The Higgs boson eleven years later: a theoretical perspective

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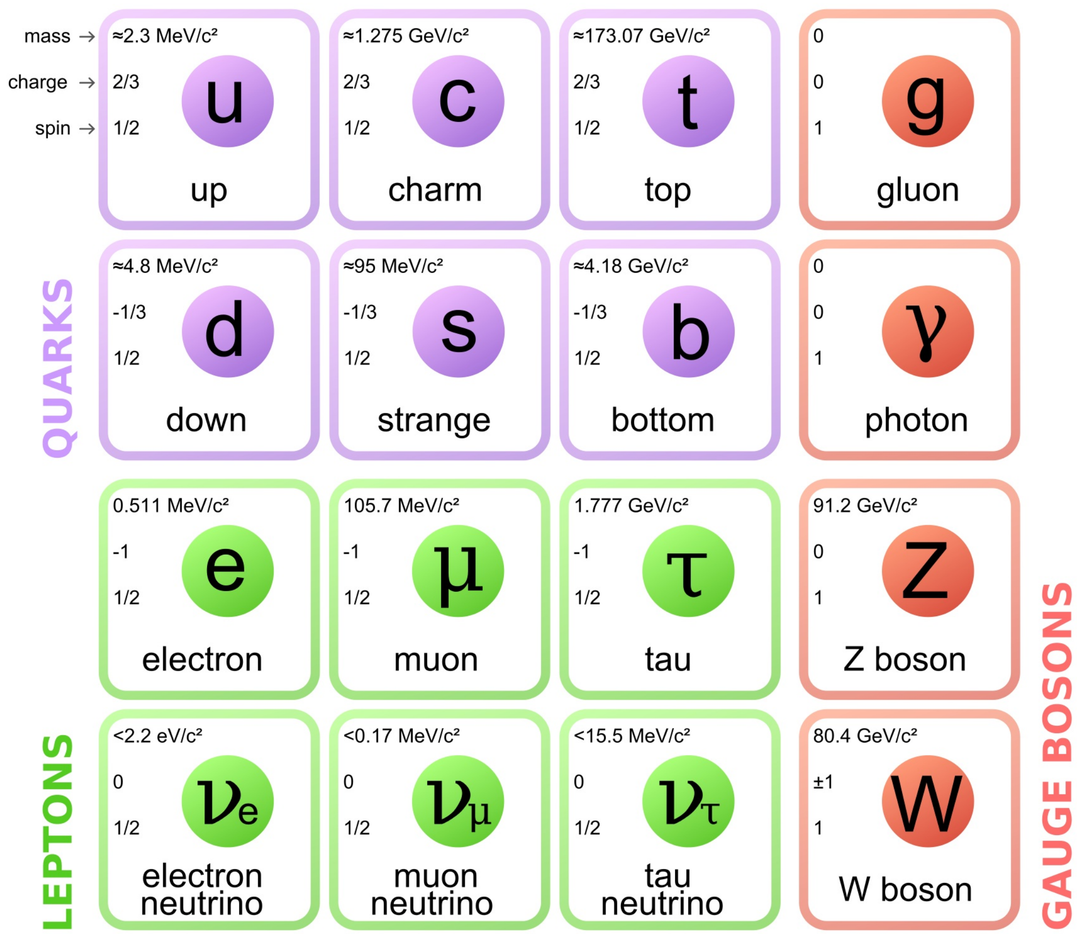
FNSNF SWISS NATIONAL SCIENCE FOUNDATION

The Standard Model



3 families of quarks (u, d, c, s, t, b) and leptons $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$ interacting with three forces: electroweak (W, Z, γ) and strong (g)

Forces among particles are associated to (local) symmetries

Electromagnetic force corresponds to local invariance of particle wave function under phase rotations

More precisely the model is a quantum field theory with a local symmetry

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

"Quantum Chromodynamics" (QCD)

Electroweak theory

The Standard Model

This construction is a based on Quantum Mechanics + Special Relativity

Elementary particles introduced as representations of Poincare group labelled with

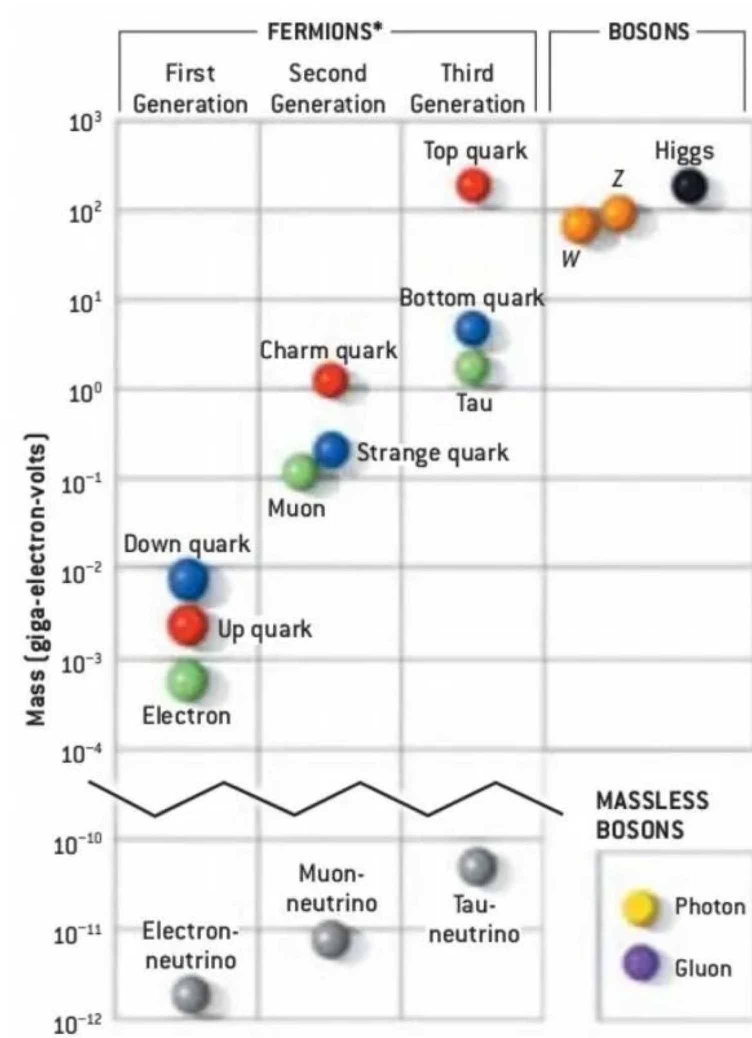
$$(\text{spin}, \text{mass}) \otimes \text{internal quantum numbers}$$

quantised continuous charges under gauge group

This is perfectly consistent with what we observe except for the fact that (chiral) gauge theories require particles to be massless

Gauge boson $\rightarrow$ Massless

(Chiral) fermion $\rightarrow$ Massless



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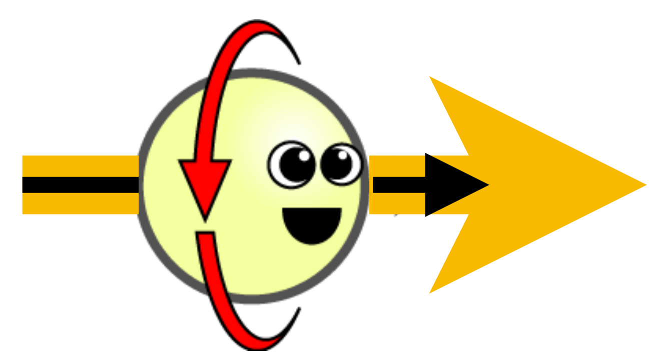

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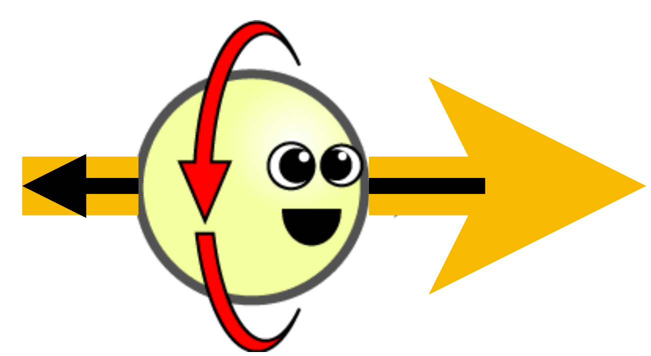


Spontaneous Symmetry breaking

How can we overcome this problem ? A solution exists and is borrowed from statistical mechanics, and it relies on the concept of spontaneous symmetry breaking (SSB)

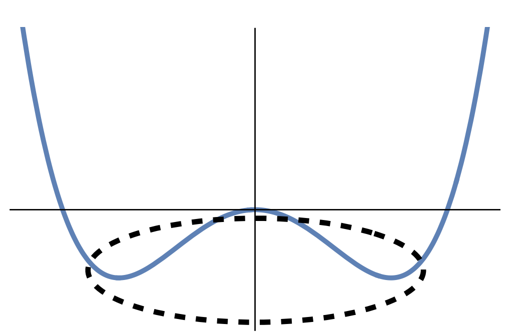
The way in which the symmetry is implemented at the quantum level depends on the behaviour of the vacuum

- If $Q|0\rangle = 0$ the symmetry is implemented *à la Wigner*: the vacuum is invariant and physical states can be constructed out of the vacuum and classified according to the irreducible representations of the symmetry group

- If $Q|0\rangle \neq 0$ the symmetry is implemented *à la Goldstone*: the vacuum is not invariant and thus the symmetry is not realised in the particle spectrum

In the case of the $SU(2)_L \otimes U(1)_Y$ symmetry Nature has chosen the second option and we have

$$SU(2)_L \otimes U(1)_Y \to U(1)_{EM}$$



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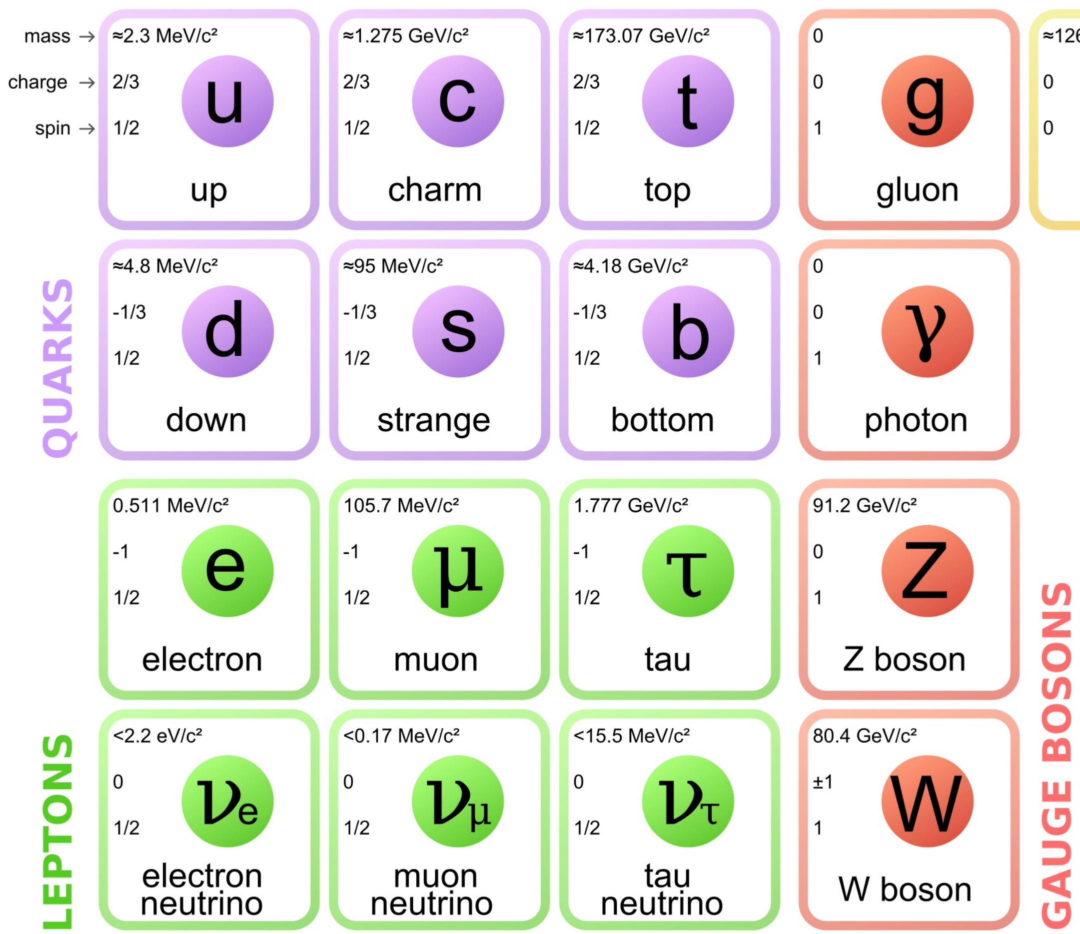


The discovery of the Higgs boson at the CERN Large Hadron Collider (LHC) in 2012 has crowned the Standard Model as a successful description of elementary particles and their interactions

The electroweak $SU(2)_L \otimes U(1)_Y$ symmetry is spontaneously broken to $U(1)_{EM}$ and the Higgs boson is the agent of this breaking, providing masses to the other particles

$$\mathcal{L}_{SM} = \overbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi} i \not{D}\, \psi}^{\mathcal{L}_{\text{gauge}}} + \overbrace{(D_\mu\phi)^\dagger(D_\mu\phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 + \left(\lambda^{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right)}^{\mathcal{L}_{\text{SB}}}$$

The Higgs is the last particle in the SM so the SM is complete, right ?

The mysteries

- **What is the nature of dark matter ?**

  Astrophysical observations indicate that most of the matter existing in our Universe is not accounted for by the known elementary particles

  Dark matter most likely implies physics beyond the SM

- **What is the origin of the large matter-antimatter asymmetry ?**

  The Big Bang should have created equal amounts of matter and antimatter but today everything we see from the smallest life forms on Earth to the largest stellar objects is made almost entirely of matter

- **How can gravitational interactions be embedded in the picture ?**

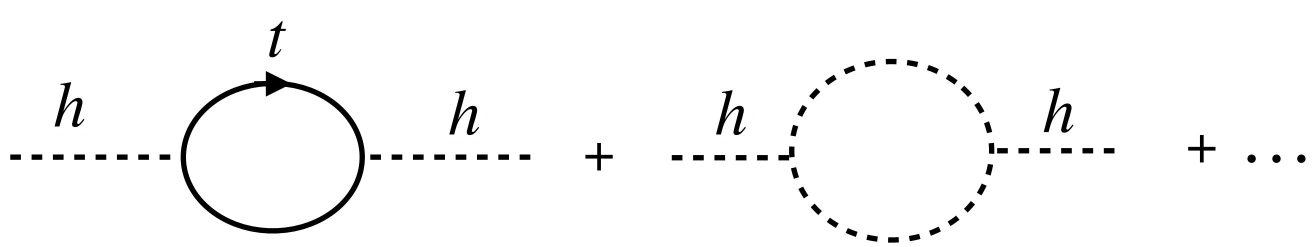
→ The SM can only be an effective description of Nature valid up to some scale Λ at which New Physics must show up

Naturalness

Fermion masses m_f can be naturally light: chiral symmetry is restored as $m_f \to 0$

➡ Radiative corrections to the fermion mass must be proportional to the mass itself, so as to preserve chiral symmetry in the massless limit

By contrast the Higgs boson mass is not protected by any symmetry: even if we set it to its experimental value at tree level, radiative corrections are quadratic



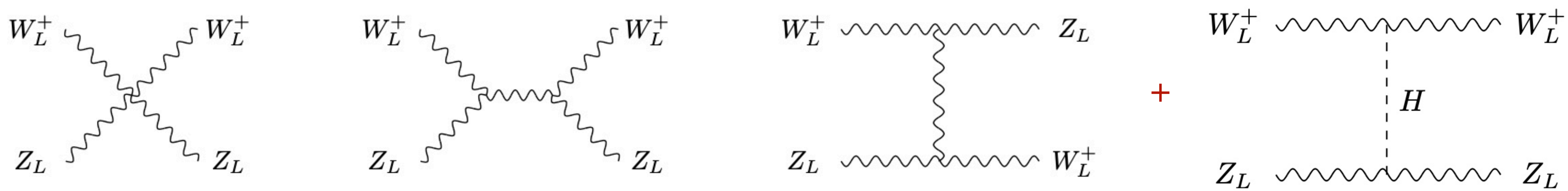
➡ **this naturally leads to $m_H \sim \Lambda$**

This is not a problem if new physics is nearby

Main point: evident contradiction between the “excessive” success of the SM that seem to suggest Λ very far and the consistency of the SM as an effective field theory that requires Λ to be low

Higgs, unitarity and Naturalness

In the SM the Higgs boson preserves unitarity in high energy vector boson scattering



➡ No-lose theorem: something had to happen at the TeV scale !

Once the Higgs is in place, the necessity of new physics invoking Naturalness is not a theorem any more ! In the end we have the same problem with the cosmological constant….

Anthropic solution, multiverse ?

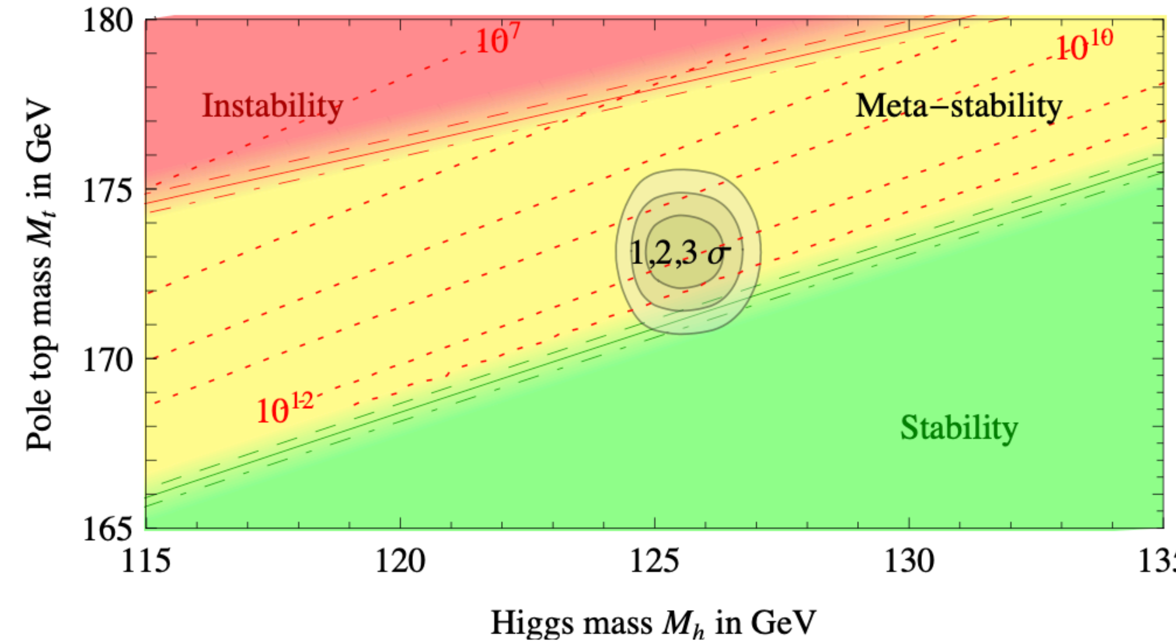
"Perhaps Λ_c must be small enough to allow the Universe to evolve to its present nearly empty and flat state because otherwise there would be no scientists to worry about it." Weinberg (1987)

But the multiverse is inconsistent with S-matrix formalism

Dvali (2021)

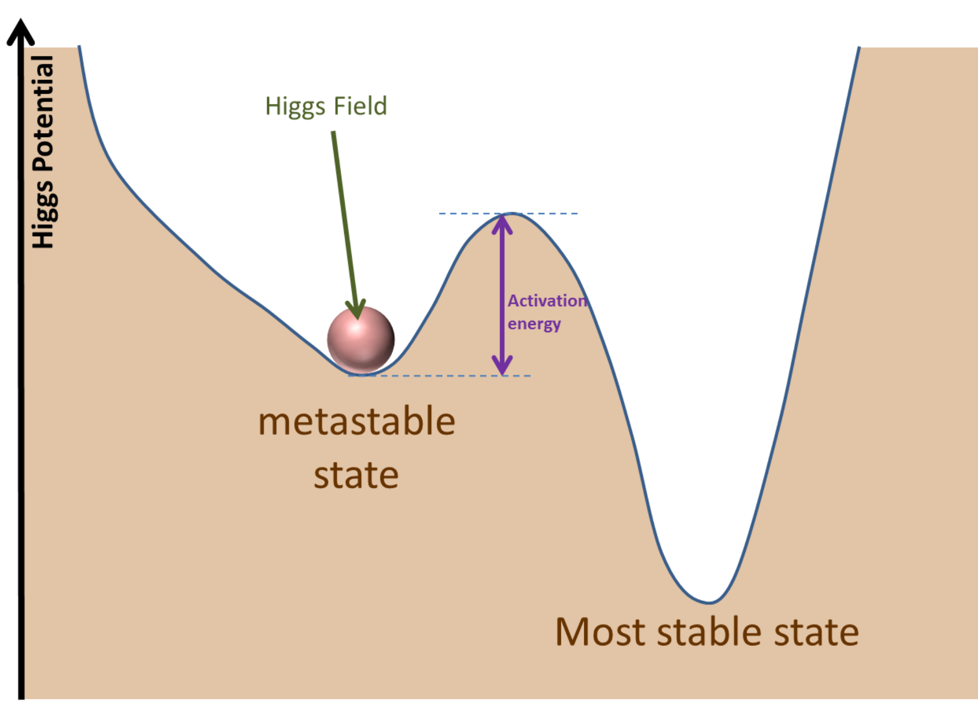
Vacuum (Meta-)Stability

With the measured values of the top and Higgs mass the Higgs potential is likely to be metastable



Degrassi et al. (2012)

This means that the SM Higgs sector has a ground state with lower energy than the state we live in



Hence, quantum mechanics would allow a “tunneling” process through which our whole universe can decay, even though with lifetime larger than that of the universe

