Why do we need another collider?

Maria Ramos

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To continue the experimental programme

Our knowledge is still incomplete. Need to test the Standard Model in conditions we did not have access to before.

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Why do we need ....

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To build the FCC

Provides an integrated programme that **pushes both the precision and energy frontiers** up to unprecedent level.

FCC-ee produces LEP dataset in just 30s!

FCC-hh is expected to reach 7 times the energy of the LHC, and collect over 5 times the luminosity of the HL-LHC.

The problems we are searching for

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}\gamma^\mu D_\mu\psi + |D_\mu H|^2$$
$$- V_0 + \mu^2 H^\dagger H - \lambda(H^\dagger H)^2 + \bar{\psi}_L y_\psi H \psi_R + \text{h.c.}$$

$$+\mathcal{L}(m_\nu) + \mathcal{L}(\Omega_D) + \mathcal{L}(\eta_{\rm obs.}) + \dots$$

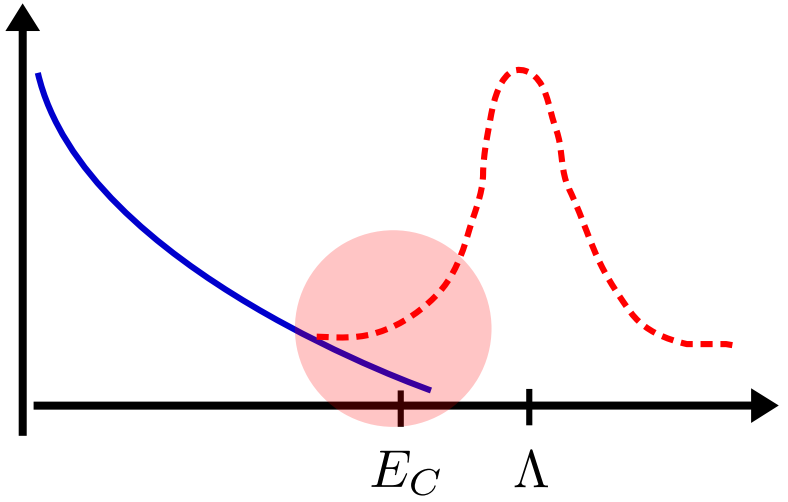
1. Parameters/correlations that remain loosely probed
(CKM elements, Higgs self coupling, Yukawa couplings to light gen., etc.)

2. Theoretical puzzles: **naturalness**, **vacuum stability**, **flavor**

3. **Missing pieces**

We do not know what is the theory that completes the SM, or at which scale it should appear.
Luckily, we do not have to guess.

The strategy to follow



We can search for the new physics indirectly, via **non-renormalizable couplings which are universal**.

The best guidance into high-E!

Λ ↓ p

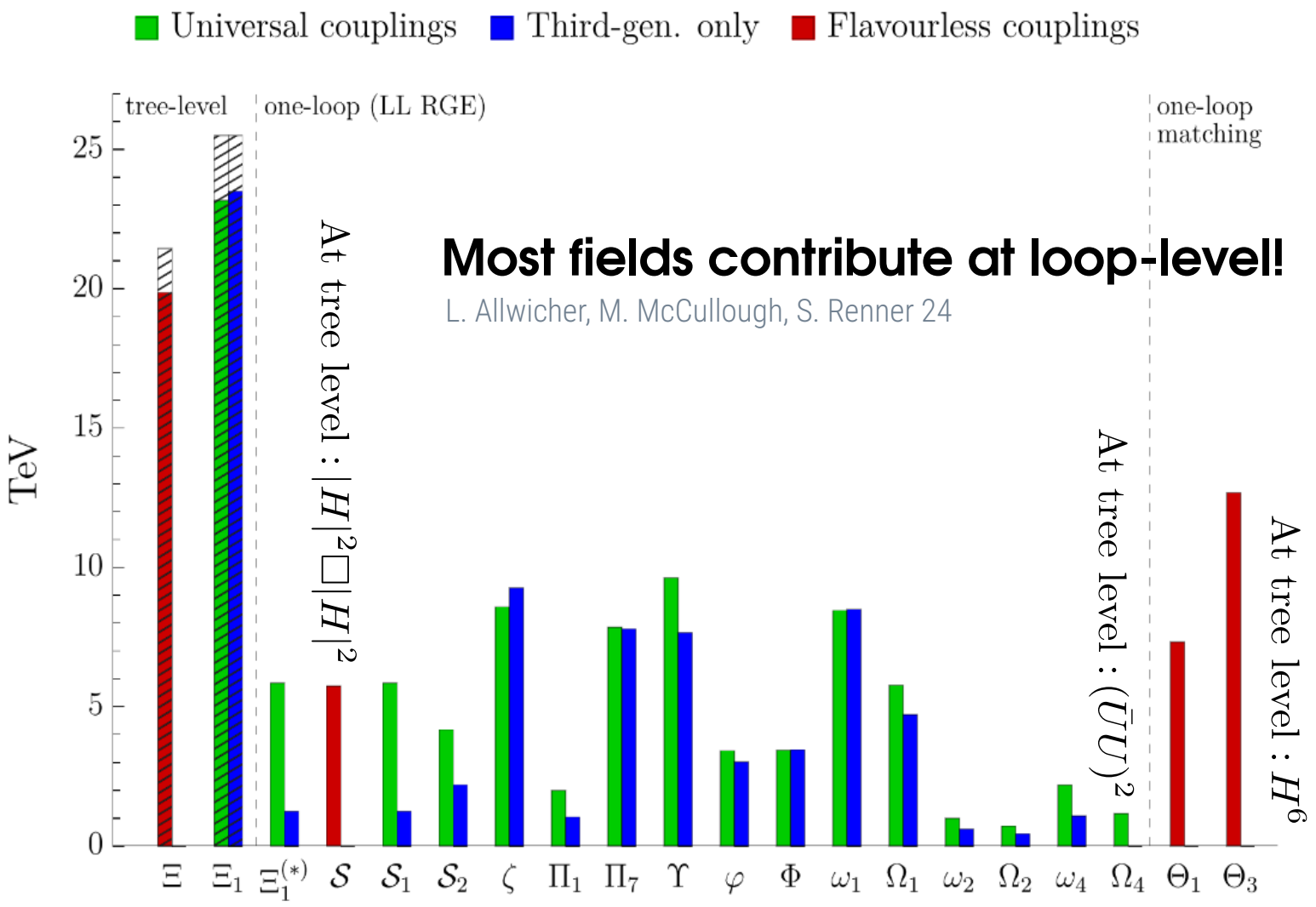
$$\mathcal{L}_{\rm UV} = ???$$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{\mathcal{L}_{\rm W}}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

