Future circular colliders

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Lect 1,2

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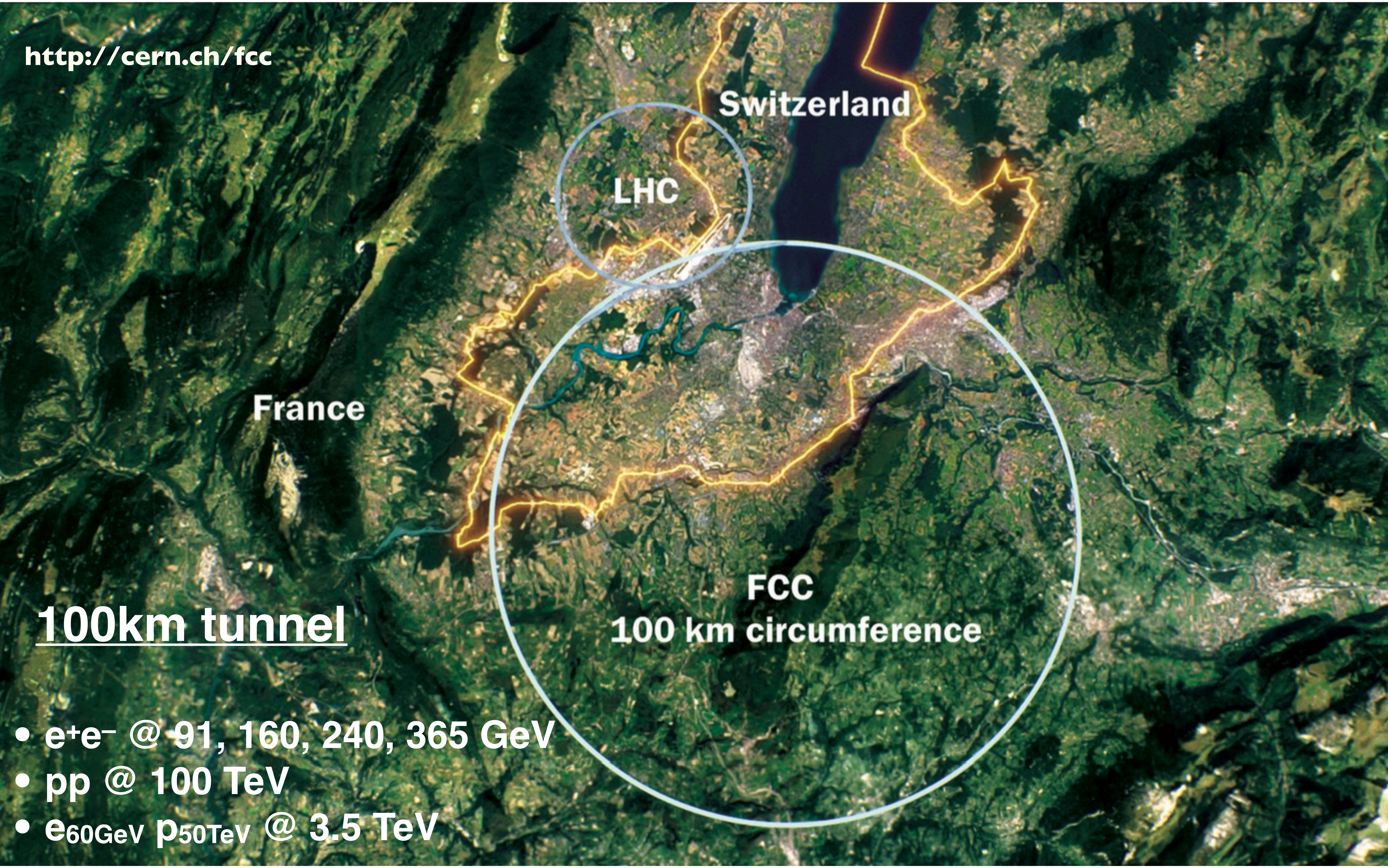
Future Circular Collider



http://cern.ch/fcc

100km tunnel

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

Plan

- **Today**:
  - Setting the landscape: lecture 1 & 2 merged, 1:15’ + 15’ discussion
- **Tomorrow**
  - Concrete examples of the FCC physics potential: lecture 3 & 4 merged, 1:15’ + 15’ discussion

- Will avoid direct comparisons between FCC and other planned facilities
- As requested by conveners, lecture-style presentation
- Ask questions anytime
- slides are on indico

References

- FCC Physics Opportunities, Eur.Phys.J. C79 (2019) no.6, 474
- FCC-ee: Your Questions Answered, arXiv:1906.02693
- FCC-ee Conceptual Design Report, Eur.Phys.J.ST 228 (2019) no.2, 261-623
- FCC-hh CDR, Eur.Phys.J.ST 228 (2019) no.4, 755-1107
- Physics at the FCC-hh, a 100 TeV pp collider, arXiv:1710.06353

- European Strategy, Preparatory Group documents:
    - Higgs Boson Studies at Future Particle Colliders, arXiv:1905.03764
    - Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020, arXiv:1910.11775

Why a bigger collider?
Why circular?

The next steps in HEP build on

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

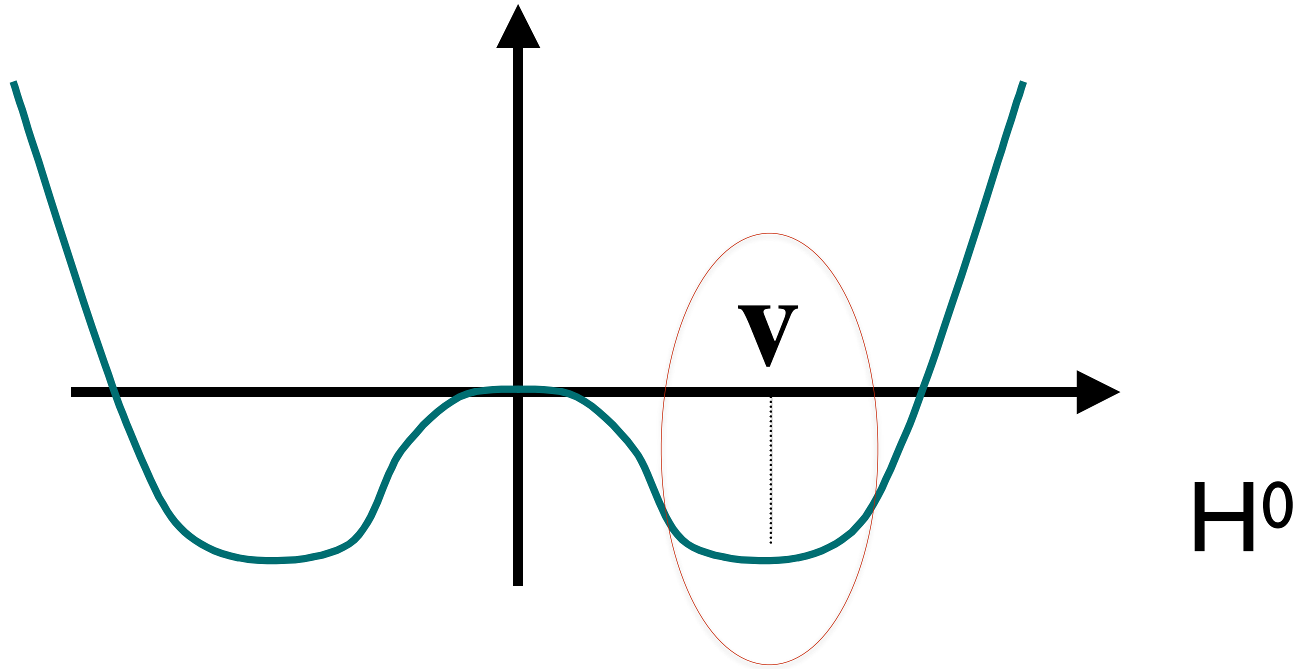
The important questions

- **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)
  - Quantum gravity
  - Origin of inflation
  - …

The opportunities

- For none of these 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….



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

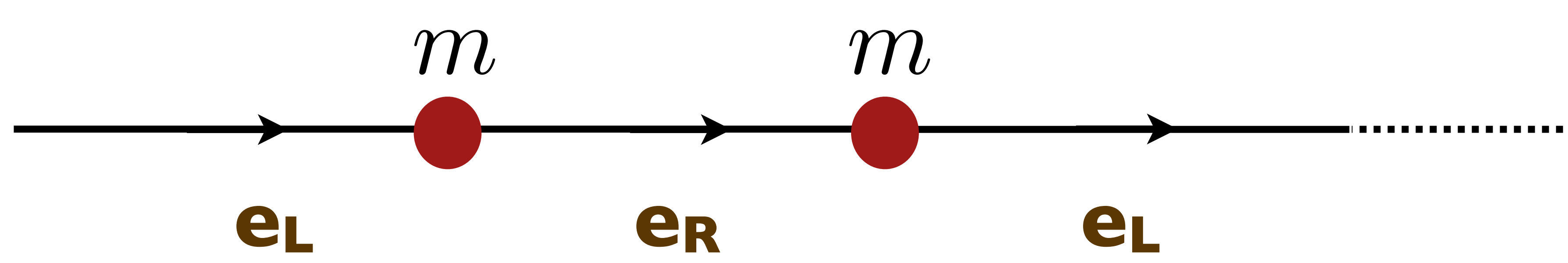
Who ordered that ?

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

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

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

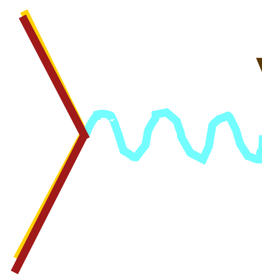


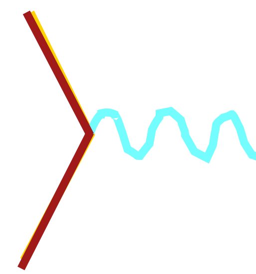
For a massive particle, chirality does not commute with the Hamiltonian, so it cannot be conserved

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

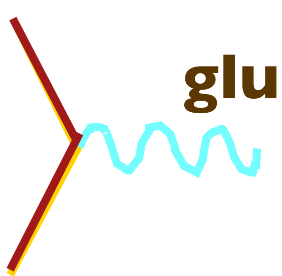
Nothing wrong with that in principle .... unless chirality is associated to a conserved charge!

