# Higgs Studies at Future Colliders

## ECFA WG for the European Strategy Update

*Snowmass EF01 kick-off meeting*

*May 13, 2020*

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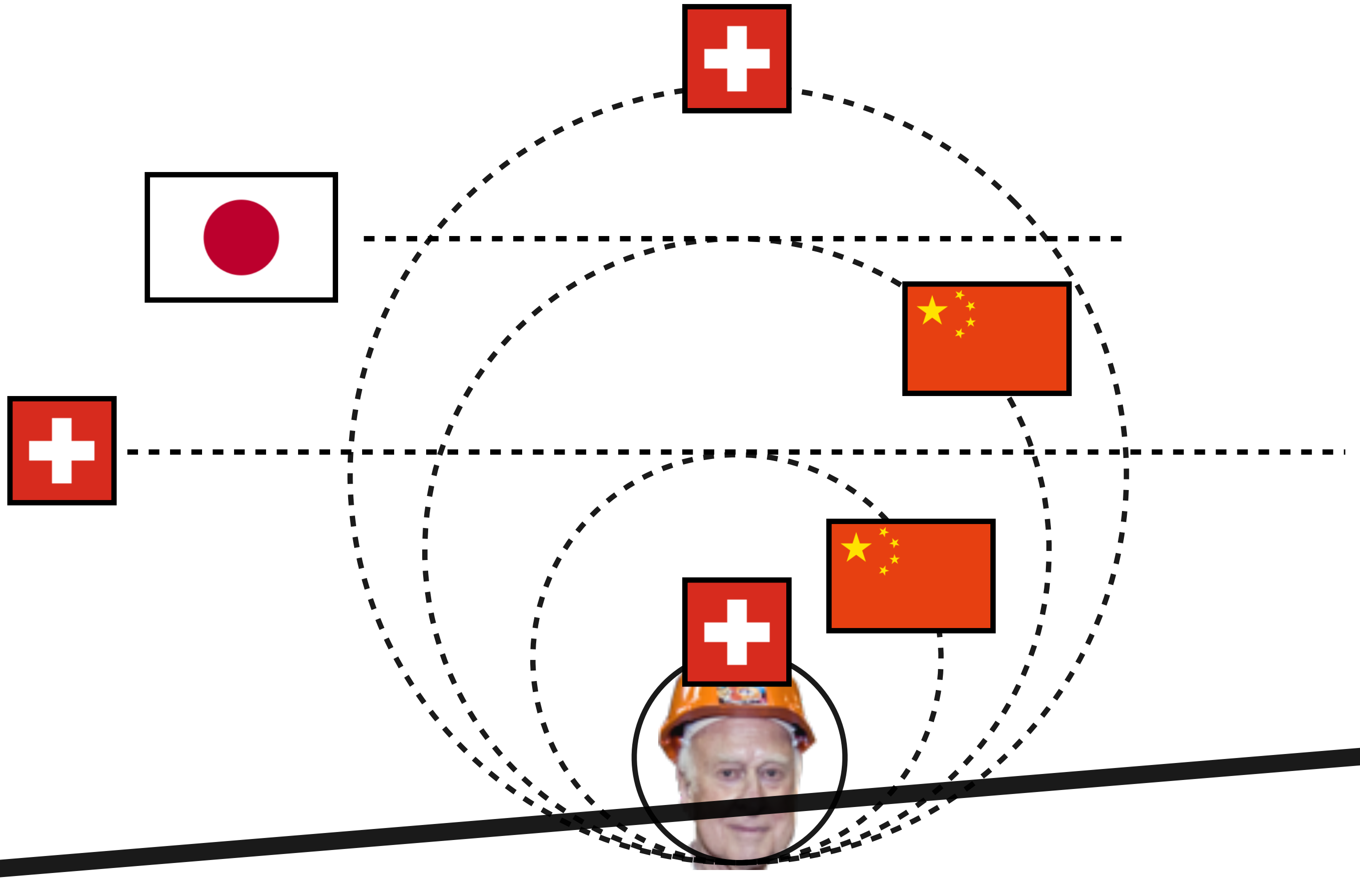


# European Strategy Update

A bottom-up process

to pave the near-term, mid-term and longer-term future

Call for proposals

community/national inputs/national laboratories input

Open Symposium

Physics Preparatory Group (Who they are: here)

Briefing Book

European Strategy Group (Who they are: here)

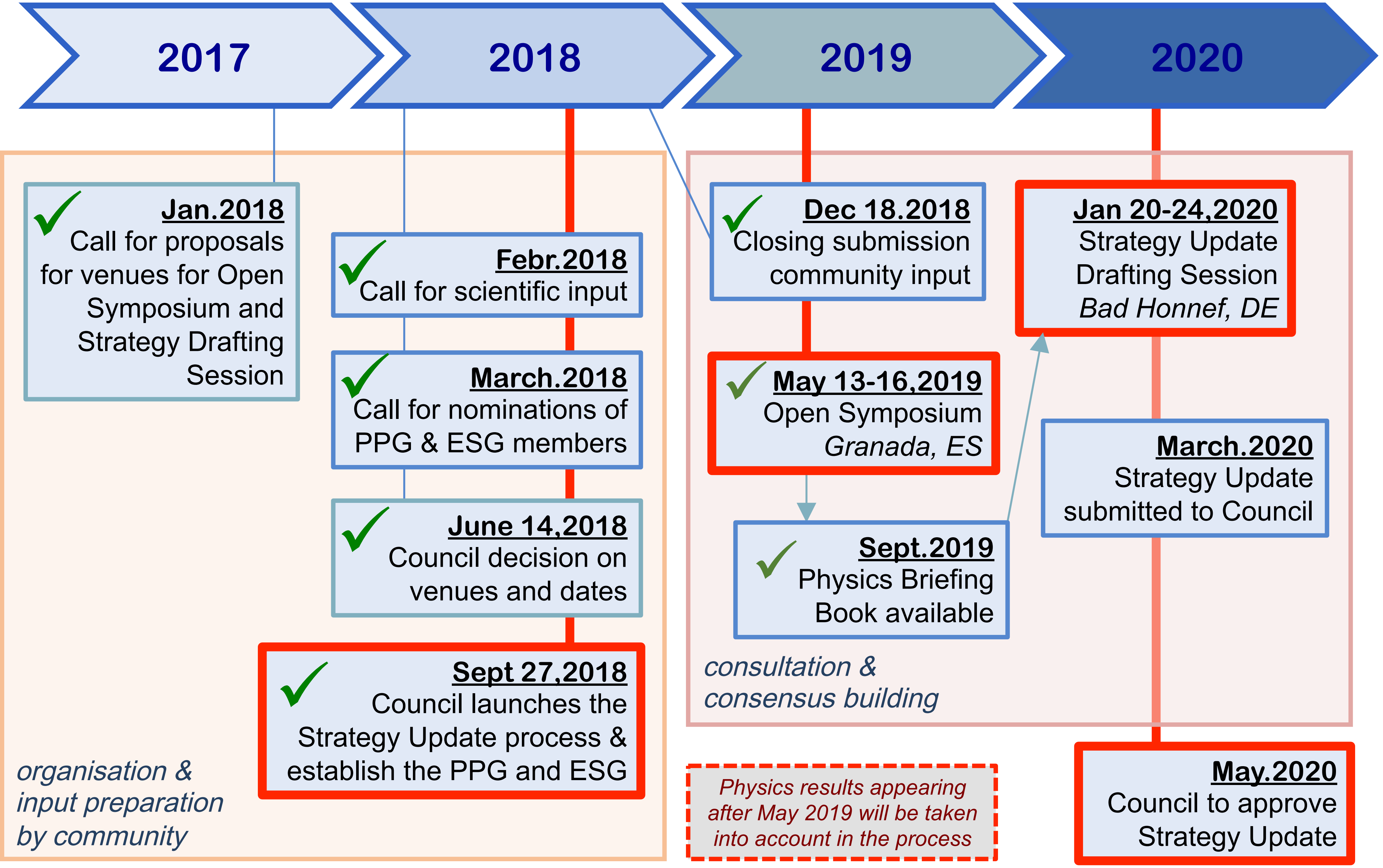
European Strategy Update recommendations

CERN Council

Decision

# European Strategy Update

## A bottom-up process
## to pave the near-term, mid-term and longer-term future




Draft is still confidential

Budapest meeting (25.05)

has been postponed

(only remote council meeting)

No official timeline for release

# The Higgs@FC WG Mandate

## A Mandate agreed by RECFA in consultation with the PPG "Higgs physics with future colliders in parallel and beyond the HL-LHC"

In the context of exploring the Higgs sector, provide a coherent comparison of the reach with all future collider programmes proposed for the European Strategy update, and to project the information on a timeline.

- For the benefit of the comparison, motivate the choice for an adequate interpretation framework (e.g. EFT, $\kappa$, ...) and apply it, and map the potential prerequisites related to the validity and use of such framework(s).
- For at least the following aspects, where achievable, comparisons should be aim for:
  - Precision on couplings and self-couplings (through direct and indirect methods);
  - Sensitivities to anomalous and rare Higgs decays (SM and BSM), and precision on the total width;
  - Sensitivity to new high-scale physics through loop corrections;
  - Sensitivities to flavour violation and CP violating effects.
- In all cases the future collider information is to be combined with the expected HL-LHC reach, and the combined extended reach is to be compared with the baseline reach of the HL-LHC.
- In April 2019, provide a comprehensive and public report to inform the community.
- ECFA helps in the creation of a working group relevant for the Strategy process, especially for the Physics Preparatory Group (PPG).
- Towards the Open Symposium the working group will work together with the PPG to provide a comprehensive and public report to inform the community, i.e. this is not an ECFA report.
- The working group has a scientific nature, i.e. not a strategic nature; it uses the input submitted to the Strategy process to map the landscape of Higgs physics at future colliders.

