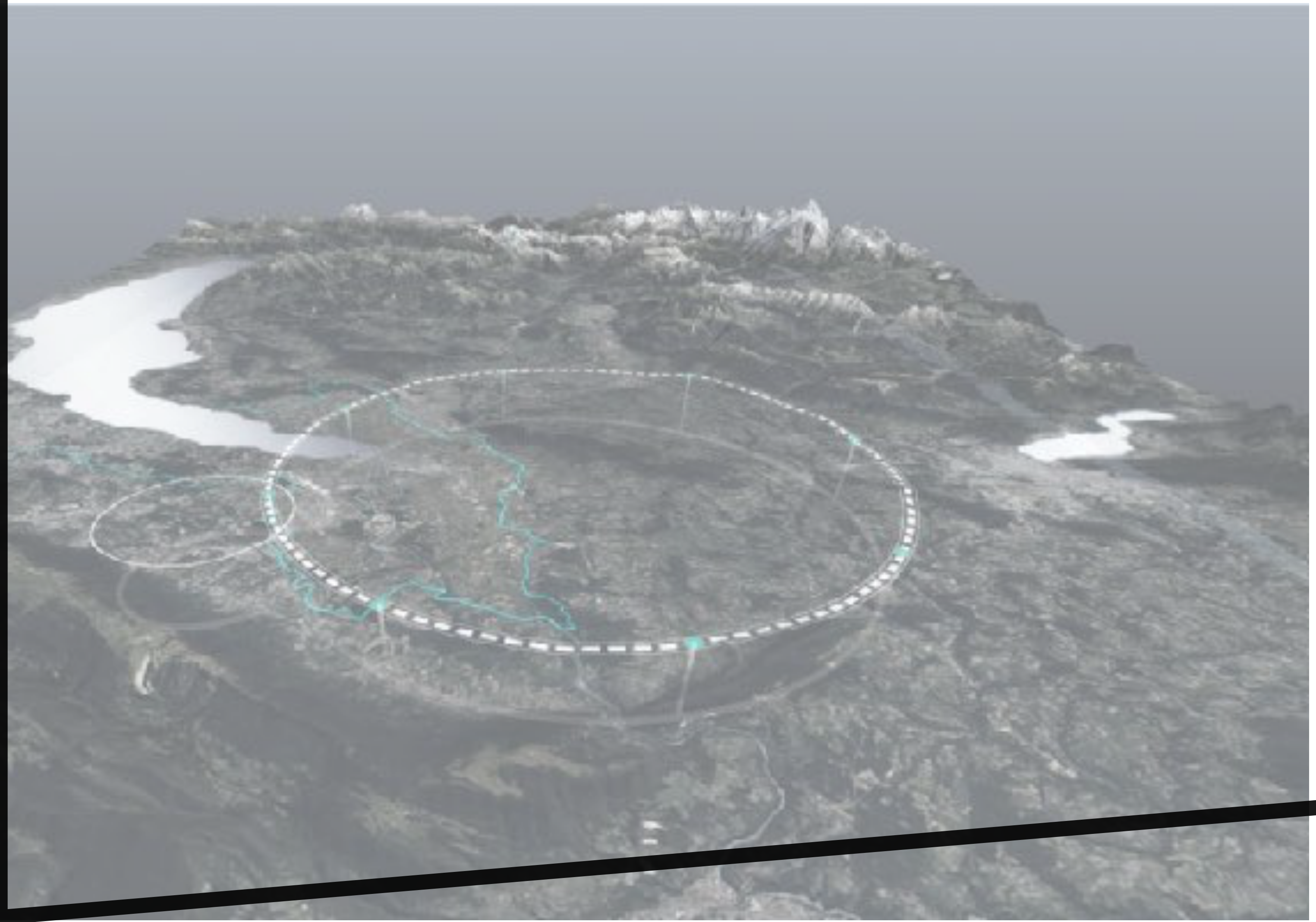
Future Circular Collider
— What? Why? When? —

Congrès de la Société Française de Physique, Troyes, 4 juillet 2025



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SCIENCES • PHYSIQUE

Les chercheurs du CERN dessinent leur plan de travail des prochaines années

Six cents scientifiques se sont réunis à Venise afin d'aider le conseil de l'Organisation pour la recherche nucléaire à trancher entre plusieurs options essentielles pour l'avenir européen de la physique des particules.

Par David Larousserie

Publié aujourd'hui à 16h30, modifié à 16h34 • Lecture 2 min.

July 4th, 13 years ago

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)

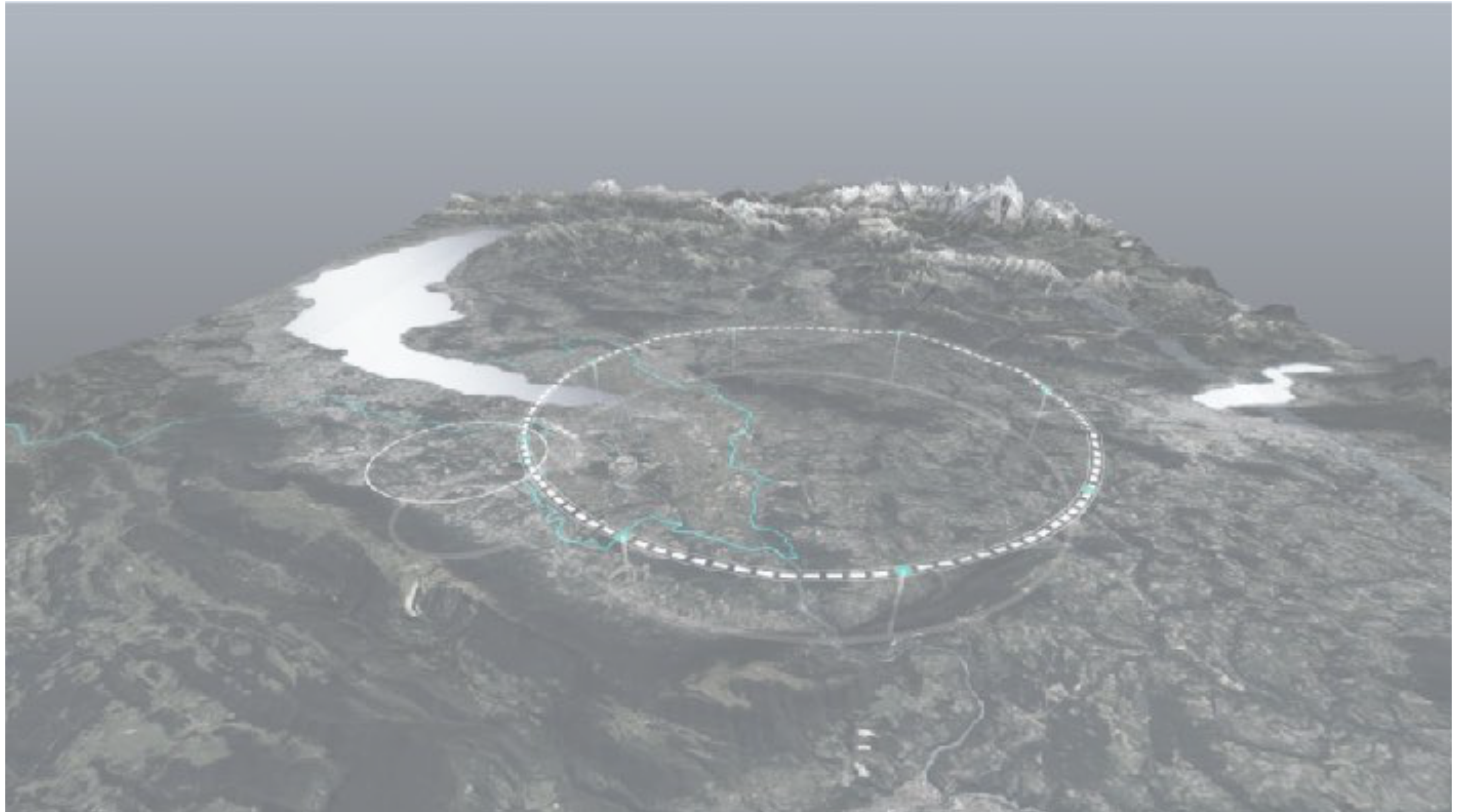
(LHC = Higgs + Nothing*) $\Rightarrow$ More energy & More precision

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 Future Circular Collider integrated programme fits the bill.

Future Circular Collider

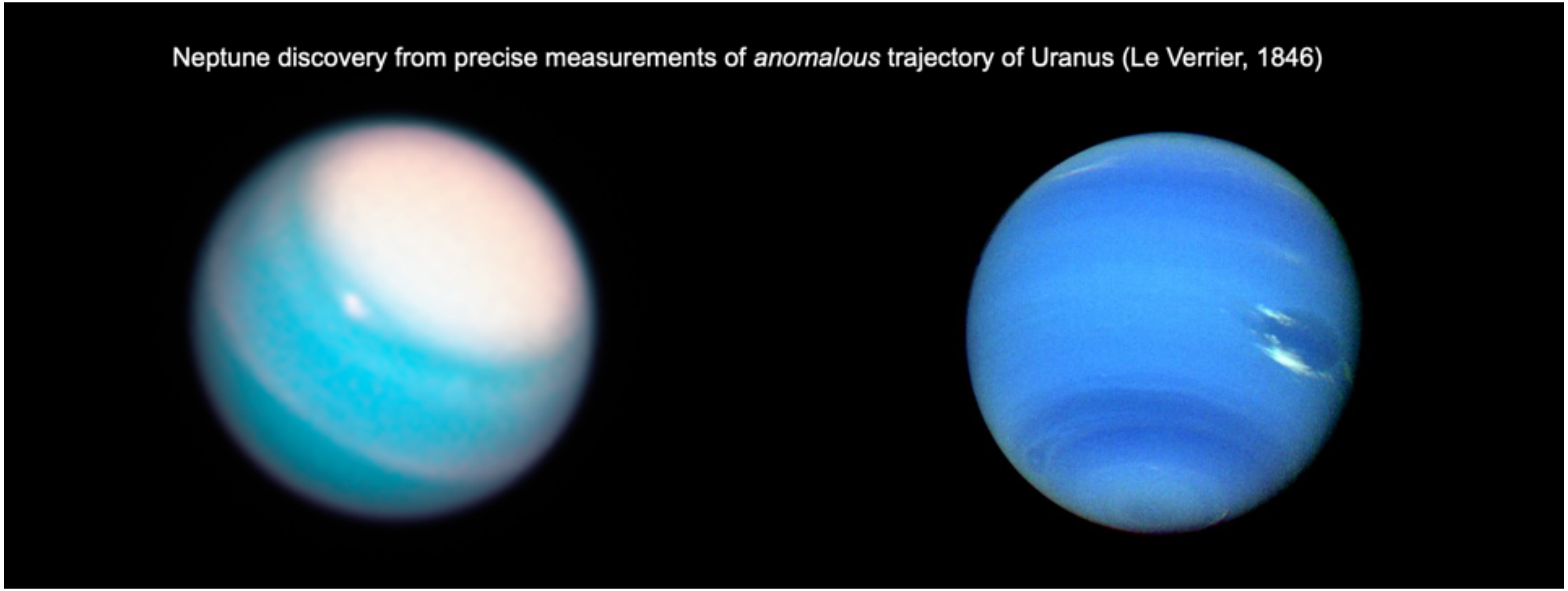
- A versatile particle collider, with four interaction poins, housed in a 200m-underground 91 km ring around CERN.
- Implemented in several stages:
  - an e^+e^- “Higgs/EW/Flavour/top/QCD” factory running at 90-365 GeV ▶ **FCC-ee**
  - followed by a high-energy pp collider reaching 100 TeV ▶ **FCC-hh**



Precision as a Discovery Tool

Many historical examples

- Uranus anomalous trajectory ⇢ Neptune



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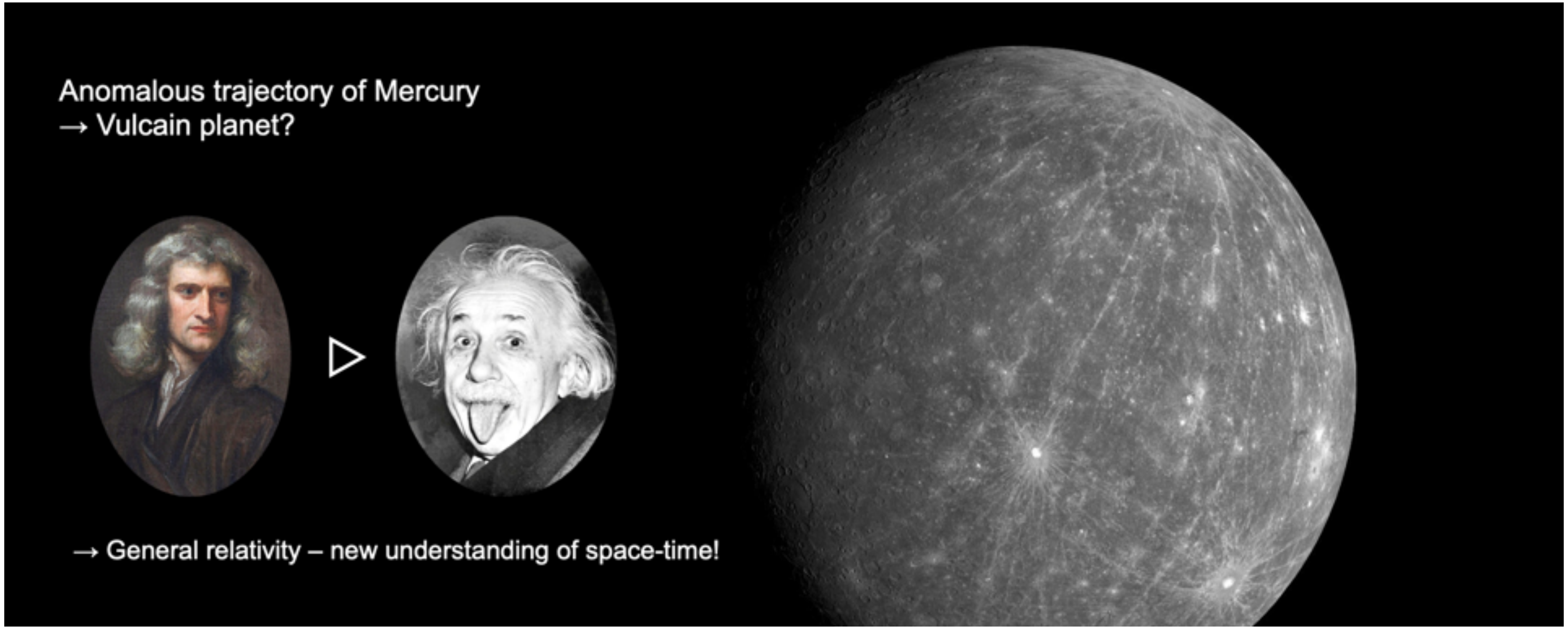

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- …

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

The Higgs Requires More Precision

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The knowledge of the values of the **Higgs couplings** is essential
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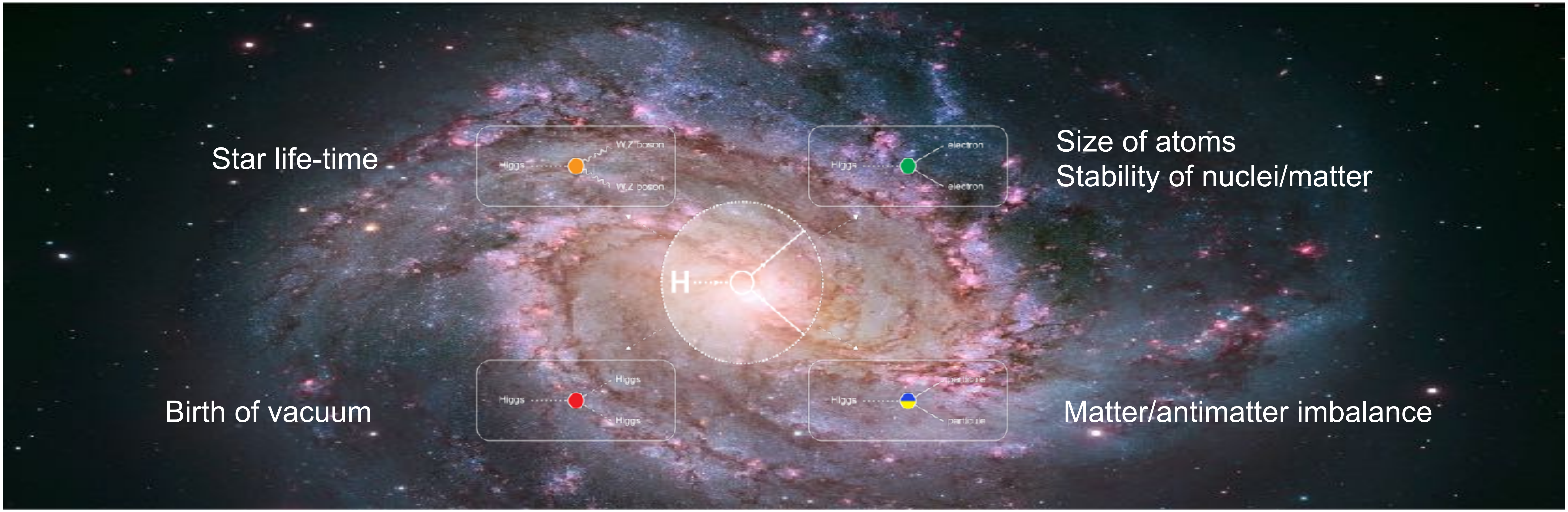

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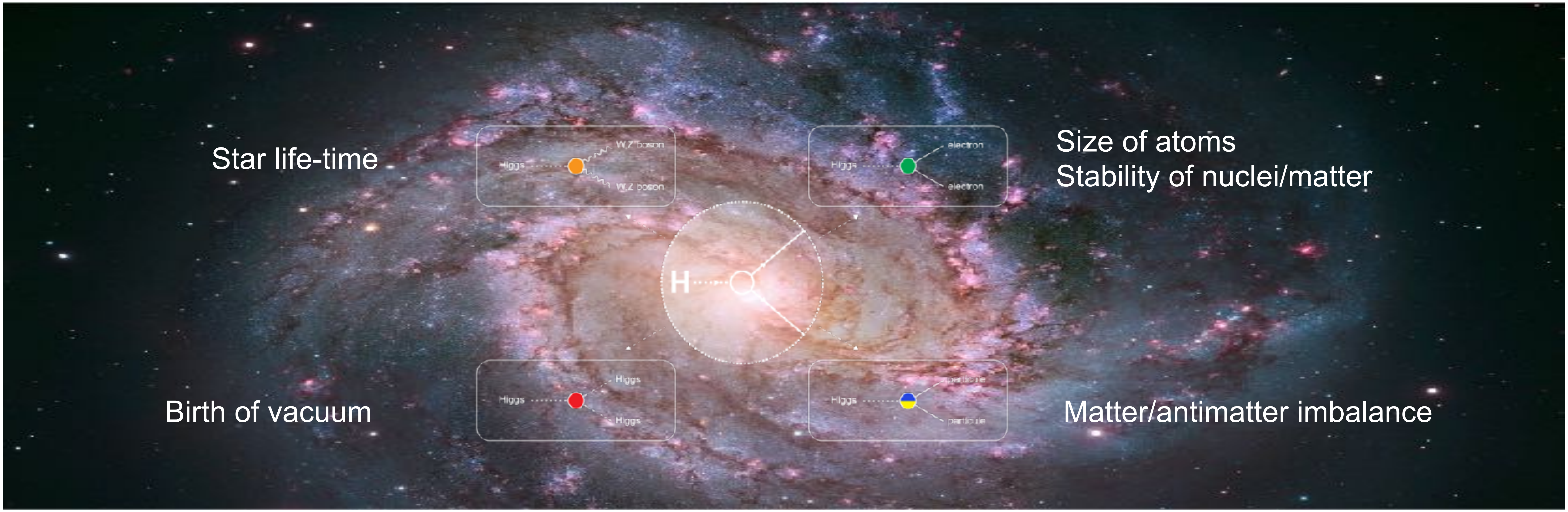

(HL)-LHC will make remarkable progress
(O(100M) Higgs=already a Higgs Factory).
But it won't be enough.
A new collider is needed!

The Higgs Requires More Precision

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

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

Broad FCC-ee programme is key to success.

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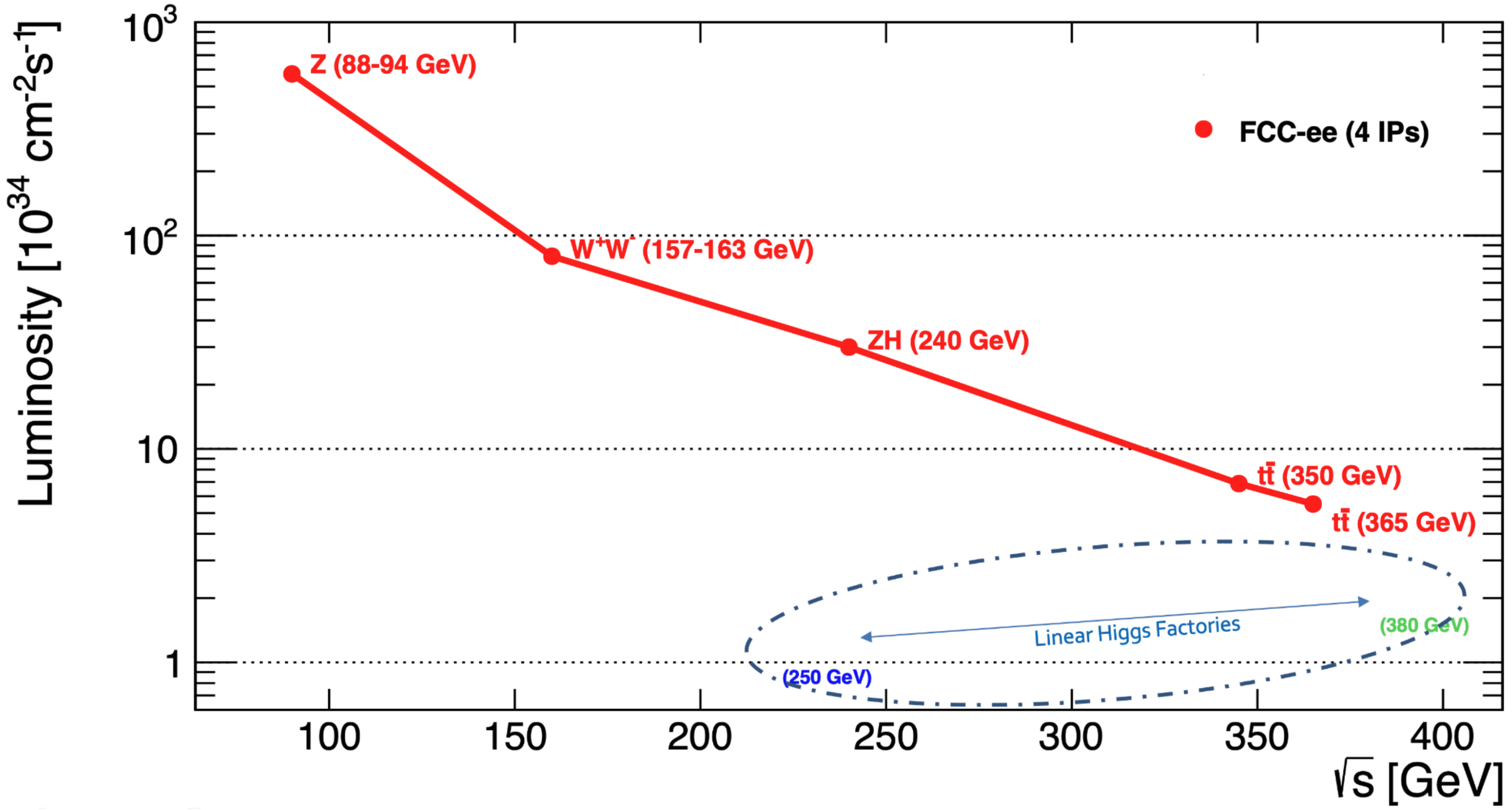
Herwig Schopper in CERN Courier:
"It is almost forgotten that the LEP tunnel size was only chosen in view of the LHC."
(While LEP didn't benefit from LHC, FCC-ee will benefit from FCC-hh.)

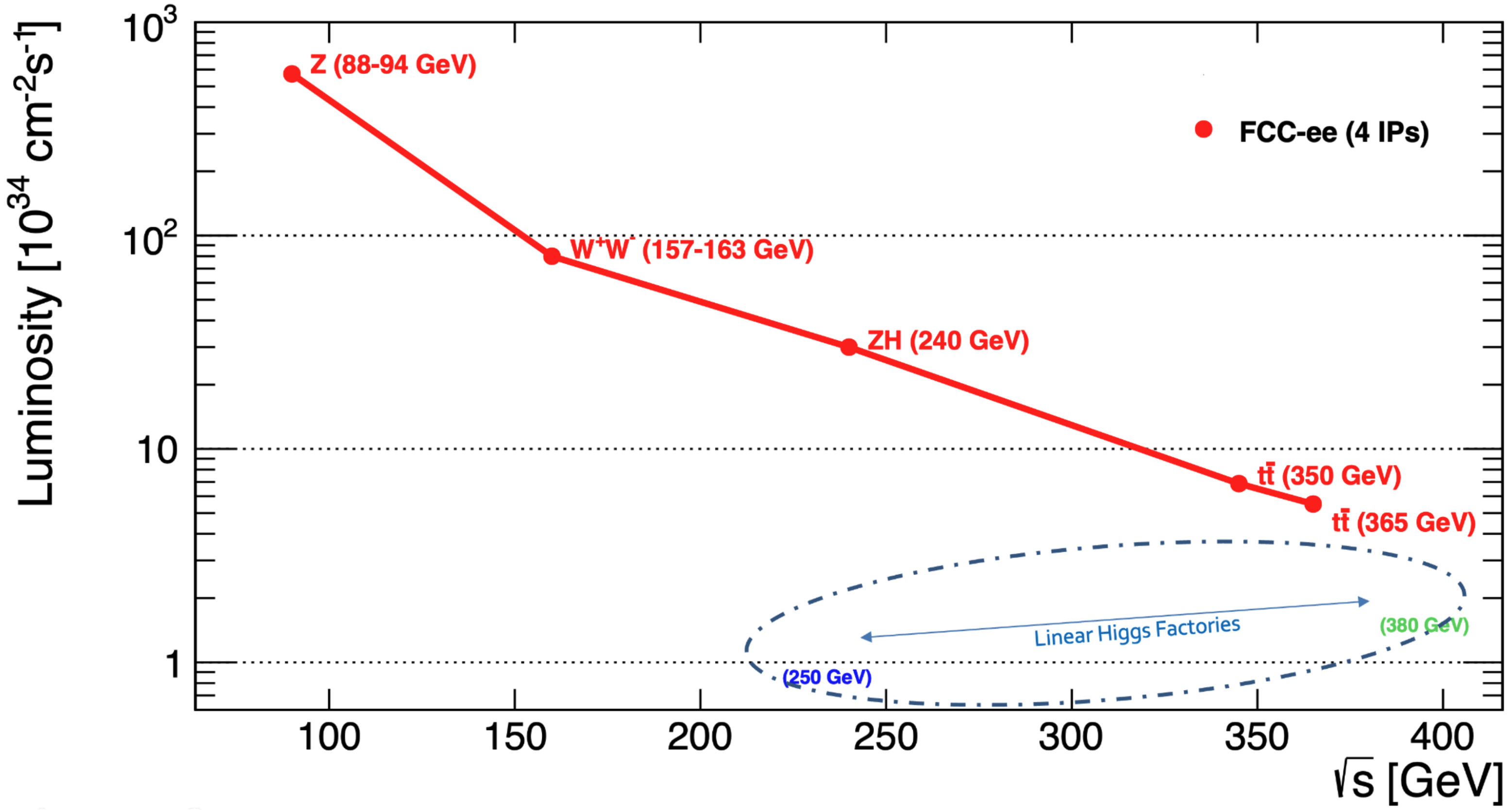
FCC-ee Run Plan



FCC-ee Run Plan

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

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



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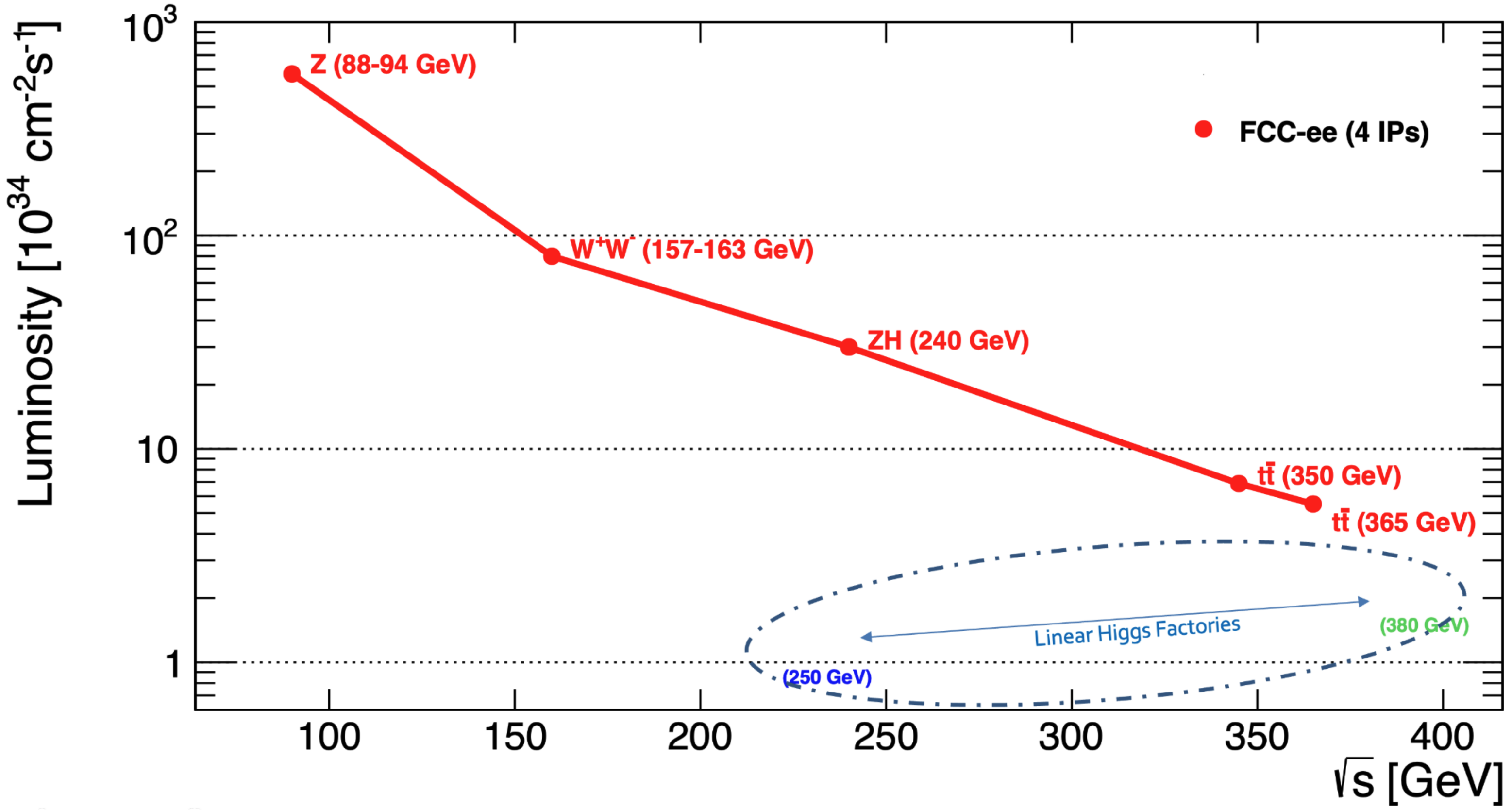

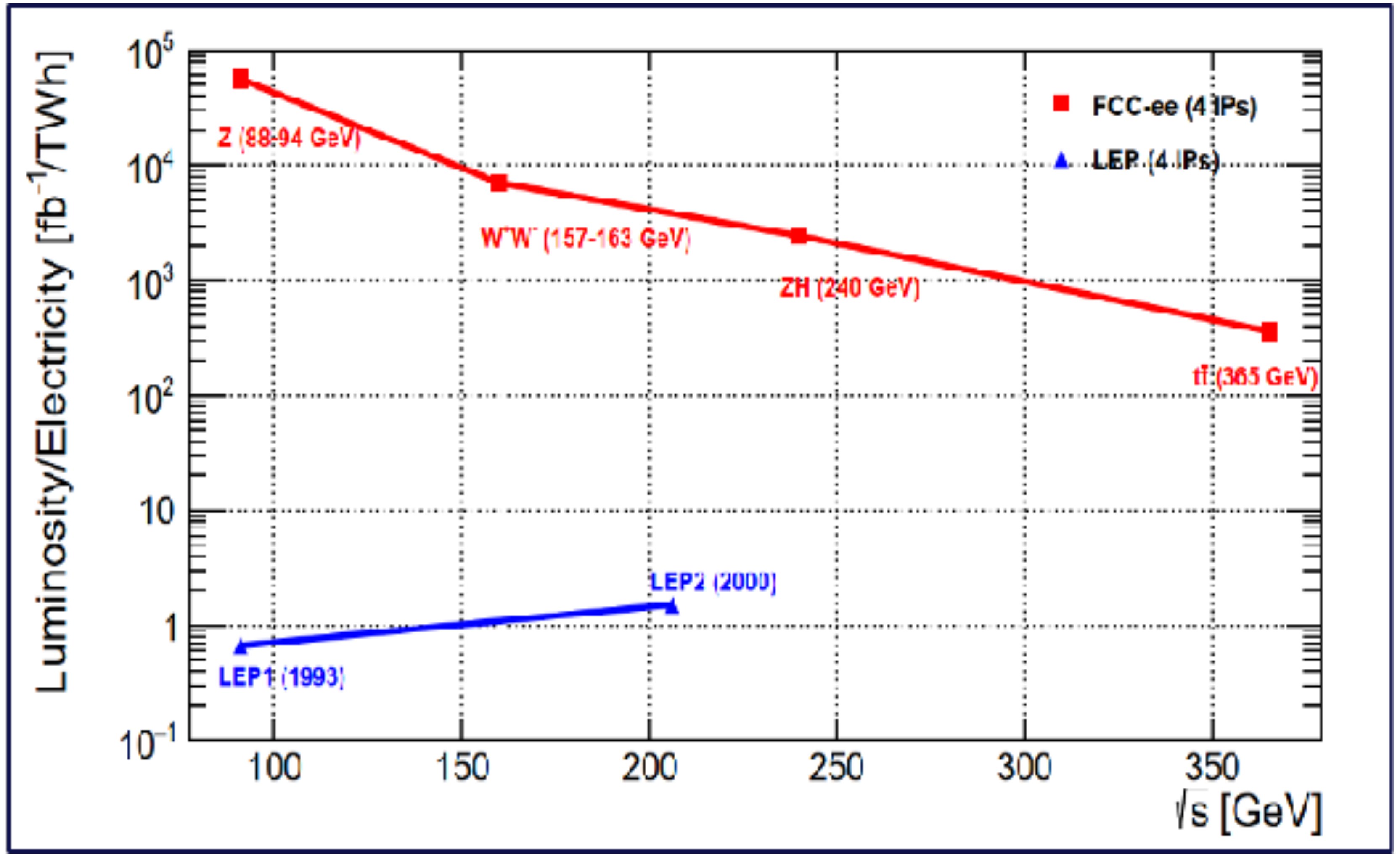

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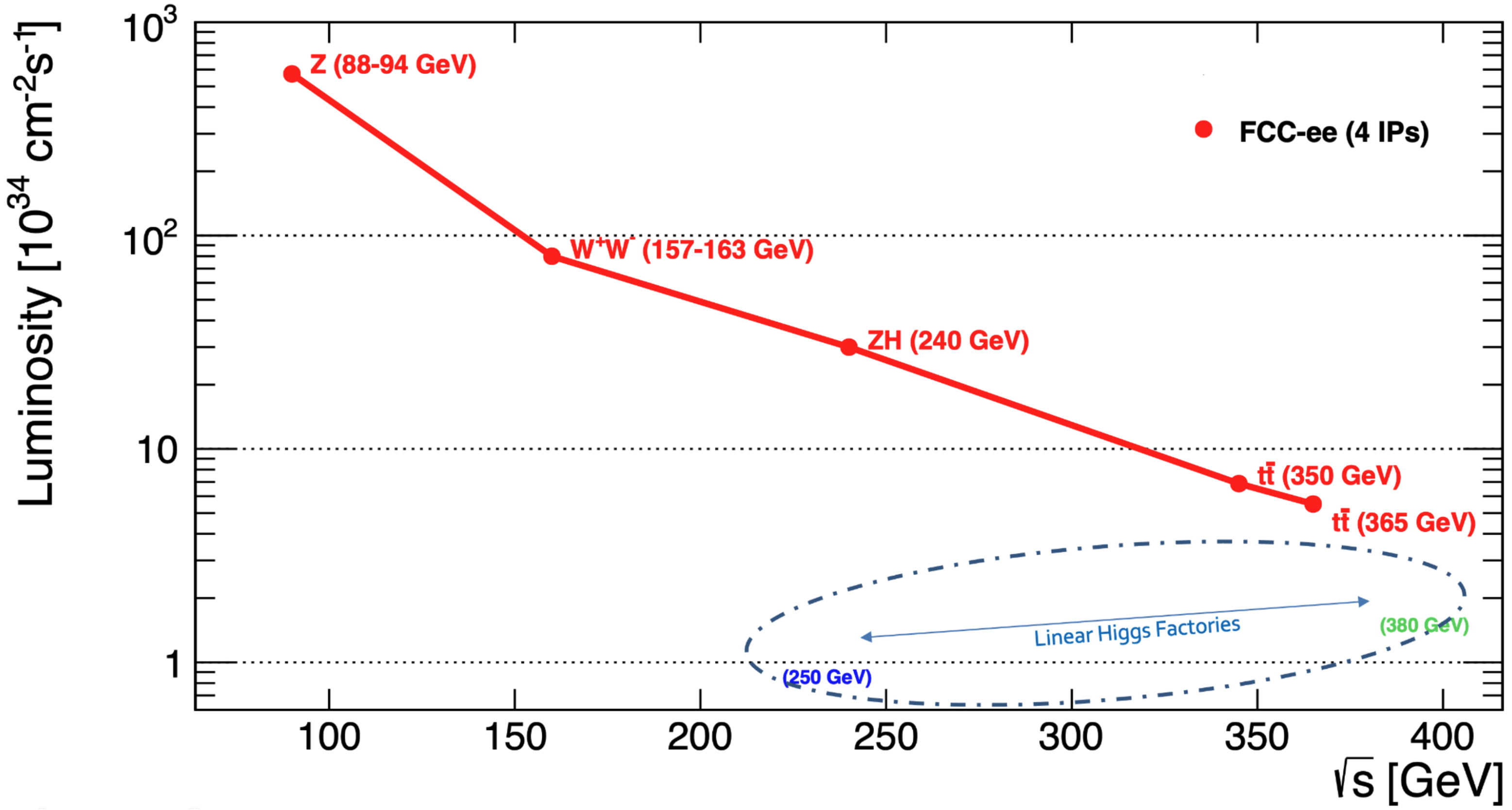

— Superb statistics achieved in only 15 years —

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

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

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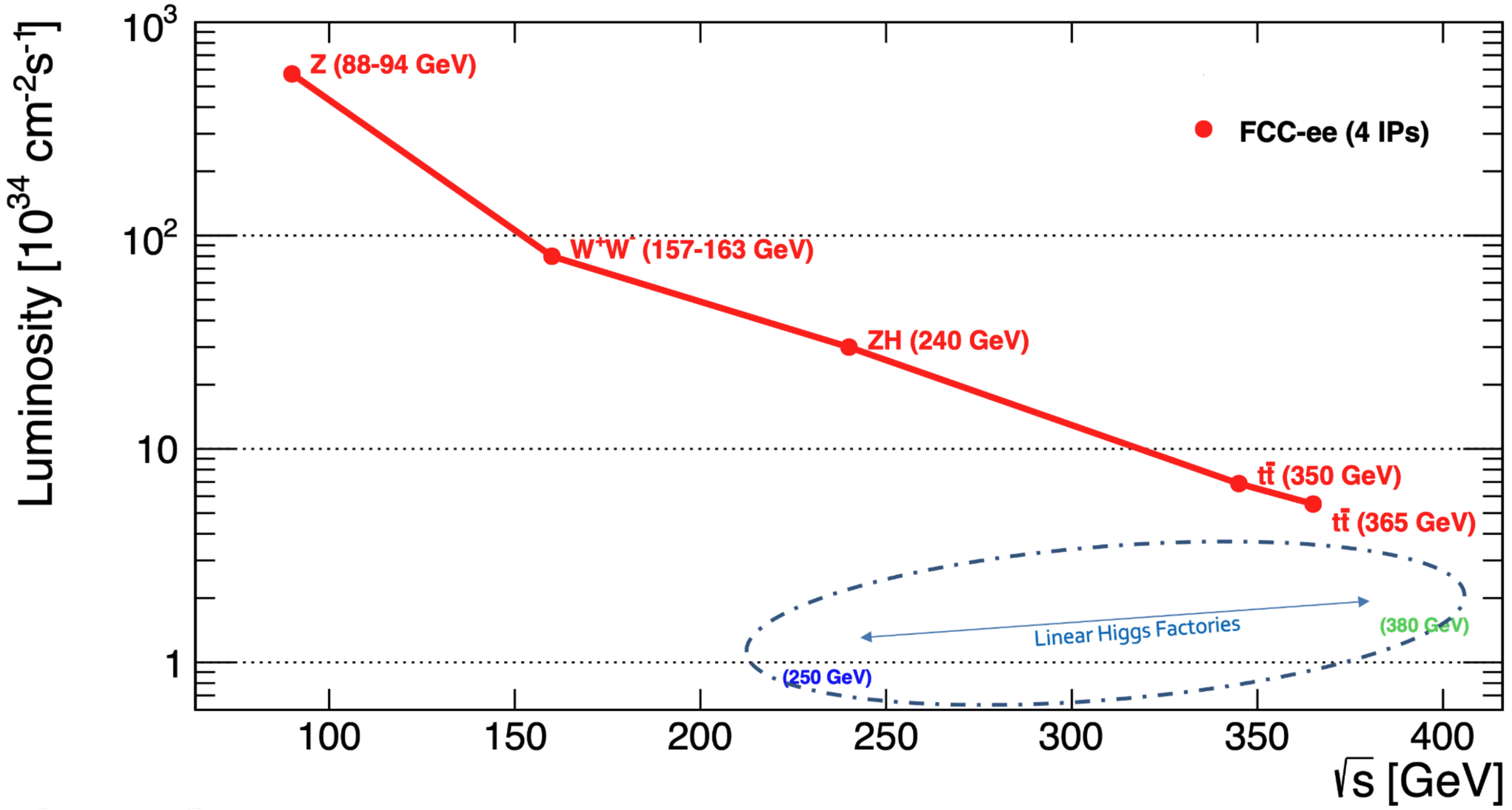

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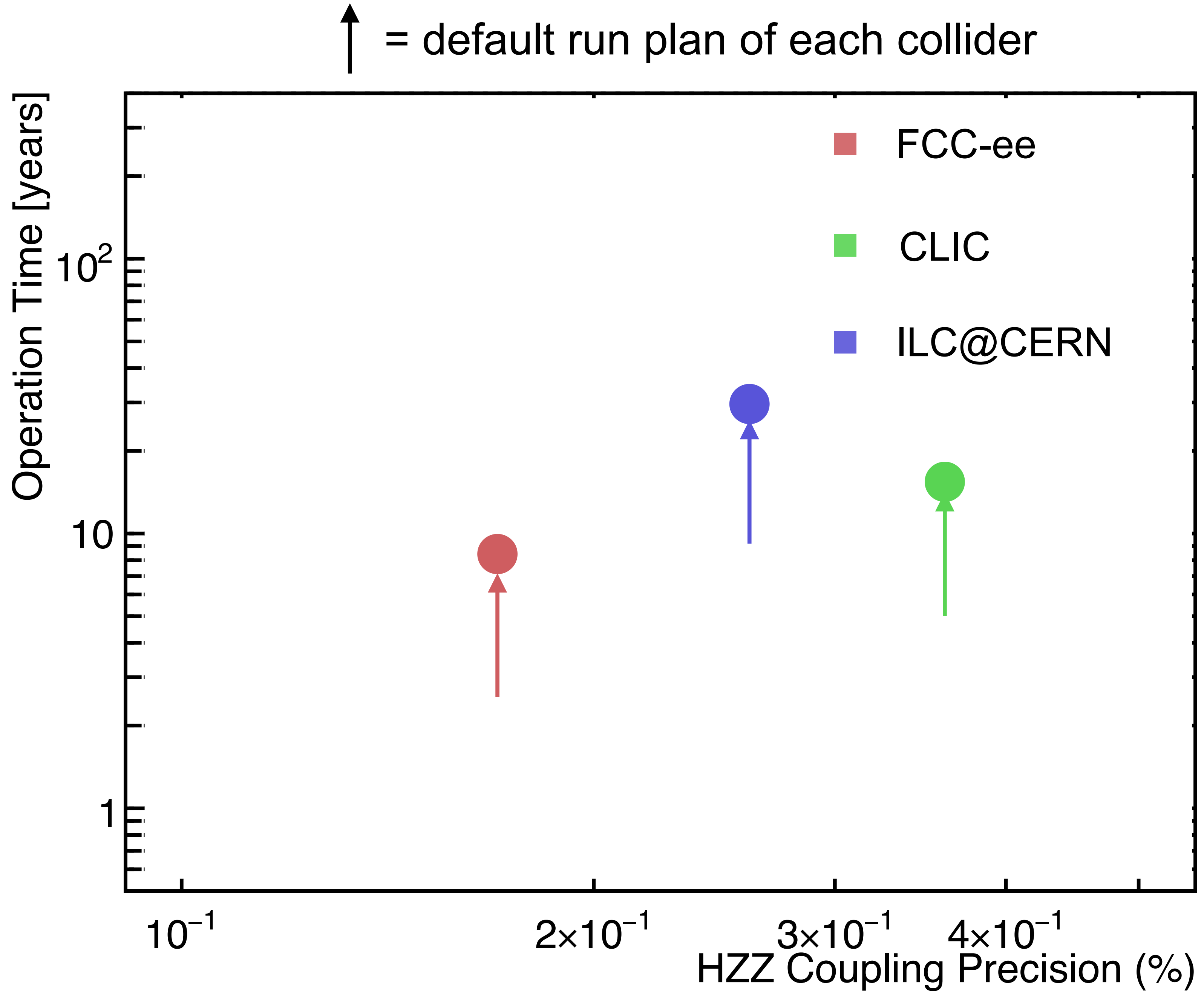
Exciting & diverse programme with different priorities every few years.

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.

