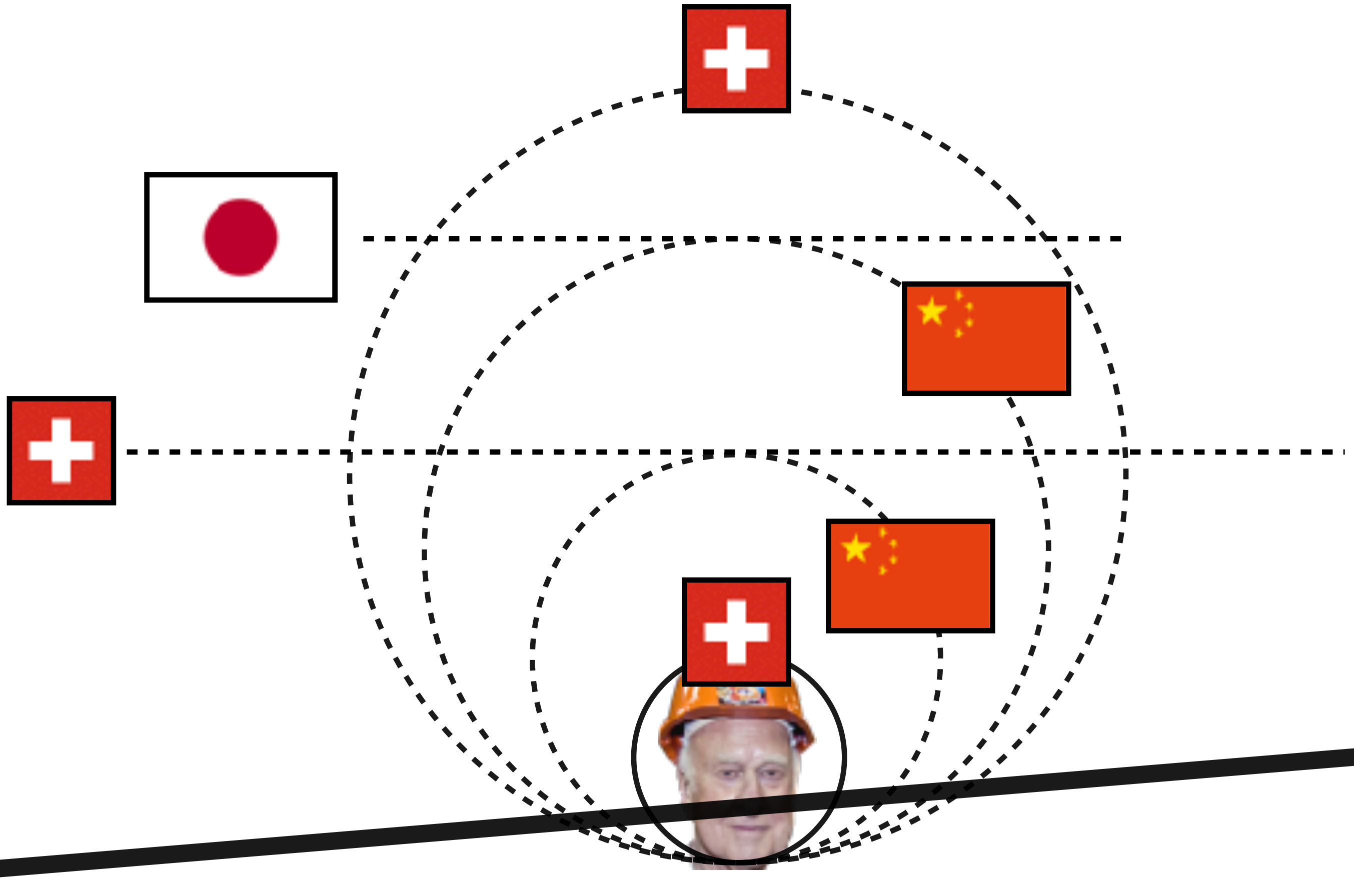
Higgs Physics @ FCC-ee

Snowmass Energy Frontier Workshop
March 23, 2021

Christophe Grojean



Why a Higgs Factory?

The Higgs discovery in 2012 has been an important milestone for HEP.
Many of us are still excited about it. And others should be excited too.
Unique phenomena never observed before in Nature.
Consequences and implications are immense for different areas of physics & beyond.
Almost every BSM scenario will have important implications in the Higgs sector.

Are we done? What's next?

Remember May 1, 2003

"Mission accomplished" speech by G.W. Bush

That was certainly not the end of the story and there were (are) still a lot of things to do

Ian Low just explained why we need to continue, I'll tell you how to do it and what can be learnt.

Which Machine(s)?

Choice between different options: delicate balance between
physics return, technological challenges and feasibility,
time scales for completion and exploitation, financial and political realities

Exploration machines are at the heart of HEP
Current consensus towards European Strategy Update:
the best way to go to **“energy frontier”** is to start with a **e^+e^- Higgs factory**

Linear or Circular?

- Can be easily extended in energy
- Polarised (longitudinal) beams

- Higher luminosity, several IPs
- Dedicated Z-pole program with high lum.

Three relevant questions to address to help taking a decision:
1) Impact of Z pole measurements?
2) Is low energy a limitation?
3) Benefit of beam polarisation?

Snowmass 2021 Higgs Factory Considerations

J. Bagger+ arXiv:2203.06164

— Physics Considerations —

P1	P2	P3	P4	P5	P6	P7
Precision Higgs measurements to SM particles	Measurements of Higgs self-coupling(s)	Sensitivity to rare and exotic Higgs decays	New Physics discovery potential	Direct measure of EW/Yukawa top coupling	Indirect sensitivity to New Physics	Improved measurements of α_s

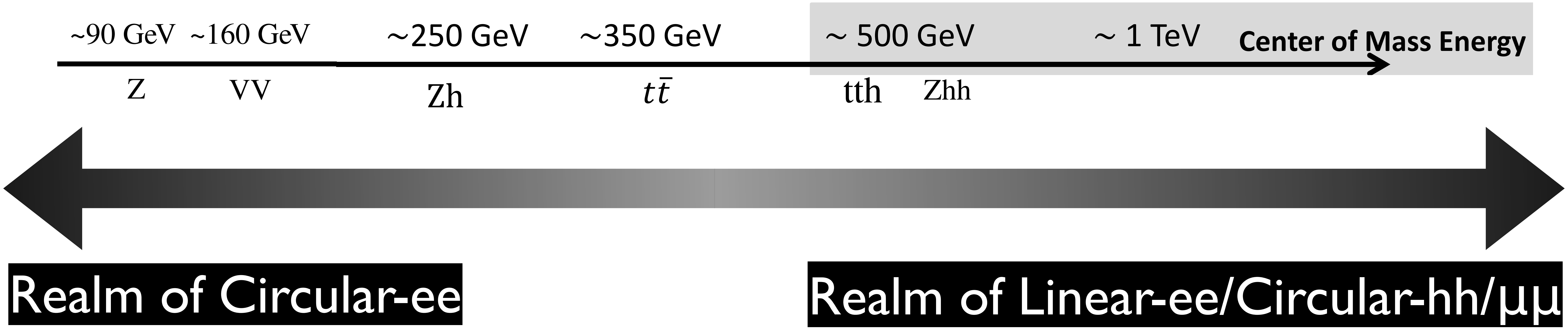
— Technological Considerations —

T1	T2	T3	T4	T5	T6	T7
Range of operating E/ease of changing E	Annual integrated luminosity	Upgradability to higher energy/ luminosity	Extent and cost of remaining R&D	Ability to operate at the tt threshold	Ability to run at the Z pole	Ability to run at the WW threshold

T8	T9	T10	T11	T12-T13	T14-T15	T16
Stability and calibration of collision energy	Beam stability and luminosity calibration	Ability to control beam-related backgrounds	Ability to provide independent confirmation of new discoveries	Ability to provide polarised electrons/ positrons	Possibility to reconfigure as $\gamma\gamma$, $e^-\gamma$, e^-e^-, ep, pp collider	Opportunities for beam dumps experiments

T17
Need for, and scientific utility of, technology demonstrators

Physics Thresholds

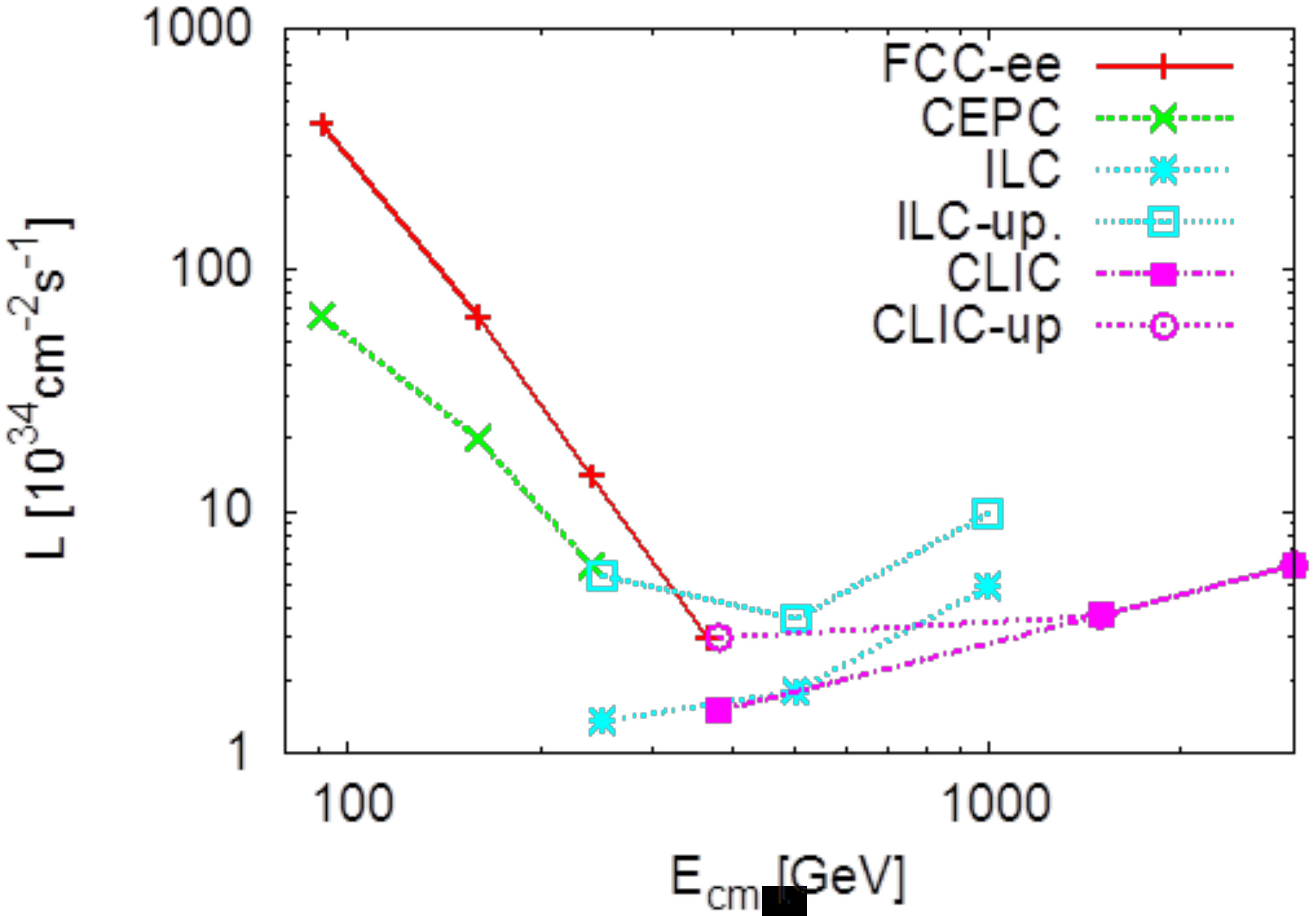


~90 GeV ~160 GeV ~250 GeV ~350 GeV ~ 500 GeV ~ 1 TeV **Center of Mass Energy**

Z VV Zh $t\bar{t}$ tth Zhh

Realm of Circular-ee

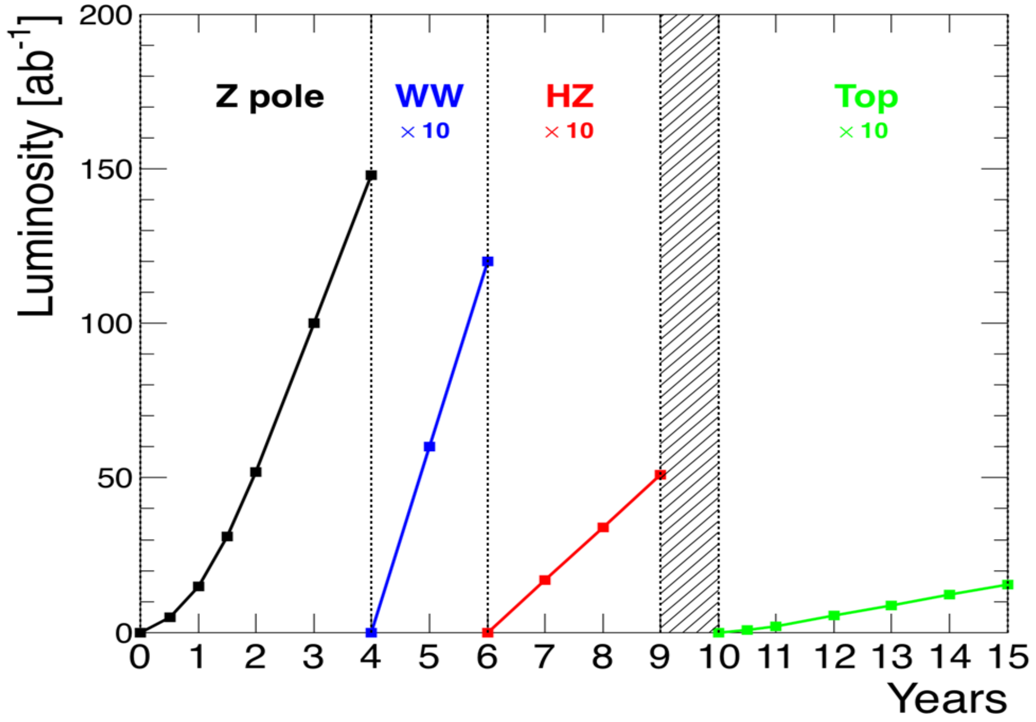
Realm of Linear-ee/Circular-hh/μμ

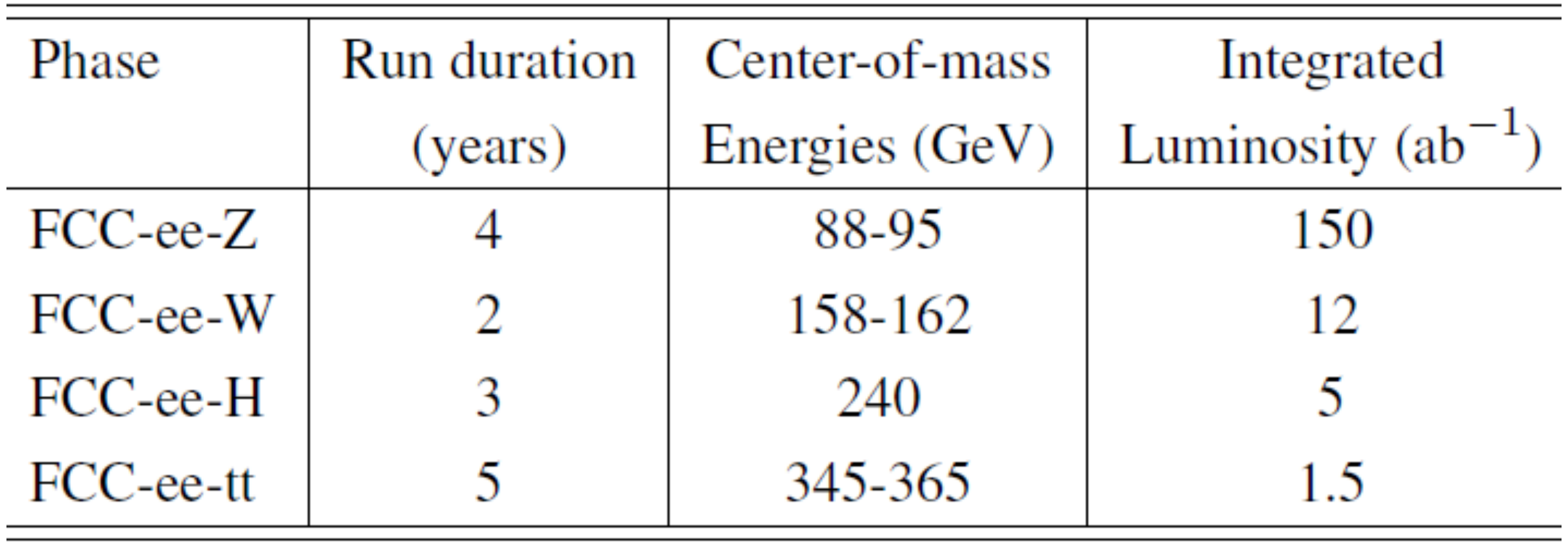


FCC-ee Run Plan

LEP data accumulated in first 3 mn. Then exciting & diverse programme with different priorities every few years.

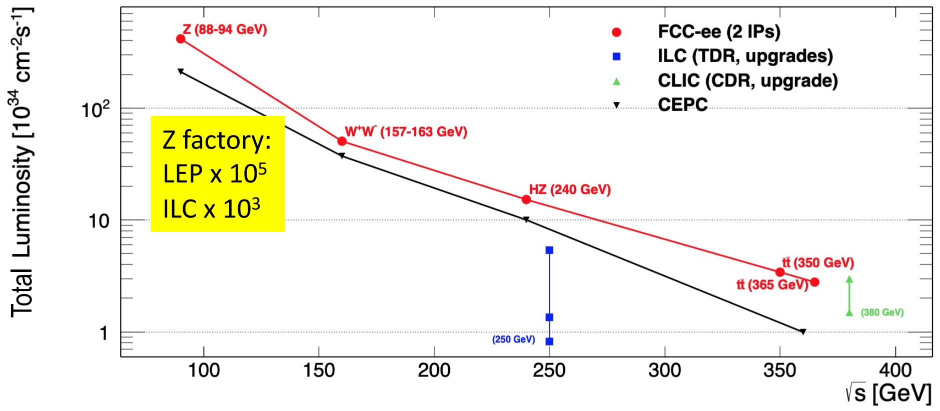
(order of the different stages still subject to discussion/optimisation)





Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

— Superb statistics achieved in only 15 years —



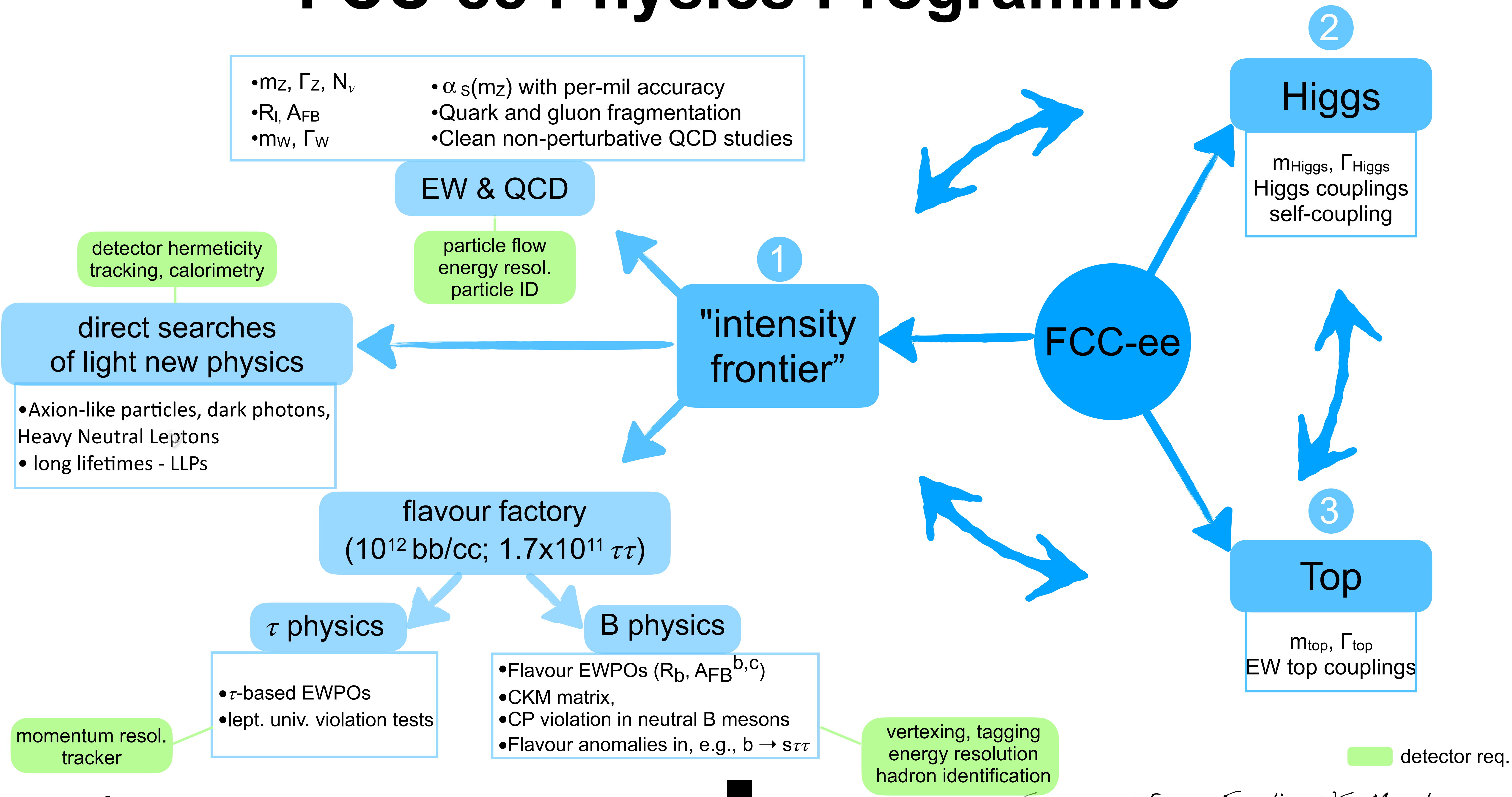
Z factory:
LEP x 10^5
ILC x 10^3

Event statistics (2IP)

					E_{CM} errors:
Z peak	E_{cm} : 91 GeV	4yrs	5 10^{12} e+e- → Z	LEP x 10^5	<100 keV
WW threshold	$E_{cm} \geq$ 161 GeV	2yrs	>10^8 e+e- → WW	LEP x 2.10^3	<300 keV
ZH maximum	E_{cm} : 240 GeV	3yrs	> 10^6 e+e- → ZH	Never done	1 MeV
s-channel H	*E_{cm} : m_H*	*(3yrs?)*	*O(5000) e+e- → H*	*Never done*	<< 1 MeV
$t\bar{t}$	E_{cm} : ≥ 350 GeV	5yrs	10^6 e+e- → $t\bar{t}$	Never done	2 MeV

in each detector: 10^5 Z/sec, 10^4 W/hour, 1500 Higgs/day, 1500 top/day

FCC-ee Physics Programme



- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

EW & QCD

particle flow
energy resol.
particle ID

detector hermeticity
tracking, calorimetry

direct searches of light new physics

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

1

"intensity frontier"

FCC-ee

2

Higgs

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

flavour factory
(10^{12} bb/cc; $1.7\text{x}10^{11}$ $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}{}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

3

Top

m_{top}, Γ_{top}
EW top couplings

🟩 detector req.