$$\mathcal{L}_d = c_i \mathcal{O}_i$$
$$[\mathcal{O}_i] = d$$

Crucial implications to neutrino masses, proton decay, FCNCs, EWPT, ...

Tera-Z: where *nothing* can hide

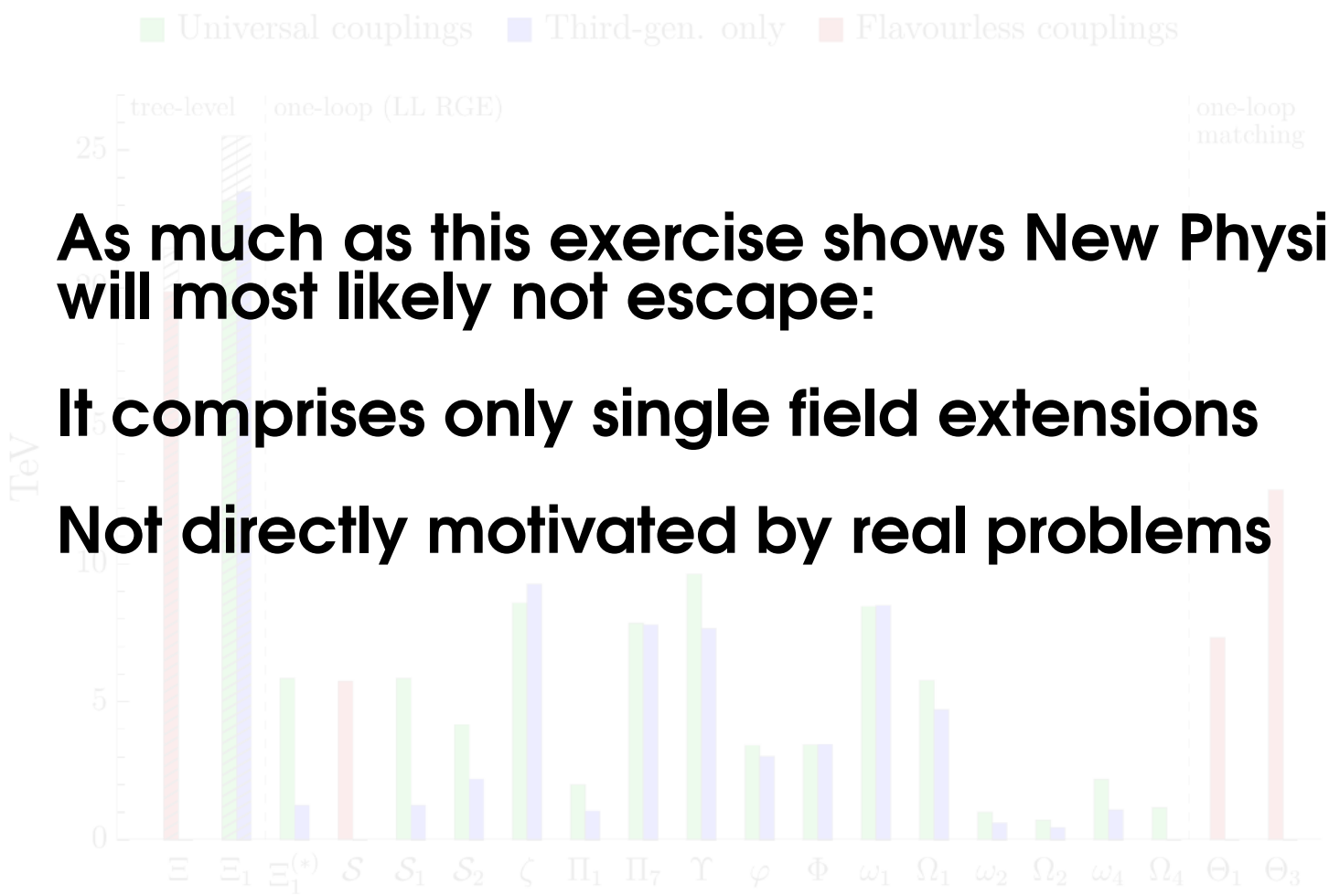


Most fields contribute at loop-level!