# The Higgs@FC WG Composition

members were nominated by the community and chosen by RECFA

- **Aleandro Nisati** (INFN - Roma) - *working group chair*
- **Beate Heinemann** (DESY & Freiburg Univ.) - *ex-officio*
- **Christoph Grojean** (DESY & Humboldt Univ.)
- **Elisabeth Petit** (CPPM - Marseille) [joined in March]
- **Fabio Maltoni** (Louvain/Bologna)
- **Jorge de Blas** (University of Padova and INFN - Padova)
- **Jorgen D'Hondt** (Brussels) - *ex-officio*
- **Keith Ellis** (Durham) - *ex-officio*
- **Maria Cepeda** (CIEMAT)
- **Riccardo Rattazzi** (EPFL)
- **Wouter Verkerke** (NIKHEF)

# WG Work Organisation

- (Almost) **weekly meetings** from January till July 2019 (and a more afterwards till the finalisation of the Briefing Book in Oct. 2019) + One internal workshop on March 21-22, 2019

- Scrutinised with care the documents submitted as input to the Update of the *European Strategy Symposium* in Granada (May 2019)

- Invited talks at our weekly meetings from experts from FC communities on Higgs physics potential
  - FCC-ee, FCC-hh, CEPC, HE-LHC, ILC, CLIC, LHeC/HE-LHeC/FCC-eh
  - Muon Collider expert invited, talk scheduled
  - Many interactions with Higgs FC experts

- **Output:**
  - A standalone report: “Higgs Boson Studies at Future Particle Colliders” *JHEP* 01 (2020) 139 • 1905.03764 [hep-ph]
  - Contribution to Briefing Book: “Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020” • 1910.11775 [hep-ex]

# Colliders Studied

| Collider | Type | $\sqrt{s}$ | $\mathcal{P}$ [%] $[e^-/e^+]$ | N(Det.) | $\mathcal{L}_{\text{inst}}$ $[10^{34}]$ $\text{cm}^{-2}\text{s}^{-1}$ | $\mathcal{L}$ $[\text{ab}^{-1}]$ | Time [years] | Refs. | Abbreviation |
|---|---|---|---|---|---|---|---|---|---|
| HL-LHC | $pp$ | 14 TeV | — | 2 | 5 | 6.0 | 12 | [13] | HL-LHC |
| HE-LHC | $pp$ | 27 TeV | — | 2 | 16 | 15.0 | 20 | [13] | HE-LHC |
| FCC-hh$^{(*)}$ | $pp$ | 100 TeV | — | 2 | 30 | 30.0 | 25 | [1] | FCC-hh |
| FCC-ee | $ee$ | $M_Z$ | 0/0 | 2 | 100/200 | 150 | 4 | [1] | |
| | | $2M_W$ | 0/0 | 2 | 25 | 10 | 1–2 | | |
| | | 240 GeV | 0/0 | 2 | 7 | 5 | 3 | | FCC-ee$_{240}$ |
| | | $2m_{\text{top}}$ | 0/0 | 2 | 0.8/1.4 | 1.5 | 5 | | FCC-ee$_{365}$ |
| | | | | | | | (+1) | (1y SD before $2m_{\text{top}}$ run) | |
| ILC | $ee$ | 250 GeV | ±80/±30 | 1 | 1.35/2.7 | 2.0 | 11.5 | [3, 14] | ILC$_{250}$ |
| | | 350 GeV | ±80/±30 | 1 | 1.6 | 0.2 | 1 | | ILC$_{350}$ |
| | | 500 GeV | ±80/±30 | 1 | 1.8/3.6 | 4.0 | 8.5 | | ILC$_{500}$ |
| | | | | | | | (+1) | (1y SD after 250 GeV run) | |
| | | 1000 GeV | ±80/±20 | 1 | 3.6/7.2 | 8.0 | 8.5 | [4] | ILC$_{1000}$ |
| | | | | | | | (+1-2) | (1–2y SD after 500 GeV run) | |
| CEPC | $ee$ | $M_Z$ | 0/0 | 2 | 17/32 | 16 | 2 | [2] | CEPC |
| | | $2M_W$ | 0/0 | 2 | 10 | 2.6 | 1 | | |
| | | 240 GeV | 0/0 | 2 | 3 | 5.6 | 7 | | |
| CLIC | $ee$ | 380 GeV | ±80/0 | 1 | 1.5 | 1.0 | 8 | [15] | CLIC$_{380}$ |
| | | 1.5 TeV | ±80/0 | 1 | 3.7 | 2.5 | 7 | | CLIC$_{1500}$ |
| | | 3.0 TeV | ±80/0 | 1 | 6.0 | 5.0 | 8 | | CLIC$_{3000}$ |
| | | | | | | | (+4) | (2y SDs between energy stages) | |
| LHeC | $ep$ | 1.3 TeV | — | 1 | 0.8 | 1.0 | 15 | [12] | LHeC |
| HE-LHeC | $ep$ | 1.8 TeV | — | 1 | 1.5 | 2.0 | 20 | [1] | HE-LHeC |
| FCC-eh | $ep$ | 3.5 TeV | — | 1 | 1.5 | 2.0 | 25 | [1] | FCC-eh |

pp

ee

ep

Different level of sophistication (fast versus full simulations, parametric modelling…).

As part of our mandate, we use the data of the different reports as provided, and highlight the important comparison points, without removing/modifying information.

# Methodology

We re-analysed of all the input data (mostly σ*BR for what concerns Higgs physics) in order to provide a fair and apple-to-apple comparison between colliders

Two steps:

1) **κ-fit**: could be compared to the fits often performed by the various FC collaborations ➙ validation of our procedure/code (in particular the treatment of uncertainties and correlations and the combination of ATLAS-CMS data/projections)
2) **Global EFT fit**

Collect inputs from collaborations (see our report for data used)

Likelihood constructed with HEPfit (1910.14012) from:

- SM predictions injected as future experimental measurements
- Errors given by projected uncertainties (experimental, theoretical - parametric and intrinsic)

# Examples of Experimental Uncertainties

## Electroweak precision measurements

| Quantity | Current | HL-LHC | FCC-ee | CEPC | ILC Giga-Z | ILC 250 GeV | CLIC Giga-Z | CLIC 380 GeV |
|---|---|---|---|---|---|---|---|---|
| $\delta m_{\rm top}$ [MeV] | $\sim$500 [a)] | $\sim$400 [a)] | 20 [b)] | – | – | 17 [b)] | – | 20-22 [b)] |
| $\delta M_Z$ [MeV] | 2.1 | – | 0.1 | 0.5 | – | – | – | – |
| $\delta \Gamma_Z$ [MeV] | 2.3 | – | 0.1 | 0.5 | 1 | – | 1 | – |
| $\delta \Gamma_{Z\to{\rm had}}$ [MeV] | 2.0 | – | – | – | 0.7 | – | 0.7 | – |
| $\delta \sigma^0_{\rm had}$ [pb] | 37 | – | 4 | 5 | – | – | – | – |
| $\delta M_W$ [MeV] | 12 | 7 | 0.7 | 1.0 (2-3) [c)] | – | 2.4 [d)] | – | 2.5 |
| $\delta \Gamma_W$ [MeV] | 42 | – | 1.5 | 3 | – | – | – | – |
| $\delta {\rm BR}_{W\to e\nu}[10^{-4}]$ | 150 | – | 3 | 3 | – | 4.2 | – | 11 |
| $\delta {\rm BR}_{W\to \mu\nu}[10^{-4}]$ | 140 | – | 3 | 3 | – | 4.1 | – | 11 |
| $\delta {\rm BR}_{W\to \tau\nu}[10^{-4}]$ | 190 | – | 4 | 4 | – | 5.2 | – | 11 |
| $\delta {\rm BR}_{W\to {\rm had}}[10^{-4}]$ | 40 | – | 1 | 1 | – | – | – | – |
| $\delta A_e$ $[10^{-4}]$ | 140 | – | 1.1 [e)] | 3.2 [e)] | 5.1 | 10 | 10 | 42 |
| $\delta A_\mu$ $[10^{-4}]$ | 1060 | – | – | – | 5.4 | 54 | 13 | 270 |
| $\delta A_\tau$ $[10^{-4}]$ | 300 | – | 3.1 [e)] | 5.2 [e)] | 5.4 | 57 | 17 | 370 |
| $\delta A_b$ $[10^{-4}]$ | 220 | – | – | – | 5.1 | 6.4 | 9.9 | 40 |
| $\delta A_c$ $[10^{-4}]$ | 400 | – | – | – | 5.8 | 21 | 10 | 30 |
| $\delta A^\mu_{\rm FB}$ $[10^{-4}]$ | 770 | – | 0.54 | 4.6 | – | – | – | – |
| $\delta A^b_{\rm FB}$ $[10^{-4}]$ | 160 | – | 30 [f)] | 10 [f)] | – | – | – | – |
| $\delta A^c_{\rm FB}$ $[10^{-4}]$ | 500 | – | 80 [f)] | 30 [f)] | – | – | – | – |
| $\delta R_e$ $[10^{-4}]$ | 24 | – | 3 | 2.4 | 5.4 | 11 | 4.2 | 27 |
| $\delta R_\mu$ $[10^{-4}]$ | 16 | – | 0.5 | 1 | 2.8 | 11 | 2.2 | 27 |
| $\delta R_\tau$ $[10^{-4}]$ | 22 | – | 1 | 1.5 | 4.5 | 12 | 4.3 | 60 |
| $\delta R_b$ $[10^{-4}]$ | 31 | – | 2 | 2 | 7 | 11 | 7 | 18 |
| $\delta R_c$ $[10^{-4}]$ | 170 | – | 10 | 10 | 30 | 50 | 23 | 56 |
| $\delta R_\nu$ $[10^{-3}]$ [g)] | – | – | – | – | – | – | – | 9.4 |
| $\delta R_{\rm inv}$ $[10^{-3}]$ [g)] | – | – | 0.27 | 0.5 | – | – | – | – |

## Higgs measurements: Circular lepton colliders

| | FCC-ee$_{240}$ | FCC-ee$_{365}$ | CEPC |
|---|---|---|---|
| $\delta\sigma_{ZH}$ | 0.005 | 0.009 | 0.005 |
| $\delta\mu_{ZH,bb}$ | 0.003 | 0.005 | 0.0031 |
| $\delta\mu_{ZH,cc}$ | 0.022 | 0.065 | 0.033 |
| $\delta\mu_{ZH,gg}$ | 0.019 | 0.035 | 0.013 |
| $\delta\mu_{ZH,WW}$ | 0.012 | 0.026 | 0.0098 |
| $\delta\mu_{ZH,ZZ}$ | 0.044 | 0.12 | 0.051 |
| $\delta\mu_{ZH,\tau\tau}$ | 0.009 | 0.018 | 0.0082 |
| $\delta\mu_{ZH,\gamma\gamma}$ | 0.09 | 0.18 | 0.068 |
| $\delta\mu_{ZH,\mu\mu}$ | 0.19 | 0.40 | 0.17 |
| $\delta\mu_{ZH,Z\gamma}$ | – | – | 0.16 |
| $\delta\mu_{\nu\nu H,bb}$ | 0.031 | 0.009 | 0.030 |
| $\delta\mu_{\nu\nu H,cc}$ | – | 0.10 | – |
| $\delta\mu_{\nu\nu H,gg}$ | – | 0.045 | – |
| $\delta\mu_{\nu\nu H,ZZ}$ | – | 0.10 | – |
| $\delta\mu_{\nu\nu H,\tau\tau}$ | – | 0.08 | – |
| $\delta\mu_{\nu\nu H,\gamma\gamma}$ | – | 0.22 | – |
| ${\rm BR}_{\rm inv}$ | $<$0.0015 | $<$0.003 | $<$0.0015 |

… (full collection in our report)

