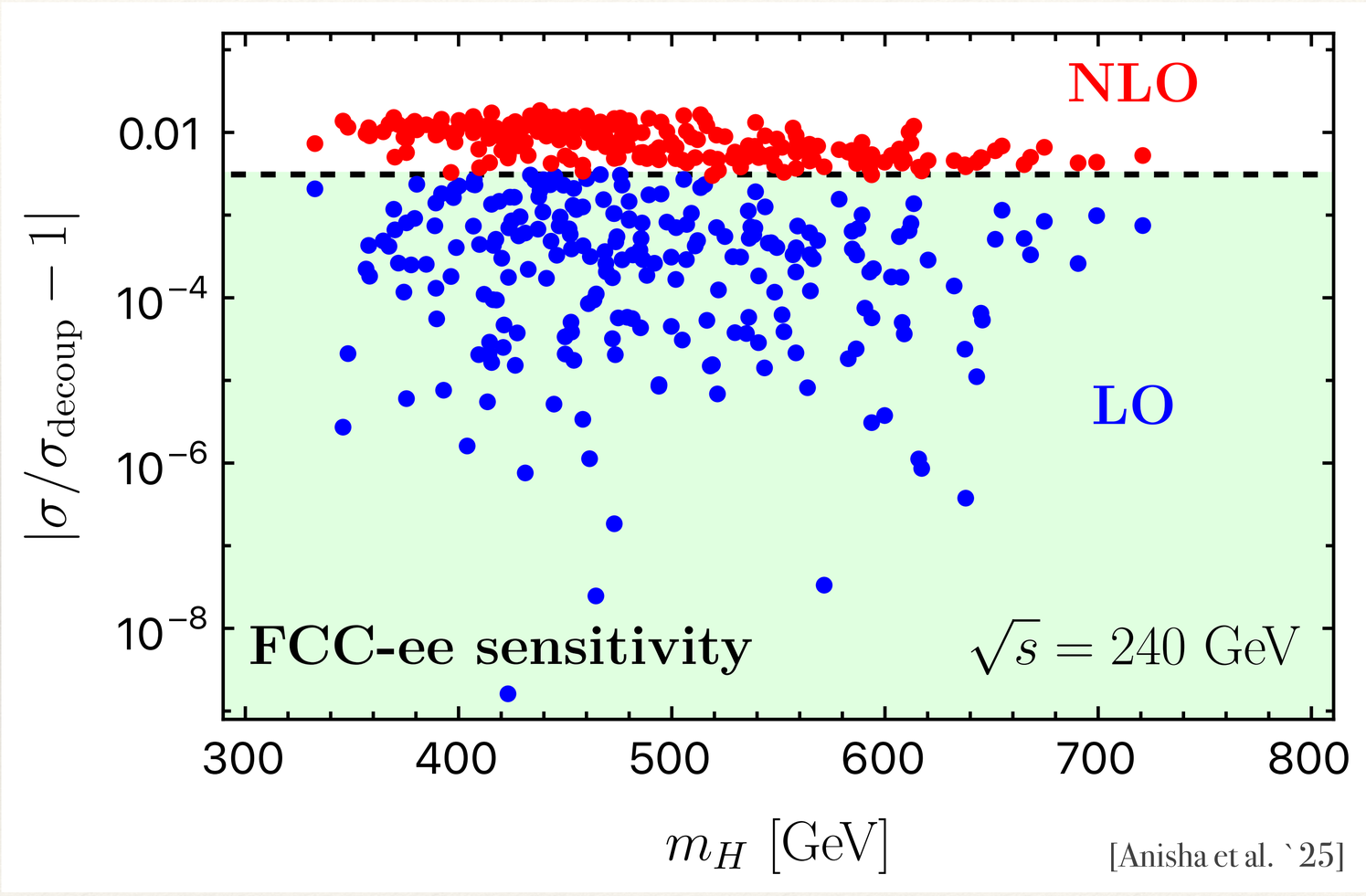
& BSM facts of life

||

alignment without decoupling

||

discovery at e^+e^- <u>at the latest</u>



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