HEP Theory
(part 1)

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A partial list of goals for HEP theory work

- **Answer open questions:**
  - **Data driven:**
    - What is DM?
    - What's the origin of neutrino masses?
    - What's the origin of the matter vs antimatter asymmetry?
    - What is Dark energy?
    - …
  - **Theory driven:**
    - The hierarchy problem and naturalness
    - The flavour problem (origin of fermion families, mass/mixing pattern)
    - Quantum gravity
    - Origin of inflation
    - …
- **Develop the tools required to extract/interpret data:**
  - improve precision of theoretical predictions for accelerator expts
    - perturbative calculations, higher loops, …
    - MC modeling of final states
  - introduce/improve new exptl opportunities (eg tabletop expts, astro/cosmo observables, …)
  - …

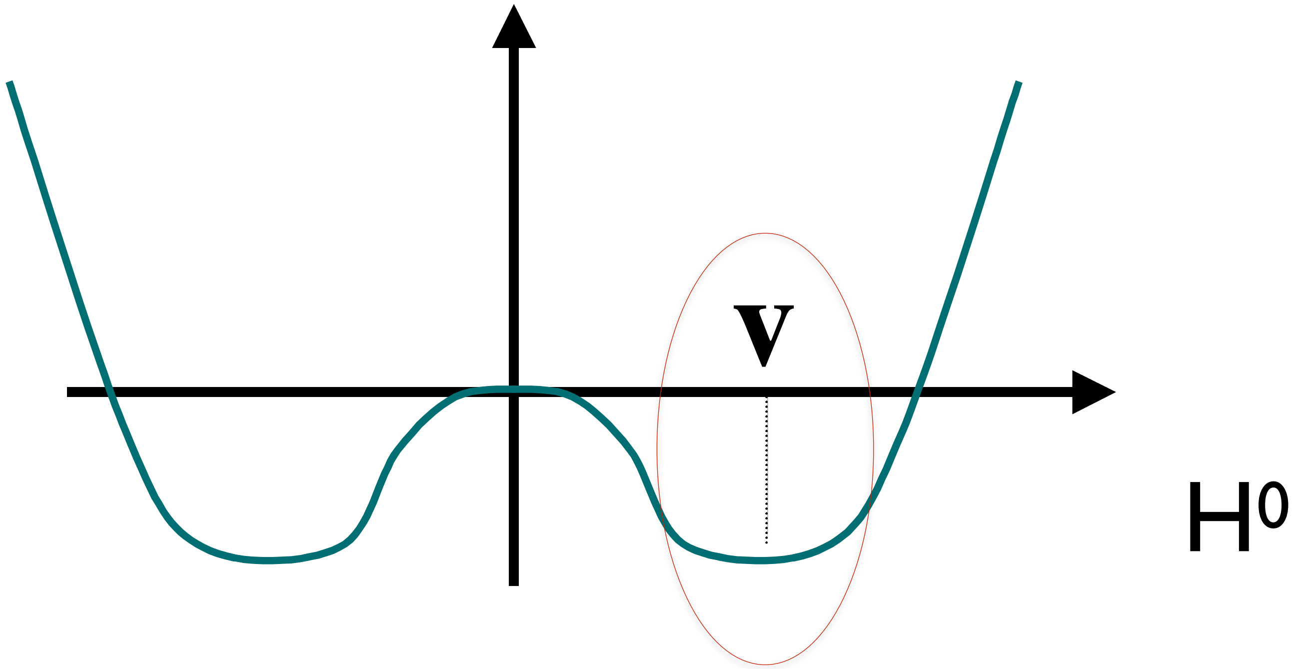
The next steps in HEP research build on

- having important questions to pursue *(see previous slide)*
- creating opportunities to answer them
- being able to constantly add to our knowledge, while seeking those answers

The experimental opportunities

- For none of the open questions, the path to an answer is unambiguously 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….



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

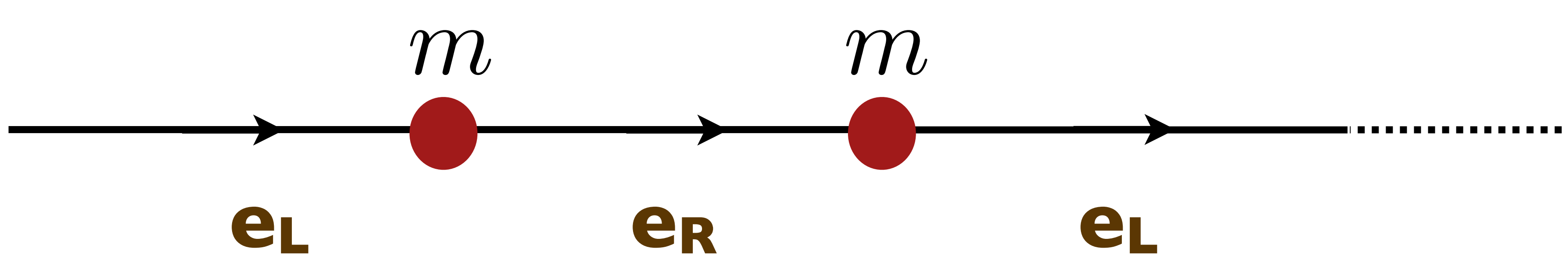
Who ordered that ?

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

Parity asymmetry and mass for spin-1/2 particles

$\gamma_5 \, \psi_{L,R} = \pm \, \psi_{L,R}$

$$H \propto i\overline{\psi_L}\,\partial\cdot\gamma\,\psi_L + i\overline{\psi_R}\,\partial\cdot\gamma\,\psi_R + m\,\overline{\psi_L}\,\psi_R$$

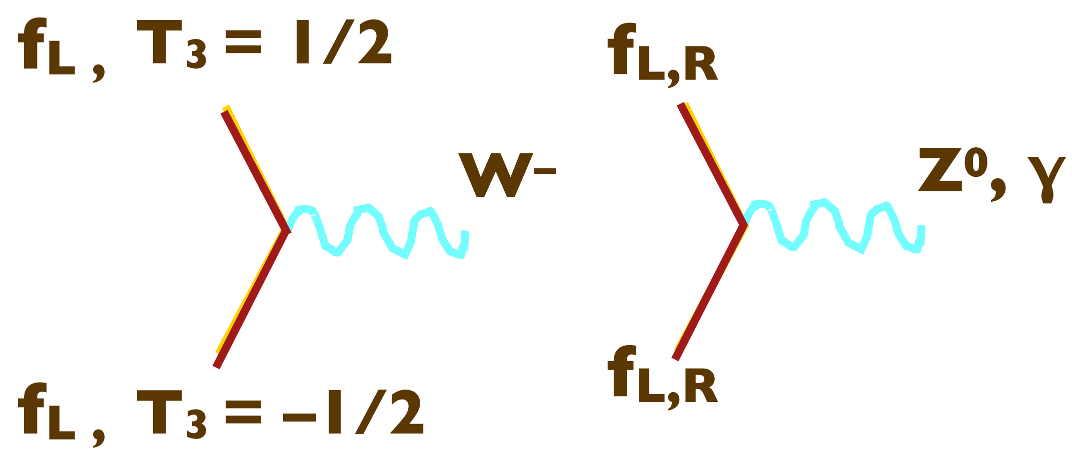


For a massive particle, chirality does not commute with the Hamiltonian, so it cannot be conserved

