High energy physics & future colliders

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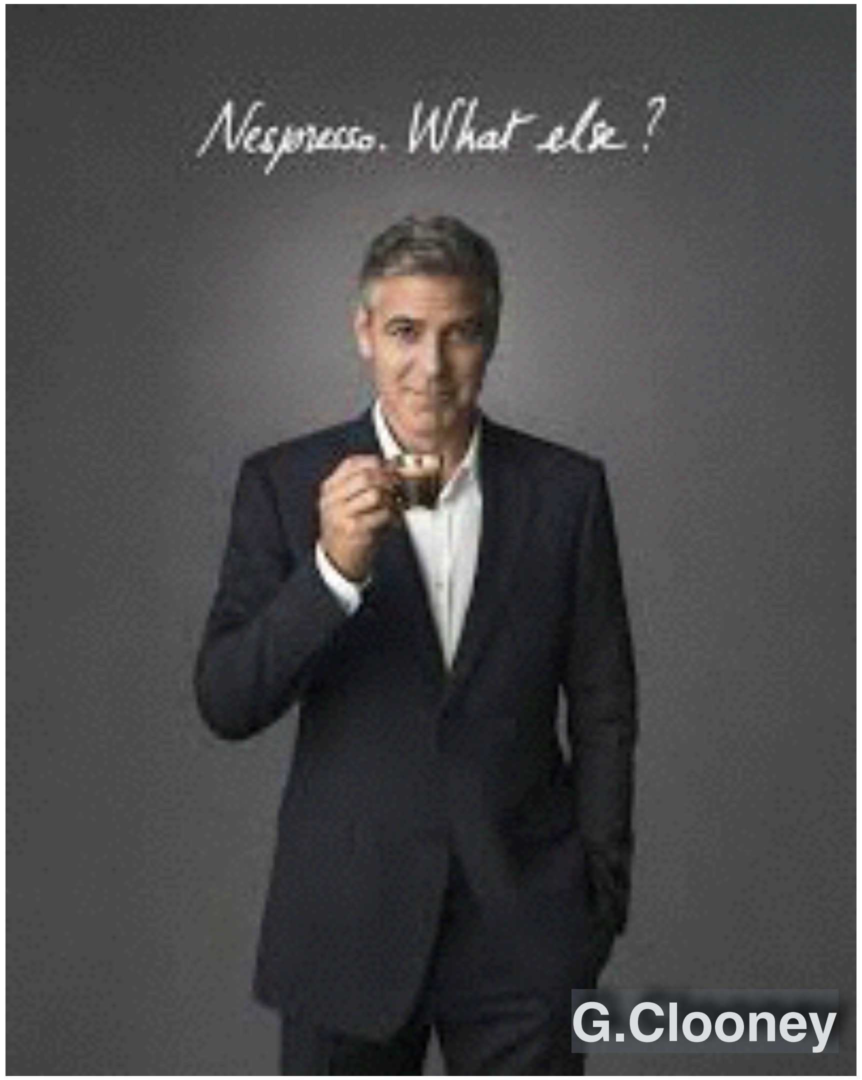
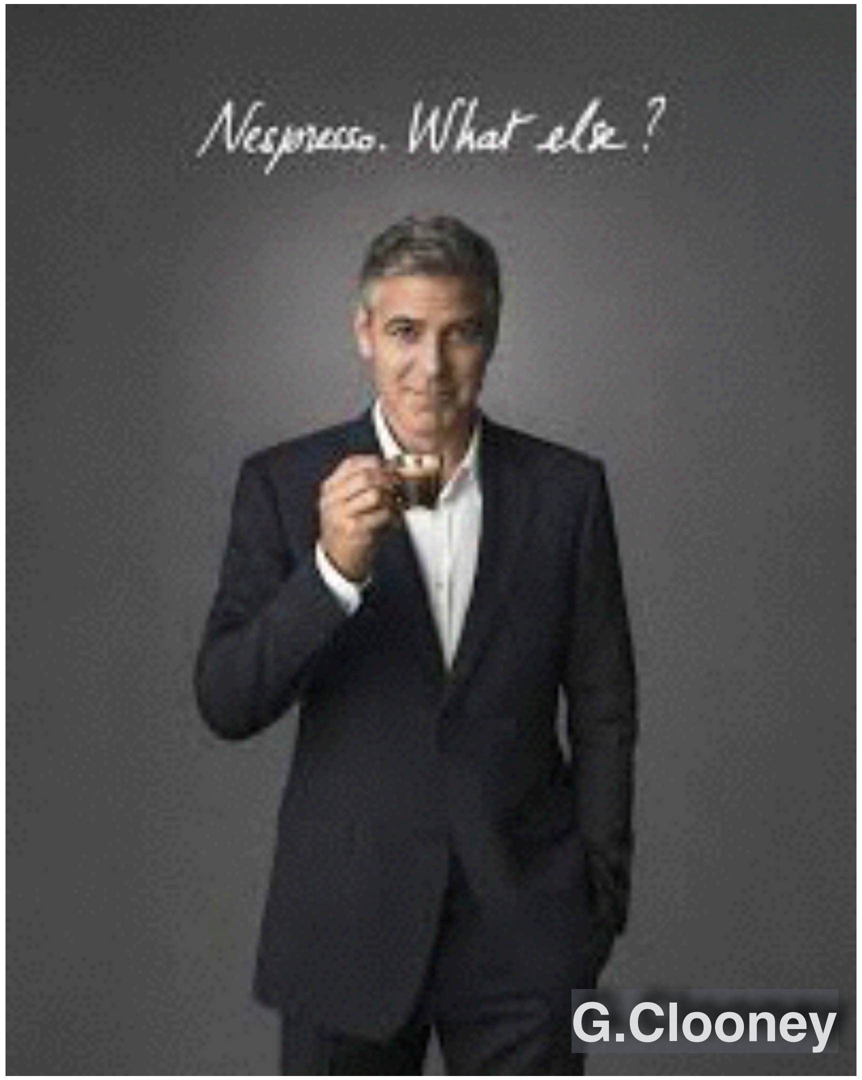


Higgs ….

what else?



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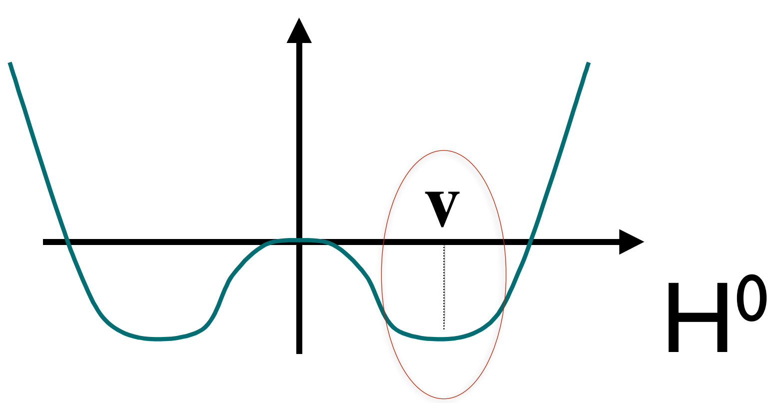
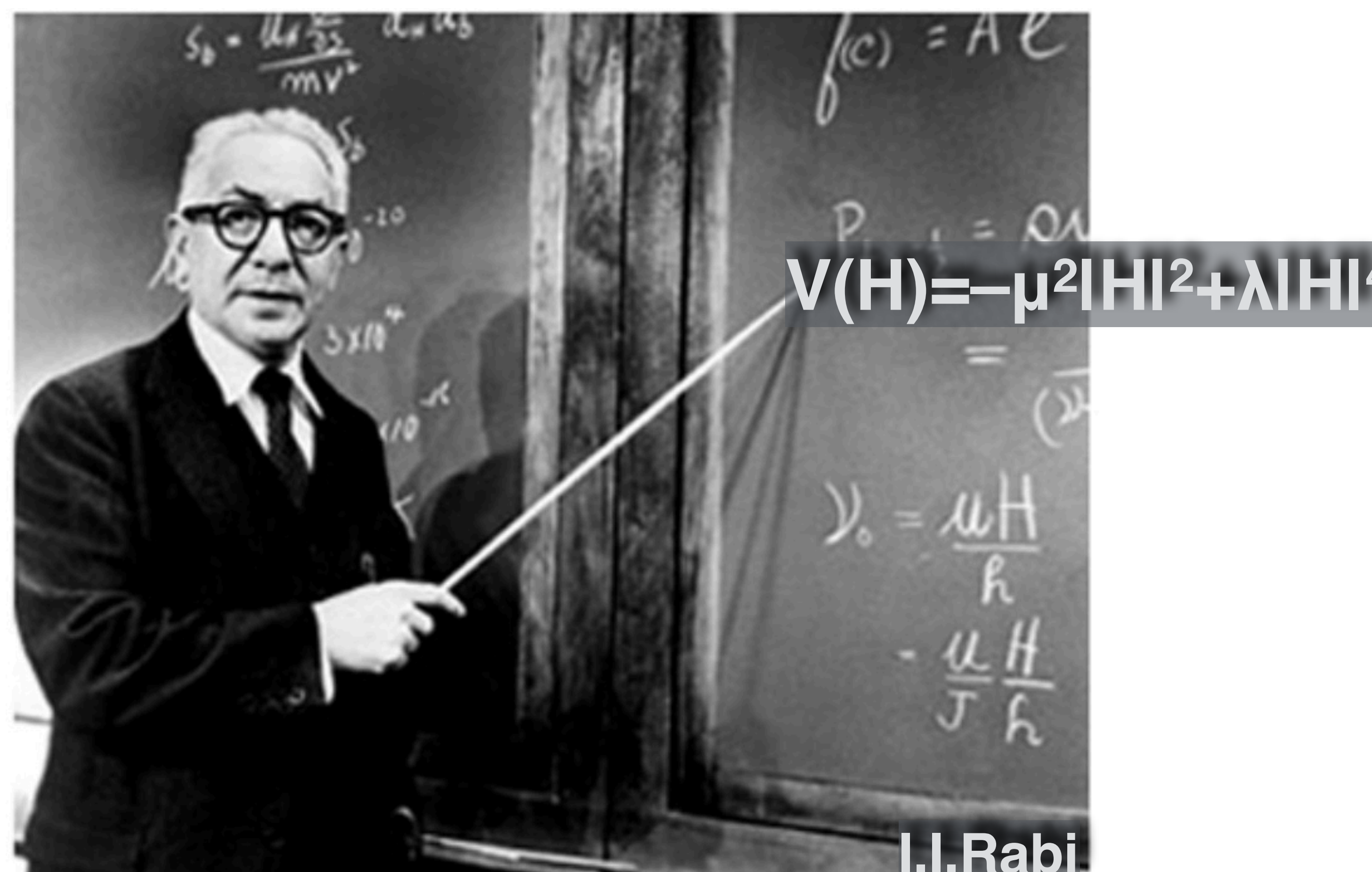
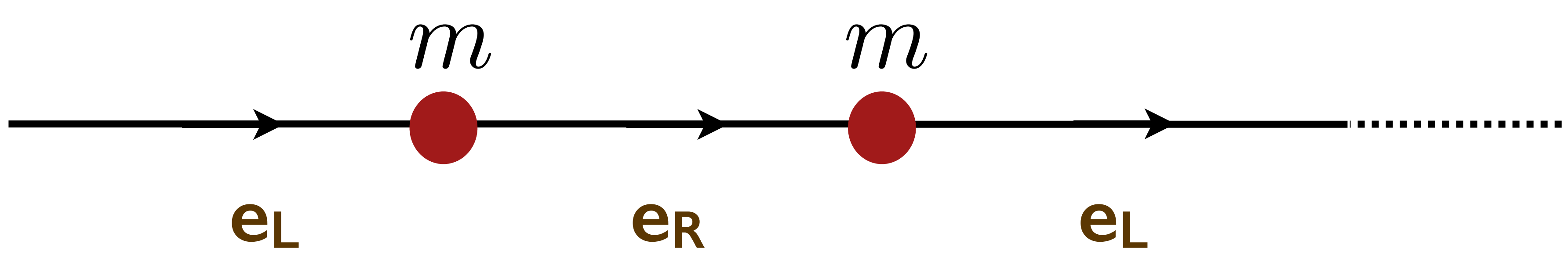




Parity asymmetry and mass for spin-1/2 particles

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

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



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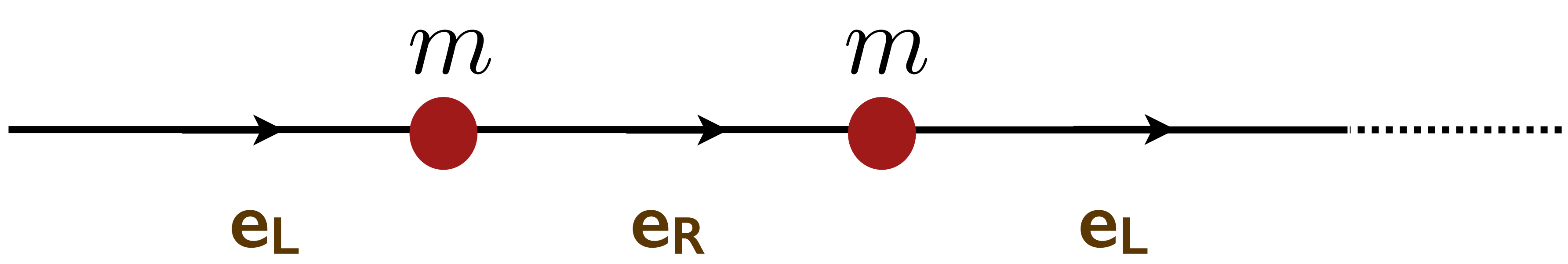
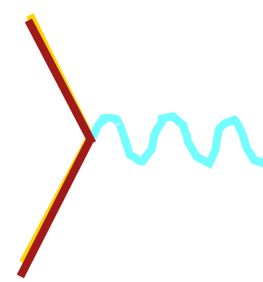


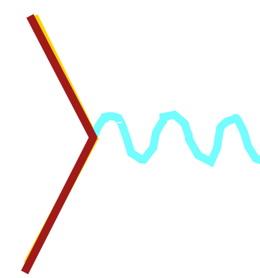
For a massive particle, chirality does not commute with the Hamiltonian, so it cannot be conserved

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

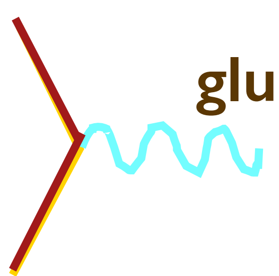
Nothing wrong with that in principle .... unless chirality is associated to a conserved charge!

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





SU(3)



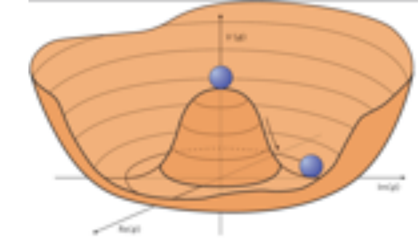
$\begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix}_L^{i=1,2,3}$	$u^i{}_R\,,\ d^i{}_R$
$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$	$e^-{}_R$
L-chirality	**R-chirality**

+ 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

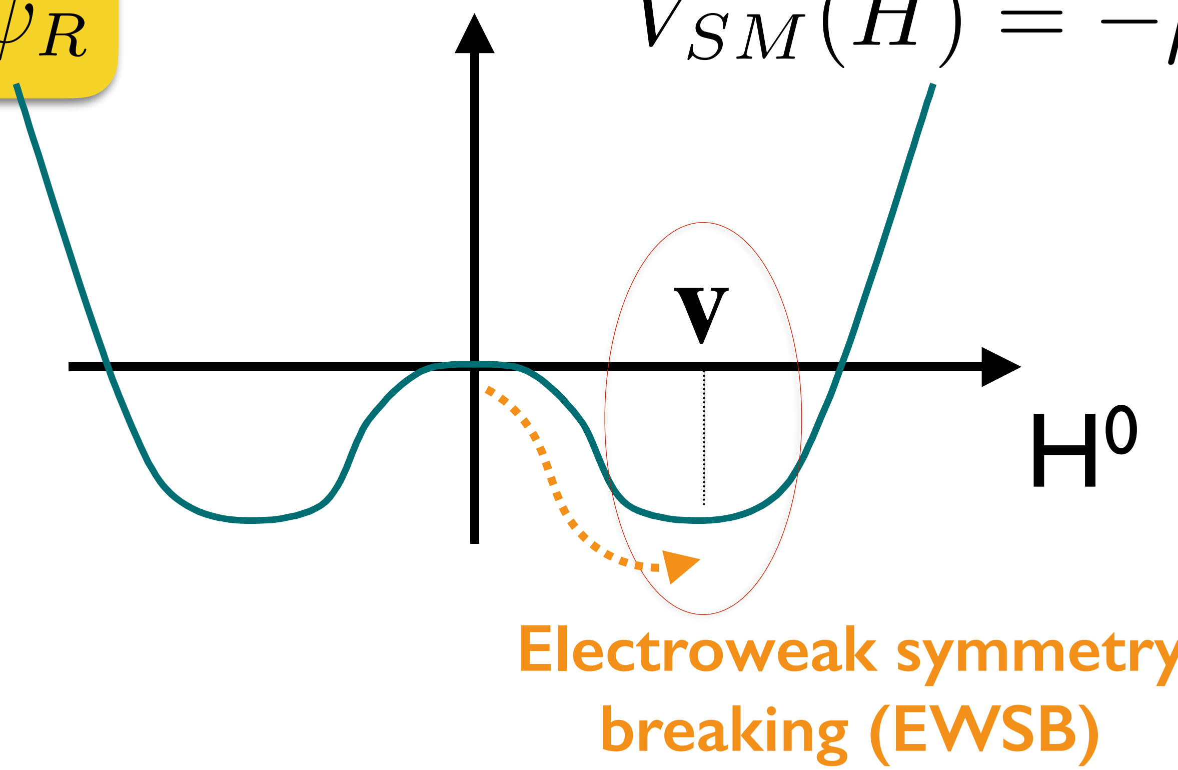
The SM solution: Higgs mechanism



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

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

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



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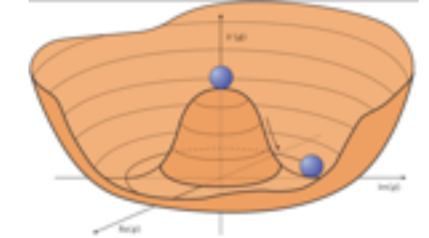

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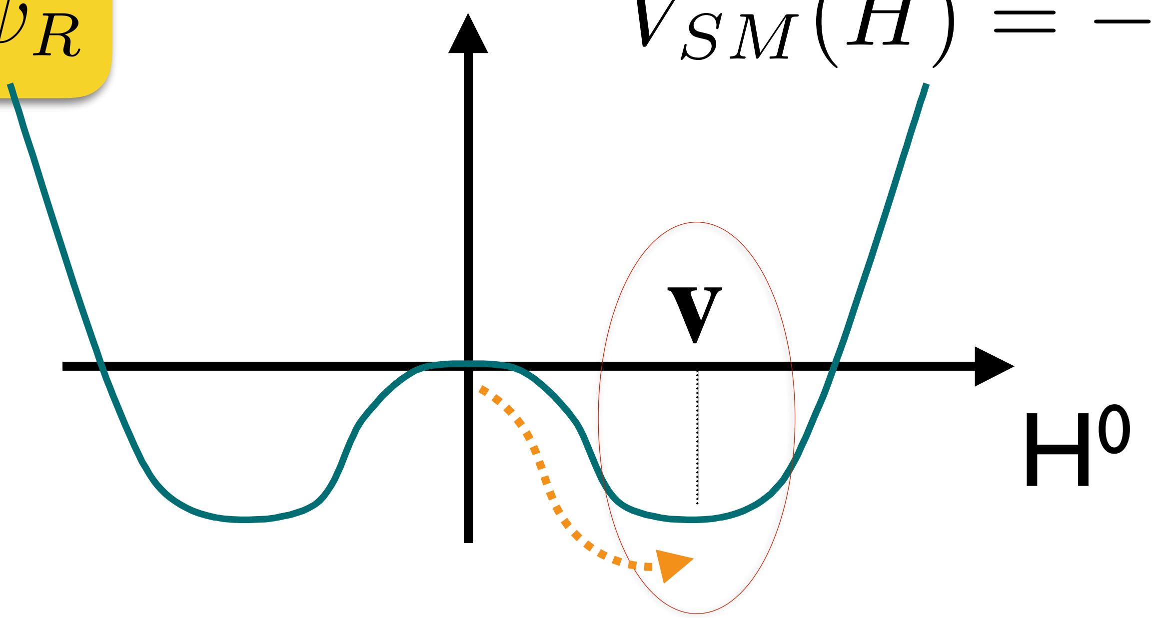
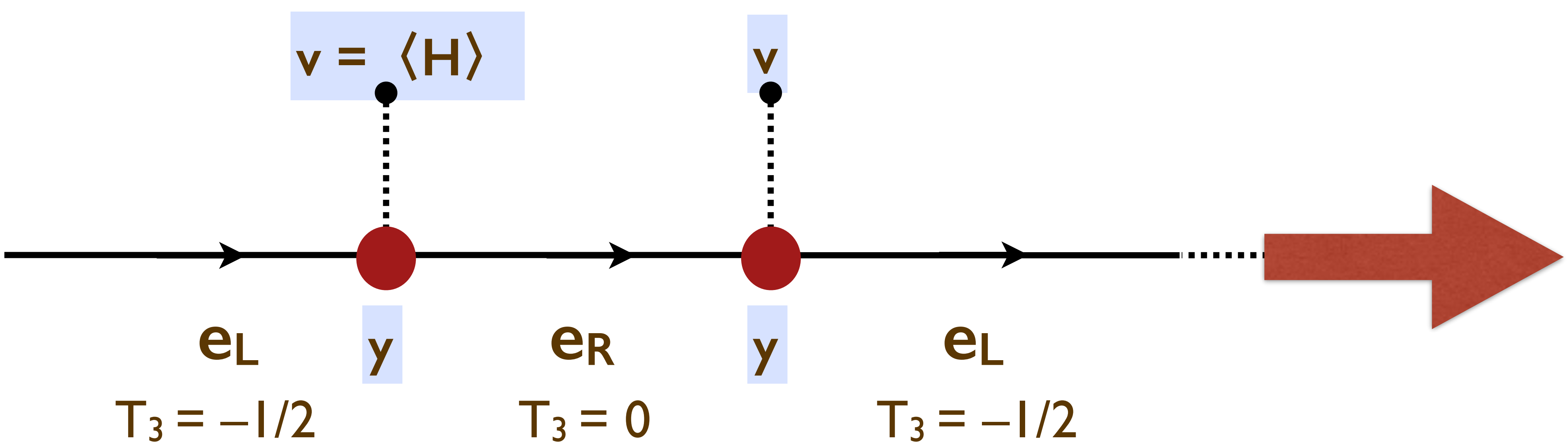
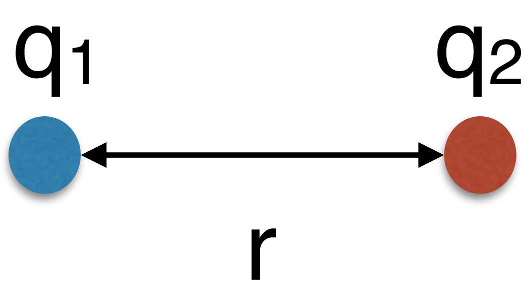




m = y v

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



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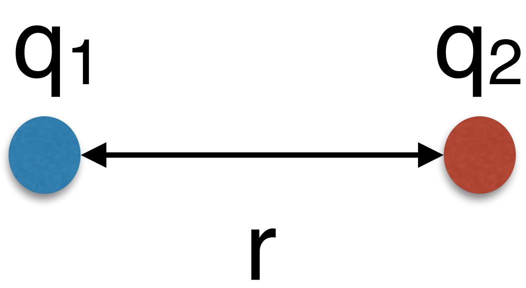

quantized, in units of fixed charge

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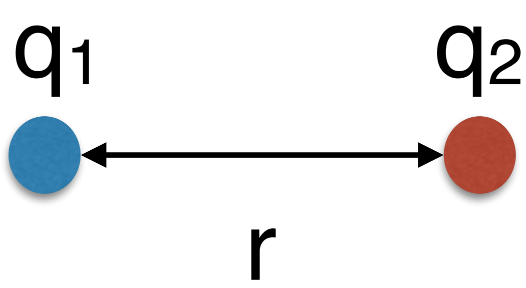