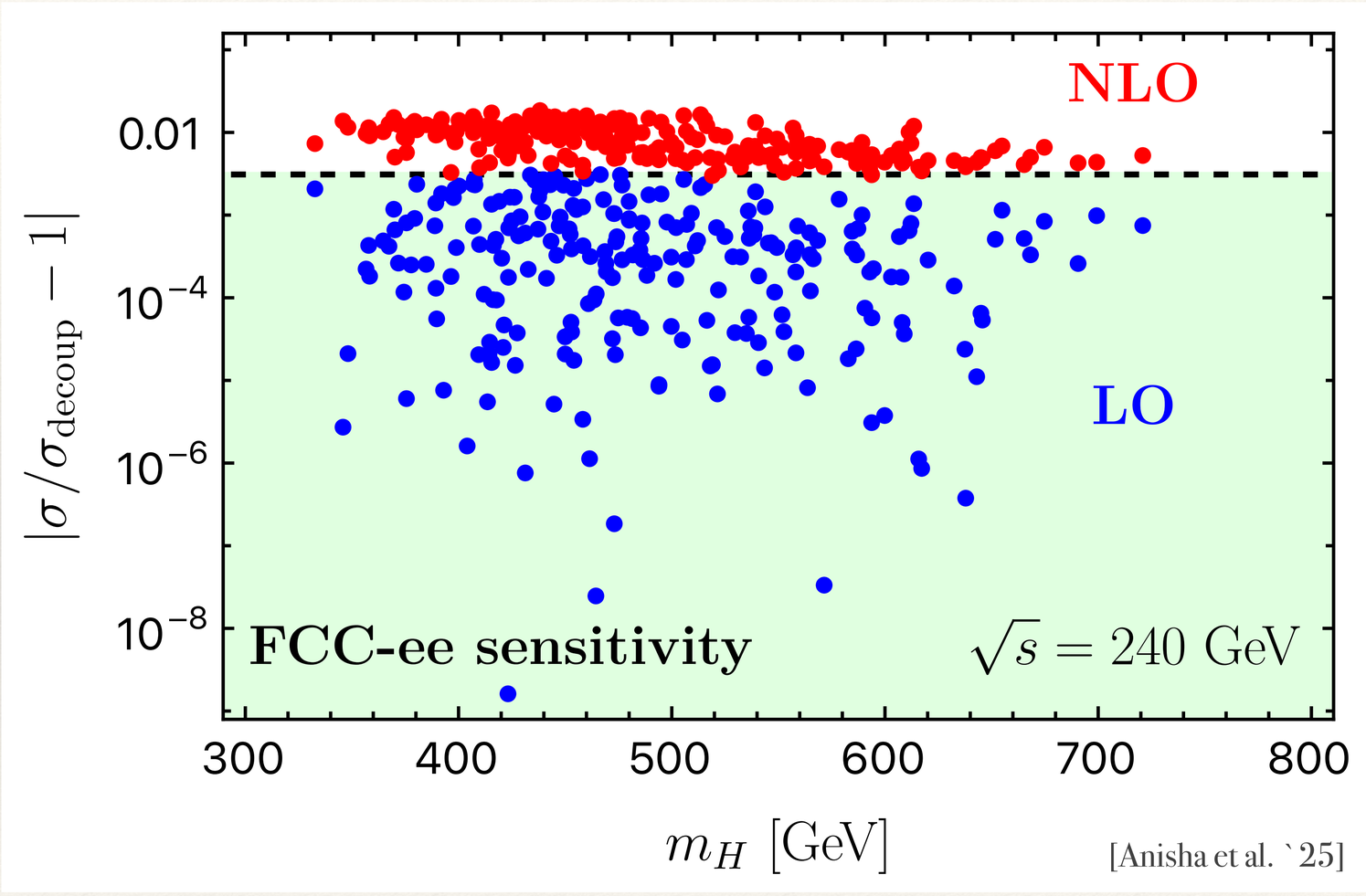
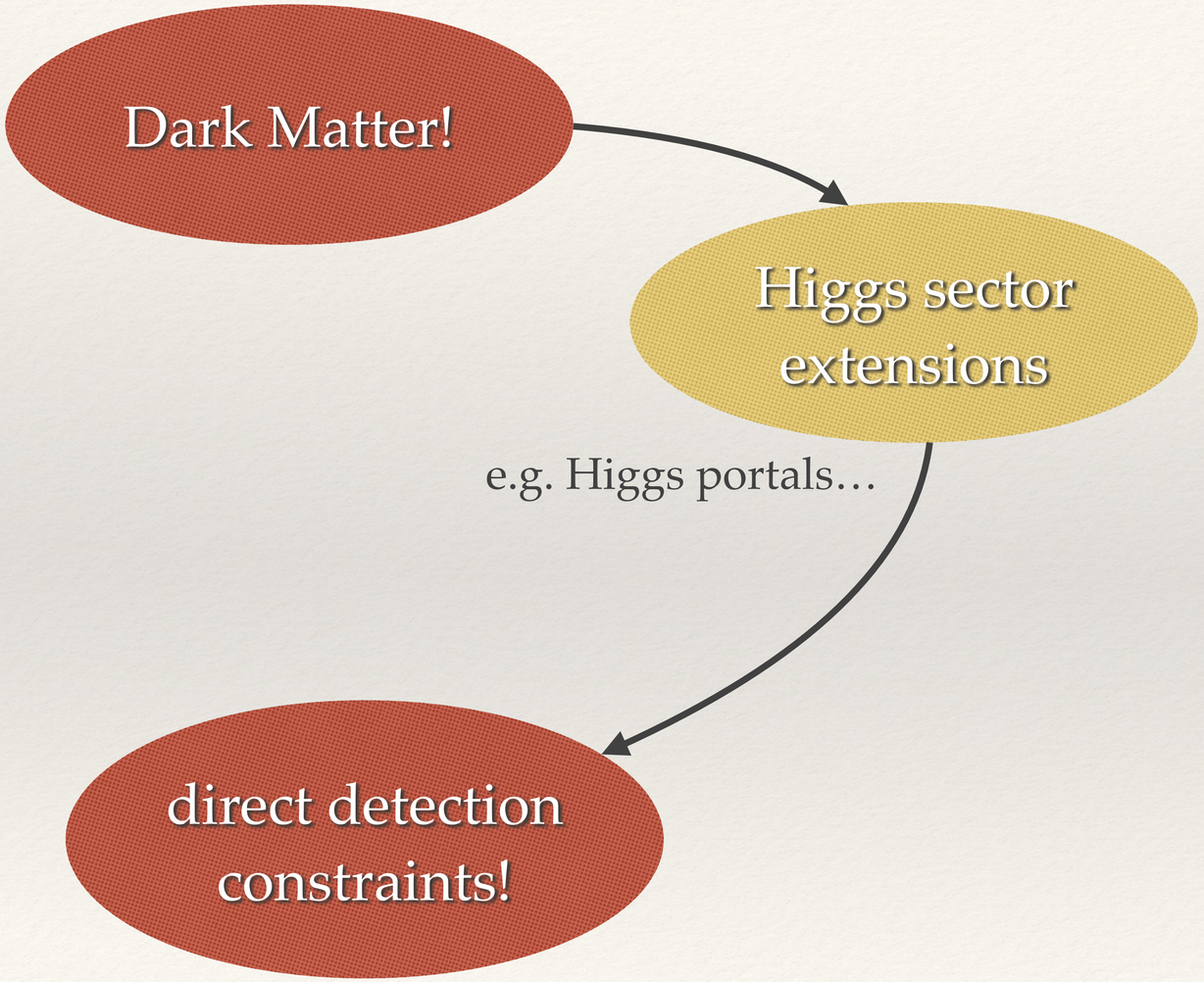


My eyes are turning to CEPC - a huge opportunity for discovery-led research

dark sectors?



