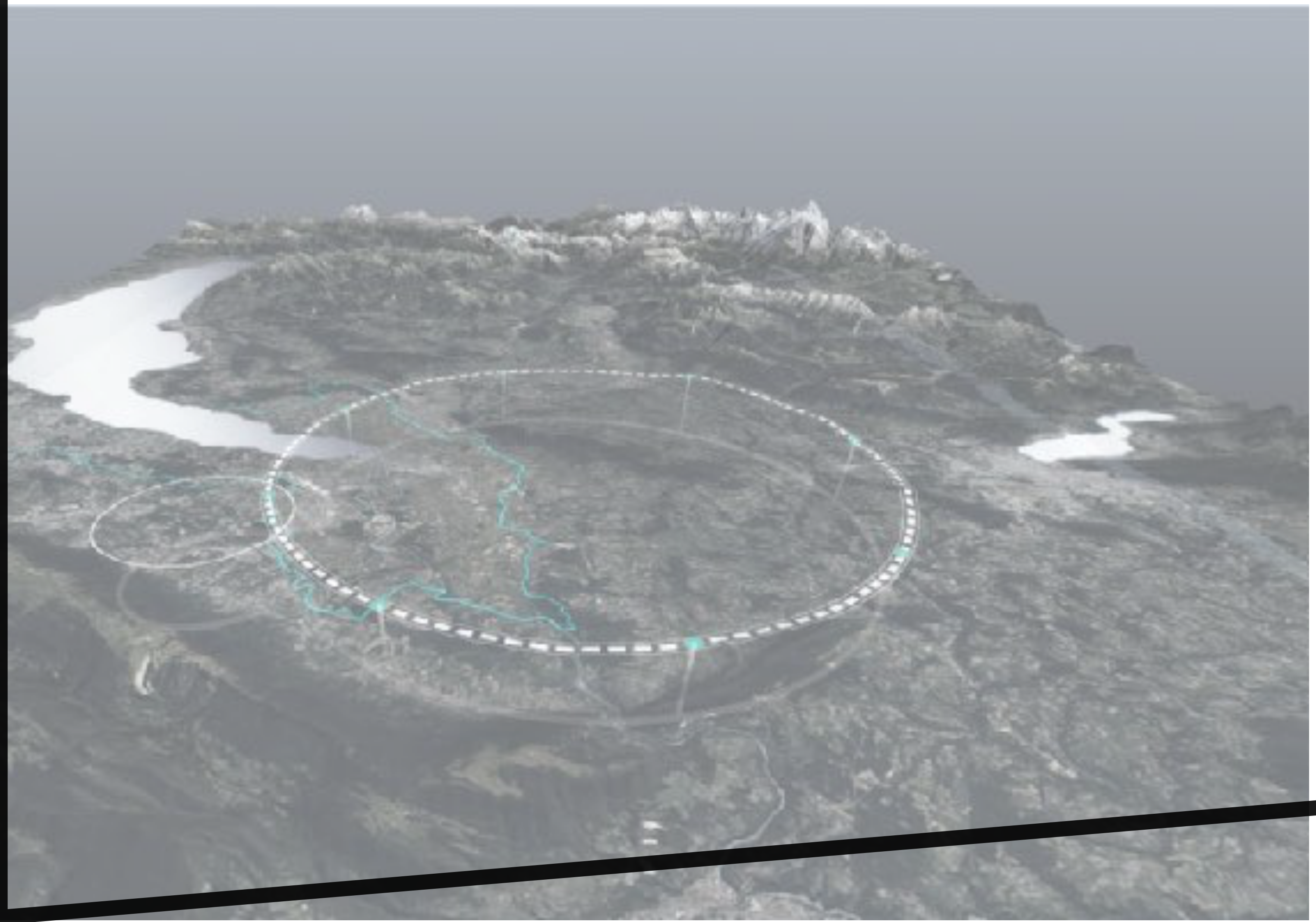
EFT
— for —
Future Colliders

" Standard Model EFT meets Chiral EFT", TRIUMF, 30 September 2025



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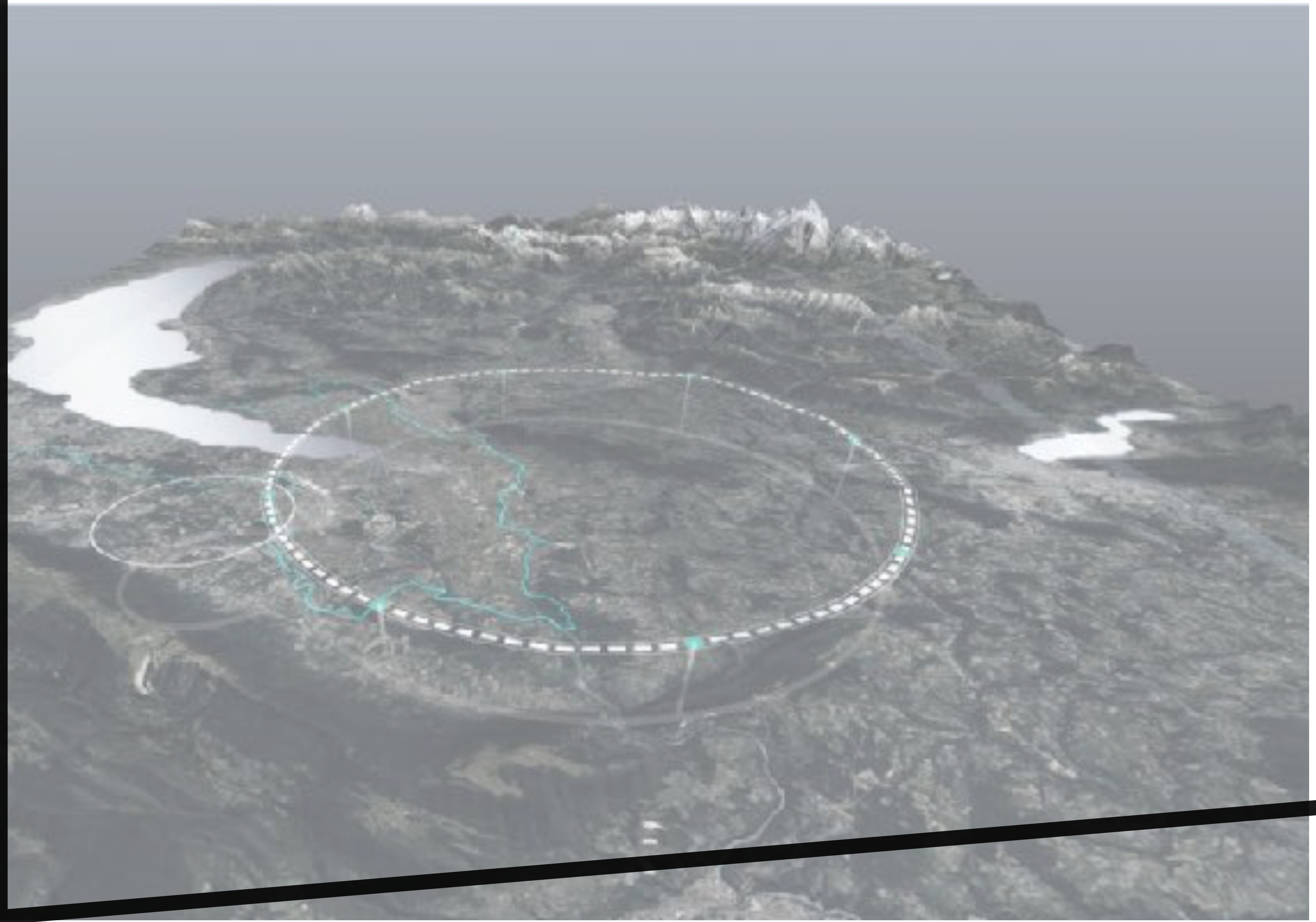

Outline

- Introduction - FCC Feasibility Study and ESPPU
- FCC Physics Overview
- (SM)EFT for Higgs@FCC
- (SM)EFT for EW@FCC
- (SM)EFT for Flavour@FCC
- Conclusions

The LHC Legacy (so far)

(LHC = Higgs + Nothing*) $\Rightarrow$ More energy & More precision

* actually a lot progress in our understanding of the SM:
1) Improved measurements of SM processes; 2) Precise measurements in flavour physics; 3) New frontiers in heavy-ion studies.

Thanks to a firm control of EXP & TH systematic uncertainties, the LHC became a precision machine.

The LHC Legacy (so far)

(LHC = Higgs + Nothing*) ⇒ More energy & More precision

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.

The Future Circular Collider integrated programme fits the bill.

FCC Feasibility Study Report

CERN-FCC-PHYS-2025-0002

Future Circular Collider
Feasibility Study Report

Volume 1

Physics, Experiments, Detectors

April 1, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

arXiv:2505.00272

CERN-FCC-ACC-2025-0004

Future Circular Collider
Feasibility Study Report

Volume 2

Accelerators, Technical Infrastructure and Safety

March 31, 2025

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Future Circular Collider
Feasibility Study Report

Volume 3

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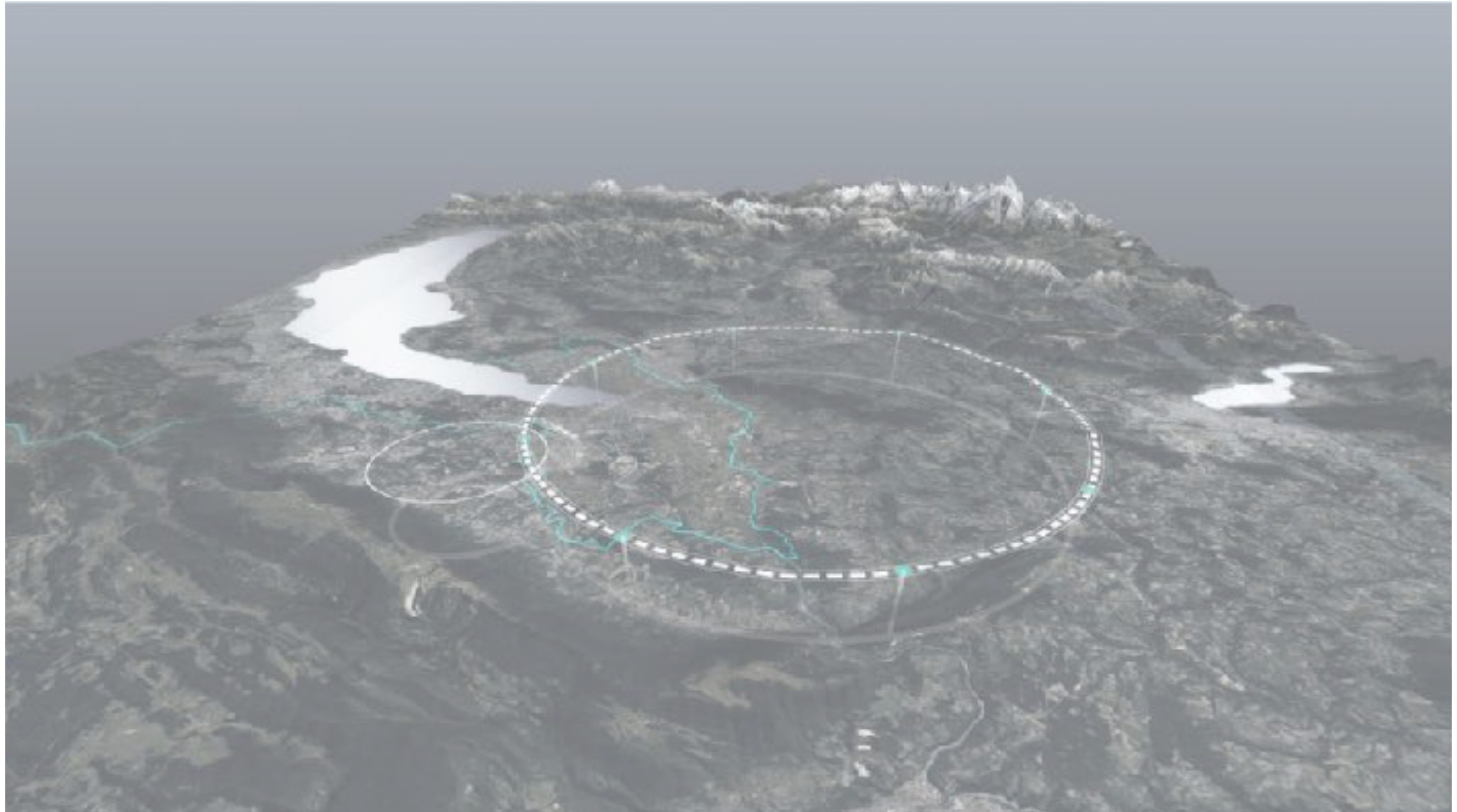
Future Circular Collider

- A versatile particle collider, with four interaction poins, housed in a 200m-underground 91 km 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**



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More Energy and more Precision for more sensitivity to New Physics

The Higgs Requires More Precision

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The knowledge of the values of the **Higgs couplings** is essential
to understand the deep structure of matter/Universe.

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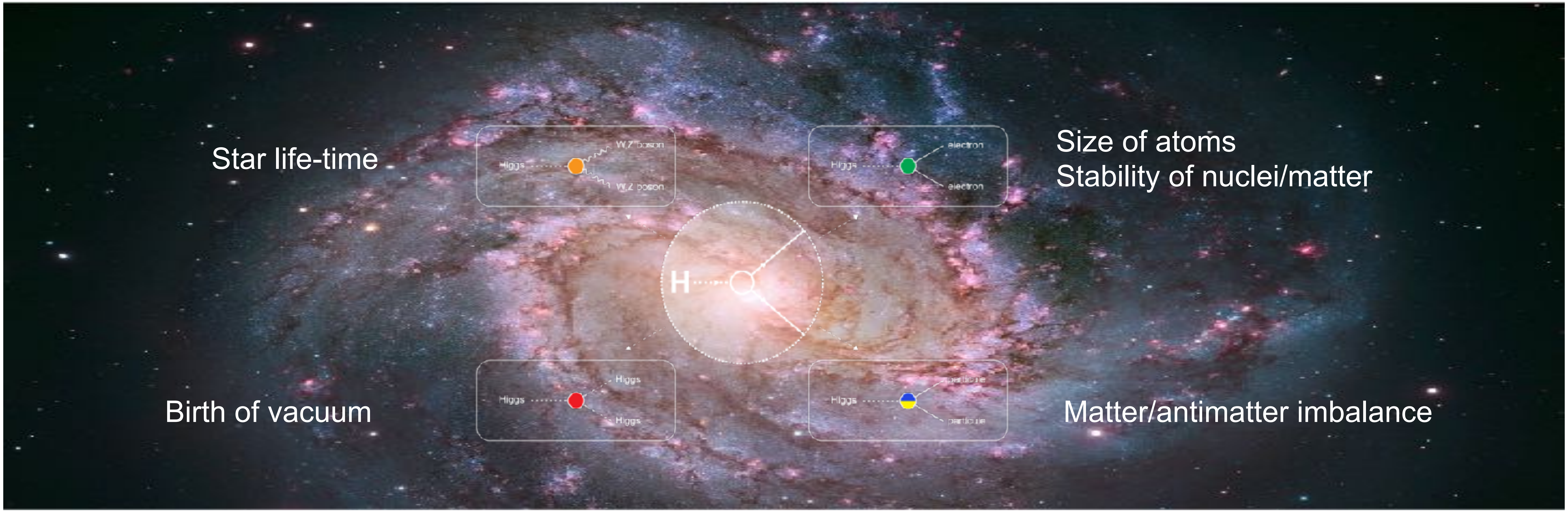

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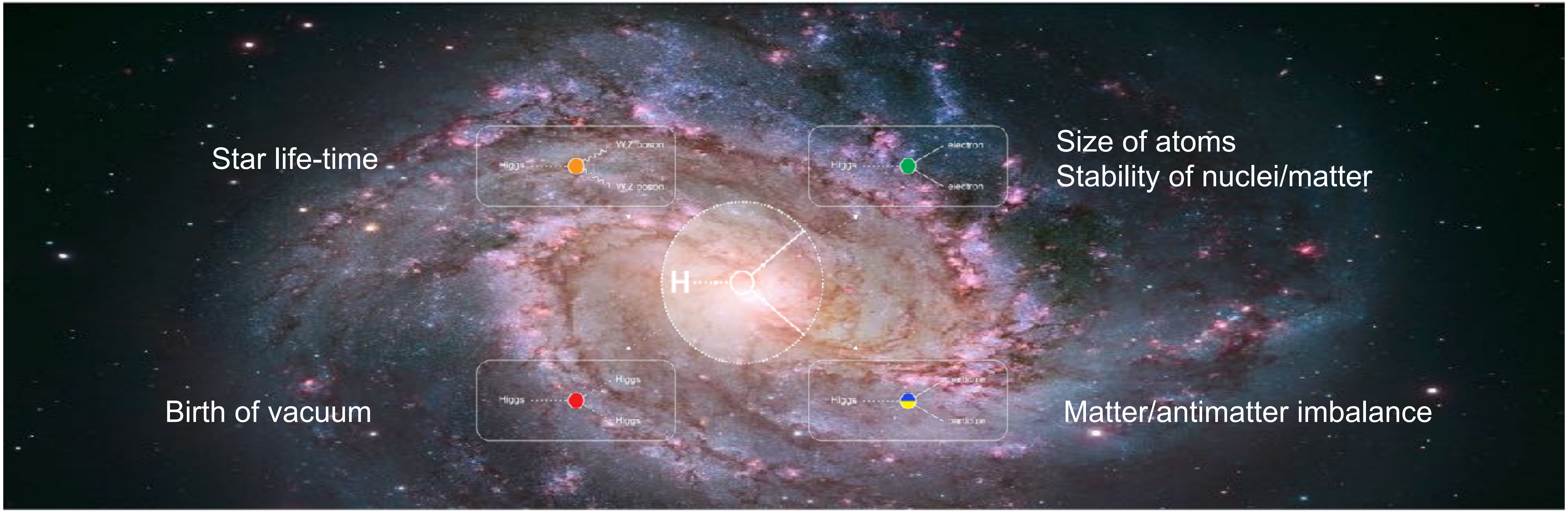
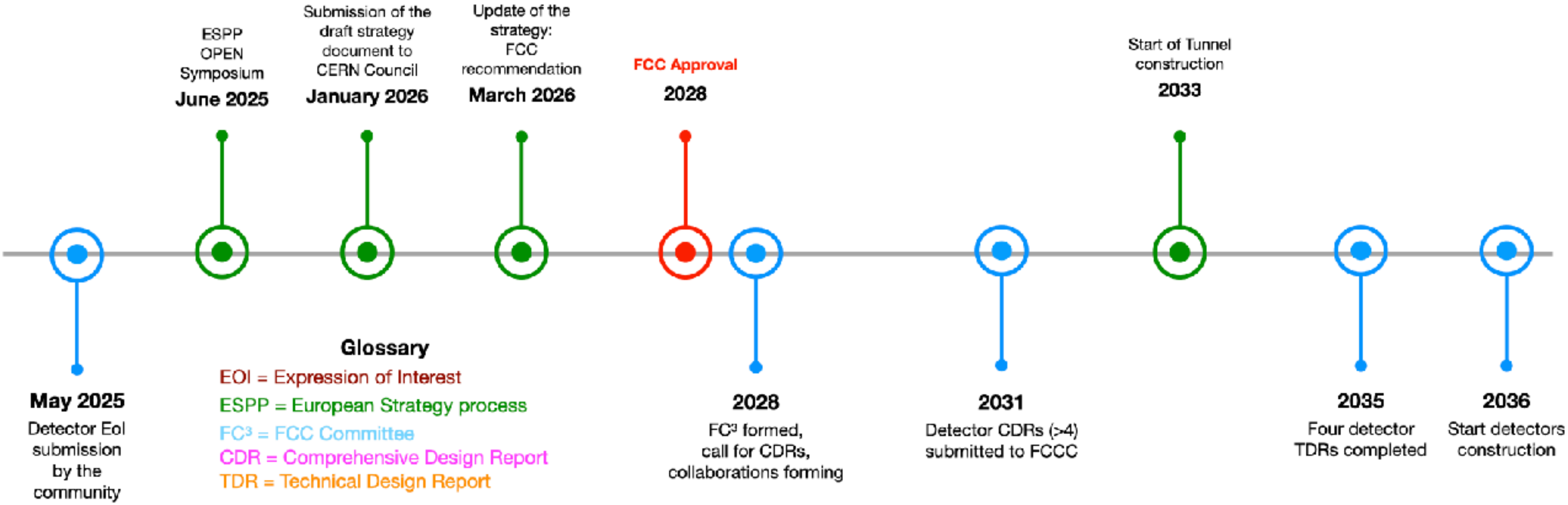


(HL)-LHC will make remarkable progress
(O(100M) Higgs=already a Higgs Factory).
But it won't be enough.
A new collider is needed!

Timeline

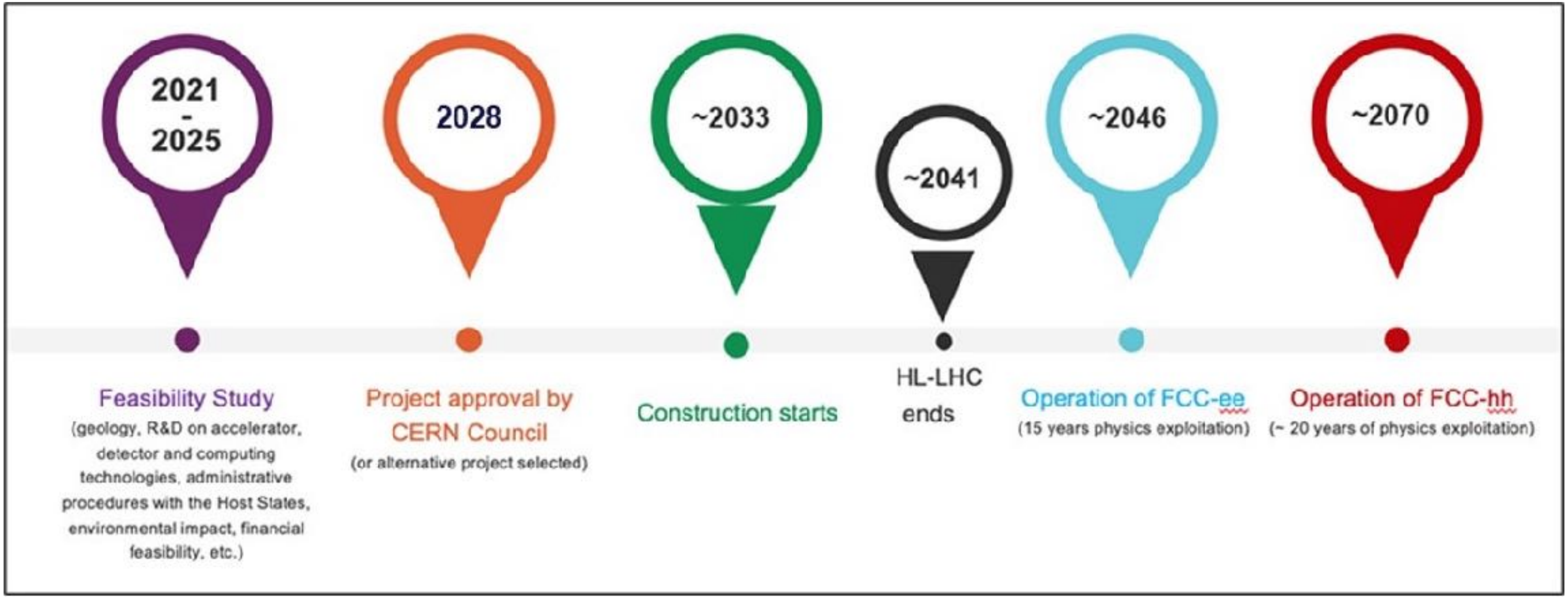
European Strategy for Particle Physics

Timeline



P. Janot/P. Giacomelli

Timeline


2021 - 2025
2028
~2033
~2041
~2046
~2070
Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)
Project approval by CERN Council
(or alternative project selected)
Construction starts
HL-LHC ends
Operation of FCC-ee
(15 years physics exploitation)
Operation of FCC-hh
(~ 20 years of physics exploitation)

US and CA Statements of Intent

Deirdre Mulligan Fabiola Gianotti

"Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the **United States** intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals."

White House, April 26, 2024

"Should the CERN Member States determine that the FCC is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, **Canada** intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals.

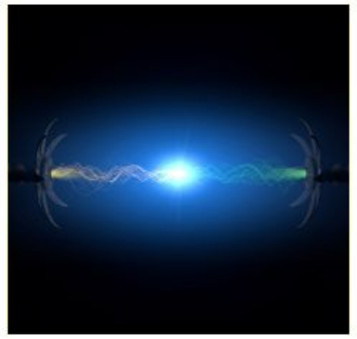
March 21, 2025

EU Support

- **EU Competitiveness Report: 400-page report made public by Mario Draghi on Monday 9/9/24024:**
  - Handed to Ursula von der Leyen (European Commission president) for subsequent action
  - Urges the EU to invest 800 billion euros annually [with specific guidance] to close the economic gap between the US and China (consistently seen as a threat throughout the report)
  - CERN mentioned 19 times in the report (and FCC 3 times)!
    - *“Refinancing CERN and ensuring its continued global leadership in frontier research should be regarded as a top EU priority.”*
    - *“One of CERN’s most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC): a 90-km ring designed initially for an electron collider and later for a hadron collider.”*
- **Speech of Ursula von der Leyen at CERN@70 celebration** (Youtube recording from 38'12" onwards)
    - *“CERN has become the centre of the world for particle physics”*
    - *“I am proud that we have funded the FCC Feasibility Study”*
    - *“I want the increase research budget just as you wish, Fabiola”*
- **July 16, 2025: Commission’s proposal for the next Multiannual Financial Framework 2028–34 and the European Competitiveness Fund: 410 billion EUR**
    - *FCC is one of the 11 “moonshots” with up-to 20% of the project funded by EU.*

EU Support

Moonshots



Future Circular Collider

What: Sustain Europe's leadership in particle physics by investing in CERN's next-generation collider.

How: Co-invest with other CERN countries, leveraging Horizon Europe funding.

Clean Aviation

What: Lead the world in developing the next generation of CO_2-free aircraft.

How: Develop applications from medicine to climate, solving previously impossible problems for 450 million citizens

Quantum Computing

What: Make Europe the first continent with fully integrated quantum computing in daily life.

How: Develop applications from medicine to climate, solving previously impossible problems for 450 million citizens.

Next Generation AI

What: Model the new AI on the laws of nature and grounded in physics and biology.

How: AI developed by, with, and for European scientists and industry, drawing to Europe the world's best minds.

Data Sovereignty

What: Make Europe the global leader and safest hub for critical research data.

How: Provide access to critical data for researchers, universities and companies, offering competitive advantage in tackling global challenges.

Automated Transport and Mobility

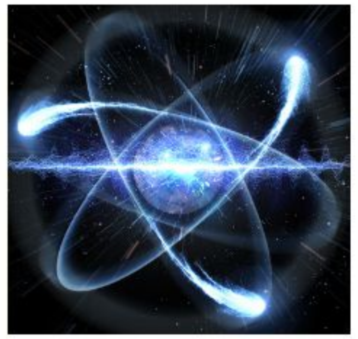
What: Advance safe, inclusive, and emission-reducing automated transport and mobility in Europe.

How: Invest in smart transport systems to improve traffic, reduce emissions, and enhance access.

Regenerative Therapies

What: Deliver breakthrough therapies to improve people's health and lives.

How: Harness Europe's scientific strengths to treat incurable diseases and personalise medicine.



Fusion Energy

What: The first commercial nuclear fusion power plant, generating safe, consistent, and reliable electricity.

How: Overcome the scientific and technological challenges necessary to put fusion on the grid in Europe by 2034.

Space Economy

What: Make Europe the leader in the space economy.

How: Develop the next generation launch vehicles such as reusable rockets, able to deploy massive cargo by 2040.

Zero Water Pollution

What: Move towards zero pollution of water in the EU.

How: Stimulate innovation to build a true water-smart economy which secures sufficient, clean and affordable water and sanitation to all at all times.

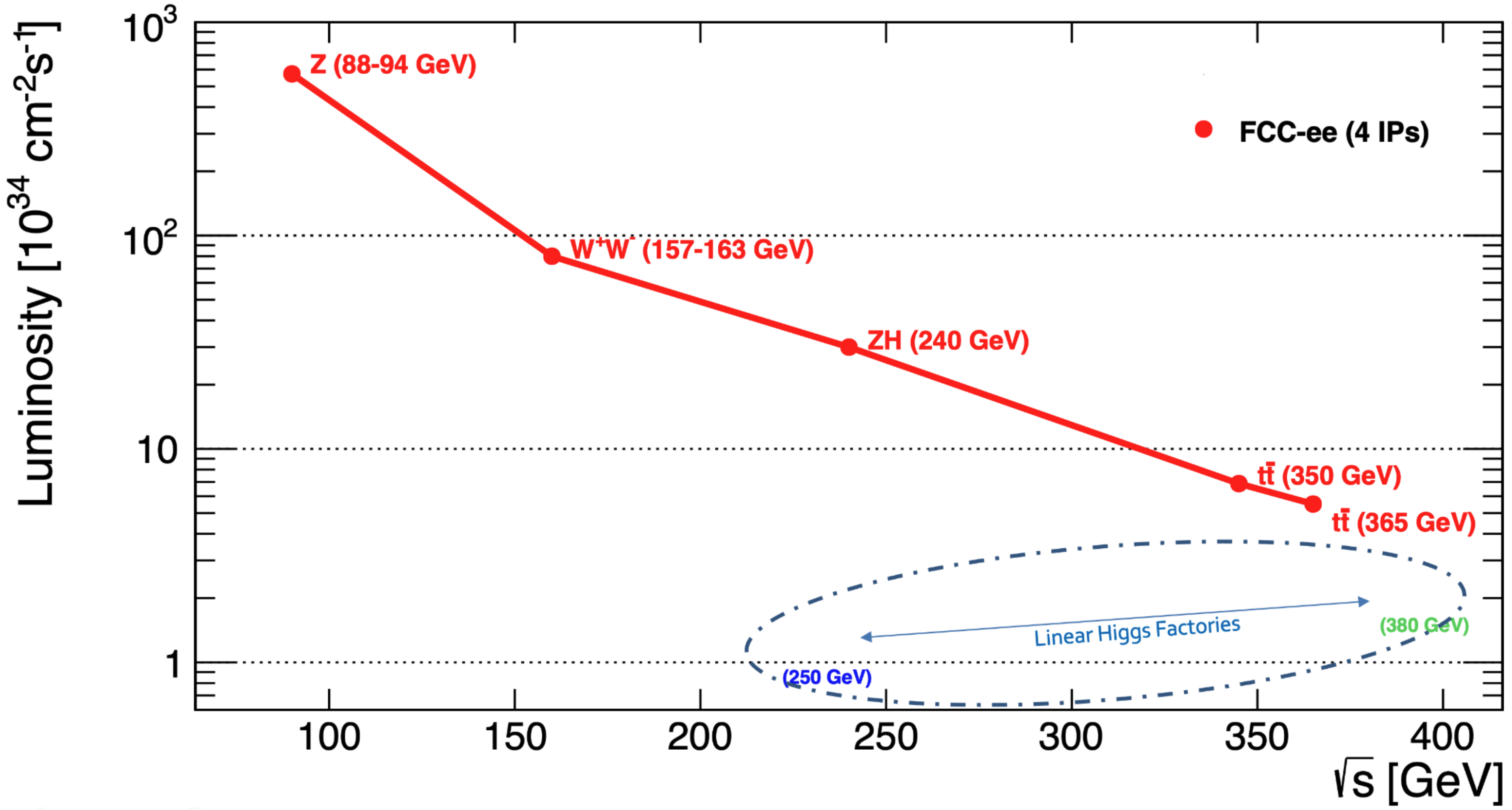
Ocean Observation

What: Achieving strategic autonomy in ocean observation infrastructure, data and information services.

How: Developing, connecting, governing and securing the next generation of European ocean observing technologies

— FCC —
Physics Overview

FCC-ee Run Plan



FCC-ee Run Plan

LEP1 data accumulated in **every 2 mn**.

(for the same power consumption, i.e. machine 100’000 more efficient).