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power determined by gauge invariance/charge conservation/Gauss theorem

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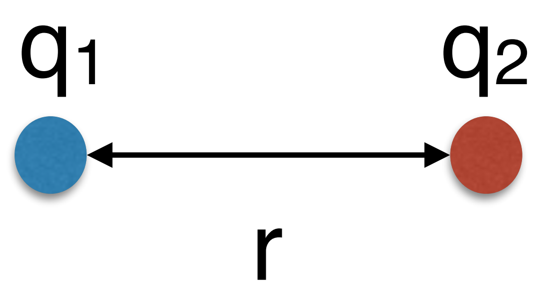

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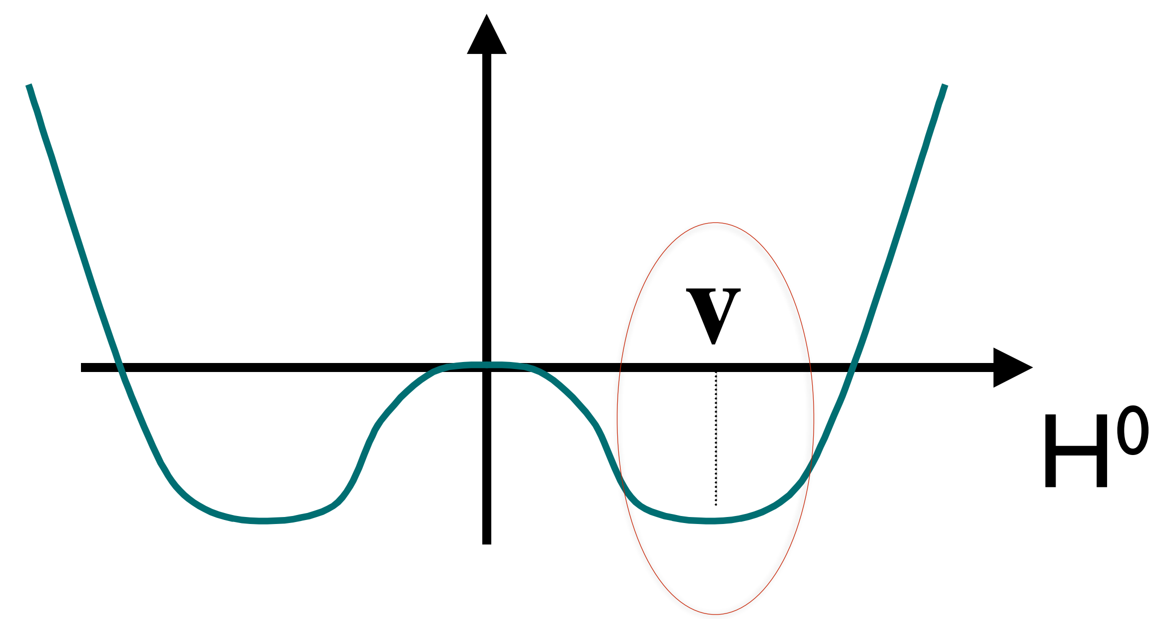

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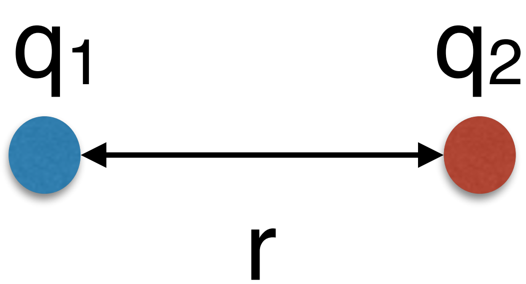

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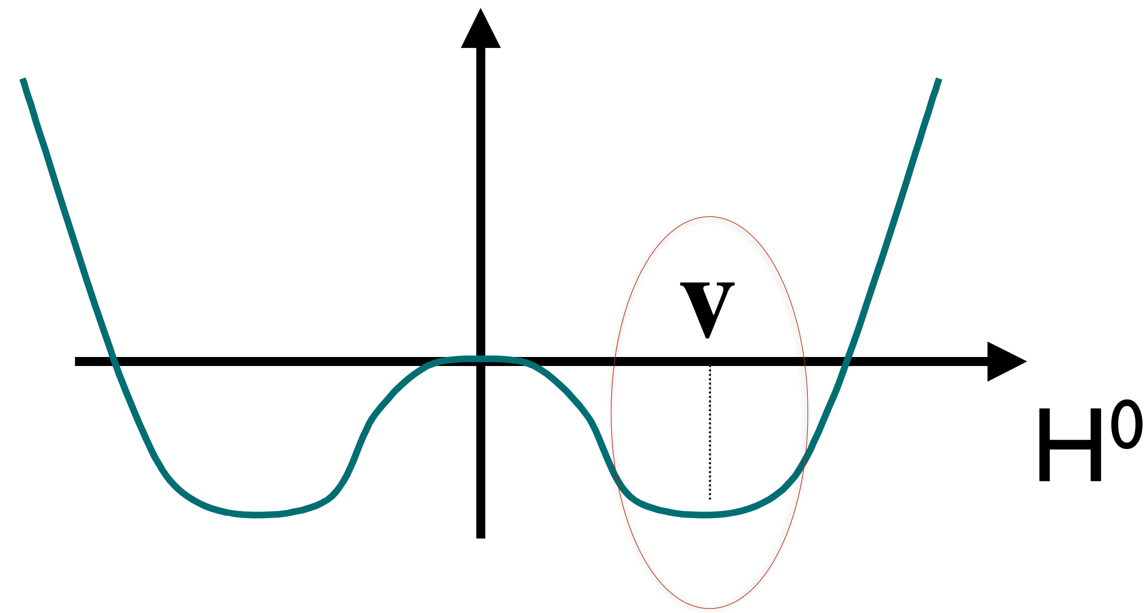

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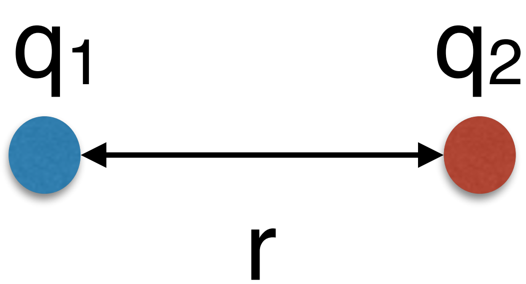

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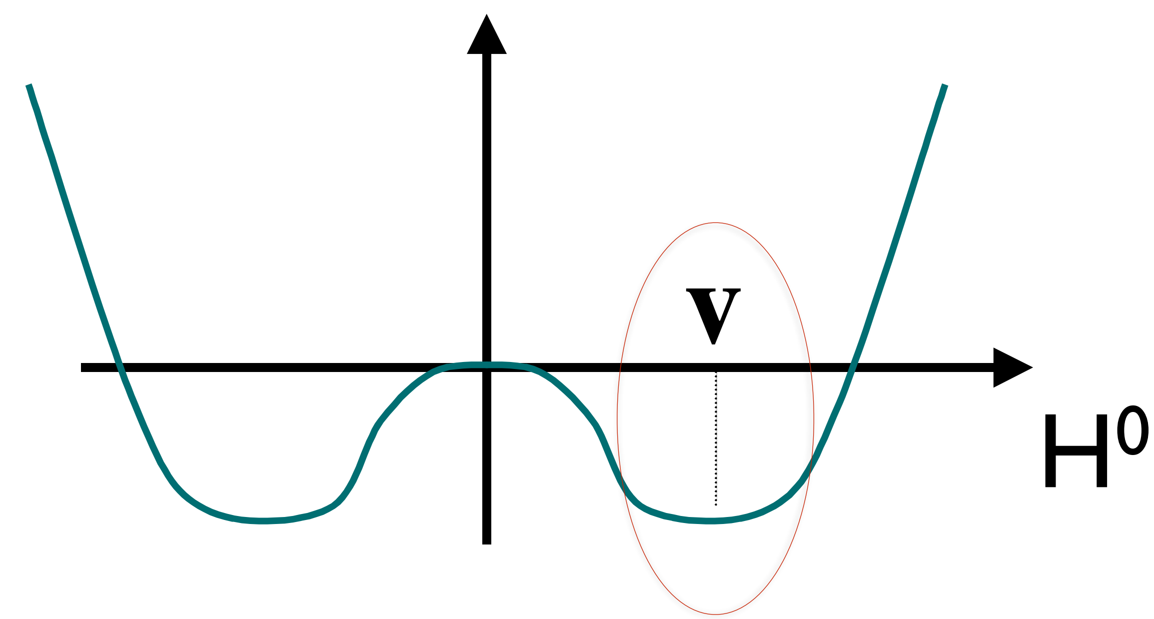

any function of $|H|^2$ would be ok wrt known symmetries

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a historical example: superconductivity

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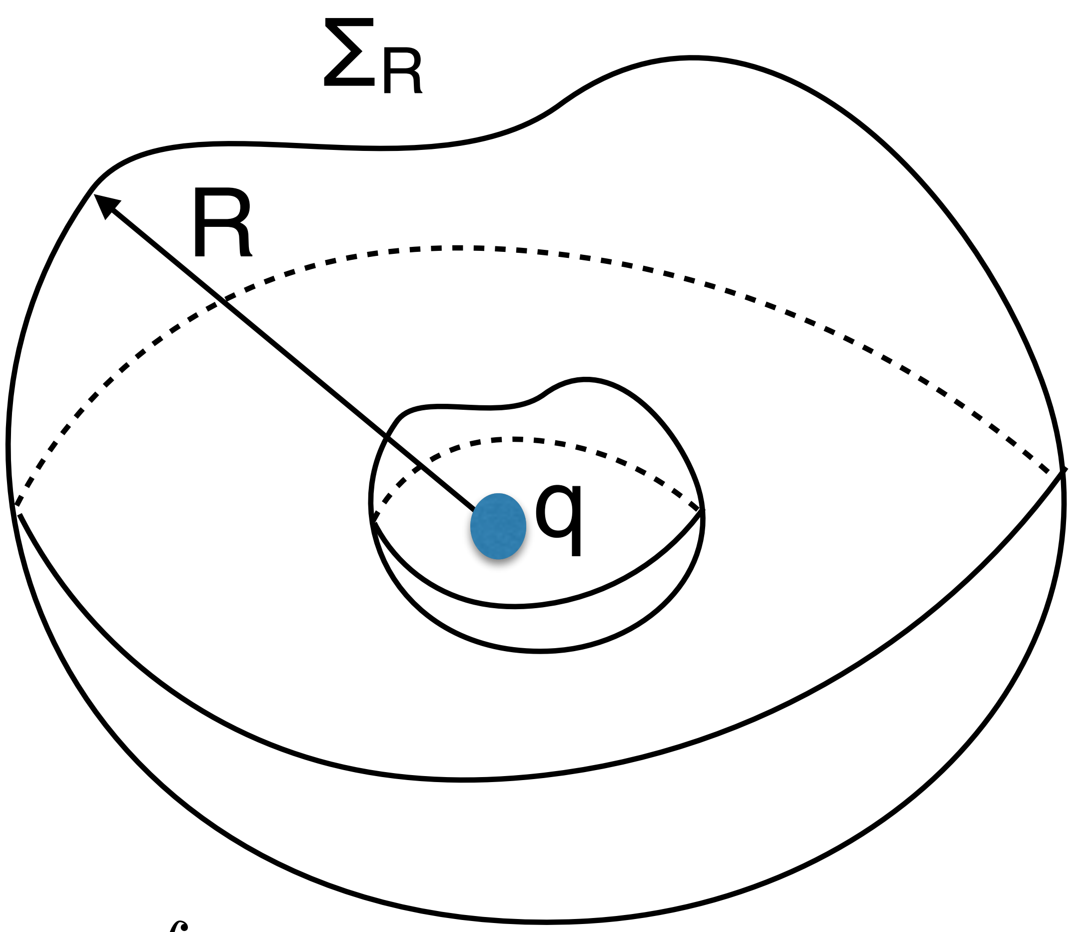
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases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

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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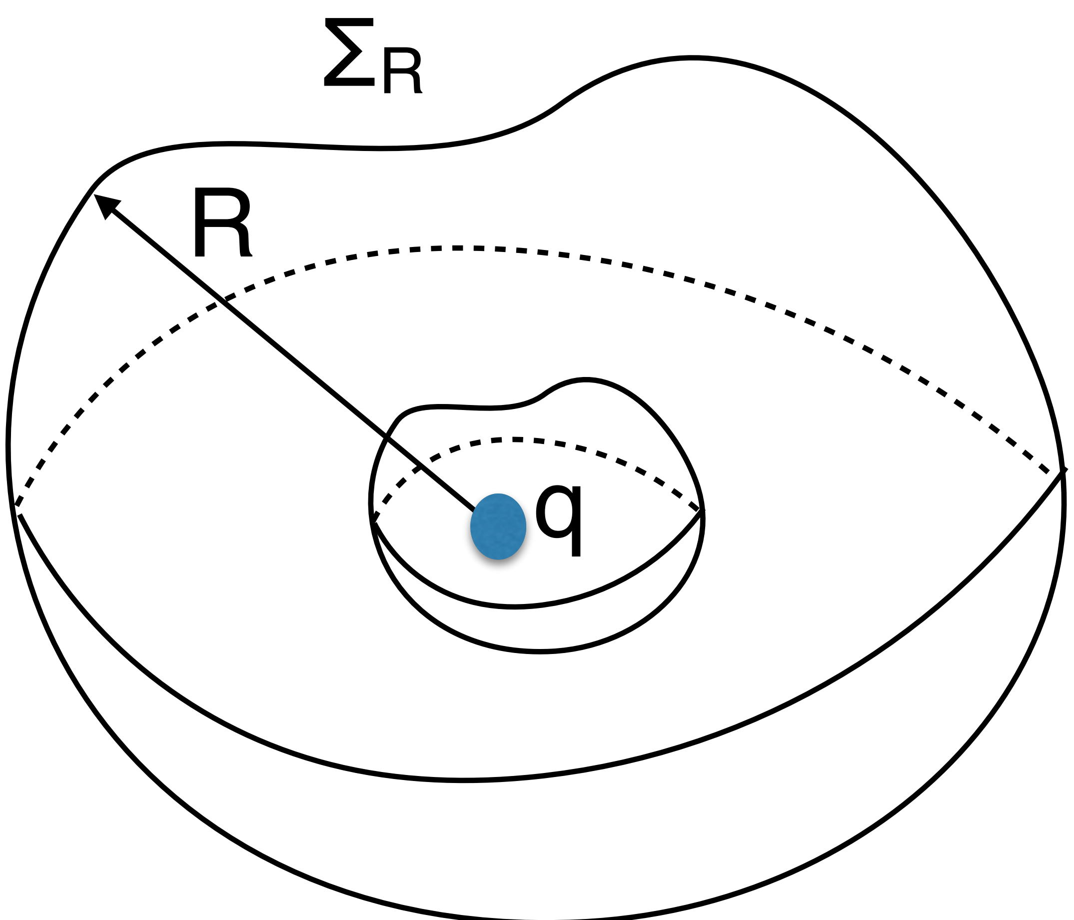

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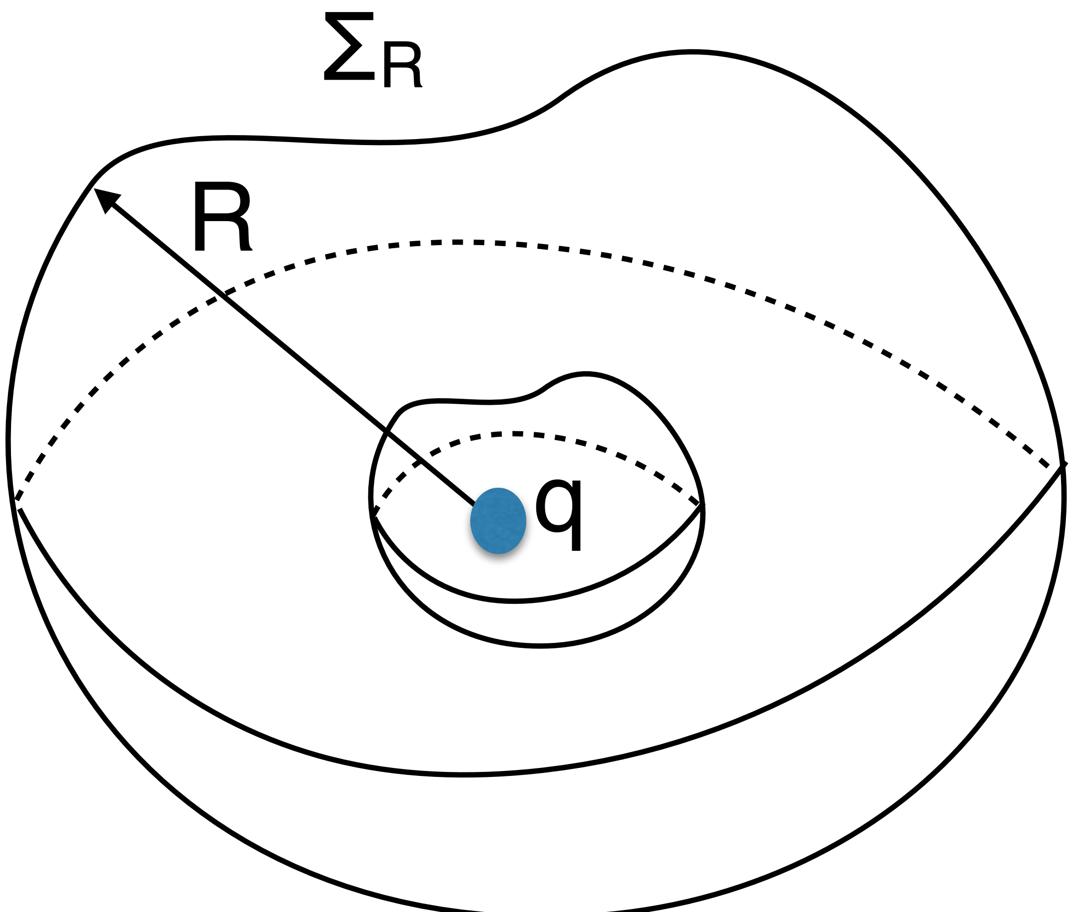

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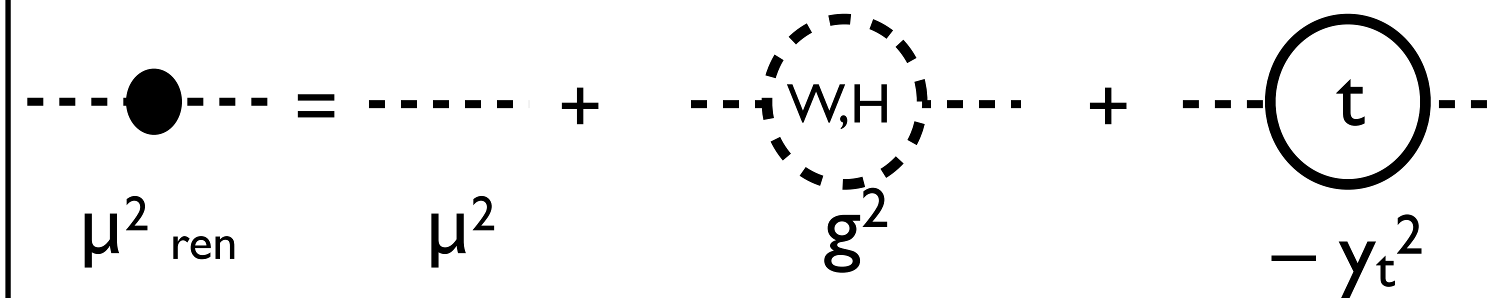

