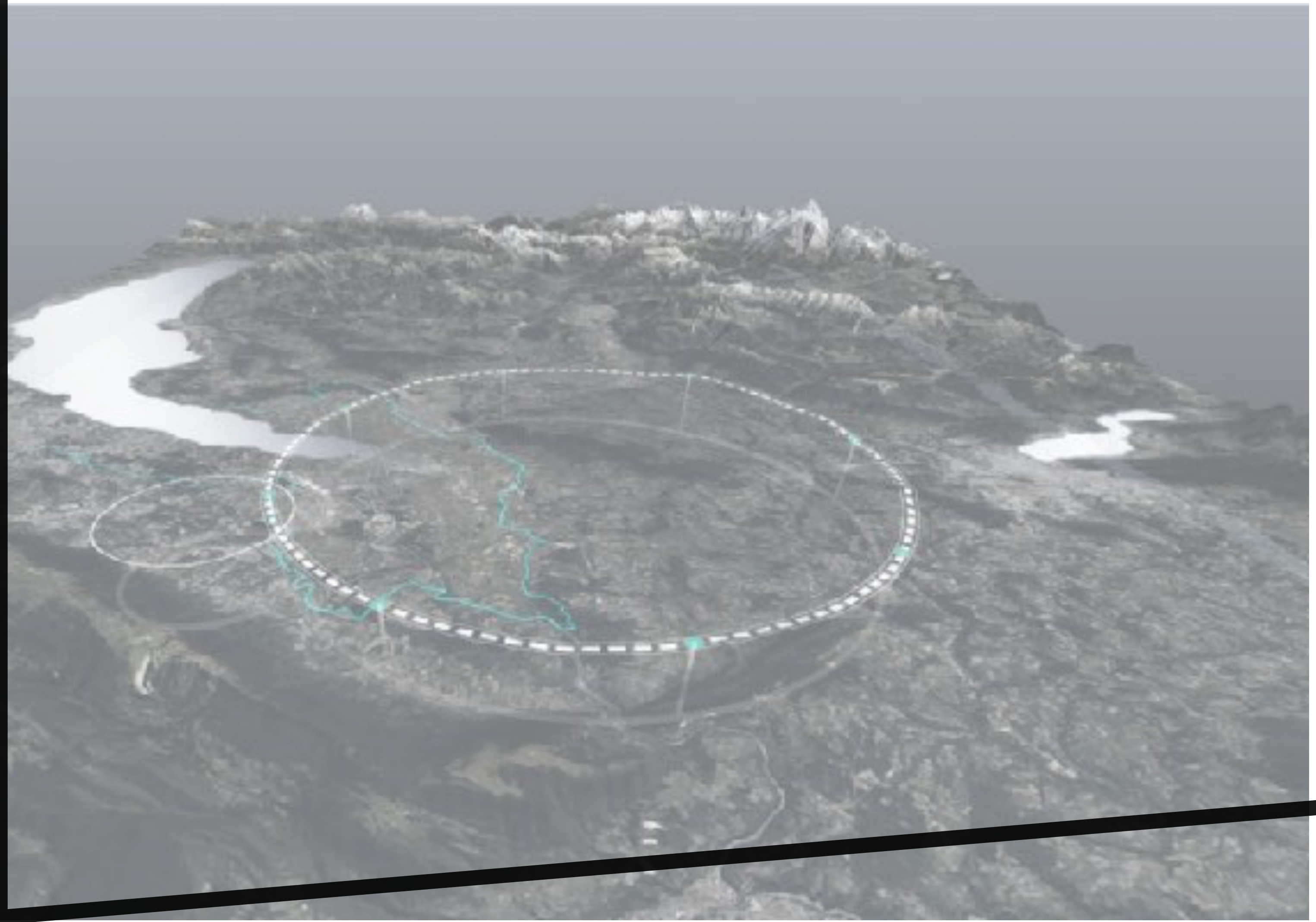
Future Circular Collider — A Physics Manifesto —

SLAC Theory, 29 August 2025



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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. syst. uncertainties, the LHC became a precision machine.

The LHC Legacy (so far)

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

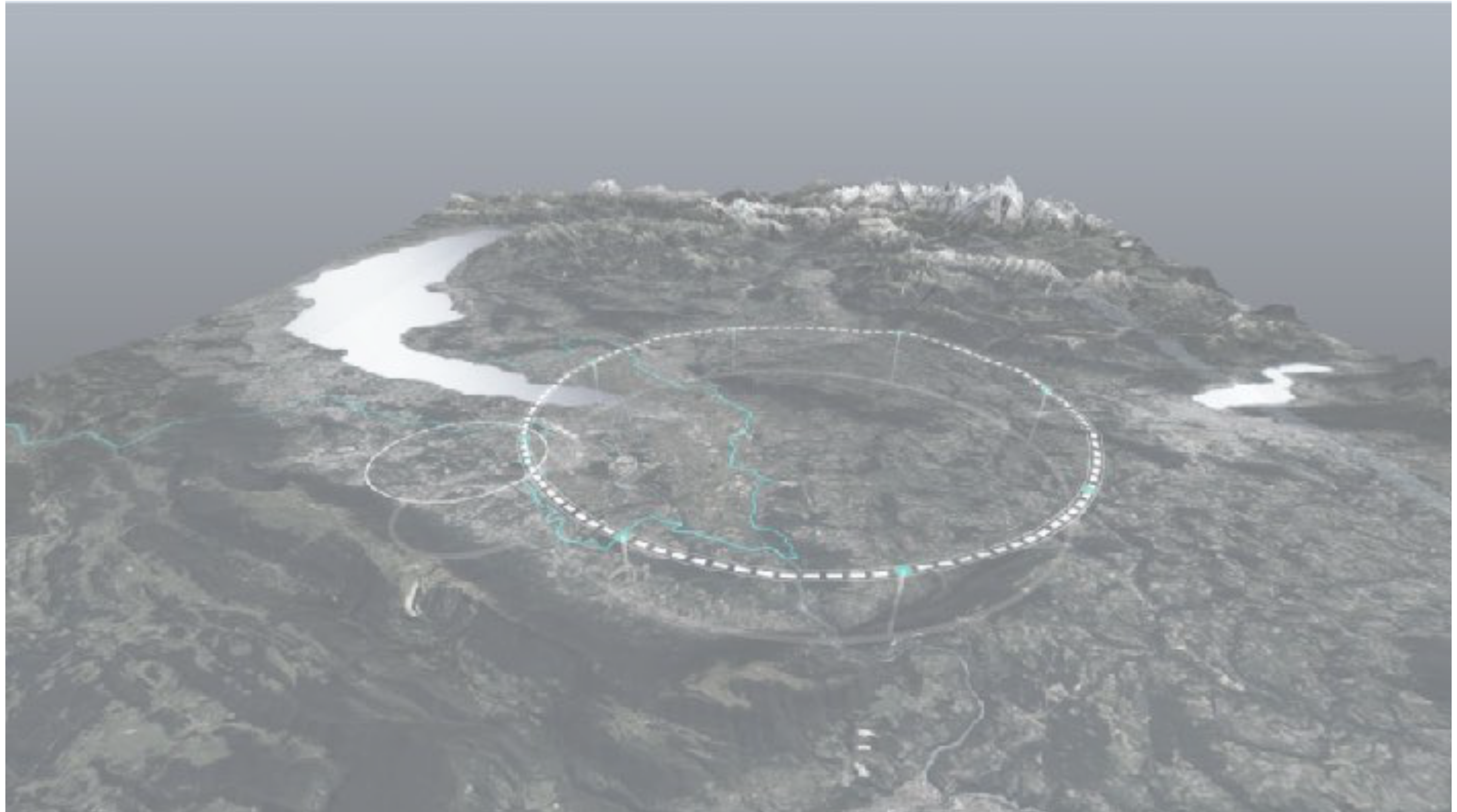
We need a broad, versatile and ambitious programme that can

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.

Future Circular Collider

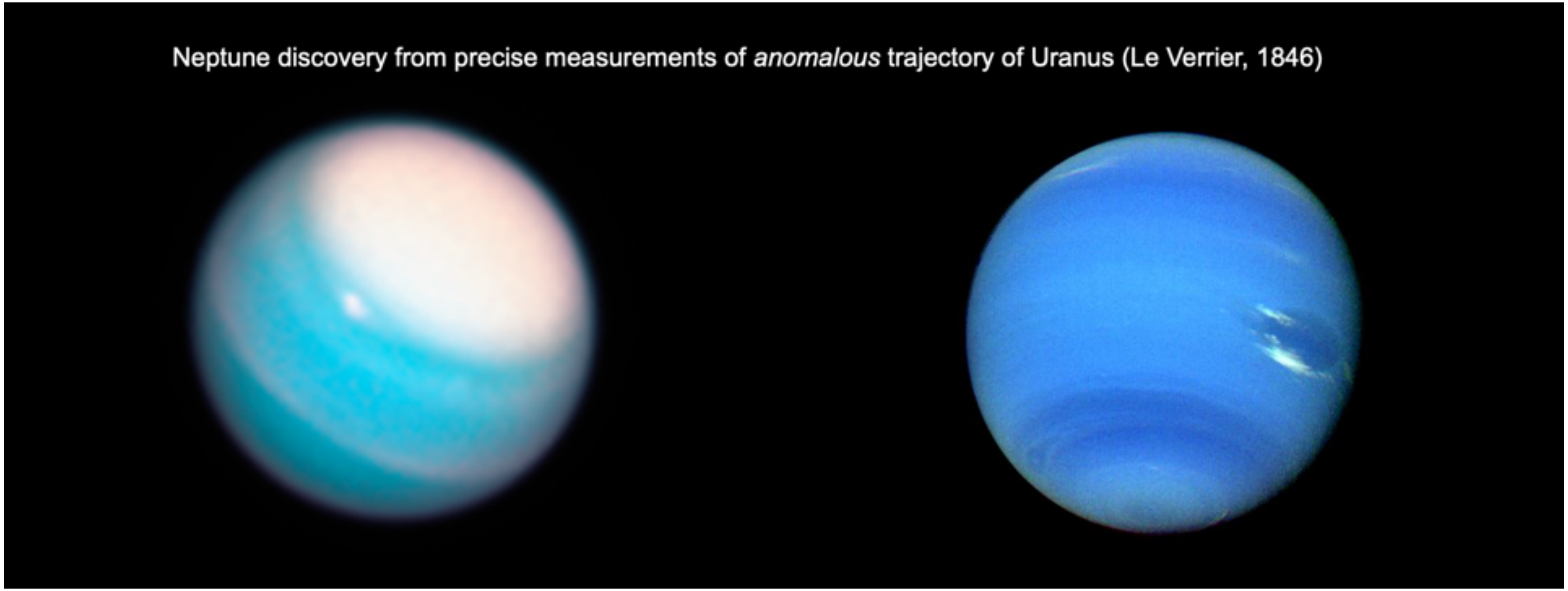
- A versatile particle collider, with four interaction poins, housed in a 200m-underground 91 km ring around CERN.
- Implemented in several stages:
  - an e^+e^- “Higgs/EW/Flavour/top/QCD” factory running at 90-365 GeV ▶ **FCC-ee**
  - followed by a high-energy pp collider reaching 100 TeV ▶ **FCC-hh**



Precision as a Discovery Tool

Many historical examples

- Uranus anomalous trajectory ⇢ Neptune



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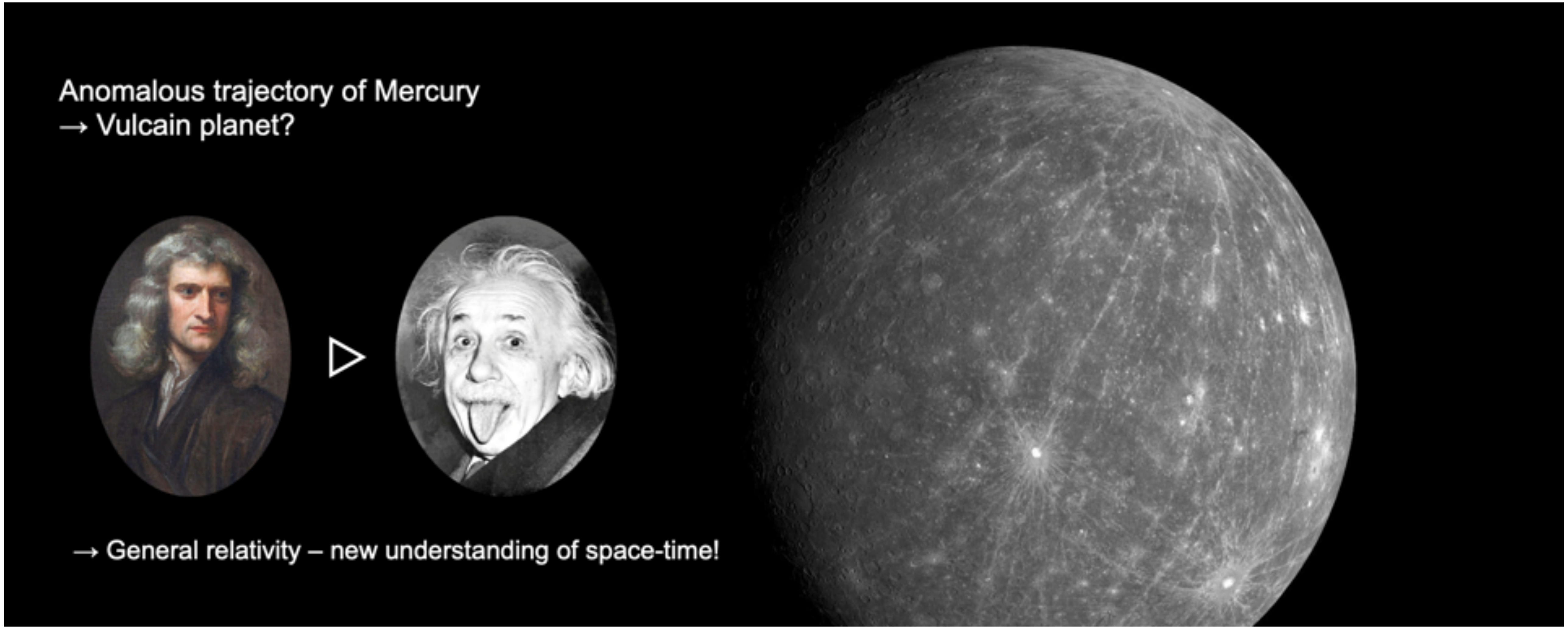

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- …

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- …

Herwig Schopper in CERN Courier:
LEP was a transformative machine
"It changed high-energy physics from a 10% to a 1% science."

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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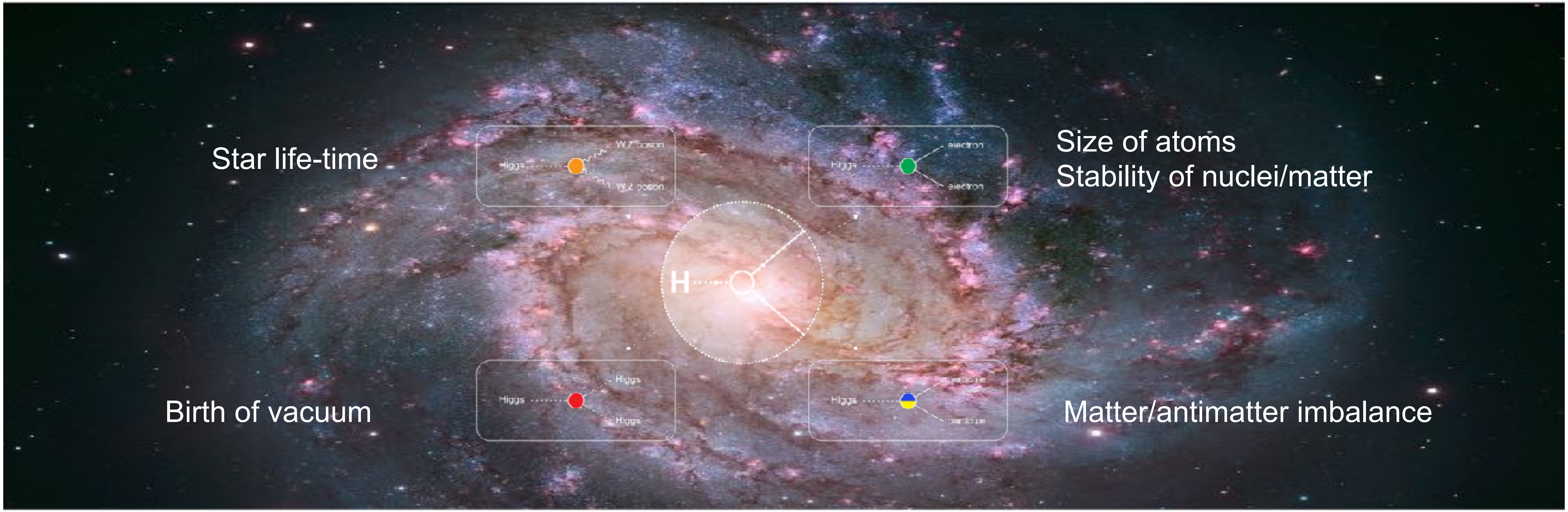

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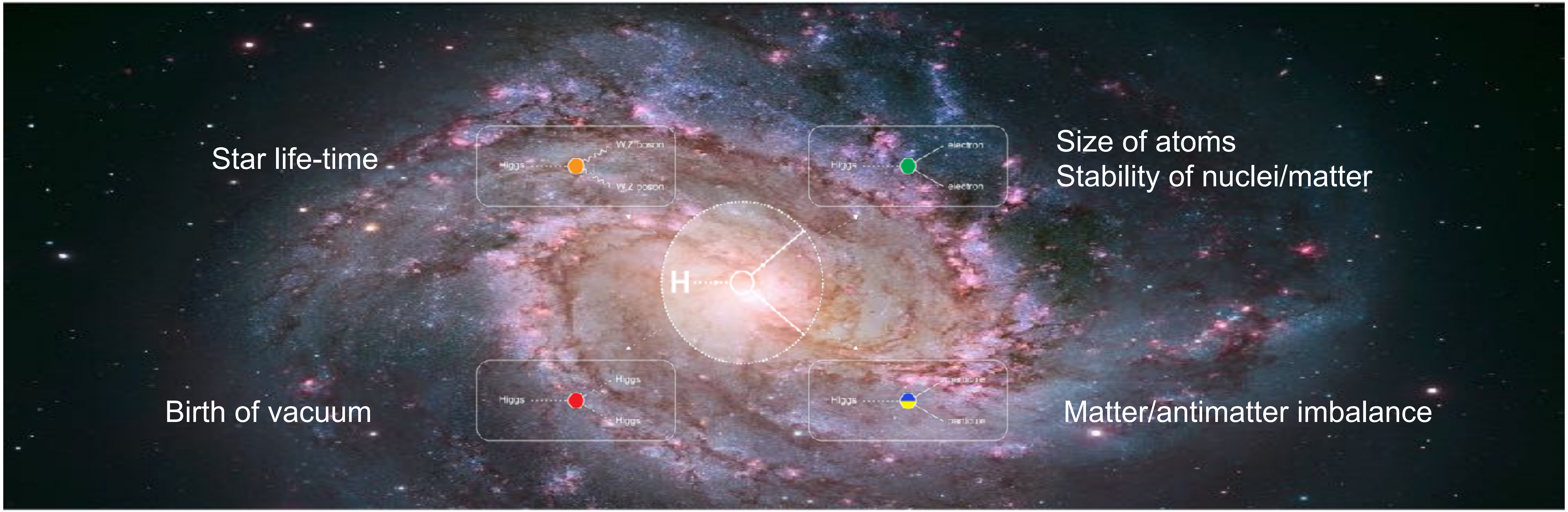


(HL)-LHC will make remarkable progress
(O(100M) Higgs=already a Higgs Factory).
But it won't be enough.
A new collider is needed!

The Higgs Requires More Precision

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

The Higgs boson certainly plays a unique role in the SM.
It is important to study it well, and FCC-ee will do it with an incredible precision.
On the other hand, precision shouldn't be limited to the Higgs sector.
And FCC-ee offers a unique and broad precision programme.
Well, at the end, the confirmation of GR didn't follow from the study of the latest discovered and still mysterious planet but from the careful measurement of an already well-known one.

Broad FCC-ee programme is key to success.

FCC Feasibility Study

The launch of the feasibility study

"An **electron-positron** Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a **proton-proton** collider at the highest achievable energy."

— CERN council approved the Strategy and CERN management implemented it —

FCC Feasibility Study (FS) started in 2021 and has completed in April 2025.

Mid-term review in 2023.

Objectives of FCC feasibility study

- Demonstration of the **geological, technical, environmental and administrative feasibility** of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure.
- Pursuit, together with the Host States, of the preparatory **administrative processes** required for a potential project approval to identify and remove any showstopper.
- Optimisation of the design of the **colliders and their injector chains**, supported by R&D to develop the needed key technologies.
- Elaboration of a sustainable **operational model** for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency.
- Development of a consolidated **cost estimate**, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation.
- Identification of substantial **resources** from outside CERN's budget for the implementation of the first stage of a possible future project (**tunnel and FCC-ee**).
- Consolidation of the **physics case and detector concepts** for both colliders.

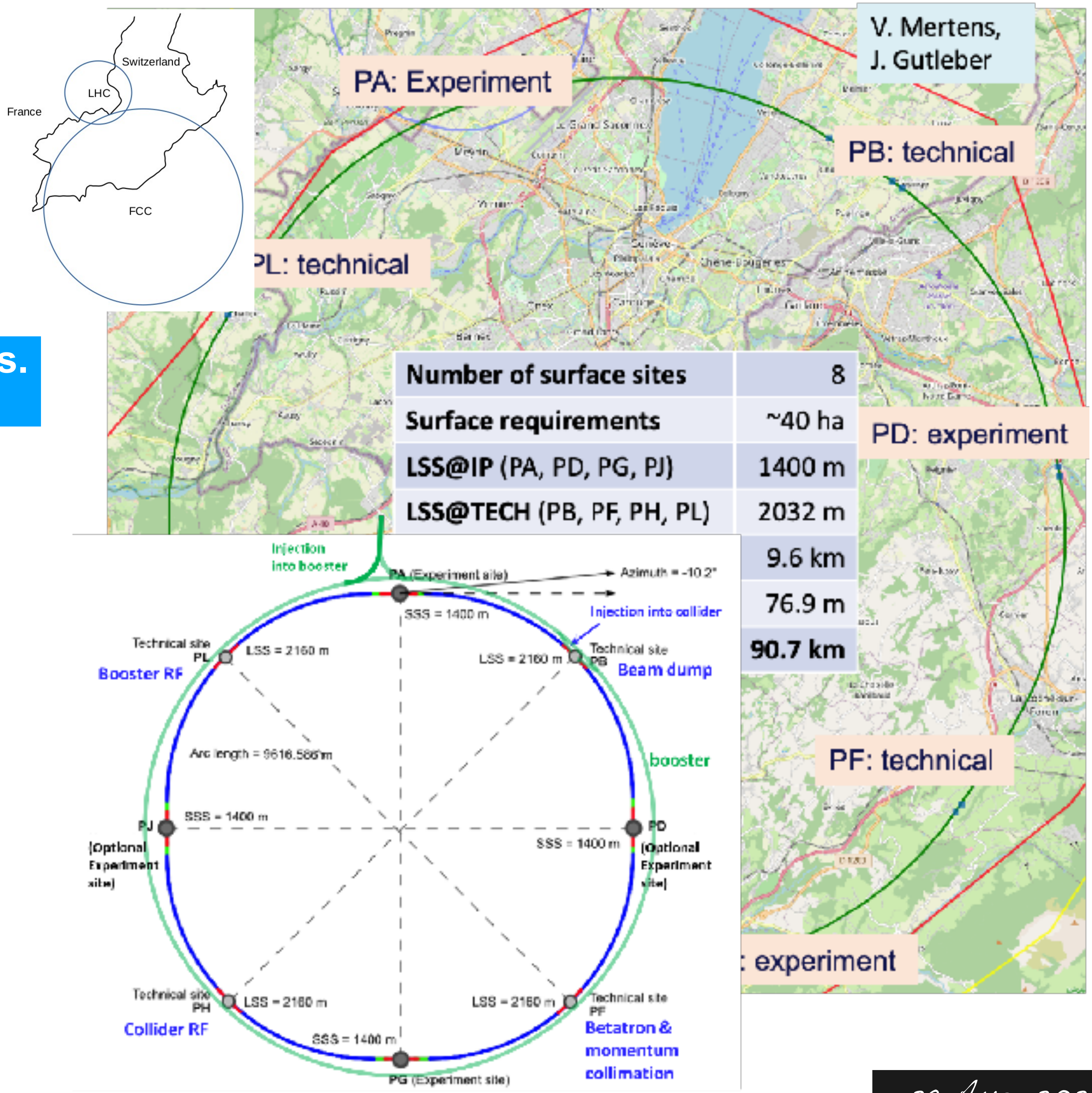
Optimized placement and layout

M. Benedikt @ CERN 13.02.24

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“Avoid-reduce-compensate” principle of EU and French regulation

Overall lowest-risk baseline: 90.7 km ring, 8 surface points.
Whole project now adapted to this placement



Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
	9.6 km
	76.9 m
	90.7 km

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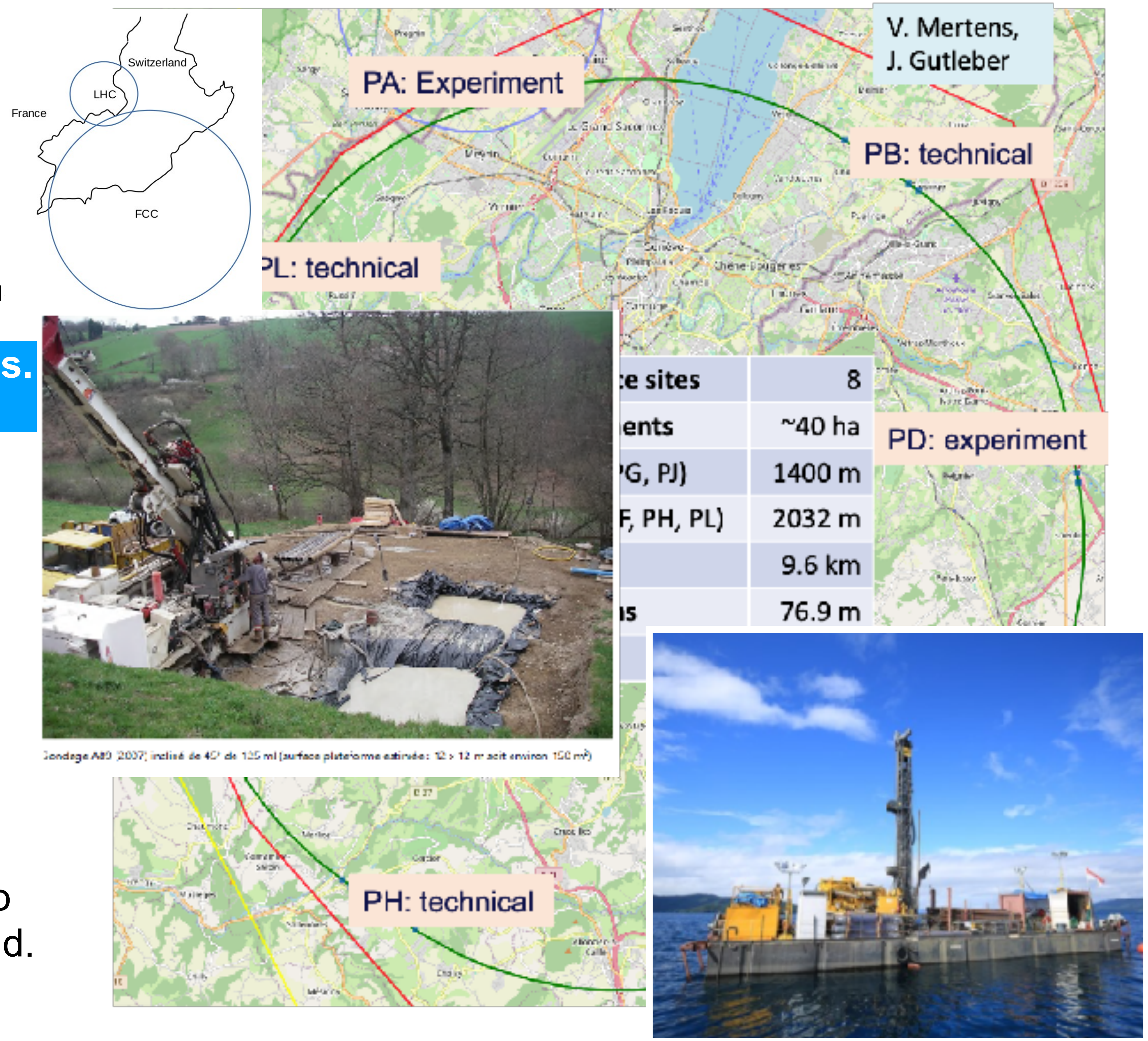
- **Site investigations in areas with uncertain geological conditions:**
  - 28 boreholes and 80 km of seismics planned between October 2024 and December 2025.
  - South part: All drillings completed (logging and testing ongoing); preliminary results positive, confirming 3D geol model.
  - North part: 3 drill sites in France currently active, 2 more to start soon; still pending permits for the works in Switzerland.



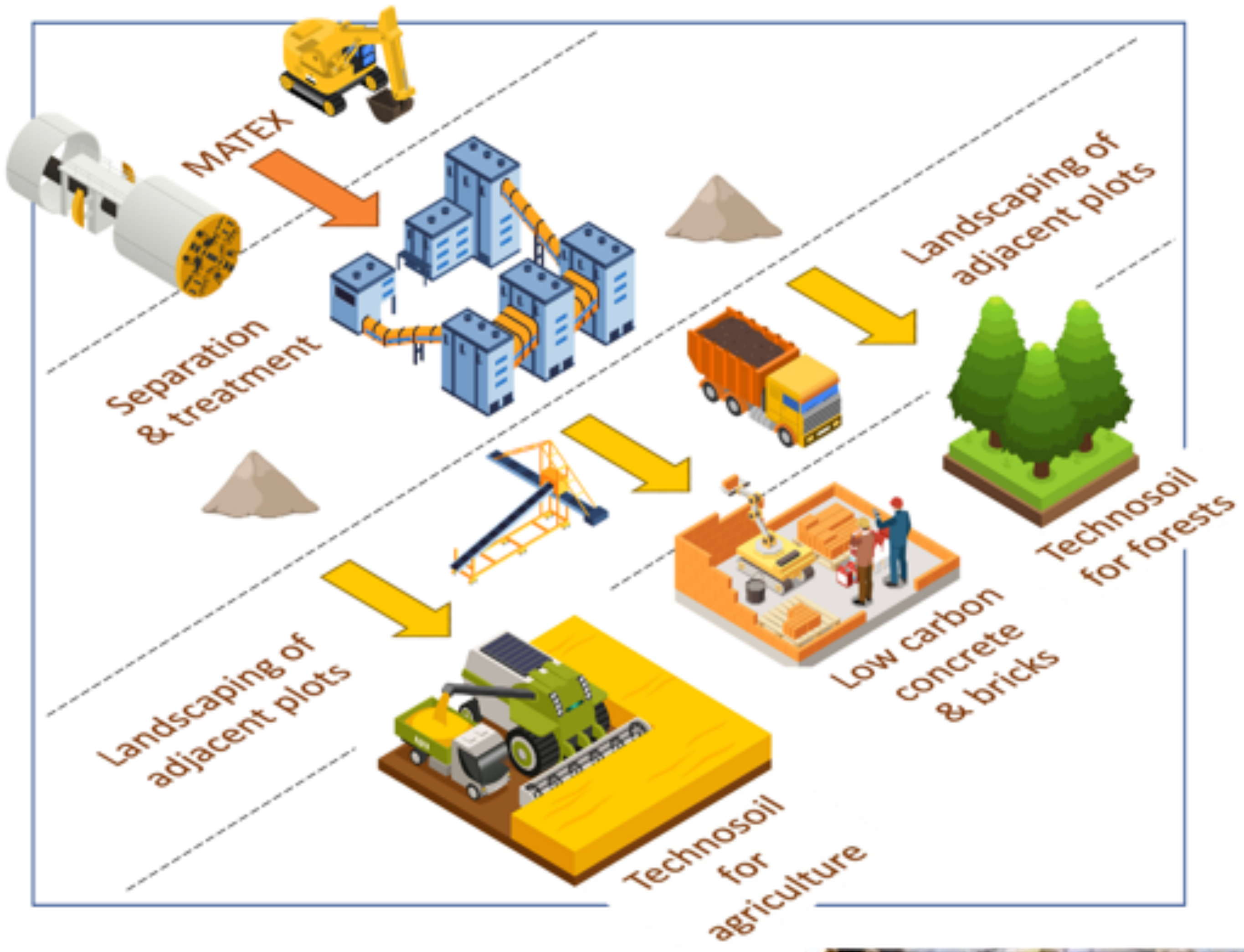
Drilling works on the lake

Environmental considerations

M. Benedikt @ CERN 13.02.24

- **Excavated material** from FCC subsurface infrastructures: 6.5 Mm^3 in situ, 8.4 Mm^3 excavated
- **Priority : reuse, minimize disposal**
- 2021-2022: International competition **“Mining the Future”**, launched with the support of the EU Horizon 2020 grant, to find innovative and realistic ideas for the reuse of molasse (96% of excavated materials)
- 2023: **“OpenSky Laboratory”** project: Objective - Develop and test an innovative process to transform sterile “molasse” into fertile soil for agricultural use and afforestation. Trial with 5’000t of excavated local molasse → convert it to arable soil (agricultural/forestry)

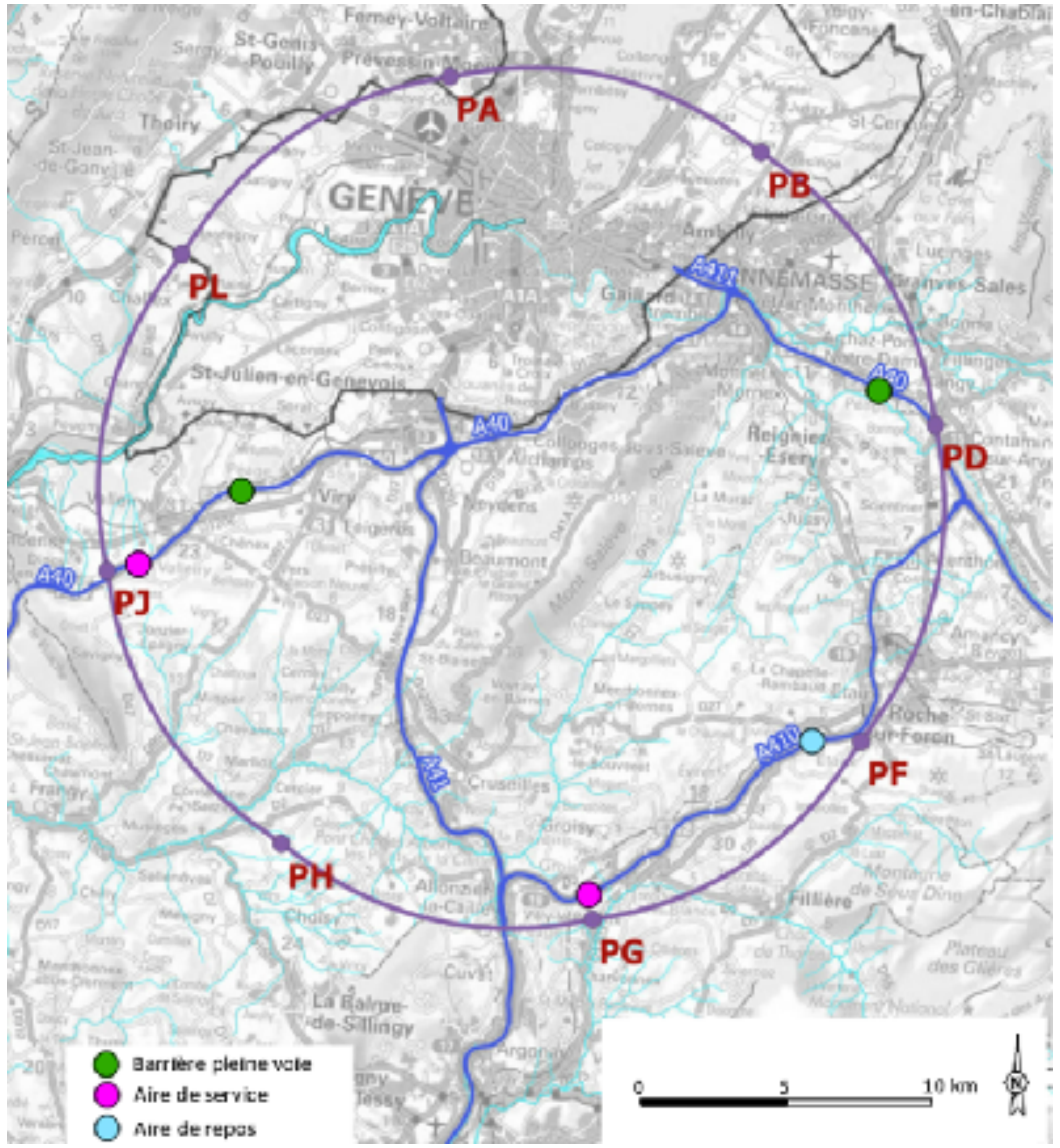
- **Heat:**
  - heating for local houses
  - cheese factories in Jura and Haute-Savoie expressed special interest



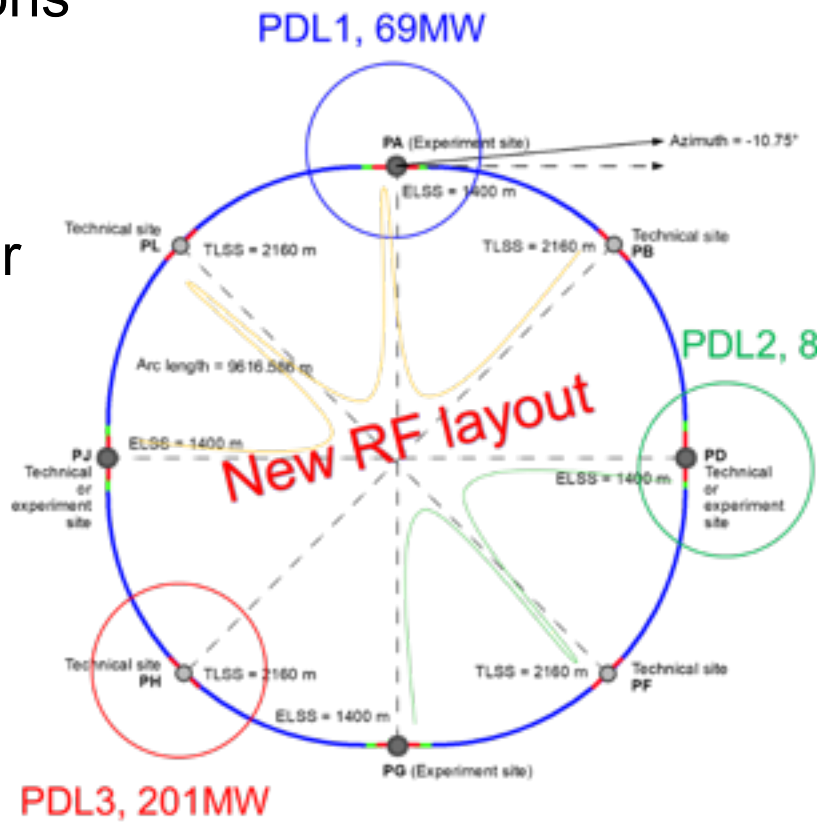
Connections with local infrastructure

M. Benedikt @ CERN 13.02.24

- **Road accesses** developed for all 8 surface sites
  - Four possible highway connections defined
  - Less than 4 km new departmental roads required



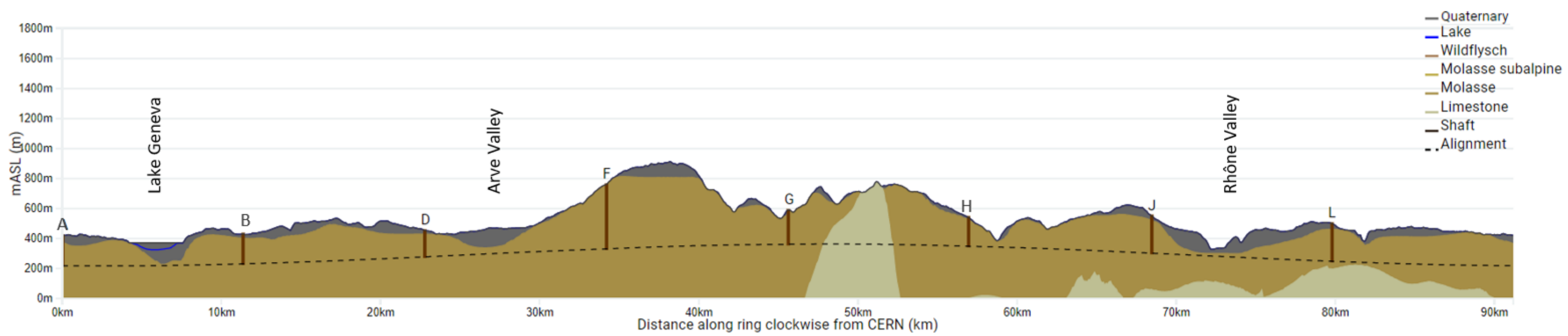
- **Connections to electrical grid**
  - Electrical connection concept studied by RTE (French electrical grid operator) → requested loads have no significant impact on grid
  - Powering concept and power rating of the three sub-stations compatible with FCC-hh
  - R&D efforts aiming at further reduction of the energy consumption of FCC-ee and FCC-hh

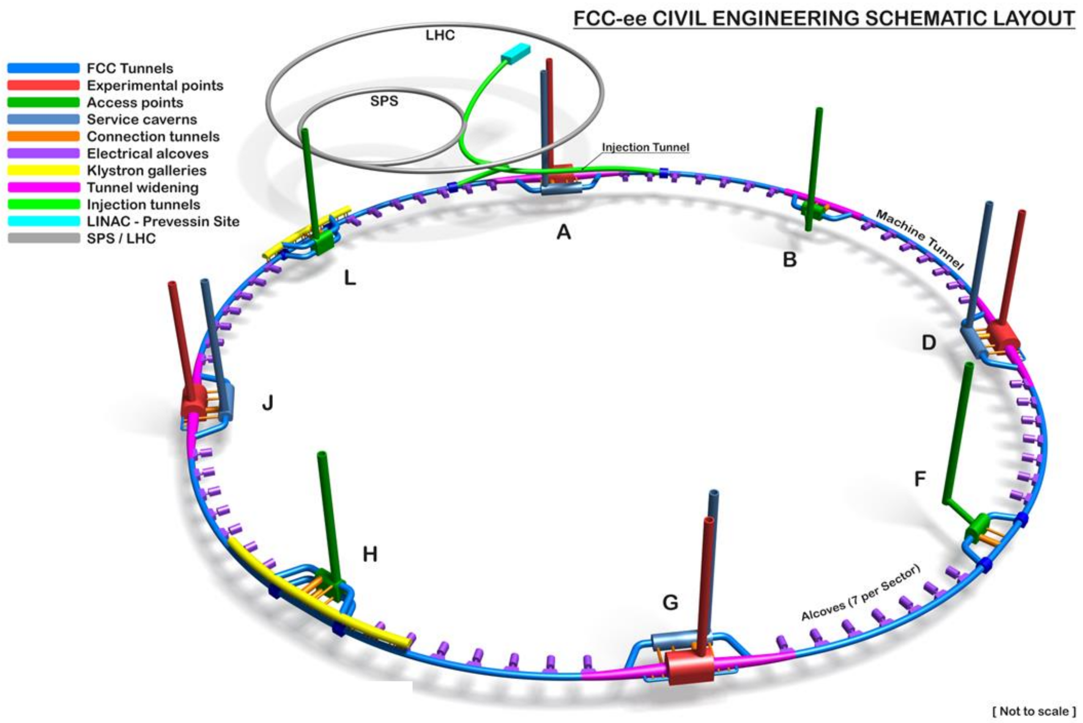


FCC-ee elecrtical energy consumption	Z	W	H	TT
Beam energy [GeV]	45.6	80	120	182.5
Peak power during beam operation [MW]	**250**	**275**	**297**	**381**
Total FCC-ee yearly consumption [TWh]	**1.2**	**1.3**	**1.4**	**1.85**

