Perspectives in Fundamental Physics
Discussing the future of Particle Physics
Joint Seminar INFN, Dipartimento di Fisica
and Scuola Normale Superiore Pisa
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The theory perspective

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The vision for particle physics builds on

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- having important questions to pursue

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- creating opportunities to answer them

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

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- **Data driven:**
    - DM
    - Neutrino masses
    - Matter vs antimatter asymmetry
    - Dark energy
    - …

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  - 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
  - …

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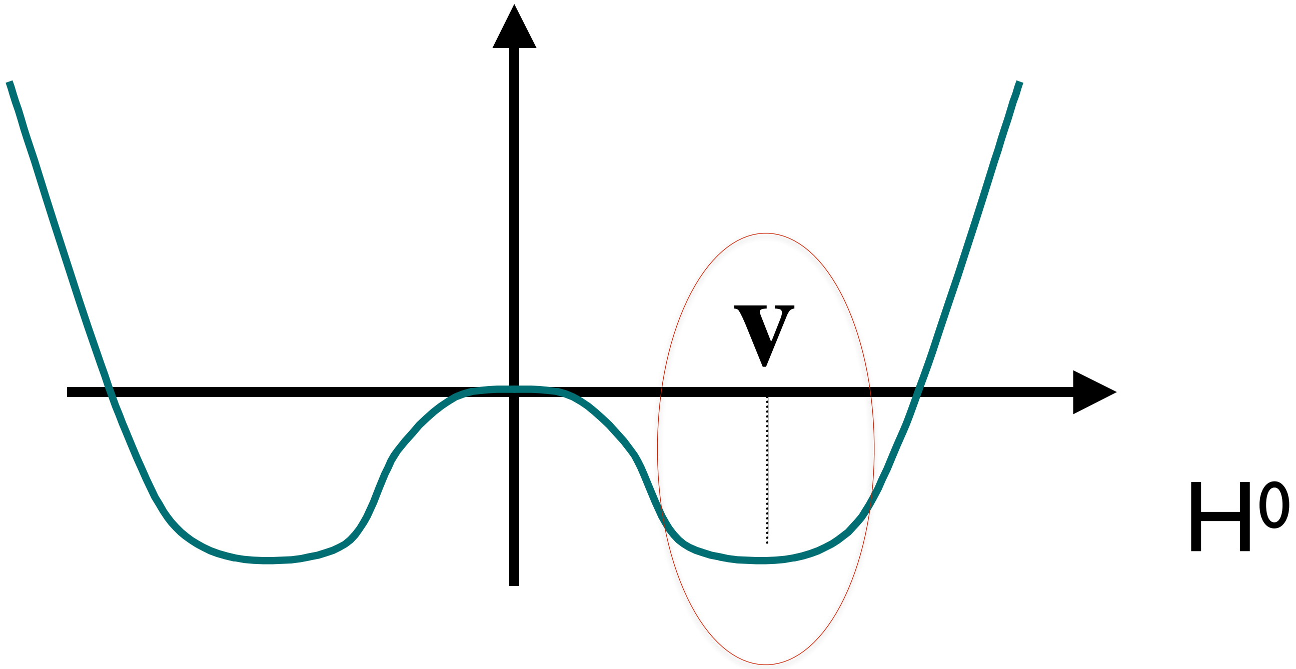
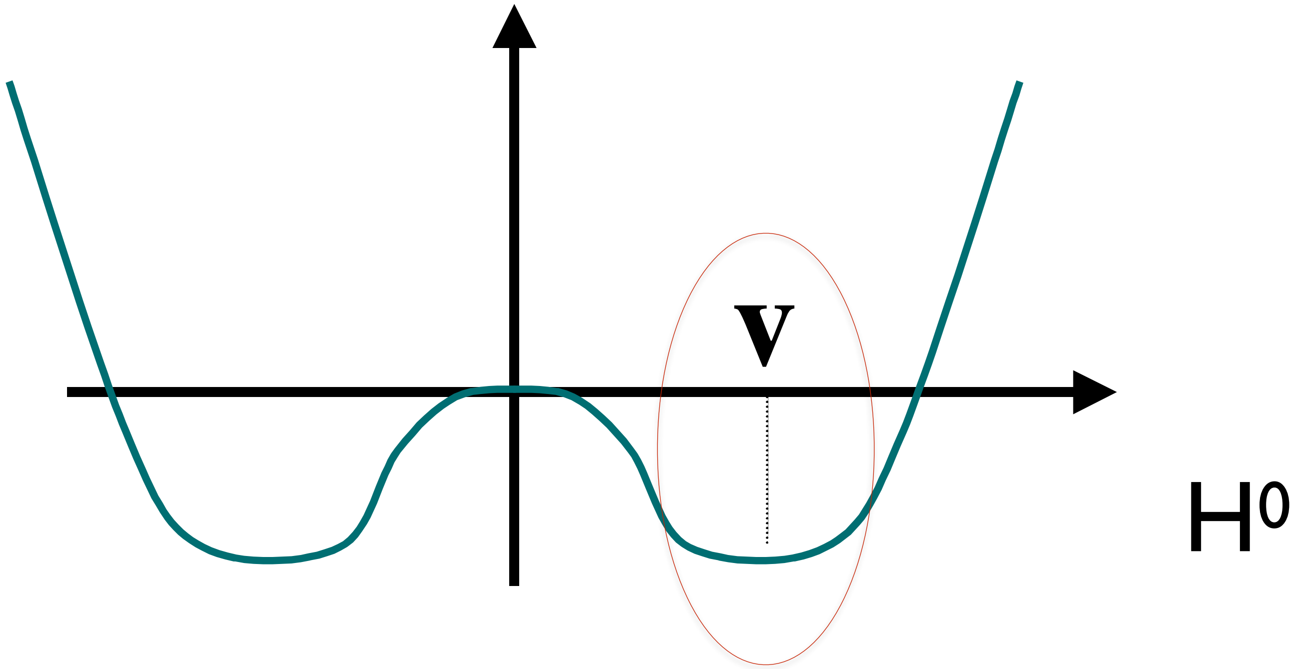
One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction….



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

Who ordered that ?



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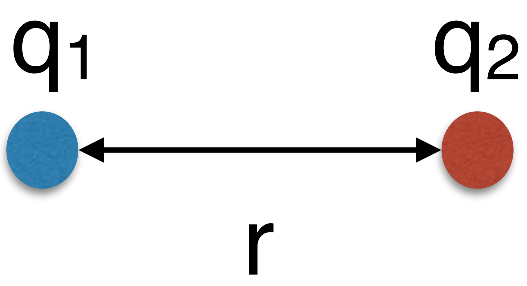
We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

Electromagnetic vs Higgs dynamics



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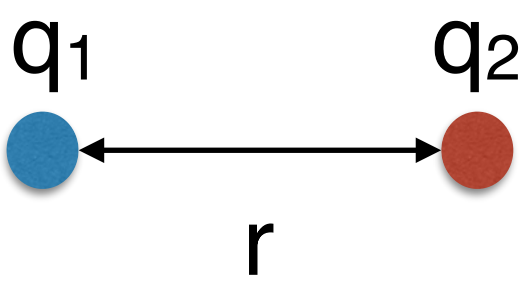

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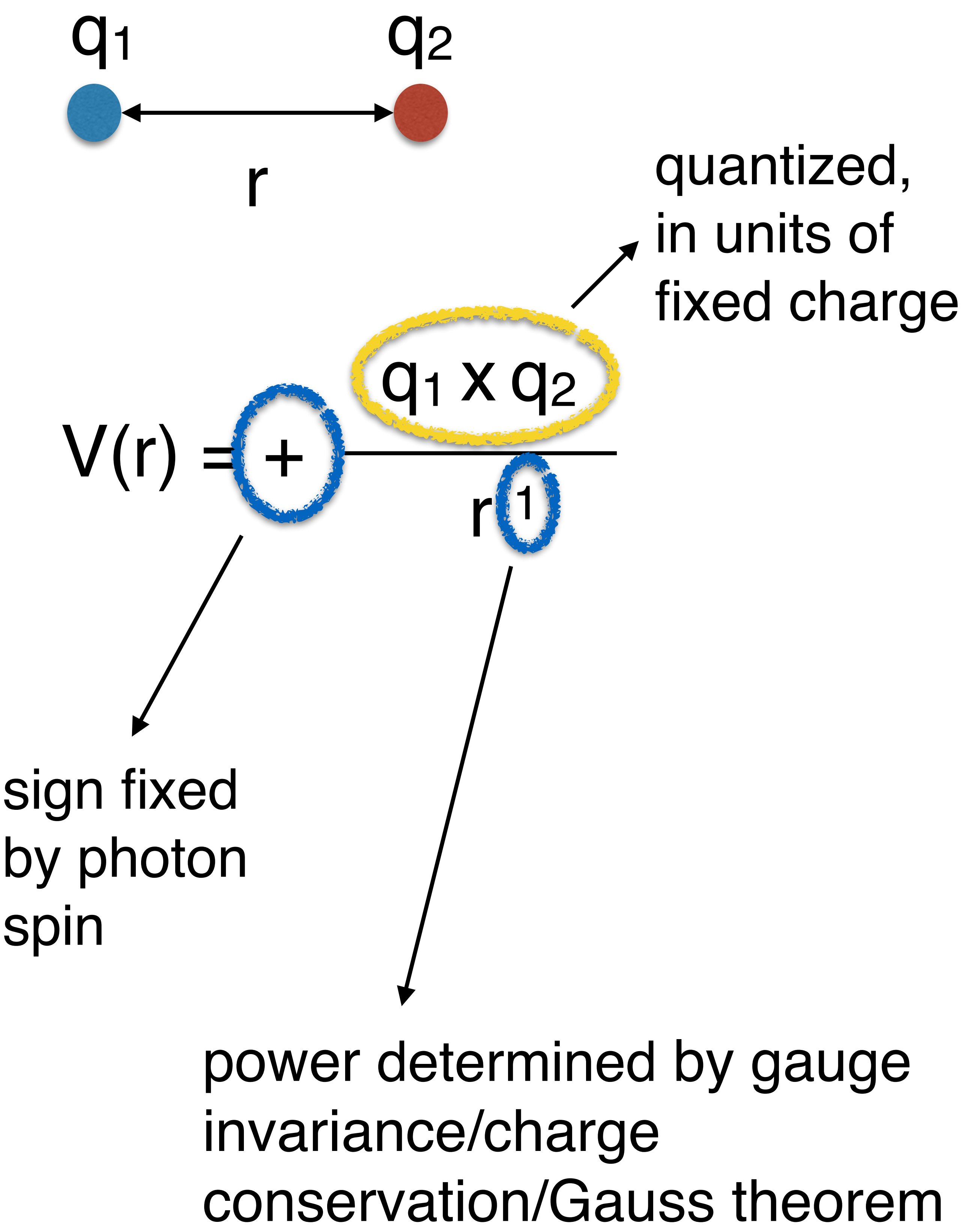

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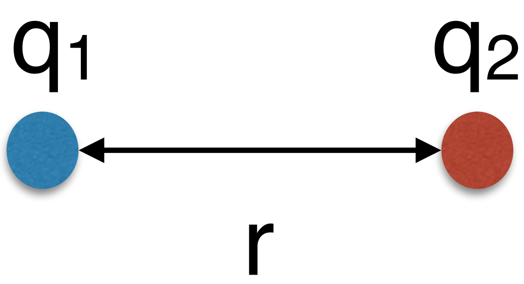

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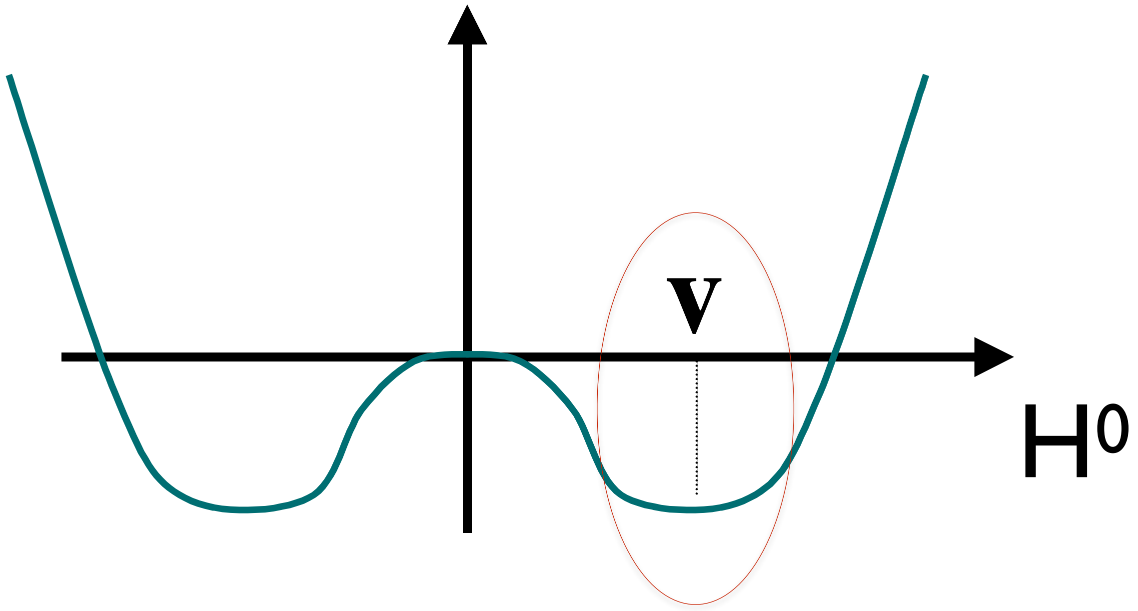

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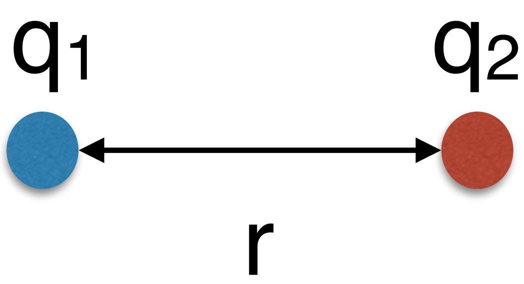

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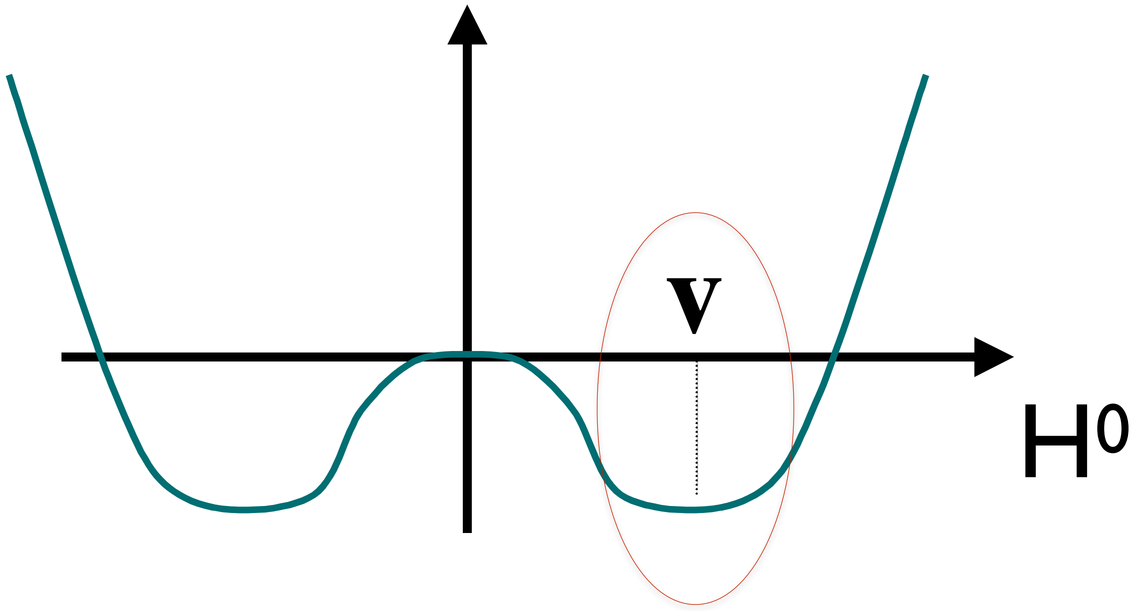

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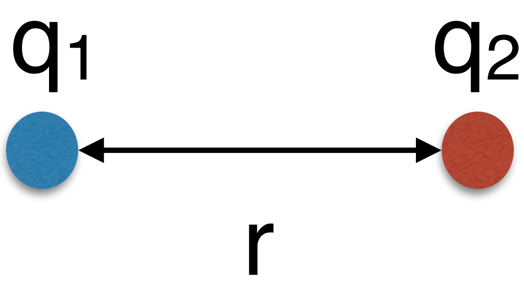

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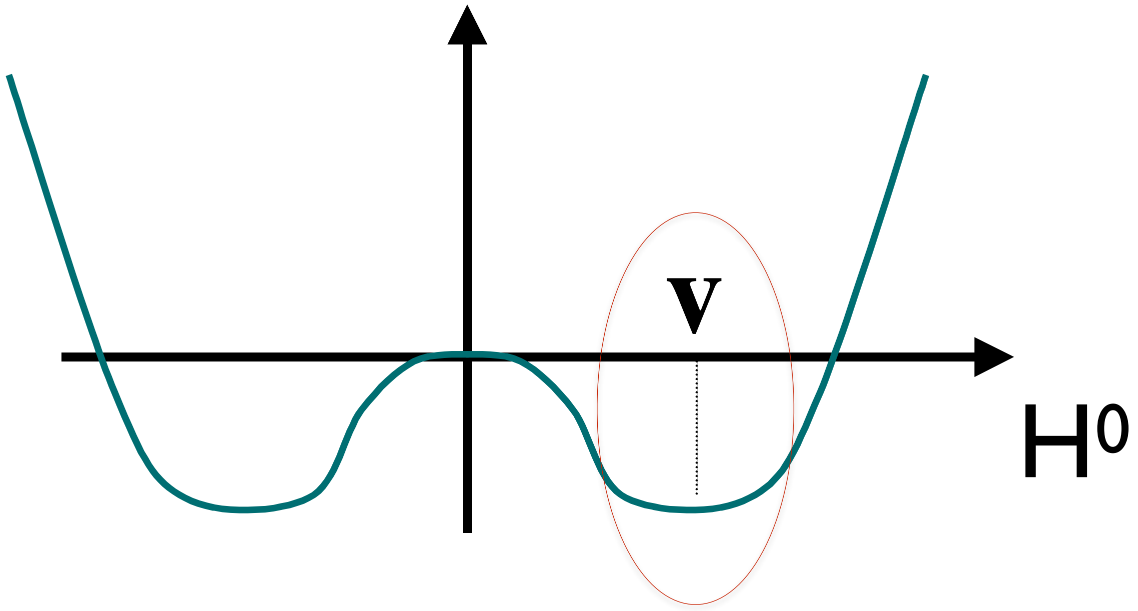

any function of $|H|^2$ would be ok wrt known symmetries

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>0 to ensure stability, but otherwise arbitrary

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- 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.