FCC-ee Physics Programme

2

Higgs

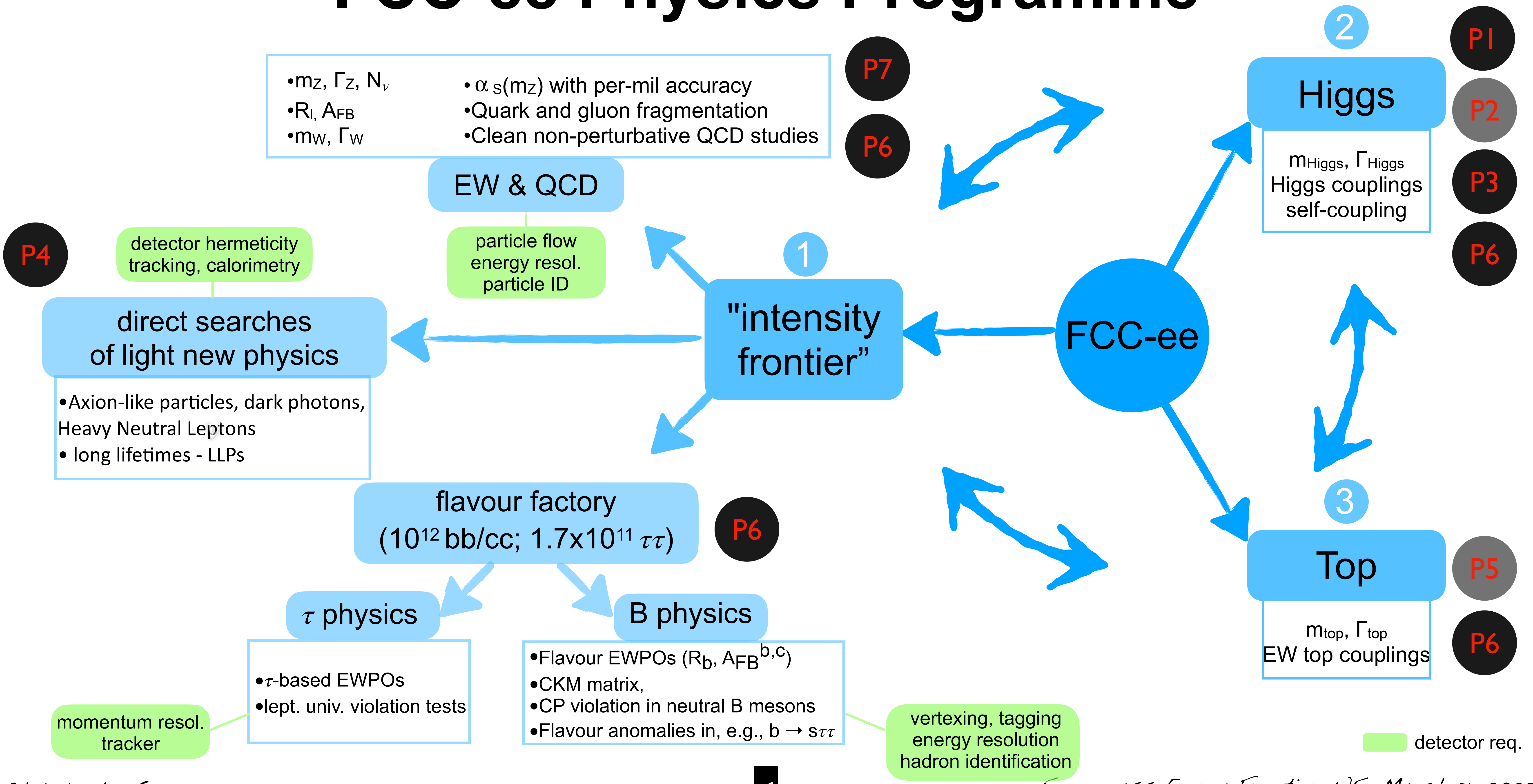
m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

Higgs sector definition imposes initial requirements on **hadronic resolution, tracking and vertexing**

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_\mathrm{T}) \sim 2 \times 10^{-5}$ $\oplus 1 \times 10^{-3}/(p_\mathrm{T} \sin\theta)$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^\mathrm{jet}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

🟩 detector req.

FCC-ee Physics Programme



FCC-ee

1 "intensity frontier"

2 **Higgs**

P1 P2 P3 P6

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

3 **Top**

P5 P6

m_{top}, Γ_{top}
EW top couplings

EW & QCD

P7 P6

- m_Z, Γ_Z, N_ν
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particle flow
energy resol.
particle ID

direct searches of light new physics

P4

detector hermeticity
tracking, calorimetry

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

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P6

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vertexing, tagging
energy resolution
hadron identification

🟩 detector req.

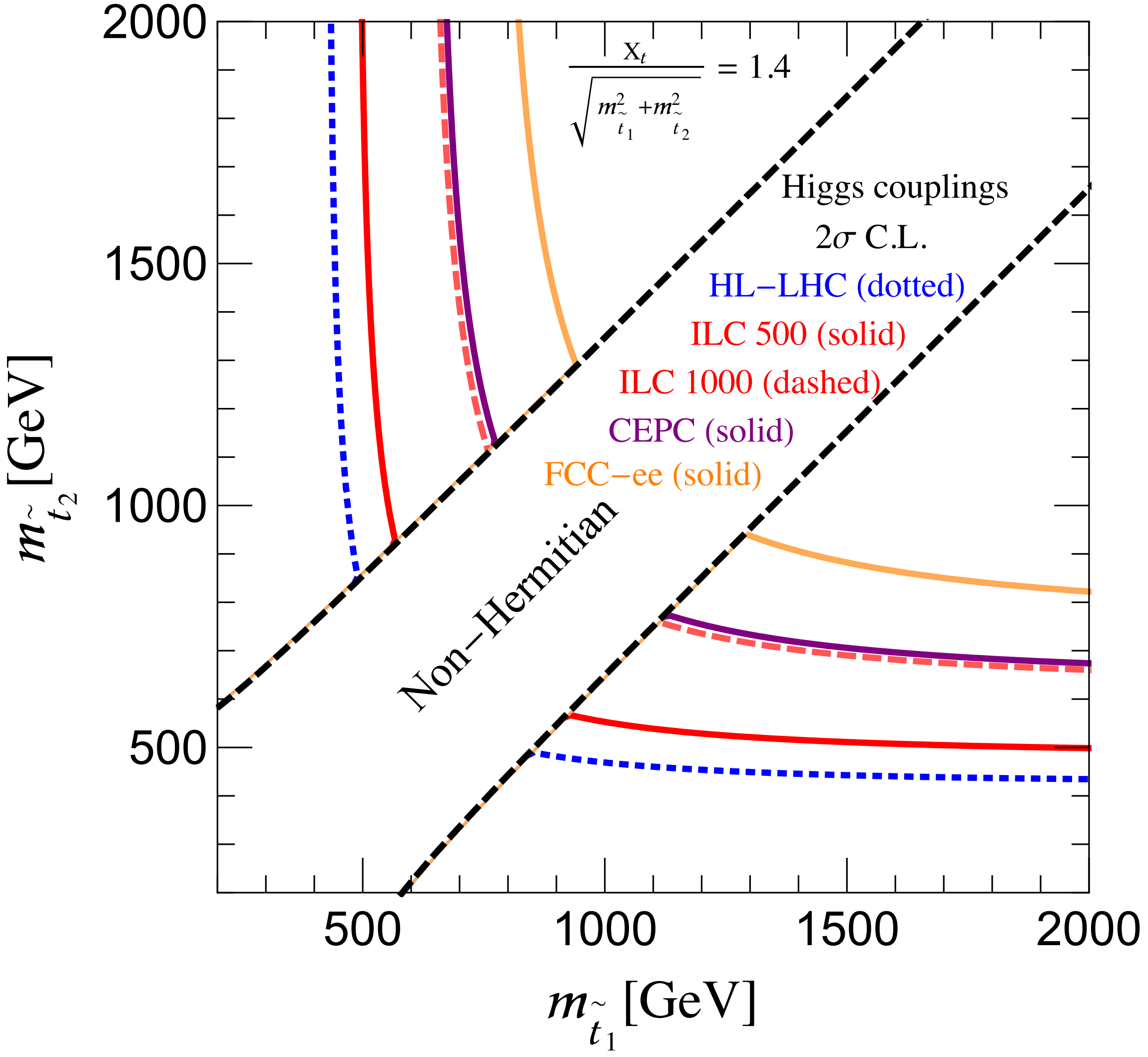
Discovery Potential Beyond LHC

P6

Precisely measured EW and Higgs observables are sensitive to heavy New Physics

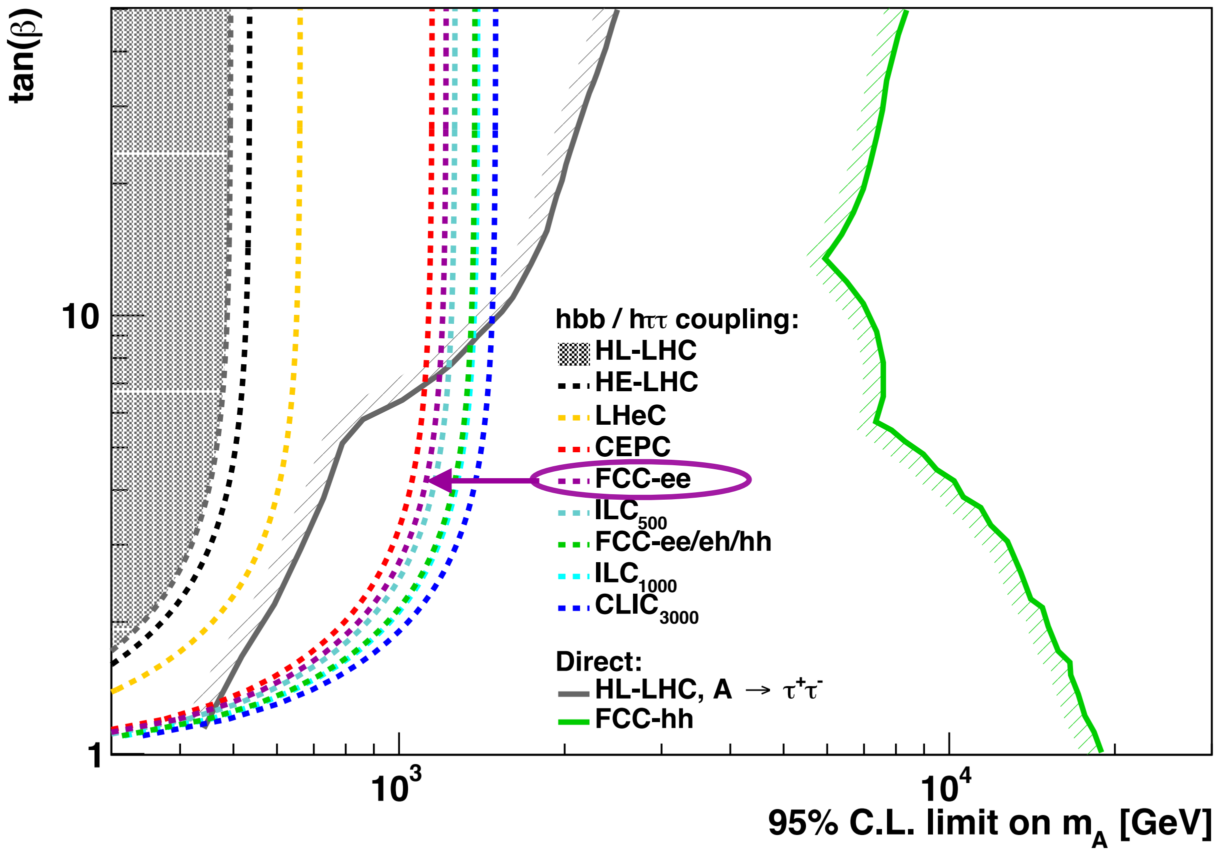
Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY

stops



Fan, Reece, Wang '14

Heavy neutral Higgses

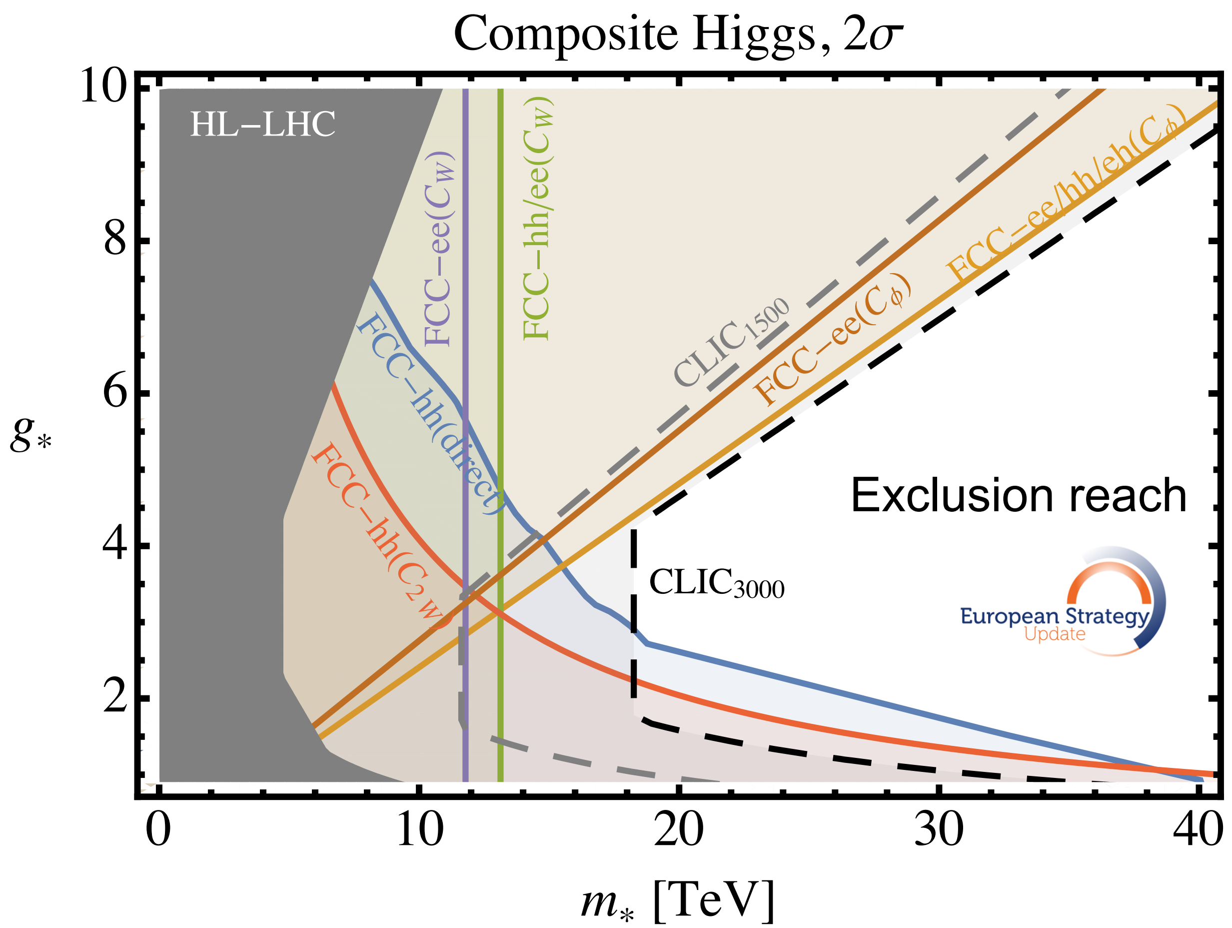


ESU Physics BB '19

Discovery Potential Beyond LHC

Precisely measured EW and Higgs observables are sensitive to heavy New Physics

Examples of improved sensitivity wrt direct reach @ HL-LHC: Composite Higgs



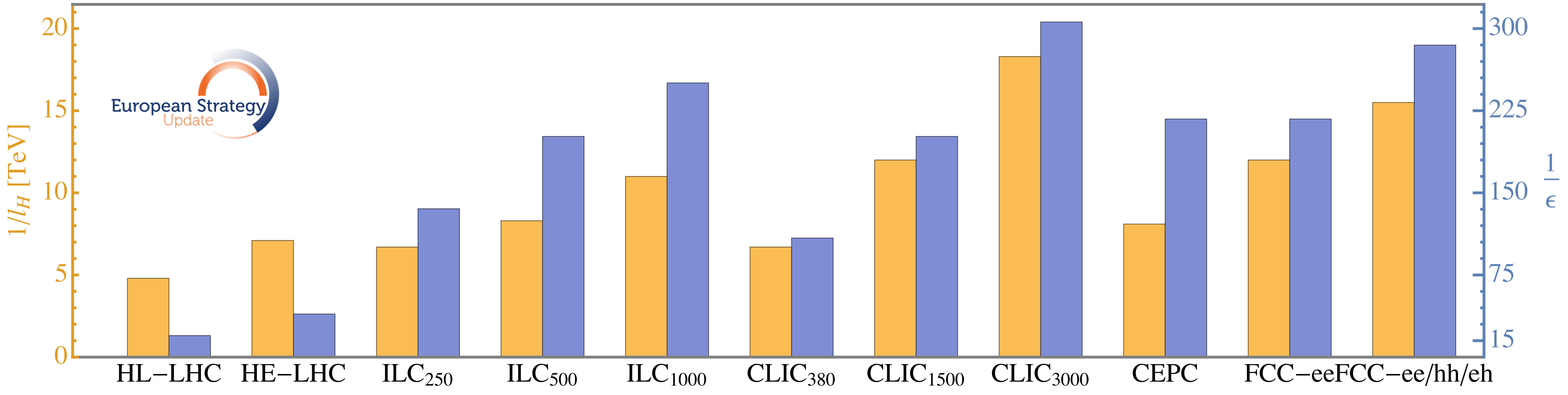


Fig. 8.5: Exclusion reach of different colliders on the inverse Higgs length $1/\ell_H = m_*$ (orange bars, left axis) and the tuning parameter $1/\varepsilon$ (blue bars, right axis), obtained by choosing the weakest bound valid for any value of the coupling constant g_*.

