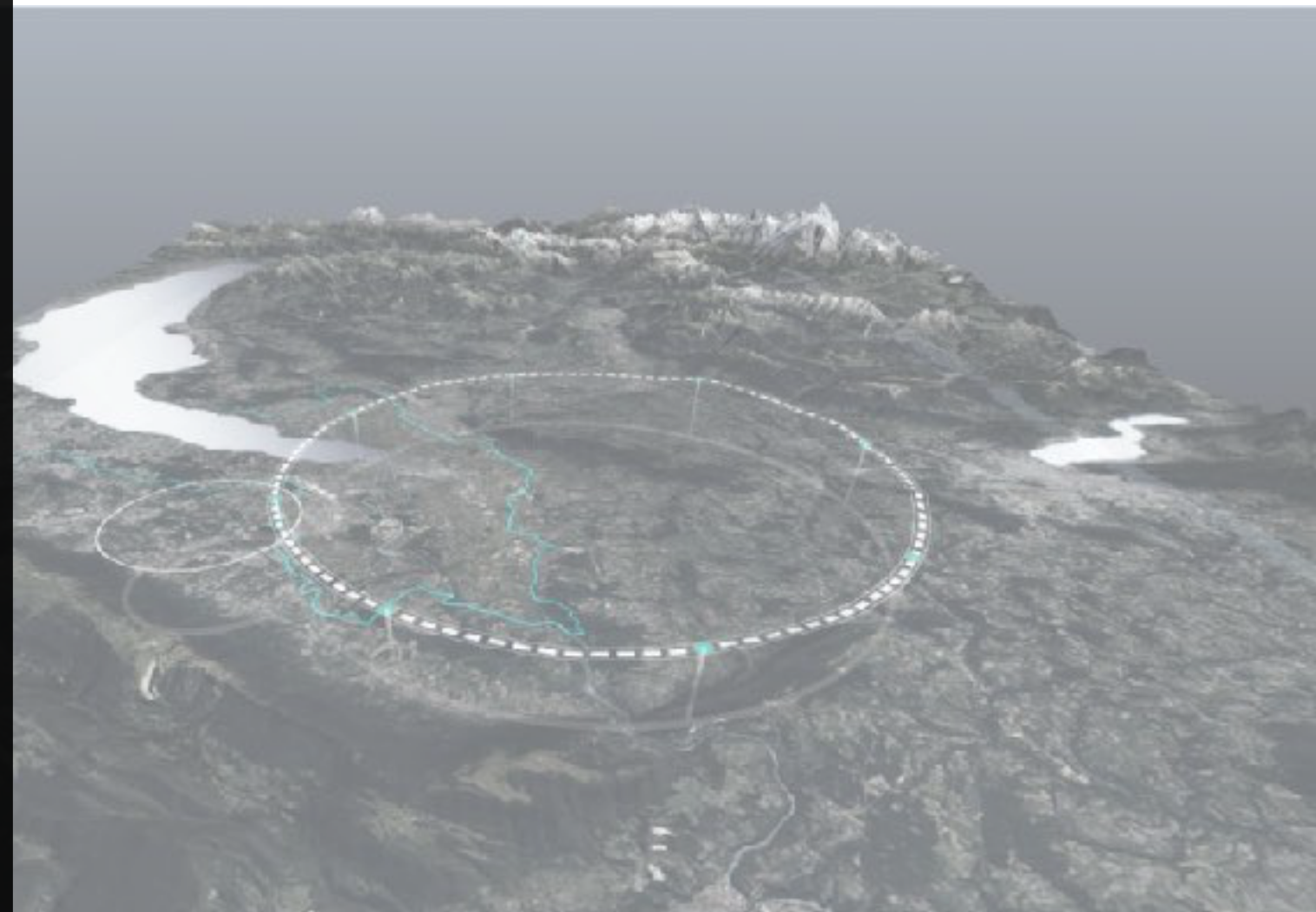


Future Circular Collider — Physics Manifesto —

Planck 2025 "From the Planck Scale to the Electroweak Scale"





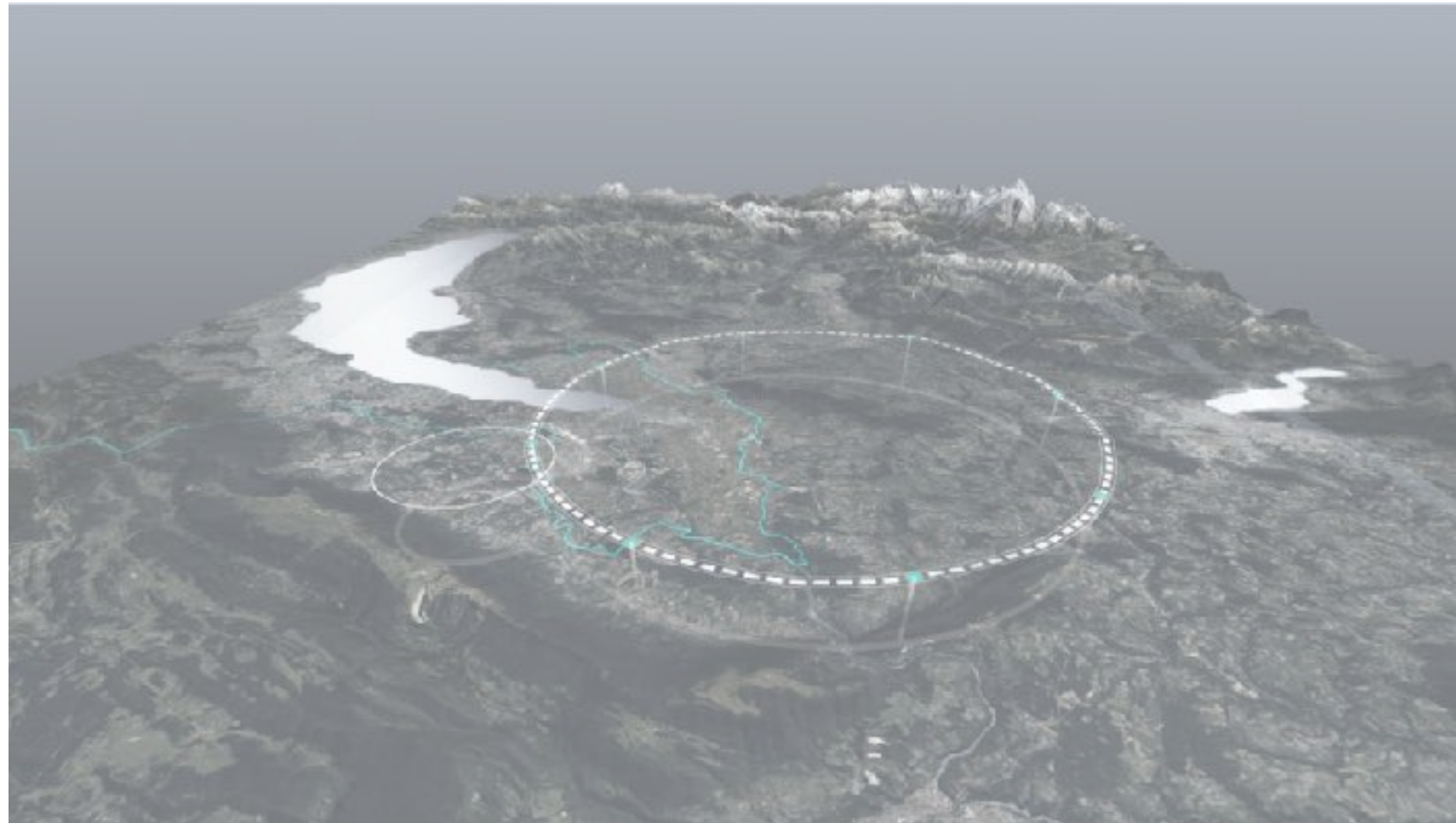
Christophe Grojean

DESY (Hamburg)
Humboldt University (Berlin)

(christophe.grojean@desy.de)

Future Circular Collider

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



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*) \Rightarrow More energy & More precision

We need a broad, versatile and ambitious programme that can

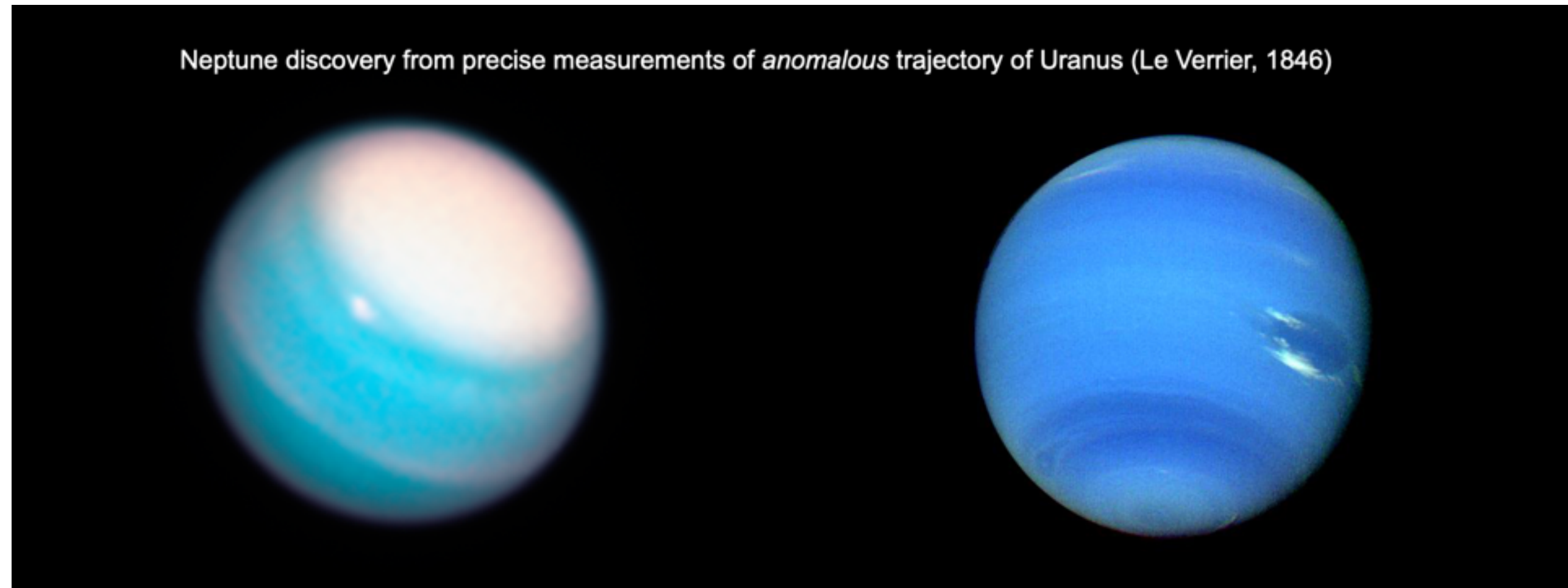
1. sharpen our knowledge of already discovered physics
2. push the frontiers of the unknown at **high** and **low** scales

The FCC integrated programme (ee+hh) fits the bill

Precision as a Discovery Tool

Many historical examples

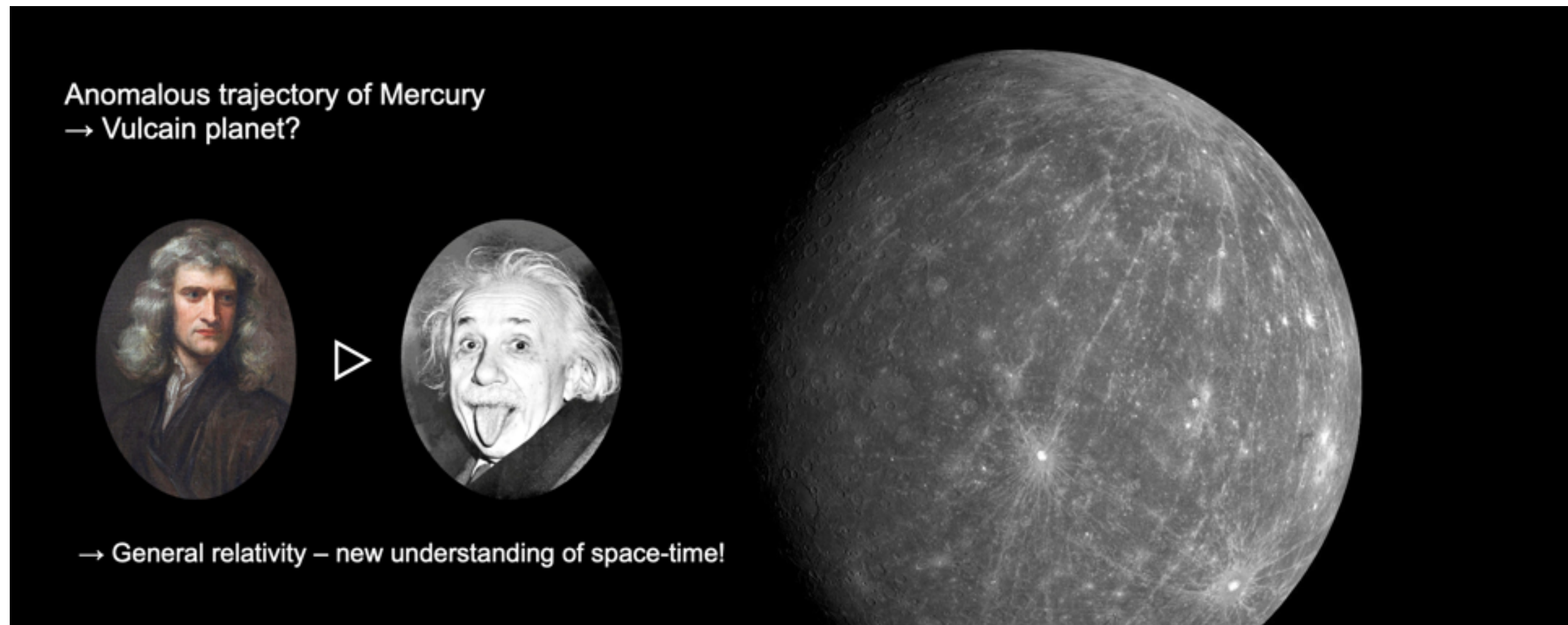
- Uranus anomalous trajectory \rightsquigarrow Neptune



Precision as a Discovery Tool

Many historical examples

- ▶ Uranus anomalous trajectory \rightsquigarrow Neptune
- ▶ Mercury perihelion \rightsquigarrow General Relativity



Precision as a Discovery Tool

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- ▶ Uranus anomalous trajectory \rightarrow Neptune
- ▶ Mercury perihelion \rightarrow General Relativity
- ▶ Z/W interactions to quarks and leptons \rightarrow Higgs boson
- ▶ ...

Sometimes, these discoveries were expected based on theoretical arguments
(e.g. Rayleigh-Jeans UV catastrophe for QM, unitarity breakdown for the Higgs)
but precision gave valuable additional clues.

In any case, experimentalists shouldn't lean too heavily on theorist priors/prejudices
(remember discovery of P violation).

At times when we don't have a precise theoretical guidance, we need powerful experimental tools to make progress.

Precision as a Discovery Tool

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At times when we don't have a precise theoretical guidance, we need powerful experimental tools to make progress.

Herwig Schopper in [CERN Courier](#):

LEP was a transformative machine

"It changed high-energy physics from a 10% to a 1% science."

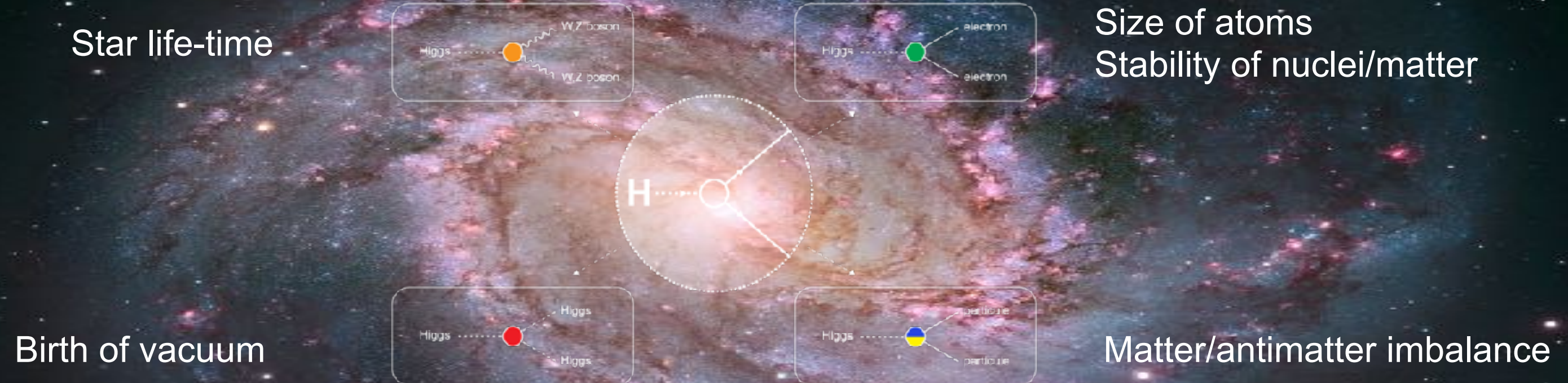
The Higgs Requires More Precision

The Higgs Requires More Precision

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

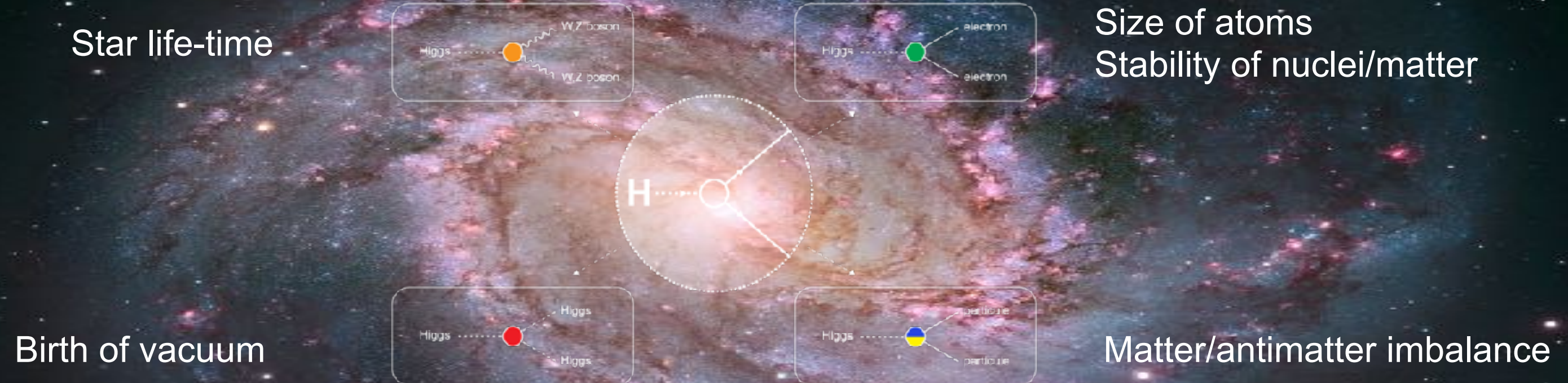
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The Higgs Requires More Precision

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



**(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.

And 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 — Physics Overview

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.

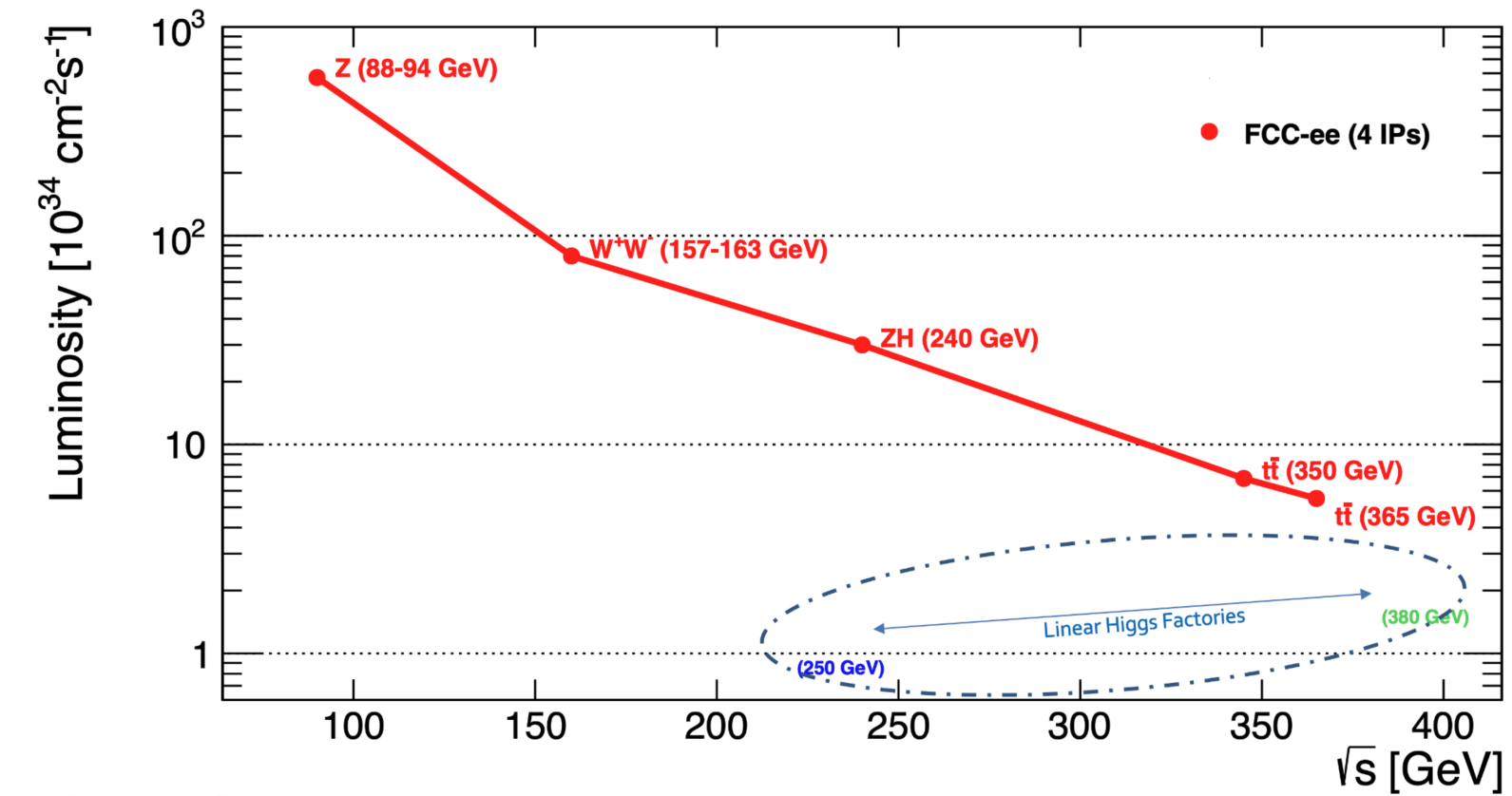
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Herwig Schopper in [CERN Courier](#):

“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.)

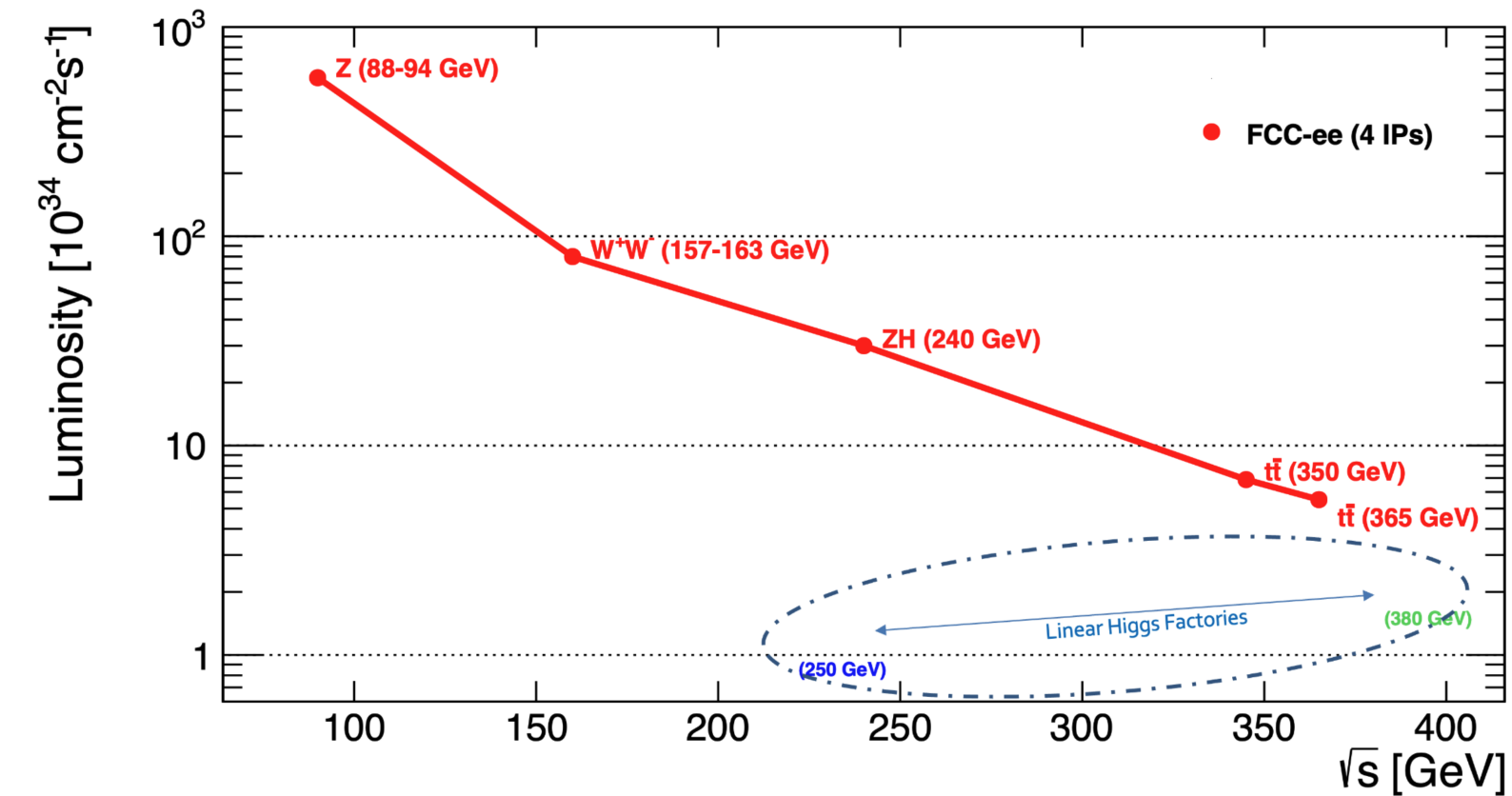
FCC-ee Run Plan



FCC-ee Run Plan

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

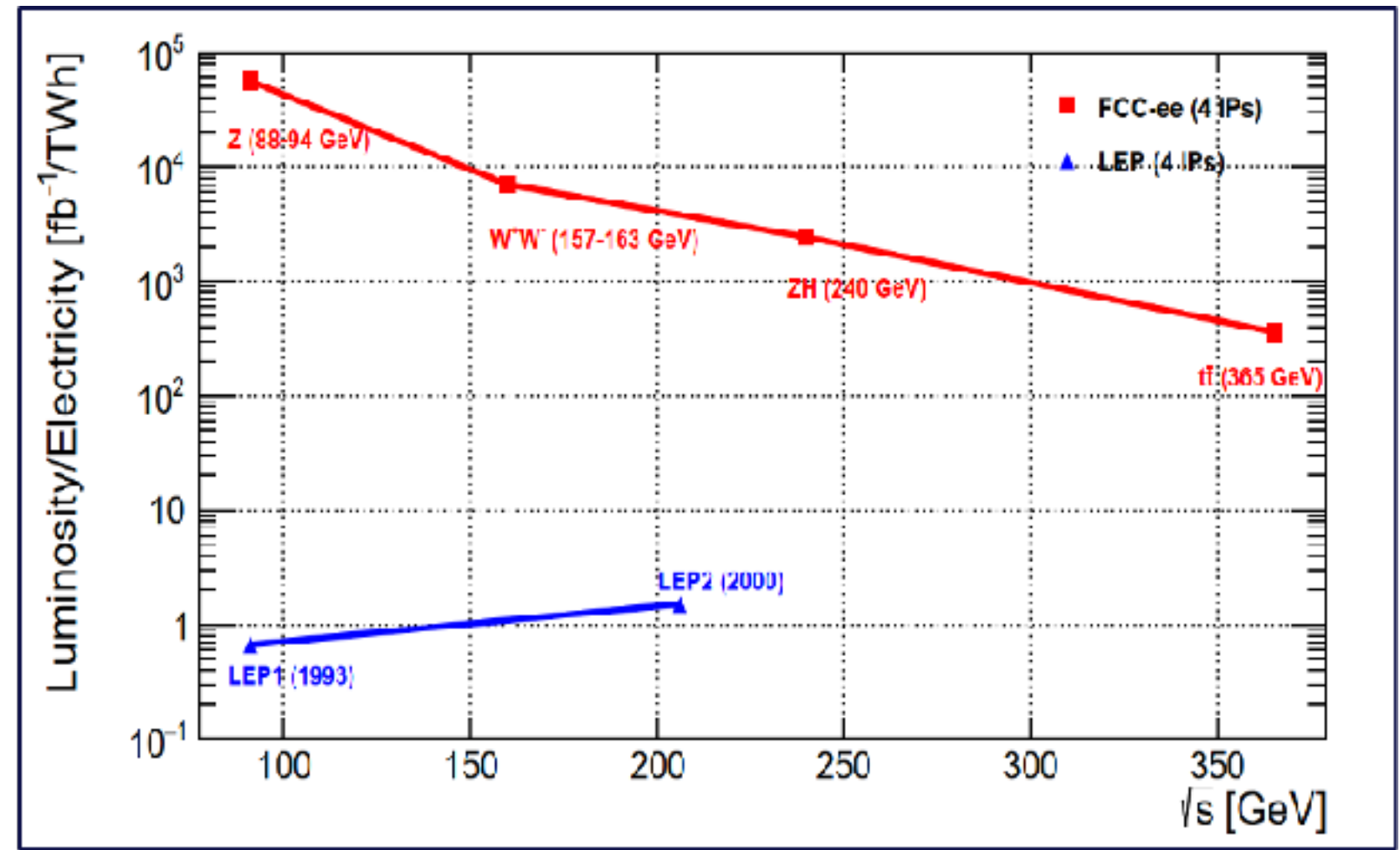
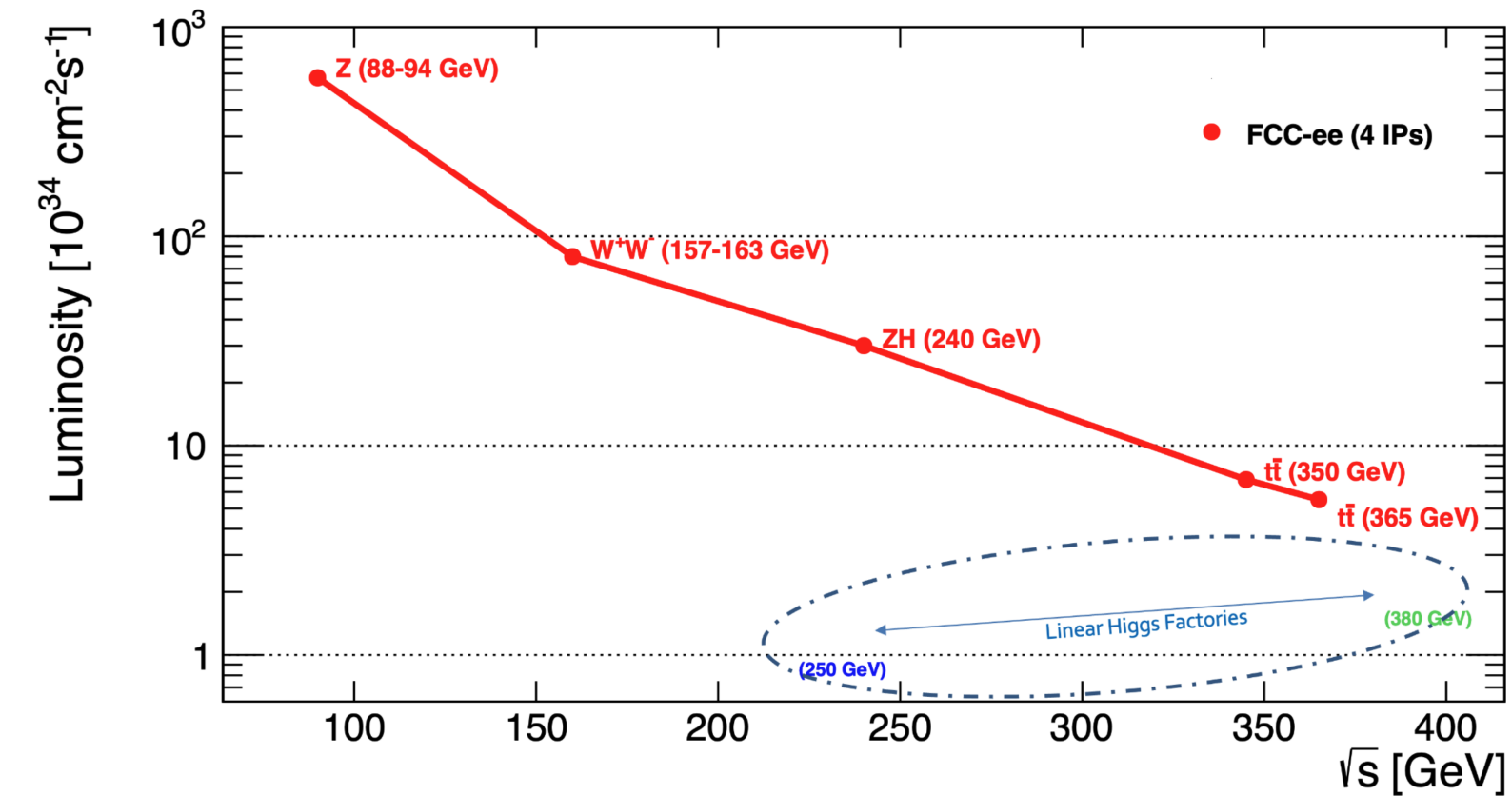
(for the same power consumption, i.e. machine 100'000 more efficient).



FCC-ee Run Plan

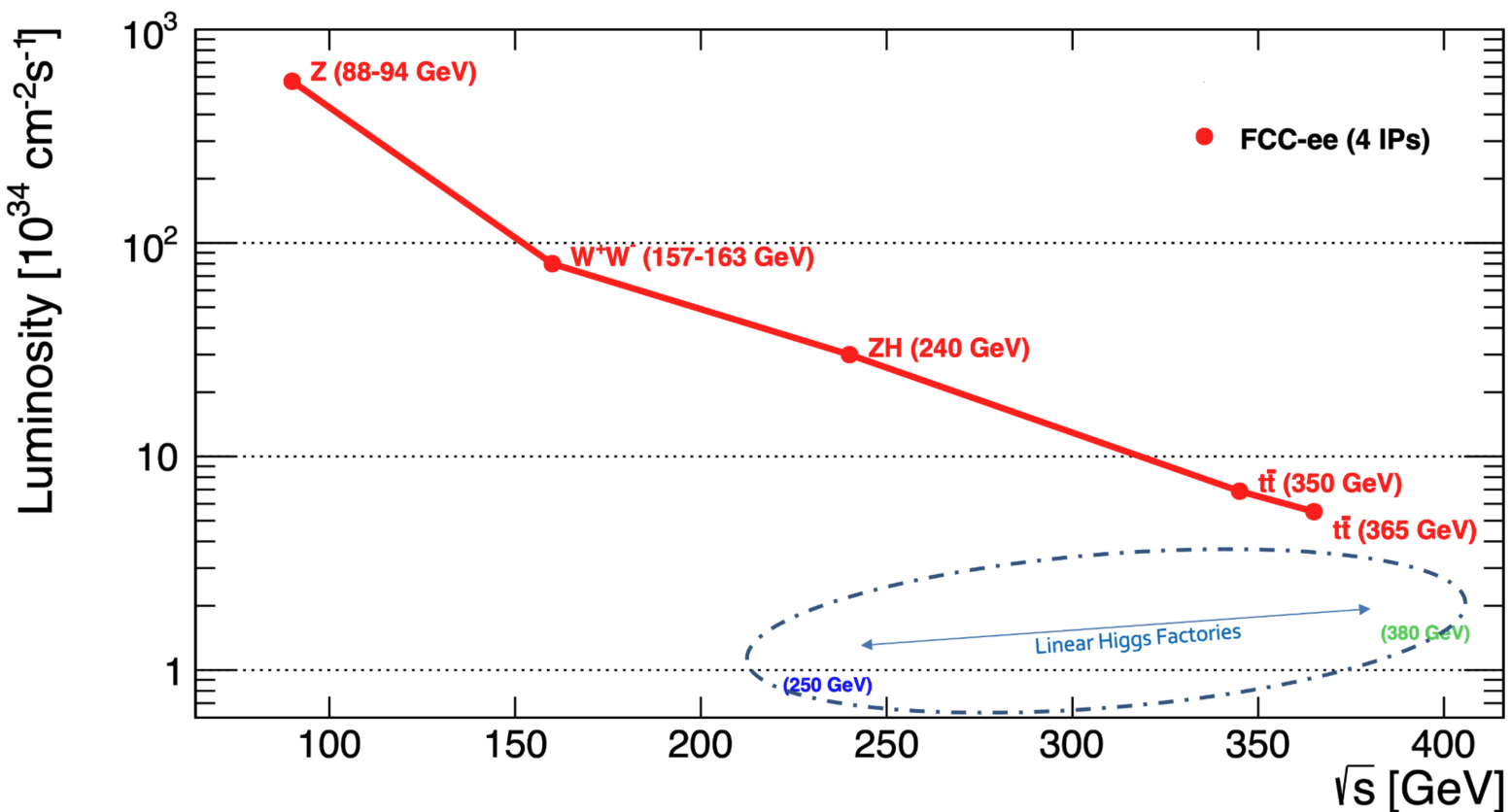
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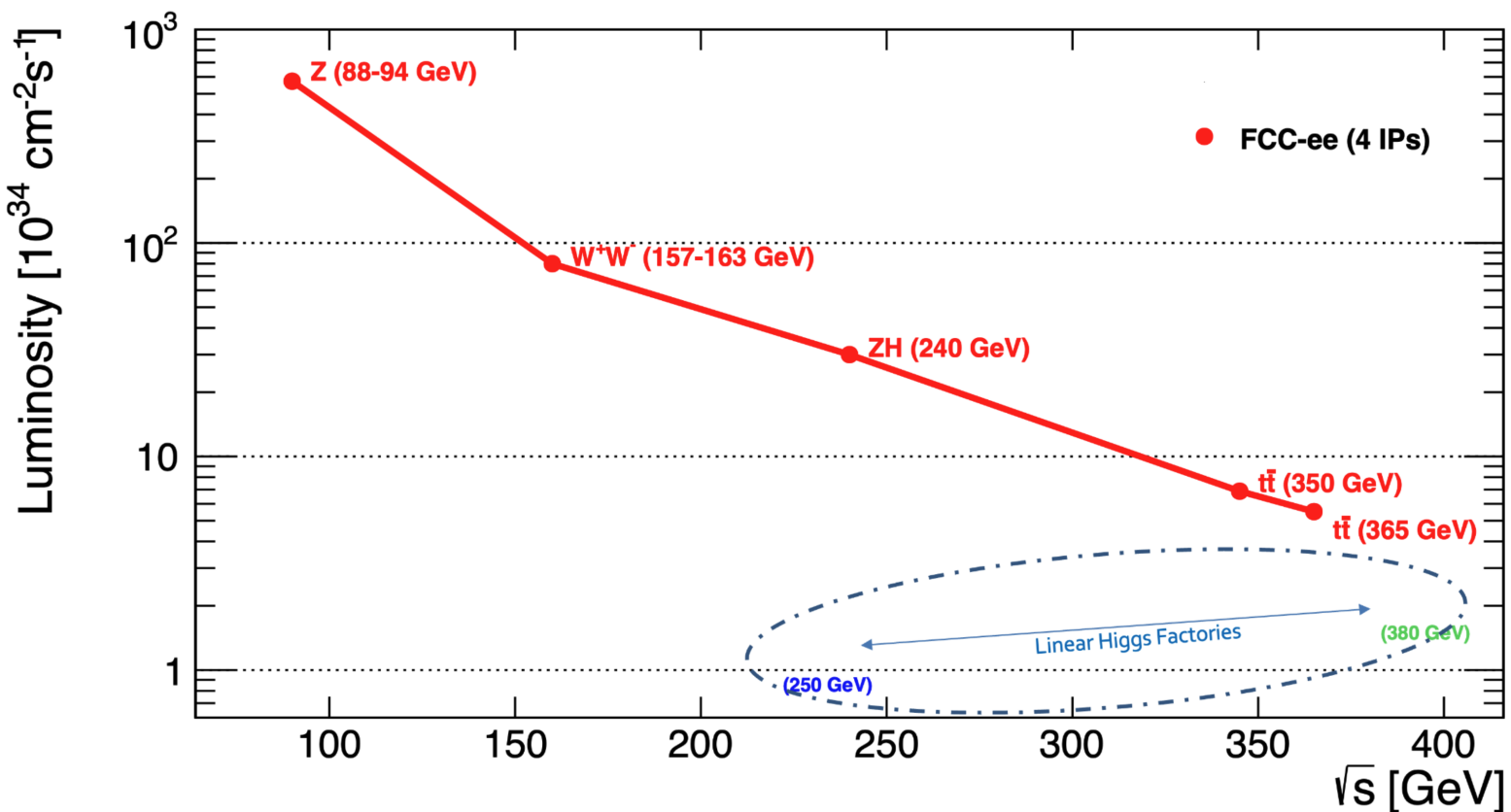
— Superb statistics achieved in only 15 years —

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

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
\sqrt{s} (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	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		2.2×10^6 ZH		2×10^6 $t\bar{t}$	
		6×10^{12} Z	2.4×10^8 WW	+	+ 370k ZH
				65k WW \rightarrow H	+ 92k WW \rightarrow H

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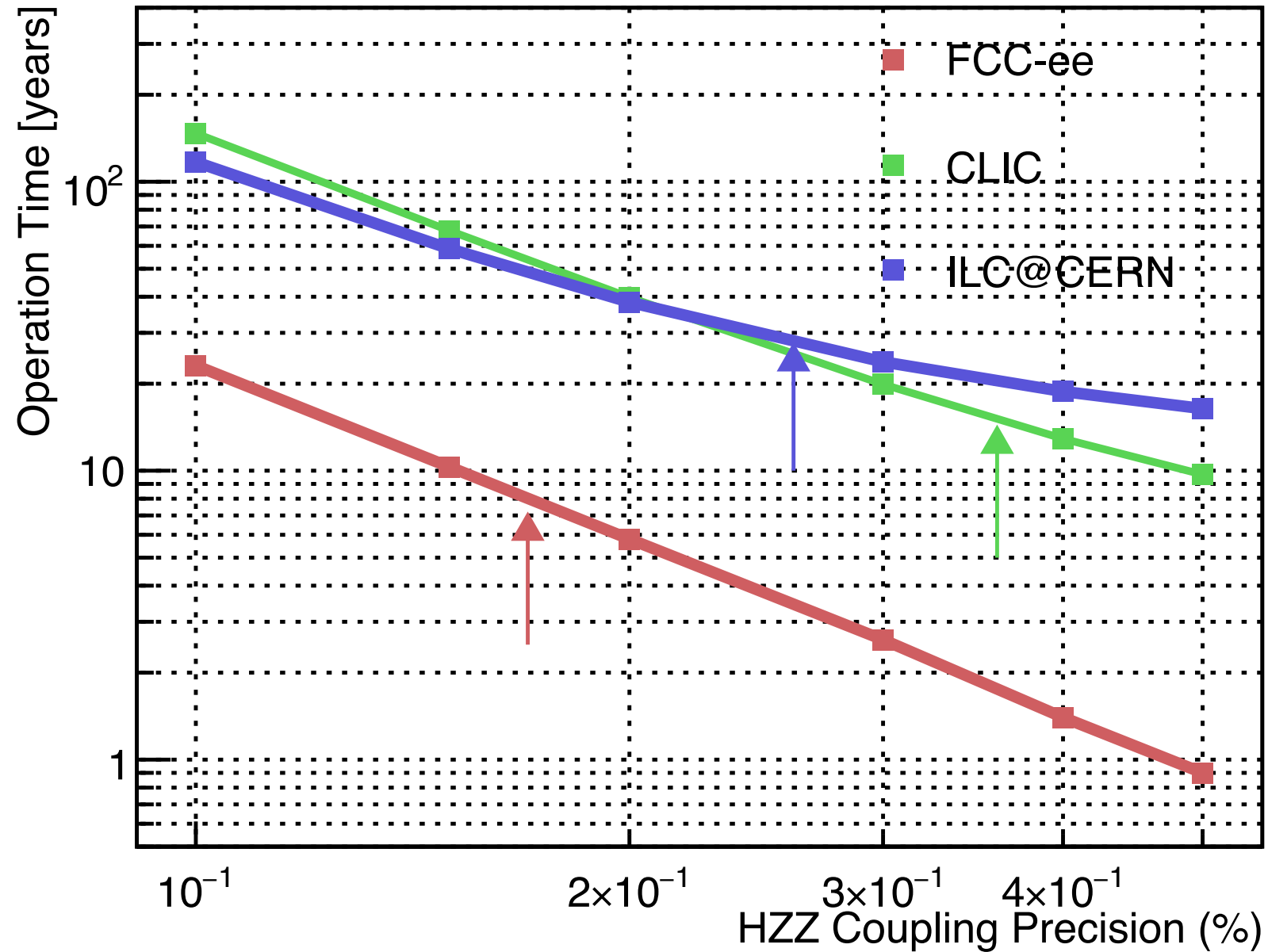
**Exciting & diverse programme with
different priorities every few years.**

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.

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A Performant Higgs Programme

↑ = default run plan of each collider



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

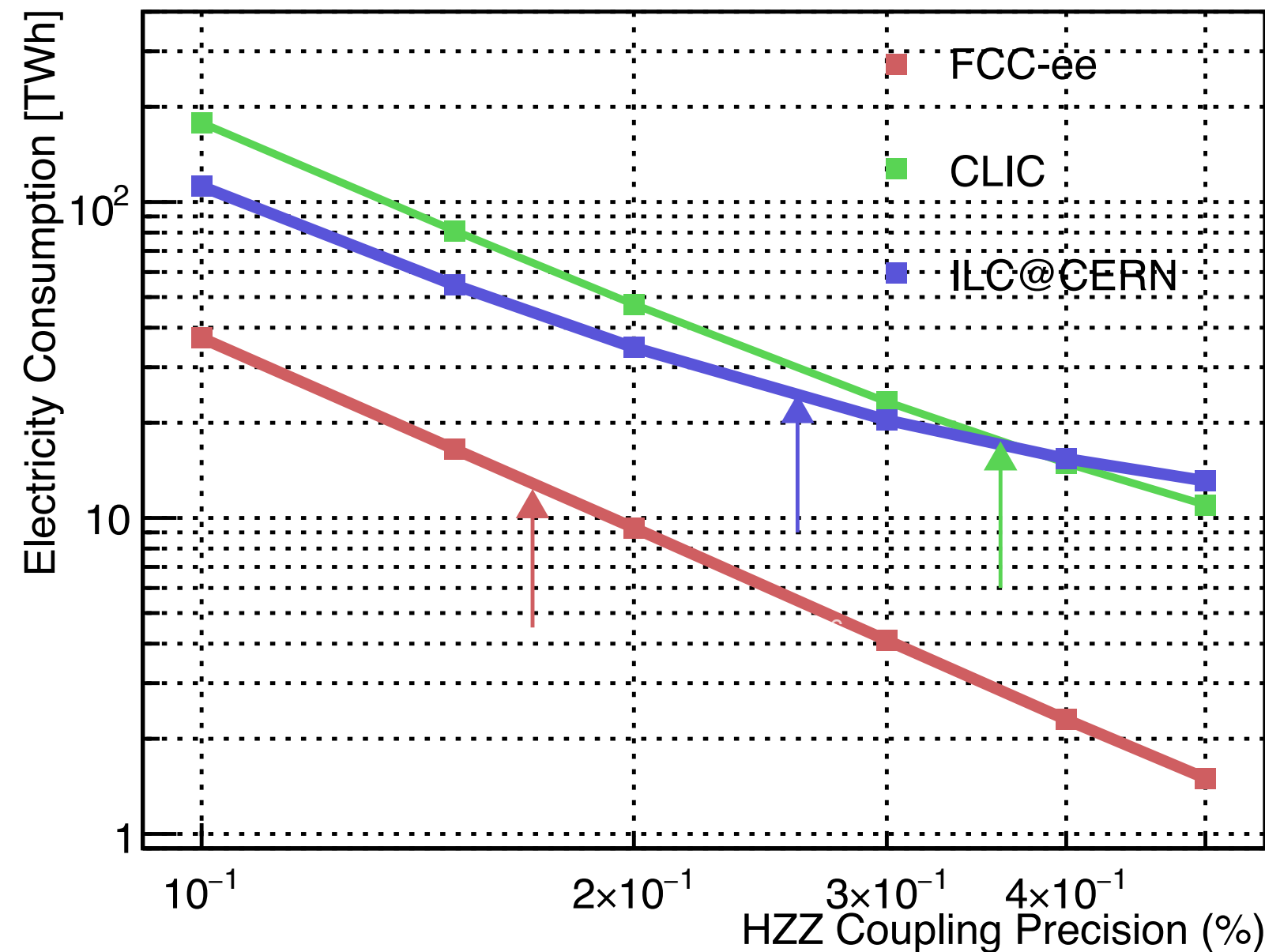
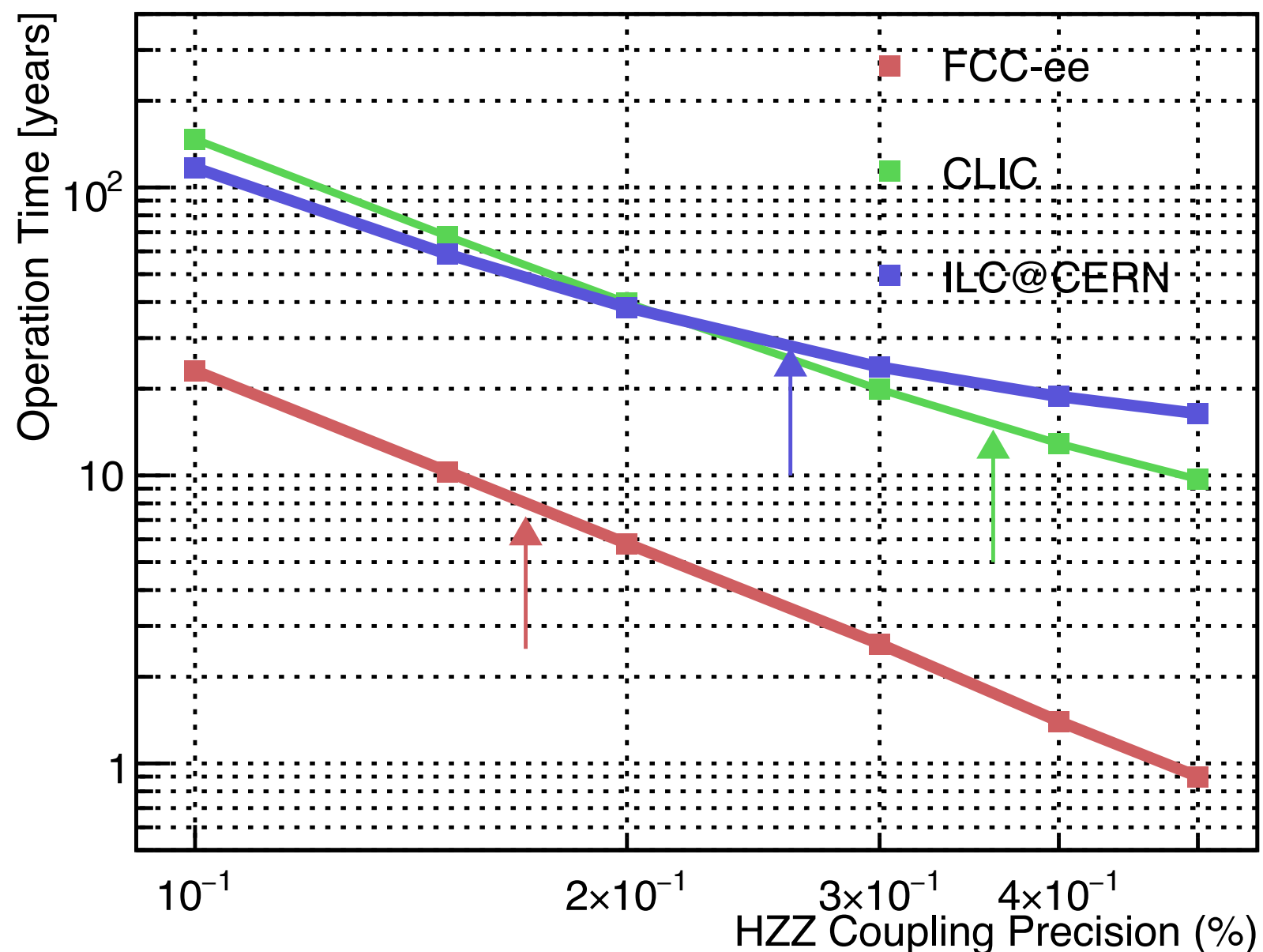
It would take about 30-50 years for other projects to achieve what can be done at FCC-ee in 8 years.