Improved efficiency thanks to

▸ Double ring collider

• many bunches, high current, like LHC and B factories, different from LEP

▸ Top-up injection

• standard at modern light sources, like SLS

• used at recent e^+e^- colliders, PEP-II (USA), KEKB (Japan), BEPCII (China)

▸ Crab-waist collision scheme

• successfully demonstrated at DAFNE (Italy) and SuperKEKB (Japan)

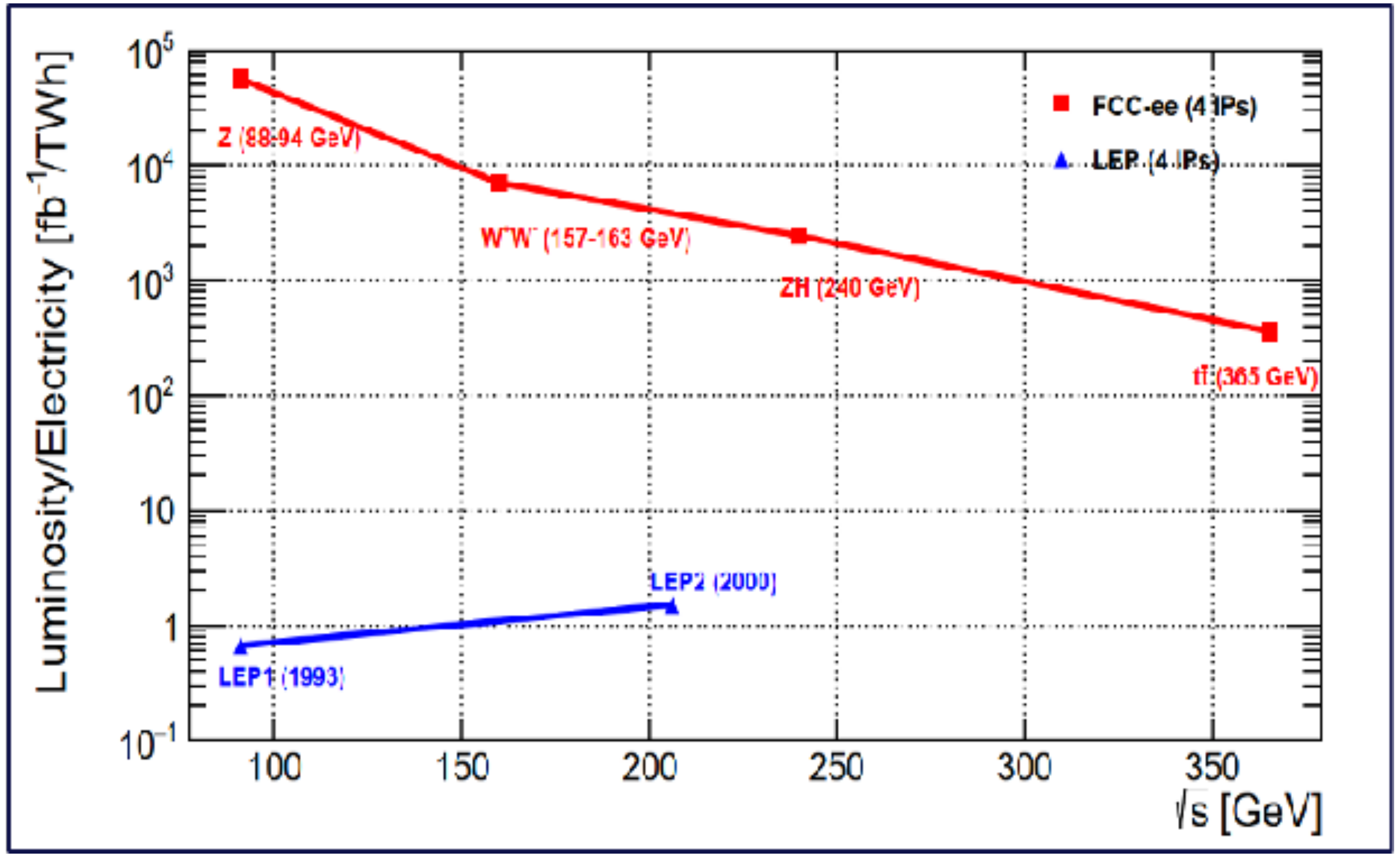
▸ Superconducting radiofrequency system

• Nb/Cu 400 MHz SC cavities pioneered at former CERN LEP

• bulk Nb 800 MHz SC cavities similar to ESS (Sweden), EuXFEL (Germany)

• revolutionary highly efficient RF power sources

• new operation scheme for flexible energy switching & reduced complexity



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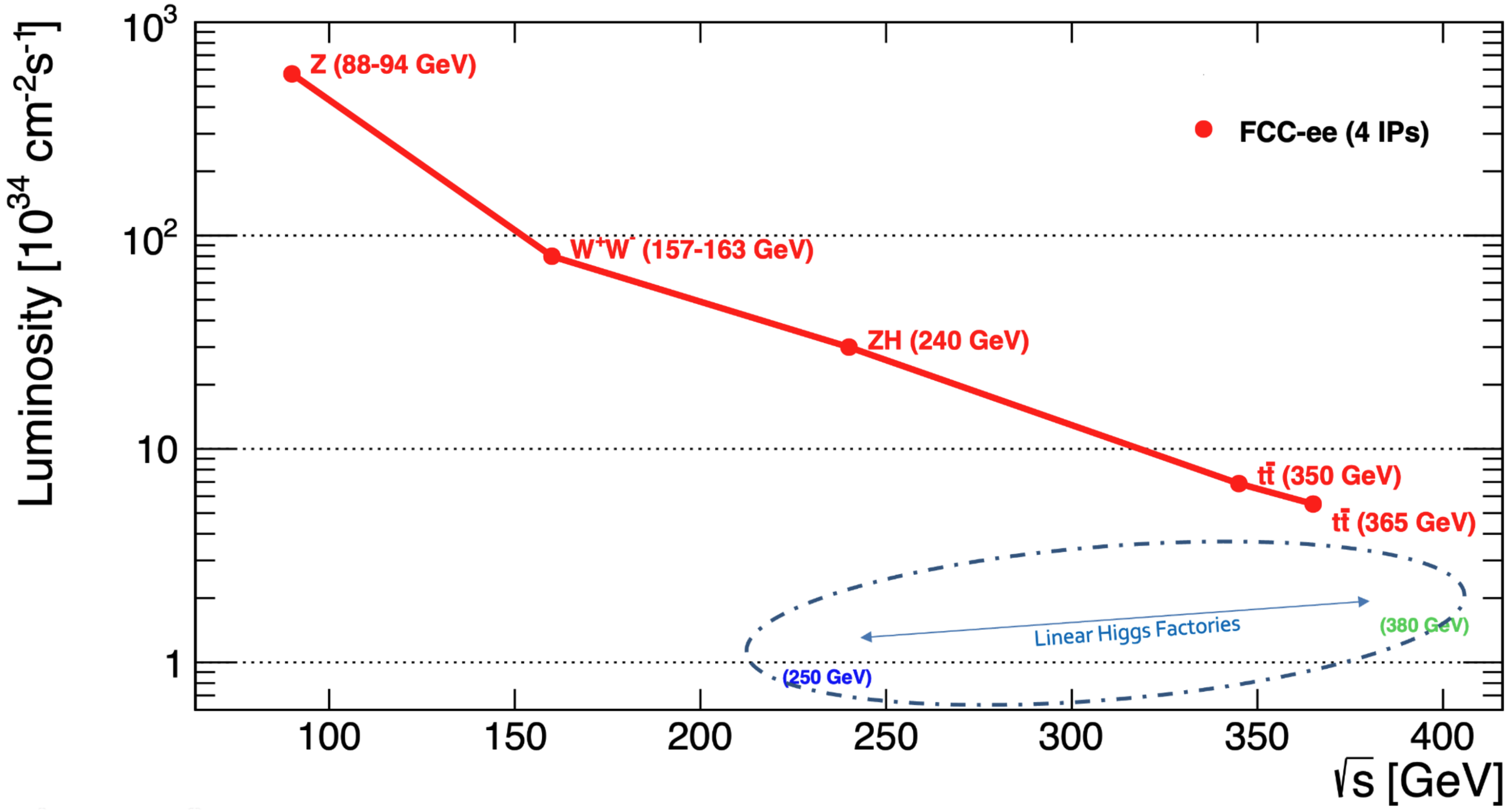

— Superb statistics achieved in only 15 years —

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

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW $\to$ H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW $\to$ H	

FCC-ee Run Plan

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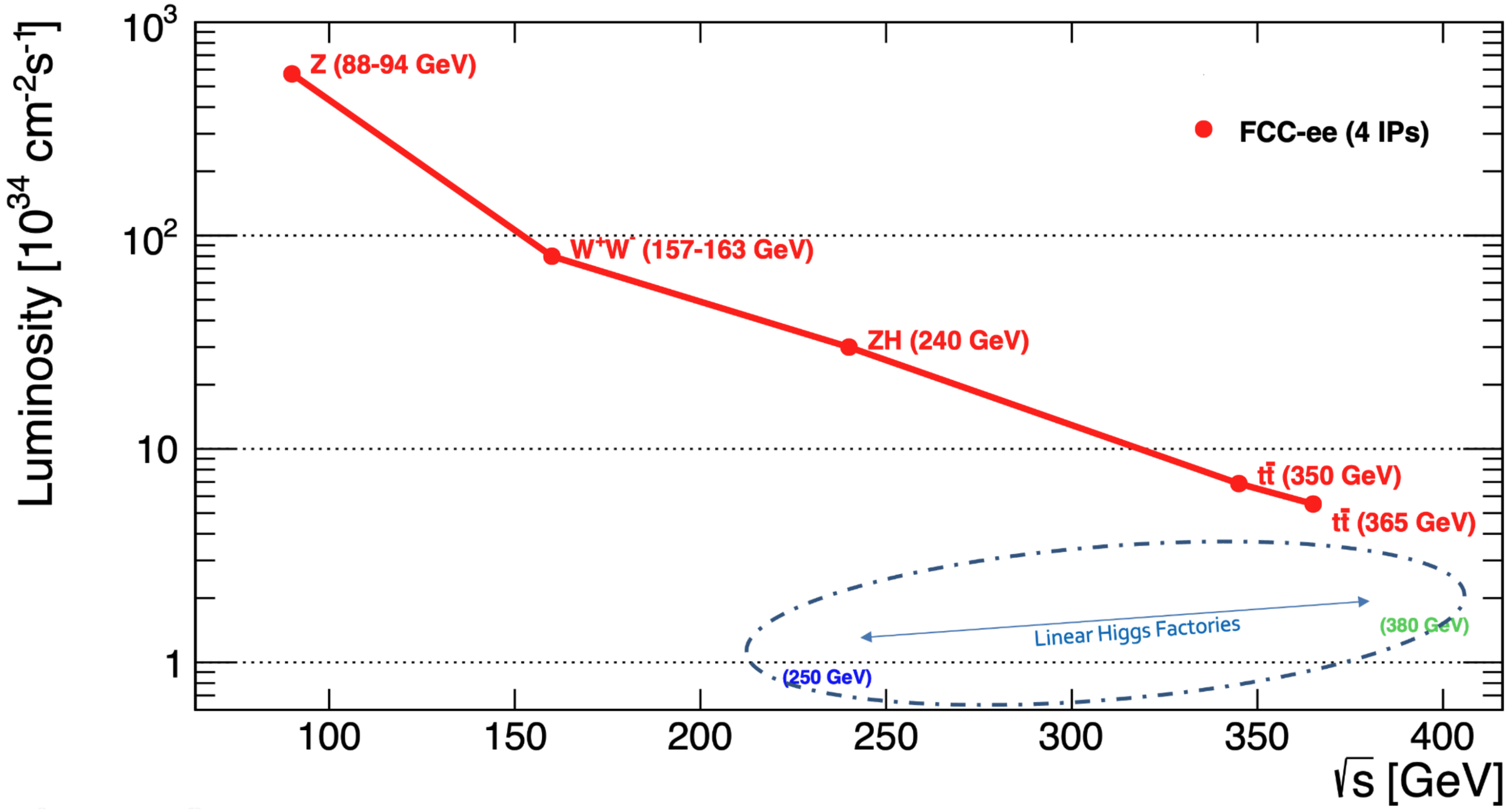
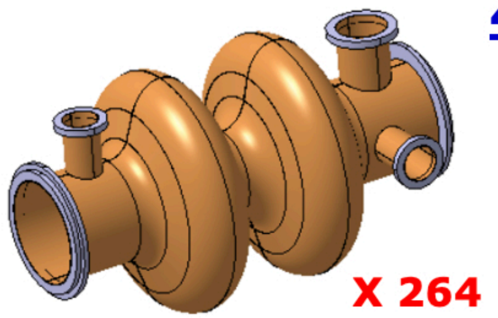


— Superb statistics achieved in only 15 years —

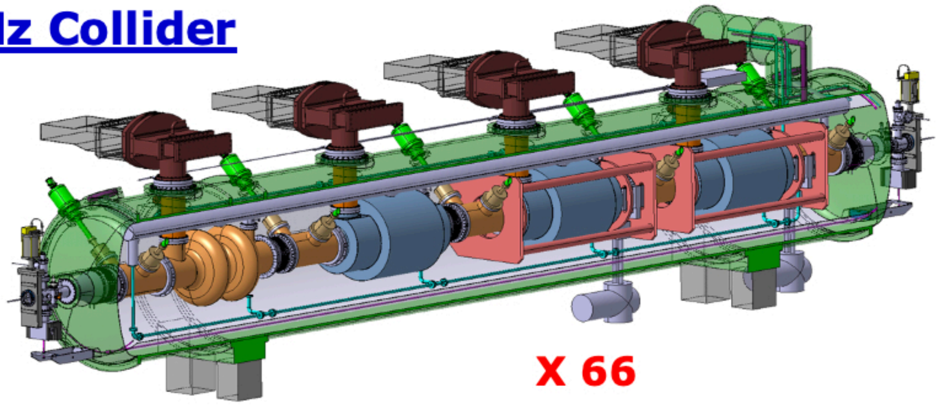
in each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

Exciting & diverse programme with different priorities every few years.

Order of the different stages still subject to discussion/optimisation. Development on **unique RF cavities** to be used from 90 to 240GeV enables great flexibility of operation.



400 MHz Collider

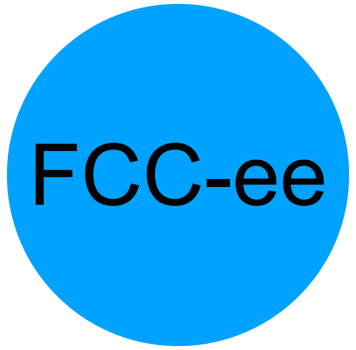


Superconducting elliptical cavity

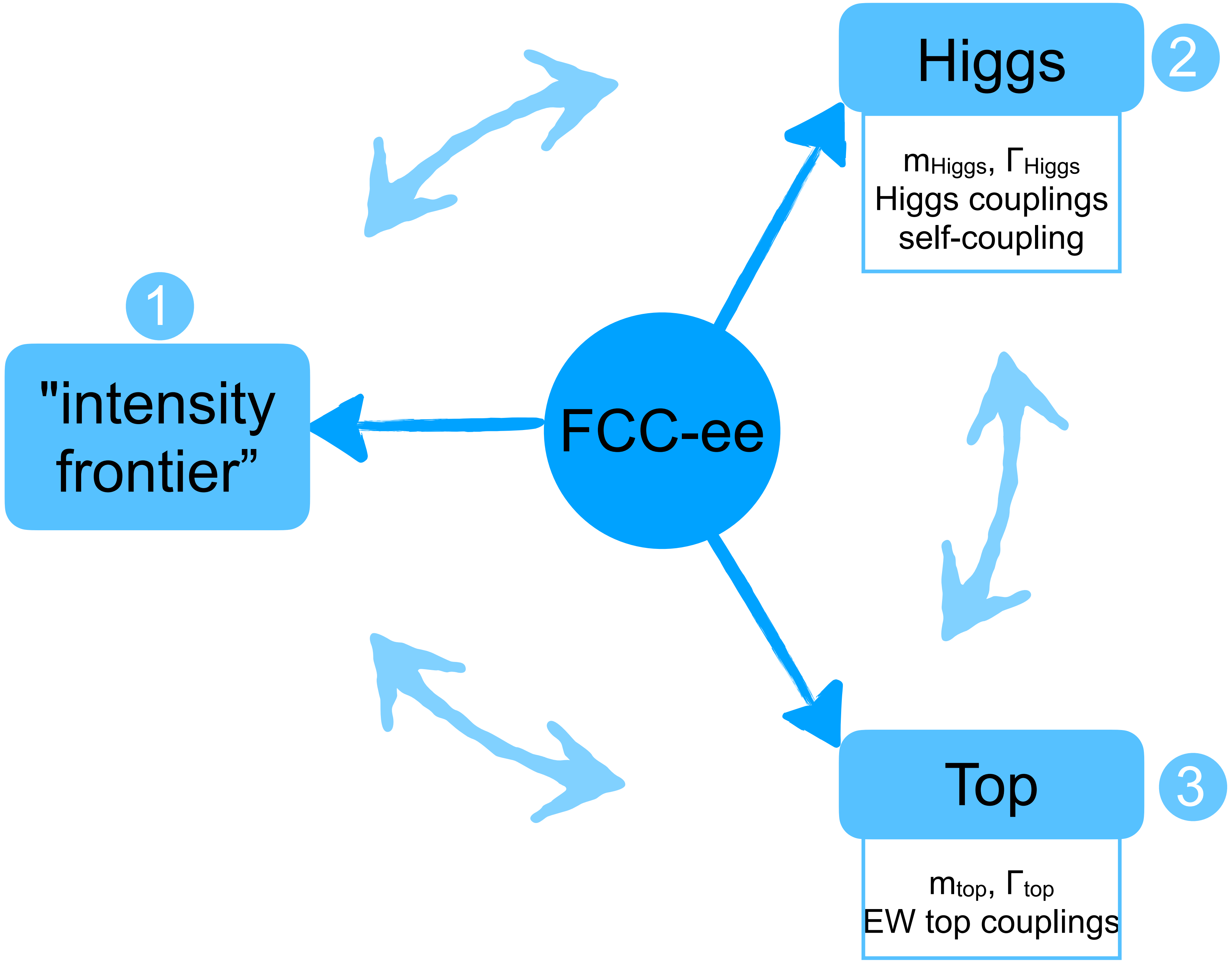
- 400 MHz, 2-cell, copper Nb coated
- 1.5 m. long

400 MHz Cryomodule

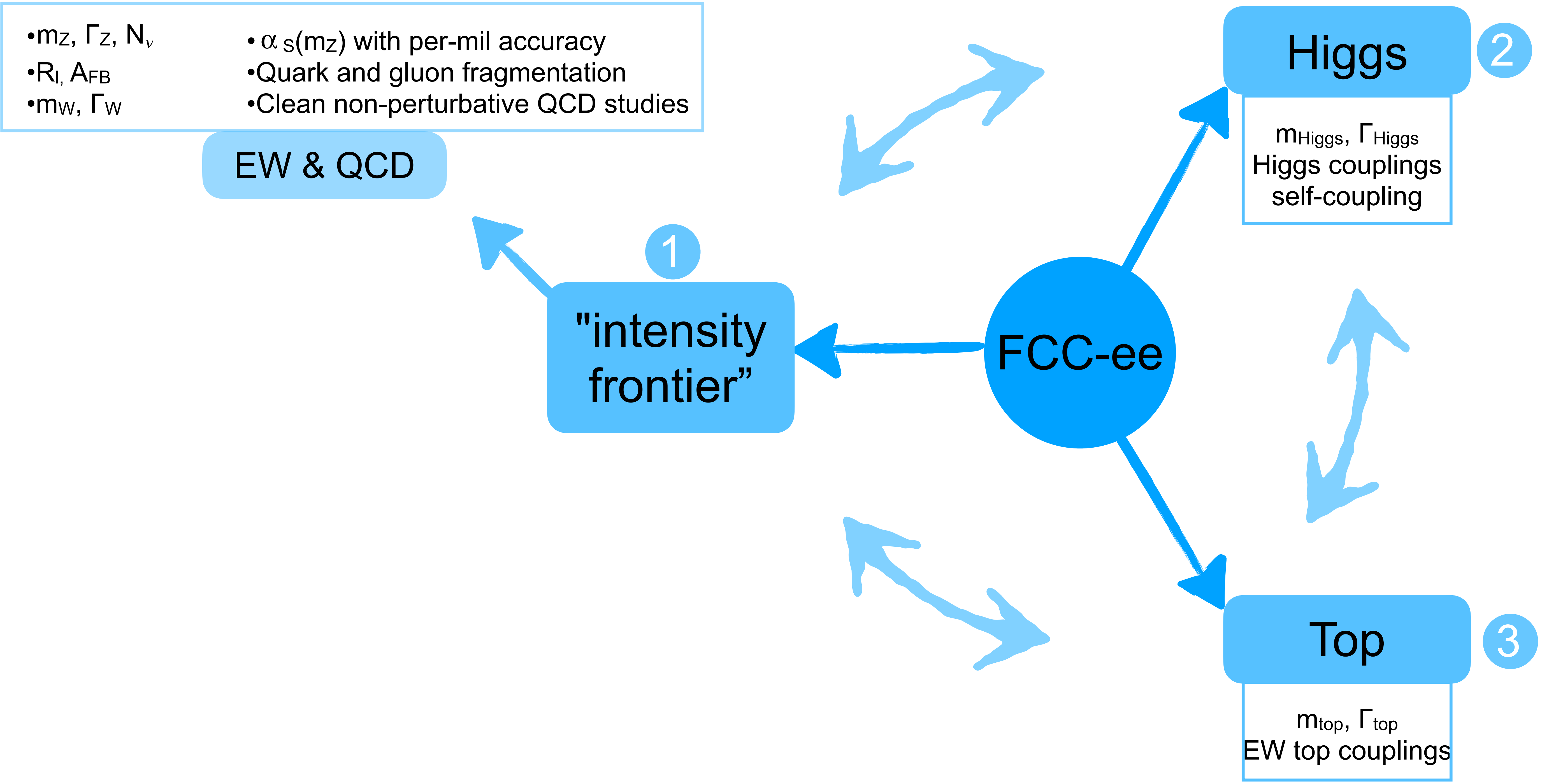
FCC-ee Physics Programme



FCC-ee Physics Programme



FCC-ee Physics Programme



FCC-ee Physics Programme

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W

- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

EW & QCD

Uncertainty	m_Z (keV)	Γ_Z (keV)	$\sin^2\theta_W^{\rm eff}$ $(\times 10^{-6})$*	$\frac{\Delta\alpha_{\rm QED}(m_Z^2)}{\alpha_{\rm QED}(m_Z^2)}$ $(\times 10^{-5})$	$A_{\rm FB}^{{\rm pol},\tau}$ $(\times 10^{-4})$
LEP	2000	2300	40	/	49
FCC-ee statistical	4	4	2	3	0.15
$\sqrt{s}$ systematic	101	12	1.2	0.5	/

Improvements in precision of $O(10^2)$ available,
provided systematic uncertainties can be controlled.
Much work already invested to this goal, e.g. calibration of collision energy (EPOL).

FCC-ee Physics Programme

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- $\alpha_S(m_Z)$ with per-mil accuracy
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EW & QCD

1

"intensity frontier"

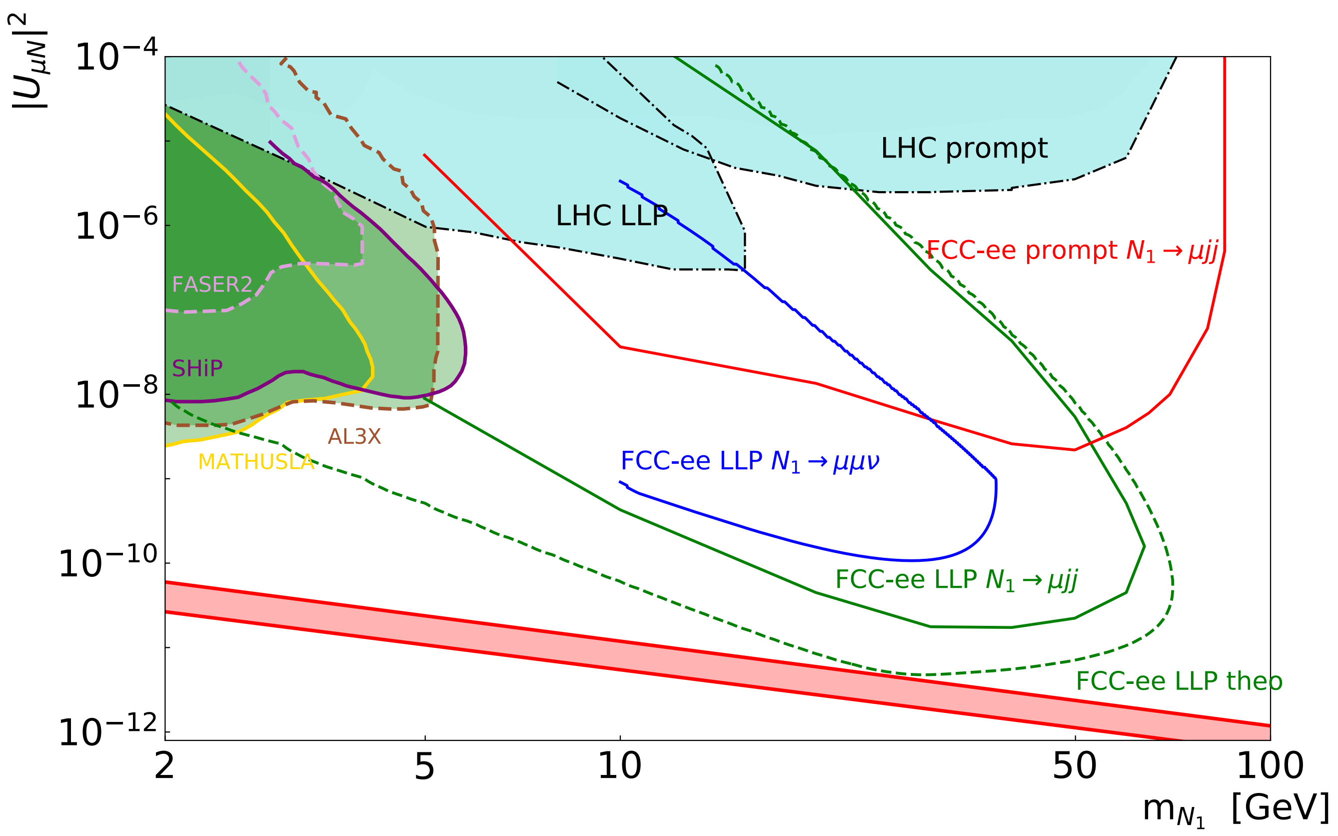
direct searches of light new physics

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

Higgs

2

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



EW top couplings

FCC-ee Physics Programme

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EW & QCD

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

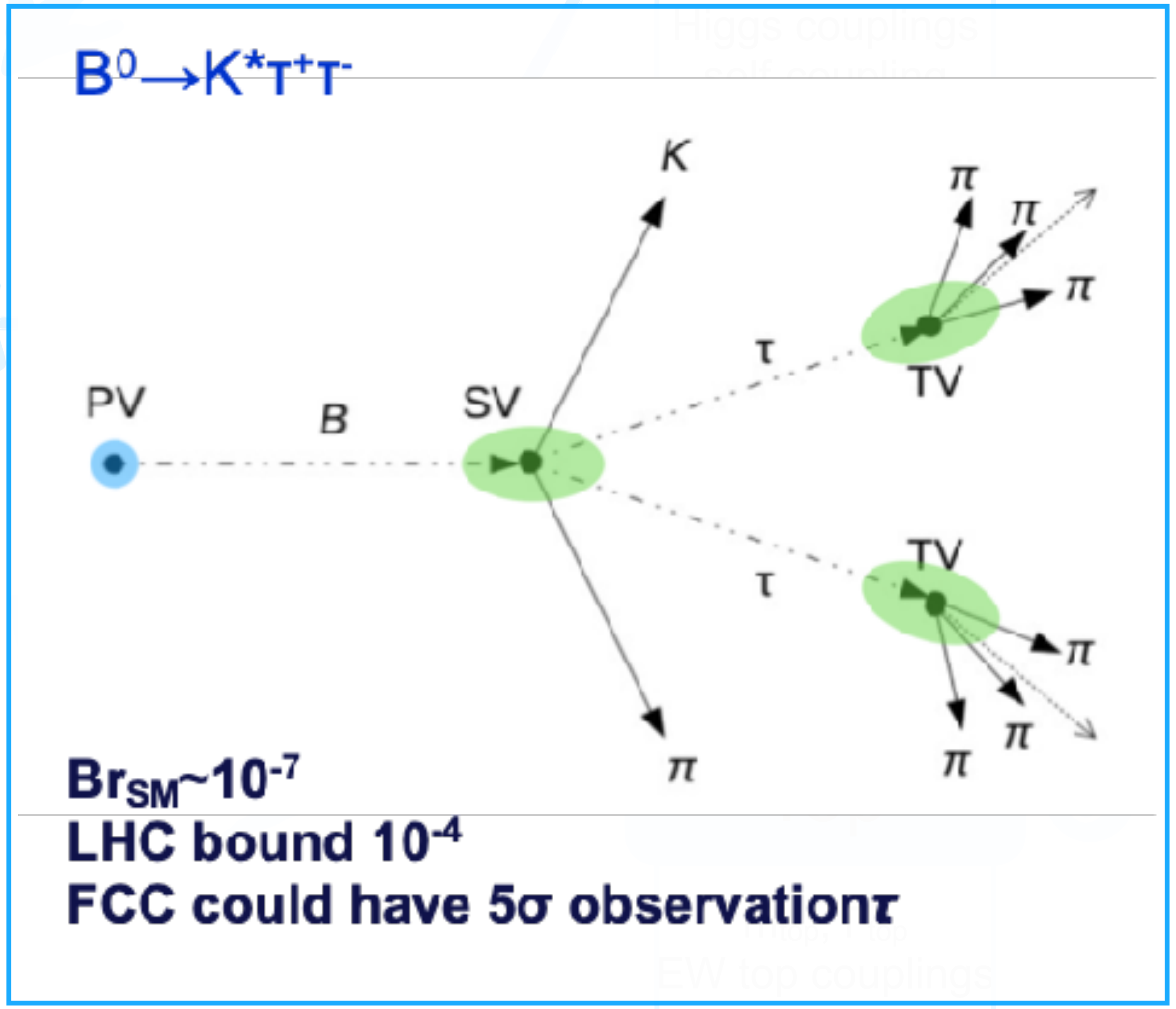
flavour factory (10^{12} bb/cc; 1.7×10^{11} $\tau\tau$)

τ physics

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

B physics

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



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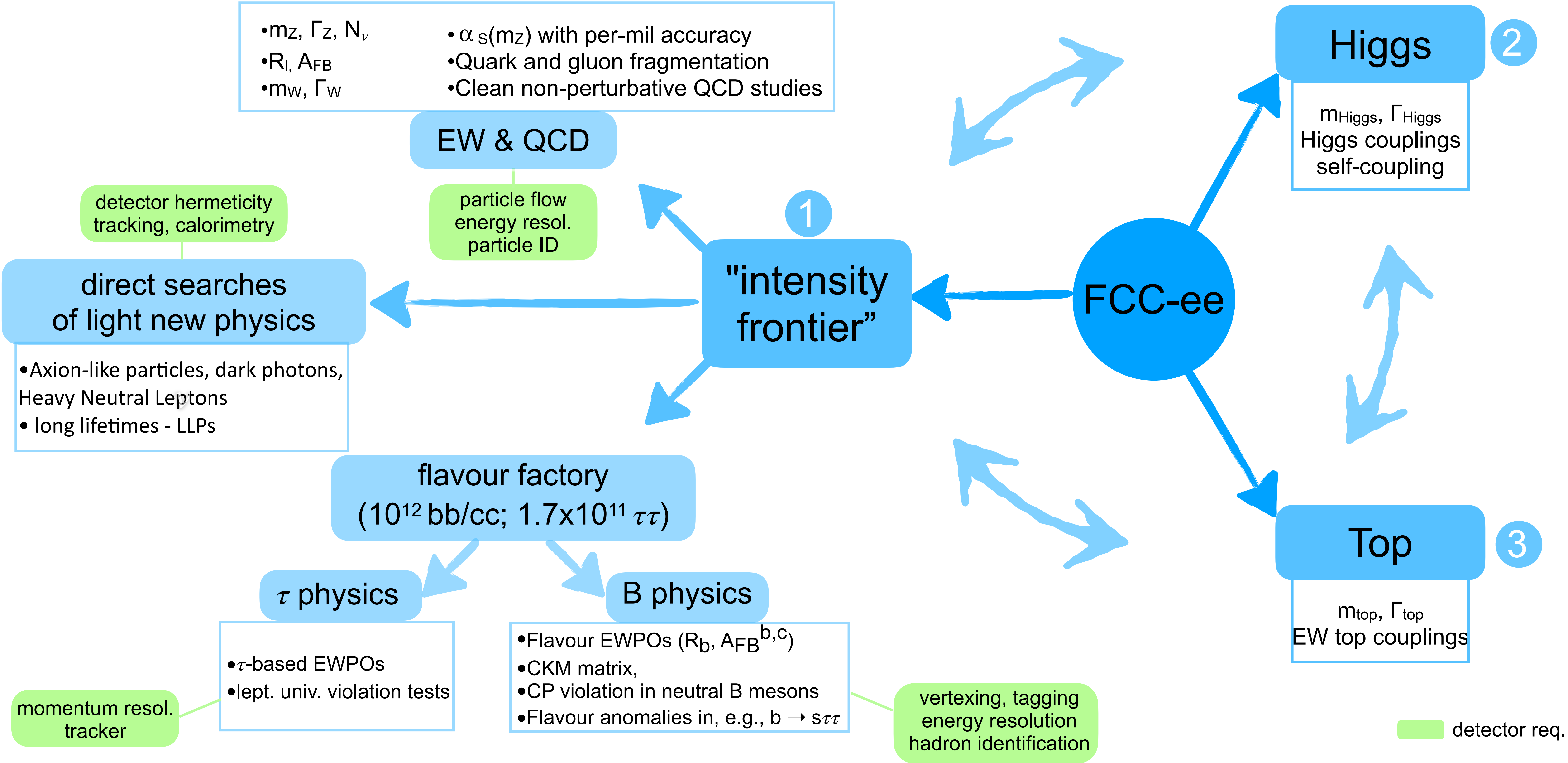


FCC-ee Physics Programme

Higgs Factory Programme

- At √s=240 and √s=365 GeV collect 2.6M HZ and 150k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \to H$ at 125 GeV

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6×10^{12} Z and 2×10^{8} WW events
- × 500 improvement of statistical precision on EWPO: $m_Z, \Gamma_Z, \Gamma_{inv}, \sin^2\theta_W, R_b, m_W, \Gamma_W, \ldots$
- 2×10^{8} tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