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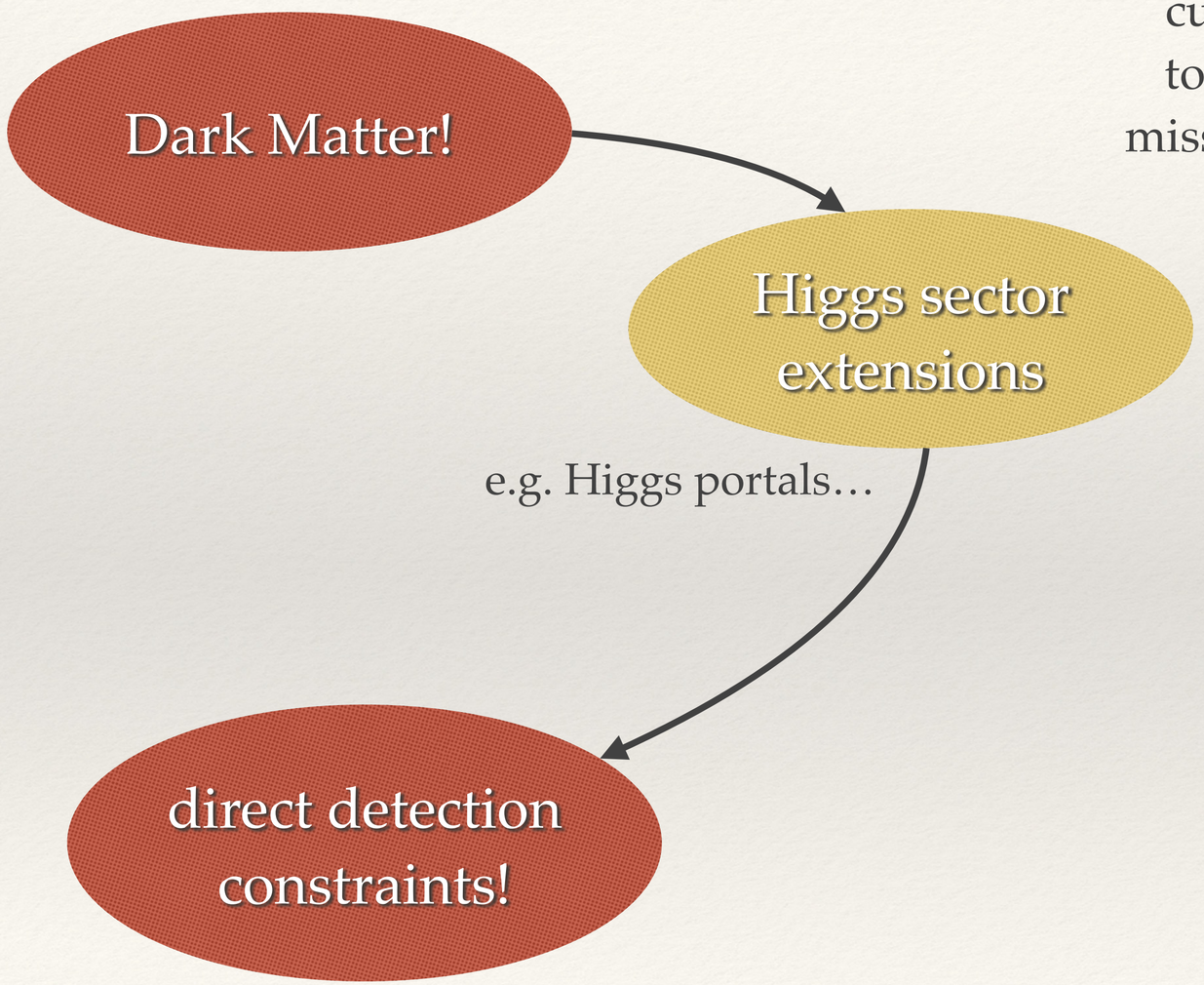

cusp-vs.-core
too big to fail
missing satellites
…

Why should a hidden sector be trivial?

dark sectors?

Dark Matter!

Higgs sector extensions

e.g. Higgs portals…

direct detection constraints!

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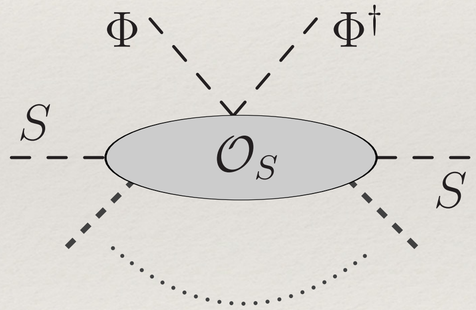

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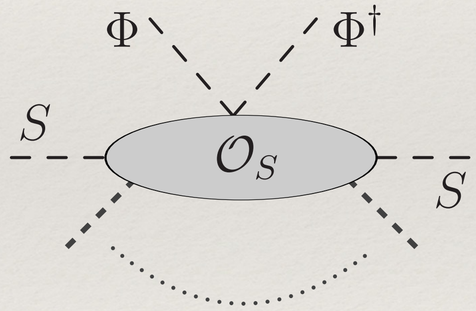

[Källén `52]
[Lehmann `54]

$$\langle 0|T\{S(x)S(0)\}|0\rangle = i\int_0^\infty \mathrm{d}q^2\,\rho_S(q^2)\int\frac{\mathrm{d}^4p}{(2\pi)^4}\,\frac{e^{-ip\cdot x}}{p^2-q^2+i\epsilon},$$

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spectral density contains vast amount of physically relevant information

poles, branch cuts, LSZ factors,…

(most complicated) dark sectors?

- extreme case: S arises as an interpolating field in broken CFT with large anomalous dimension ("unparticles") [Georgi `07]

$$2\pi\,\theta(q^2)\theta(q^0)\,\rho_S(q^2) = A_{d_\mathcal{U}}\,\theta(q^2)\theta(q^0)\,q^{2d_\mathcal{U}-4}$$

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$1 \le d_\mathcal{U} < 2$

$$-i\,\langle 0|T\{S(x)S(0)\}|0\rangle = \frac{A_{d_\mathcal{U}}}{2\sin(d_\mathcal{U}\pi)}\int\frac{\mathrm{d}^4p}{(2\pi)^4}\frac{e^{-ip\cdot x}}{(-p^2-i\epsilon)^{2-d_\mathcal{U}}} \overset{d_\mathcal{U}\to 1}{\longrightarrow} \int\frac{\mathrm{d}^4p}{(2\pi)^4}\frac{e^{-ip\cdot x}}{p^2+i\epsilon}.$$

- non-local theory with propagator scaling $\sim x^{-2d_\mathcal{U}}$ (expected for prim. operators)

- IR CFT breaking scale relatively straightforward: $q^2 \to q^2 - \mu^2$ [Fox et al. `07]

(not so complicated) dark sectors!

