Physics at future colliders: inputs for the European Strategy

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- Introduction
- Current open questions for future colliders
- A few examples
- Conclusions

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INTRODUCTION

- The SM Lagrangian

$$\mathscr{L}_{SM} = \mathscr{L}_{SU(3)\otimes SU(2)\otimes U(1)} + \mathscr{L}_{fermion} + \mathscr{L}_{Higgs} + \mathscr{L}_{Yukawa}$$

reproduces all available exp data thanks to accidental symmetries: B & L conservation, no tree-level FCNC, custodial SU(2). However, it provides no explanation for

- the miracle of (hyper)charges
- the absence of strong CPV
- neutrino masses
- dark matter

It also does not include gravity

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reproduces all available exp data thanks to accidental symmetries: B & L conservation, no tree-level FCNC, custodial SU(2). However, it provides no explanation for

- the miracle of (hyper)charges ⇒ Grand Unification
- the absence of strong CPV ⇒ Peccei-Quinn
- neutrino masses ⇒ See-saw, SO(10)
- dark matter

It also does not include gravity

- enlarge the SM field content
- break accidental symmetries
- spoil agreement with experiment
- hierarchy problem

FROM THE SM TO THE SMEFT

- The SMEFT Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \Lambda^4 + \Lambda^2 |\phi|^2 + \mathscr{L}_5/\Lambda + \mathscr{L}_6/\Lambda^2 + \ldots$$

Determine the CC and the EW scale: want (super)small Λ

Violate accidental symmetries: want (super)large Λ

Hierarchy (fine tuning) problem

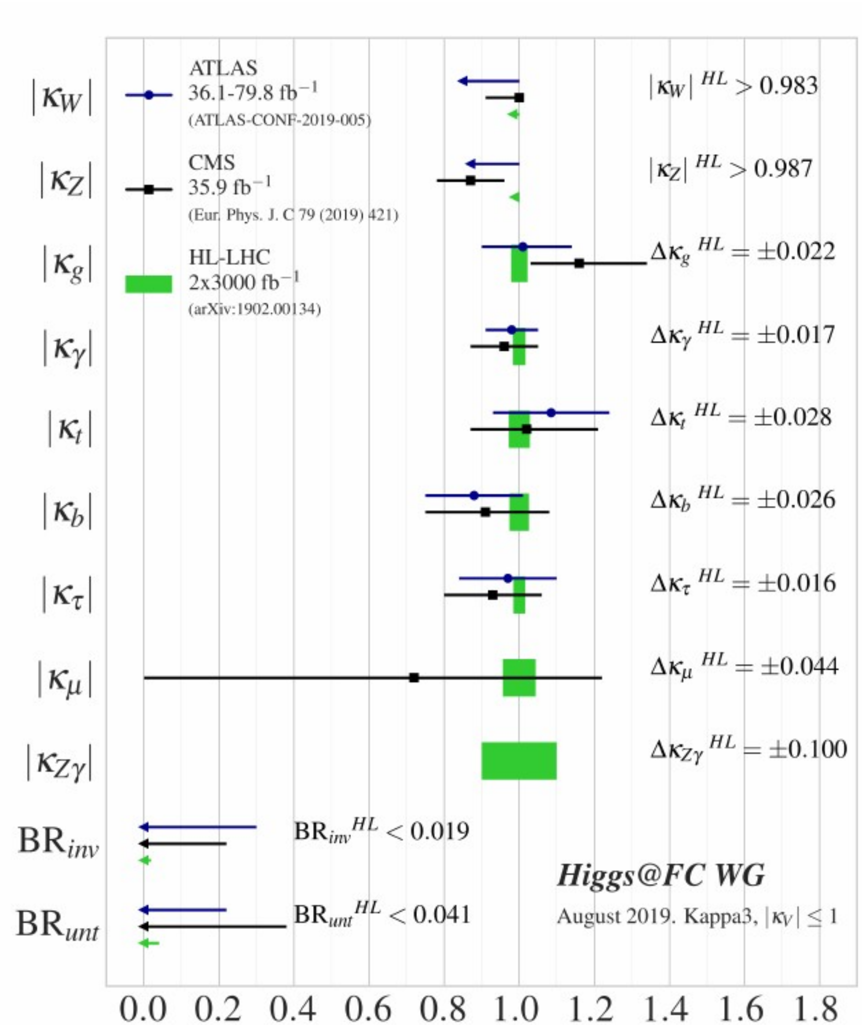
The hierarchy problem

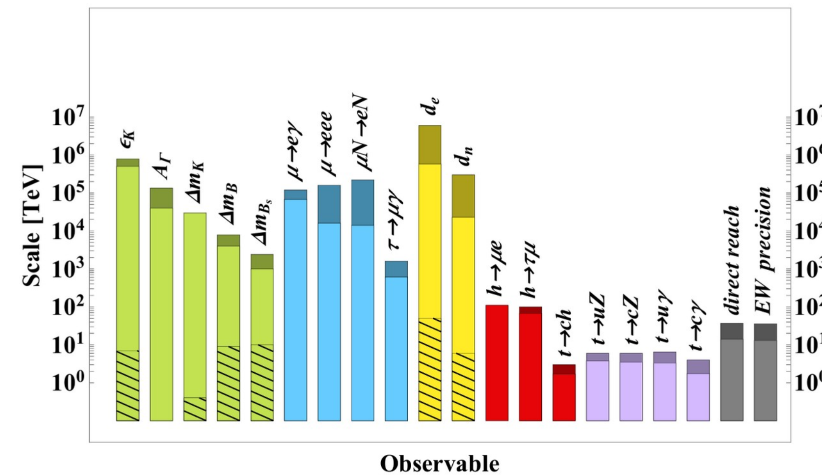
- No known NP model avoids tuning of weak scale and/or accidental symmetry violation (flavour, custodial, B and L). Need:
  - new theoretical ideas
  - experimental progress:
    - direct NP searches: more energy & more luminosity
    - indirect NP searches: better accuracy on accidental symmetries (flavour, EW, Higgs, B and L)