Civil engineering

T. Watson @ Annecy FCC Physics ‘24



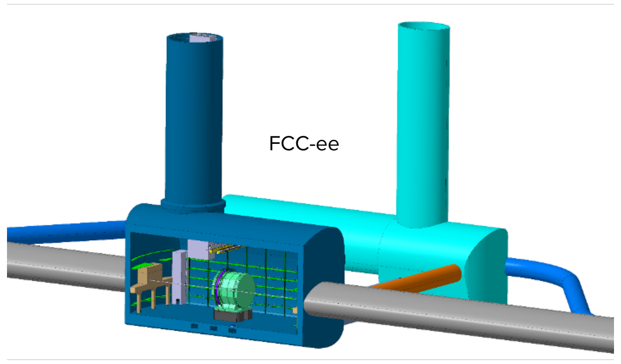


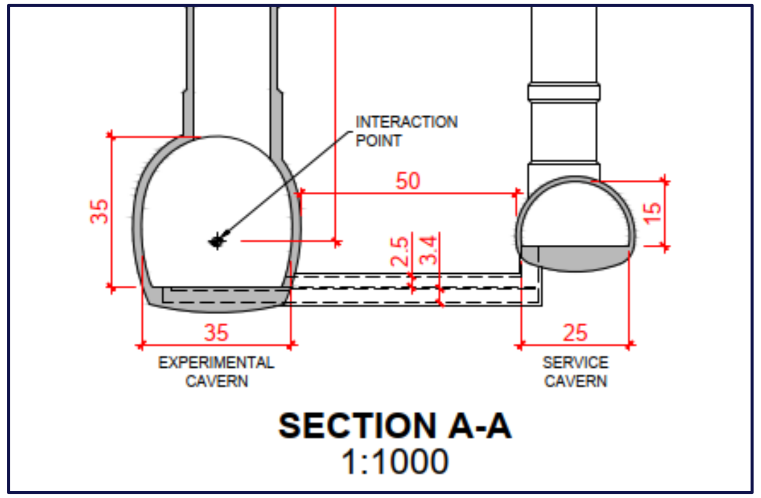
Shaft depths:

A: 201 m B: 201 m D: 181 m F: 400 m G: 226 m H: 235 m J: 253 m L: 250 m

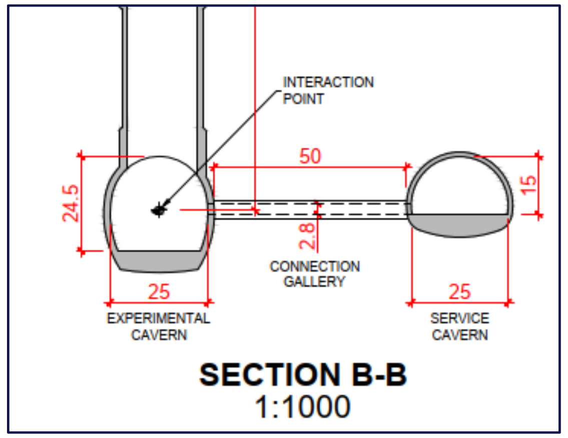
Tunnel Boring Machine (TBM)

- Tunnel Boring Machines (TBMs) are designed to work almost continuously 24/7 other than periodic maintenance. Rate of 18m/day in the Molasse → 8 years.
- 12 shafts
- 2/2 large/small caverns

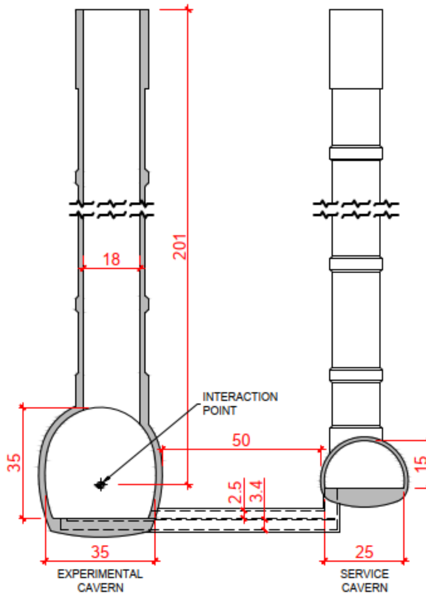




large cavern complex

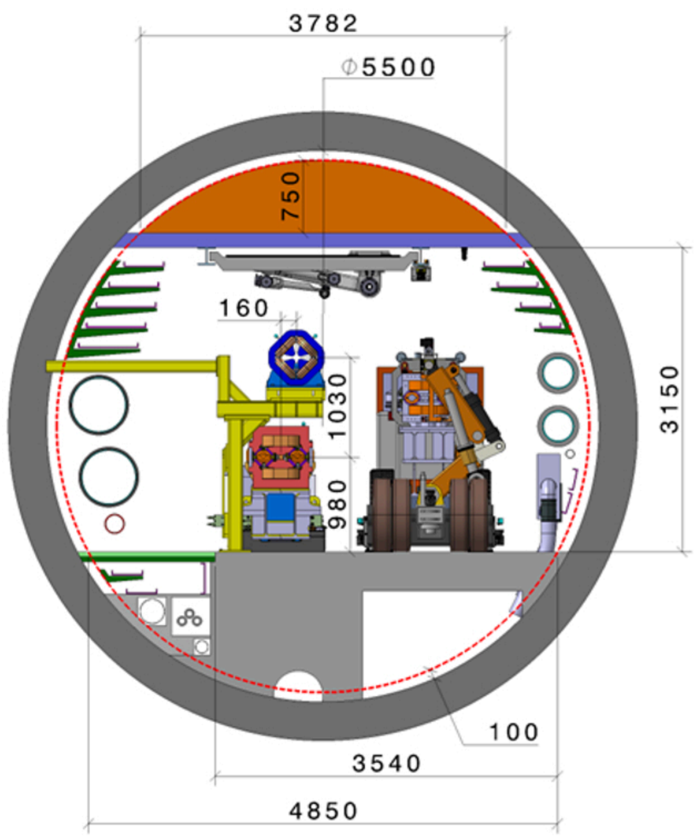


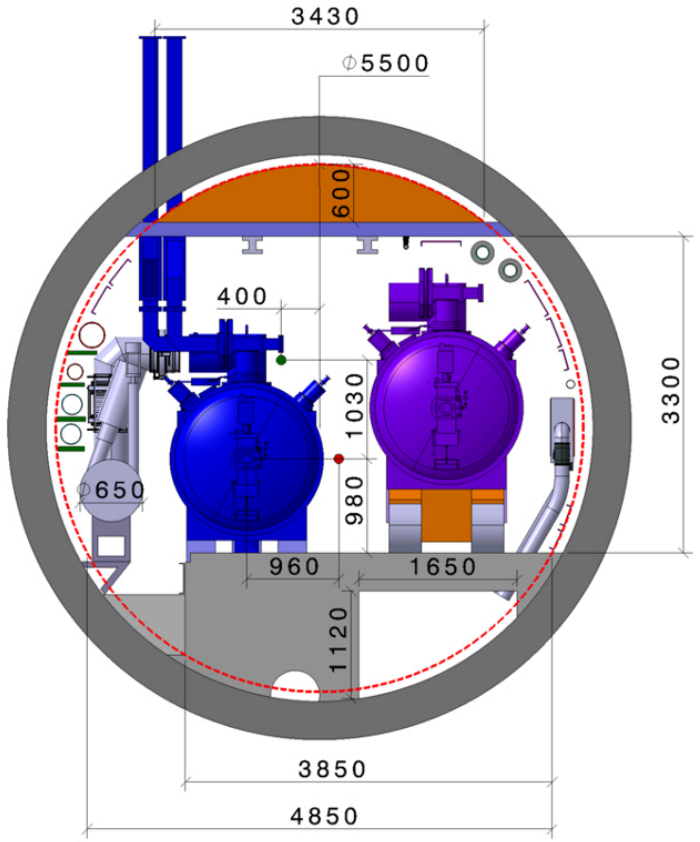
small cavern complex



shaft @ exp. site

Civil engineering



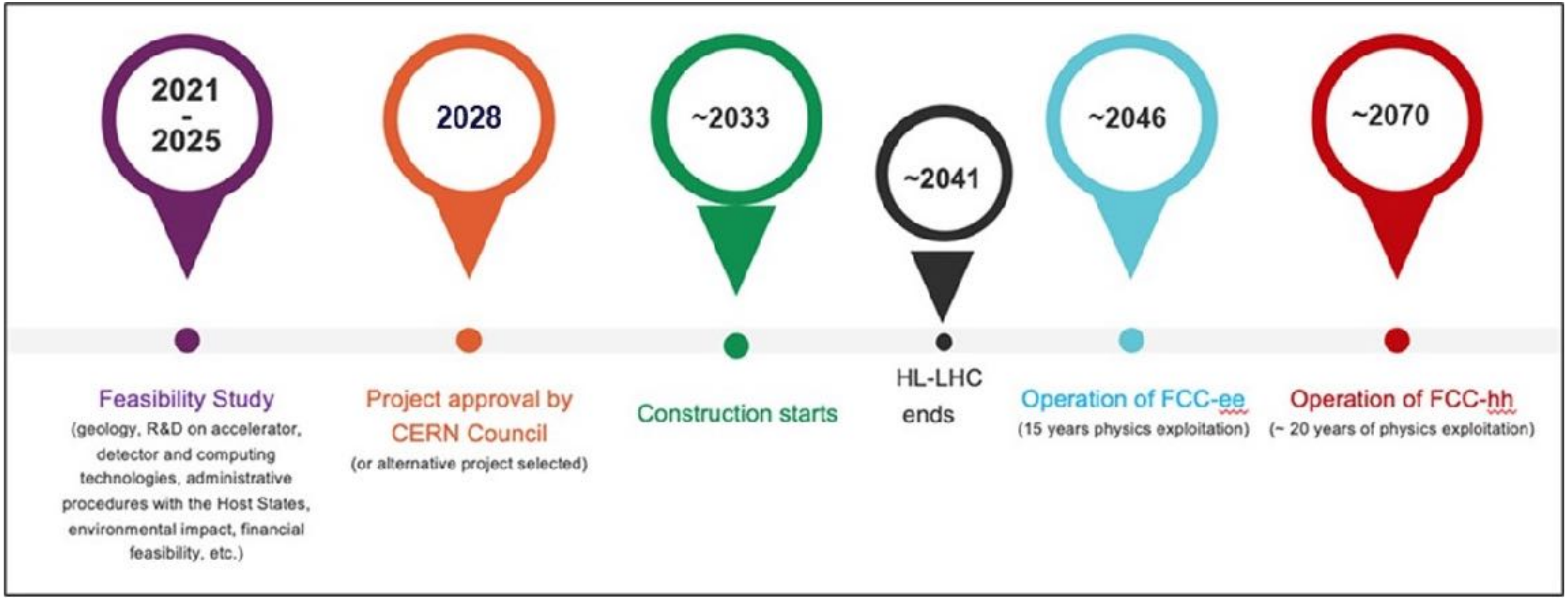


- 90.7 km main tunnel with an internal diameter of 5.5 m.
- Depth varies between 50m and 560m.
- 12 shafts up to 400 m deep and 18 m in diameter.
- 2 larger experiment caverns (35m span).
- 2 smaller experiment caverns (span 25m).
- >70 small caverns.
- 5 km transfer tunnel from the surface.
- 3 km of klystron gallery tunnels.
- Technical buildings on 8 surface sites
- Injector FCC-ee: high-energy linac at CERN Prevessin site

Timeline

European Strategy for Particle Physics

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.

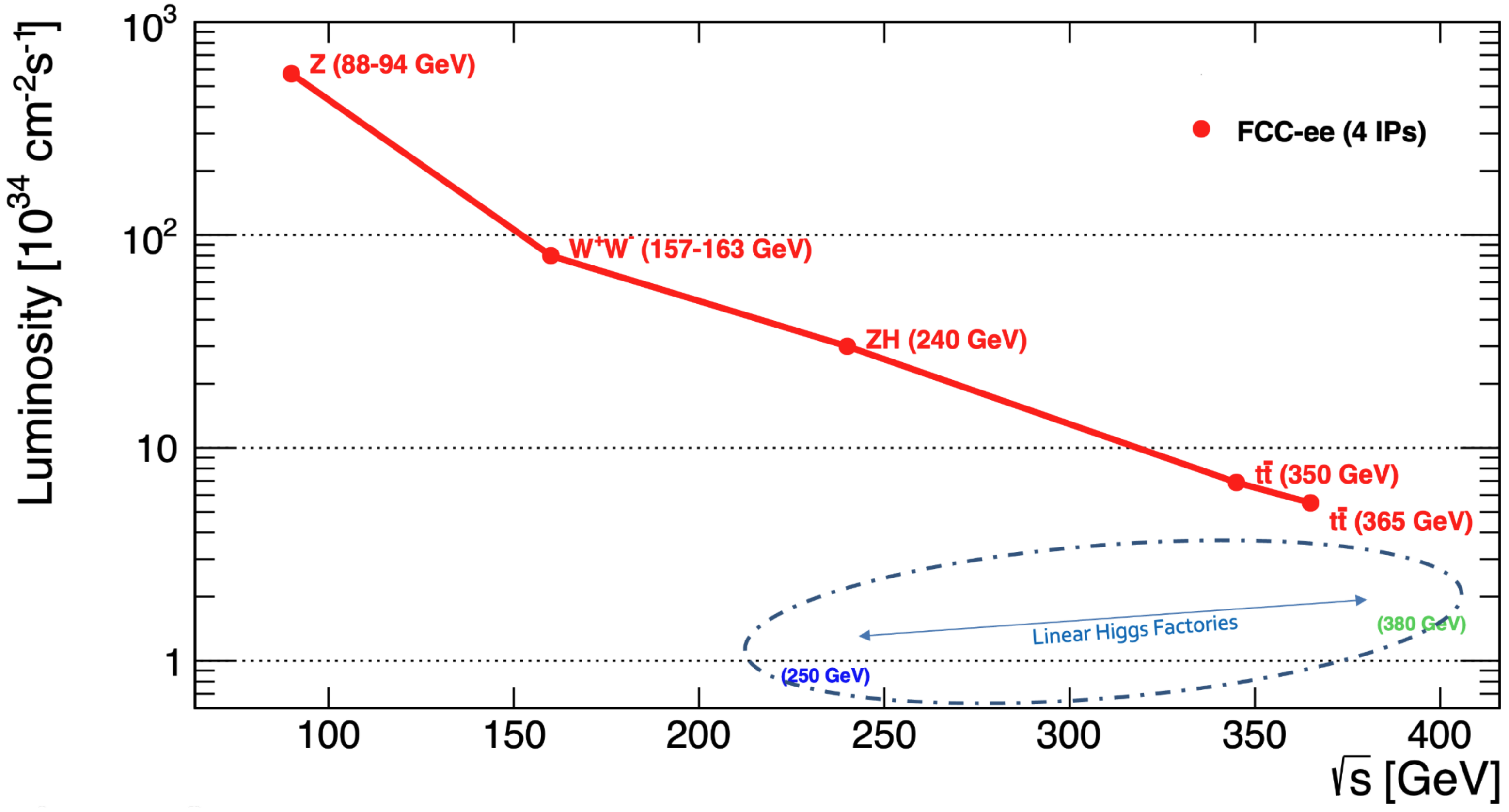
March 21, 2025

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.*

— 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**

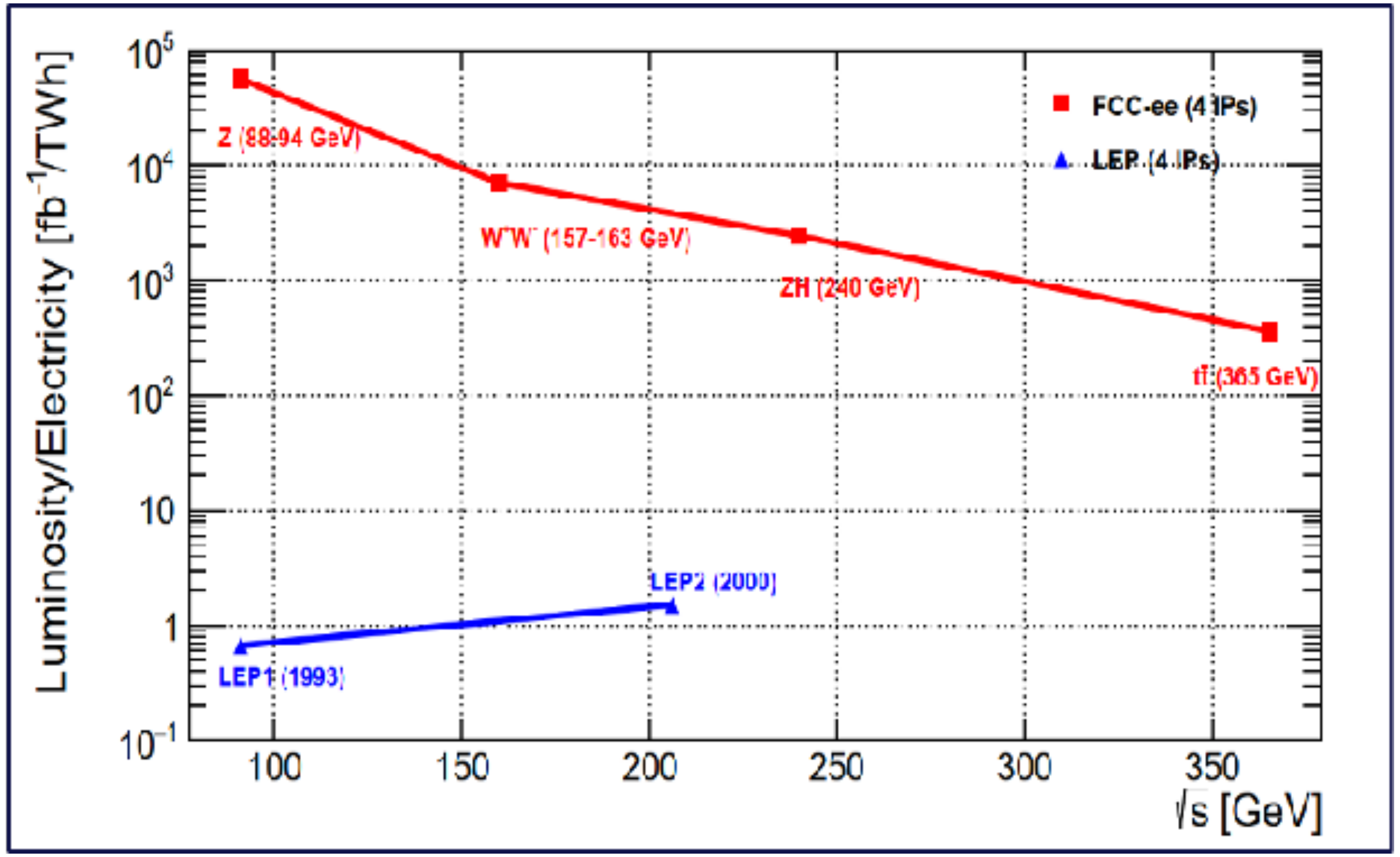
- standard at modern light sources, like SLS
- used at recent e^+e^- colliders, PEP-II (USA), KEKB (Japan), BEPCII (China)

▸ **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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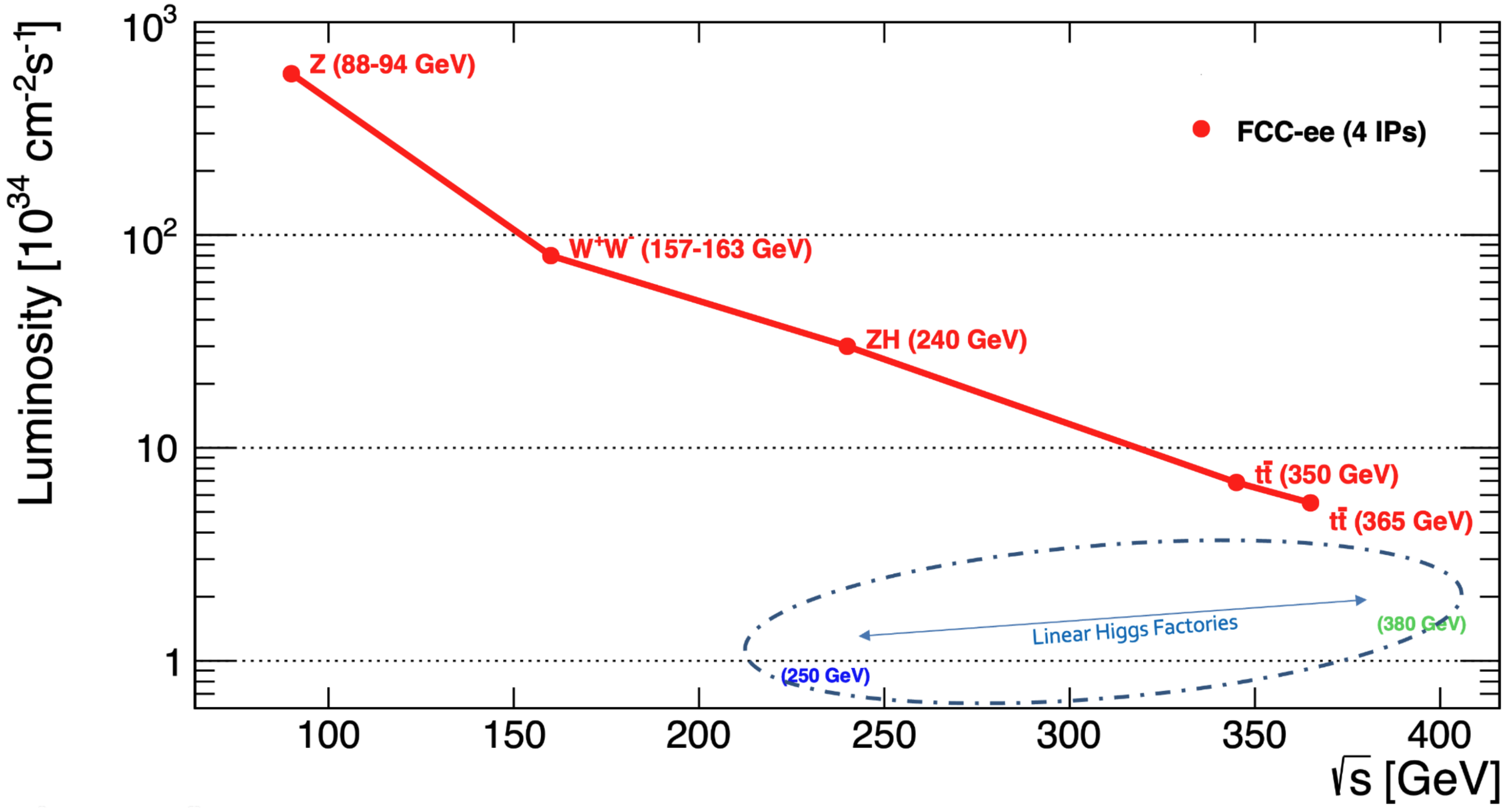

— Superb statistics achieved in only 15 years —

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 → H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW → H	

FCC-ee Run Plan

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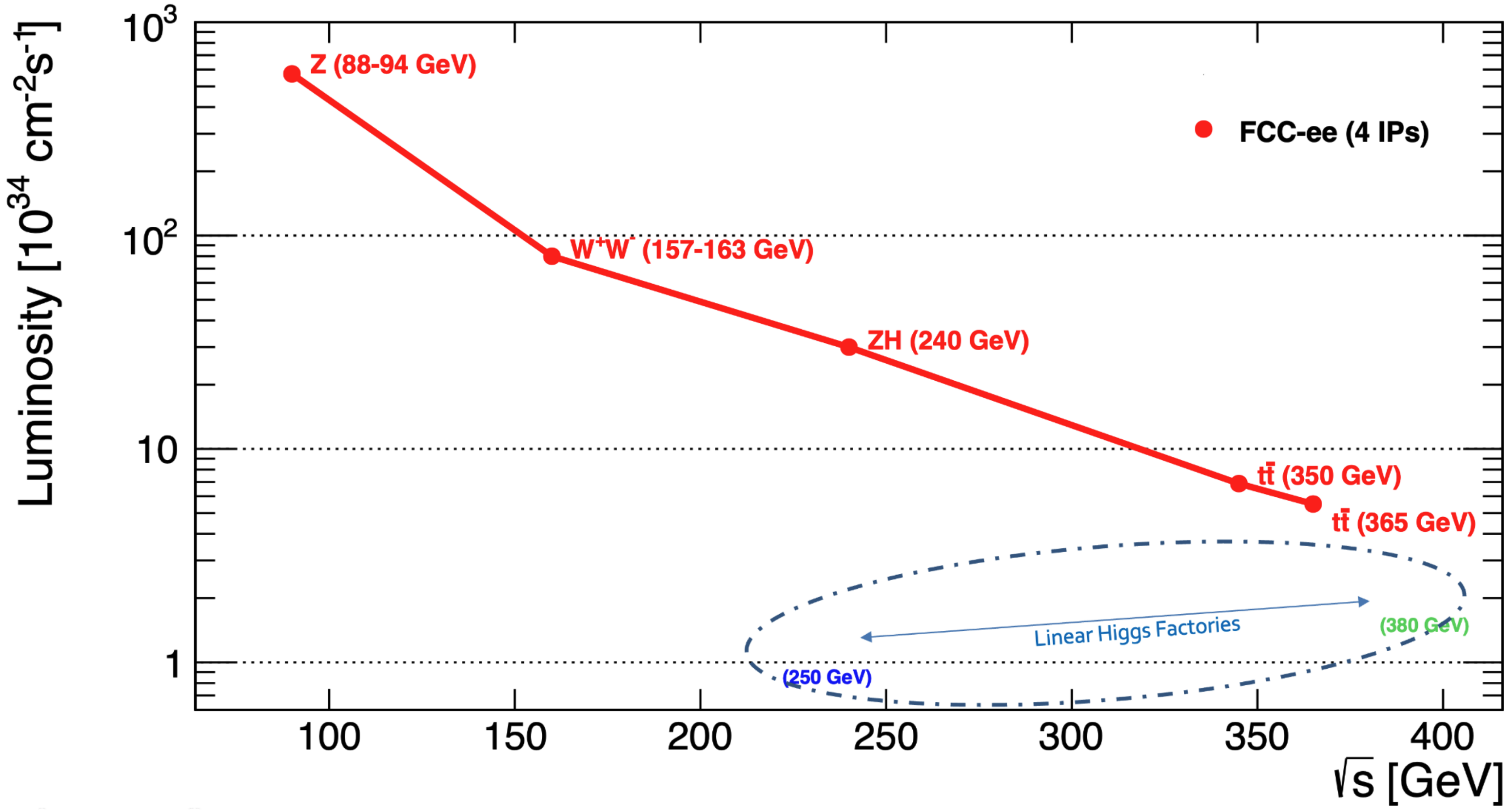

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in each detector:
10^5 Z/sec, 10^4 W/hour,
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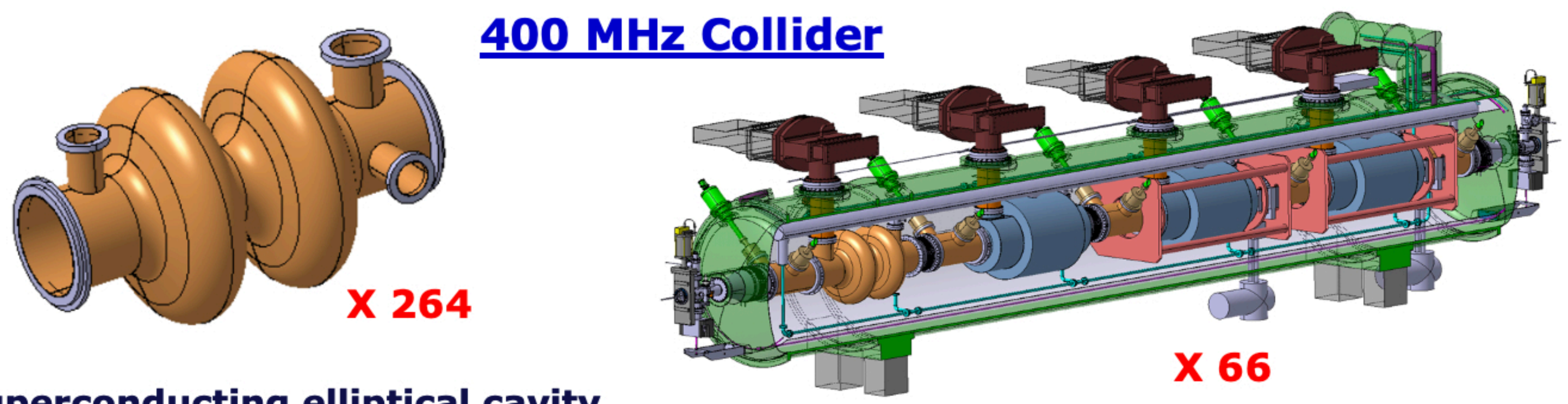
Exciting & diverse programme with different priorities every few years.

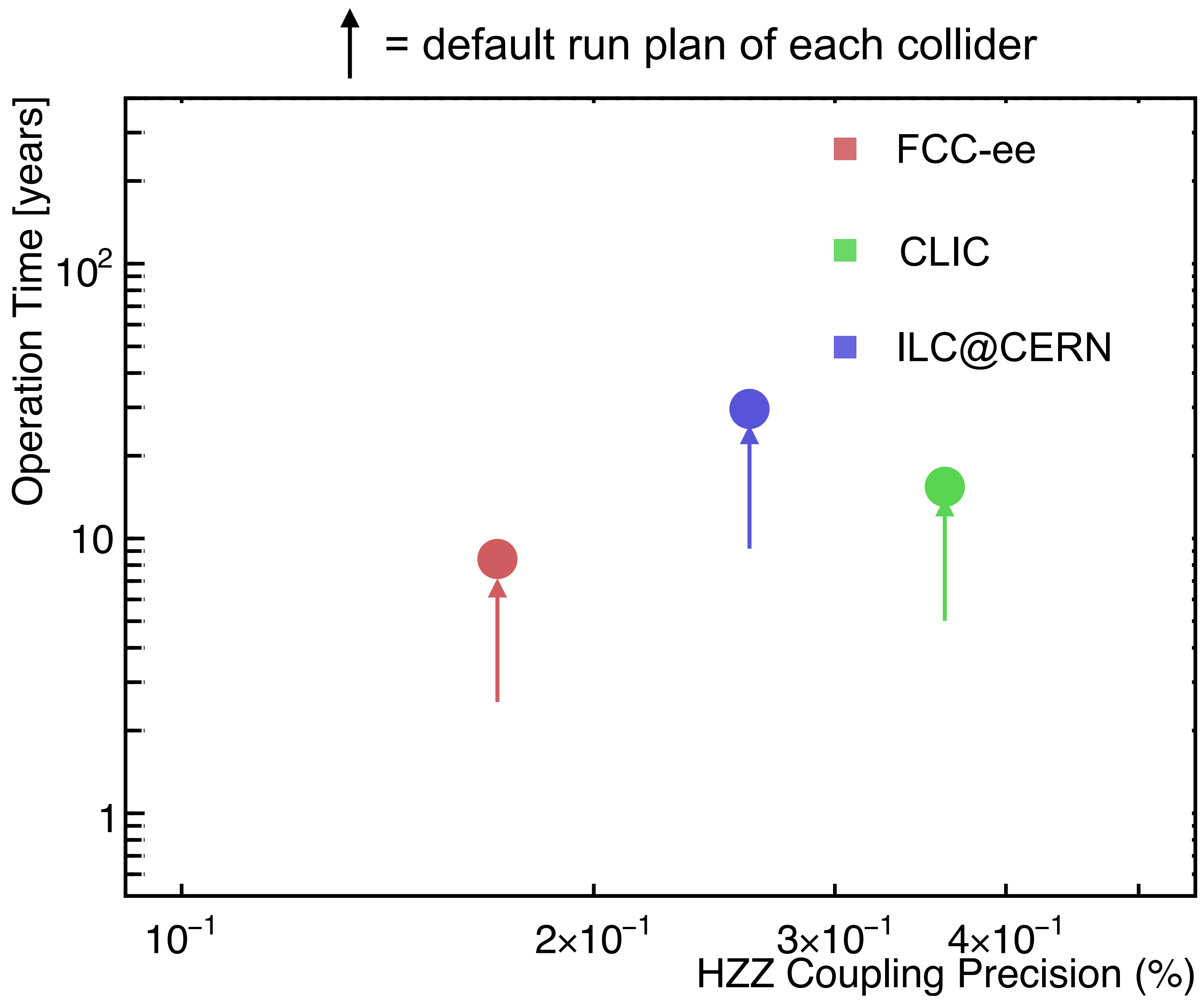
Order of the different stages still subject to discussion/optimisation. Development on **unique RF cavities** to be used from 90 to 240GeV enables great flexibility of operation.



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

400 MHz Cryomodule

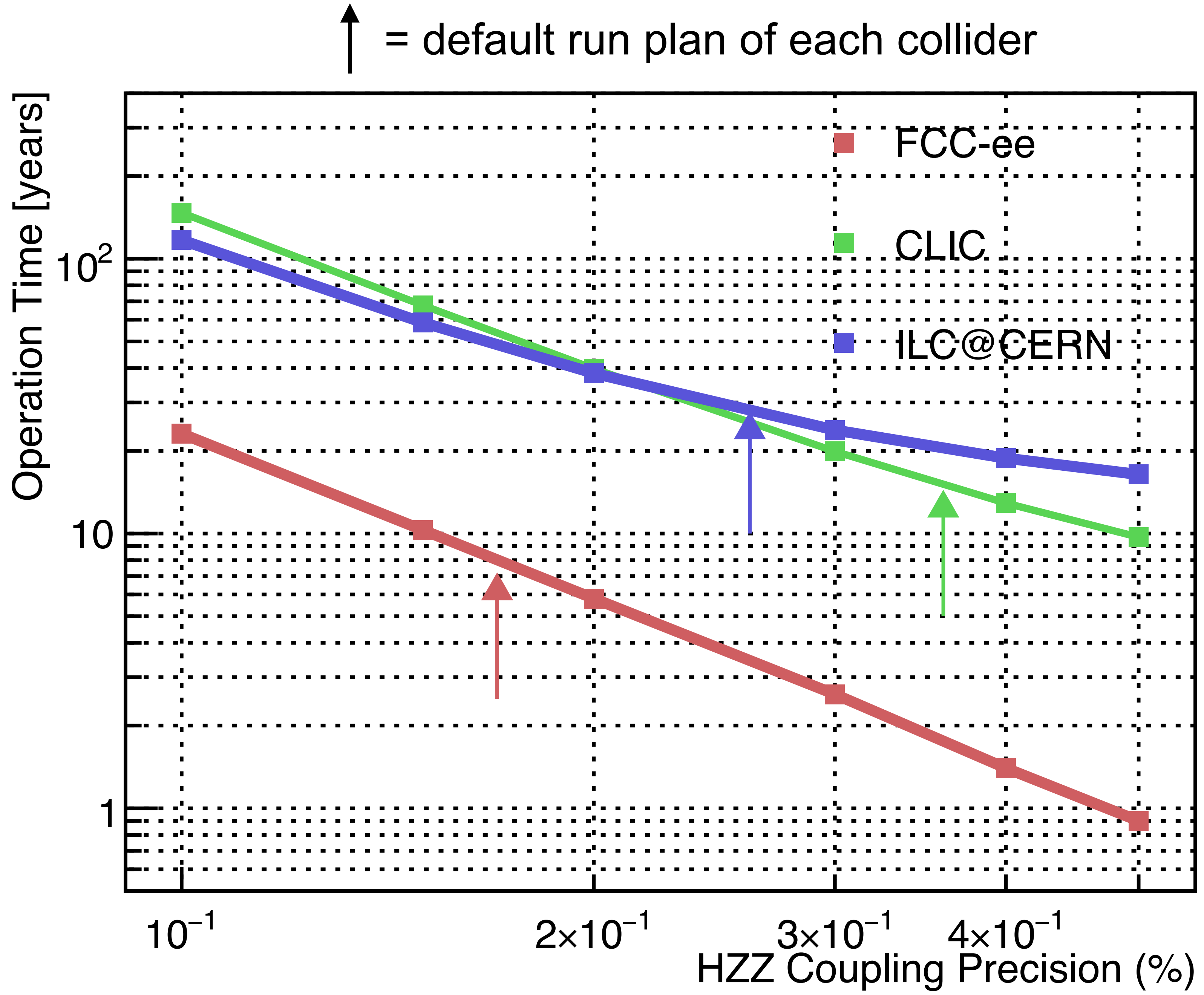
A Performant Higgs Programme



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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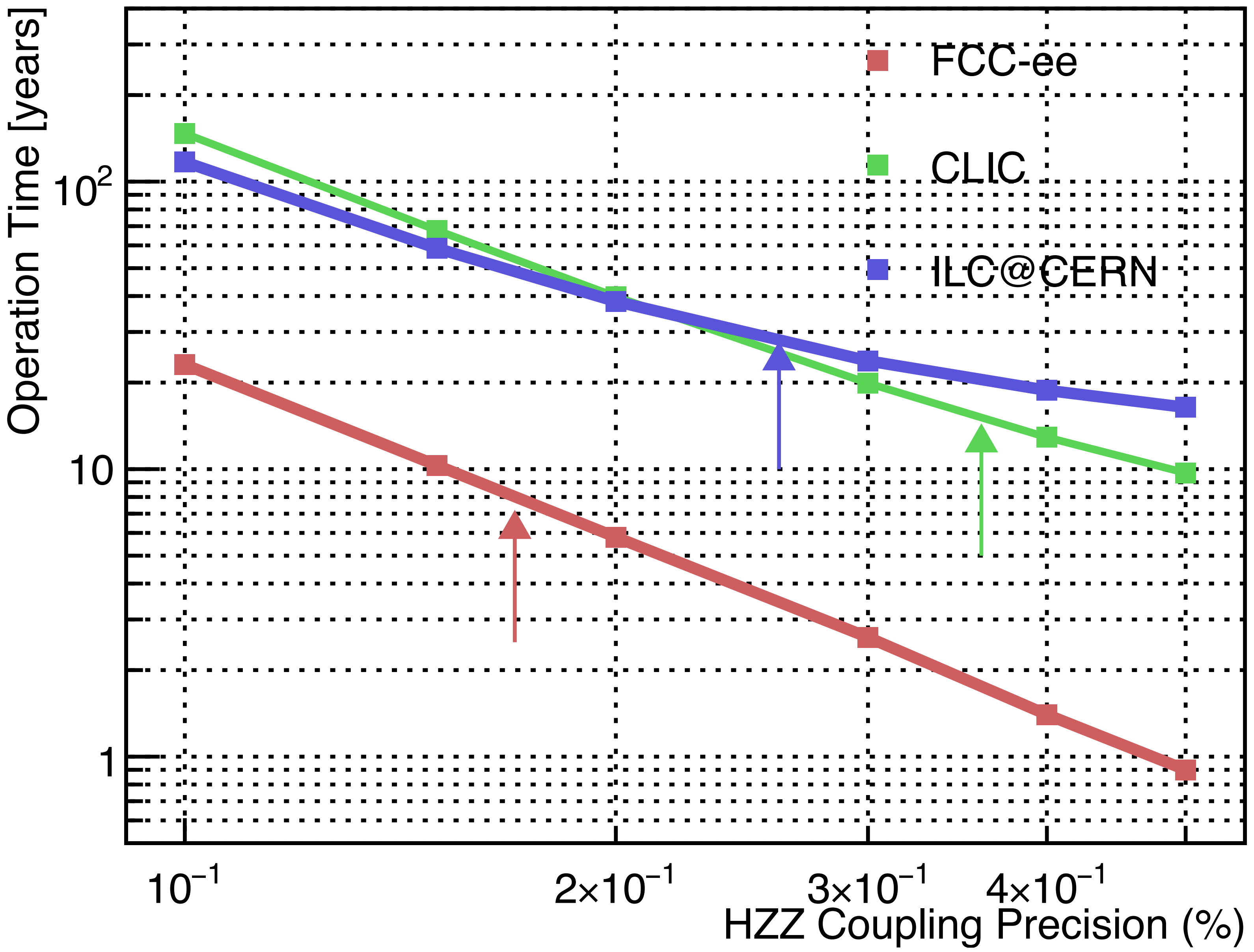
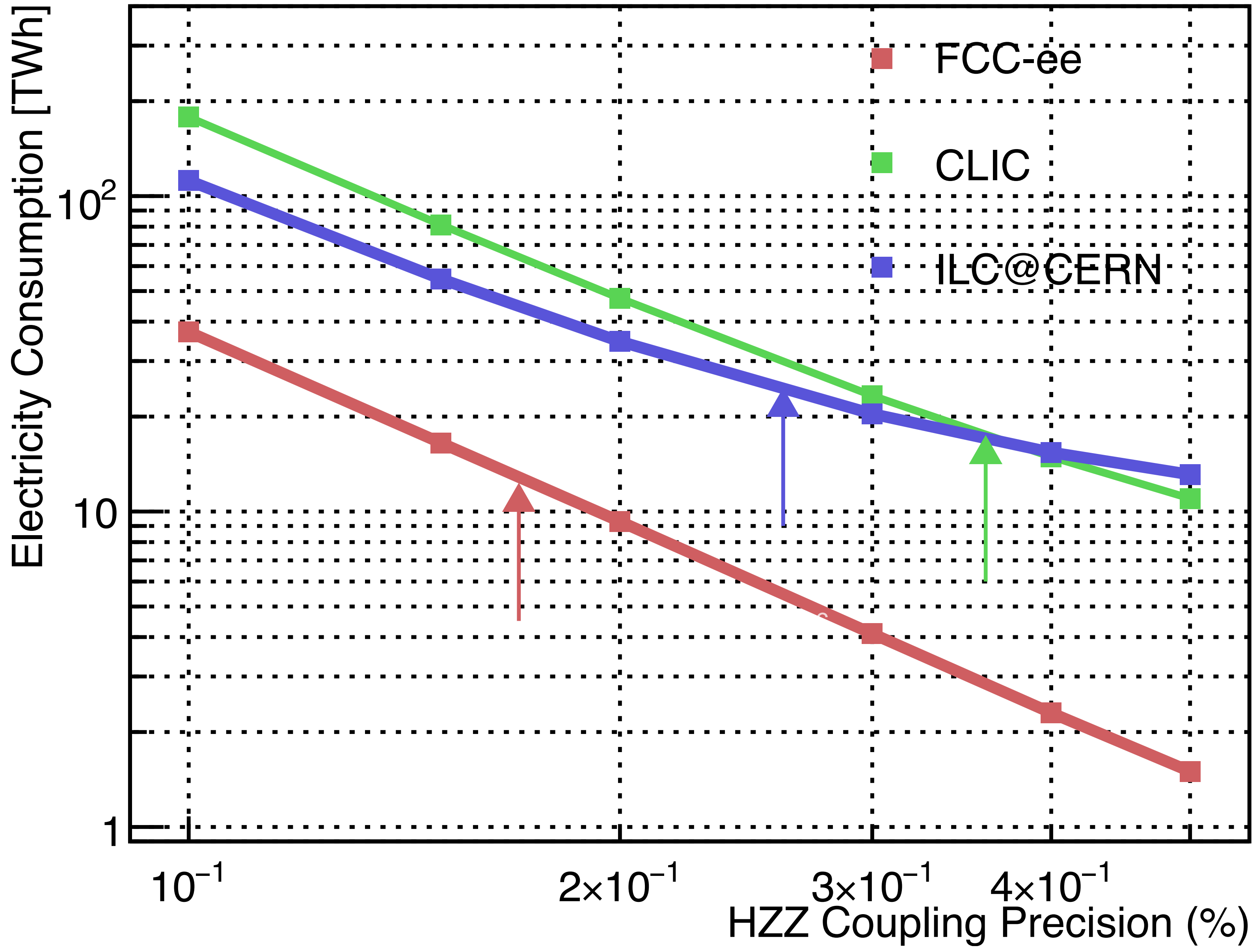
A Performant Higgs Programme