This has consequences in terms of electricity/money/carbon footprint.

A Performant Higgs Programme

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More time = more TWh



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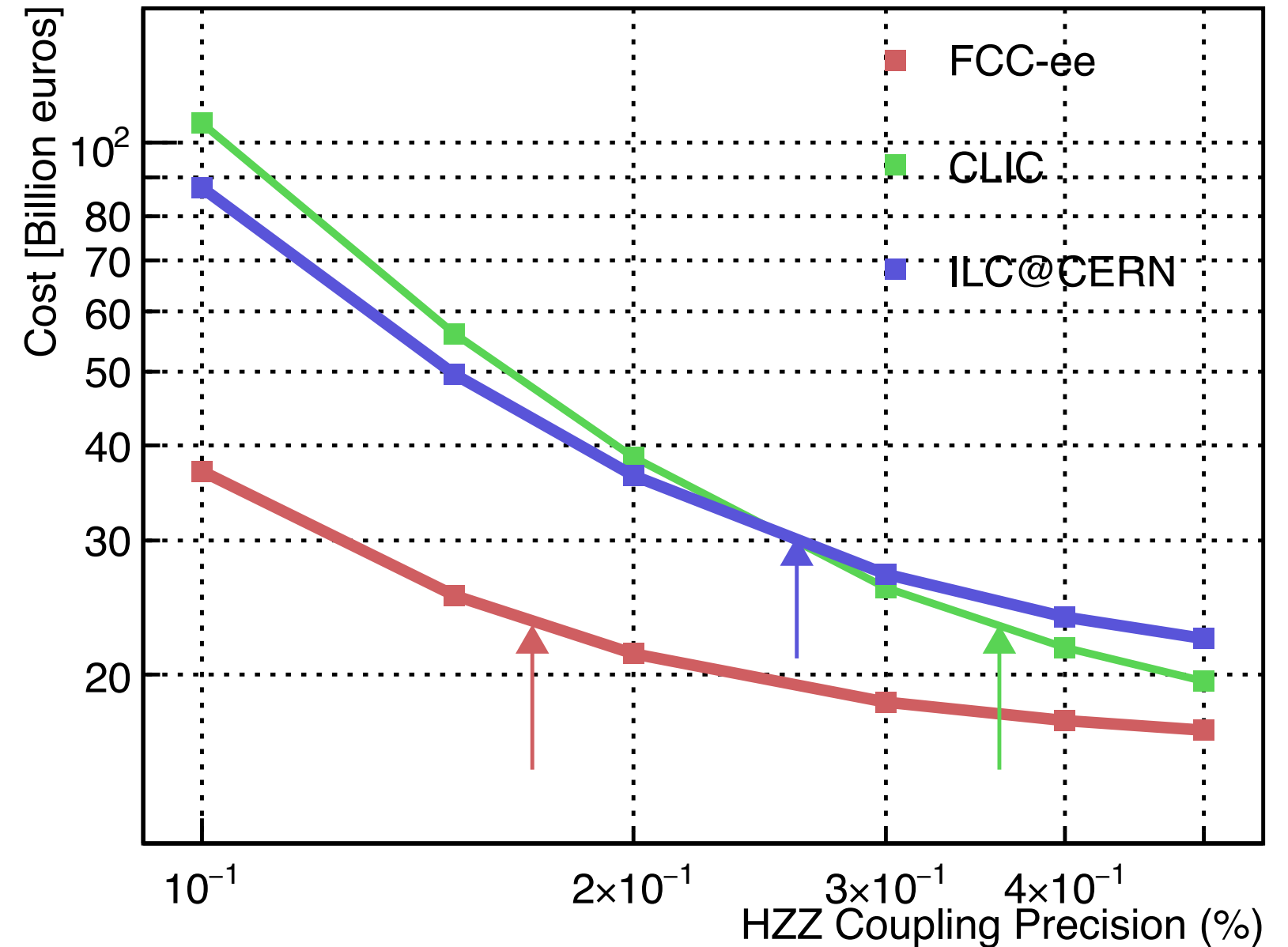
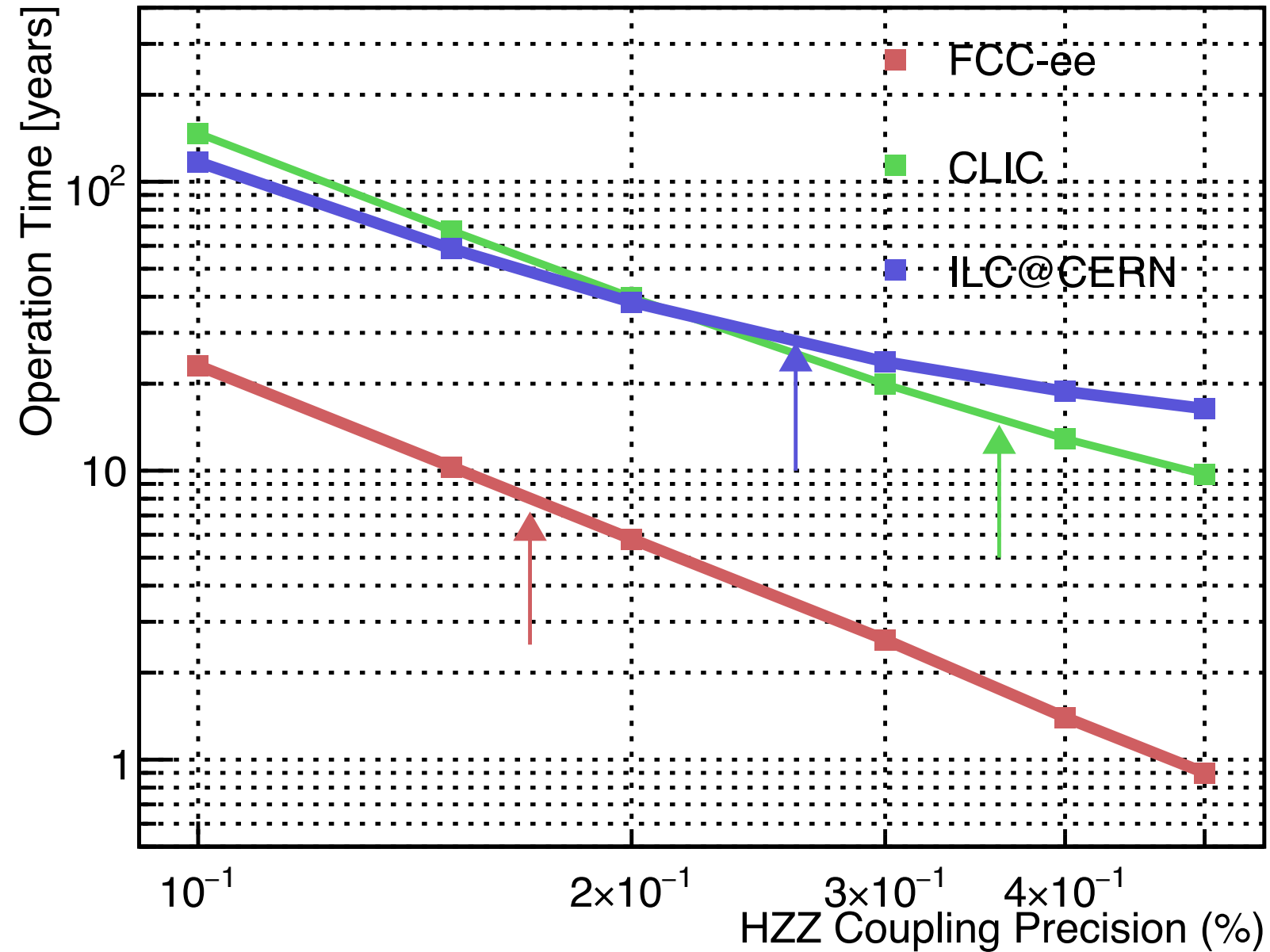
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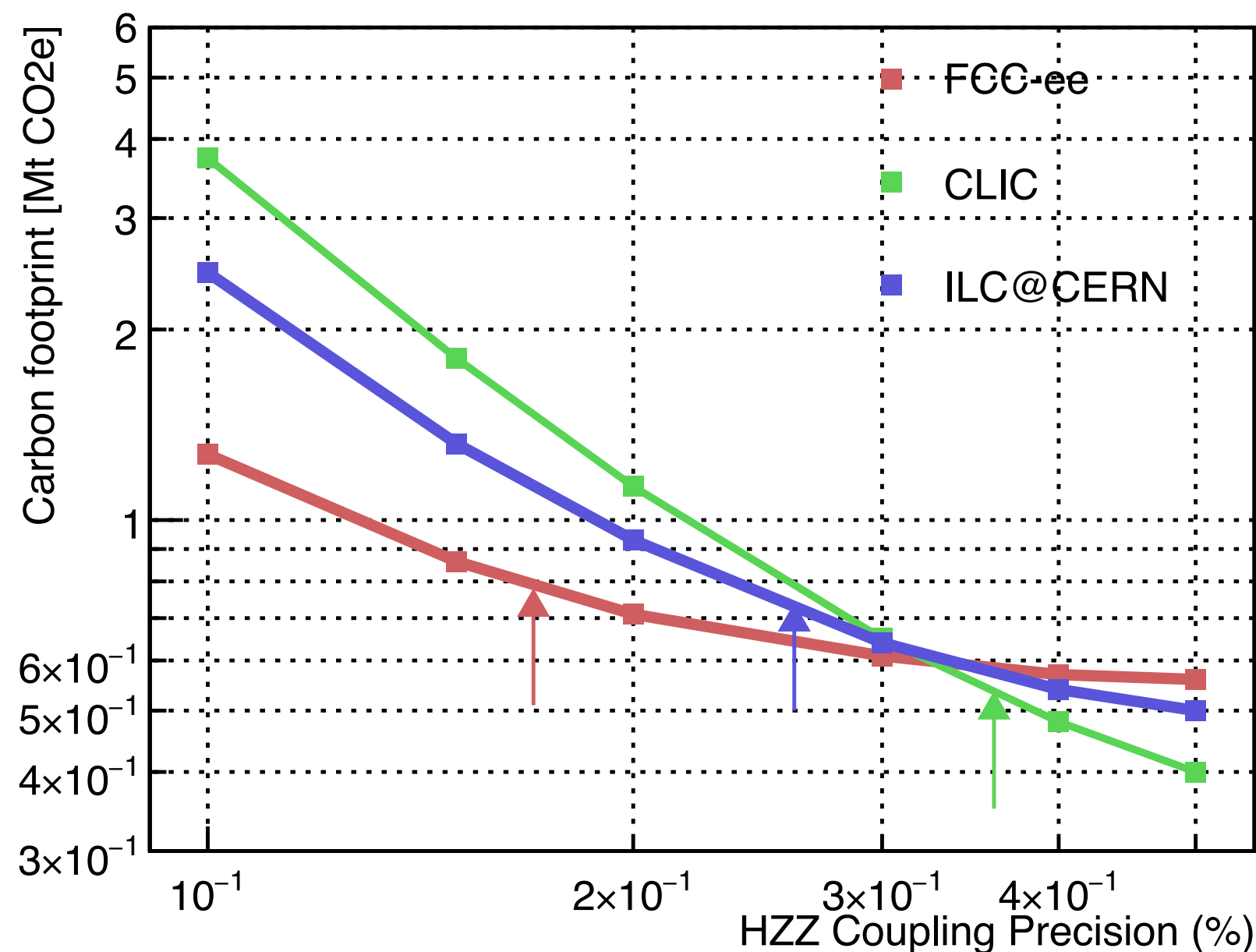
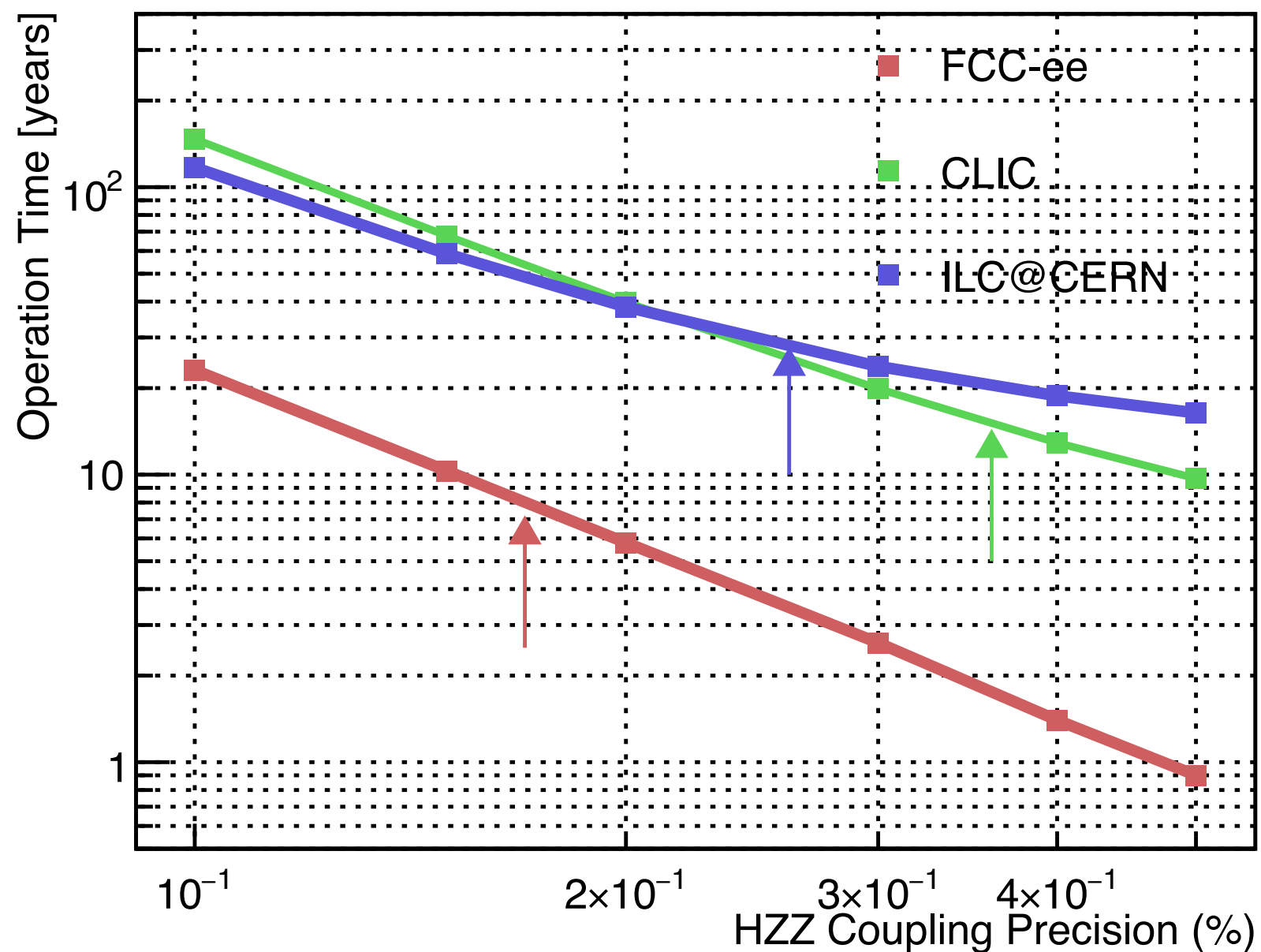
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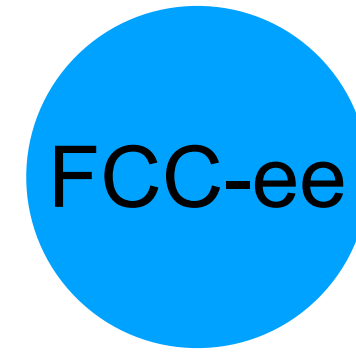


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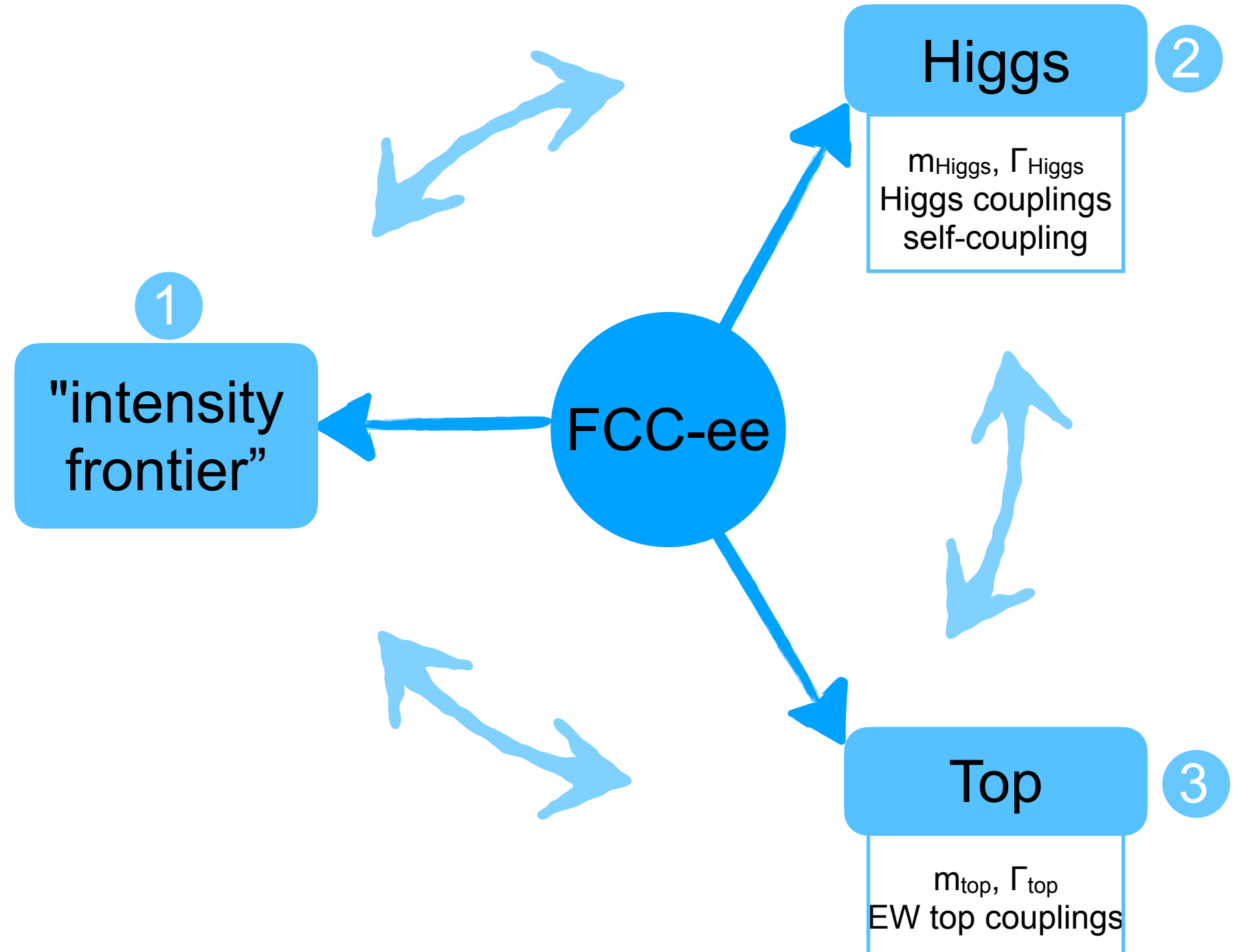
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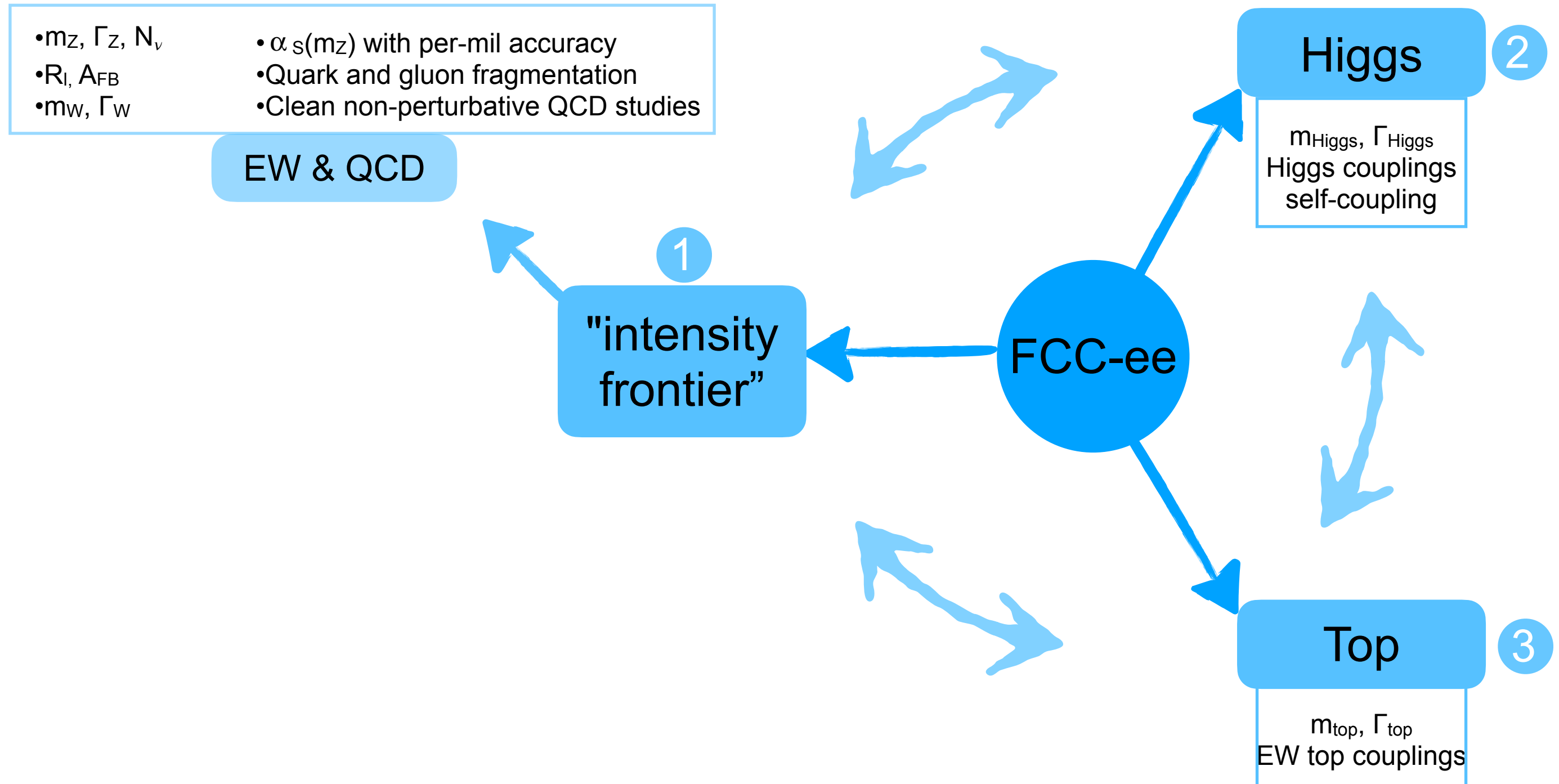
FCC-ee Physics Programme



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).

Higgs

$m_{\text{Higgs}}, \Gamma_{\text{Higgs}}$
Higgs couplings
self-coupling

2

Top

$m_{\text{top}}, \Gamma_{\text{top}}$
EW top couplings

3

FCC-ee Physics Programme

- m_Z, Γ_Z, N_ν
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EW & QCD

1

direct searches
of light new physics

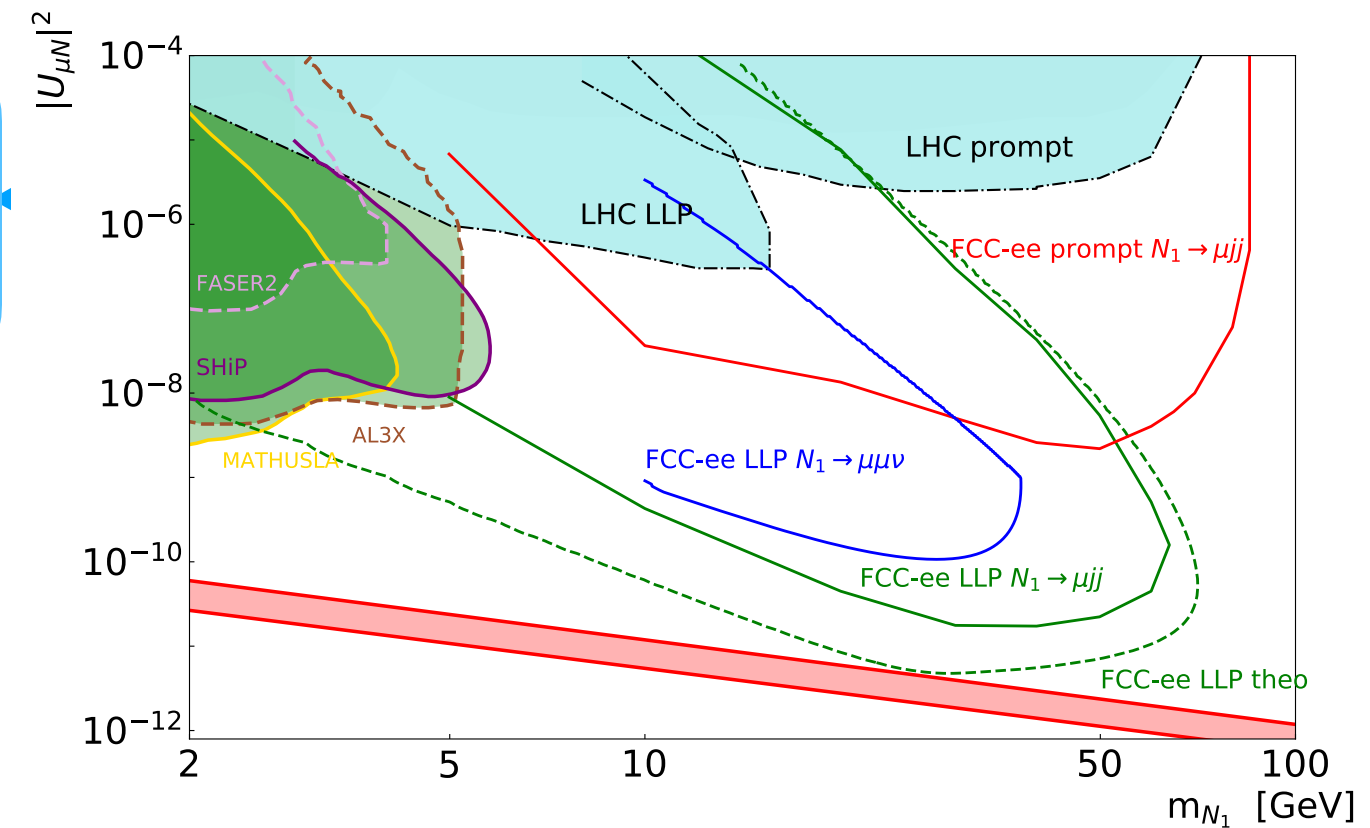
- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

"intensity
frontier"

Higgs

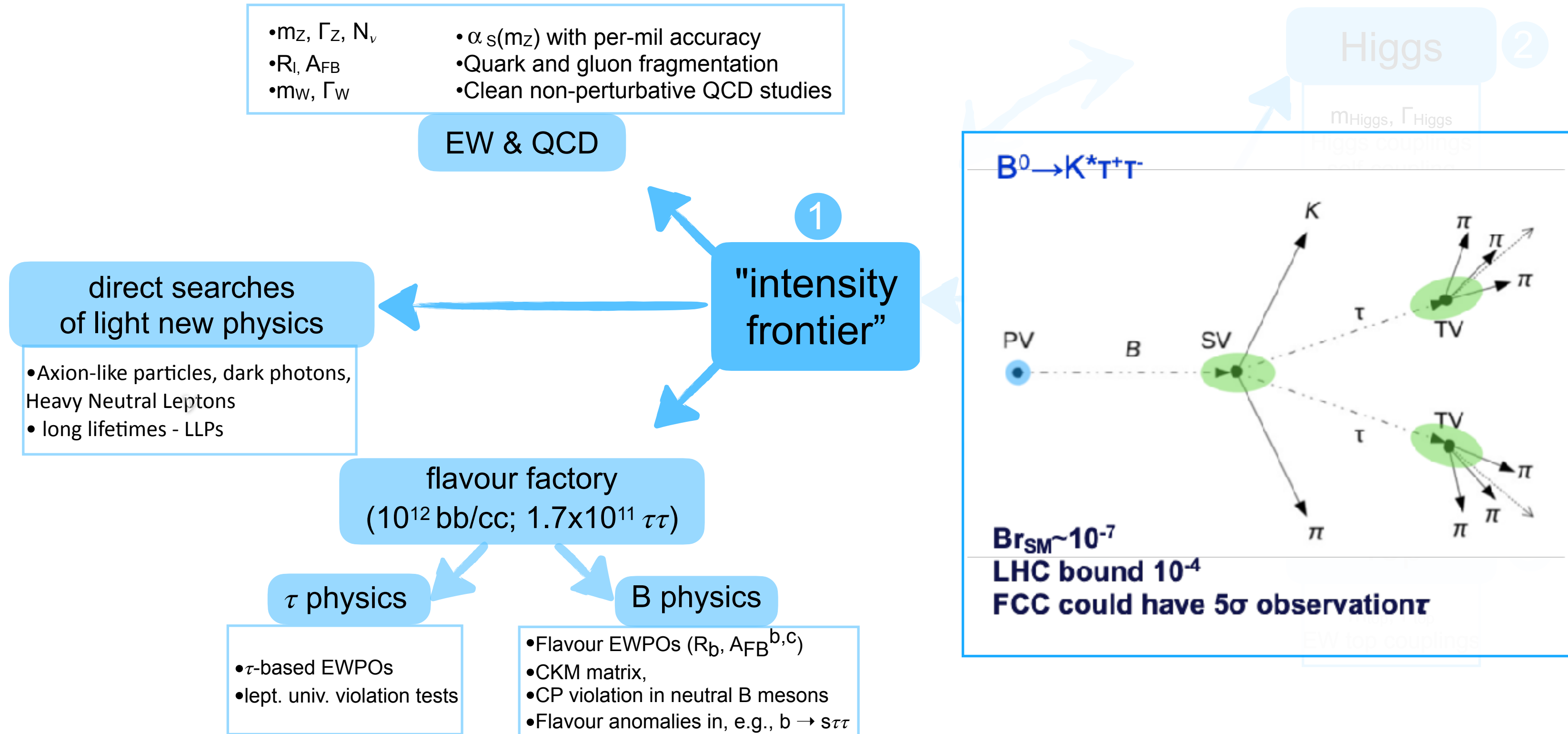
2

$m_{Higgs}, \Gamma_{Higgs}$
Higgs couplings
self-coupling

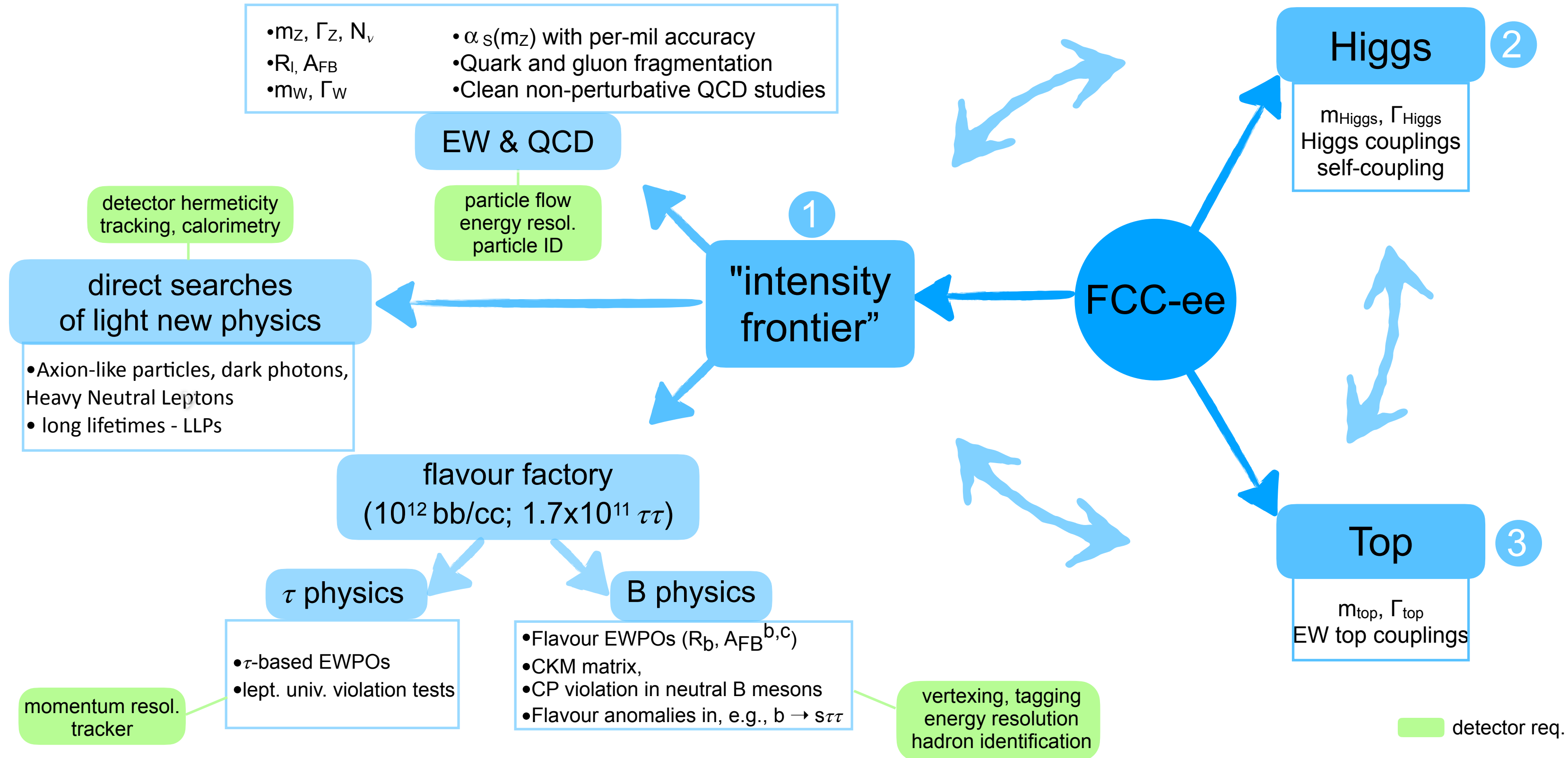


EW top couplings

FCC-ee Physics Programme



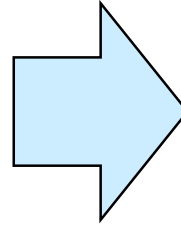
FCC-ee Physics Programme



FCC-ee Physics Programme

Higgs Factory Programme

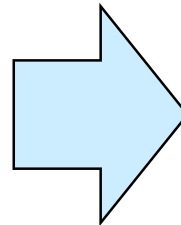
- At $\sqrt{s}=240$ and $\sqrt{s}=365$ GeV collect 2.6M HZ and 150k WW \rightarrow H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \rightarrow H$ at 125 GeV



- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
- $\sigma(p)/p$ limited by multiple scattering \rightarrow minimise material
- **Jet $\sigma(E)/E \simeq 3-4\%$ 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

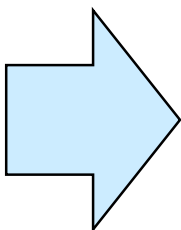
- 6×10^{12} Z and 2×10^8 WW events
- $\times 500$ improvement of statistical precision on EWPO:
 $m_Z, \Gamma_Z, \Gamma_{inv}, \sin^2\theta_W, R_b, m_W, \Gamma_W, \dots$
- 2×10^8 tt events: $m_{top}, \Gamma_{top},$ EW couplings
- Indirect sensitivity to new physics up to tens of TeV



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

Heavy Flavour Programme

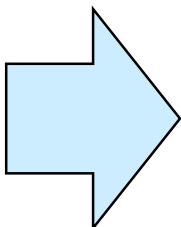
- 10^{12} bb, cc, 2×10^{12} $\tau\tau$ (clean and boosted): $10 \times$ Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality



- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/VE**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/ π separation over wide p range \rightarrow 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 \rightarrow m)**
- tracking: more layers, "continuous" tracking
- calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

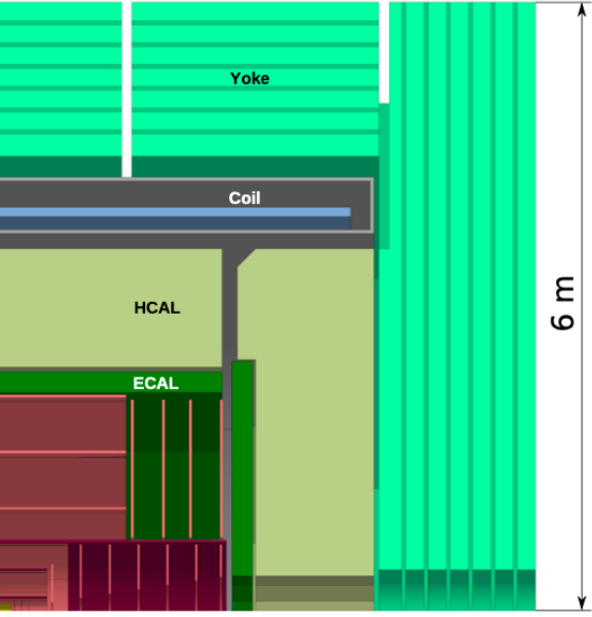
FCC-ee Physics Programme

Summary of detector requirements

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

FCC-ee Physics Programme

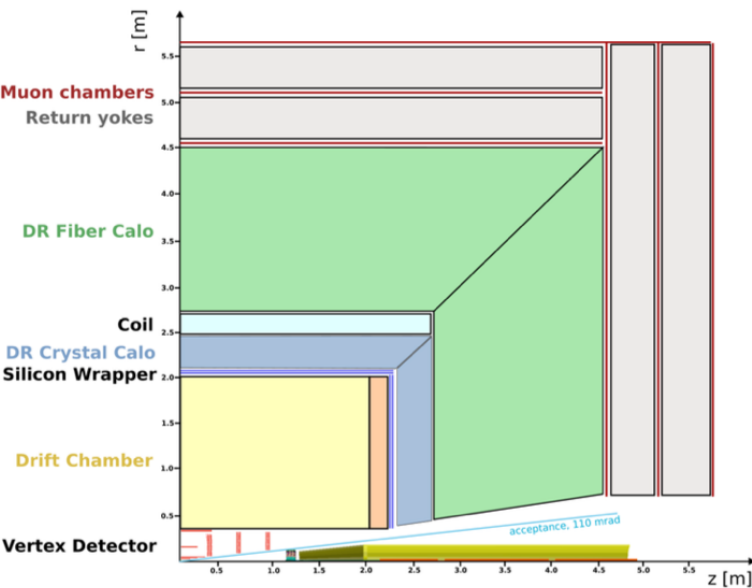
CLD



- 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](https://arxiv.org/abs/1911.12230)

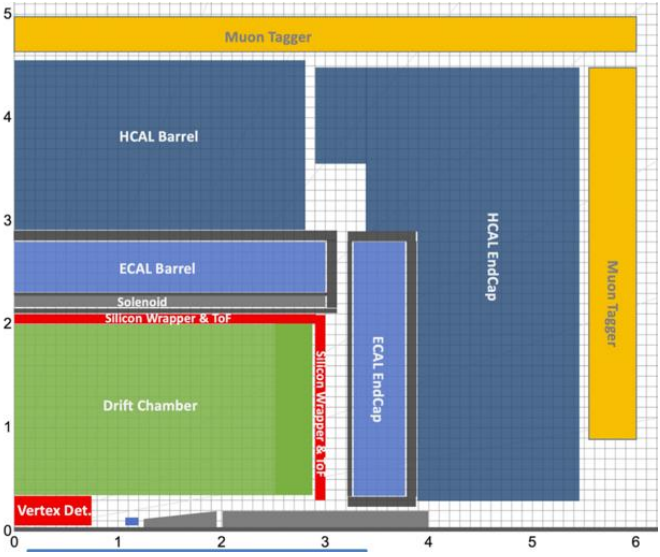
IDEA



- 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

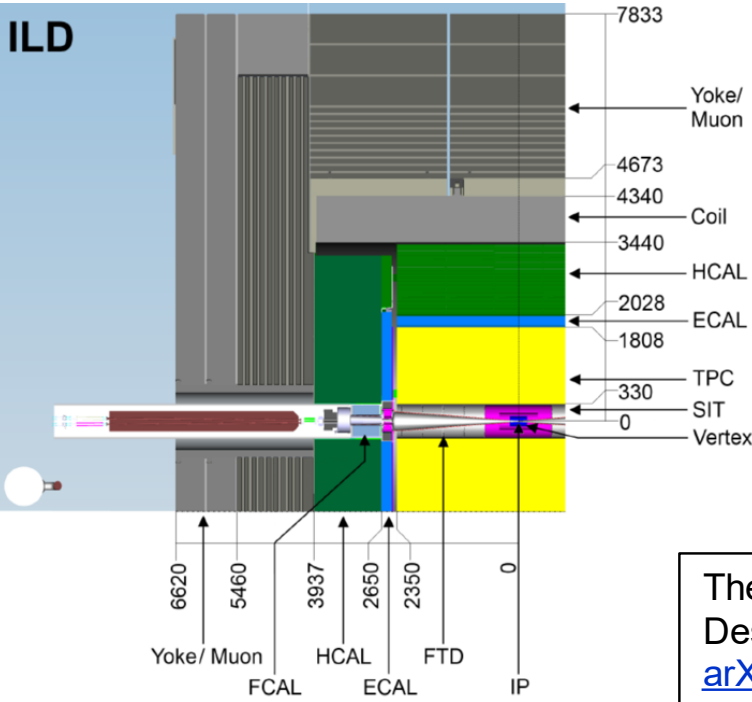
<https://doi.org/10.48550/arXiv.2502.21223>

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](https://arxiv.org/abs/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](https://arxiv.org/abs/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.

FCC-ee
=
10 x Belle II

Particle species	B^0	B^-	B_s^0	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				
$B^0 \rightarrow K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \rightarrow K^*(892)\tau^+\tau^-)$	~ 10	—	—	~ 1000
$B_s \rightarrow \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \rightarrow \mu^+\mu^-$	~ 5	—	~ 50	~ 100
$\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$				
Leptonic decays				
$B^+ \rightarrow \mu^+\nu_{mu}$	5%	—	—	3%
$B^+ \rightarrow \tau^+\nu_{tau}$	7%	—	—	2%
$B_c^+ \rightarrow \tau^+\nu_{tau}$	n/a	—	—	5%
CP / hadronic decays				
$B^0 \rightarrow J/\Psi K_S (\sigma_{\sin(2\phi_d)})$	$\sim 2 \cdot 10^6 (0.008)$	41500 (0.04)	$\sim 0.8 \cdot 10^6 (0.01)$	$\sim 35 \cdot 10^6 (0.006)$
$B_s \rightarrow D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \rightarrow J/\Psi \phi (\sigma_{\phi_s} \text{ rad})$	n/a	96000 (0.049)	$\sim 2 \cdot 10^6 (0.008)$	$16 \cdot 10^6 (0.003)$

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

out of reach
at LHCb/Belle

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

See S. Monteil, Flavour@FCC'22

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.

FCC-ee
=
10 x Belle II

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

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

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

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

Decay mode

EW/H per

$B^0 \rightarrow K^*(8$

$\mathcal{B}(B^0 \rightarrow K$

$B_s \rightarrow \mu^+\mu^-$

$B^0 \rightarrow \mu^+\mu^-$

$\mathcal{B}(B_s \rightarrow \tau^+$

Leptonic d

$B^+ \rightarrow \mu^+\nu$

$B^+ \rightarrow \tau^+\nu$

$\mathcal{B}_c^+ \rightarrow \tau^+\nu$

CP / hadr

$B^0 \rightarrow J/\Psi$

$B_s \rightarrow D_s^\pm K^\mp$

$B_s(B^0) \rightarrow J/\Psi\phi$ (σ_{ϕ_s} rad)

n/a

6000

96000 (0.049)

~ 200000

$\sim 2.10^6$ (0.008)

$\sim 30 \cdot 10^6$

$16 \cdot 10^6$ (0.003)

out of reach
at LHCb/Belle

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

See S. Monteil, Flavour@FCC'22

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 \rightarrow 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:
 - $\tau \rightarrow \mu \gamma$: 4×10^{-8} @ Belle2021 $\rightarrow 10^{-9}$ @ FCC-ee
 - $\tau \rightarrow 3\mu$: 2×10^{-8} @ Belle $\rightarrow 3 \times 10^{-10}$ @ BelleII $\rightarrow 10^{-11}$ @ FCC-ee
 - tau lifetime uncertainty:
 - 2000 ppm \rightarrow 10 ppm
 - tau mass uncertainty:
 - 70 ppm \rightarrow 14 ppm
- **Semi-leptonic mixing asymmetries** a_{sl}^s and a_{sl}^d
- ...

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.

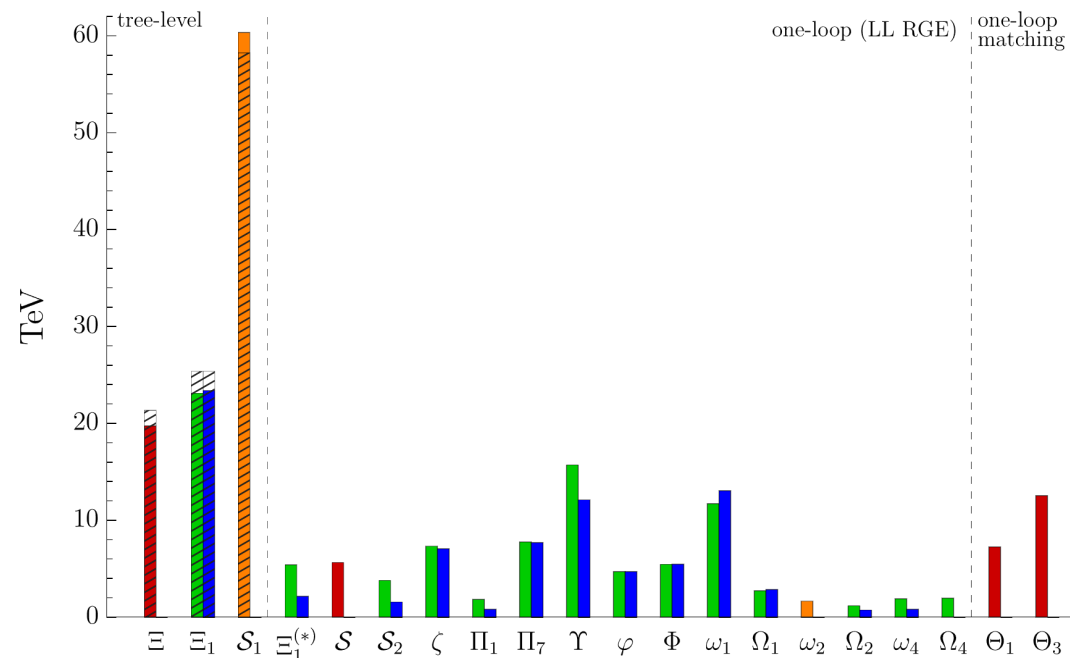
New Physics Reach @ Z-pole

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.