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





SU(3)



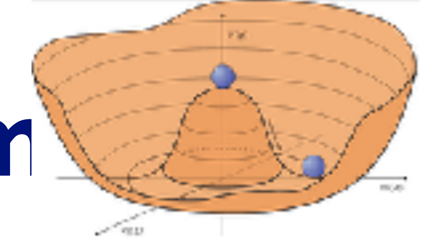
L-chirality	R-chirality
$\begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix}_L^{i=1,2,3}$	$u^i{}_R$, $d^i{}_R$
$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$	$e^-{}_R$

+ 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

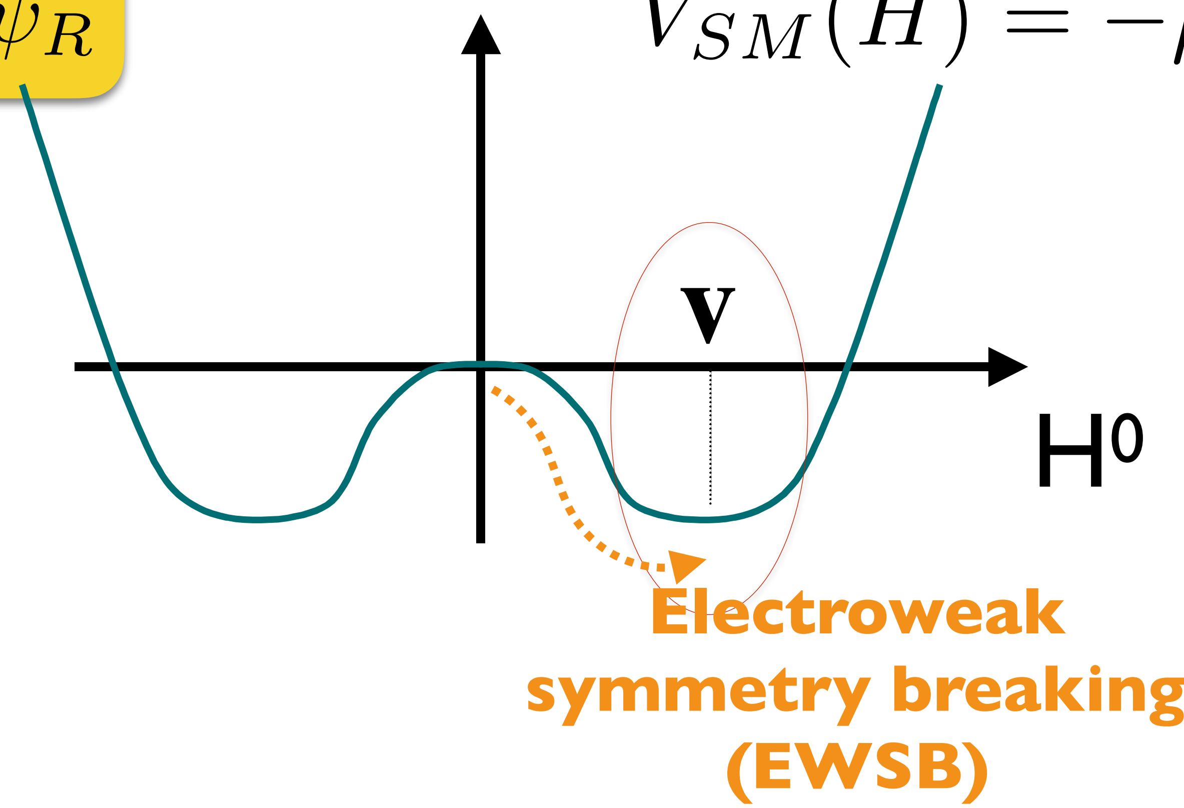
The SM solution: Higgs mechanism

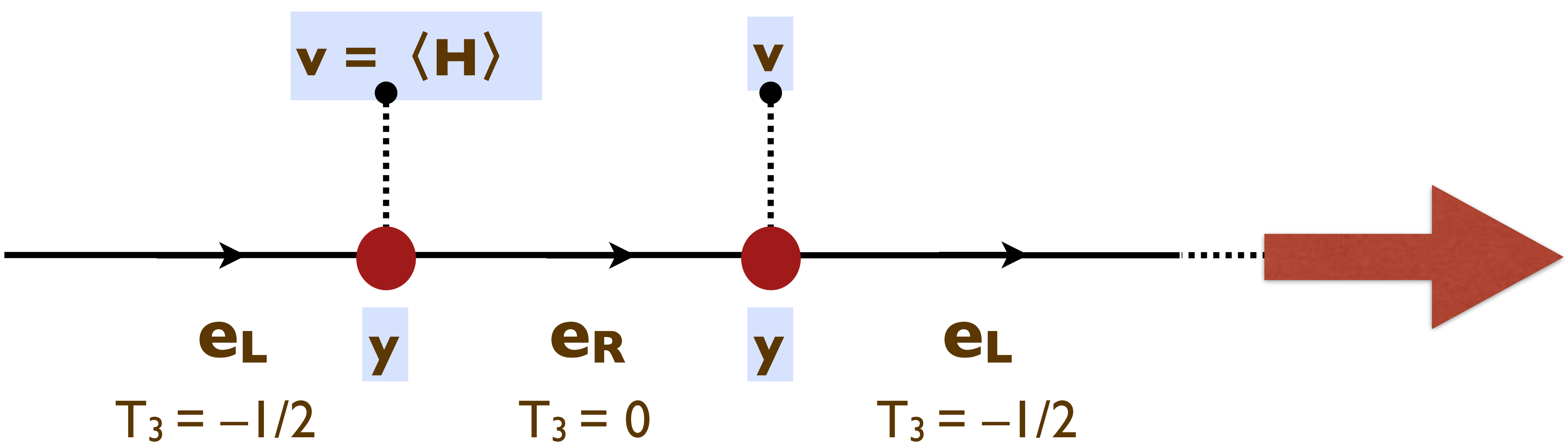


$$m\,\overline{\psi_L}\,\psi_R \rightarrow \lambda H\,\overline{\psi_L}\,\psi_R$$

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

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





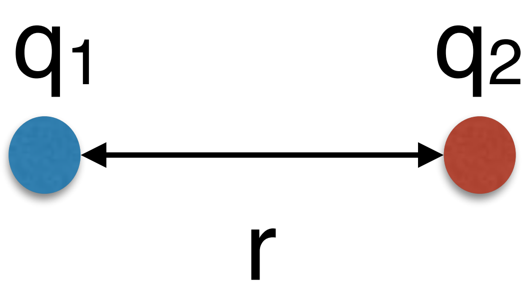
m = y v

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.

The SM Higgs mechanism provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us ...

Electromagnetic vs Higgs dynamics

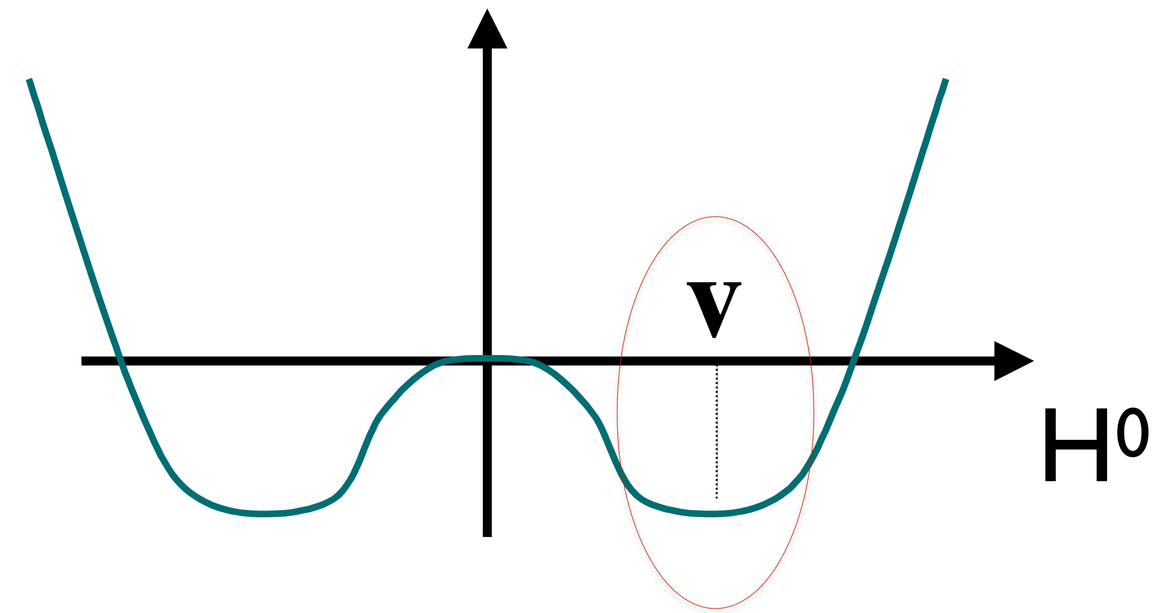


quantized,
in units of
fixed charge

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

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 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.**

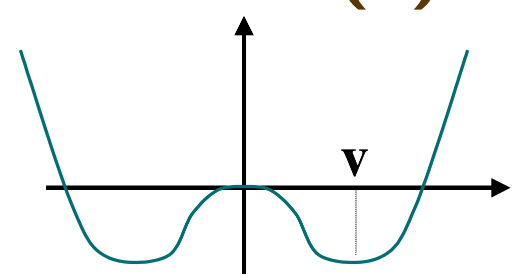
examples of possible scenarios

- **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**:

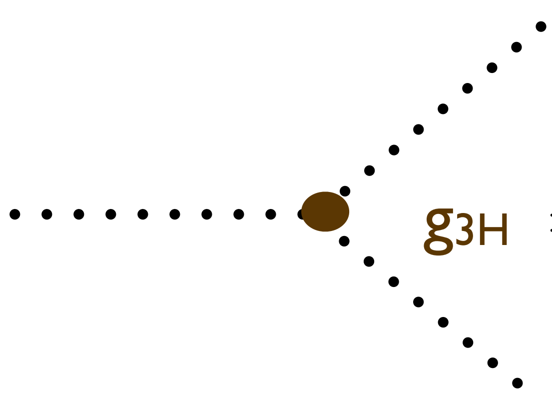
$$V_{SM}(H) = -\mu^2\,|H|^2 + \lambda\,|H|^4$$



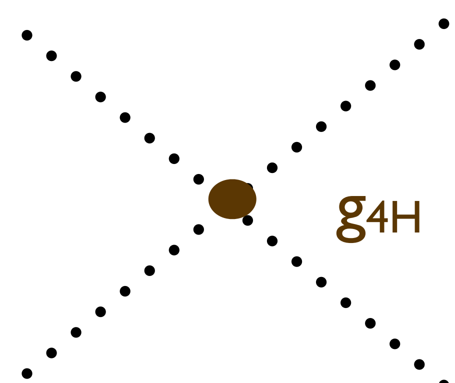
$$v = (\sqrt{2}G_F)^{-1/2} \sim 246 \text{ GeV}$$

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

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



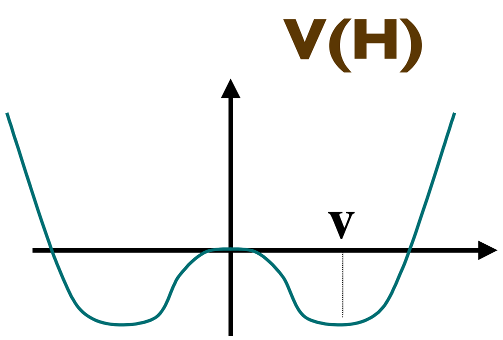
$g_{3H} \Rightarrow 4\lambda v = \boxed{\dfrac{2m_H^2}{v}}$