↑ = default run plan of each collider

More time = more TWh





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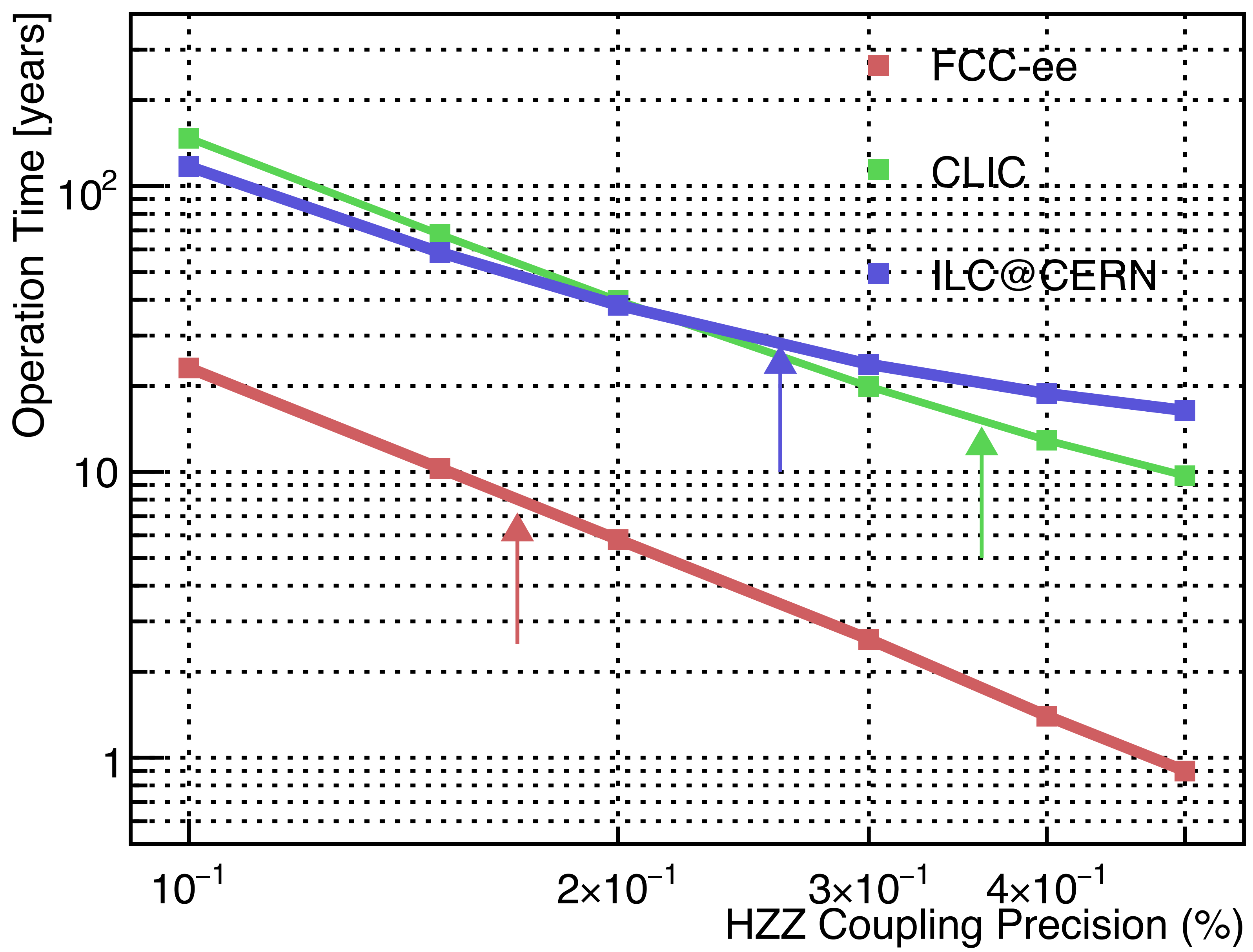

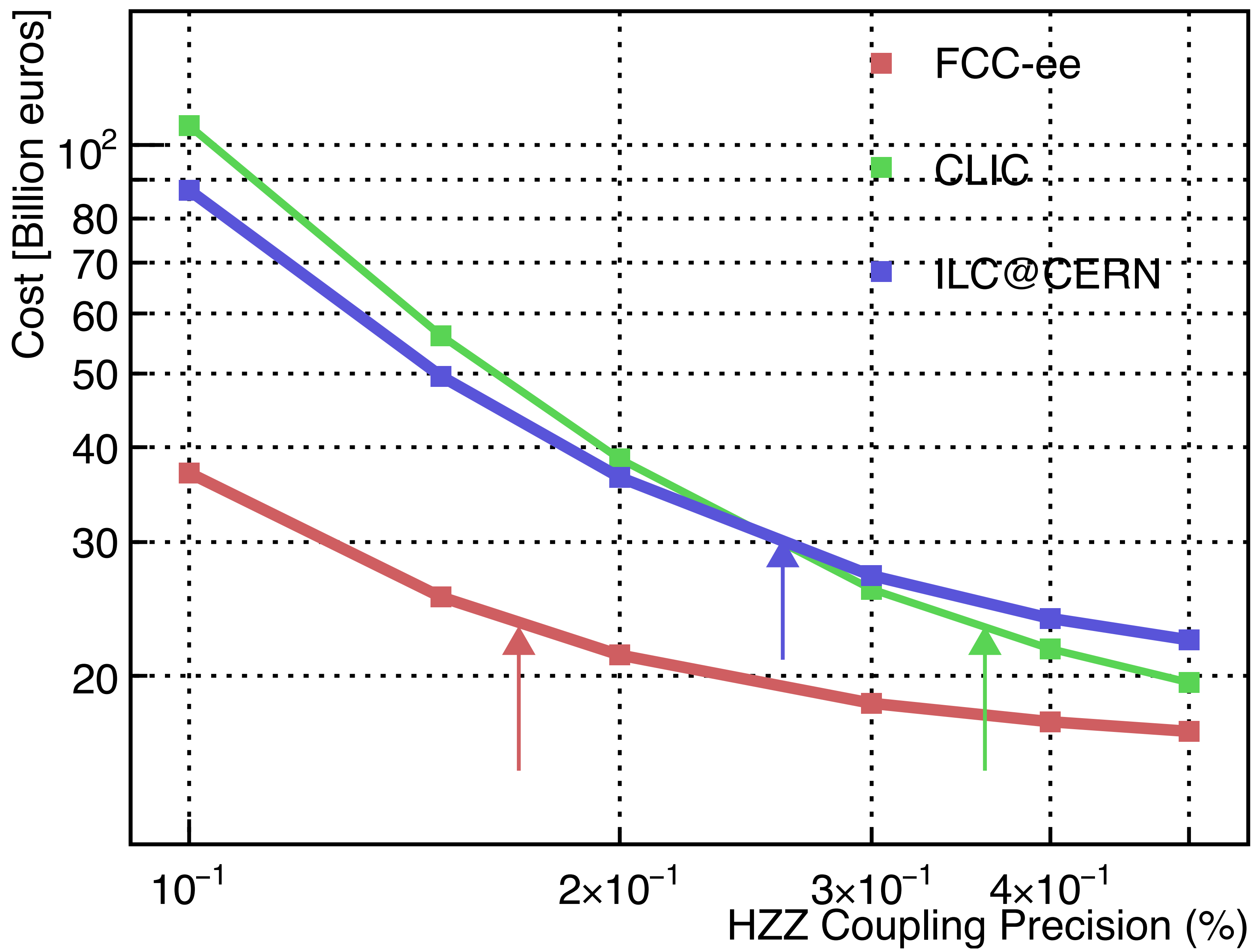

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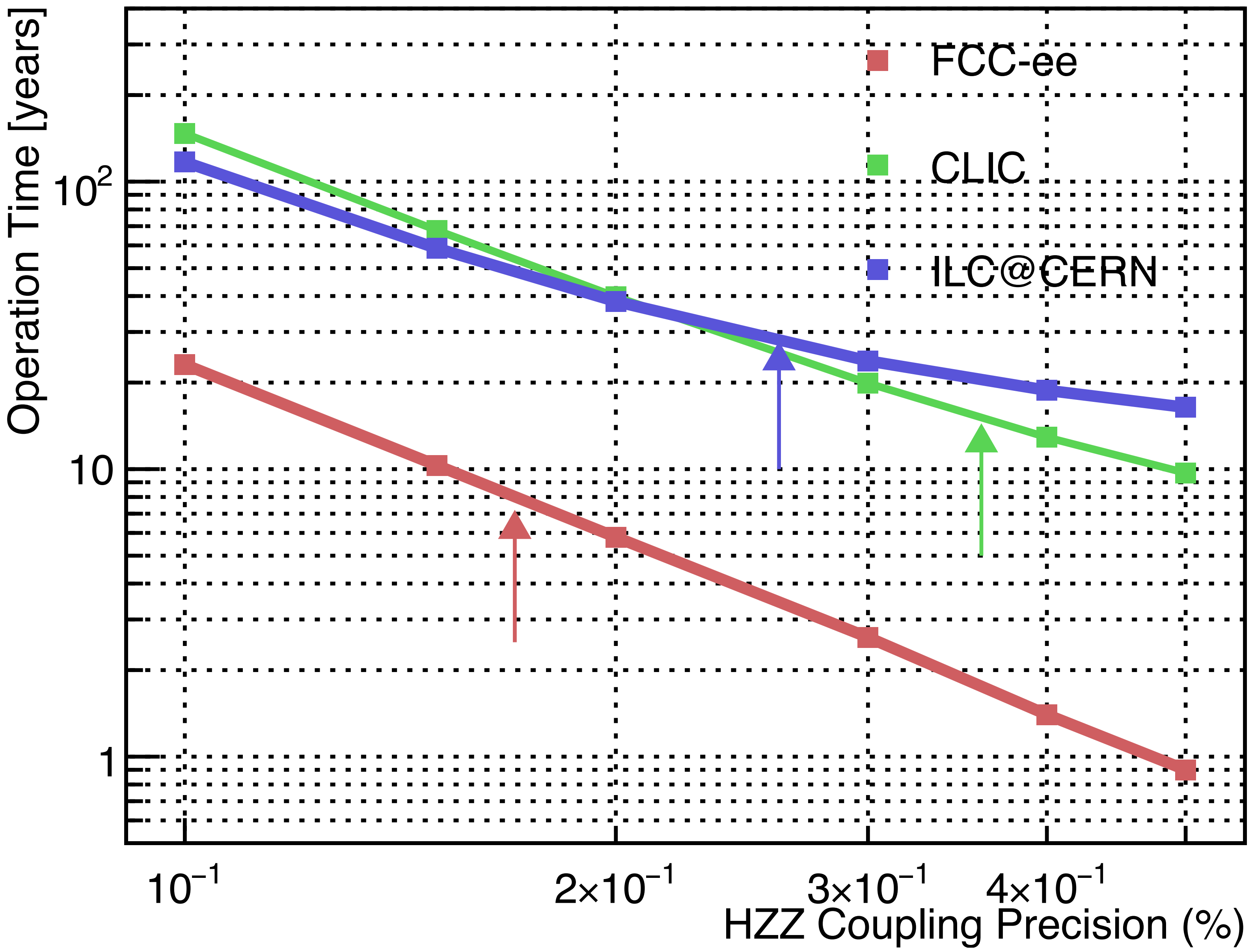
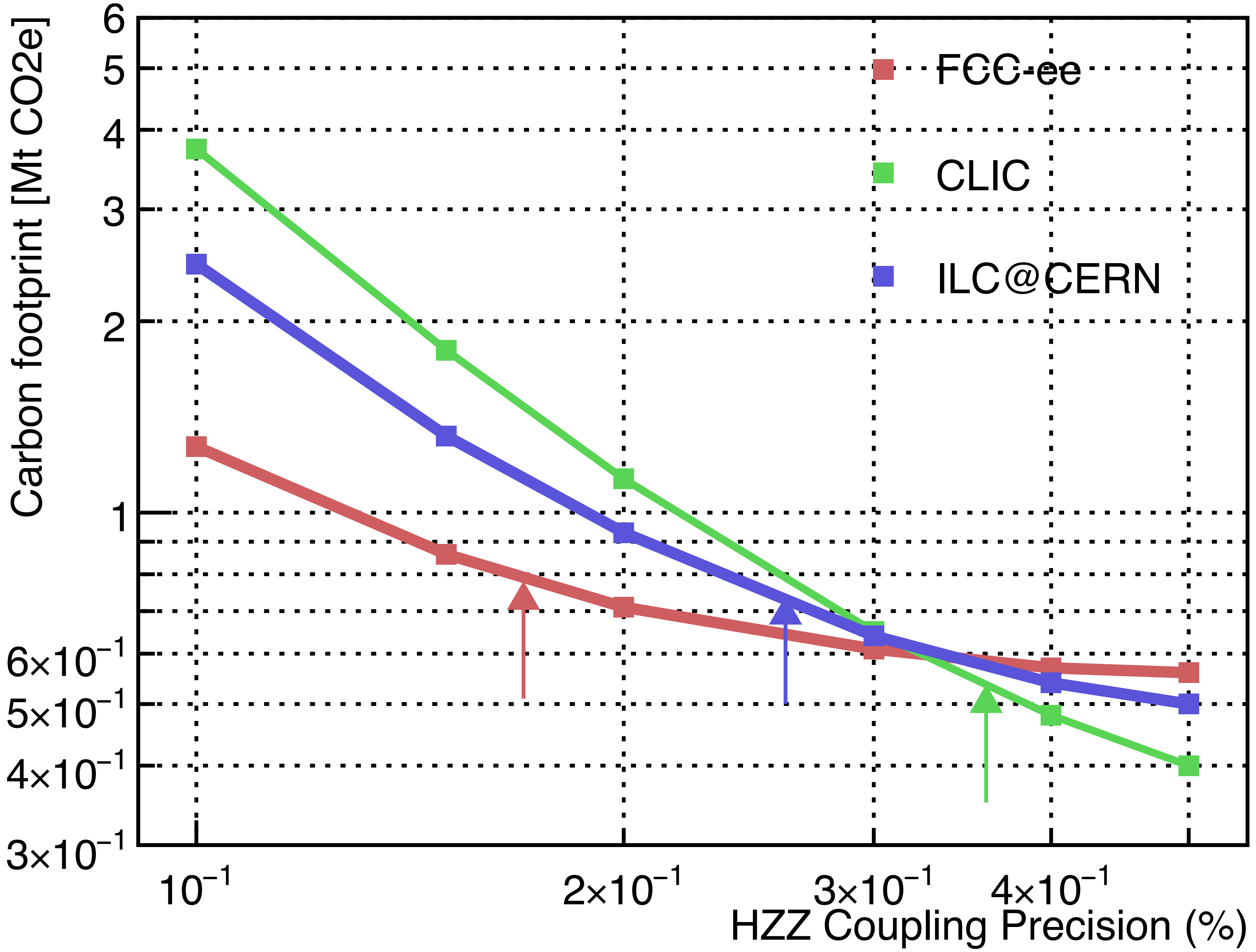
More time = more CO2eq





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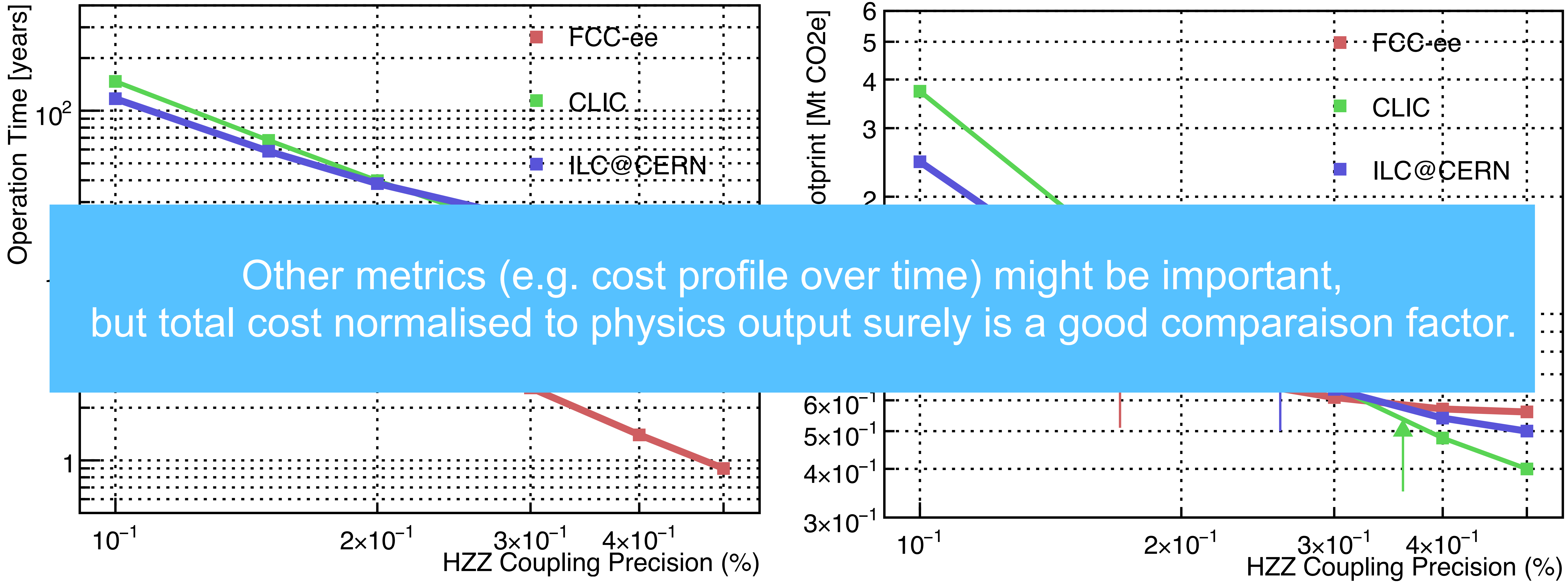

Other metrics (e.g. cost profile over time) might be important, but total cost normalised to physics output surely is a good comparaison factor.

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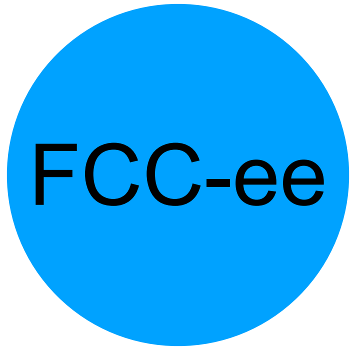
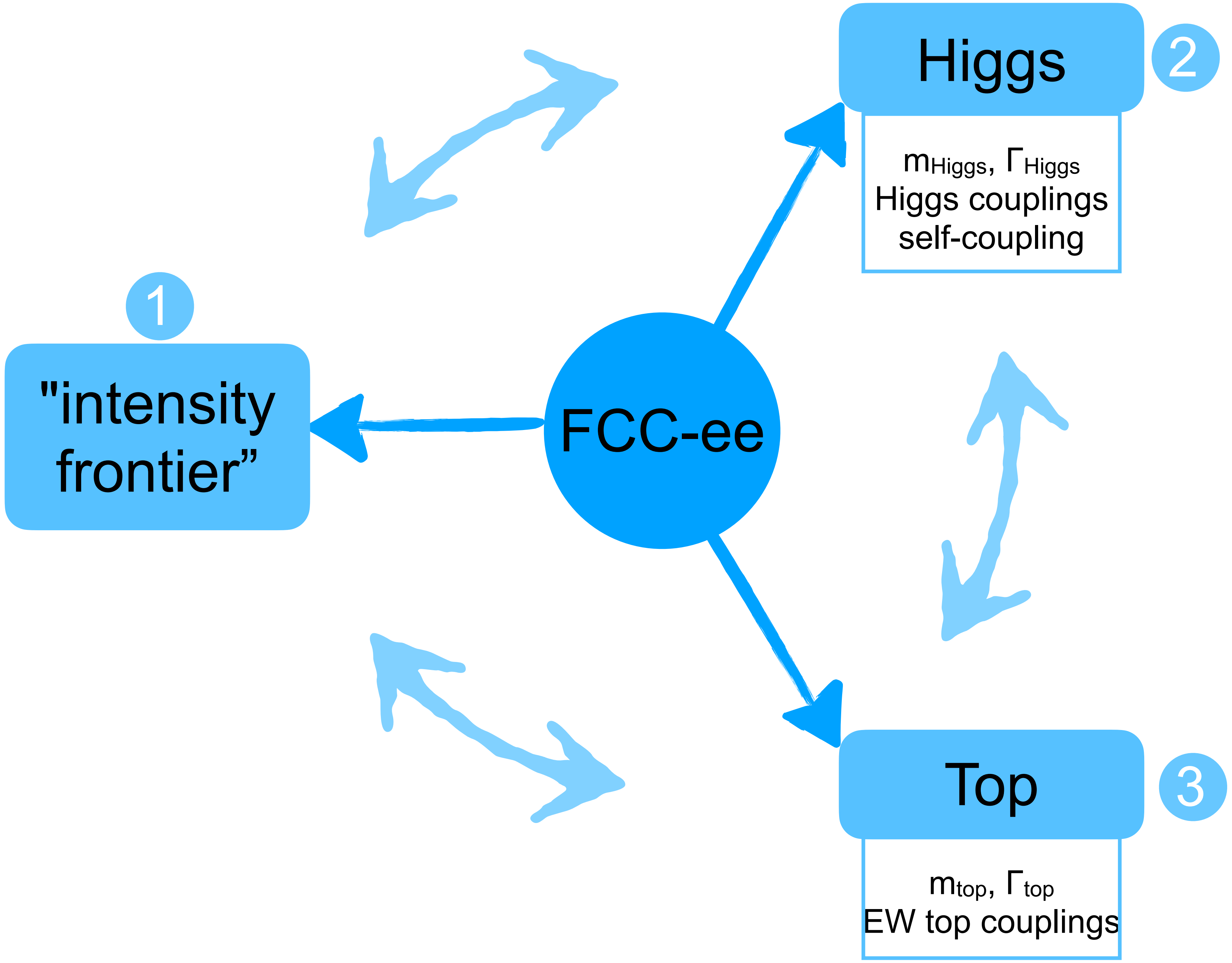
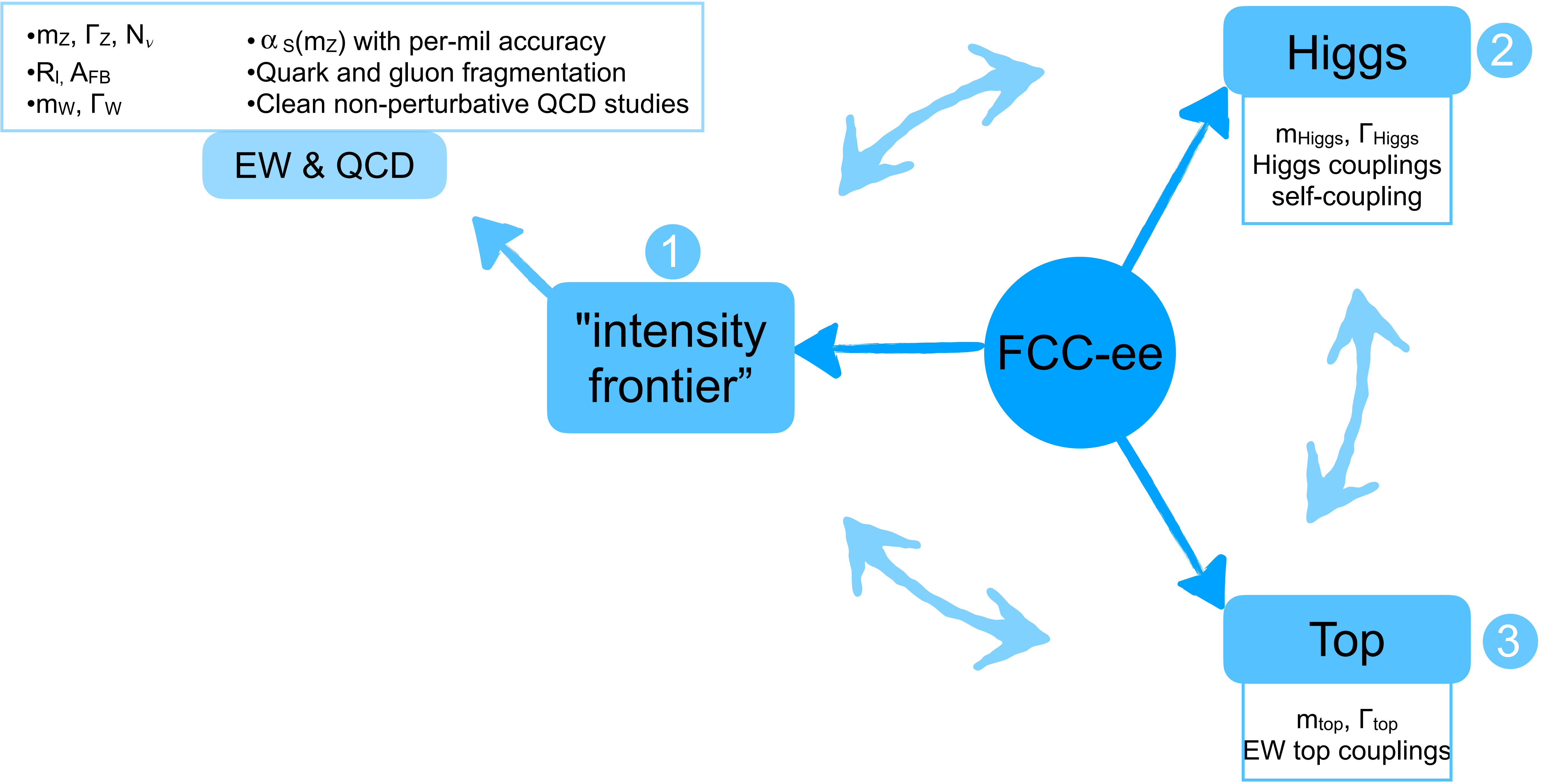
FCC-ee Physics Programme



FCC-ee Physics Programme



FCC-ee Physics Programme



FCC-ee Physics Programme

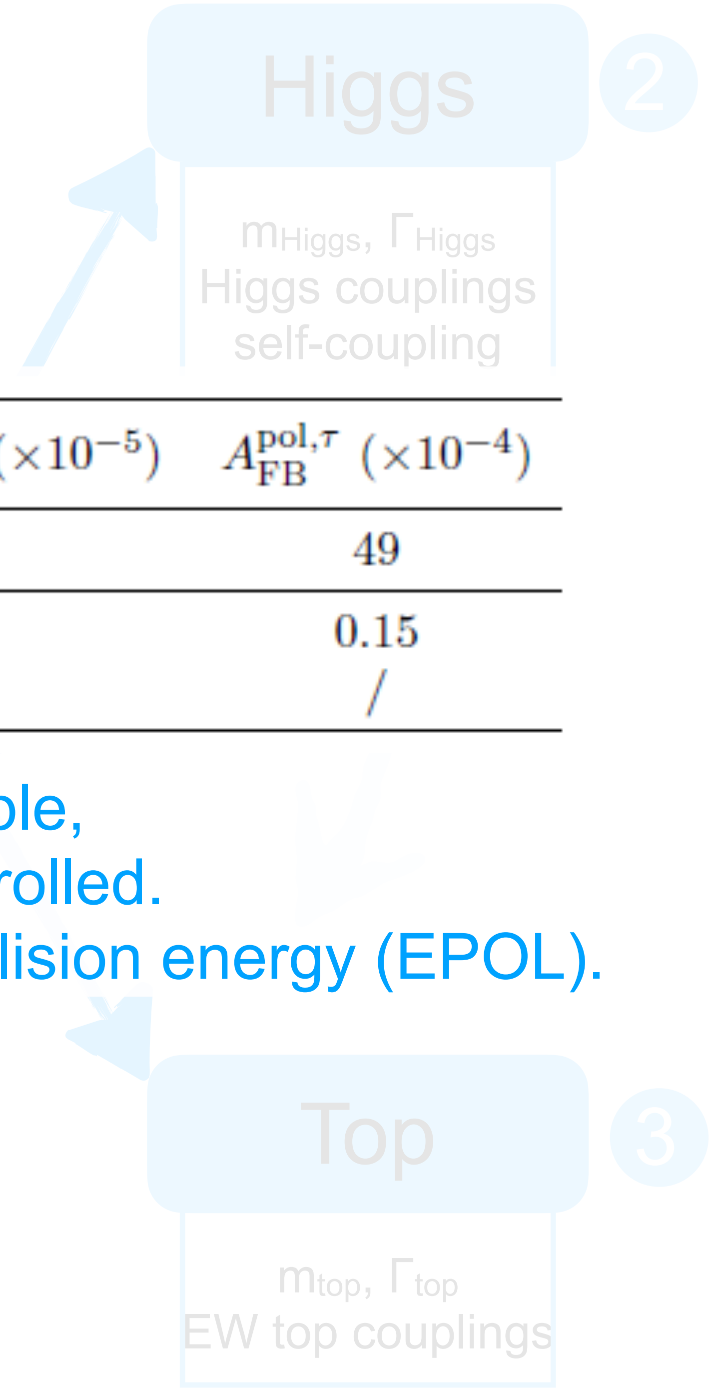
- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W

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

EW & QCD

Uncertainty	m_Z (keV)	Γ_Z (keV)	$\sin^2\theta_W^{\text{eff}}$ ($\times 10^{-6}$)*	$\frac{\Delta\alpha_{\text{QED}}(m_Z^2)}{\alpha_{\text{QED}}(m_Z^2)}$ ($\times 10^{-5}$)	$A_{\text{FB}}^{\text{pol},\tau}$ ($\times 10^{-4}$)
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).



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EW & QCD

1

"intensity frontier"

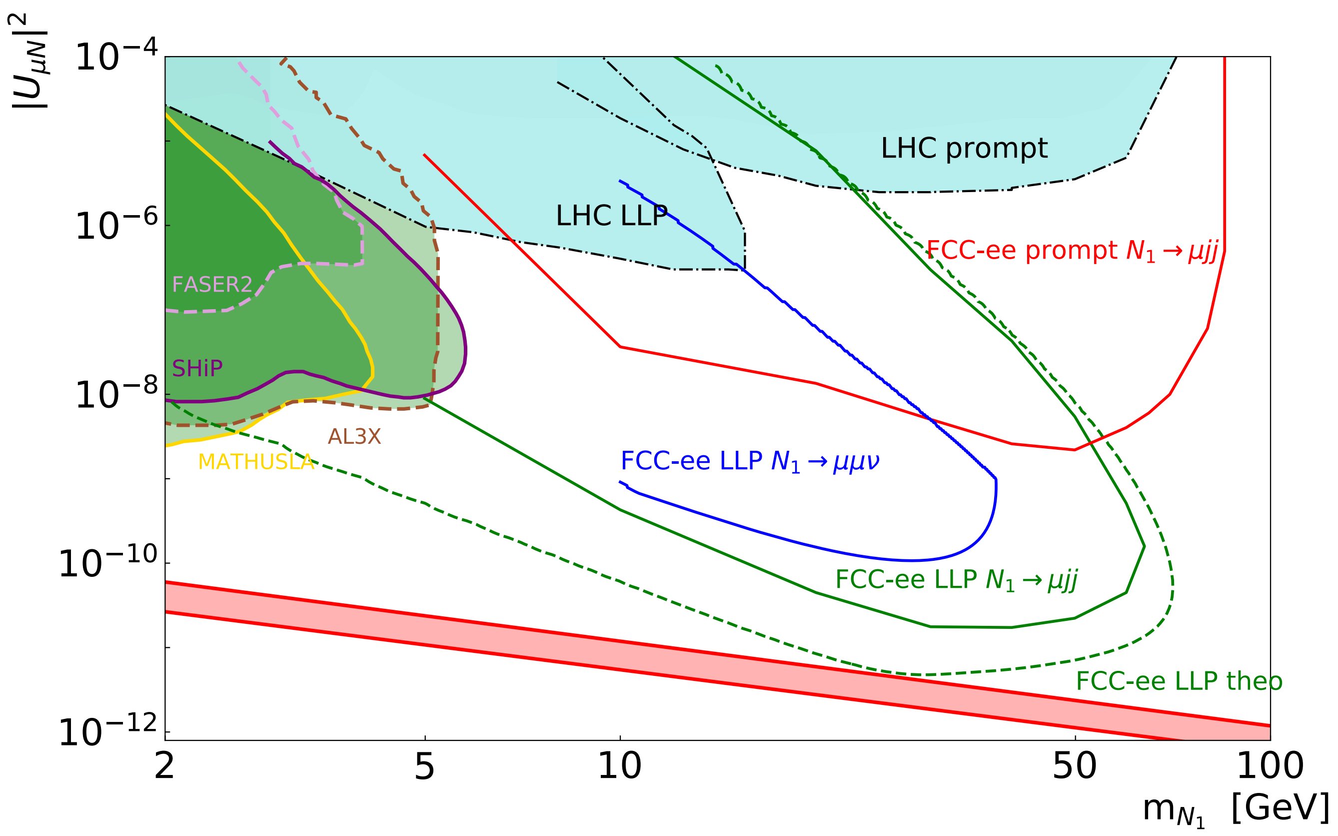
direct searches of light new physics

- 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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- R_l, A_{FB}
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EW & QCD

1

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direct searches of light new physics

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- long lifetimes - LLPs

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

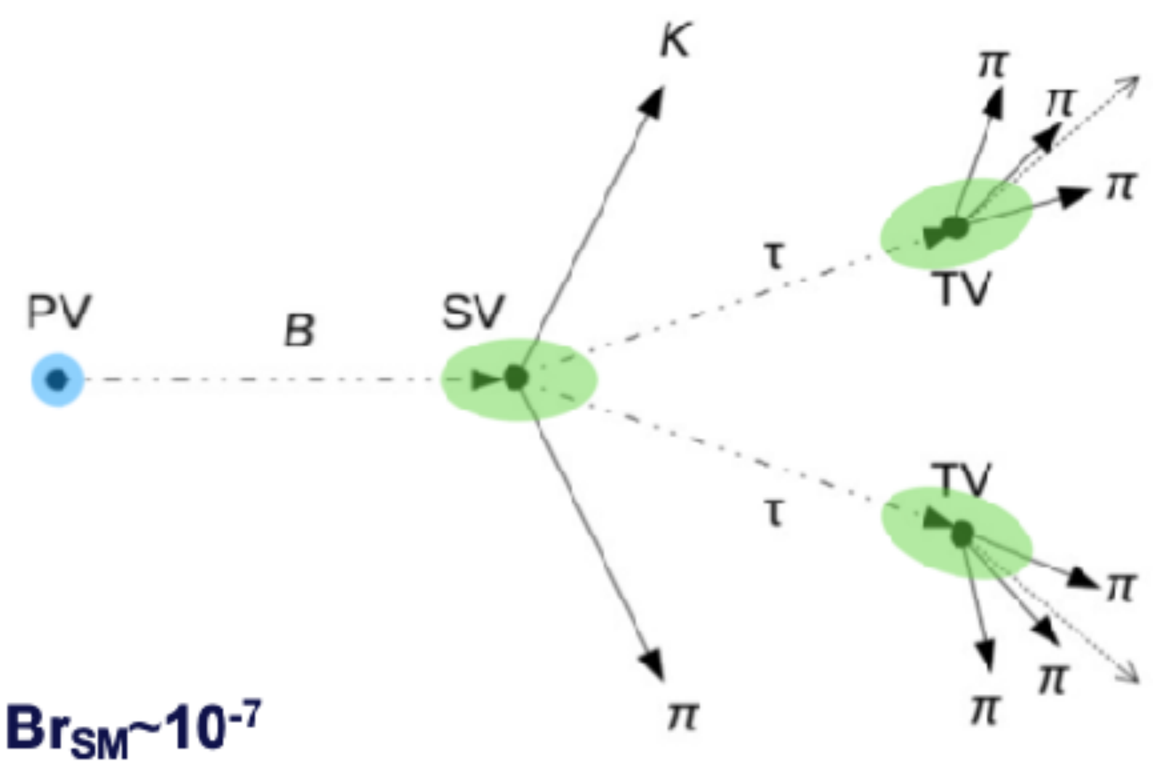
τ physics

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

B physics

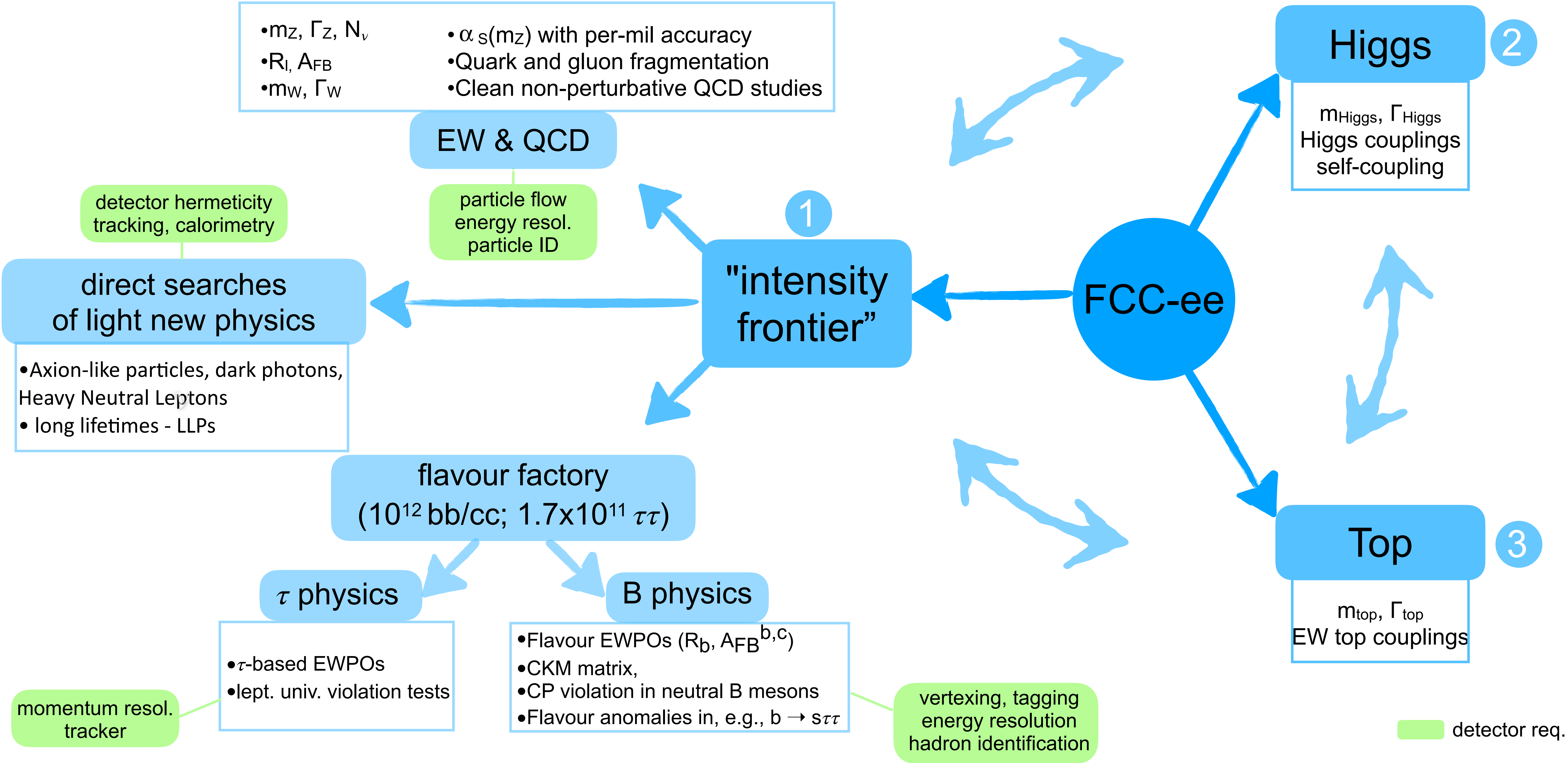
- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., b → s$\tau\tau$

$B^0 \to K^* \tau^+ \tau^-$



$Br_{SM} \sim 10^{-7}$
LHC bound 10^{-4}
FCC could have 5σ observation

FCC-ee Physics Programme



FCC-ee Physics Programme

Higgs Factory Programme

- At $\sqrt{s}$=240 and $\sqrt{s}$=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 $e^+e^- \rightarrow$ 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, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, R_b, m_W, Γ_W, …
- 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 $\leq 10^{-5}$ (e.g. Γ_{had}/Γ_ℓ)**
  - 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 %/$\sqrt{E}$**
- **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**

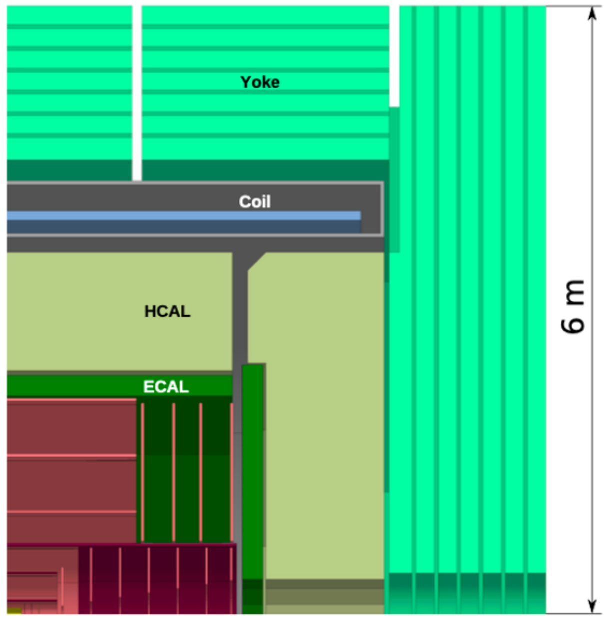
FCC-ee Physics Programme

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
		$\delta L = 5$ 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 $\mathrm{Z} \to \tau\mu$
		t.b.d.	$\sigma_\theta < 0.1$ mrad	$\delta\Gamma_\mathrm{Z}(\mathrm{BES}) < 10$ 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

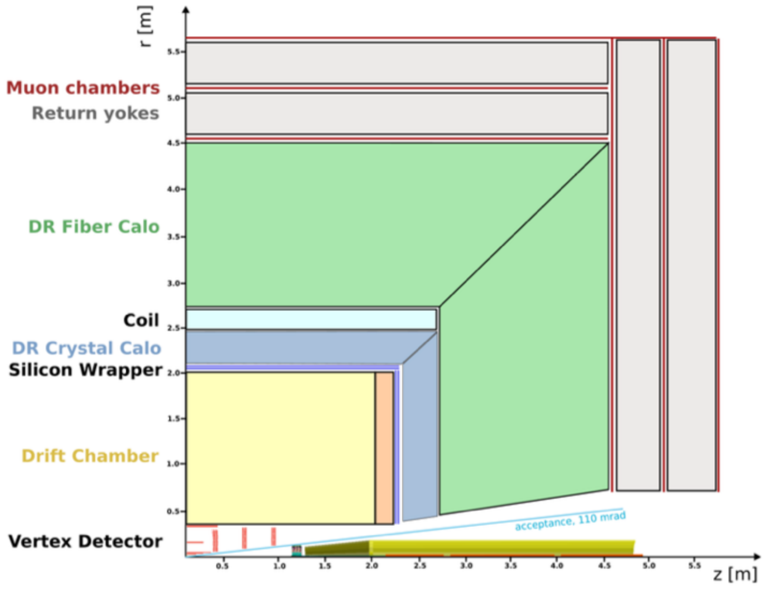
CLD



- 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

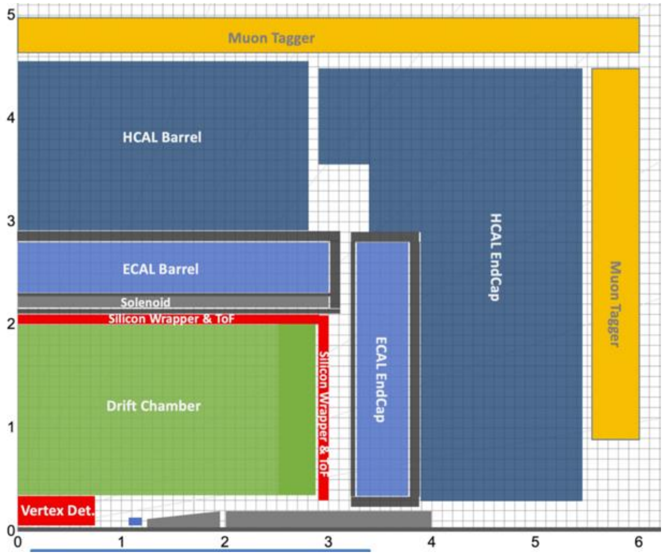
IDEA



- 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

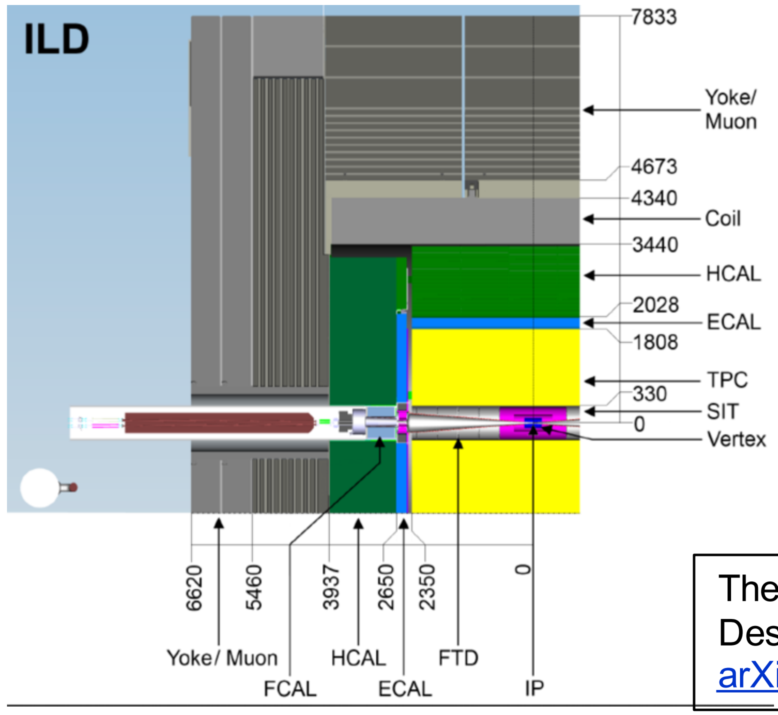
https://doi.org/10.48550/arXiv.2502.21223

