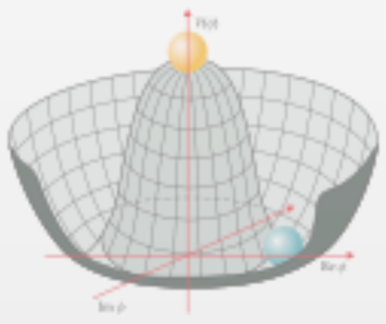
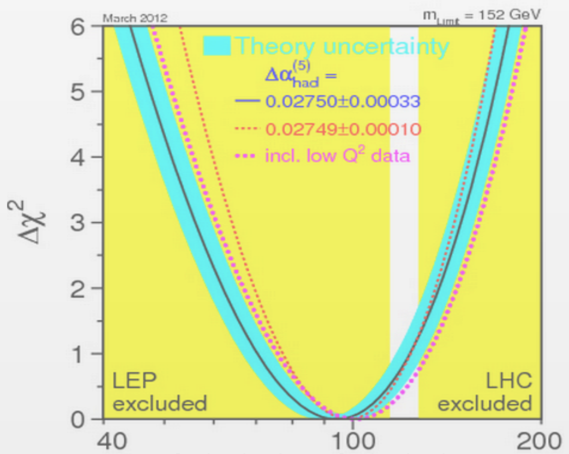
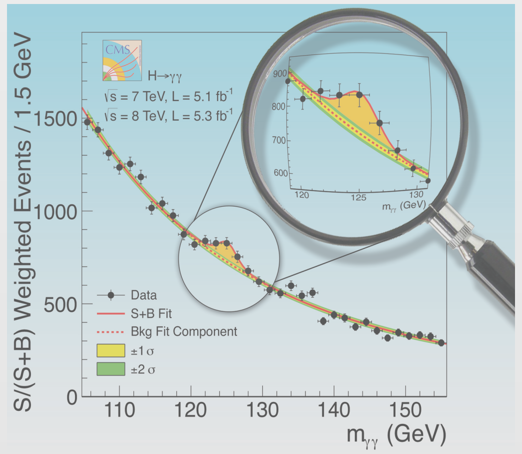


1964



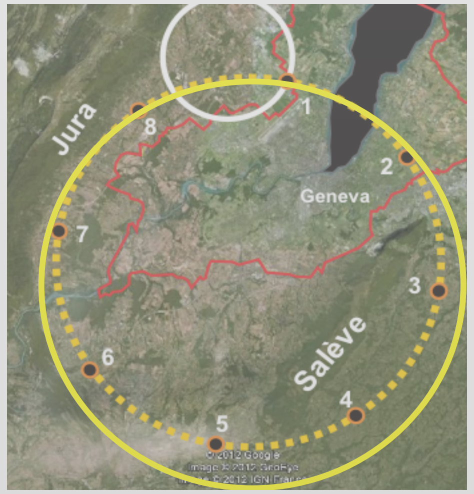
1992-1999

2010



2012

2020



2040

e+e- Z pole pgme

—Overview—

(‘WHY?’ and ‘HOW?’)

ECFA HTE meeting on Z pole physics
Sept. 23, 2022

Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)

(christophe.grojean@desy.de)

LHC: driving cultural change forward

Absence (so far) of new physics where it was expected (TeV)
&
progresses in string theory/quantum gravity (swampland, no global symmetries)

question our description of Nature in terms of effective quantum field theories
(non-locality, IR/UV correlation)

IR parameters are functions of some fields whose value vary during the cosmological history or throughout a complex vacuum structure

Axion: $\mathcal{L}_{\rm dim=4} = \frac{g_s^2}{32\pi^2}\,\bar\theta G^a_{\mu\nu}\tilde G^{\mu\nu,a}$ $\quad \bar\theta \longrightarrow a$

Higgs mass: relaxion, etc. $\quad \mu|H|^2 \to g\Lambda\phi|H|^2$

"Weak Scale Triggers"

cosmological naturalness power counting

mass of the cosmological mediator

its coupling to SM

$$\frac{m_\phi^2}{\mu^2} \simeq \frac{\tilde v^{2q-j} v^j}{\Lambda_H^{2q}} \lesssim \frac{v^{2q}}{\Lambda_H^{2q}}$$

EW scale

Higgs cutoff

q = integer defines the BSM model

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"Weak Scale Triggers"

"Intensity frontier" is not only about precise measurements but
it could reveal light and weakly coupled structures as solution to the main open HEP questions.

This makes FCC-ee valuable on its own and not only through the synergy with FCC-hh.

Why More Precision?

1 Indirect sensitivity to New Physics (see quantitative concrete examples later)

LEP
$(10^6$ Z$)$

$$\frac{c}{\Lambda^2} < \Delta \xrightarrow[\text{observables}]{\text{stat. dominated}} \frac{c}{\Lambda^2} < 10^{-3}\Delta$$

FCC-ee
$(10^{12}$ Z$)$

i.e. improve bounds by ↗ a factor **1000** on c
↘ a factor **30** on Λ

2 The precise values of the Higgs couplings control the structure of matter/Universe

$m_W, m_Z \leftrightarrow$ Higgs couplings ✓
↑
lifetime of stars
(why $t_{\text{Sun}} \sim t_{\text{life evolution}}$?)

$\underbrace{m_e}_{\text{size of atoms}}, \underbrace{m_u, m_d}_{\text{nuclei stability}} \leftrightarrow$ Higgs couplings ?

EW @ $t \sim 10^{-10}$s $\leftrightarrow$ Higgs self-coupling ?

matter/anti-matter $\leftrightarrow$ CPV in Higgs sector ?

Why More Precision?

3 The values of the EFT interactions among SM fields will reveal the “selection rules” of the SM, with intimate links to new structure/symmetries

Contino, Falkowski, Goertz, Grojean, Riva ‘16

Examples of symmetries leading to different selection rules

Operator	Naive (maximal) scaling with g_*	Symmetry/Selection Rule and corresponding suppression
$O_{y_\psi} = \|H\|^2 \bar{\psi}_L H \psi_R$	g_*^3	Chiral: y_f/g_*
$O_T = (1/2)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	g_*^2	Custodial: $(g'/g_*)^2$, $y_t^2/16\pi^2$
$O_{GG} = \|H\|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$ $O_{BB} = \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	g_*^2	Shift symmetry: $(y_t/g_*)^2$ Elementary Vectors: $(g_s/g_*)^2$ (for O_{GG}) $(g'/g_*)^2$ (for O_{BB}) Minimal Coupling: $g_*^2/16\pi^2$
$O_6 = \|H\|^6$	g_*^4	Shift symmetry: λ/g_*^2

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \cdots$$

Dimensional arguments impose

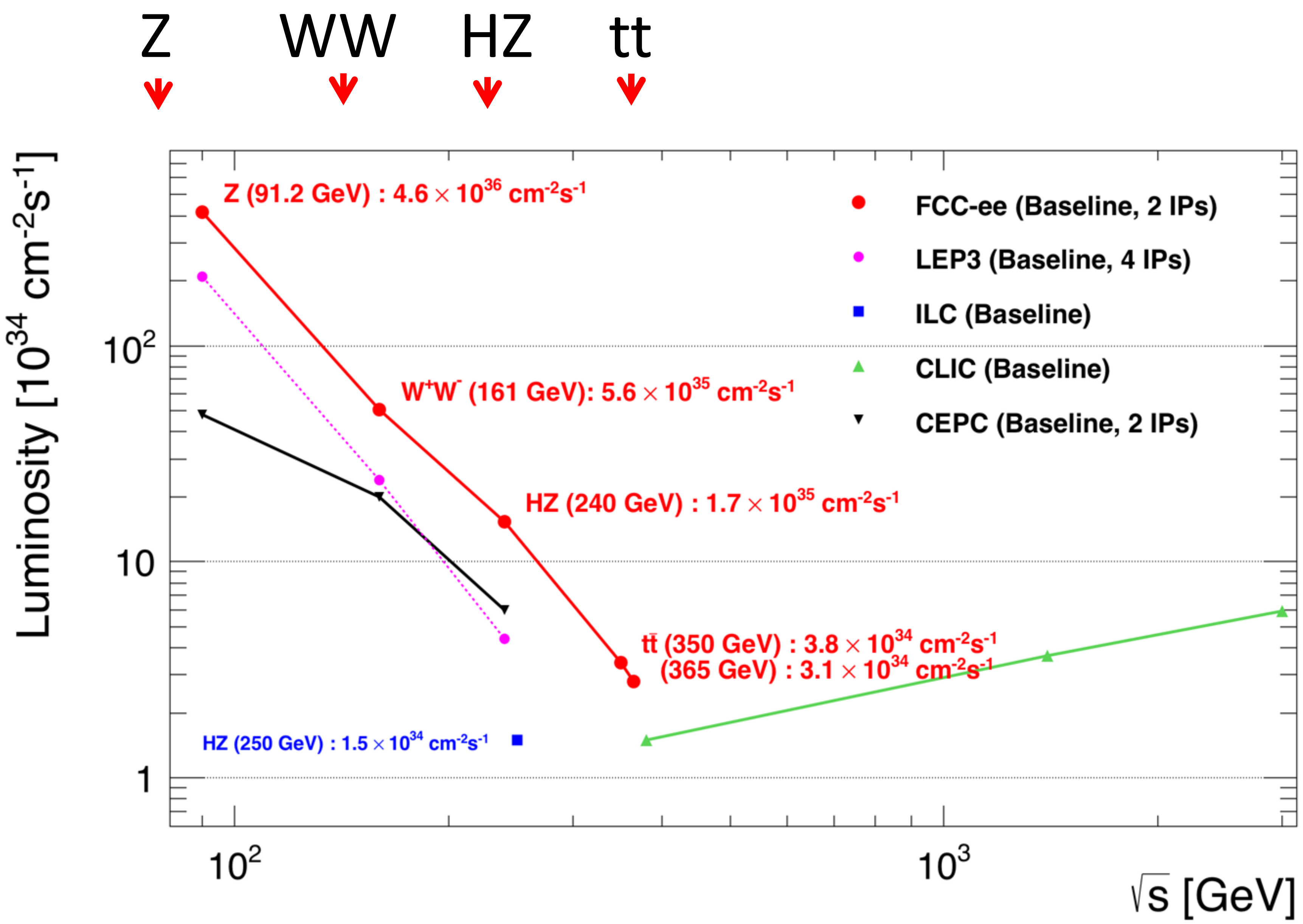
$$c_i^{(D)} \sim (\text{coupling})^{n_i - 2}$$

n_i=number of fields in operator $\mathcal{O}_i^{(D)}$ (independant of D)

generically, (coupling ~ g_*) coupling of New Physics to SM
but there might exist **“selection rules”** that lead to other scaling

Precision physics exp. (EDMs, g-2…) usually constrains one operator.
Need a collider to have access to several of them and
then understand the underlying structure.

ee Higgs Factory Luminosity

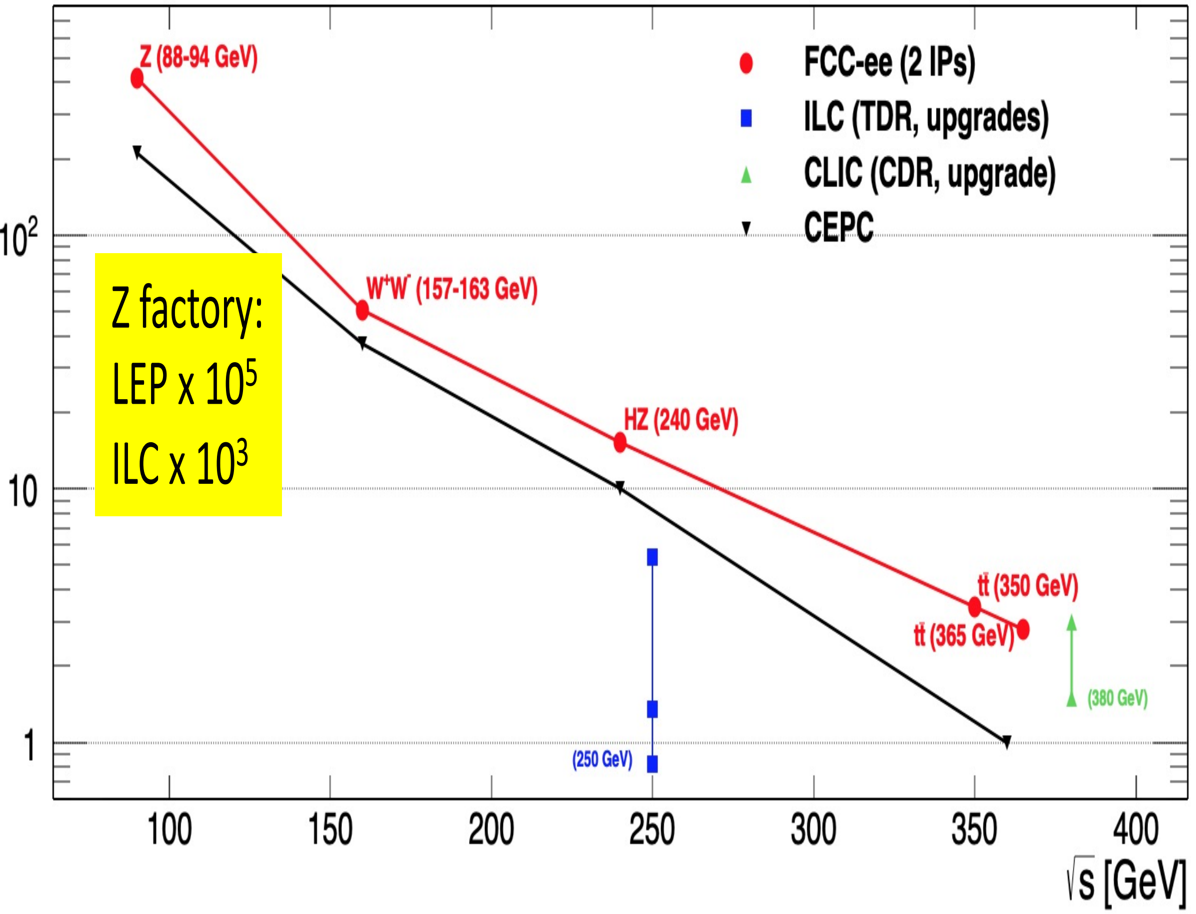


Linear collider can achieve Z-pole programme (10^6 Z) via radiative return or dedicated low luminosity run (10^9 Z).
Circular collider can collect 10^{12} Z in only a few years.

FCC-ee Run Plan

LEP data accumulated in first 3 mn. Then exciting & diverse programme with different priorities every few years.

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



Z factory:
LEP x 10^5
ILC x 10^3

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

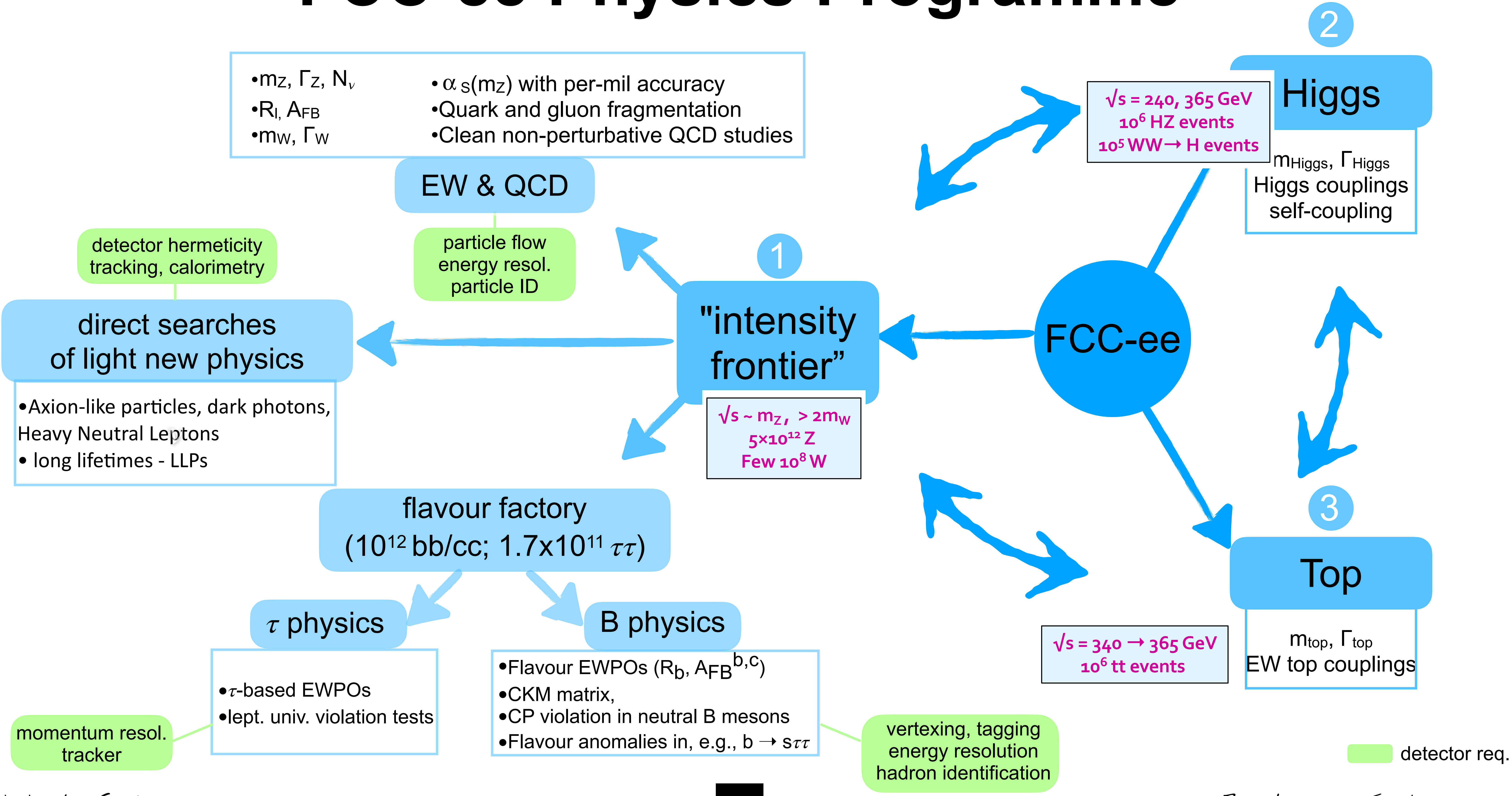
— Superb statistics achieved in only 15 years —

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

Event statistics (2IP)

					E_{CM} errors:
Z peak	**E_{cm} : 91 GeV**	**4yrs**	**5 10^{12} e+e- → Z**	**LEP x 10^5**	<100 keV
WW threshold	**$E_{cm} \geq$ 161 GeV**	**2yrs**	**>10^8 e+e- → WW**	**LEP x 2.10^3**	<300 keV
ZH maximum	**E_{cm} : 240 GeV**	**3yrs**	**> 10^6 e+e- → ZH**	**Never done**	1 MeV
s-channel H	***E_{cm} : m_H***	***(3yrs?)***	***O(5000) e+e- → H***	***Never done***	<< 1 Me
$\bar{t}t$	**E_{cm} : $\geq$ 350 GeV**	**5yrs**	**10^6 e+e- → $\bar{t}t$**	**Never done**	2 MeV

FCC-ee Physics Programme



FCC-ee

1

"intensity frontier"

$\sqrt{s} \sim m_Z$, $> 2m_W$
5×10^{12} Z
Few 10^8 W

EW & QCD

- 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

particle flow
energy resol.
particle ID

direct searches of light new physics

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

detector hermeticity
tracking, calorimetry

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

τ physics

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

momentum resol.
tracker

B physics

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

vertexing, tagging
energy resolution
hadron identification

2

Higgs

$\sqrt{s}$ = 240, 365 GeV
10^6 HZ events
10^5 WW→ H events

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

3

Top

$\sqrt{s}$ = 340 → 365 GeV
10^6 tt events

m_{top}, Γ_{top}
EW top couplings

🟩 detector req.

FCC-ee Physics Programme

②

Higgs

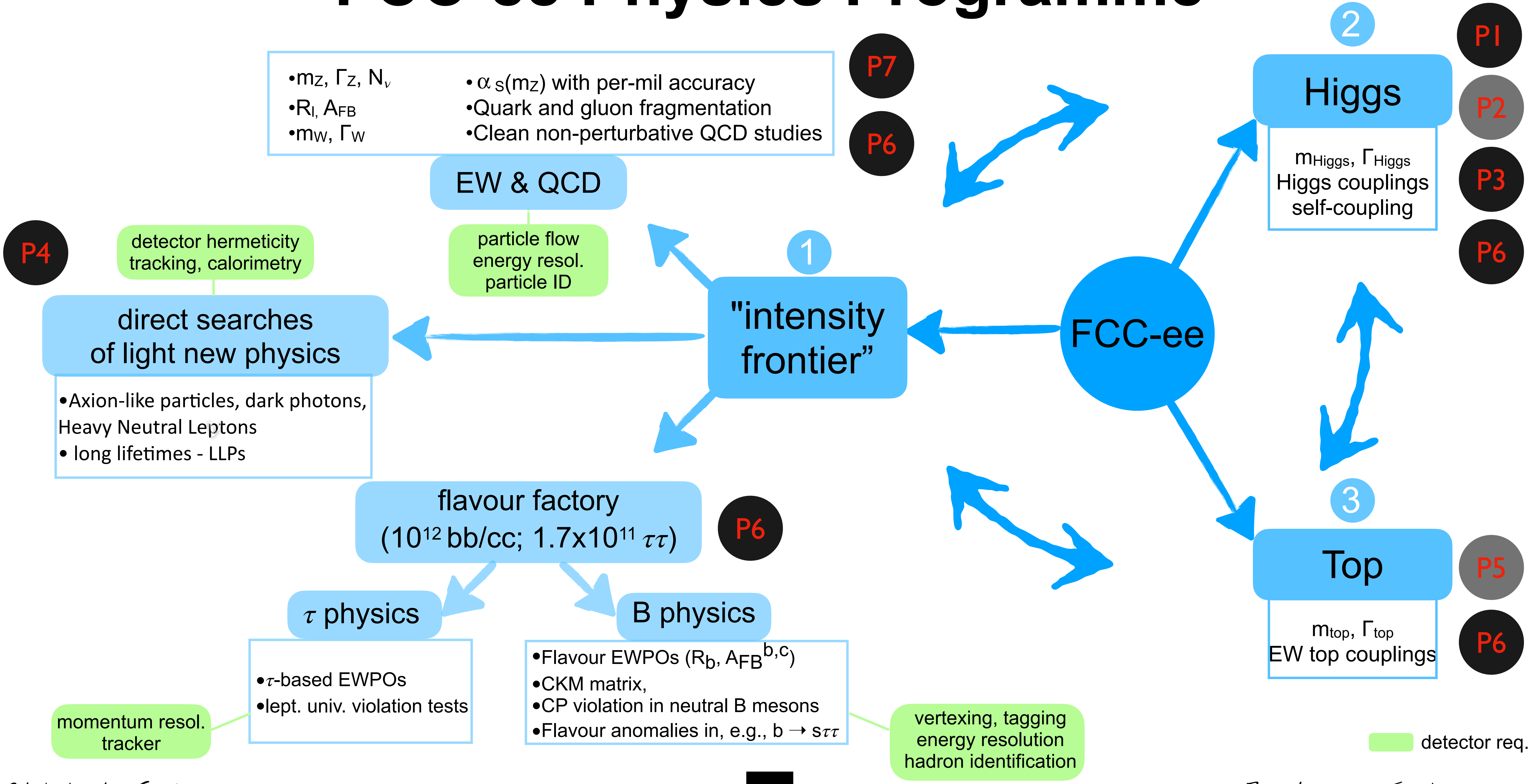
m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

Higgs sector definition imposes initial requirements on **hadronic resolution, tracking and vertexing**

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_\mathrm{T}) \sim 2 \times 10^{-5}$ $\oplus 1 \times 10^{-3}/(p_\mathrm{T} \sin\theta)$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\text{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

🟩 detector req.