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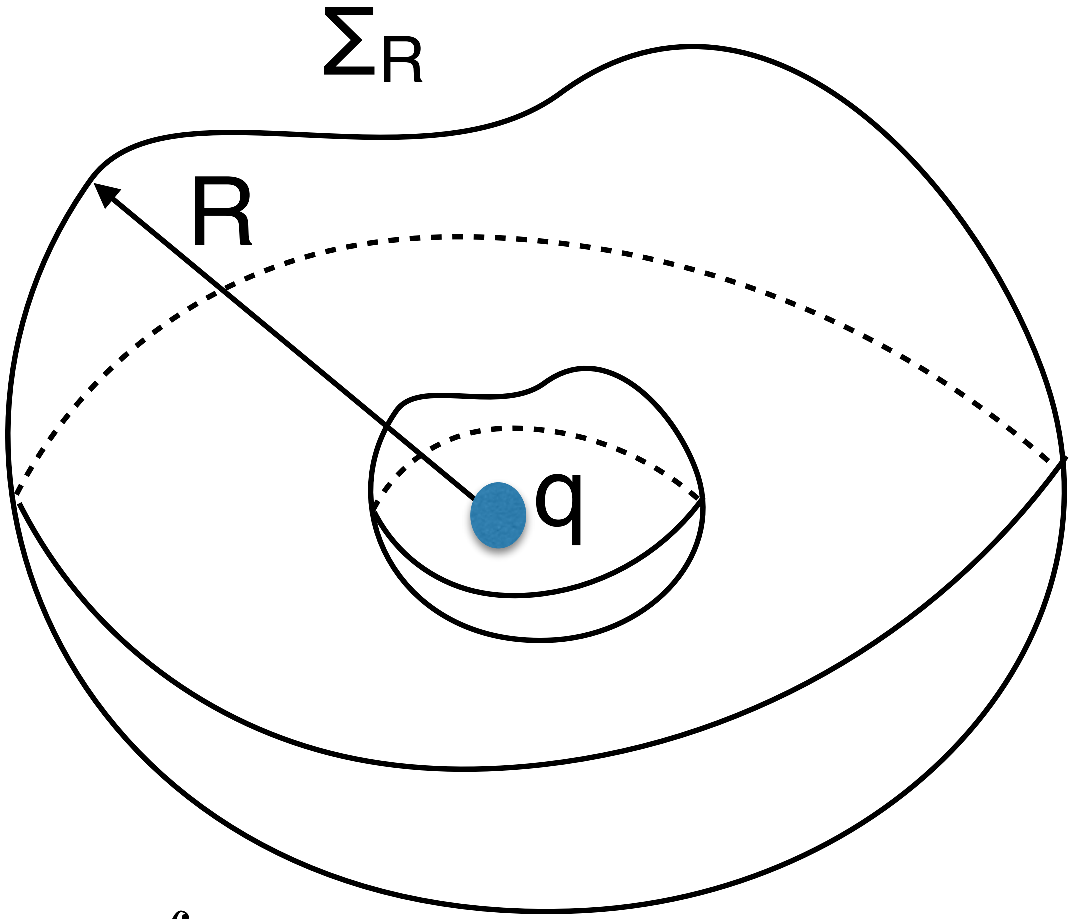
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either 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 λ) determined by the parameters of SUSY breaking
- …

Decoupling of high-frequency modes

E&M



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

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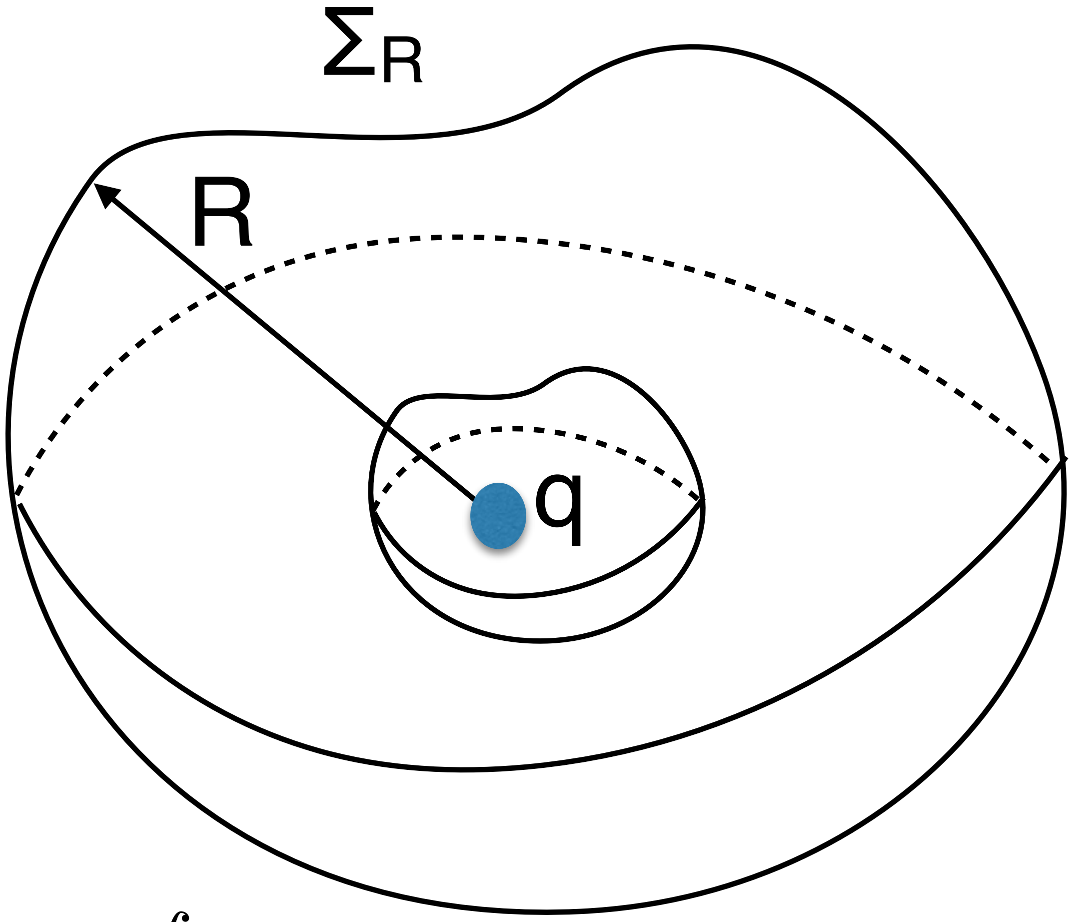

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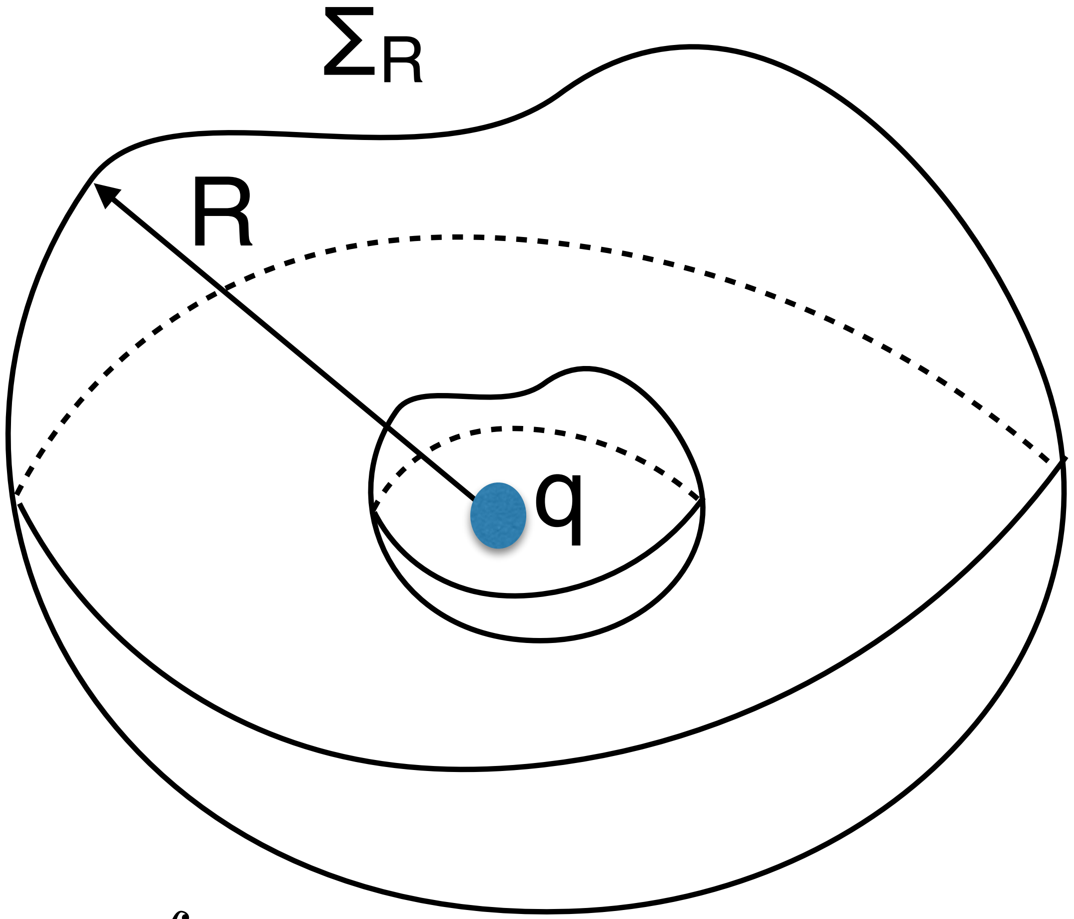

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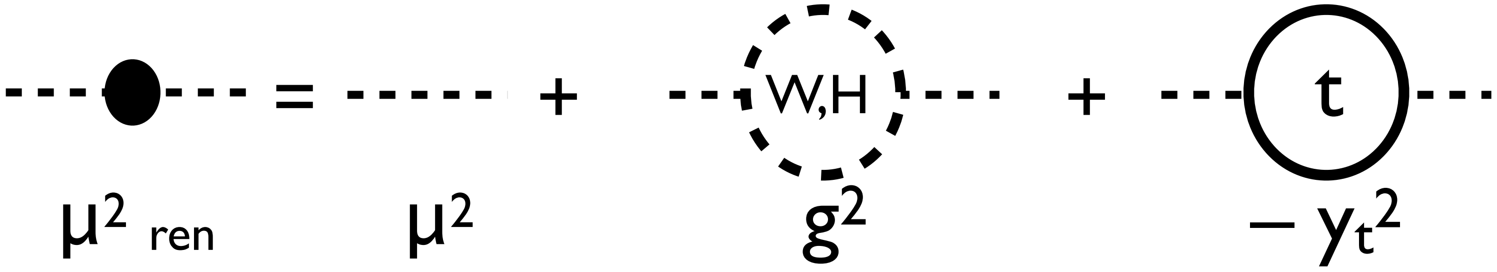

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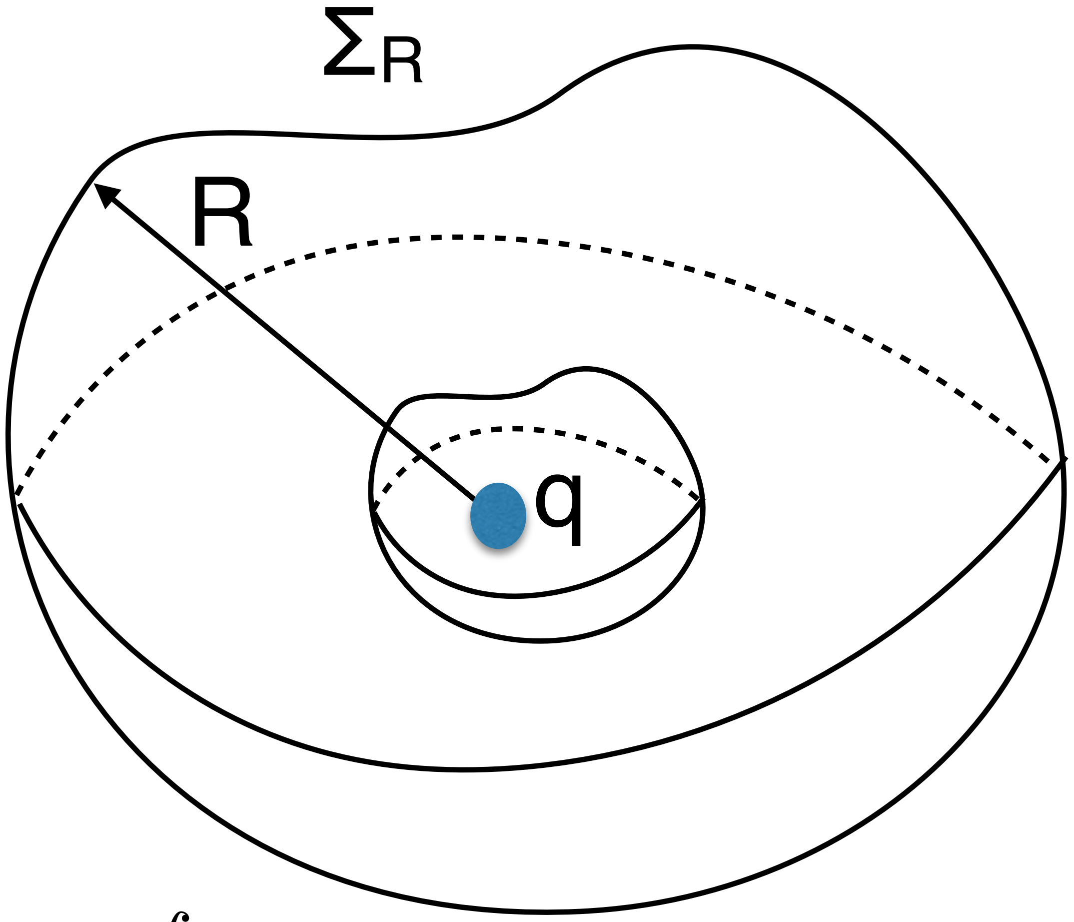

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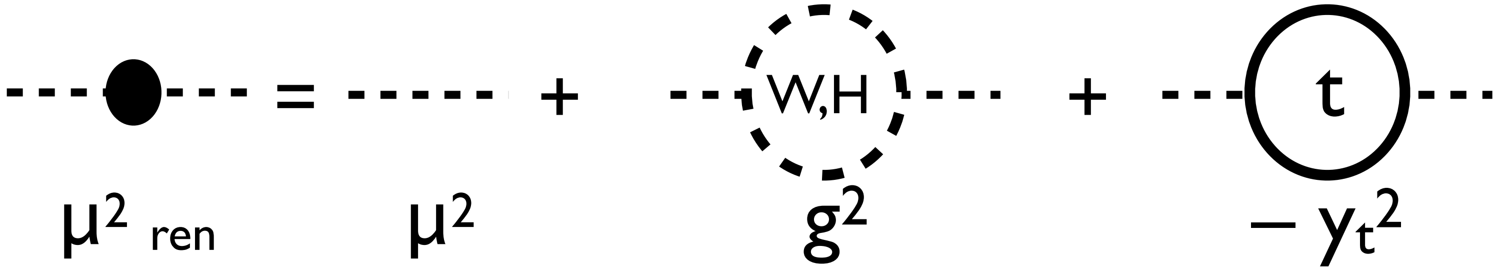

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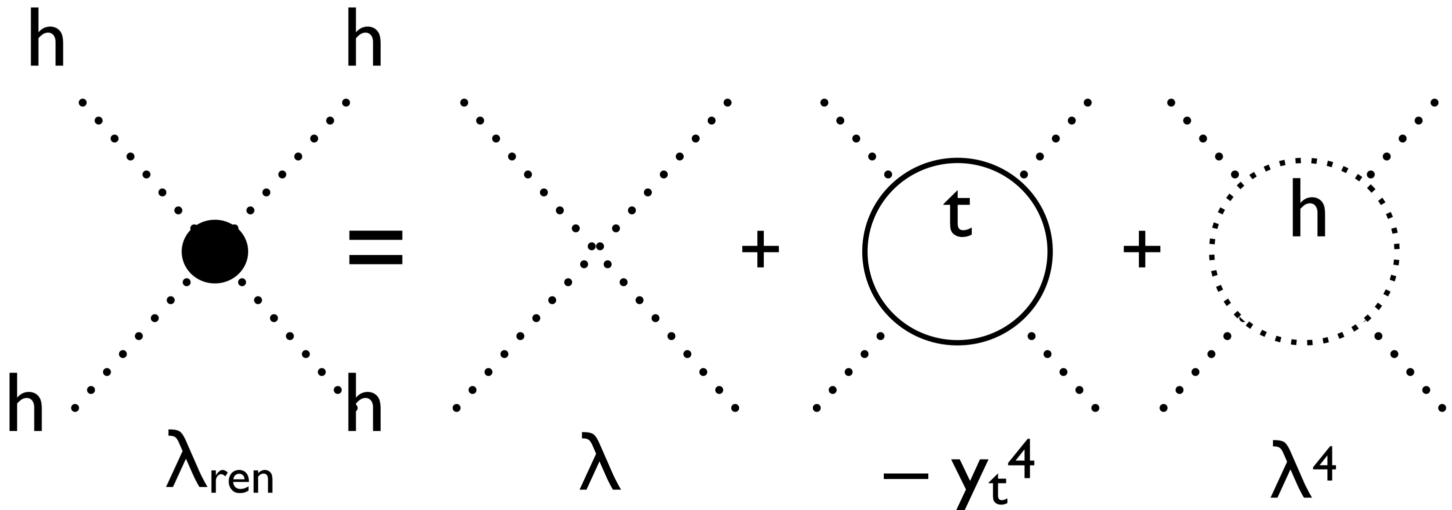

$$\Rightarrow \frac{d\lambda}{d\log\mu} \propto \lambda^4 - y_t^4 \quad \propto a\, m_H^4 - b\, m_t^4$$

high-energy modes can change size and sign of both μ^2 and λ, 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**