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)

— FCC-ee —
Concrete Examples of Diverse/Complete Physics Programme

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

FCC-ee = 10 x Belle II

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

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

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

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	✓		(✓)

boosted b's/τ's at FCC-ee

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

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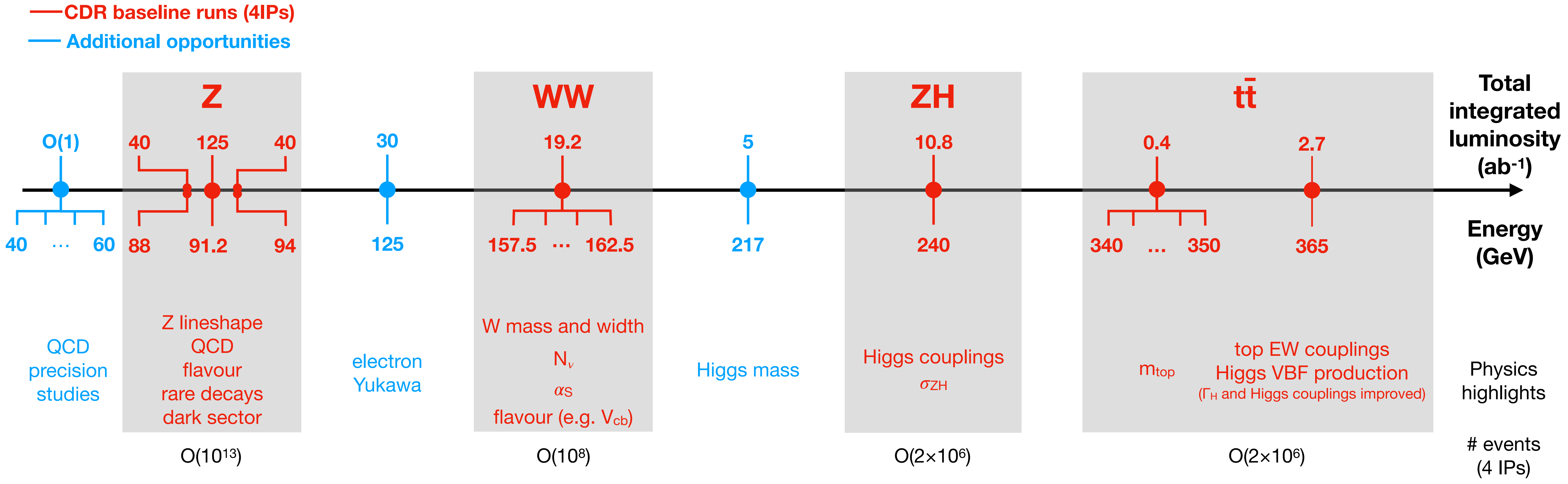
FCC-ee Flavour Opportunities

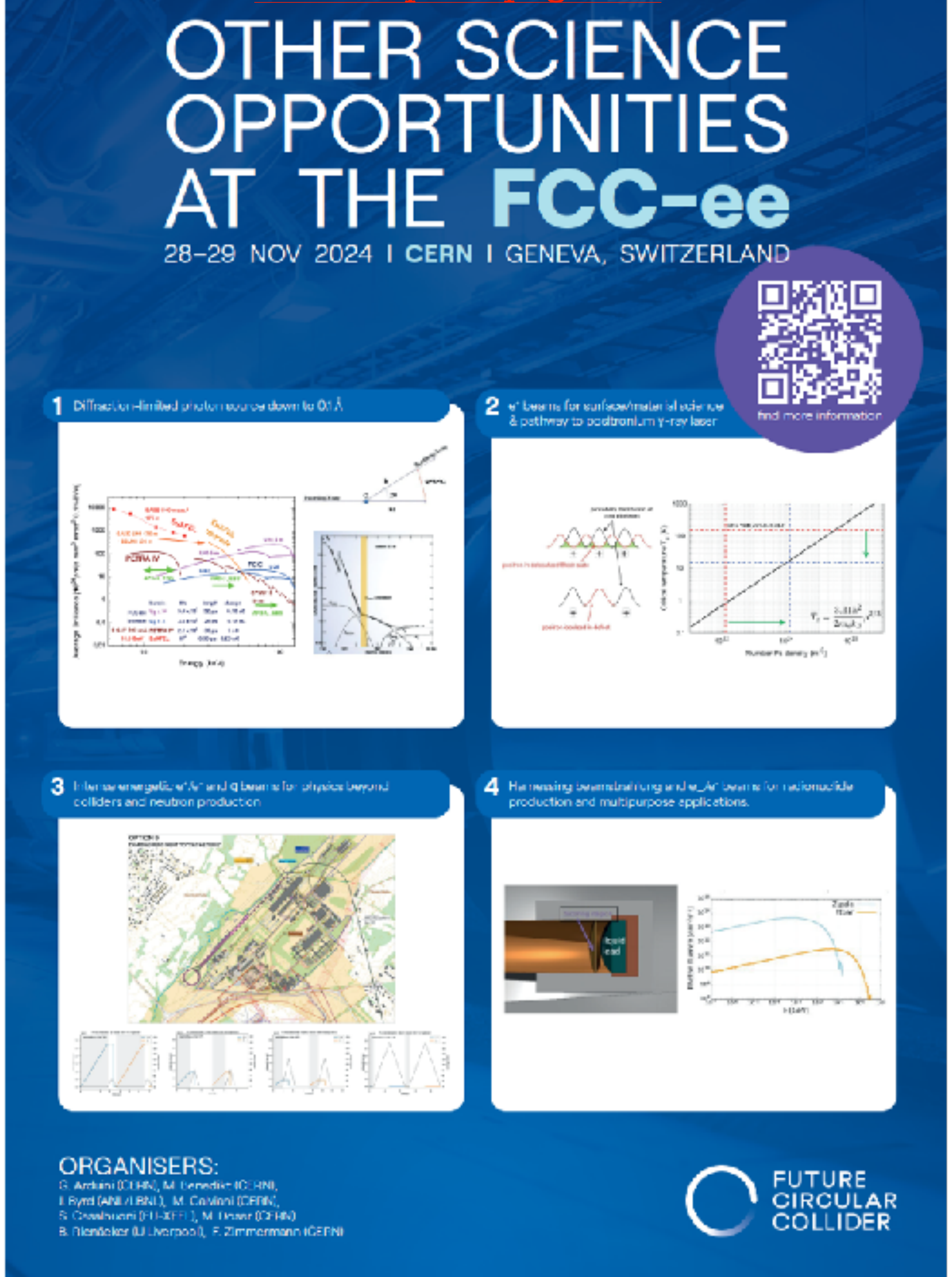
- **CKM elements:**
  - **CPV angles** (γ, β, ϕ_s) at sub-degree precision
  - **V_{cb}** (critical for normalising the Unitarity Triangle) from WW decays:
    - 3.4% @ now → 0.52-0.14% @ FCC-ee (depending on tracking) see Marzocca et al (2024)
- **Tau physics** (>10^{11} pairs of tau's produced in Z decays)
  - test of lepton flavour universality: G_F from tau decays @ 10 ppm @ FCC-ee (0.5 ppm from muon decays)
  - lepton flavour violation:
    - $\tau \to \mu\gamma$: $4\text{x}10^{-8}$ @Belle2021→10^{-9} @ FCC-ee
    - $\tau \to 3\mu$: $2\text{x}10^{-8}$ @Belle → $3\text{x}10^{-10}$ @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}
- …

Collider Programme (and beyond)



- **Opportunities** beyond the baseline plan ($\sqrt{s}$ 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)

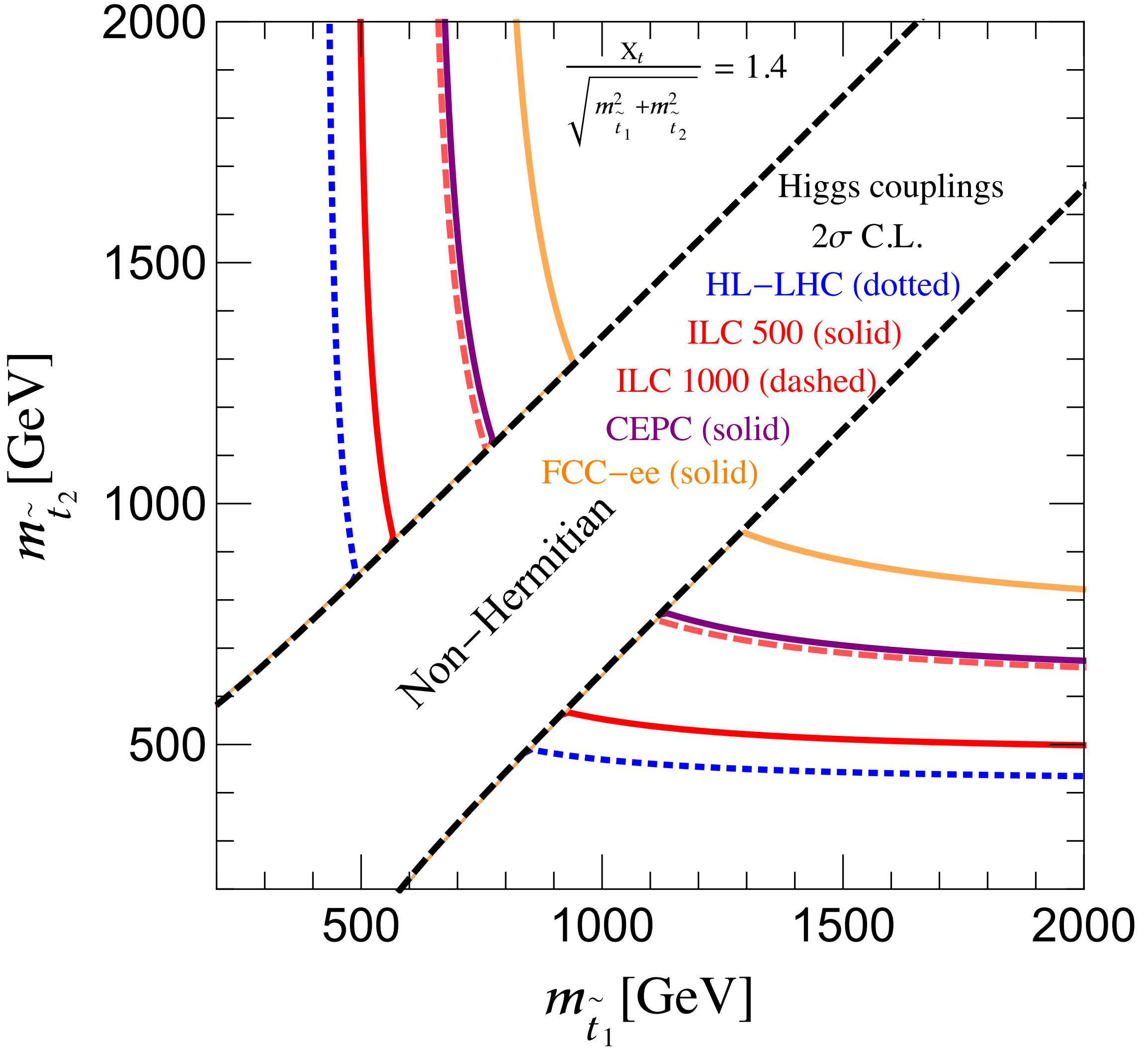
Direct discovery potential beyond LHC

Discovery Potential Beyond LHC

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

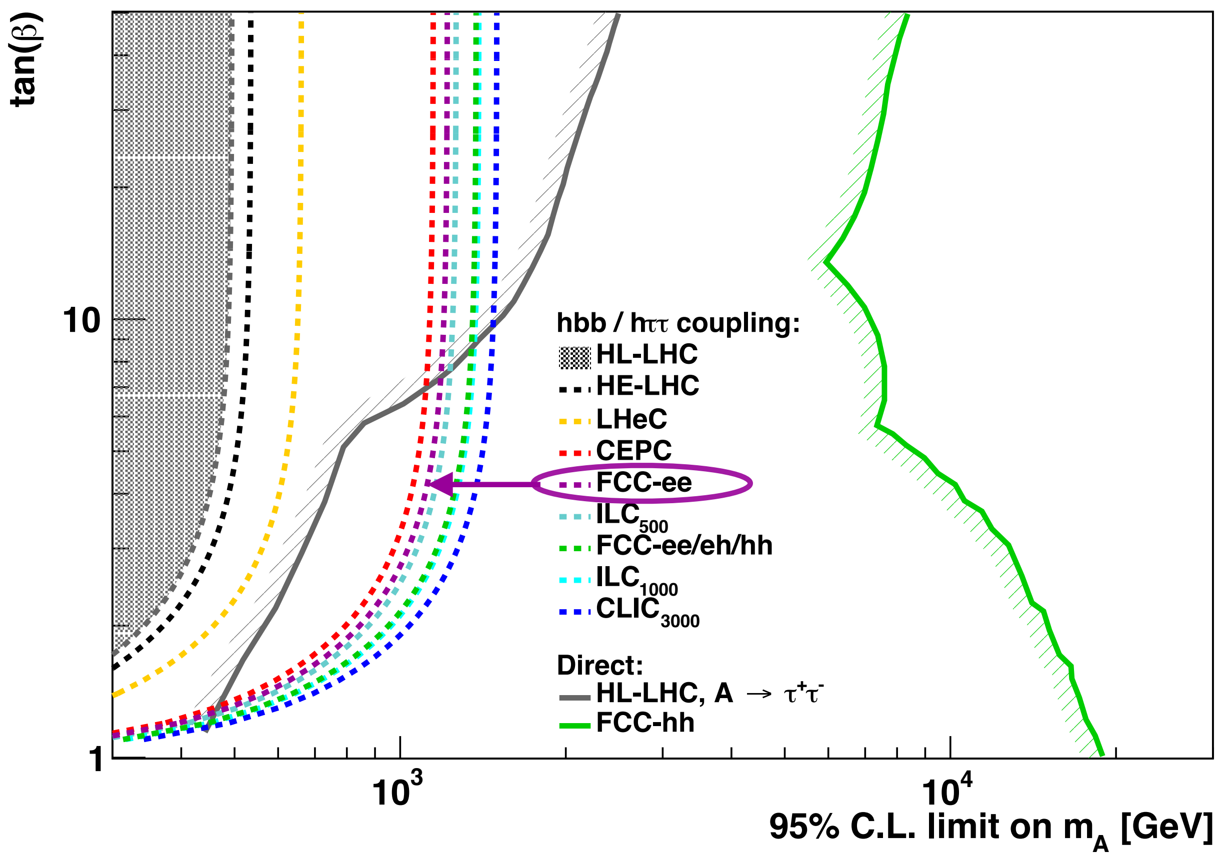
Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY

stops



Fan, Reece, Wang '14

Heavy neutral Higgses

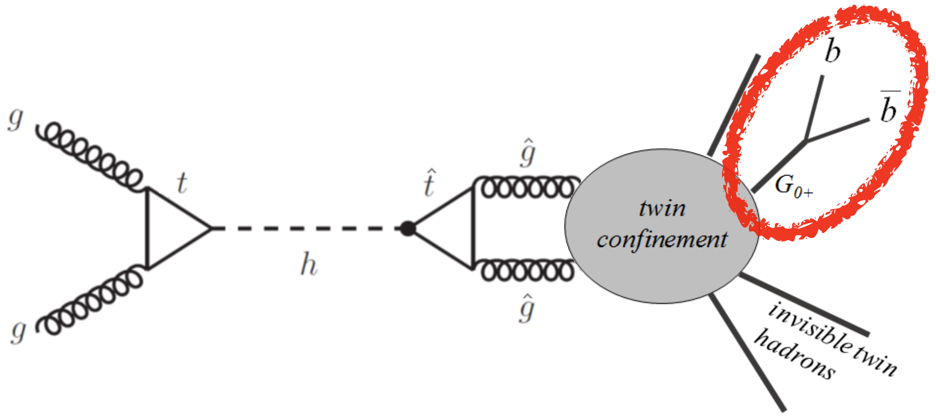


ESU Physics BB '19

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

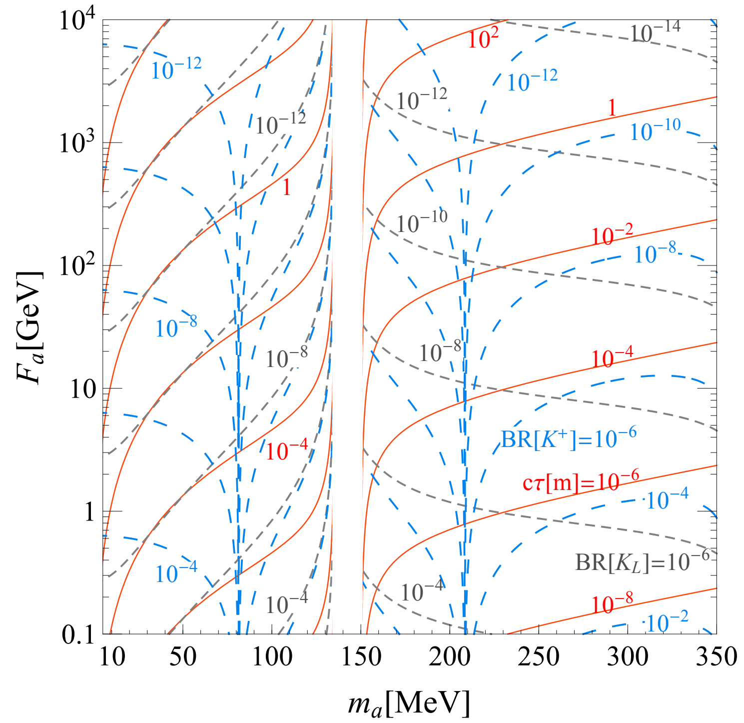
Craig et al, arXiv:1501.05310



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

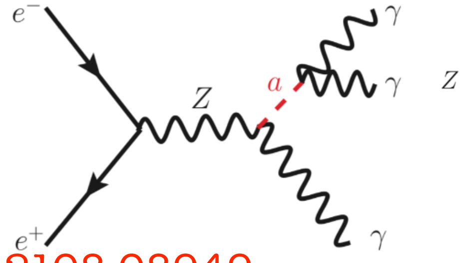
$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \text{ (KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \text{ (NA62)}$$

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

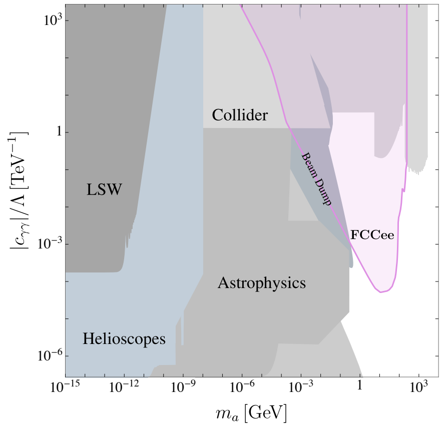


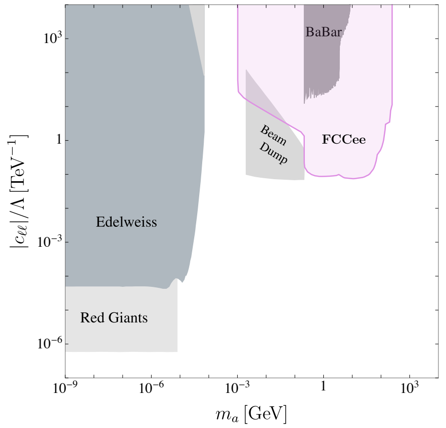
- **ALPs@ colliders**
  e.g. $e^+e^- \to \gamma a$

  $e^+e^- \to ha$



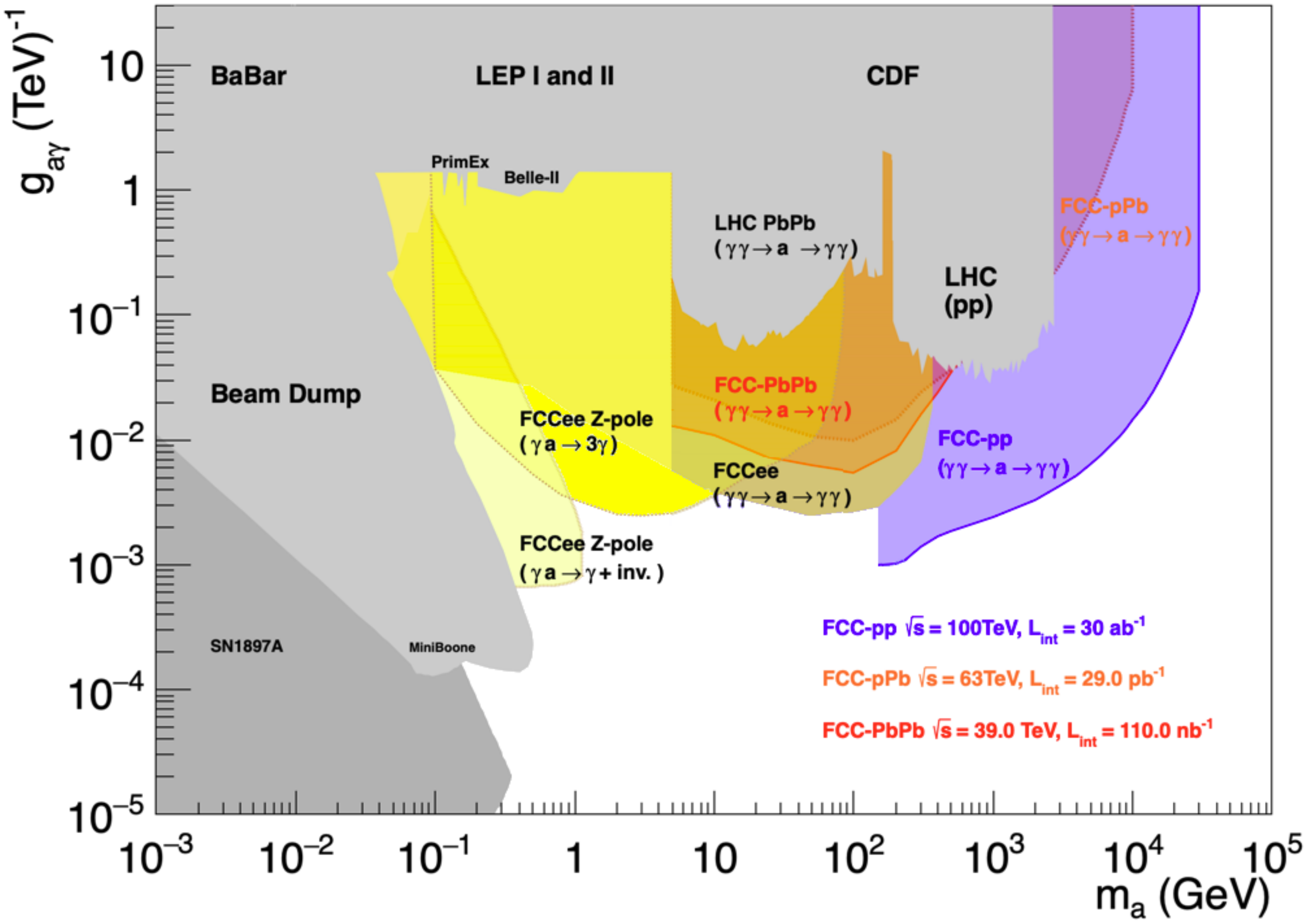
Knapen, Thamm arXiv:2108.08949





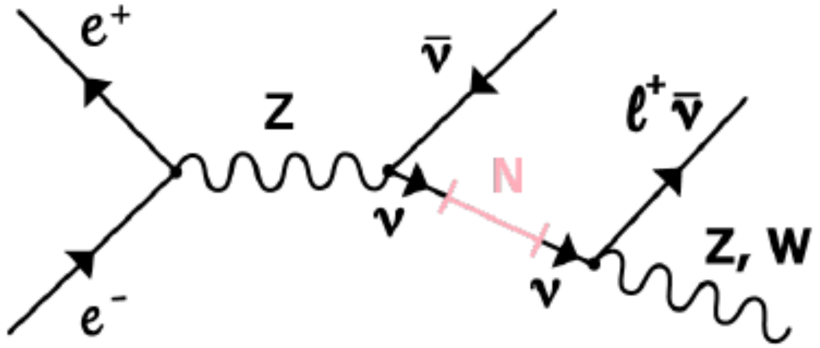
Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

Direct Searches for ALPs

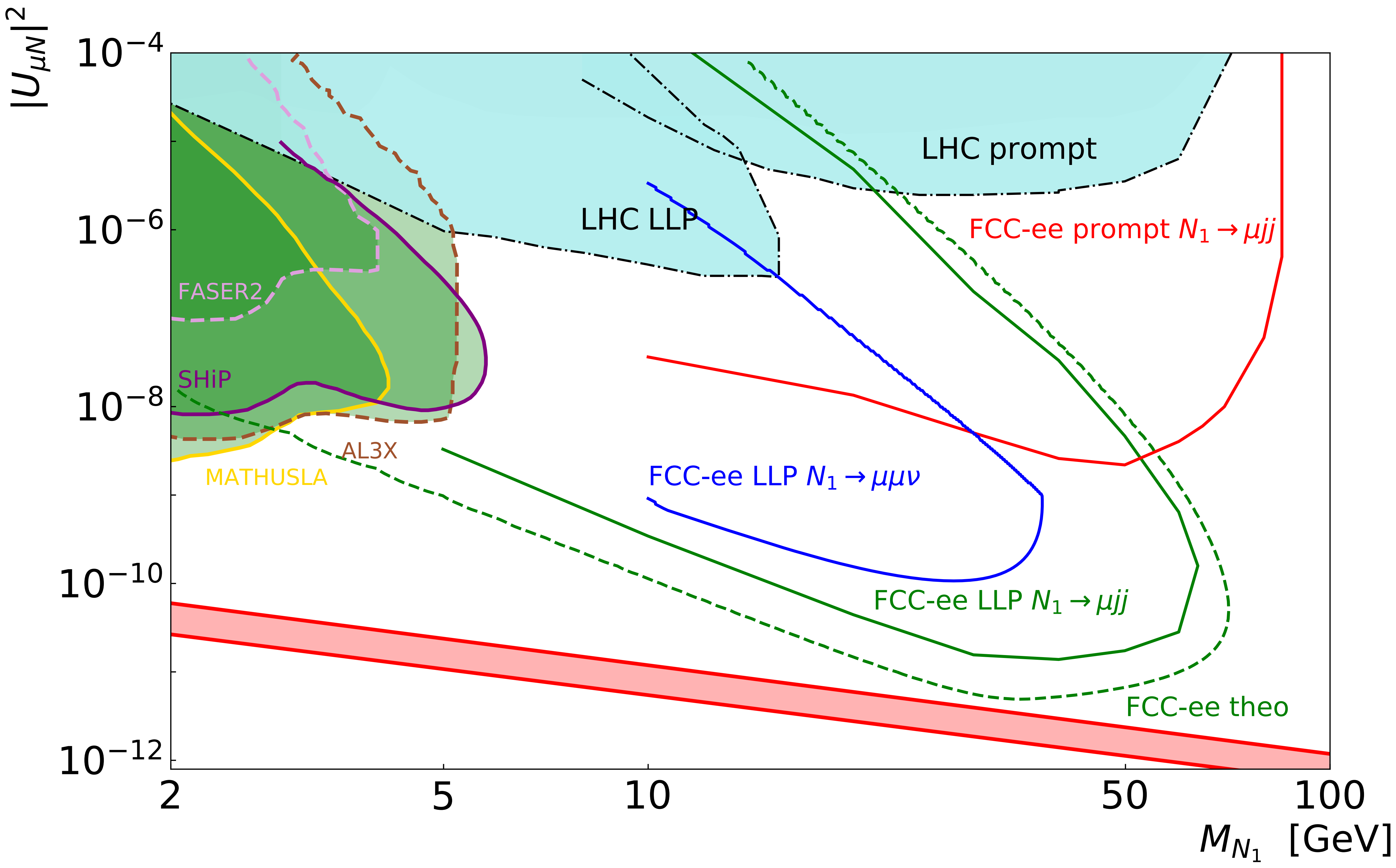


Search for ν_{RH}.

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



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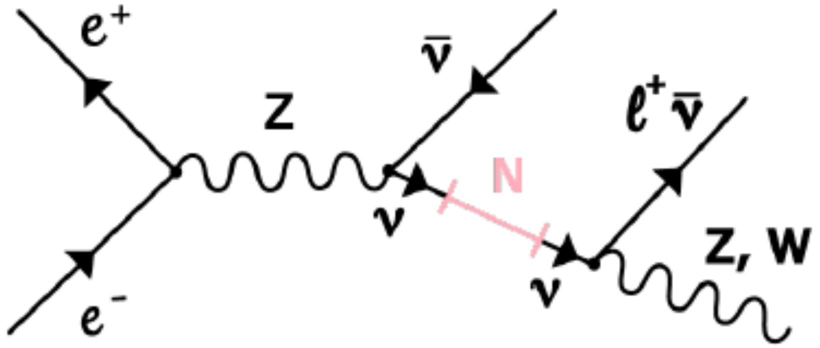

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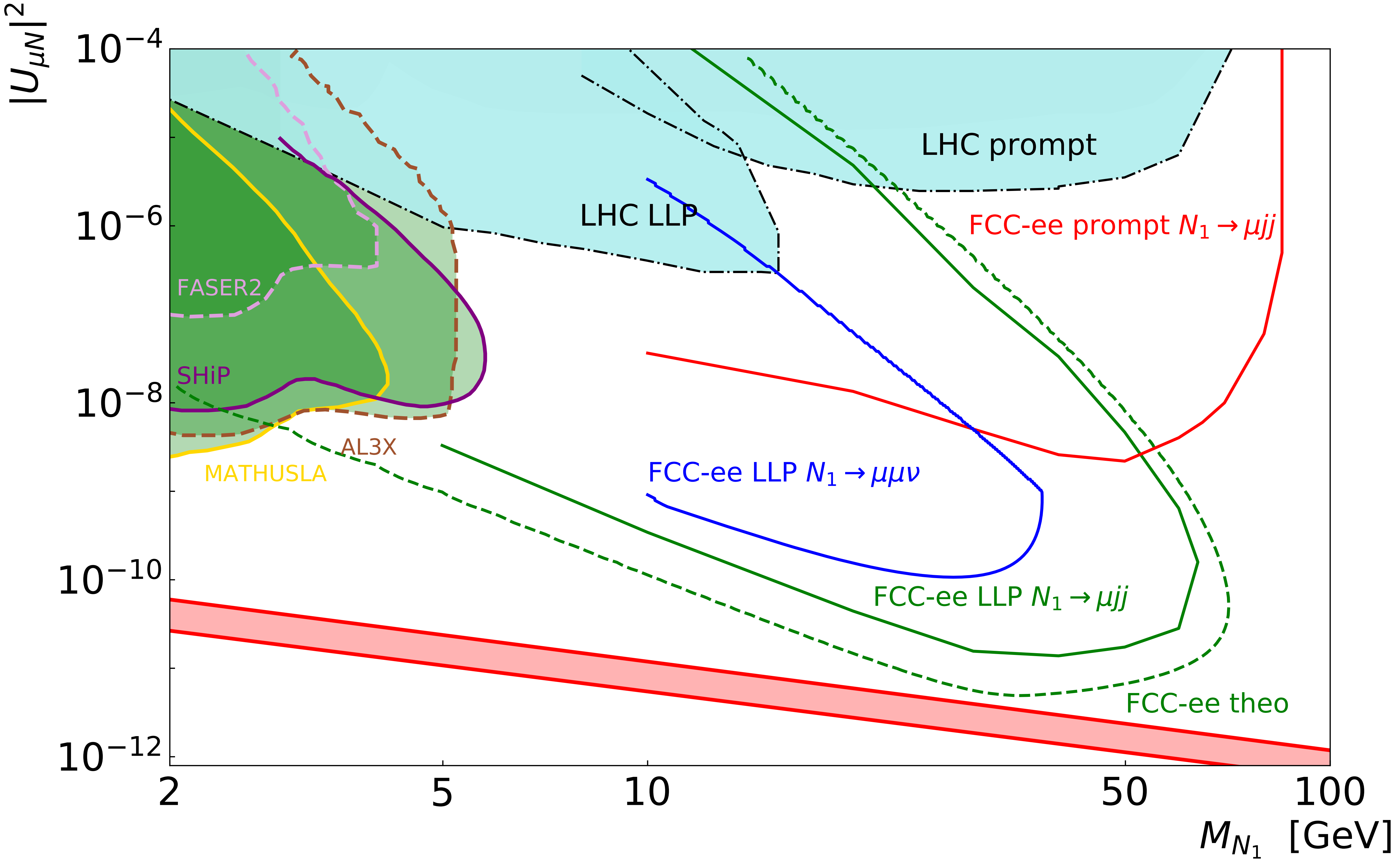
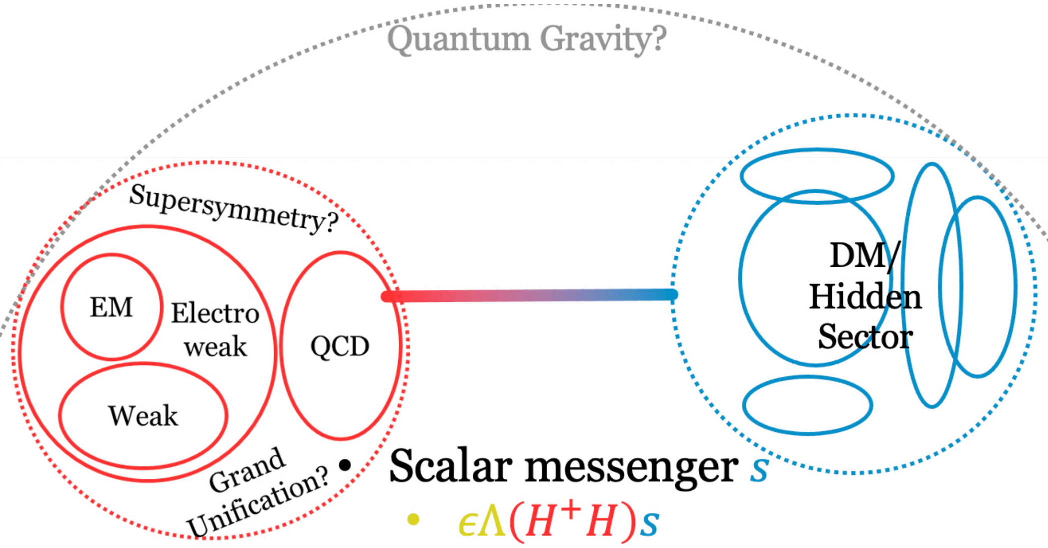


Exotics/Long Lived Particles.

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

LHC's strength

Hard at LHC due to missing energy

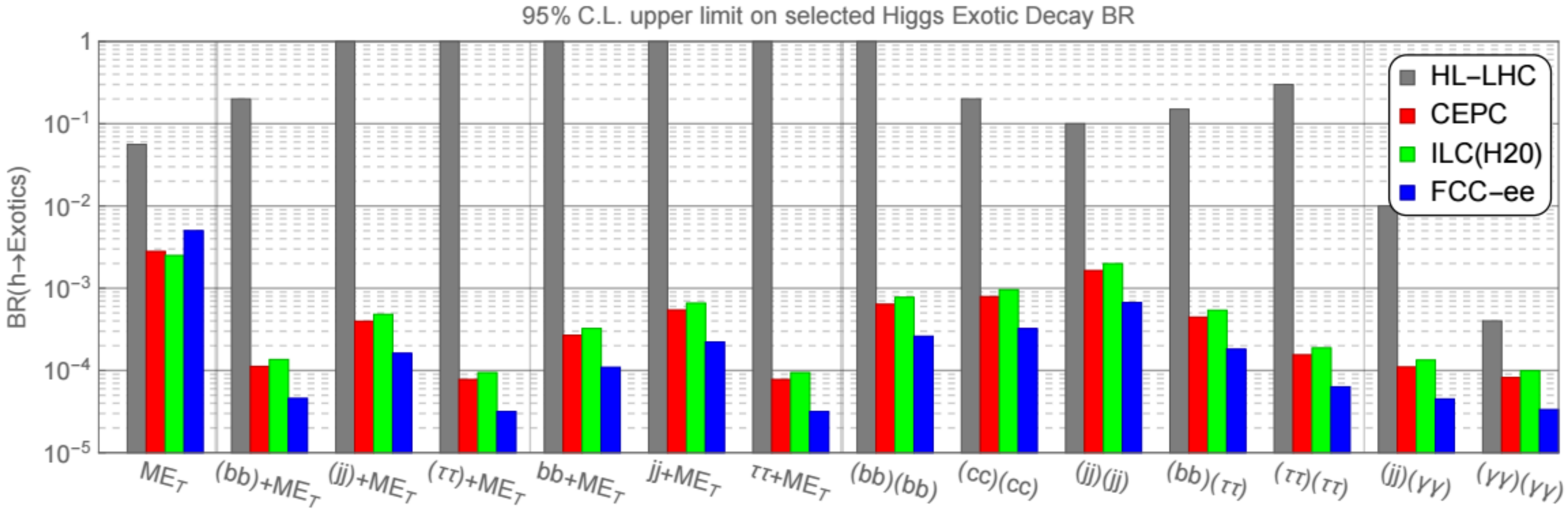
Hard at LHC due to hadronic background

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

Indirect discovery potential

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

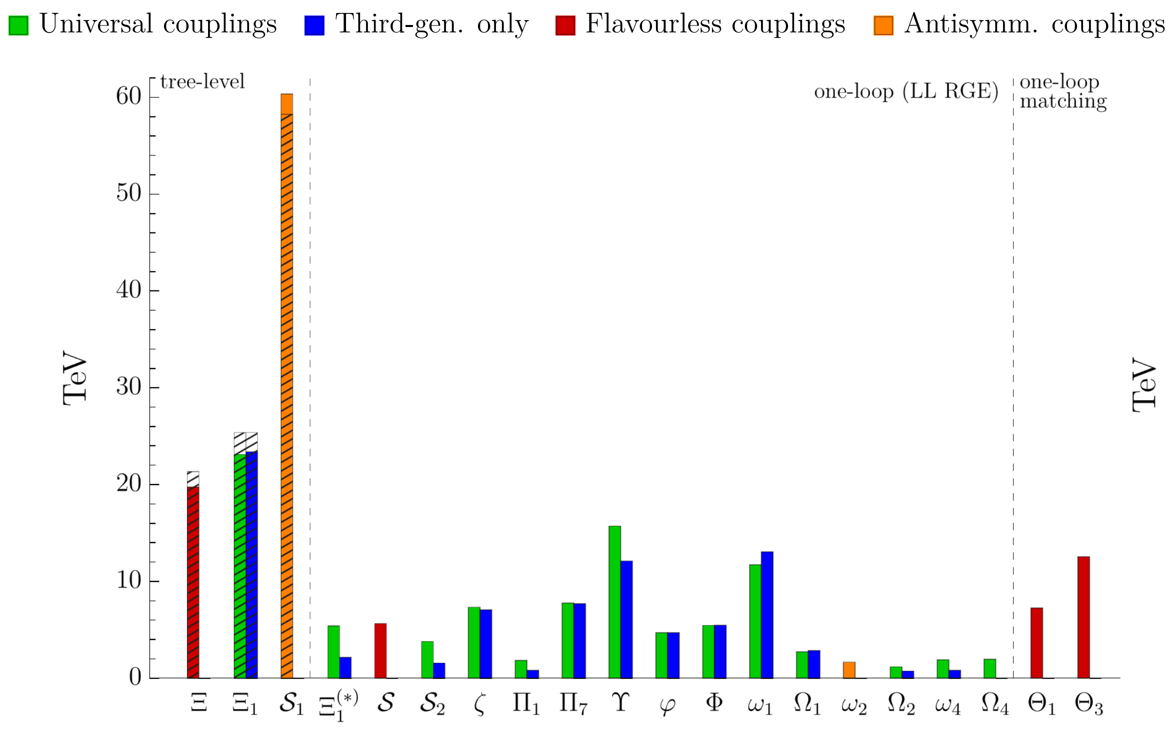
They are not all affecting EW observables at tree-level.

New Physics Reach @ Z-pole

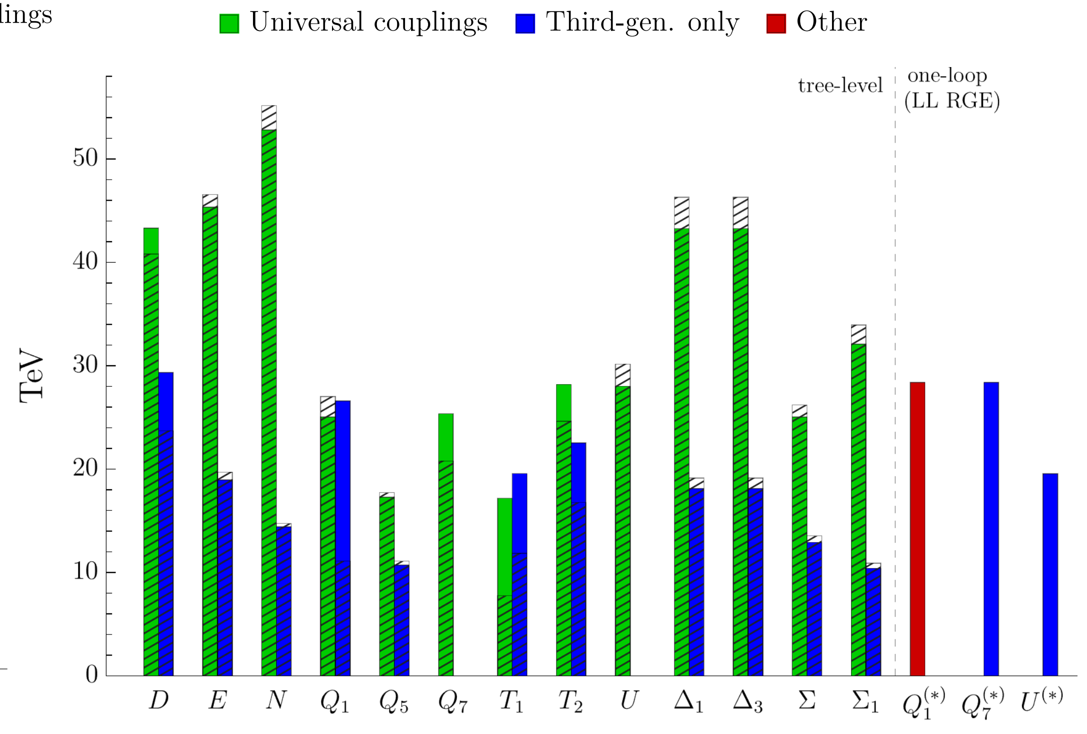
There are 48 different types of particles that can have tree-level linear interactions to SM.

