Electroweak Physics & SM precision tests

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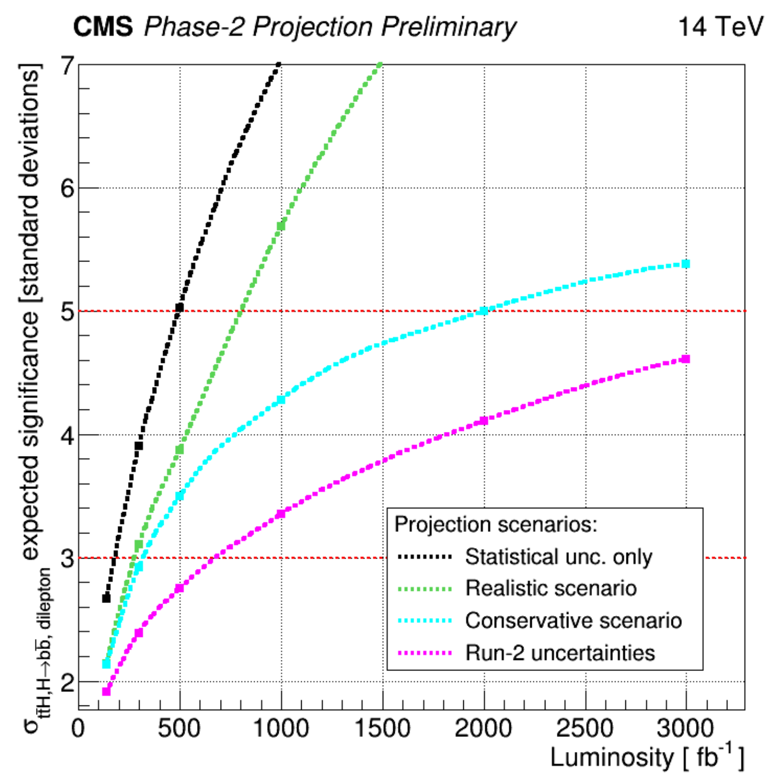
European Strategy for Particle Physics Update:
1st meeting of the SM and beyond WG (GT1)
4th of October 2024

Context

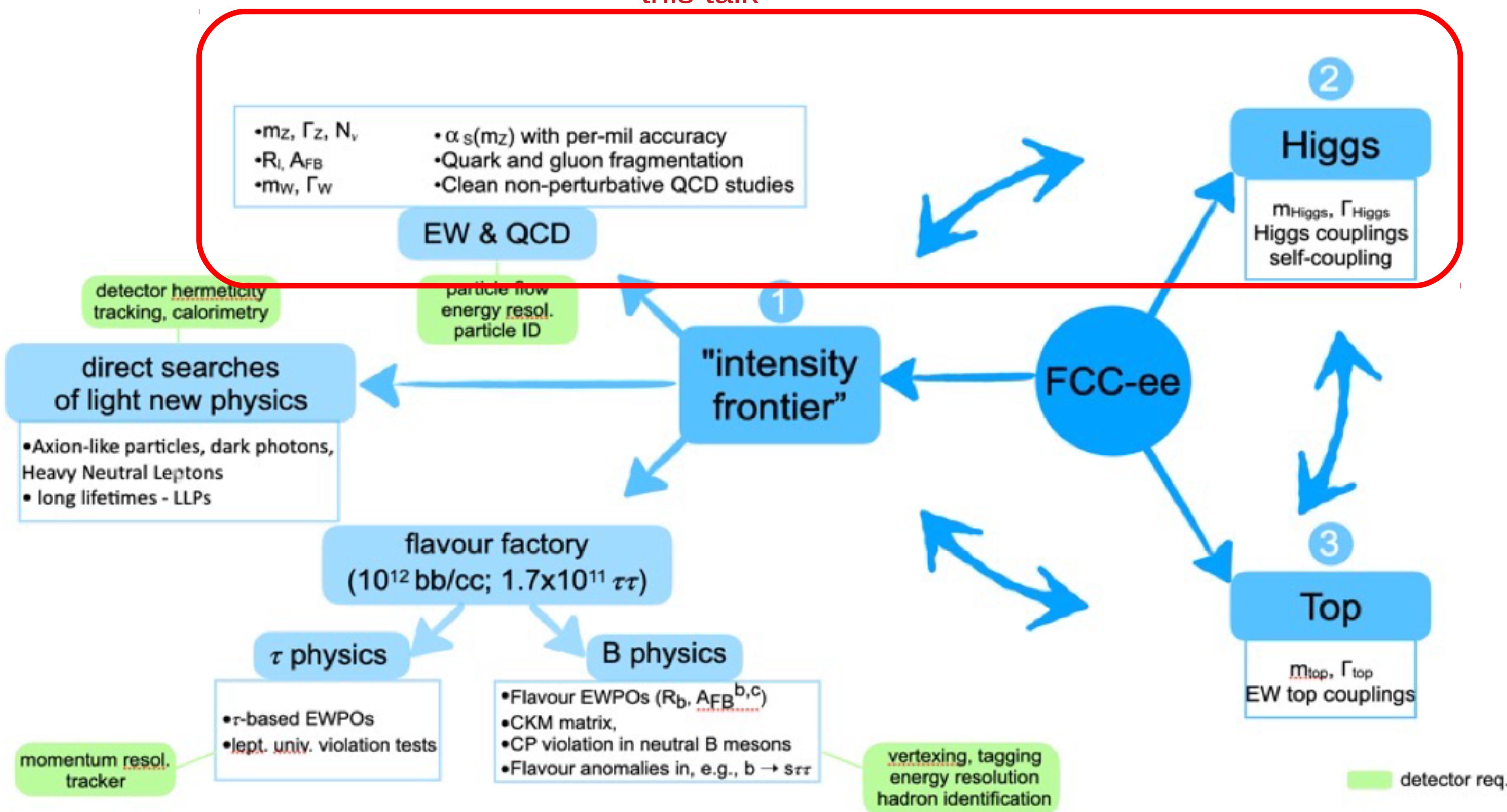
- European Strategy for Particle Physics 2018-2020
  - CERN Yellow Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC (link)
  - symposium in 2019 + briefing book (link) + conclusions (link)
- US Snowmass process 2020-2022
  - proceedings end of 2022
  - White paper by ATLAS and CMS (link)



- Assumption on systematics for HL-LHC studies:
  - statistics-driven: data → $\sqrt{L}$, simulation → 0
  - theory uncertainties typically halved
  - intrinsic detector limitations stay ~constant
  - luminosity uncertainty 1%
  - PDF uncertainties reduced by a factor 3 to 4

FCC-ee physics case (true for most ee colliders)