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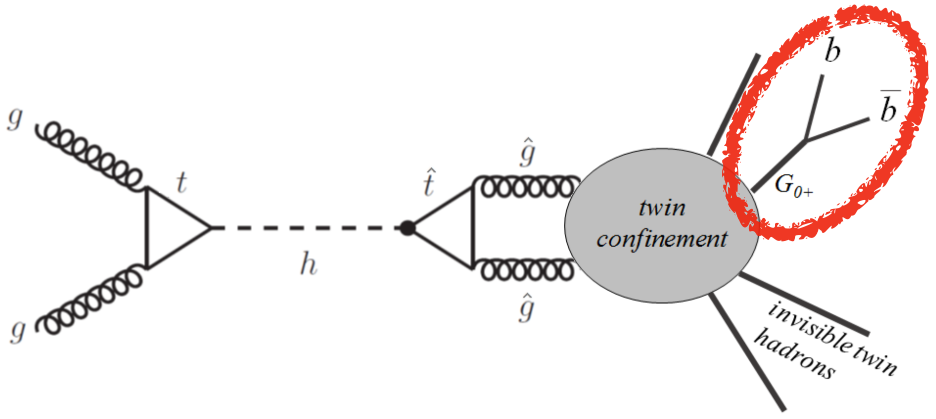
Direct Searches for Light New Physics

P4

- **LLP searches with displaced vertices**
  e.g. in twin Higgs models glueballs that mix with the Higgs and decay back to b-quarks

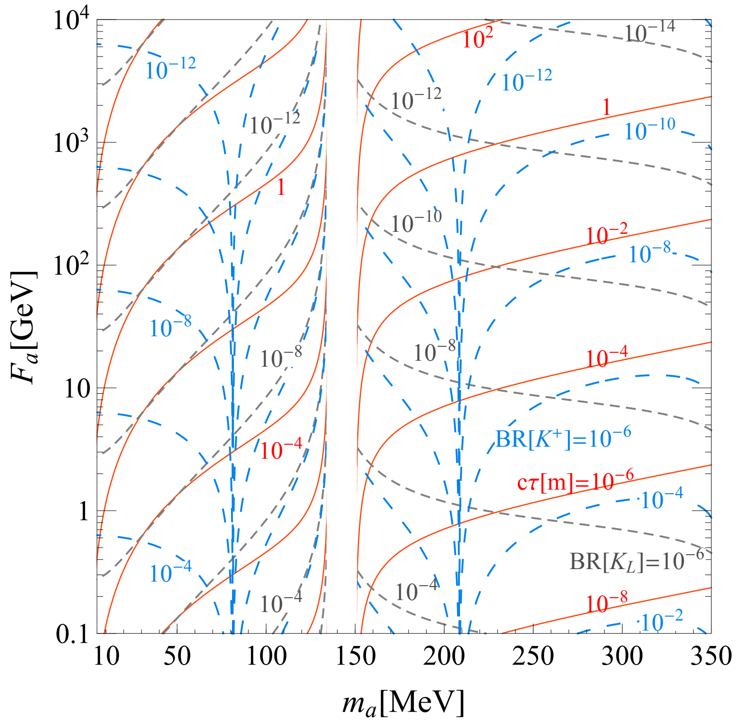
Craig et al, arXiv:1501.05310



- **Rare decays** Gori et al arXiv:2005.05170
  e.g. ALP mixing w/ SM mesons:

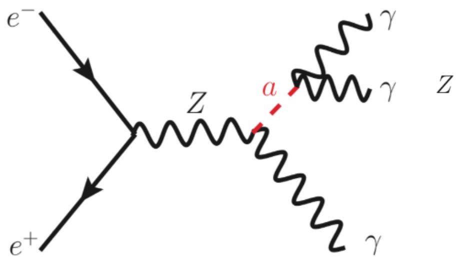
$$K_L \to \pi^0 a \to \pi^0\gamma\gamma \text{ (KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+\gamma\gamma \text{ (NA62)}$$

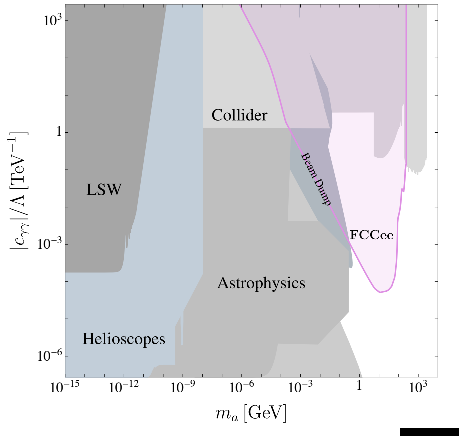
$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu}\tilde{G}^{\mu\nu}$$

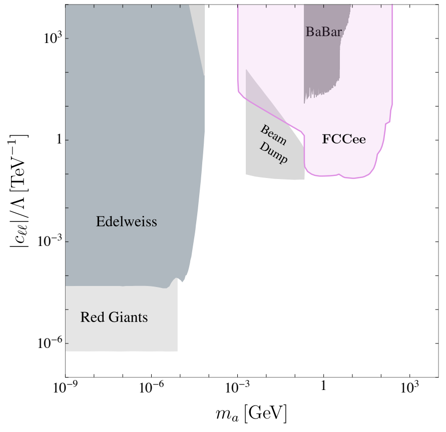


- **ALPs@ colliders**
  e.g. $e^+e^- \to \gamma a$

$e^+e^- \to ha$







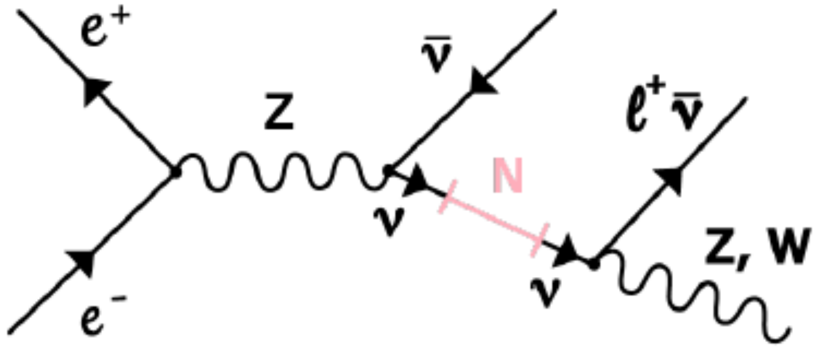
Knapen, Thamm arXiv:2108.08949

Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

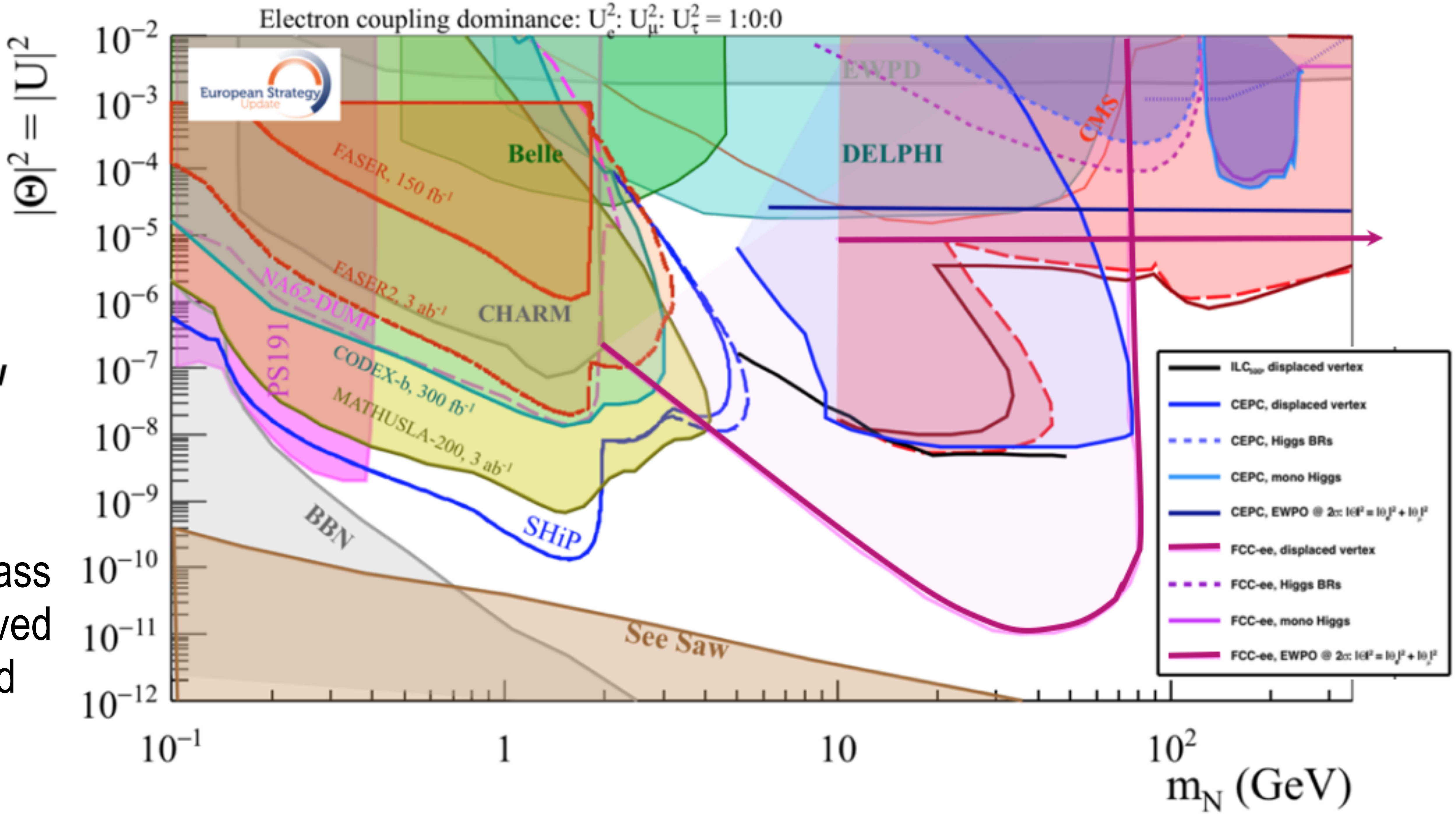
Search for ν_{RH}

P4

Direct observation in Z decays from LH-RH mixing



Important to understand
1. how neutrinos acquired mass
2. if lepton number is conserved
3. if leptogenesis is realised



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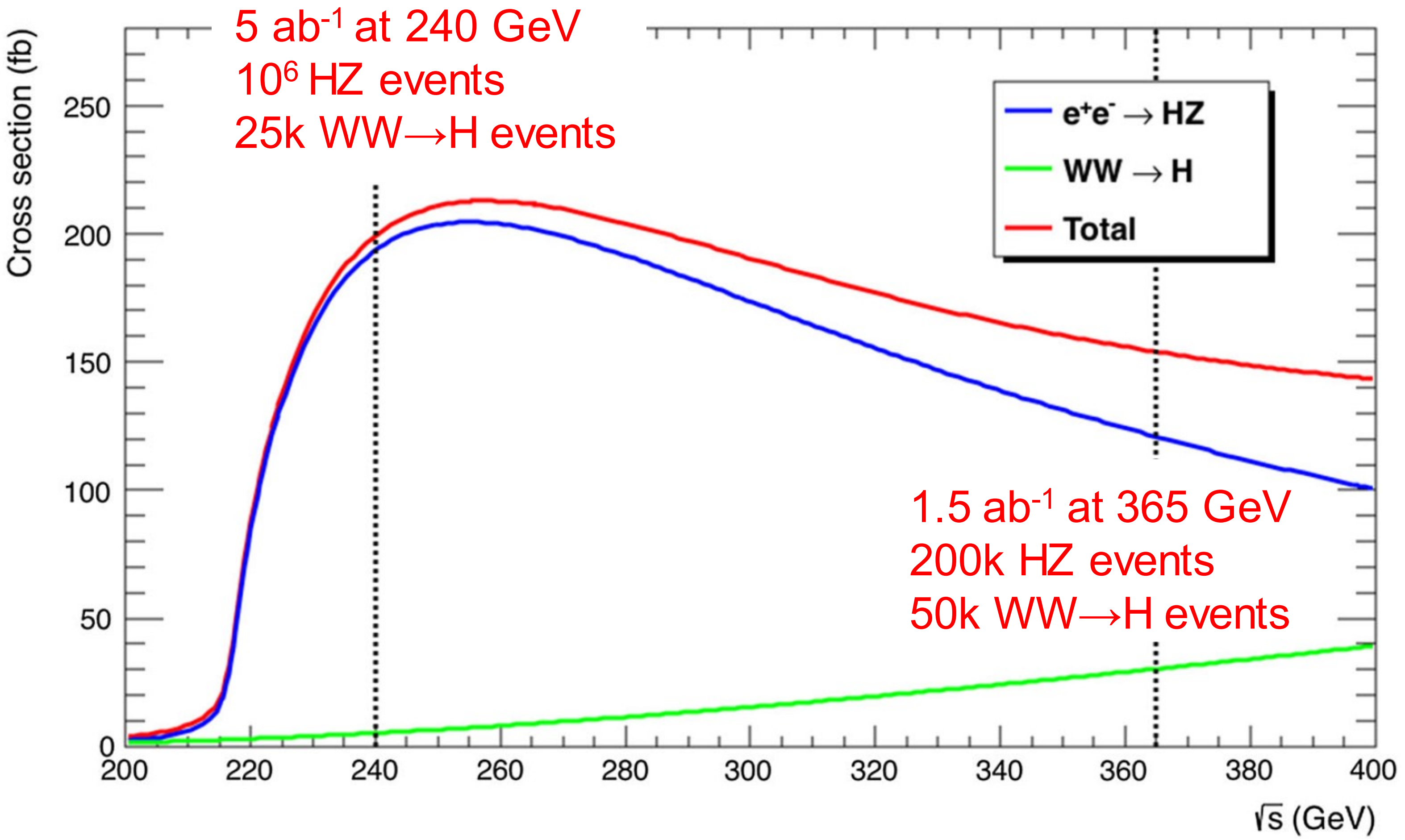
Higgs @ FCC-ee

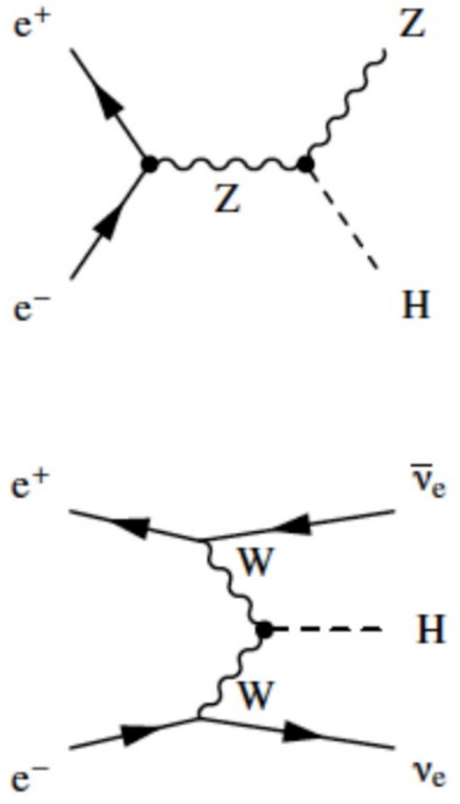
Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)% precision. Achieved through operation at two energy points.

G. Wilkinson, FCC Physics WS '22



5 ab^{-1} at 240 GeV
10^{6} HZ events
25k WW→H events

1.5 ab^{-1} at 365 GeV
200k HZ events
50k WW→H events



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

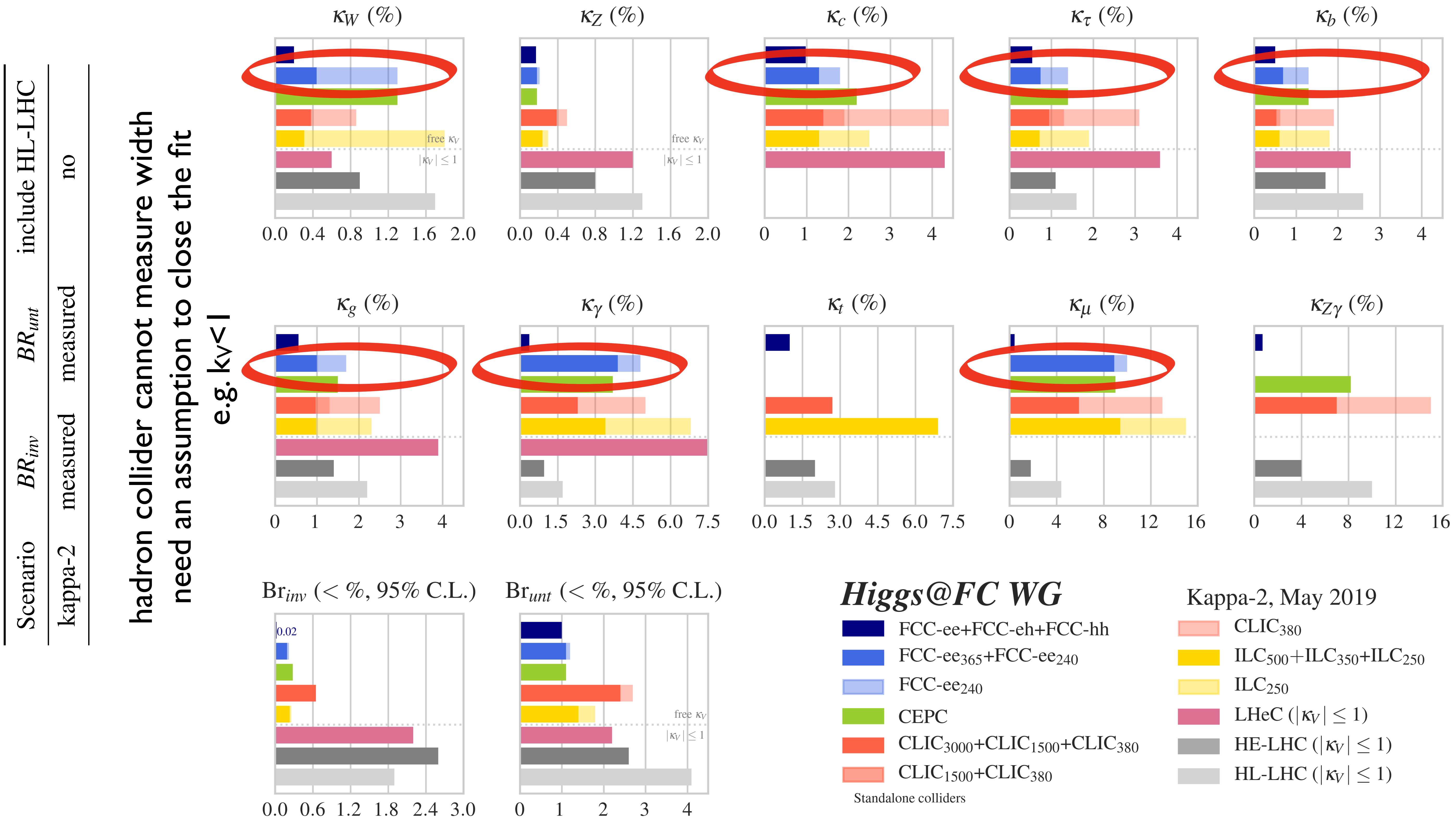
Table 8: Operation costs of low-energy Higgs factories, expressed in Euros per Higgs boson.

Collider	ILC$_{250}$	CLIC$_{380}$	FCC-ee$_{240}$
Cost (Euros/Higgs)	7,000 to 12,000	2,000	255

FCC-ee, 1906.02693

Higgs @ FCC-ee: Complementarity of 240/365 GeV

ECFA Higgs study group '19



hadron collider cannot measure width

need an assumption to close the fit

e.g. κ_V<1

Higgs @ FCC-ee: Complementarity with HL-LHC

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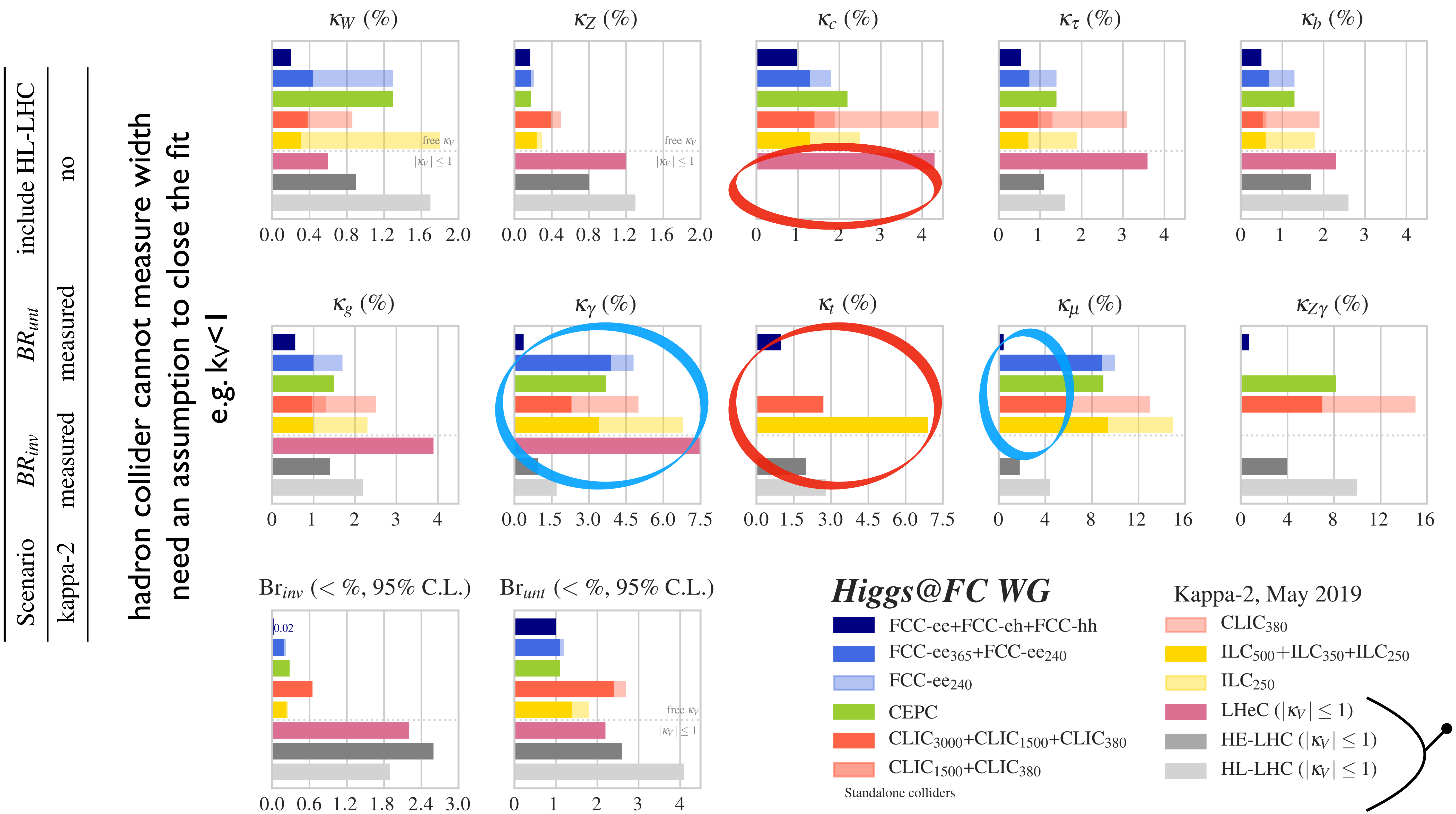

hadron collider cannot measure width
need an assumption to close the fit
e.g. $\kappa_V<1$