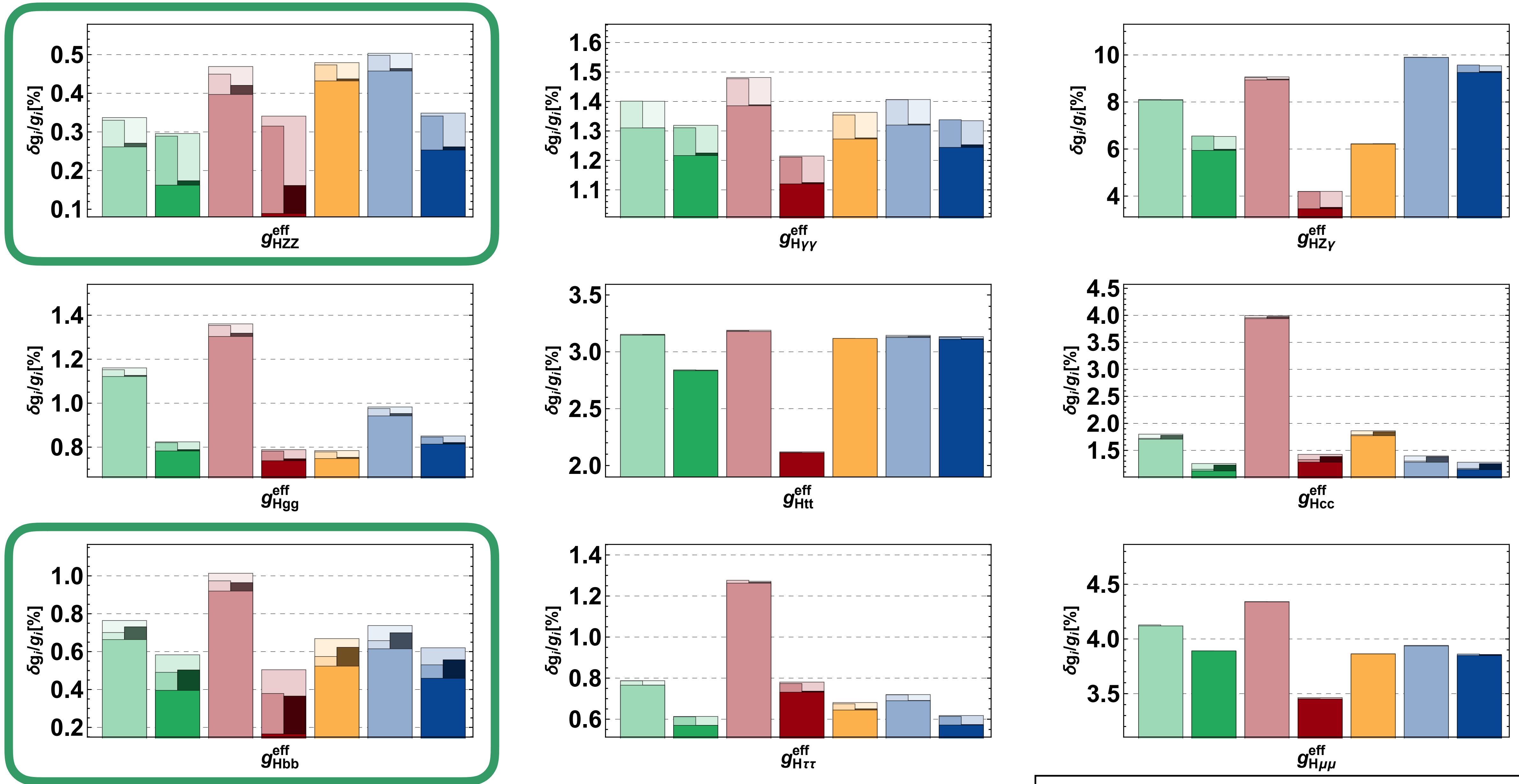
# Theoretical Uncertainties

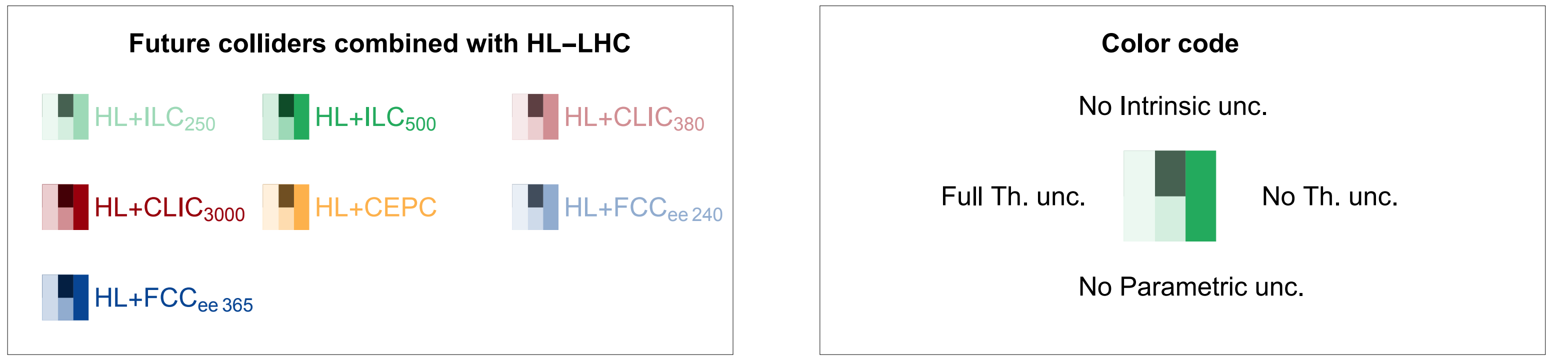
the effect increases in relevance as the measurements become more experimentally precise in the last stages of the future colliders program

- **HL/HE** use S2 uncertainties (theory 1/2 wrt today), including in combinations of HL with other colliders. We also considered S2' scenario (with an extra factor 1/2 for theory and syst.) ➙ default scenario for our plots ➙ most of the improvement of HE-LHC compared to HL-LHC comes from this assumption
- **FCC-hh:** for production x luminosity a 1% is assumed in the original documentation (accounting for future improvements)
- **LHeC**: 0.5% production uncertainty
- **Lepton colliders**: intrinsic uncertainties for the ee→ZH and ee→Hvv, estimated to be 0.5% (assuming NNLO EW can be reached)

When the TH uncertainties were not already included in the projections, we simply added nuisance parameters to the predictions with priors given by the corresponding theory uncertainty, and then marginalised over them in the results

# Impact of Theoretical Uncertainties




**Largest effect on HVV couplings**

Differences in other couplings mainly due to unc. in production

Exception: Hbb

# Higgs Couplings: Kappa vs EFT

Complementarity between the two approaches

**Kappa:**

- Close connection to exp. measurements
- Widely used
- Exploration tool (very much like epsilons for LEP)
- Doesn't require BSM theoretical computations
- Could still valid even with light new physics, i.e. exotic decays
- Captures leading effects of UV motivated scenarios (SUSY, composite)
- Main drawbacks: focused on inclusive quantities, not general

$$g_{hXX} = \kappa_X \, g_{hXX}^{\rm SM}$$

HEFT

**(SM)EFT:**

- Allows to put Higgs measurements in perspective with other measurements (EW, diboson, flavour…)
- Connects measurements at different scales (particularly relevant for high-energy colliders CLIC, FCC-hh)
- Fully exploits more exclusive observables (polarisation, angular distributions…)
- Can accommodate subleading effects (loops, dim-8…)
- Fully QFT consistent framework
- Assumptions about symmetries more transparent
- Valid only if heavy new physics
- Main drawbacks: assume mass gap with New Physics, not general (no new particle with a Higgs-generated mass)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d,i} \frac{c_i \, \mathcal{O}_d^i}{\Lambda^{d-4}}$$

# Kappa Fits

**10+2 parameters: $\kappa_{W,Z,g,\,\gamma,\,\gamma Z,\,t,\,c,\,b,\,\tau,\,\mu}$ + $BR_{inv}$ + $BR_{unt}$**

- **$\kappa_{s,d,u,e}$** only weakly constrained from very rare decays/productions and not included in the fits
- **$\kappa_\gamma$, $\kappa_{\gamma Z}$, $\kappa_g$** are treated as independent effective coupling modifiers
  - alone, low energy colliders, below ttH/tH threshold, are not sensitive to $\kappa_{top}$
  - no sensitivity to the signs of κ's (single top + h could provide such a sensitivity, but not included in our fits)
- Usual framework extended to accommodate **Invisible and Untagged decays**
  - **invisible width**: experimentally directly constrained at all future colliders (ZH, VBF H→invisible)
  - **untagged width**: h(125)->??. BSM, but also rare SM decays not directly probed by searches
  - $\Gamma_H$ and untagged are 100% correlated

$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1-(BR_{\mathrm{inv}}+BR_{\mathrm{unt}})} \qquad \kappa_H^2 \equiv \sum_j \frac{\kappa_j^2 \Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

| Scenario | $BR_{\mathrm{inv}}$ | $BR_{\mathrm{unt}}$ | include HL-LHC |
|---|---|---|---|
| kappa-0 | fixed at 0 | fixed at 0 | no |
| kappa-1 | measured | fixed at 0 | no |
| kappa-2 | measured | measured | no |
| kappa-3 | measured | measured | yes |

# Higgs Coupling Fit (Future Collider Standalone)

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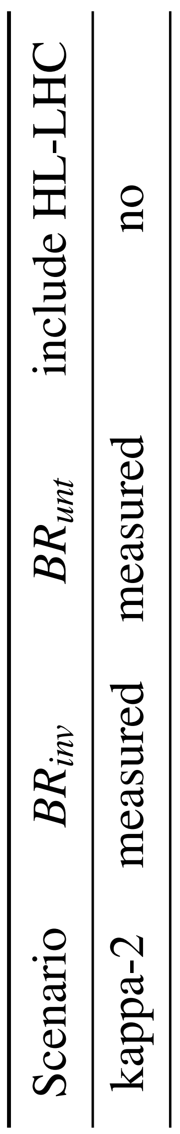
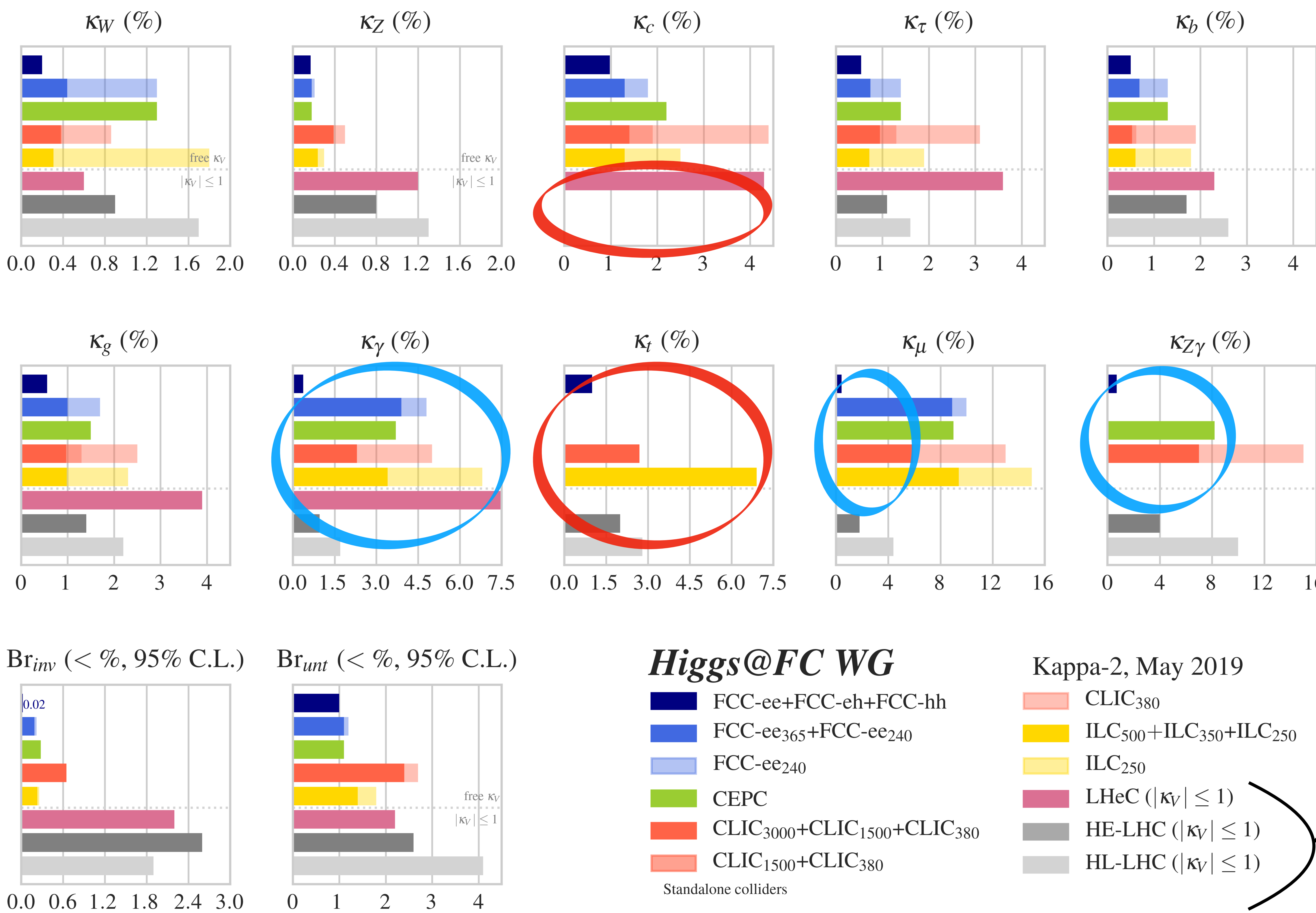