L. Allwicher, M. McCullough, S. Renner 24

Granada Dictionary: J. de Blas, J. C. Criado, M. Pérez-Victoria, J. Santiago 18

Tera-Z: where *nothing* can hide



As much as this exercise shows New Physics will most likely not escape:

It comprises only single field extensions

Not directly motivated by real problems

More concrete questions
What's up with the Higgs?

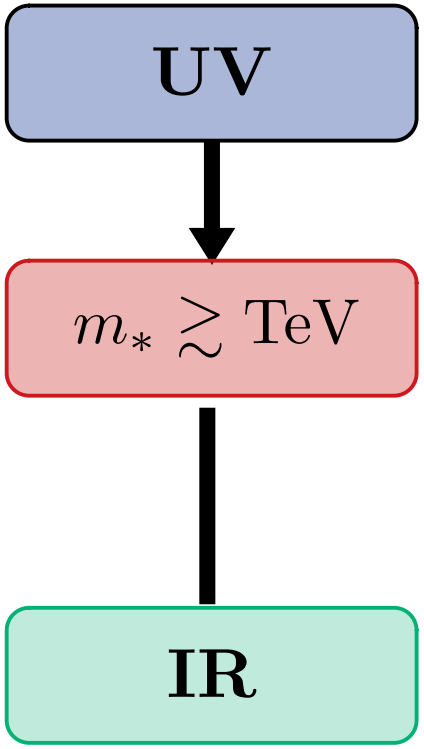
The Higgs is something we have never observed before.
An elementary scalar is in the restricted menu of spins that can appear in consistent theories (0, ½, 1, 3/2, 2).

The Higgs makes the SM self-consistent up to very high energies.
We can match a theory of massive spin d.o.f. into another of massless objects.

There is no protection for a small Higgs mass.
Why doesn't the Higgs have an enormous mass?

To answer these profound questions, need to know more and better the Higgs.

More concrete questions
Is the Higgs composite?



$\sim \rho_{\rm QCD}$ V_μ, L, Q $\mathcal{G} \sim \frac{\lambda}{\Lambda^{d_\mathcal{O}-5/2}} \bar{q}\mathcal{O}_F$ ℓ, q

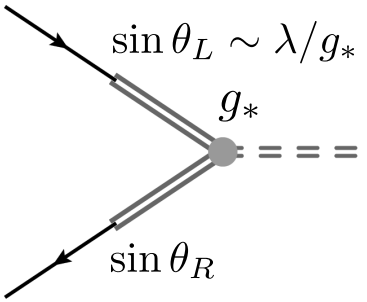
$\sim \pi_{\rm QCD}$ $H, \eta, \kappa \ldots$

D. B. Kaplan and H. Georgi 84
D. B. Kaplan, H. Georgi, and S. Dimopoulos 84
D. B. Kaplan. 91
K. Agashe, R. Contino, A. Pomarol 05

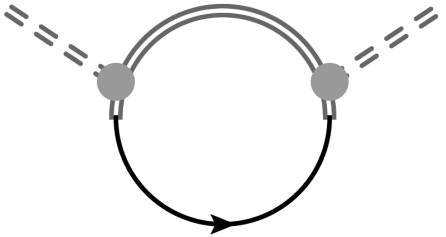
R. Barbieri, B. Bellazzini, V. S. Rychkov, and A. Varagnolo 07
B. Gripaios, A. Pomarol, F. Riva, and J. Serra 09
B. Bellazzini, C. Csáki, and J. Serra.14
Etc.

Non-minimal models can naturally evade several experimental constraints, while producing interesting candidates for the open problems in the SM.

More concrete questions
Smoking guns of compositeness



$\sim y^\psi$



$\sim N_c \frac{g_*^2 \lambda_t^2}{16\pi^2} f^2$

Top partners affect mostly the Higgs mass. Currently probed up to the TeV.
However, their properties depend on the model and on the **assumption of minimality**!