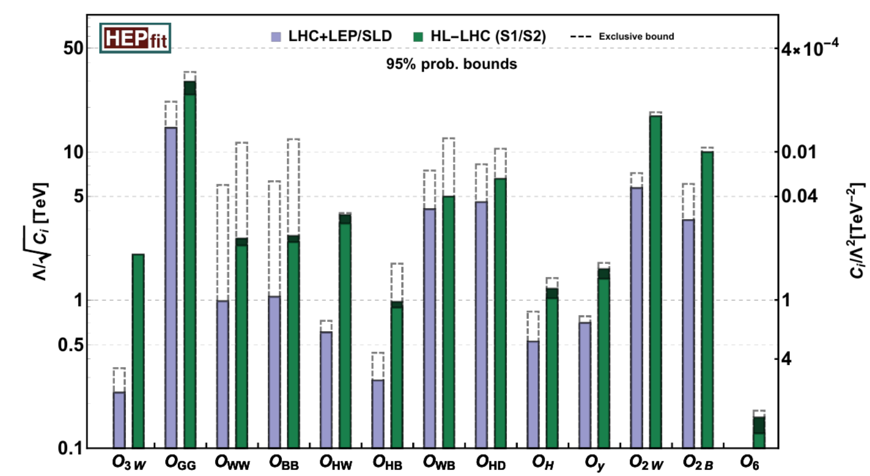
Open questions for future colliders

- Does the Higgs sector coincide with the SM one?
  - additional charged/neutral Higgs bosons
  - elementary or composite?
  - Yukawa couplings & flavour hierarchy
- What stabilizes the weak scale?
  - are there new particles coupled to the Higgs?
  - is there any deviation from the SM in EW and flavour?
- What are the properties of Dark Matter?
  - is it a WIMP?
- Is there any feebly interacting new particle?

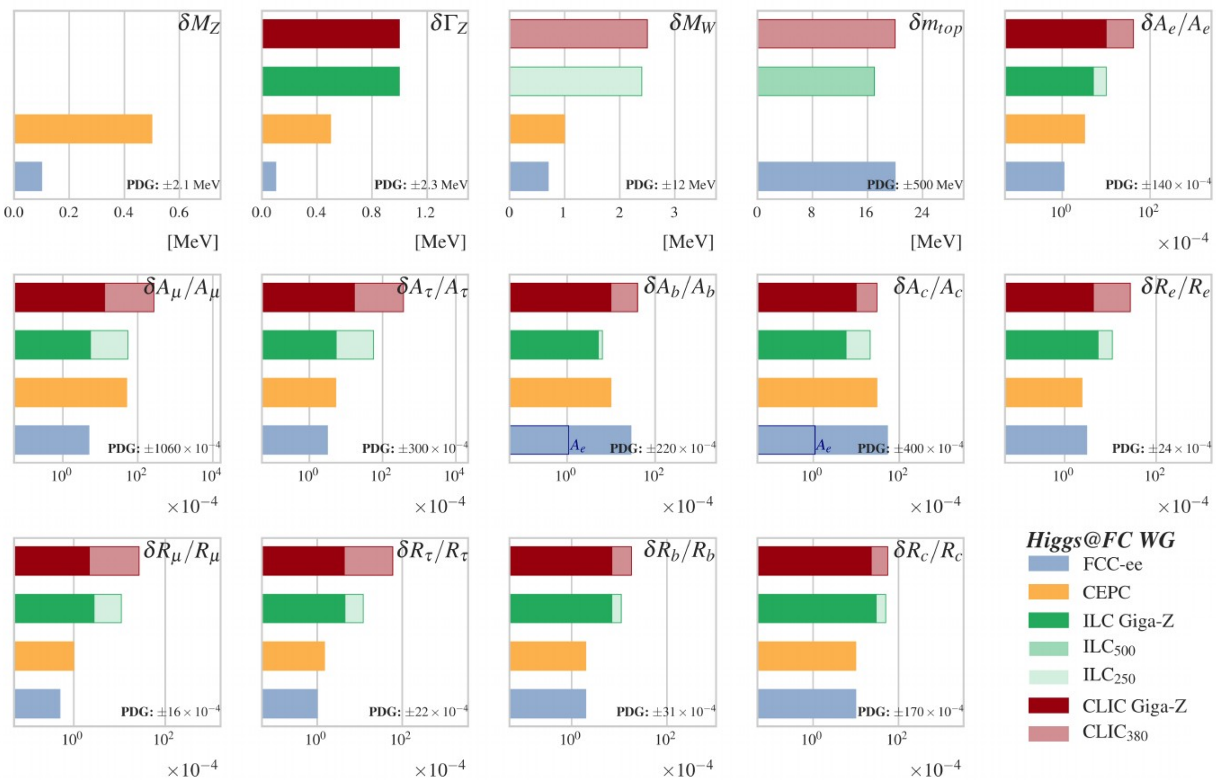
Expectations until my retirement (~2035)