this talk

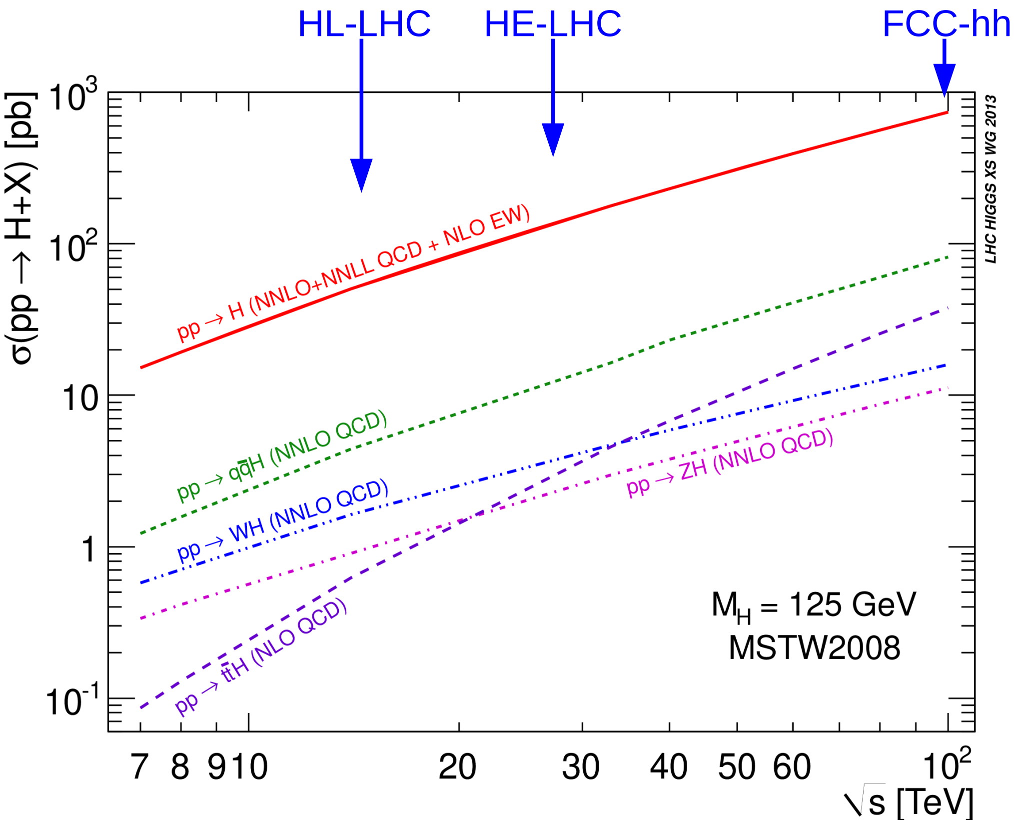


C. Grojean

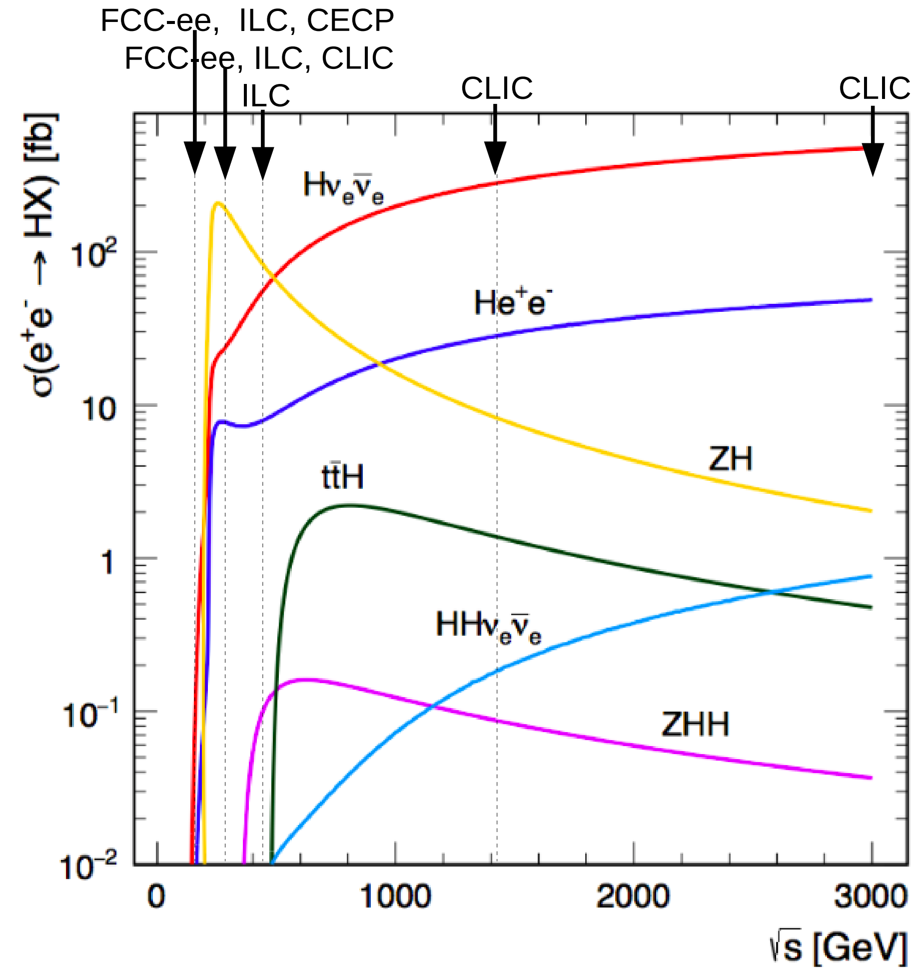
Higgs boson physics

Higgs production at pp and ee colliders

- pp colliders



- ee colliders



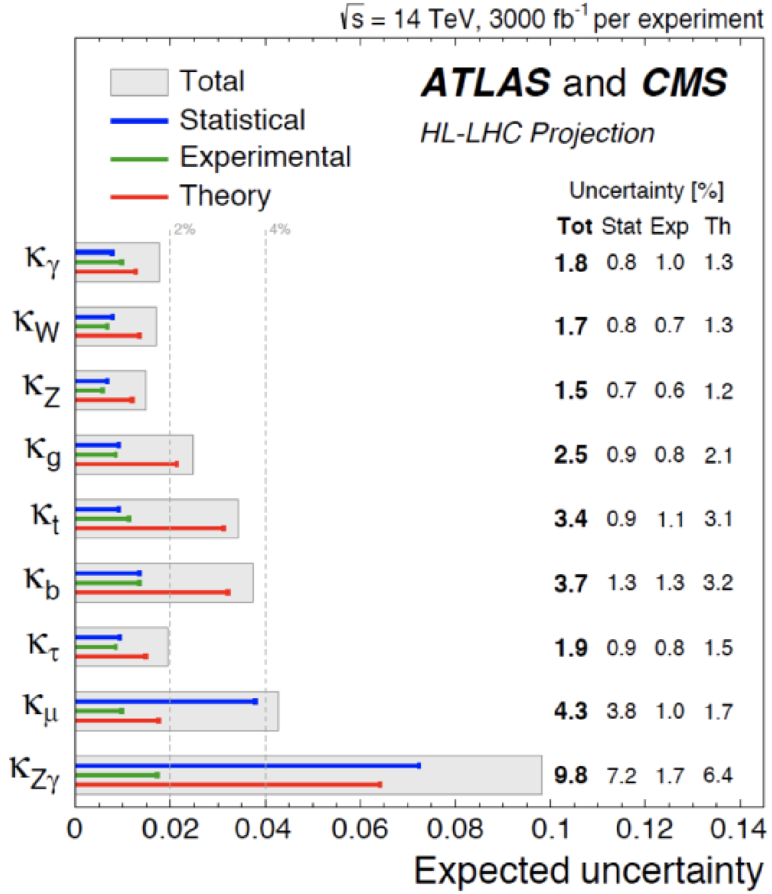
- High cross-section and luminosity
  - from 2.10^7 (LHC) to 3.10^10 (FCC-hh) produced Higgs bosons

- Two important thresholds:
  √s ~250 GeV for ZH, 500 GeV for ttH

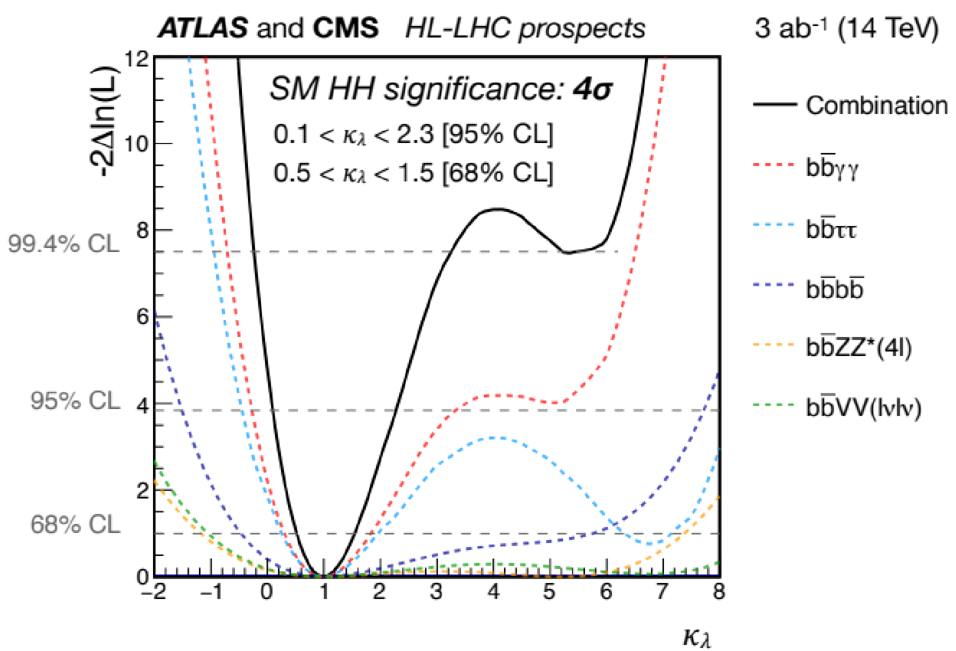
Higgs boson physics at HL-LHC (1)