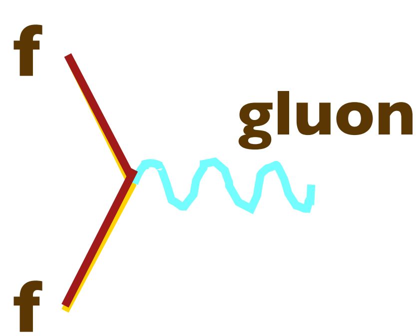
Chirality eigenstates of a massive particle cannot be Hamiltonian (physical) eigenstates

Nothing wrong with that in principle .... unless chirality is associated to a conserved charge!

$SU(2)_L \otimes U(1)$ → **Electroweak (EW) gauge symmetry**



SU(3)



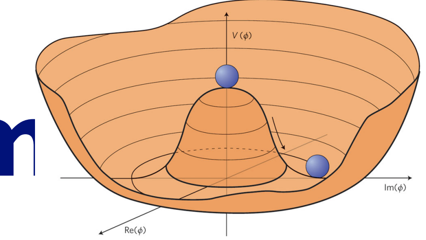
	L-chirality	R-chirality
quarks	$\begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix}_L^{i=1,2,3}$	$u^i{}_R$, $d^i{}_R$
leptons	$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$	$e^-{}_R$

+ 2 more "families" differing from the 1st one only in the mass of their elements

The symmetry associated with the conservation of the weak charge must therefore be broken for leptons and quarks to have a mass

In this process, weak gauge bosons must also acquire a mass. This needs the existence of new degrees of freedom

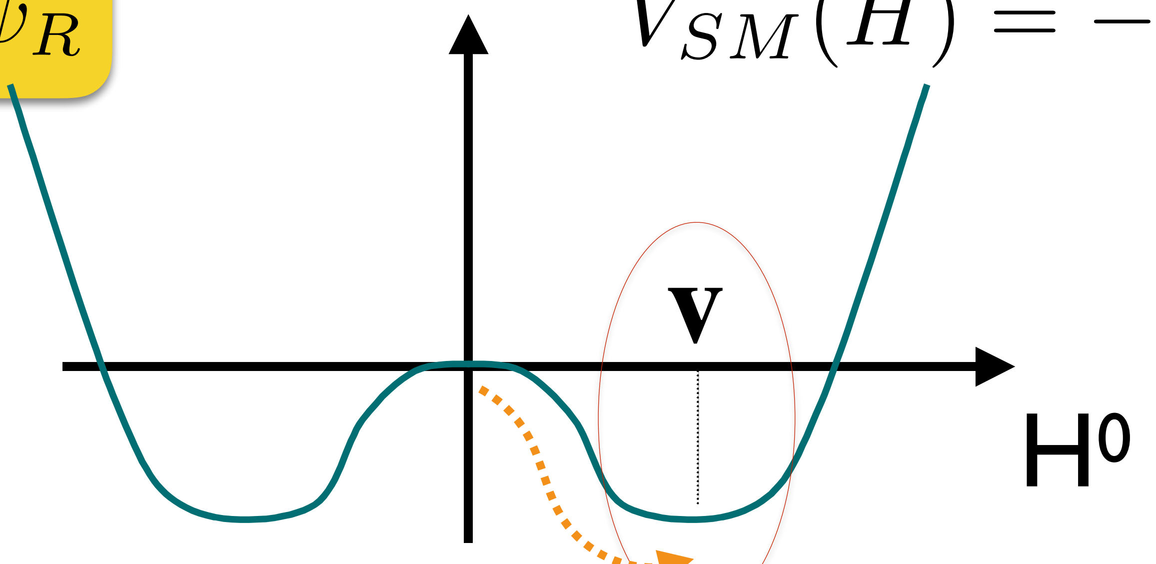
The SM solution: Higgs mechanism

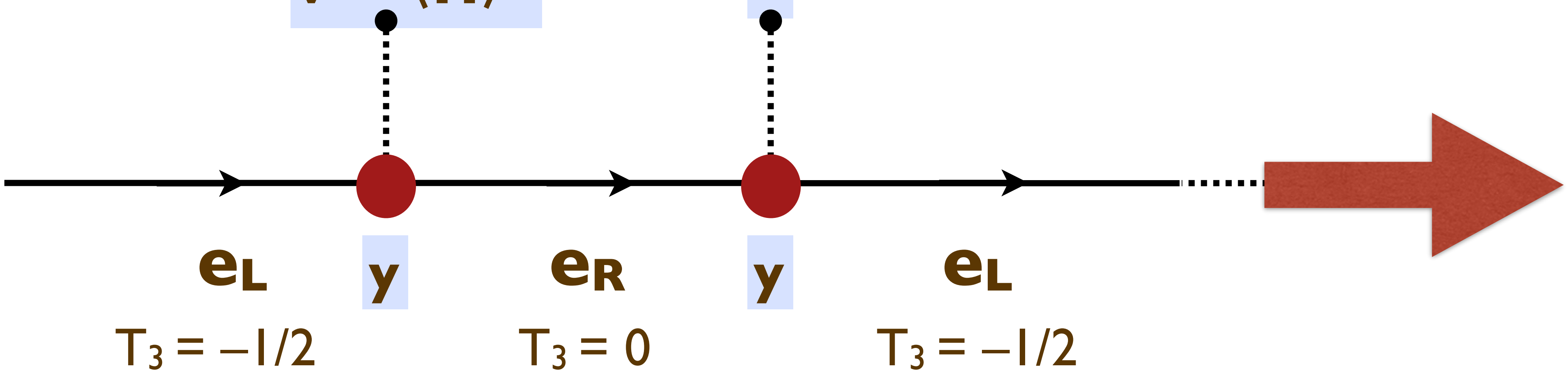


$$m\,\overline{\psi_L}\,\psi_R \rightarrow \lambda H\,\overline{\psi_L}\,\psi_R$$

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

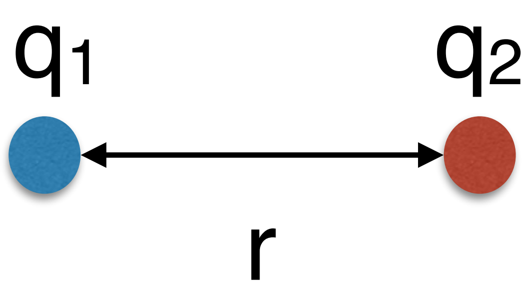
$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$$





The transition between L and R states, and the absorption of the changes in weak charge, are ensured by the interaction with a background scalar field, **H**. Its "vacuum density" provides an infinite reservoir of weak charge.