- **Absolute normalisation of luminosity to 10^{-4}**
- **Relative normalisation to ≤ 10^{-5} (e.g. $\Gamma_{had}/\Gamma_{\ell}$)**
  - Acceptance definition to $\mathcal{O}$(10 μm)
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2×10^{12} ττ (clean and boosted): 10 × Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/√E**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

FCC-ee Physics Programme

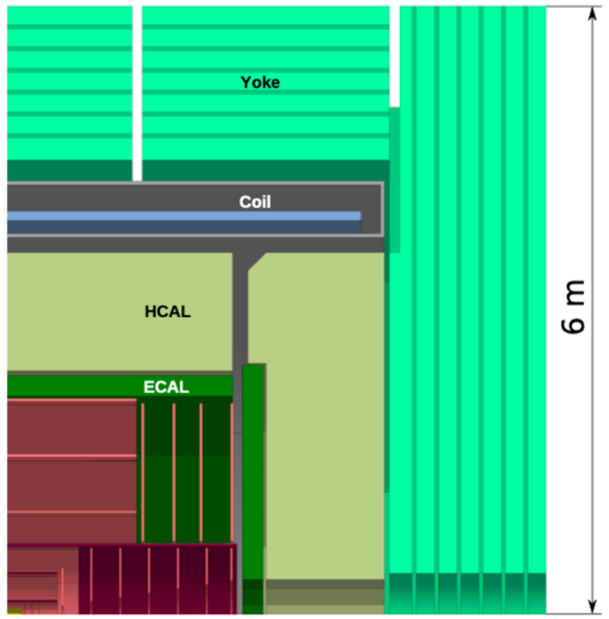
Summary of detector requirements

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

FCC-ee Physics Programme

M. Dam @ FCC week 2025

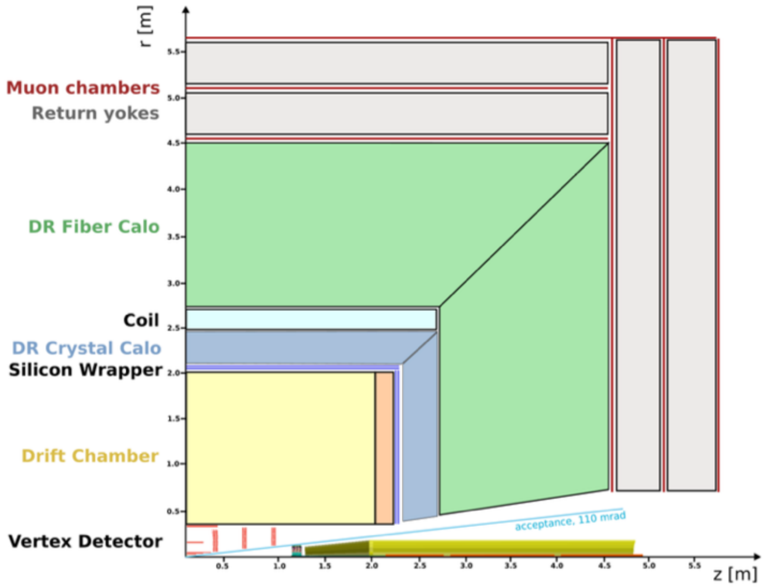
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si VTX + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

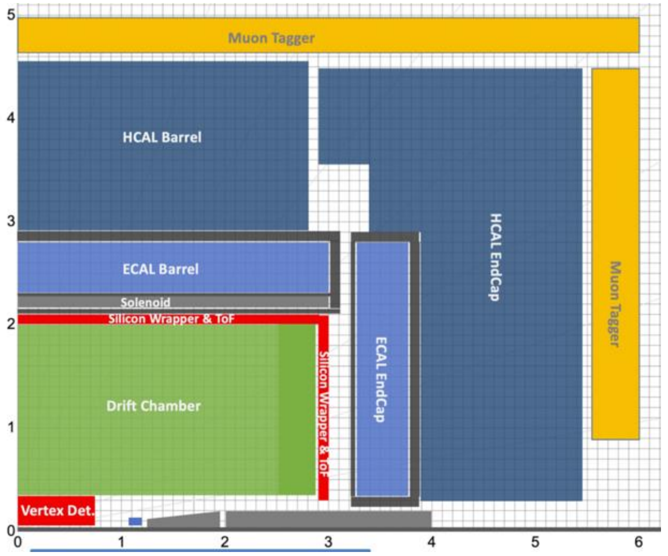
IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VTX detector; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

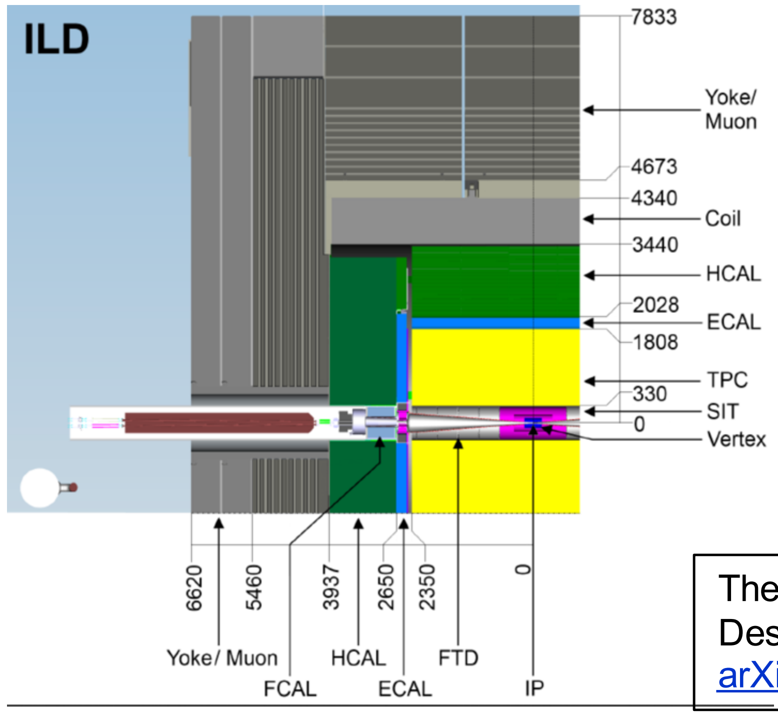
https://doi.org/10.48550/arXiv.2502.21223

Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VTX detector
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
  - Large-volume time projection chamber (TPC)

The International Linear Collider Technical Design Report - Volume 4: Detectors
arXiv:1306.6329

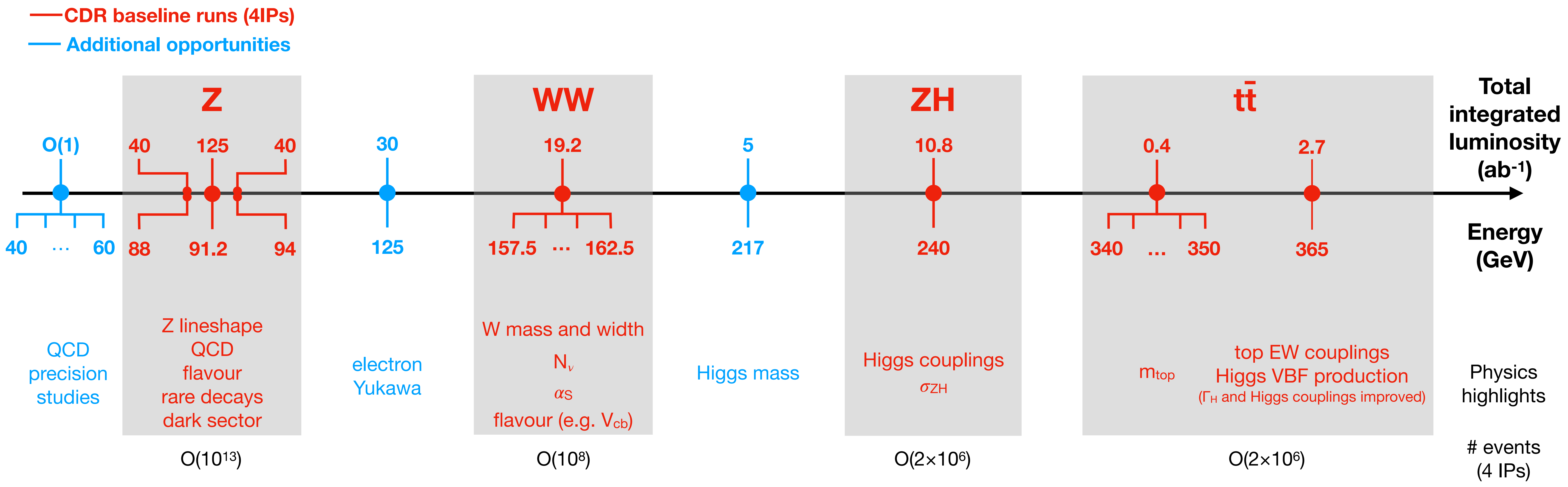
FCC-ee Physics Programme

Quizz: what is the mapping with the 4 LEP detectors?

- ALEPH: reasonably new technologies, homogeneous detector, granularity more than energy resolution.
- DELPHI: very new technologies, larger variety of techniques
- L3: measure leptons (and photons) with high resolution
- OPAL: only proven and reliable technologies, to be sure at least one of these huge detectors would be ready in time

(C. Paus @ FCC week 2025)

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.

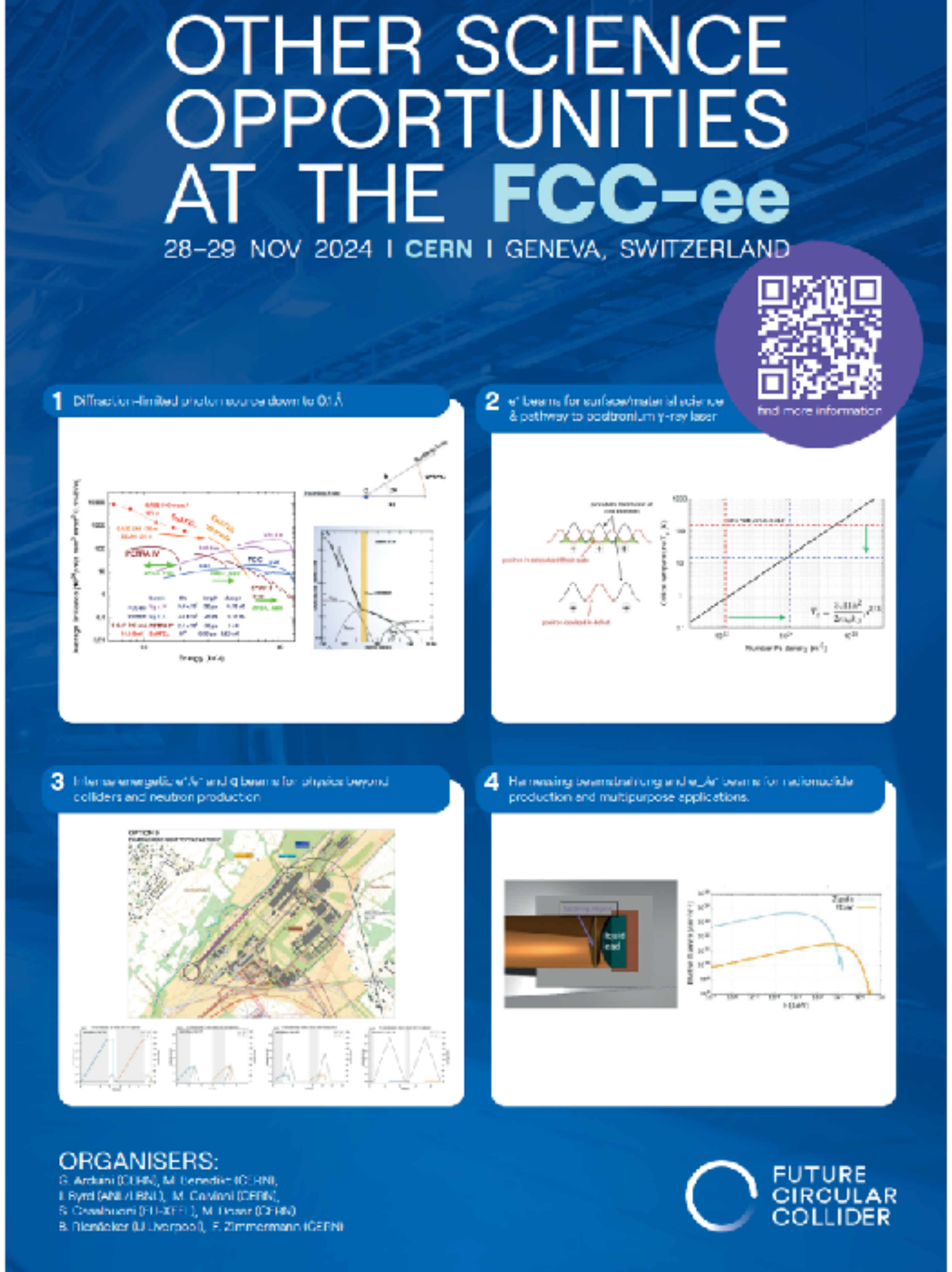
photon science

(light source,
Compton Backscattering sources)

HEP applications

(strong QED, dark sector)

workshop webpage link



e^+ applications

(surface science,
Ps Bose-Einstein Condensate,
511 keV X-ray laser)

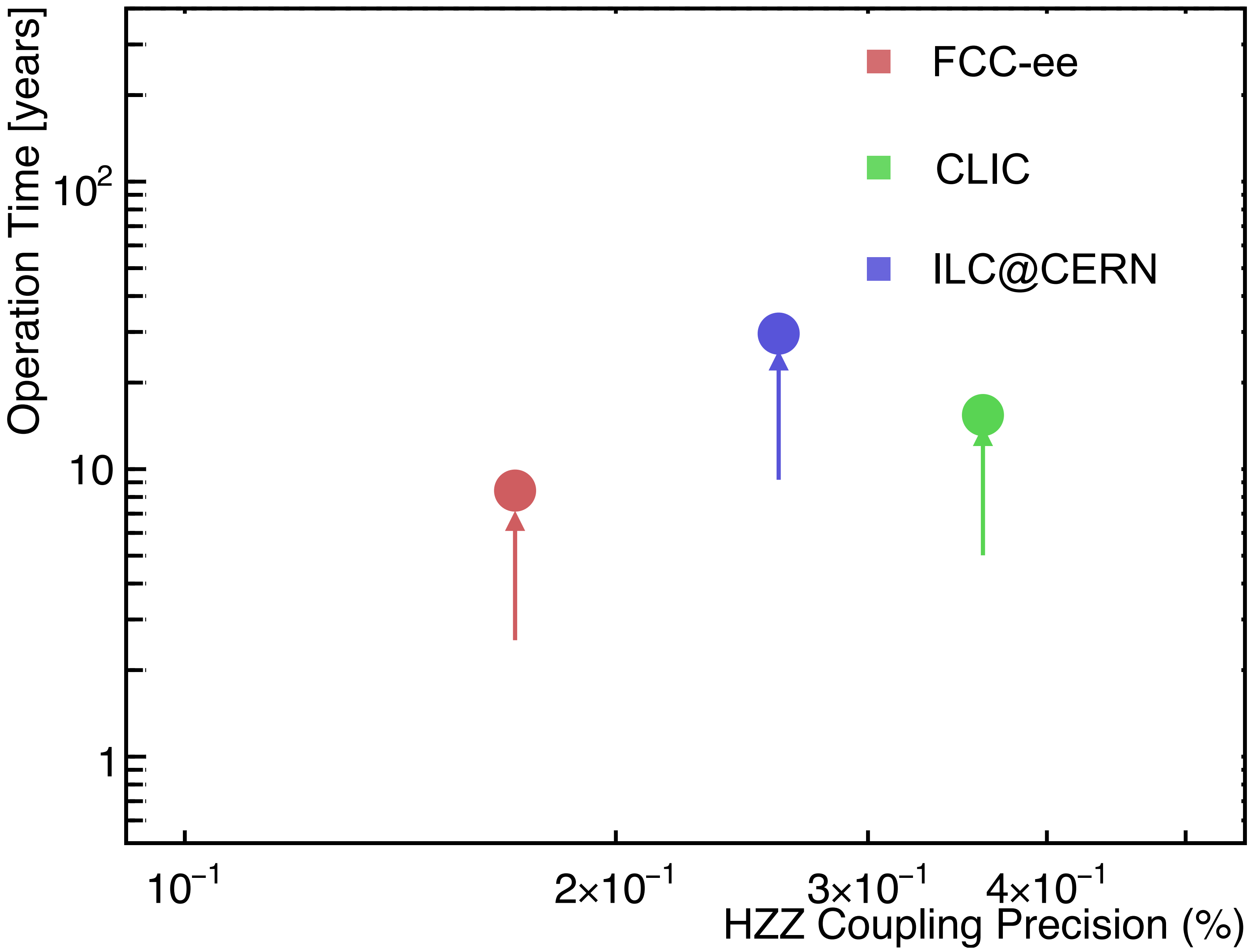
multipurpose applications of the e^-/e^+ beams

(radionuclide production,
neutron source)

(SM)EFT for Higgs @ FCC

A Performant Higgs Programme

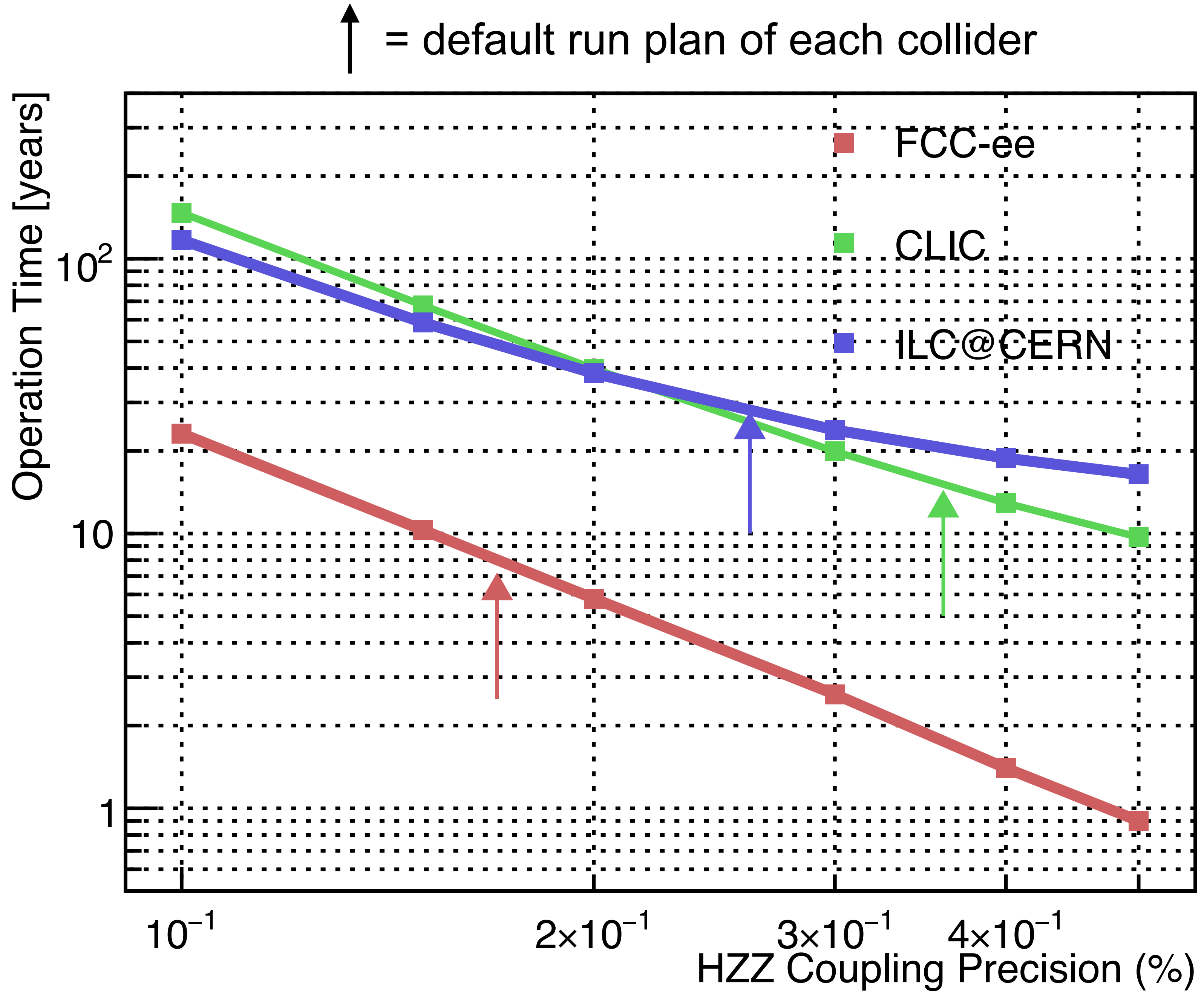
↑ = default run plan of each collider



Collider cost has to be normalised to its physics output, e.g. Higgs precision.
It would take about 30-50 years for other projects to achieve what can be done at FCC-ee in 8 years.
This has consequences in terms of electricity/money/carbon footprint.

arXiv:2412.13130

A Performant Higgs Programme



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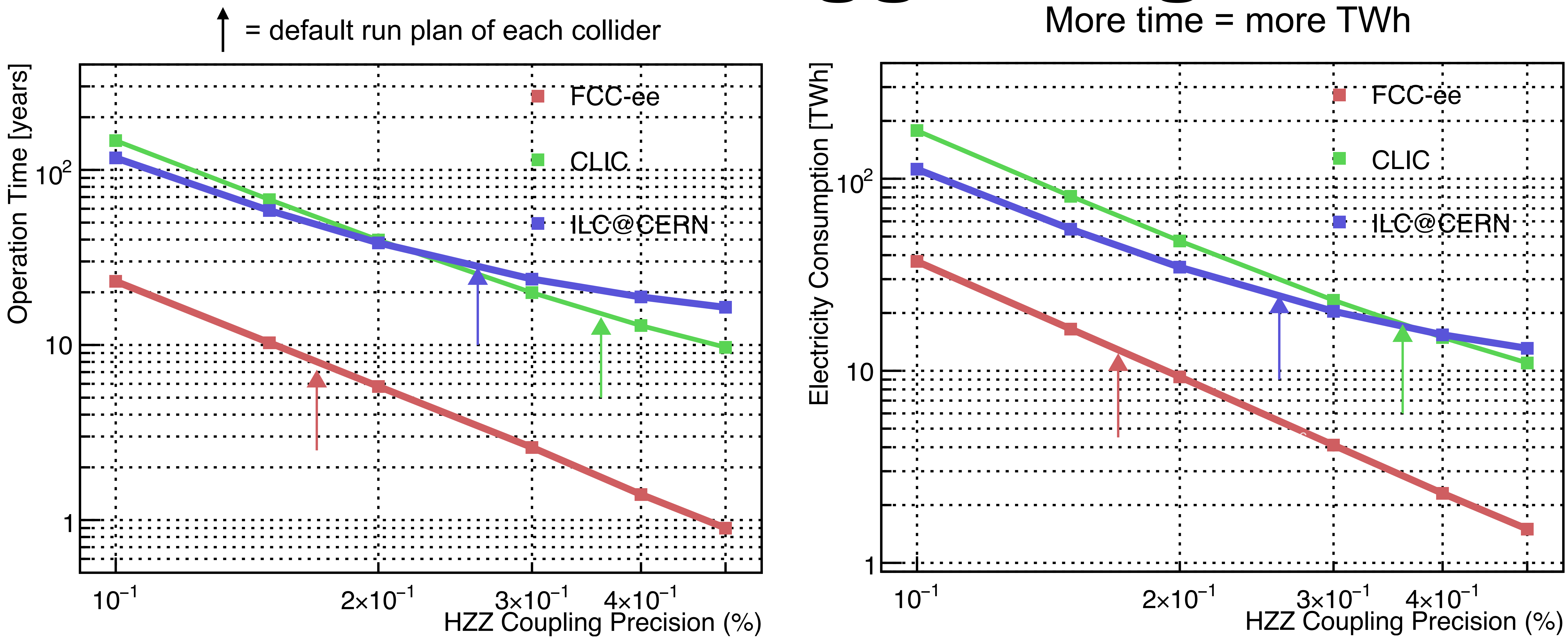

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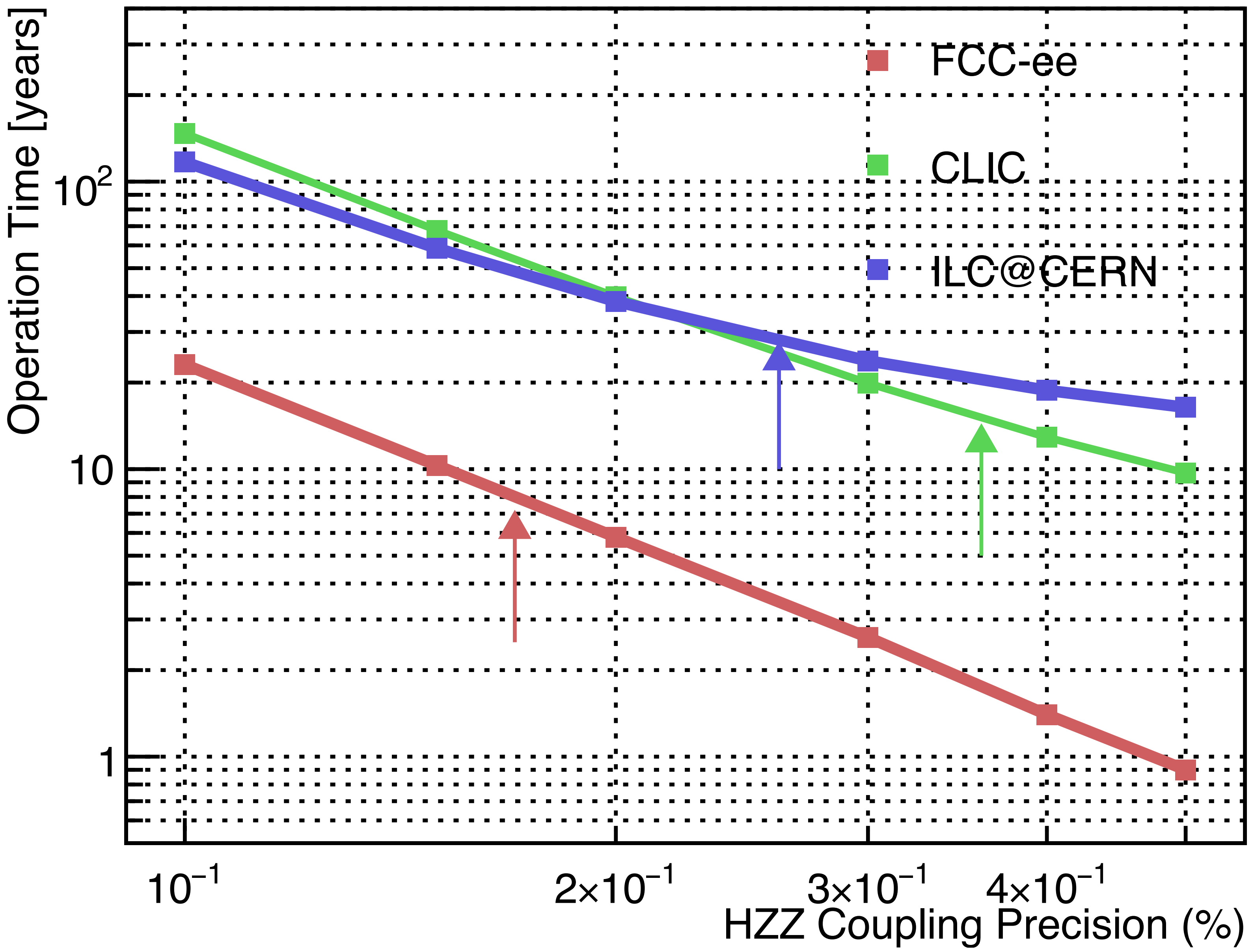
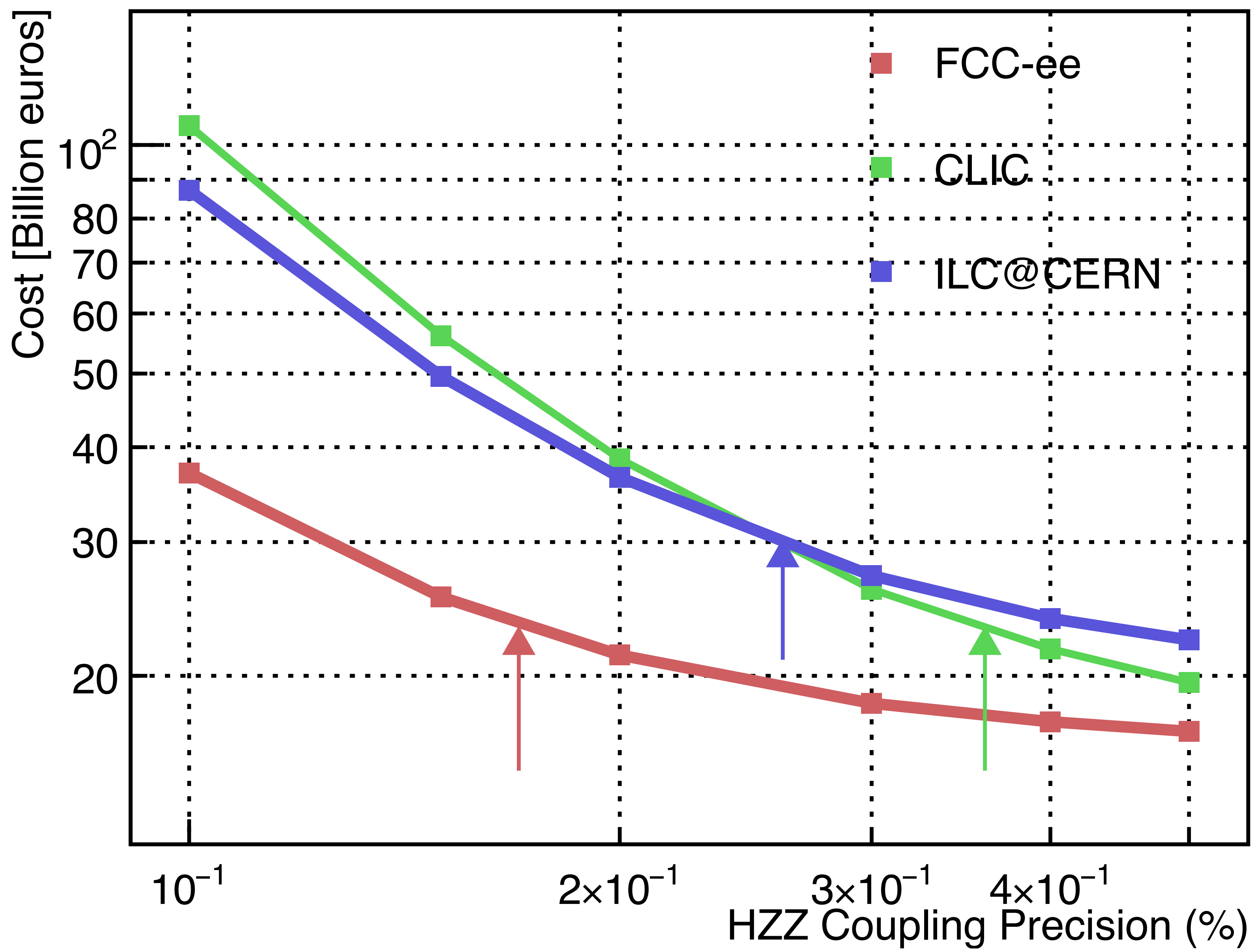
More time = more EUR