- extension to $d_{\mathcal{U}} > 2$ non-trivial: <u>local</u> subtraction terms to regularise behaviour

[Cacciapaglia et al. `07, `08]

perturbatively this means a momentum expansion in the S self-energies

- a similar argument carries over to amplitudes

$$\langle 0|\mathcal{O}_{\rm SM}(x_1)\mathcal{O}_S(x_2)\mathcal{O}_S(x_3)|0\rangle \sim \frac{1}{|x_{23}|^{2+2d_{\mathcal{U}}}}\,.$$

$$\sim \Phi^\dagger\Phi$$

….regularise divergent behaviour gives local effective theory [Froissart `61]

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

standard portal

emerging low-energy effective interactions

(not so complicated) dark sectors!

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- this Lagrangian is unqiue at dimension-6, tree-level and intact $\mathbb{Z}_2$ [Song et al.`23, `23]
- at a technical level transparant treatment in the HEFT e.g. [Anisha `24]
- such a theory is immediately constructed by SM + dark QCD SU(3)²/SU(3)

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

…big hullabaloo - but does it work?

Kinetically resurrecting the Higgs portal

- relax Higgs signal strength constraints for $\eta_S \approx \eta_{KS} \dfrac{m_H^2 - 2m_S^2}{\Lambda^2}$.

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

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- direct constraints (Higgs to invisible, on/offshell)
- indirect constraints

$$= -i\hat{\Sigma}_{HH}(q^2)$$

$$= -i\Sigma^{\text{Loop}}_{HH}(q^2) + i\left(\delta Z_H(q^2 - m_{\text{H}}^2) - \delta m_{\text{H}}^2\right) + i\frac{2a_{\Box\Box}}{v^2}q^4 ,$$

universal Higgs coupling mods

offshell probes (*HH*, *ZZ*, 4 tops)

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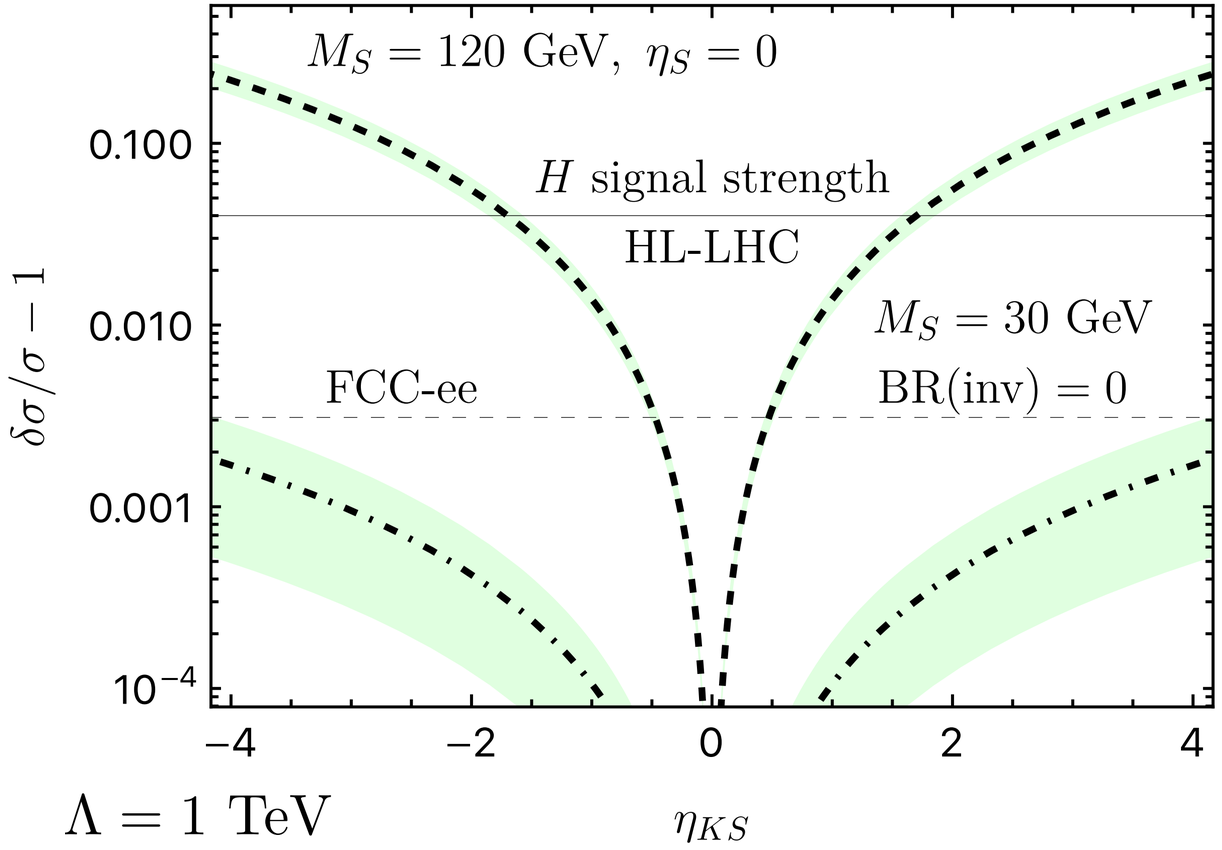
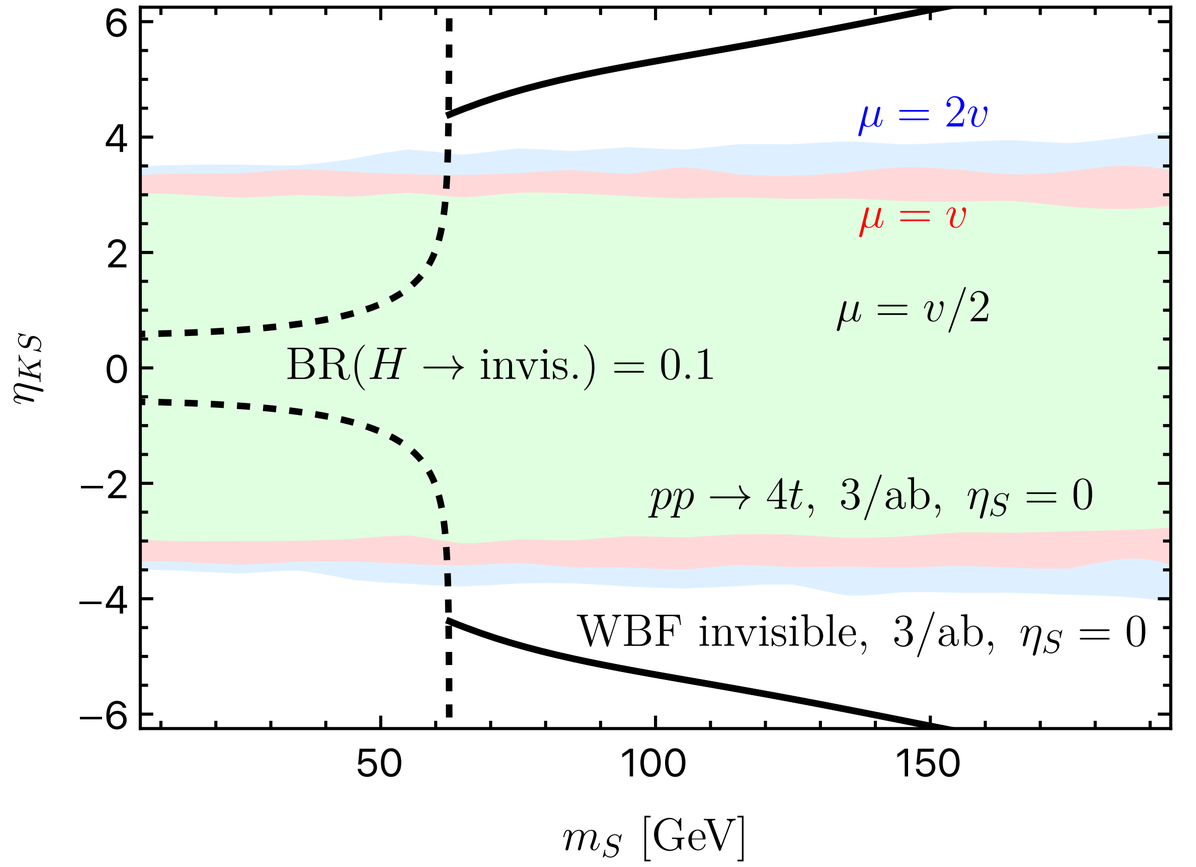
- violation of positivity [Adams `06]
- UV sensitivity/strong coupling