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

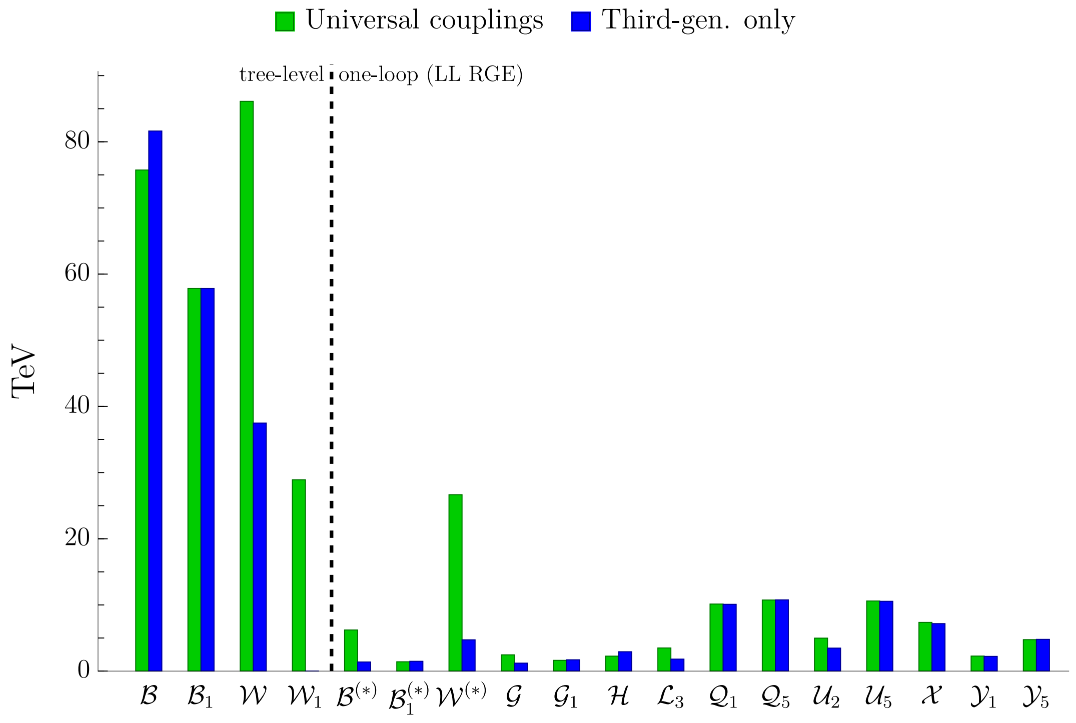
Allwicher, McCullough, Renner, arXiv: 2408.03992



Scalars



Fermions

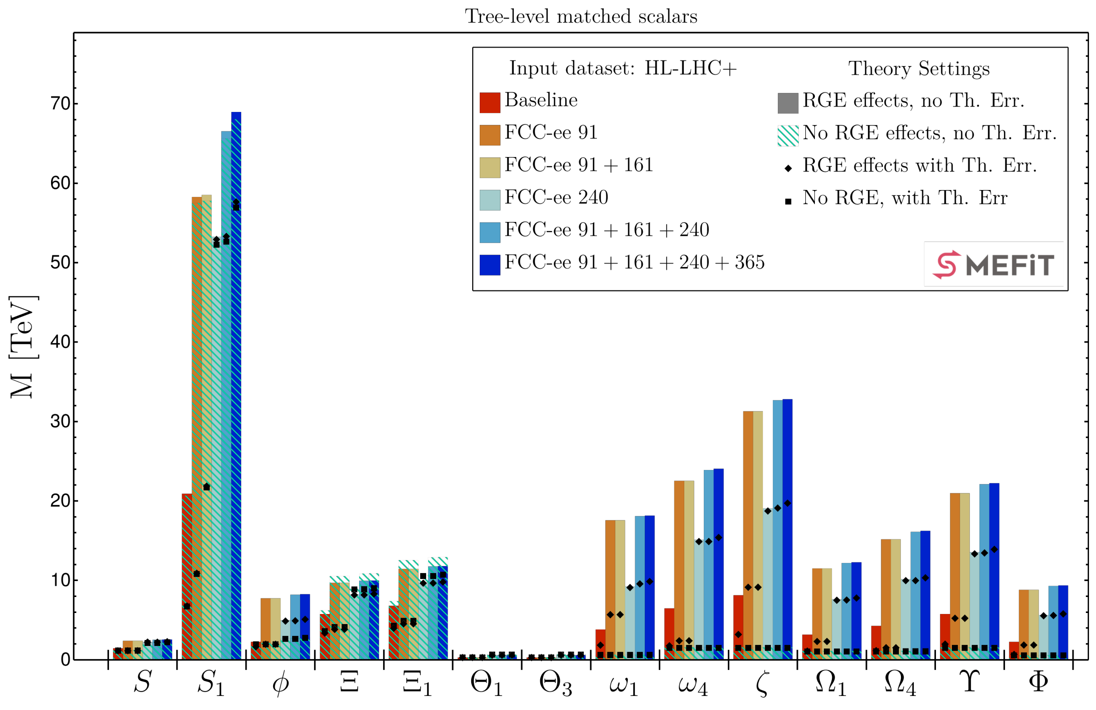


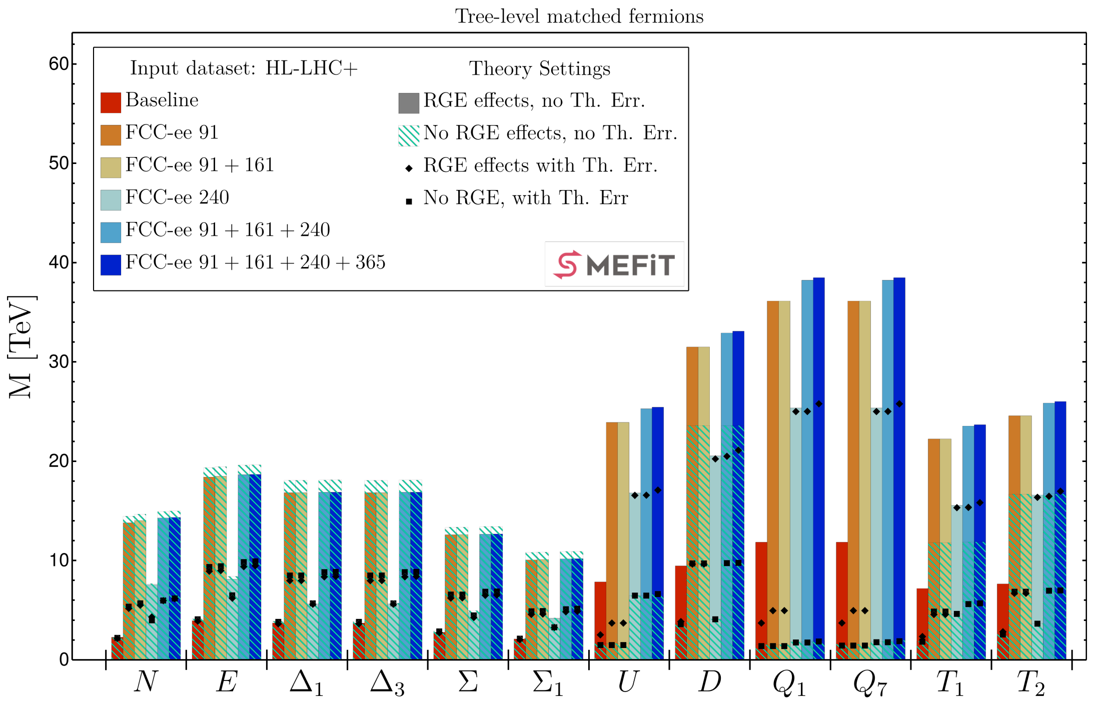
Vectors

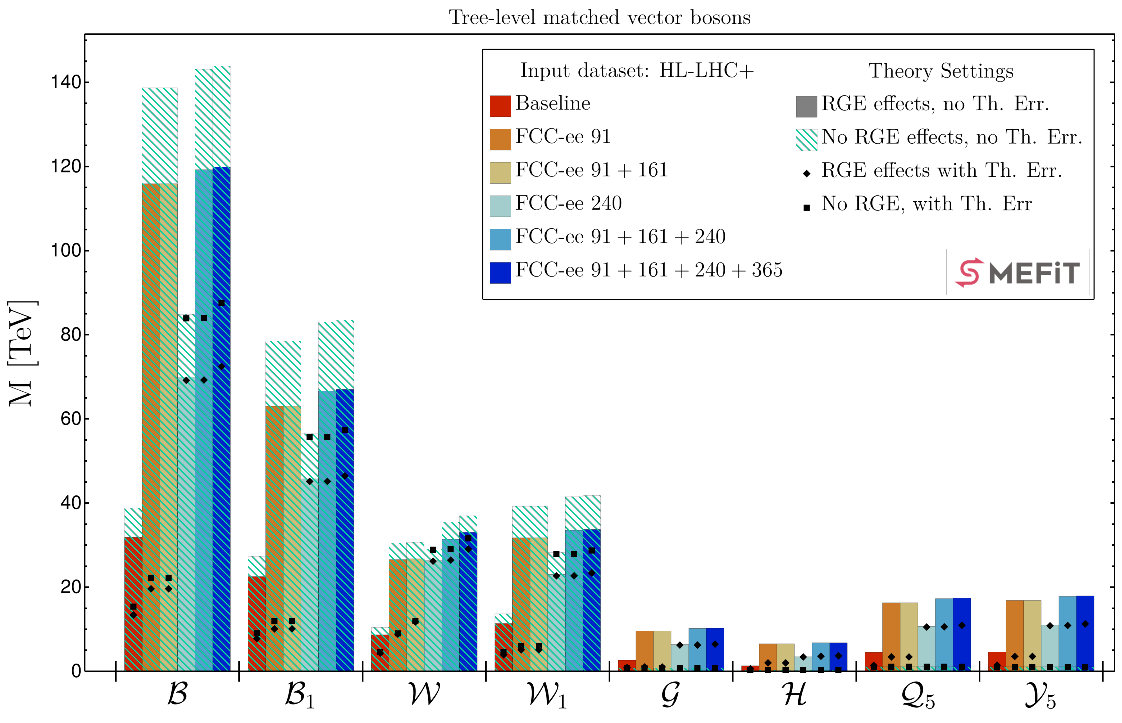
Tree-level matching and running from 1 TeV to Z mass.
W- and Z-pole observables only (no Higgs, no LEP-2 like observables)

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

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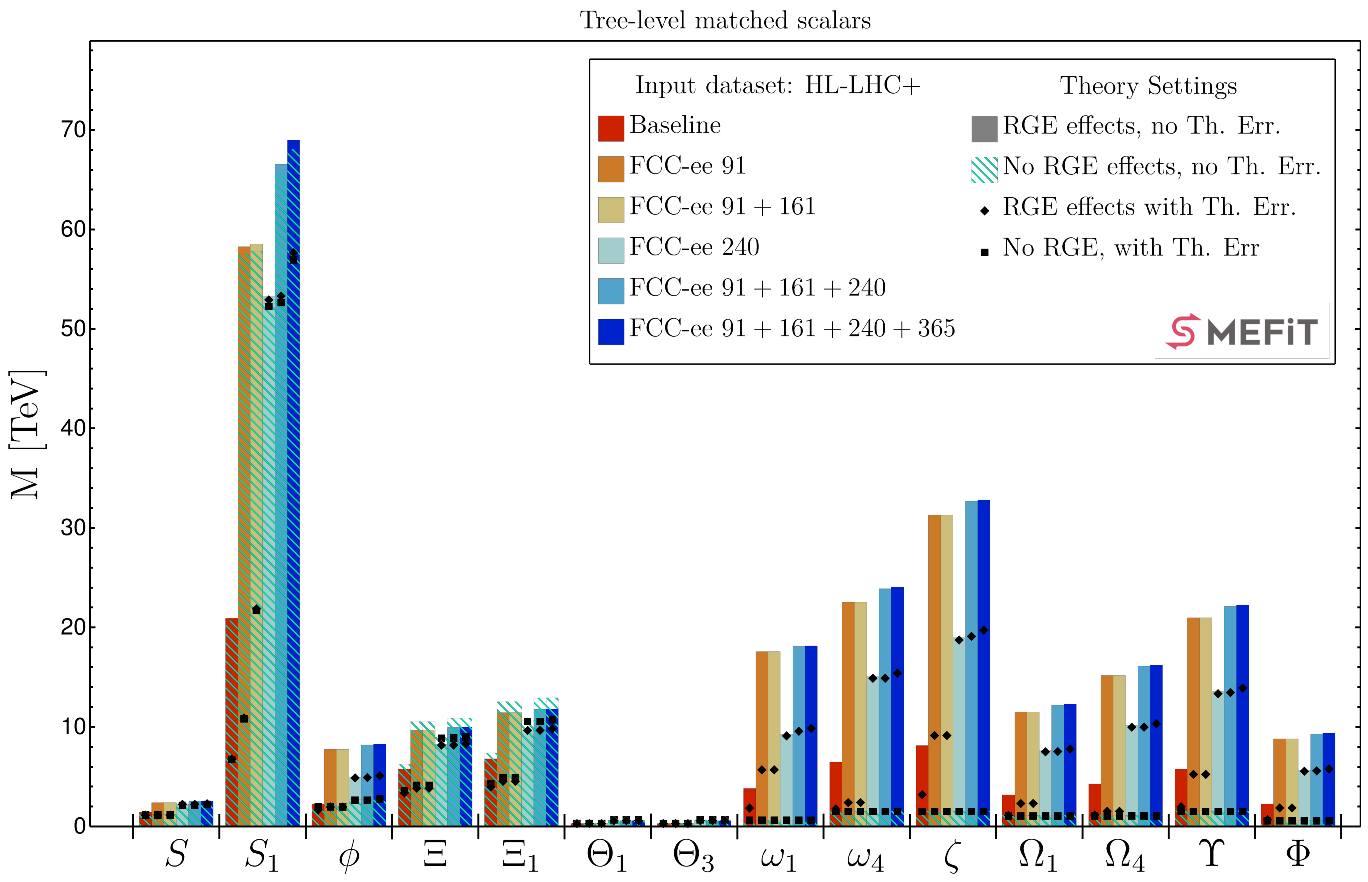
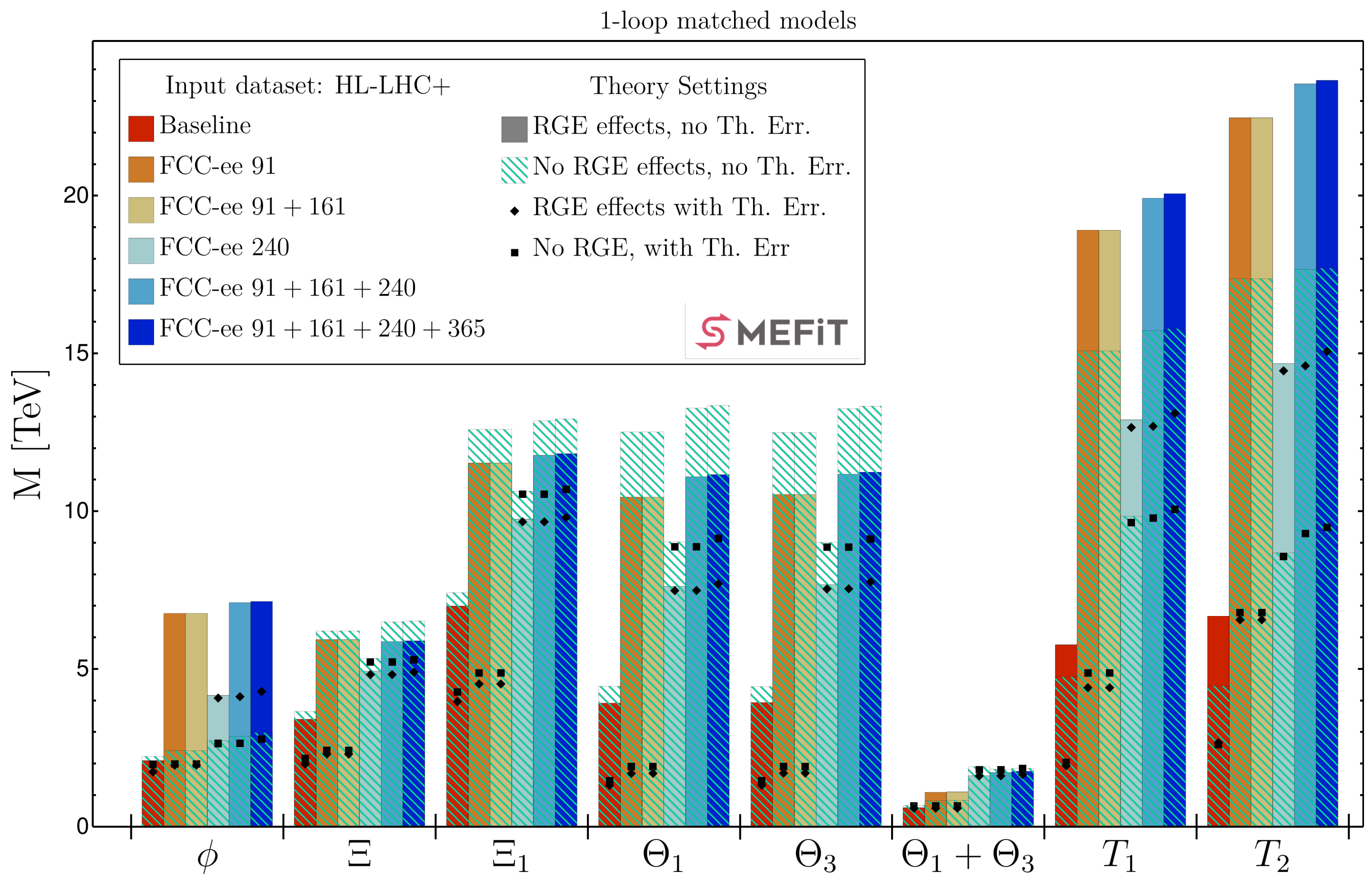




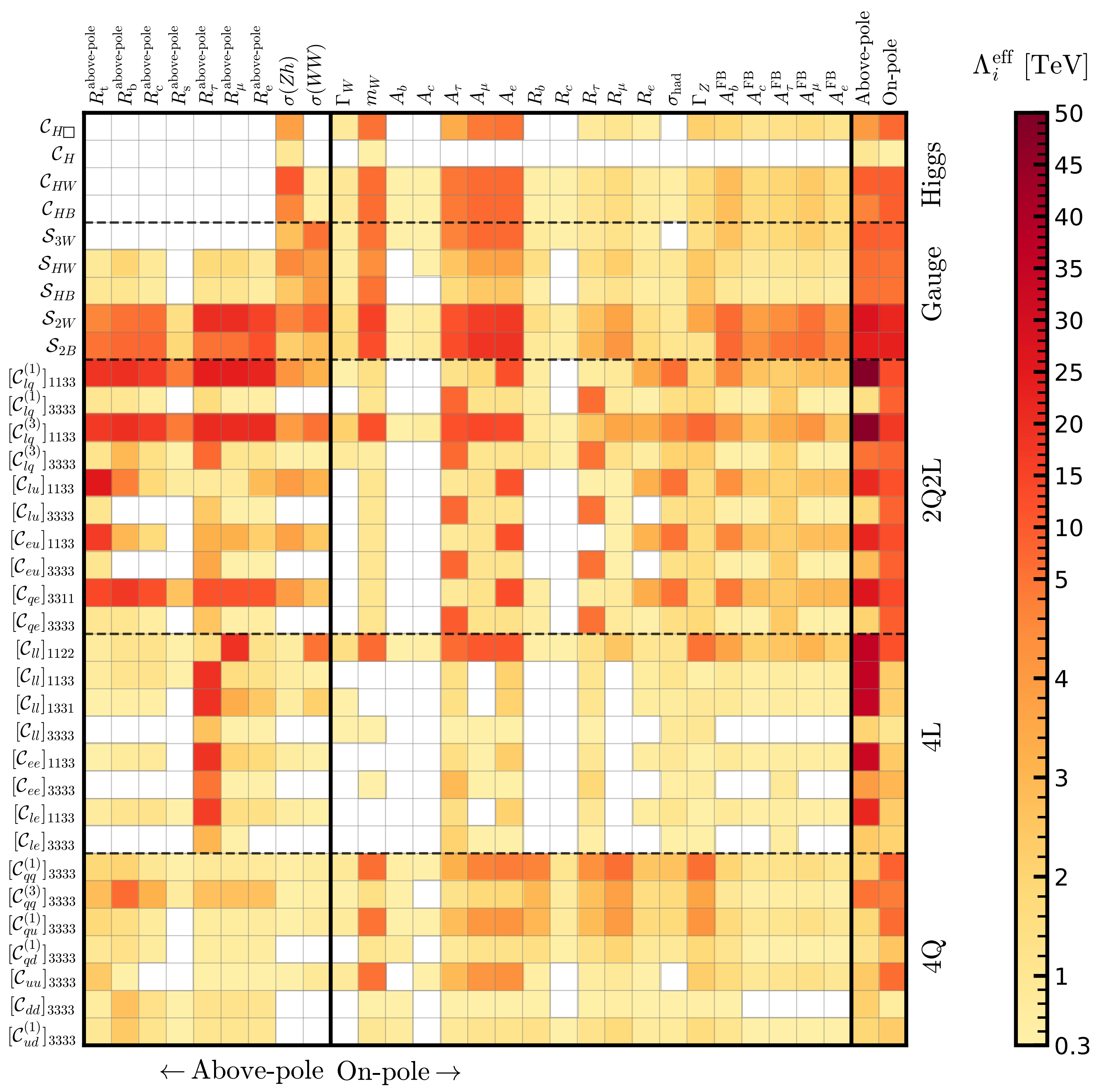
Importance of full 1-loop matching
(finite pieces matter)

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.

Z-pole vs High Energy



Maura, Stefanek, You arXiv:2412.14241

Conclusions

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, and to gain incredible sensitivity to heavy particles coupled to the SM up to scales of 10’s of TeV.
  - to make TeraZ a useful flavour factory;
  - for transverse polarisation to be available all the way to the WW threshold in pilot bunches (allowing a precise W mass measurement);
  - for the top-pair production threshold to be reached and exceeded.

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Herwig Schopper in CERN Courier:
"It is almost forgotten that the LEP tunnel size was only chosen in view of the LHC."
(While LEP didn't benefit from LHC, FCC-ee will benefit from FCC-hh.)

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**

Photo Trevor Sherwin

Karl Jakobs: “Key messages from the Symposium”
Venice, Friday 27 June

“The time is ripe to forge a brilliant future for our field in Europetogether with our global partners”
F. Gianotti

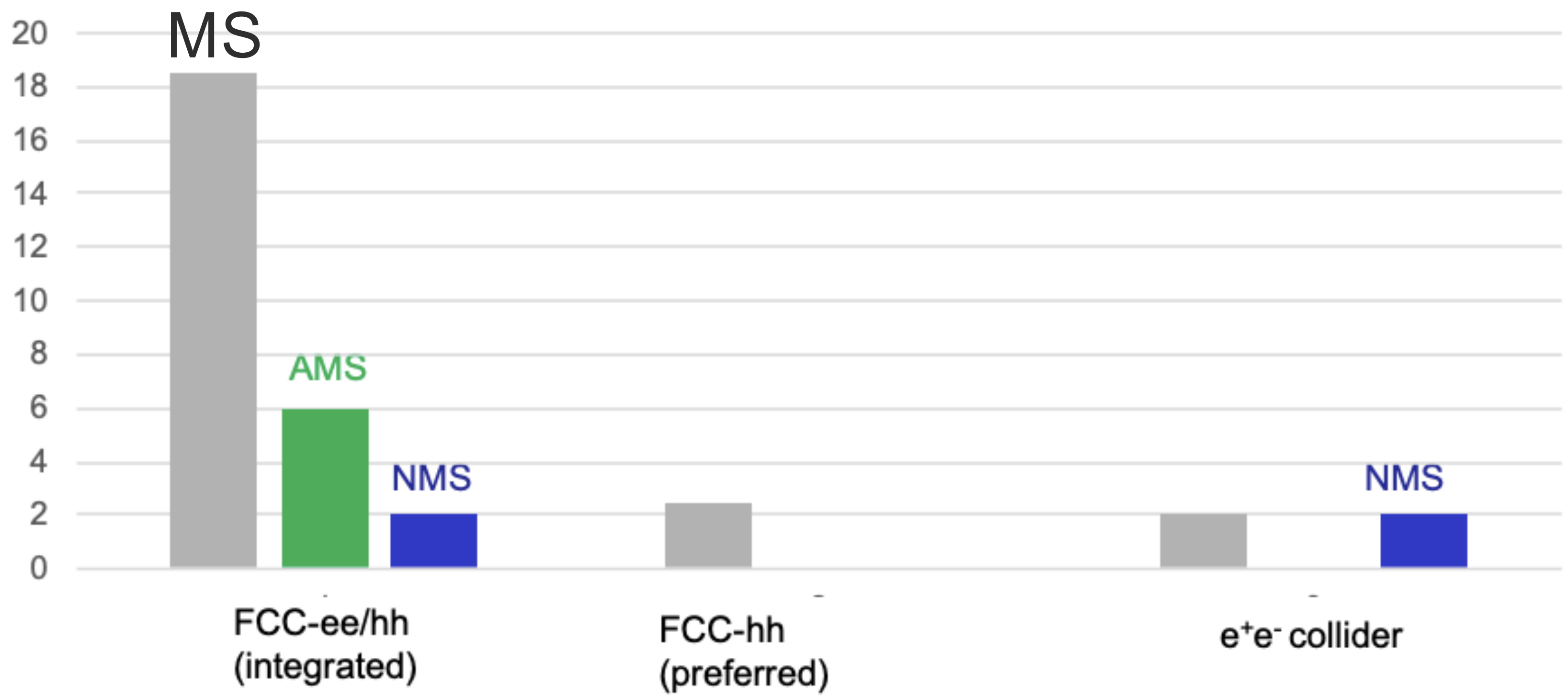
Final Words

Over the past years very significant progress has been made towards the realisation of the next flagship project at CERN

- FCC: Successful completion of the Feasibility Study; No technical showstoppers identified
- Overwhelming support for the integrated FCC-ee/hh programme by the HEP communities in the CERN Member and Associate Member states and beyond;

  The strong support is largely based on the superb physics potential and the long-term prospects (FCC-ee /hh)
- Discussions on the financial feasibility are ongoing (CERN management and Council)

Back from Venice
(European Strategy Symposium)



FCC-ee/hh (integrated)	MS: Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Israel, Italy, Norway, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, Switzerland, (United Kingdom) AMS: Brazil, Croatia, Lithuania, Pakistan, Slovenia, Ukraine NMS: Canada, USA
FCC-hh preferred (but accept ee first)	Czech Republic, Serbia, (United Kingdom)
e^+e^- collider	MS: Austria, Bulgaria NMS: Australia, Japan

K. Jakobs, CERN Council, 20th June 2025

Twenty Year from First Collisions

Twenty Year from First Collisions

Twenty Year from First Collisions

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
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  - FCC Integrated Programme Stage 2: The FCC-hh (ESPPU#247); CDS
  - The FCC Integrated Programme: A physics manifesto (ESPPU#241); CDS; arXiv:2504.02634
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  - Prospects in BSM physics at FCC (ESPPU#242); FCC note
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  - Prospects for flavour physics at FCC (ESPPU#196); FCC note
  - Prospects for physics at FCC-hh (ESPPU#227); FCC note
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BONUS

Cost Estimates

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.

FCC-ee

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-)

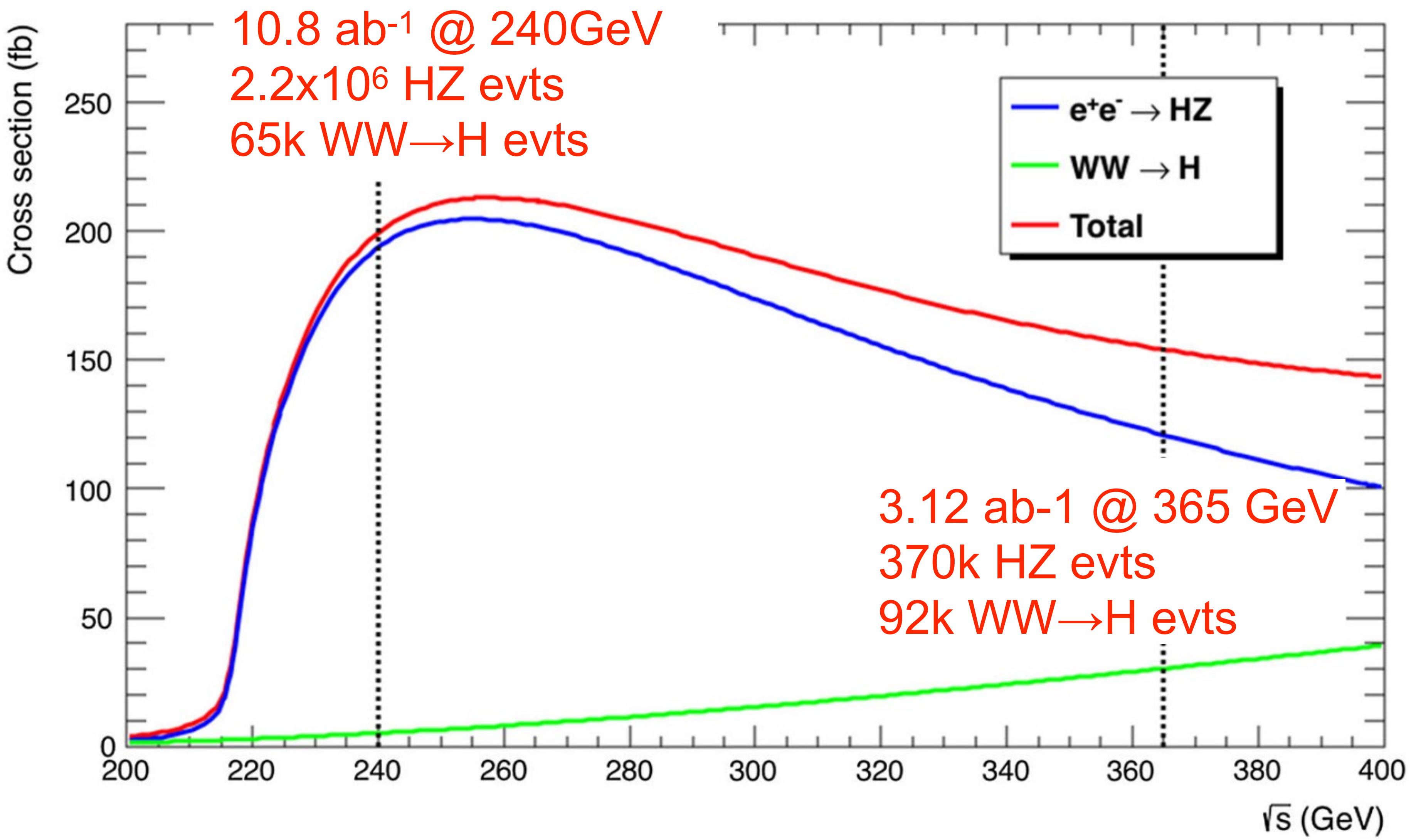
Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1756MCHF

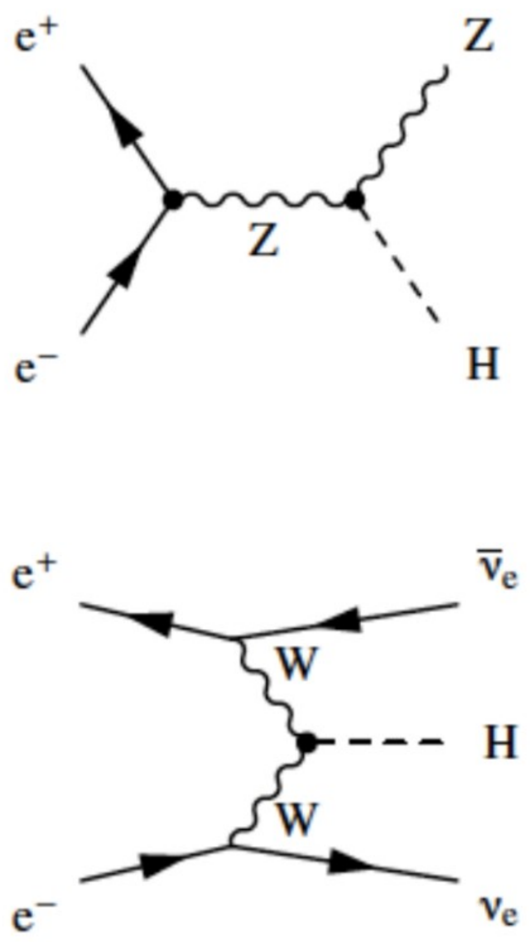
→ ~2 BCHF (2025)

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.





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
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
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{\mathrm{inv}}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{\mathrm{unt}}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

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

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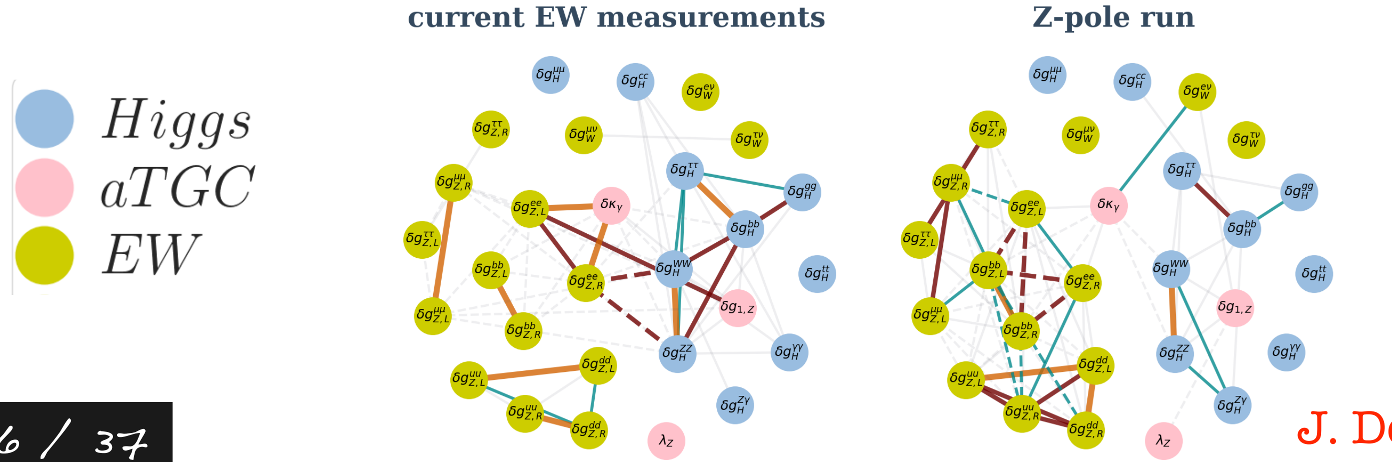
— Higgs programme needs Z-pole —



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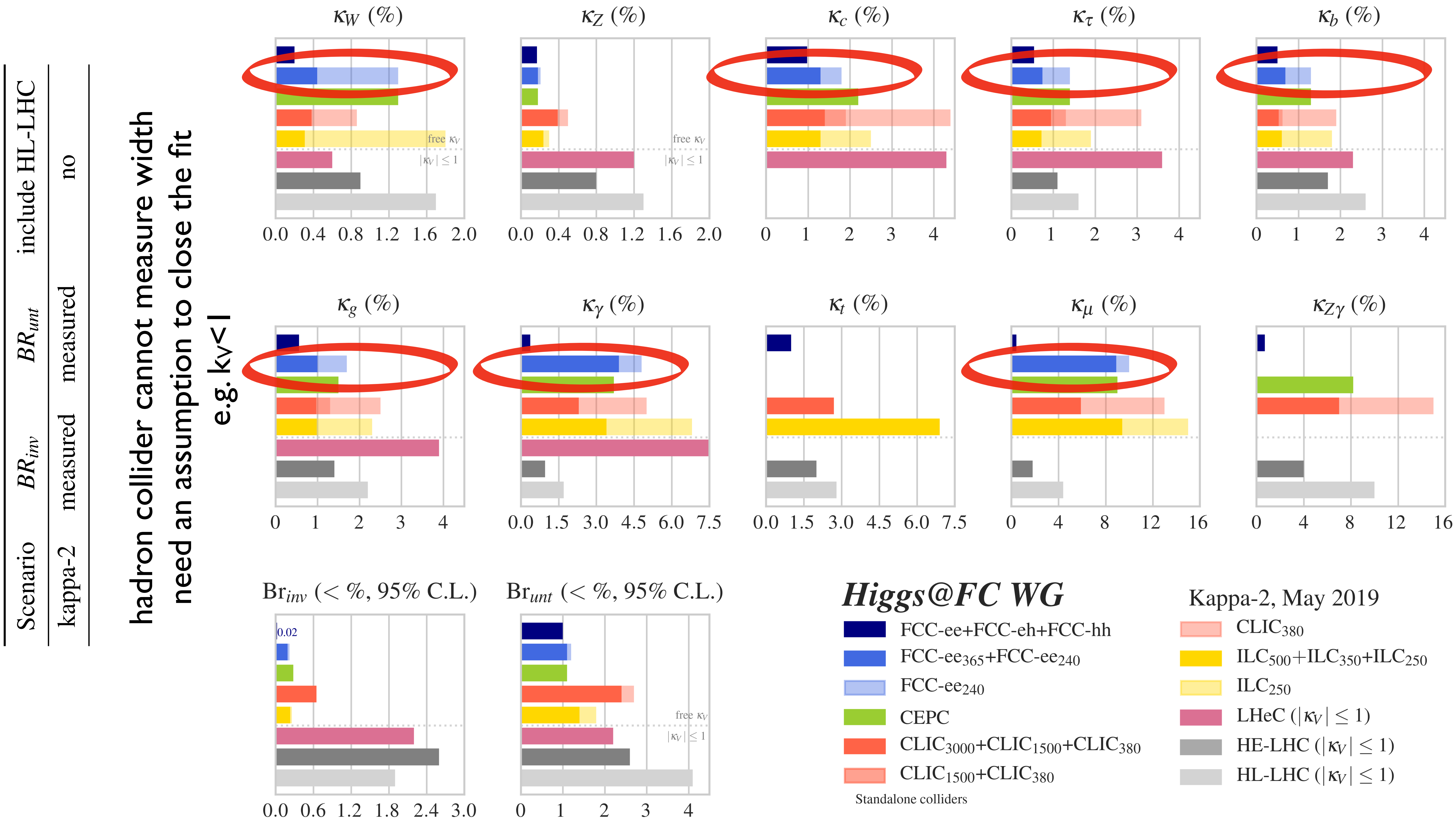
$$\kappa_X = \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}}$$

J. De Blas et al. 1907.04311

Complementarity 240↔365 GeV

ECFA Higgs study group '19

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



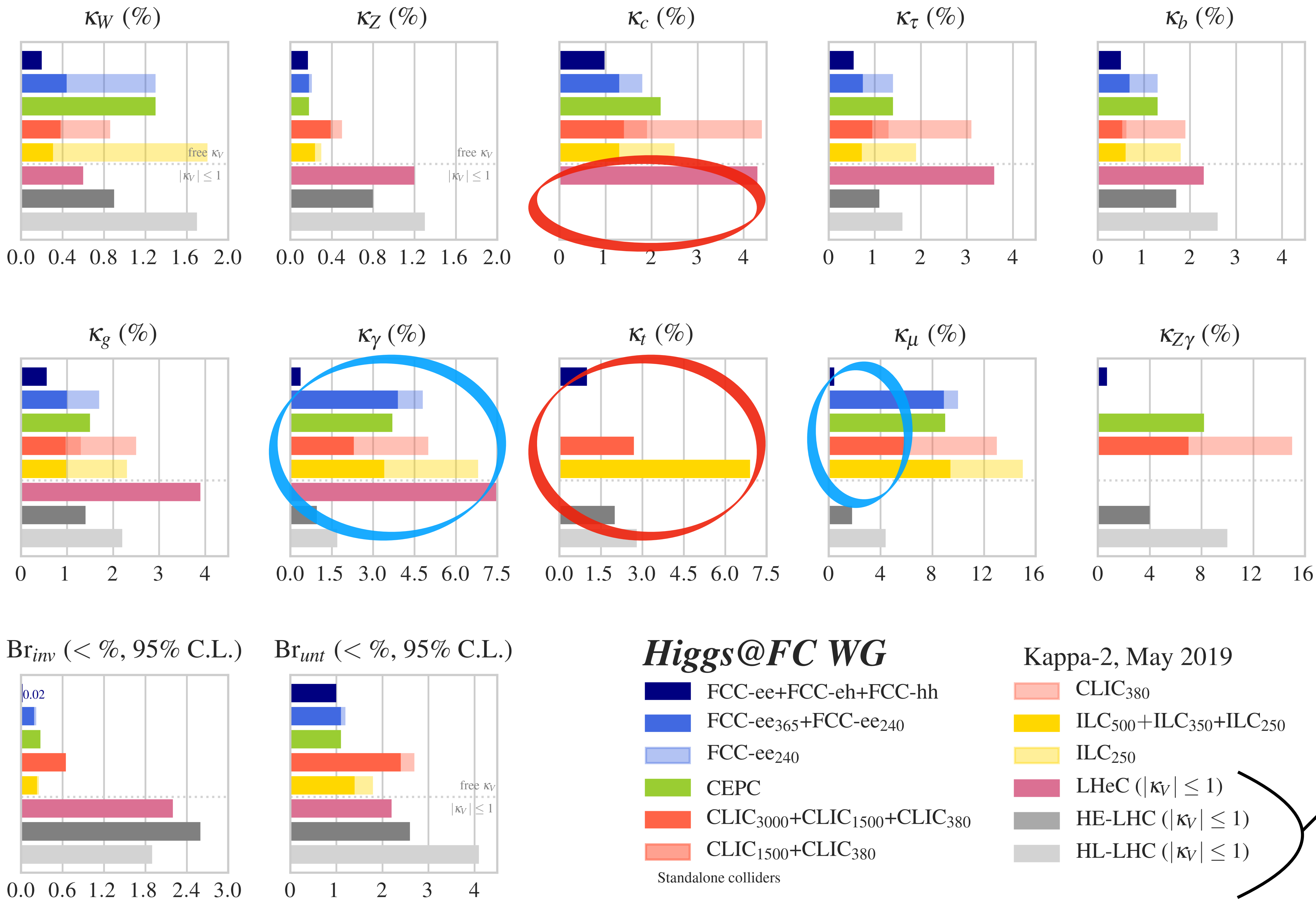
back to main discussion

Complementarity FCC-ee↔HL-LHC

ECFA Higgs study group '19

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

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



assumption needed for the fit to close at hadron machines

back to main discussion

Complementarity FCC-ee↔HL-LHC

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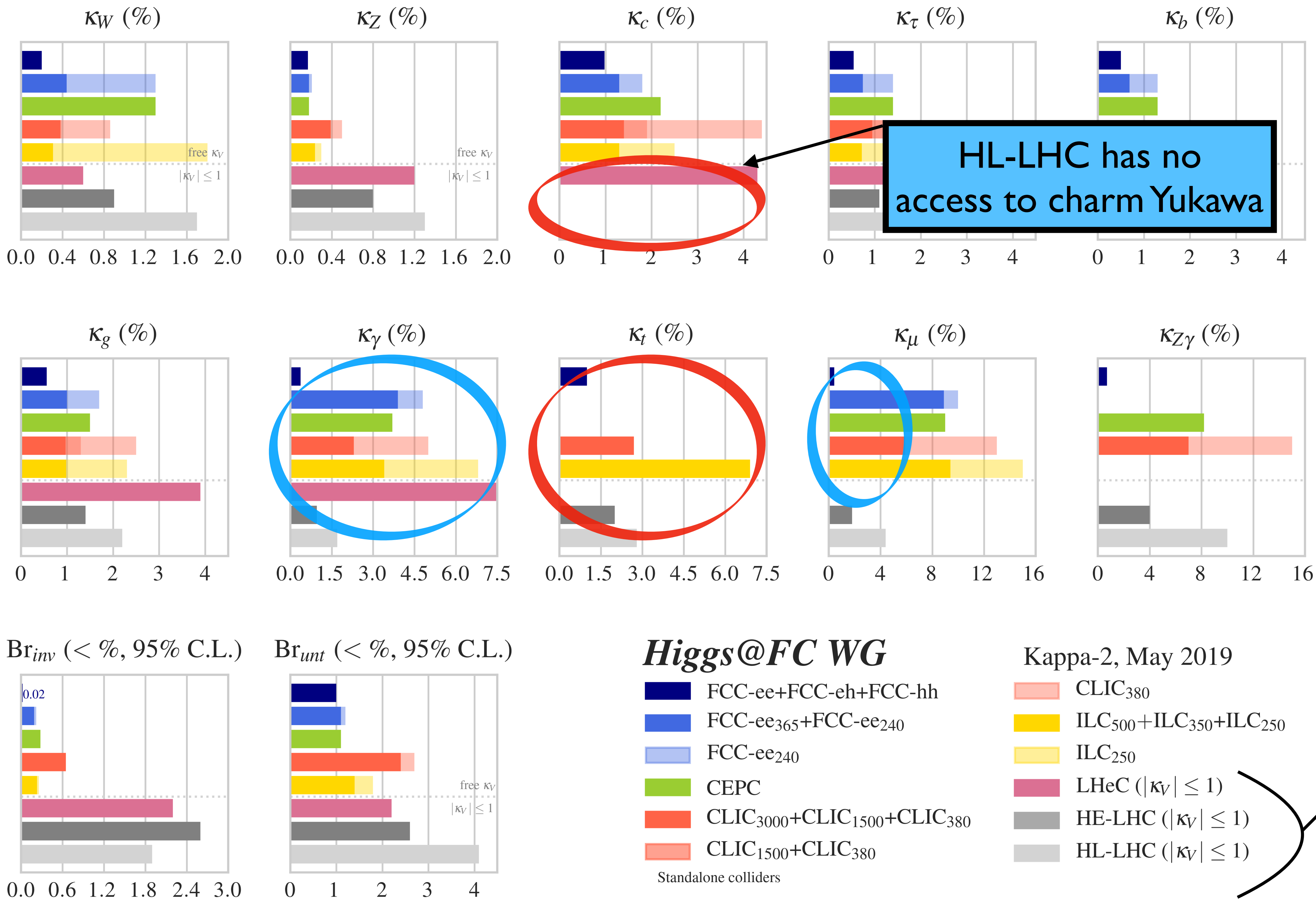