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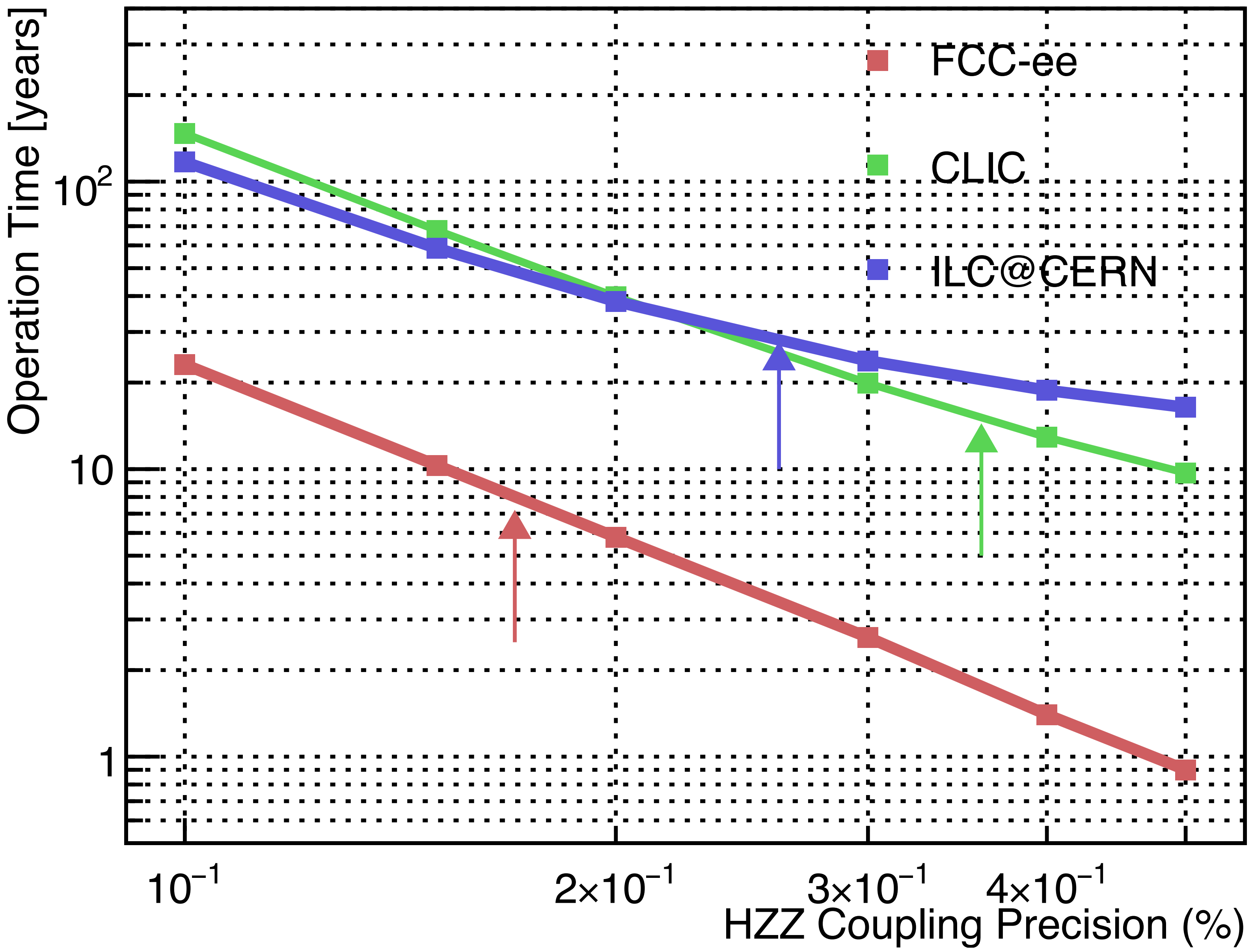
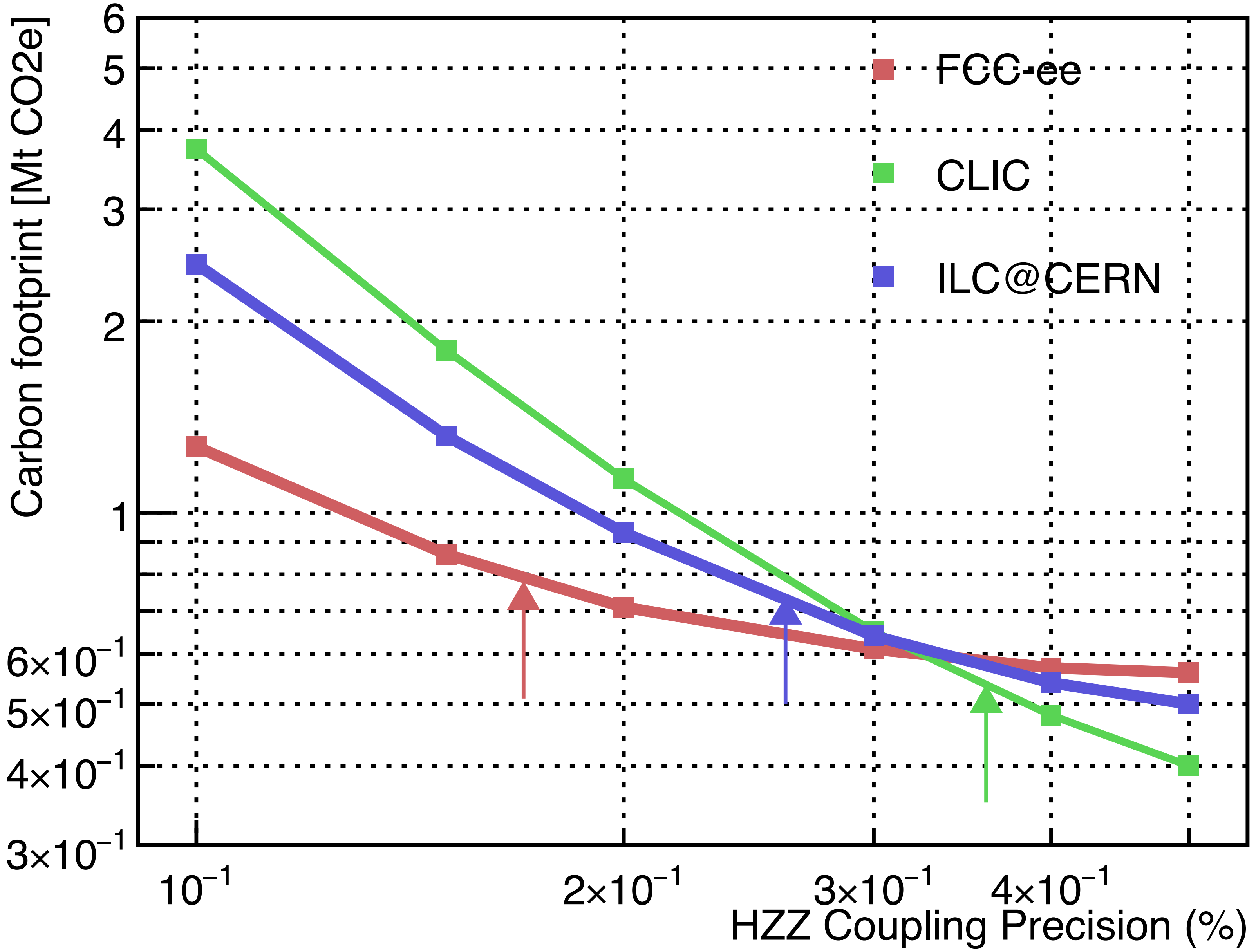
More time = more CO2eq





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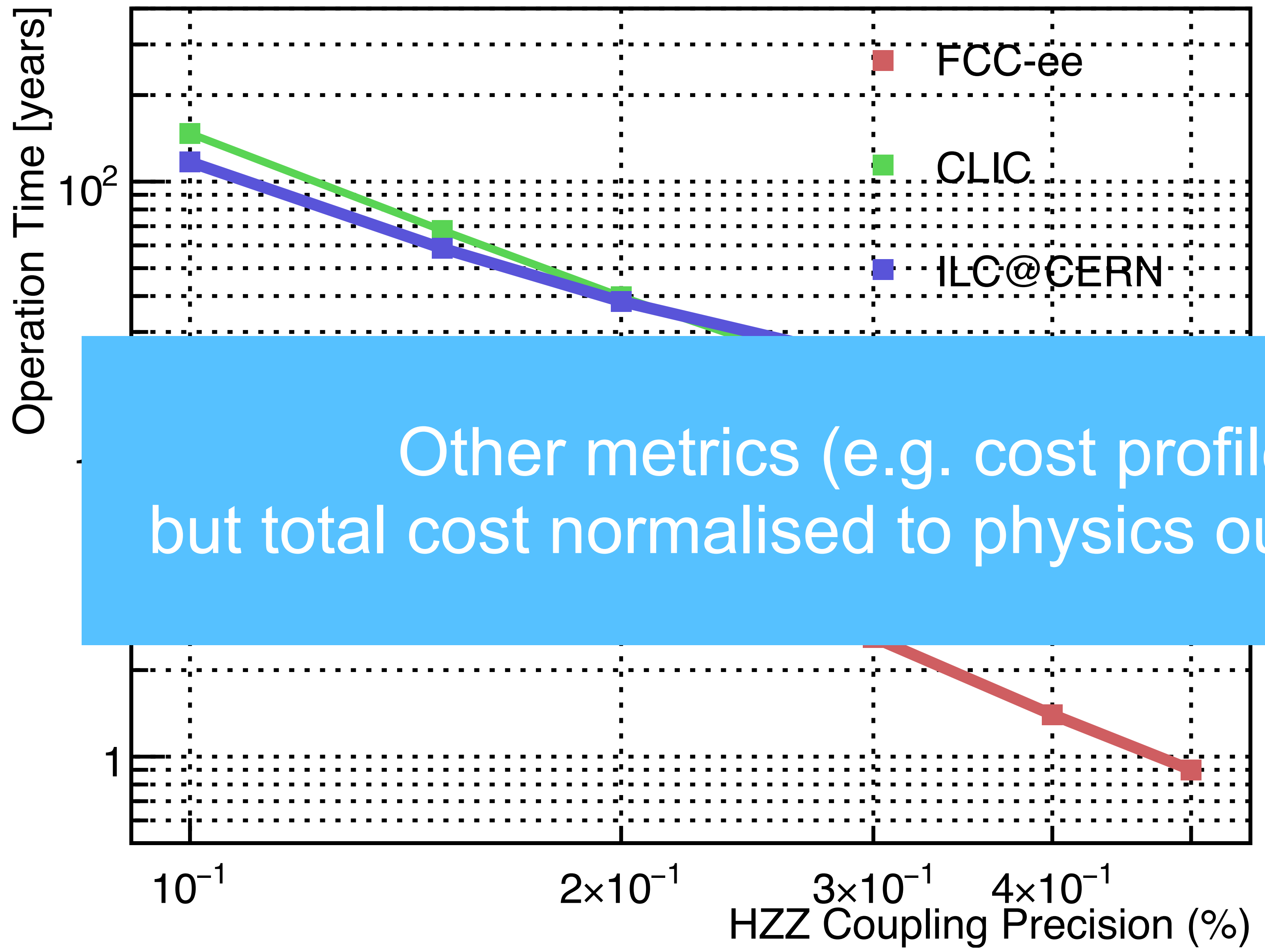

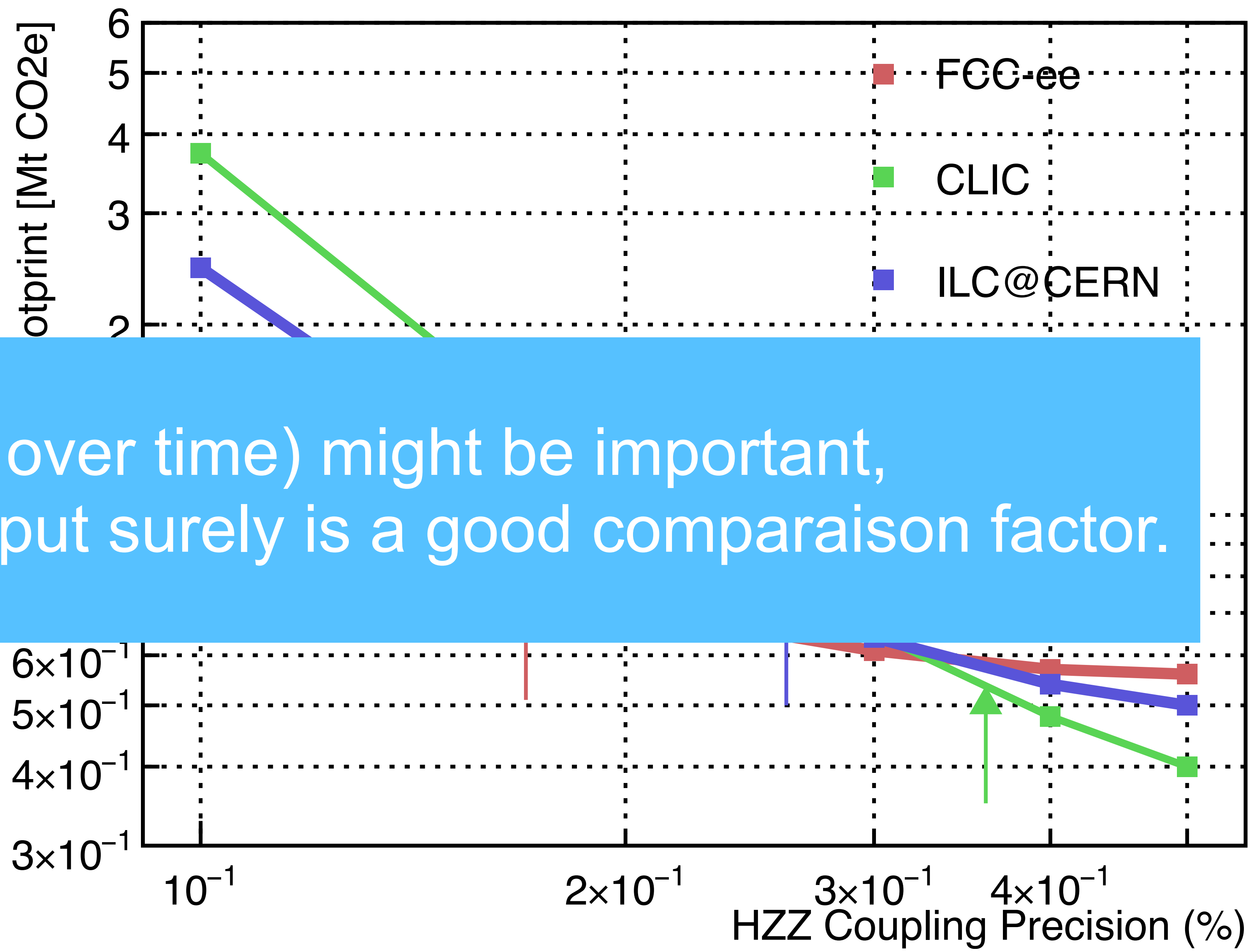

Other metrics (e.g. cost profile over time) might be important,
but total cost normalised to physics output surely is a good comparaison factor.

Collider cost has to be normalised to its physics output, e.g. Higgs precision.
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arXiv:2412.13130

Higgs @ FCC-ee

- Sub-percent precision for most interesting couplings, often with order of magnitude improvement on HL-LHC expectation.
- Asses, for the first time, second generation quarks (H→cč and H→sš) thanks to clean environment and efficient flavour tagging algorithms
- Higgs width measured O(1%) (model independent!) → absolute normalisation of the couplings.
- Mass measured to O(4) MeV (vs. 20 MeV at HL-LHC) .
- Tantalising possibility to get close to SM expectation for H→e⁺e⁻ (unique to FCC-ee)

68%CL relative precision & 95%CL upper bound

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\|\kappa_s\|$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

Results of a SMEFT fit projected onto effective κ Higgs couplings

Higgs programme achieved in a compact period of eight years of operation.

Higgs @ FCC-ee

some of the measurements are limited
by SM parametric uncertainties (e.g. m_b).
Results show precision without/with these uncertainties

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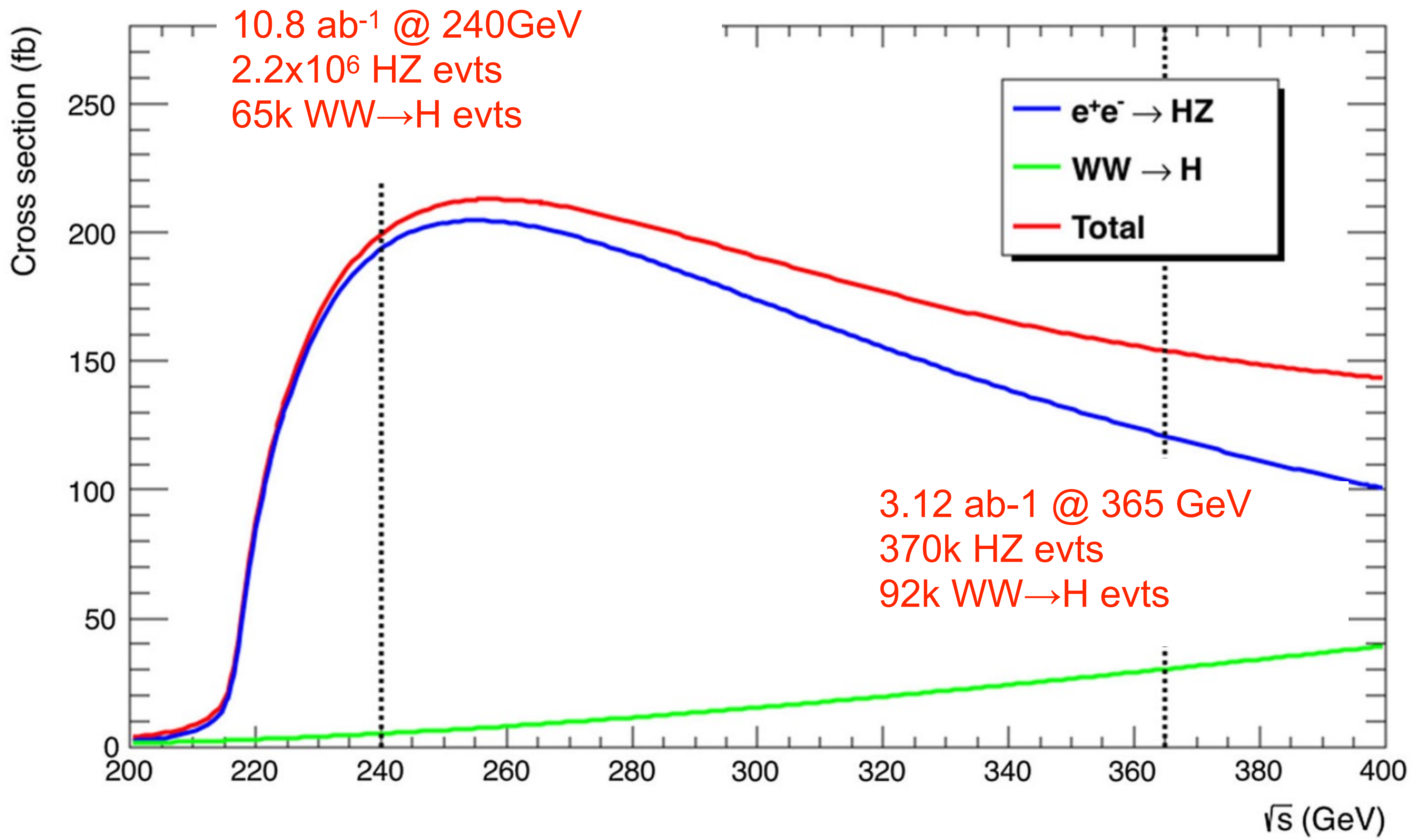
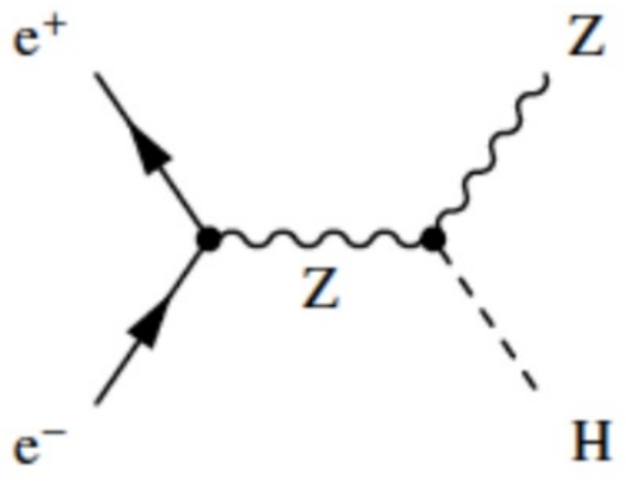
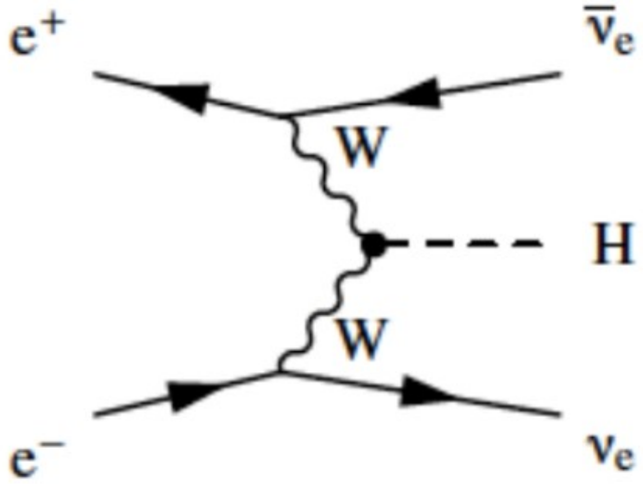

10.8 ab-1 @ 240GeV
2.2x10^6 HZ evts
65k WW→H evts
3.12 ab-1 @ 365 GeV
370k HZ evts
92k WW→H evts
Cross section (fb)
√s (GeV)
e+e- → HZ
WW → H
Total


e+
e−
Z
Z
H


e+
e−
W
W
H

Higgs @ FCC-ee

- 3 years at √s = 240 GeV → 10.8 ab^{-1}

  ⇒ 2.2M ZH events & 65k VBF events

- 5 years at √s = 340–365 GeV → 3.12 ab^{-1}

  ⇒ 370k ZH events & 92k VBF events

Projected 68% CL precision on Higgs measurements as obtained from FCC-ee simulations at √s=240 and 365 GeV. Experimental systematics include background normalisation uncertainties. Efficiencies and luminosity systematics are expected to be negligible. Entries preceded by “<” sign represent 95% CL upper limit on BR. A (*) indicates that the values are rescaled from the FCC CDR to the baseline integrated luminosity.

$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → ττ	±0.58		±1.2	±5.6 (*)
H → μμ	±11		±25	
H → WW*	±0.80		±1.8 (*)	±2.1 (*)
H → ZZ*	±2.5		±8.3 (*)	±4.6 (*)
H → γγ	±3.6		±13	±15
H → Zγ	±11.8		±22	±23
H → νννν	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

“Prospects in Electroweak, Higgs and Top physics at FCC”

Supporting doc. to FSR Vol. 1

Higgs @ FCC-ee

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Per-mil sensitivity on Higgs coupling measurement

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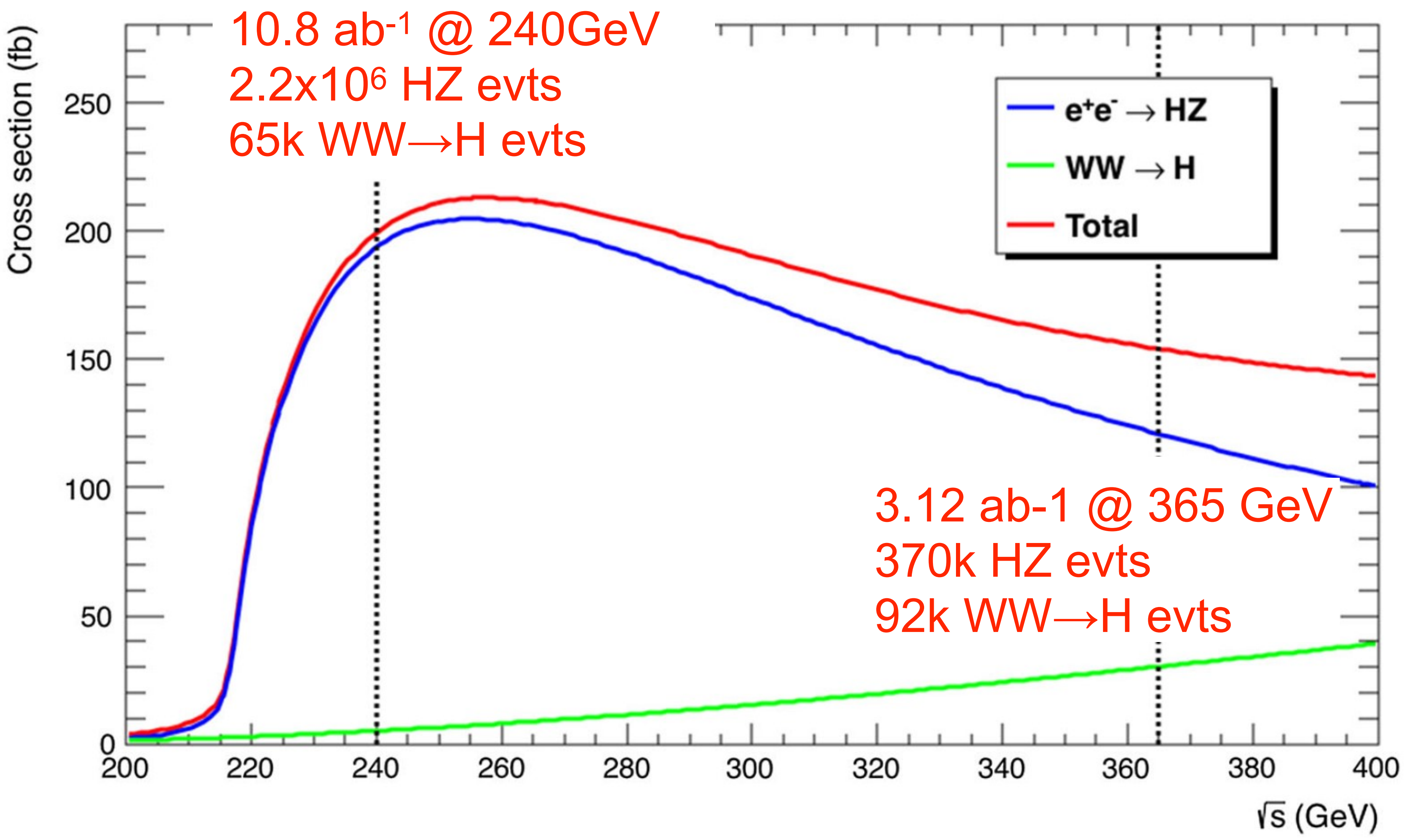
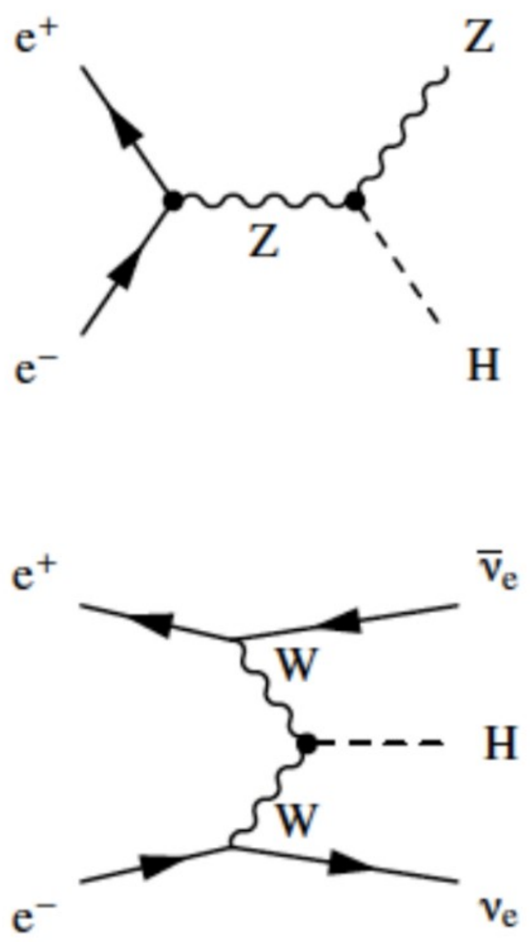




Sensitivity to both processes very helpful in improving precision on couplings.

Complementarity with 365GeV ↔ 240GeV

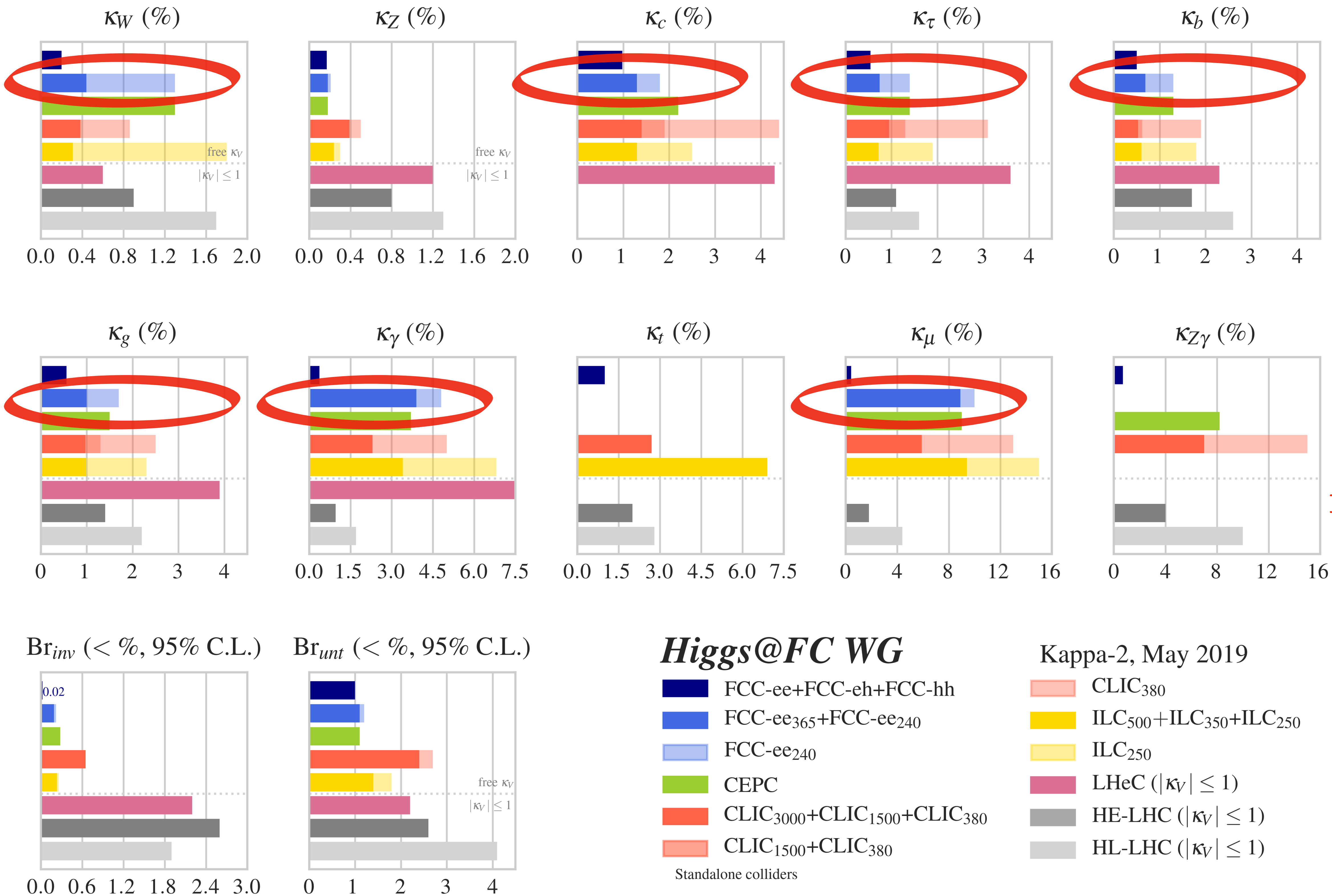
improvement factor: ∞/3/2/1.5/1.2 on $\kappa_\lambda/\kappa_W/\kappa_b/\kappa_g,\kappa_c/\kappa_\gamma$

Complementarity 240↔365 GeV

ECFA Higgs study group '19

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

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



Plots to be updated for ESPPU 2025 Physics Briefing (to be publicly released today)

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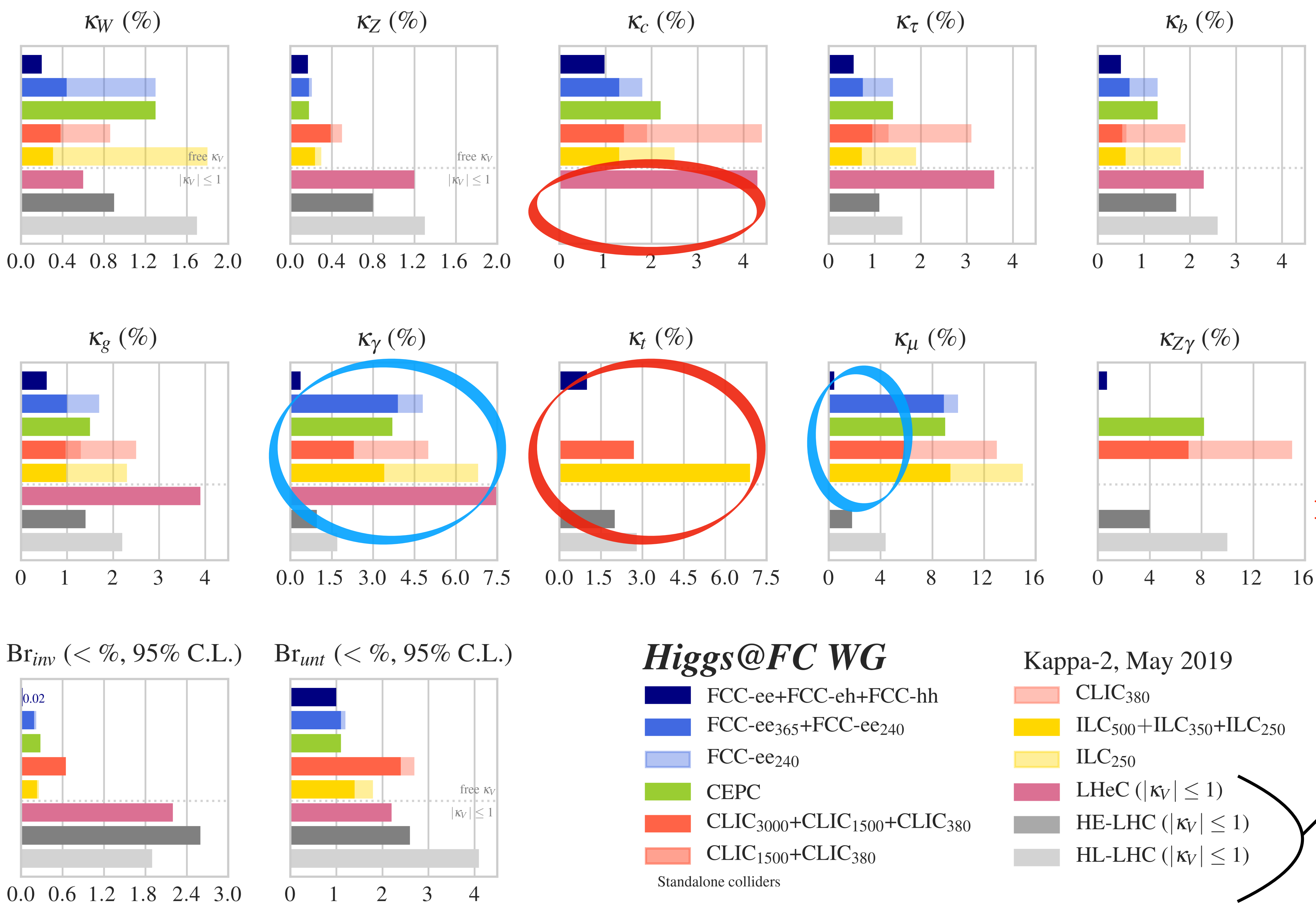

