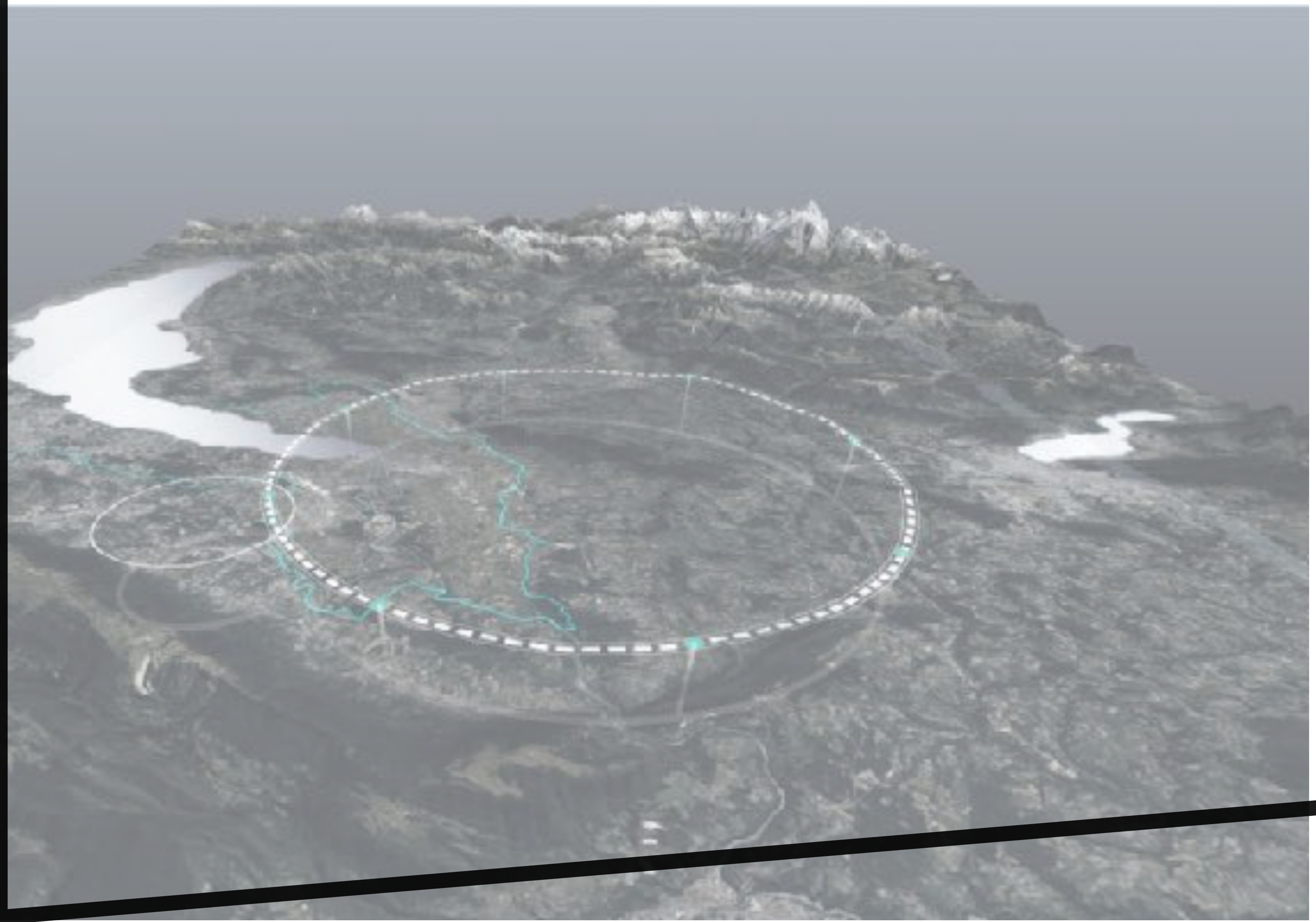
Physics prospects at future (circular) colliders

— theoretical perspective —



Mini-workshop on the European Strategy Update

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Why a new collider?

- At school, when you finish a book and go to the next class, you need a new book.
- With the new book, you want to learn more, go to the next step of knowledge.
- We are all students, nature is our teacher, colliders our books.
- Why a bigger collider? Well, the book has more pages and is bigger, because things become more difficult in the higher class.

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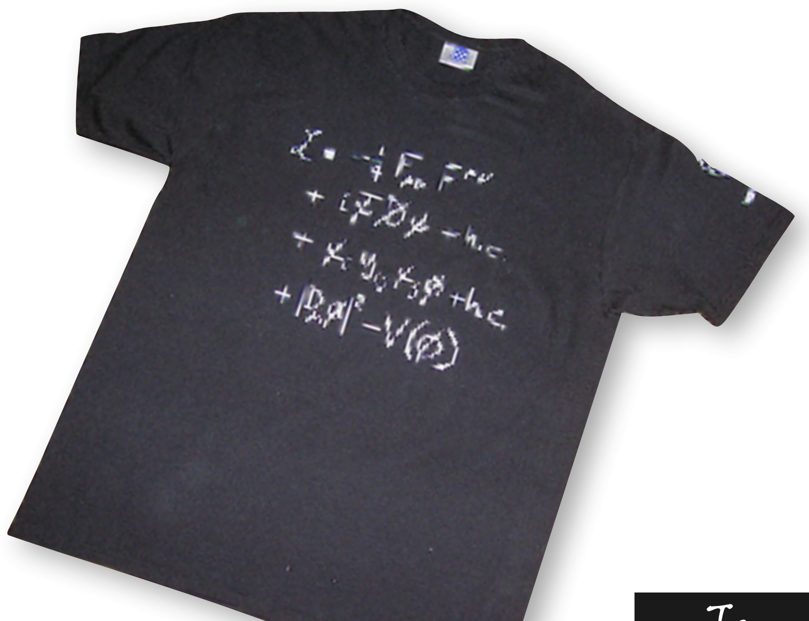

The LHC Legacy (so far)

- **Standard Model (SM) confirmed to high accuracy up to energies of several TeV**
  (thanks to a firm control of exp. & th. syst. uncertainties, the LHC became a precision machine)

- **Higgs boson discovered** at the mass predicted* by LEP precision EW measurements
  *within the Standard Model

- **Absence of new physics** —
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  - New approaches: relaxion, Nnaturalness, clockwork…

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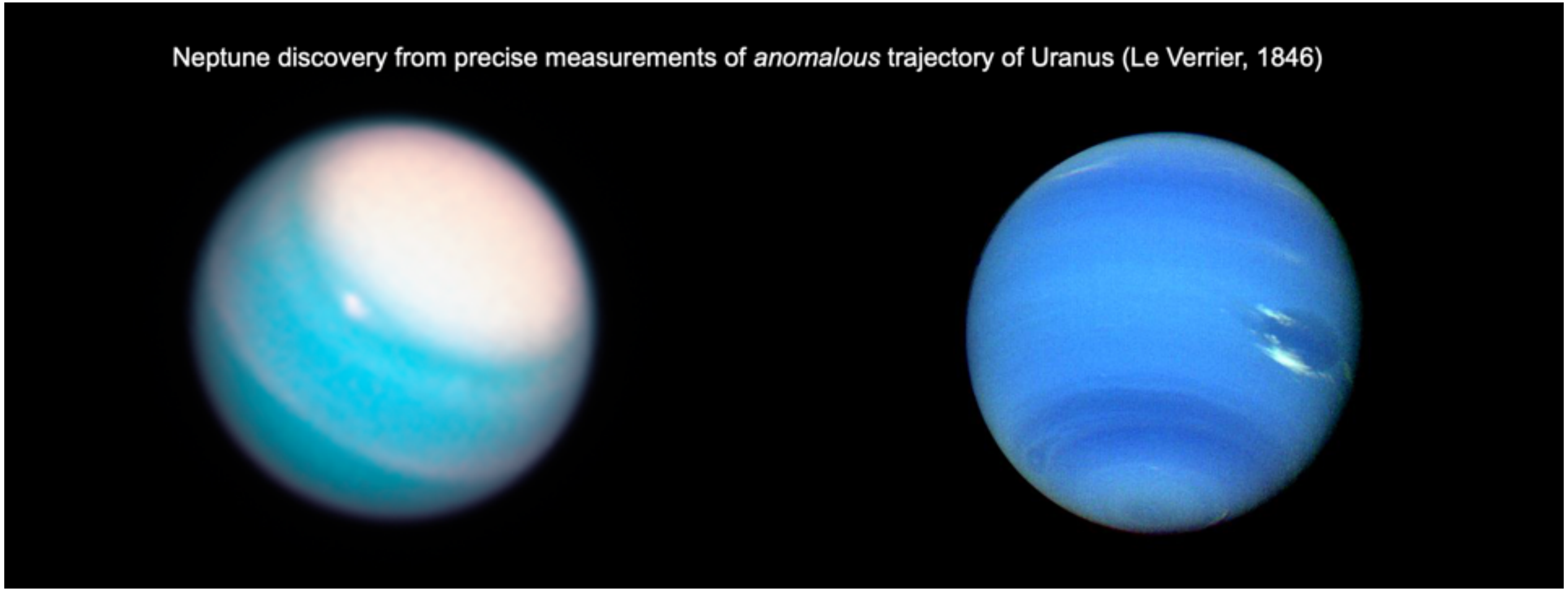
We need a broad, versatile and ambitious programme that can
1. sharpen our knowledge of already discovered physics
2. push the frontiers of the unknown at high and low scales

more PRECISION and more ENERGY, for more SENSITIVITY to New Physics

Precision as a discovery tool

Many historical examples

- Uranus anomalous trajectory ⇢ Neptune



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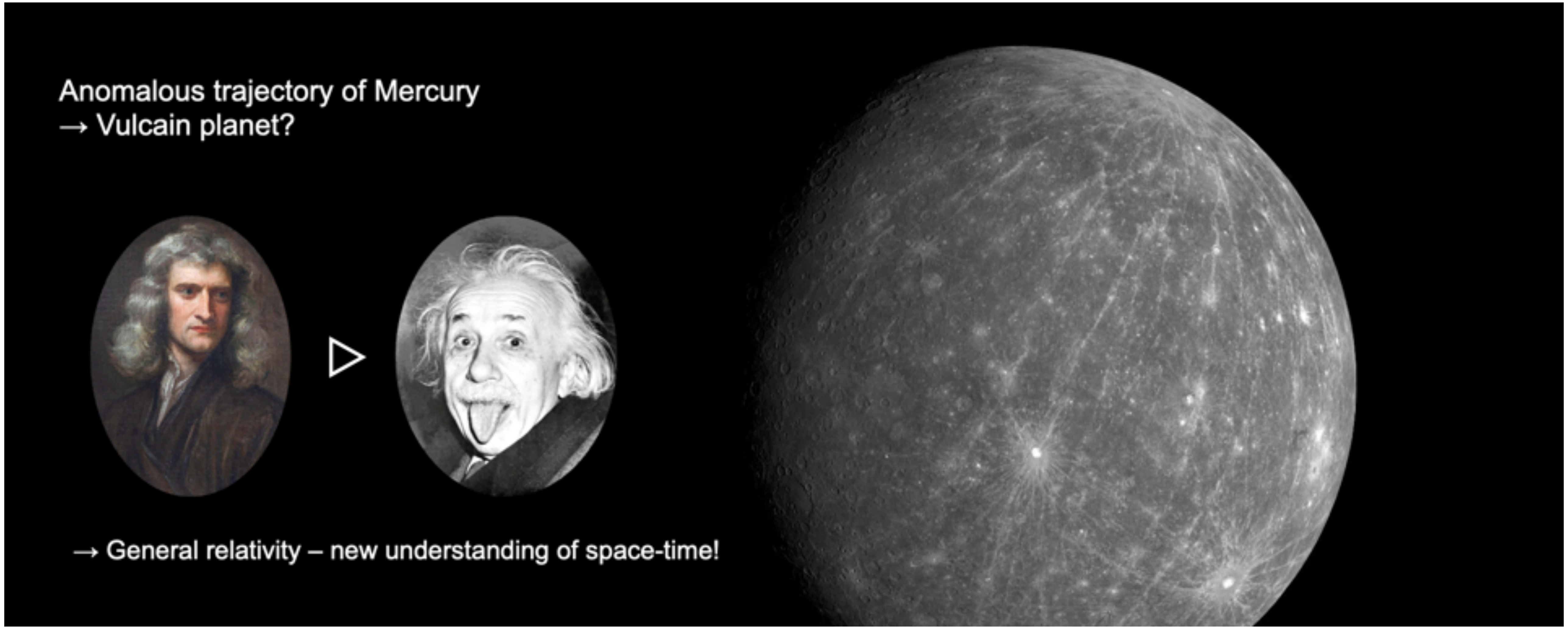

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- …

Sometimes, these discoveries were expected based on theoretical arguments
(e.g. Rayleigh-Jeans UV catastrophe for QM, unitarity breakdown for the Higgs)
but precision gave valuable additional clues.
In any case, experimentalists shouldn't lean too heavily on theorist priors/prejudices
(remember discovery of P violation).
At times when we don't have a precise theoretical guidance, we need powerful experimental tools to make progress.

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Herwig Schopper in CERN Courier:
People often say "not much came out from LEP". That is completely wrong.
What people forget is that LEP changed high-energy physics from a 10% to a 1% science.

The Higgs requires more precision

"The Higgs isn't everything !"

The Higgs requires more precision

"The Higgs isn't everything; it's the only thing!"*

The scalar discovery in 2012 has been an important milestone for HEP.
Many of us are still excited about it. Others should be too.

* M.E. Peskin paraphrasing UCLA football coach H.R. Sanders

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— The discovery of the Higgs opens new deep questions —

- What is the origin of the Higgs boson?
- Is it elementary and isolated, or does it emerge from a deeper underlying dynamics?
- Which role did the Higgs play during the big bang, and how did it influence the evolution of the Universe?
- Does the Higgs boson play a role in explaining other fundamental open questions in particle physics which the SM cannot address (flavour, DM, baryogenesis, inflation…)

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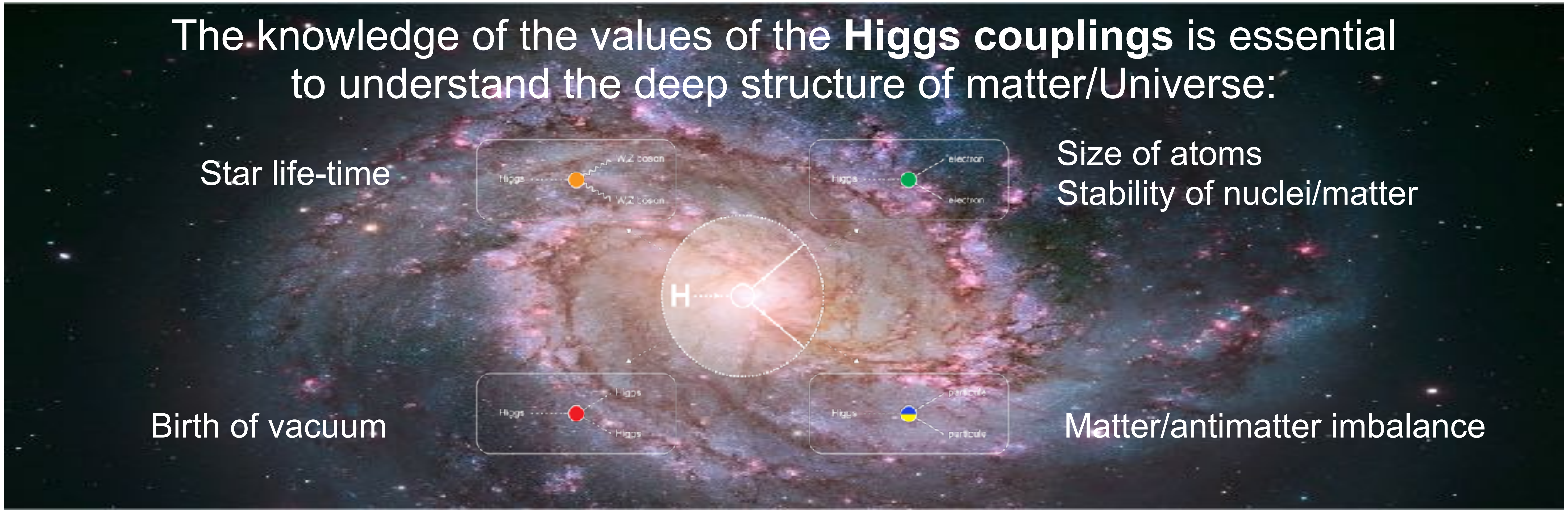
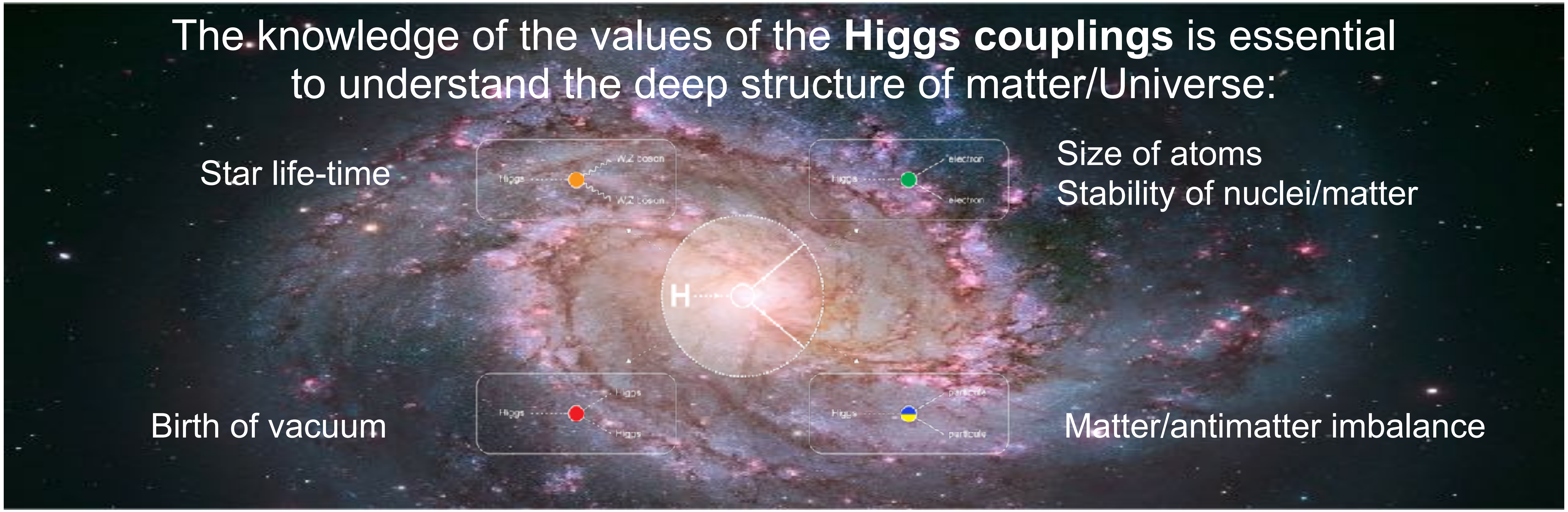


The Higgs requires more precision

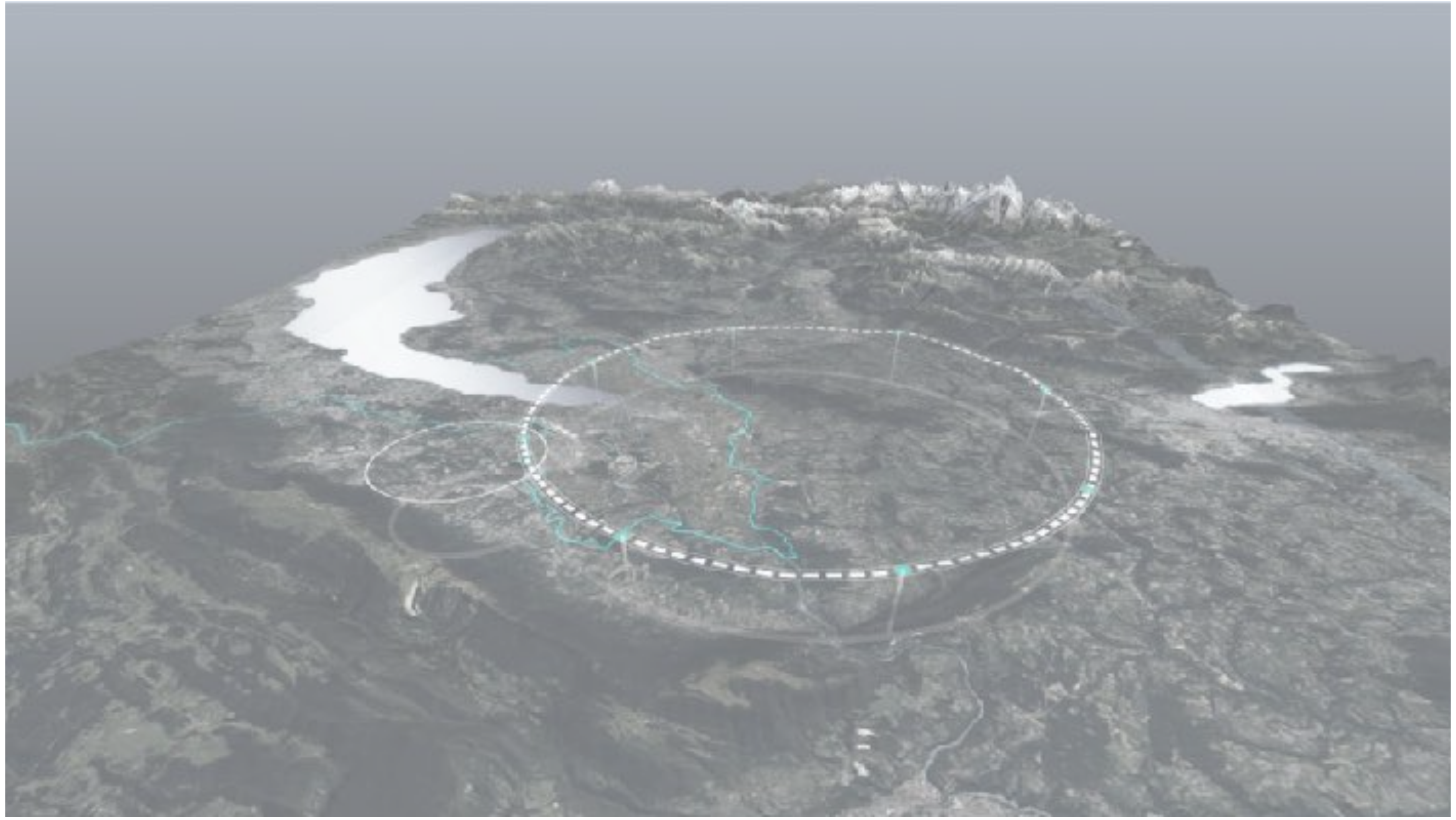
(HL)-LHC will make remarkable progress.
But it won't be enough.
A new collider is needed!



— FCC —
Physics Overview

Future Circular Collider

- A versatile particle collider housed in a 91km underground ring around CERN.
- Implemented in several stages:
  - an e^+e^- “Higgs/EW/Flavour/top/QCD” factory running at 90-365 GeV ▶ **FCC-ee**
  - followed by a high-energy pp collider reaching 100 TeV ▶ **FCC-hh**



FCC Project on a Fast Track

After just over a decade of pioneering work, huge progress has been achieved:

- The first proposal of a high-luminosity **e^+e^- circular collider** to study the Higgs boson was made **thirteen years** ago (December 2011) [A. Blondel & F. Zimmermann following discussions with P. Janot at CERN cafeteria on a bright 2011 summer night speculating on the rumours of a Higgs at 140 GeV];

- The Future Circular Collider collaboration was created **ten years** ago, towards the conceptual design study of a **100 TeV pp collider**, with an e^+e^- Higgs factory as a potential intermediate step;

- The **Conceptual Design Reports** of the FCC physics case, and of the FCC-ee and FCC-hh colliders, were published **six years** ago and submitted to the 2018-19 European Strategy Update;

- The CERN Council updated the European Strategy **four years** ago, stating that an e^+e^- Higgs factory would be the highest priority next collider, to be followed by a proton-proton collider at the highest achievable energy;

- **Three years** ago, the CERN Council consequently initiated and funded a **technical and financial feasibility** study for FCC with focus on an e^+e^- electroweak and Higgs factory as a first stage, study to be completed by the time of the next European Strategy Update;

- **A year** ago, a 700+ pages **mid-term report** about the FCC feasibility was submitted to the CERN Council for a thorough review, with a conclusion expected at the beginning of 2025. Very positive feedback from CERN council in **Feb. 2, 2024.**

FCC-hh tunnel is great for FCC-ee

- **80-100 km is needed to accelerate pp up to 100 TeV**
- **80-100 km is also exactly what is needed**
  - to get enough luminosity (5 times more than in 27 km) to get sensitivity to the Higgs self coupling, the electron Yukawa coupling, or sterile neutrinos,
  - to make TeraZ a useful flavour factory,
  - for transverse polarisation to be available all the way to the WW threshold (allowing a precise W mass measurement)
  - for the top threshold to be reached and exceeded.

FCC-ee Run Plan

LEP1 data accumulated in **every 2 mn**. Exciting & diverse programme with different priorities every few years.

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

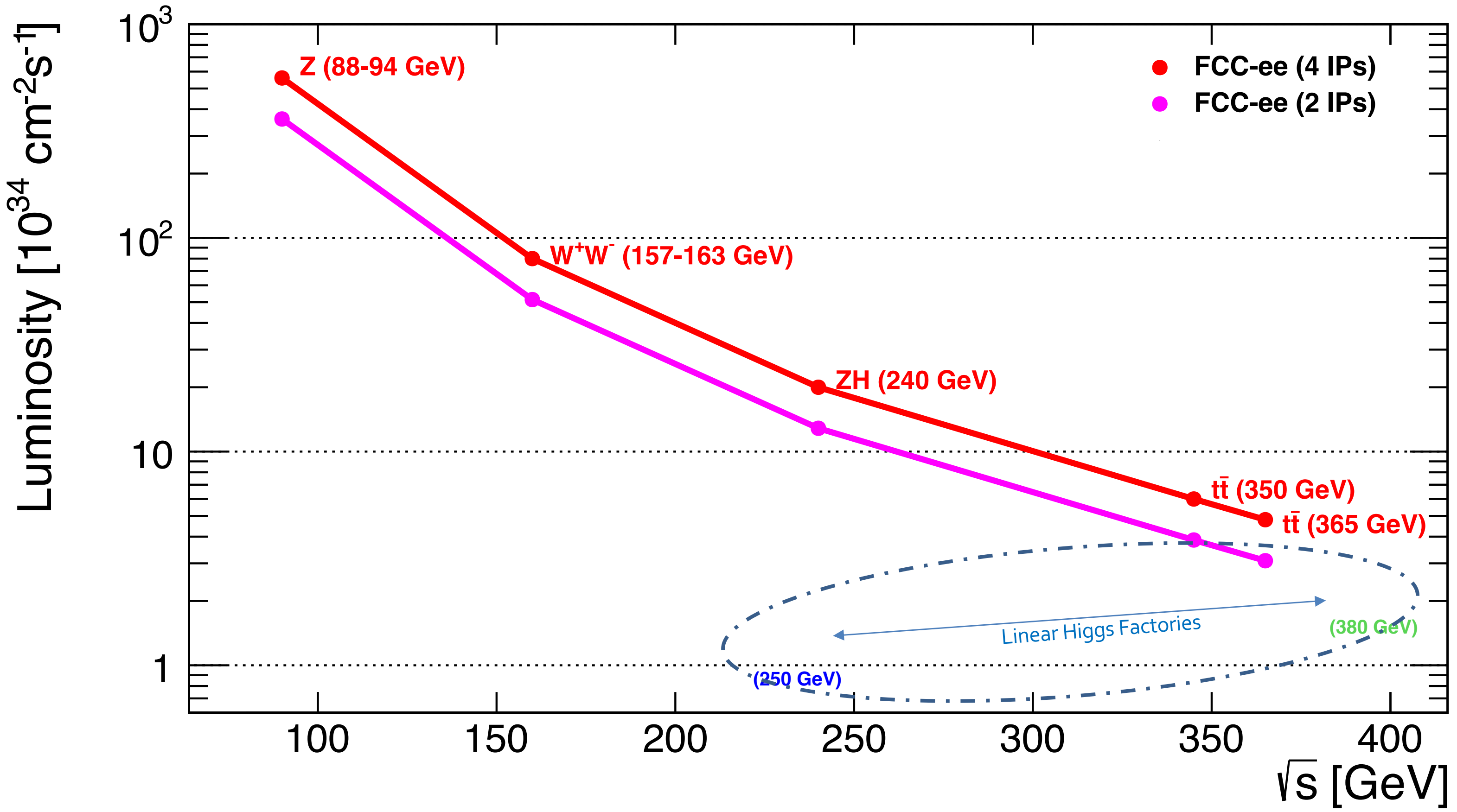


Fig. to be updated: new optics design (May 2024) gives 50% more lumi @ 240 GeV.

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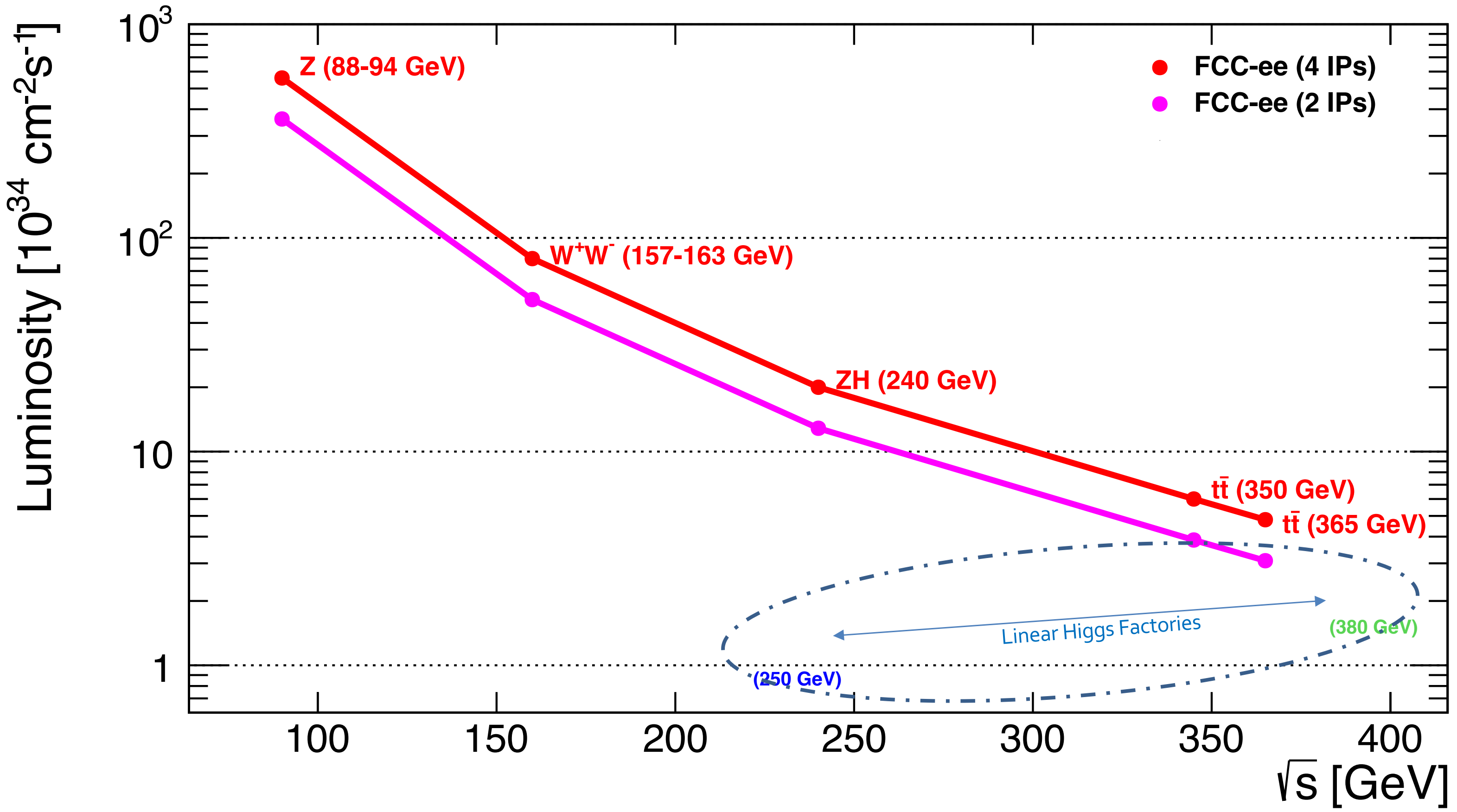

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Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)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

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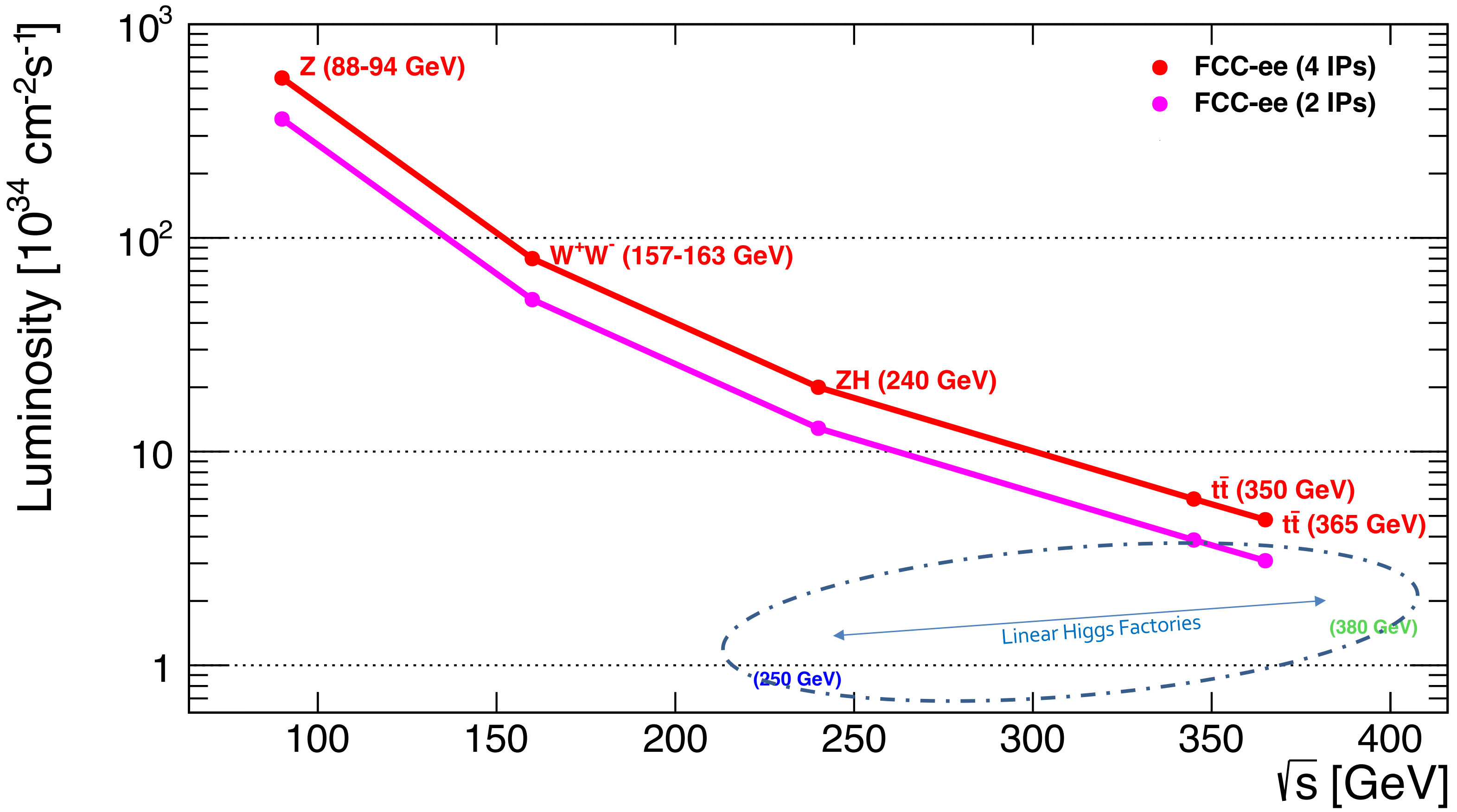

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— Superb statistics achieved in only 15 years —

in each detector:
10^5 Z/sec, 10^4 W/hour,
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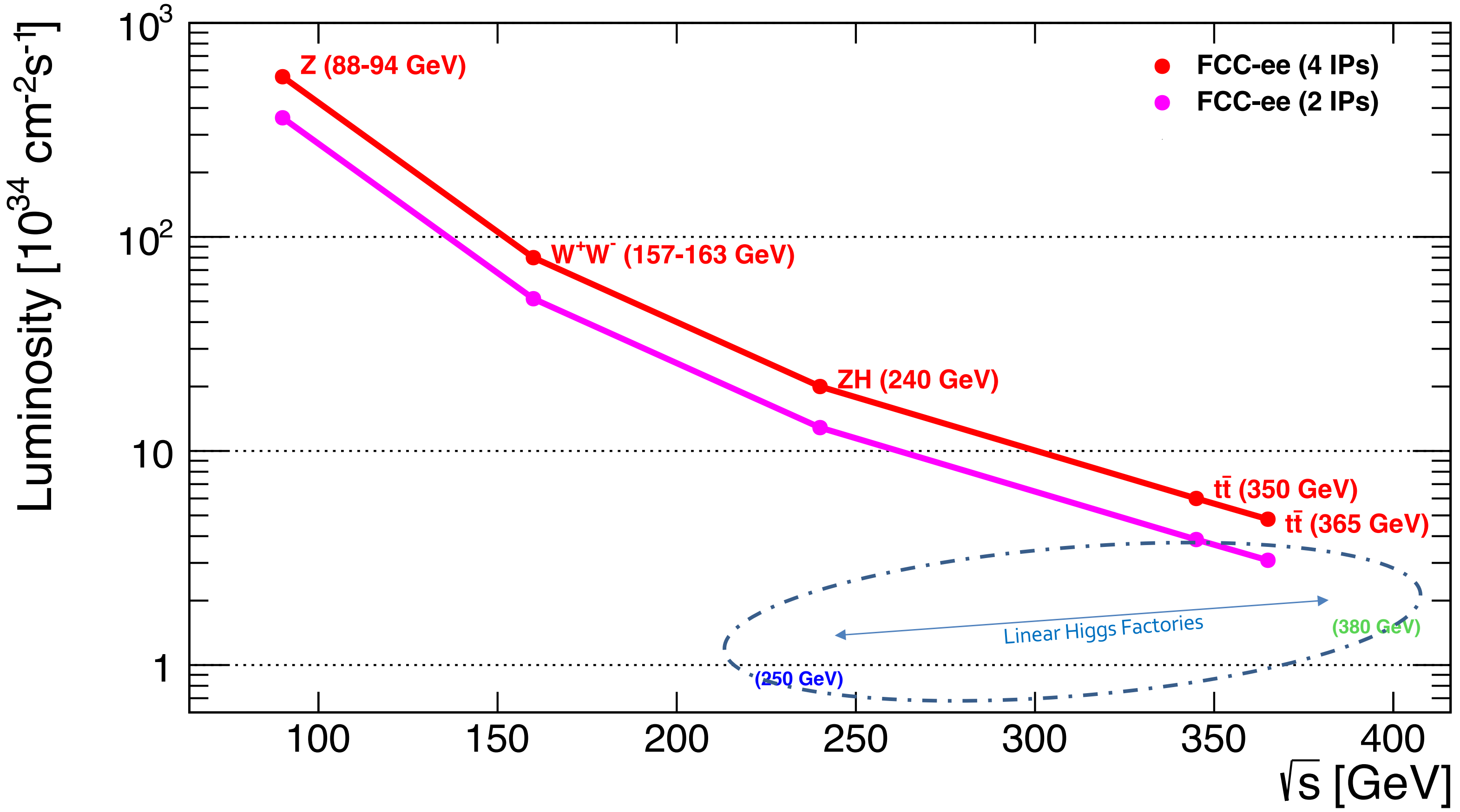

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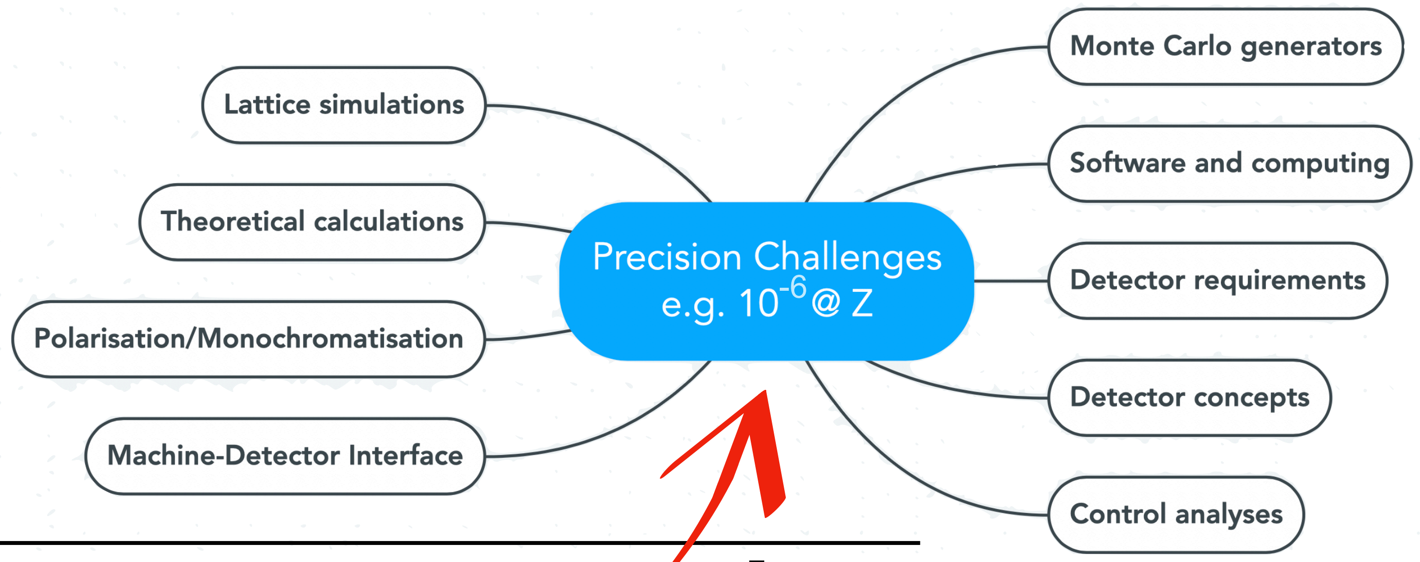

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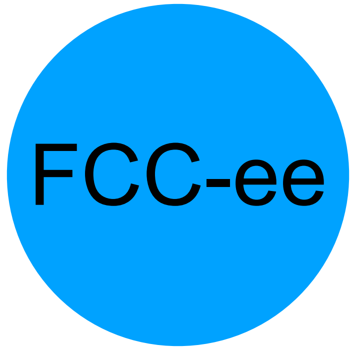
FCC-ee Run Plan

E_{CM}-related uncertainties on selected EWPOs
(E_{CM} determined by resonant spin depolarisation)

Uncertainty	Observable				
	m_Z [keV]	Γ_Z [keV]	$\sin^2\theta_W^{eff}$ [$\times 10^{-6}$]	$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)}$ [$\times 10^{-5}$]	m_W [keV]
Absolute	100	2.5	/	0.1	150
Point-to-point	14	11	1.2	0.5	50
Sample size	1	1	0.1	/	3
Energy spread	/	5	/	0.1	/
Total $\sqrt{s}$ related	101	12	1.2	0.5	158
FCC-ee statistical	4	4	2	3	180

For these observables, dominant experimental uncertainty now probably comes from the luminosity
Need to also control theoretical uncertainties to the same level!

