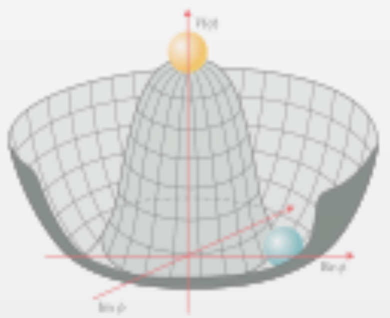
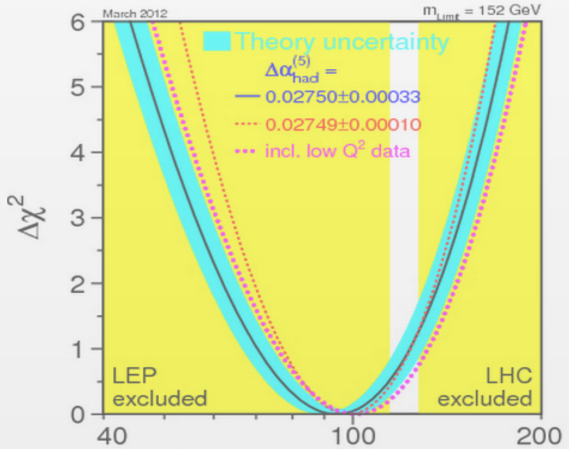
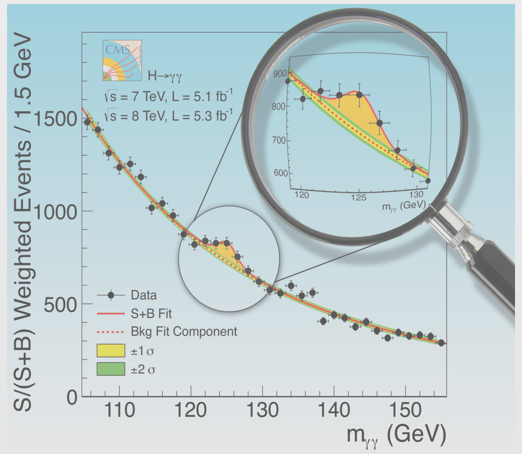


1964



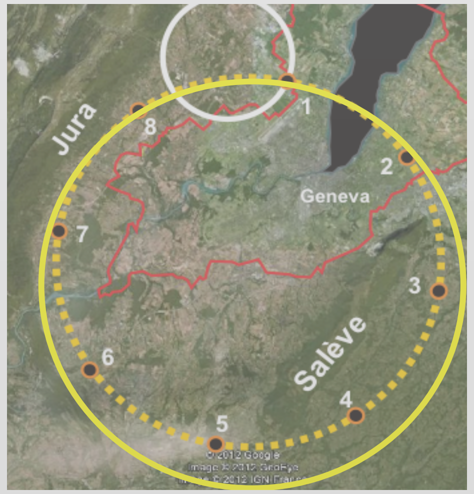
1992-1999

2010



2012

2020



2040

— FCC —

Motivations for Precision

(focus on ‘why?’ rather than ‘how?’)

FCC EPOL Workshop
CERN, Sept. 20, 2022

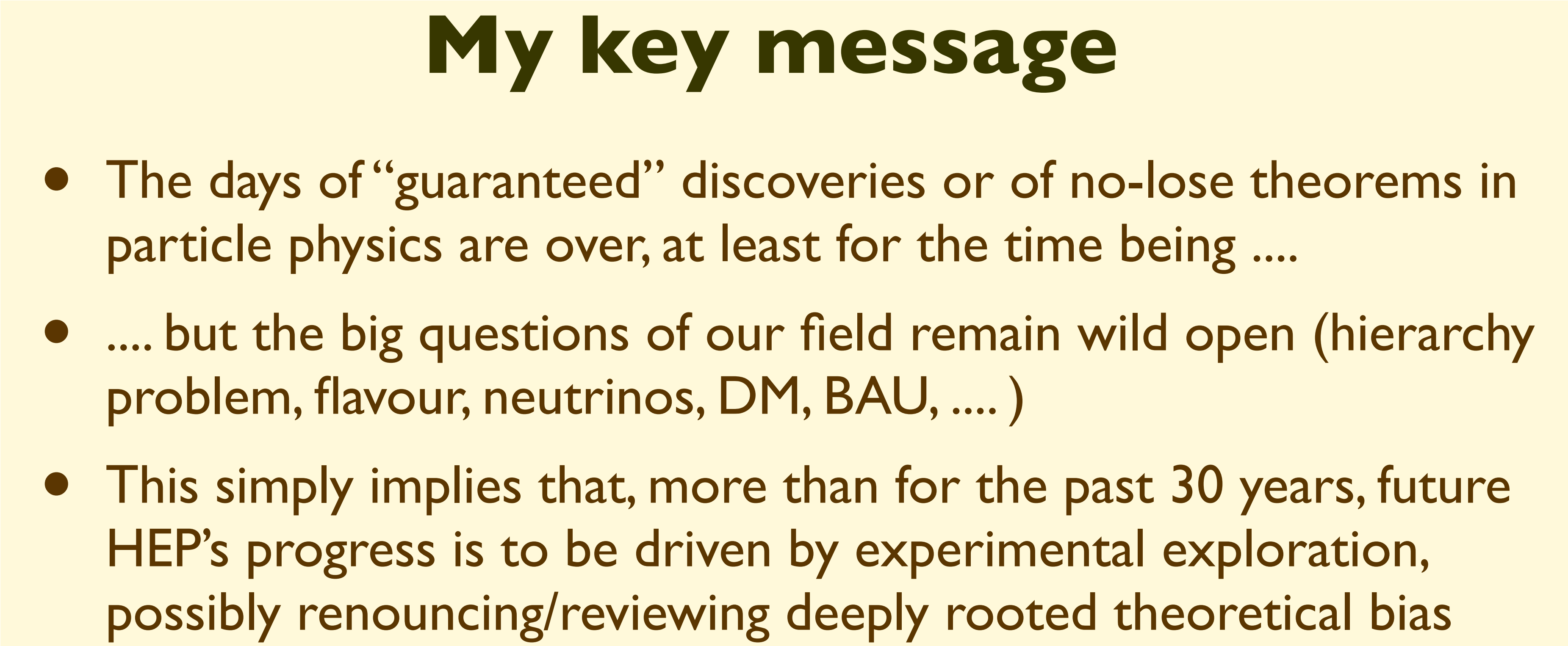
Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)

(christophe.grojean@desy.de)

The HEP landscape after LHC$_{\text{I-II}}$

Nicely summarised by

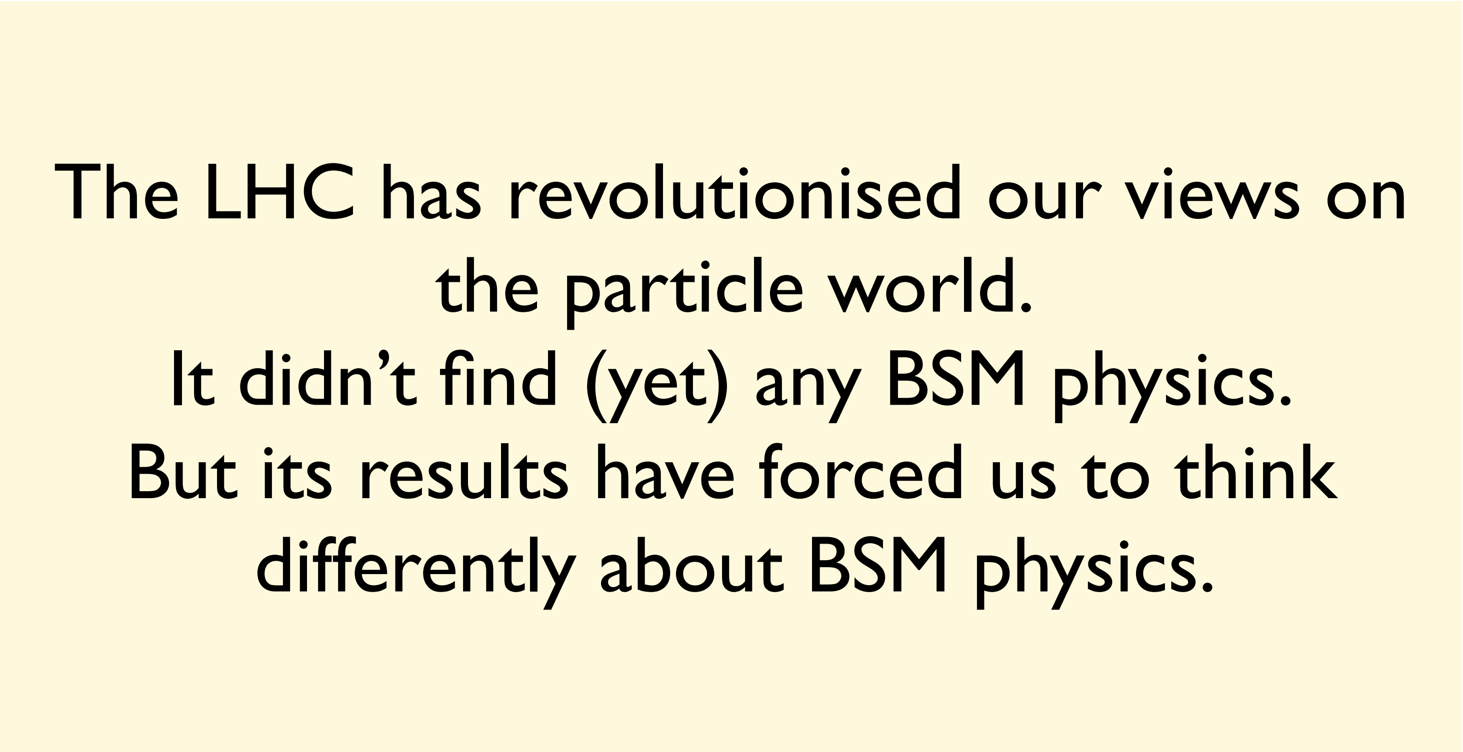
MLM@Aspen'14



My key message

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

G. Giudice@DESY'22



The LHC has revolutionised our views on the particle world.
It didn't find (yet) any BSM physics.
But its results have forced us to think differently about BSM physics.

The HEP landscape after LHC$_{\text{I-II}}$

Nicely summarised by

MLM@Aspen’14

My key message

- The days of “guaranteed” discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP’s progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

G. Giudice@DESY’22

The LHC has revolutionised our views on the particle world.
It didn’t find (yet) any BSM physics.
But its results have forced us to think differently about BSM physics.

Precision measurements will serve as a **guide** to further exploration at higher energies:
1) they will set strong bounds on new physics
2) they could indirectly reveal new physics
3) importantly, they could identify structural properties of new physics (e.g. new symmetries)

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)

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

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

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

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

cosmological naturalness power counting

mass of the cosmological mediator

its coupling to SM

EW scale

Higgs cutoff

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

q = integer defines the BSM model

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)

We need a broad, versatile and ambitious programme that
1. sharpens our knowledge of already discovered physics
2. pushes the frontiers of the unknown in the intensity and energy frontiers

— FCC-ee+eh+hh combine these different aspects —

more PRECISION, more ENERGY for more SENSITIVITY to New Physics

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)

We need a broad, versatile and ambitious programme that
1. sharpens our knowledge of already discovered physics
2. pushes the frontiers of the unknown in the intensity and energy frontiers

— FCC-ee+eh+hh combine these different aspects —

more PRECISION, more ENERGY for more SENSITIVITY to New Physics

“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.

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)

We need a broad, versatile and ambitious programme that

1. sharpens our knowledge of already discovered physics
2. pushes the frontiers of the unknown in the intensity and energy frontiers

— FCC-ee+eh+hh combine these different aspects —

more PRECISION, more ENERGY for more SENSITIVITY to New Physics

“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, though the synergy with FCC-hh remains invaluable.

Why More Precision?

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

LEP
(10^6 Z)

$$\frac{c}{\Lambda^2} < \Delta$$

$$\xrightarrow[\text{observables}]{\text{stat. dominated}}$$

FCC-ee
(10^{12} Z)

$$\frac{c}{\Lambda^2} < 10^{-3}\Delta$$

i.e. improve bounds by

a factor 1000 on c

a factor 30 on Λ

Why More Precision?

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

LEP
(10^6 Z)

$\frac{c}{\Lambda^2} < \Delta$

stat. dominated → observables

FCC-ee
(10^{12} Z)

$\frac{c}{\Lambda^2} < 10^{-3}\Delta$

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 ↔ Higgs couplings ✓
↑
lifetime of stars
(why $t_{Sun} \sim t_{life\ evolution}$?)

m_e, m_u, m_d ↔ Higgs couplings ?
size of atoms (m_e, m_u)
nuclei stability (m_u, m_d)

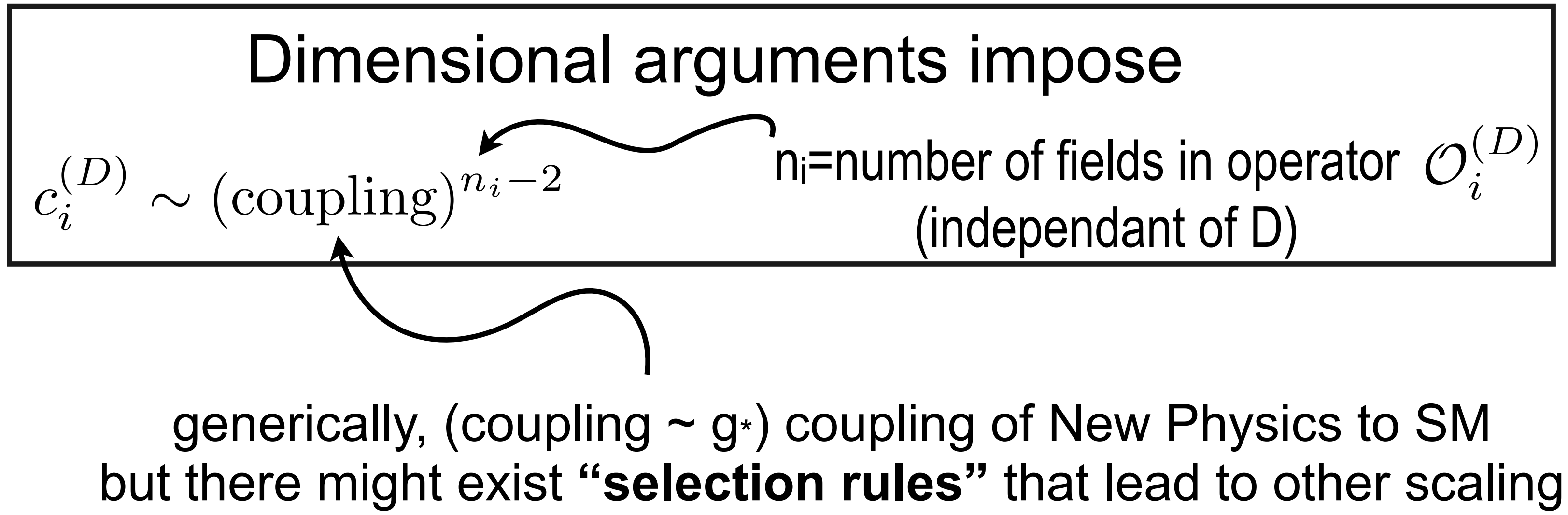
EW @ t~10^{-10}s ↔ Higgs self-coupling ?

matter/anti-matter ↔ 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

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



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

Why More Precision?

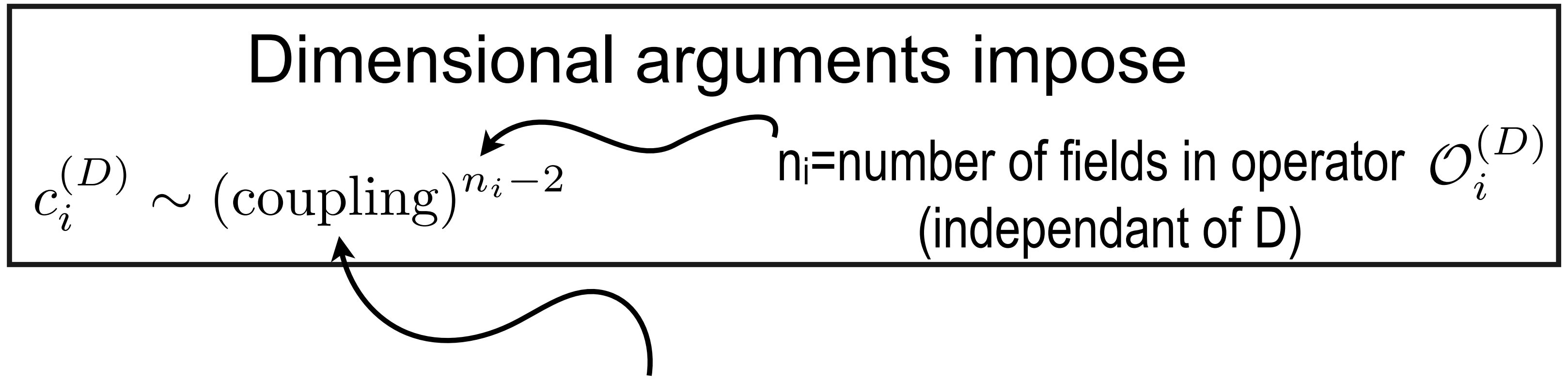
3 The values of the EFT interactions among SM fields will reveal the “selection rules” of the SM, with intimate links to new structure/symmetries

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)

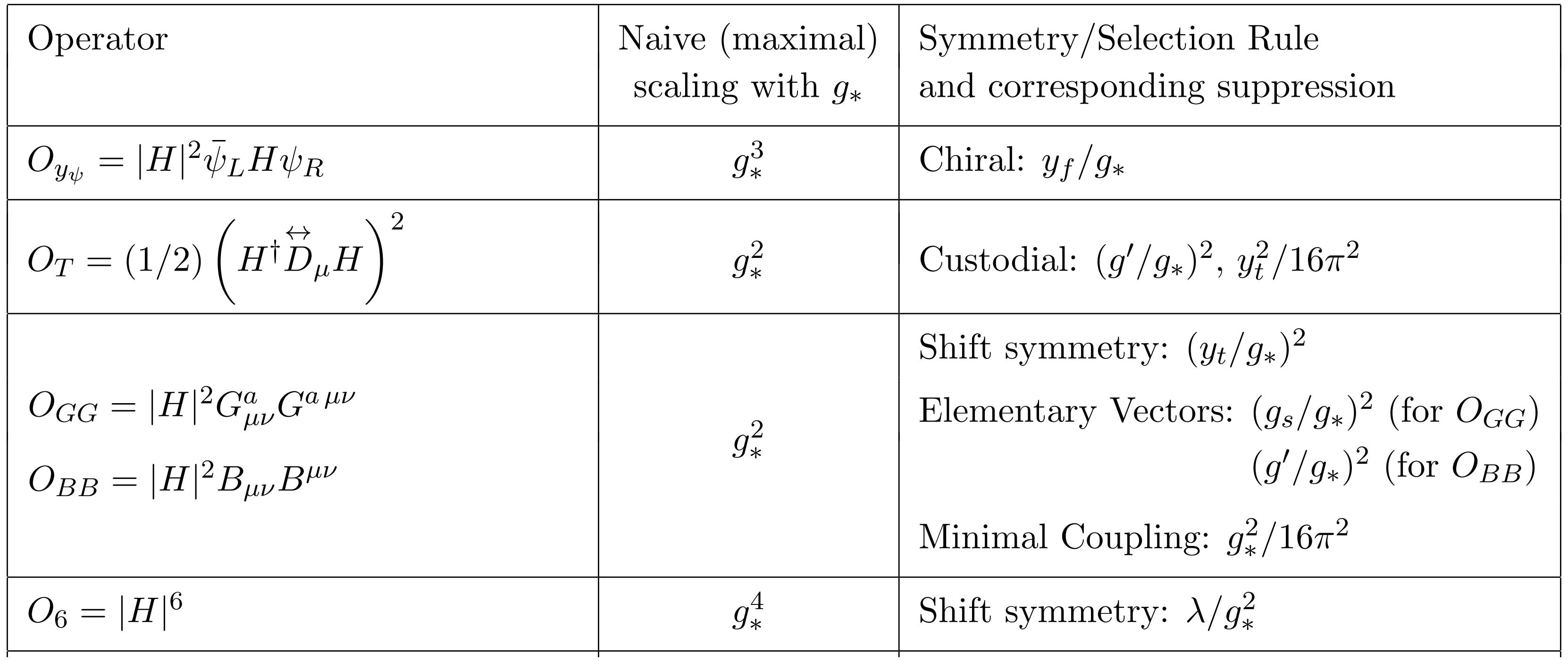
generically, (coupling ~ g_*) coupling of New Physics to SM
but there might exist **“selection rules”** that lead to other scaling

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
$O_{y_\psi} = \lvert H\rvert^2 \bar{\psi}_L H \psi_R$	g_*^3	Chiral: y_f/g_*
$O_T = (1/2)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	g_*^2	Custodial: $(g'/g_*)^2$, $y_t^2/16\pi^2$
$O_{GG} = \lvert H\rvert^2 G^a_{\mu\nu} G^{a\,\mu\nu}$ $O_{BB} = \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	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: $g_*^2/16\pi^2$
$O_6 = \lvert H\rvert^6$	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)

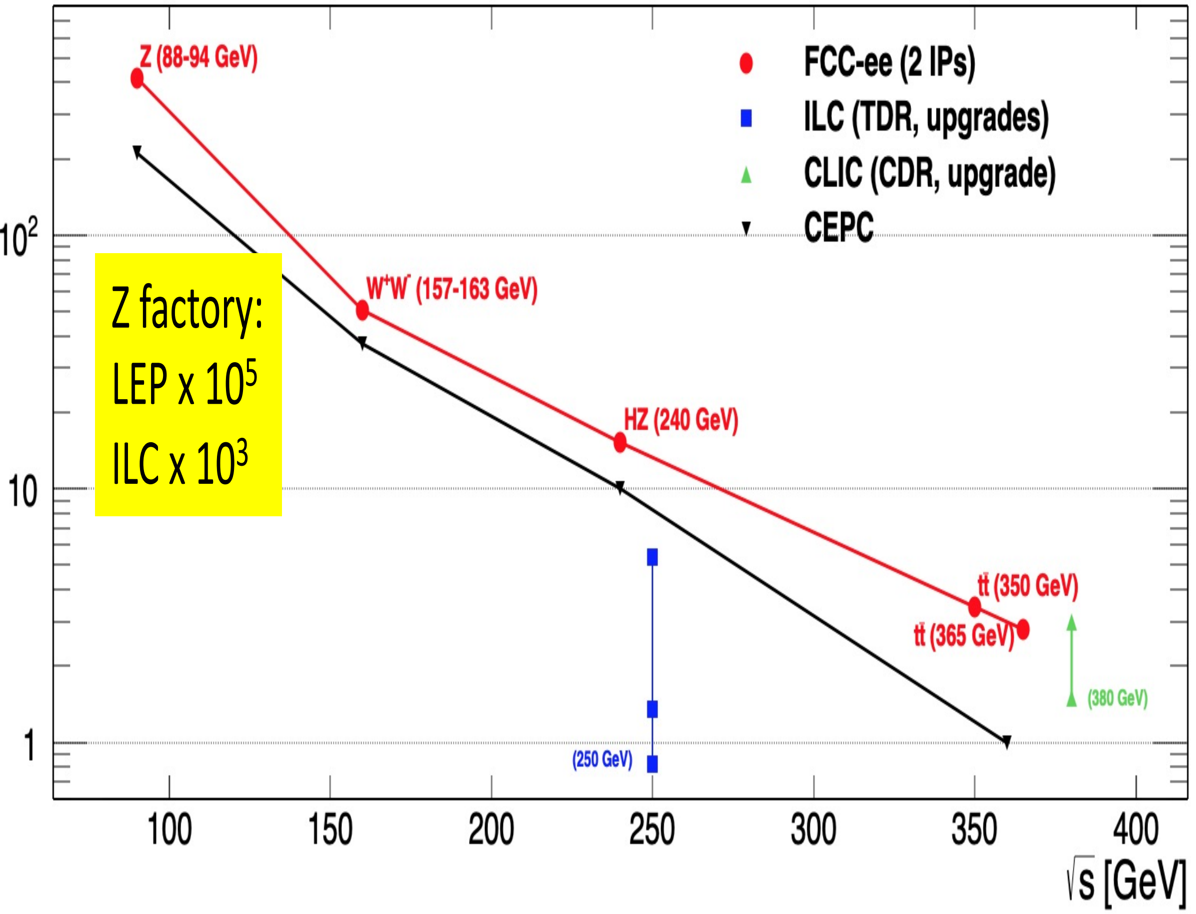
generically, (coupling ~ g_*) coupling of New Physics to SM
but there might exist **“selection rules”** that lead to other scaling

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.

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

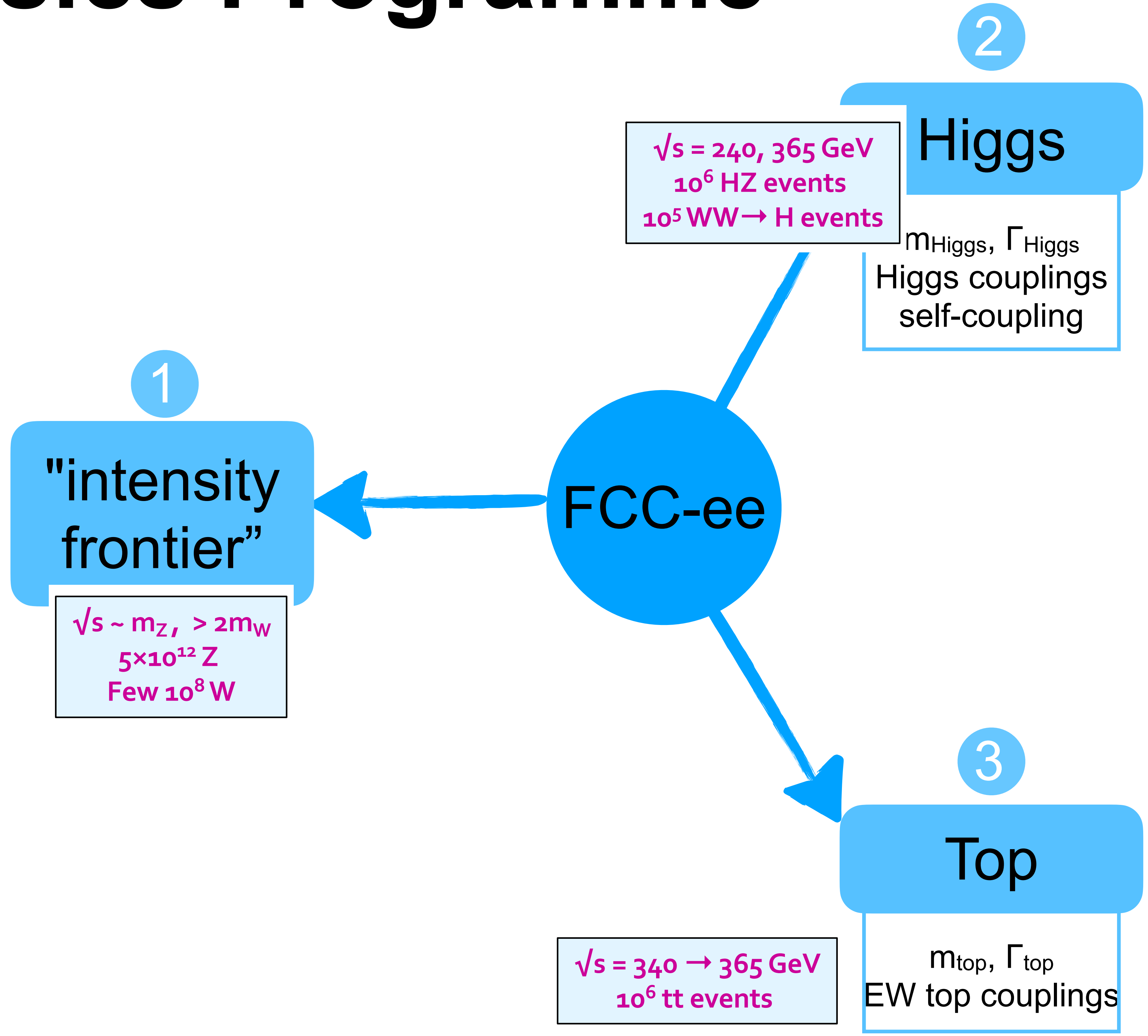
Event statistics (2IP)

					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
$t\bar{t}$	E_{cm} : $\geq$ 350 GeV	5yrs	10^6 e+e- → $t\bar{t}$	Never done	2 MeV

FCC-ee Physics Programme

FCC-ee

FCC-ee Physics Programme



FCC-ee

1

"intensity frontier"

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

2

Higgs

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

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

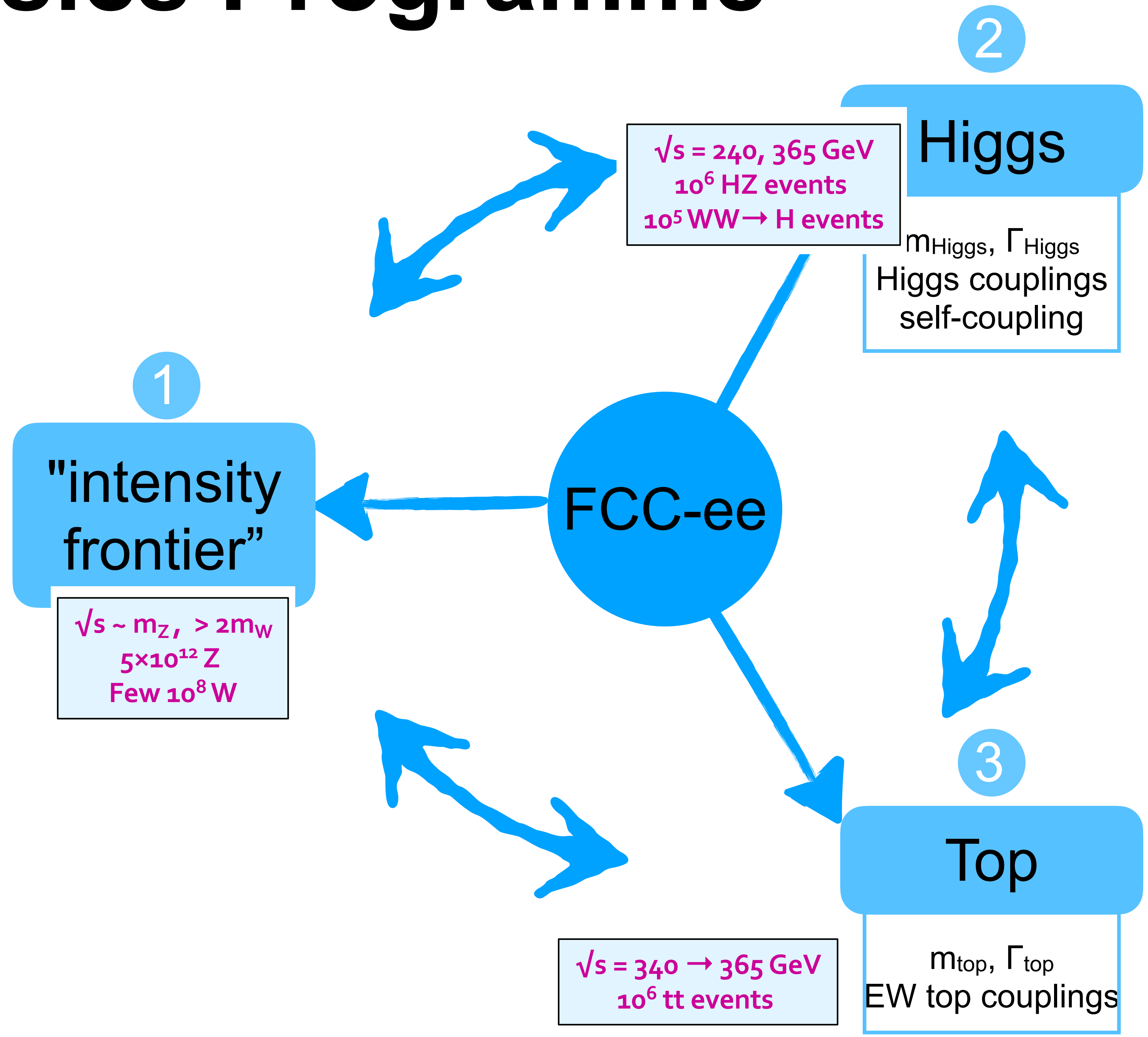
3

Top

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

m_{top}, Γ_{top}
EW top couplings

FCC-ee Physics Programme



FCC-ee

1

"intensity frontier”