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assumption needed for the fit to close at hadron machines

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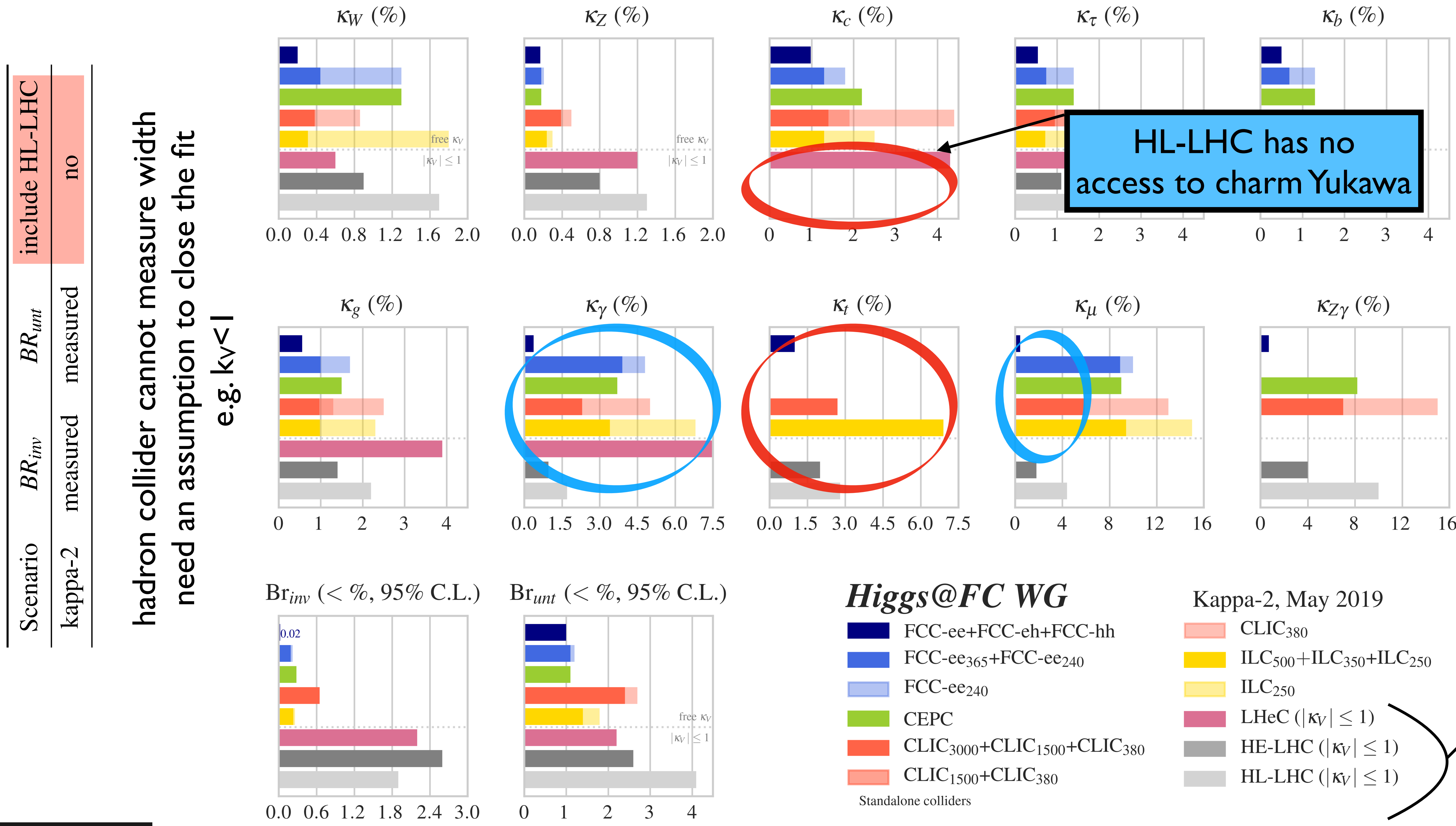

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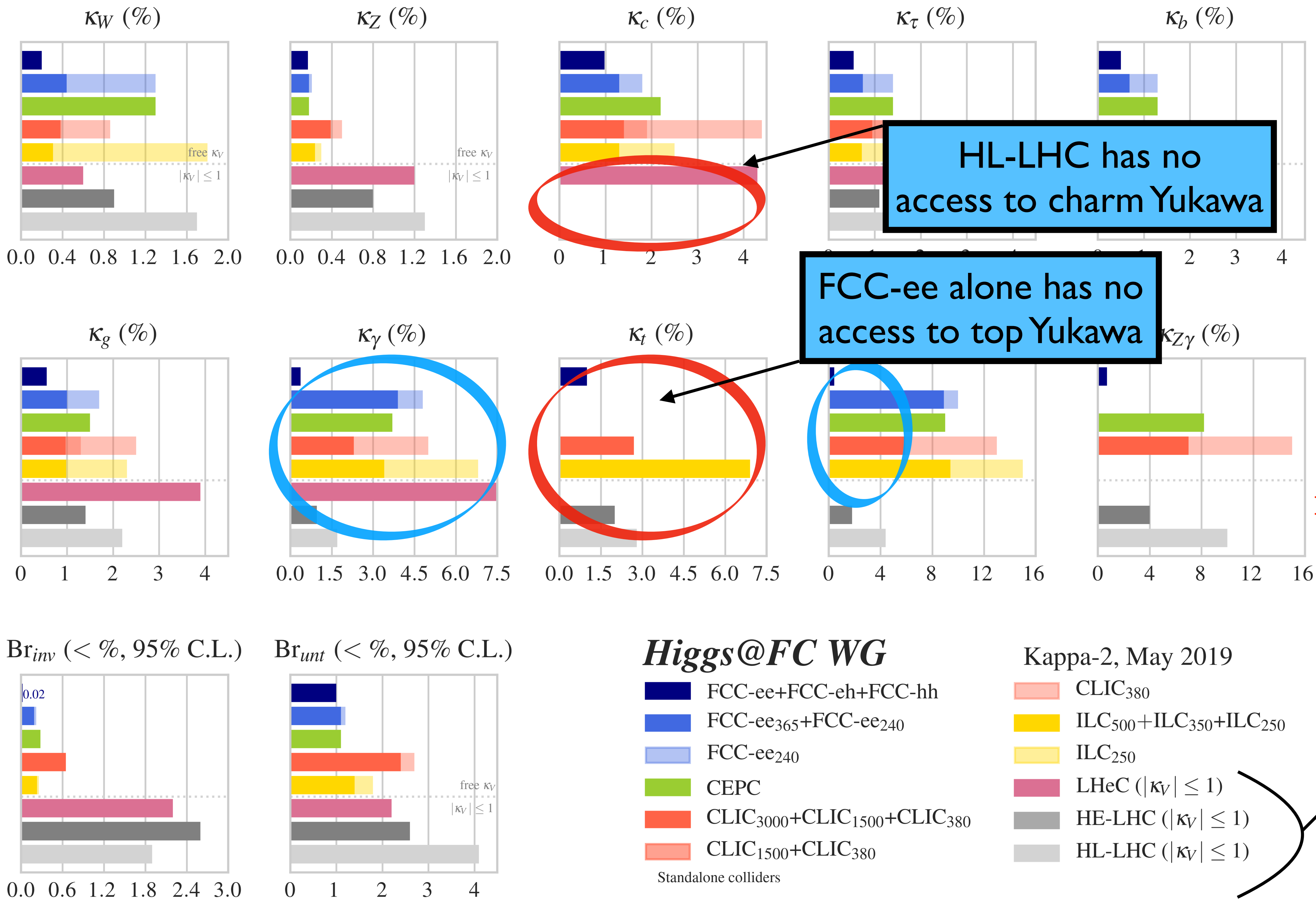

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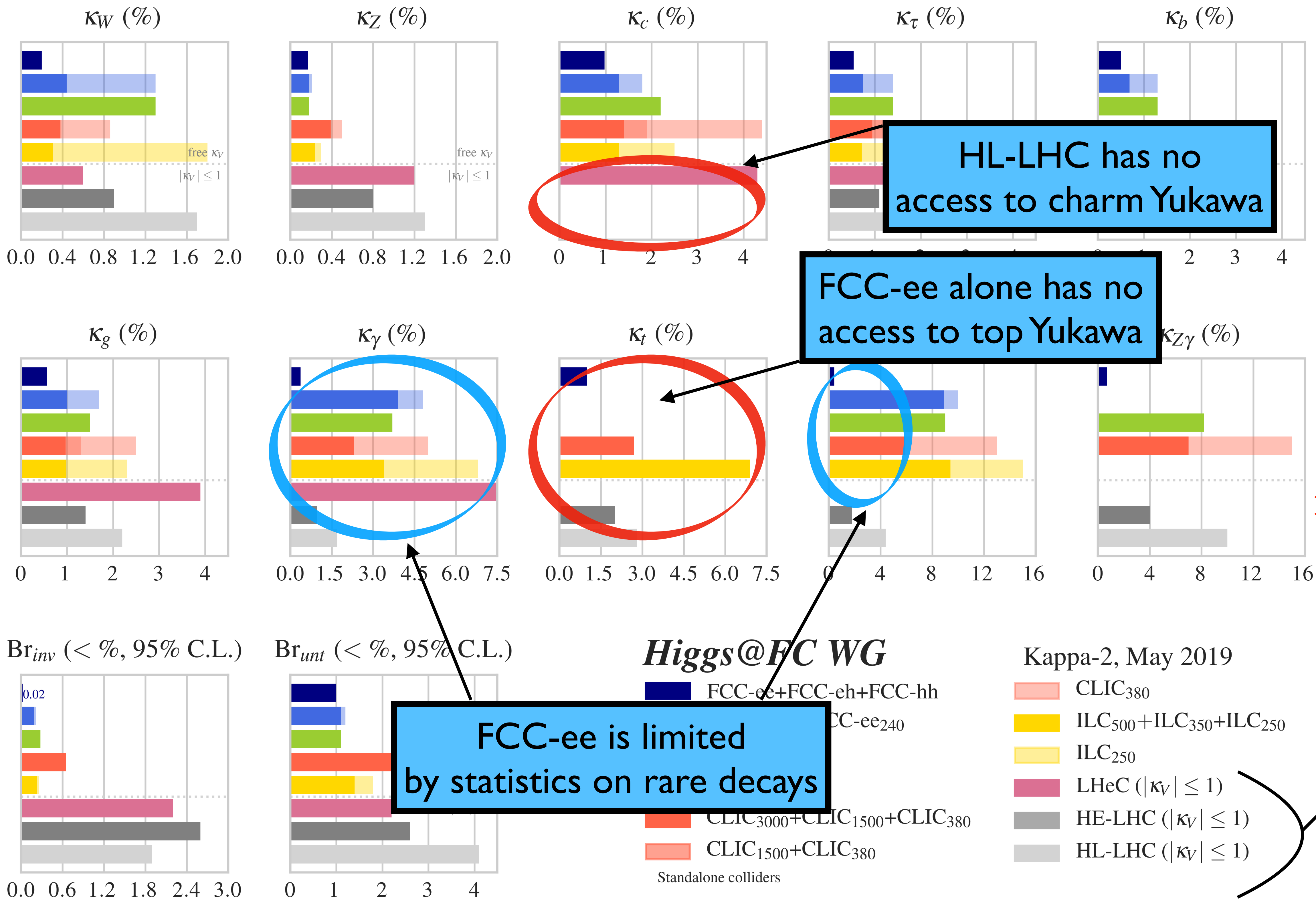

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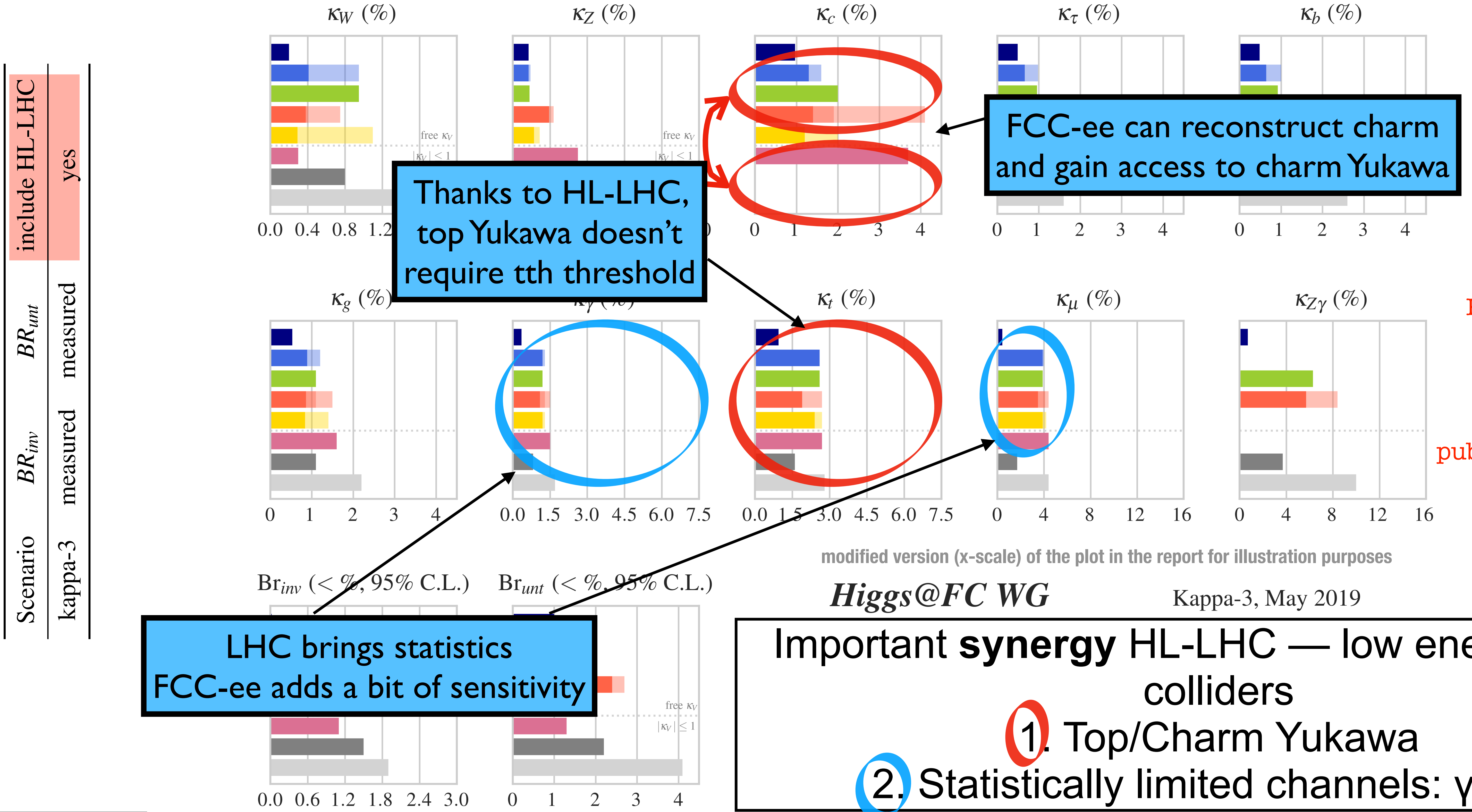

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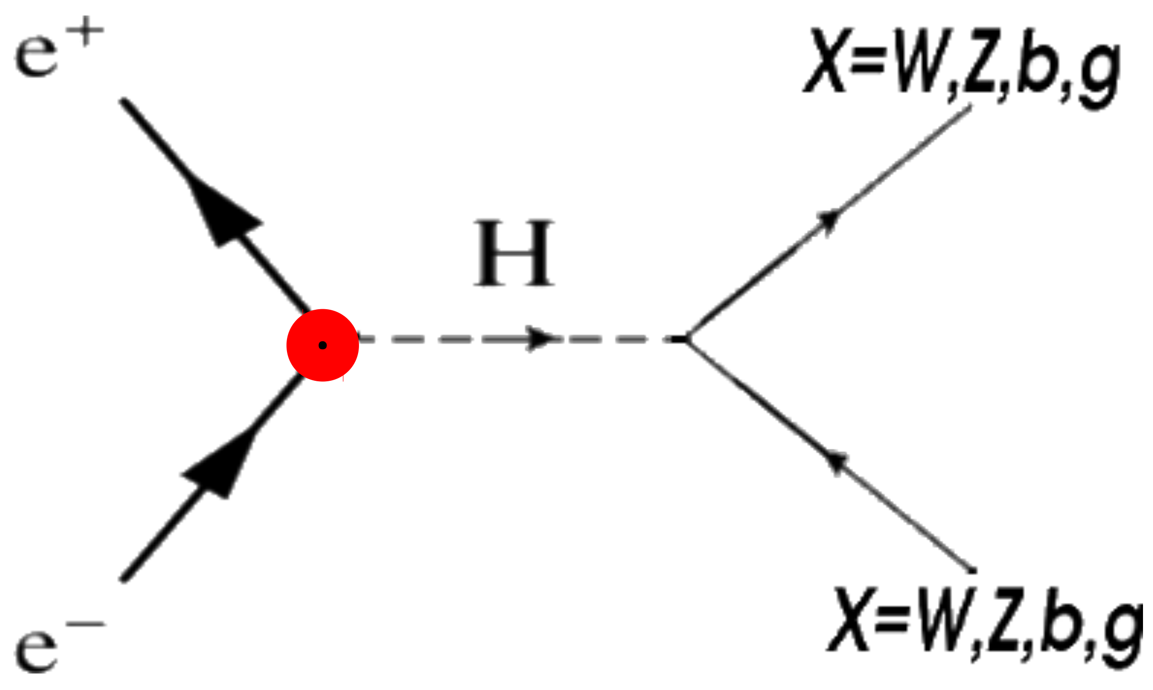
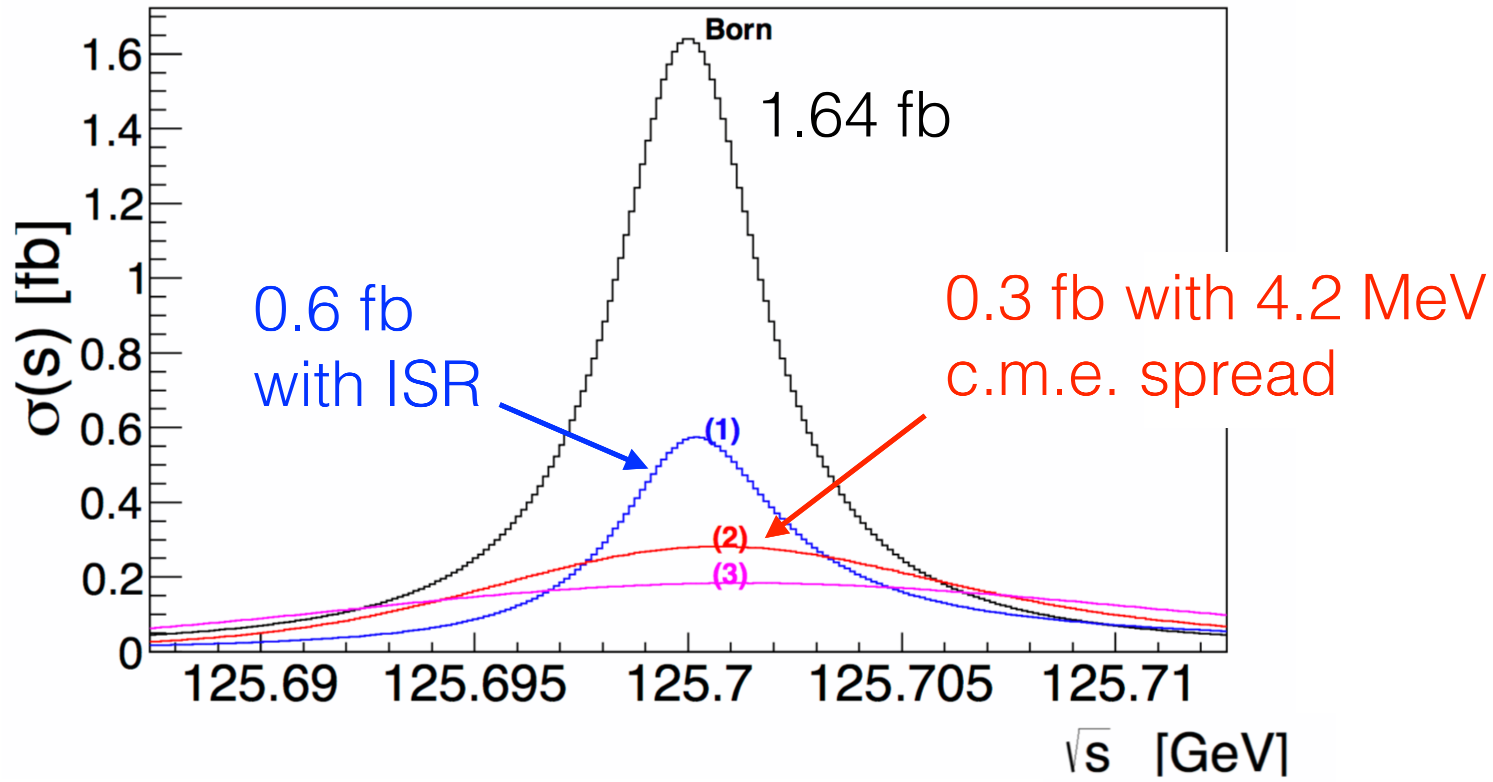
Important **synergy** HL-LHC — low energy lepton colliders
1. Top/Charm Yukawa
2. Statistically limited channels: γγ, μμ

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



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

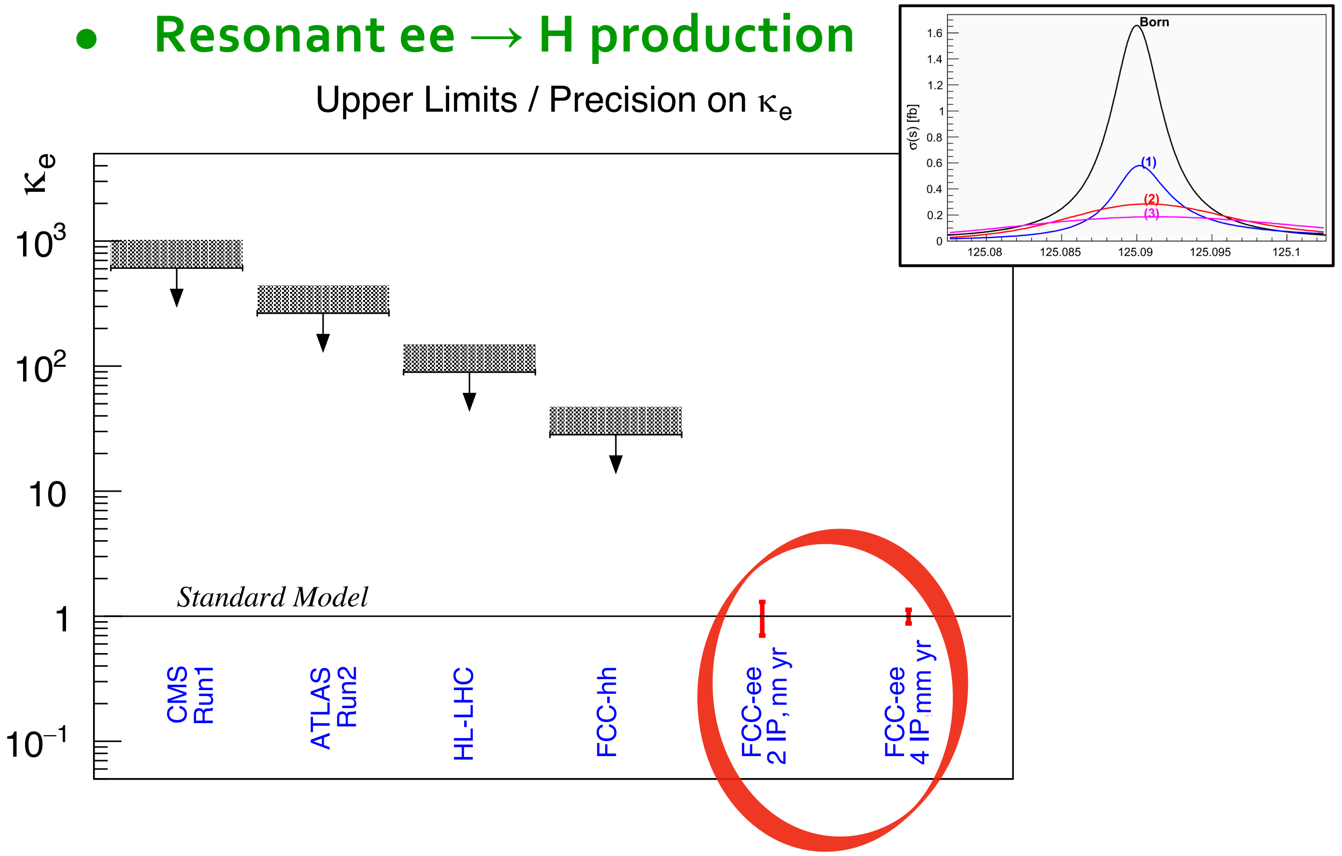
$\sigma_{spread+ISR}(e^+e^- \rightarrow H) = 0.17 \times \sigma(e^+e^- \rightarrow H) = 290$ ab

(note that natural E_{cm} spread is 100 MeV, challenging operation mode)

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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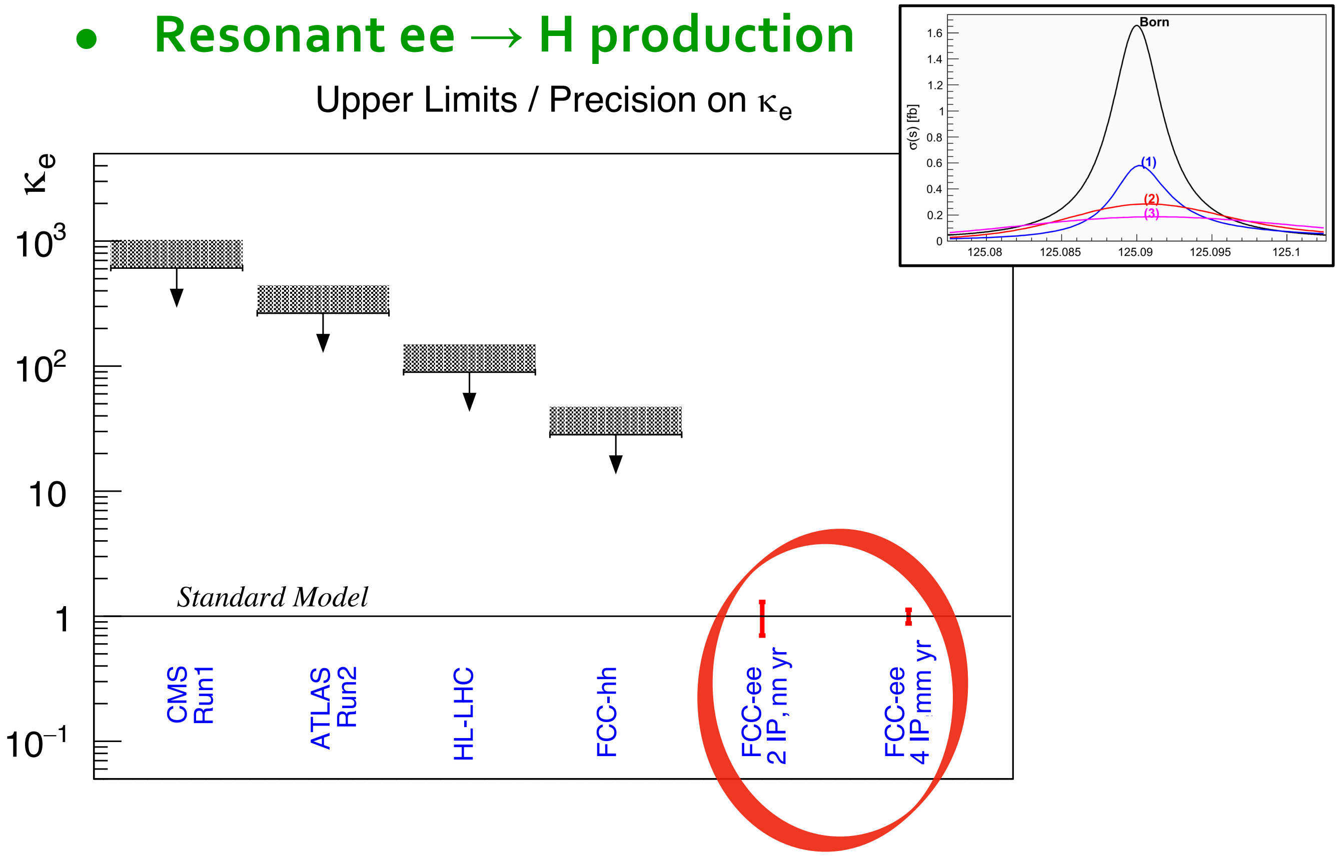
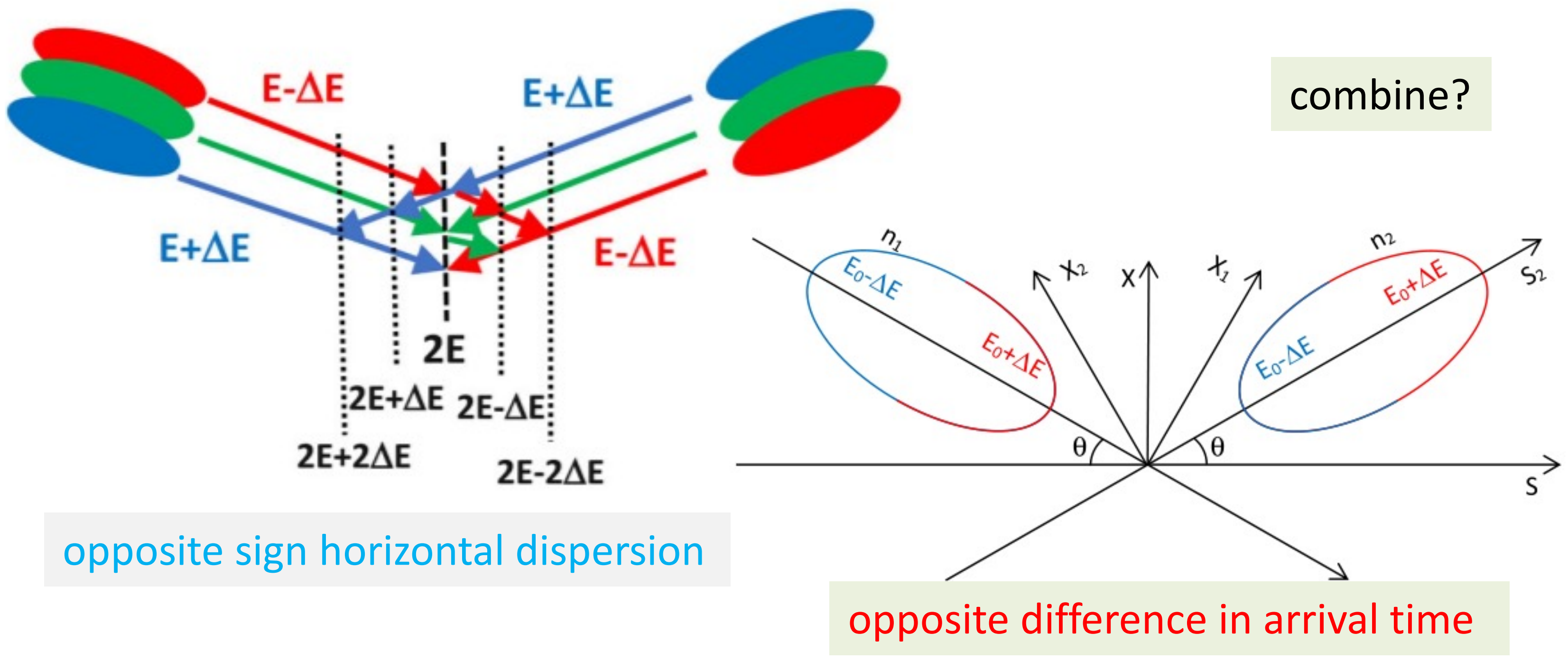


Monochromatisation

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)