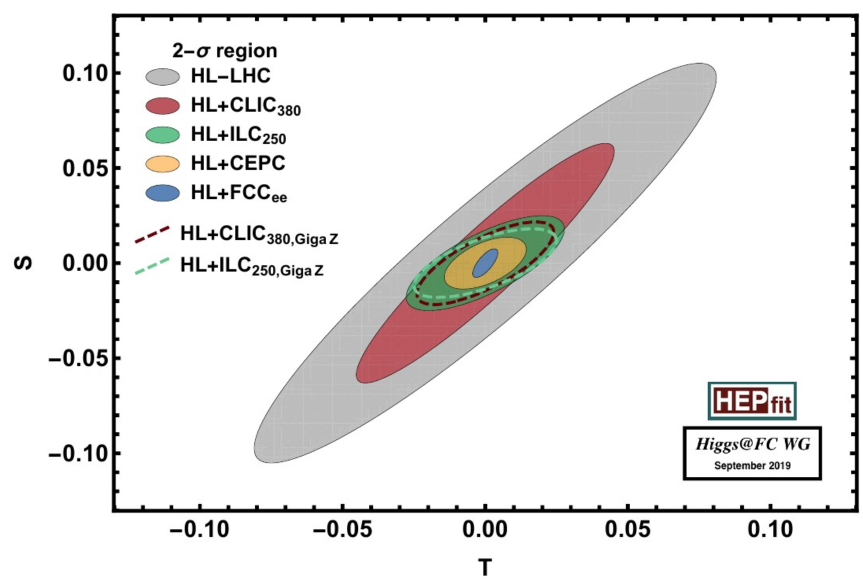


What awaits younger generations? 1) Higgs & EW



$\varepsilon = m_H^2/\Delta m_H^2 = 1/\Delta$

Method	Dependence	Current Constraint
Direct searches: soft models	$\Delta m_H^2 \sim m_T^2$	$\varepsilon \lesssim 1\%$
Direct searches: super-soft models	$\Delta m_H^2 \sim 3y_t^2/(4\pi^2)m_T^2$	$\varepsilon \lesssim 10\%$
Direct searches: hyper-soft models	$\Delta m_H^2 \sim 3\lambda_h/(16\pi^2)m_T^2$	$\varepsilon \lesssim 100\%$
Higgs couplings	$m_H^2/\Delta m_H^2 \sim \delta g_h/g_h$	$\varepsilon \lesssim 10\%$
Oblique parameters (CH models)	$m_H^2/\Delta m_H^2 \sim \delta O \times 3$	$\varepsilon \lesssim 30\%$
Oblique parameters (SUSY models)	$m_H^2/\Delta m_H^2 \sim \delta O \times 10^3$	n.a.



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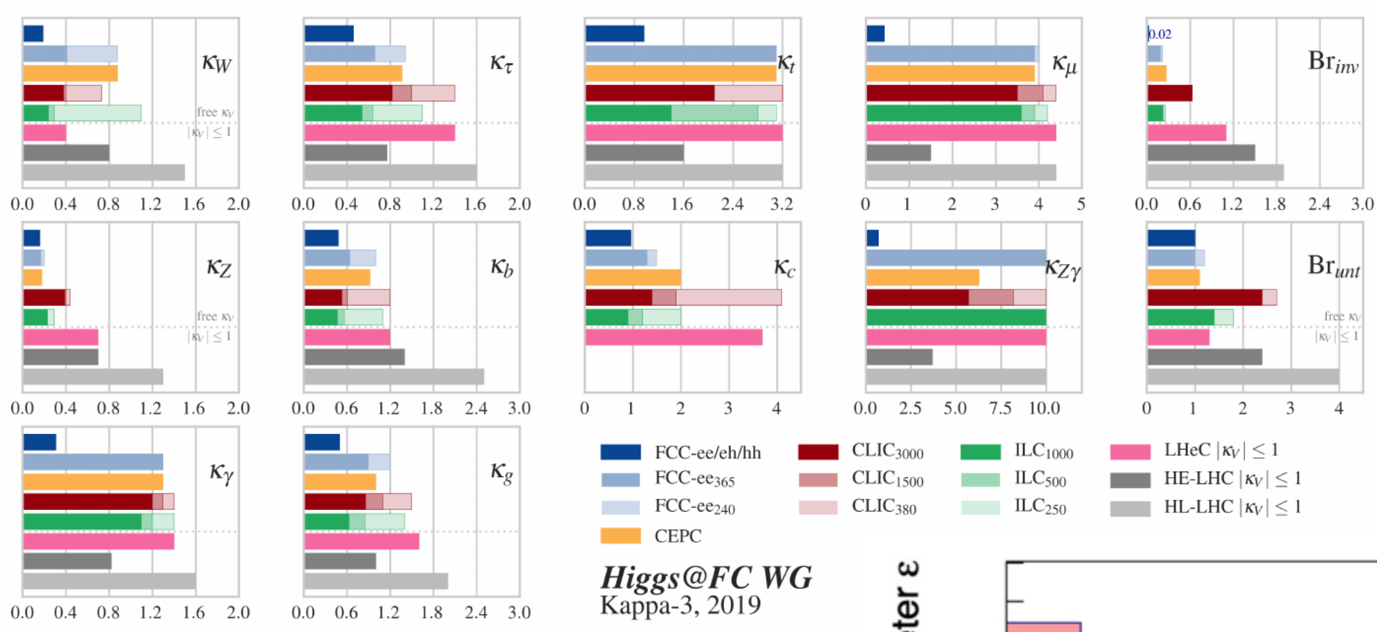
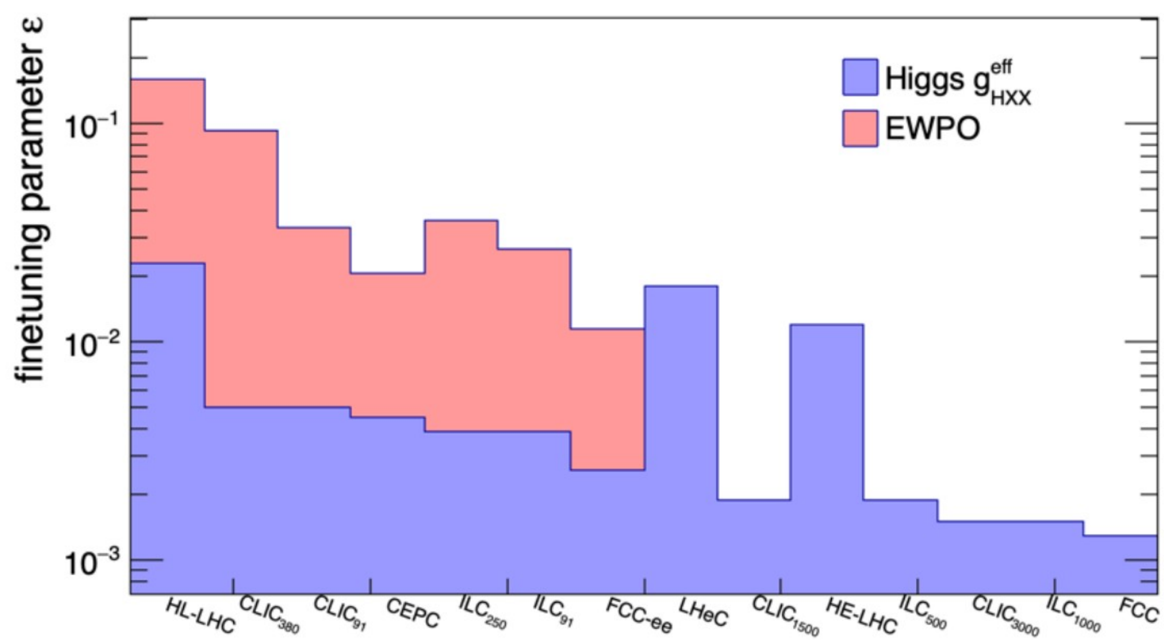