- Yellow Report released end of 2018 with many updates of Physics Prospective with ATLAS and CMS (link to Higgs chapter)

- Single-Higgs:
  - O(%) uncertainties



- Di-Higgs:
  - 4σ significance
  - 50% uncertainty on λ_{HHH}



Higgs boson physics at HL-LHC (2)

CERN-2019-007
ATL-PHYS-PUB-2022-018/
CMS-PAS-FTR-22-001

ATL-PHYS-PUB-2024-016

- Examples of progress in the past years:
- Coupling to muons through H→ μμ
  - expected precision on signal strength (YR2018 uncertainties):

	Statistical	Experimental	Theoretical	Total
ATLAS YR2018	$^{+12\%}_{-13\%}$	2.00%	$^{+5\%}_{-4\%}$	**13%**
CMS Snowmass2013				**14%**
CMS YR2018	9%	2%	3%	**10%**
CMS Snowmass2021	6%	2%	2%	**7%**

factor 2 in 8 years!

  - 5σ can be expected at the end of Run 3

- Di-Higgs: YR2018 ATLAS+CMS: expected significance of 4σ
  - improvement in ATLAS HH→ bbττ only

	Stat-only	Stat+Syst
YR 2018	2.5σ	2.0σ
Snowmass 2021	4.0σ	2.8σ
ATLAS-PHYS-2024-016	4.9σ	3.8σ

- Also a lot of recent progress on couplings to charm quarks
  - thought to be impossible at the beginning of LHC

Higgs couplings at Future Colliders

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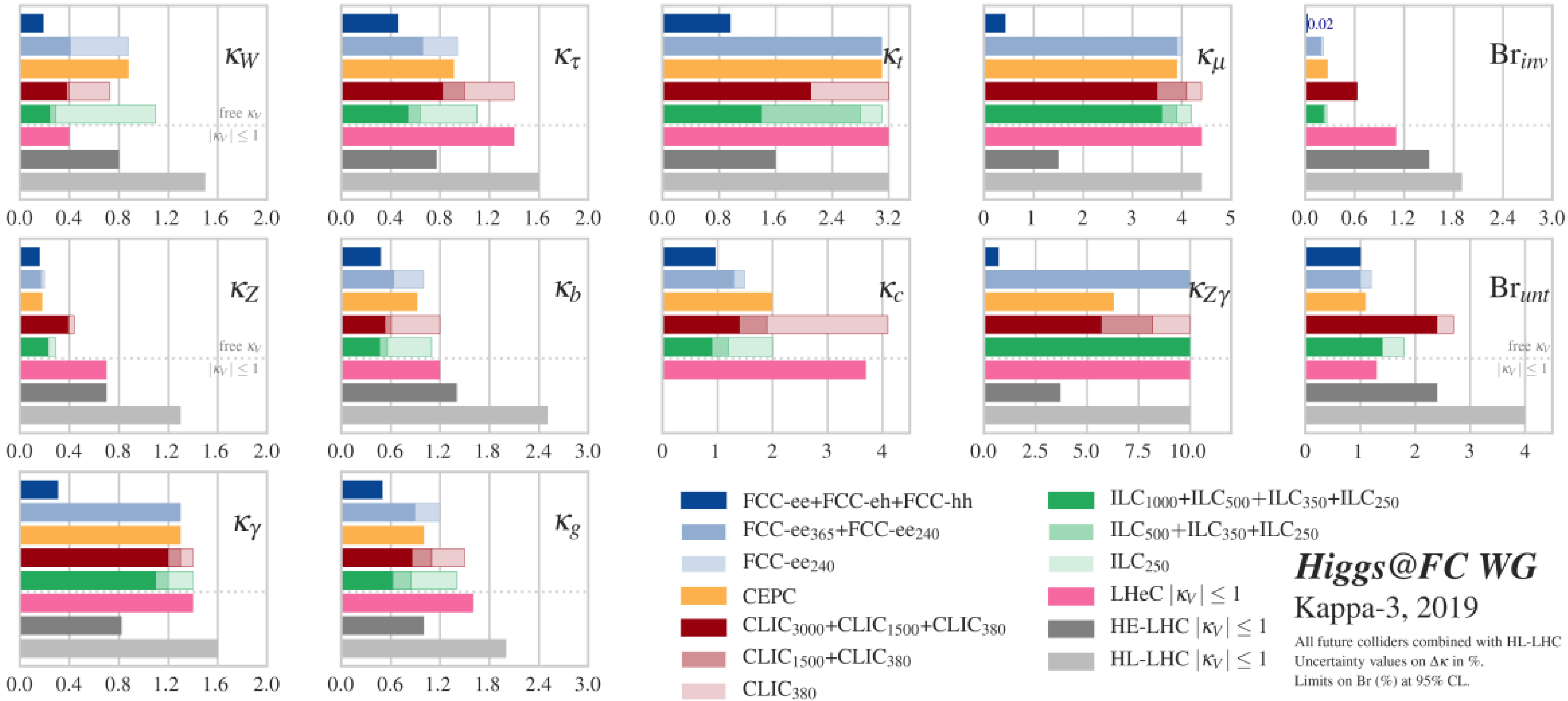

Fig. 3.8: Expected relative precision of the κ parameters and 95% CL upper limits on the branching ratios to invisible and untagged particles for the various colliders. All values are given in %. For the hadron colliders, a constraint $|\kappa_V| \leq 1$ is applied, and all future colliders are combined with HL-LHC. Figure is from Ref. [39].

Higgs self-couplings at Future Colliders

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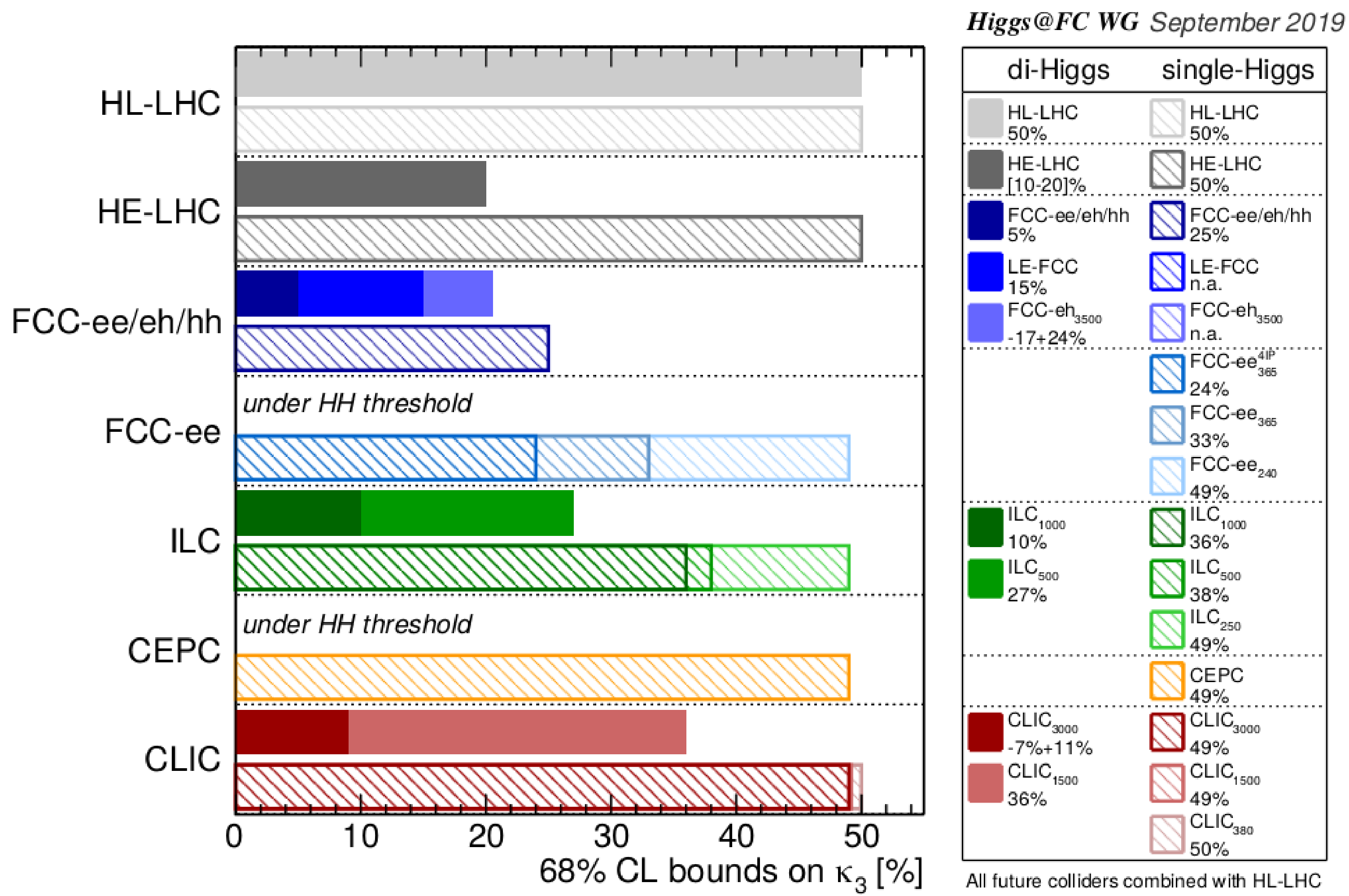