assumption
needed for the fit
to close at hadron
machines

Higgs @ FCC-ee: Complementarity with HL-LHC

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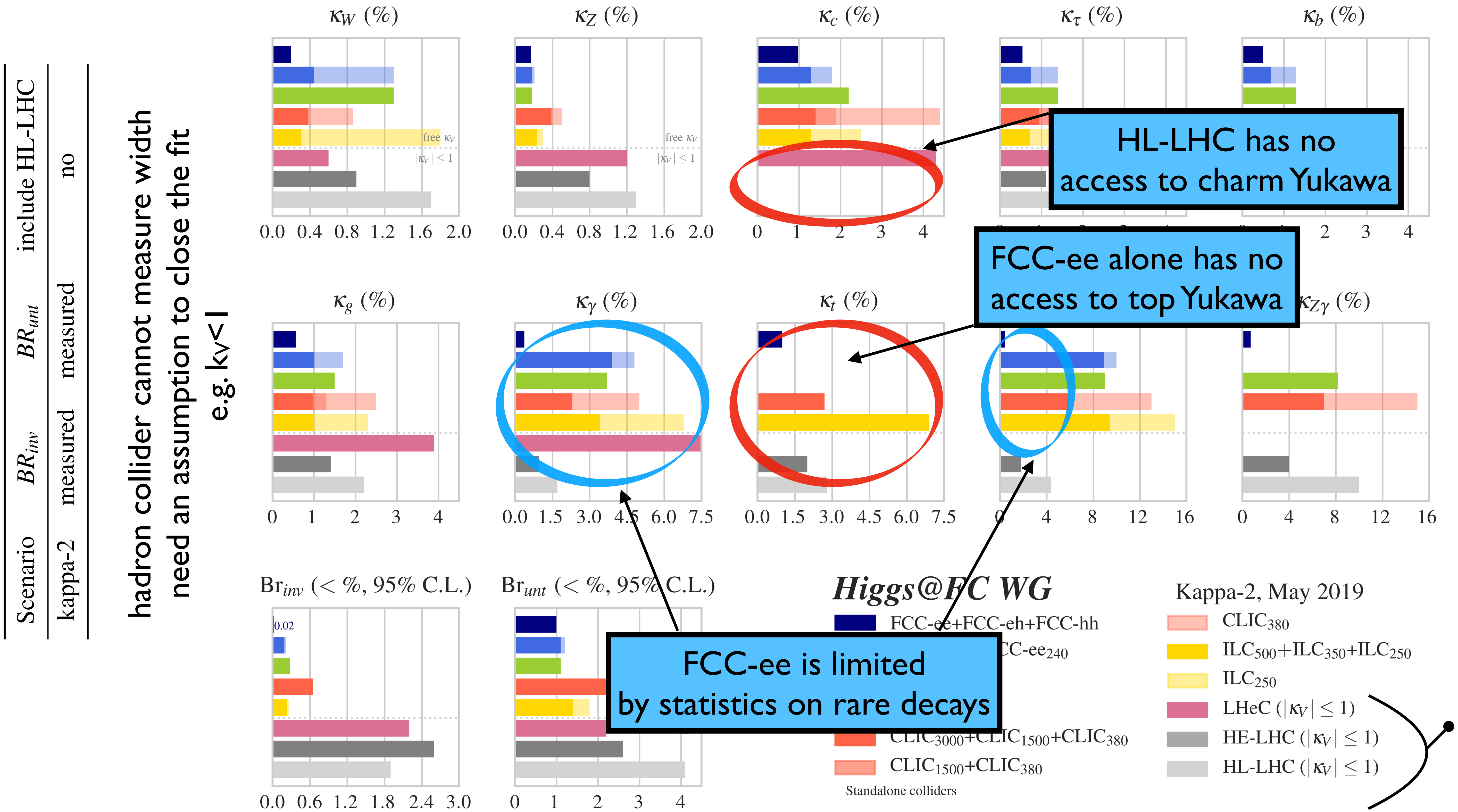


hadron collider cannot measure width
need an assumption to close the fit
e.g. kV<1

HL-LHC has no
access to charm Yukawa

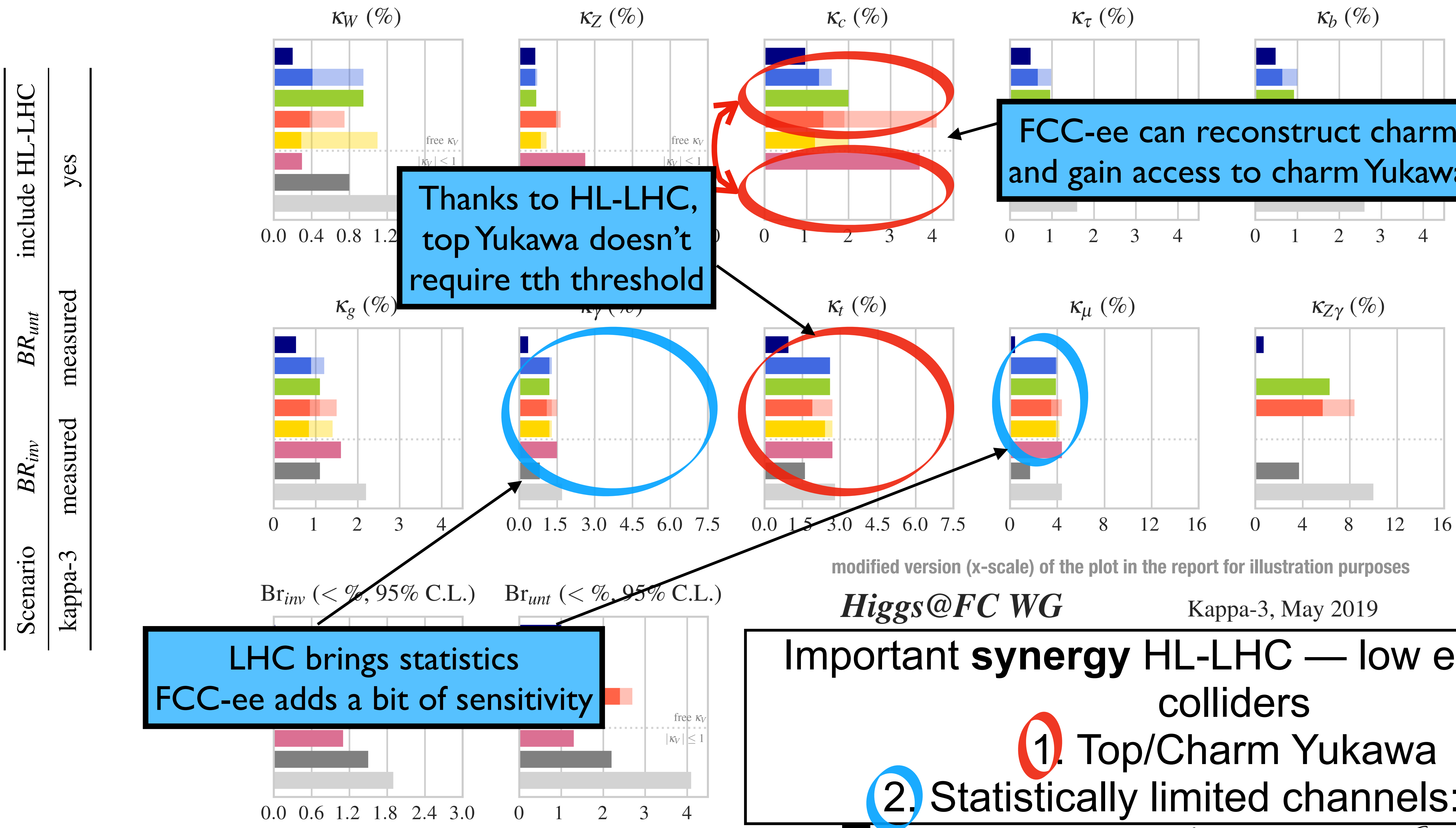
FCC-ee alone has no
access to top Yukawa

FCC-ee is limited
by statistics on rare decays

assumption
needed for the fit
to close at hadron
machines

Higgs @ FCC-ee: Complementarity with HL-LHC

ECFA Higgs study group ‘19



FCC-ee can reconstruct charm and gain access to charm Yukawa

Thanks to HL-LHC, top Yukawa doesn’t require tth threshold

LHC brings statistics
FCC-ee adds a bit of sensitivity

modified version (x-scale) of the plot in the report for illustration purposes

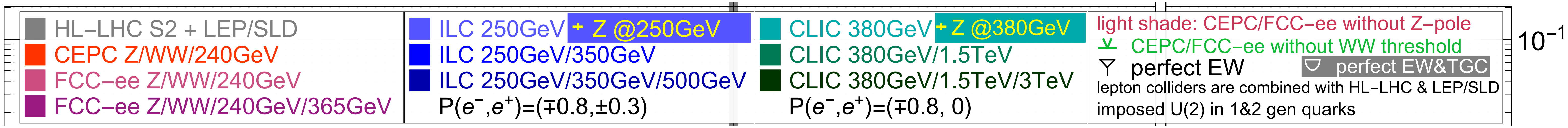
Important **synergy** HL-LHC — low energy lepton colliders

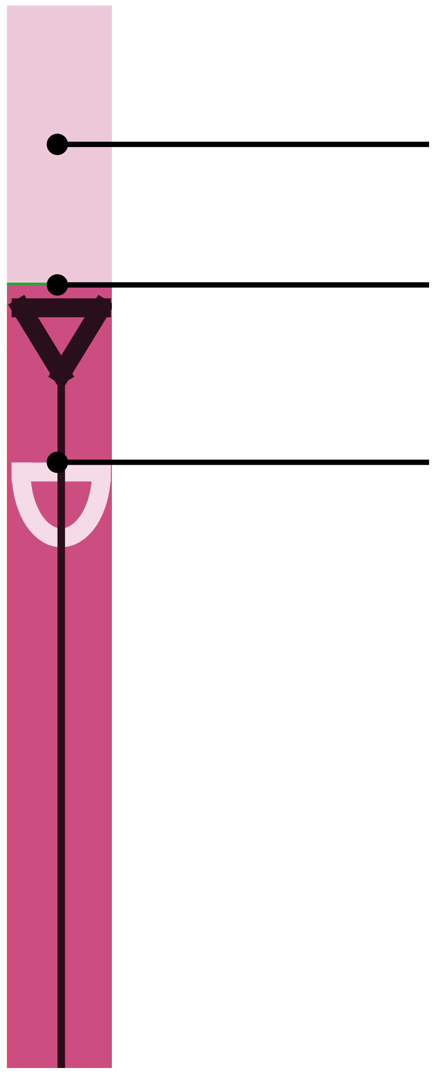
1. Top/Charm Yukawa
2. Statistically limited channels: γγ, μμ

Impact of Z-pole measurements

J. De Blas et al. 1907.04311

Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements





without Z-pole

with new EW&TGC

perfect EW&TGC

FCC-ee Z/WW/240GeV

Impact of Z-pole measurements

J. De Blas et al. 1907.04311

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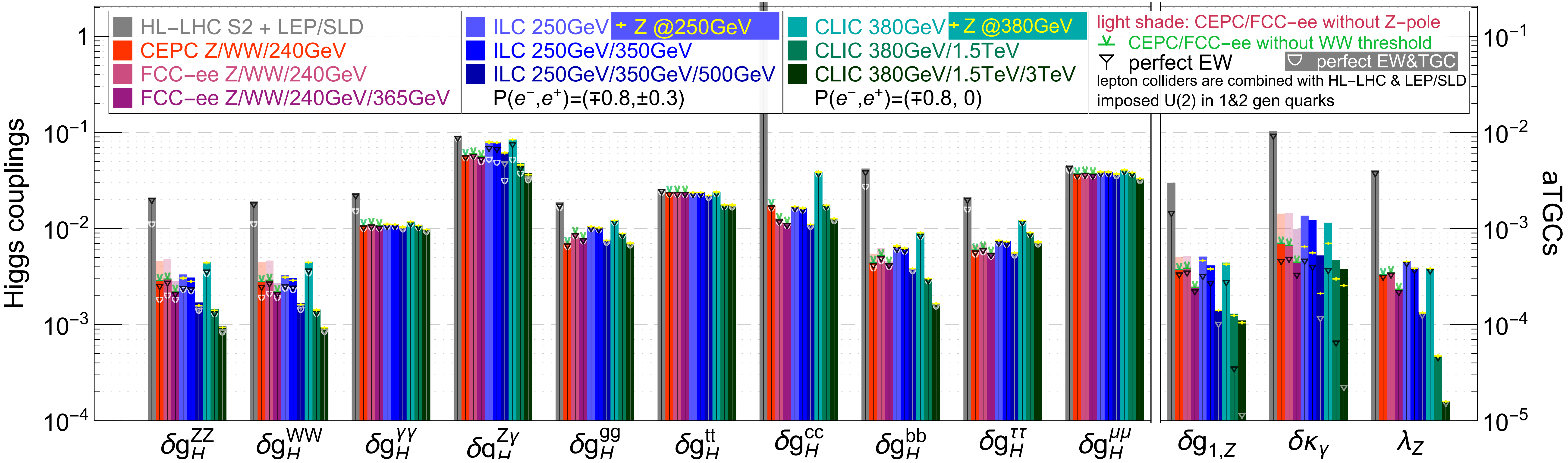

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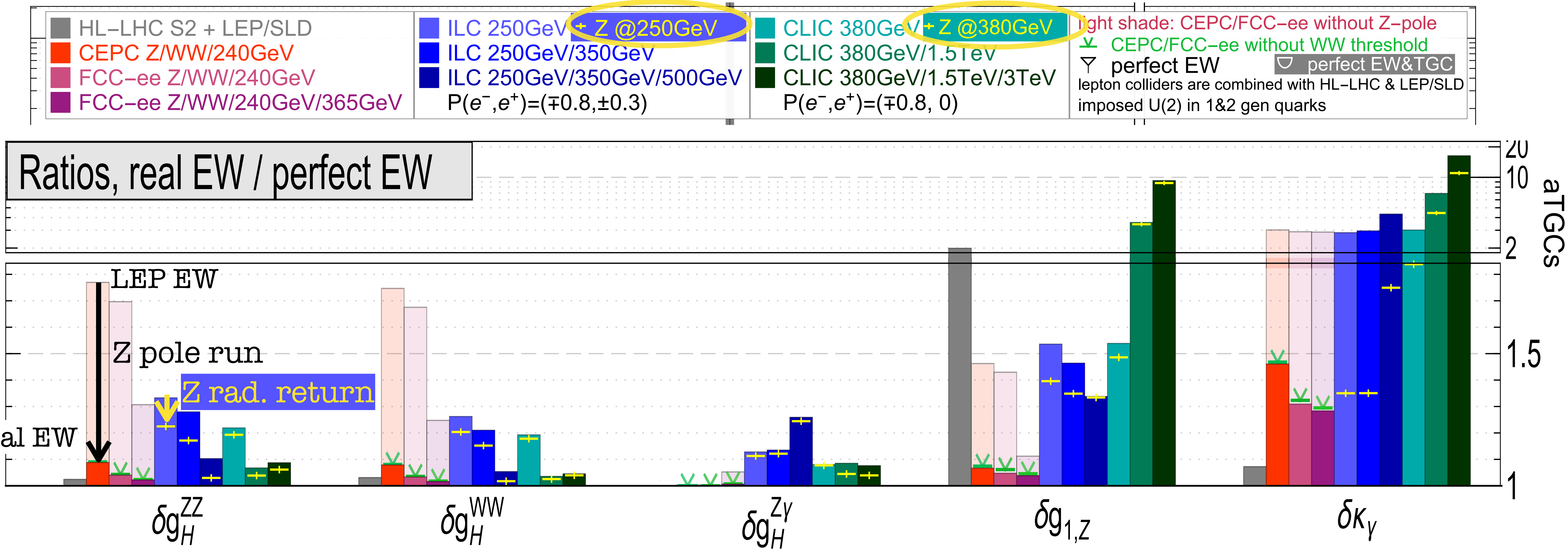
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



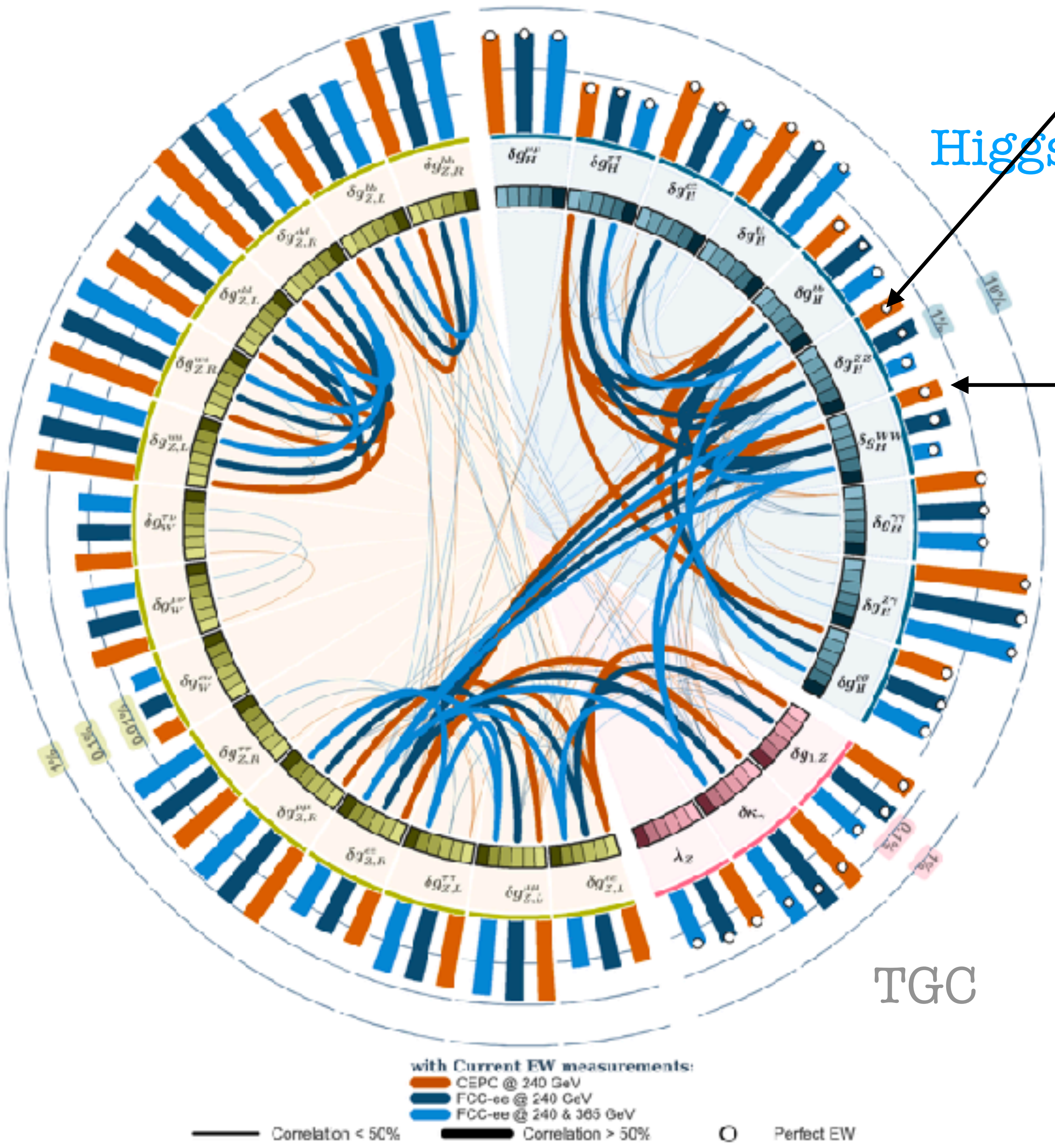
- FCC-ee and CEPC benefit a lot (factor O(2) improvement on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs
  But EW measurements at high energy (via Z-radiative return) help mitigating this issue