The pNGB Higgs EFT below the strong dynamics:

$\mathcal{H} \supset SO(4)$

$$D_\mu H^\dagger D^\mu H - \frac{1}{2f^2}(H^\dagger H)\Box(H^\dagger H) + \frac{1}{2f^2}(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H)$$

Other universal deviations:

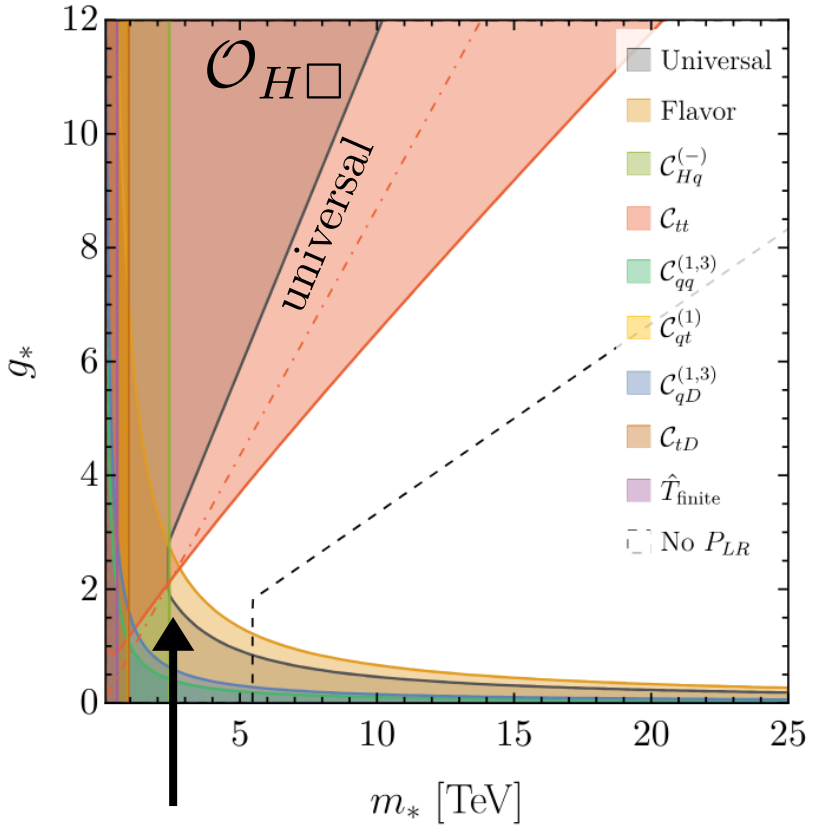
$m_* = g_* f$

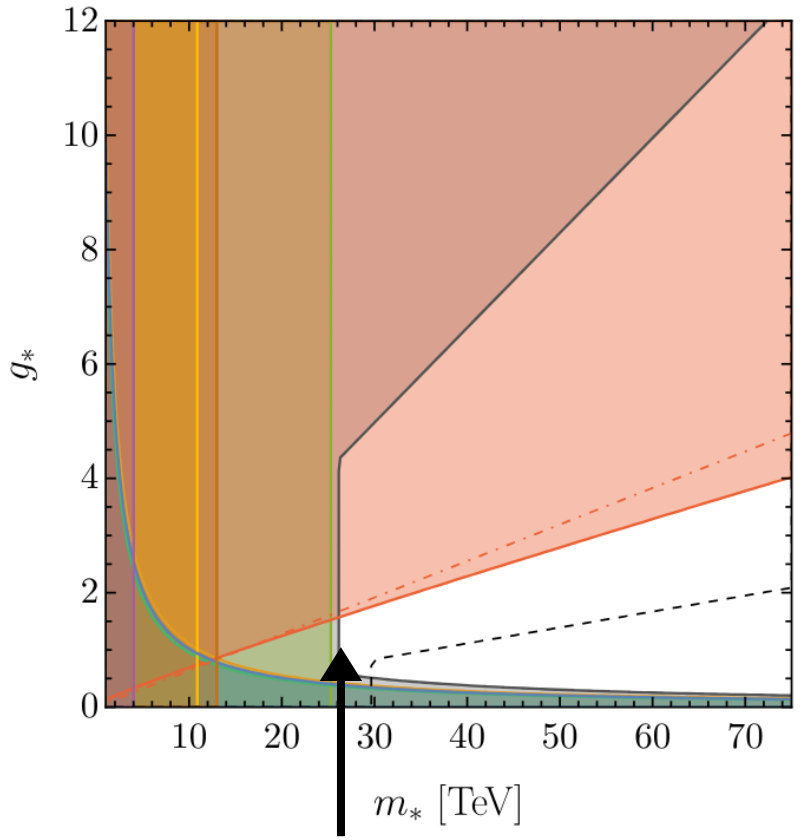
$$\frac{g^2 v^2}{4}\left(|W|^2 + \frac{1}{2c_w^2}Z^2\right)\left[2\sqrt{1-\xi}\,\frac{h}{v} + (1-2\xi)\,\frac{h^2}{v^2} - \frac{4}{3}\xi\sqrt{1-\xi}\,\frac{h^3}{v^3} + \ldots\right] \qquad \boxed{\xi = \frac{v}{f}}$$

See G. Panico and A. Wulzer 16 for a review.

More concrete questions
Smoking guns of compositeness

B. A. Stefanek 24





40x more point-like than the pion!

Radically new BSM?

*Non-universal bounds assume right compositeness scenario.

More concrete questions
What is dark matter?