FCC-ee Physics Programme



FCC-ee

1

"intensity frontier"

P7

P6

EW & QCD

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
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particle flow
energy resol.
particle ID

P4

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detector hermeticity
tracking, calorimetry

flavour factory

(10^{12} bb/cc; $1.7\text{x}10^{11}$ $\tau\tau$)

P6

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vertexing, tagging
energy resolution
hadron identification

2

Higgs

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

P1

P2

P3

P6

3

Top

m_{top}, Γ_{top}
EW top couplings

P5

P6

🟩 detector req.

Snowmass 2021 Higgs Factory Considerations

J. Bagger+ arXiv:2203.06164

— Physics Considerations —

P1	P2	P3	P4	P5	P6	P7
Precision Higgs measurements to SM particles	Measurements of Higgs self-coupling(s)	Sensitivity to rare and exotic Higgs decays	New Physics discovery potential	Direct measure of EW/Yukawa top coupling	Indirect sensitivity to New Physics	Improved measurements of α_s

— Technological Considerations —

T1	T2	T3	T4	T5	T6	T7
Range of operating E/ease of changing E	Annual integrated luminosity	Upgradability to higher energy/ luminosity	Extent and cost of remaining R&D	Ability to operate at the tt threshold	Ability to run at the Z pole	Ability to run at the WW threshold

T8	T9	T10	T11	T12-T13	T14-T15	T16
Stability and calibration of collision energy	Beam stability and luminosity calibration	Ability to control beam-related backgrounds	Ability to provide independent confirmation of new discoveries	Ability to provide polarised electrons/ positrons	Possibility to reconfigure as γγ, $e^-\gamma$, e^-e^-, ep, pp collider	Opportunities for beam dumps experiments

T17
Need for, and scientific utility of, technology demonstrators

Z-Factories are great Flavour Factories

See S. Monteil, Flavour@FCC '22

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

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

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

out of reach
at LHCb/Belle

boosted b's/τ's
at FCC-ee

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

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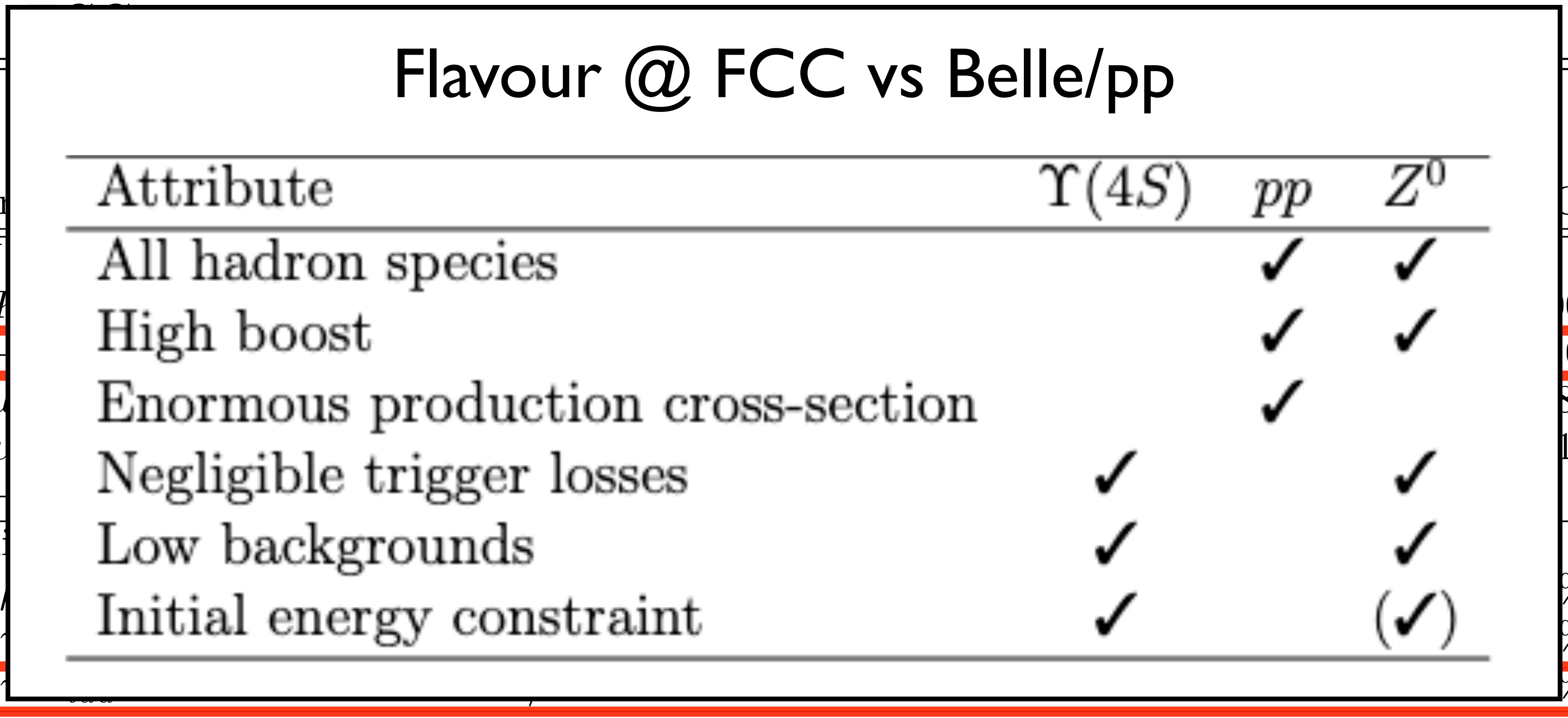


Flavour @ FCC vs Belle/pp

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

Decay				C-ee
EW/H				
$B^0 \to$				0000
$\mathcal{B}(B^0 -$				000
$B_s \to \mu$				800
$B^0 \to \mu$				100
$\mathcal{B}(B_s -$				
Leptoni				
$B^+ \to$				%
$B^+ \to$				%
$B_c^+ \to$				%
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)

See S. Monteil, Flavour@FCC '22

out of reach
at LHCb/Belle

boosted b's/τ's
at FCC-ee

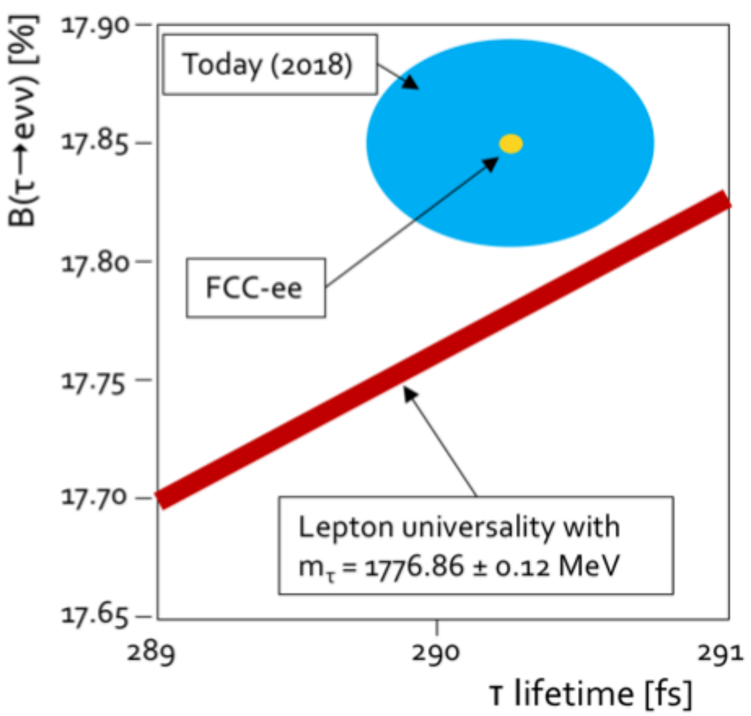
Makes possible
a topological rec.
of the decays
w/ miss. energy

Probing New Physics w/ τ Decays

"3 more tau's than at Belle II"

Allwicher, Isidori, Semilovic '21

$$\left|g_e^{(\tau)}/g_e^{(\mu)}\right|^2 \equiv \frac{\Gamma(\tau\to e\nu\bar{\nu})}{\Gamma(\mu\to e\nu\bar{\nu})}\left[\frac{\Gamma_{\rm SM}(\tau\to e\nu\bar{\nu})}{\Gamma_{\rm SM}(\mu\to e\nu\bar{\nu})}\right]^{-1}$$



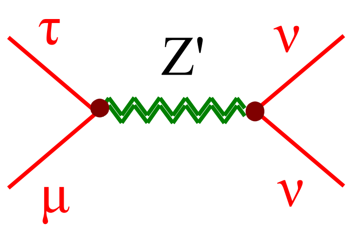
sensitivity good enough to probe BSM models "explaining" current flavour R_K anomalies

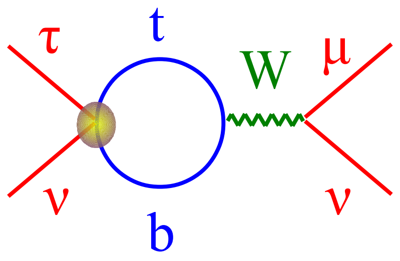
($b\to c\tau\nu$)

E.g.: (I) LFU tests in tau decays aka measurement of GF with taus

A. Pich '13

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)			





"Model-independent" effect linked to present anomalies

- NP expectation from current anomalies in the range (0.2 – 4.0) × 10^{-3}
- SM theory precision ~ 10^{-5}
- Belle-II can (at most) reach an error ~ 0.3 × 10^{-3}
- FCC-ee could go below 10^{-4} !

Unique opportunity !

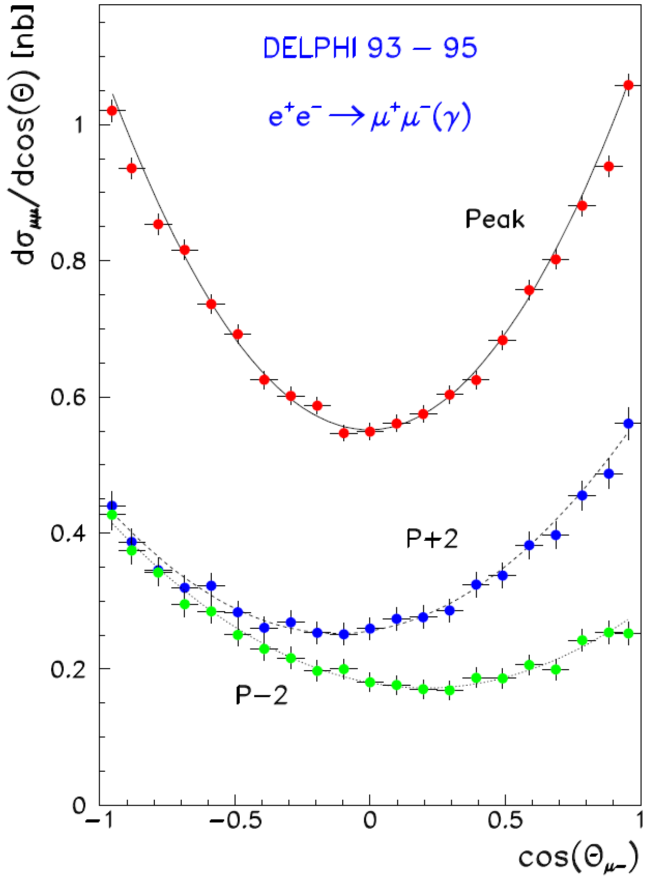
Example of EW measurements @ Tera Z

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

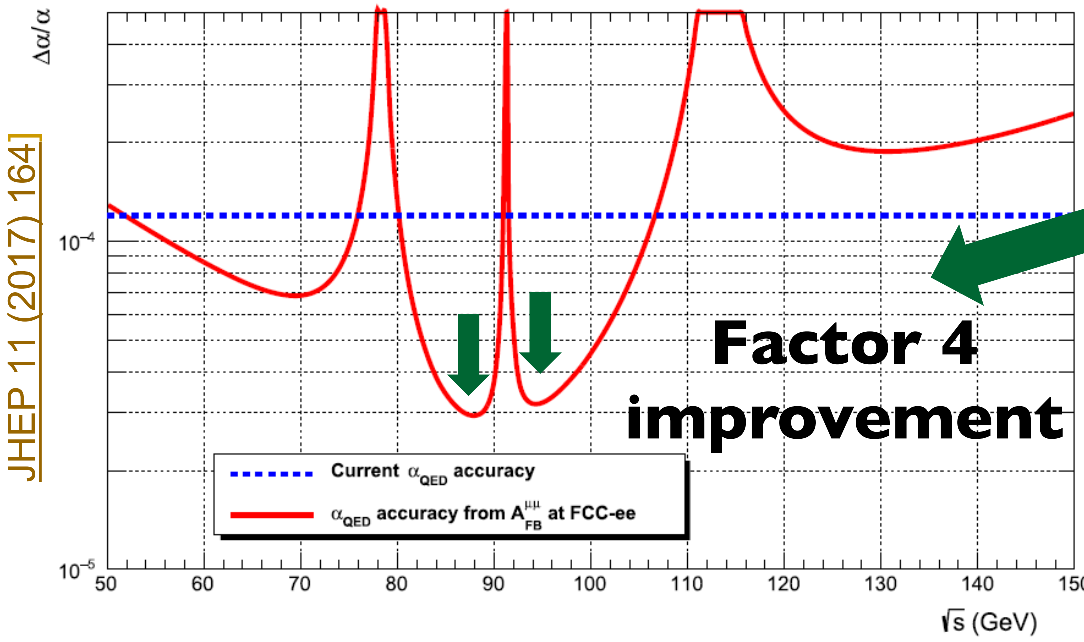
strongly depends on √s ←
direct measurement of $\alpha_{QED}(s)$ at √s != m_Z ←
measure $\sin^2\theta_W$ to high precision ←

$$A^{\mu\mu}_{\rm FB}(s) \simeq \frac{3}{4}\mathcal{A}_{\rm e}\mathcal{A}_{\mu} \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{\rm QED}(s)}{m_{\rm Z}^2 G_{\rm F}\left(1-4\sin^2\theta_{\rm W}^{\rm eff}\right)^2}\,\frac{s-m_{\rm Z}^2}{2s}\right]$$

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



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



Factor 4 improvement

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

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

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

G. Wilkinson @ FCC week 2021

Example of EW measurements @ Tera Z

Z → μμ forward/backward asymmetry also used to measure ewk mixing angle $\sin^2\theta_W$ at Z-pole = 91.2 GeV:

$$A^{\mu\mu}_{\mathrm{FB}}(s) \simeq \frac{3}{4}\mathcal{A}_e\mathcal{A}_\mu \longrightarrow \mathcal{A}_e = \frac{{g_{\mathrm{L,e}}}^2 - {g_{\mathrm{R,e}}}^2}{{g_{\mathrm{L,e}}}^2 + {g_{\mathrm{R,e}}}^2} = \frac{2v_\mathrm{e}/a_\mathrm{e}}{1+(v_\mathrm{e}/a_\mathrm{e})^2}, \text{with } v_\mathrm{e}/a_\mathrm{e} \equiv 1 - 4\sin^2\theta^{\mathrm{eff}}_{\mathrm{W}}$$

$\Delta A^{\mu\mu}_{\mathrm{FB}}(s)$ ~ 3×10^{-6} (stat) + 4×10^{-6} (syst)

→ Measure $\sin^2\theta_W$ to 3×10^{-6} abs. precision (currently 1.6×10^{-4})

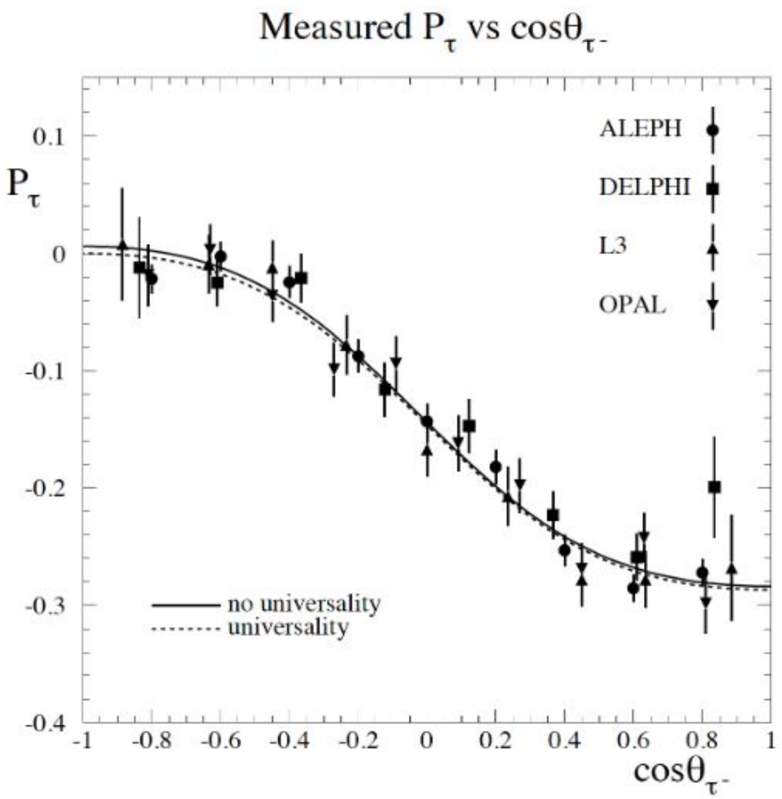
→ *Assumes lepton universality*: $A_e = A_\mu$

→ Mainly dominated by energy calibration (point-to-point)

Tau polarization used to constrain the mixing angle to a similar precision

- *No assumption on lepton universality* (direct separation A_e and A_τ)
- A_τ from P_τ: benefit from high statistics and very robust measurement

$$P_\tau(\cos\theta) = \frac{A_{pol}(1+\cos^2\theta) + \frac{8}{3}A^{FB}_{pol}\cos\theta}{(1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta} \Longrightarrow P_\tau \equiv \frac{\sigma(\tau_\mathrm{R}) - \sigma(\tau_\mathrm{L})}{\sigma(\tau_\mathrm{R}) + \sigma(\tau_\mathrm{L})} \simeq -2(1-4\sin^2\theta_\mathrm{W})$$



J. Eysermans @ EPS2021

Example of EW measurements @ Tera Z

→ **Mass** ± 4 keV (stat) ± 100 keV (syst) [LEP 2.1 MeV]

- Systematics limited due to beam calibration uncertainties (RDP ~ 100 keV)

→ **Width** ± 4 keV (stat) ± 25 keV (syst) [LEP 2.3 MeV]

- Systematics dominated by:
  - Relative (point-to-point) uncertainty on the √s ~ 22 keV
  - Impact on beam-energy spread uncertainty ~ 10 keV
    - Absolute uncertainty on BES ~ 84 MeV
    - Constrained using $e^+e^- \to \mu^+\mu^-(\gamma)$ events:

      → Constrain BES uncertainty to per-mille level

      → Taking into account asymmetric beam optics (x-angle α 30 mrad) and γ-ISR

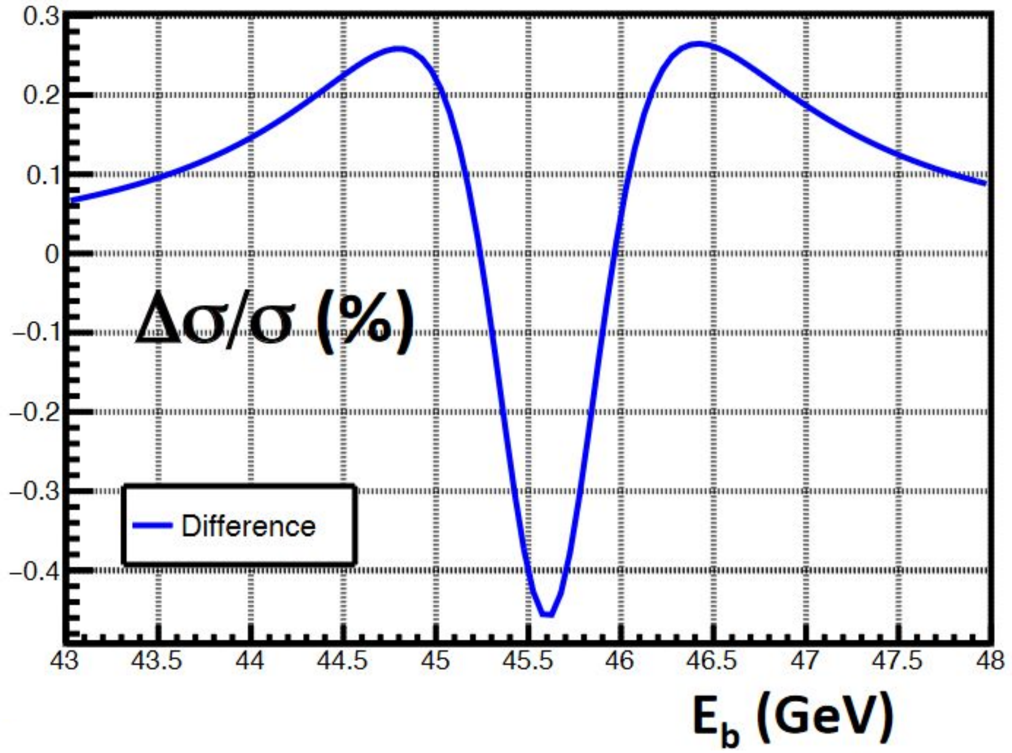
      → Muon angular resolution ~ 0.1 mrad required

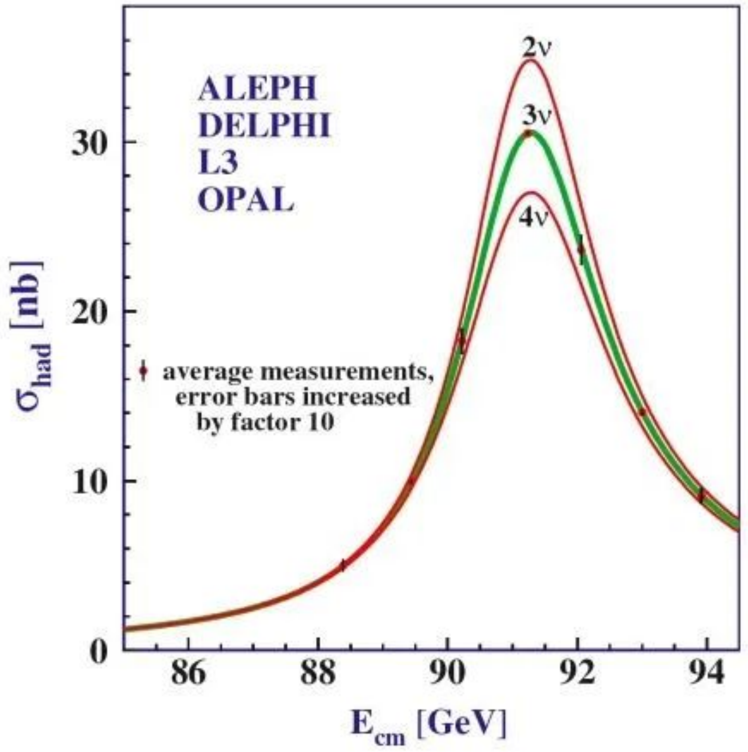
→ **Hadronic cross-section** σ^0_{had}: ± 4 pb [LEP 37 pb]