A Performant Higgs Programme



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

arXiv:2412.13130

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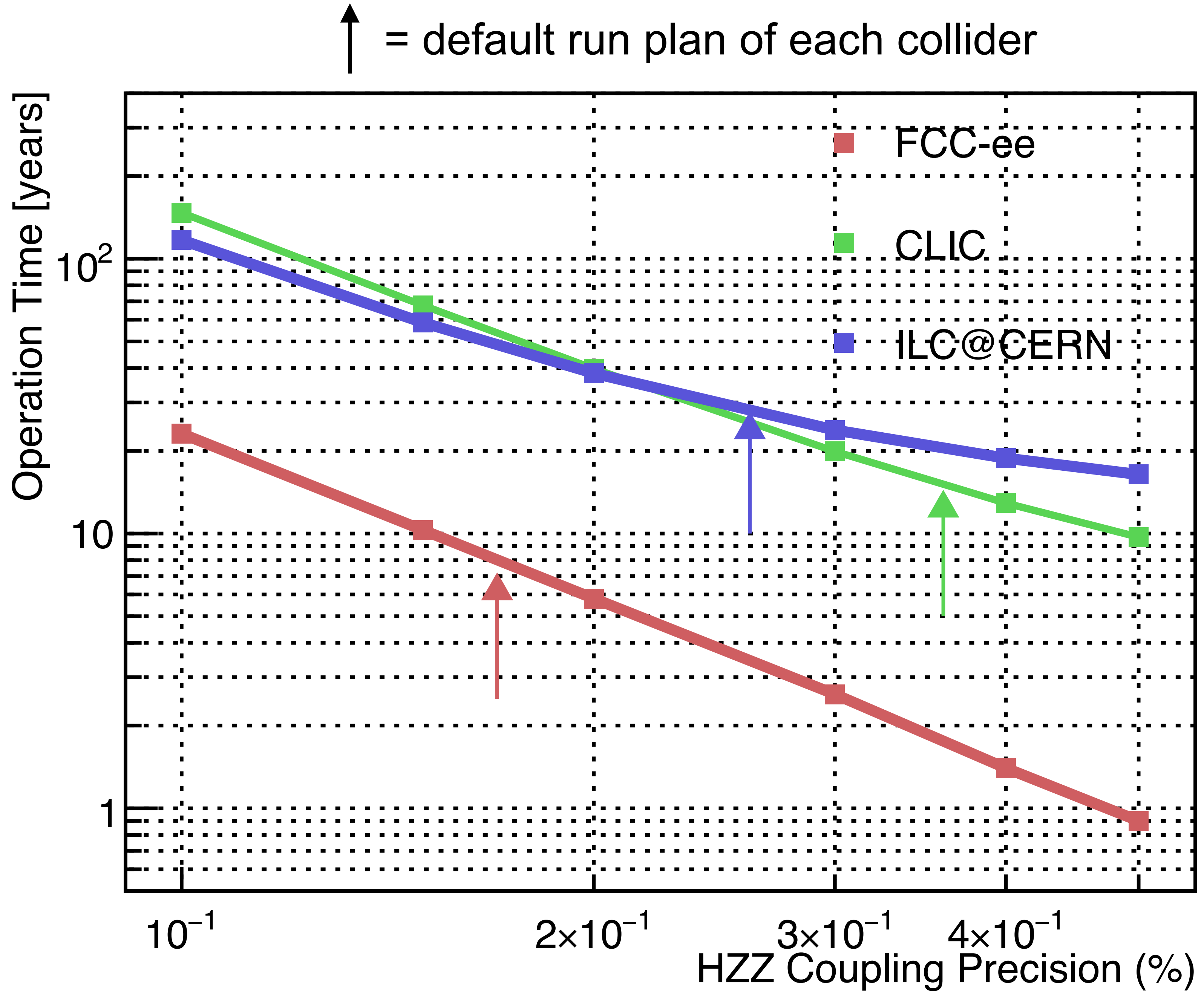

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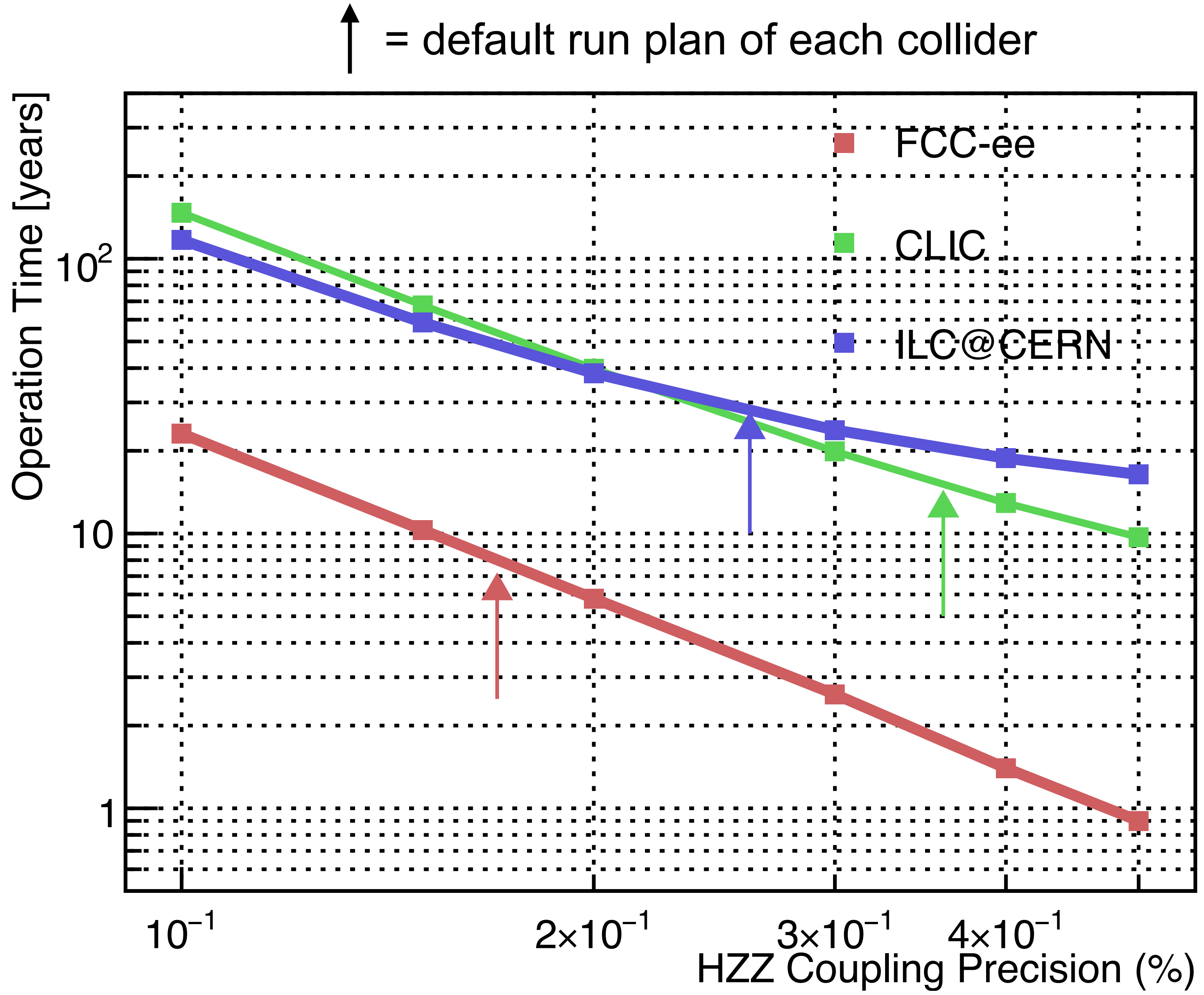

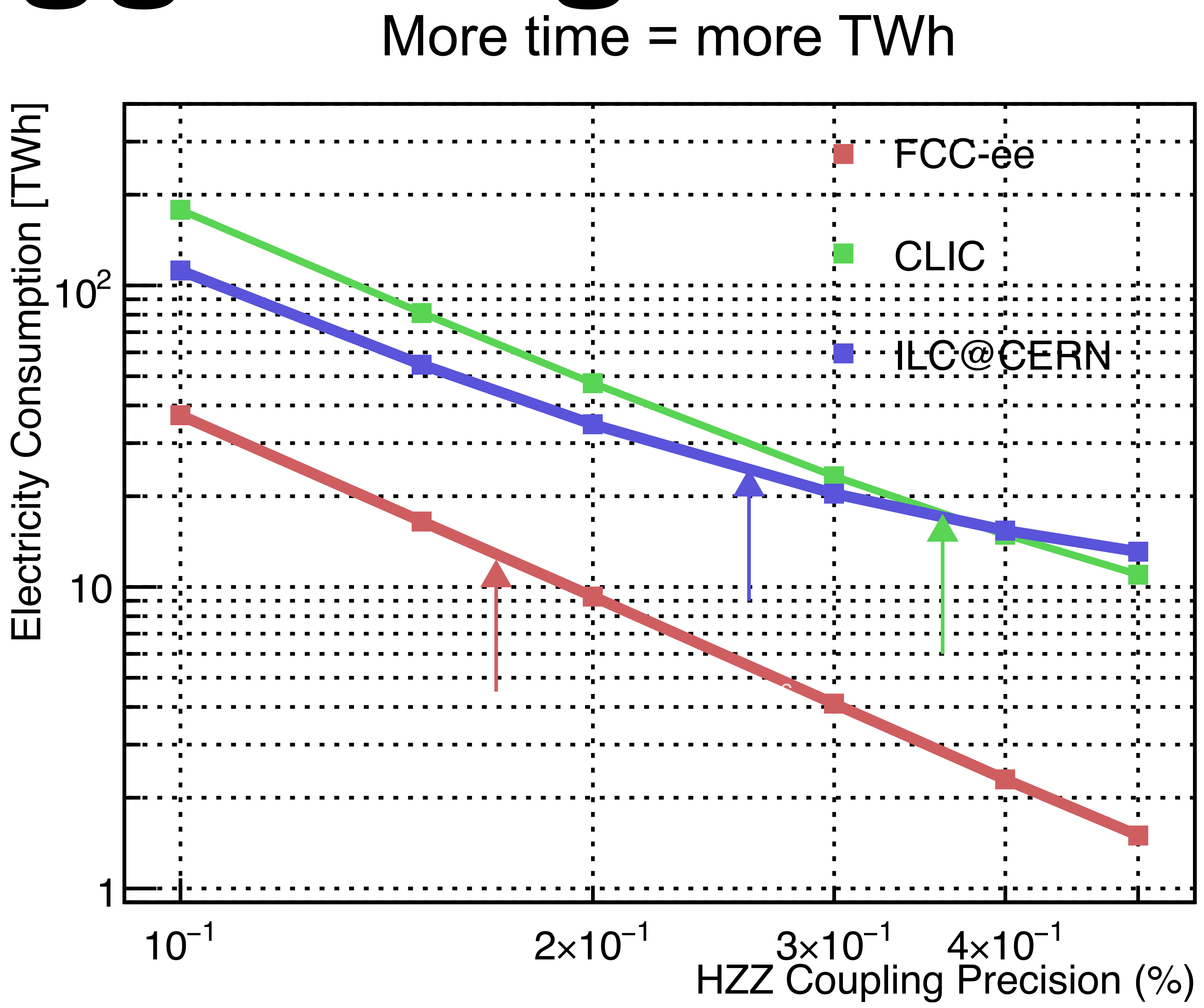

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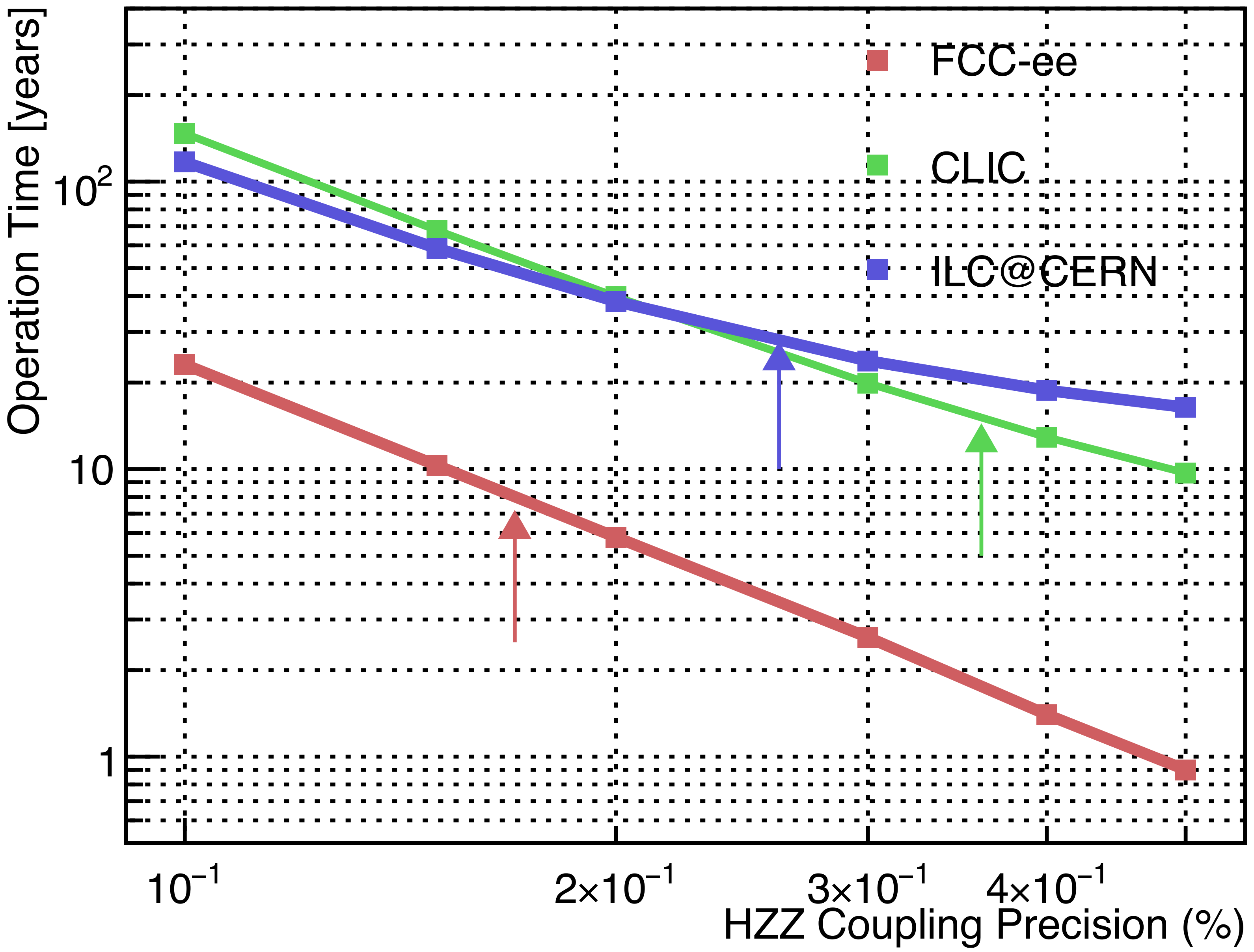
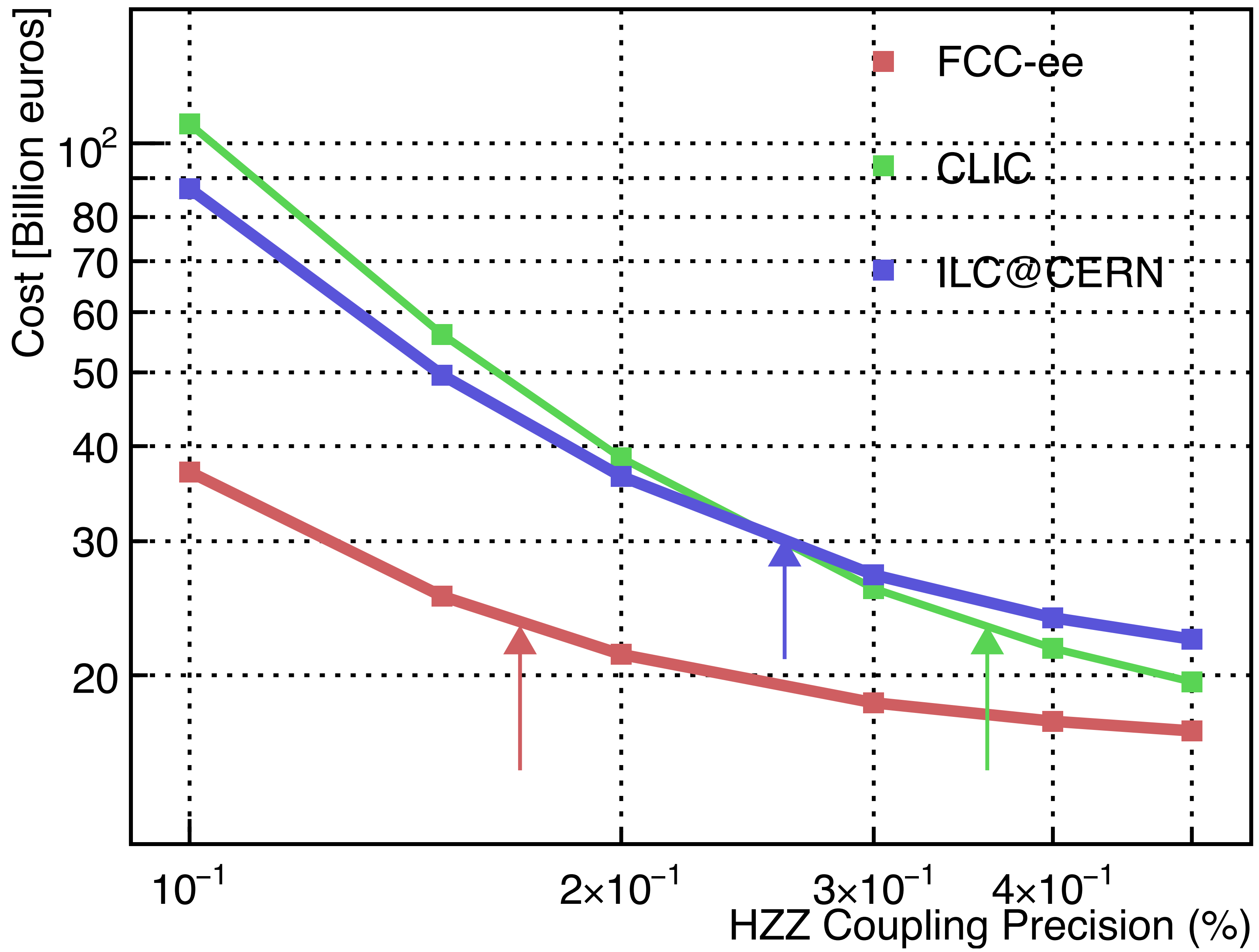
A Performant Higgs Programme

↑ = default run plan of each collider

More time = more EUR





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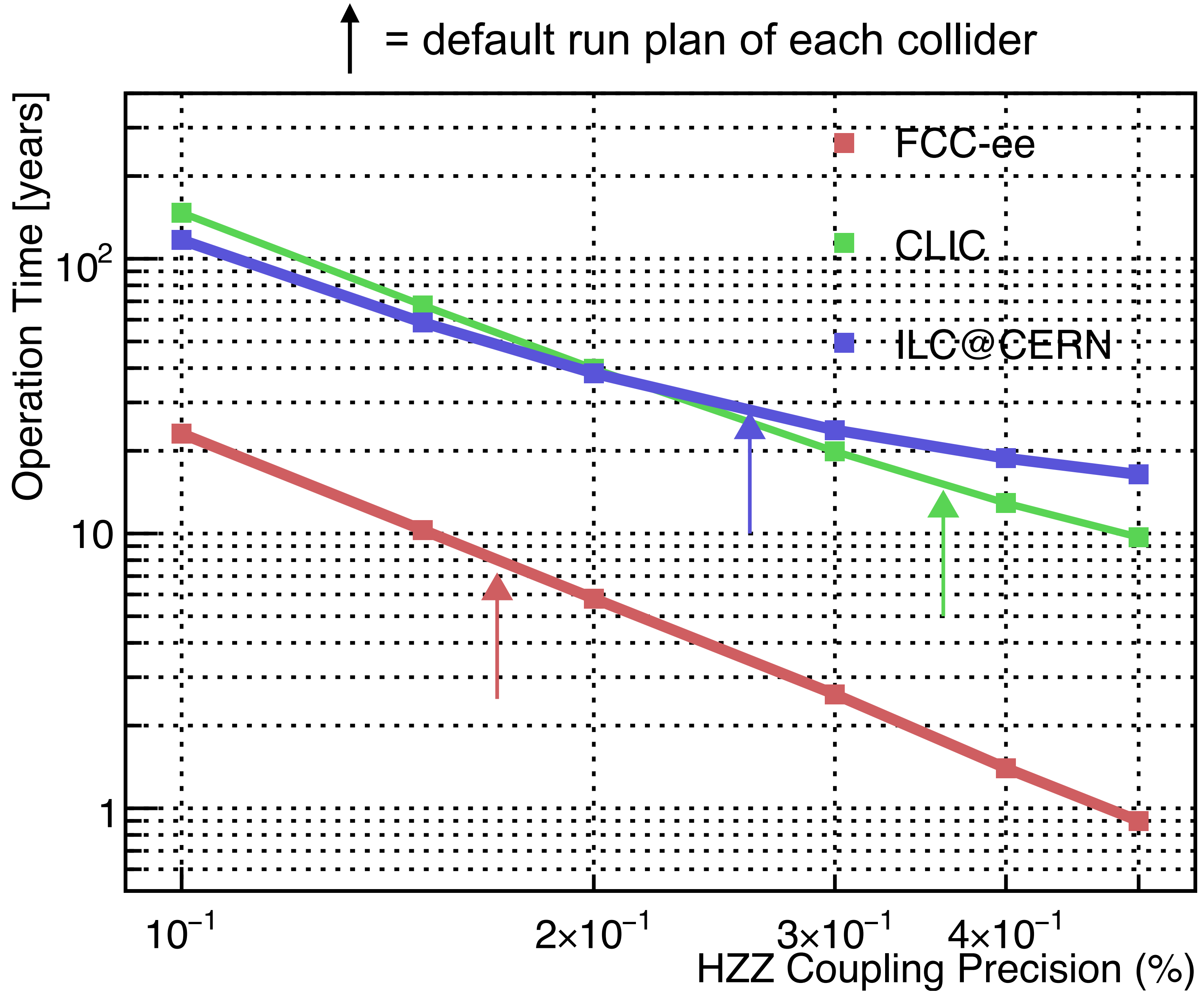
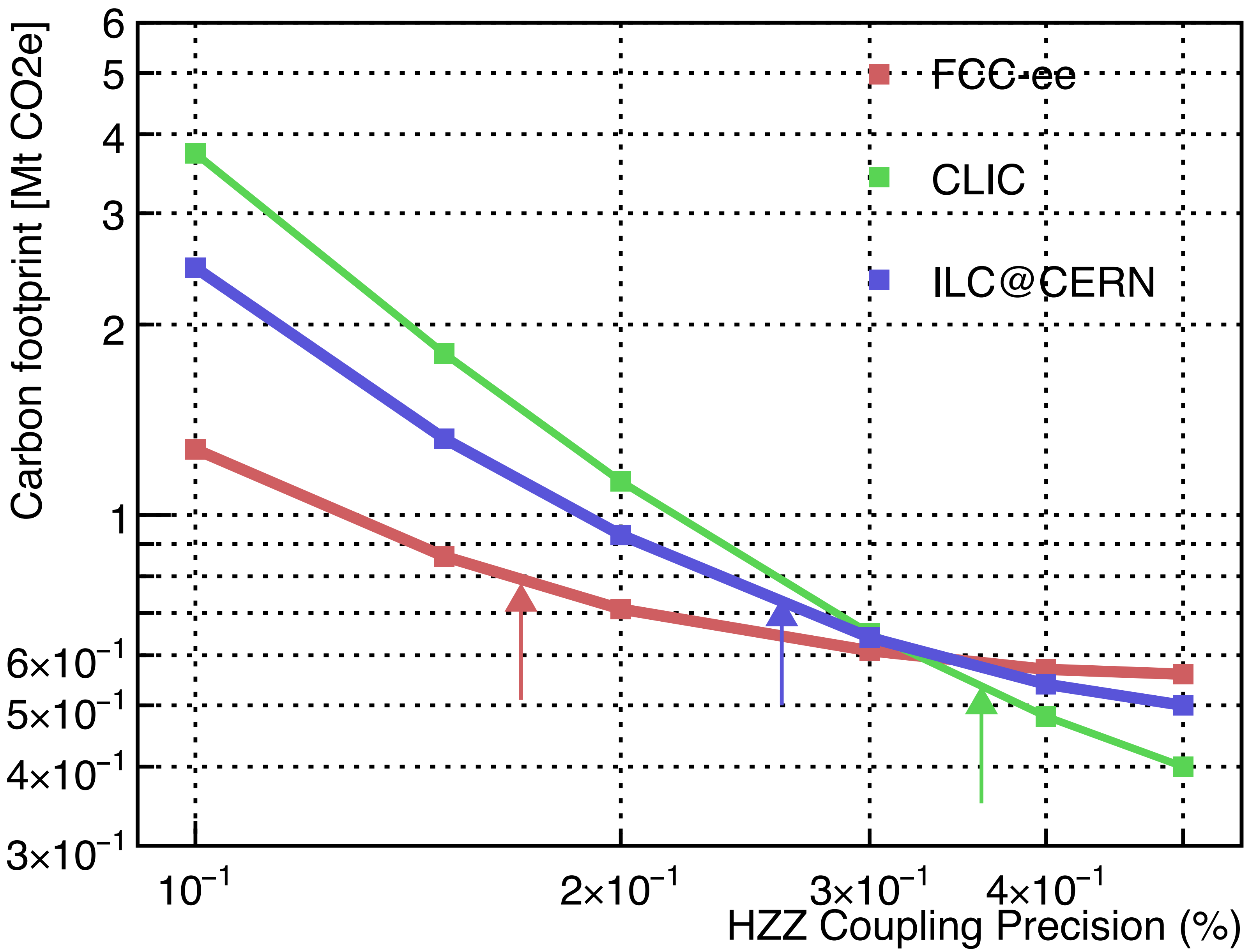


More time = more CO2eq



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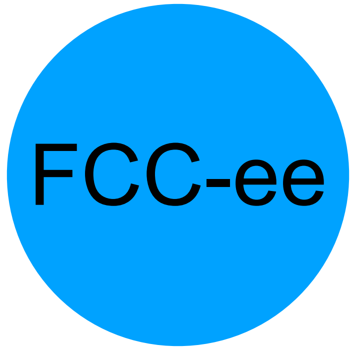
FCC-ee Physics Programme



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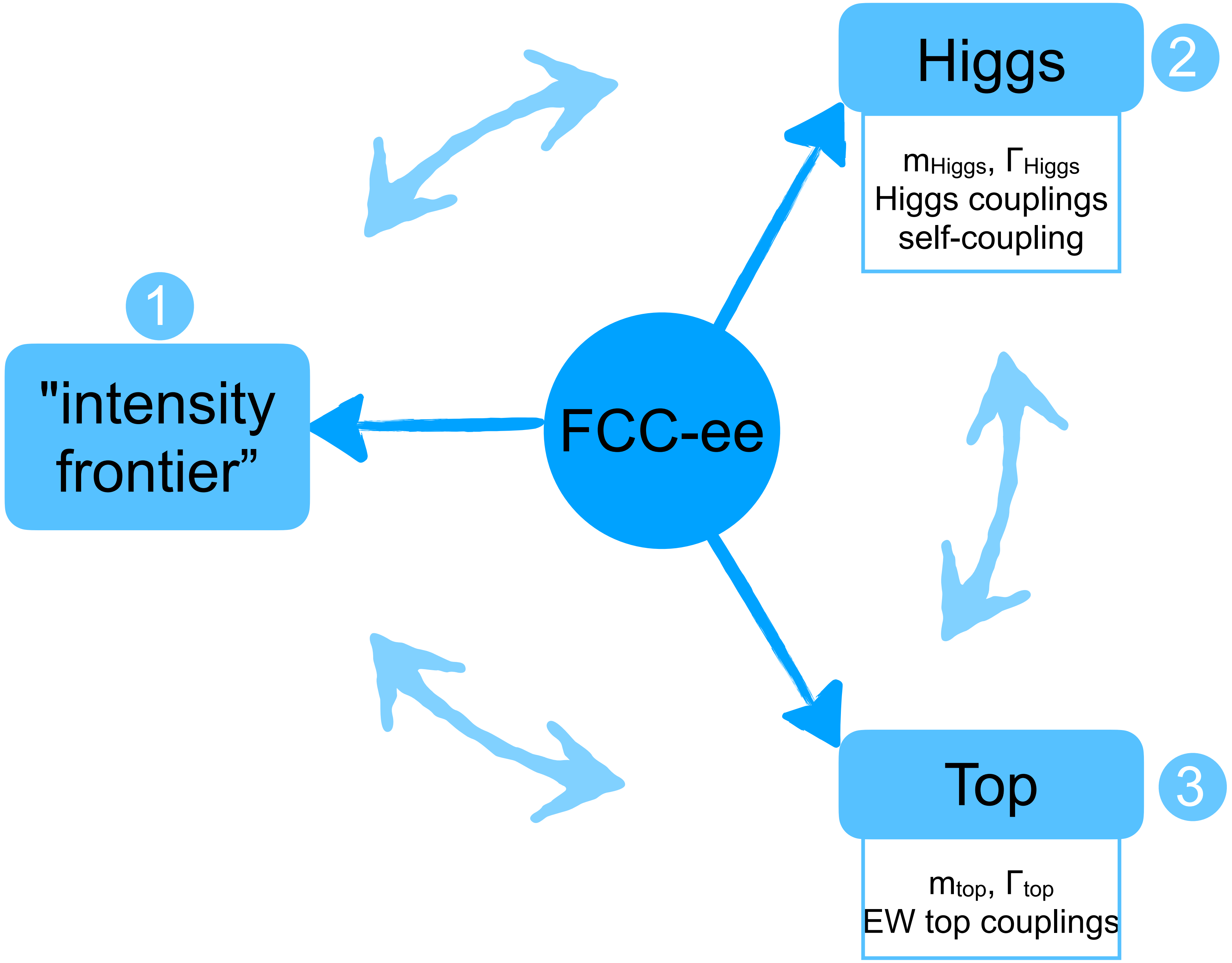

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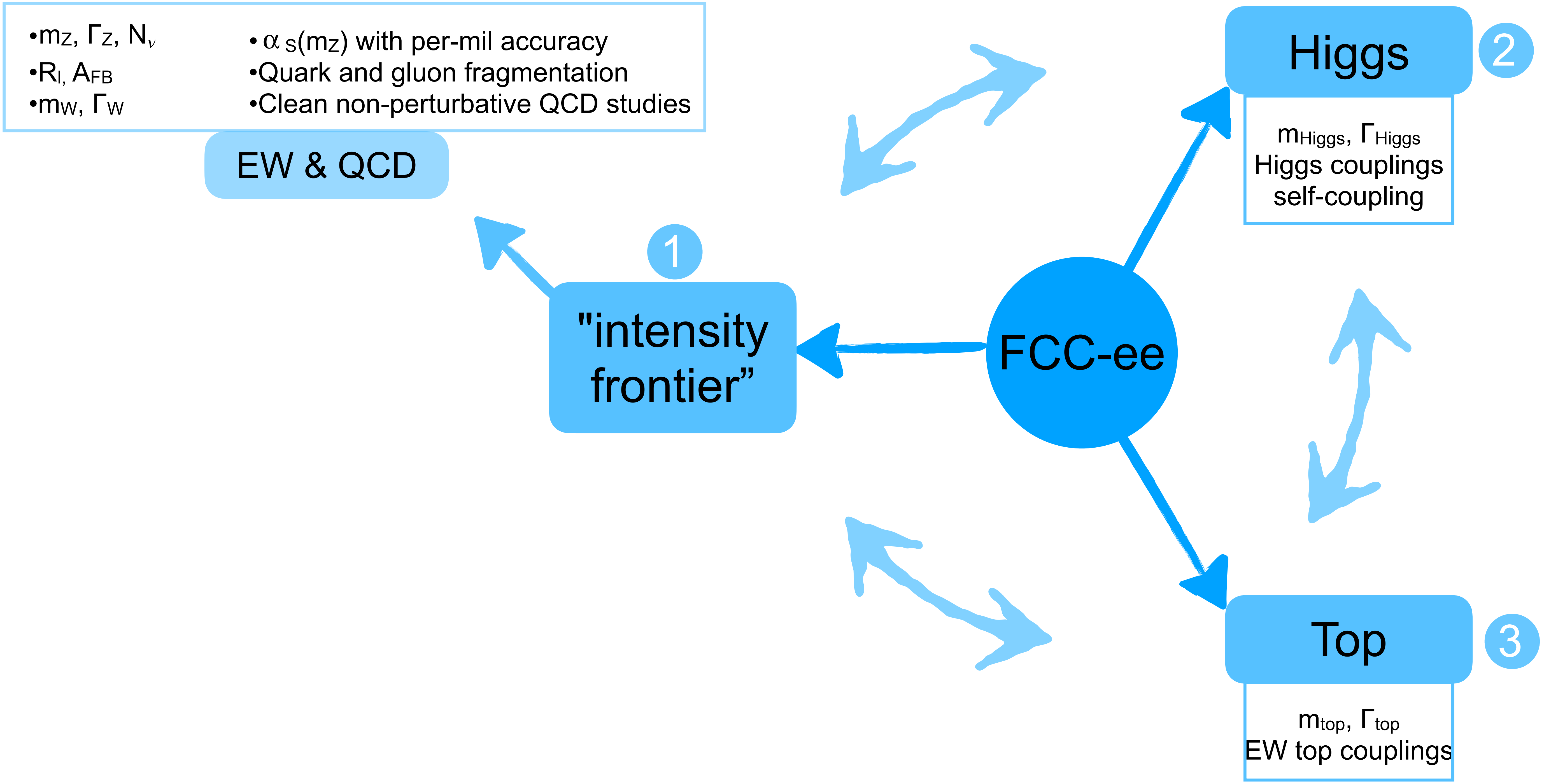

FCC-ee Physics Programme

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

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

EW & QCD

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

Improvements in precision of O(10²) available,
provided systematic uncertainties can be controlled.
Much work already invested to this goal, e.g. calibration of collision energy (EPOL).

Higgs 2
$m_{\rm Higgs}$, $\Gamma_{\rm Higgs}$
Higgs couplings
self-coupling

Top 3
$m_{\rm top}$, $\Gamma_{\rm top}$
EW top couplings

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EW & QCD

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"intensity frontier"

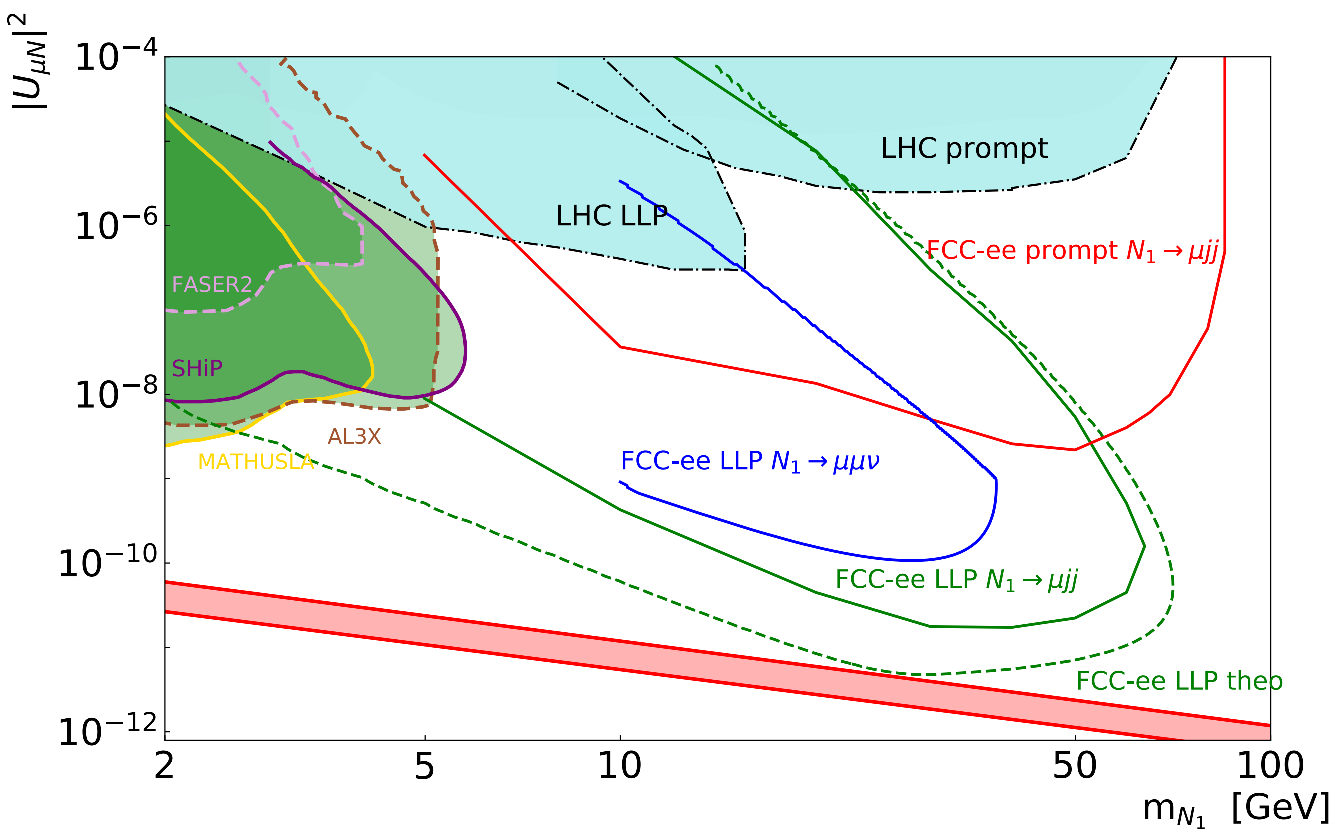
direct searches of light new physics

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

Higgs 2

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

m_{top}, Γ_{top}
EW top couplings



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EW & QCD

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

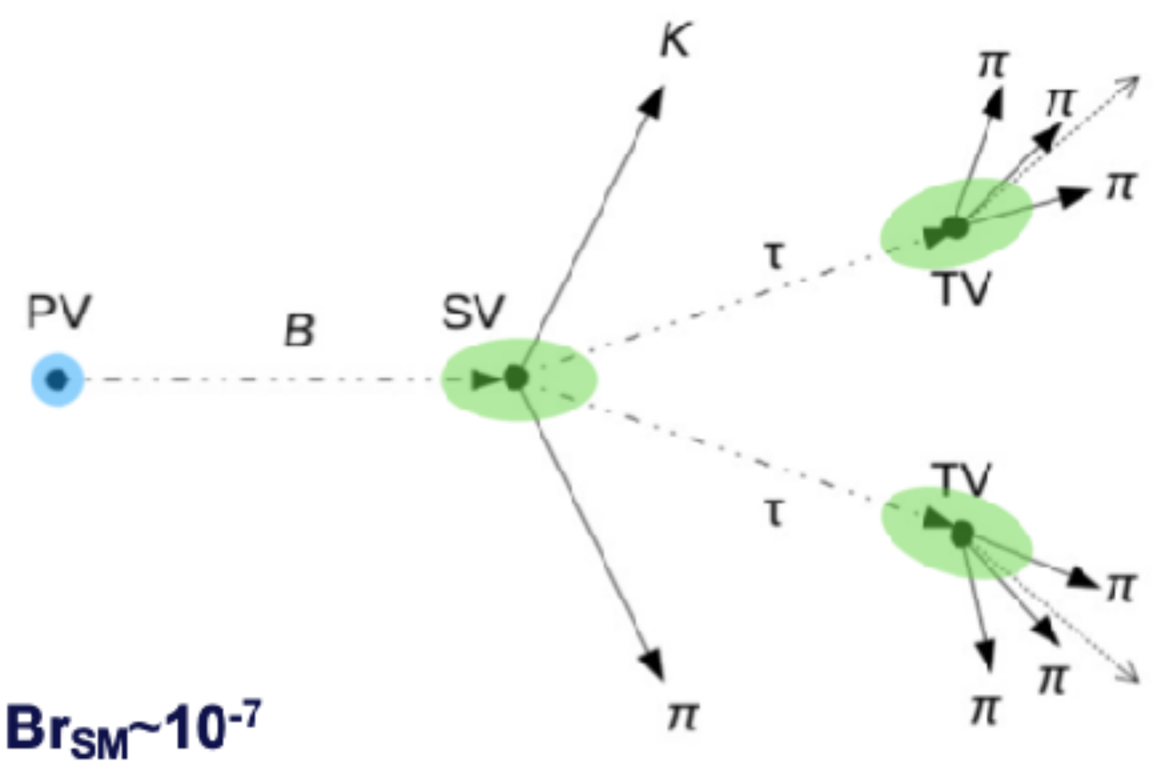
τ physics

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

B physics

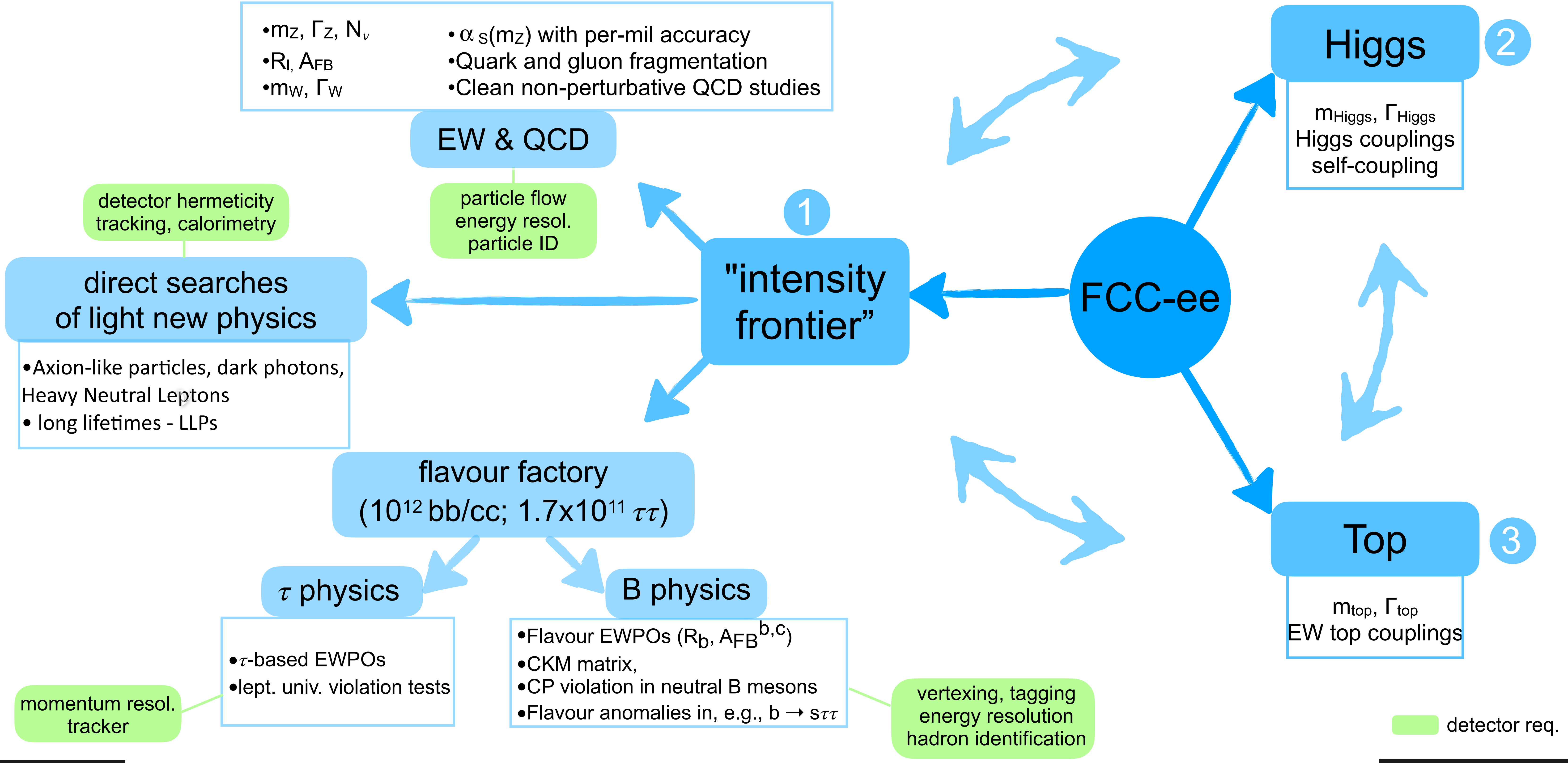
- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

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



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

FCC-ee Physics Programme



FCC-ee Physics Programme

Higgs Factory Programme

- At $\sqrt{s}$=240 and $\sqrt{s}$=365 GeV collect 2.6M HZ and 150k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \to H$ 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 → 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
- × 500 improvement of statistical precision on EWPO:
  $m_Z, \Gamma_Z, \Gamma_{inv}, \sin^2\theta_W, R_b, m_W, \Gamma_W$, …
- 2×10^{8} tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

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

Heavy Flavour Programme

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

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

Feebly coupled particles Beyond SM

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

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

FCC-ee Physics Programme

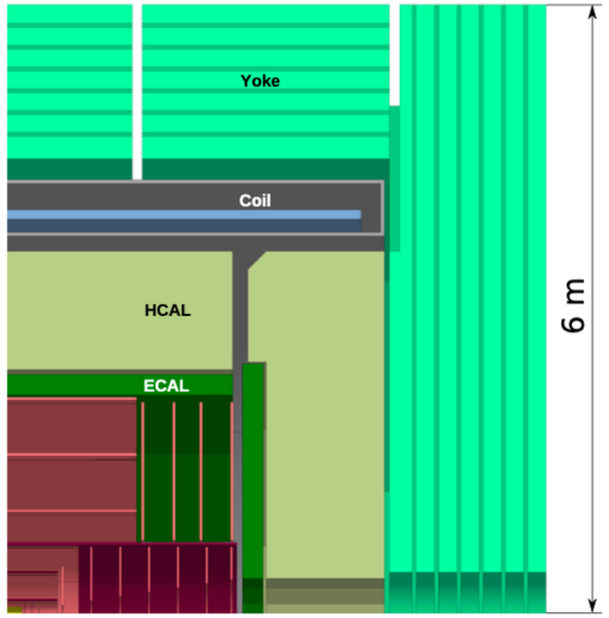
Summary of detector requirements

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

FCC-ee Physics Programme

M. Dam @ FCC week 2025

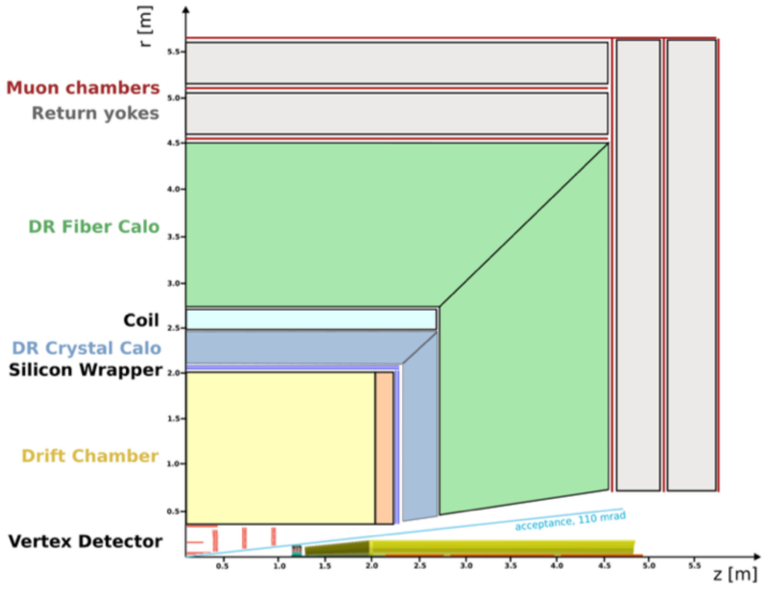
CLD



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

arXiv:1911.12230

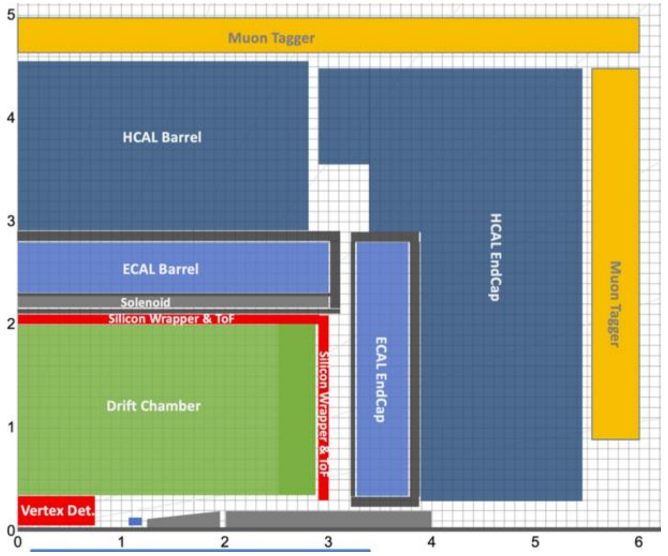
IDEA



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

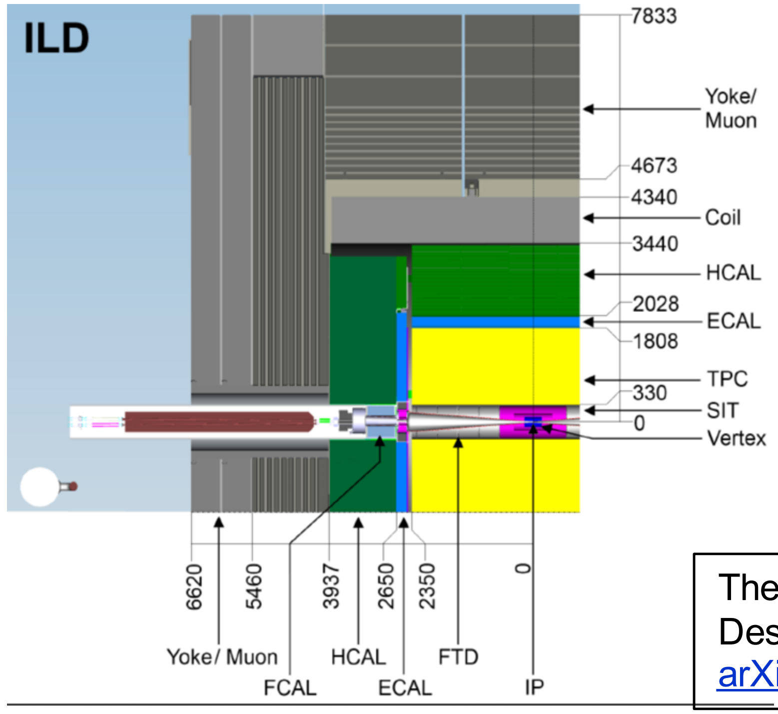
https://doi.org/10.48550/arXiv.2502.21223

Allegro



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

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



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

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

FCC-ee Physics Programme

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

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

(C. Paus @ FCC week 2025)

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

Flavour Potential of TeraZ

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

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

See S. Monteil, Flavour@FCC '22

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

FCC-ee = 10 x Belle II

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

out of reach at LHCb/Belle

boosted b's/τ's at FCC-ee

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

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

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

Flavour Potential of TeraZ

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

FCC-ee = 10 x Belle II

Decay mod…				
EW/H per…				
$B^0 \to K^*(8$…				0
$\mathcal{B}(B^0 \to K$…				
$B_s \to \mu^+\mu$…				
$B^0 \to \mu^+\mu$…				
$\mathcal{B}(B_s \to \tau^+$…				
Leptonic d…				
$B^+ \to \mu^+\nu$…				
$B^+ \to \tau^+\nu$…				
$B_c^+ \to \tau^+\nu$…				
CP / hadr…				
$B^0 \to J/\Psi$…				.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

out of reach at LHCb/Belle

Flavour @ FCC vs Belle/pp

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

boosted b's/τ's at FCC-ee

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

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

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

FCC-ee Flavour Opportunities

- **CKM elements:**
  - **CPV angles** (γ, β, ϕ_s) at sub-degree precision
  - **V_{cb}** (critical for normalising the Unitarity Triangle) from WW decays:
    - 3.4% @ now → 0.52-0.14% @ FCC-ee (depending on tracking) see Marzocca et al (2024)
- **Tau physics** (>10^{11} pairs of tau's produced in Z decays)
  - test of lepton flavour universality: G_F from tau decays @ 10 ppm @ FCC-ee (0.5 ppm from muon decays)
  - lepton flavour violation:
    - $\tau \to \mu\gamma$: 4×10^{-8} @Belle2021→10^{-9} @ FCC-ee
    - $\tau \to 3\mu$: 2×10^{-8} @Belle → 3×10^{-10} @BelleII → 10^{-11} @ FCC-ee
  - tau lifetime uncertainty:
    - 2000 ppm → 10 ppm
  - tau mass uncertainty:
    - 70 ppm → 14 ppm
- **Semi-leptonic mixing asymmetries** a^s_{sl} and a^d_{sl}
- …

New Physics Reach @ Z-pole

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

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

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

Scalars

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

Fermions

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

Vectors

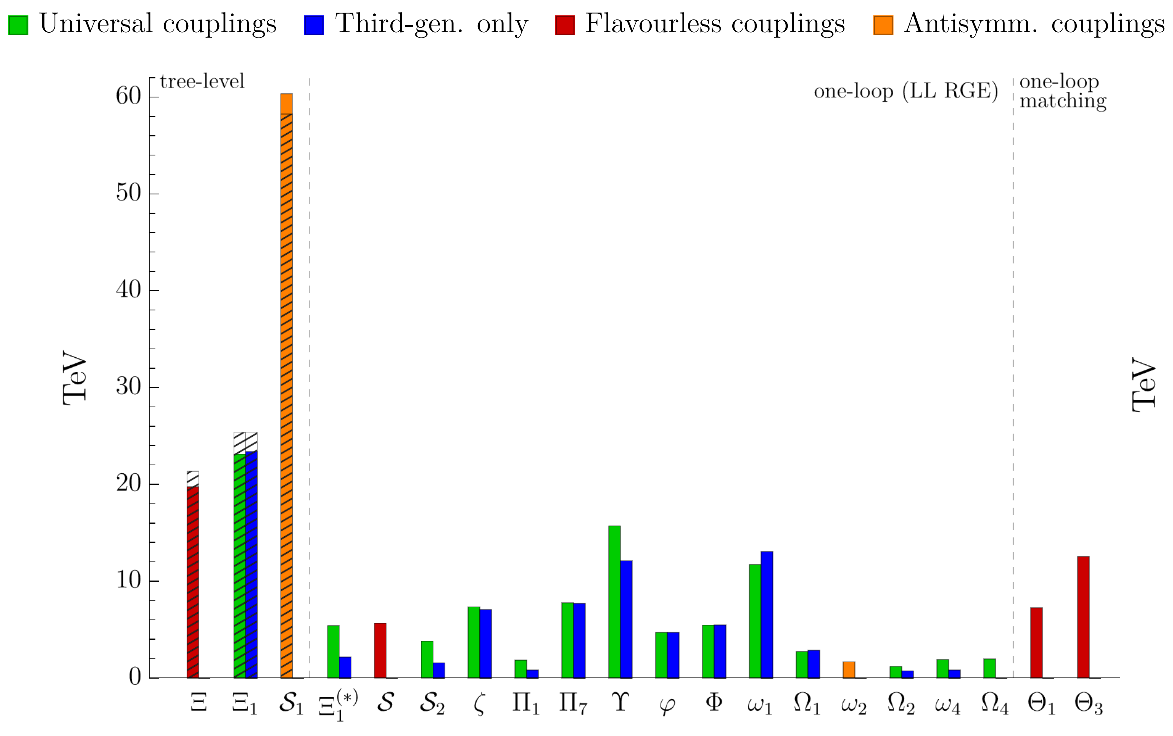
They are not all affecting EW observables at tree-level.