Uncertainties in % on modified Higgs couplings

Roma, 21/9/2020

$\varepsilon = m_H^2/\Delta m_H^2 = 1/\Delta$



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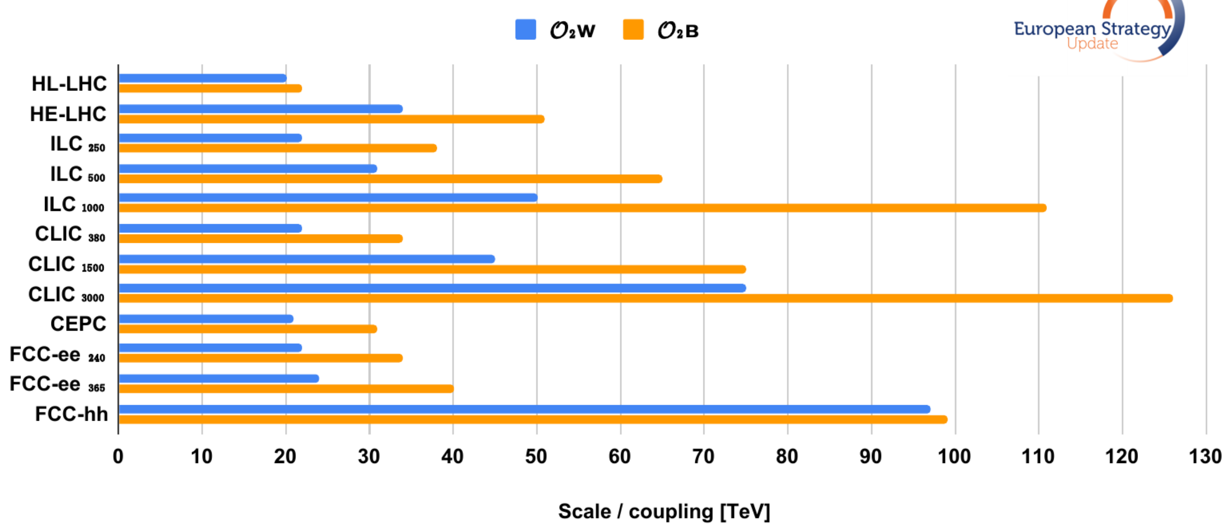
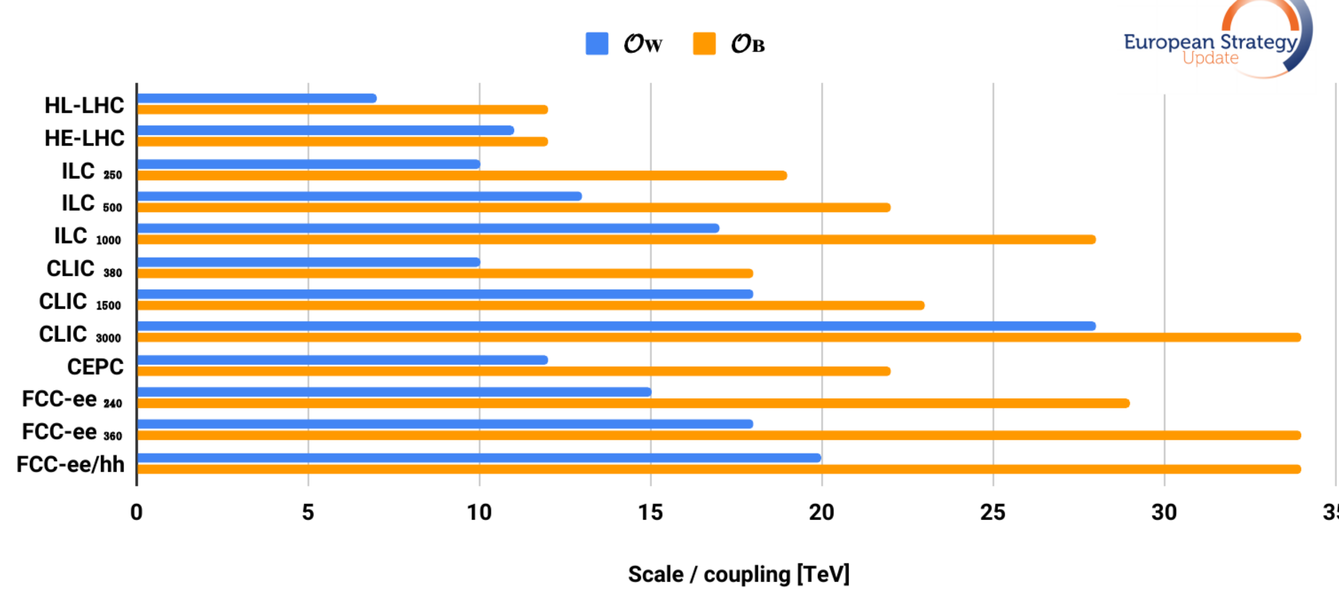
95% CL scale limits on 4-fermion contact interactions