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

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

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

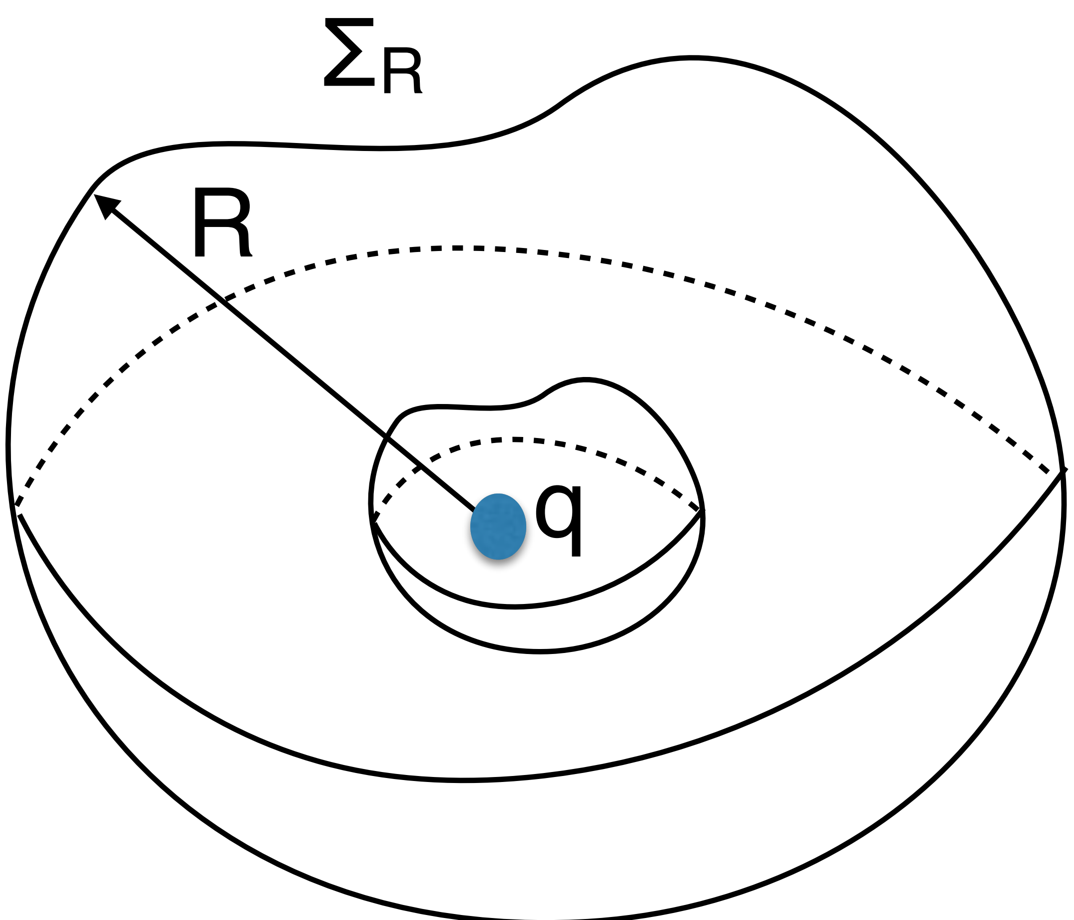
If n=6, the Higgs self-coupling is modified by a factor of 5/3 wrt the SM relation. This is a big effect!
(Notice however that the n=4 term will always be there, even if only induced by loop corrections or RG evolution of whatever higher-dimension term)

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

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

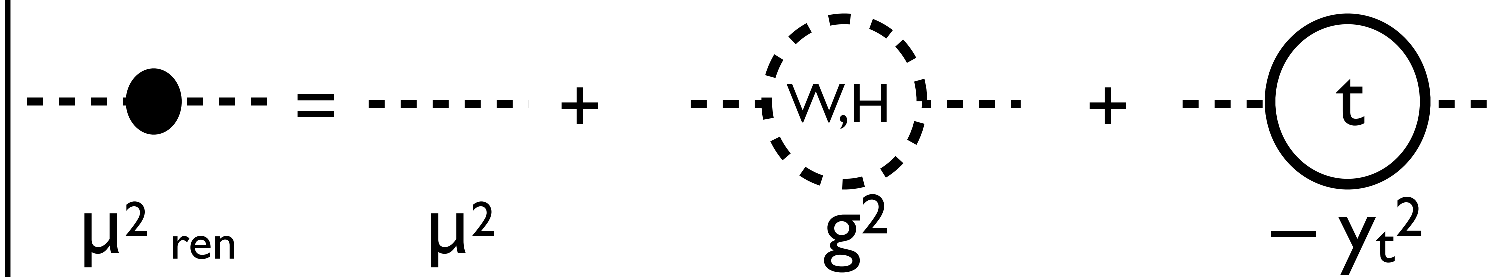
E&M



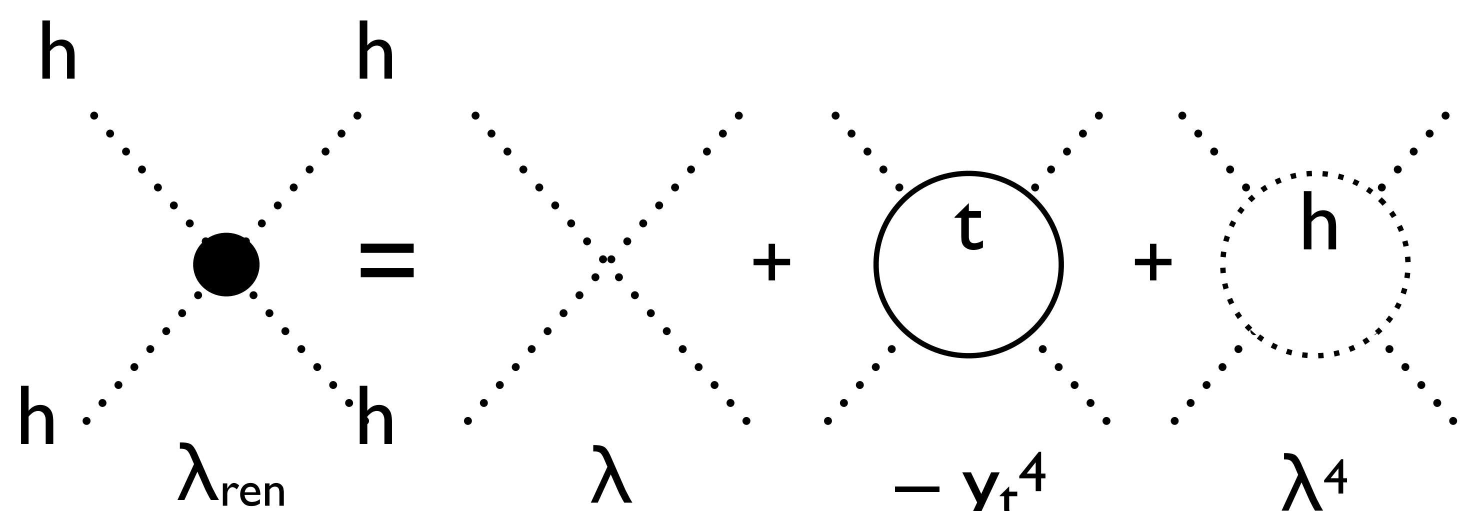
$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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**

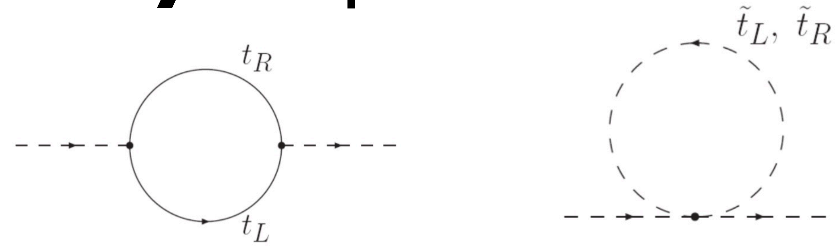
bottom line

- 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

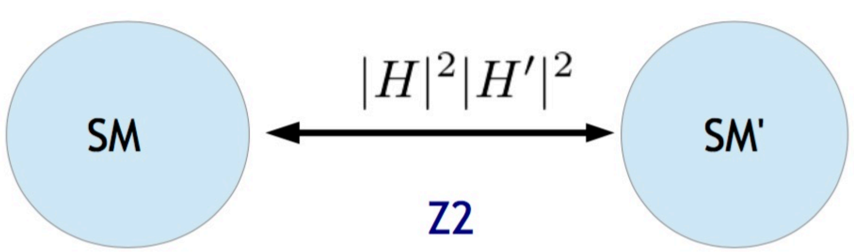
$\Rightarrow$ **naturalness**

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

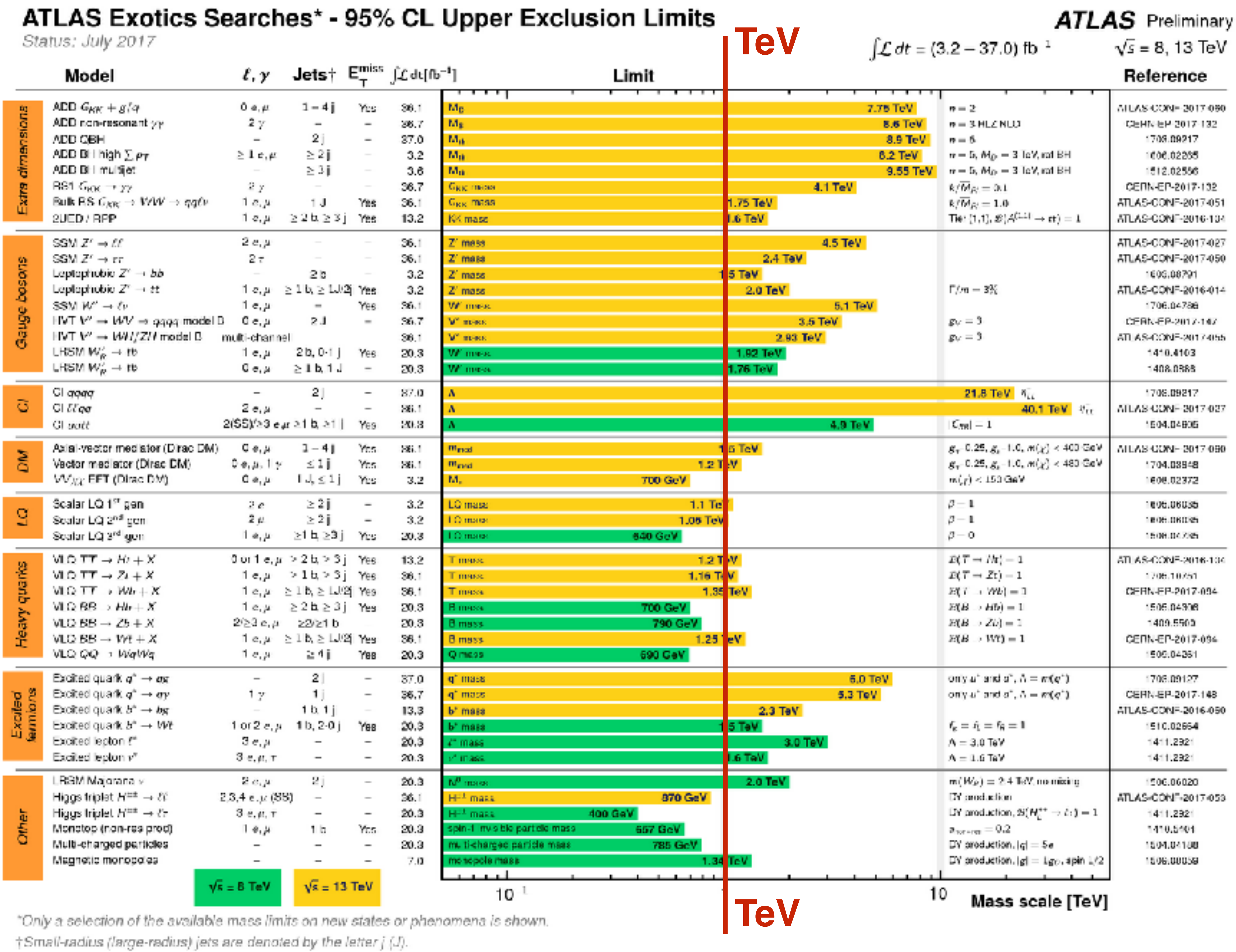
In search of the origin of known departures from the SM