New Physics Reach @ Z-pole

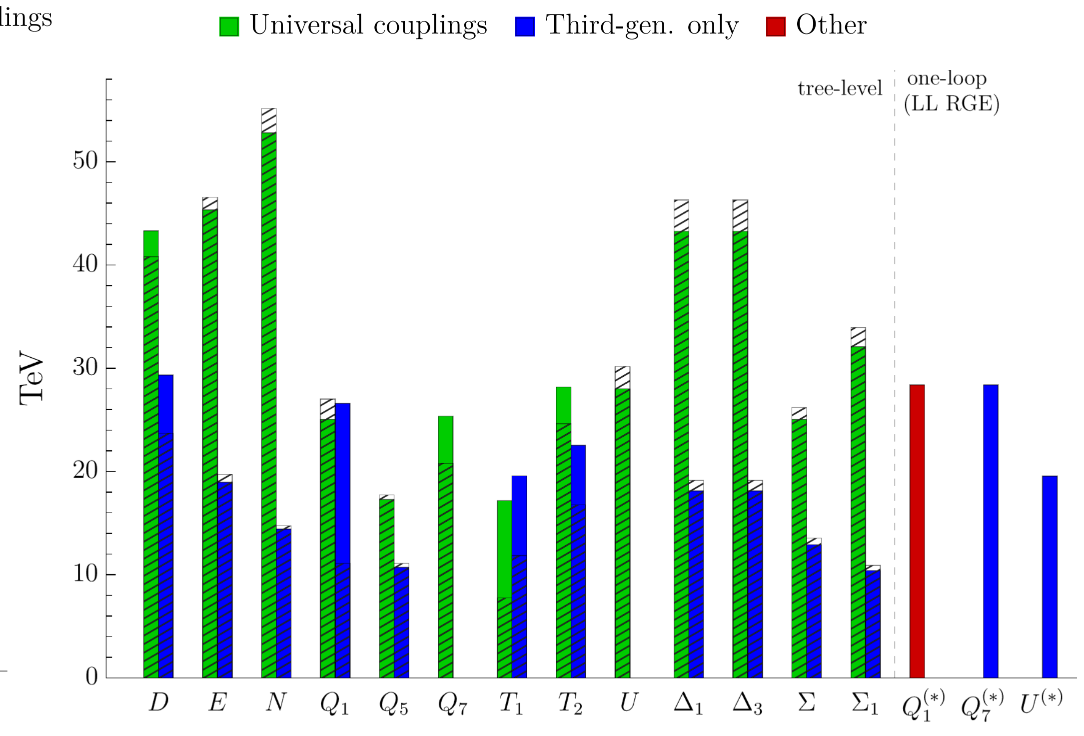
There are 48 different types of particles that can have tree-level linear interactions to SM.

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

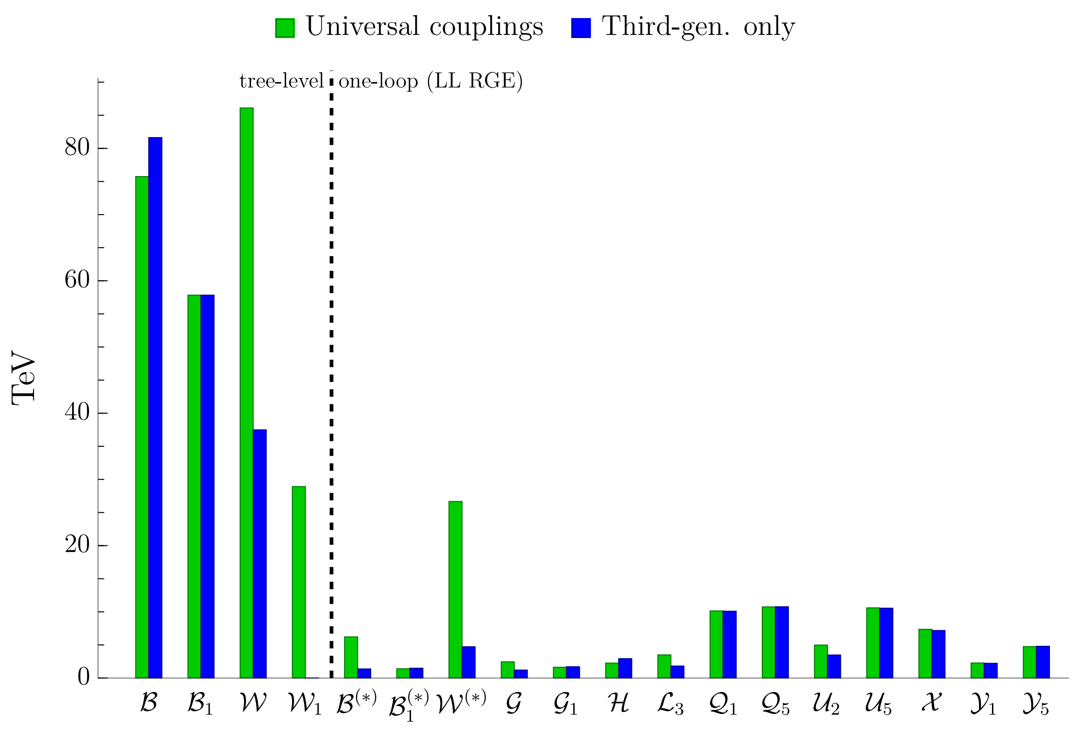
Allwicher, McCullough, Renner, arXiv: 2408.03992



Scalars



Fermions

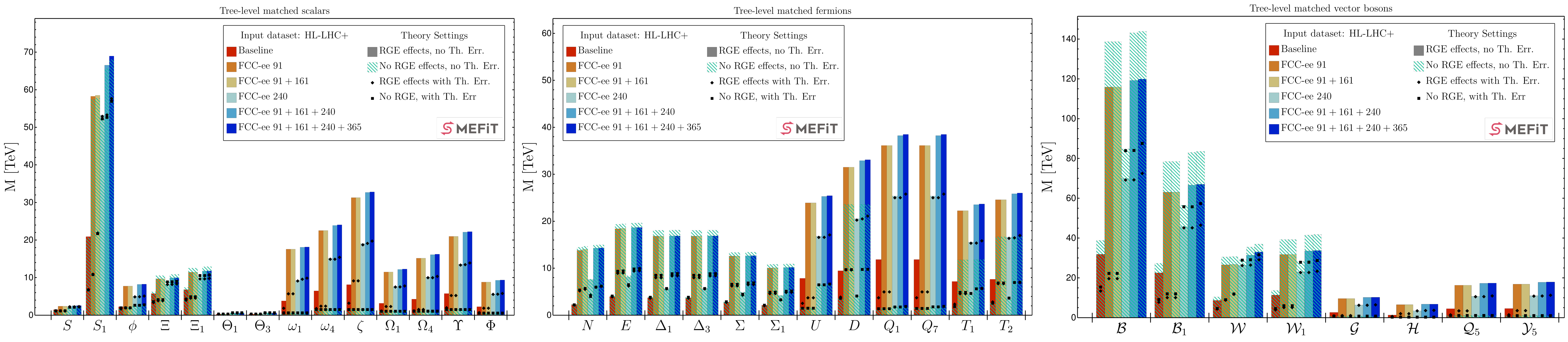


Vectors

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

New Physics Reach @ Z-pole

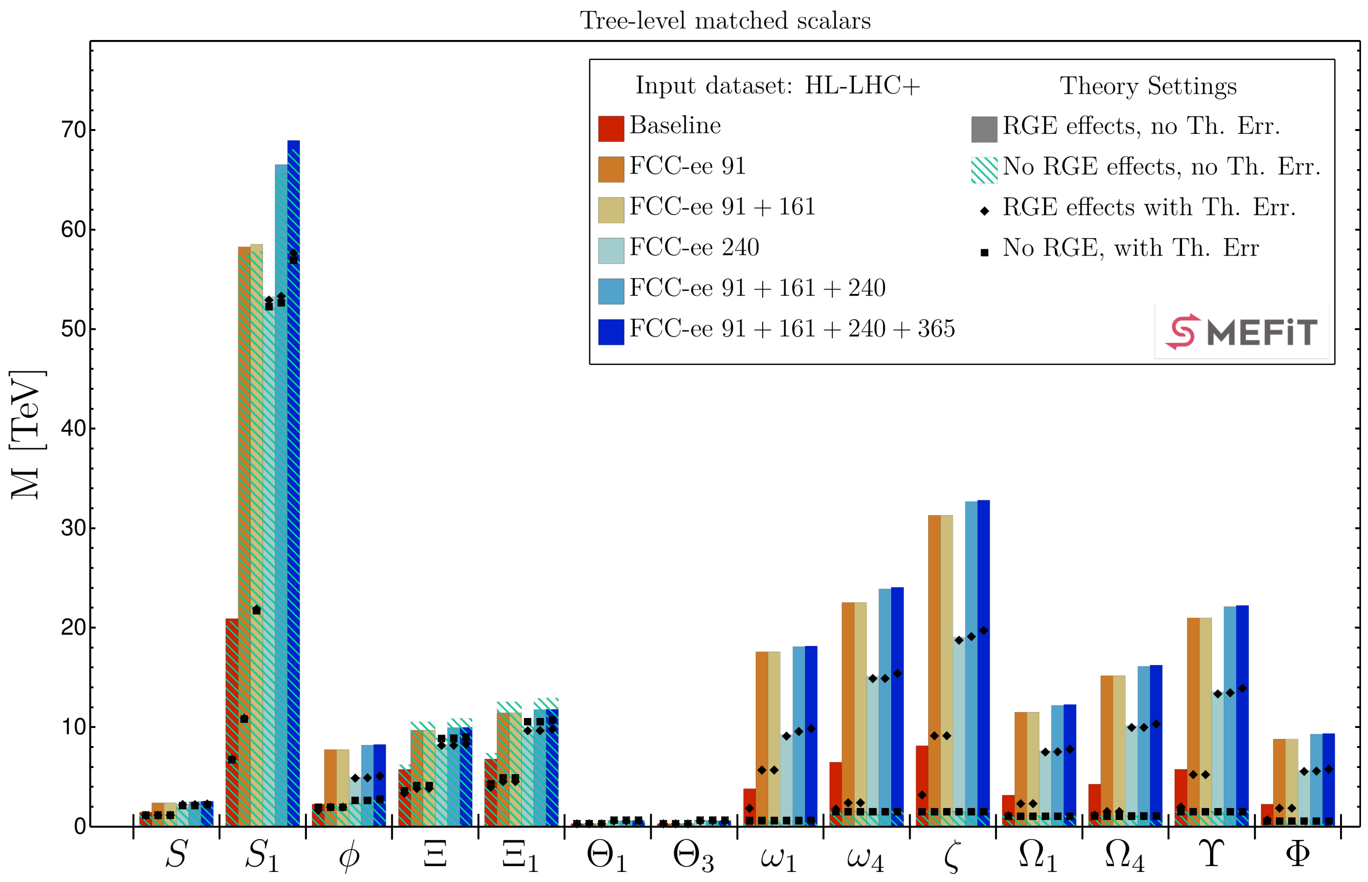
There are 48 different types of particles that can have tree-level linear interactions to SM.

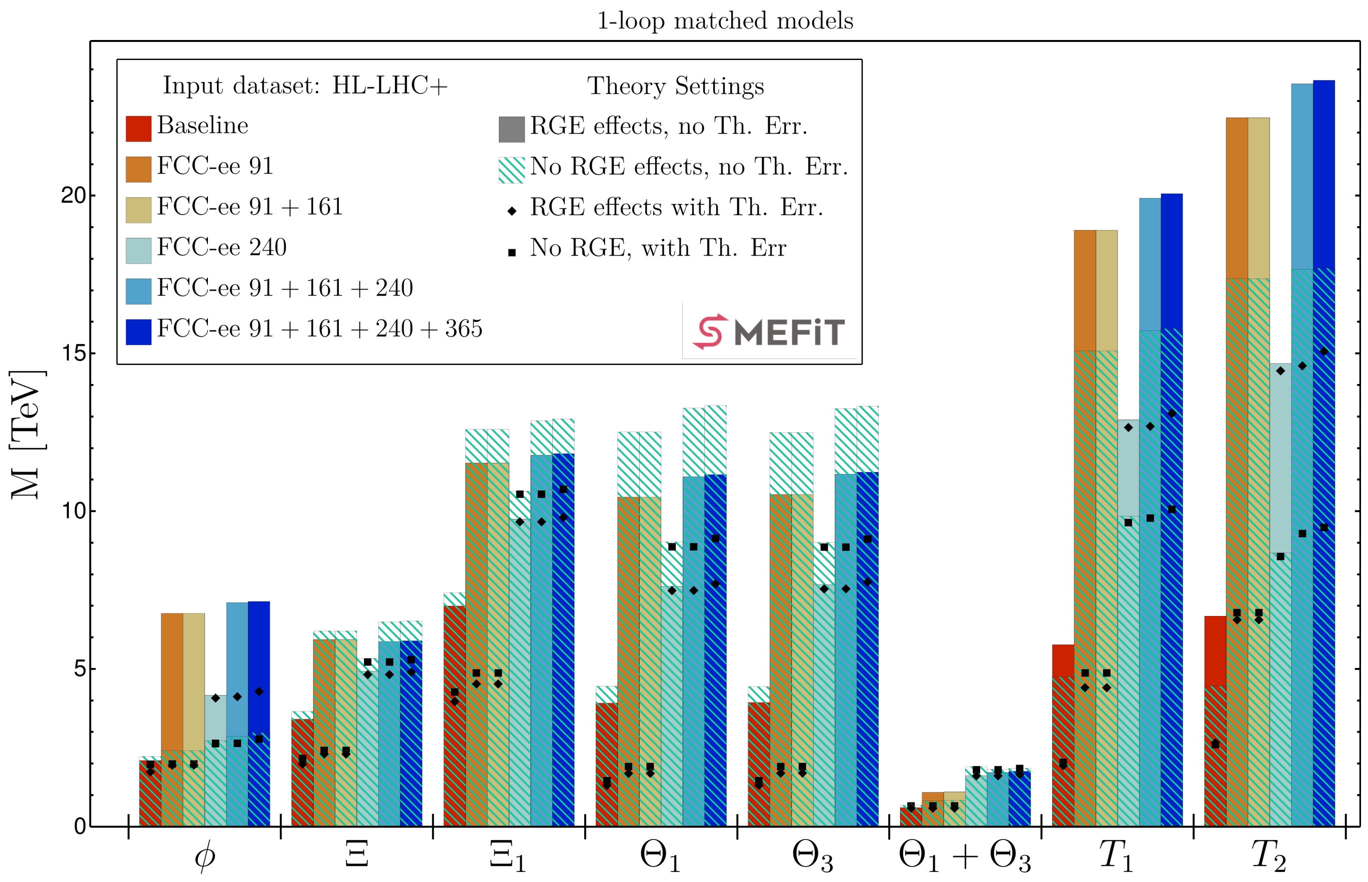


Importance of controlling/reducing the TH syst. errors to exploit Z-pole data.
Role of ZH and tt runs.

New Physics Reach @ Z-pole

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





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

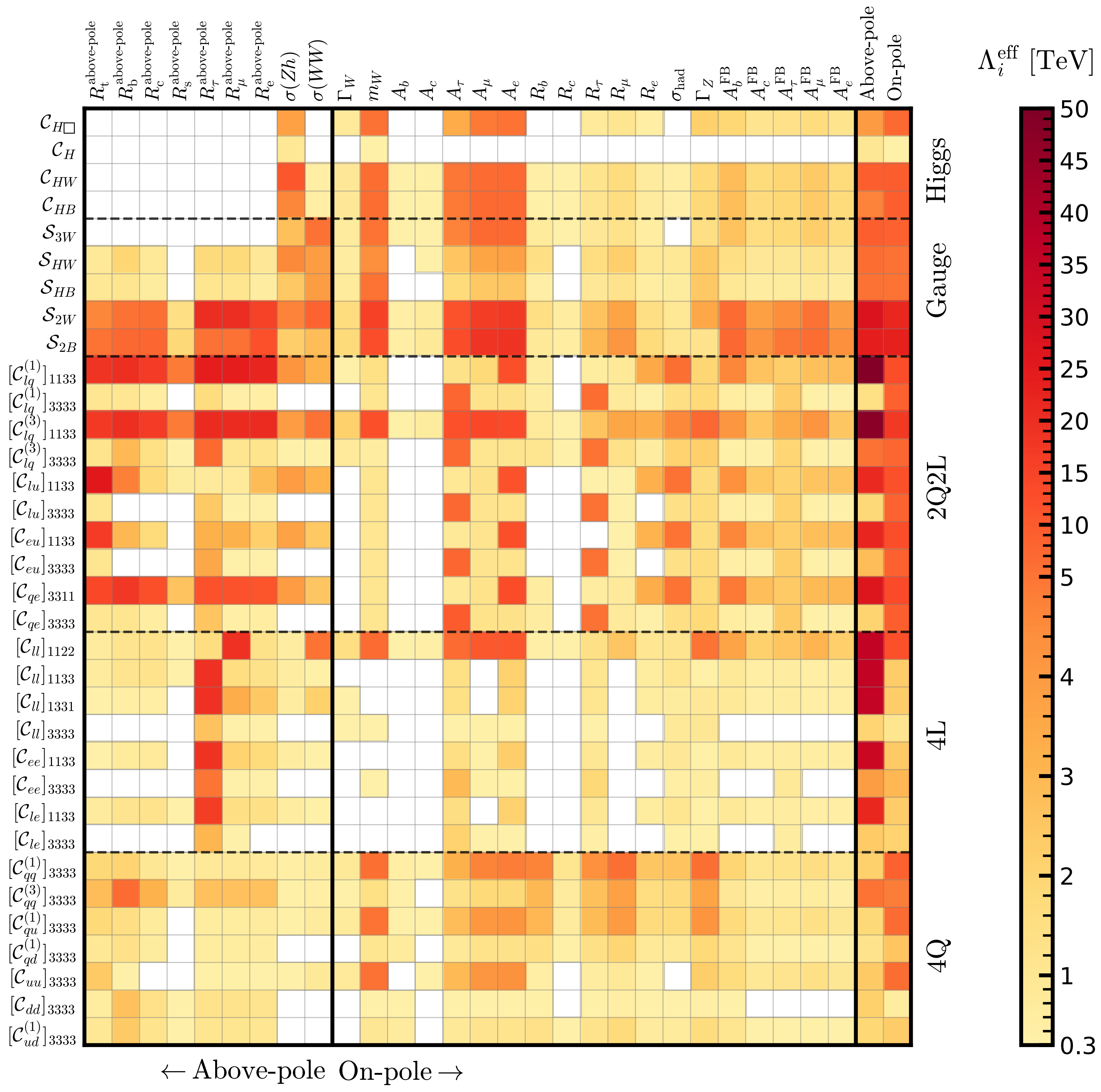
New Physics Reach @ Z-pole

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

Tera-Z programme gives comprehensive coverage of new physics coupled to SM.
If a signature shows up elsewhere, it will also show up at Tera-Z.
Tera-Z is not just a high-power LEP exploring the EW sector.
It takes full advantage of the quantum nature of HEP
to maximise sensitivity to New Physics.

Z-pole vs High Energy

Maura, Stefanek, You arXiv:2412.14241



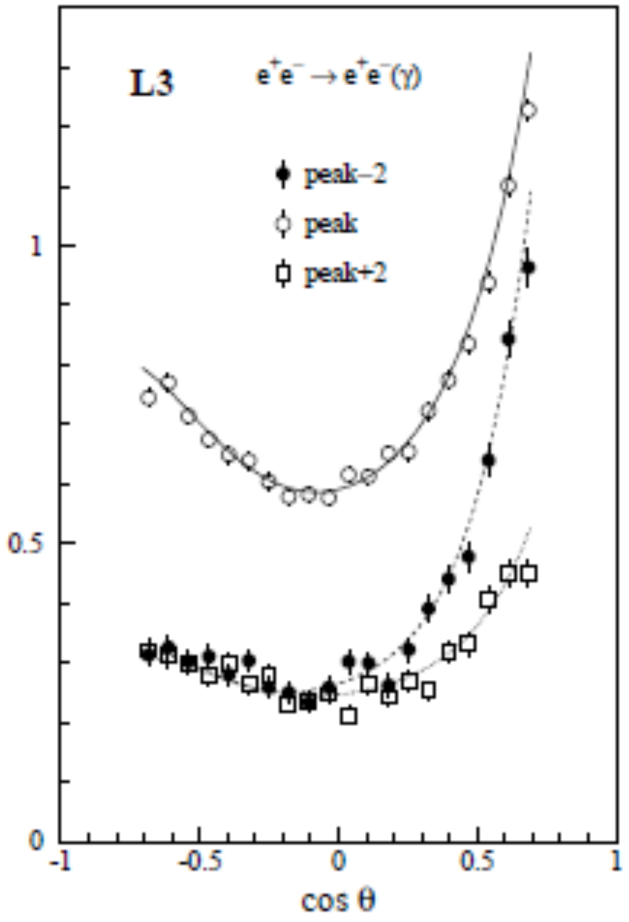
More on EW Precision: $\alpha_{QED}(m_Z)$

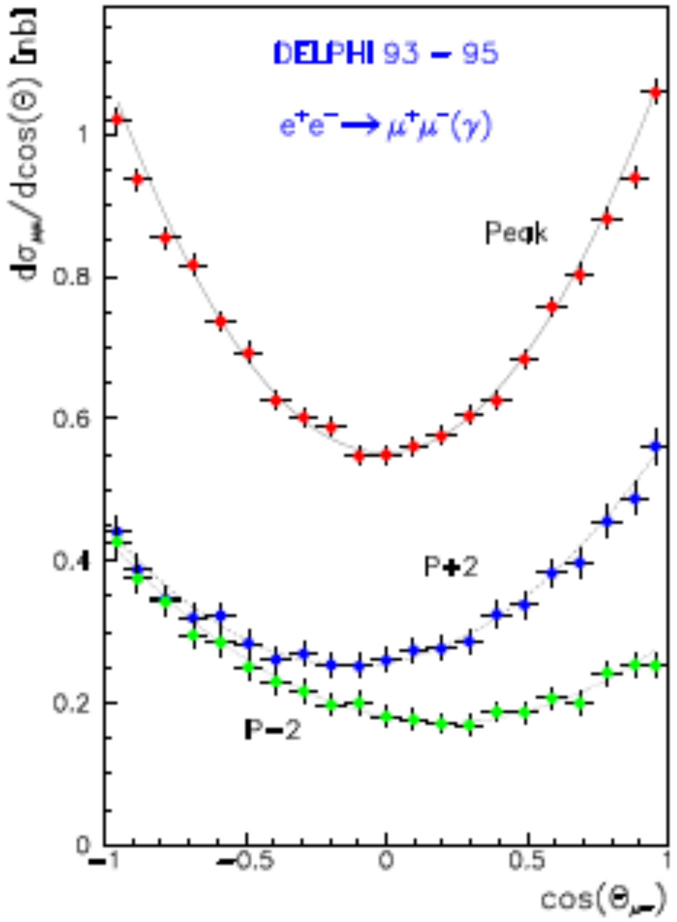
currently **10^{-4}**, a limiting factor to many BSM searches

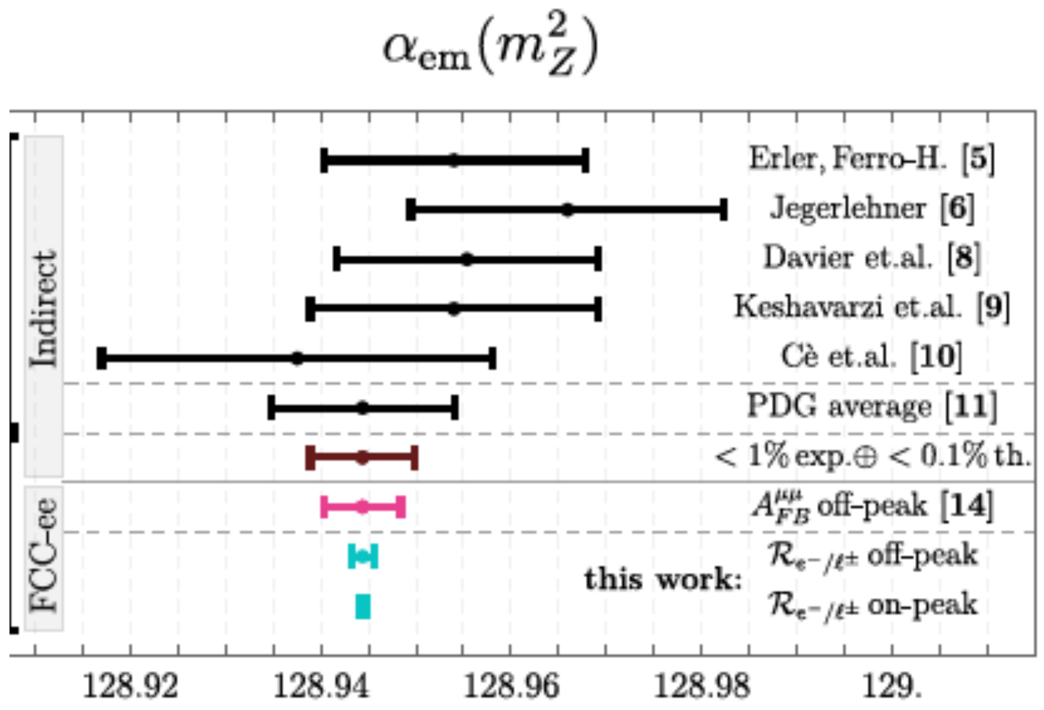
Unique to circular machines, since it requires $\gg 10^{12}$ Z and line shape scan

- **Off-pole** (Janot 2015): so far determined from the slope of $A_{FB}^{\mu\mu}$ vs $\sqrt{s}$ → **±3x10^{-5}**
- **On-pole** (Riembau 2025): both s and t- channel $e^+e^- \to e^+e^-$ and $\mu^+\mu^-$ at the Z pole → **±0.6x10^{-5}**

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

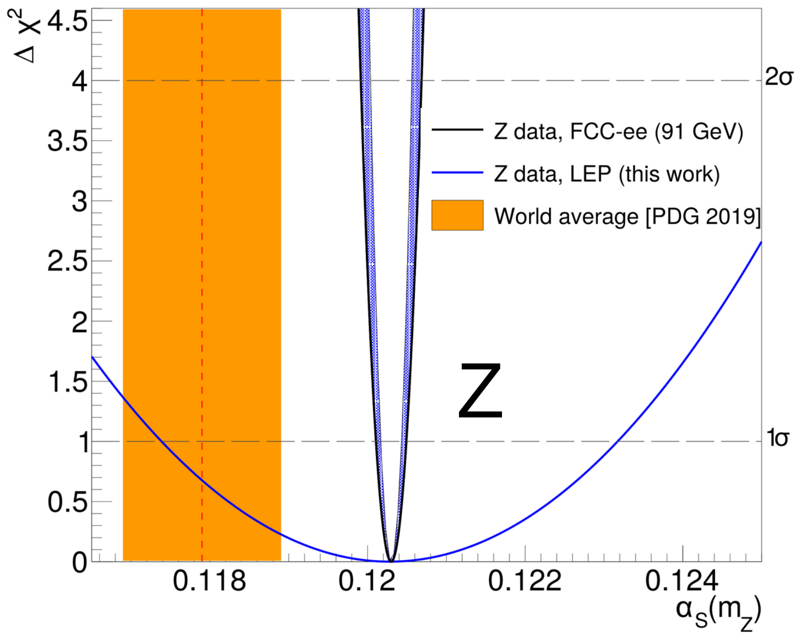


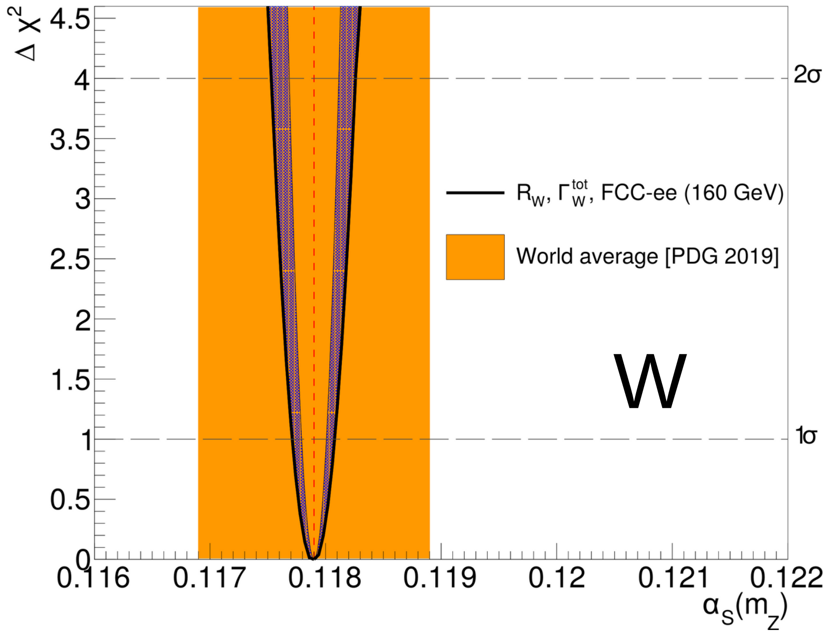




FCC-ee as a QCD factory

S. Kluth @ FCC week 2025



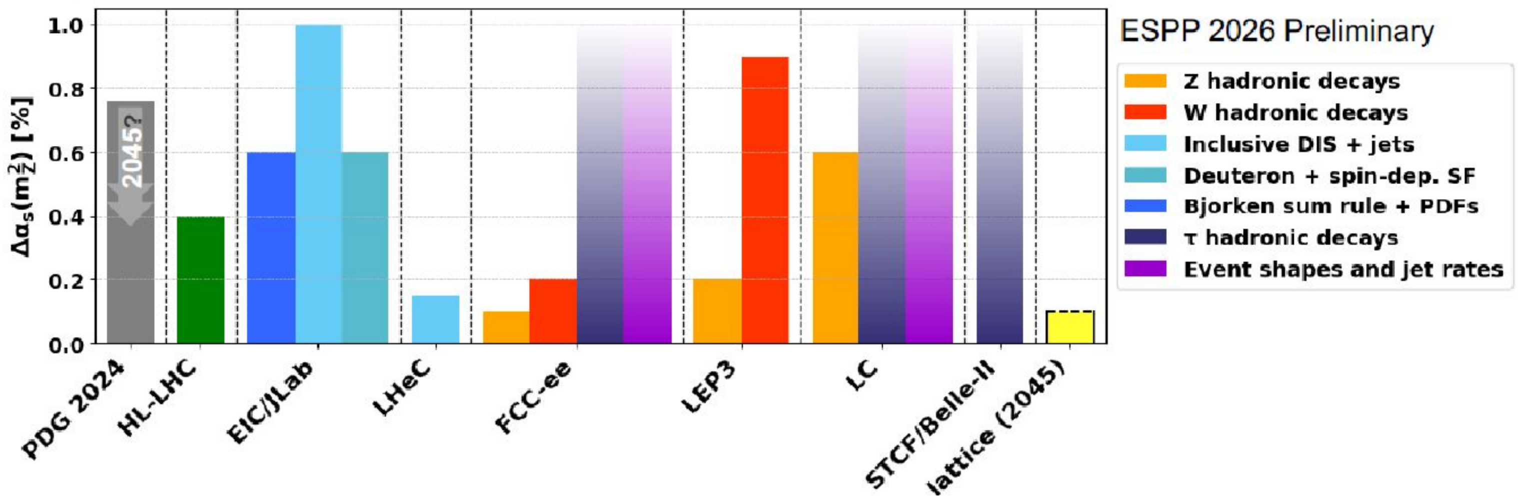


FCC-ee: improved α_{QED}, $|V_{cs}|$, $|V_{cd}|$, m_W; assume N4LO QCD

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

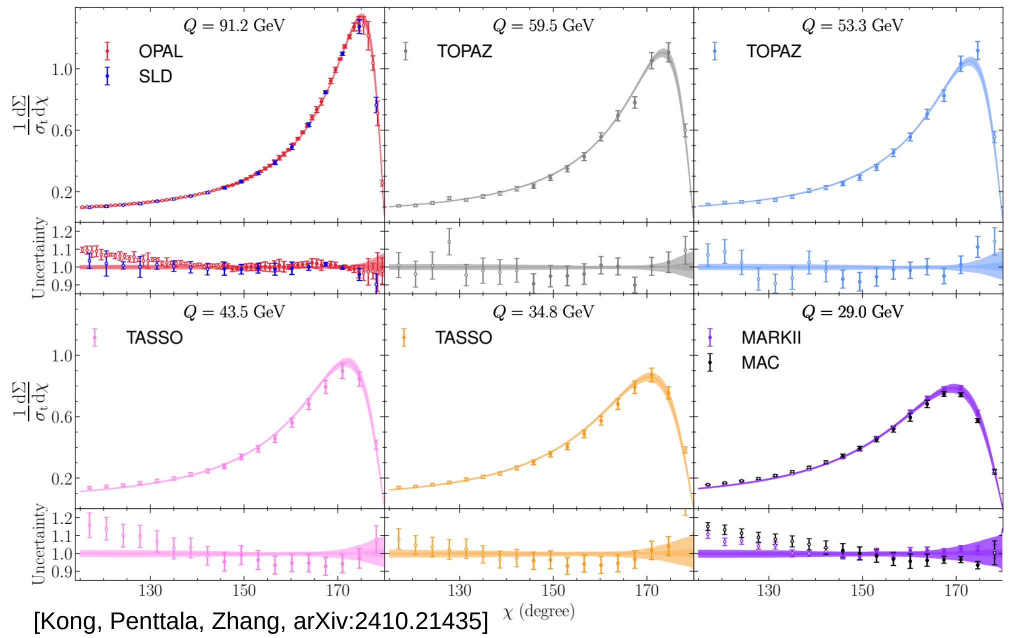
W: $\alpha_S(m_Z) = 0.11790 \pm 0.00012_{exp} \pm 0.00004_{par} \pm 0.00019_{theo}$

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



Semi-inclusive EECs

$d\Sigma/d\chi = 1/(\Delta\chi N) \int_{bin} \Sigma_{events} \Sigma_{ij} E_i E_j / s\ \delta(\chi' - \theta_{ij})\ d\chi'$



[Kong, Penttala, Zhang, arXiv:2410.21435]

EEC is energy weighted distribution of angles between particle pairs

QCD NNLO+N3LL resum.

np effects from TMD factorisation in N3LL

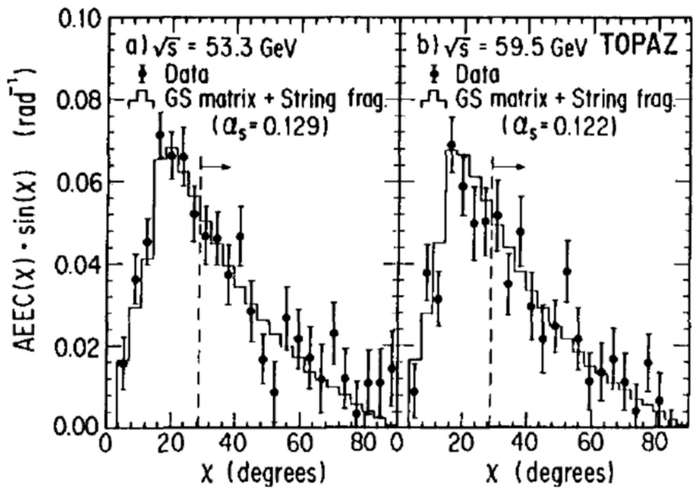
$\alpha_S(m_Z) = 0.1193 \pm 0.0009_{exp} \pm 0.0011_{theo}$

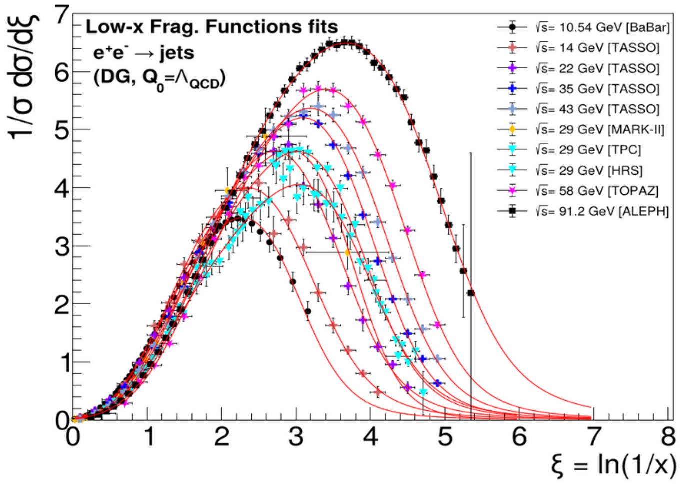
FCC-ee as a QCD factory

S. Kluth @ FCC week 2025

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

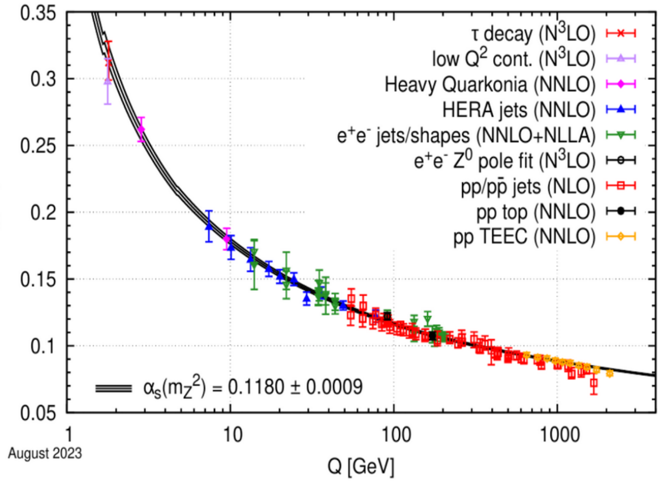
Hard vs soft QCD, Hadronisation

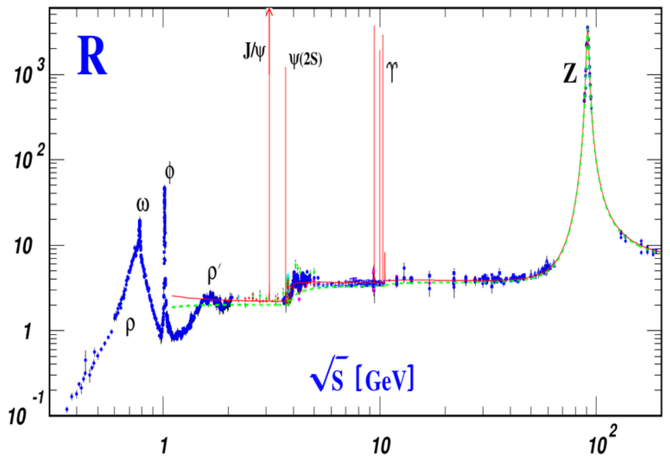




Fragmentation, QCD, MCs, Hadronisation

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





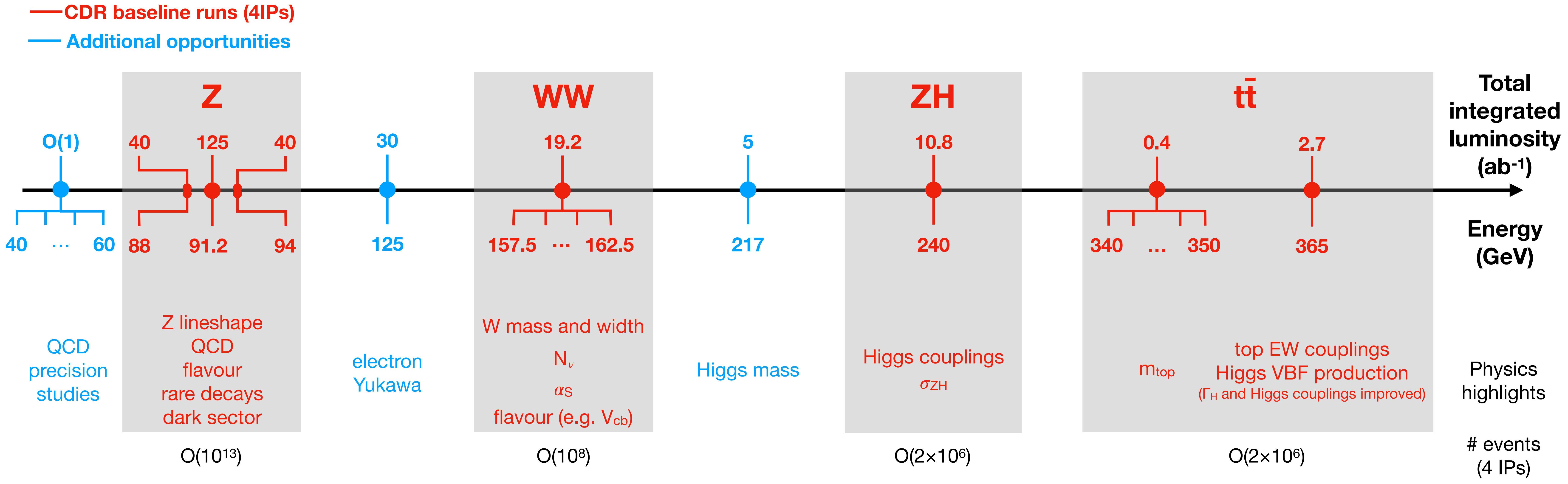
$R = \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$

α_s(20-40 GeV) at 0.1%?

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

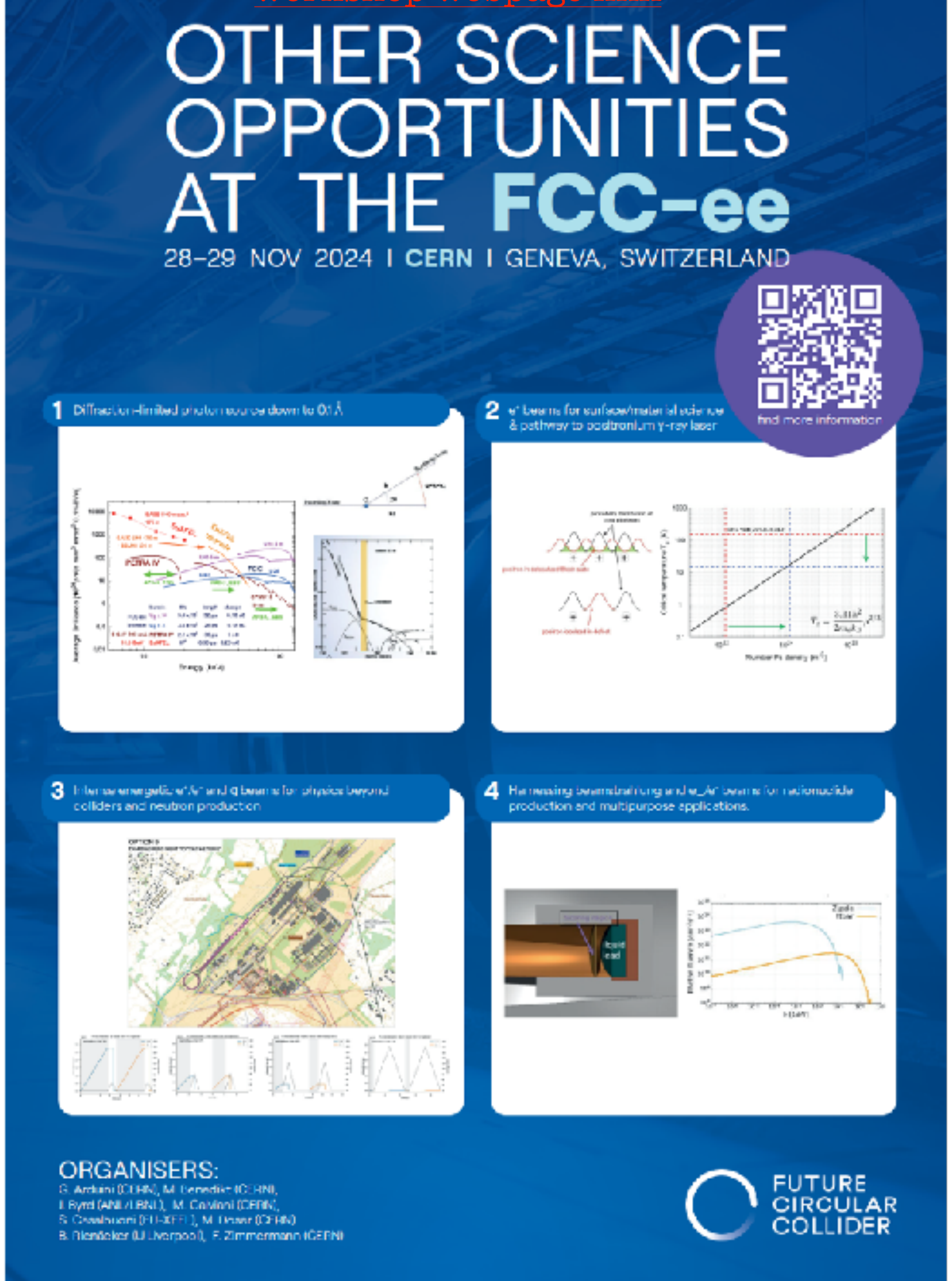
Bonus EWPOs: A_{FB} $e^+e^- \to f\bar{f} \Rightarrow \sin^2(\theta_W)(Q)$

Collider Programme (and beyond)



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

workshop webpage link



photon science
(light source,
Compton Backscattering sources)

HEP applications
(strong QED, dark sector)

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

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

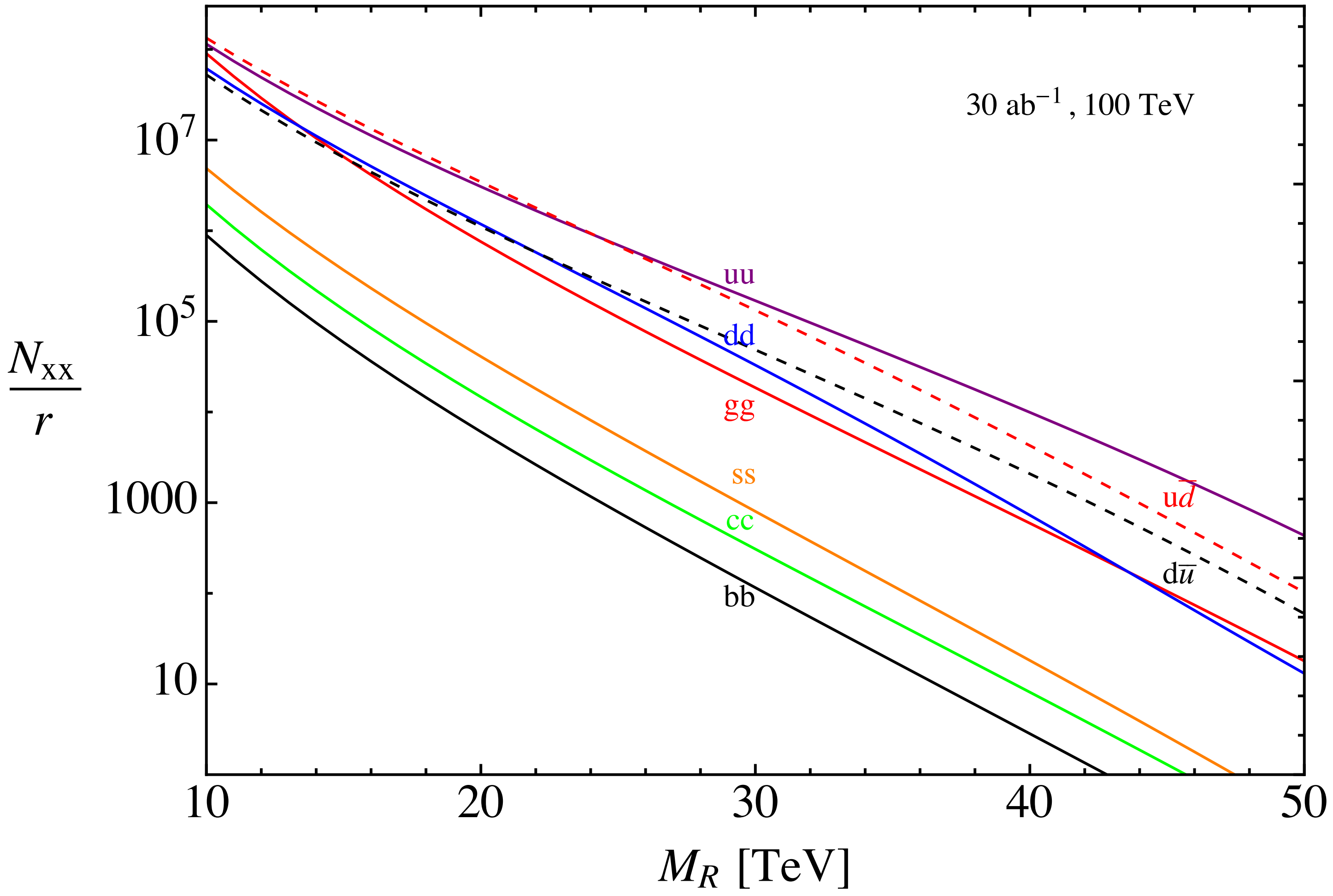
Exploration potential at high-energy with FCC-hh

Resonance production.