95% CL scale limits on 2-fermion 2-boson contact interactions



What awaits younger generations? 1) Higgs & EW

μ collider @

$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

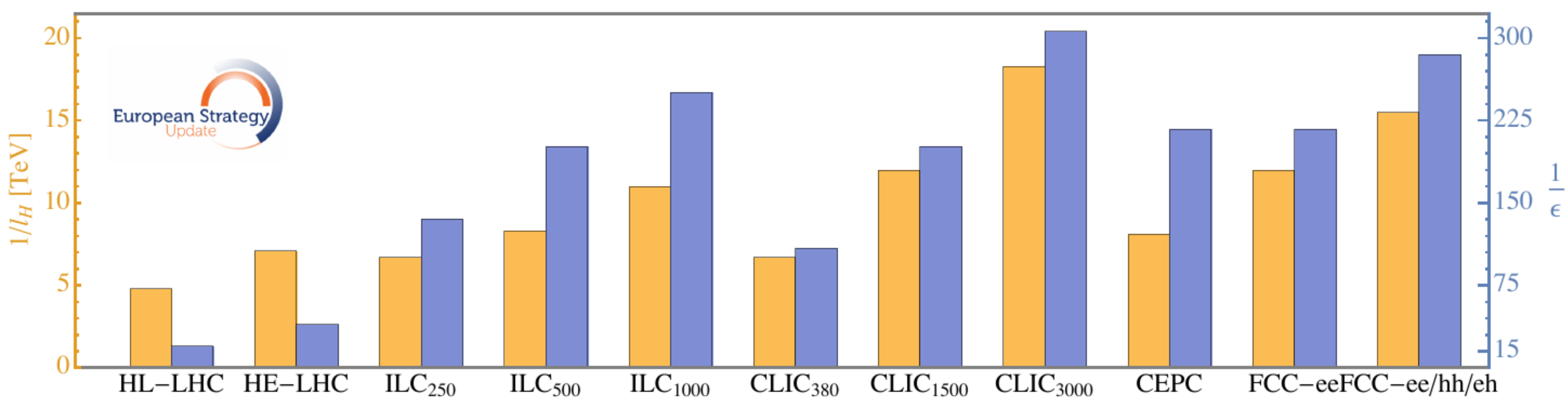
(CLIC)

(CEPC)

(ILC)

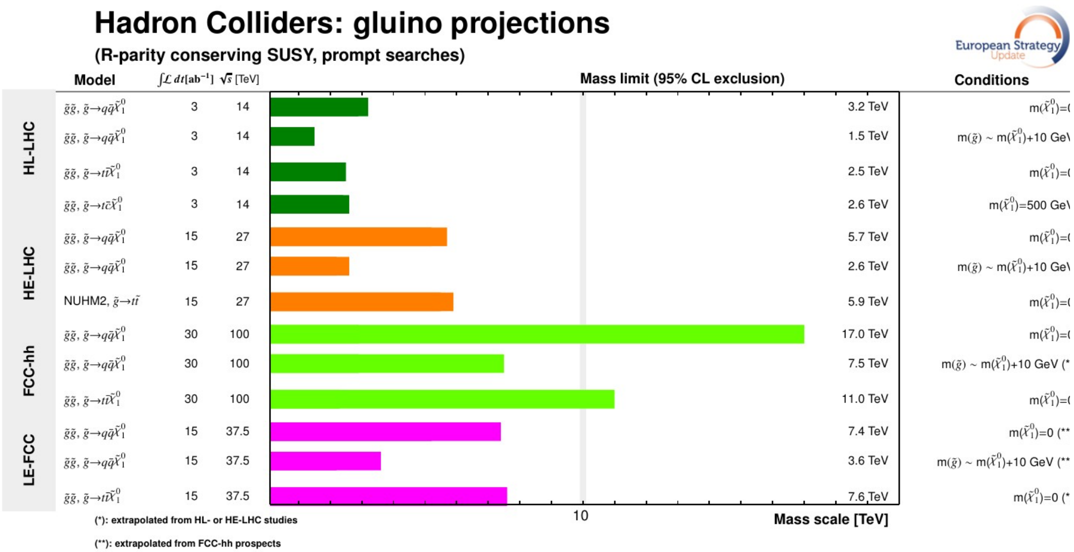
(FCC-hh)