- HL-LHC will exclude the absence of the Higgs self-interaction at 95%CL
- Several of the proposed FCs will reach a sensitivity of ~20% ⇒ establish the existence of the self-interaction at 5σ
- CLIC3000/FCC-hh can reach a sensitivity of ~10%/5% ⇒ can start probing the size of the quantum corrections to the Higgs potential directly

Higgs boson mass

JHEP01(2020)139
DOI 10.17181

- Current experimental precision ~0.1% (150 MeV)
- Needs a 10 MeV precision to avoid any limitation on the ZZ/WW couplings
- Prospects at the time of ESPPU2020:

impact on the H → ZZ* partial decay width

Collider	Strategy	δm_H (MeV)	Ref.	$\delta(\Gamma_{ZZ^*})$ [%]
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	[96]	1.9
HL-LHC	$m(ZZ)$	10-20	[13]	0.12-0.24
ILC_{250}	ZH recoil	14	[3]	0.17
$CLIC_{380}$	ZH recoil	78	[98]	0.94
$CLIC_{1500}$	$m(bb)$ in $H\nu\nu$	30[20]	[98]	0.36
$CLIC_{3000}$	$m(bb)$ in $H\nu\nu$	23	[98]	0.28
FCC-ee	ZH recoil	11	[99]	0.13
CEPC	ZH recoil	5.9	[2]	0.07

- Can be used to compare detector concepts
  - NB: nominal δ_{mH} of 4 MeV in latest FCC-ee studies

- Assuming "perfect" (generator-level) momentum resolution → Ideal resolution
- Nominal 2 T magnetic field → 3 T (stronger field → better tracking) → Magnetic Field 3T
- IDEA drift chamber → CLD silicon tracker → CLD 2T (silicon tracker)

	Combined
Nominal	4.01
Ideal resolution	3.33
Magnetic Field 3T	3.54
CLD 2T (silicon tracker)	4.66

Ang Li

Higgs width

JHEP01(2020)139
DOI 10.17181/4wxpk-1zy78

- Impossible to achieve at pp colliders without assumptions
- Mass recoil: mesure inclusive cross-section of ZH without assumption on the Higgs boson's BRs: $\frac{\sigma(e^+e^-\to ZH)}{\mathrm{BR}(H\to ZZ^*)} = \frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$
  - mild model dependence
- Prospects at the ESPPU2020:

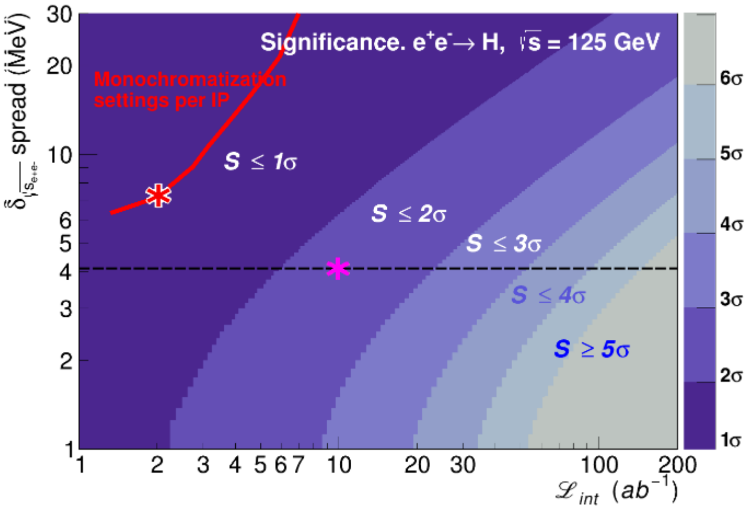
Collider	$\delta\Gamma_H$ [%] from ref.	Extraction technique for standalone result
ILC_{250}	2.3	EFT fit [3, 4]
ILC_{500}	1.6	EFT fit [3, 4, 14]
ILC_{1000}	1.4	EFT fit [4]
CLIC_{380}	4.7	κ-framework [98]
CLIC_{1500}	2.6	κ-framework [98]
CLIC_{3000}	2.5	κ-framework [98]
CEPC	2.8	κ-framework [103, 104]
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]

- Still ongoing effort, 27 channels to cover!

New ideas for Higgs boson measurements

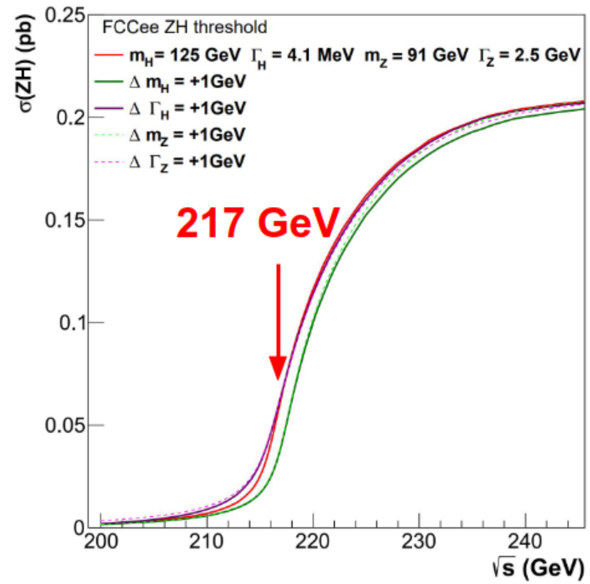
2107.02686
2106.15438

- e+ e– → H at √s = 125 GeV: probe electron-Yukawa coupling
  - only way to do it?
- Small cross-section ⇒ large dataset
- Beams must be monochromatized (spread of $E_{CM} \sim \Gamma_H$) while keeping large beam luminosities
- m_H must be known at 4 MeV level



- Significance of 1.3σ/IP/year can be achieved

- e+ e– → ZH at √s = 217 GeV: probe Higgs mass from threshold
- Needs accurate measurements of Z mass and width at the Z-pole
- SM-only assumptions → new physics can break the dependency
- Syst. effects to be evaluated



- 5 MeV uncertainty can be achieved with 5 ab-1
  - 10 MeV more realistically

Example of possible Higgs studies at FCC-ee

Where are we today?