- **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

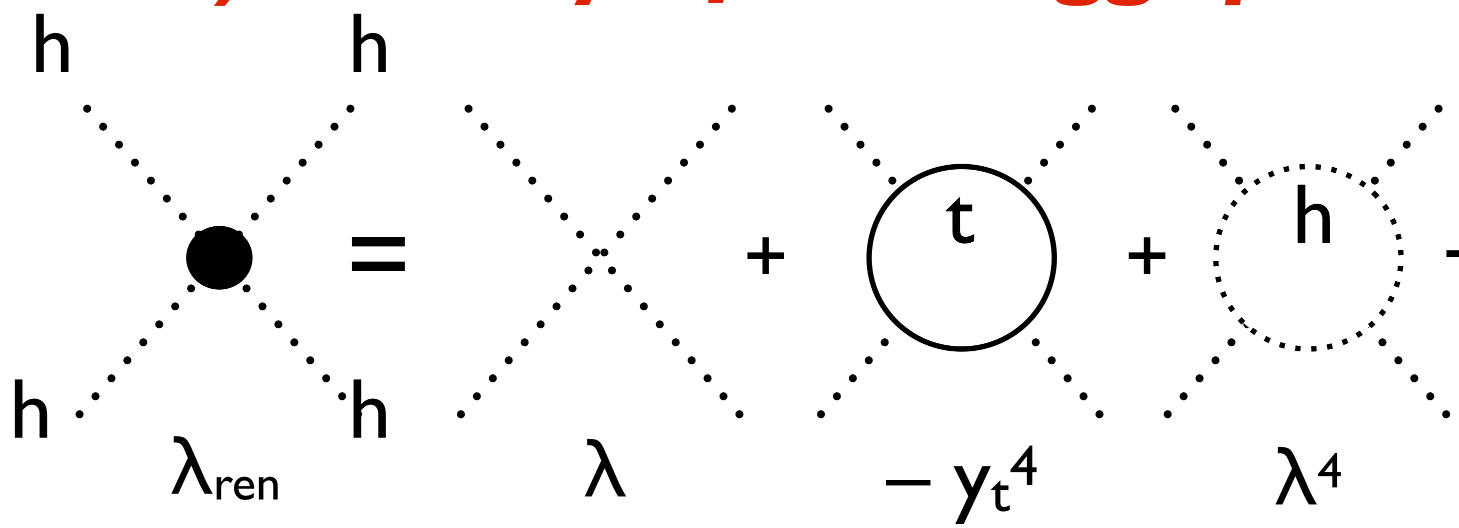
Other important open issues on the Higgs sector

- 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 **<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? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?

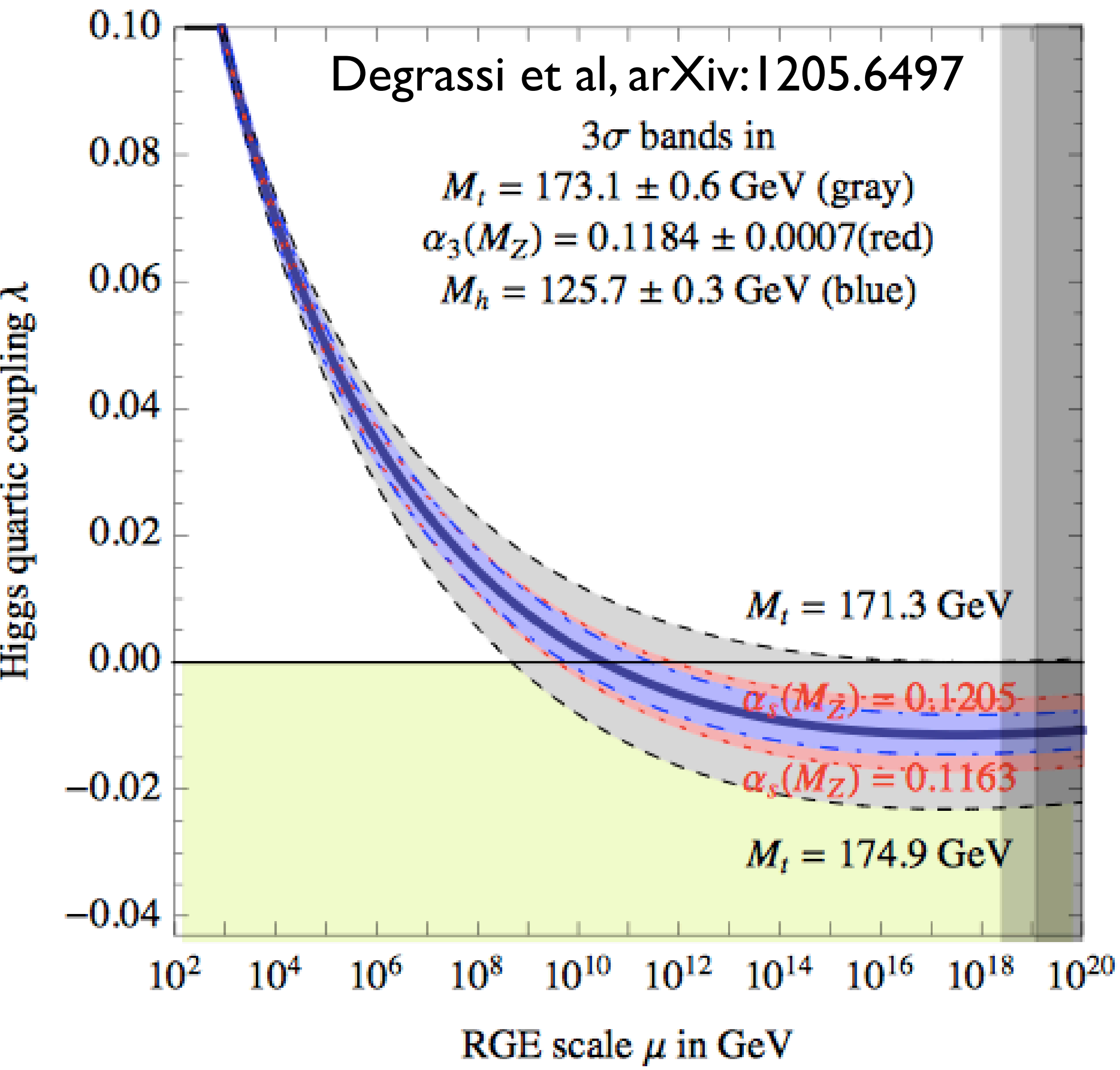
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

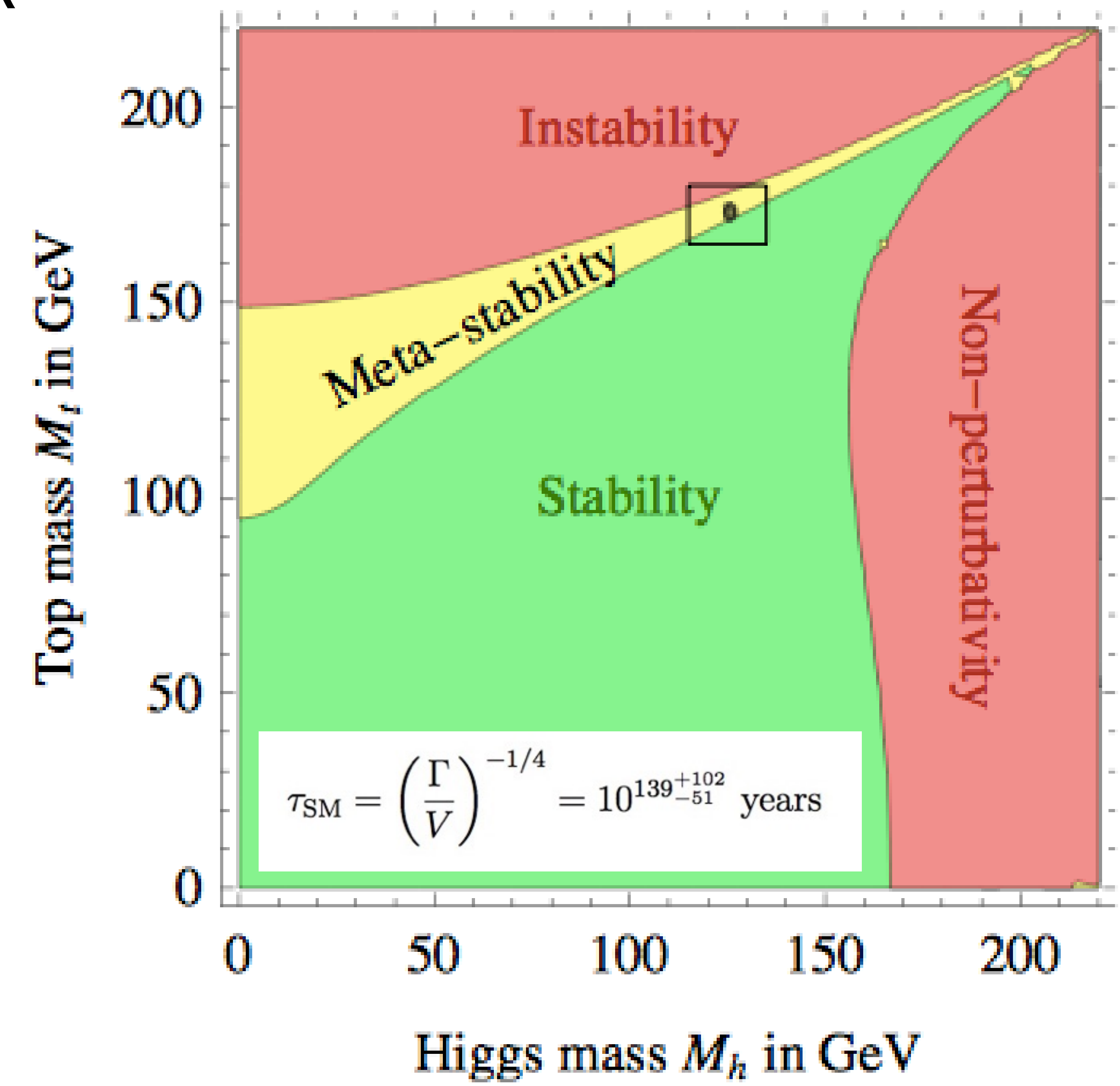
(meta)Stability of the Higgs potential

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 (?!)