FCC-ee Physics Programme



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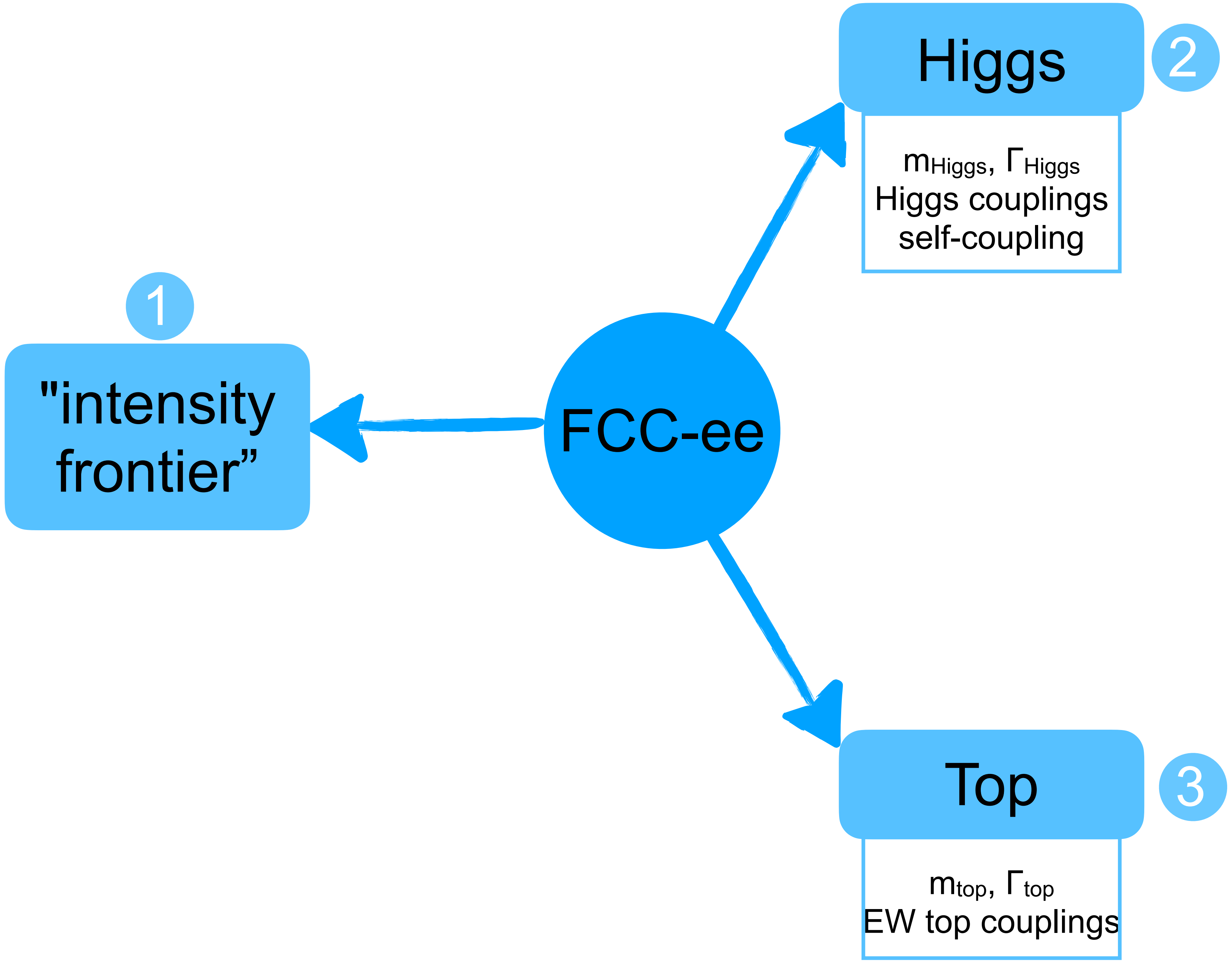

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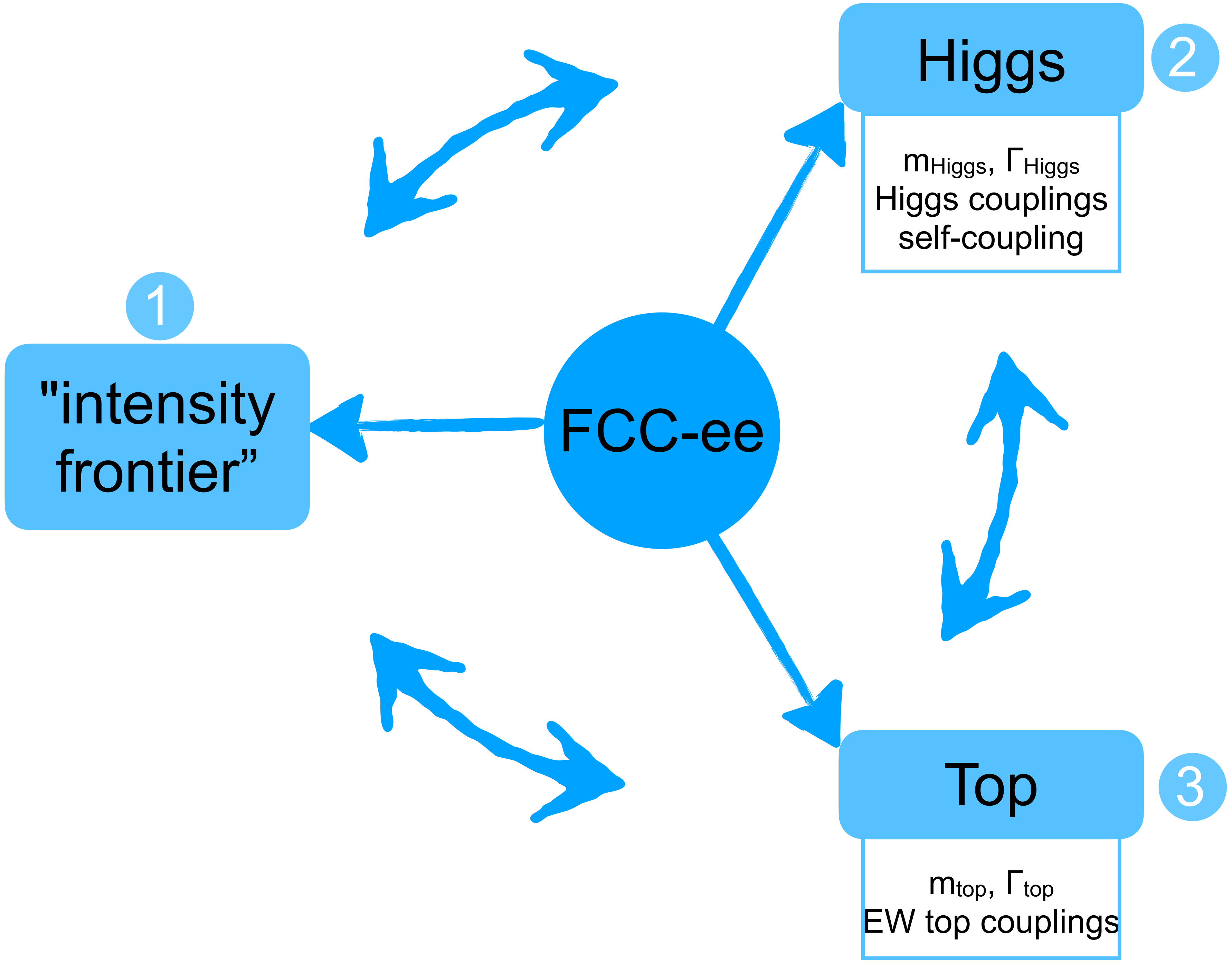

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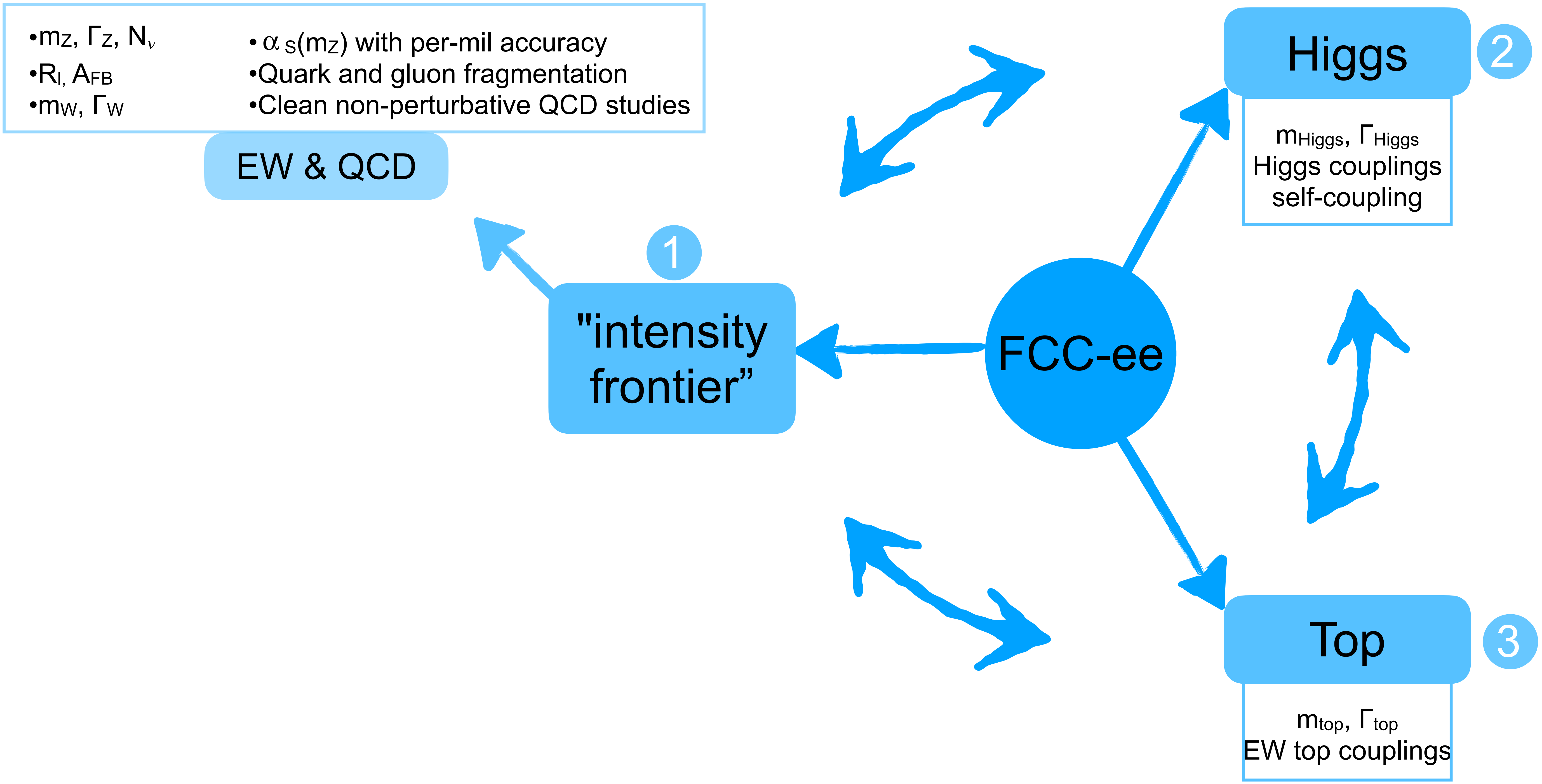

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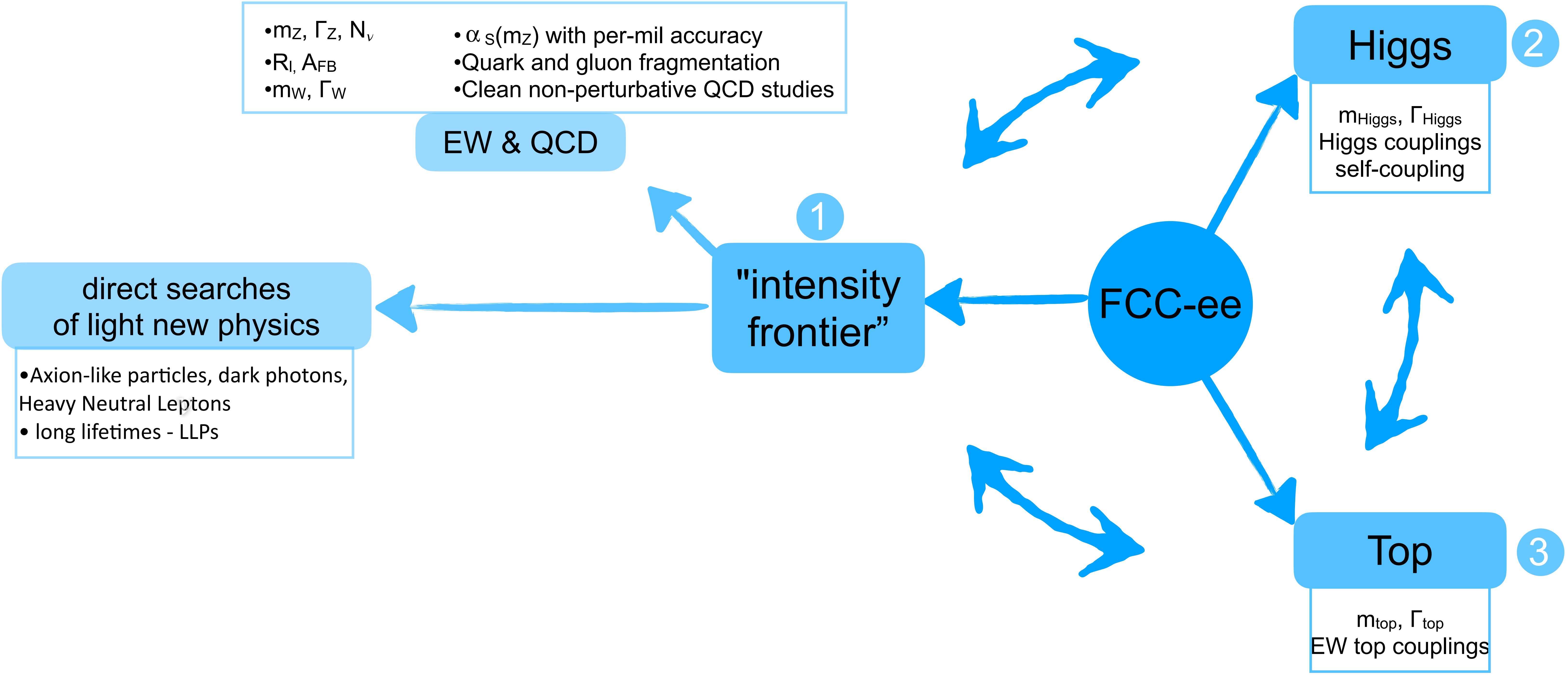

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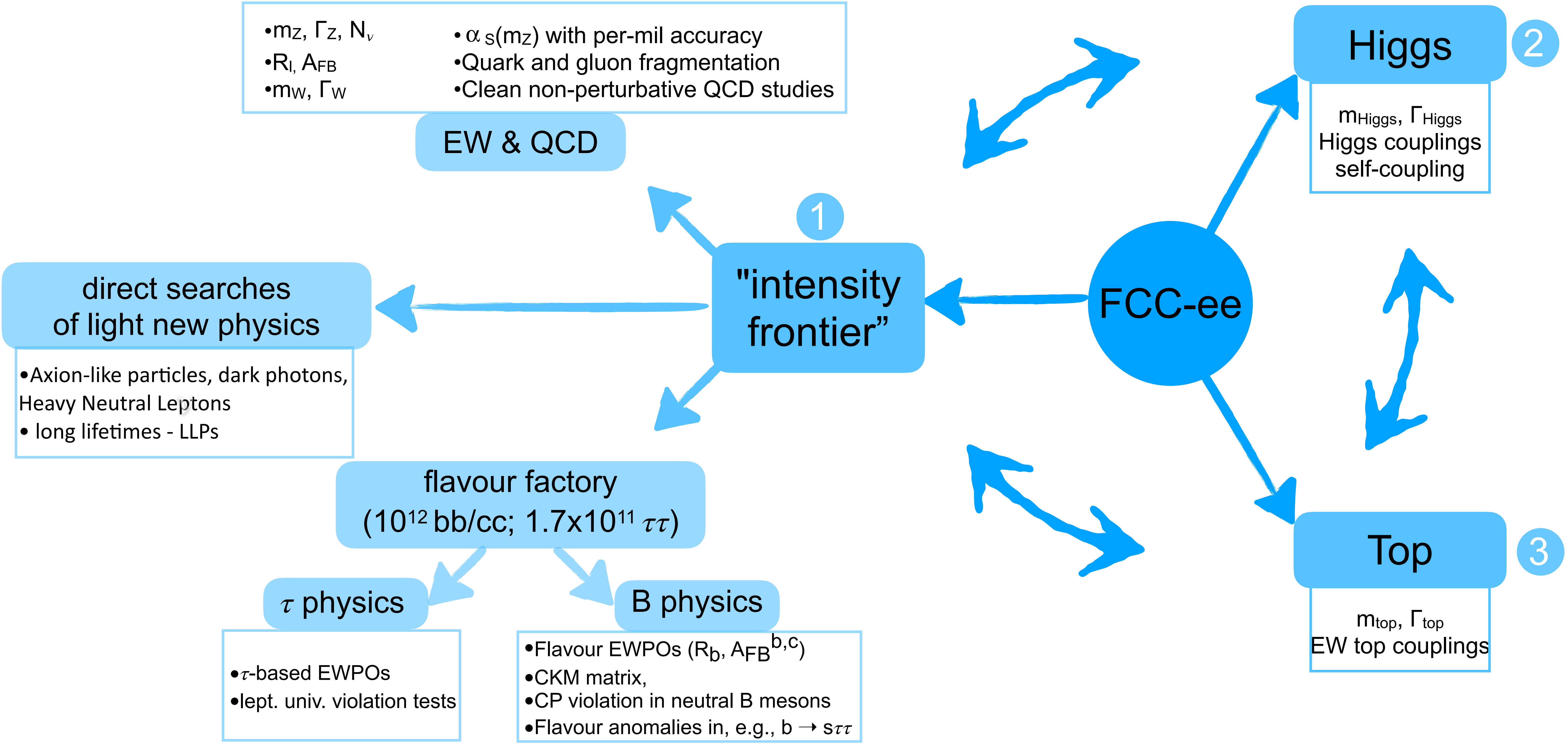

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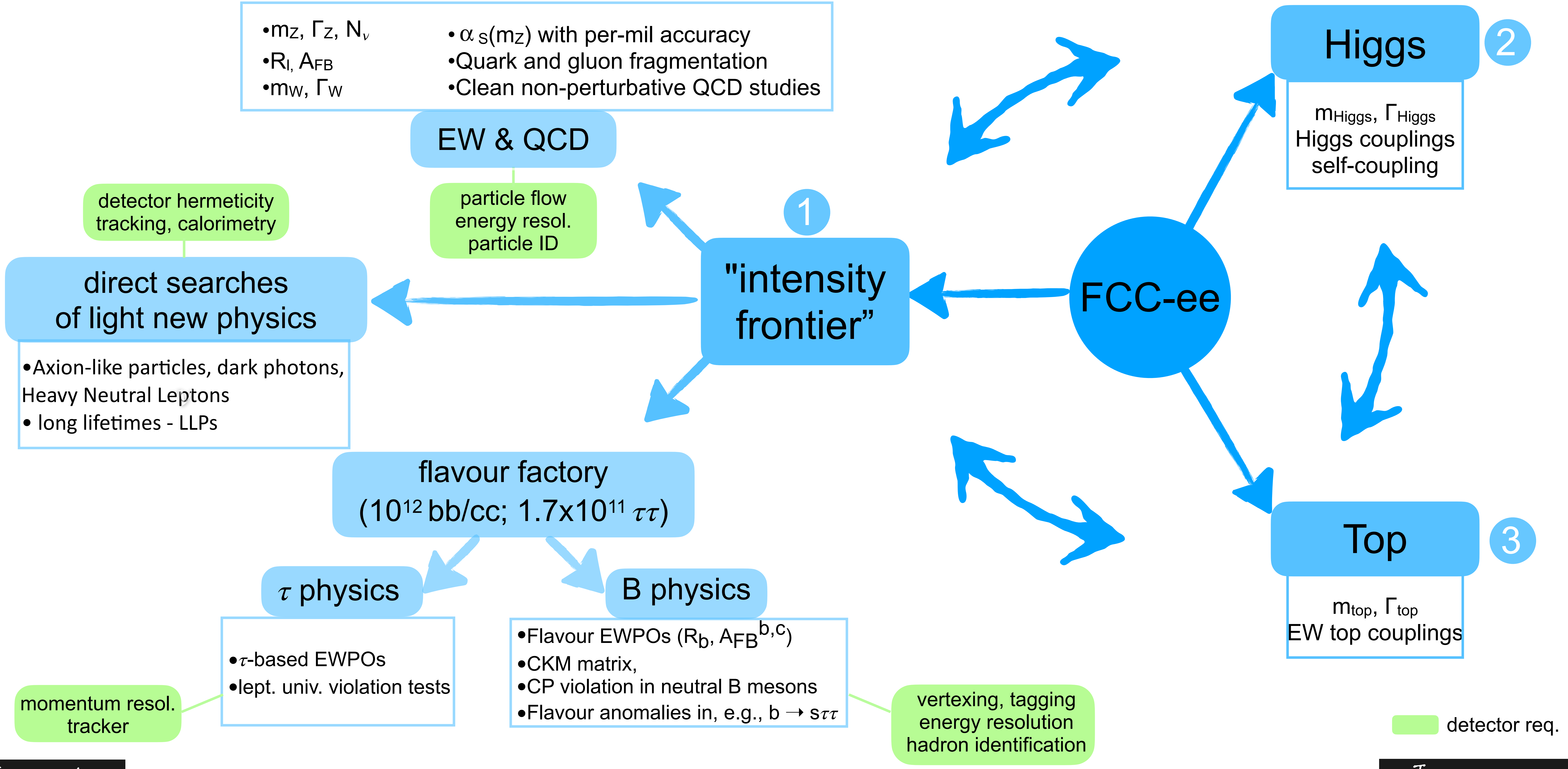


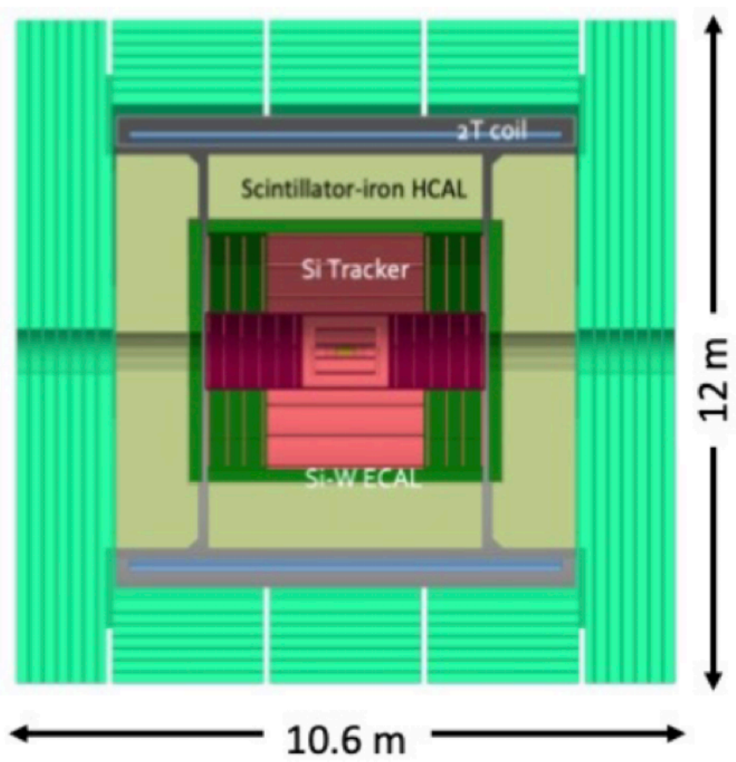
FCC-ee Physics Programme

Summary of detector requirements

		Aggressive	Conservative	Comments
Beam-pipe		$\frac{X}{X_0} < 0.5\%$	$\frac{X}{X_0} < 1\%$	$B \to K^*\tau\tau$
Vertex		$\sigma(d_0) = 3 \oplus 15\,/\,(p\sin^{3/2}\theta)$ µm $\frac{X}{X_0} < 1\%$	–	$B \to K^*\tau\tau$ R_c
		$\delta L = 5$ ppm	–	$\delta\tau_\tau < 10$ ppm
Tracking		$\frac{\sigma_p}{p} < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\frac{\sigma_p}{p} < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4$ MeV $\delta\Gamma_Z = 15$ keV $Z \to \tau\mu$
		t.b.d.	$\sigma_\theta < 0.1$ mrad	$\delta\Gamma_Z(\mathrm{BES}) < 10$ keV
ECAL		$\frac{\sigma_E}{E} = \frac{3\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}}$	$Z \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
		$\Delta x \times \Delta y = 2 \times 2$ mm^2	$\Delta x \times \Delta y = 5 \times 5$ mm^2	τ polarization boosted π^0 decays bremsstrahlung recovery
		$\delta z = 100$ µm, $\delta R_{\min} = 10$ µm ($\theta = 20°$)	–	alignment tolerance for $\delta\mathcal{L} = 10^{-4}$ with $\gamma\gamma$ events
HCAL		$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$	$H \to s\bar{s}$, $c\bar{c}$, gg, invisible HNLs
		$\Delta x \times \Delta y = 2 \times 2$ mm^2	$\Delta x \times \Delta y = 20 \times 20$ mm^2	$H \to s\bar{s}$, $c\bar{c}$, gg
Muons		low momentum ($p < 1$ GeV) ID	–	$B_s \to \nu\bar{\nu}$
Particle ID		3σ K/π $p < 40$ GeV	3σ K/π $p < 30$ GeV	$H \to s\bar{s}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal		tolerance $\delta z = 100$ µm, $\delta R_{\min} = 1$ µm acceptance 50-100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance		100 mrad	–	$e^+e^- \to \gamma\gamma$ $e^+e^- \to e^+e^-\tau^+\tau^-(c\bar{c})$

FCC-ee Physics Programme

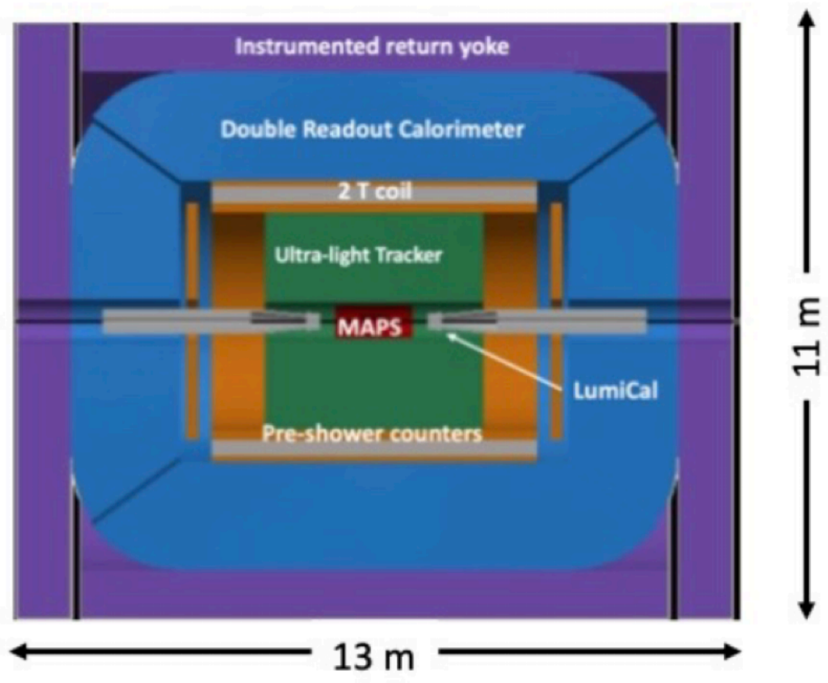
CLD



Based on CLIC detector design, arXiv:1911.12230

Full silicon vertex detector and tracker
3D-imaging highly-granular calorimeter system
Coil outside calorimeter system

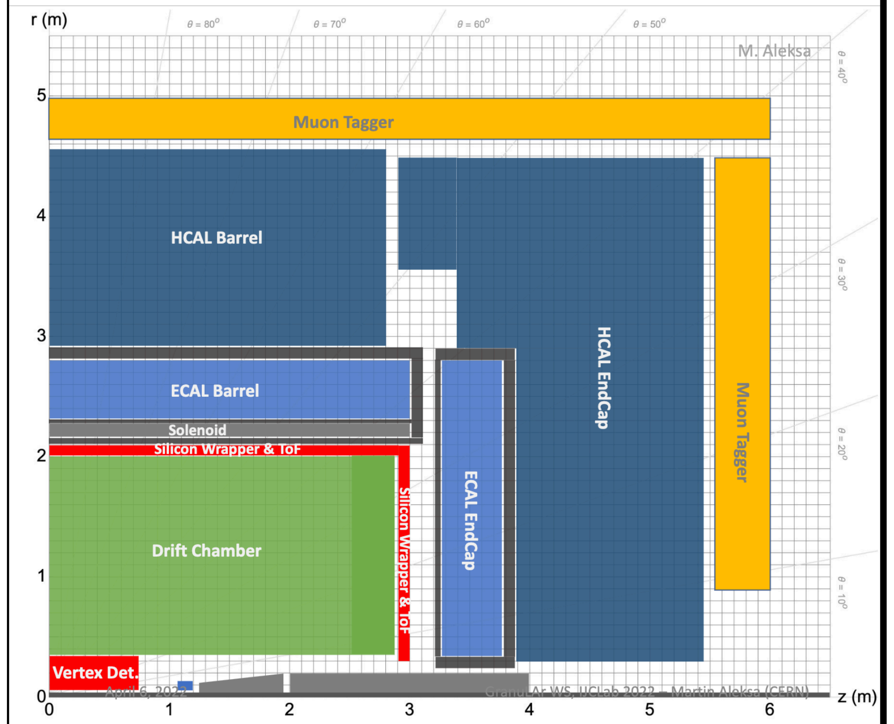
IDEA



Innovative, possibly cheaper than CLD
https://pos.sissa.it/390/819
Baseline in many ongoing studies

Silicon vertex detector
Short-drift, ultra-light wire chamber
Dual-readout calorimeter
Thin and light solenoid coil inside calorimeter system

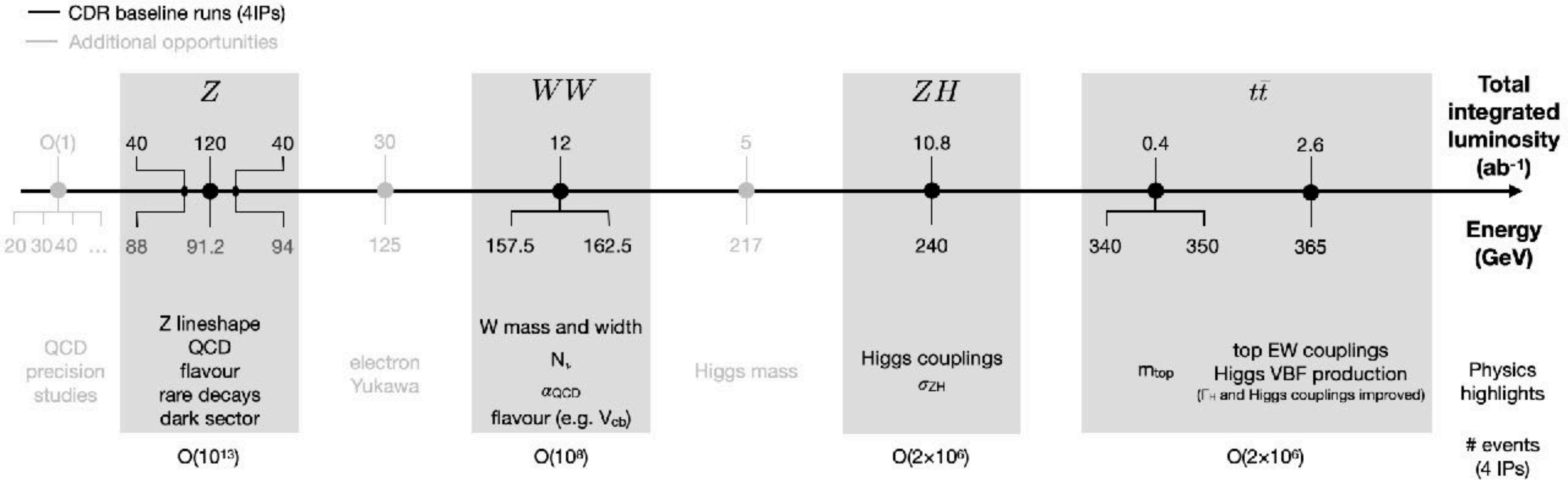
ALLEGRO



GranuLAr WS, IJCLab 2022 – Martin Aleksa

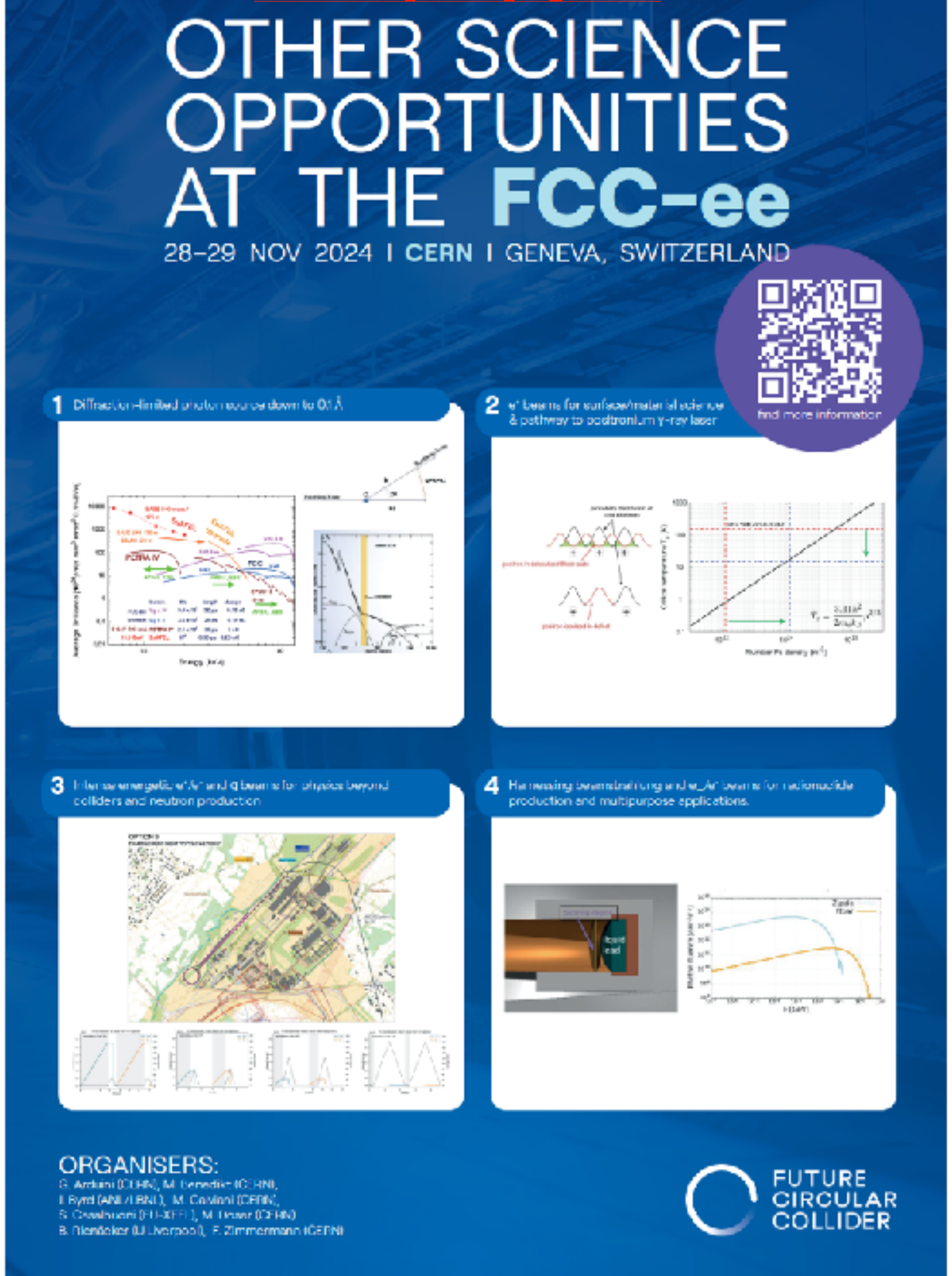
Highly granular noble-liquid calorimeter
Thin 2T solenoid in the calorimeter cryostat.

Collider Programme (and beyond).



- **Opportunities** beyond the baseline plan (√s below Z, 125GeV, 217GeV; larger integrated lumi…)
- **Opportunities** to exploit FCC facility differently (to be studied more carefully):
  - using the electrons from the injectors for beam-dump experiments,
  - extracting electron beams from the booster,
  - reusing the synchrotron radiation photons.

[workshop webpage link]



photon science
(light source,
Compton Backscattering sources)

HEP applications
(strong QED, dark sector)

e^+ applications
(surface science,
Ps Bose-Einstein Condensate,
511 keV X-ray laser)

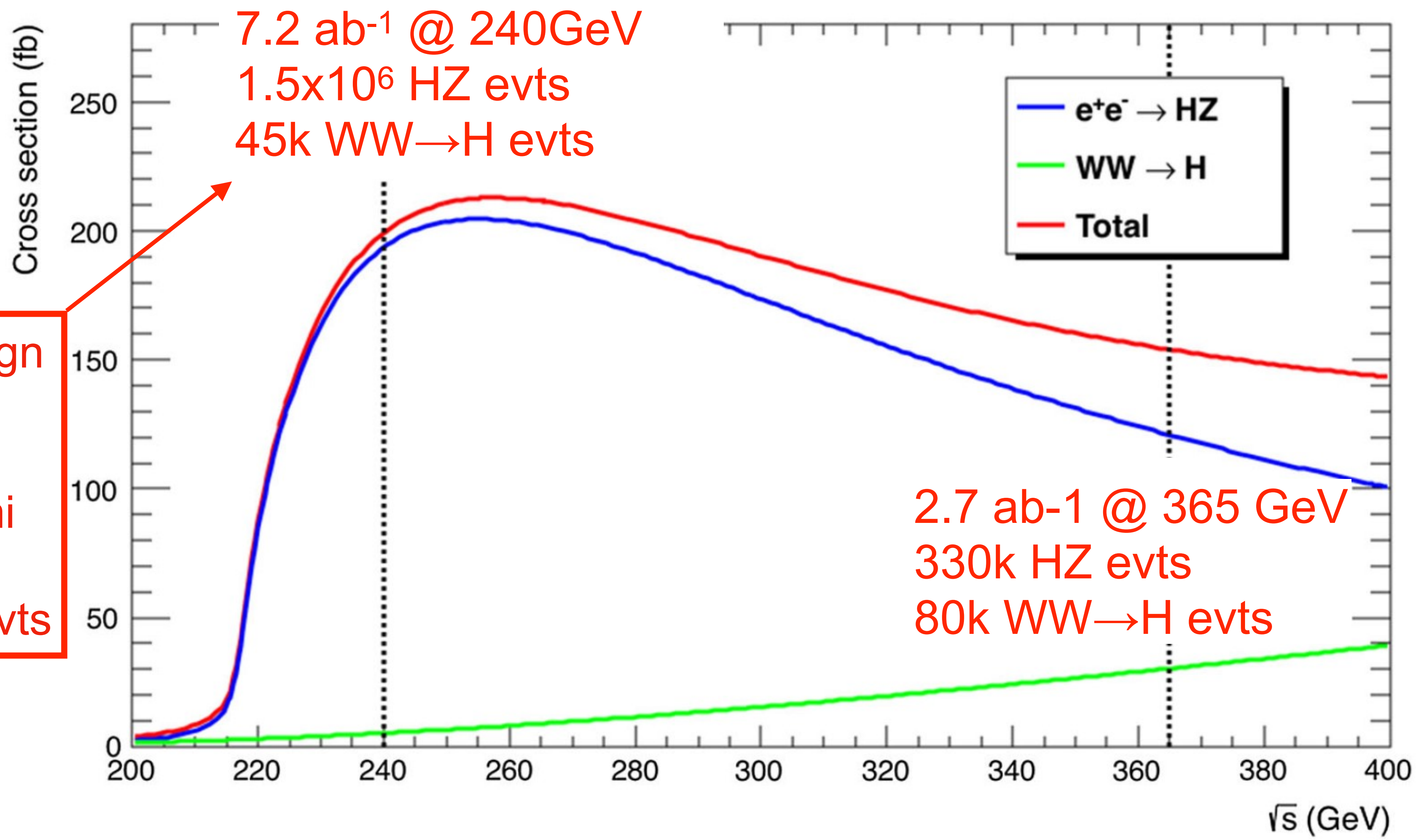
multipurpose applications of the e^-/e^+ beams
(radionuclide production,
neutron source)

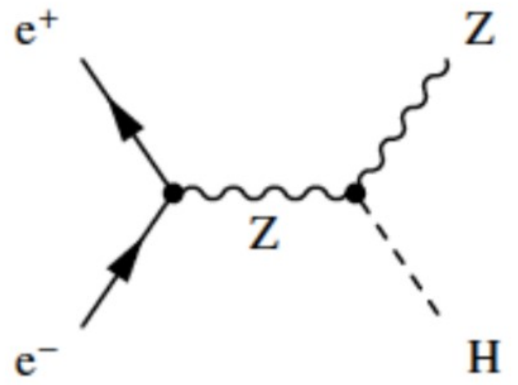
Higgs Factory

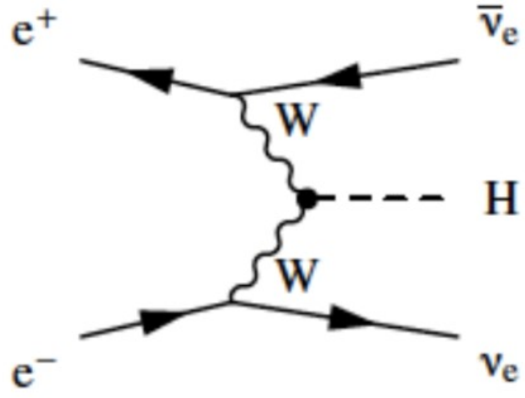
Higgs @ FCC-ee.

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

new optics design (May 2024) gives 50% more lumi @ 240 GeV ⇒ 2.5×10^{6} HZ evts







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

Complementarity with 365GeV on top of 240GeV improvement factor: ∞/3/2/1.5/1.2 on $\kappa_\lambda / \kappa_W / \kappa_b / \kappa_g, \kappa_c / \kappa_\gamma$ (plot in bonus)

Higgs @ FCC-ee.

- Absolute normalisation of couplings (by recoil method). The LHC fit doesn't converge w/o making any assumption.
- Measurement of width (from ZH>ZZZ* and WW>H)
- $\delta\Gamma_H \sim 1\%, \delta m_H \sim 3\,\mathrm{MeV}$ (resp. 25%, O(20) MeV @ HL-LHC)
- Model-independent coupling determination and improvement factor up to 10 compared to LHC
- (Indirect) sensitivity to new physics up to 70-100 TeV (for maximally strongly coupled models)
  $(\delta\kappa_X = v^2/f^2 \quad \& \quad m_{\mathrm{NP}} = g_{\mathrm{NP}} f)$
- Unique access to electron Yukawa

Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

Table from mid-term report
(new luminosity at 240GeV will further improve the coupling reach, e.g. 0.11% for κZ)

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

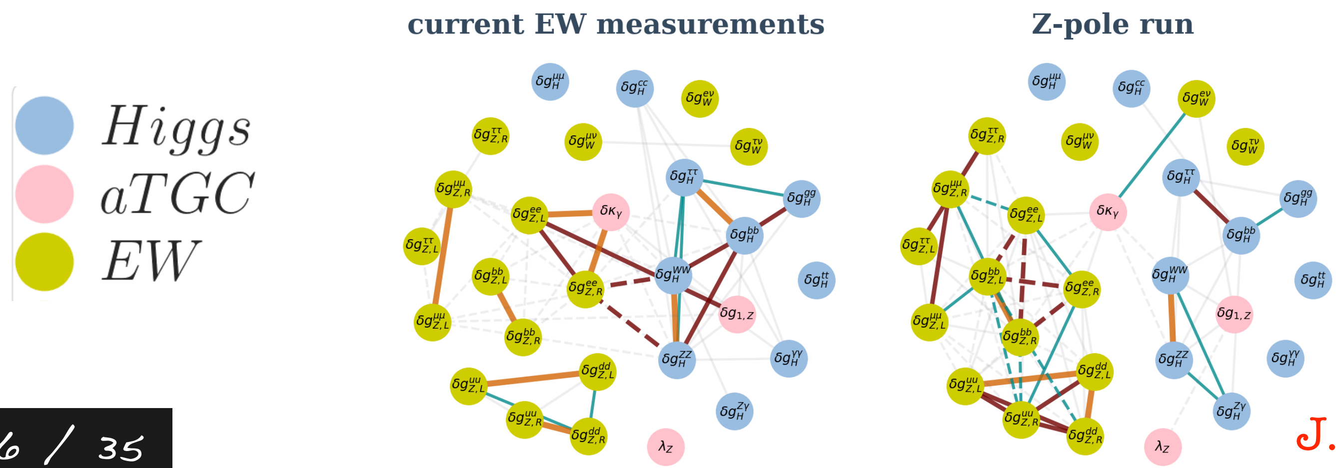
Higgs @ FCC-ee.

- Absolute normalisation of couplings (by recoil method). The LHC fit doesn't converge w/o making any assumption.
- Measurement of width (from ZH>ZZZ* and WW>H)
- $\delta\Gamma_H \sim 1\%, \delta m_H \sim 3\,\mathrm{MeV}$ (resp. 25%, O(20) MeV @ HL-LHC)
- Model-independent coupling determination and improvement factor up to 10 compared to LHC
- (Indirect) sensitivity to new physics up to 70-100 TeV (for maximally strongly coupled models)

$$(\delta\kappa_X = v^2/f^2 \quad \& \quad m_{\mathrm{NP}} = g_{\mathrm{NP}} f)$$

- Unique access to electron Yukawa

— Higgs programme needs Z-pole —



J. De Blas et al. 1907.04311

Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
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Table from mid-term report (new luminosity at 240GeV will further improve the coupling reach, e.g. 0.11% for κZ)

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

Higgs @ FCC-ee.

The fastest, greenest, cheapest way to Higgs precision

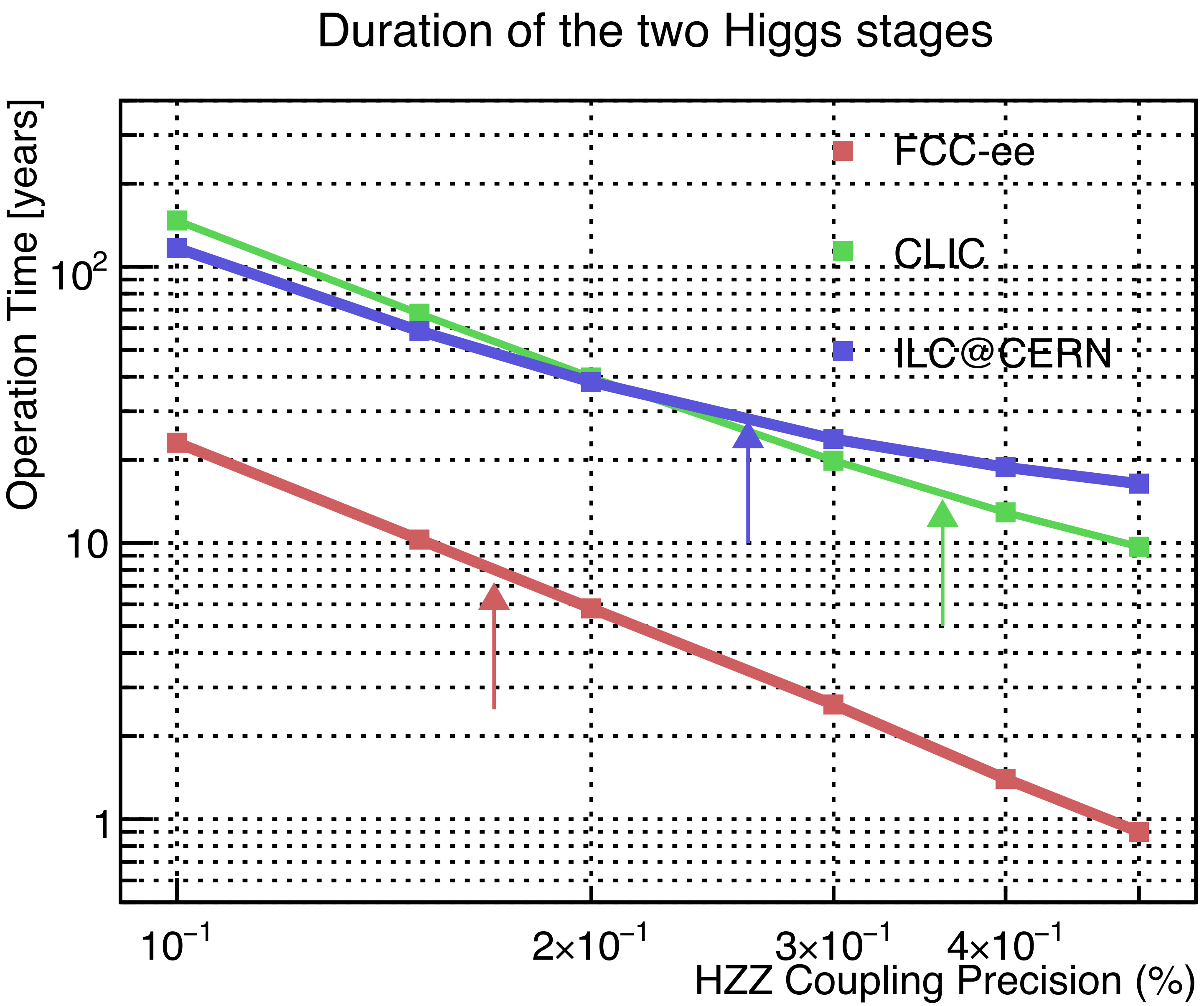


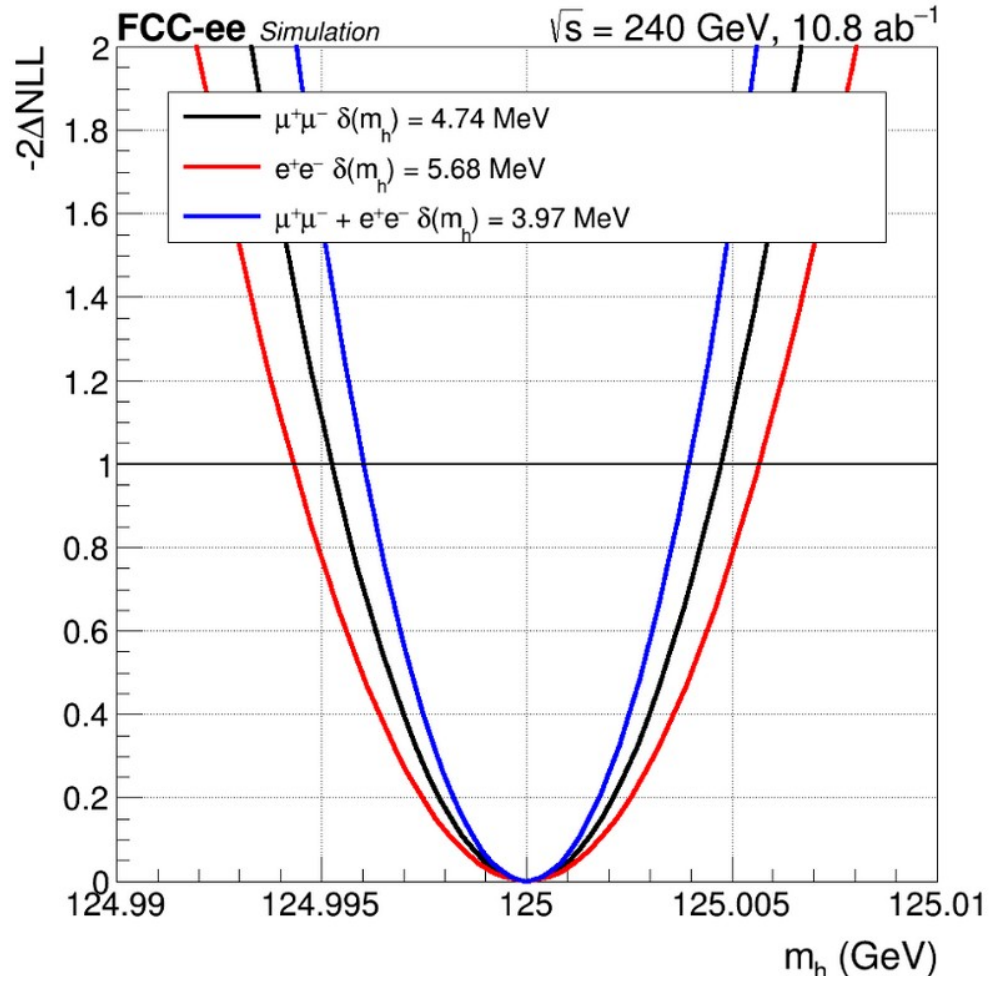
Table 7: Time needed for $CLIC_{380+1500}$ and for $ILC_{250+500}$ @CERN to deliver the integrated luminosity needed to reach the same precision as $FCC\text{-}ee_{240+365}$ in eight years, for selected couplings. The last row indicates the total energy consumption for the average 46 years of operation. (The CLIC duration for the coupling to the b seems off, probably because of rounding errors after/before the fit in Ref. [11], but is conservatively included in the average.)