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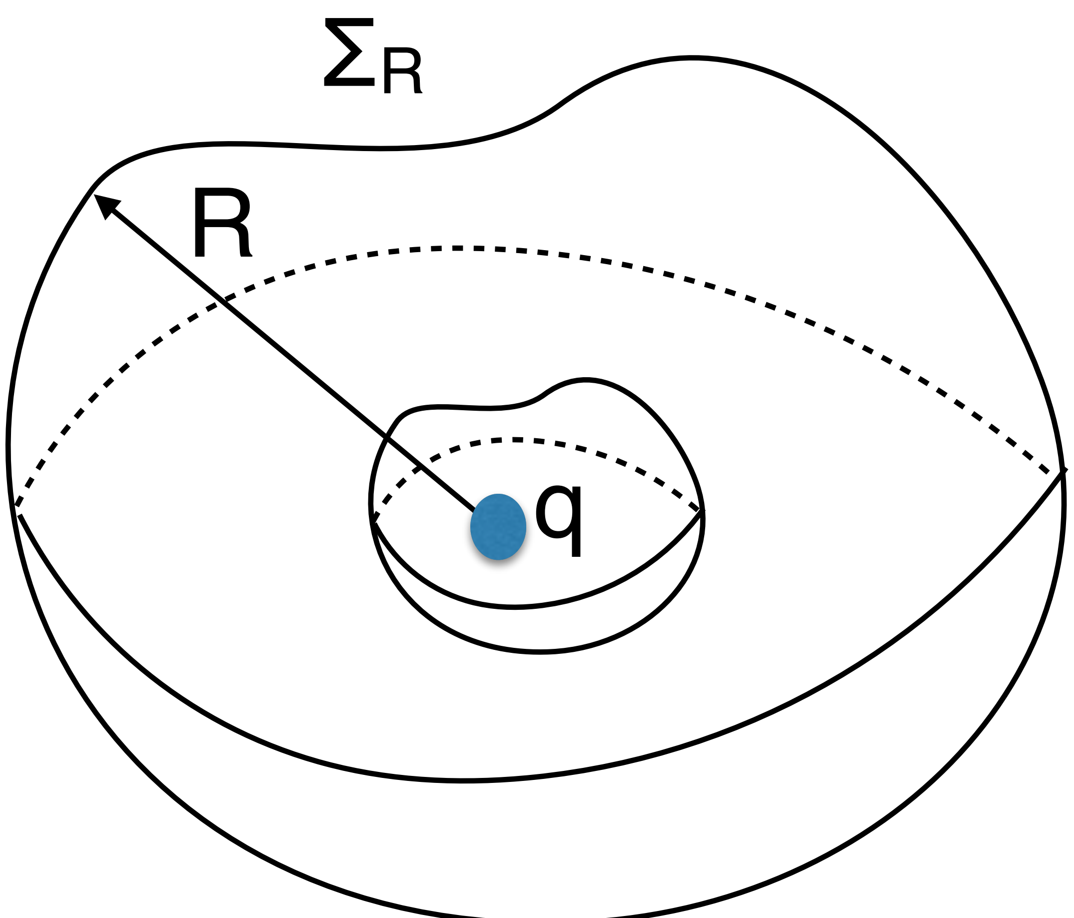

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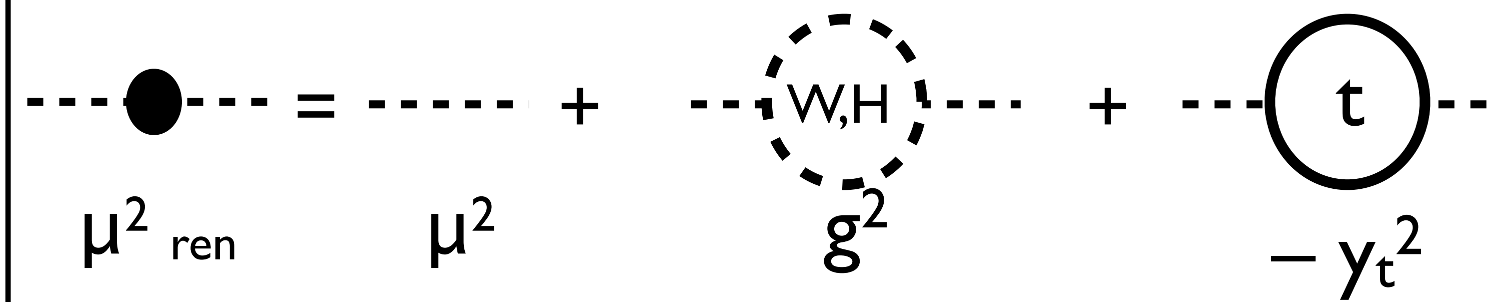

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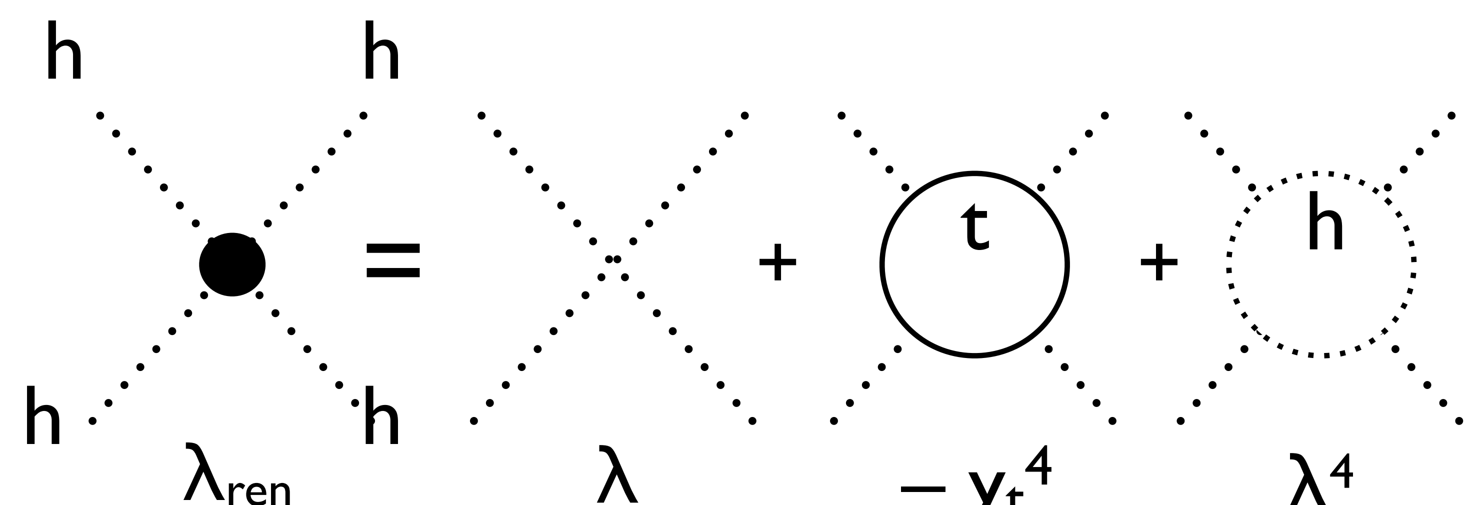

$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \quad \propto a\, m_H^4 - b\, m_t^4$$

high-energy modes can change size and sign of both μ^2 and λ, dramatically altering the stability and dynamics

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

⇒ **naturalness**

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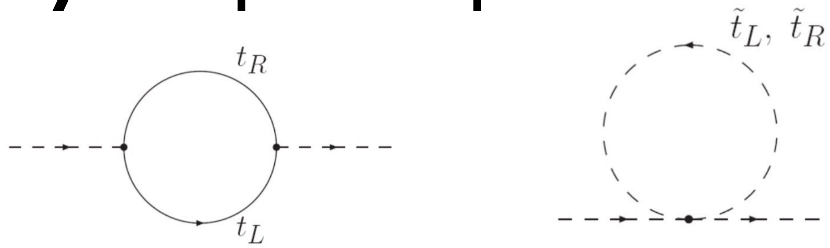

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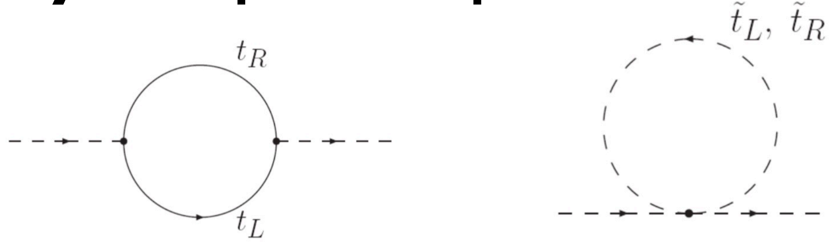

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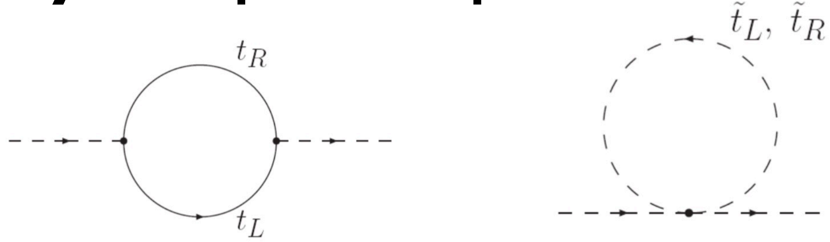

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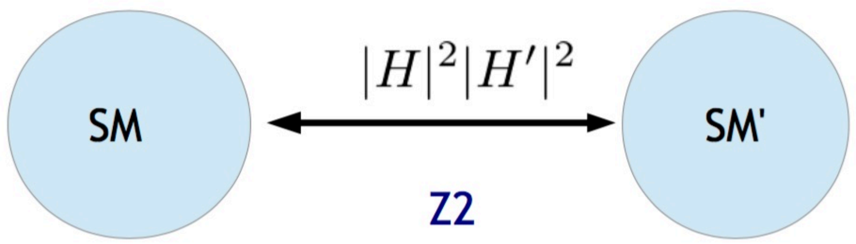

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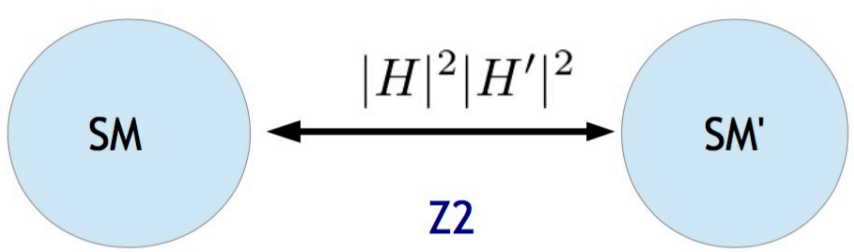


  - folded SUSY ($SU(3)_B$ stops cancel Higgs couplings to $SU(3)_A$ tops)

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

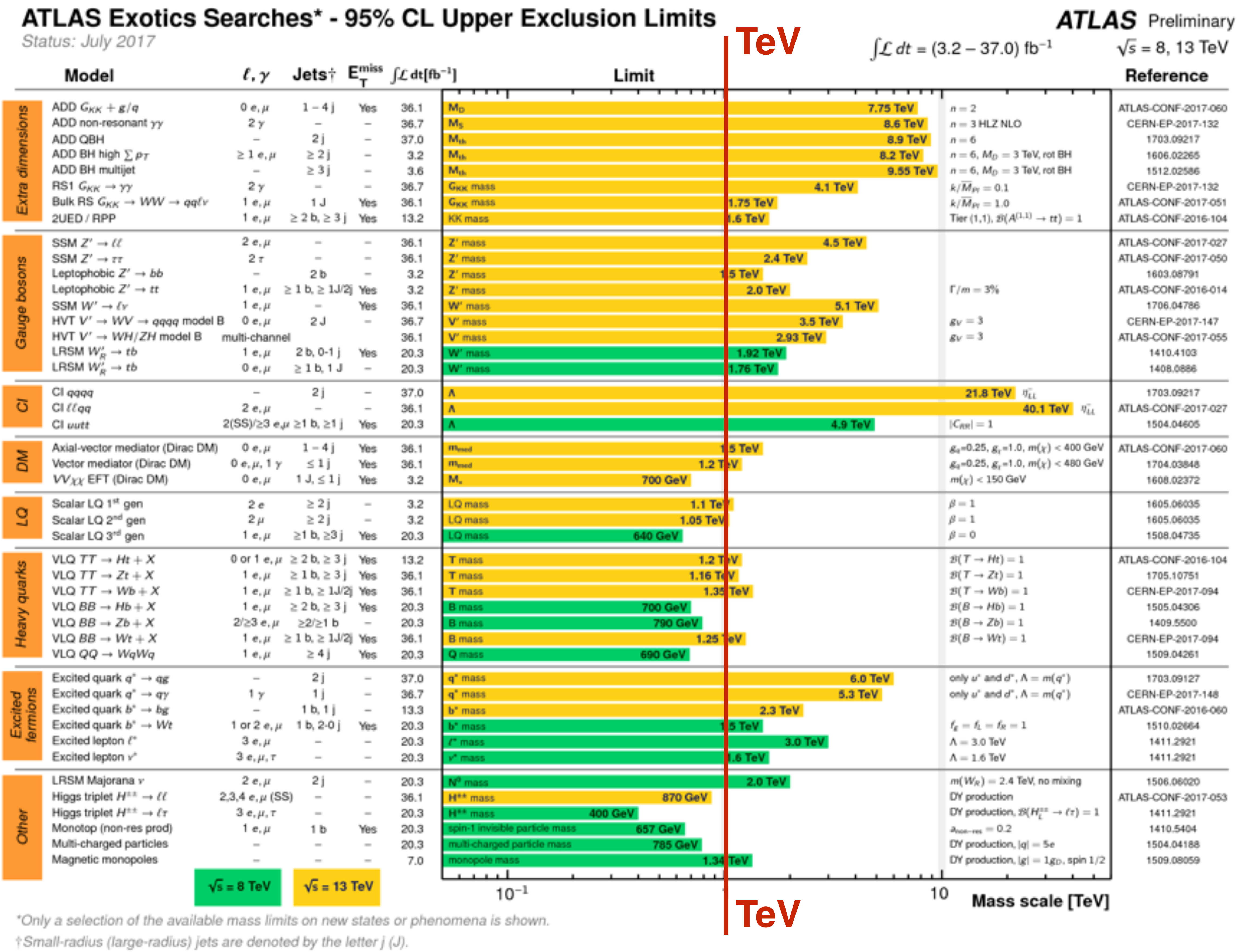
In search of the origin of known departures from the SM

- 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



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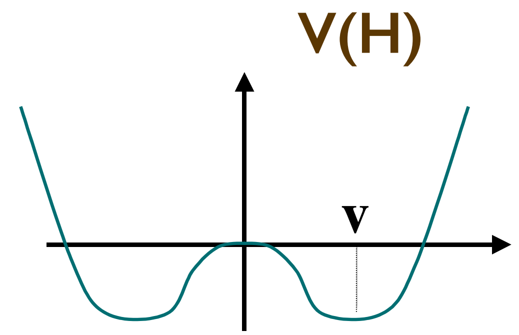
=> all this justifies the focus on the program of precision Higgs physics measurements

The Higgs potential

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

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



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

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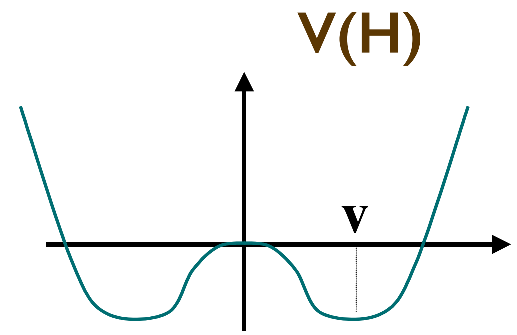

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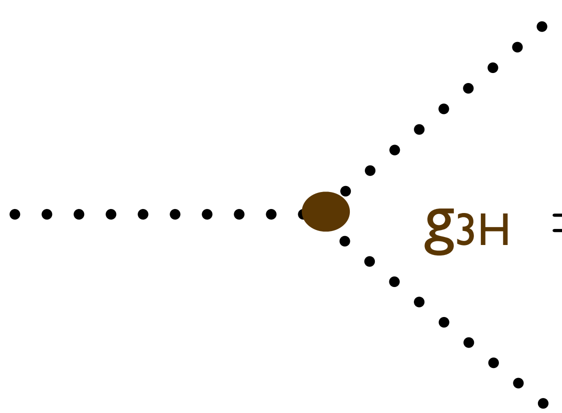
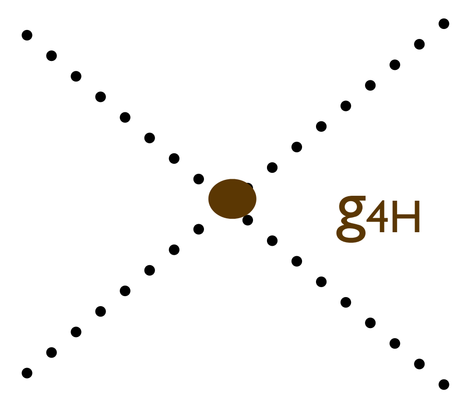
These relations uniquely determine the strength of Higgs selfcouplings in terms of the two now-known parameters m_H and v



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

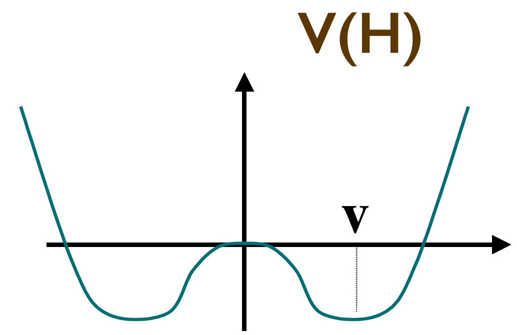


$g_{4H} \Rightarrow \lambda = \dfrac{m_H^2}{2v^2}$

The Higgs potential

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

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



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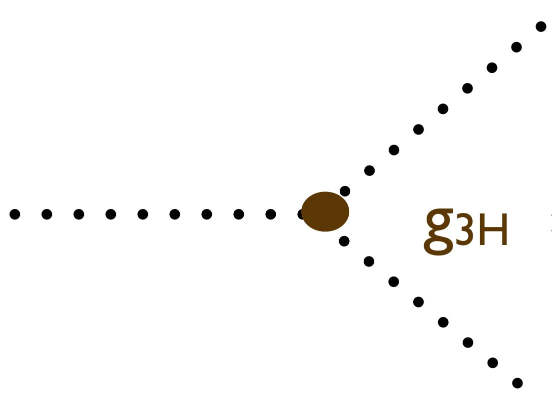

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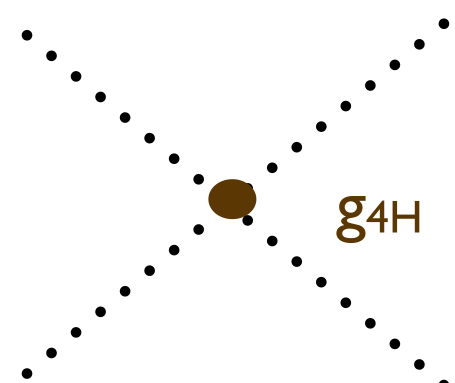
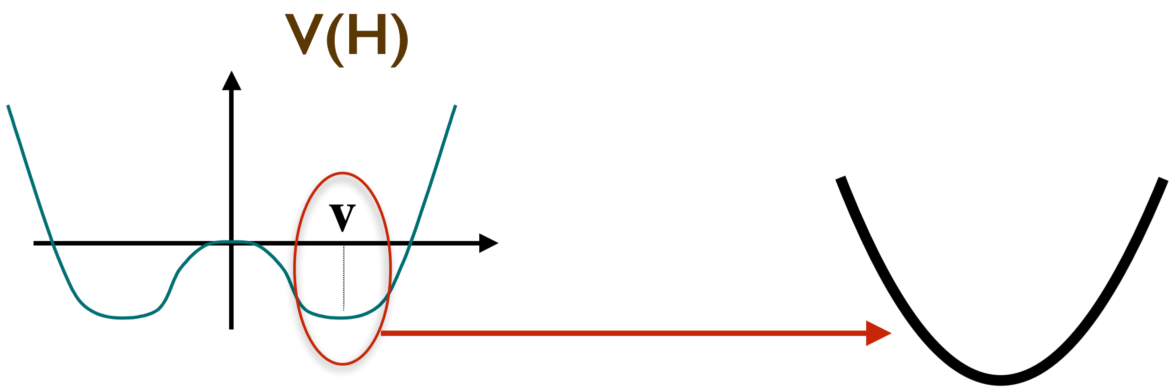


$g_{4H} \Rightarrow \lambda = \frac{m_H^2}{2v^2}$

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

How far have we tested the Higgs potential?