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➡ *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*

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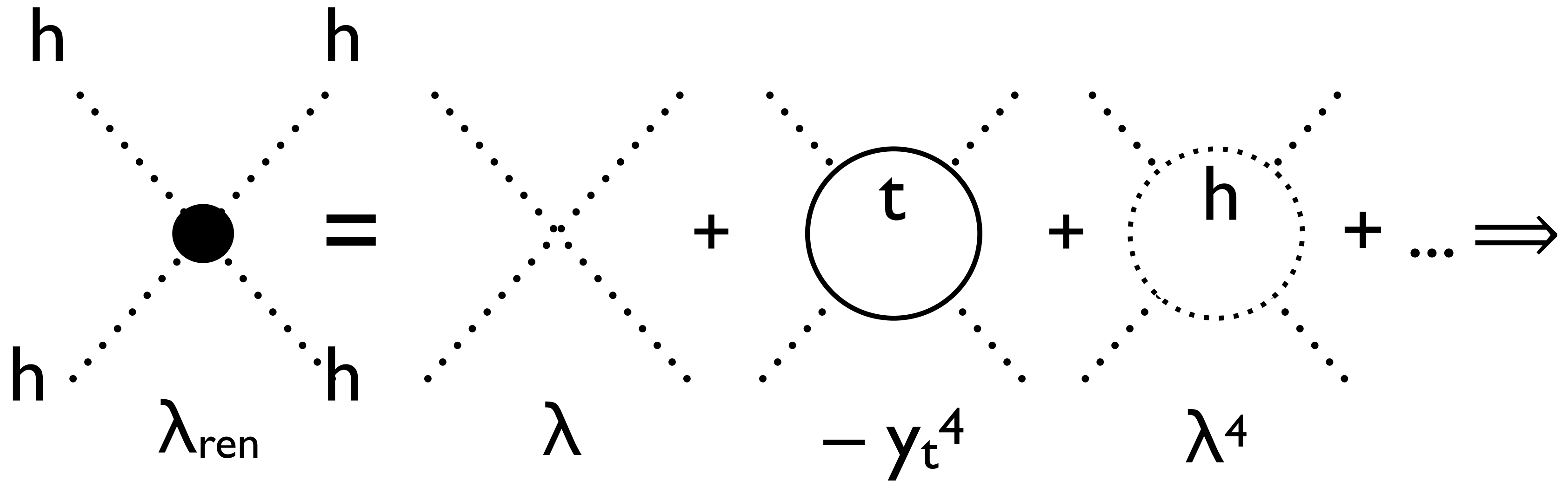
(meta)Stability of the Higgs potential

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



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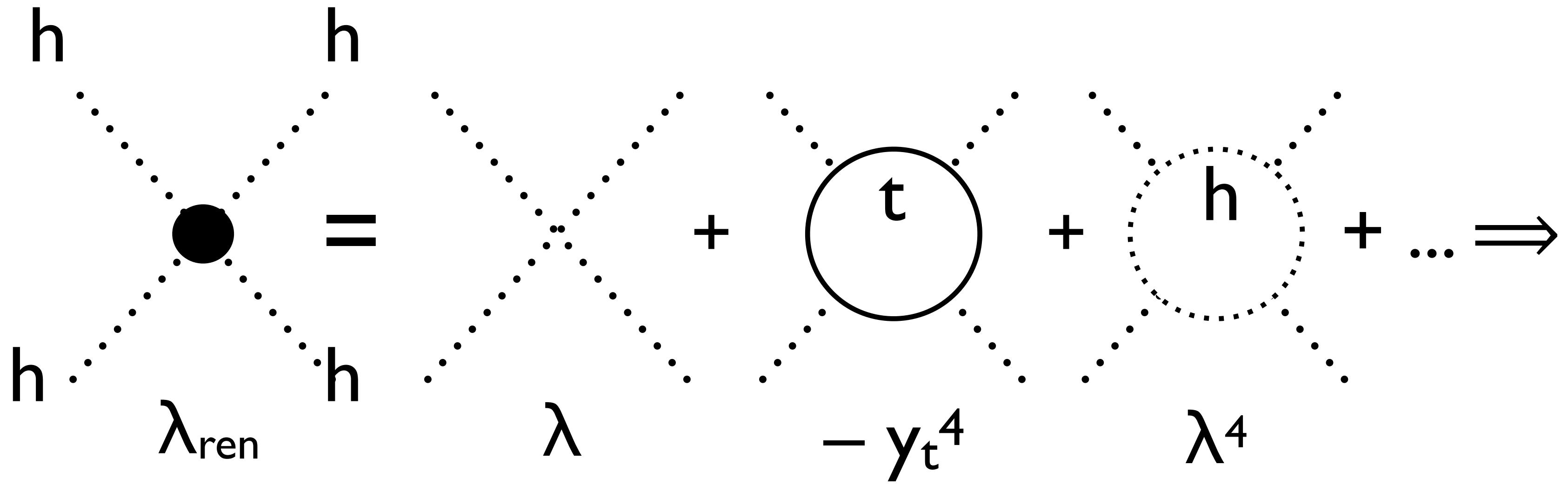

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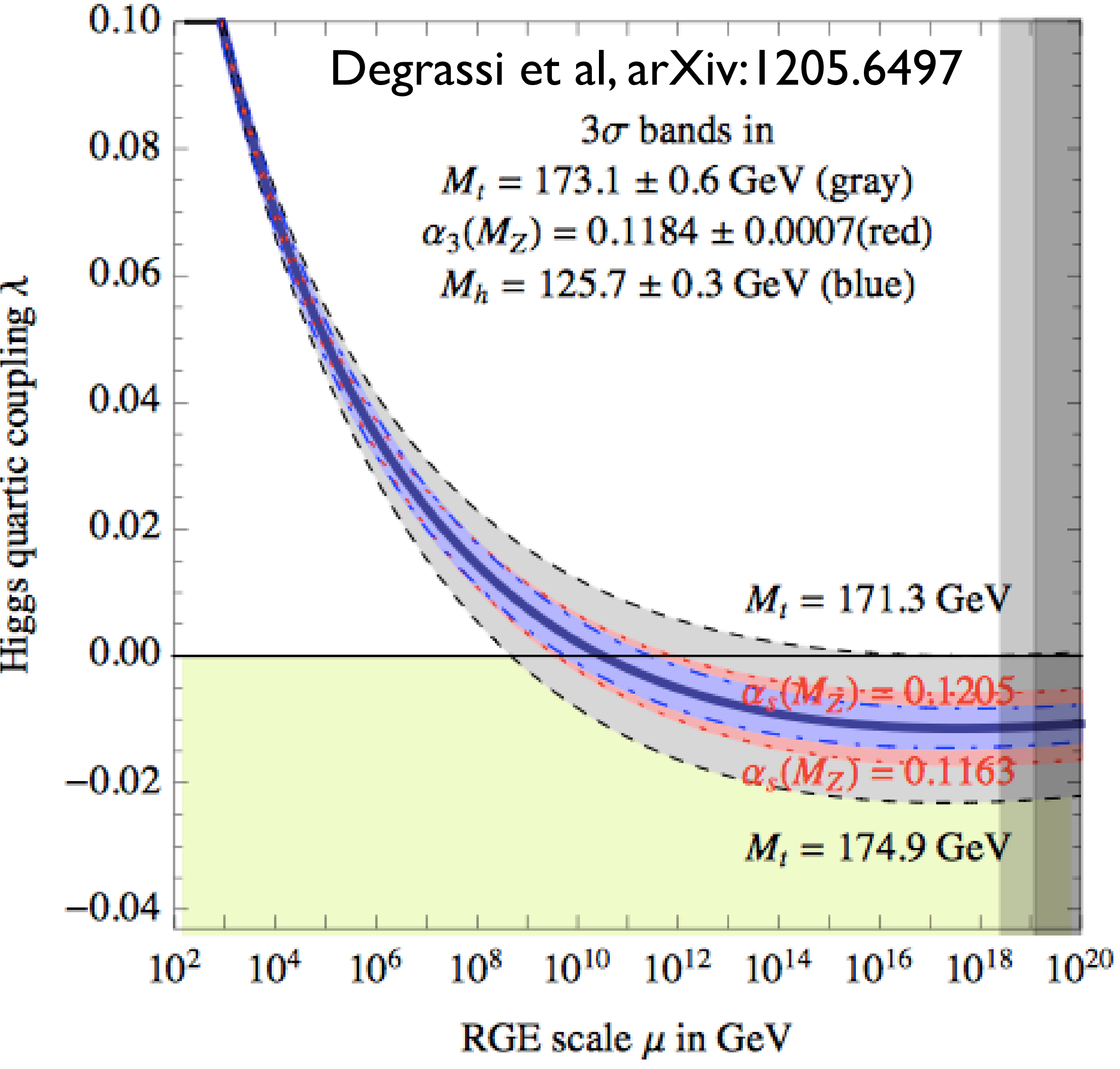
Degrassi et al, arXiv:1205.6497

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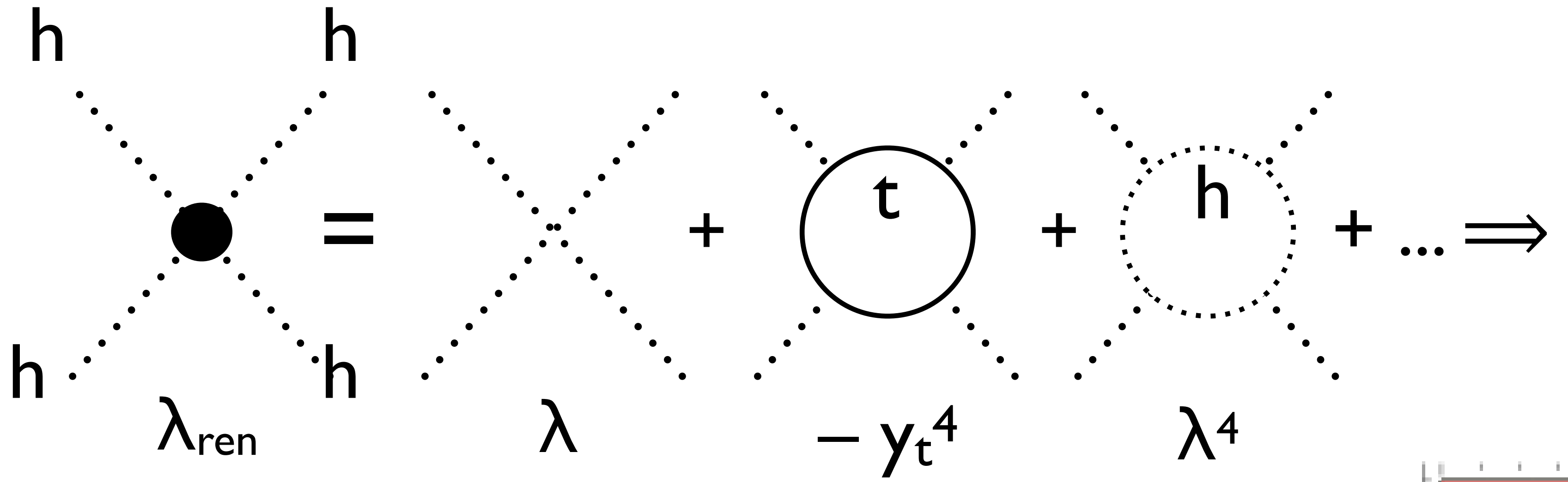

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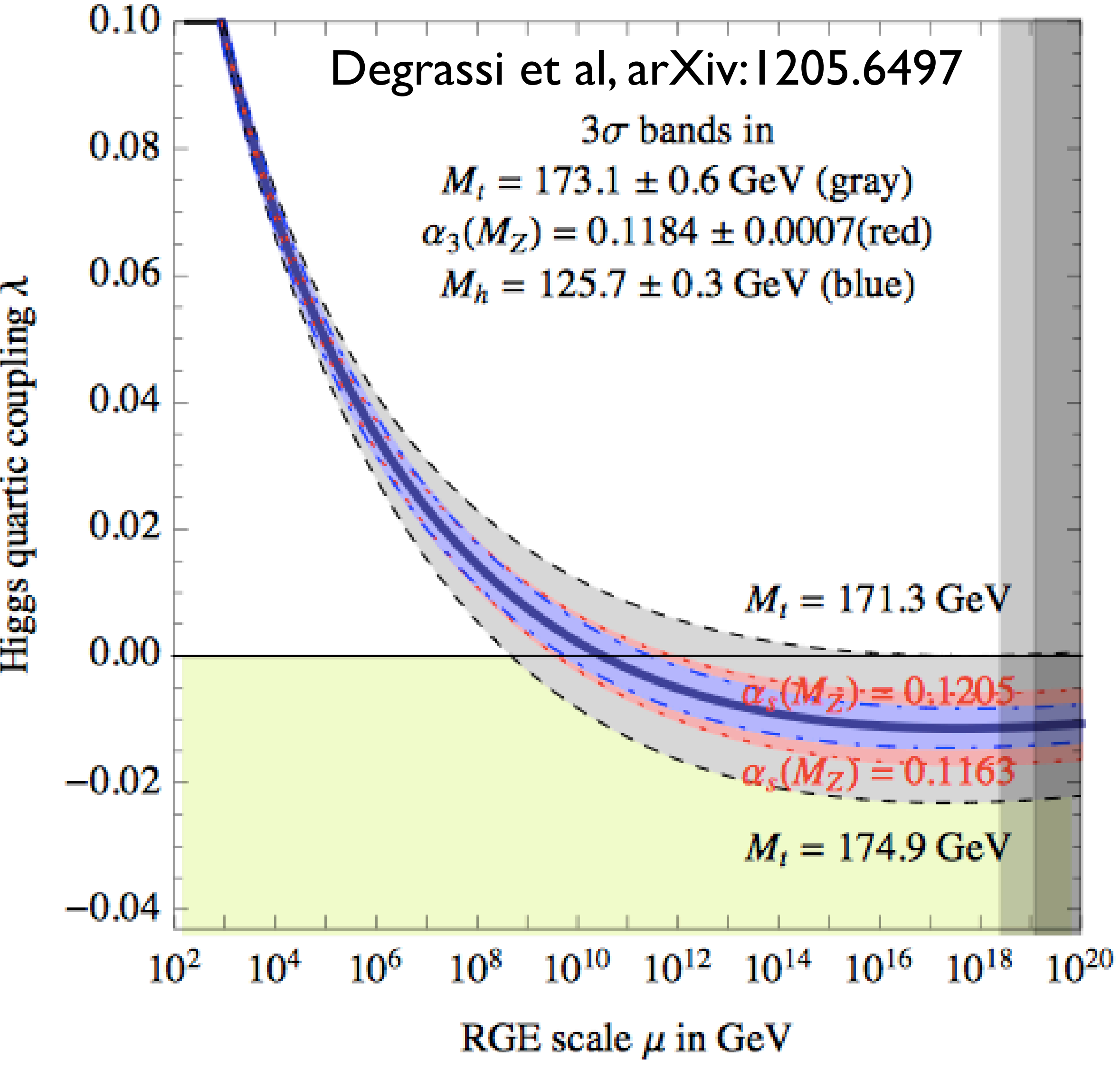

