ROMA TRE
UNIVERSITÀ DEGLI STUDI

**XXII Roma Tre Topical Seminar on Subnuclear Physics**

**“Future colliders: physics reach and enabling technologies"**

*Roma, 29 Jan 2020*

# Future challenges of particle physics: the collider perspective


*Michelangelo L. Mangano*
*TH Department*
*CERN, Geneva*

- **Why colliders ?**

- **Which collider ?**

# The future of particle physics relies on

- having important questions to pursue
- creating opportunities to answer them
- being able to constantly add to our knowledge, while seeking those answers

# The important questions

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Origin of inflation
  - Quantum gravity
  - …

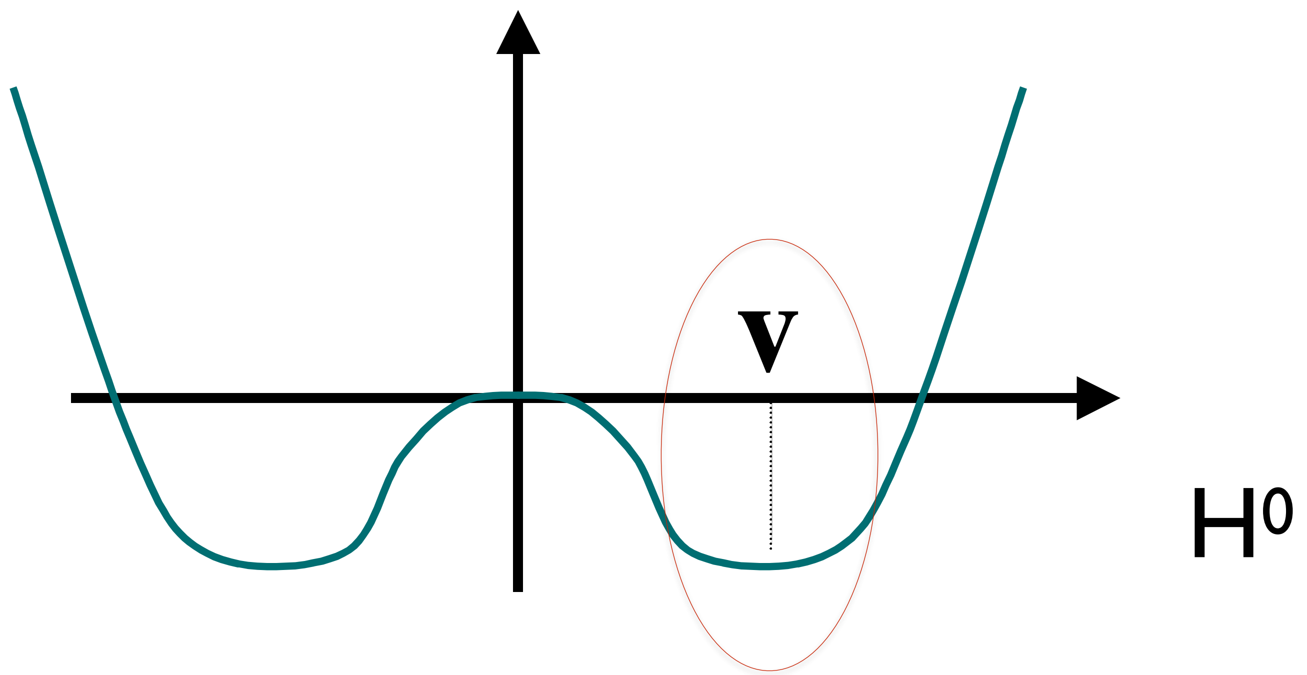
# The opportunities

**For most of these questions, the path to an answer is not uniquely defined.**

- Two examples:
  - DM: could be anything from fuzzy $10^{-22}$ eV scalars, to O(TeV) WIMPs, to multi-$M_\odot$ primordial BHs, passing through axions and sub-GeV DM
    - ***a vast array of expts*** is needed, even though most of them will end up empty-handed…
  - Neutrino masses: could originate anywhere between the EW and the GUT scale
    - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \to e\gamma$, $H \to \mu\tau$, …): as for DM, ***a broad range of options***

- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/inflation/dark energy, …)

***One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction….***

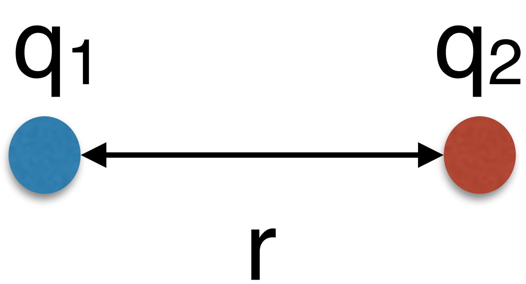



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

**Who ordered that ?**

***We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics***

# Electromagnetic vs Higgs dynamics

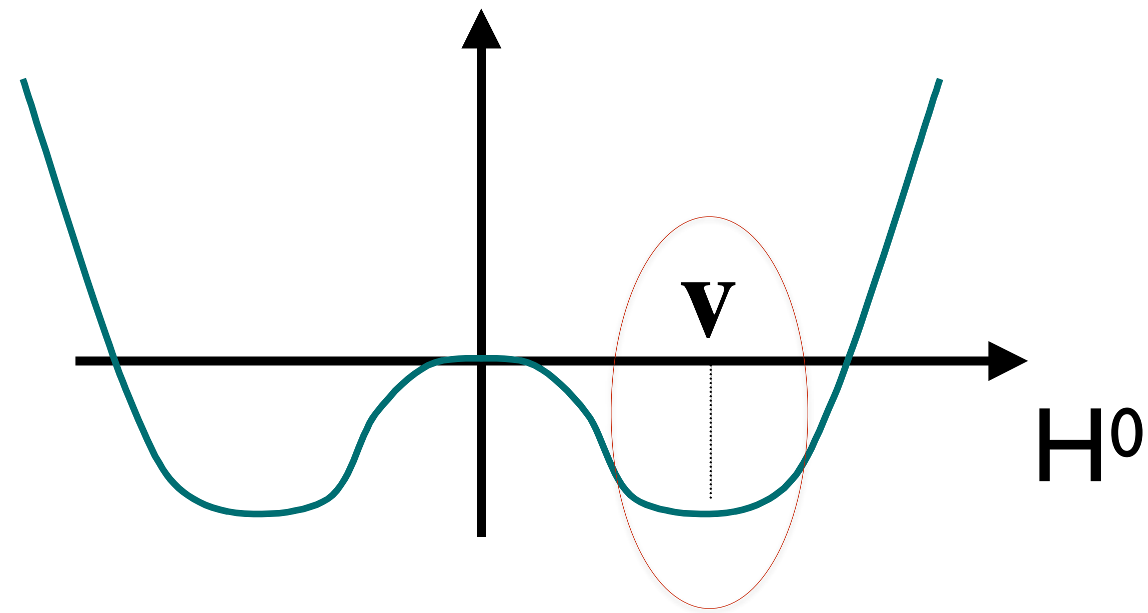



quantized, in units of fixed charge

$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

sign fixed by photon spin

power determined by gauge invariance/charge conservation/Gauss theorem




any function of $|H|^2$ would be ok wrt known symmetries

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

# a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

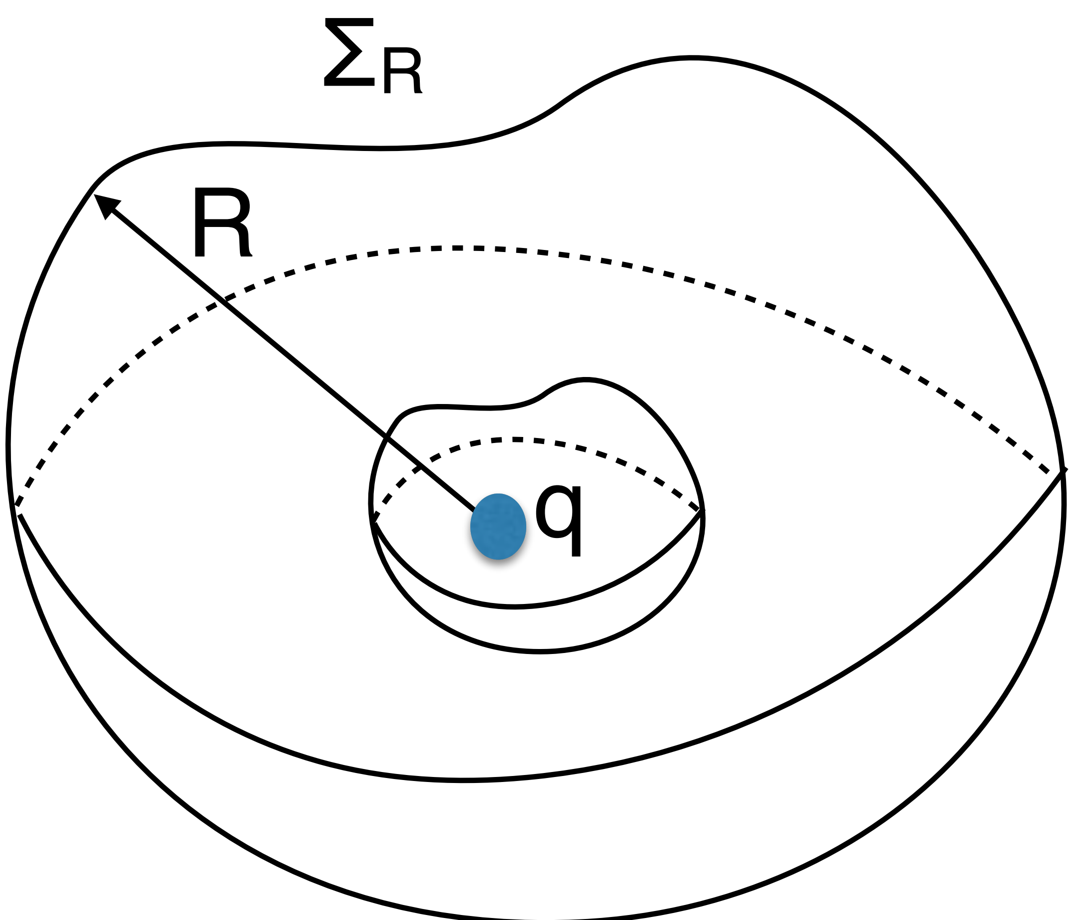
- For superconductivity, this came later, with the identification of $e^-e^-$ Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either case we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

# examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2 + g'^2$ , it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus $m_H$ and $\lambda$) determined by the parameters of SUSY breaking
- …

# Decoupling of high-frequency modes

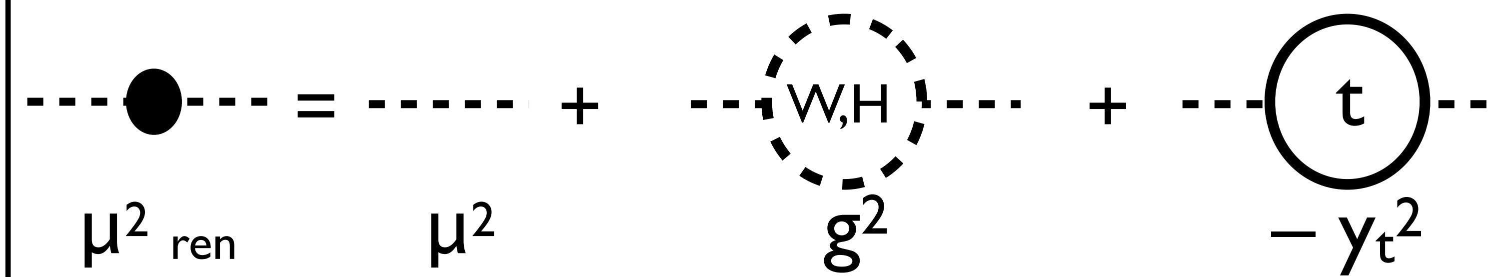
**E&M**



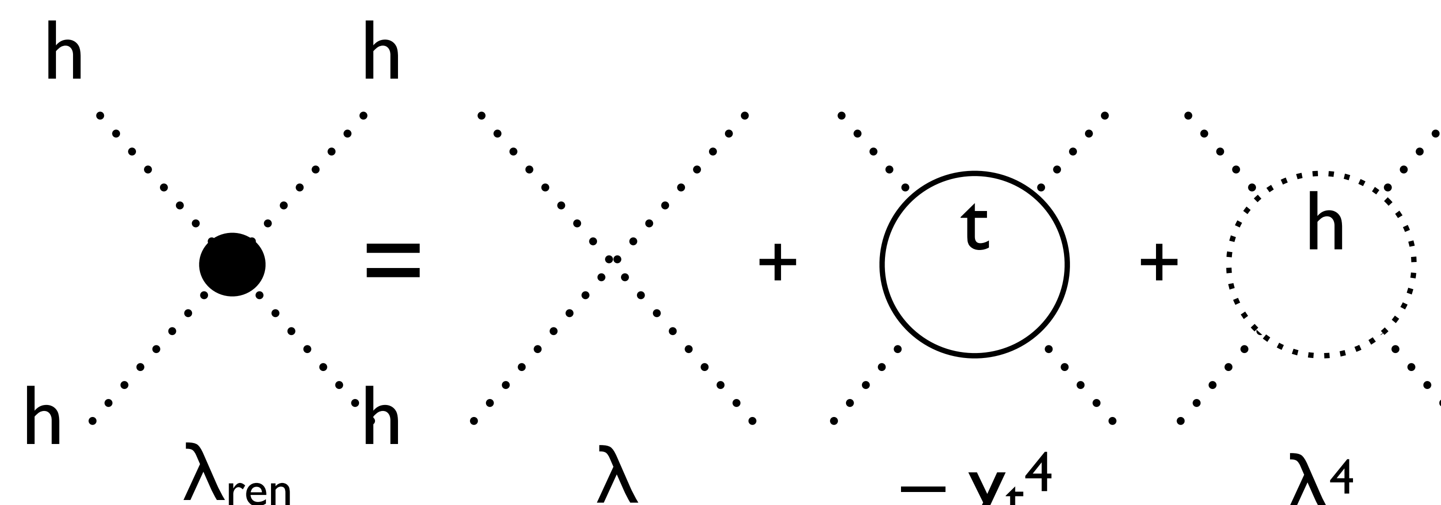

$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

short-scale physics does not alter the charge seen at large scales

$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$




$\Delta\mu^2 \sim ( c_B \, m_B^2 - c_F \, m_F^2 ) \times ( \Lambda / v)^2$




$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \quad \propto a \, m_H^4 - b \, m_t^4$$

high-energy modes can change size and sign of both $\mu^2$ and $\lambda$, dramatically altering the stability and dynamics => **hierarchy problem**

# bottom line

- The Higgs dynamics is sensitive to all that happens at any scale larger than the Higgs mass !!! A very unnatural **fine tuning** is required to protect the Higgs dynamics from the dynamics at high energy
- This issue goes under the name of **hierarchy problem**
- Solutions to the hierarchy problem require the introduction of new symmetries (typically leading to the existence of new particles), which decouple the high-energy modes and allow the Higgs and its dynamics to be defined at the "natural" scale defined by the measured parameters v and $m_H$

  ⇒ **naturalness**

# The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is likewise unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.

- Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties

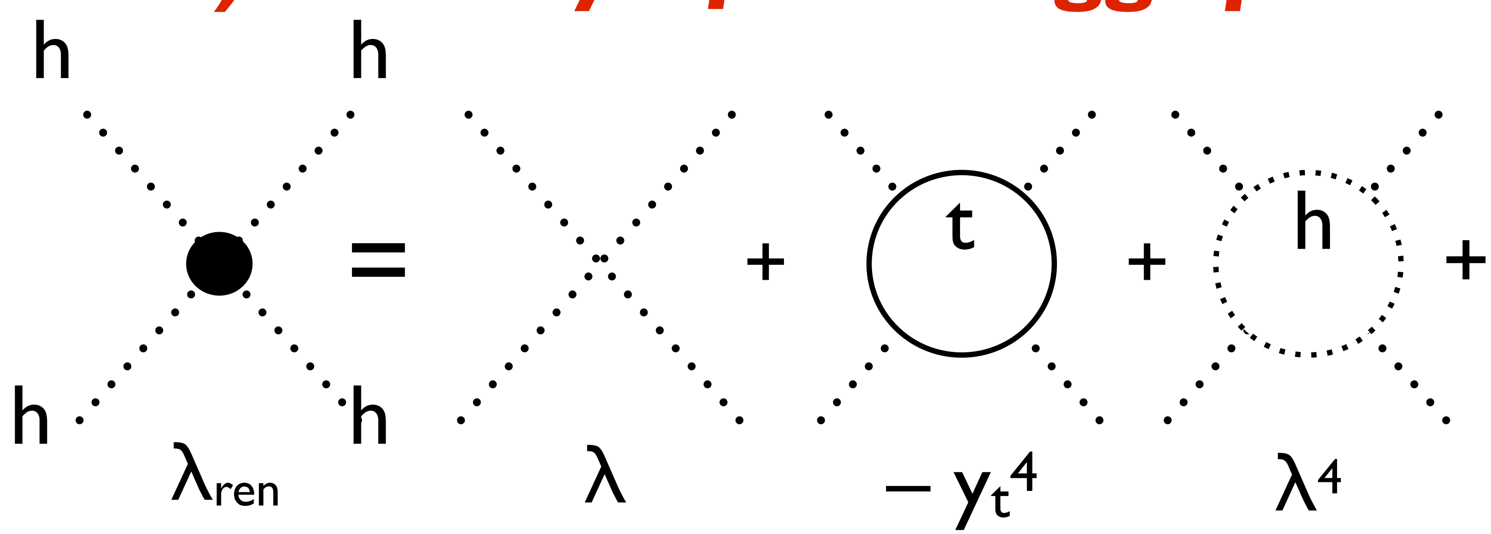
➡ *the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which can only rely on a future generation of colliders*

# Other important open issues on the Higgs sector

- Is the Higgs elementary, or composite?
- Is it Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^{\pm}$, $A^0$, $H^{\pm\pm}$, ... , EW-singlets, ....) ?
  - Do all SM families get their mass from the **<u>same</u>** Higgs field?
  - Do $I_3$=1/2 fermions (up-type quarks) get their mass from the **<u>same</u>** Higgs field as $I_3$=–1/2 fermions (down-type quarks and charged leptons)?
- Do Higgs couplings conserve flavour? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