Thermal WIMPs with EW interactions reproduce the relic abundance.

$$\Omega h^2 \approx 0.12 \sim \frac{2\times 10^{-26}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle_{\mathrm{th}}} \sim \frac{g^4/(100\mathrm{GeV})^2}{\langle\sigma v\rangle_{\mathrm{th}}}$$

Which WIMP?

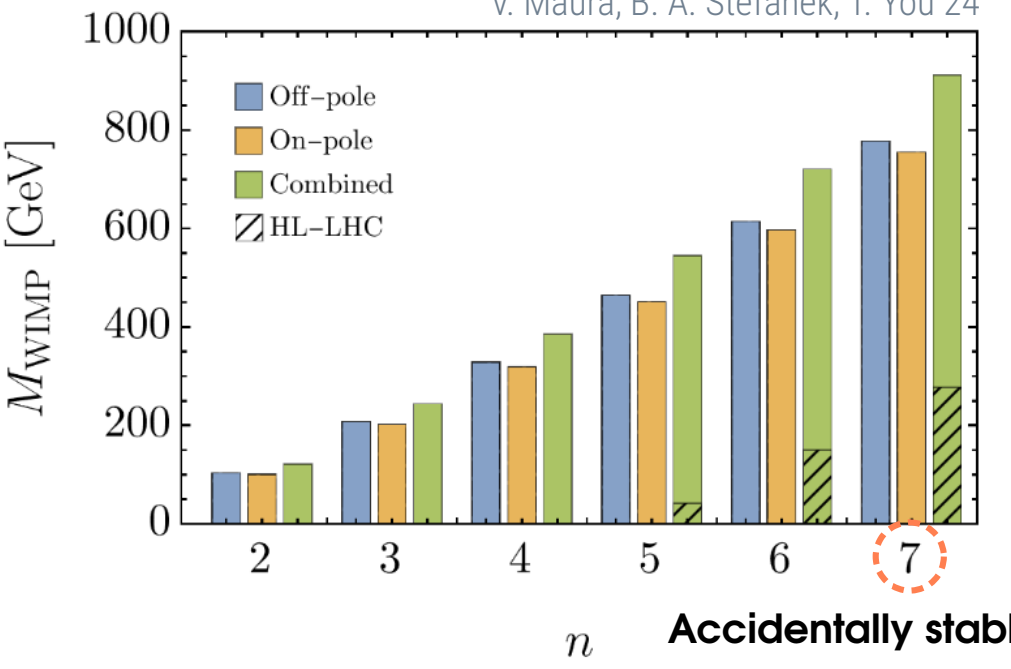
Assume that DM has only **minimal** interactions with the gauge sector.

$$m_{n=3} \sim 2\,\mathrm{TeV}$$
$$m_{n=5} \sim 5\,\mathrm{TeV}$$
$$m_{n=7} \sim 8\,\mathrm{TeV}$$

M. Cirelli, N. Fornengo, A. Strumia 07

Thermal masses updated in:
A. Mitridate, M. Redi, J. Smirnov, A. Strumia, 17
S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, 4, 2 D. Redigolo, L. Vittorio 22

V. Maura, B. A. Stefanek, T. You 24



Accidentally stable!

More concrete questions
What is dark matter?