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

2

Higgs

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

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

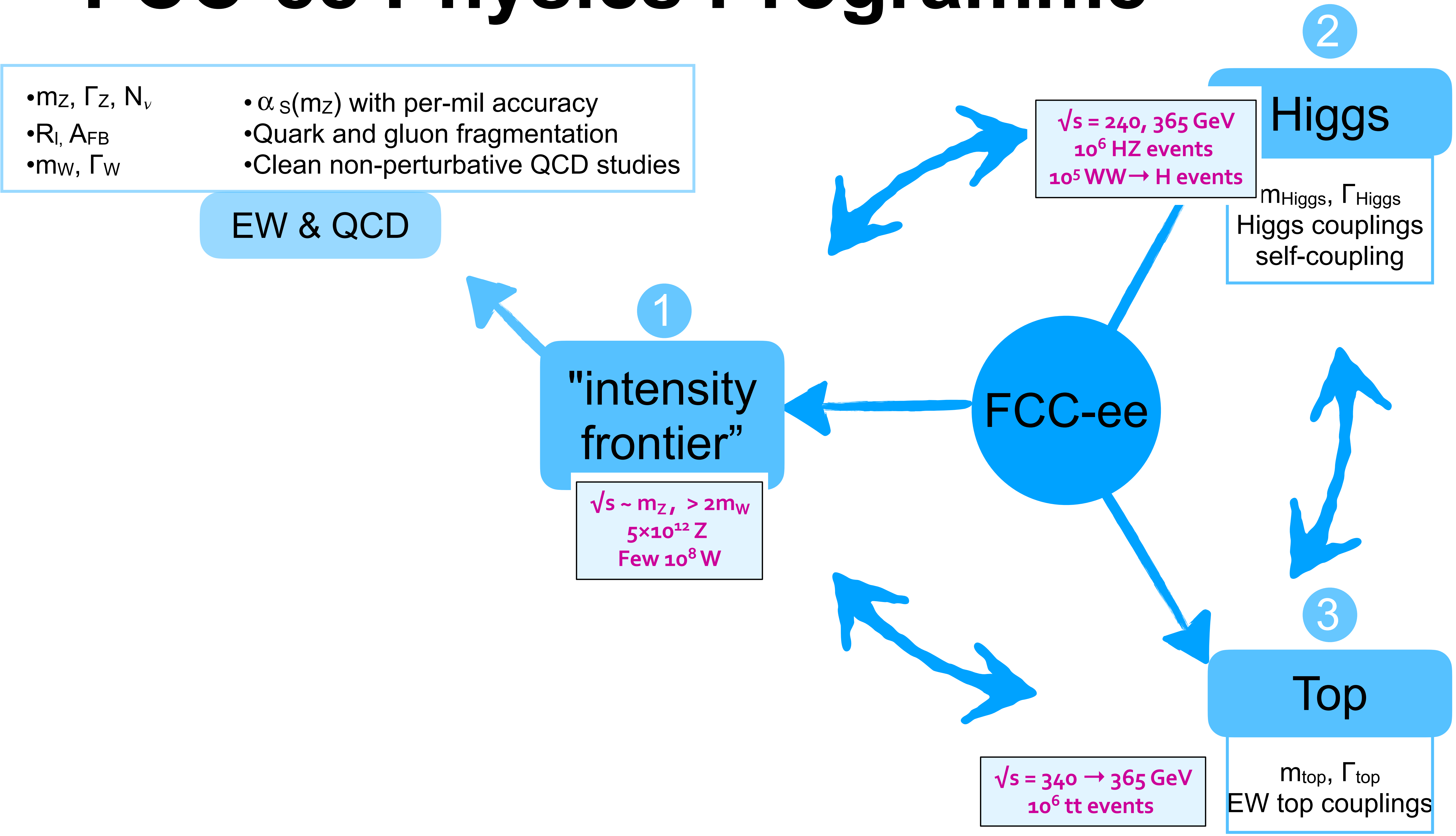
3

Top

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

m_{top}, Γ_{top}
EW top couplings

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

1

"intensity frontier"

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

FCC-ee

2

Higgs

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

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

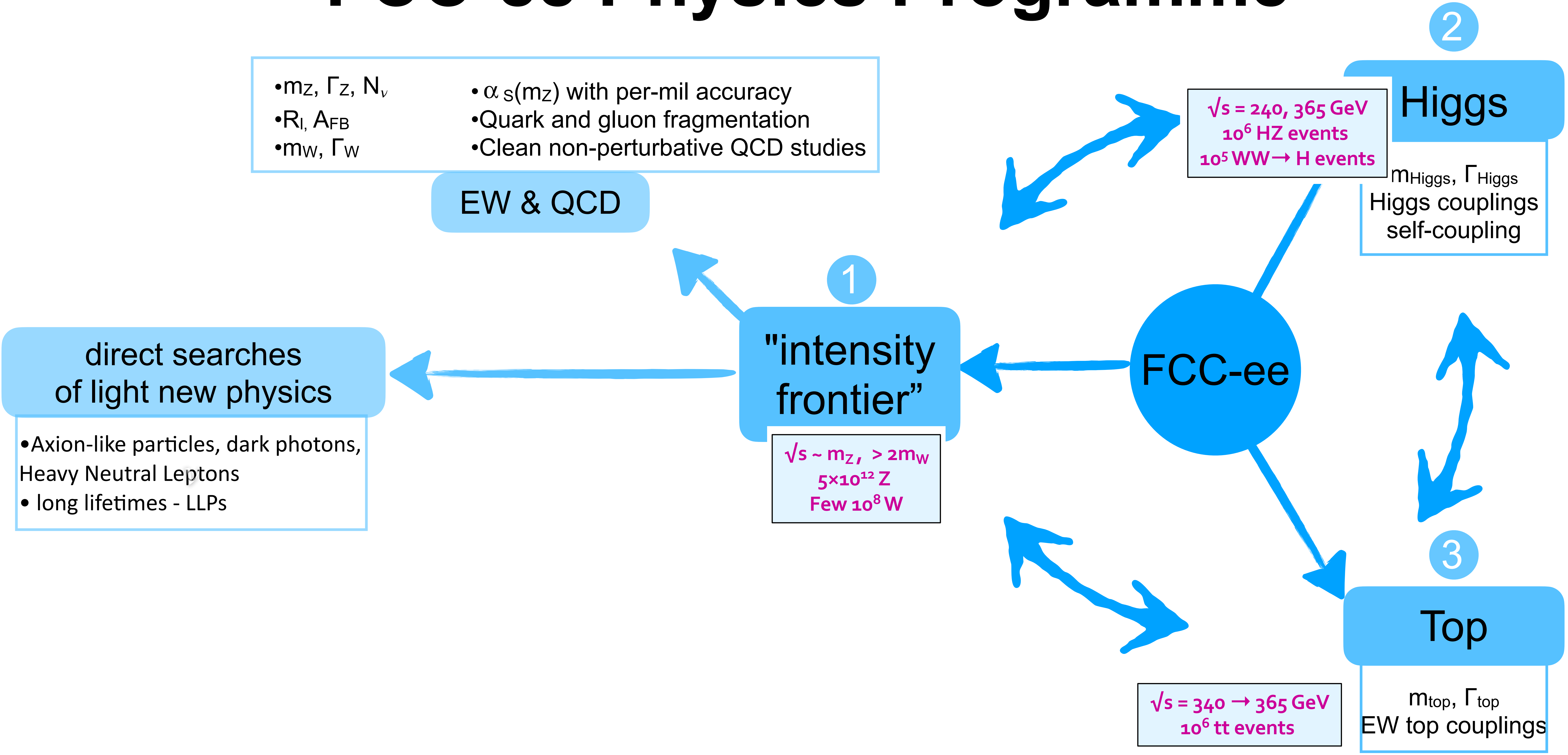
3

Top

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

m_{top}, Γ_{top}
EW top couplings

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

direct searches of light new physics

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

1

"intensity frontier"

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

FCC-ee

2

Higgs

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

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

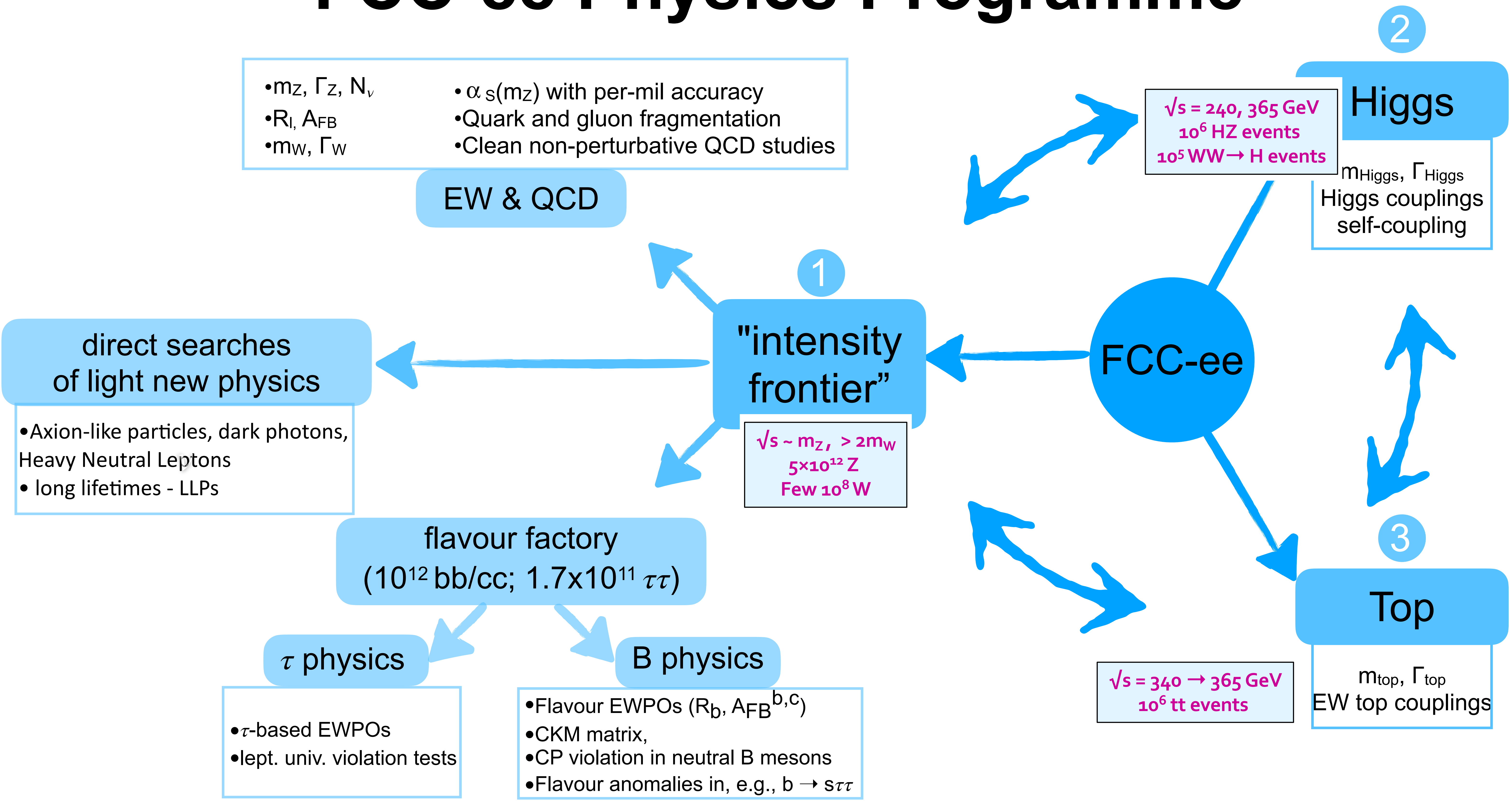
3

Top

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

m_{top}, Γ_{top}
EW top couplings

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

direct searches of light new physics

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

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

τ physics

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

B physics

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

2

Higgs

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

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

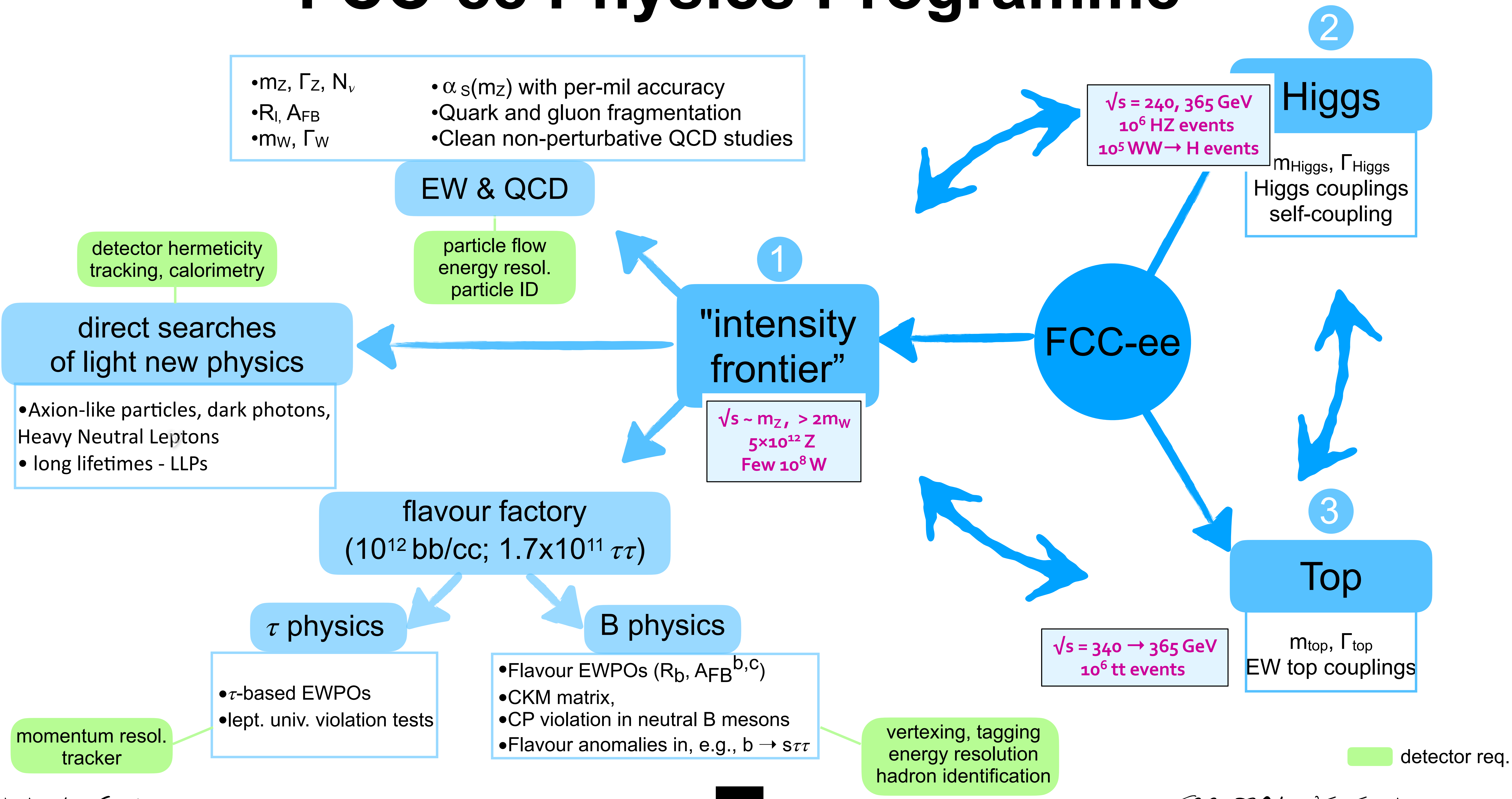
3

Top

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

m_{top}, Γ_{top}
EW top couplings

FCC-ee Physics Programme



FCC-ee

1

"intensity frontier"

$\sqrt{s} \sim m_Z$, > $2m_W$
$5{\times}10^{12}$ 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; $1.7{\times}10^{11}$ $\tau\tau$)

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

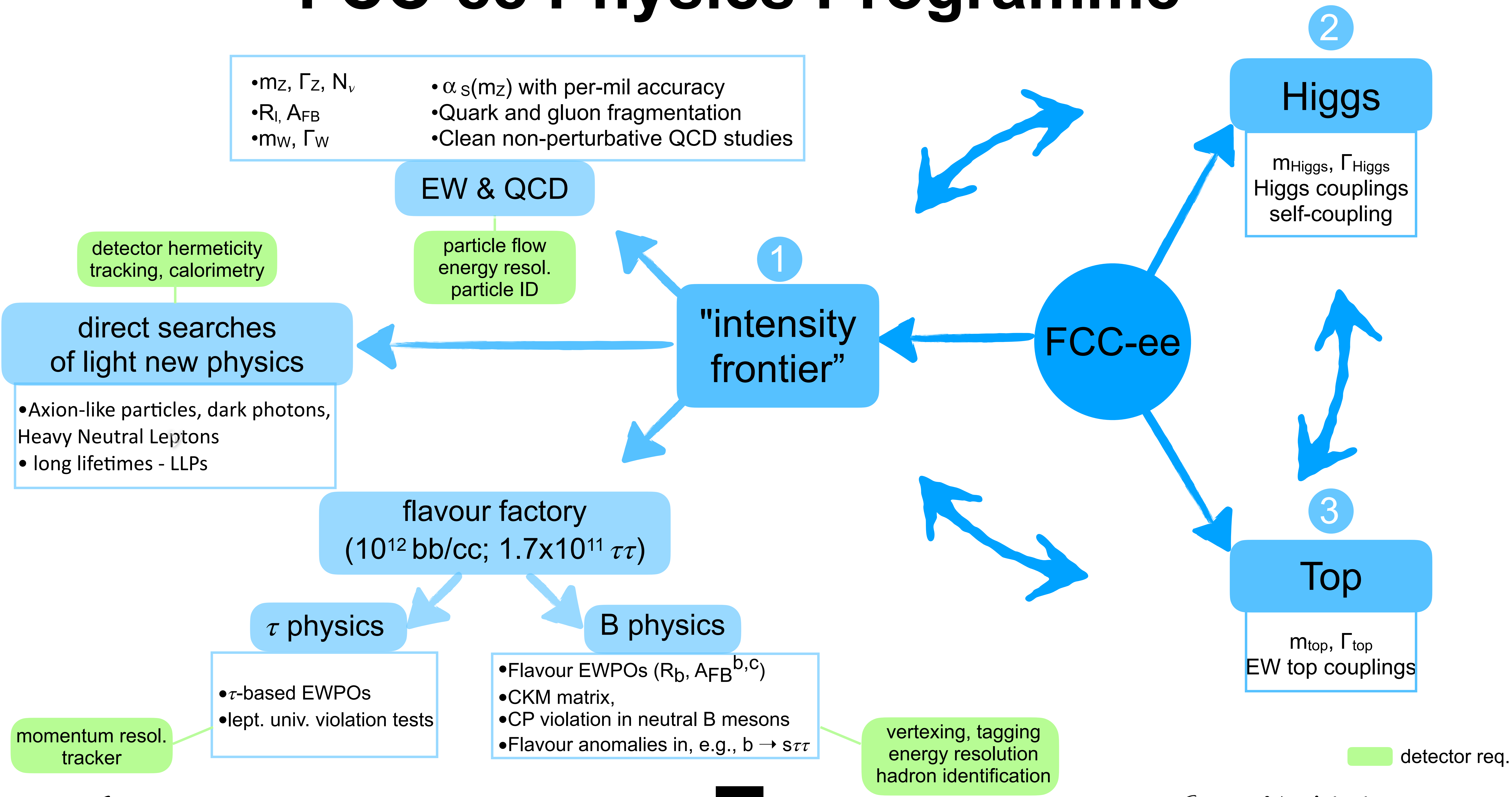
m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

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	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

🟩 detector req.

FCC-ee Physics Programme



FCC-ee

①

"intensity frontier"

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; 1.7×10^{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

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

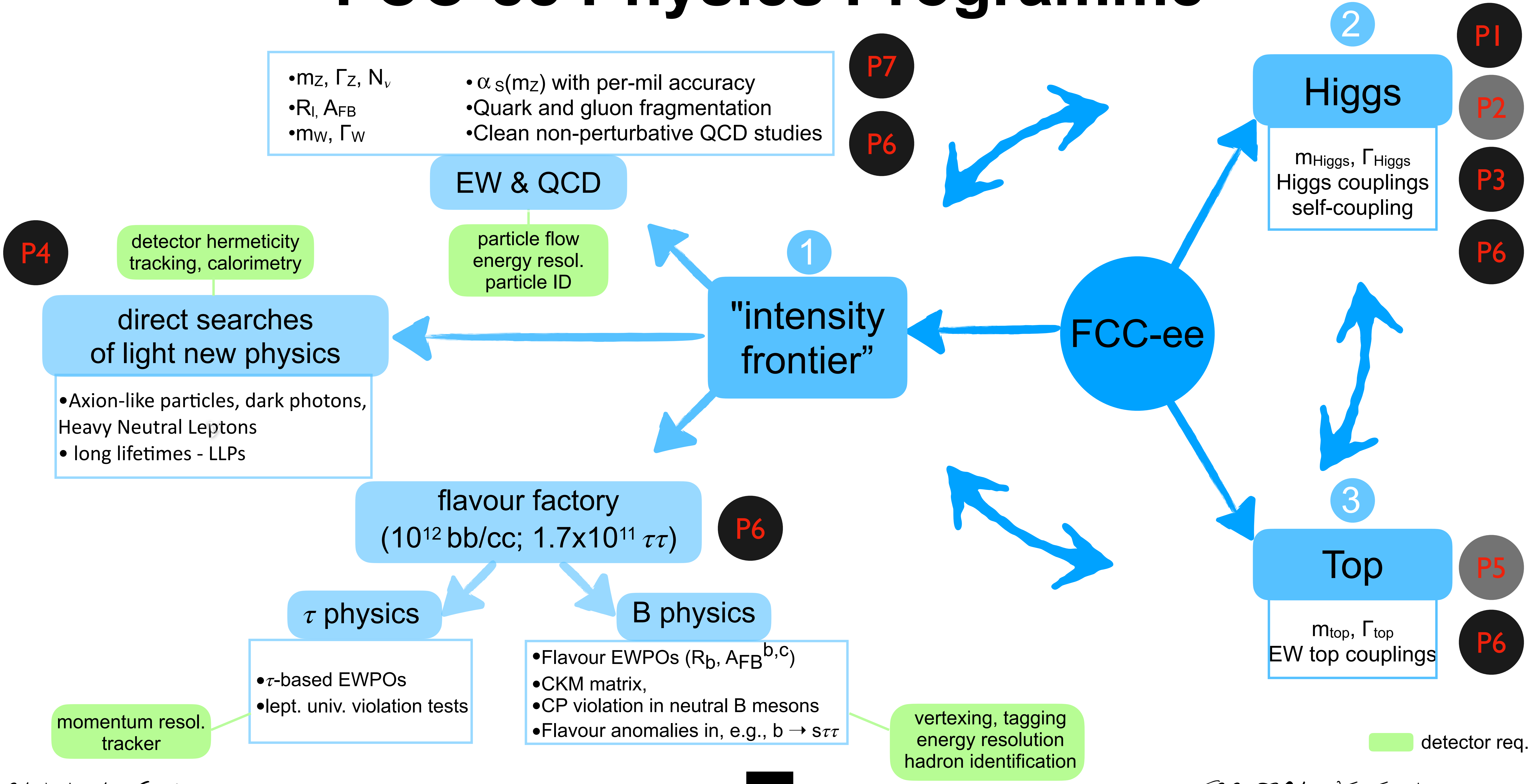
③

Top

m_{top}, Γ_{top}
EW top couplings

🟩 detector req.

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

P7

P6

EW & QCD

particle flow
energy resol.
particle ID

2

Higgs

P1

P2

P3

P6

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

P4

detector hermeticity
tracking, calorimetry

direct searches of light new physics

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

1

"intensity frontier"

FCC-ee

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

P6

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

3

Top

P5

P6

m_{top}, Γ_{top}
EW top couplings

🟩 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 / $\overline{\Lambda}_b$	$c\overline{c}$	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

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 / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
						150

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

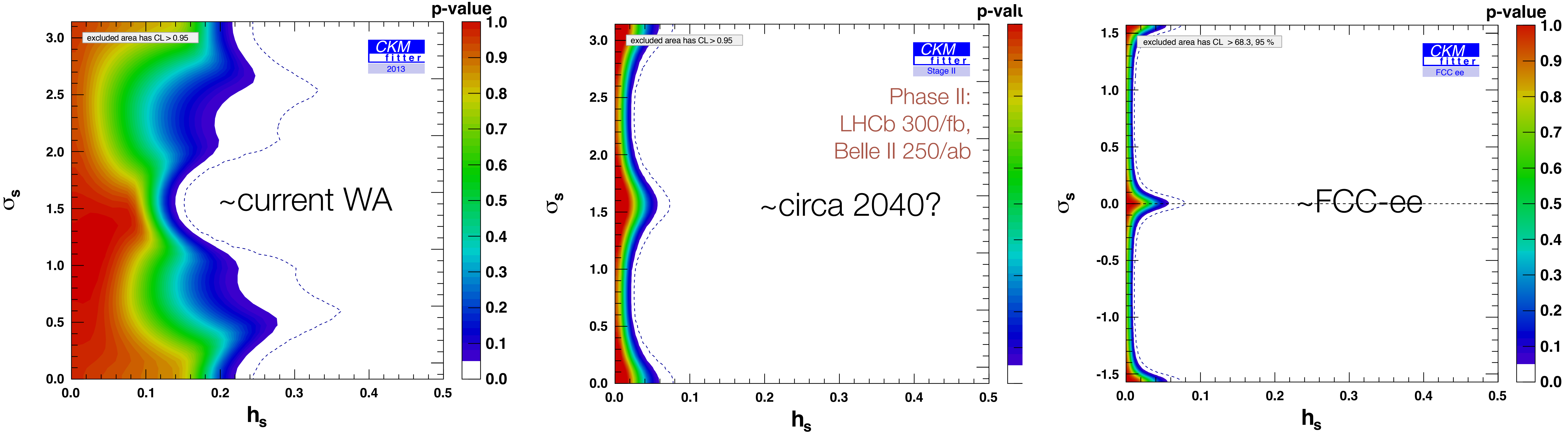
boosted b's/τ's at FCC-ee

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

Z-Factories are great Flavour Factories

Kamenik @ FCC Physics WS ‘22

$$\langle B_q|\mathcal{H}^{\mathrm{SM+NP}}_{\Delta B=2}|\bar{B}_q\rangle = \langle B_q|\mathcal{H}^{\mathrm{SM}}_{\Delta B=2}|\bar{B}_q\rangle \left(1+h_q e^{i\sigma_q}\right)$$



~current WA

Phase II:
LHCb 300/fb,
Belle II 250/ab

~circa 2040?

~FCC-ee

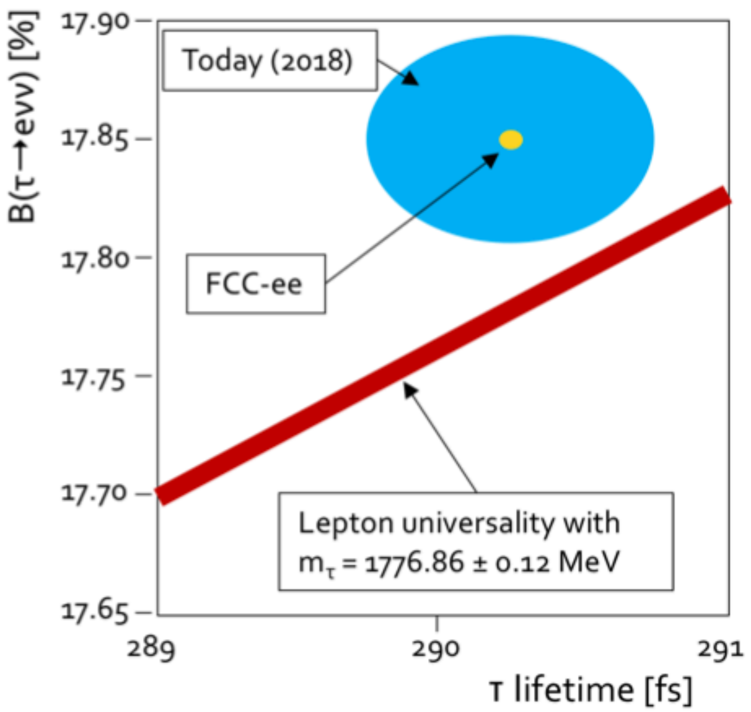
FCC-ee: sensitivity of scale of new physics (with MVF structure) > 20 TeV

Probing New Physics w/ τ Decays

“10 more tau’s than at Belle II”

Allwicher, Isidori, Semilovic ’21

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



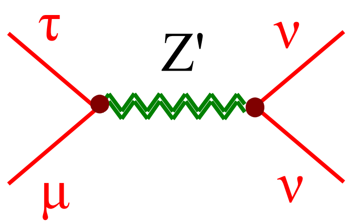
sensitivity good enough to probe BSM models “explaining” current flavour R_K anomalies

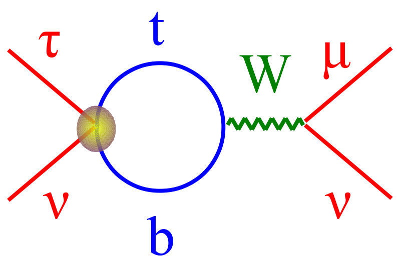
($b\to c\tau\nu$)

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 $(0.2 – 4.0) \times 10^{-3}$
- 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 !