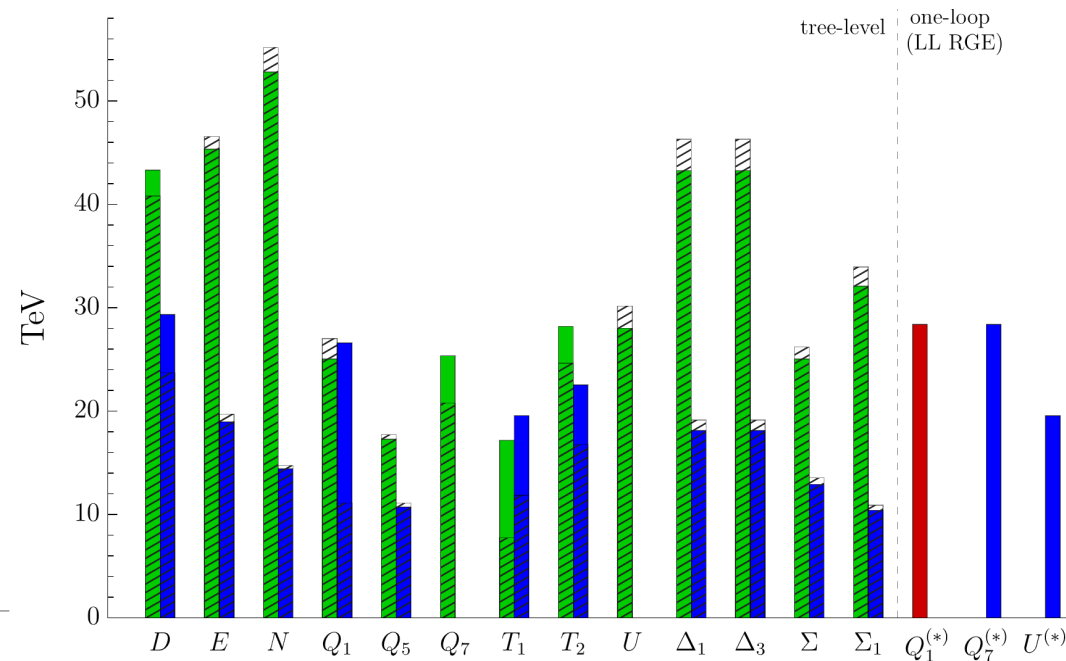
Allwicher, McCullough, Renner, arXiv: 2408.03992

■ Universal couplings ■ Third-gen. only ■ Flavourless couplings ■ Antisymm. couplings



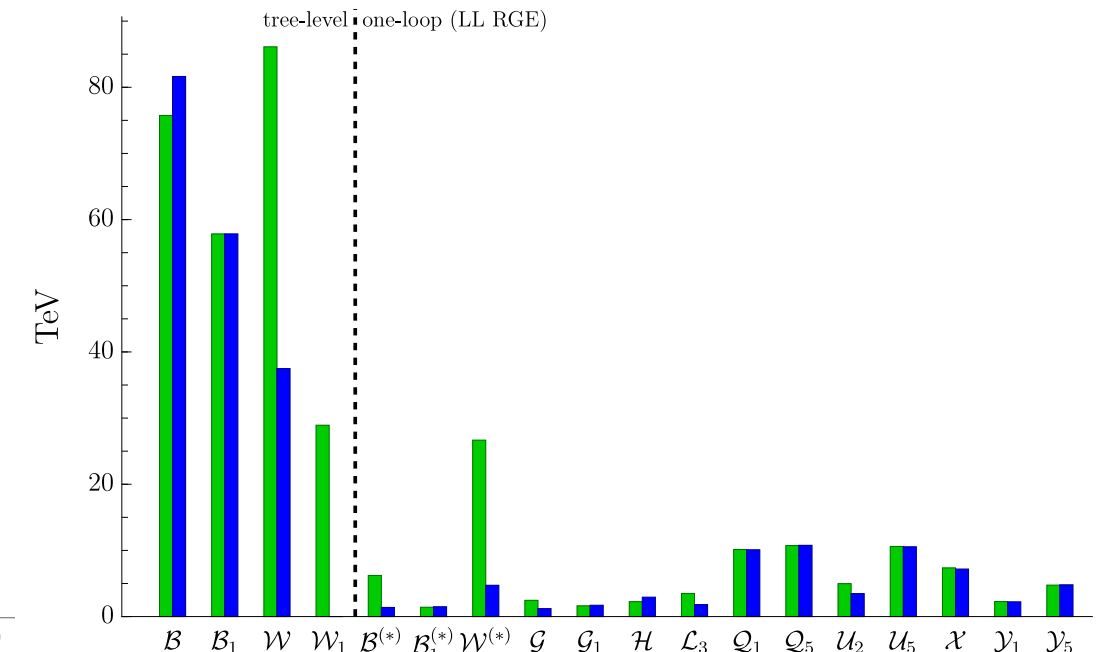
Scalars

■ Universal couplings ■ Third-gen. only ■ Other



Fermions

■ Universal couplings ■ Third-gen. only

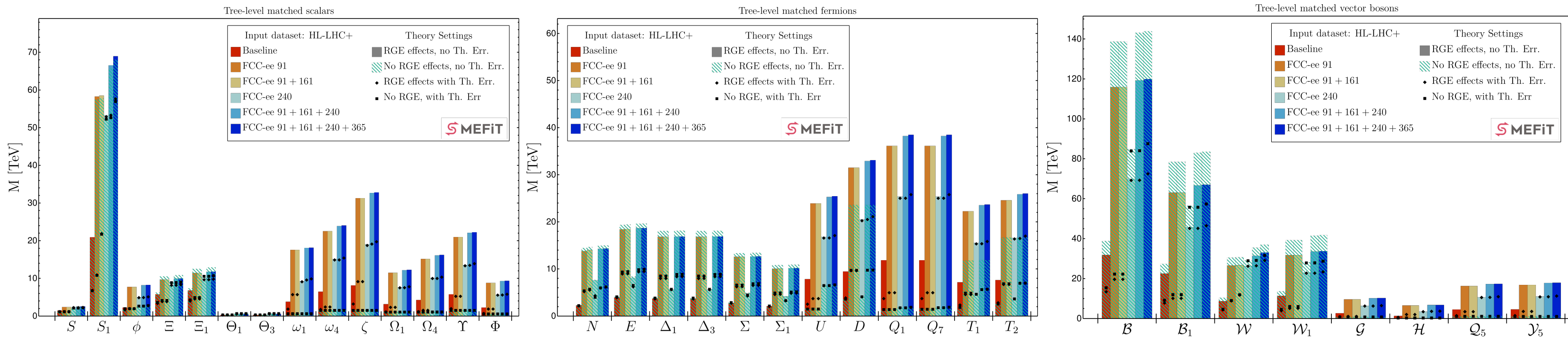


Vectors

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

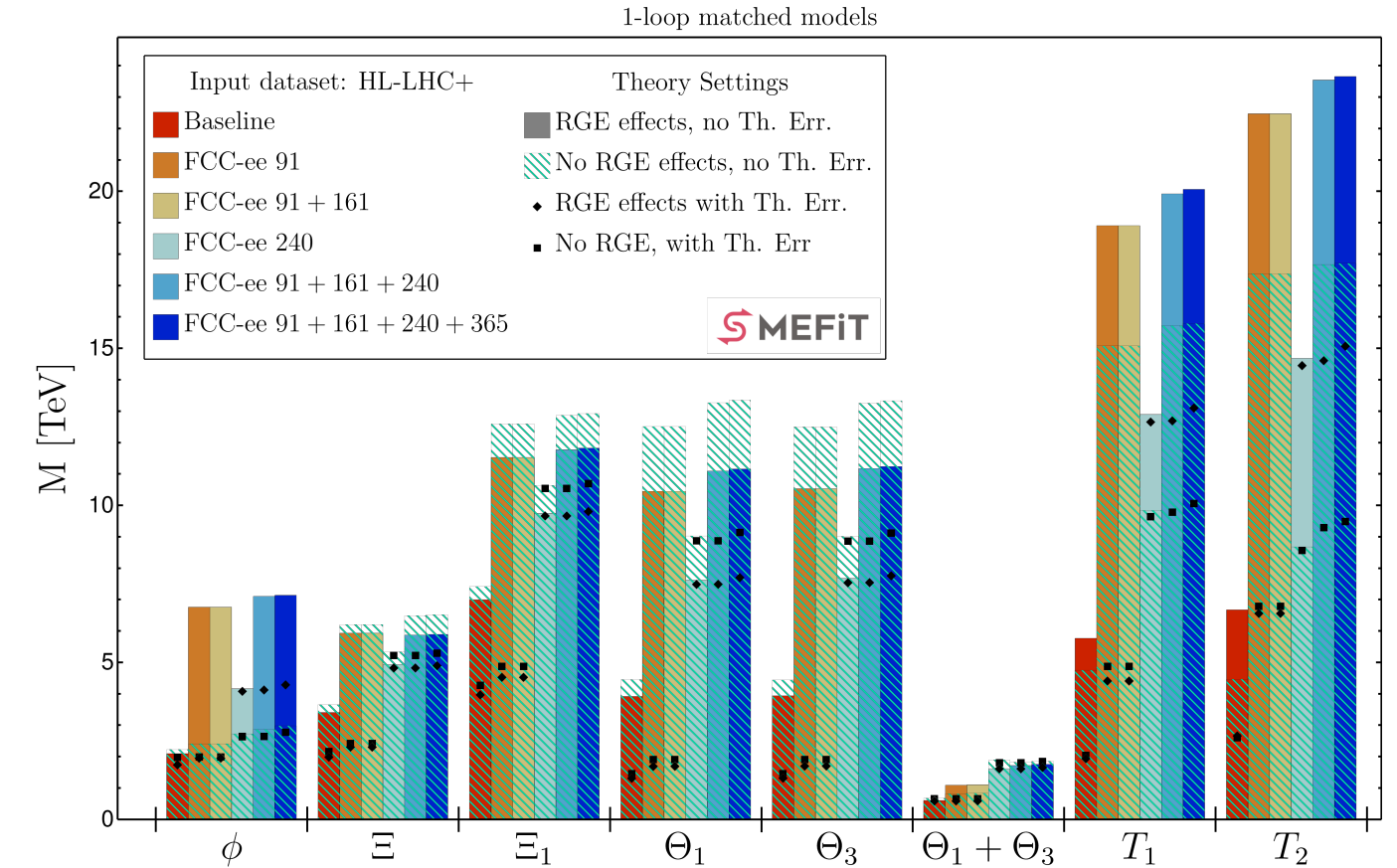
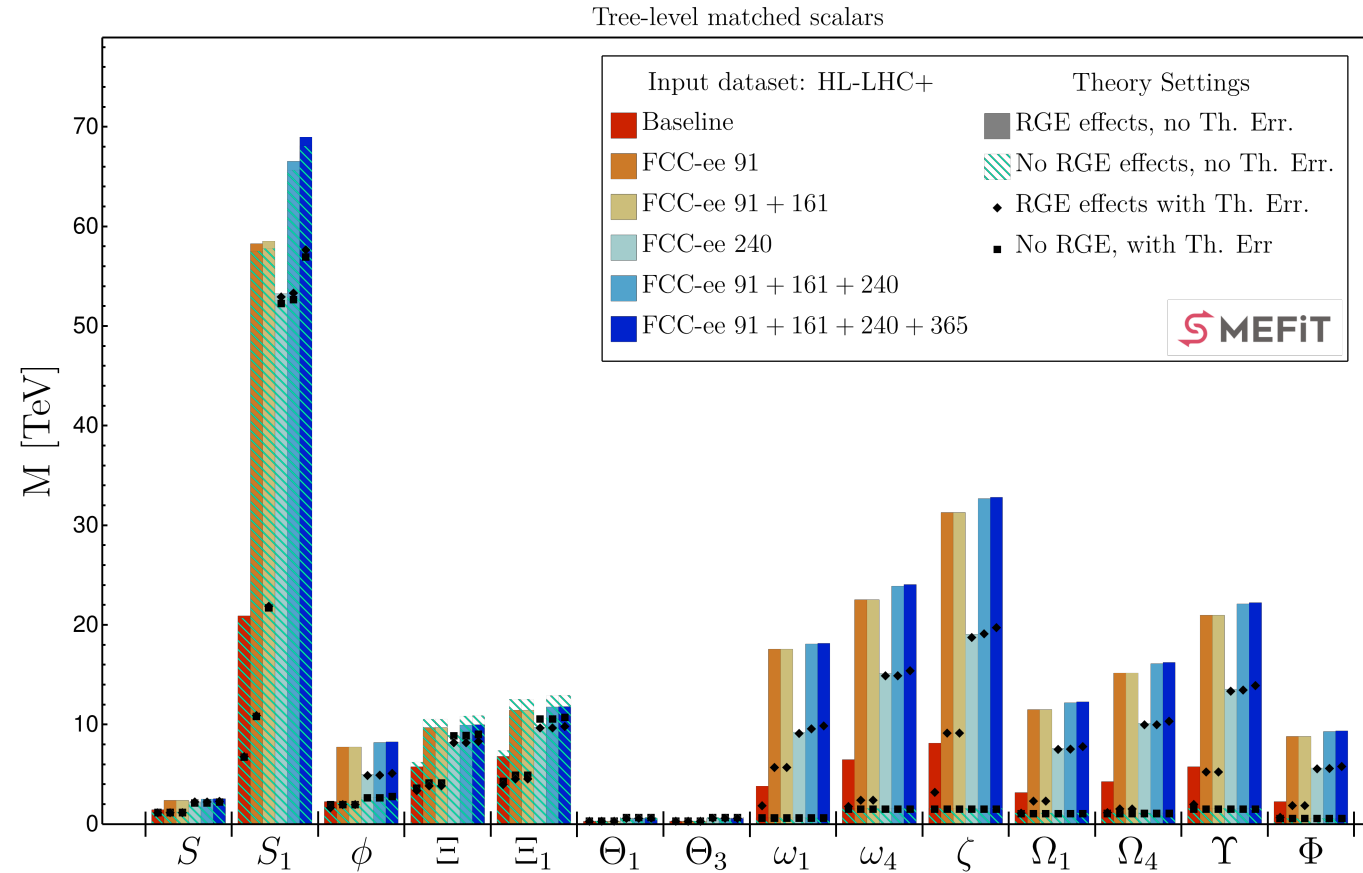
There are 48 different types of particles that can have tree-level linear interactions to SM.



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.

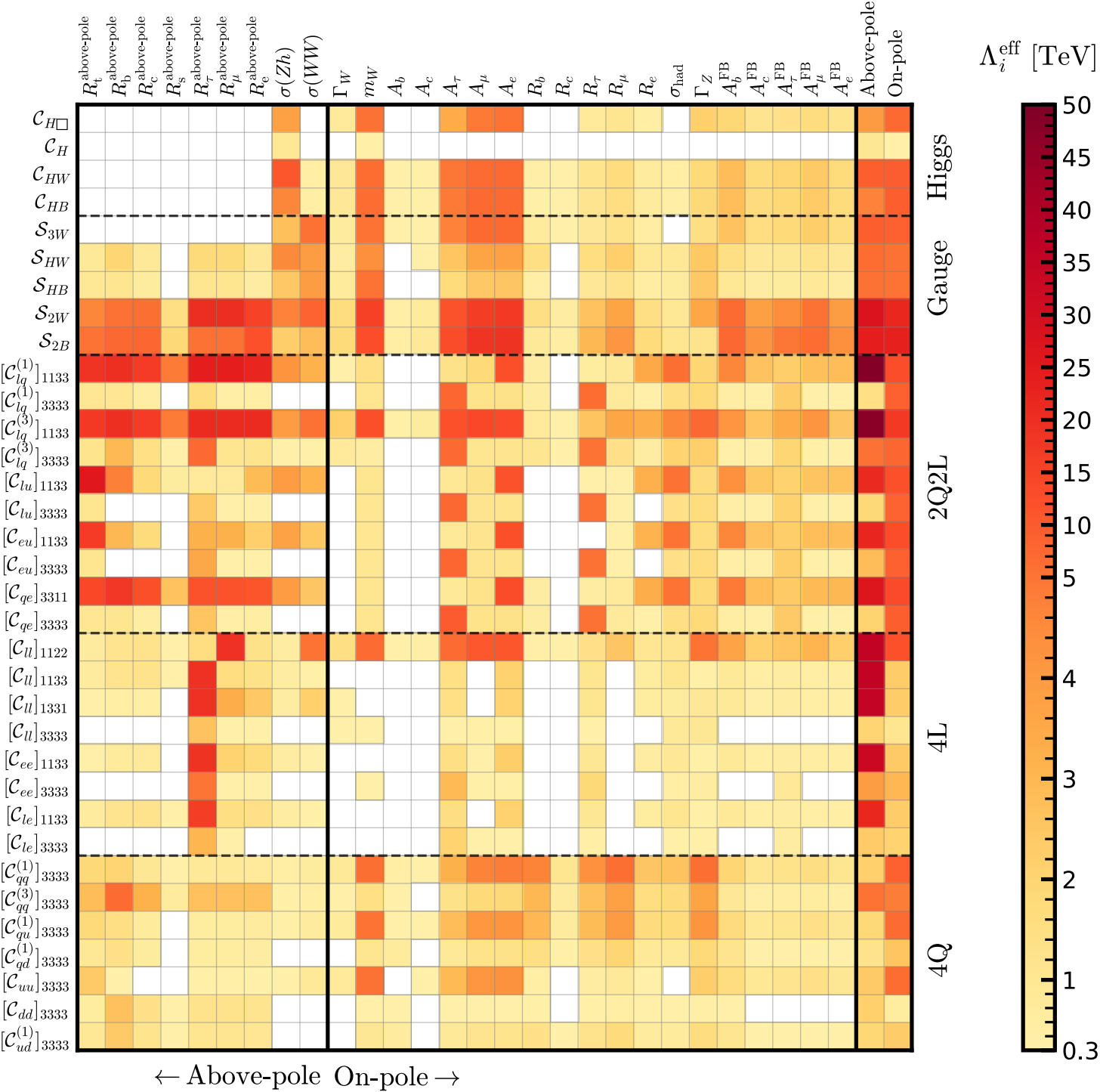
If a signature shows up elsewhere, it will also show up at Tera-Z.

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.

Z-pole vs High Energy

Maura, Stefanek, You arXiv:2412.14241

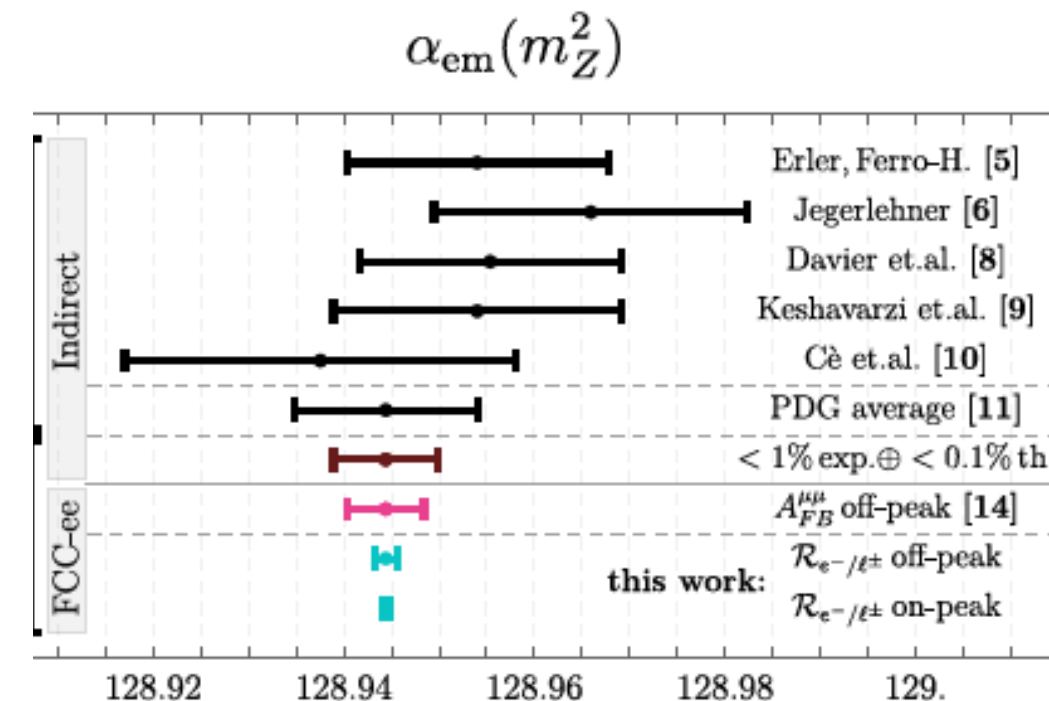
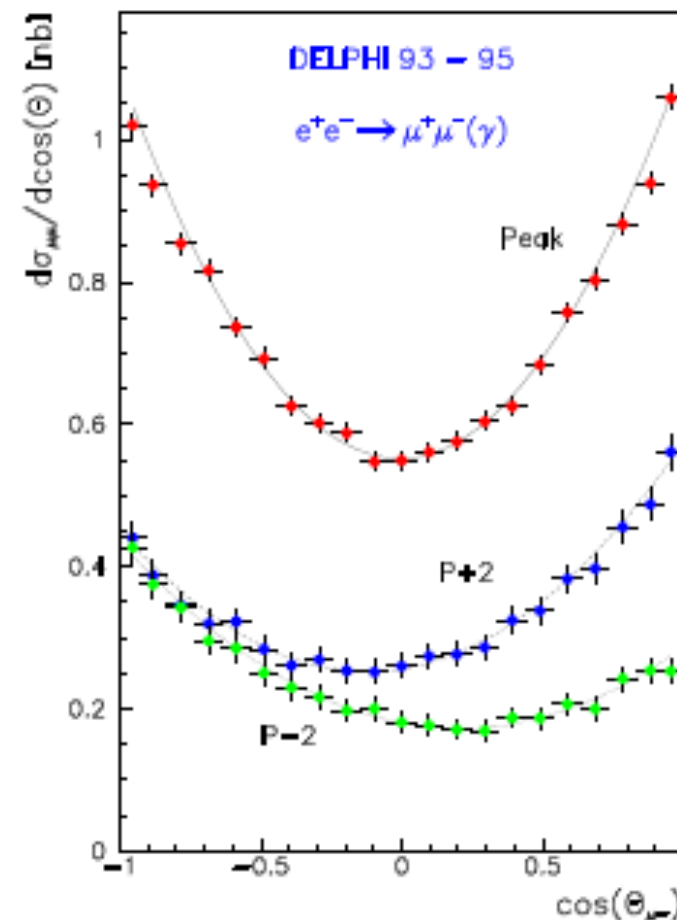
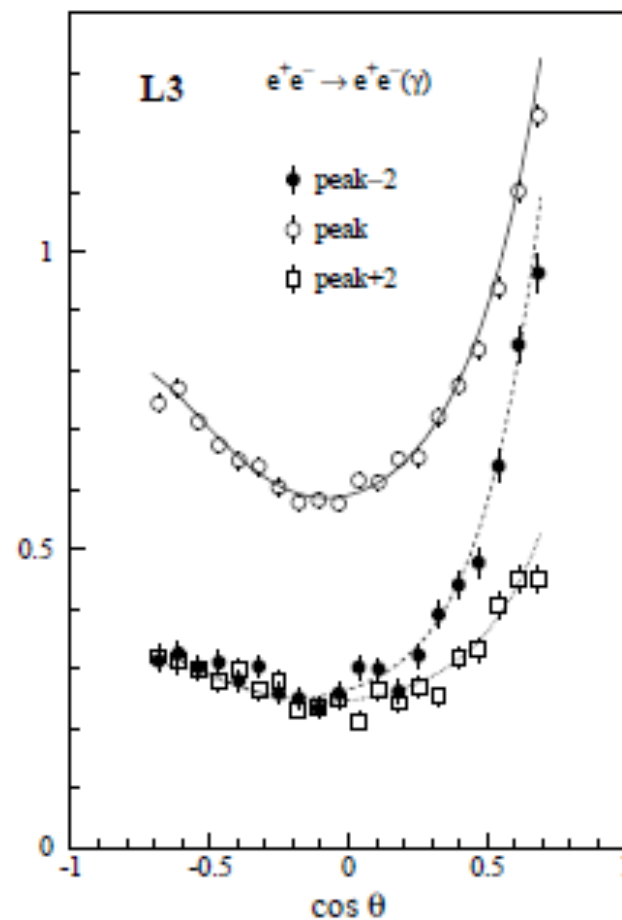


More on EW Precision: $\alpha_{\text{EM}}(m_Z^2)$

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

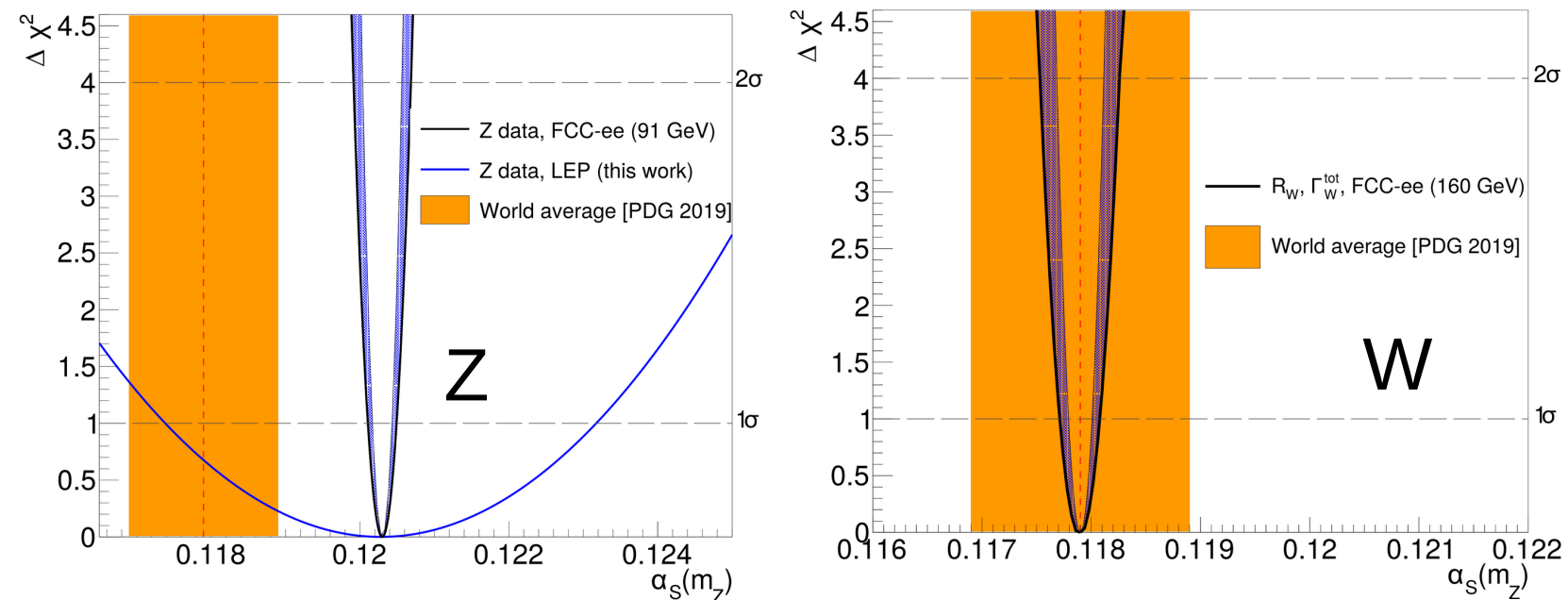
Unique to circular machines, since it requires $\gg 10^{12}$ Z and line shape scan

- **Off-pole** ([Janot 2015](#)): so far determined from the slope of $A_{\text{FB}}^{\mu\mu}$ vs $\sqrt{s} \rightarrow \pm 3 \cdot 10^{-5}$
- **On-pole** ([Riembau 2025](#)): both s and t- channel $e^+e^- \rightarrow e^+e^-$ and $\mu^+\mu^-$ at the Z pole $\rightarrow \pm 0.6 \times 10^{-5}$
Can this be improved by using tau final states, etc...?



FCC-ee as a QCD factory

S. Kluth @ FCC week 2025



FCC-ee: improved α_{QED} , $|V_{cs}|$, $|V_{cd}|$, m_W ; assume N4LO QCD

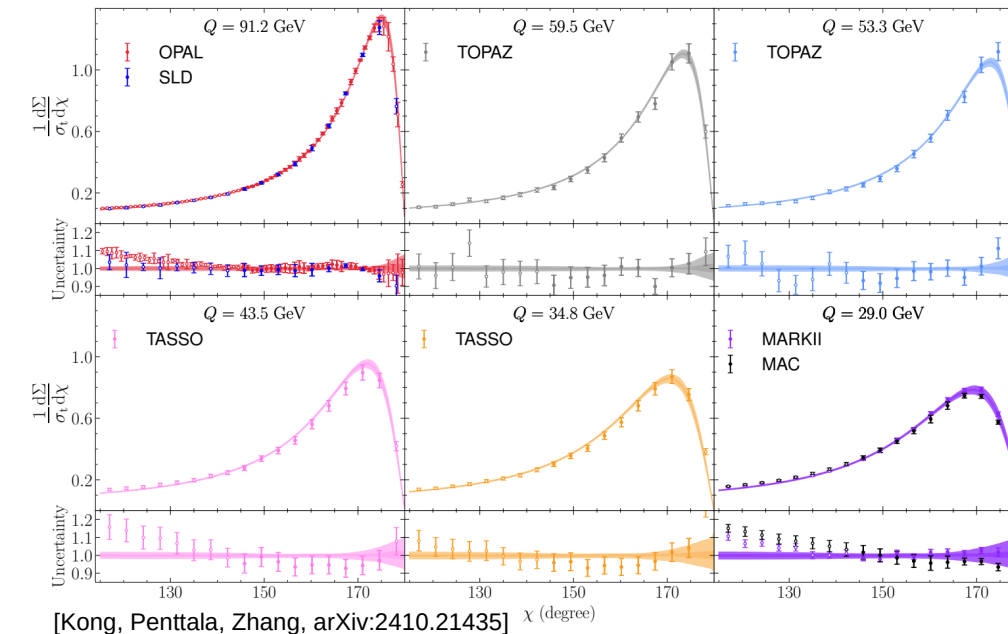
Z: $\alpha_s(m_Z) = 0.12020 \pm 0.00013_{\text{exp}} \pm 0.00005_{\text{par}} \pm 0.00022_{\text{theo}}$

W: $\alpha_s(m_Z) = 0.11790 \pm 0.00012_{\text{exp}} \pm 0.00004_{\text{par}} \pm 0.00019_{\text{theo}}$

[D. d'Enterria, in arxiv: 2203.08271]

Semi-inclusive EECs

$$\frac{d\Sigma}{d\chi} = \frac{1}{(\Delta\chi N)} \int_{\text{bin}} \sum_{\text{events}} \sum_{ij} E_i E_j / s \delta(\chi' - \theta_{ij}) d\chi'$$
 EEC is energy weighted distribution of angles between particle pairs



QCD NNLO+N3LL resum.

np effects from TMD factorisation in N3LL
 $\alpha_s(m_Z) = 0.1193 \pm 0.0009_{\text{exp}} \pm 0.0011_{\text{theo}}$

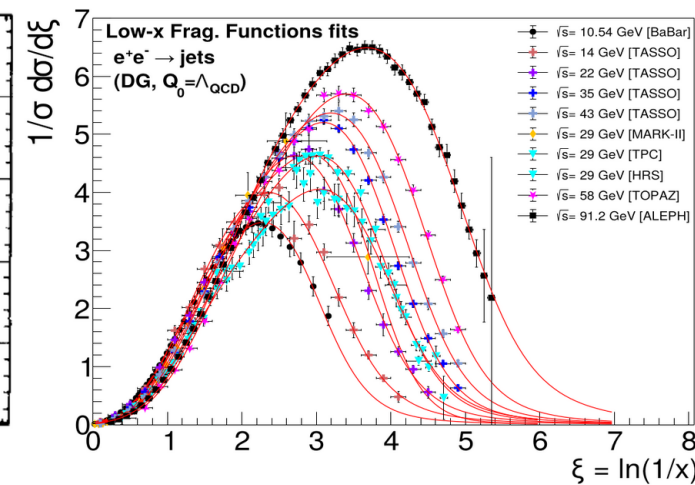
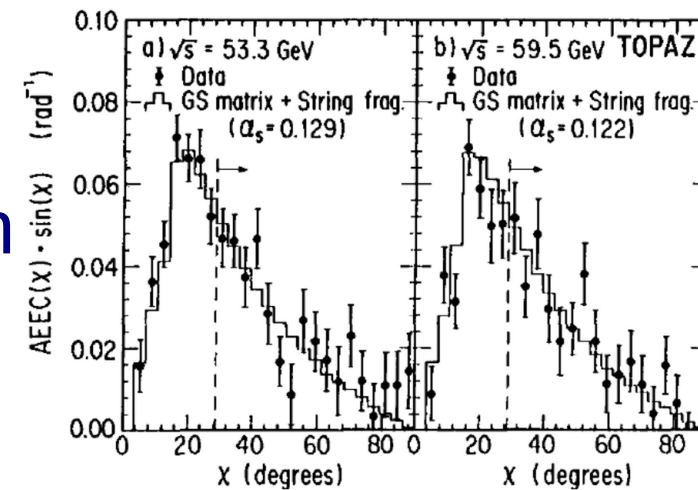
Potential for $\Delta\alpha_s(m_Z) < 1\%$ at FCC-ee

FCC-ee as a QCD factory

S. Kluth @ FCC week 2025

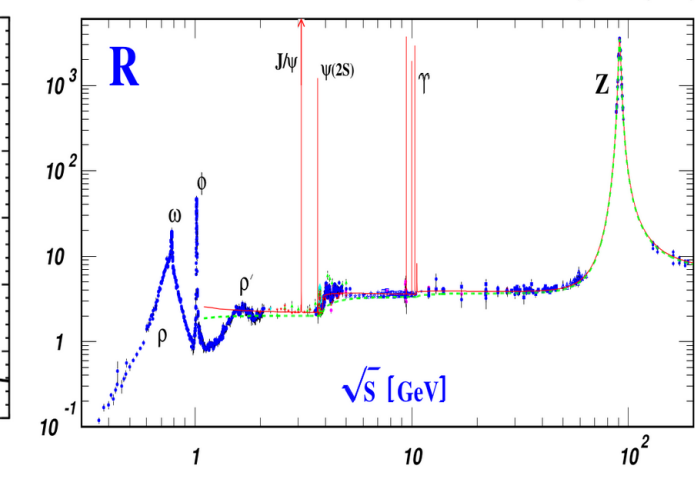
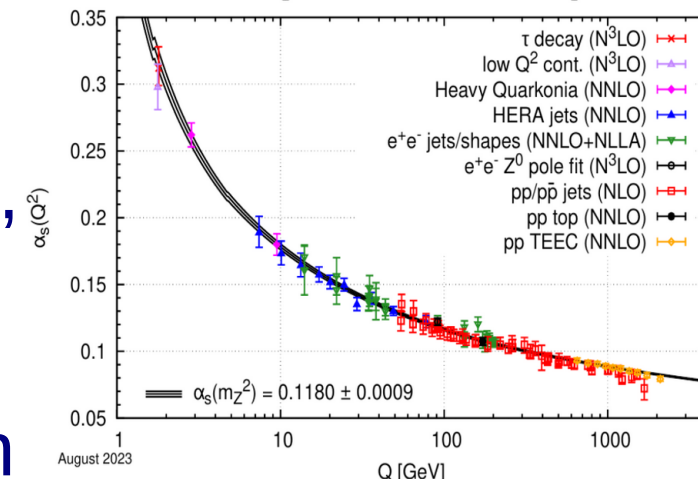
FCC-ee low energy $\sqrt{s} < m_Z$

Hard vs soft
QCD,
Hadronisation



Fragmentation,
QCD, MCs,
Hadronisation

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



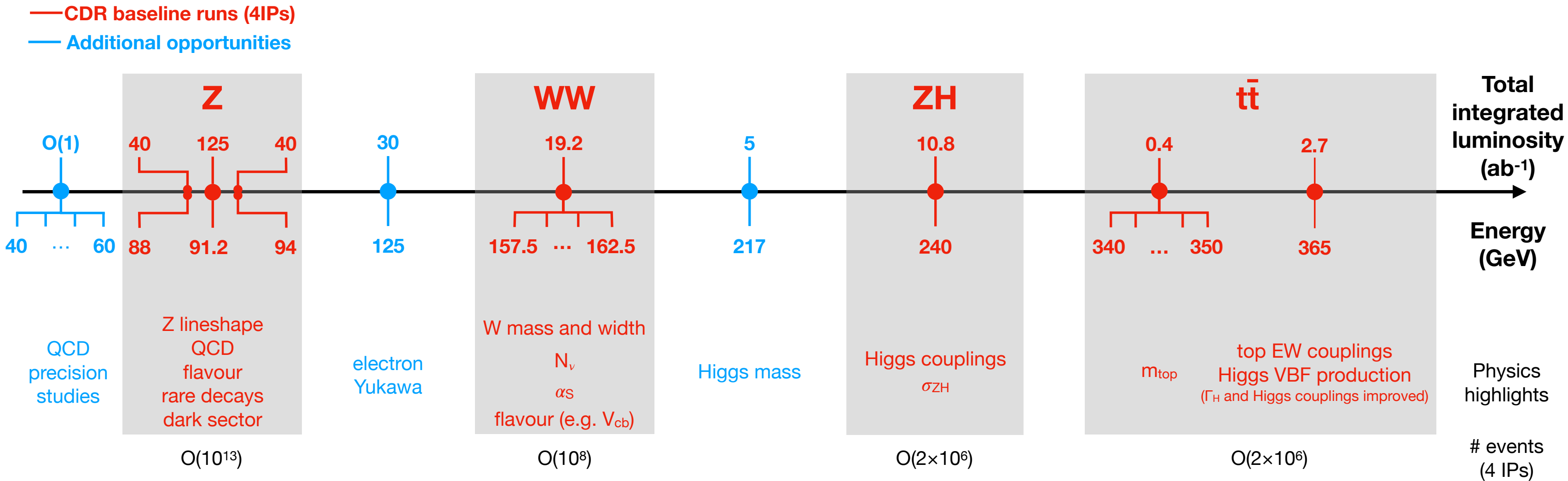
$R = \sigma(\text{hadrons}) / \sigma(\mu^+\mu^-)$

$\alpha_s(20\text{-}40 \text{ GeV})$
at 0.1%?

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

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

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.

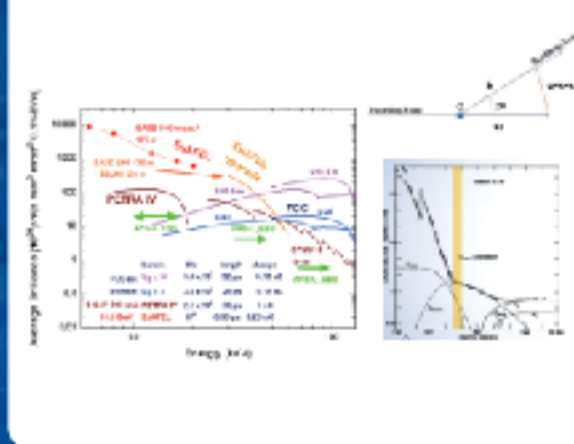
OTHER SCIENCE OPPORTUNITIES AT THE FCC-ee

28-29 NOV 2024 | CERN | GENEVA, SWITZERLAND

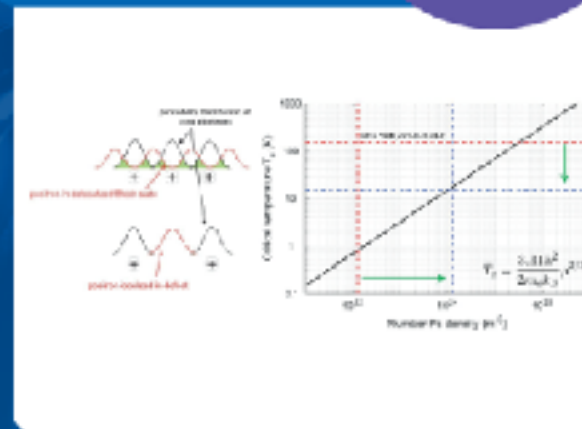


find more information

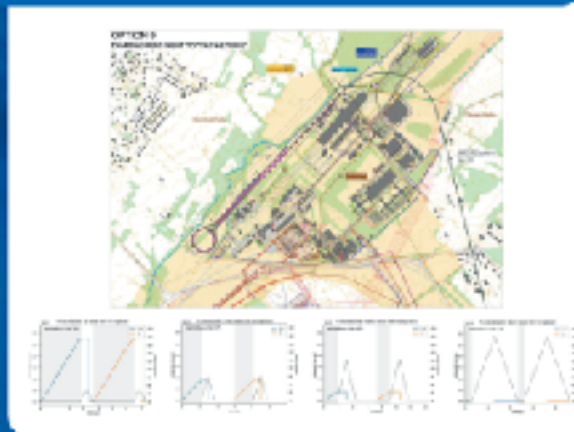
1 Diffraction-limited photon source down to 0.1 Å



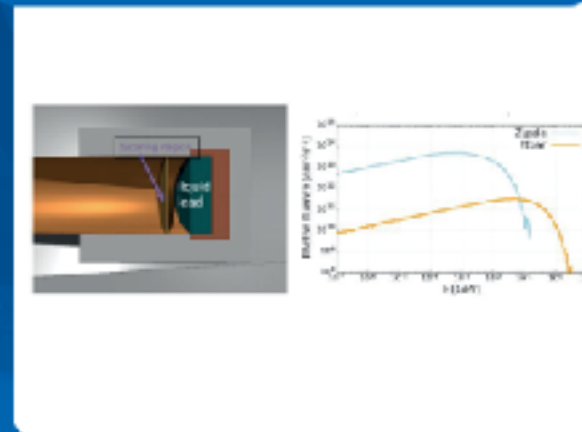
2 e^+ beams for surface/material science & pathway to positronium γ -ray laser



3 Intense energetic e^-/e^+ and γ beams for physics beyond colliders and neutron production



4 Heliumless bremsstrahlung and e^-/e^+ beams for radionuclide production and multipurpose applications



ORGANISERS:

G. Ardani (CERN), M. Benedikt (CERN),
I. Byrd (ANL/LBNL), M. Cariani (CERN),
S. Chavhan (FHI-JEFF), M. Hoser (CERN),
B. Kieneker (U Liverpool), P. Zimmermann (CERN)



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)

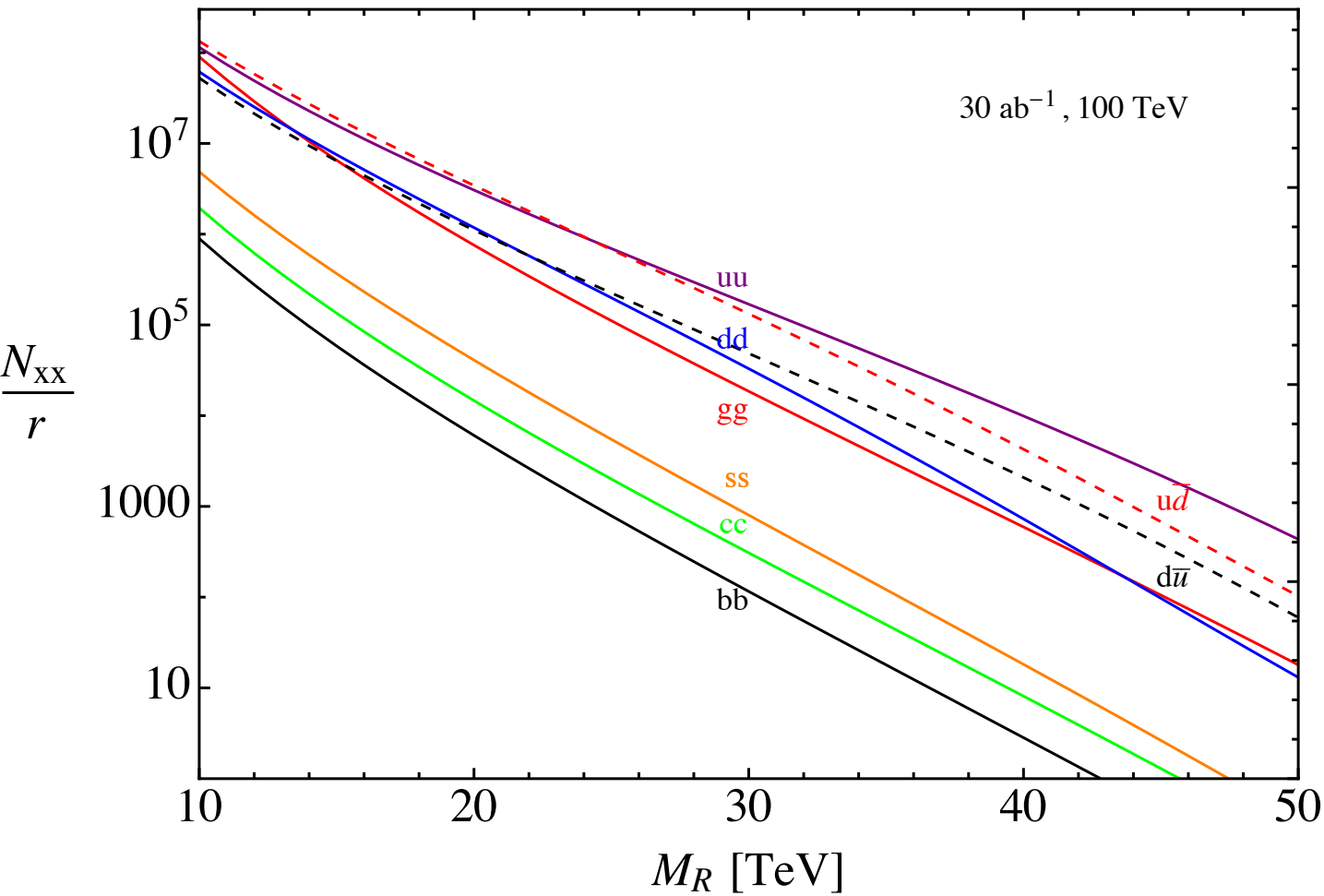
Exploration potential at high-energy with FCC-hh

Resonance production.

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

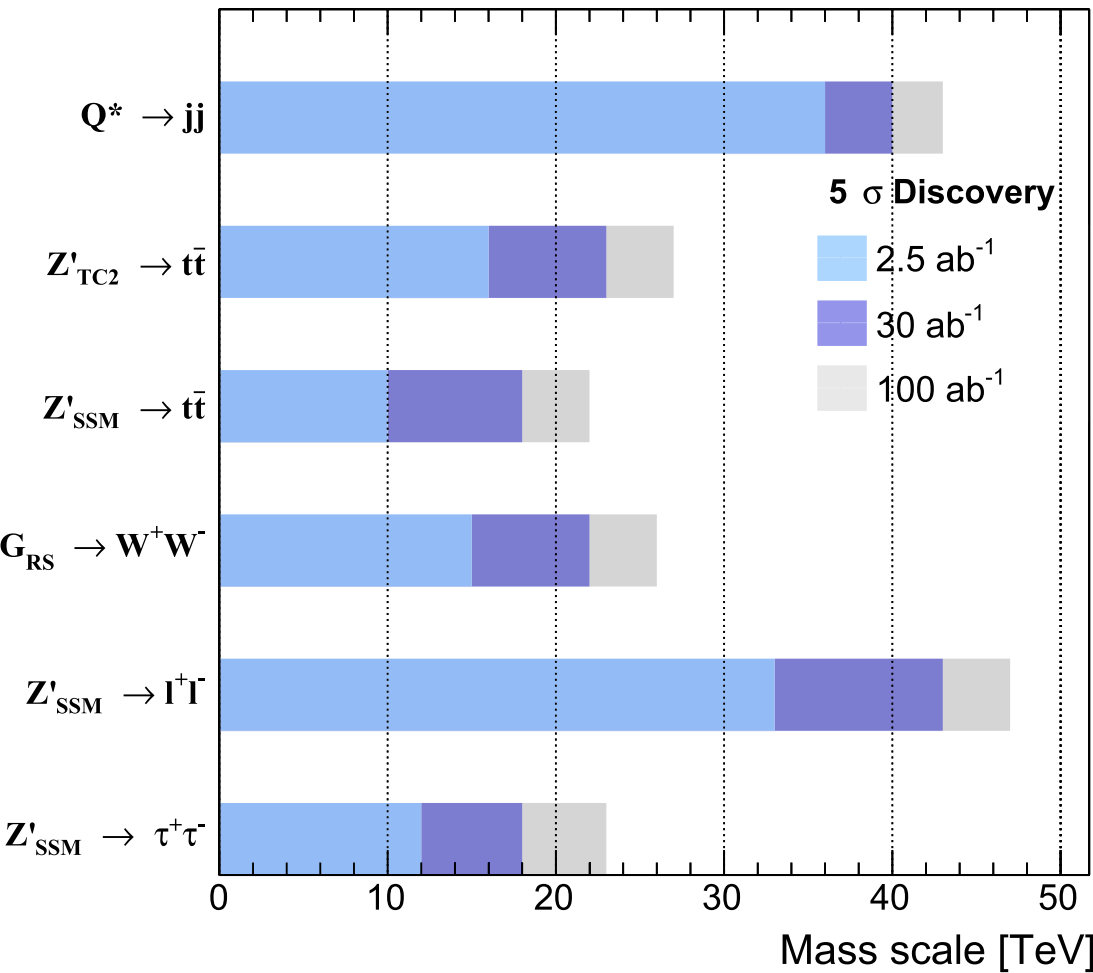
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

resonances produced



Plot from mid-term report

FCC-hh mass reach



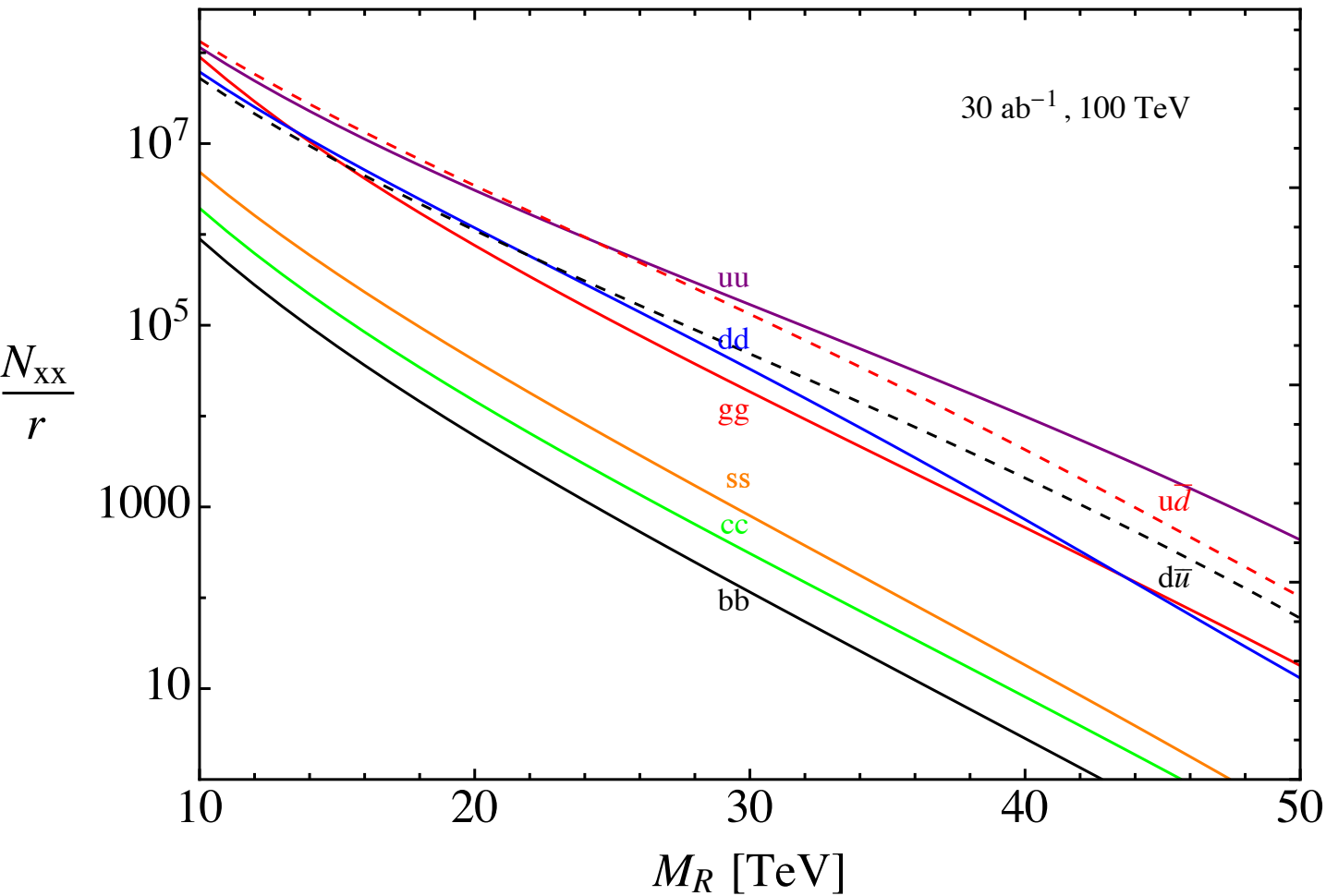
Plot from FCC CDR

Resonance production.