Kinetically resurrecting the Higgs portal: pheno

universal Higgs coupling modifications



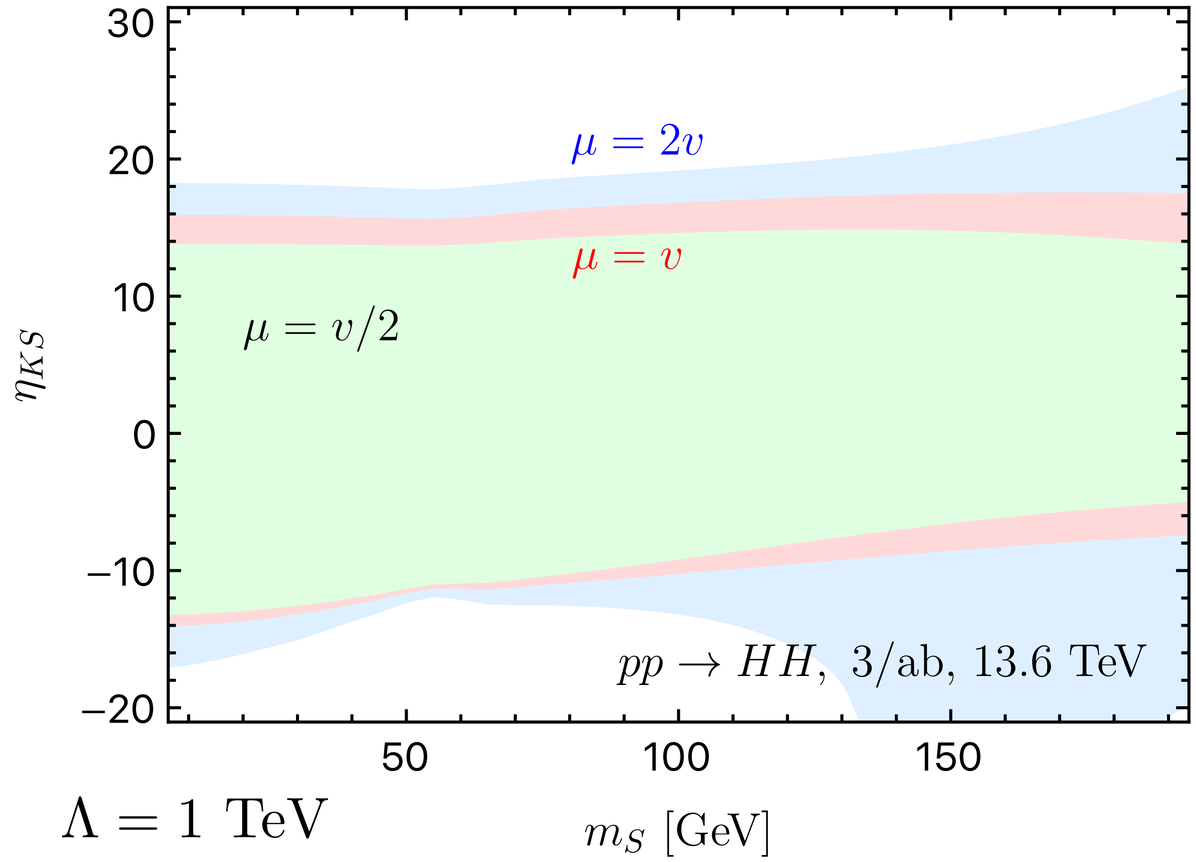
Higgs propagation in 4 top production



[Anisha et al. `25]