Tera-Z EW precision measurements

- Tera-Z allows one to have access to kinematic regions to reduce syst. uncertainties
- Exquisite √s precision (100keV@Z, 300keV@WW) reduces beam uncertainties

➡ 100 times better precision than LEP/LSD on EW precision observables

Need TH results to fully exploit Tera-Z

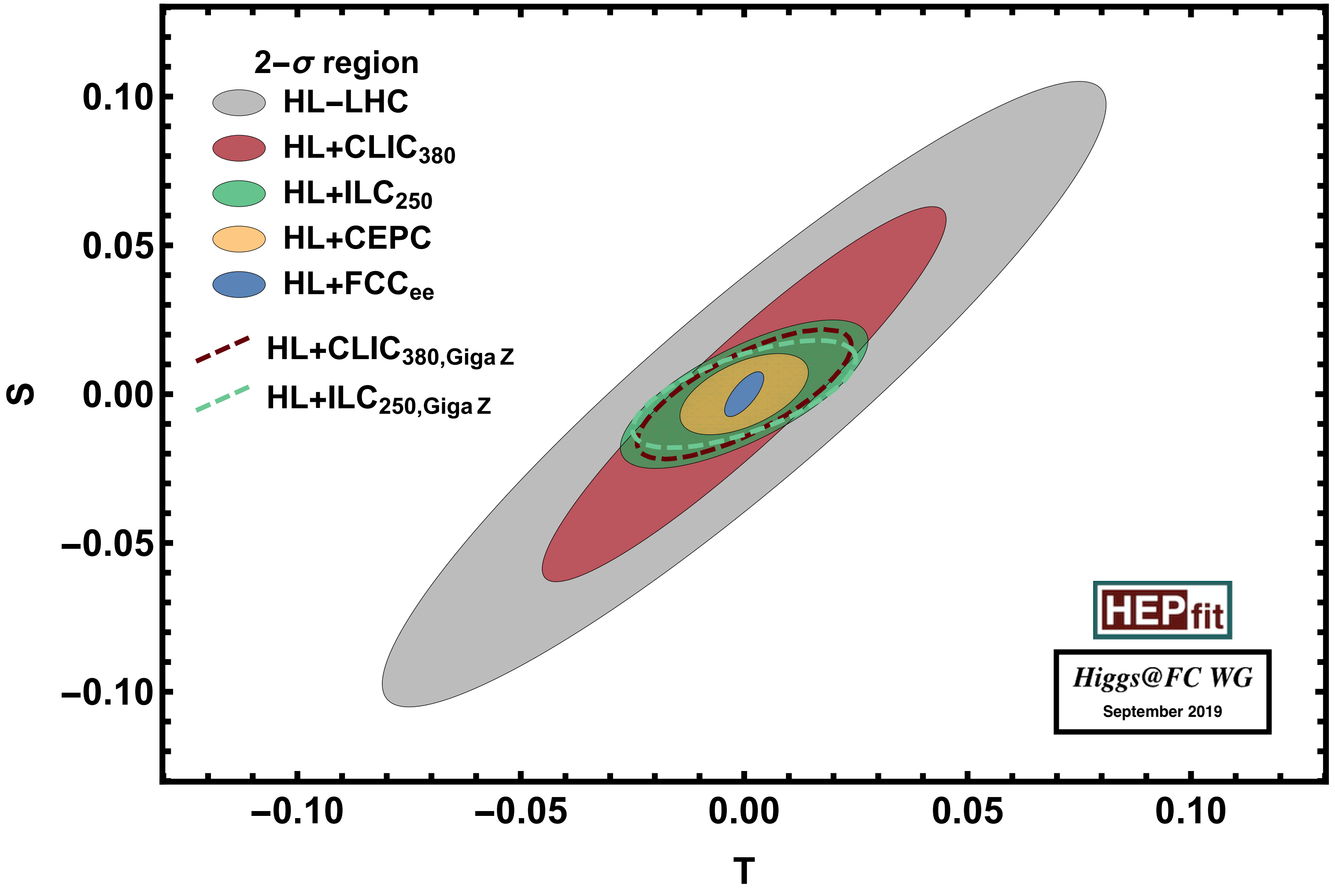
	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
$\Delta M_\mathrm{Z}[\mathrm{MeV}]$	2.1	–	0.1			
$\Delta \Gamma_\mathrm{Z}[\mathrm{MeV}]$	2.3	1	0.025	0.4	$\alpha^3, \alpha^2\alpha_\mathrm{s}, \alpha\alpha_\mathrm{s}^2$	0.15
$\Delta \sin^2\theta^\ell_\mathrm{eff}[10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_\mathrm{s}$	1.5
$\Delta R_\mathrm{b}[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_\mathrm{s}$	5
$\Delta R_\ell[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_\mathrm{s}$	1.5

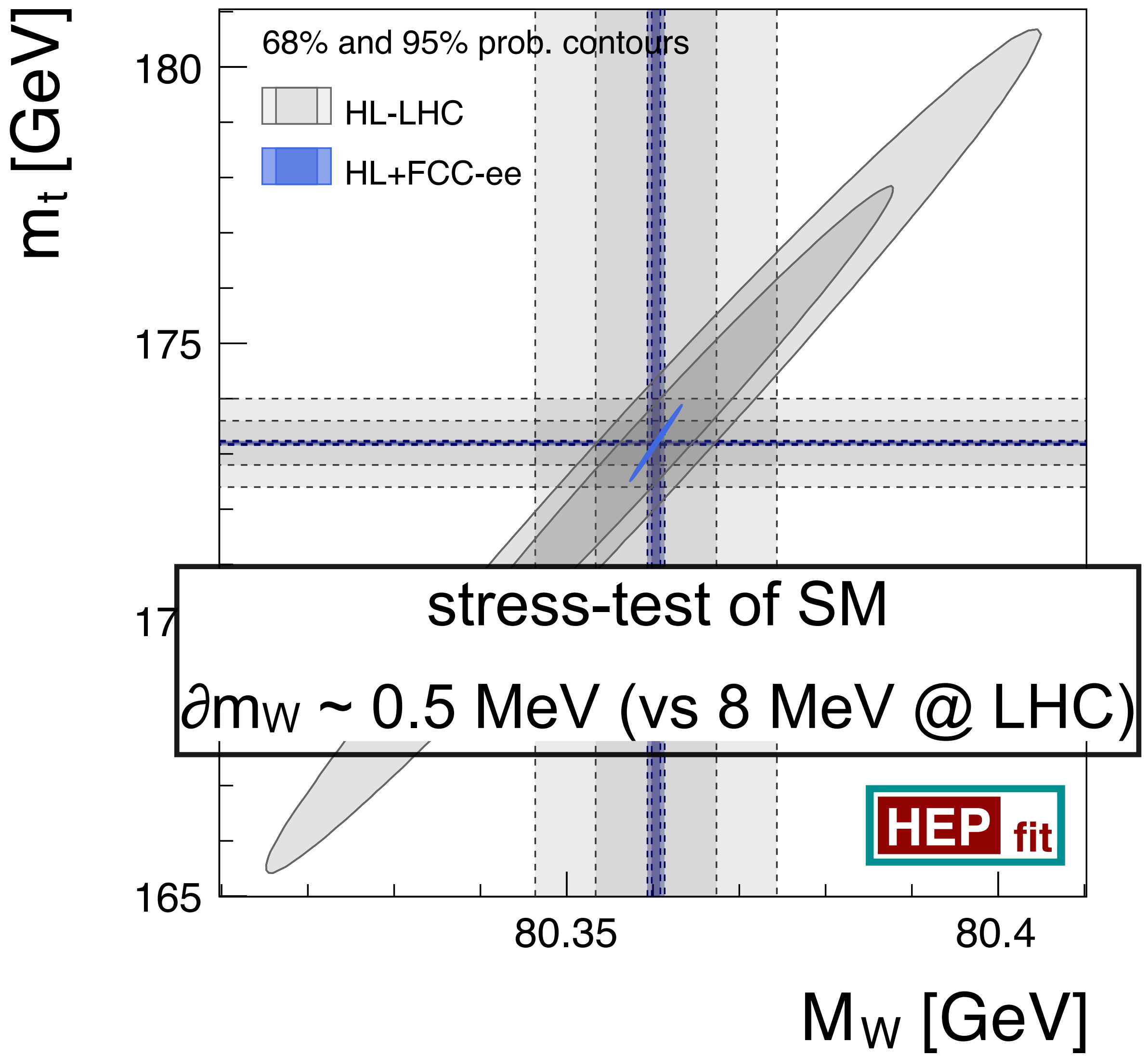
For the impact of the theory uncertainties on the EW fit, see backup slides

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)

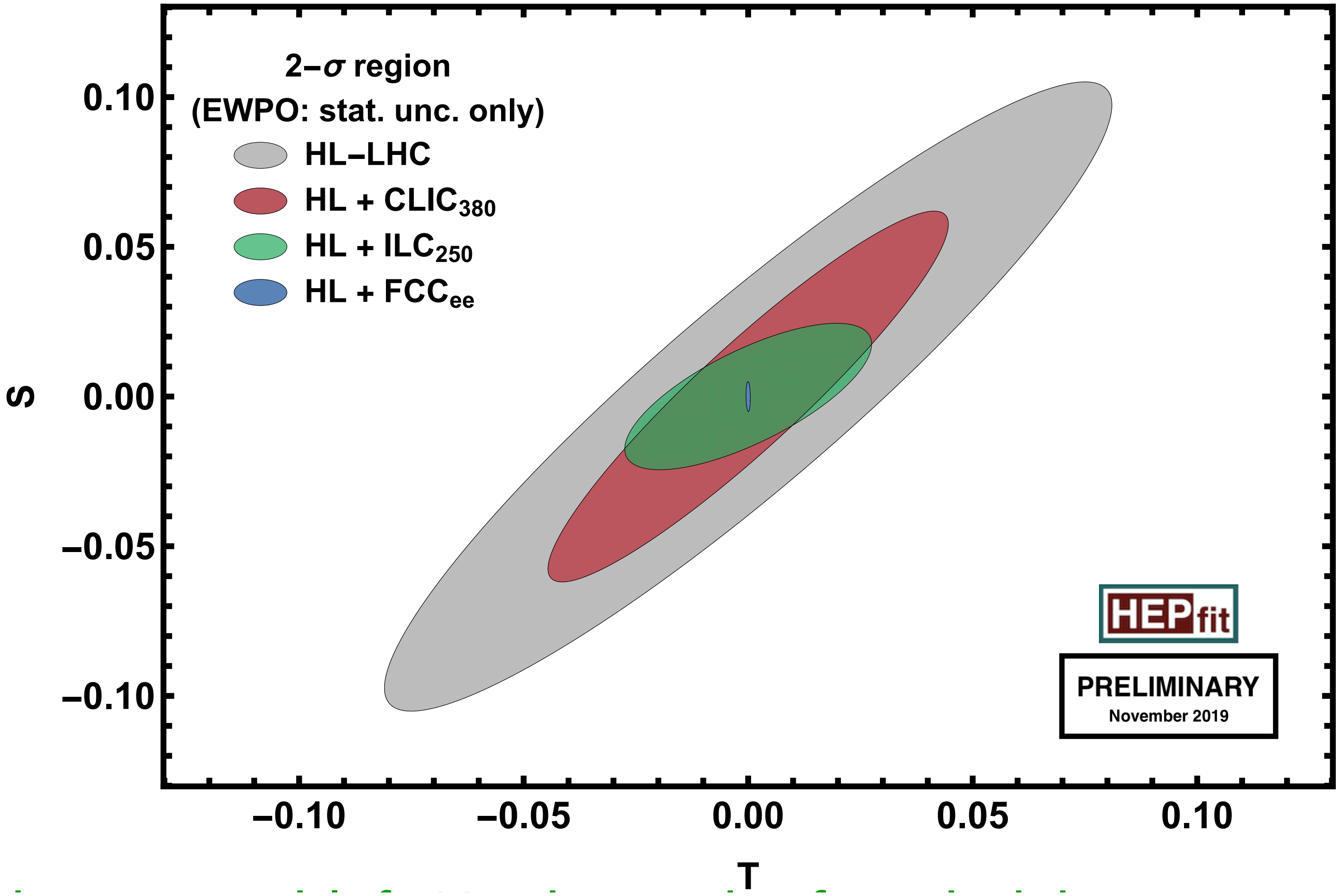
2) reduced parametric uncertainties for other measurements

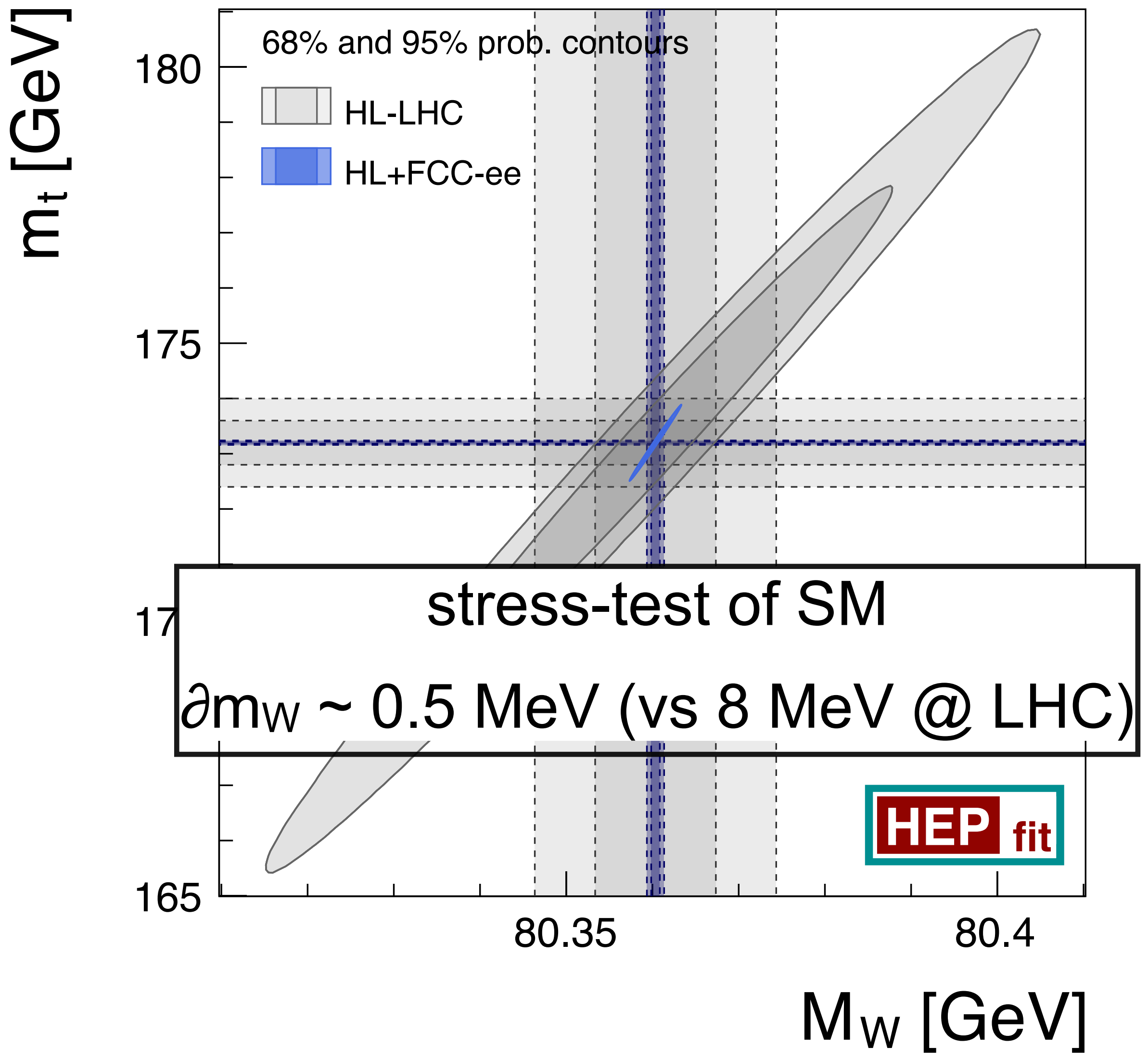
3) reduced degeneracies in a global fit for Higgs couplings

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. and param. only





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~10^{-2} → M~70 TeV)
2) reduced parametric uncertainties for other measurements
3) reduced degeneracies in a global fit for Higgs couplings

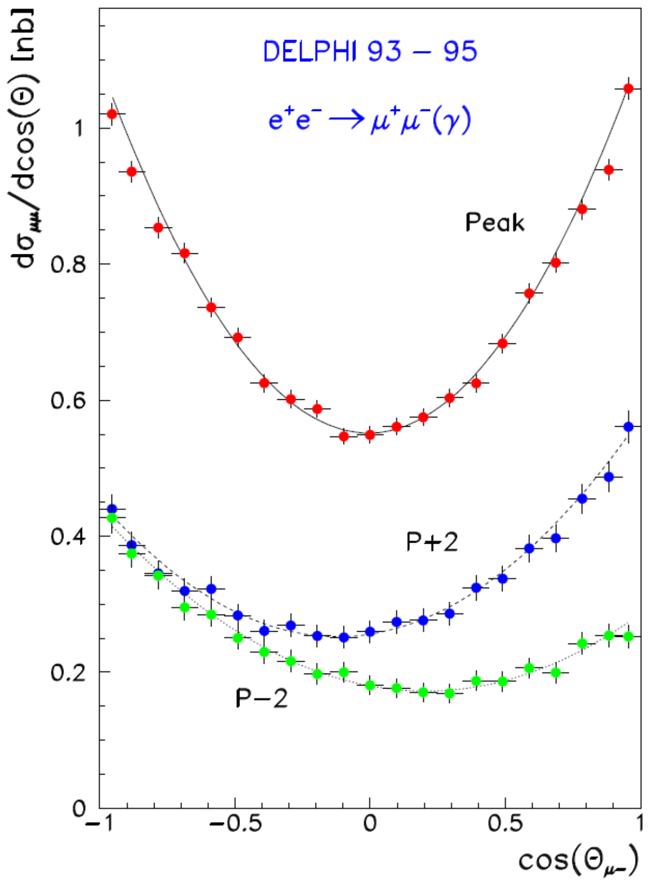
Example of EW measurements @ Tera Z

G. Wilkinson @ FCC week 2021

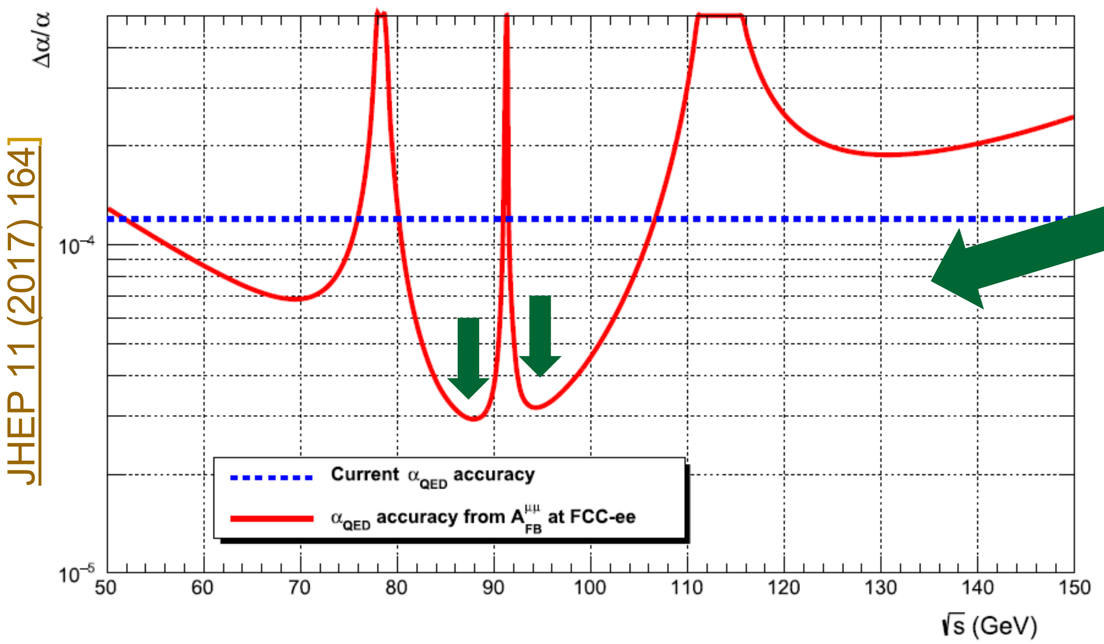
Excellent experimental control of off-peak di-muon asymmetry motivates campaign to collect 50-80 ab^{-1} off peak to gain highest sensitivity to Z-γ interference

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

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}



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.

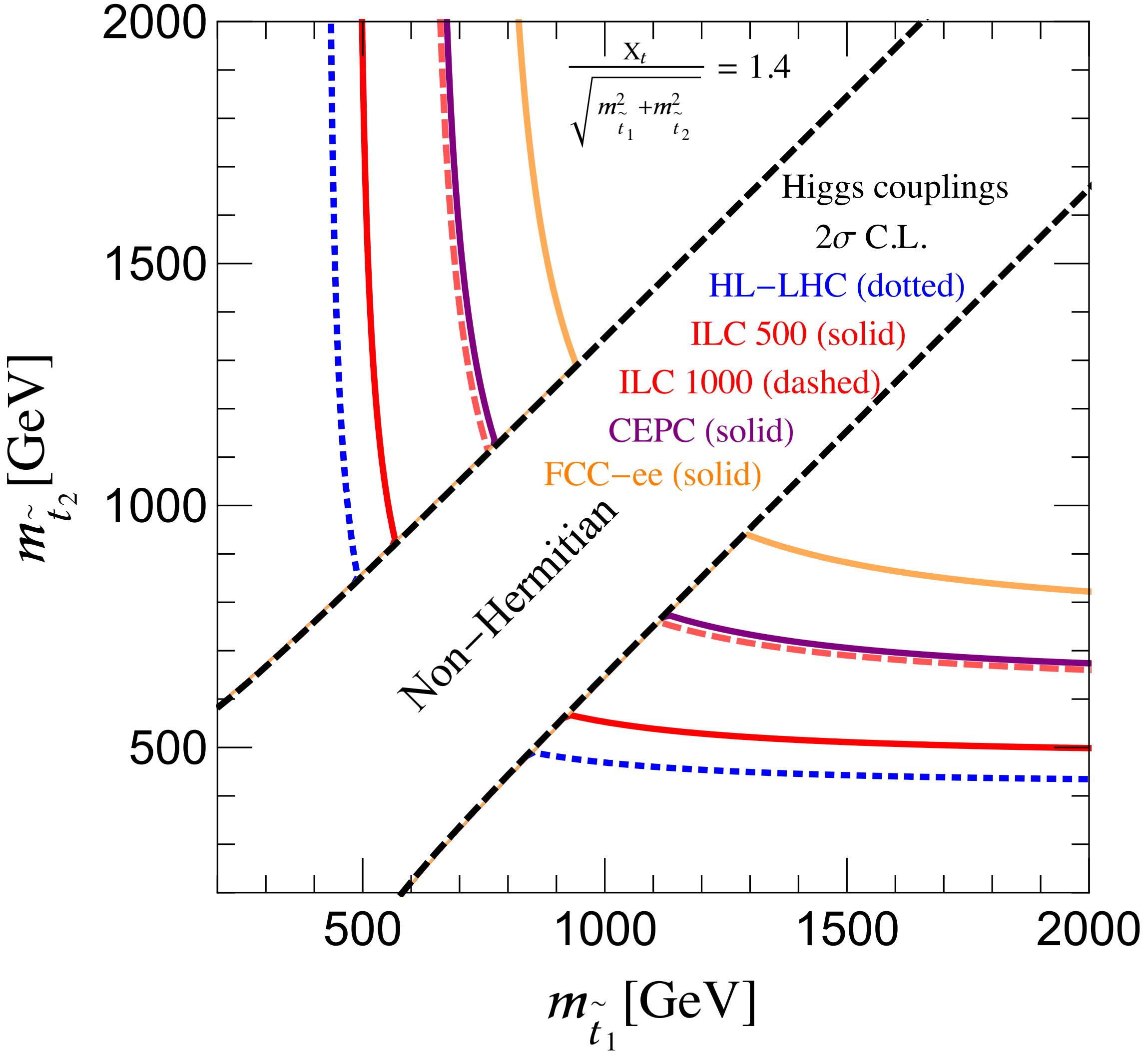
Goal: measure $1/\alpha_{QED}(m_Z^2)$ to +/- 0.003.

Discovery Potential Beyond LHC

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

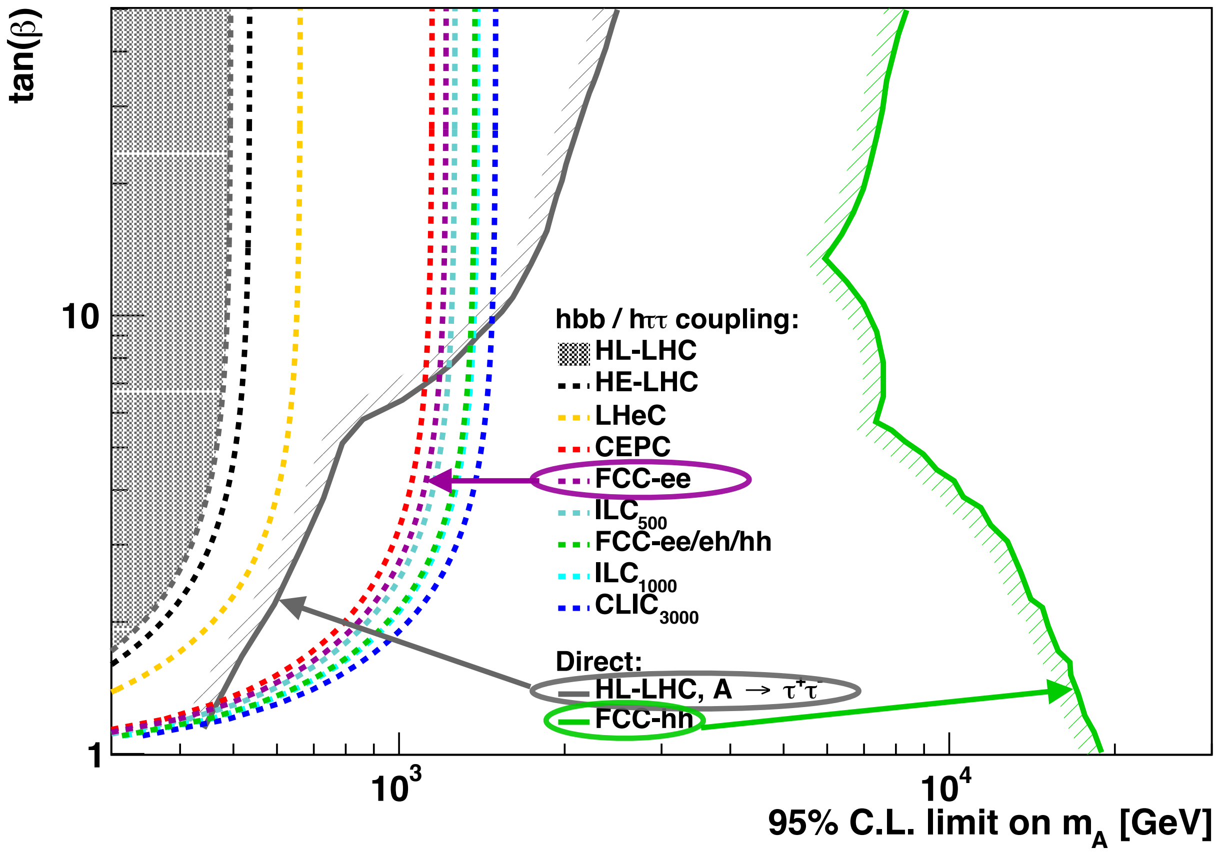
Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY

stops



Fan, Reece, Wang '14

Heavy neutral Higgses

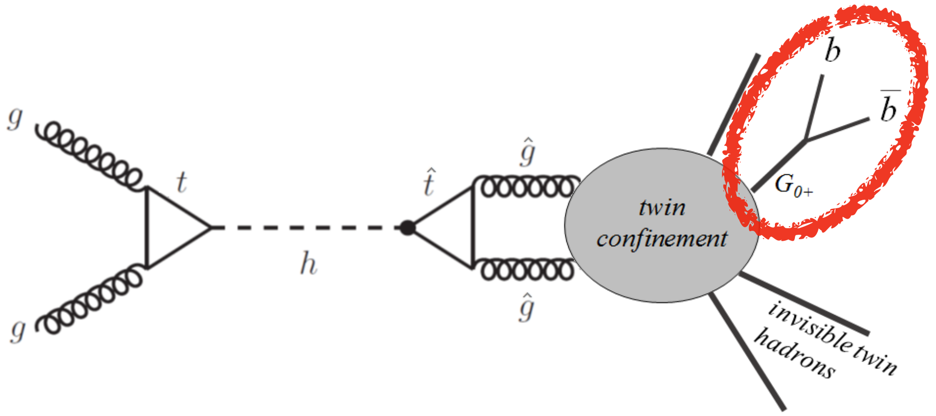


ESU Physics BB '19

Direct Searches for 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

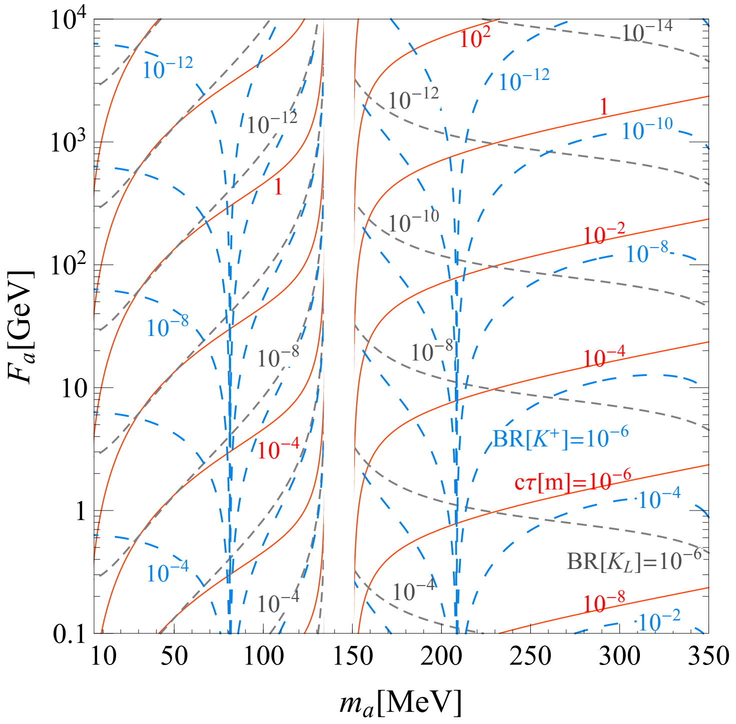
Craig et al, arXiv:1501.05310



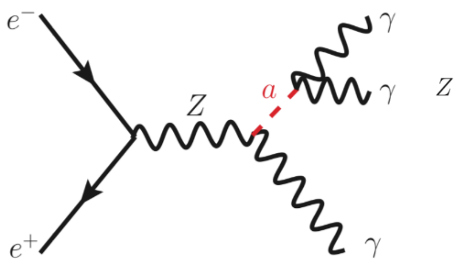
- **Rare decays** Gori et al arXiv:2005.05170
  e.g. ALP mixing w/ SM mesons:

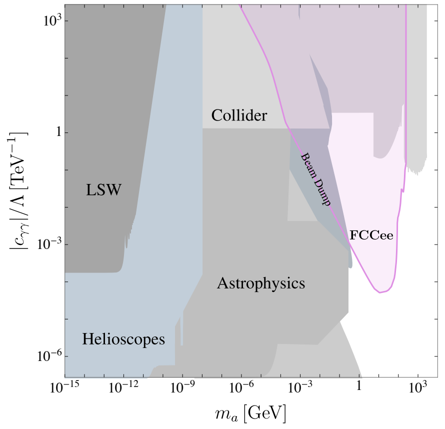
$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \text{ (KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \text{ (NA62)}$$