FUTURE CIRCULAR COLLIDER

Made a lot of progress over the past years, mainly focused at the 240 GeV threshold

Missing elements for the Feasibility Study for next 1.5 years

- Higgs @ 240 GeV: WW, ZZ (expansion of H width efforts)
- Higgs @ 365 GeV: the total cross-section, couplings, width
- Tau physics
  - Higgs → tau tau can put unique detector requirements for tau ID and reconstruction
  - Synergies with Tau polarization at Z pole
- Others: angular analysis, differential measurements

Top activities

- Threshold mass, width
- EW couplings ttZ, Vts, FCNCs

Parameter	FCC-ee CDR	FCCee today
H→WW	1 %	–
H→ZZ	3.6 %	4.6 %
H→gg	1.6 %	0.94 %
H→γγ	7.5 %	3.5 %
H→cc	1.8 %	1.92 %
H→bb	0.25 %	0.22 %
H→μμ	15.8 %	19.5 %
H→$\tau\tau$	0.75 %	–
Invisible	< 0.25 %	< 0.18 %
H→ss	–	124 %
m_H	5 MeV	4 MeV
Γ_H	1 %	4%
κ_λ	42 %	30%

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J. Eysermans, FFC Physics workshop, Jan 2024

EW precision observables

EWPO: introduction

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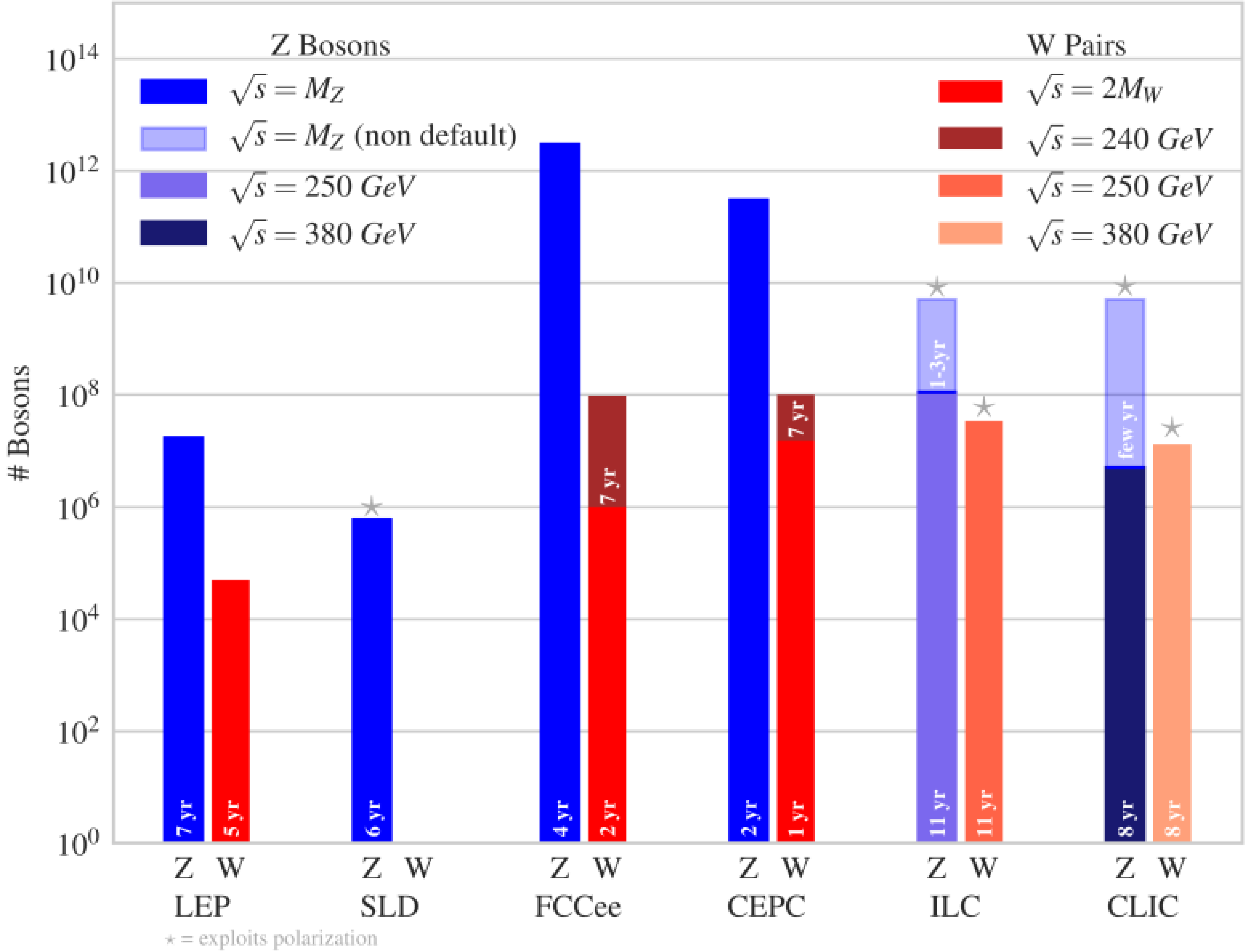
- Number of expected weak bosons:



W mass measurement

W-boson mass measurements vs. prediction from μ decay

ILC: Baak et al., 1310.6708   FCC-ee: Freitas et al., 1906.05379

	experimental accuracy				theory uncertainty				
		σ_{WW} @ threshold			intrinsic			parametric	
	current	LEP2	ILC	FCC-ee	current	source	prospect	prospect	source
ΔM_W [MeV]	13	200	3–6	0.5–1	3	$\alpha^3, \alpha^2\alpha_s$	1	1(0.6)	$\Delta\alpha_{had}$

current: complicated reconstructions (Amoroso et al., 2308.09417)

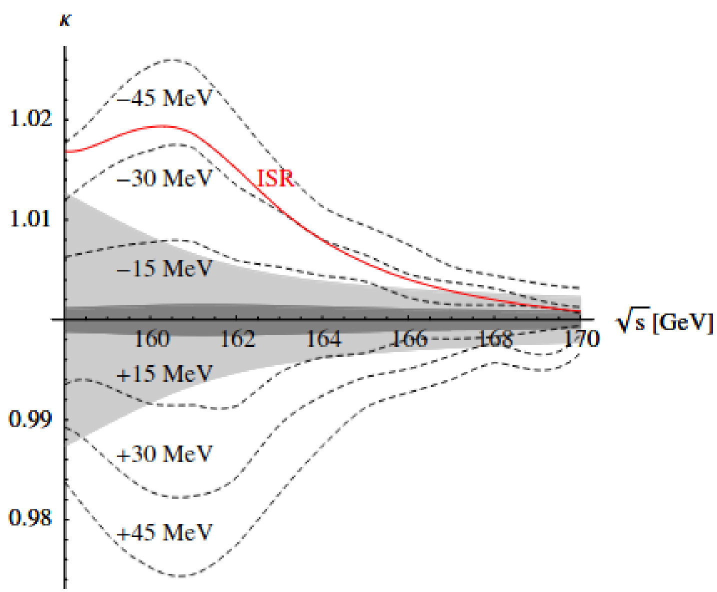
LEP2 / ILC / FCC-ee: basically counting experiments

theory uncertainty: M_W calculated from μ decay

Theory challenges

- Full NLO $e^+e^- \to 4f$ prediction for each $4f$ type
- ISR to very high orders
- full NNLO calculation in threshold EFT + improvements
- for M_W analysis: M_W prediction from μ decay at 3 loops

Sensitivity of σ_{WW} to M_W: Beneke et al. '07



$$\kappa = \frac{\sigma_{WW}(s, M_W + \delta M_W)}{\sigma_{WW}(s, M_W)}$$

$\Delta\kappa = 0.1\%\,(0.02\%) \leftrightarrow \delta M_W = 1.5\,(0.3)\,\mathrm{MeV}$
for $\sqrt{s} = 161\,\mathrm{GeV}$

$\Rightarrow$ FCC-ee requires
$\Delta_{TH} \sim 0.01$–0.04% in σ_{WW}

Shaded areas / ISR curve:
some uncertainties of NLO(EFT) calculation,
improveable via full NLO($ee \to 4f$) and NNLO(EFT)

Physics at the Z pole

link

Physics at the Z pole – central EW precision (pseudo-)observables

FCC-ee: Freitas et al., 1906.05379; ILC: Moortgat-Pick et al., 1504.01726

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	–	0.1			
$\Delta \Gamma_Z$[MeV]	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^{\ell}_{eff}[10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

Theory requirements for Z-pole pseudo-observables:

- needed:
  - EW and QCD–EW 3-loop calculations
  - $1 \to 2$ decays, fully inclusive
- problems:
  - technical: massive multi-loop integrals, γ_5
  - conceptual: pseudo-obs. on the complex Z-pole

Theory challenges

- Z Lineshape at NNLO EW precision (massive 2-loop, concept of unstable particles)
- higher-order ISR corrections way beyond NNLO
- concept of pseudo-observables at much higher level

Electroweak observables

- Dedicated program at FCC-ee CEPC

Precision EWK Observables

Submission Inputs: 29, 145, 101, 132, 135

EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	< 1
$\sin^2\theta_W^{\text{eff}}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

LHeC can measure $\sin^2\theta_W$ as f(E).