parameters of the potential

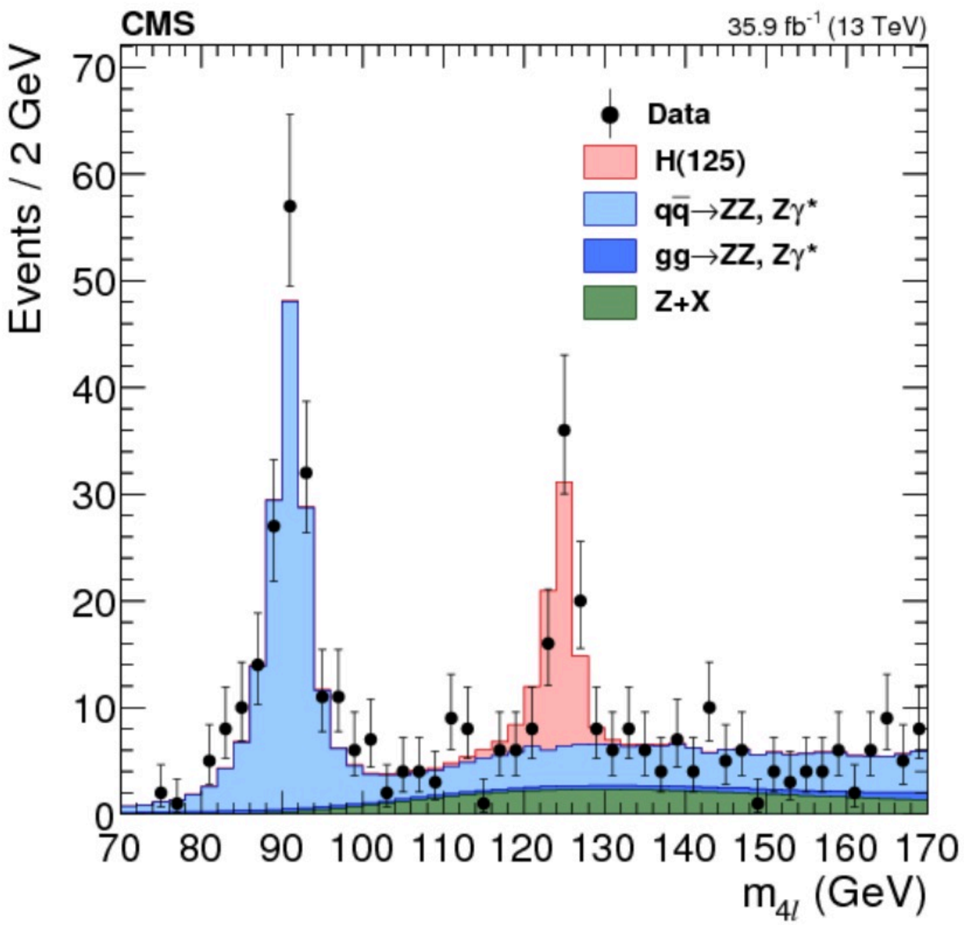


$V(H) \sim m_H^2\,(H - \mathbf{v})^2$

v=246 GeV, from weak decays

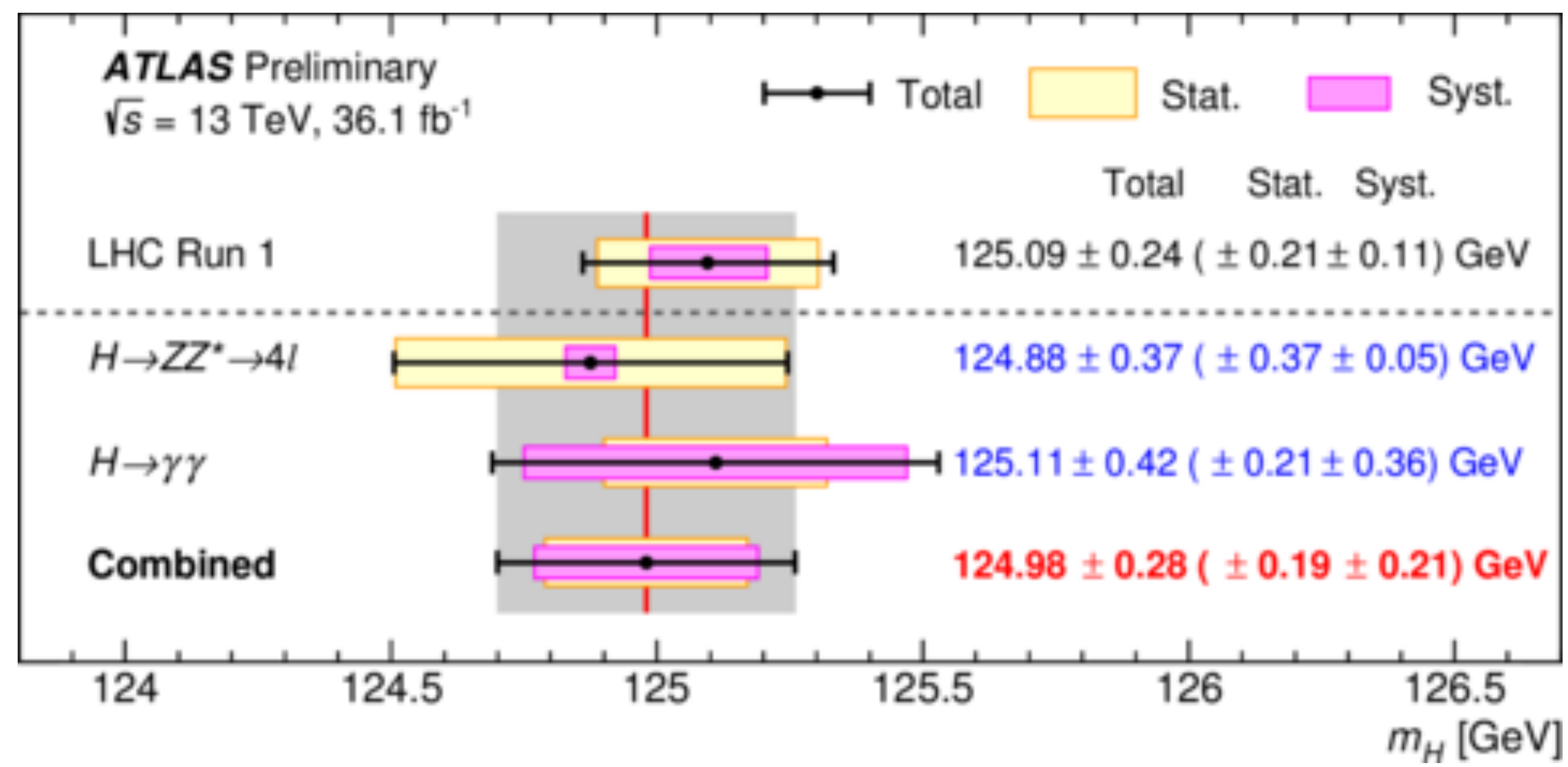
Higgs mass, 2017

CMS



arXiv:1706.09936

ATLAS



ATLAS-CONF-2017-046

3D likelihood fit (m_{4l}, ZZ bg, δm) ⇒

m_H = 125.26 ± 0.20$_{stat}$ ± 0.08$_{syst}$ GeV

= 125.26 ± 0.22 GeV

γγ and 4ℓ combination, run 1+2 ⇒

m_H = 124.98 ± 0.19$_{stat}$ ± 0.21$_{syst}$ GeV

= 124.98 ± 0.26 GeV

⇒ 2 x 10^{-3} precision ….

it took over 6 years from 1983 discovery to get below 5 x 10^{-3} on m_Z (1989: CDF, SLC, LEP)

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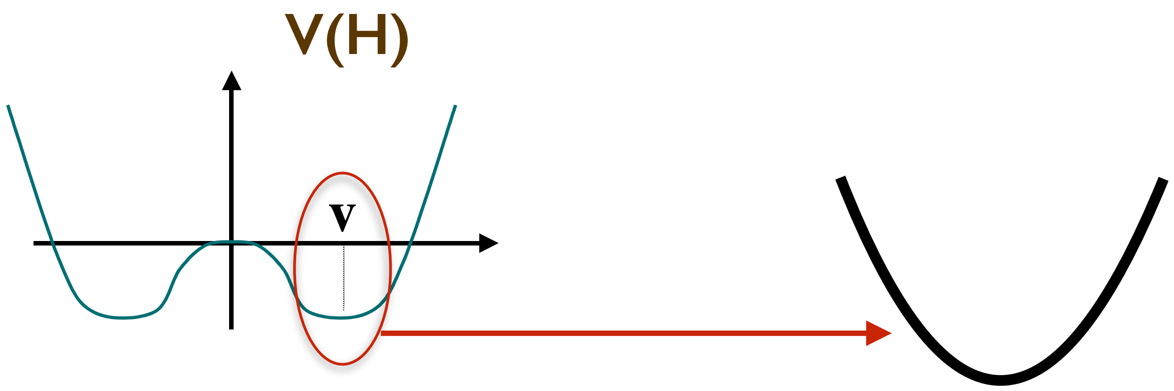

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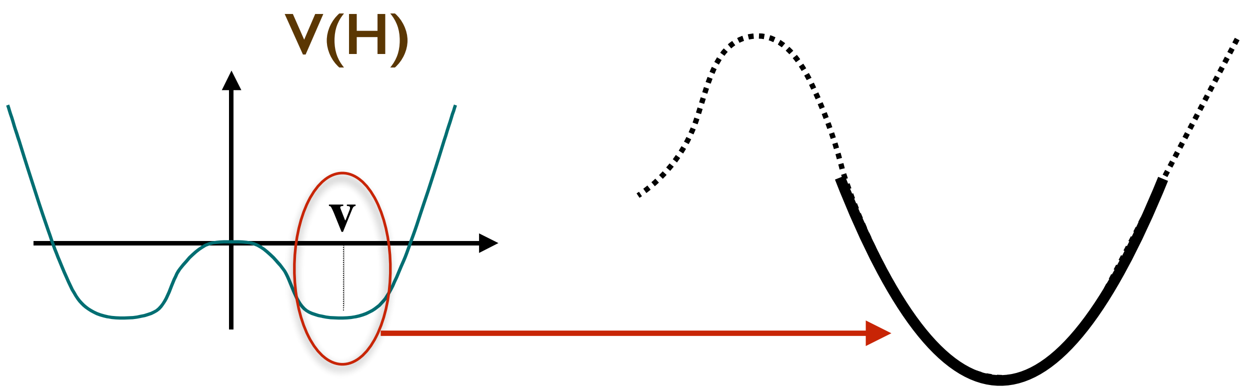
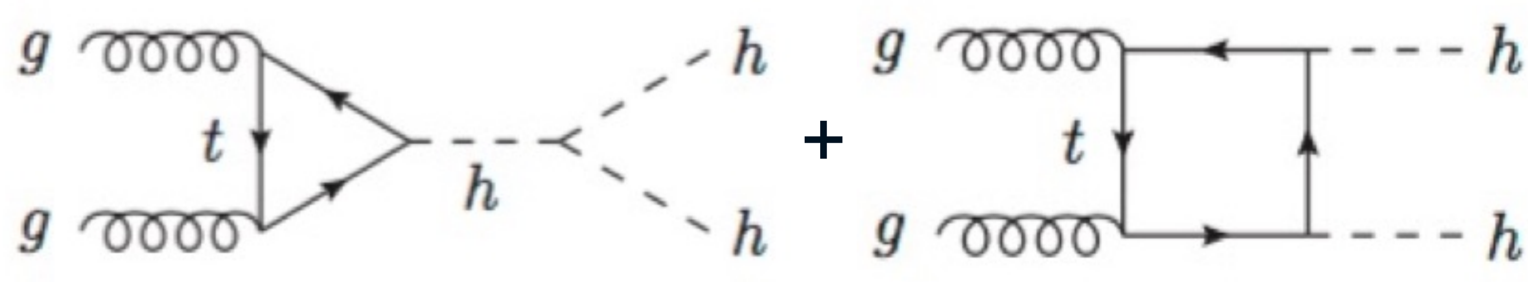
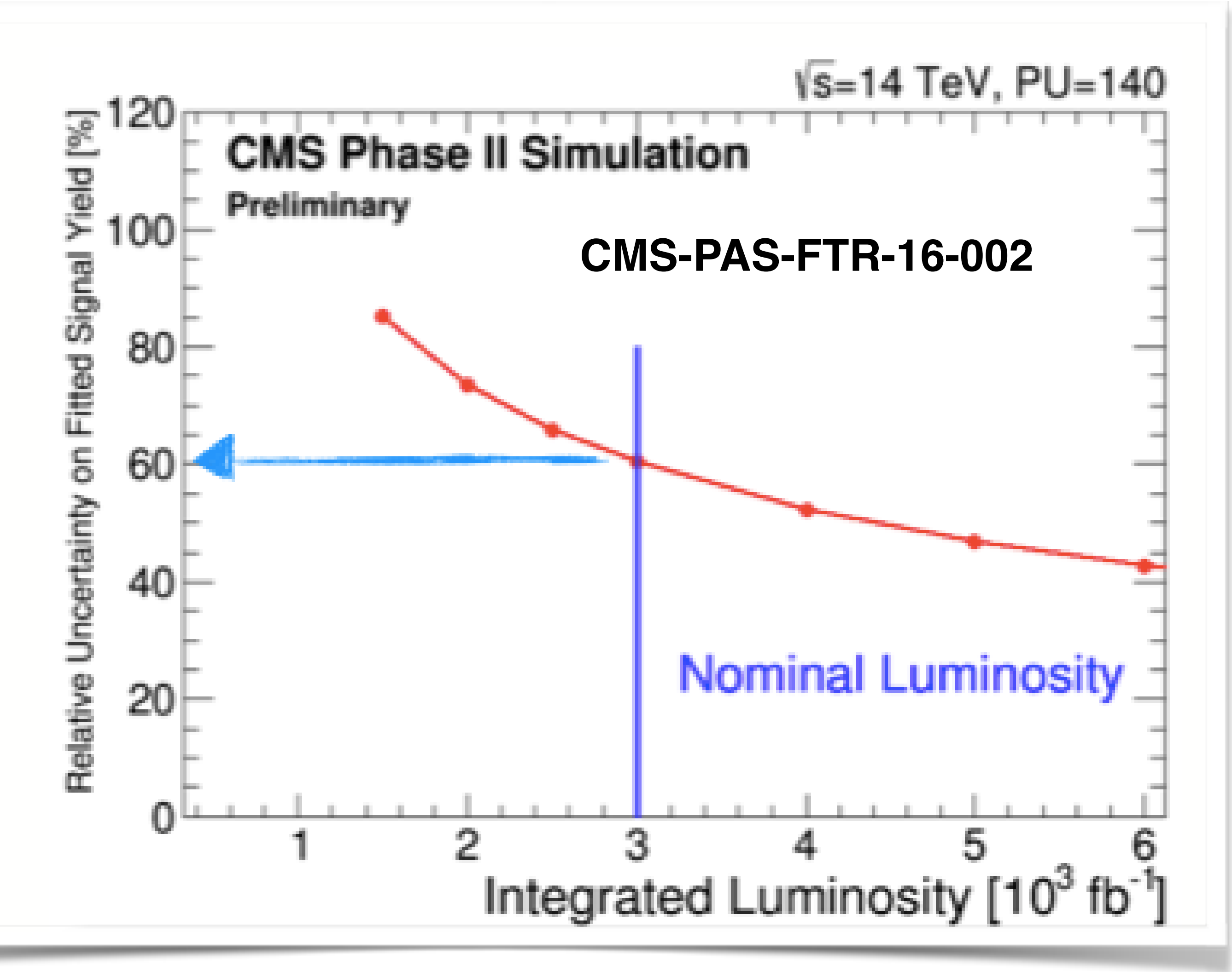


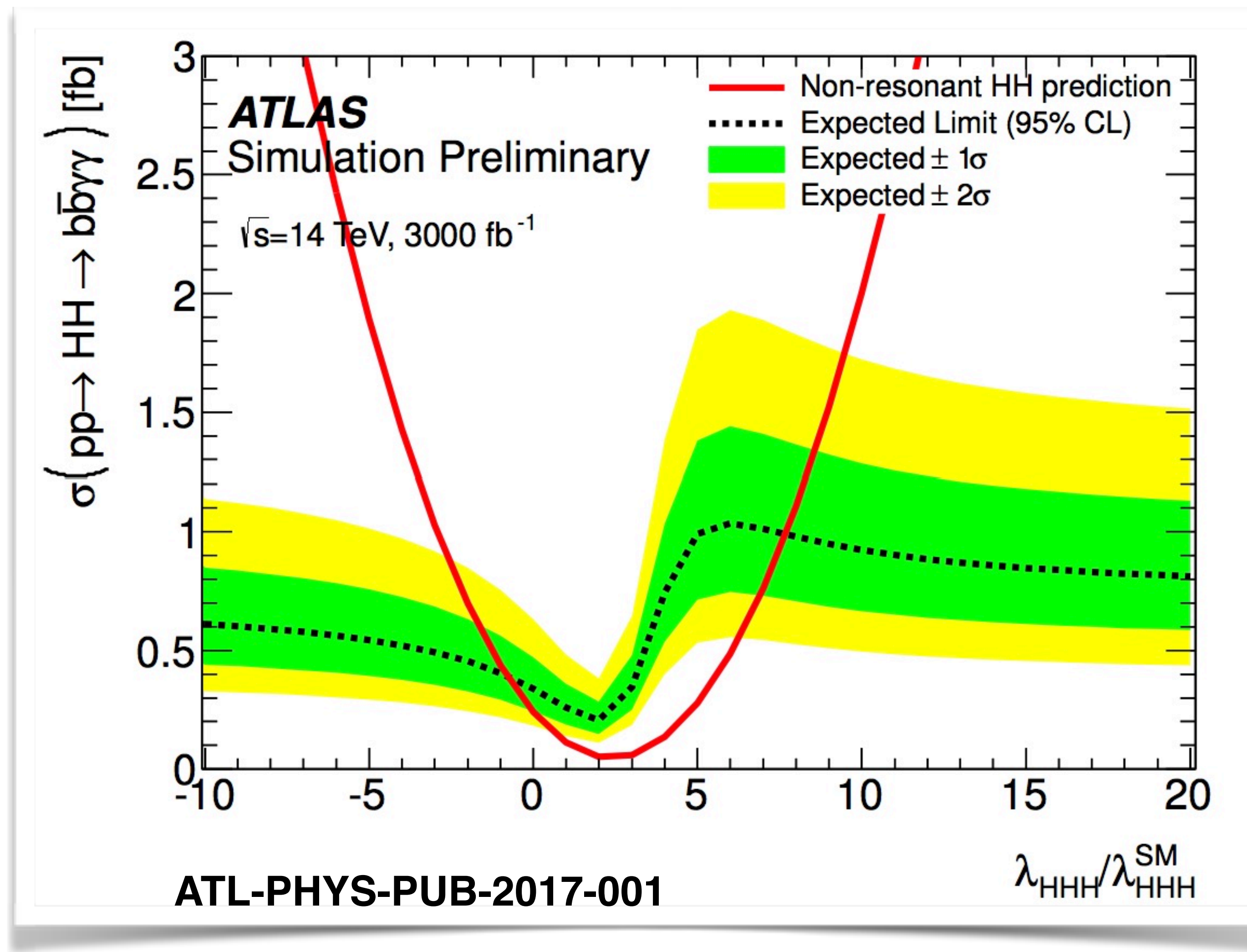
$V(H) \sim m_H^2\,(H - v)^2 \quad + \,???$

What will HL-LHC tells us about the Higgs potential?



- Strong negative interference between the two diagrams near threshold
- Selfcoupling diagram suppressed well above threshold, due to 1/S behaviour
- => it's hard!!





Barely 1-2σ evidence for Higgs pair production, but no quantitatively significant determination of λ: $-0.8 < \lambda/\lambda_{SM} < 7.7$ **@95%CL**

$-0.2 < \lambda/\lambda_{SM} < 2.6$
w. kinematical analysis

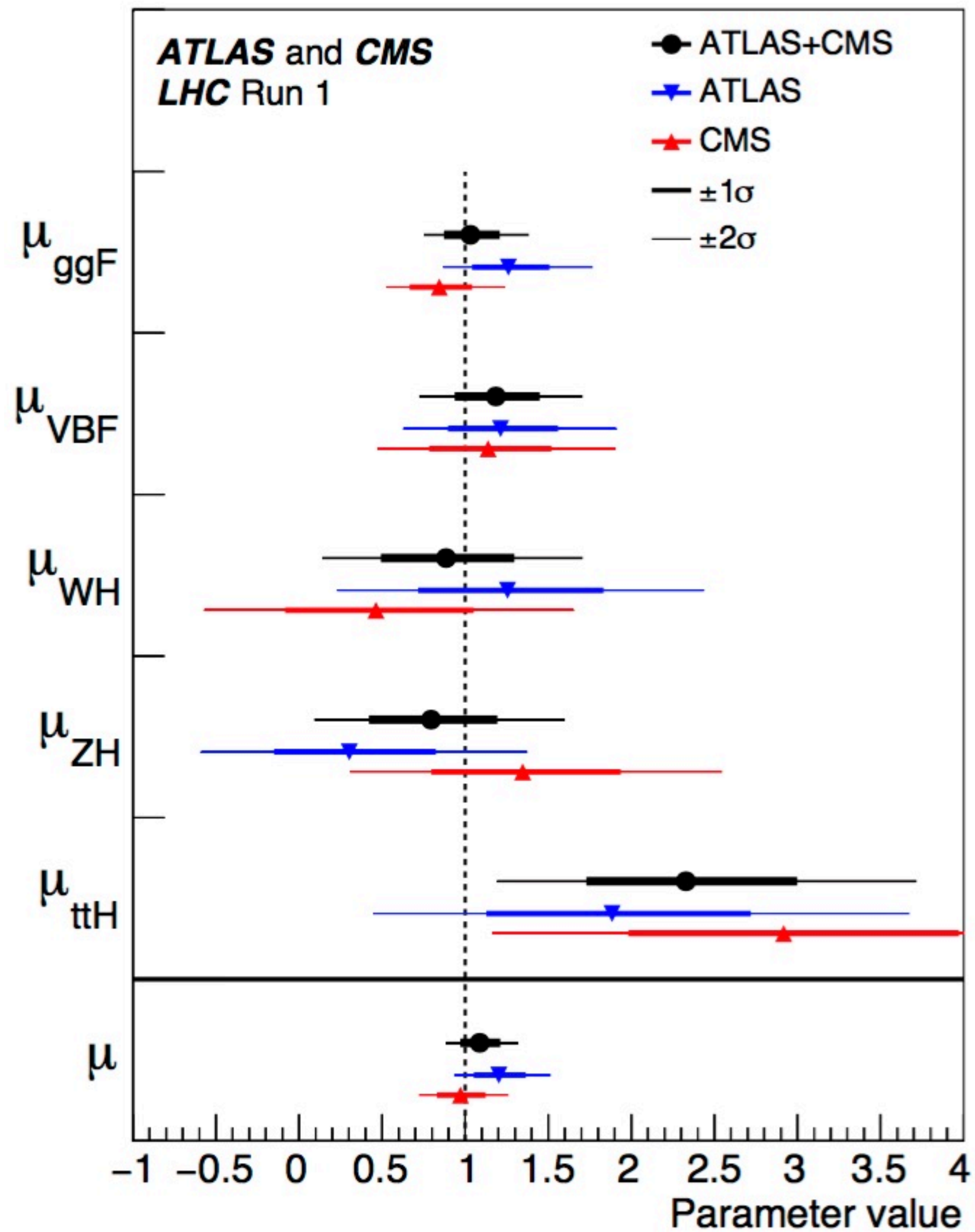
Higgs couplings: global fit of run 1 (2010-12) data

$\lambda H \, \overline{\psi_L} \, \psi_R \qquad g H V^\mu V_\mu$

μ = σxBR / [σxBR]SM
assuming SM BR's in data

ATLAS+CMS
JHEP 1608 (2016) 045

μ = 1.09 ± 0.11



- combination of different production and decay channels, explicit constraints on individual couplings are much less precise than 10% !!