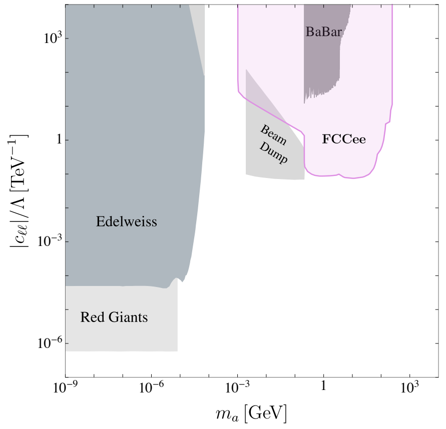
$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu} \tilde{G}^{\mu\nu}$$



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





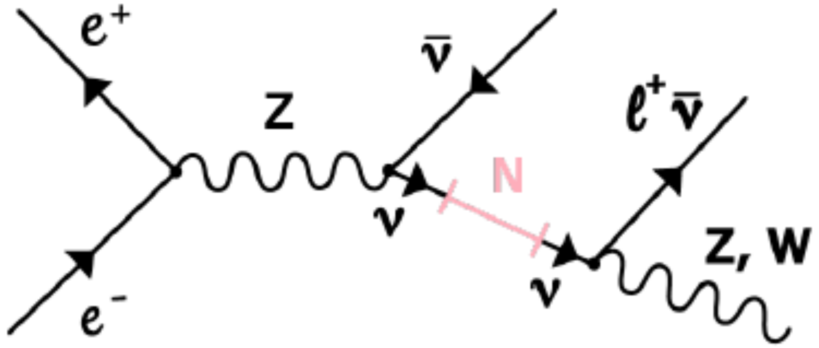


Knapen, Thamm arXiv:2108.08949

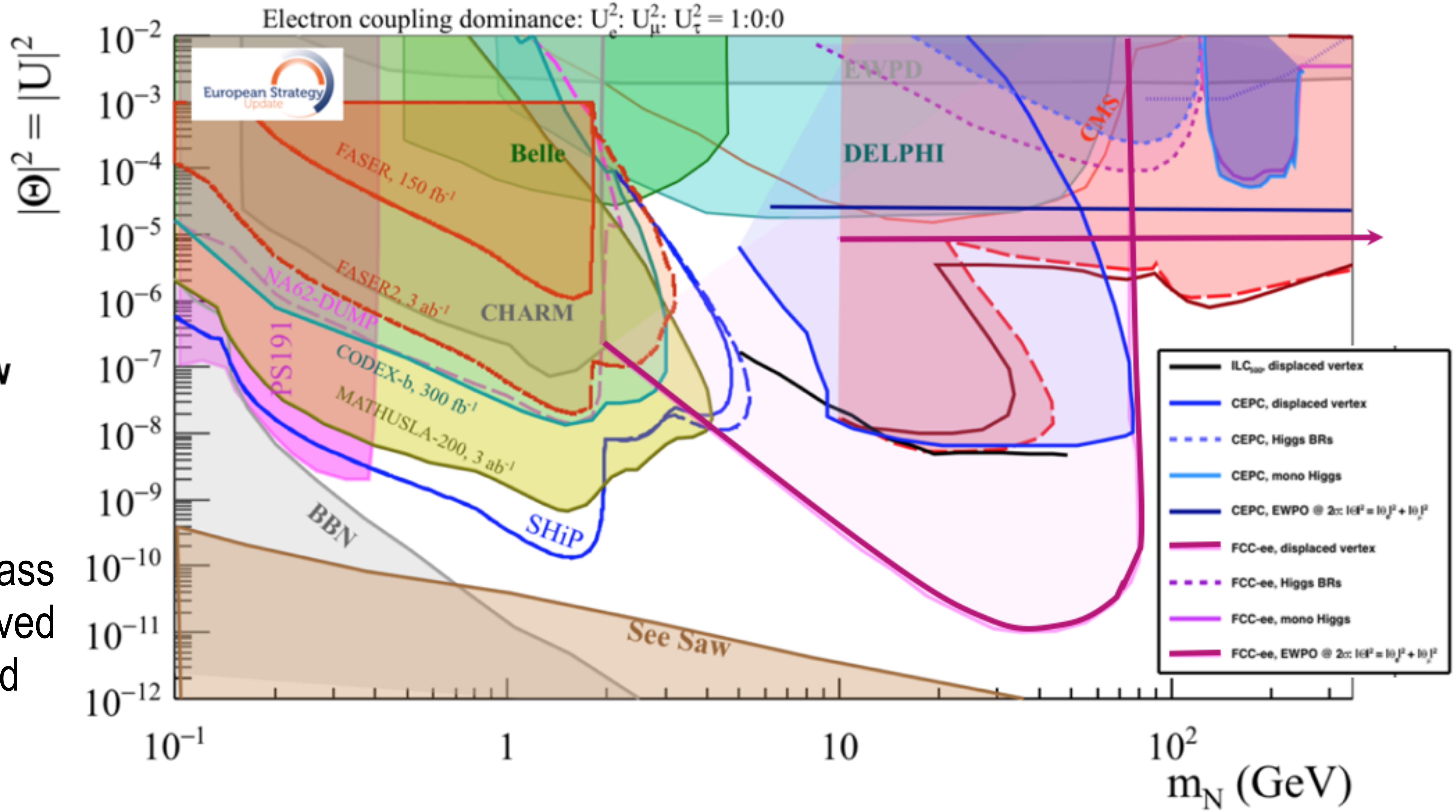
Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

Search for ν_{RH}

Direct observation
in Z decays
from LH-RH mixing



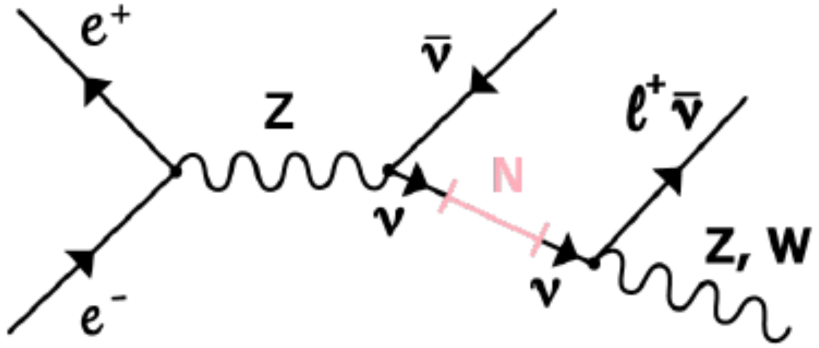
Important to understand
1. how neutrinos acquired mass
2. if lepton number is conserved
3. if leptogenesis is realised



ESU Physics BB '19

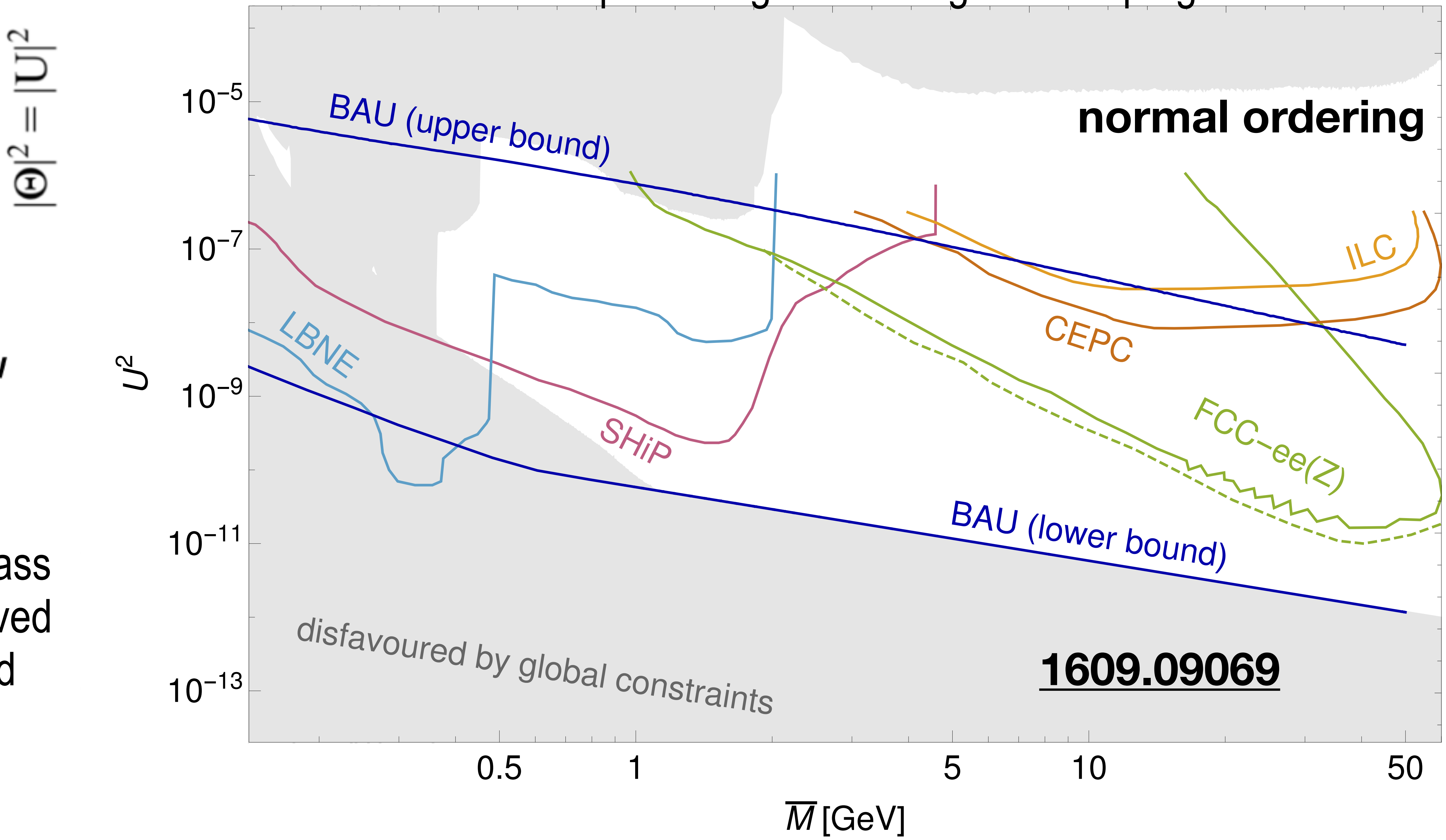
Search for ν_{RH}

Direct observation
in Z decays
from LH-RH mixing



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

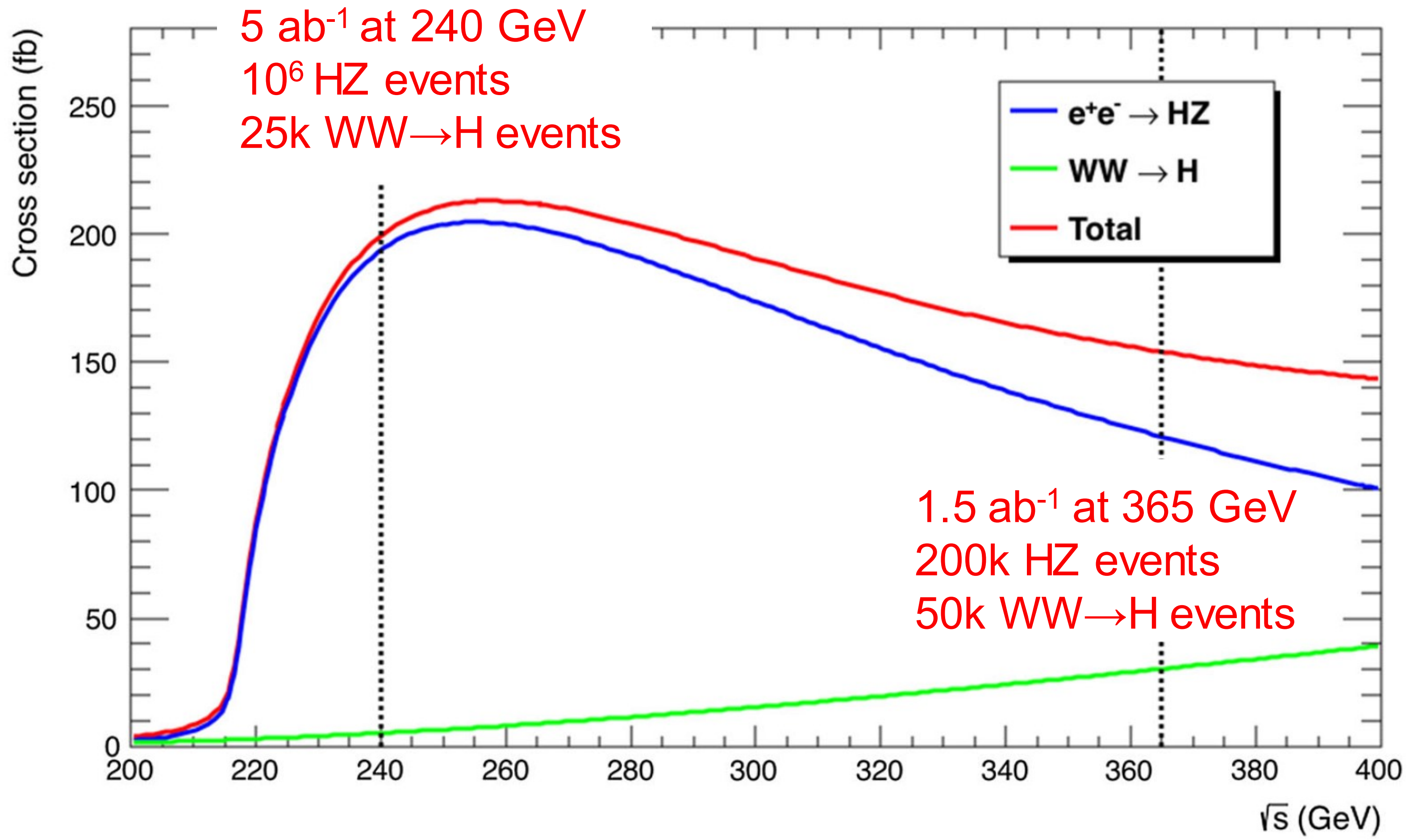
FCC-ee can probe large viable regions of leptogenesis



Higgs @ FCC-ee

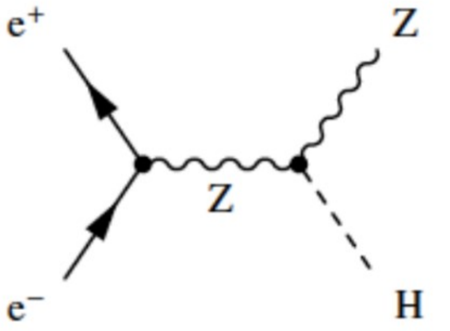
Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)% precision. Achieved through operation at two energy points.

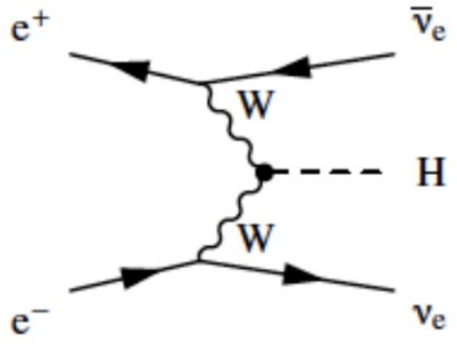
G. Wilkinson, FCC Physics WS '22



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.

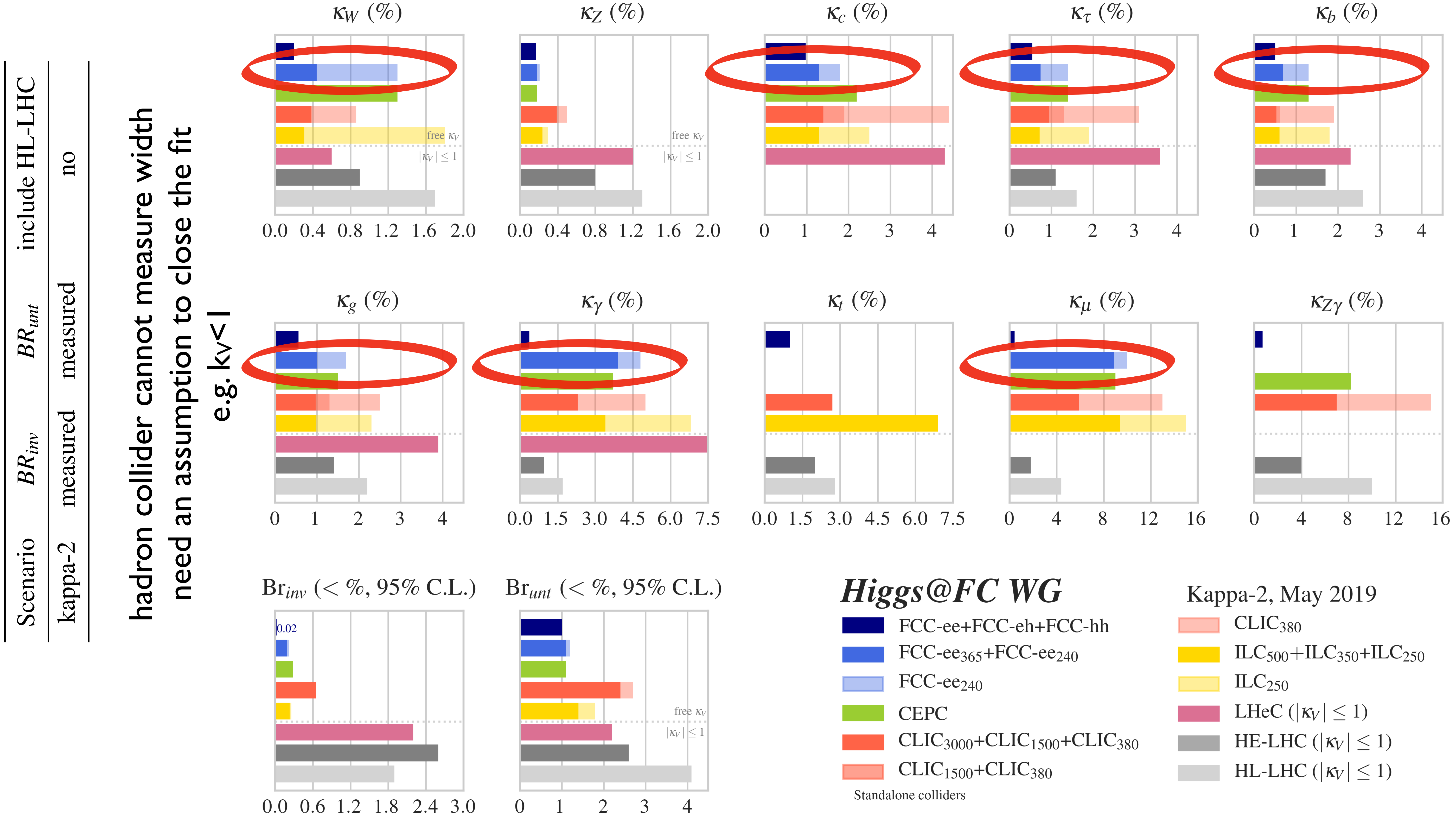
Table 8: Operation costs of low-energy Higgs factories, expressed in Euros per Higgs boson.

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



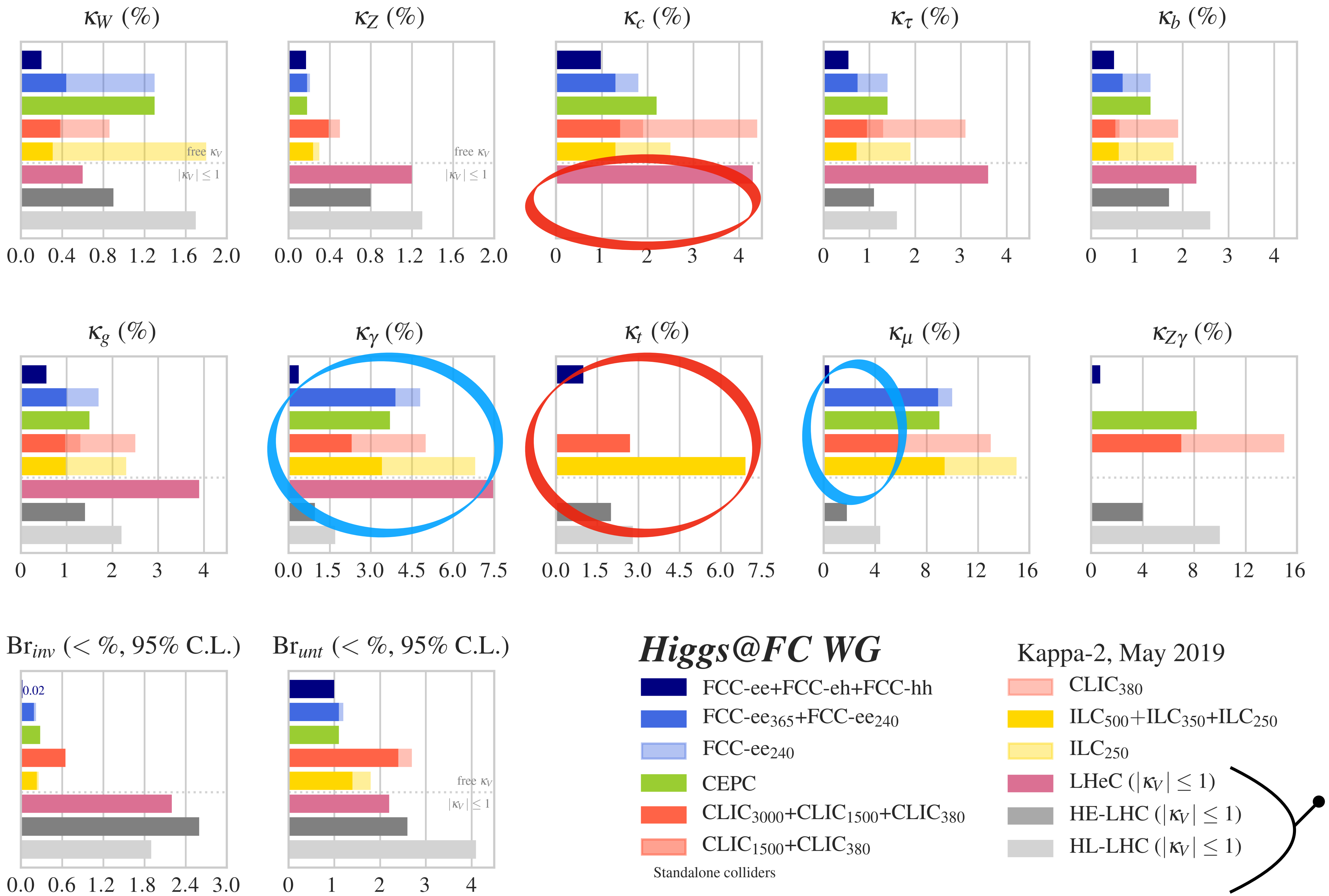
hadron collider cannot measure width
need an assumption to close the fit
e.g. $\kappa_V<1$

Higgs @ FCC-ee: Complementarity with HL-LHC

ECFA Higgs study group ‘19

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

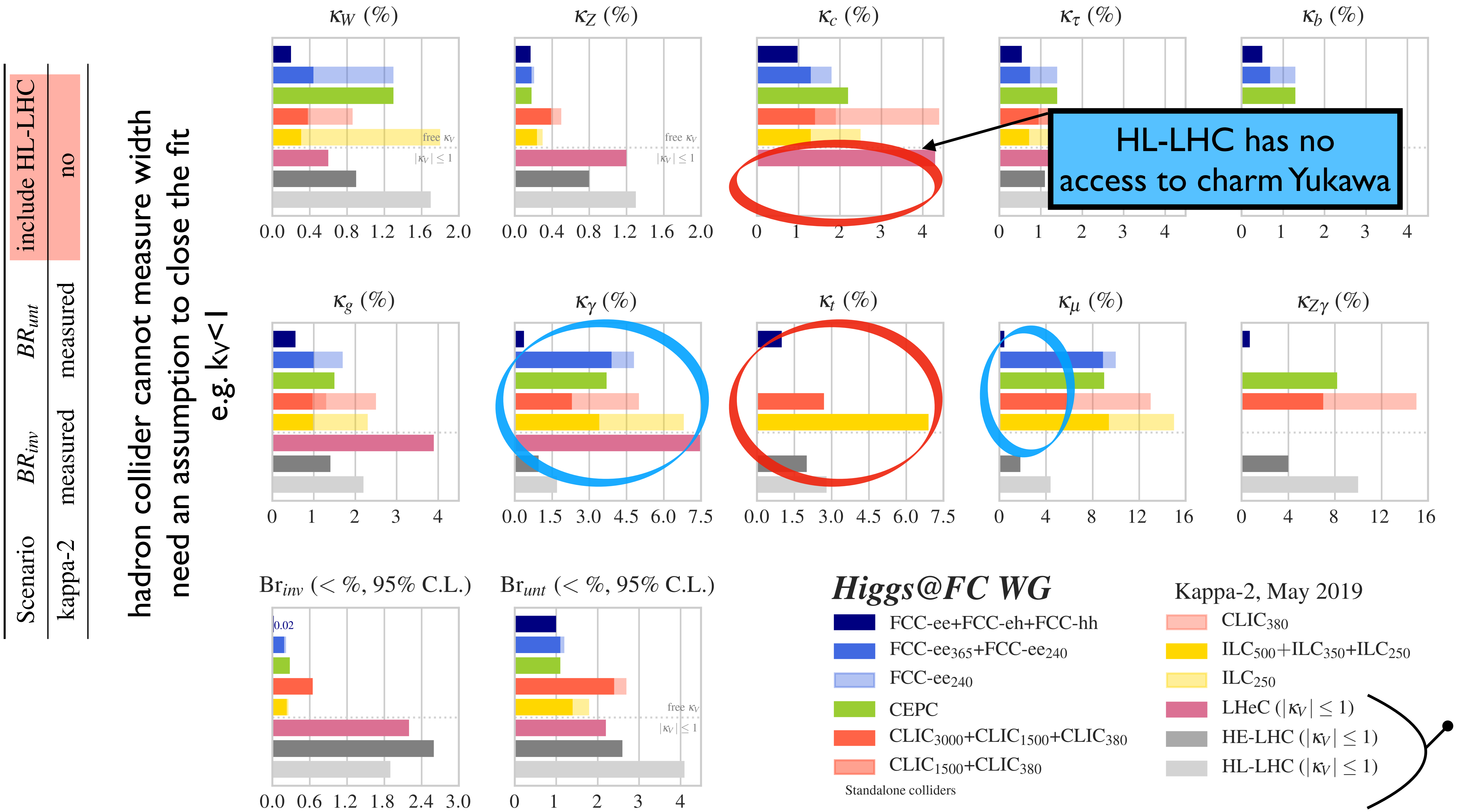
hadron collider cannot measure width
need an assumption to close the fit
e.g. $\kappa_V<1$



assumption needed for the fit to close at hadron machines

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

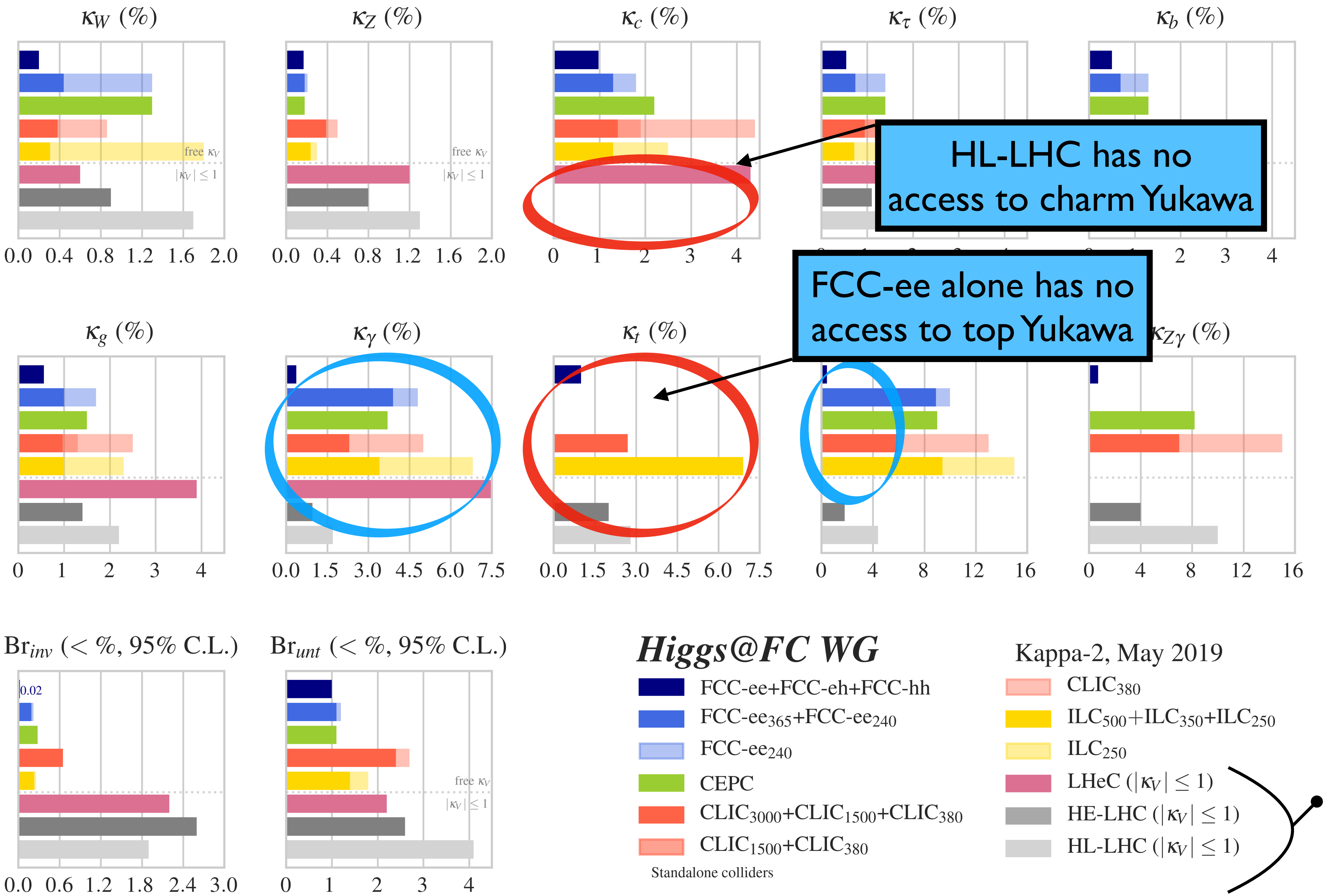
assumption needed for the fit to close at hadron machines