Duration (years)	$FCC\text{-}ee_{240+365}$	$CLIC_{380+1500}$	$ILC_{250+500}$
b	8	26	43
c	8	50	41
τ	8	54	47
Z	8	54	49
W	8	56	49
Average duration (years)	8	48	46
Electricity consumption (TWh)	13	55	41

Blondel et al 2412.13130

Higgs Mass

- Recoil mass in Z(ll)H events (l=e,μ)
- Thorough study of detector design impact
  - Larger variations from track resolution
  - High field & lighter tracker beneficial



Robust prospects to reach and even go below the natural 4.1 MeV limit set by the SM Higgs width

Nominal configuration → Nominal

Crystal ECAL to Dual Readout → Degradation electron resolution

Nominal 2 T → field 3 T → Magnetic field 3T

IDEA drift chamber → CLD Si tracker → Silicon tracker

Impact of Beam Energy Spread → BES 6% uncertainty, Disable BES

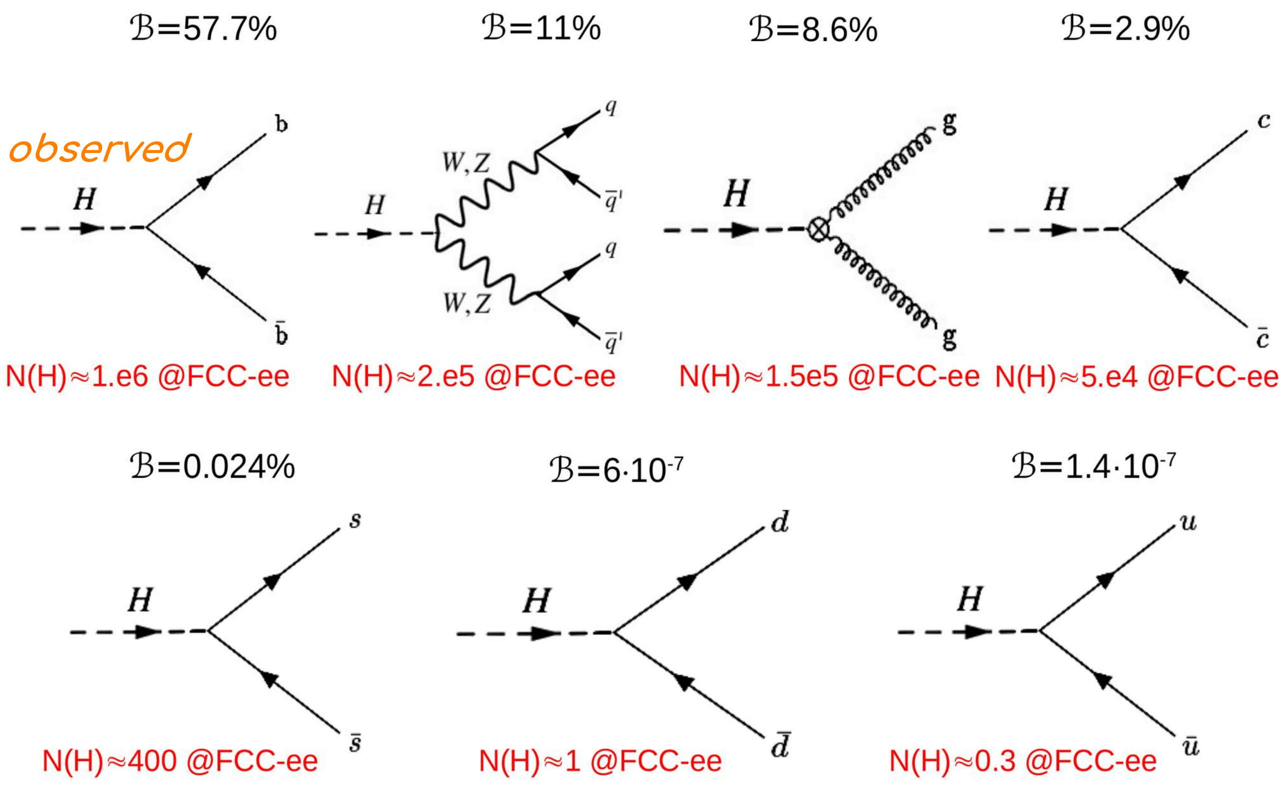
Perfect (=gen-level) momentum resolution → Ideal resolution

Final state	Muon 240 GeV	Electron 240 GeV	Combination 240 GeV
Nominal	3.92(4.74)	4.95(5.68)	3.07(3.97)
Inclusive	3.92(4.74)	4.95(5.68)	3.10(3.97)
Degradation electron resolution	3.92(4.74)	5.79(6.33)	3.24(4.12)
Magnetic field 3T	3.22(4.14)	4.11(4.83)	2.54(3.52)
Silicon tracker	5.11(5.73)	5.89(6.42)	3.86(4.55)
BES 6% uncertainty	3.92(4.79)	4.95(5.92)	3.07(3.98)
Disable BES	2.11(3.31)	2.93(3.88)	1.71(2.92)
Ideal resolution	3.12(3.95)	3.58(4.52)	2.42(3.40)
Freeze backgrounds	3.91(4.74)	4.95(5.67)	3.07(3.96)
Remove backgrounds	3.08(4.13)	3.51(4.58)	2.31(3.45)

Hadronic Decays

- 80% of the Higgs decays are fully hadronic
  - challenging for LHC
  - good prospects for FCC-ee thanks to clean environment and optimised tagging algorithms

	δ(σ×BR) [%]			
	Z(ll)H	Z(νν)H	Z(qq)H	Comb.
$H \to bb$	0.7	0.4	0.3	0.22
$H \to cc$	4.1	2.2	3.3	1.7
$H \to ss$	230	150	440	120
$H \to gg$	2.2	1.1	3.1	0.9



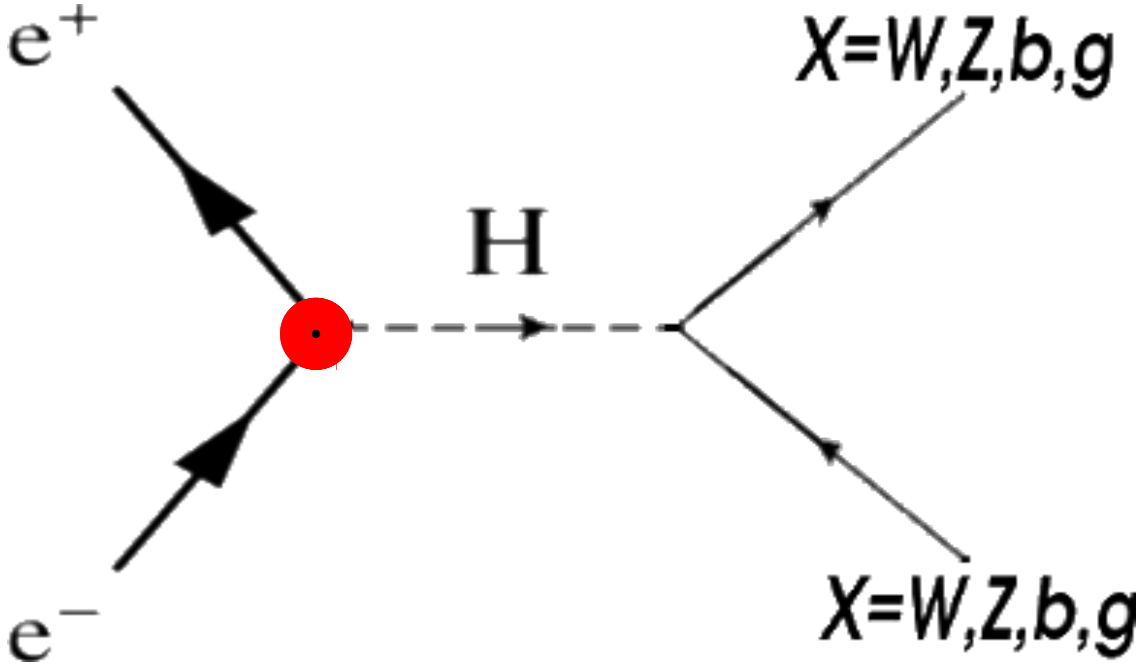
Solid measurements in 2nd generation

Interesting prospects for 1st generation and FCNC decays

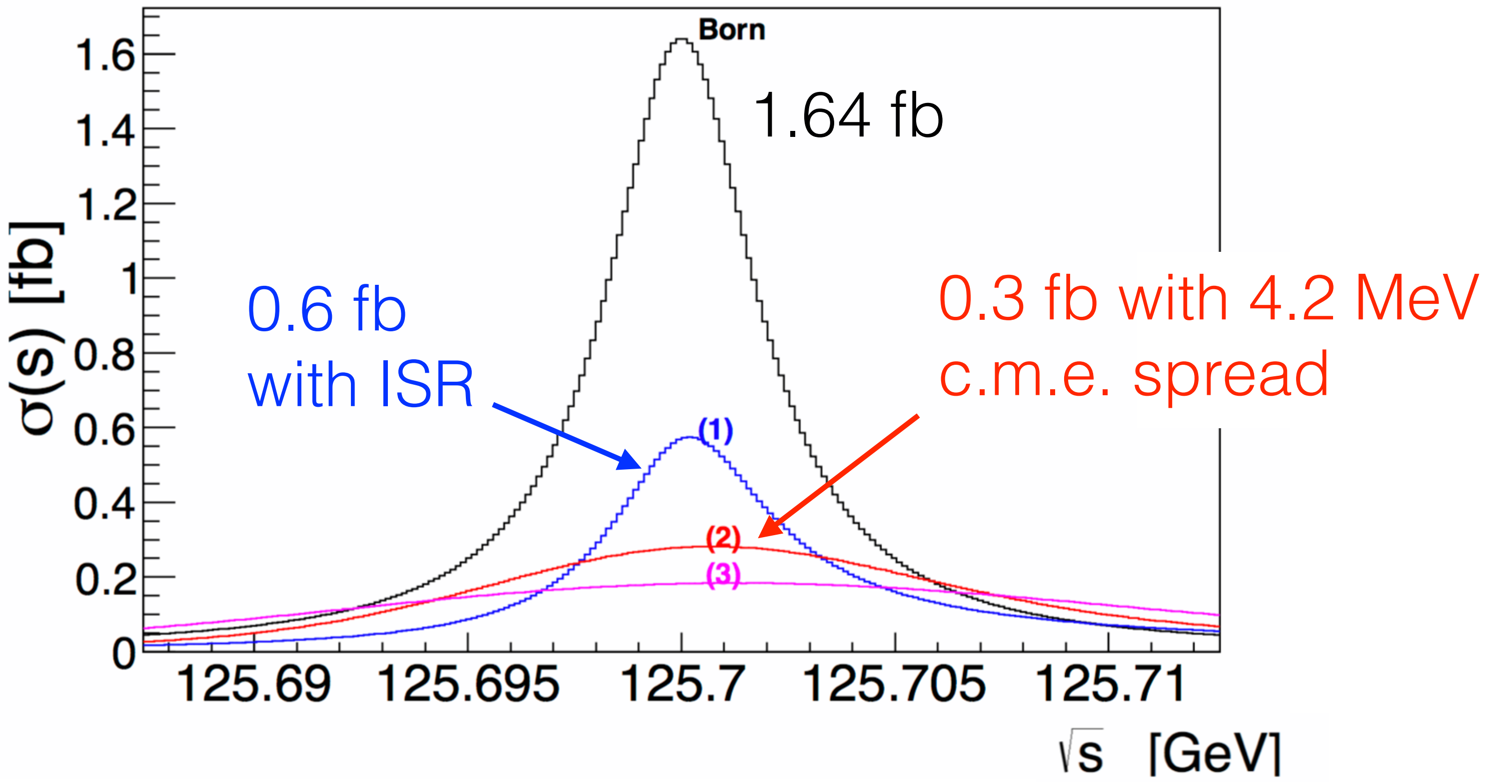
	σ×BR 95% CL	BR(SM)
$H \to dd$	1.4e-03	6e-07
$H \to uu$	1.5e-03	1.4e-07
$H \to bs$	3.7e-04	e-07
$H \to bd$	2.7e-04	e-09
$H \to sd$	7.7e-04	e-11
$H \to cu$	2.5e-04	e-20

Electron Yukawa

The high luminosity, the precise control of the beam √s, the clean reconstruction of final states make it possible to observe:



Jadach+, arXiv: 1509.02406



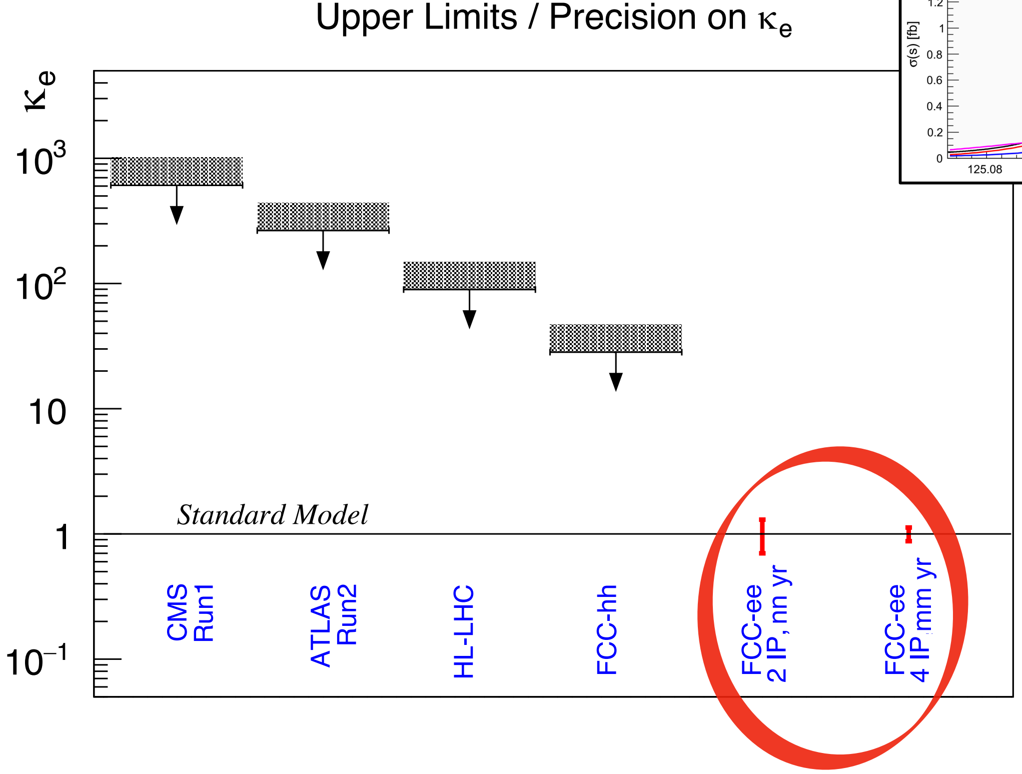
$\sigma(e^+e^-\to H) = 1.64$ fb

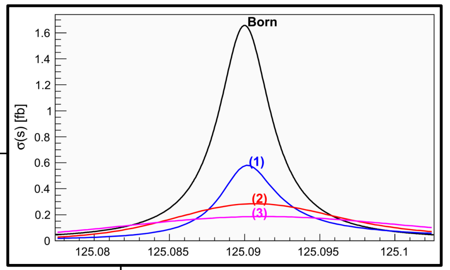
$\sigma_{spread+ISR}(e^+e^-\to H)=0.17\times\sigma(e^+e^-\to H)=290$ ab

Electron Yukawa

The high luminosity, the precise control of the beam √s, the clean reconstruction of final states make it possible to observe:

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





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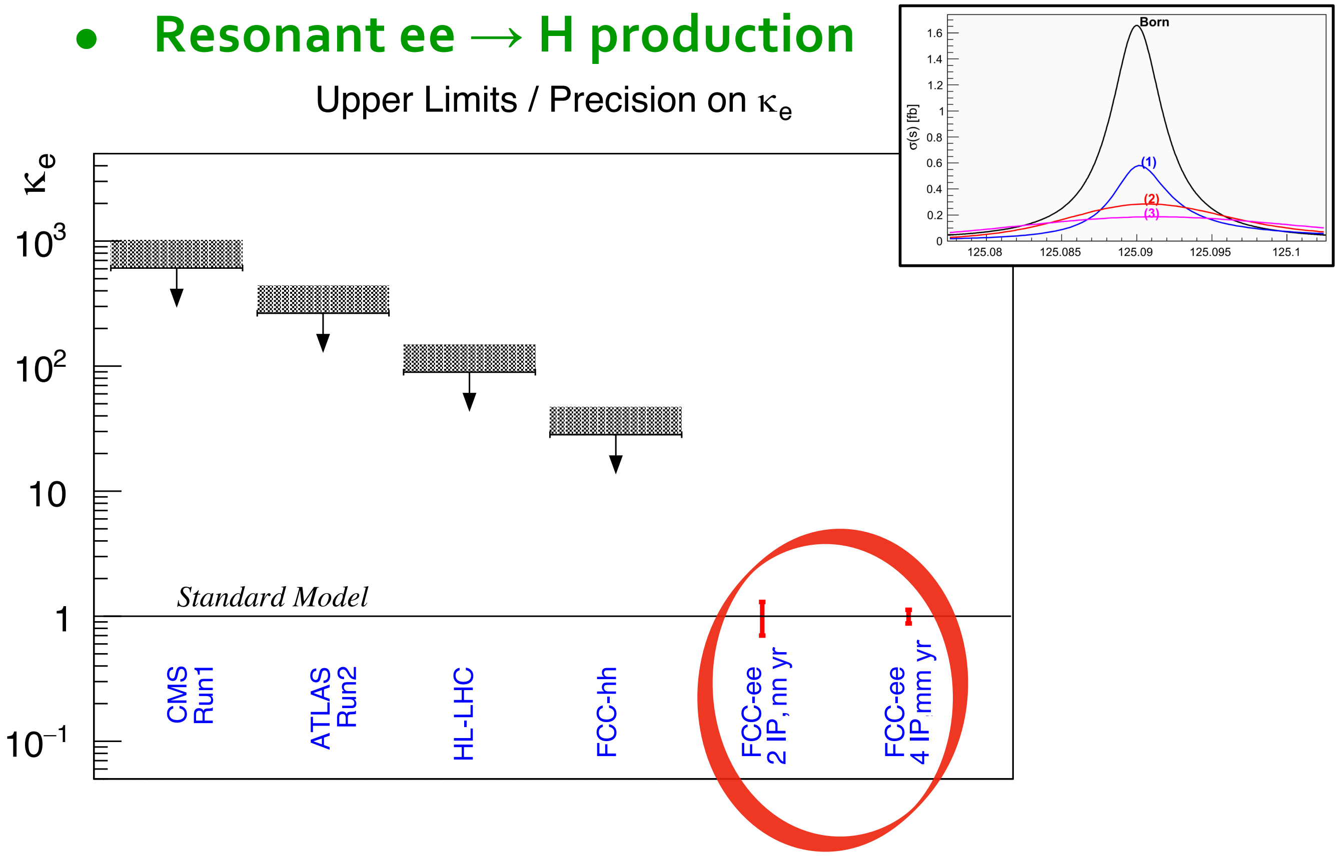
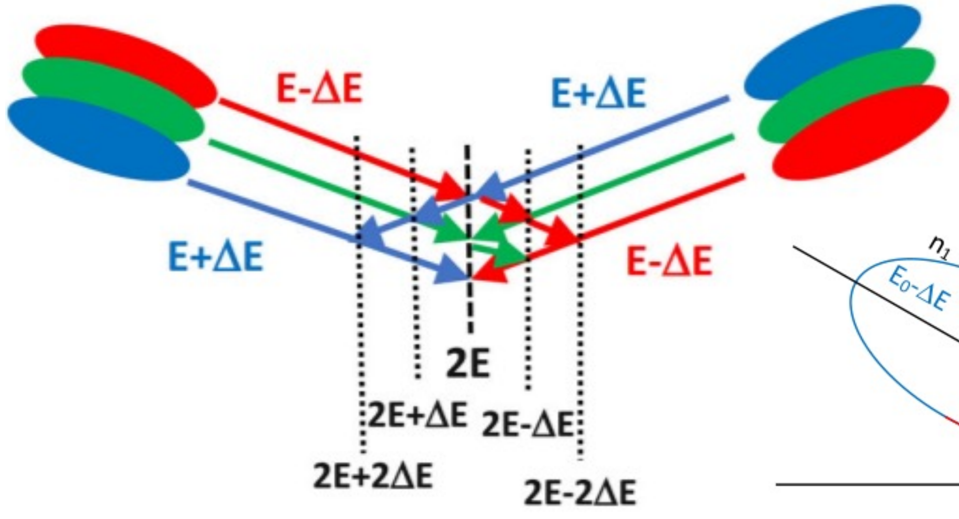


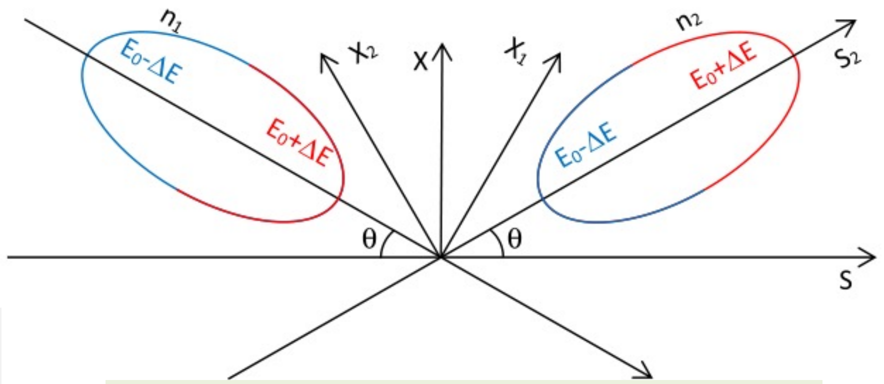
Monochromatisation

Monochromatization: **UNDER STUDY**
taking advantage of the separate e+ and e- rings, one can distribute in opposite way high and low energies in the beam (in x, z time)

combine?



opposite sign horizontal dispersion



opposite difference in arrival time

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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	$\mathcal{O}(10^{-3})$
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$e^+e^- \to H \to ZZ^* \to 2\ell\, 2j$	2.6%×70%×10%×2	1 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2j$	136 ab	$\mathcal{O}(10^{-2})$
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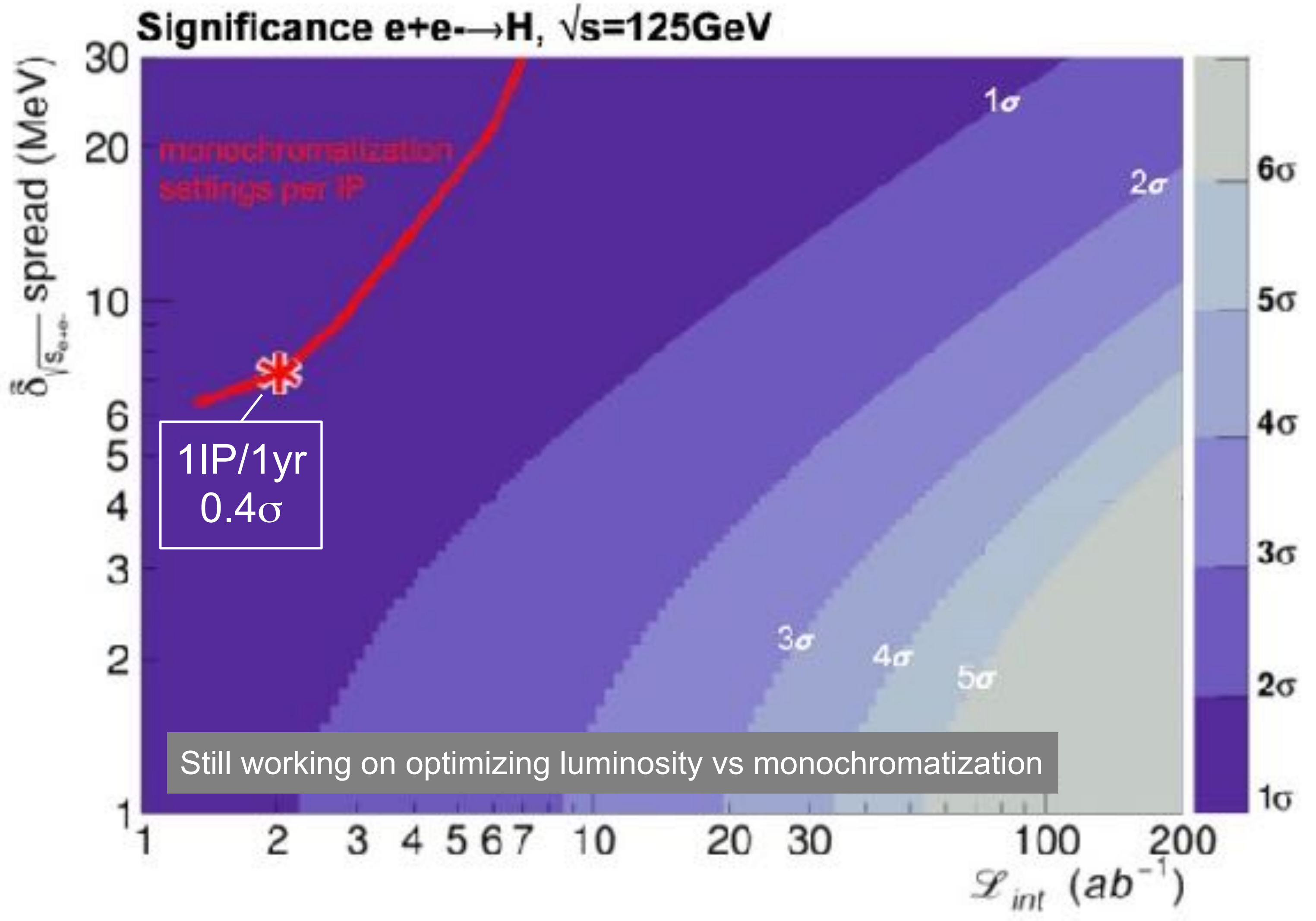
w. 10/ab

$H \to gg$	$H \to WW^* \to \ell\nu\, 2j;\ 2\ell\, 2\nu;\ 4j$	$H \to ZZ^* \to 2j\, 2\nu;\ 2\ell\, 2j;\ 2\ell\, 2\nu$	$H \to b\bar{b}$	$H \to \tau_{had}\tau_{had};\ c\bar{c};\ \gamma\gamma$	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



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w. 10/ab

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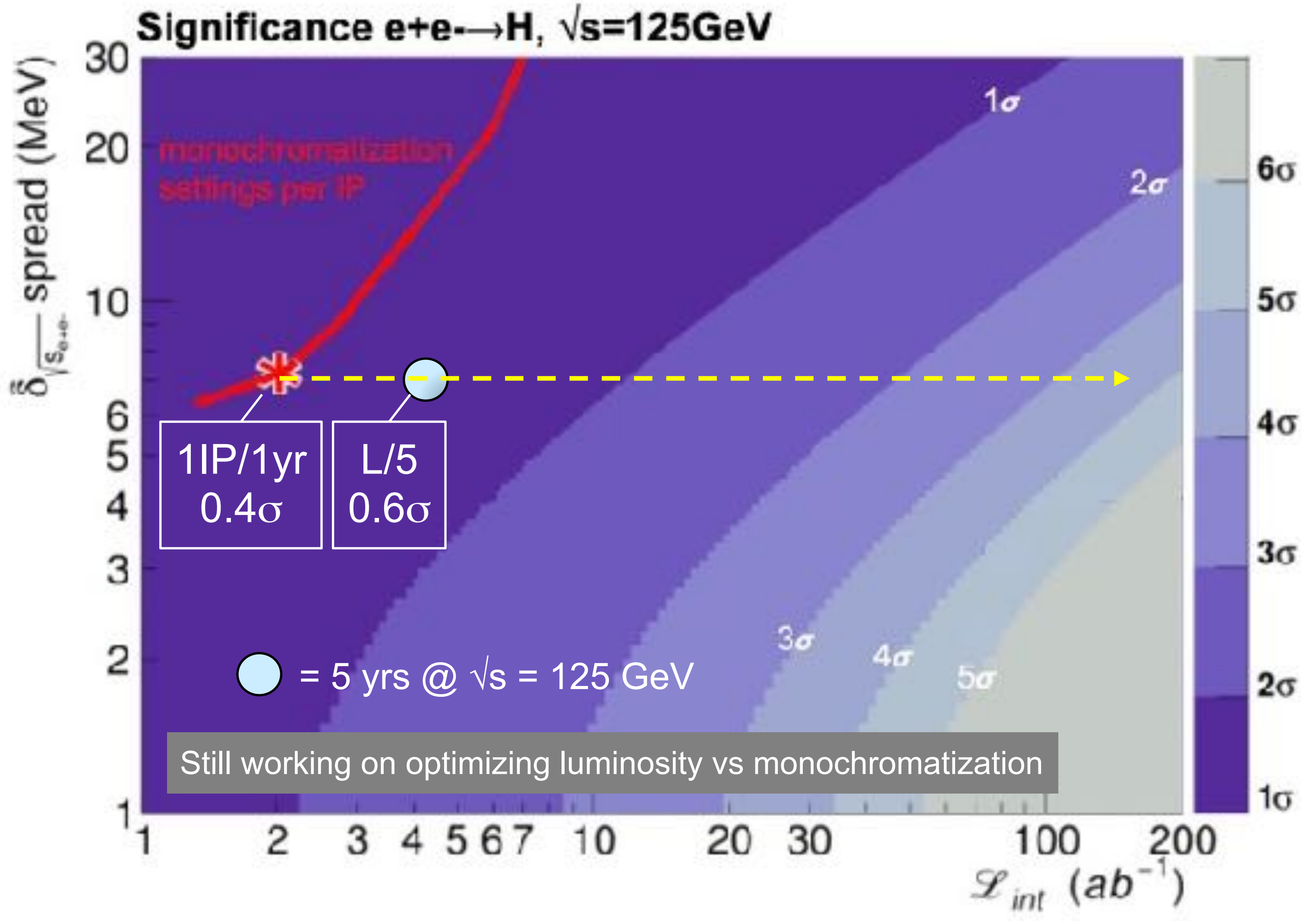

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w. 10/ab

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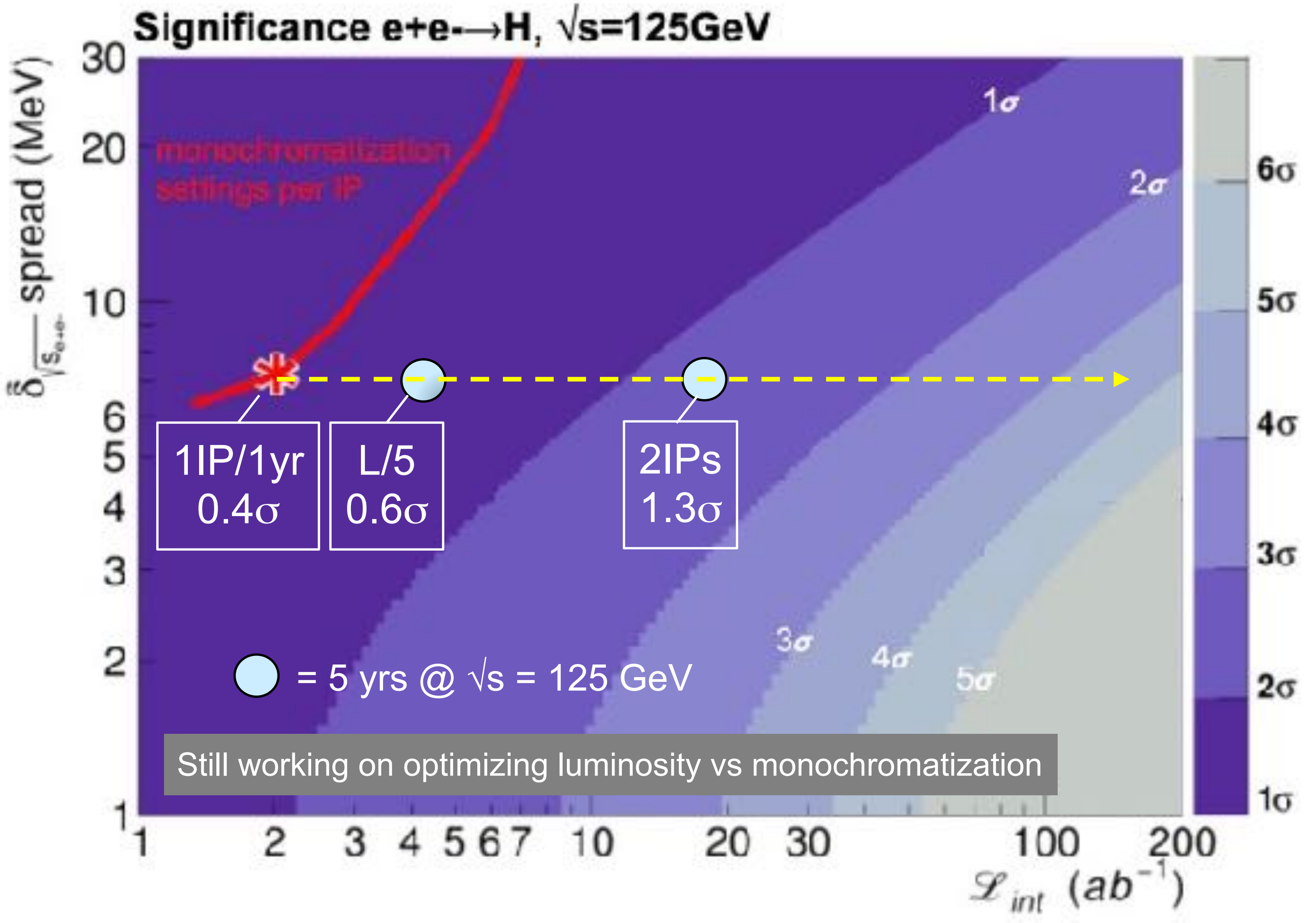

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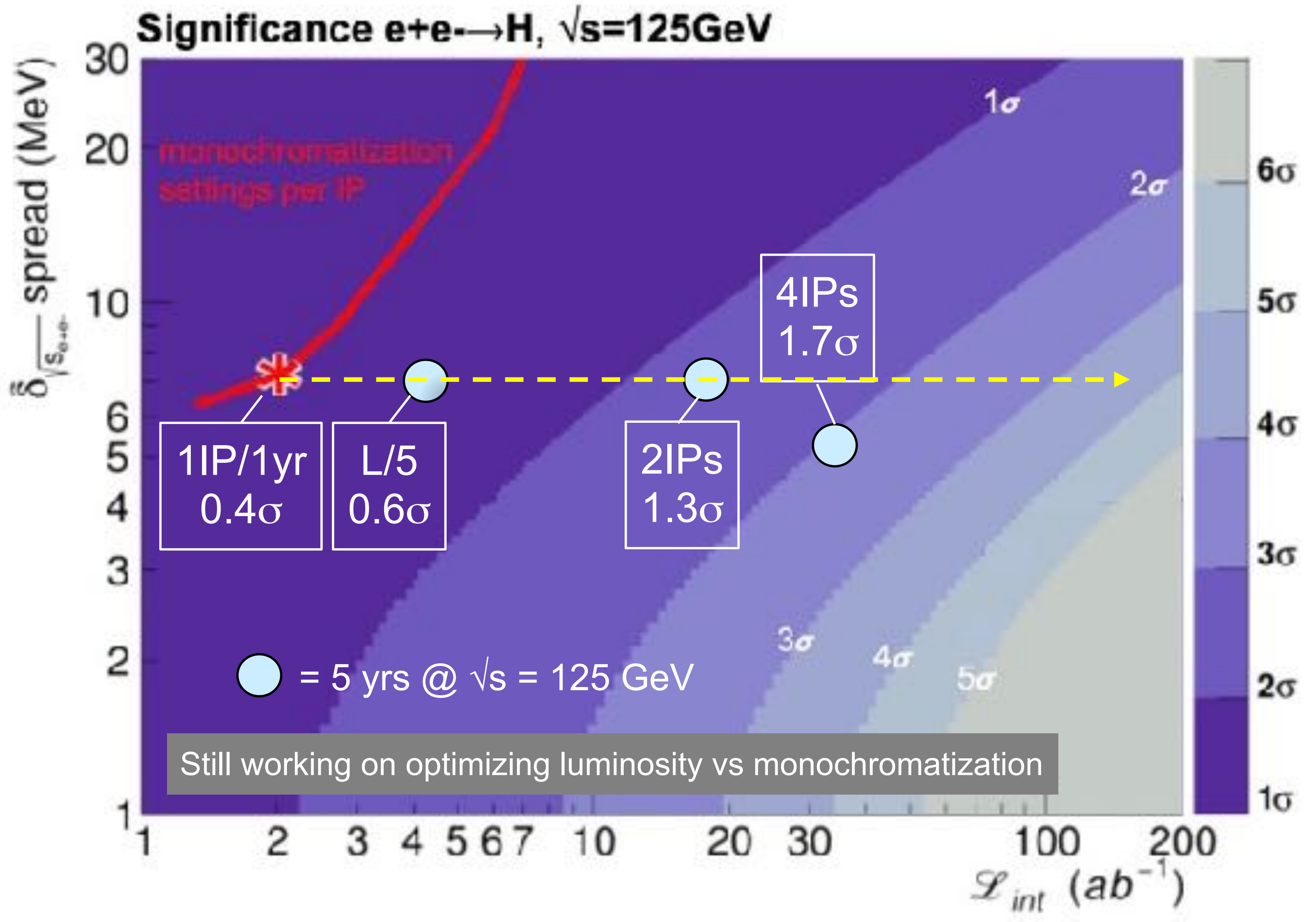
w. 10/ab

$H \to gg$	$H \to WW^* \to \ell\nu\, 2j;\ 2\ell\, 2\nu;\ 4j$	$H \to ZZ^* \to 2j\, 2\nu;\ 2\ell\, 2j;\ 2\ell\, 2\nu$	$H \to b\bar{b}$	$H \to \tau_{had}\tau_{had};\ c\bar{c};\ \gamma\gamma$	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



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- **Monochromatization $\sigma_{\sqrt{s}}$ ~ 1-2 × Γ_H ~ 6 to 10 MeV**

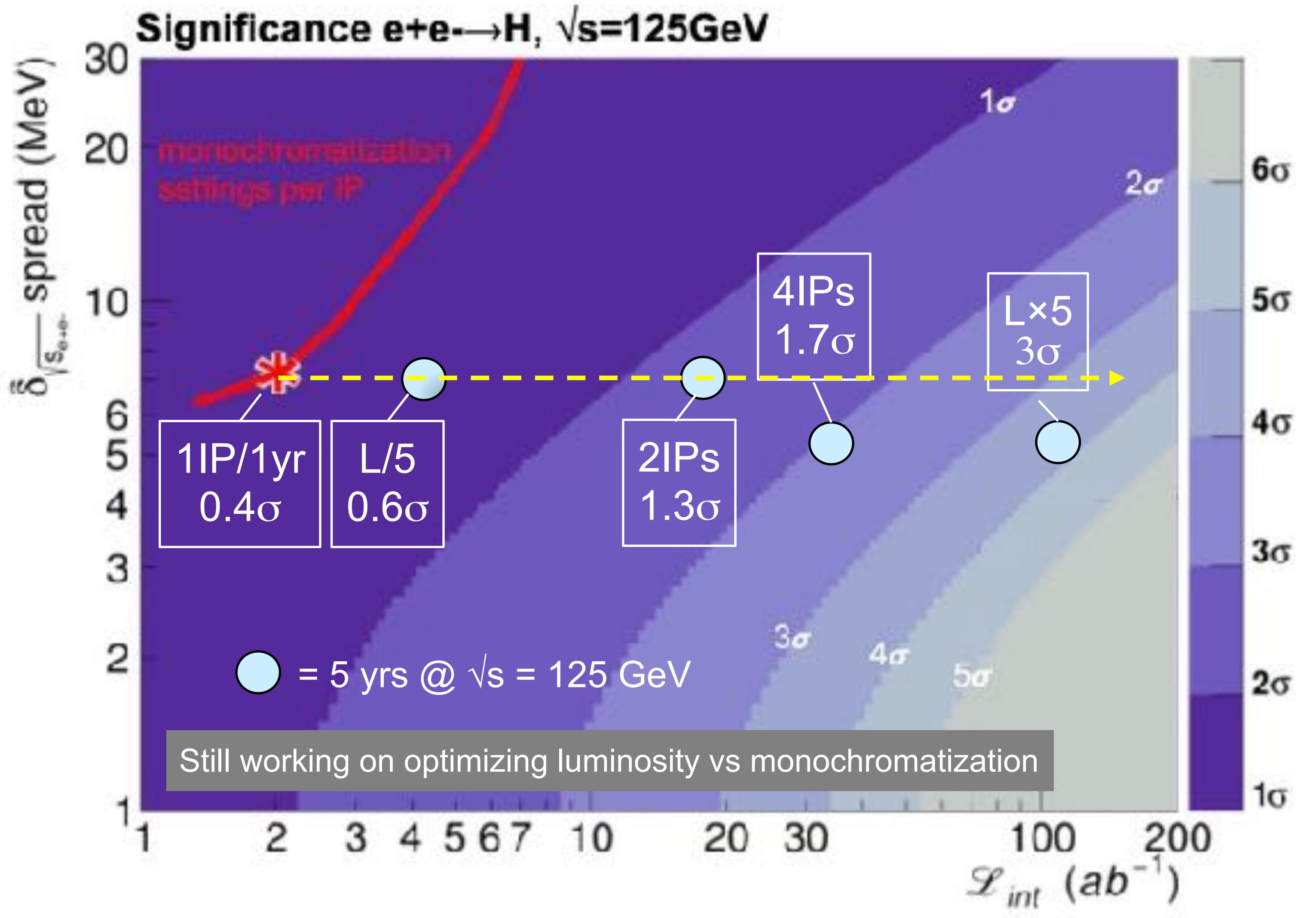
d'Enterria+. arXiv: 2107.02686

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

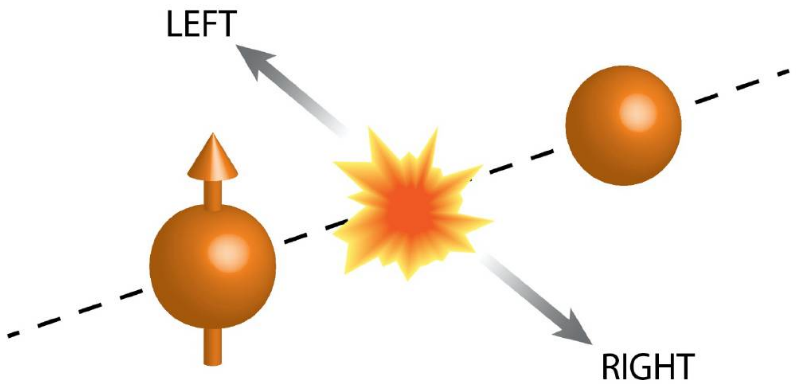
$H \to gg$	$H \to WW^* \to \ell\nu\, 2j;\, 2\ell\, 2\nu;\, 4j$	$H \to ZZ^* \to 2j\, 2\nu;\, 2\ell\, 2j;\, 2\ell\, 2\nu$	$H \to b\bar{b}$	$H \to \tau_{had}\tau_{had};\, c\bar{c};\, \gamma\gamma$	Combined
1.1σ	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$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

w/ 10/ab: S~55, B~2400 → 1.1σ



Electron Yukawa

A recent pheno study (Boughezal et al 2407.12975) shows that transverse spin asymmetries can increase the sensitivity to the electron Yukawa



$$A = \frac{N}{D}$$

Electron polarized, positron unpolarized (SP^0):

$$N = \frac{1}{2}(\sigma^{+0} - \sigma^{-0})$$
$$D = \frac{1}{2}(\sigma^{+0} + \sigma^{-0})$$

Electron transversely polarized, positron longitudinally polarized (DP):

$$N = \frac{1}{4}(\sigma^{++} - \sigma^{+-} - \sigma^{-+} + \sigma^{--})$$
$$D = \frac{1}{4}(\sigma^{++} + \sigma^{+-} + \sigma^{-+} + \sigma^{--})$$

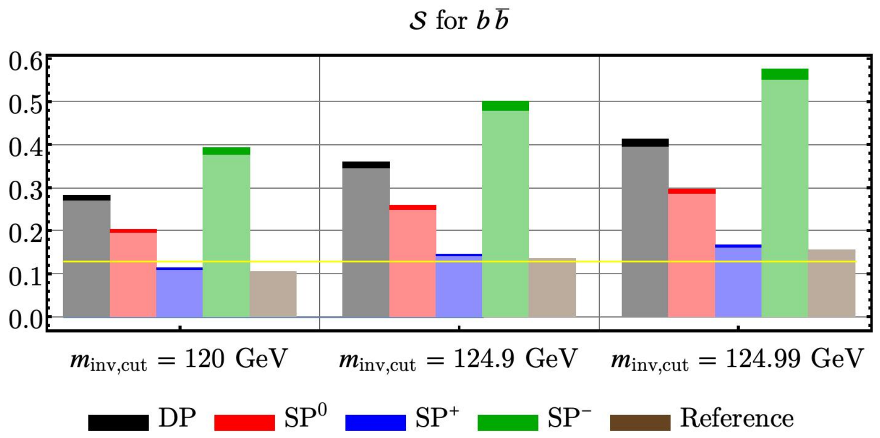
Electron transversely polarized, positron longitudinally polarized (SP^+):

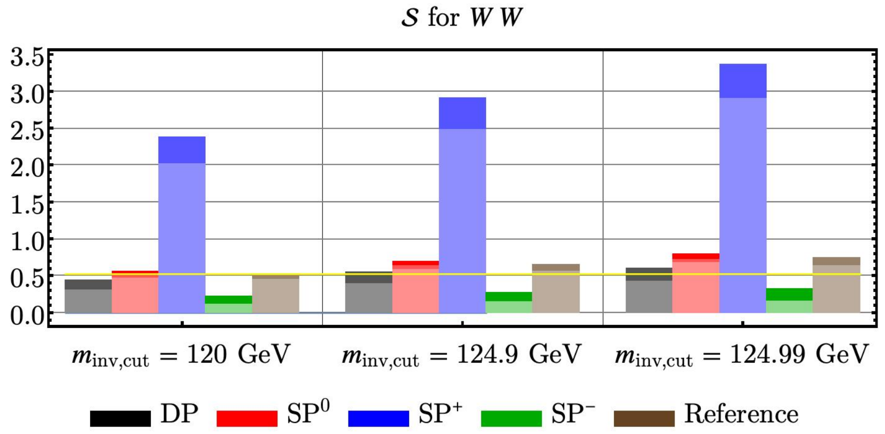
$$N = \frac{1}{2}(\sigma^{++} - \sigma^{-+})$$
$$D = \frac{1}{2}(\sigma^{++} + \sigma^{-+})$$

Electron transversely polarized, positron longitudinally polarized (SP^-):

$$N = \frac{1}{2}(\sigma^{+-} - \sigma^{--})$$
$$D = \frac{1}{2}(\sigma^{+-} + \sigma^{--})$$

8

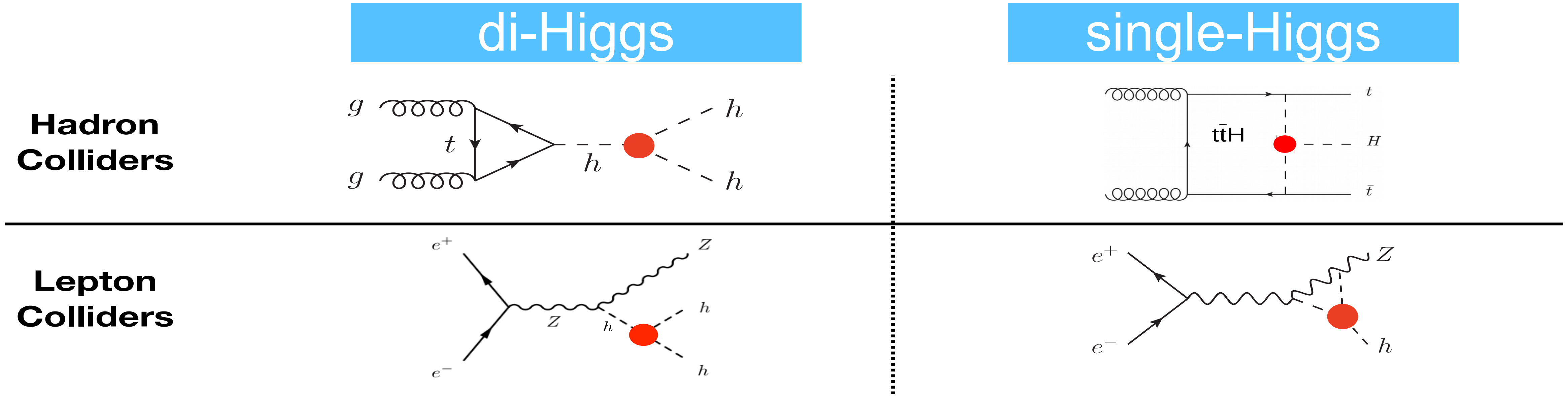




Major improvements of up to factors of 6 possible for bb and WW (doesn't work for gg)

Higgs Self-Coupling

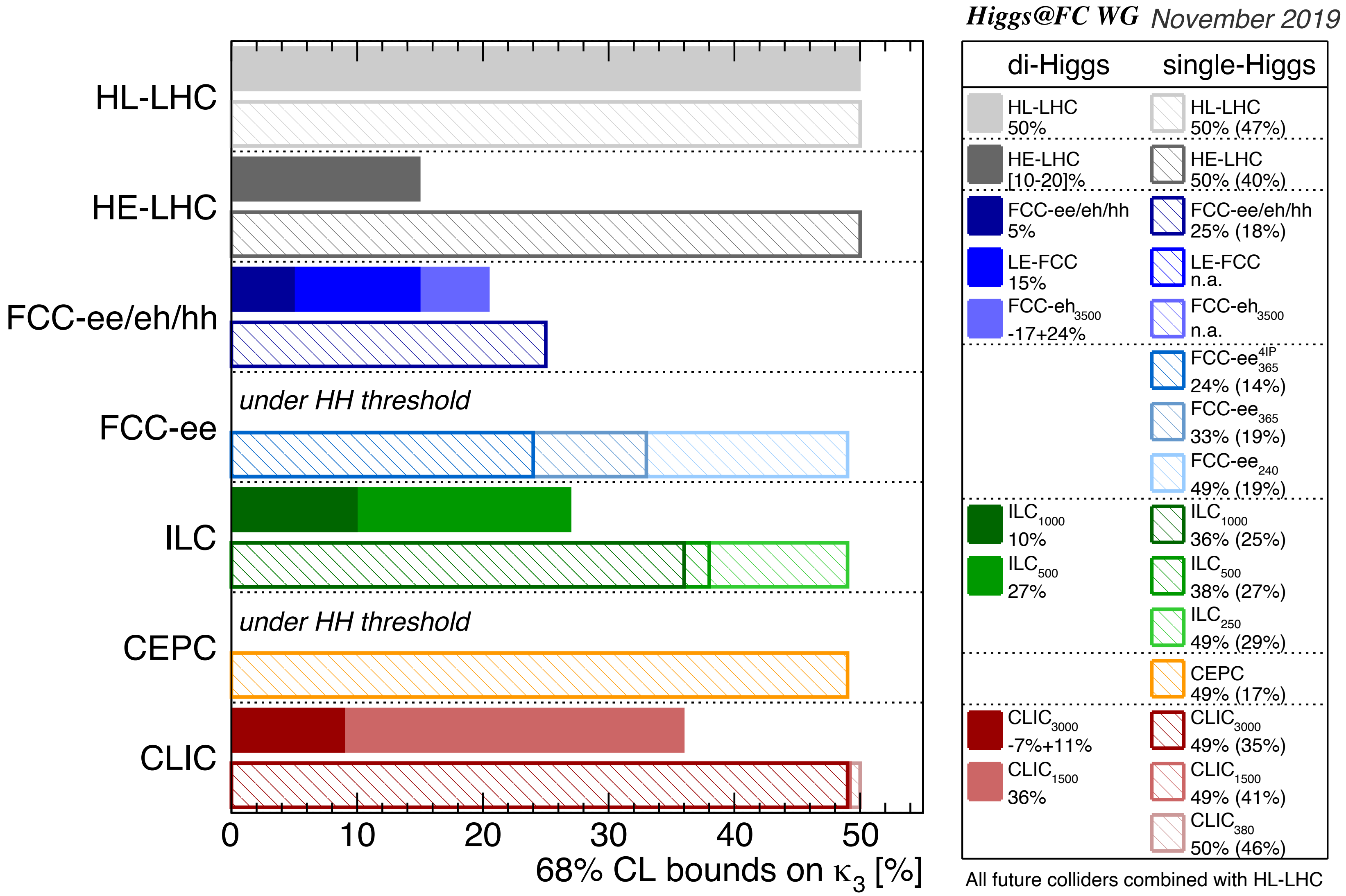
How much can it deviate from SM given the tight constraints on other Higgs couplings?
Do we need to reach HH production threshold to constrain h^3 coupling?



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



1

Don't need to reach HH threshold to have access to h^3.

Runs at different energies are essential (e.g. 240 and 365 GeV)

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

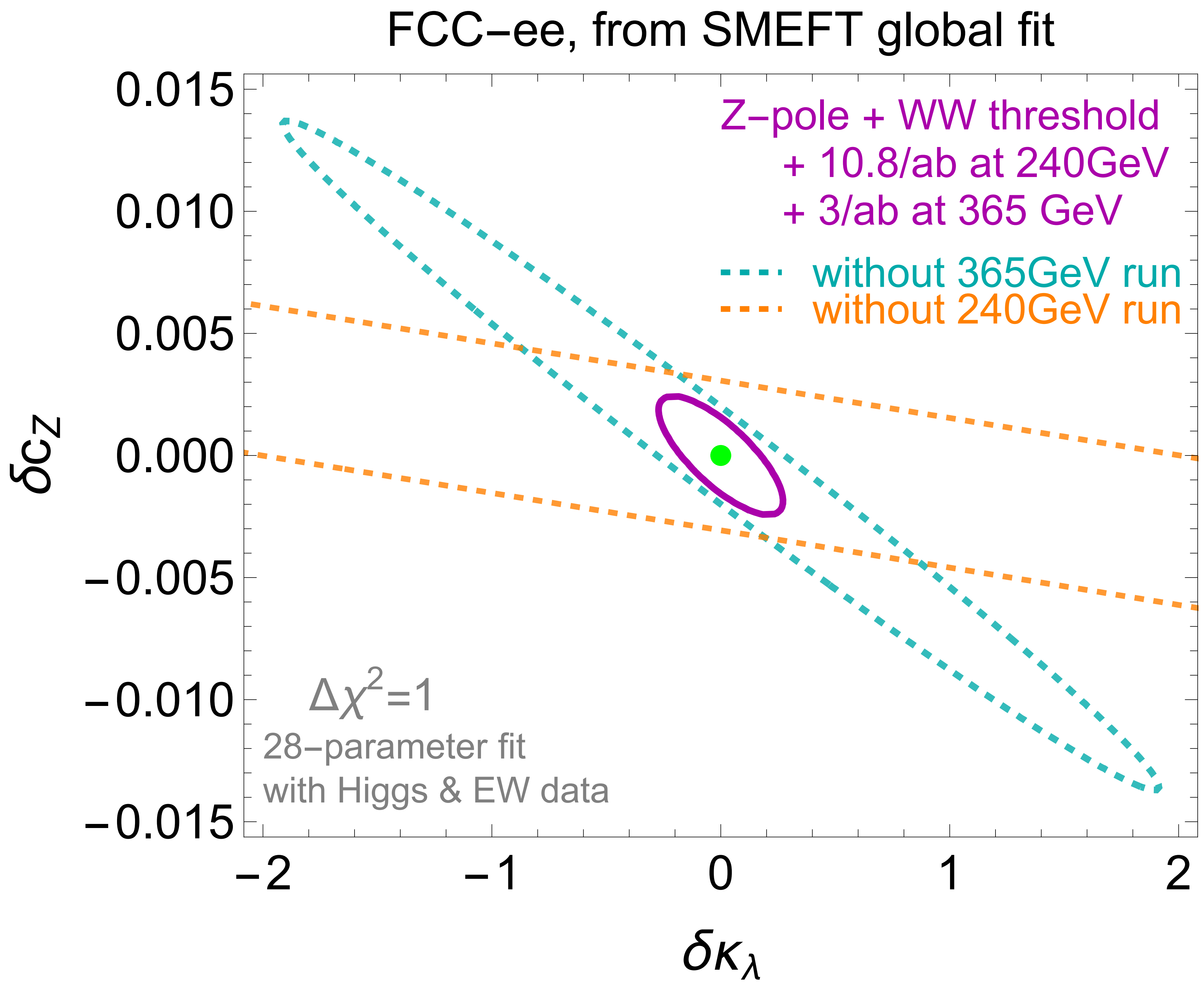
Precision measurement of y_t needs FCC-ee.