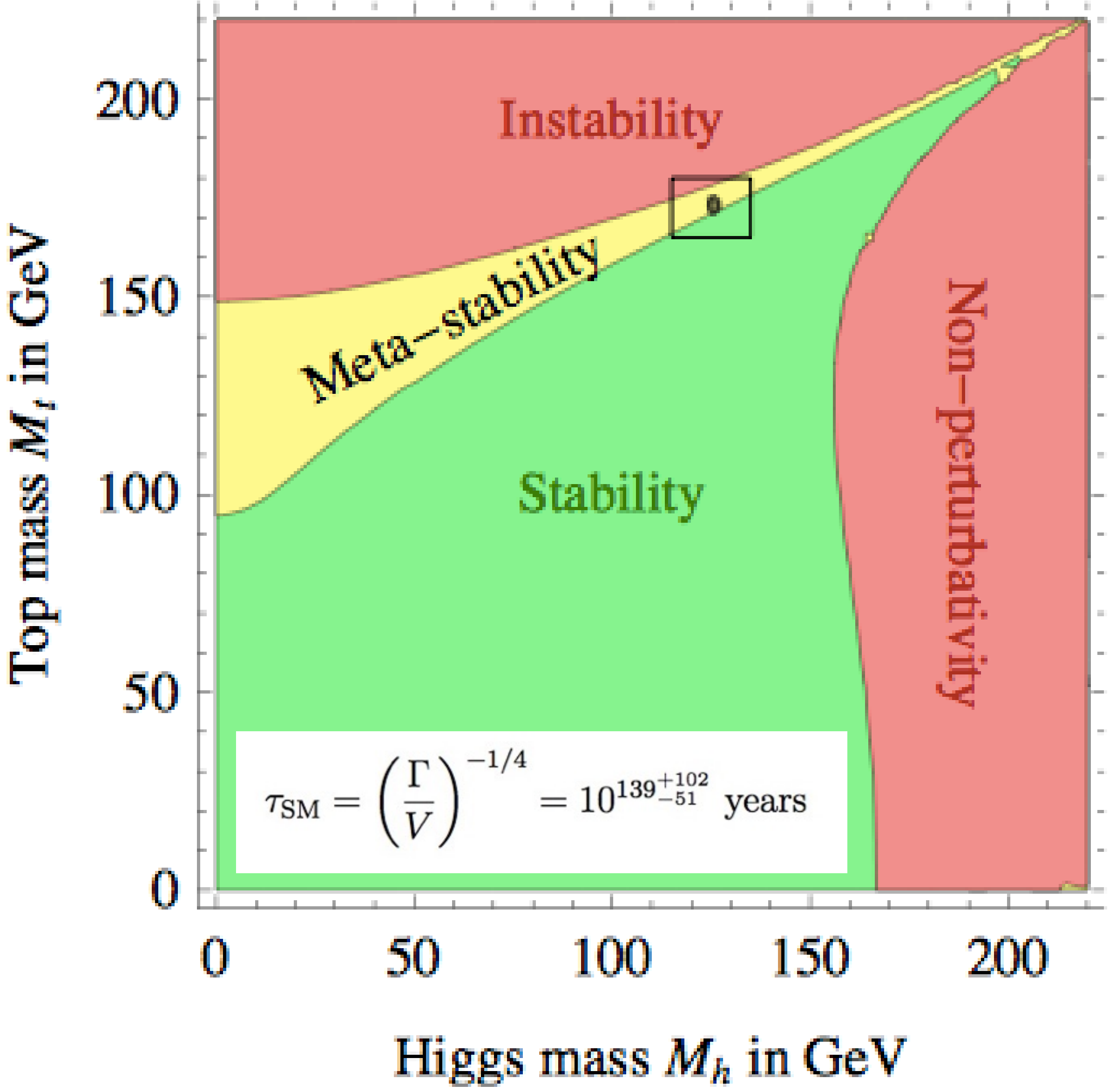

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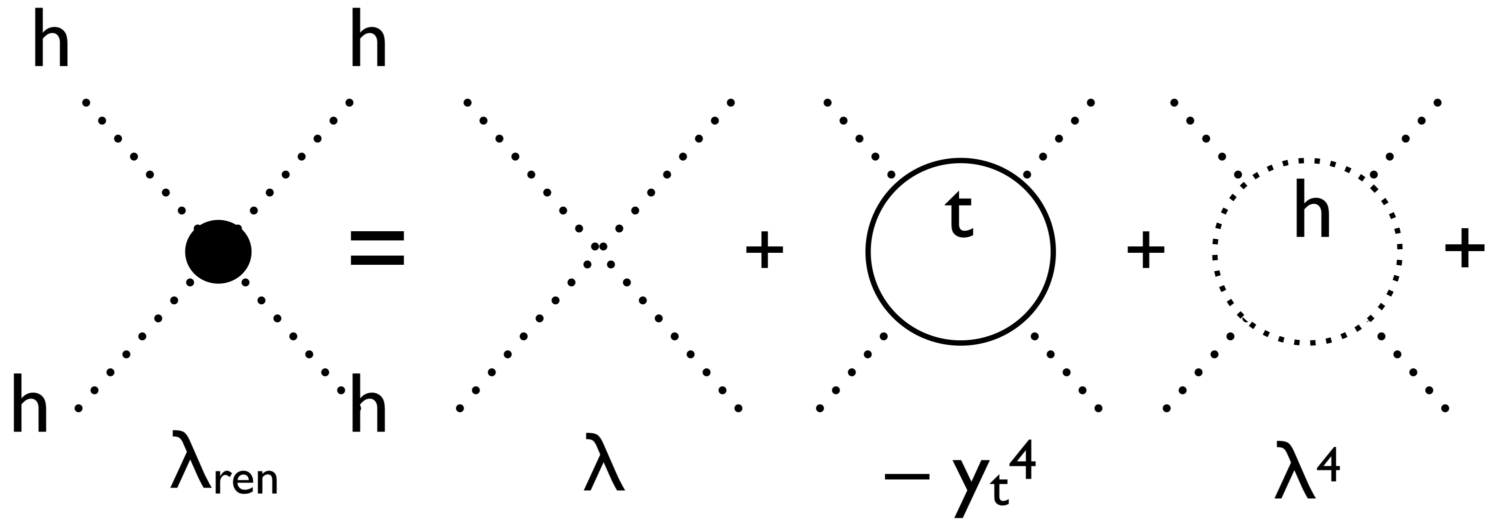

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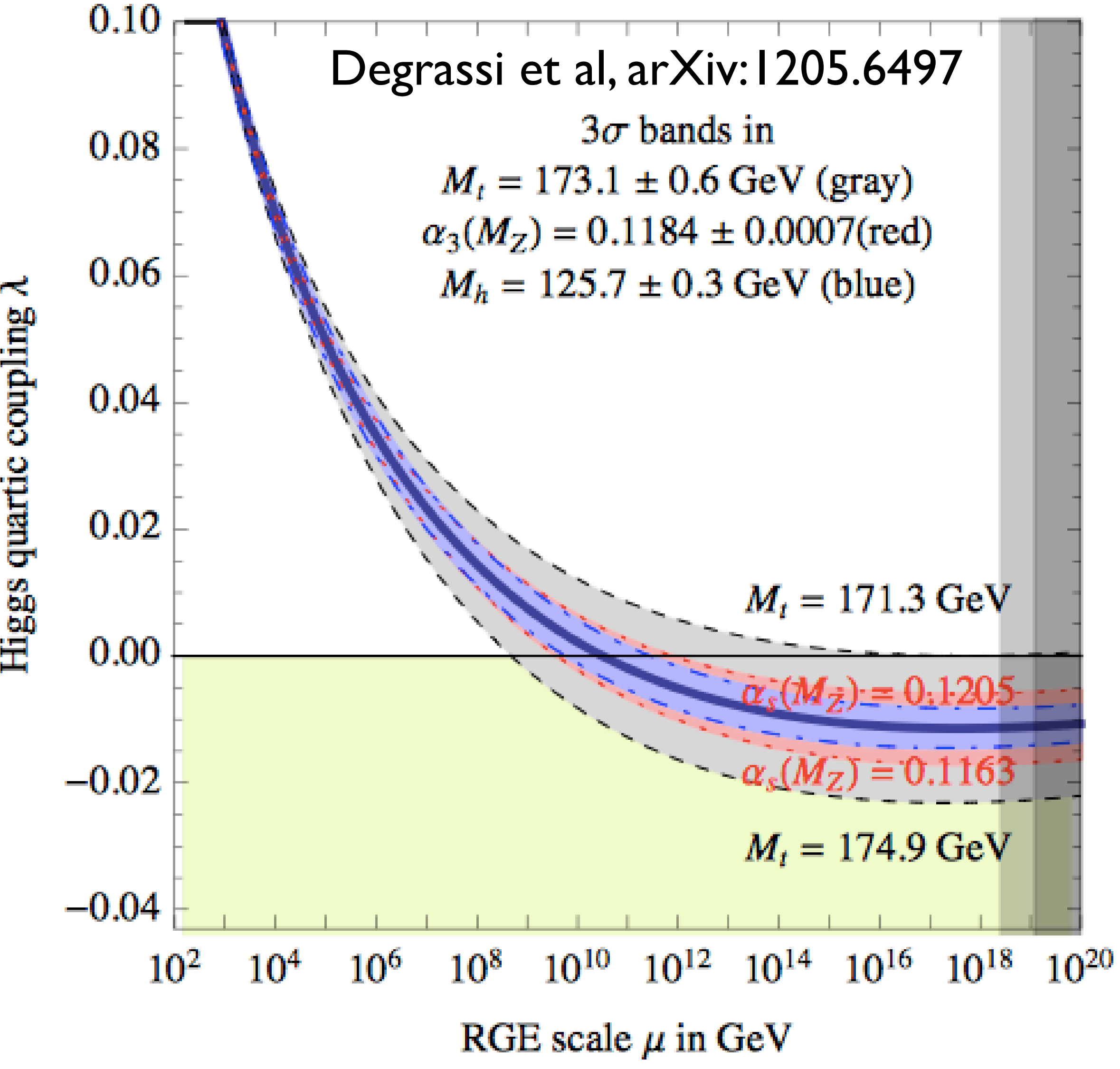

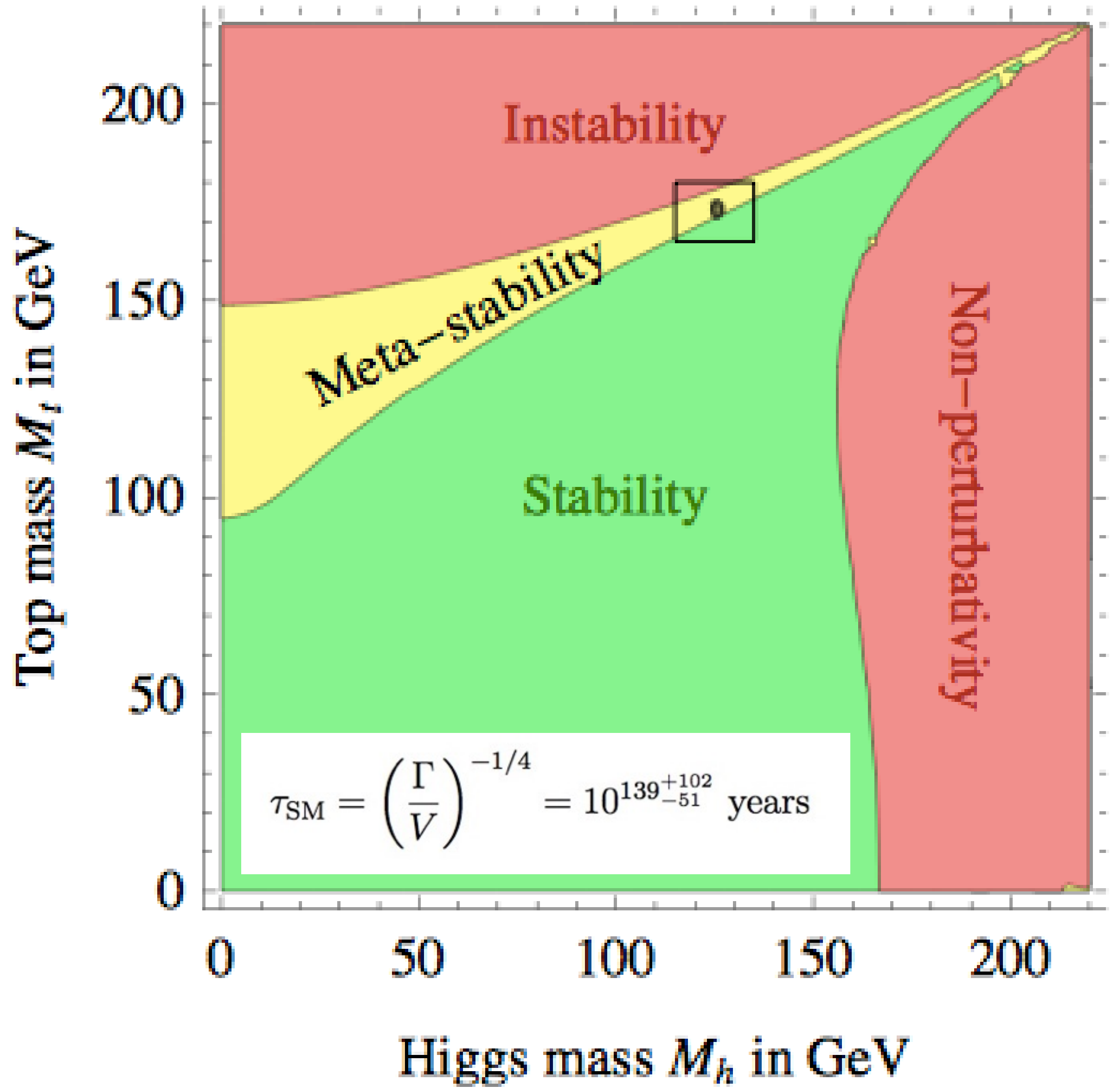

Not an issue of concern for the human race…. but the closeness of mtop to the critical value where the Higgs selfcoupling becomes 0 at M_{Planck} (namely 171.3 GeV) might be telling us something fundamental about the origin of EWSB … incidentally, y_{top}=1 (?!)

Other important open issues on the Higgs sector

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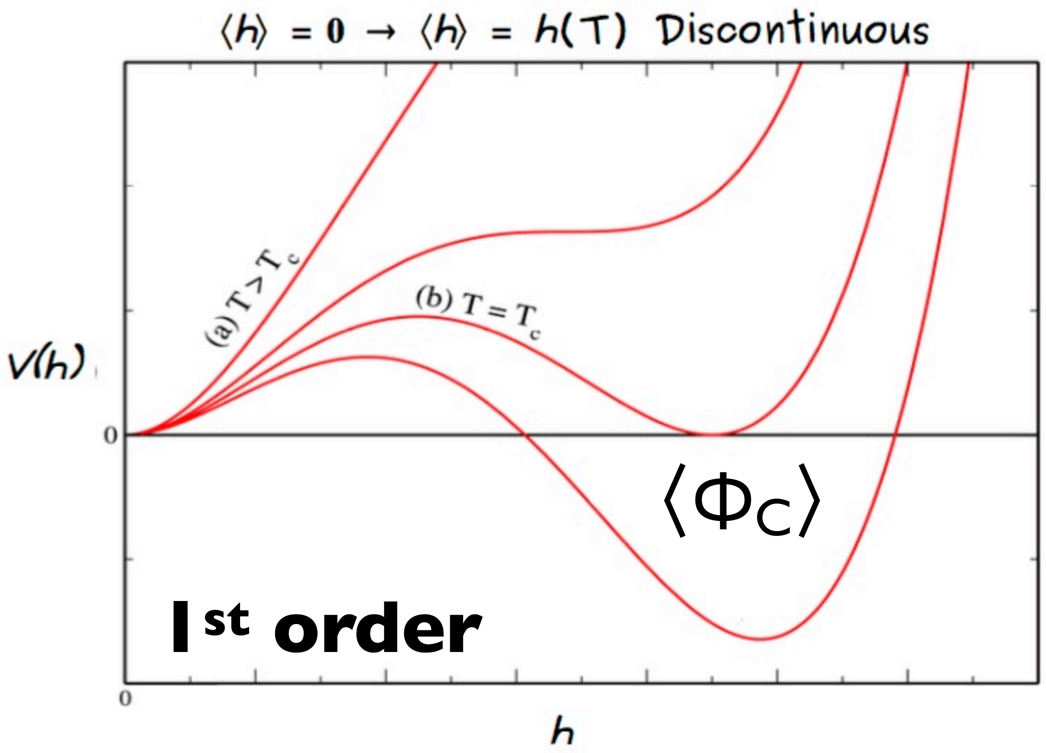
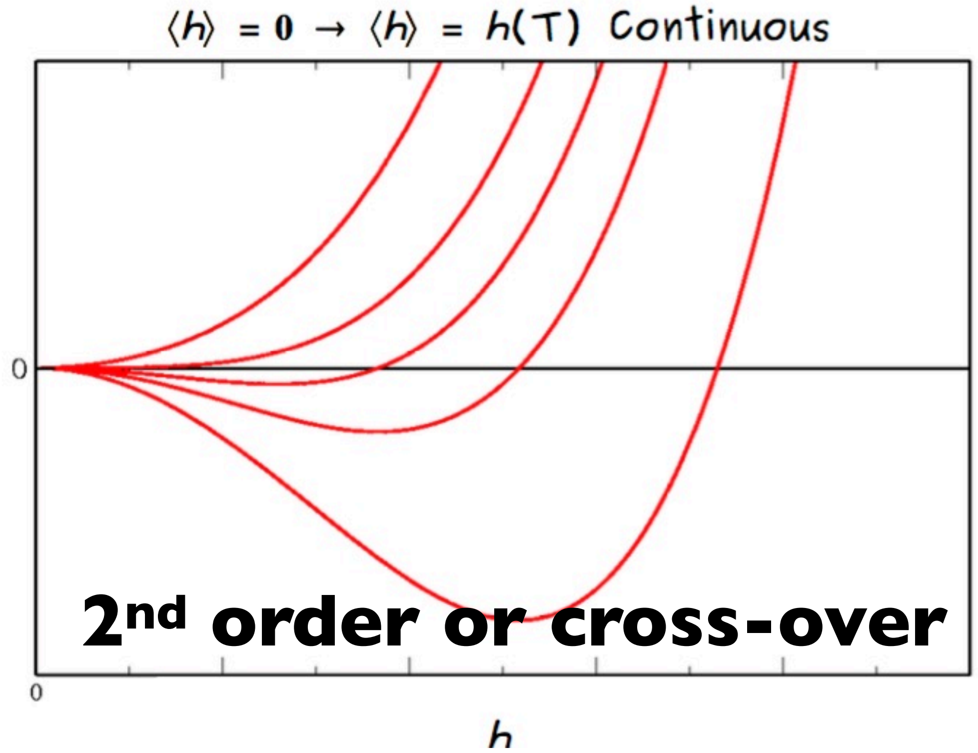
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

The nature of the EW phase transition



1st order



2nd order or cross-over

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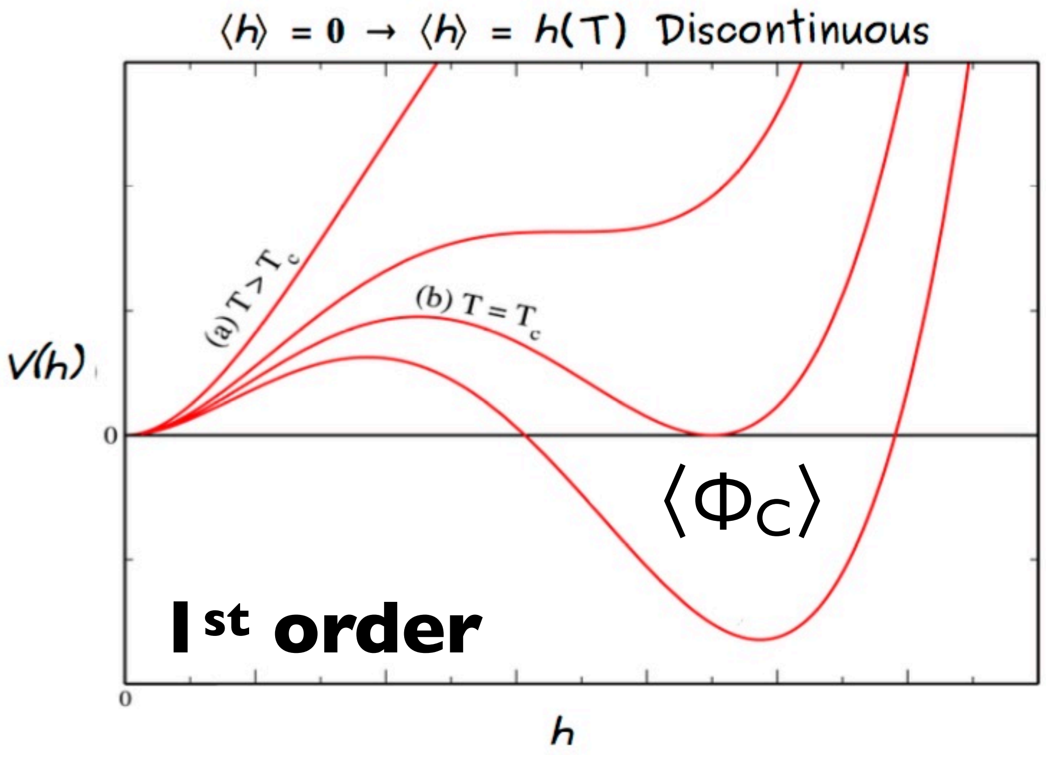