Higgs @ FCC-ee: Complementarity with HL-LHC

ECFA Higgs study group '19

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

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



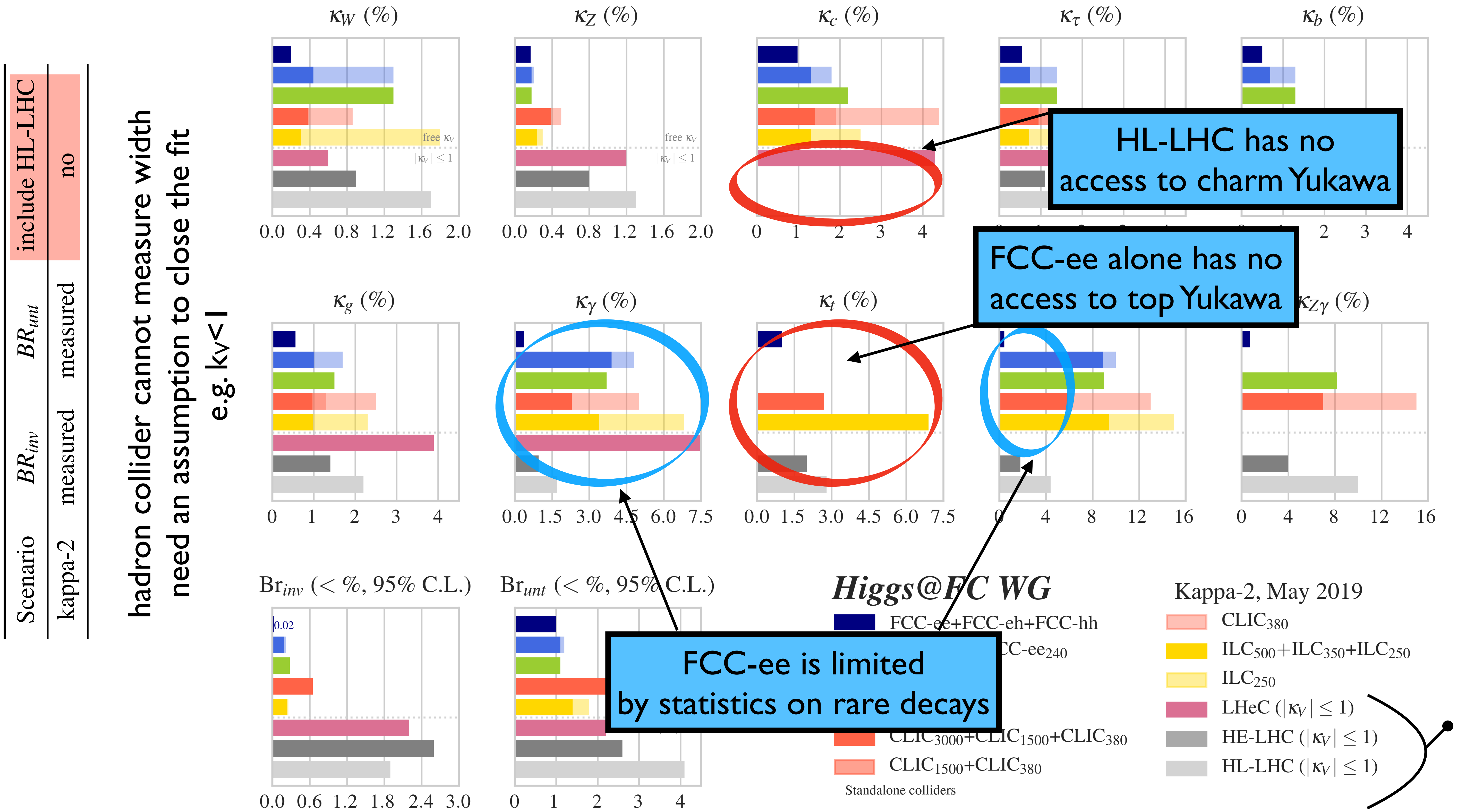
HL-LHC has no access to charm Yukawa

FCC-ee alone has no access to top Yukawa

assumption needed for the fit to close at hadron machines

Higgs @ FCC-ee: Complementarity with HL-LHC

ECFA Higgs study group '19



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

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

HL-LHC has no access to charm Yukawa

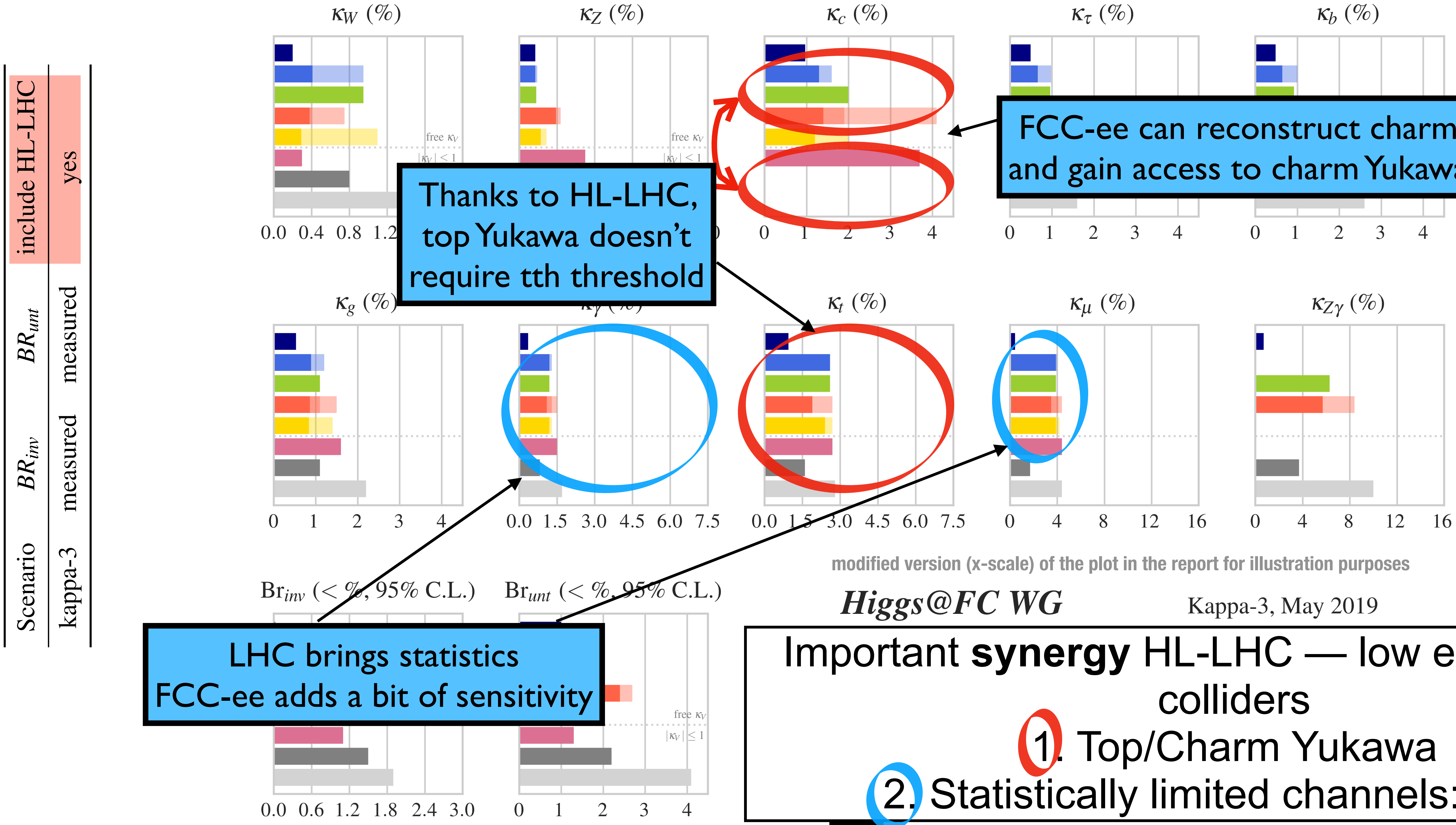
FCC-ee alone has no access to top Yukawa

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



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

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

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

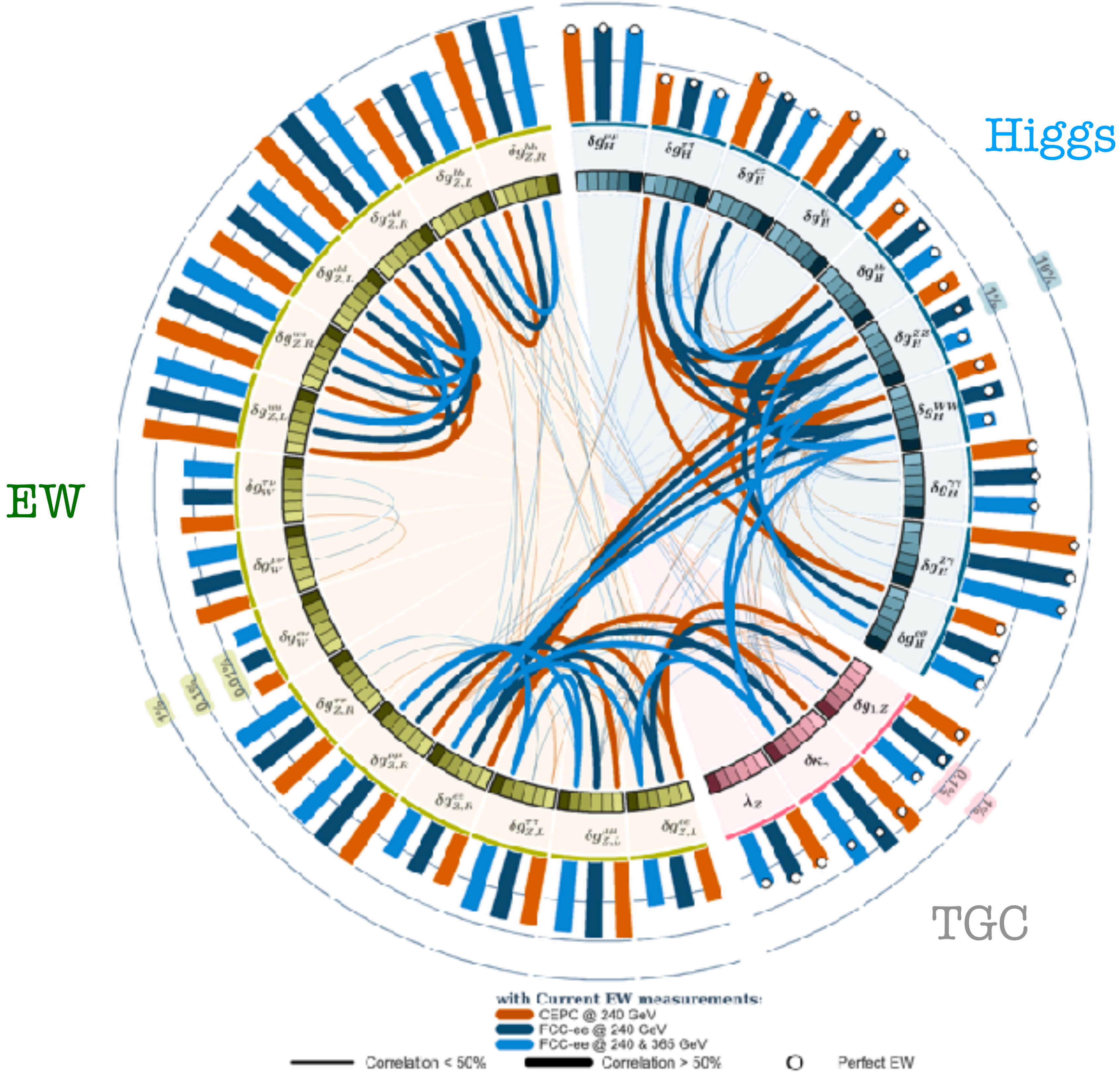
LHC brings statistics
FCC-ee adds a bit of sensitivity

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

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

Impact of Z-pole Measurements

J. De Blas et al. 1907.04311

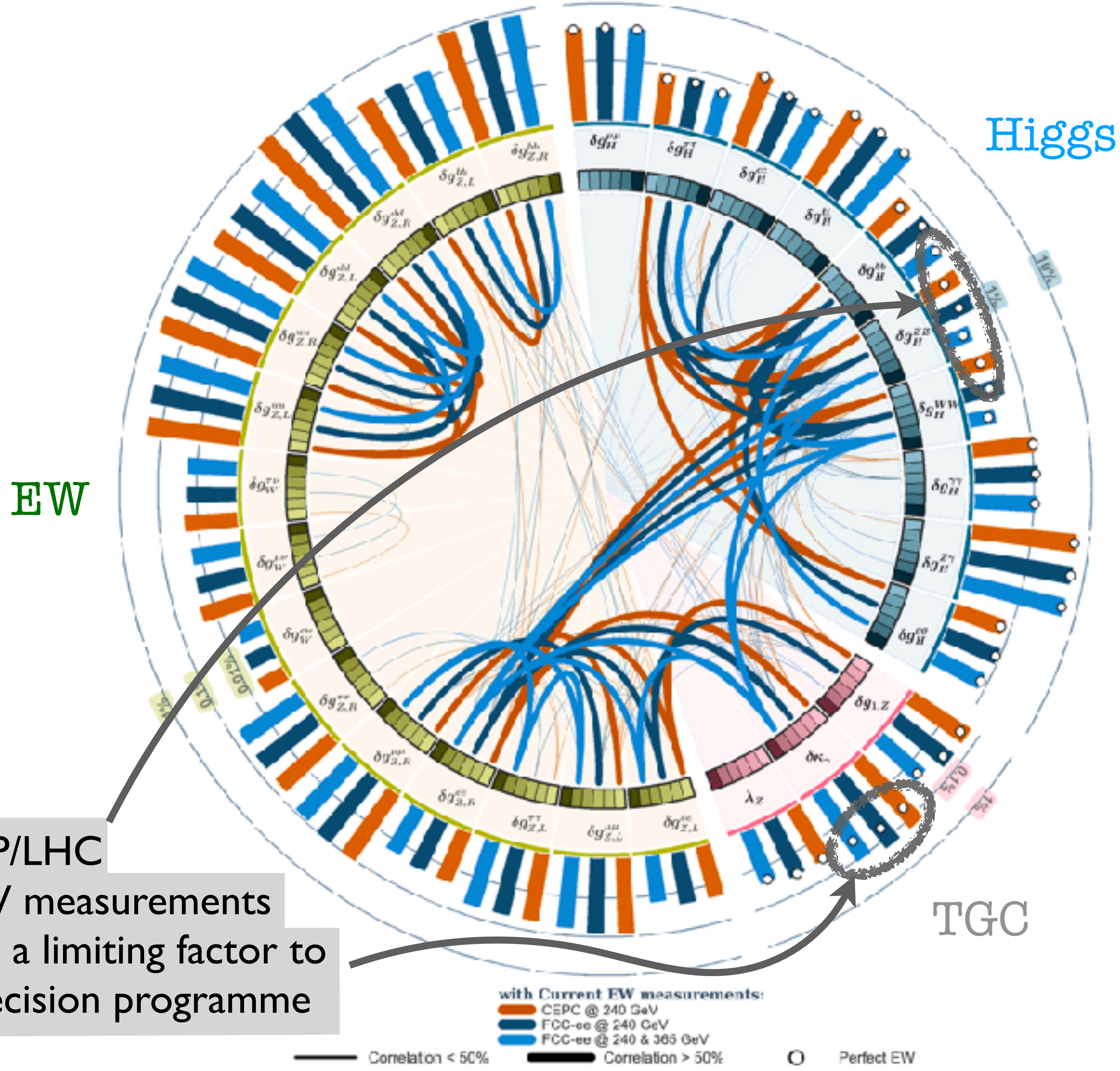


Contamination EW/TGC/Higgs can be understood by looking at correlations

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

Impact of Z-pole Measurements

J. De Blas et al. 1907.04311



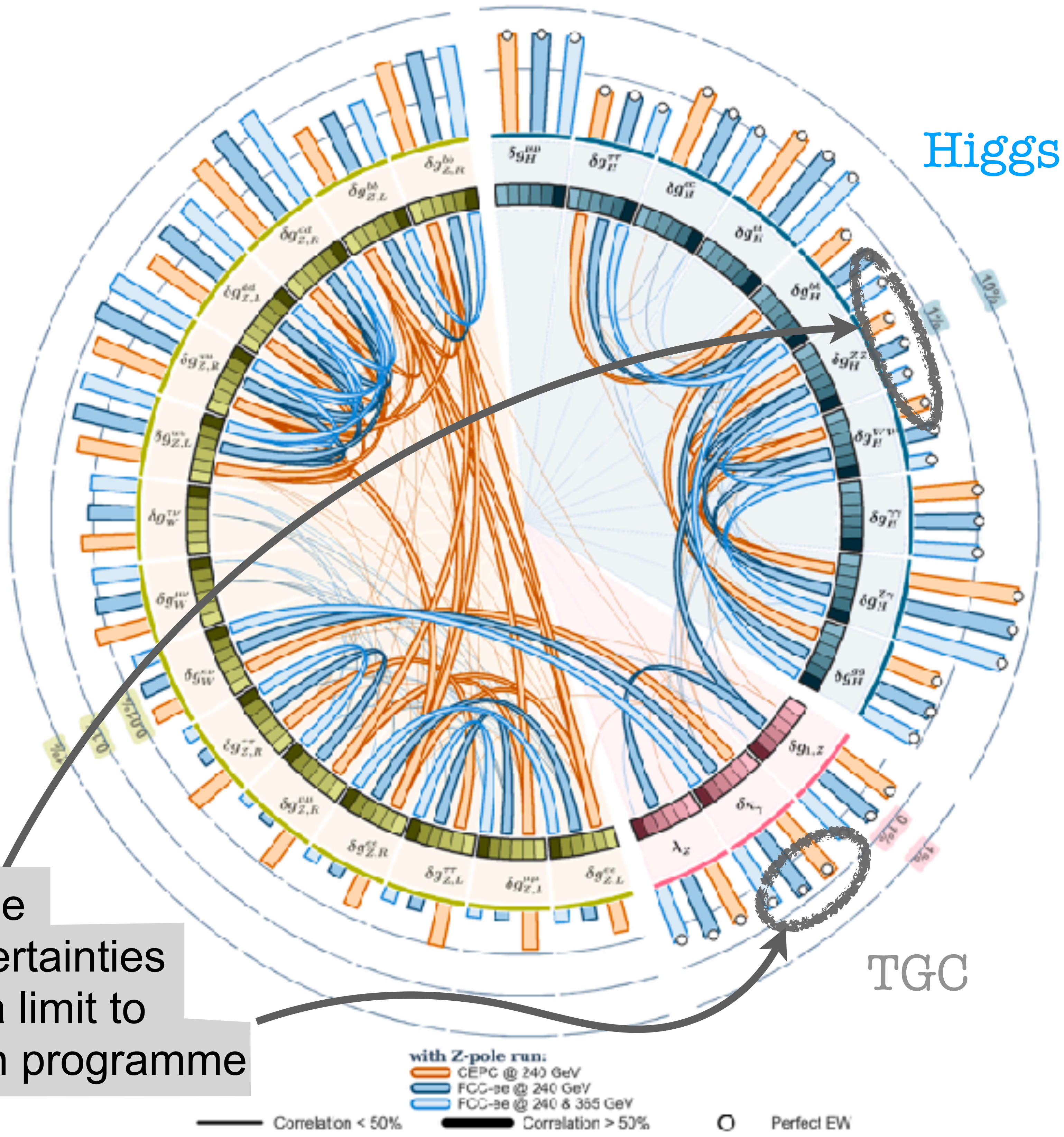
Contamination EW/TGC/Higgs can be understood by looking at correlations

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



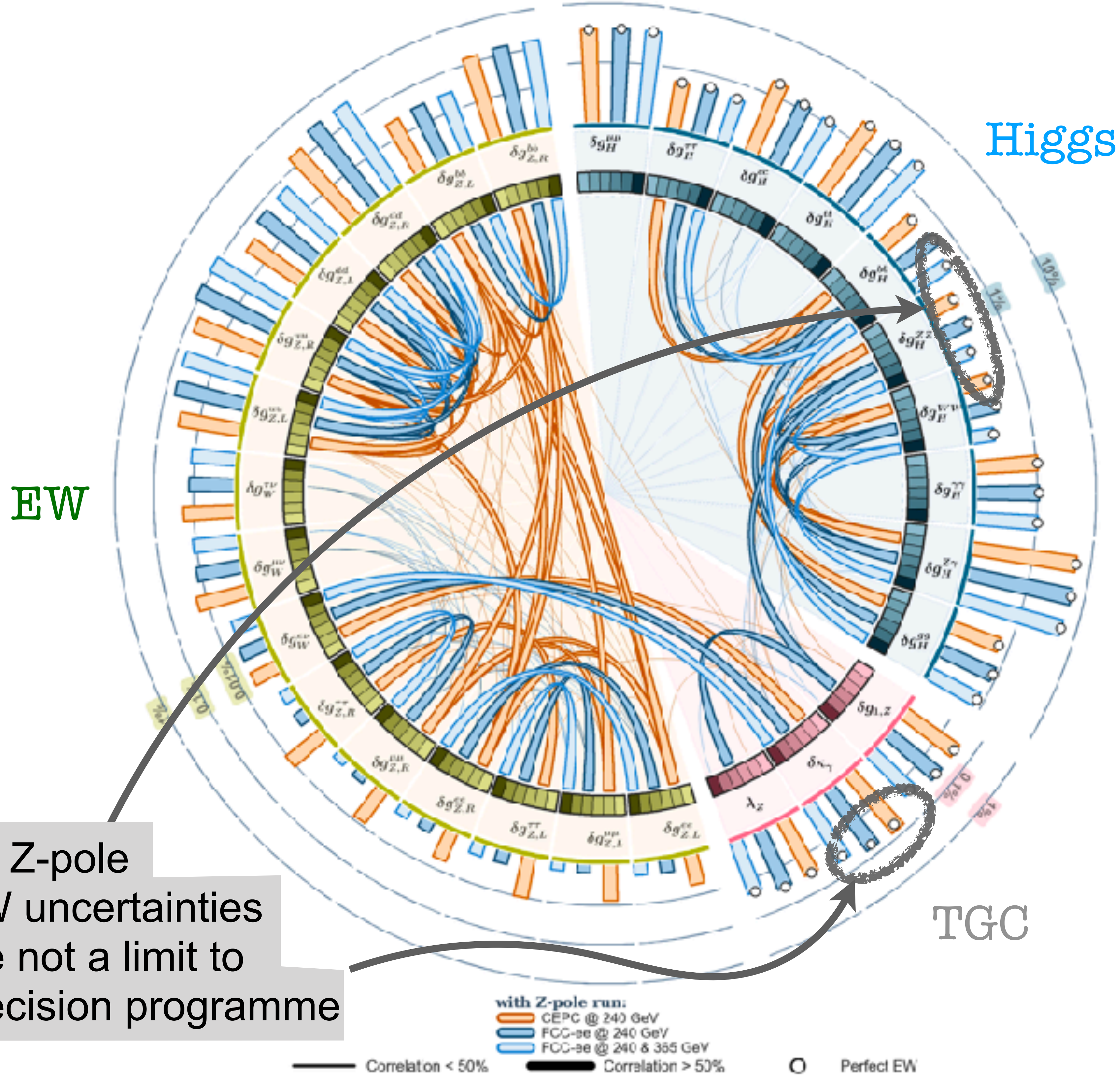
Contamination EW/TGC/Higgs can be understood by looking at correlations