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

Higgs Self-Coupling

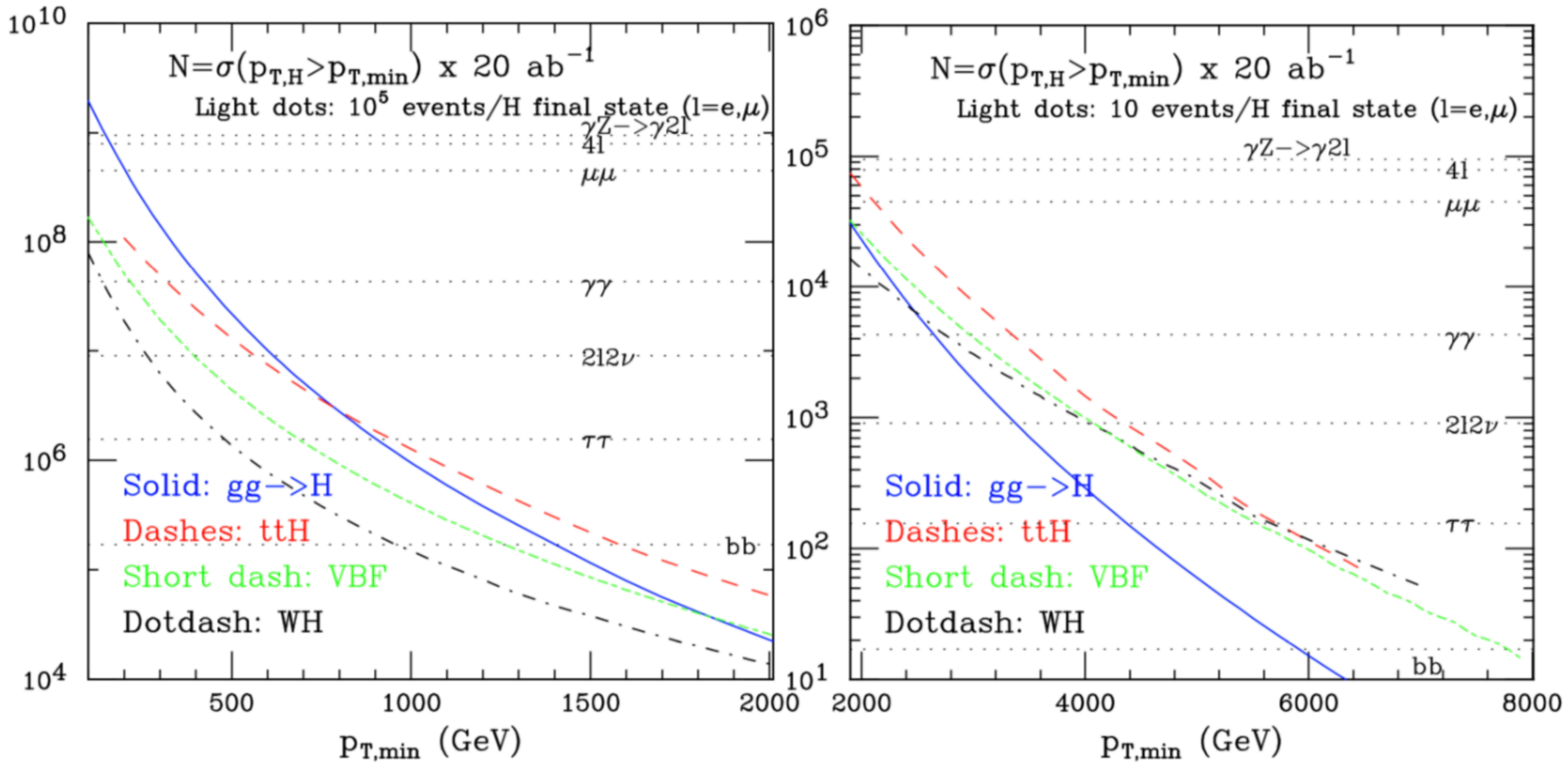


Higgs @ FCC-hh.

The Higgs exploration territory

	ggH (N^3LO)	VBF (N^2LO)	WH (N^2LO)	ZH (N^2LO)	$t\bar{t}H$ (N^2LO)	HH (NLO)
N100	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N100/N14	180	170	100	110	530	390

$(\mathrm{N100} = \sigma_{100\,\mathrm{TeV}} \times 30\,\mathrm{ab}^{-1} \quad \& \quad \mathrm{N14} = \sigma_{14\,\mathrm{TeV}} \times 3\,\mathrm{ab}^{-1})$



- Large rate (> 10^{10}H, > 10^7 HH)
  - unique sensitivity to **rare decays** ($\gamma\gamma$, γZ, $\mu\mu$, exotic/BSM)
  - few % sensitivity to **self-coupling**
- Explore extreme phase space:
  - e.g. 10^6 H w/ pT>1 TeV
  - clean samples with high S/B
  - small systematics

Electroweak Factory

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

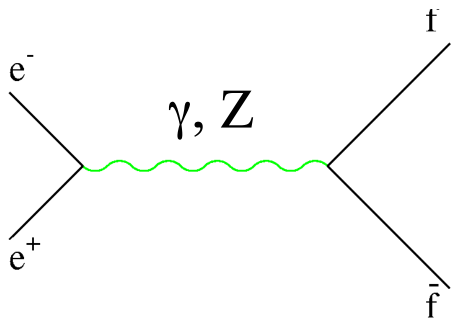
EW Precision Measurements at FCC-ee

Experimental (statistical and systematic) precision of a selection of measurements accessible at FCC-ee, compared with the present world-average precision. FCC-ee syst. scaled down from LEP estimates. Room for improvement with dedicated studies. Note that **syst**. go down also with **stat**. (e.g. beam energy determination from ee→Z/γ thus the associated uncertainty decreases with luminosity).

Table from mid-term report

Example of EW measurements @ Tera Z

measure $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$ at (a) judicious $\sqrt{s}$



The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$
The Z exchange term is proportional to G^2_F, hence independent of α_{QED}
The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$

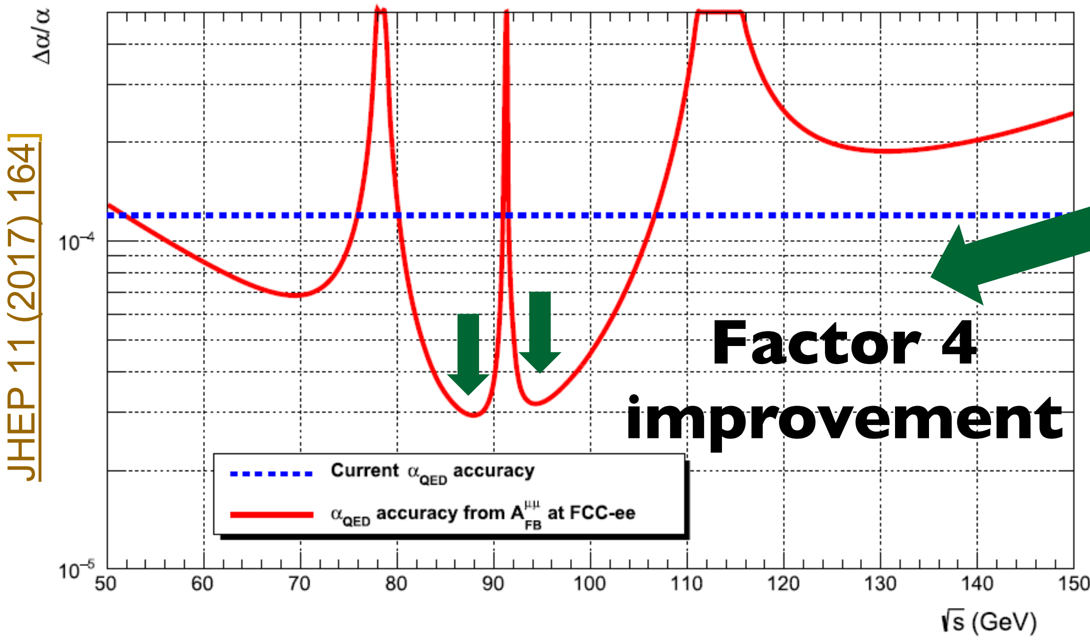
Excellent experimental control of off-peak di-muon asymmetry motivates campaign to collect 50-80 ab^{-1} off peak to gain highest sensitivity to Z-γ interference

$$A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4}\mathcal{A}_e\mathcal{A}_\mu \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{QED}(s)}{m_Z^2 G_F \left(1 - 4\sin^2\theta_W^{eff}\right)^2}\frac{s - m_Z^2}{2s}\right]$$

← strongly depends on $\sqrt{s}$
← **direct** measurement of $\alpha_{QED}(s)$ at $\sqrt{s}$!= m_Z
← measure $\sin^2\theta_W$ to high precision (later)

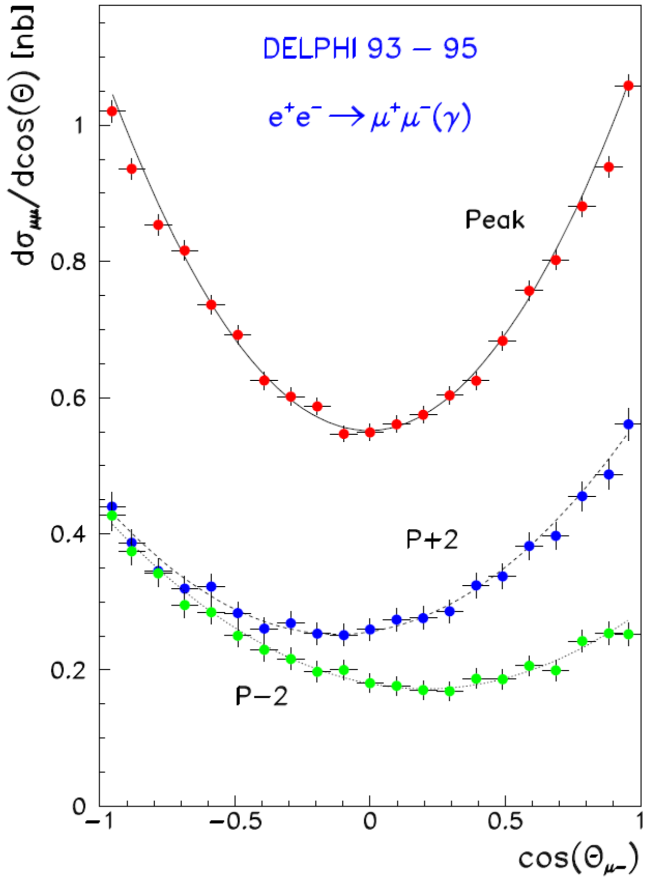
Allows for clean determination of $\alpha_{QED}(m_Z^2)$, which is a *critical* input for m_W closure tests (see later).

relative α_{QED} uncertainty with 80 ab^{-1}



P.Janot '16 [JHEP 02 (2016) 053, JHEP 11 (2017) 164]

This dependence, & location of half-integer spin tunes, guides the choice of off-peak energies: 87.8 & 93.9 GeV.



→ Measure $\alpha_{QED}(m_Z^2)$ to 3×10^{-5} rel. precision (currently 1.1×10^{-4})
→ Stat. dominated; syst. uncertainties < 10^{-5} (dominated by $\sqrt{s}$ calib)
→ Theoretical uncertainties ~ 10^{-4}, higher order calcs needed

G. Wilkinson @ FCC week 2021

W Mass

Two independent W mass and width measurements @FCCee :

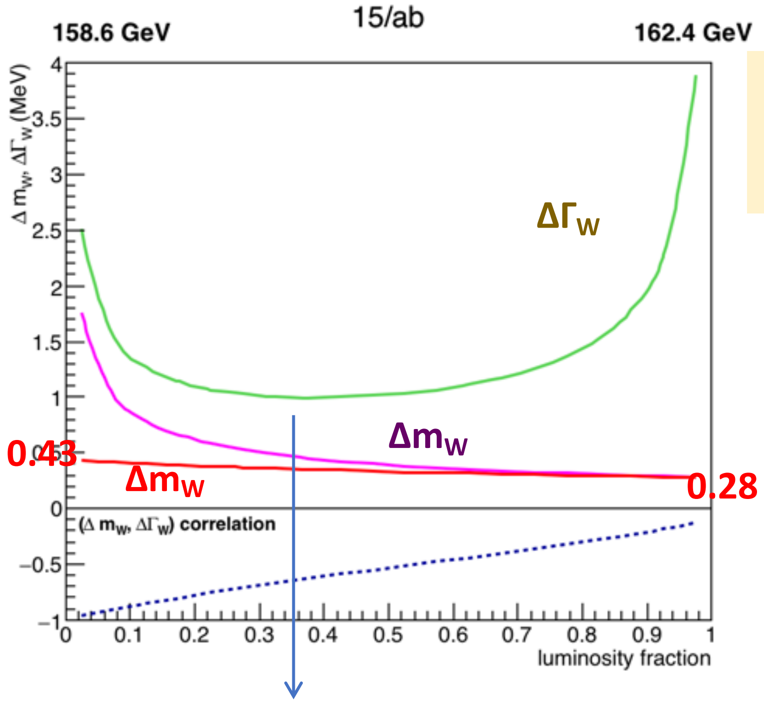
1. **The** m_W and Γ_W determinations from the WW threshold cross section lineshape, with 12/ab at $E_{CM} \simeq$ 157.5-162.5 GeV

   Δm_W=0.4 MeV $\Delta\Gamma_W$=1 MeV

2. Other measurements of m_W and Γ_W from the decay products kinematics at $E_{CM} \simeq$ 162.5-240-365 GeV

   Δm_W , $\Delta\Gamma_W$= 2-5 MeV ?

Scans of possible E_1 E_2 data taking energies and luminosity fractions f (at the E_2 point)



Δm_W =0.45 MeV , $\Delta\Gamma_W$=1 MeV (r=-0.6)
Δm_W=0.35 MeV

A -minimum of **$\Delta\Gamma_W$=0.91 MeV** with **Δm_W=0.55 MeV**
taking data at E_1=**156.6** GeV E_2=**162.4** GeV f=**0.25**
yields **Δm_W=0.47 MeV** (as single par)

B- minimum of **Δm_W=0.28 MeV** **$\Delta\Gamma_W$=3.3 MeV** with
E_1=**155.5** GeV E_2=**162.4** GeV f=**0.95**
yields **Δm_W=0.28 MeV** (as single par)

C- minimum of **$\Delta\Gamma_W$=0.96 MeV** +**Δm_W=0.41 MeV** with
E_1=**157.5** GeV E_2=**162.4** GeV f=**0.45**
yields and **Δm_W=0.37 MeV** (as single par)

Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both
Δm_W : error on W mass from fitting only m_W

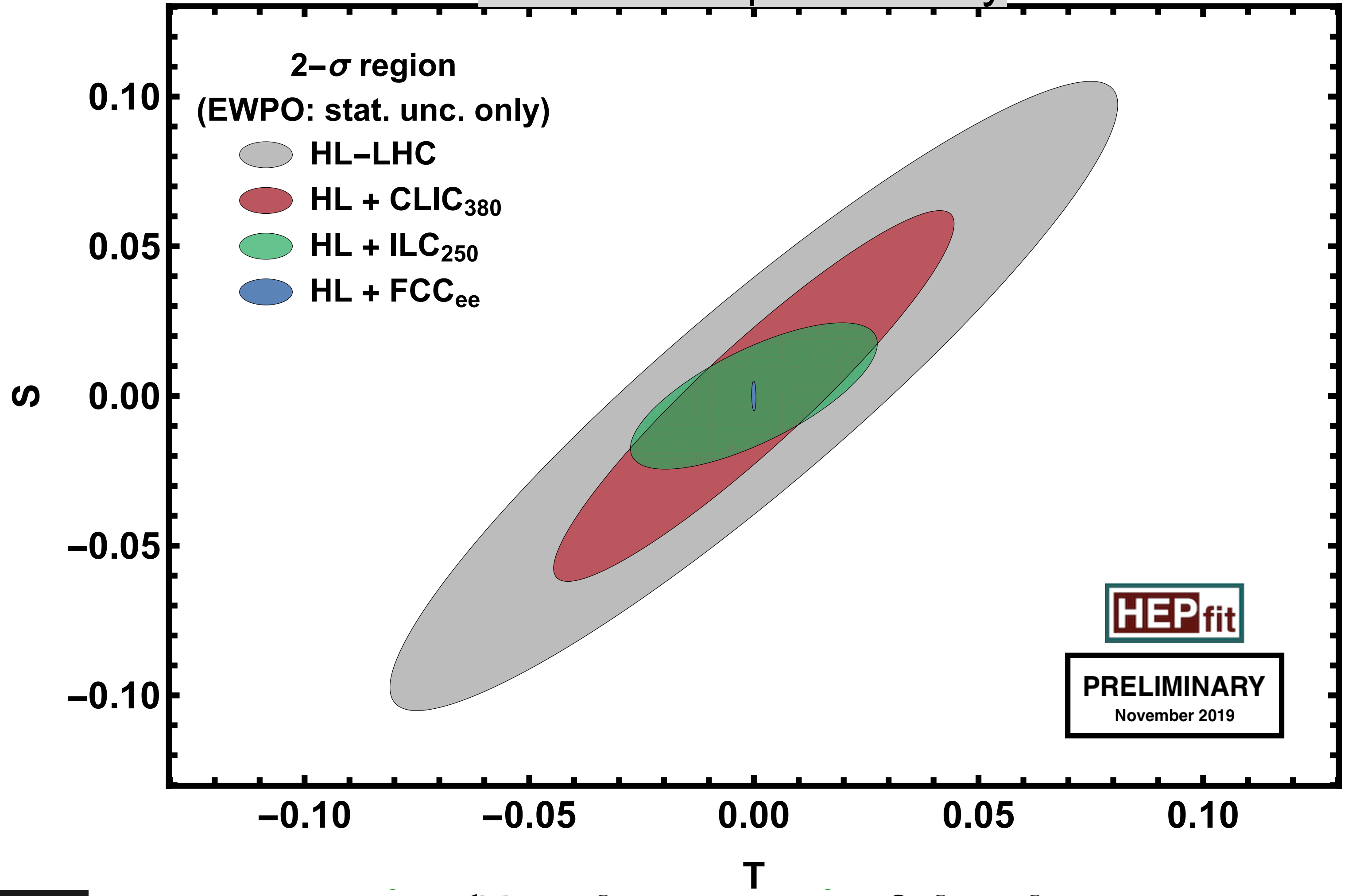
Comparable in sensitivity with value from EWPO fit.

Tera-Z EW precision measurements.

- The target is to reduce syst. uncertainties to the level of stat. uncertainties.
  (exploit the large samples and innovative control analyses)
- Exquisite √s precision (100keV@Z, 300keV@WW) reduces beam uncertainties (EPOL)

➡ ~50 times better precision than LEP/LSD on EW precision observables
(stat. improvement alone is a factor **300-2'000** and innovative analyses/improved detectors can bring syst. down too)

w/ stat. and param. only



Indirect sensitivity to 70TeV-scale sector connected to EW/Higgs

(For the impact of the theory uncertainties on the EW fit, see bonus slides)

Tera-Z EW precision measurements.

- The target is to reduce syst. uncertainties to the level of stat. uncertainties.
  (exploit the large samples and innovative control analyses)
- Exquisite √s precision (100keV@Z, 300keV@WW) reduces beam uncertainties (EPOL)

➡ ~50 times better precision than LEP/LSD on EW precision observables

(stat. improvement alone is a factor **300-2'000** and innovative analyses/improved detectors can bring syst. down too)

Need TH results to fully exploit Tera-Z

Table from mid-term report

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement†
m_Z Γ_Z $\sin^2\theta^\ell_{\rm eff}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $e^+e^-\to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^-\to f\bar{f}$
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to 4f$ or EFT framework)	NNLO for $ee\to WW$, $W\to ff$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^-\to ZH$	NLO + NNLO QCD	NNLO electroweak
$m_{\rm top}$	100 MeV	17 MeV	threshold scan $e^+e^-\to t\bar{t}$	N^{3}LO QCD, NNLO EW, resummations up to NNLL	Matching fixed orders with resummations, merging with MC, α_s (input)

†The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.

Indirect sensitivity to 70TeV-scale sector connected to EW/Higgs

New Physics Reach @ Z-pole.

There are 48 different types of particles that can have tree-level linear interactions to SM.

de Blas, Criado, Perez-Victoria, Santiago, arXiv: 1711.10391

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Scalars

Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Fermions

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Vectors

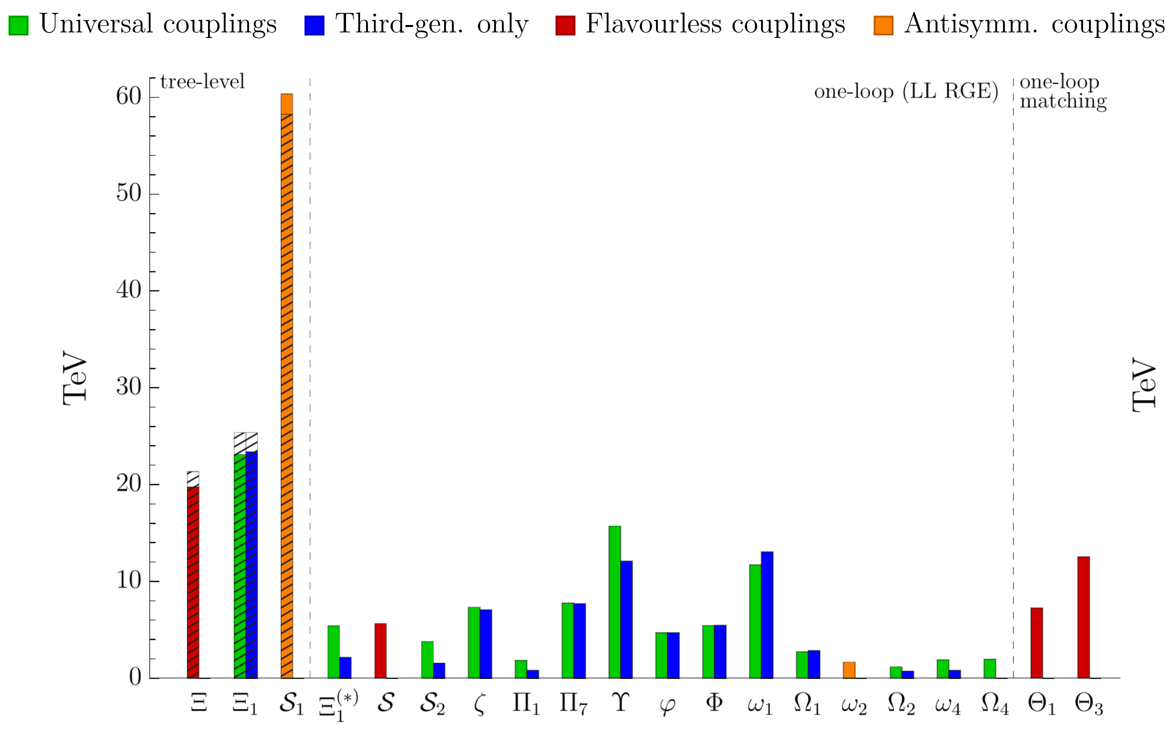
They are not all affecting EW observables at tree-level.

New Physics Reach @ Z-pole.

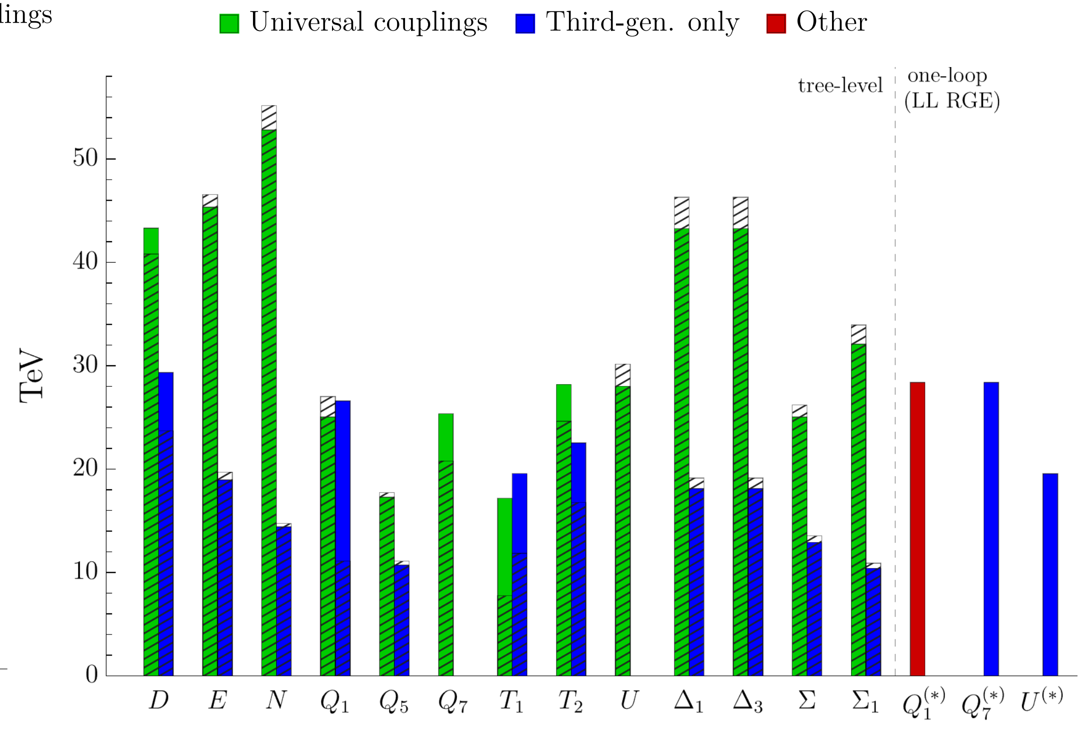
There are 48 different types of particles that can have tree-level linear interactions to SM.

They are not all affecting EW observables at tree-level.
However, all, but a few, have leading log. running into EW observables.

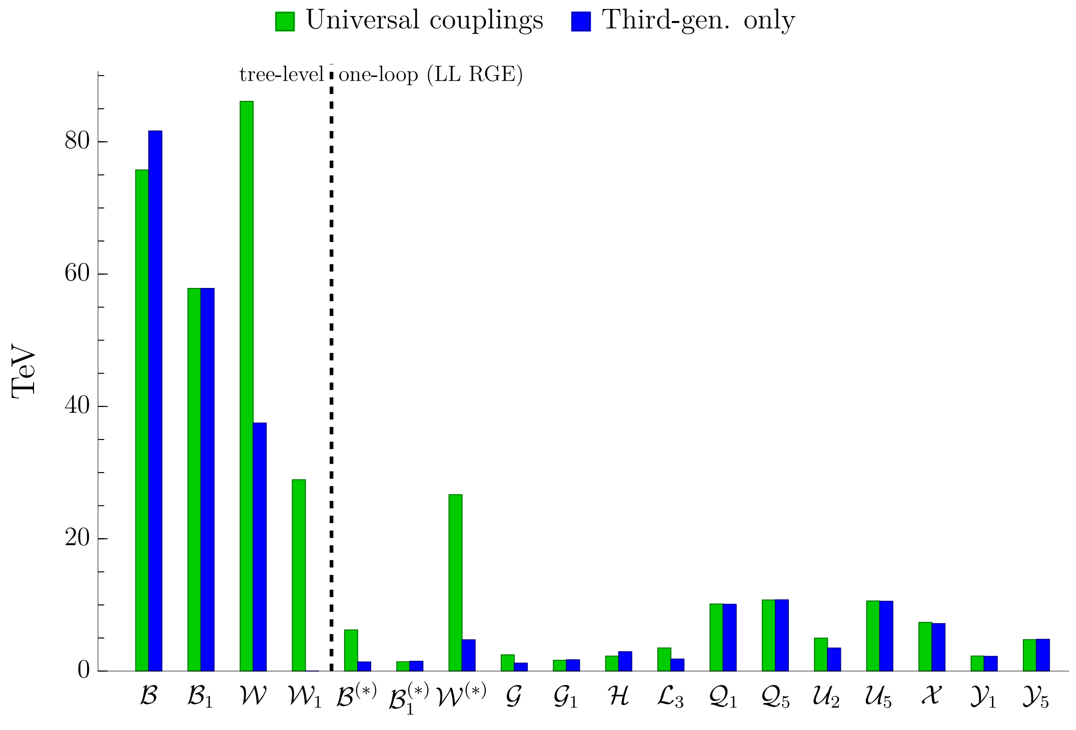
Allwicher, McCullough, Renner, arXiv: 2408.03992



Scalars



Fermions

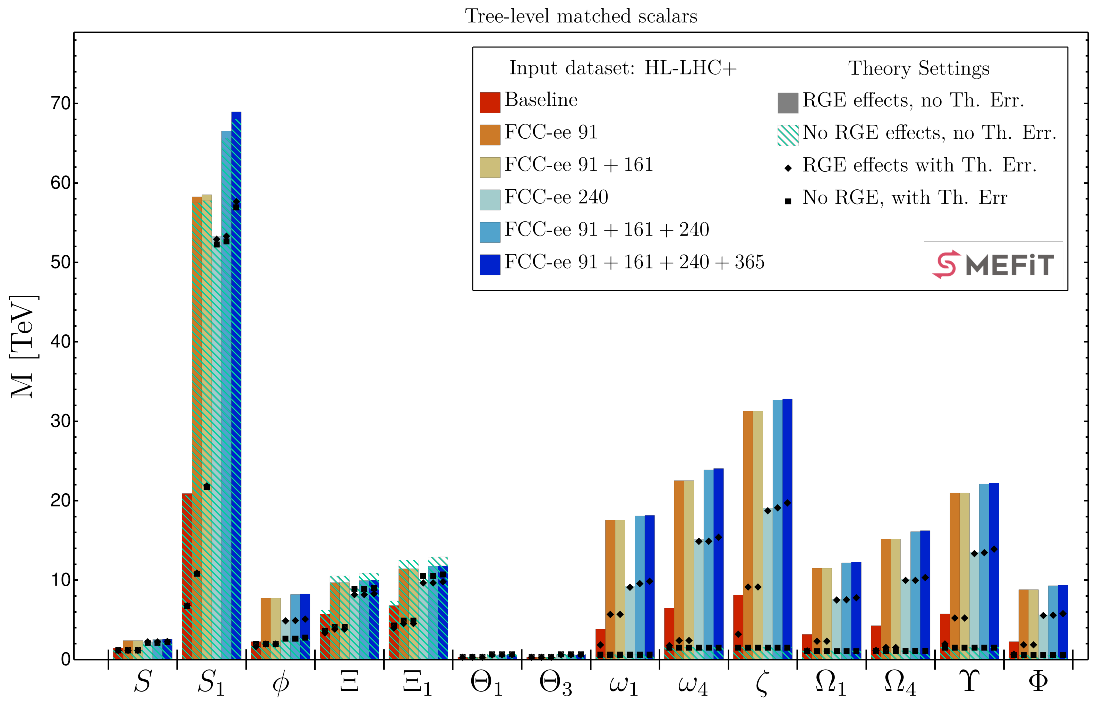


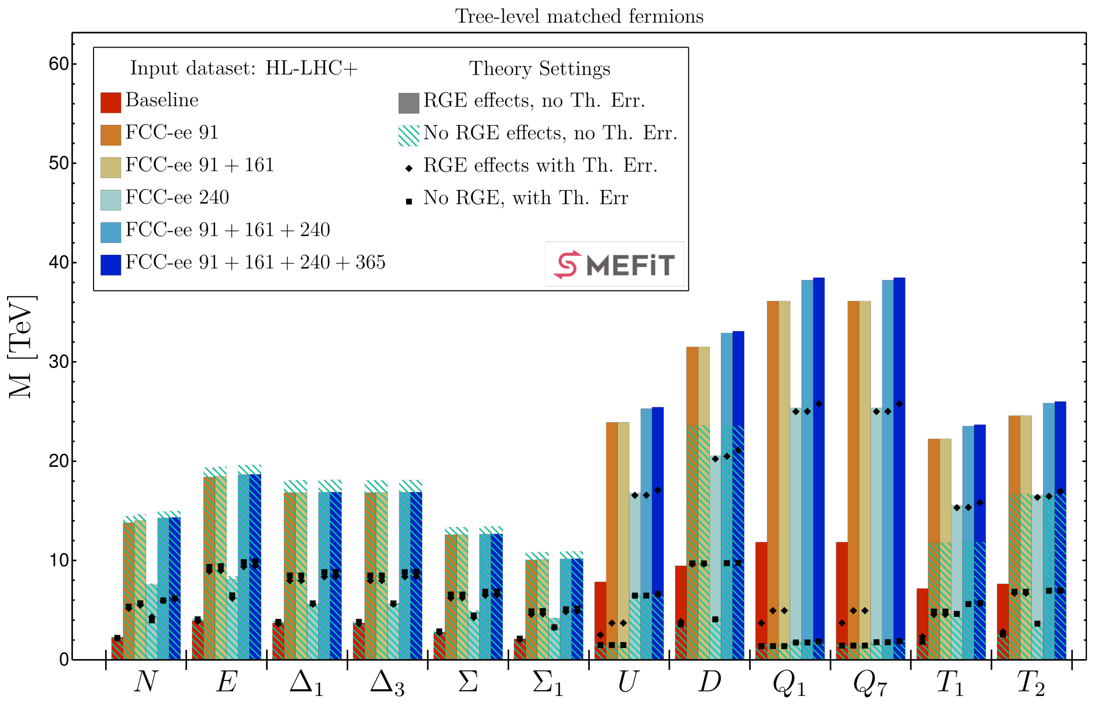
Vectors

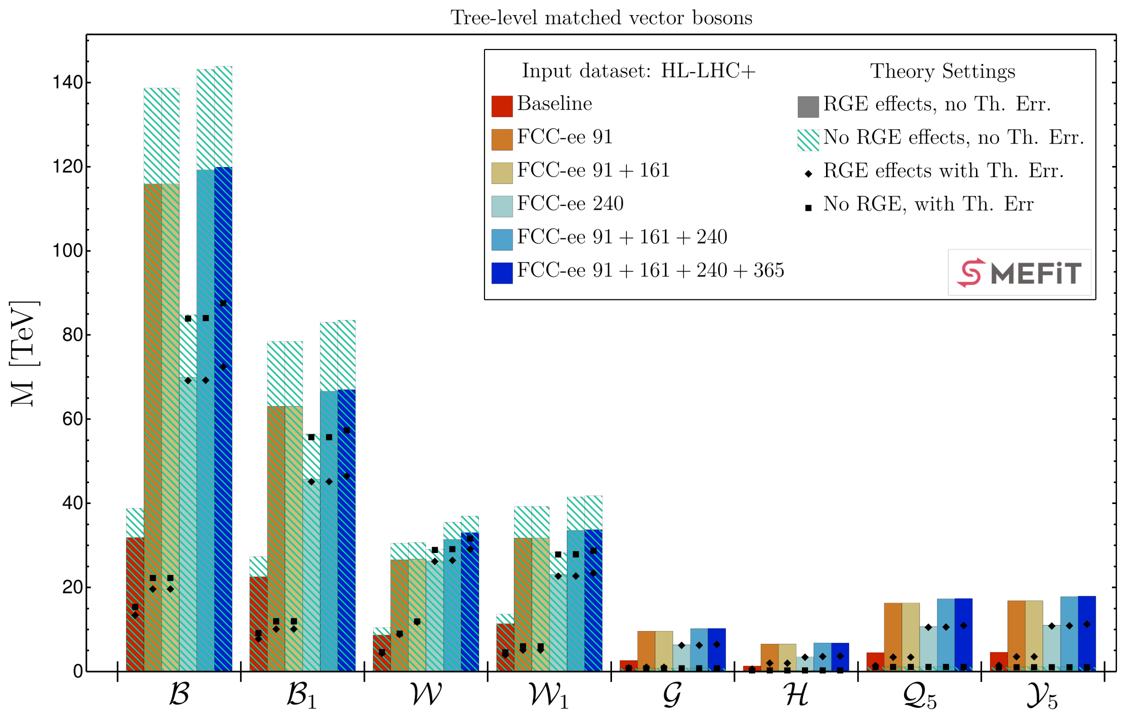
Tree-level matching and running from 1 TeV to Z mass.
W- and Z-pole observables only (no Higgs, no LEP-2 like observables)

New Physics Reach @ Z-pole.

There are 48 different types of particles that can have tree-level linear interactions to SM.



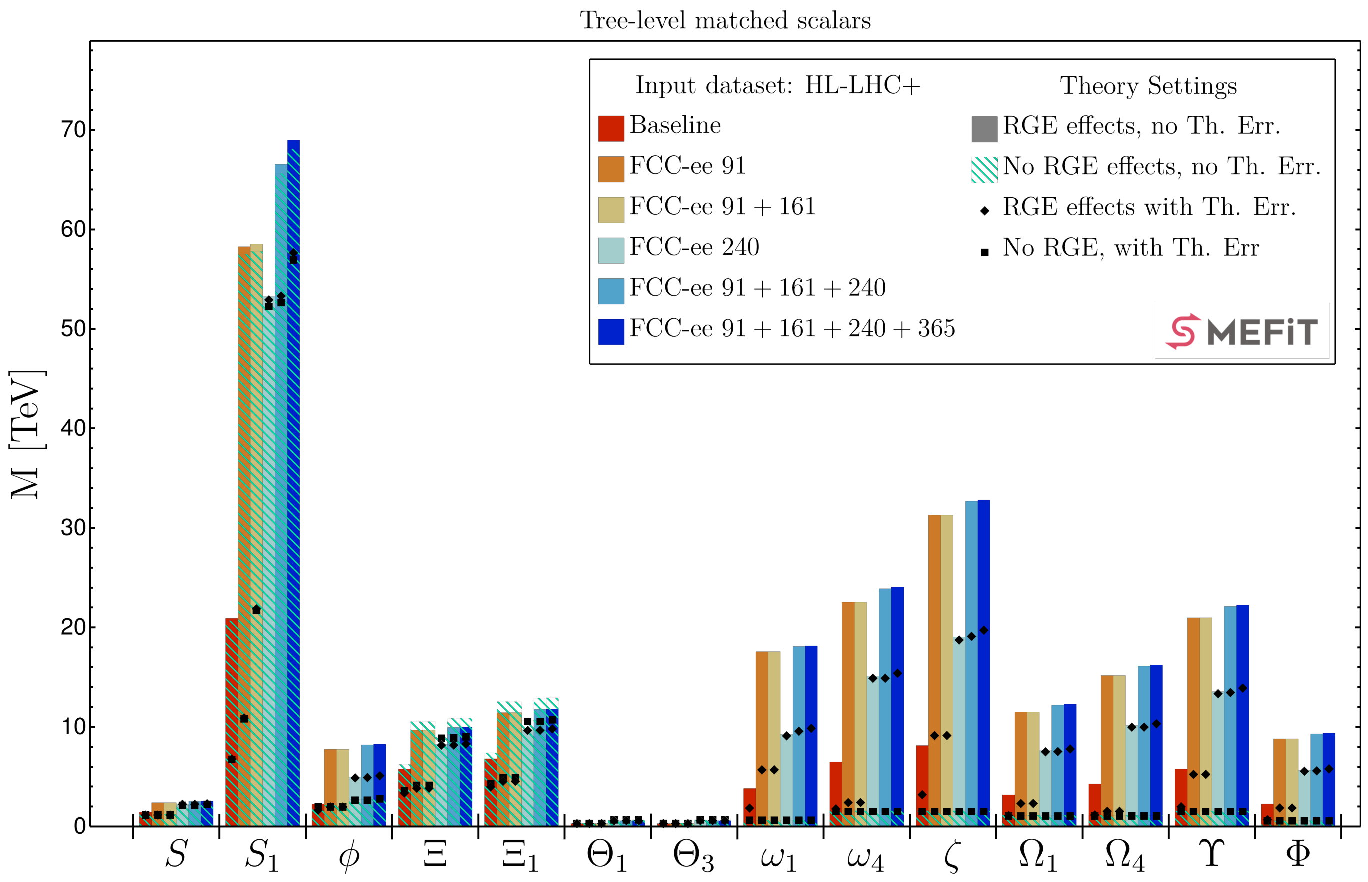


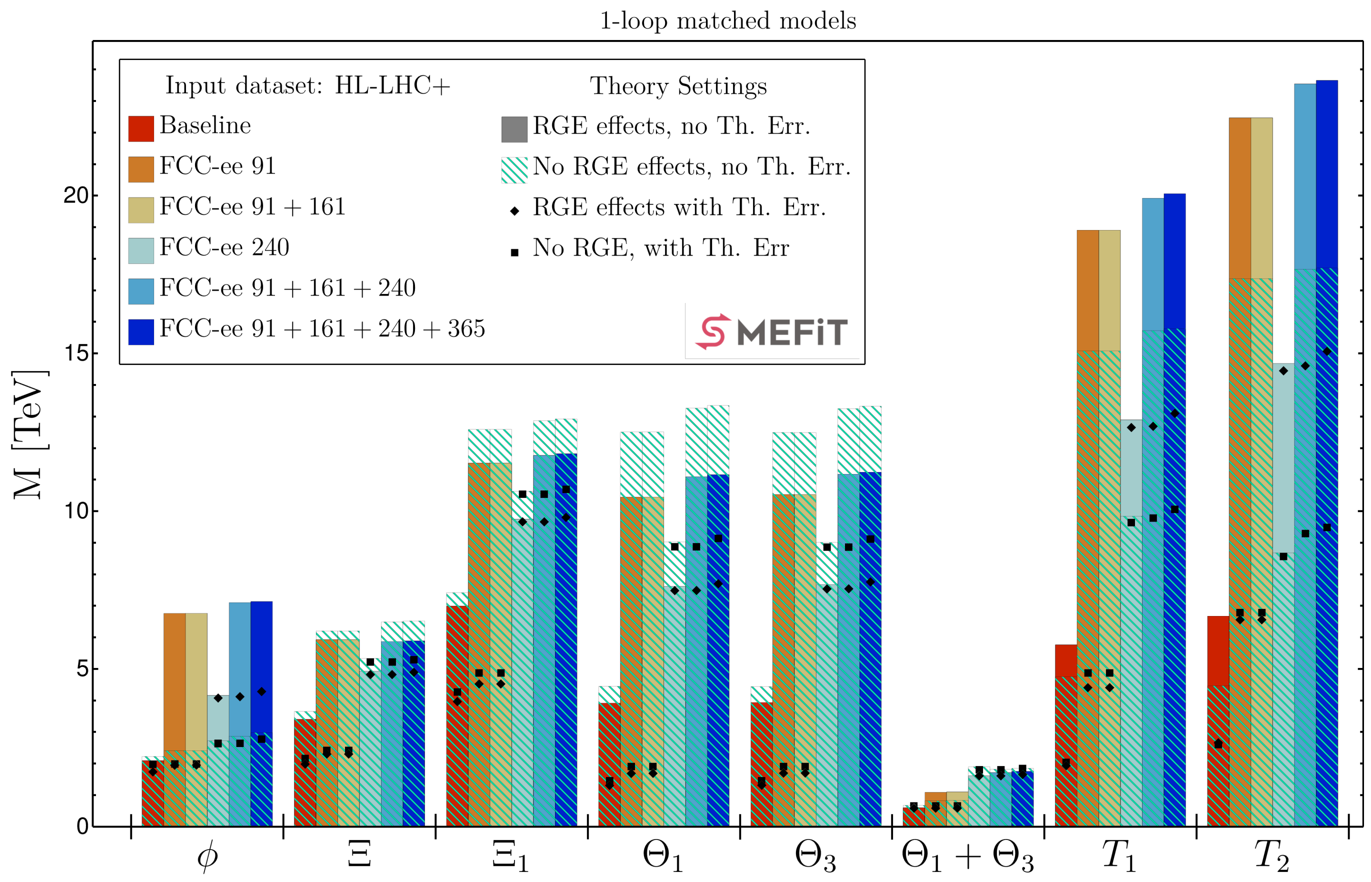


Importance of controlling/reducing the TH syst. errors to exploit Z-pole data.
Role of ZH and tt runs.

New Physics Reach @ Z-pole.

There are 48 different types of particles that can have tree-level linear interactions to SM.





Importance of full 1-loop matching
(finite pieces matter)

New Physics Reach @ Z-pole.

There are 48 different types of particles that can have tree-level linear interactions to SM.

Tera-Z programme gives comprehensive coverage of new physics coupled to SM.

If a signature shows up elsewhere, it will also show up at Tera-Z.

Tera-Z is not just a high-power LEP exploring the EW sector.

FCC-ee as a flavour factory

Flavour potential.

At present (Z/h/NewPhysics) FCNCs mostly constrained by low energy observables.

The large statistics of FCC will open on-shell opportunities.

See S. Monteil, Flavour@FCC '22

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

FCC-ee = 10 x Belle II

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2. * 10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

out of reach at LHCb/Belle

boosted b's/τ's at FCC-ee

Makes possible a topological rec. of the decays w/ miss. energy

Flavour potential.

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See S. Monteil, Flavour@FCC '22

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						45
						150

FCC-ee = 10 x Belle II

Flavour @ FCC vs Belle/pp

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Decay mode				FCC-ee
EW/H				
$B^0 \to$				0000
$\mathcal{B}(B^0 -$				000
$B_s \to \mu$				800
$B^0 \to \mu$				100
$\mathcal{B}(B_s -$				
Leptoni				
$B^+ \to$				%
$B^+ \to \tau^+\nu_{tau}$	7%			2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
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All hadron species		✓	✓
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Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Decay				-ee
EW/H				
$B^0 \to$				0000
$\mathcal{B}(B^0 -$				000
$B_s \to \mu$				800
$B^0 \to \mu$				100
$\mathcal{B}(B_s -$				
Leptoni				
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$B^+ \to \nu_{tau}$				%
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out of reach at LHCb/Belle

boosted b's/τ's at FCC-ee

Makes possible a topological rec. of the decays w/ miss. energy

Flavour defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements.

FCC-ee flavour opportunities.

- **CKM element V_{cb}** (critical for normalising the Unitarity Triangle) from WW decays
- **Tau physics** (>10^{11} pairs of tau's produced in Z decays)
  - test of lepton flavour universality: G_F from tau decays @ 10 ppm @ FCC-ee (0.5 ppm from muon decays)
  - lepton flavour violation:
    - $\tau\rightarrow\mu\gamma$: 4×10^{-8} @Belle2021→10^{-9} @ FCC-ee
    - $\tau\rightarrow3\mu$: 2×10^{-8} @Belle → 3×10^{-10} @BelleII → 10^{-11} @ FCC-ee
  - tau lifetime uncertainty:
    - 2000 ppm → 10 ppm
  - tau mass uncertainty:
    - 70 ppm → 14 ppm
- **Semi-leptonic mixing asymmetries** a^s_{sl} and a^d_{sl}
- …

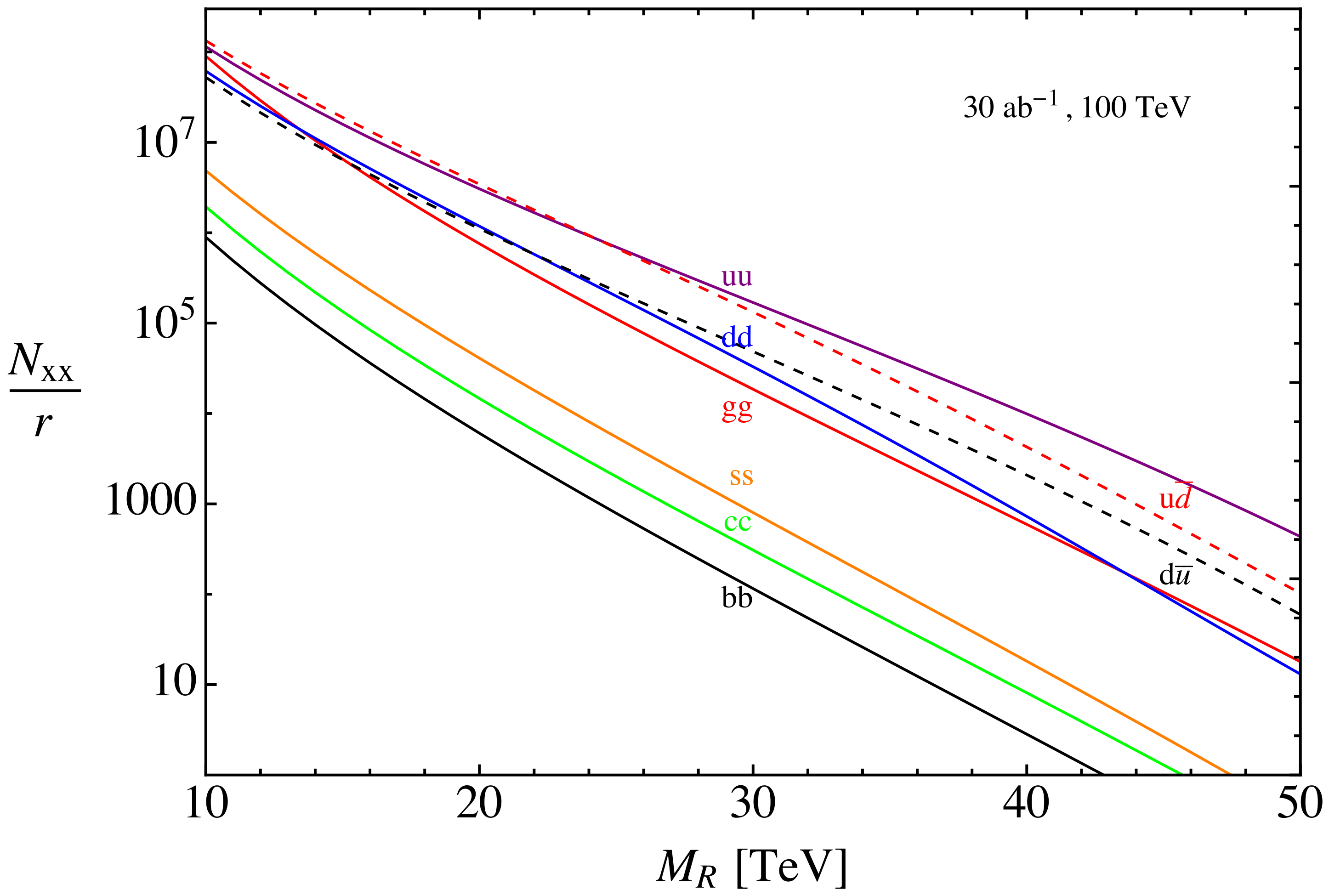
Exploration potential at high-energy

Resonance production.