Electromagnetic vs Higgs dynamics

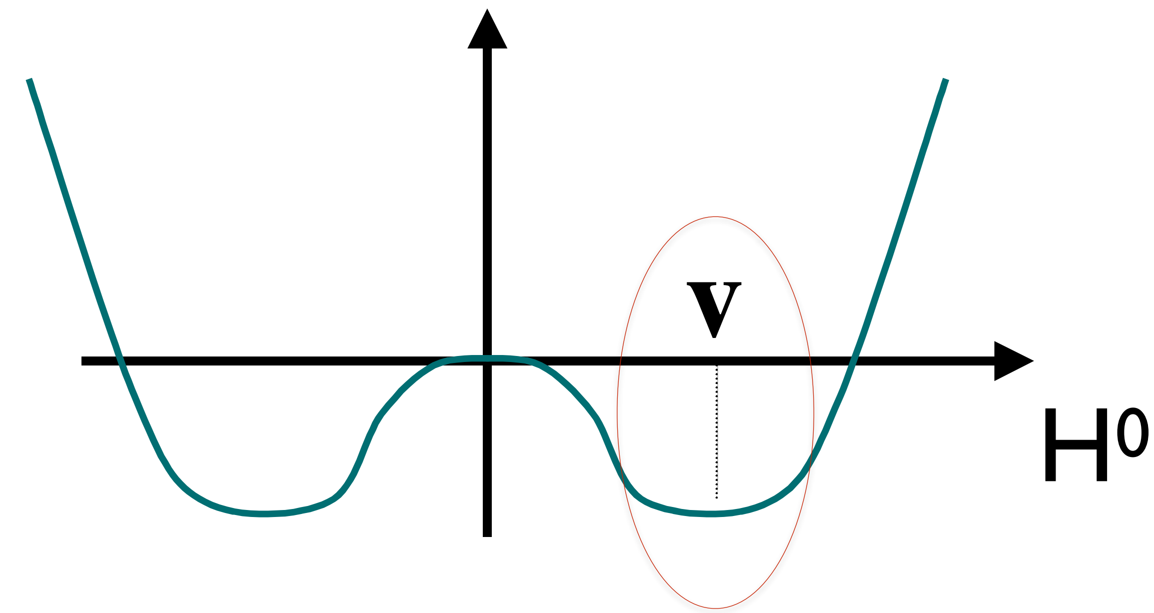


$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

quantized, in units of fixed charge

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 both cases 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.**

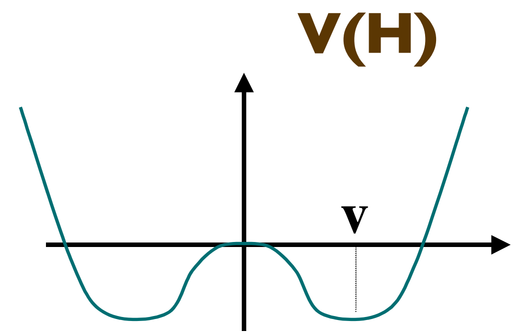
examples of possible scenarios

- **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
- …

The Higgs potential, a closer look

The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

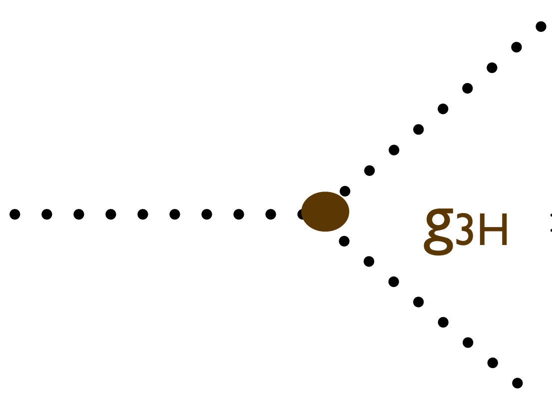
$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$



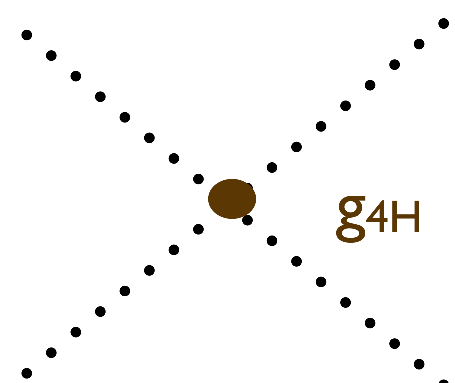
$$v = (\sqrt{2} G_F)^{-1/2} \sim 246 \text{ GeV}$$

$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \quad \Rightarrow \quad \begin{array}{rcl} \mu & = & m_H \\ \lambda & = & \dfrac{m_H^2}{2v^2} \end{array}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of the two now-known parameters m_H and v



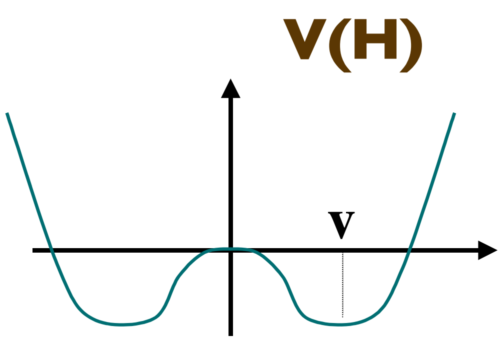
$g_{3H} \Rightarrow 4\lambda v = \dfrac{2m_H^2}{v}$



$g_{4H} \Rightarrow \lambda = \dfrac{m_H^2}{2v^2}$

These relations between Higgs self-couplings, m_H and v entirely depend on the functional form of the Higgs potential. Their measurement is therefore an important test of the SM nature of the Higgs mechanism

Example: a different Higgs potential



$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{n}\phi^n$$

$$\begin{cases} \langle \phi \rangle = v \\ m_\phi^2 = \partial^2 V(\phi)/\partial\phi^2 \,|_{\phi=v} \end{cases}$$

$$v^{n-2} = \frac{\mu^2}{\lambda} \quad , \quad m_\phi^2 = (n-2)\mu^2$$

μ provides the overall scale of the Higgs mass, but the precise value depends on n : μ describes the potential near the origin, but the mass is defined by the curvature at the minimum

$$\lambda_{\phi\phi\phi} = \frac{\partial^3 V}{\partial\phi^3}\,|_{\phi=v} = (n-1)\frac{m_\phi^2}{v}$$