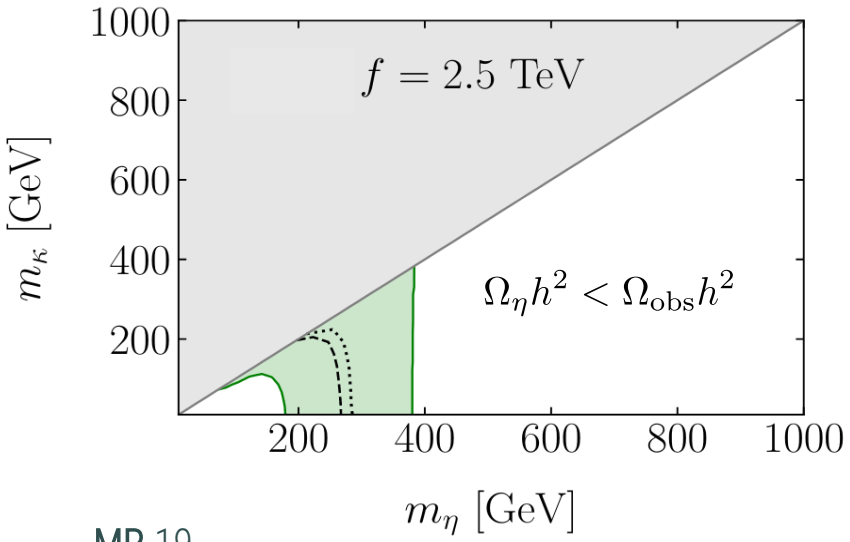
pNGB WIMP singlet (η) from a **CHM:**

$$\vec{\pi} = \{h,\ \kappa,\ \dots\}$$

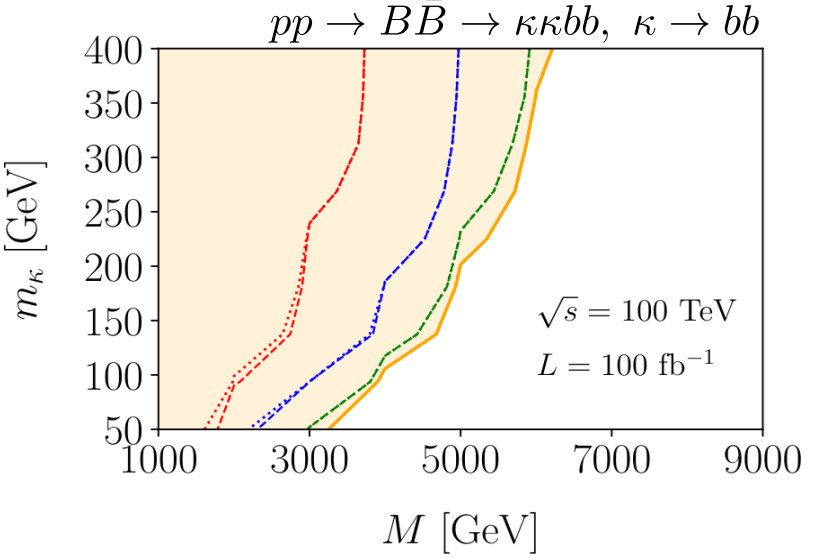
M. Frigerio, A. Pomarol, F. Riva, A. Urbano 12

$$\mathcal{L}_{\partial^2} \supset \frac{(\eta\partial_\mu\eta)(\pi_i\partial^\mu\pi^i)}{f^2} \rightarrow \sigma v \propto \left(\lambda - \frac{4m_\eta^2}{f^2}\right)^2$$

Non-minimal coset enhances the DM annihilation and allows it to freeze-out in the dark



Can be probed with novel decays of top partners at high-E colliders!

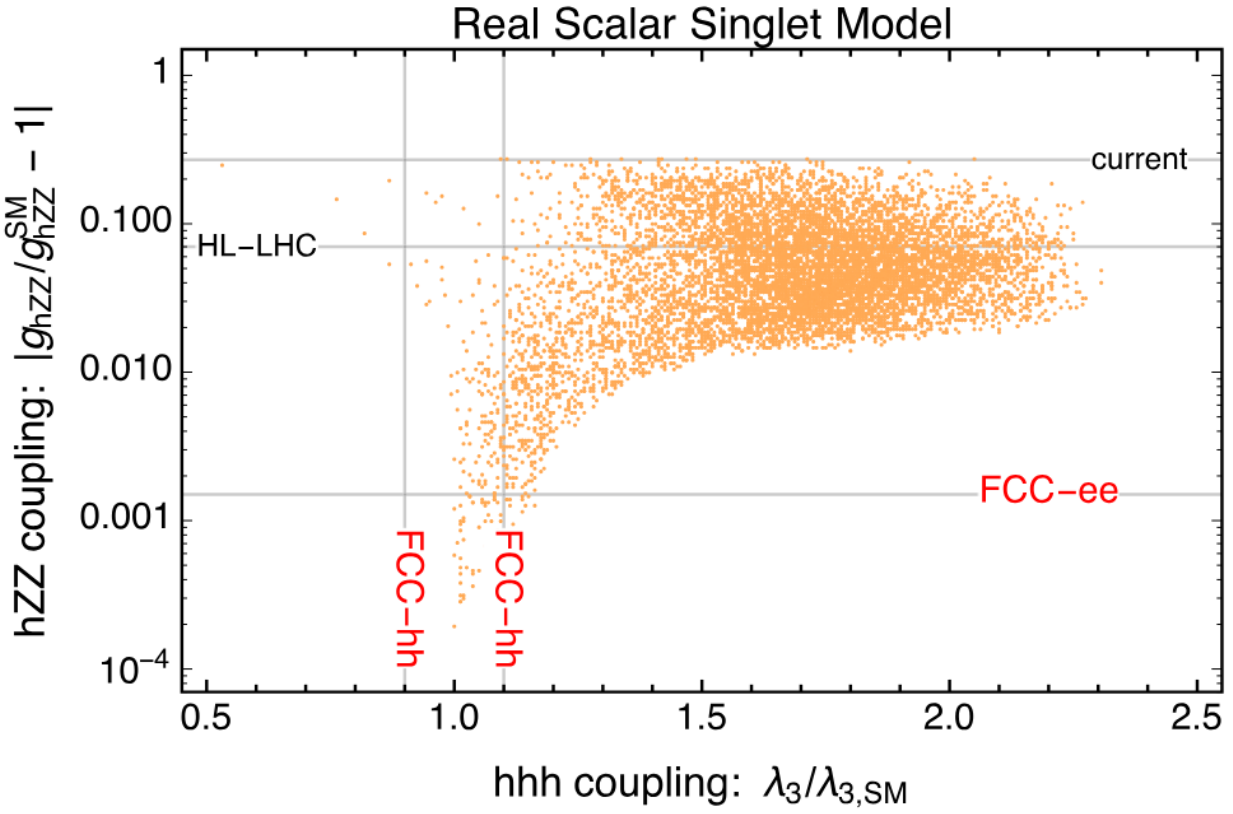


MR 19

See also: R. Balkin, M. Ruhdorfer, E. Salvioni , A. Weiler 17,18, M. Ruhdorfer, E. Salvioni, A. Weiler 19.