→ **Number of neutrino families:** 1×10^{-3} (abs) [LEP 7×10^{-3}]

- Dominated by luminosity uncertainty

Lineshape cross-section



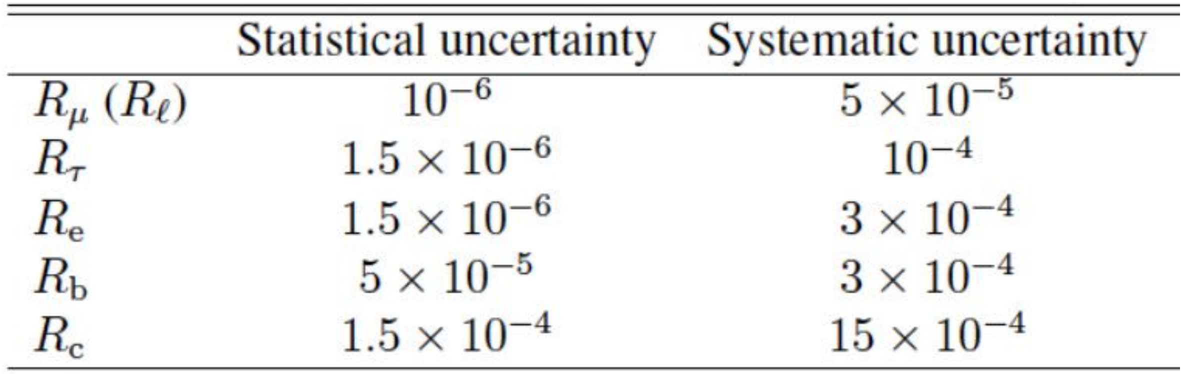


J. Eysermans @ EPS2021

Example of EW measurements @ Tera Z

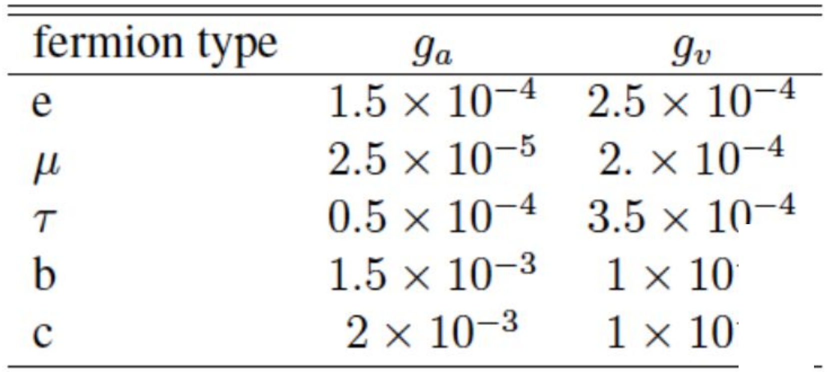
Couplings measured from ratio of hadronic and leptonic partial widths

→ need control on detector precision: detector acceptances: detector precision ~ 10 μm



	Statistical uncertainty	Systematic uncertainty
R_μ (R_ℓ)	10^{-6}	5×10^{-5}
R_τ	1.5×10^{-6}	10^{-4}
R_e	1.5×10^{-6}	3×10^{-4}
R_b	5×10^{-5}	3×10^{-4}
R_c	1.5×10^{-4}	15×10^{-4}

Relative stat. and syst. unc. (similar)



fermion type	g_a	g_v
e	1.5×10^{-4}	2.5×10^{-4}
μ	2.5×10^{-5}	$2. \times 10^{-4}$
τ	0.5×10^{-4}	3.5×10^{-4}
b	1.5×10^{-3}	1×10
c	2×10^{-3}	1×10

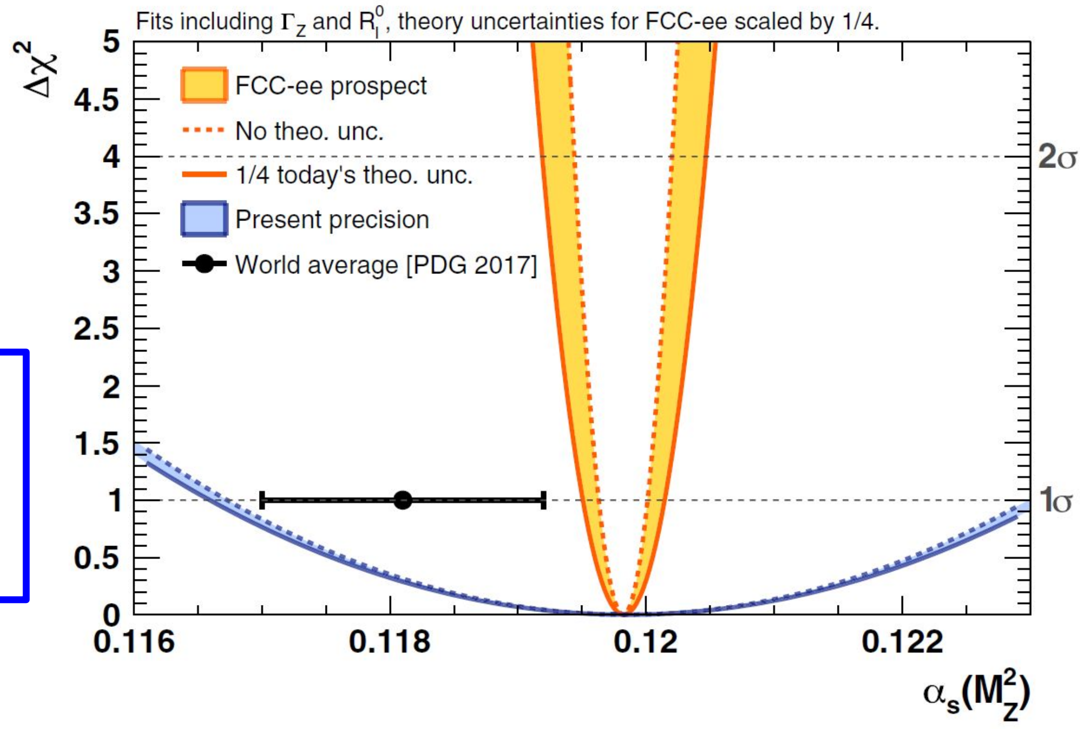
Relative unc. on couplings

1-2 orders of magnitude
Improvement w.r.t. LEP

Extract strong coupling constant $\alpha_S(m_Z^2)$ using leptonic/hadronic width ratio: $R_l = \Gamma_{had}/\Gamma_{lep}$

→ $\Delta\alpha_S(m_Z)$ ~ 1×10^{-5} (stat) + 1.5×10^{-4} (syst) abs. (current value $\Delta\alpha_S$ 30×10^{-4})

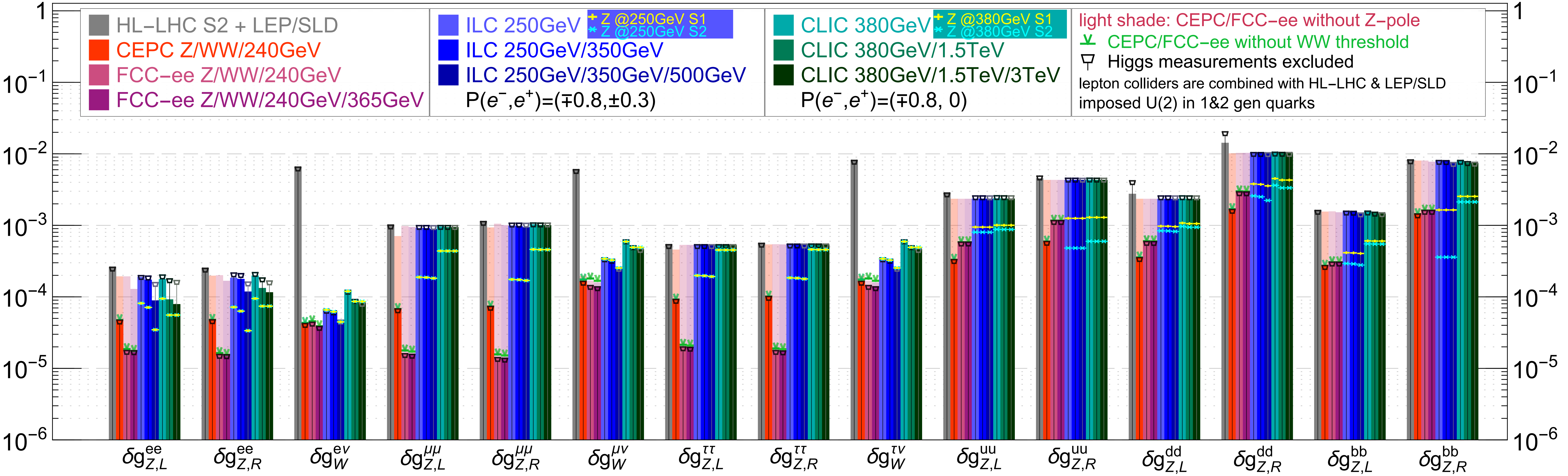
→ Systematically dominated (acceptance)



J. Eysermans @ EPS2021

Sensitivity on EW couplings

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



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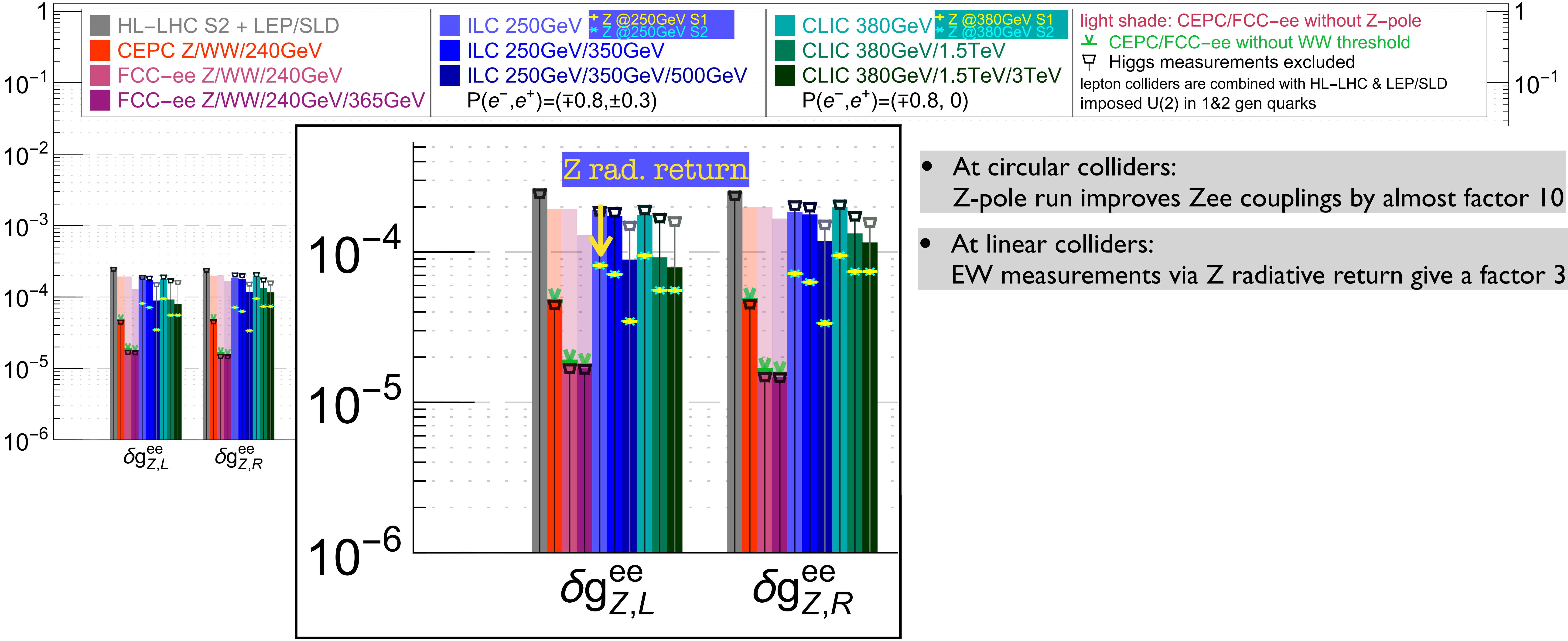
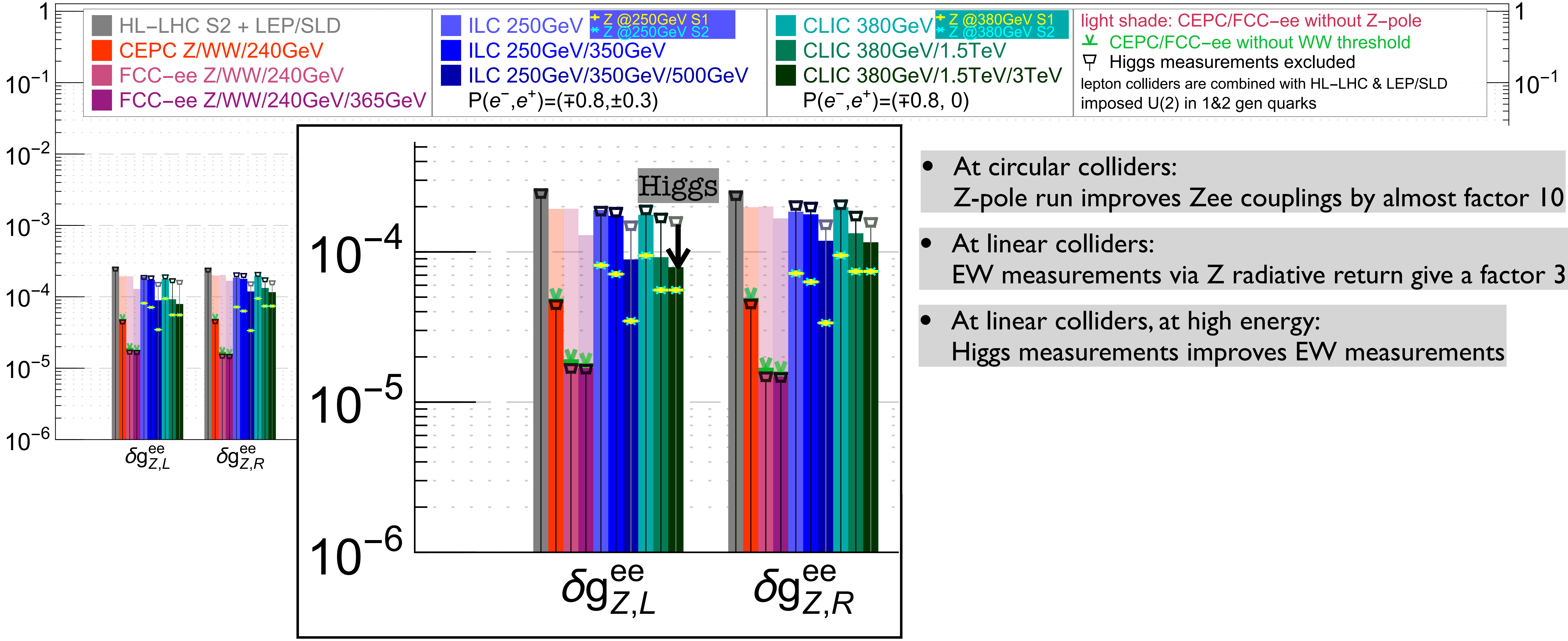


- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3

Sensitivity on EW couplings

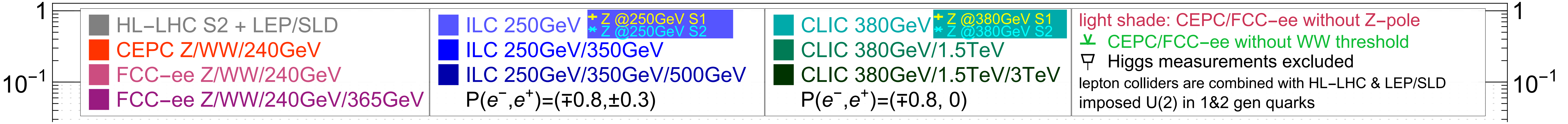
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



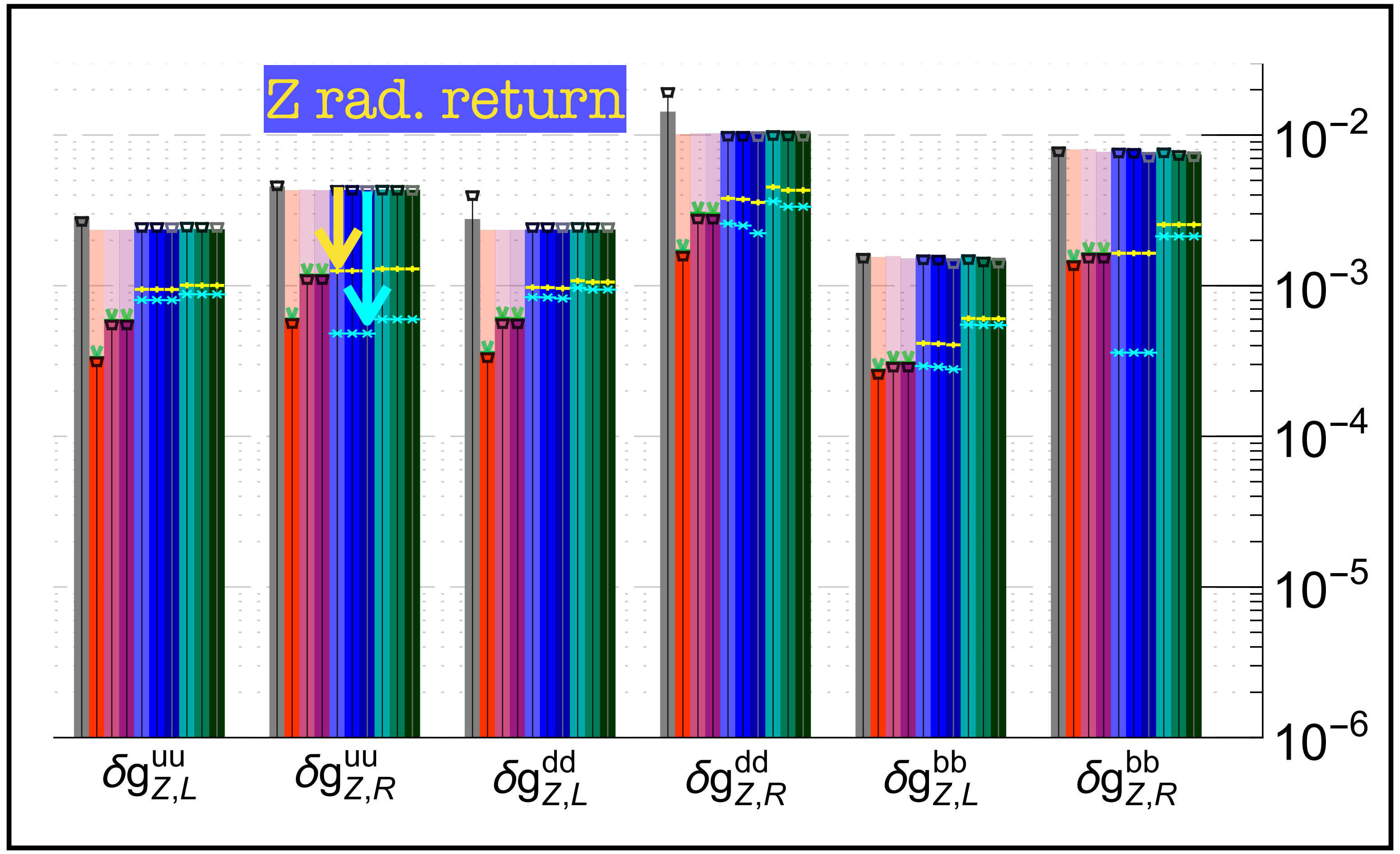
- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings

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

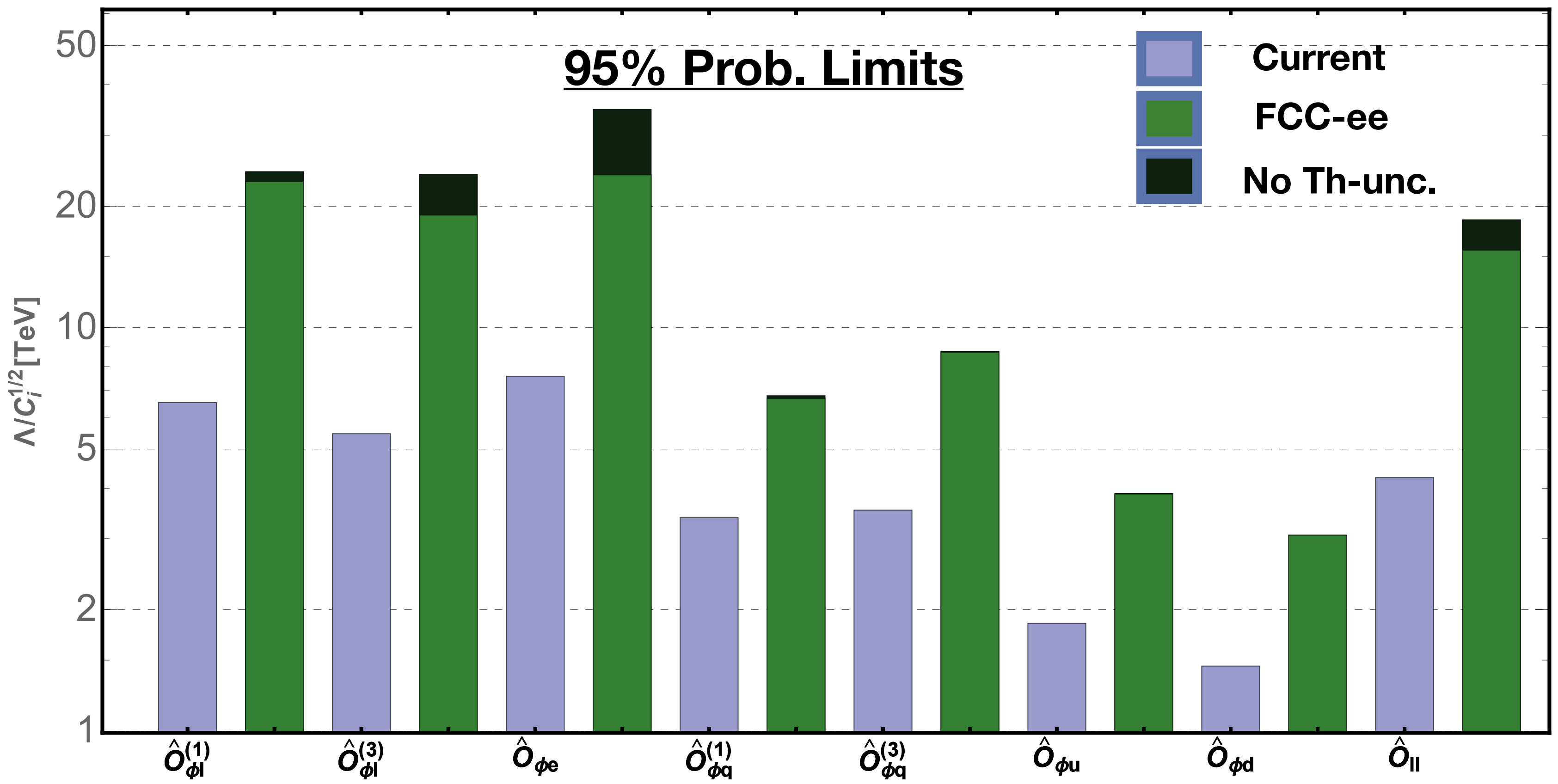


- At linear colliders, at high energy: EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
  - Yellow: LEP/SLD systematics / 2
  - Blue: small EXP and TH systematics