Vacuum (Meta-)Stability

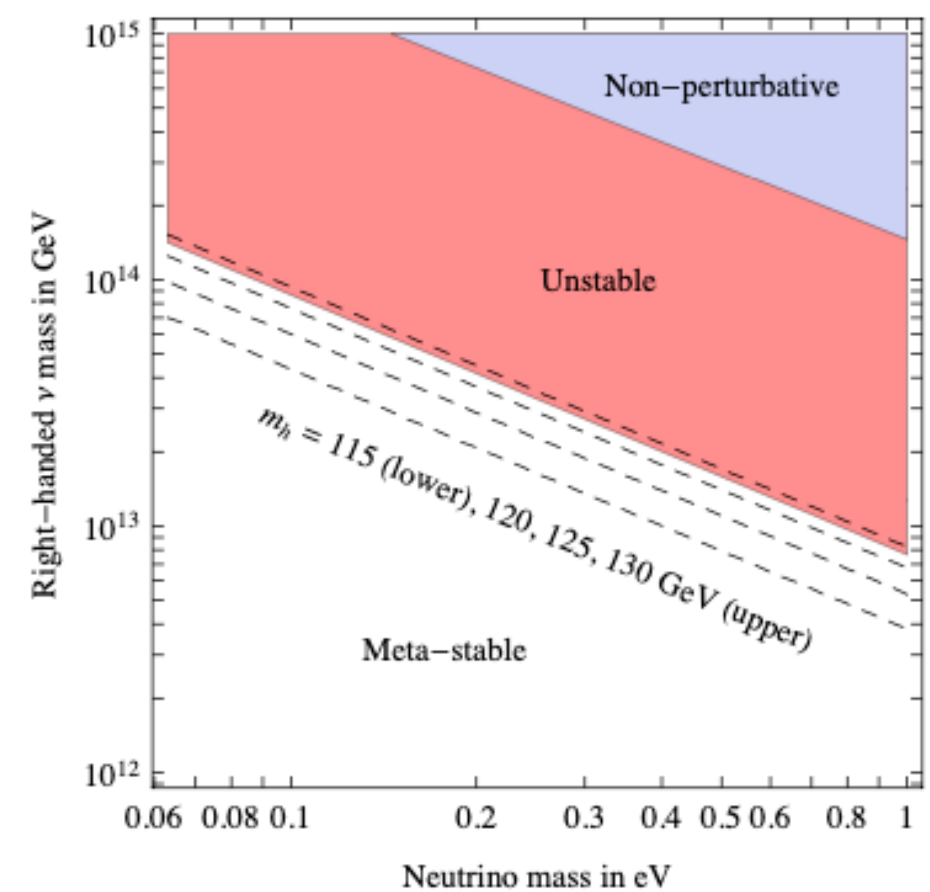
But the conclusion on metastability requires absence of new-physics up to the Planck scale

Branchina, Messina (2013)

If the SM Higgs potential were unstable this would have been a clear signal that new physics must appear. But this is not the case, which means that in principle the SM can be extrapolated up to extremely high scales

We know that new-physics is there: Neutrino masses !
Simple see-saw mechanism would not spoil vacuum stability

If the new physics is nearby then the stability question has to be posed in a broader context



Elias-Miró et al (2011)

Flavour

The flavour sector has a large number of parameters and there is clearly a strong hierarchical structure of quark and charged-lepton masses

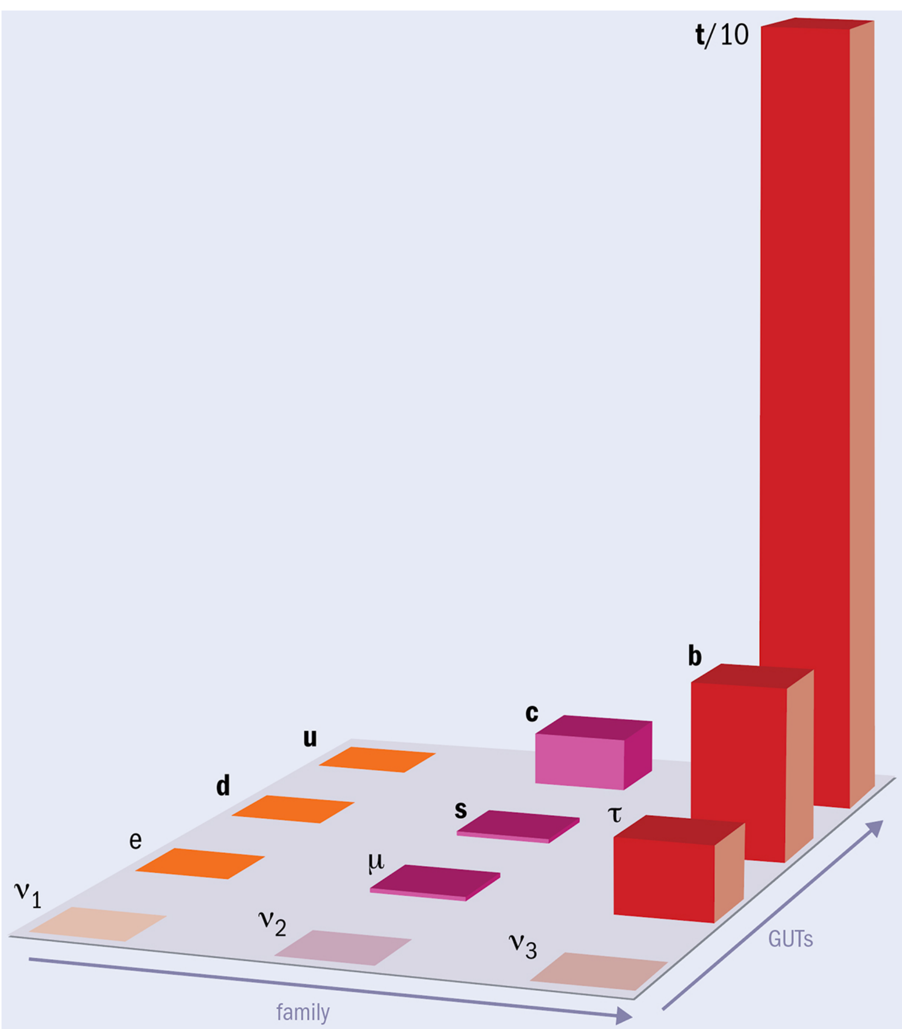


Image: CERN Courier (2020)

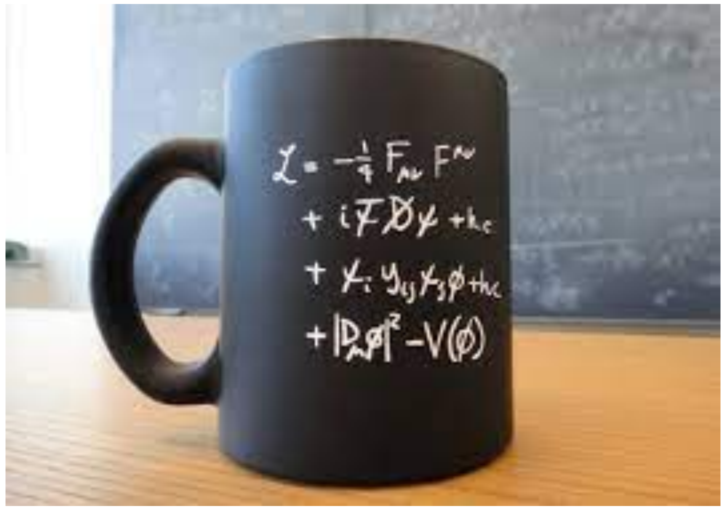
Key questions:

- What determines this pattern ?
- Are there new symmetries, or symmetry breaking patterns ?
- Can we probe energy scales not directly accessible by now ?
- Has the third generation a special role ?

The Lagrangian

$$\mathcal{L}_{SM} = \overbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi} i \not{D}\, \psi}^{\mathcal{L}_{\text{gauge}}} + \overbrace{(D_\mu\phi)^\dagger(D_\mu\phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 + \left(\lambda^{ij}\bar{\psi}^i_L\phi\psi^j_R + \mathrm{h.c.}\right)}^{\mathcal{L}_{\text{SB}}}$$

- natural
- highly symmetric
- precisely tested over the last 50 years
- UV insensitive



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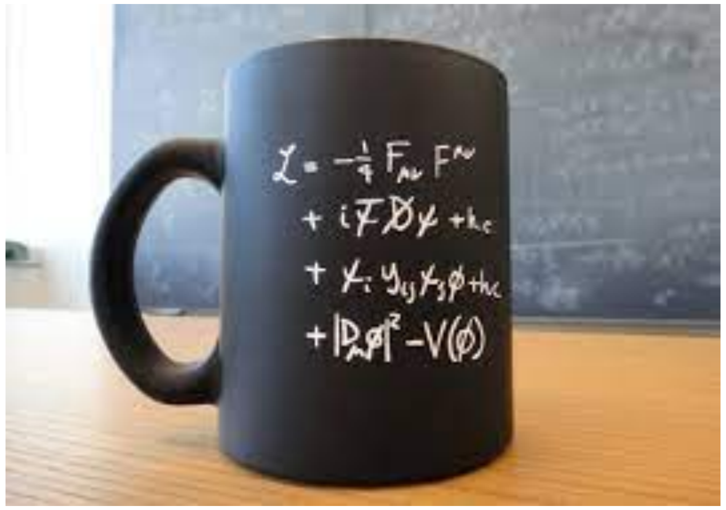
$\Delta\mu^2 \sim \Delta m_H^2 \sim \Lambda^2$

vacuum (meta)stability

Flavour problem

source of most of the SM problems but at the time the simplest solution providing the necessary ingredients to break the EW symmetry

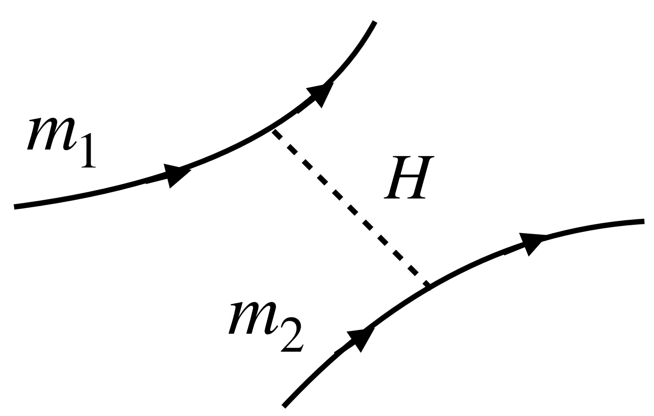


....and so what ?

The Higgs sector provides an effective description of the symmetry breaking phenomenon, but we miss a deep understanding of the relevant dynamics

- An elementary scalar (for the first time not a gauge boson !) appears to **mediate a new kind of force**, which is proportional to particle masses

The force mediated by the Higgs Boson is **similar to the gravitational force**, though, contrary to it, it has **short range**



- Or is it composite ?

Composite Higgs

A new strongly coupled sector is assumed just above the EW scale

Analogy with QCD used to make the Higgs boson a composite scalar, like a pion

$G \to H$ pseudo Goldstone bosons (PGB) belong to the coset G/H

Pions are naturally light and are not quadratically sensitive to the new-physics scale Λ

Fine tuning parametrised by $\xi = \left(\frac{v}{f}\right)^2$ where $\xi \lesssim 10-20\,\%$ to be consistent with data

PGB decay constant

H Higgs "size" $r_H \sim 1/M$ controlled by mass of the new resonances

Example: minimal composite Higgs model: $SO(5)/SO(4)$

➡ $10 - 6 = 4$ PGB: three give mass to the W and Z bosons and one is identified with the Higgs

Agashe, Contino, Pomarol (2005)

Is it unique ?

A single Higgs doublet provides the minimal solution to give masses to all fermions

In principle we could introduce one Higgs doublet for up and one for down-type fermions (or even an additional one for charged leptons !)

This possibility may have implications for baryogenesis: indeed in the SM the amount of CP violation in the CKM matrix is insufficient

Two-Higgs doublet models also including an $SU(2)_L$ singlet can provide explicit CP violation, a first order EW phase transition and even a stable dark matter candidate

see e.g. Mühlleitner et al (2023)

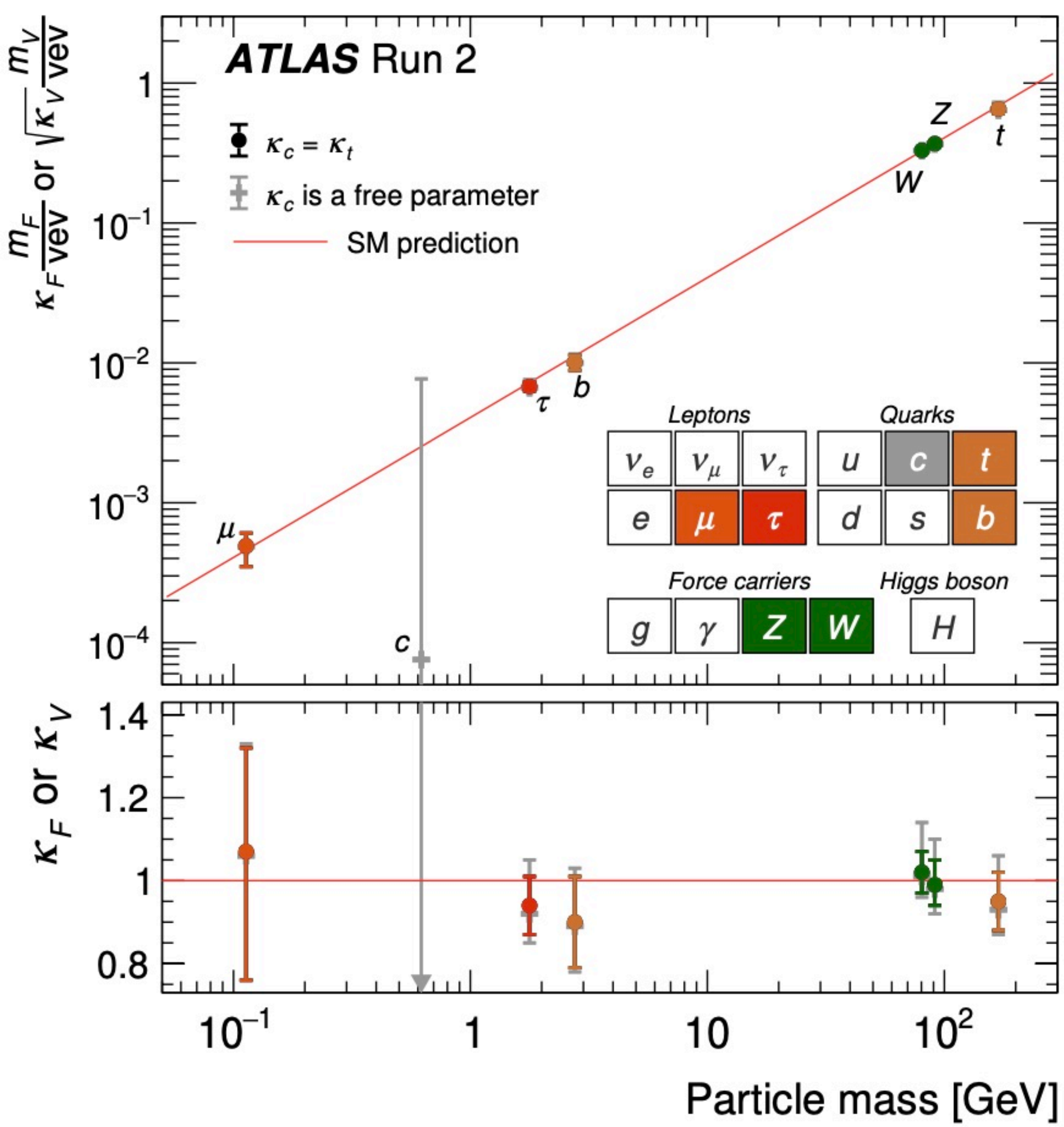
Baryogenesis occurring at the EW phase transition can generate the observed baryon asymmetry in our Universe

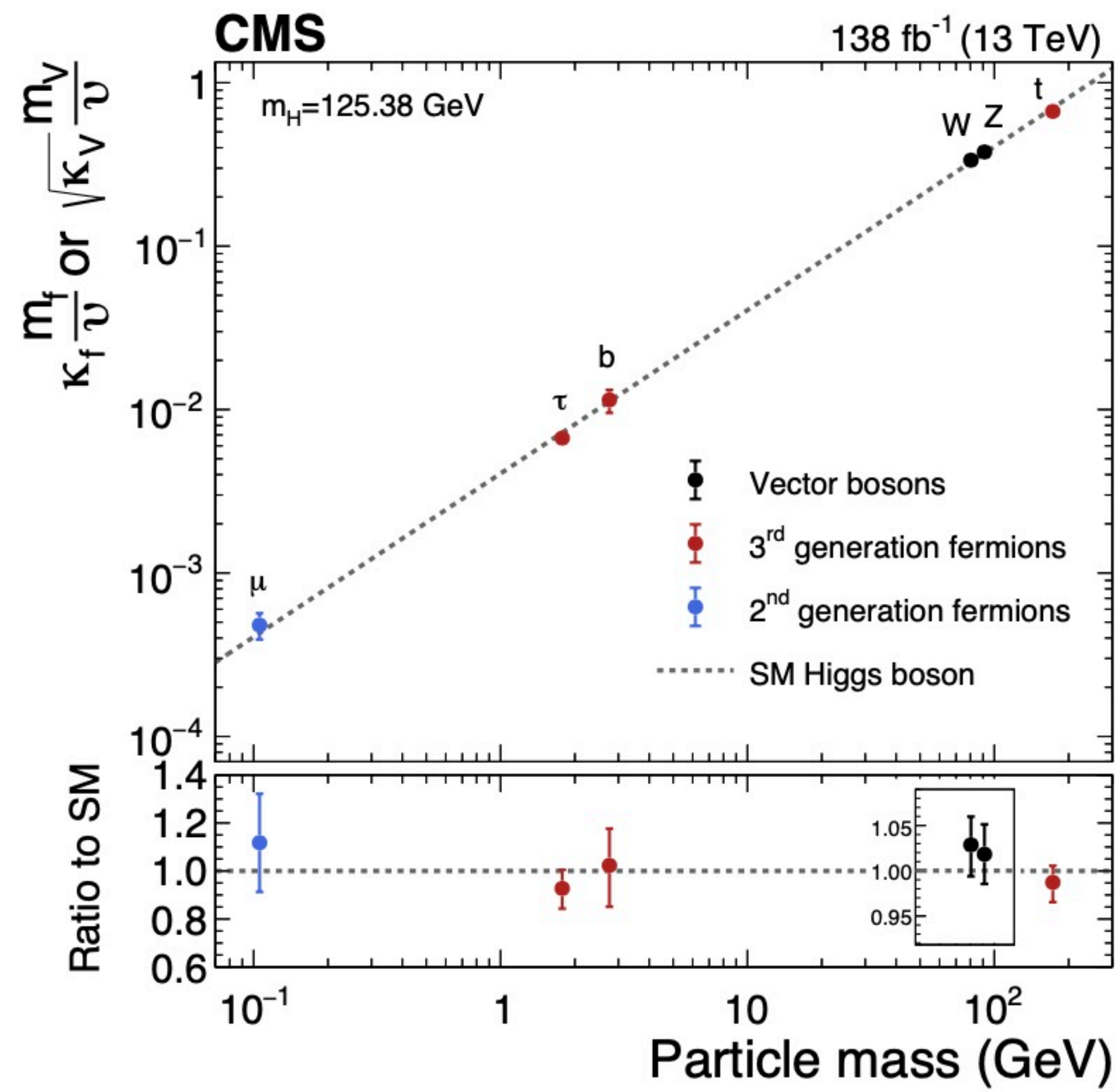
Analogous considerations hold for models with just additional singlets and Higgs portal models

Frugiuele et al (2016)

How well do we know the Higgs sector ?

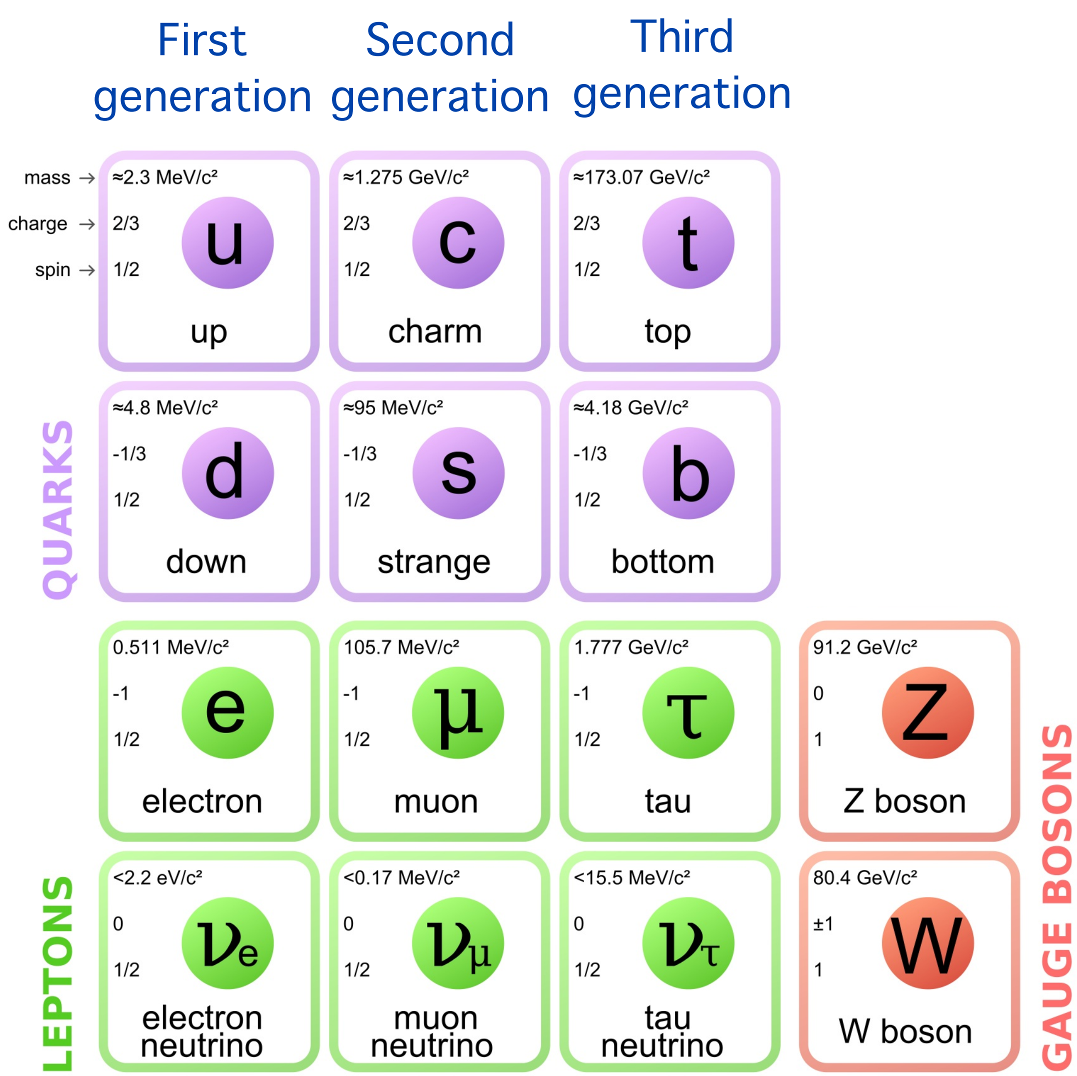
Higgs couplings





Agreement with SM within three order of magnitude in mass !