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

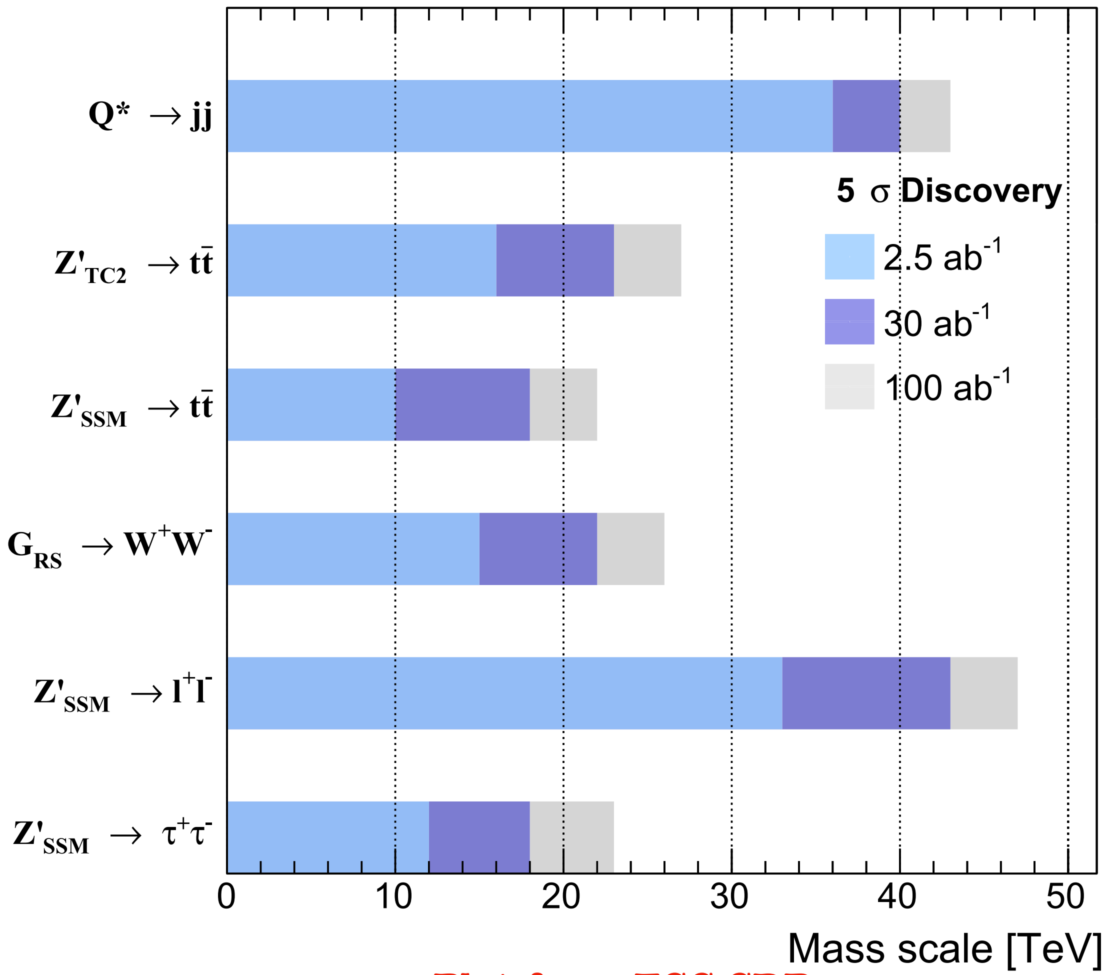
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

resonances produced



Plot from mid-term report

FCC-hh mass reach



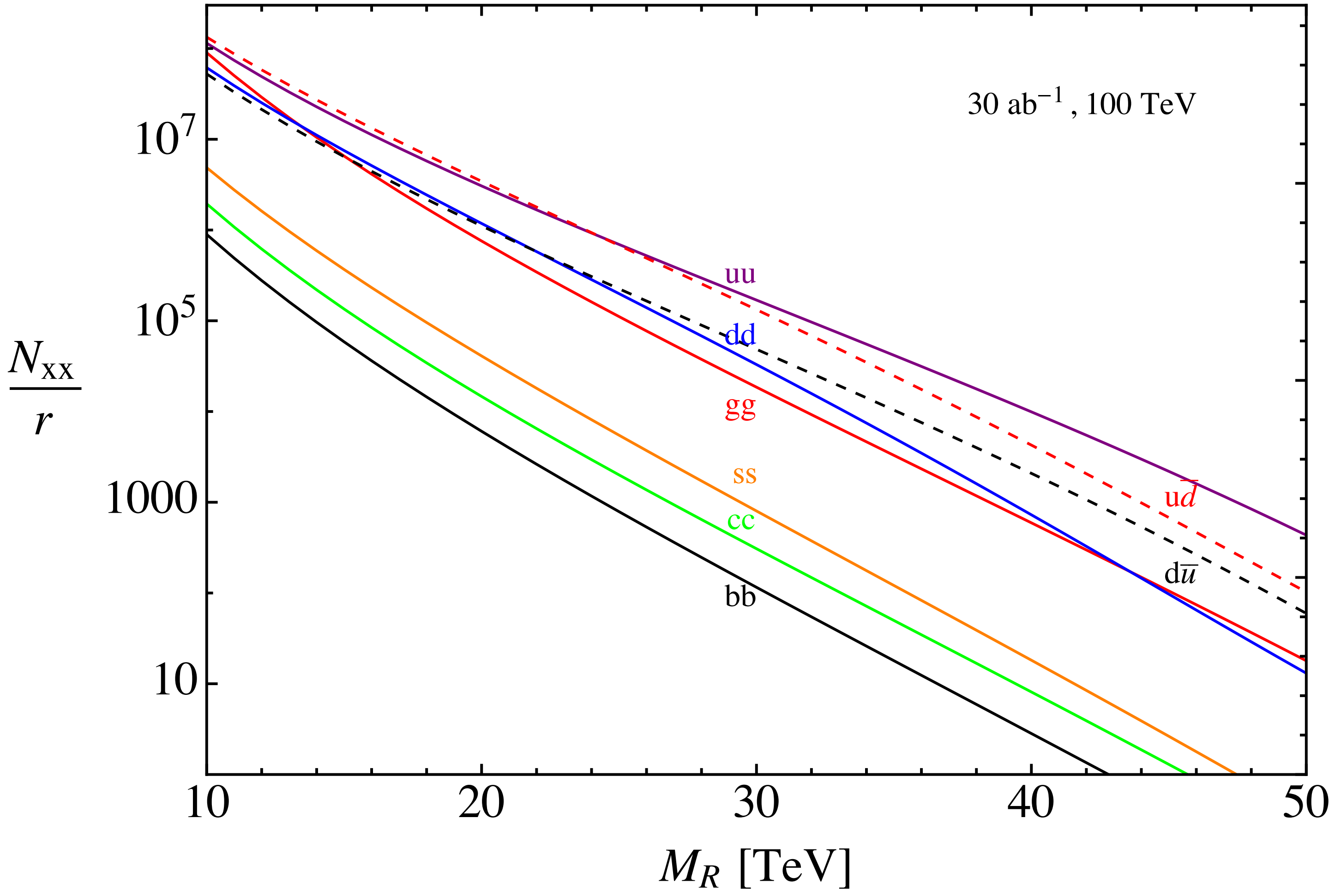
Plot from FCC CDR

Resonance production.

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

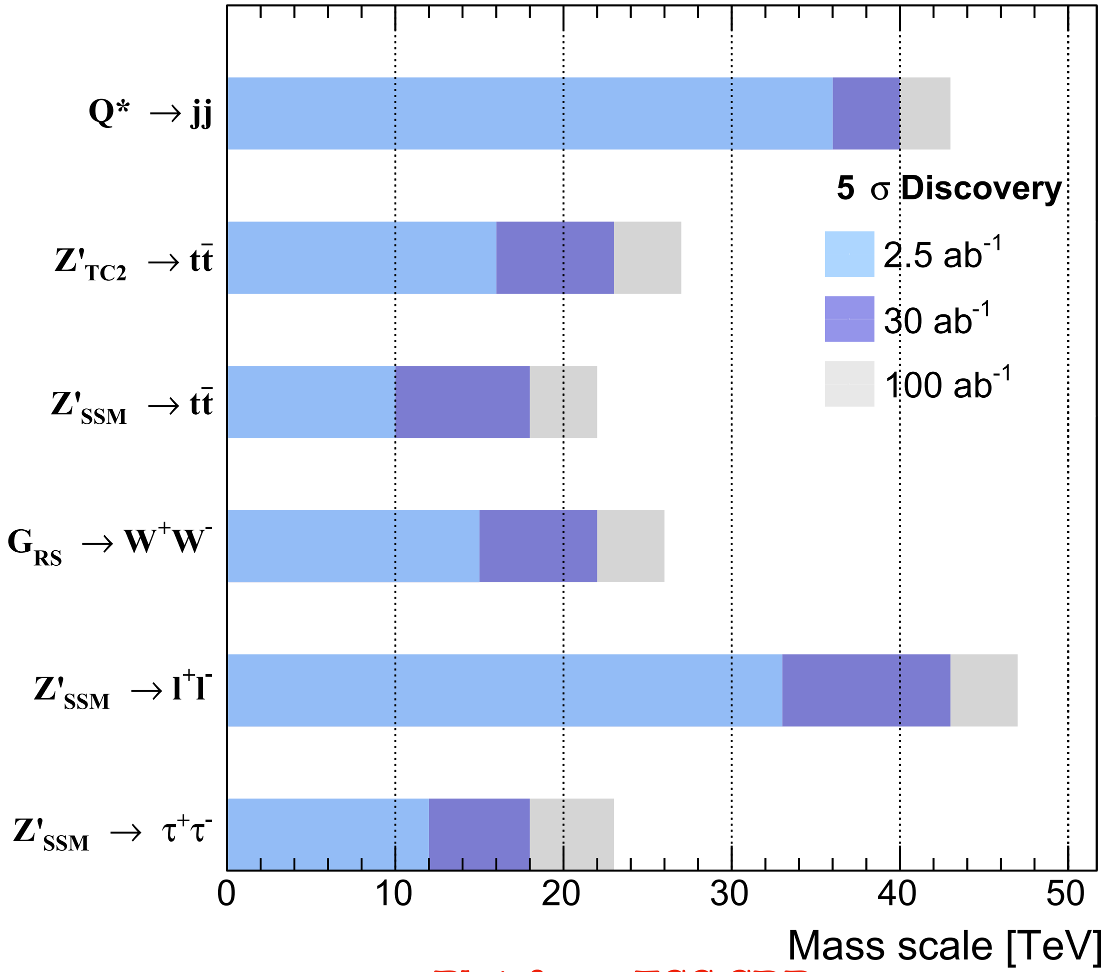
FCC-hh effectively collides 196 different initial states = perfect exploratory machine

resonances produced



Plot from mid-term report

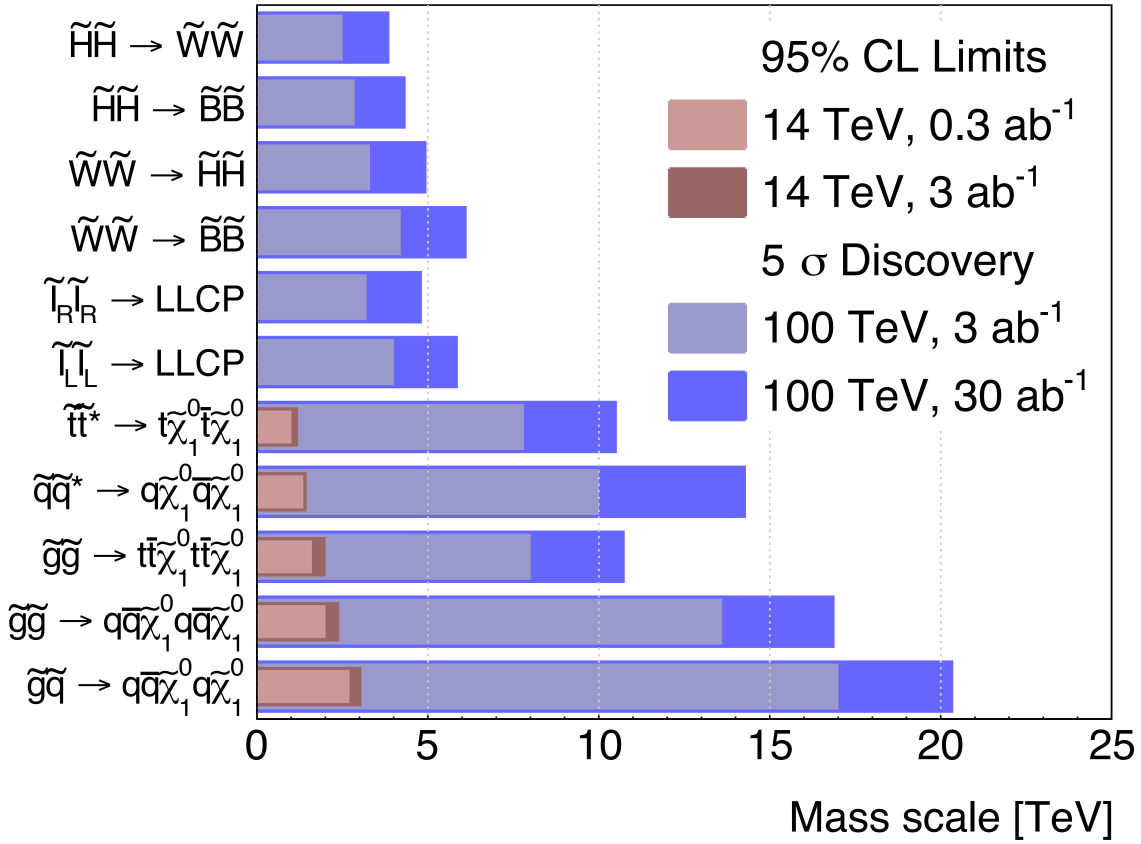
FCC-hh mass reach



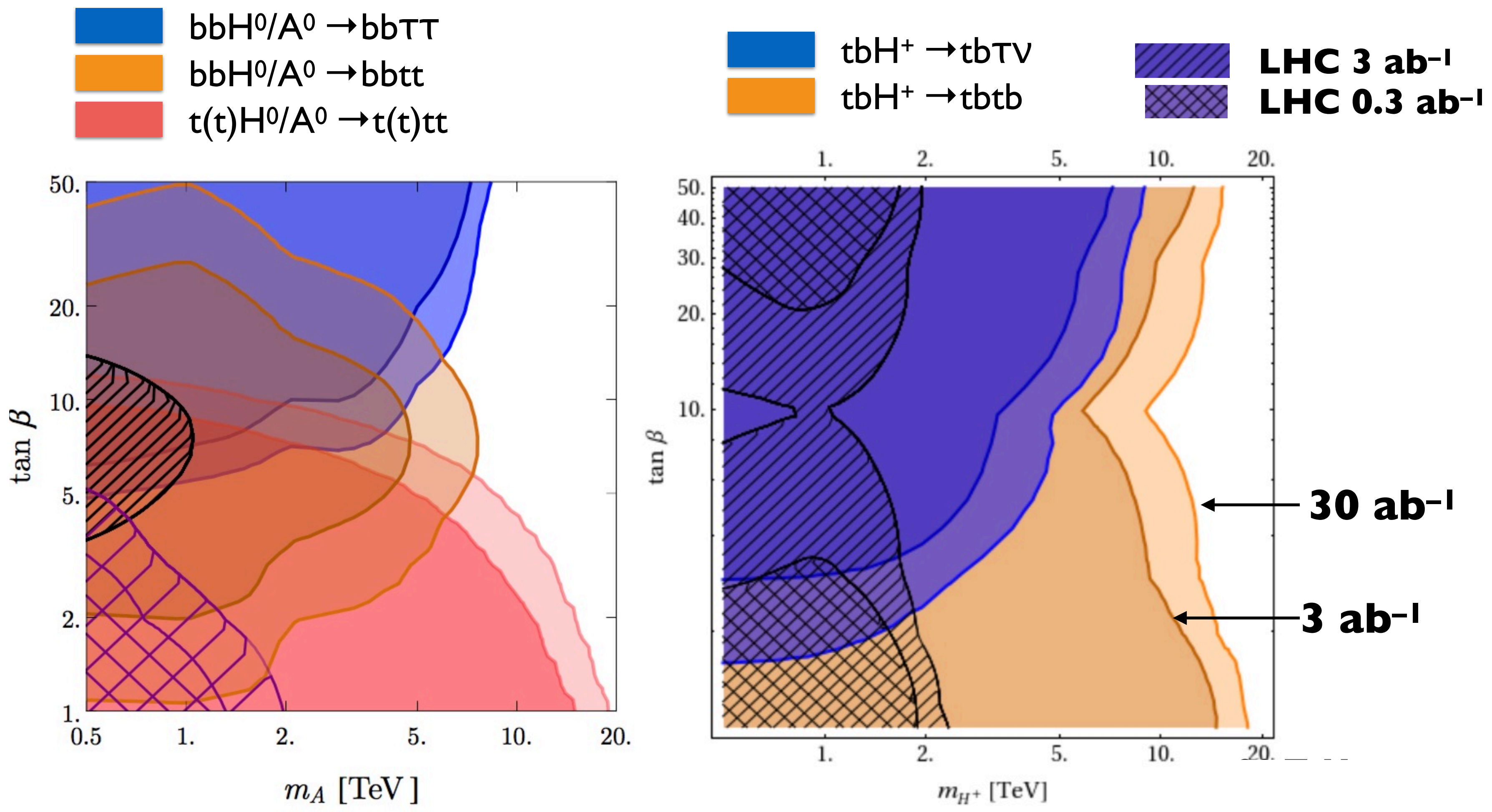
Plot from FCC CDR

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

Pushing limits of SUSY.



Plot from arXiv:1606.00947



Plot from arXiv:1605.08744 and arXiv:1504.07617

15-20TeV squarks/gluinos

require kinematic threshold 30-40TeV:

FCC-hh is more than a $\sqrt{\hat{s}}$~10TeV factory

Factor 10 increase on the HL-LHC limits.

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 Nb_3Sn magnets with higher lumi vs. 100TeV w. 16T vs. 120TeV w. 20T HTS)

FCC-ee has a rich and broad physics potential:

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

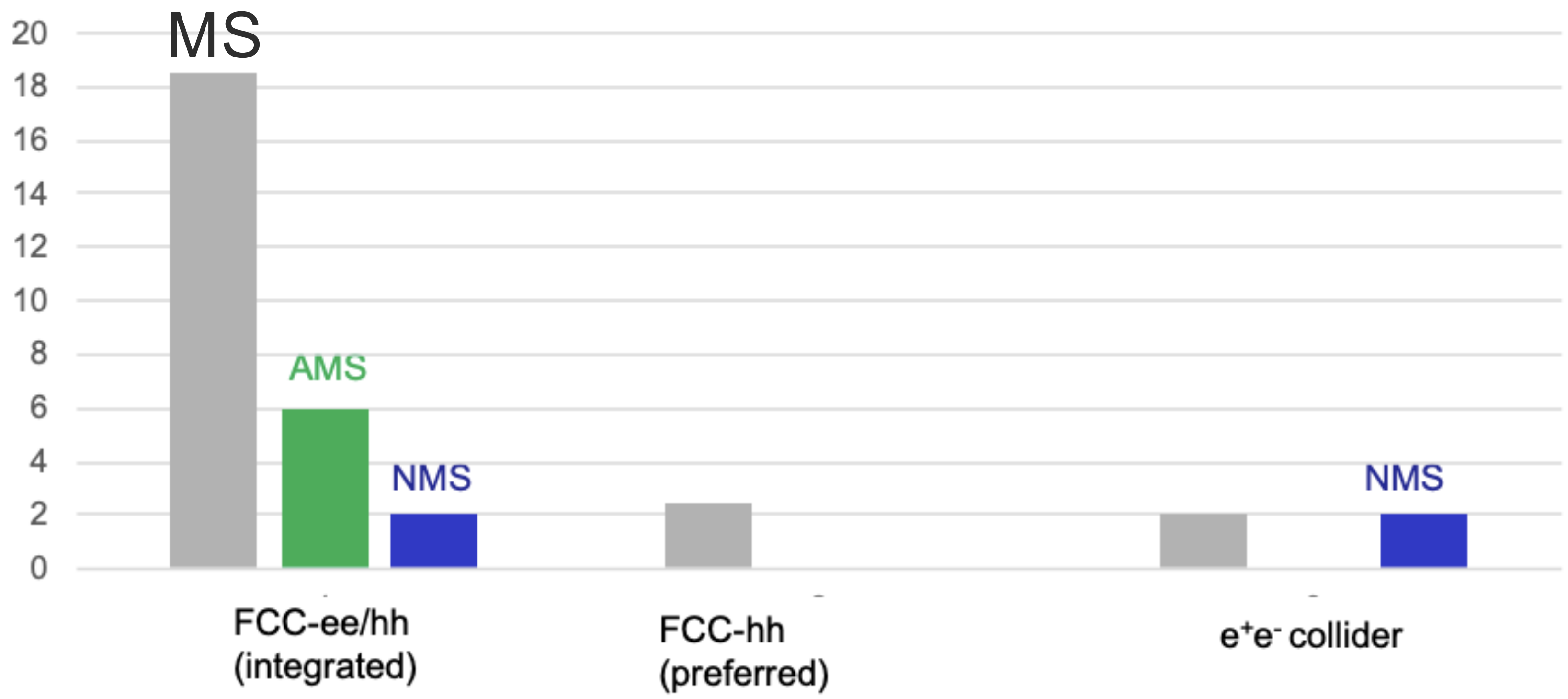
— parts of the SM central to the model and/or to the world around us are yet to be established —

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

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

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

Back from Venice
(European Strategy Symposium)



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

K. Jakobs, CERN Council, 20th June 2025

Photo Trevor Sherwin

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

Final Words

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

- FCC: Successful completion of the Feasibility Study; No technical showstoppers identified

- Overwhelming support for the integrated FCC-ee/hh programme by the HEP communities in the CERN Member and Associate Member states and beyond;

  The strong support is largely based on the superb physics potential and the long-term prospects (FCC-ee /hh)

- Discussions on the financial feasibility are ongoing (CERN management and Council)

Twenty Year from First Collisions

Twenty Year from First Collisions

Twenty Year from First Collisions

Reading Material

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

Reading Material

- **Feasibility Study Report** (backup documents) ESPPU#261
  - Volume 1: Physics, Experiments, Detectors (291 pages) CDS arXiv:2505.00272
  - Volume 2: Accelerators, technical infrastructure and safety (615 pages) CDS arXiv:2505.00274
  - Volume 3: Civil Engineering, Implementation and Sustainability (360 pages) CDS arXiv:2505.00273
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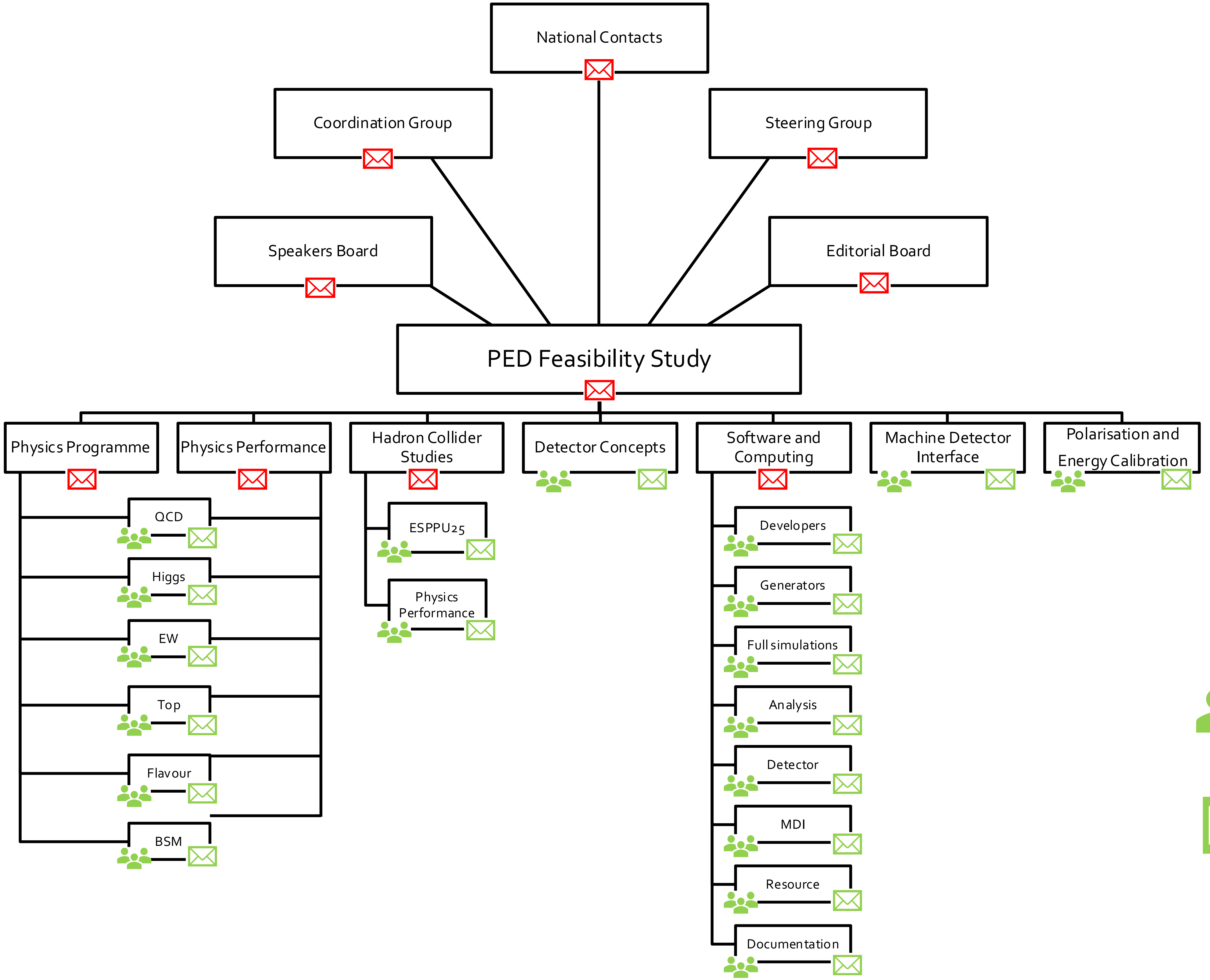
Join Us



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

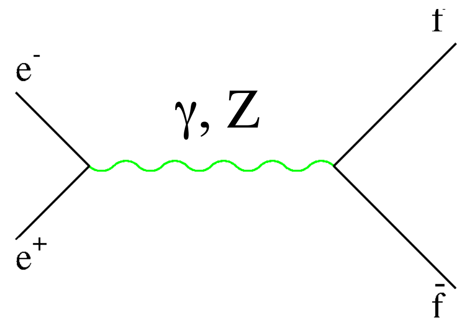
Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty	improvement factor / now
m_Z (keV)	91 187 600	±	2000	**4**	$\boxed{100}$	From Z line shape scan Beam energy calibration	20
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration	200
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	150
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate	
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons	
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit	
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement	
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement	
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons	2000
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge	
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics	
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass	
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR	
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency	
m_W (MeV)	80 360.2	±	9.9	$\boxed{\mathbf{0.18}}$	0.16	From WW threshold scan Beam energy calibration	50
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration	
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit	
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns	
m_{top} (MeV)	172 570	±	290	$\boxed{\mathbf{4.2}}$	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate	70
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate	
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate	
ttZ couplings		±	30%	**0.5–1.5** %	small	From $\sqrt{s} = 365$ GeV run	

EW Precision Measurements at FCC-ee

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

Example of EW measurements @ Tera Z

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



The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$

The Z exchange term is proportional to G^2_F, hence independent of α_{QED}

The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$

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

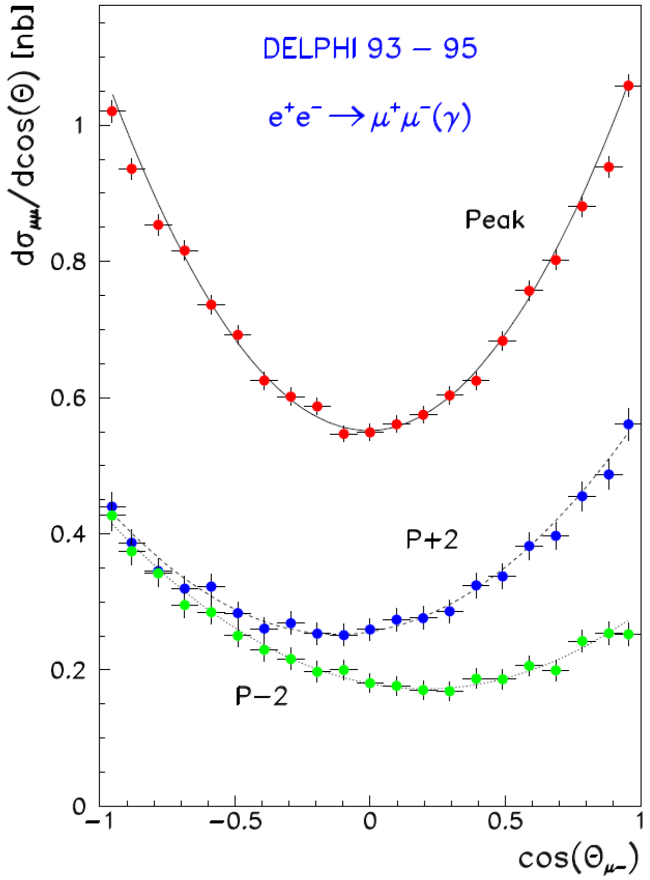
$$\leftarrow \quad \leftarrow \quad \leftarrow \qquad A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4}\mathcal{A}_e\mathcal{A}_\mu \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{QED}(s)}{m_Z^2 G_F\left(1 - 4\sin^2\theta_W^{\rm eff}\right)^2}\frac{s - m_Z^2}{2s}\right]$$

strongly depends on $\sqrt{s}$

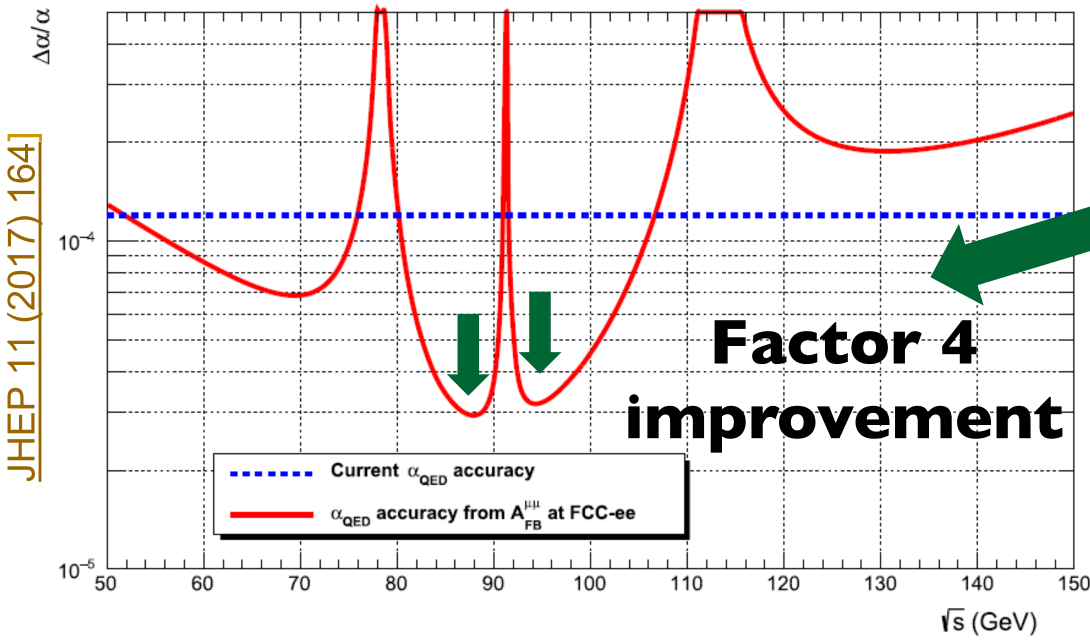
direct measurement of $\alpha_{QED}(s)$ at $\sqrt{s}$!= m_Z

measure $\sin^2\theta_W$ to high precision (later)

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



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



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

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

→ Measure $\alpha_{QED}(m_Z^2)$ to 3×10^{-5} rel. precision (currently 1.1×10^{-4})

→ Stat. dominated; syst. uncertainties < 10^{-5} (dominated by $\sqrt{s}$ calib)

→ Theoretical uncertainties ~ 10^{-4}, higher order calcs needed

W Mass

Two independent W mass and width measurements @FCCee :

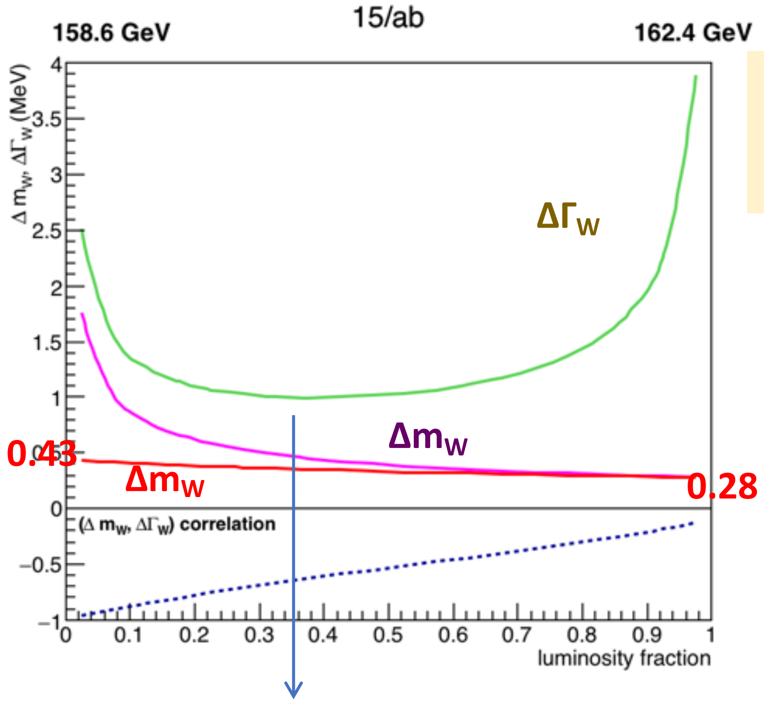
1. **The** m_W and Γ_W determinations from the WW threshold cross section lineshape, with 12/ab at $E_{CM} \simeq$ 157.5-162.5 GeV

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

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

   Δm_W , $\Delta\Gamma_W$= 2-5 MeV ?

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



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

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

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

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

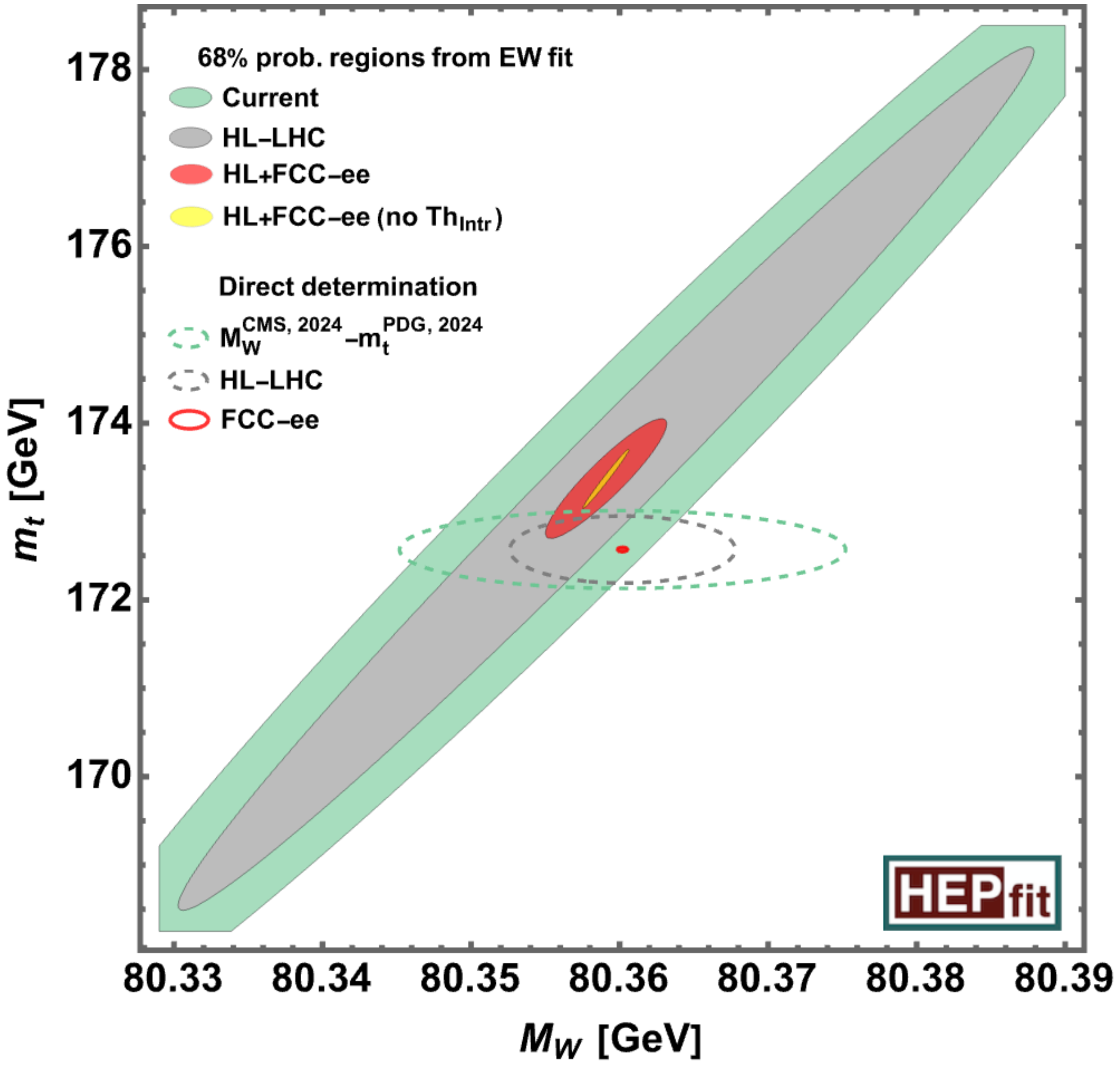
Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both
Δm_W : error on W mass from fitting only m_W

Comparable in sensitivity with value from EWPO fit.

Tera-Z EW precision measurements.

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

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



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 $e^+e^- \to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^- \to f\bar{f}$
Γ_Z (MeV)	2.3	0.004 (0.012)			
$\sin^2\theta^\ell_{eff}$	1.6×10^{-4}	$1.2\ (1.2)\times10^{-6}$			
m_W (MeV)	9.9	0.18 (0.16)	lineshape of $e^+e^- \to WW$ near threshold	NLO ($e^+e^- \to 4f$ or EFT framework)	NNLO for $e^+e^- \to WW$, $W \to f\bar{f}'$ in EFT setup
HZZ coupling	–*	0.1%	cross section for $e^+e^- \to ZH$	NLO EW plus partial NNLO QCD/EW	full NNLO EW
m_{top} (MeV)	290	4.2 (4.9)	threshold scan $e^+e^- \to t\bar{t}$	N^{3}LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}$(30 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

FCC-ee special

$\alpha_{QED}(m_Z)$: Stat. 3×10^{-5}

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

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

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

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

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

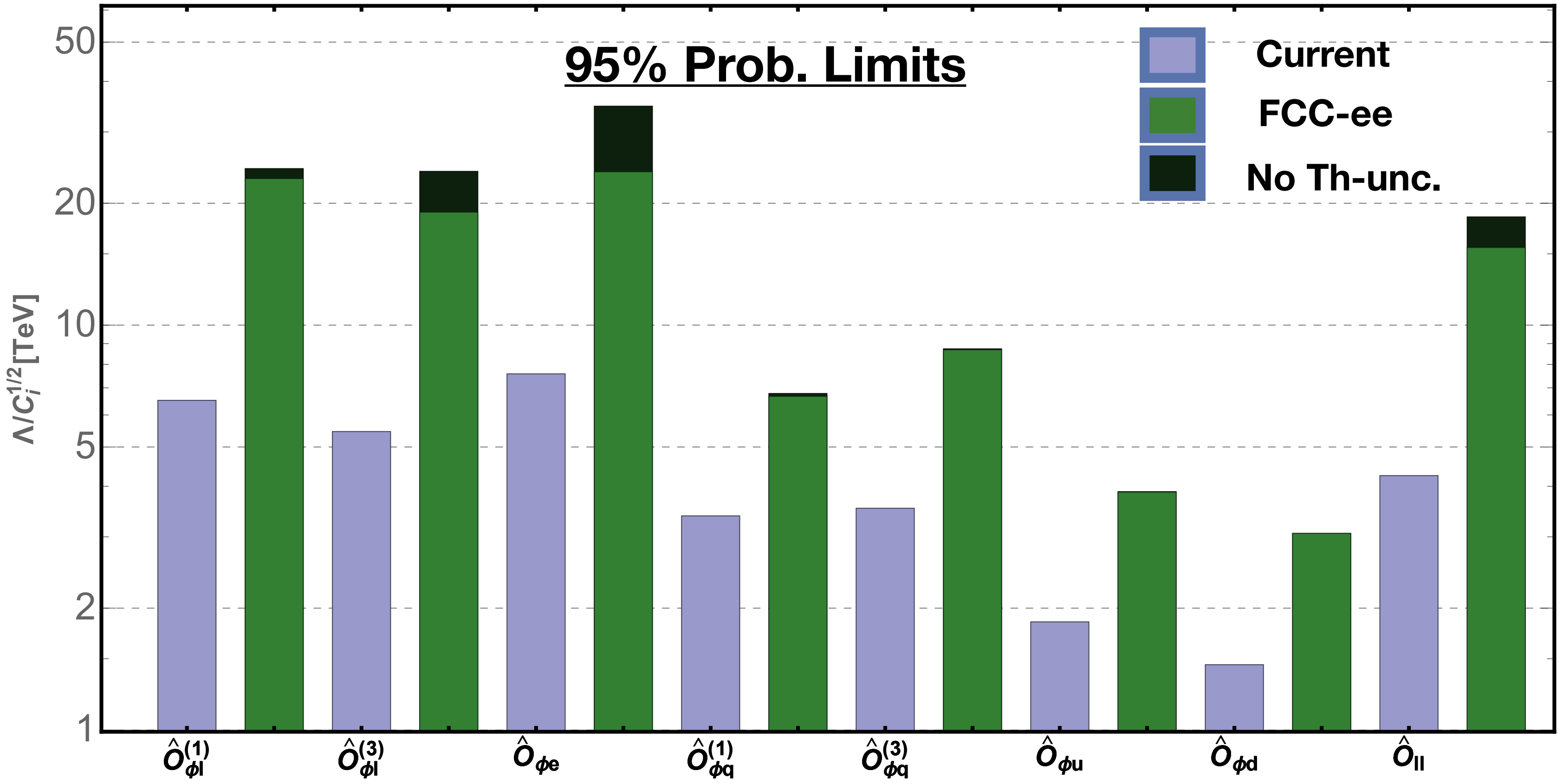
Z (and W) mass: Stat. 4 keV (250 keV)

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

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

Impact of TH uncertainties.

J. de Blas, FCC CDR overview '19

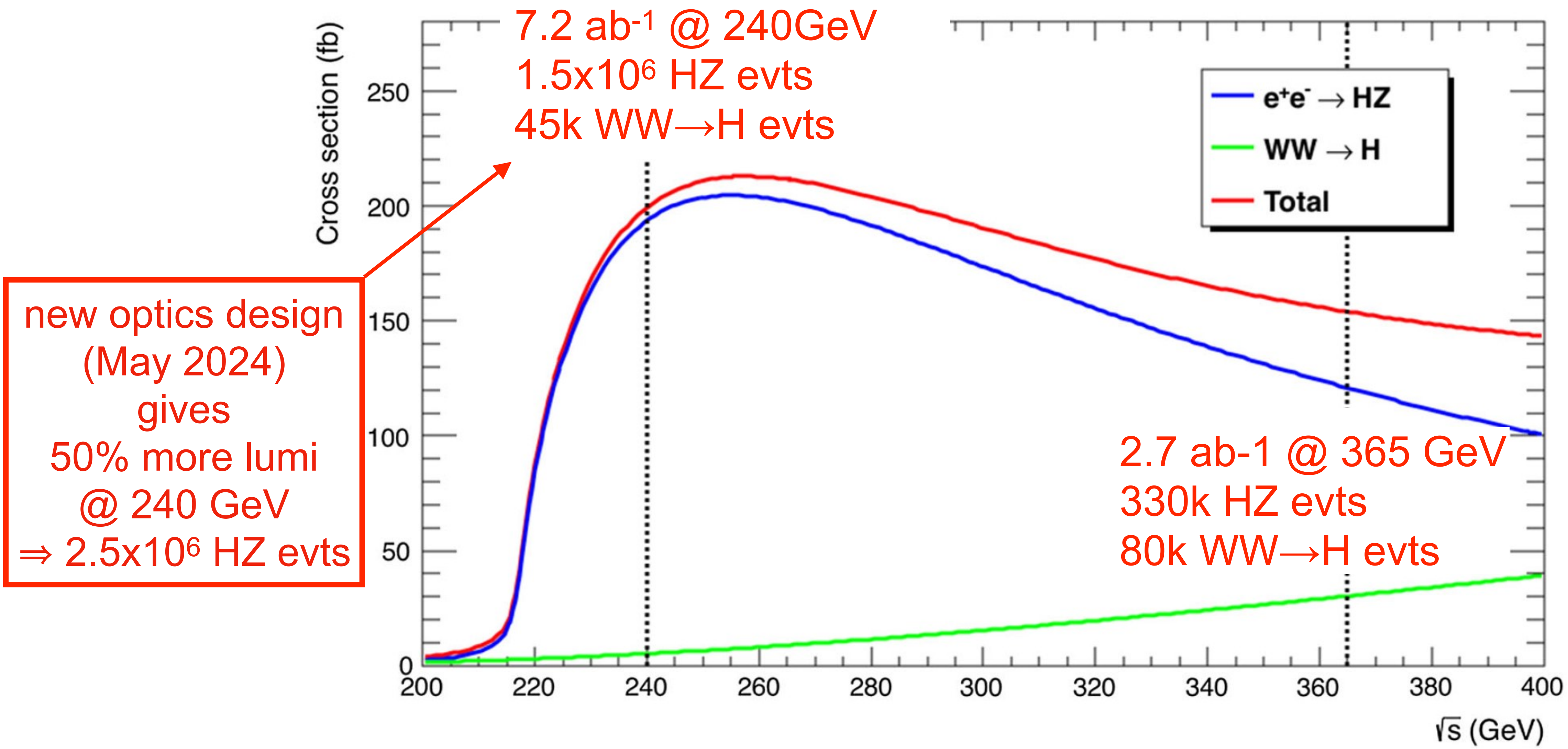


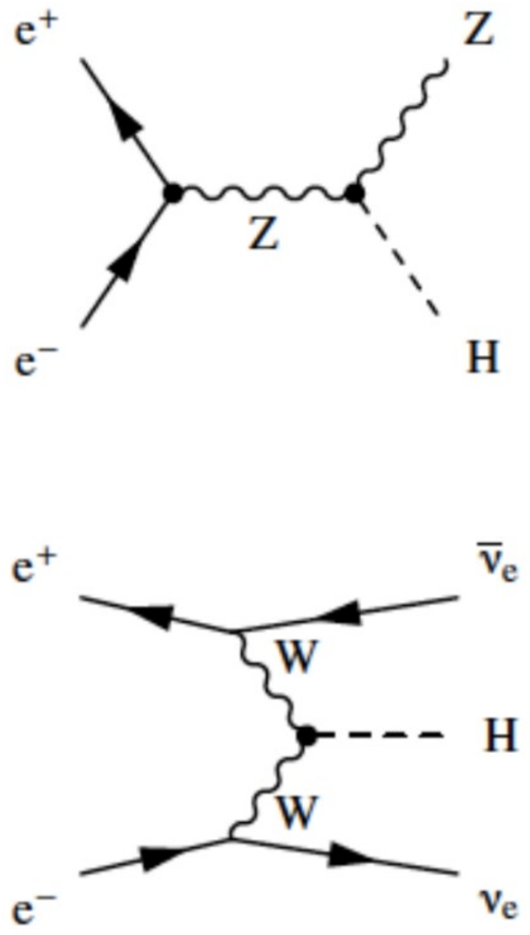
	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
δM_W [MeV]	± 15	± 8	± 1	$\pm 0.6/\pm 1$	± 1
$\delta \Gamma_Z$ [MeV]	± 2.3	± 0.73	± 0.1	± 0.1	± 0.2
$\delta \mathcal{A}_\ell\,[\times 10^{-5}]$	± 210	± 93	± 2.1	$\pm 8/\pm 14$	± 11.8
$\delta R_b^0\,[\times 10^{-5}]$	± 66	± 3	± 6	± 0.3	± 5

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: ∞/3/2/1.5/1.2 on $\kappa_\lambda / \kappa_W / \kappa_b / \kappa_g, \kappa_c / \kappa_\gamma$ (plot in bonus)

Higgs @ FCC-ee.