Impact of TH uncertainties

J. de Blas, FCC CDR overview '19

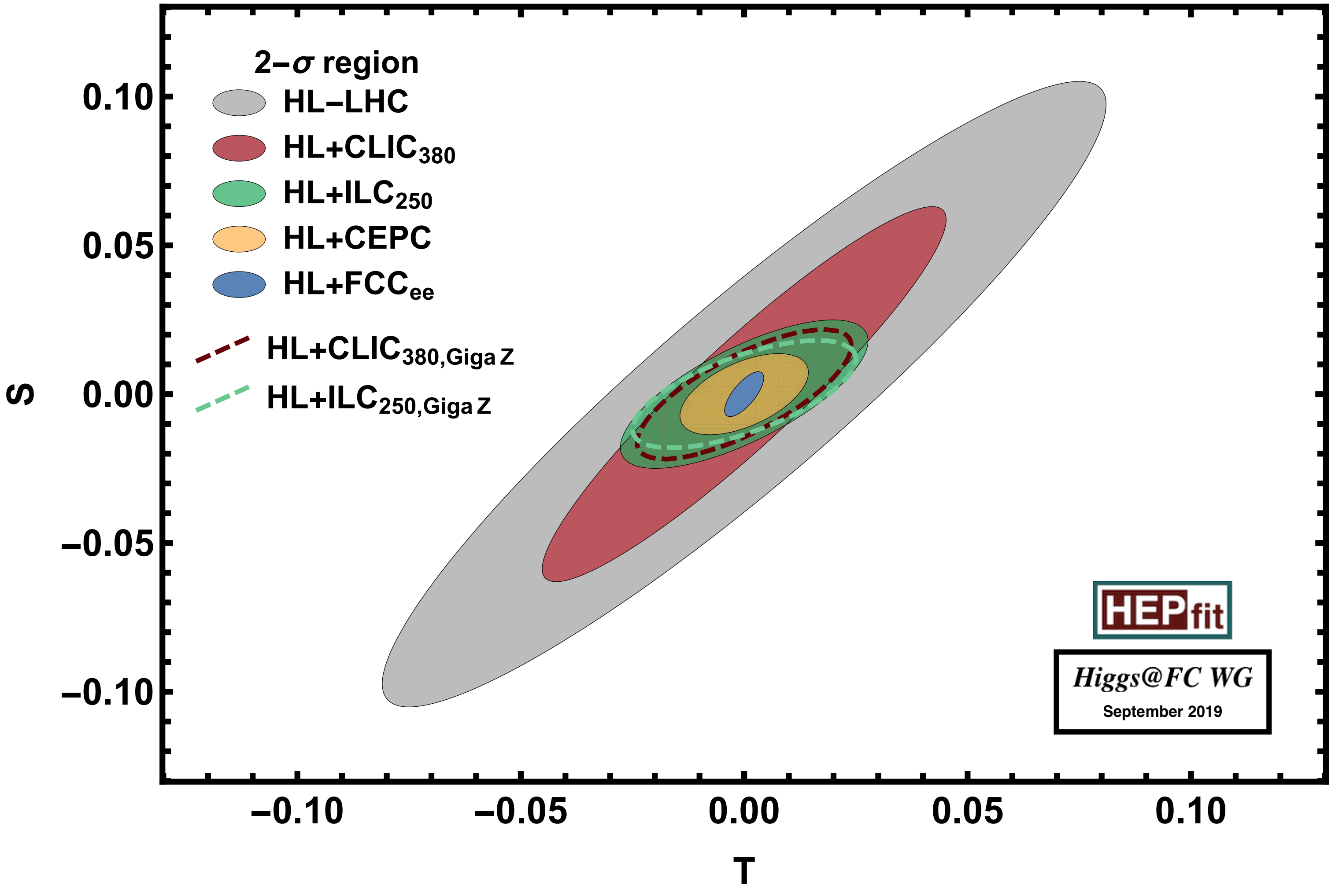


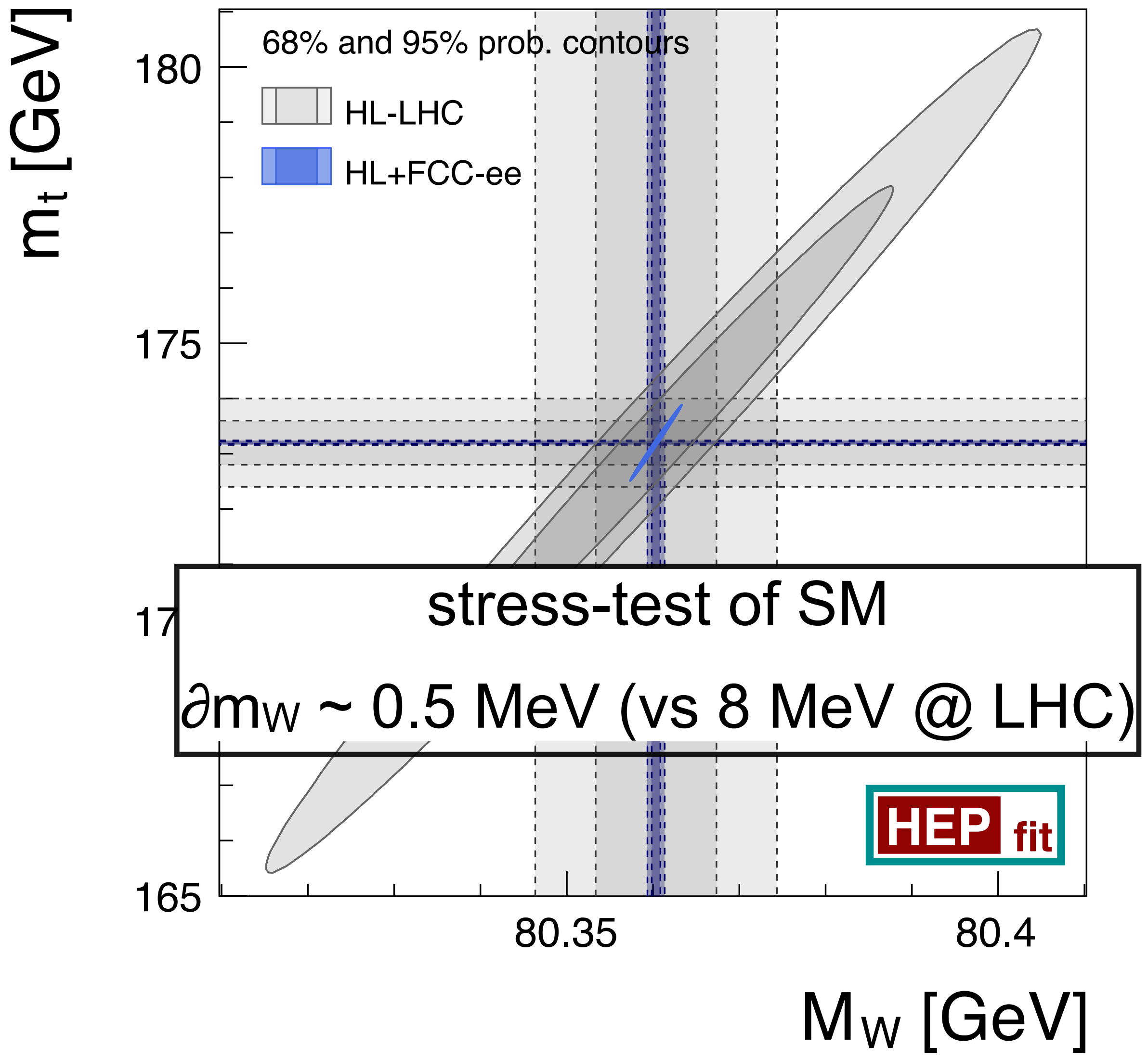
	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
δM_W [MeV]	± 15	± 8	± 1	$\pm 0.6/\pm 1$	± 1
$\delta \Gamma_Z$ [MeV]	± 2.3	± 0.73	± 0.1	± 0.1	± 0.2
$\delta \mathcal{A}_\ell\,[\times 10^{-5}]$	± 210	± 93	± 2.1	$\pm 8/\pm 14$	± 11.8
$\delta R_b^0\,[\times 10^{-5}]$	± 66	± 3	± 6	± 0.3	$\pm$ 5

Improvements of EW measurements

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

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





stress-test of SM

∂m_W ~ 0.5 MeV (vs 8 MeV @ LHC)

The importance of improved EW measurements is threefold:

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

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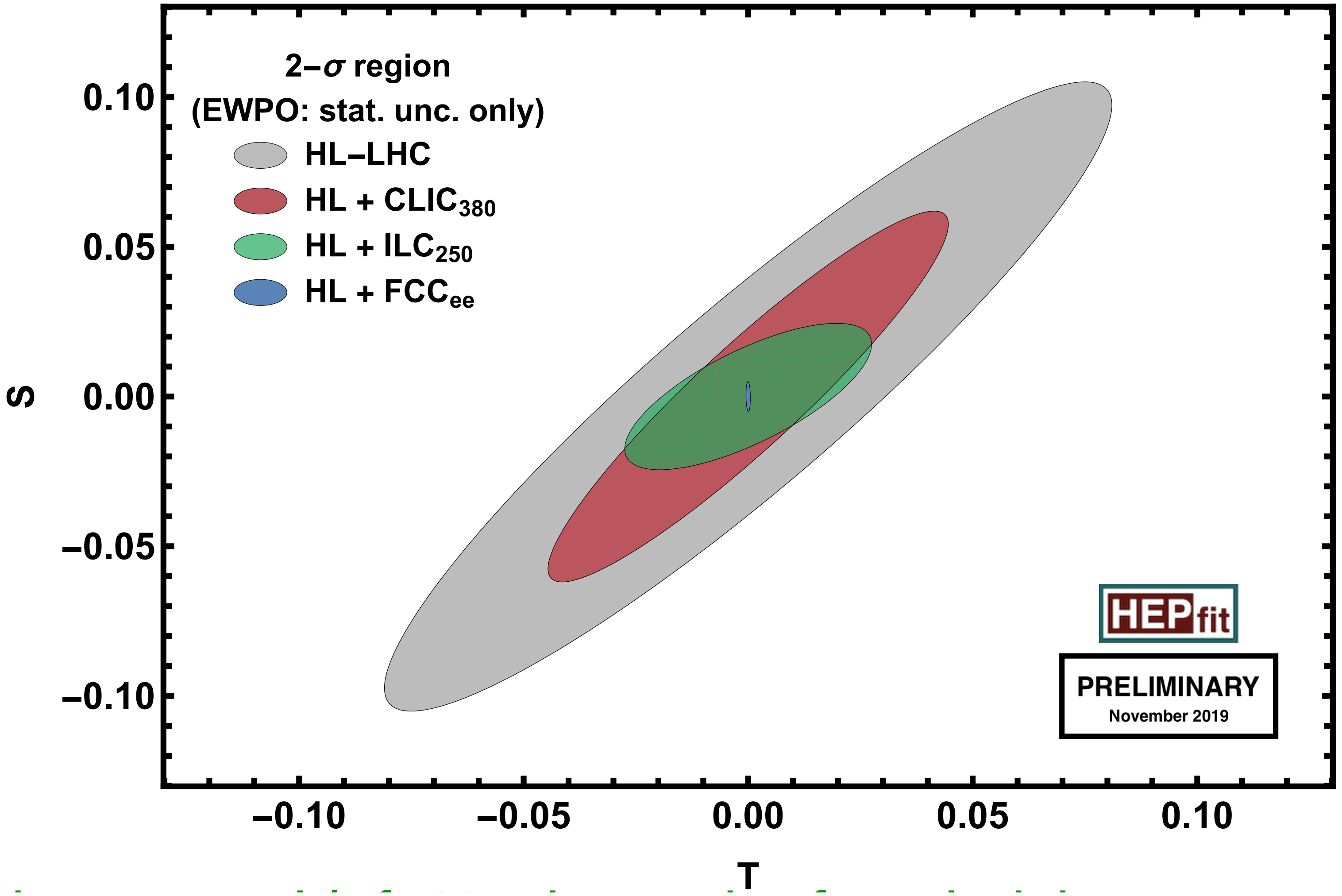
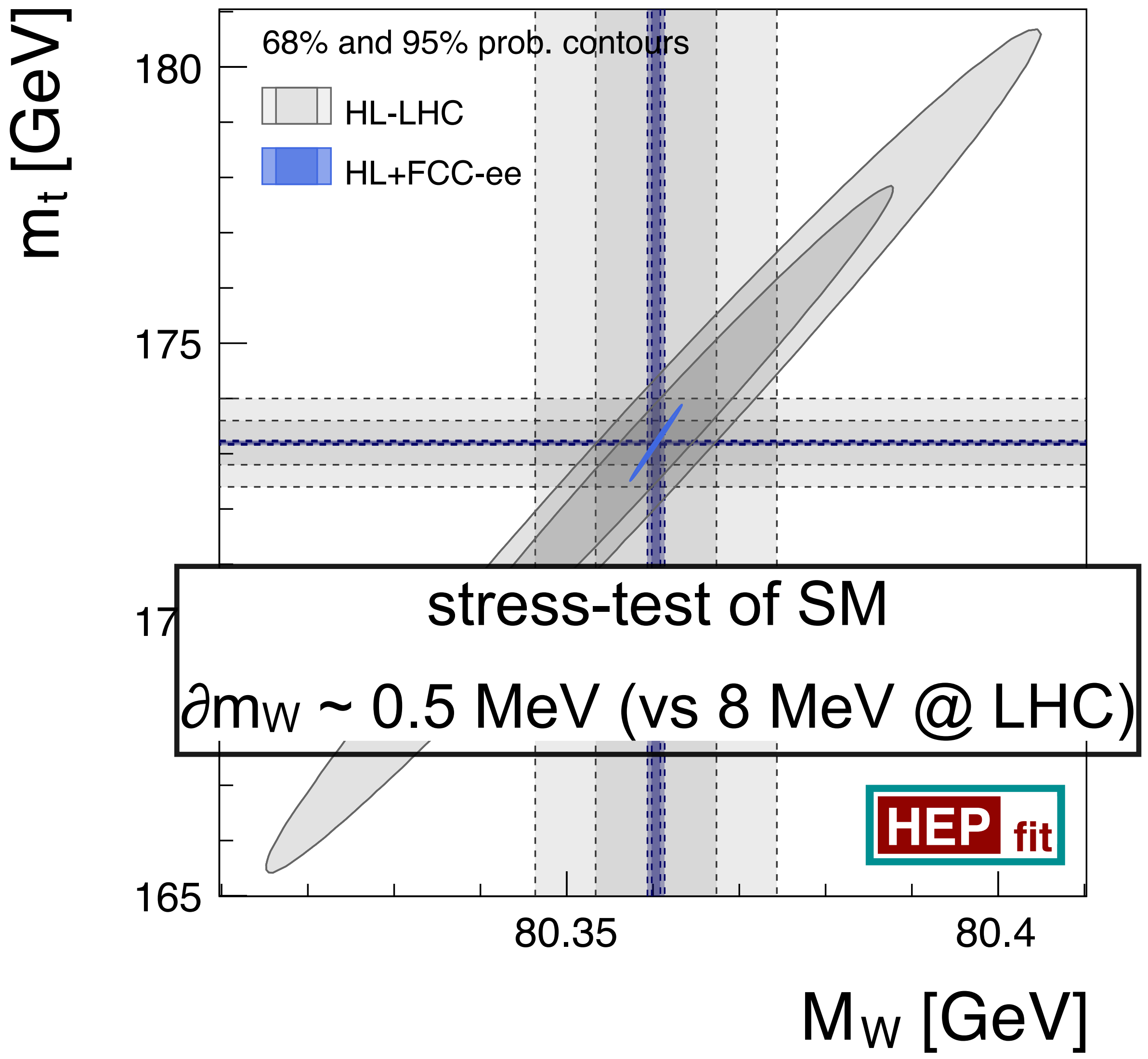
w/ stat. and param. only





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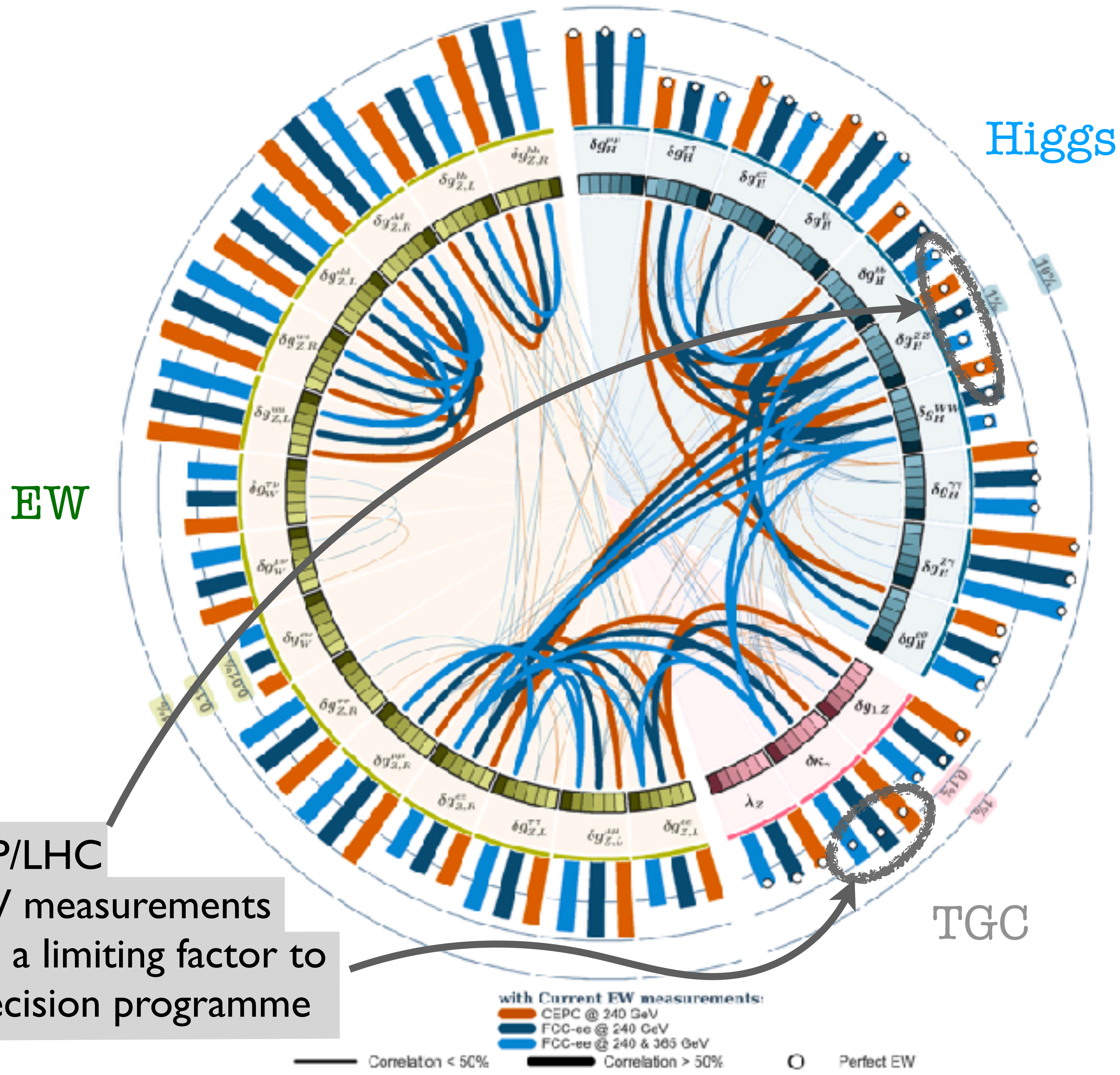
Impact of Z-pole Measurements

J. De Blas et al. 1907.04311



Contamination EW/TGC/Higgs can be understood by looking at correlations

Without Z-pole runs, there are large correlations between EW and Higgs

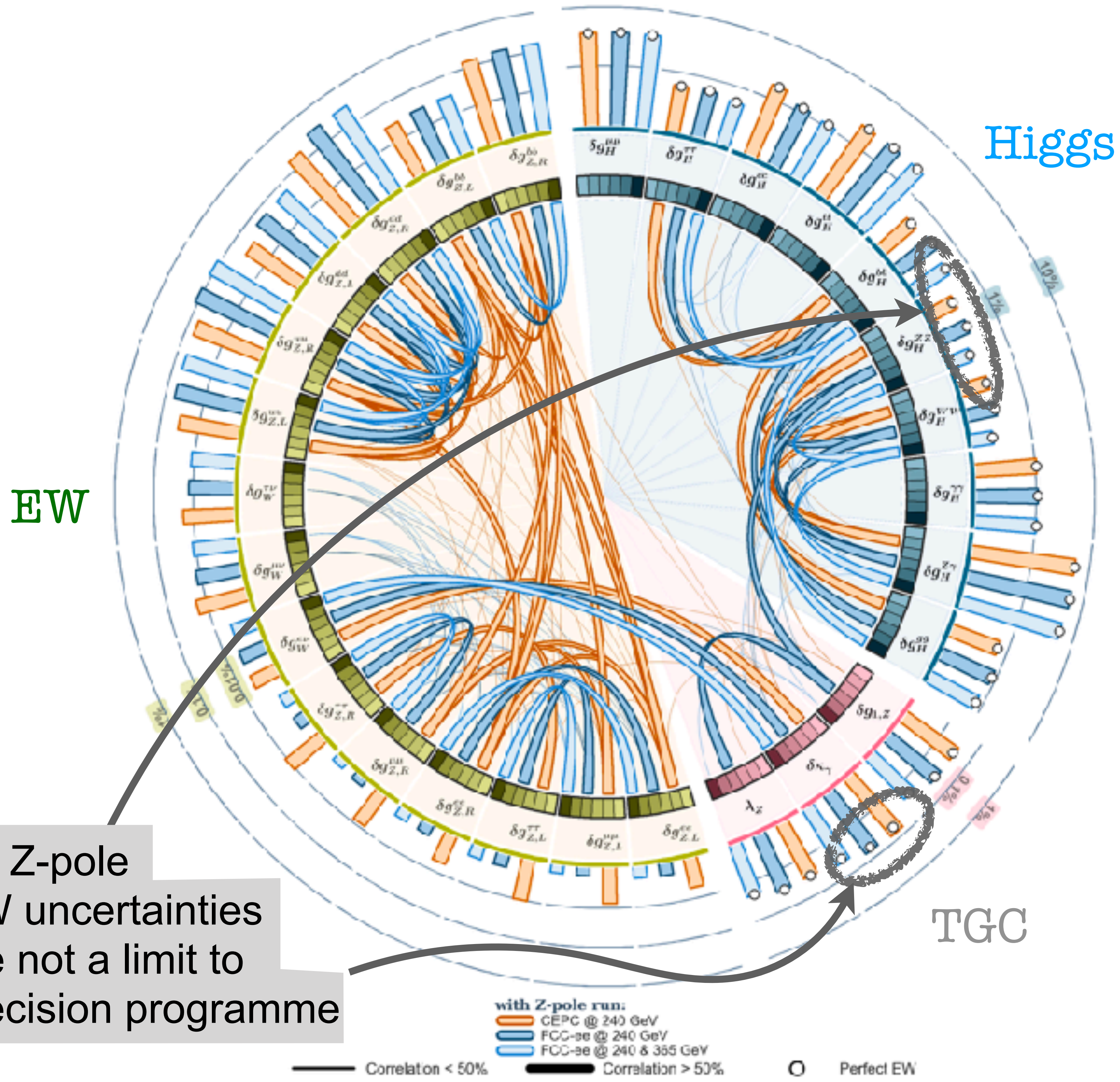
LEP/LHC
EW measurements
are a limiting factor to
precision programme