- essential to establish couplings individually, through combinations of different production and decay channels

Since run 2 started in 2015:

$H \to \tau\tau$, bb, Htt coupling, all established at >5σ

$H \to \mu\mu$: limits at < 2.8 SM (ATLAS) and 2.6 SM (CMS)

⇒ so far, so good, the Higgs behaves as predicted by the SM, why do we need to do better?

Sensitivity of various Higgs couplings to examples of beyond-the-SM phenomena

.

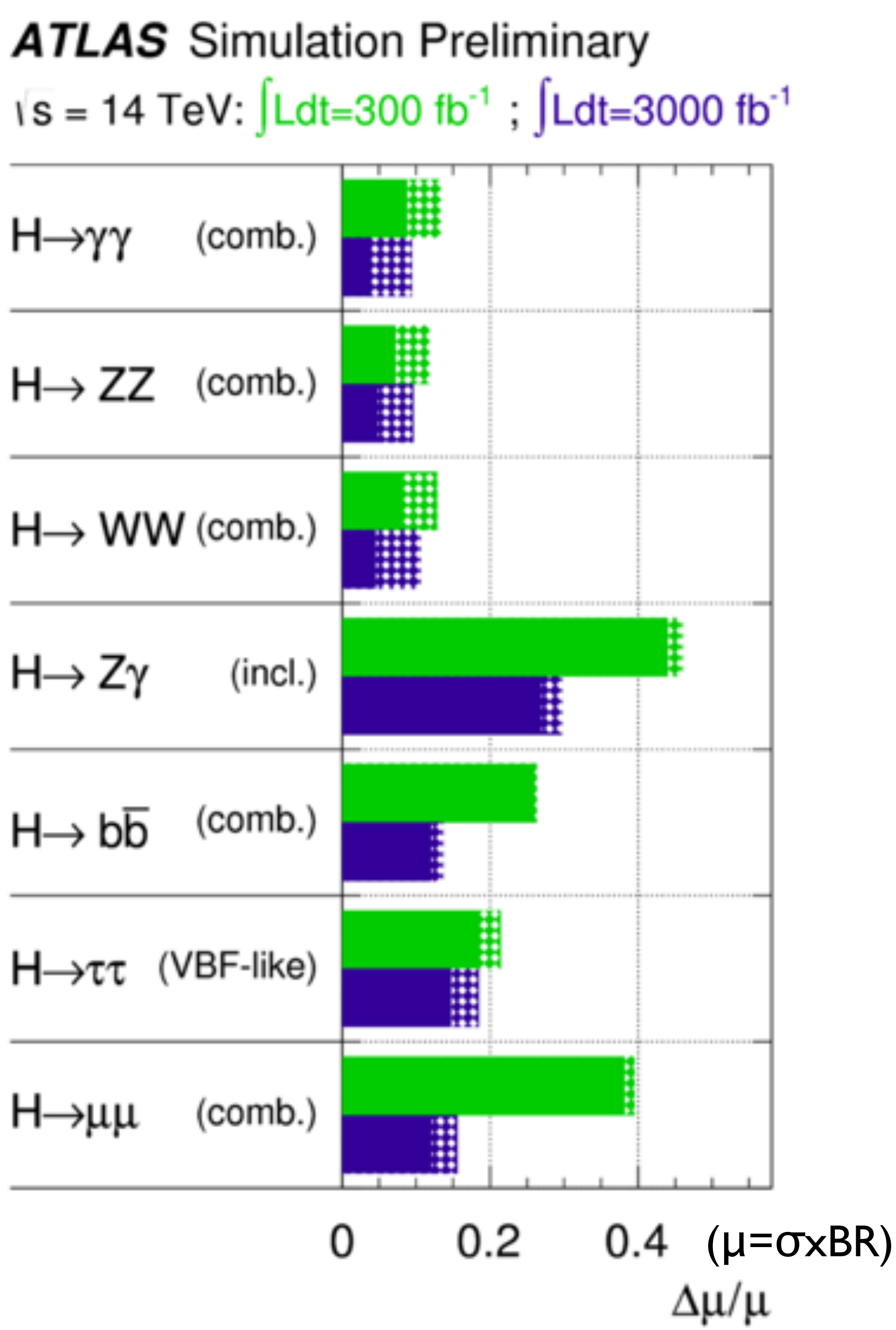
arXiv:1310.8361

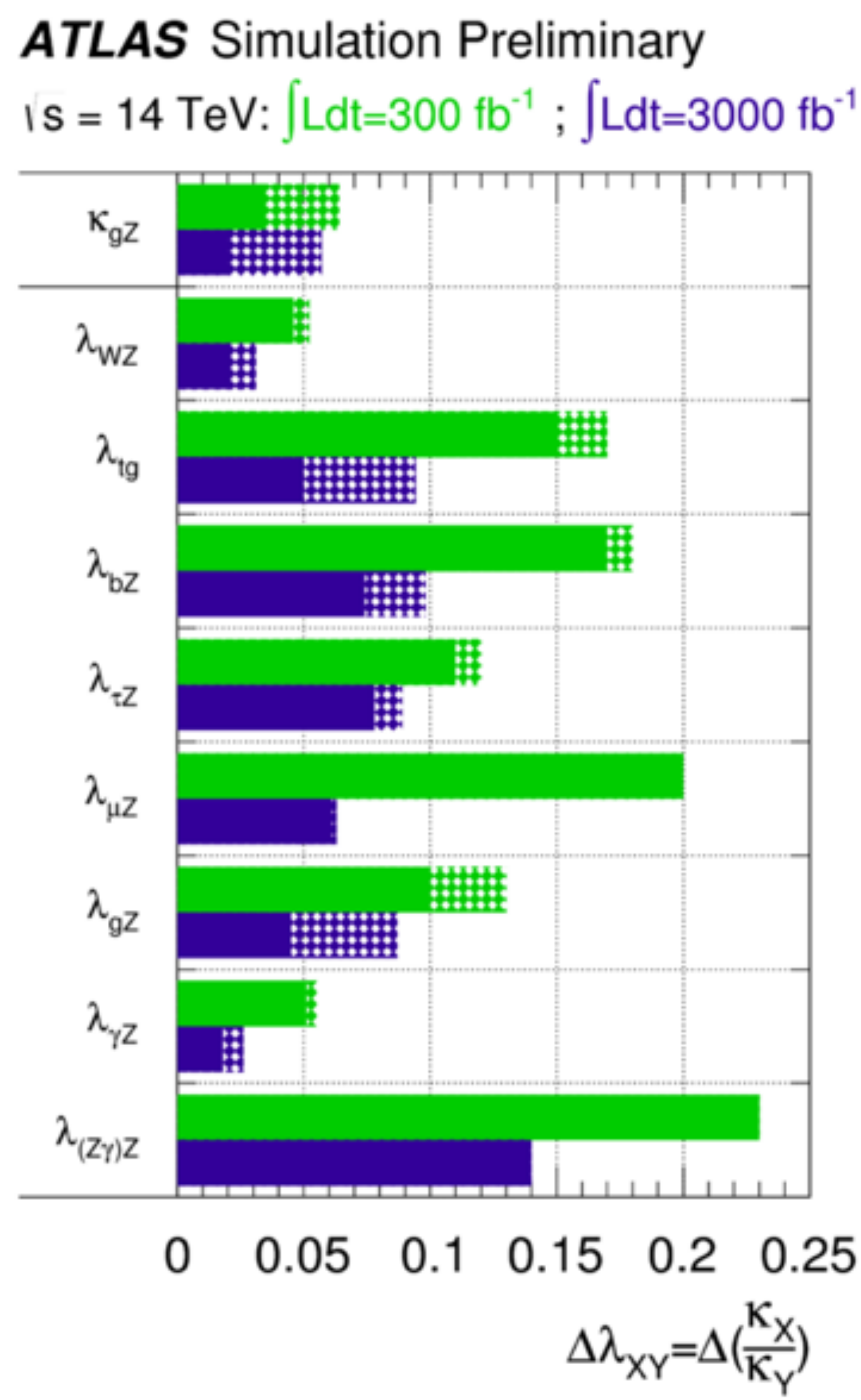
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

=> the goal should be (sub)percent precision!

Projected precision on H couplings at HL-LHC

ATL-PHYS-PUB-2014-016





solid areas: no TH systematics

shaded areas: with TH systematics

Why do we care so much?

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  - what's the order of the phase transition?
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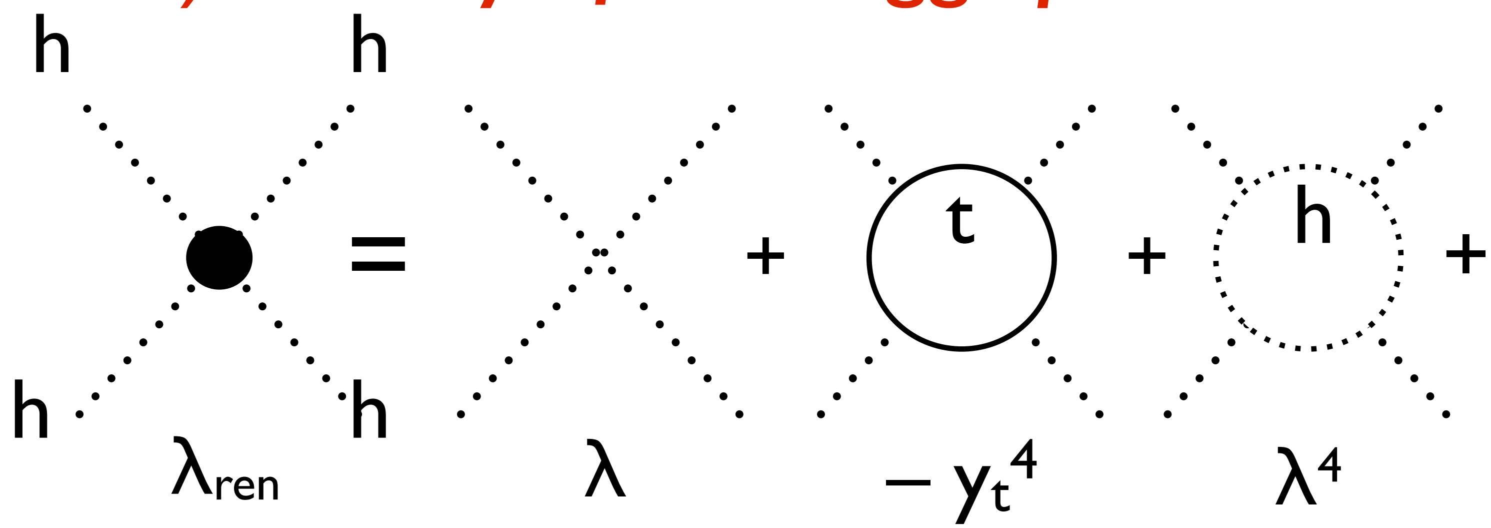
- Is there a relation between any amongst Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

(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



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

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

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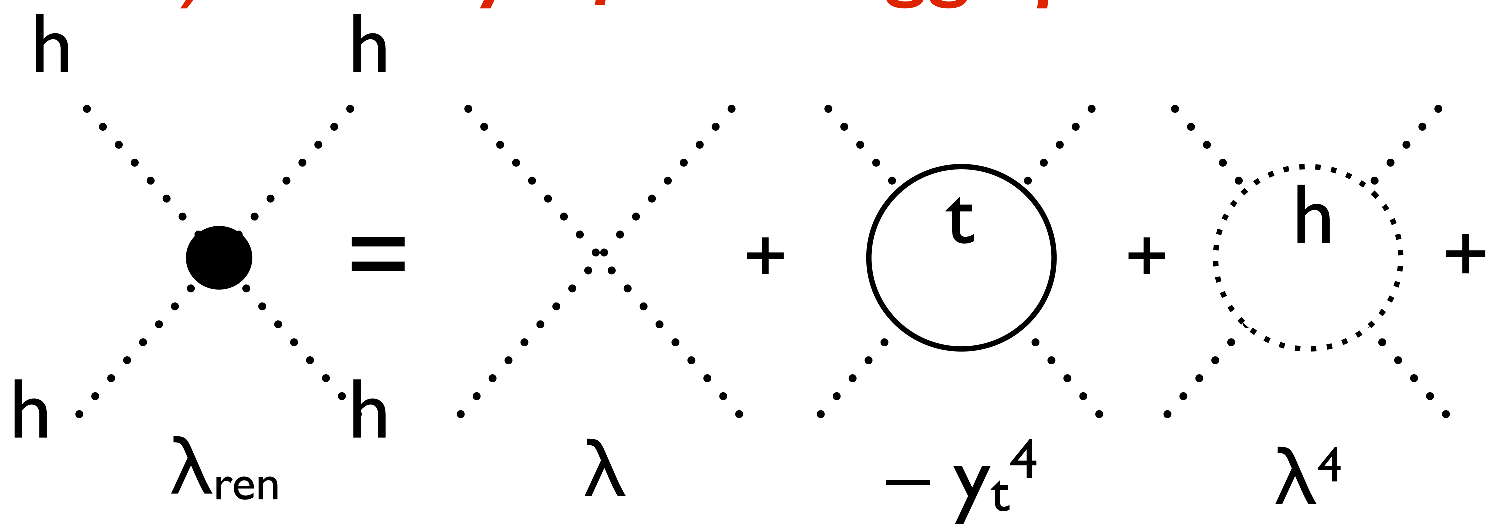

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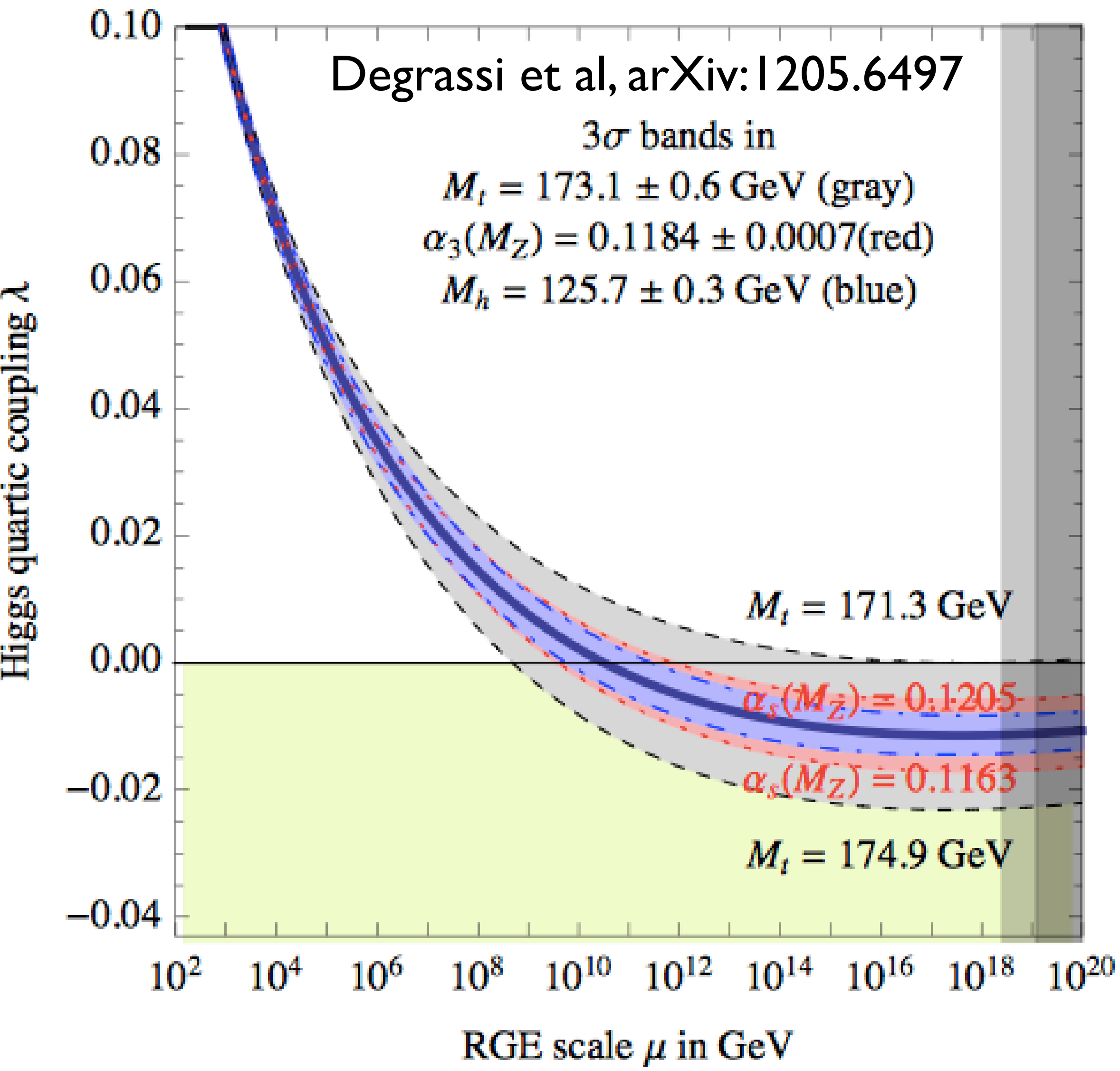

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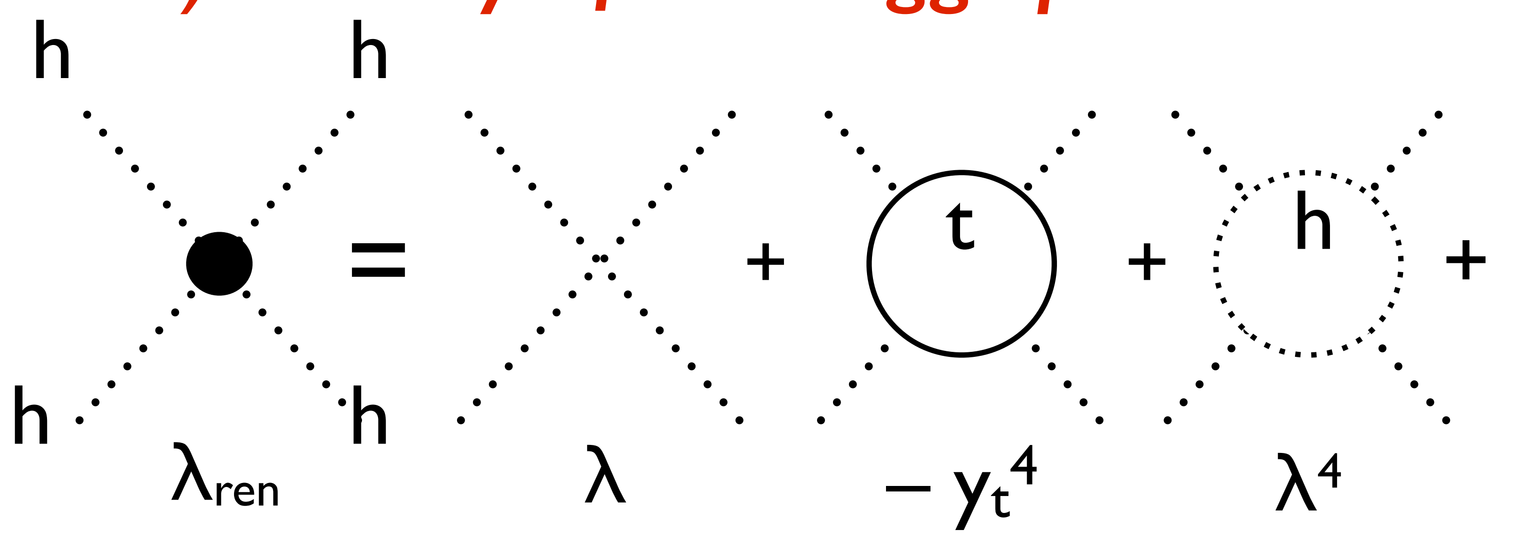