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

Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee
κ_{Z} (%)	1.3*	0.10
κ_{W} (%)	1.5*	0.29
κ_{b} (%)	2.5*	0.38 / 0.49
κ_{g} (%)	2*	0.49 / 0.54
κ_{τ} (%)	1.6*	0.46
κ_{c} (%)	–	0.70 / 0.87
κ_{γ} (%)	1.6*	1.1
$\kappa_{\mathrm{Z}\gamma}$ (%)	10*	4.3
κ_{t} (%)	3.2*	3.1
κ_{μ} (%)	4.4*	3.3
$\lvert\kappa_{\mathrm{s}}\rvert$ (%)	–	$^{+29}_{-67}$
Γ_{H} (%)	–	0.78
$\mathcal{B}_{\mathrm{inv}}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{\mathrm{unt}}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

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

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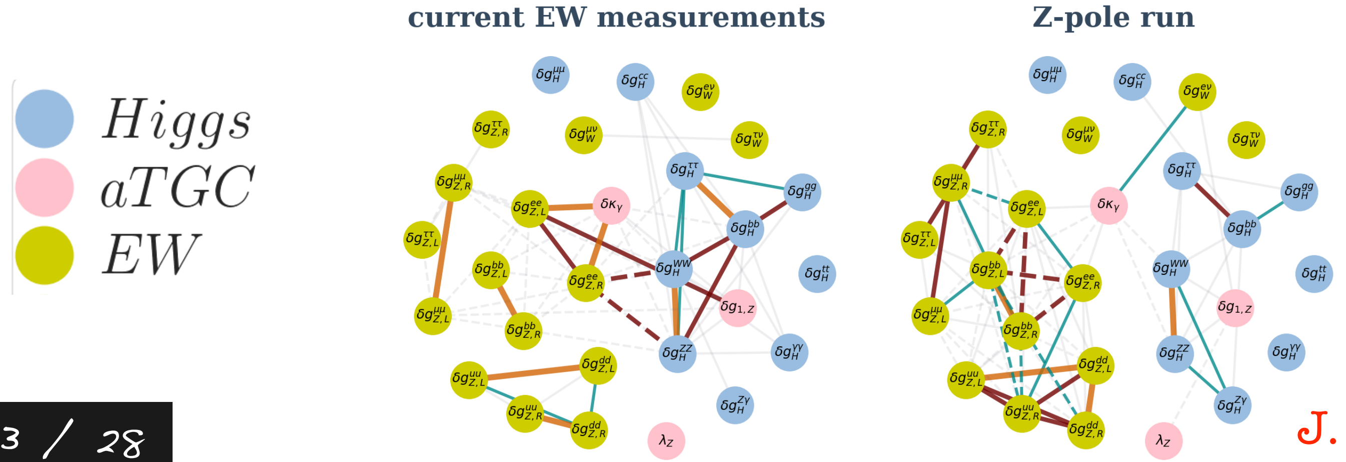
— Higgs programme needs Z-pole —



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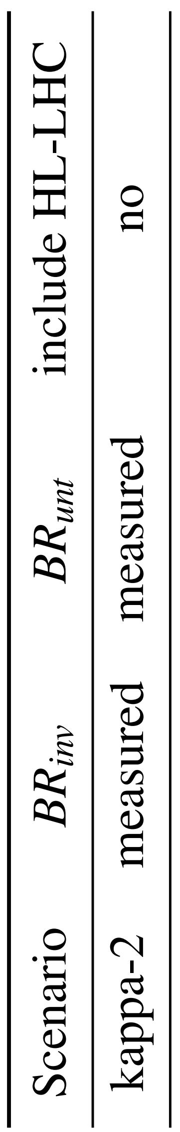
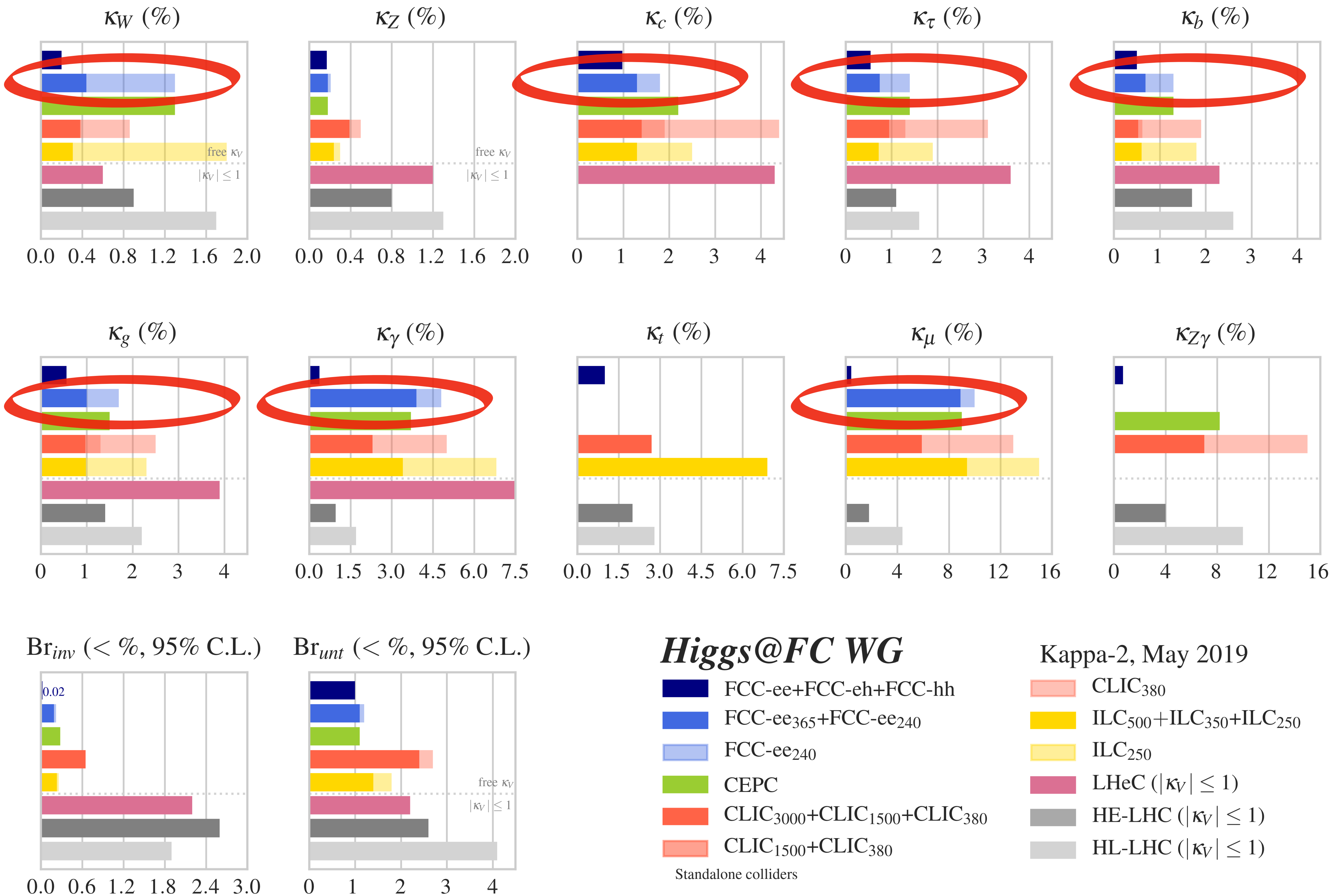
J. De Blas et al. 1907.04311

Complementarity 240↔365 GeV.

ECFA Higgs study group '19



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



back to main discussion

Complementarity FCC-ee↔HL-LHC.

ECFA Higgs study group '19

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

hadron collider cannot measure width
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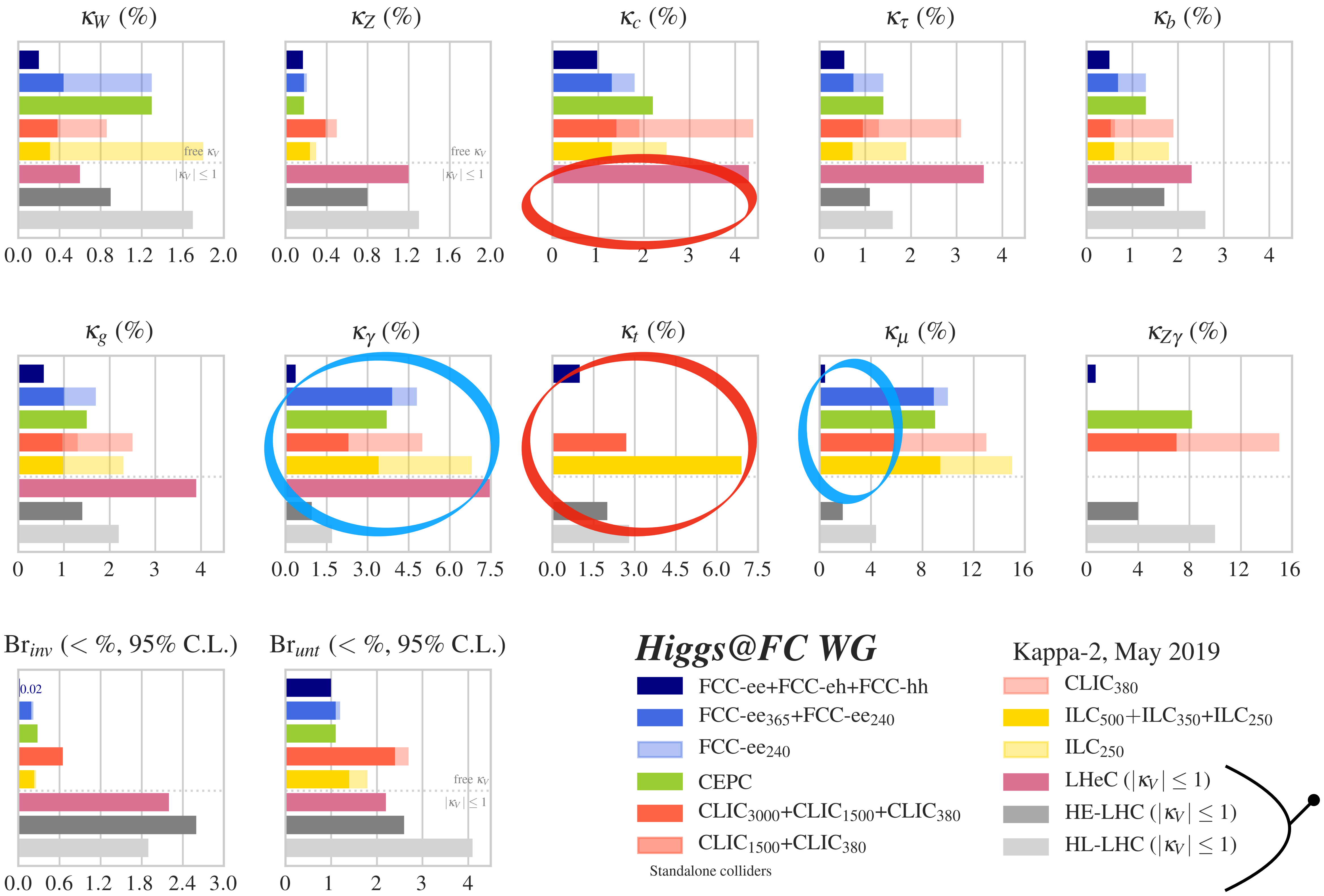
e.g. κ_V<1



assumption needed for the fit to close at hadron machines

back to main discussion

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ECFA Higgs study group ‘19

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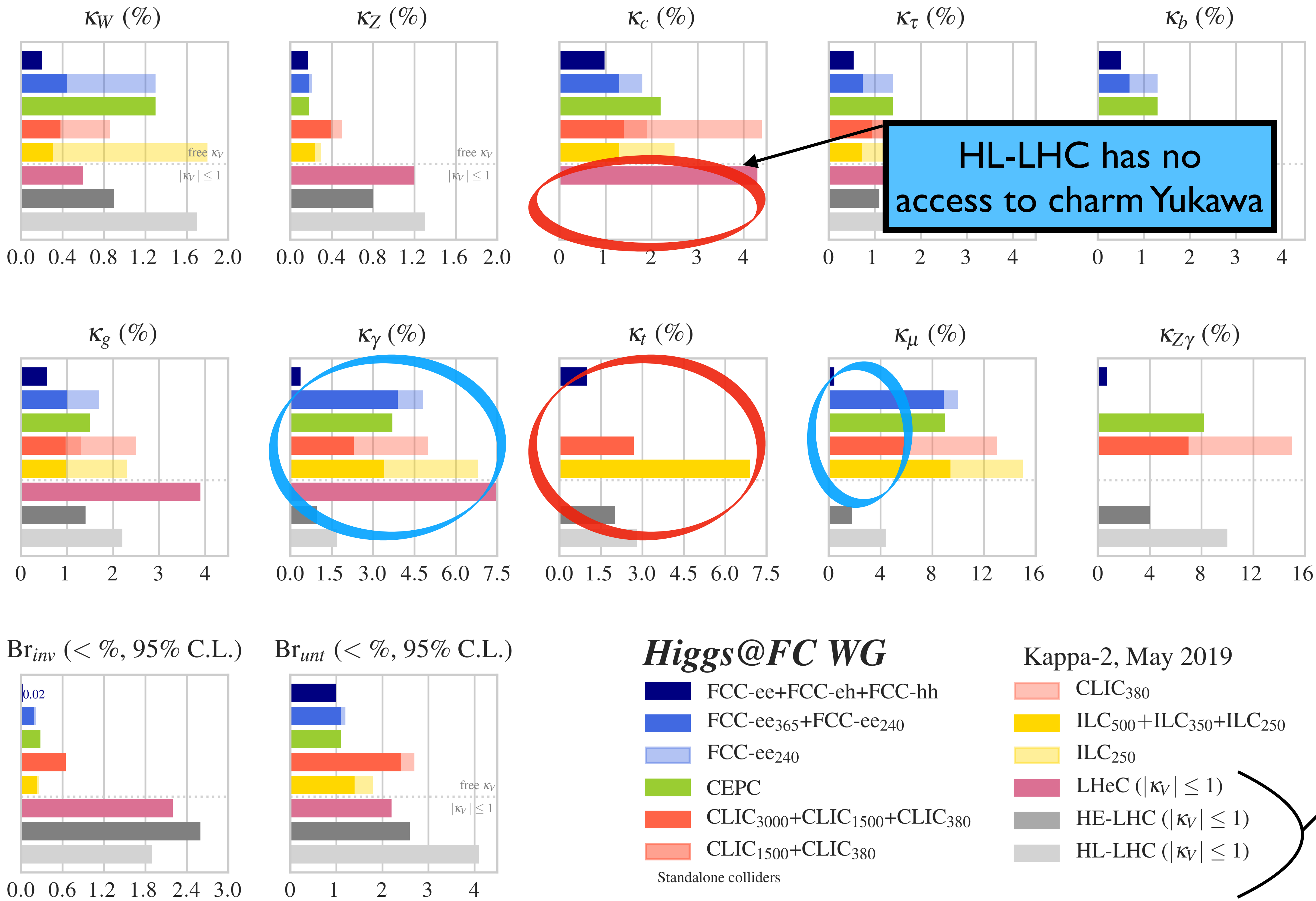

HL-LHC has no access to charm Yukawa

assumption needed for the fit to close at hadron machines

back to main discussion

Complementarity FCC-ee↔HL-LHC.

ECFA Higgs study group '19

Scenario	kappa-2
BR_{inv}	measured
BR_{unt}	measured
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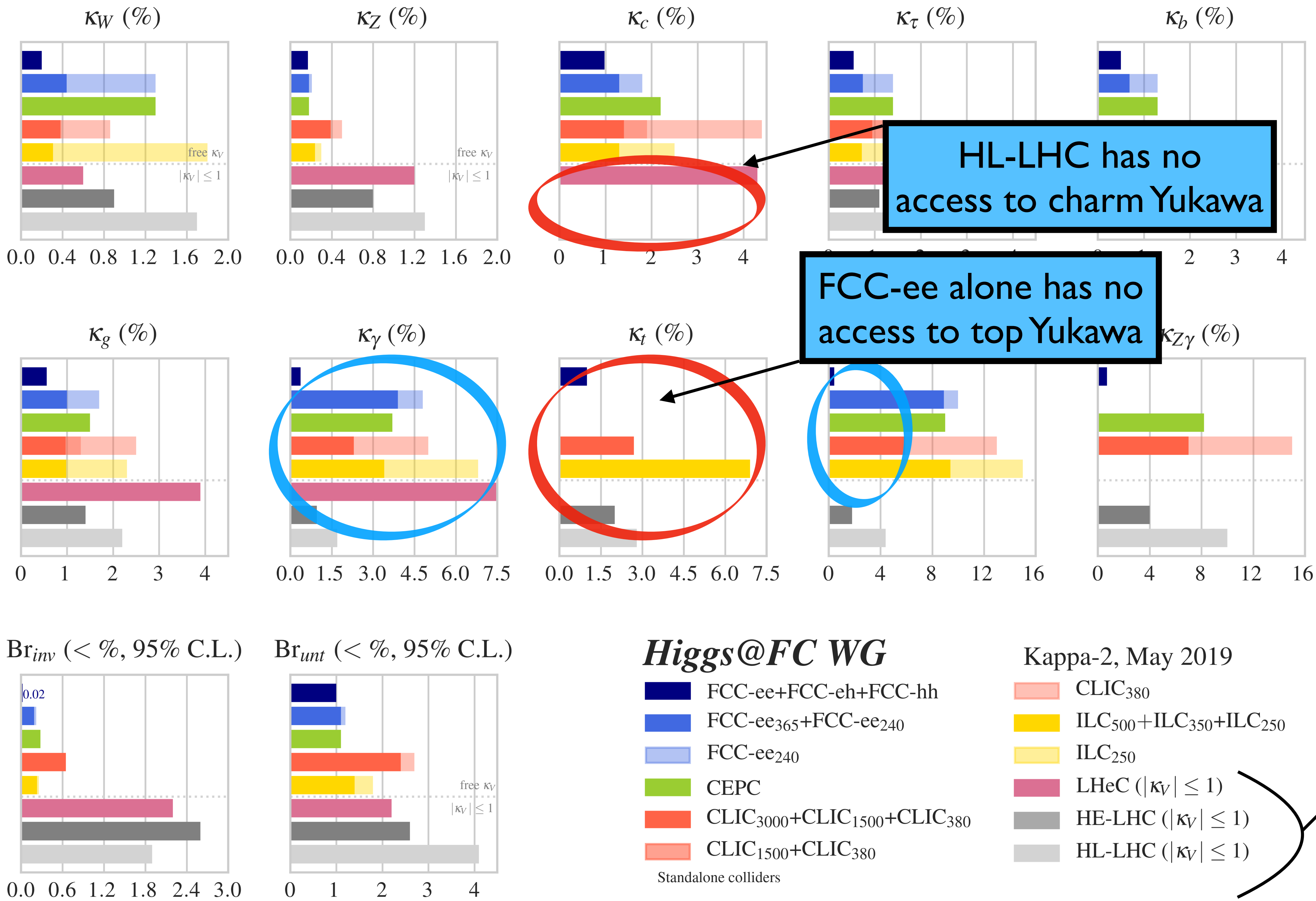

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back to main discussion

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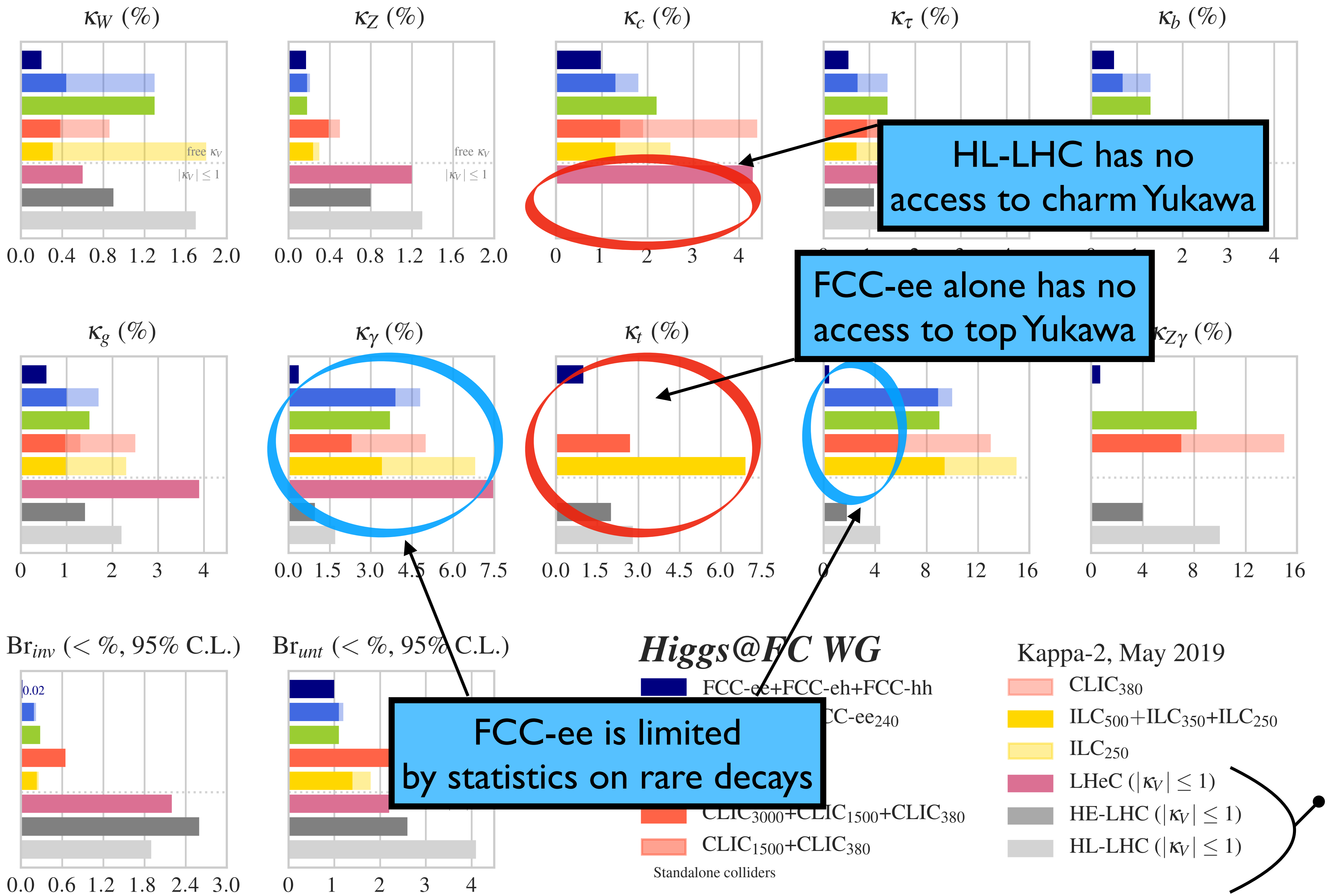

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back to main discussion

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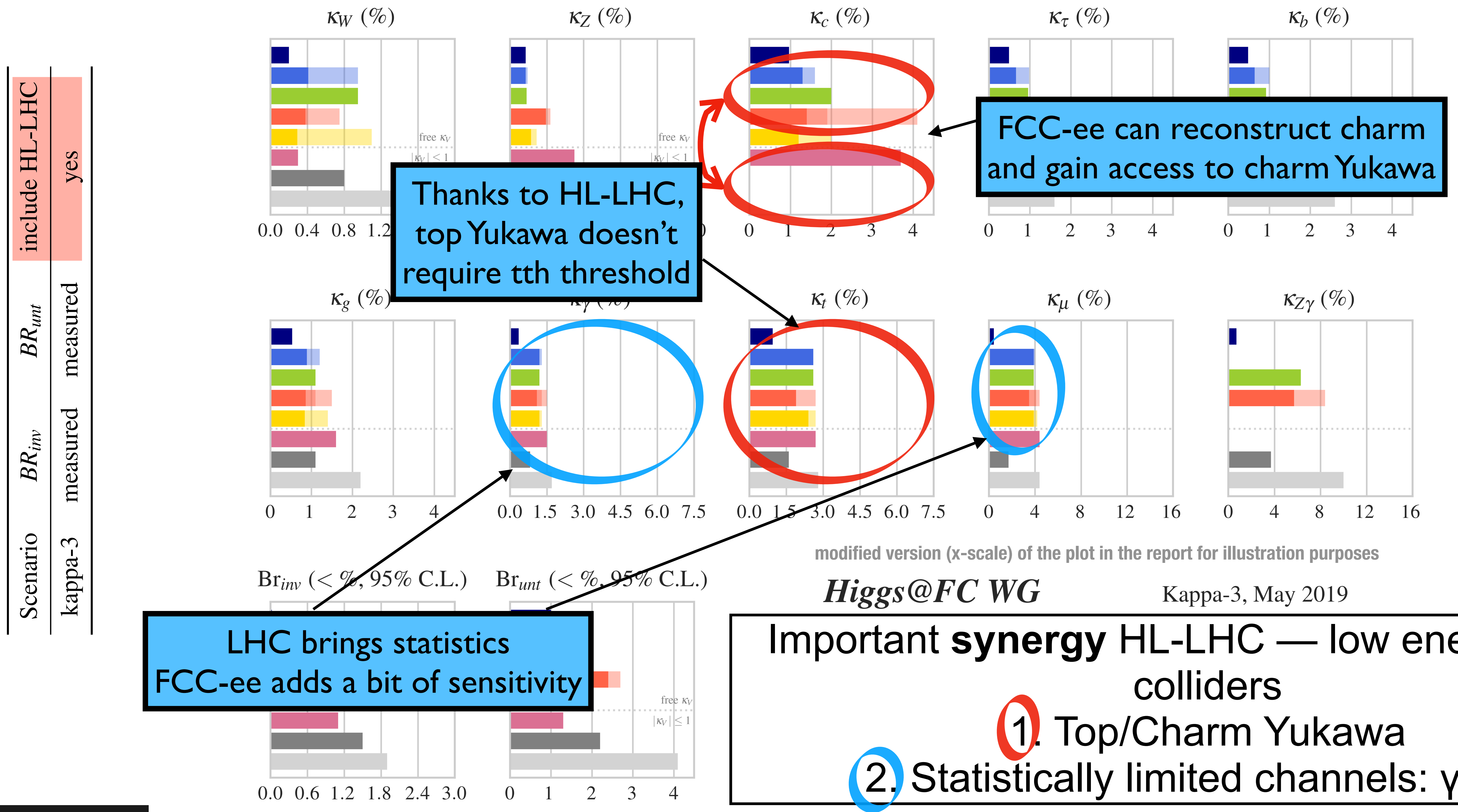


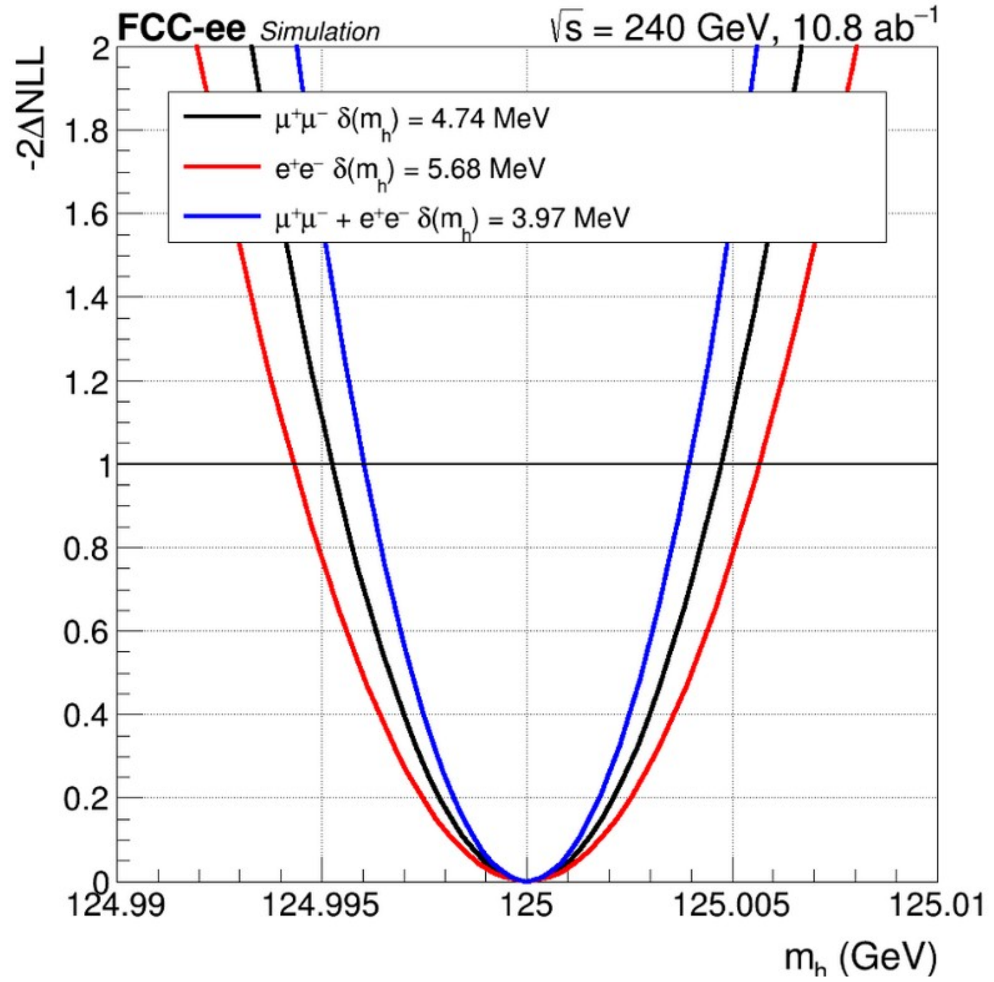
back to main discussion

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

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

Higgs Mass

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



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

Nominal configuration → Nominal

Crystal ECAL to Dual Readout → Degradation electron resolution

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

IDEA drift chamber → CLD Si tracker → Silicon tracker

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

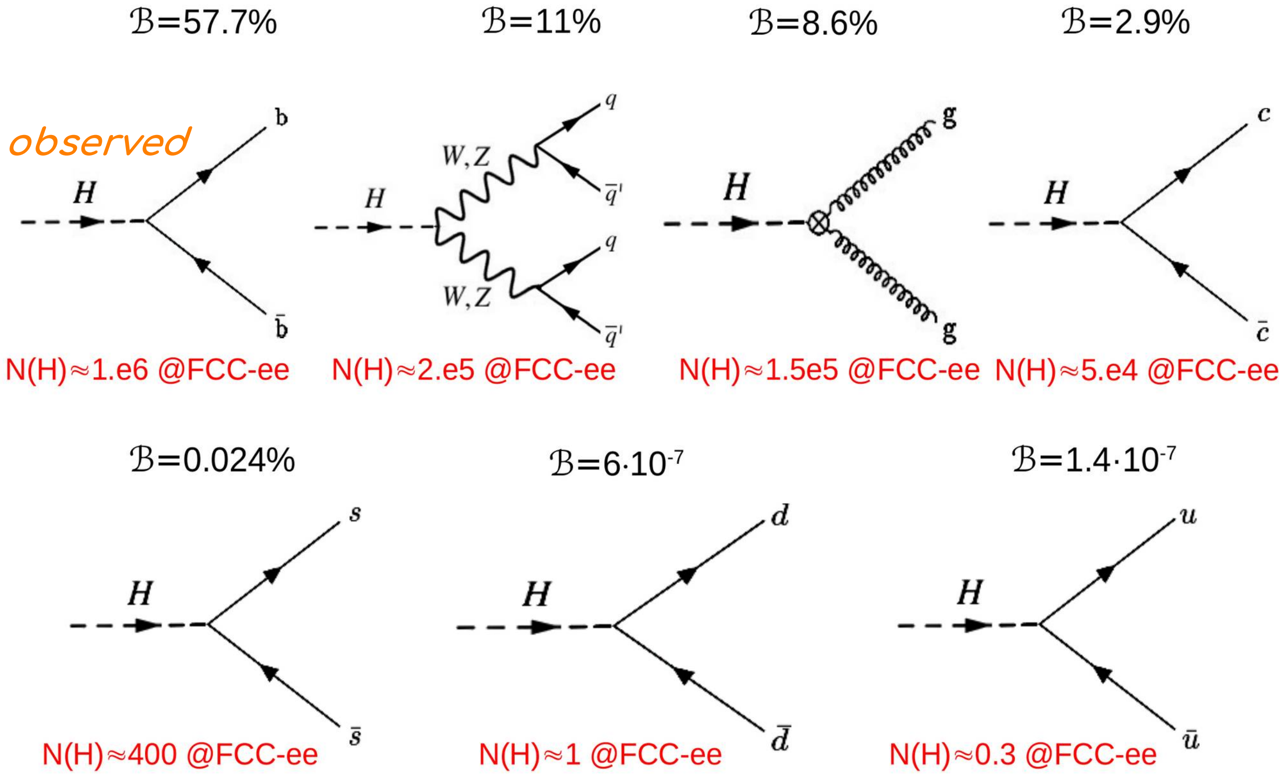
Perfect (=gen-level) momentum resolution → Ideal resolution

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

Hadronic Decays

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

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



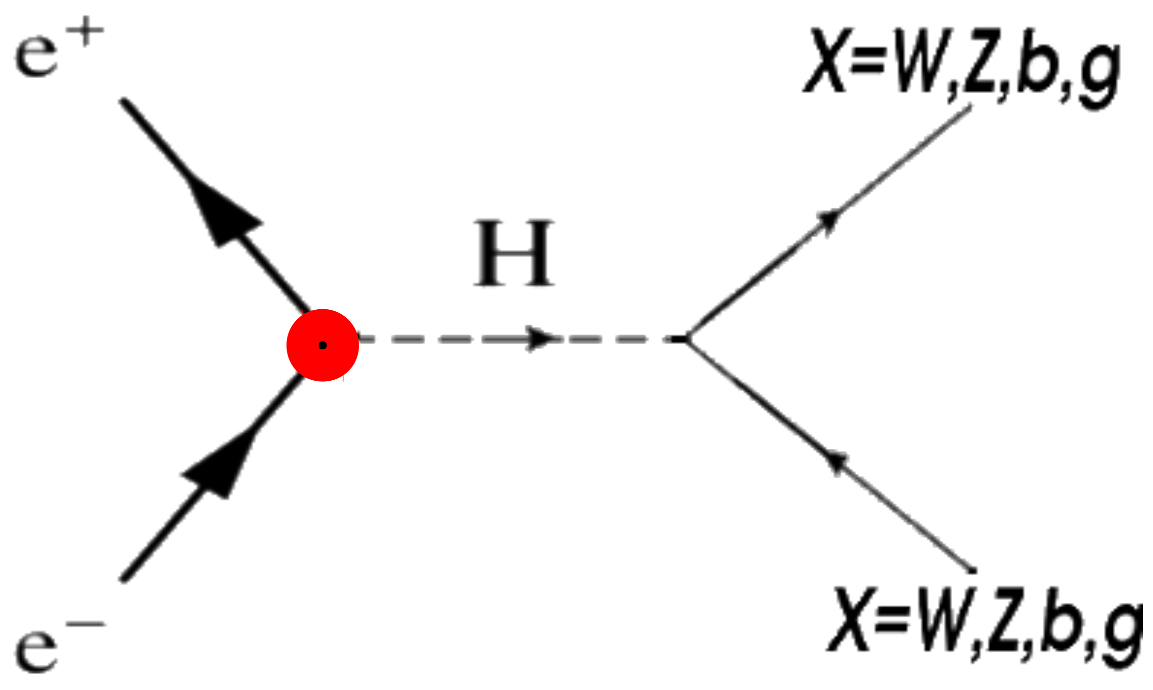
Solid measurements in 2nd generation

Interesting prospects for 1st generation and FCNC decays

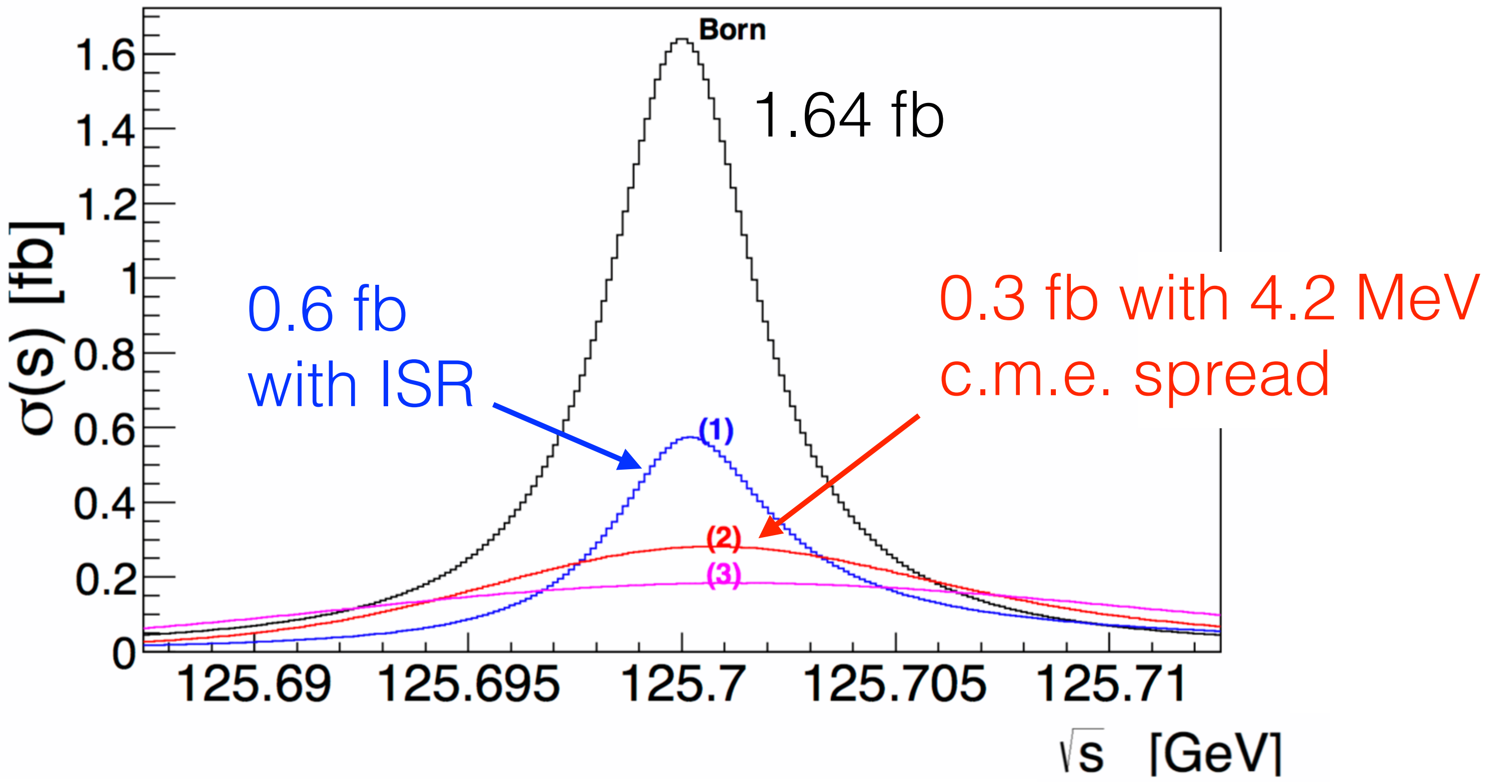
	σ×BR 95% CL	BR(SM)
H→dd	1.4e-03	6e-07
H→uu	1.5e-03	1.4e-07
H→bs	3.7e-04	e-07
H→bd	2.7e-04	e-09
H→sd	7.7e-04	e-11
H→cu	2.5e-04	e-20

Electron Yukawa

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



Jadach+, arXiv: 1509.02406



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

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

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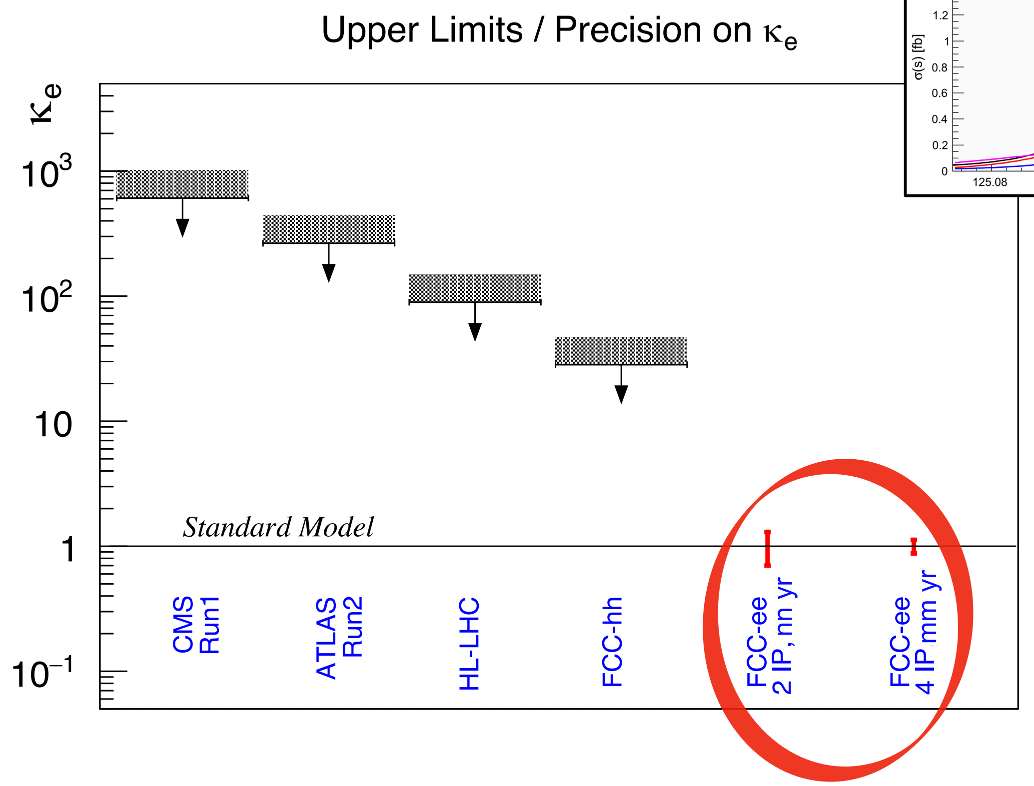
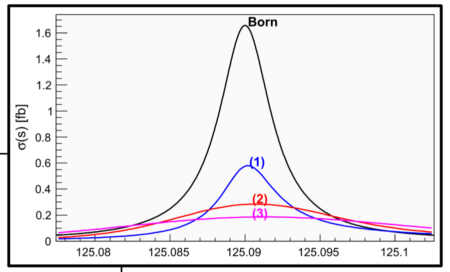
- **20 ab^{-1} / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}}$ ~ 1-2 × Γ_H ~ 6 to 10 MeV**
  - **Resonant ee → H production**





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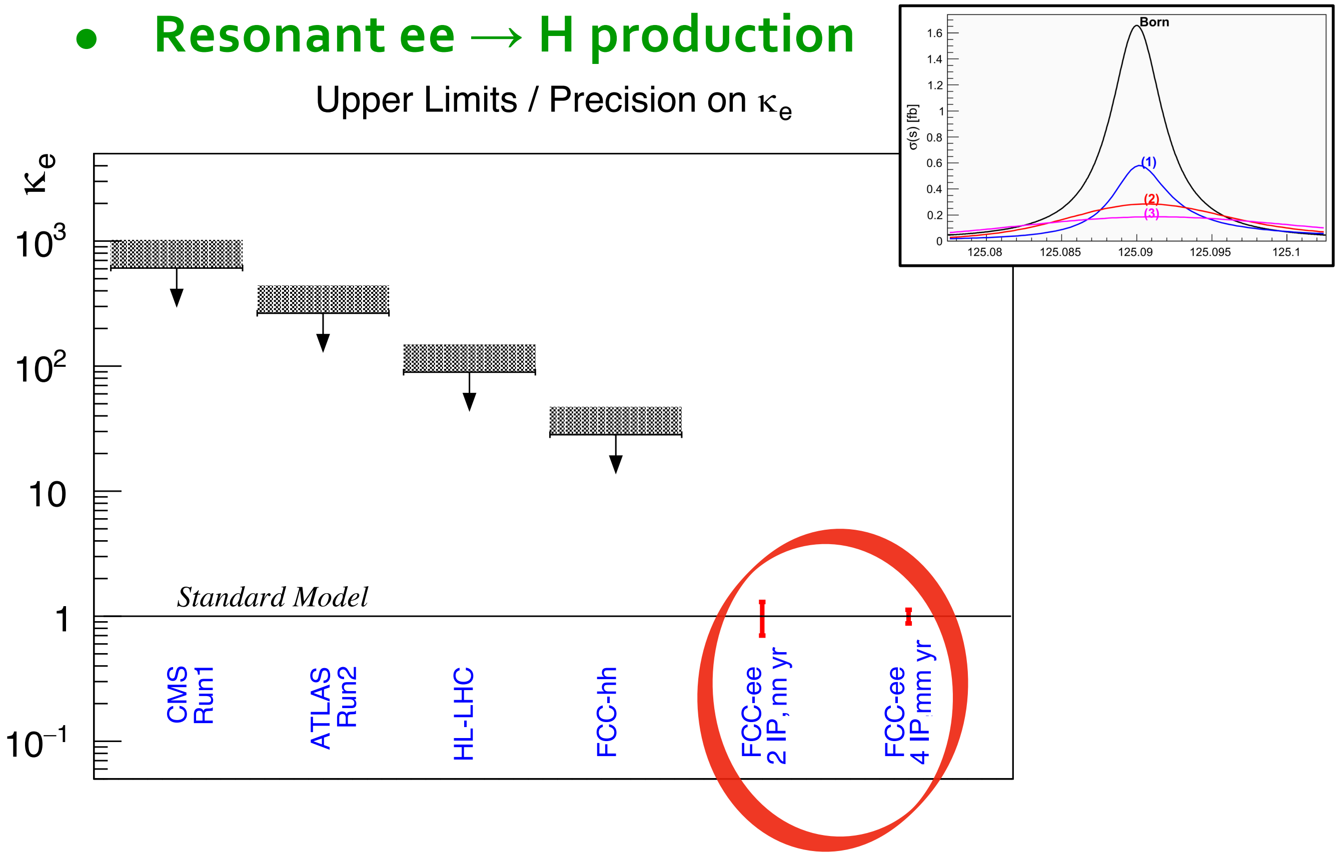
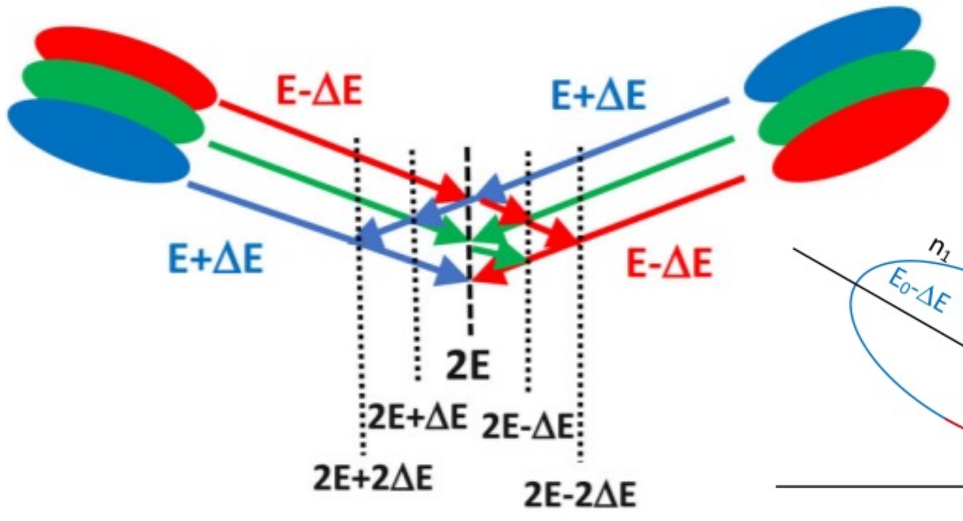


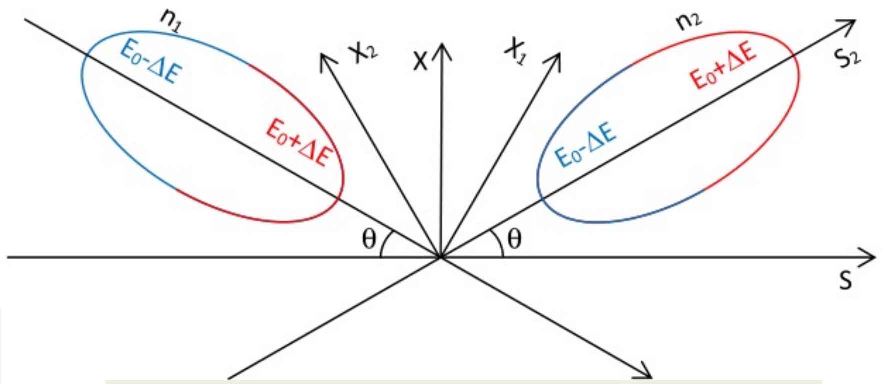
Monochromatisation

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

combine?



opposite sign horizontal dispersion



opposite difference in arrival time

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d'Enterria+. arXiv: 2107.02686

Higgs decay channel	$\mathcal{B}$	$\sigma\times\mathcal{B}$	Irreducible background	σ	S/B
$e^+e^-\to H\to b\bar{b}$	58.2%	164 ab	$e^+e^-\to b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^-\to H\to gg$	8.2%	23 ab	$e^+e^-\to q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^-\to H\to \tau\tau$	6.3%	18 ab	$e^+e^-\to \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^-\to H\to c\bar{c}$	2.9%	8.2 ab	$e^+e^-\to c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
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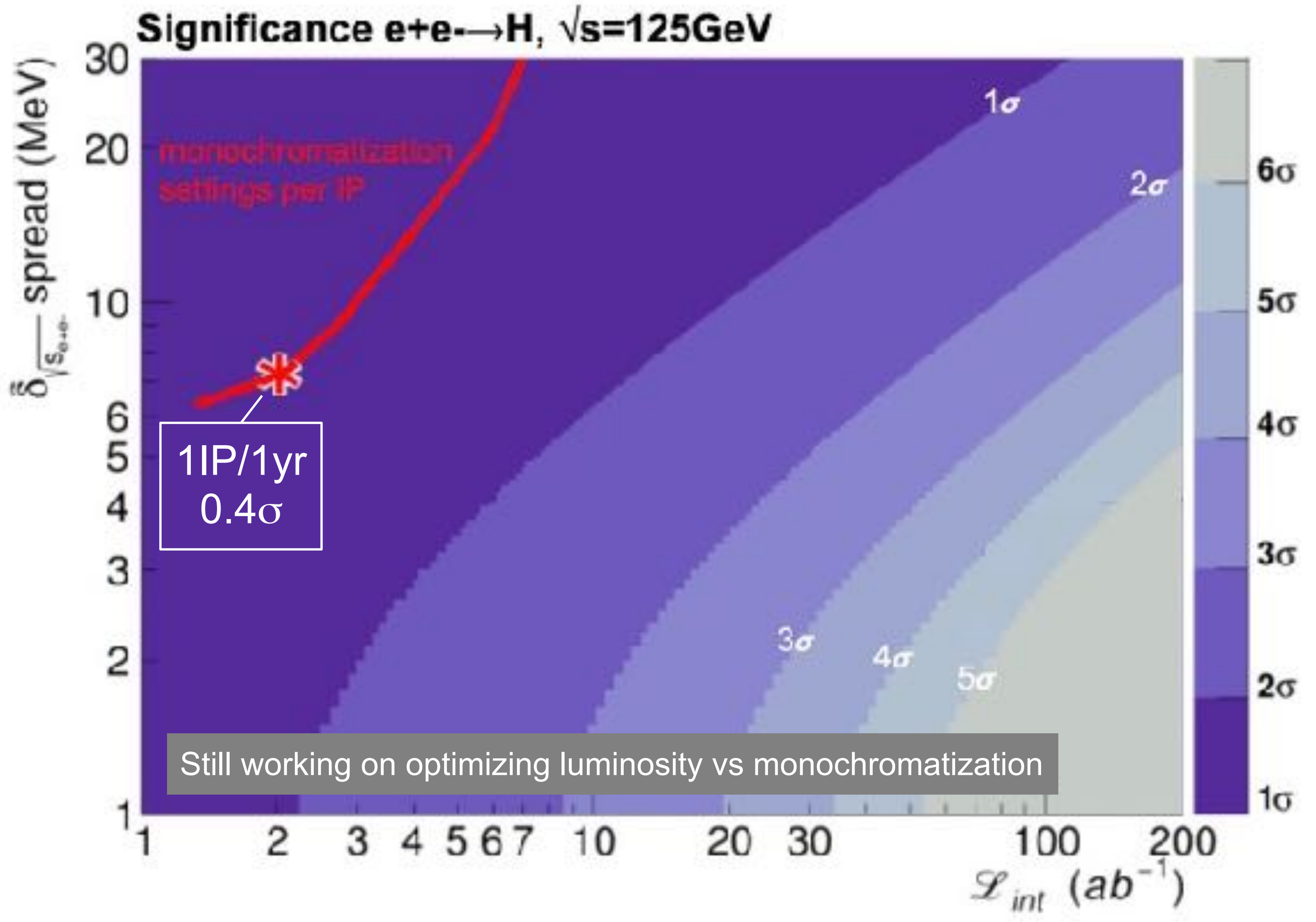
w. 10/ab