LHeC : Mw to 10 MeV but can measure PDFs allowing HL-LHC to half PDF uncertainty and achieve O(5 MeV) Mw.
ILC/CLIC : Mw to 5 MeV similar to HL-LHC/TeV average.

- ILC:
  - studies of radiative return to the Z at 250 GeV
  - possibility of a 1-year run at the Z pole (3 x 10^9 Z's)

Properties related to the EW bosons

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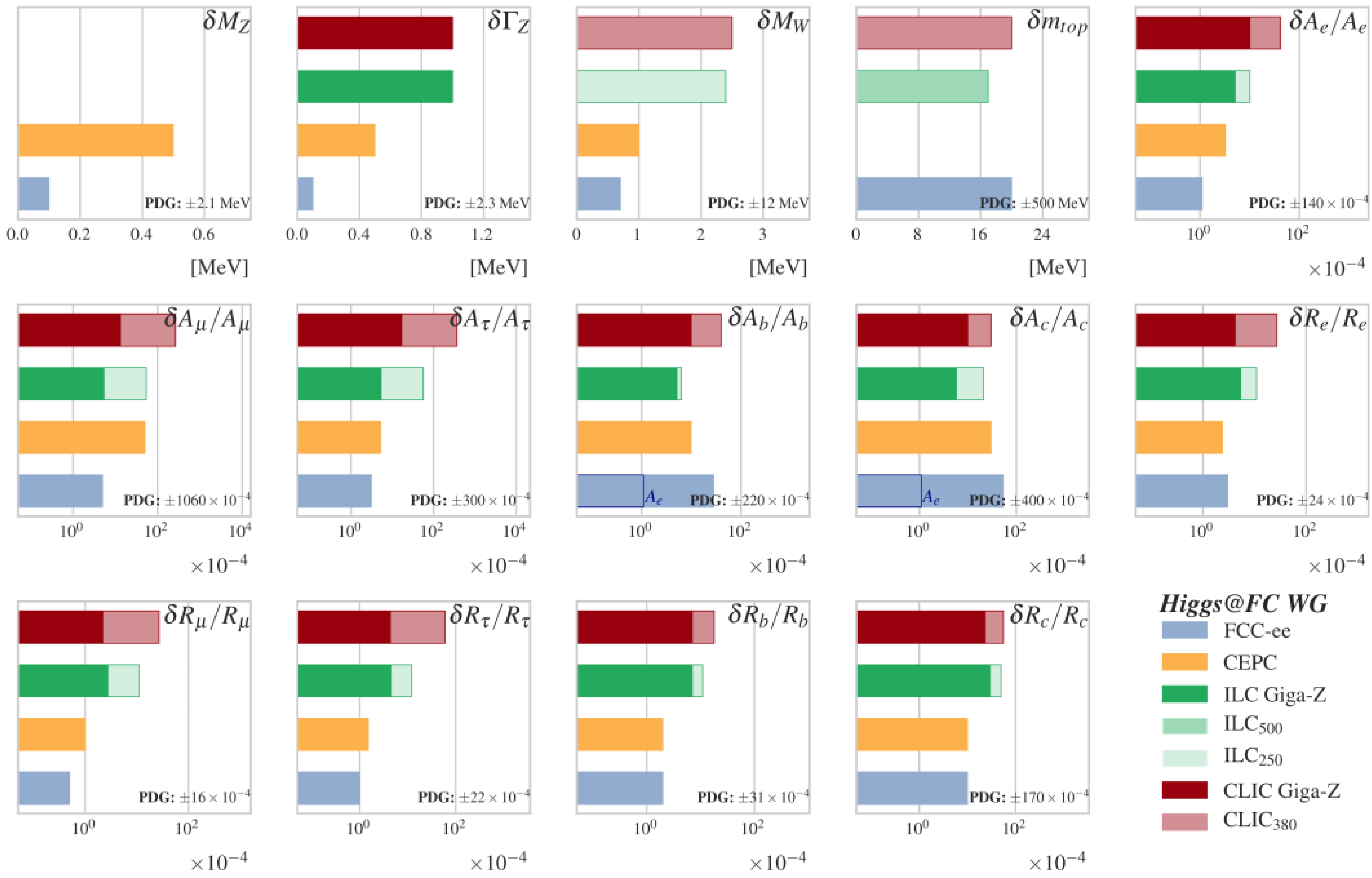
- > factor 10 improvement wrt current values



More on the detector requirements

All stolen from this link

- General requirements:

"Higgs Factory" Programme

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{pT}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.

- Benchmarks for the vertex detector
  - $H \rightarrow b\bar{b}/c\bar{c}$ couplings
  - $Br(B \rightarrow K^*\tau\tau) \sim 10^{-7}$
- Benchmarks for the inner tracker momentum resolution
  - Higgs boson mass
  - $K_s \rightarrow \pi^+\pi^-$ (decay of B^+ meson)
- Benchmarks for Particle ID
  - Flavor physics measurements: $B^0_S \rightarrow D^{\pm}_S K^{\mp}$, $B \rightarrow K^*\nu\nu$, $B_s \rightarrow \phi\nu\nu$, …
  - s-quark jet identification → kaon ID ($H \rightarrow s\bar{s}$, V_{ts}, V_{bs}, $H \rightarrow bs$, FCNCs, …)
- Benchmarks for calorimetry
  - hadronic: $H \rightarrow WW/ZZ$ jet separation
  - electromagnetic: flavor physics ($B_s \rightarrow D_s K$, $B_0 \rightarrow \pi^0\pi^0$, $Bs \rightarrow K^*\tau\tau$), Higgs, new physics searches (e.g. $Z \rightarrow \mu e$, $\tau \rightarrow \mu\gamma$, $e+e- \rightarrow a\gamma \rightarrow \gamma\gamma\gamma$), bremsstrahlung recovery, tau polarization (separate $\tau^{\pm} \rightarrow \rho^{\pm}\nu \rightarrow \pi^{\pm}\pi^0\nu$ and $\tau^{\pm} \rightarrow \pi^{\pm}\nu$)
- Benchmarks for muon spectrometer
  - $B^0 \rightarrow \mu\mu$

Conclusion

- Priority of ESPPU2020 to build a e^+e^- collider
  - \> factor 10 improvement on EW precision variables and Higgs boson parameters
    - sensitive to order of magnitude heavier NP in loops
  - some measurements impossible at pp colliders (Higgs boson mass and width)

- Continuous progress in the prospective studies
  - but will have to fulfil the assumptions on the systematic uncertainties

- Now that we are progressing to the design of detectors, several EW or Higgs benchmarks can help comparing the options