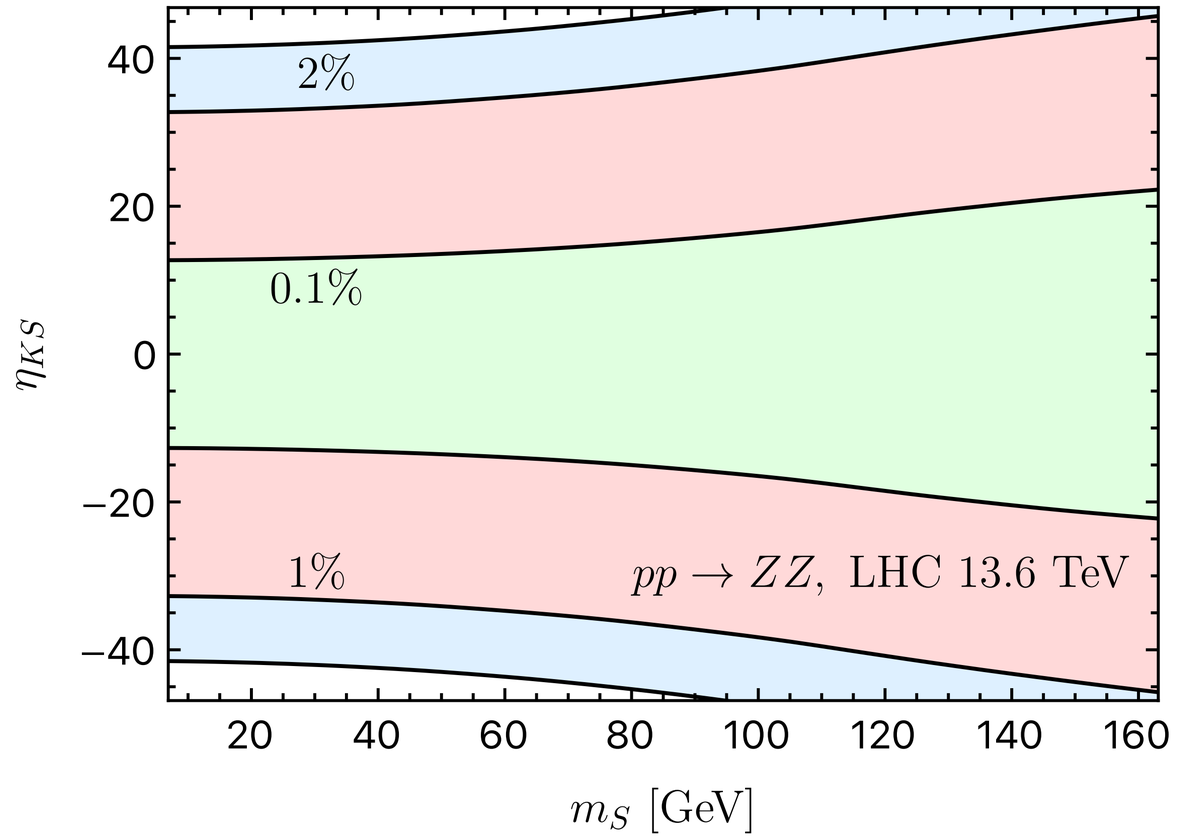
Kinetically resurrecting the Higgs portal: pheno

Higgs pair production (inc H^3 interactions)



offshell Higgs to Z pairs

[Anisha et al. `25]