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

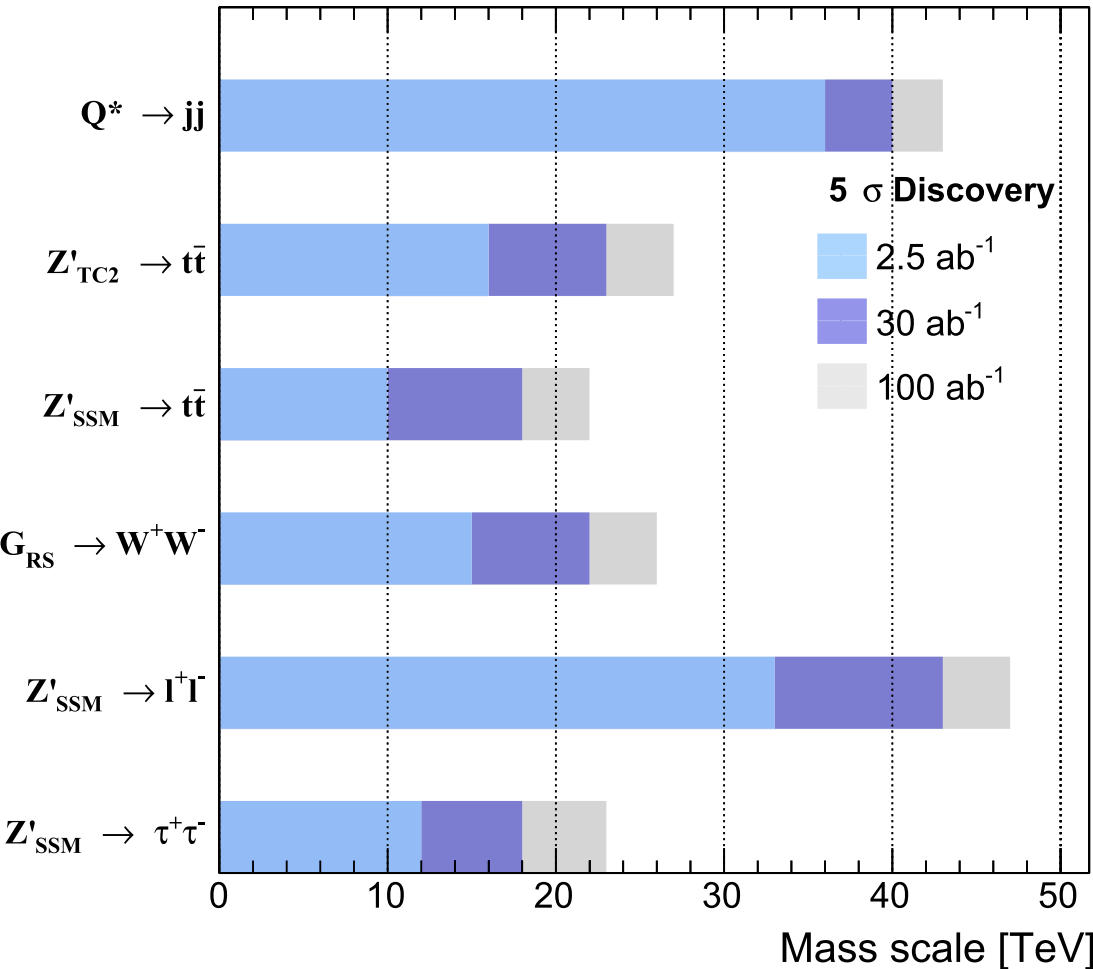
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

resonances produced



Plot from mid-term report

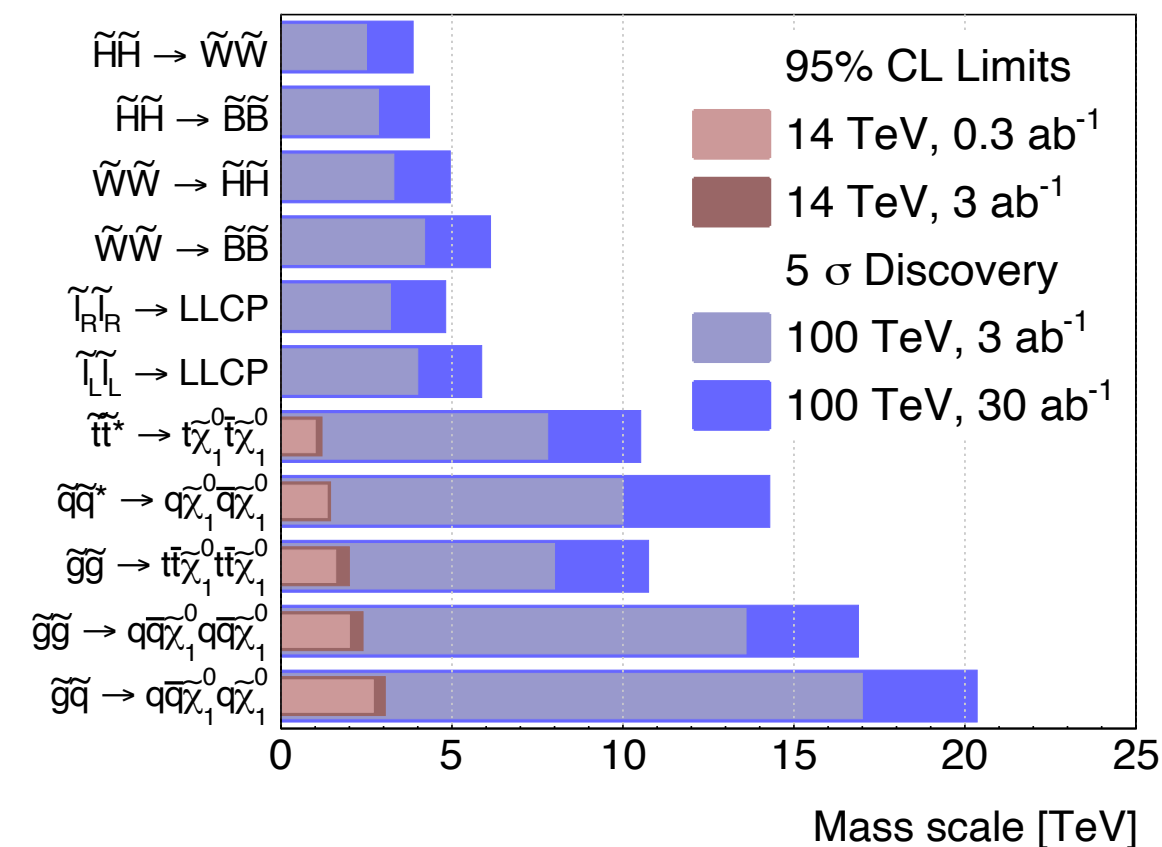
FCC-hh mass reach



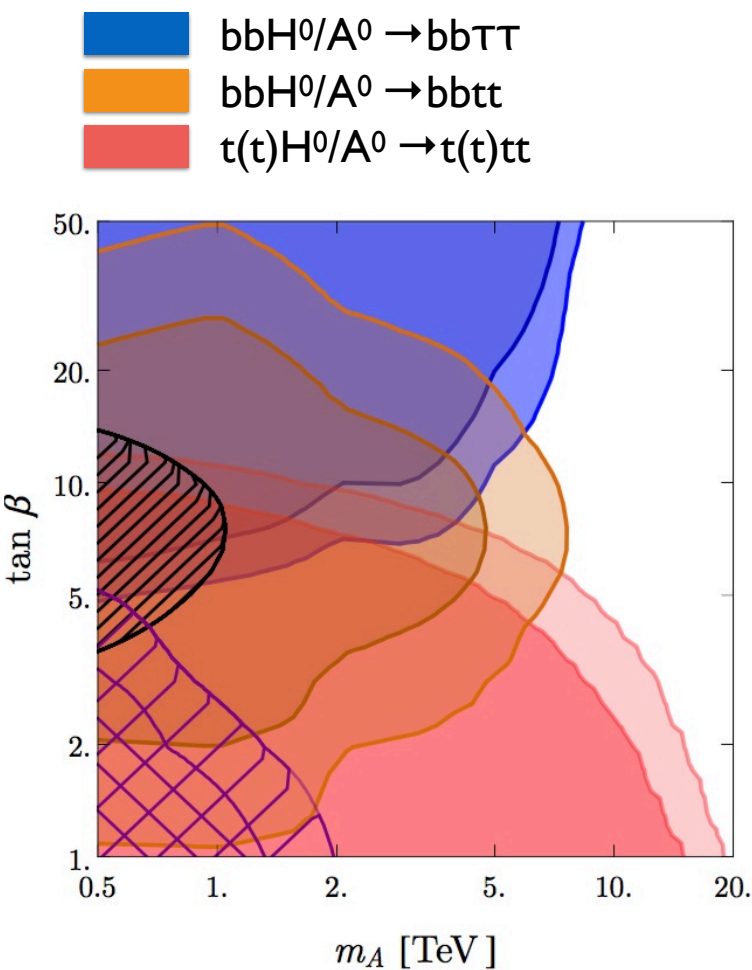
Plot from FCC CDR

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.

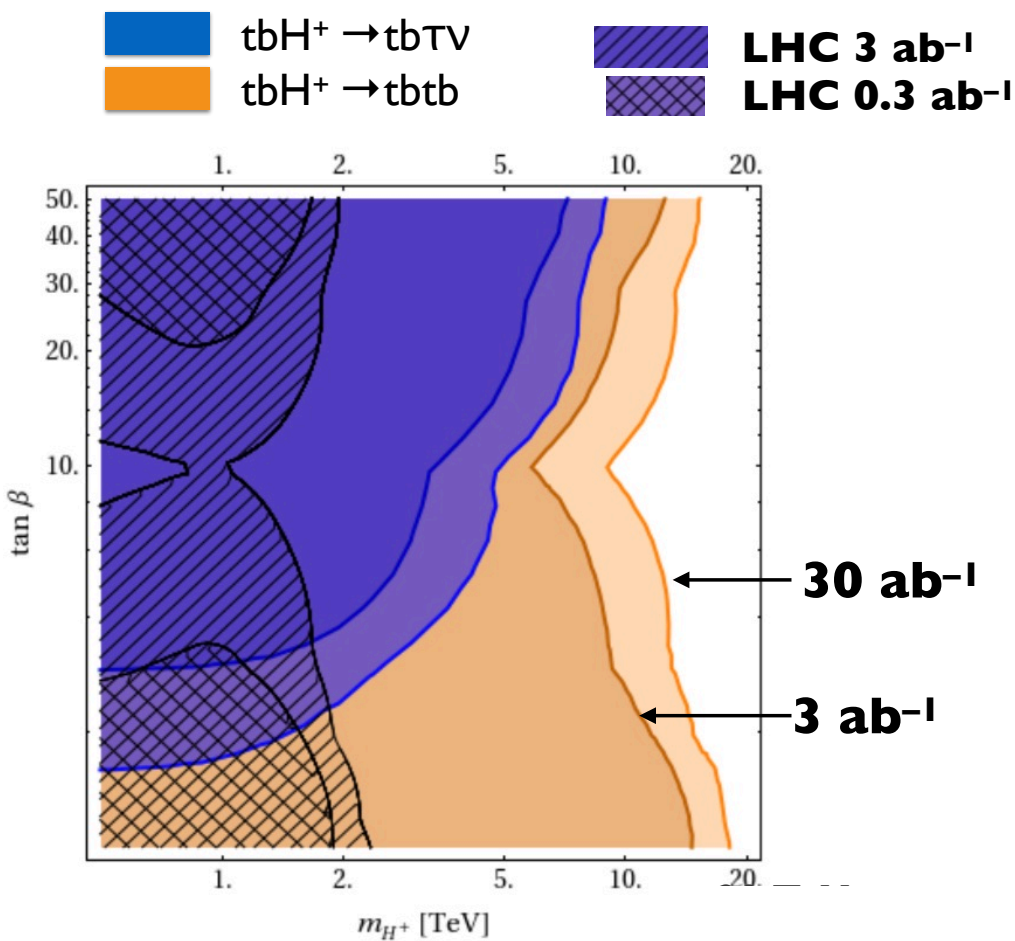
Pushing limits of SUSY.



Plot from [arXiv:1606.00947](#)



Plot from [arXiv:1605.08744](#) and [arXiv:1504.07617](#)



Factor 10 increase on the HL-LHC limits.

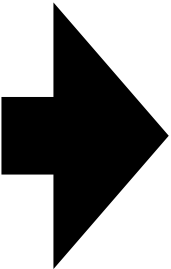
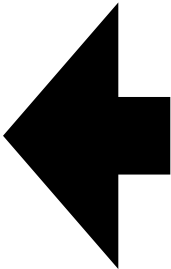
15-20TeV squarks/gluinos
require kinematic threshold 30-40TeV:
FCC-hh is more than a $\sqrt{s} \sim 10\text{TeV}$ factory

Conclusions & Outlook

Much progress in the course of the Feasibility Study:

- ▶ 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 Nb₃Sn magnets with higher lumi vs. 100TeV w. 16T vs. 120TeV w. 20T HTS)

FCC-ee has a rich 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.

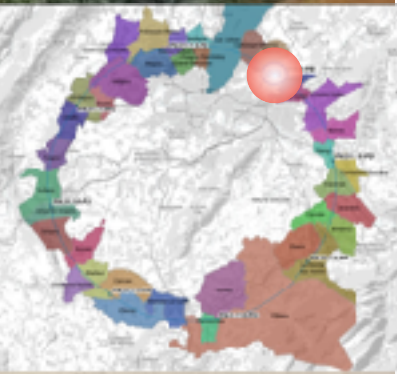
The FCC project perfectly fits the **needs of HEP after LHC**:

- ▶ guaranteed deliverables & broad exploration potential ◀

Physics Manifesto

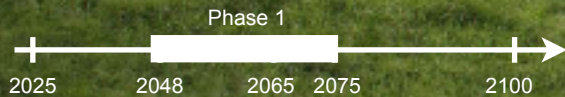
"Physics is born free and everywhere it is in chains."

Twenty Year from First Collisions



Site PB (Choulex, CH)

Twenty Year from First Collisions



Twenty Year from First Collisions



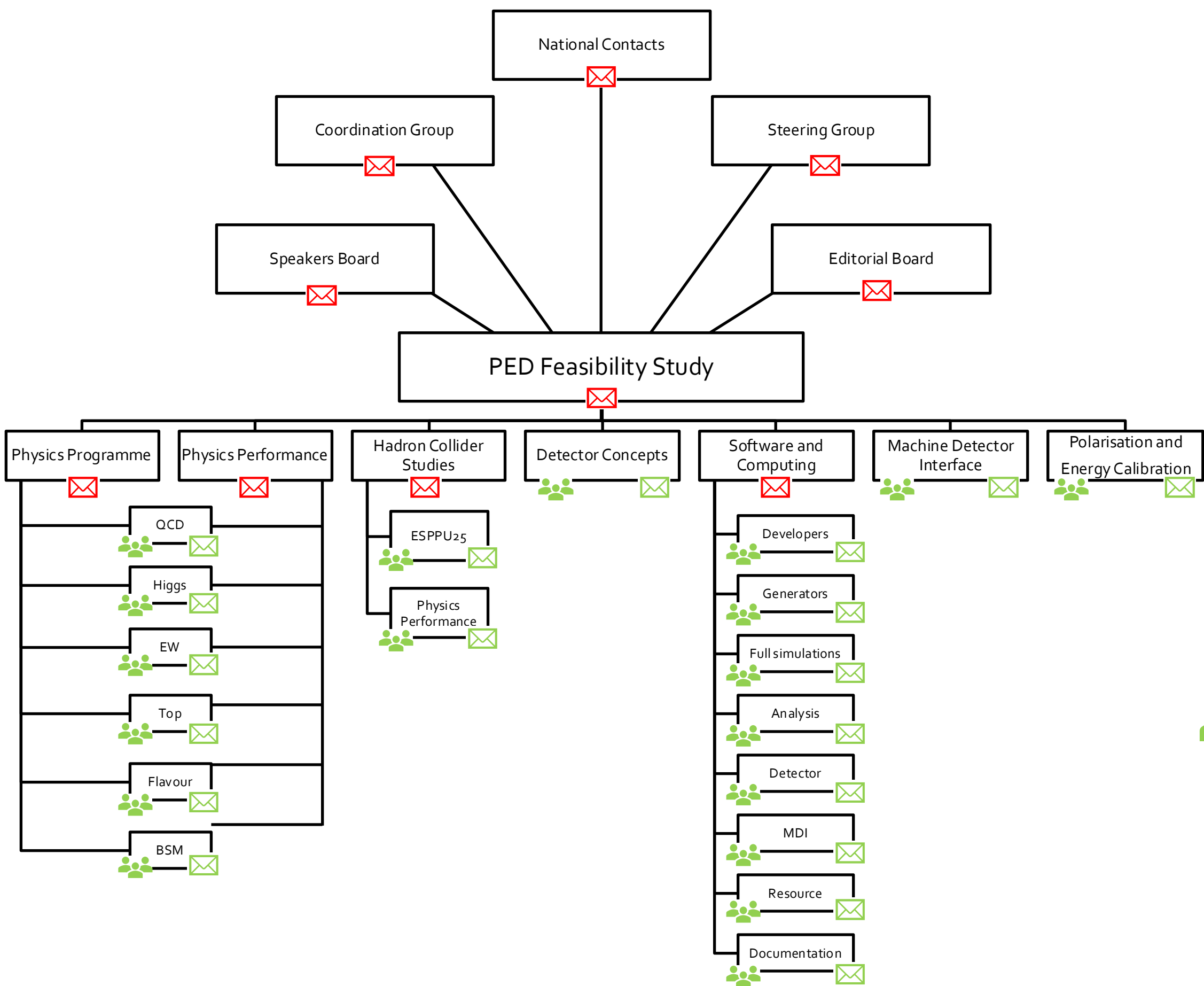
Reading Material

- **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 1: The FCC-ee (ESPPU#233); [CDS](#)
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 - The FCC Integrated Programme: A physics manifesto (ESPPU#241); CDS; [arXiv:2504.02634](#)
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 - FCC: QCD physics (ESPPU#209); [FCC note](#)
 - Prospects for flavour physics at FCC (ESPPU#196); [FCC note](#)
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 - Summary (ESPPU#95); [FCC note](#)
 - Backup document ((ESPPU#96)

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Join Us



Link to e-group



Send a mail

BONUS

Electroweak Factory

Experimental Inputs.

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

A linear ee Higgs factory
operating above Z-pole
can also preform
EW measurements
via **Z-radiative** return

A linear ee Higgs factory
could also operate on the
Z-pole though at lower lumi
(**GigaZ**)

	Higgs	aTGC	EWPO	Top EW
FCC-ee	Yes (μ , σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.) <i>Warning</i>	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ , σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit) <i>Warning</i>	LEP/SLD (Z-pole) + HL-LHC + W (ILC)	Yes (500 GeV, Ztt)
CEPC	Yes (μ , σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom) <i>Warning</i>	Yes	No
CLIC	Yes (μ , σ_{ZH})	Yes (Full EFT parameterization)	LEP/SLD (Z-pole) + HL-LHC + W (CLIC)	Yes
HE-LHC	Extrapolated from HL-LHC	N/A \rightarrow LEP2	LEP/SLD + HL-LHC (M_W , $\sin^2\theta_w$)	-
FCC-hh	Yes (μ , BR_i/BR_j) Used in combination with FCCee/eh	From FCC-ee	From FCC-ee	-
LHeC	Yes (μ)	N/A \rightarrow LEP2	LEP/SLD + HL-LHC (M_W , $\sin^2\theta_w$)	-
FCC-eh	Yes (μ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + Zuu, Zdd	-

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_W^{\text{eff}} (\times 10^6)$	231,480	±	160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	±	14	3.9 0.8	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	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 $R_\ell^Z, \Gamma_{\text{tot}}^Z, \sigma_{\text{had}}^0$ fit
$\sigma_{\text{had}}^0 (\times 10^3)$ (nb)	41 480.2	±	32.5	0.03	0.8	Peak hadronic cross section Luminosity measurement
$N_v (\times 10^3)$	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
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	±	16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	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
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 $R_\ell^W, \Gamma_{\text{tot}}^W$ fit
$N_v (\times 10^3)$	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
Γ_{top} (MeV)	1 420	±	190	10	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2	±	0.3	0.015	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
$t\bar{t}Z$ couplings		±	30%	0.5–1.5 %	small	From $\sqrt{s} = 365$ GeV run

improvement
factor / now

20

200

150

EW Precision Measurements at FCC-ee

2000

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.**

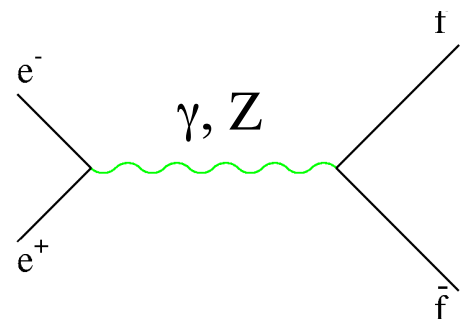
(e.g. beam energy determination from $ee\rightarrow Z/\gamma$ thus the associated uncertainty decreases with luminosity).

50

70

Example of EW measurements @ Tera Z

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



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

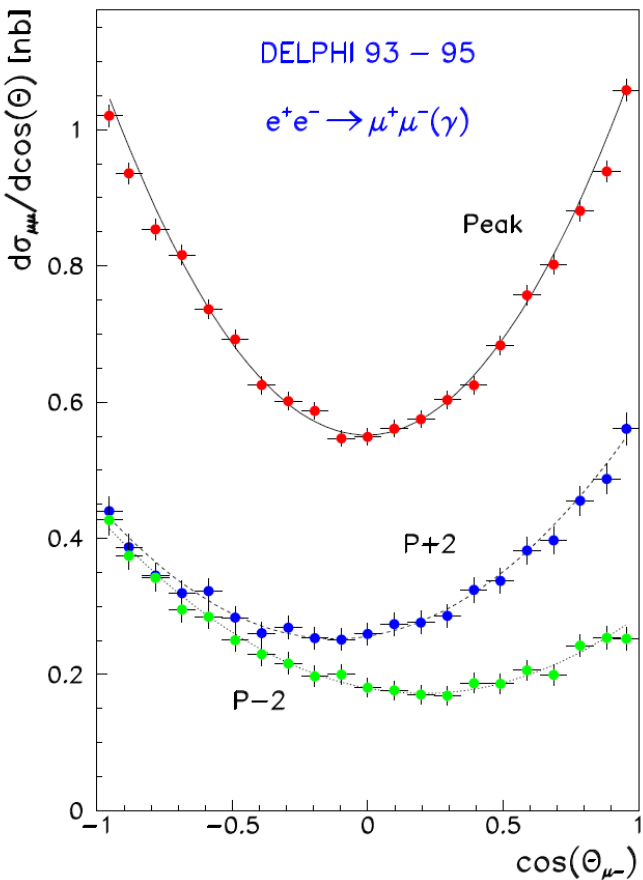
strongly depends on \sqrt{s}
direct measurement of $\alpha_{QED}(s)$ at $\sqrt{s} \neq m_Z$
measure $\sin^2\theta_W$ to high precision (later)

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

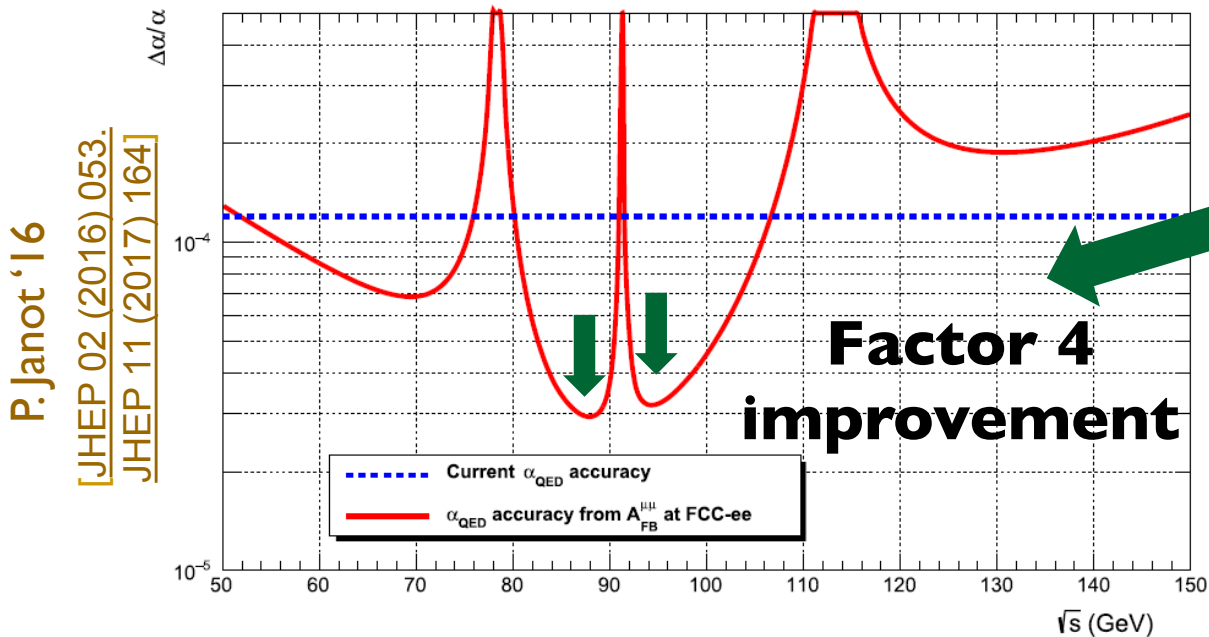
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$$A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4} \mathcal{A}_e \mathcal{A}_\mu \times \left[1 + \frac{8\pi \sqrt{2} \alpha_{QED}(s)}{m_Z^2 G_F (1 - 4 \sin^2 \theta_W^{\text{eff}})^2} \frac{s - m_Z^2}{2s} \right]$$

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



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



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

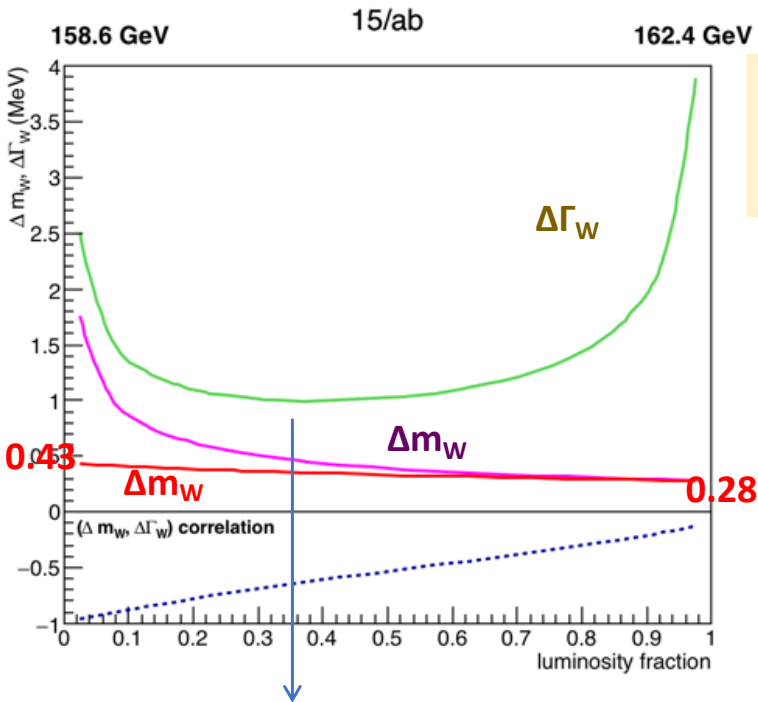
- Measure $\alpha_{QED}(m_Z^2)$ to 3×10^{-5} rel. precision (currently 1.1×10^{-4})
- Stat. dominated; syst. uncertainties $< 10^{-5}$ (dominated by \sqrt{s} calib)
- Theoretical uncertainties $\sim 10^{-4}$, higher order calcs needed

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 $E_{CM} \simeq 157.5\text{-}162.5$ GeV $\Delta m_W=0.4$ MeV $\Delta \Gamma_W=1$ MeV
- 2. Other measurements of m_W and Γ_W from the decay products kinematics at $E_{CM} \simeq 162.5\text{-}240\text{-}365$ GeV $\Delta m_W, \Delta \Gamma_W= 2\text{-}5$ MeV ?

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



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

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

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

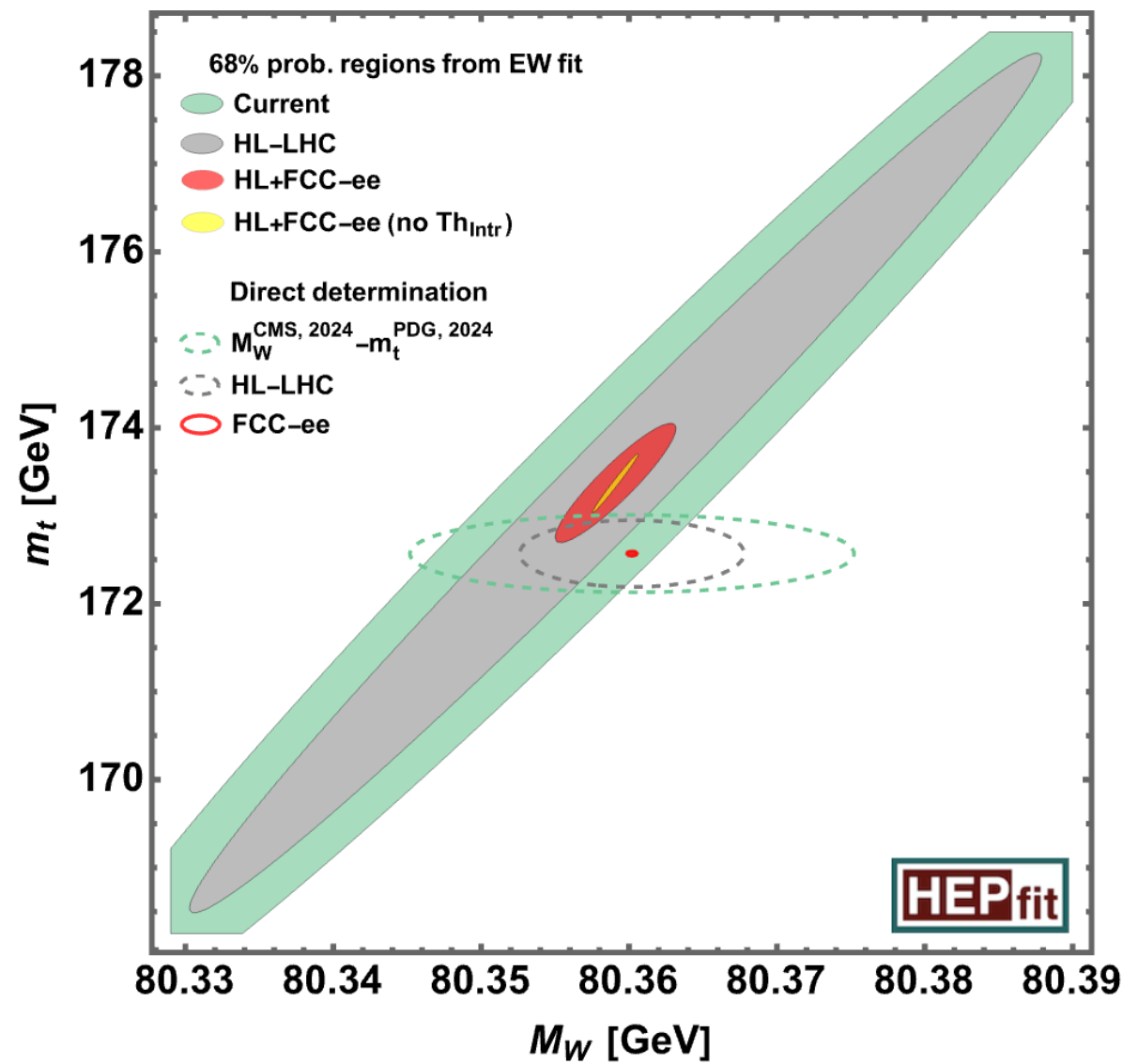
C- minimum of $\Delta \Gamma_W=0.96$ MeV + $\Delta m_W=0.41$ MeV with
 $E_1=157.5$ GeV $E_2=162.4$ GeV $f=0.45$
yields and $\Delta m_W=0.37$ MeV (as single par)

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

Comparable
in sensitivity
with value
from
EWPO fit.

Tera-Z EW precision measurements.

- ▶ The target is to reduce syst. uncertainties to the level of stat. uncertainties.
(exploit the large samples and innovative control analyses)
 - ▶ Exquisite \sqrt{s} precision (100keV@Z, 300keV@WW) reduces beam uncertainties (EPOL)
- ➡ ~50 times better precision than LEP/LSD on EW precision observables
(stat. improvement alone is a factor **300-2'000** and innovative analyses/improved detectors can bring syst. down too)



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

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Need TH results to fully exploit Tera-Z

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Theory status as of today	Needed theory improvement [†]
m_Z (MeV)	2.0	0.004 (0.1)	non-resonant $e^+e^- \rightarrow f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6 th order	NNLO for $e^+e^- \rightarrow f\bar{f}$
Γ_Z (MeV)	2.3	0.004 (0.012)			
$\sin^2 \theta_{\text{eff}}^\ell$	1.6×10^{-4}	$1.2 (1.2) \times 10^{-6}$			
m_W (MeV)	9.9	0.18 (0.16)	lineshape of $e^+e^- \rightarrow WW$ near threshold	NLO ($e^+e^- \rightarrow 4f$ or EFT framework)	NNLO for $e^+e^- \rightarrow WW$, $W \rightarrow f\bar{f}'$ in EFT setup
HZZ coupling	– *	0.1%	cross section for $e^+e^- \rightarrow ZH$	NLO EW plus partial NNLO QCD/EW	full NNLO EW
m_{top} (MeV)	290	4.2 (4.9)	threshold scan $e^+e^- \rightarrow t\bar{t}$	N ³ LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}(30 \text{ MeV})$ scale uncert.	Matching fixed orders with resummations, merging with MC, α_S (input)

[†] The necessary theory calculations mentioned are a minimum baseline; additional partial higher-order contributions may also be required.

* No absolute value for the HZZ coupling can be extracted from the LHC data without additional assumptions.

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

Systematics vs. Statistics.

PED @ CERN-SPC '2022

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

- ◆ Take the Z lineshape

$\alpha_{\text{QED}}(m_Z)$: Stat. 3×10^{-5}

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

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

FCC-ee
special

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

Error dominated by point-to-point energy uncertainties.

Based on in-situ comparisons between \sqrt{s} (e.g. with muon pairs), with measurements made every few minutes (100's times per day)

Boils down to

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

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

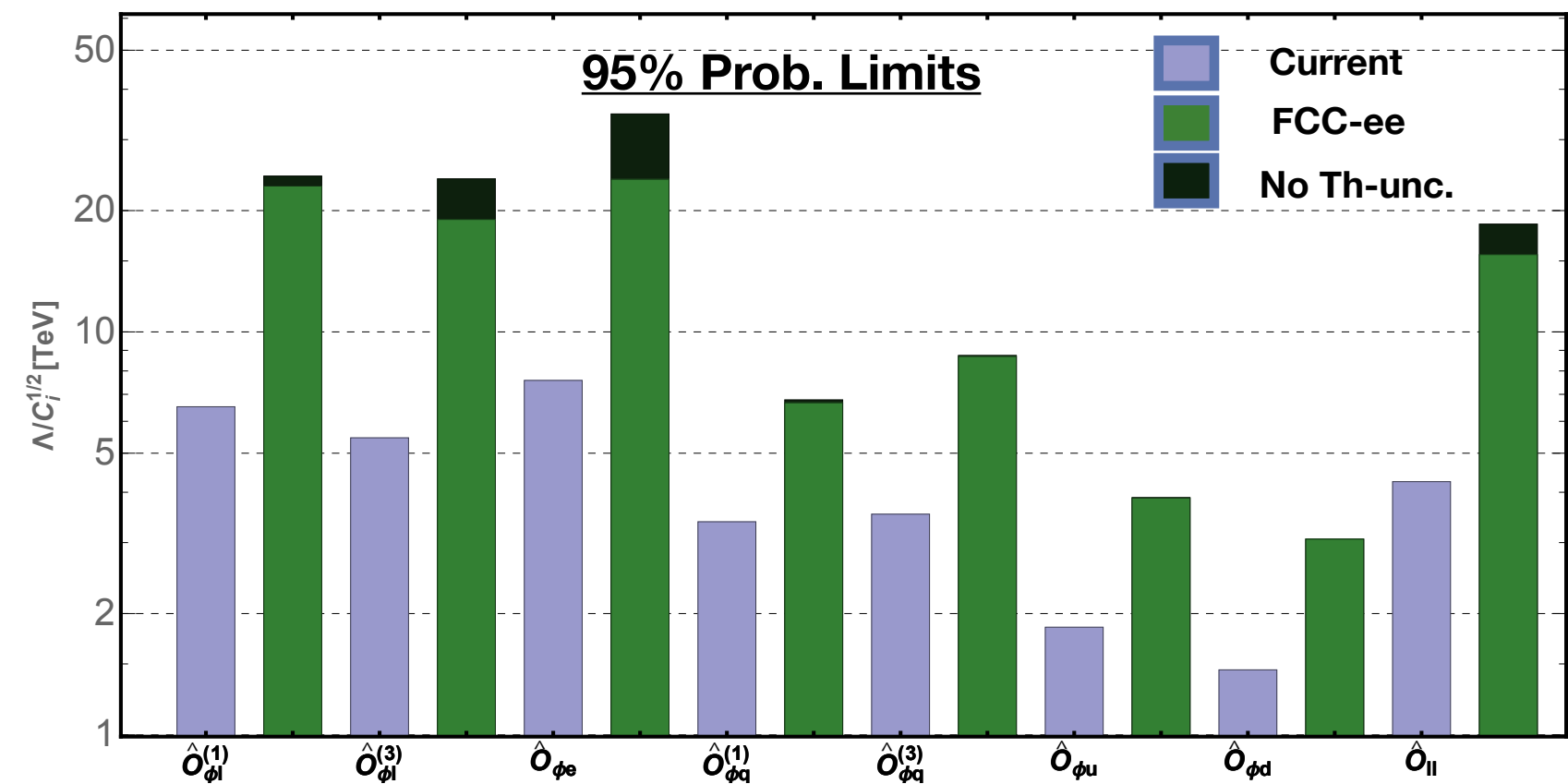
Error dominated by \sqrt{s} determination with resonant depolarization.

As more understanding is gained, progress are made at a constant pace, and this error approaches regularly the statistical limit

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

Impact of TH uncertainties.

J. de Blas, FCC CDR overview '19

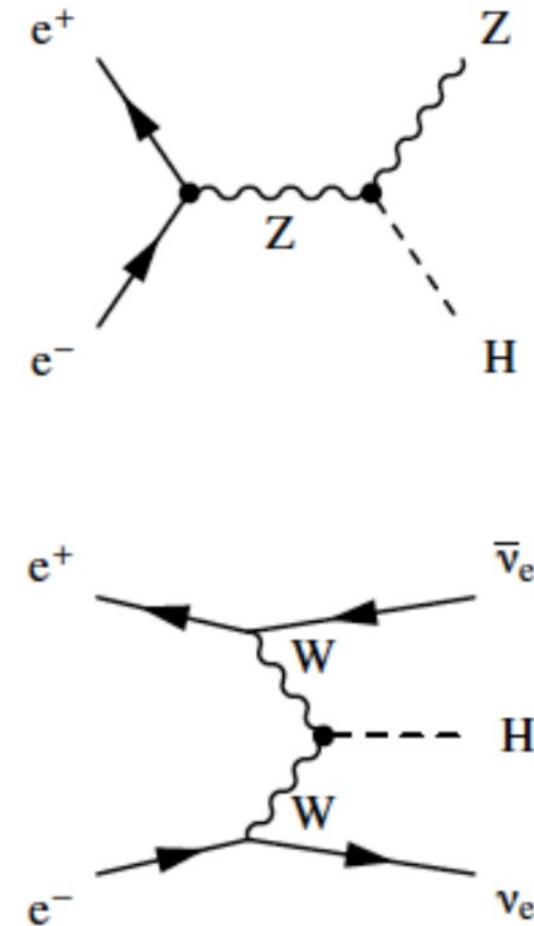
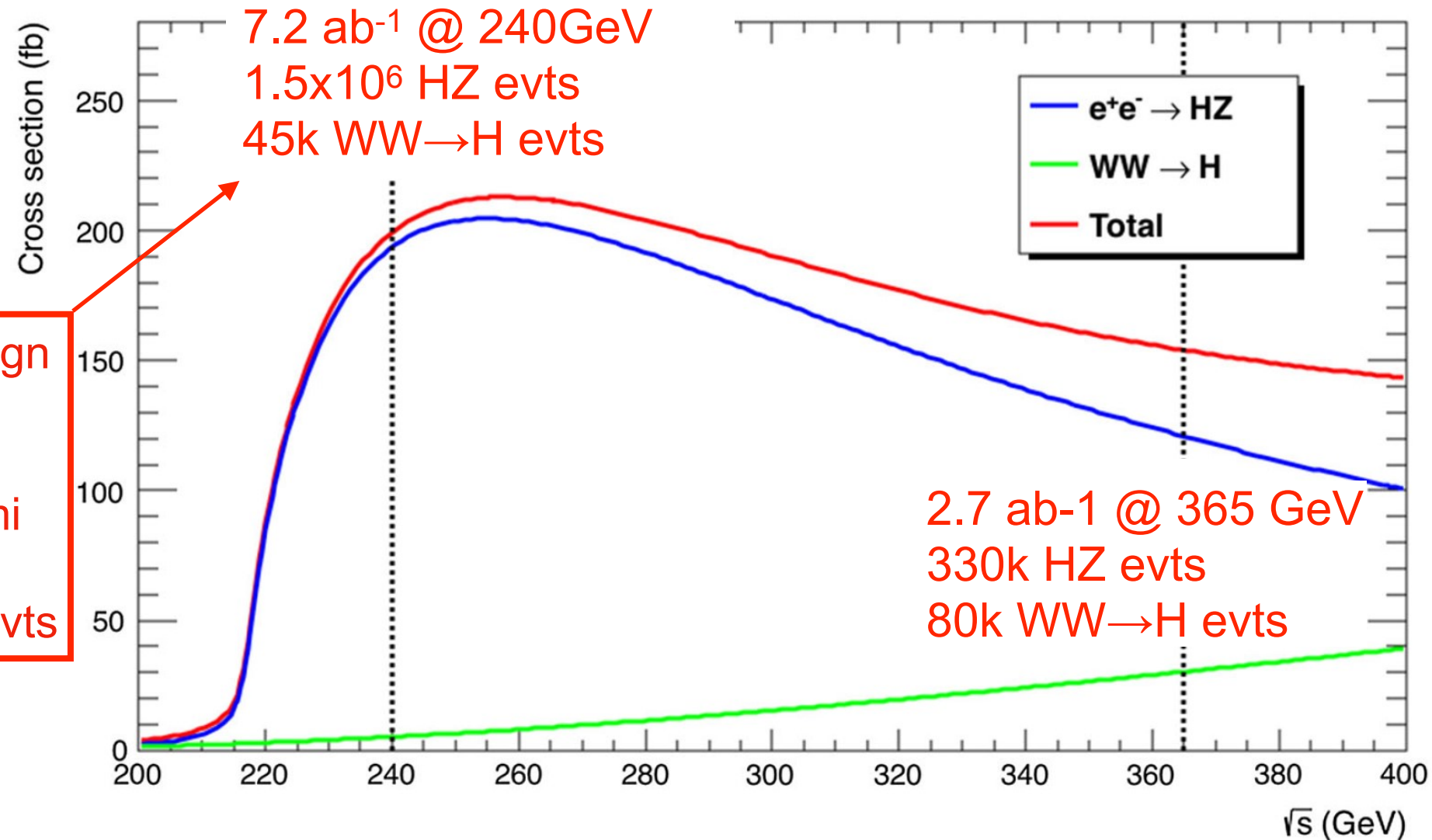


	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
δM_W [MeV]	± 15	± 8	± 1	$\pm 0.6/\pm 1$	± 1
$\delta \Gamma_Z$ [MeV]	± 2.3	± 0.73	± 0.1	± 0.1	± 0.2
$\delta \mathcal{A}_\ell$ [$\times 10^{-5}$]	± 210	± 93	± 2.1	$\pm 8/\pm 14$	± 11.8
δR_b^0 [$\times 10^{-5}$]	± 66	± 3	± 6	± 0.3	± 5

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: $\infty/3/2/1.5/1.2$ 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 $ZH \rightarrow ZZZ^*$ and $WW \rightarrow H$)
- $\delta\Gamma_H \sim 1\%$, $\delta m_H \sim 3\text{ MeV}$ (resp. 25%, 0(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)
 $(\delta\kappa_X = v^2/f^2 \quad \& \quad m_{\text{NP}} = g_{\text{NP}} f)$
- Unique access to electron Yukawa

Higgs coupling sensitivity

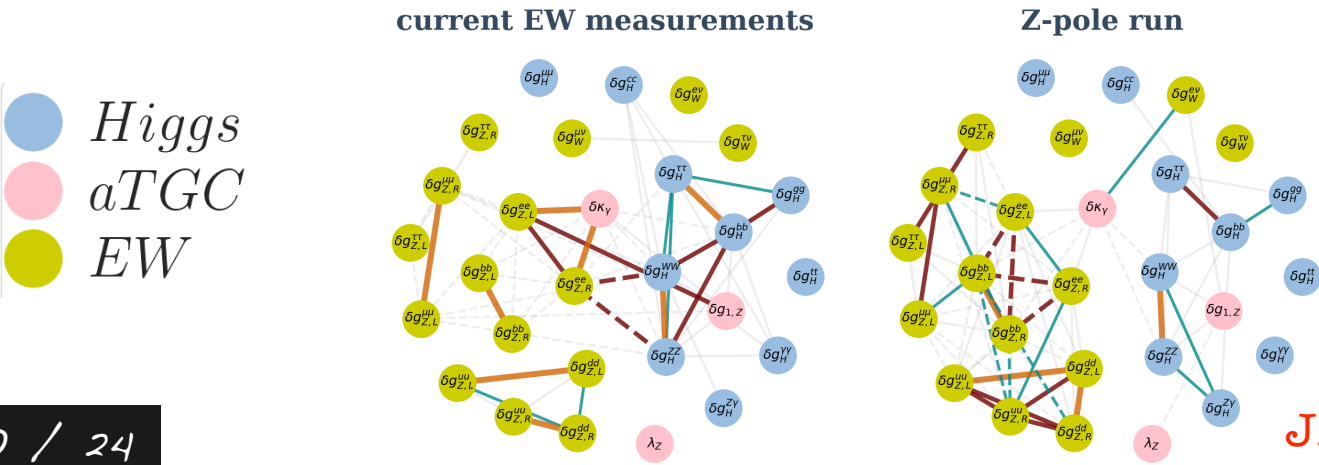
Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$ \kappa_s $ (%)	–	+29 –67
Γ_H (%)	–	0.78
$\mathcal{B}_{\text{inv}} (<,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

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

Higgs @ FCC-ee.

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— Higgs programme needs Z-pole —



Higgs coupling sensitivity

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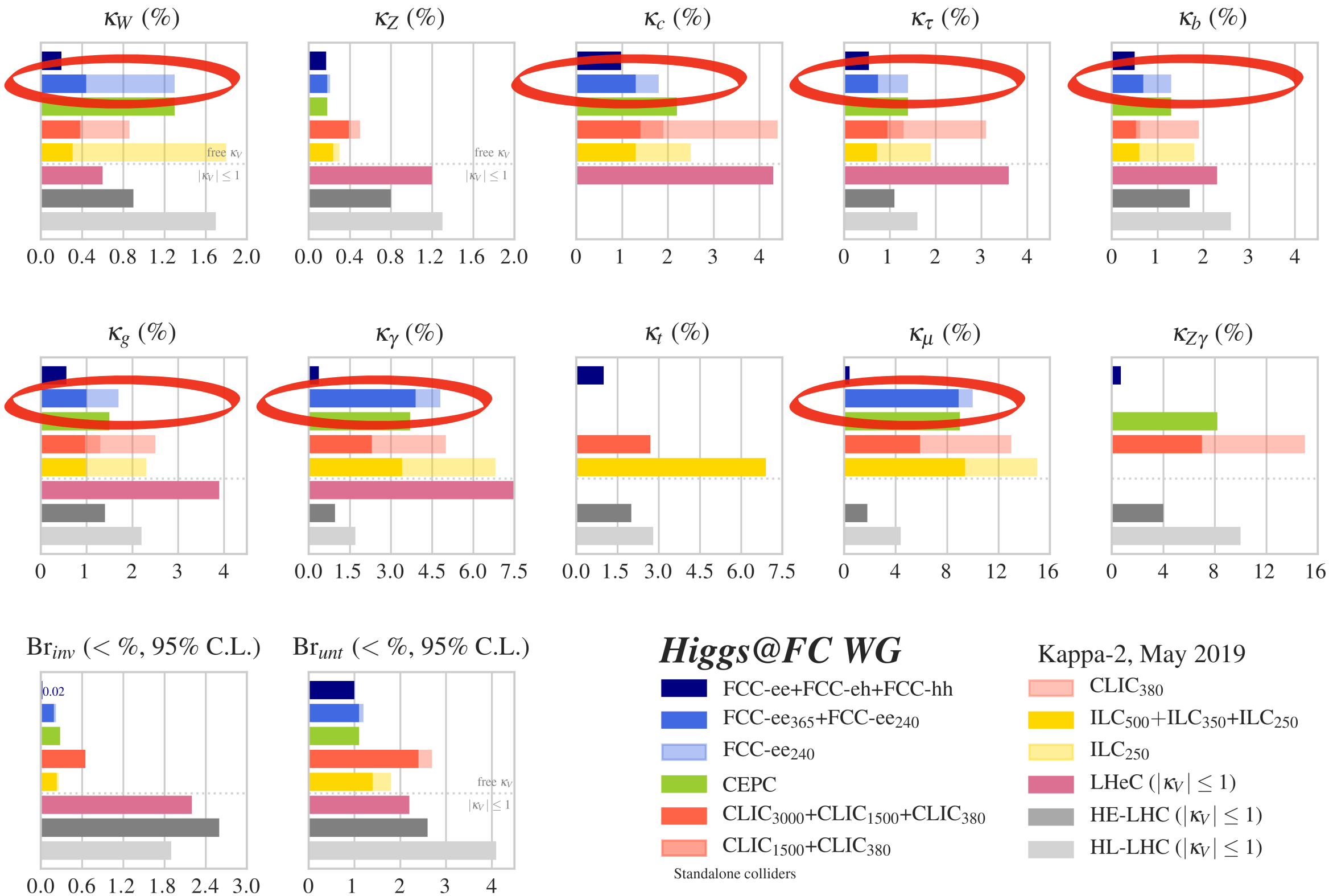
Complementarity 240↔365 GeV.