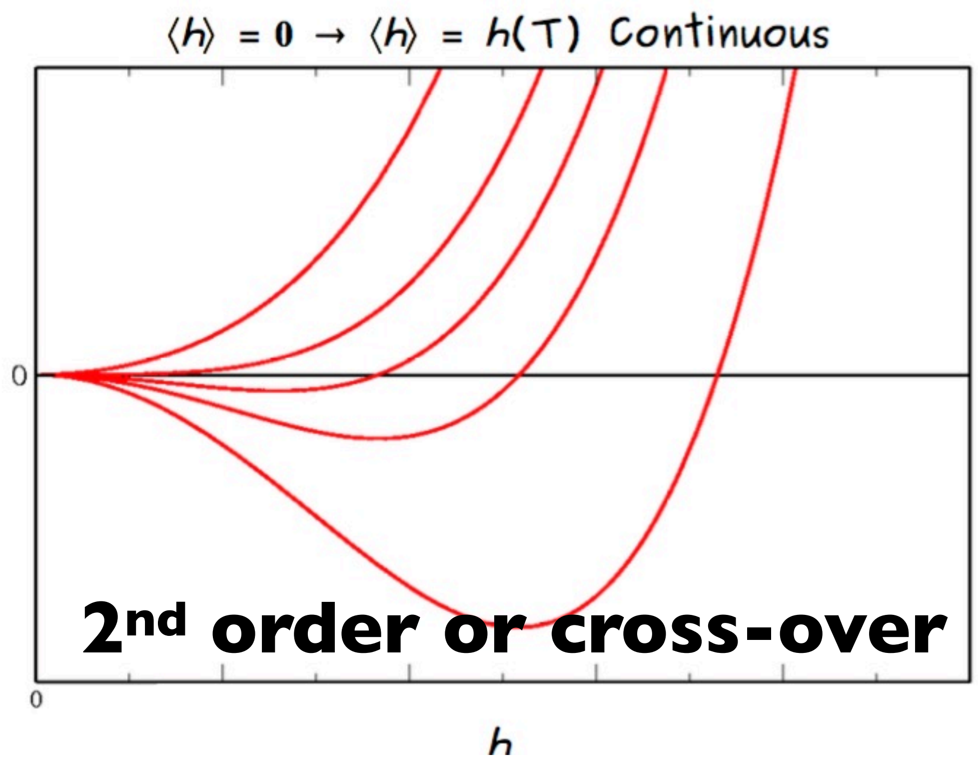

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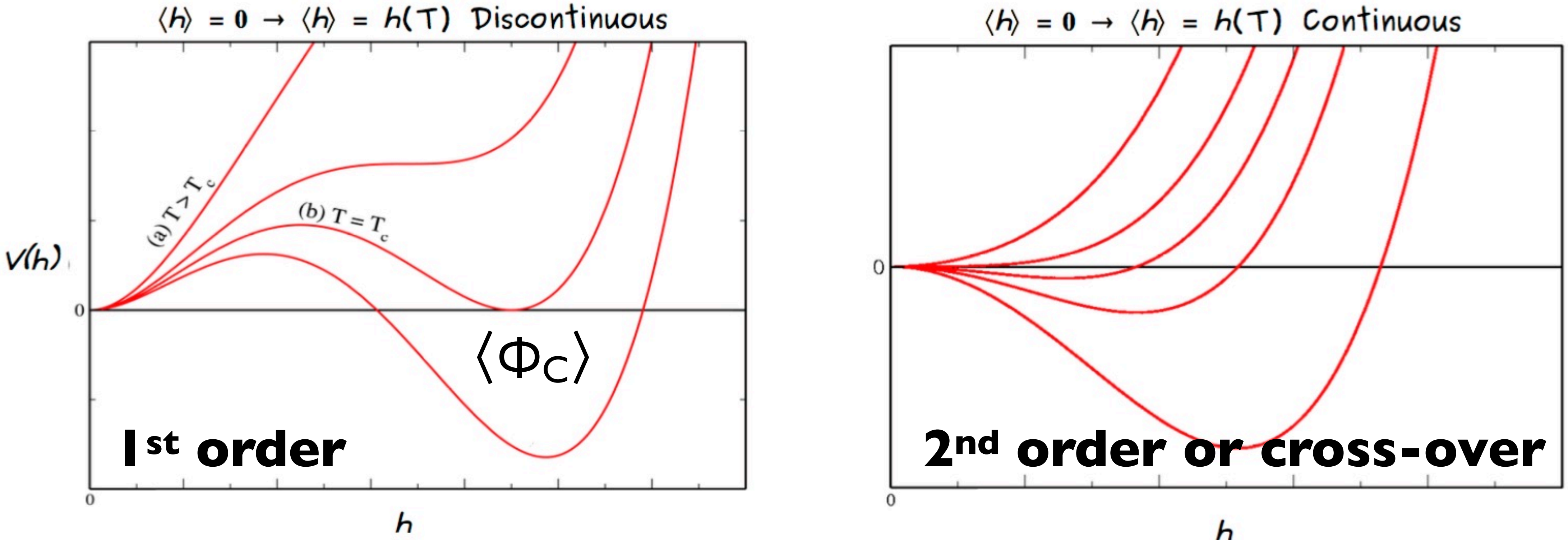

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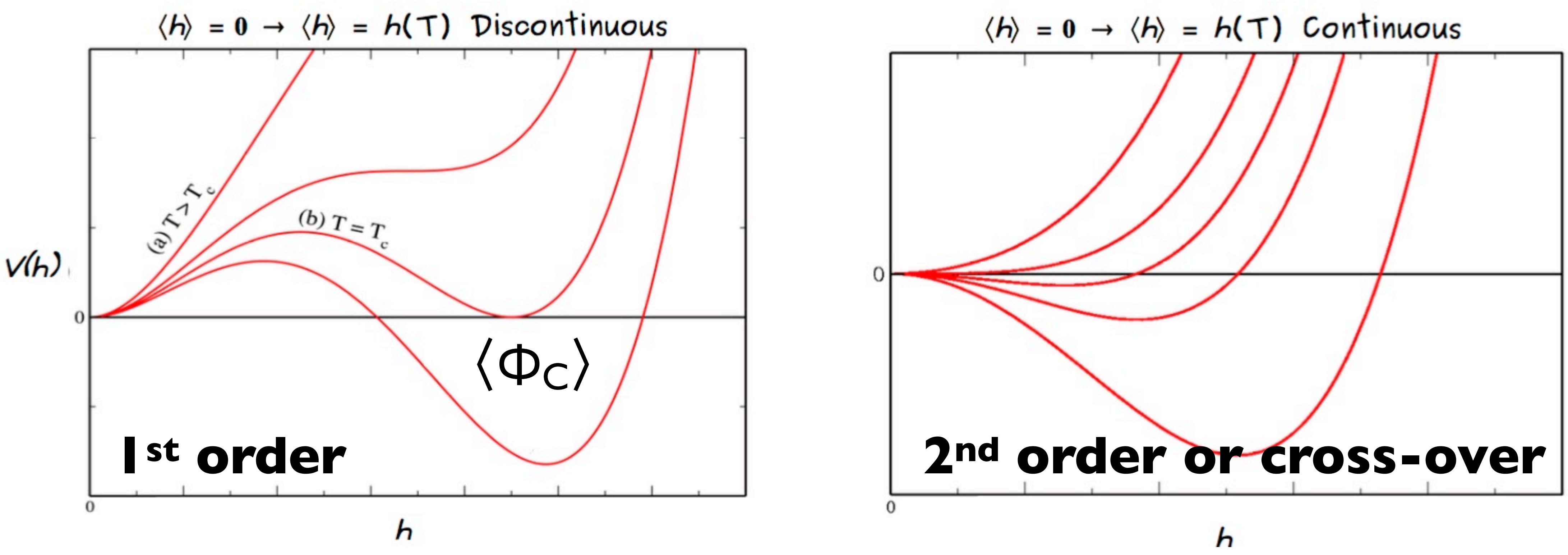
Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

The nature of the EW phase transition



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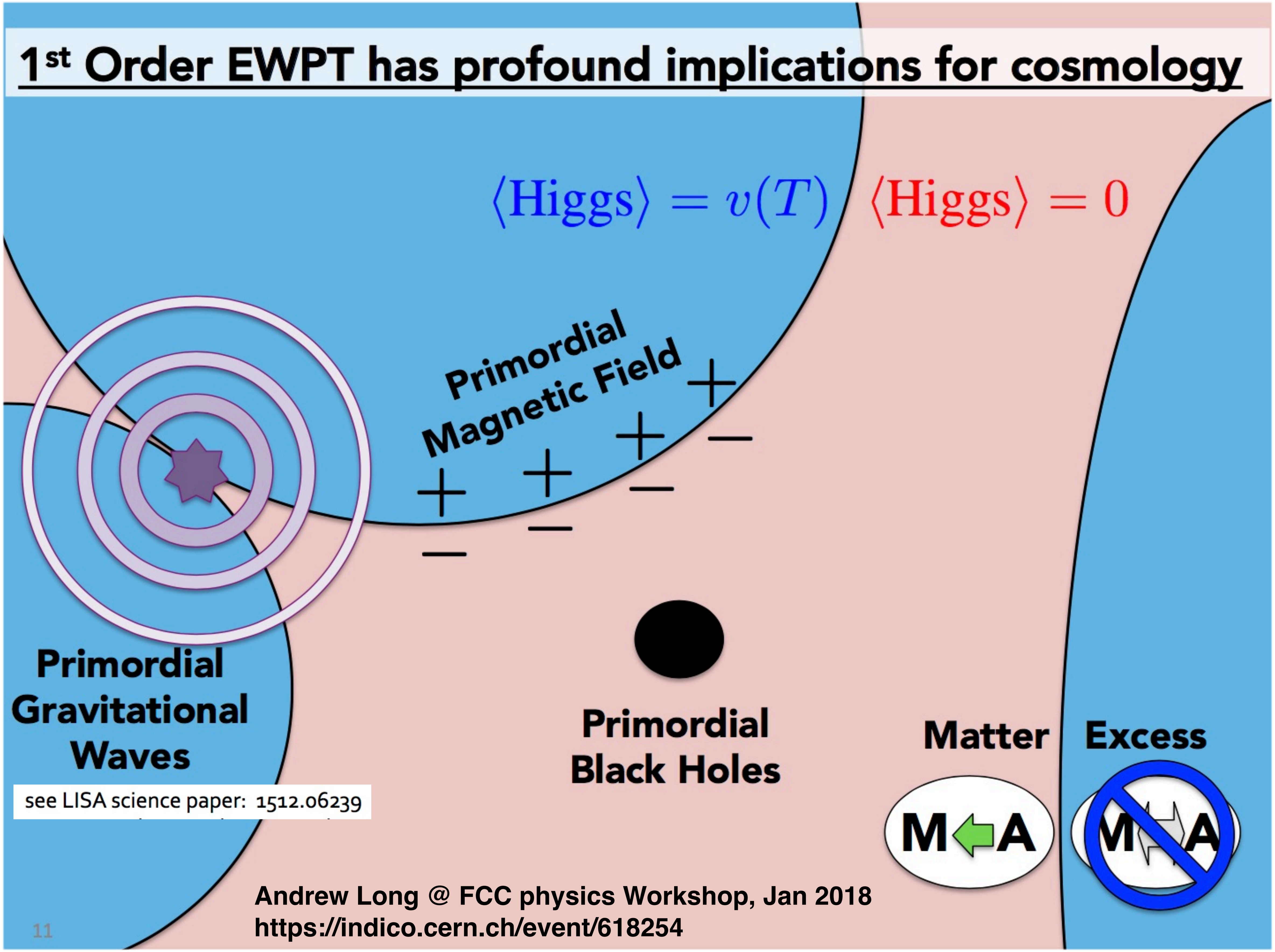
Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **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

$\langle \text{Higgs} \rangle = v(T)$ $\langle \text{Higgs} \rangle = 0$

Primordial Magnetic Field

Primordial Gravitational Waves

see LISA science paper: 1512.06239

Primordial Black Holes

Matter Excess

Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254

Other important open issues in 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, produced in a collider

What are we talking about when we're talking future colliders: at CERN…

HiLumi
HL-LHC PROJECT

pp @ 14 TeV, $3ab^{-1}$

✓Approved
2026-37

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e^+e^- @ 380 GeV, 1.5 & ~3 TeV

CDR 2012+
update '16

CDR: Conceptual Design Report

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CDR: Conceptual Design Report

CDR (end '18)

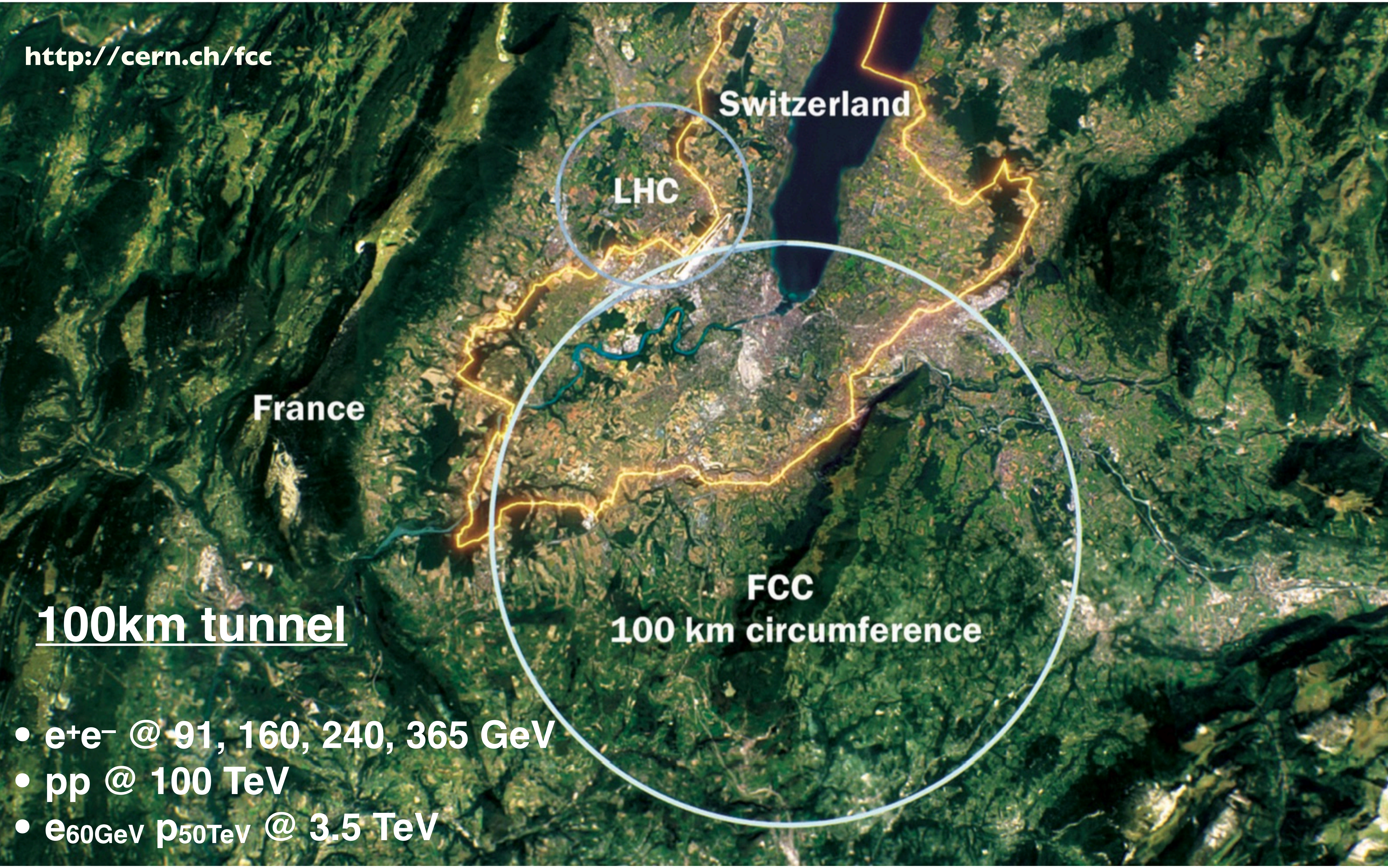
100km tunnel

- pp @ 100 TeV
- e$^+$e$^-$ @ 91, 160, 240, 365 GeV
- e_{60GeV} p_{50TeV} @ 3.5 TeV

LHC tunnel: HE-LHC

- pp @ 27 TeV, 15ab^{-1}

Future Circular Collider



http://cern.ch/fcc

100km tunnel

- e^+e^- @ 91, 160, 240, 365 GeV
- pp @ 100 TeV
- $e_{60GeV}\,p_{50TeV}$ @ 3.5 TeV

… and in the rest of the world:

e^+e^- @ 250, 350, 500 GeV

TDR 2012,

decision postponed
to end 2020

TDR: Technical Design Report

CDR (Fall ’18)

100km tunnel

- e^+e^- @ 91, 240 GeV (but possibly 160 & 350)
- Future possible pp @ ~70 TeV and $e_{60\text{GeV}}\ p_{35\text{TeV}}$

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 ?

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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*

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- 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?
  - …

Some examples

=>
see Franco’s talk for more details about the e+e– physics potential.