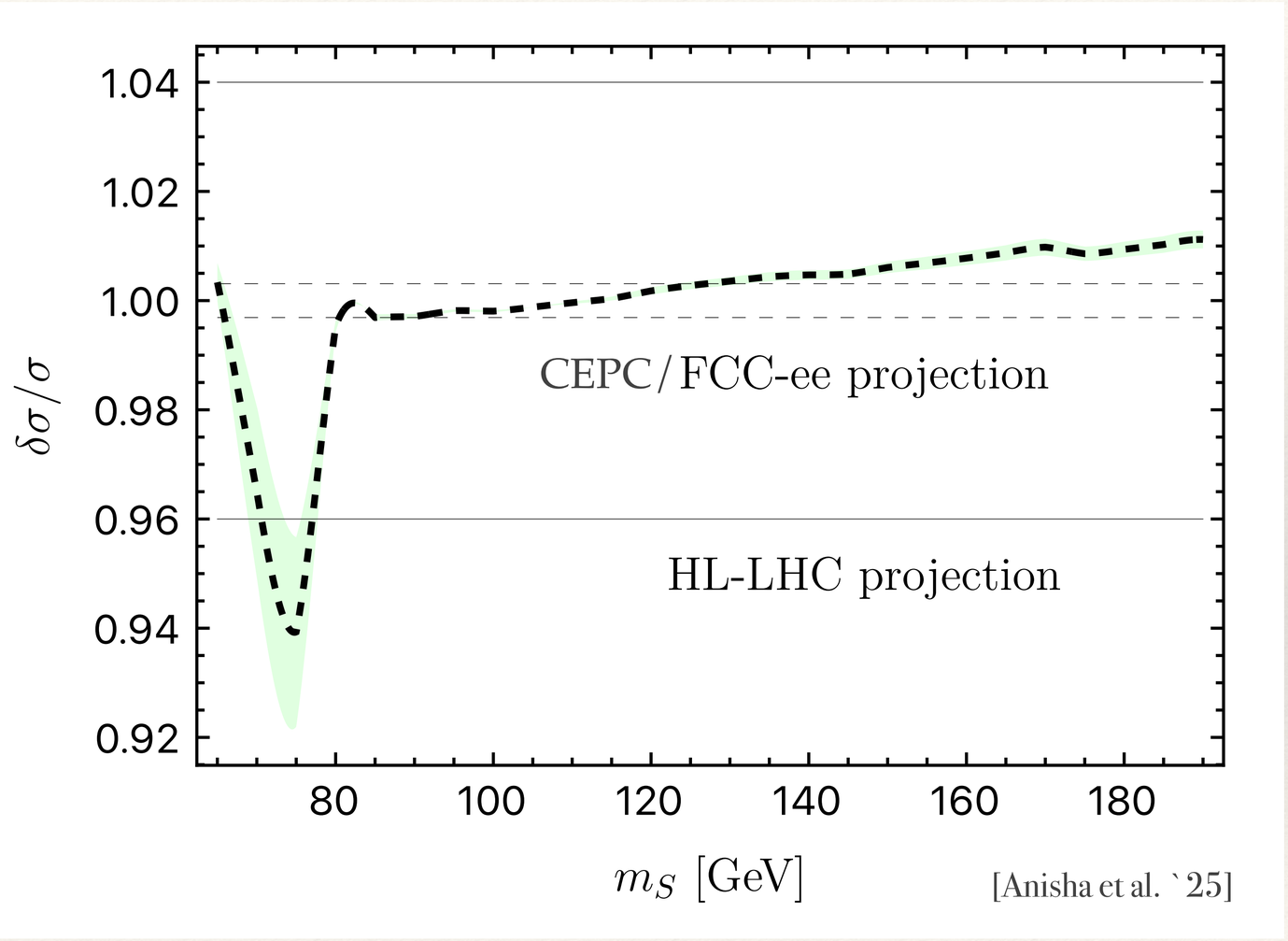


…sensitivity diluted through cancellations of momentum dependencies [CE, Giudice, Greljo, McCullough `19]

Kinetically resurrecting the Higgs portal: astrophysics

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

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



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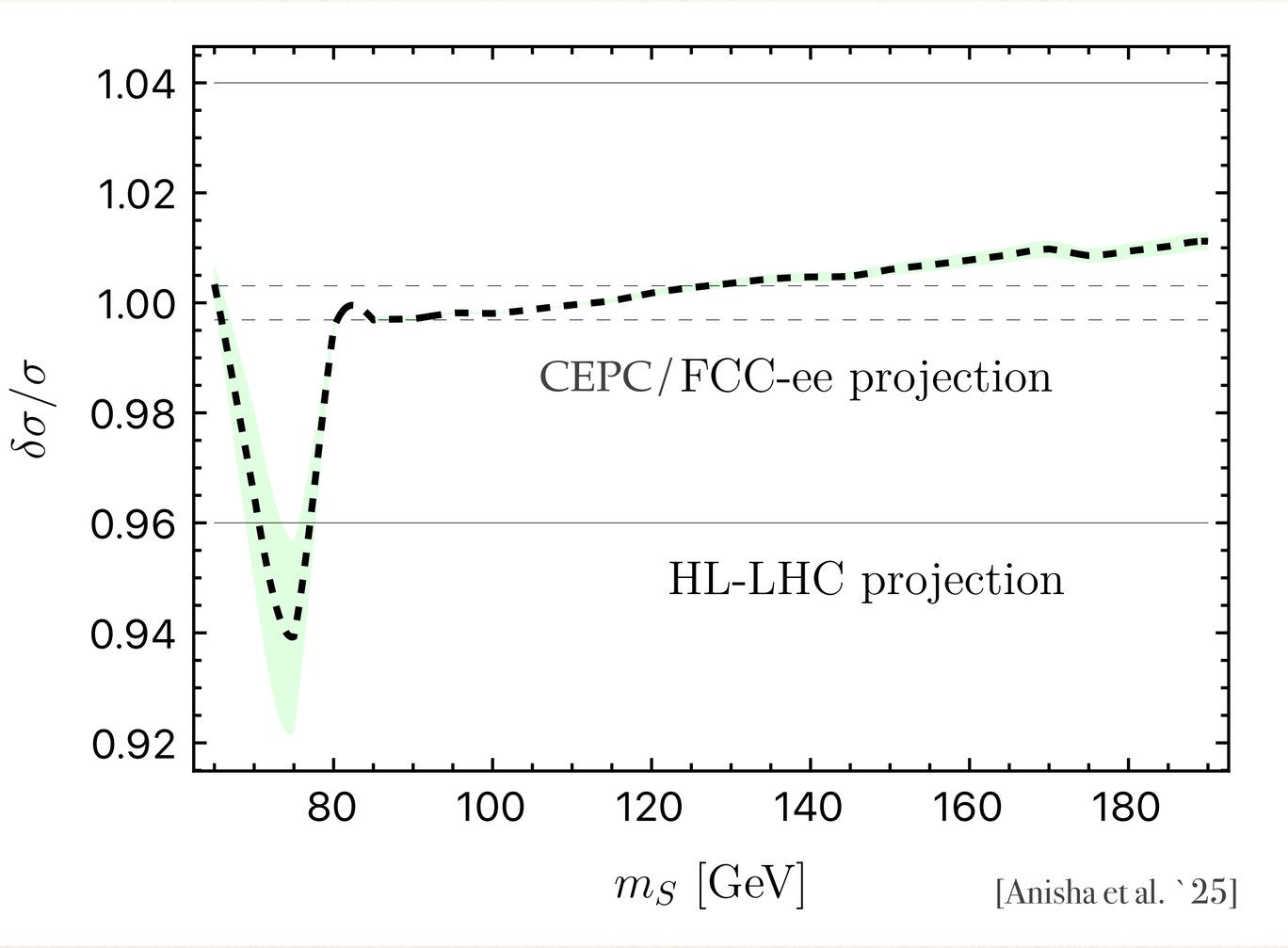