Protons are made of 5 quarks, gluons, photons, W/Z

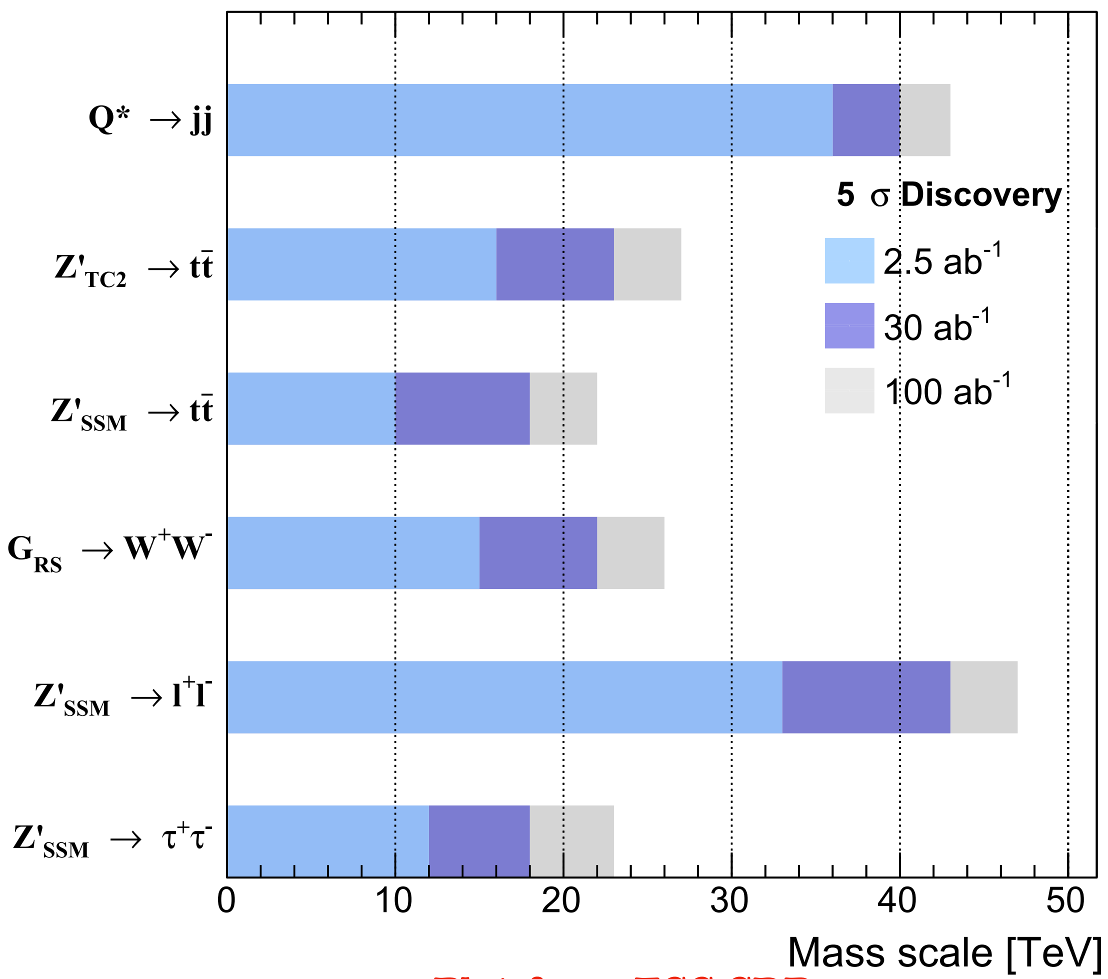
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

resonances produced



Plot from mid-term report

FCC-hh mass reach



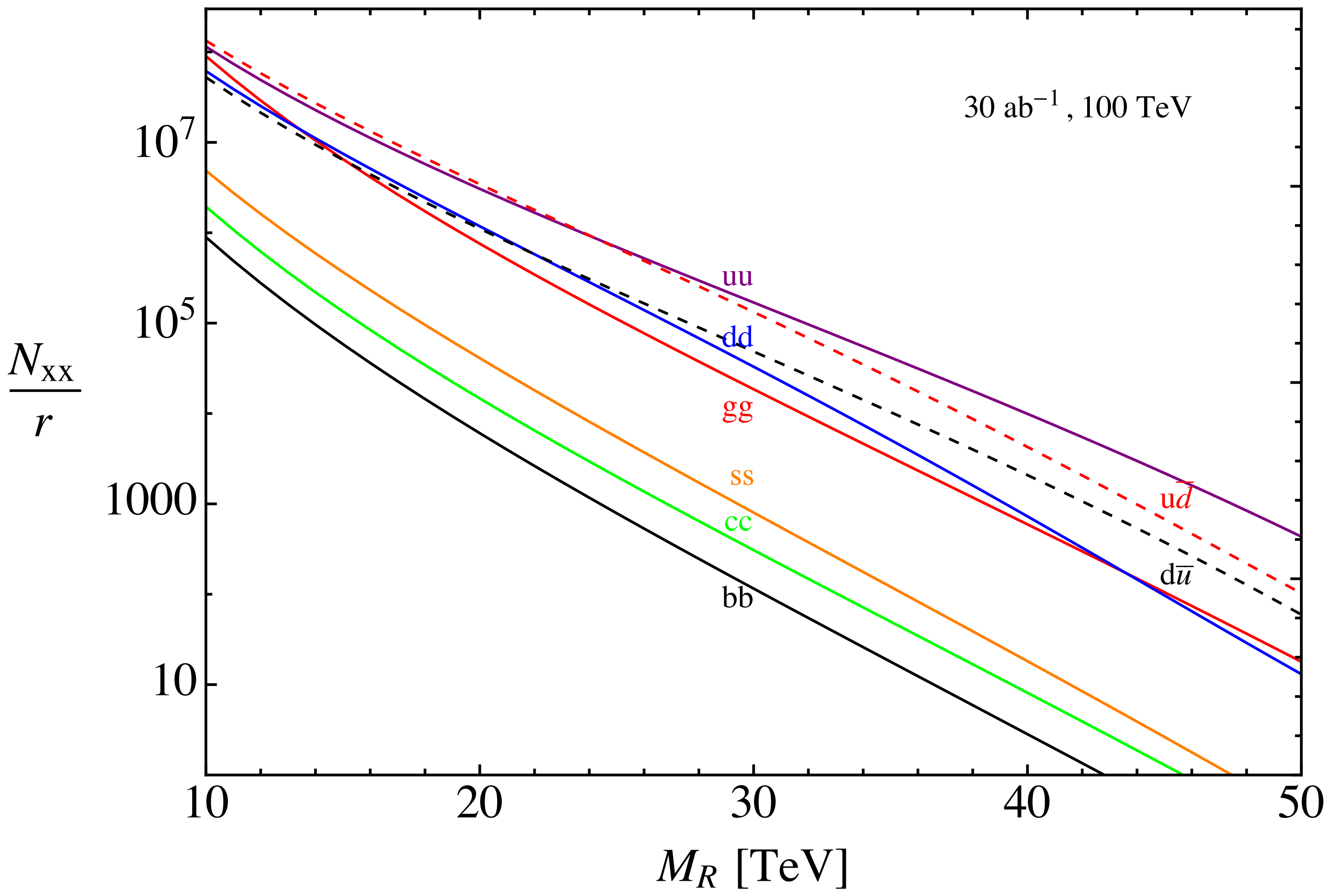
Plot from FCC CDR

Resonance production.

Protons are made of 5 quarks, gluons, photons, W/Z

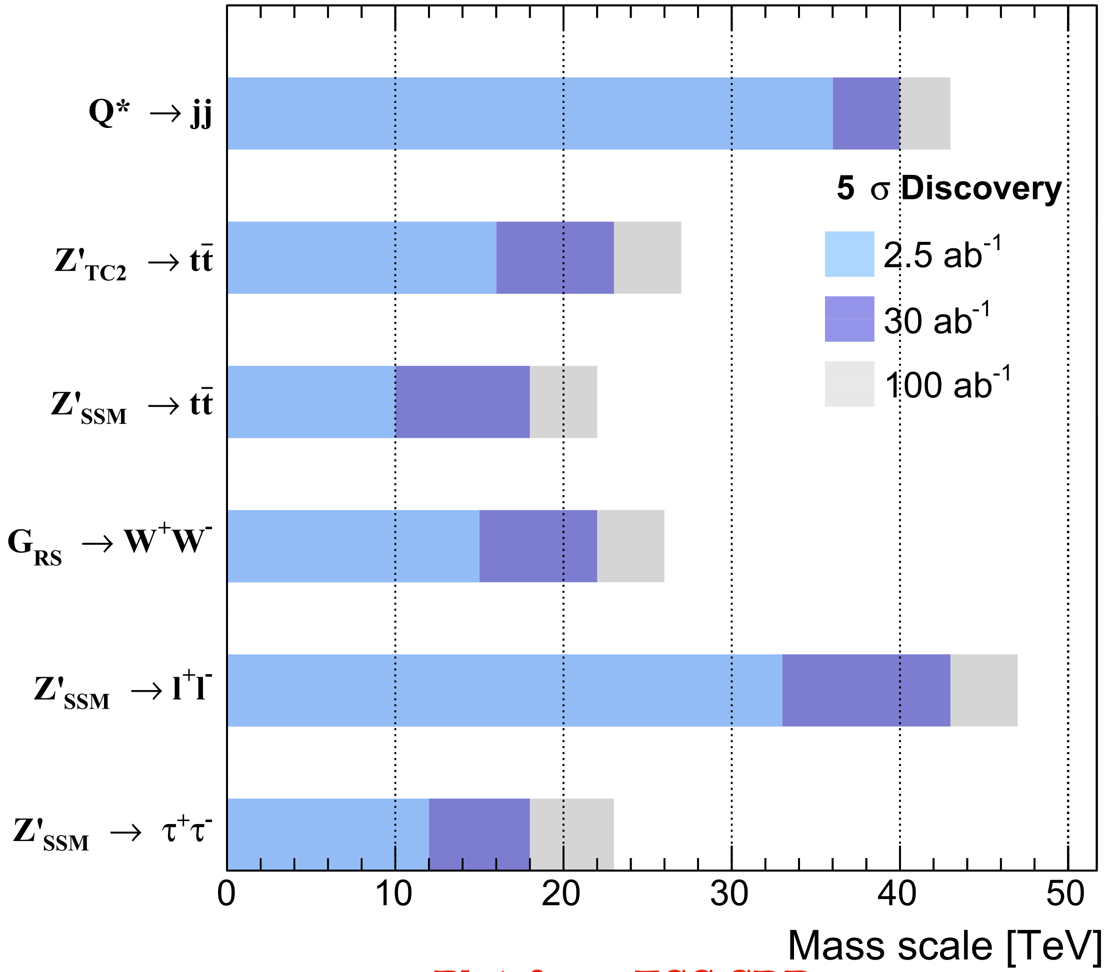
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

\# resonances produced



Plot from mid-term report

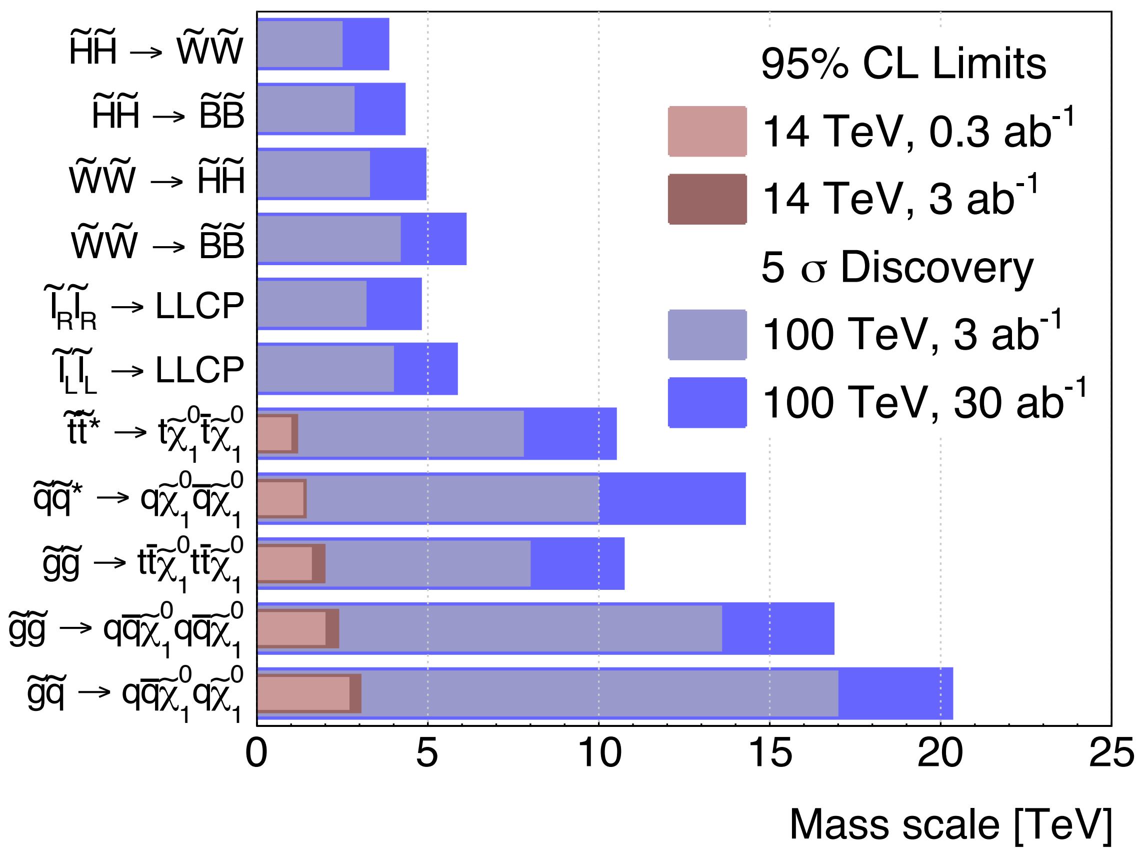
FCC-hh mass reach



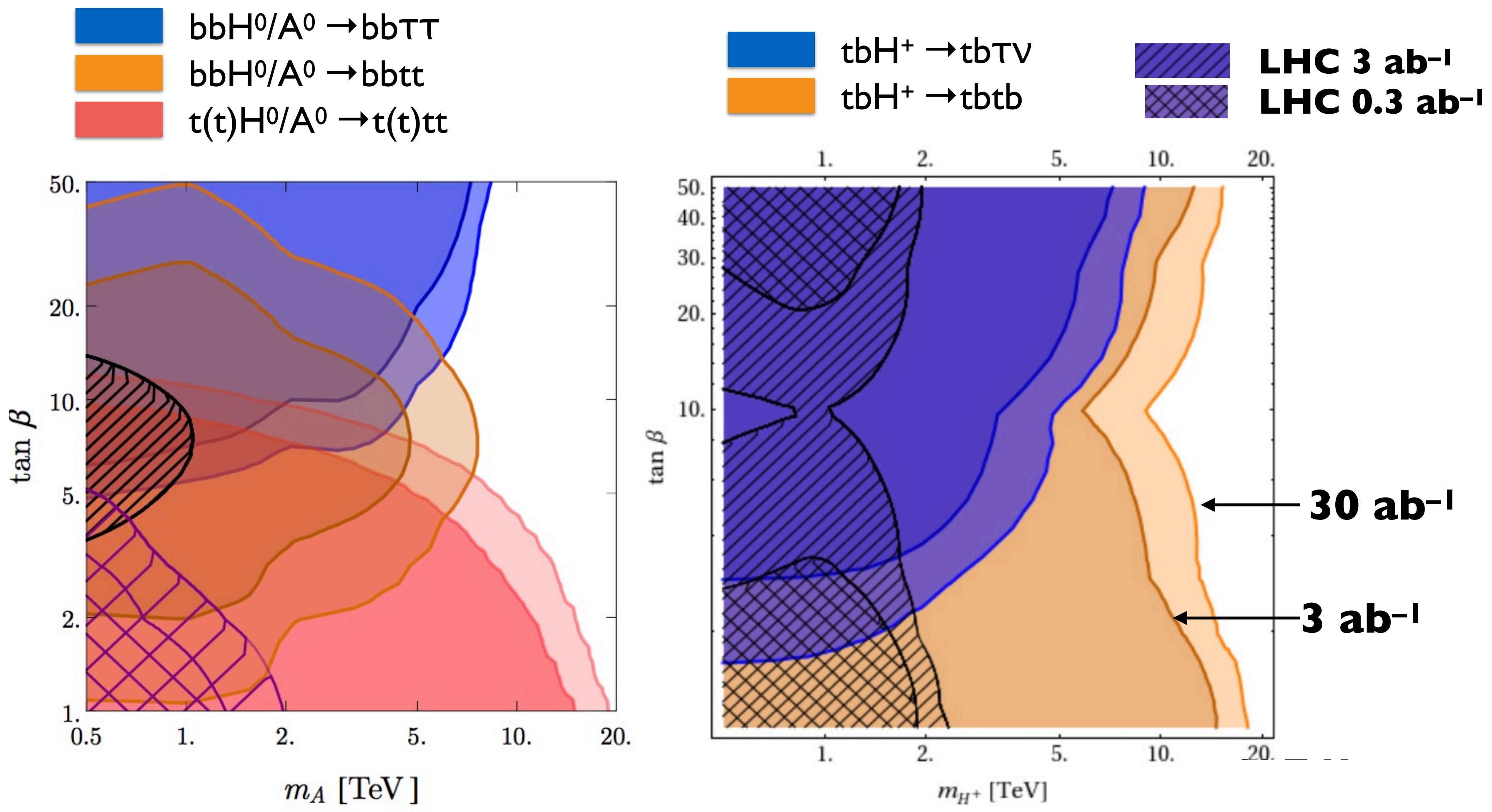
Plot from FCC CDR

FCC-hh allows the direct exploration of new physics at energy scales up to 40 TeV, including any physics that may be indirectly indicated by precision Higgs and EW measurements at FCC-ee.

Pushing limits of SUSY.



Plot from arXiv:1606.00947



Plot from arXiv:1605.08744 and arXiv:1504.07617

15-20TeV squarks/gluinos

require kinematic threshold 30-40TeV:

FCC-hh is more than a √ŝ~10TeV factory

Factor 10 increase on the HL-LHC limits.

Conclusions & Outlook

- ○ LHC changed the HEP landscape (Higgs and nothing else - yet?)
- ○ Much progress in the course of the Feasibility Study:
  - ‣ 4 IPs as baseline
  - ‣ new RF system totally flexible between 90 and 240 GeV
  - ‣ new optics design with more luminosity
  - ‣ identification of other science opportunities

⬇ ⬇

A **circular "Higgs factory"** like FCC-ee has a rich potential:

⦿ Quantum leap in testing the Standard Model

⦿ Search directly *and* indirectly for New Physics

And FCC-ee is the springboard to the energy frontier.

The FCC project perfectly fits the **needs of HEP after LHC**:
▶ guaranteed deliverables & broad exploration potential ◀

Acknowledgement.

This project is supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

BONUS

FCC Feasibility Organisation Chart.

FCC Feasibility Study

Study Support and Coordination
Study Leader: Michael Benedikt
Deputy Study Leader: Frank Zimmermann

- **EU Projects** – NN
- **Collaboration building** – Gregorio Bernardi, Tadeusz Lesiak, Emmanuel Tsesmelis,
- **Communications** – Panagiotis Charitos, Arnaud Marsollier

Study Support Unit
IT: Sylvain Girod
Procurement: Adam Horridge
Quality management: Beatriz Arias
Resources: Sylvie Prodon
Secretariat: Julie Hadre

Physics, Experiments and Detectors
Patrick Janot, Christophe Grojean

- **Physics programme** – Matthew McCullough, Frank Simon
- **Detector concept** – Mogens Dam, Marc-André Pleier, Felix Sefkow
- **Physics performance** – Patrizia Azzi, Emmanuel Perez, Michele Selvaggi
- **Software and computing** – Gerardo Ganis, Brieuc François
- **EPOL** – Jacqueline Keintzel, Guy Wilkinson
- **MDI** – Manuela Boscolo, Fabrizio Palla

Accelerators
Tor Raubenheimer, Frank Zimmermann

- **FCC-ee accelerator design** – Christian Carli, Frank Zimmermann
- **FCC-ee technical implementation** – Jean-Paul Burnet, Tor Raubenheimer
- **FCC-ee injector** – Paolo Craievich, Alexej Grudiev
- **FCC transfer lines** – Wolfgang Bartmann
- **FCC-hh design** – Massimo Giovannozzi

Technical Infrastructures
Jean-Paul Burnet, Klaus Hanke

- **Integration** – Jean-Pierre Corso
- **Geodesy & survey** – Hélène Mainaud Durand
- **Electricity and energy management** – Jean-Paul Burnet
- **Cooling and ventilation** – Guillermo Peon
- **Cryogenics systems** – Laurent Delprat
- **Computing and controls infrastructure, communication and network** – Pablo Saiz
- **Safety** – Thomas Otto
- **Operation, maintenance, availability, reliability** – Jesper Nielsen
- **Transport, installation concepts** – Roberto Rinaldesi

Host State processes and civil engineering
Timothy Watson

- **Administrative processes** – Friedemann Eder
- **Placement studies** – Johannes Gutleber
- **Environmental evaluation** – Johannes Gutleber
- **Tunnel, subsurface design** – John Osborne
- **Surface sites layout, access and building design** – A. Mayoux

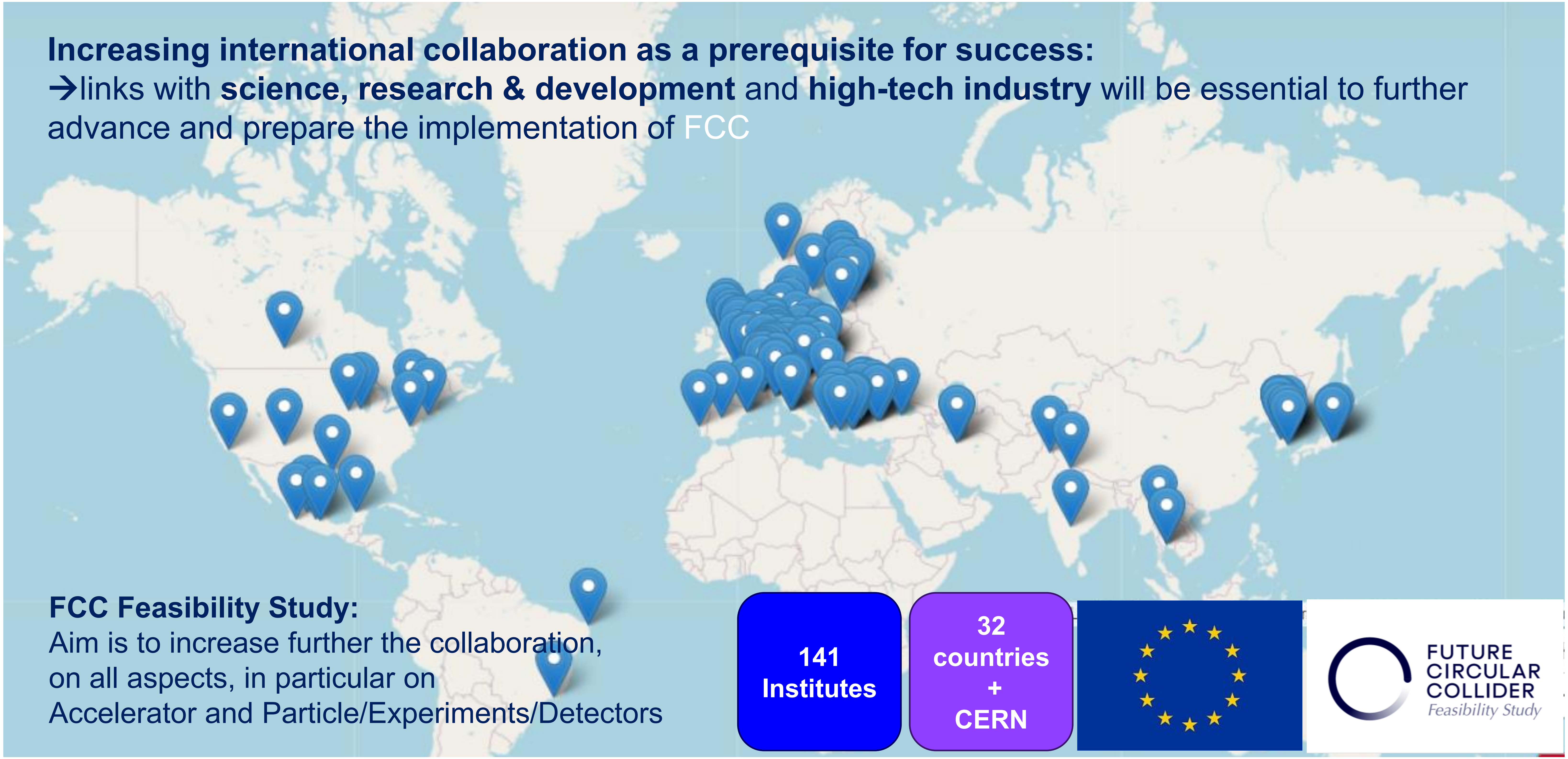
Organisation and financing models
Florian Sonnemann

- **Project organisation model** – NN
- **Financing model** – Florian Sonnemann
- **Procurement strategy and rules** – Anders Unnervik
- **In-kind contributions** – Anders Unnervik
- **Operation model** – Verena Kain

Many opportunities to engage.
Get in touch with the WG conveners!

Links:
- FCC feasibility study
- Physics, Experiments and Detectors (PED)

FCC: an international enterprise.



Increasing international collaboration as a prerequisite for success:
→links with **science, research & development** and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

FCC Feasibility Study:
Aim is to increase further the collaboration, on all aspects, in particular on Accelerator and Particle/Experiments/Detectors

141 Institutes

32 countries + CERN

FUTURE CIRCULAR COLLIDER
Feasibility Study

Some work ahead of us.

- Development of a common software and the estimate of the computing needs
- Evaluation of the physics performance and requirements for detectors
- Conceptualisation of detectors capable of delivering these requirements
- Mitigation of the interaction region constraints on detectors and vice versa
- Design of methods and tools for centre-of-mass energy calibration, beam polarisation, and monochromatization
- Understanding and optimisation of the physics programm
- Exploration of the physics opportunities
- Development of the theoretical tools and observables needed to meet the measurement targets

Construction Cost/Cost of Operation

Construction cost

Main domains for the FCC-ee project :

- Accelerators: 3 847 MCHF
- Injectors & transfer lines: 585 MCHF
- Civil engineering: 5 538 MCHF
- Technical infrastructures: 2 490 MCHF
- Experiments: 150 MCHF
- Territorial development: 191 MCHF

The total cost for FCC-ee, considering two IPs for experiments and the first three stages of operation (Z, W and ZH) is estimated to be **12 801** MCHF.

- 2 → 4 IPs: + 710 MCHF
- 365 GeV run: +1 465 MCHF

Energy and carbon footprint

- FCC-ee total instantaneous power demand at each centre-of-mass energies

J.-P. Burnet, FCC Week'22

		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Magnet current		25%	44%	66%	100%
Power ratio		6%	19%	43%	100%
PRF EL (MW)	Storage	146	146	146	146
PRFb EL (MW)	Booster	2	2	2	2
Pcryo (MW)	all	1,3	12,6	15,8	47,5
Pcv (MW)	all	33	34	36	40.2
PEL magnets (MW)	Stroage	6	17	39	89
PEL magnets (MW)	Booster	1	3	5	11
Experiments (MW)	Pt A & G	8	8	8	8
Data centers (MW)	Pt A & G	4	4	4	4
General services (MW)		36	36	36	36
Power during beam operation (MW)		237	262	291	384

Ongoing R&D

Ongoing R&D

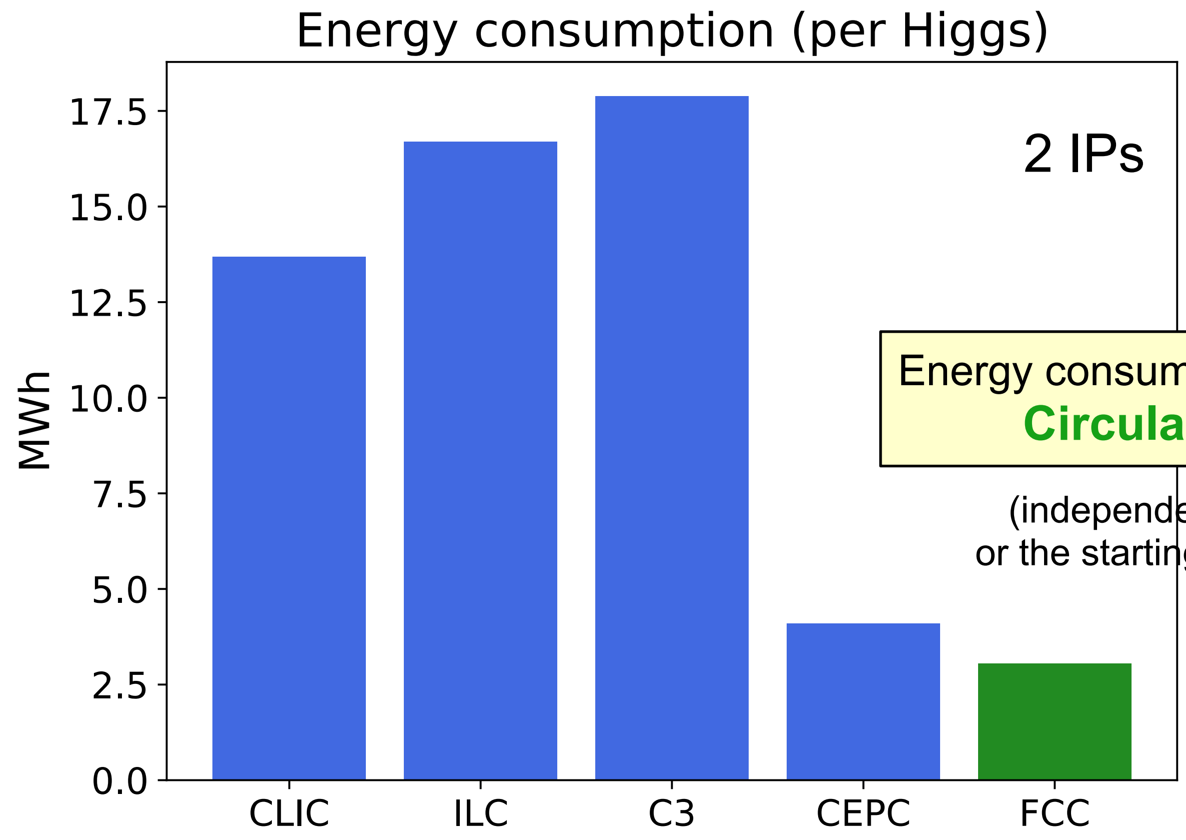
Potential energy savings

- At 240 GeV, the instantaneous power of FCC-ee amounts to 291 MW
  - As a comparison, $P(ILC_{250})$=140 MW, $P(CLIC_{380})$=110 MW : less power hungry than FCC-ee?
    - Not clear: both produce (2 to 4 times) less Higgs than FCC-ee_{240}, with (3 to 6 times) longer running time

Energy and carbon footprint

- Our first responsibility (as particle physicists) is to do the maximum of science
  - With the minimal energy consumption and the minimal environmental impact for our planet
    - Should become one of our top-level decision criteria for design, choice and optimization of a collider

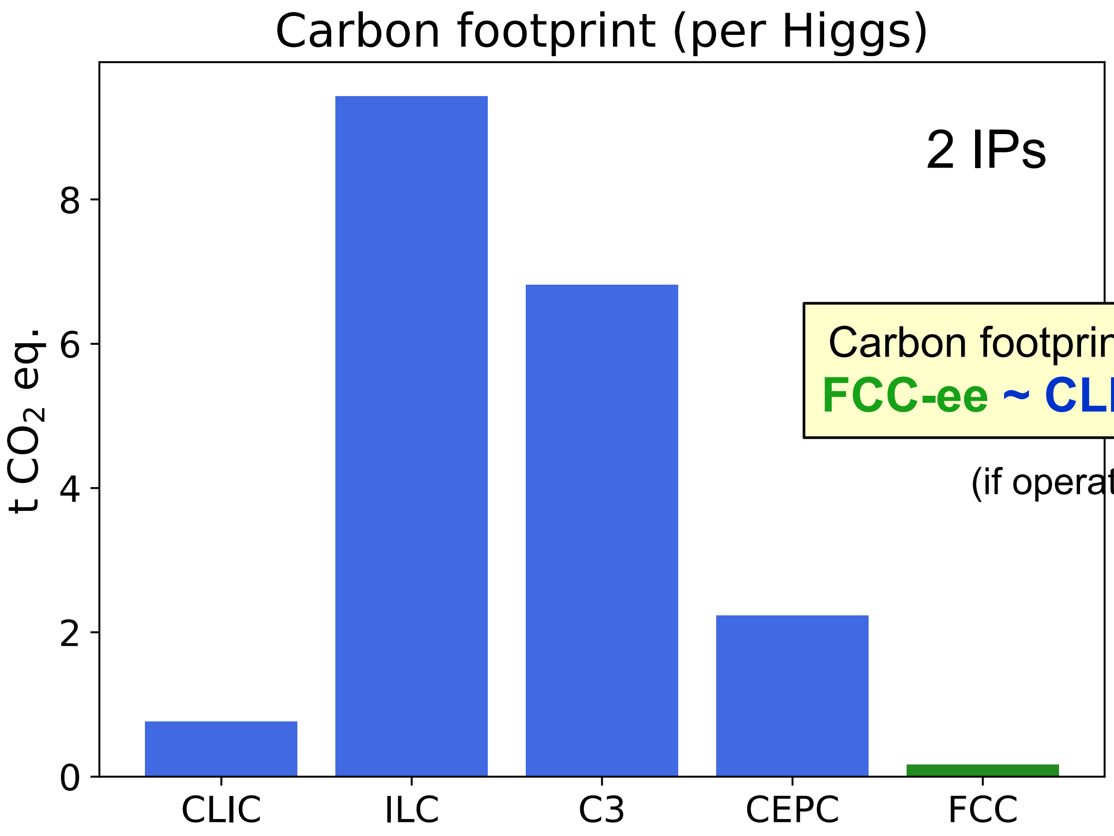
- All Higgs factories have a "similar" physics outcome (ESU'20 and Snowmass'21)
  - Natural question: what is their energy consumption or carbon footprint for the same physics outcome?
    - Circular colliders have a much larger instantaneous luminosity and operate several detectors
    - FCC-ee is at CERN, where electricity is already almost carbon-free (and will be even more so in 2048)



arXiv:2208.10466

Energy consumption / Higgs with 2IP
Circular ~ Linear / 5

(independently of the location or the starting time of the collider)



Carbon footprint / Higgs with 2IP
FCC-ee ~ CLIC / 5 ~ ILC / 50

(if operating today)

Cost of Operation

The total electrical energy consumption over the fourteen years of the FCC-ee research programme is estimated to be around 27 TWh [58], corresponding to an average electricity consumption of 1.9 TWh/year over the entire operation programme, to be compared with the 1.2 TWh/year consumed by CERN today and the expected 1.4 TWh/year for HL-LHC[9]. At the CERN electricity prices from 2014/15, the electricity cost for FCC-ee collider operation would be about 85 MEuro per year. In the HZ running mode, about one million Higgs bosons are expected to be produced in three years, which sets the price of each FCC-ee Higgs boson at 255 Euros. A similar exercise can be done for the first stage of CLIC, expected to consume 0.8 TWh/year over 8 years at 380 GeV to produce about 150,000 Higgs bosons, which sets the price of a CLIC Higgs boson at about 2000 Euros. Finally, with the official ILC operation cost in Japan of 330 MEuro per year [10], its 11.5 to 18.5 years of operation (Section 5), and the 500,000 Higgs bosons produced in total, the price of an ILC Higgs boson is between 7,000 and 12,000 Euros, i.e., between 30 and 50 times more expensive than at FCC-ee. These operation costs are summarized in Table 8.

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

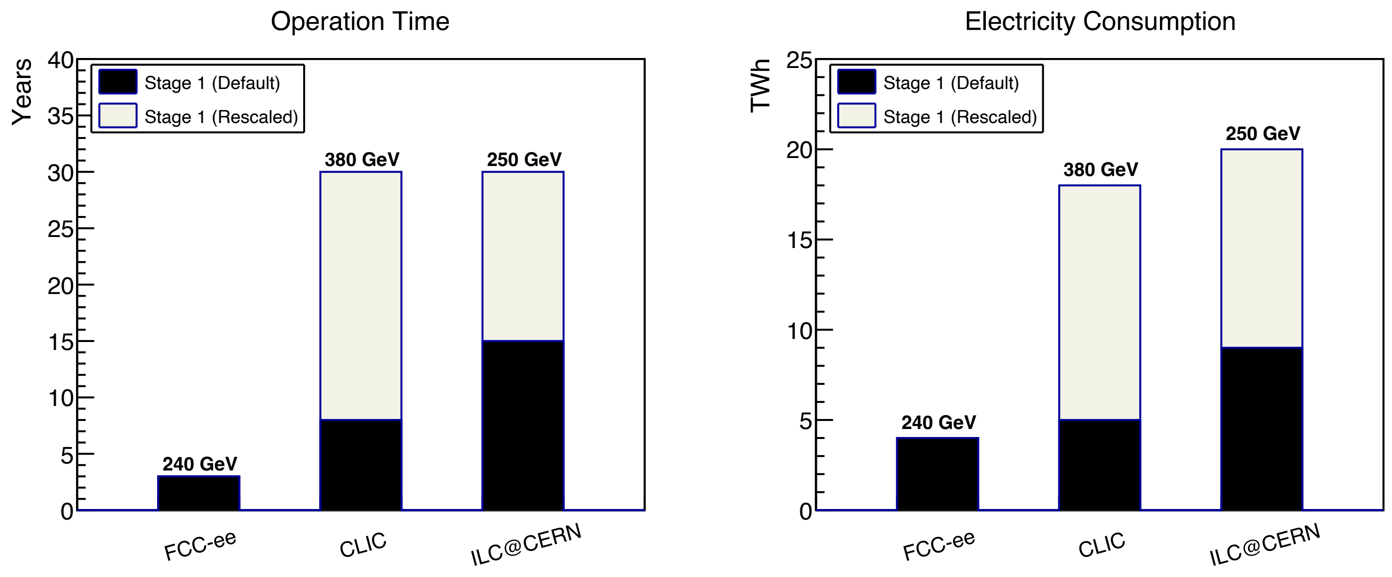
Duration of Operation

normalised to same physics/Higgs output

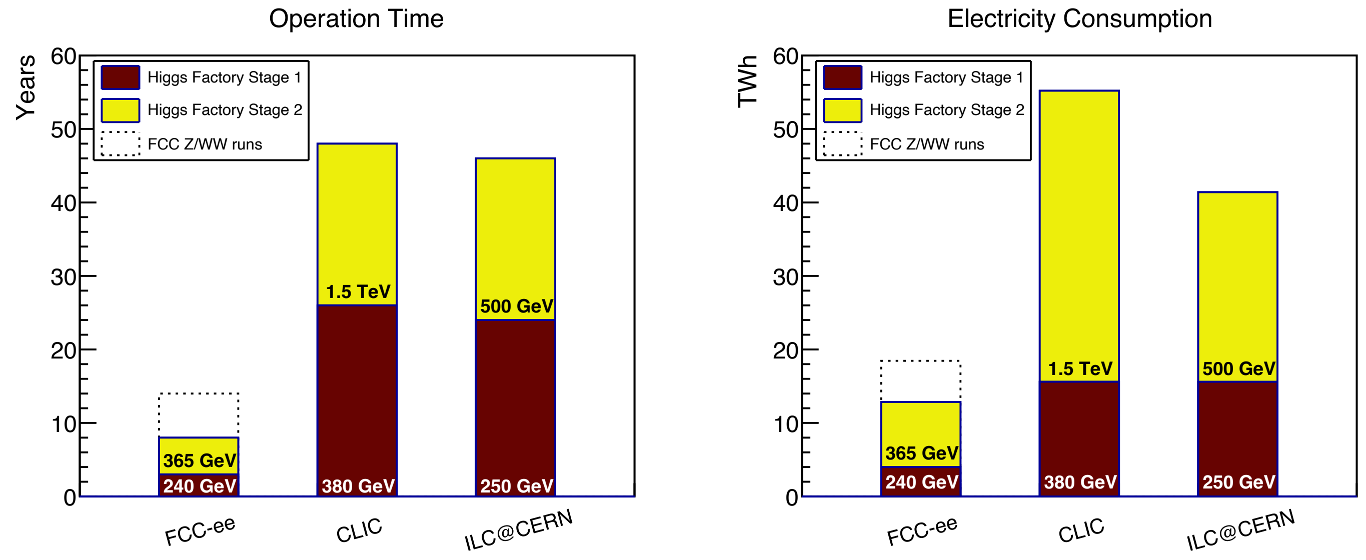
baseline plans

Collider	Longitudinal Polarisation (e^-, e^+) (%)	$\sqrt{s}$ (GeV)	Integrated Luminosity (ab^{-1})	Time (Years)
FCC-ee	$0, 0$	240	**10.8**	3
		350	**0.42**	1
		365	**2.70**	4
CLIC	$\pm 80, 0$	380	**1.5**	8
		1500	2.5	7
ILC	$\pm 80, \pm 30$	250	2	**15**
		350	0.1	**1.5**
		500	4	**11.5**
	$\pm 80, \pm 20$	1000	8	**13**

but different physics output



first energy stage (240GeV FCC)



upgraded energy stage (365GeV FCC)

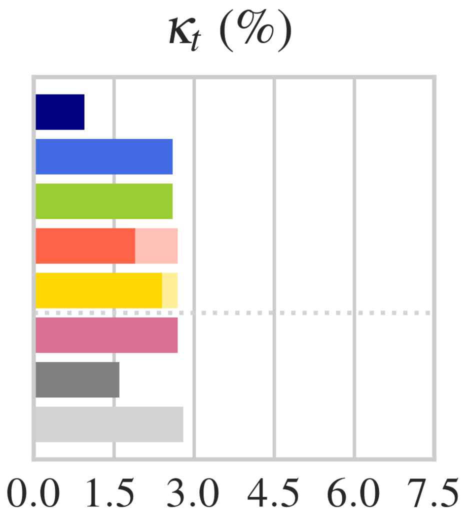
FCC-ee/FCC-hh Interplay

Synergy ee↔hh.

1 FCC-hh without ee could bound BR_{inv} but it could say nothing about $BR_{untagged}$ (FCC-ee needed for absolute normalisation of Higgs couplings)

2 FCC-hh is determining top Yukawa through ratio tth/ttZ

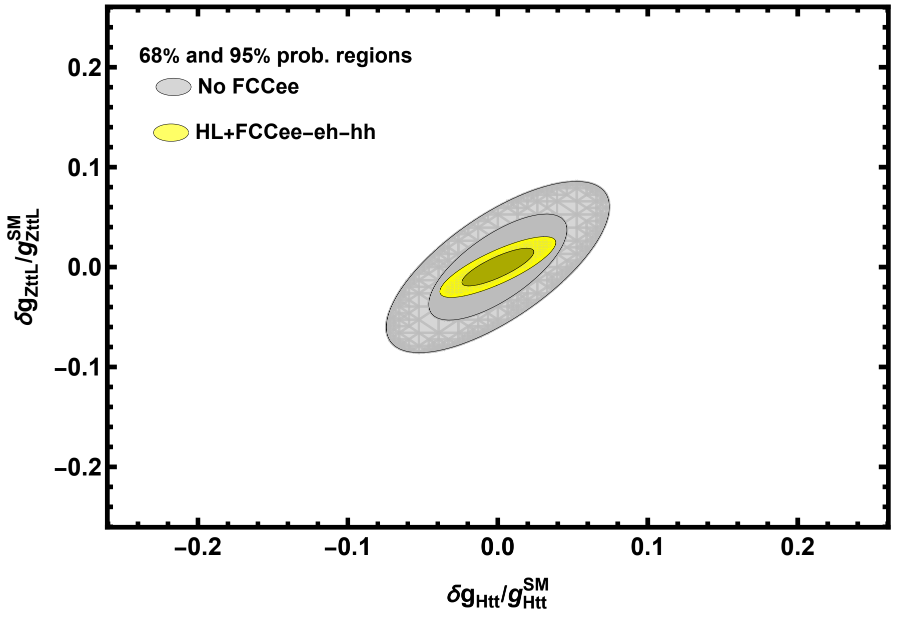
So the extraction of top Yukawa heavily relies on the knowledge of ttZ from FCC-ee



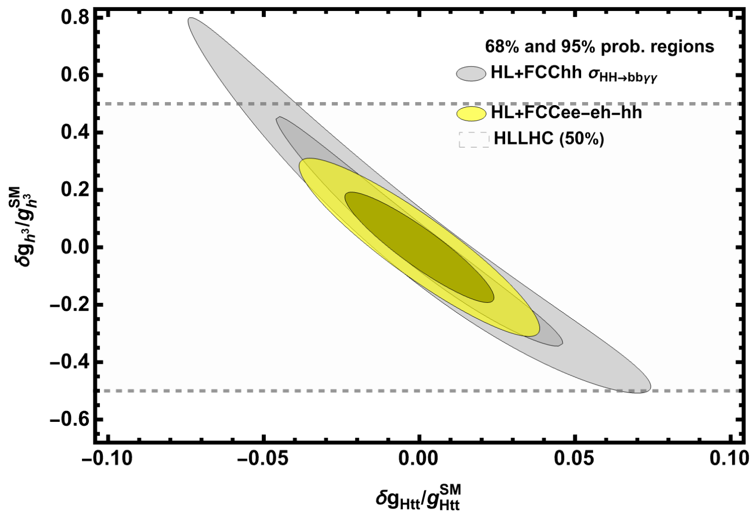
Mangano+ '15

	$\sigma(t\bar{t}H)$[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)



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



Plots from mid-term report

Higgs and EW measurements

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.) Warning	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit) **Warning**	LEP/SLD (Z-pole) + HL-LHC + W (ILC)	Yes (500 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom) Warning	Yes	No
CLIC	Yes (μ, σ_{ZH})	Yes (Full EFT parameterization)	LEP/SLD (Z-pole) + HL-LHC + W (CLIC)	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	-

EW Precision Measurements at FCC-ee

Observable	present value	±	error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

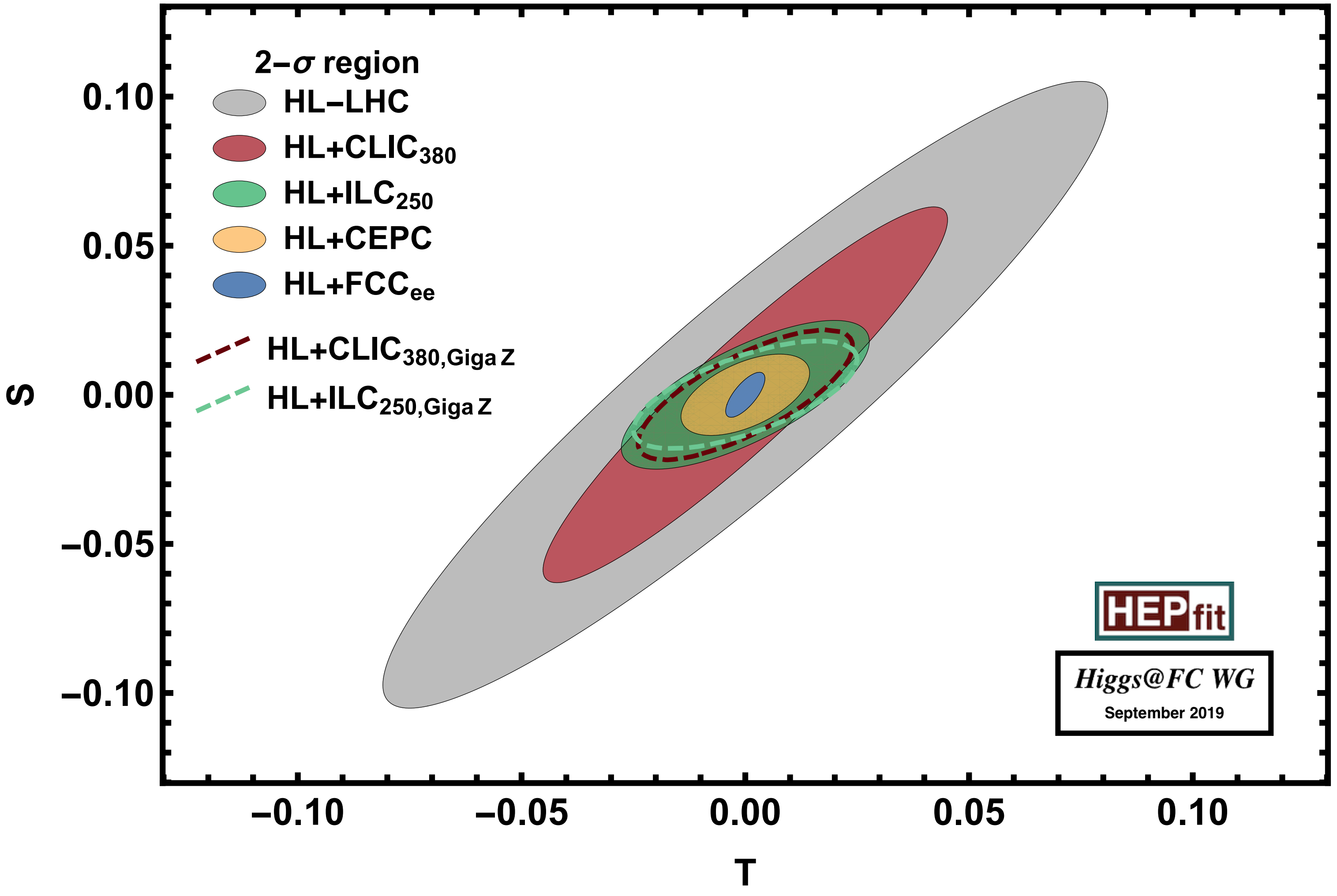
Experimental (statistical and systematic) precision of a selection of measurements accessible at FCC-ee, compared with the present world-average precision. FCC-ee syst. scaled down from LEP estimates. Room for improvement with dedicated studies. Note that syst. go down also with stat. (e.g. beam energy determination from ee→Z/γ thus goes down with luminosity).