hadron collider cannot measure width
need an assumption to close the fit
e.g. $\kappa_V$<1




assumption needed for the fit to close at hadron machines

# Higgs Coupling Fit (HL-LHC+Future Collider)

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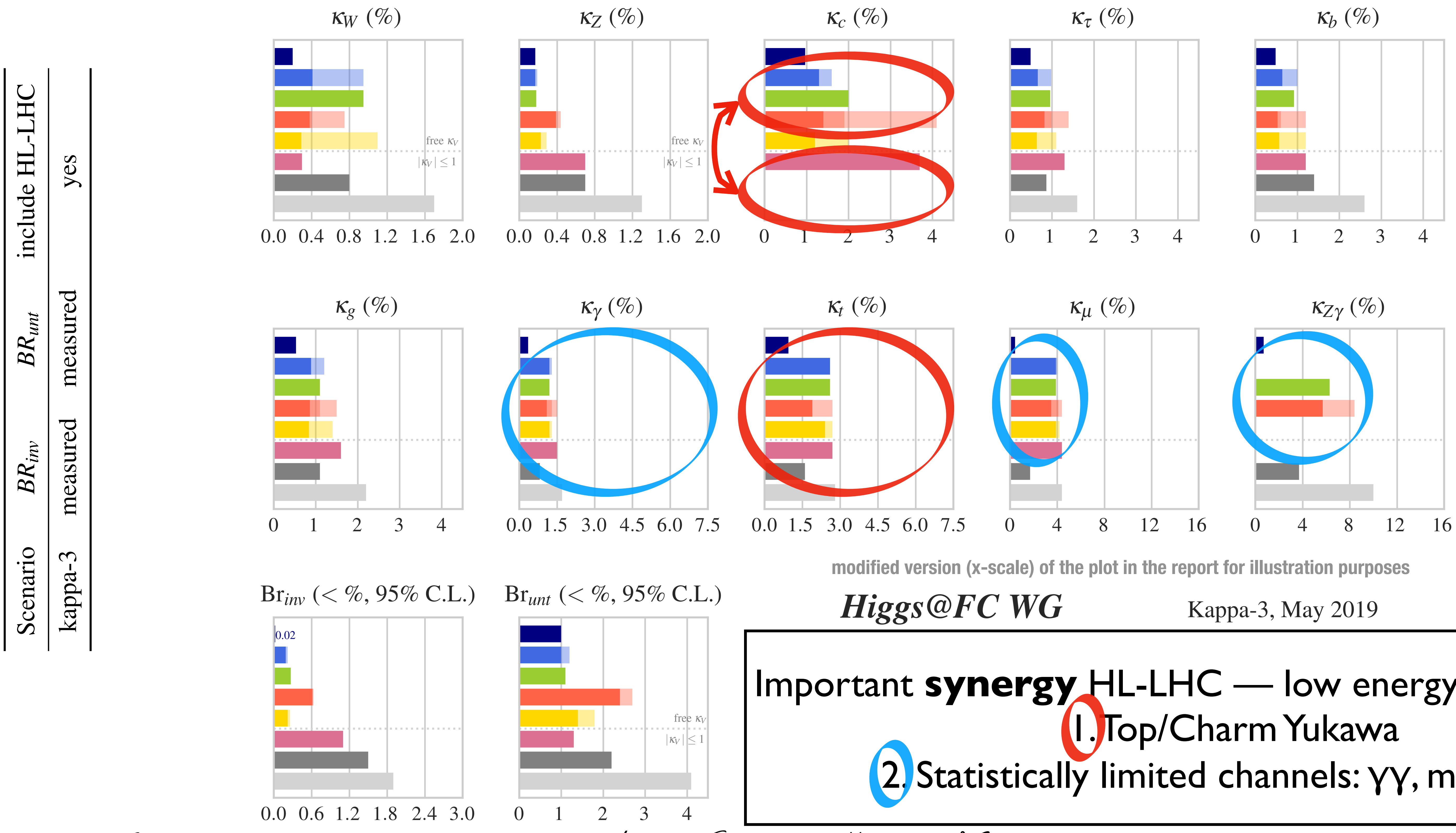
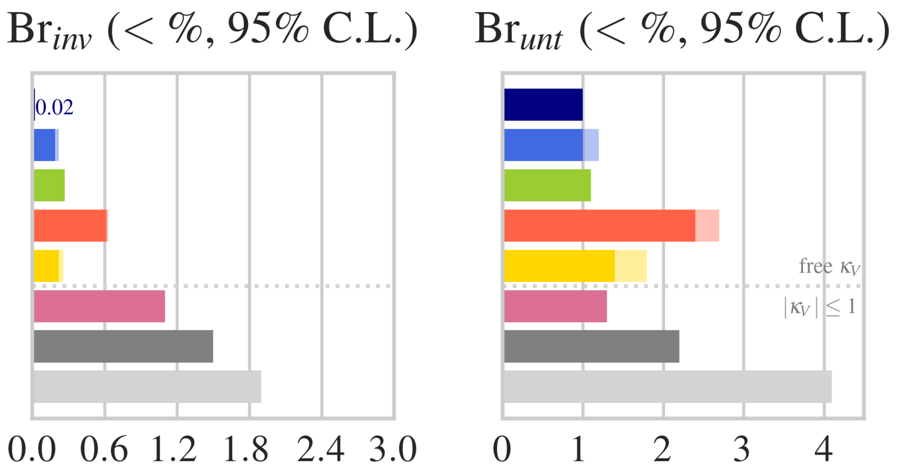


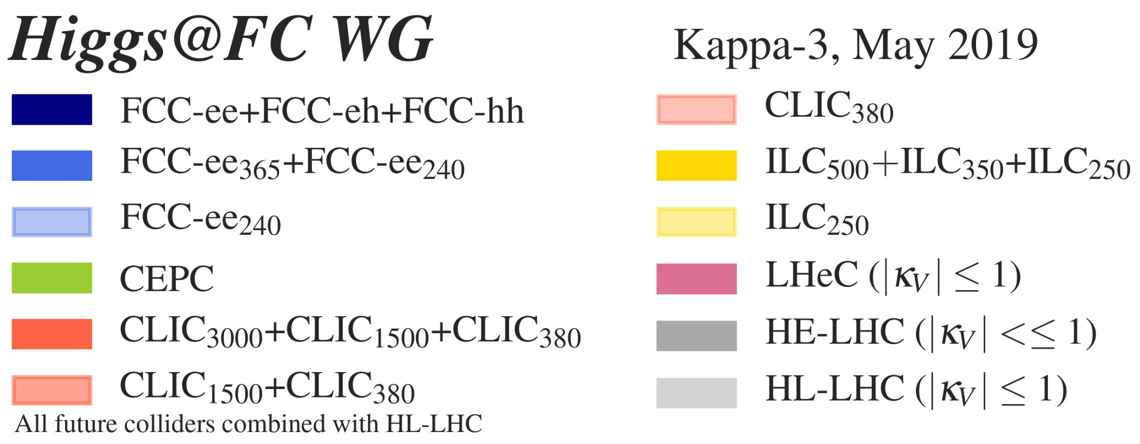

Important **synergy** HL-LHC — low energy lepton colliders

1. Top/Charm Yukawa

2. Statistically limited channels: γγ, mumu, Zγ

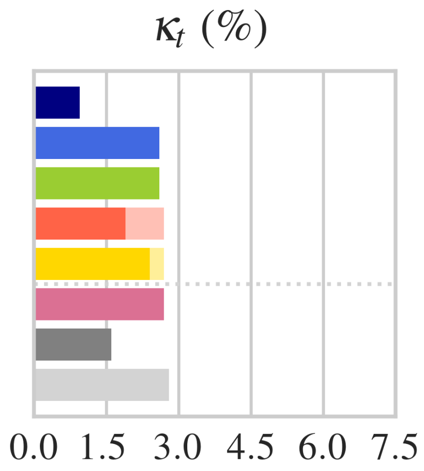
# Synergy ee-hh



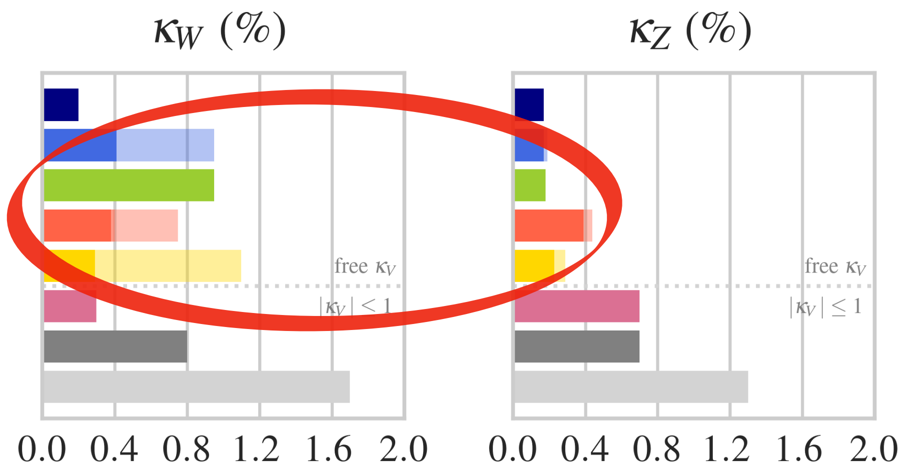




FCC-hh without ee could still bound $BR_{inv}$

but it could say nothing about $BR_{unt}$




FCC-hh is determining top Yukawa through ratio tth/ttZ
So the extraction of top Yukawa heavily relies on the knowledge of ttZ from FCC-ee