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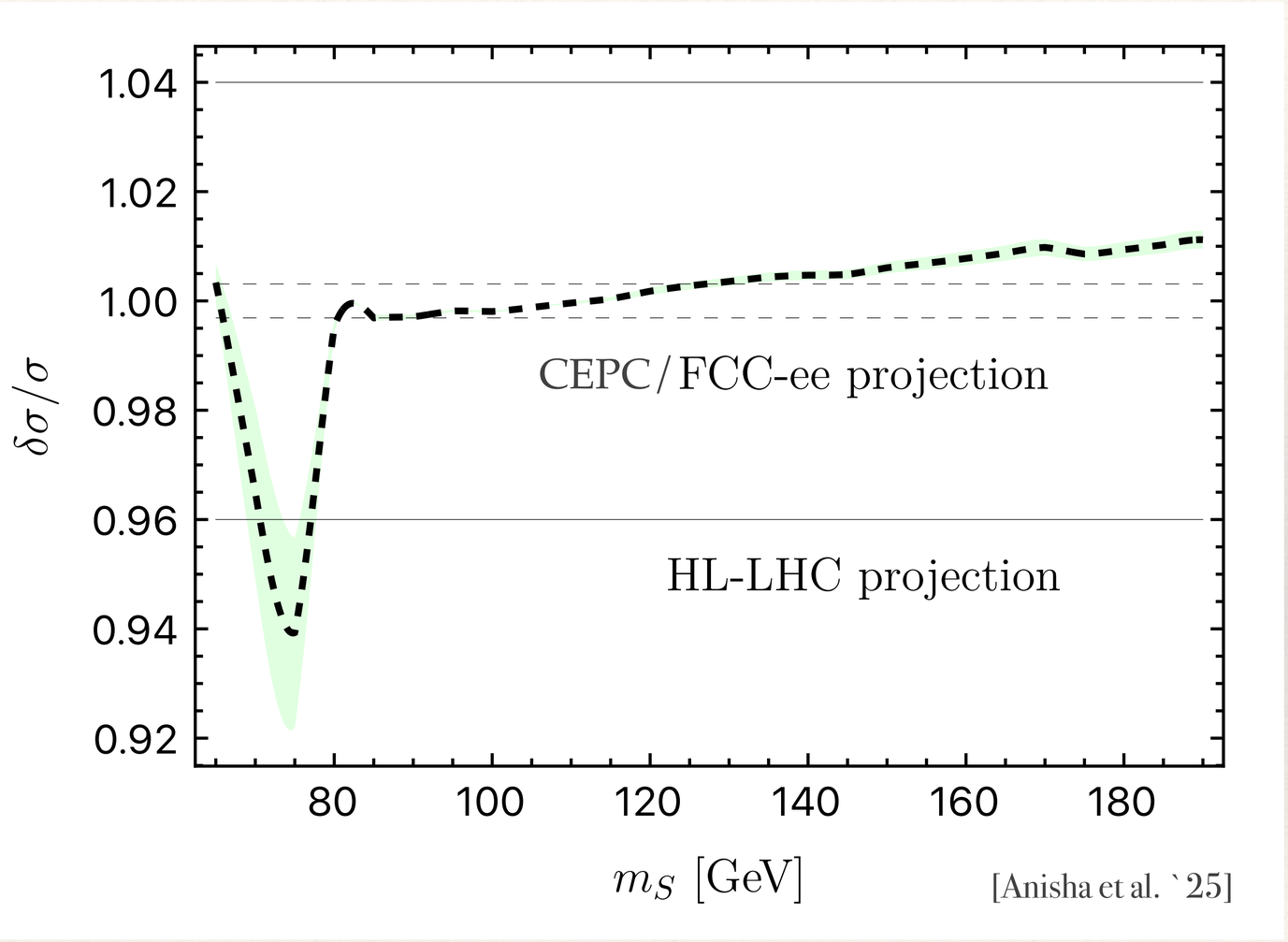

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Summary & Conclusions

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[many talks at this workshop!]

- …interpretation of reports of the dearth of new physics is greatly exaggerated!

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- the weak scale, or even collider-based particle physics, might not reveal it…

[many talks at this workshop!]

- …interpretation of reports of the dearth of new physics is greatly exaggerated!

- there is mounting theoretical evidence that a precision lepton (or high-energy proton) collider will signpost something more profound

Summary & Conclusions

- **We know that new physics is there!**

- the weak scale, or even collider-based particle physics, might not reveal it…

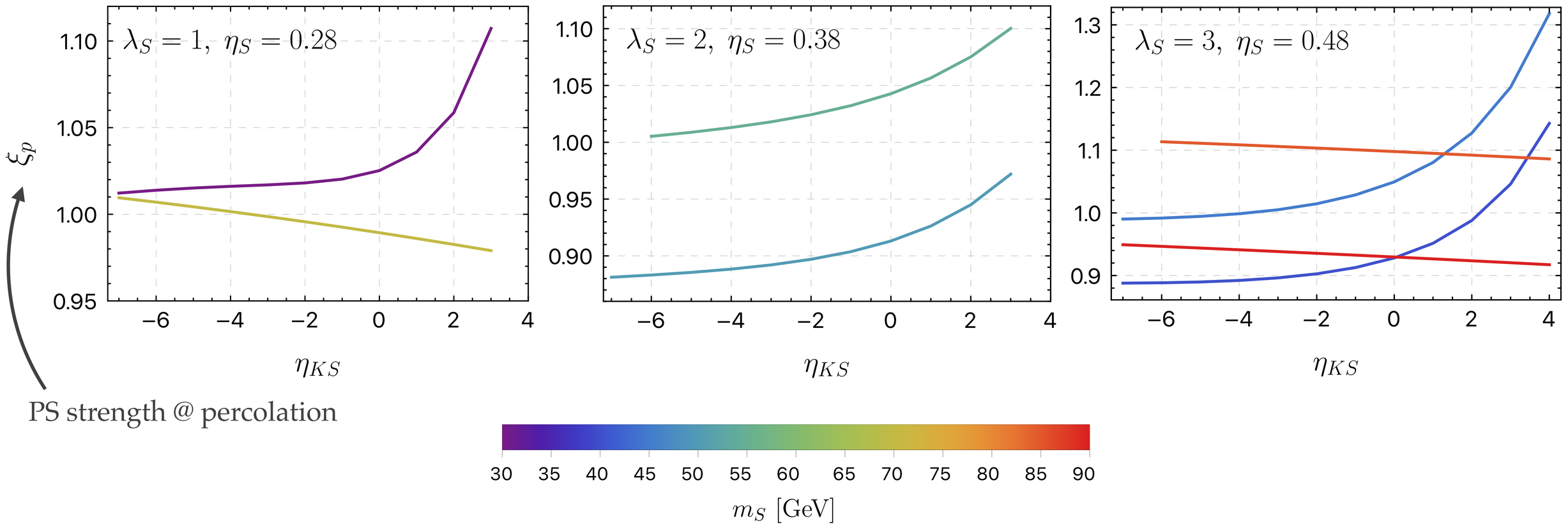
[many talks at this workshop!]

- …interpretation of reports of the dearth of new physics is greatly exaggerated!

- there is mounting theoretical evidence that a precision lepton (or high-energy proton) collider will signpost something more profound

- **…this might still happen towards the HL-LHC phase!**

Kinetically resurrecting the Higgs portal: SFOEWPT



…difficult with EFT alone, but additional UV degrees of freedom can drastically change this expectation….