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

w/ 10/ab: S~55, B~2400 → 1.1σ



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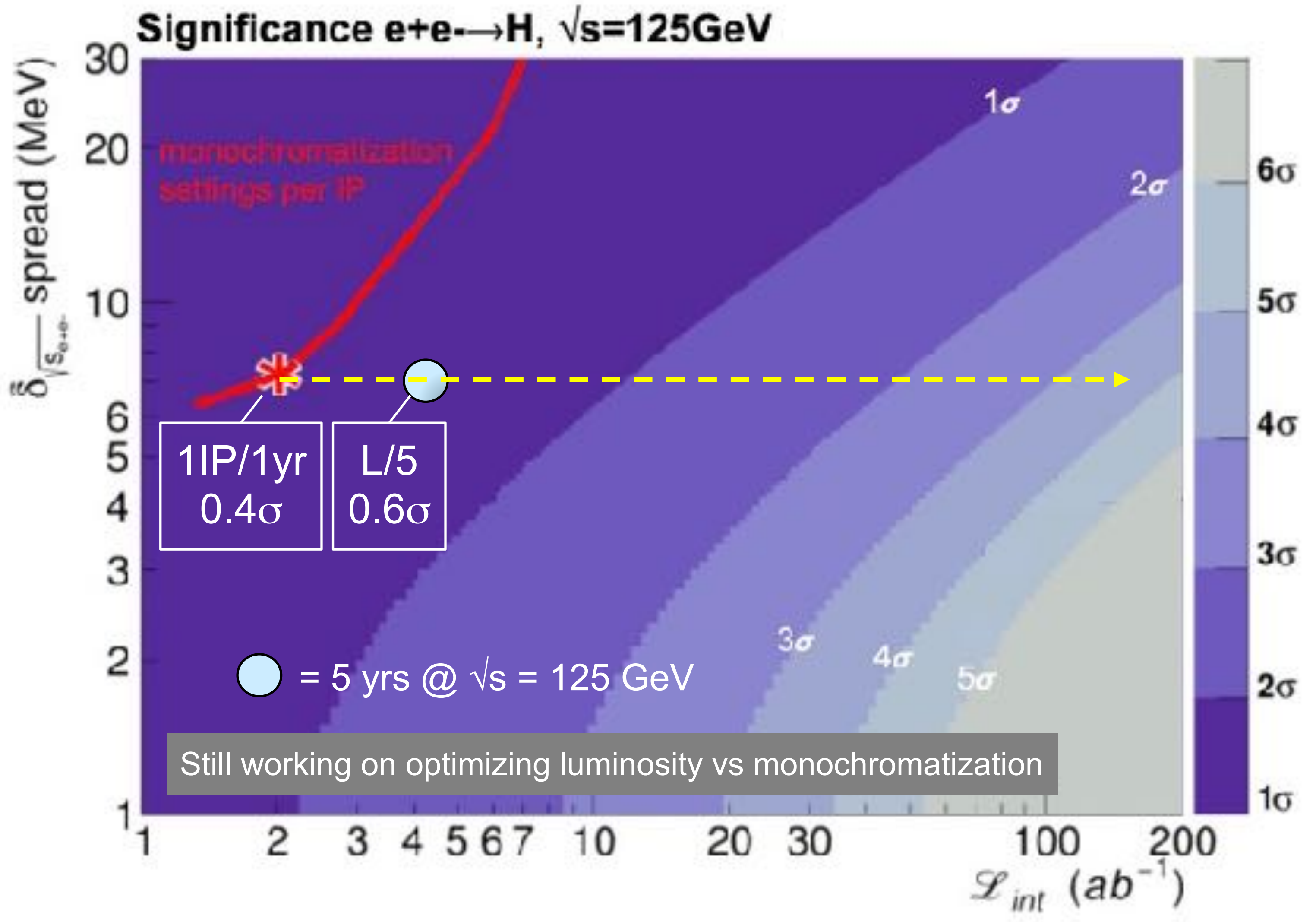

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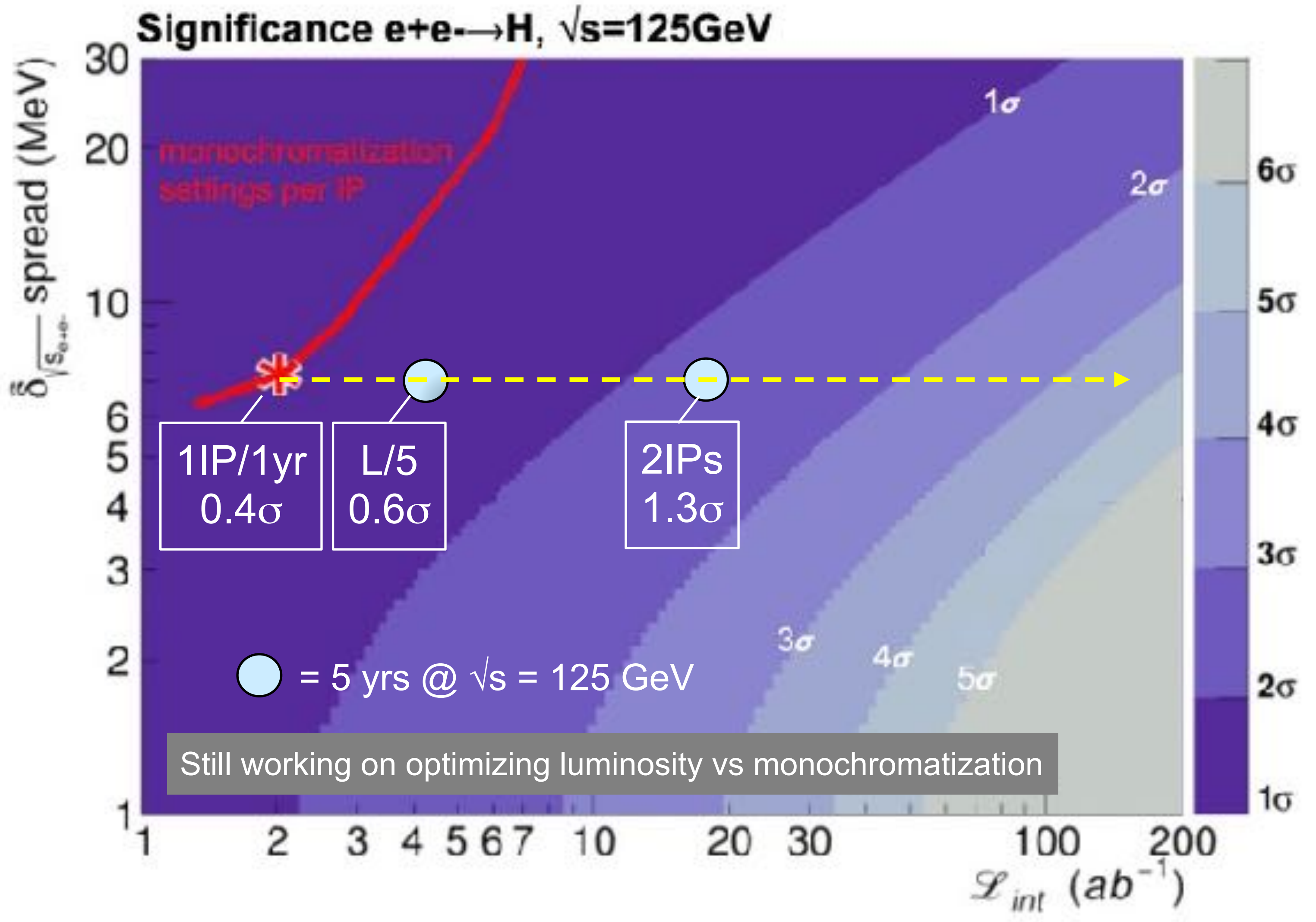

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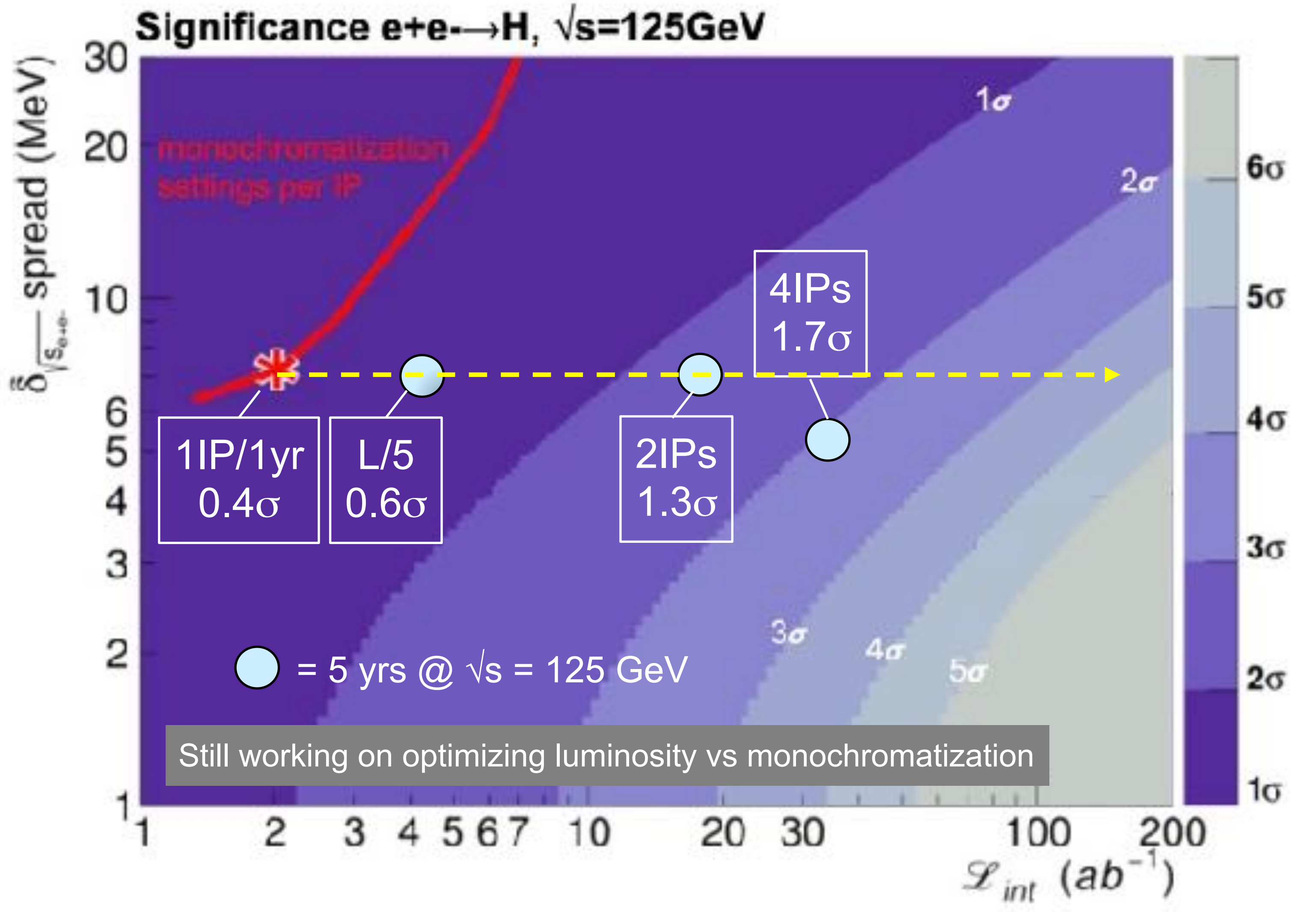

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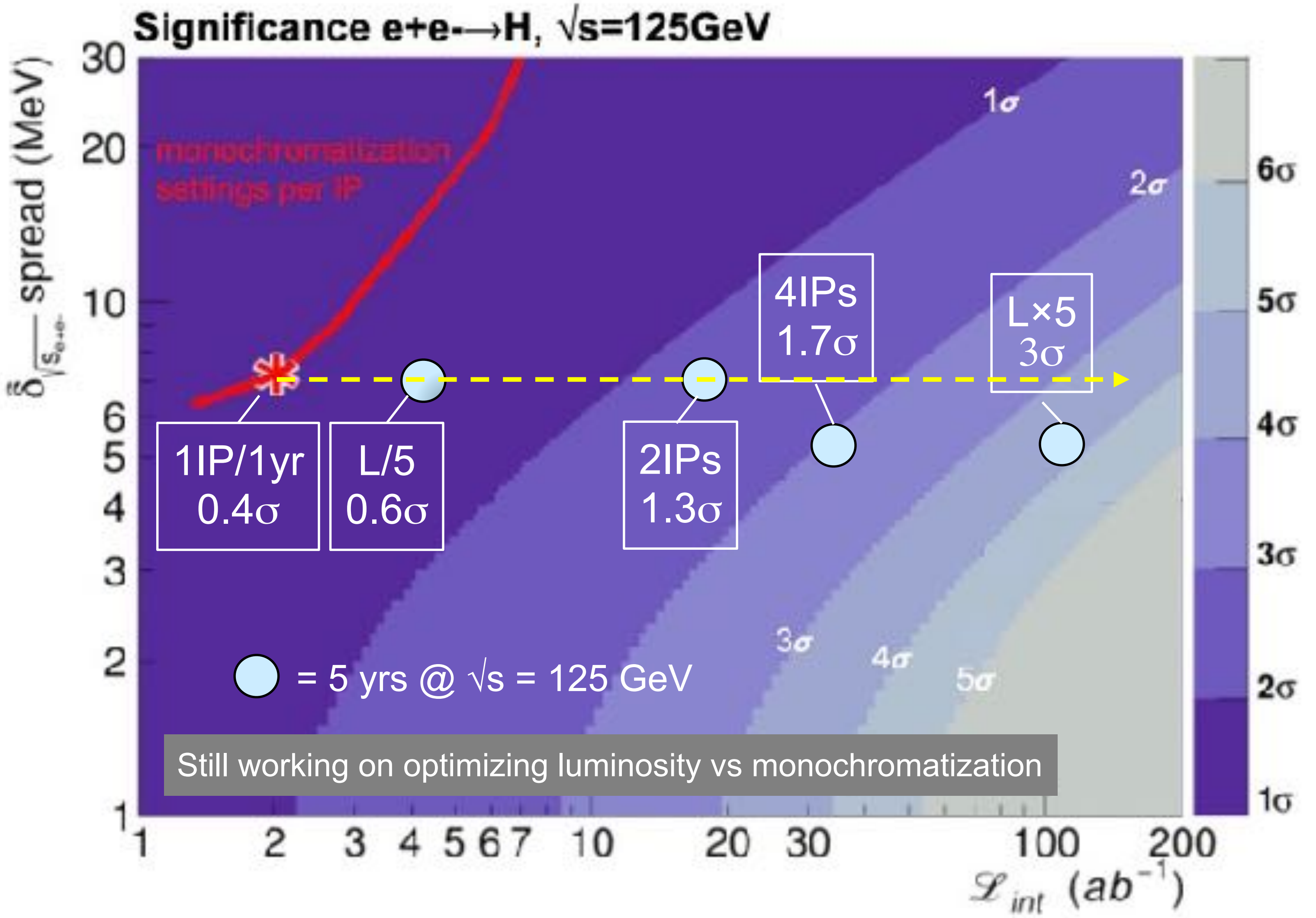
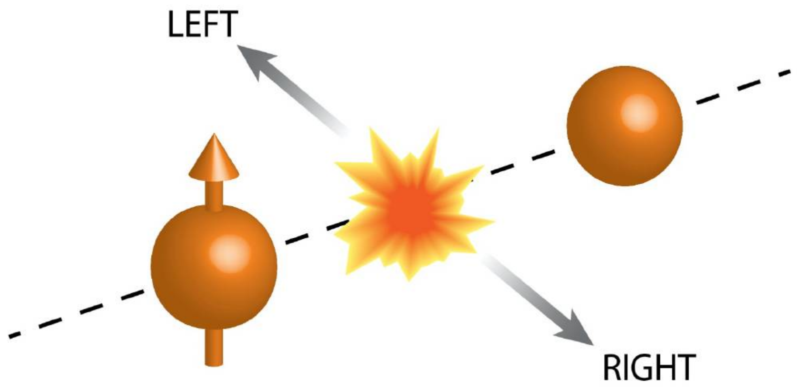


Electron Yukawa

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



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

Electron polarized, positron unpolarized (SP⁰):

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

Electron transversely polarized, positron longitudinally polarized (DP):

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

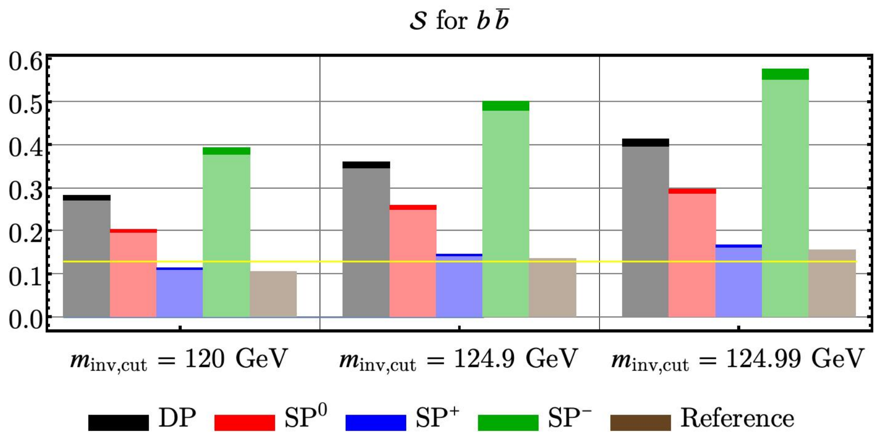
Electron transversely polarized, positron longitudinally polarized (SP⁺):

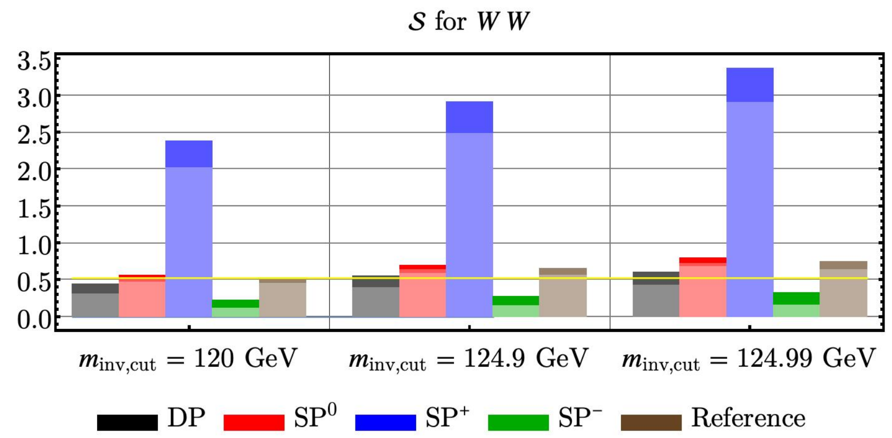
$$N = \frac{1}{2}(\sigma^{++} - \sigma^{-+}) \qquad D = \frac{1}{2}(\sigma^{++} + \sigma^{-+})$$

Electron transversely polarized, positron longitudinally polarized (SP⁻):

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

8



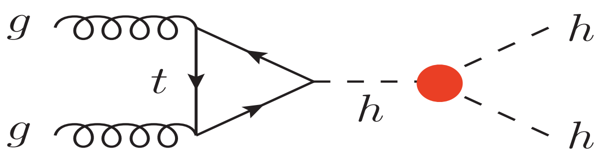
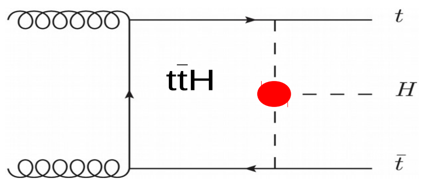
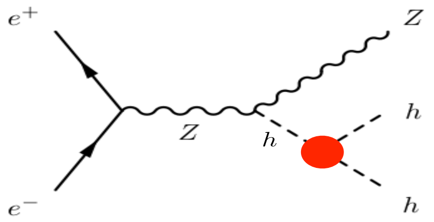
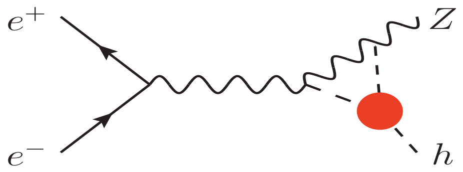


Major improvements of up to factors of 6 possible for bb and WW (doesn't work for gg)

Higgs Self-Coupling

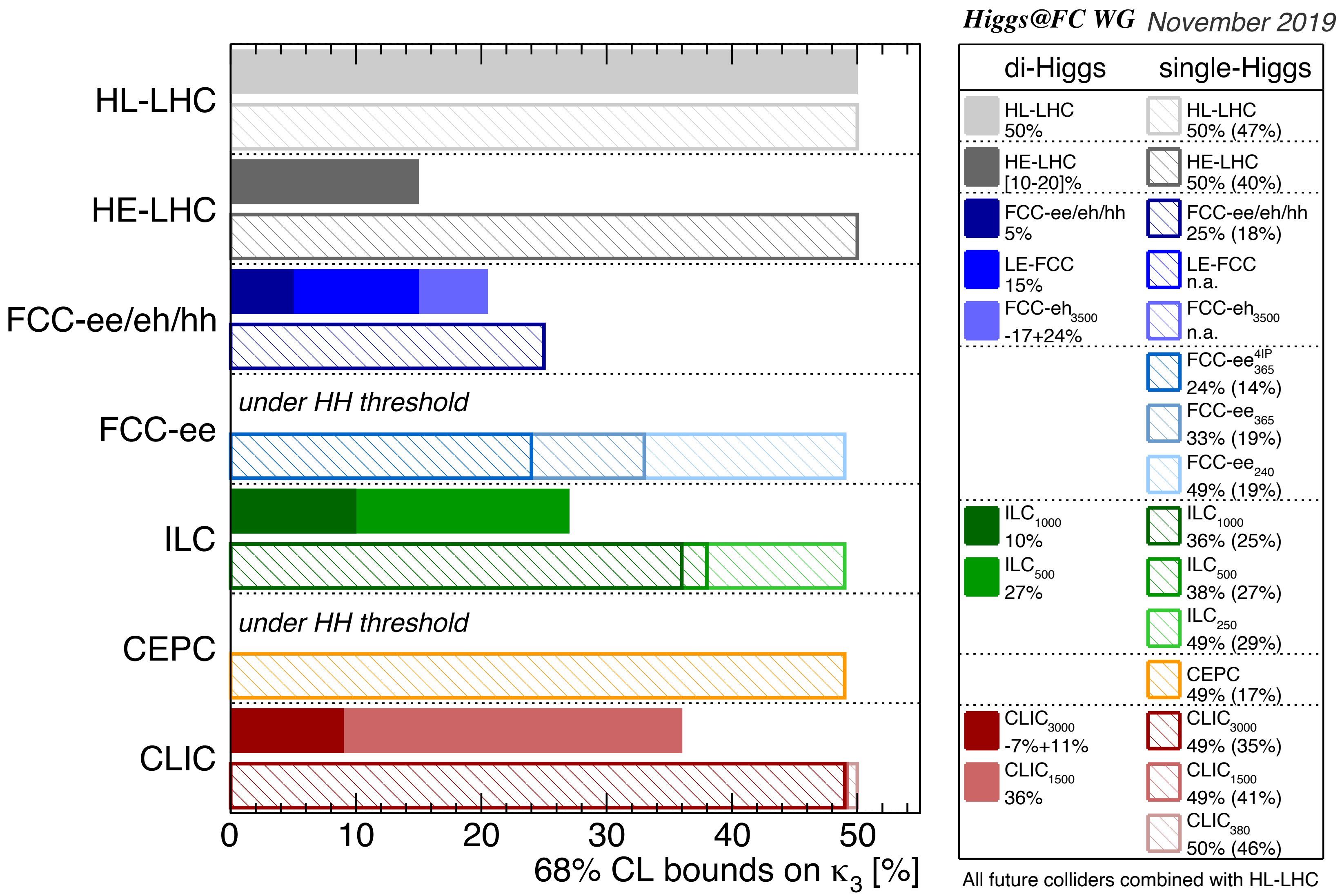
How much can it deviate from SM given the tight constraints on other Higgs couplings?
Do we need to reach HH production threshold to constrain h^3 coupling?

ECFA Higgs study group '19

	di-Higgs	single-Higgs
Hadron Colliders		
Lepton Colliders		

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

Higgs Self-Coupling

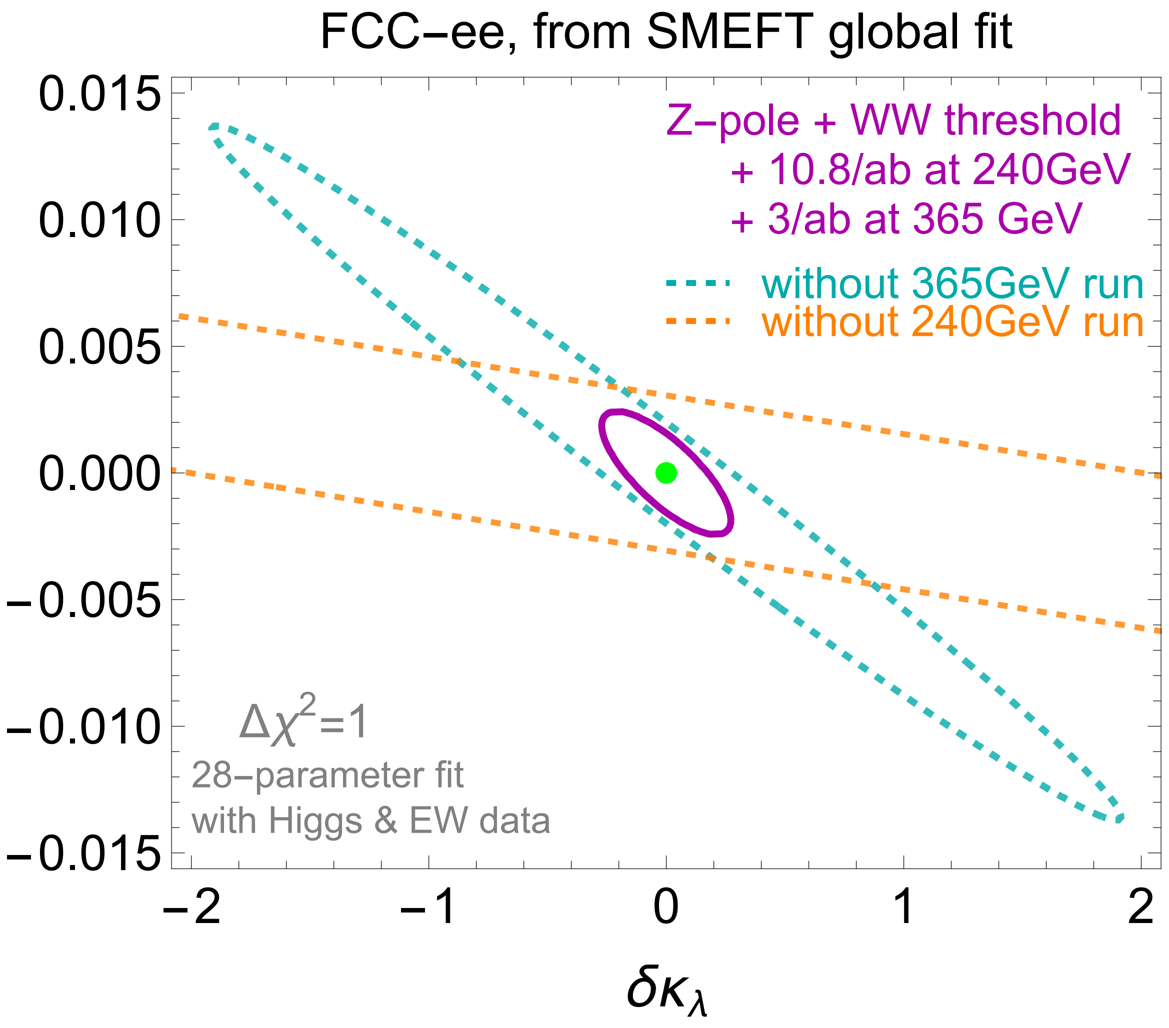


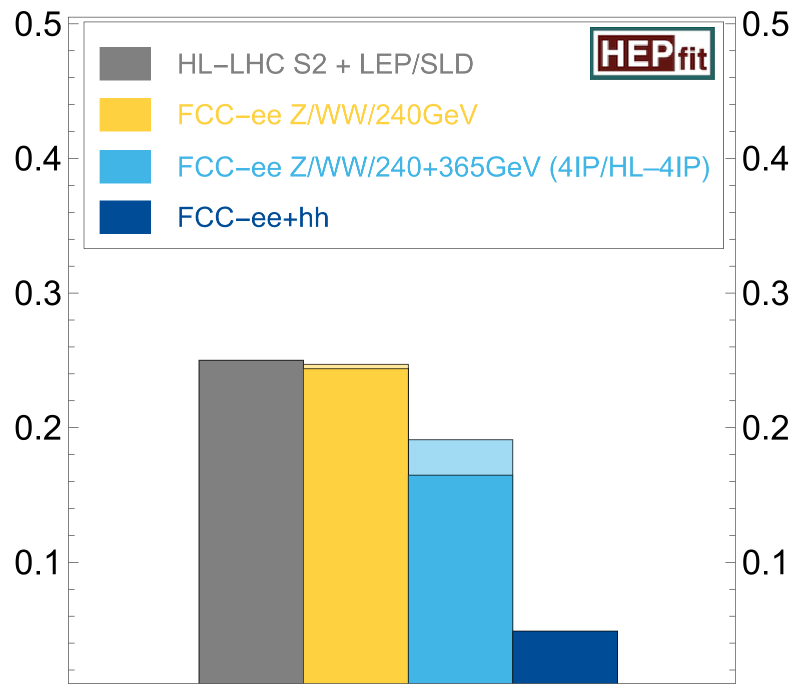
1. Don't need to reach HH threshold to have access to h^3. Runs at different energies are essential (e.g. 240 and 365 GeV)

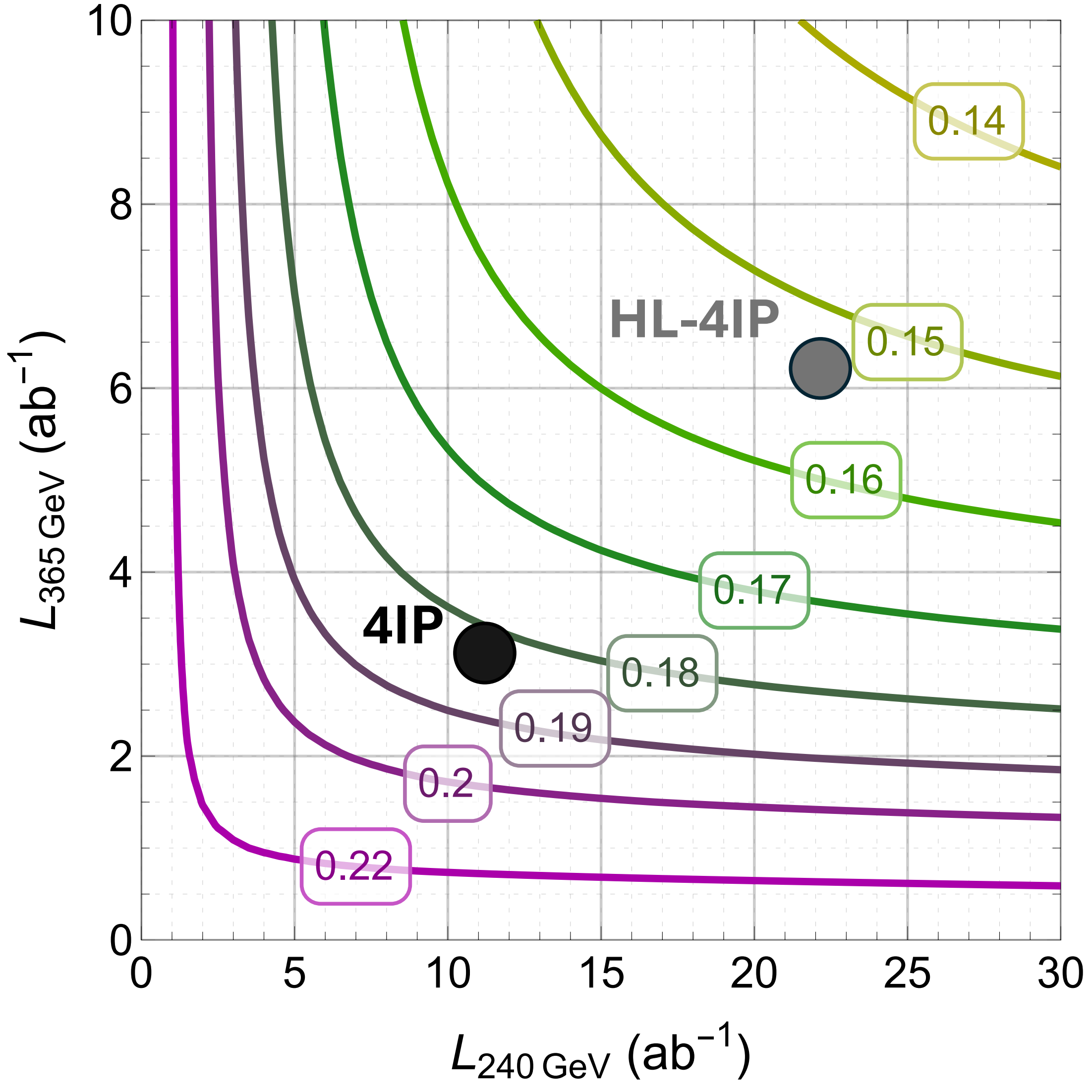
2. The determination of h^3 at FCC-hh relies on HH channel, for which FCC-ee is of little direct help. But the extraction of h^3 requires precise knowledge of y_t. $1\%\ y_t \leftrightarrow 5\%\ h^3$. Precision measurement of y_t needs FCC-ee.

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

Higgs Self-Coupling







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

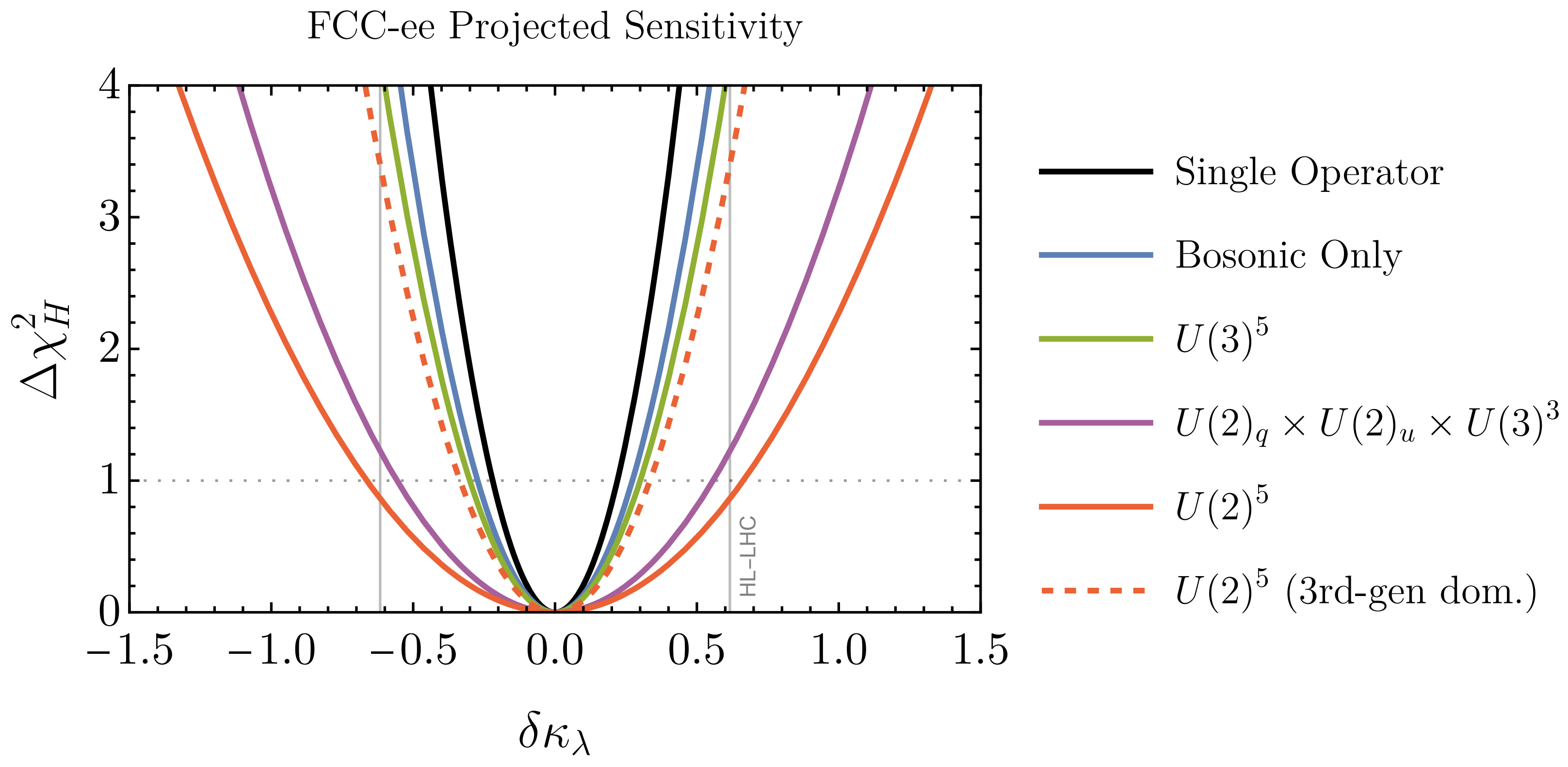
Higgs Self-Coupling

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

Maura, Stefanek, You arXiv:2503.13719

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

Scenario	$\sigma_H\,[\mathrm{TeV}^{-2}]$	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%

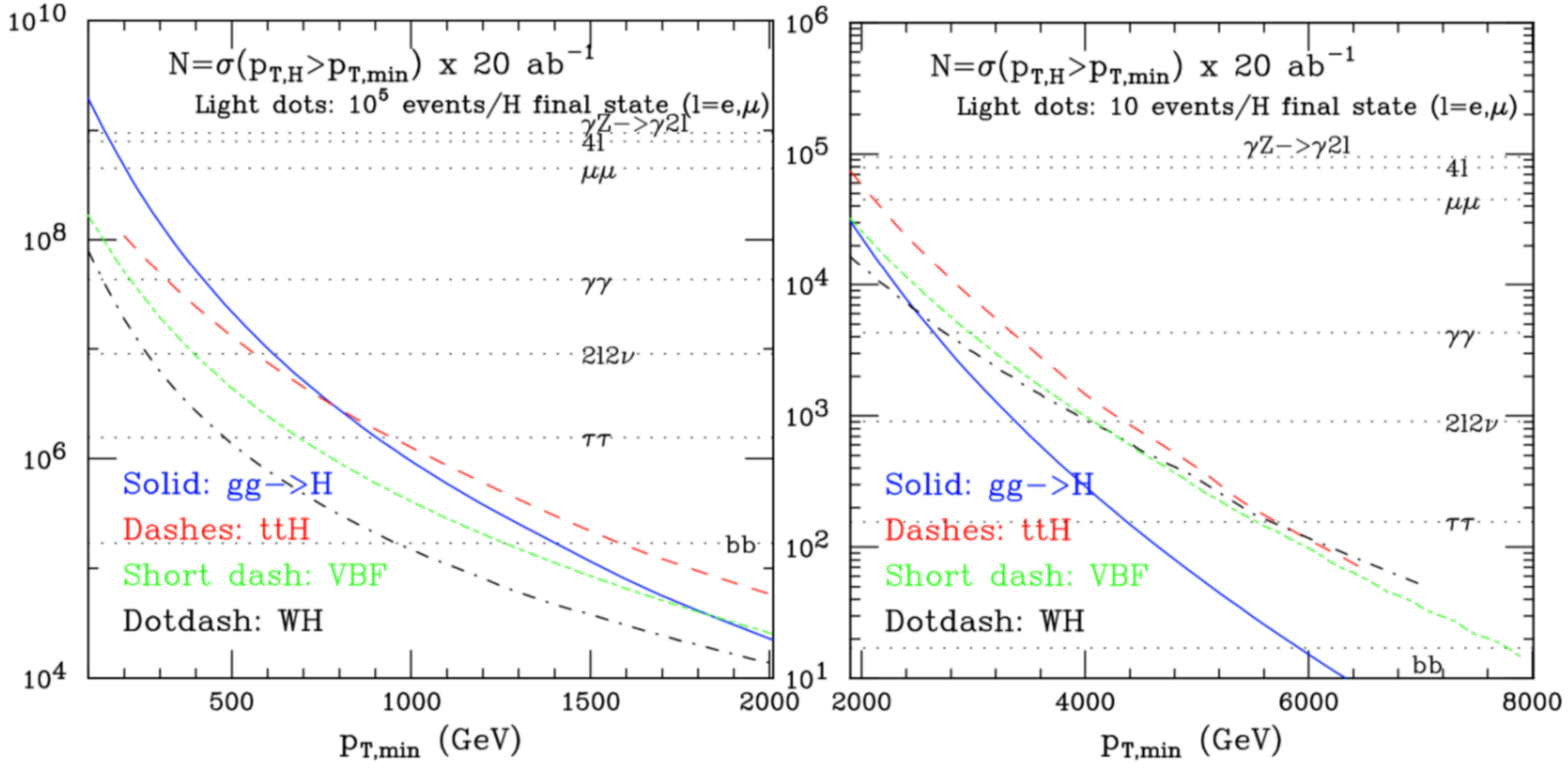


Higgs @ FCC-hh.

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

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



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

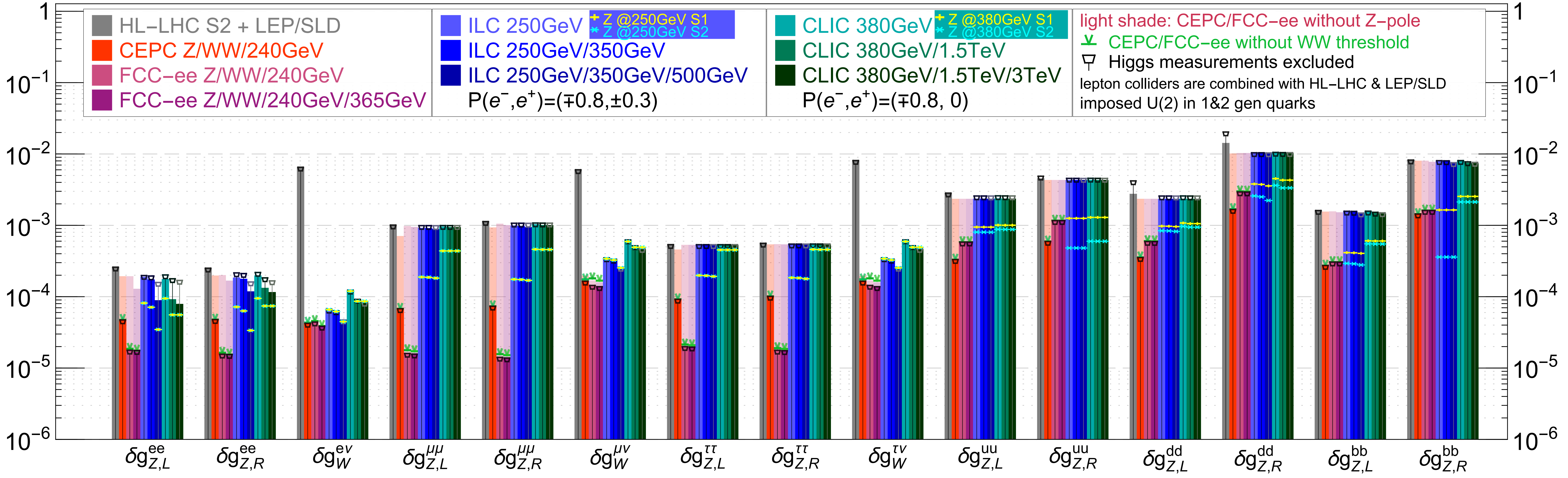
Higgs @ FCC-hh.

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
$\kappa_{\mathrm{Z}\gamma}$ (%)	10^*	4.3	0.67
κ_{t} (%)	3.2^*	3.1	0.75
κ_{μ} (%)	4.4^*	3.3	0.42
$\lvert\kappa_{\mathrm{s}}\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_{H} (%)	–	0.78	0.69
$\mathcal{B}_{\mathrm{inv}}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\mathrm{unt}}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

Higgs and EW measurements

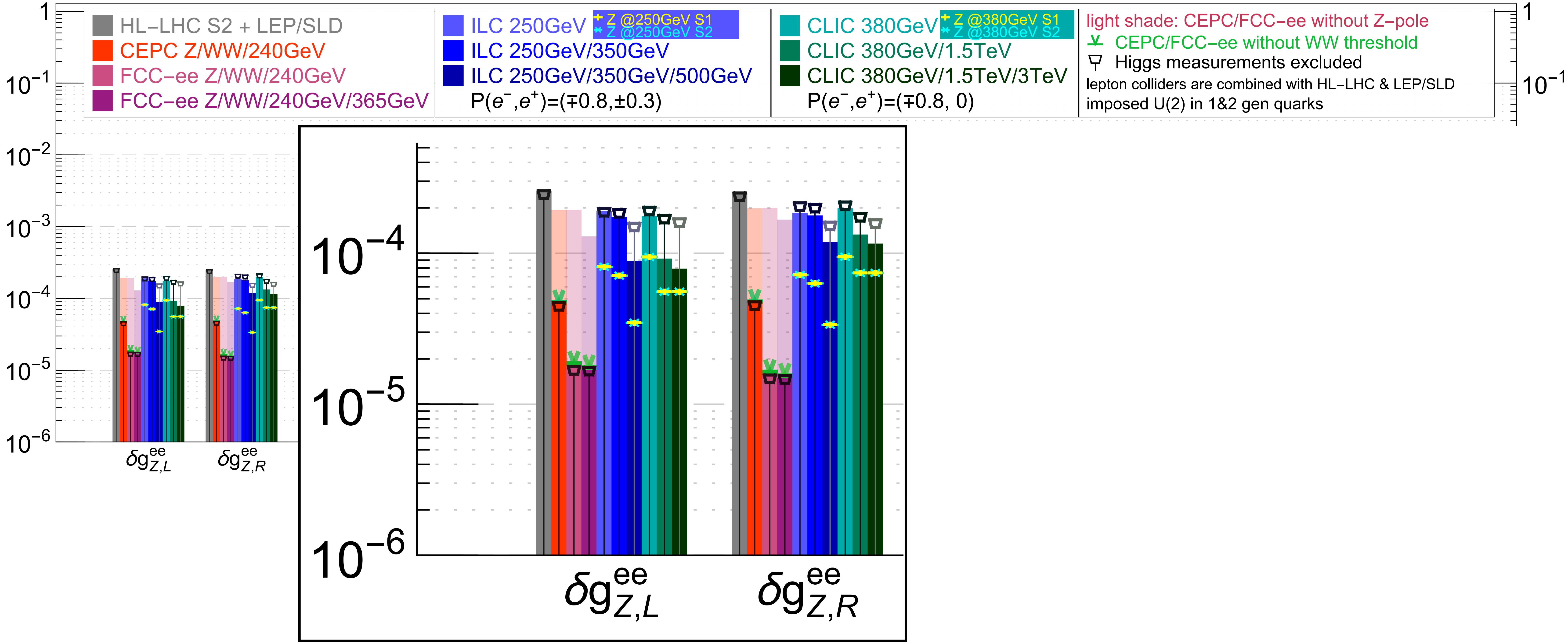
Sensitivity on EW couplings.

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



Sensitivity on EW couplings.