Here I **focus on pp@100 TeV** and its complementarity/synergy with ee

Higgs couplings (κ fit): HL-LHC → FCC-ee → hh

	HL-LHC(§)	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM(§§)	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	**4.3**	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	**1.8**	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	**3.4**	–	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**9.8**	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**6.5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

§ M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, Higgs Physics at the HL-LHC and HE-LHC, arXiv:1902.00134

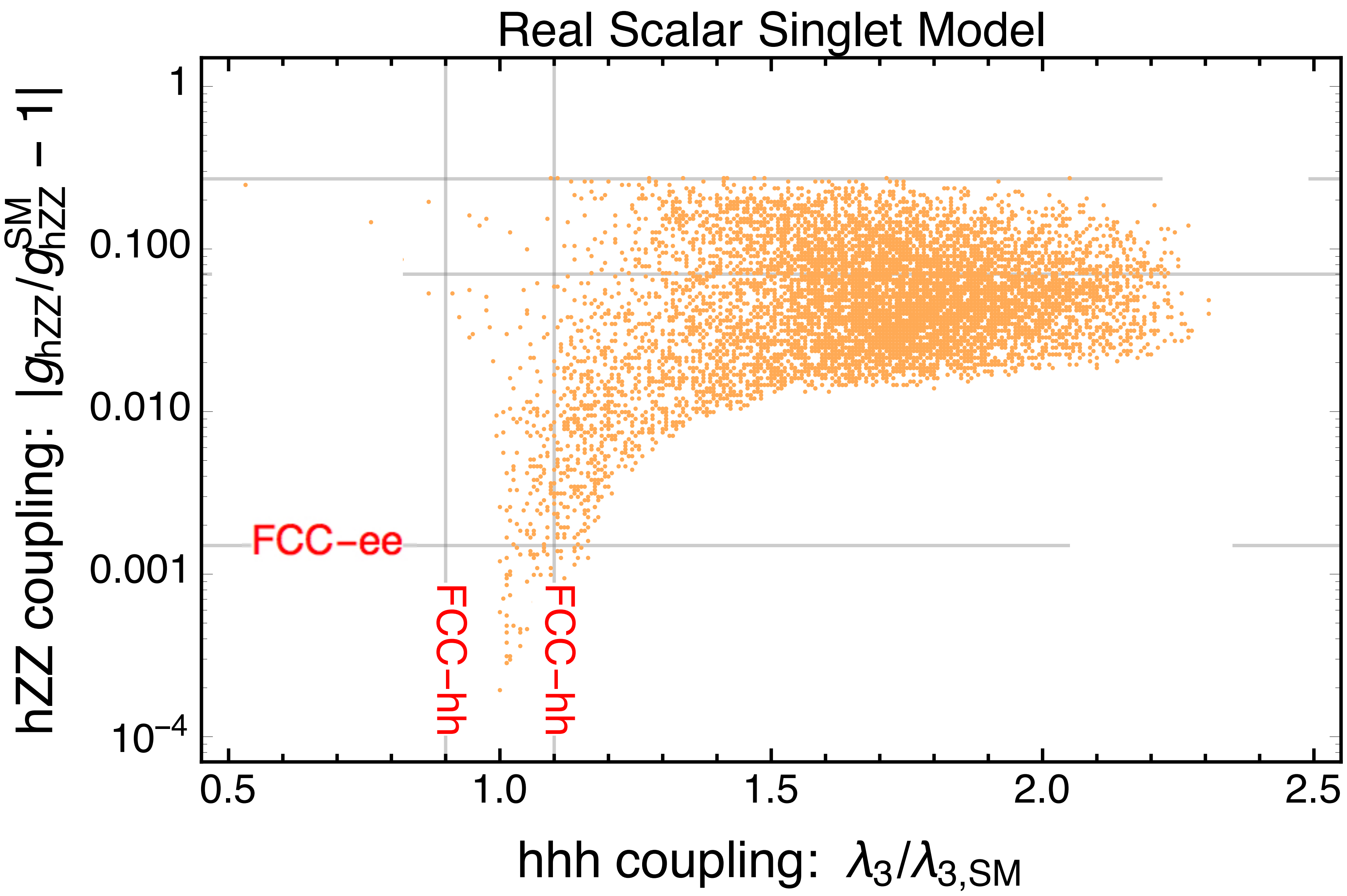
§§ SM width assumed in the global fit. Will be measured to ~20% (68%CL) via off-shell H->4l, to ~5% (95%CL) from global fit of Higgs production cross sections.

* From BR ratios wrt B(H→4lept) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

Constraints on models with 1st order phase transition: after the HL-LHC

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



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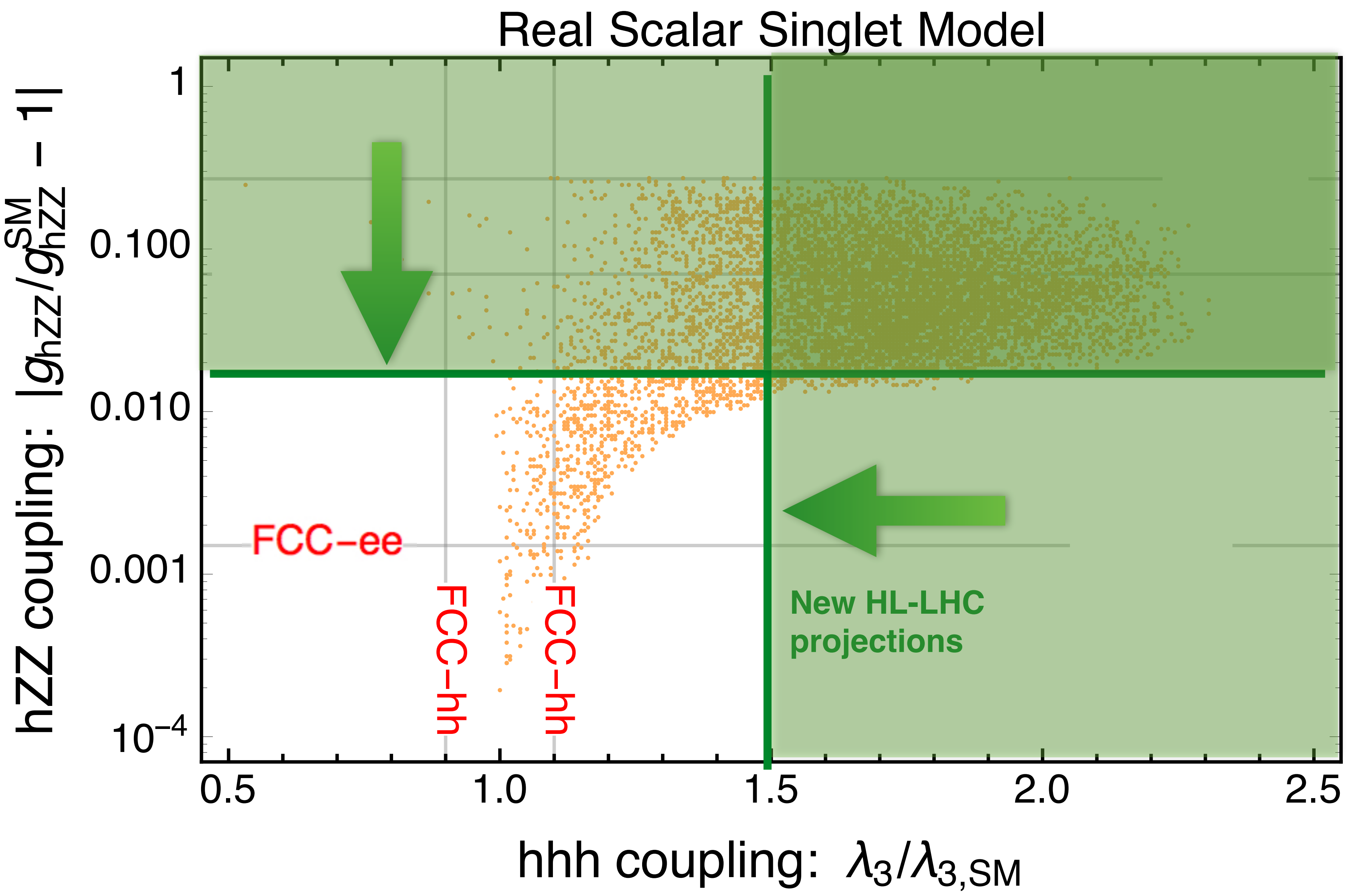

Bringing the HL-LHC sensitivity to the ±50% level, makes a big dent in this class of BSM models!

Constraints on models with 1st order phase transition: after the FCC

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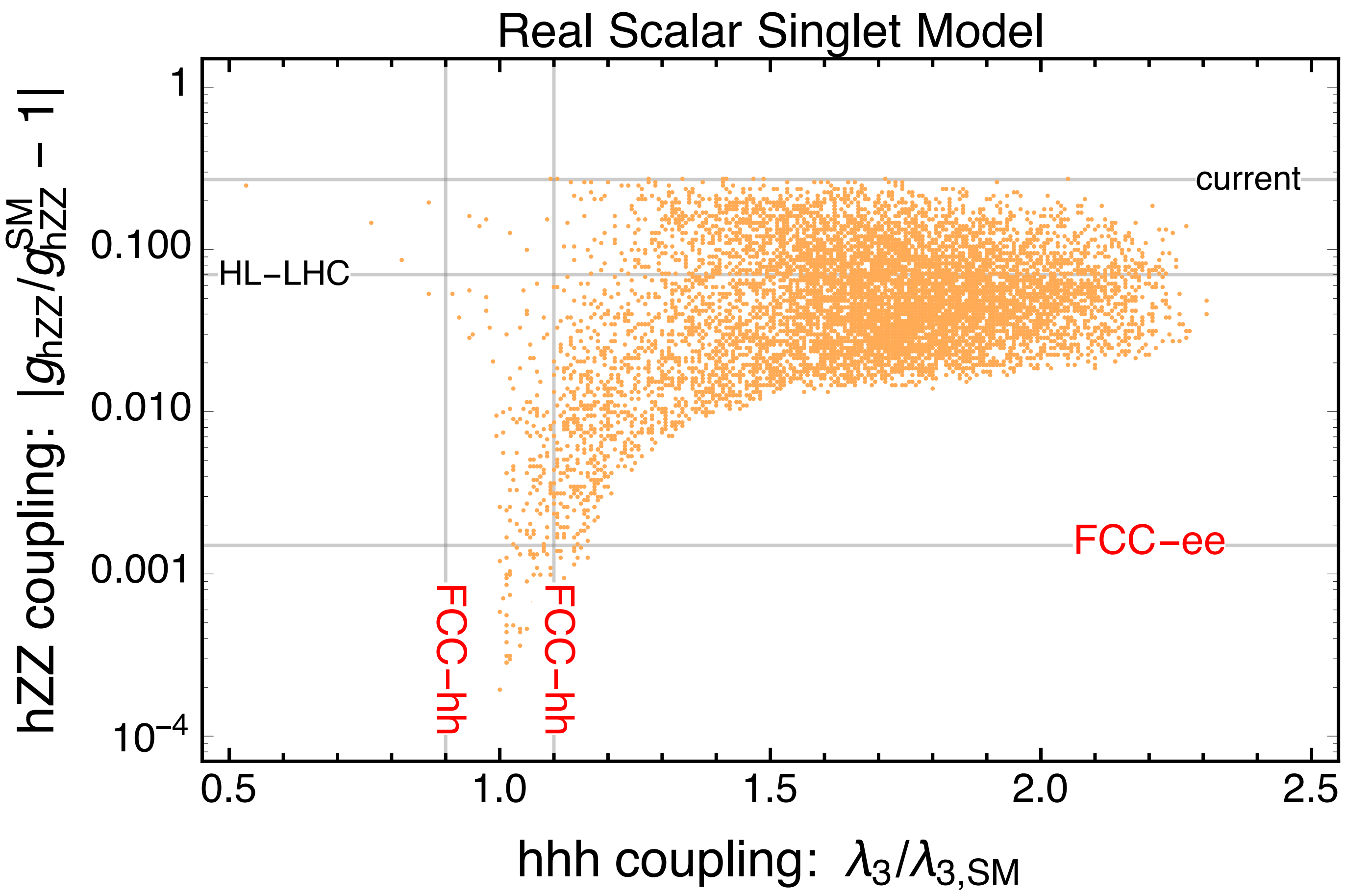
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



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

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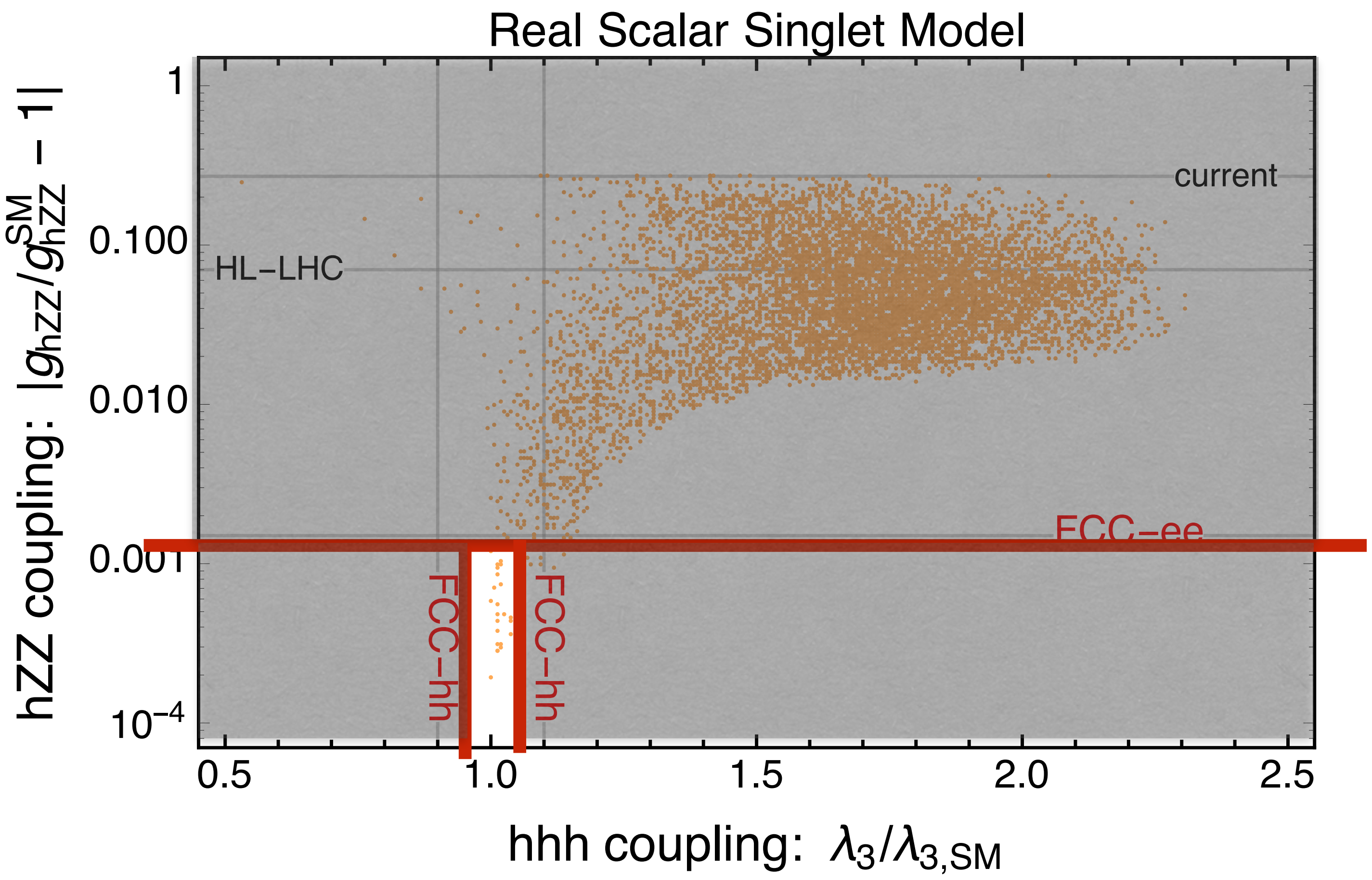

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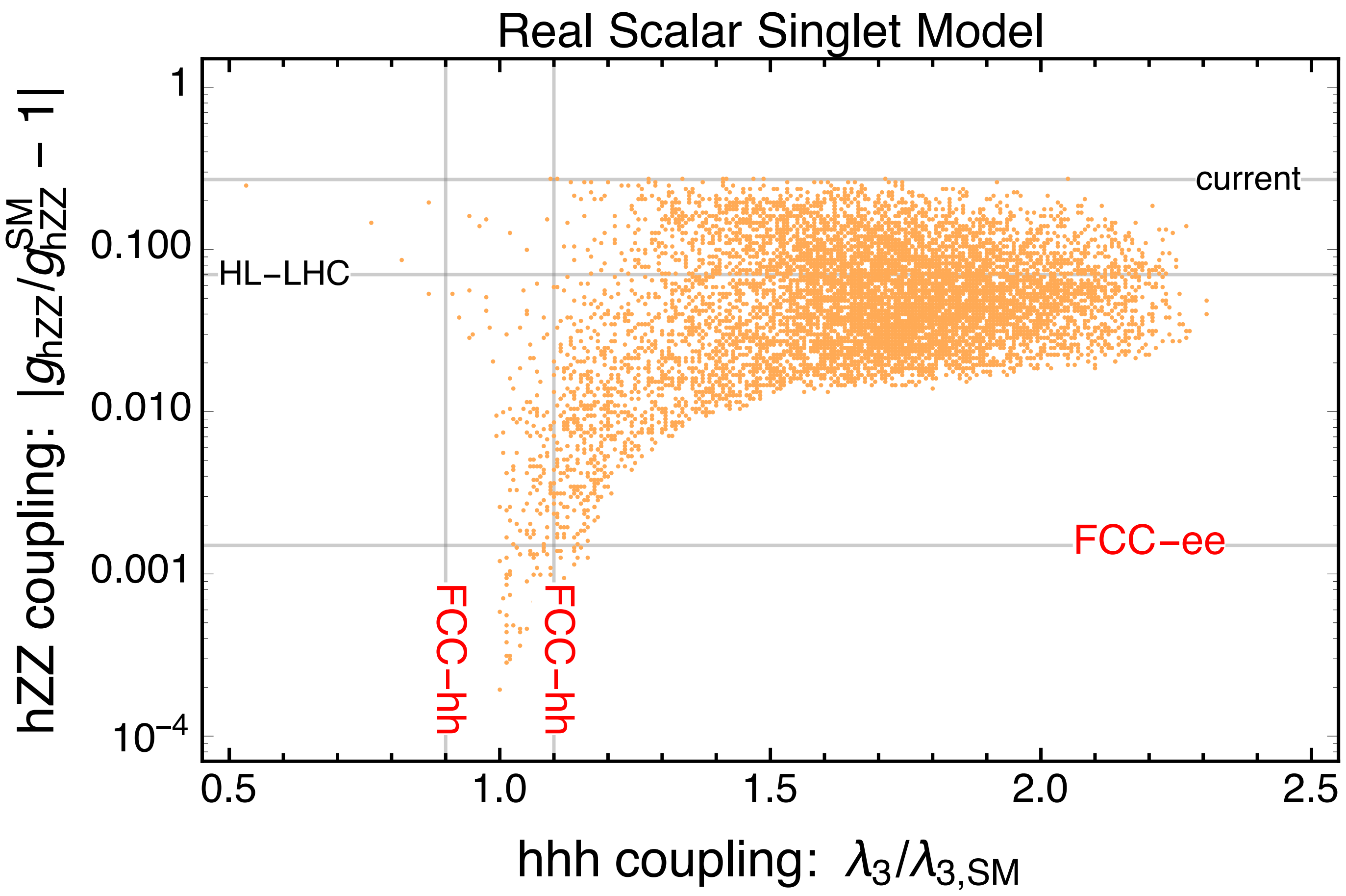