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

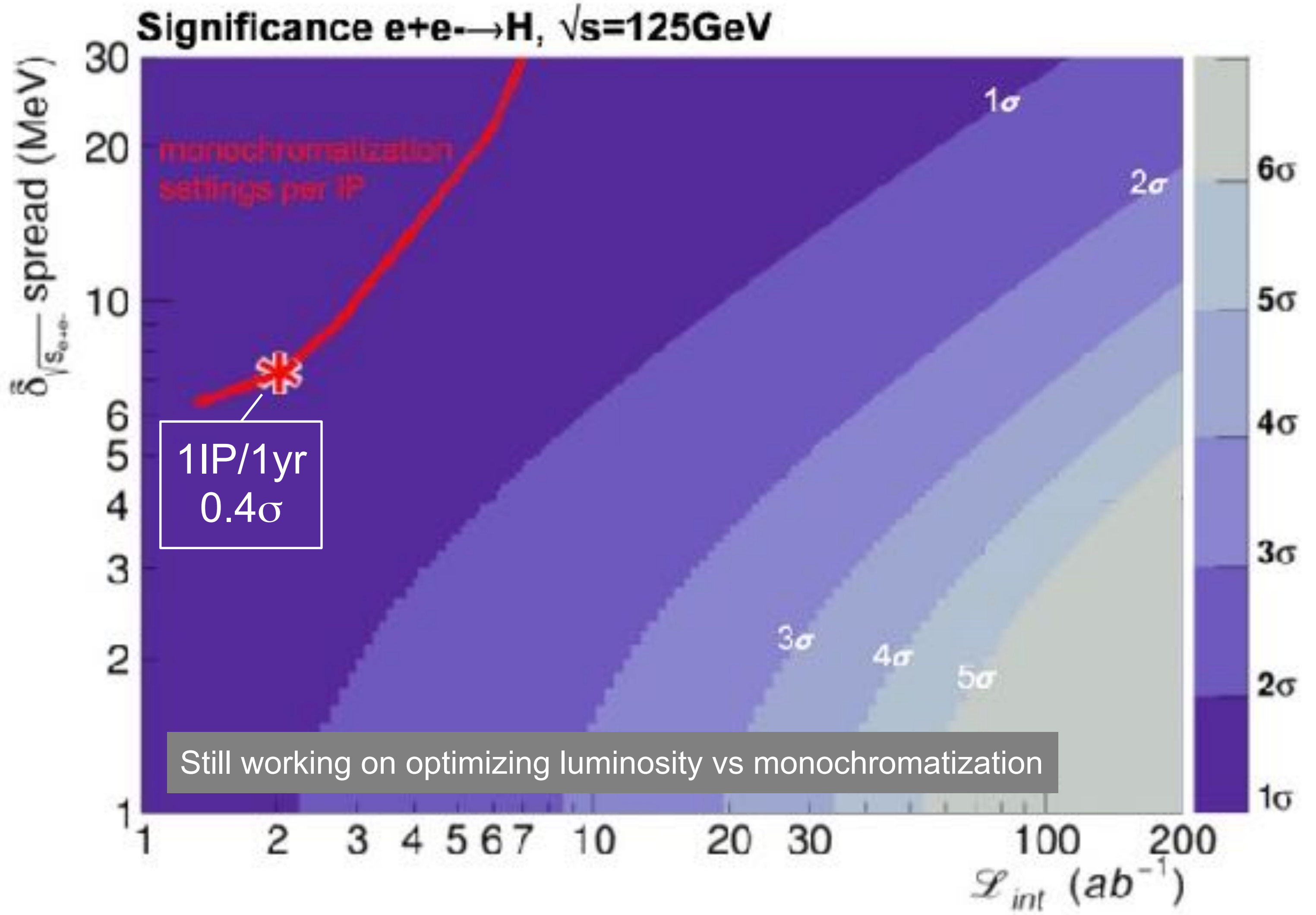
d'Enterria+. arXiv: 2107.02686

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



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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	$\mathcal{O}(10^{-5})$
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$e^+e^- \to H \to \tau\tau$	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	$\mathcal{O}(10^{-7})$
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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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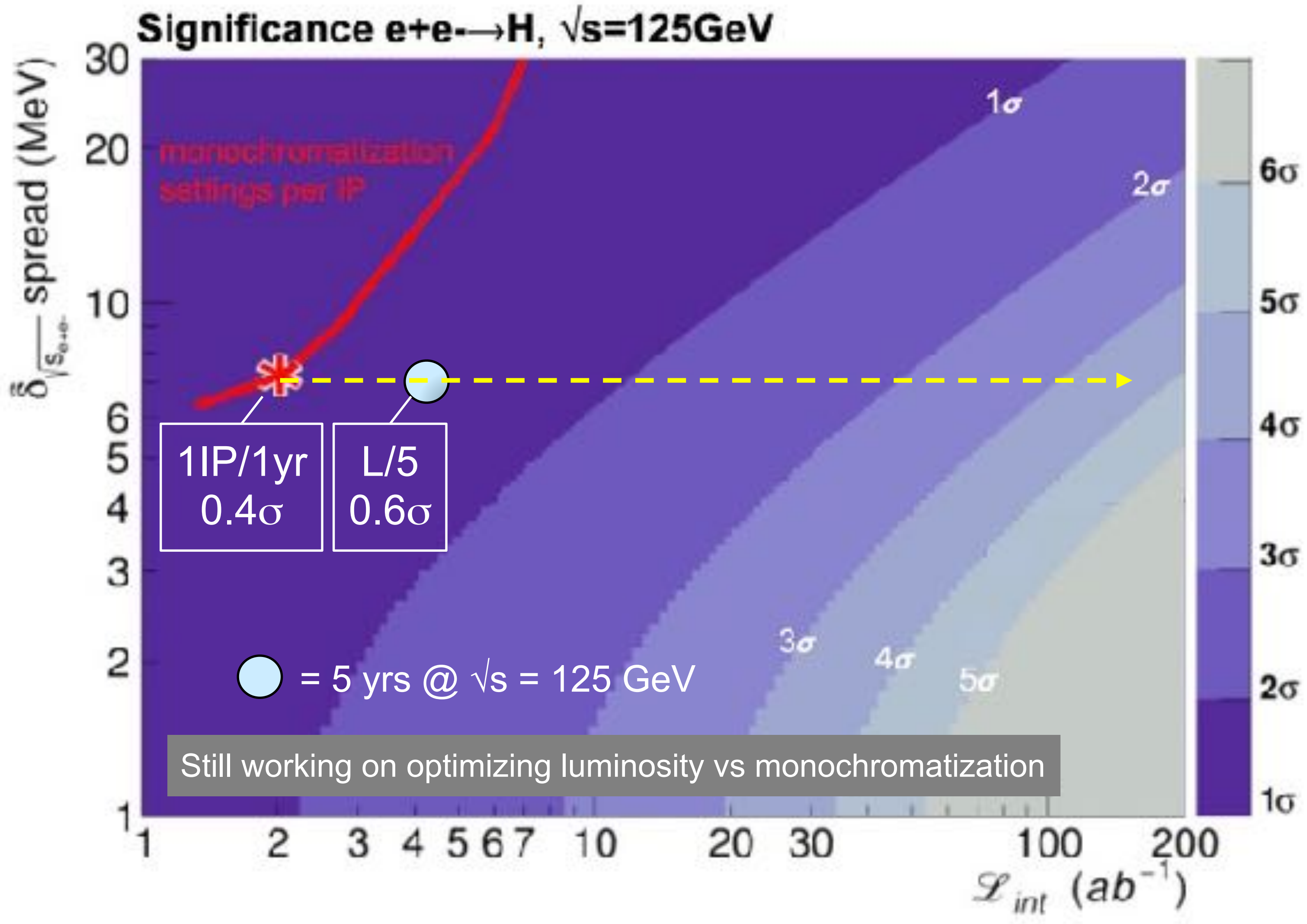

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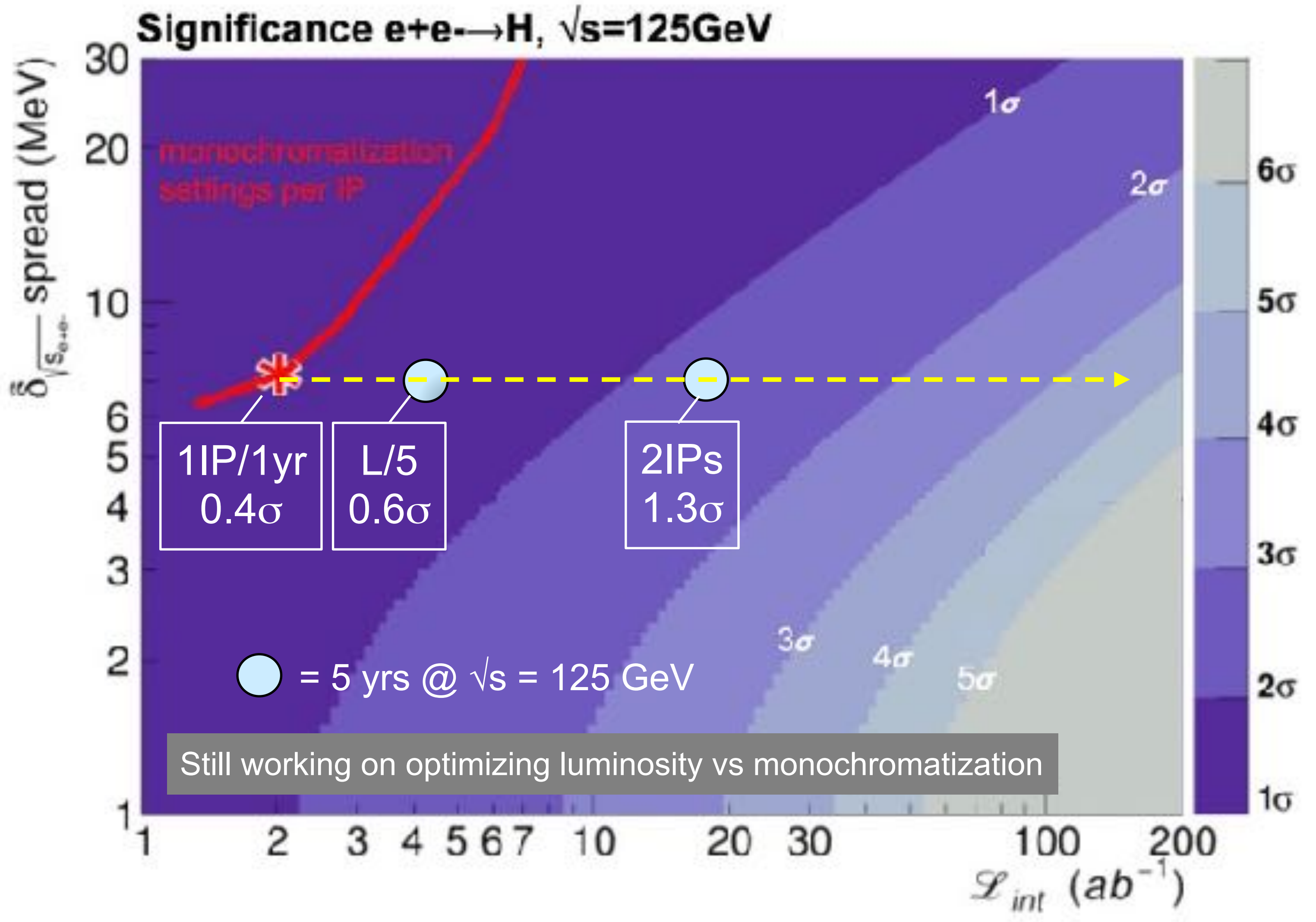

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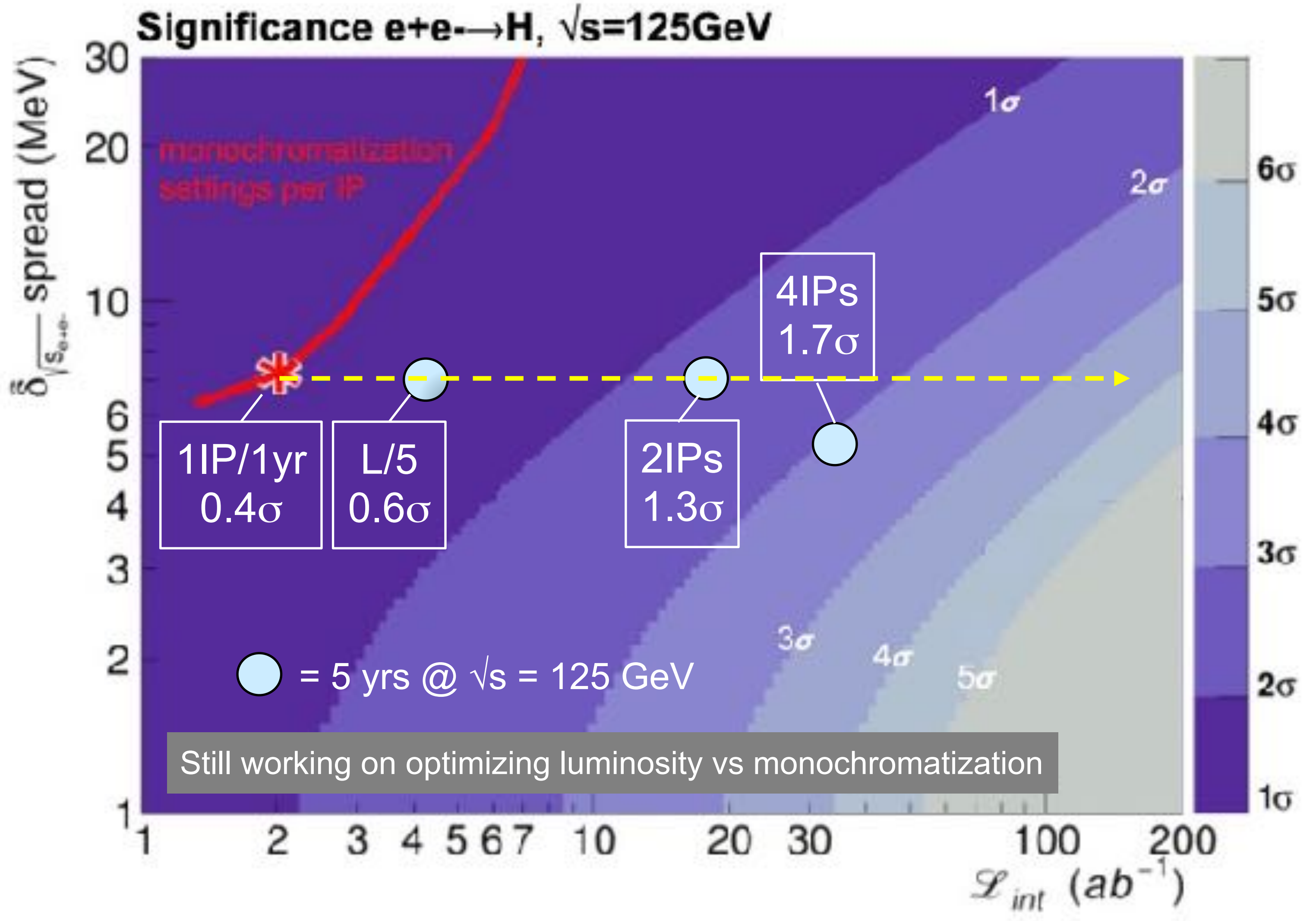

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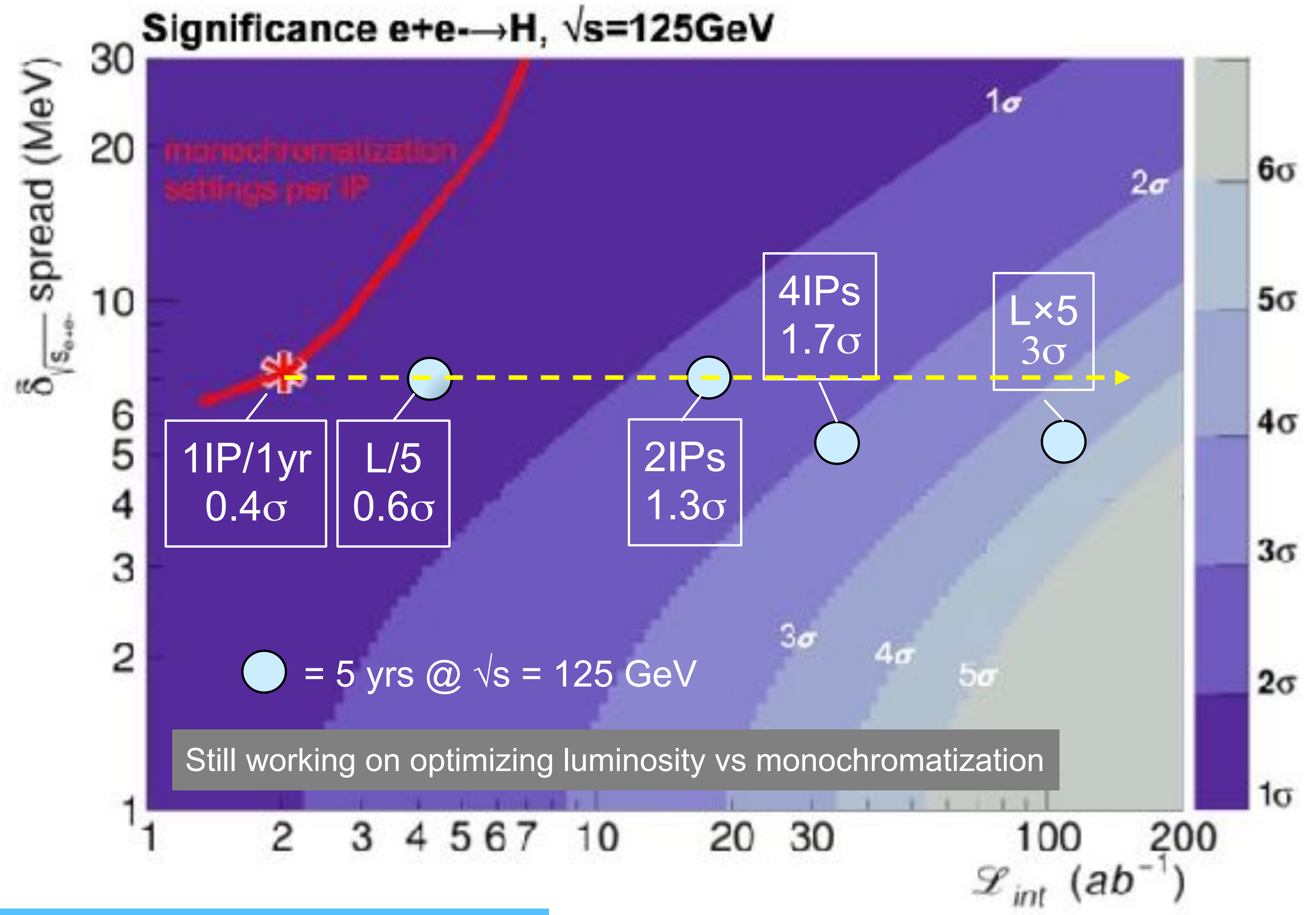
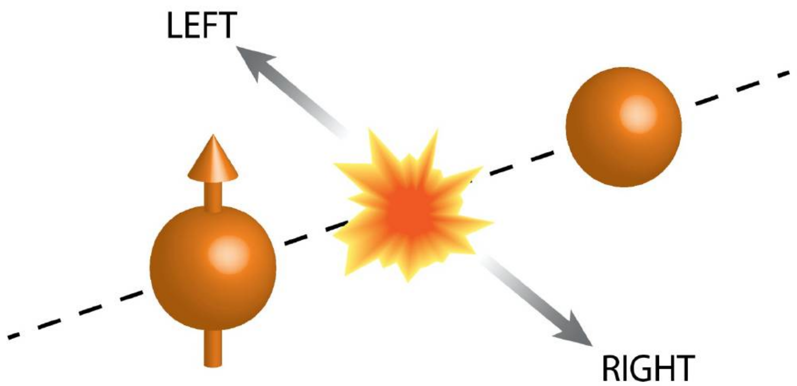


4σ expected with 4 IP in 4 years
or
95%CL on 2.5 x SM value in 1 year

Electron Yukawa

A recent pheno study (Bougheal 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 (SP⁰):

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

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⁺):

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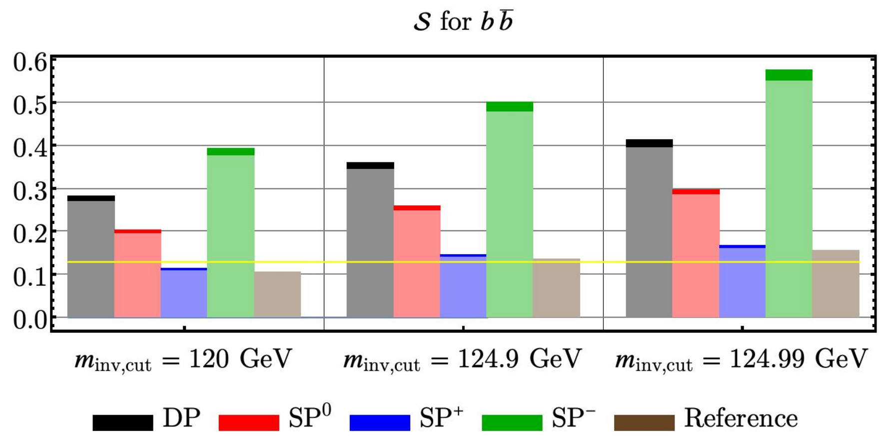
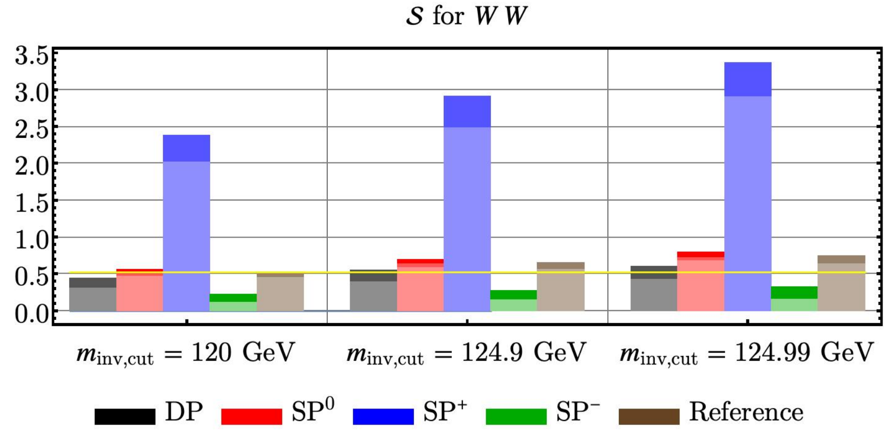
8





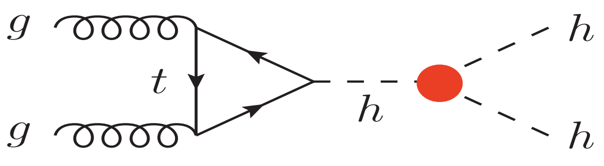
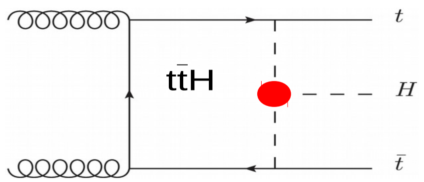
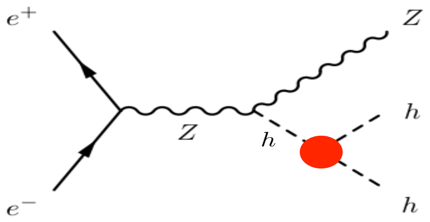
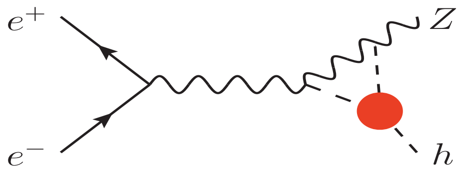
Major improvements of up to factors of 6 possible for bb and WW (doesn't work for gg)

4σ expected with 4 IP in 4 years
or
95%CL on 2.5 x SM value in 1 year

Higgs Self-Coupling

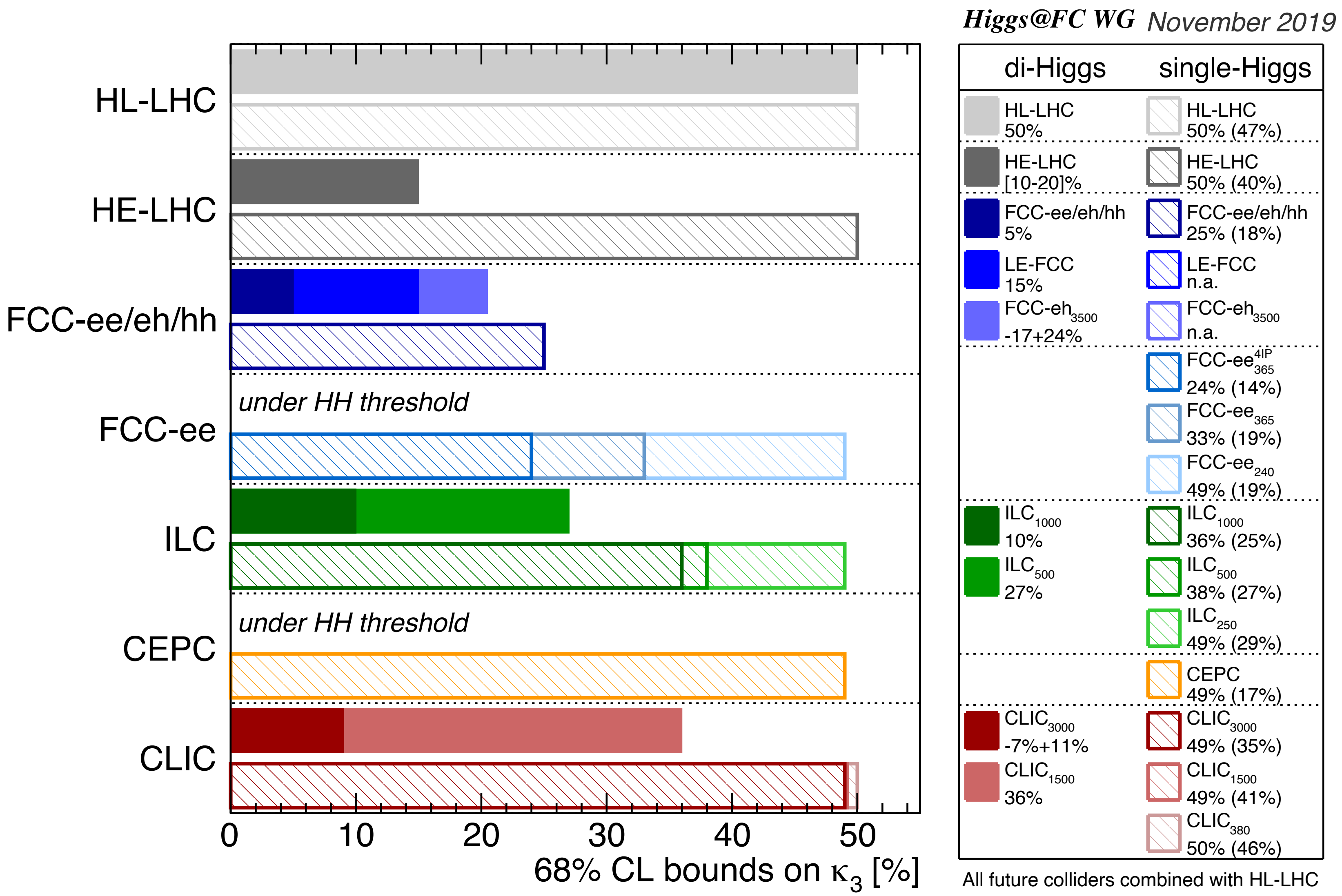
How much can it deviate from SM given the tight constraints on other Higgs couplings?
Do we need to reach HH production threshold to constrain h^3 coupling?

ECFA Higgs study group '19

	di-Higgs	single-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

Higgs Self-Coupling



1

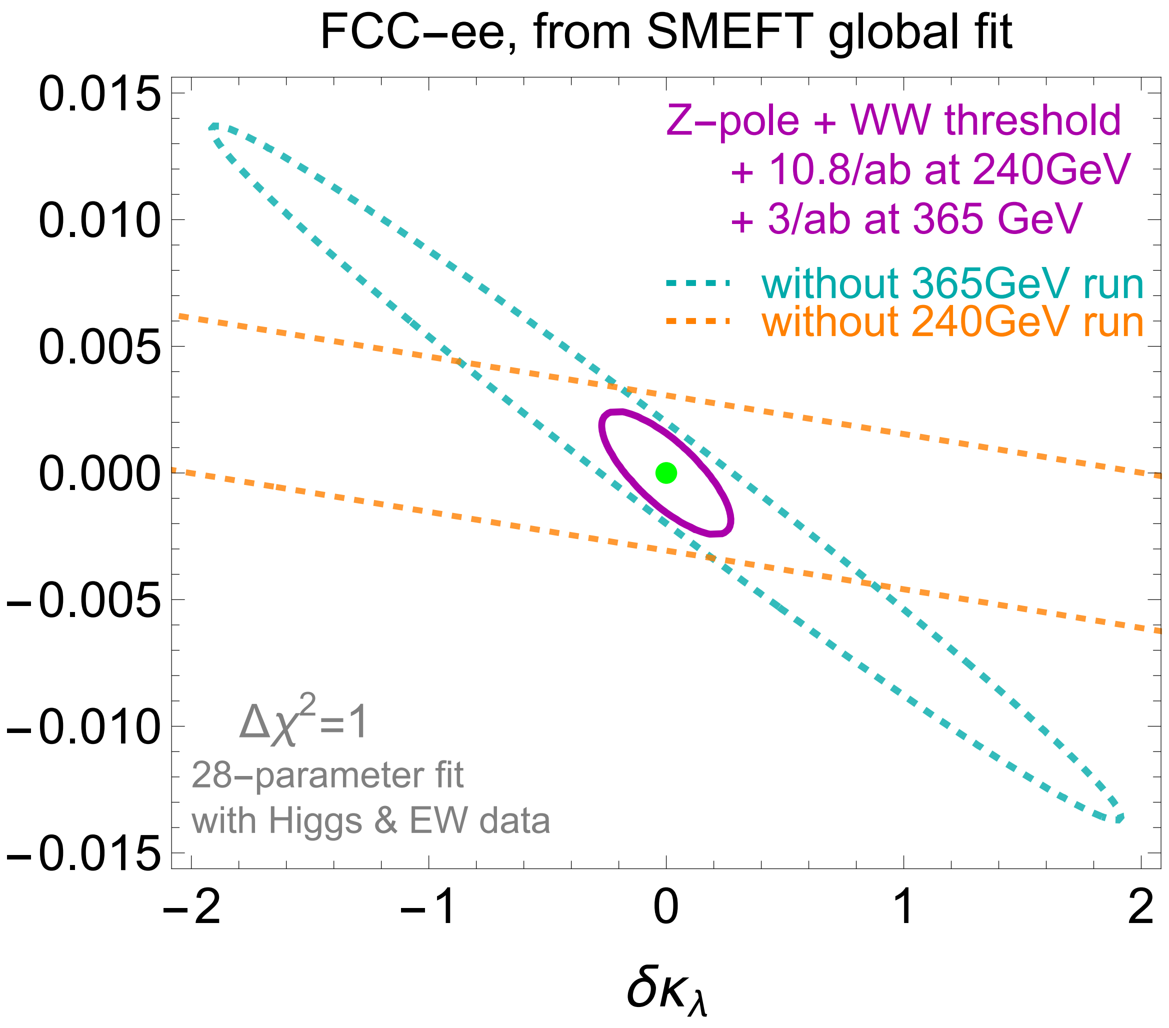
Don't need to reach HH threshold to have access to h^3.
Runs at different energies are essential
(e.g. 240 and 365 GeV)

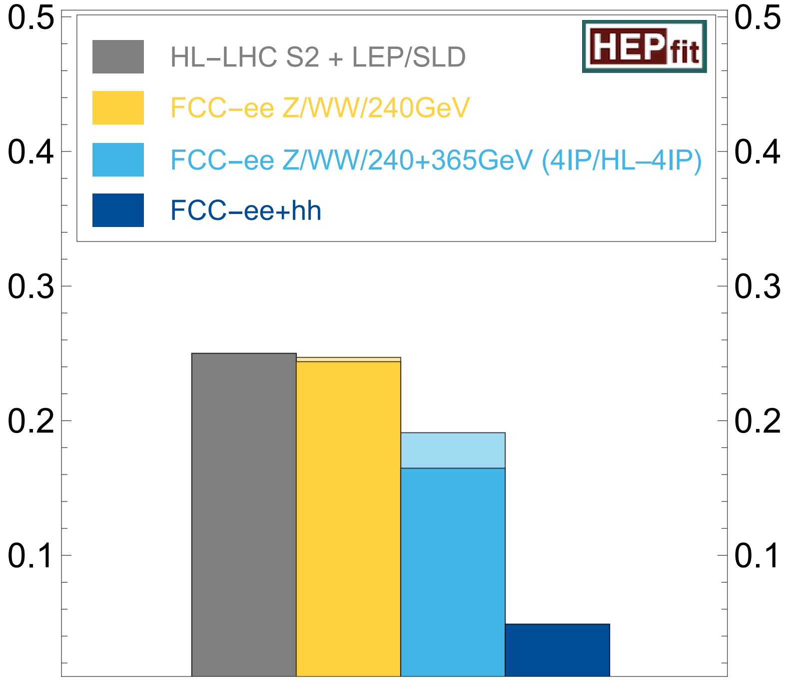
2

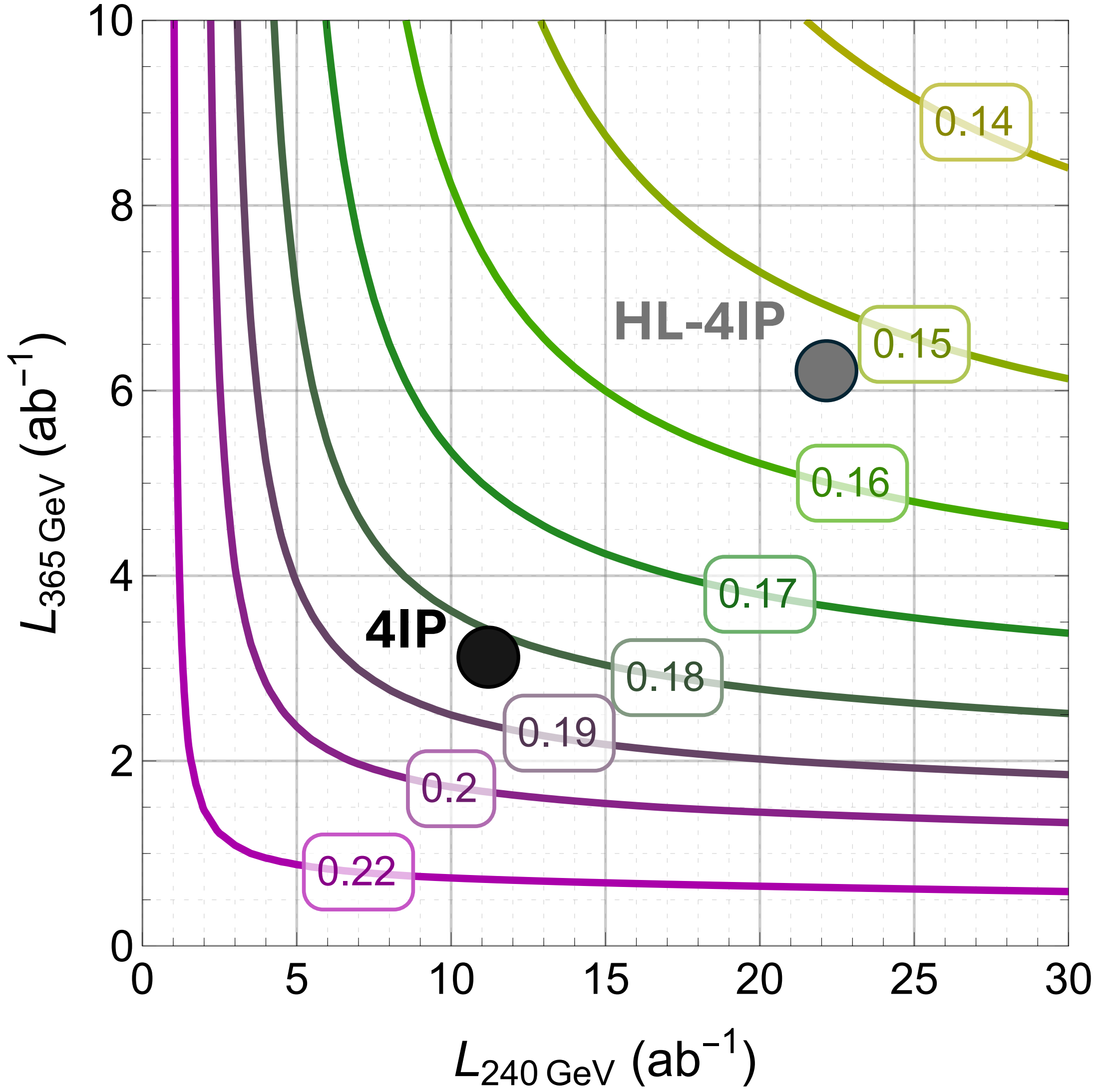
The determination of h^3 at FCC-hh relies on HH channel,
for which FCC-ee is of little direct help.
But the extraction of h^3 requires precise knowledge of y_t.
1% $y_t \leftrightarrow$ 5% h^3
Precision measurement of y_t needs FCC-ee.