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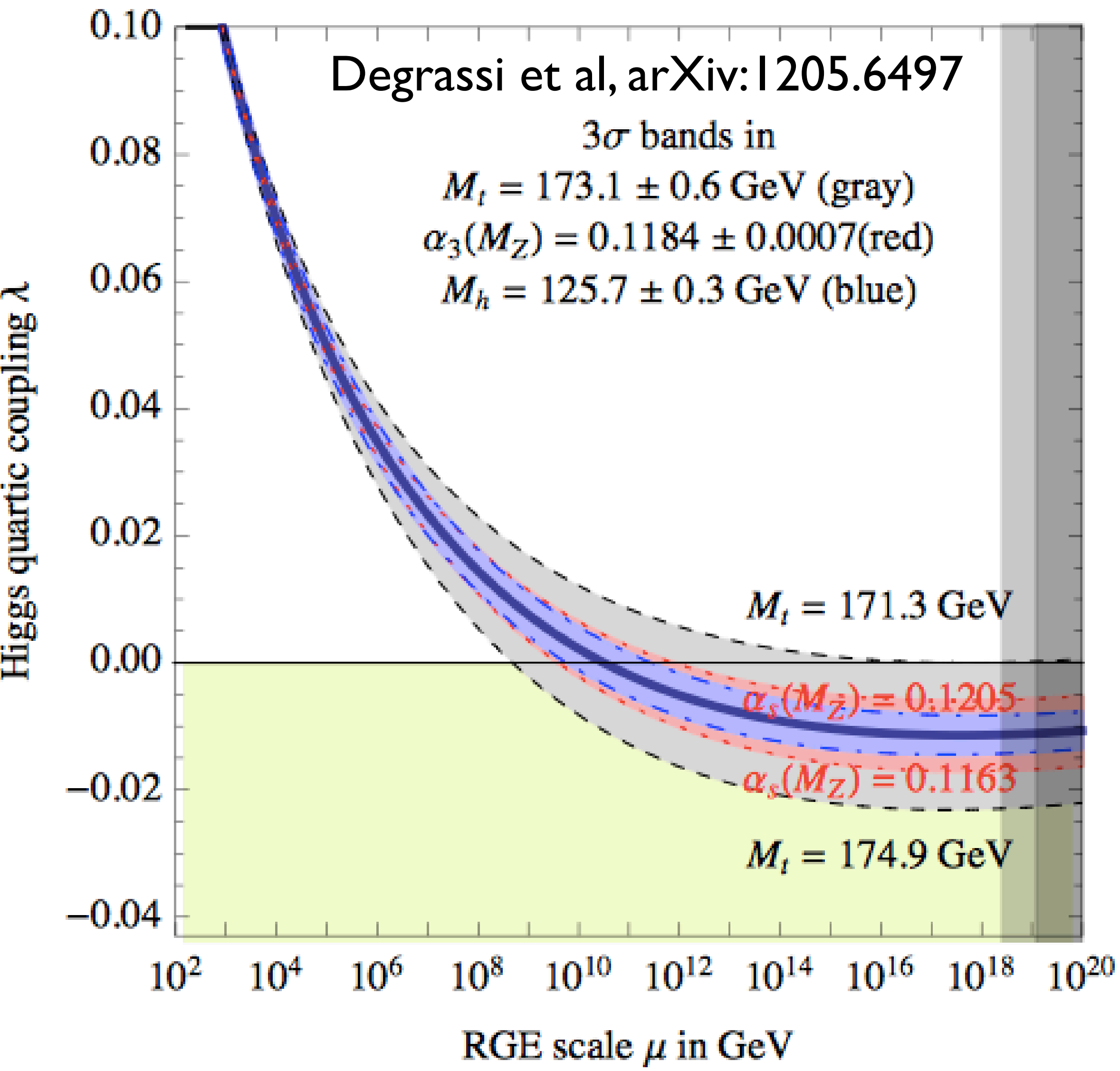

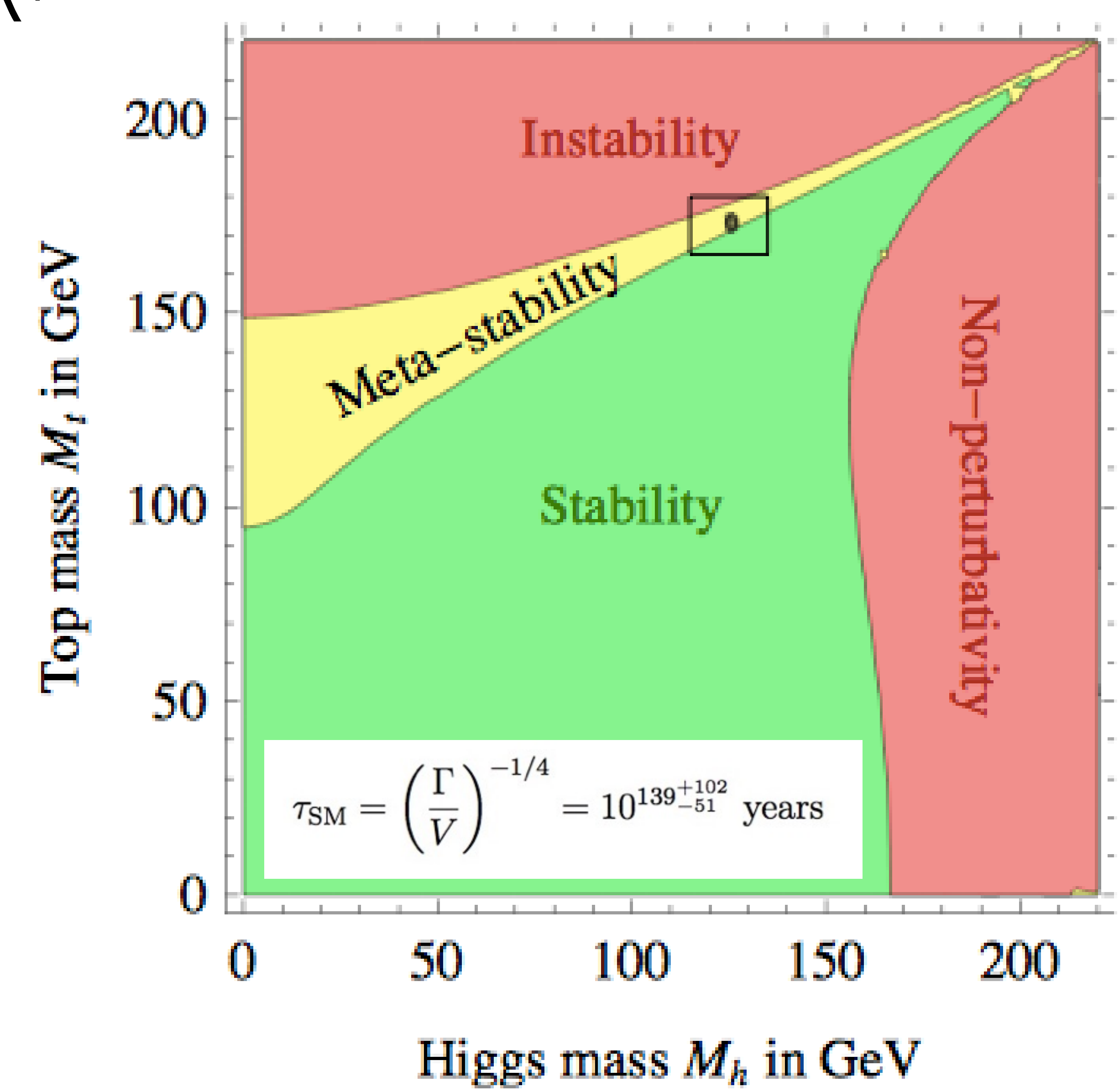

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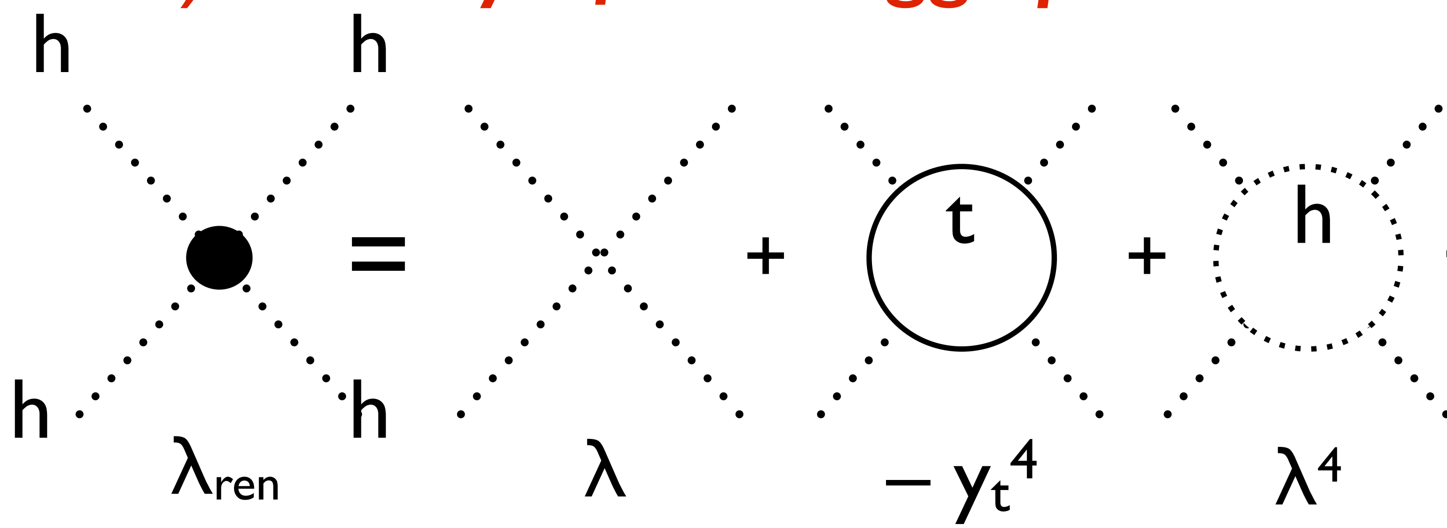

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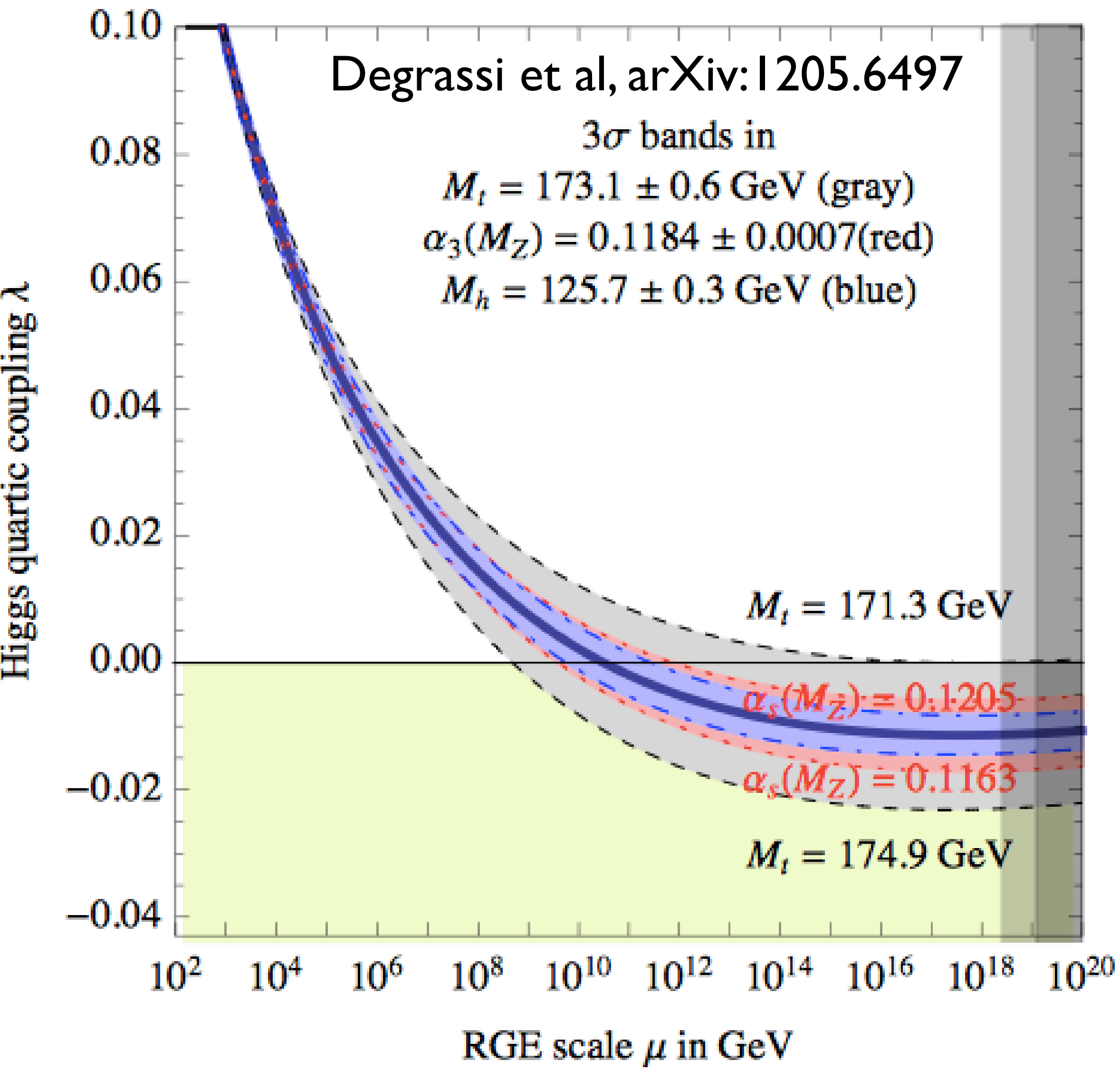
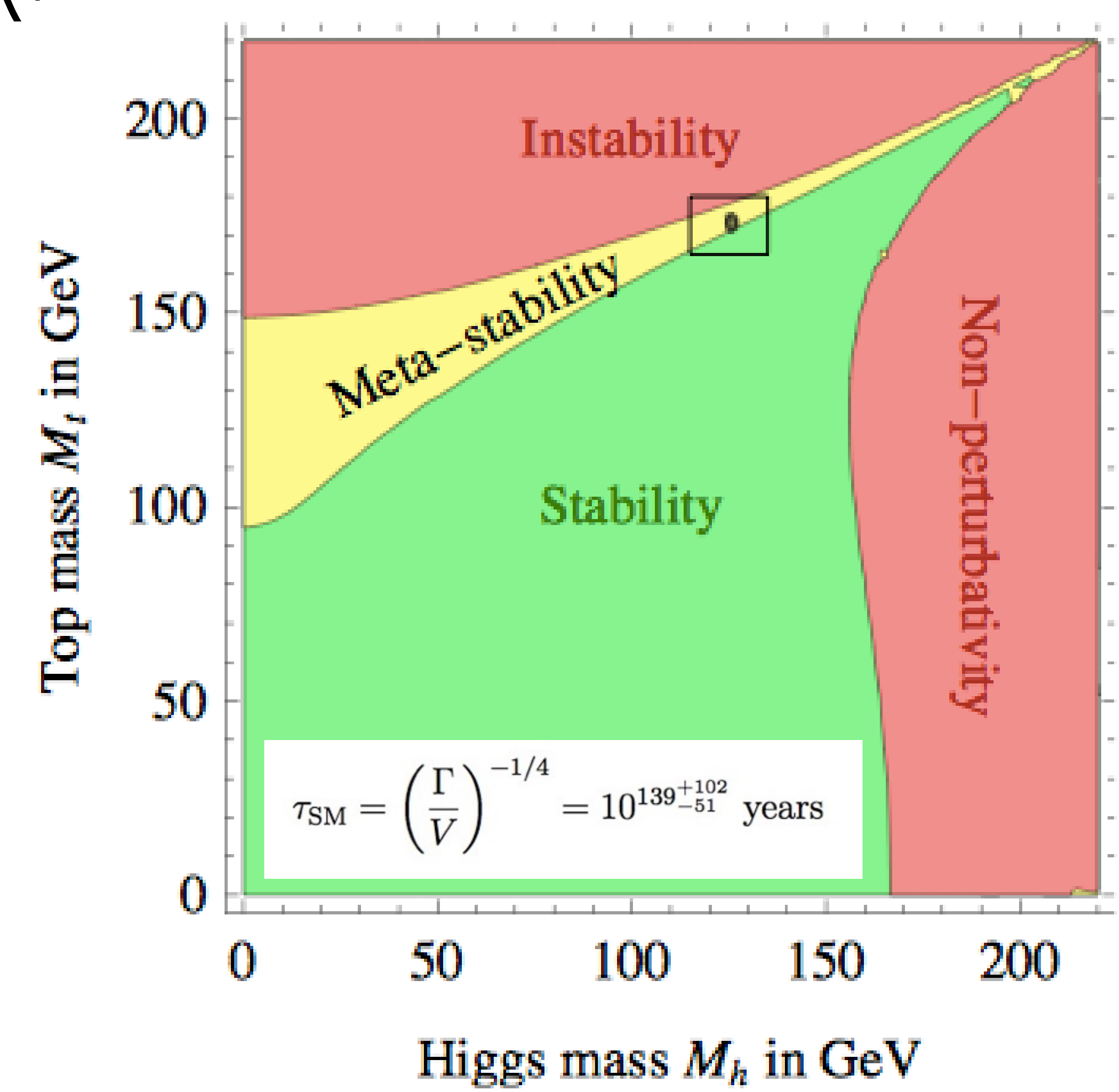
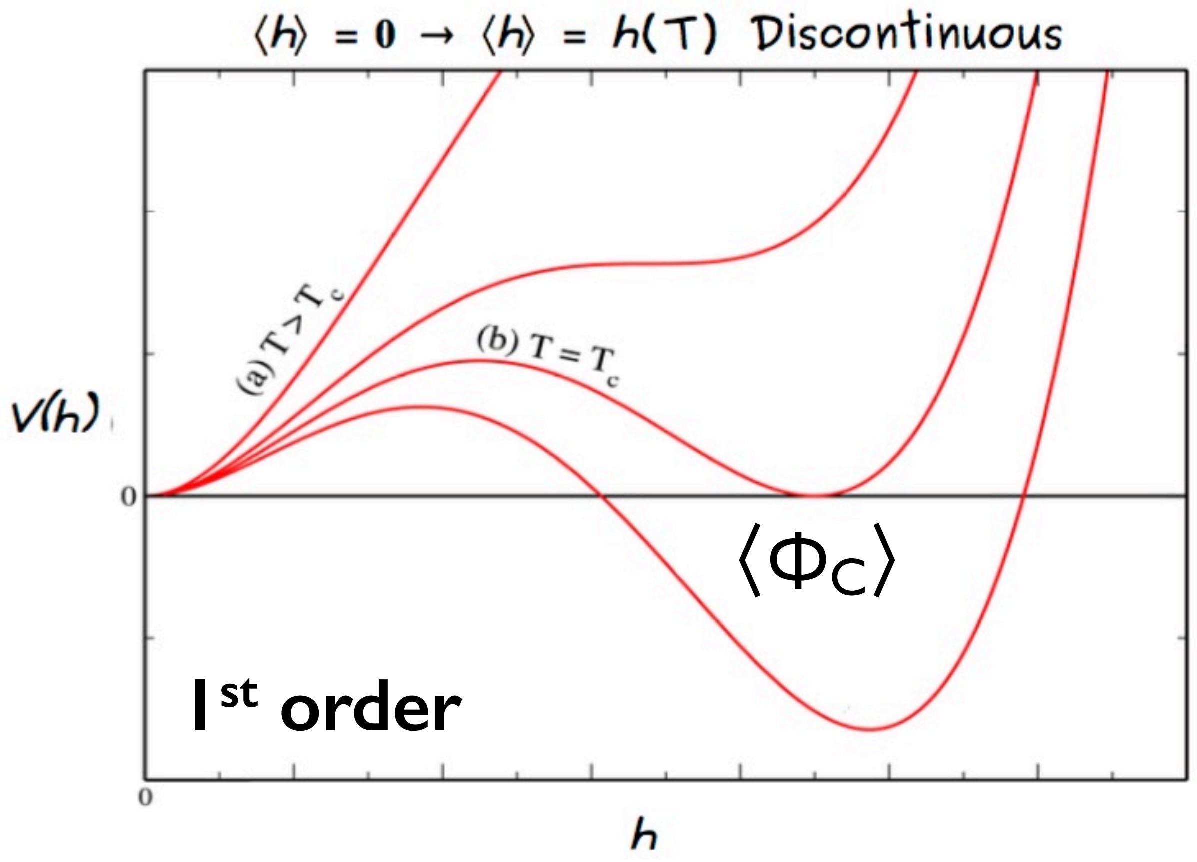
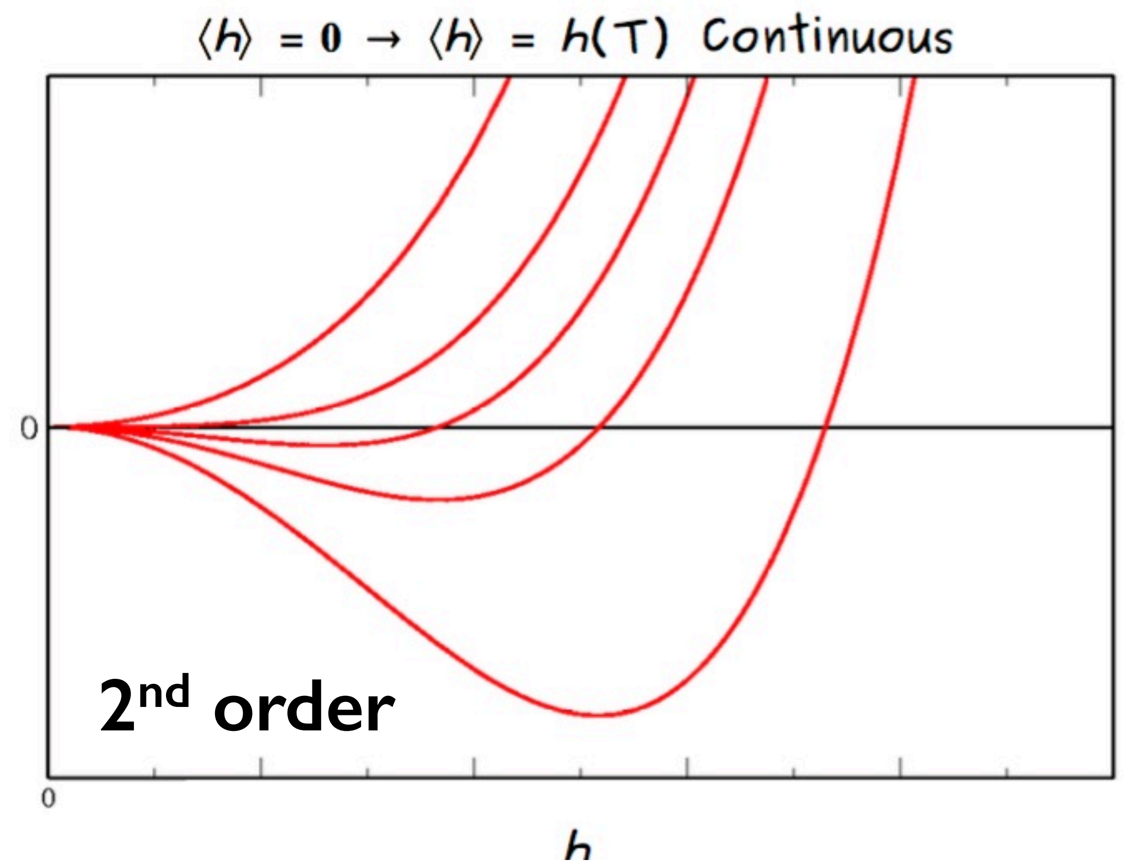




Not an issue of concern for the human race…. but the closeness of mtop to the critical value where the Higgs selfcoupling becomes 0 at M_{Planck} (namely 171.3 GeV) might be telling us something fundamental about the origin of EWSB … incidentally, y_{top}=1 (?!)