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. $\kappa_V \leq 1$



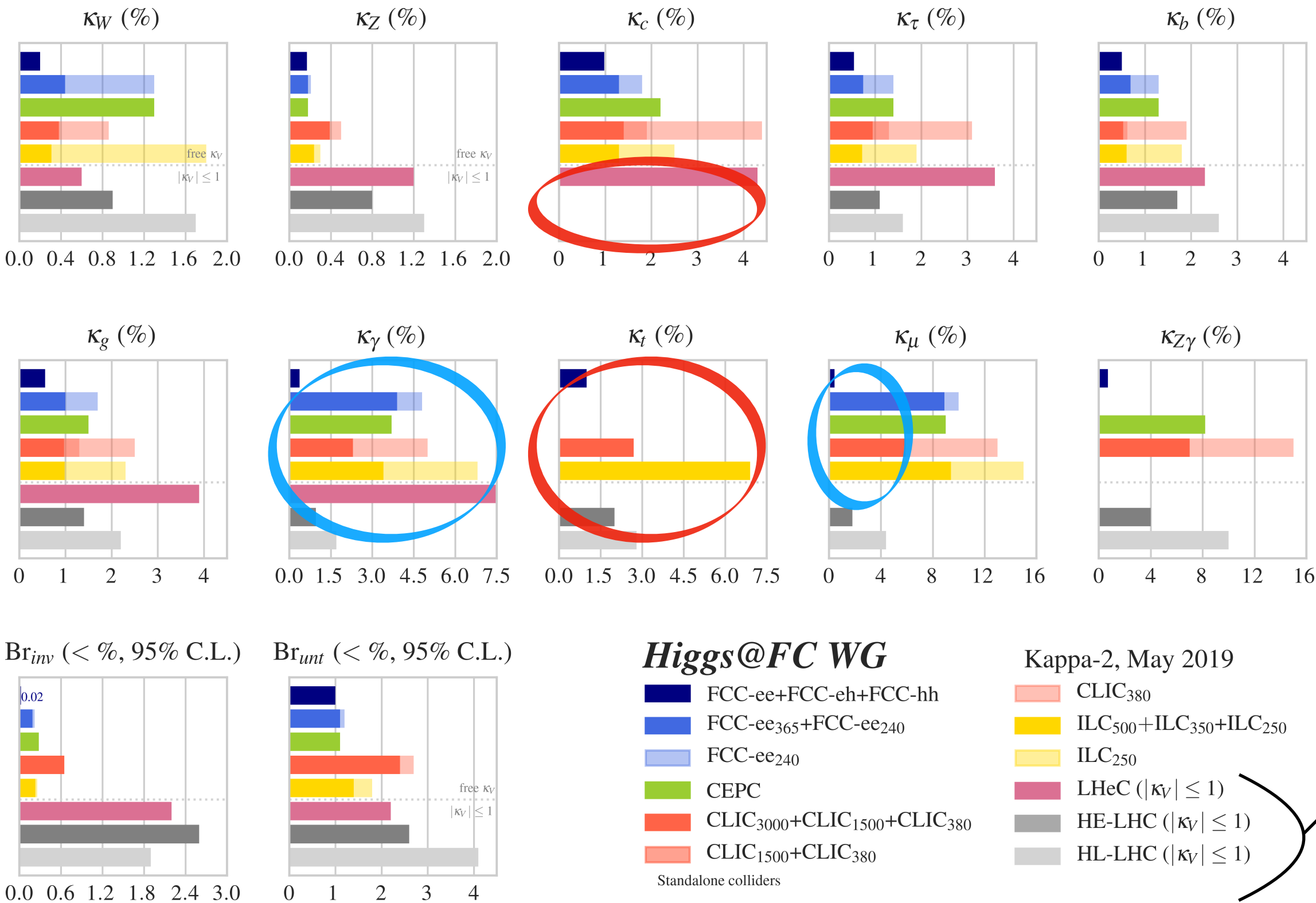
[back to main discussion](#)

Complementarity FCC-ee↔HL-LHC.

ECFA Higgs study group '19

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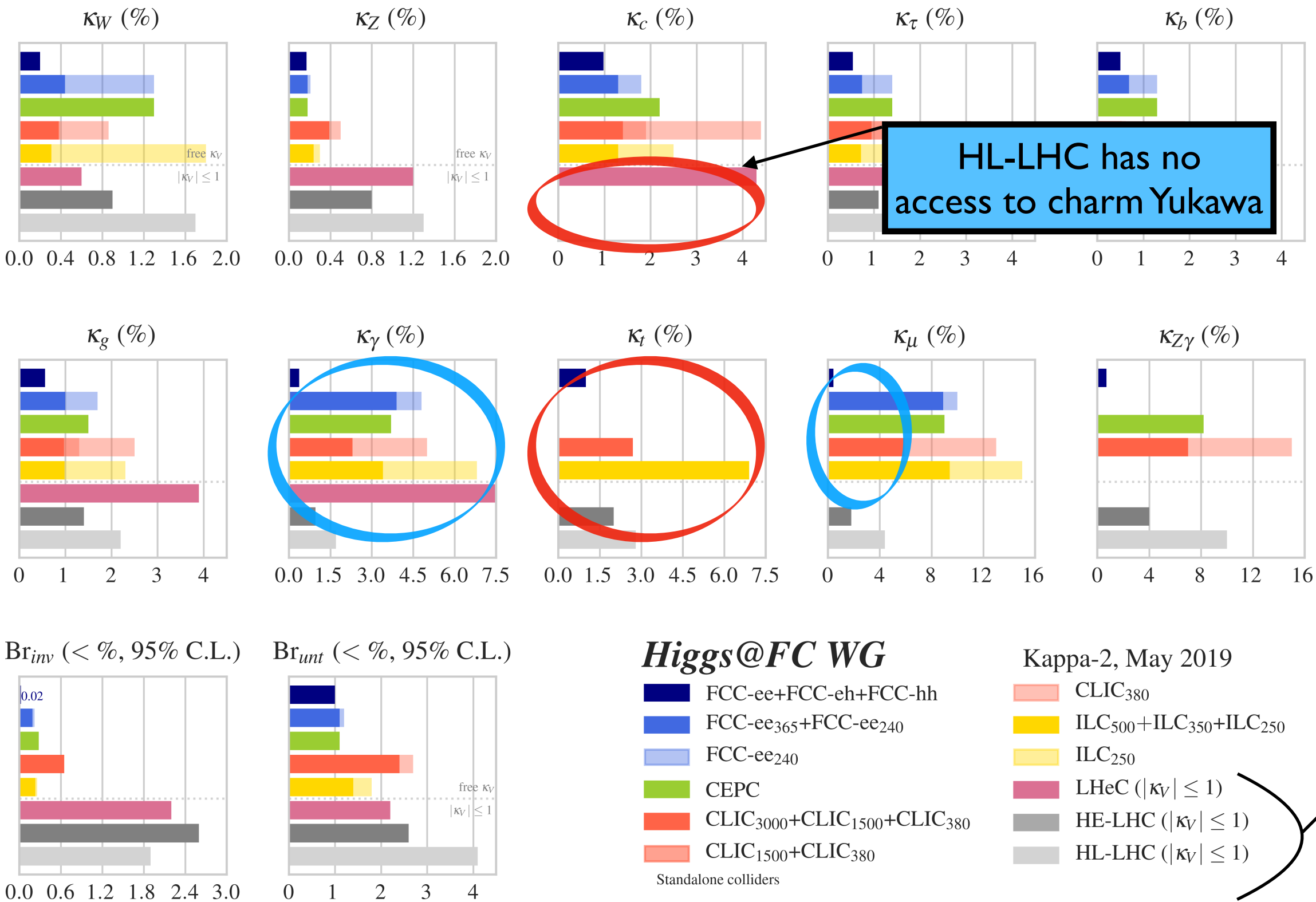
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ECFA Higgs study group '19

Scenario	include HL-LHC	
	yes	no
kappa-2	measured	
	BR _{inv}	BR _{unt}

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e.g. $\kappa_V \leq 1$



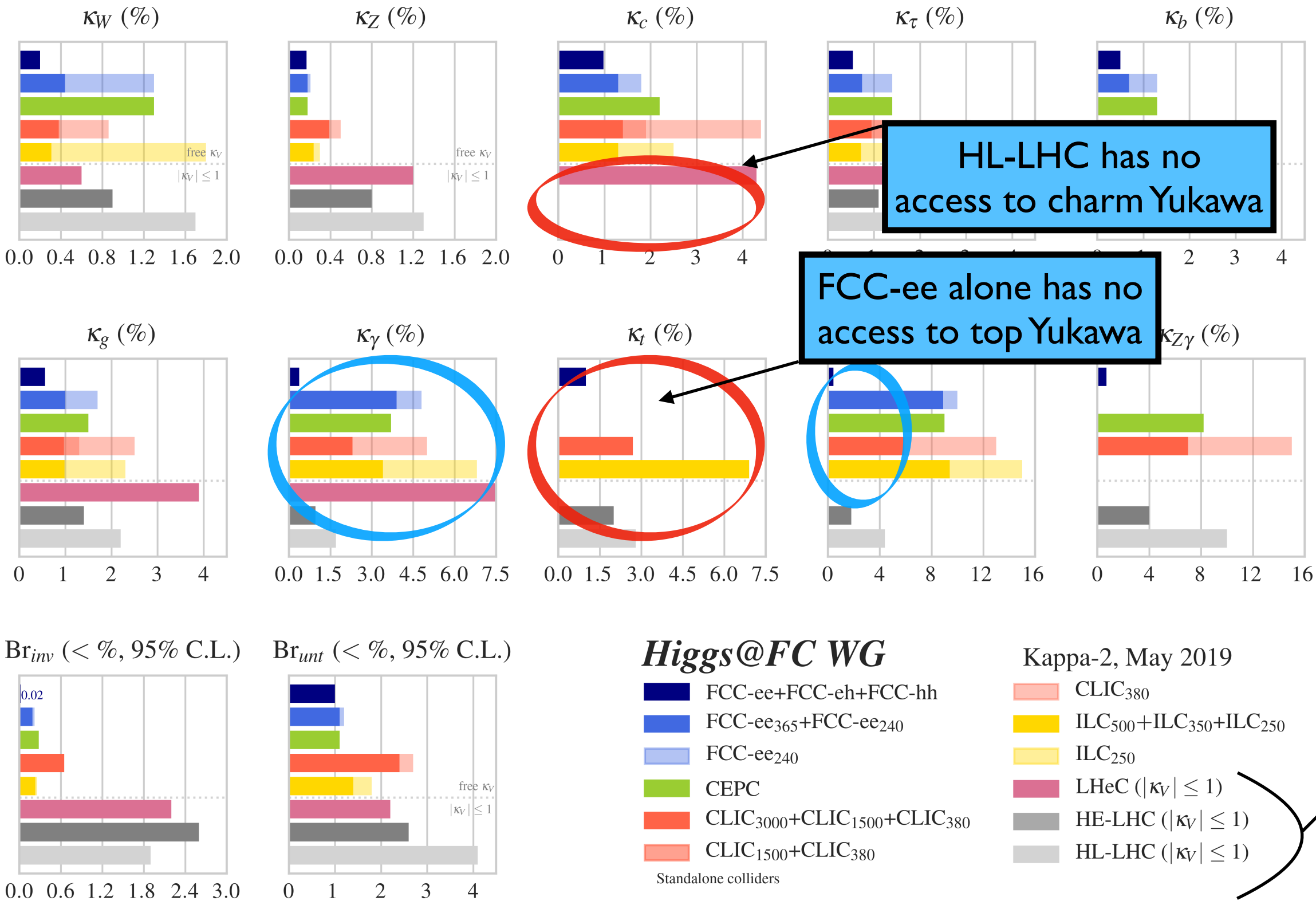
[back to main discussion](#)

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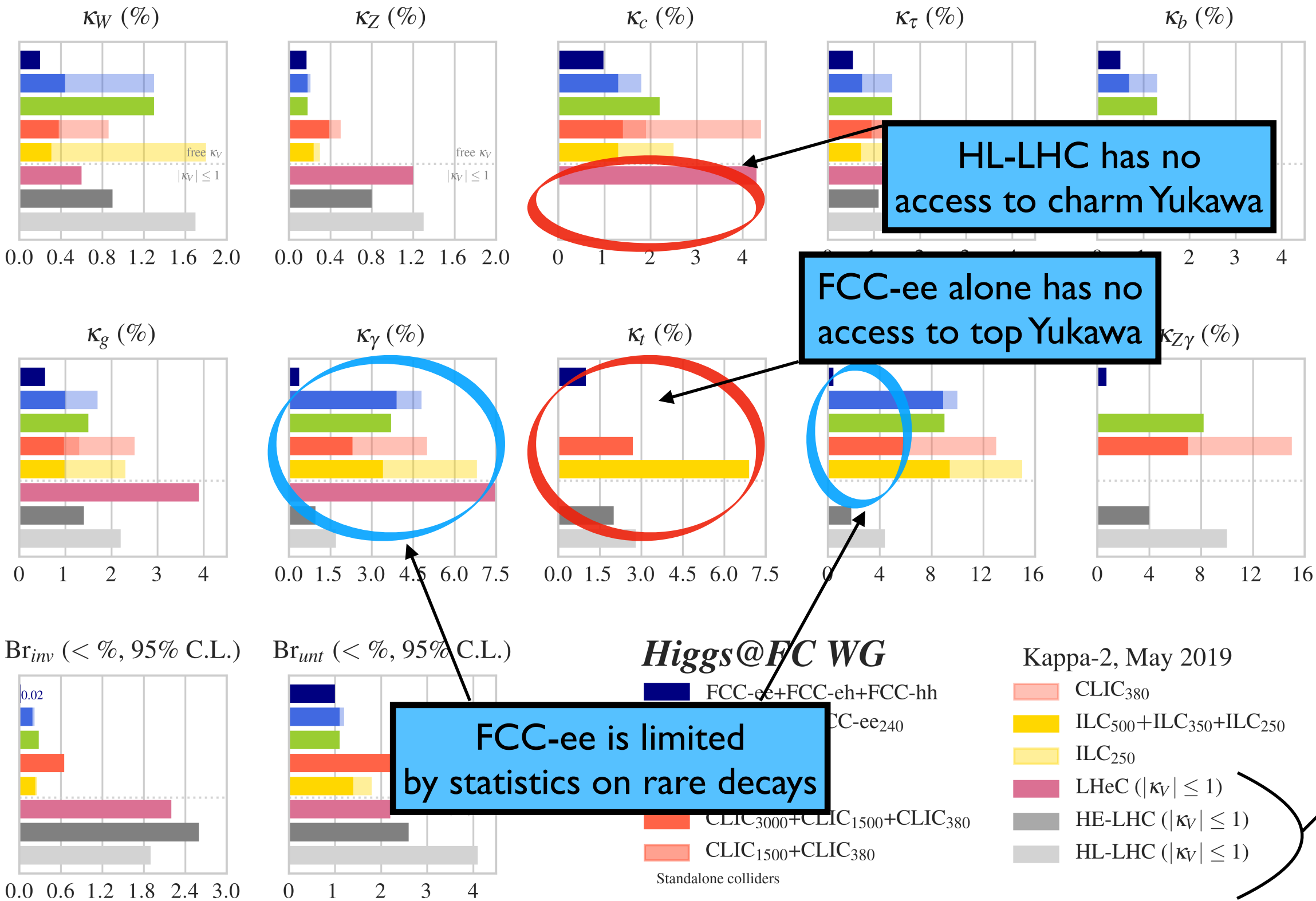
[back to main discussion](#)

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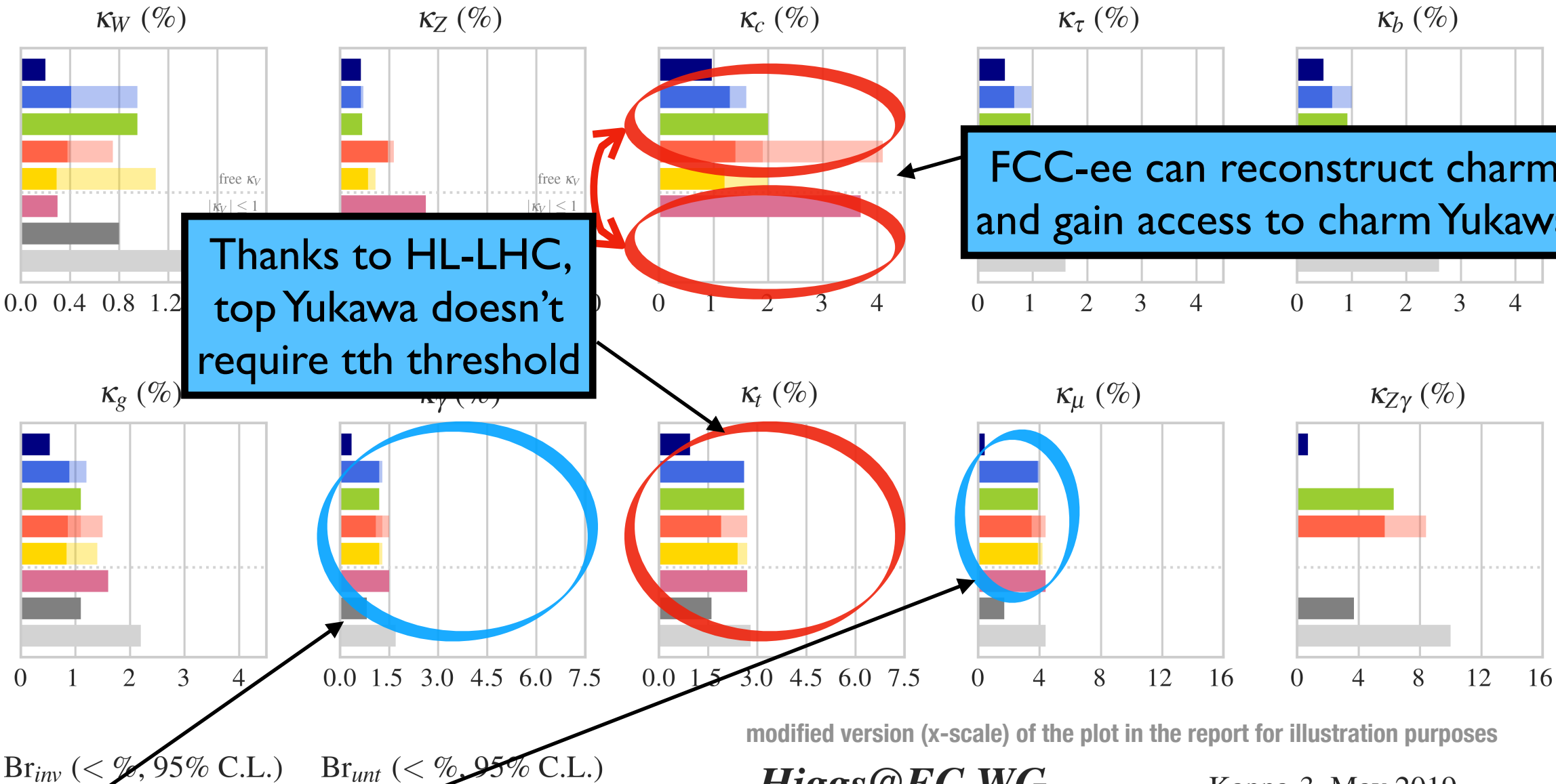


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Complementarity FCC-ee↔HL-LHC.

ECFA Higgs study group '19

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-3	measured	measured	yes



[back to main discussion](#)

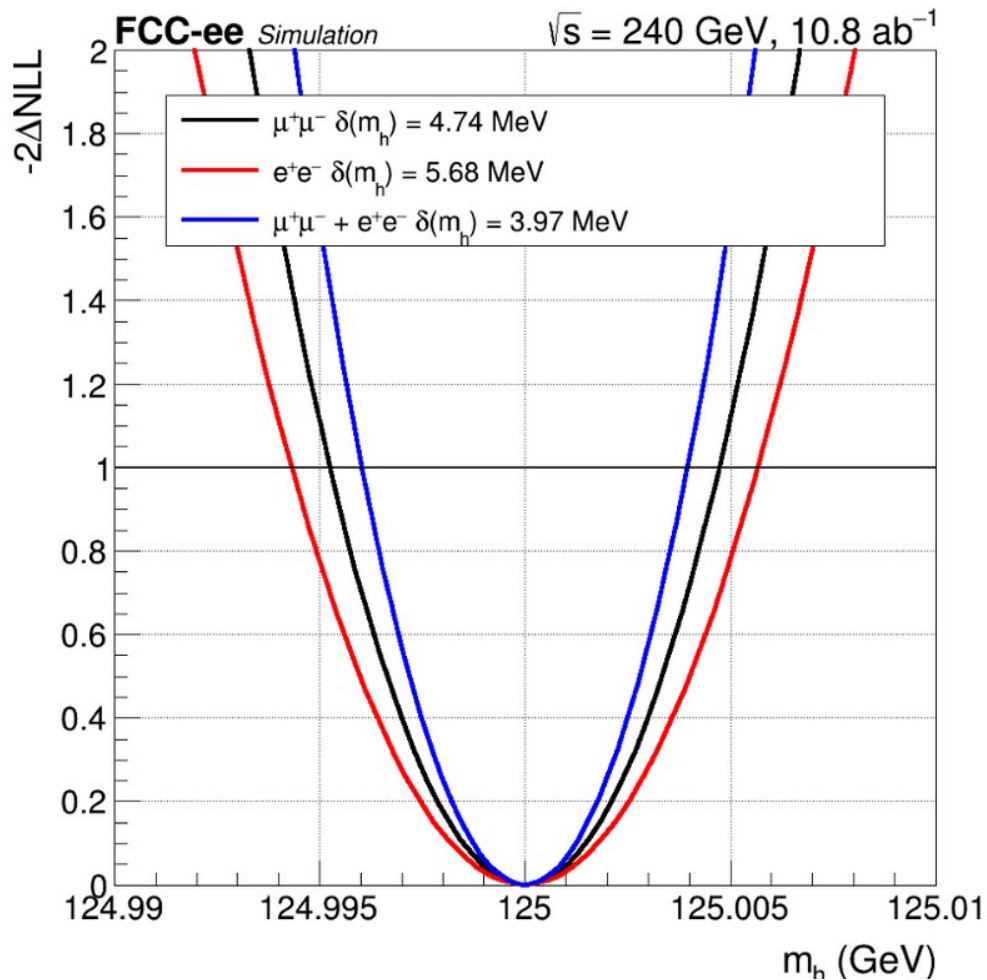
LHC brings statistics
FCC-ee adds a bit of sensitivity

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

1. Top/Charm Yukawa
2. Statistically limited channels: $\gamma\gamma$, $\mu\mu$

Higgs Mass

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



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

Nominal configuration

Crystal ECAL to Dual Readout

Nominal 2 T → field 3 T

IDEA drift chamber → CLD Si tracker

Impact of Beam Energy Spread

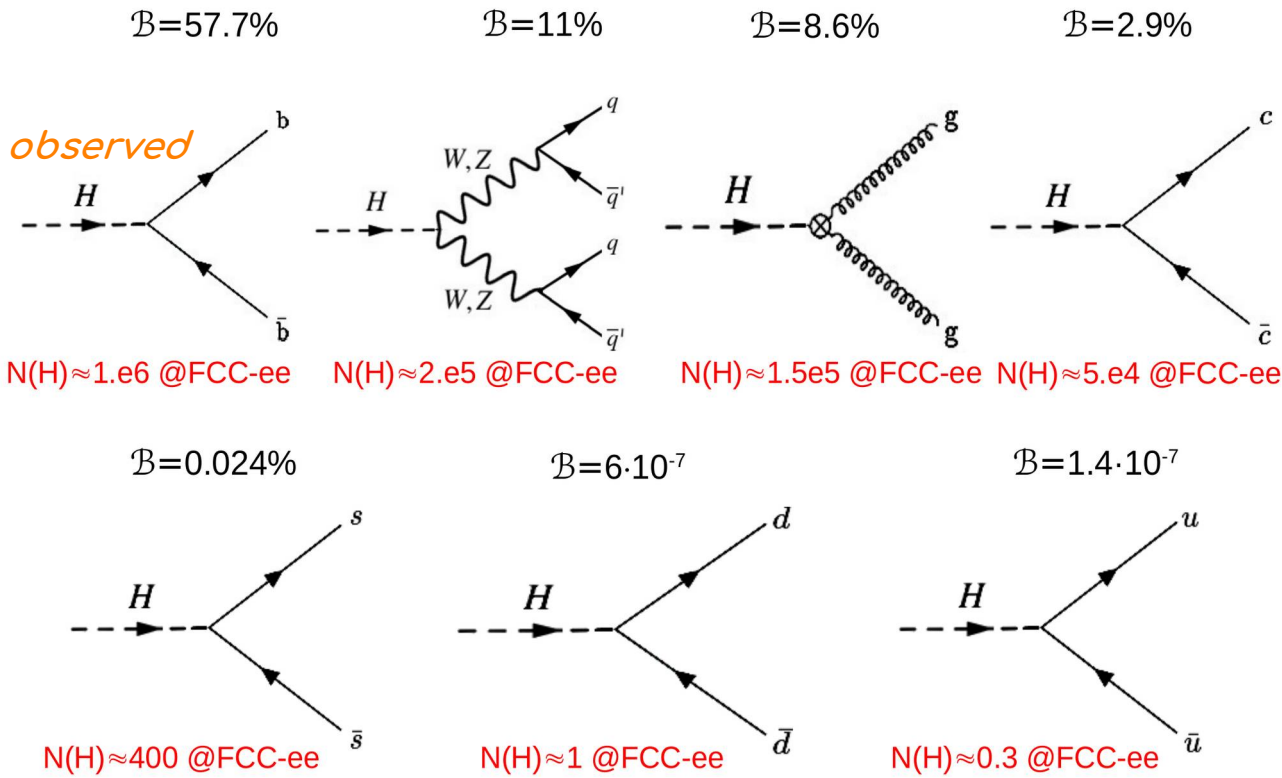
Perfect (=gen-level) momentum resolution

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

Hadronic Decays

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

	$\delta(\sigma \times \text{BR})$ [%]			
	Z(l \bar{l})H	Z($\nu\bar{\nu}$)H	Z(q \bar{q})H	Comb.
H \rightarrow bb	0.7	0.4	0.3	0.22
H \rightarrow cc	4.1	2.2	3.3	1.7
H \rightarrow ss	230	150	440	120
H \rightarrow gg	2.2	1.1	3.1	0.9



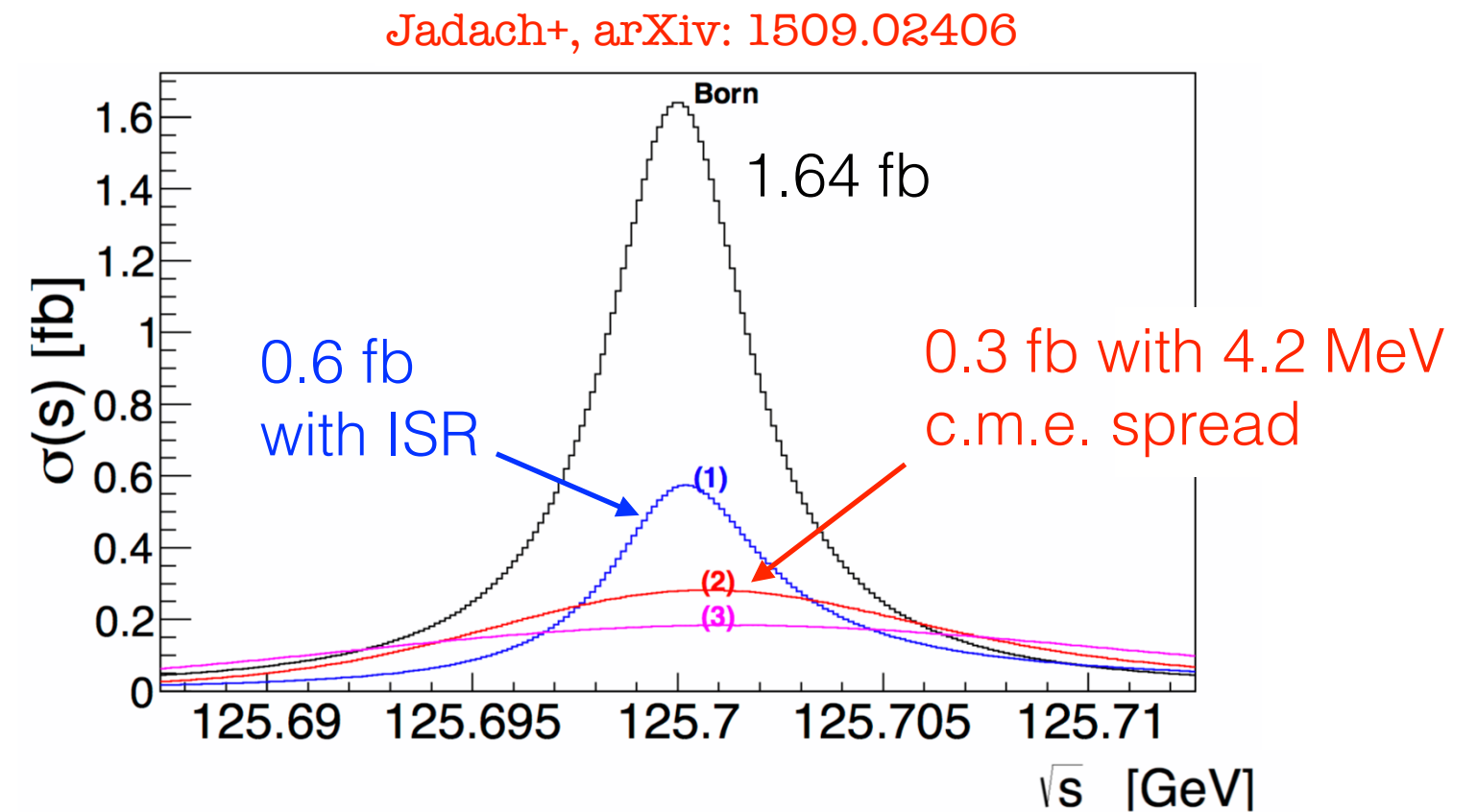
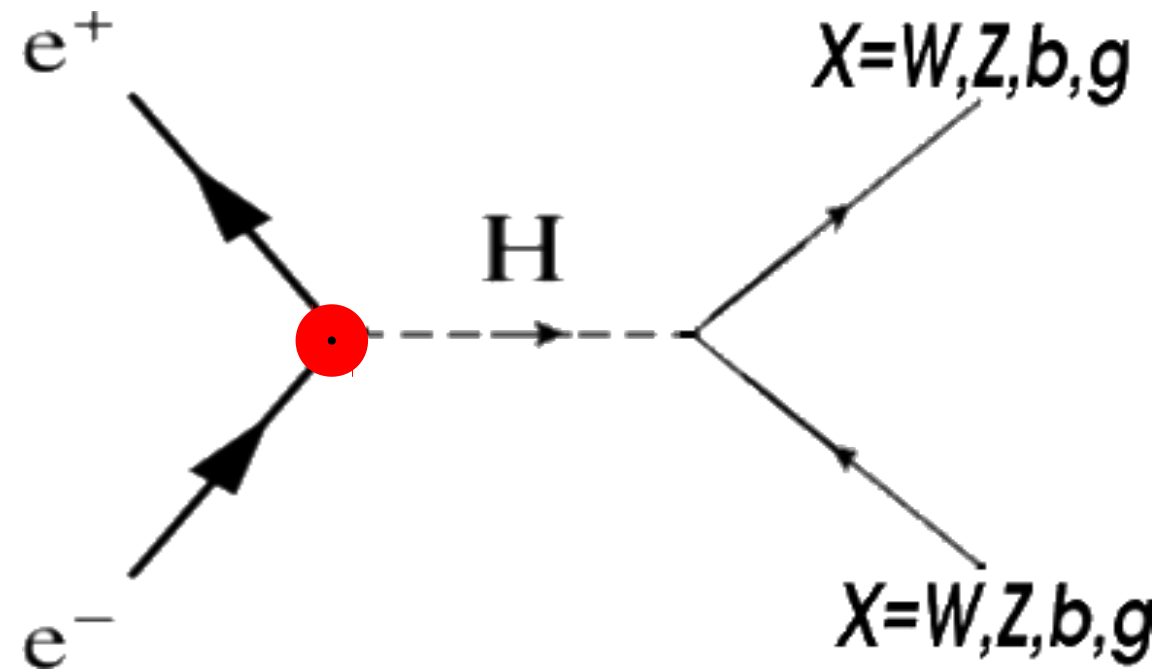
Solid measurements in 2nd generation

Interesting prospects for 1st generation and FCNC decays

	$\sigma \times \text{BR}$ 95% CL	BR(SM)
H \rightarrow dd	1.4e-03	6e-07
H \rightarrow uu	1.5e-03	1.4e-07
H \rightarrow bs	3.7e-04	e-07
H \rightarrow bd	2.7e-04	e-09
H \rightarrow sd	7.7e-04	e-11
H \rightarrow cu	2.5e-04	e-20

Electron Yukawa

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



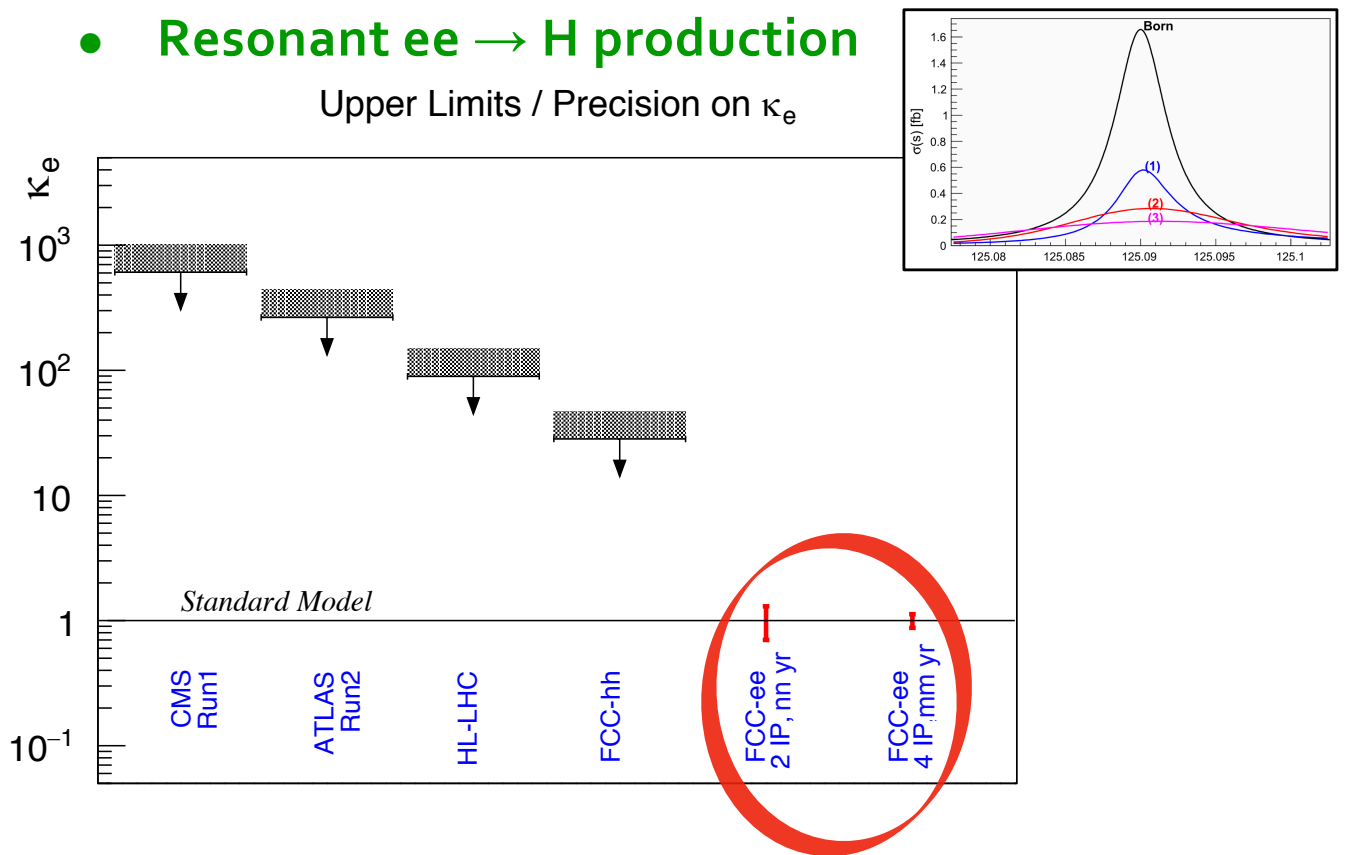
$$\sigma(e^+e^- \rightarrow H) = 1.64 \text{ fb}$$

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

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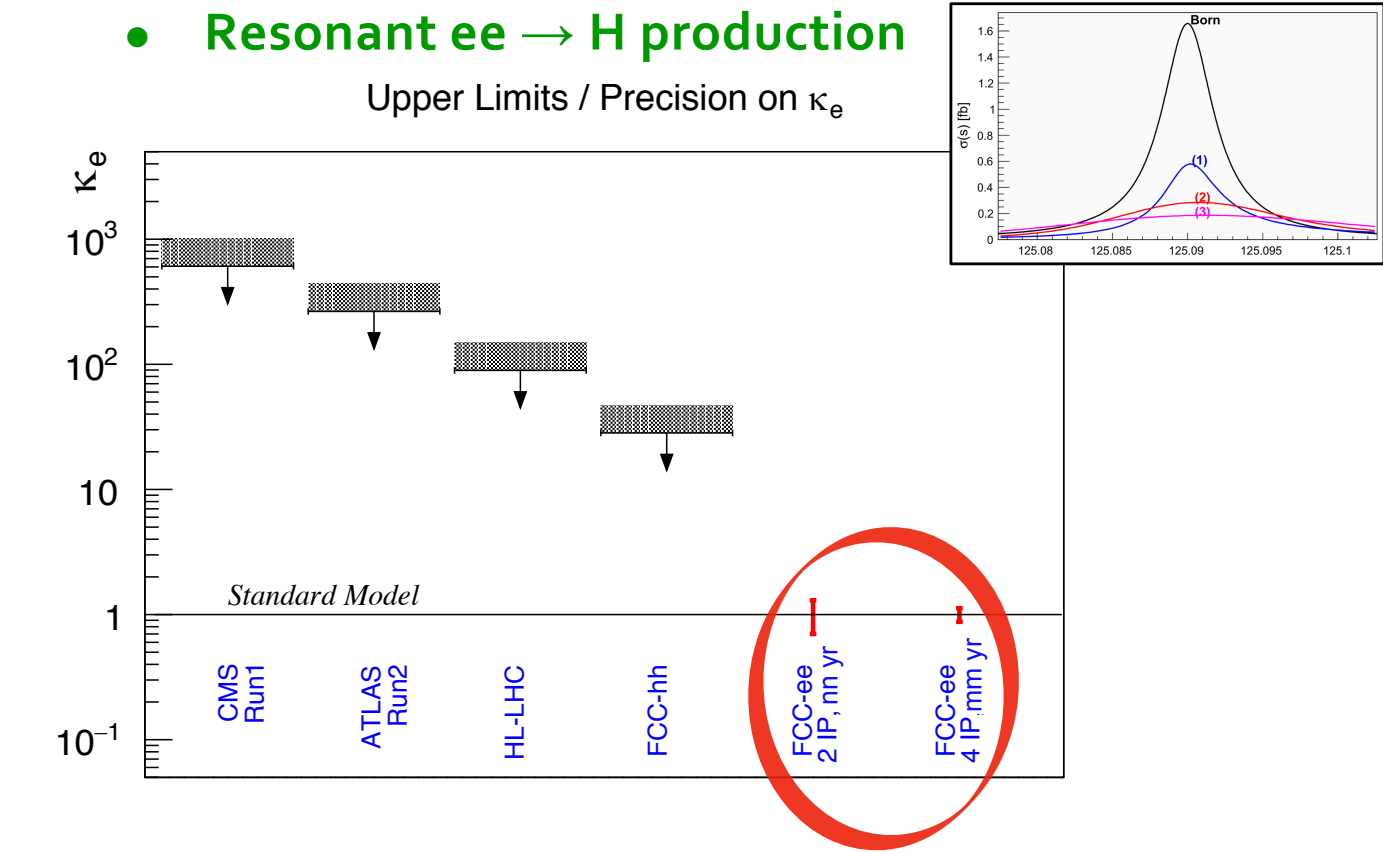
- ◆ 20 ab^{-1} / year at $\sqrt{s} = 125 \text{ GeV}$ (not in baseline FCC-ee)
- ◆ Monochromatization $\sigma_{\sqrt{s}} \sim 1\text{-}2 \times \Gamma_H \sim 6 \text{ to } 10 \text{ MeV}$
 - Resonant $ee \rightarrow H$ production



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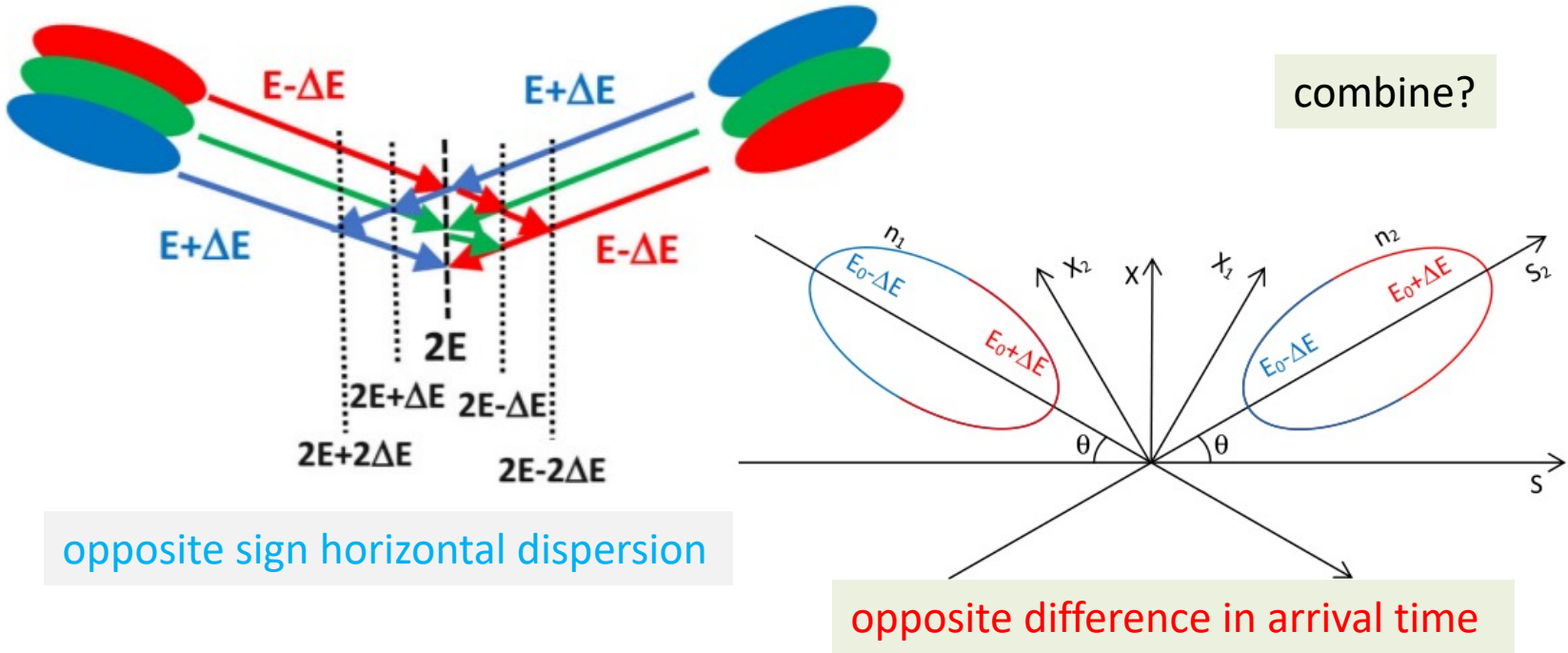
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Monochromatisation

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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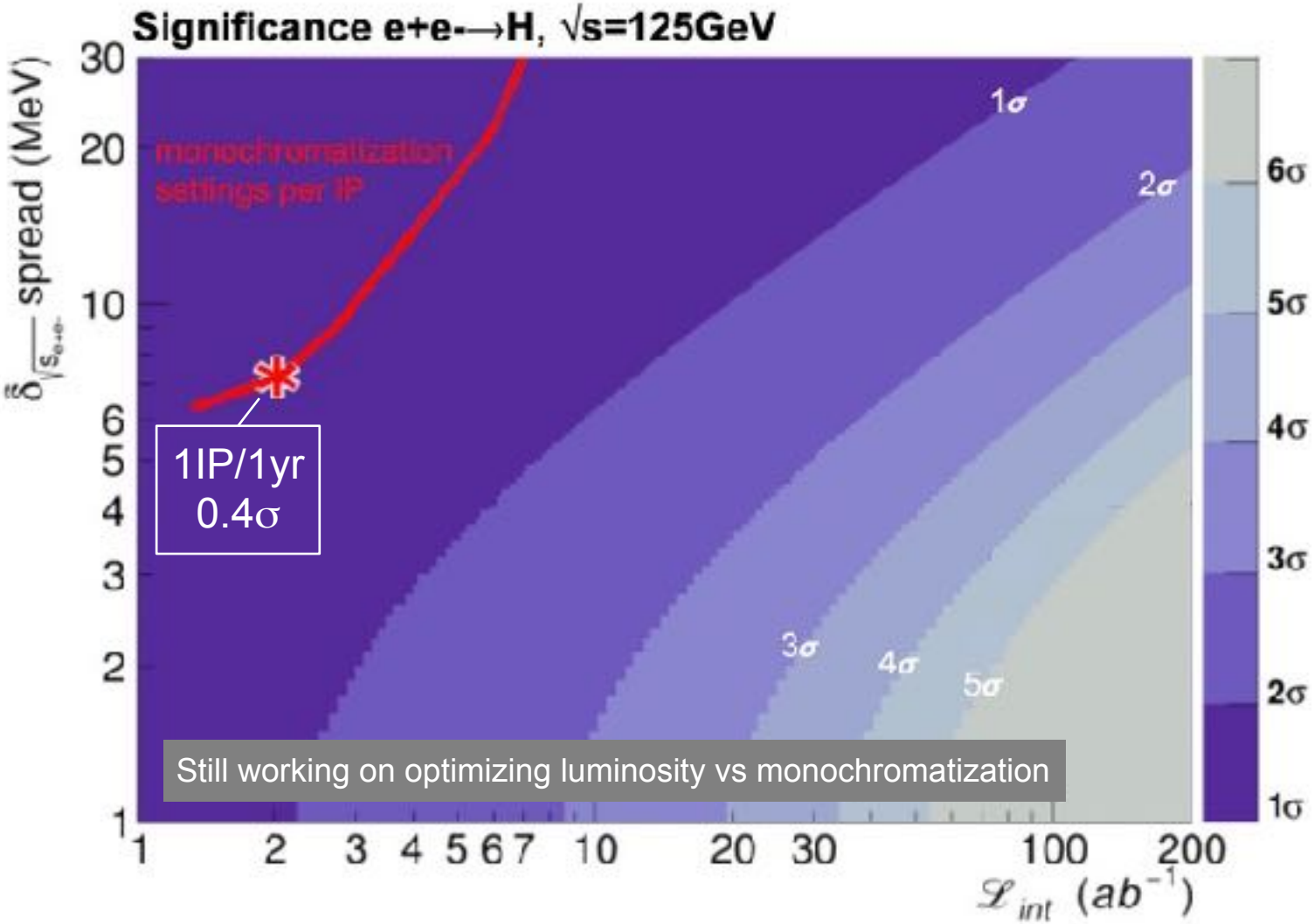
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d'Enterria+. arXiv: 2107.02686