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







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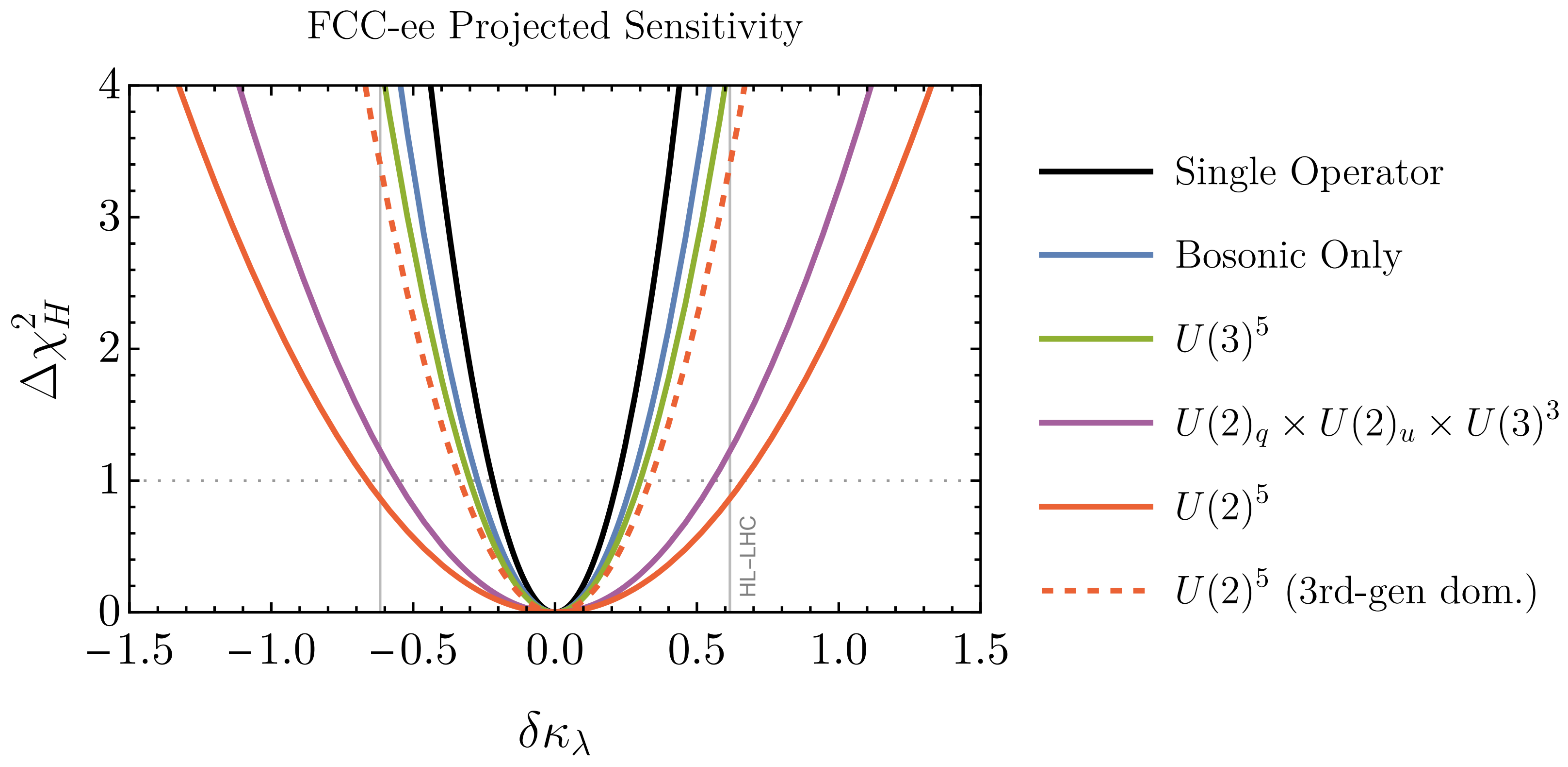
Higgs Self-Coupling

Previous fits were done for Higgs flavour diagonal couplings.
New fits explored impact of different flavour scenarios.

Maura, Stefanek, You arXiv:2503.13719

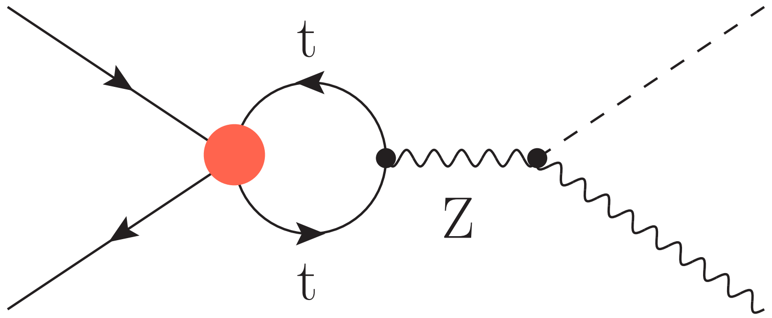
Flavour symmetry	CP-even parameters
$U(3)^5$	41
$U(2)_q \times U(2)_u \times U(3)^3$	72
$U(2)^5$	124
$U(2)^5$ (third-gen. dominance)	53

Scenario	$\sigma_H\,[\text{TeV}^{-2}]$	68% CL $\delta\kappa_\lambda$
C_H Only	0.47	22%
Bosonic Only	0.58	27%
$U(3)^5$	0.64	30%
$U(2)_q \times U(2)_u \times U(3)^3$	1.19	56%
$U(2)^5$	1.41	66%
$U(2)^5$ (3rd-gen. dominance)	0.71	33%

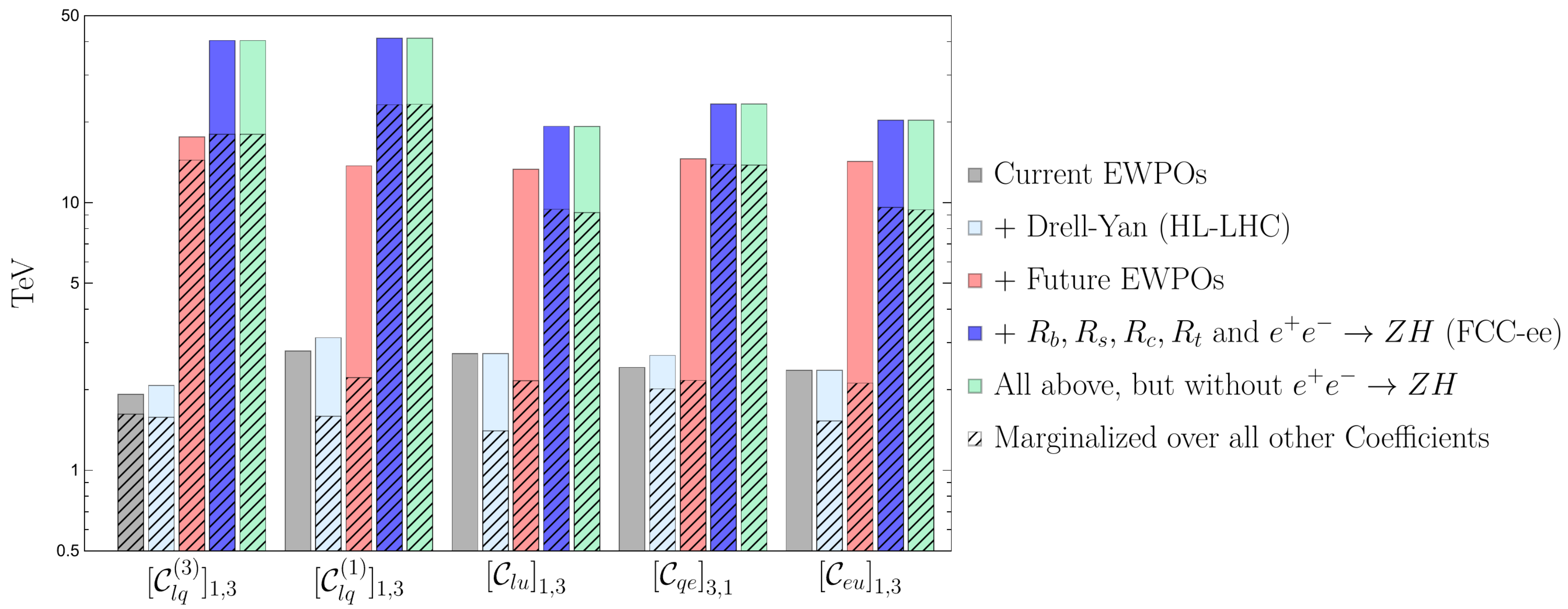


Higgs Self-Coupling

Could a priori poorly constrained eett operators spoil the sensitivity to Higgs self-coupling?



Asteriadis, Dawson, Giardino, Szafron: arXiv:2406.03557



non zero SMEFT-Coefficients	$\delta\kappa_3$
None	0.169
One *eett*-coefficient	0.169
All *eett*-coefficients	0.172
All *eett*, w/o R_q above pole	0.176

precision on 3 actually robust

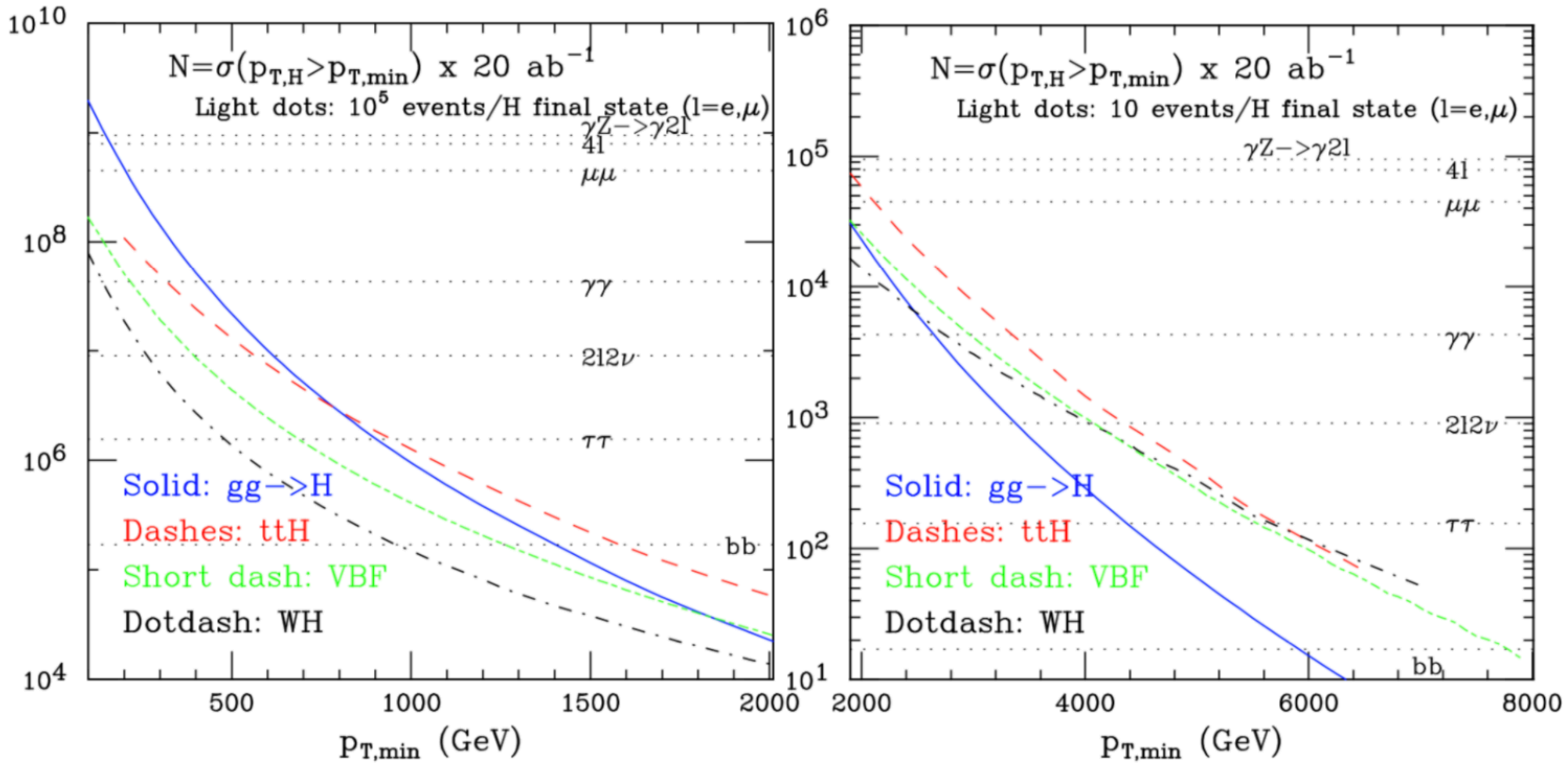
Allwicher, Grojean, Tablet: to appear

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

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



- 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

Higgs @ FCC-hh

FCC-hh completes the job.

The dataset of 20 billion Higgs bosons allows for precise measurements of the rare decay modes (γ, Zγ,μ) with high pT events.

Top coupling shows a nice synergy: FCC-hh mesures ttH/ttZ and denominator comes from FCC-ee

Normalisation provided by FCC-ee measurements allows for full model independence, and higher precision.

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1 →	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3 →	0.67
κ_t (%)	3.2*	3.1 →	0.75
κ_μ (%)	4.4*	3.3 →	0.42
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

(SM)EFT for EW @ FCC

EW Precision Measurements at FCC-ee

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty	improvement factor / now
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration	20
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration	200
$\sin^2\theta_W^{\rm eff}$ $(\times 10^6)$	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	150
$1/\alpha_{\rm QED}(m_Z^2)$ $(\times 10^3)$	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate	
R_ℓ^Z $(\times 10^3)$	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons	
$\alpha_S(m_Z^2)$ $(\times 10^4)$	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, $\Gamma_{\rm tot}^Z$, $\sigma_{\rm had}^0$ fit	
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement	
$N_\nu (\times 10^3)$	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement	
R_b $(\times 10^6)$	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons	2000
$A_{FB}^{b,0}$ $(\times 10^4)$	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge	
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics	
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass	
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR	
τ leptonic $(\mu\nu_\mu\nu_\tau)$ BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency	
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration	50
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration	
$\alpha_S(m_W^2)$ $(\times 10^4)$	1 010	±	270	**2**	2	Combined R_ℓ^W, $\Gamma_{\rm tot}^W$ fit	
N_ν $(\times 10^3)$	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns	
$m_{\rm top}$ (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate	70
$\Gamma_{\rm top}$ (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate	
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. 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.

(EFT) Work Ahead

Observable	Missing higher-order & power-suppressed corrections
Hadronic Z width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha_s^6)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$
Hadronic W width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha_s^2\alpha)$
Hadronic τ width	$\mathcal{O}(\alpha_s^5)$
Hadronic event shapes (Z, W, H decays)	N^3LO differential, $N^{3,4}LL$ resummation, power corrections
Inclusive jet rates	3-jet cross-sections at N^3LO, 4-jets at N^2LO, 5-jets at NLO
Lattice QCD results	$\mathcal{O}(\alpha_s^6)$ β-function; $\mathcal{O}(\alpha_s^5)$ heavy quark decoupling; $\mathcal{O}(\alpha_s^4)$ static potential
(α_s extr.; quark masses m_c, m_b)	$\mathcal{O}(\alpha_s^3)$ lattice perturbation theory matching (lattice coupling to $\alpha_s^{\overline{MS}}$ etc.)
$\sigma(e^+e^- \to W^+W^-)$ vs. $\sqrt{s}$	EW N^2LO: $\mathcal{O}(\alpha^2)$, Mixed EW-QCD: $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha_s^2\alpha)$
$\sigma(e^+e^- \to t\bar{t})$ vs. $\sqrt{s}$	NRQCD: $\mathcal{O}(\alpha_s^5)$, Non-resonant: $\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha_s^3)$ differential; QED: $\mathcal{O}(\alpha^3)$ at NNLL
$H \to b\bar{b}$ width	N^4LO ($m_b \neq 0$); N^4LO differential ($m_b = 0$)
$H \to gg$ width	N^5LO (heavy-top limit), N^4LO ($m_t \neq 0$); N^4LO differential, N^3LO differential ($m_t \neq 0$)
MC simulations for $e^+e^- \to X$ processes	$N^{2,3}LO$ matched to $N^{2,3}LL$ PS. Permille control of non-pQCD effects (hadronization, CR, ...)

Preview of ESPPU 2025 Physics Briefing Book

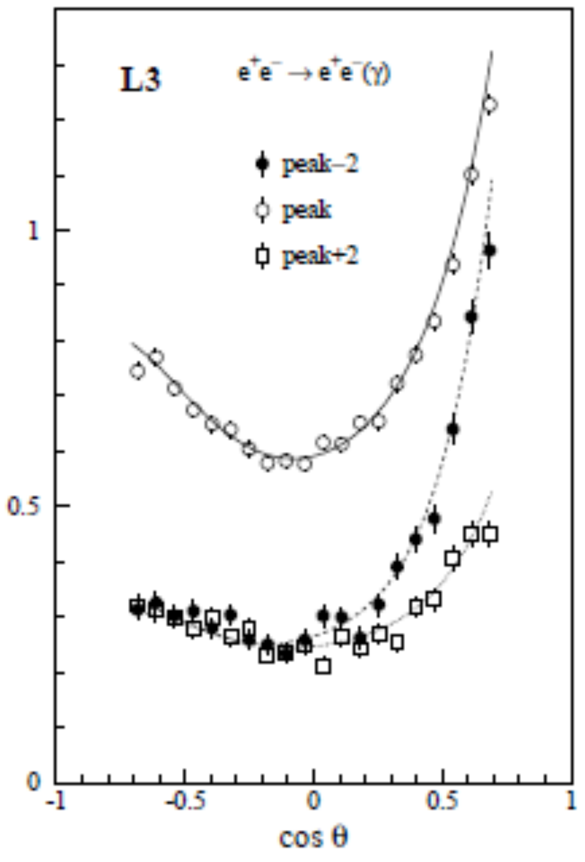
$\alpha_{QED}(m_Z)$

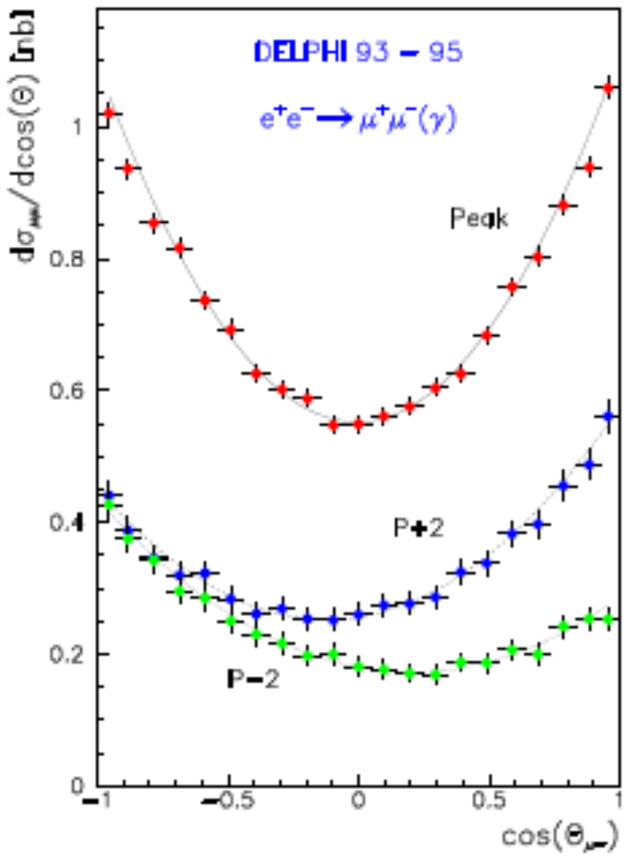
currently **10^{-4}**, a limiting factor to many BSM searches

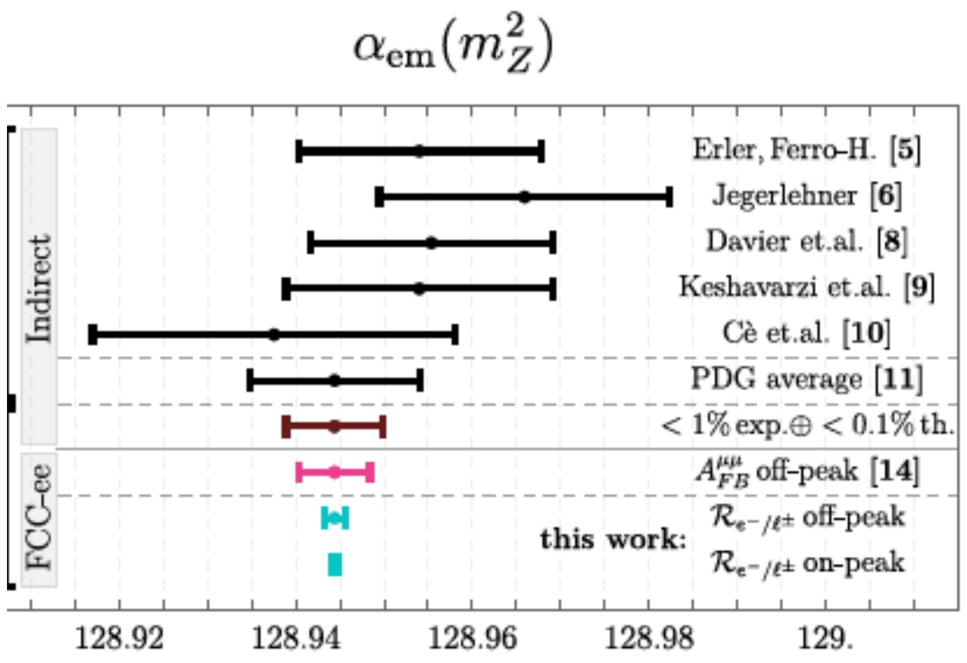
Unique to circular machines (it requires ≫10^{12} Z and line shape scan)

- **Off-pole** (Janot 2015): so far determined from the slope of $A_{FB}^{\mu\mu}$ vs $\sqrt{s}$ (interference Z and γ channels) → **±3x10^{-5}**
- **On-pole** (Riembau 2025): both s and t- channel $e^+e^- \to e^+e^-$ and $\mu^+\mu^-$ at the Z pole (larger data set), sizeable photon contribution for e^- only, not for μ^- → **±0.6x10^{-5}**

What are exp. systematics? Can this be improved by using tau final states, etc...?







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

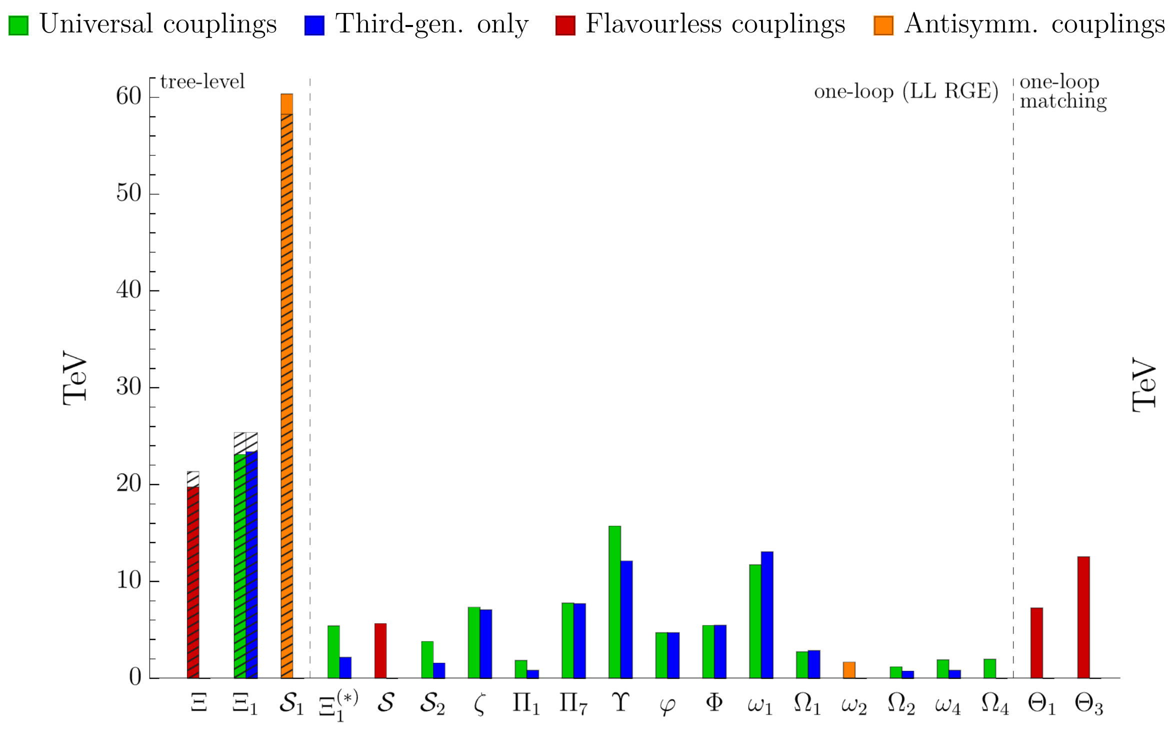
They are not all affecting EW observables at tree-level.

New Physics Reach @ Z-pole

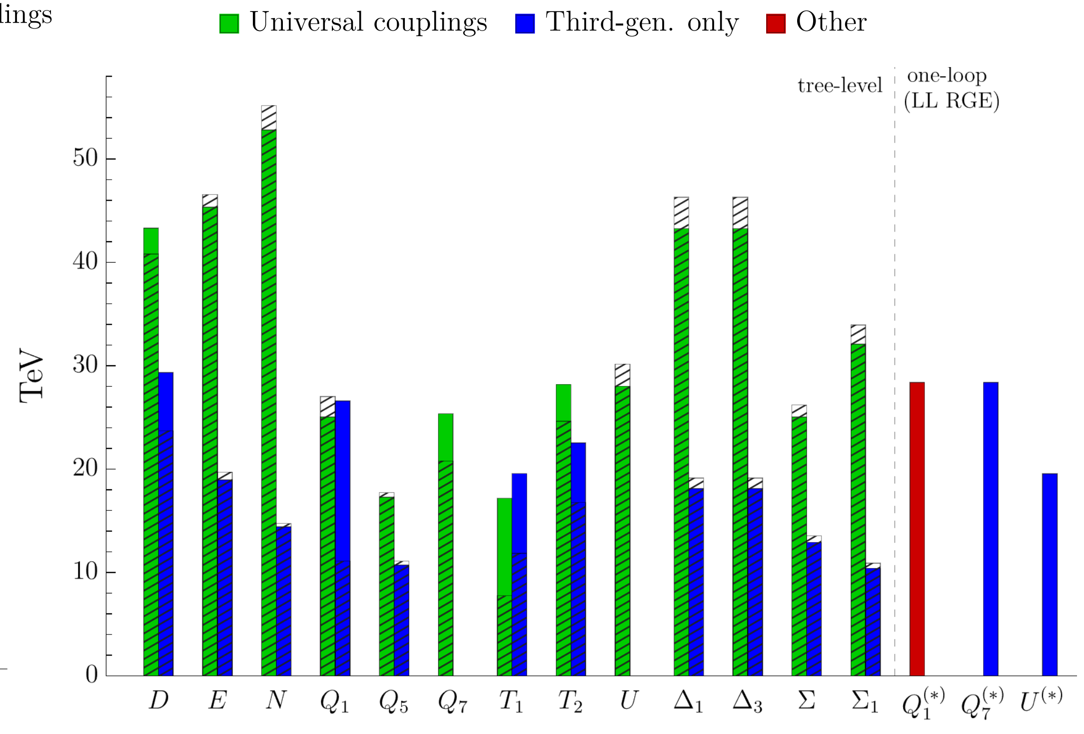
There are 48 different types of particles that can have tree-level linear interactions to SM.