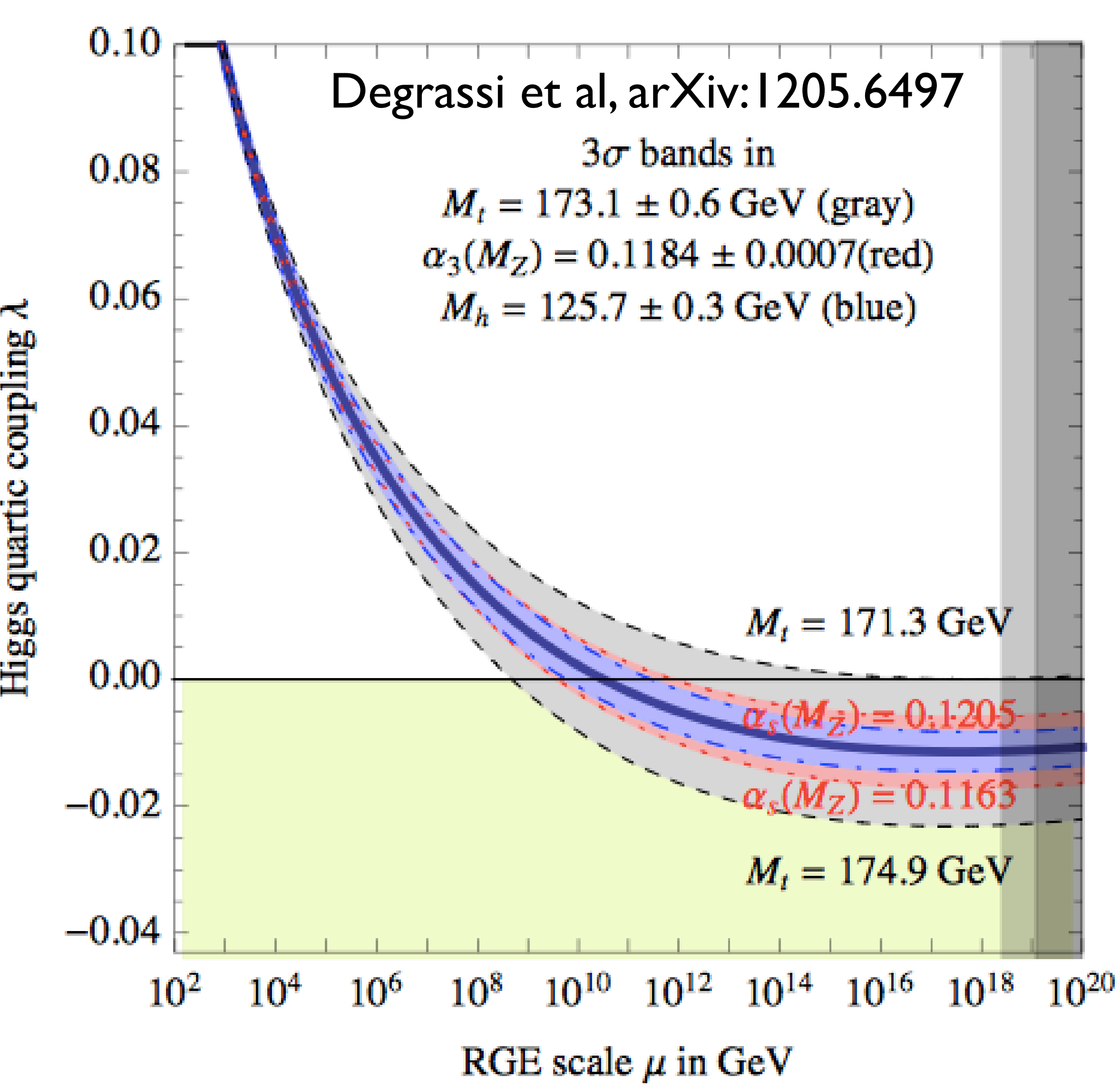
# *(meta)Stability of the Higgs potential*

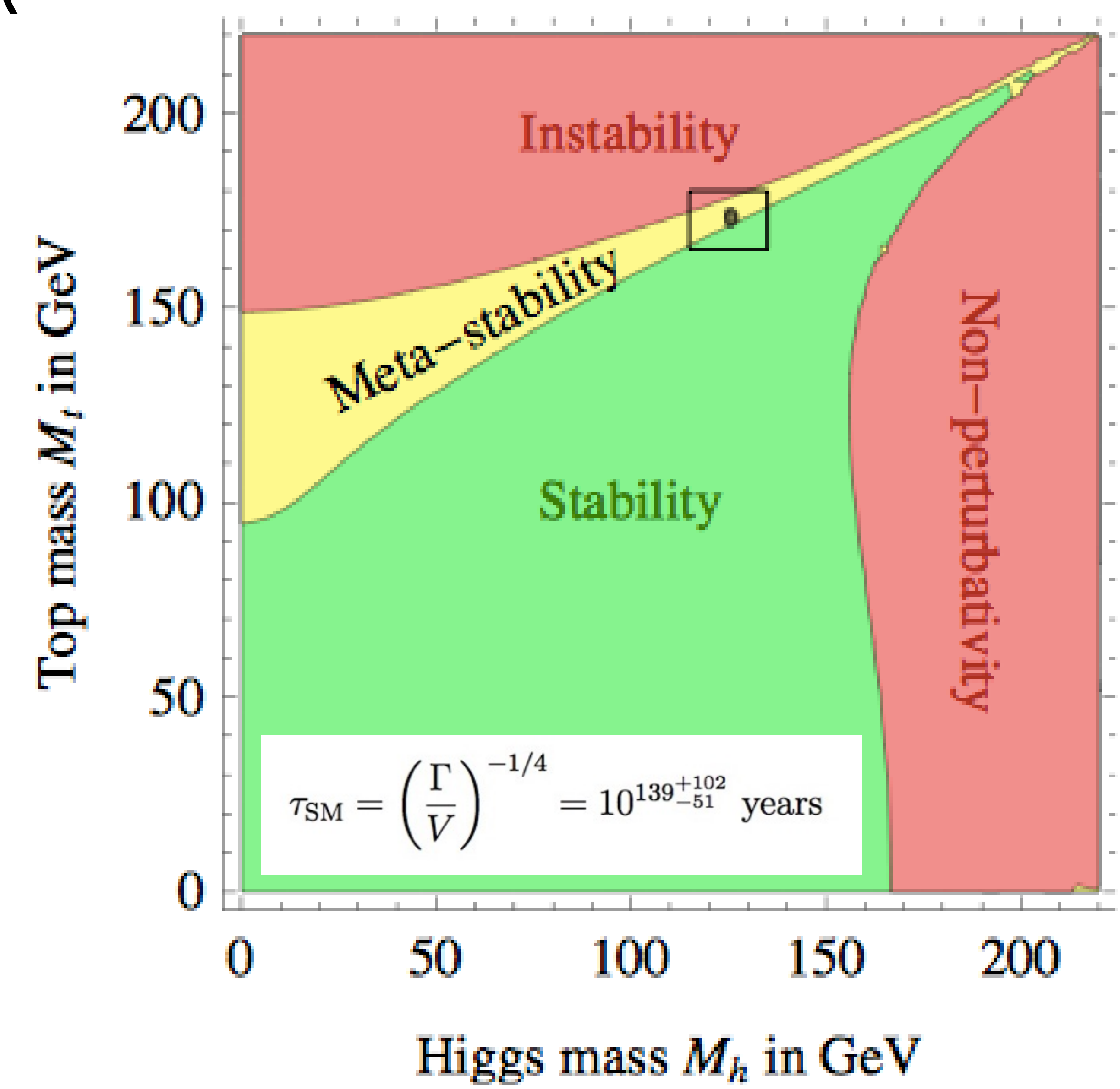
*Higgs selfcoupling and coupling to the top are the key elements to define the stability of the Higgs potential*