$k_W$ improves significantly with energy increase

But it also benefits a lot from a synergy with EW measurements.
This cannot be captured by the kappa's and requires a full EFT analysis

# Global EFT Fit

include not only Higgs but also top, di-boson and EWK precision observables

- No 4 fermion operators (except the one that contributes to muon decay and then affects $G_F$) since they are better constrained outside Higgs processes
- No dipole operators (chiral suppression in production, contribution only to 3-body decays). Top dipoles could be relevant but neglected in our analyses.
- Flavour assumptions
  - flavour universality: 19 independent parameters + 5 SM inputs
  - flavour diagonality: 31 independent parameters + 5 SM inputs

working at linear-level in the EFT effects

# Experimental Inputs

A circular ee Higgs factory starts as a Z/EW factory (**TeraZ**)

A linear ee Higgs factory operating above Z-pole can also preform EW measurements via **Z-radiative** return

A linear ee Higgs factory could also operate on the Z-pole though at lower lumi (**GigaZ**)

| | Higgs | aTGC | EWPO | Top EW |
|---|---|---|---|---|
| **FCC-ee** | Yes ($\mu$, $\sigma_{ZH}$) (Complete with HL-LHC) | Yes (aTGC dom.) | Yes | Yes (365 GeV, Ztt) |
| **ILC** | Yes ($\mu$, $\sigma_{ZH}$) (Complete with HL-LHC) | Yes (HE limit) | Yes (Rad. Return, Giga-Z) | Yes (500 GeV, Ztt) |
| **CEPC** | Yes ($\mu$, $\sigma_{ZH}$) (Complete with HL-LHC) | Yes (aTGC dom) | Yes | No |
| **CLIC** | Yes ($\mu$, $\sigma_{ZH}$) | Yes (Full EFT parameterization) | Yes (Rad. Return, Giga-Z) | Yes |
| **HE-LHC** | Extrapolated from HL-LHC | N/A → LEP2 | LEP/SLD + HL-LHC ($M_W$, $\sin^2\theta_W$) | - |
| **FCC-hh** | Yes ($\mu$, $BR_i/BR_j$) Used in combination with FCCee/eh | From FCC-ee | From FCC-ee | - |
| **LHeC** | Yes ($\mu$) | N/A → LEP2 | LEP/SLD + HL-LHC ($M_W$, $\sin^2\theta_W$) | - |
| **FCC-eh** | Yes ($\mu$) Used in combination with FCCee/hh | From FCC-ee | From FCC-ee + Zuu, Zdd | - |

# Effective Higgs Couplings from EFT Fits

EFT fits can be performed in different bases (difficult to compare results among different analyses) and seldom the meaning on the sensitivity on the various Wilson coefficients is transparent

— **Practical approach** —

perform the fit in any basis you like and project the results on **effective/pseudo couplings**

(need a special care for top coupling and self-coupling)

$$g_{HX}^{\text{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\text{SM}}}$$

Effective Higgs couplings

**Similar definition as κ modifiers, but different interpretation, e.g.**

$$\frac{\Gamma_{ZZ^*}}{\Gamma_{ZZ^*}^{\text{SM}}} \simeq \underline{1 + 2\,\delta c_Z} - 0.15\,c_{ZZ} + 0.41\,c_{Z\Box} + \ldots \text{ (EW } Vff,\ hVff\text{)}$$

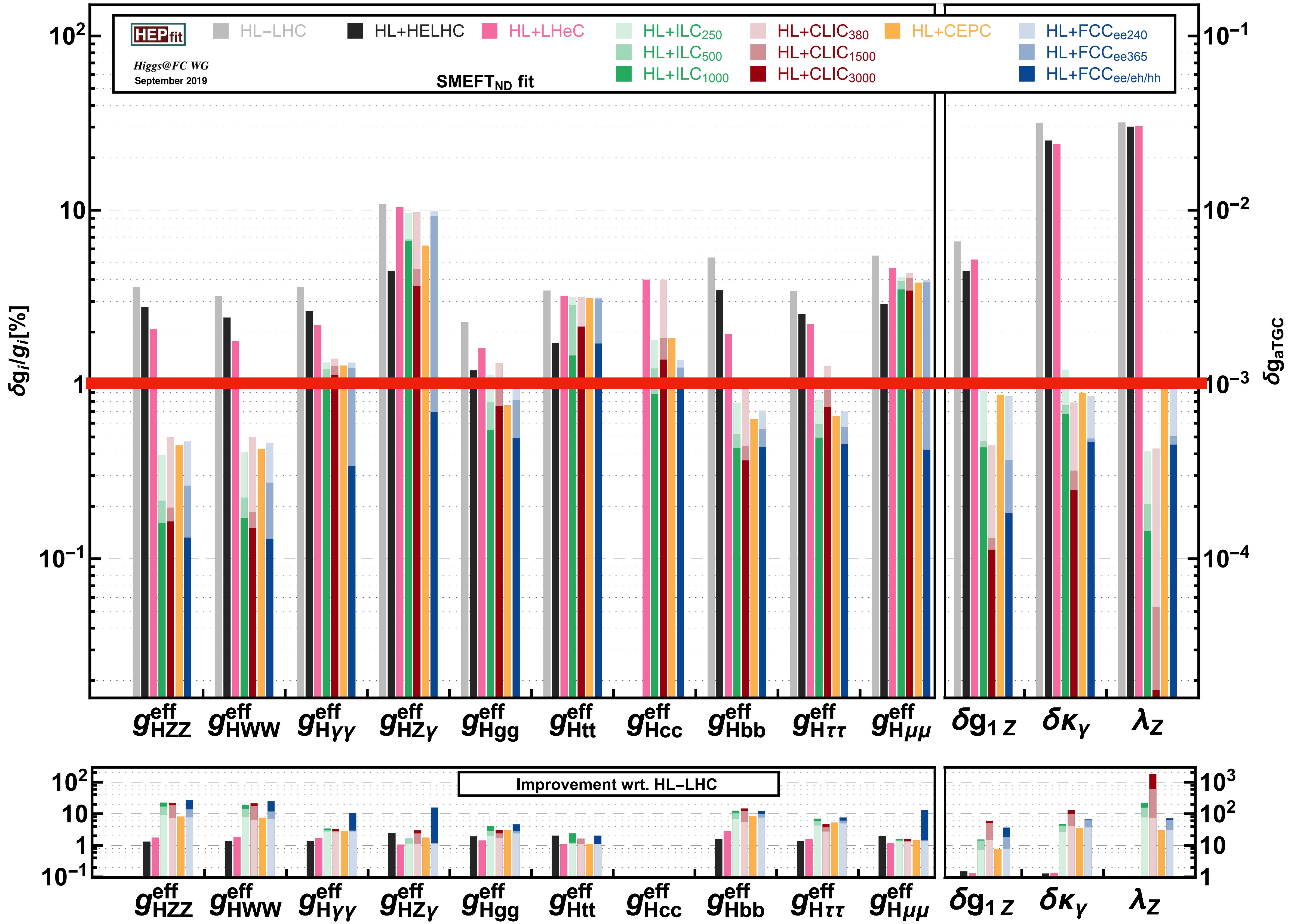
Only these are described in κ-framework

**Not enough to match EFT d.o.f : Add also aTGC**

Similarly, for EW interactions, **project results into effective *Zff* couplings** defined from EWPO, e.g.

$$\Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w \cos^2\theta_w}\left(|g_L^e|^2 + |g_R^e|^2\right), \qquad A_e = \frac{|g_L^e|^2 - |g_R^e|^2}{|g_L^e|^2 + |g_R^e|^2}$$

# Global EFT Fit

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1% magic threshold

There is life beyond HL-LHC

# Figures of Merit with Respects to HL-LHC

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**Factor of improvement in different channels viz. HL-LHC**

| | LHeC | HE-LHC | $\mathrm{ILC}_{250}$ | $\mathrm{ILC}_{500}$ | $\mathrm{CLIC}_{380}$ | $\mathrm{CLIC}_{1500}$ | $\mathrm{CLIC}_{3000}$ | CEPC | $\mathrm{FCCee}_{240}$ | $\mathrm{FCCee}_{365}$ | FCCee/eh/hh |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $g^{\mathrm{eff}}_{HZZ}$ | 1.7 | 1.2 | 7.7 | ≥ 10 | 5.5 | ≥ 10 | ≥ 10 | 6.9 | 7.7 | ≥ 10 | ≥ 10 |
| $g^{\mathrm{eff}}_{HWW}$ | 1.8 | 1.3 | 6.7 | ≥ 10 | 4.9 | ≥ 10 | ≥ 10 | 6.3 | 7.0 | ≥ 10 | ≥ 10 |
| $g^{\mathrm{eff}}_{H\gamma\gamma}$ | 1.7 | 1.3 | 2.8 | 3.4 | 2.6 | 3.1 | 3.4 | 3.1 | 3.1 | 3.1 | ≥ 10 |
| $g^{\mathrm{eff}}_{HZ\gamma}$ | 1.1 | 2.4 | 1.1 | 1.6 | 1.1 | 2.3 | 3.0 | 1.7 | 1.1 | 1.2 | ≥ 10 |
| $g^{\mathrm{eff}}_{Hgg}$ | 1.4 | 1.7 | 2.0 | 2.8 | 1.7 | 2.3 | 2.9 | 2.8 | 2.3 | 2.7 | 4.5 |
| $g^{\mathrm{eff}}_{Htt}$ | 1.1 | 1.7 | 1.1 | 1.2 | 1.1 | 1.4 | 1.4 | 1.1 | 1.1 | 1.1 | 1.8 |
| $g^{\mathrm{eff}}_{Hcc}$ | ⋆ | | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ |
| $g^{\mathrm{eff}}_{Hbb}$ | 2.7 | 1.5 | 6.1 | 9.8 | 5.1 | ≥ 10 | ≥ 10 | 7.6 | 7.3 | 9.1 | ≥ 10 |
| $g^{\mathrm{eff}}_{H\tau\tau}$ | 1.6 | 1.3 | 4.1 | 5.8 | 2.7 | 3.8 | 4.8 | 5.0 | 5.0 | 6.1 | 7.8 |
| $g^{\mathrm{eff}}_{H\mu\mu}$ | 1.2 | 1.8 | 1.3 | 1.4 | 1.3 | 1.4 | 1.6 | 1.4 | 1.4 | 1.4 | ≥ 10 |
| $\delta g_{1Z}[\times 10^2]$ | 1.3 | 1.4 | 6.7 | ≥ 10 | ≥ 10 | ≥ 10 | ≥ 10 | 7.3 | 7.8 | ≥ 10 | ≥ 10 |
| $\delta\kappa_\gamma[\times 10^2]$ | 1.3 | 1.2 | ≥ 10 | ≥ 10 | ≥ 10 | ≥ 10 | $\geq 10^2$ | ≥ 10 | ≥ 10 | ≥ 10 | ≥ 10 |
| $\lambda_Z[\times 10^2]$ | 1.1 | 1.0 | ≥ 10 | $\geq 10^2$ | ≥ 10 | $\geq 10^2$ | $\geq 10^3$ | ≥ 10 | ≥ 10 | ≥ 10 | ≥ 10 |