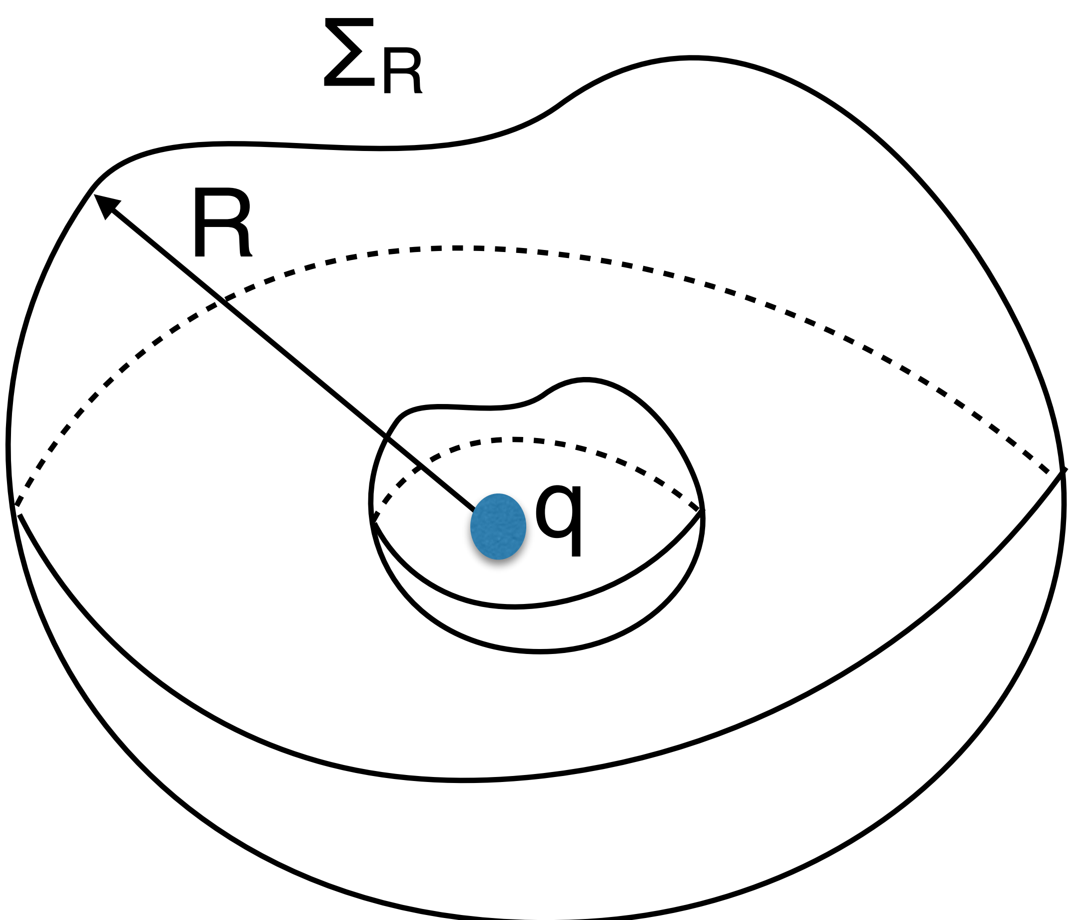
If n=6, the Higgs self-coupling is modified by a factor of 5/3 wrt the SM relation. This is a big effect!
Notice however that the n=4 term will always be there, even if only induced by loop corrections or RG evolution of whatever higher-dimension term

$$m_\phi^2 = \frac{\lambda_{\phi\phi\phi}}{n-1}\, v$$

For all SM particles, m=gv, where g is their coupling to the Higgs. For the Higgs, the relation between self-coupling and mass is not universal, it depends on the detailed structure of the Higgs potential

Decoupling of high-frequency modes

E&M

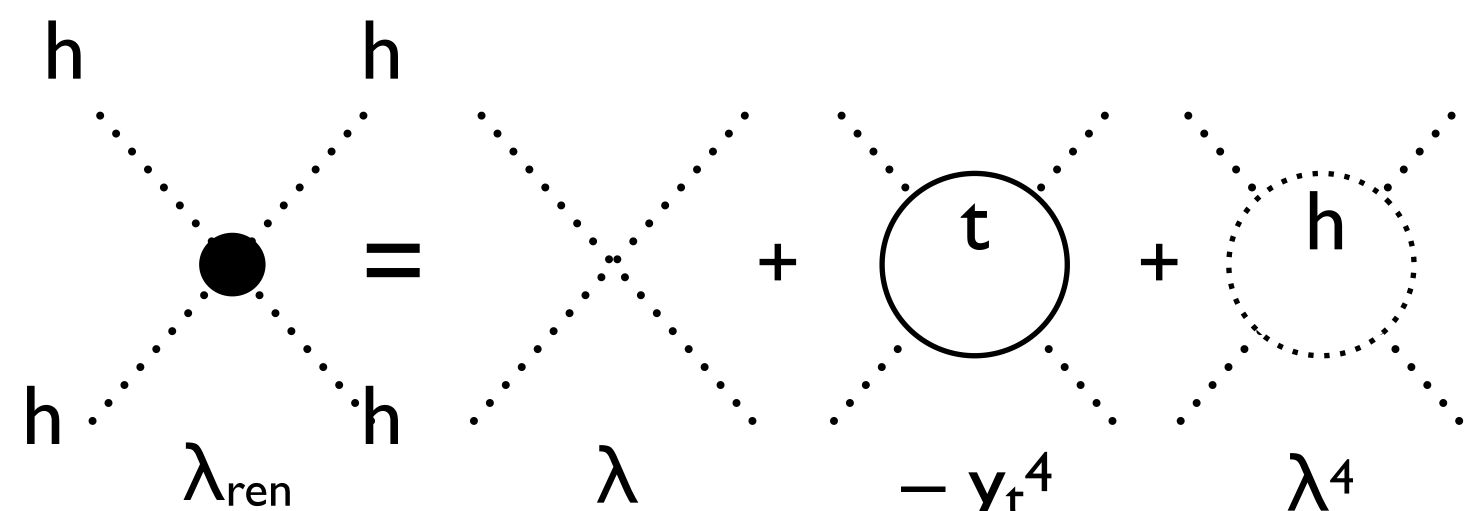


$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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 μ^2 and λ, dramatically altering the stability and dynamics => **hierarchy problem**