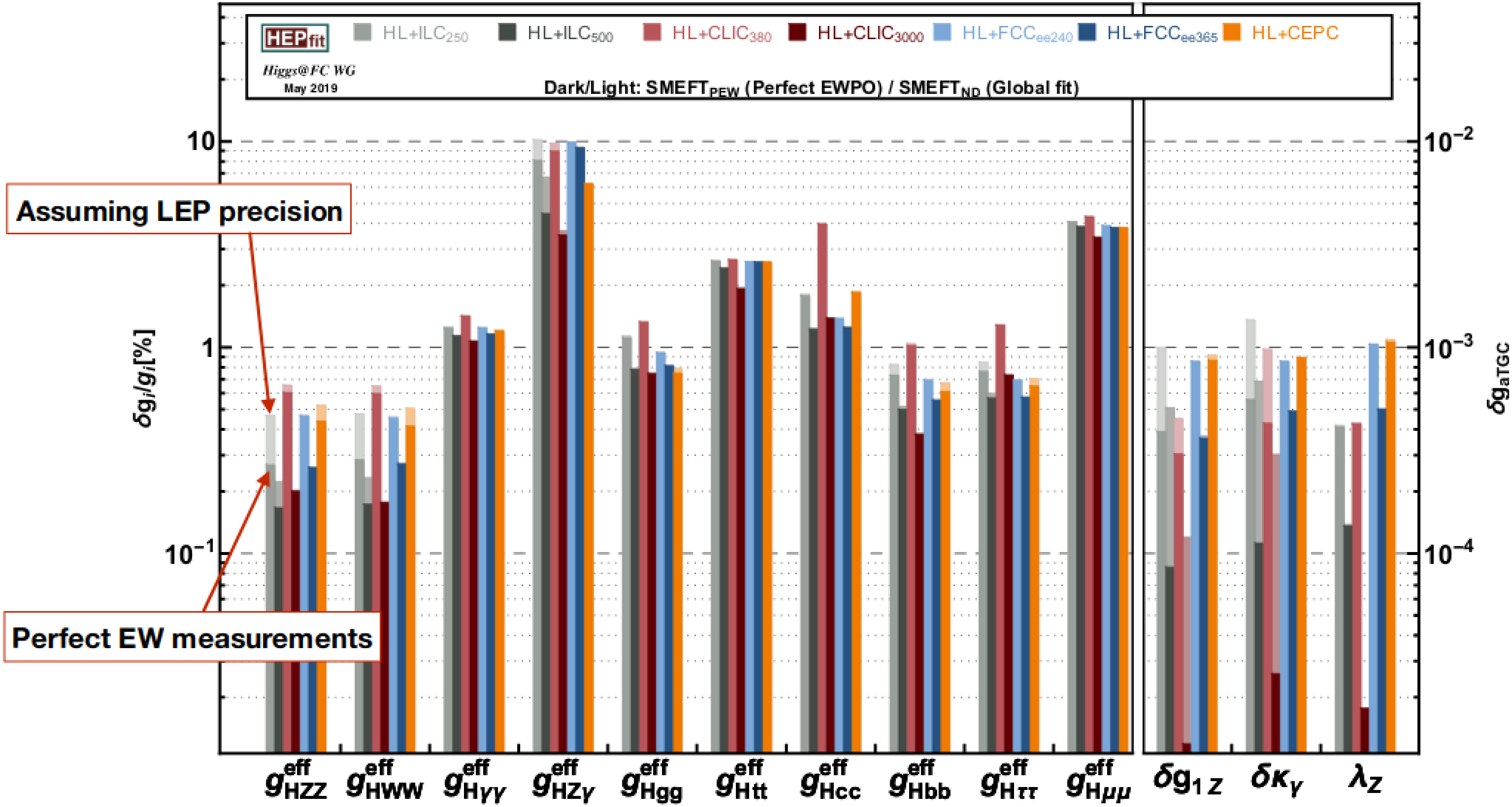
Back-up

EWPO: improvement wrt HL-LHC

	gZveveL	gZvmuvmuL	gZvtavtaL	gZeeL	gZeeR	gZmumuL	gZmumuR	gZtataL	gZtataR	gZuuL	gZuuR	gZccL	gZccR	gZttL	gZttR	gZddL	gZddR	gZssL	gZssR	gZbbL	gZbbR
ILC_{250}	≥ 10	1.2	1.5	1.1	1.1	1.0	1.0	1.0	1.0	1.1	1.0	1.1	1.0	1.0		1.2	1.5	1.2	1.5	1.0	1.0
ILC_{500}	≥ 10	1.2	1.6	1.3	1.8	1.0	1.0	1.0	1.0	1.1	1.0	1.1	1.0	≥ 10	⋆	1.2	1.5	1.2	1.5	1.0	1.0
$CLIC_{380}$	≥ 10	5.1	9.6	1.7	1.4	1.1	1.1	1.0	1.0	1.1	1.0	1.1	1.0	1.0		1.2	1.6	1.2	1.6	1.0	1.0
$CLIC_{1500}$	≥ 10	5.3	≥ 10	2.7	1.9	1.1	1.1	1.0	1.0	1.1	1.1	1.1	1.1	≥ 10	⋆	1.3	1.6	1.3	1.6	1.0	1.0
$CLIC_{3000}$	$\geq 10^2$	5.4	≥ 10	3.1	2.4	1.1	1.1	1.0	1.0	1.1	1.1	1.1	1.1	≥ 10	⋆	1.3	1.6	1.3	1.6	1.0	1.0
CEPC	1.0	1.0	1.0	1.8	2.0	≥ 10	≥ 10	1.1	1.0	1.1	1.0	1.1	1.0	1.0		1.2	1.5	1.2	1.5	≥ 10	≥ 10
$FCCee_{240}$	≥ 10	≥ 10	≥ 10	7.9	9.2	≥ 10	≥ 10	≥ 10	≥ 10	4.2	2.9	4.2	2.9	1.0		4.6	4.4	4.6	4.4	4.6	4.4
$FCCee_{365}$	≥ 10	≥ 10	≥ 10	9.9	10.0	≥ 10	≥ 10	≥ 10	≥ 10	4.2	2.9	4.2	2.9	7.5	⋆	4.6	4.4	4.6	4.4	4.6	4.4
FCCee/eh/hh	≥ 10	≥ 10	≥ 10	9.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	9.1	⋆	≥ 10	≥ 10	≥ 10	≥ 10	4.6	4.4

- Trilinear gauge couplings
  - will achieve precision 10^{-3}-10^{-4}
  - about 2-3 orders of magnitude better than LEP

Impact of EWPO (Z pole meas.) on Higgs couplings

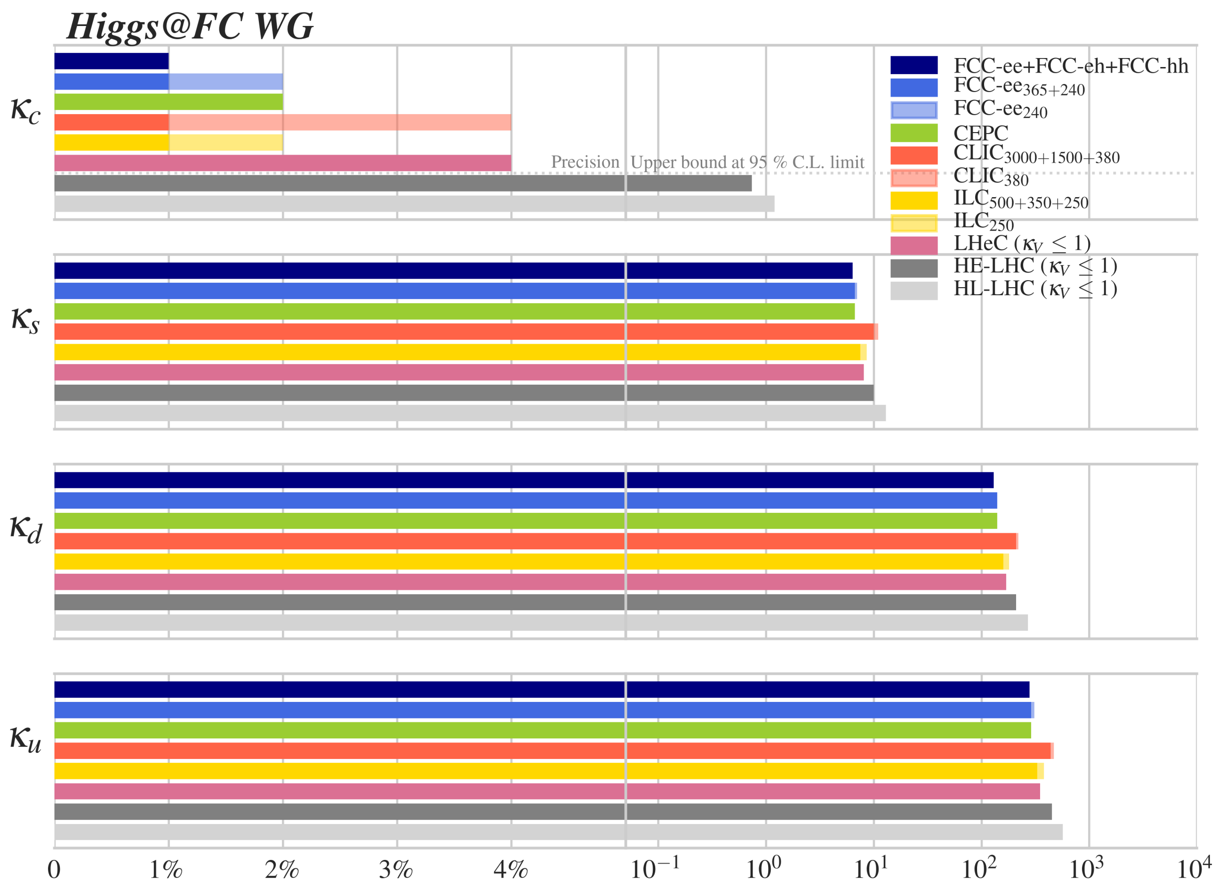


Difference due to absence of precise enough EWPO at LC (no Z pole run)