Higgs couplings



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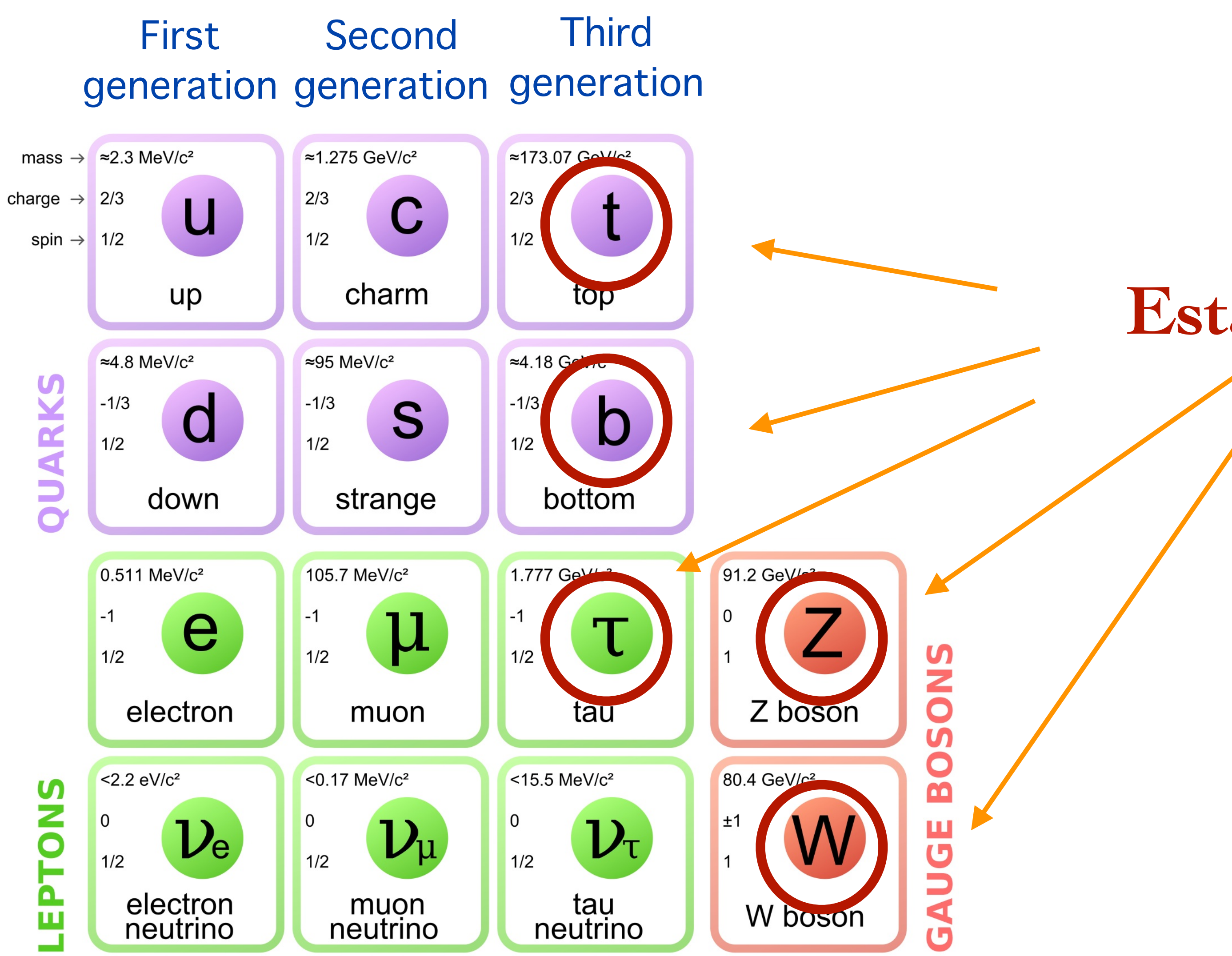
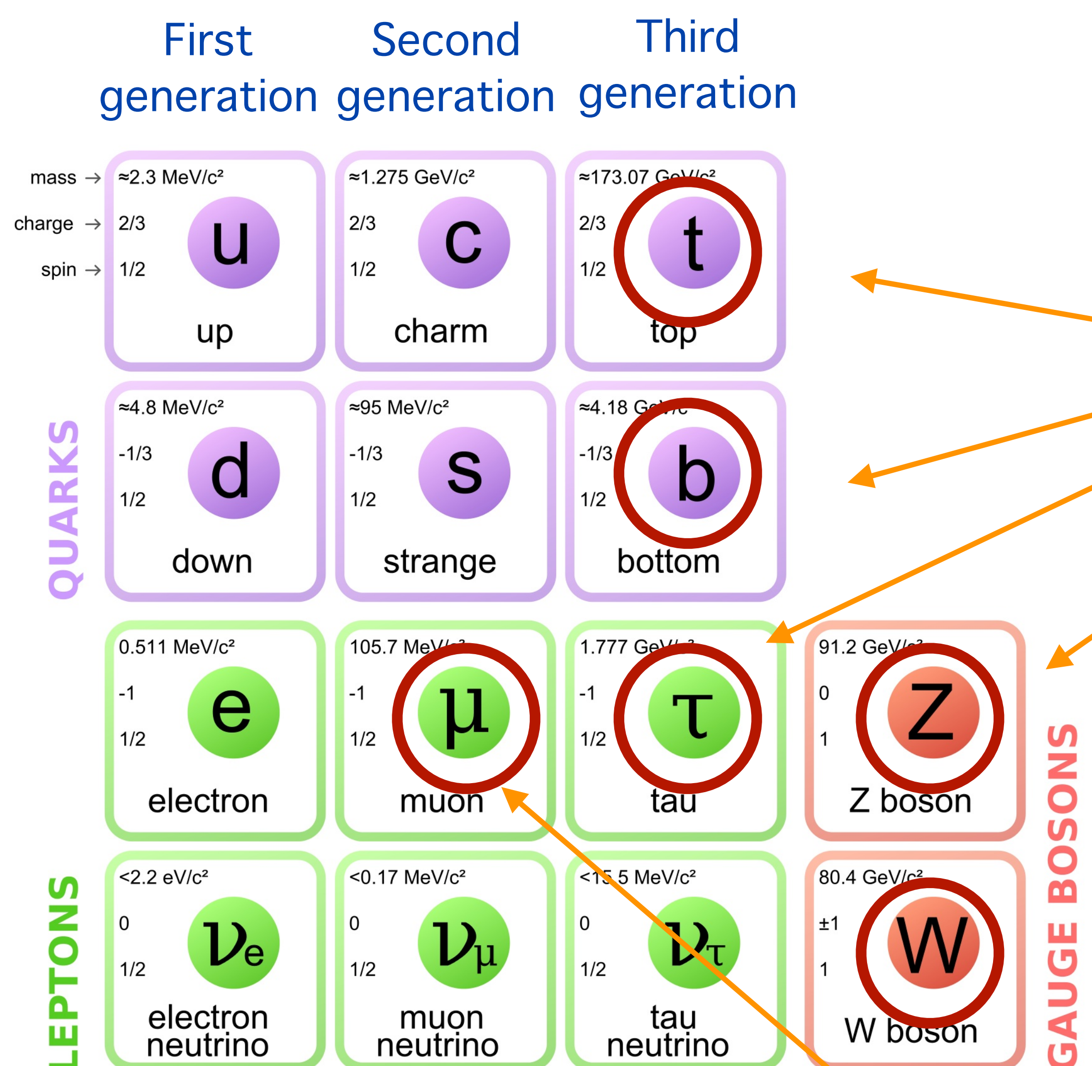


Established at the LHC at 5σ

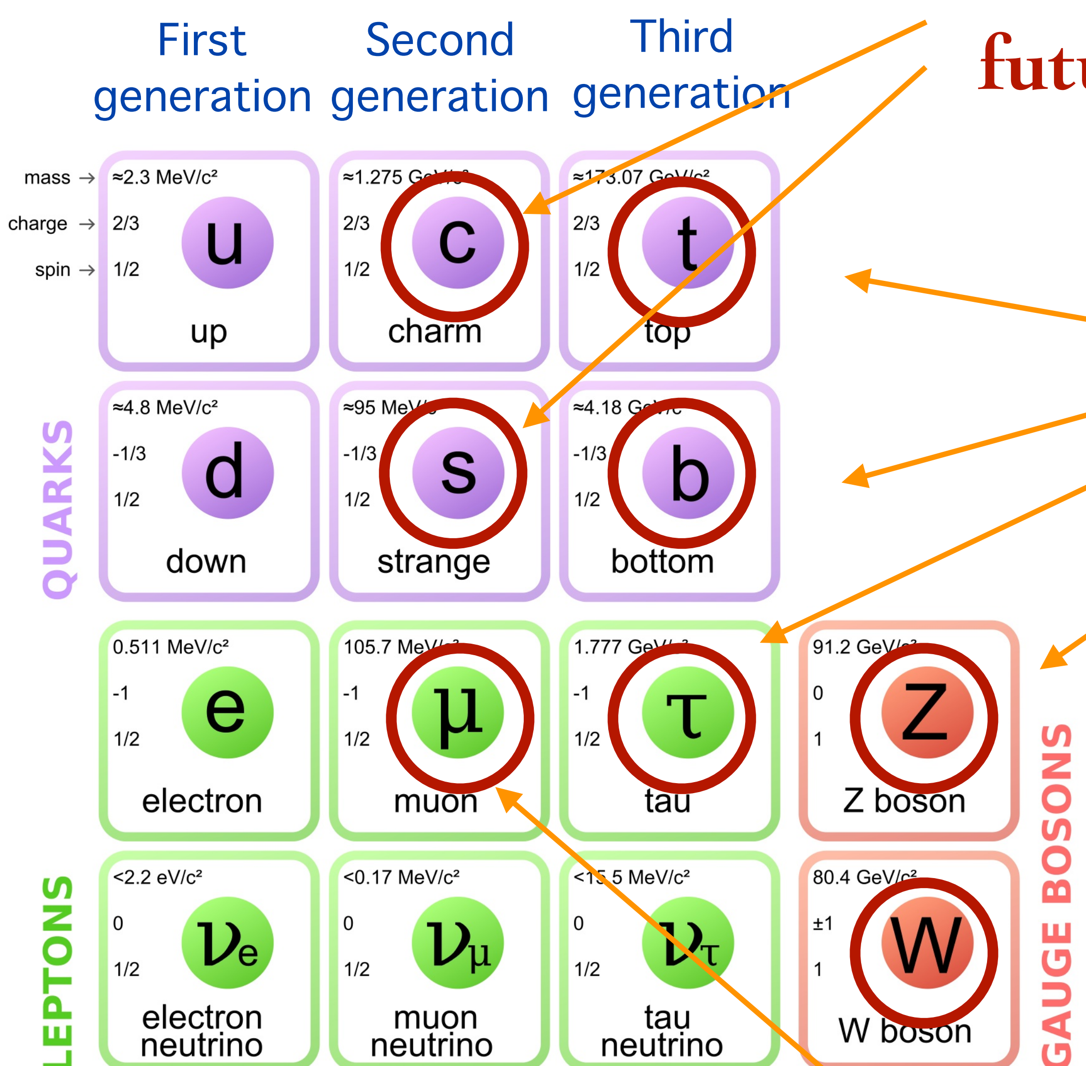
Higgs couplings



Established at the LHC at 5σ

First evidence (3σ) to be established at the HL-LHC

Higgs couplings



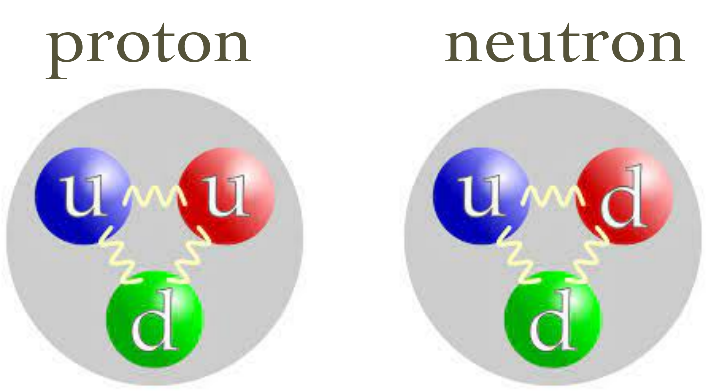
Should/could be possible at future linear colliders !

Established at the LHC at 5σ

First evidence (3σ) to be established at the HL-LHC

How about couplings to up, down and electron ?

Higgs couplings



$m_u = 2.2\,\text{MeV}$

$m_d = 4.7\,\text{MeV}$

Protons are stable because lighter than neutrons

$m_p = 938.3\,\text{MeV}$ $m_n = 939.6\,\text{MeV}$

The hydrogen atom, chemistry and biology as we know them are a consequence of this !

In the SM this happens because the Higgs boson interacts with the down quark in a slightly stronger way than with the up quark

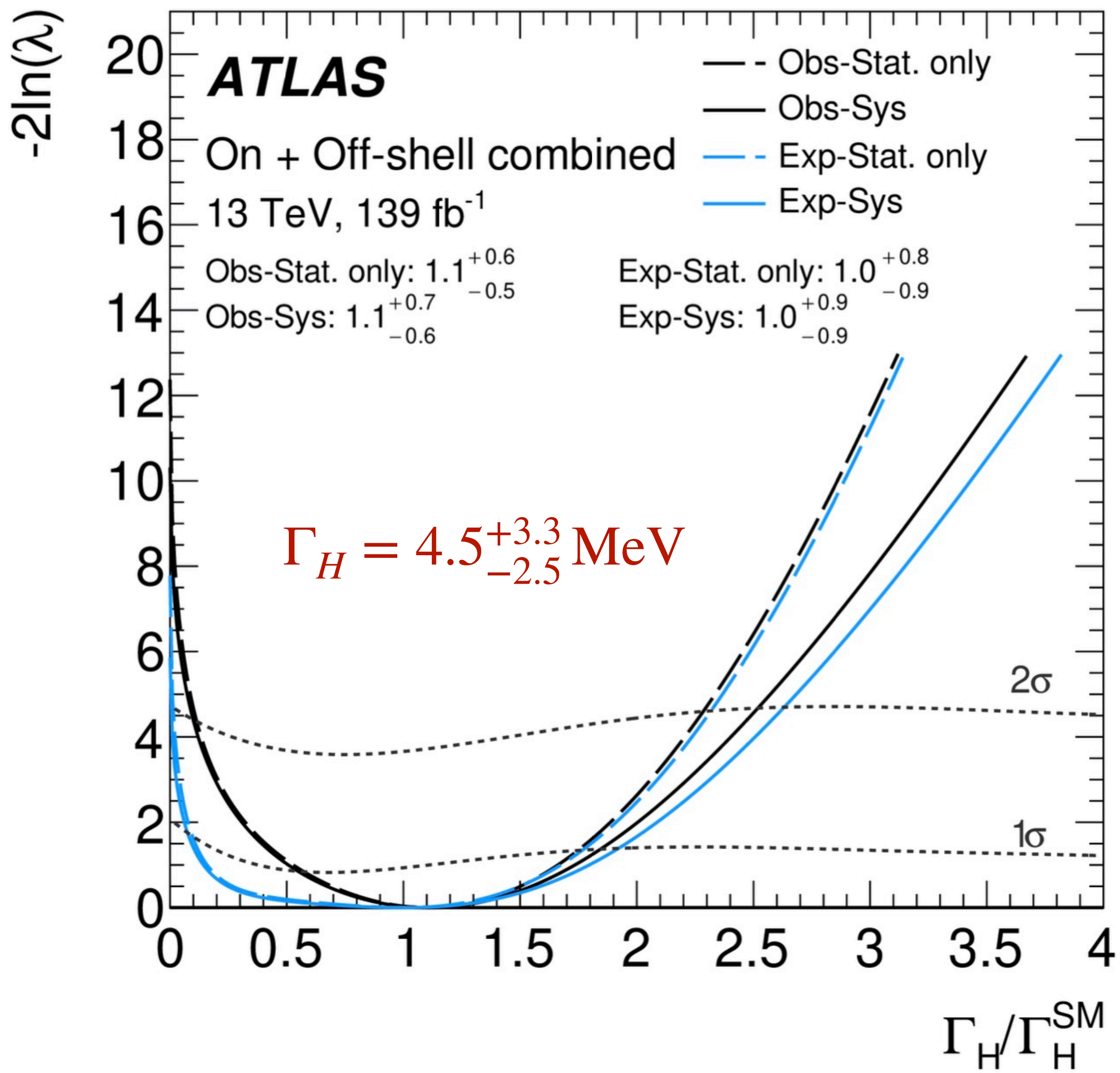
Similar considerations can be done for the electron mass

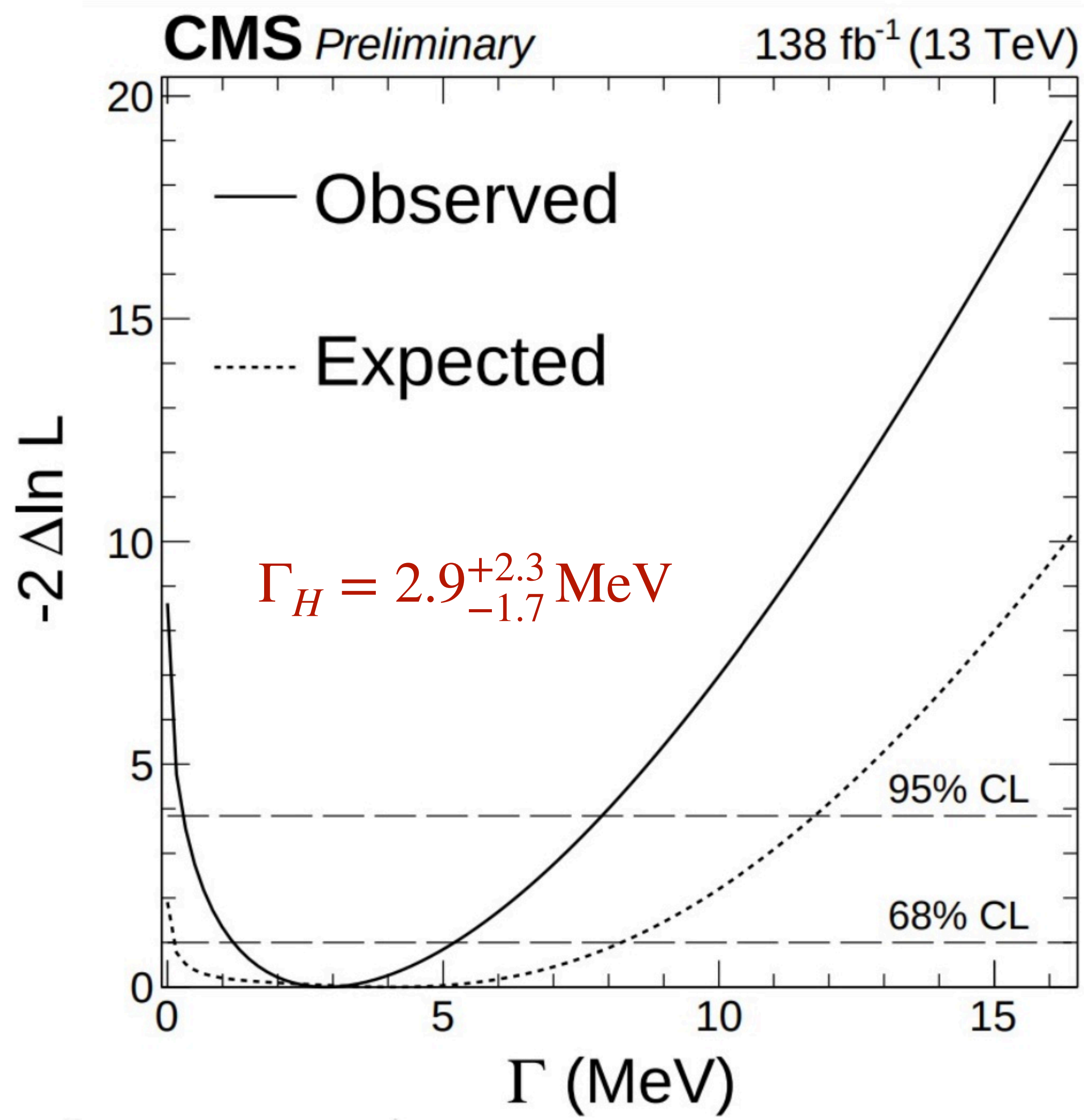
$$a_0 = \frac{\hbar}{m_e c \alpha}$$

The Bohr radius depends on the electron mass and in turn fixes the size of the atoms

See e.g. Salam, Wang, Zanderighi (2022)

Width





Experiments are now really getting sensitive to Γ_H but these results are obtained indirectly through the ratio $\sigma_{\text{off shell}}/\sigma_{\text{on shell}}$ and thus model dependent