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back to main discussion

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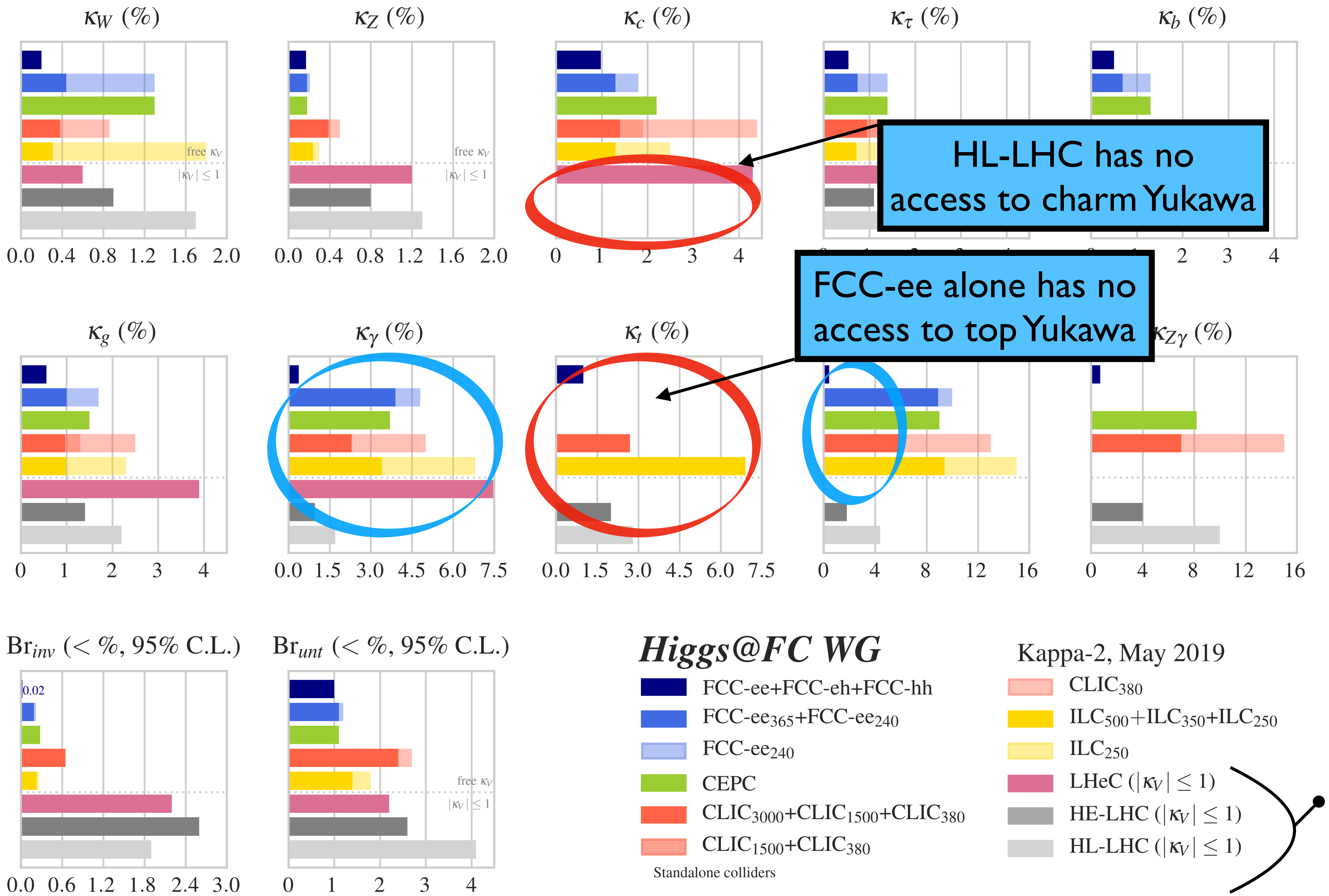

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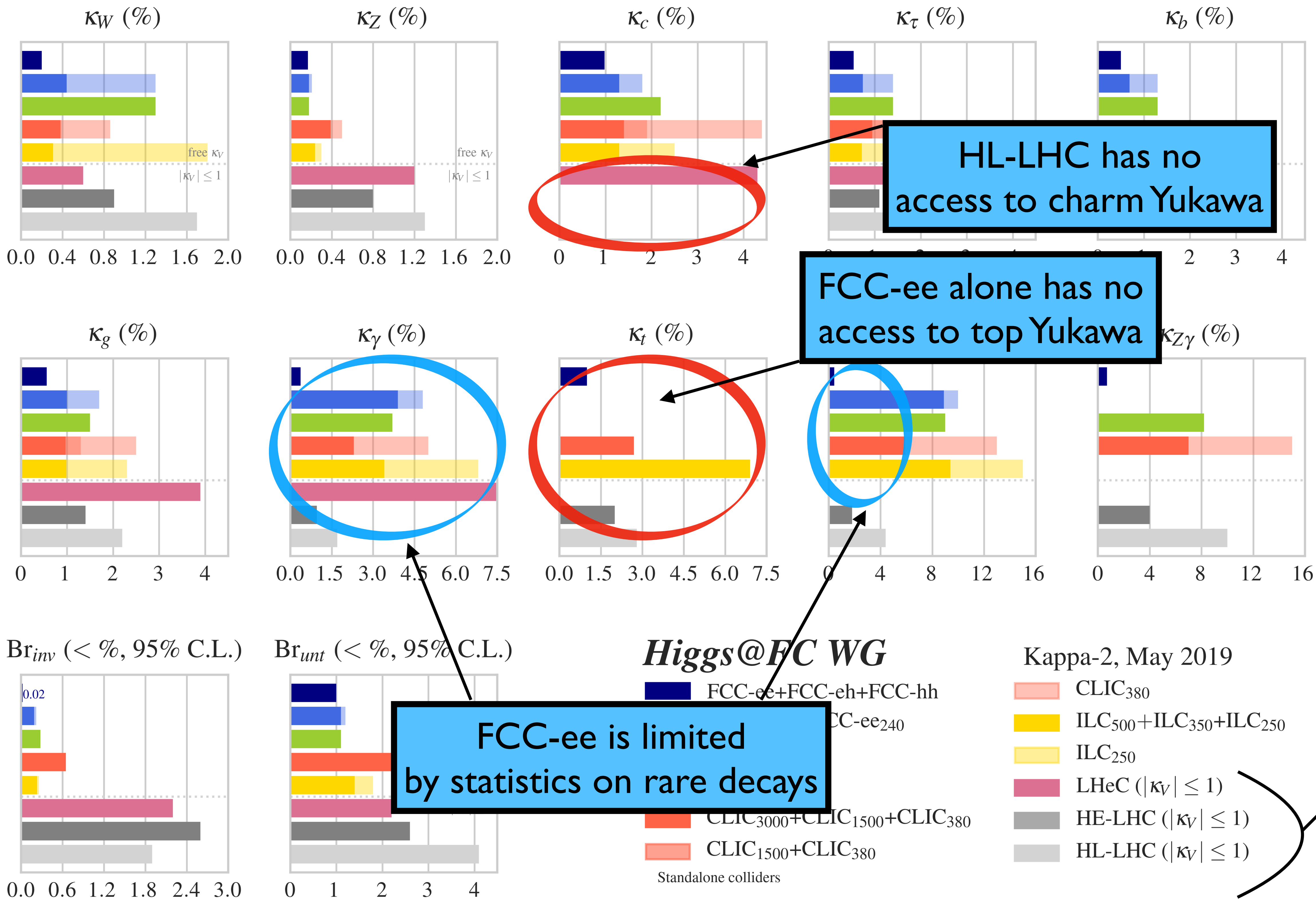


HL-LHC has no access to charm Yukawa

FCC-ee alone has no access to top Yukawa

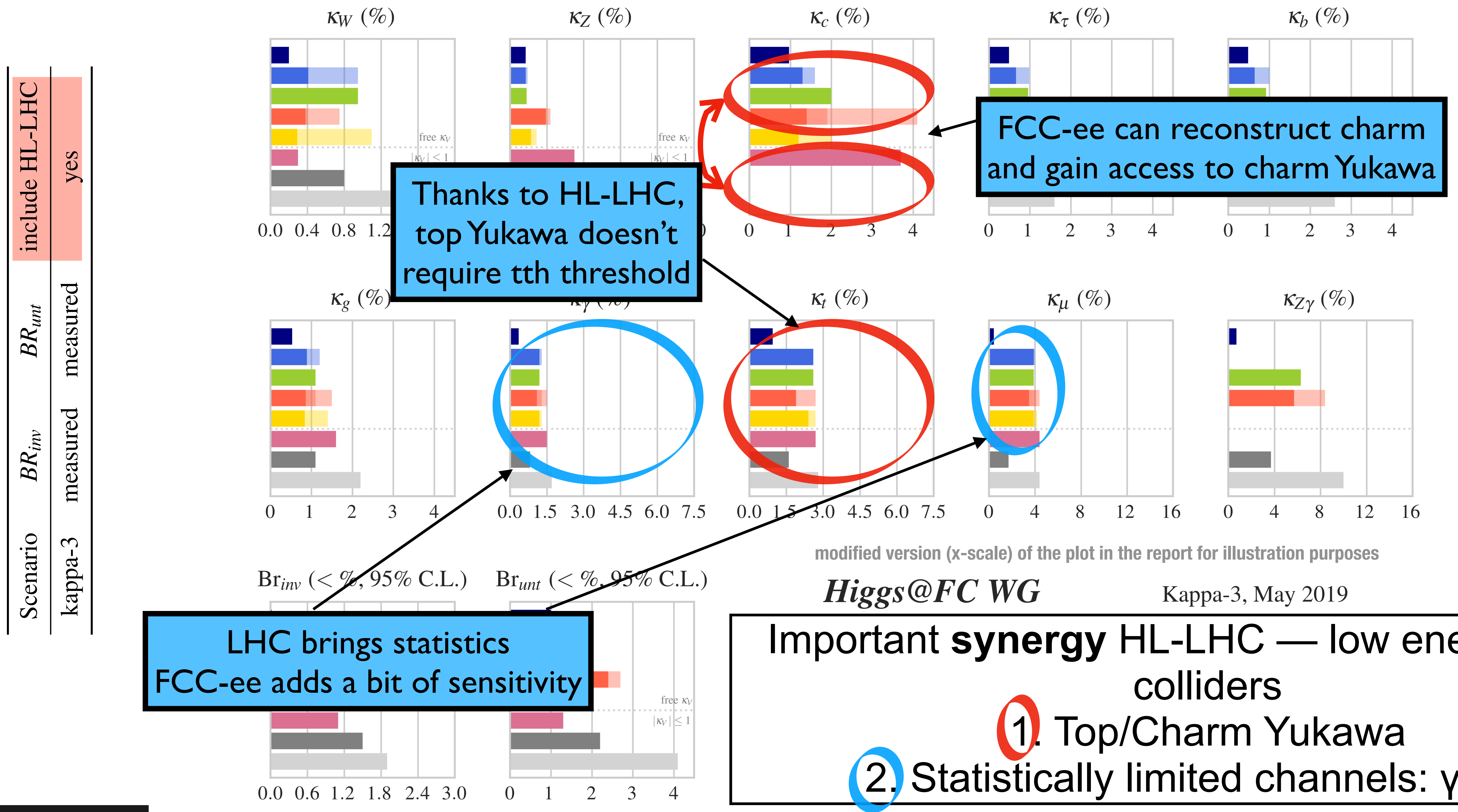
FCC-ee is limited by statistics on rare decays

assumption needed for the fit to close at hadron machines

back to main discussion

Complementarity FCC-ee↔HL-LHC

ECFA Higgs study group '19



back to main discussion

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

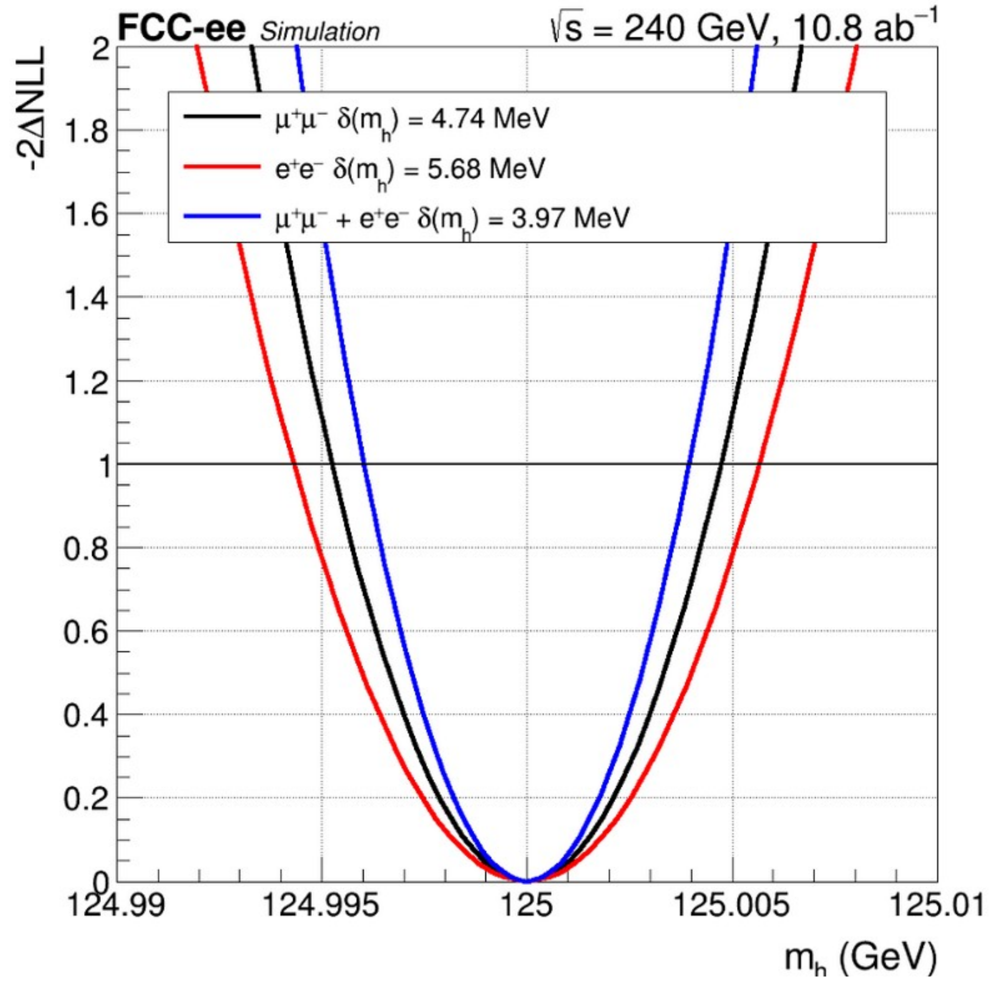
1. Top/Charm Yukawa
2. Statistically limited channels: γγ, μμ

Higgs Mass

FCC note (J. Eysermans et al)

Today ~150 MeV → HL-LHC ~20 MeV → FCC-ee ~4 MeV

- 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

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)

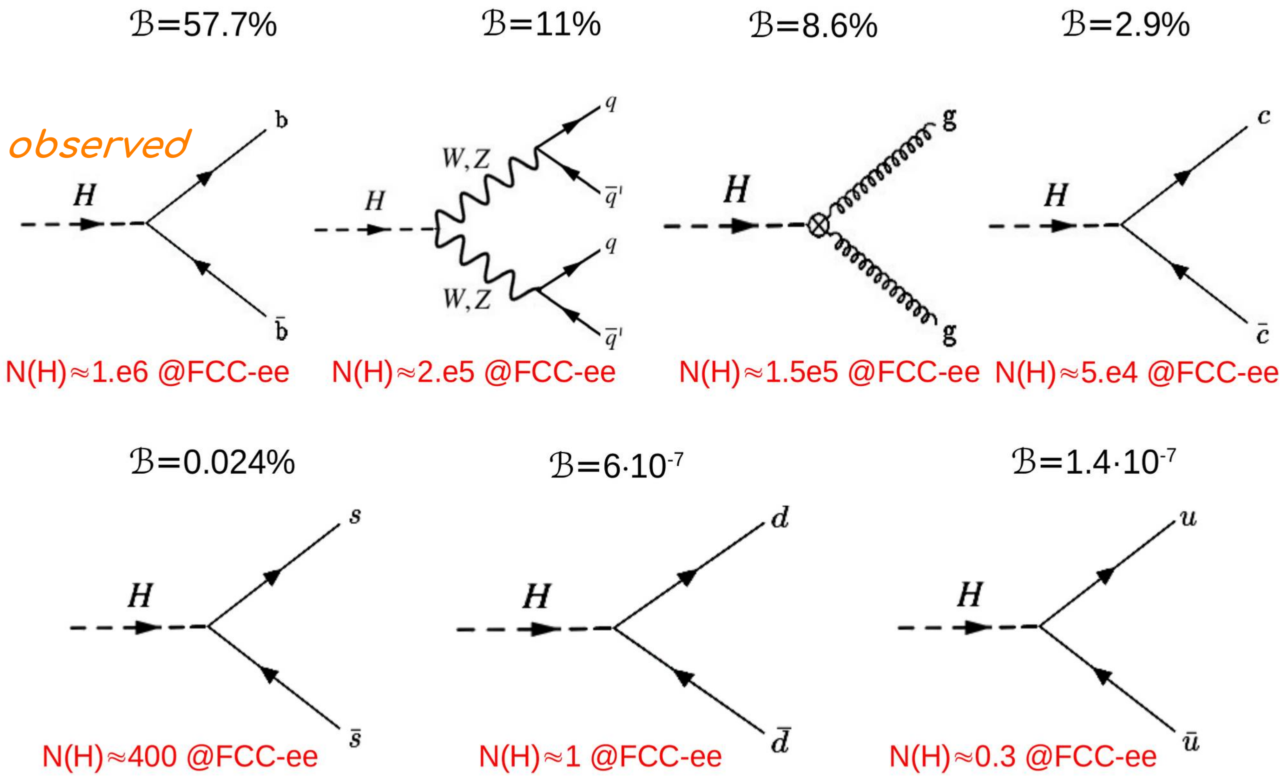
Nominal configuration → Nominal
Crystal ECAL to Dual Readout → Degradation electron resolution
Nominal 2 T → field 3 T → Magnetic field 3T
IDEA drift chamber → CLD Si tracker → Silicon tracker
Impact of Beam Energy Spread → BES 6% uncertainty / Disable BES
Perfect (=gen-level) momentum resolution → Ideal resolution

Statistical (stat+syst) uncertainty on the Higgs mass (MeV) for various fit configurations

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→bb	0.7	0.4	0.3	0.22
H→cc	4.1	2.2	3.3	1.7
H→ss	230	150	440	120
H→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→dd	1.4e-03	6e-07
H→uu	1.5e-03	1.4e-07
H→bs	3.7e-04	e-07
H→bd	2.7e-04	e-09
H→sd	7.7e-04	e-11
H→cu	2.5e-04	e-20

Electron Yukawa

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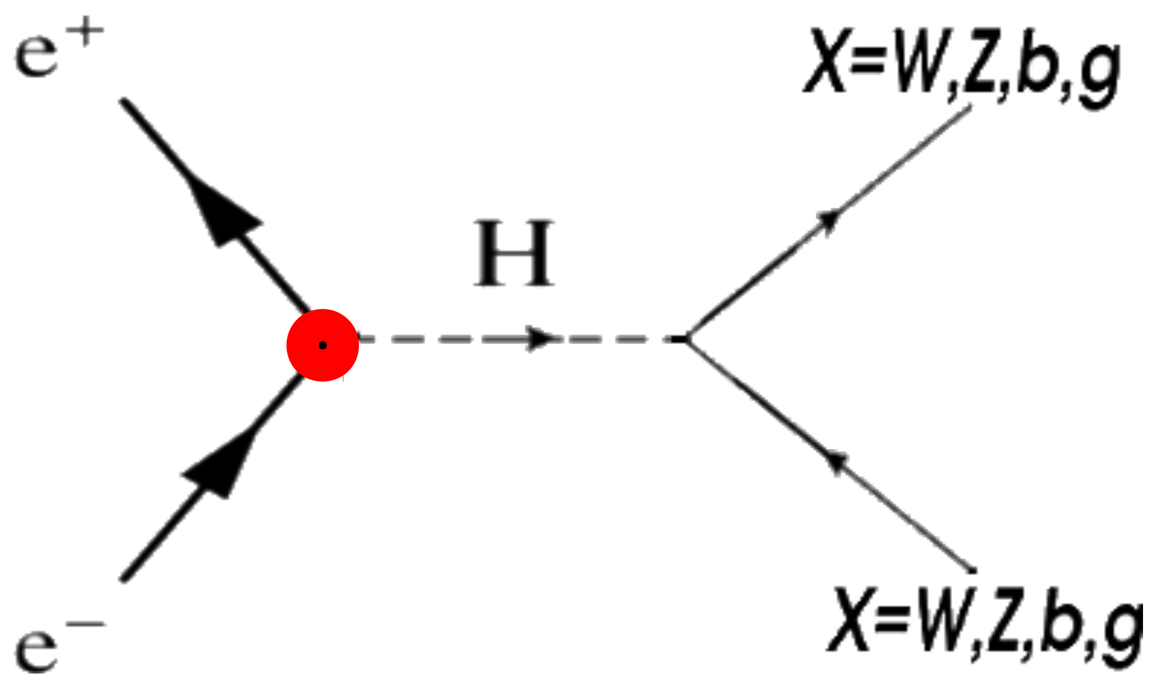
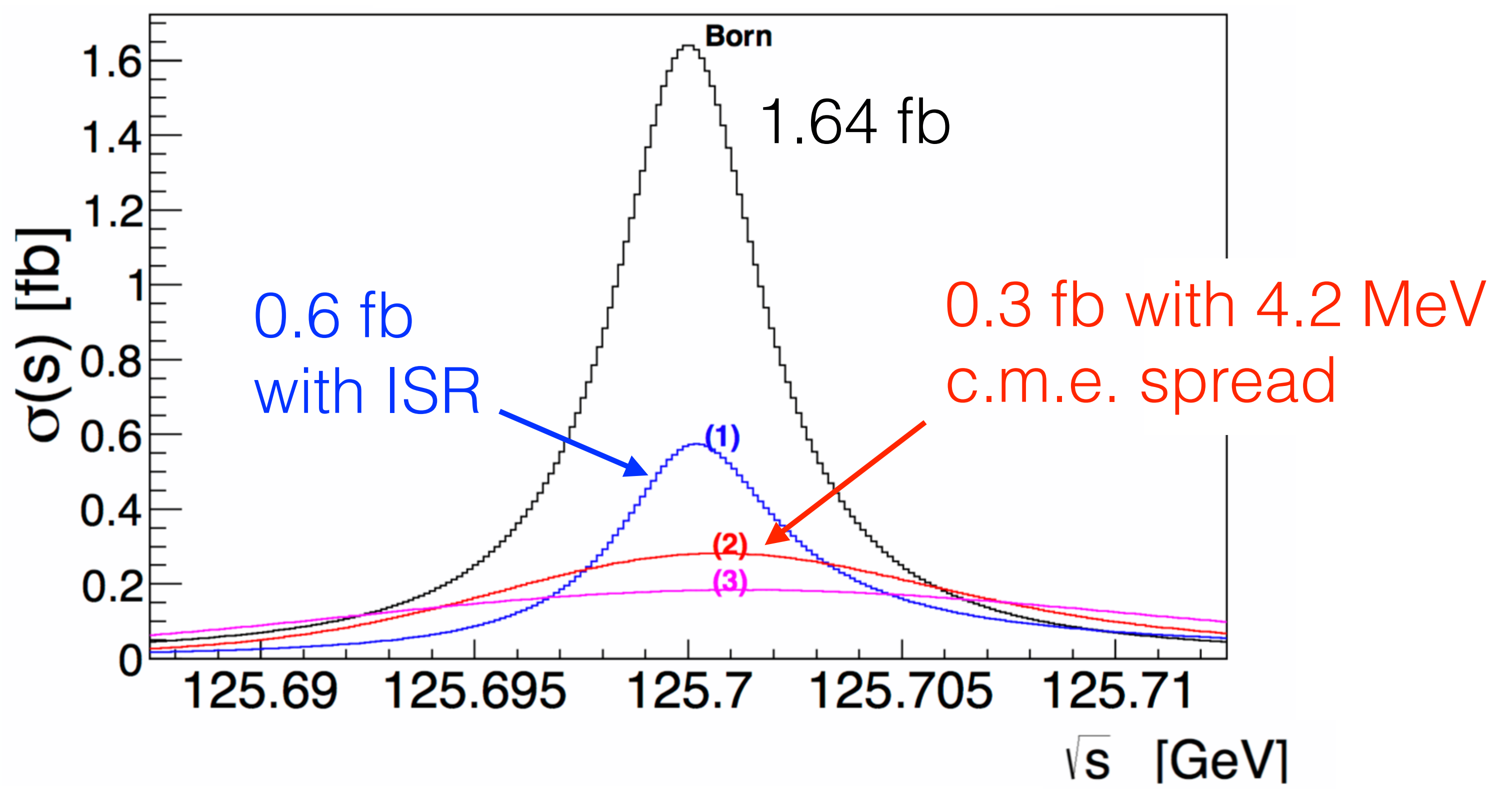


Jadach+, arXiv: 1509.02406



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

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

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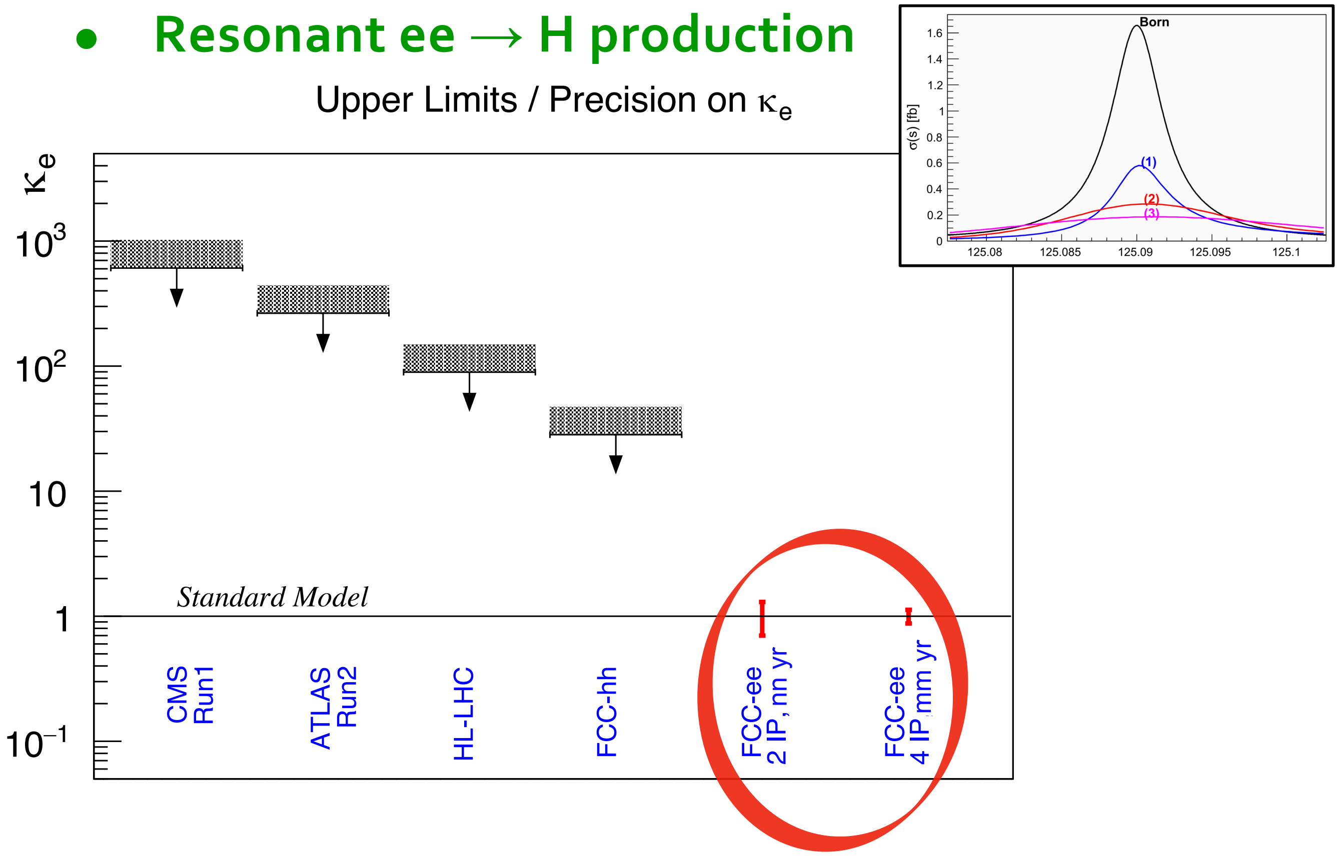
- **20 ab^{-1} / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}} \sim 1\text{-}2 \times \Gamma_H \sim$ 6 to 10 MeV**
  - **Resonant ee → H production**



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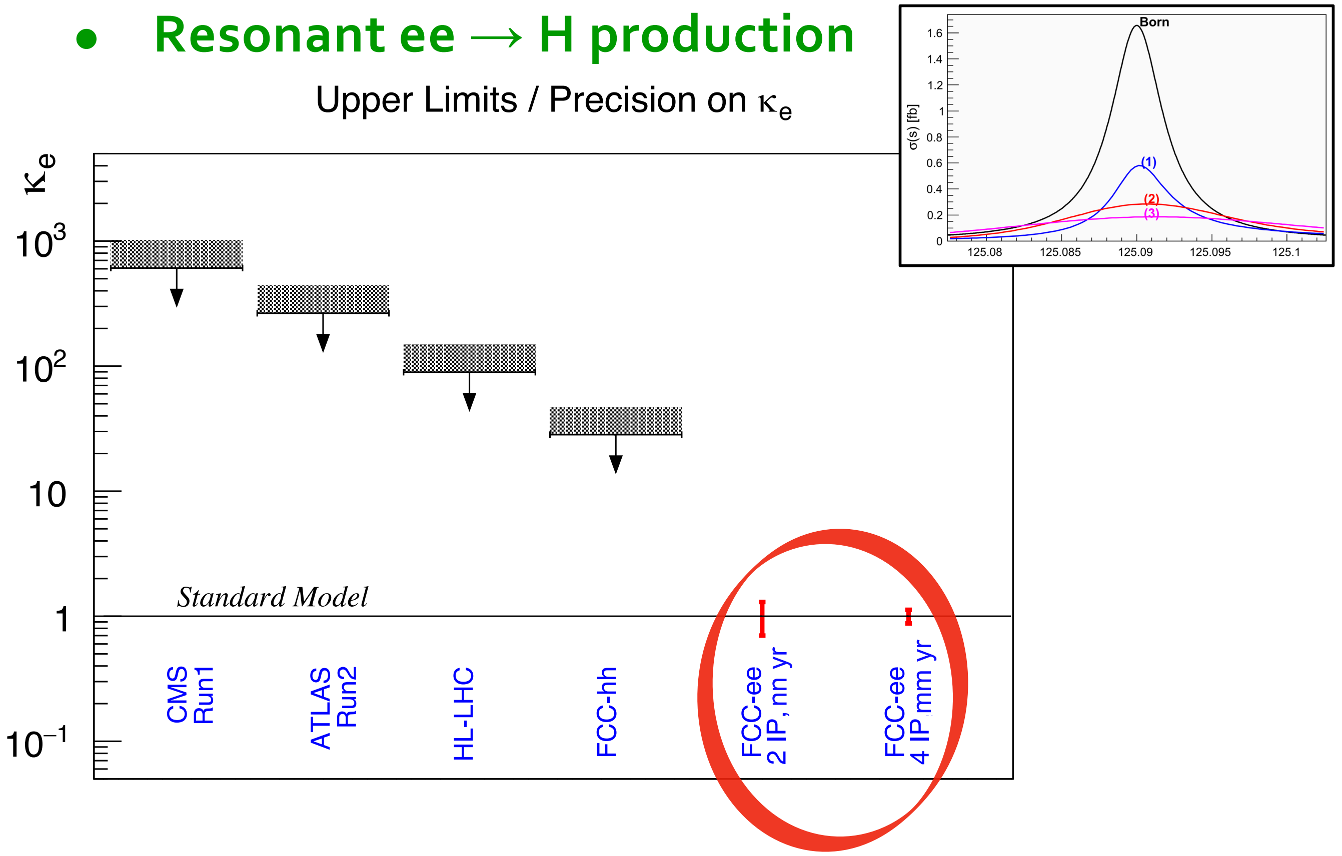
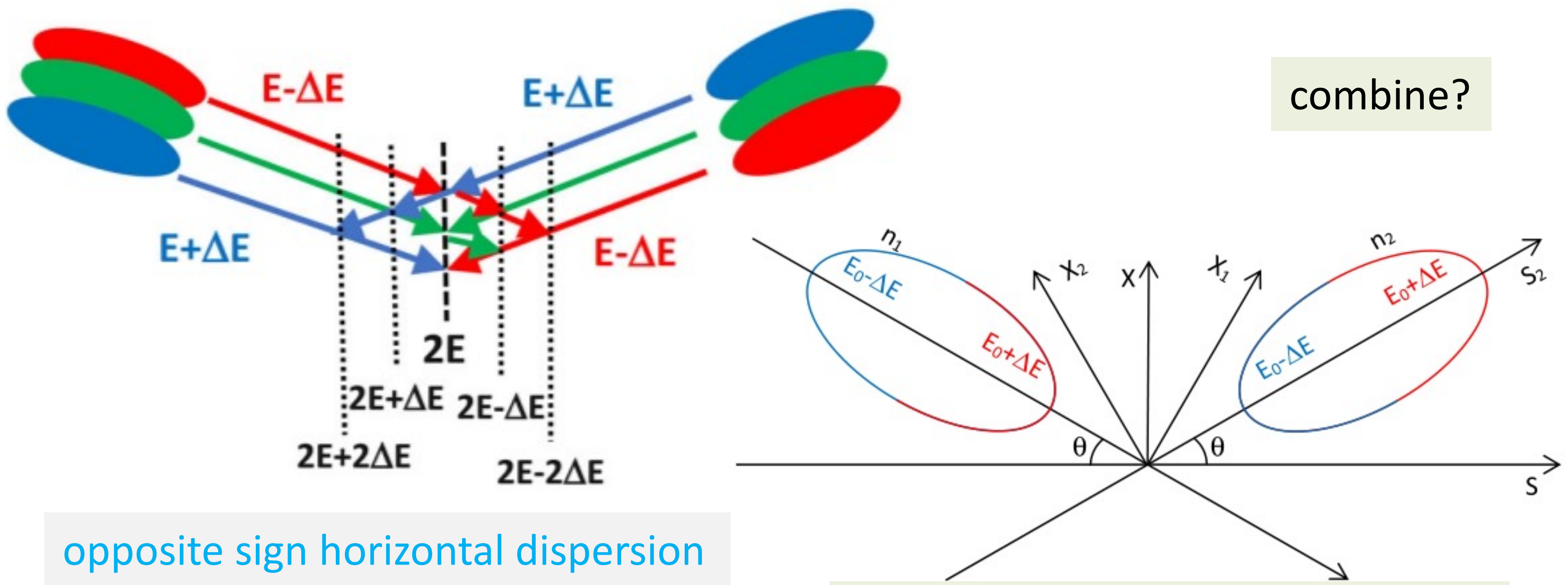


Monochromatisation

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)



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	$\mathcal{O}(10^{-6})$
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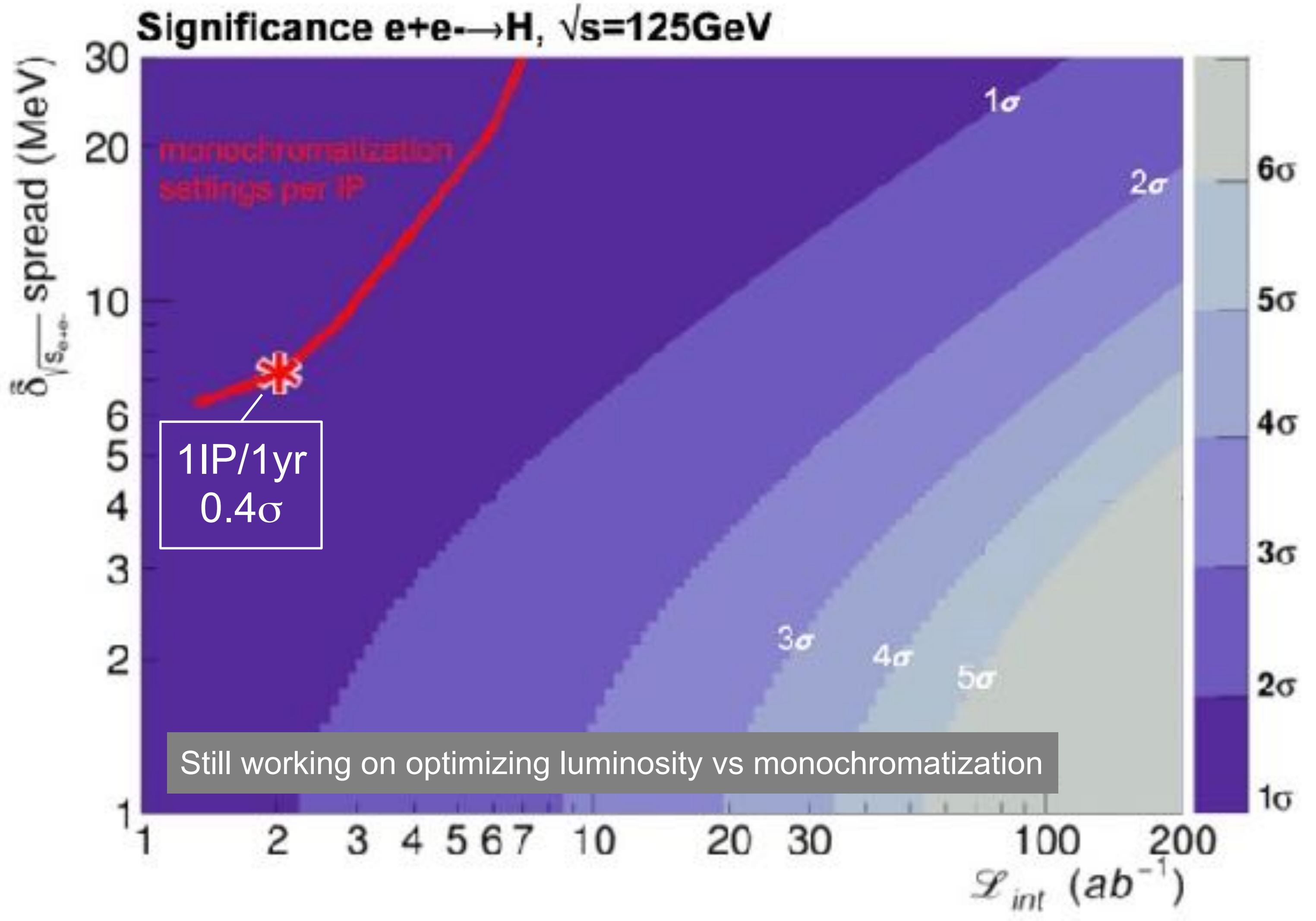
w. 10/ab

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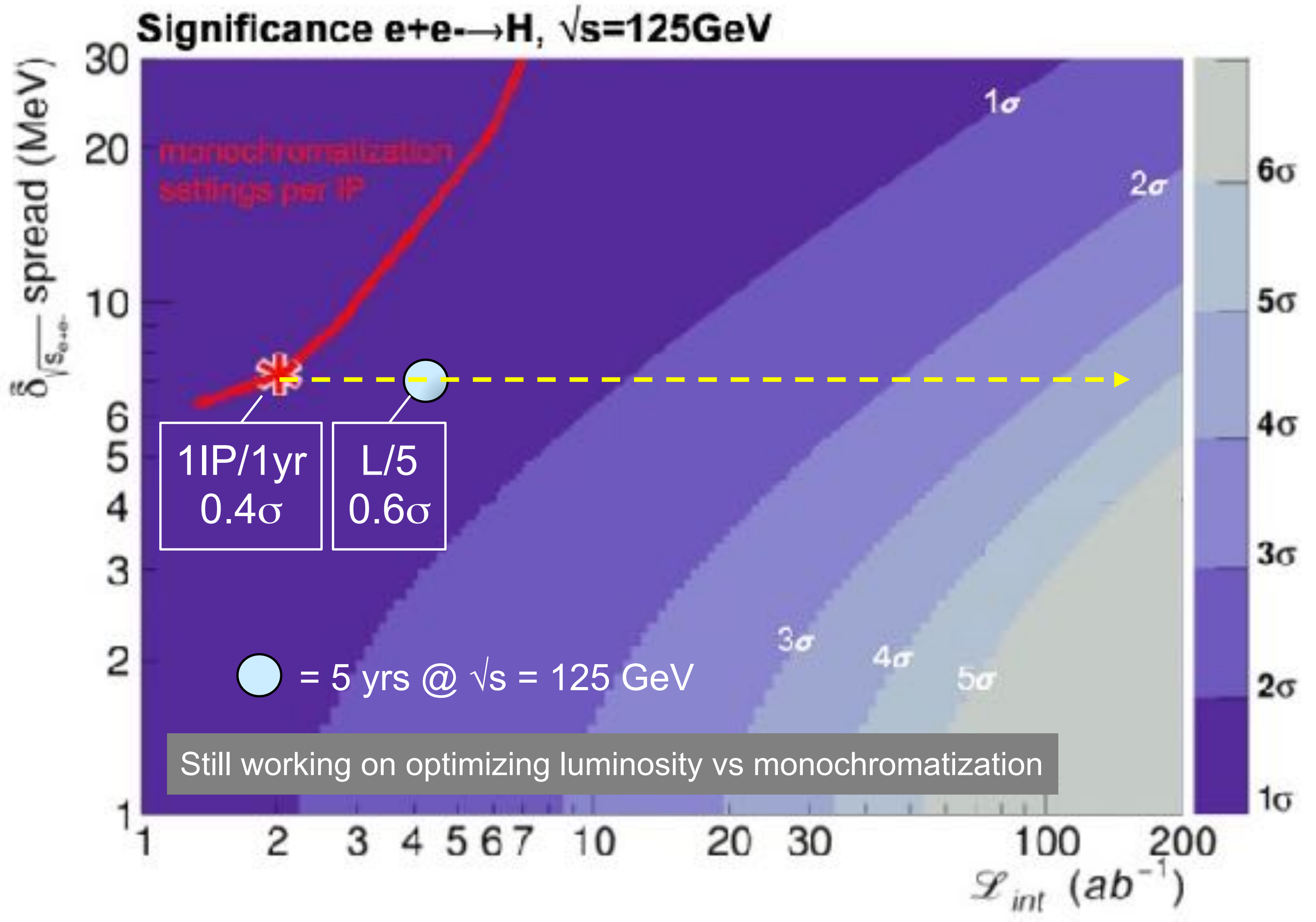