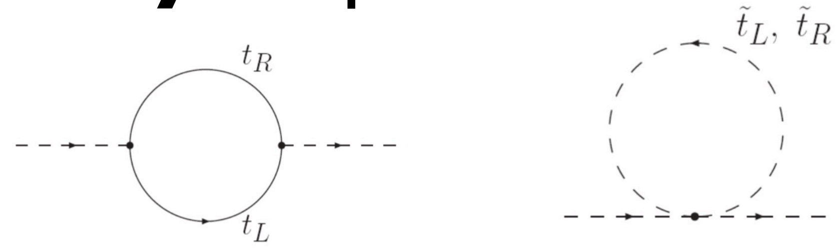
bottom line

- To predict the properties of EM at large scales, we don't need to know what happens at short scales
- 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

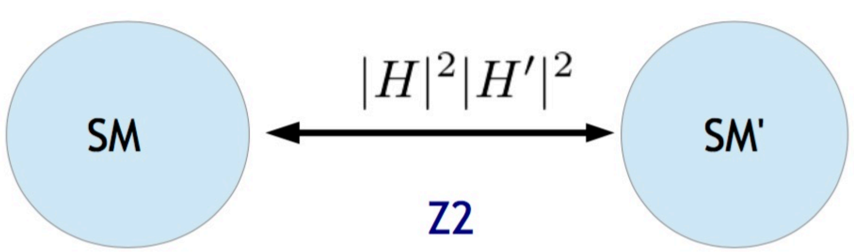
$\Rightarrow$ **naturalness**

Examples

- **Supersymmetry**: stop vs top (colored naturalness)



- **Extra-dimensions**: Planck scale closer than in 4-D, or Higgs as 4-D scalar component of a higher-dim gauge vector (KK modes, etc)
- **Little Higgs**: Higgs as a pseudo-Nambu-Goldstone boson of a larger symmetry, mass protected by global symmetries (top partners)
- **Neutral naturalness**: top contributions canceled by triplets of new particles neutral under SM gauge groups, but sharing the Higgs couplings with SM fermions (Higgs portals). Typically comes with doubling of (part of) SM gauge group (eg $SU(3)_A \times SU(3)_B$).
  - twin Higgs



  - folded SUSY ($SU(3)_B$ stops cancel Higgs couplings to $SU(3)_A$ tops)

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

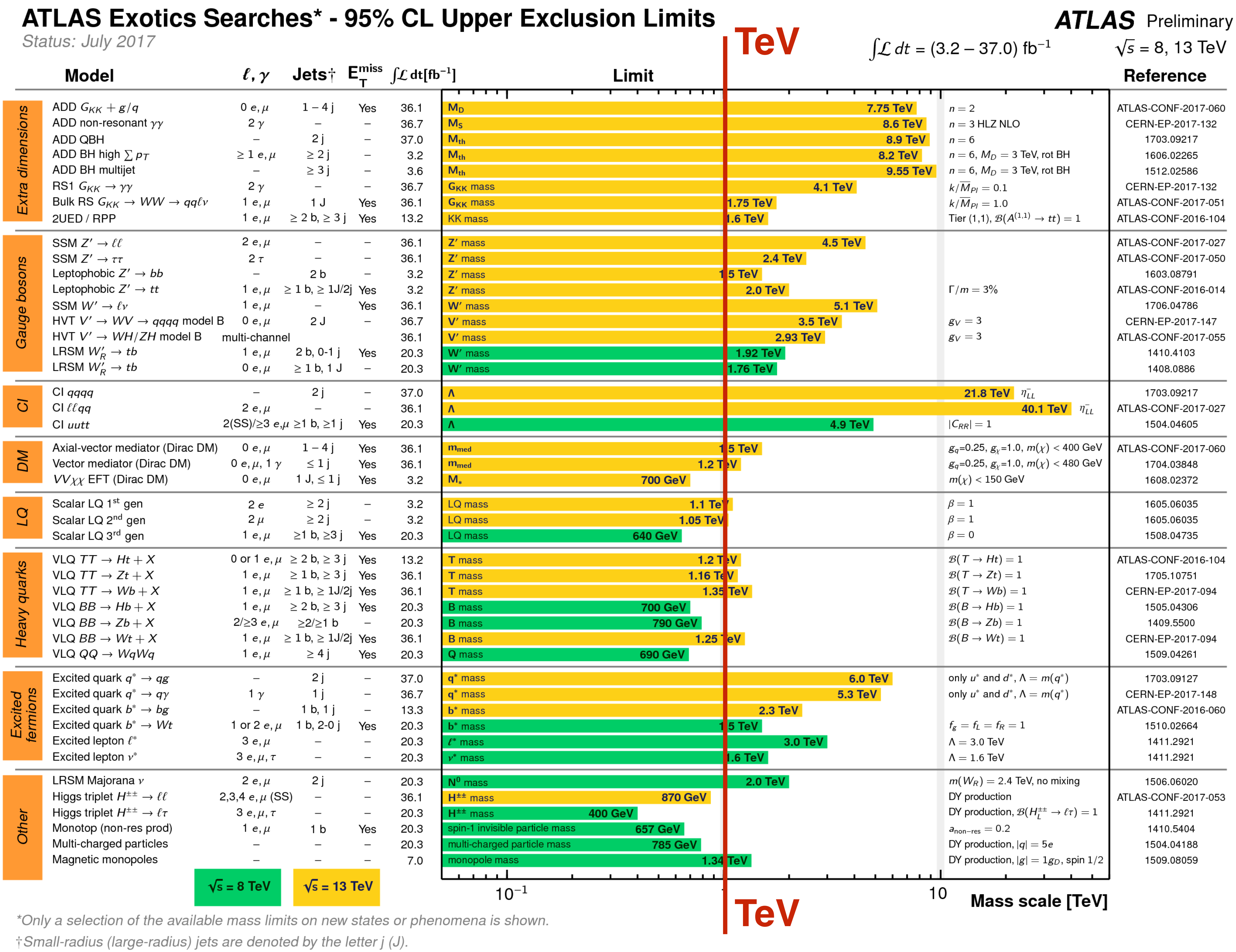
In search of the origin of known departures from the SM

- **Dark matter, long lived particles**
- **Neutrino masses**
- **Matter/antimatter asymmetry of the universe**

To explore alternative extensions of the SM

- **New gauge interactions (Z’, W’) or extra Higgs bosons**
- **Additional fermionic partners of quarks and leptons, leptoquarks, ...**
- **Composite nature of quarks and leptons**
- **Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, ...)**
- **Extra dimensions**
- **New flavour phenomena**
- **unanticipated surprises ...**

So far, no *conclusive* signal of physics beyond the SM



- The hierarchy problem, and the search for a ***natural*** explanation of the separation between the Higgs and Planck scales, 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 (eg SUSY), forces us to review our biases, and to **take a closer look even at the most basic assumptions about Higgs** properties

- We often ask "is the Higgs like in SM?" ….The right way to set the issue is rather, more humbly, **"what is the Higgs?"** …

  - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification.