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

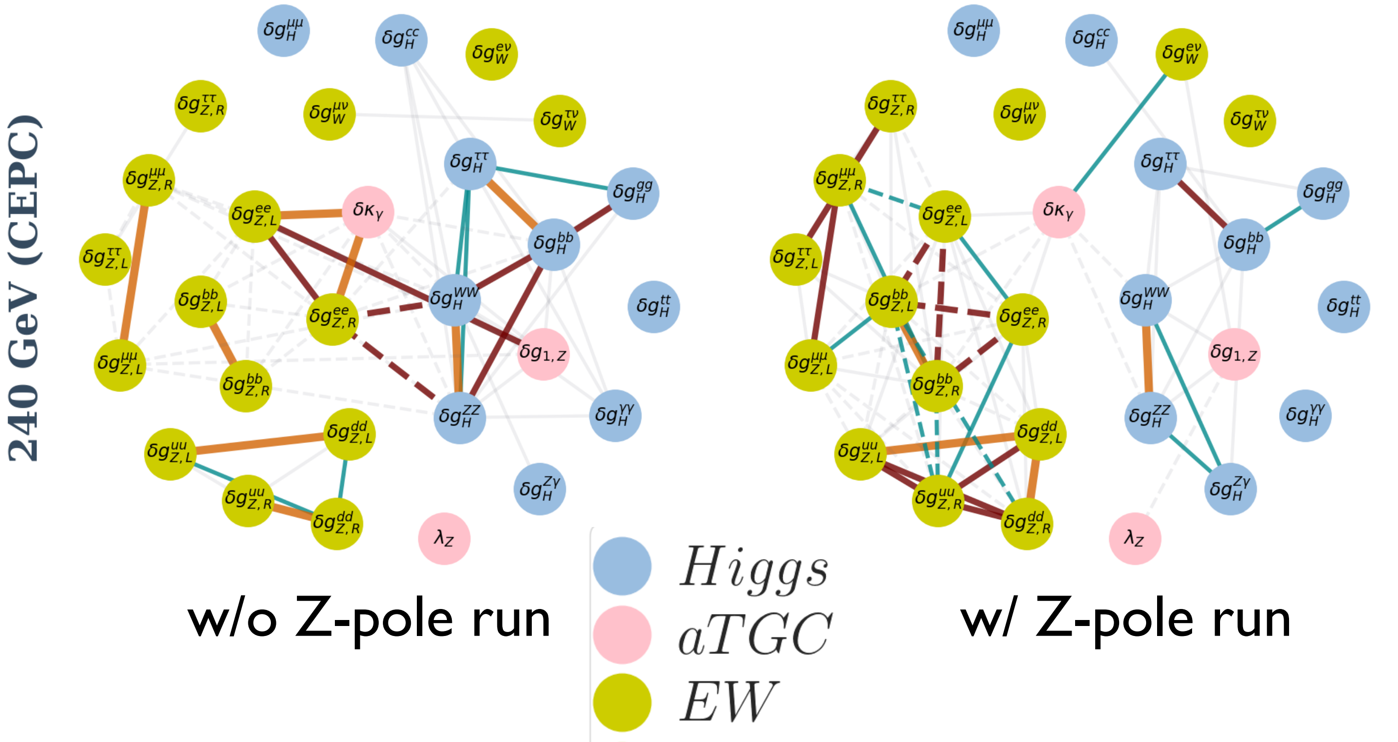
J. De Blas et al. 1907.04311



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

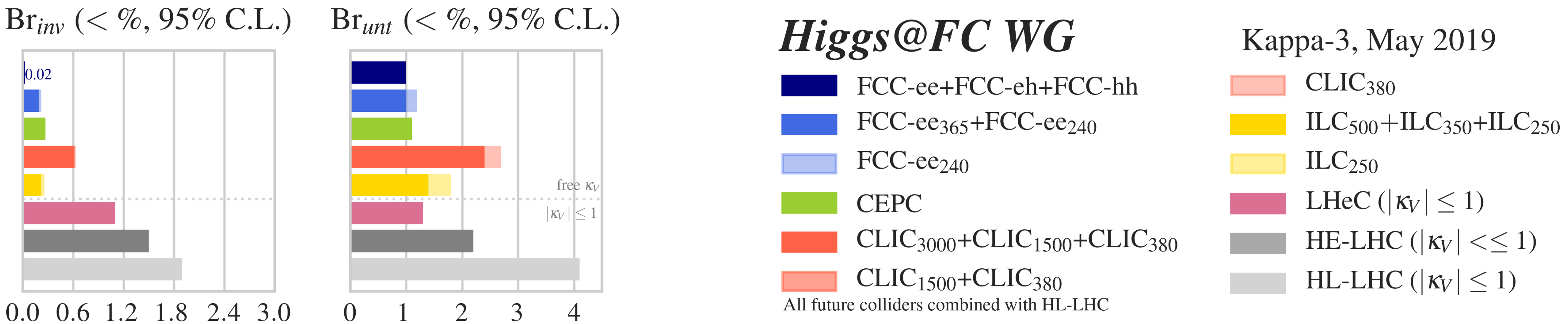


w/o Z-pole run

w/ Z-pole run

Higgs @ FCC-ee: Pivot between LHC and FCC-hh

1

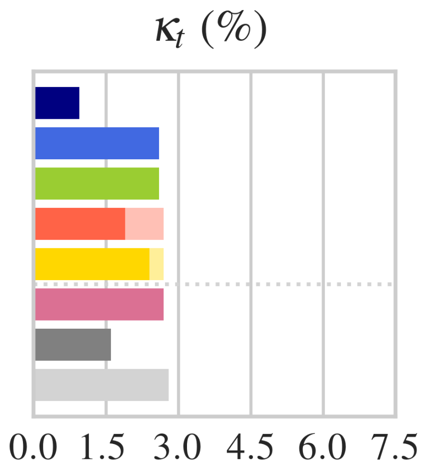


FCC-hh without ee could still bound BR_{inv}

but it could say nothing about BR_{unt}

FCC-ee needed for absolute normalisation of Higgs couplings

2

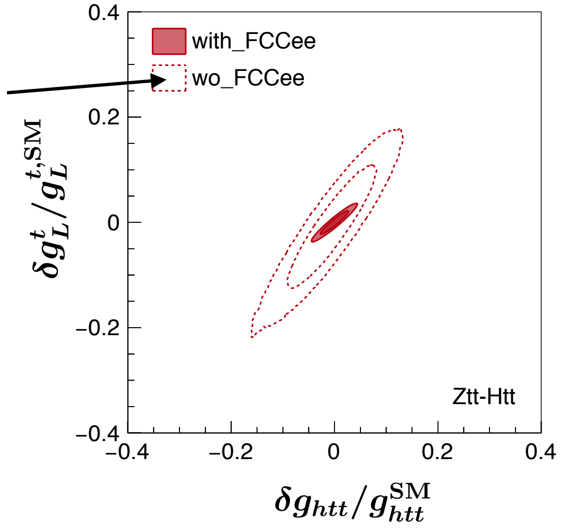


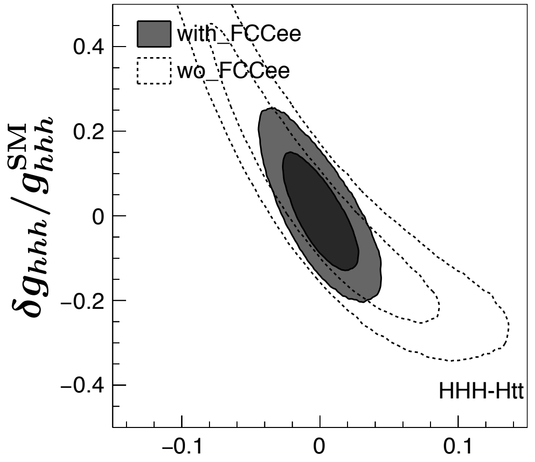
Mangano+ '15

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

	$\sigma(t\bar{t}H)$[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



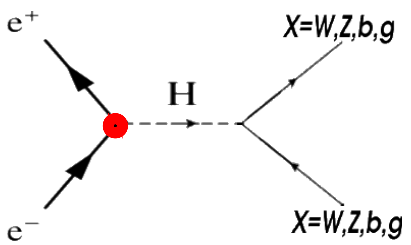


Plots by J. de Blas, '19

3

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

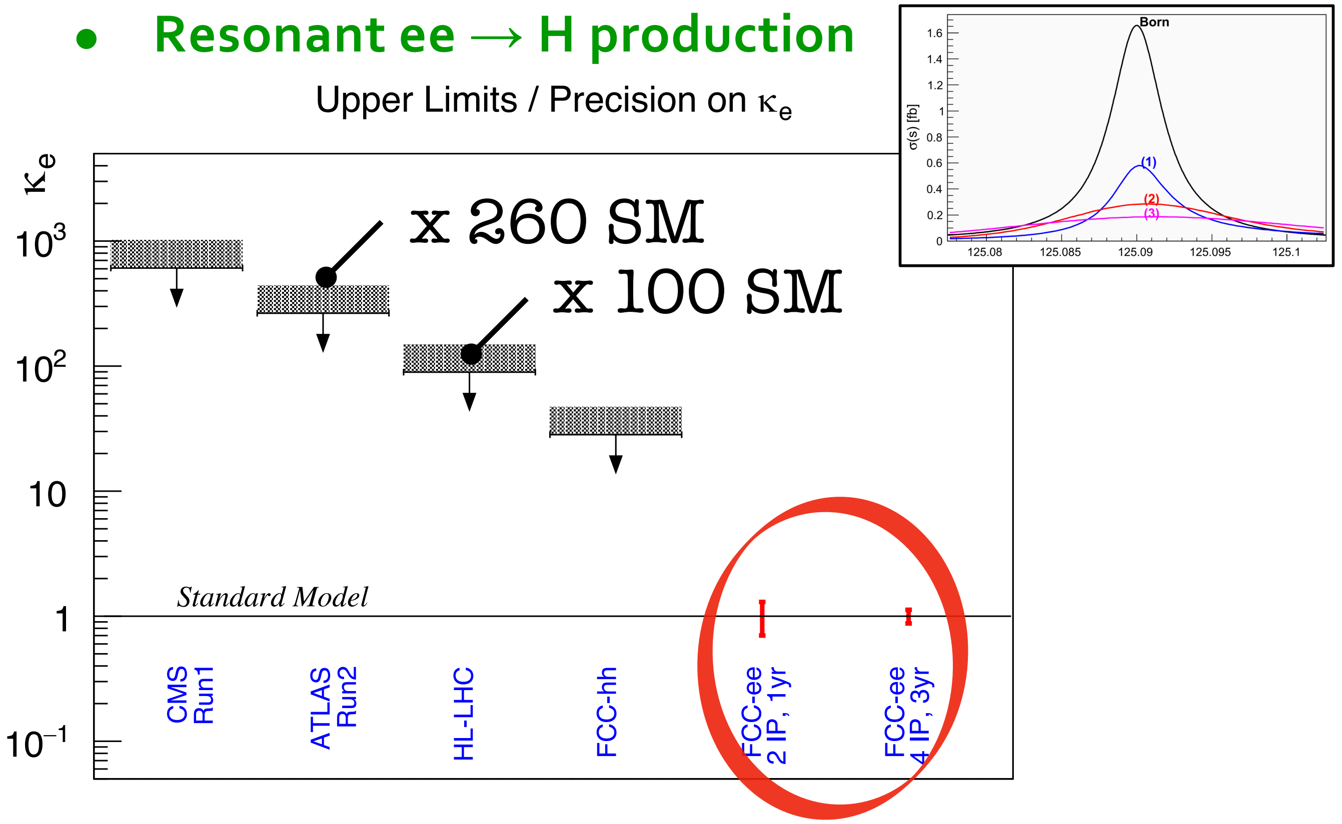
Access to e- Yukawa



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

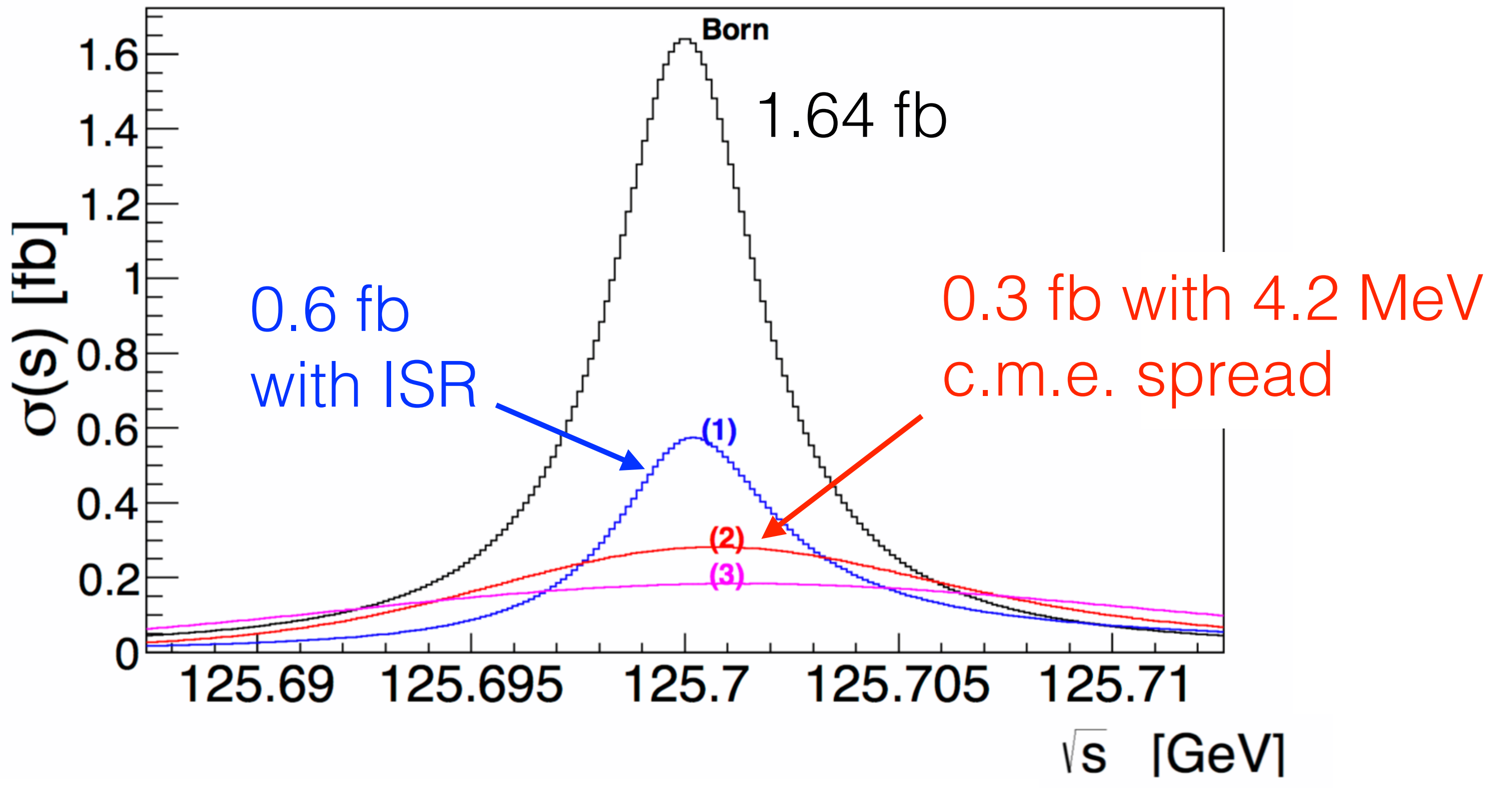
$\sigma_{\text{spread+ISR}}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H)$ = 290 ab

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

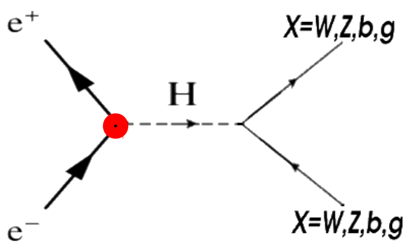


  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Jadach+, arXiv: 1509.02406



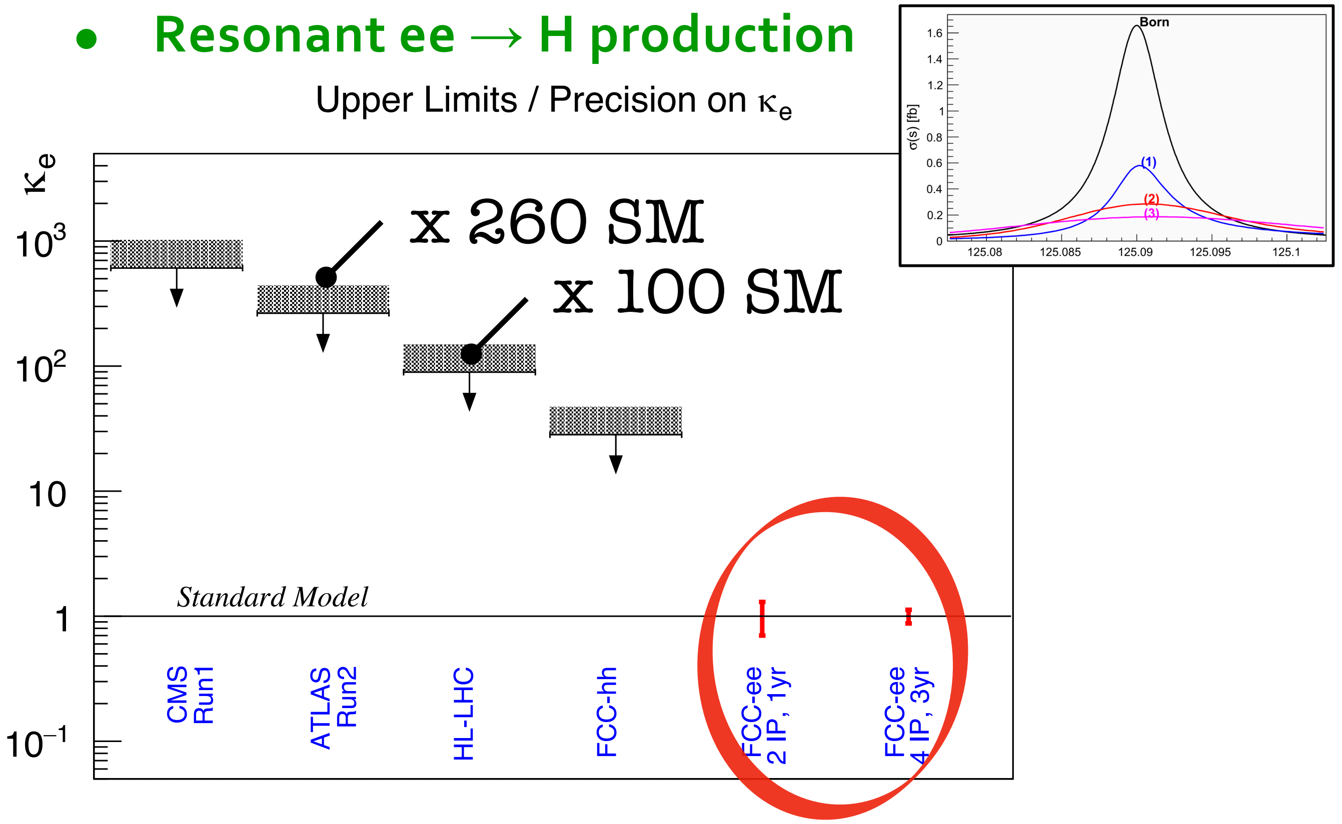
Access to e$^-$ Yukawa



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

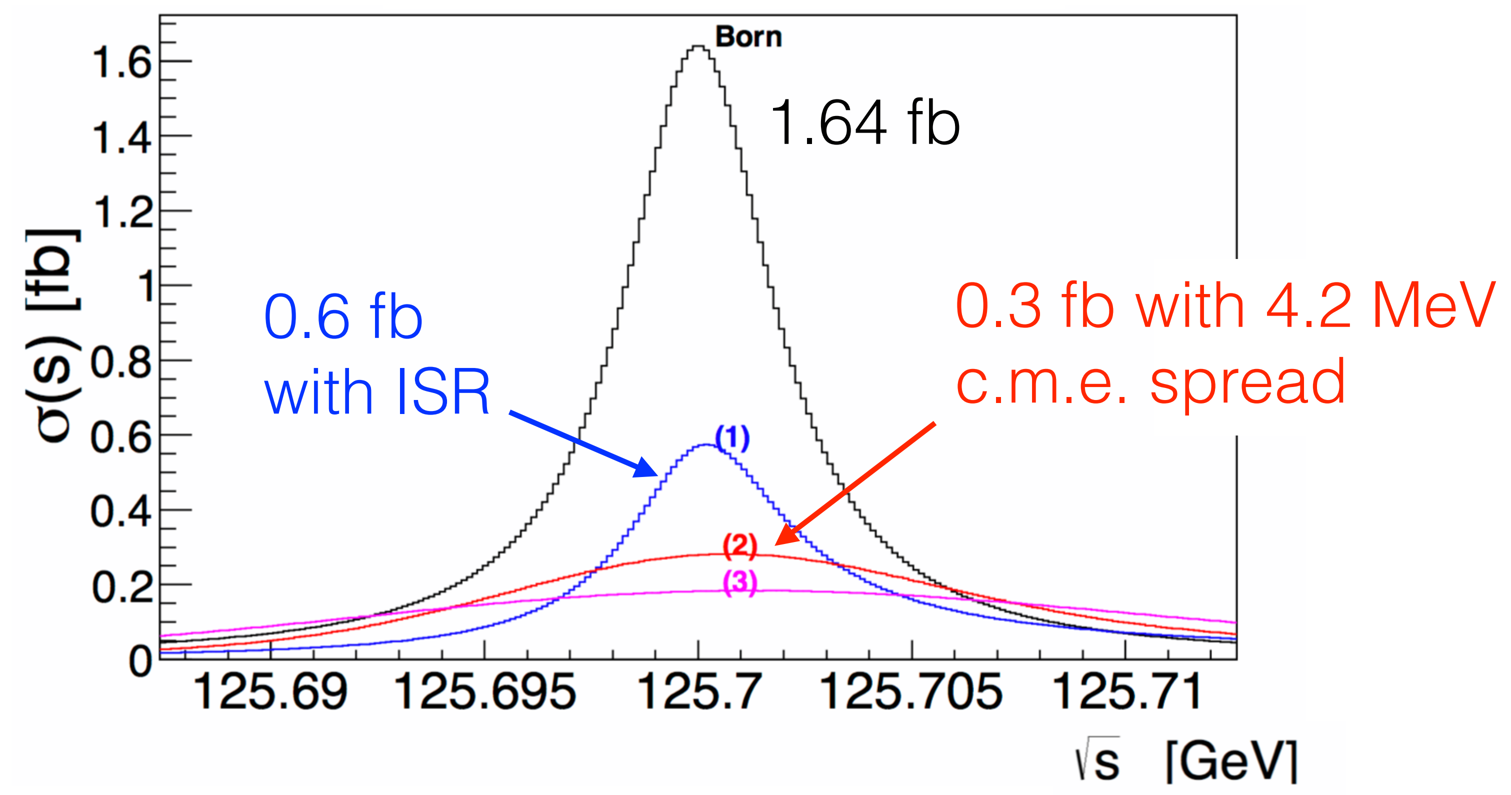
$\sigma_{\text{spread+ISR}}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H) = 290$ ab

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



  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Jadach+, arXiv: 1509.02406

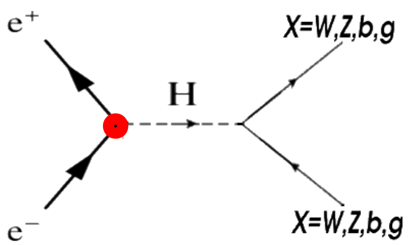


Monochromatisation is essential:

very demanding measurement!
-- requires measurement of ECM boost and ECM spread across the luminous region

-- should be tested at Z pole (more stats)
-- but m_higgs should be known @ < +- 2-4 MeV)
➔ should be run after both the Z pole and the ZH point
➔ request some flexibility in machine settings

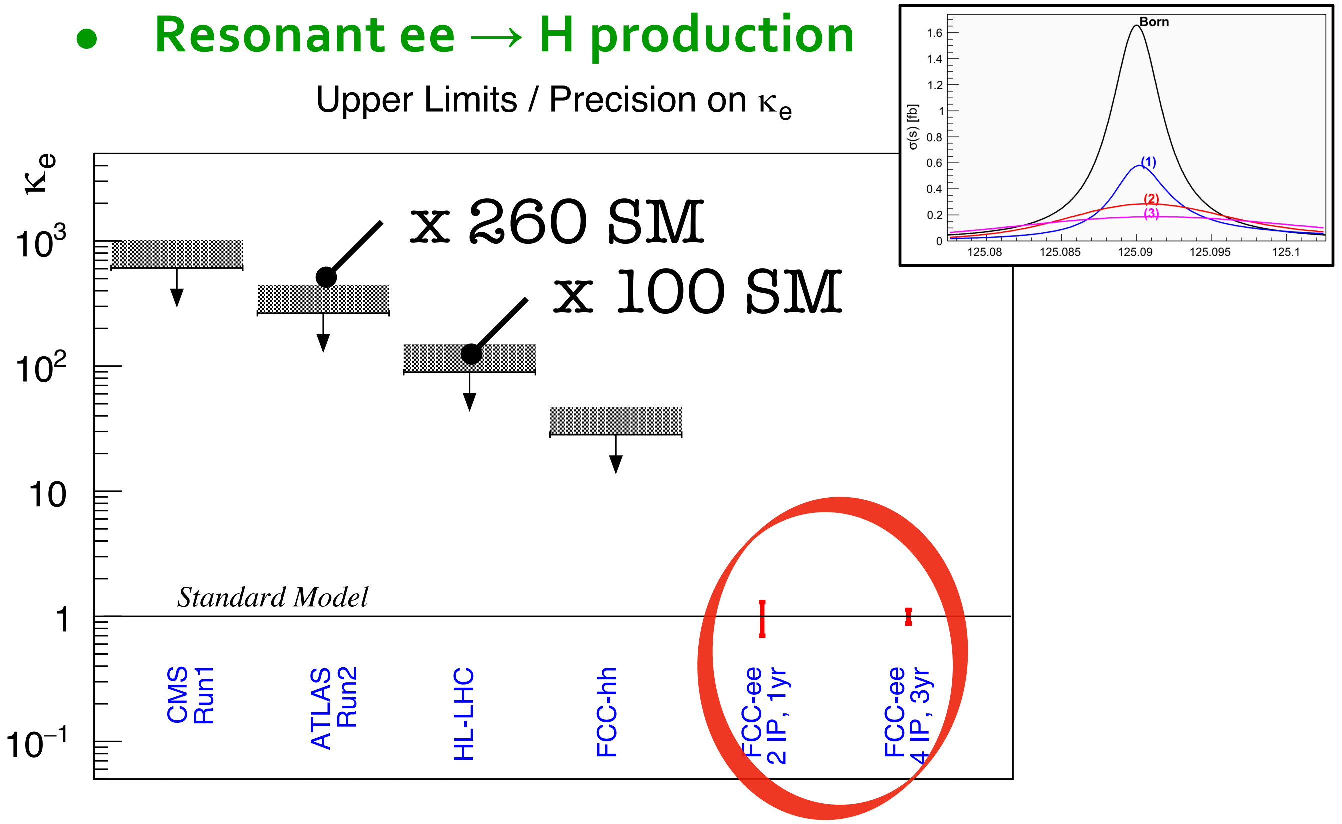
Access to e- Yukawa



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

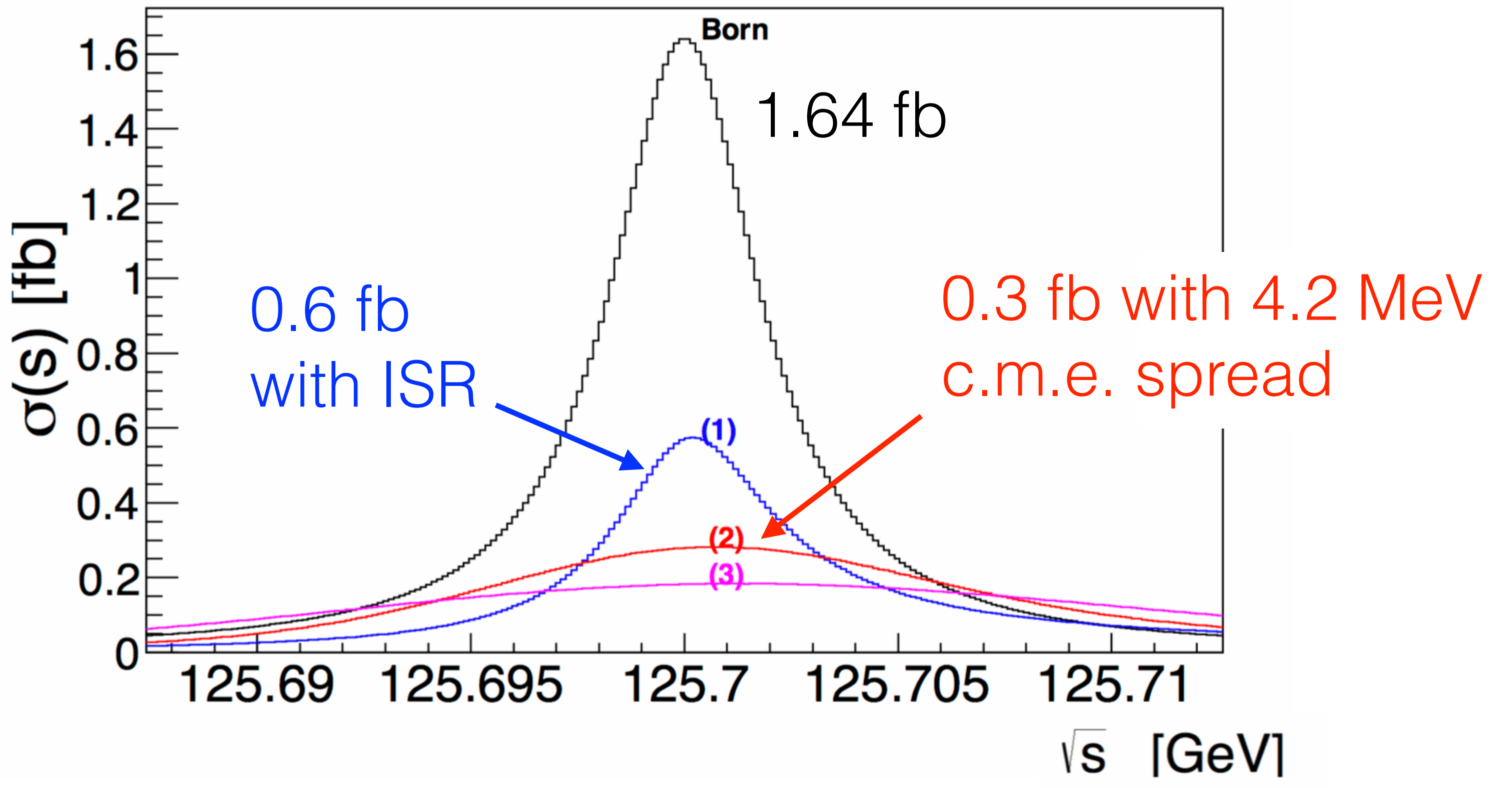
$\sigma_{\text{spread+ISR}}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H) = 290$ ab

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



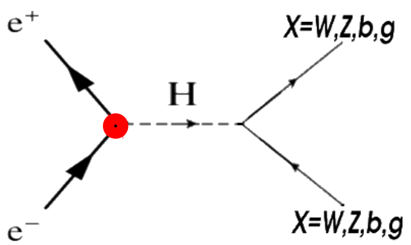
  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Jadach+, arXiv: 1509.02406



Producing these Higgses is not enough.
One needs to "see" them too.
To distinguish them from offshell Z's,
better to look at decays to particles that don't couple to Z's

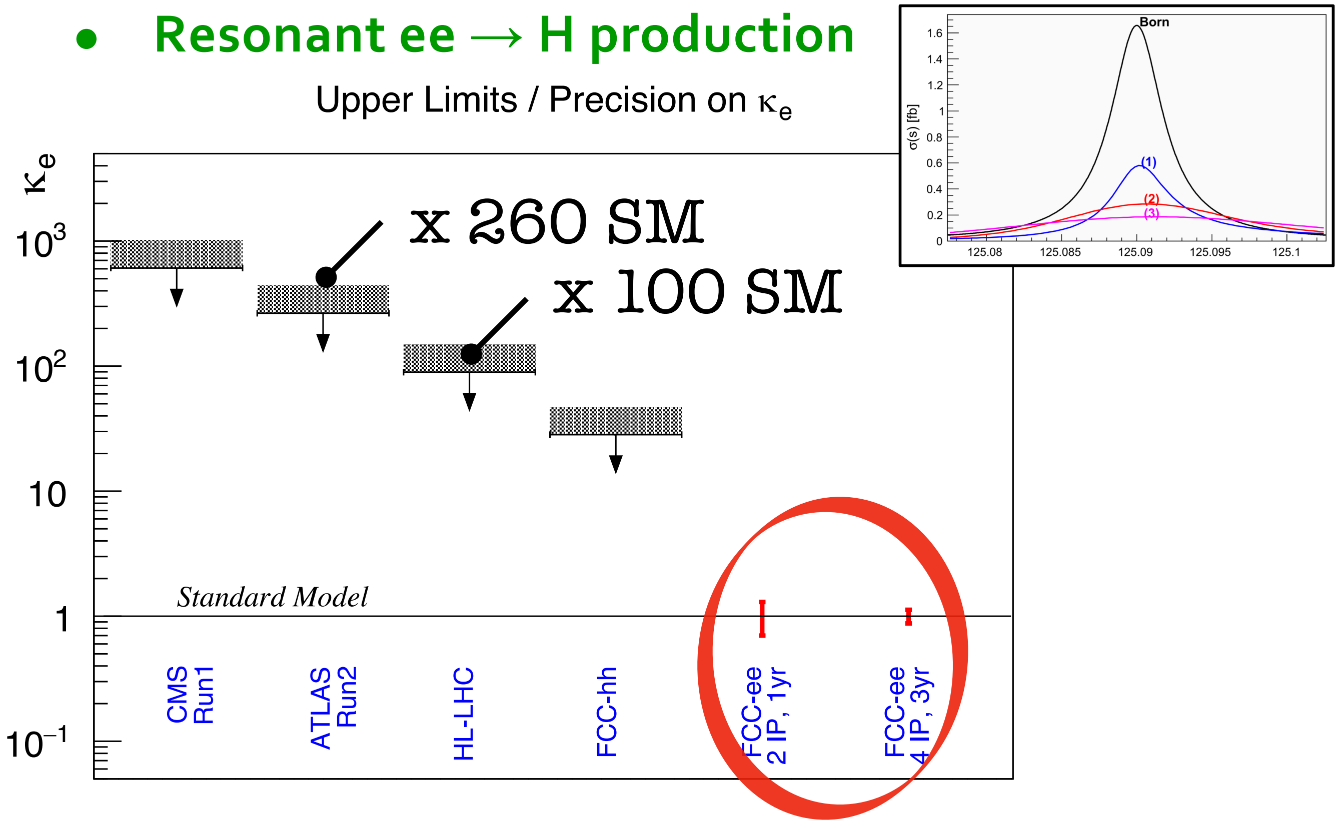
Access to e$^-$ Yukawa



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

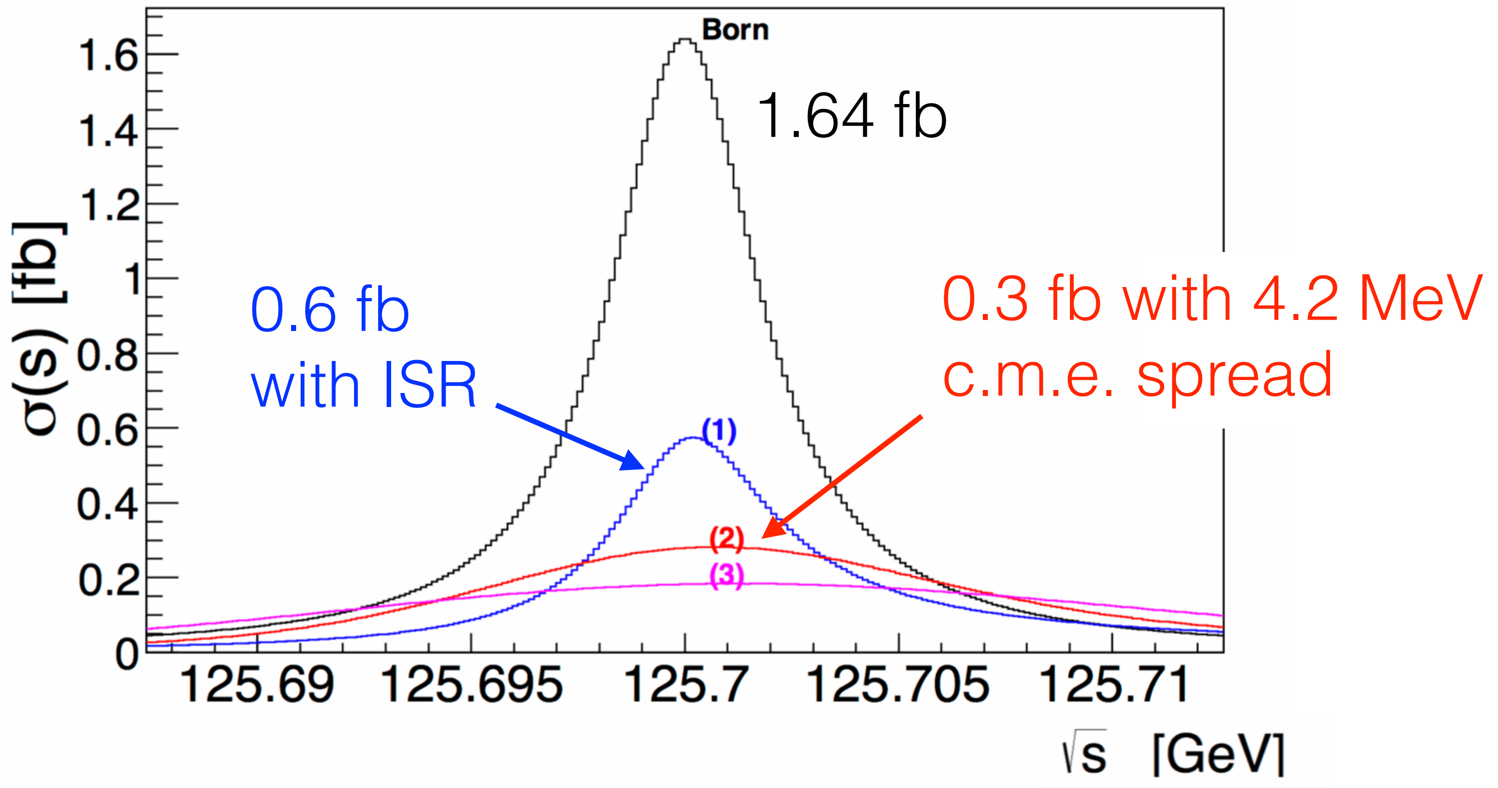
$\sigma_{\text{spread+ISR}}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H) = 290$ ab