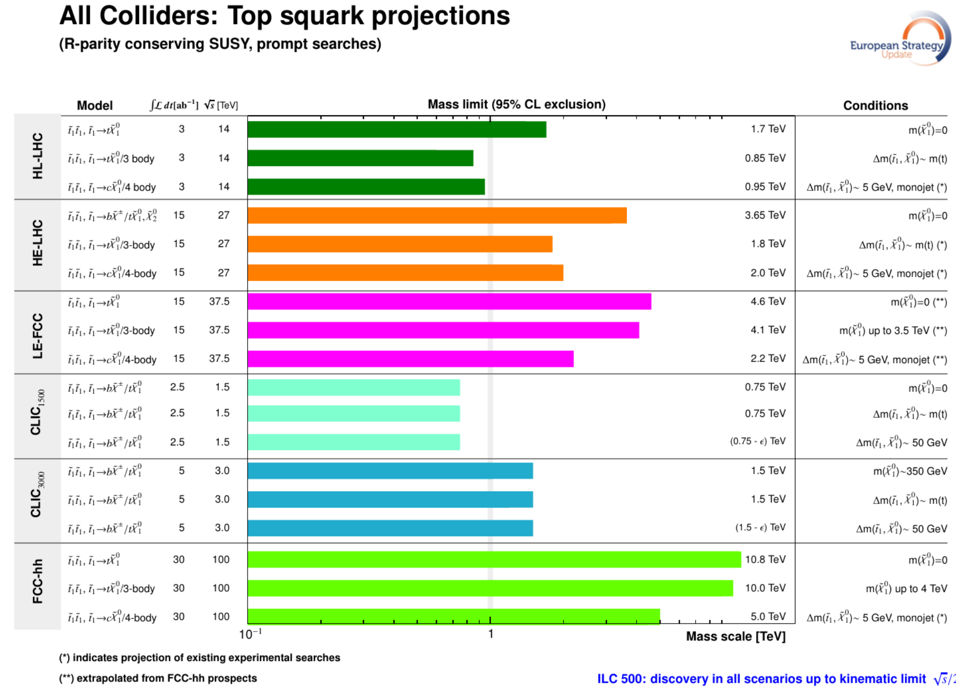
Han et al '20

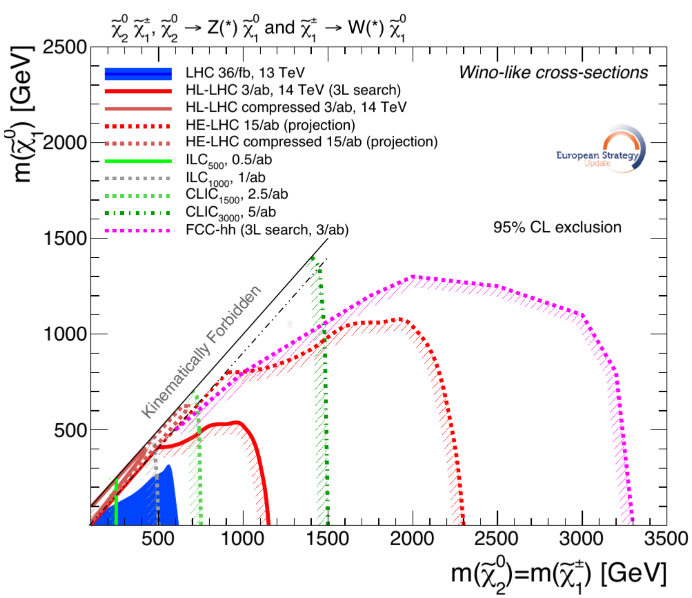


Higgs compositeness scale and fine-tuning parameter

What awaits younger generations? 2) direct searches

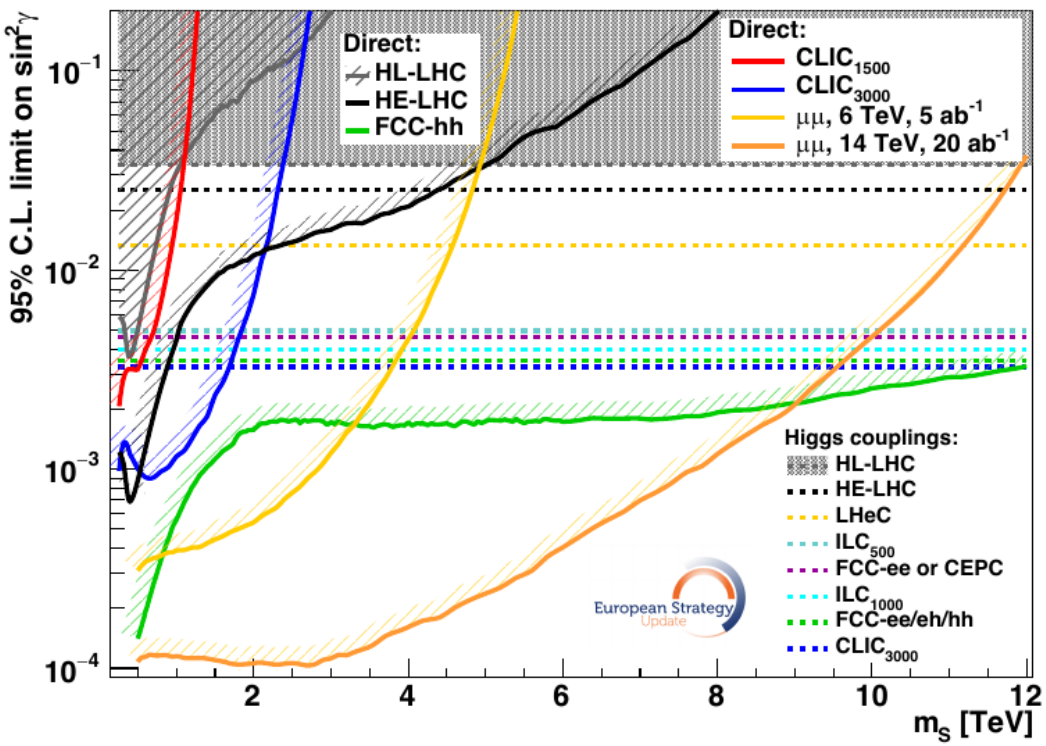


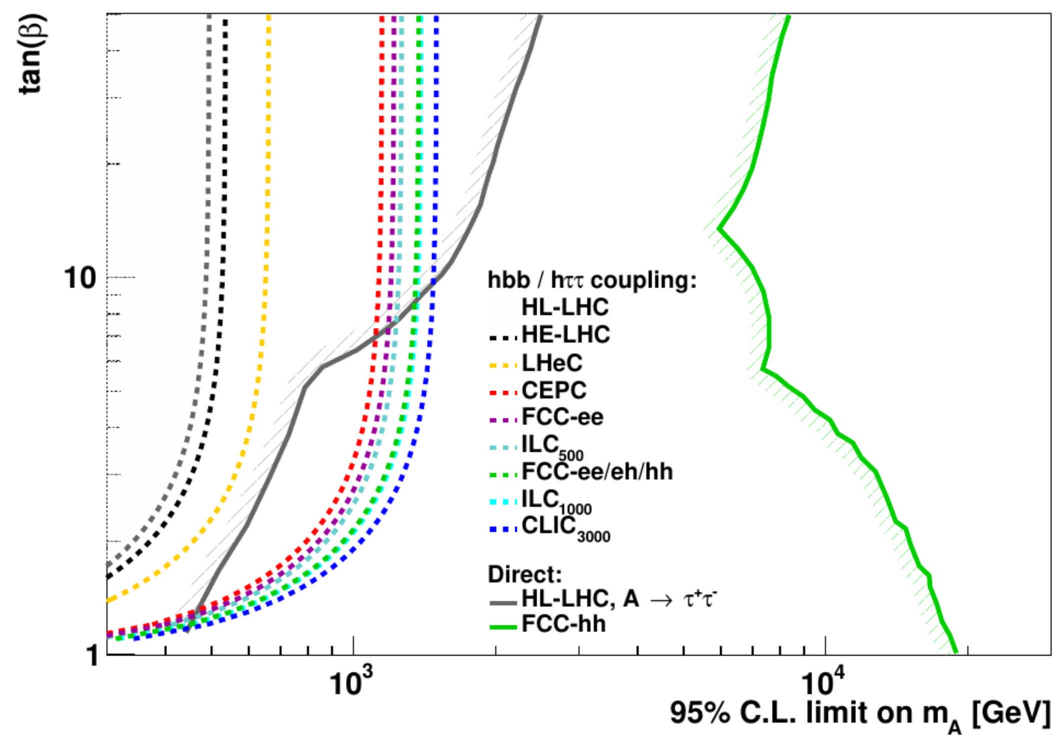




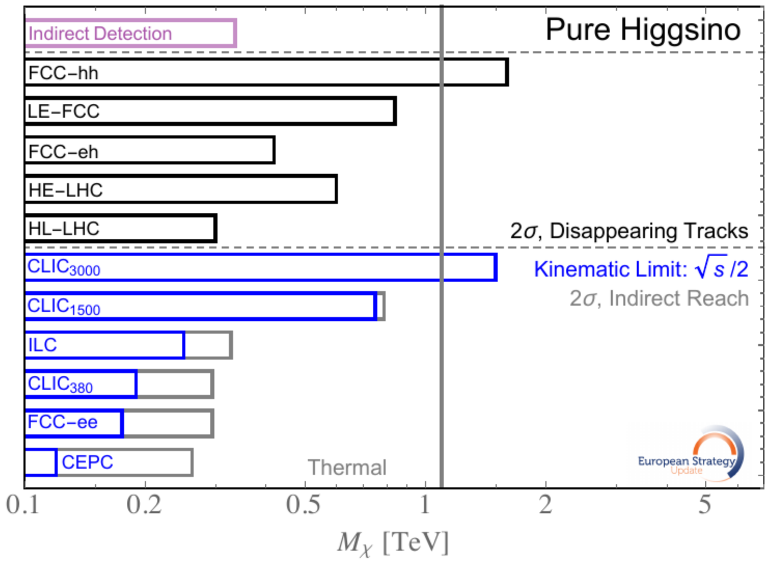
ε	High-scale mediation	Low-scale mediation
stop	$5\times10^{-5}\left(\frac{10\text{ TeV}}{m_{\tilde t}}\right)^2$	$2\times10^{-3}\left(\frac{10\text{ TeV}}{m_{\tilde t}}\right)^2$
gluino	$7\times10^{-6}\left(\frac{17\text{ TeV}}{m_{\tilde g}}\right)^2$	$6\times10^{-3}\left(\frac{17\text{ TeV}}{m_{\tilde g}}\right)^2$