The Higgs potential

In the SM the Higgs potential

$$V(\Phi^\dagger\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \qquad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

is completely determined once m_H (and $v = 1/\sqrt{\sqrt{2}G_F}$) are fixed

Using $\quad m_H^2 = 2\lambda v^2 \qquad v^2 = -\dfrac{\mu^2}{\lambda}$

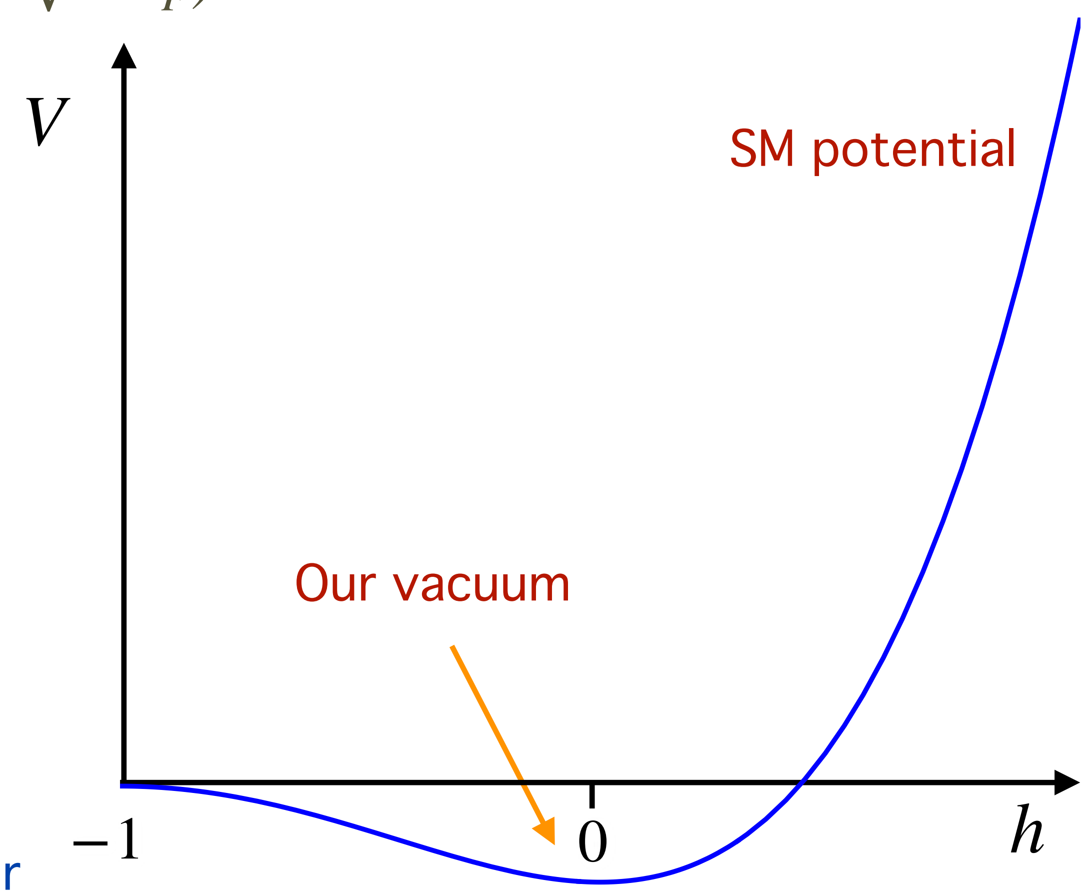
we can write ($h \equiv H/v$)

$$V = \frac{m_H^2 v^2}{8}\left(-1 + 4h^2 + 4h^3 + h^4\right)$$

Mass term

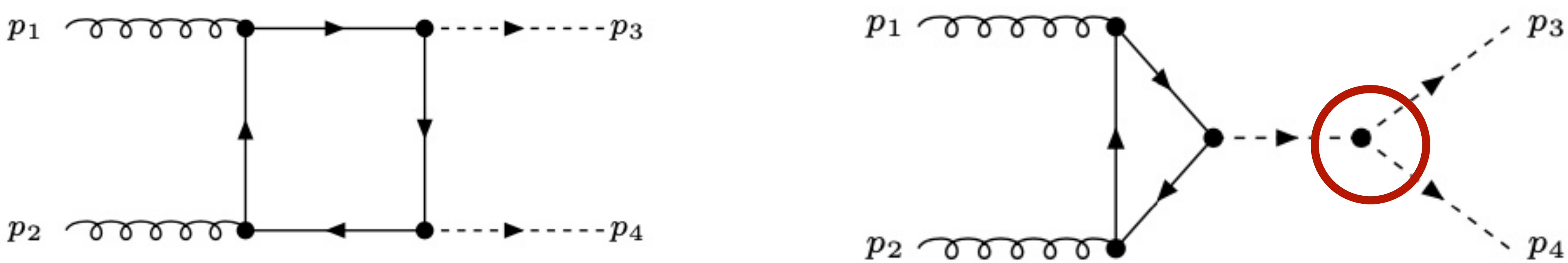
Trilinear
(can be different by
modifier factor κ_λ)

Quadrilinear



BSM physics can modify the potential !

The Higgs potential



The best way to access the Higgs trilinear coupling is through double Higgs production and gluon fusion is the main production channel

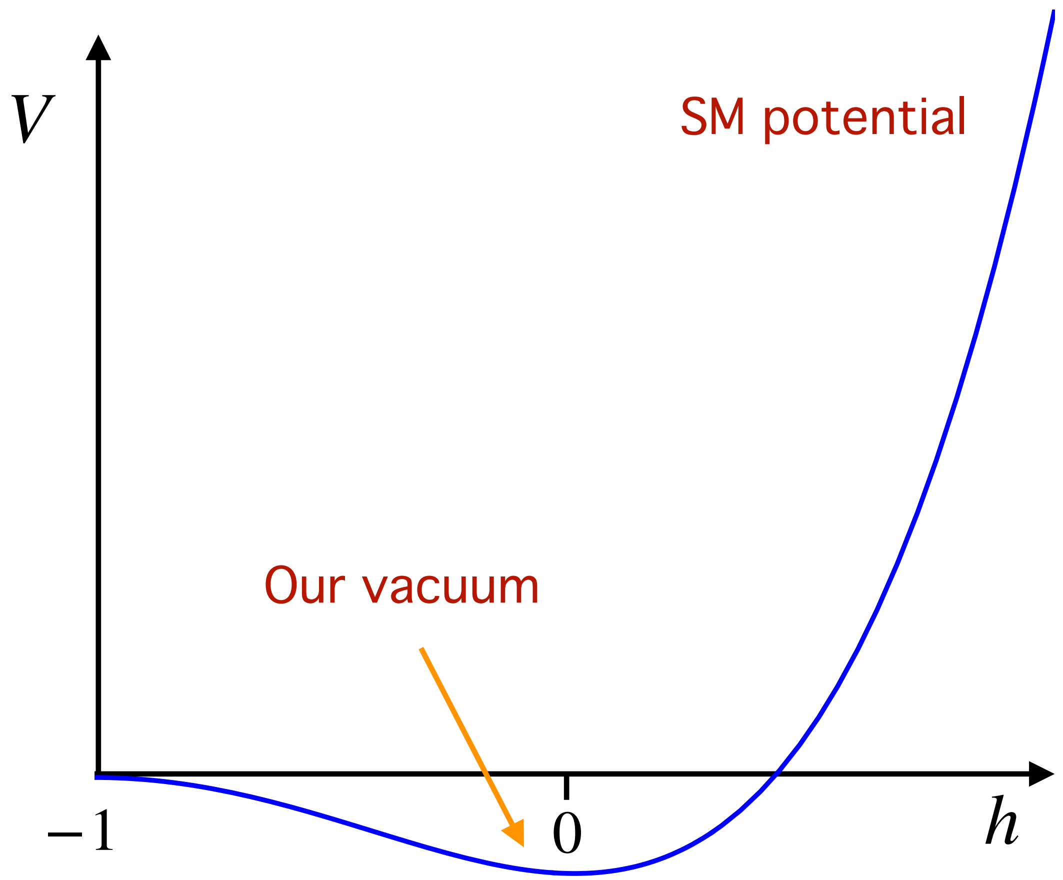
The contributing Feynman diagrams are boxes and triangles but only the triangles are sensitive to the trilinear coupling

The diagrams interfere destructively making the overall production rate even smaller than we would have in the absence of a trilinear coupling

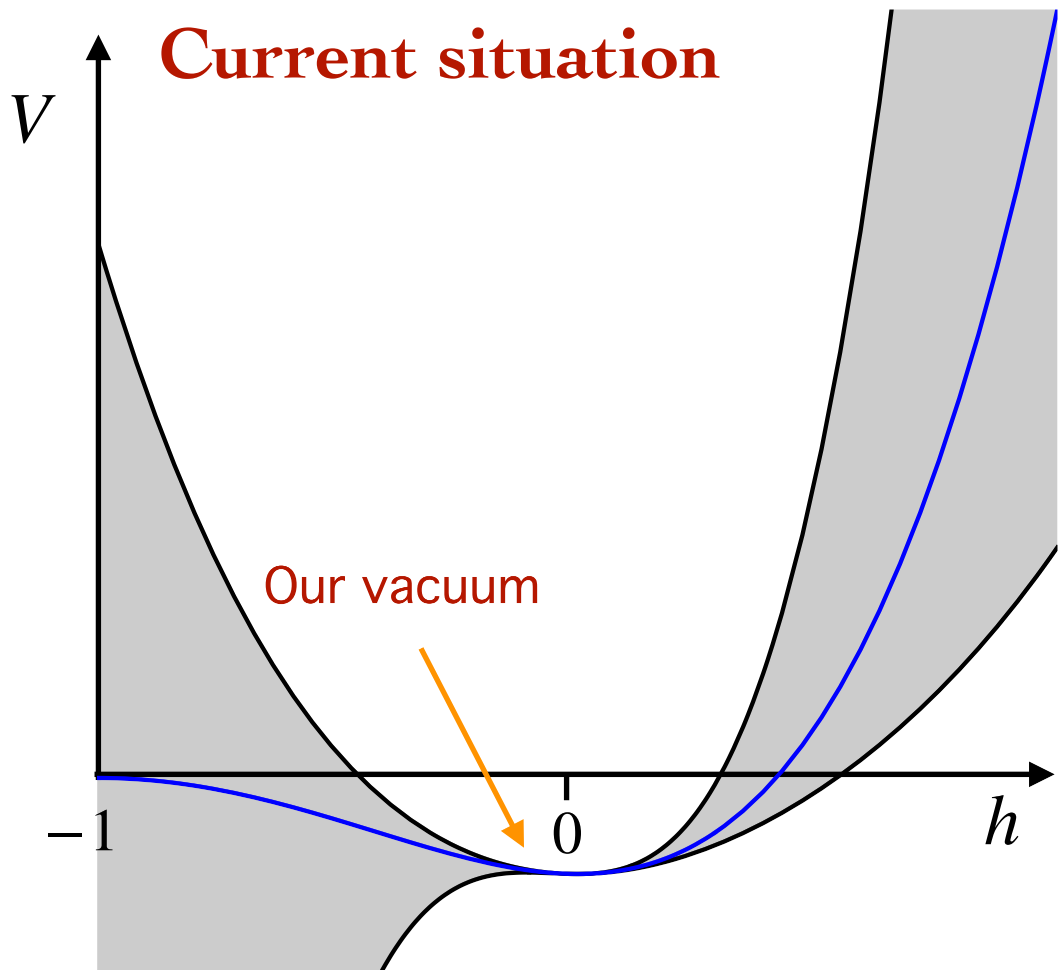
Additional sensitivity on the trilinear coupling can be obtained from virtual effects in single Higgs production

Maltoni et al (2017)

The Higgs potential



The Higgs potential

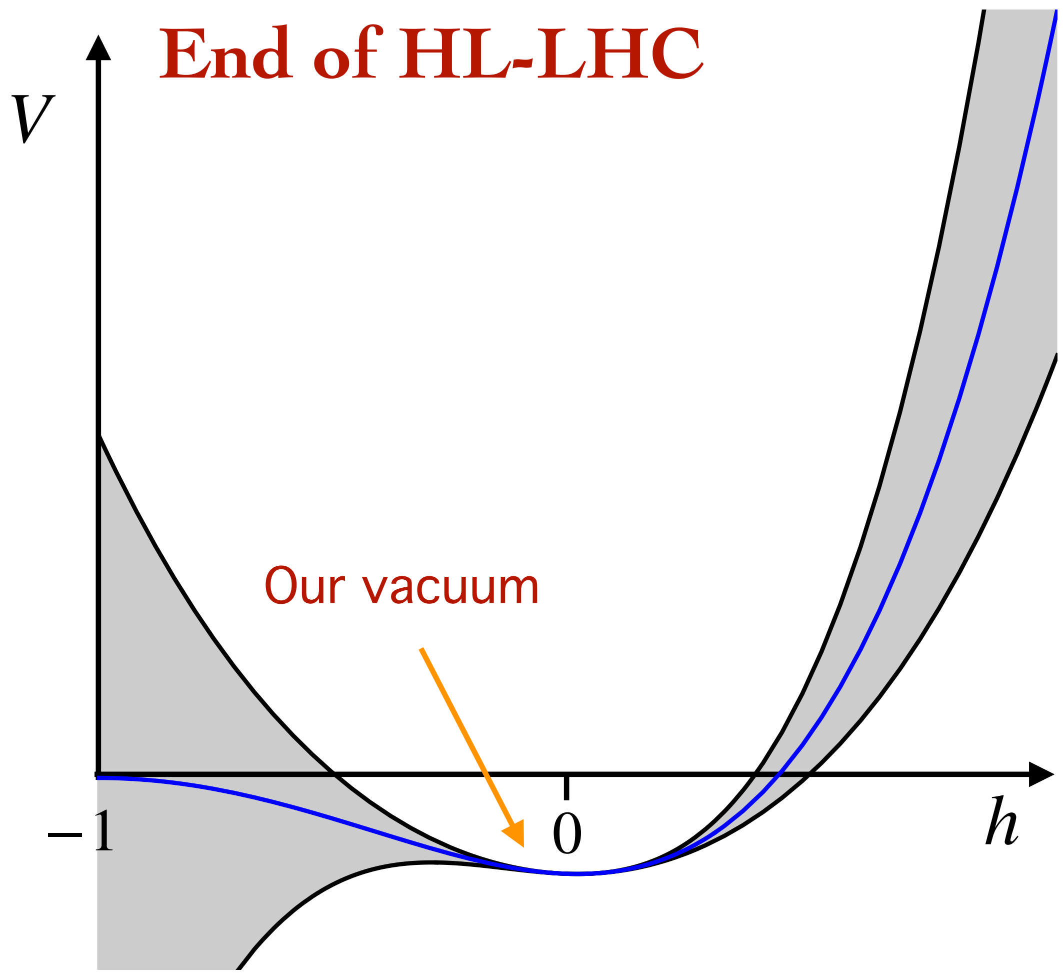


e.g. ATLAS H+HH combination: $-0.4 < \kappa_\lambda < 6.3$

Note that:

- We are assuming the quadrilinear coupling to be that of the SM
- BSM physics may lead to more complicated Higgs sectors with additional scalars

The Higgs potential



e.g. ATLAS+CMS HH combination with 3ab^{-1}:
$0.1 < \kappa_\lambda < 2.3$

Note that:

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Going beyond the SM

The κ-framework

The failure in finding new physics at the LHC till now has changed our approach: abandon Model Building and go for model independent approaches

The main measurements of Higgs-boson properties are based on five production modes: ggF, VBF, WH, ZH, ttH and five decay modes: $\gamma\gamma$, WW, ZZ, $\tau\tau$, $b\bar{b}$

The rate measurements in these production and decay channels held measurements of the couplings in the so called κ-framework

- The signals observed originate from a single narrow resonance treated in the narrow width approximation

$$(\sigma \cdot \mathrm{BR})(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- Only modifications of the coupling strengths are considered, while the tensor structure of the couplings is assumed to be the same as in the SM

Modifications of the coupling strength are introduced by rescaling (some of) them with appropriate factors κ_i

Also the effective couplings to gluons and photons are modified by separate scaling factors

The κ-framework

The failure in finding new physics at the LHC till now has changed our approach: abandon Model Building and go for model independent approaches

LHCHXSWG-2012-001

LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle

LHC Higgs Cross Section Working Group, Light Mass Higgs Subgroup
A. David[1], A. Denner[2], M. Dührssen[3], M. Grazzini[4], C. Grojean[3], G. Passarino[5], M. Schumacher[6], M. Spira[7], G. Weiglein[8], and M. Zanetti[9].*

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[8] DESY, Hamburg, Germany
[9] Massachusetts Institute of Technology, Cambridge, USA

Abstract
This document presents an interim framework in which the coupling structure of a Higgs-like particle can be studied. After discussing different options and approximations, recommendations on specific benchmark parametrizations to be used to fit the data are given.

It is interesting to observe that the κ-framework we introduced in 2012 to explore Higgs couplings as "interim recommendation" is still at the basis of the analyses !

The SMEFT paradigm

Standard Model Effective Field Theory:
The EFT constructed with Standard Model fields and symmetries

The SM Lagrangian is supplemented with higher-dimensional gauge-invariant operators built from SM fields

It offers a powerful method to parametrise BSM physics

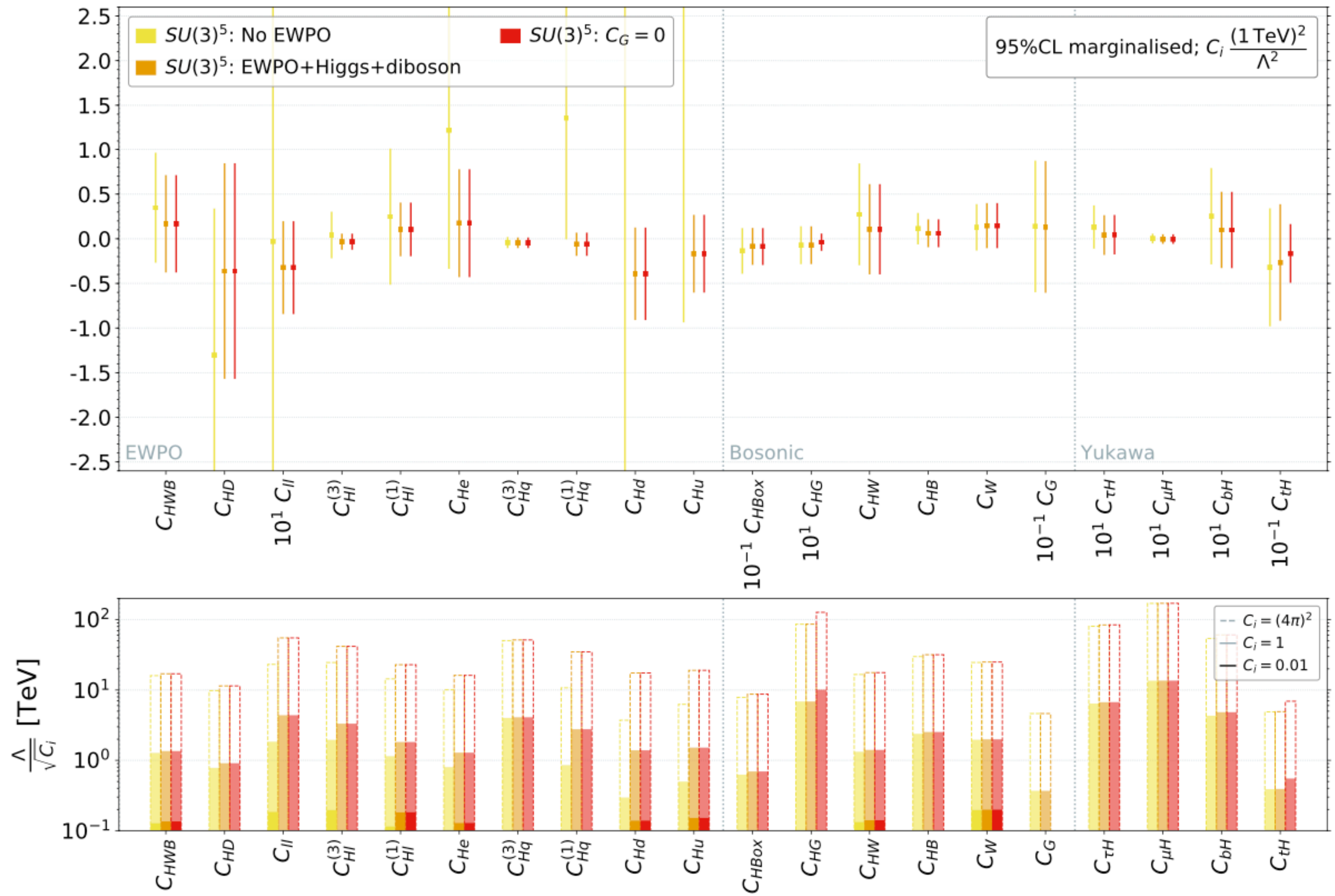
With the assumption that new physics fulfils the decoupling theorem the effect of these operators is suppressed by powers of the new-physics scale Λ

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \ldots .$$

Buchmüller and Wyler (1986)
Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)

If no further assumptions are made 2499 dimension-6 operators contribute !