- **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**


Upper Limits / Precision on κ_e

  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Jadach+, arXiv: 1509.02406



d'Enterria+, arXiv: 2107.02686

Higgs decay channel	$\mathcal{B}$	$\sigma \times \mathcal{B}$	Irreducible background	σ	S/B
$e^+e^- \to H \to b\bar{b}$	58.2%	164 ab	$e^+e^- \to b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^- \to H \to gg$	8.2%	23 ab	$e^+e^- \to q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to \tau\tau$	6.3%	18 ab	$e^+e^- \to \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^- \to H \to c\bar{c}$	2.9%	8.2 ab	$e^+e^- \to c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
$e^+e^- \to H \to WW^* \to \ell\nu\, 2j$	21.4%×67.6%×32.4%×2	26.5 ab	$e^+e^- \to WW^* \to \ell\nu\, 2j$	23 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to WW^* \to 2\ell\, 2\nu$	21.4%×32.4%×32.4%	6.4 ab	$e^+e^- \to WW^* \to 2\ell\, 2\nu$	5.6 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to WW^* \to 4j$	21.4%×67.6%×67.6%	27.6 ab	$e^+e^- \to WW^* \to 4j$	24 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to ZZ^* \to 2j\, 2\nu$	2.6%×70%×20%×2	2 ab	$e^+e^- \to ZZ^* \to 2j\, 2\nu$	273 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to ZZ^* \to 2\ell\, 2j$	2.6%×70%×10%×2	1 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2j$	136 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to ZZ^* \to 2\ell\, 2\nu$	2.6%×20%×10%×2	0.3 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2\nu$	39 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to \gamma\gamma$	0.23%	0.65 ab	$e^+e^- \to \gamma\gamma$	79 pb	$\mathcal{O}(10^{-8})$

w. 10/ab

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

The future: other directions not explored yet

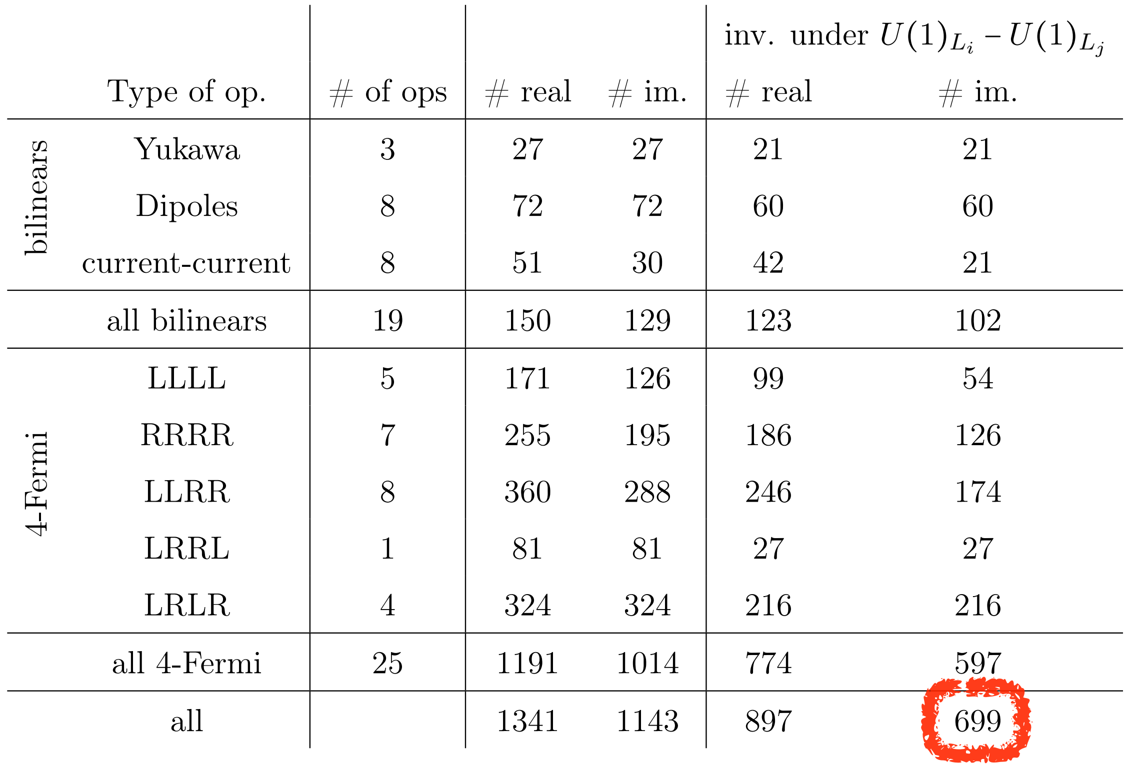
- **Non-diagonal flavour structures:**
  1. in SM, no Higgs FCNC
  2. in BSM, Higgs FCNC are the rule rather than the exception
  3. combination with flavour data

- **CP violation couplings: CPV is a collective effect**
  1. in SM, a single CPV phase captured by Jarlskog invariant: $J_4 = \mathrm{Im}\mathrm{Tr}\left([Y_u Y_u^\dagger, Y_d Y_d^\dagger]^3\right)$
  2. how many at dim-6 level?

large parameter space,
largely unconstrained

—

potentially large new physics effects
since they do not suffer from same
collective suppression factor of the SM



	Type of op.	# of ops	# real	# im.	inv. under $U(1)_{L_i} - U(1)_{L_j}$ # real	# im.
bilinears	Yukawa	3	27	27	21	21
	Dipoles	8	72	72	60	60
	current-current	8	51	30	42	21
	all bilinears	19	150	129	123	102
4-Fermi	LLLL	5	171	126	99	54
	RRRR	7	255	195	186	126
	LLRR	8	360	288	246	174
	LRRL	1	81	81	27	27
	LRLR	4	324	324	216	216
	all 4-Fermi	25	1191	1014	774	597
	all		1341	1143	897	699

699
new
Jarlskog
BSM invariants

Bonnefoy+ 2112.03889

- **Beyond SMEFT** analyses, e.g. HEFT

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.

Summary of Physics Potential

FCC-ee note, 1906.02693

	e^+e^- collisions							pp collisions		
$\sqrt{s}$ → Physics ↓	m_Z	$2m_W$	HZ max. 240-250 GeV	$2m_{top}$ 340-380 GeV	500 GeV	1.5 TeV	3 TeV	28 TeV 37 TeV 48 TeV	100 TeV	Leading Physics Questions
Precision EW (Z, W, top)	🟩 Transverse polarization	🟩 Transverse polarization		🟦 m_W, α_S						Existence of more SM-Interacting particles
QCD (α_S) QED (α_{QED})	🟩 5×10^{12} Z	🟦 3×10^{8} W	🟦 10^5 H→gg							Fundamental constants and tests of QED/QCD
Model-independent Higgs couplings	🟩 ee → H $\sqrt{s} = m_H$		🟦 1.2×10^6 HZ and 75k WW→H at two energies						🟦 <1% precision (*)	Test Higgs nature
Higgs rare decays									🟩 <1% precision (*)	Portal to new physics
Higgs invisible decays									🟦 10^{-4} BR sensitivity	Portal to dark matter
Higgs self-coupling			🟩 3 to 5σ from loop corrections to Higgs cross sections						🟦 5% (HH prod) (*)	Key to EWSB
Flavours (b, τ)	🟩 5×10^{12} Z									Portal to new physics Test of symmetries
RH ν's, Feebly interacting particles	🟩 5×10^{12} Z								🟩 10^{11} W	Direct NP discovery At low couplings
Direct search at high scales					▨ M_χ<250GeV Small ΔM	▨ M_χ<750GeV Small ΔM	▨ M_χ<1.5TeV Small ΔM		🟦 Up to 40 TeV	Direct NP discovery At high mass
Precision EW at high energy							🟥 ***Y***		🟦 ***W, Z***	Indirect Sensitivity to Nearby new physics
Quark-gluon plasma Physics w/ injectors									🟦	QCD at origins

Green = Unique to FCC; **Blue = Best with FCC**; **(*) = if FCC-hh is combined with FCC-ee**; **Pink = Best with other colliders**

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).

And FCC-ee is an essential part of an **integrated** programme to probe the energy frontier.

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).

And FCC-ee is an essential part of an **integrated** programme to probe the energy frontier.

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	-

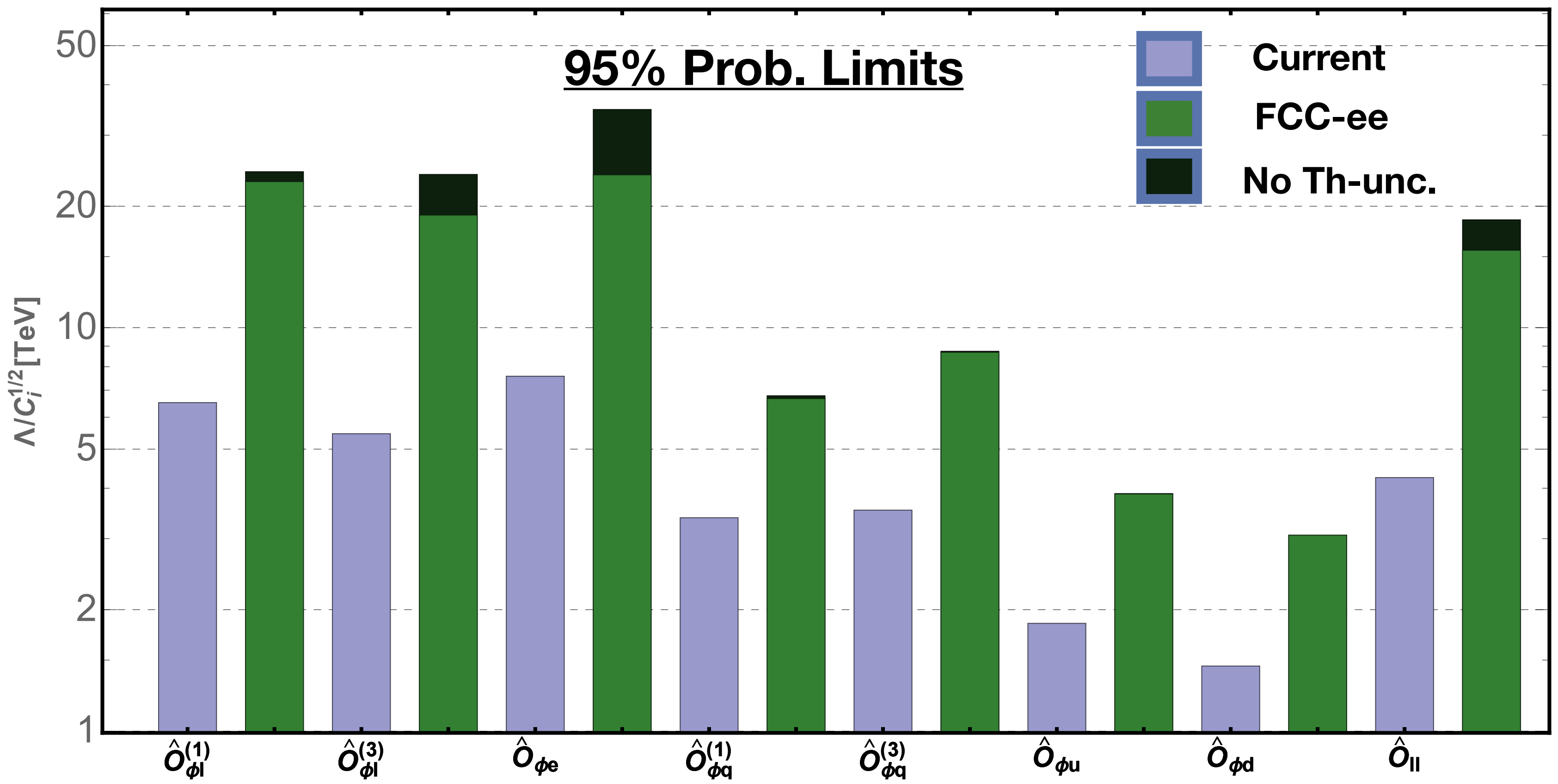
EW Precision Measurements at FCC-ee

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
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	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
σ_{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
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	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_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	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, 'to appear

Impact of TH uncertainties

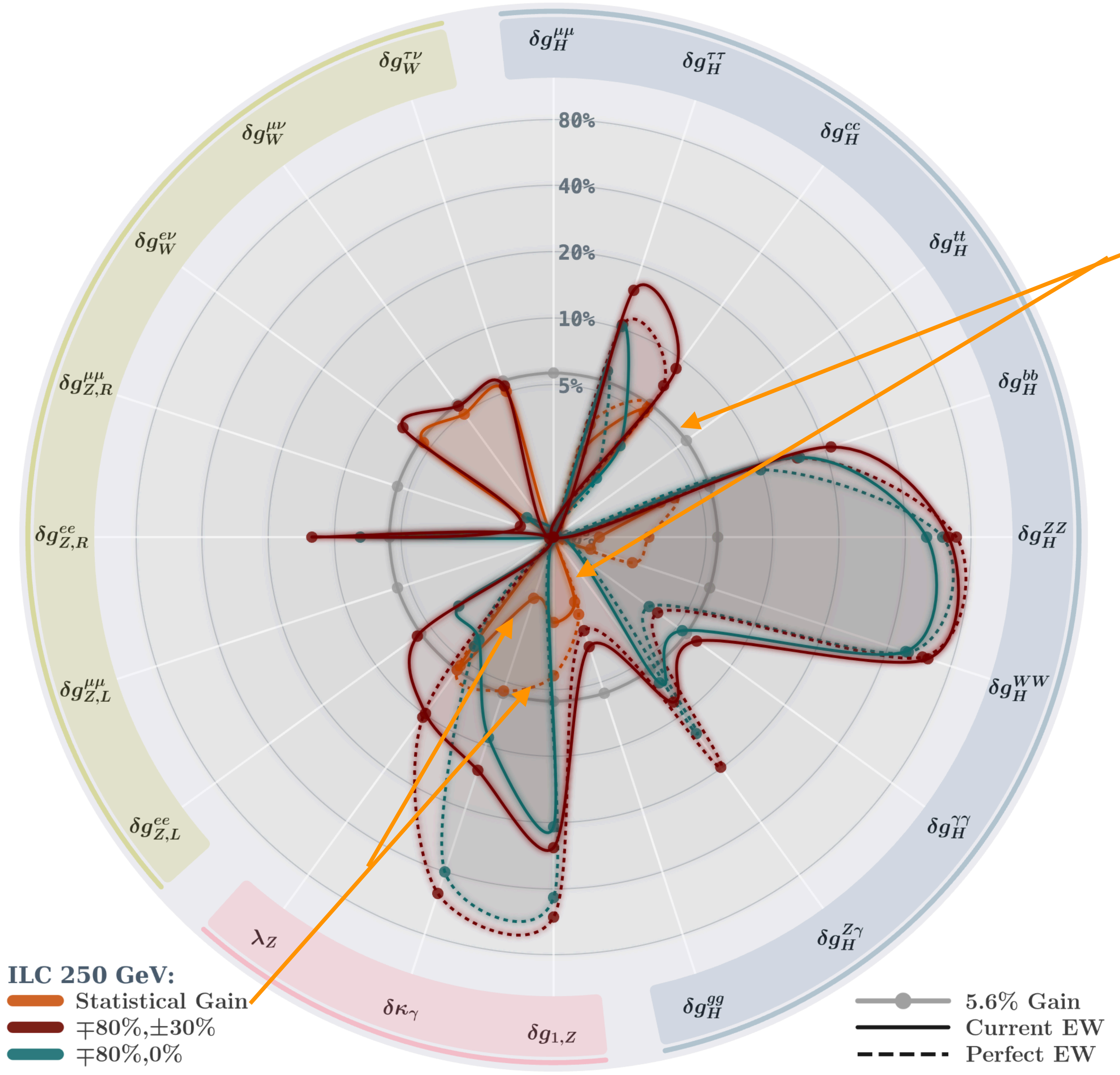
J. de Blas, FCC CDR overview '19



	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
δM_W [MeV]	±15	±8	±1	±0.6/±1	±1
$\delta\Gamma_Z$ [MeV]	±2.3	±0.73	±0.1	±0.1	±0.2
$\delta\mathcal{A}_\ell\,[\times10^{-5}]$	±210	±93	±2.1	±8/±14	±11.8
$\delta R_b^0\,[\times10^{-5}]$	±66	±3	±6	±0.3	± 5

Impact of Beam Polarisation (@250GeV)

J. De Blas et al. 1907.04311



Statistical gain from increased rates

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

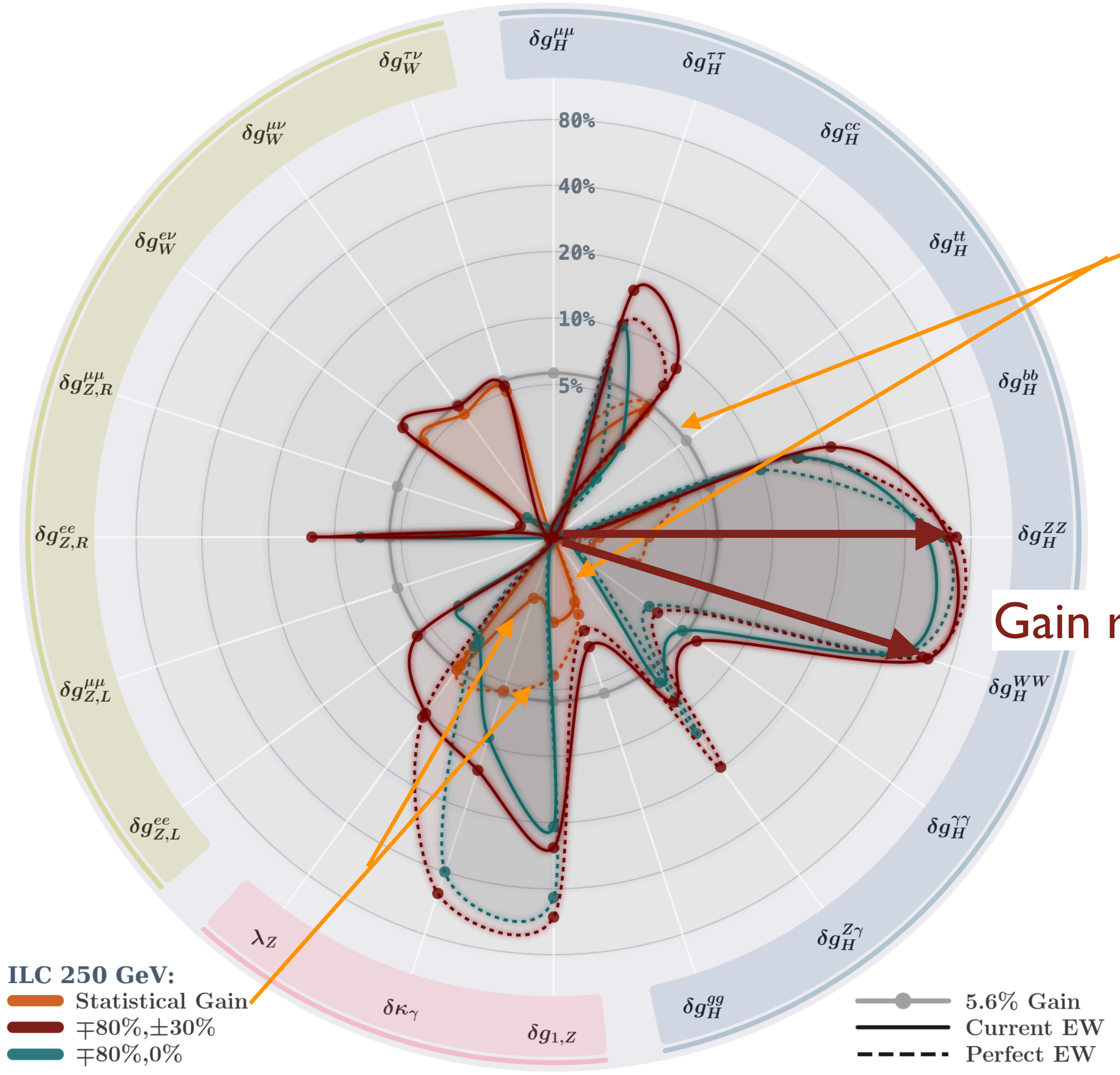
From ee→Zh, A_{LR}~0.15 so $\sigma_{-80,+30} \sim 1.4\,\sigma_0$

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

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

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 $\sigma_{-80,+30} \sim 1.4\,\sigma_0$

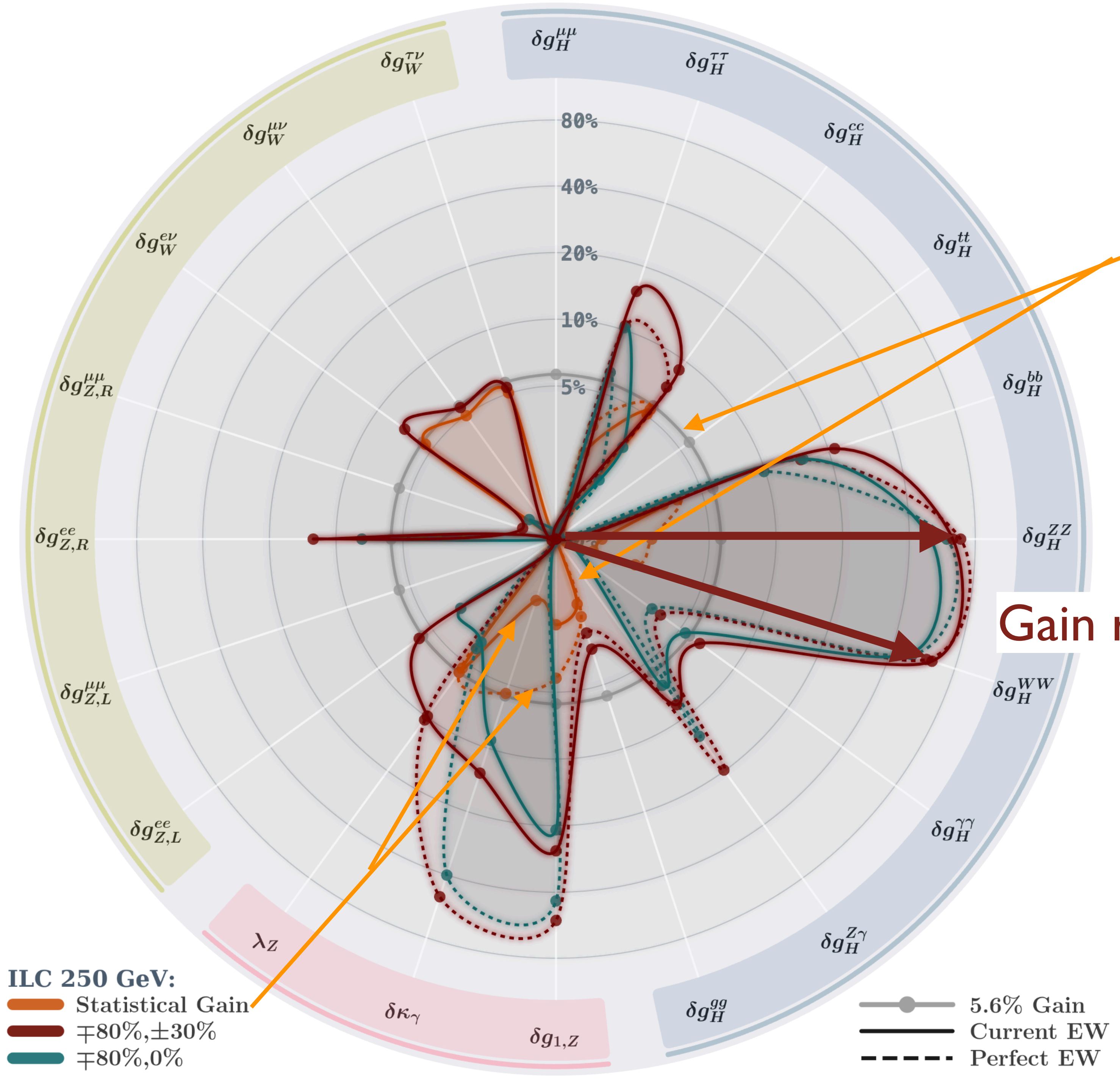
overall, one could expect
O(6%) increased coupling sensitivity

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

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

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

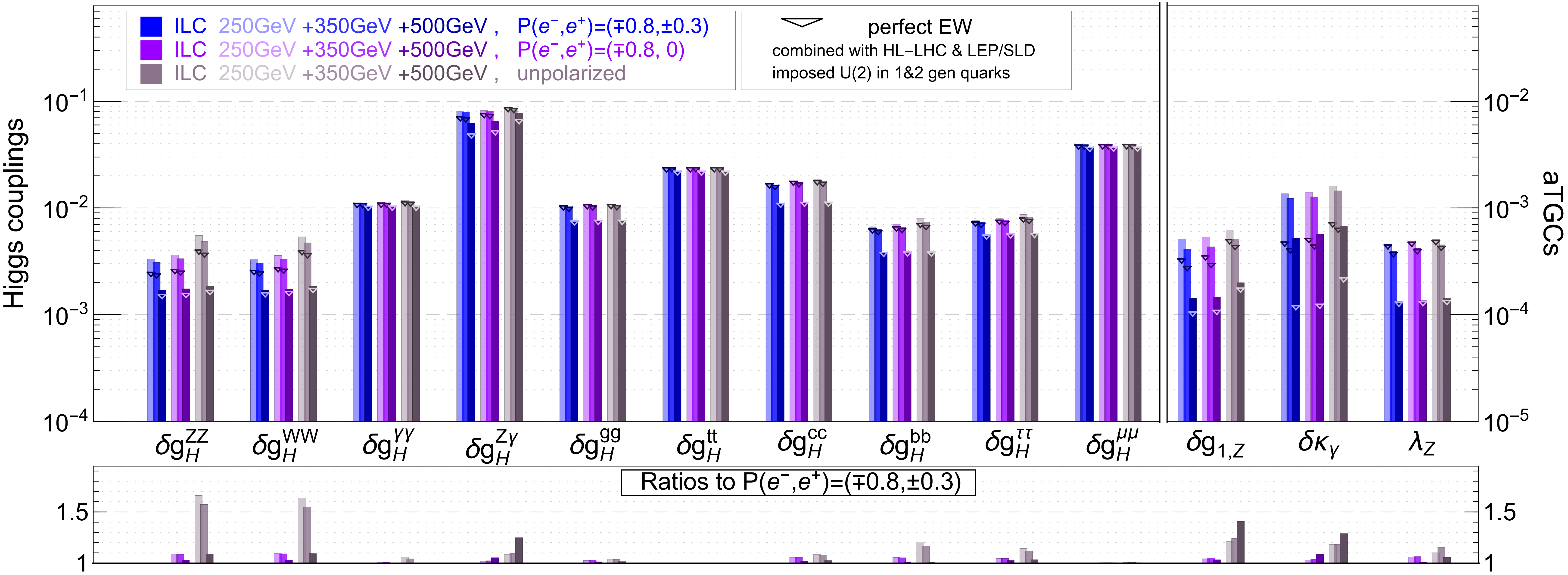
Gain is much higher in global EFT fit since polarisation removes degeneracies among operators