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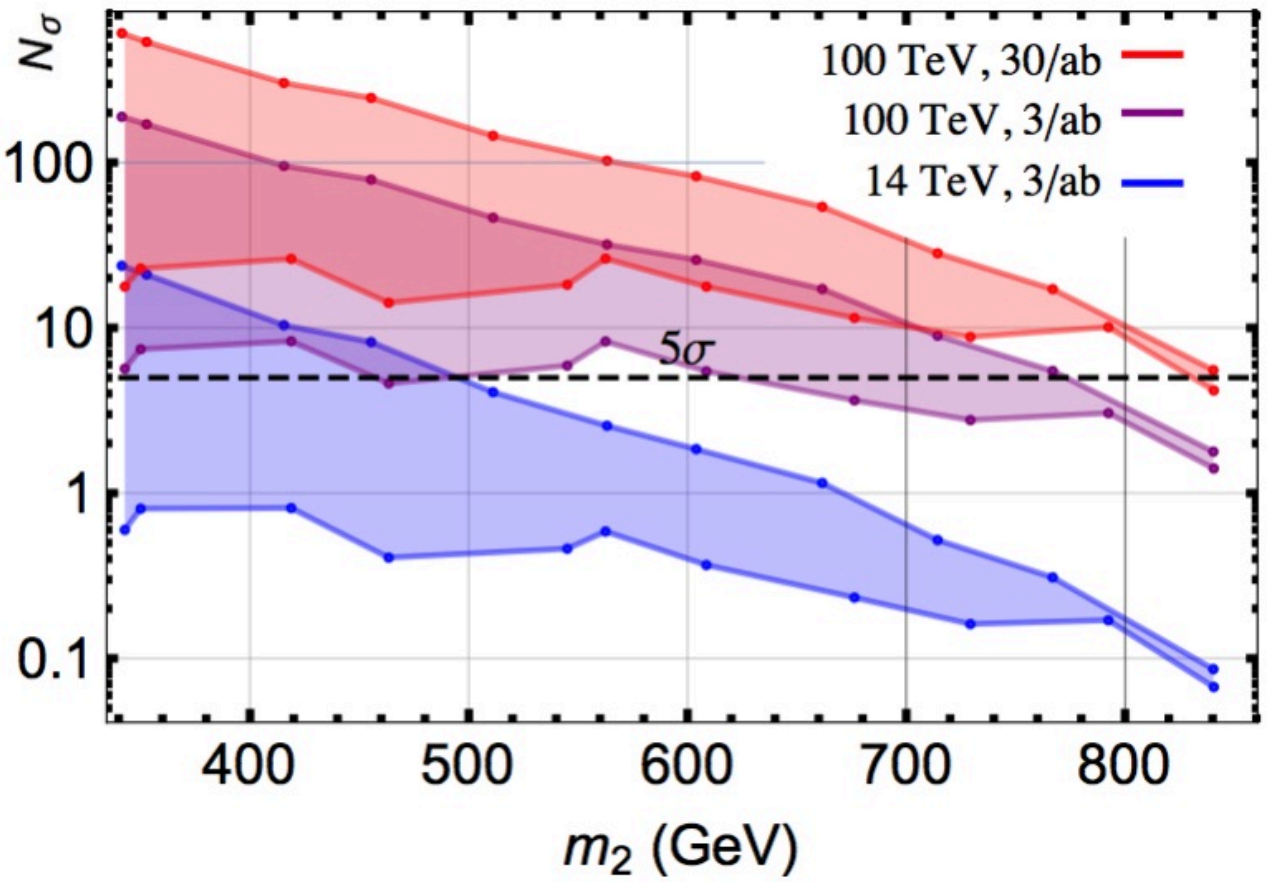
Direct detection of extra Higgs states at FCC-hh



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

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

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

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

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

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

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Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV

Example: high mass DY

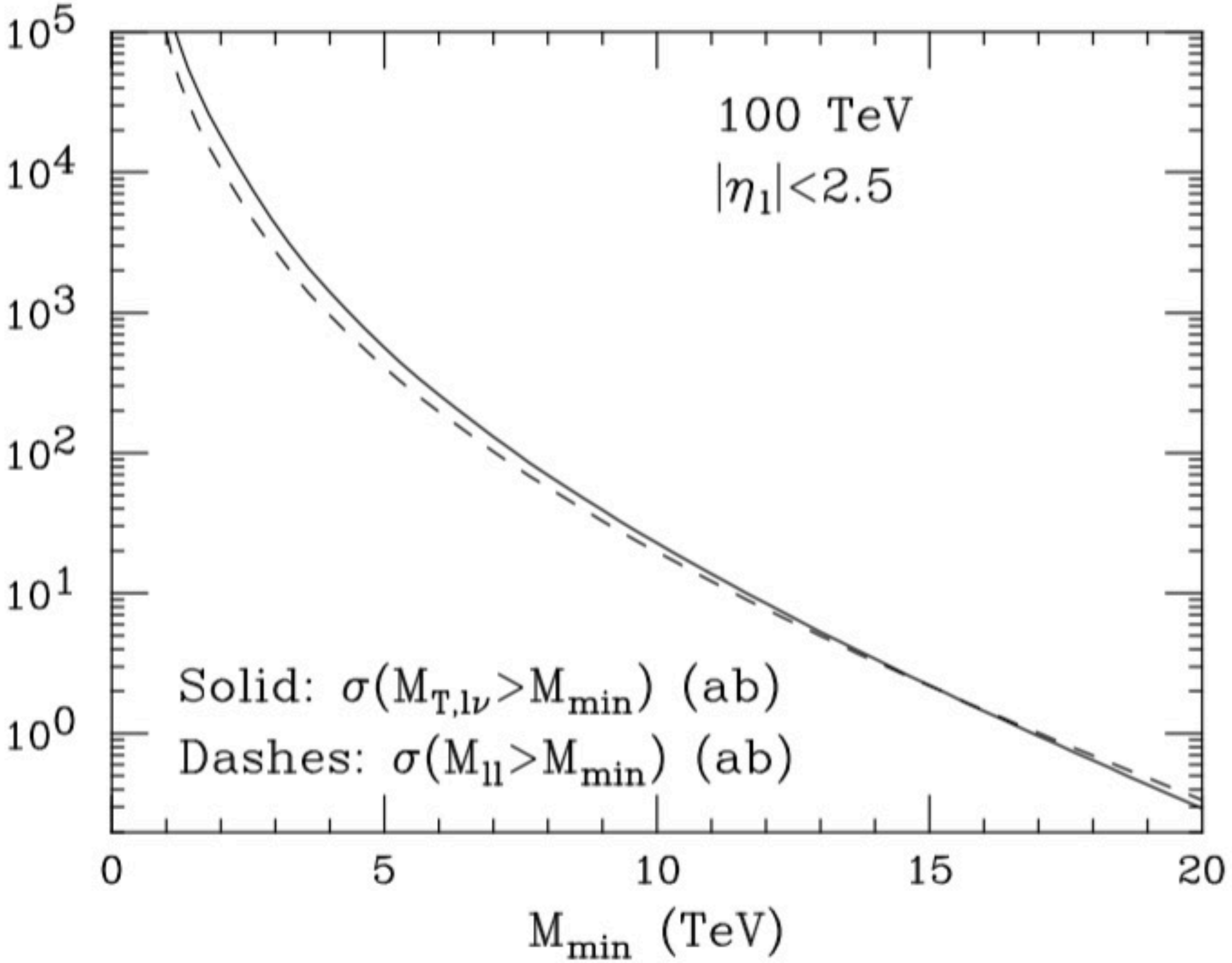
Farina et al, arXiv:1609.08157

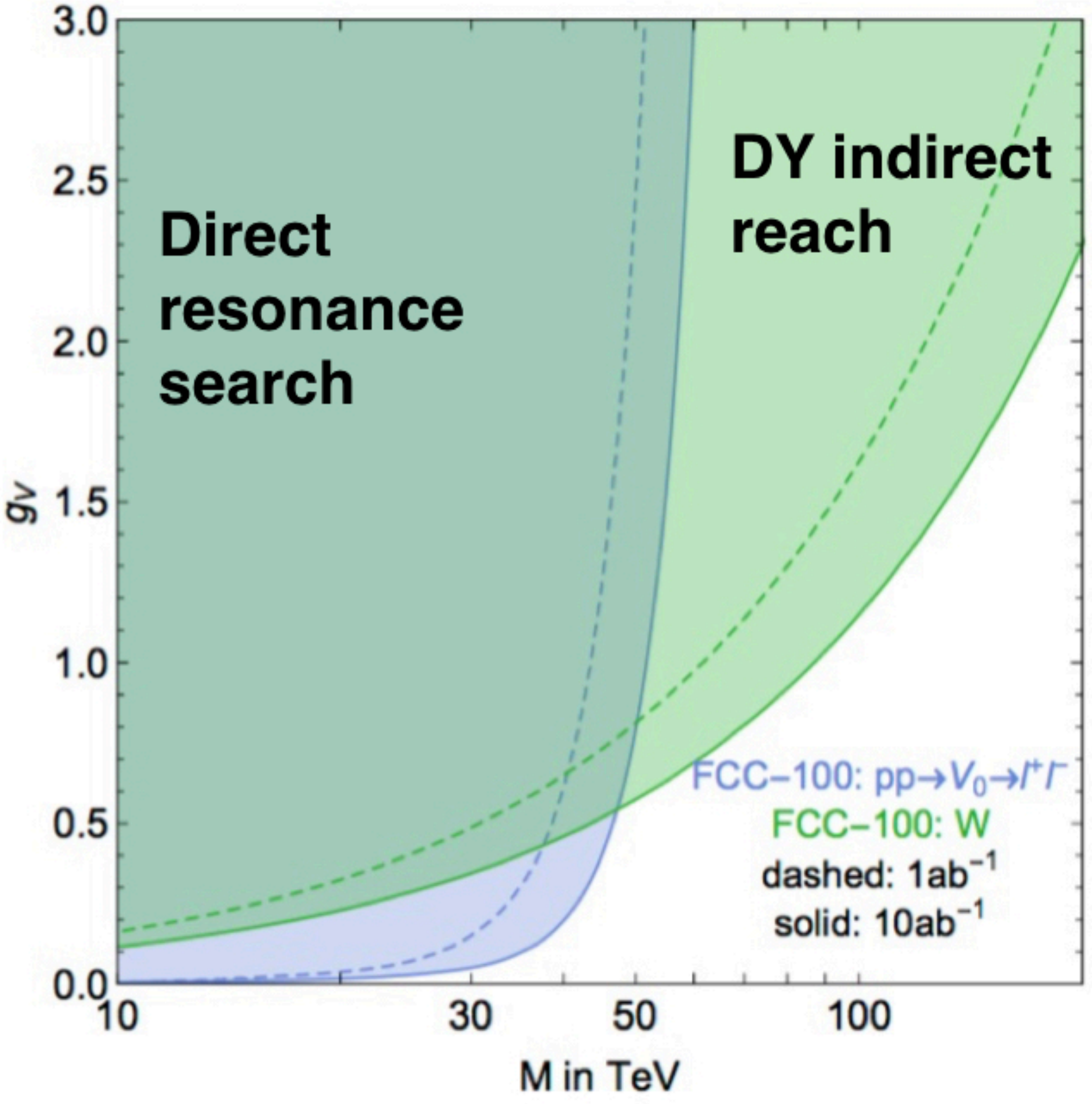
Constraints on Higher-dim op's

$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

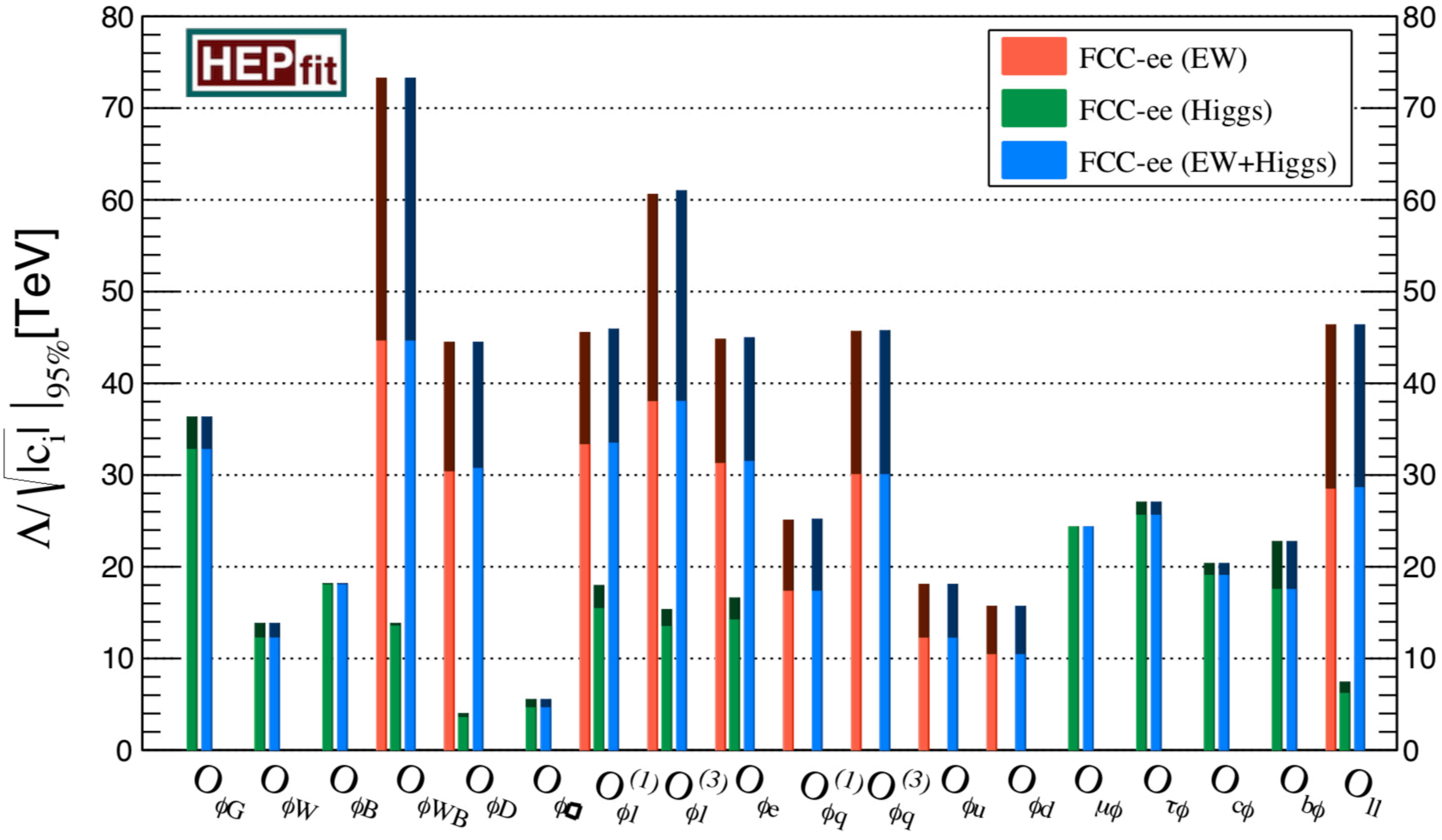
	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2\times10^7\,Z$	0.3/ab	3/ab	10/ab	$10^9\,Z$	$10^{12}\,Z$	$10^{10}\,Z$	3/ab	1/ab	1/ab
$W\ \times10^4$	$[-19,3]$	±0.7	±0.45	±0.02	±4.2	±1.2	±3.6	±0.3	±0.5	±0.15
$Y\ \times10^4$	$[-17,4]$	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2	$\sim\pm0.5$	$\sim\pm0.15$

$W / 4m_W^2 \;<\; 1/(100\ \text{TeV})^2$





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.