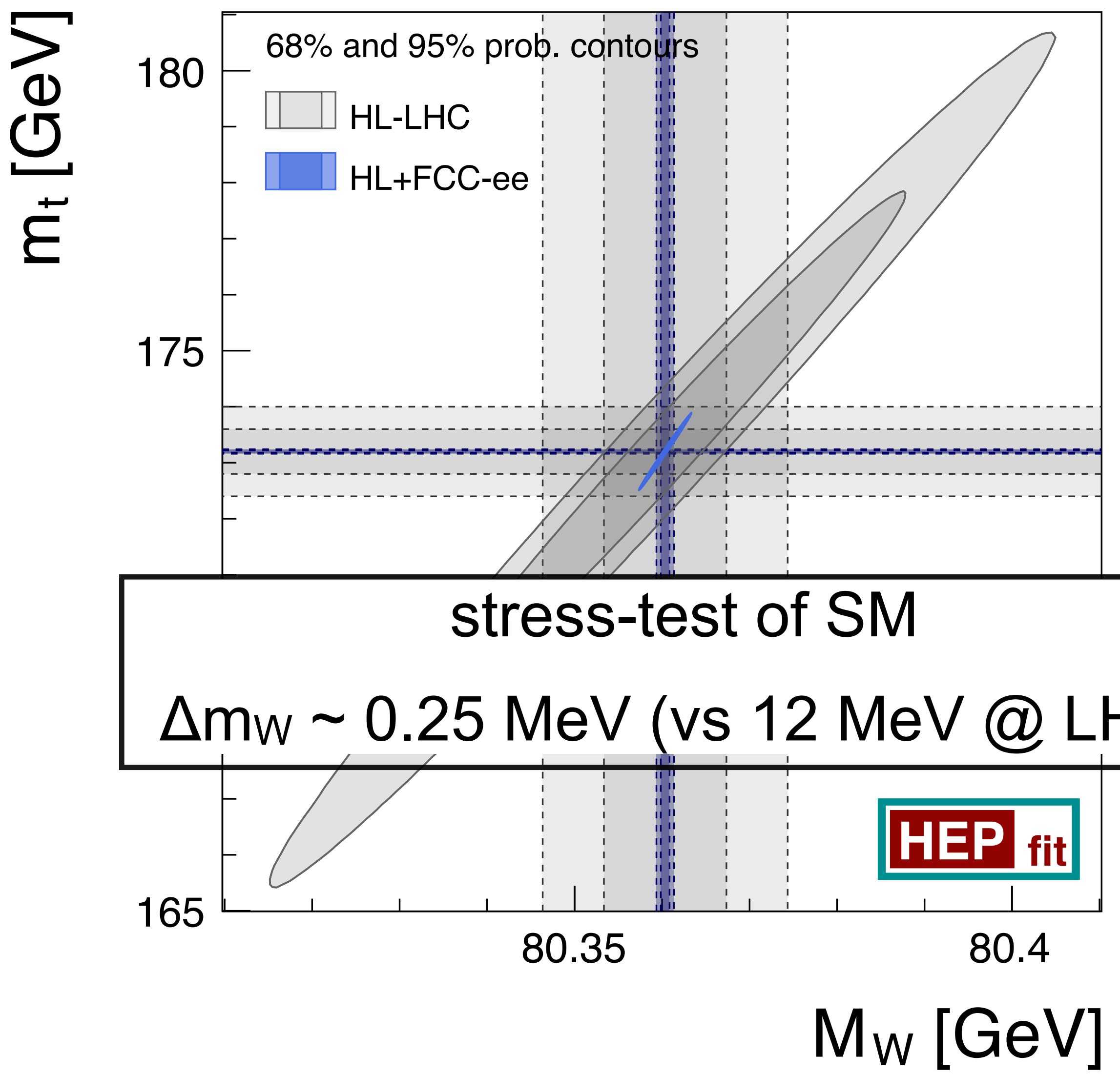
Table from mid-term report

Improvements of EW measurements

Exquisite measurements of m_Z (100 keV) , Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5}) (all unique to FCC-ee)

w/. stat.+ param. + th-exp syst.





stress-test of SM

Δm_W ~ 0.25 MeV (vs 12 MeV @ LHC)

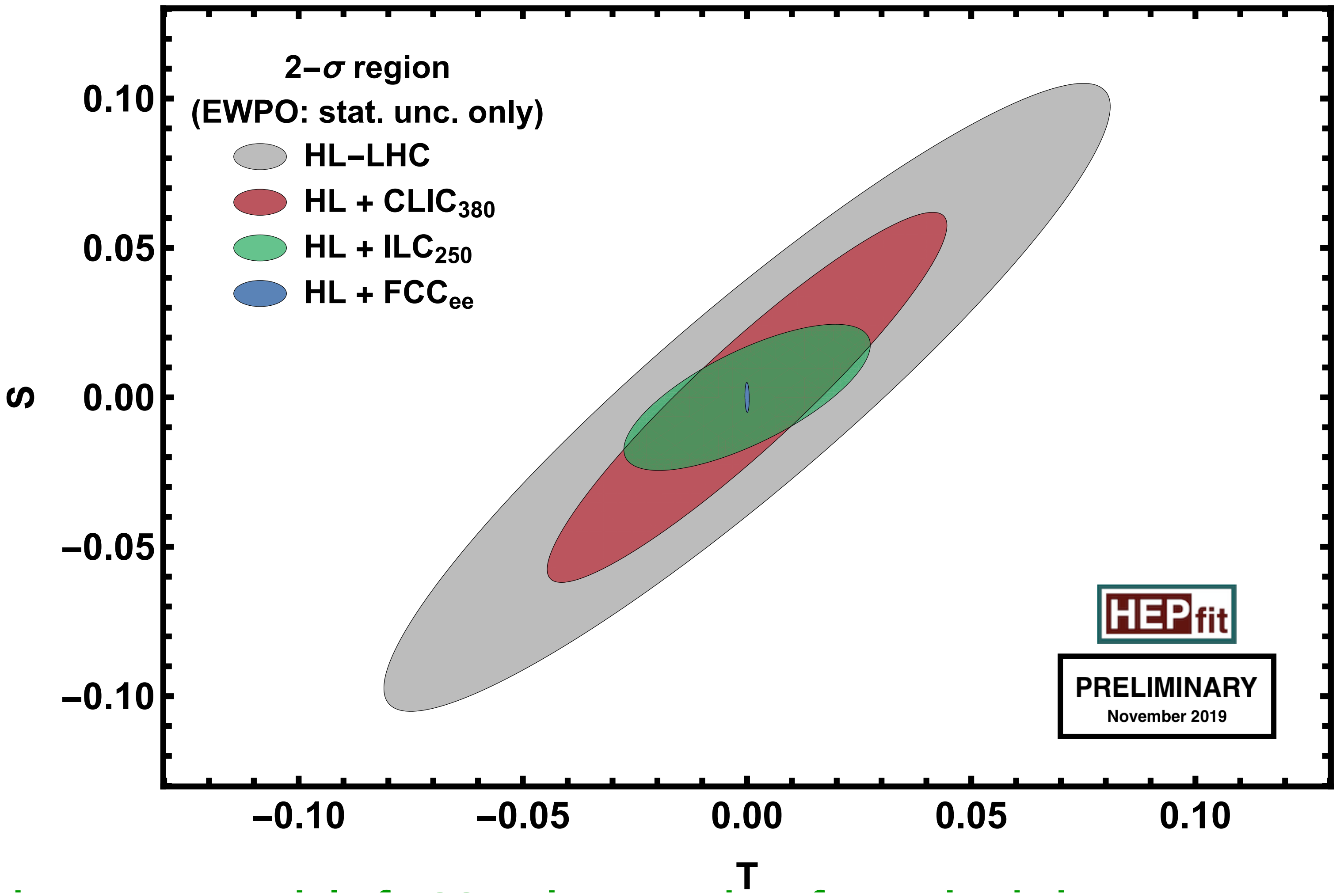
The importance of improved EW measurements is threefold:

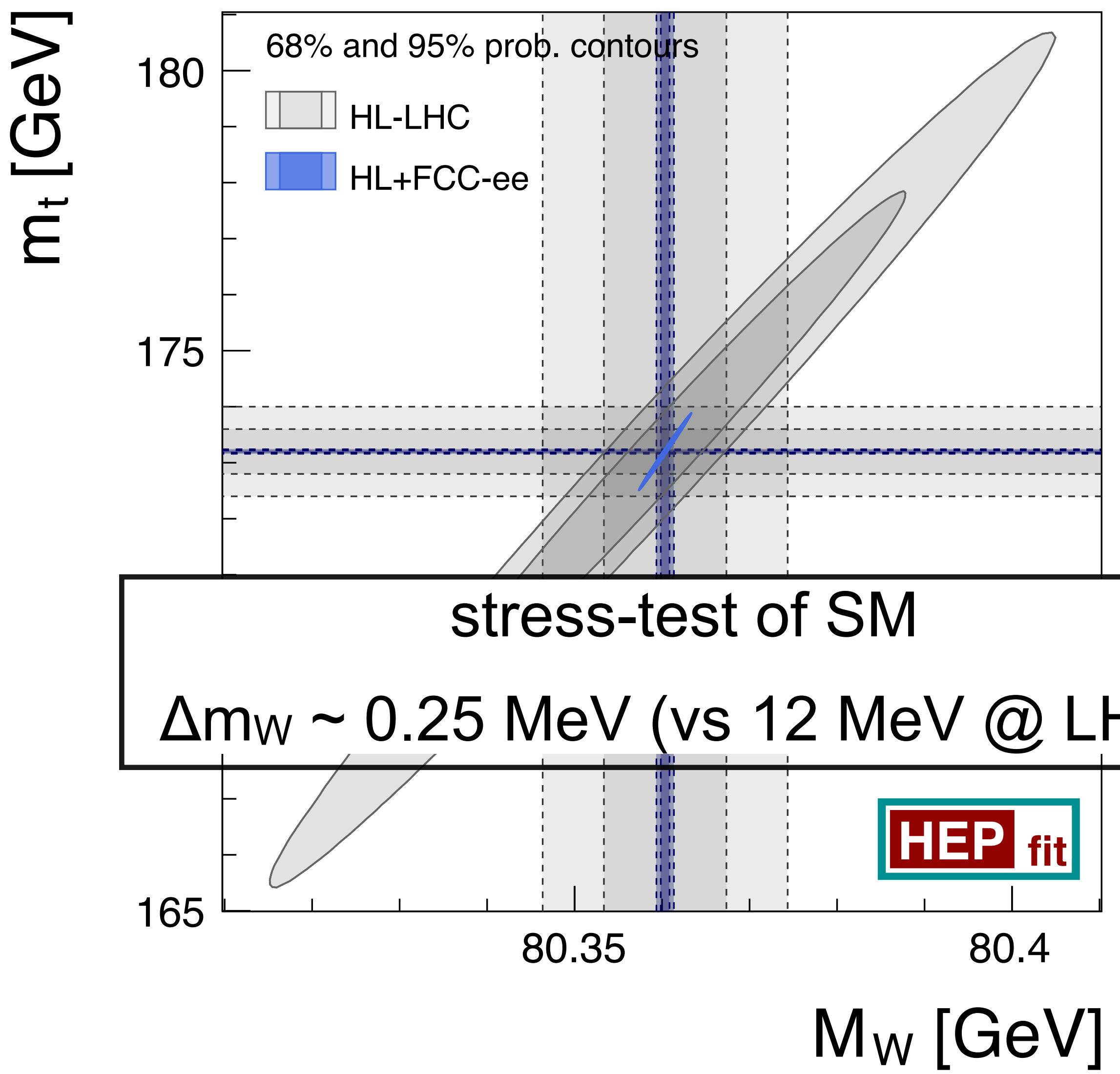
1) improve mass reach in indirect search for NP ($S \sim 10^{-2} \rightarrow M \sim 70$ TeV)
2) reduced parametric uncertainties for other measurements
3) reduced degeneracies in a global fit for Higgs couplings

Improvements of EW measurements

Exquisite measurements of m_Z (100 keV) , Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5}) (all unique to FCC-ee)

w/ stat. and param. only





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Systematics vs. Statistics.

- We often hear that more Z pole statistics is useless, because they are systematics-limited
  - This is a passive attitude, which leads to pessimistic expectations and wrong conclusions/planning
    - Experience shows that a careful experimental systematic analysis boils down to a statistical problem
    - If well prepared, theory will go as far as deemed useful : this preparation starts today (and needs SUPPORT)
    - We are working in the spirit of matching systematic errors to expected statistics for all precision measurements
  - Take the Z lineshape

FCC-ee special

$\alpha_{QED}(m_Z)$: Stat. 3×10^{-5}

Obtained at FCC-ee from off-peak asymmetries (87.9 & 94.3 GeV): for the first time, it is a direct measurement of this quantity (game changer)

- Enters as a limiting parametric uncertainties in the new physics interpretation many past and future measurements.
- Is statistics limited and will directly benefit from more luminosity
- No useful impact on $\alpha_{QED}(m_Z)$ with five times less luminosity

$\sin^2\theta_W^{eff}$ and Γ_Z (also m_W vs m_Z) : Stat. 2×10^{-6} and 4 keV

Error dominated by point-to-point energy uncertainties.
Based on in-situ comparisons between $\sqrt{s}$ (e.g. with muon pairs), with measurements made every few minutes (100's times per day)
Boils down to

- statistics (the more data the better, scales down as $1/\sqrt{L}$)
- detector systematics (uncorrelated between experiments, scales down a $1/\sqrt{N_{experiments}}$)

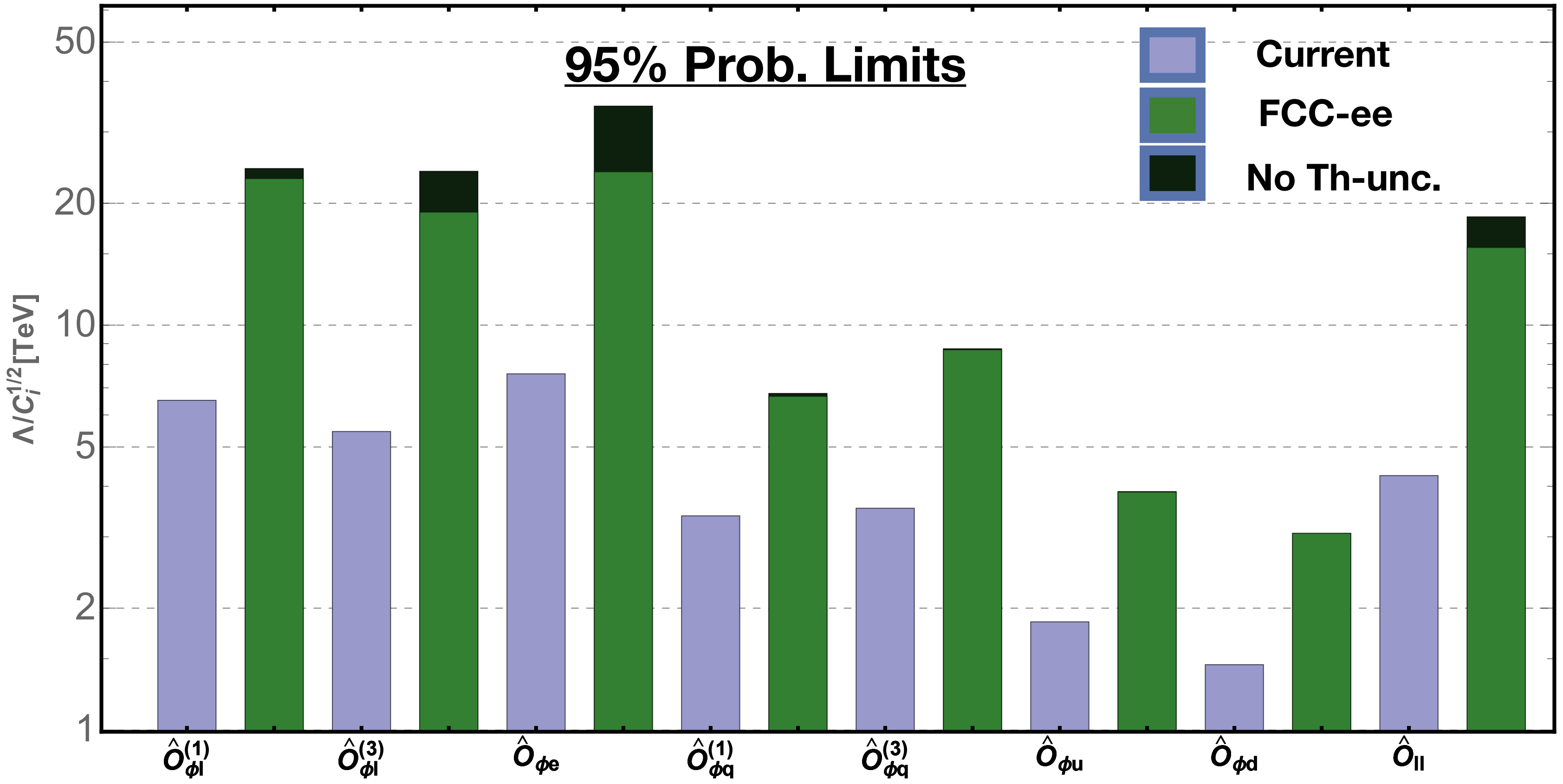
Z (and W) mass: Stat. 4 keV (250 keV)

Error dominated by $\sqrt{s}$ determination with resonant depolarization.
As more understanding is gained, progress are made at a constant pace, and this error approaches regularly the statistical limit

- Most of the work is (will be) on systematics
  - But huge statistics will turn into better precision
    - ➔ A real chance for discovery

Impact of TH uncertainties.

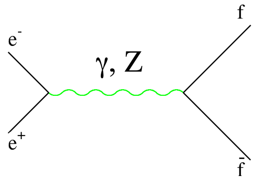
J. de Blas, FCC CDR overview ‘19



	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
δM_W [MeV]	± 15	± 8	± 1	$\pm 0.6/\pm 1$	± 1
$\delta \Gamma_Z$ [MeV]	± 2.3	± 0.73	± 0.1	± 0.1	± 0.2
$\delta \mathcal{A}_\ell\,[\times 10^{-5}]$	± 210	± 93	± 2.1	$\pm 8/\pm 14$	± 11.8
$\delta R_b^0\,[\times 10^{-5}]$	± 66	± 3	± 6	± 0.3	$\pm$ 5

Some EW measurements @ Tera

measure $\sigma(e^+e^- \to \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$ at (a) judicious $\sqrt{s}$



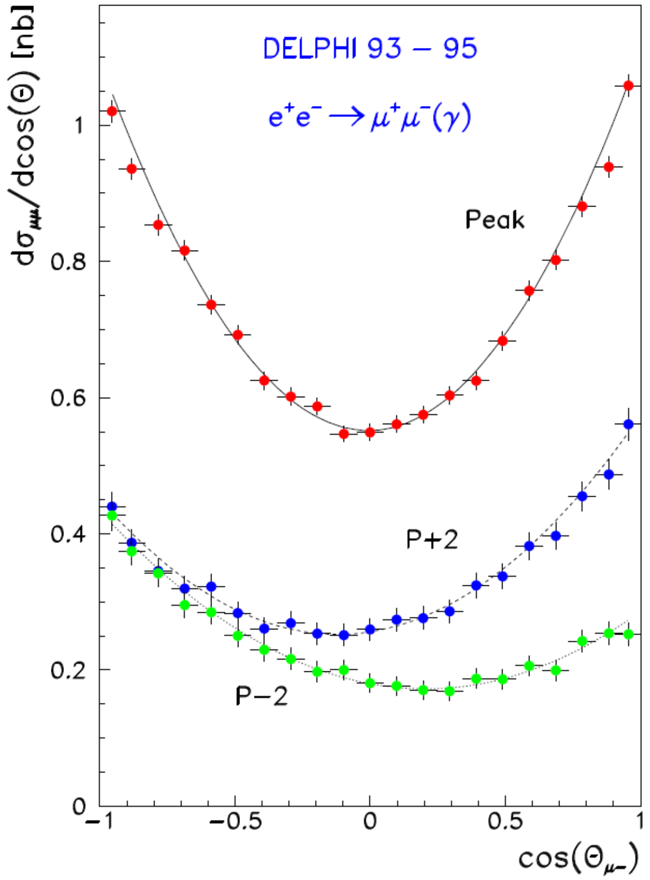
The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$
The Z exchange term is proportional to G^2_F, hence independent of α_{QED}
The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$

Excellent experimental control of off-peak di-muon asymmetry motivates campaign to collect 50-80 ab^{-1} off peak to gain highest sensitivity to Z-γ interference

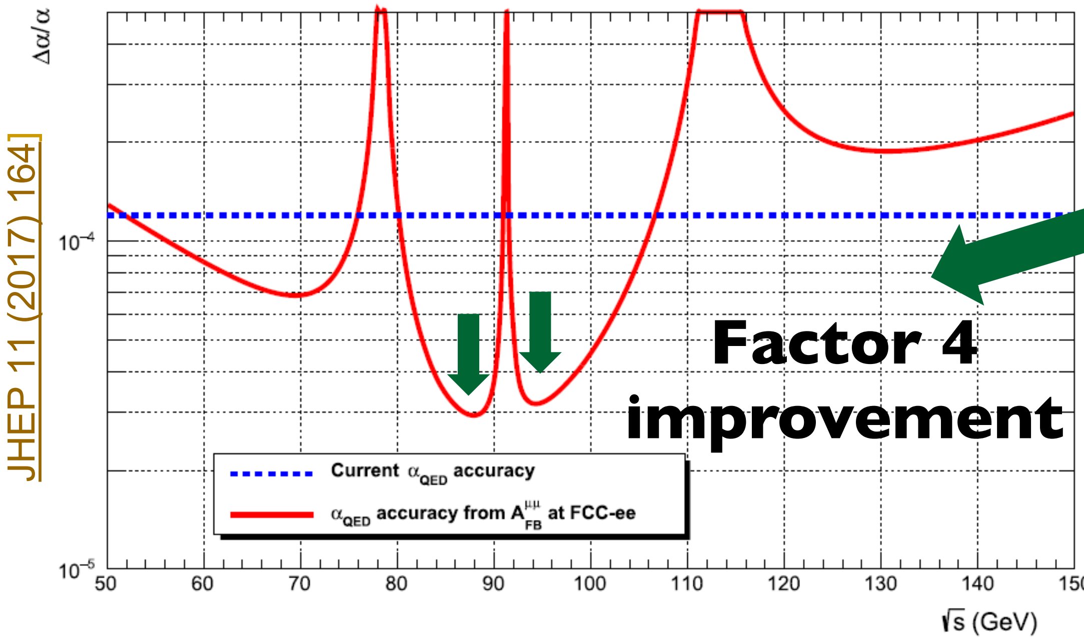
strongly depends on $\sqrt{s}$ ←
direct measurement of $\alpha_{QED}(s)$ at $\sqrt{s}$!= m_Z ←
measure $\sin^2\theta_W$ to high precision ←

$$A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4}\mathcal{A}_e\mathcal{A}_\mu \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{QED}(s)}{m_Z^2 G_F\left(1-4\sin^2\theta_W^{eff}\right)^2}\frac{s-m_Z^2}{2s}\right]$$

Allows for clean determination of $\alpha_{QED}(m_Z^2)$, which is a *critical* input for m_W closure tests (see later).



relative α_{QED} uncertainty with 80 ab^{-1}



Factor 4 improvement

P.Janot '16
[JHEP 02 (2016) 053,
JHEP 11 (2017) 164]

This dependence, & location of half-integer spin tunes, guides the choice of off-peak energies: 87.8 & 93.9 GeV.

→ Measure $\alpha_{QED}(m_Z^2)$ to 3×10^{-5} rel. precision (currently 1.1×10^{-4})
→ Stat. dominated; syst. uncertainties < 10^{-5} (dominated by $\sqrt{s}$ calib)
→ Theoretical uncertainties ~ 10^{-4}, higher order calcs needed

G. Wilkinson @ FCC week 2021

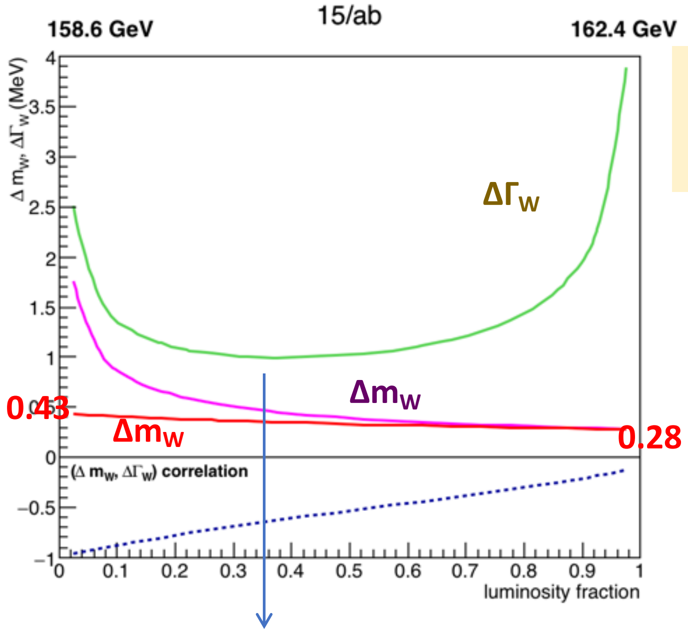
Mw.

- Two independent W mass and width measurements @FCCee :

1. **The** m_W and Γ_W determinations from the WW threshold cross section lineshape, with 12/ab at $E_{CM} \simeq$ 157.5-162.5 GeV **Δm_W=0.4 MeV $\Delta\Gamma_W$=1 MeV**

2. Other measurements of m_W and Γ_W from the decay products kinematics at $E_{CM} \simeq$ 162.5-240-365 GeV **Δm_W, $\Delta\Gamma_W$= 2-5 MeV ?**

Scans of possible E_1 E_2 data taking energies and luminosity fractions f (at the E_2 point)



Δm_W =0.45 MeV , $\Delta\Gamma_W$=1 MeV (r=-0.6)
Δm_W=0.35 MeV

A -minimum of **$\Delta\Gamma_W$=0.91 MeV** with **Δm_W=0.55 MeV**
taking data at E_1=**156.6** GeV E_2=**162.4** GeV f=**0.25**
yields **Δm_W=0.47 MeV** (as single par)

B- minimum of **Δm_W=0.28 MeV** **$\Delta\Gamma_W$=3.3 MeV** with
E_1=**155.5** GeV E_2=**162.4** GeV f=**0.95**
yields **Δm_W=0.28 MeV** (as single par)

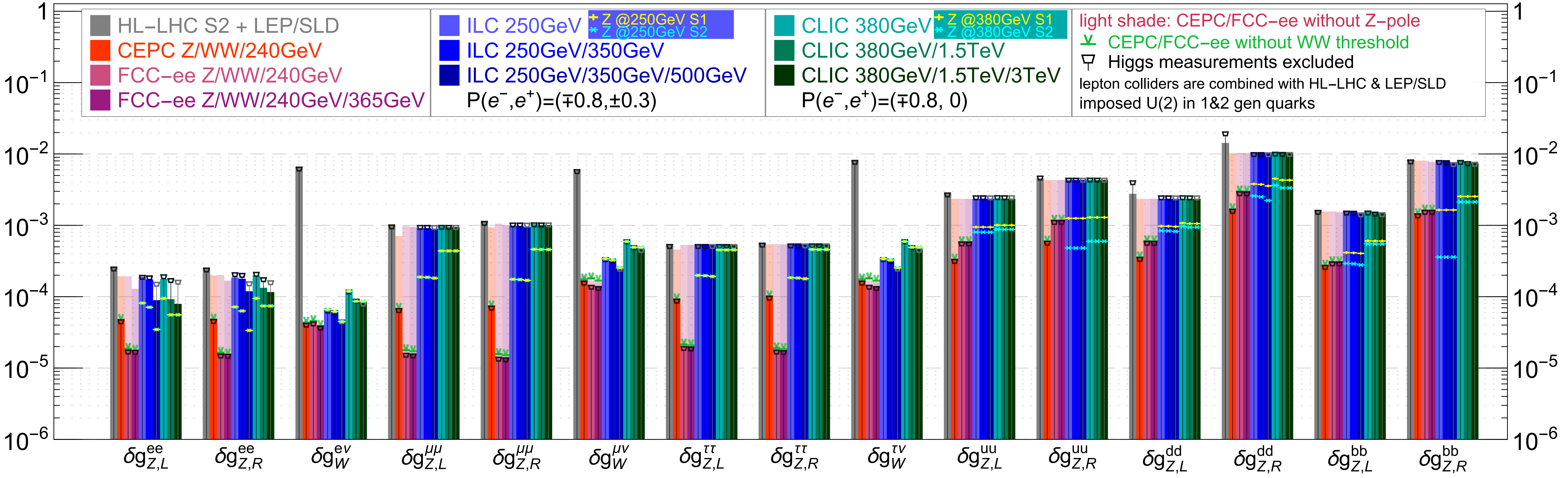
C- minimum of **$\Delta\Gamma_W$=0.96 MeV** +**Δm_W=0.41 MeV** with
E_1=**157.5** GeV E_2=**162.4** GeV f=**0.45**
yields and **Δm_W=0.37 MeV** (as single par)

Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both
Δm_W : error on W mass from fitting only m_W

FCC workshop - 27 Jan 2023 P.Azzurri - W mass and width

Sensitivity on EW couplings.

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



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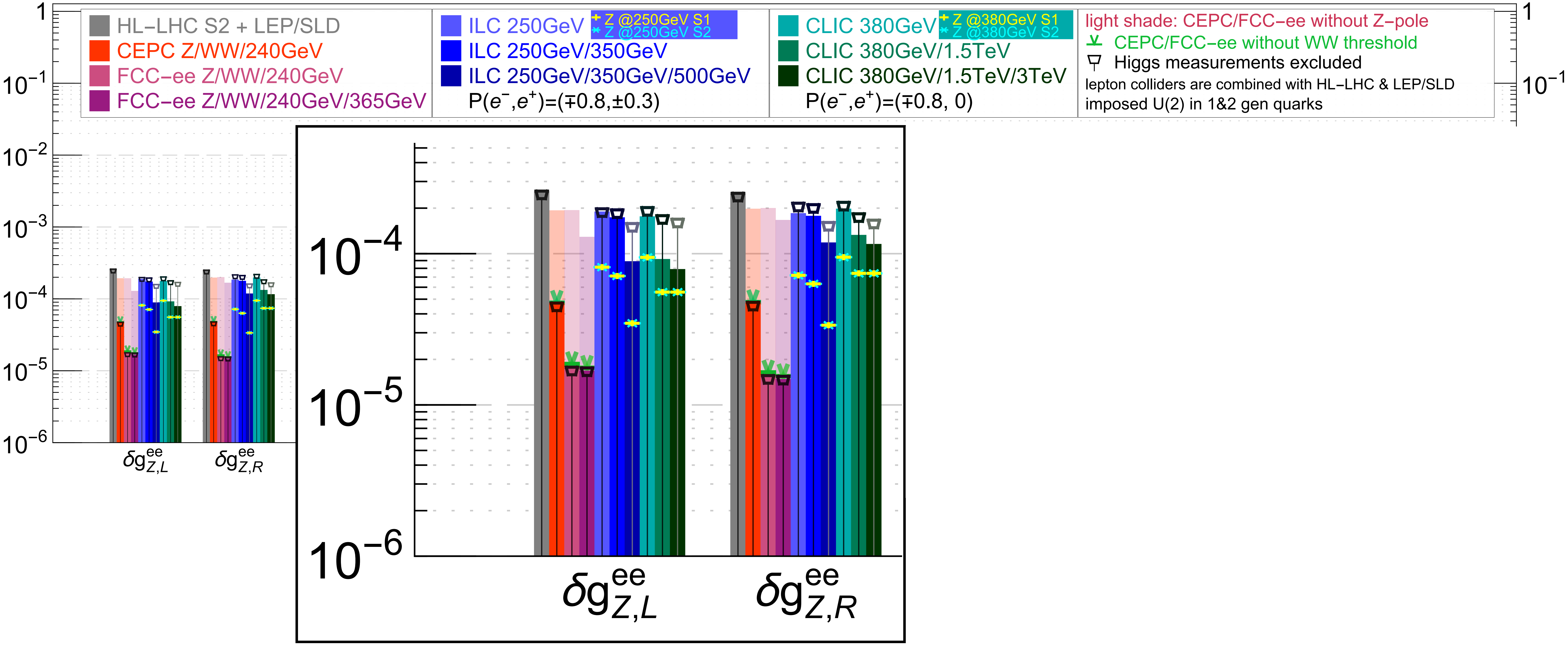

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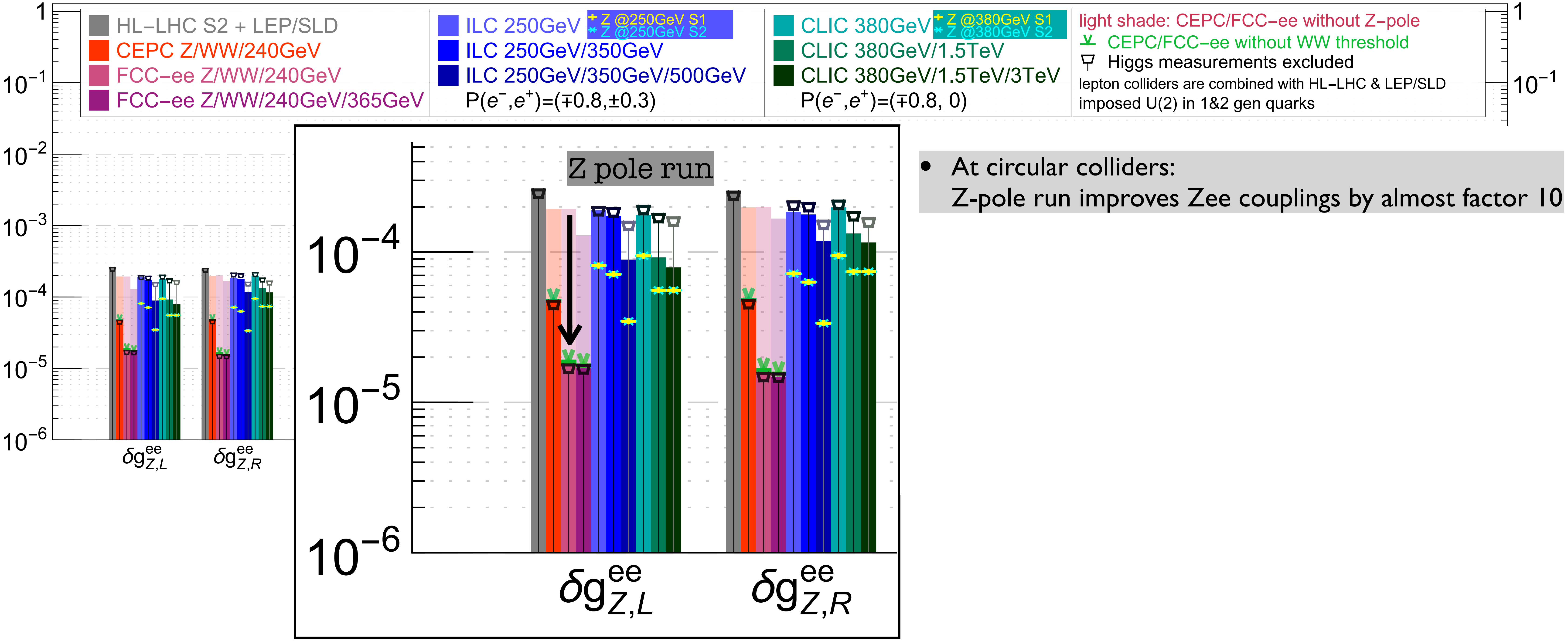

- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10

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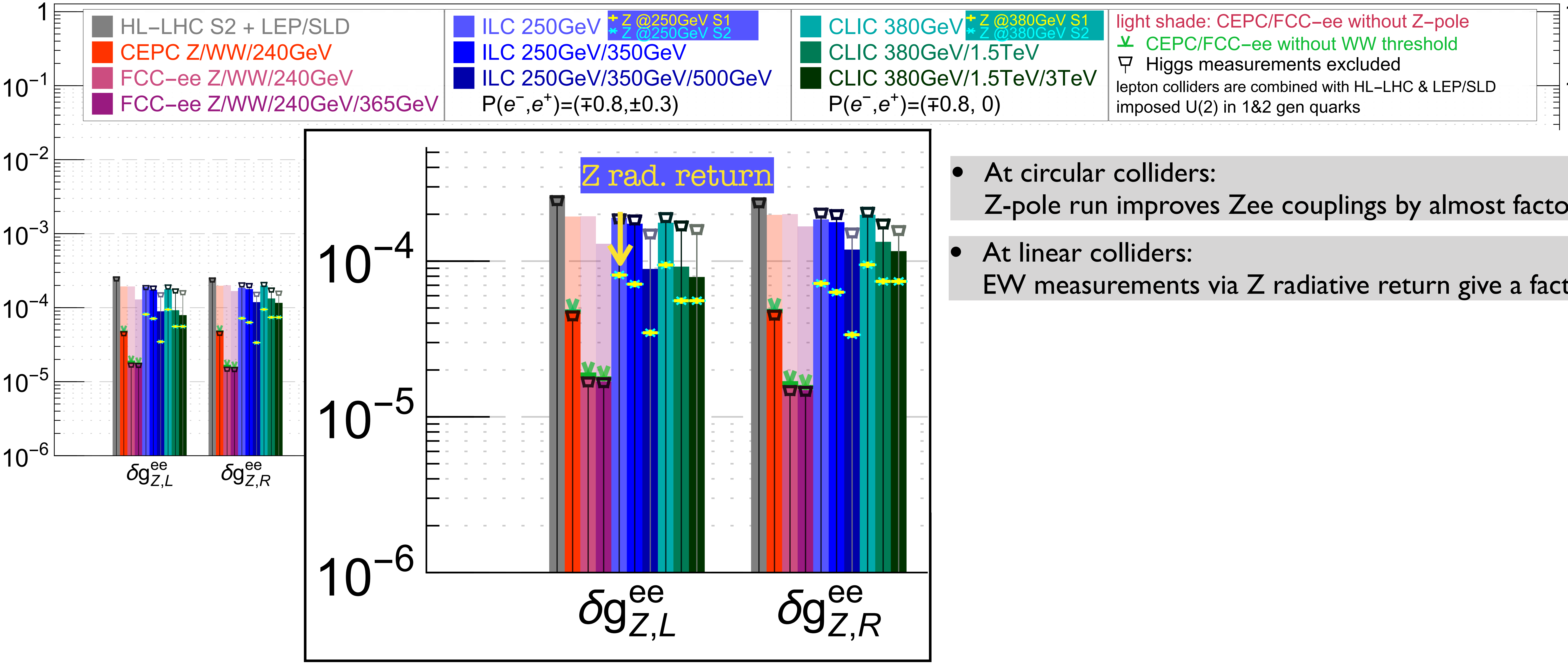
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



- At circular colliders:
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- At linear colliders:
  EW measurements via Z radiative return give a factor 3

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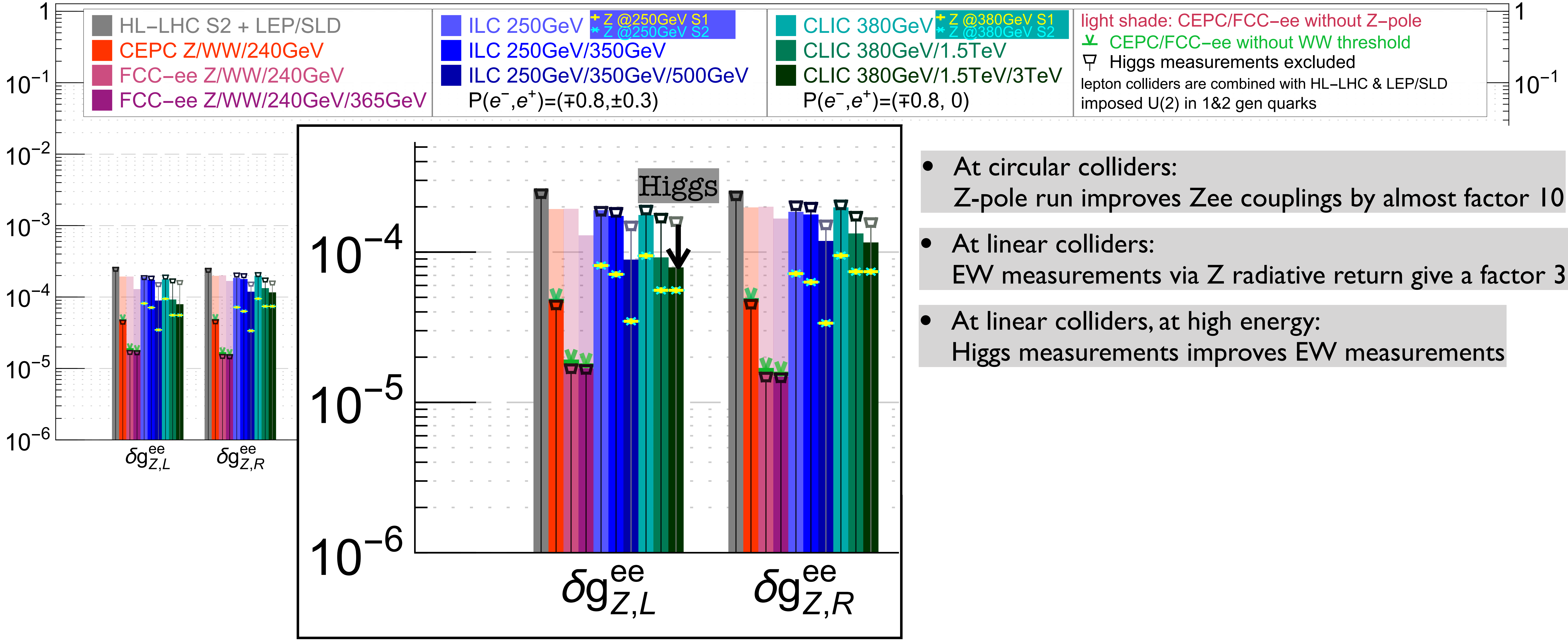
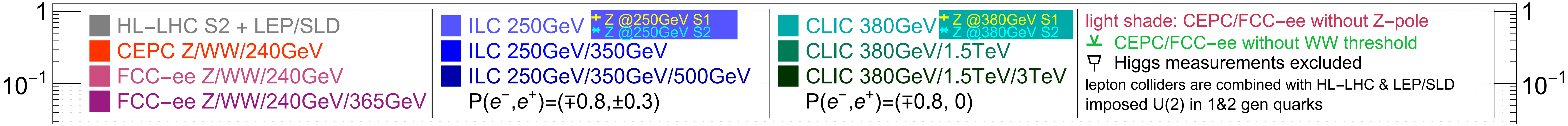


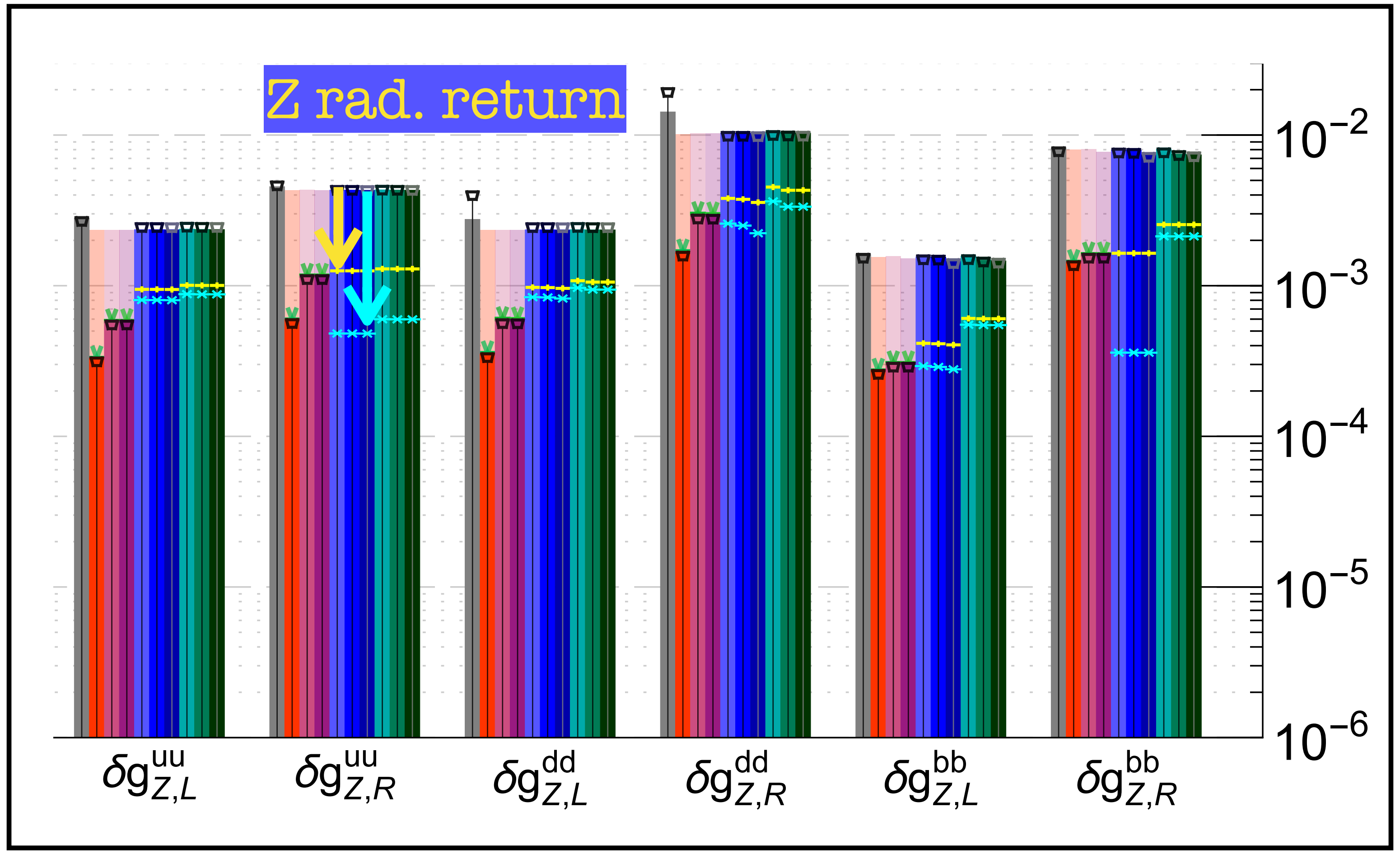
- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings.

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

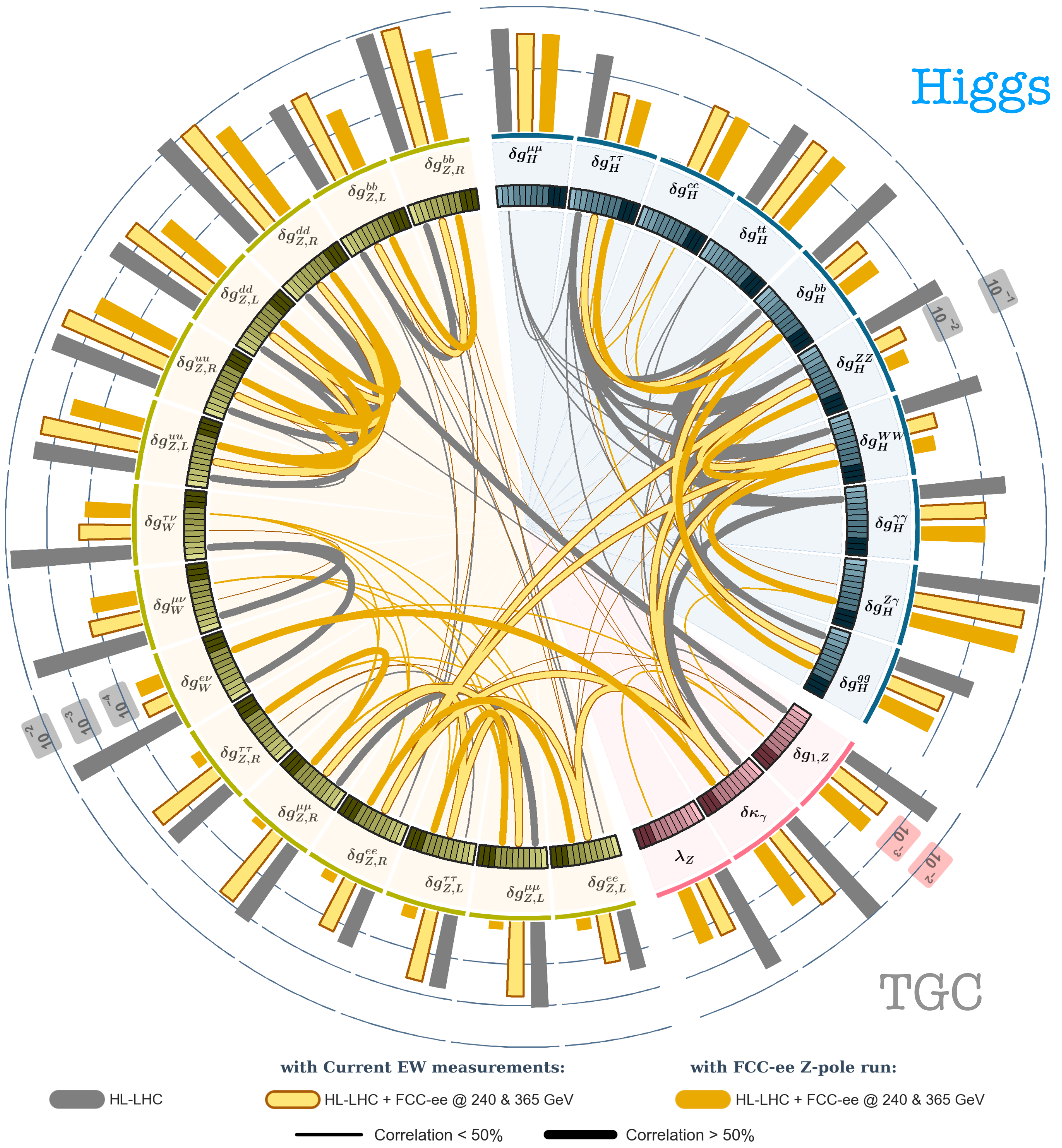


- At linear colliders, at high energy:
  EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
  Yellow: LEP/SLD systematics / 2
  Blue: small EXP and TH systematics



Why Z-pole for Higgs?