SMEFT ND (⋆) not measured at HL-LHC

Stat. limited

Top quark channels
(LHC is a top factory and it is not so easy to outperform)

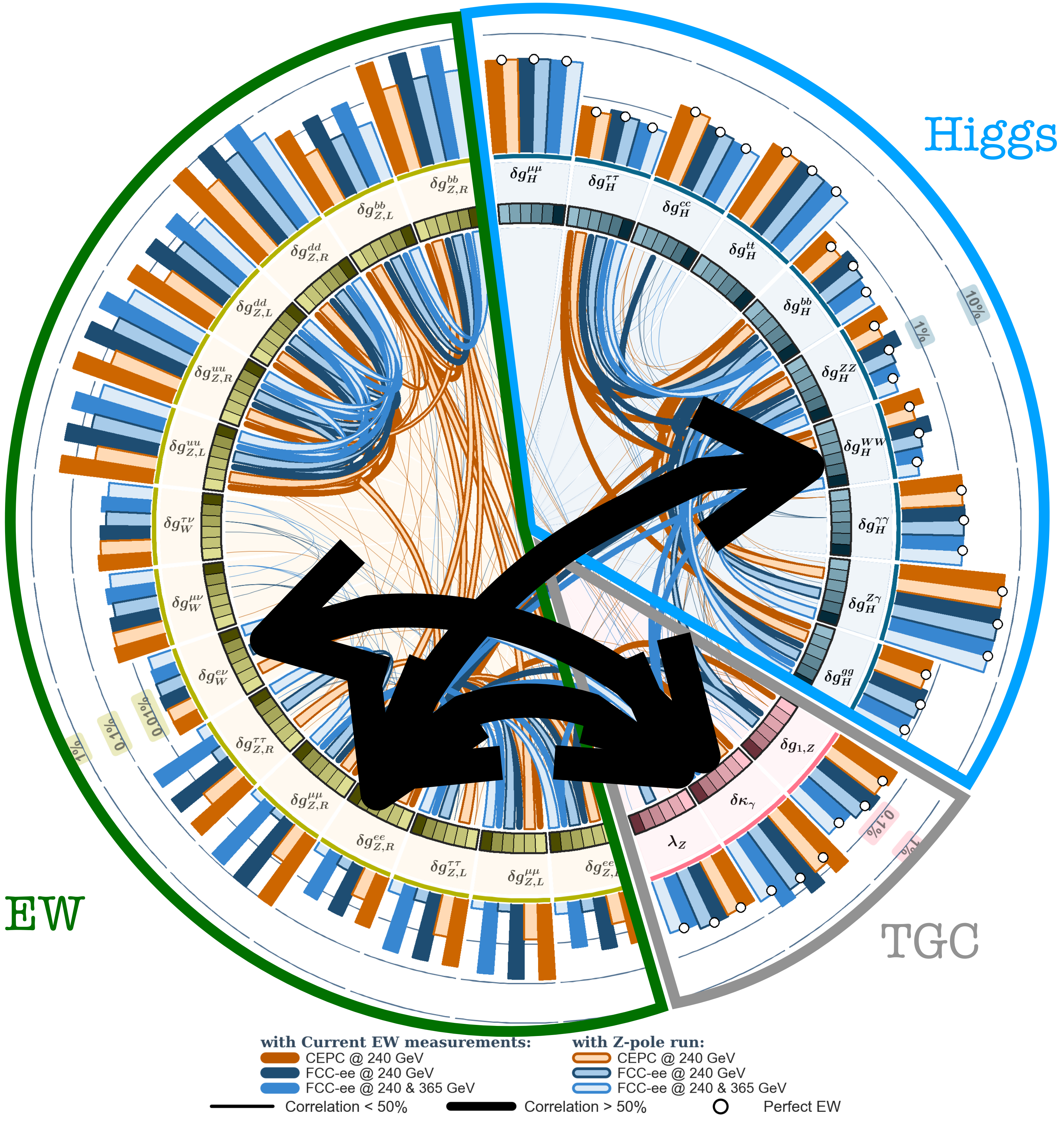
5

If no deviation seen at HL-LHC 5σ discovery still possible at Future Collider

There is life after HL-LHC

# Importance of Correlations

J. De Blas et al. 1907.04311

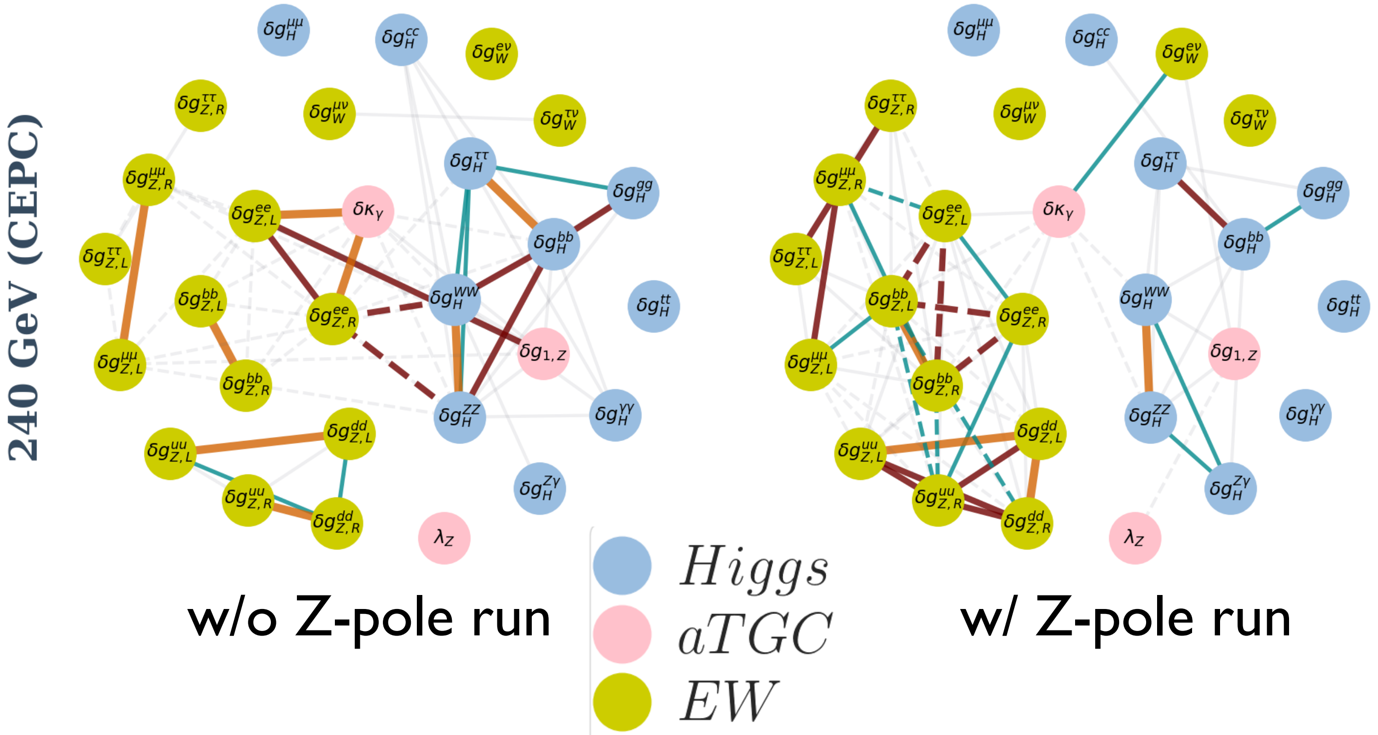



Contamination EW/TGC/Higgs can be understood by looking at correlations

Without Z-pole runs, there are large correlations between EW and Higgs

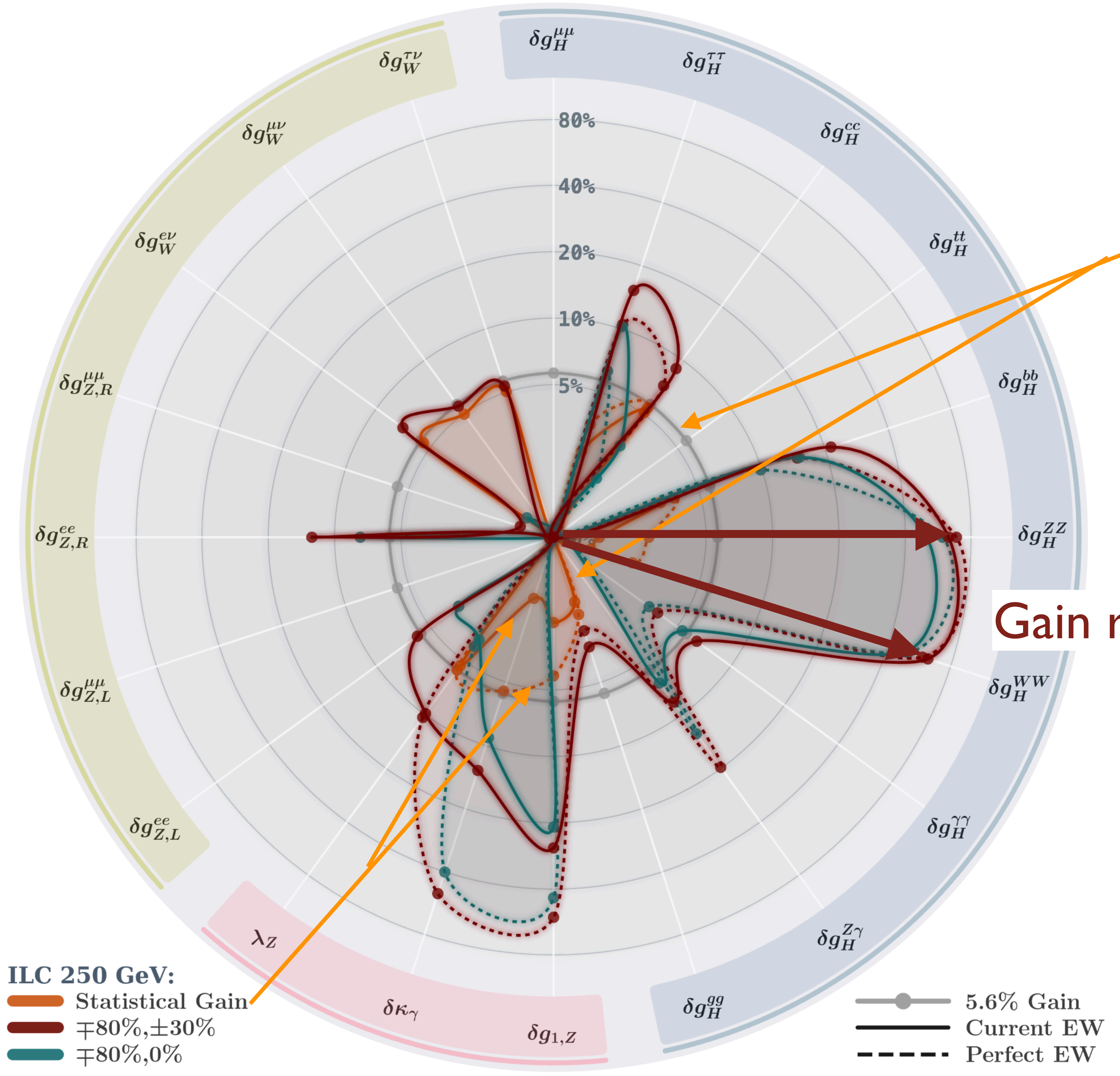
With Z-pole runs, only correlations between EW and TGC remain