=> all this justifies the focus on the program of precision Higgs physics measurements

=> colliders are the only facilities that make this possible

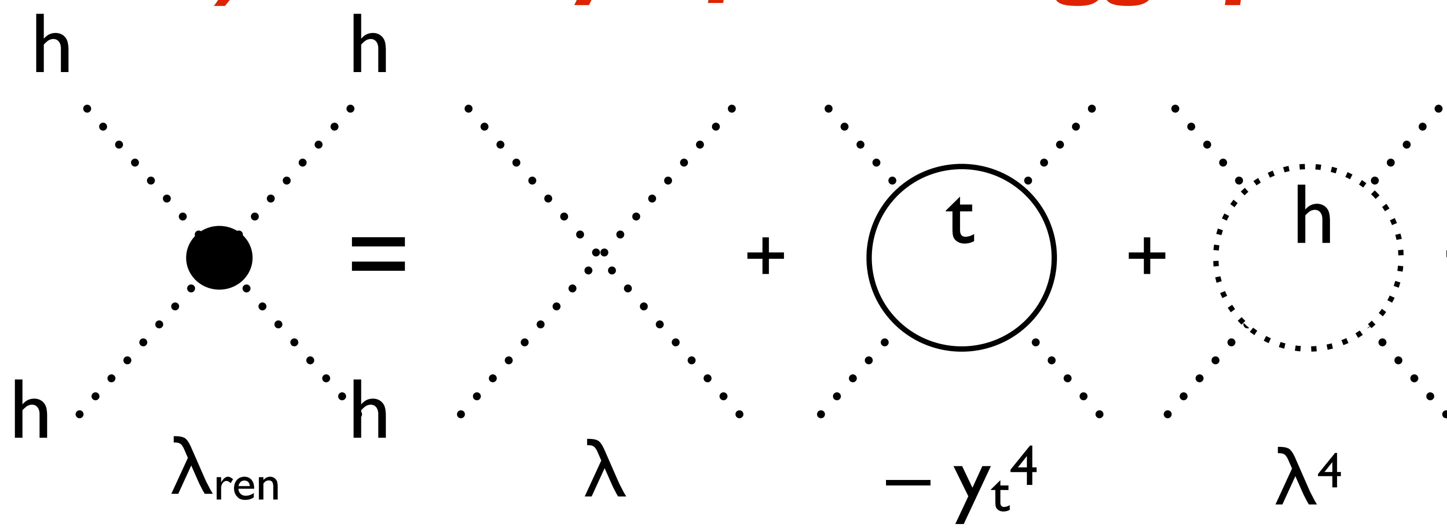
Other important open issues on the Higgs sector

- Is the 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?