The nature of the EW phase transition





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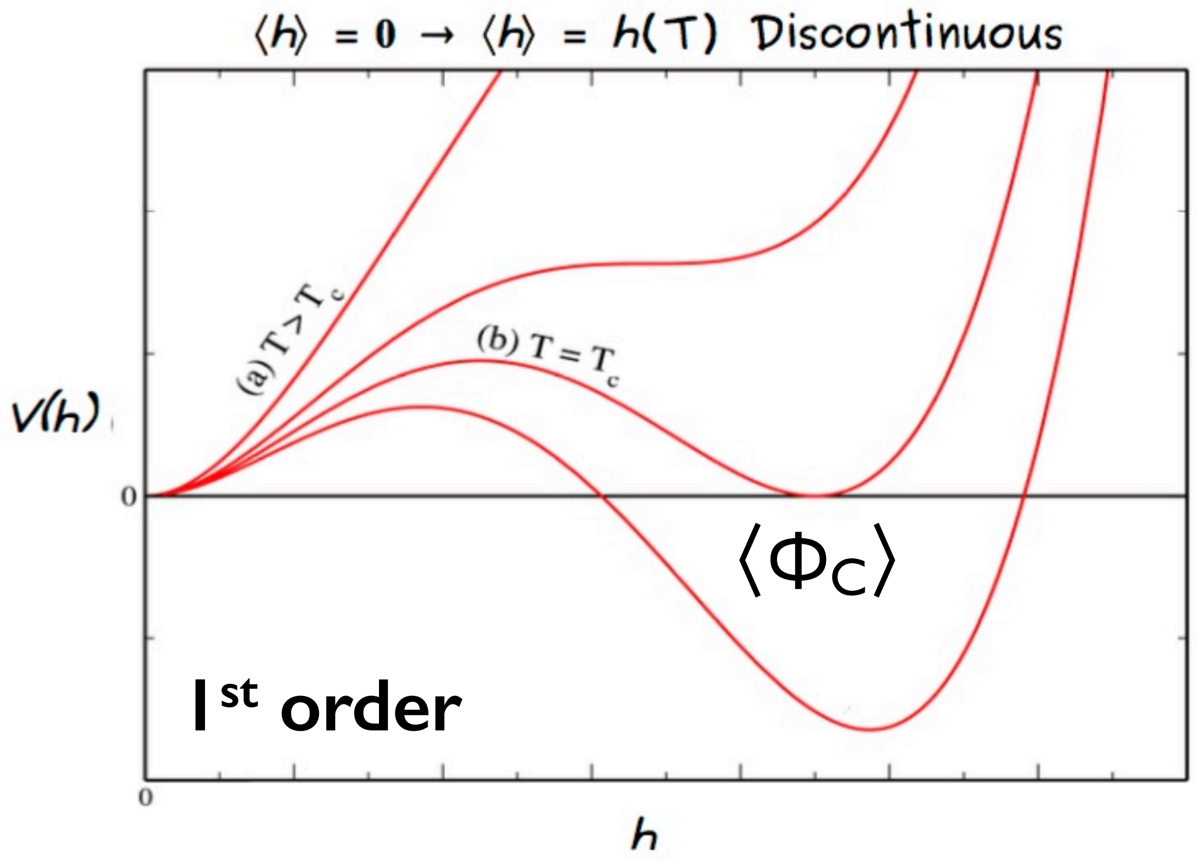

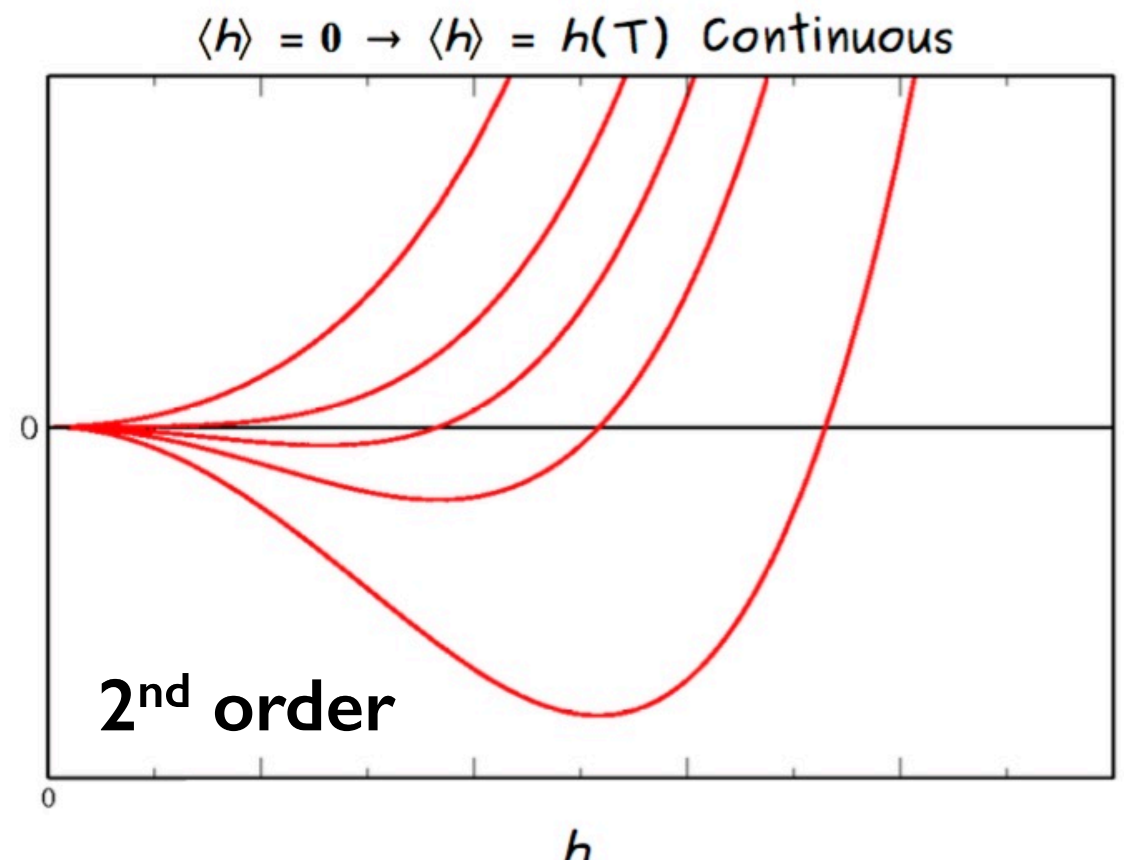

Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

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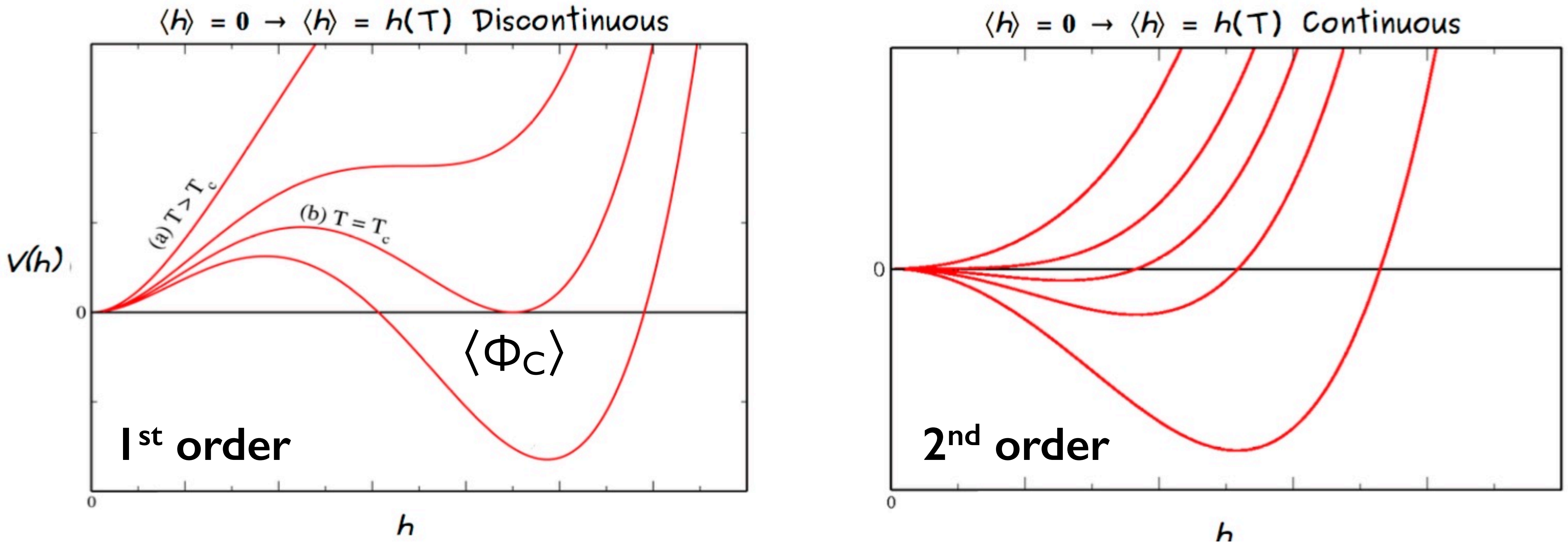

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In the SM this requires $m_H \lesssim 80$ GeV, else transition is a smooth crossover.

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

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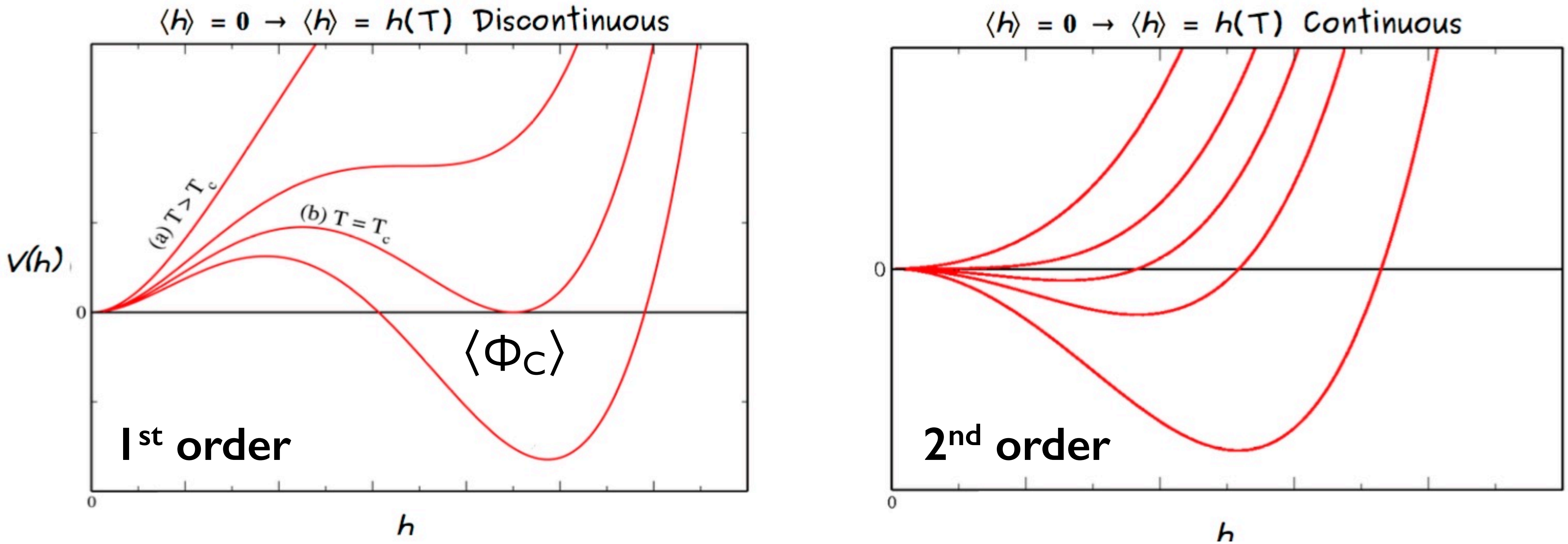

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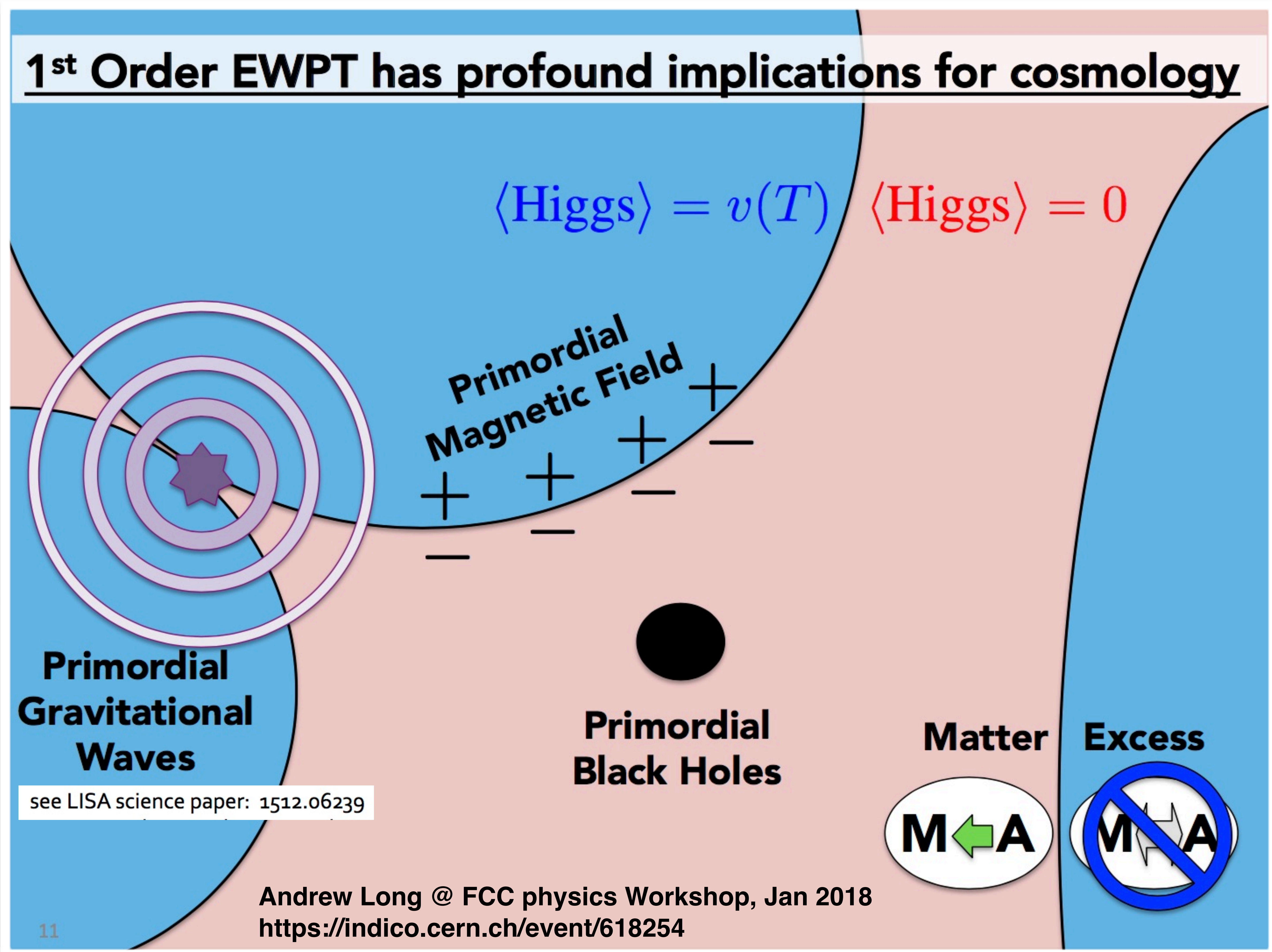
- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**


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
11
Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254

<u>Key question for the future developments of HEP:</u>

Why don't we see the new physics we expected to be present around the TeV scale ?

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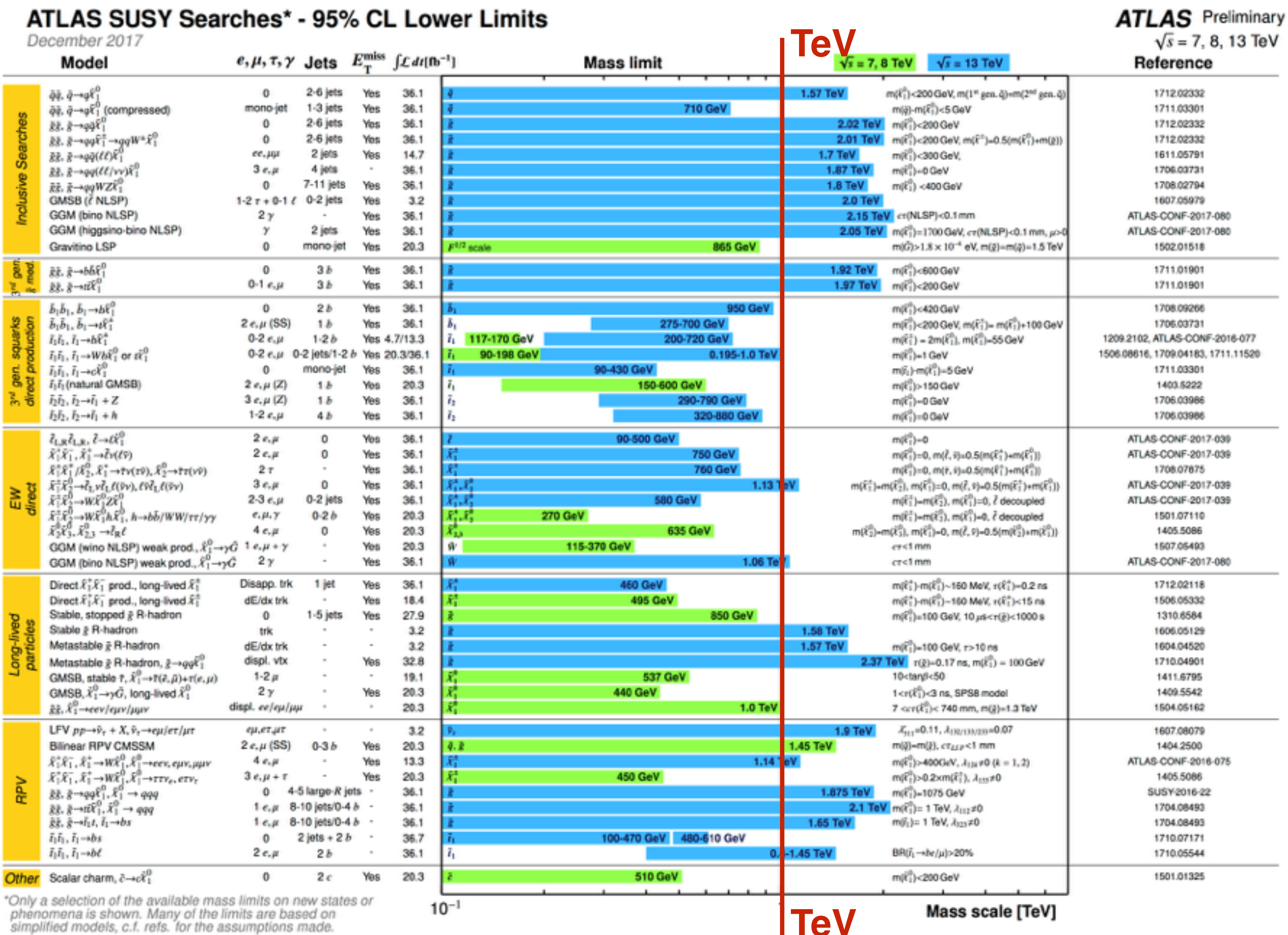
So far, no *conclusive* signal of physics beyond the SM