Impact of Z-pole Measurements

J. De Blas et al. 1907.04311

Contamination EW/TGC/Higgs can be understood by looking at correlations

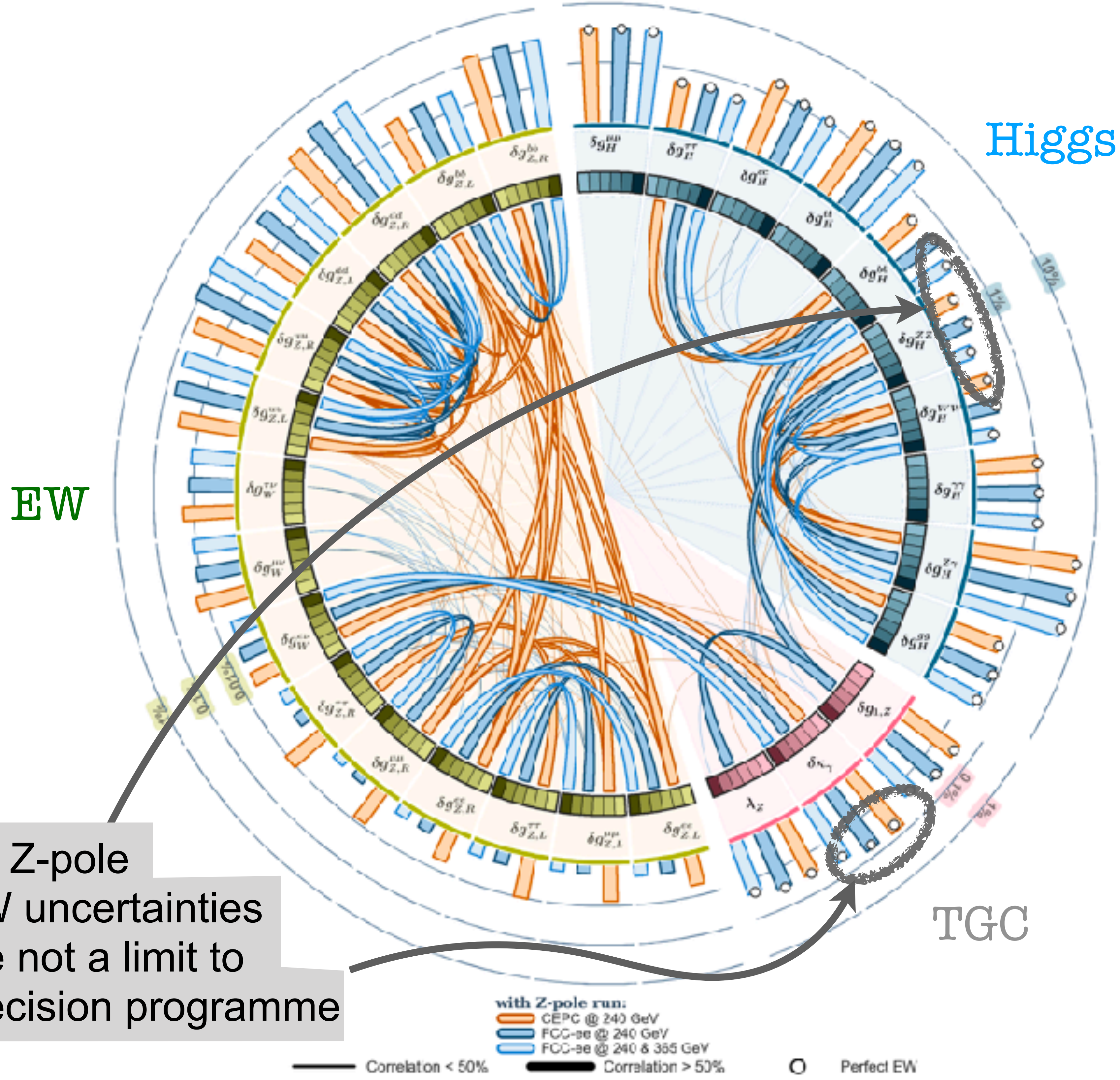
With Z-pole runs, only correlations between EW and TGC remain



w/. Z-pole
EW uncertainties
are not a limit to
precision programme

Impact of Z-pole Measurements

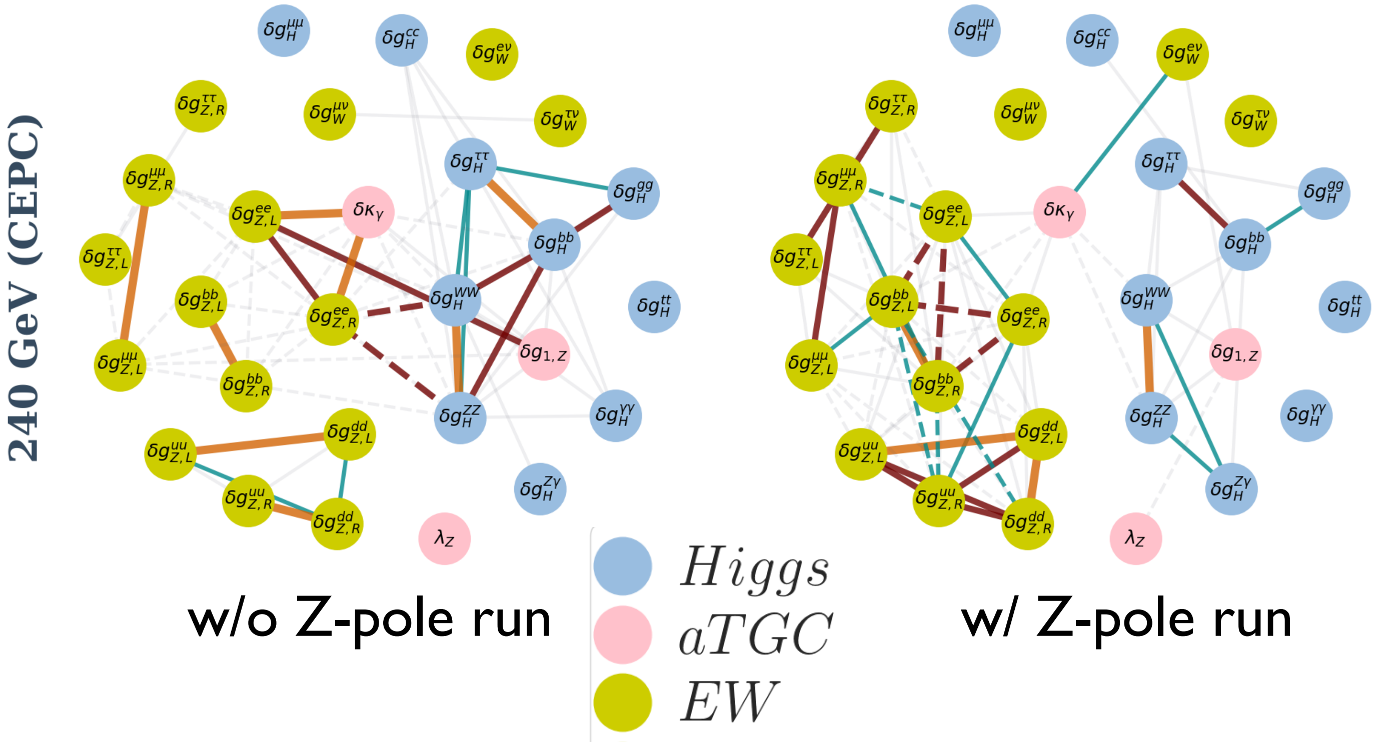
J. De Blas et al. 1907.04311



w/. Z-pole
EW uncertainties
are not a limit to
precision programme

Contamination EW/TGC/Higgs can be understood by looking at correlations

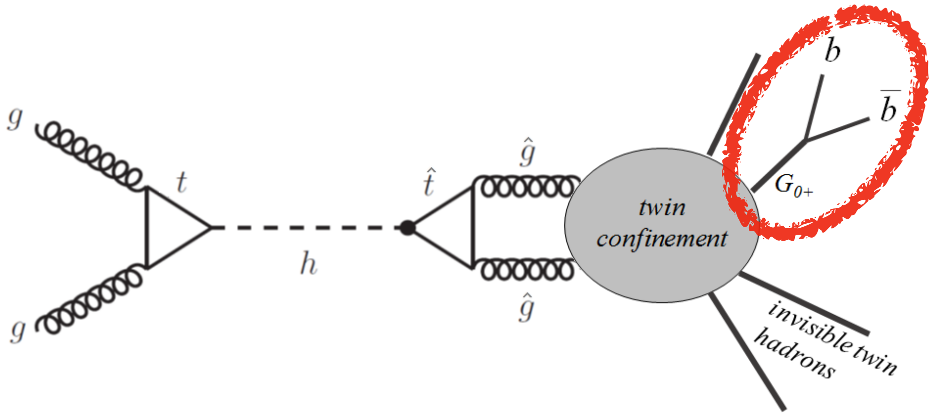
Z-pole runs at circular colliders isolate EW and Higgs sectors from each others



Direct Searches for Light New Physics

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

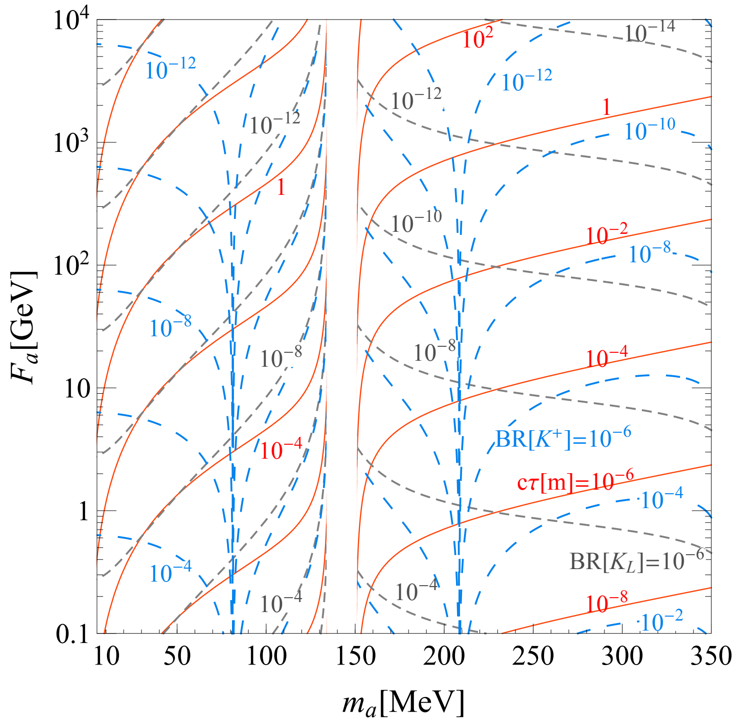
Craig et al, arXiv:1501.05310



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

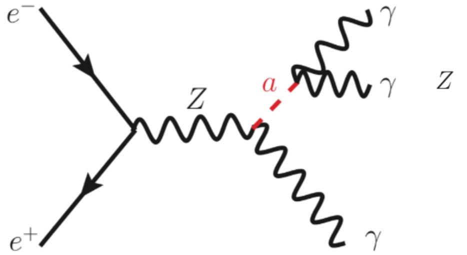
$$K_L \to \pi^0 a \to \pi^0\gamma\gamma \text{ (KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+\gamma\gamma \text{ (NA62)}$$

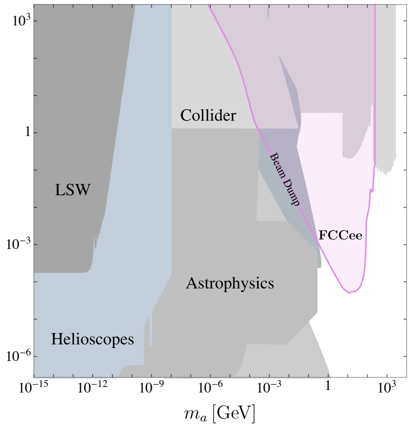
$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu}\tilde{G}^{\mu\nu}$$

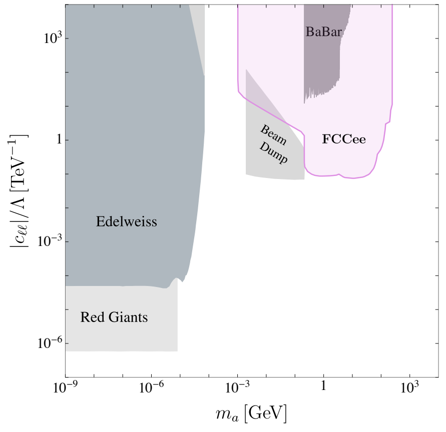


- **ALPs@ colliders**
  e.g. $e^+e^- \to \gamma a$

$e^+e^- \to ha$





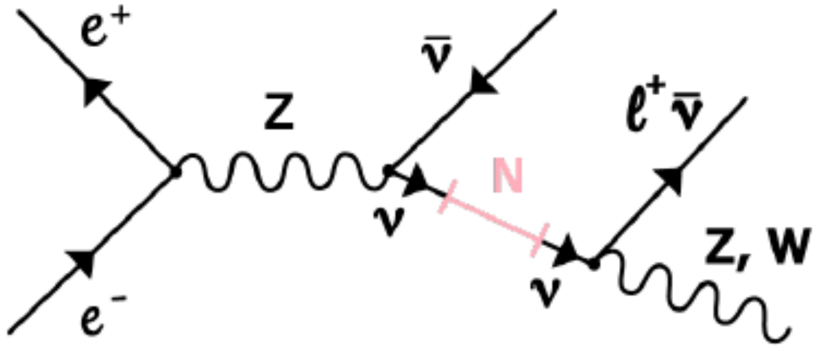


Knapen, Thamm arXiv:2108.08949

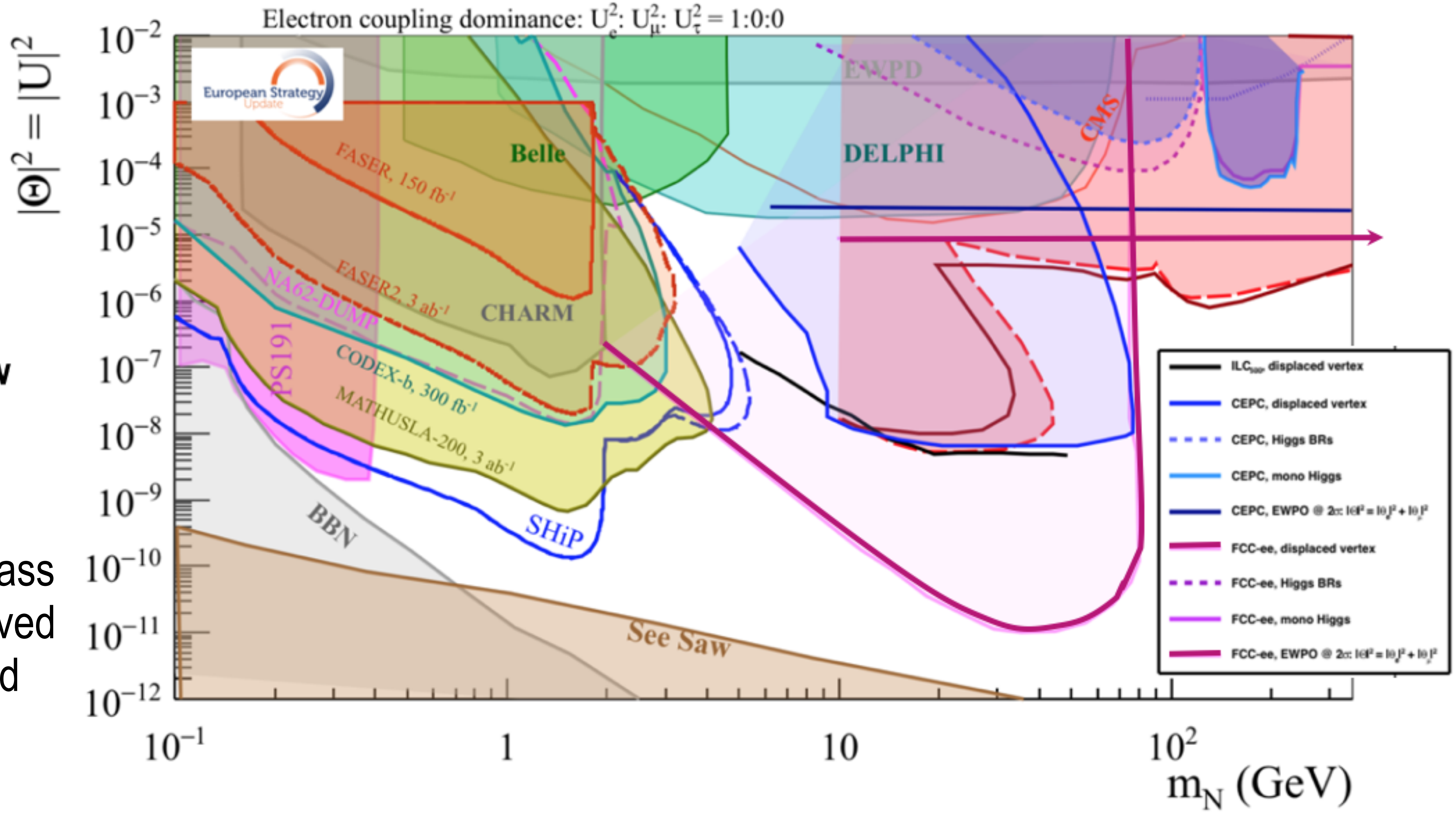
Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

Search for ν_{RH}

Direct observation
in Z decays
from LH-RH mixing



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

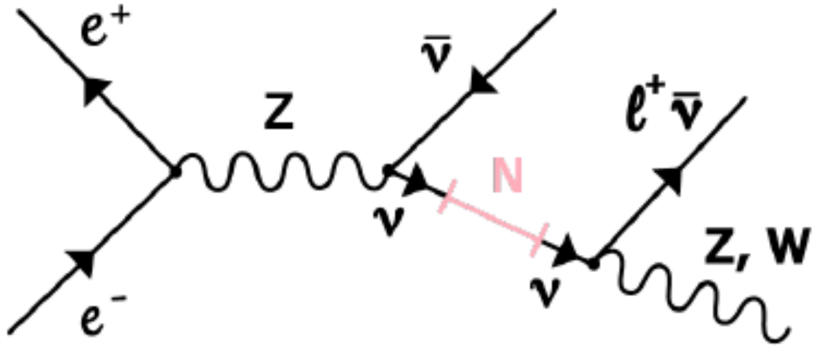


ESU Physics BB '19

Search for ν_{RH}

Direct observation
in Z decays
from LH-RH mixing

$|\Theta|^2 = |U|^2$



Important to understand
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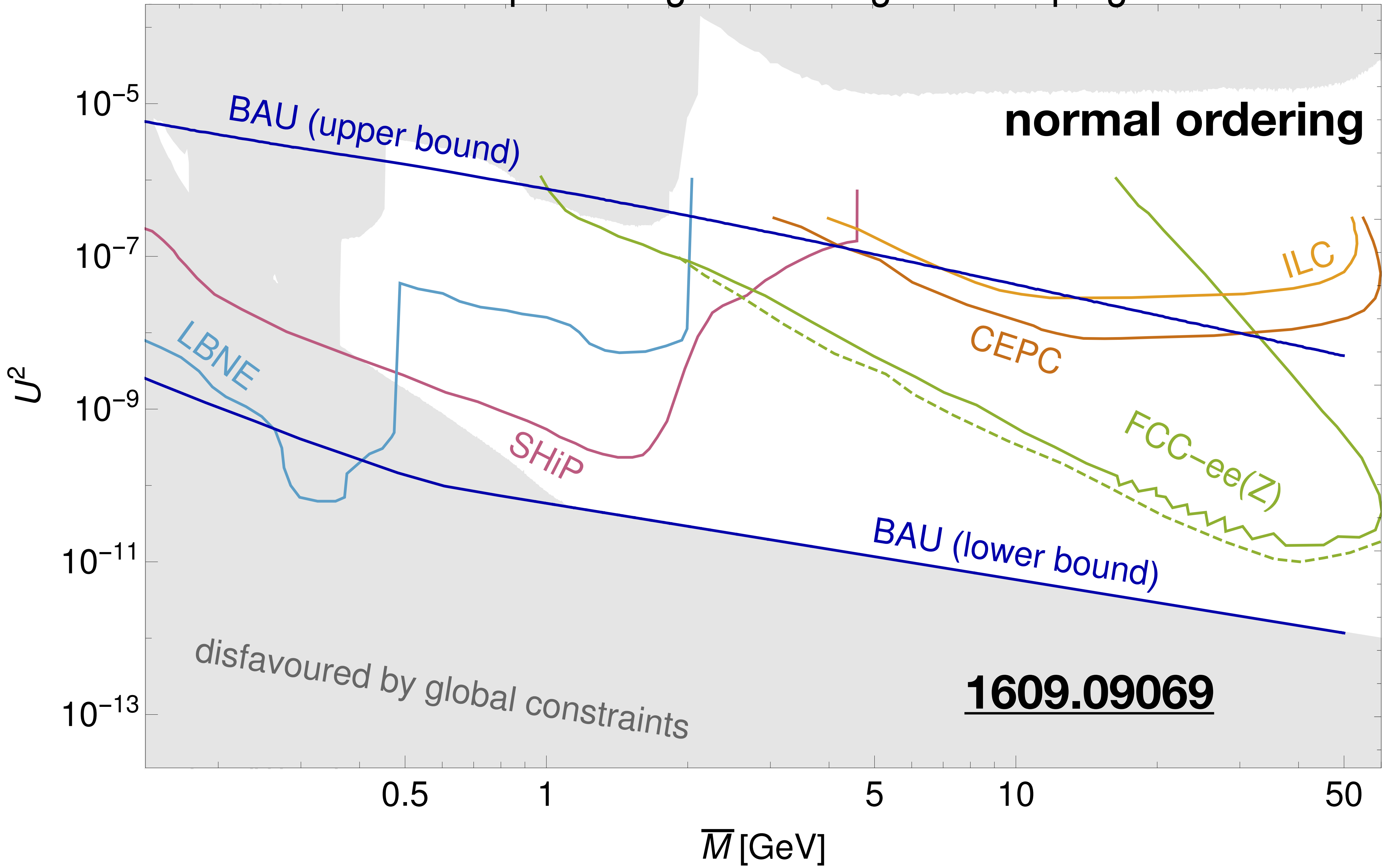
FCC-ee can probe large viable regions of leptogenesis



1609.09069

Short-term Goals

1. Documentation of the specificities of the FCC-ee and FCC-hh **physics cases** and their complementarity for the characterisation of the Standard Model Higgs boson and beyond;
    - identify key topics and observables
    - propose new benchmark measurements

2. Strategic plans for improved **theoretical calculations** needed to reduce the theoretical uncertainties towards matching the FCC-ee expected statistical precision for the most important measurements: QCD and EW sectors

3. A first list of coherent sets of **detector requirements** to fully exploit the FCC-ee physics opportunities, in particular to reduce the experimental systematic uncertainties towards matching the FCC-ee expected statistical precision for the most important measurements.