J. De Blas et al. 1907.04311



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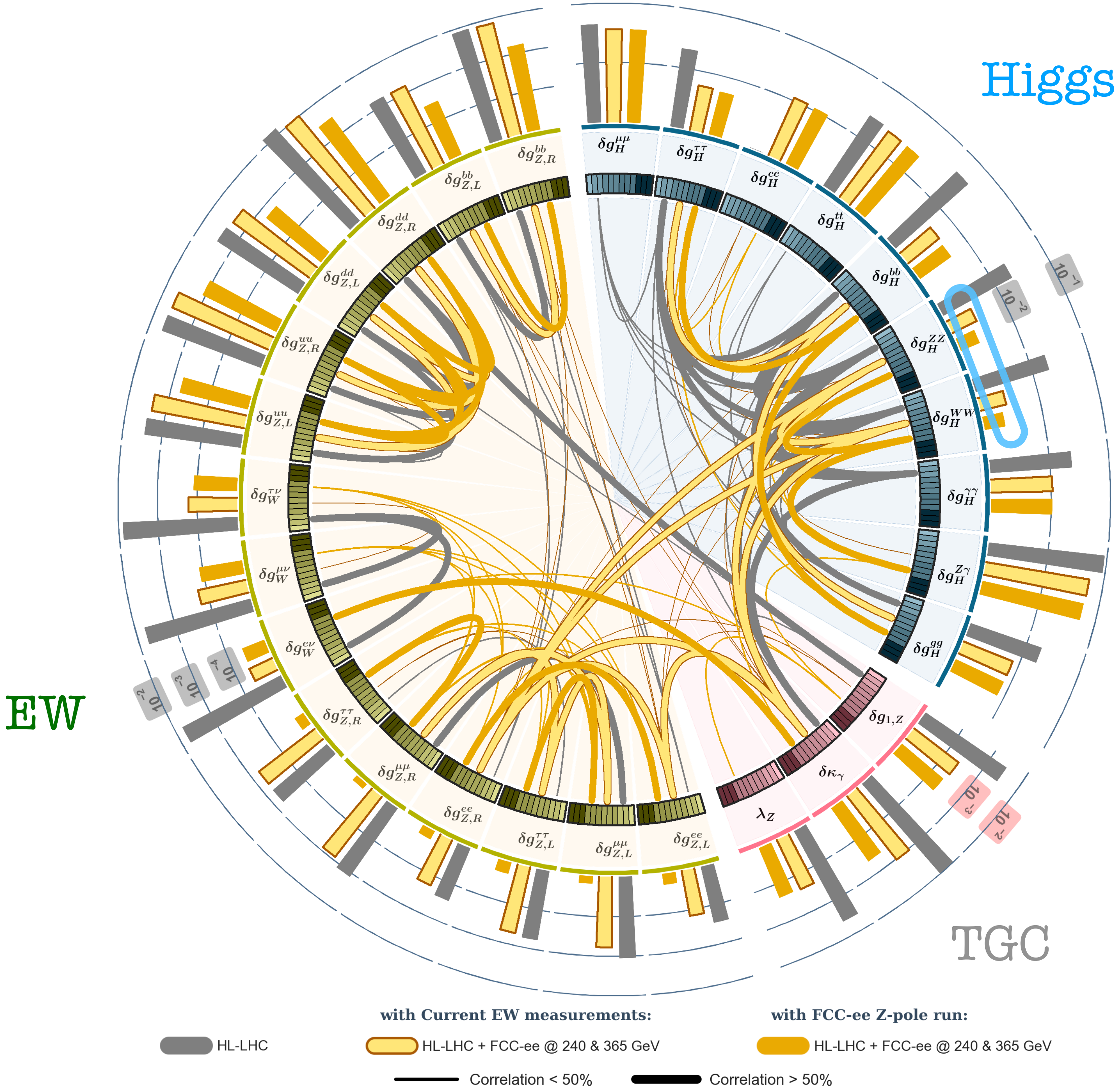

With Z-pole measurements,
Higgs coupling determination improves
by up to 50%

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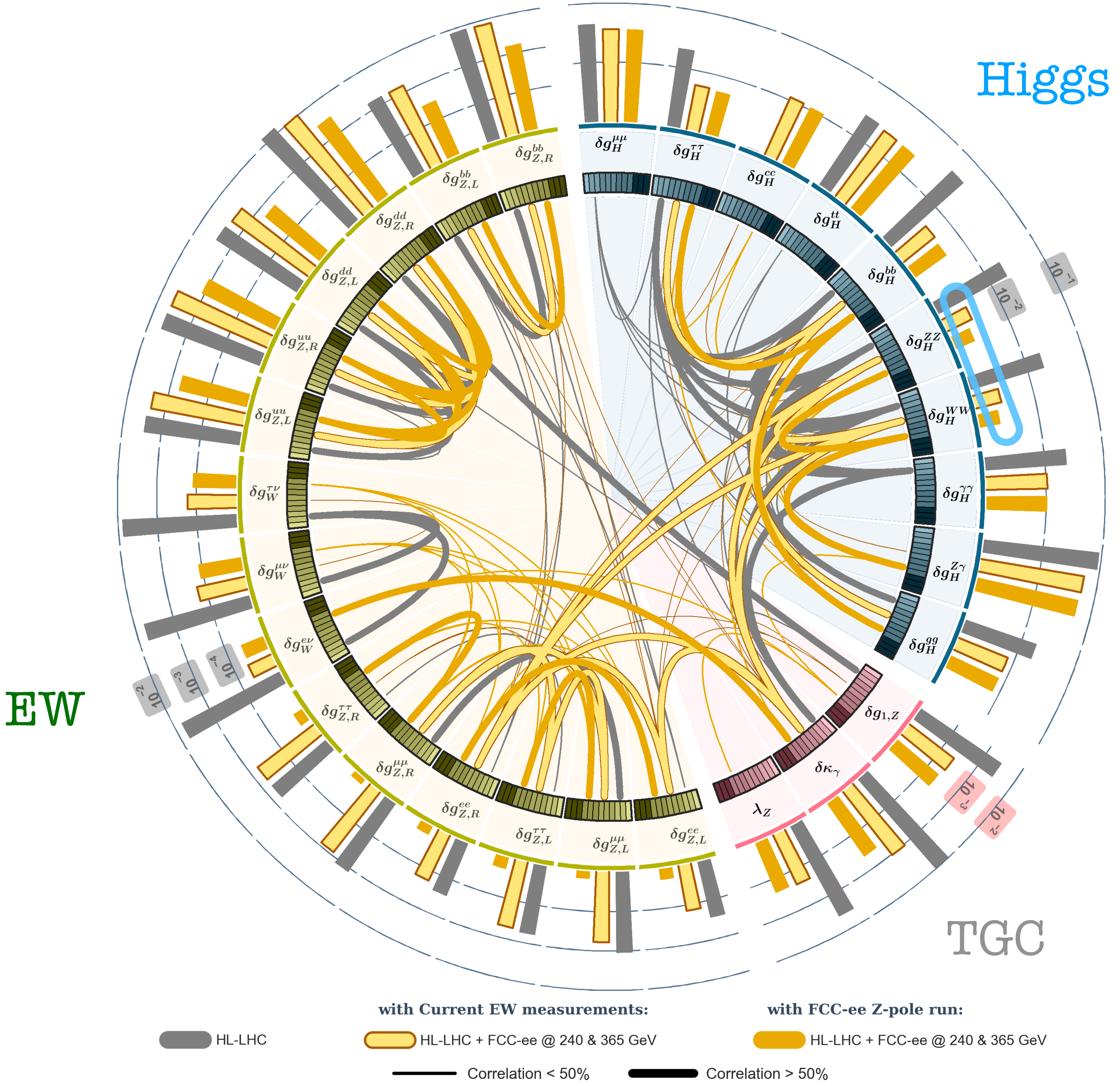

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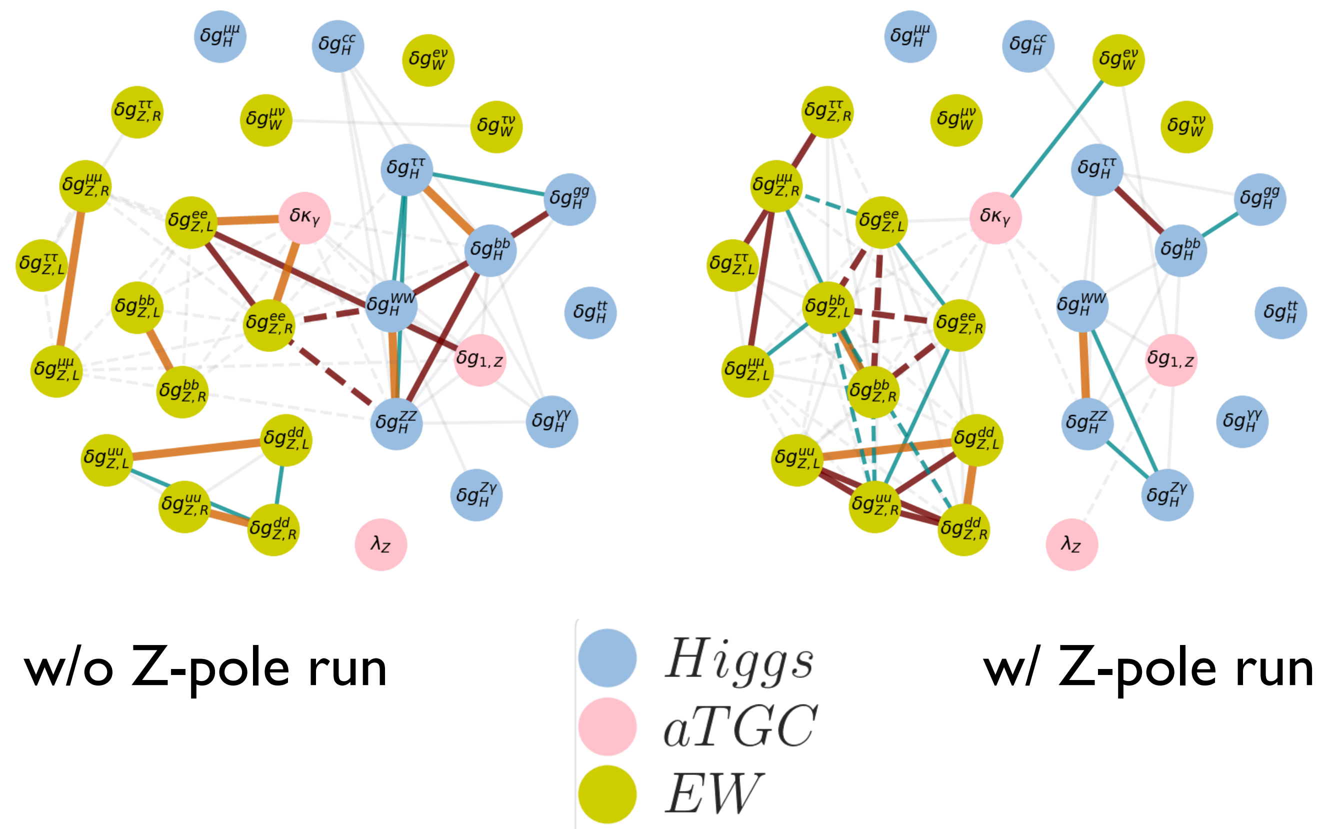
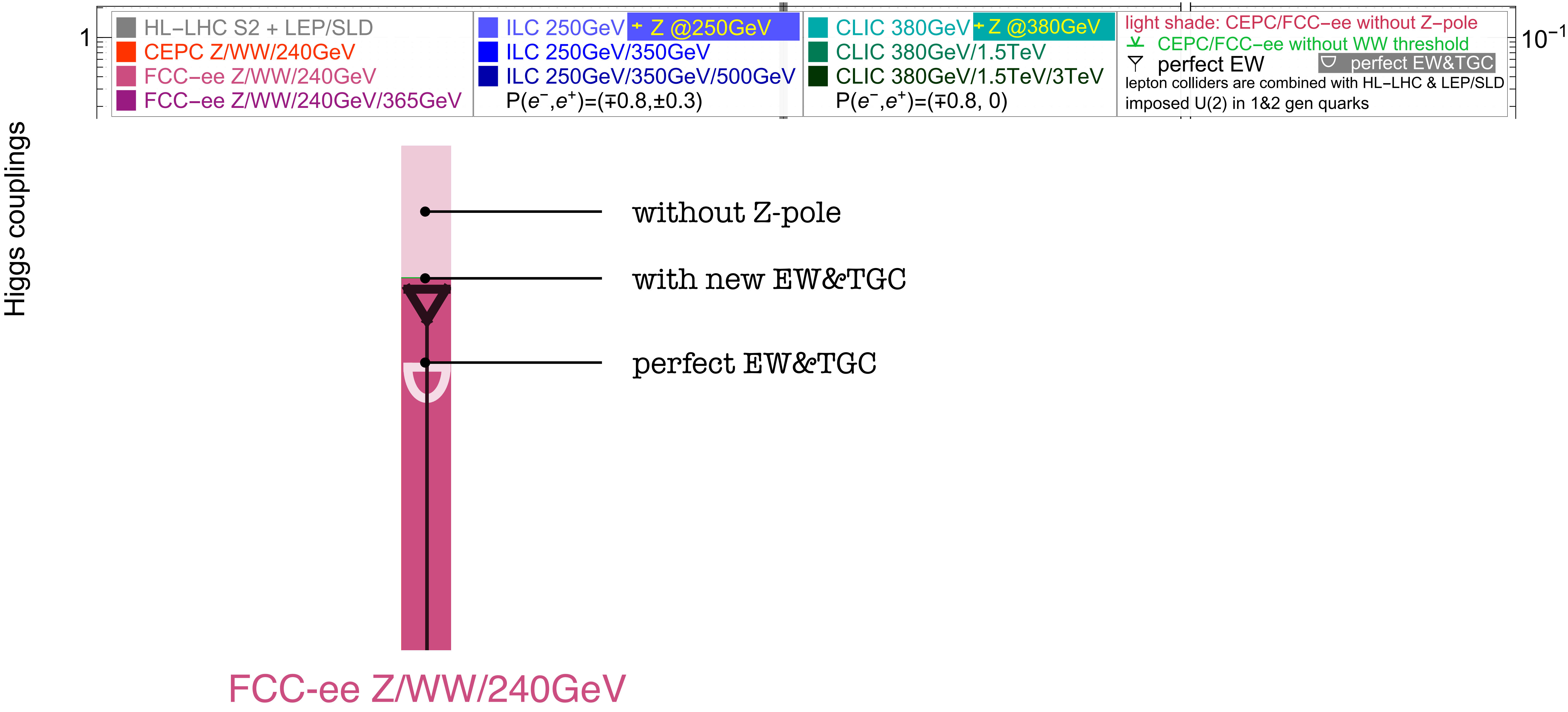
Z-pole run at circular colliders
decorrelates EW and Higgs sectors
from each other



Impact of Z-pole on Higgs.

J. De Blas et al. 1907.04311

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



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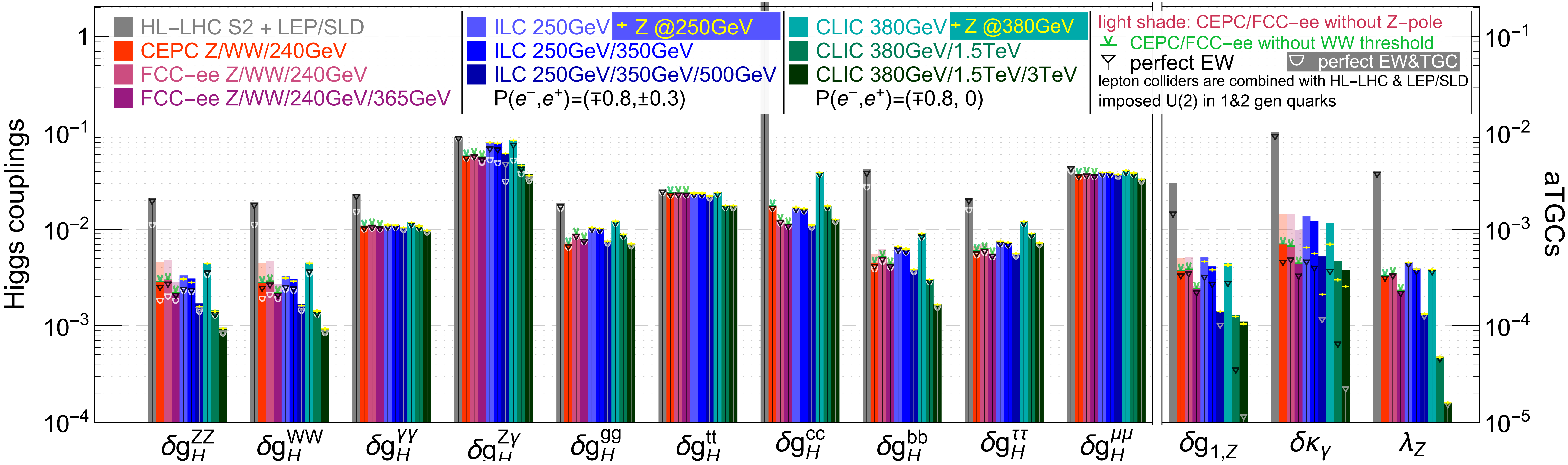

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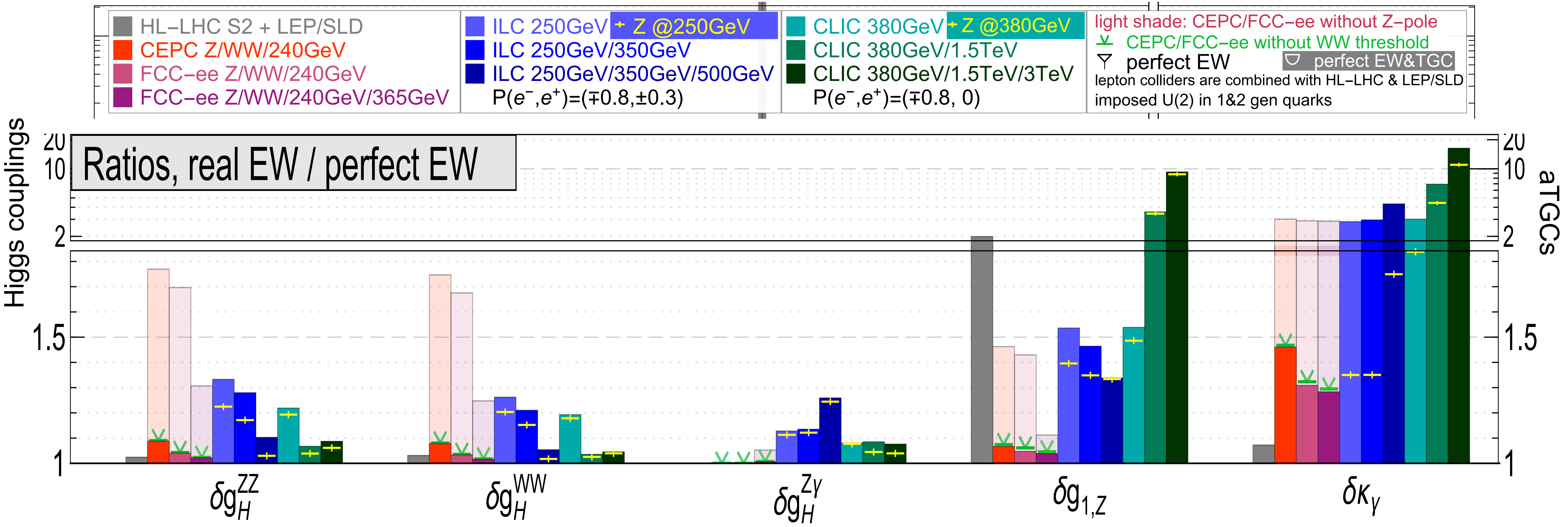

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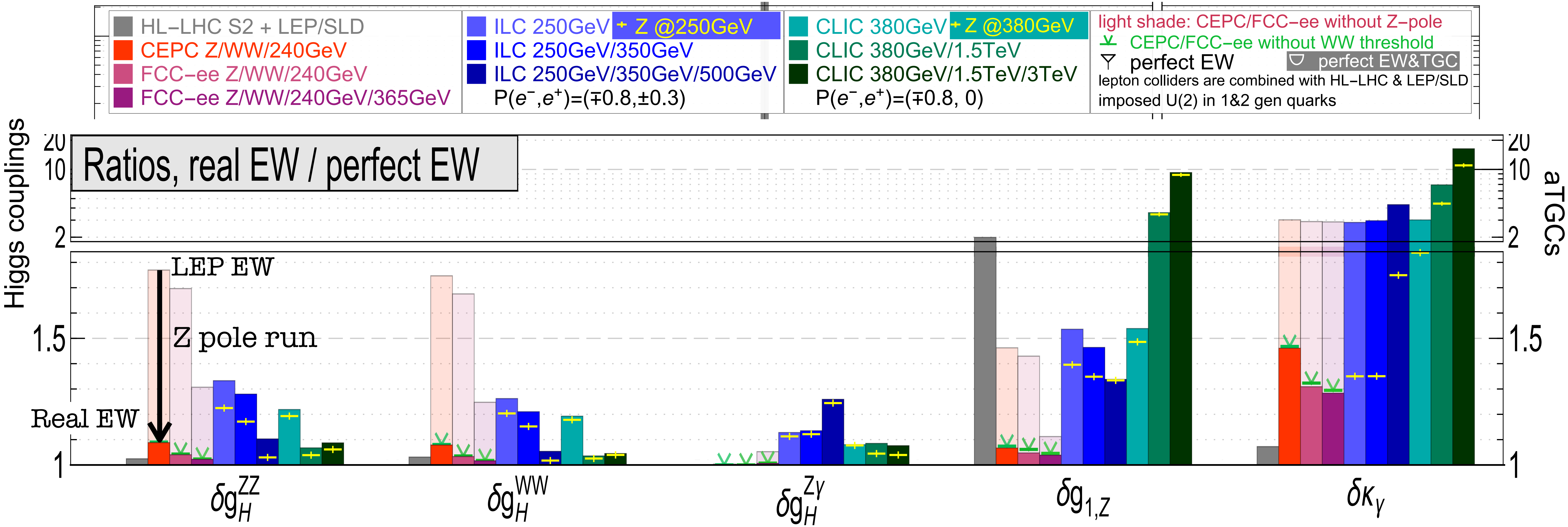

- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).

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J. De Blas et al. 1907.04311

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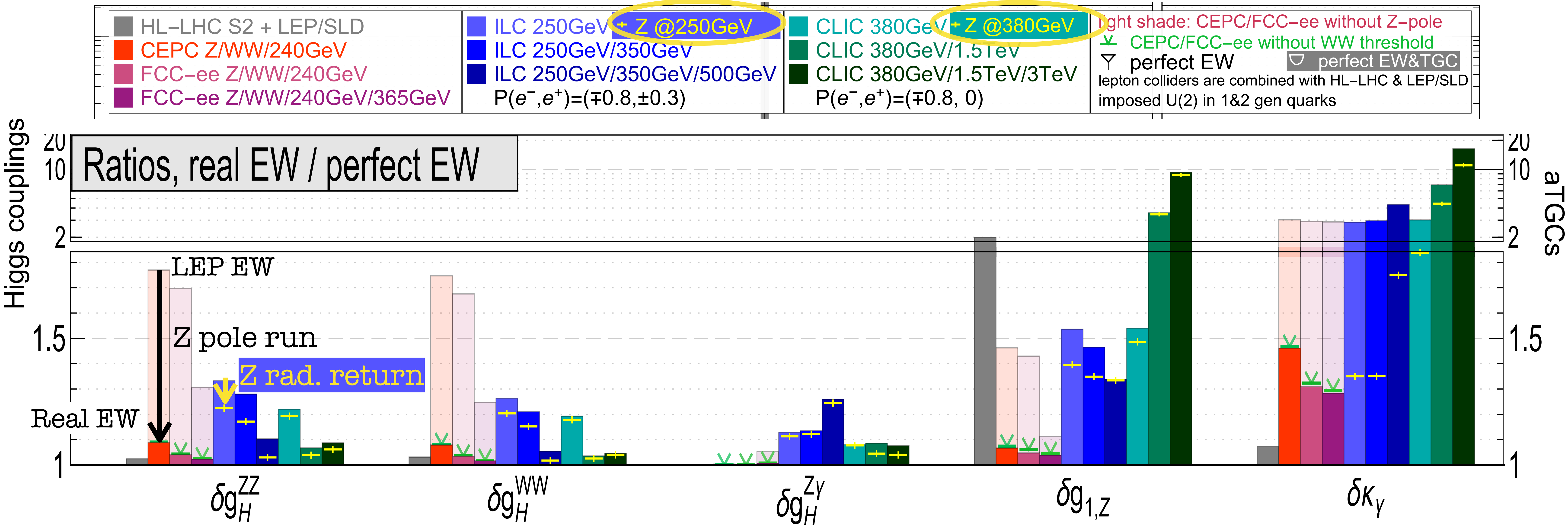
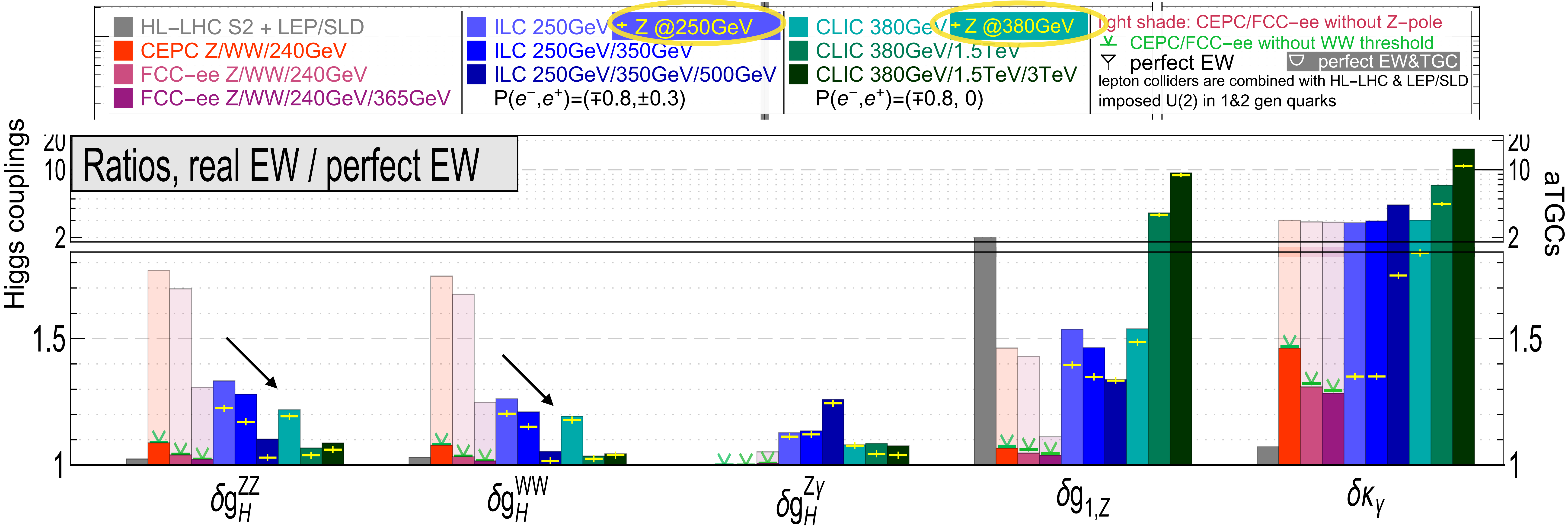


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs
  But EW measurements at high energy (via Z-radiative return) help mitigating this issue

Impact of Z-pole on Higgs.

J. De Blas et al. 1907.04311

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

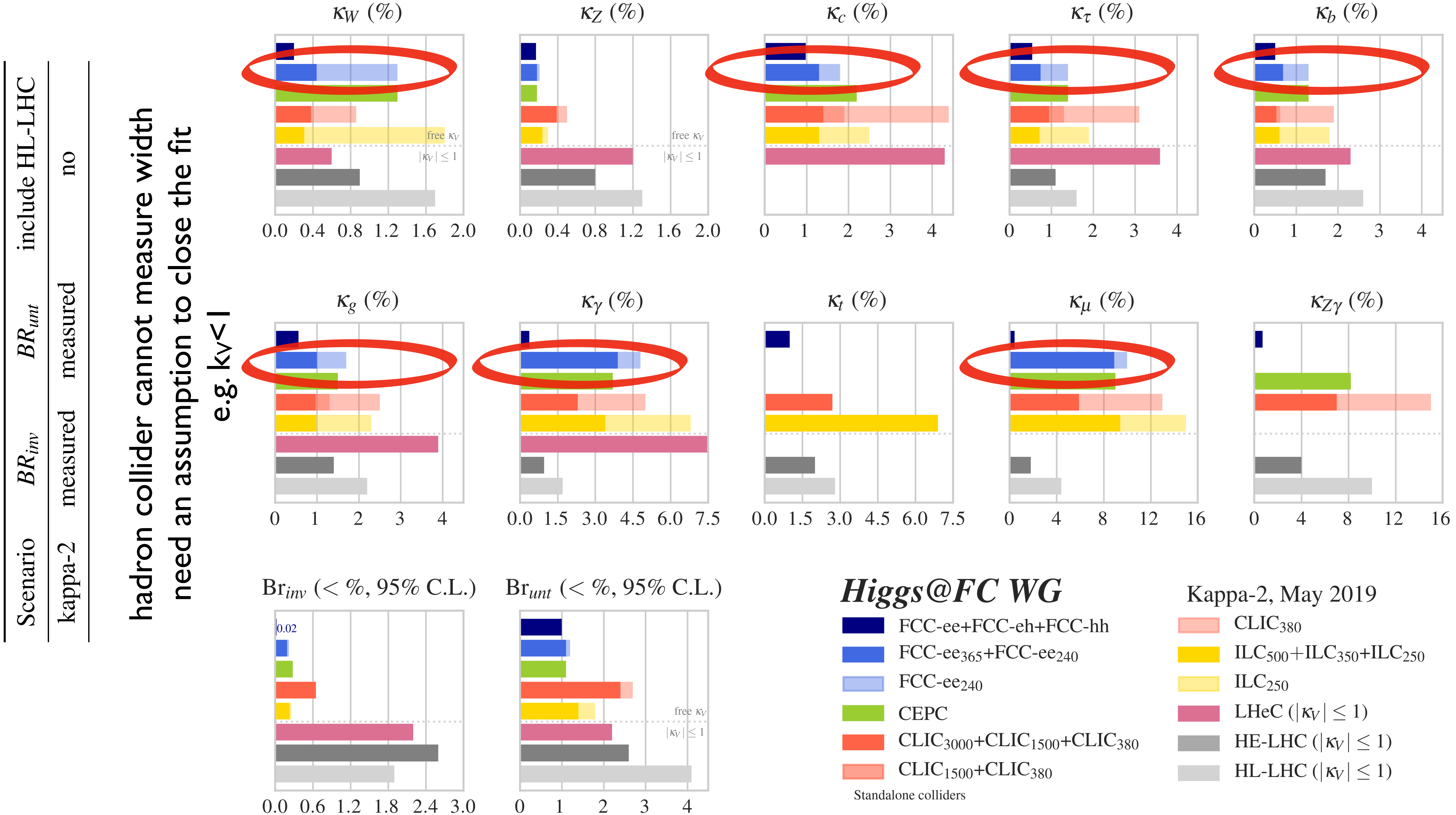


- Higher energy runs reduce the EW contamination in Higgs coupling extraction

Complementarity 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



back to main discussion

Complementarity FCC-ee↔HL-LHC.

ECFA Higgs study group '19

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-2	measured	measured	no

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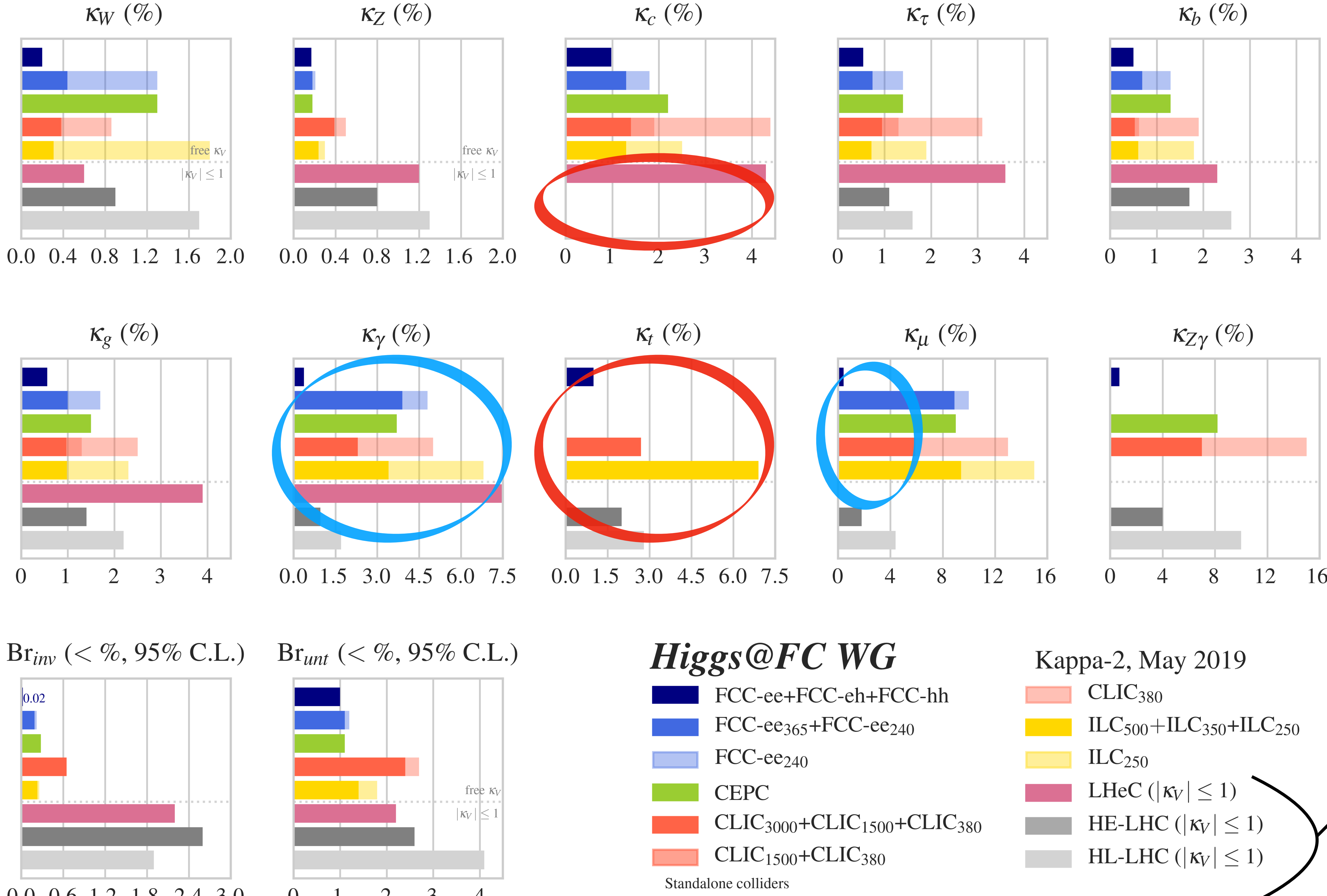

assumption needed for the fit to close at hadron machines

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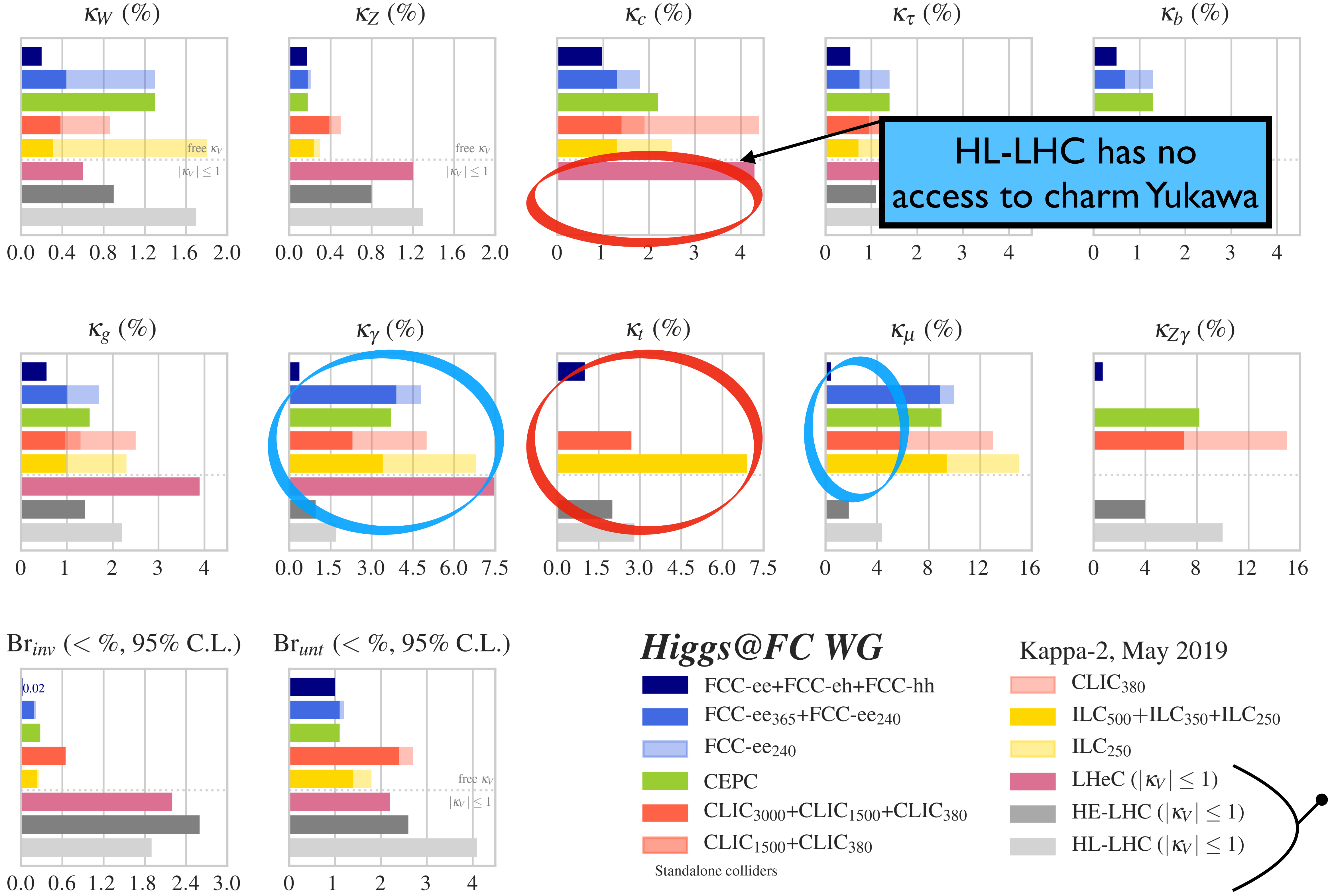

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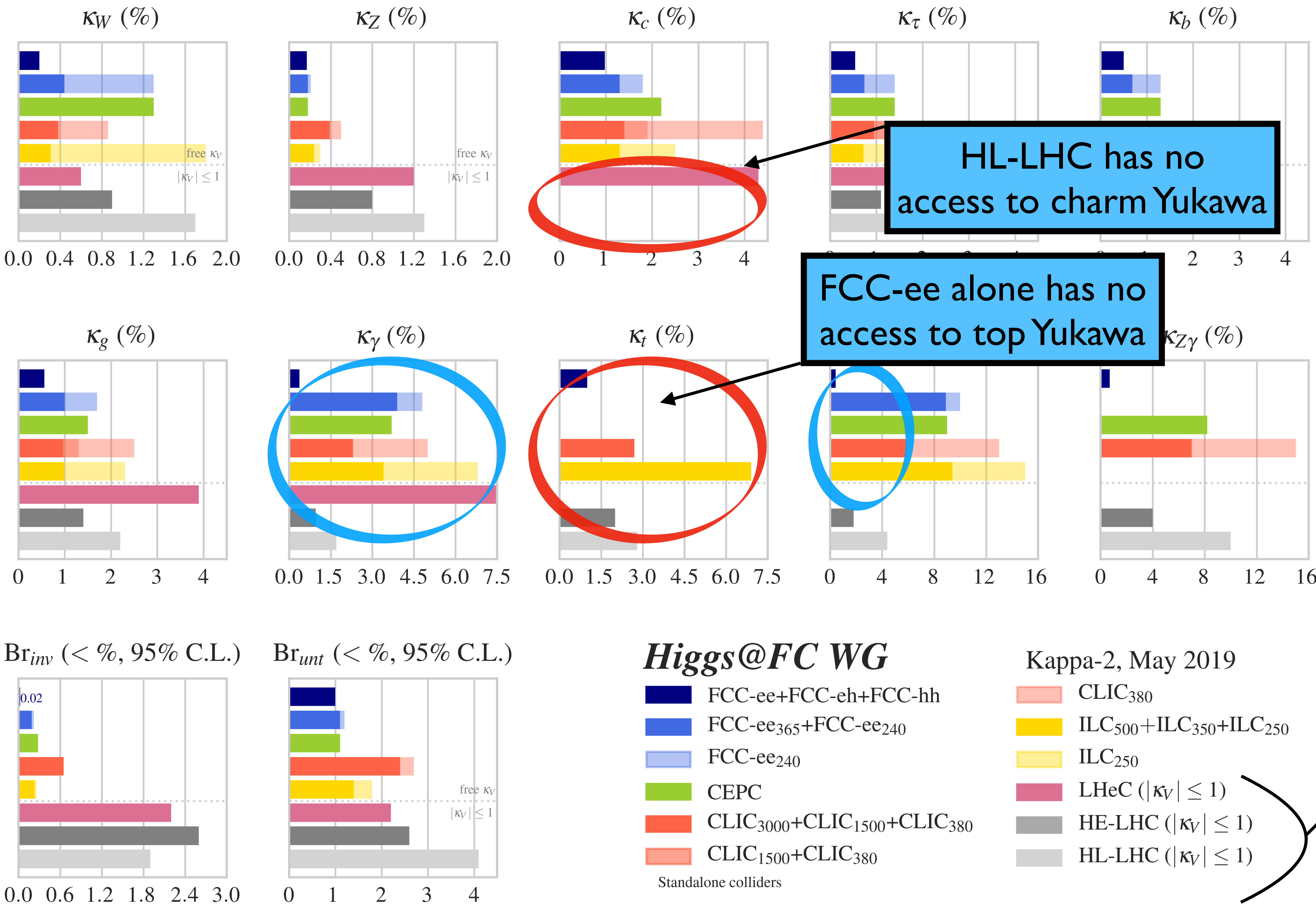

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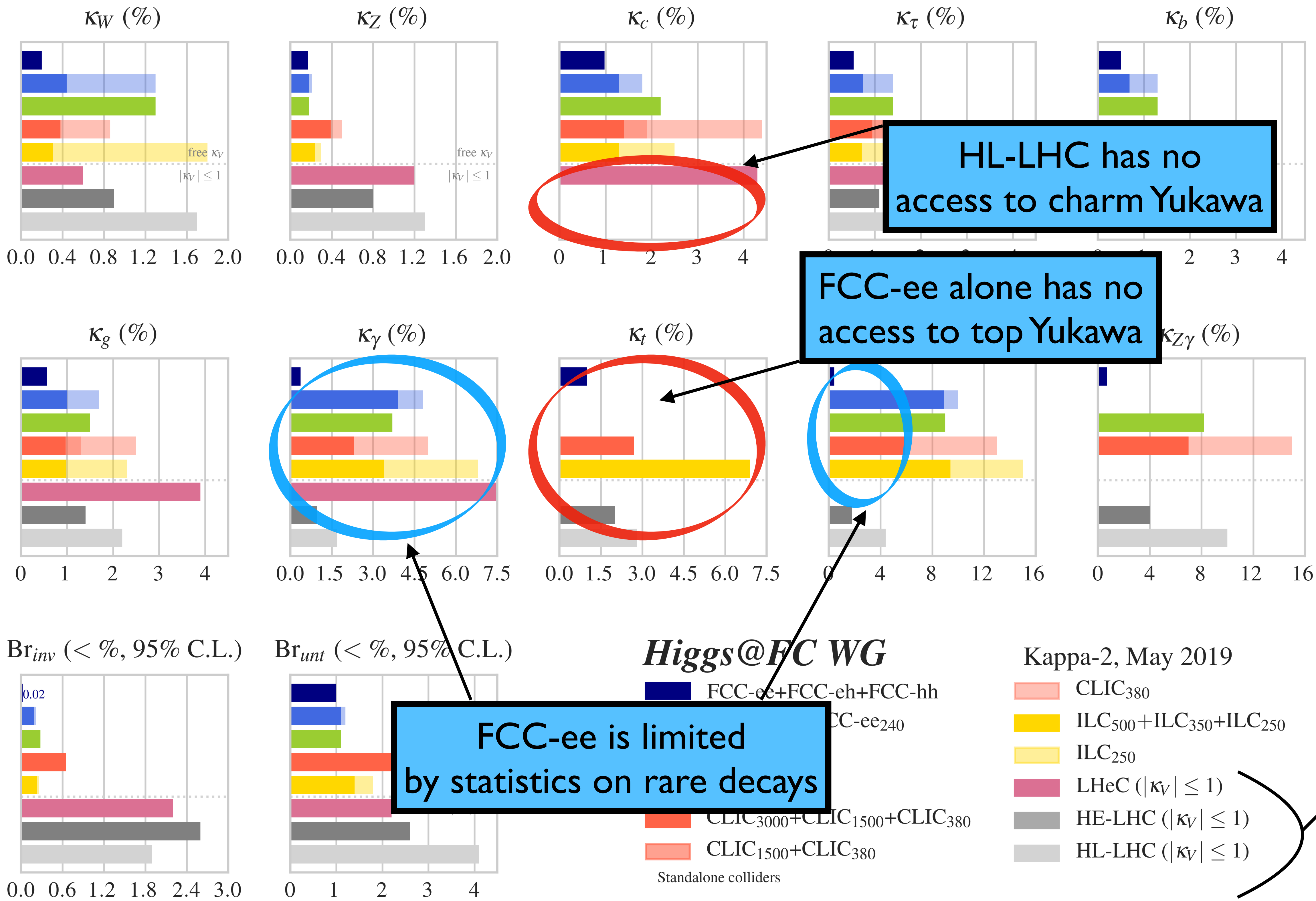

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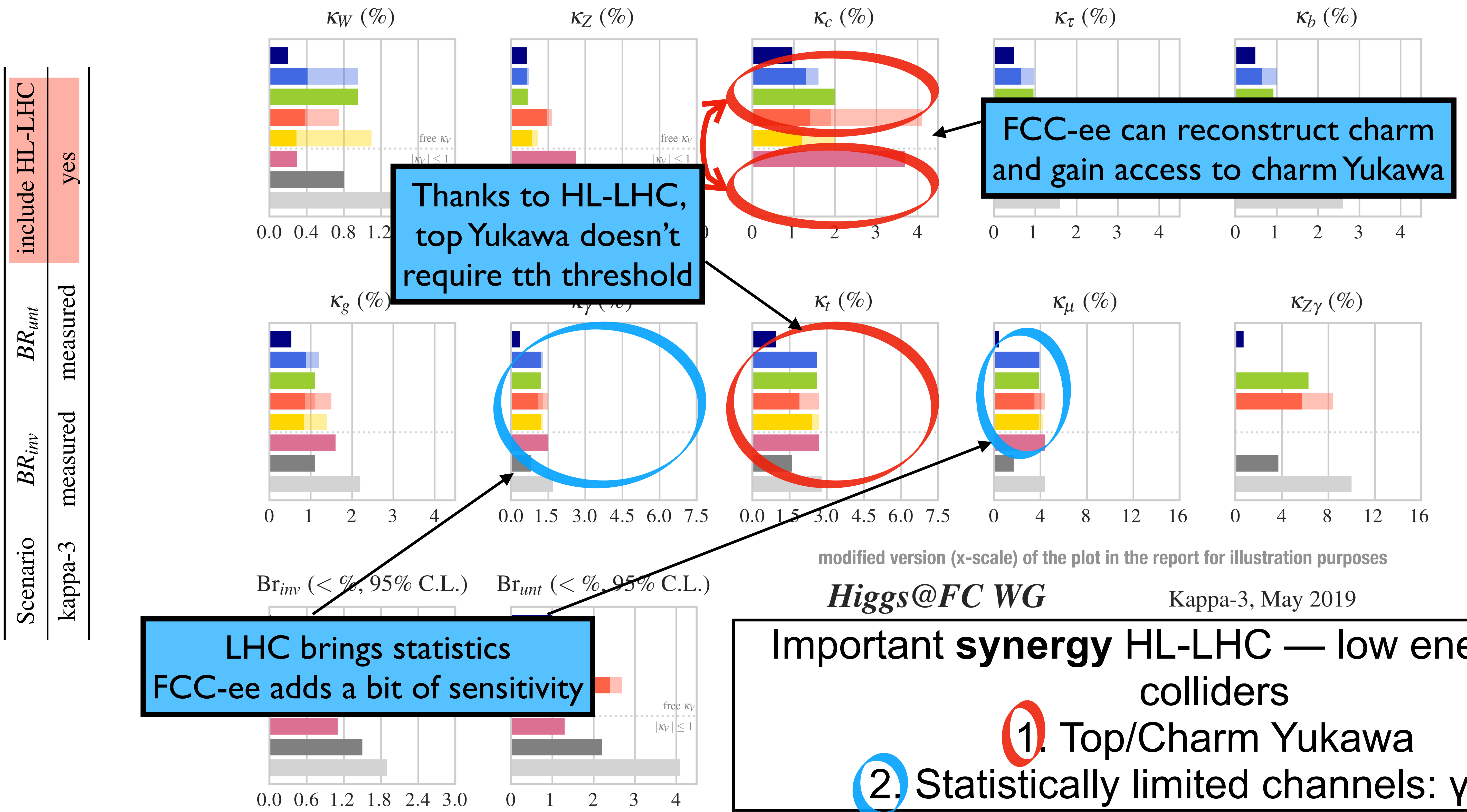


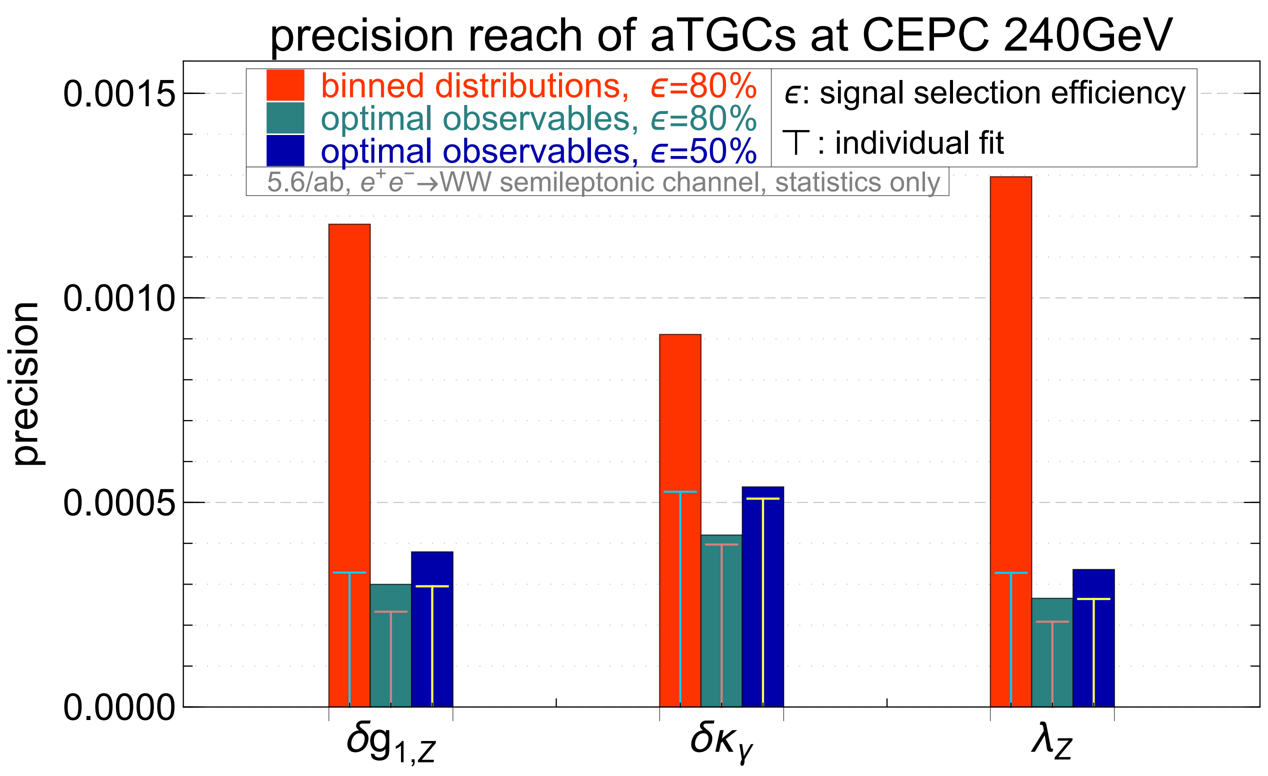
Important **synergy** HL-LHC — low energy lepton colliders

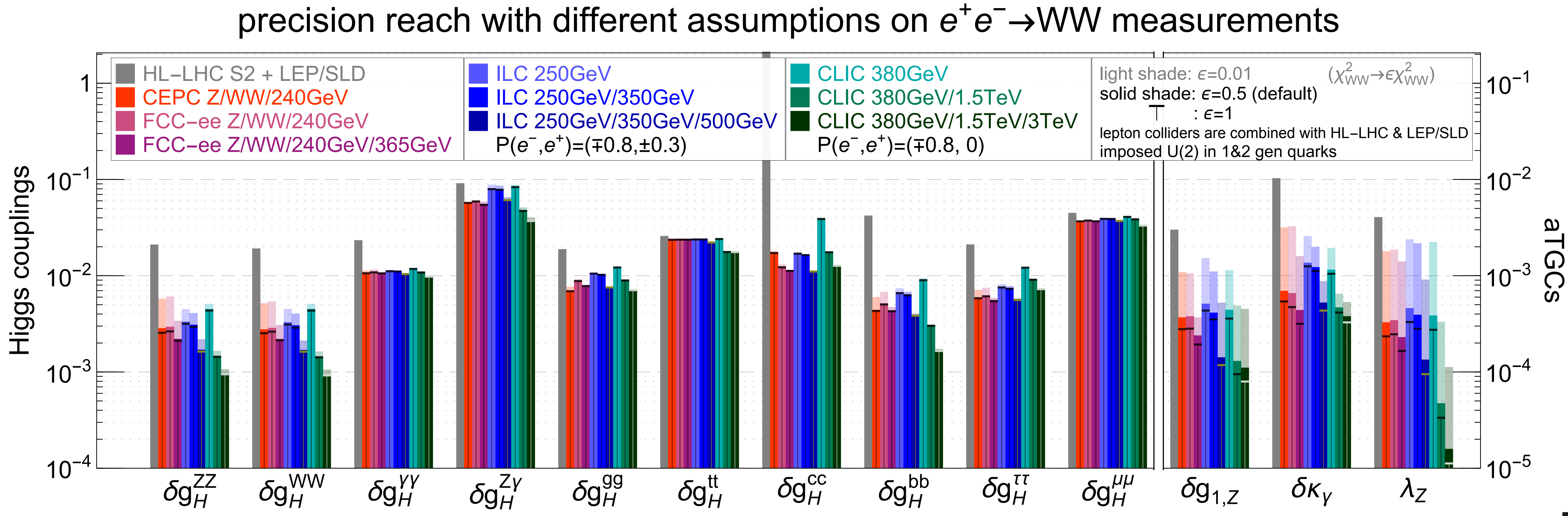
1. Top/Charm Yukawa
2. Statistically limited channels: γγ, μμ

back to main discussion

Impact of Diboson Systematics.