$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4$$

$$\propto a\, m_H^4 - b\, m_t^4$$



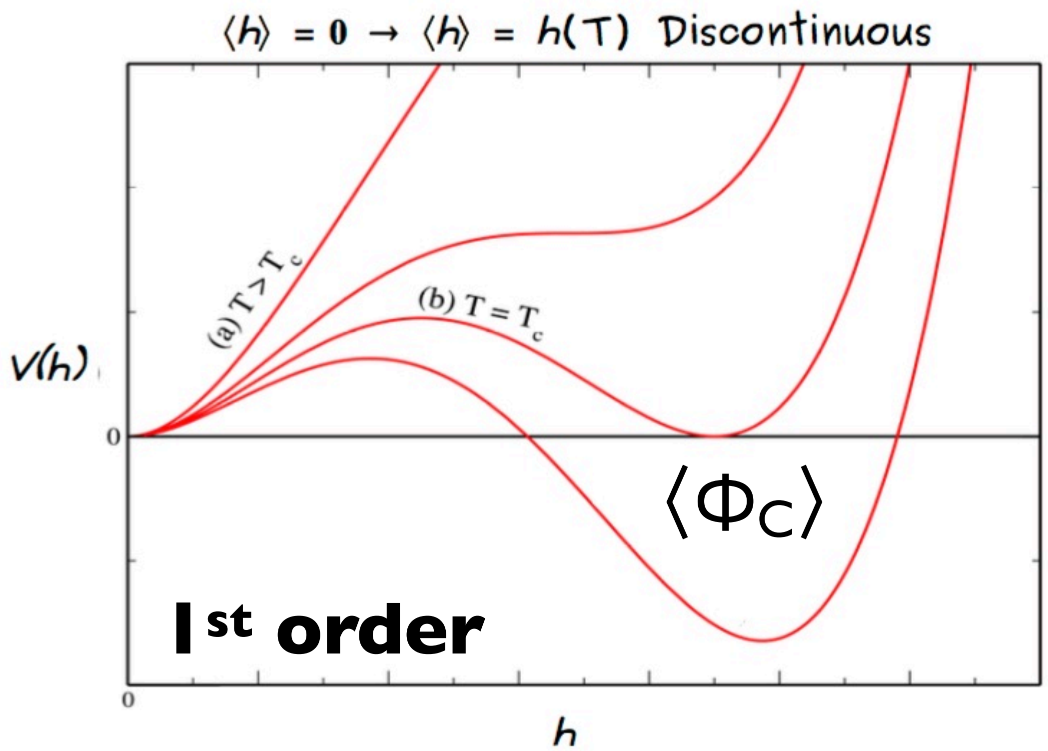

**Not an issue of concern for the human race…. but the closeness of mtop to the critical value where the Higgs selfcoupling becomes 0 at $M_{Planck}$ (namely 171.3 GeV) might be telling us something fundamental about the origin of EWSB … incidentally, $y_{top}$=1 (?!)**

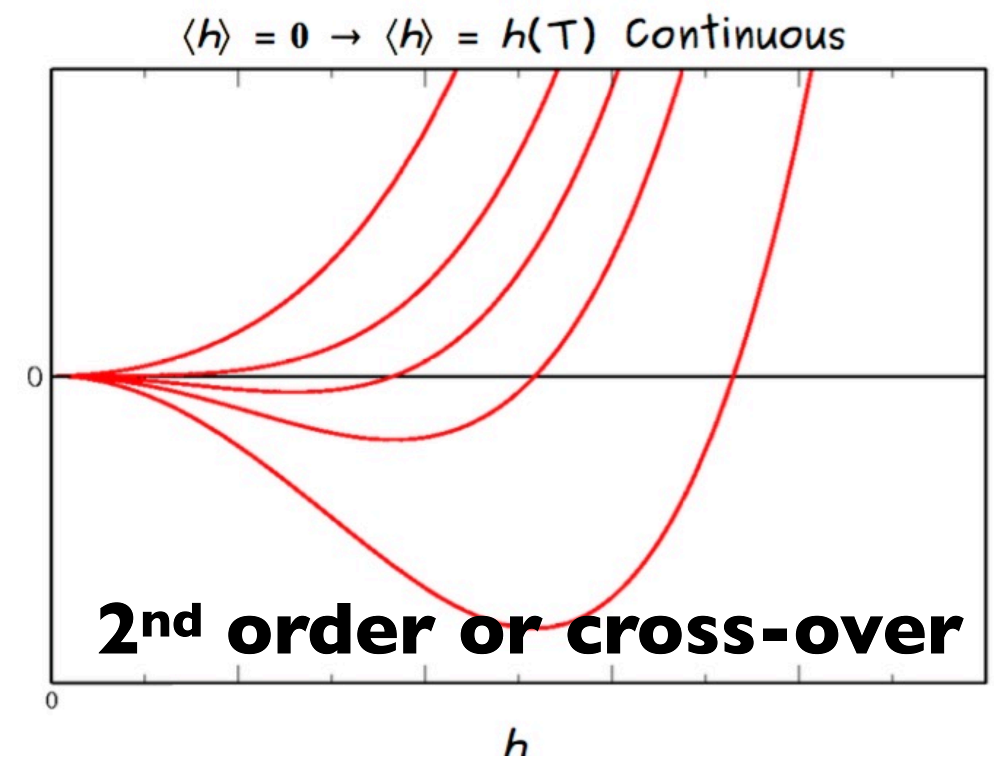
# Other important open issues on the Higgs sector

- Is the Higgs elementary, or composite?
- Is it Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^{\pm}$, $A^0$, $H^{\pm\pm}$, ... , EW-singlets, ....) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3$=1/2 fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3$=–1/2 fermions (down-type quarks and charged leptons)?
- Do Higgs couplings conserve flavour? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

# The nature of the EW phase transition



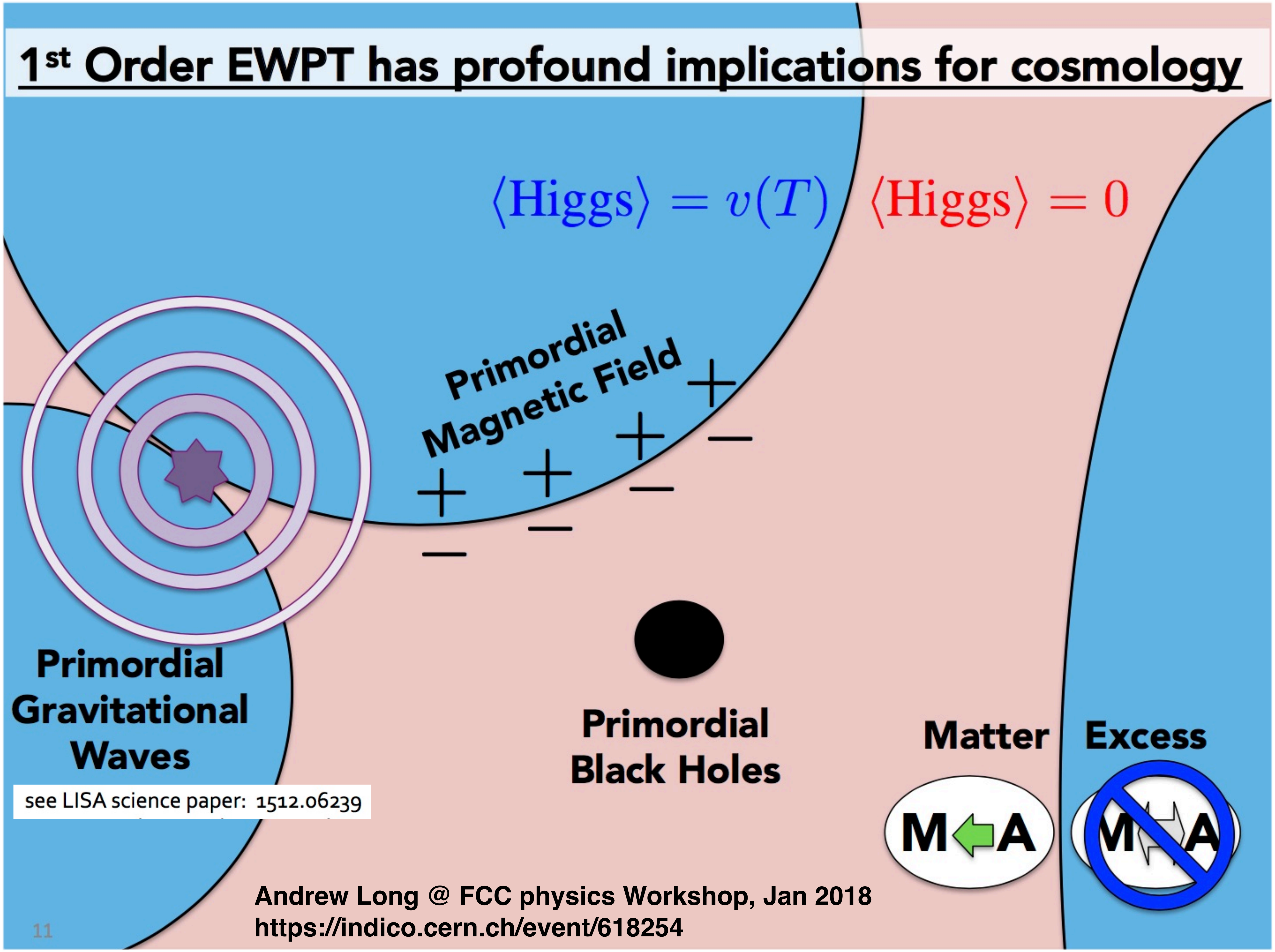

Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

**Strong** 1st order phase transition $\Rightarrow \langle \Phi_C \rangle > T_C$

**In the SM this requires $m_H \lesssim 80$ GeV, else transition is a smooth crossover.**

Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**


1st Order EWPT has profound implications for cosmology
⟨Higgs⟩ = v(T)
⟨Higgs⟩ = 0
Primordial Magnetic Field
Primordial Gravitational Waves
see LISA science paper: 1512.06239
Primordial Black Holes
Matter Excess
M A
M A
Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254
11

# Other important open issues on the Higgs sector

- Is the Higgs elementary, or composite?
- Is it Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^{\pm}$, $A^0$, $H^{\pm\pm}$, ... , EW-singlets, ....) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3$=1/2 fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3$=–1/2 fermions (down-type quarks and charged leptons)?
- Do Higgs couplings conserve flavour? $H \to \mu\tau$? $H \to e\tau$? $t \to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

- Is there a relation between Higgs and Dark Matter?

- etc.etc.