Impact of Z-pole Measurements

J. De Blas et al. 1907.04311

Sensitivity with prefect EW measurement

Actual sensitivity



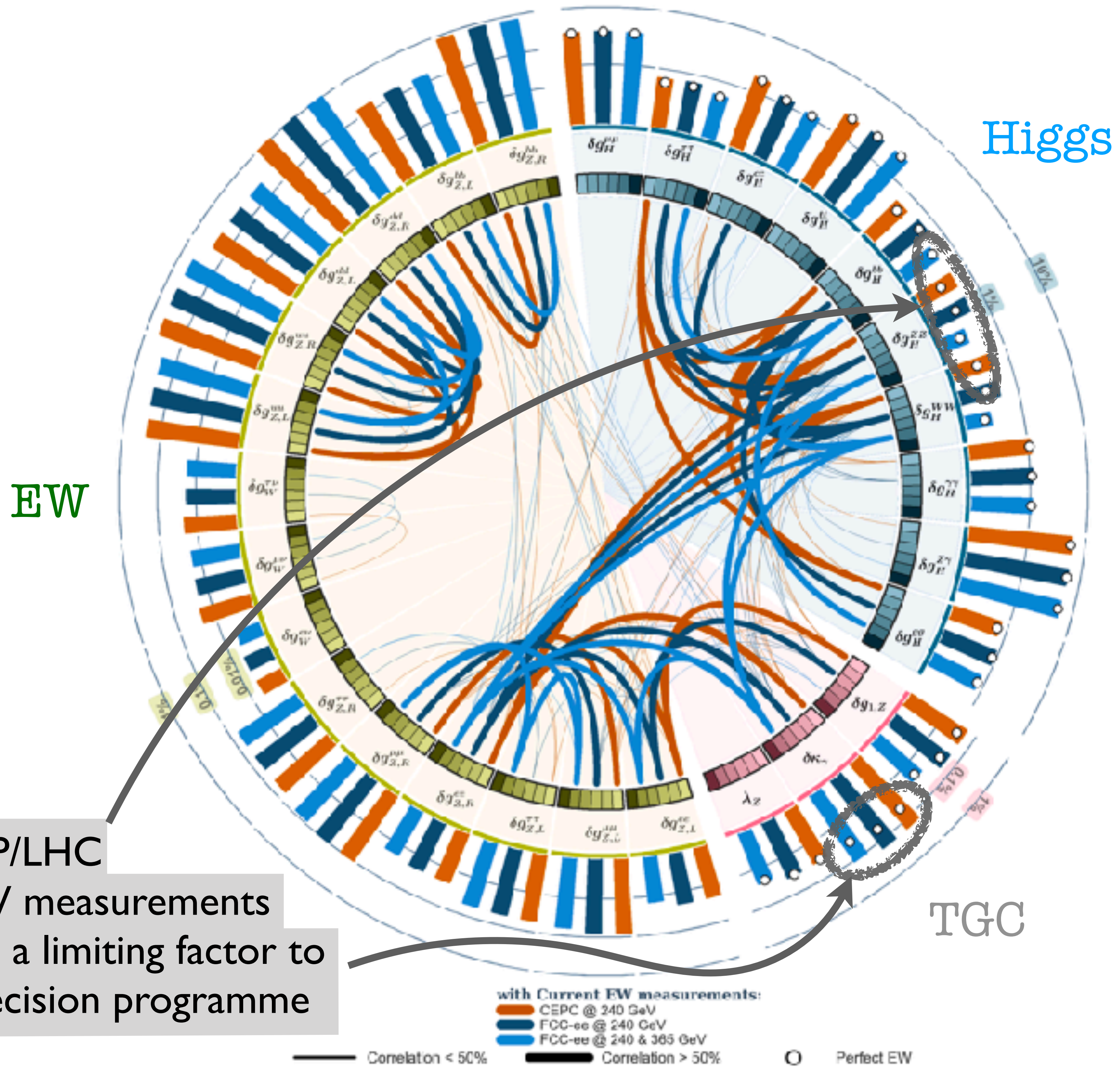
Higgs

EW

TGC

Impact of Z-pole Measurements

J. De Blas et al. 1907.04311



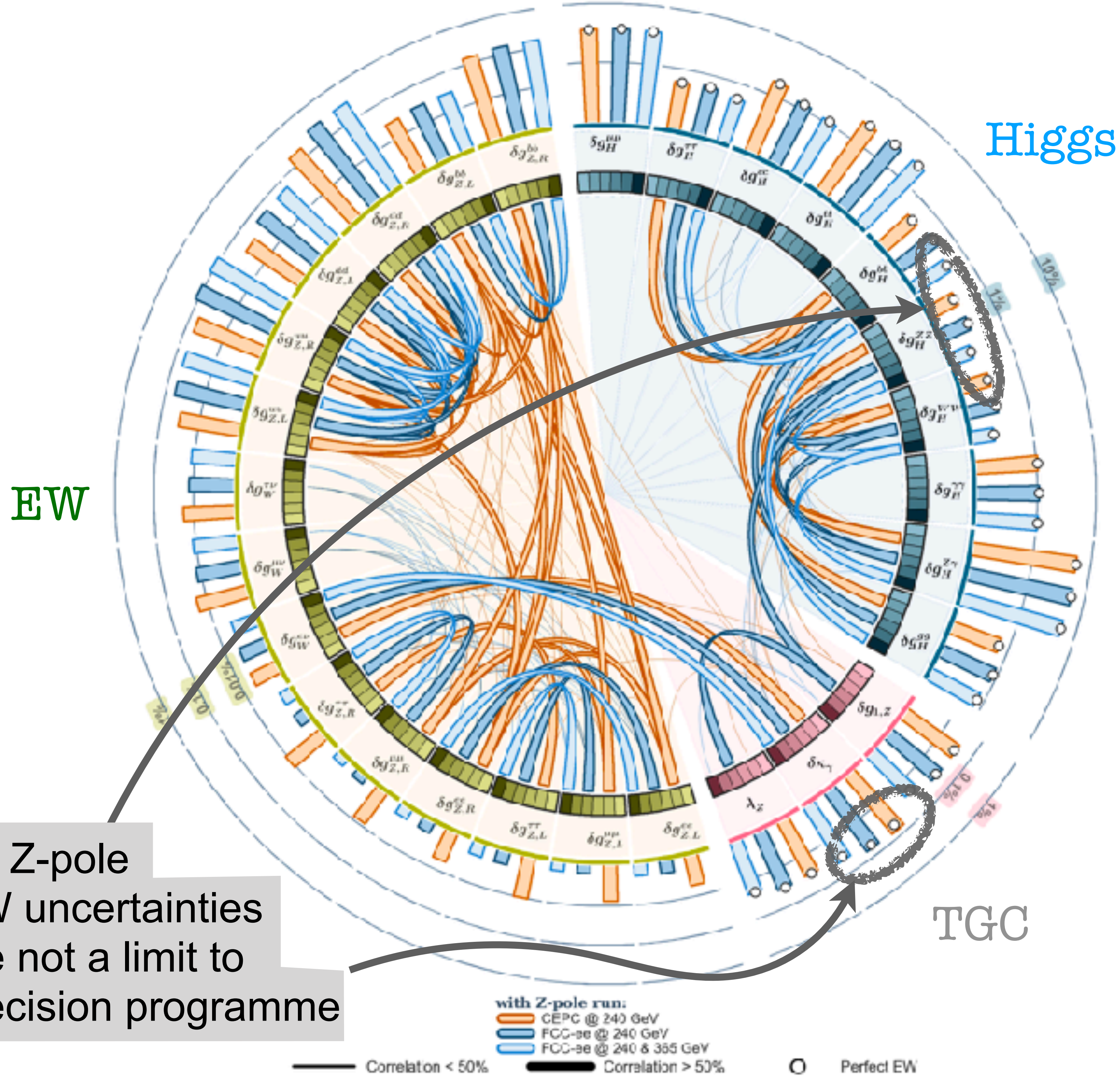
LEP/LHC
EW measurements
are a limiting factor to
precision programme

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

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

Impact of Z-pole Measurements

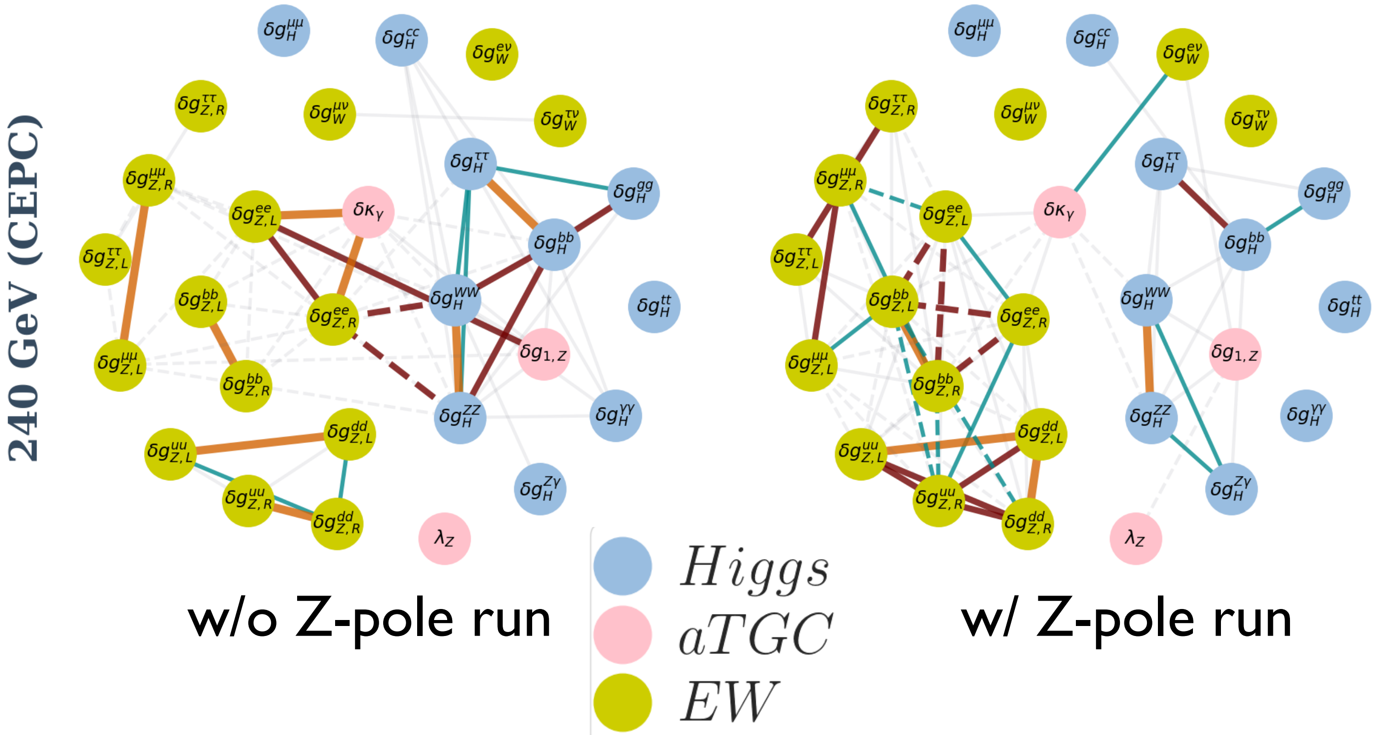
J. De Blas et al. 1907.04311



w/. Z-pole
EW uncertainties
are not a limit to
precision programme

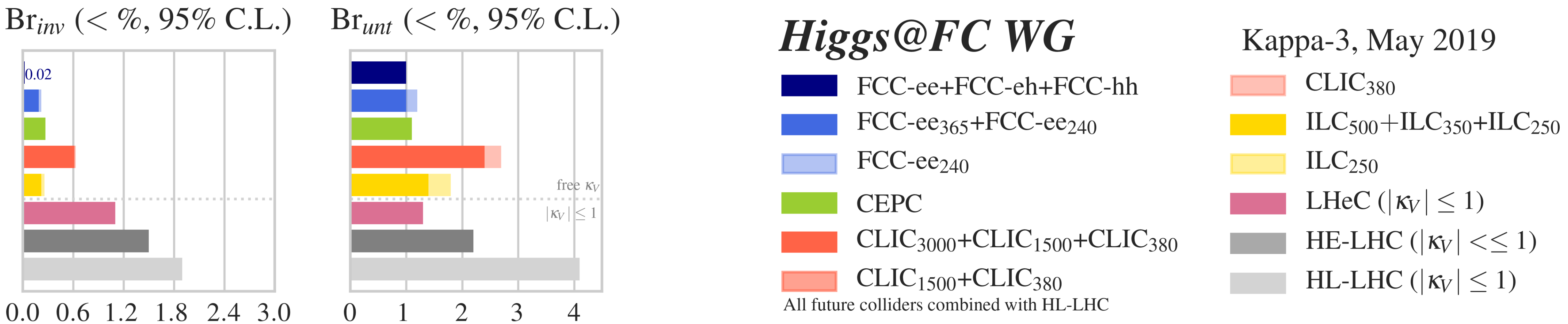
Contamination EW/TGC/Higgs can be understood by looking at correlations

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



Higgs @ FCC-ee: Complementarity with FCC-hh

1

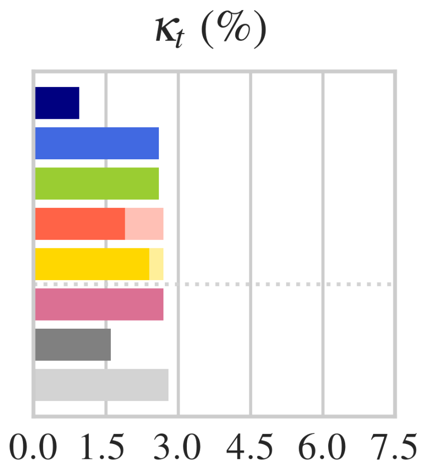


FCC-hh without ee could still bound BR_{inv}

but it could say nothing about BR_{unt}

FCC-ee needed for absolute normalisation of Higgs couplings

2

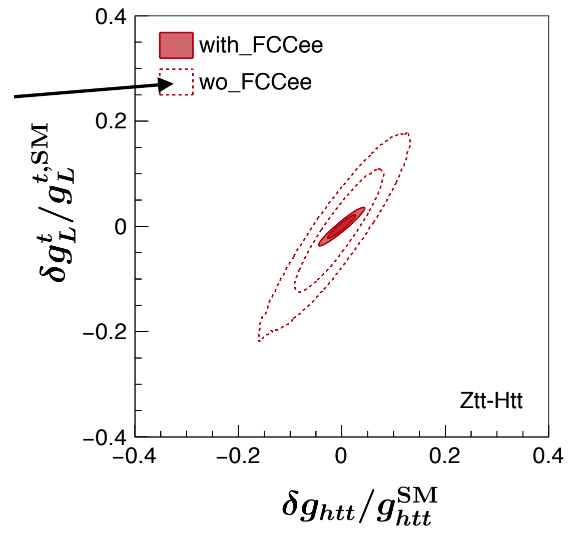


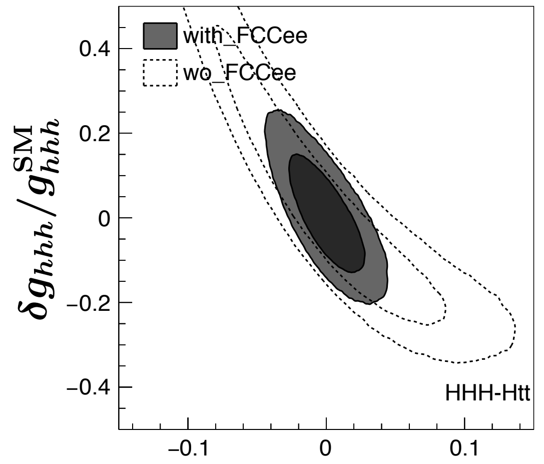
Mangano+ '15

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

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

uncertainty drops in ratio





Plots by J. de Blas, '19

3

Subsequently, the 1% sensitivity on tth is essential to determine h^3 at O(5%) at FCC-hh

Access to s Yukawa

Improved jet flavour tagging opens up new opportunities

Selvaggi @ FCC week 2021

BR(H⟶ ss) = BR (H⟶ cc) $(m_s/m_c)^2$ ~ 2.3 10^{-4}

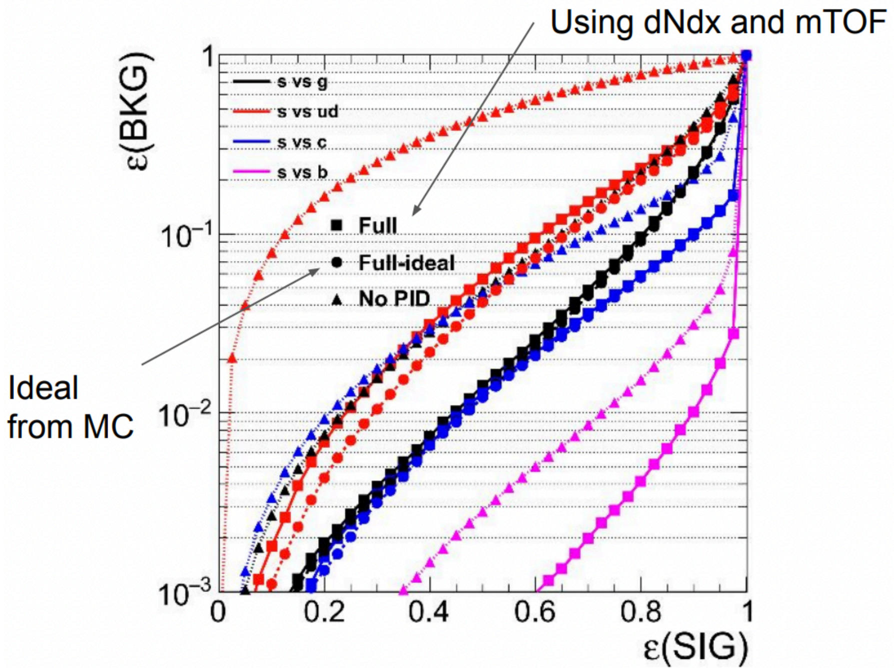
FCCee: σ_{ZH}~200fb, L ~ 5 ab^{-1} (2 IP): **~1M ZH**
[600k H⟶bb, 100k H⟶gg, 30k H⟶cc, **200 H⟶ ss**]

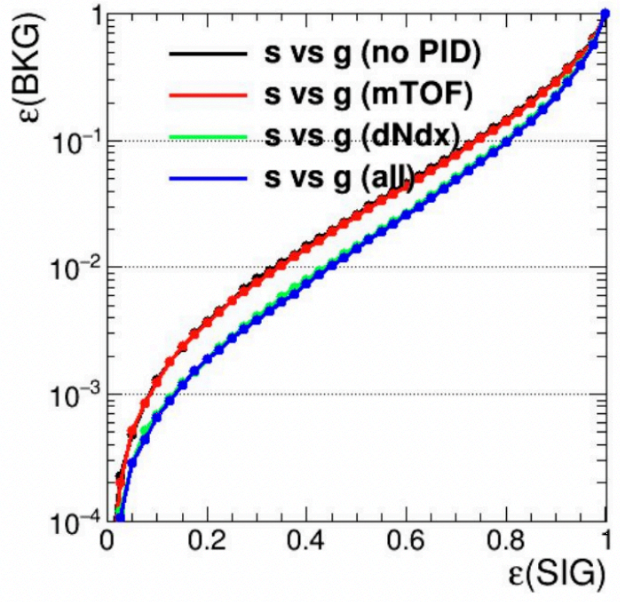
Use Loose WP:
[**s-tag: 90%**, **g-mist: 10%**, c-mist: 1%, b-mist: 0.4%

- **Scenario 1:** Z(⟶all)H:

N_{ss} = 150, N_b = 1000
(neglecting ee⟶ VV backgrounds)

δ(σxBR)/σxBR (%) ~ 21 % (~ 5σ) [no systematics, only higgs backgrounds, no combinatorics]





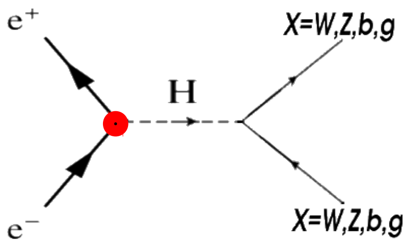
- **Scenario 2:** Z(⟶νν)H:

N_{ss} = 30, N_b = 200
(neglecting ee ⟶ ννqq and ee ⟶ qq, can be important given large q ⟶ s fake prob.)

δ(σxBR)/σxBR (%) ~ 49% (~ 2σ) [no systematics]

WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	10%	20%	6%	0.4%

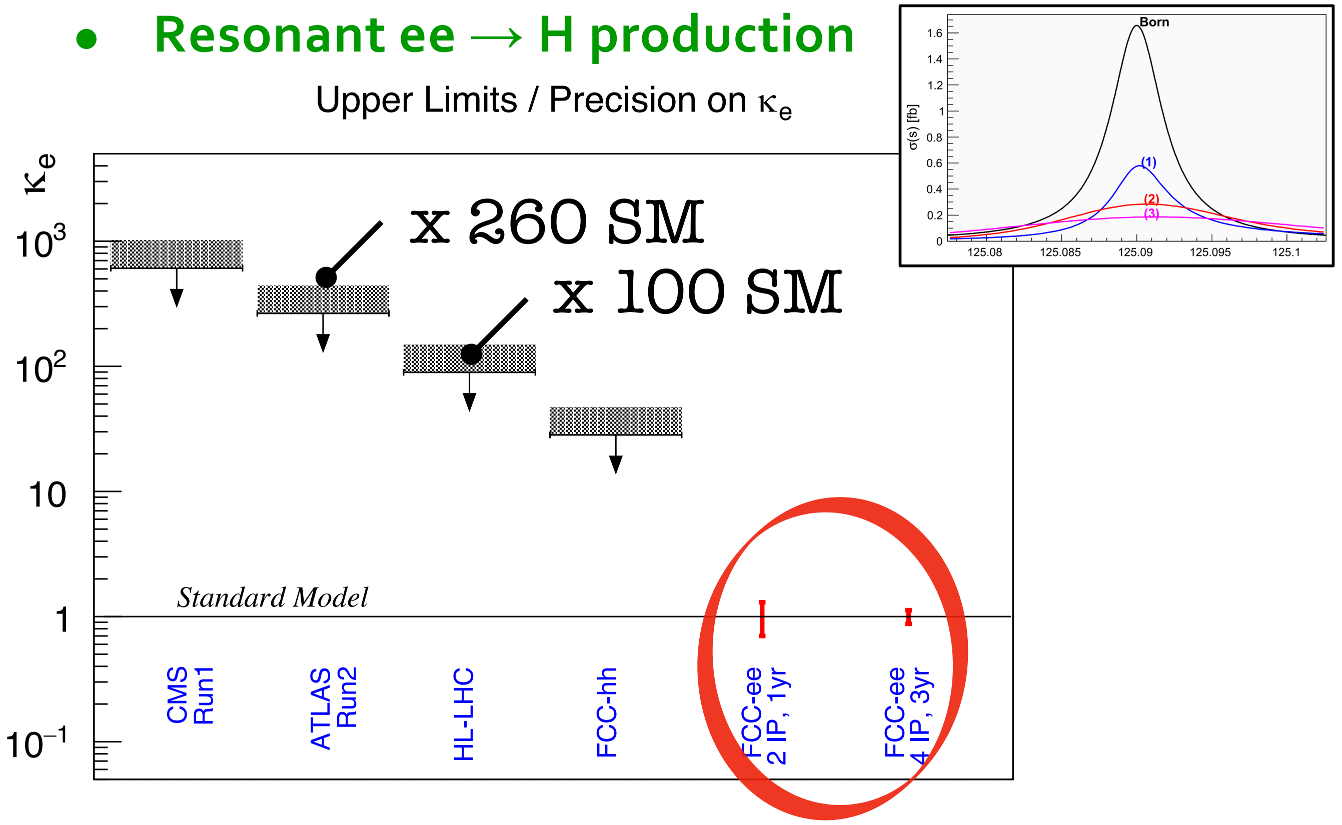
Access to e$^-$ Yukawa



$\sigma(e^+e^- \to H)$ = 1.64 fb

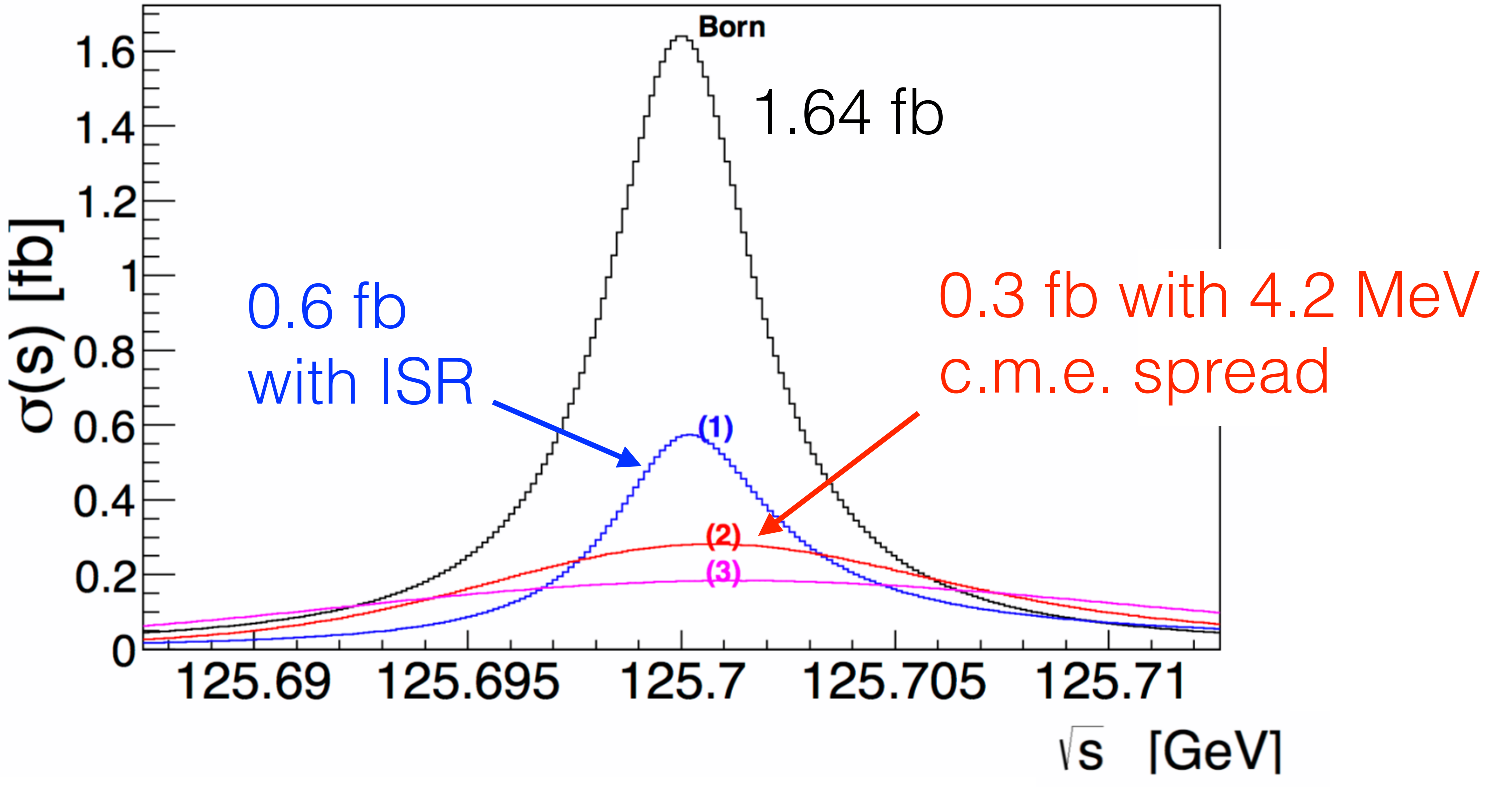
$\sigma_{\text{spread+ISR}}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H)$ = 290 ab

- **20 ab^{-1} / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}} \sim 1\text{-}2 \times \Gamma_H \sim$ 6 to 10 MeV**
  - **Resonant ee → H production**



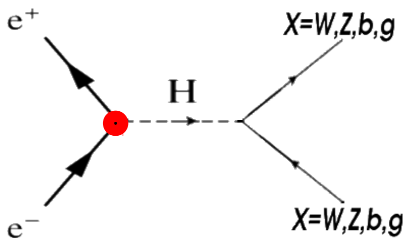
  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Jadach+, arXiv: 1509.02406



Producing these Higgs is not enough.
One needs to "see" them too.
To distinguish them from off=shell Z,
better to look at decays to particles that don't couple to Z's.

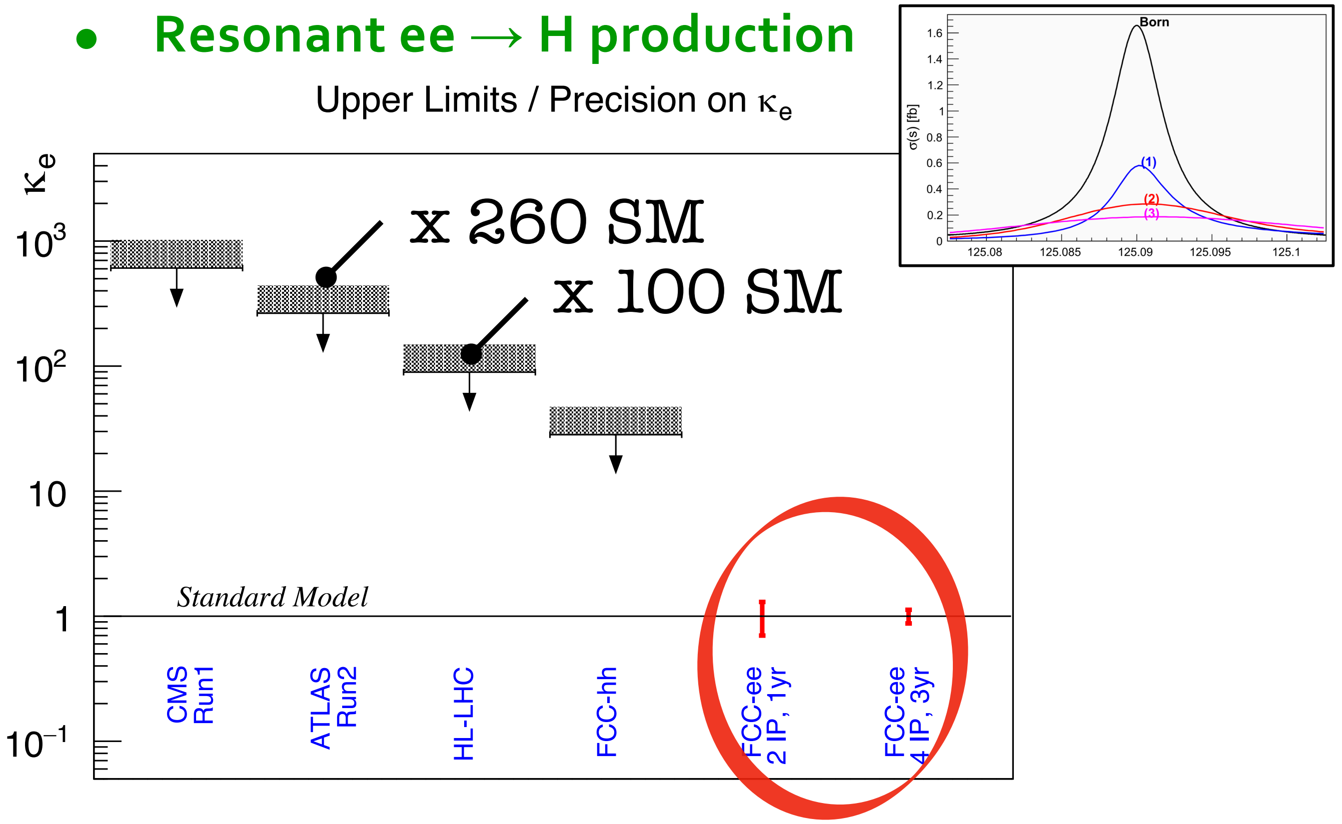
Access to e^- Yukawa



$\sigma(e^+e^-\to H)$ = 1.64 fb

$\sigma_{\text{spread+ISR}}(e^+e^-\to H)=0.17\times\sigma(e^+e^-\to H)=290$ ab

- **20 ab^{-1} / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}}$ ~ 1-2 × Γ_H ~ 6 to 10 MeV**
  - **Resonant ee → H production**



  - **2σ excess in one year with 2 IP**
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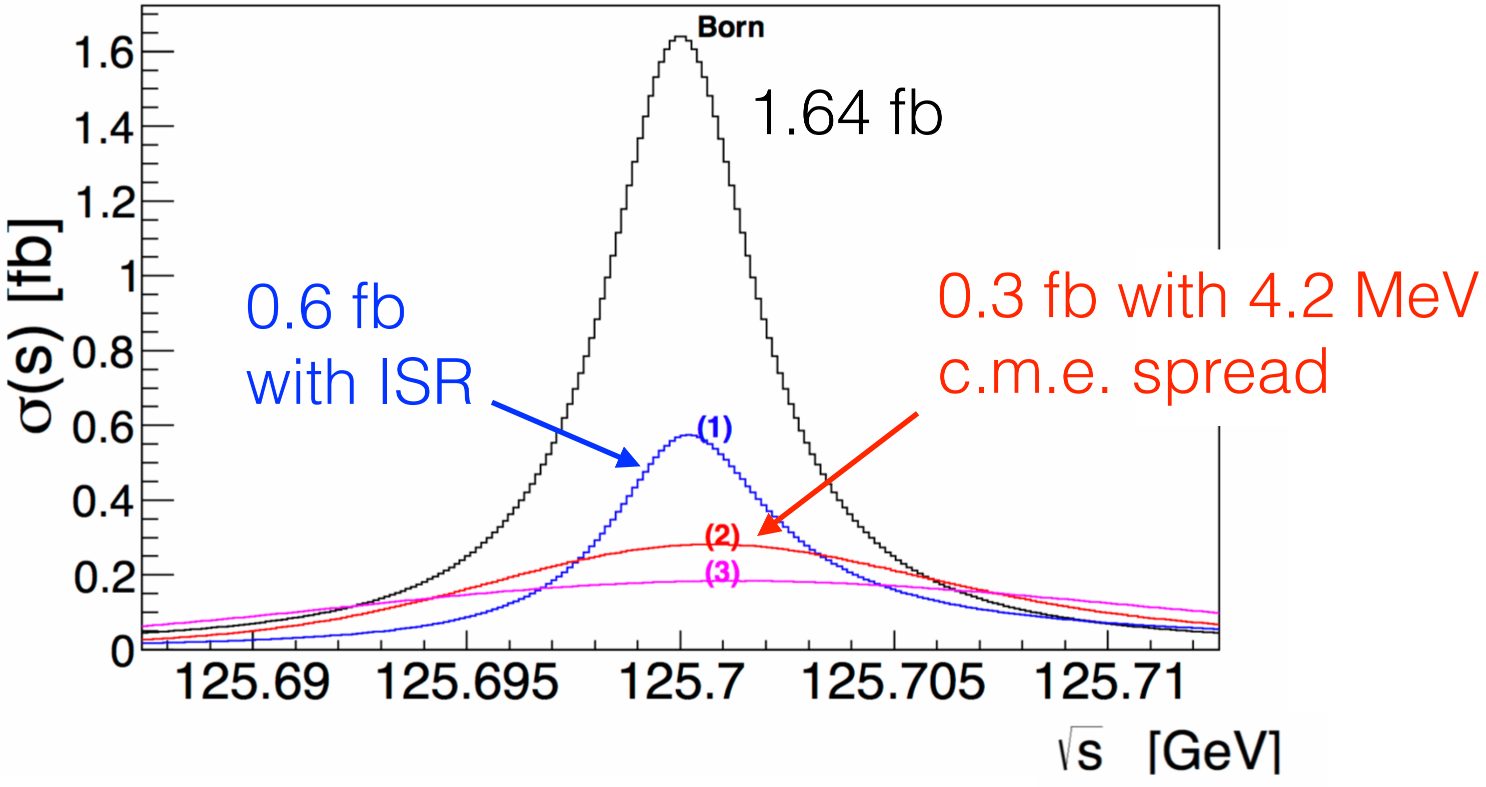


d'Enterria+, arXiv: 2107.02686

Higgs decay channel	$\mathcal{B}$	$\sigma\times\mathcal{B}$	Irreducible background	σ	S/B
$e^+e^-\to H\to b\bar{b}$	58.2%	164 ab	$e^+e^-\to b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^-\to H\to gg$	8.2%	23 ab	$e^+e^-\to q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^-\to H\to \tau\tau$	6.3%	18 ab	$e^+e^-\to \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^-\to H\to c\bar{c}$	2.9%	8.2 ab	$e^+e^-\to c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
$e^+e^-\to H\to WW^*\to \ell\nu\, 2j$	21.4%×67.6%×32.4%×2	26.5 ab	$e^+e^-\to WW^*\to \ell\nu\, 2j$	23 fb	$\mathcal{O}(10^{-3})$
$e^+e^-\to H\to WW^*\to 2\ell\, 2\nu$	21.4%×32.4%×32.4%	6.4 ab	$e^+e^-\to WW^*\to 2\ell\, 2\nu$	5.6 fb	$\mathcal{O}(10^{-3})$
$e^+e^-\to H\to WW^*\to 4j$	21.4%×67.6%×67.6%	27.6 ab	$e^+e^-\to WW^*\to 4j$	24 fb	$\mathcal{O}(10^{-3})$
$e^+e^-\to H\to ZZ^*\to 2j\, 2\nu$	2.6%×70%×20%×2	2 ab	$e^+e^-\to ZZ^*\to 2j\, 2\nu$	273 ab	$\mathcal{O}(10^{-2})$
$e^+e^-\to H\to ZZ^*\to 2\ell\, 2j$	2.6%×70%×10%×2	1 ab	$e^+e^-\to ZZ^*\to 2\ell\, 2j$	136 ab	$\mathcal{O}(10^{-2})$
$e^+e^-\to H\to ZZ^*\to 2\ell\, 2\nu$	2.6%×20%×10%×2	0.3 ab	$e^+e^-\to ZZ^*\to 2\ell\, 2\nu$	39 ab	$\mathcal{O}(10^{-2})$
$e^+e^-\to H\to \gamma\gamma$	0.23%	0.65 ab	$e^+e^-\to \gamma\gamma$	79 pb	$\mathcal{O}(10^{-8})$

w. 10/ab

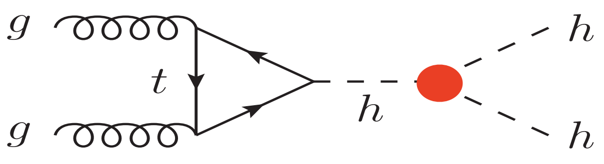
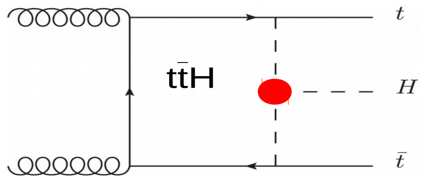
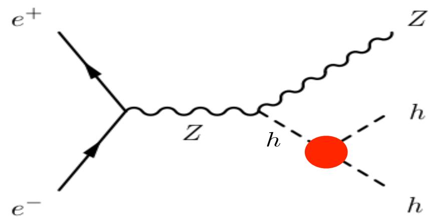
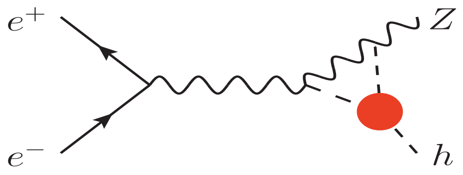
$H\to gg$	$H\to WW^*\to \ell\nu\, 2j;\ 2\ell\, 2\nu;\ 4j$	$H\to ZZ^*\to 2j\, 2\nu;\ 2\ell\, 2j;\ 2\ell\, 2\nu$	$H\to b\bar{b}$	$H\to \tau_{\text{had}}\tau_{\text{had}};\ c\bar{c};\ \gamma\gamma$	Combined
1.1σ	$(0.53\otimes 0.34\otimes 0.13)\sigma$	$(0.32\otimes 0.18\otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

w/ 10/ab: S~55, B~2400 → 1.1σ

Higgs Self-Coupling

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

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

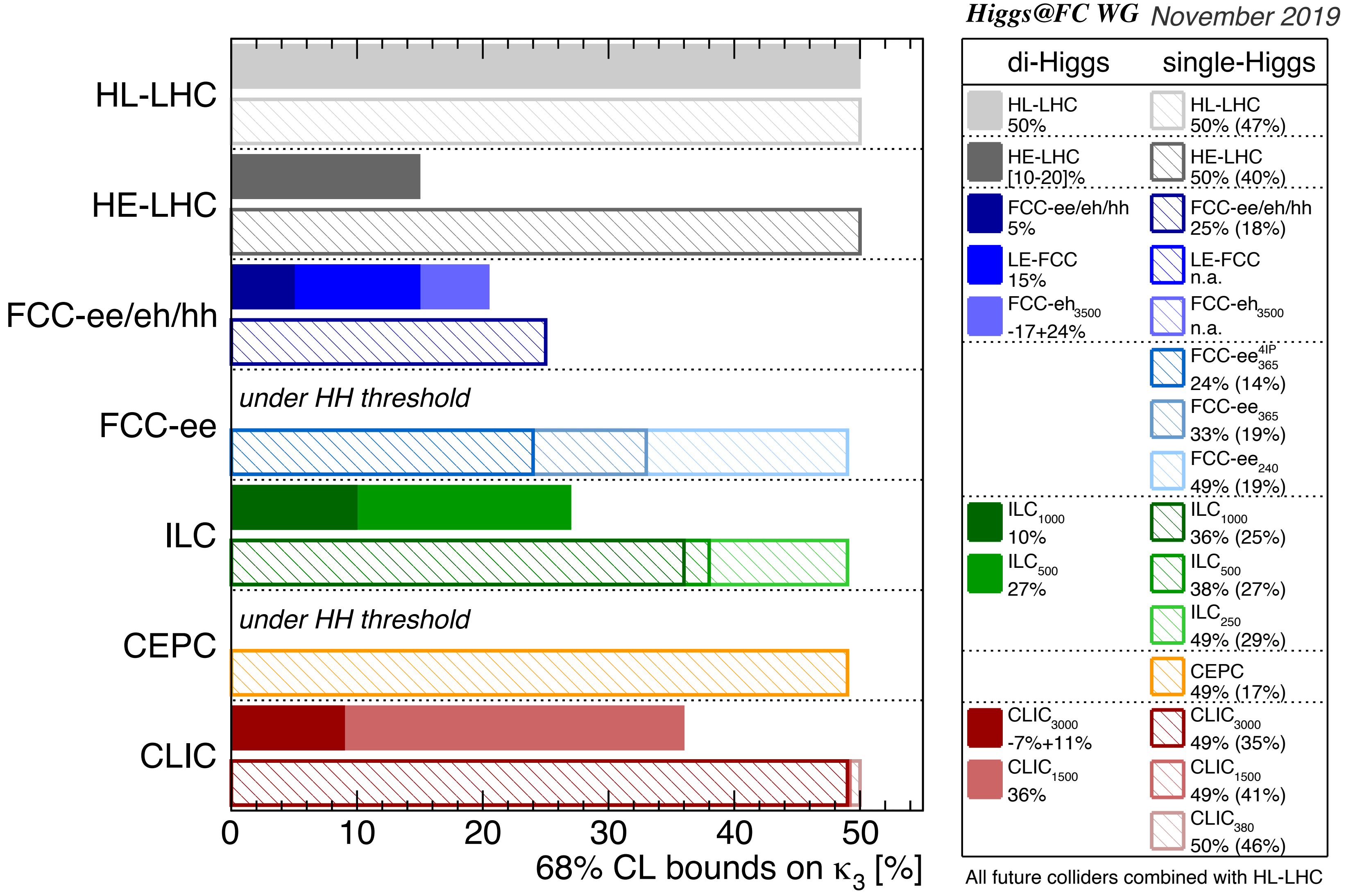
	Directly: Higgs-pair prod	**Indirectly: via single Higgs**
Hadron Colliders		
Lepton Colliders		

ECFA Higgs study group '19

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • 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 h^3. Both 240&365GeV runs are needed.

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 FCC-ee.