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



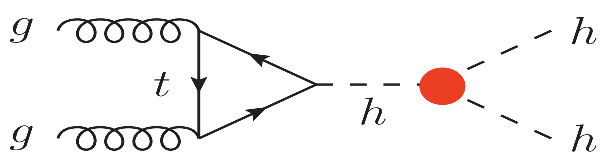
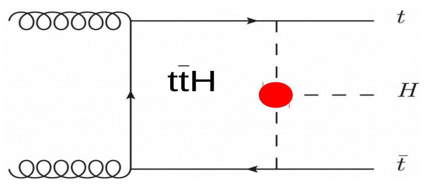
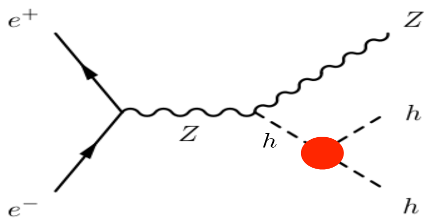
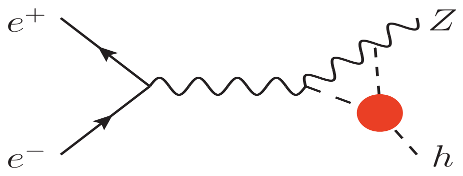


Higgs self-coupling.

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?

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.** • 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

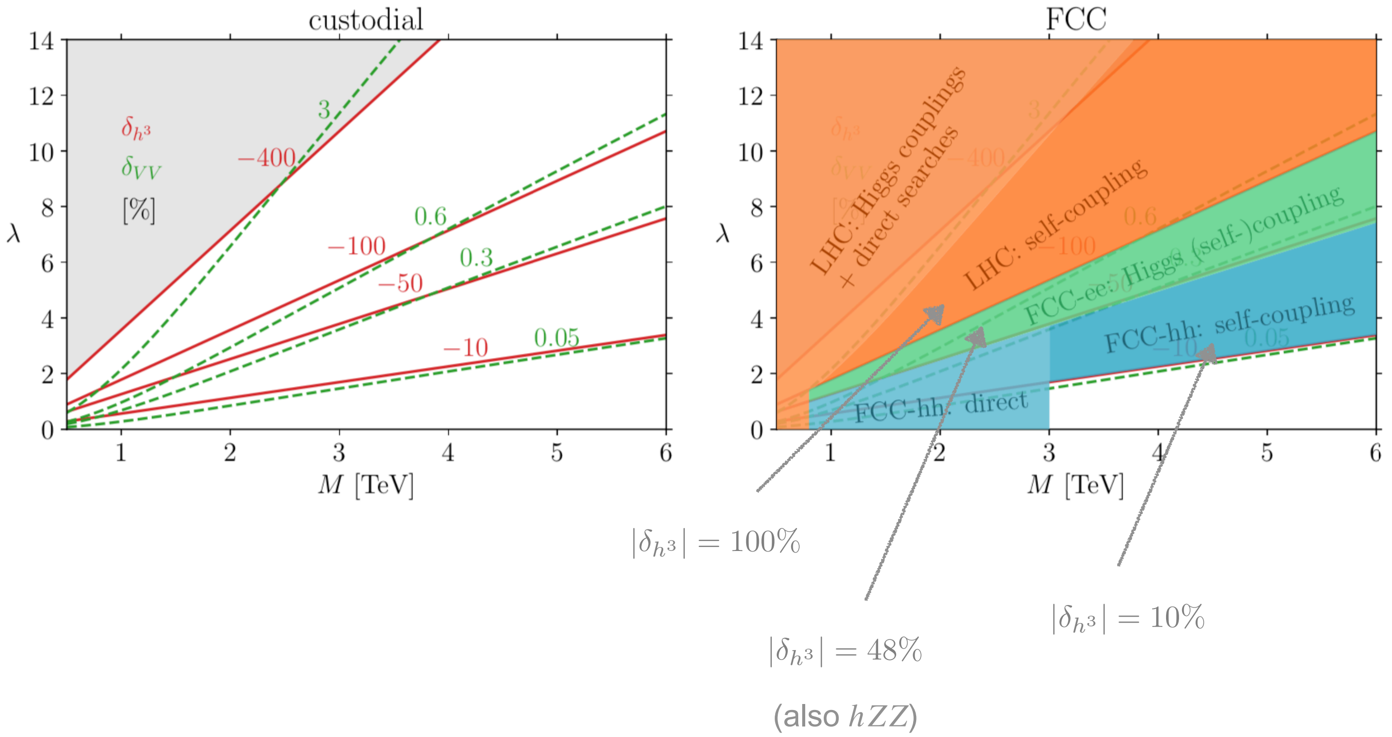
Large self-coupling scenarios.

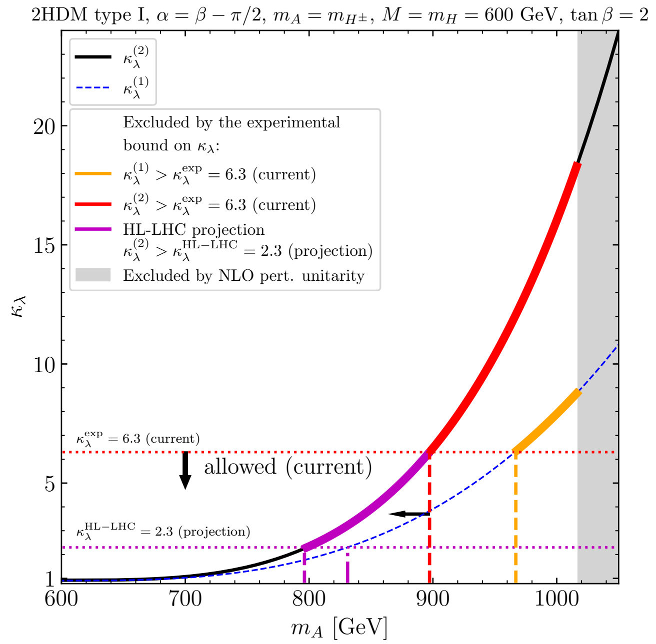
Generically: $\left|\frac{\delta_{h^3}}{\delta_{\text{single } h}}\right| \sim O(1)$ (composite Higgs/susy)

Particular exceptions: Higgs DM-portal models or custodial EW quadruplet

DiVita et al,: 1704.01953 Falkowski, Rattazzi: 1902.05936 Durieux, McCullough, Salvioni: 2209.00666

h^3 generically is not a tool to discover BSM but exceptions exist.



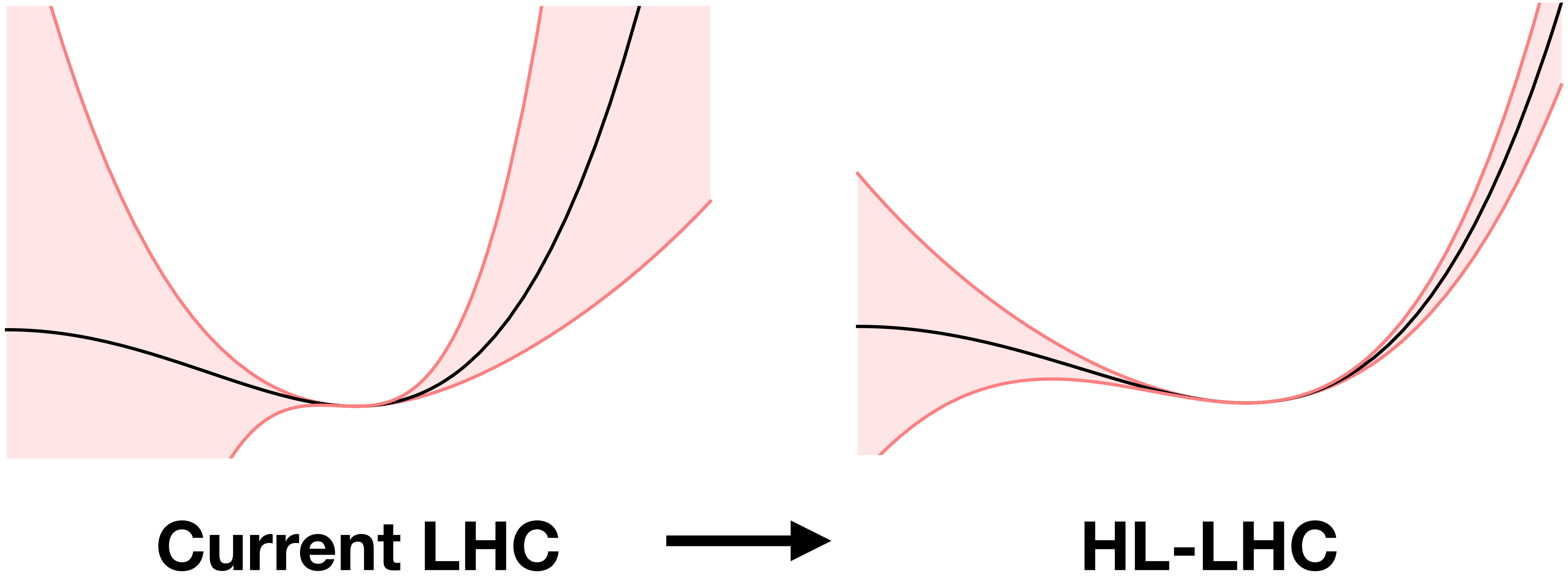


Other exceptions: non-decoupled/fine-tuned spectra

Bahl, Braathen, Weiglein: 2202.03453

Large self-coupling scenarios.

It is true that we haven't "measured" the Higgs potential but
there are only peculiar physics scenarios that produce large deviations in the shape of the potential without leaving imprints elsewhere.

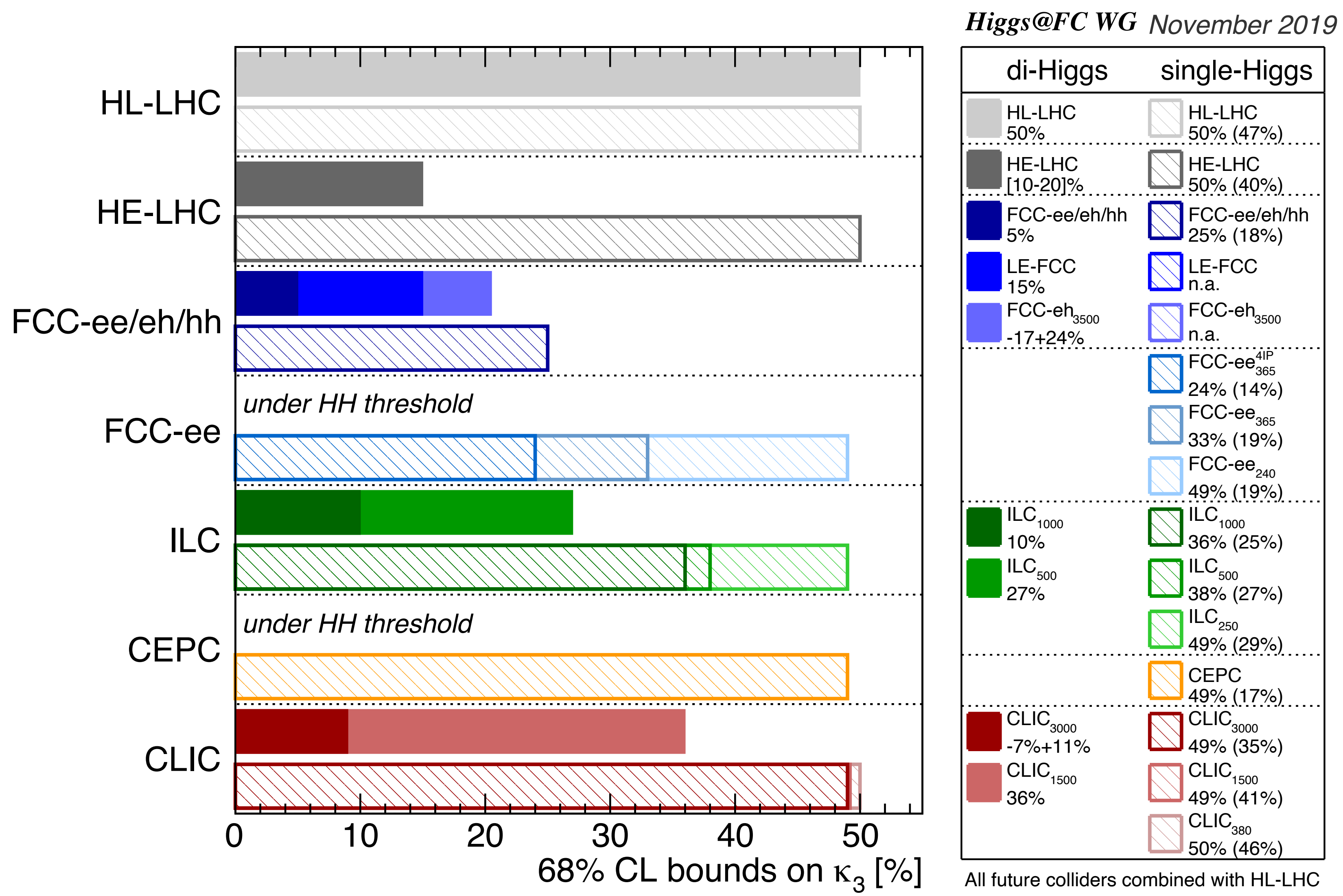


R. Petrossian-Byrne/N. Craig @ LCWS'23

Important to understand which dynamics is really probed when embarking into challenging measurements.
Actually, double Higgs production is also interesting to probe new physics in its tail rather than near threshold (where the sensitivity to Higgs self-coupling comes from).

Higgs self-coupling.

ECFA Higgs study group ‘19



1

Don’t need to reach HH threshold
to have access to h^3.
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: 5σ discovery of the SM h^3 coupling
5% sensitivity: getting sensitive to quantum corrections to Higgs potential

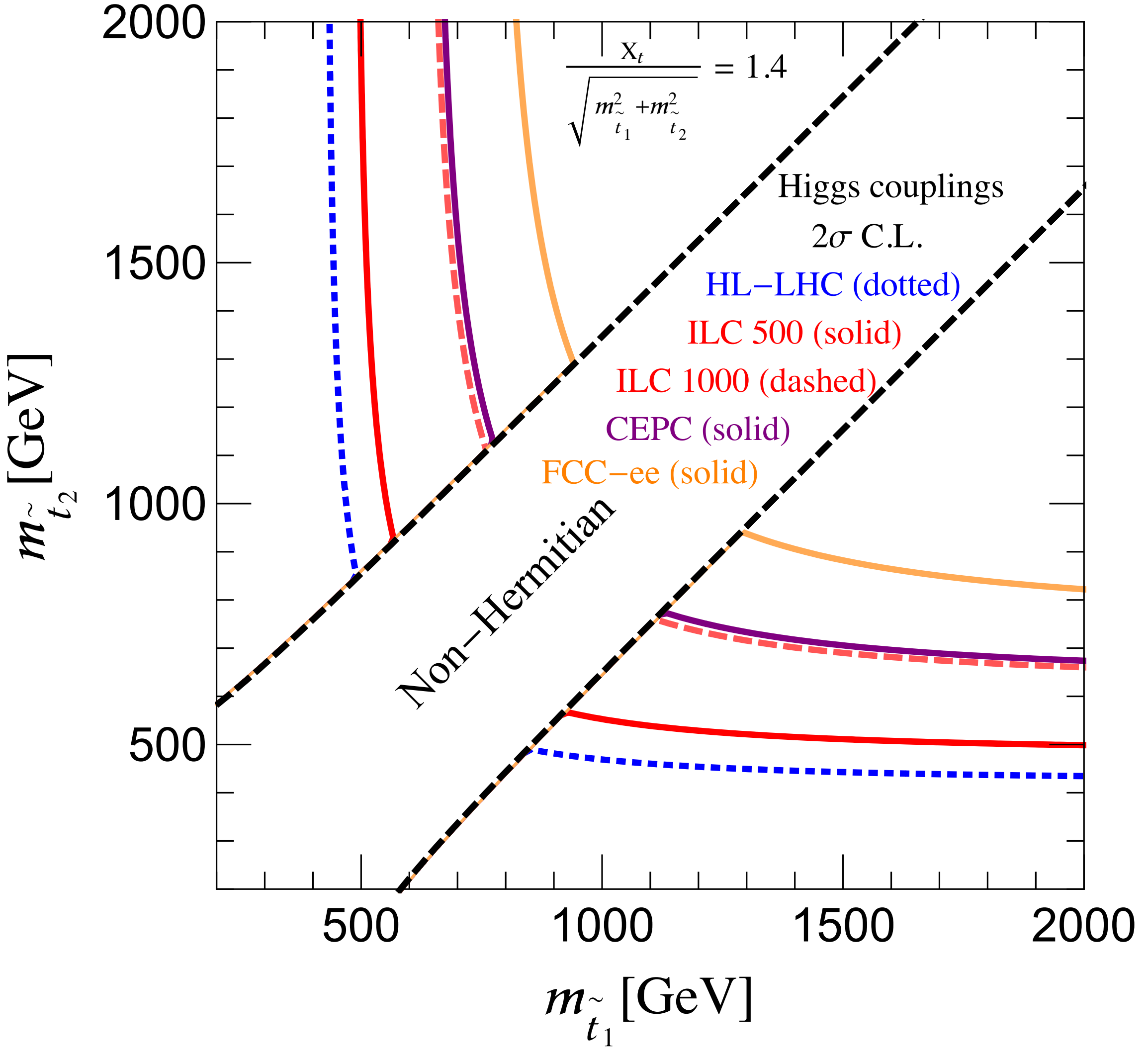
Discovery potential beyond LHC

Discovery Potential Beyond LHC.

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

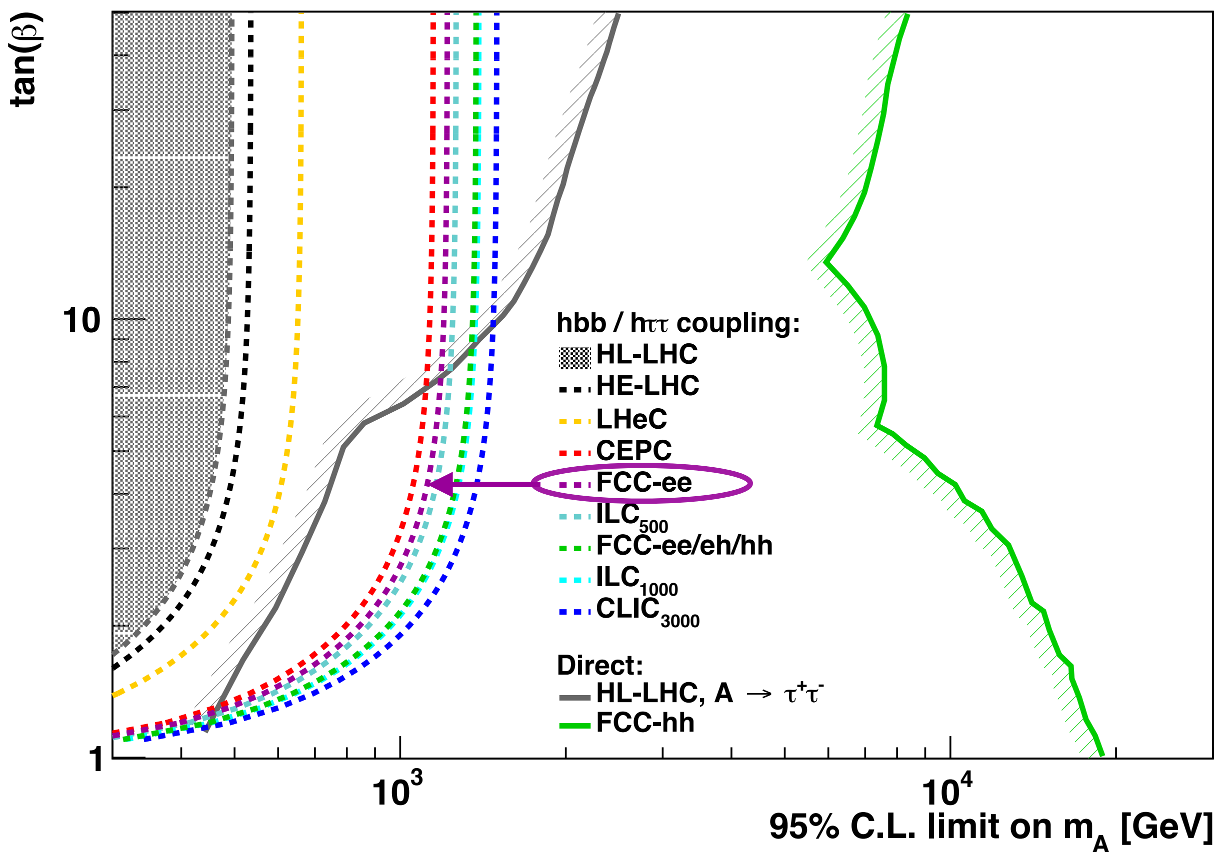
Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY

stops



Fan, Reece, Wang '14

Heavy neutral Higgses

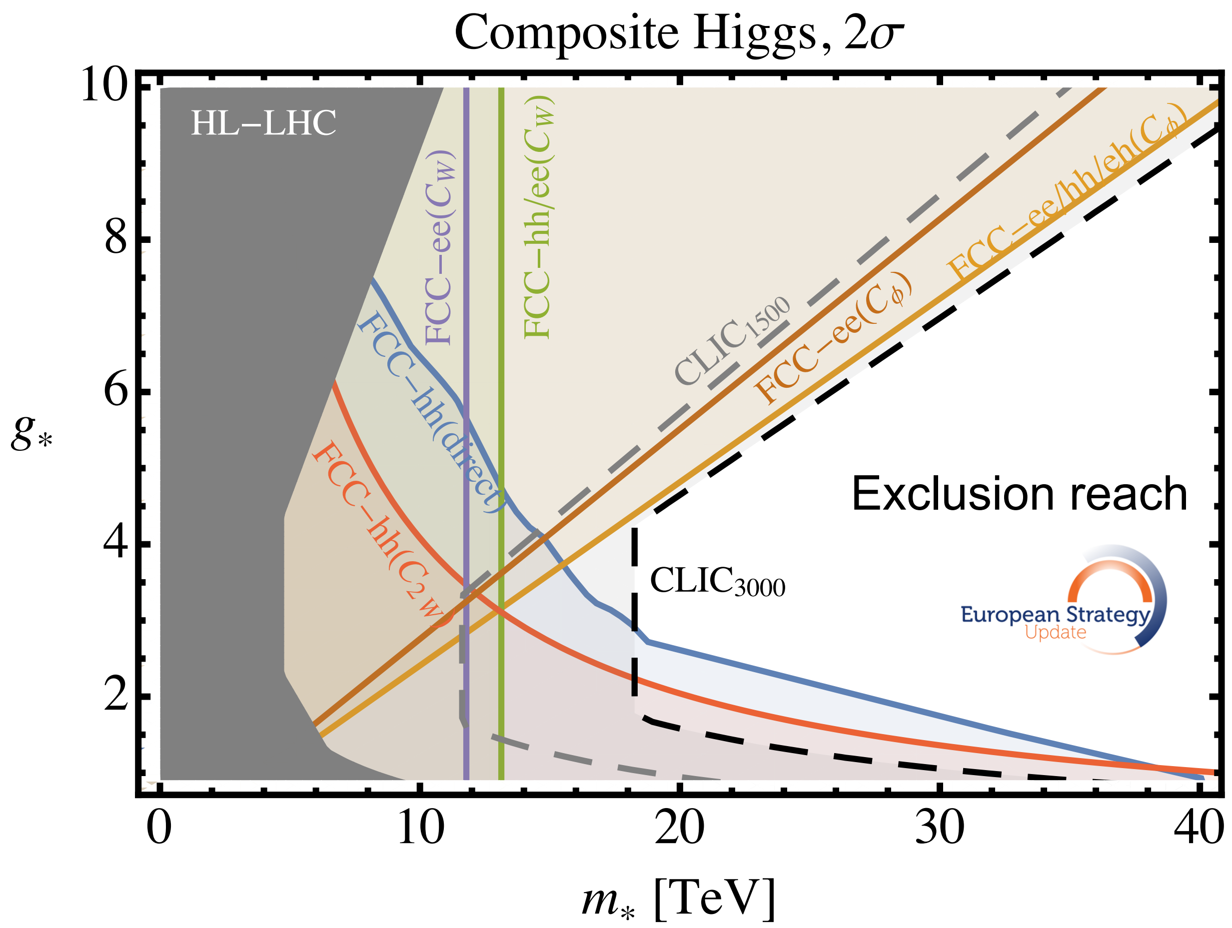


ESU Physics BB '19

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



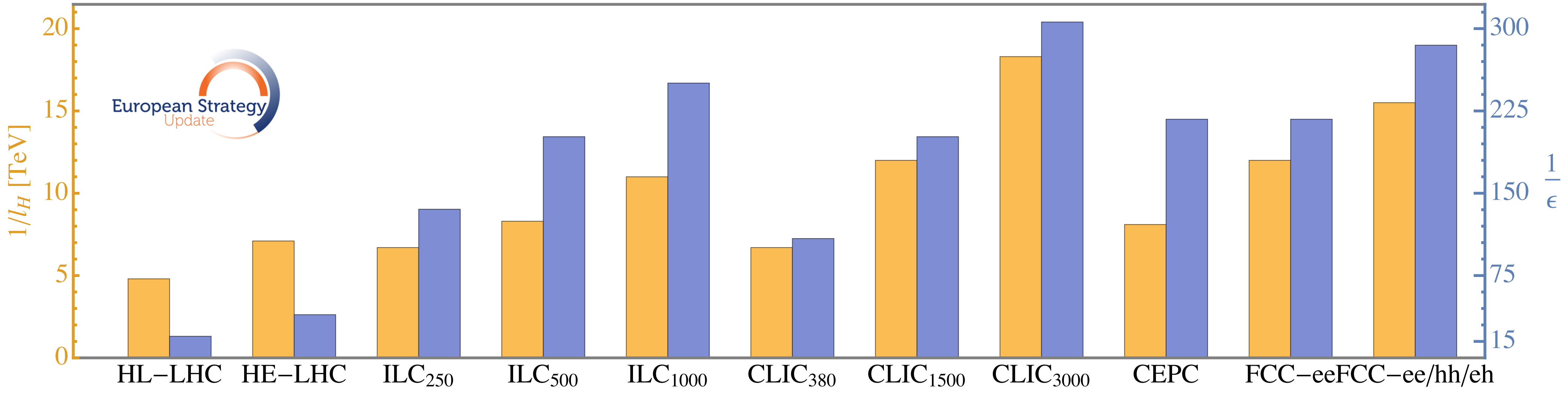


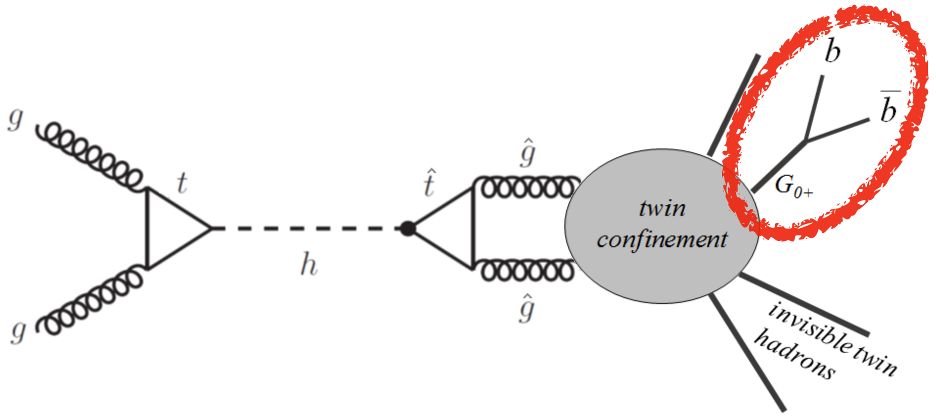
Fig. 8.5: Exclusion reach of different colliders on the inverse Higgs length $1/\ell_H = m_*$ (orange bars, left axis) and the tuning parameter $1/\varepsilon$ (blue bars, right axis), obtained by choosing the weakest bound valid for any value of the coupling constant g_*.

ESU Physics BB '19

Direct Searches for Elusive New Physics

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

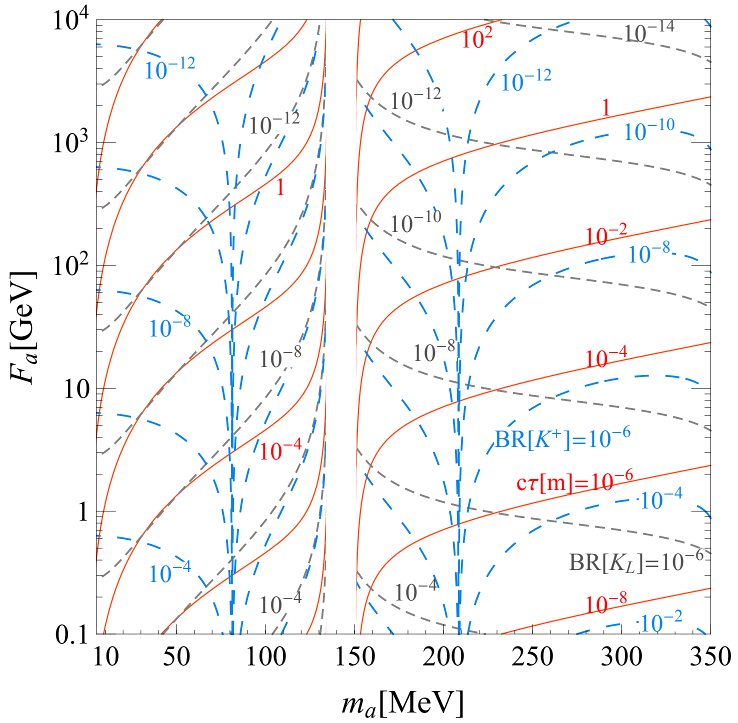
Craig et al, arXiv:1501.05310



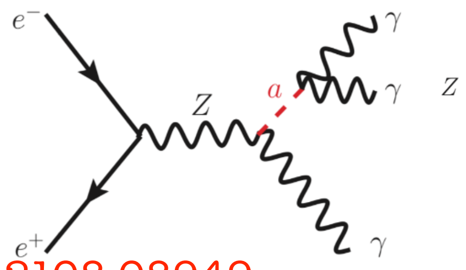
- **Rare decays** Gori et al arXiv:2005.05170
  e.g. ALP mixing w/ SM mesons:

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

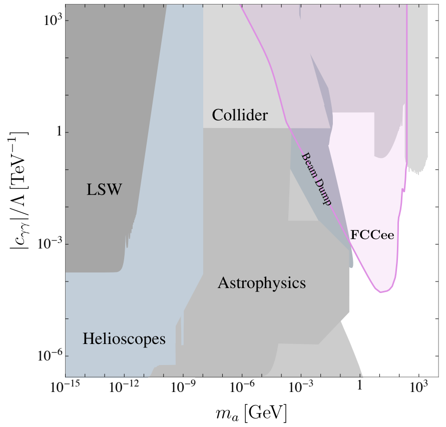
$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu}\tilde{G}^{\mu\nu}$$

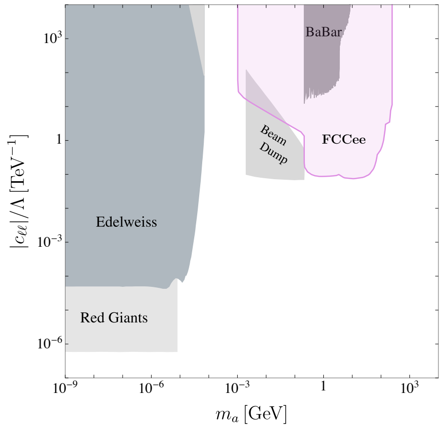


- **ALPs@ colliders**
  e.g. $e^+e^- \to \gamma a$
  $e^+e^- \to ha$



Knapen, Thamm arXiv:2108.08949

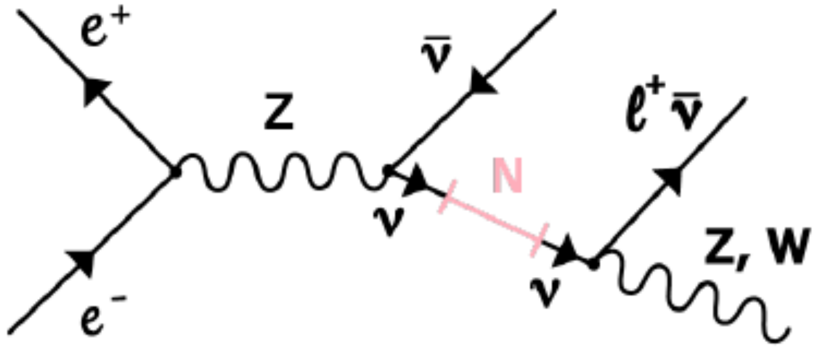




Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

Search for ν_{RH}.

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

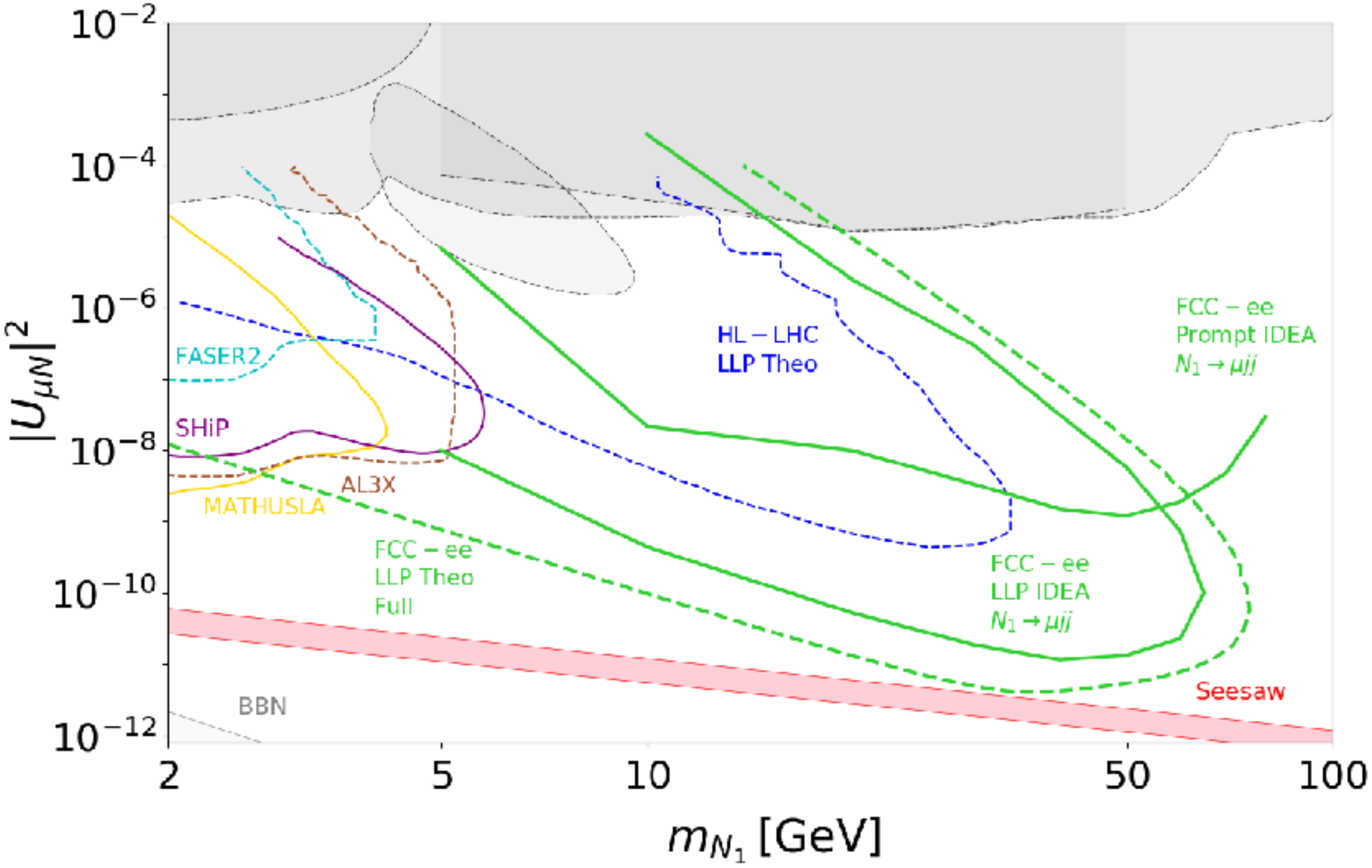
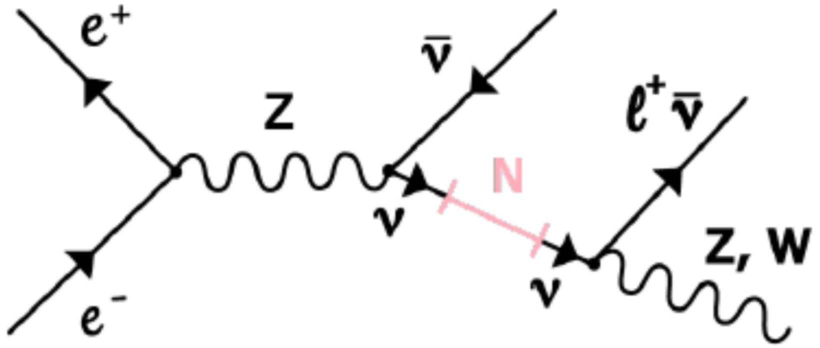


Fig. from mid-term report

Search for ν_{RH}.

Direct observation
in Z decays
from LH-RH mixing



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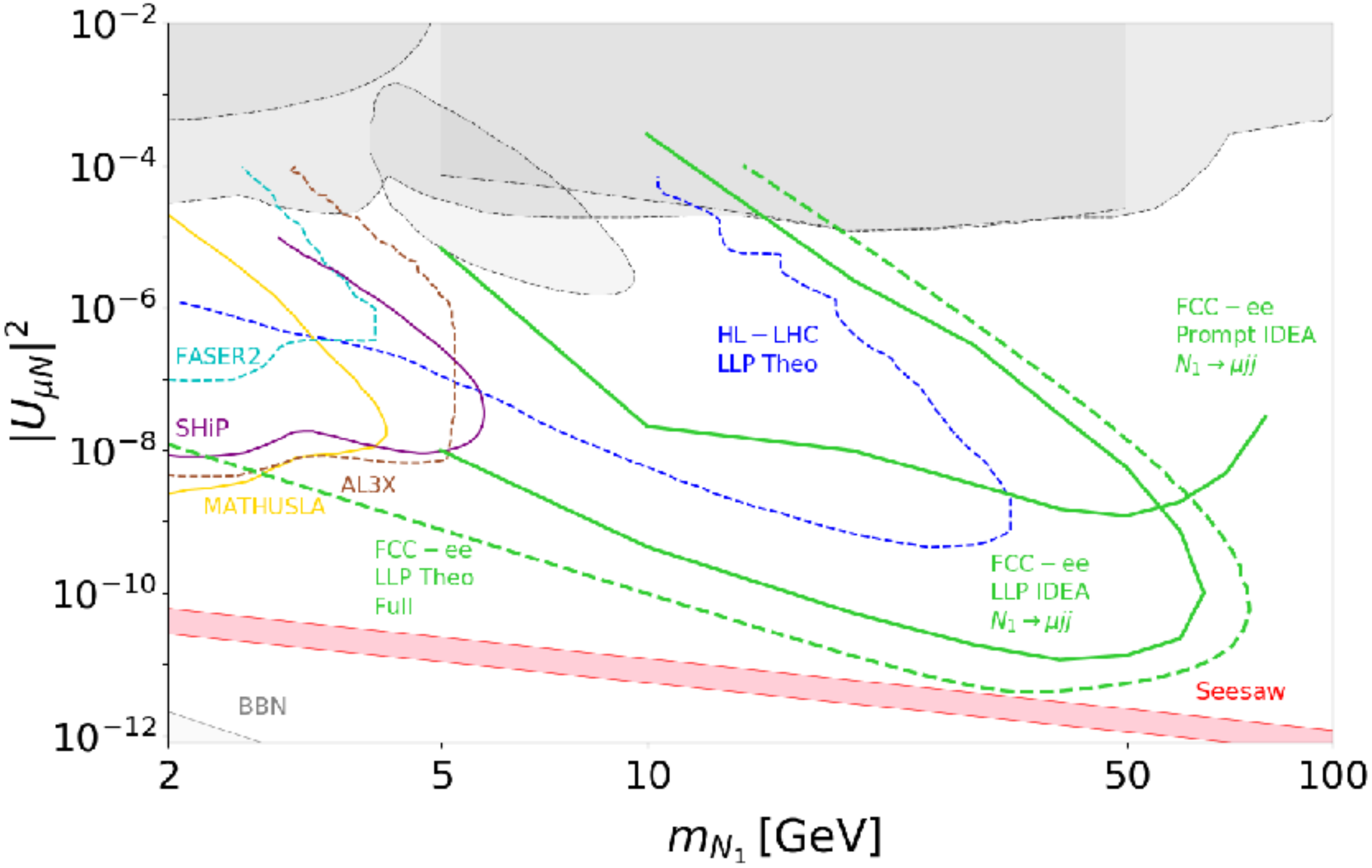
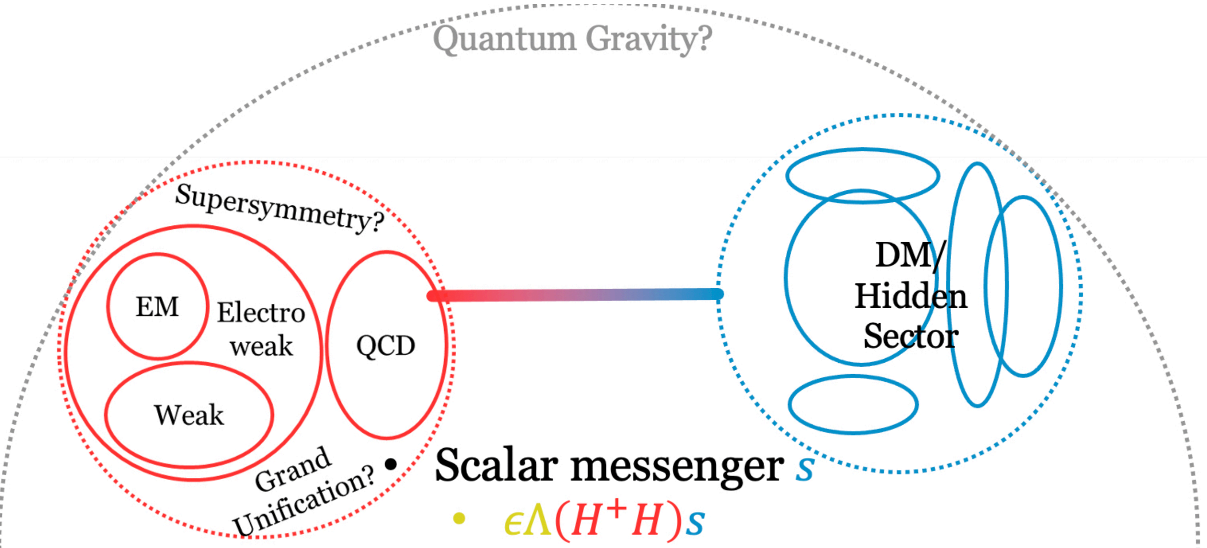


Fig. from mid-term report

Exotics/Long Lived Particles.

Z. Liu @ CEPC 2020



- Scalar messenger s
  - $\epsilon\Lambda(H^+H)s$
  - $\epsilon(H^+H)(s^+s)$
- Vector messenger A'_μ
  - $\epsilon F^{\mu\nu}F'_{\mu\nu}$
  - $\epsilon\, J^{\mu}_{SM}A'_\mu$
- Neutrino messenger N
  - $\epsilon(LH)N$
- Axion messenger a
  - $\frac{a}{f_a}(\frac{\alpha_3}{8\pi}G\tilde{G}+\frac{\alpha_2}{8\pi}W\tilde{W})$

The Higgs could be a good portal to Dark Sector

— rich exotic signatures —

Decay Topologies	Decay mode $\mathcal{F}_i$
$h\to 2$	$h\to \not\!\!E_T$
$h\to 2\to 3$	$h\to\gamma+\not\!\!E_T$
	$h\to(b\bar{b})+\not\!\!E_T$
	$h\to(jj)+\not\!\!E_T$
	$h\to(\tau^+\tau^-)+\not\!\!E_T$
	$h\to(\gamma\gamma)+\not\!\!E_T$
	$h\to(\ell^+\ell^-)+\not\!\!E_T$
$h\to 2\to 3\to 4$	$h\to(b\bar{b})+\not\!\!E_T$
	$h\to(jj)+\not\!\!E_T$
	$h\to(\tau^+\tau^-)+\not\!\!E_T$
	$h\to(\gamma\gamma)+\not\!\!E_T$
	$h\to(\ell^+\ell^-)+\not\!\!E_T$
	$h\to(\mu^+\mu^-)+\not\!\!E_T$
$h\to 2\to(1+3)$	$h\to b\bar{b}+\not\!\!E_T$
	$h\to jj+\not\!\!E_T$
	$h\to\tau^+\tau^-+\not\!\!E_T$
	$h\to\gamma\gamma+\not\!\!E_T$
	$h\to\ell^+\ell^-+\not\!\!E_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h\to 2\to 4$	$h\to(bb)(bb)$
	$h\to(b\bar{b})(\tau^+\tau^-)$
	$h\to(b\bar{b})(\mu^+\mu^-)$
	$h\to(\tau^+\tau^-)(\tau^+\tau^-)$
	$h\to(\tau^+\tau^-)(\mu^+\mu^-)$
	$h\to(jj)(jj)$
	$h\to(jj)(\gamma\gamma)$
	$h\to(jj)(\mu^+\mu^-)$
	$h\to(\ell^+\ell^-)(\ell^+\ell^-)$
	$h\to(\ell^+\ell^-)(\mu^+\mu^-)$
	$h\to(\mu^+\mu^-)(\mu^+\mu^-)$
	$h\to(\gamma\gamma)(\gamma\gamma)$
	$h\to\gamma\gamma+\not\!\!E_T$
$h\to 2\to 4\to 6$	$h\to(\ell^+\ell^-)(\ell^+\ell^-)+\not\!\!E_T$
	$h\to(\ell^+\ell^-)+\not\!\!E_T+X$
$h\to 2\to 6$	$h\to\ell^+\ell^-\ell^+\ell^-+\not\!\!E_T$
	$h\to\ell^+\ell^-+\not\!\!E_T+X$

LHC's strength

Hard at LHC due to missing energy

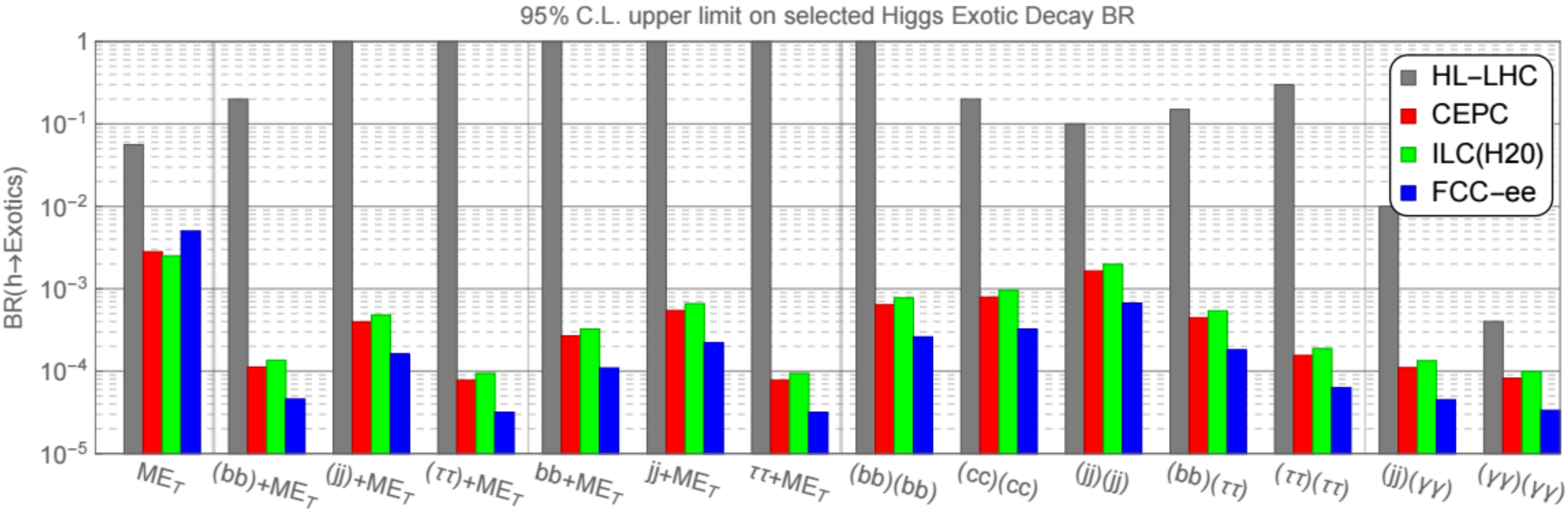
Hard at LHC due to hadronic background

Lepton colliders' strength

Exotics/Long Lived Particles.

Z. Liu @ CEPC 2020

The Higgs could be a good portal to Dark Sector
— rich exotic signatures —



How to improve?
> Dedicated detectors, see e.g. talk by R. Gonzalez Suarez @ FCC week 2021