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



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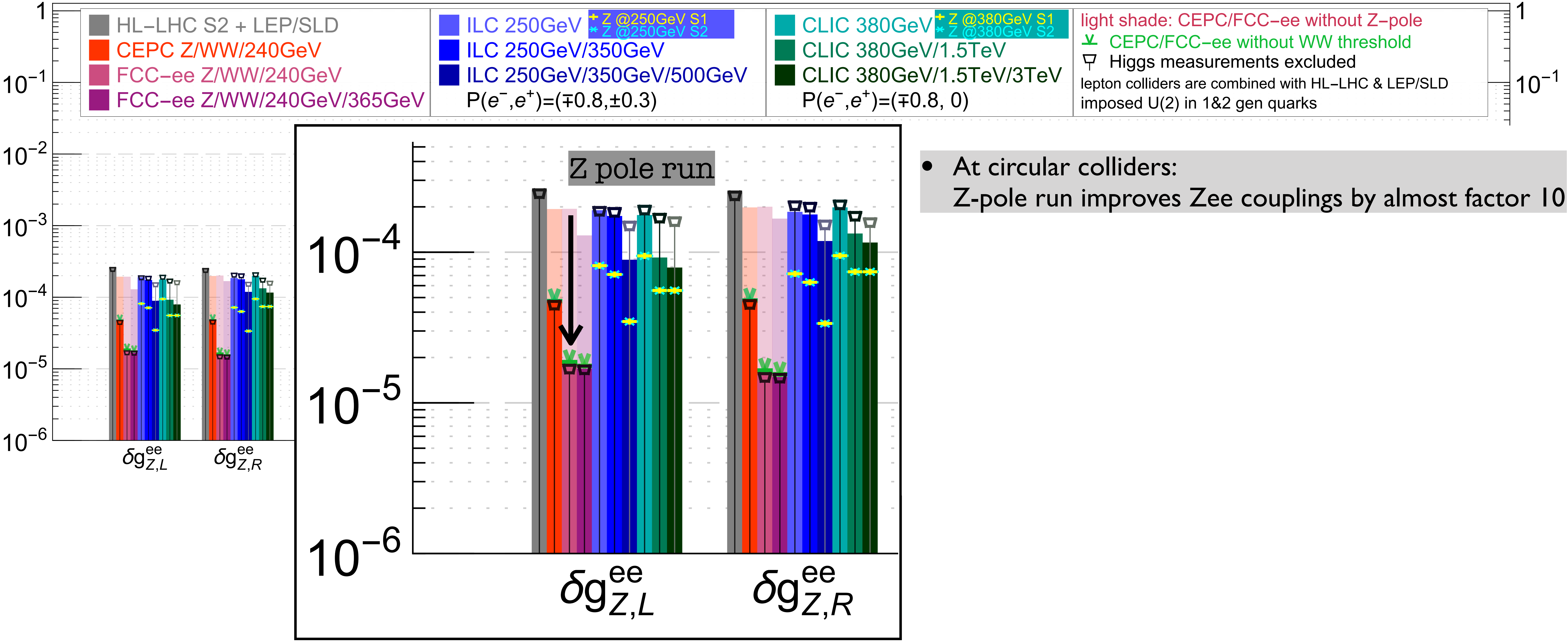
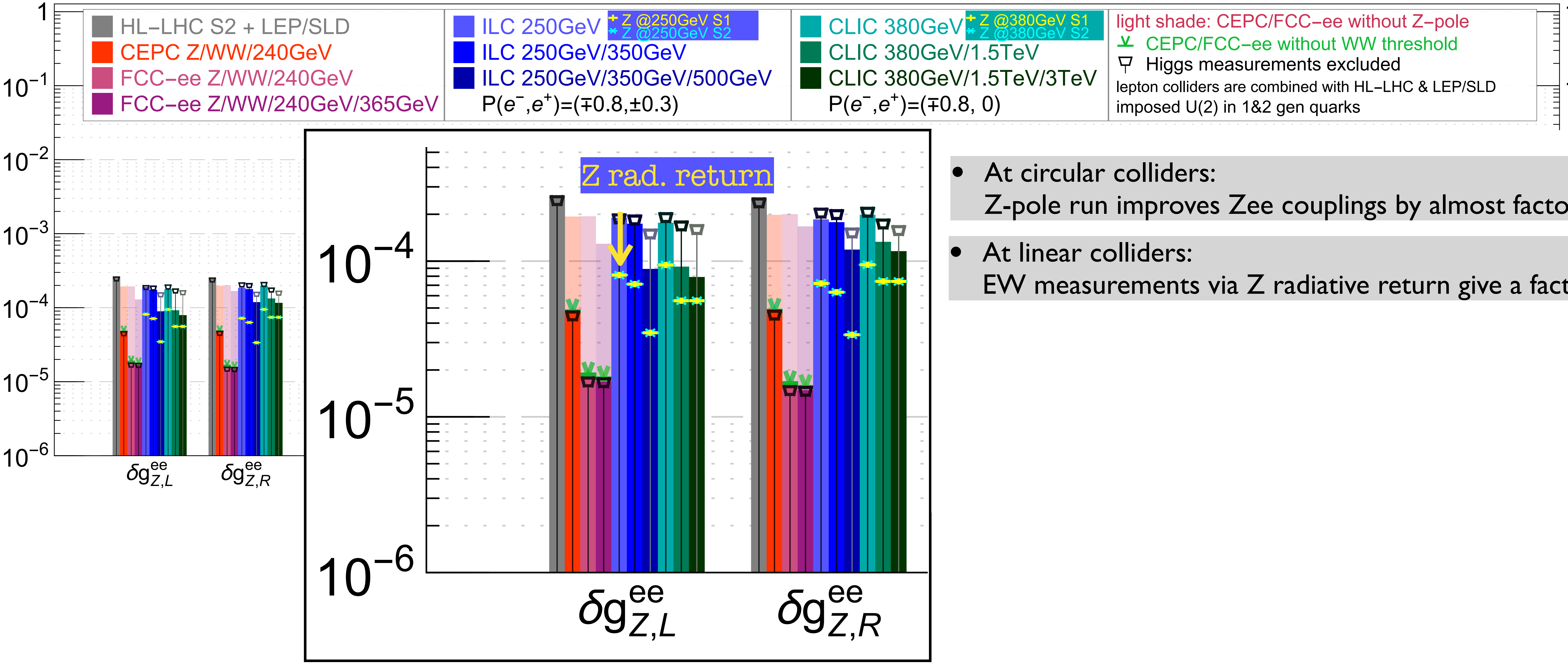


- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10

Sensitivity on EW couplings.

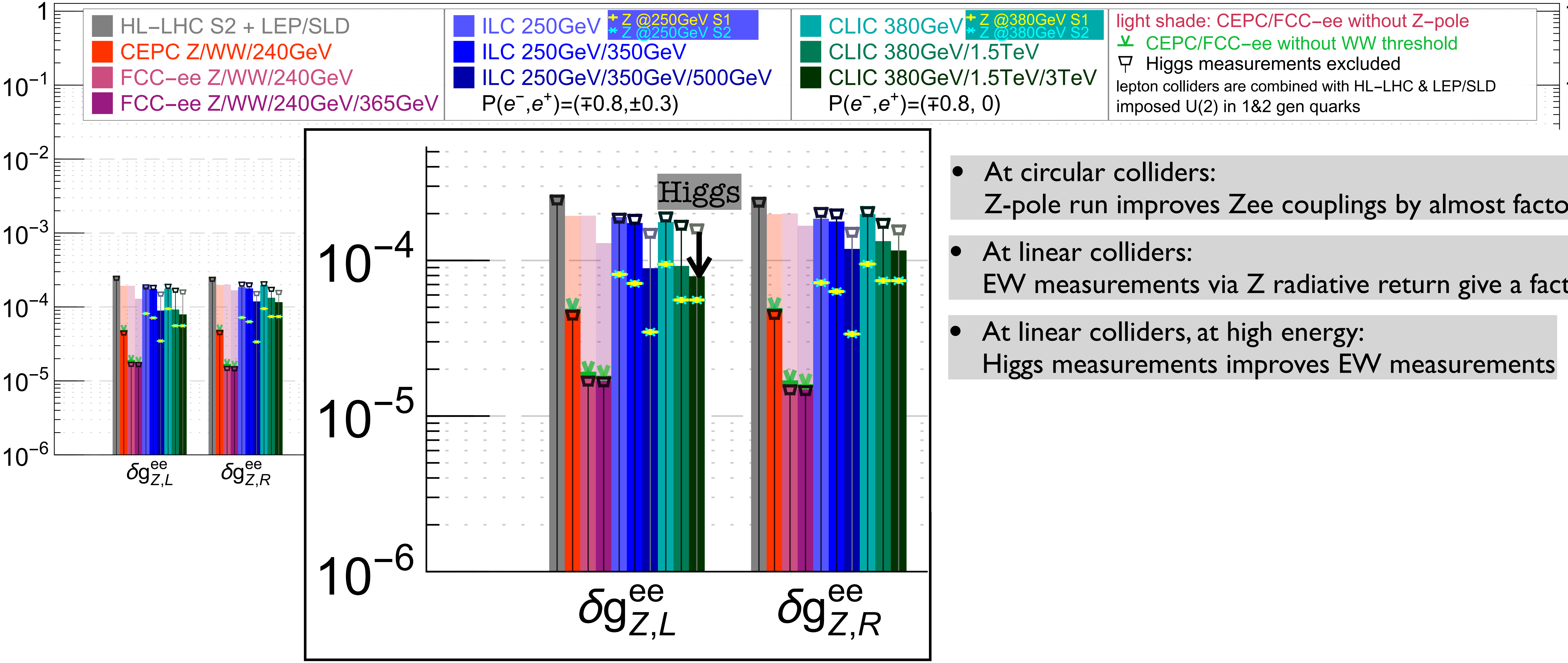
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



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

Sensitivity on EW couplings.

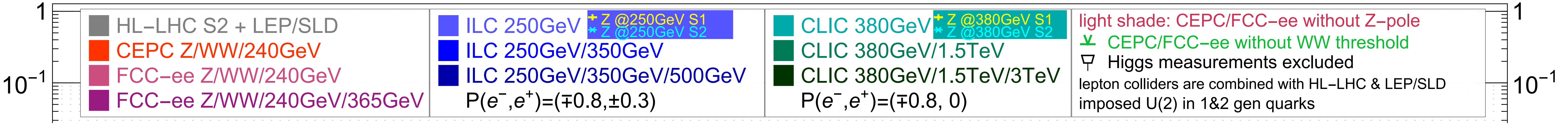
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



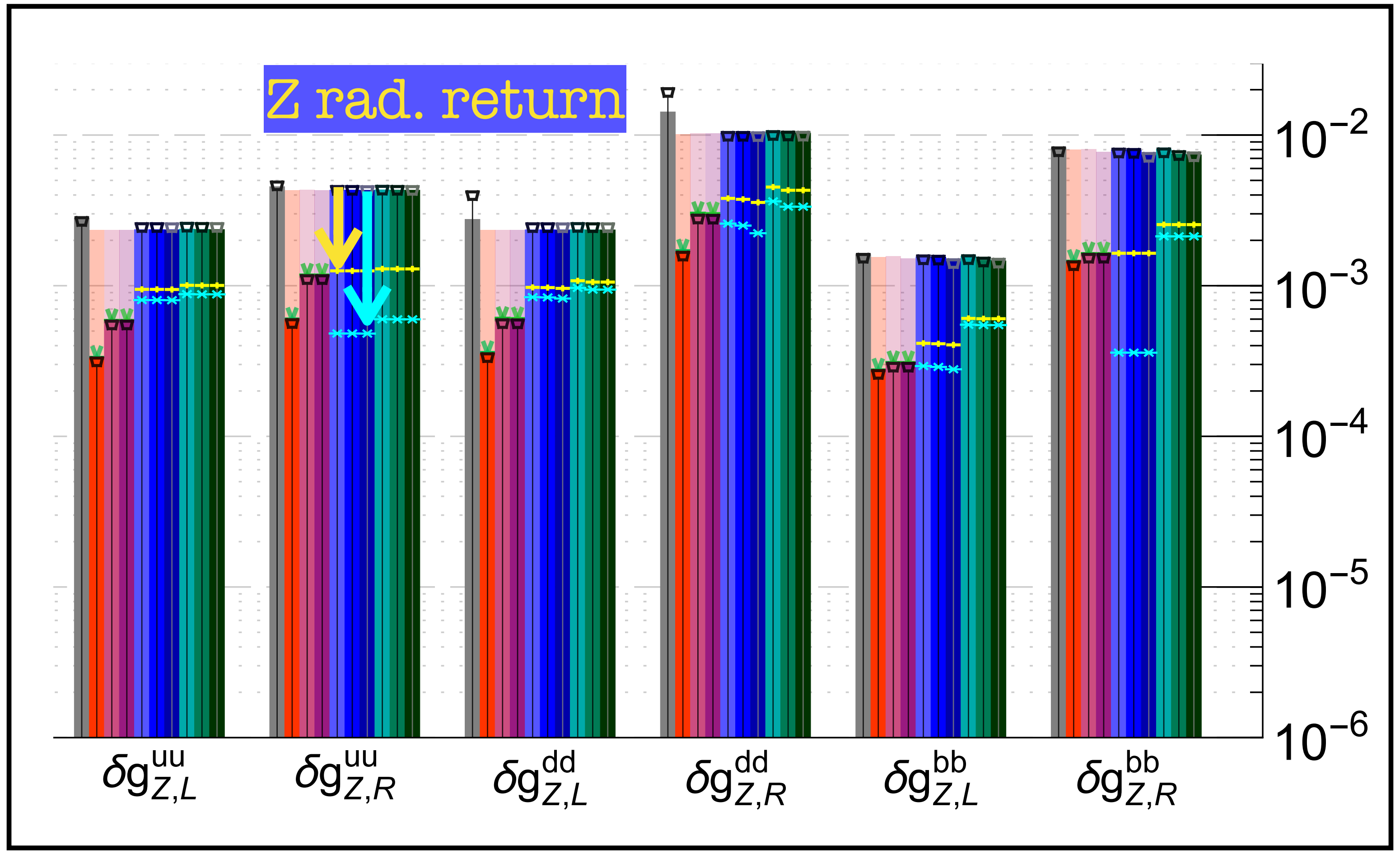
- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings.

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

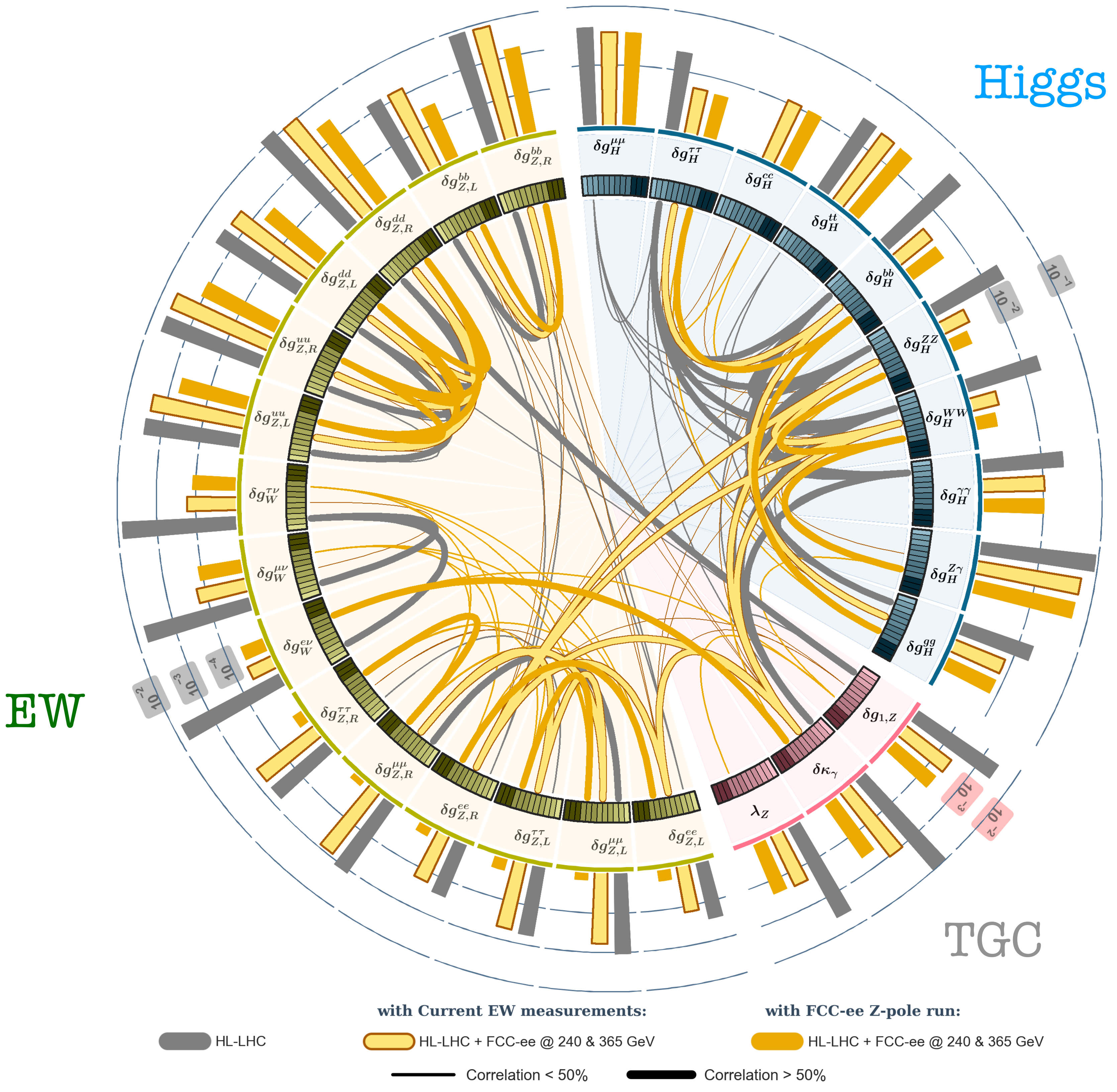


- At linear colliders, at high energy:
  EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
  Yellow: LEP/SLD systematics / 2
  Blue: small EXP and TH systematics



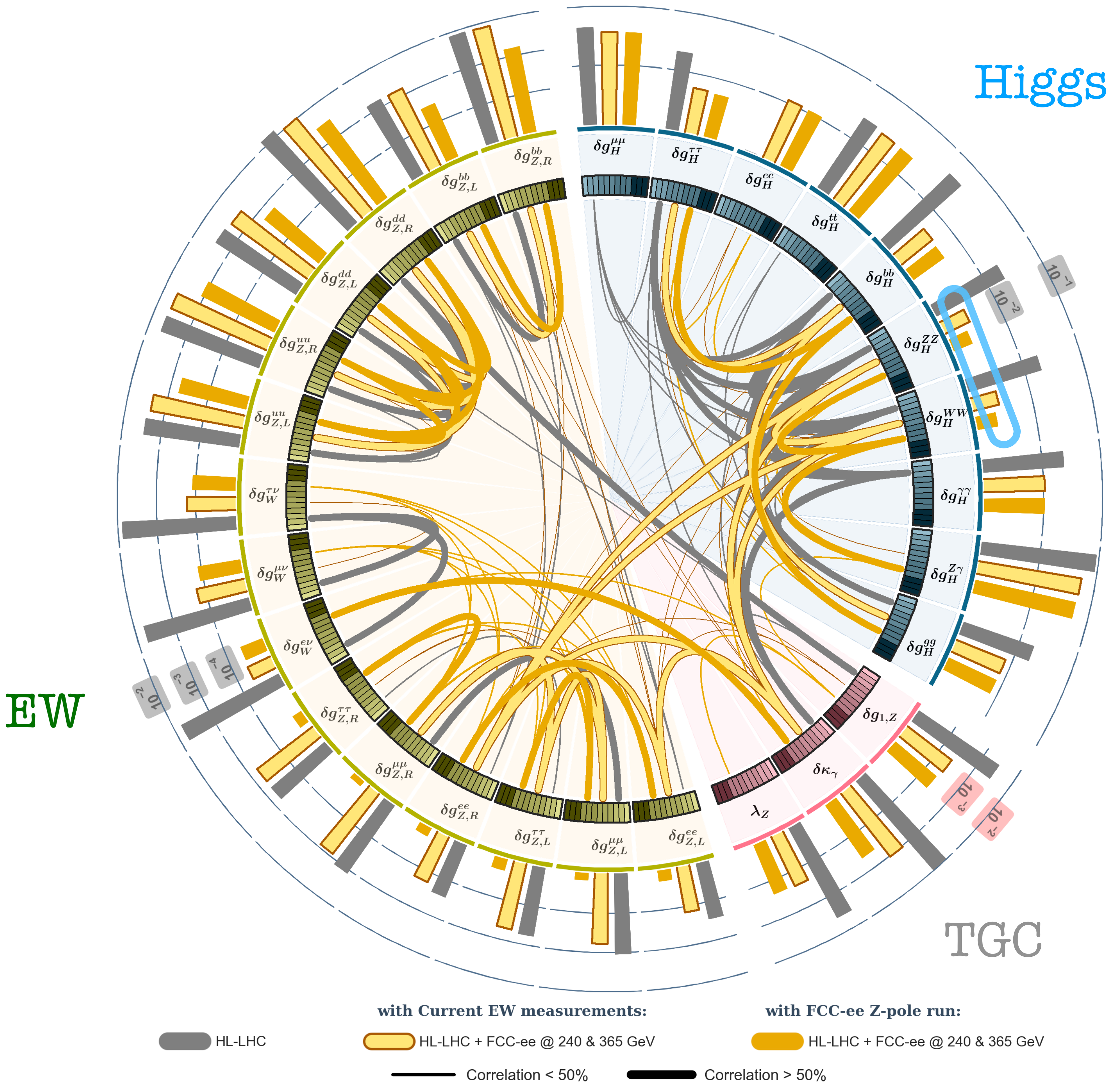
Why Z-pole for Higgs?

J. De Blas et al. 1907.04311



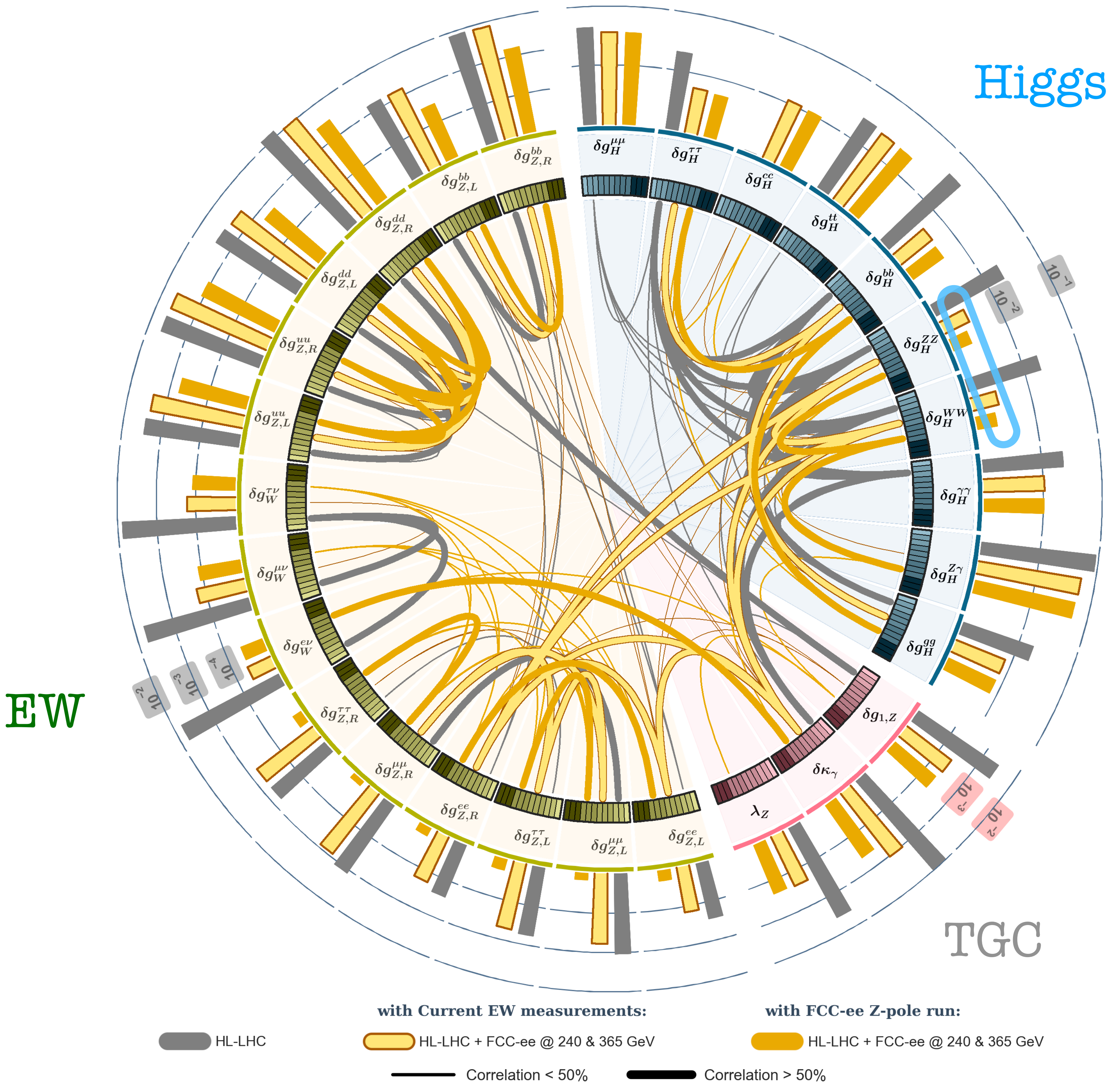
Why Z-pole for Higgs?

J. De Blas et al. 1907.04311



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

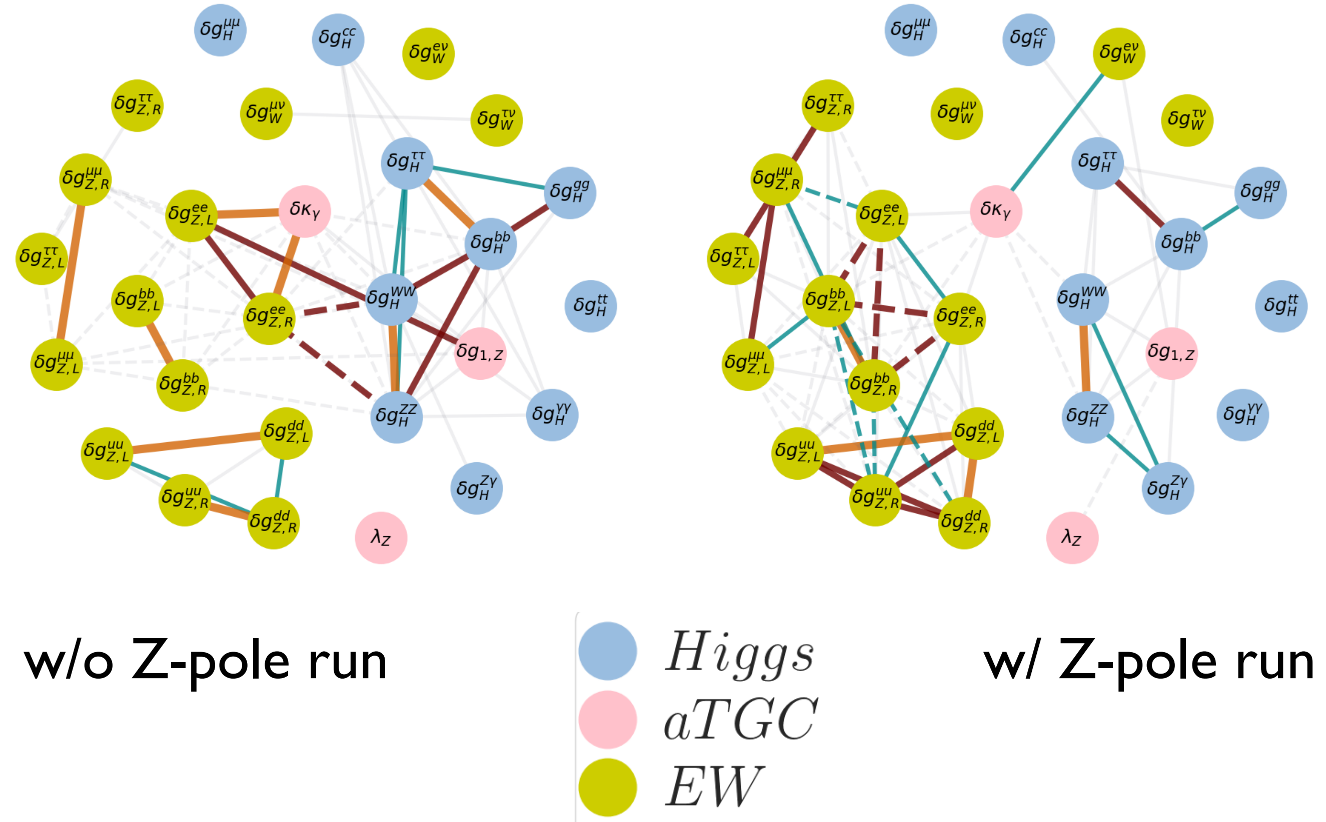
Why Z-pole for Higgs?



J. De Blas et al. 1907.04311

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

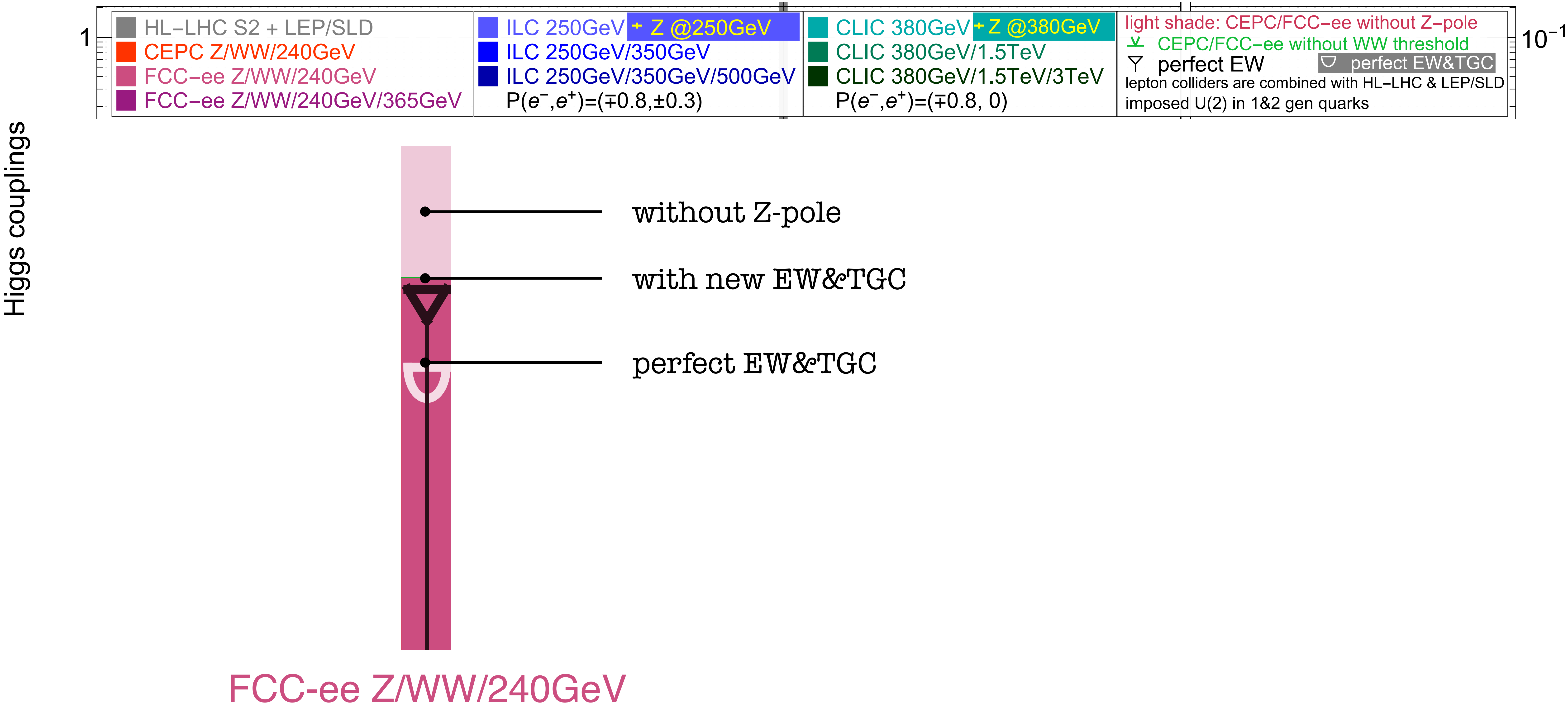
Z-pole run at circular colliders decorrelates EW and Higgs sectors from each other



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



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J. De Blas et al. 1907.04311

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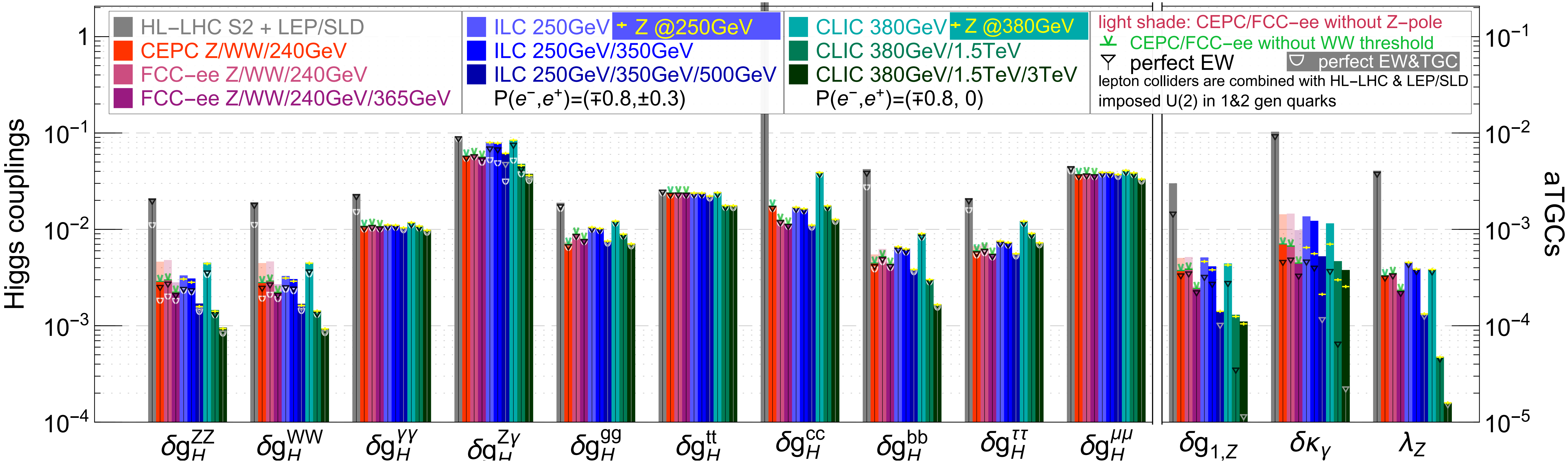

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J. De Blas et al. 1907.04311

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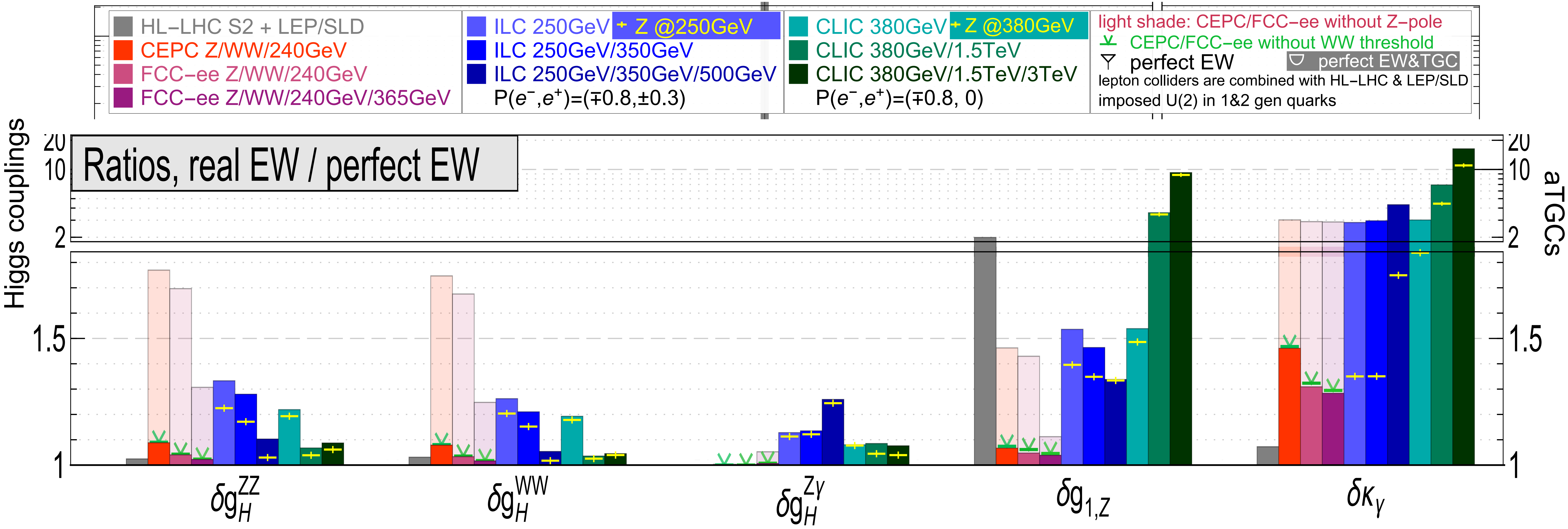
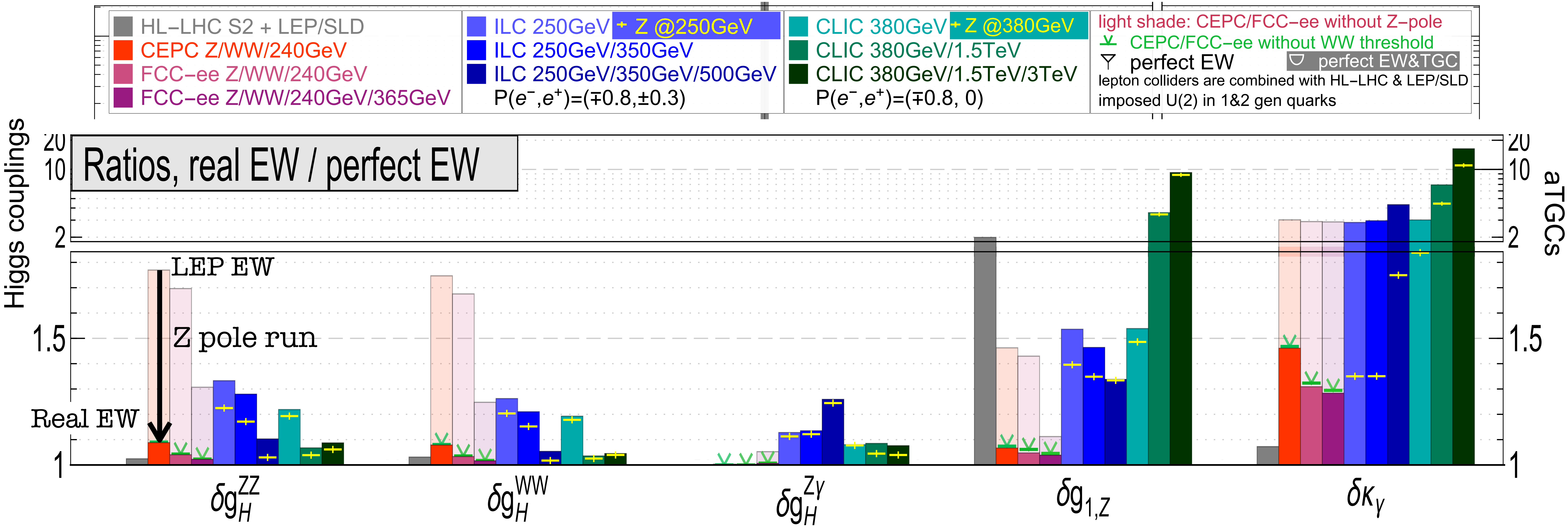


Impact of Z-pole on Higgs.

J. De Blas et al. 1907.04311

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

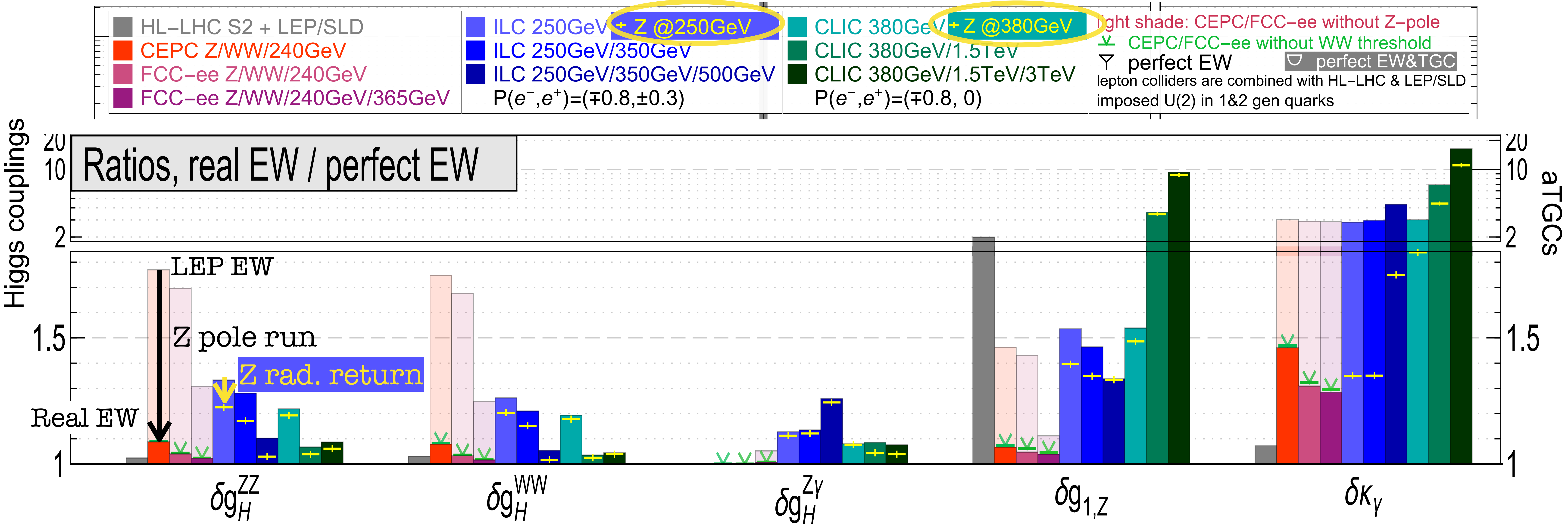


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).

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

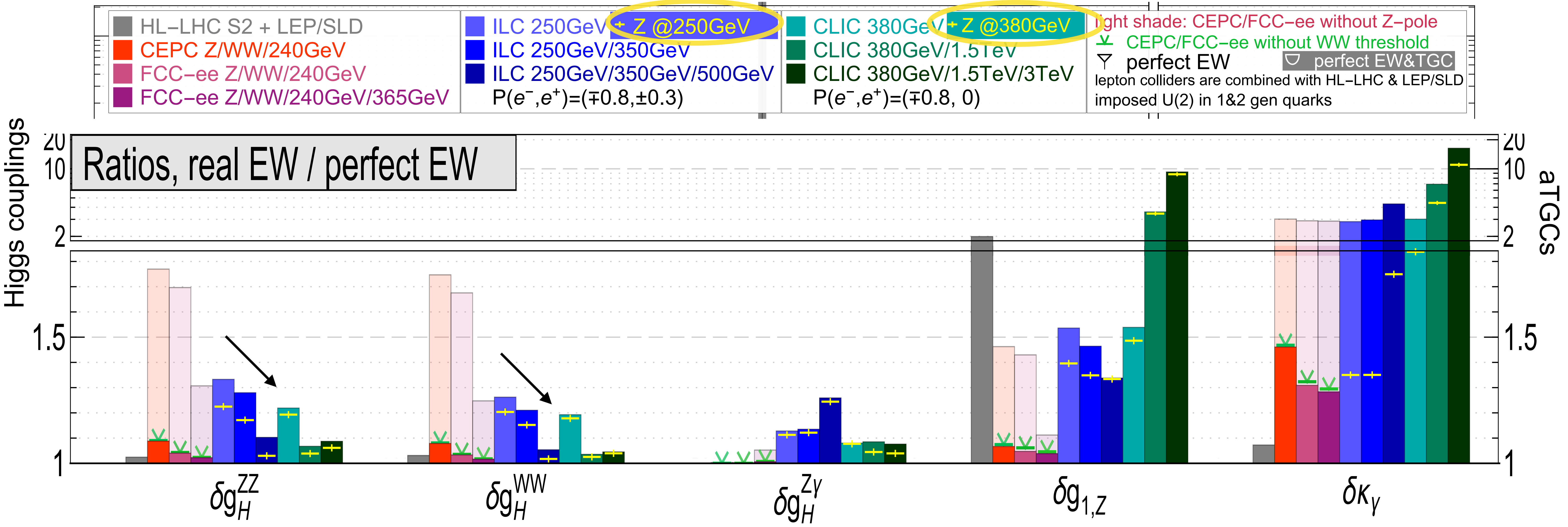


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs
  But EW measurements at high energy (via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

Impact of Z-pole on Higgs.

J. De Blas et al. 1907.04311

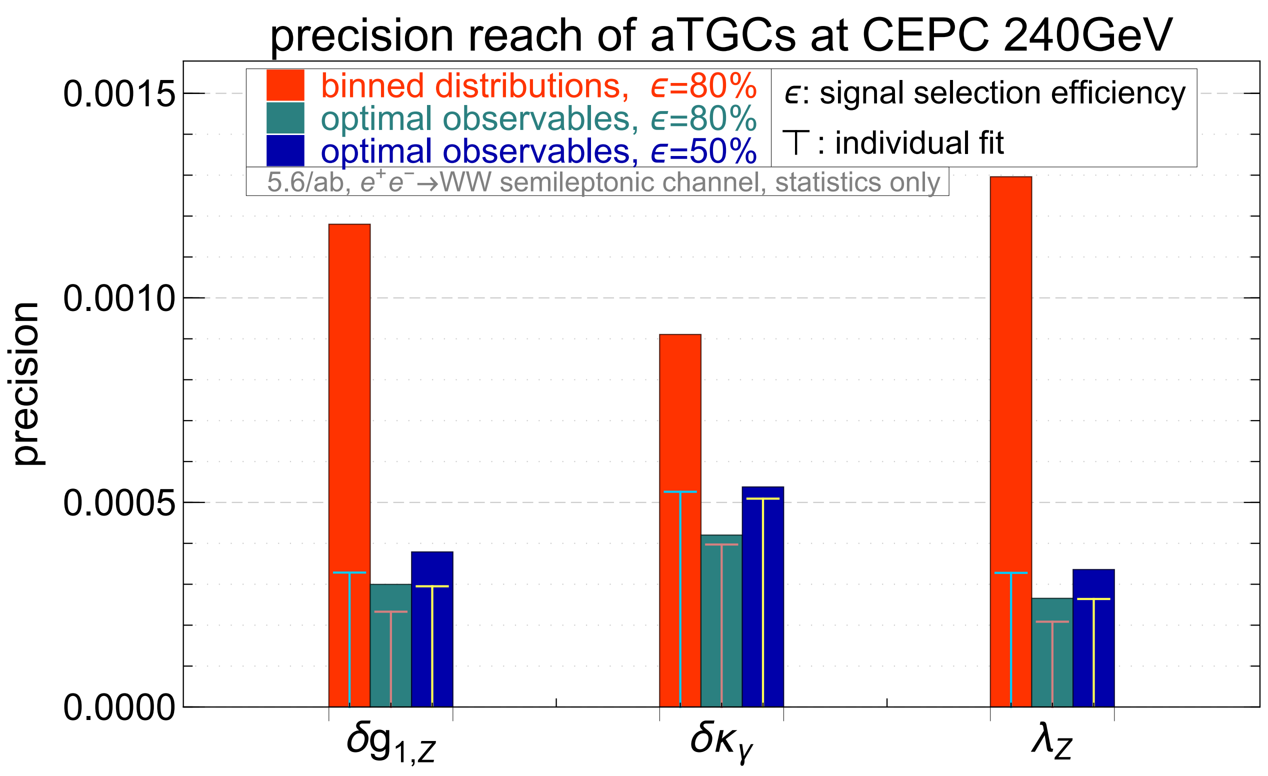
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements

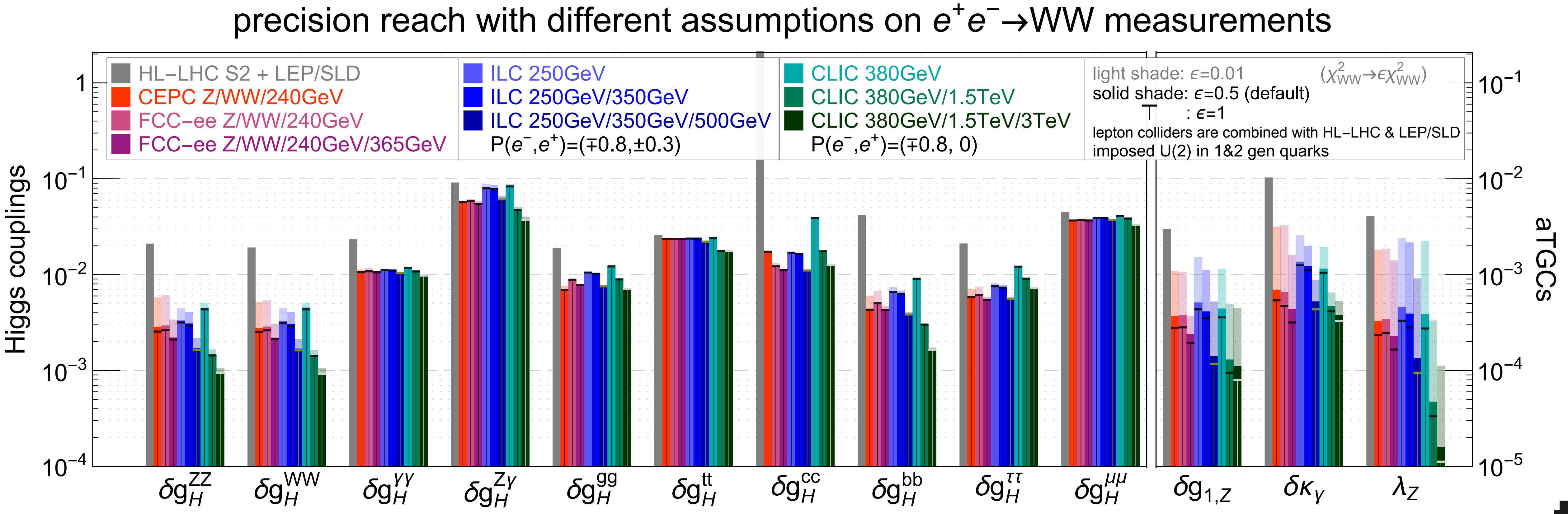


- Higher energy runs reduce the EW contamination in Higgs coupling extraction

Impact of Diboson Systematics.

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

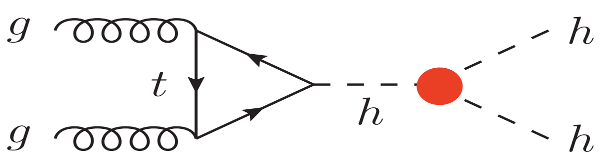
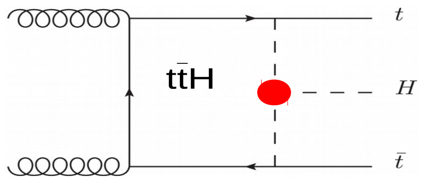
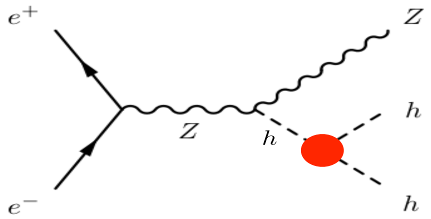
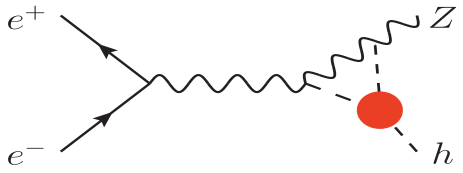




Higgs self-coupling.