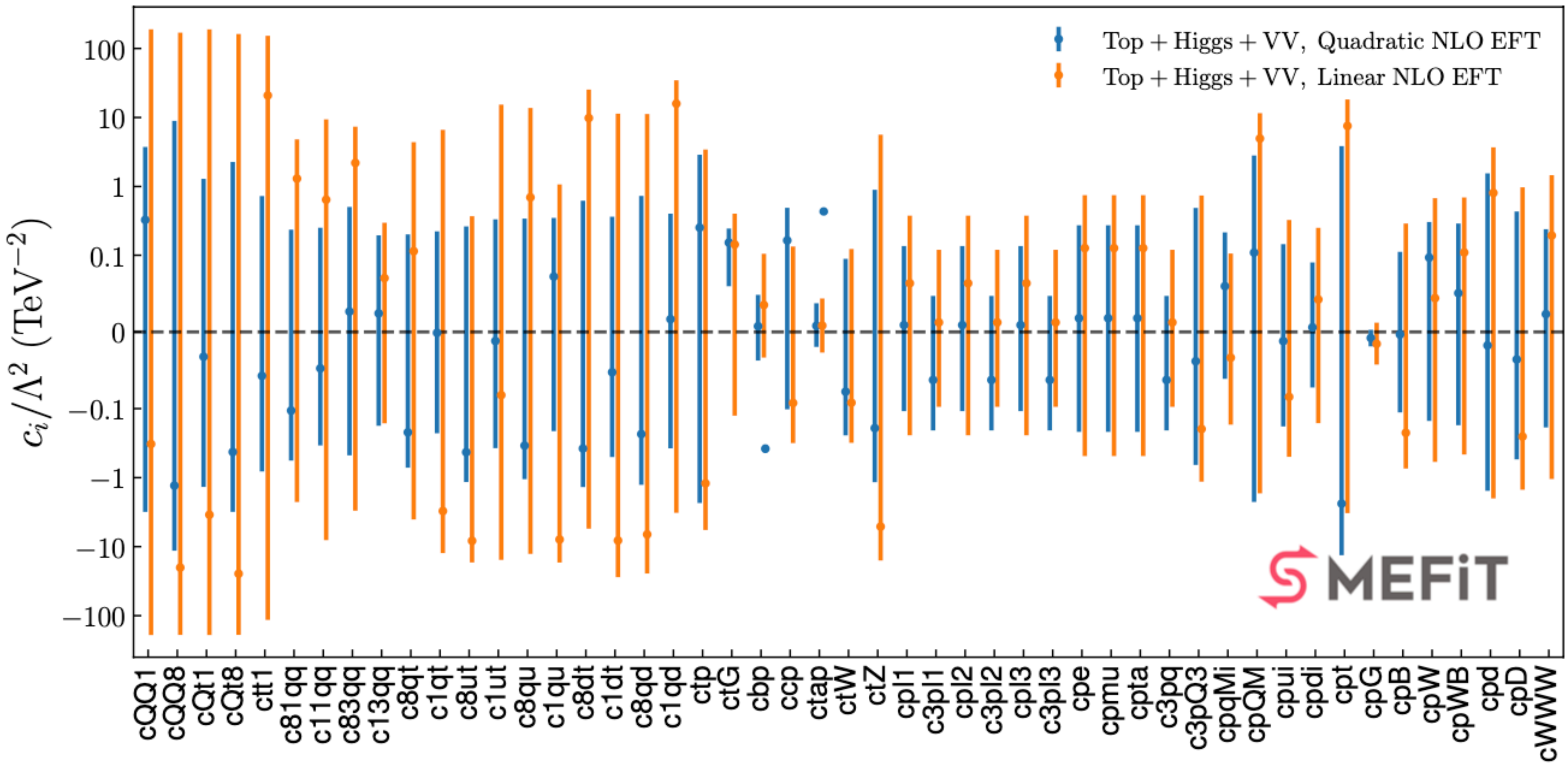
The SMEFT paradigm



Higgs+EW+Top combination, 34 parameters

Sanz et al (2020)

The SMEFT paradigm



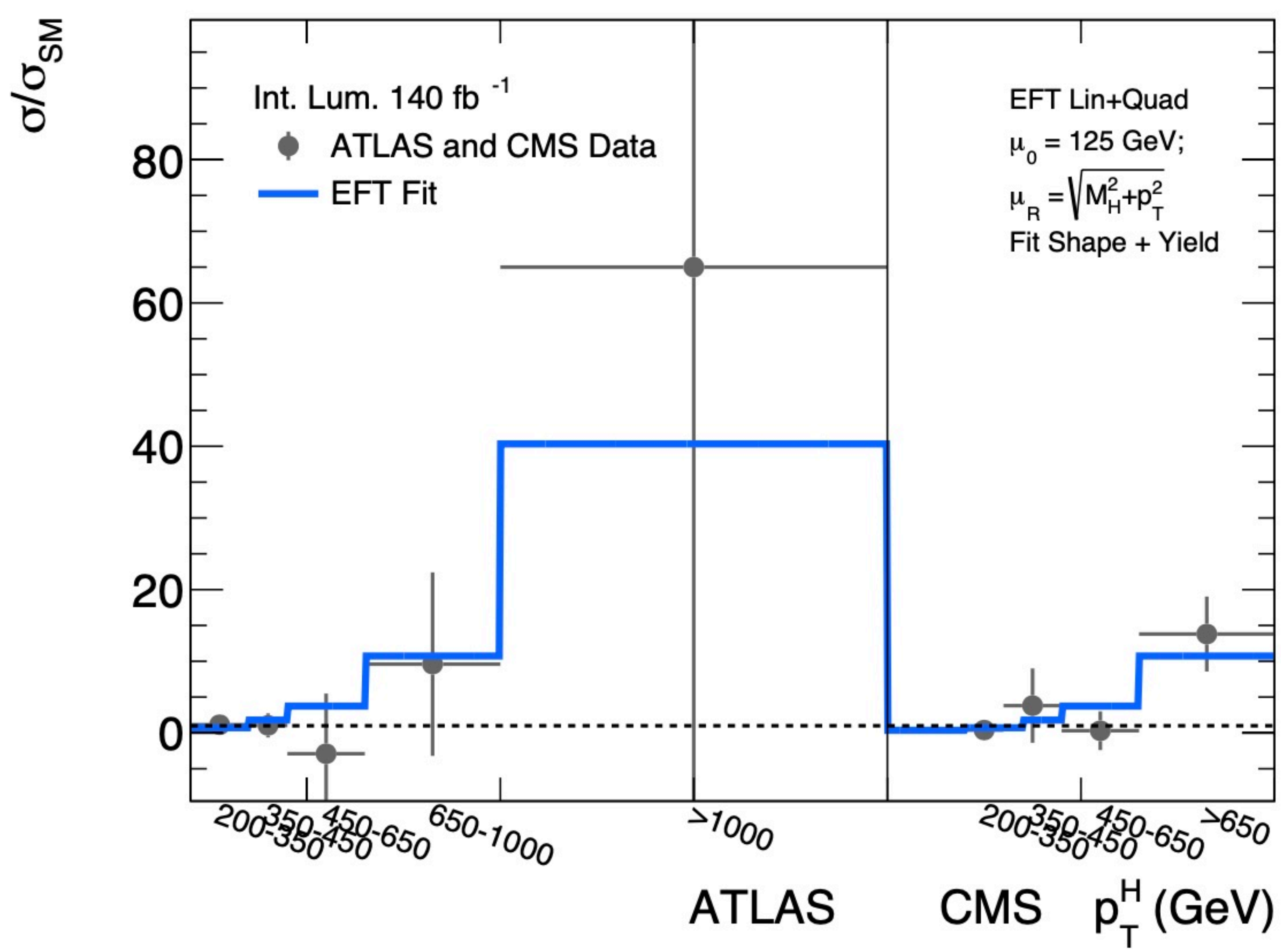
Higgs+EW+Top combination, NLO QCD, 50 parameters

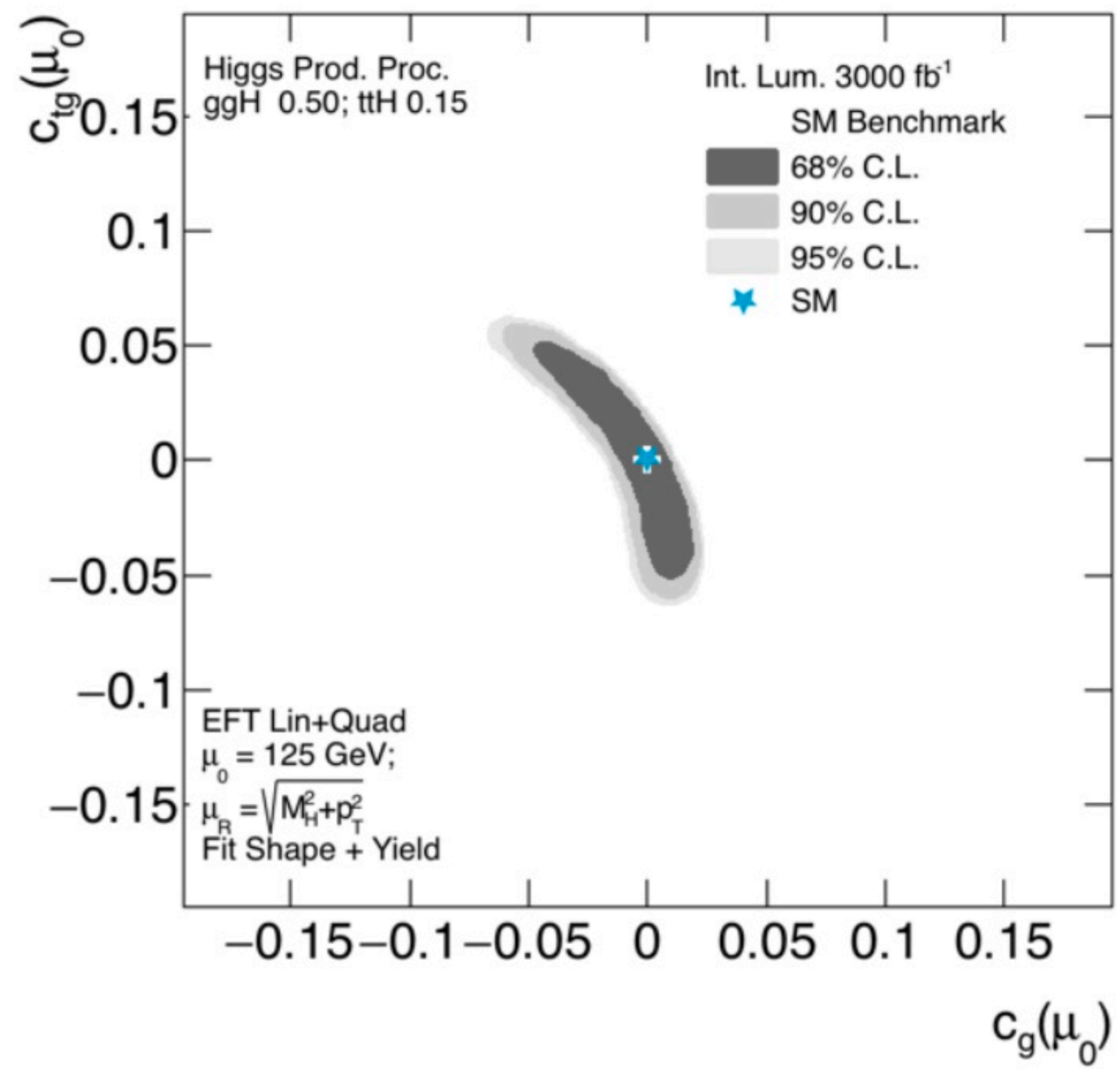
Maltoni et al (2021)

The SMEFT paradigm

More stringent constraints by limiting to specific set of operators: see e.g. Higgs p_T

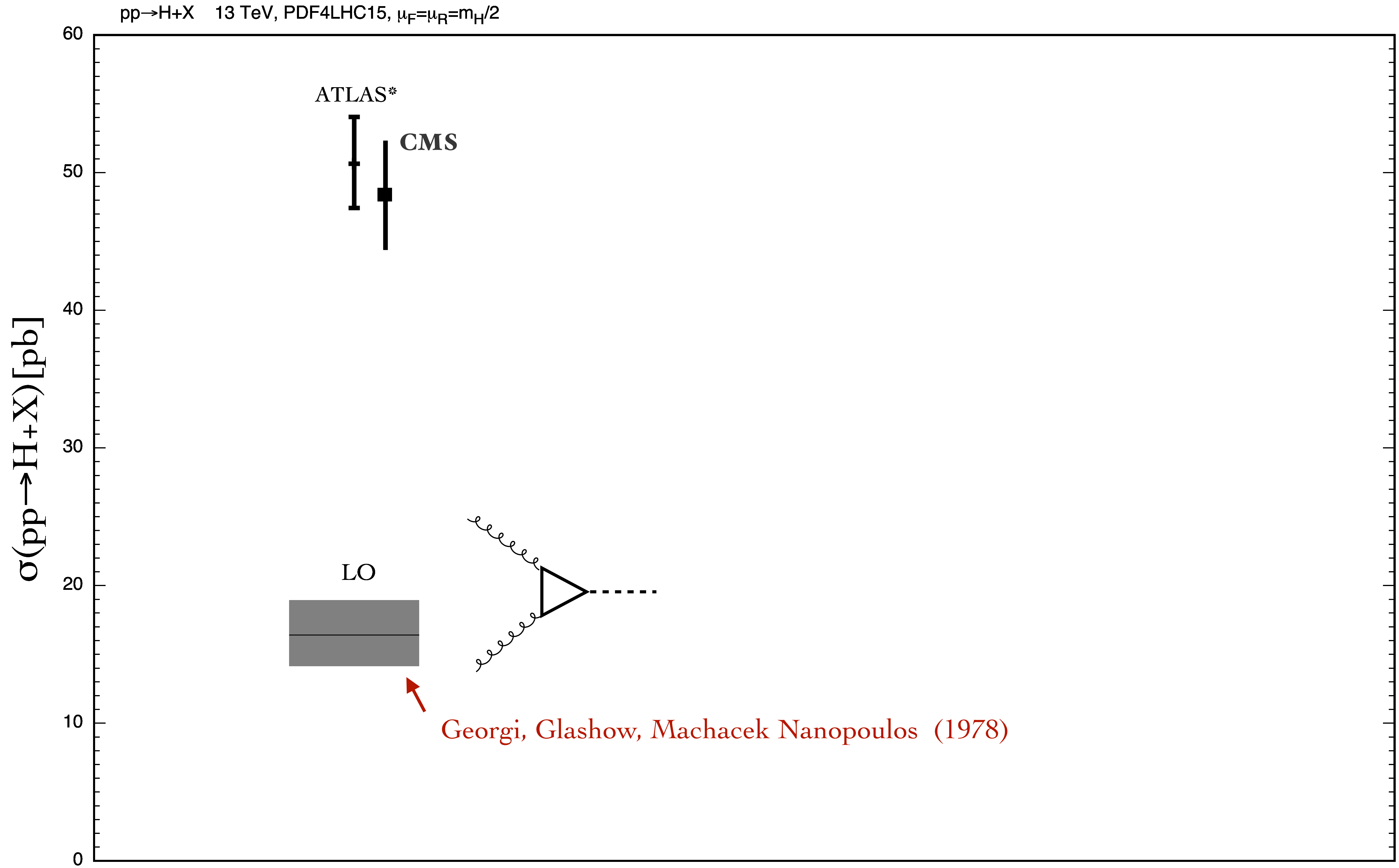
$$\begin{aligned}
\mathcal{O}_1 &= |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}\,, \\
\mathcal{O}_2 &= |H|^2 \bar{Q}_L H^c t_R + h.c.\,, \\
\mathcal{O}_3 &= \bar{Q}_L H \sigma^{\mu\nu} T^a t_R G^a_{\mu\nu} + h.c.\,,
\end{aligned}$$



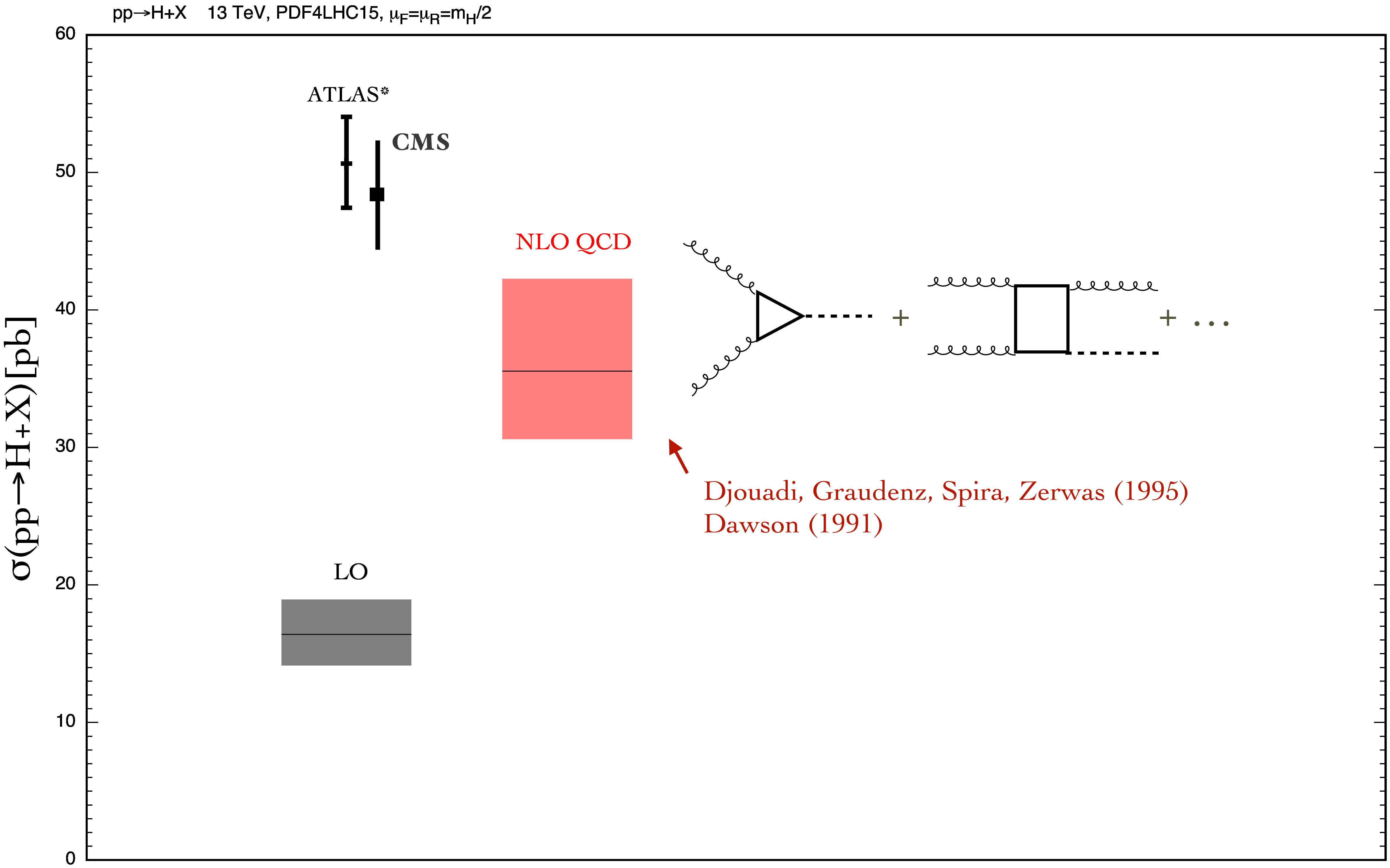


Battaglia, Spira, Wiesemann, MG (2021)