Z-pole runs at circular colliders isolate EW and Higgs sectors from each others



# Impact of Beam Polarisation (@250GeV)

J. De Blas et al. 1907.04311




increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

**Statistical gain from increased rates**

$$\sigma_{P_{e^+}P_{e^-}} = \sigma_0(1 - P_{e^+}P_{e^-})\left[1 - A_{LR}\frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}\right]$$

From ee→Zh, $A_{LR}$~0.15 so $\sigma_{-80,+30} \sim 1.4\,\sigma_0$

overall, one could expect
O(6%) increased coupling sensitivity

Gain is much higher in global EFT fit since polarisation removes degeneracies among operators

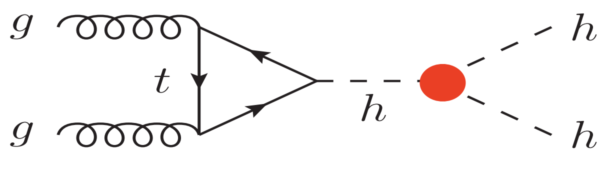
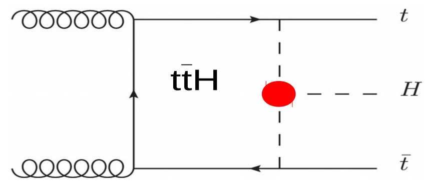
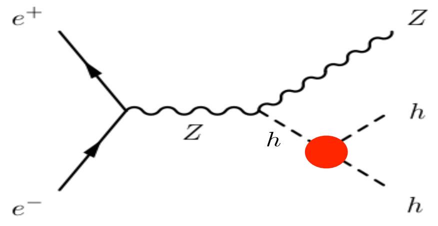
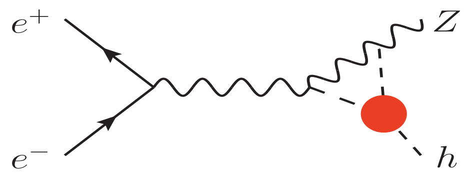
Polarisation benefit diminishes when other runs at higher energies are added and basically left only with statistical gain

# Higgs Self-Coupling

Higgs self-couplings is very interesting for a multitude of reasons
(vacuum stability, hierarchy, baryogenesis, GW, EFT probe…).

**How much different from the SM can it be given the tight constraints on other Higgs couplings?**
**Do you need to reach HH production threshold to constrain $h^3$ coupling?**

ECFA Higgs study group '19

| | Directly: Higgs-pair prod | Indirectly: via single Higgs |
|---|---|---|
| **Hadron Colliders** |  |  |
| **Lepton Colliders** |  |  |





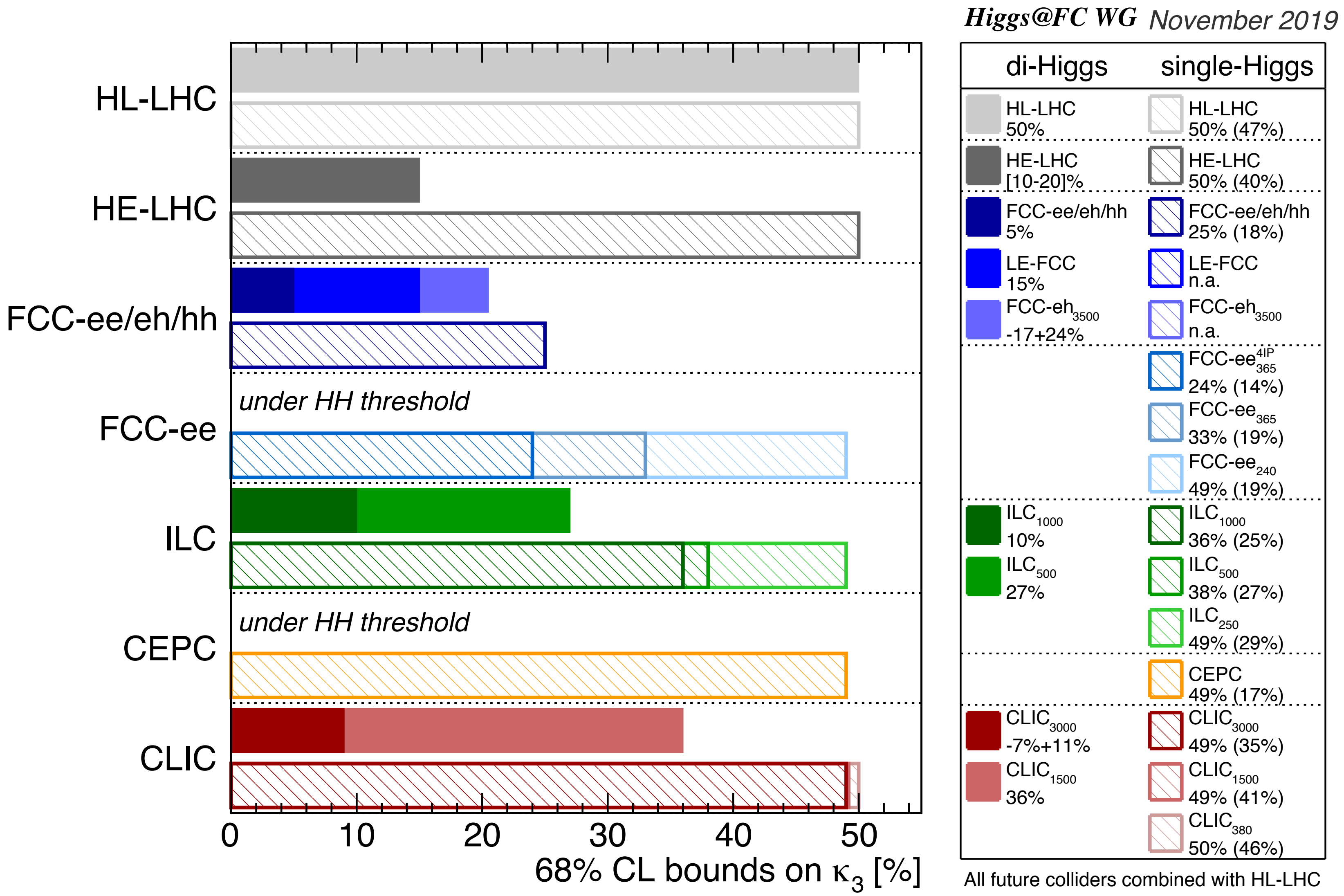




| | di-Higgs | single-H |
|---|---|---|
| exclusive | **1. di-H, excl.**<br>• Use of σ(HH)<br>• only deformation of κλ | **3. single-H, excl.**<br>• single Higgs processes at higher order<br>• only deformation of κλ |
| global | **2. di-H, glob.**<br>• Use of σ(HH)<br>• deformation of κλ + of the single-H couplings<br>(a) do not consider the effects at higher order of κλ to single H production and decays<br>(b) these higher order effects are included | **4. single-H, glob.**<br>• single Higgs processes at higher order<br>• deformation of κλ + of the single Higgs couplings |

# Higgs Self-Coupling

ECFA Higgs study group '19




1

Don't need to reach HH threshold
to have access to h3.
Z-pole run is very important
if the HH threshold cannot be reached

2

The determination of $h^3$ at FCC-hh
relies on HH channel,
for which FCC-ee is of little direct help.
But the extraction of $h^3$
requires precise knowledge of $y_t$.
$1\%\ y_t \leftrightarrow 5\%\ h^3$

Precision measurement of $y_t$ needs ee

**50% sensitivity:** establish that $h^3 \neq 0$ at 95%CL
**20% sensitivity:** $5\sigma$ discovery of the SM $h^3$ coupling
**5% sensitivity:** getting sensitive to quantum corrections to Higgs potential

# Other Studies Beyond Coupling Fits

ECFA Higgs study group '19

no new study, mostly summary/reinterpretation of existing projections

- Higgs mass
- Invisible width
  - diphoton interferences
  - signal strength fit (assuming $|\kappa_V|<1$ and $BR_{unt}=0$)
  - off-shell channel
  - direct measurement from Z-recoil at lepton colliders
- Rare decays constraints on light Yukawa's
- Higgs CP
  - hVV: rates and angular distributions
  - h$\tau\tau$: angular distributions
  - ttH and tH: rates and angular distributions
  - indirect constraints from EDM

# Future Directions - I

European Strategy Studies focused on inclusive measurements
They don't do justice to richness of kinematical distributions accessible
at either leptonic machines (thanks to clean environment) or high-energy hadronic machines

- Higgs couplings at high-energy (relying on STXS?)
  1. off-shell $gg \to h^* \to ZZ \to 4l$
  2. boosted Higgs: Higgs + high-$p_T$ jet
  3. VH at large invariant mass (double differential distributions sometime needed to restore BSM/SM interference)

- High pT distribution**: "energy helps accuracy" (☞ beware of EFT validity)
  1. BSM effects often grow with energy
  2. study of poorly populated phase space regions with smaller systematics