Higgs decay channel	\mathcal{B}	$\sigma \times \mathcal{B}$	Irreducible background	σ	S/B
$e^+e^- \rightarrow H \rightarrow b\bar{b}$	58.2%	164 ab	$e^+e^- \rightarrow b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^- \rightarrow H \rightarrow gg$	8.2%	23 ab	$e^+e^- \rightarrow q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow \tau\tau$	6.3%	18 ab	$e^+e^- \rightarrow \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^- \rightarrow H \rightarrow c\bar{c}$	2.9%	8.2 ab	$e^+e^- \rightarrow c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
$e^+e^- \rightarrow H \rightarrow WW^* \rightarrow \ell\nu\ 2j$	$21.4\% \times 67.6\% \times 32.4\% \times 2$	26.5 ab	$e^+e^- \rightarrow WW^* \rightarrow \ell\nu\ 2j$	23 fb	$\mathcal{O}(10^{-3})$
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$H \rightarrow gg$	$H \rightarrow WW^* \rightarrow \ell\nu\ 2j; 2\ell\ 2\nu; 4j$	$H \rightarrow ZZ^* \rightarrow 2j\ 2\nu; 2\ell\ 2j; 2\ell\ 2\nu$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau_{\text{had}}\tau_{\text{had}}; c\bar{c}; \gamma\gamma$	Combined
1.1 σ	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13 σ	$< 0.02\sigma$	1.3 σ

w/ 10/ab: S~55, B~2400 \rightarrow 1.1 σ



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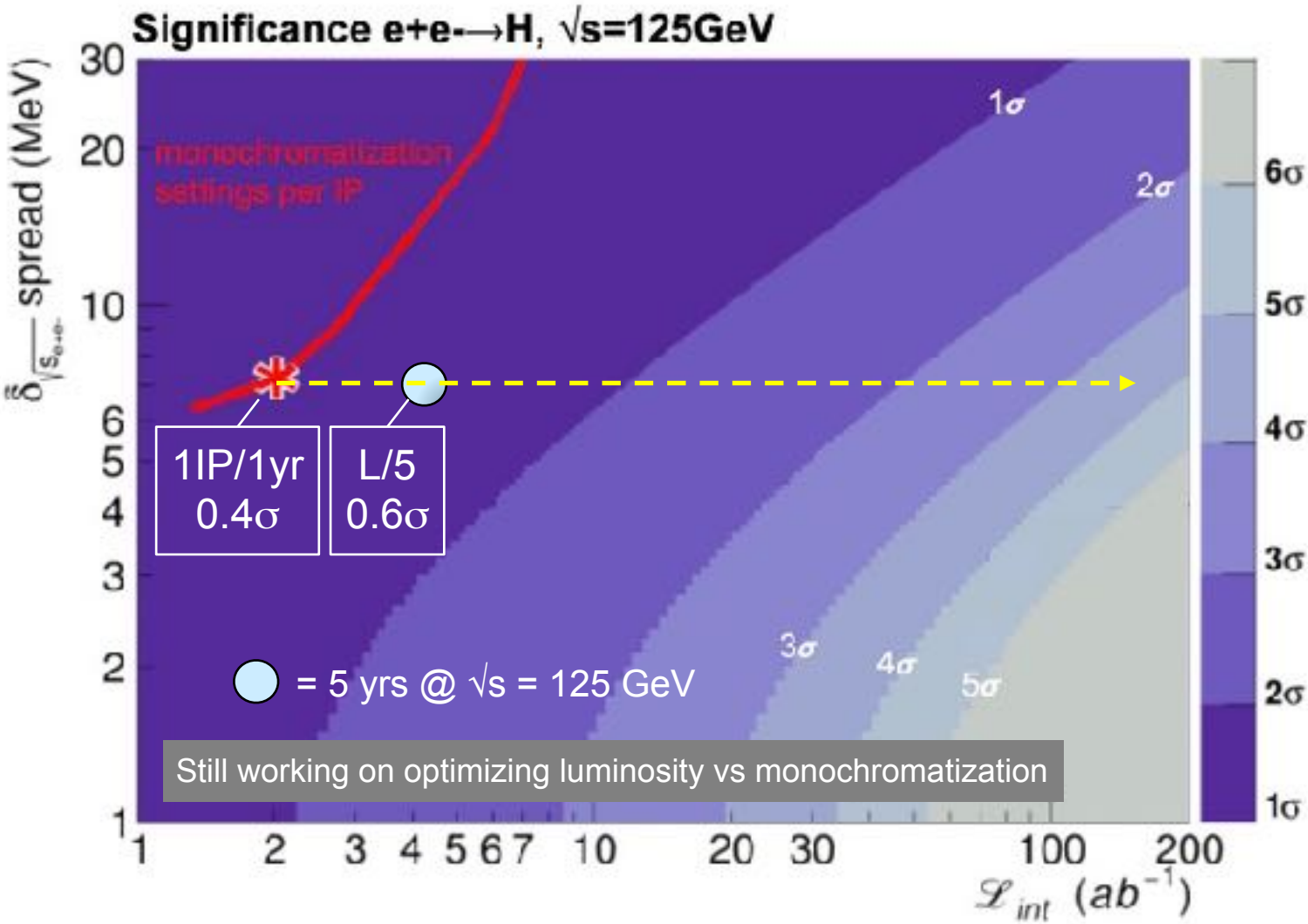
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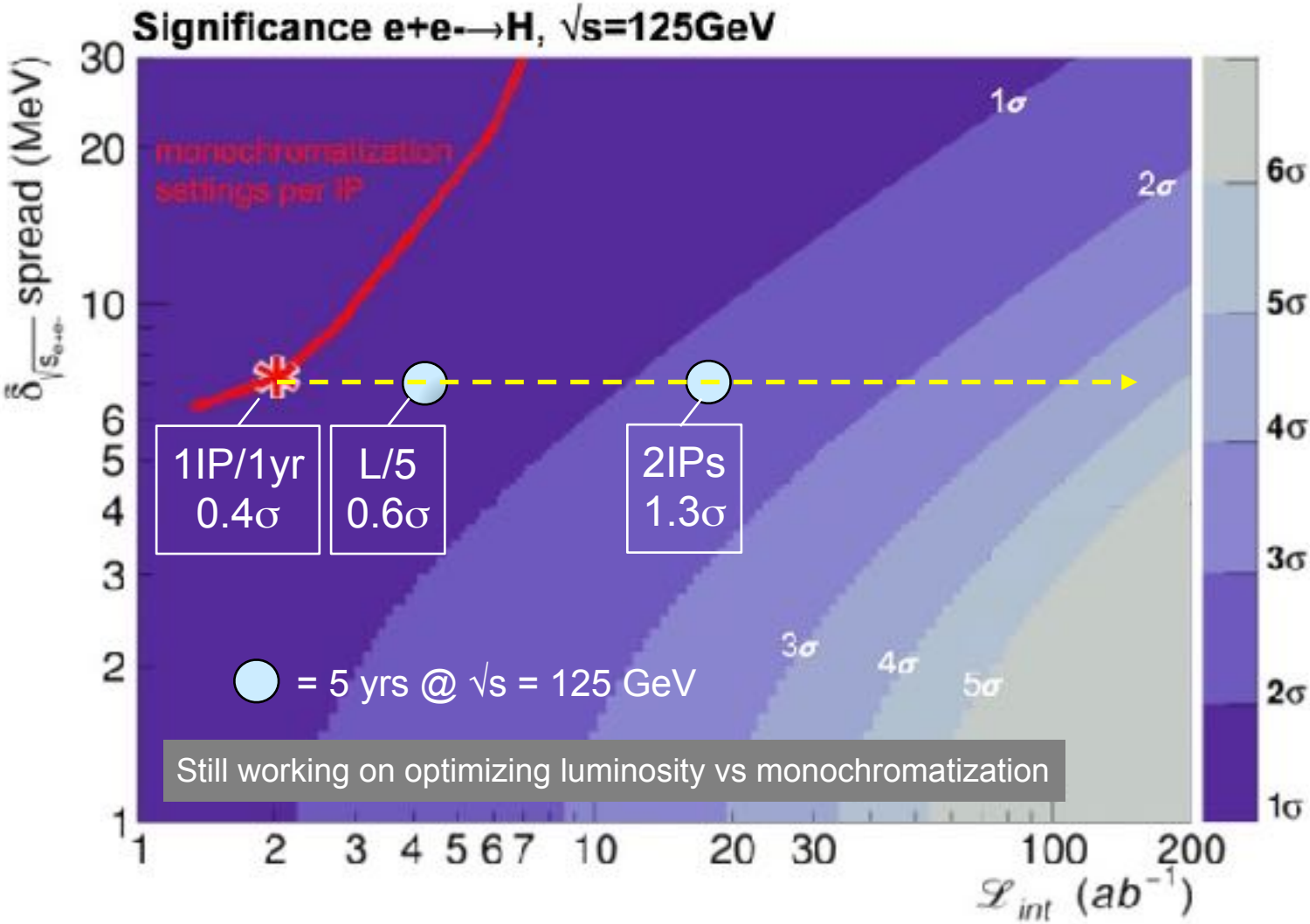
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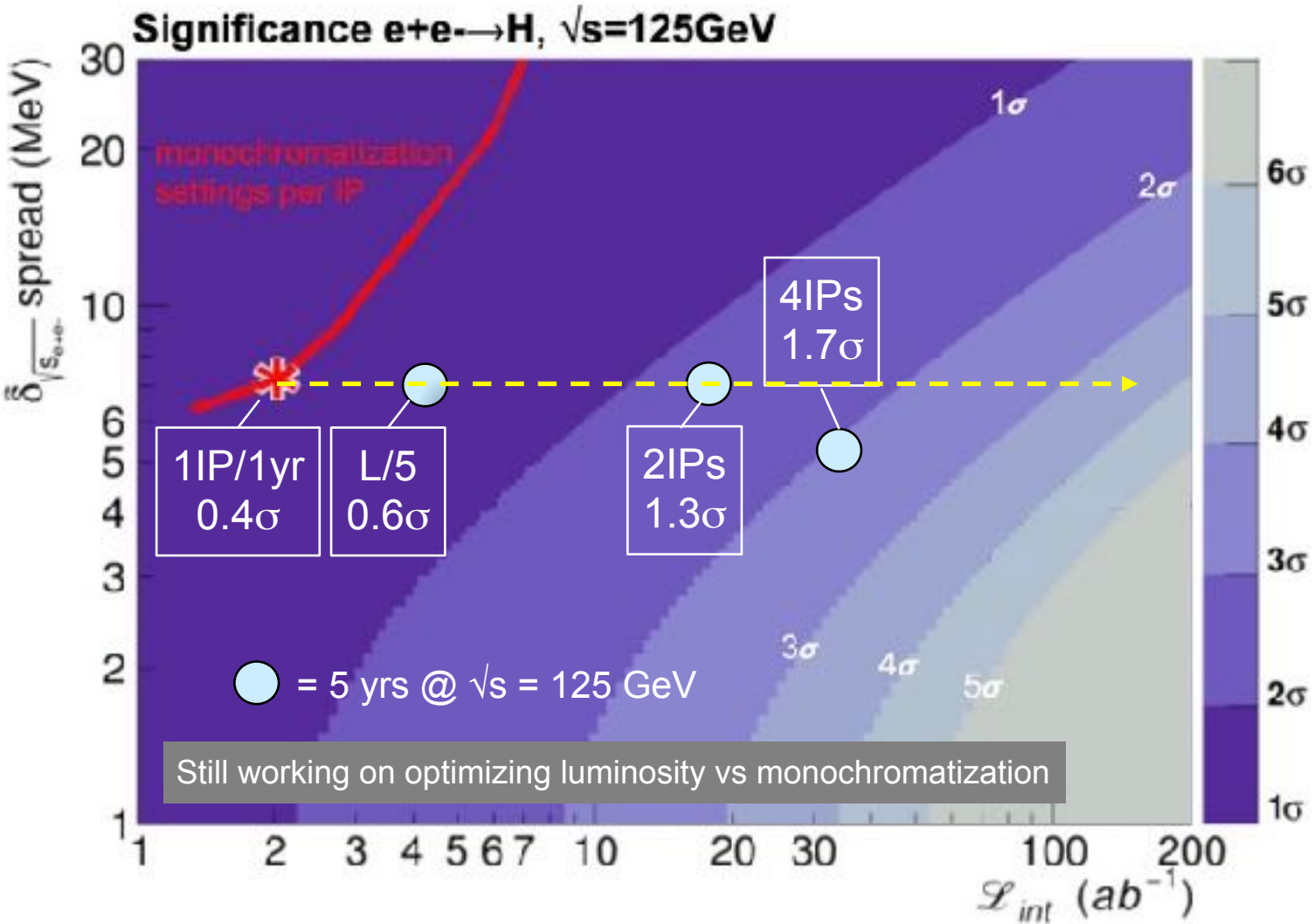
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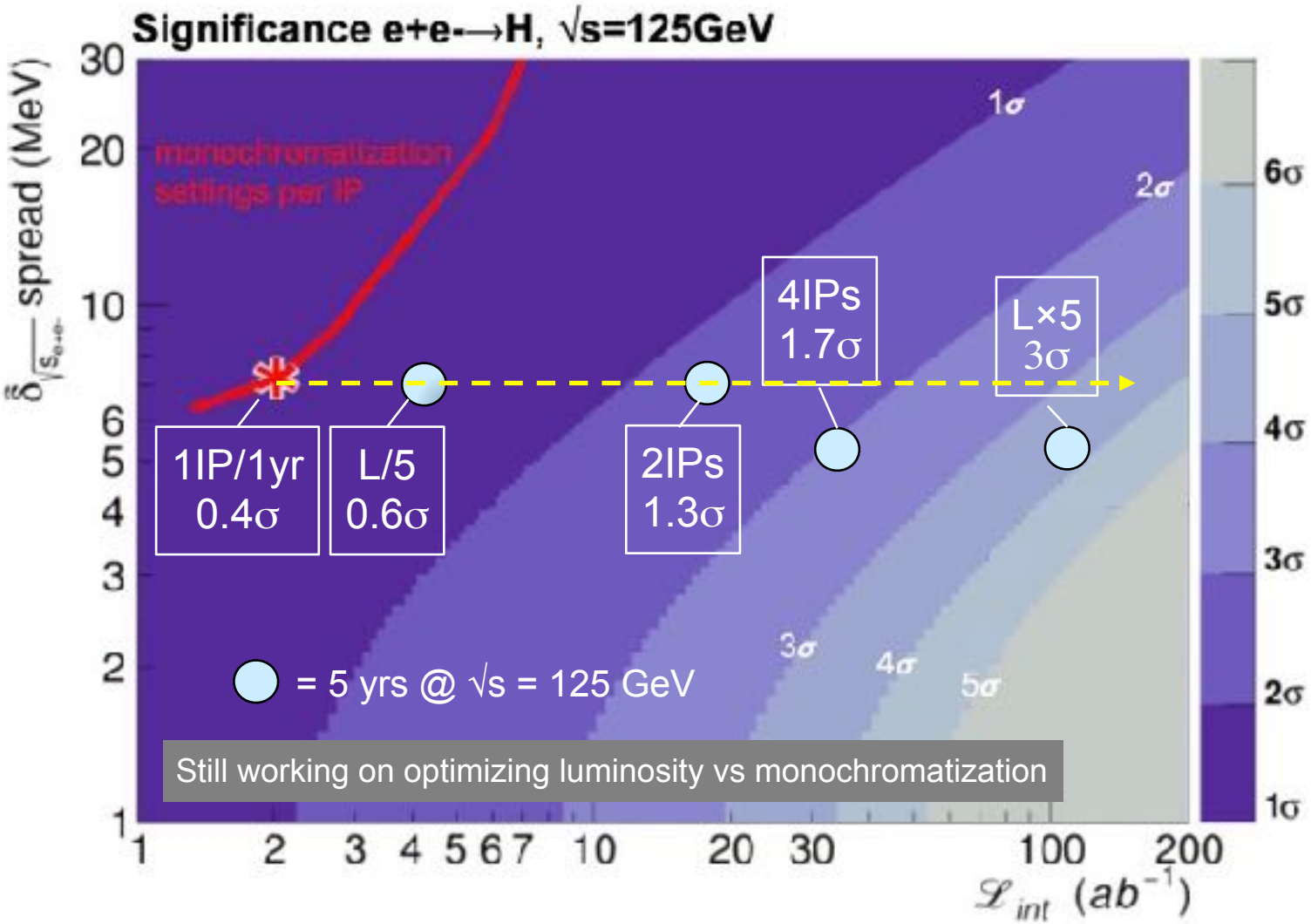
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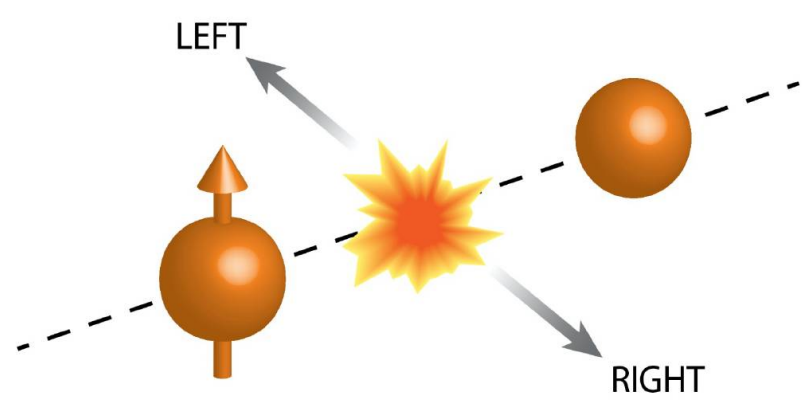
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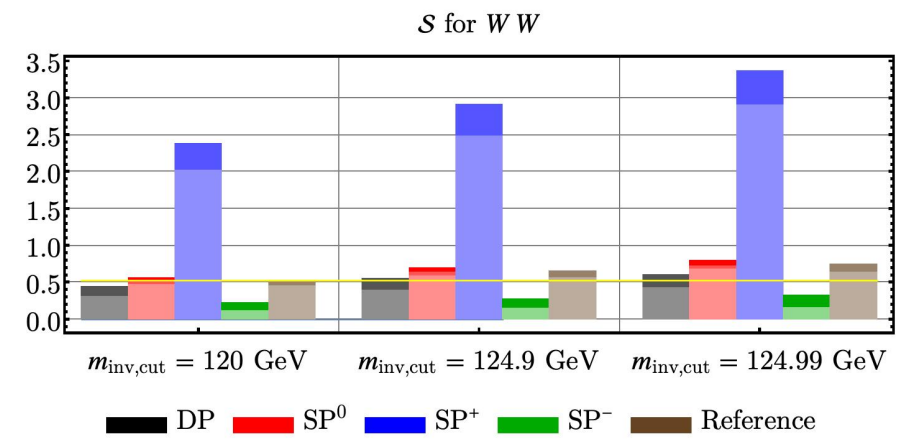
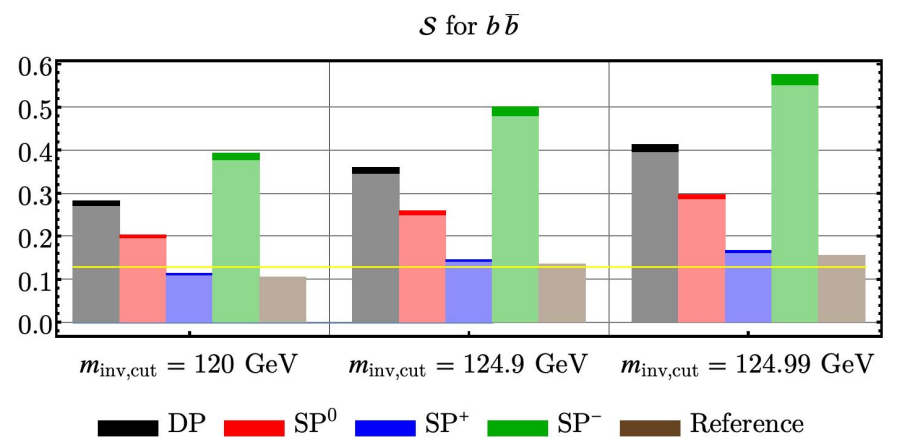
A recent pheno study ([Boughezal et al 2407.12975](#)) shows that transverse spin asymmetries can increase the sensitivity to the electron Yukawa



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

Electron polarized, positron unpolarized (SP ⁰):	$N = \frac{1}{2}(\sigma^{+0} - \sigma^{-0})$ $D = \frac{1}{2}(\sigma^{+0} + \sigma^{-0})$
Electron transversely polarized, positron longitudinally polarized (DP):	$N = \frac{1}{4}(\sigma^{++} - \sigma^{+-} - \sigma^{-+} + \sigma^{--})$ $D = \frac{1}{4}(\sigma^{++} + \sigma^{+-} + \sigma^{-+} + \sigma^{--})$
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8

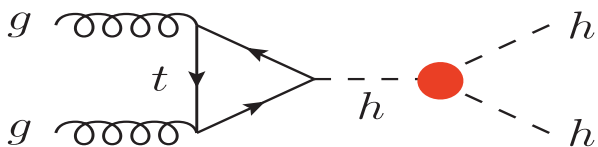
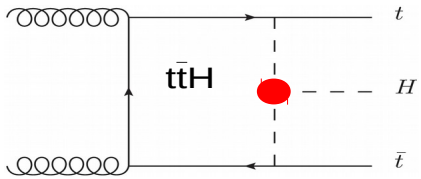
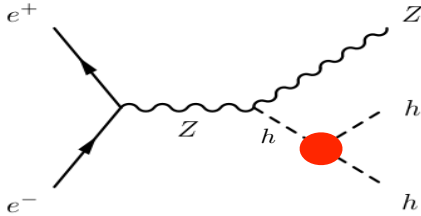
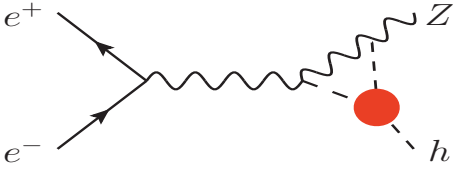


Major improvements of up to factors of 6 possible for bb and WW (doesn't work for gg)

Higgs Self-Coupling

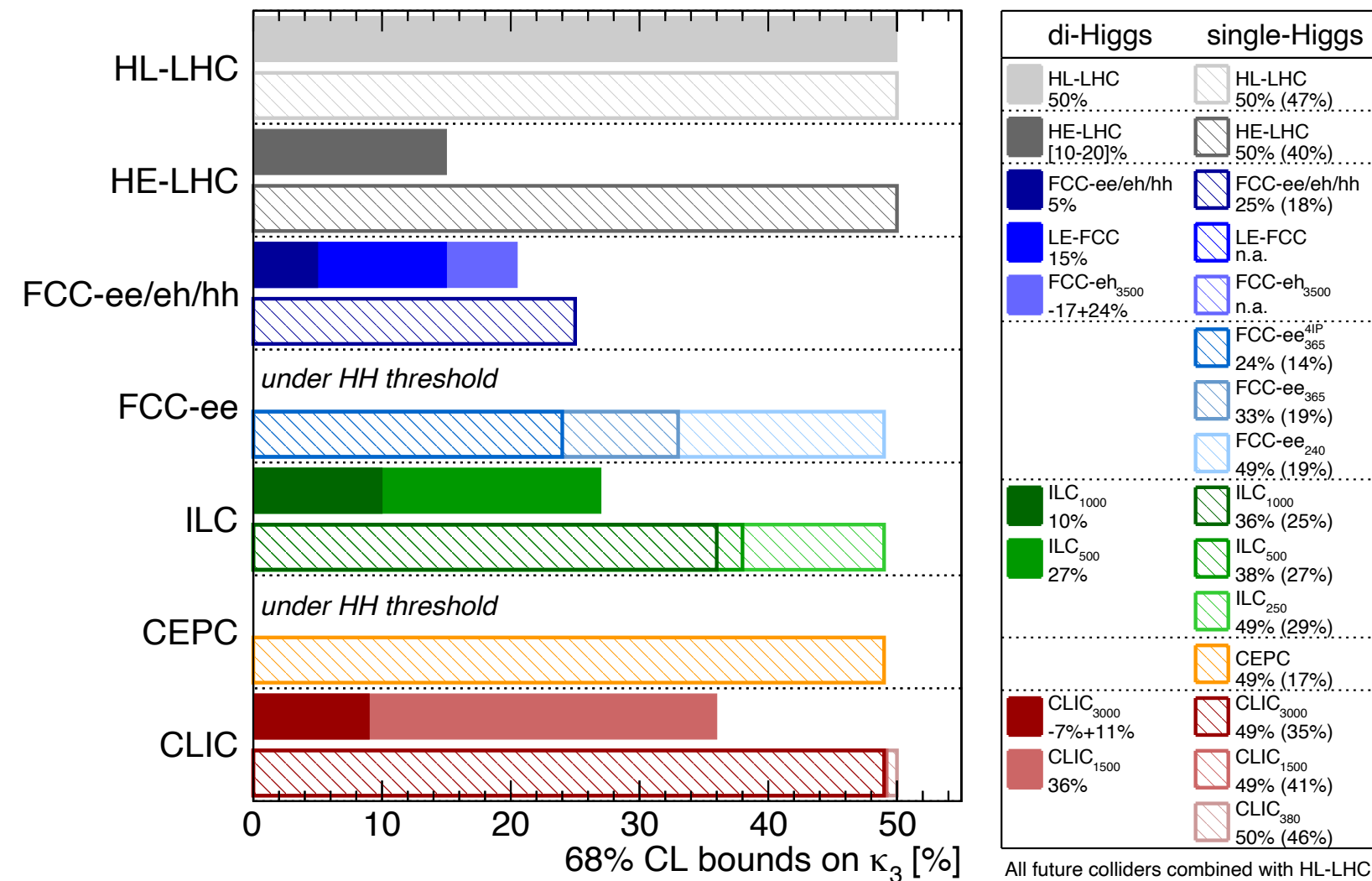
How much can it deviate from SM given the tight constraints on other Higgs couplings?
Do we need to reach HH production threshold to constrain h^3 coupling?

ECFA Higgs study group '19

	di-Higgs	single-Higgs
Hadron Colliders		
Lepton Colliders		
	di-Higgs	single-H
exclusive	1. di-H, excl. <ul style="list-style-type: none">• Use of $\sigma(HH)$• only deformation of $\kappa\lambda$	3. single-H, excl. <ul style="list-style-type: none">• single Higgs processes at higher order• only deformation of $\kappa\lambda$
global	2. di-H, glob. <ul style="list-style-type: none">• Use of $\sigma(HH)$• deformation of $\kappa\lambda$ + of the single-H couplings(a) do not consider the effects at higher order of $\kappa\lambda$ to single H production and decays(b) these higher order effects are included	4. single-H, glob. <ul style="list-style-type: none">• single Higgs processes at higher order• deformation of $\kappa\lambda$ + of the single Higgs couplings

Higgs Self-Coupling

Higgs@FC WG November 2019



1

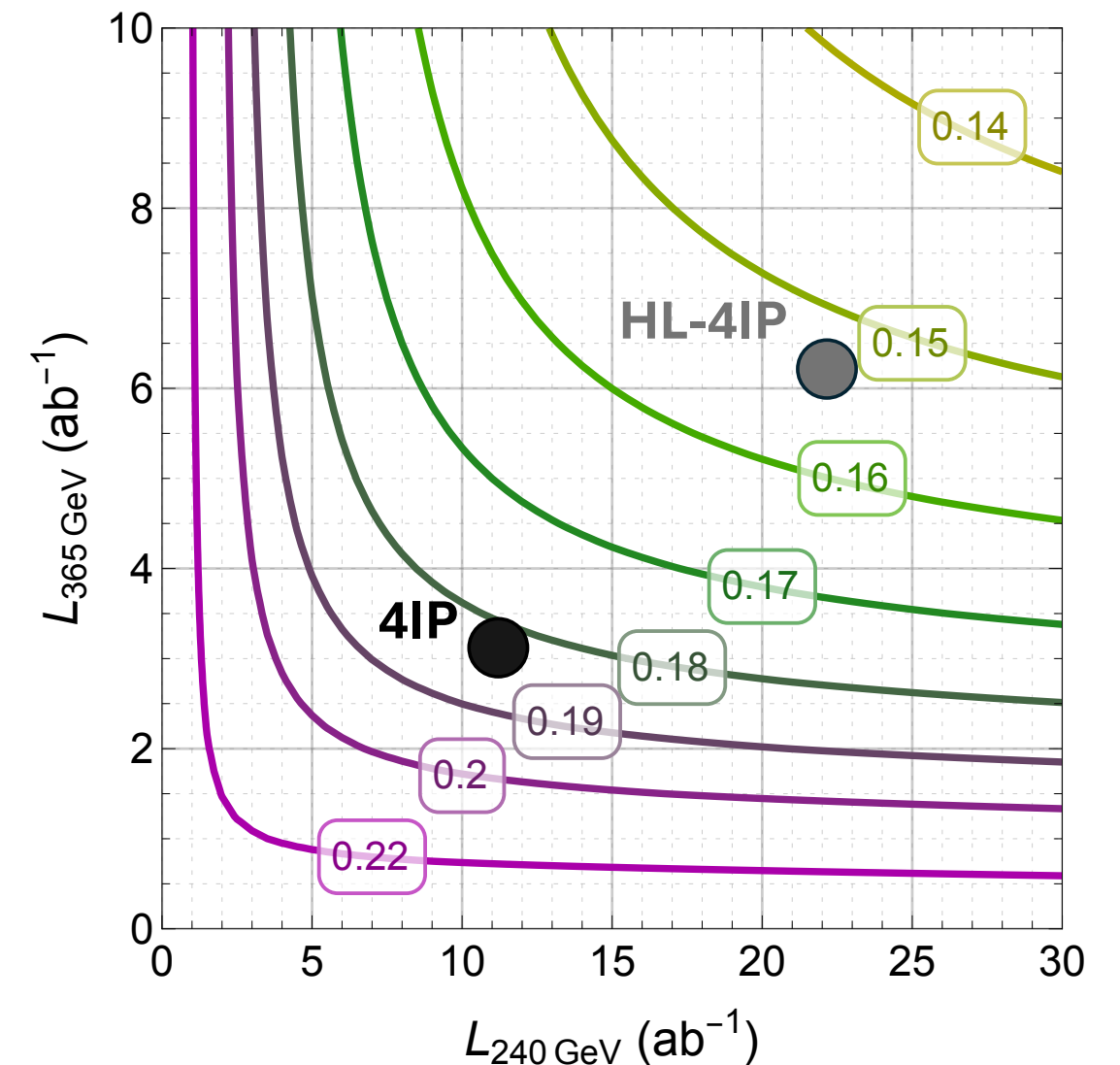
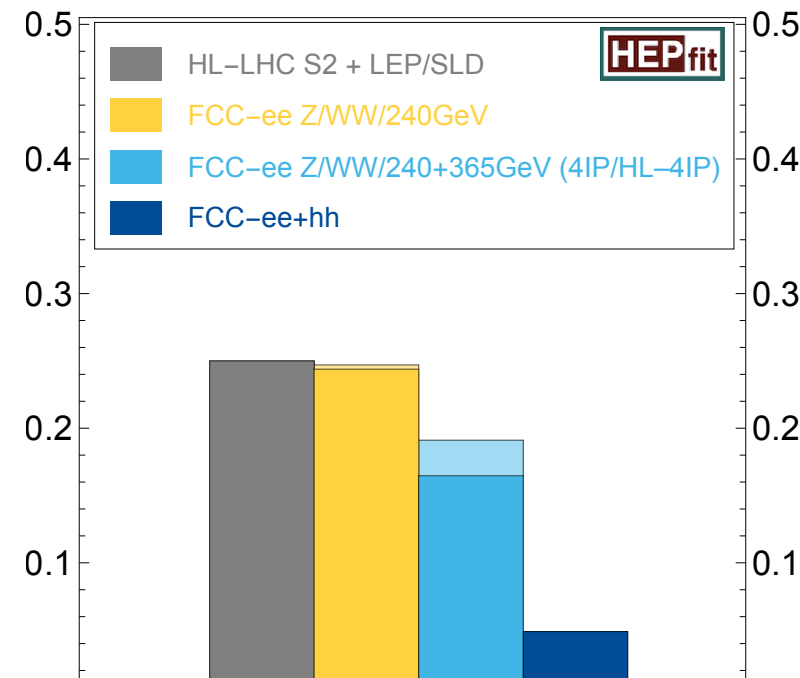
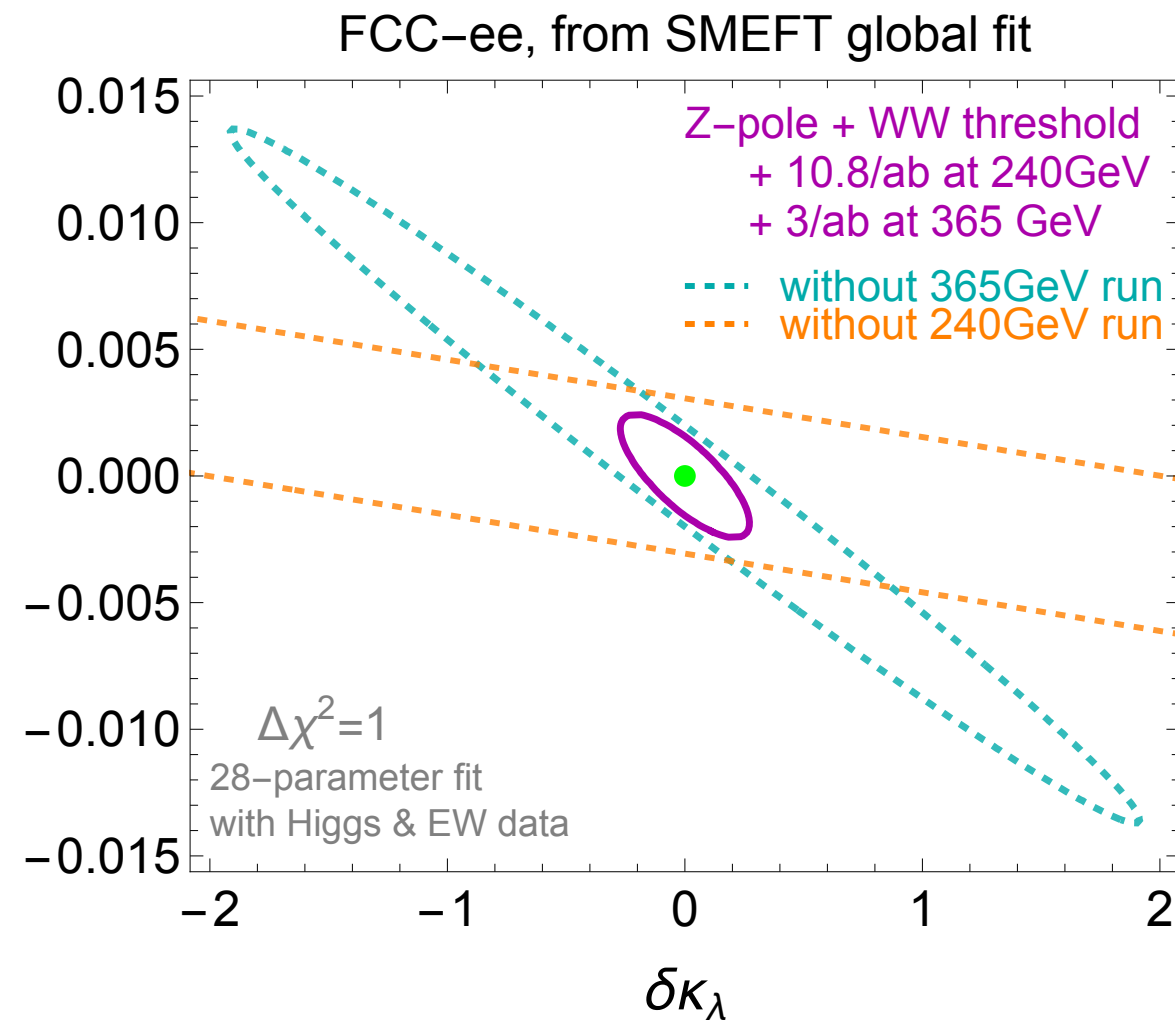
Don't need to reach HH threshold to have access to h^3 .
Runs at different energies are essential (e.g. 240 and 365 GeV)

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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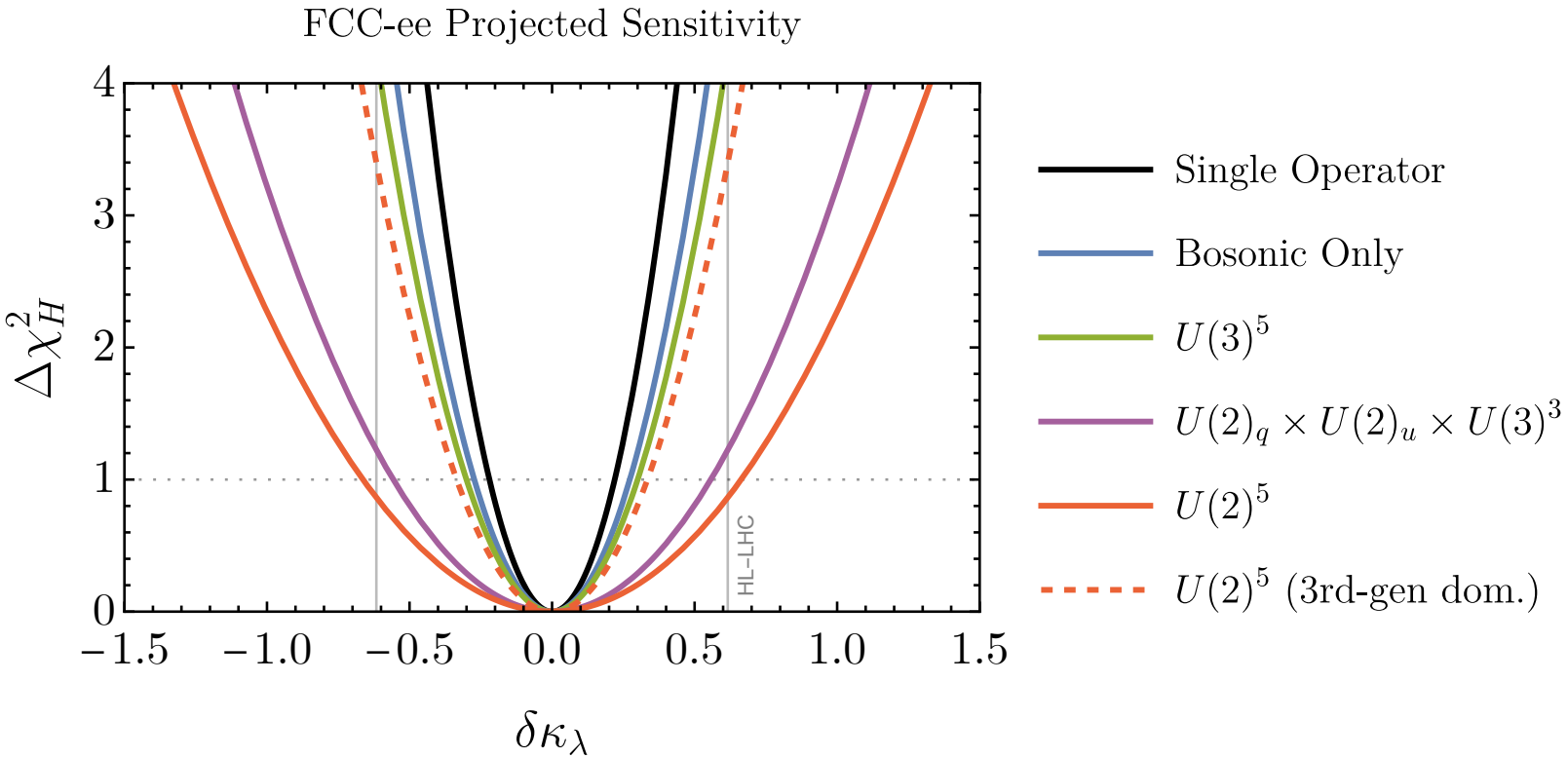
Higgs Self-Coupling

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%

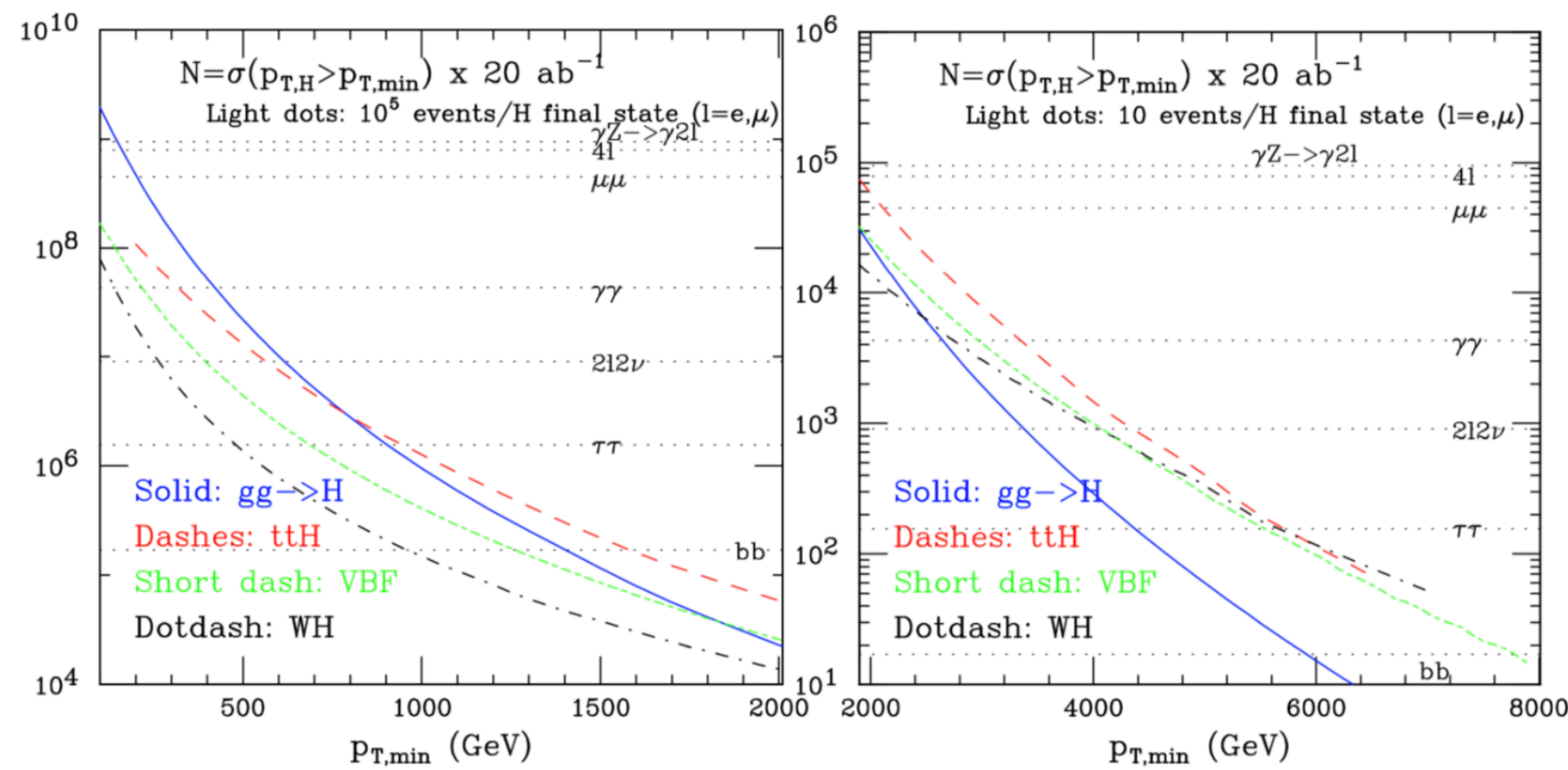


Higgs @ FCC-hh.

The Higgs exploration territory

	ggH (N ³ LO)	VBF (N ² LO)	WH (N ² LO)	ZH (N ² LO)	t \bar{t} H (N ² LO)	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

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



- 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/ $p_T > 1$ TeV
 - clean samples with high S/B
 - small systematics

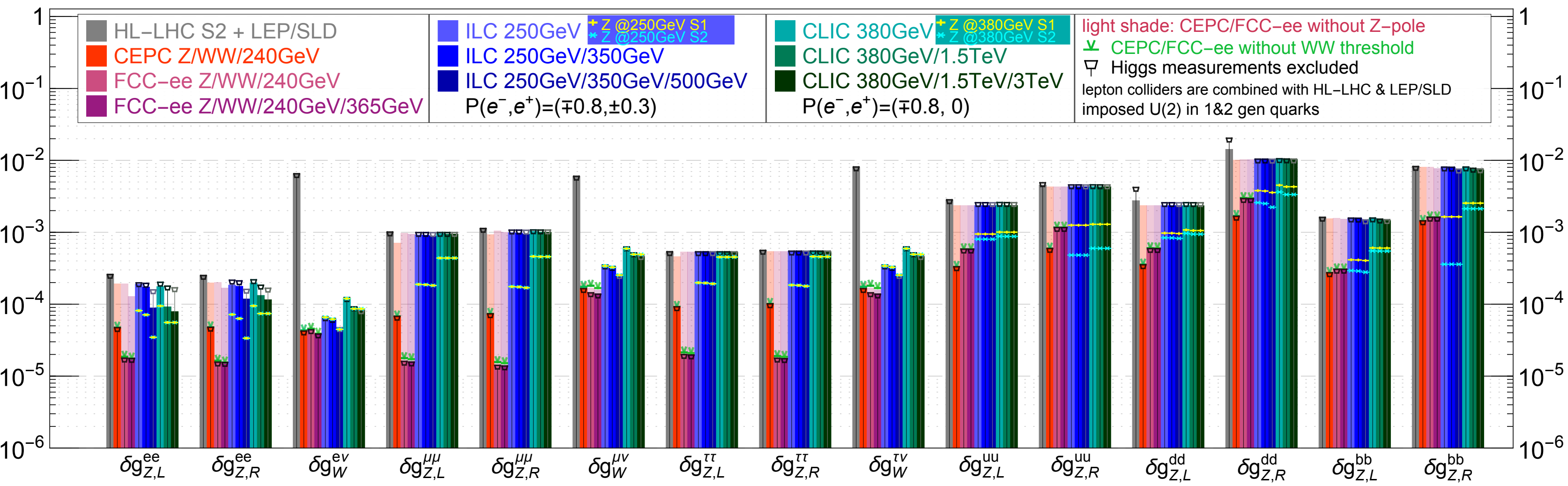
Higgs @ FCC-hh.

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
$ \kappa_s $ (%)	—	+29 −67	+29 −67
Γ_H (%)	—	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

Higgs and EW measurements

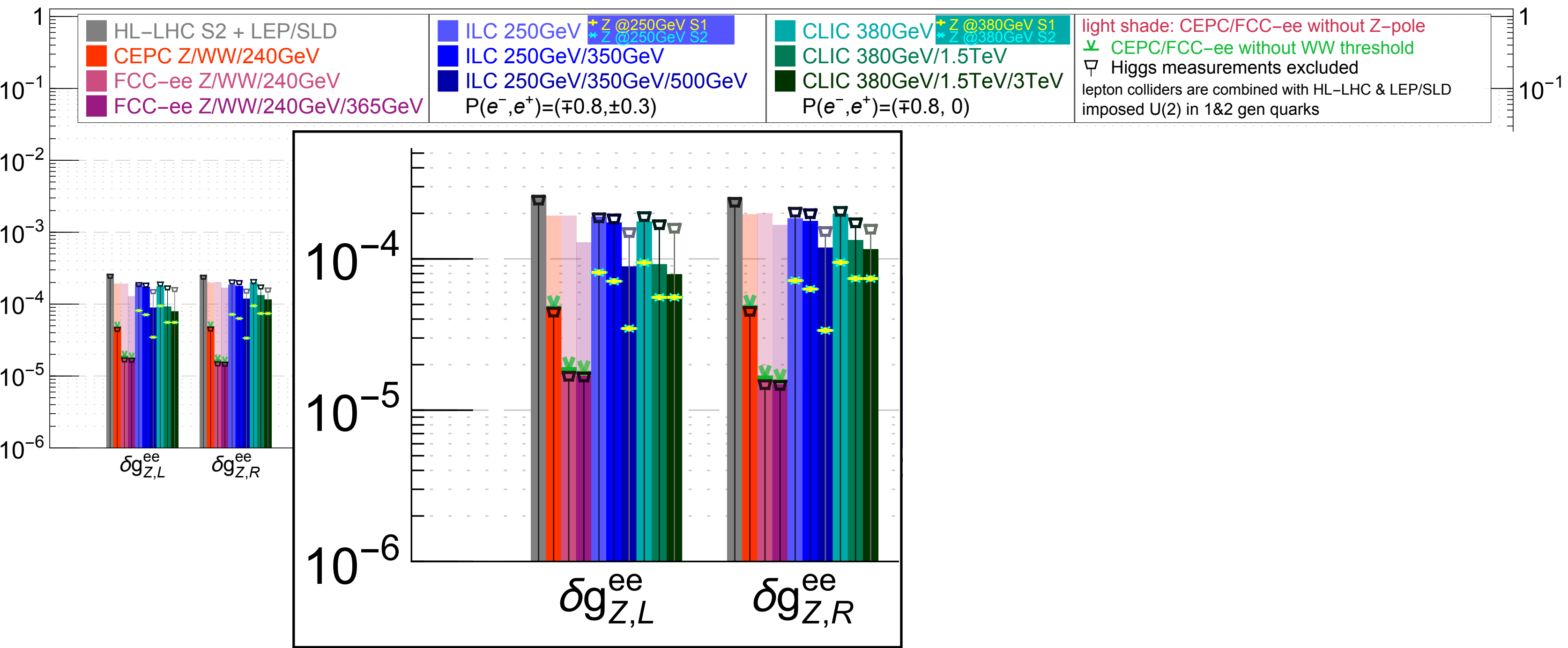
Sensitivity on EW couplings.