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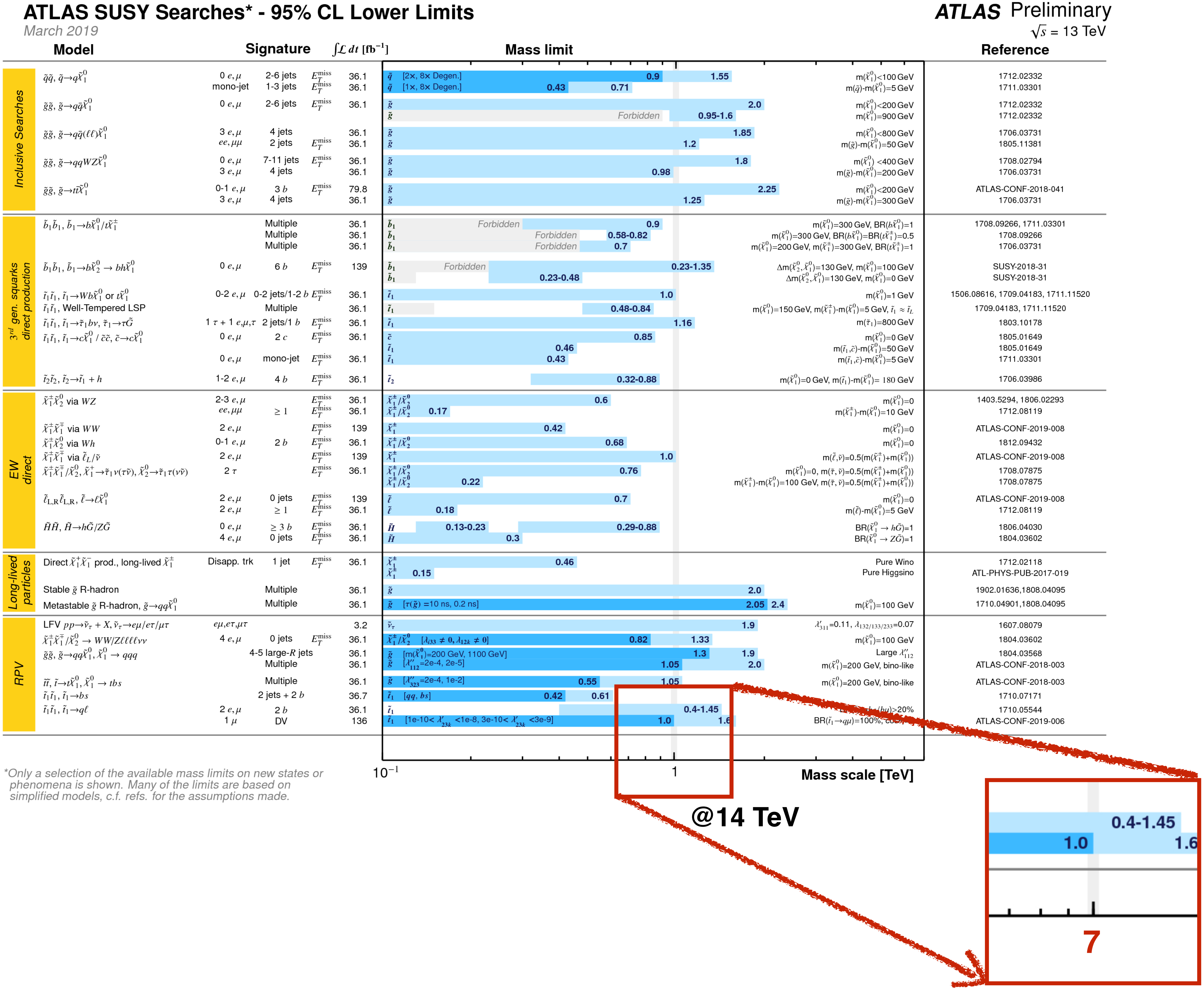
  - *m(e) => just a parameter; m(p)=> just QCD dynamics; Higgs couplings => ???*
- … but who knows how important a given measurement can become, to assess the validity of a future theory?
  - the day some BSM signal is found somewhere, the available precision measurements, will be crucial to establish the nature of the signal, whether they agree or deviate from the SM

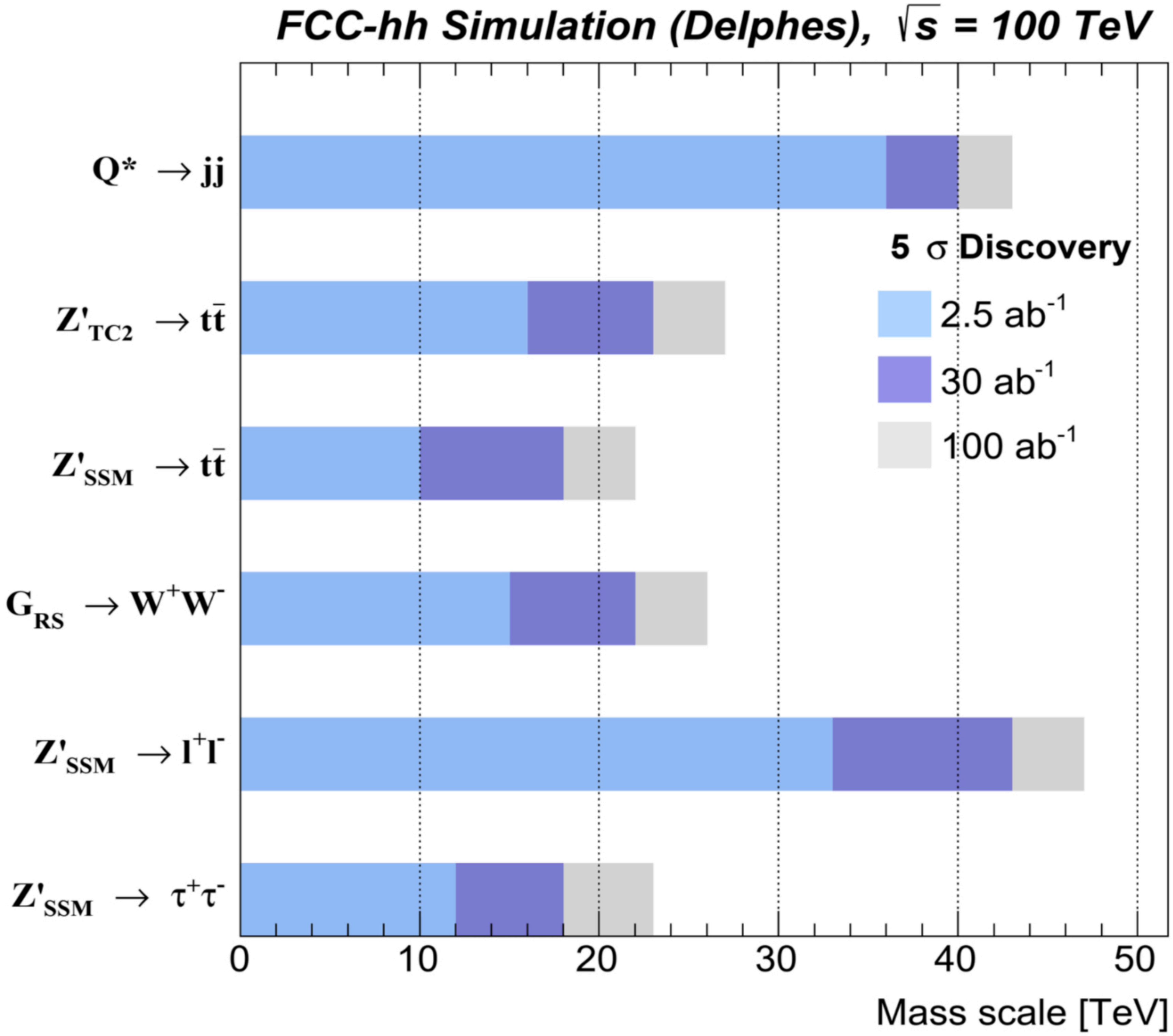
Direct discovery potential at 100 TeV



@14 TeV

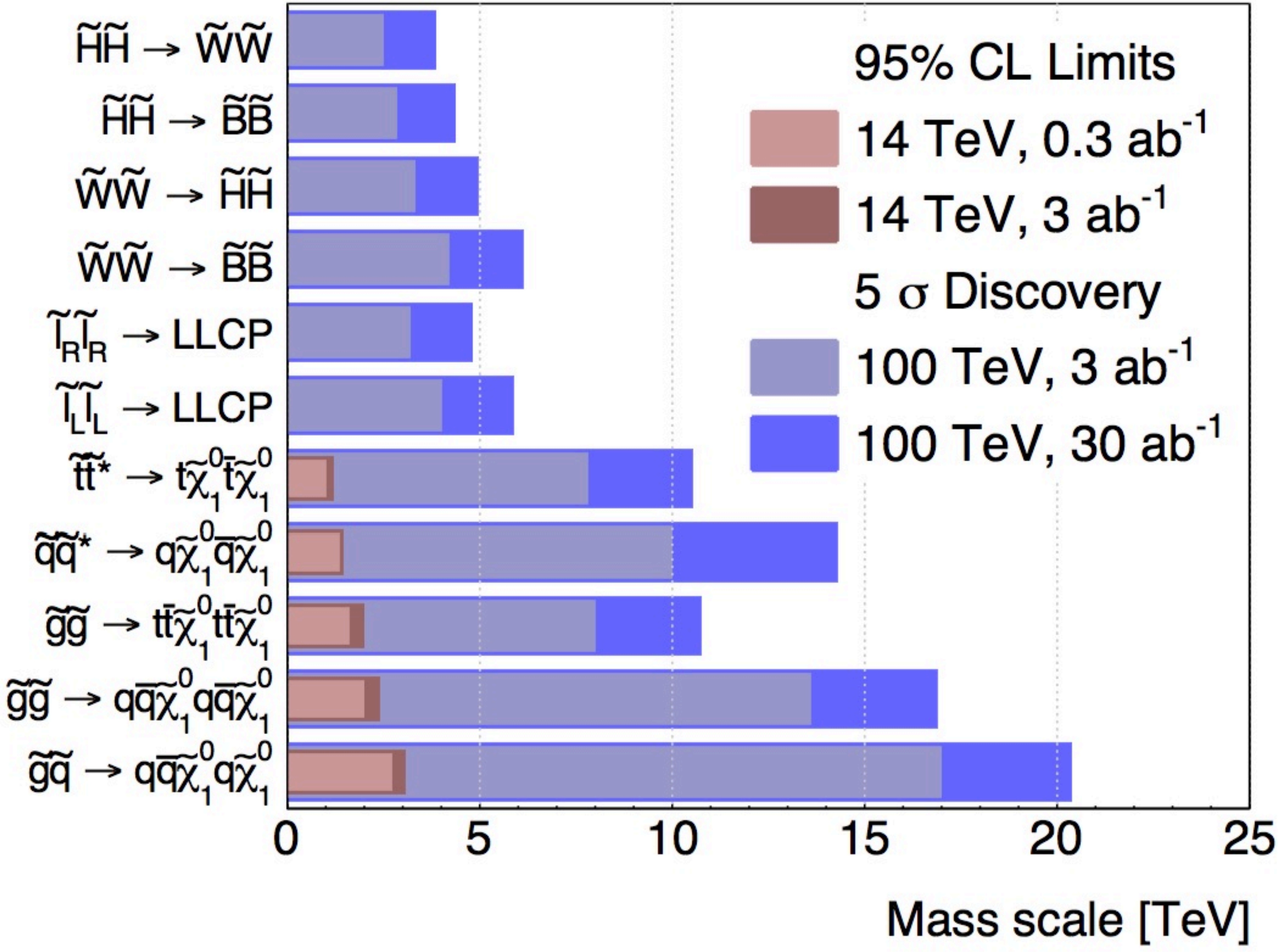
@100 TeV

Direct discovery reach: s-channel resonances



FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV



Dark Matter

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
- More in general, no experiment can guarantee an answer to the question ”what is DM?”
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- **We would like to understand whether a future collider can answer more specific questions, such as:**
  - do WIMPS contribute to DM?
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders? Is there sensitivity to the explicit detection of DM-SM mediators?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, (χ χ ↔ SM)

$$\Omega_{\mathrm{DM}} h^2 \sim \frac{10^9 \mathrm{Ge}V^{-1}}{M_{\mathrm{pl}}} \frac{1}{\langle \sigma v \rangle}$$

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$$\langle \sigma v \rangle \sim g_{\rm eff}^4 / M_{\rm DM}^2$$

⟹

$$\Omega_{\rm DM} h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}} \right)^2 \left(\frac{0.3}{g_{\rm eff}} \right)^4$$

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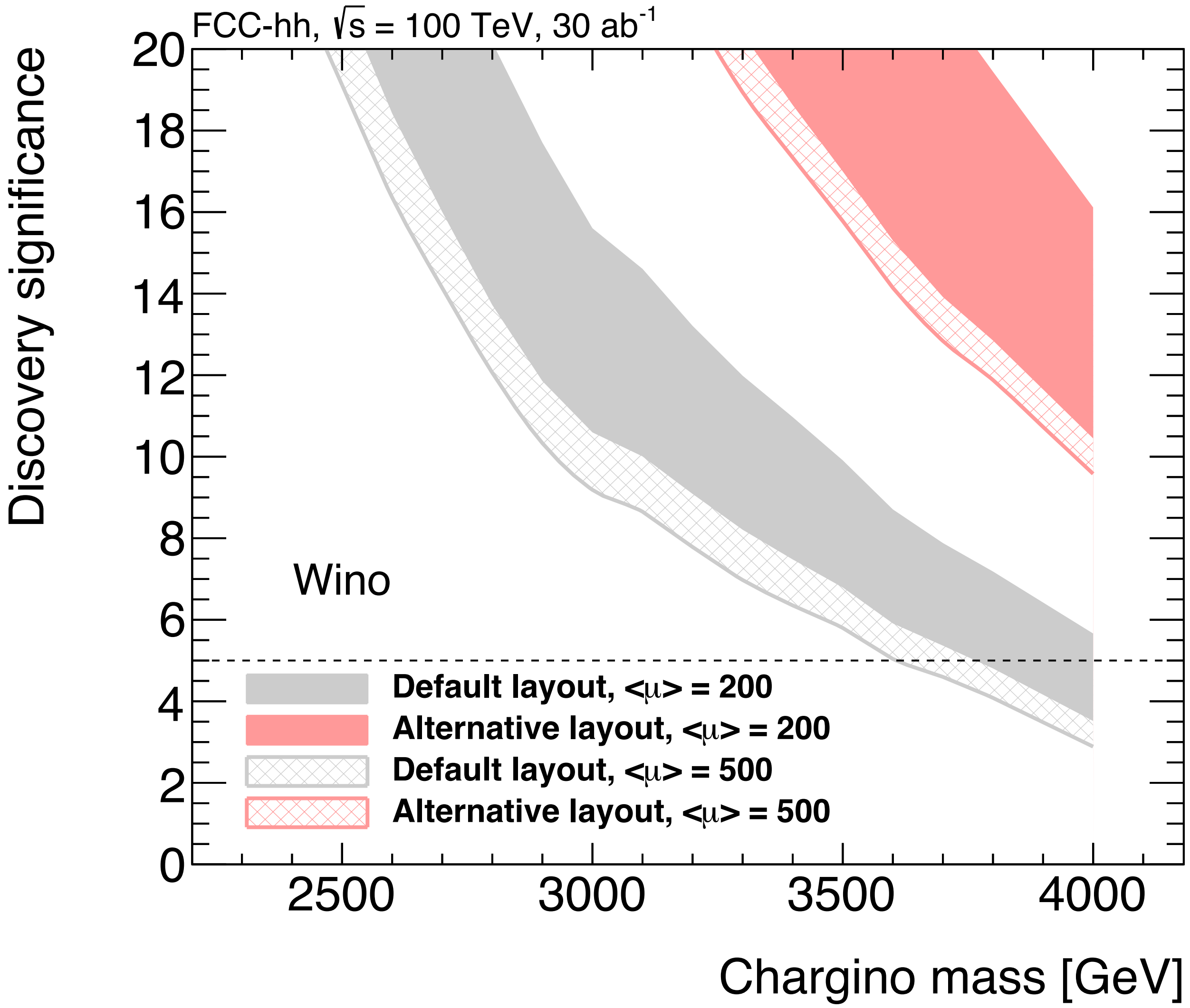
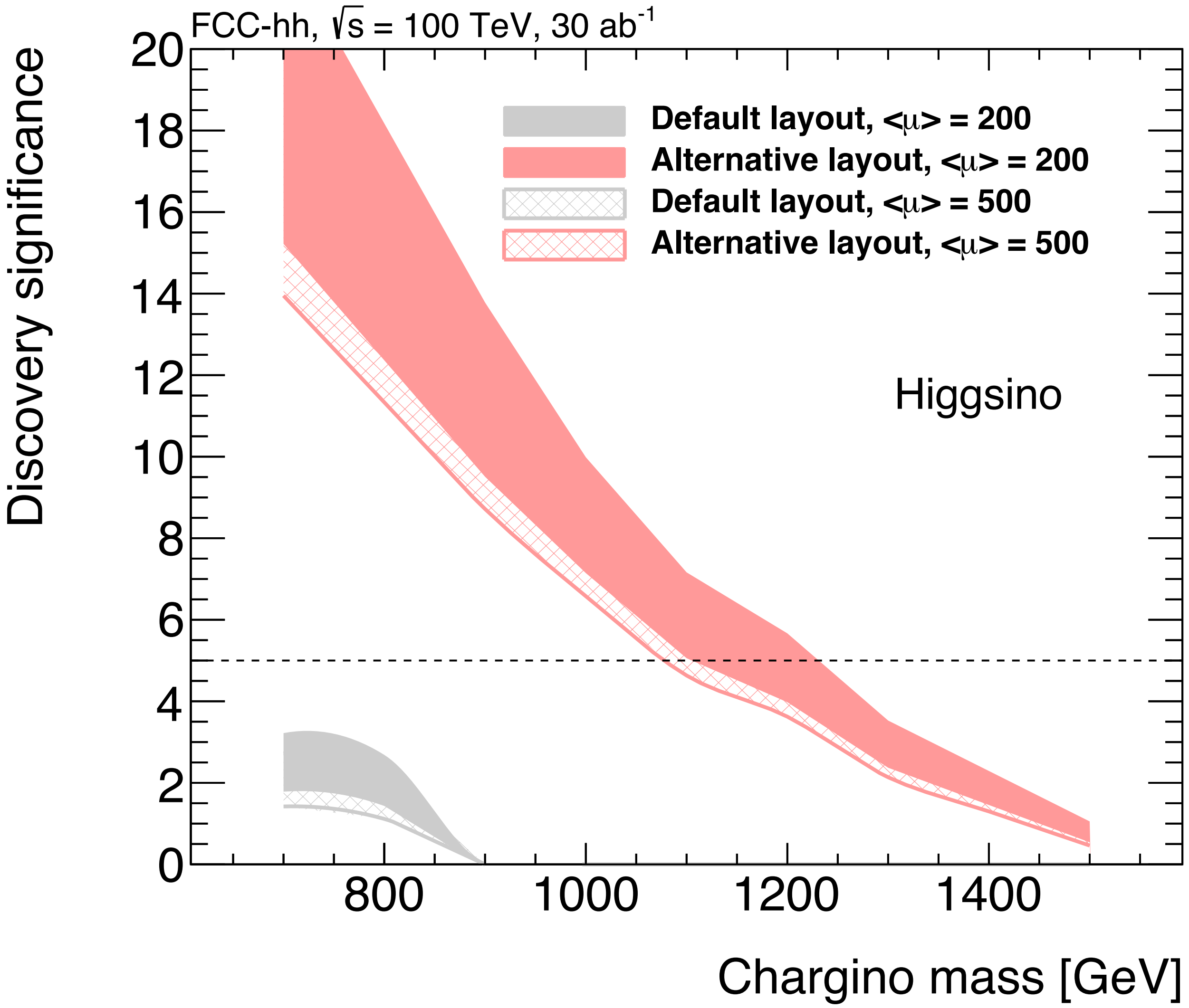
$$\Omega_{wimp}\ h^2 \lesssim 0.12$$

$$M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3} \right)^2$$

Disappearing charged track analyses

(at ~full pileup)





New detector performance studies

K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

Prospects to discover/exclude WIMP DM:

coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$$\boxed{M_{wimp} \lesssim 2\ \mathrm{TeV} \left(\frac{g}{0.3}\right)^2 \Rightarrow m_{\mathrm{wino}} < 3.5\ \mathrm{TeV}\ , \quad m_{\mathrm{higgsino}} < 1\ \mathrm{TeV}}$$

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- eh collisions
- Heavy ion collisions
- Dedicated detectors for flavour physics (like LHCb)
- Forward physics (LHCf, TOTEM)
- Dedicated detectors for long-lifetime particles (like FASER, Mathusla)

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- The sequence of FCC-ee and FCC-hh provides the most complete, detailed and accurate picture of Higgs properties achievable with the currently planned facilities, and gives direct access to the largest mass scales allowed by foreseeable technology