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

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

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

ECFA Higgs study group '19

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

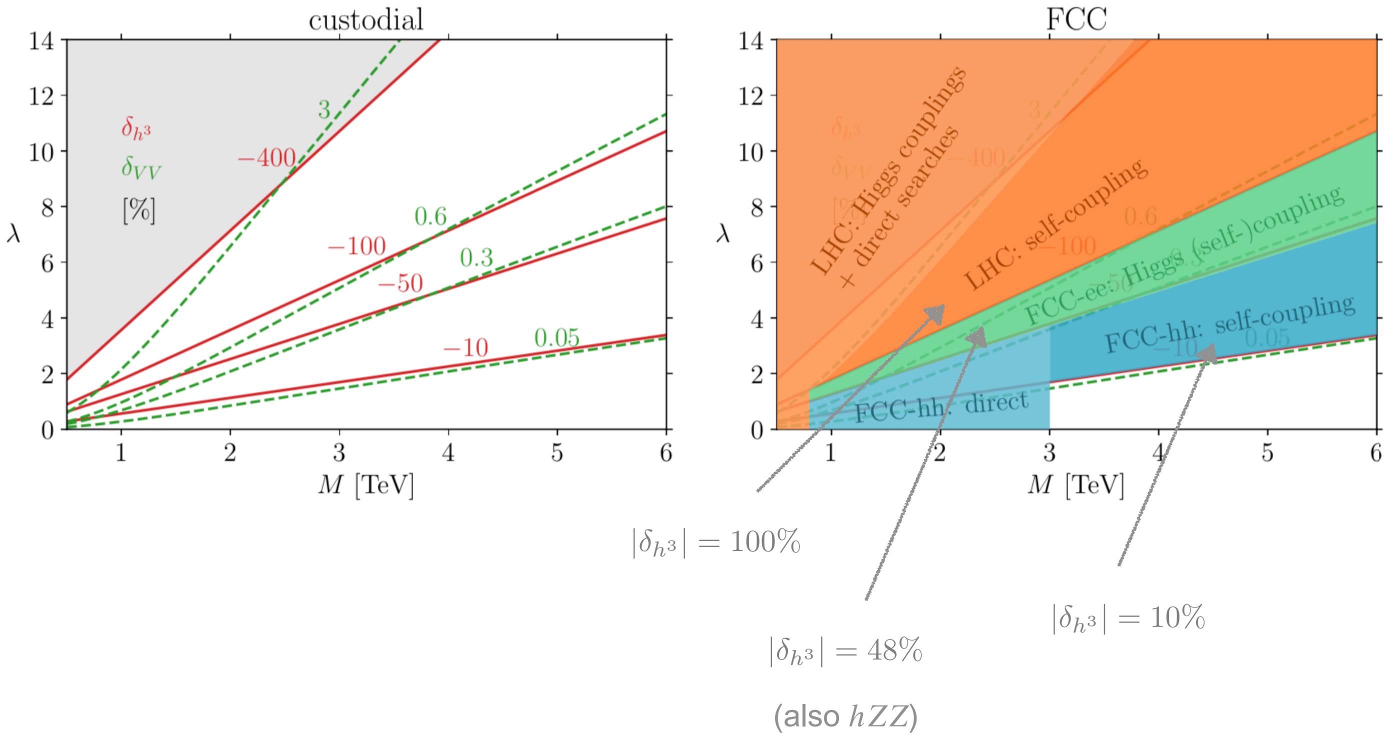
Large self-coupling scenarios.

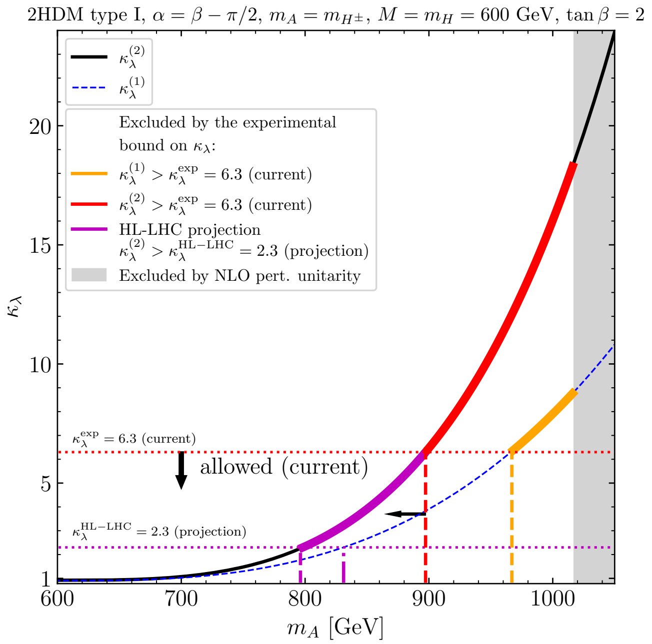
Generically: $\left|\frac{\delta_{h^3}}{\delta_{\text{single } h}}\right| \sim O(1)$ (composite Higgs/susy)

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.



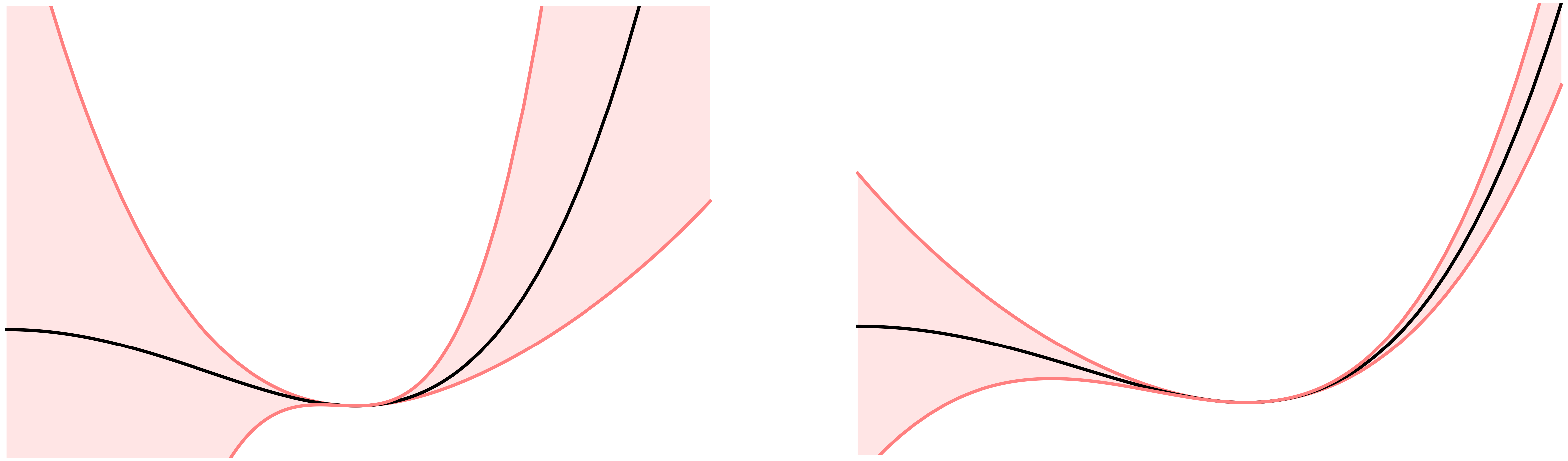


Other exceptions: non-decoupled/fine-tuned spectra

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.



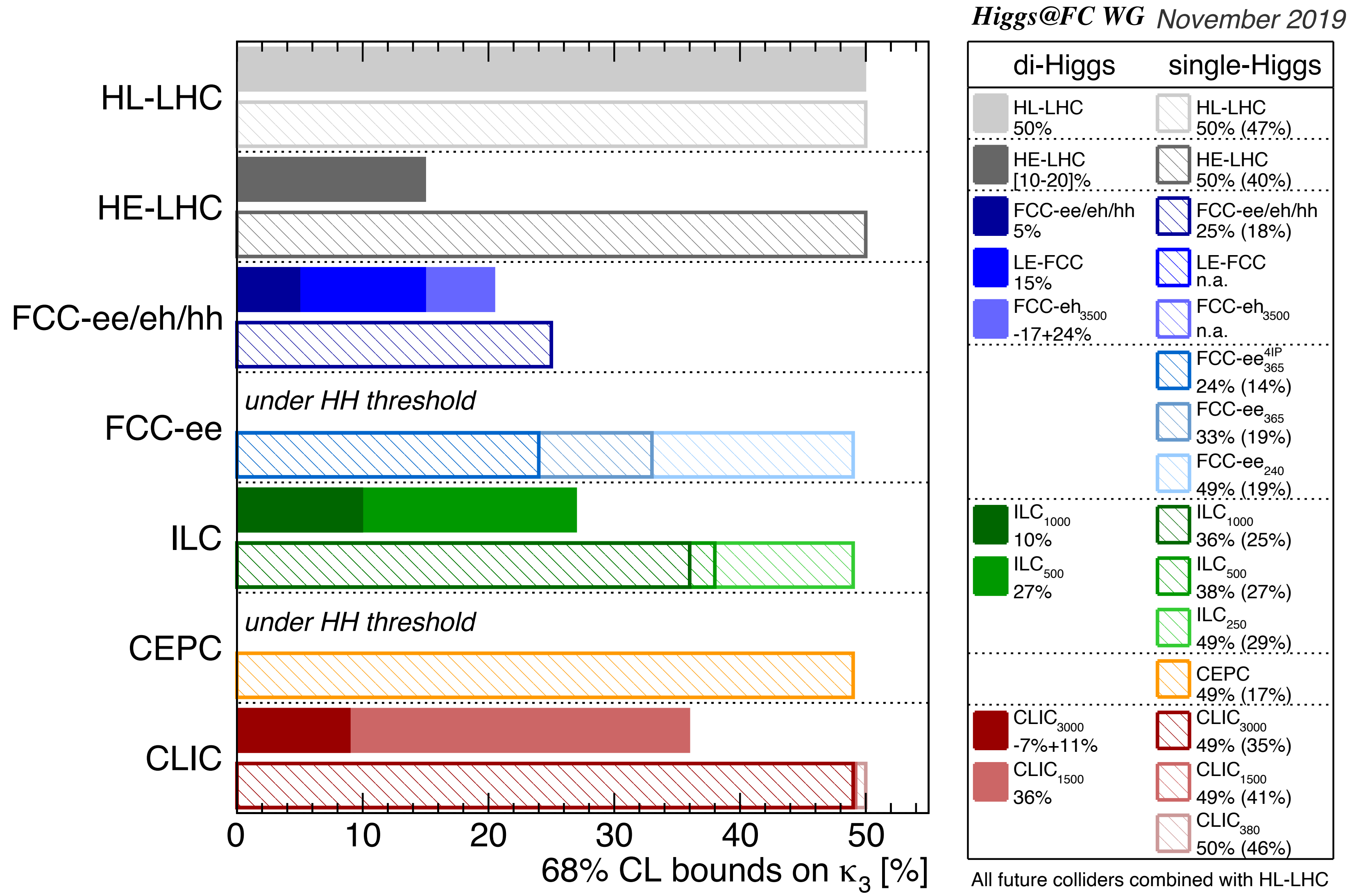
Current LHC → HL-LHC

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

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

Higgs self-coupling.

ECFA Higgs study group '19



1

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

2

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

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

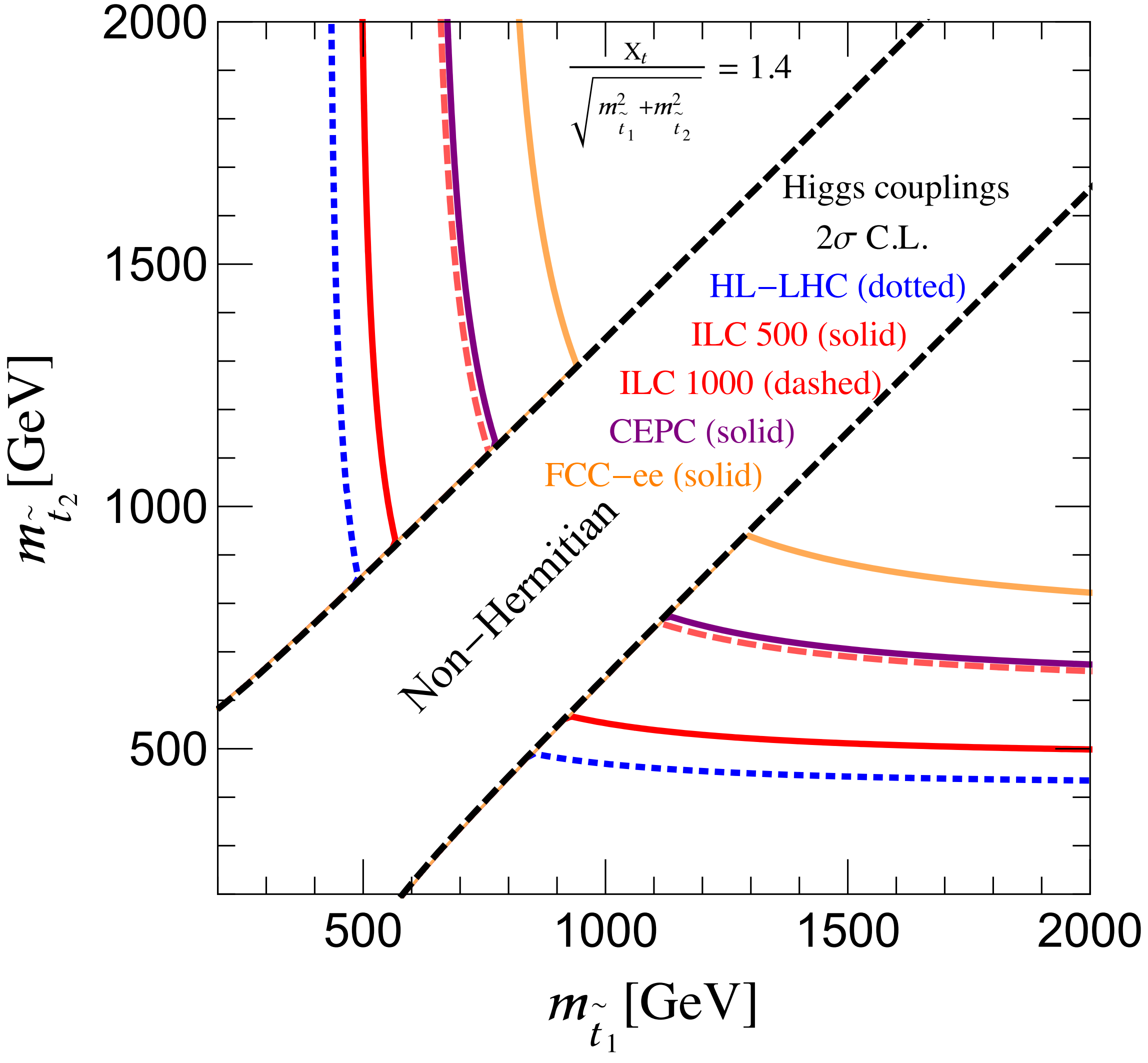
Discovery potential beyond LHC

Discovery Potential Beyond LHC.

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

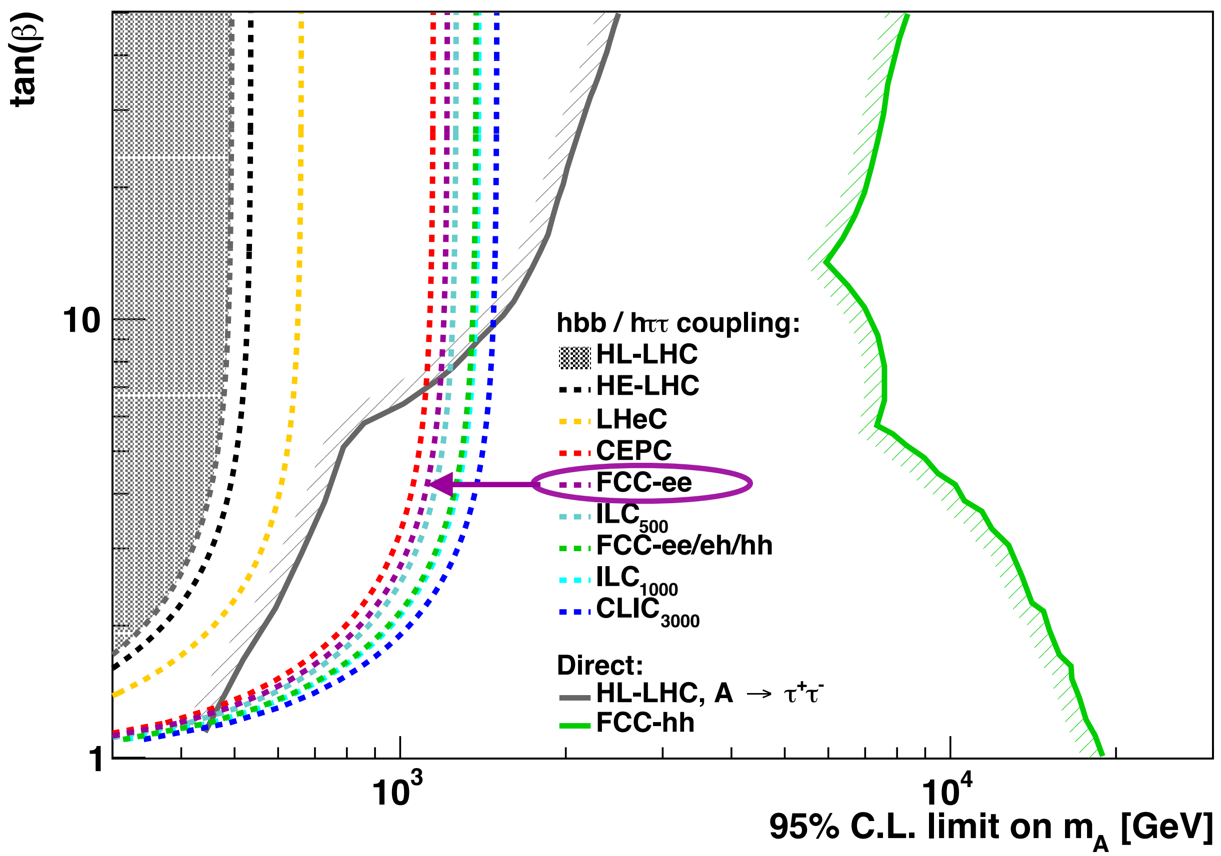
Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY

stops



Fan, Reece, Wang '14

Heavy neutral Higgses

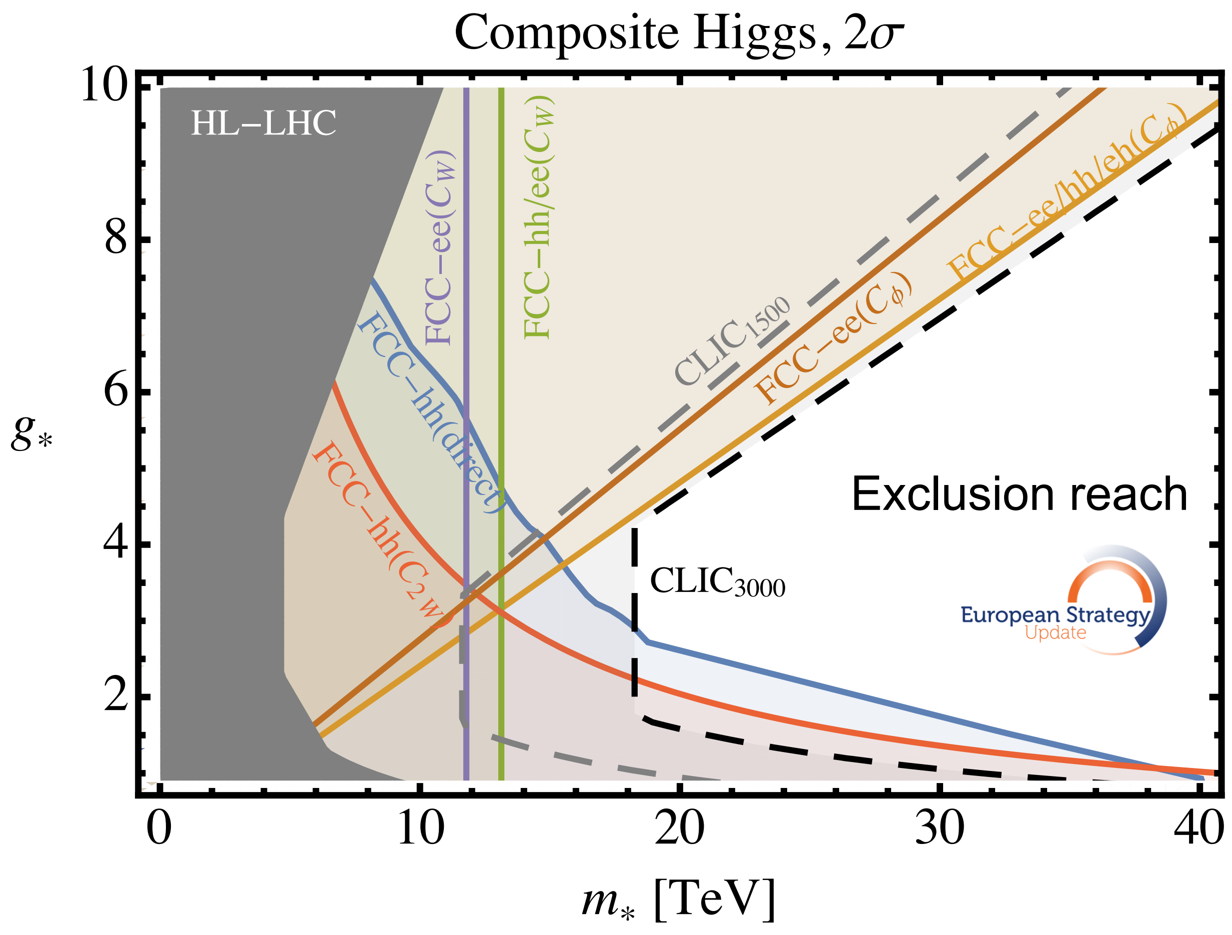


ESU Physics BB '19

Discovery Potential Beyond LHC.

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

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



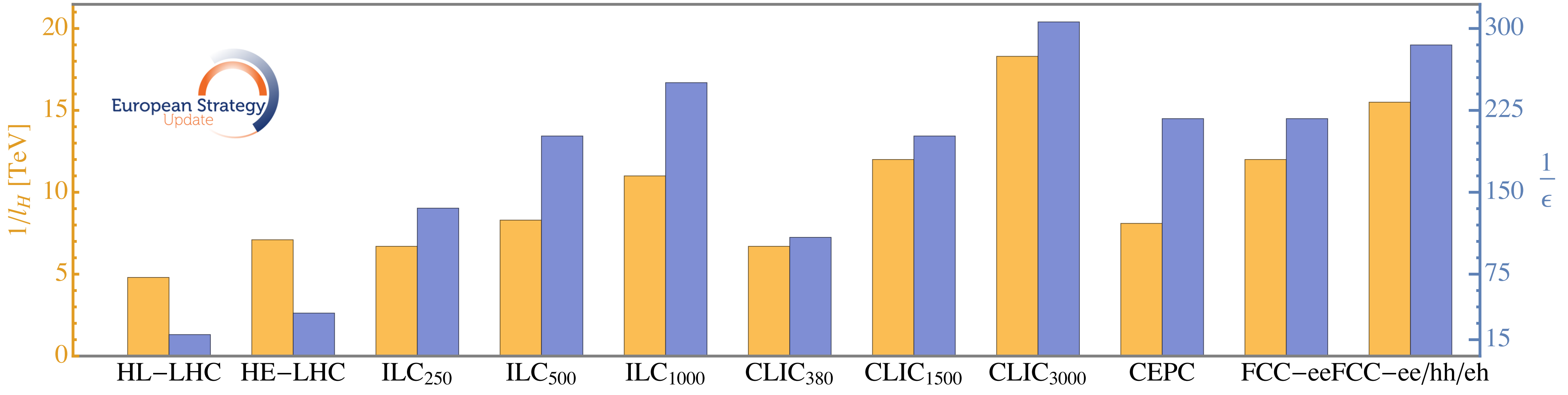


Fig. 8.5: Exclusion reach of different colliders on the inverse Higgs length $1/\ell_H = m_*$ (orange bars, left axis) and the tuning parameter $1/\varepsilon$ (blue bars, right axis), obtained by choosing the weakest bound valid for any value of the coupling constant g_*.

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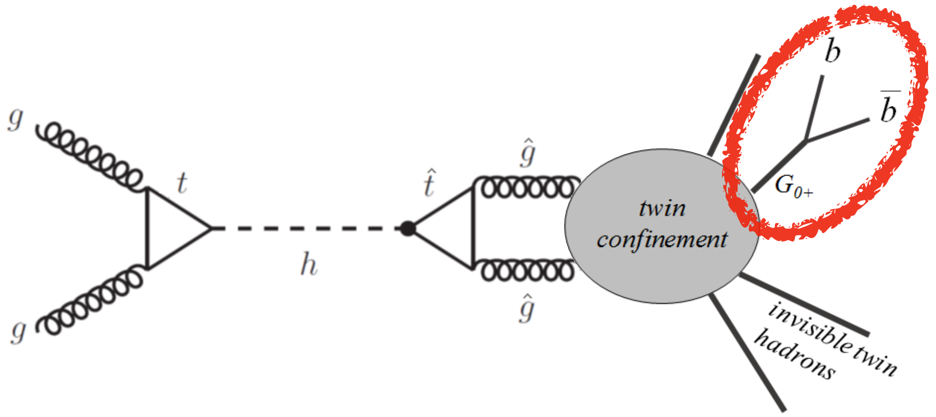
Direct Searches for Elusive New Physics

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

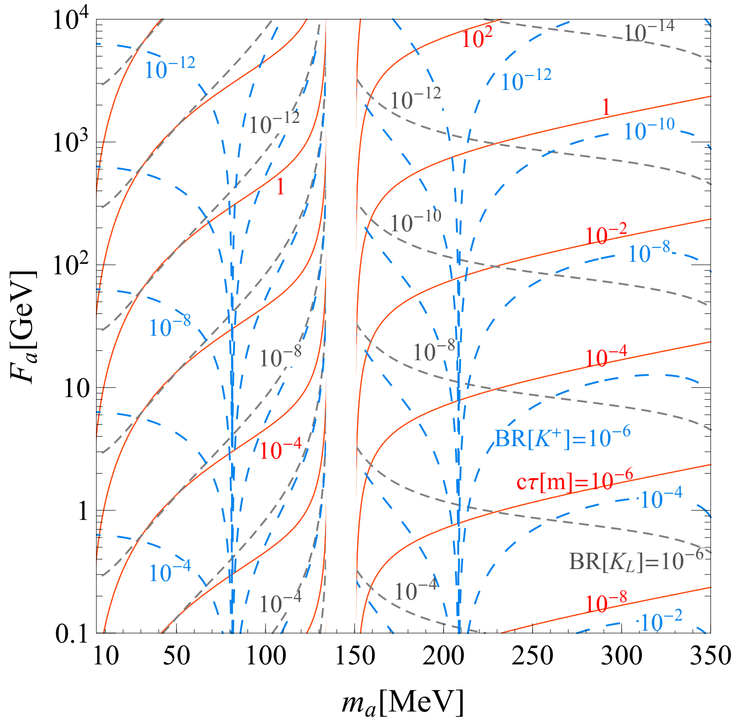
Craig et al, arXiv:1501.05310



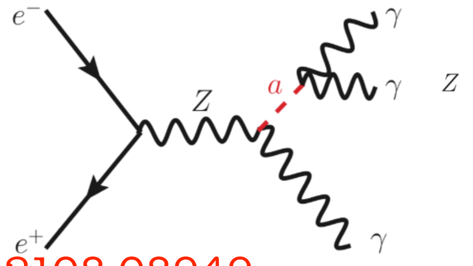
- **Rare decays** Gori et al arXiv:2005.05170
  e.g. ALP mixing w/ SM mesons:

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

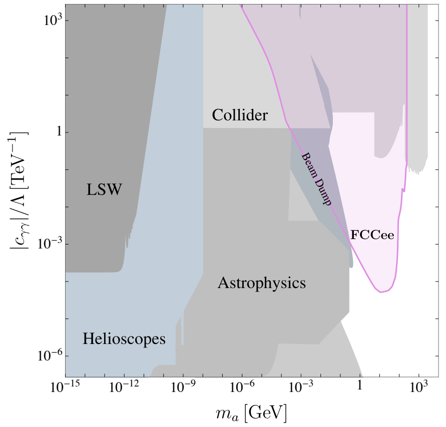
$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu} \tilde{G}^{\mu\nu}$$

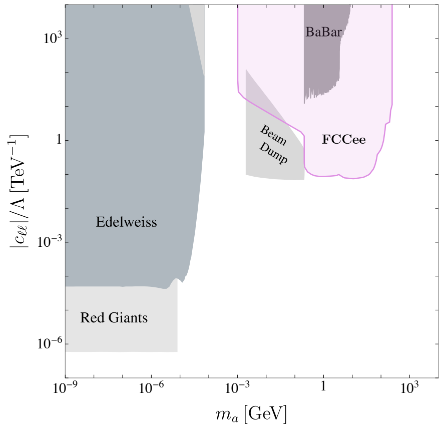


- **ALPs@ colliders**
  e.g. $e^+e^- \to \gamma a$
  $e^+e^- \to ha$



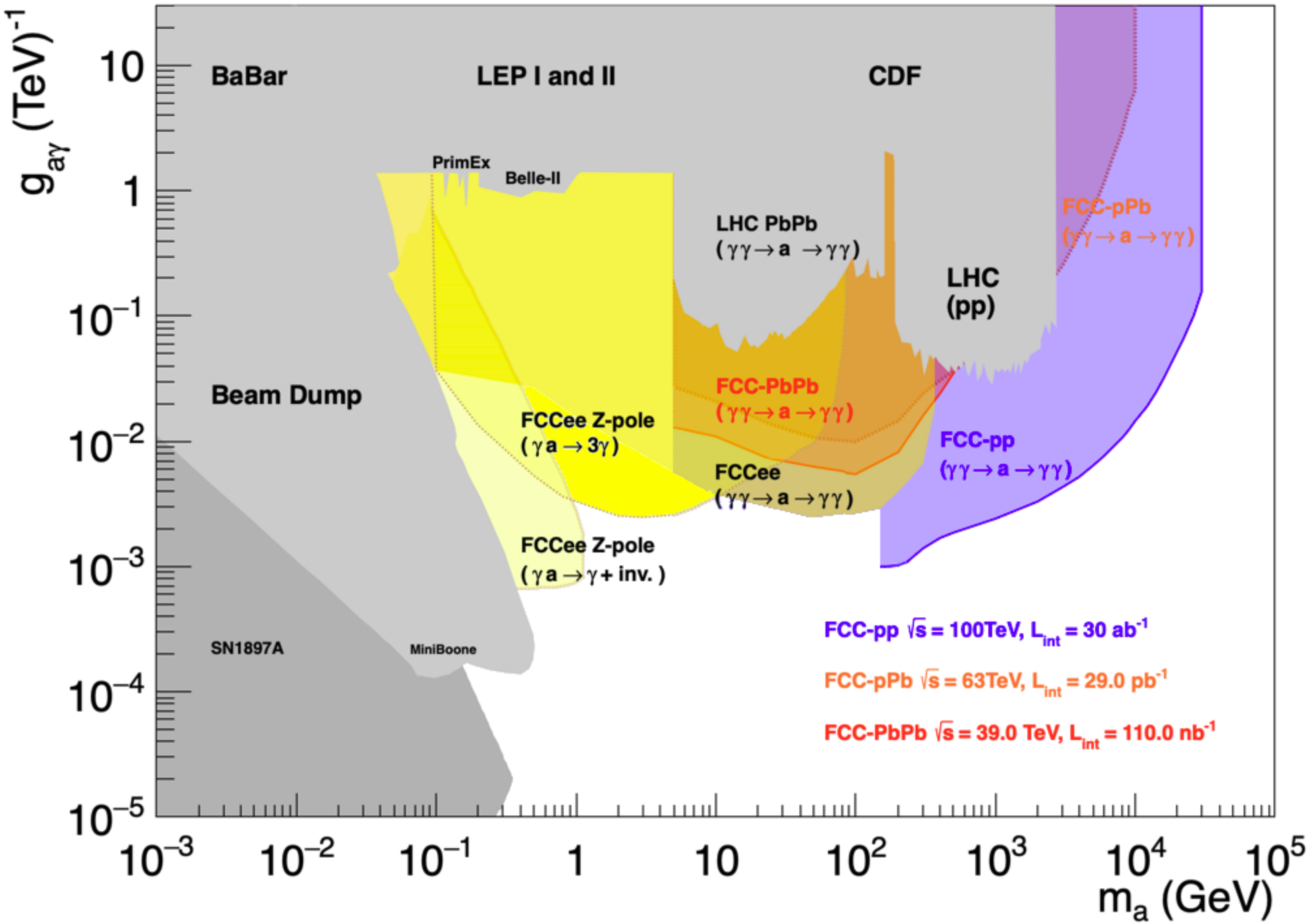
Knapen, Thamm arXiv:2108.08949





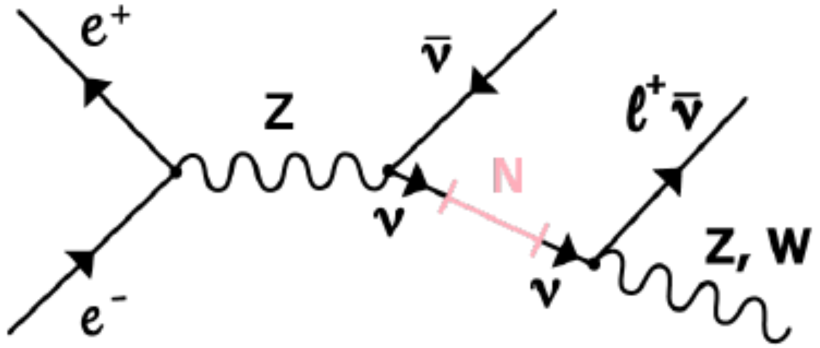
Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

Direct Searches for ALPs

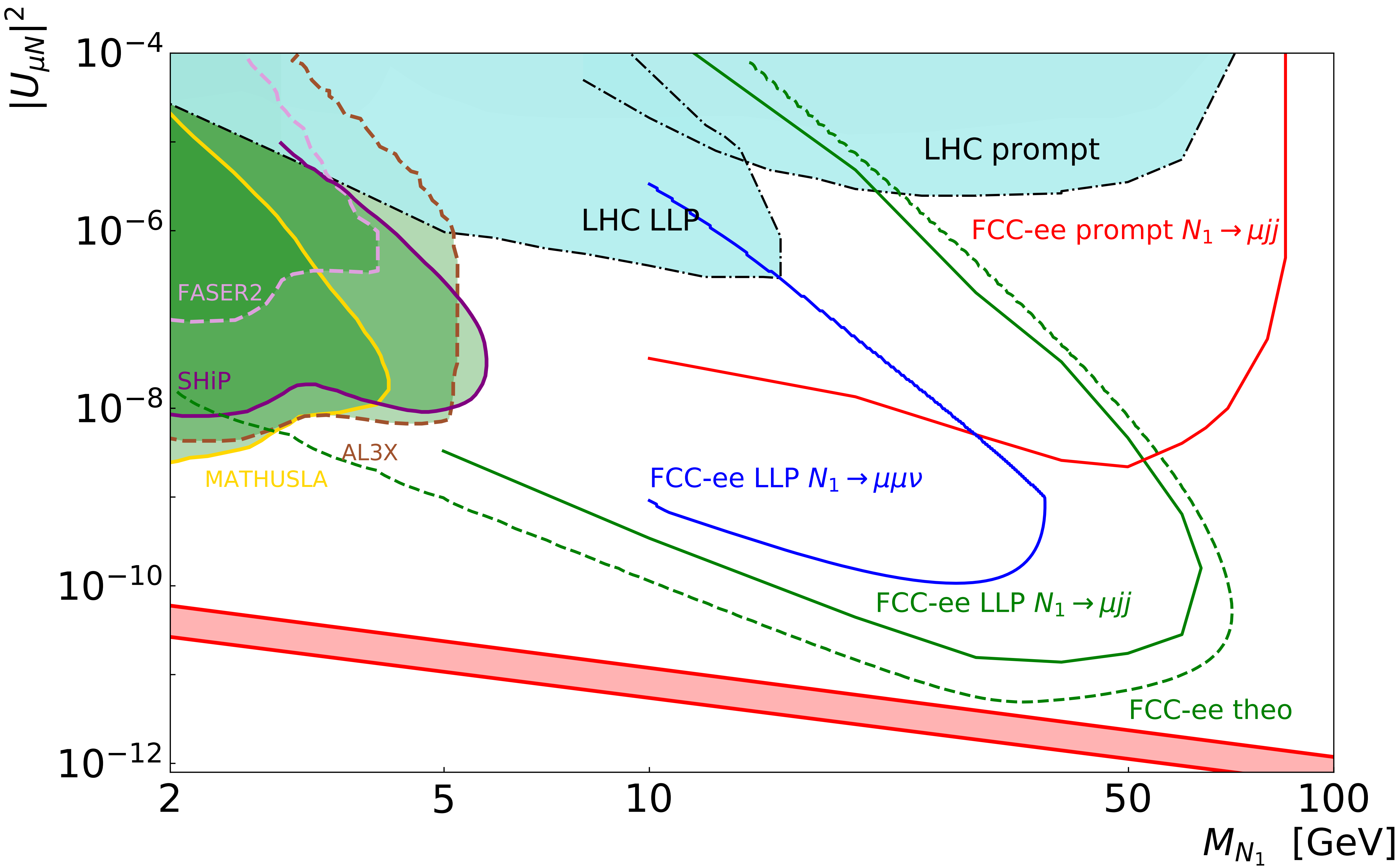


Search for ν_{RH}.

Direct observation in Z decays from LH-RH mixing



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



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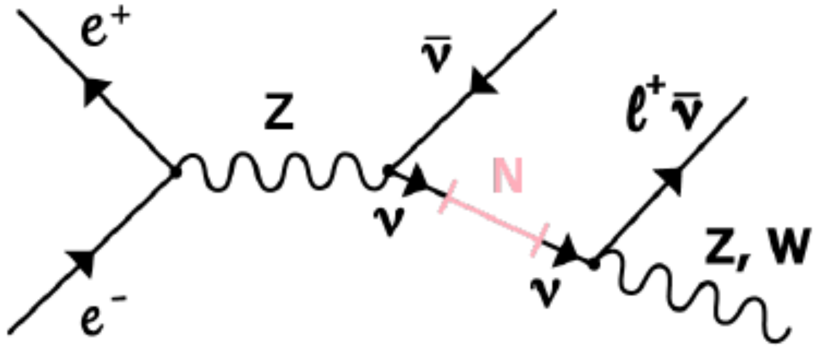

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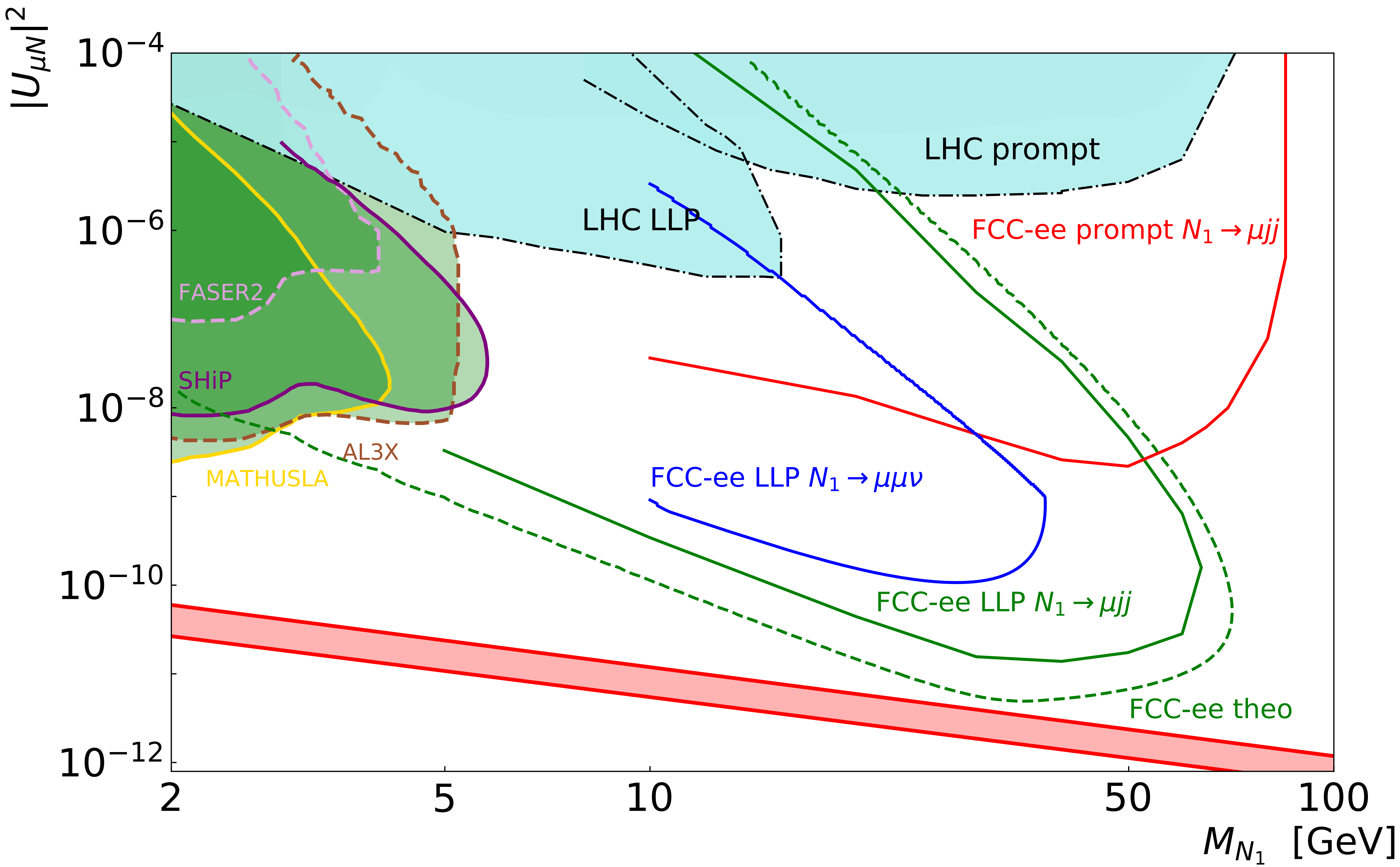
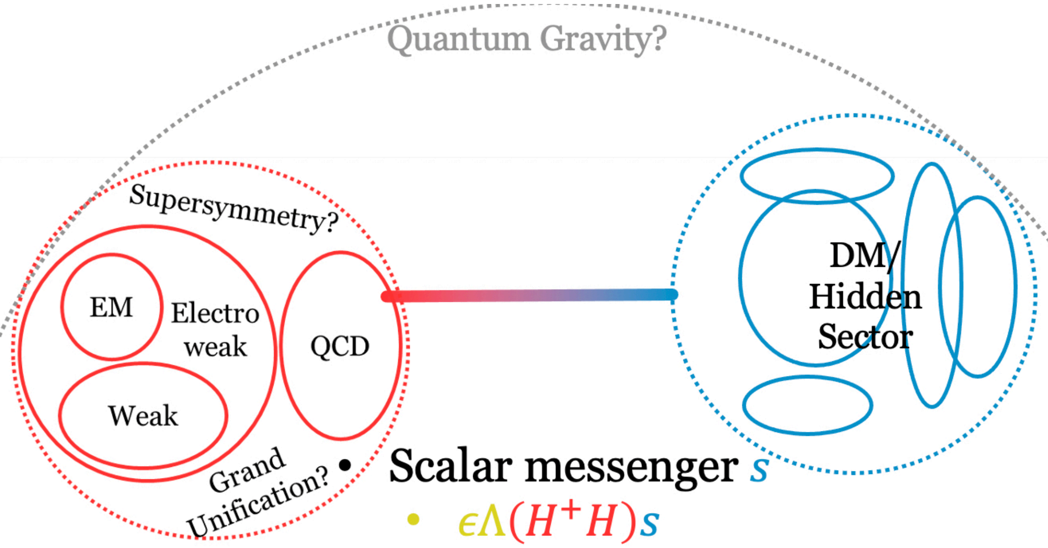


Exotics/Long Lived Particles.

Z. Liu @ CEPC 2020



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

The Higgs could be a good portal to Dark Sector

— rich exotic signatures —

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

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

LHC's strength

Hard at LHC due to missing energy

Hard at LHC due to hadronic background

Lepton colliders' strength

Exotics/Long Lived Particles.

Z. Liu @ CEPC 2020

The Higgs could be a good portal to Dark Sector
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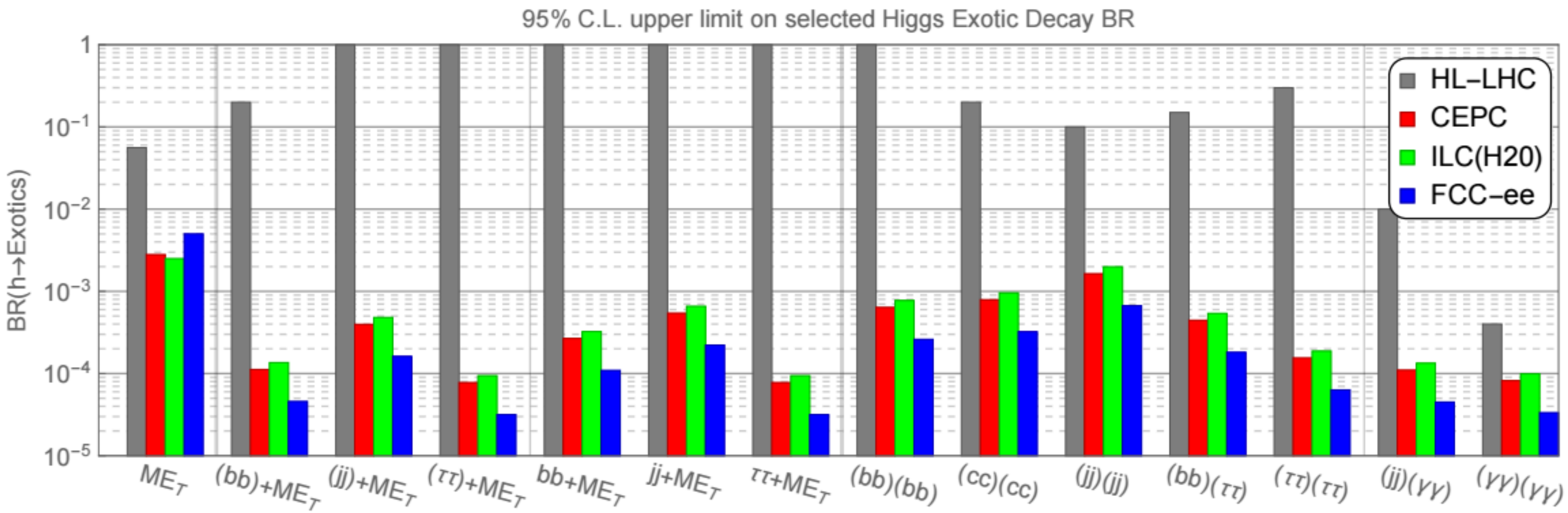


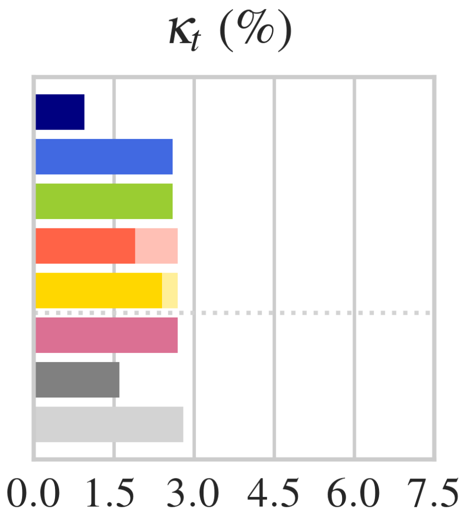
How to improve?
> Dedicated detectors, see e.g. talk by R. Gonzalez Suarez @ FCC week 2021

FCC-ee/FCC-hh Interplay

Synergy ee↔hh.

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

2



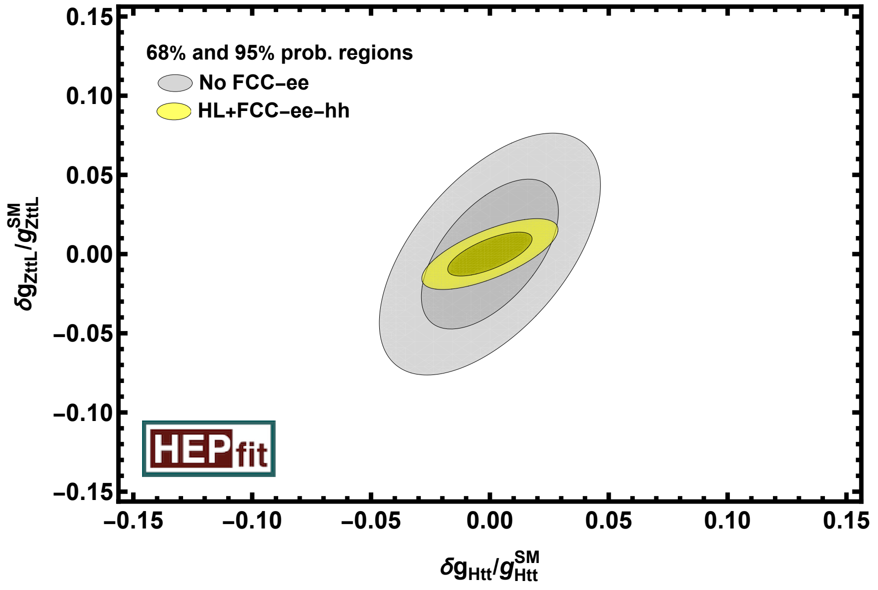
FCC-hh is determining top Yukawa through ratio tth/ttZ

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

Mangano+ '15

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

(uncertainty drops in ratio)



3 Subsequently, the 1% sensitivity on tth is essential to determine h³ at O(5%) at FCC-hh