Conclusions

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

- Direct and indirect sensitivity to New Physics.
- Establish new organising principles of Nature (LEP→ gauge symmetries, FCC→??).
- Probe the **HEP-Cosmo connections** thanks to the high statistics of the Z-pole run (omitting this exploration would be ignoring the outcome of LHC. 10+ years of LHC have changed the HEP landscape).

FCC-ee is an essential part of an **integrated** programme to probe New Physics.

We have profound questions and we need create opportunities to answer them.

— FCC-ee will for sure contribute —

BONUS

Experimental Inputs

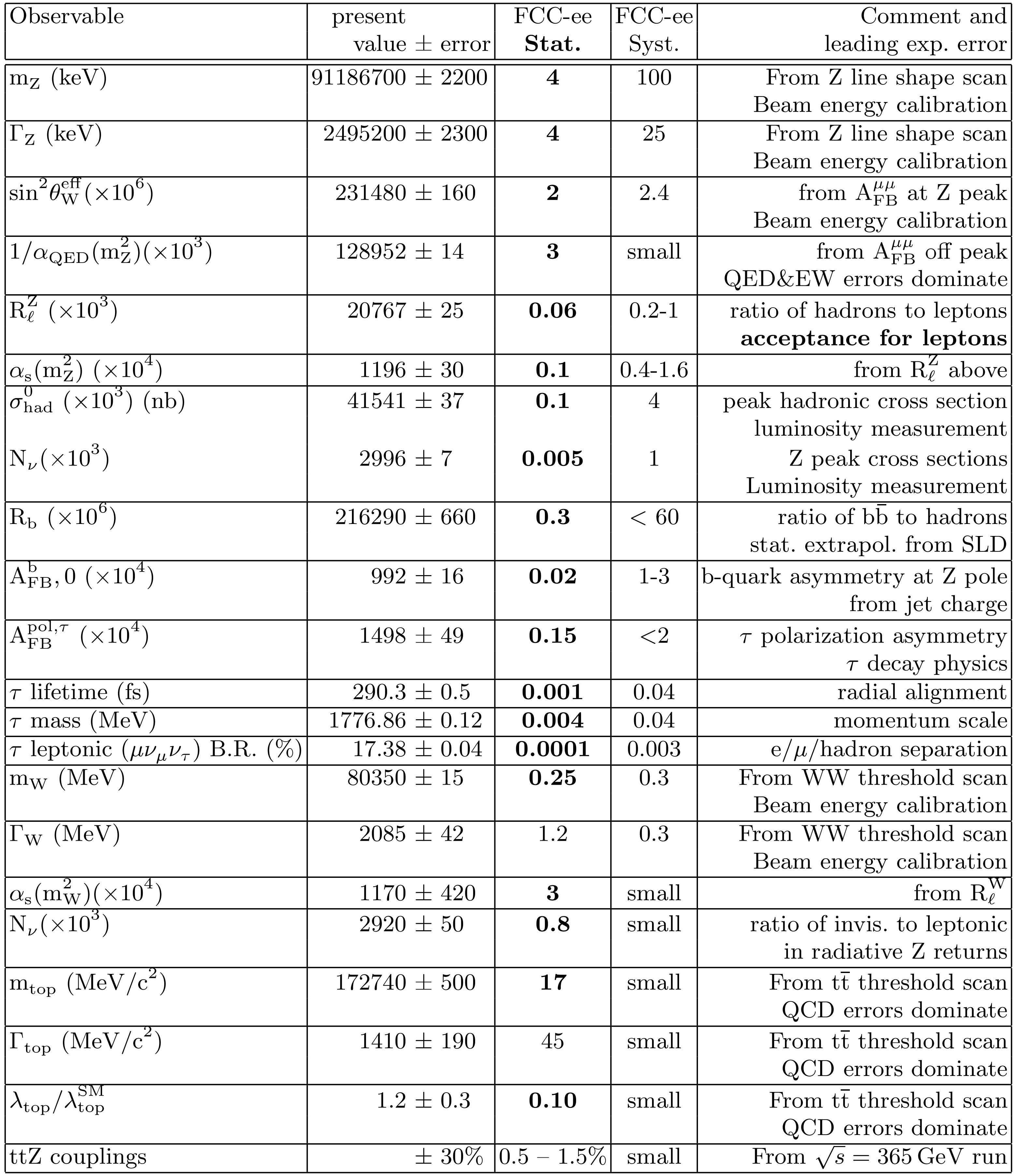
A circular ee Higgs factory
starts as a Z/EW factory
(**TeraZ**)

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**)
Not included in the analyses yet

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

EW Precision Measurements at FCC-ee



Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ $({\rm MeV}/c^2)$	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ $({\rm MeV}/c^2)$	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

Blondel, Janot
arXiv: 2106.13885

Example of measurements @ WW threshold

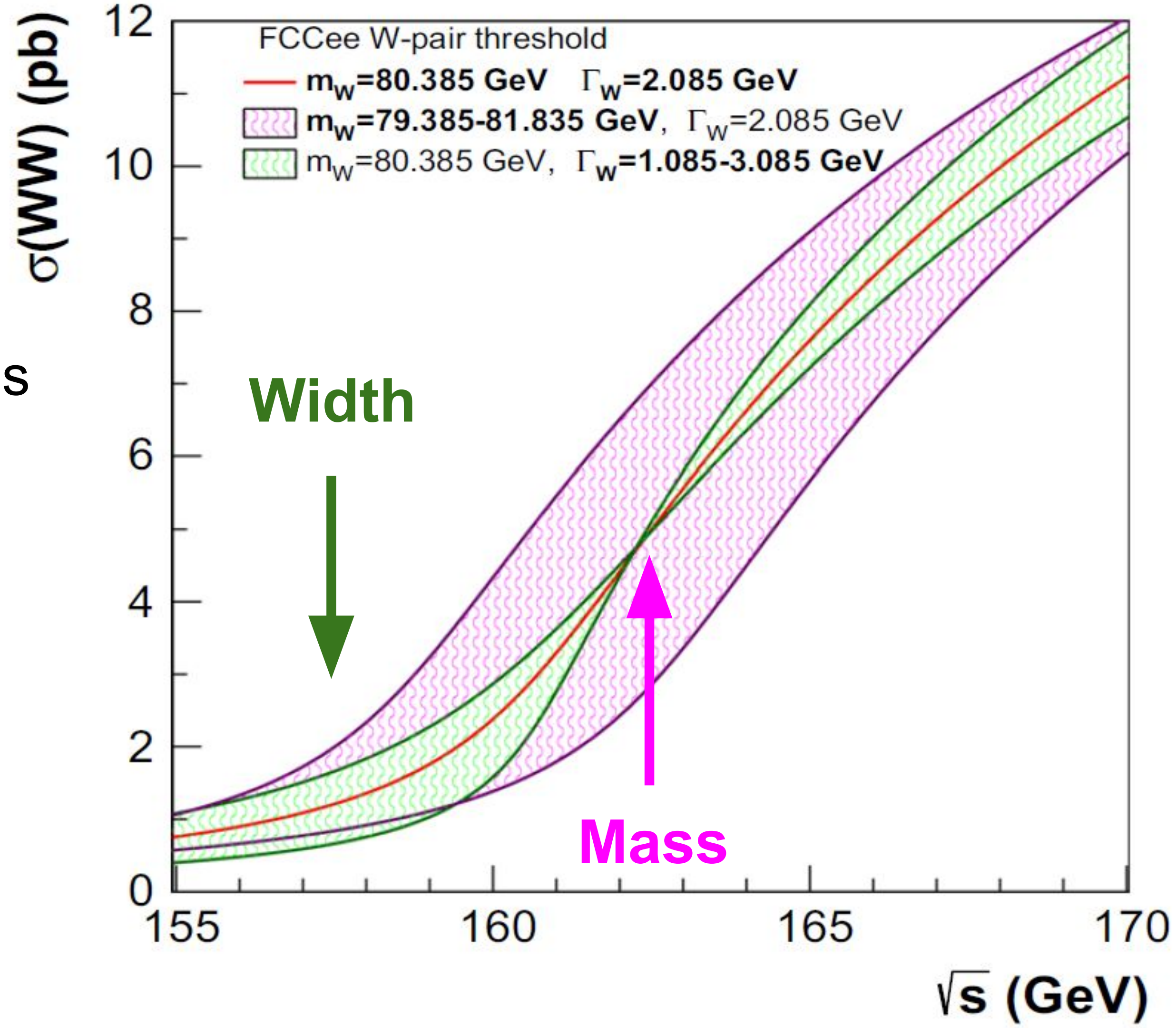
W mass and width extracted from line-scans using WW xsec

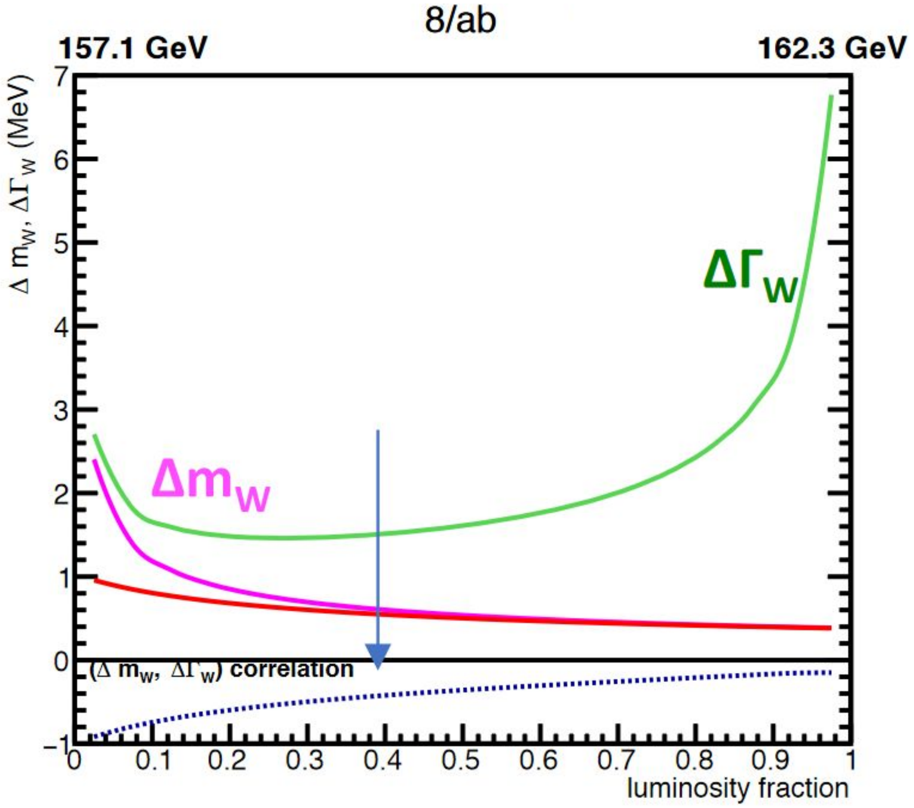
2 energy points determined from Δm_W and $\Delta\Gamma_W$ sensitivities on WW xsec:

→ **157.1 GeV width measurement:** maximum sensitivity on width

→ **162.5 GeV mass measurement:** minimal impact on width, max. on mass

Luminosity ($<10^{-4}$) and center-of-mass (< 0.5 MeV) uncertainties to be controlled, but weaker constraints than on Z pole





Combined fit with optimized lumi fraction (f=0.4: 5 /ab at 157.1, 7 /ab at 162.5)

→ precision m_W to 0.25 (stat) + 0.3 (syst) MeV (present 15 MeV)

→ precision Γ_W to 1.2 (stat) + 0.3 (syst) MeV (present 42 MeV)

J. Eysermans @ EPS2021

Example of measurements @ WW threshold

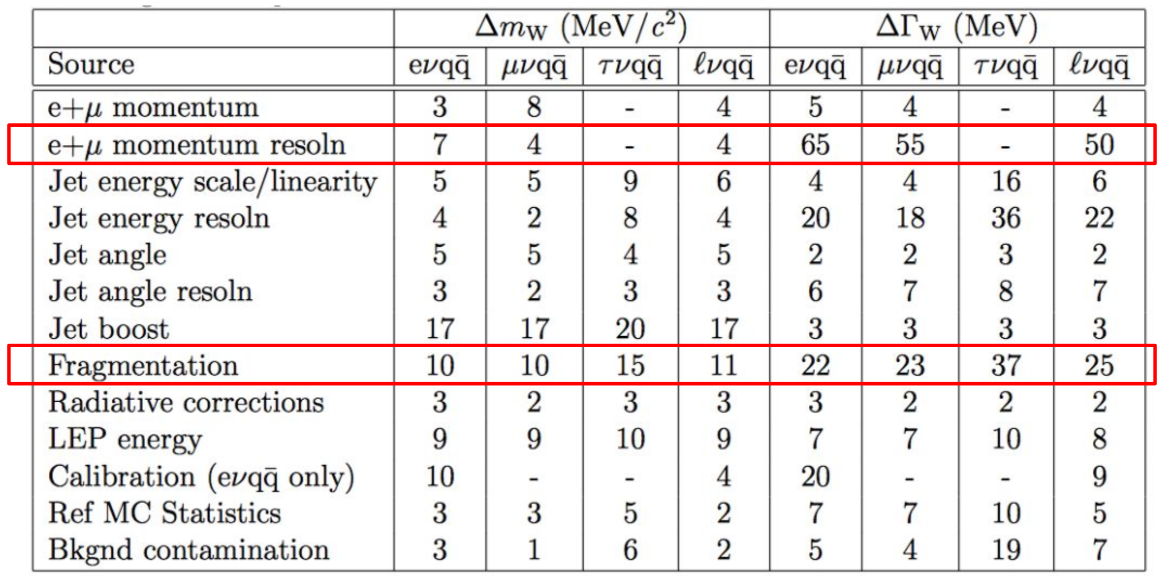
Independent analysis on W mass and width using kinematic reconstruction techniques in WW → qqlv events

- Profit from precise angle and velocity (β) measurements
- Run at all kinematically accessible energy points (WW, ZH and tt)
- Put conditions on detector requirements

Δm_W (stat) ~ 250 keV → similar as xsec measurement

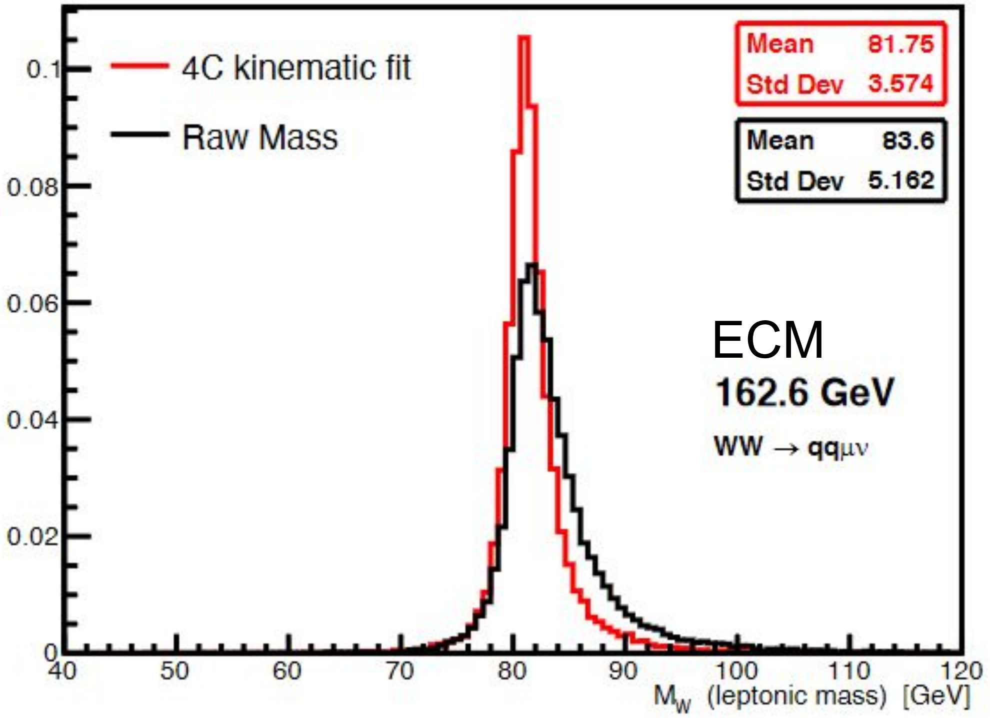
$\Delta\Gamma_W$ (stat) ~ 350 keV → reduction factor 2-3

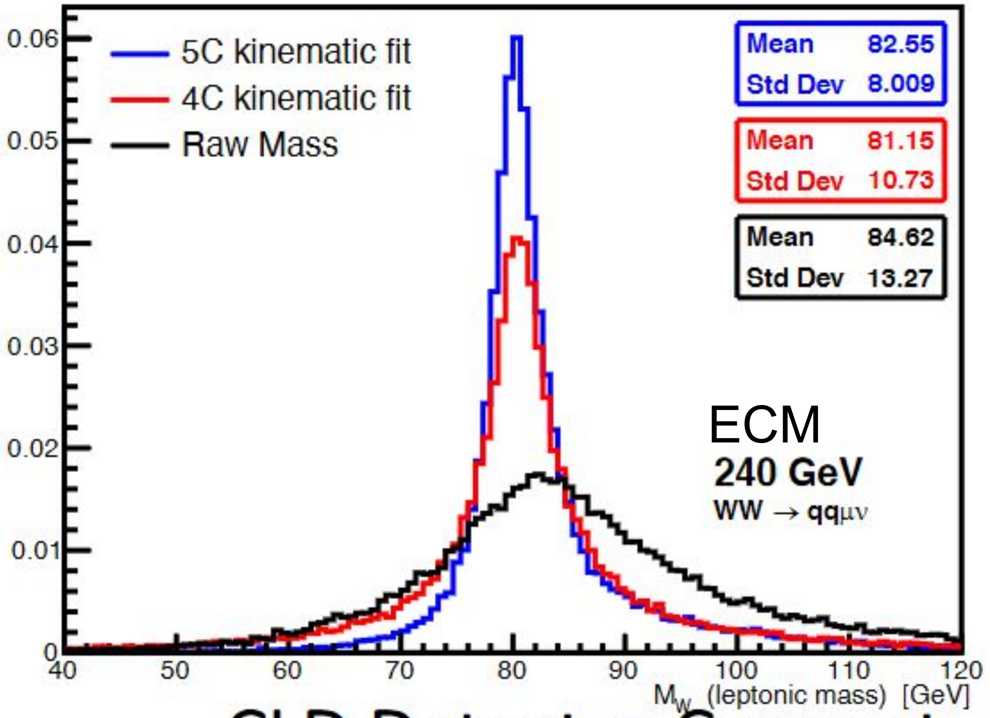
Limited by systematics (beam energy, resolution, fragmentation) → constrain

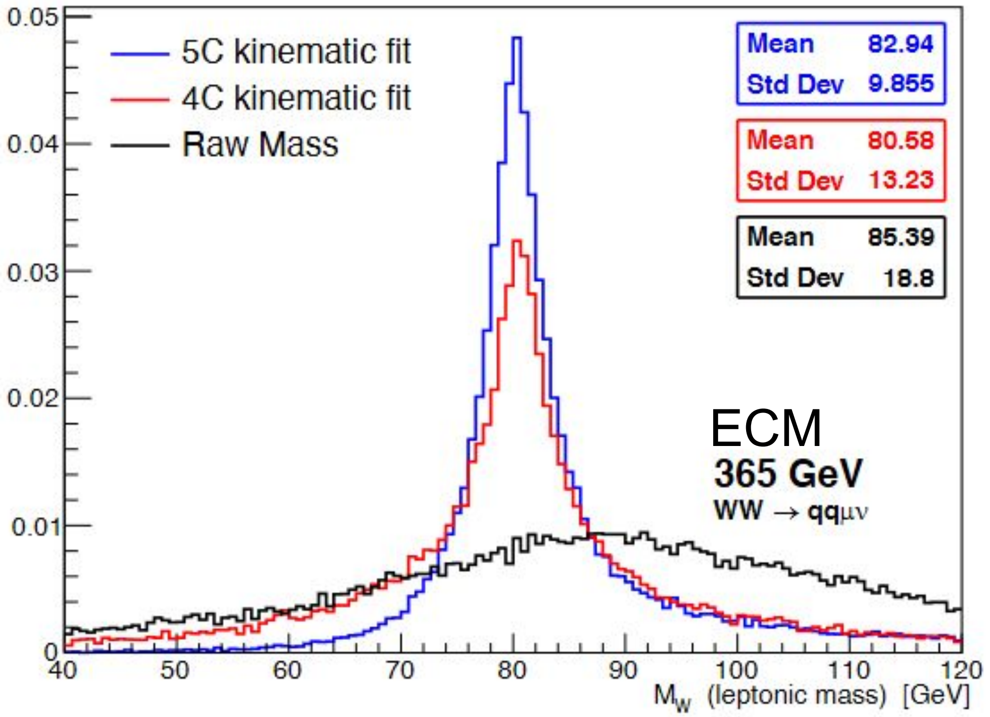


	Δm_W (MeV/c^2)				$\Delta\Gamma_W$ (MeV)			
Source	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$
e+μ momentum	3	8	-	4	5	4	-	4
e+μ momentum resoln	7	4	-	4	65	55	-	50
Jet energy scale/linearity	5	5	9	6	4	4	16	6
Jet energy resoln	4	2	8	4	20	18	36	22
Jet angle	5	5	4	5	2	2	3	2
Jet angle resoln	3	2	3	3	6	7	8	7
Jet boost	17	17	20	17	3	3	3	3
Fragmentation	10	10	15	11	22	23	37	25
Radiative corrections	3	2	3	3	3	2	2	2
LEP energy	9	9	10	9	7	7	10	8
Calibration ($e\nu q\bar{q}$ only)	10	-	-	4	20	-	-	9
Ref MC Statistics	3	3	5	2	7	7	10	5
Bkgnd contamination	3	1	6	2	5	4	19	7