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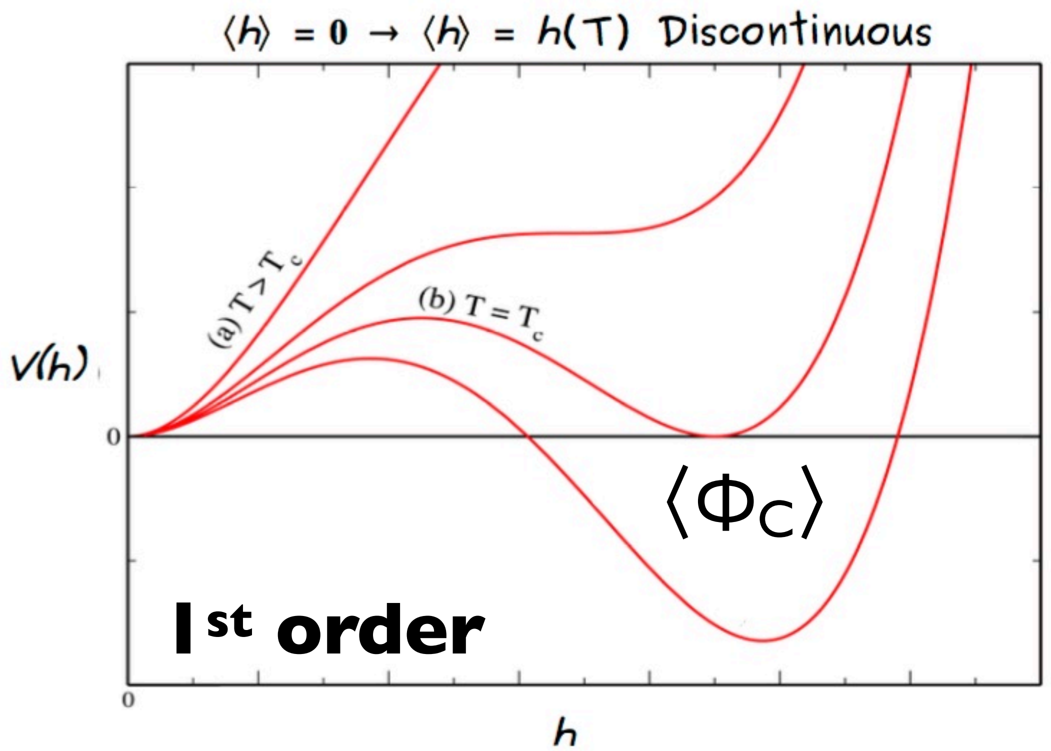
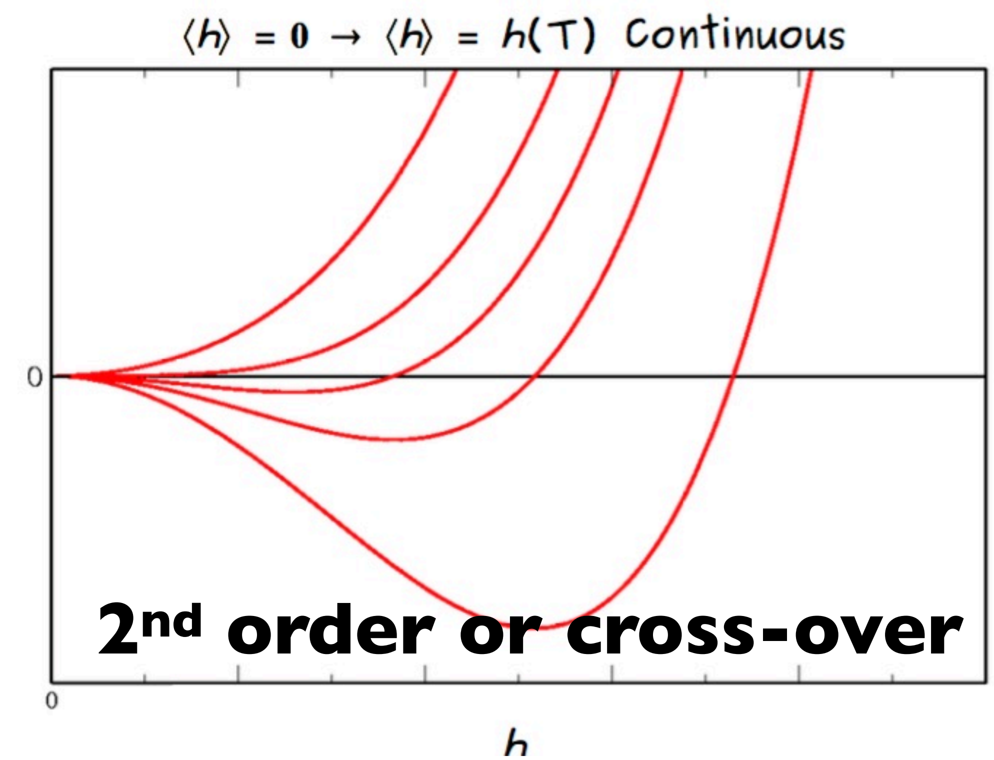
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

- 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





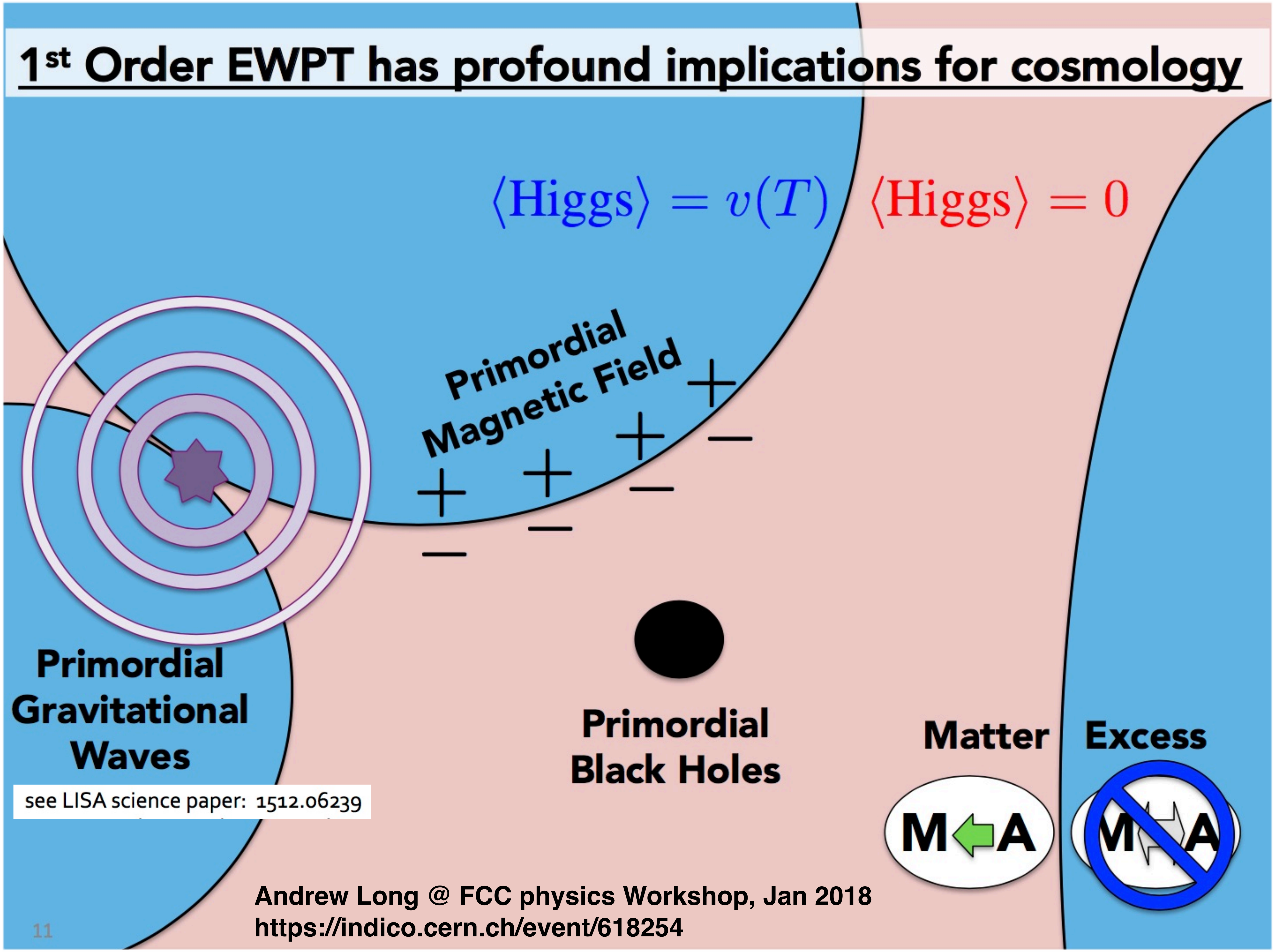
Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

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

- 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, ...) ?
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- 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 among Higgs/EWSB, baryogenesis, Dark Matter, inflation?

Key question for the future developments of HEP: 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:

- *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

The physics potential (the "case") of a future facility for HEP should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

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

What a future circular collider can offer

- 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
    - *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?
  - …

Table 2.1: Machine parameters of the FCC-ee for different beam energies.

		Z	WW	ZH	$\mathrm{t\bar{t}}$	
Circumference	[km]	97.756				
Bending radius	[km]	10.760				
Free length to IP ℓ^*	[m]	2.2				
Solenoid field at IP	[T]	2.0				
Full crossing angle at IP θ	[mrad]	30				
SR power / beam	[MW]	50				
Beam energy	[GeV]	45.6	80	120	175	182.5
Beam current	[mA]	1390	147	29	6.4	5.4
Bunches / beam		16640	2000	328	59	48
Average bunch spacing	[ns]	19.6	163	994	2763[a]	3396[??]
Bunch population	[10^{11}]	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x	[nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y	[pm]	1.0	1.7	1.3	2.7	2.9
Arc cell phase advances	[deg]	60/60		90/90		
Momentum compaction α_p	[10^{-6}]	14.8		7.3		
Arc sextupole families		208		292		
Horizontal β^*_x	[m]	0.15	0.2	0.3	1.0	
Vertical β^*_y	[mm]	0.8	1.0	1.0	1.6	
Horizontal size at IP σ^*_x	[µm]	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ^*_y	[nm]	28	41	36	66	68
Energy spread (SR/BS) σ_δ	[%]	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.186	0.150/0.192
Bunch length (SR/BS) σ_z	[mm]	3.5/12.1	3.0/6.0	3.15/5.3	2.01/2.62	1.97/2.54
Piwinski angle (SR/BS) ϕ		8.2/28.5	3.5/7.0	3.4/5.8	0.8/1.1	0.8/1.0
Length of interaction area L_i	[mm]	0.42	0.85	0.90	1.8	1.8
Hourglass factor R_{HG}		0.95	0.89	0.88	0.84	0.84
Crab sextupole strength[b]	[%]	97	87	80	40	40
Energy loss / turn	[GeV]	0.036	0.34	1.72	7.8	9.2
RF frequency	[MHz]	400			400 / 800	
RF voltage	[GV]	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Synchrotron tune Q_s		0.0250	0.0506	0.0358	0.0818	0.0872
Longitudinal damping time	[turns]	1273	236	70.3	23.1	20.4
RF bucket height	[%]	1.9	3.5	2.3	3.36	3.36
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.4	
Polarisation time t_p	[min]	15000	900	120	18.0	14.6
Luminosity / IP	[10^{34}/cm^{2}s]	230	28	8.5	1.8	1.55
Horizontal tune Q_x		269.139	269.124	389.129	389.108	
Vertical tune Q_y		269.219	269.199	389.199	389.175	
Beam-beam ξ_x/ξ_y		0.004/0.133	0.010/0.113	0.016/0.118	0.097/0.128	0.099/0.126
Allowable e^+e^- charge asymmetry	[%]	±5	±3			
Lifetime by rad. Bhabha scattering	[min]	68	59	38	40	39
Actual lifetime due to beamstrahlung	[min]	>200	>200	18	24	18