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

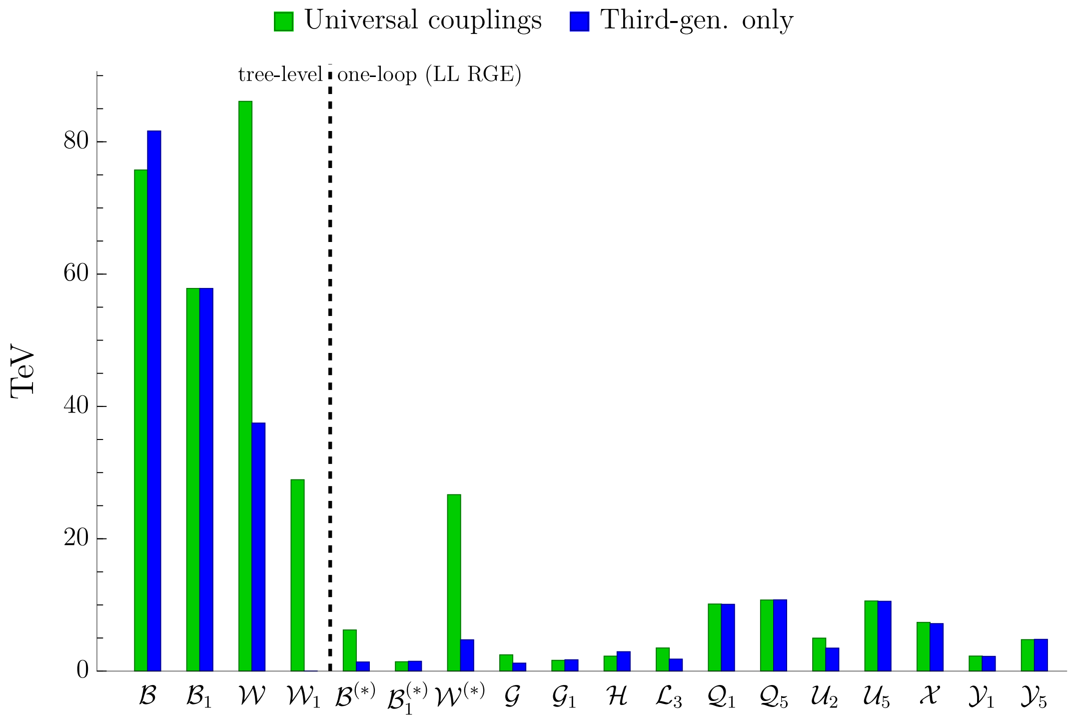
Allwicher, McCullough, Renner, arXiv: 2408.03992



Scalars



Fermions

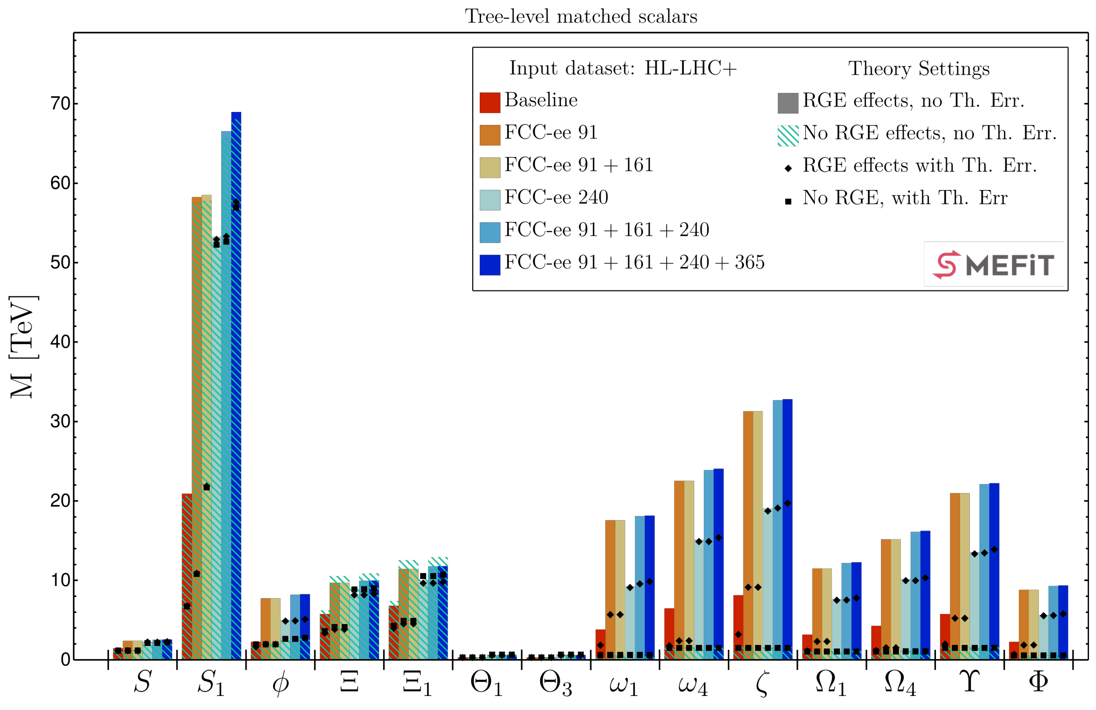


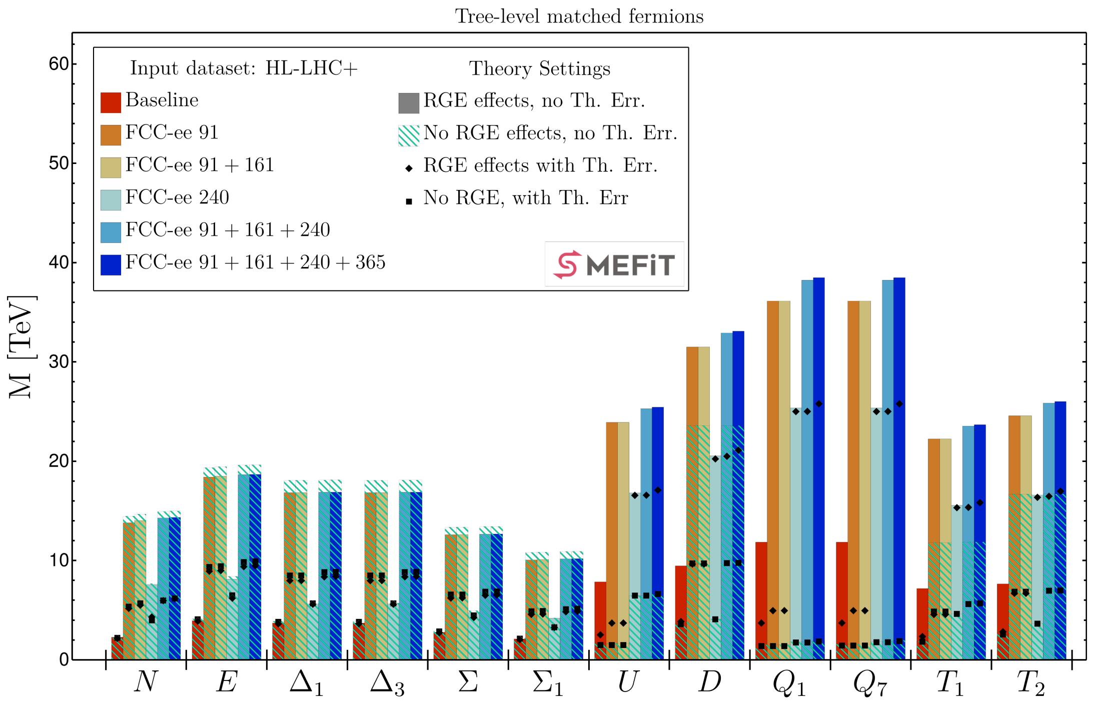
Vectors

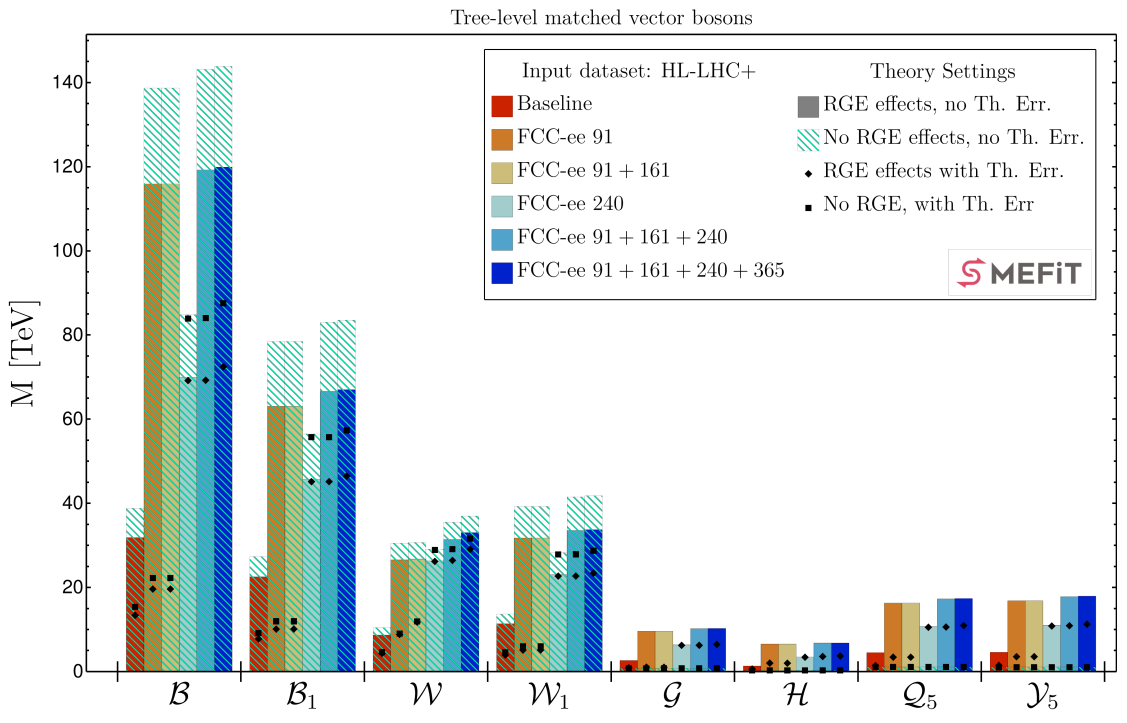
Tree-level matching and running from 1 TeV to Z mass.
W- and Z-pole observables only (no Higgs, no LEP-2 like observables)

New Physics Reach @ Z-pole

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



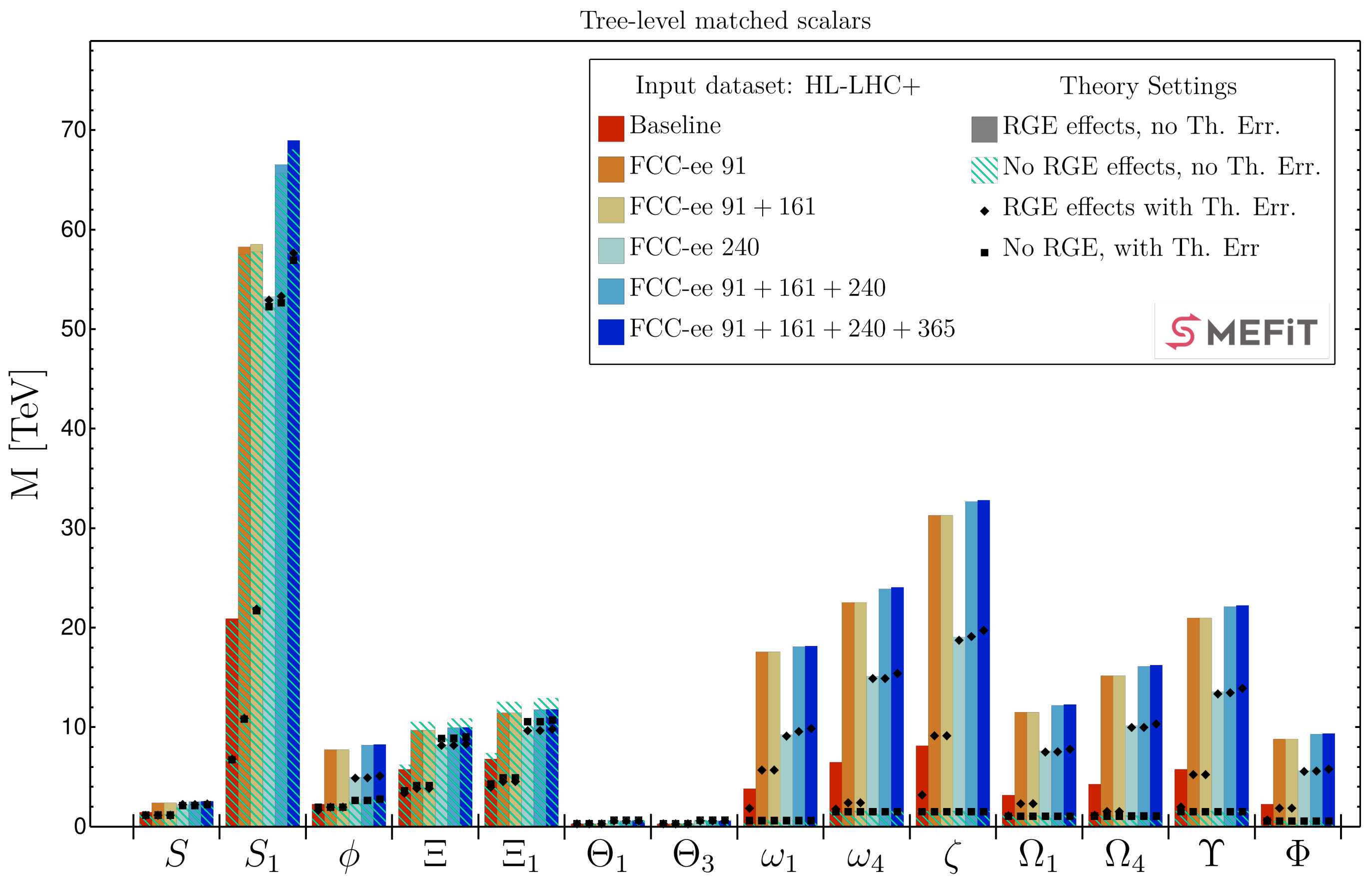


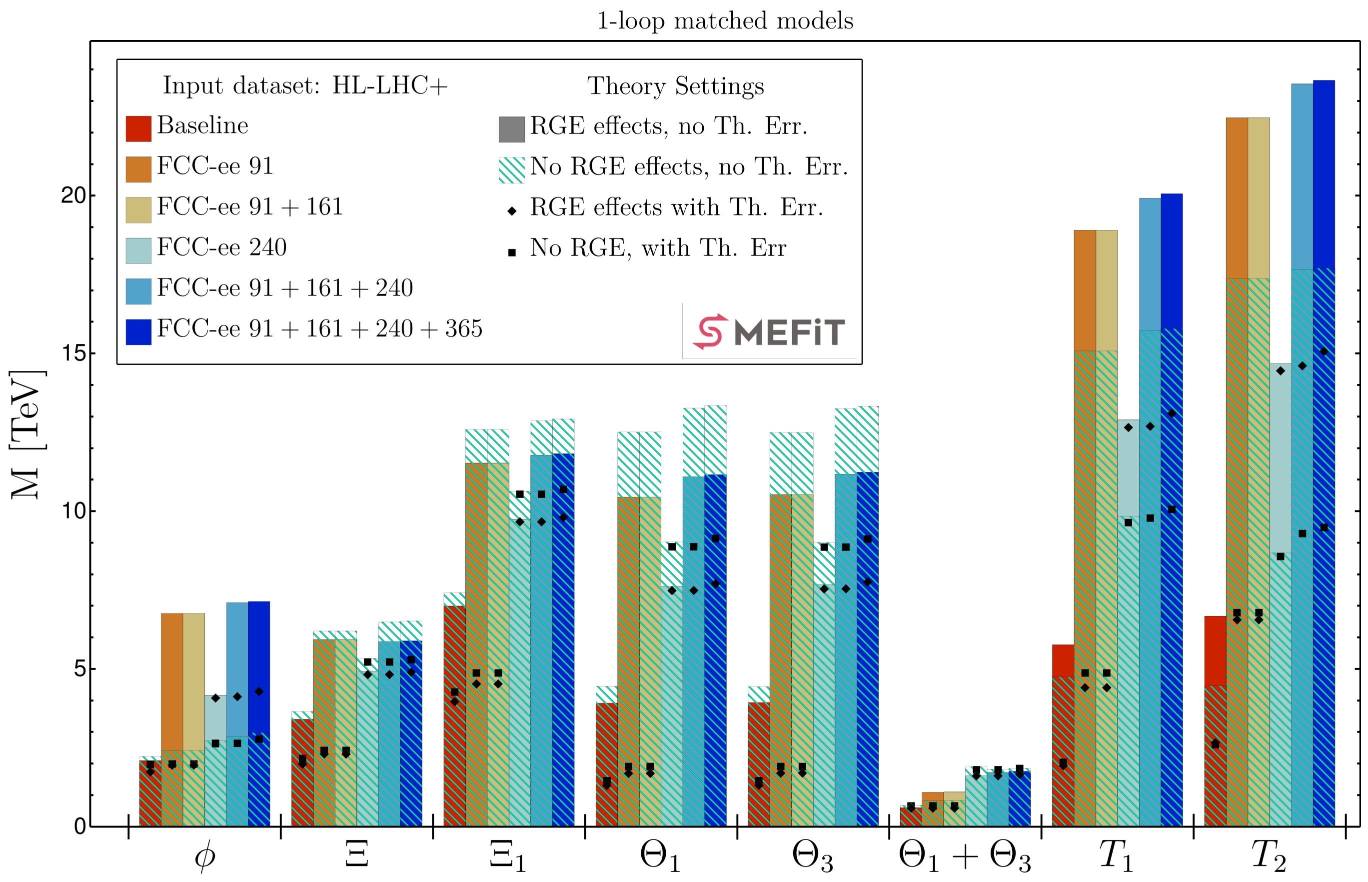


Importance of controlling/reducing the TH syst. errors to exploit Z-pole data.
Role of ZH and tt runs.

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.
It takes full advantage of the quantum nature of HEP
to maximise sensitivity to New Physics.

(SM)EFT for Flavour @ FCC

Flavour Potential of TeraZ

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 species	B^0	B^-	B^0_s	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

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

$\langle E_{X_b}\rangle = 75\% \times E_{\text{beam}}; \langle\beta\gamma\rangle \sim 6$

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

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

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Yield (10^9)	740	740	180	160	3.6	720	200

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 mod…
EW/H pen…
$B^0 \to K^*($…
$\mathcal{B}(B^0 \to K$…
$B_s \to \mu^+\mu$…
$B^0 \to \mu^+\mu$…
$\mathcal{B}(B_s \to \tau^+$…
Leptonic d…
$B^+ \to \mu^+\nu$…
$B^+ \to \tau^+\nu$…
$B_c^+ \to \tau^+\nu$…
CP / hadr…
$B^0 \to J/\Psi$…

$B_s \to D_s^\pm K^\mp$	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)

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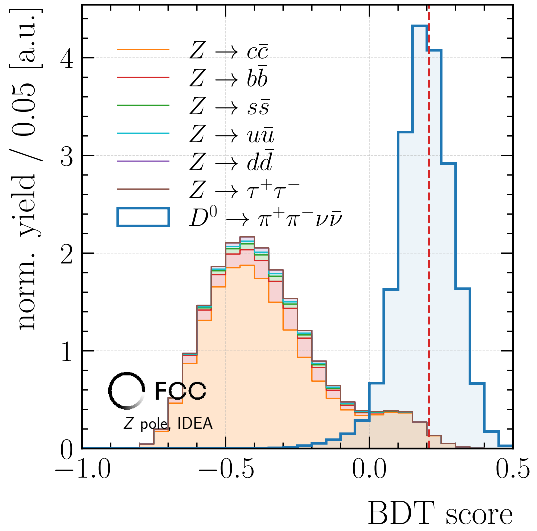
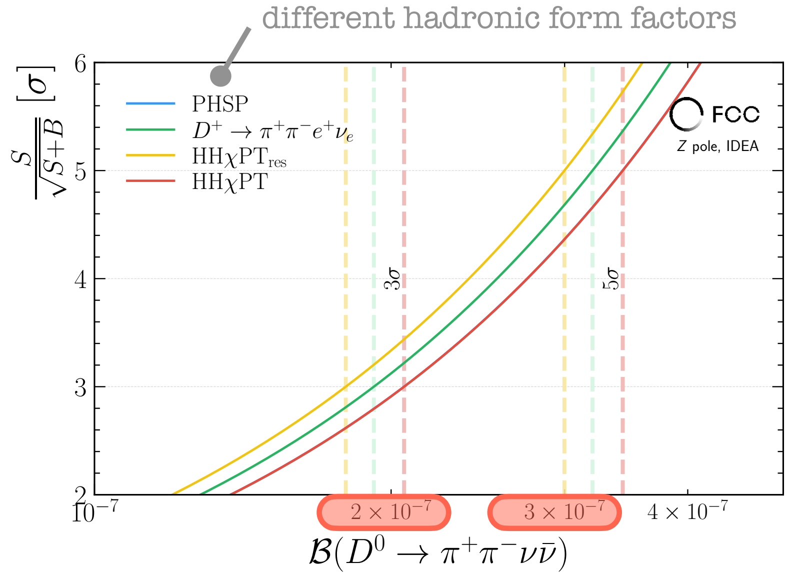
FCC-ee Flavour Opportunities

- **CKM elements:**
  - **CPV angles** (γ, β, ϕ_s) at sub-degree precision
  - **V_{cb}** (critical for normalising the Unitarity Triangle) from WW decays:
    - 3.4% @ now → 0.52-0.14% @ FCC-ee (depending on tracking) see Marzocca et al (2024)
- **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:
    - $\tau \to \mu\gamma$: 4×10^{-8} @Belle2021→10^{-9} @ FCC-ee
    - $\tau \to 3\mu$: 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}
- …

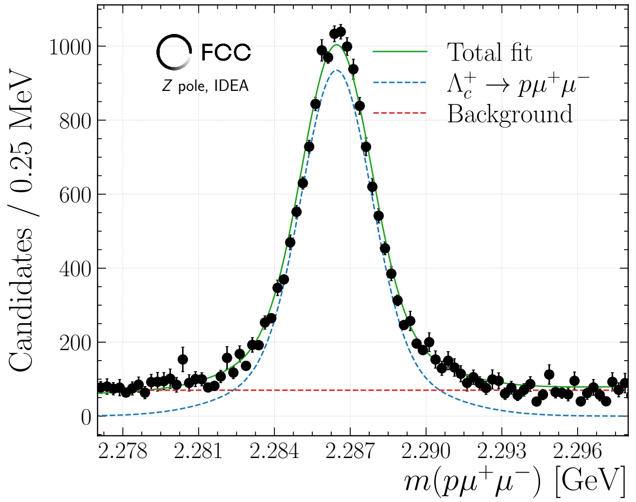
Charm @ FCC-ee

- **Charm** physics plays a unique role in searches for NP in the up-type quark sector
  - charm FCNC induced by quantum loops of down-type quarks, $\Delta m_{down} << m_W \Rightarrow$ high suppression in SM
  - FCC-ee: large rate (like LHCb), clean environment (like BelleII, BESIII)
  - charm meson produced from Z decay and not pp interactions $\Rightarrow$ sizeable polarisation, enabling additional angular observables in $c \rightarrow u\ell\ell (\ell = e, \mu)$ transitions
- $D^0 \rightarrow \pi^+\pi^-\nu\bar{\nu}$





- $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

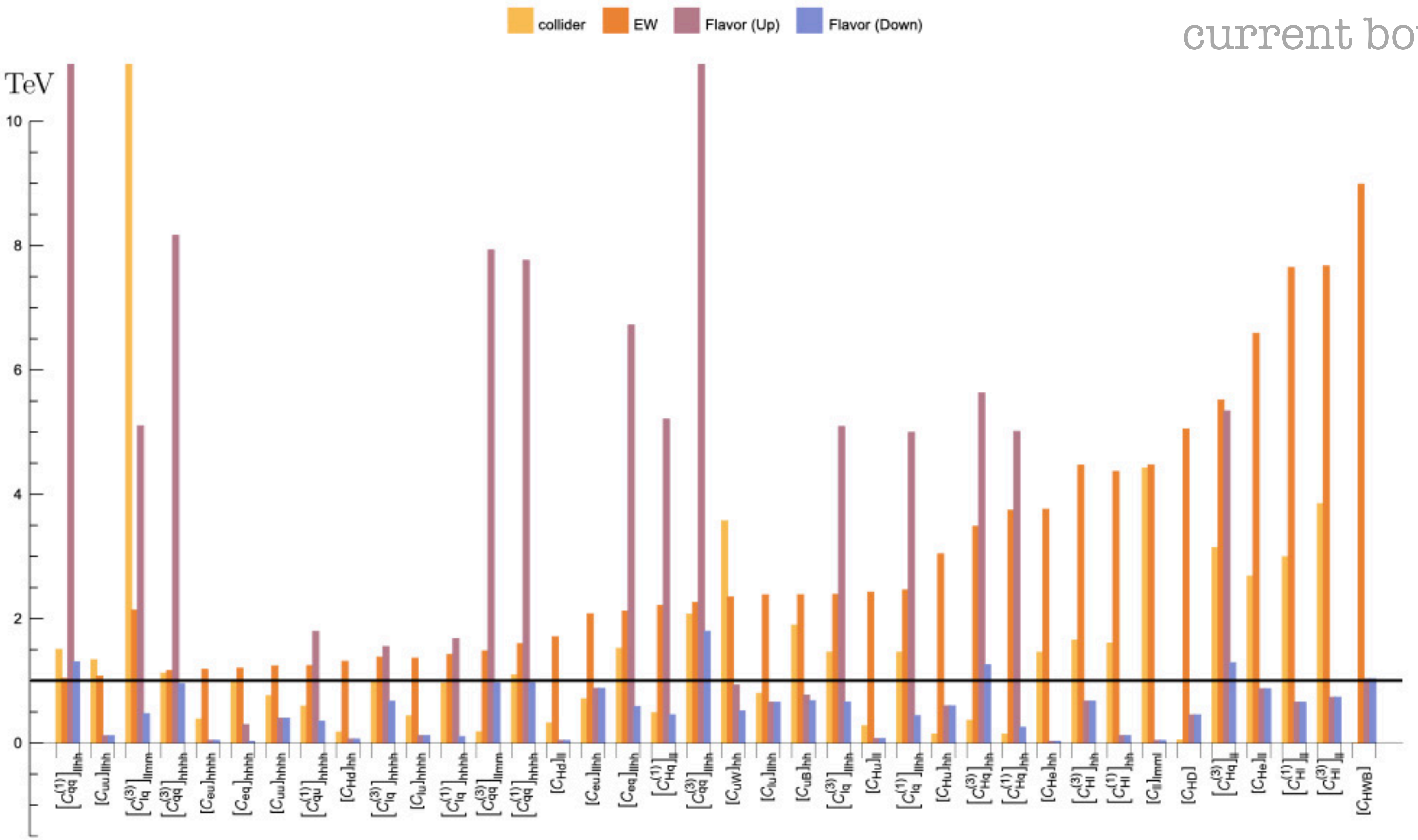


see arXiv:2509.10447

Interplay EW-Flavour at FCC

Allwicher, Cornella, Isidori, Stefanek arXiv:2311.00020

current bounds



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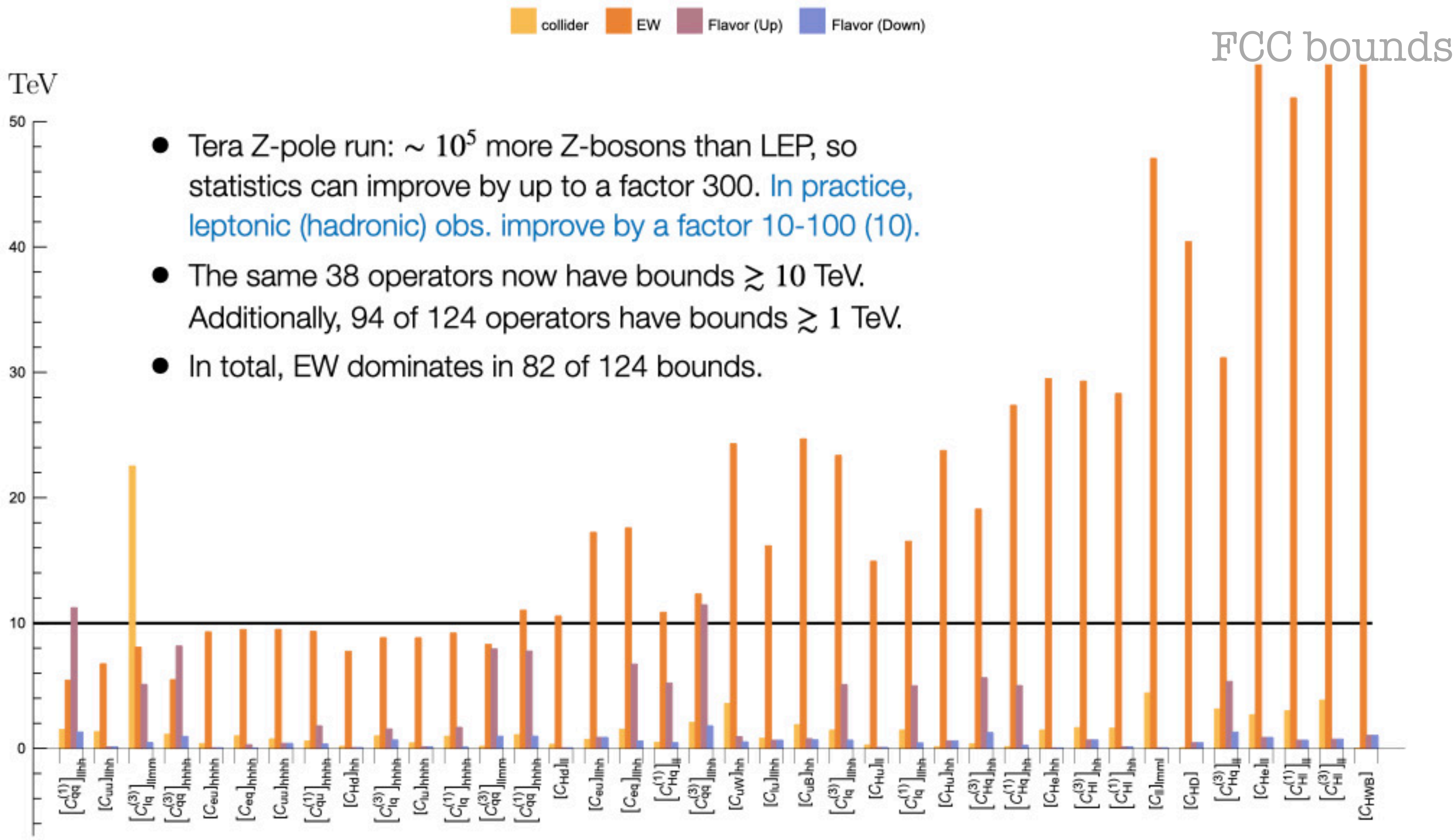

- Tera Z-pole run: $\sim 10^5$ more Z-bosons than LEP, so statistics can improve by up to a factor 300. In practice, leptonic (hadronic) obs. improve by a factor 10-100 (10).
- The same 38 operators now have bounds $\gtrsim 10$ TeV. Additionally, 94 of 124 operators have bounds $\gtrsim 1$ TeV.
- In total, EW dominates in 82 of 124 bounds.

Conclusions & Outlook

During the **feasibility study**, the FCC-ee accelerator complex has been optimised for geology, surface constraints, environment, local infrastructure and accelerator performance

- 4 IPs as baseline
- new RF system totally flexible between 90 and 240 GeV
- identification of other science opportunities
- importance of FCC-ee to maximise the FCC-hh physics potential
- refined FCC-hh plan (85TeV w. 14T Nb_3Sn magnets with higher lumi vs. 100TeV w. 16T vs. 120TeV w. 20T HTS)

FCC-ee has a rich and broad physics potential:

⦿ Quantum leap in testing the Standard Model broadly (**"guaranteed deliverables"**)

— parts of the SM central to the model and/or to the world around us are yet to be established —

⦿ Search directly *and* indirectly for New Physics (**"exploration potential"**)

And it is the perfect springboard to the energy frontier aka FCC-hh.

The FCC project perfectly fits the **needs of HEP after LHC**

BONUS

Reading Material

- **Feasibility Study Report** (backup documents) ESPPU#261
  - Volume 1: Physics, Experiments, Detectors (291 pages) CDS arXiv:2505.00272
  - Volume 2: Accelerators, technical infrastructure and safety (615 pages) CDS arXiv:2505.00274
  - Volume 3: Civil Engineering, Implementation and Sustainability (360 pages) CDS arXiv:2505.00273
- **Several 10-page general summaries**
  - FCC Integrated Programme Stage 1: The FCC-ee (ESPPU#233); CDS
  - FCC Integrated Programme Stage 2: The FCC-hh (ESPPU#247); CDS
  - The FCC Integrated Programme: A physics manifesto (ESPPU#241); CDS; arXiv:2504.02634
  - Other Science Opportunities at the FCC-ee CDS
- **Several 10-page more topical summaries**
  - Prospects in Electroweak, Higgs and Top physics at FCC (ESPPU#217); FCC note
  - Prospects in BSM physics at FCC (ESPPU#242); FCC note
  - FCC: QCD physics (ESPPU#209); FCC note
  - Prospects for flavour physics at FCC (ESPPU#196); FCC note
  - Prospects for physics at FCC-hh (ESPPU#227); FCC note
- **Expressions of Interest for the development of Detector Concepts and Sub-detector Systems for FCC**
  - Summary (ESPPU#95); FCC note
  - Backup document ((ESPPU#96)

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  - Prospects in Electroweak, Higgs and Top physics at FCC (ESPPU#217); FCC note
  - Prospects in BSM physics at FCC (ESPPU#242); FCC note
  - FCC: QCD physics (ESPPU#209); FCC note
  - Prospects for flavour physics at FCC (ESPPU#196); FCC note
  - Prospects for physics at FCC-hh (ESPPU#227); FCC note
- **Expressions of Interest for the development of Detector Concepts and Sub-detector Systems for FCC**
  - Summary (ESPPU#95); FCC note
  - Backup document ((ESPPU#96)

Cost Estimates

FCC-ee

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF

LCF CLIC

Unit: MCHF	LCF 250 (LP)	Δ LCF 550 (FP)	CLIC 380	Δ CLIC 1500
Collider	3864	4204	2471	4684
Main Beam inj./transfer	1181	86	1046	23
Drivebeam inj./transfer	-	-	1060	302
Civil Engineering	2338	0	1403	703
Technical Infrastructure	1109	1174	1361	1404
Sum	**8492**	**5464**	**7341**	**7116**

LEP3

Cost Element	2 new Xpts	2 Exist Xpts
Accelerator	2705	2705
Injectors and Transfer Lines	295	295
Technical Infrastructures	435	435
Experiments	130	60
Civil Engineering	165	165
LHC Removal/LEP3 Installation	140	140
Total CERN (MCHF)	**3870**	**3800**
Experiments non-CERN part	900	270

FCC-hh
(after FCC-ee)

Cost summary table in 2024 MCHF for the construction of FCC-hh.

Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	**19080**

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

Muon Collider

LHeC (cost estimate 2018, 60 GeV e-)

Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1756MCHF

→ ~2 BCHF (2025)