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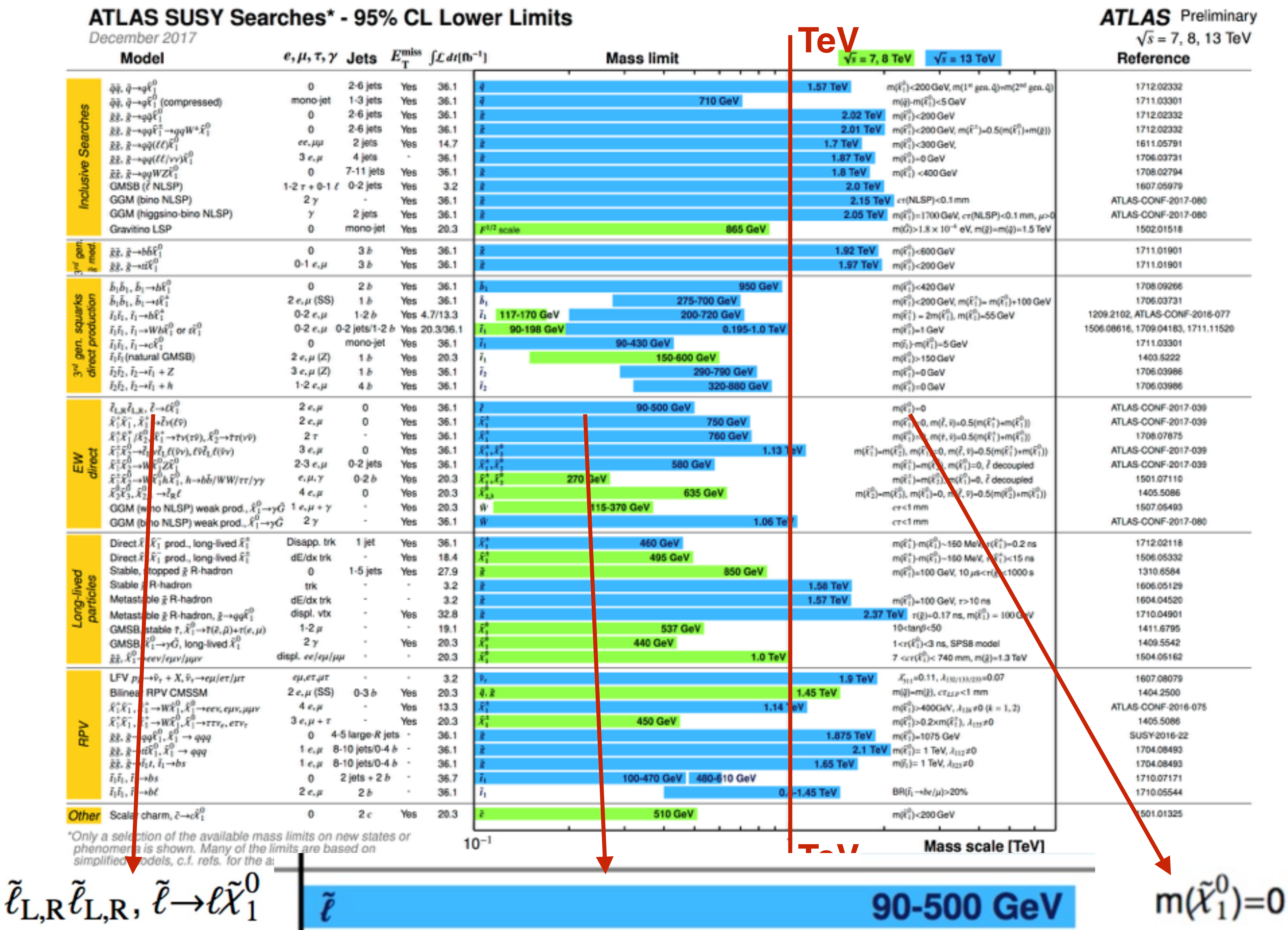
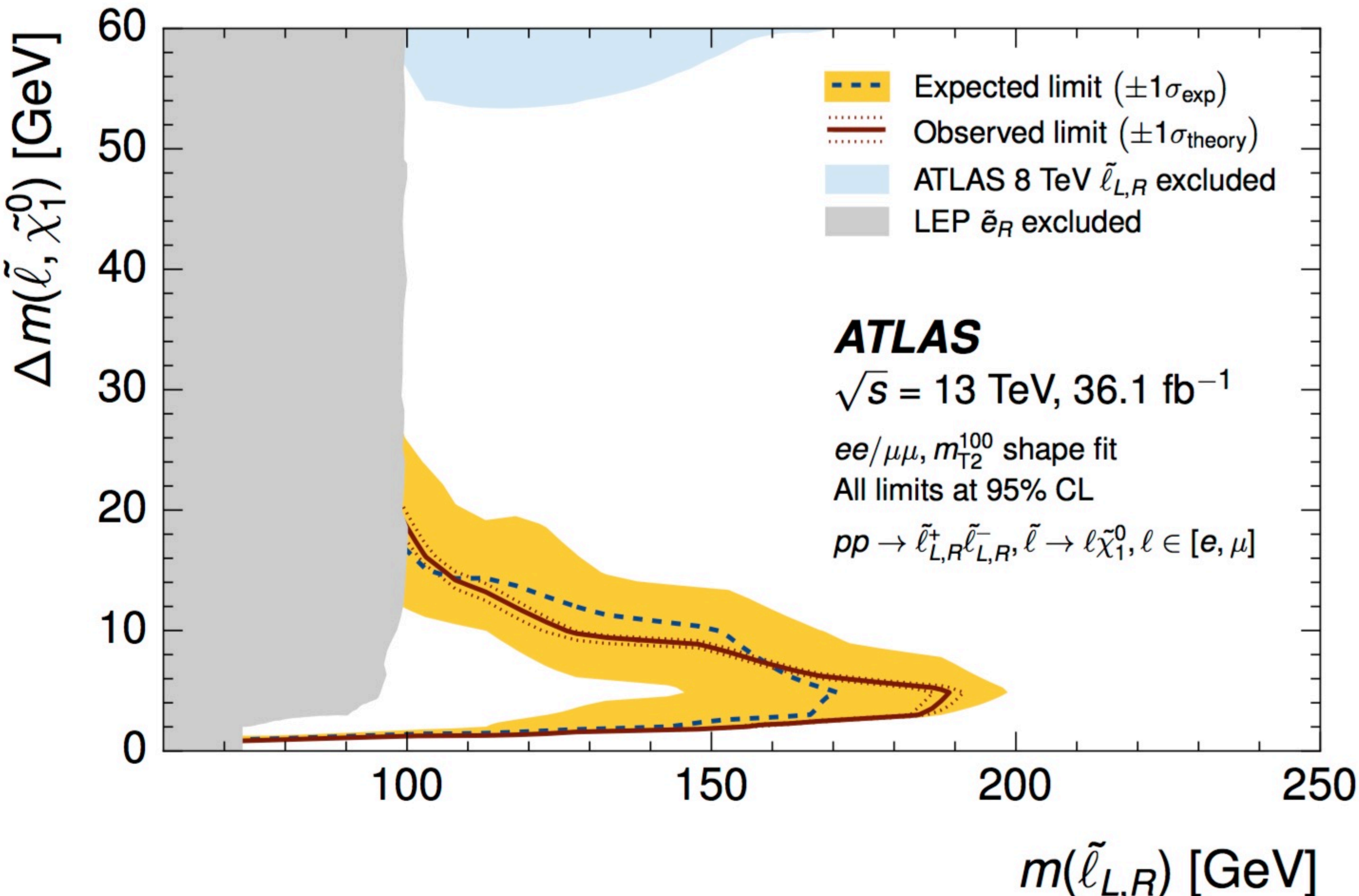


relaxing the $m(\chi^0)=0$ constraint …

… LHC has barely improved LEP2 limits …



=> in principle there is still room for discoveries well below the TeV scale

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

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

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

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

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(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

Dark Matter

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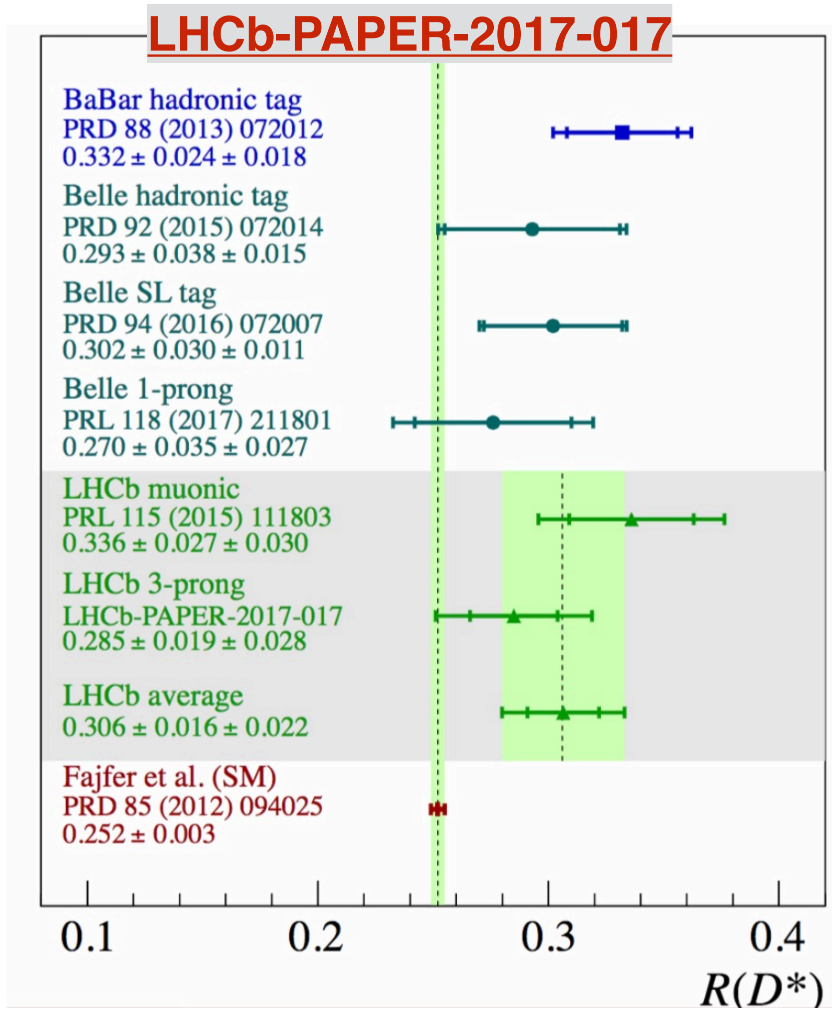
- More in general, no experiment can guarantee an answer to the question "what is DM?"
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- **We would like to understand whether a future collider can answer more specific questions, such as:**
  - do WIMPS contribute 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, ...)?

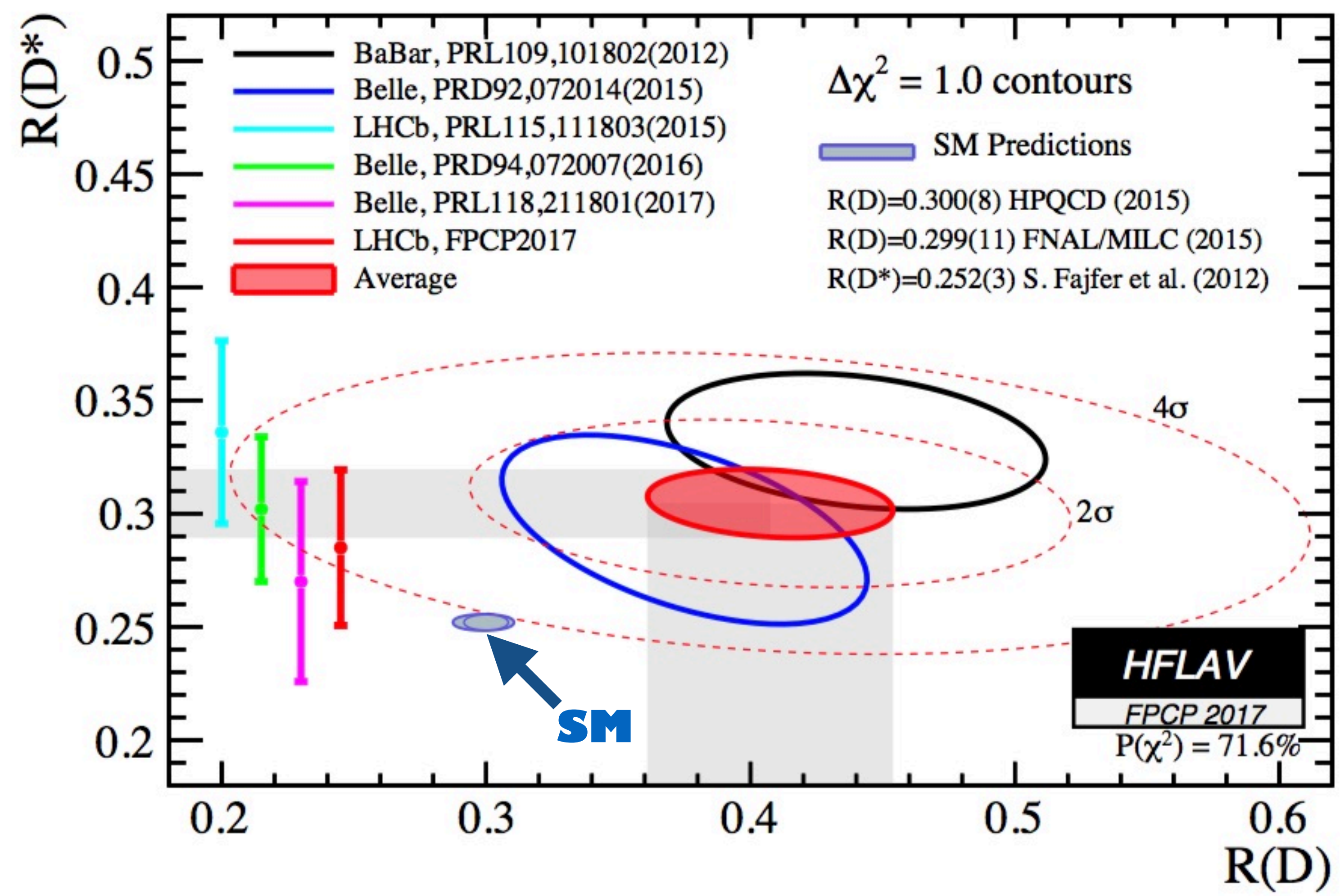
Flavour anomalies at LHC & Bfact's

$b \to c \ell \nu$

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$$



Overall combination of R(D) and R(D*) is 4.1σ from SM



$b \to s \ell \ell$

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

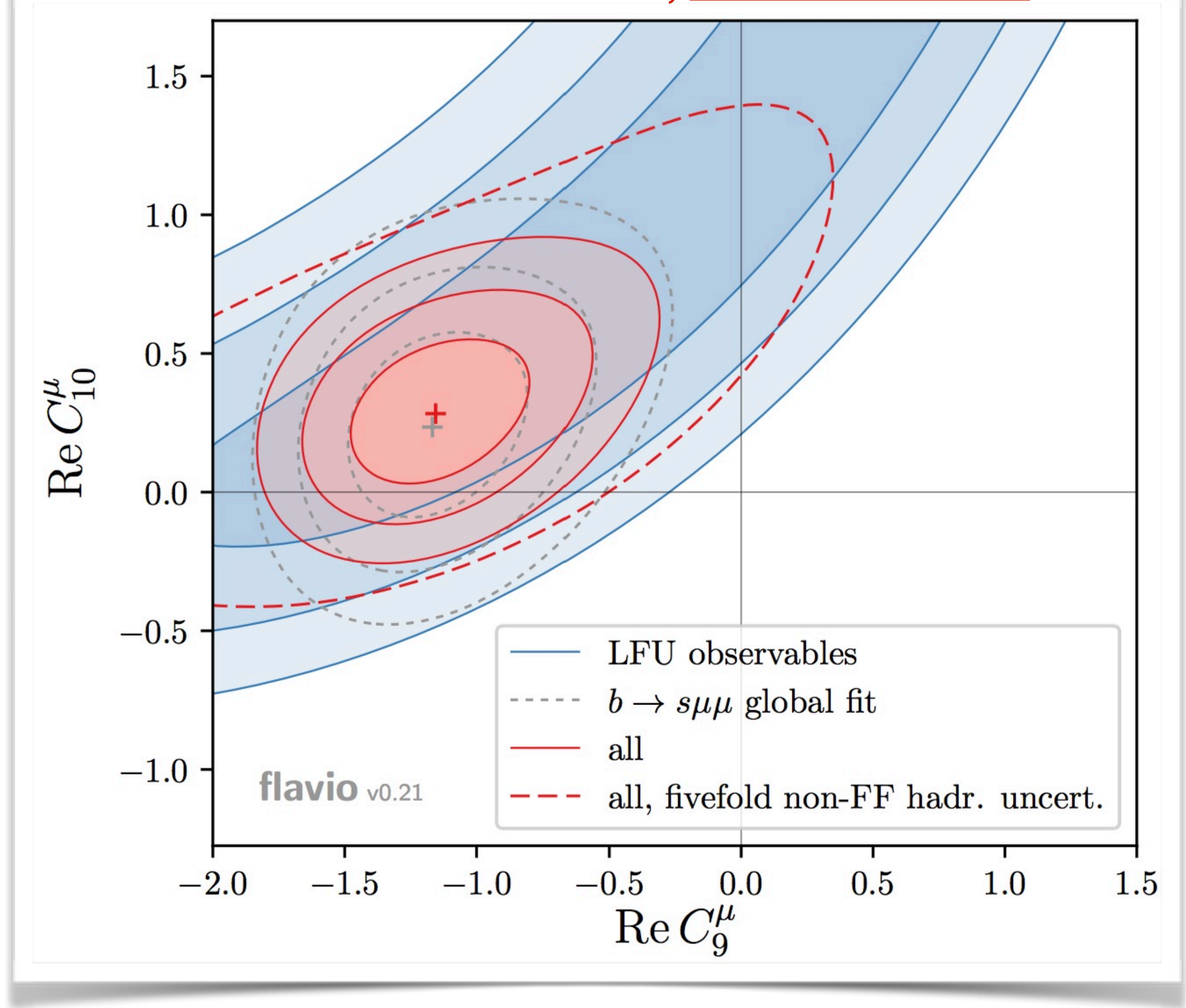
m_{ll} [mass range]	SM	Exp.
$R_K^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$

LHCb, PRL 113 (2014) 151601 , arXiv:1705.05802

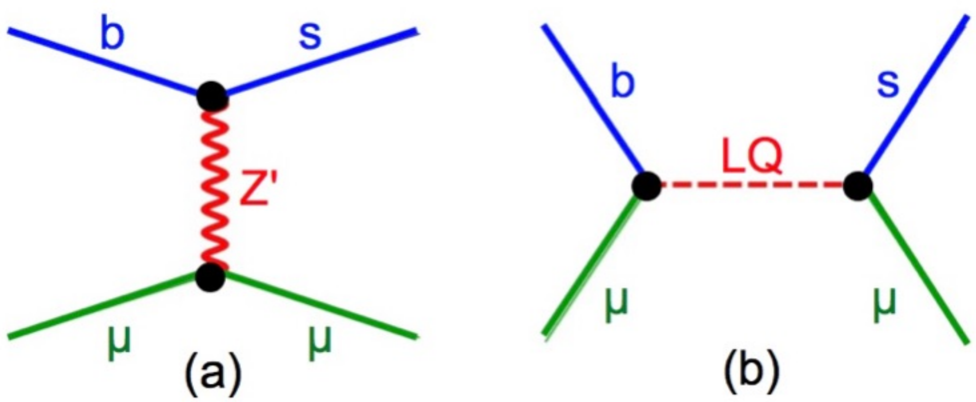
Example of EFT interpretation of R_K

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

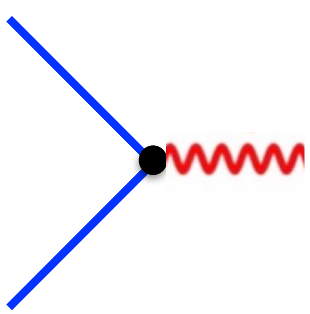
Altmannshoffer et al, arxiv:1704.05435



Possible explicit realizations:

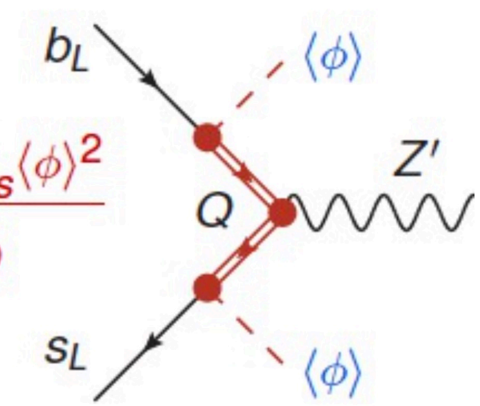


where, e.g. ,



⇒

$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2m_Q^2}$$



Upper limits on Z' and Leptoquark masses are model-dependent, and constrained also by other low-energy flavour phenomenology, but typically lie in the range of 1→O(10) TeV

⇒ if anomalies confirmed, we may want a no-lose theorem to identify the next facility!

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much to be inspired by in the forthcoming lectures of this School!