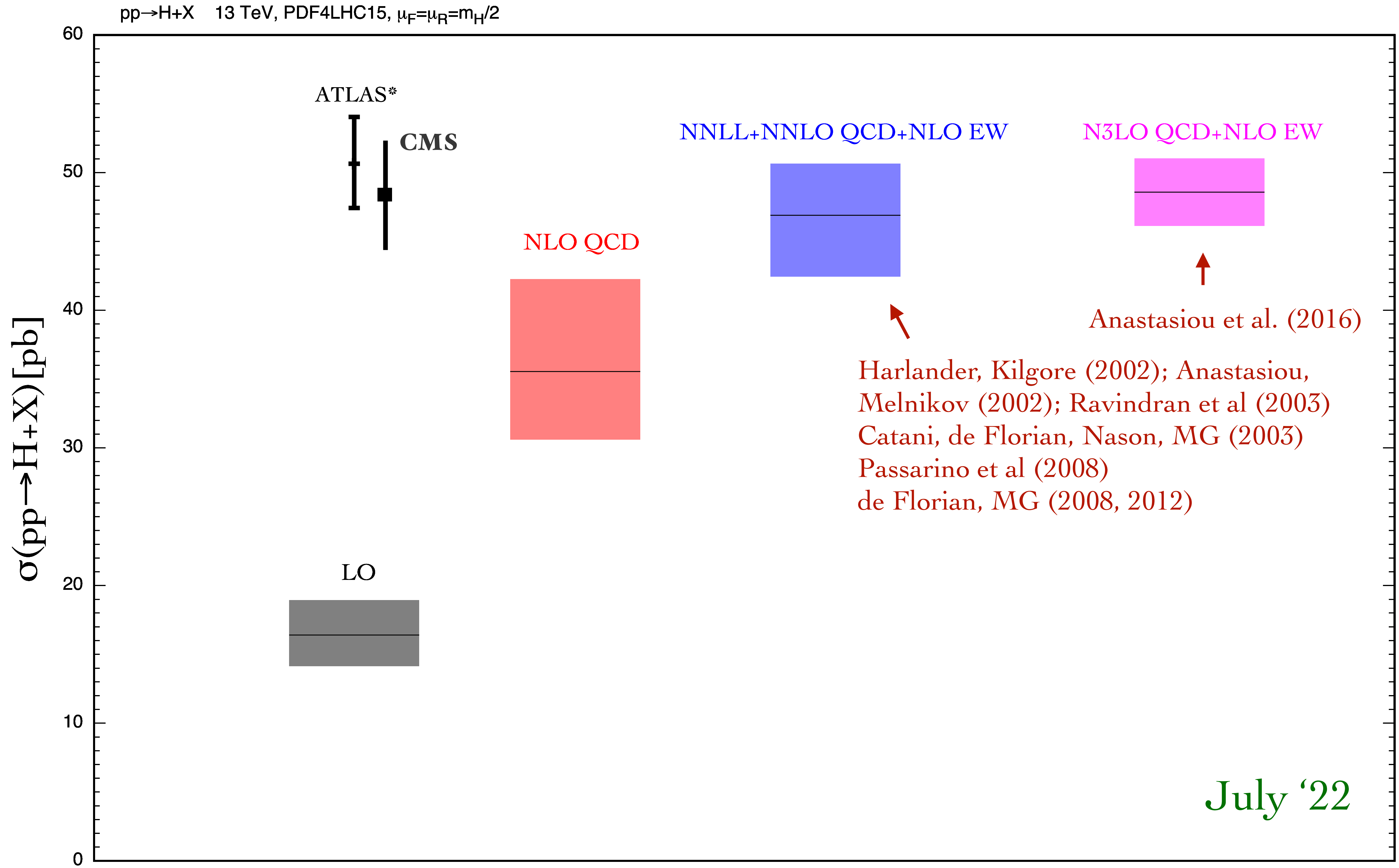
The role of precision theory



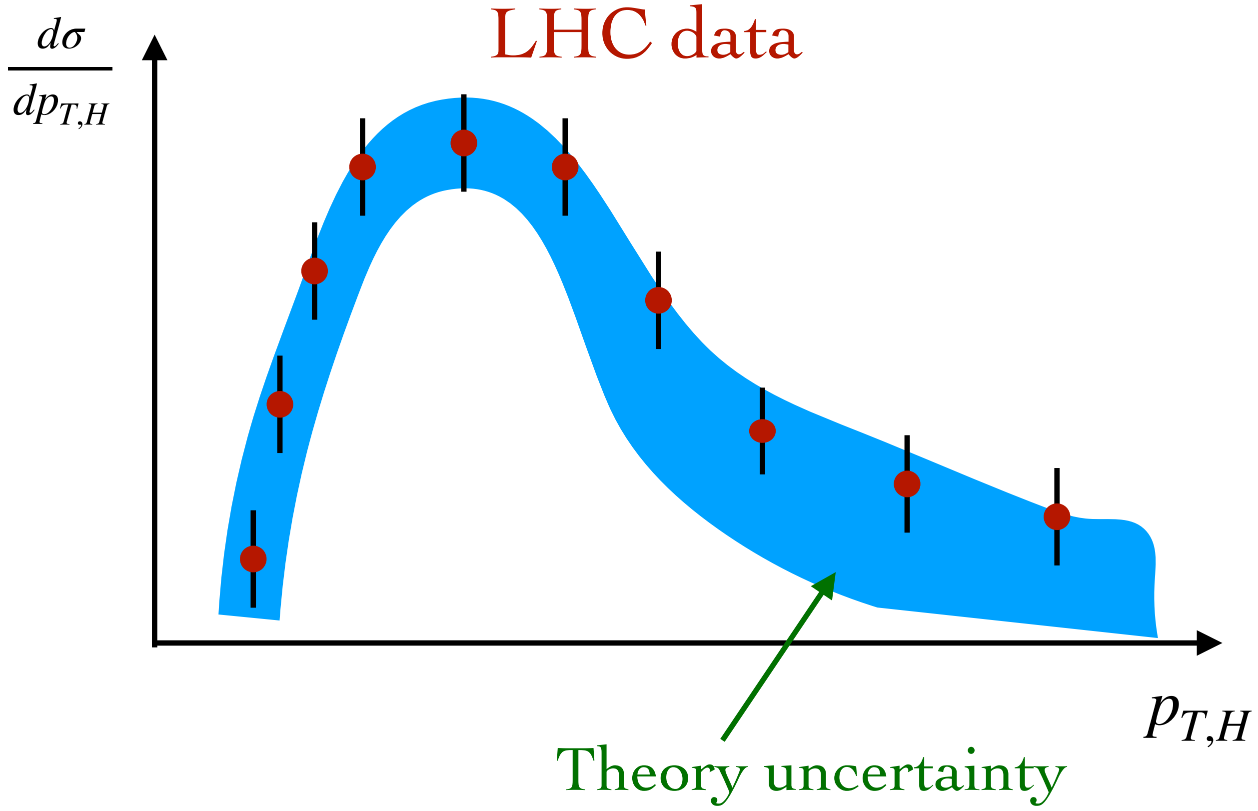
The role of precision theory



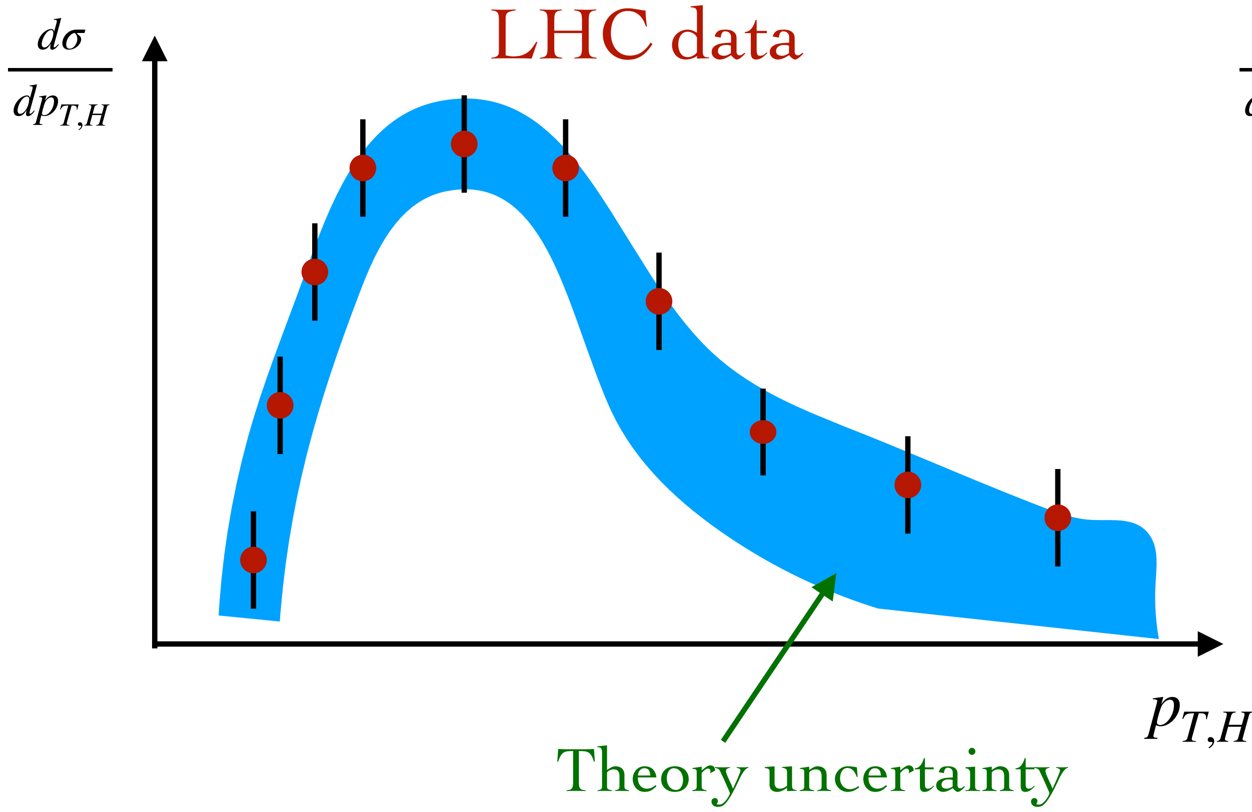
The role of precision theory

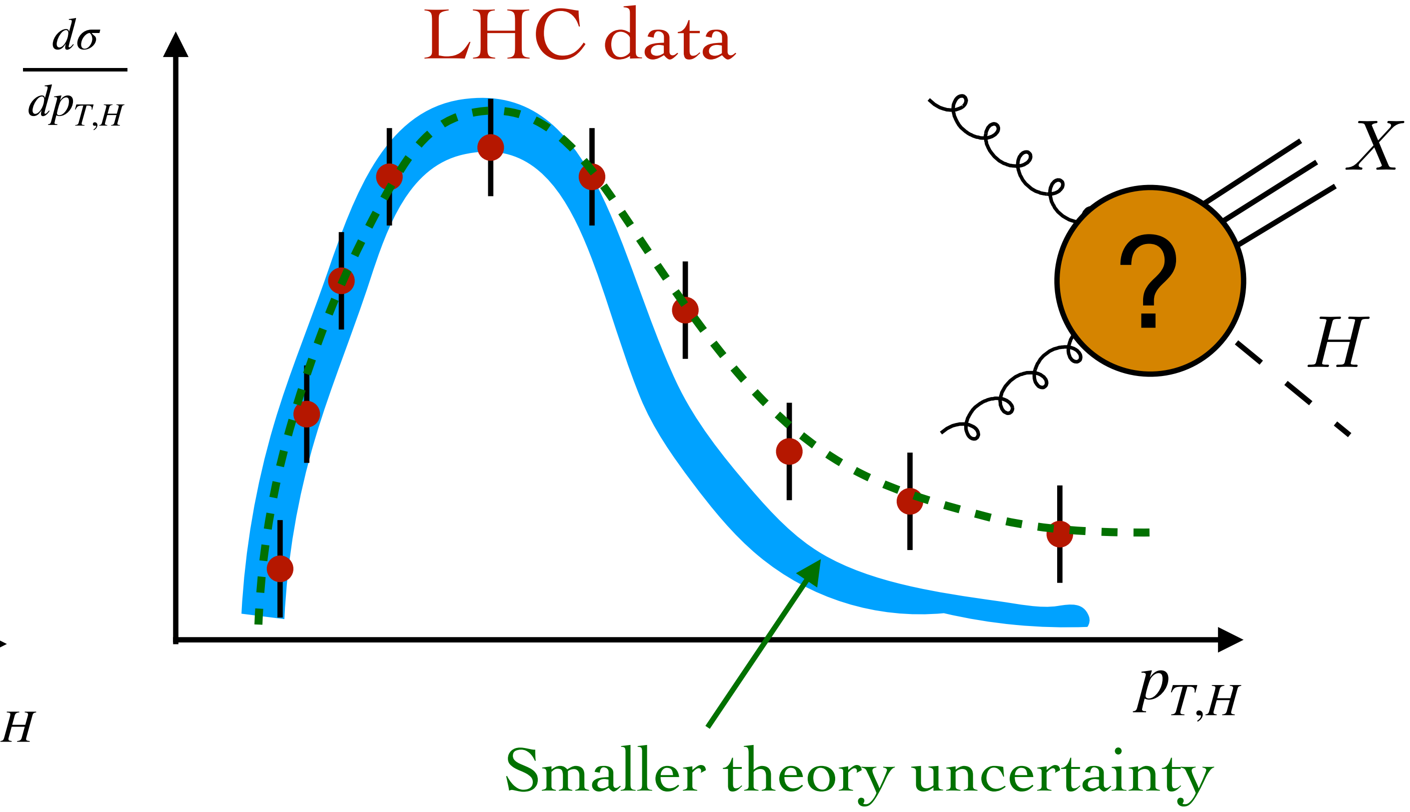


The role of precision theory

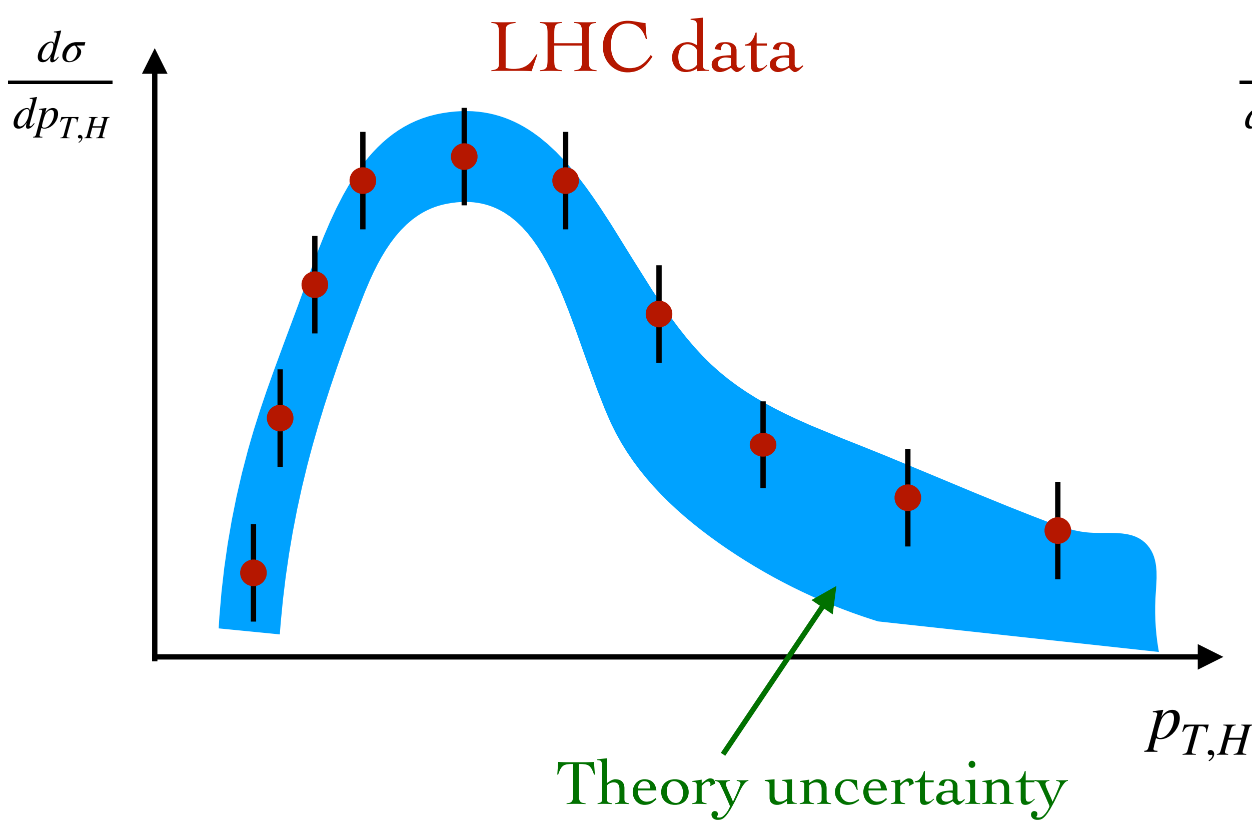


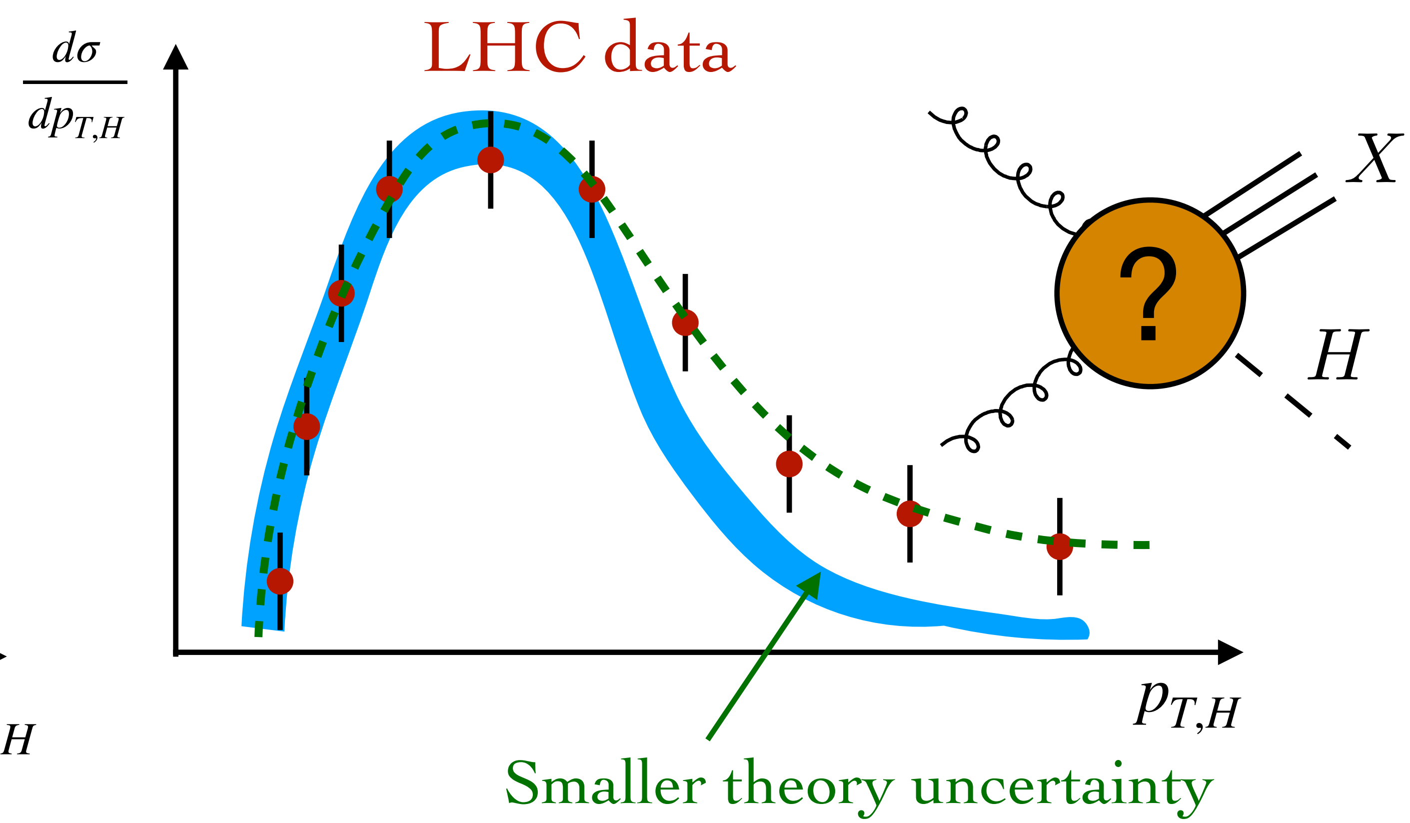
The role of precision theory





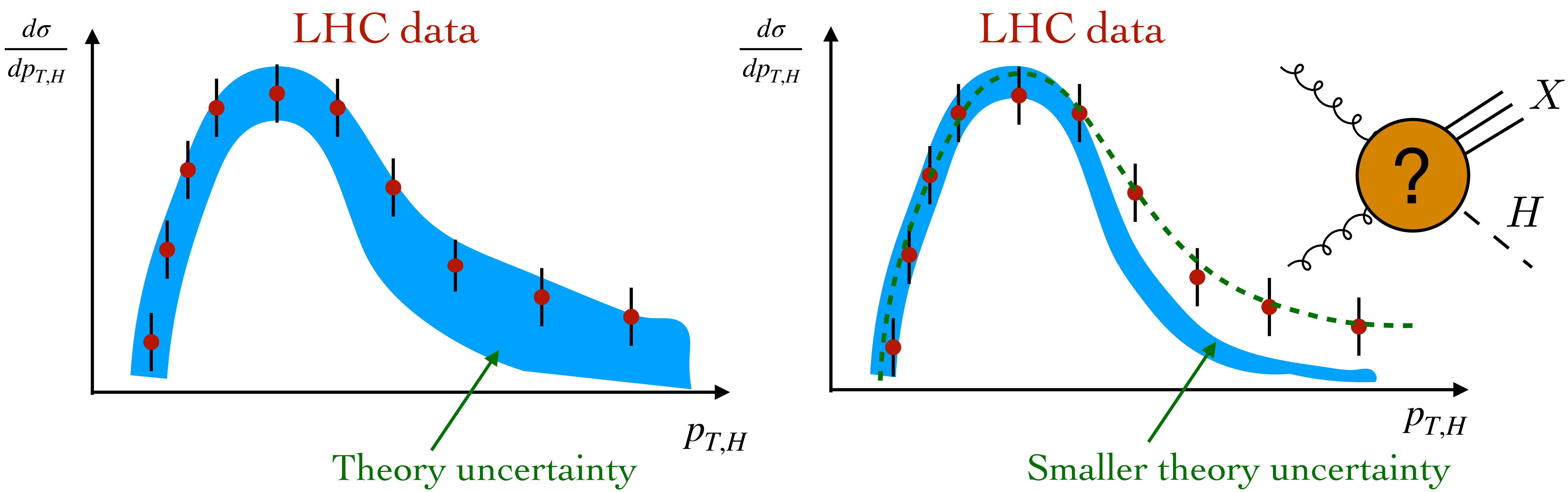
The role of precision theory





Larger theory uncertainties may lead to miss (or at least delay) new discoveries

The role of precision theory



Larger theory uncertainties may lead to miss (or at least delay) new discoveries

Exact NLO QCD corrections to Higgs p_T spectrum computed only recently

Jones, Kerner, Luisoni (2018)
Chen, Huss, Jones, Kerner, Lang Lindert, Zhang (2021)
Bonciani et al. (2022)

Combined with NNLO in the EFT

Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier (2016)
Boughezal et al (2015)

→ accurate predictions for boosted analyses

LHCHXSWG-2019-002

What else ?

The Great Depression

Particle physicists ~ 10 years after the Higgs discovery are generally depressed

- No new discovery…
- The Higgs is very SM like…

1980 — You will find new physics at LEP

1990 — You will find new physics at the Tevatron

2000 — You will certainly find new physics at the LHC, it's now or never

Maybe this is the theorists' fault ?

Tito D'Agnolo, Higgs Hunting 2023

I find this attitude largely unjustified !

Up to now only less than 10 % of the expected data set has been analysed and the picture is consistent with the SM but the exploration of the Higgs sector is still in its infancy and surprises are still well possible

The Higgs couplings to W and Z bosons and to third generation fermions are known with precision between 5 and 20 %

This is far from the percent level precision with which we know the strong coupling $\alpha_S(m_Z)$ (not to speak about the QED coupling α !)