FCC-ee run plan

phase	Run duration (yrs)	$\sqrt{s}$ (GeV)	L_{int} (ab^{-1})	Event stats
ee→Z	4	88-95	150	3×10^{12} had Z decays
ee→WW	2	158-192	12	3×10^{8} WW
ee→ZH	3	240	5	10^{6} ZH
machine modification for RF installation and rearrangement: 1 year				
ee→tt	5	345-365	1.5	10^{6} tt + 4×10^{4} Hνν
ee→H	(3)	(125)	(21)	(H resonance)

Total programme duration: 14 years (including machine modifications)
plus optional 3years @ H resonance

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

Goal: 20-30 ab^{-1} during the collider lifetime

FCC-he & HE-LHC-ep parameters

parameter	FCC-he	ep at HE-LHC	ep at HL-LHC	LHeC
E_p [TeV]	50	12.5	7	7
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	**3.5**	**1.7**	1.3	1.3
bunch spacing [ns]	25	25	25	25
protons / bunch [10^{11}]	1	2.5	2.2	1.7
$\gamma\varepsilon_p$ [μm]	2.2	2.5	2.0	3.75
electrons / bunch [10^9]	2.3	2.3	2.3	1.0
electron current [mA]	15	15	15	6.4
IP beta function β_p* [m]	15	10	7	10
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
proton-ring filling factor	0.8	0.8	0.8	0.8
luminosity [10^{33} cm^{-2}s^{-1}]	**11**	**9**	8	1.3

Event rates: examples

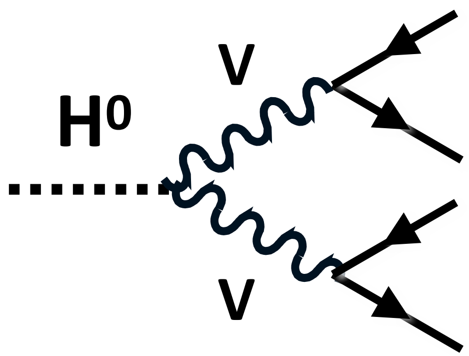
FCC-ee	H	Z	W	t	τ(←Z)	b(←Z)	c(←Z)
	10^6	5×10^{12}	10^8	10^6	3×10^{11}	1.5×10^{12}	10^{12}

FCC-hh	H	b	t	W(←t)	τ(←W←t)
	2.5×10^{10}	10^{17}	10^{12}	10^{12}	10^{11}

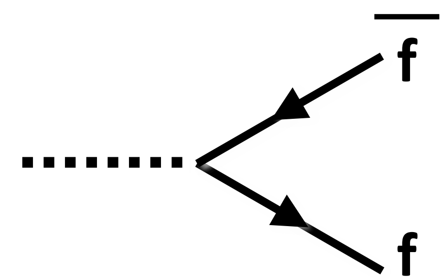
FCC-eh	H	t
	$2.5\ 10^6$	$2\ 10^7$

Higgs observables: decay BRs

Tree-level couplings



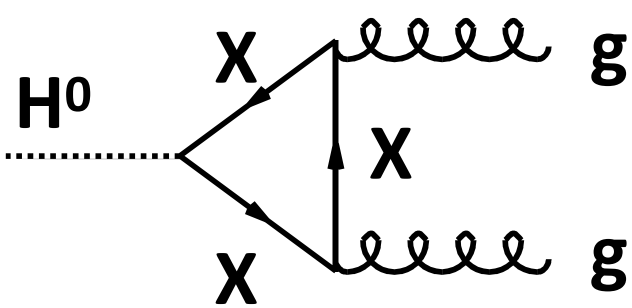
coupling to EW gauge bosons ⇒ g,g’



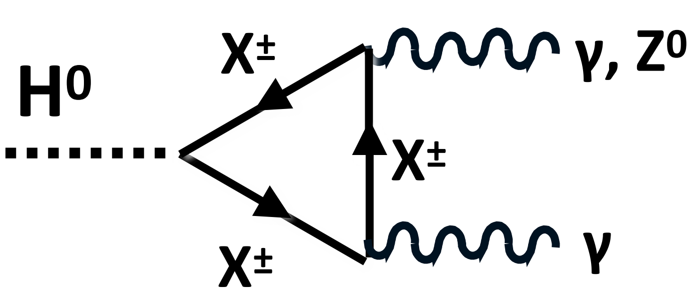
coupling to fermions
⇒ m_f / v

$m_f < m_H / 2$

Loop-level couplings



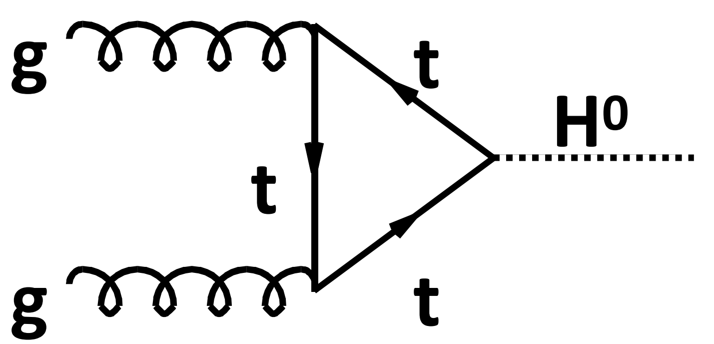
X_{SM} =t,b,c X_{BSM} = T, stop, …?

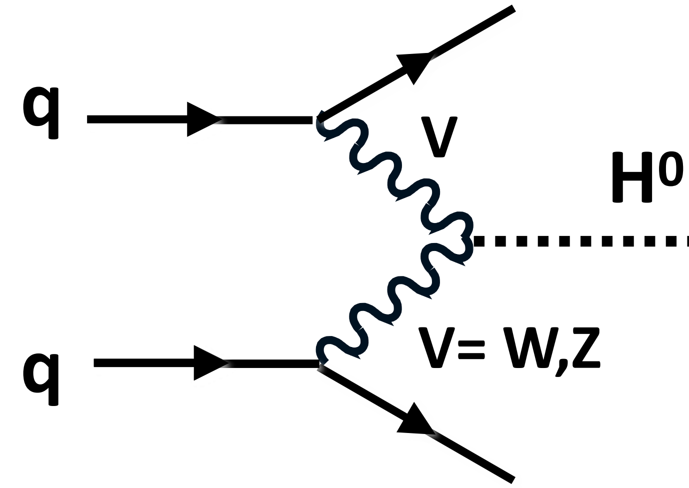


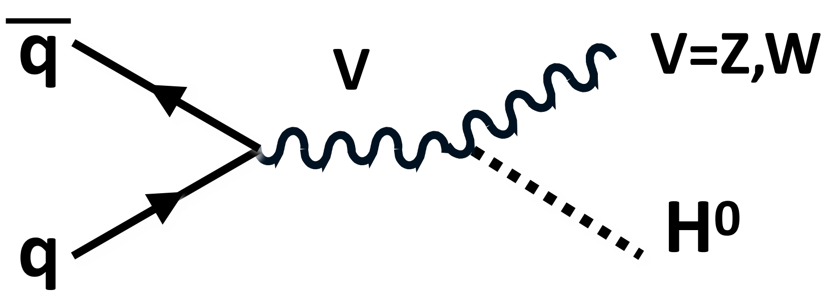
X_{SM} =t, $W^\pm$ X_{BSM} = T, stop, chargino, …?