**The only way we know how to address these questions is by directly studying the properties of the Higgs boson, which can only be done with a collider**

# Which collider ?

## Key question for the future steps of LHC and beyond: Why don't we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**

- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *extended energy/mass reach*
- *sensitivity (to elusive signatures)*
- *precision*

# What we want from a future collider

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**
- Exploration potential:
  - exploit both direct (large $Q^2$) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration broad and well justified BSM scenarios
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*
- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

# Remarks on precision measurements and indirect BSM probes

# On the role of measurement

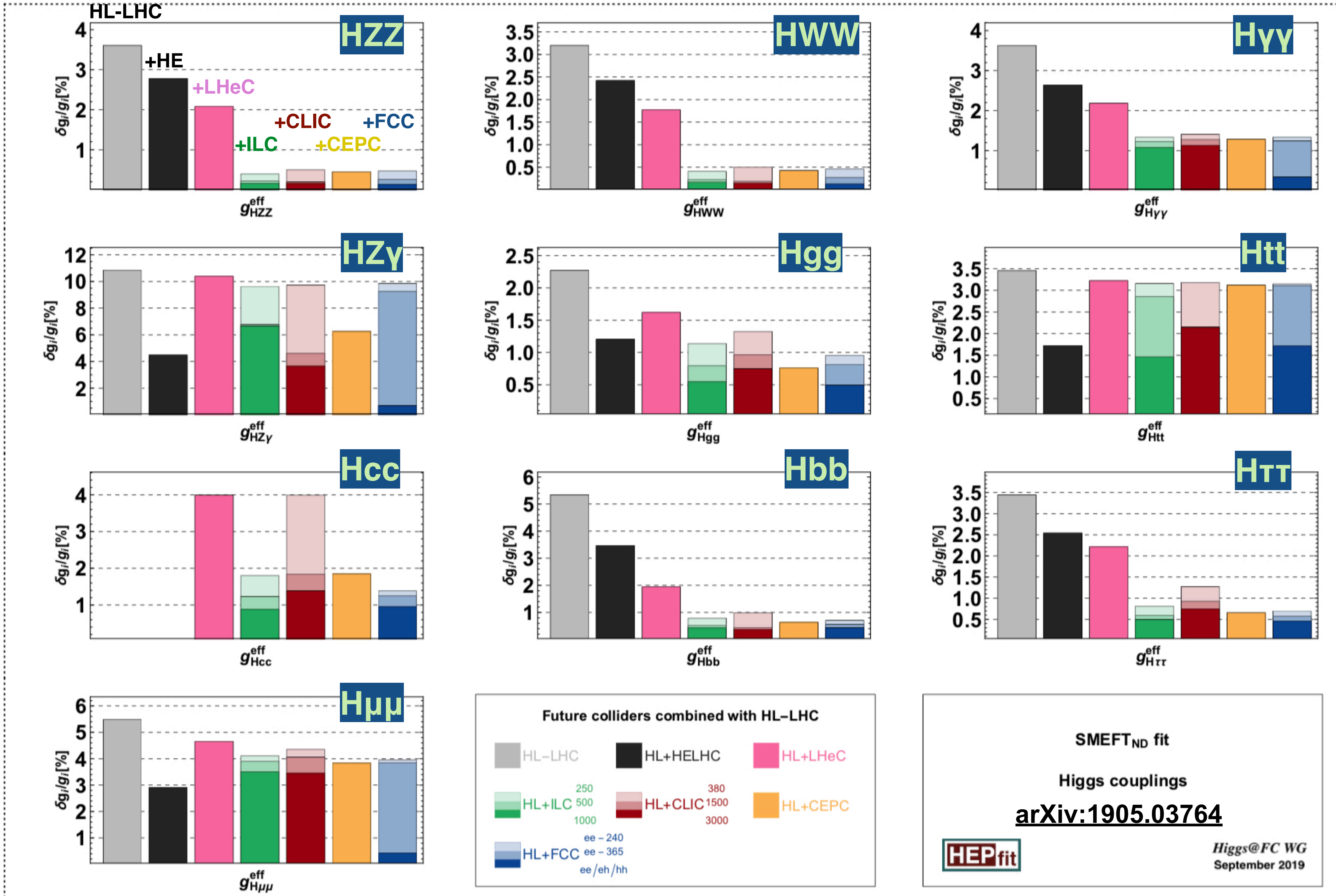
- Aside from exceptional moments in the development of the field, research is not about proving a theory is right or wrong, it's about finding out how things work
- We do not measure Higgs couplings precisely to **find** deviations from the SM. We measure them to **know** them!
- LEP's success was establishing SM's amazing predictive power!
- *Precision for the sake of it is not necessarily justified. Improving X10 the precision on m(electron) or m(proton) is not equivalent to improving X10 the Higgs couplings:*
  - *m(e) => just a parameter; m(p)=> just QCD dynamics; Higgs couplings => ???*
- … but who knows how important a given measurement can become, to assess the validity of a future theory?
  - the day some BSM signal is found somewhere, the available precision measurements, will be crucial to establish the nature of the signal, whether they agree or deviate from the SM

# Single Higgs couplings

## Results in the SMEFT-framework (Higgs)

**EFT results projected into effective Higgs couplings and aTGC**

$$g^{\text{eff}\,2}_{HX} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}}$$



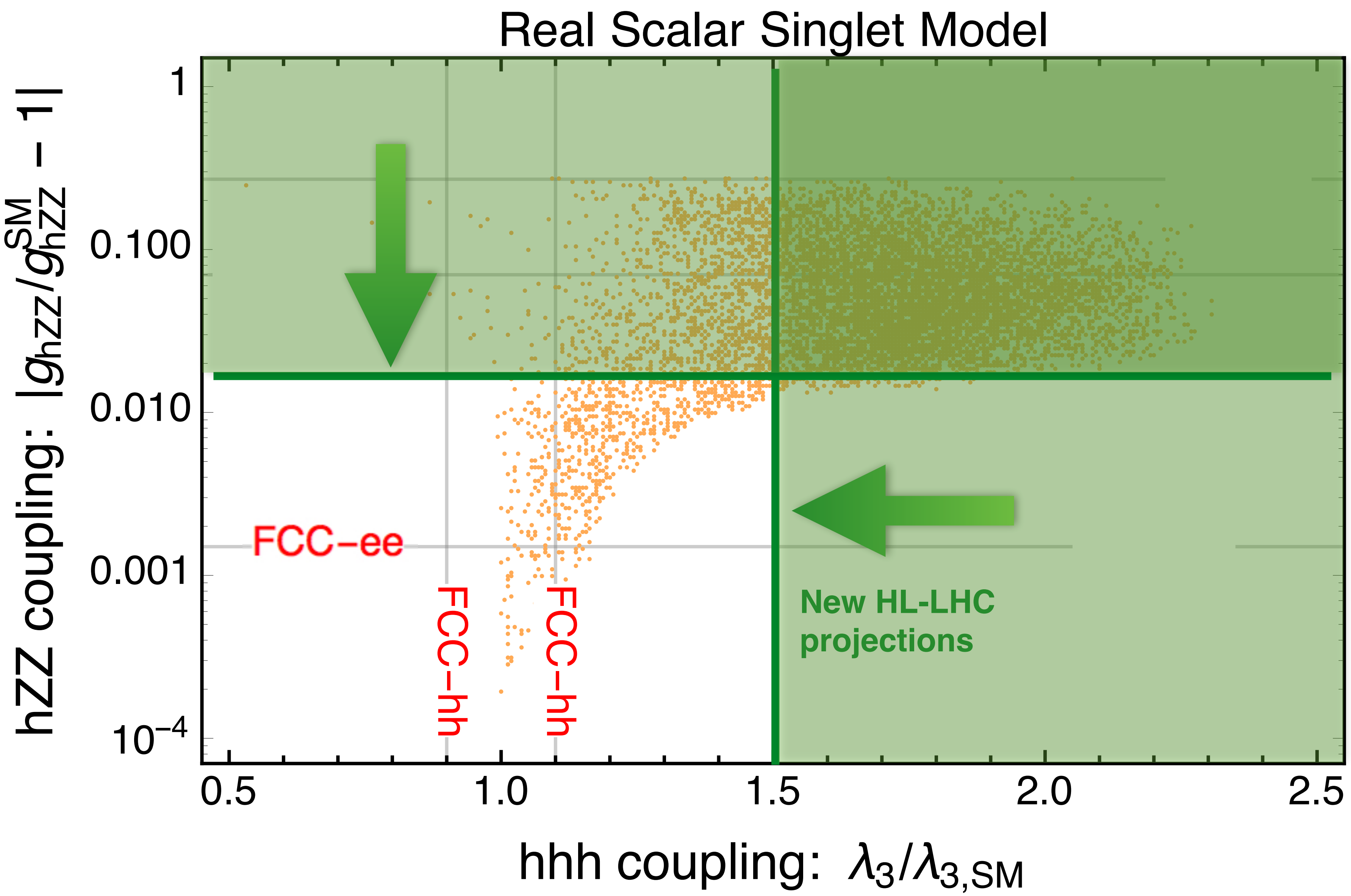
# Remarks and key messages

- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
  - Projections will improve as **new** analyses, allowed by higher statistics, will be considered

1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings' precision to the sub-% level
2. Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as $H\gamma\gamma$, $H\mu\mu$, $HZ\gamma$, $Htt$