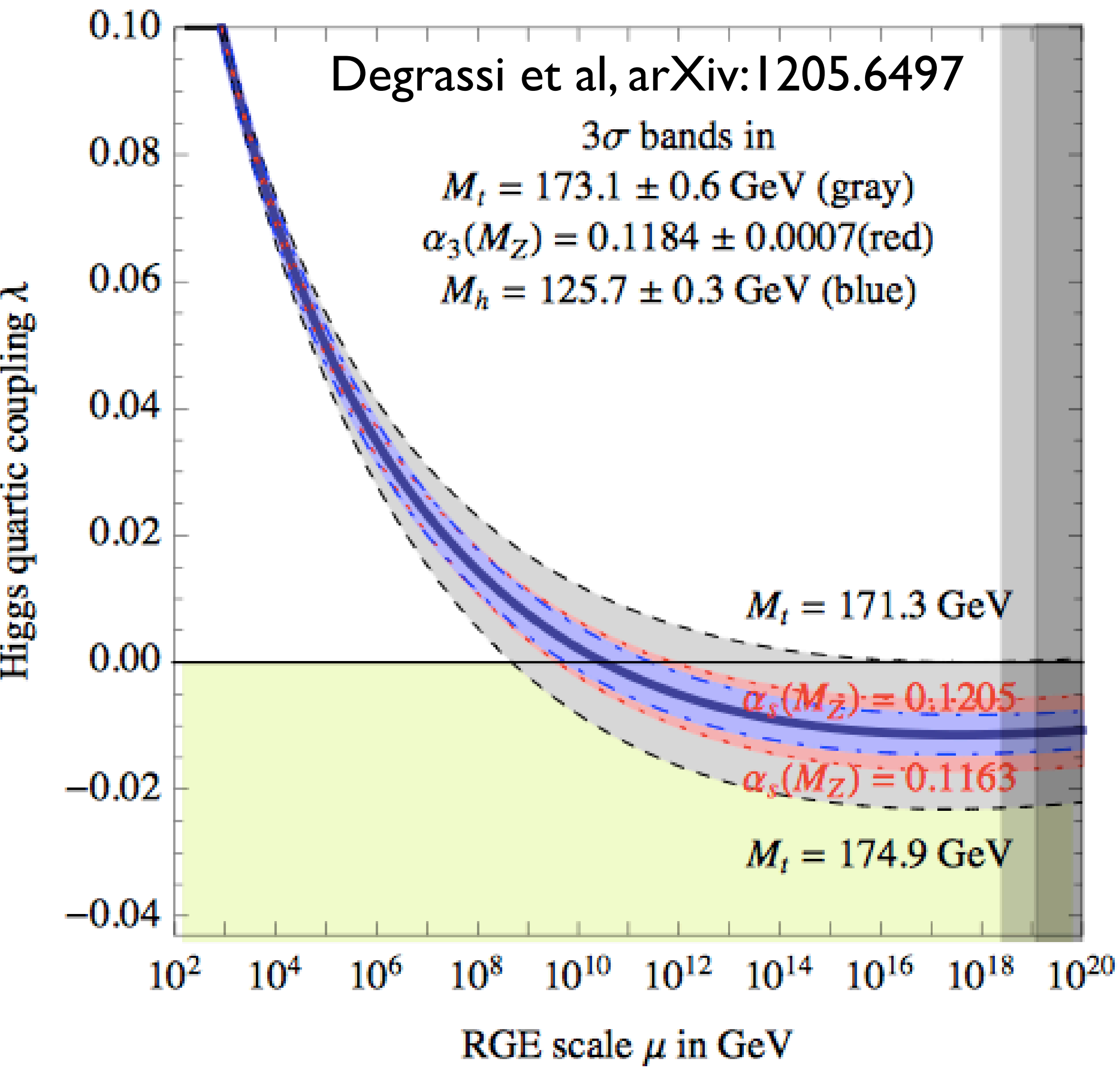
(meta)Stability of the Higgs potential

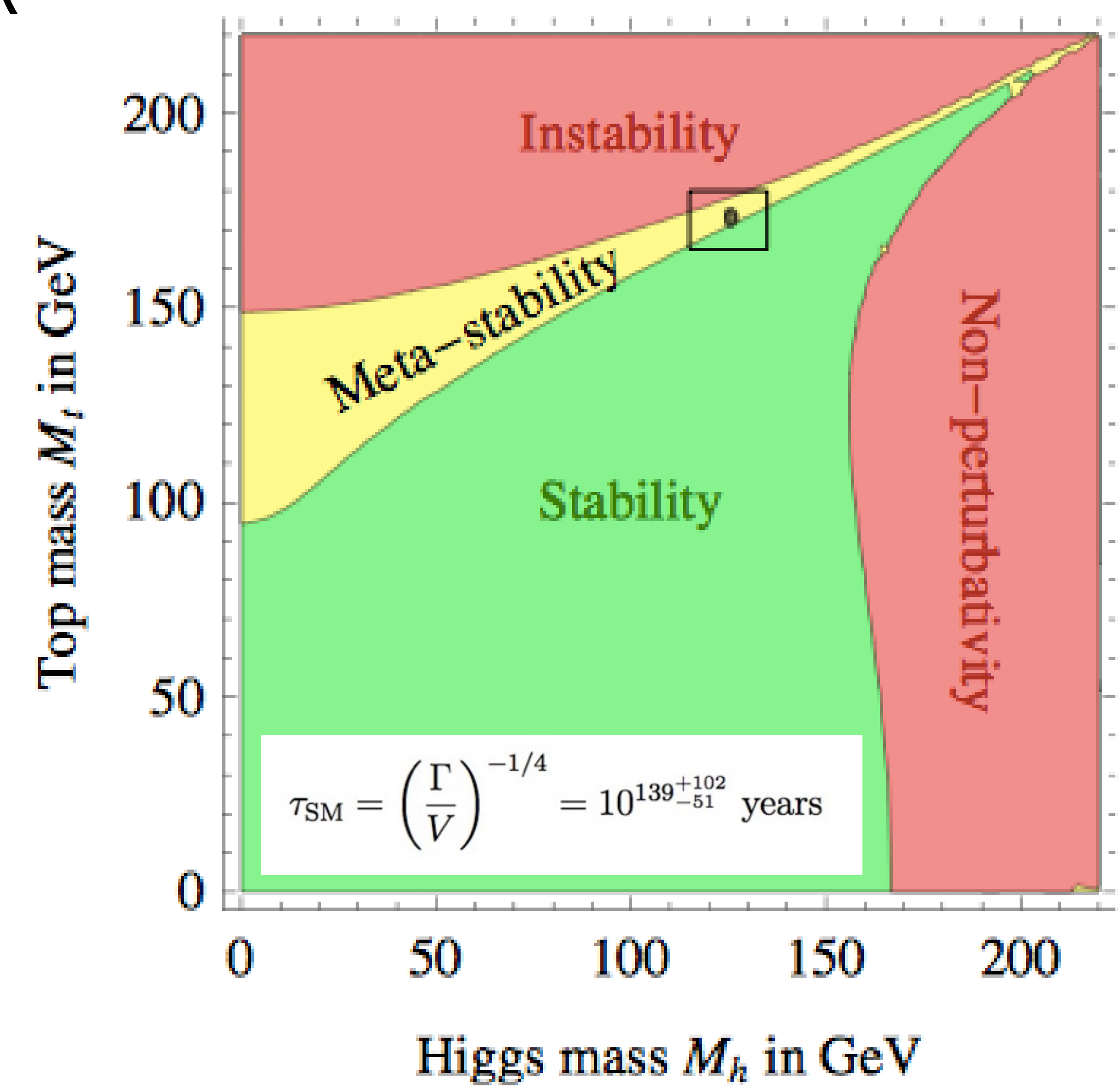
Higgs selfcoupling and coupling to the top are the key elements to define the stability of the Higgs potential



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

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





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 (?!)

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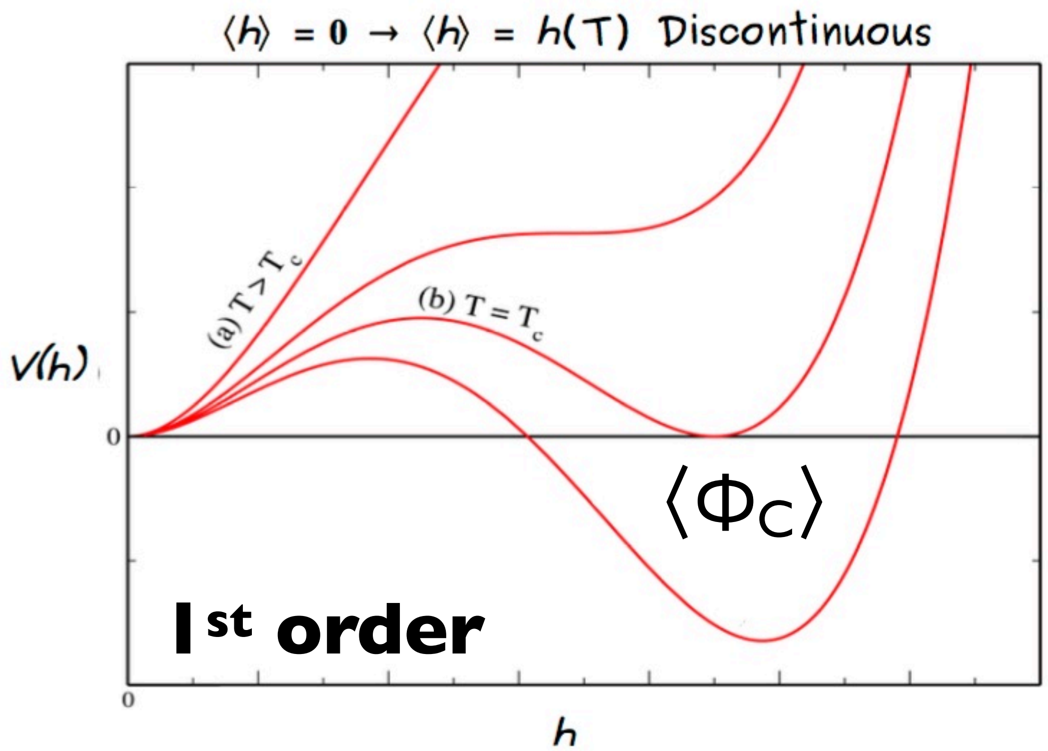
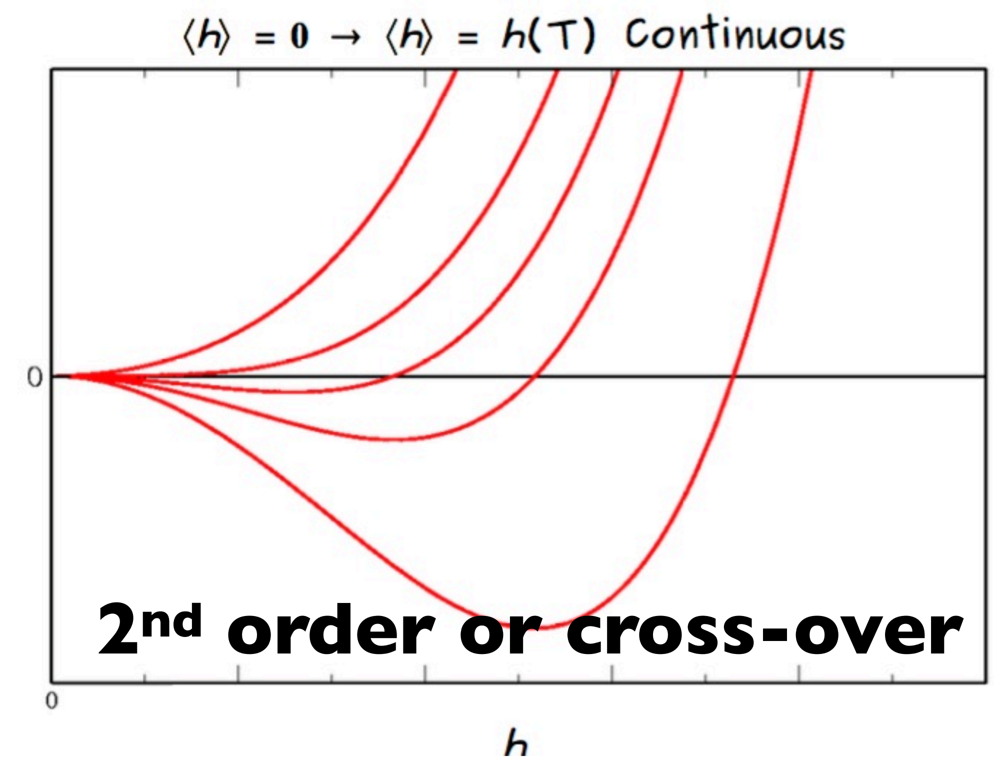
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