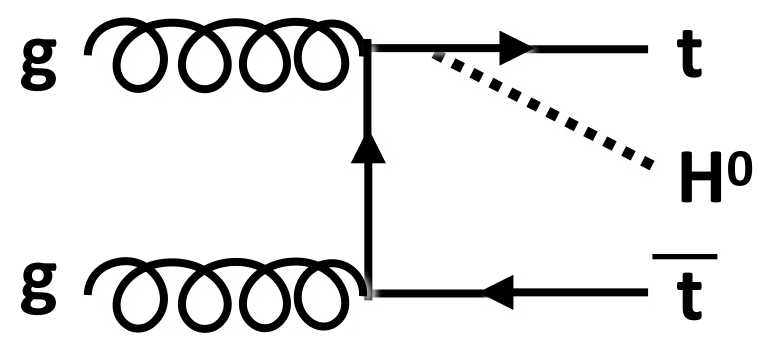
Higgs observables: production rates

Hadronic collisions

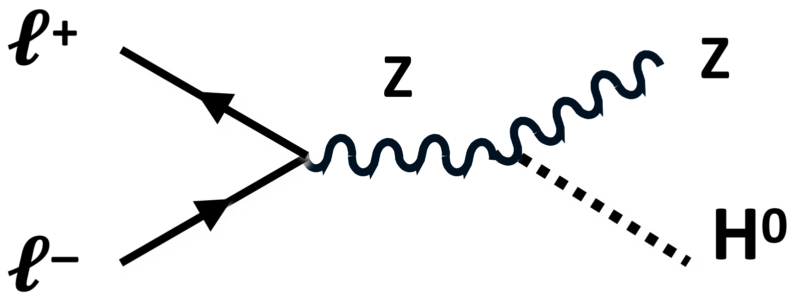


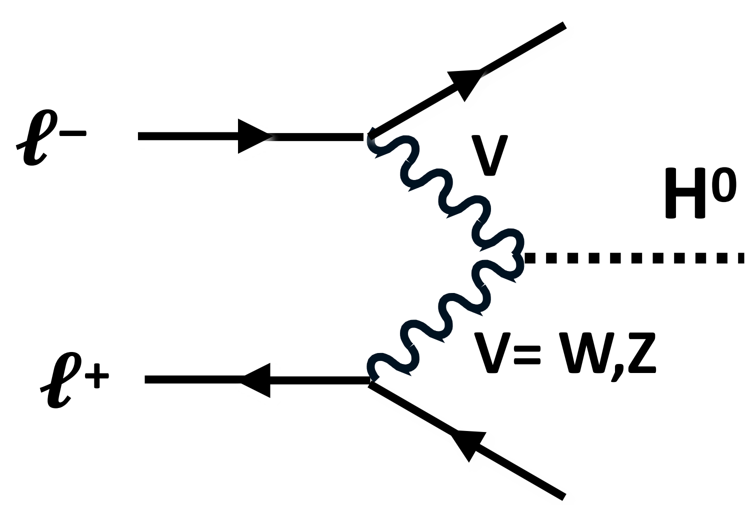


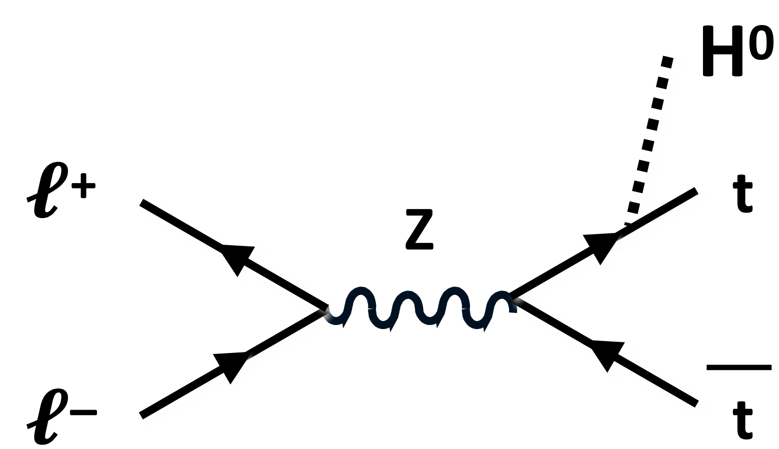




Laptonic collisions







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

arXiv:1310.8361

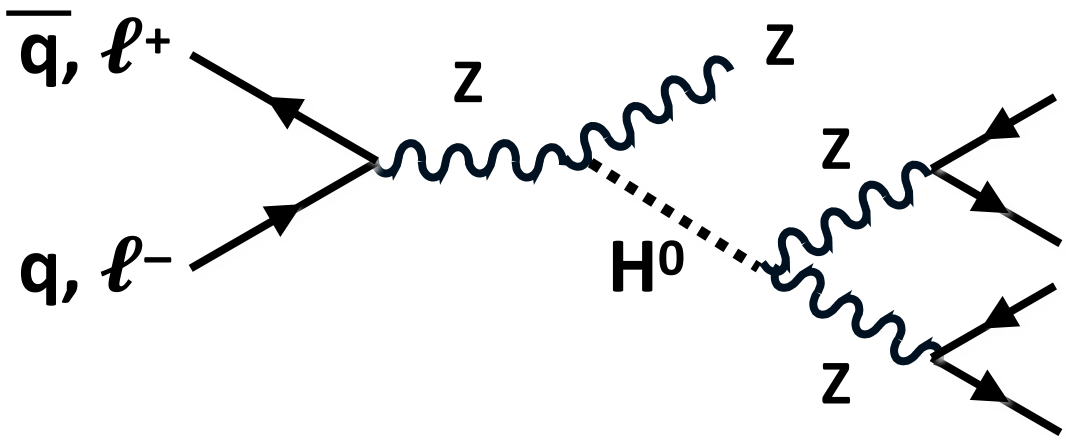
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

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

Extracting couplings from measurements

Example

(A)

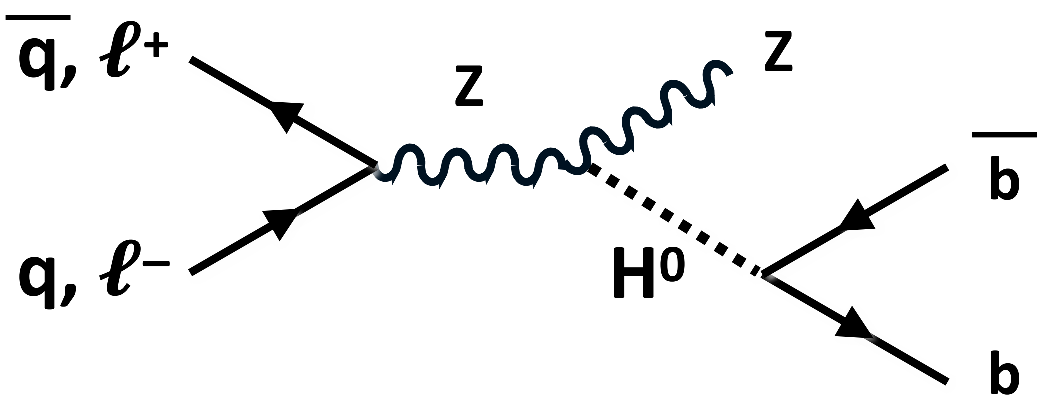


$$\sigma\left(pp/ee \to ZH[\to ZZ^*]\right) \propto g_{HZZ}^2 \times \boxed{\frac{g_{HZZ}^2}{\Gamma_H}}$$

1 measurement, 2 parameters!

$B(H \to ZZ^*)$

(B)



$$\sigma\left(pp/ee \to ZH[\to b\bar{b}]\right) \propto g_{HZZ}^2 \times \boxed{\frac{g_{Hbb}^2}{\Gamma_H}}$$

1 new measurement, but
1 more parameter…

$B(H \to b\bar{b})$

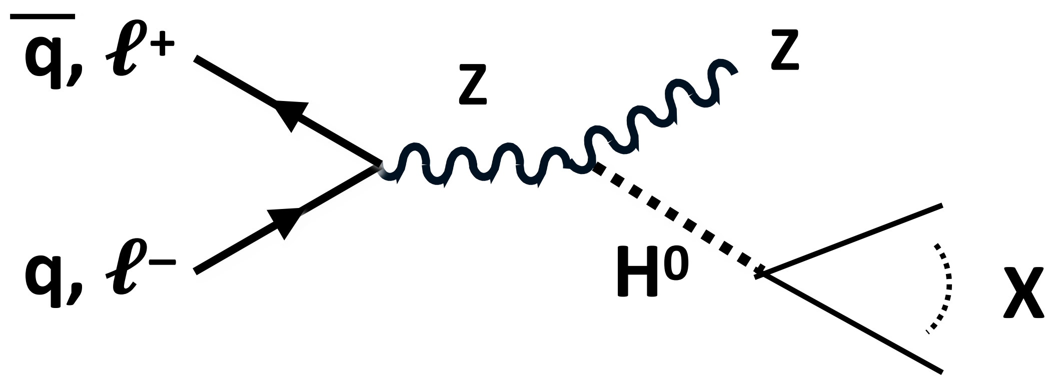
… little progress, except we now know

$$\frac{g_{HZZ}^2}{g_{Hbb}^2} = \frac{\sigma_A}{\sigma_B}$$

Overall constraint: $\sum_X B(H \to X) = 1$

Therefore:

$$\sum_X \sigma\Big($$

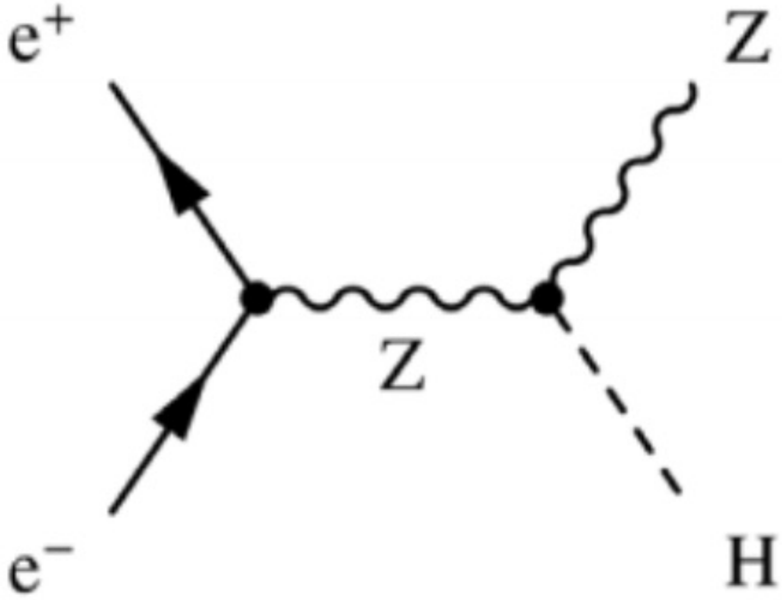


$$\Big) = \sigma(ZH) \propto g^2_{HZZ}$$

How can we hope to detect ALL possible decays of the Higgs boson??

If the goal is to test its properties, we cannot make assumptions, and must be open to possible unexpected decays, possibly invisible, like H→dark matter…

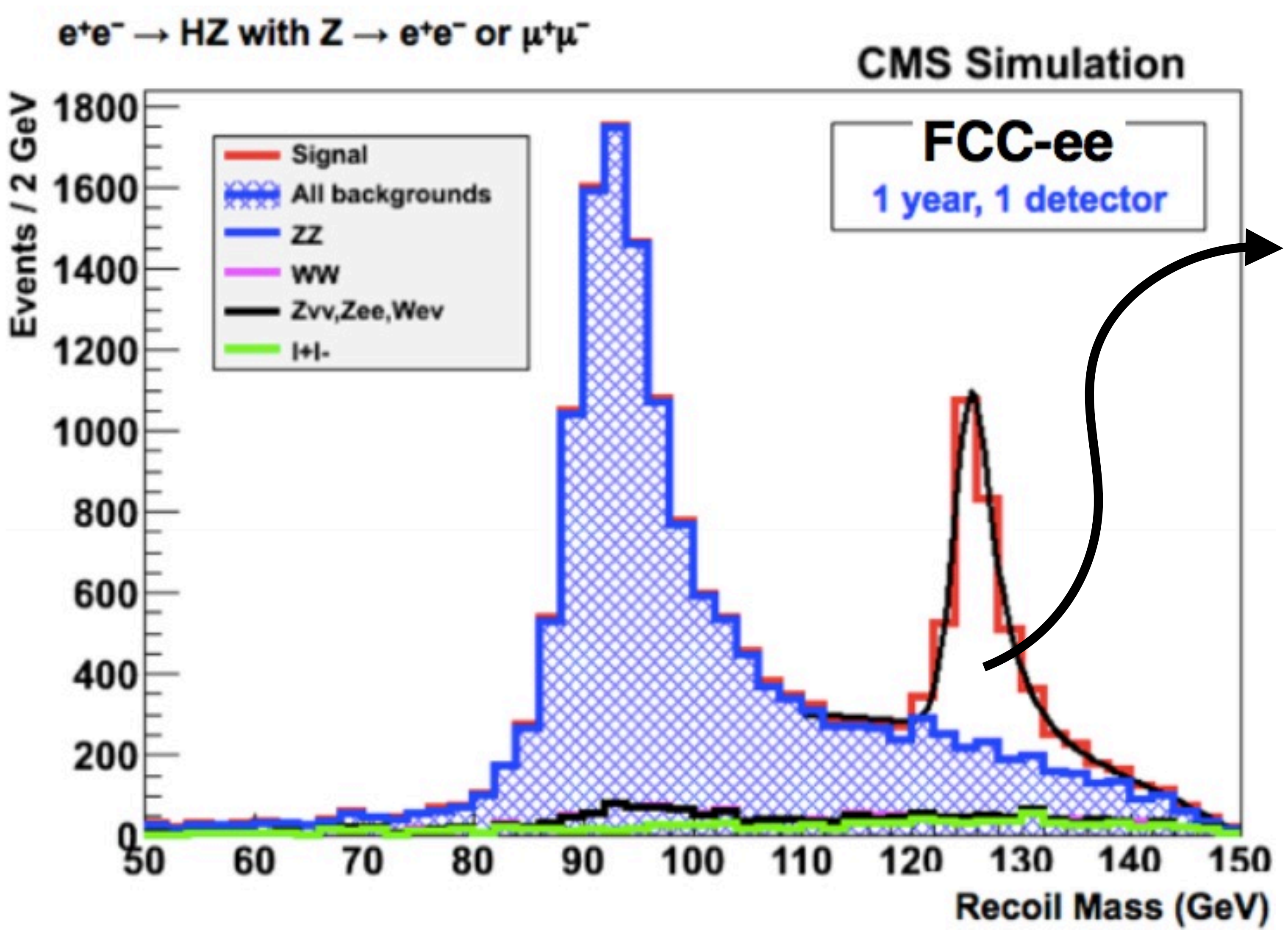
An $\ell^+\ell^-$ collider provides the solution ….