More precise determinations of these couplings could uncover differences that might in turn be due to new physics

Despite the prospects for the improvements in the extraction of couplings to vector bosons and third generation fermions, we would ideally like to establish the interactions with electron and up and down quarks, which are those relevant to our everyday life: this is clearly not possible at present

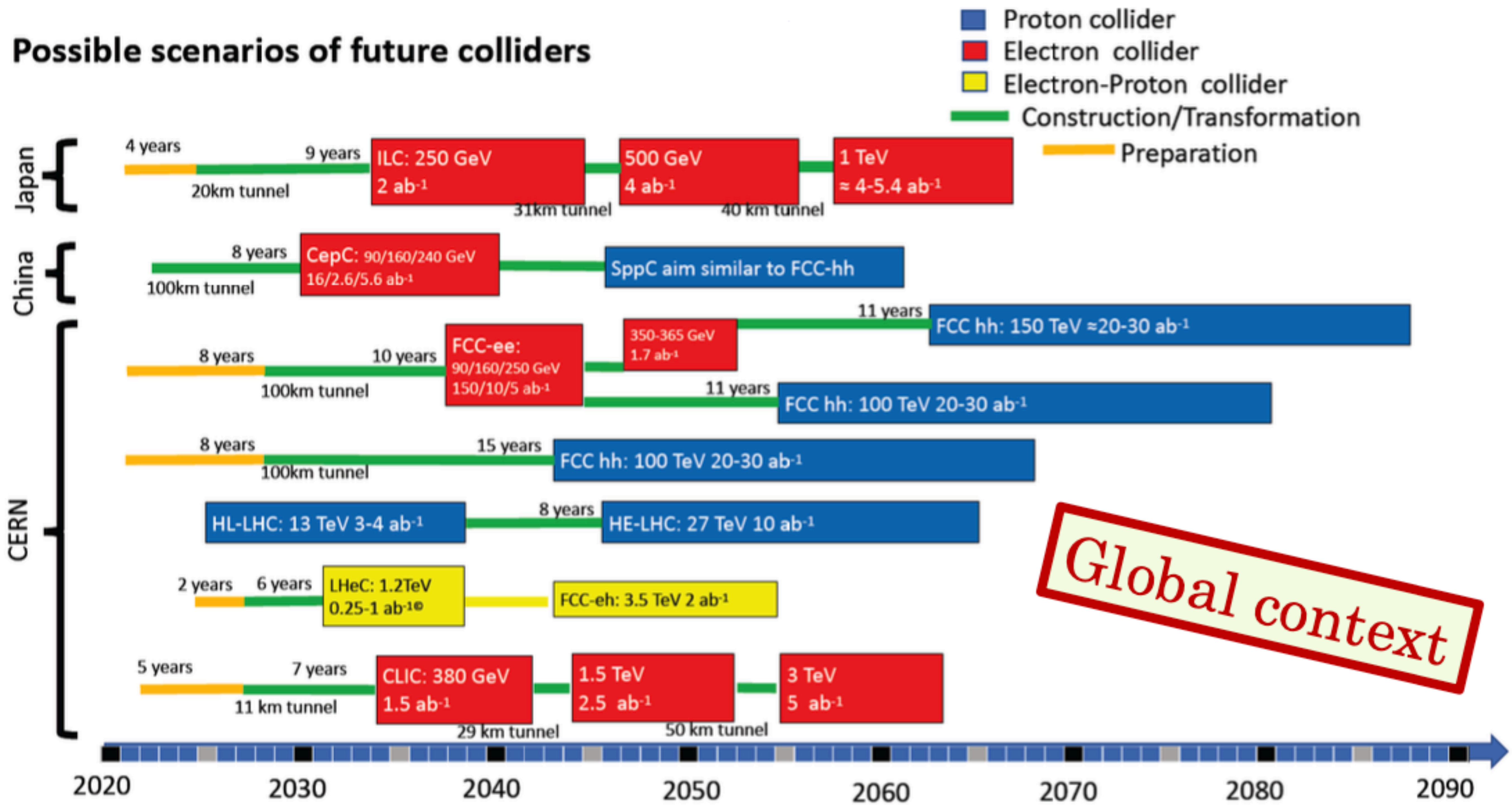
Nonetheless the second generation fermions are much more accessible and we have seen that establishing $H \to \mu^+\mu^-$ is within reach, while recent results suggest that $H \to c\bar{c}$ will also become accessible at HL-LHC

Studying the Higgs potential and establishing if it is the one predicted by the SM is still far in the future and double Higgs production is the best process to access it: SM within reach in Run 3 by combining ATLAS and CMS

This programme has an immense value by itself, regardless on whether we will find New Physics or not !

Going beyond this we clearly need a new collider

The future is bright….



…but stay healthy and live long !

FCC

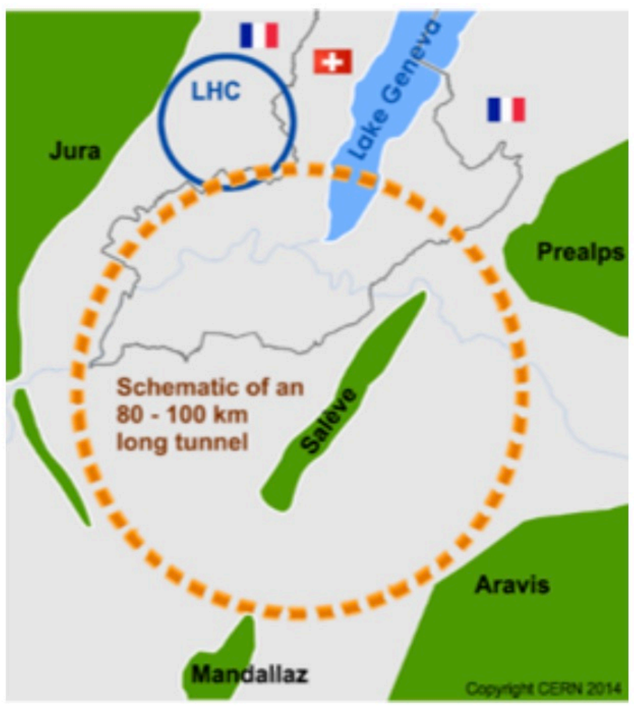
FCC integrated program

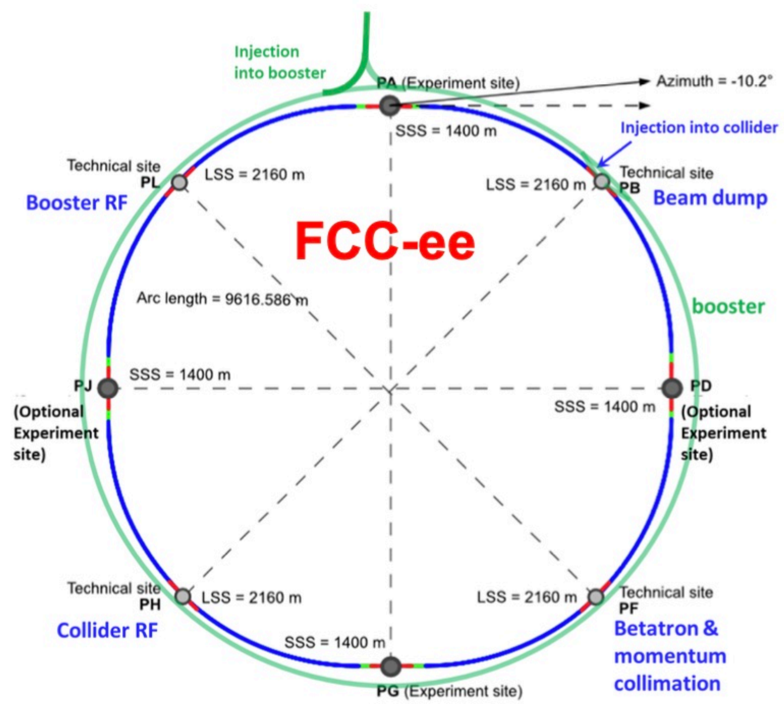
FUTURE CIRCULAR COLLIDER

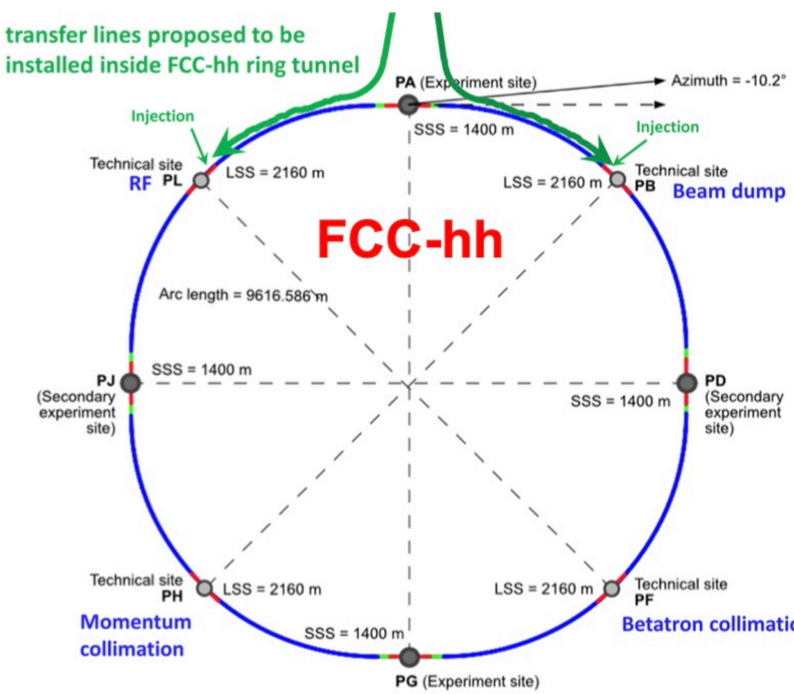
2

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







2020 - 2040 | 2045 - 2063 | 2070 - 2095

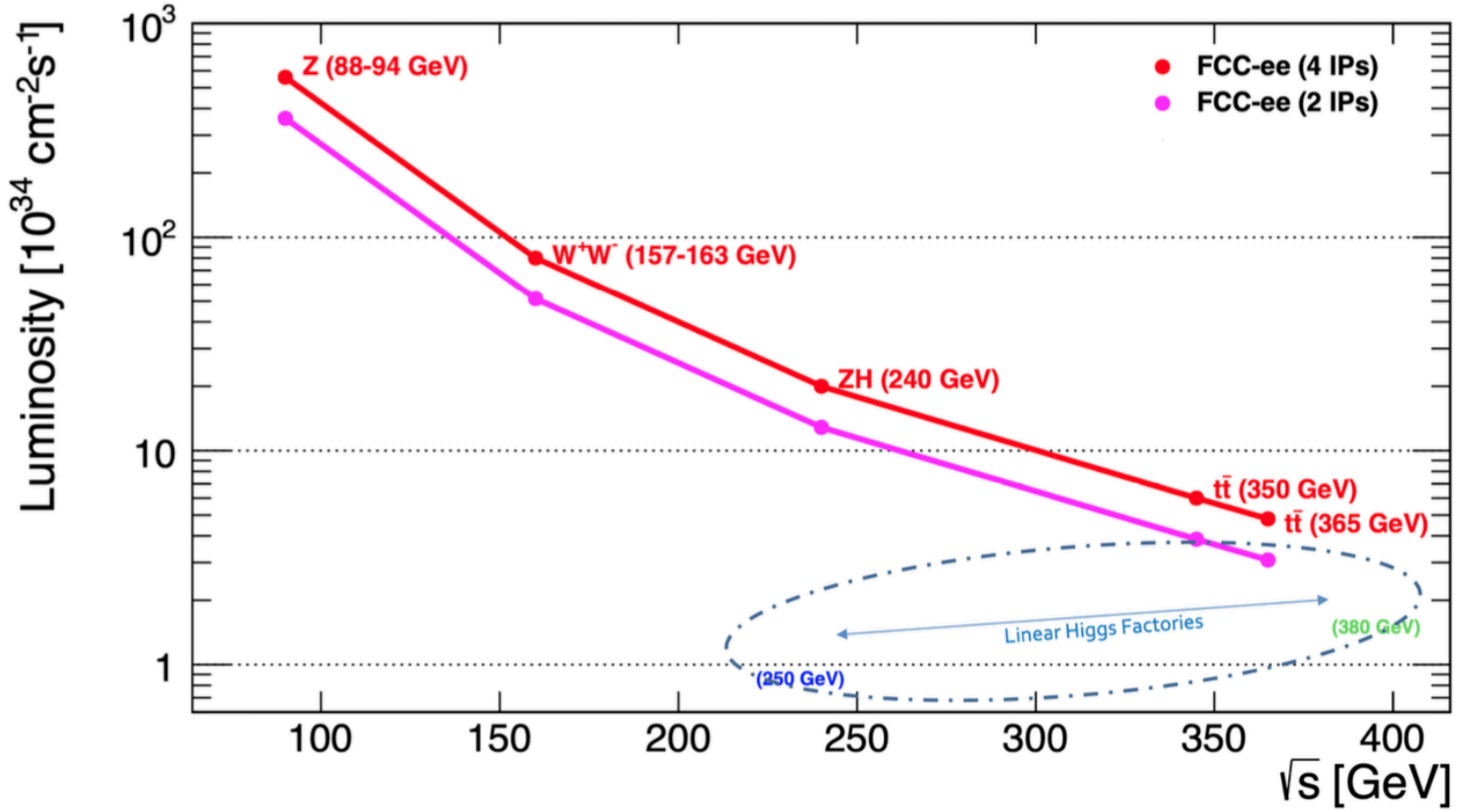
CERN

Slide from Micheal Benedikt

FCC-ee

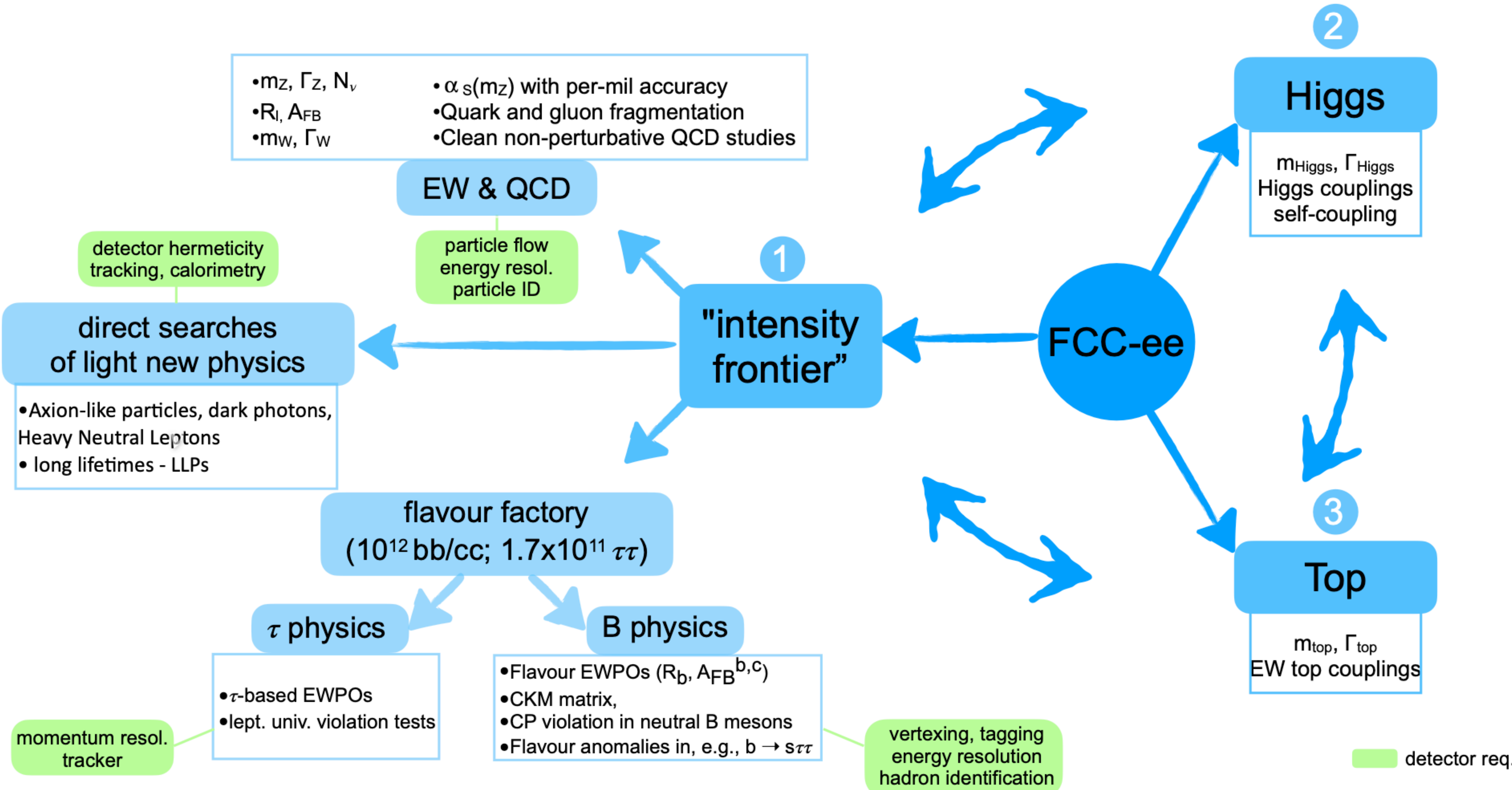
All the heaviest SM particles produced in a clean environments

LEP data accumulated in the first 3min !



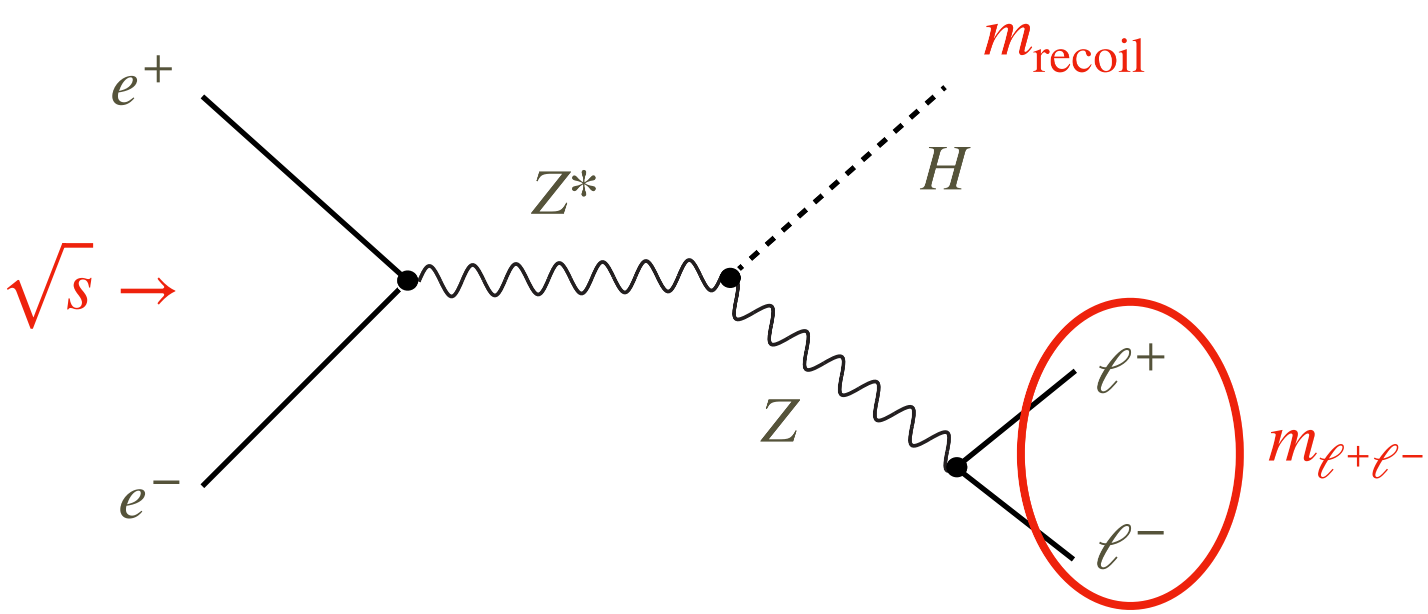
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