The nature of the EW phase transition





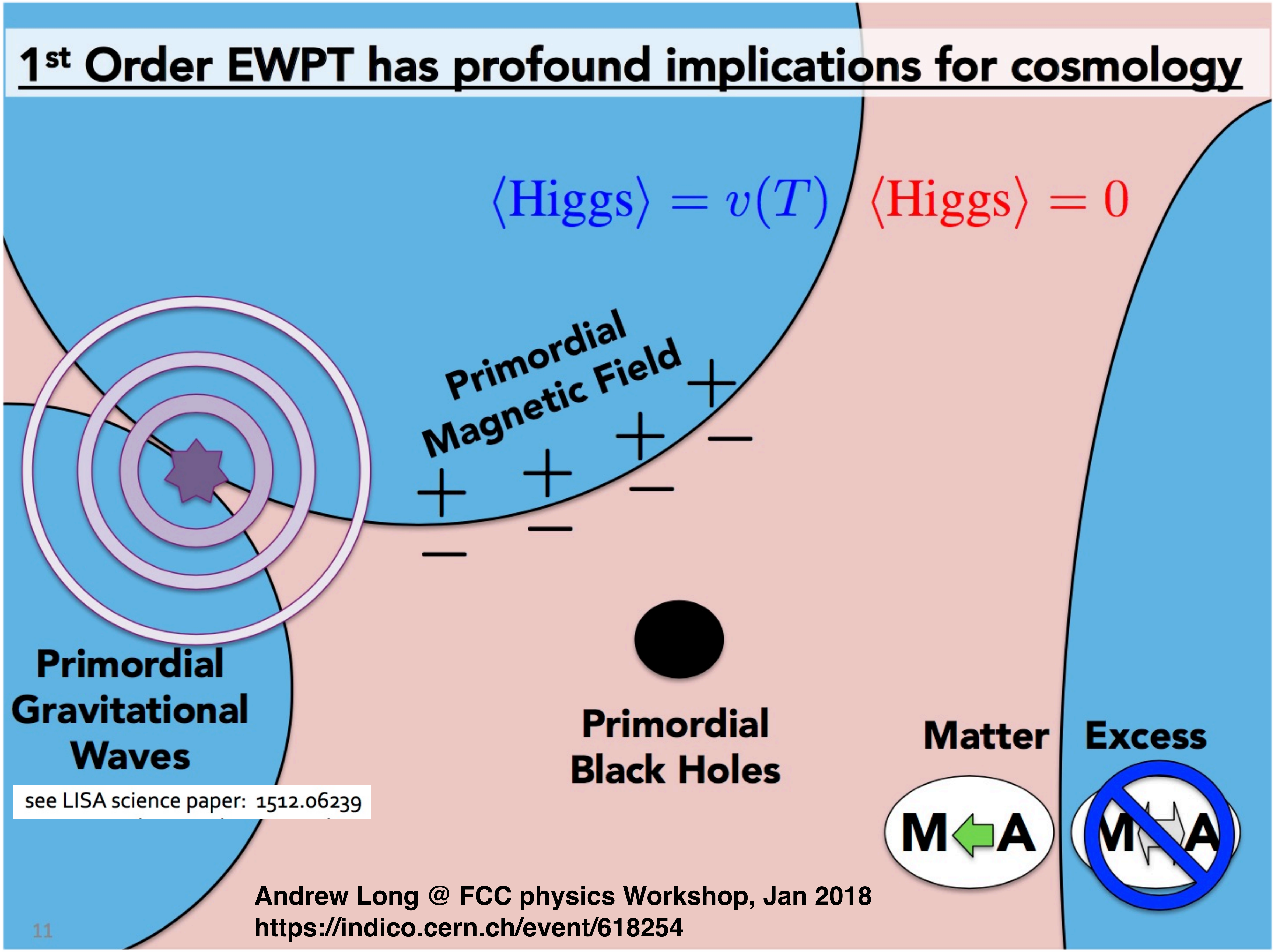
Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

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

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
$\langle \text{Higgs} \rangle = v(T)$
$\langle \text{Higgs} \rangle = 0$
Primordial Magnetic Field
Primordial Gravitational Waves
see LISA science paper: 1512.06239
Primordial Black Holes
Matter Excess
M A
M A
Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254
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Other important open issues in 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?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?