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



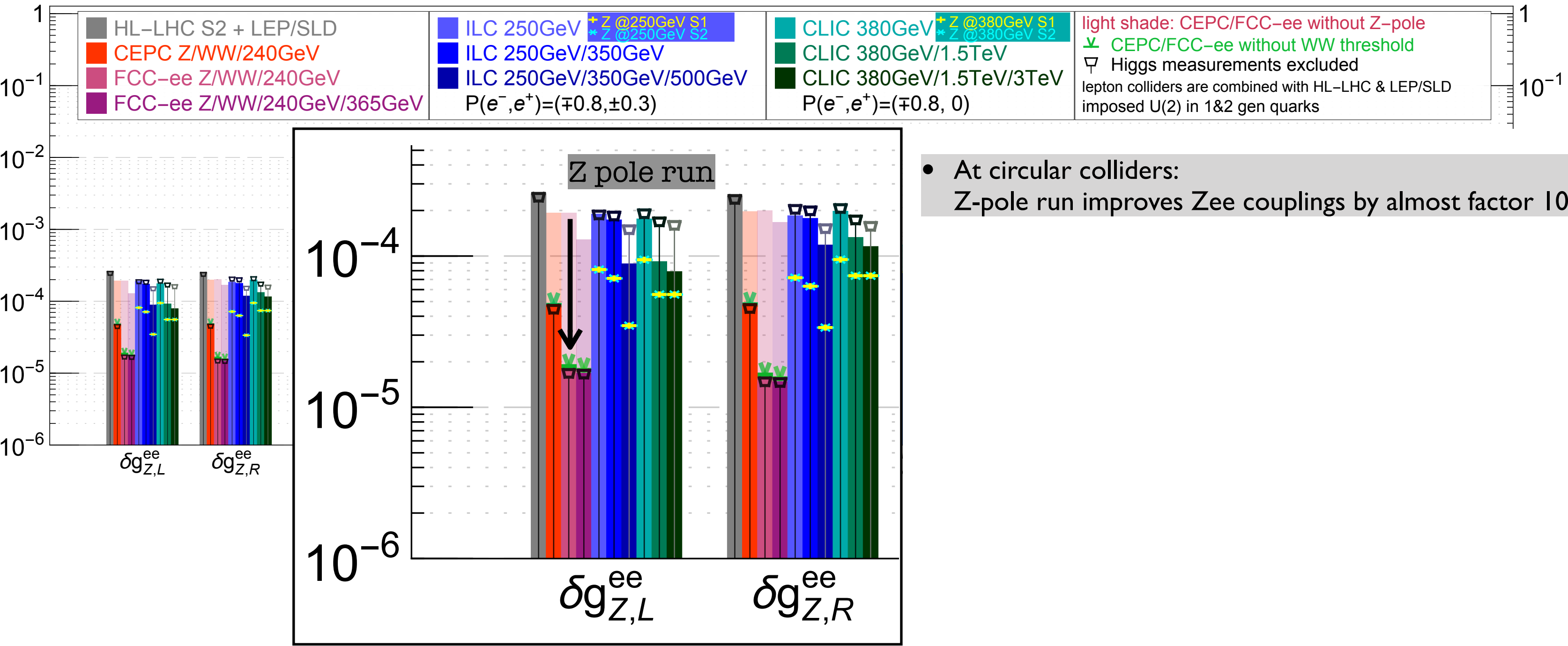
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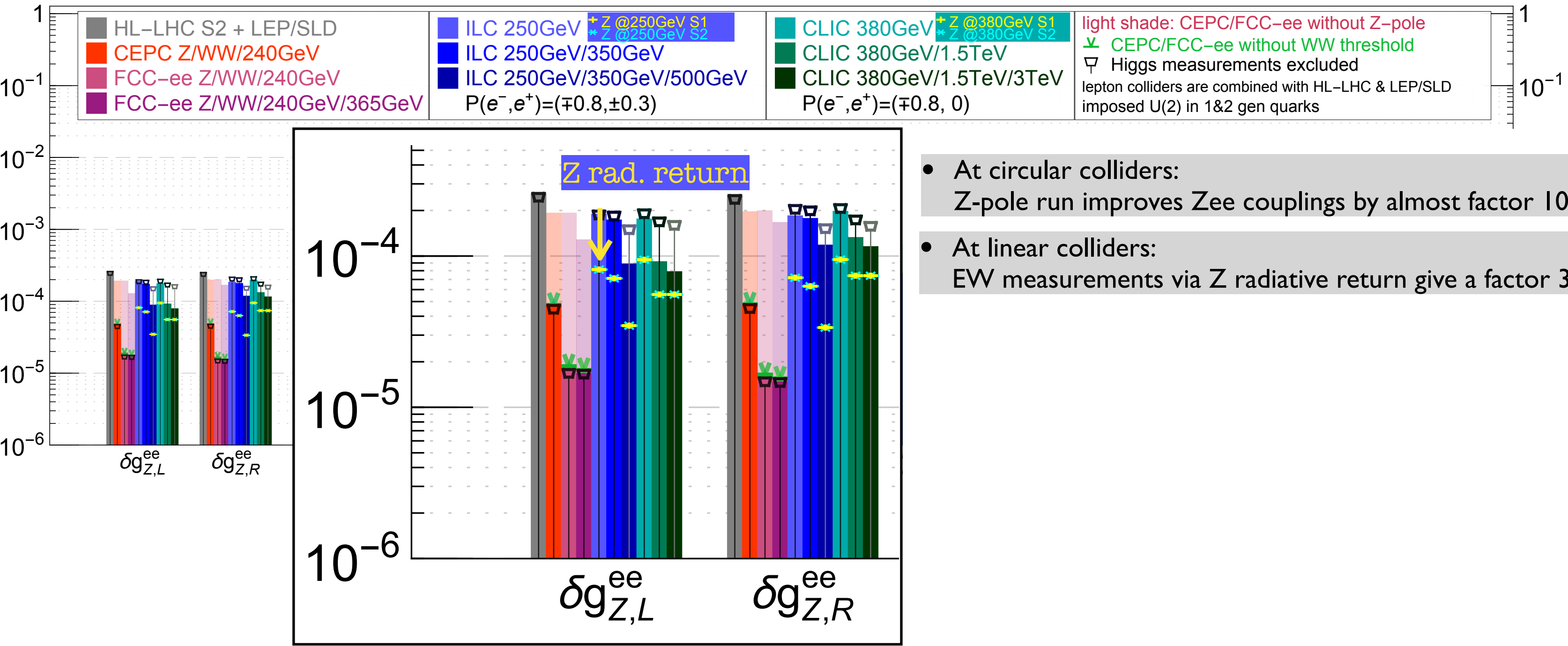
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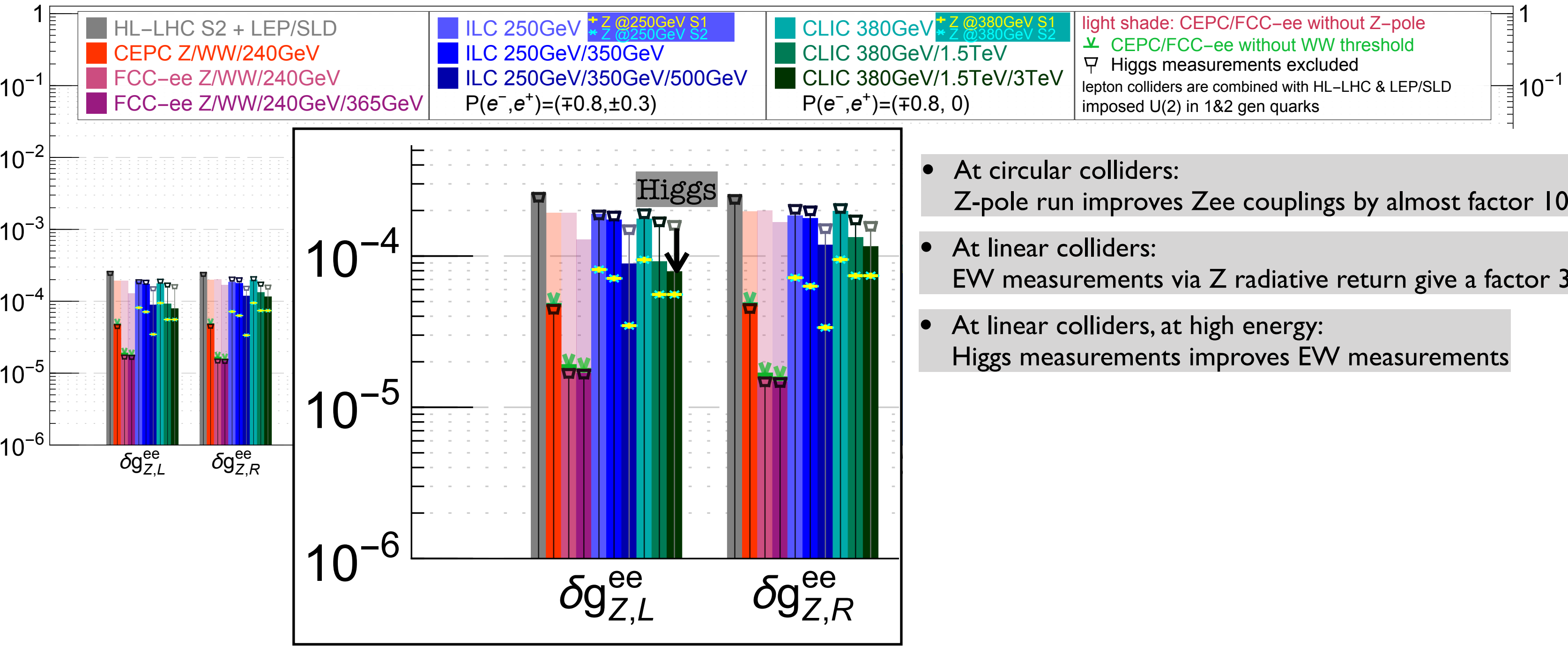
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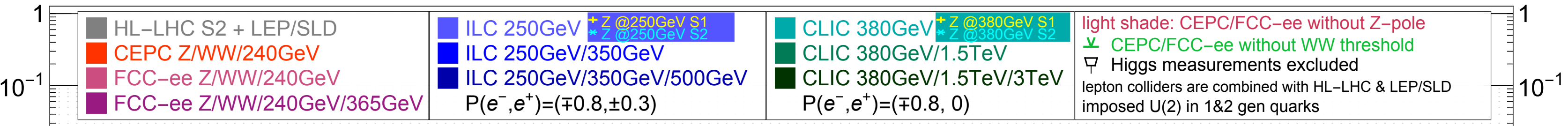
Sensitivity on EW couplings.

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

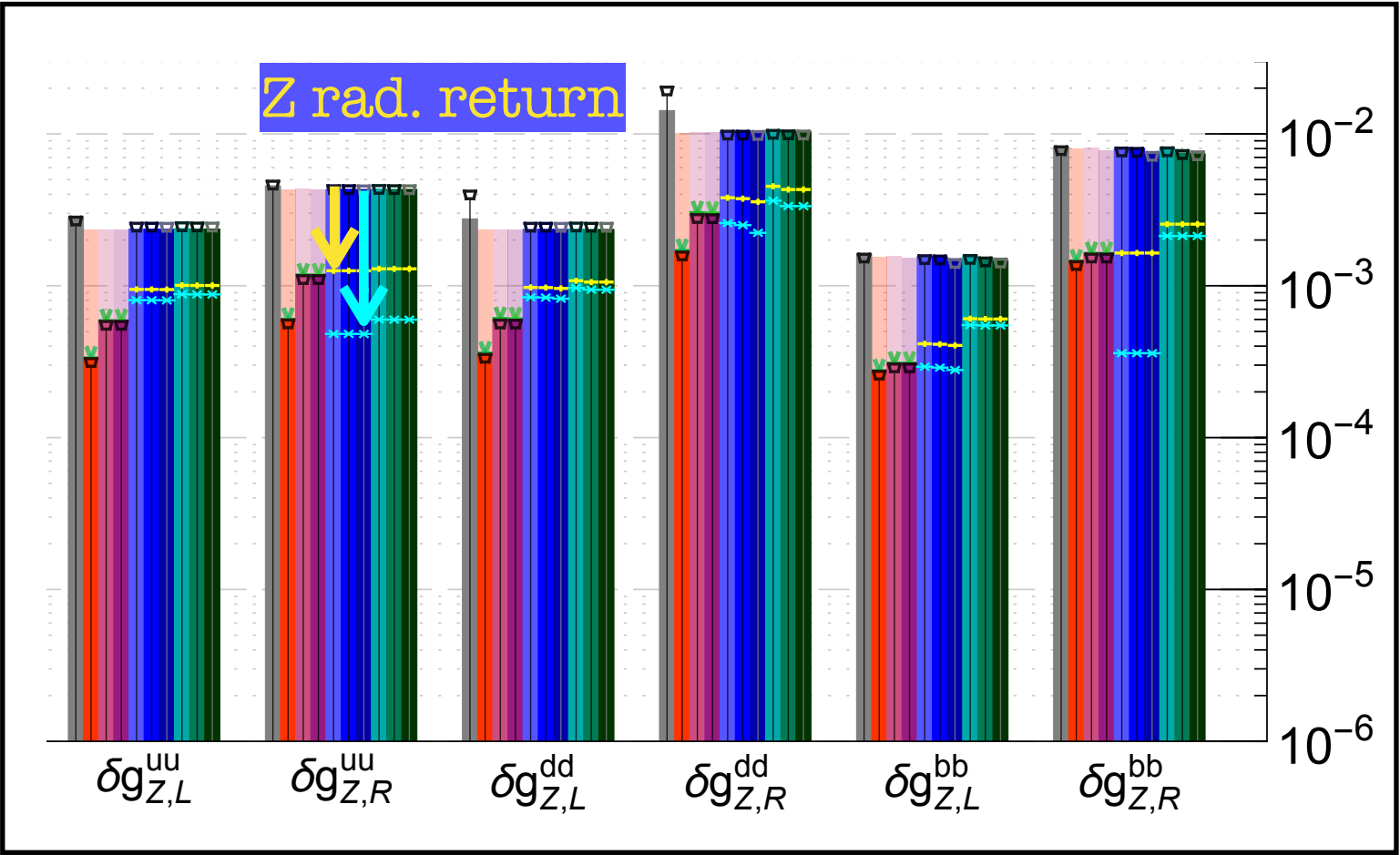


Sensitivity on EW couplings.

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



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



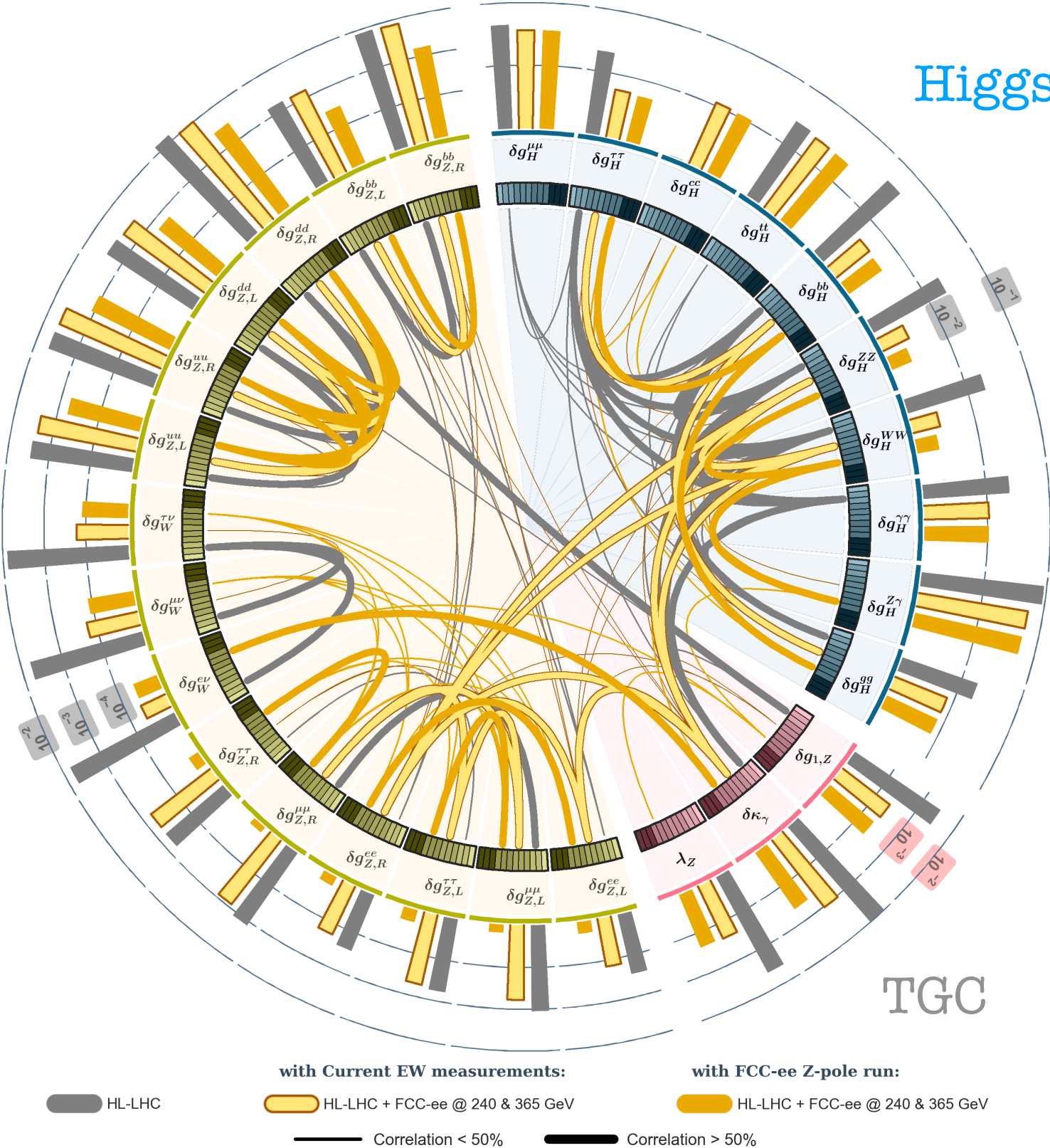
Why Z-pole for Higgs?

J. De Blas et al. 1907.04311

EW

Higgs

TGC



Why Z-pole for Higgs?

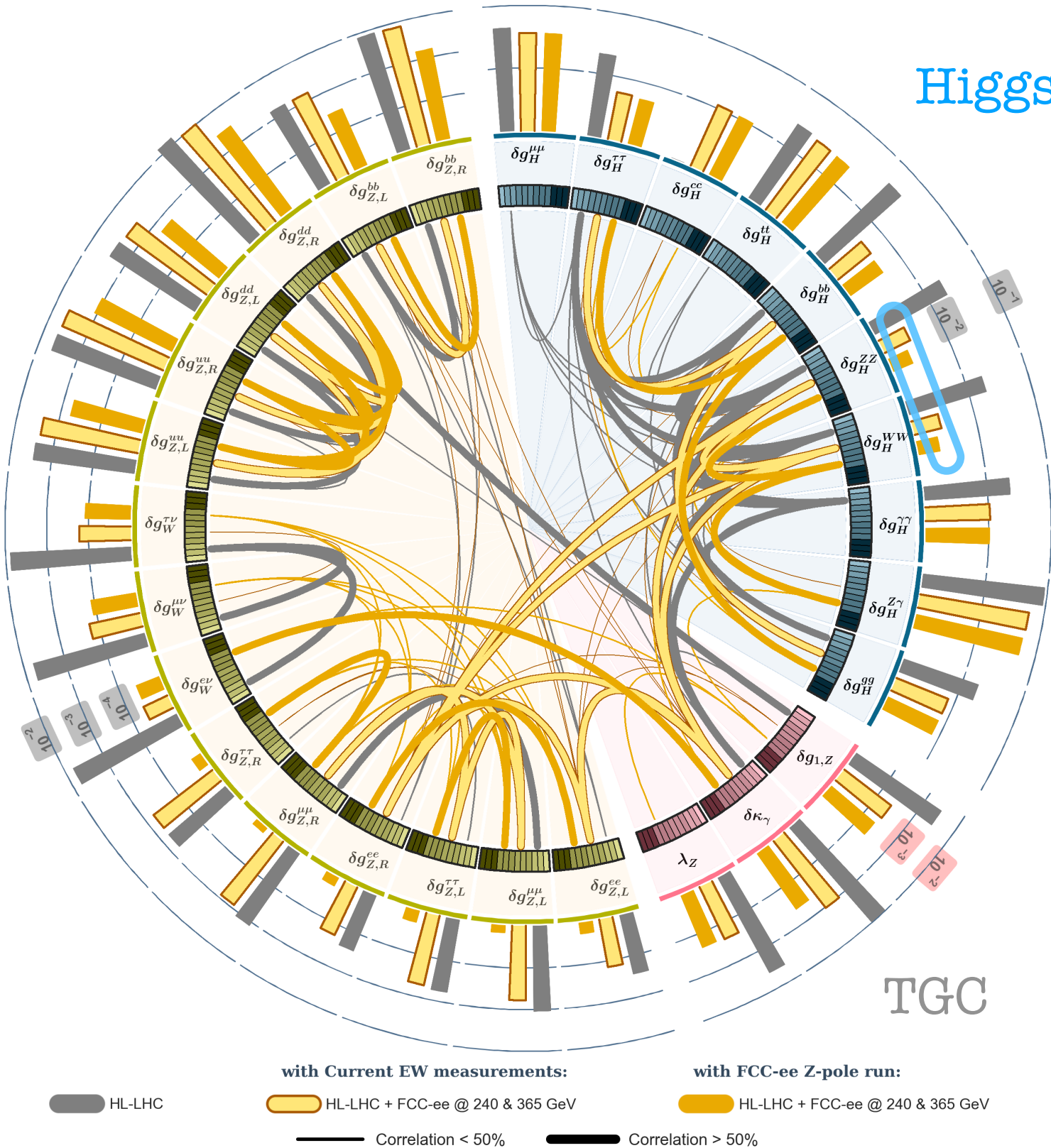
J. De Blas et al. 1907.04311

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

EW

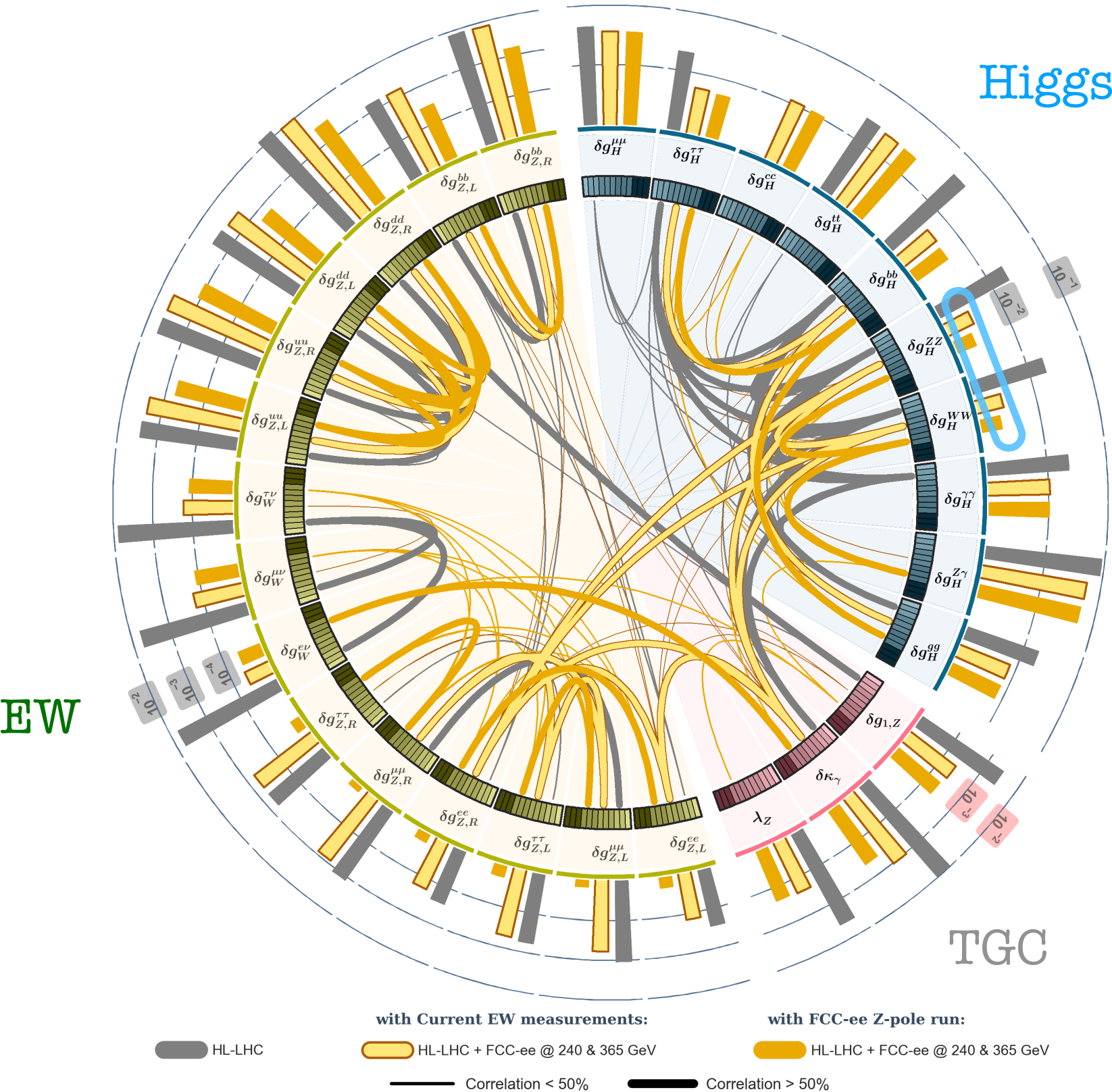
Higgs

TGC



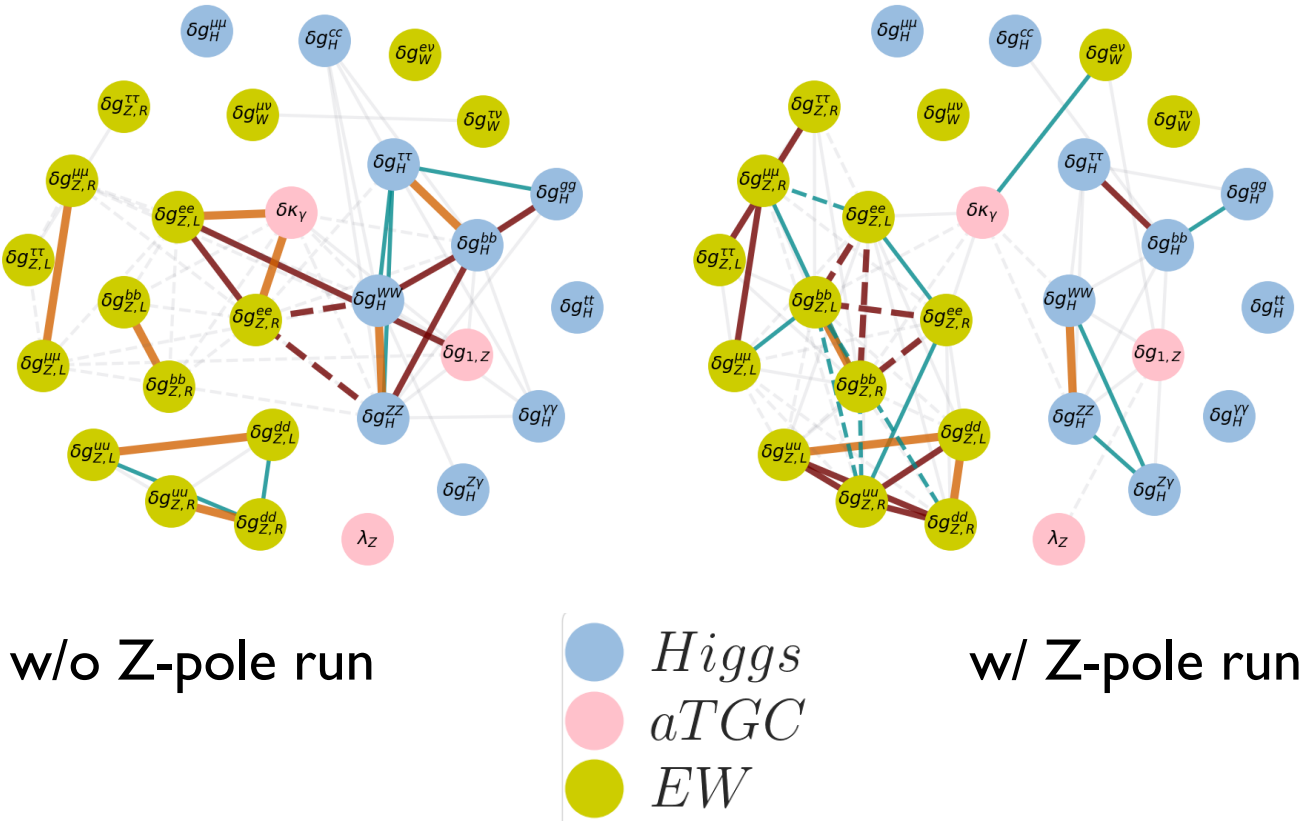
Why Z-pole for Higgs?

J. De Blas et al. 1907.04311



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

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

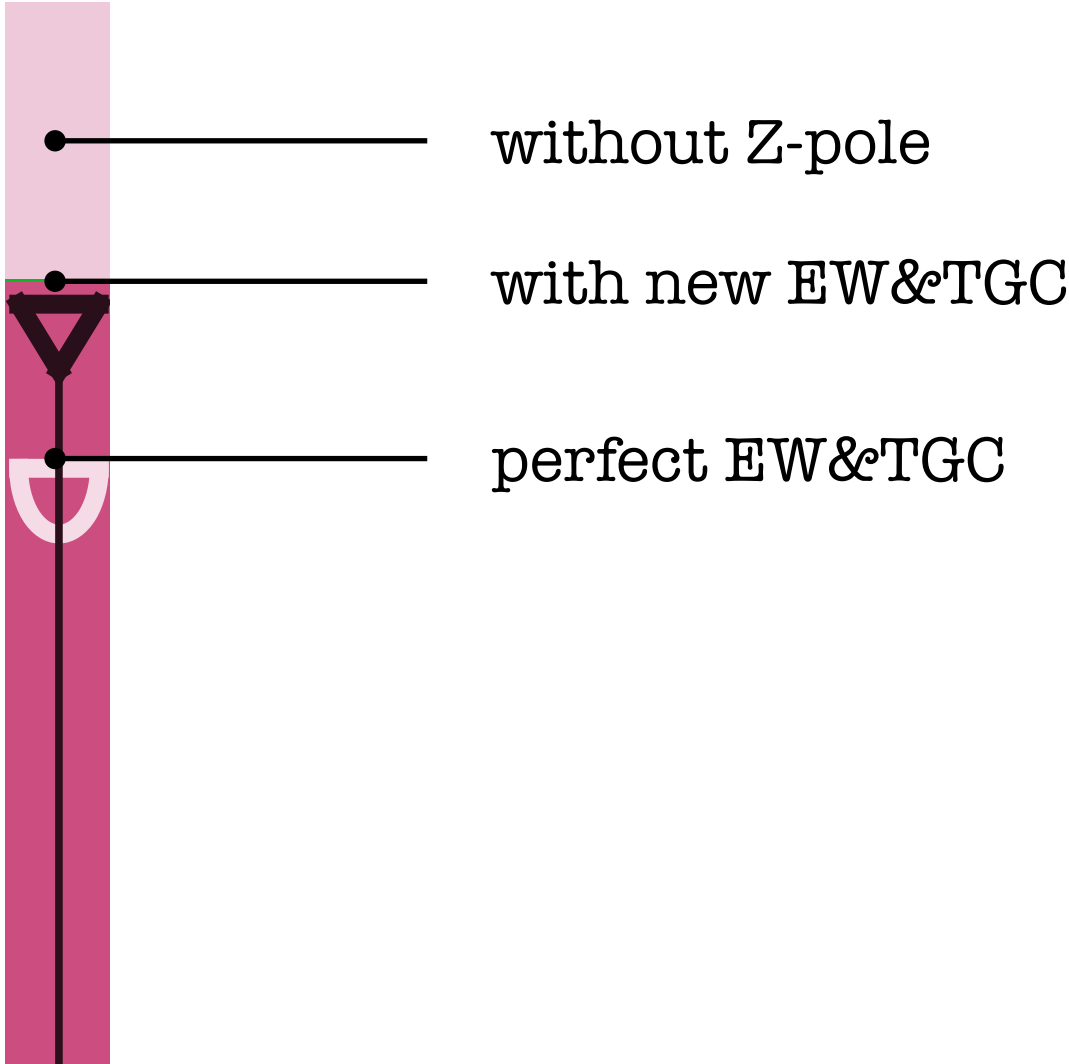
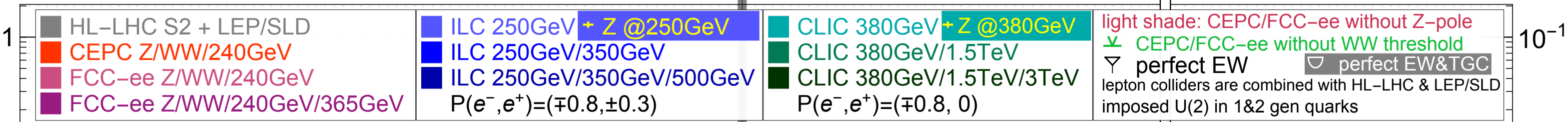


Impact of Z-pole on Higgs.

J. De Blas et al. 1907.04311

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

Higgs couplings

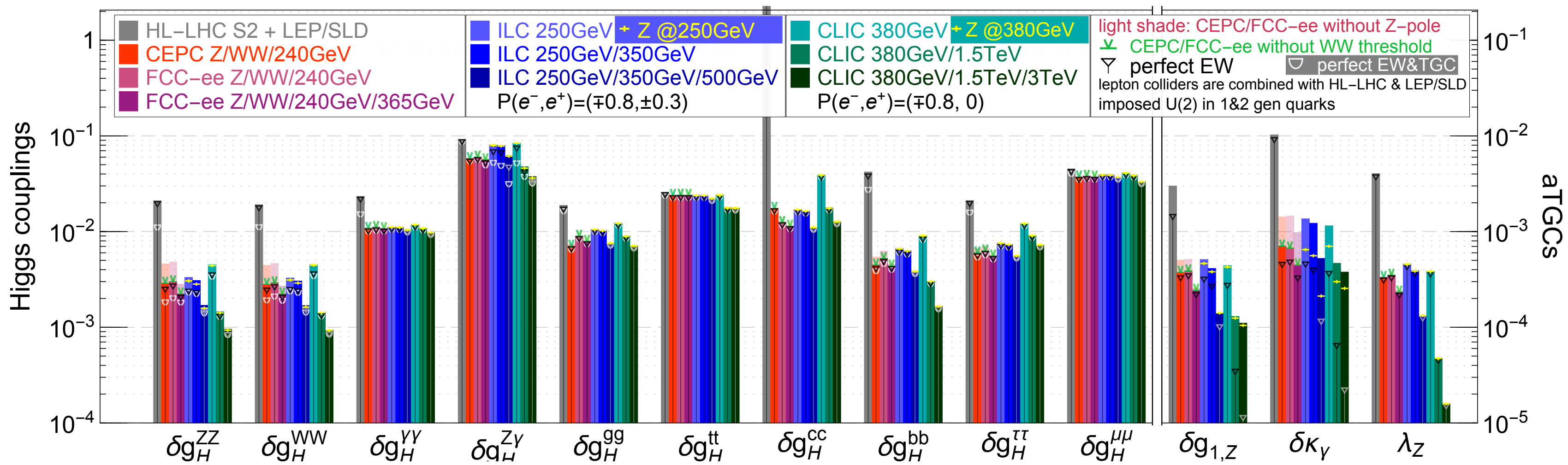


FCC-ee Z/WW/240GeV

Impact of Z-pole on Higgs.

J. De Blas et al. 1907.04311

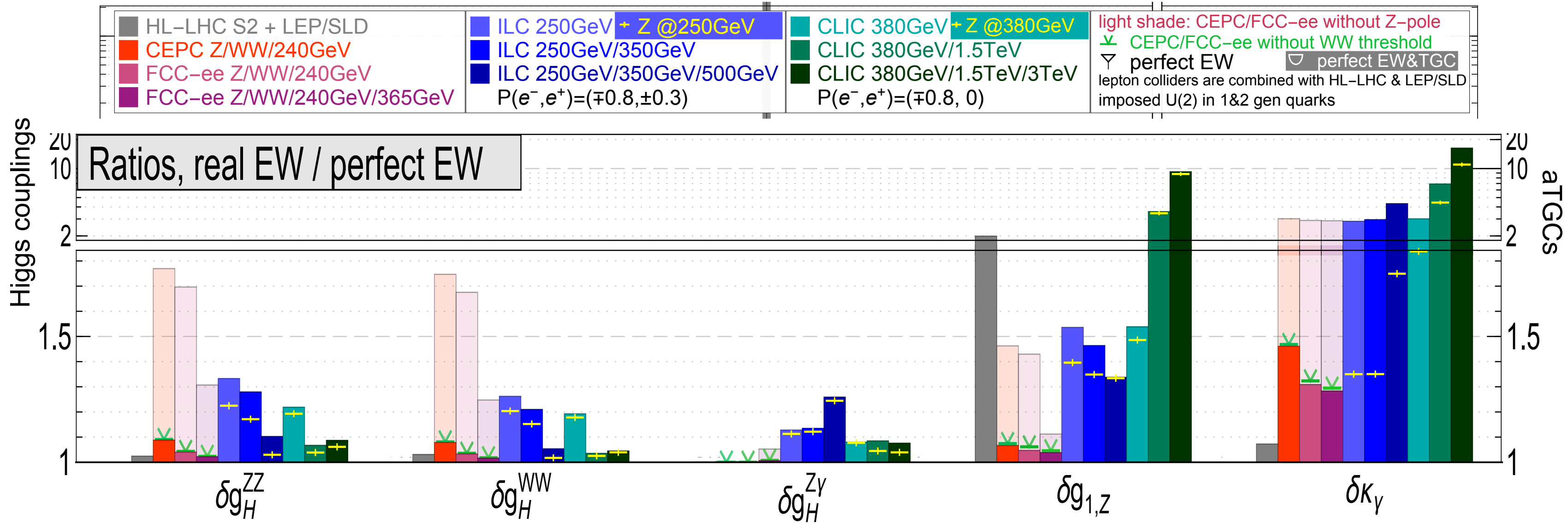
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



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J. De Blas et al. 1907.04311

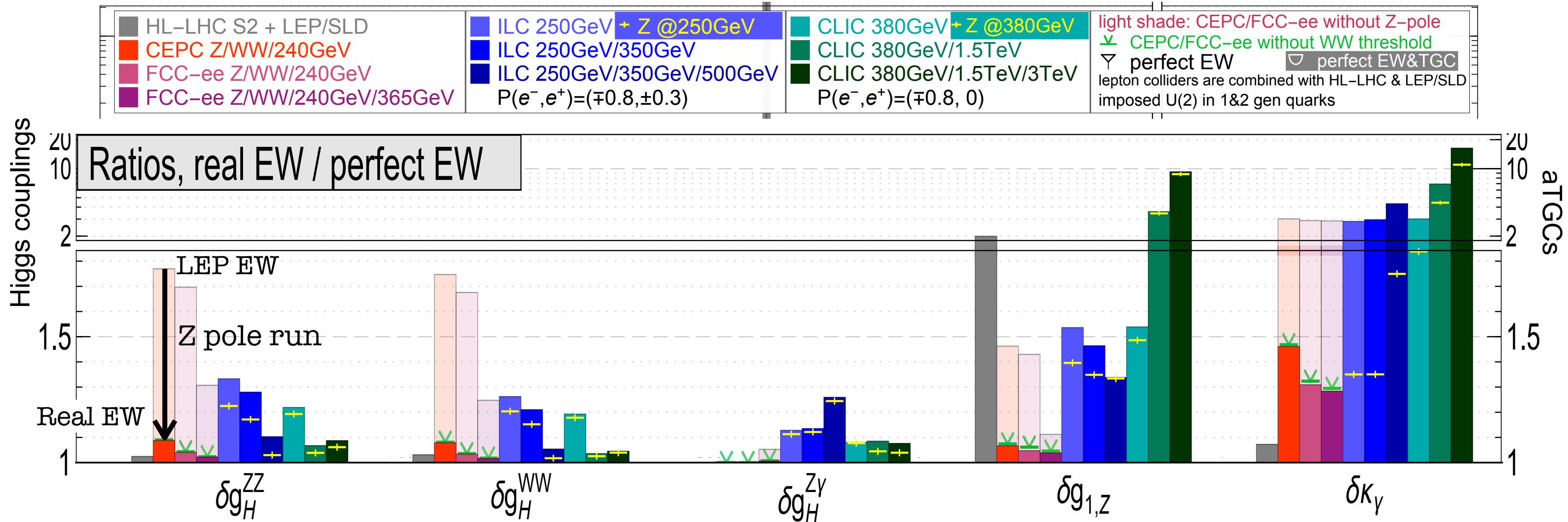
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Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements

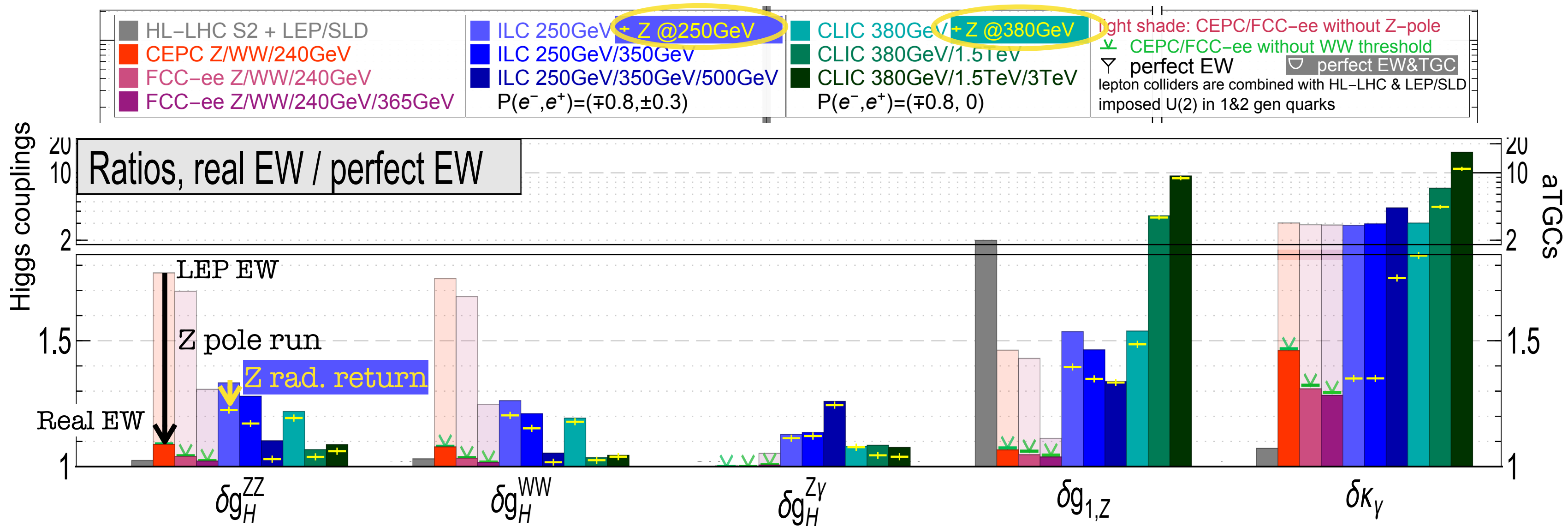


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).

Impact of Z-pole on Higgs.

J. De Blas et al. 1907.04311

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

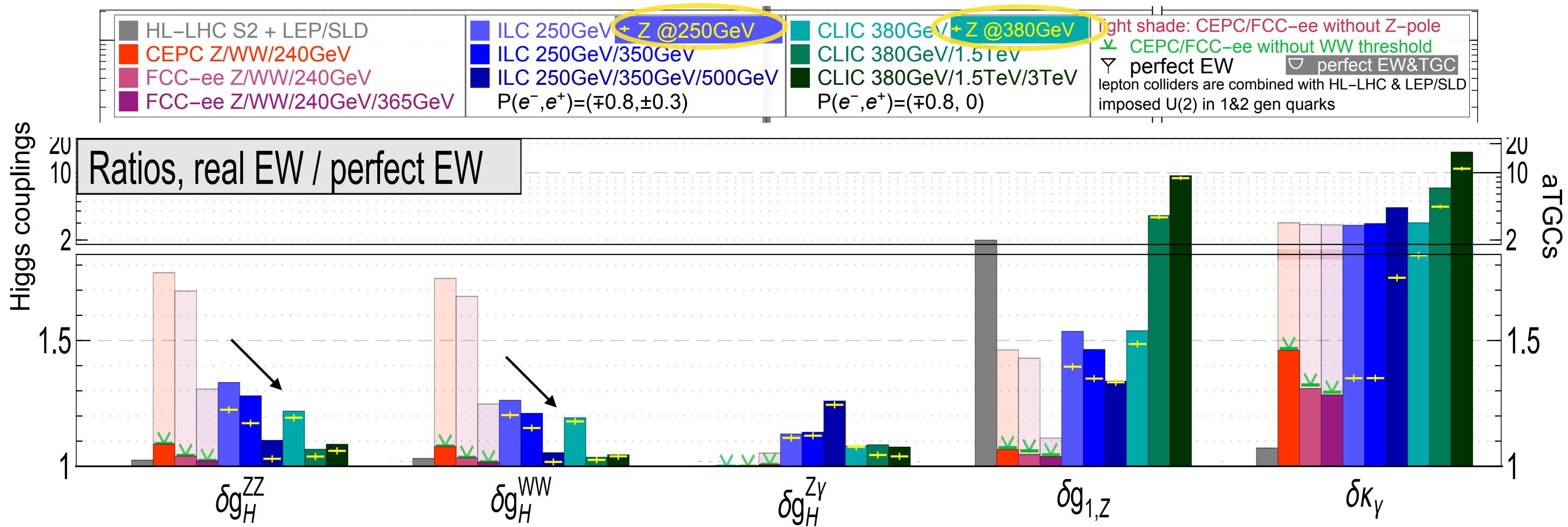


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs
But EW measurements at high energy (via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

Impact of Z-pole on Higgs.

J. De Blas et al. 1907.04311

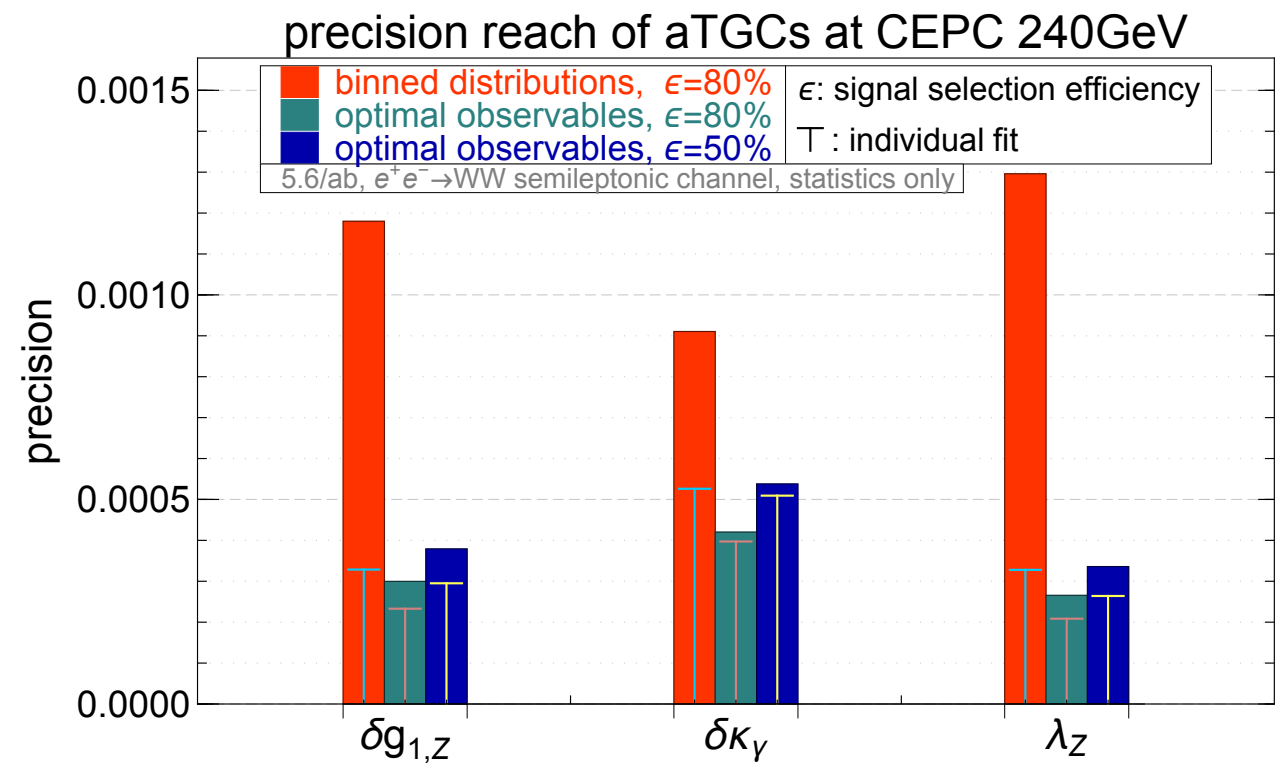
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



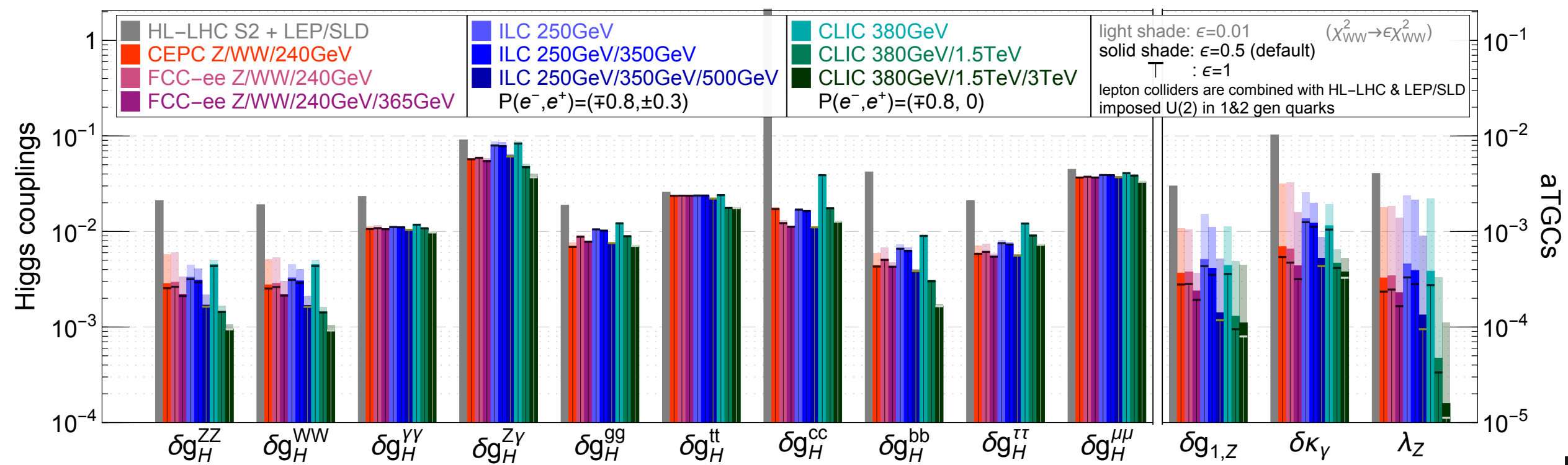
- Higher energy runs reduce the EW contamination in Higgs coupling extraction

Impact of Diboson Systematics.

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



precision reach with different assumptions on $e^+e^- \rightarrow WW$ measurements



Higgs self-coupling.

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

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

ECFA Higgs study group '19

	Directly: Higgs-pair prod	Indirectly: via single Higgs
Hadron Colliders		
Lepton Colliders		
	di-Higgs	single-H
exclusive	1. di-H, excl. <ul style="list-style-type: none">• Use of $\sigma(\text{HH})$• only deformation of $\kappa\lambda$	3. single-H, excl. <ul style="list-style-type: none">• single Higgs processes at higher order• only deformation of $\kappa\lambda$
global	2. di-H, glob. <ul style="list-style-type: none">• Use of $\sigma(\text{HH})$• deformation of $\kappa\lambda$ + of the single-H couplings(a) do not consider the effects at higher order of $\kappa\lambda$ to single H production and decays(b) these higher order effects are included	4. single-H, glob. <ul style="list-style-type: none">• single Higgs processes at higher order• deformation of $\kappa\lambda$ + of the single Higgs couplings

Large self-coupling scenarios.