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

Other Directions Not Explored Yet

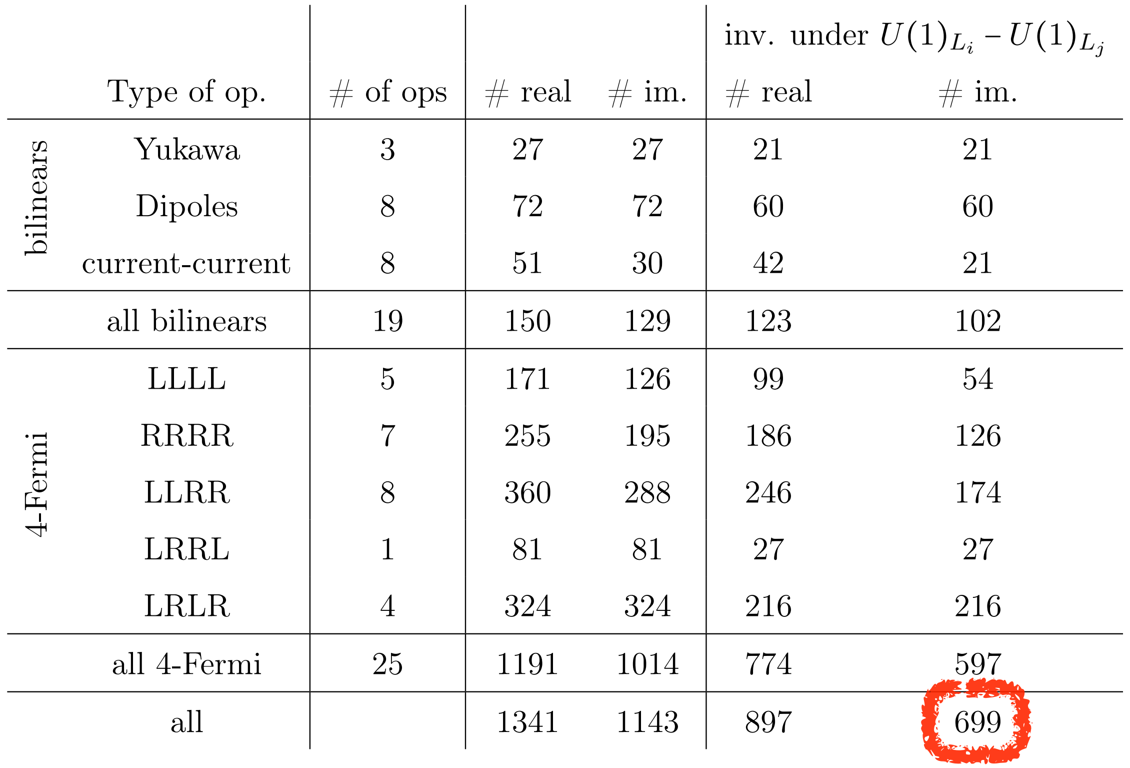
on-going work
in EF-04
global fit team
see talk by J. Gu and Y.Du

- Non-diagonal flavour structures:
  1. in SM, no Higgs FCNC
  2. in BSM, Higgs FCNC are the rule rather than the exception
  3. combination with flavour data (irrelevant in diag. flavour structure)
- CP violation couplings:
  1. in SM, a single CPV phase captured by Jarlskog invariant: $J_4 = \mathrm{ImTr}\left([Y_u Y_u^\dagger, Y_d Y_d^\dagger]^3\right)$
  2. how many at dim-6 level?

large parameter space,
largely unconstrained

—

potentially large new physics effects
since do not suffer from same
collective suppression factor of the SM



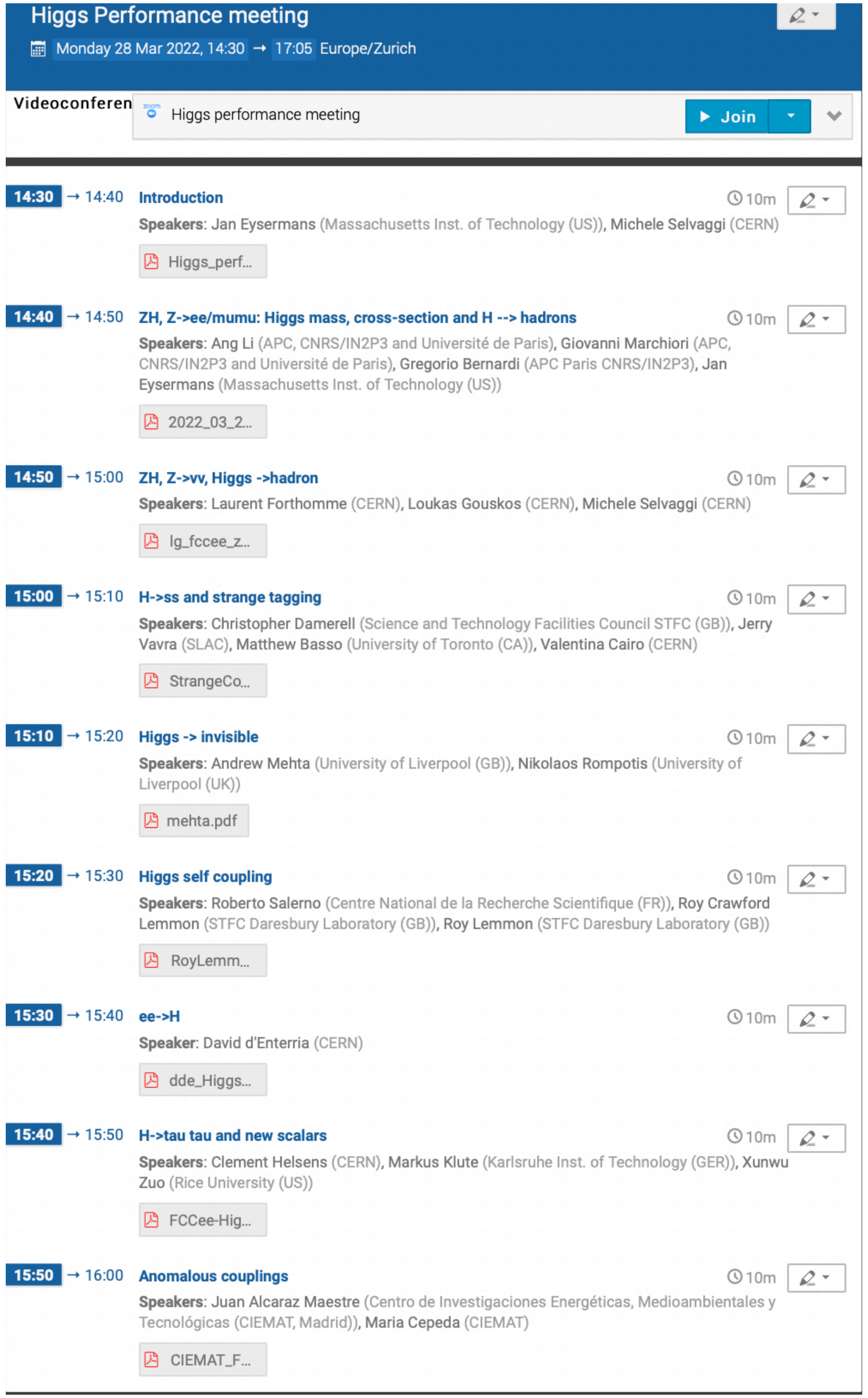
	Type of op.	# of ops	# real	# im.	inv. under $U(1)_{L_i} - U(1)_{L_j}$ # real	# im.
bilinears	Yukawa	3	27	27	21	21
	Dipoles	8	72	72	60	60
	current-current	8	51	30	42	21
	all bilinears	19	150	129	123	102
4-Fermi	LLLL	5	171	126	99	54
	RRRR	7	255	195	186	126
	LLRR	8	360	288	246	174
	LRRL	1	81	81	27	27
	LRLR	4	324	324	216	216
	all 4-Fermi	25	1191	1014	774	597
	all		1341	1143	897	699

699
new
Jarlskog
BSM invariants

Bonnefoy+ 2112.03889

- Beyond SMEFT analyses, e.g. HEFT

On-Going Studies



Higgs Performance meeting

Monday 28 Mar 2022, 14:30 → 17:05 Europe/Zurich

Videoconference: Higgs performance meeting

14:30 → 14:40 **Introduction** 10m

Speakers: Jan Eysermans (Massachusetts Inst. of Technology (US)), Michele Selvaggi (CERN)

Higgs_perf...

14:40 → 14:50 **ZH, Z->ee/mumu: Higgs mass, cross-section and H --> hadrons** 10m

Speakers: Ang Li (APC, CNRS/IN2P3 and Université de Paris), Giovanni Marchiori (APC, CNRS/IN2P3 and Université de Paris), Gregorio Bernardi (APC Paris CNRS/IN2P3), Jan Eysermans (Massachusetts Inst. of Technology (US))

2022_03_2...

14:50 → 15:00 **ZH, Z->vv, Higgs ->hadron** 10m

Speakers: Laurent Forthomme (CERN), Loukas Gouskos (CERN), Michele Selvaggi (CERN)

lg_fccee_z...

15:00 → 15:10 **H->ss and strange tagging** 10m

Speakers: Christopher Damerell (Science and Technology Facilities Council STFC (GB)), Jerry Vavra (SLAC), Matthew Basso (University of Toronto (CA)), Valentina Cairo (CERN)

StrangeCo...

15:10 → 15:20 **Higgs -> invisible** 10m

Speakers: Andrew Mehta (University of Liverpool (GB)), Nikolaos Rompotis (University of Liverpool (UK))

mehta.pdf

15:20 → 15:30 **Higgs self coupling** 10m

Speakers: Roberto Salerno (Centre National de la Recherche Scientifique (FR)), Roy Crawford Lemmon (STFC Daresbury Laboratory (GB)), Roy Lemmon (STFC Daresbury Laboratory (GB))

RoyLemm...

15:30 → 15:40 **ee->H** 10m

Speaker: David d'Enterria (CERN)

dde_Higgs...

15:40 → 15:50 **H->tau tau and new scalars** 10m

Speakers: Clement Helsens (CERN), Markus Klute (Karlsruhe Inst. of Technology (GER)), Xunwu Zuo (Rice University (US))

FCCee-Hig...

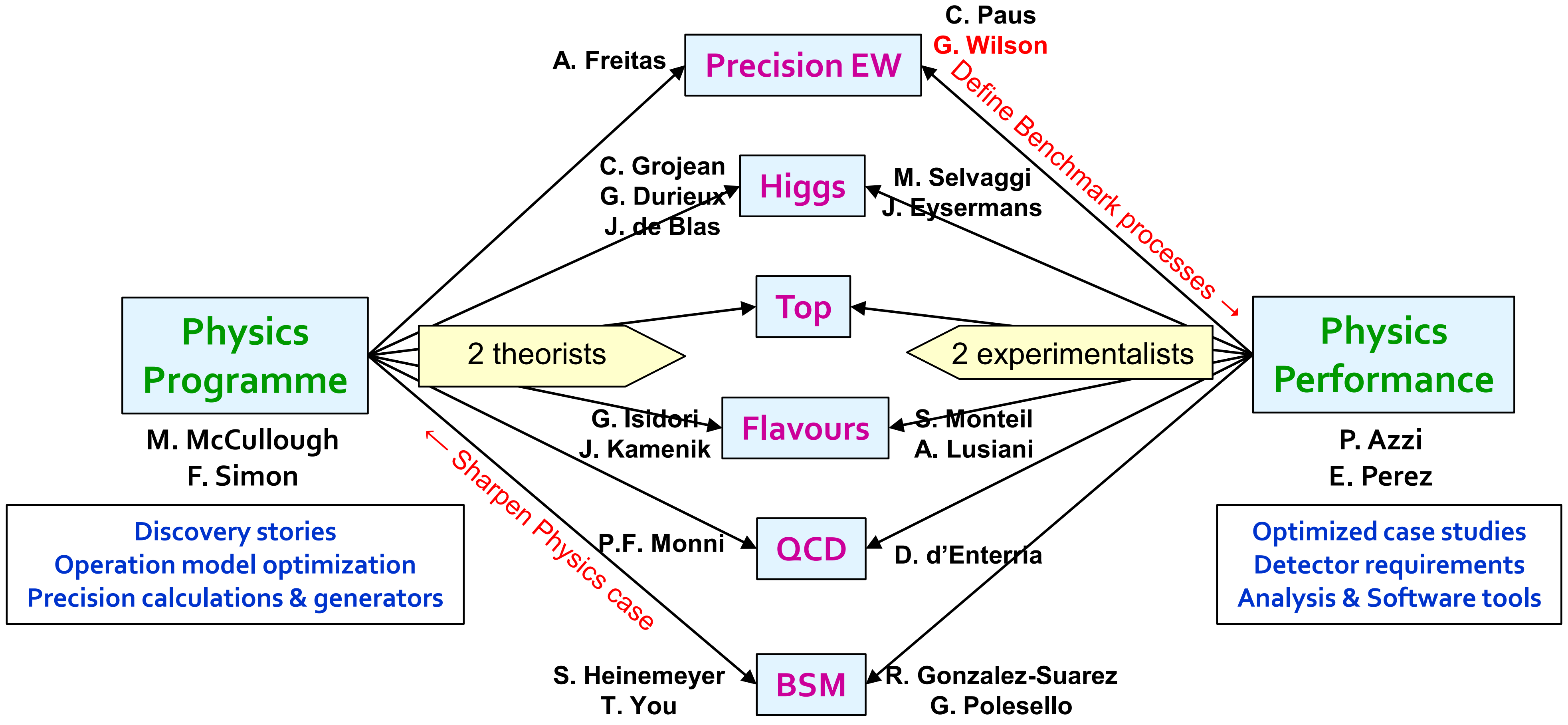
15:50 → 16:00 **Anomalous couplings** 10m

Speakers: Juan Alcaraz Maestre (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT, Madrid)), Maria Cepeda (CIEMAT)

CIEMAT_F...

Join the team!

https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Higgs



A. Freitas — **Precision EW** — C. Paus, G. Wilson

C. Grojean, G. Durieux, J. de Blas — **Higgs** — M. Selvaggi, J. Eysermans

Top

G. Isidori, J. Kamenik — **Flavours** — S. Monteil, A. Lusiani

P.F. Monni — **QCD** — D. d'Enterria

S. Heinemeyer, T. You — **BSM** — R. Gonzalez-Suarez, G. Polesello

Physics Programme

M. McCullough
F. Simon

Discovery stories
Operation model optimization
Precision calculations & generators

Physics Performance

P. Azzi
E. Perez

Optimized case studies
Detector requirements
Analysis & Software tools

2 theorists

2 experimentalists

Define Benchmark processes →

← Sharpen Physics case

EXTRA MATERIAL

Colliders Studied

Collider	Type	$\sqrt{s}$	$\mathcal{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathcal{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathcal{L}$ [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		CLIC	
					Giga-Z	250 GeV	Giga-Z	380 GeV
δm_{top} [MeV]	$\sim$500 [a]	$\sim$400 [a]	20 [b]	–	–	17 [b]	–	20-22 [b]
δM_Z [MeV]	2.1	–	0.1	0.5	–	–	–	–
$\delta\Gamma_Z$ [MeV]	2.3	–	0.1	0.5	1	–	1	–
$\delta\Gamma_{Z\to\text{had}}$ [MeV]	2.0	–	–	–	0.7	–	0.7	–
$\delta\sigma^0_{\text{had}}$ [pb]	37	–	4	5	–	–	–	–
δM_W [MeV]	12	7	0.7	1.0 (2-3) [c]	–	2.4 [d]	–	2.5
$\delta\Gamma_W$ [MeV]	42	–	1.5	3	–	–	–	–
$\delta\text{BR}_{W\to e\nu}[10^{-4}]$	150	–	3	3	–	4.2	–	11
$\delta\text{BR}_{W\to\mu\nu}[10^{-4}]$	140	–	3	3	–	4.1	–	11
$\delta\text{BR}_{W\to\tau\nu}[10^{-4}]$	190	–	4	4	–	5.2	–	11
$\delta\text{BR}_{W\to\text{had}}[10^{-4}]$	40	–	1	1	–	–	–	–
δA_e $[10^{-4}]$	140	–	1.1 [e]	3.2 [e]	5.1	10	10	42
δA_μ $[10^{-4}]$	1060	–	–	–	5.4	54	13	270
δA_τ $[10^{-4}]$	300	–	3.1 [e]	5.2 [e]	5.4	57	17	370
δA_b $[10^{-4}]$	220	–	–	–	5.1	6.4	9.9	40
δA_c $[10^{-4}]$	400	–	–	–	5.8	21	10	30
δA^μ_{FB} $[10^{-4}]$	770	–	0.54	4.6	–	–	–	–
δA^b_{FB} $[10^{-4}]$	160	–	30 [f]	10 [f]	–	–	–	–
δA^c_{FB} $[10^{-4}]$	500	–	80 [f]	30 [f]	–	–	–	–
δR_e $[10^{-4}]$	24	–	3	2.4	5.4	11	4.2	27
δR_μ $[10^{-4}]$	16	–	0.5	1	2.8	11	2.2	27
δR_τ $[10^{-4}]$	22	–	1	1.5	4.5	12	4.3	60
δR_b $[10^{-4}]$	31	–	2	2	7	11	7	18
δR_c $[10^{-4}]$	170	–	10	10	30	50	23	56
δR_ν $[10^{-3}]$ [g]	–	–	–	–	–	–	–	9.4
δR_{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	–
BR_{inv}	<0.0015	<0.003	<0.0015

… (full collection in our report)

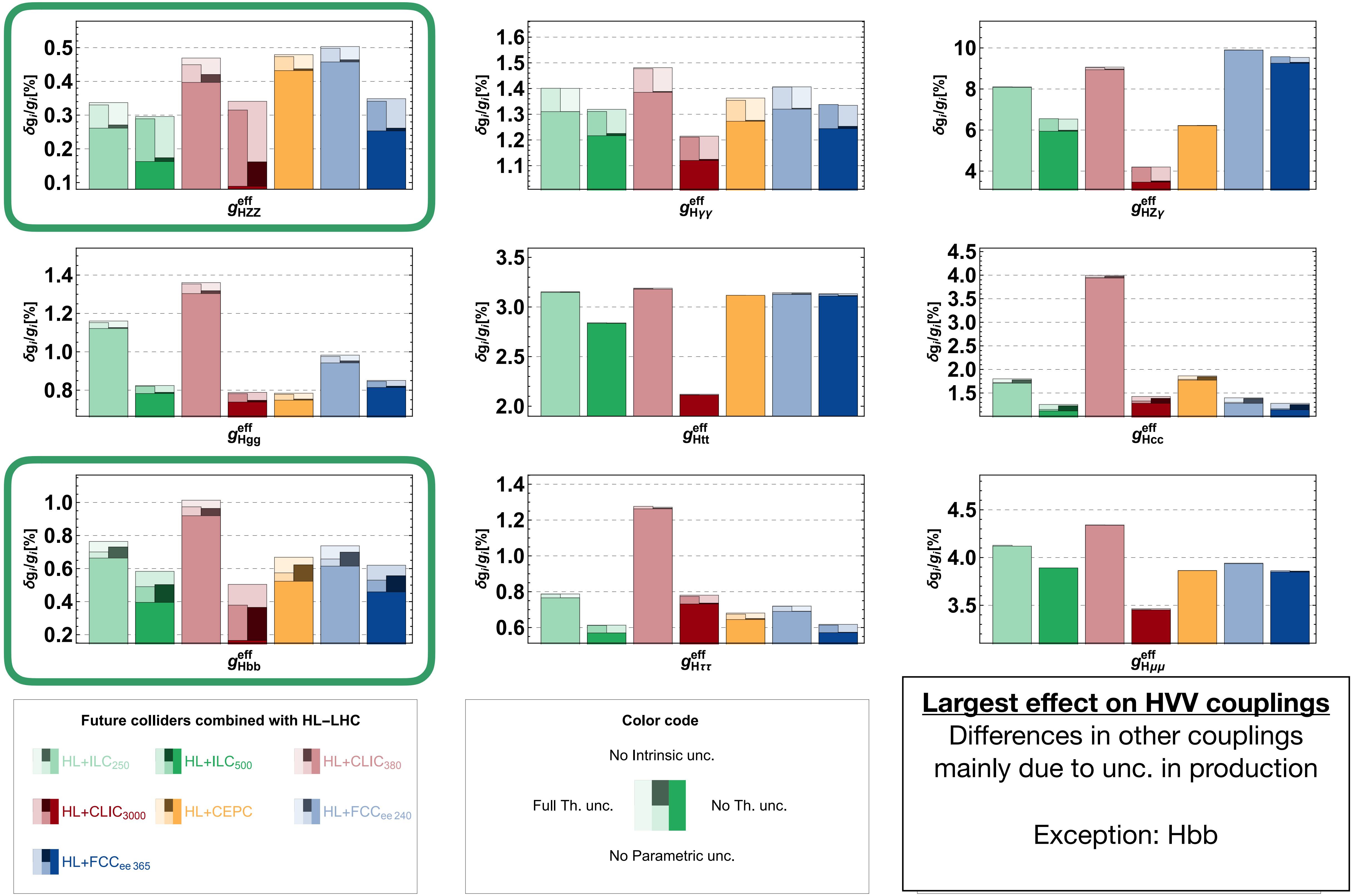
Theoretical Uncertainties

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→Hνν, 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

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

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)

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

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
- **κ_γ, $\kappa_{\gamma Z}$, κ_g** are treated as independent effective coupling modifiers
  - alone, low energy colliders, below ttH/tH threshold, are not sensitive to κ_{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
  - Γ_H and untagged are 100% correlated