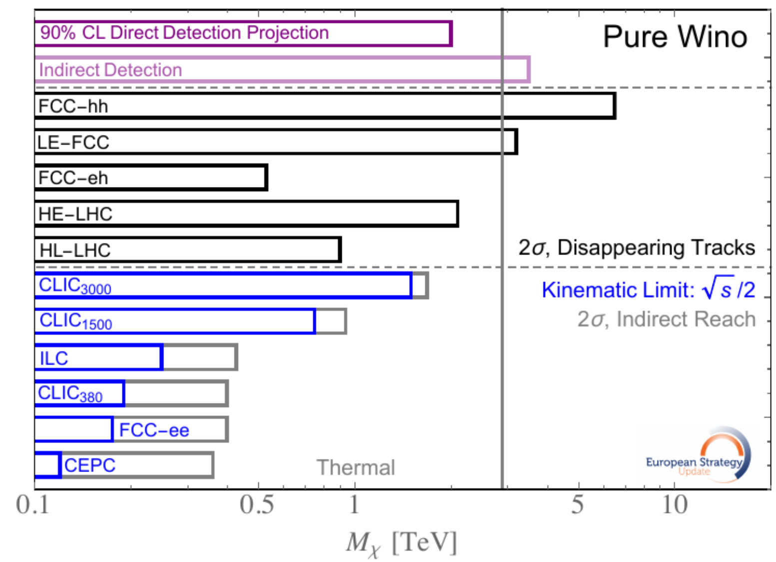
What awaits younger generations? 2) direct searches

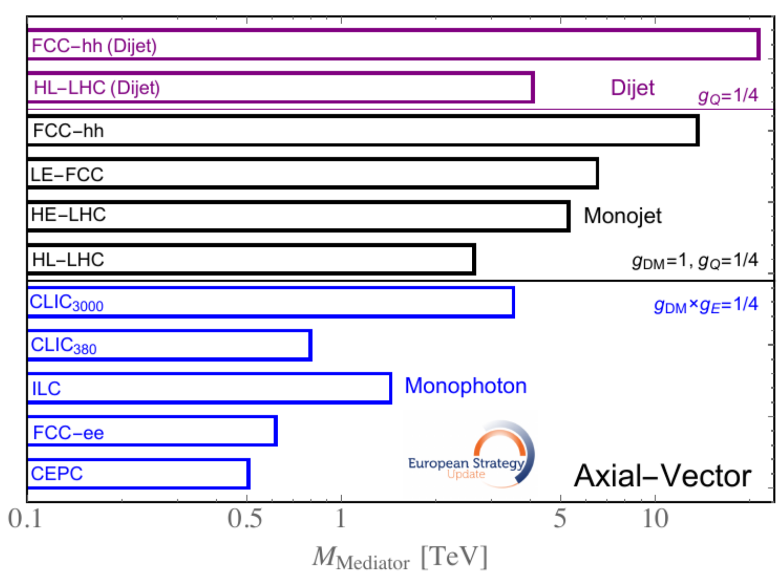


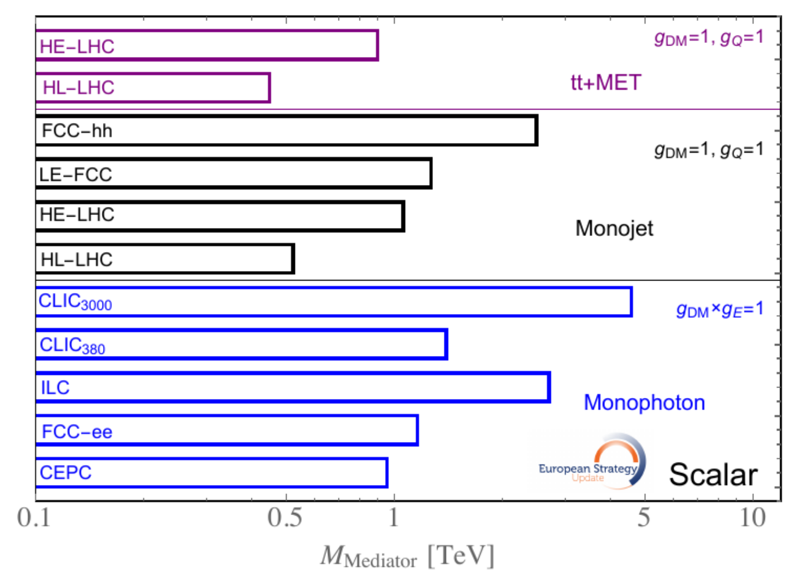


What awaits younger generations? 3) DM @ colliders









What awaits younger generations? 4) Flavour

- With suitable detectors, broad range of opportunities at both lepton and hadron colliders
- Detailed studies needed to assess reach and detector requirements
- Flavour will certainly continue playing a central role in indirect NP searches

CONCLUSIONS

- Physics expectations for future colliders:
  - probe the nature of the Higgs boson up to scales of 10-20 TeV, i.e. a ‰ degree of compositeness
  - probe new heavy particles relevant for stabilizing the EW scale up to 10-20 TeV
  - fully probe the thermal DM window for EW doublets and triplets
  - push the heavy scale probed by flavour beyond the EeV