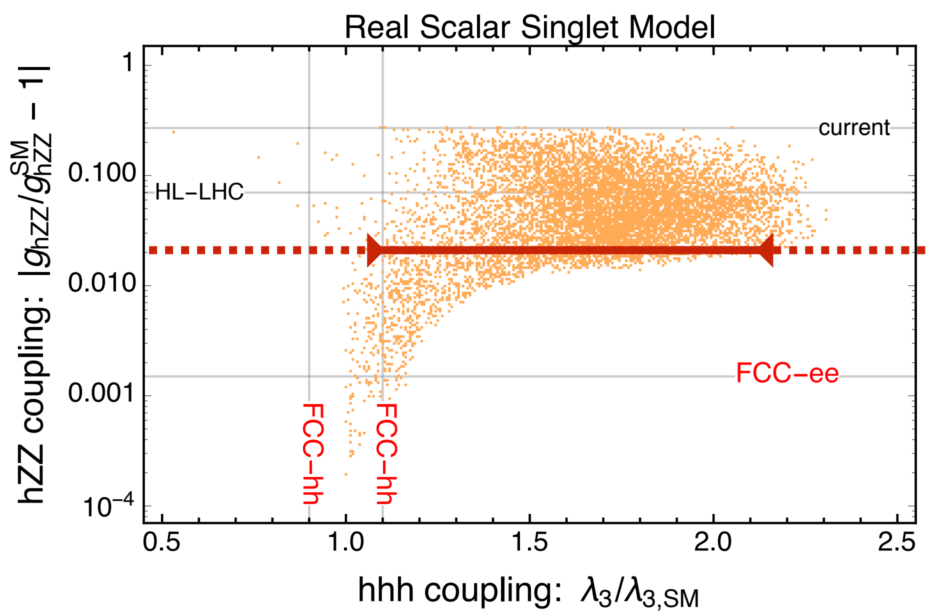
## *Example of precision implications: Probing models with 1st order phase transition at HL-LHC*

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$



# Remarks

- Apparently, adding the self-coupling constraint does not add much in terms of exclusion power, wrt the HZZ coupling measurement …
- … BUT, should HZZ deviate from the SM, $\lambda_{HHH}$ is necessary to break the degeneracy among all parameter sets leading to the same HZZ prediction

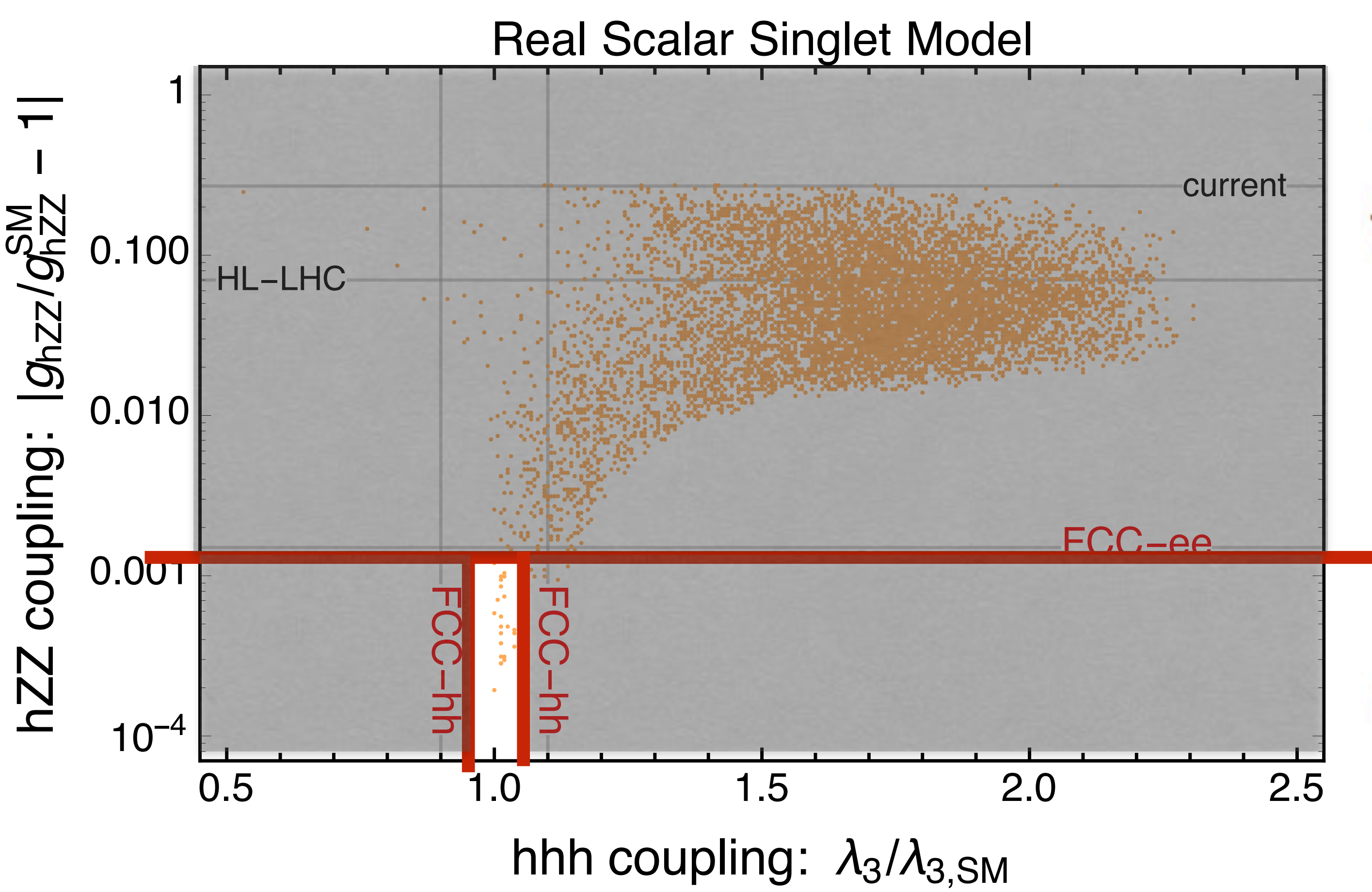



- The concept of *"which experiment sets a better constraint on a given parameter"* is a very limited comparison criterion, which looses value as we move from *"setting limits"* to *"diagnosing observed discrepancies"*
- Likewise, it's often said that some observable sets better limits than others: "all known model predict deviations in X larger than deviations in Y, so we better focus on X". But once X is observed to deviate, knowing the value of y could be absolutely crucial ….
- Redundancy and complementarity of observables is of paramount importance

# Example of precision implications:
# Probing models with 1st order phase transition at FCC

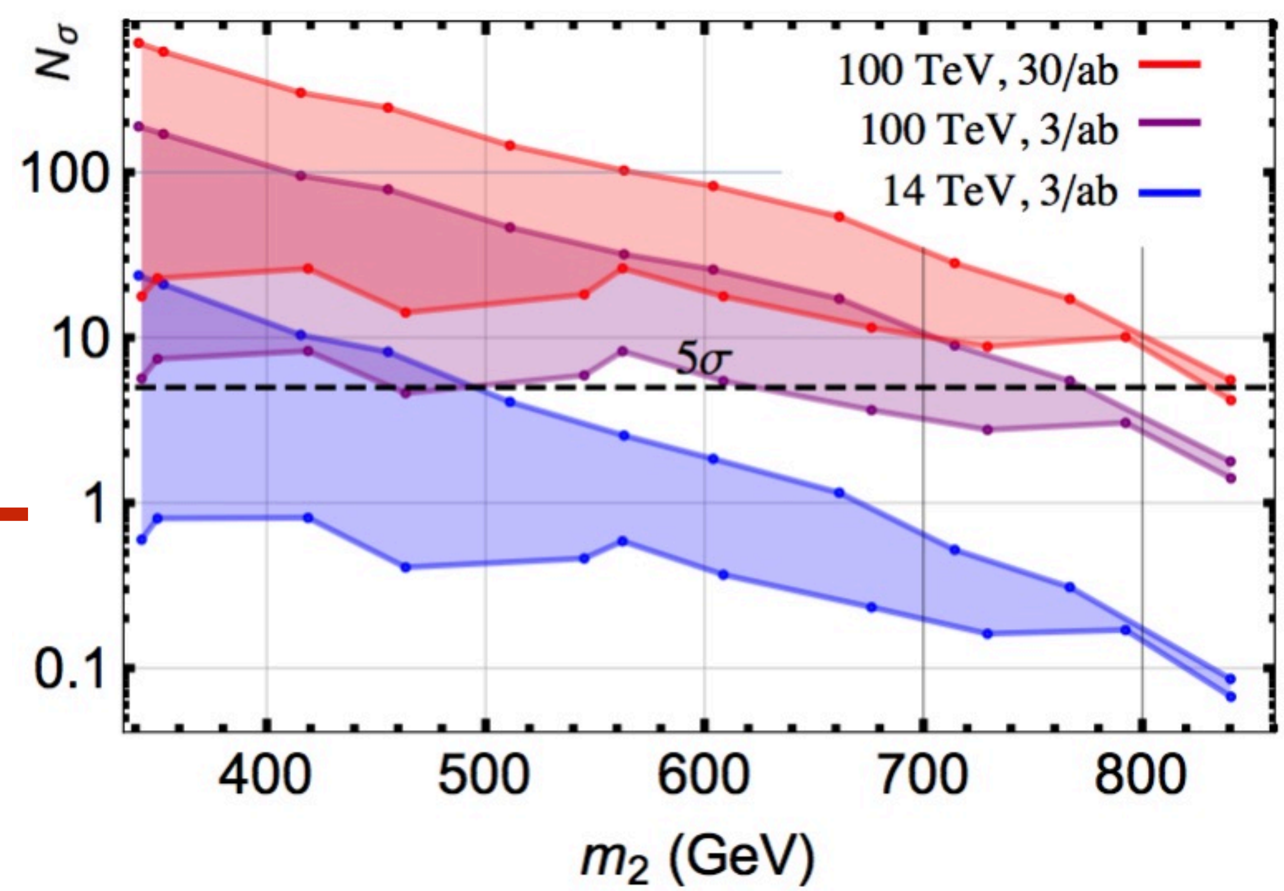
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

**Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh**




Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

**Direct detection of extra Higgs states at FCC-hh**




$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

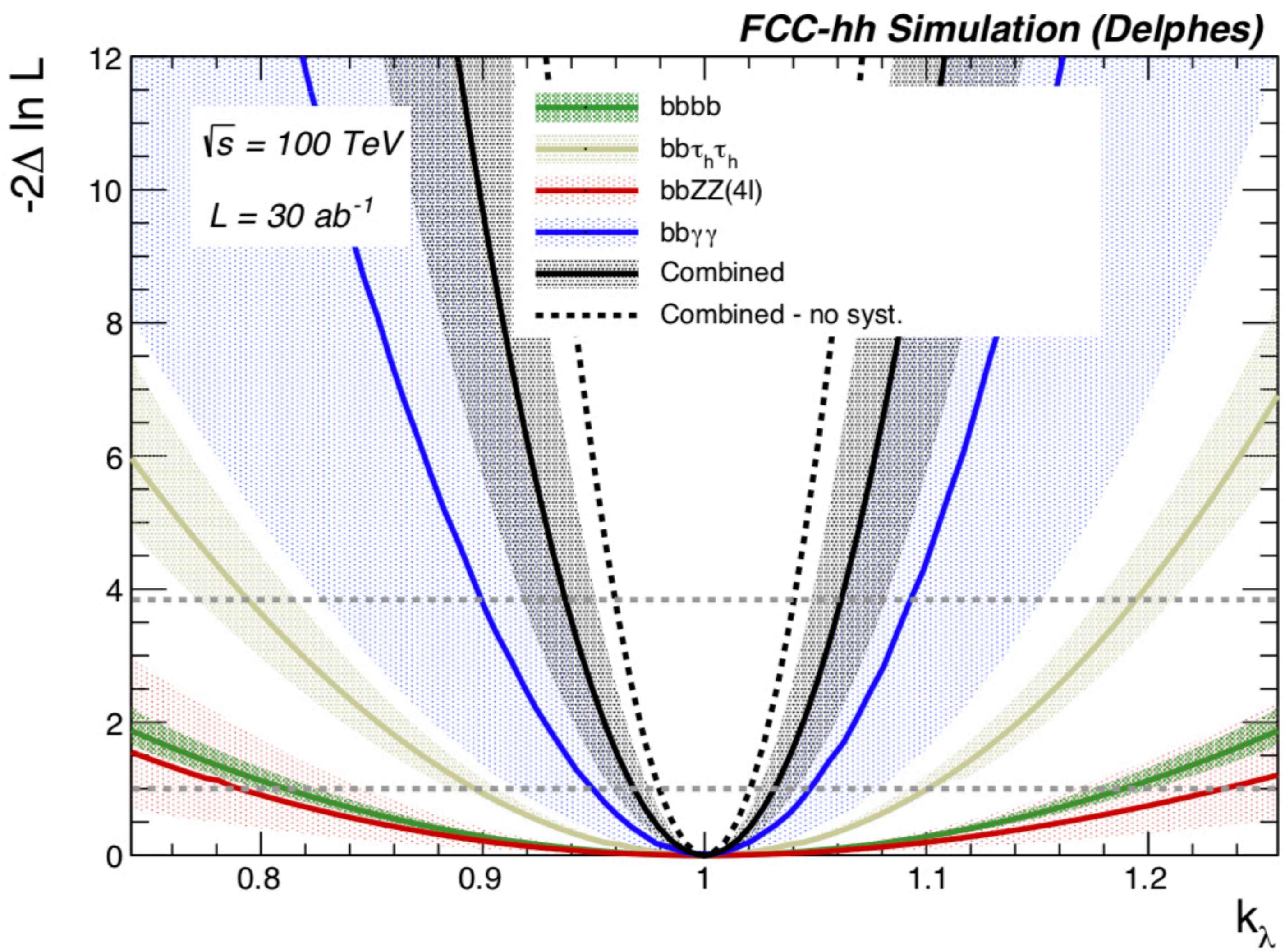
*($h_2 \sim S, \quad h_1 \sim H$)*

**incidentally …**

# Update: Higgs selfcoupling at FCC-hh

## Combination of all channels

*M. Selvaggi, shown at 3rd FCC Physics Workshop, Jan 2020*




PRELIMINARY !

Combined sensitivity:

- $\delta\kappa_\lambda$(stat) = 2 % @68% CL
- $\delta\kappa_\lambda$(stat) = 5 % @95% CL

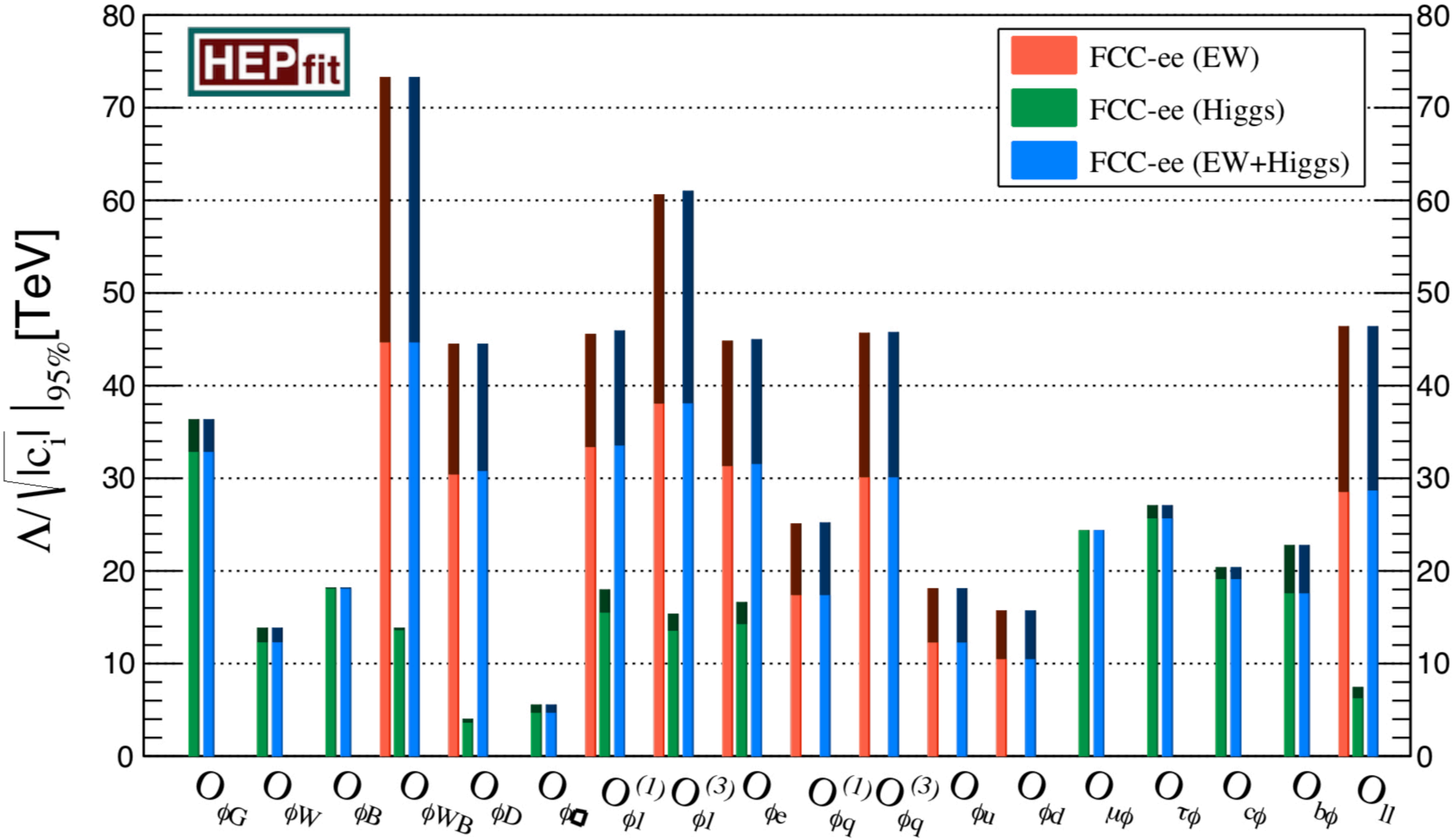
- **$\delta\kappa_\lambda$(syst) = 2.5 - 4.0 % @68% CL**
- $\delta\kappa_\lambda$(syst) = 4.0 - 8.2 % @95% CL