Can be mitigated by using: (1) High-energies (2) EWPO from radiative return

Rare decays: light quarks

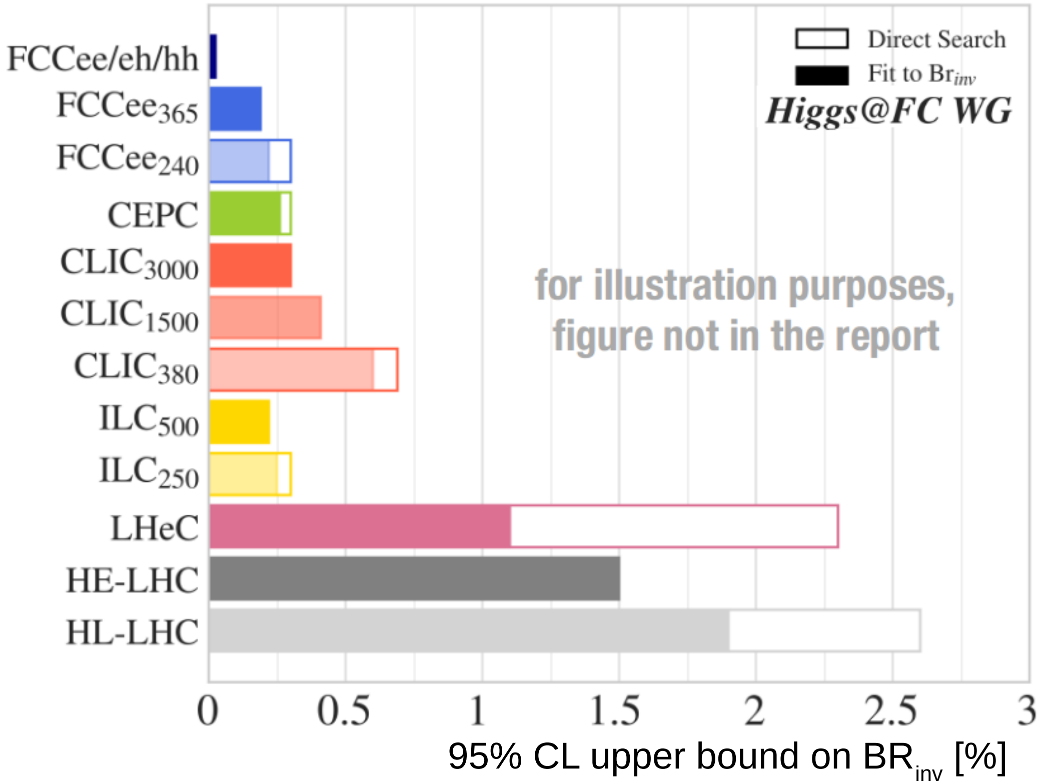
- Constraints on light Yukawa obtained from the upper limits on $BR_{untagged}$



- Hee: very challenging
  - FCC-ee: SM sensitivity could be reached in a five year run with a dedicated run at $\sqrt{s}=m_H$ → **to be extended**
- **Add also reach of H->mesons**

Invisible width

- Connection between the Higgs boson and dark matter searches
- In the SM, $BR_{SM,\, inv} = BR(H \rightarrow 4\nu) = 0.11\%$
- Current LHC limits ~ 15-20% @ 95%CL
- Direct searches for Invisible width: fundamentally different in a hadron collider (MET uncertainties) and a lepton collider (Z recoil)
  - Lepton colliders would improve upon HL-LHC limits by an order of magnitude
  - FCC-hh : another order of magnitude: values below the SM



Fine-tuning

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- The naturalness problem can be quantified by the ratio ε of the experimentally measured Higgs mass to the quantum corrections to the Higgs mass
  - $\varepsilon \sim 10^{-34}$ in SM where no New Physics below the Planck scale
  - $\varepsilon \sim 1$ if no fine-tuning

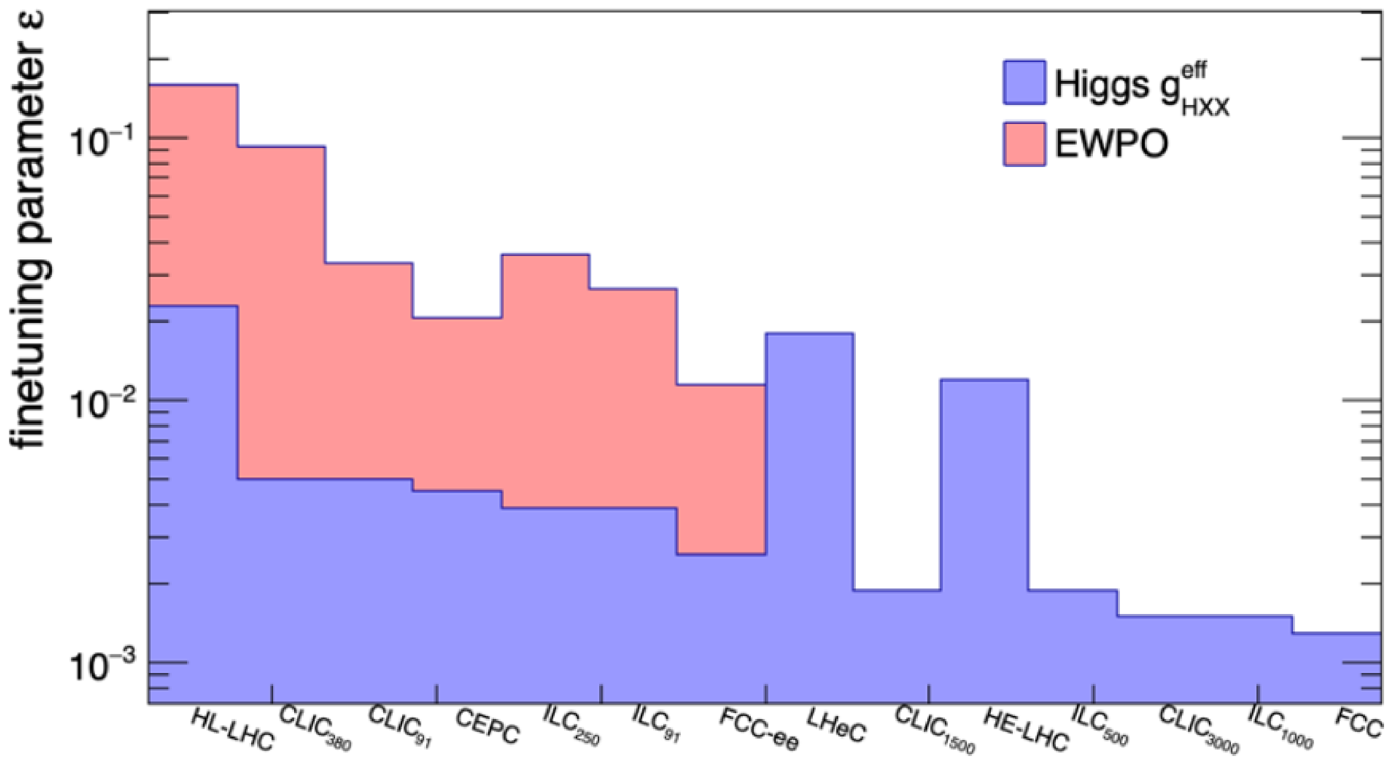

Fig. 3.11: Fine-tuning sensitivity as defined in Sect. 3.1 based on the Higgs coupling and EWPO precision projections. In each case the highest precision Higgs measurement is shown