More concrete questions
What is the origin of matter

The FCC can help to determine the thermal history of EWSB



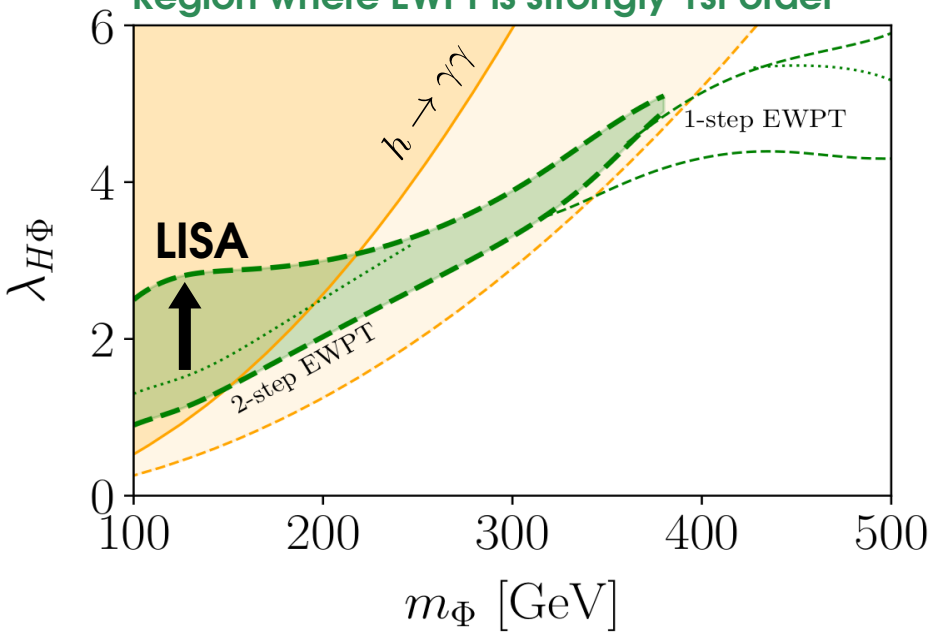
P. Huang, A. J. Long, L. Wang 17
FCC CDR Vol. 1

More concrete questions
Complementarity with astrophysics

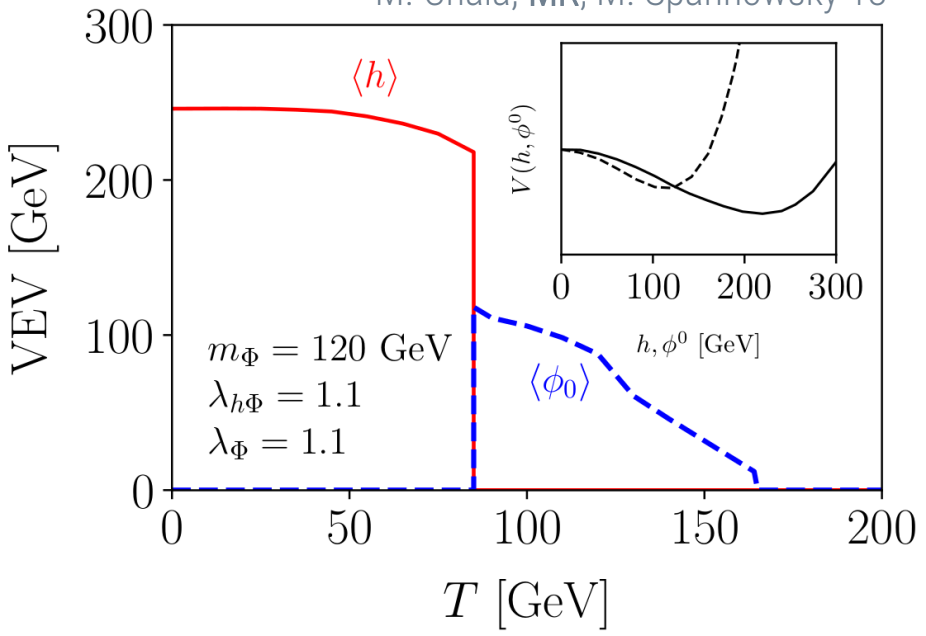
$$V = \frac{1}{2}m_h^2 H^2 + \frac{1}{2}m_\phi \Phi^2 - \frac{\lambda_h}{4}H^4 + \frac{\lambda_\phi}{4}\Phi^4$$

Pseudoscalar triplet

Region where EWPT is strongly 1st order



M. Chala, **MR**, M. Spannowsky 18



$$m_t \sim \langle h \rangle \left[y_t + i\frac{c}{f}\langle \phi_0 \rangle \right] = |m_t| e^{i\Theta_t}$$

A 2-step EWPT can provide the necessary **CPV at high-T**!