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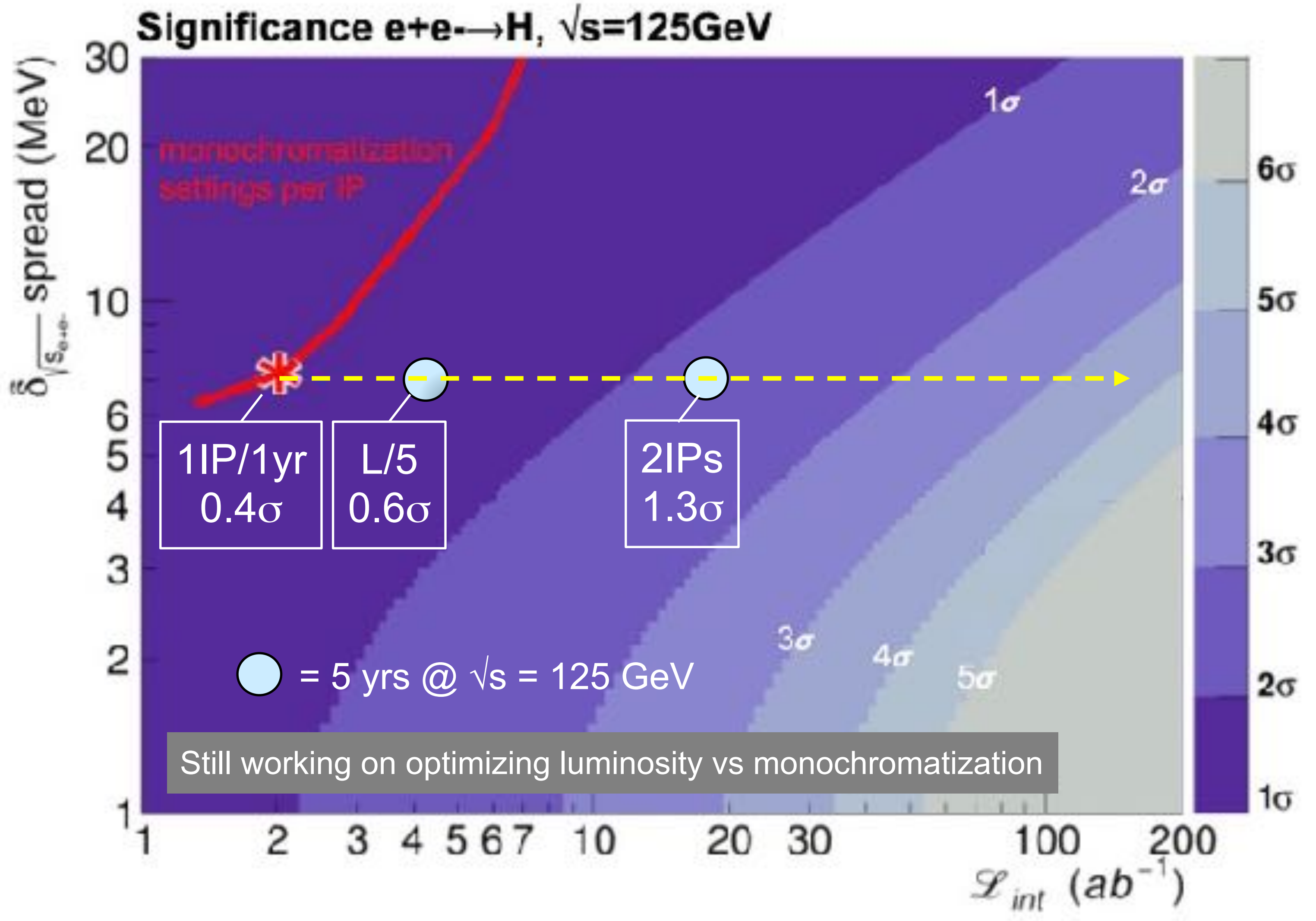

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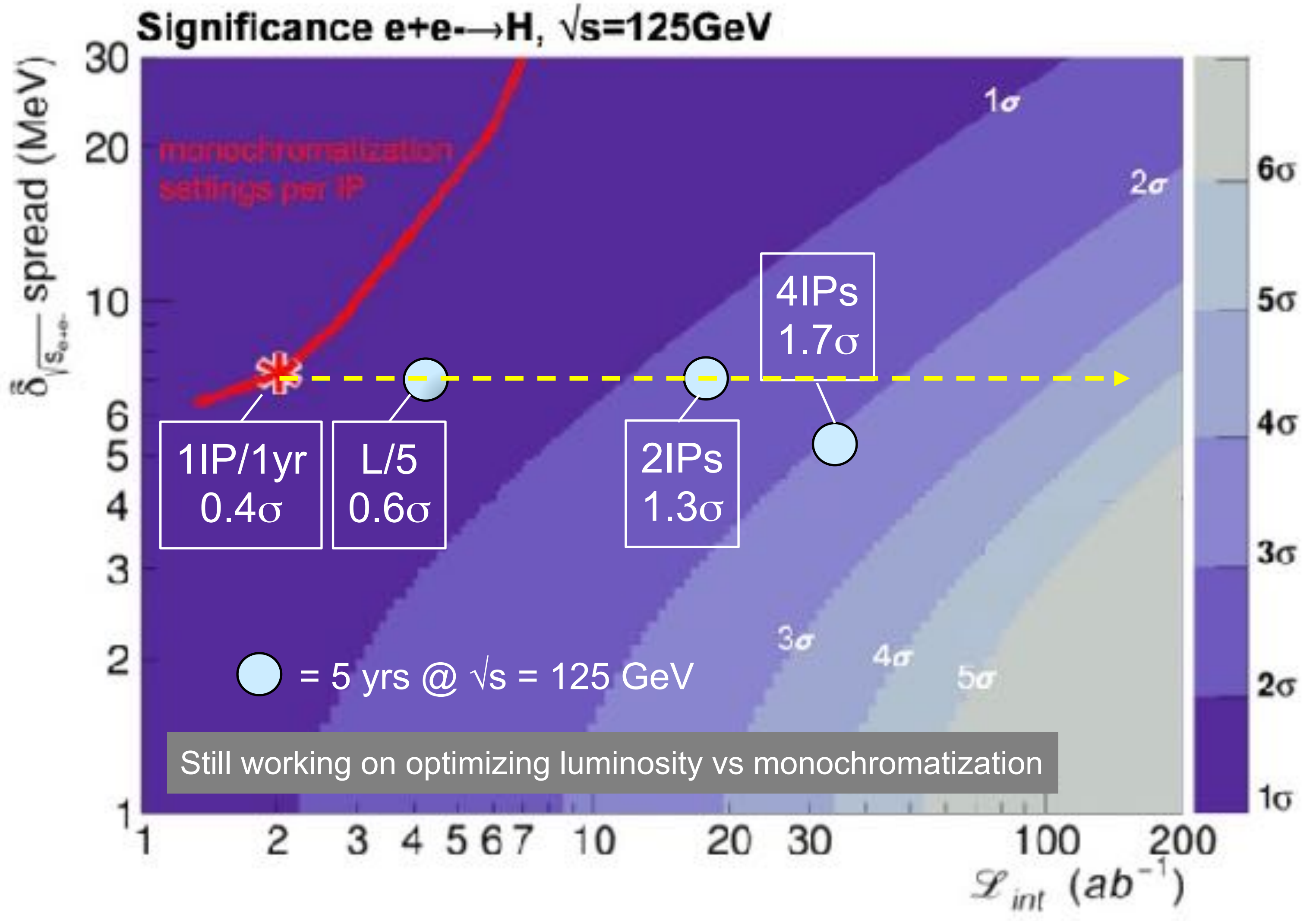

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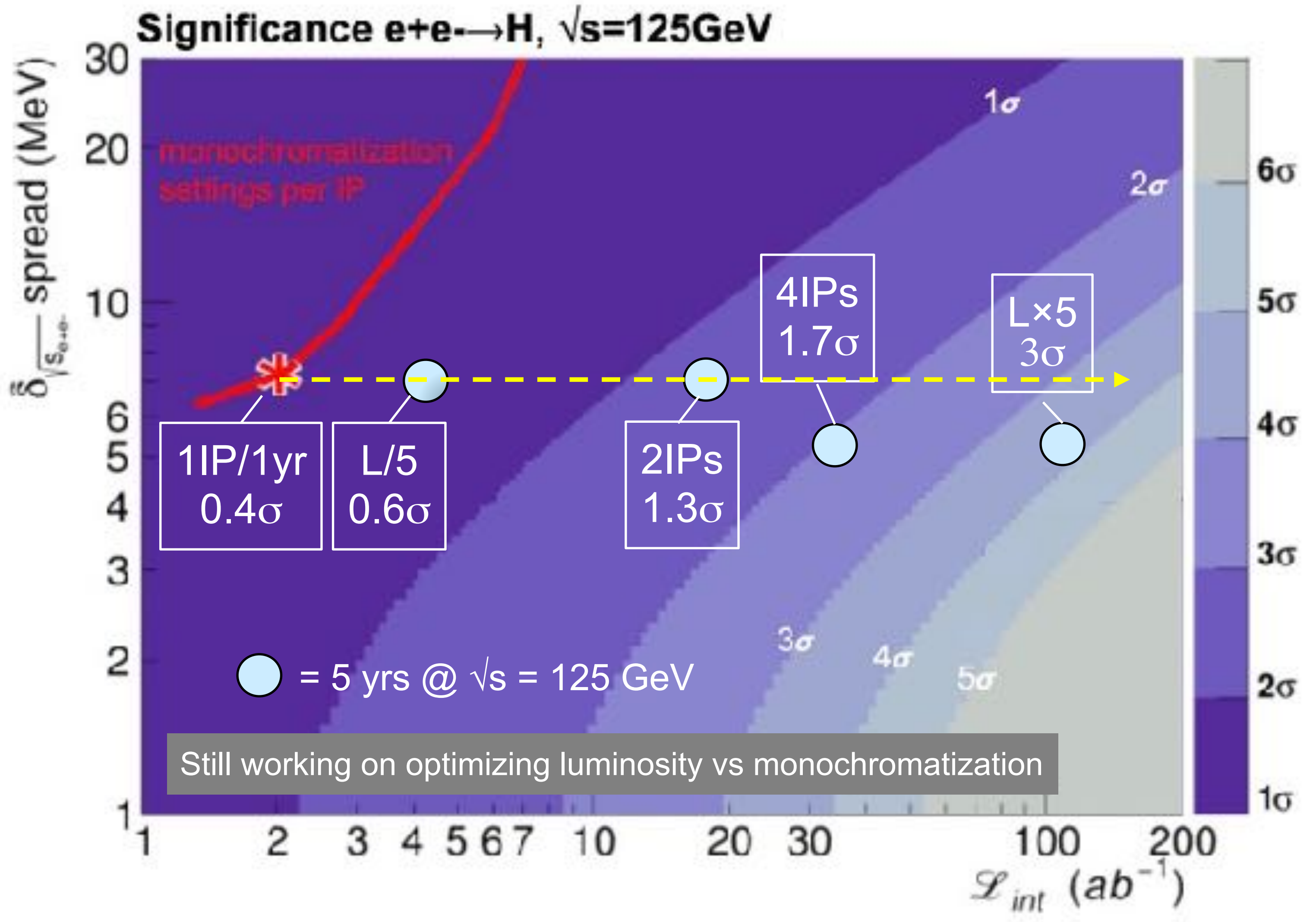
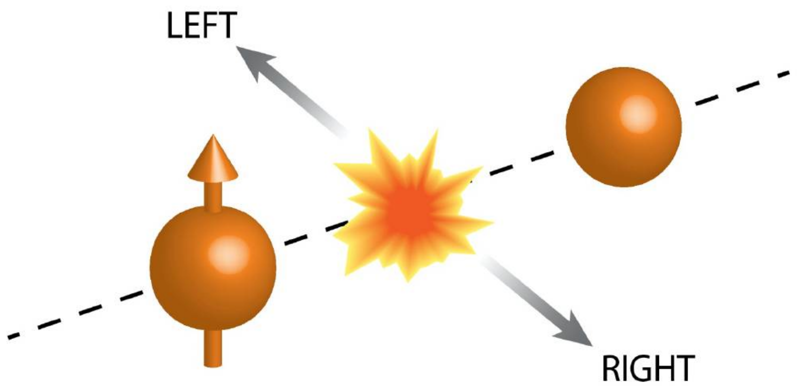


4σ expected with 4 IP in 4 years

Electron Yukawa

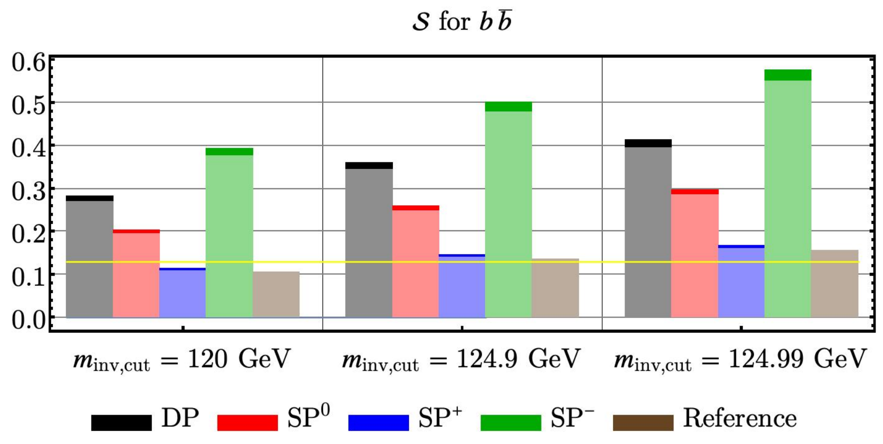
A recent pheno study (Boughezal et al 2407.12975) shows that transverse spin asymmetries can increase the sensitivity to the electron Yukawa

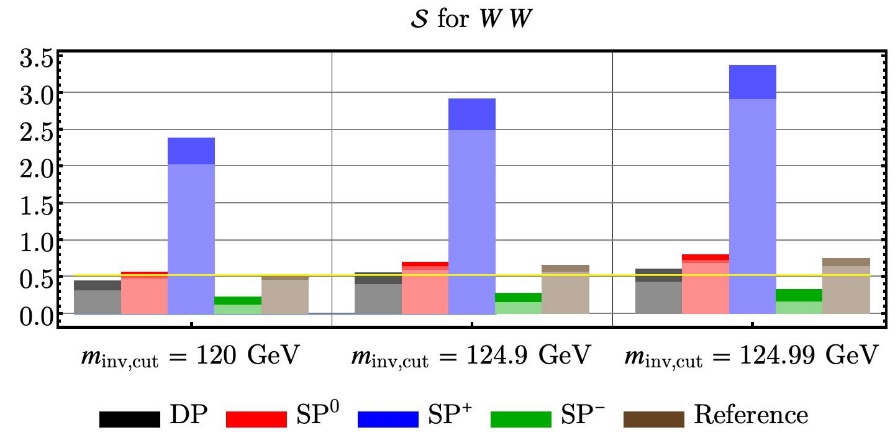


$$A = \frac{N}{D}$$

Electron polarized, positron unpolarized (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⁺):	$N = \frac{1}{2}(\sigma^{++} - \sigma^{-+})$, $D = \frac{1}{2}(\sigma^{++} + \sigma^{-+})$
Electron transversely polarized, positron longitudinally polarized (SP⁻):	$N = \frac{1}{2}(\sigma^{+-} - \sigma^{--})$, $D = \frac{1}{2}(\sigma^{+-} + \sigma^{--})$

8



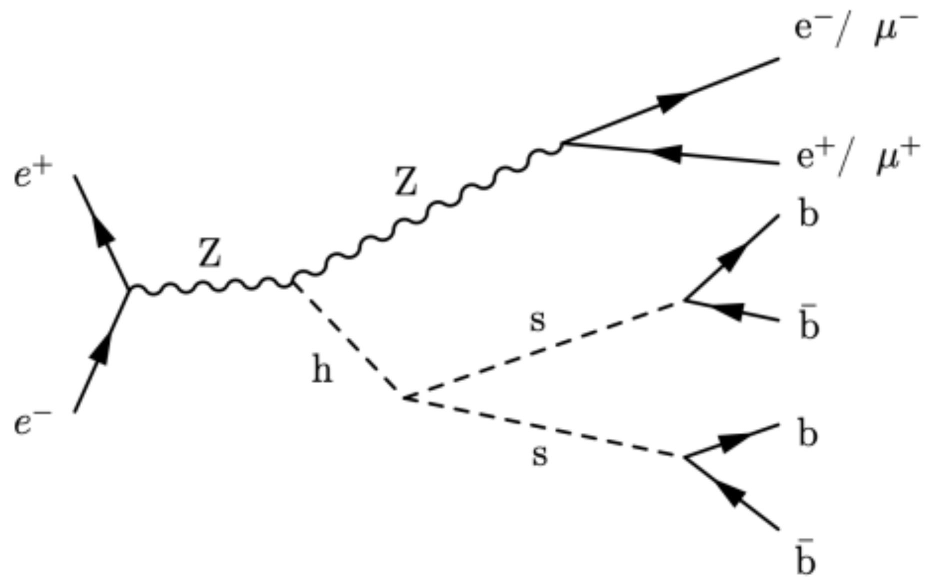


Major improvements of up to factors of 6 possible for bb and WW (doesn't work for gg)

Exotic Higgs Decays: dark scalar

Real scalar field extension (Dark Sector?)

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{kin}} + \frac{\mu_s^2}{2} S^2 - \frac{\lambda_s}{4!} S^4 - \frac{\kappa}{2} S^2 |H|^2 + \mu^2 |H|^2 - \lambda |H|^4$$



Background-free sensitivity at FCC-ee for scalars between 1 mm and 10 m decay length

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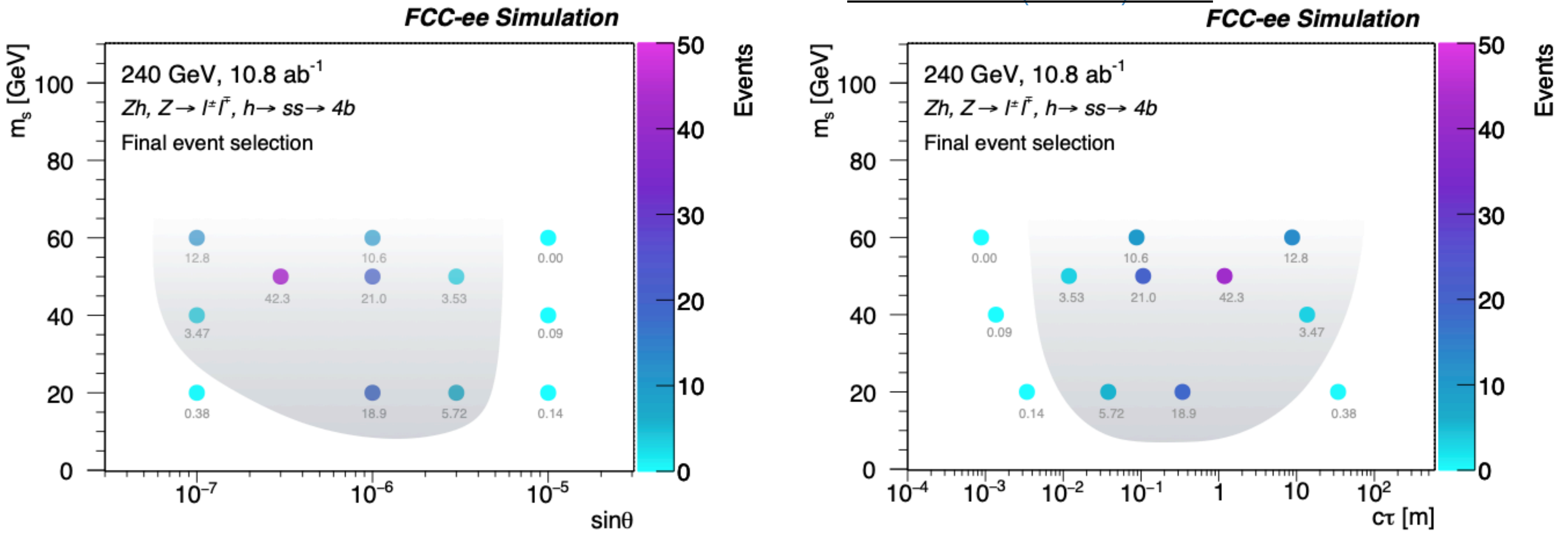
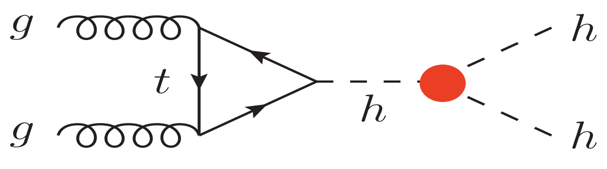
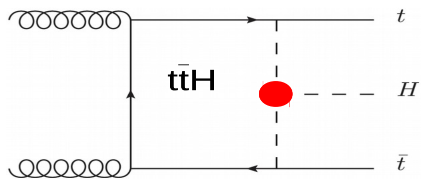
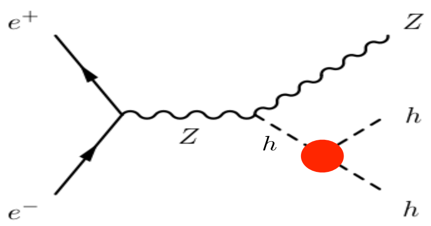
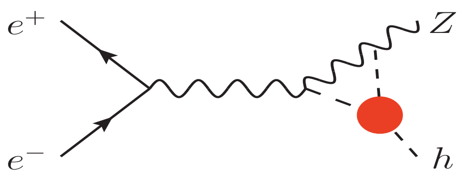


Number of selected signal events as a function of (a) dark scalar mass and mixing parameter and (b) dark scalar mass and lifetime. The shaded region is drawn around signal points with at least three events.

Higgs Self-Coupling

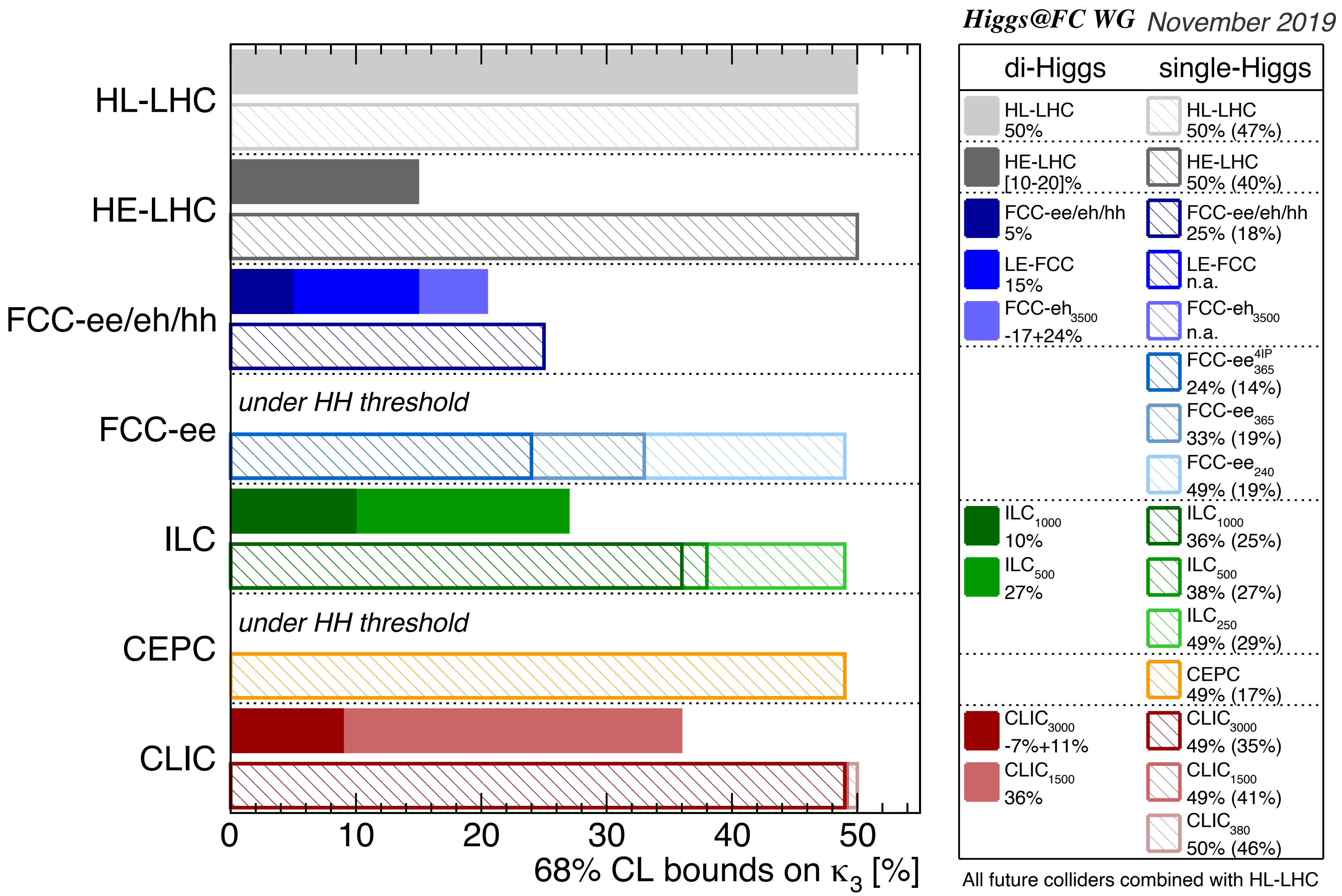
How much can it deviate from SM given the tight constraints on other Higgs couplings?
Do we need to reach HH production threshold to constrain h^3 coupling?

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

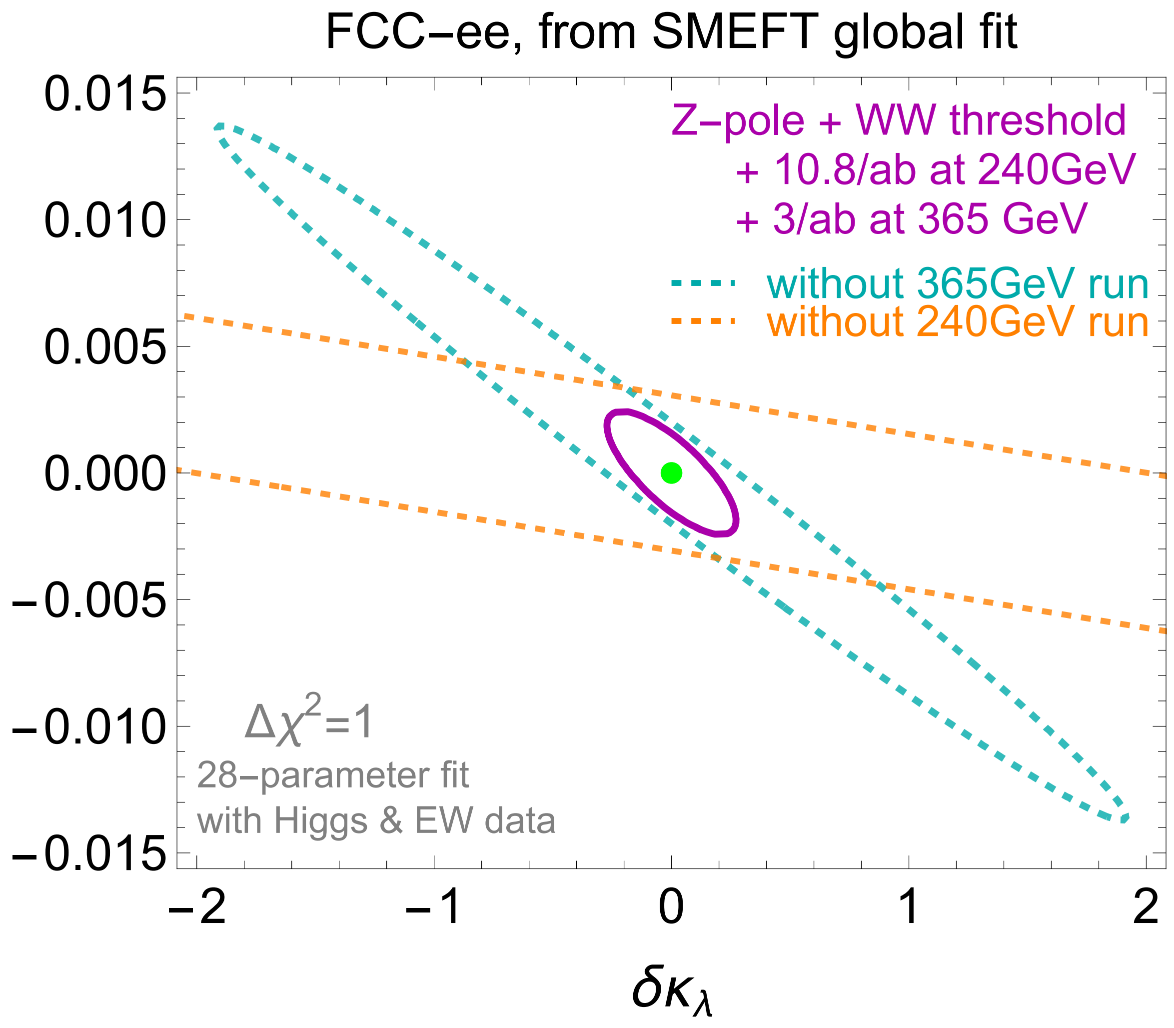


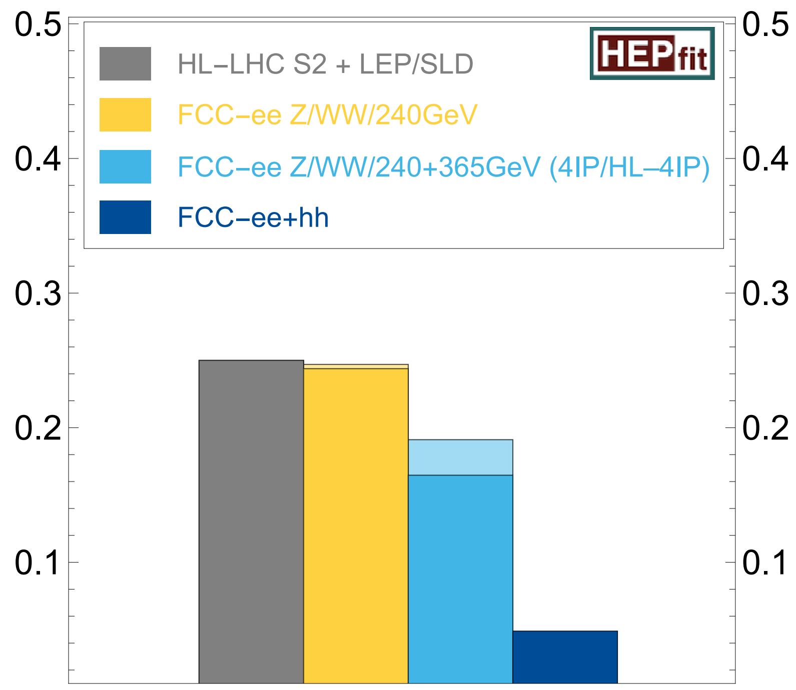
1. Don't need to reach HH threshold to have access to h^3.
Runs at different energies are essential
(e.g. 240 and 365 GeV)

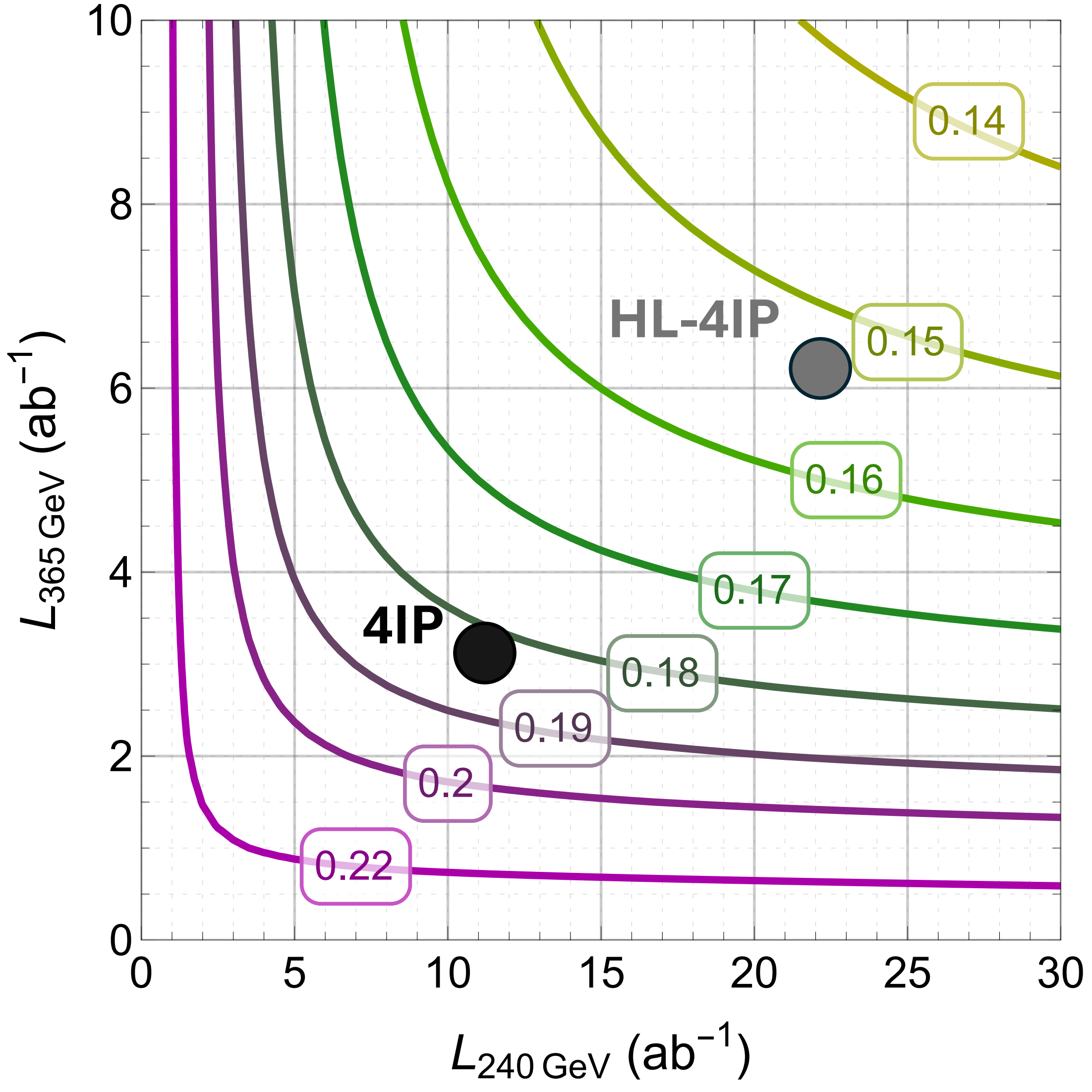
2. The determination of h^3 at FCC-hh relies on HH channel,
for which FCC-ee is of little direct help.
But the extraction of h^3
requires precise knowledge of y_t.
1% $y_t \leftrightarrow$ 5% h^3
Precision measurement of y_t needs FCC-ee.

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







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

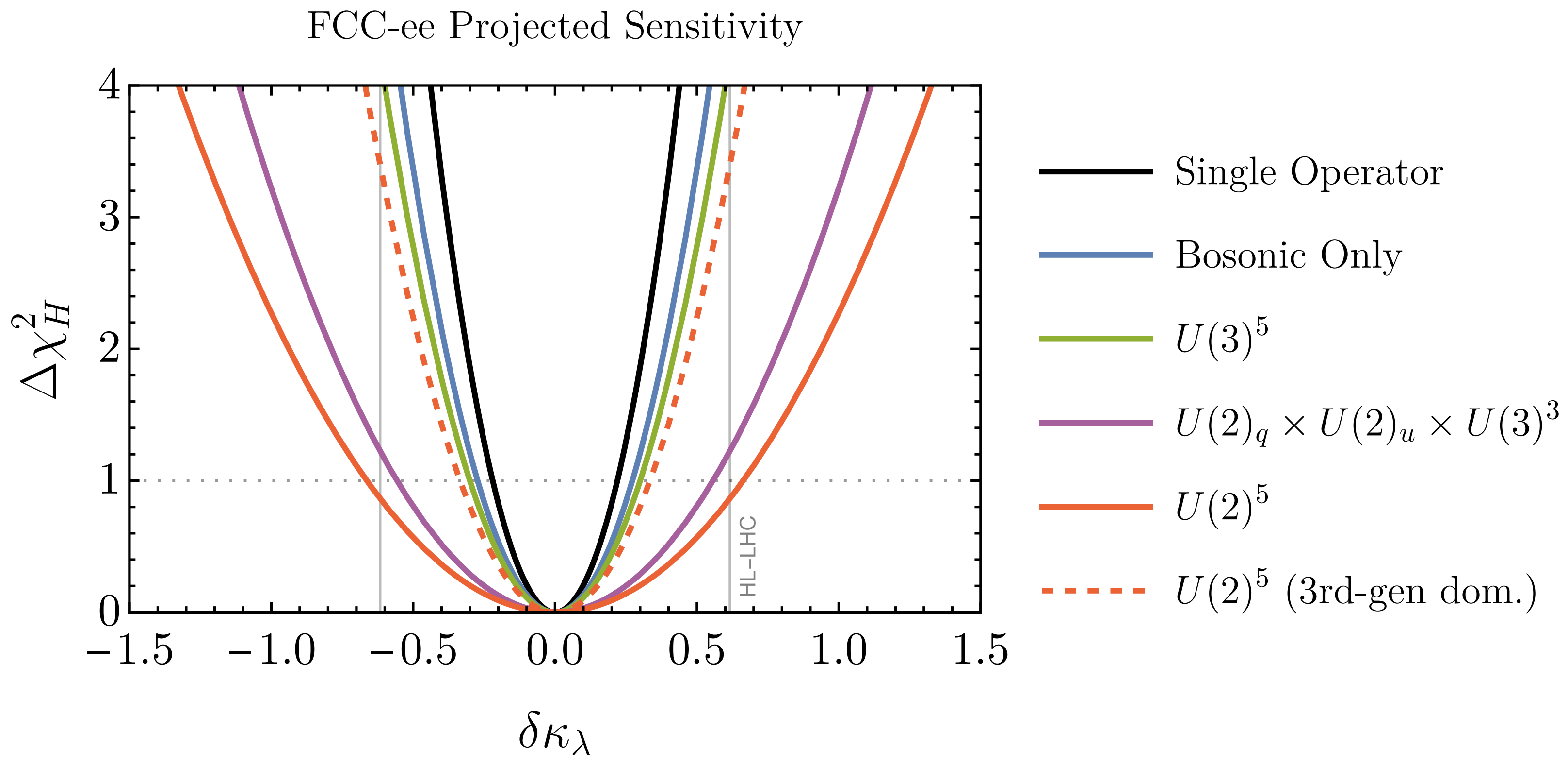
Higgs Self-Coupling

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%

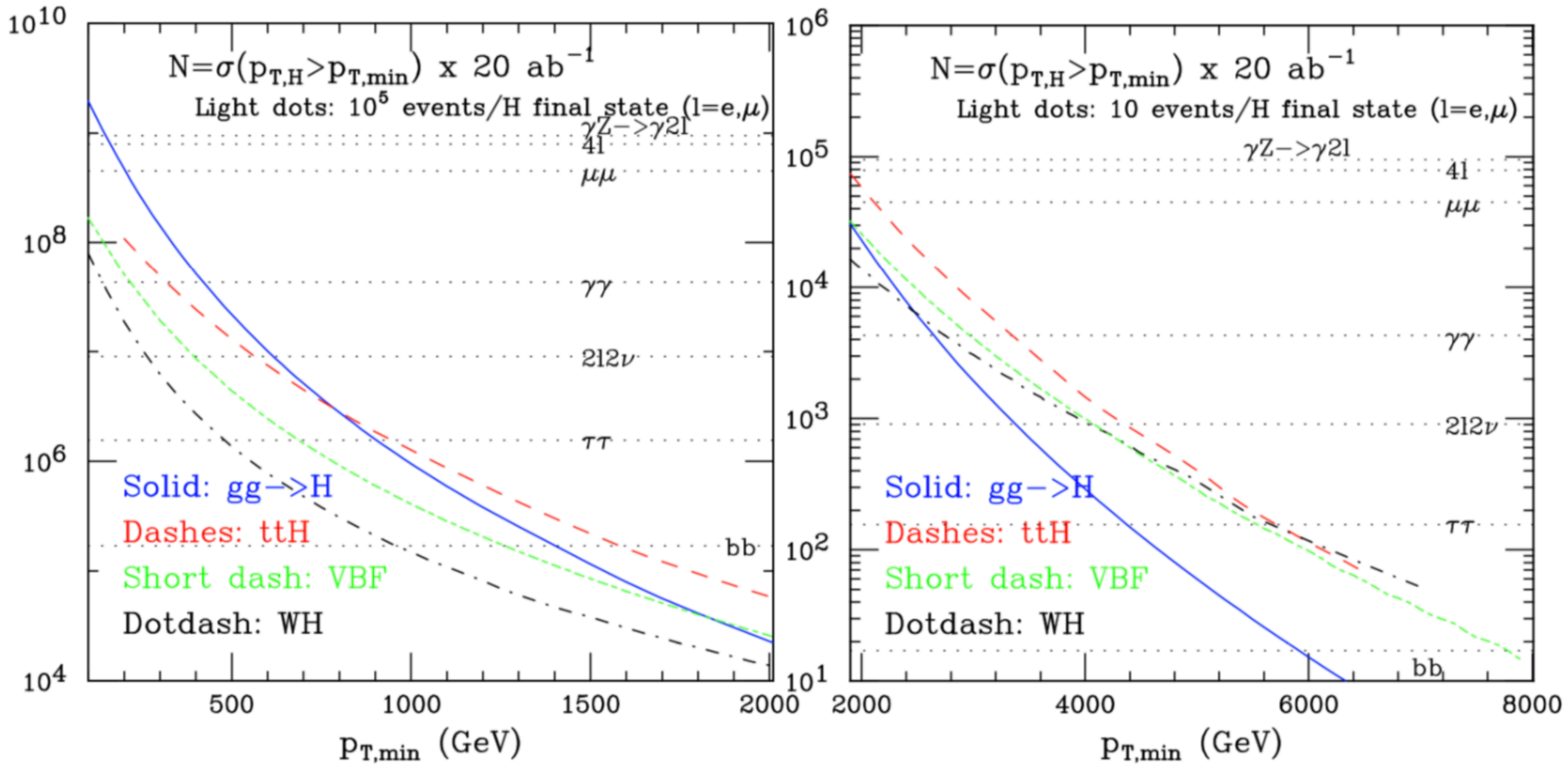


Higgs @ FCC-hh.