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

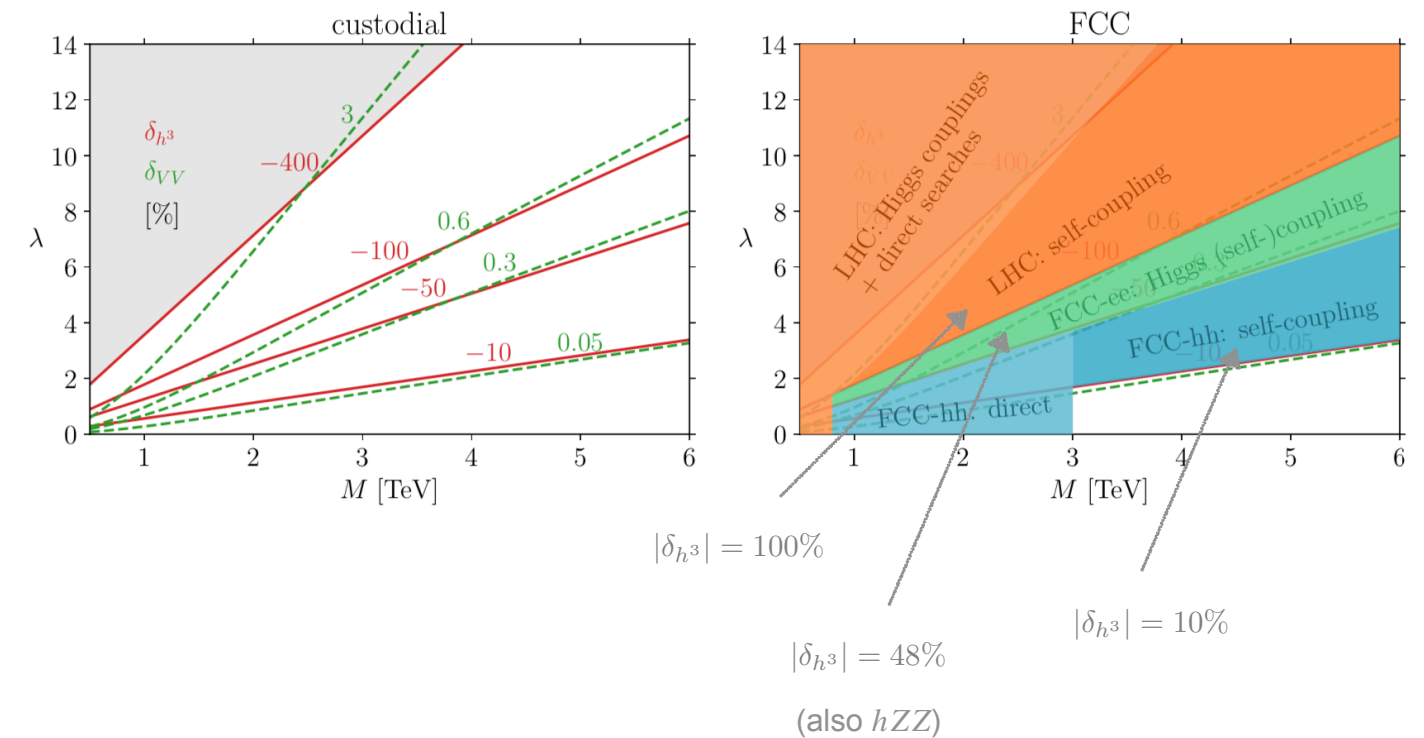
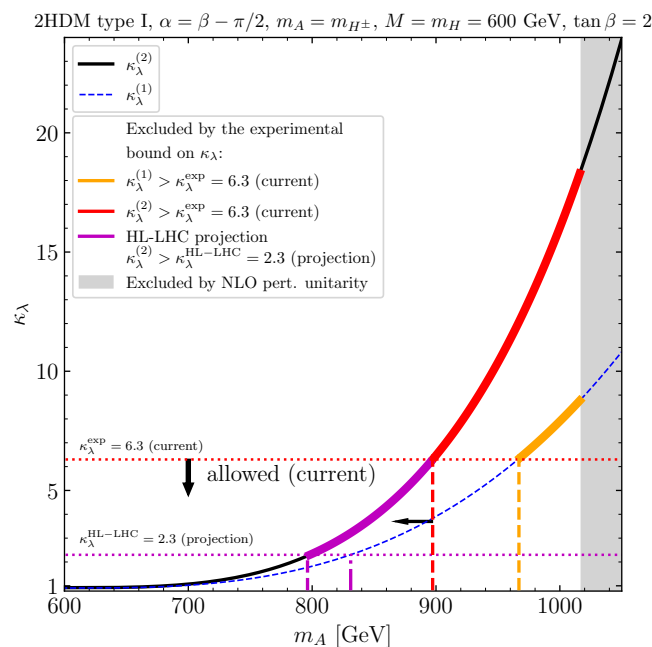
Particular exceptions: Higgs DM-portal models or custodial EW quadruplet

DiVita et al,: 1704.01953

Falkowski, Rattazzi: 1902.05936

Durieux, McCullough, Salvioni: 2209.00666

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

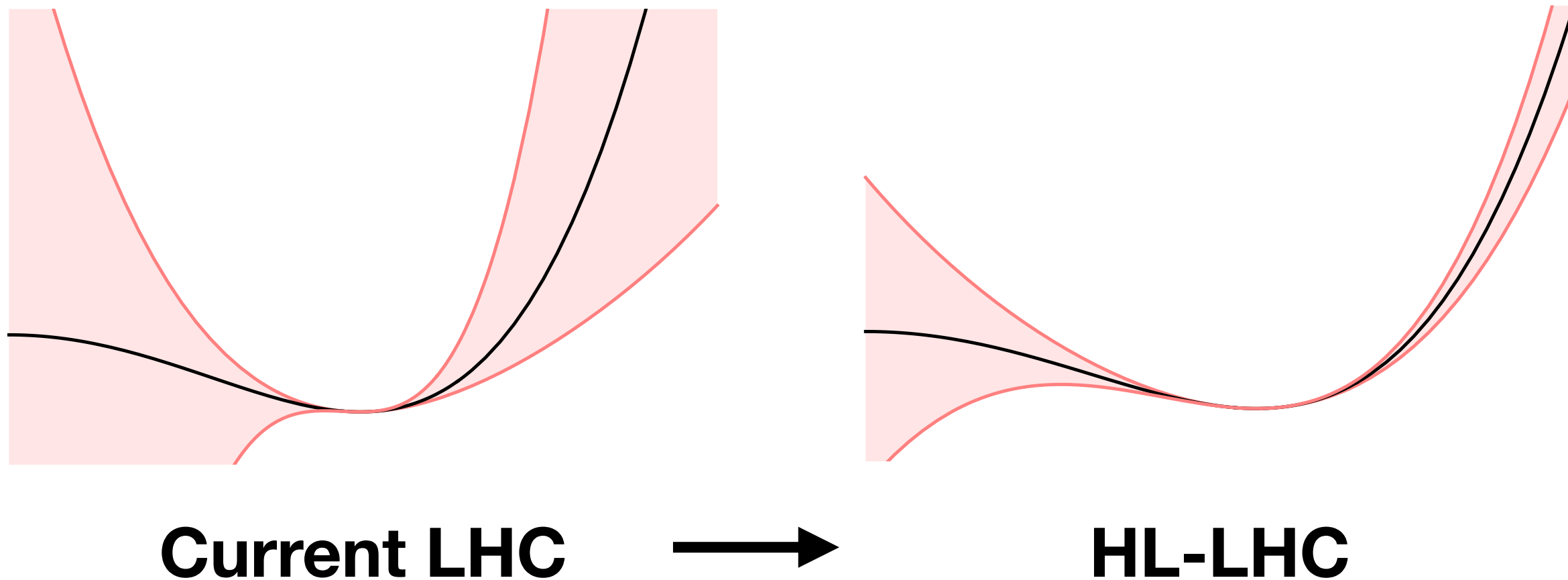


Other exceptions: non-decoupled/fine-tuned spectra

Bahl, Braathen, Weiglein: 2202.03453

Large self-coupling scenarios.

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

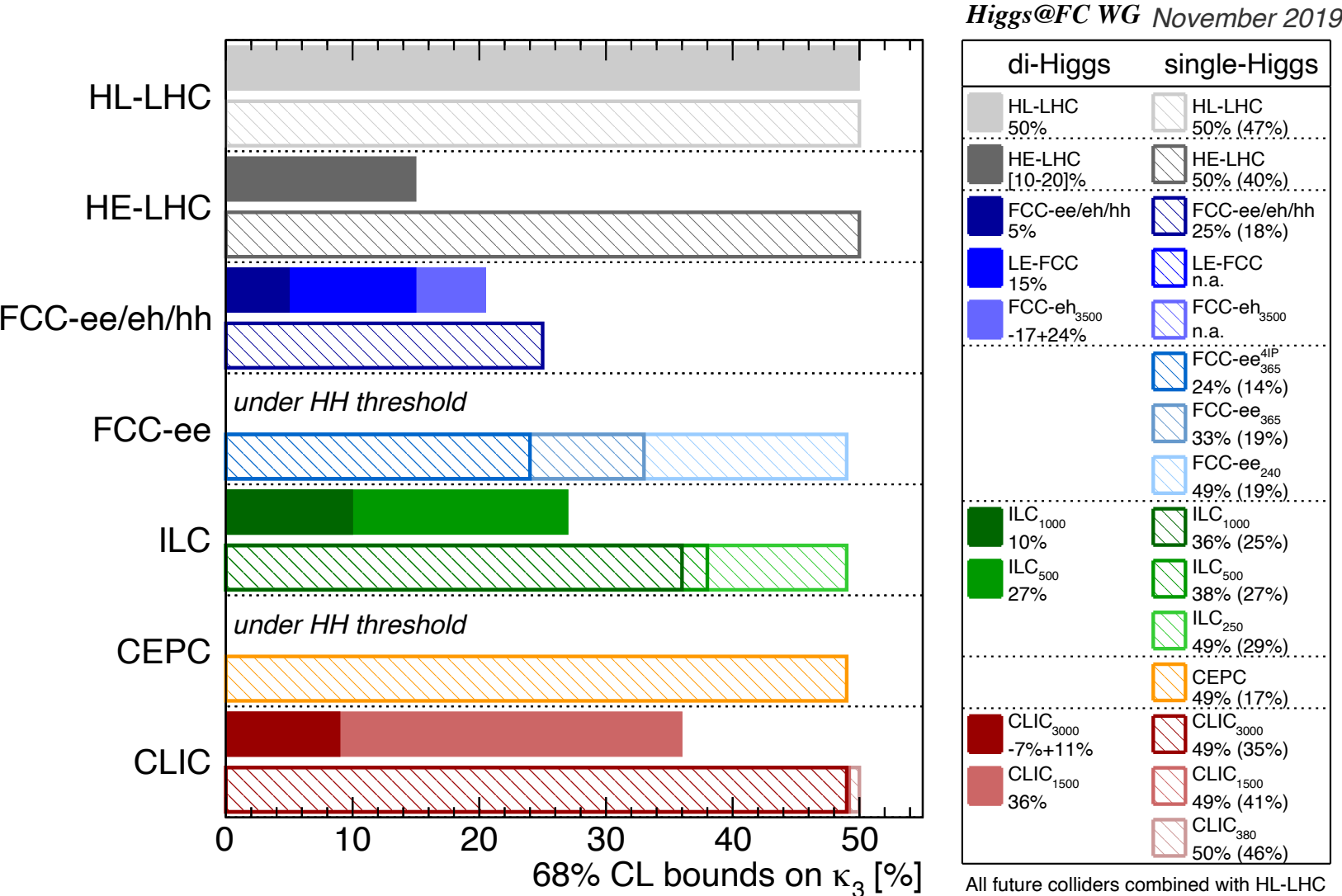


R. Petrossian-Byrne/N. Craig @ LCWS'23

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

Higgs self-coupling.

ECFA Higgs study group '19



1

Don't need to reach HH threshold to have access to h^3 .
Z-pole run is very important if the HH threshold cannot be reached

2

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

Precision measurement of y_t needs ee

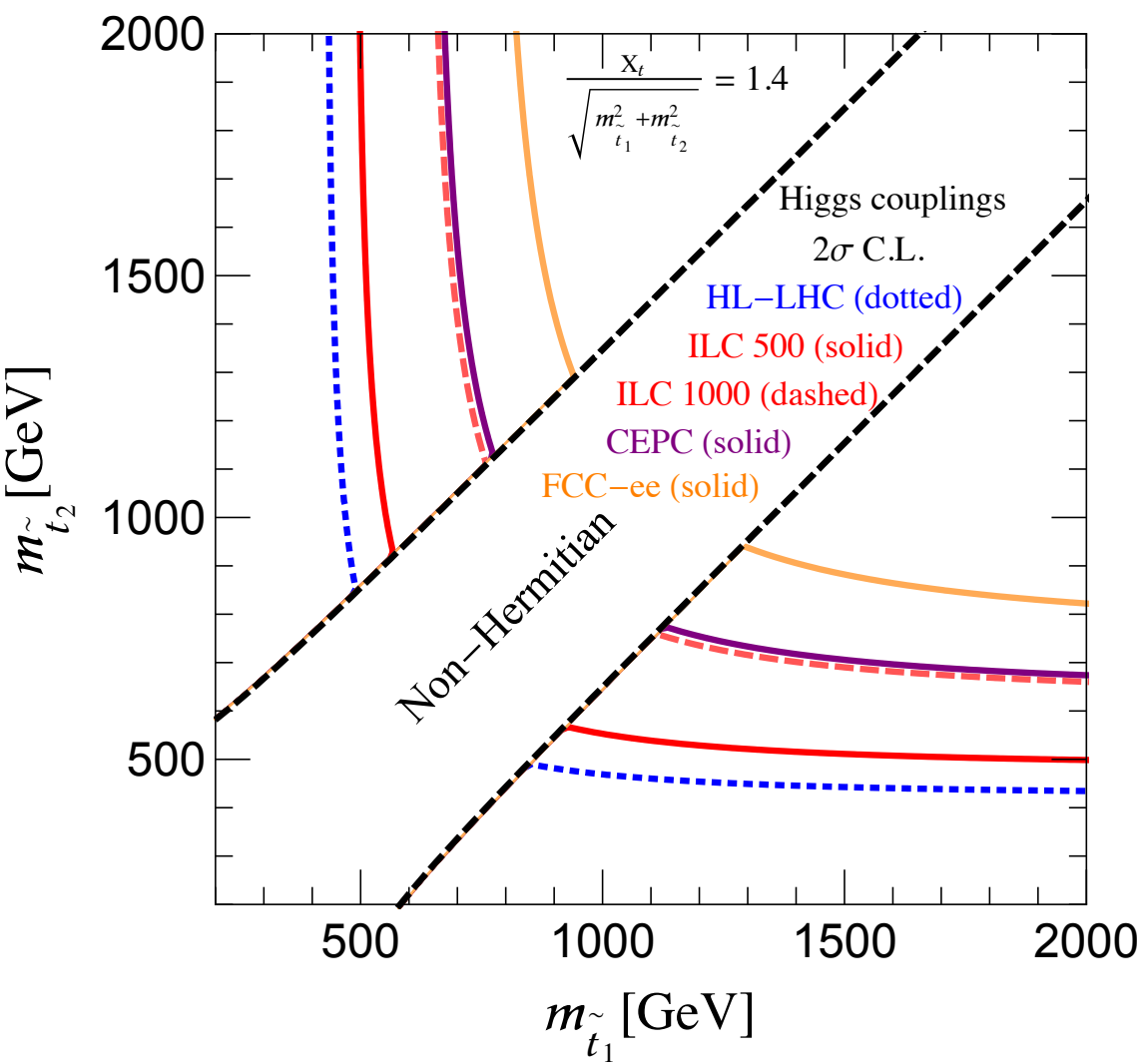
50% sensitivity: establish that $h^3 \neq 0$ at 95%CL
20% sensitivity: 5σ discovery of the SM h^3 coupling
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Discovery potential beyond LHC

Discovery Potential Beyond LHC.

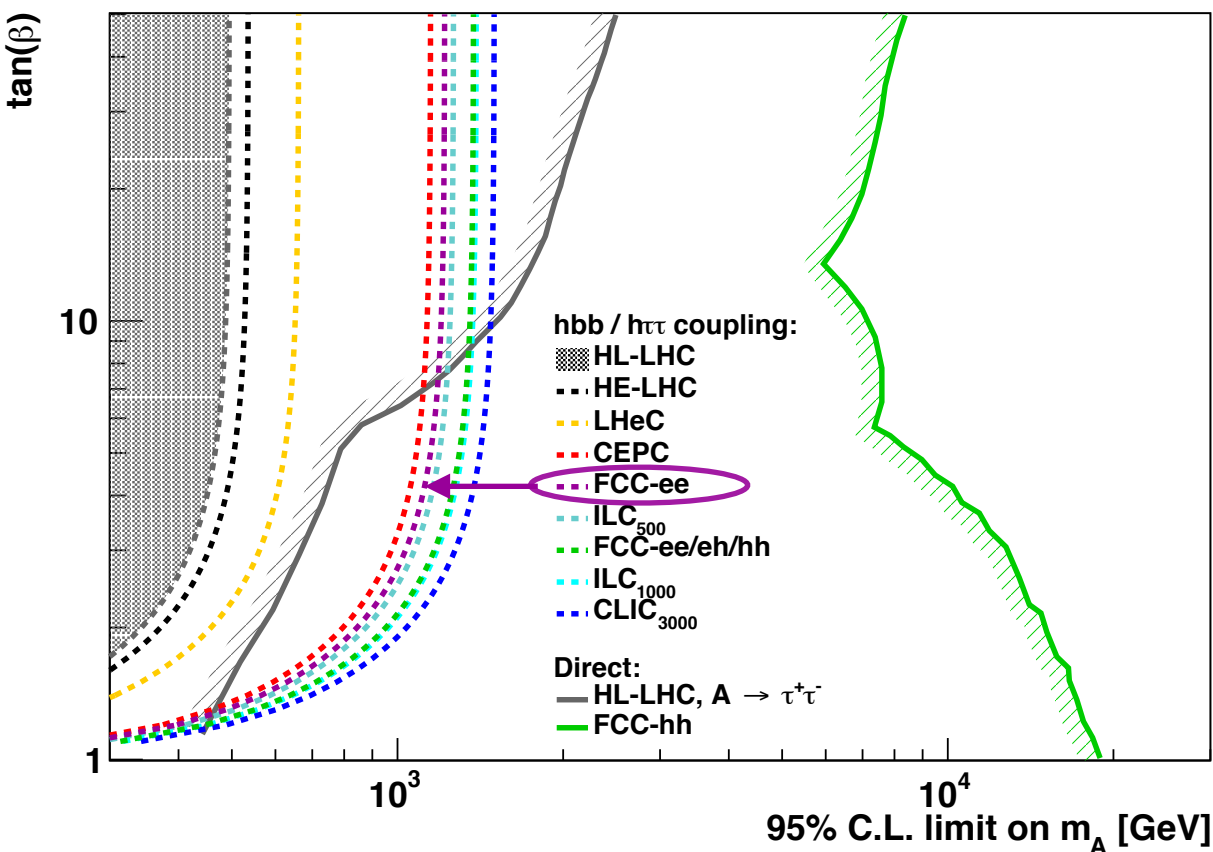
Precisely measured EW and Higgs observables are sensitive to heavy New Physics
Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY

stops



Fan, Reece, Wang '14

Heavy neutral Higgses



ESU Physics BB '19

Discovery Potential Beyond LHC.

Precisely measured EW and Higgs observables are sensitive to heavy New Physics
Examples of improved sensitivity wrt direct reach @ HL-LHC: Composite Higgs

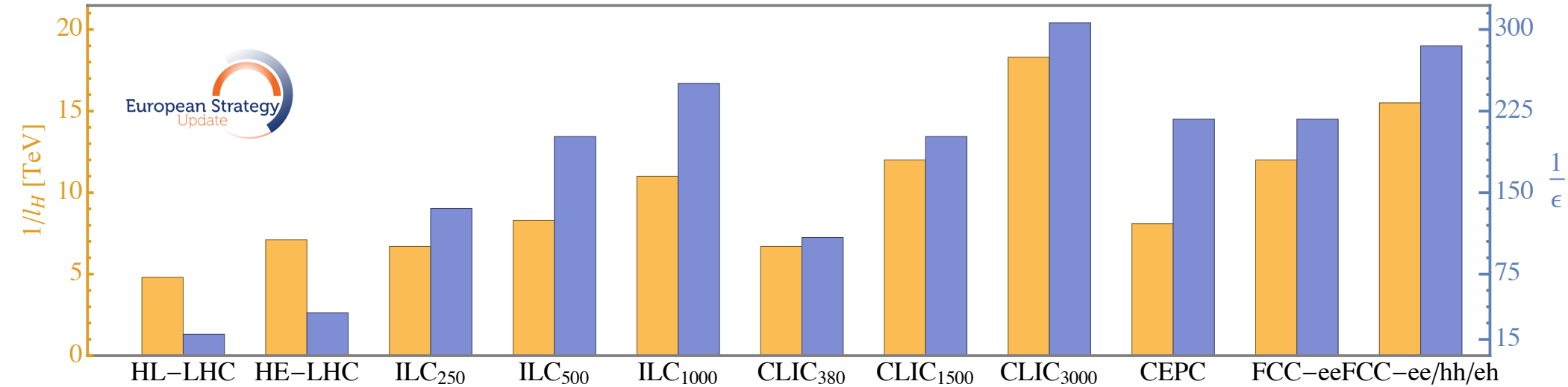
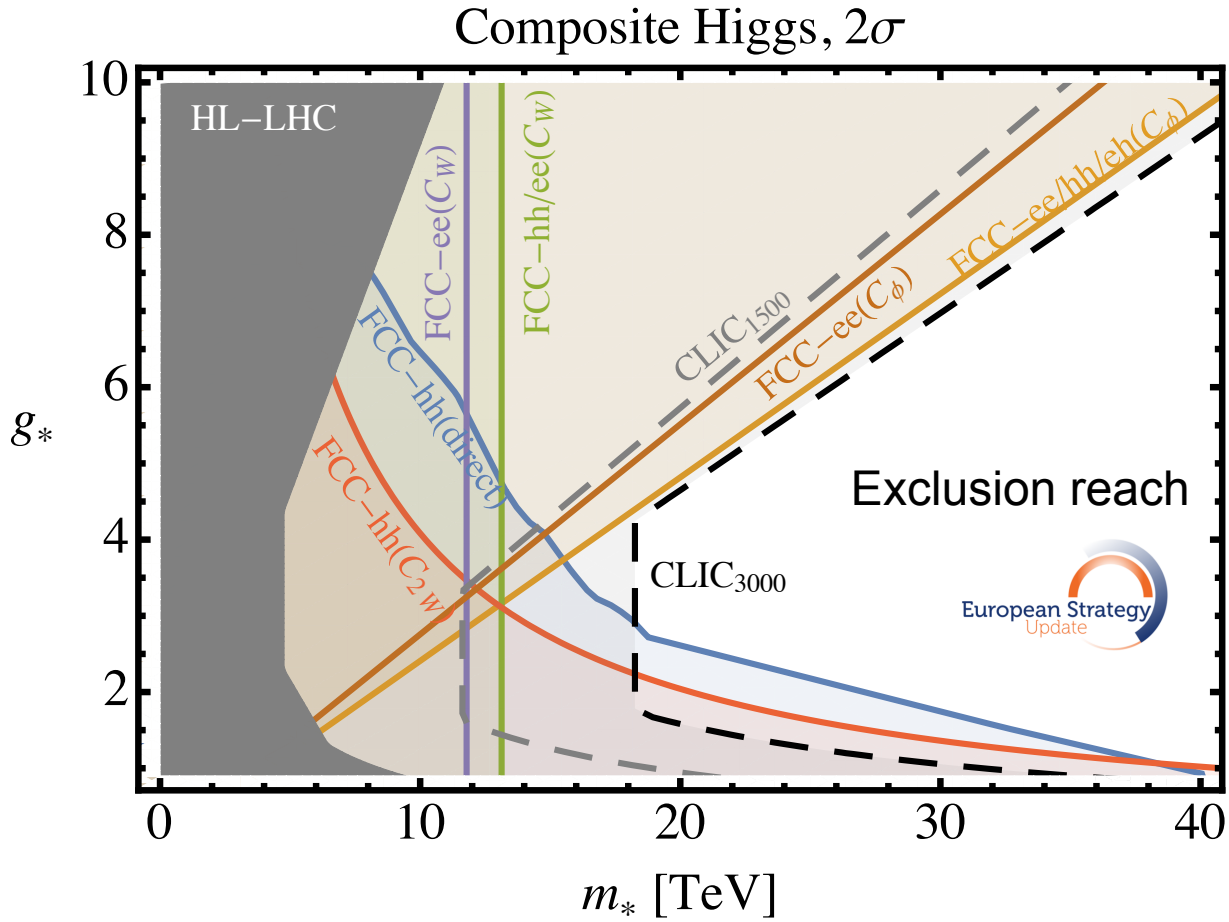
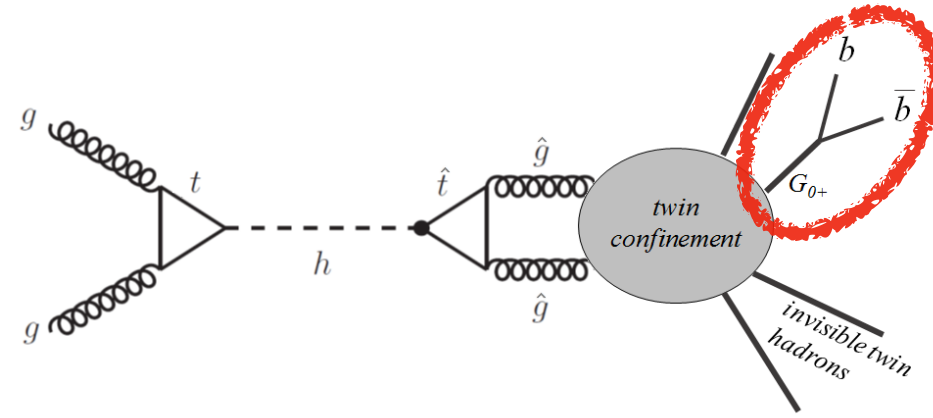


Fig. 8.5: Exclusion reach of different colliders on the inverse Higgs length $1/\ell_H = m_*$ (orange bars, left axis) and the tuning parameter $1/\epsilon$ (blue bars, right axis), obtained by choosing the weakest bound valid for any value of the coupling constant g_* .

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

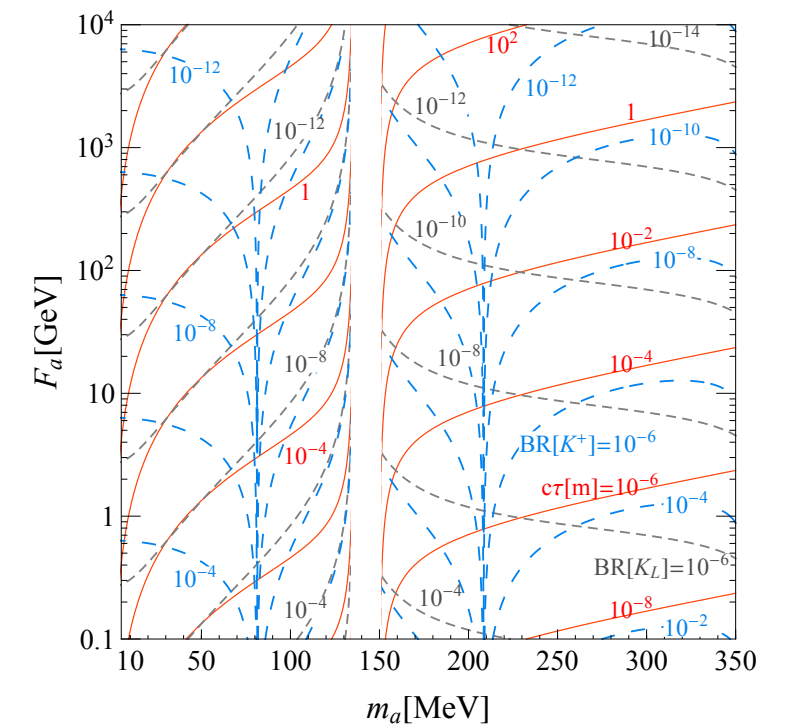


- **Rare decays** Gori et al arXiv:2005.05170
e.g. ALP mixing w/ SM mesons:

$$K_L \rightarrow \pi^0 a \rightarrow \pi^0 \gamma \gamma \text{ (KOTO)}$$

$$K^+ \rightarrow \pi^+ a \rightarrow \pi^+ \gamma\gamma \text{ (NA62)}$$

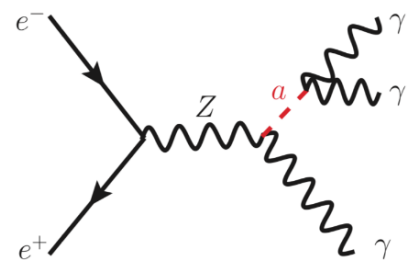
$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu} \tilde{G}^{\mu\nu}$$



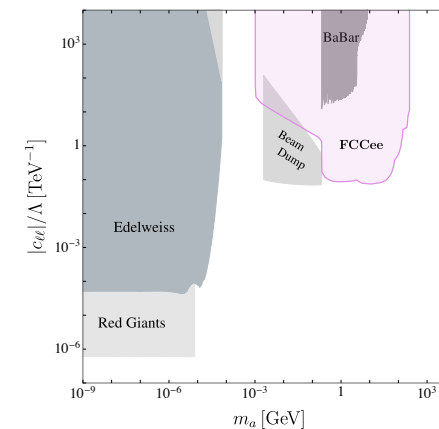
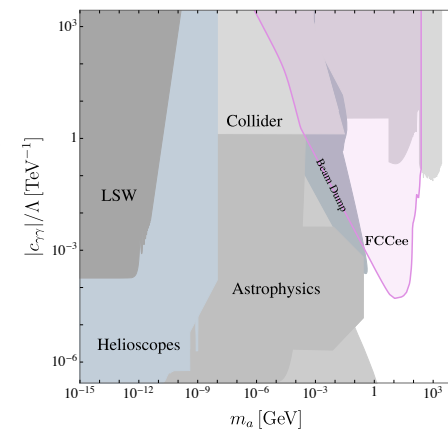
- **ALPs@ colliders**

e.g. $e^+e^- \rightarrow \gamma a$

$$e^+e^- \rightarrow ha$$

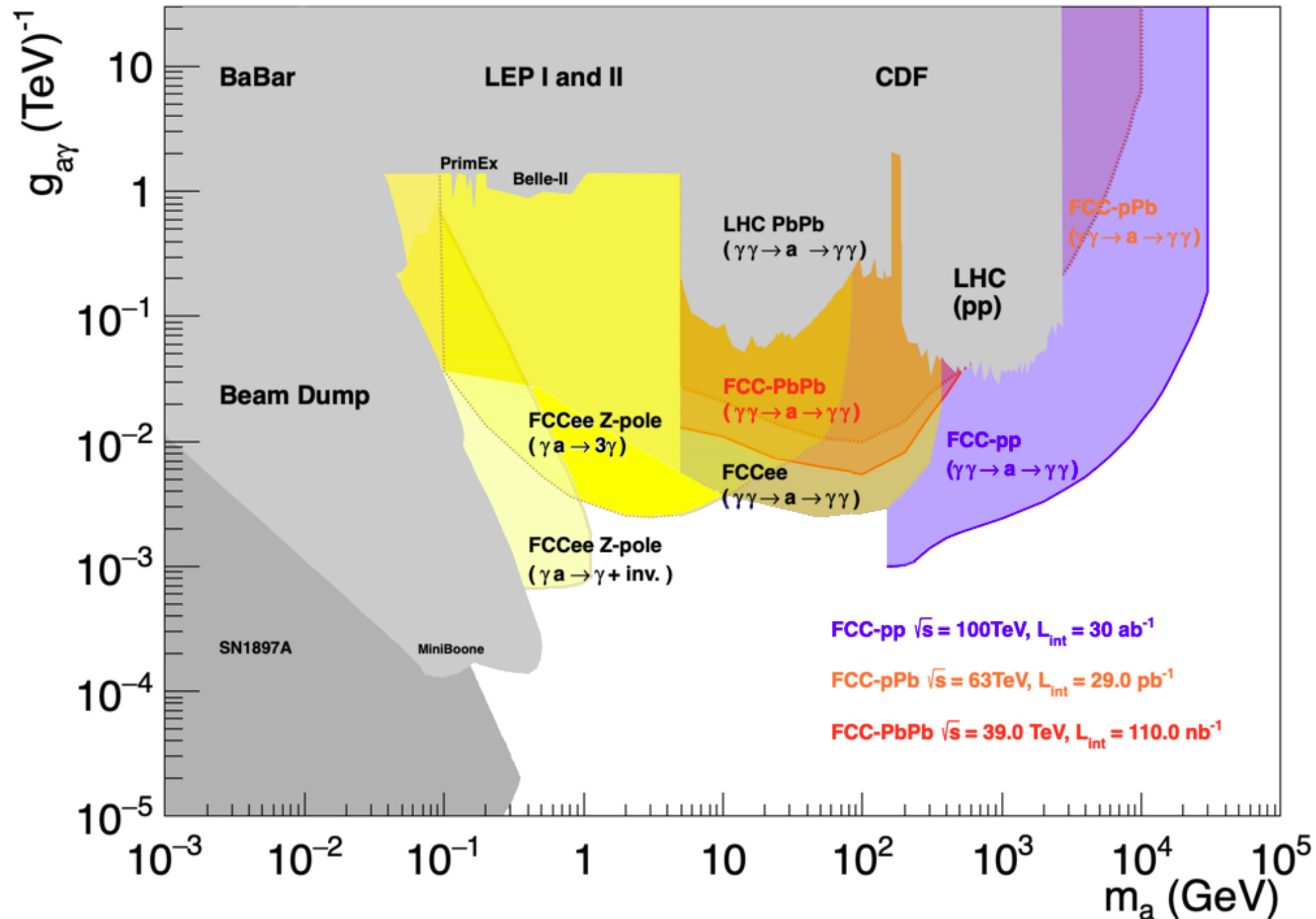


Knapen, Thamm arXiv:2108.08949



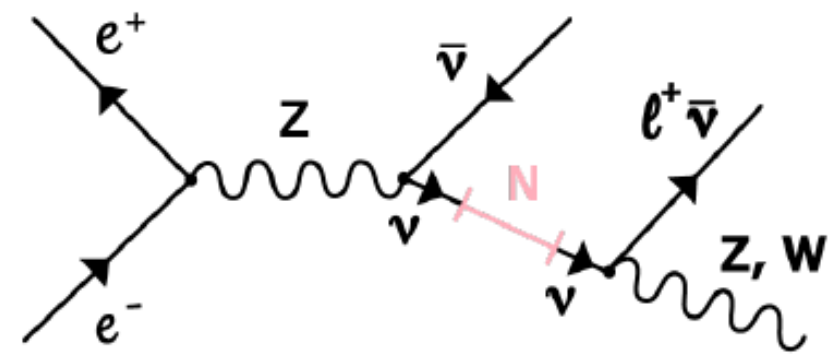
Astro/Cosmo \rightarrow long-lived ALPs
colliders \rightarrow short-lived ALPs MeV+

Direct Searches for ALPs

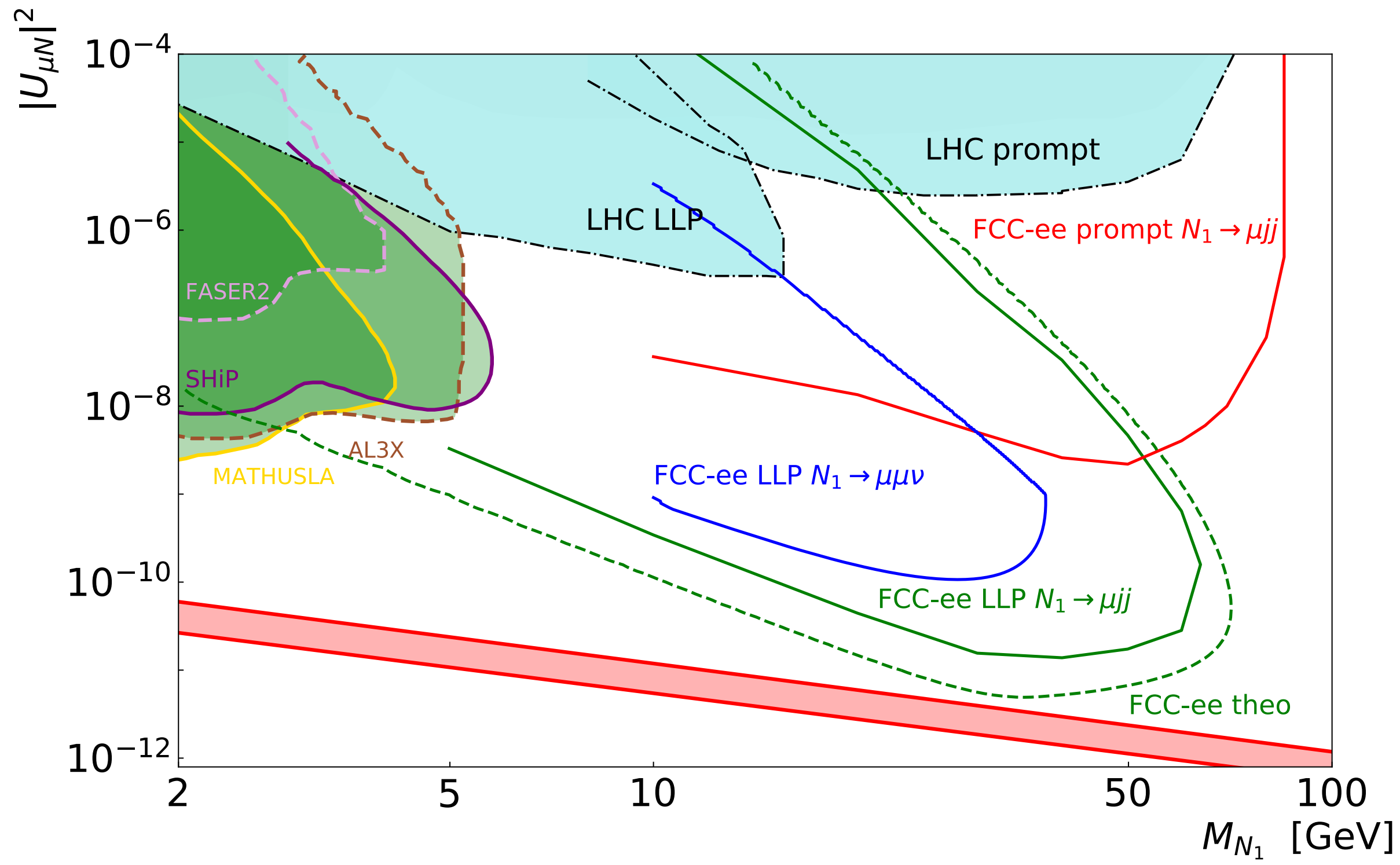


Search for ν_{RH} .

Direct observation
in Z decays
from LH-RH mixing

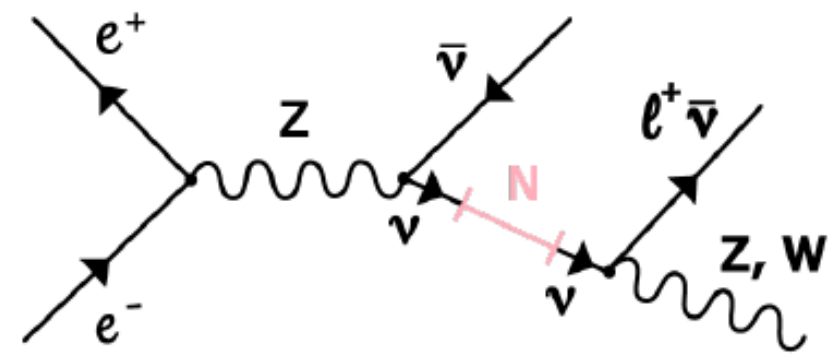


- Important to understand
1. how neutrinos acquired mass
 2. if lepton number is conserved
 3. if leptogenesis is realised

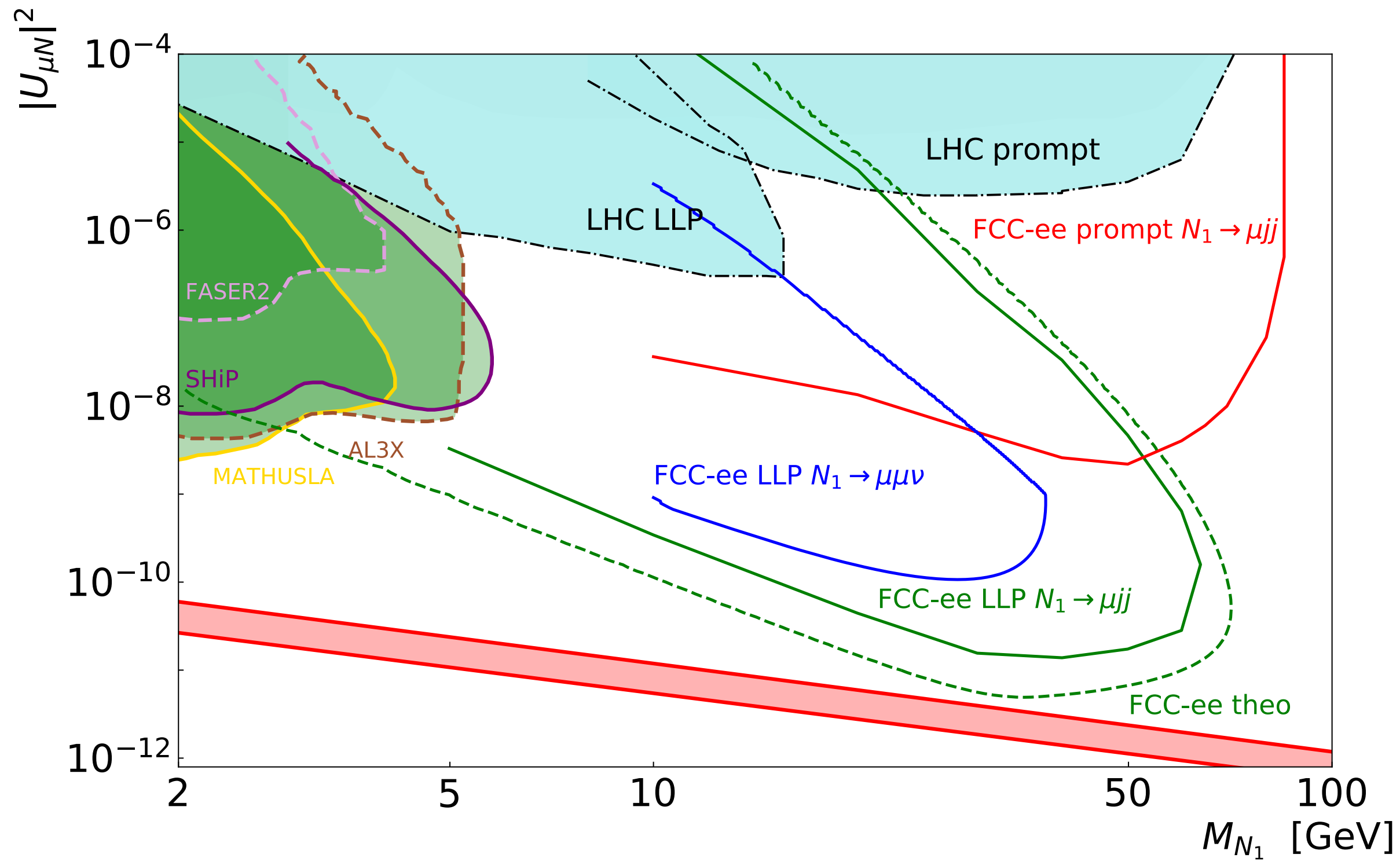


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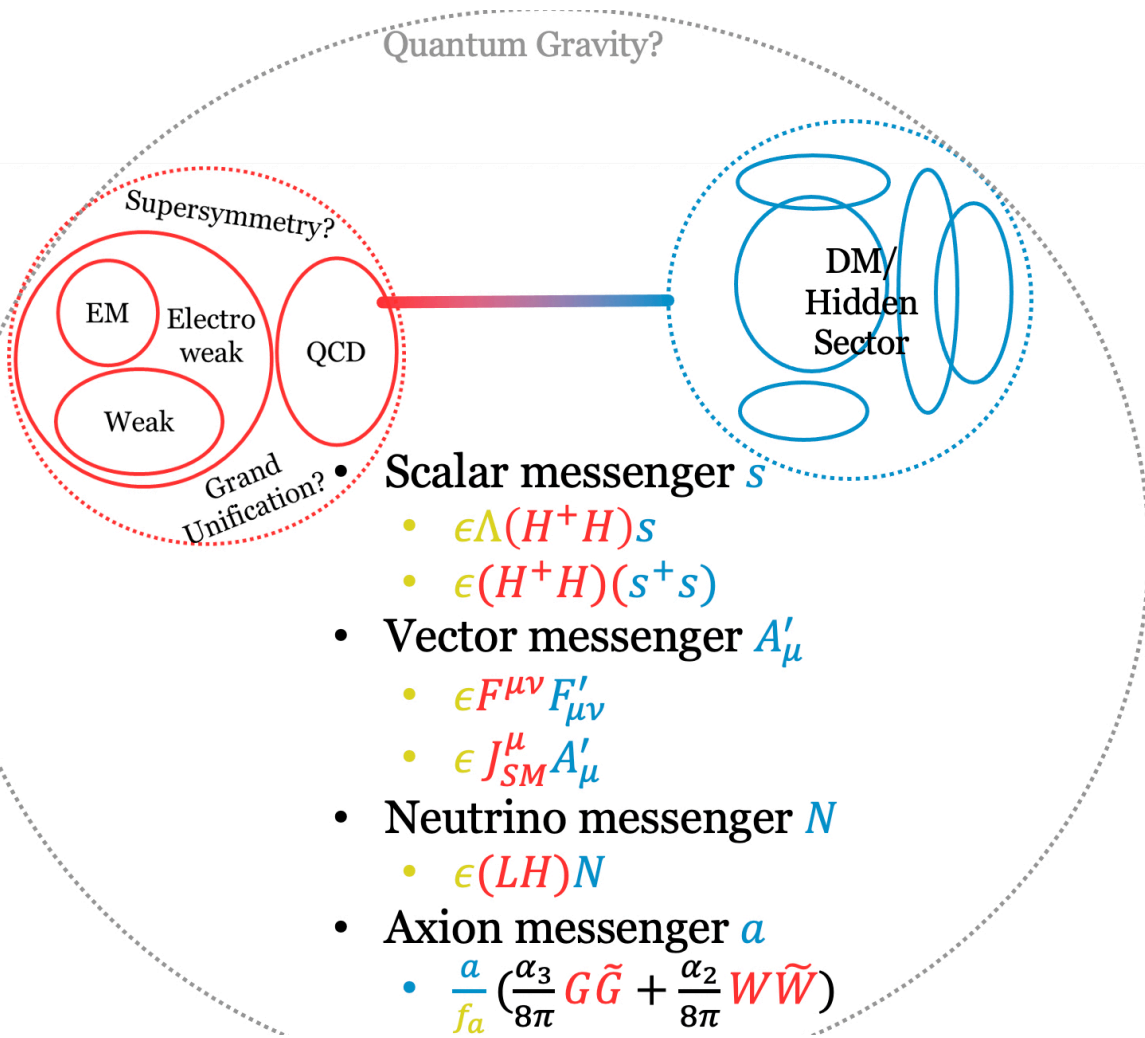
- Important to understand
1. how neutrinos acquired mass
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Exotics/Long Lived Particles.

Z. Liu @ CEPC 2020

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



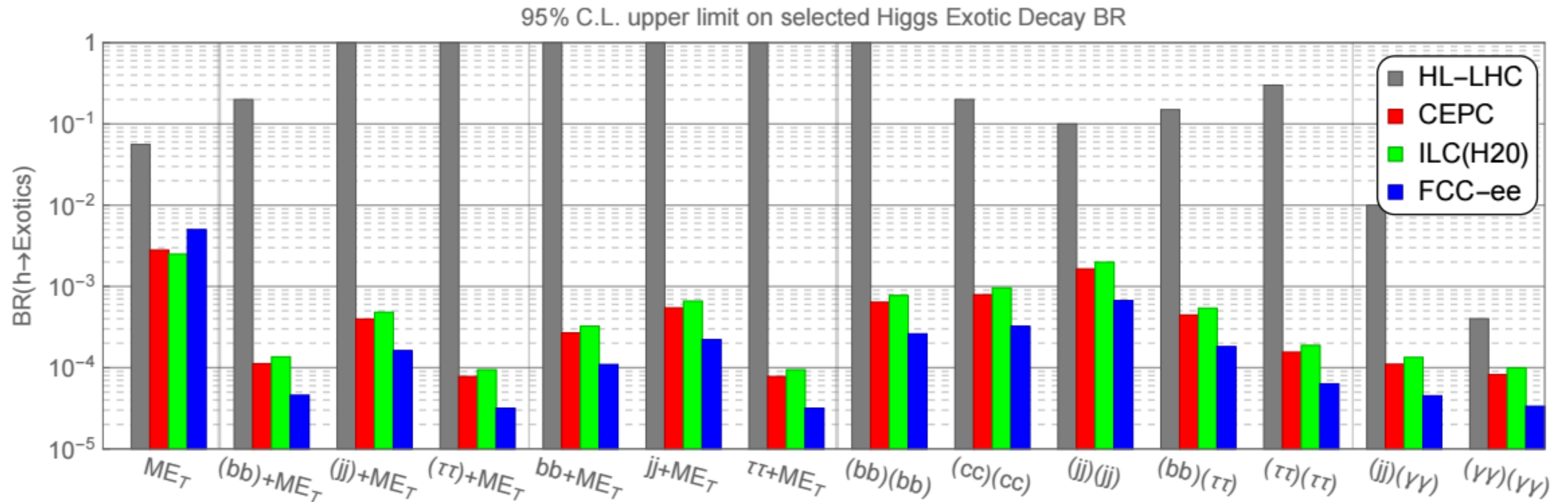
Decay Topologies	Decay mode \mathcal{F}_i	Decay Topologies	Decay mode \mathcal{F}_i
$h \rightarrow 2$	$h \rightarrow \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4$	$h \rightarrow (b\bar{b})(b\bar{b})$
$h \rightarrow 2 \rightarrow 3$	$h \rightarrow \gamma + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\tau^+ \tau^-)$
	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\mu^+ \mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\tau^+ \tau^-)(\tau^+ \tau^-)$
	$h \rightarrow (\tau^+ \tau^-) + \cancel{E}_T$		$h \rightarrow (\tau^+ \tau^-)(\mu^+ \mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (jj)(jj)$
	$h \rightarrow (\ell^+ \ell^-) + \cancel{E}_T$		$h \rightarrow (jj)(\gamma\gamma)$
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (jj)(\mu^+ \mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\ell^+ \ell^-)(\ell^+ \ell^-)$
	$h \rightarrow (\tau^+ \tau^-) + \cancel{E}_T$		$h \rightarrow (\ell^+ \ell^-)(\mu^+ \mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (\mu^+ \mu^-)(\mu^+ \mu^-)$
	$h \rightarrow (\ell^+ \ell^-) + \cancel{E}_T$		$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
	$h \rightarrow (\mu^+ \mu^-) + \cancel{E}_T$		$h \rightarrow \gamma\gamma + \cancel{E}_T$
$h \rightarrow 2 \rightarrow (1+3)$	$h \rightarrow b\bar{b} + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4 \rightarrow 6$	$h \rightarrow (\ell^+ \ell^-)(\ell^+ \ell^-) + \cancel{E}_T$
	$h \rightarrow jj + \cancel{E}_T$		$h \rightarrow (\ell^+ \ell^-) + \cancel{E}_T + X$
	$h \rightarrow \tau^+ \tau^- + \cancel{E}_T$		$h \rightarrow \ell^+ \ell^- \ell^+ \ell^- + \cancel{E}_T$
	$h \rightarrow \gamma\gamma + \cancel{E}_T$		$h \rightarrow \ell^+ \ell^- + \cancel{E}_T + X$
	$h \rightarrow \ell^+ \ell^- + \cancel{E}_T$		
		$h \rightarrow 2 \rightarrow 6$	

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](#)

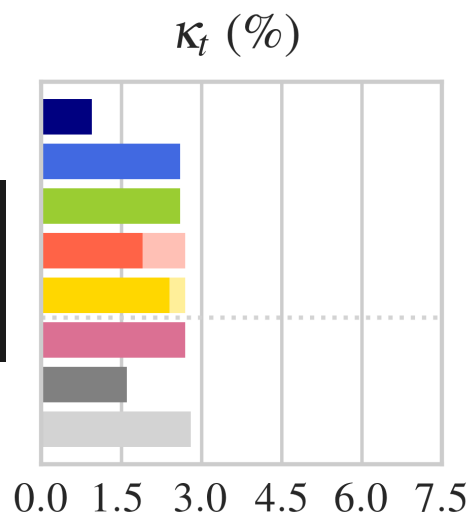
FCC-ee/FCC-hh Interplay

Synergy $ee \leftrightarrow hh$.

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 $t\bar{t}h/t\bar{t}Z$
So the extraction of top Yukawa heavily relies on the knowledge of $t\bar{t}Z$ from FCC-ee

Mangano+ '15

	$\sigma(t\bar{t}H)[\text{pb}]$	$\sigma(t\bar{t}Z)[\text{pb}]$	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
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 $t\bar{t}h$ is essential to determine h^3 at $O(5\%)$ at FCC-hh