J. Eysermans @ EPS2021







CLD Detector Concept

M. Béguin, PhD thesis, 2019 https://cds.cern.ch/record/2710098
M. Béguin, E.Locc, iPoSEPS-HEP2019(2020) https://doi.org/10.22323/1.364.0653

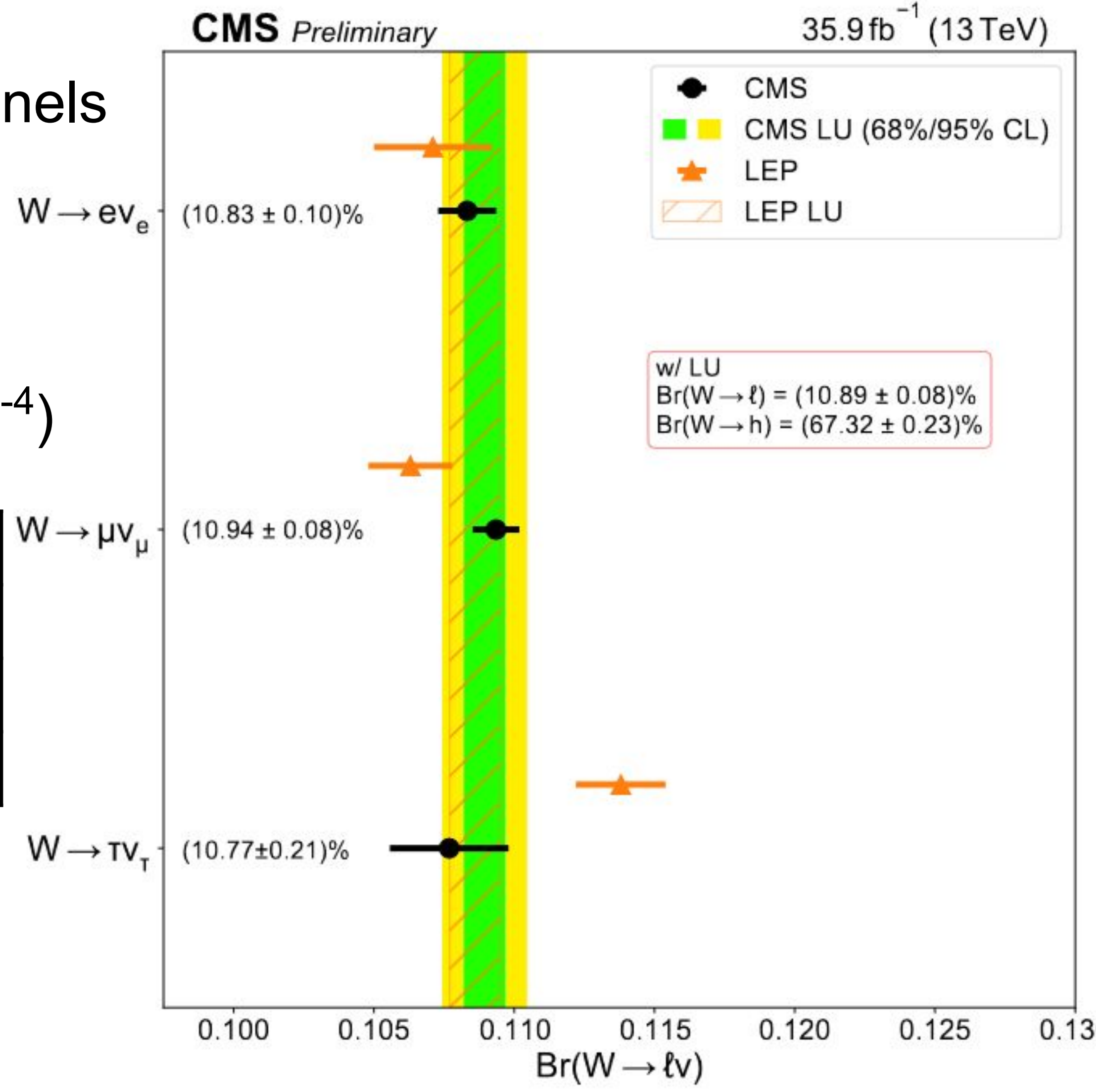
Example of measurements @ WW threshold

Precise measurement of W decays

- Precise control of lepton ID to avoid cross contamination in signal channels (e.g. τ → e,μ vs. e,μ channels)
- Precision of 10^{-4} achievable (rel.)
- Simultaneously probe lepton and q/l universality to high precision (~ 10^{-4})

Decay mode relative precision	B(W → eν)	B(W → μν)	B(W → τν)	B(W → qq)
LEP2	1.5 %	1.4 %	1.8 %	0.4 %
CMS	0.9 %	0.7 %	2 %	0.4 %
FCCee	0.03 %	0.03 %	0.04 %	0.01 %

CMS-PAS-SMP-18-011
http://cds.cern.ch/record/2758905



Flavor tagging

- Allows precise measurement CKM matrix elements V_{cs}, V_{ub}, V_{cb}
- Extract strong coupling constant at WW-threshold

$$R_W = \frac{B_q}{1-B_q} = \left(1 + \frac{\alpha_S(m_W^2)}{\pi}\right) \sum_{i=u,c;j=d,s,b} |V_{ij}|^2$$

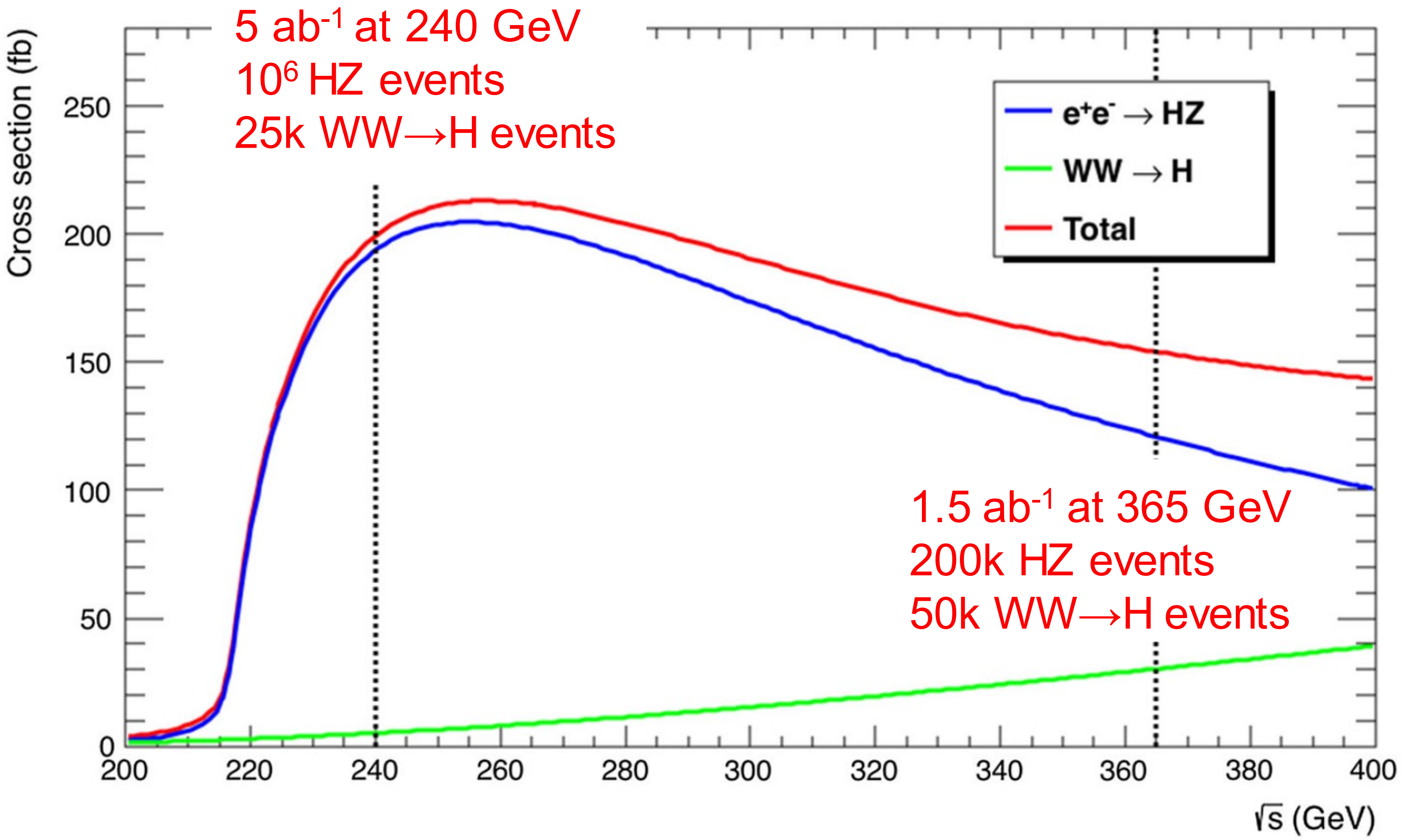
→ $\Delta\alpha_S(m_W) \sim 3\mathrm{x}10^{-4}$ (abs)
→ Statistically dominated

J. Eysermans @ EPS2021

Higgs @ FCC-ee

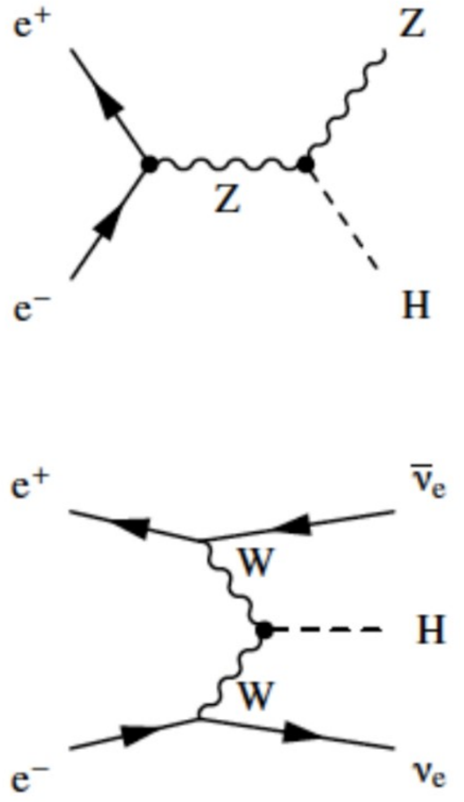
Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)% precision. Achieved through operation at two energy points.

G. Wilkinson, FCC Physics WS ‘22



5 ab^{-1} at 240 GeV
10^6 HZ events
25k WW→H events

1.5 ab^{-1} at 365 GeV
200k HZ events
50k WW→H events



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

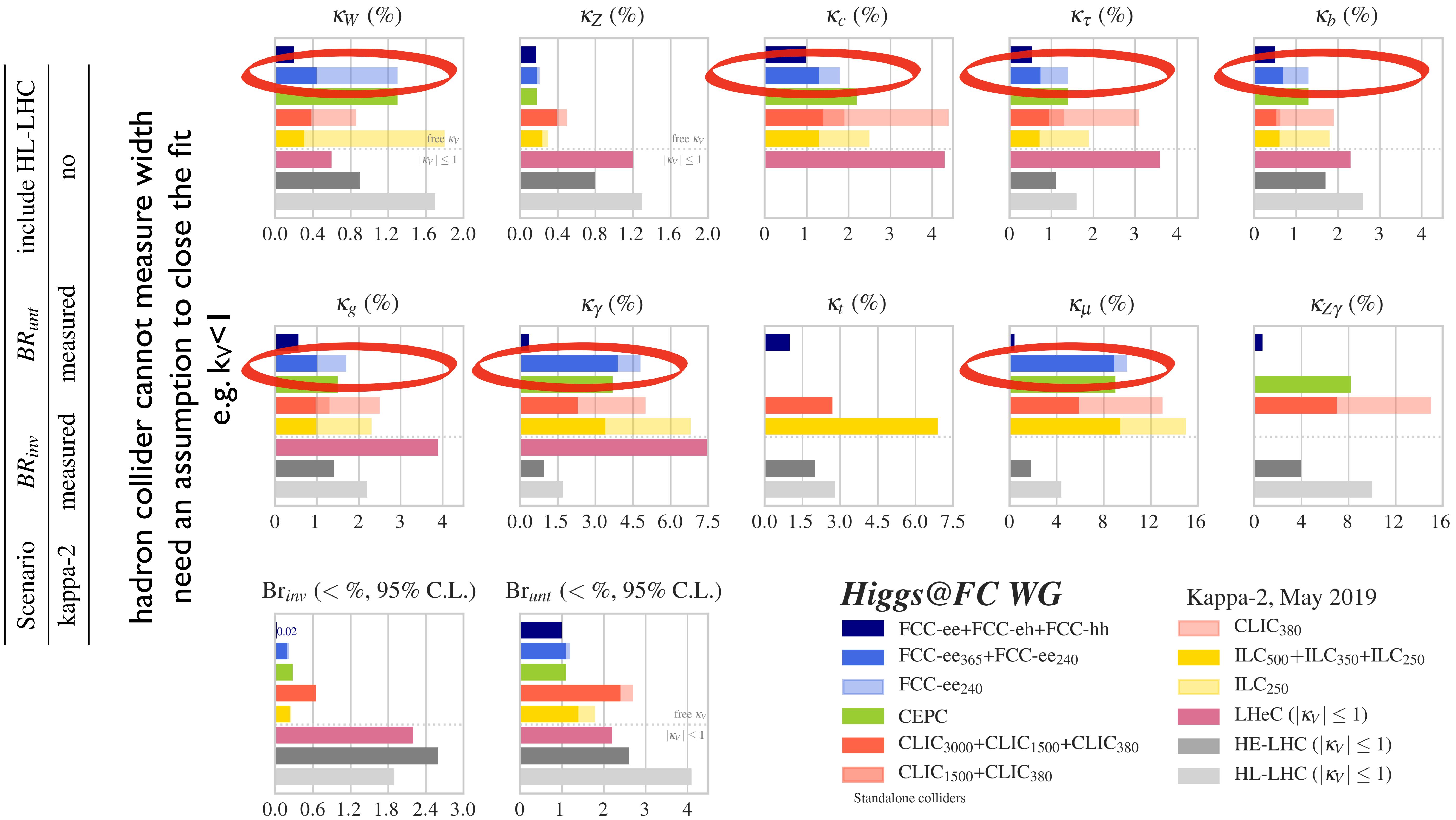
Table 8: Operation costs of low-energy Higgs factories, expressed in Euros per Higgs boson.

Collider	ILC_{250}	$CLIC_{380}$	FCC-ee_{240}
Cost (Euros/Higgs)	7,000 to 12,000	2,000	255

FCC-ee, 1906.02693

Higgs @ FCC-ee: Complementarity of 240/365 GeV

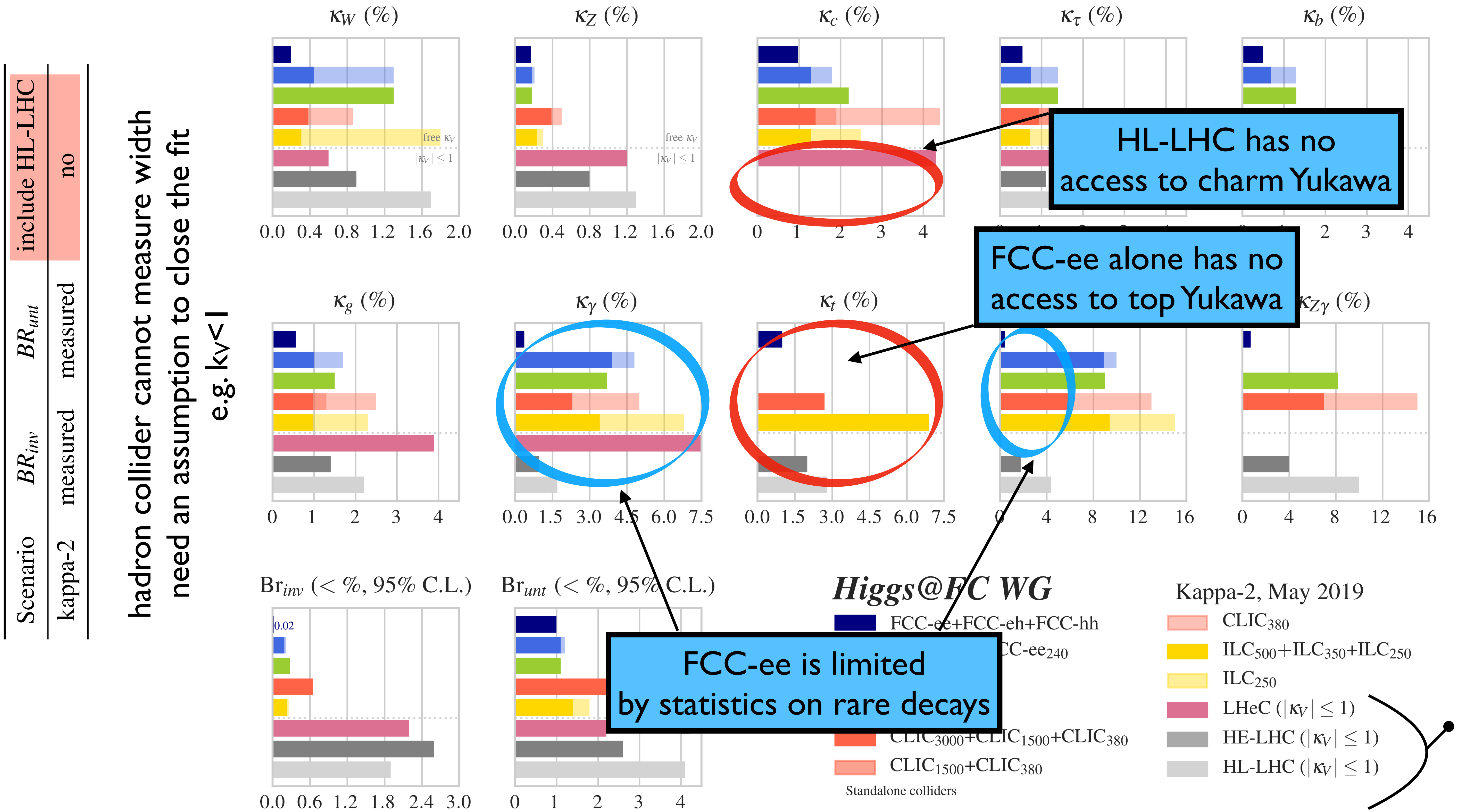
ECFA Higgs study group '19



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

Higgs @ FCC-ee: Complementarity with HL-LHC

ECFA Higgs study group '19



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

HL-LHC has no access to charm Yukawa

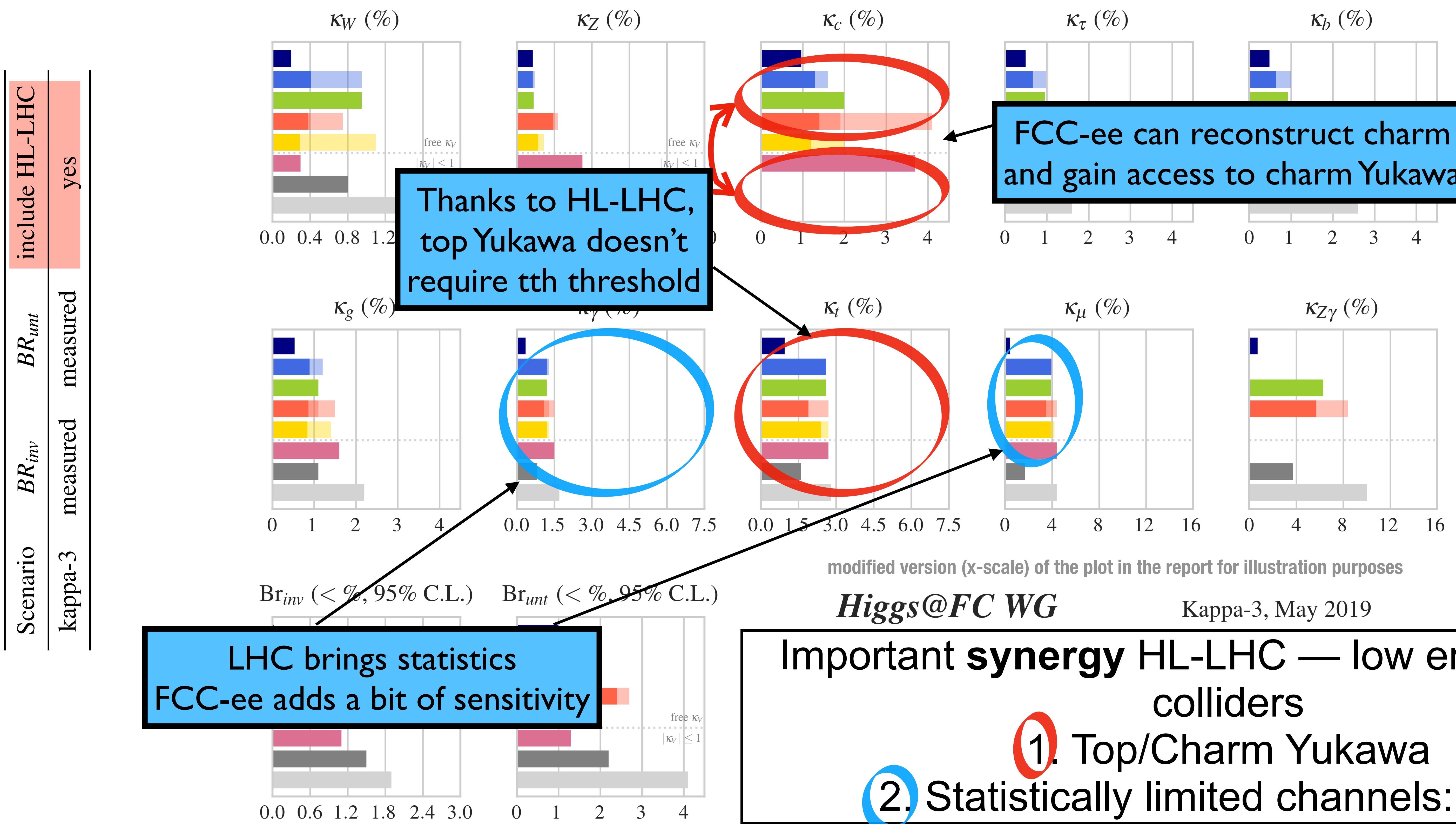
FCC-ee alone has no access to top Yukawa

FCC-ee is limited by statistics on rare decays

assumption needed for the fit to close at hadron machines

Higgs @ FCC-ee: Complementarity with HL-LHC

ECFA Higgs study group '19



FCC-ee can reconstruct charm and gain access to charm Yukawa

Thanks to HL-LHC, top Yukawa doesn't require tth threshold

LHC brings statistics
FCC-ee adds a bit of sensitivity

modified version (x-scale) of the plot in the report for illustration purposes

Higgs@FC WG Kappa-3, May 2019

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

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

Example of measurements @ tt threshold

Top mass and width measurements similar as WW line-shape

Though more energy points needed:

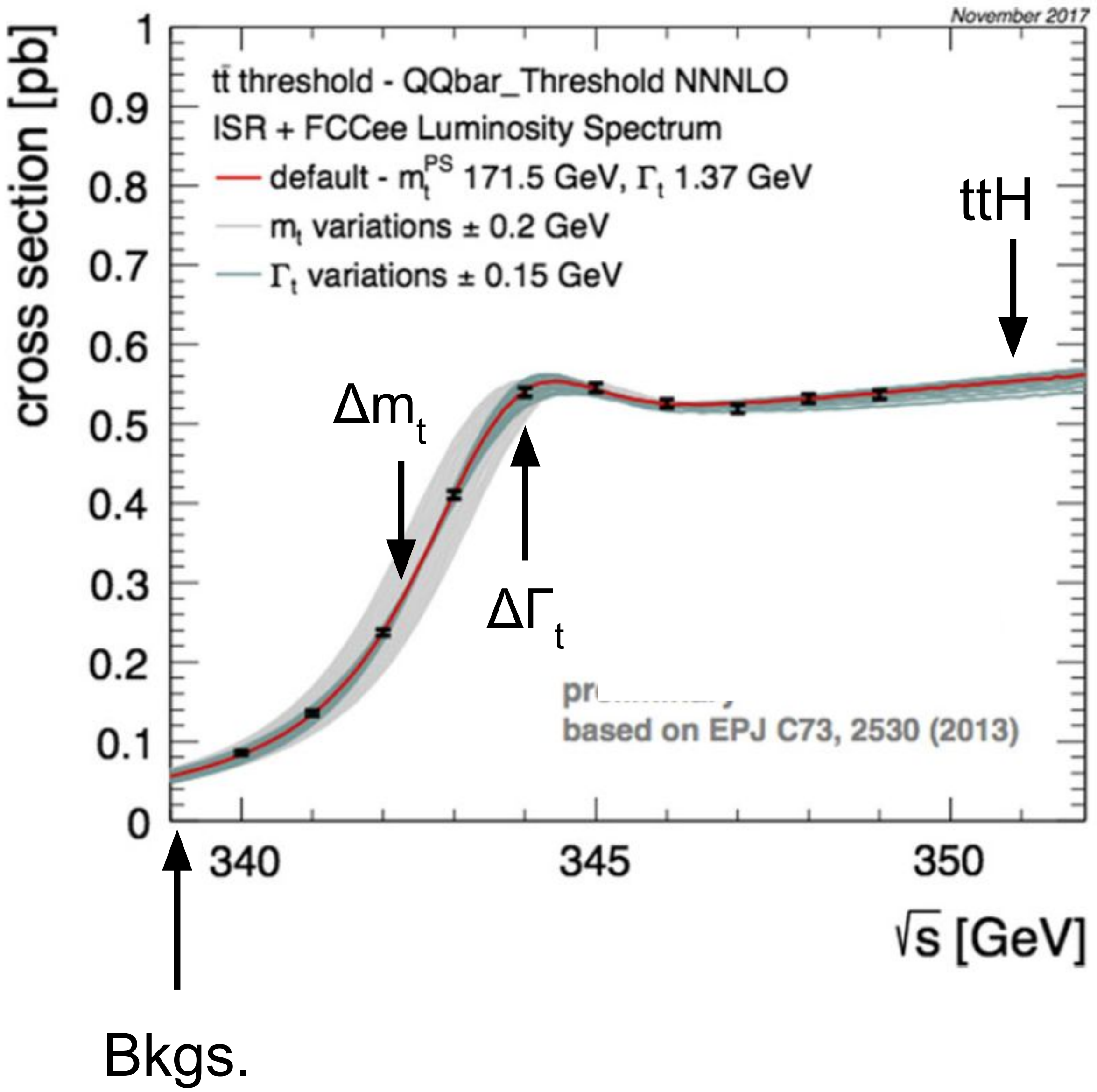
- Relative large uncertainty on top mass (+/- 0.5 GeV)
- Need to constrain shape in optimal way
- Possible to constrain backgrounds (below) and ttH (above)

→ Multipoint scan in 5 GeV window [340, 345], each ~ 25 /fb

→ Δm_t (stat) ~ 17 MeV

→ $\Delta\Gamma_t$ (stat) ~ 45 MeV

To date: theoretical QCD errors order of 40 MeV for mass and width

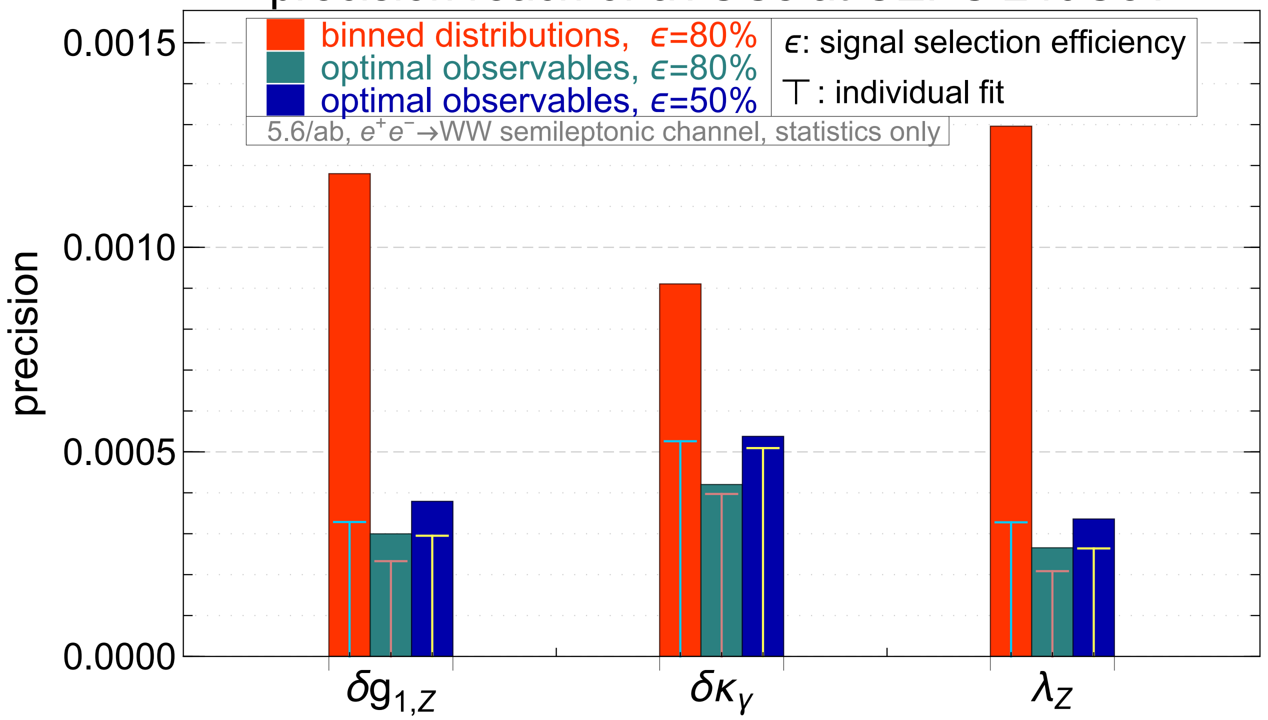


J. Eysermans @ EPS2021

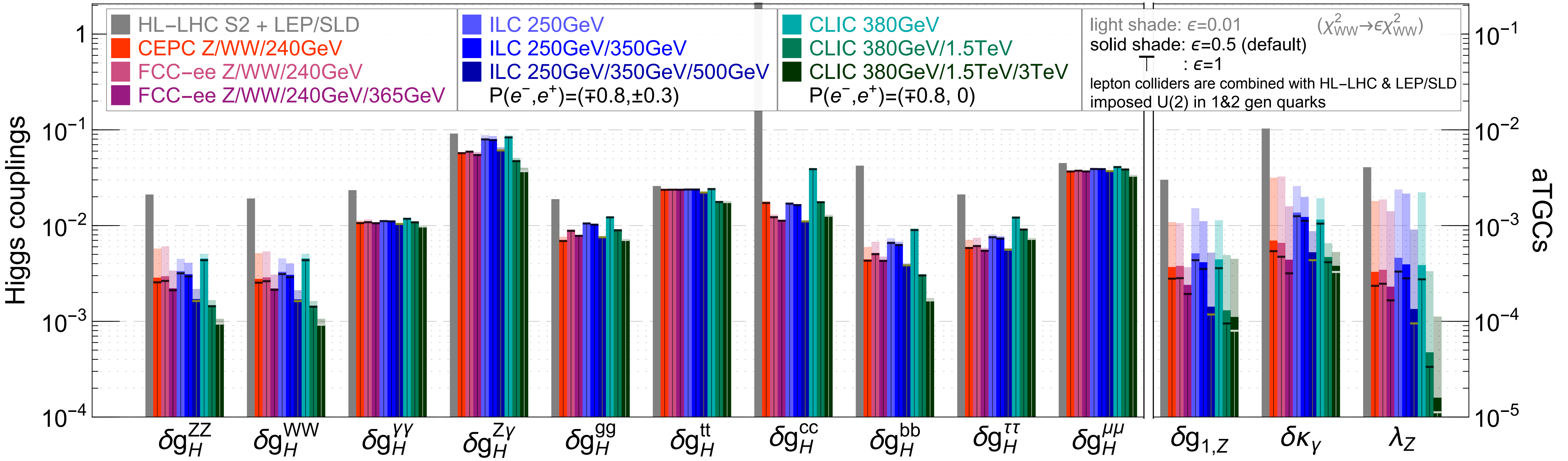
Impact of Diboson Systematics

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

precision reach of aTGCs at CEPC 240GeV

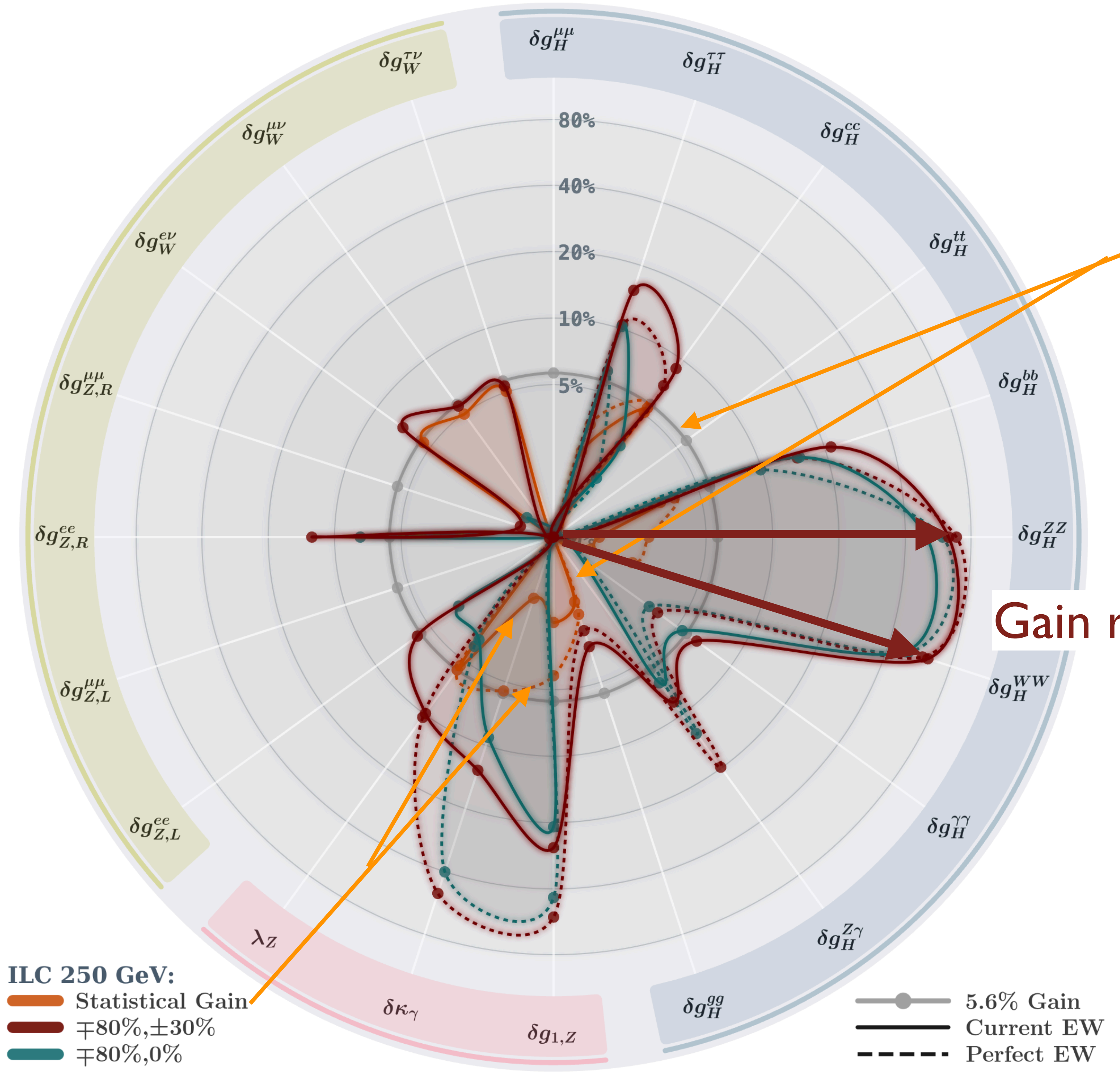


precision reach with different assumptions on $e^+e^-\to WW$ measurements



Impact of Beam Polarisation (@250GeV)

J. De Blas et al. 1907.04311



Gain reaches 80%

Statistical gain from increased rates

$$\sigma_{P_{e^+}P_{e^-}} = \sigma_0(1-P_{e^+}P_{e^-})\left[1 - A_{LR}\frac{P_{e^-}-P_{e^+}}{1-P_{e^+}P_{e^-}}\right]$$

From ee→Zh, A_{LR}~0.15 so $\sigma_{-80,+30} \sim 1.4\,\sigma_0$

overall, one could expect
O(6%) increased coupling sensitivity

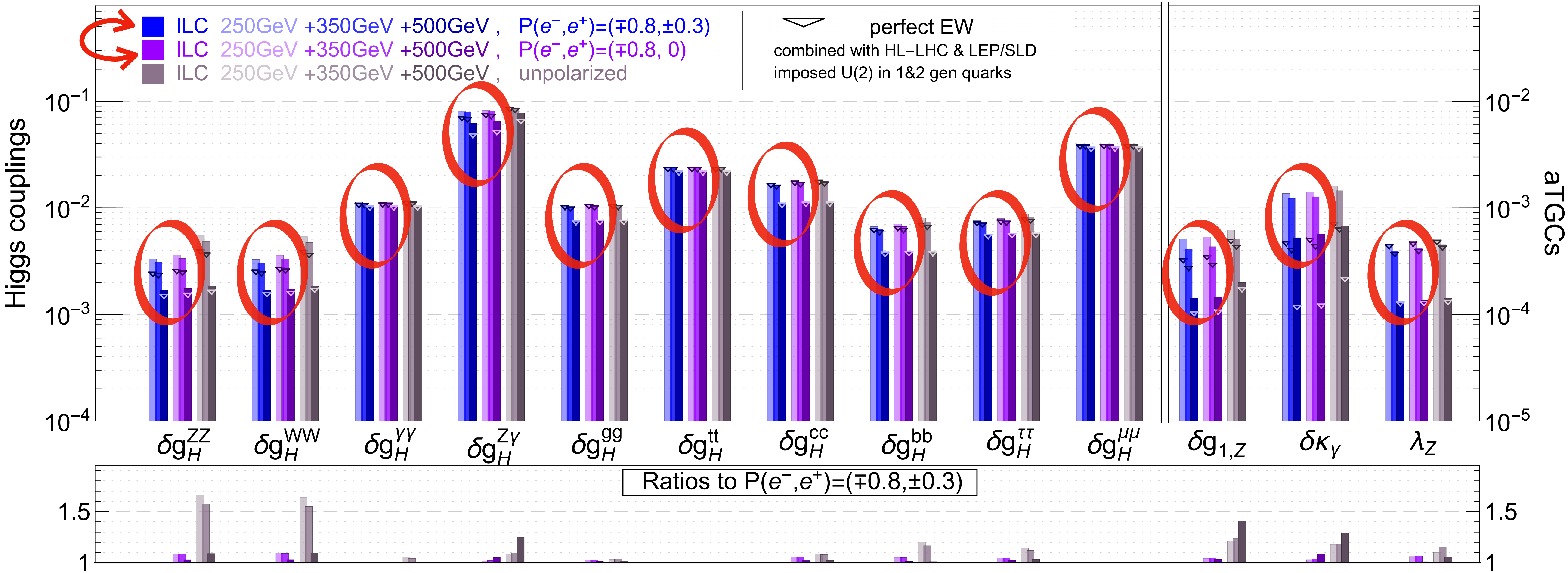
Gain is much higher in global EFT fit since polarisation removes degeneracies among operators

Polarisation benefit diminishes
when other runs at higher energies are added
and basically left only with statistical gain

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

Impact of Beam Polarisation

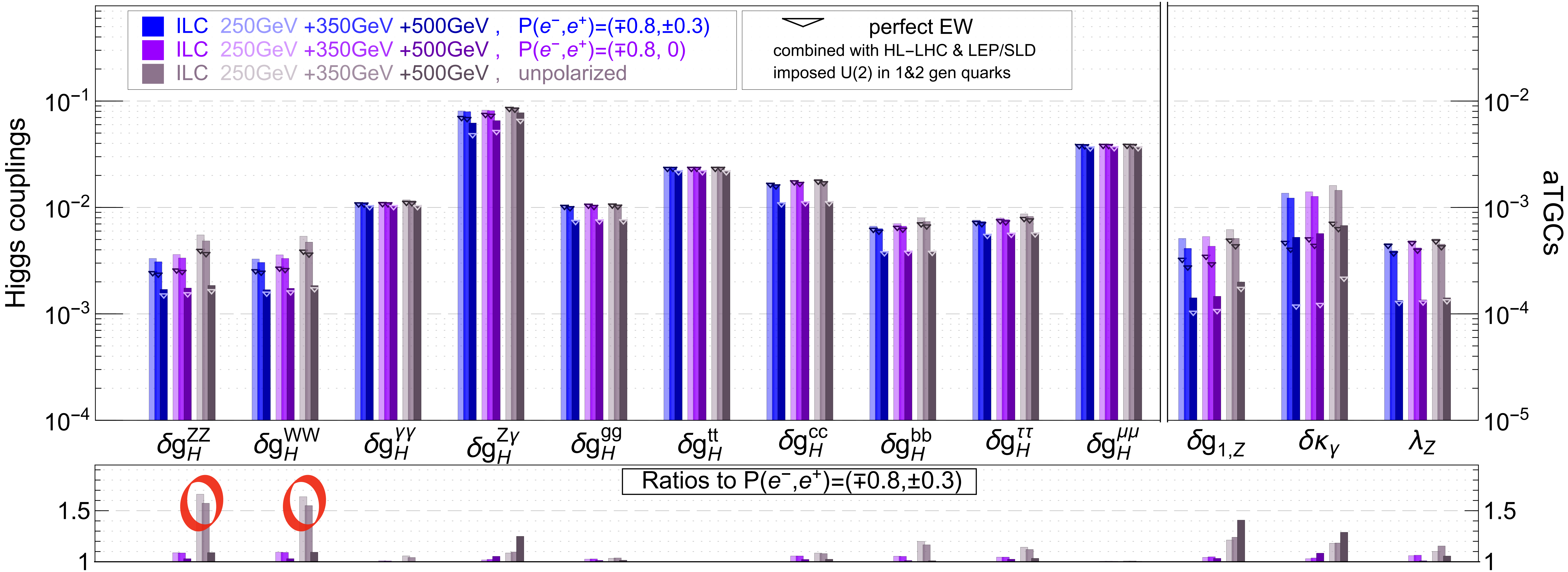
J. De Blas et al. 1907.04311



- Positron polarisation doesn't play a big role (for Higgs couplings determination)

Impact of Beam Polarisation

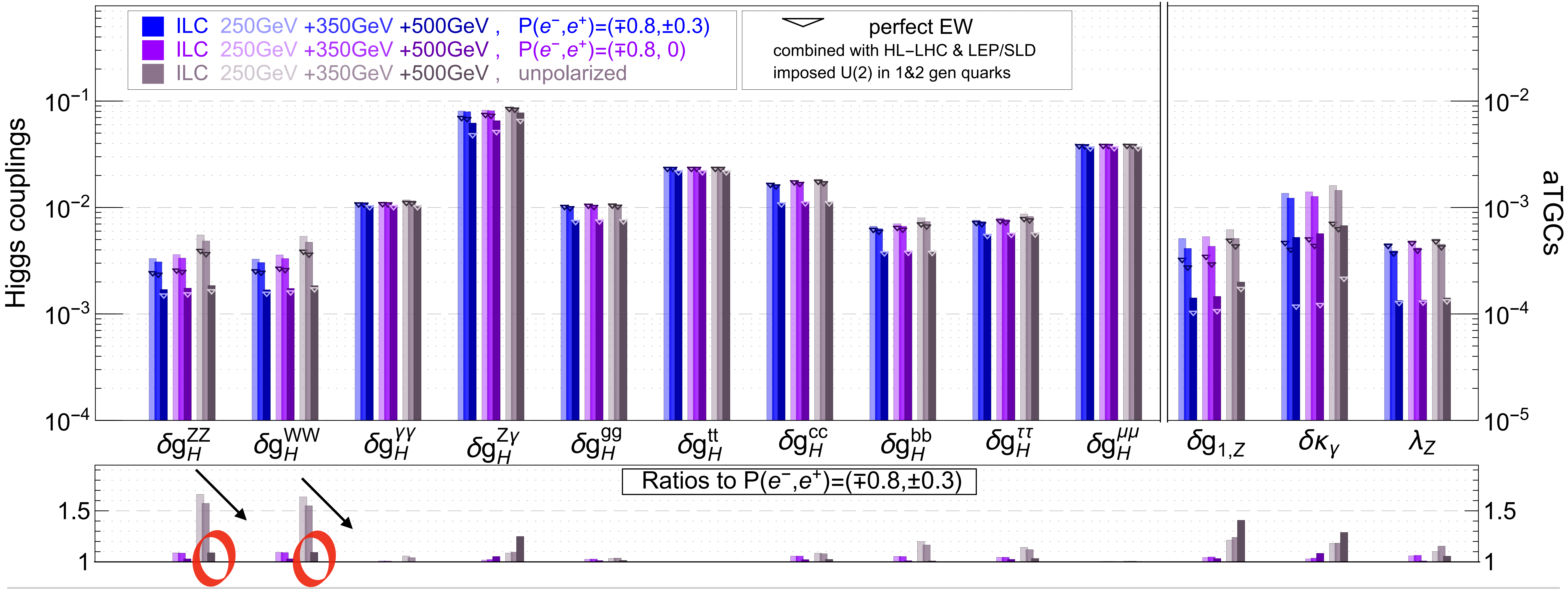
J. De Blas et al. 1907.04311



- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination

Impact of Beam Polarisation

J. De Blas et al. 1907.04311



- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination
- Polarisation-benefit diminishes (in relative and absolute terms) when other runs at higher energies are added