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

Scenario	BR_{inv}	BR_{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

Experimental Inputs

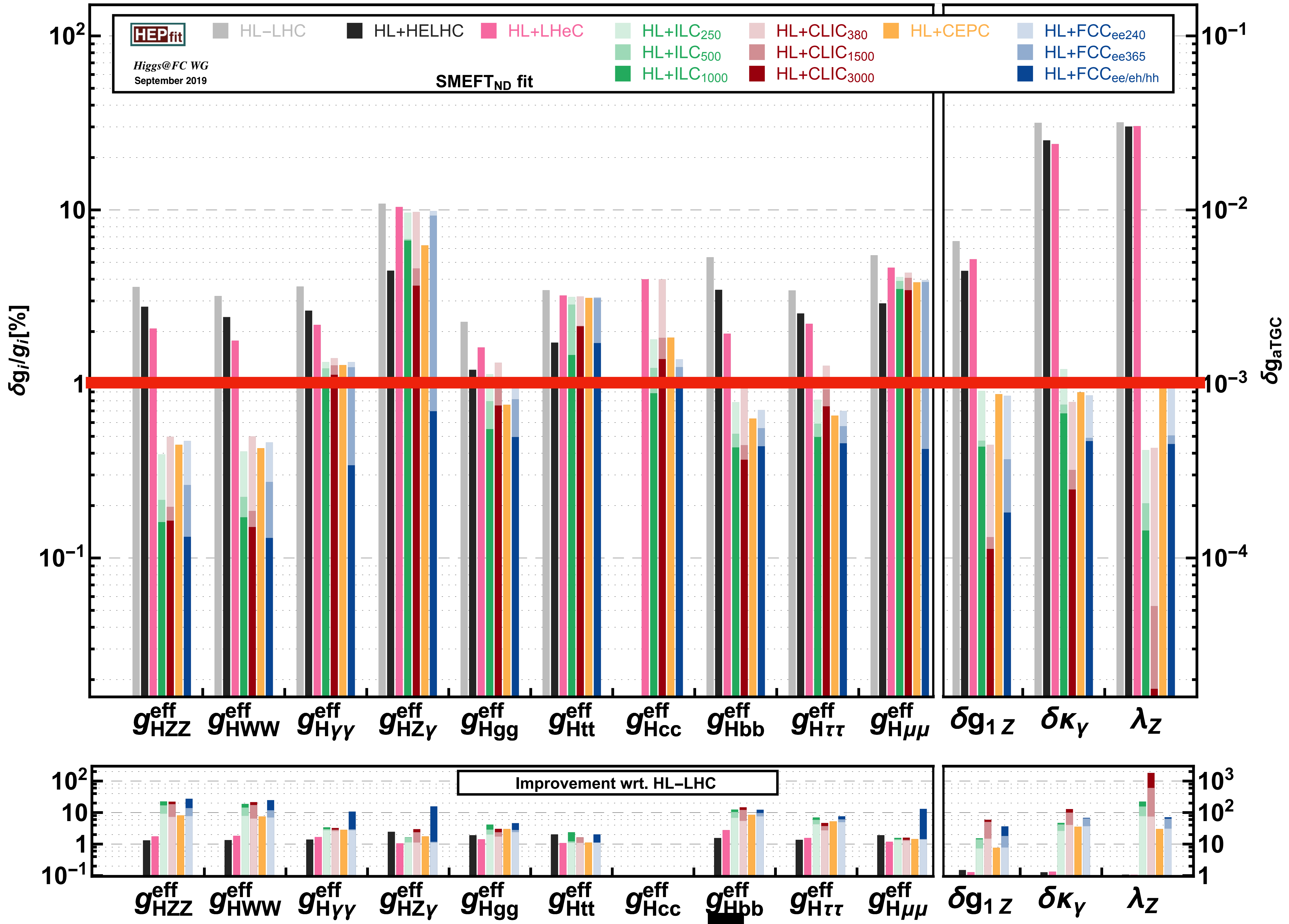
A circular ee Higgs factory starts as a Z/EW factory (**TeraZ**)

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 (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.)	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit)	Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom)	Yes	No
CLIC	Yes (μ, σ_{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 (μ, BR_i/BR_j) Used in combination with FCCee/eh	From FCC-ee	From FCC-ee	-
LHeC	Yes (μ)	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_W$)	-
FCC-eh	Yes (μ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + Zuu, Zdd	-

Global EFT Fit



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1%
magic
threshold

There is life beyond HL-LHC

Figures of Merit with Respects to HL-LHC

Factor of improvement in different channels viz. HL-LHC

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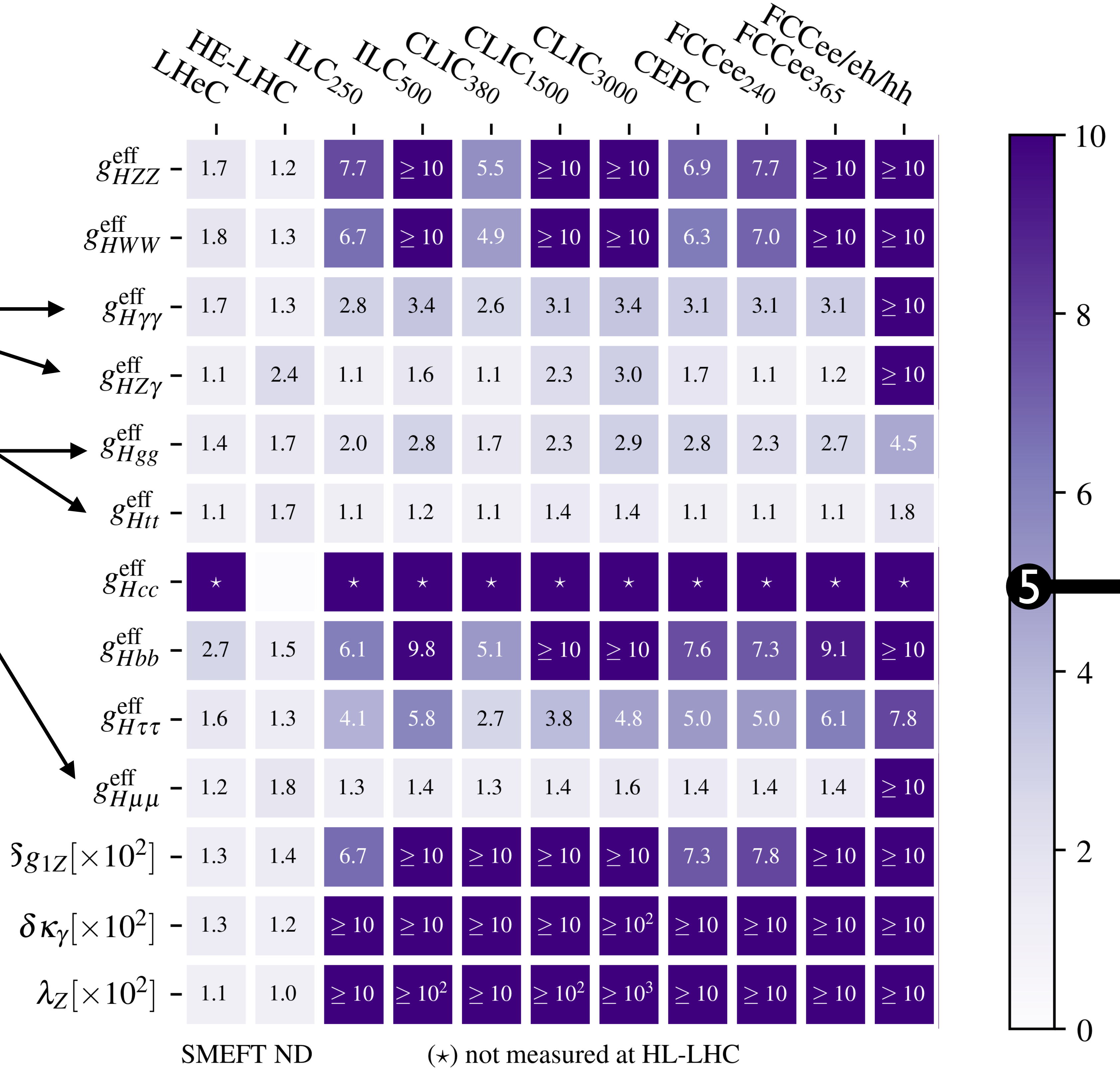


	LHeC	HE-LHC	ILC_{250}	ILC_{500}	CLIC_{380}	CLIC_{1500}	CLIC_{3000}	CEPC	FCCee_{240}	FCCee_{365}	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{\mathrm{eff}}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	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^{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^{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^{eff}_{Hcc}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{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

Stat. limited

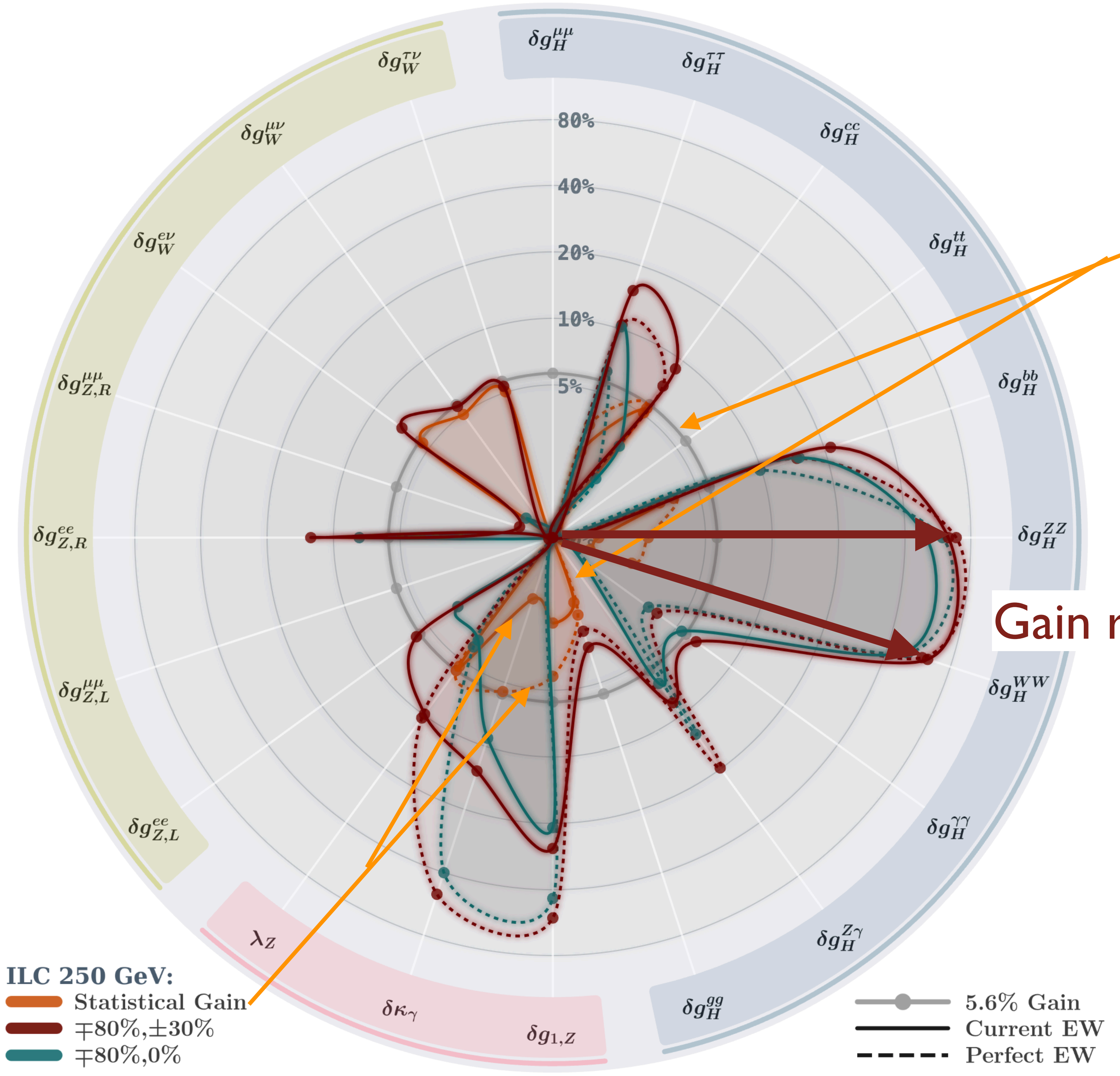
Top quark channels
(LHC is a top factory and it is not so easy to outperform)

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

There is life after HL-LHC

Impact of Beam Polarisation (@250GeV)

J. De Blas et al. 1907.04311



Gain reaches 80%

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

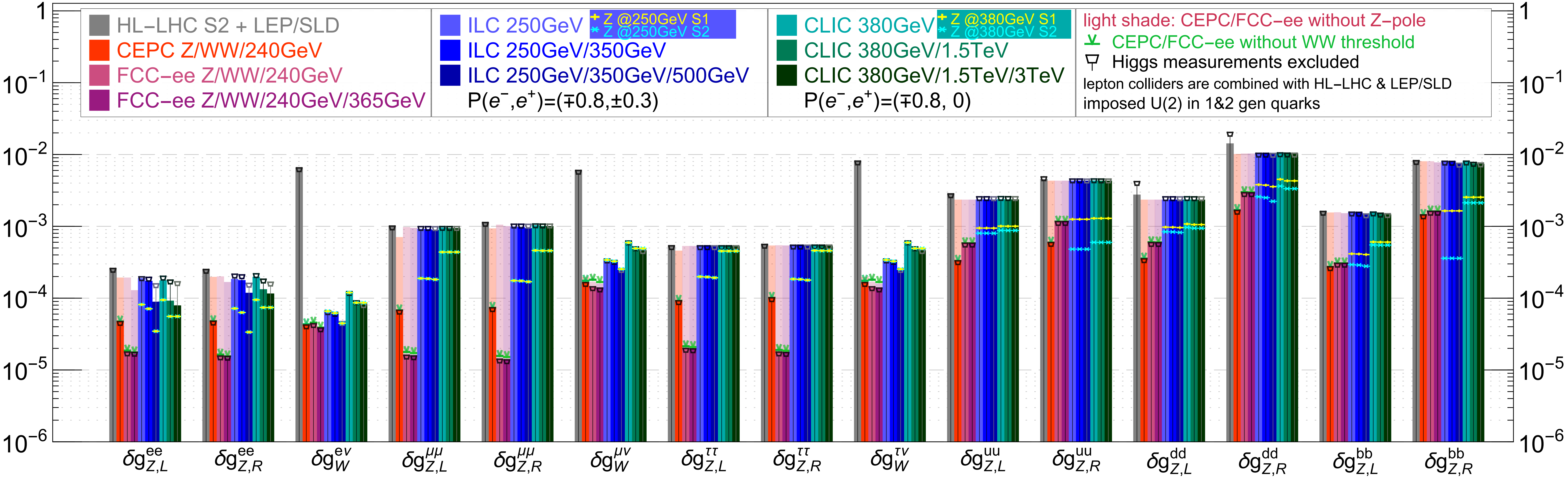
Gain is much higher in global EFT fit since polarisation removes degeneracies among operators

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

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

Sensitivity on EW couplings

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



Sensitivity on EW couplings

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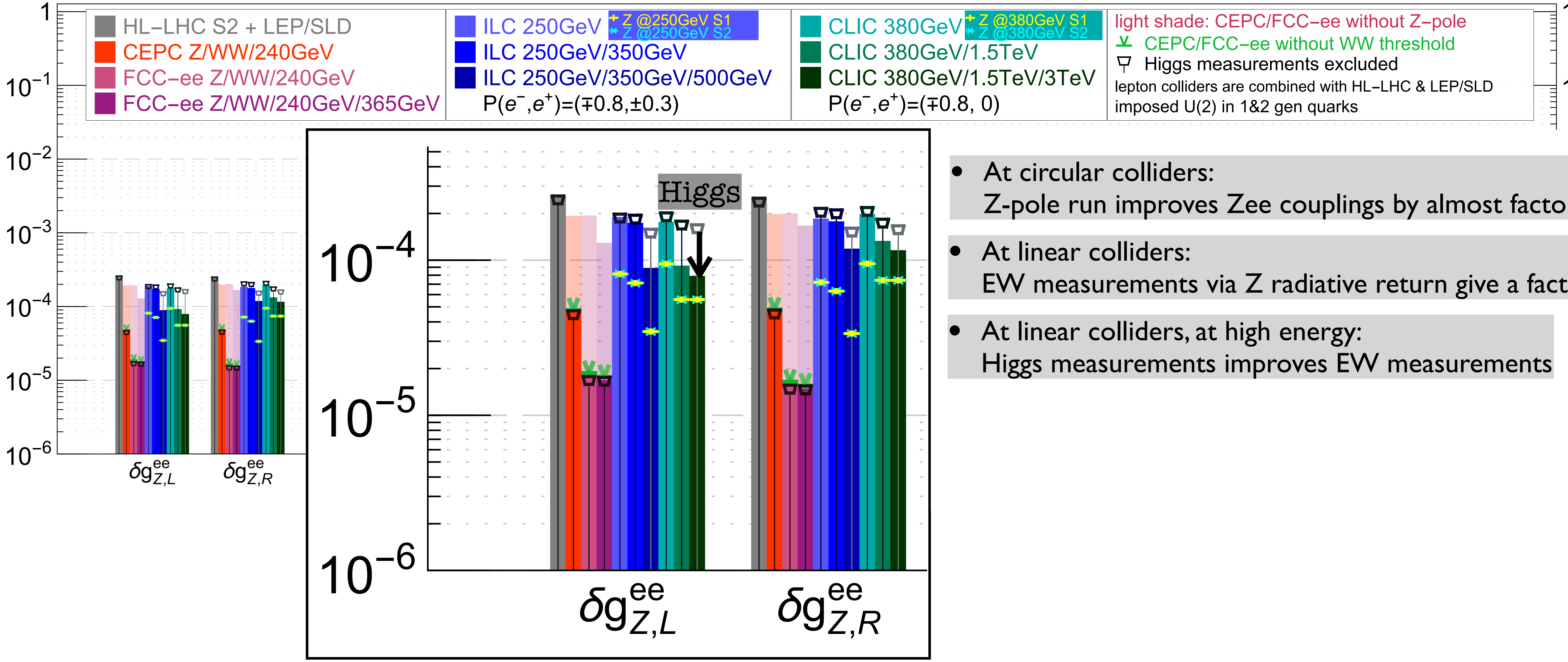
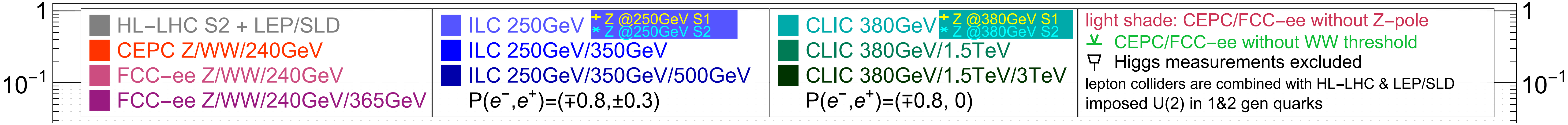


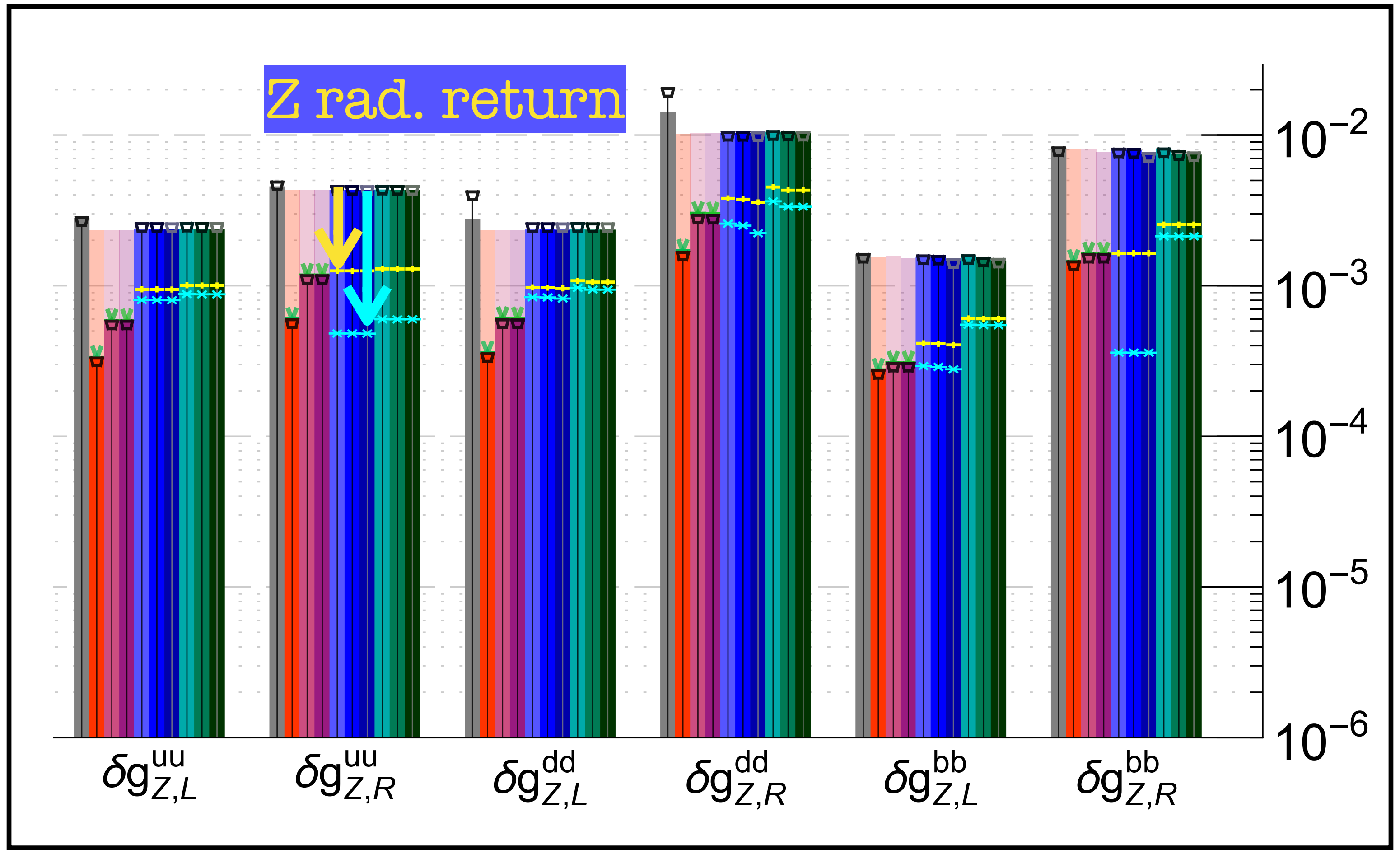
- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



- At linear colliders, at high energy:
  EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
  - Yellow: LEP/SLD systematics / 2
  - Blue: small EXP and TH systematics



Other Studies Beyond Coupling Fits

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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
  - hττ: angular distributions
  - ttH and tH: rates and angular distributions
  - indirect constraints from EDM