- bbγγ: $\delta\kappa_\lambda \approx$ 3-8% (large improvement due to MVA and use of secondary processes)
- bbττ: $\delta\kappa_\lambda \approx$ 9-12% (using $\tau_{had}\tau_{had}$)
- bb4l: $\delta\kappa_\lambda \approx$ 10-20%
- bbbb: $\delta\kappa_\lambda \approx$ 15-20%

For the first time ever a collider promises the measurement of the Higgs self-coupling to have statistical uncertainty at the % level. The challenge is now with systematics, including TH

In principle the 10% level can be reached within 3 years of running

# Global EFT fits to EW and H observables at FCC-ee




Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

# Remarks and key messages

- Higgs and EW observables are greatly complementary in constraining EFT ops and possibly exposing SM deviations

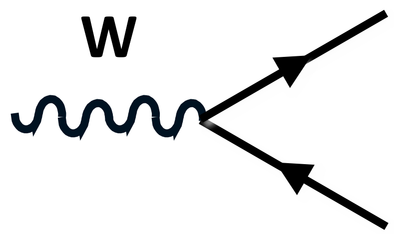
1. An ee Higgs factory needs to operate at the Z pole and WW threshold to maximize the potential of precision measurements of the EW sector

- EW&Higgs precision measurements at future ee colliders could probe scales as large as several 10's of TeV ($c_i \sim 1 \div 4\pi$)

2. To directly explore the origin of possible discrepancies, requires collisions in the several 10s of TeV region

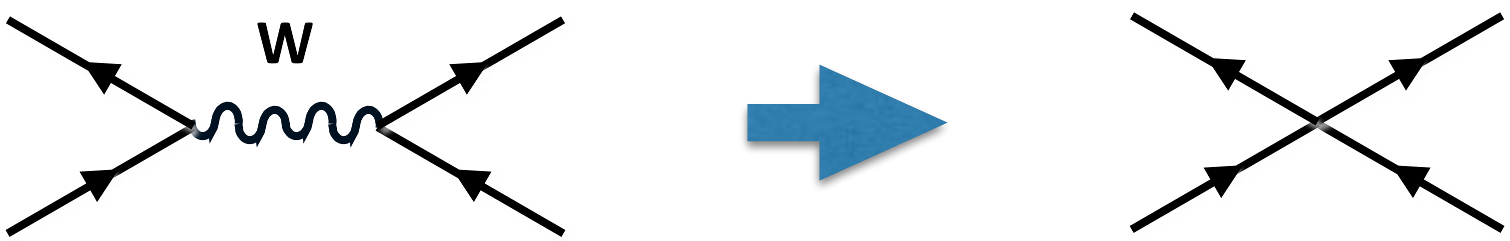
# Remarks on interpretation of EFT bounds

**Example: weak interactions**




$$\frac{g}{\sqrt{2}}\overline{\Psi}\gamma_\mu\Psi_L$$

At low energy:




$$\frac{g^2}{2M_W^2}\,\overline{\Psi}\gamma_\mu\Psi_L\,\overline{\Psi}\gamma_\mu\Psi_L$$

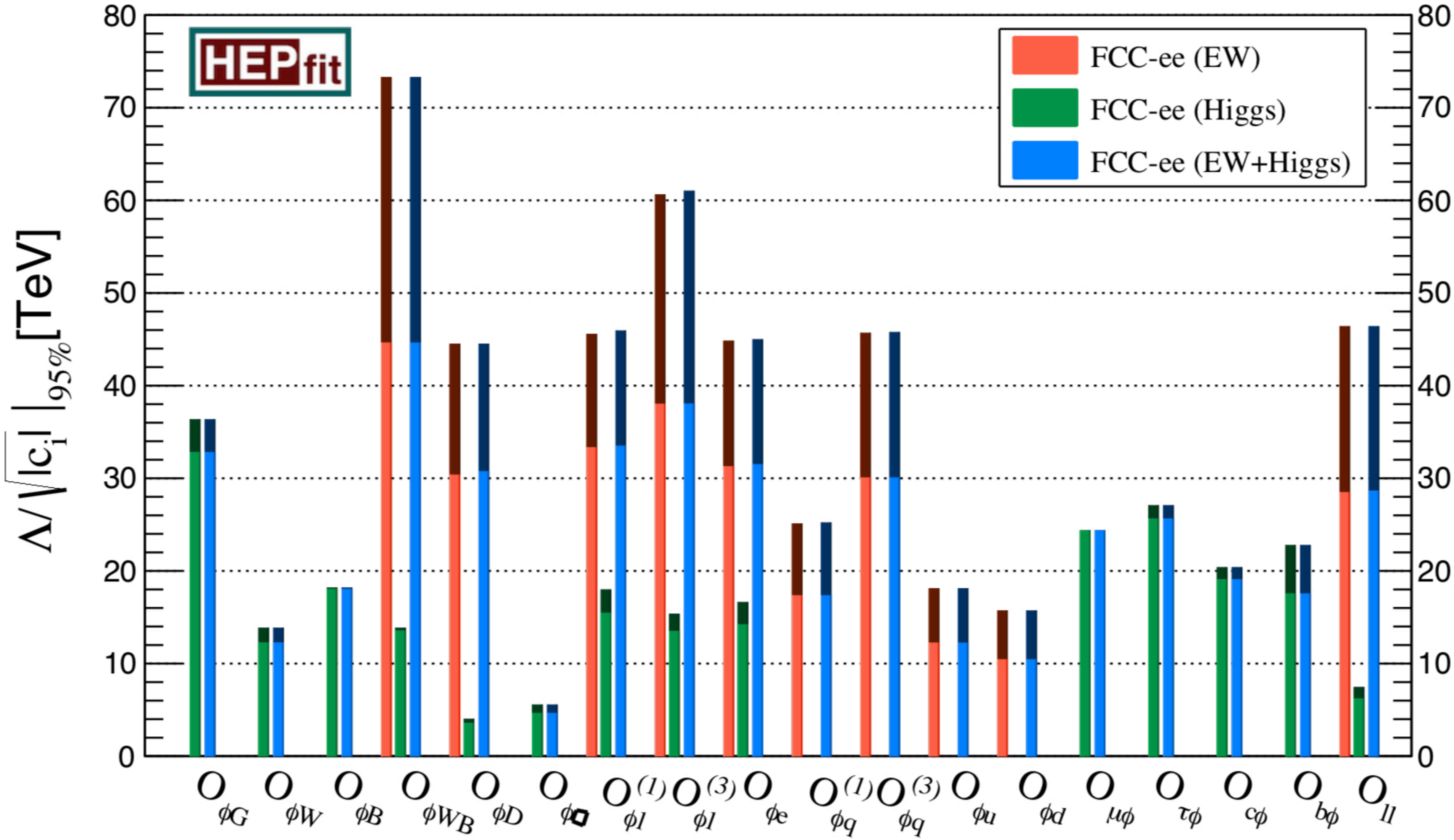
$$\frac{c}{\Lambda^2} = \frac{g^2}{2M_W^2} = 2\sqrt{2}G_F = \frac{2}{v^2} = \frac{1}{(174\,\mathrm{GeV})^2}$$

versus

$$M_W = 80\,\mathrm{GeV}$$

The limits on $c/\Lambda^2$ are typically larger than the mass scale at which new physics appears

# Global EFT fits to EW and H observables at FCC-ee




Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

# Remarks on interpretation of EFT bounds

- EFT sensitivity up to a scale Λ does not imply ability to uncover ***any*** new phenomenon up to O(Λ)
- Weakly coupled physics, or physics that affects precision observables at one-loop or beyond, or scenarios with built-in cancellations like GIM, can reduce by orders of magnitude the EFT sensitivity to new physics
- E.g.: the only constraints on SUSY from LEP (even for EWinos & sfermions, let alone gluinos) came from direct searches, not from EW precision observables
- ***Direct searches are irreplaceable for a thorough exploration of BSM scenarios***

# On the interplay of precision and kinematic reach in probing new physics indirectly

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

Ex: for H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

**e.g. δO=1% ⇒ Λ ~ 2.5 TeV**

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes large Λ even if precision is "low"

**e.g. δO=10% at Q=1.5 TeV ⇒ Λ~5 TeV**

**Complementarity between $O(10^{-3})$ measurements at ee collider and $O(10^{-1\div-2})$ studies at large-Q**

# Programme diversity

- The large cost of future colliders requires broad community support, beyond the strict "Higgs & BSM search" science goals
- LEP and LHC have provided countless opportunities for a comprehensive research programme, ranging from the fixed-target expt's relying on the injector complex, to flavour physics and heavy ions.
- Smaller dedicated expt's have been possible at the LHC (LHCf, MoEDAL, TOTEM), and are continuously being proposed and implemented (FASER, Mathusla, MilliQan, …)
- This diversity brought together a numerous and varied scientific community, enhancing the output of the individual projects
- Preserving this diversity could be key to bond the large scientific community required to support a future project, and to ensure its vitality across the many decades of its planning, implementation and operation

# Final remarks

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.

- ***Precision*** Higgs and EW measurements are an indispensable component of this programme

- They must be accompanied by an ambitious ***direct*** exploration of the new mass scales potentially revealed by precision measurements

- Scientific ***diversity*** should likely become an integral part of the planning for future facilities