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

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



- 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.

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}

Electroweak Factory

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
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	150
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	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, Γ_{tot}^Z, σ_{had}^0 fit	
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement	
N_ν($\times 10^3$)	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	
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	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, Γ_{tot}^W fit	
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns	
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate	70
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate	
$\lambda_{top}/\lambda_{top}^{SM}$	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	

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).

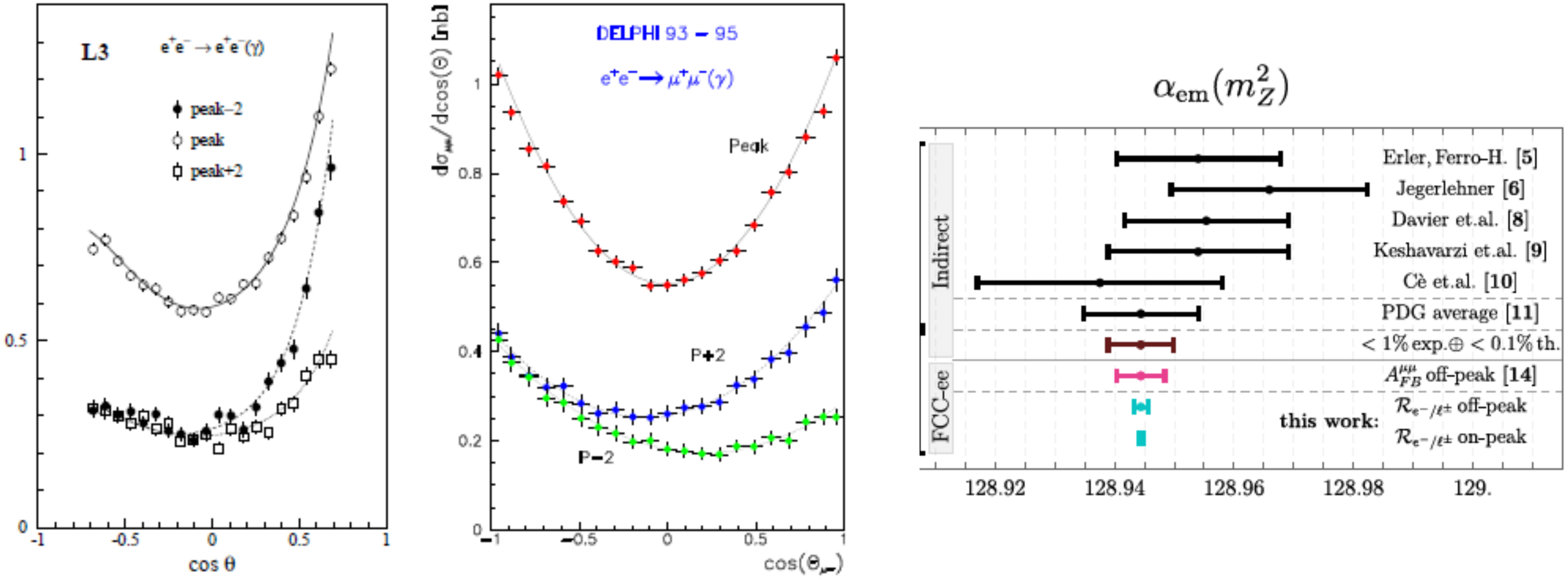
$\alpha_{QED}(m_Z)$

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 $\sqrt{s}$ → **$\pm 3\times10^{-5}$**
- **On-pole** (Riembau 2025): both s and t- channel $e^+e^- \to e^+e^-$ and $\mu^+\mu^-$ at the Z pole → **$\pm 0.6\times10^{-5}$**

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



W Mass

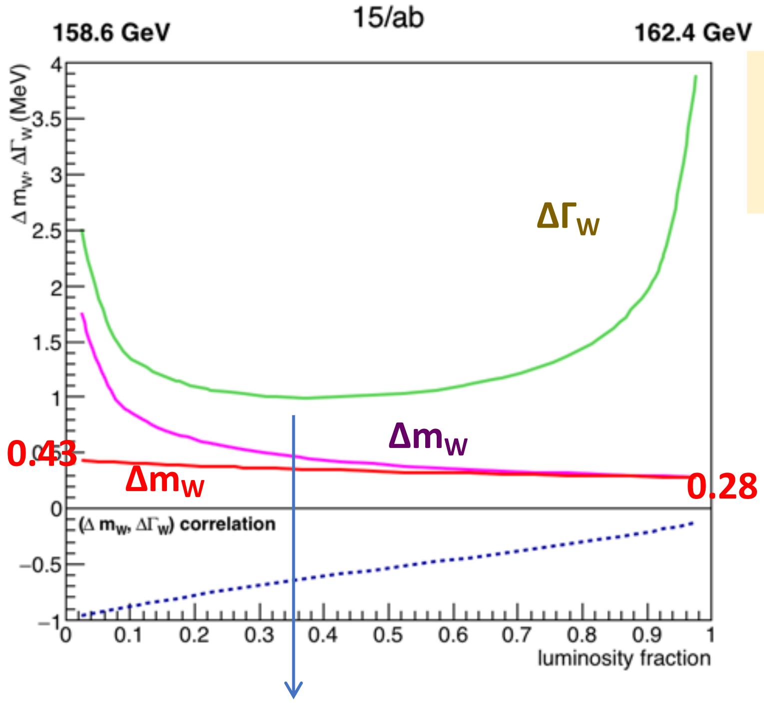
Two independent W mass and width measurements @FCCee :

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**

a factor 2 improvement from Feasibility Report

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.

QCD Factory

QCD uber alles

What is needed

- **Precise understanding of strong interaction** crucial to exploit broad range of SM measurement and BSM searches
  - **Precise determination of α_S**: prediction of all ee XS and decays
  - **Accurate pQCD calculation** (NxLO, NxLL): prediction precision, extraction of SM quantities from data
  - **Heavy/light quark/gluon separation**: ex: Higgs Yukawa couplings to q and g
  - **NP dynamics** (colour reconnection, hadronisation): impact all hadronic final states

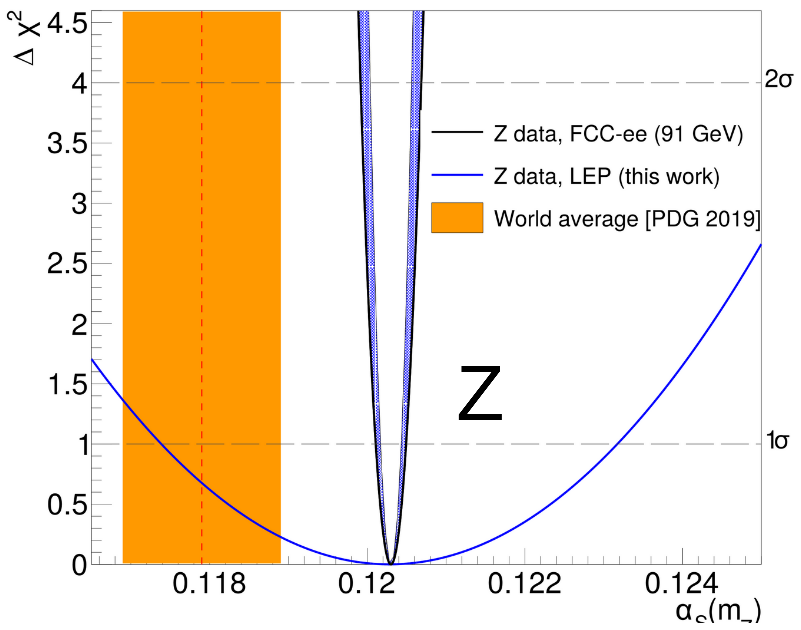
What the FCC-ee offers

- **Very high luminosity** across **wide range of energy scale**
- **Clean, controlled, well-defined setup:**
  - No PDF, no MPI, no beam remnants; uncoloured initial state
    → Well-known QED initial state
  - QCD radiations only in final state
  - Well separated jets, well defined parton flavour

→ Enables **very high-precision measurements**

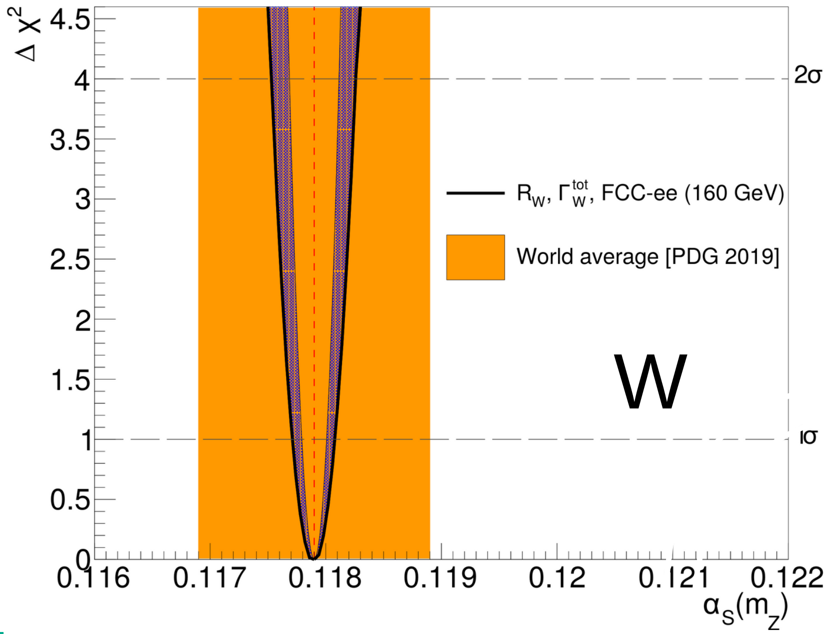
$\alpha_{QCD}(m_Z)$

Total exp rel. unc on α_{QCD}~0.1%



Combined fit at N3LO of Z boson total width Γ_Z
ratio of hadronic/leptonic branching fraction R_l^Z
total hadronic XS at the resonance peak σ^0_{had}

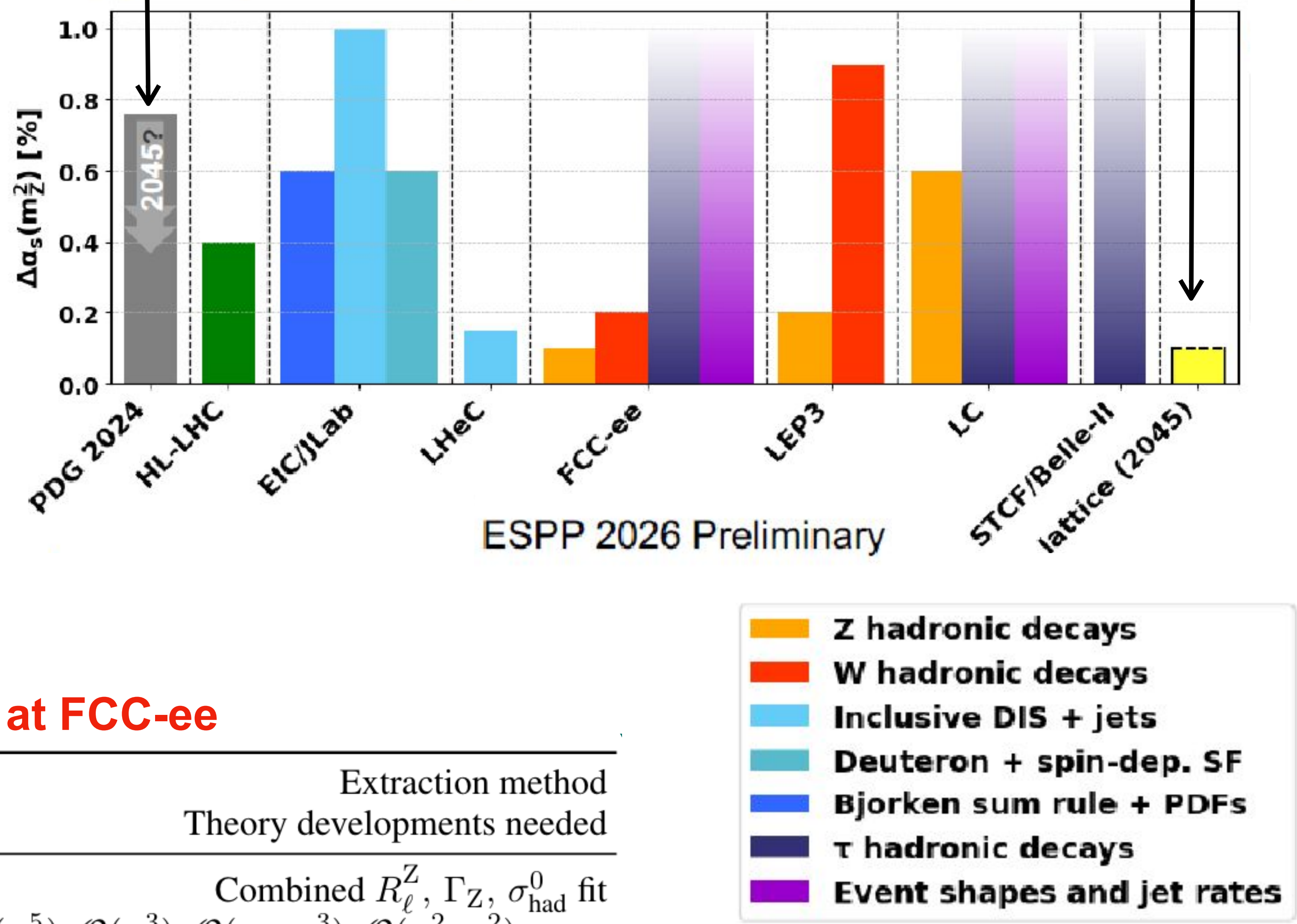
Total exp rel. unc on α_{QCD}~0.2%



Combined fit at N3LO of W boson total width Γ_W
ratio of hadronic/leptonic branching fraction R_l^W

currently $\alpha_s(m^2_Z)$ = 0.1180 ± 0.0009
i.e. 0.8% relative precision

future (lattice)
0.1 %



Foreseen α_s extractions at FCC-ee

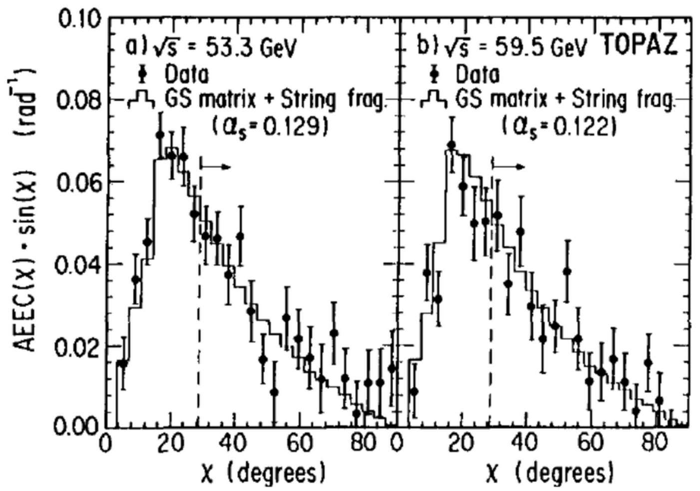
Category	present $\alpha_S(m_Z^2)$ ($\times 10^4$) value ± uncertainty	FCC-ee Stat.	FCC-ee Syst.	Extraction method / Theory developments needed
Z hadronic decays	1 208 ± 28	0.1	1	Combined R_ℓ^Z, Γ_Z, σ^0_{had} fit $\mathcal{O}(\alpha_S^5)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_S,\alpha^3)$, $\mathcal{O}(\alpha_S^2,\alpha^2)$ corrs.
W hadronic decays	1 070 ± 350	2	2	Combined R_ℓ^W, Γ_W fit $\mathcal{O}(\alpha_S^5)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_S,\alpha^3)$, $\mathcal{O}(\alpha_S^2,\alpha^2)$ corrs.
τ hadronic decays	1 178 ± 19	$\ll$1	<10	Combined $\Gamma^{\tau,had}$ and τ lifetime fit $\mathcal{O}(\alpha_S^5)$, hadronisation corrections
Event shapes & jet rates	1 171 ± 31	$\ll$1	<10	Combination of event shapes and jet rates $\mathcal{O}(\alpha_S^4)$, hadronisation corrections

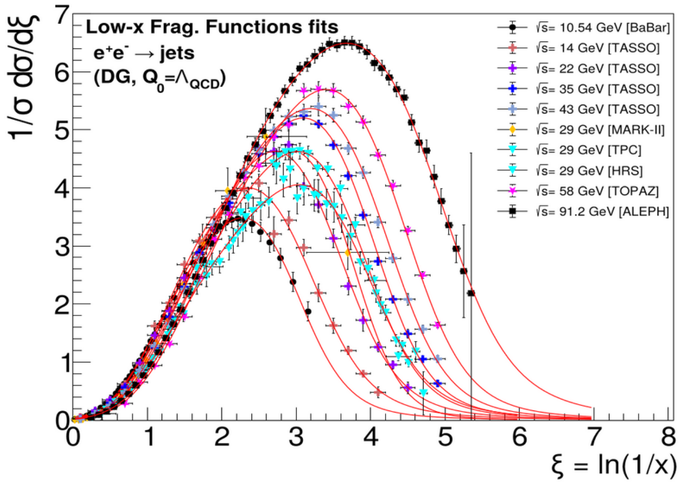
FCC-ee as a QCD factory

S. Kluth @ FCC week 2025

FCC-ee low energy $\sqrt{s} < m_Z$

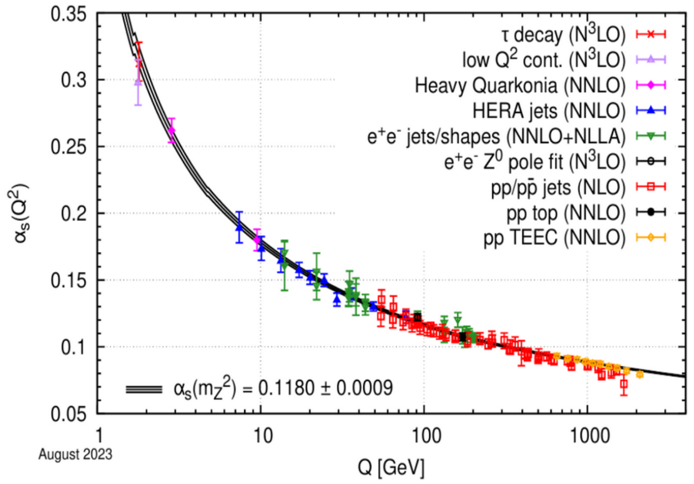
Hard vs soft QCD, Hadronisation

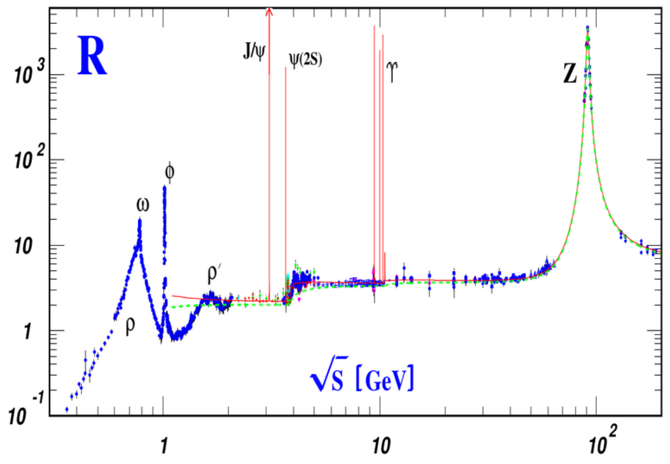




Fragmentation, QCD, MCs, Hadronisation

$\alpha_s(Q)$ event shapes, jets, FFs, EECs, Hadronisation





$R = \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$

α_s(20-40 GeV) at 0.1%?

[Back-up Document to FCC: QCD physics, arXiv:2503.23855]

Bonus EWPOs: A_{FB} $e^+e^- \to f\bar{f} \Rightarrow \sin^2(\theta_W)(Q)$

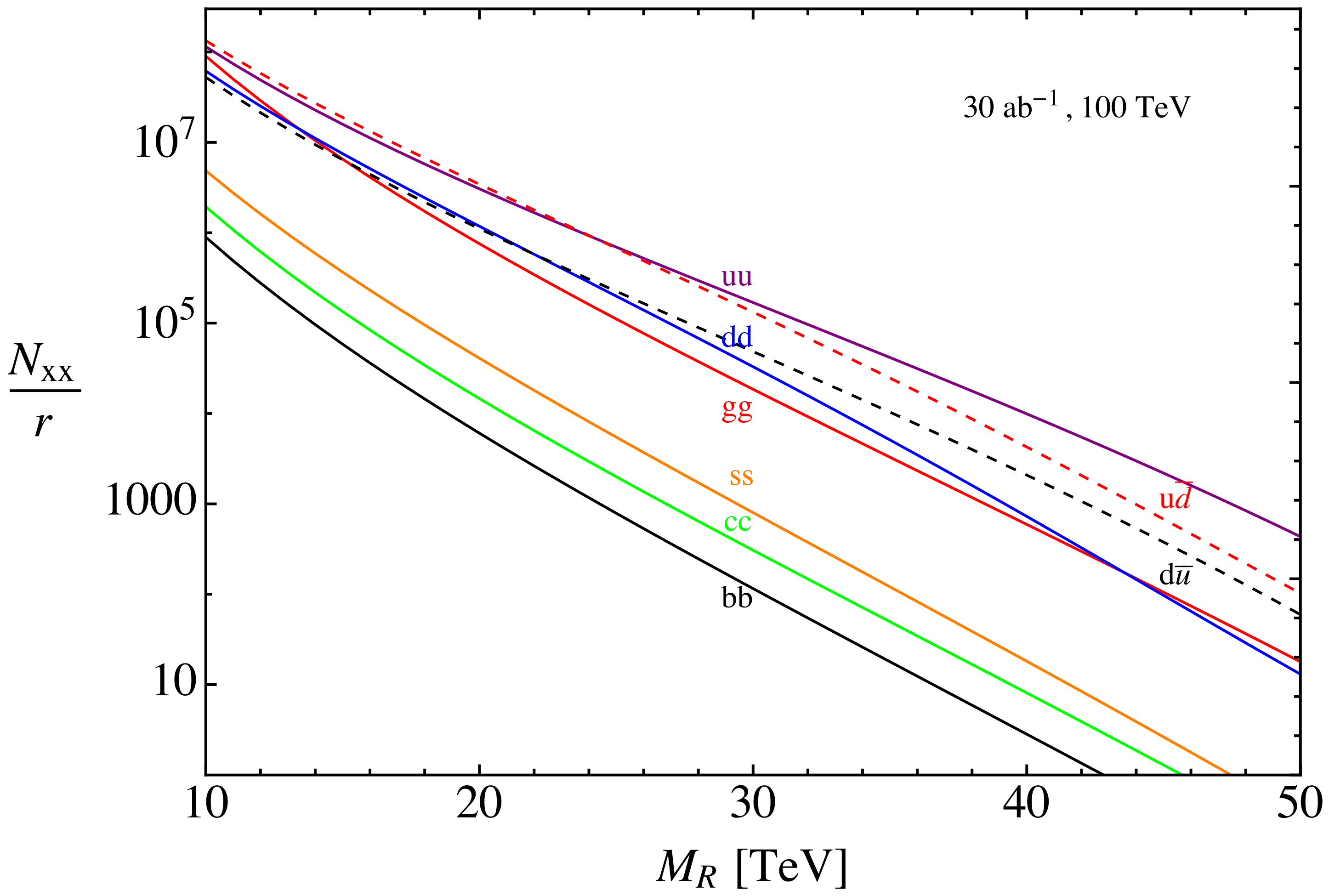
Exploration potential at high-energy with FCC-hh

Resonance production.

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

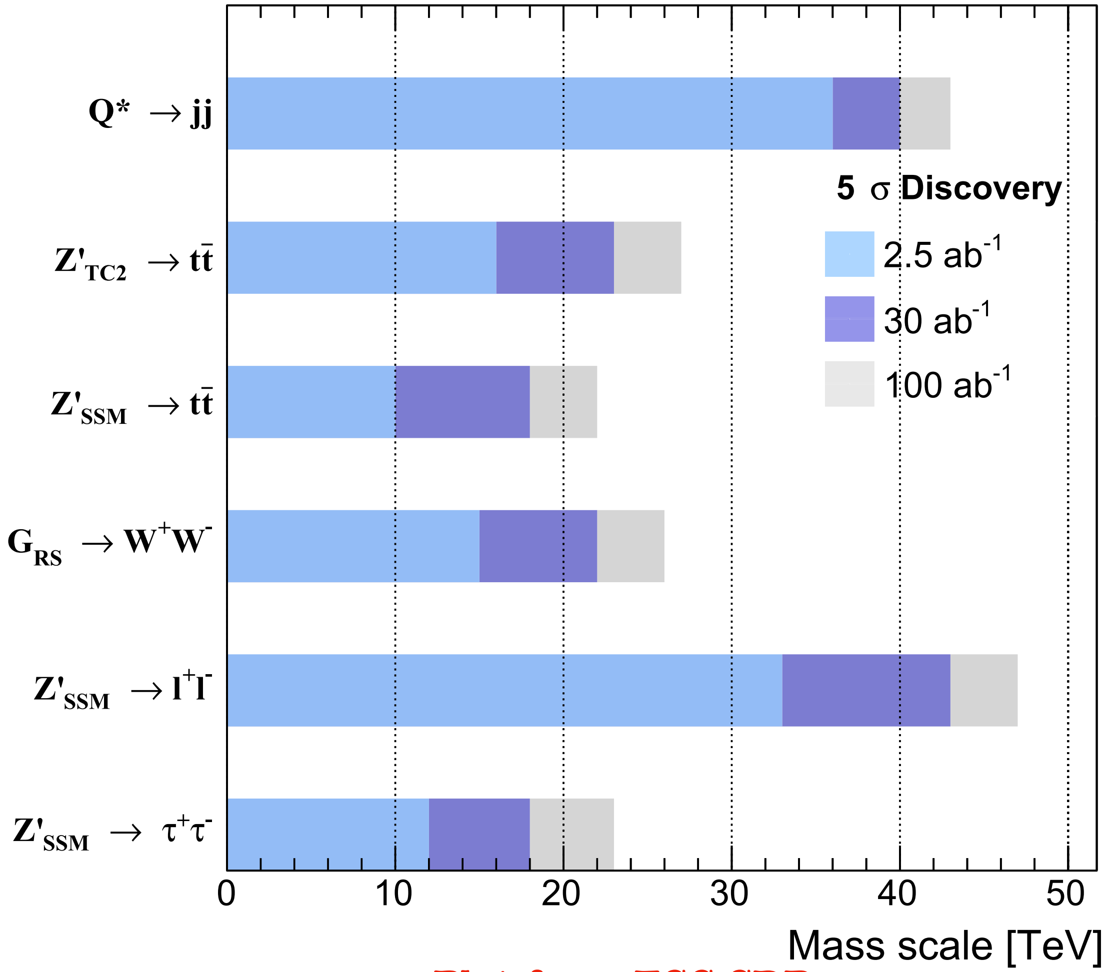
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

resonances produced



Plot from mid-term report

FCC-hh mass reach



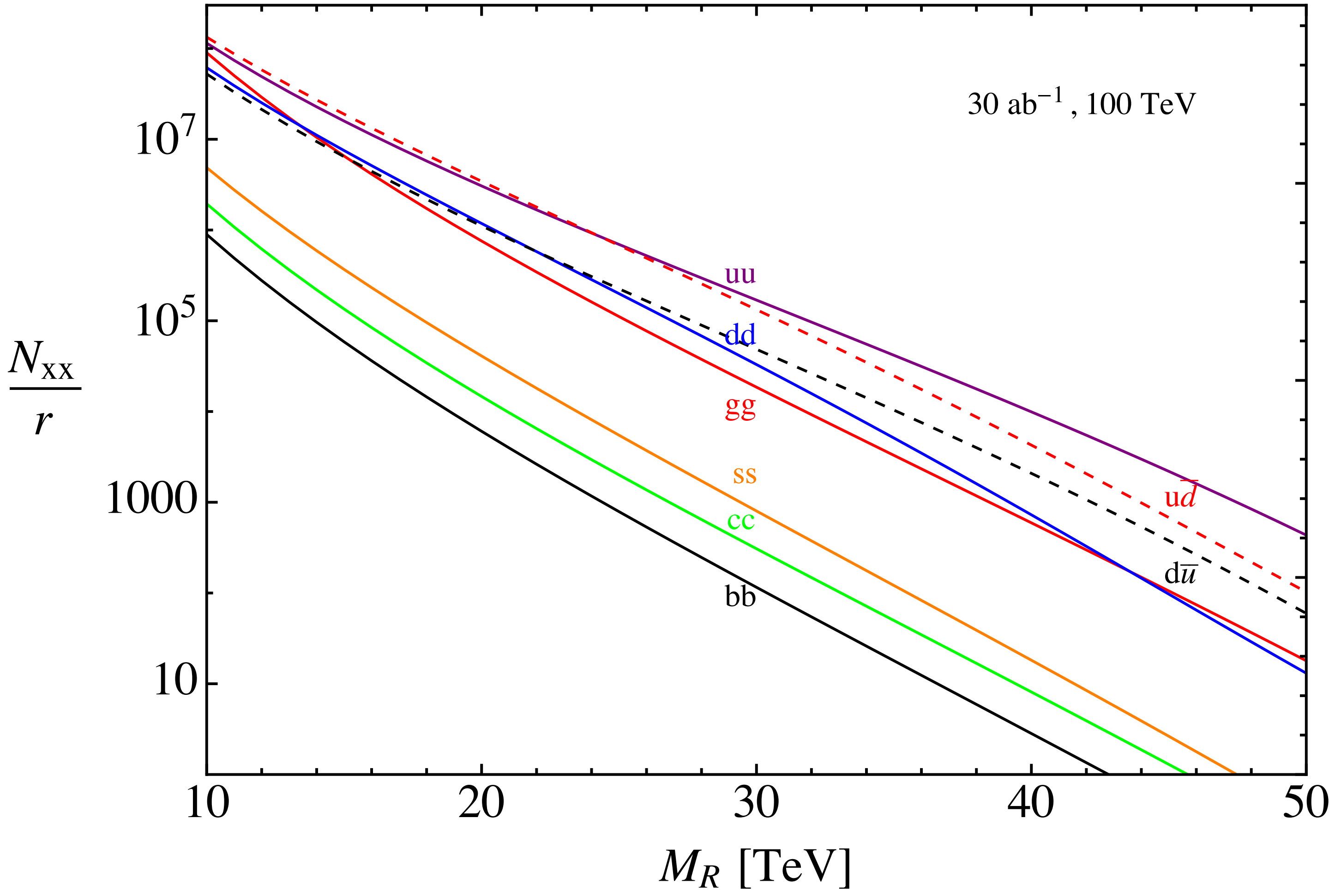
Plot from FCC CDR

Resonance production.

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

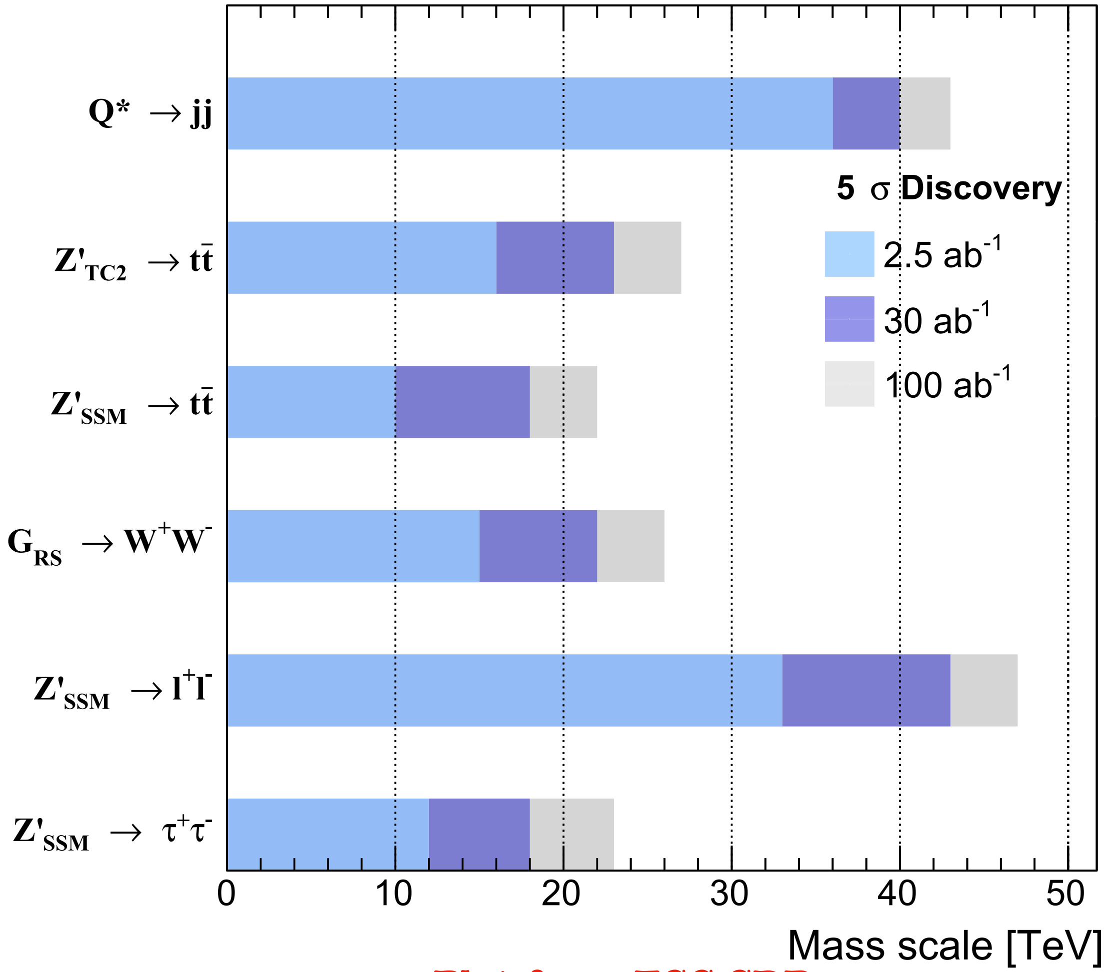
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

resonances produced



Plot from mid-term report

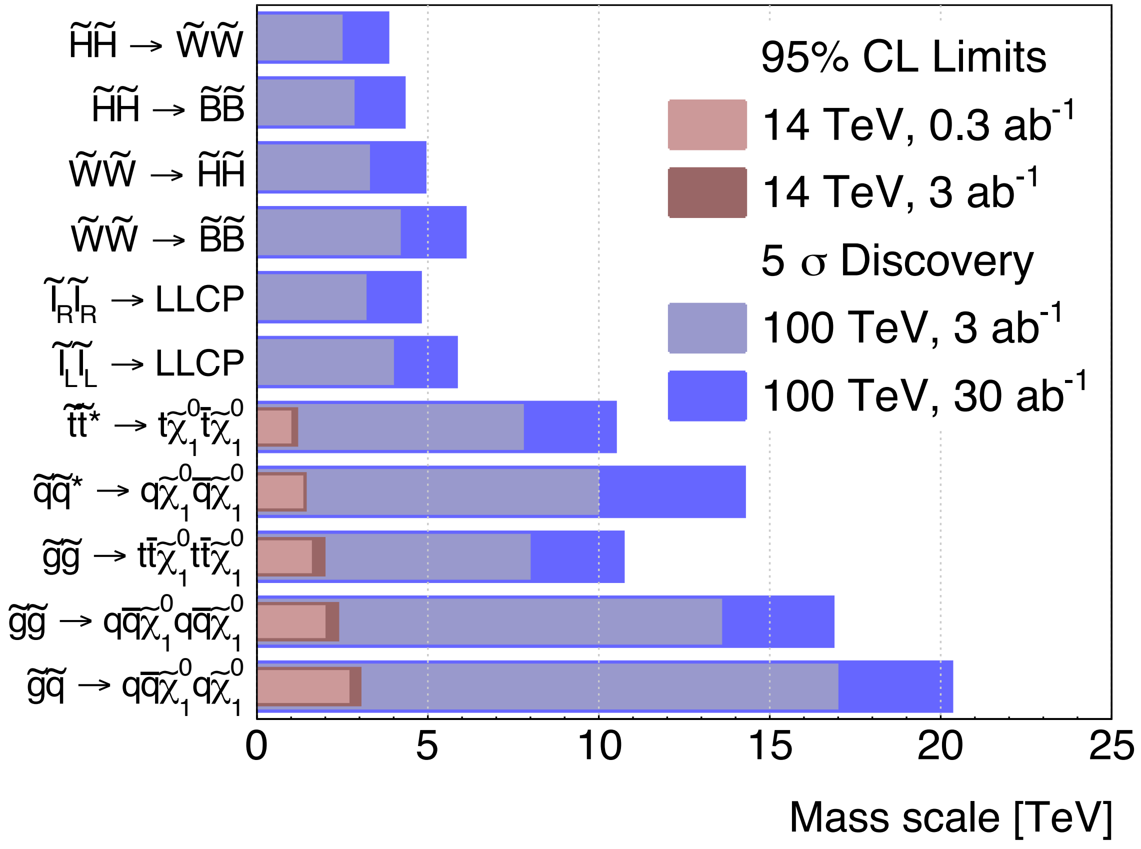
FCC-hh mass reach



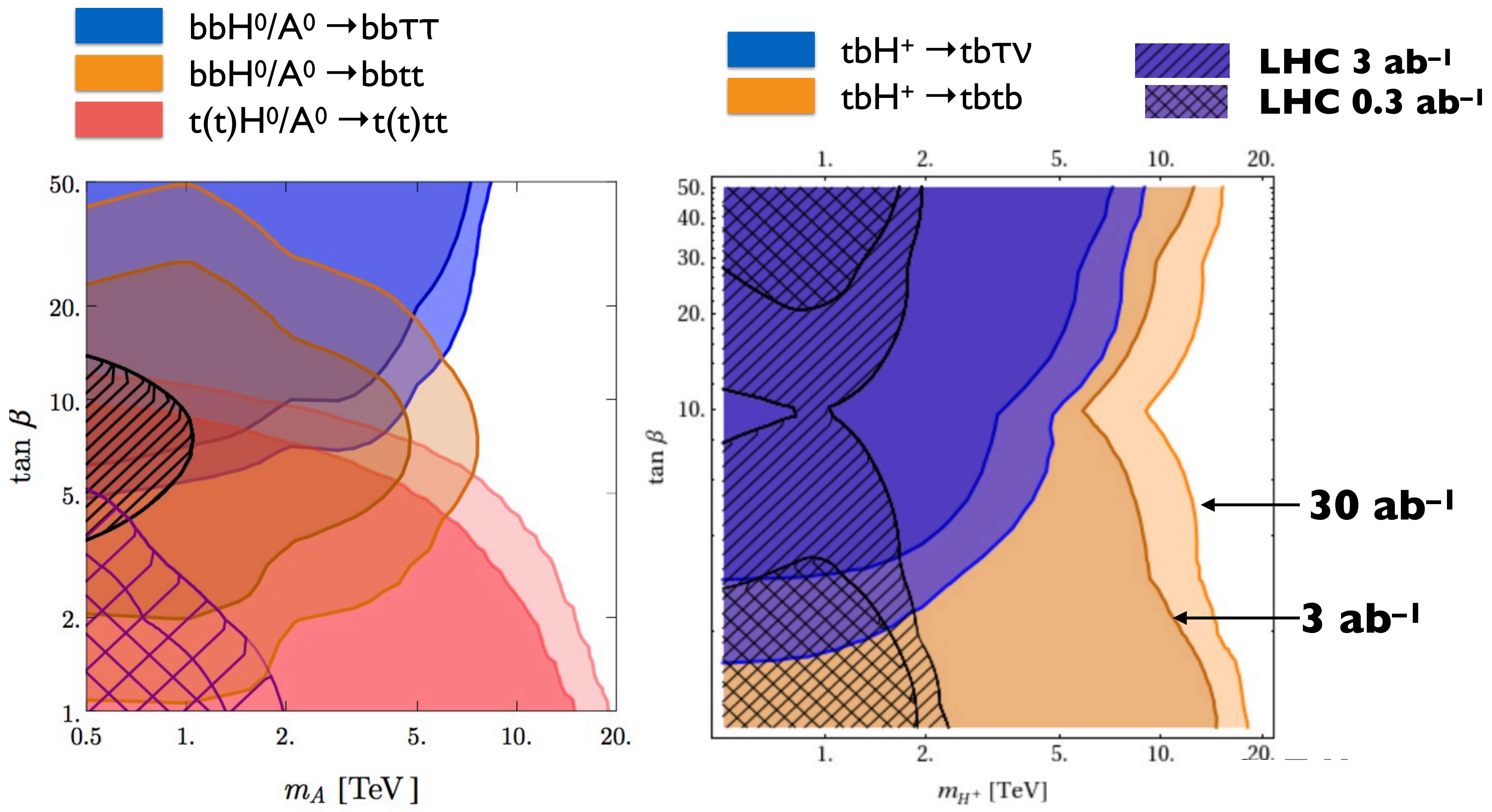
Plot from FCC CDR

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

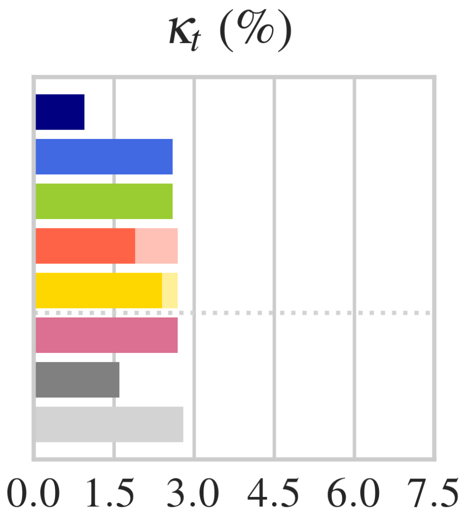
Factor 10 increase on the HL-LHC limits.

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



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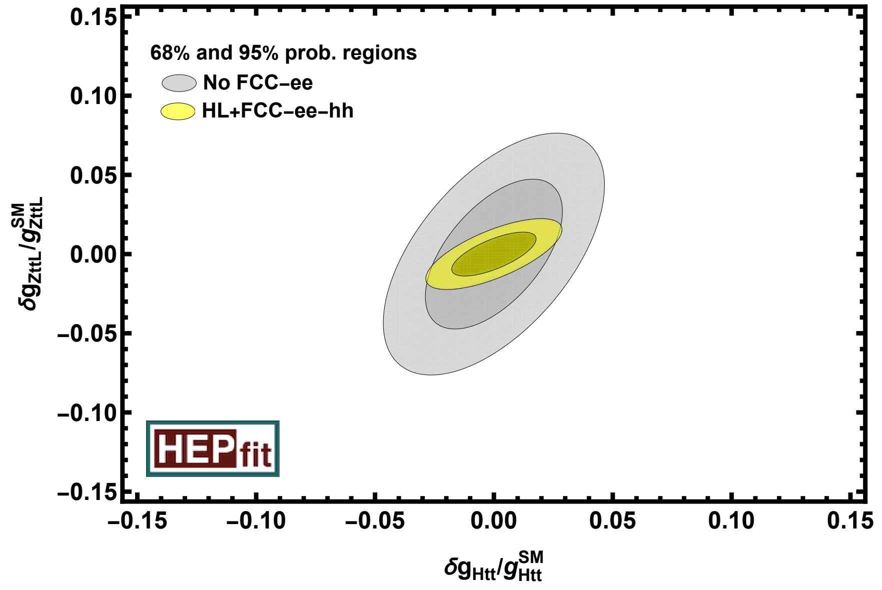
	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$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

(uncertainty drops in ratio)



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