FCC-ee



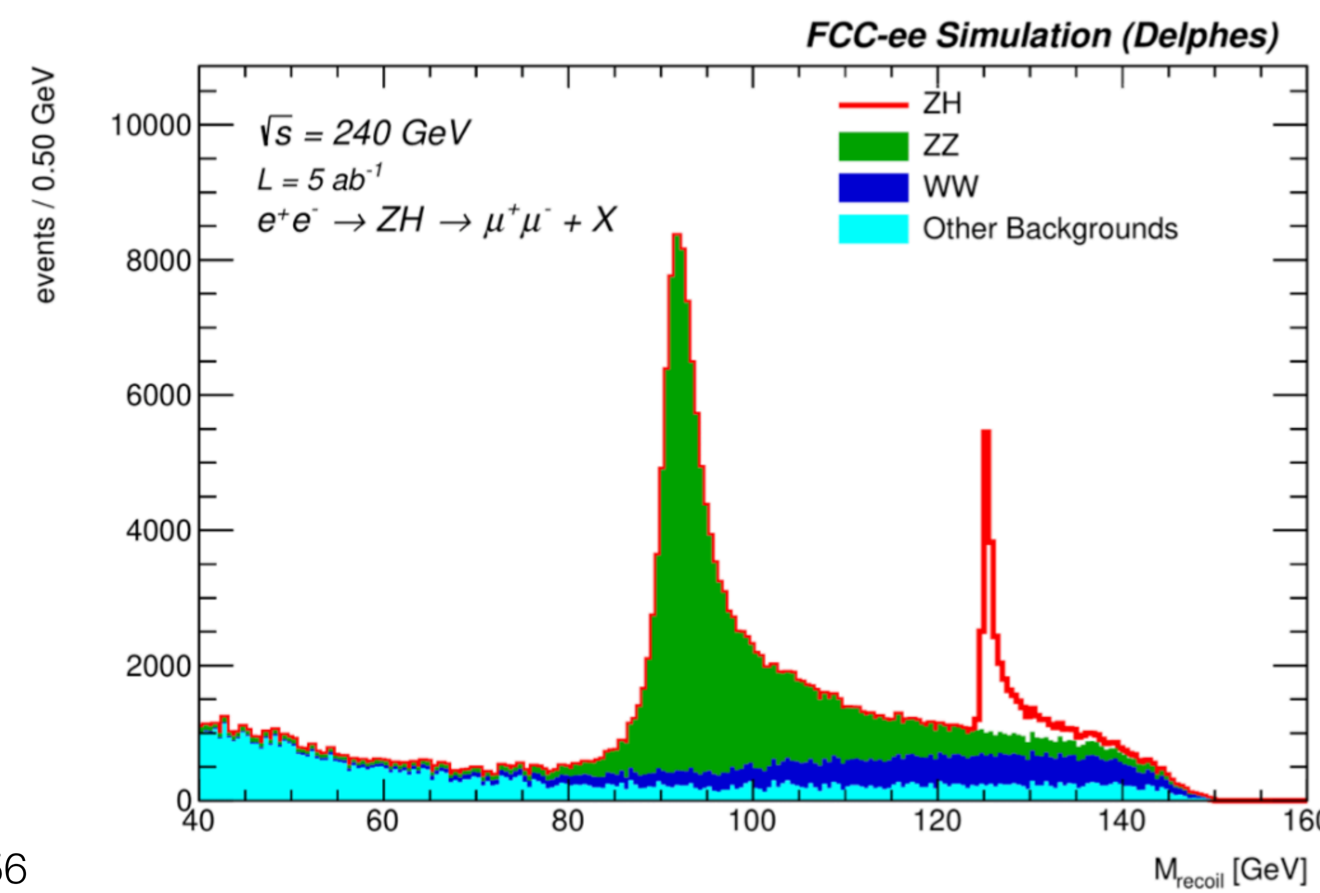
Christophe Grojean, FCC week 2022

FCC-ee



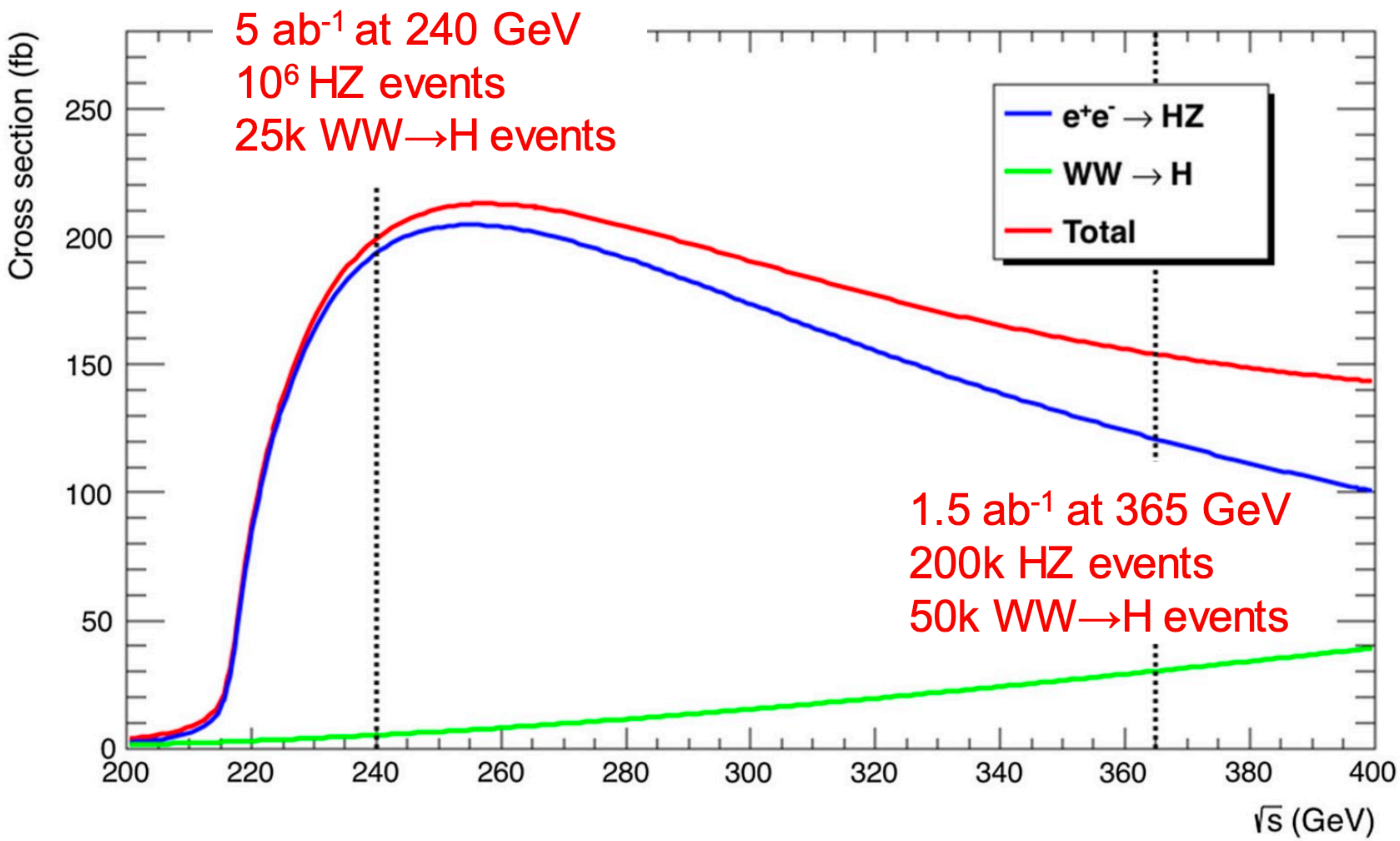
$$m^2_{\text{recoil}} = s - 2E_{\ell^+\ell^-}\sqrt{s} + m^2_{\ell^+\ell^-}$$

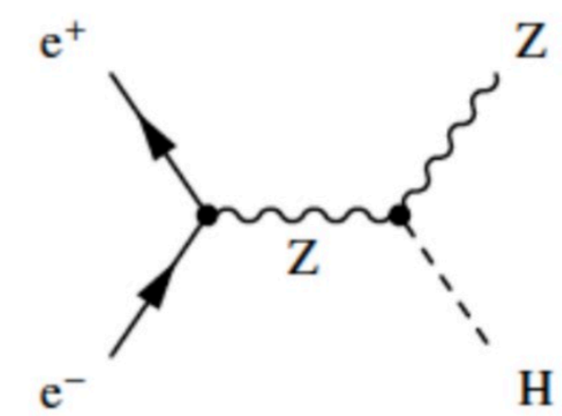
Recoil method (does not work at hadron colliders) will allow the first model independent extraction of the Higgs width

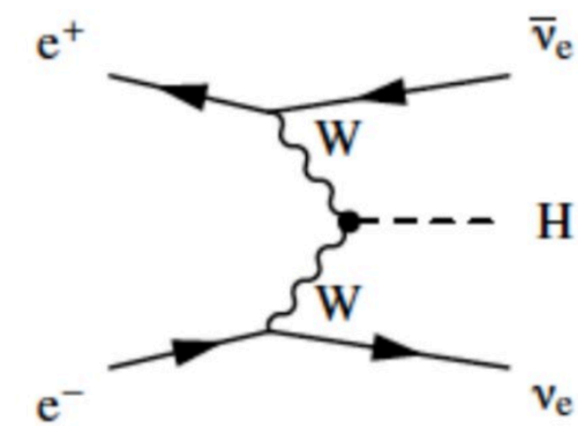


FCC-ee

Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)% precision. Achieved through operation at two energy points.







Sensitivity to both processes very helpful in improving precision on couplings.

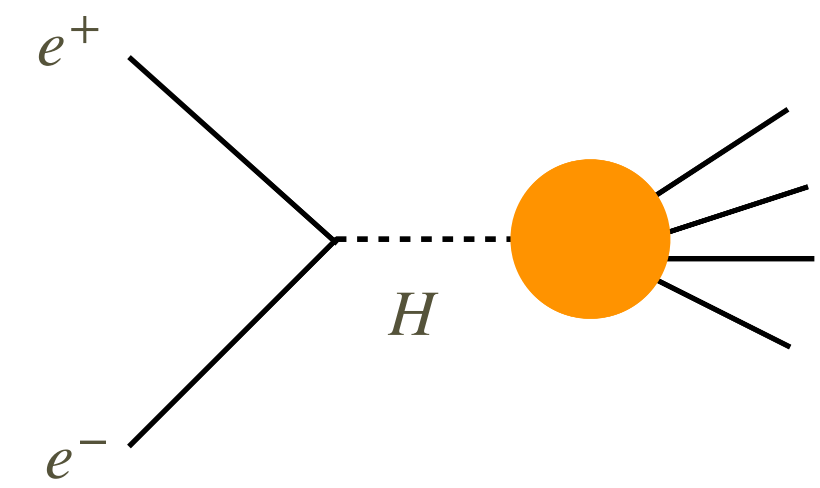
FCC-ee

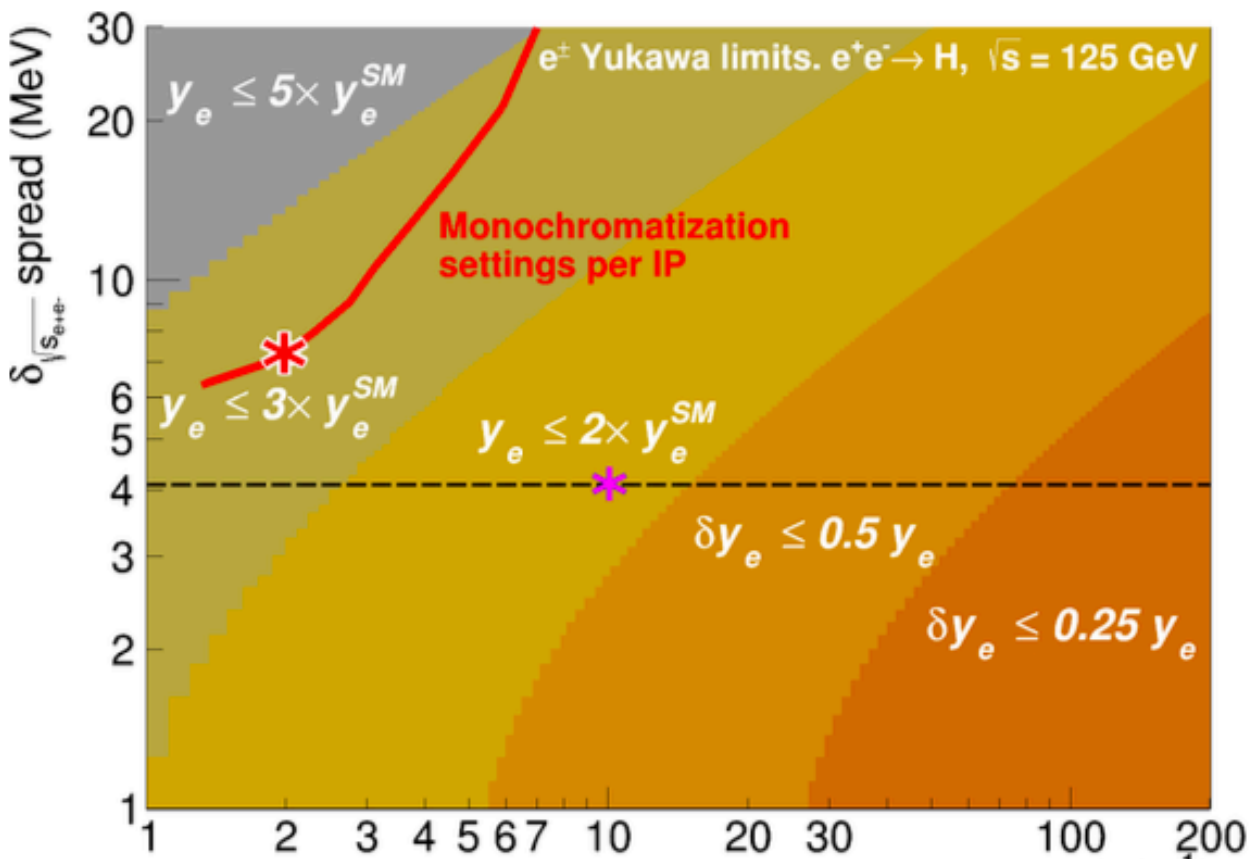
The challenge: the electron Yukawa

m_H prior knowledge to a couple of MeV

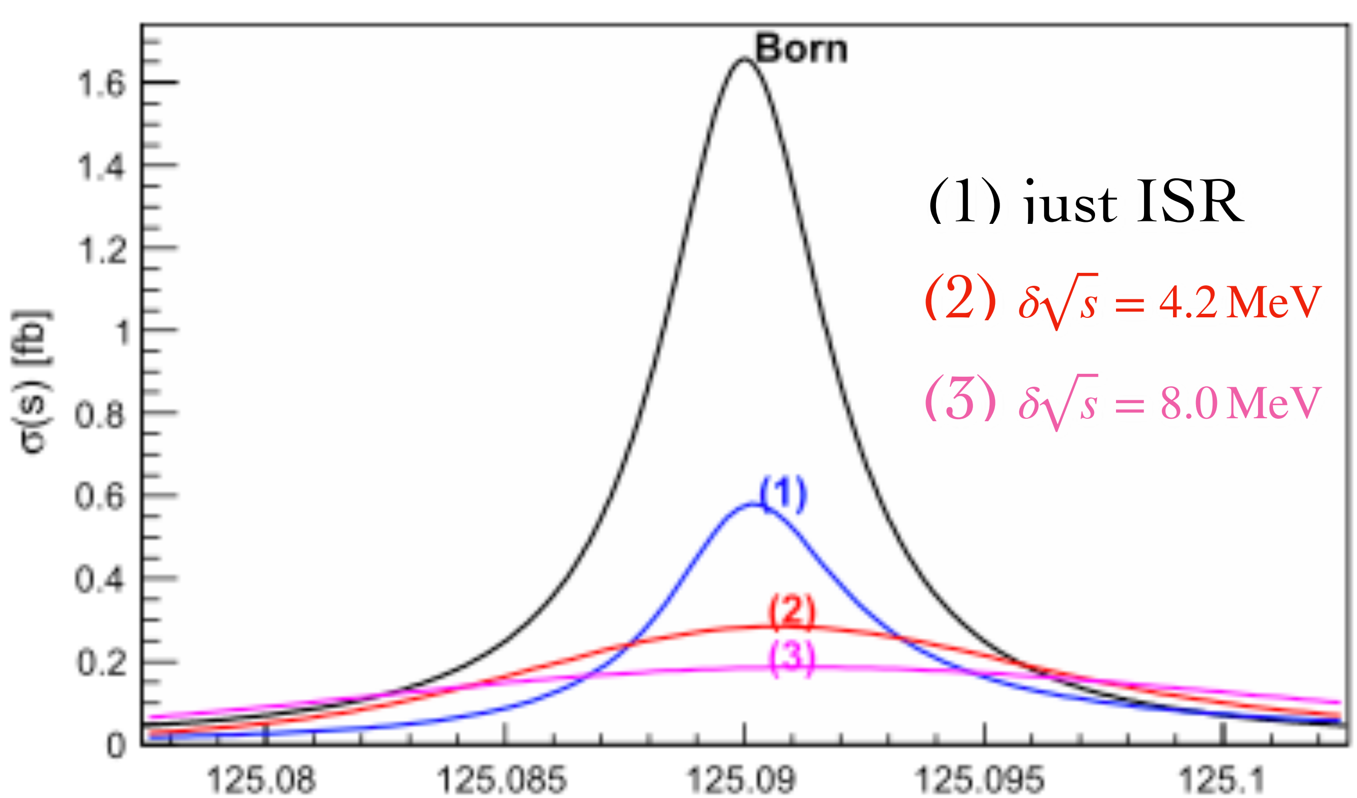
Monochromatisation: typically $\Gamma_H(4.2\,\mathrm{MeV}) \ll \delta\sqrt{s}$

Requires huge luminosity, to be achieved with few years of running (and possibly 4 IP)





Snowmass 2021 report



Jadach, Kycia (2015)

FCC-hh

What should we expect for the discovery reach ?

Tevatron
$p\bar{p}$, 1.96 TeV, 10 fb^{-1}

Exclusion limit ~ 1.2 TeV

(if they had analysed all their data in electron and muon channels; actual CDF limit 1.071 TeV, 4.7fb^{-1}, μμ only)

× 4

LHC
pp, 13.6 TeV, 139 fb^{-1}

Exclusion limit ~ 5.1 TeV

(electron and muon channels, single experiment)

Salam, FCC week (2023)

This is for a Z' with SM couplings

FCC-hh

What should we expect for the discovery reach ?

LHC
pp, 13 TeV, 139 fb^{-1}

Exclusion limit ~ 5.1 TeV

(electron and muon channels, single experiment)

× 7.8 →

FCC-hh
pp, 100 TeV, 20 ab^{-1}

Exclusion limit ~ 41 TeV

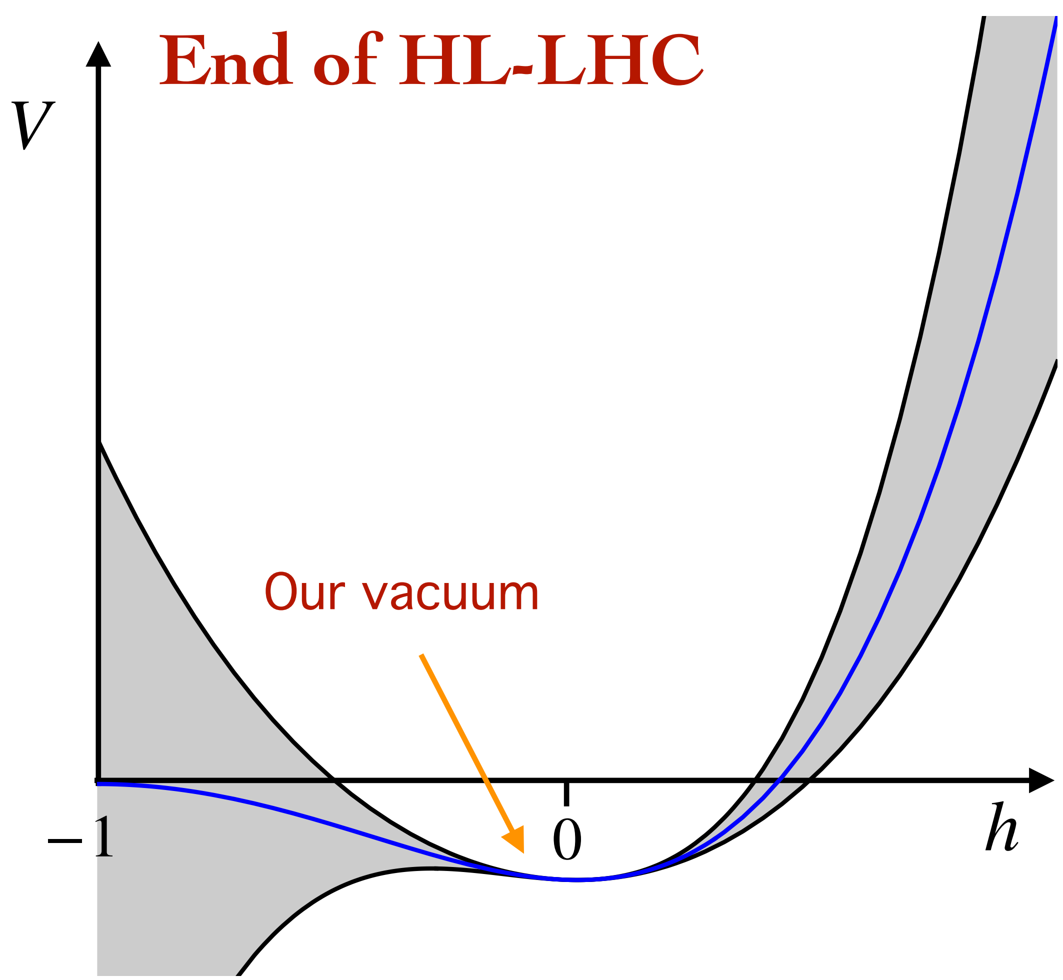
(based on PDF luminosity scaling, assuming detectors can handle muons and electrons at these energies)

Salam, FCC week (2023)

This is for a Z' with SM couplings

→ **In an era in which guaranteed discoveries are over this is the kind of step up that we would hope for !**

The Higgs potential

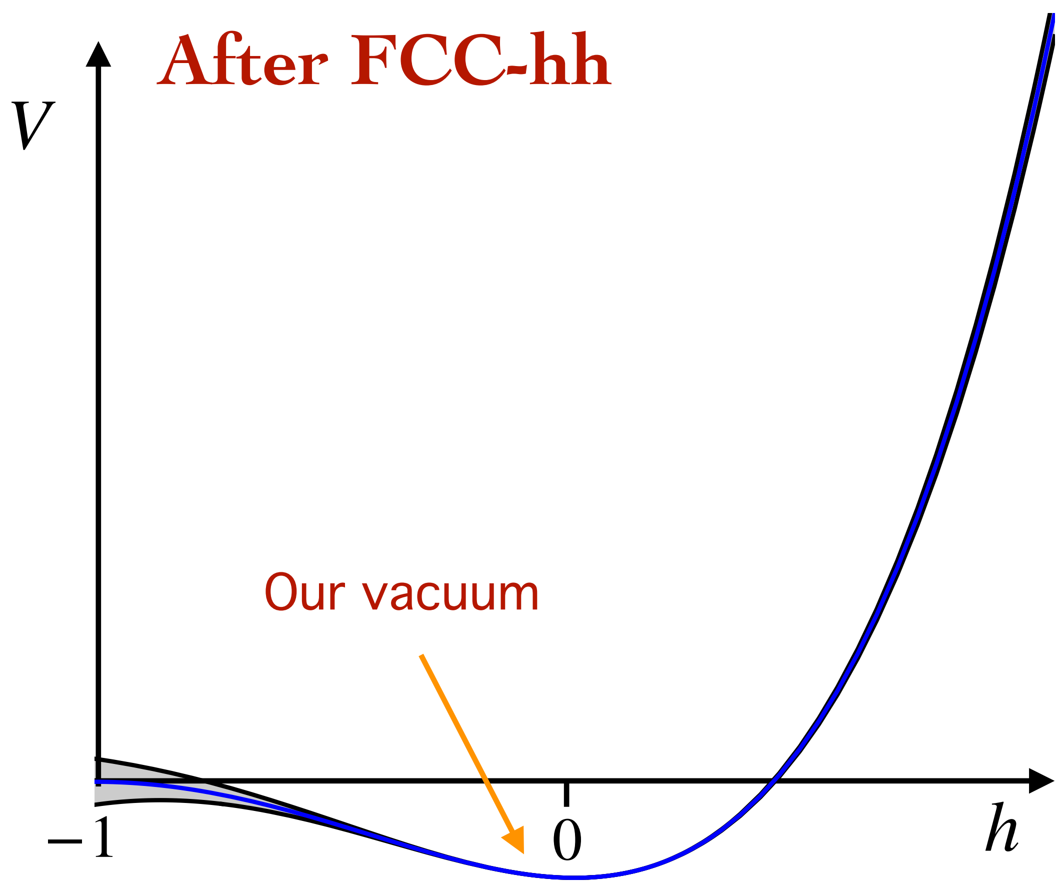


e.g. ATLAS+CMS HH combination with 3ab^{-1}:
$0.1 < \kappa_\lambda < 2.3$

Note that:

- We are assuming the quadrilinear coupling to be that of the SM
- BSM physics may lead to more complicated Higgs sectors with additional scalars

The Higgs potential



$0.94 < \kappa_\lambda < 1.06$
(statistical errors only)

Mangano, Ortona, Selvaggi (2020)

Note that:

- We are assuming the quadrilinear coupling to be that of the SM
- BSM physics may lead to more complicated Higgs sectors with additional scalars

Summary

- The Higgs boson is to some extent, the most important and mysterious particle in the SM
- Due to its unique nature, it is connected to all the fundamental questions about our Universe
- At present everything looks consistent with the SM but our picture of the Higgs sector is still quite blurry
- The HL-LHC upcoming run will improve the precision measurements of Higgs couplings and extend the search for New Physics signals
- To go beyond we need a broad and ambitious programme that can sharpen our understanding of the physics we already know and, at the same can push the boundaries of the unknown in the intensity and energy frontiers
- More precision, more energy and more sensitivity to New Physics
- The integrated FCC program provides this step forward !