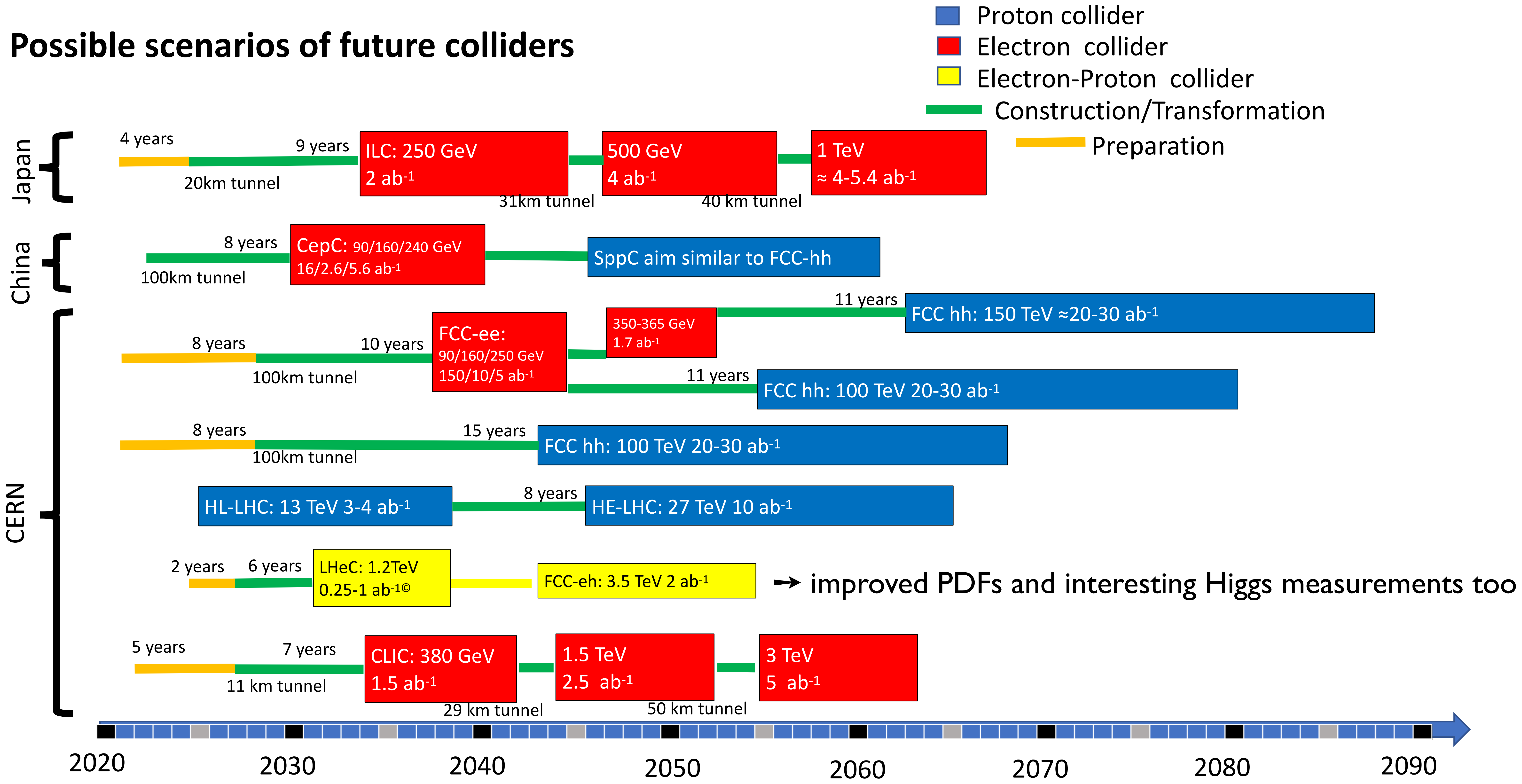
* *some pheno projections were implemented in our SILH fit: di-fermions prod., ZH(bb), WZ at high-invariant mass but no full EFT analysis available yet

# Future Directions - II

- Estimate EFT uncertainties (NLO, dim-8 effects, linear vs quadratic…), NP in backgrounds, theoretical constraints (positivity, analyticity), SMEFT vs. HEFT…
- Explore more flavour scenarios (and make connection with flavour data)
- Full-fledged EFT analysis of diboson data (away from TGC dominance assumption) with statistically optimised observables
- More combined Higgs and top analysis
    1. effects of top dipoles or 4 fermion ops. with tops
    2. constraints on top EW couplings from their NLO effects in Higgs and diboson processes (particularly relevant for low-energy colliders below ttH threshold)
- Generalisation of (pseudo)-observables to report EFT fits
    1. give justice to differential measurements
    2. well suited for a global approach with H, EW, top, flavour
- Don't forget correlations
- Provide more BSM interpretations, i.e., match to different models/UV dynamics. Which physics hypotheses do we want to test? Which consequences for cosmo?

# Conclusion

## Possible scenarios of future colliders

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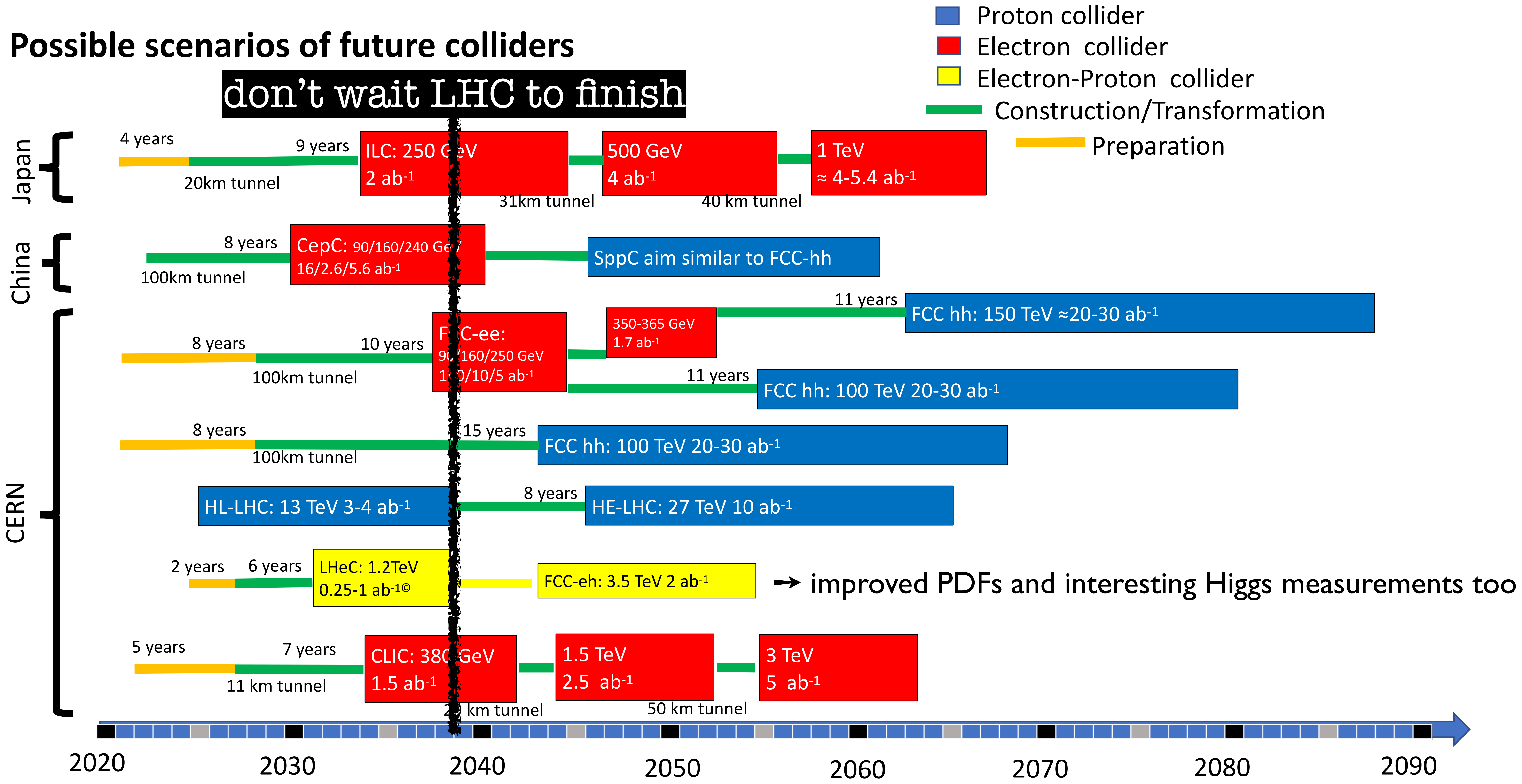
# Conclusion

## Possible scenarios of future colliders

**don't wait LHC to finish**

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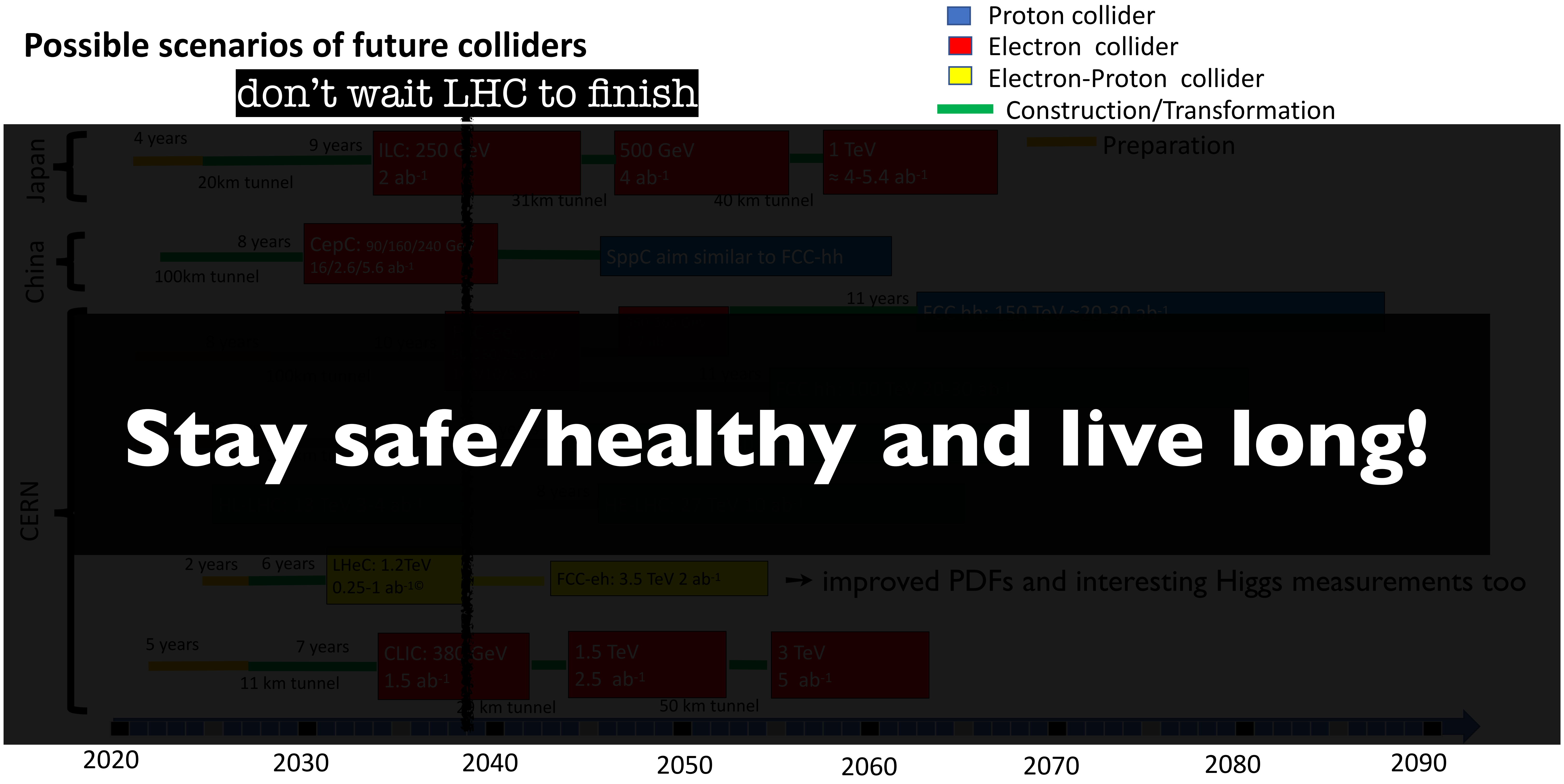
# Conclusion

**Possible scenarios of future colliders**

don’t wait LHC to finish




# Stay safe/healthy and live long!

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