See also J. R. Espinosa, B. Gripaios, T. Konstandin, F. Riva 12

More concrete questions
Complementarity with astrophysics

$$V = \frac{1}{2}m_h^2 H^2 + \frac{1}{2}m_\phi \Phi^2 - \frac{\lambda_h}{4}H^4 + \frac{\lambda_\phi}{4}\Phi^4$$

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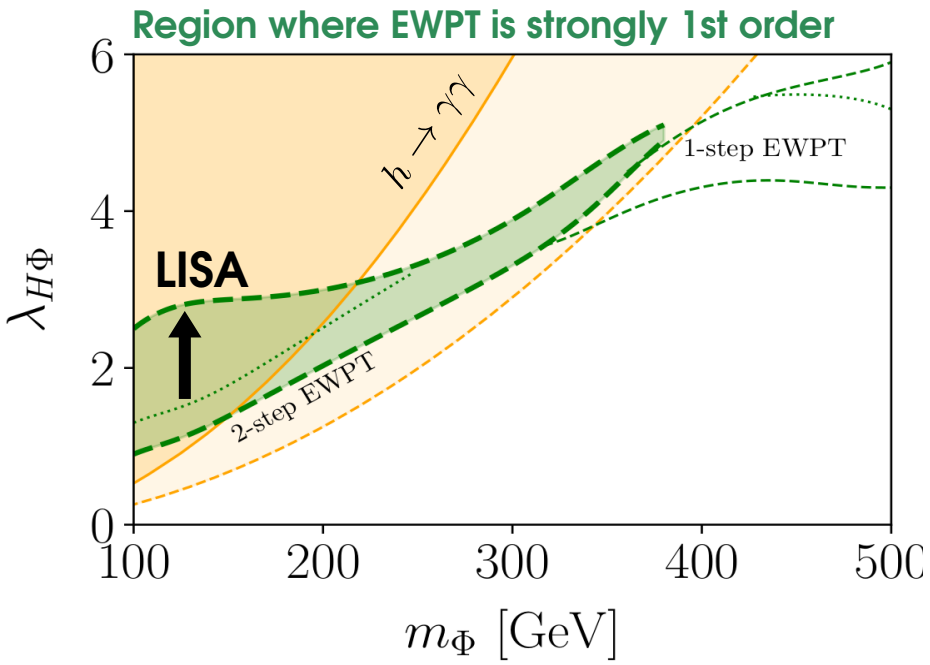

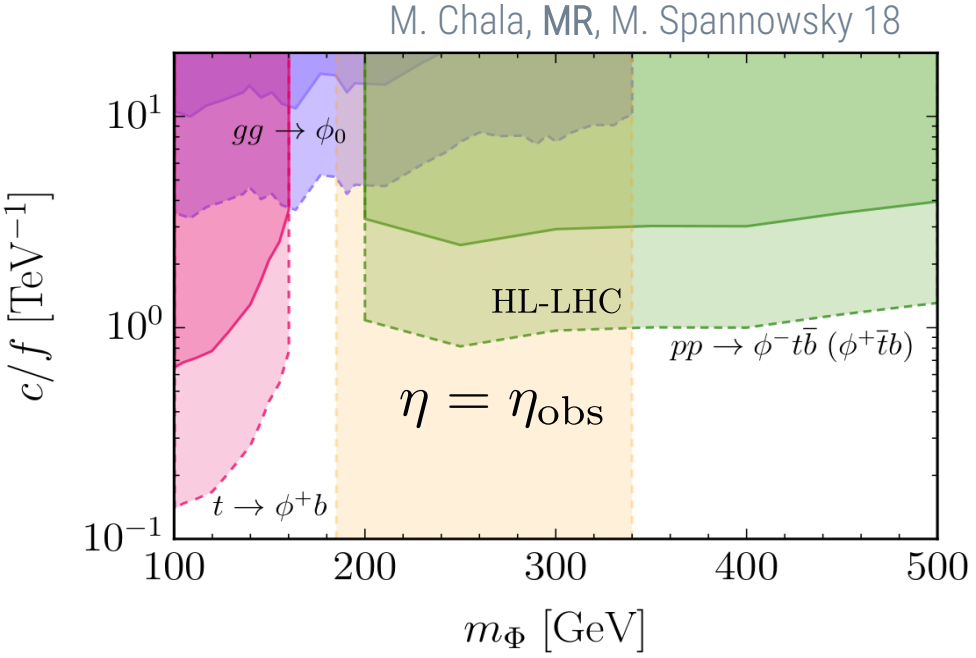

The parameter space where EWSB can occur **could be probed at the HL-LHC via**

$$pp \to \phi^\pm \phi^0 \to \bar{t}b(t\bar{b})\bar{b}b$$

Why do we need another collider?

Profound questions require exploration into the precision and high-energy frontiers.

The future of particle physics cannot be delayed and we should make the most spectacular bet that we can at the moment. That is the FCC.

Many other BSM motivations to learn about in this week's workshop!

Such as the FCC power to constrain ALPs, HNLs, CPV, flavor physics, etc.