$p(H) = p(e^-e^+) - p(Z)$

$\Rightarrow [\ p(e^-e^+) - p(Z)\ ]^2$ peaks at $m^2(H)$

reconstruct Higgs events independently of the Higgs decay mode!

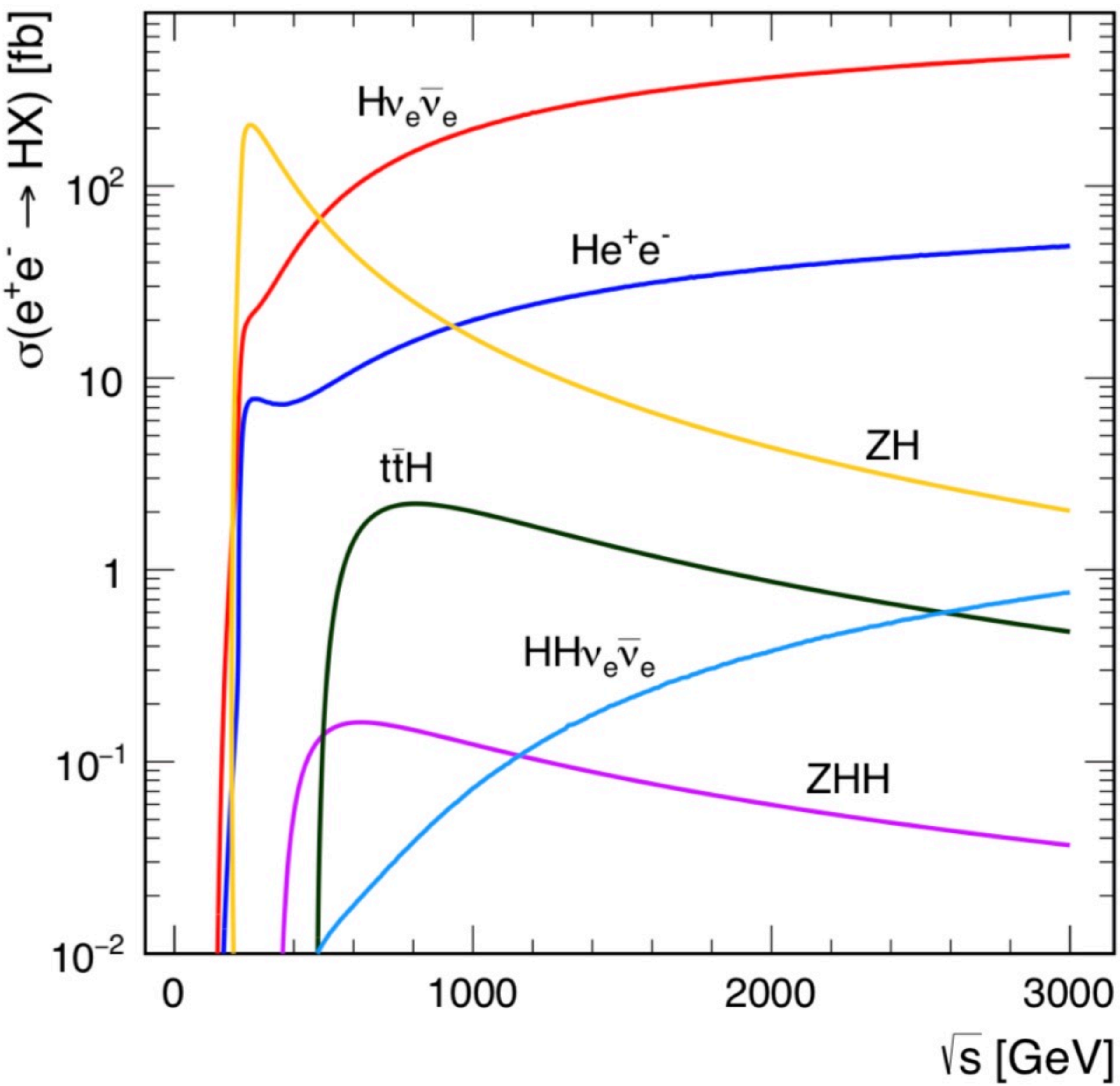


$N(ZH) \propto \sigma(ZH) \propto g_{HZZ}^2$

$N(ZH[\rightarrow ZZ]) \propto$
$\sigma(ZH) \times BR(H\rightarrow ZZ) \propto$
$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

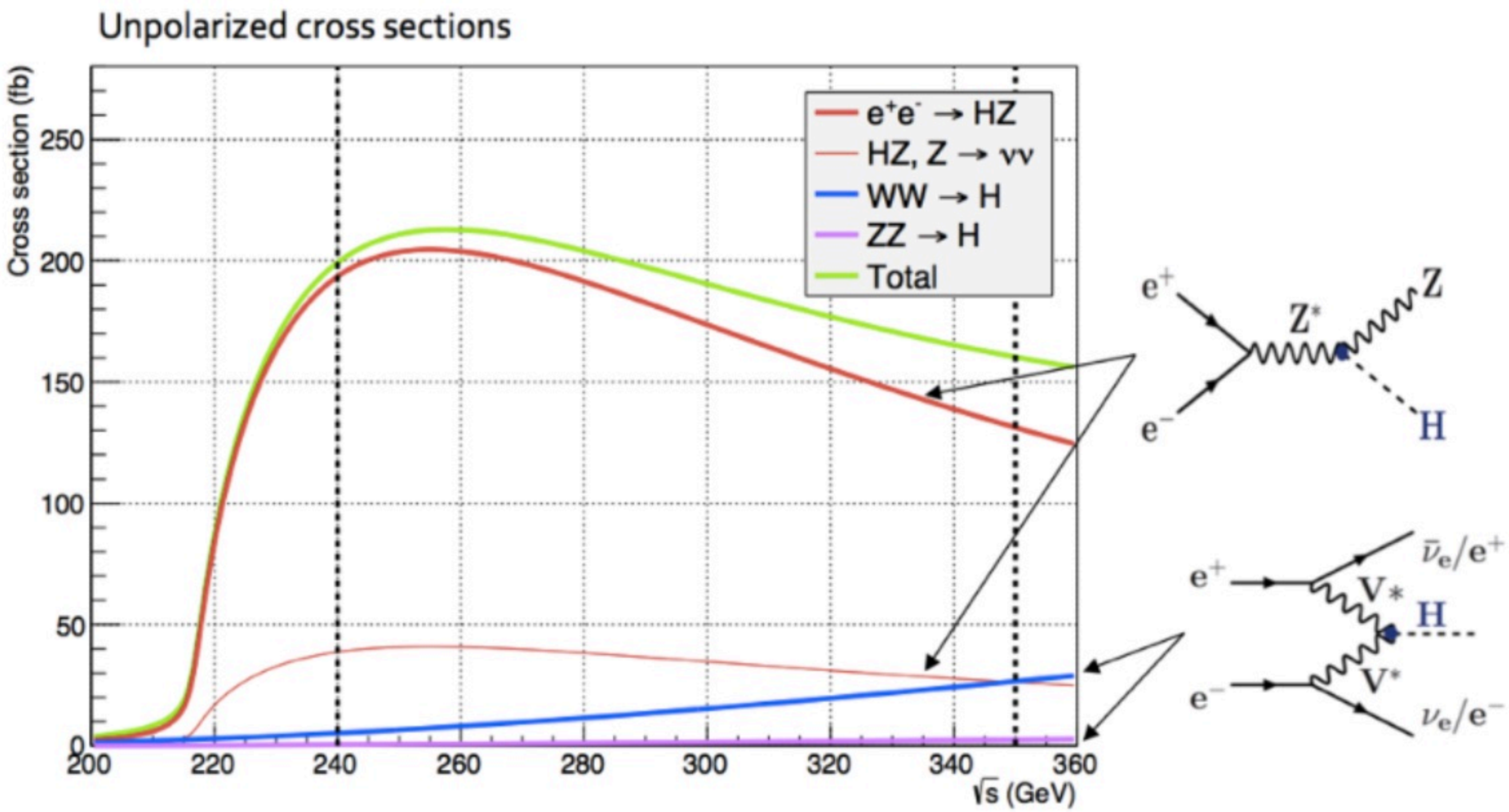
=> absolute measurement of width and couplings

$m_{recoil} = \sqrt{[\ p(e^-e^+) - p(Z)\ ]^2}$



$\sigma(e^+e^- \to HX)$ [fb]
10^2
10
1
10^{-1}
10^{-2}
0
1000
2000
3000
$\sqrt{s}$ [GeV]
$H\nu_e\bar{\nu}_e$
He^+e^-
ZH
$t\bar{t}H$
$HH\nu_e\bar{\nu}_e$
ZHH

FCC-ee



	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
# Higgs bosons from $e^+e^-\rightarrow HZ$	1,000,000	200,000
# Higgs bosons form fusion process	25,000	40,000

Higgs couplings: beyond the HL-LHC

Collider	HL-LHC	**HL-LHC update**	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240+365}$		
Lumi (ab^{-1})	3	3	2	0.5	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	25	15	7	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	50	3.6	6.3	3.6	2.6	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	**1.5**	0.3	0.40	0.32	0.25	0.20	**0.17**	**0.16**
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	**1.7**	1.7	0.8	1.7	1.2	1.3	**0.43**	**0.40**
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	**3.7**	1.7	1.3	1.8	1.3	1.3	**0.61**	**0.56**
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	**SM**	2.3	4.1	2.3	1.8	1.7	**1.21**	**1.18**
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	**2.5**	2.2	2.1	2.1	1.4	1.6	**1.01**	**0.90**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	**1.9**	1.9	2.7	1.9	1.4	1.4	**0.74**	**0.67**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	**4.3**	14.1	n.a.	12	6.2	10.1	**9.0**	**3.8**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	**1.8**	6.4	n.a.	6.1	4.7	4.8	**3.9**	**1.3**
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	**3.4**	–	–	–	–	–	–	**3.1**
BR_{EXO} (%)	SM	SM	< 1.7	< 3.0	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

Table 1: Relative statistical uncertainty on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other e^+e^- colliders exploring the 240-to-380 GeV centre-of-mass energy range. All numbers indicate 68% CL intervals, except for the last line which gives the 95% CL sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The FCC-ee accuracies are subdivided in three categories: the first sub-column give the results of the model-independent fit expected with $5\ ab^{-1}$ at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional $1.5\ ab^{-1}$ at $\sqrt{s} = 365$ GeV, and the last sub-column shows the result of the combined fit with HL-LHC. The fit to the HL-LHC projections alone (first column) requires two additional assumptions to be made: here, the branching ratios into $c\bar{c}$ and into exotic particles are set to their SM values.

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

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 Hγγ, Hμμ, HZγ, Htt