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

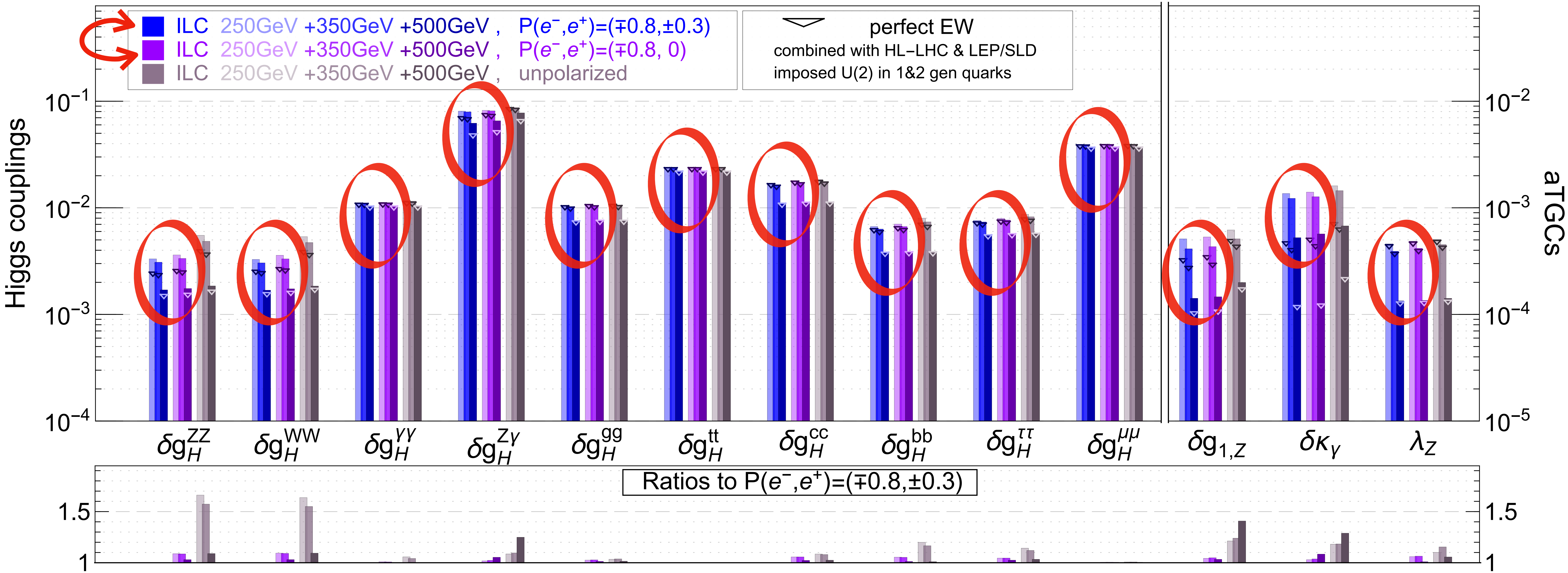
Impact of Beam Polarisation

J. De Blas et al. 1907.04311



Impact of Beam Polarisation

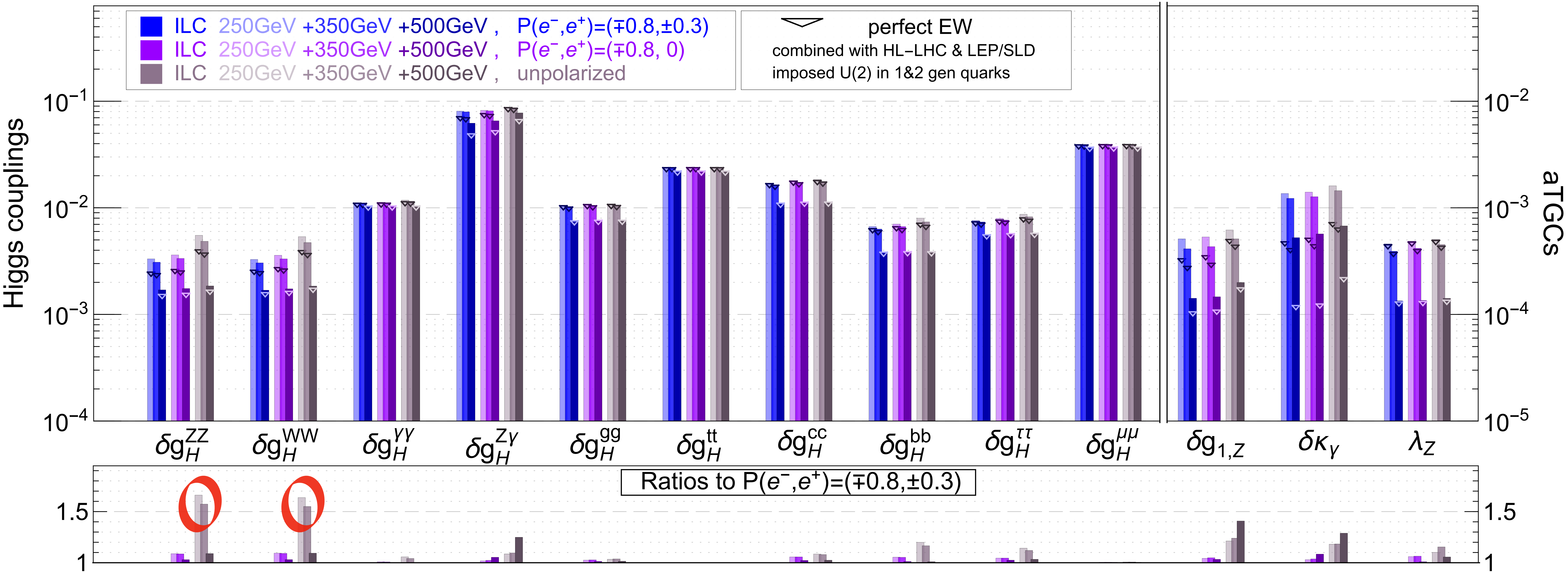
J. De Blas et al. 1907.04311



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

Impact of Beam Polarisation

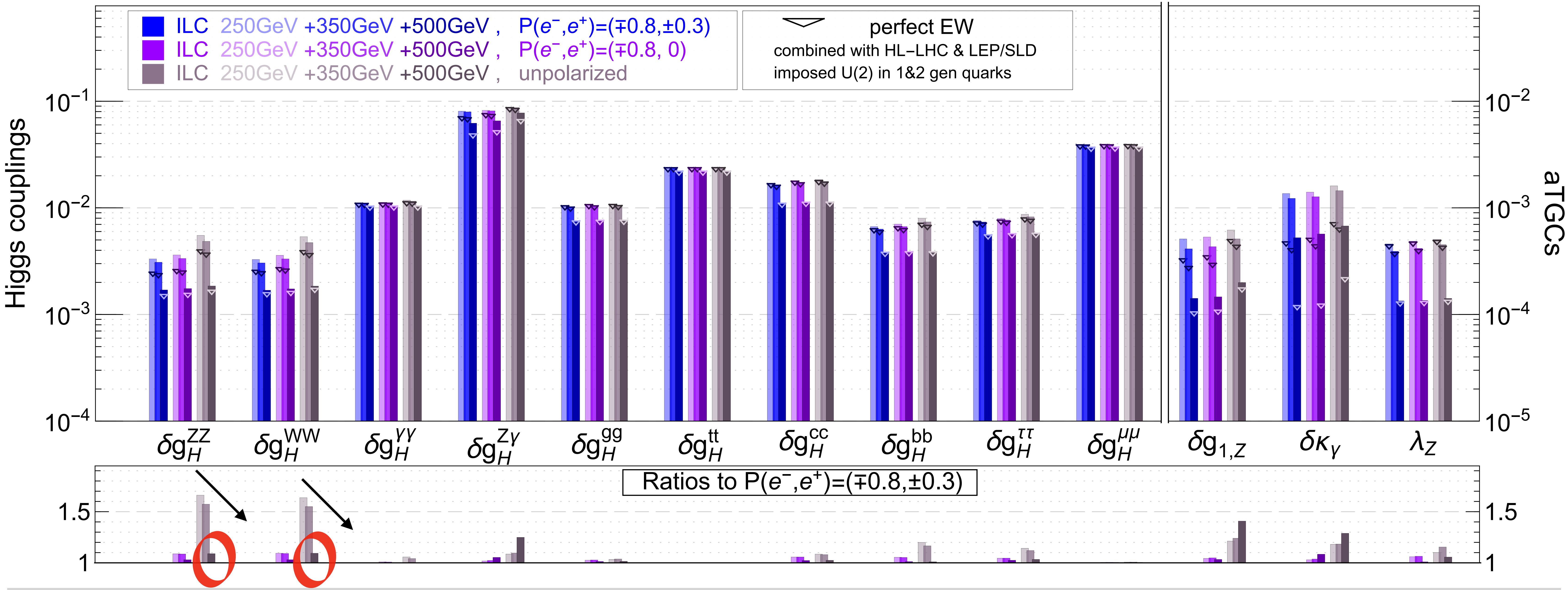
J. De Blas et al. 1907.04311



- 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



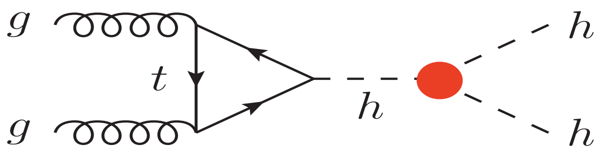
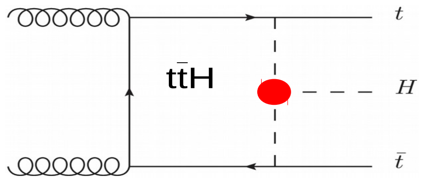
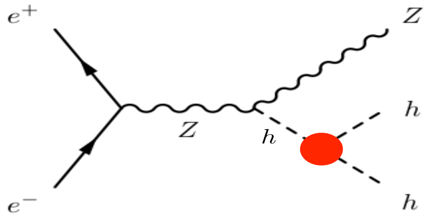
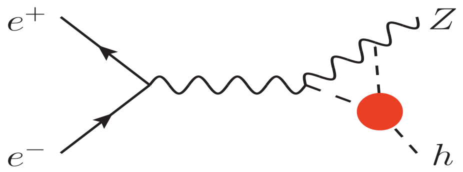
- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination
- Polarisation-benefit diminishes (in relative and absolute terms) when other runs at higher energies are added

Higgs Self-Coupling

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

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

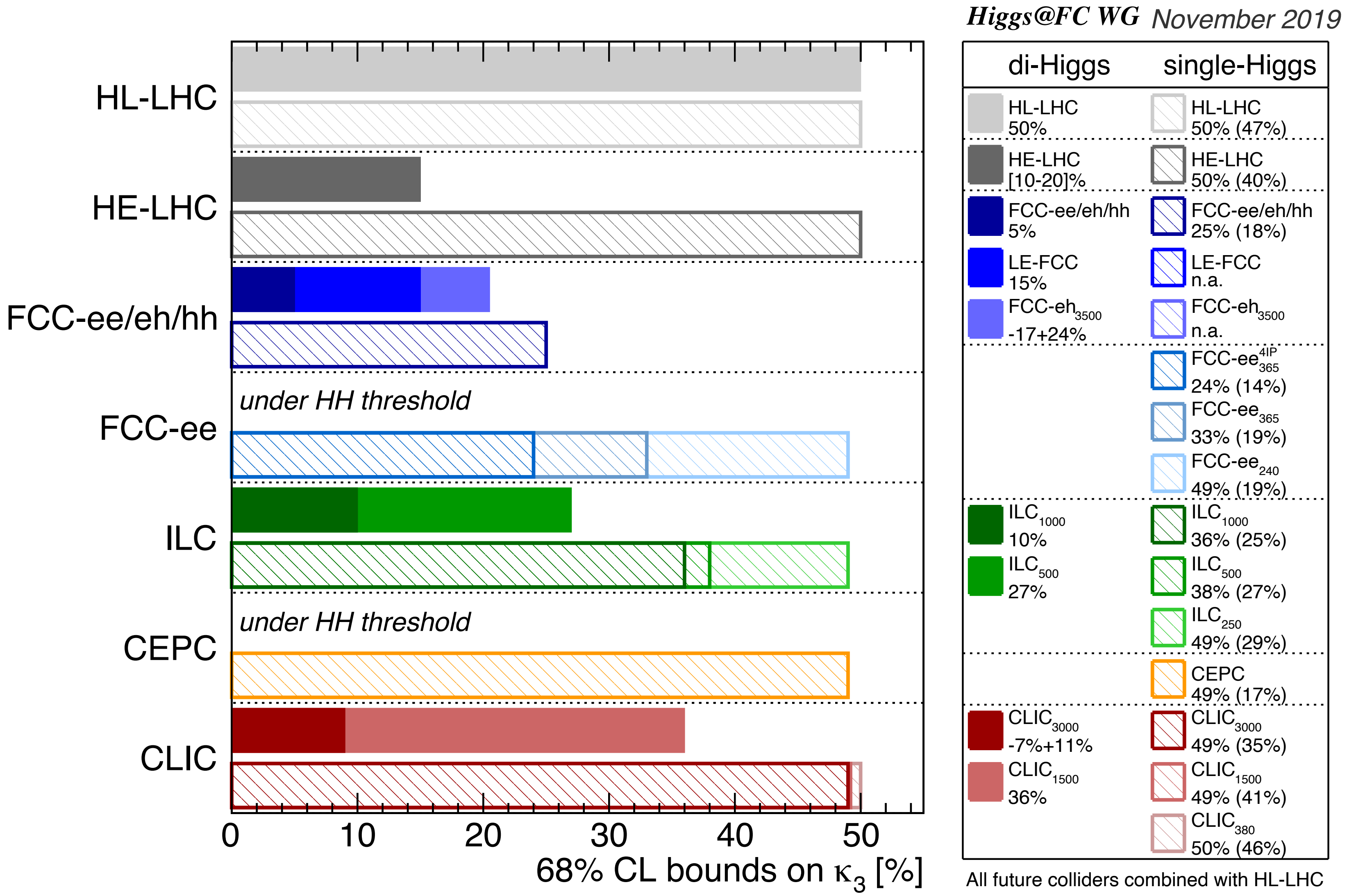
ECFA Higgs study group '19

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

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • 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

ECFA Higgs study group ‘19



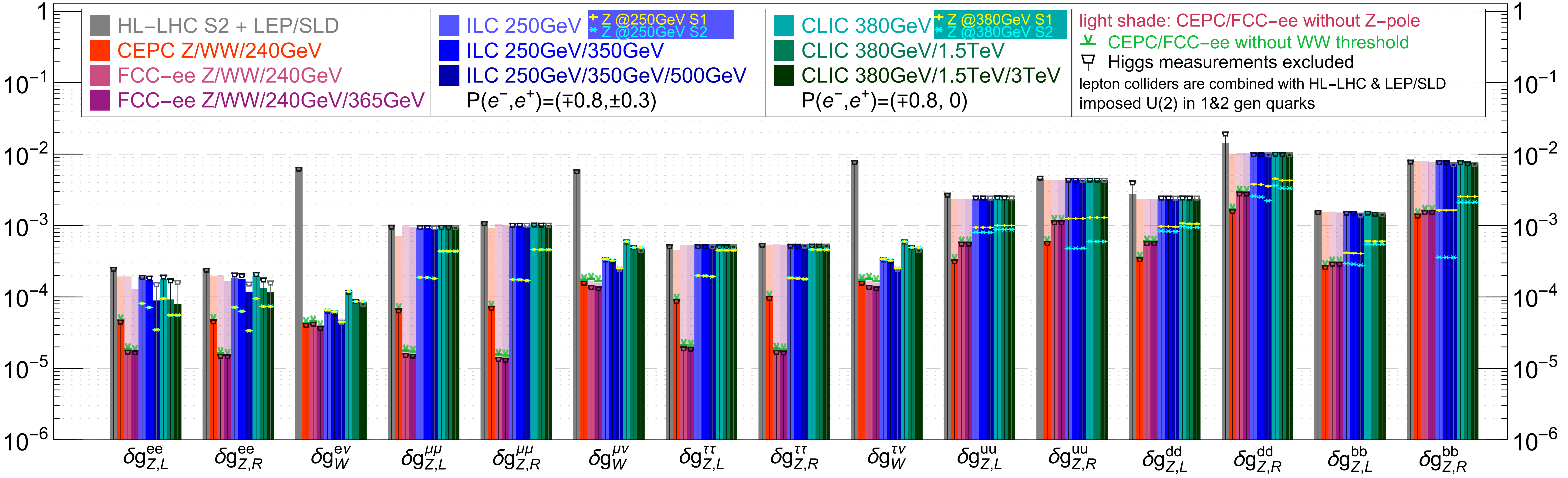
① Don’t need to reach HH threshold to have access to h^3.
Z-pole run is very important if the HH threshold cannot be reached

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

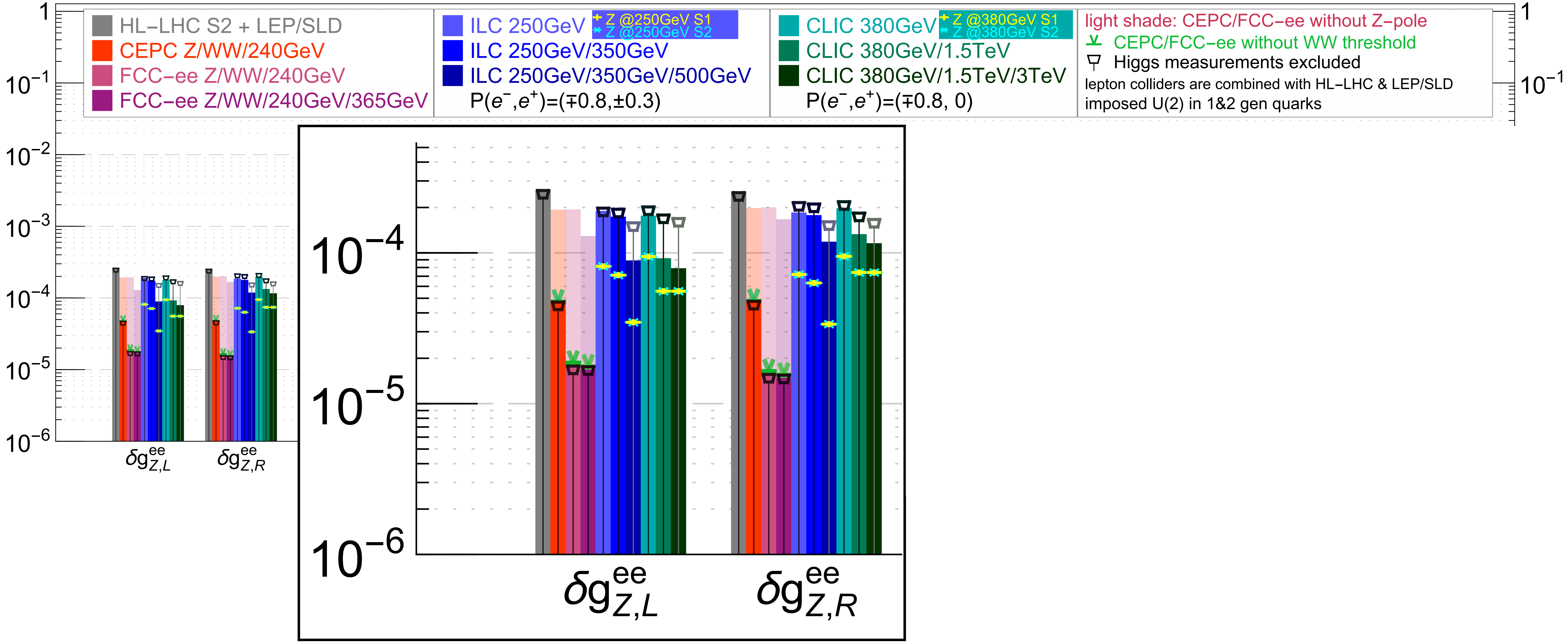
Sensitivity on EW couplings

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



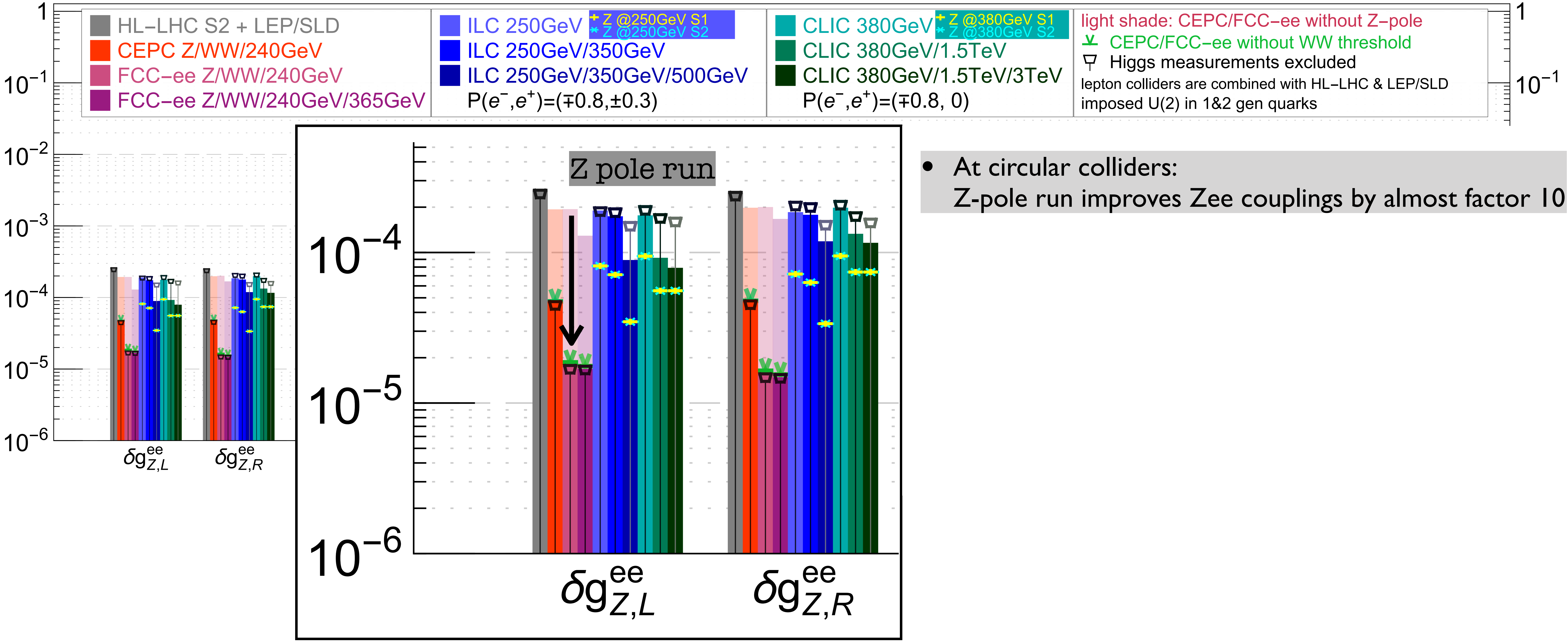
Sensitivity on EW couplings

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



Sensitivity on EW couplings

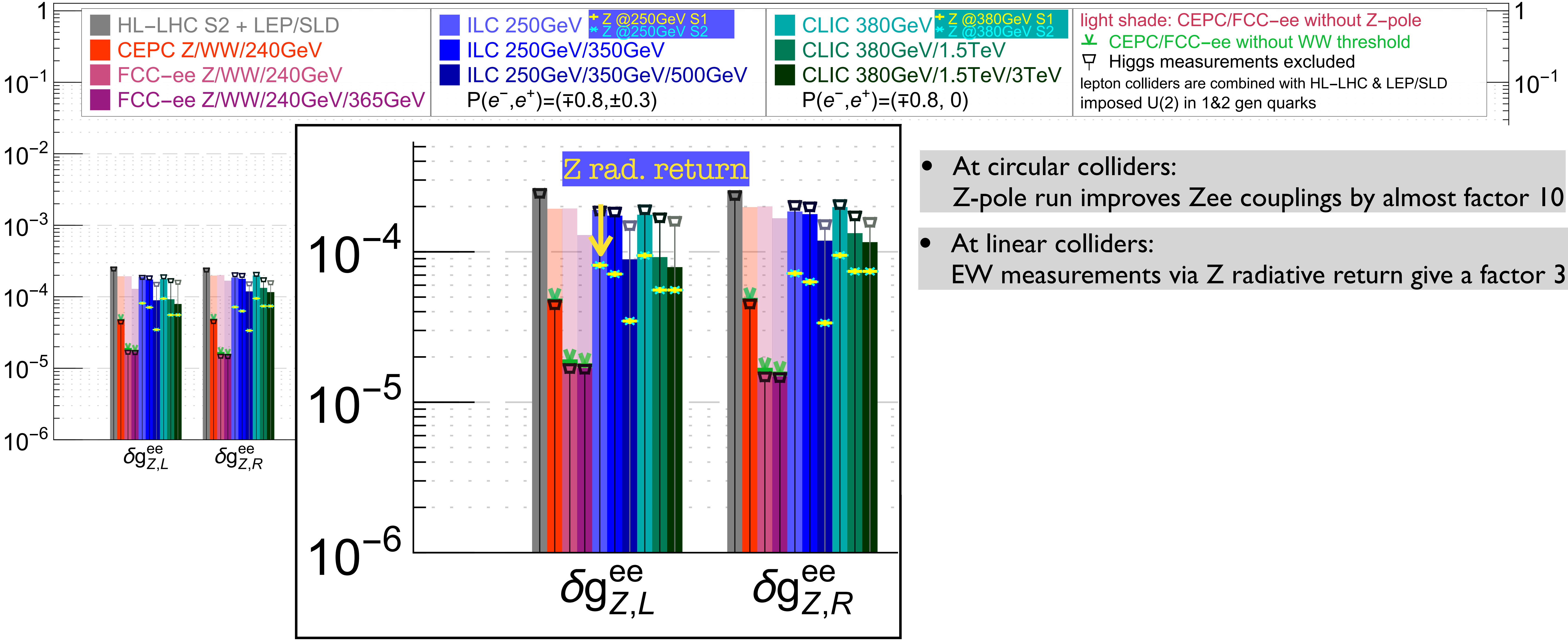
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



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

Sensitivity on EW couplings

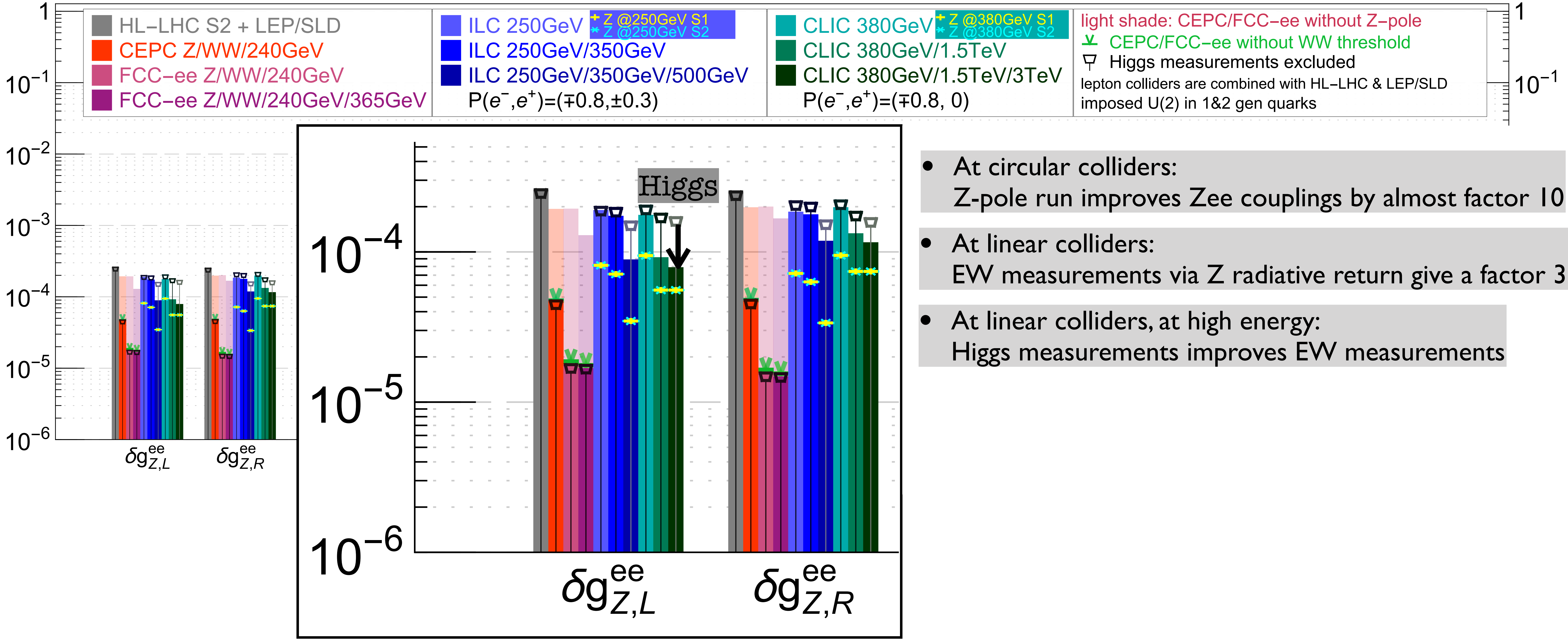
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



- 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

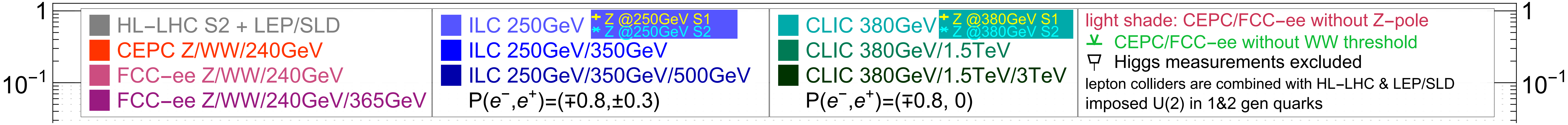
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



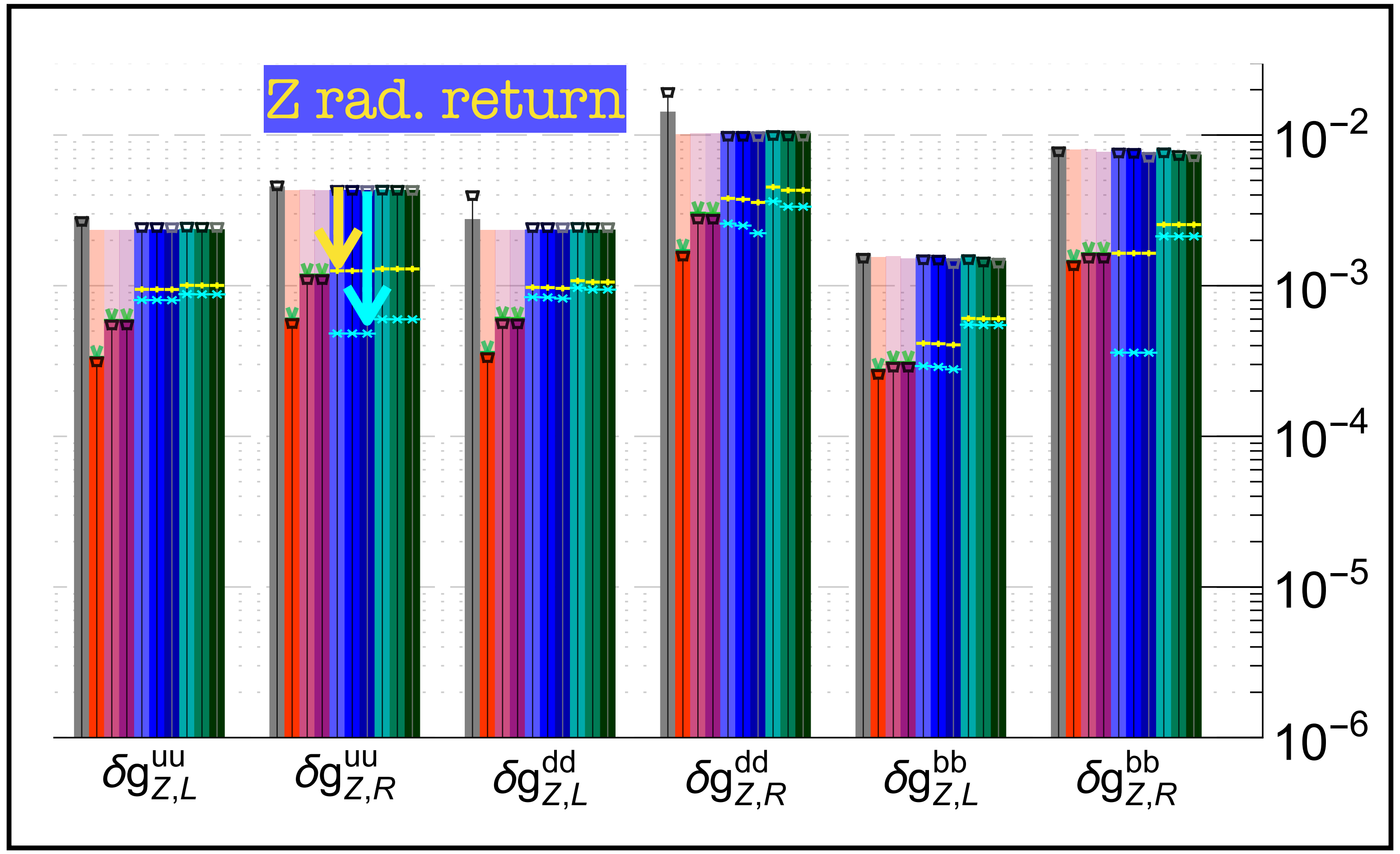
- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings

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



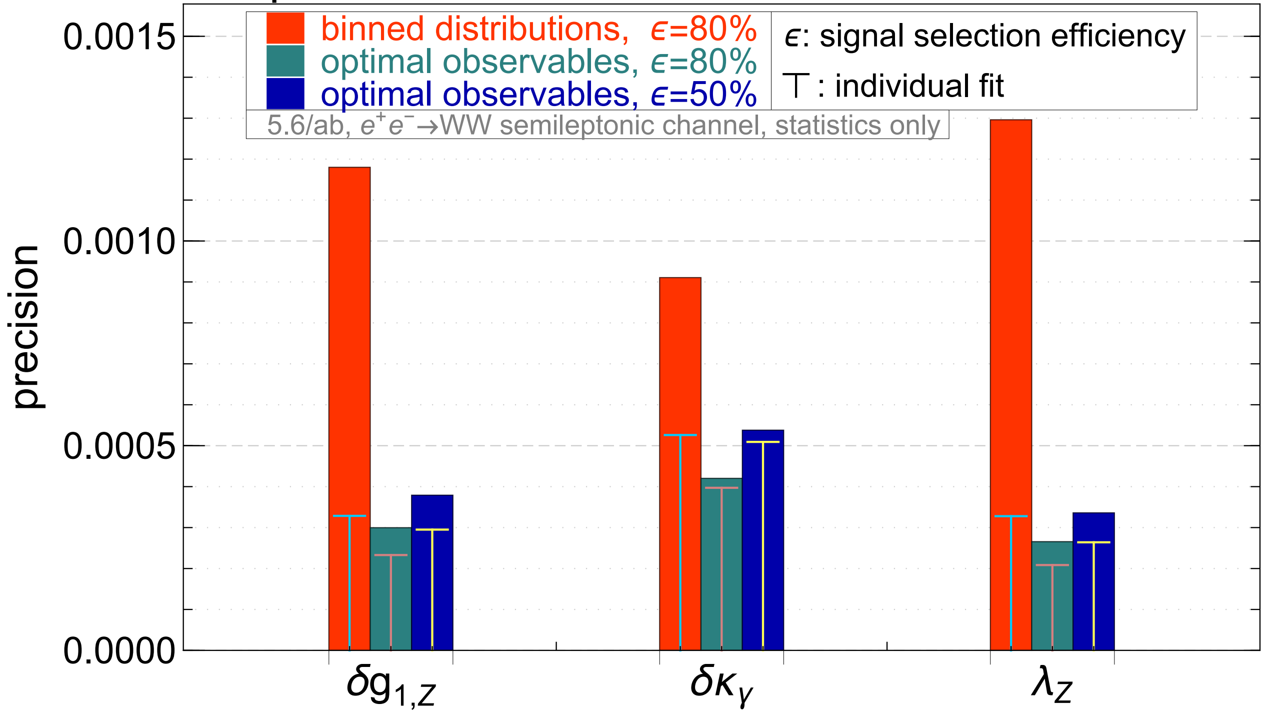
- At linear colliders, at high energy:
  EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
  - Yellow: LEP/SLD systematics / 2
  - Blue: small EXP and TH systematics



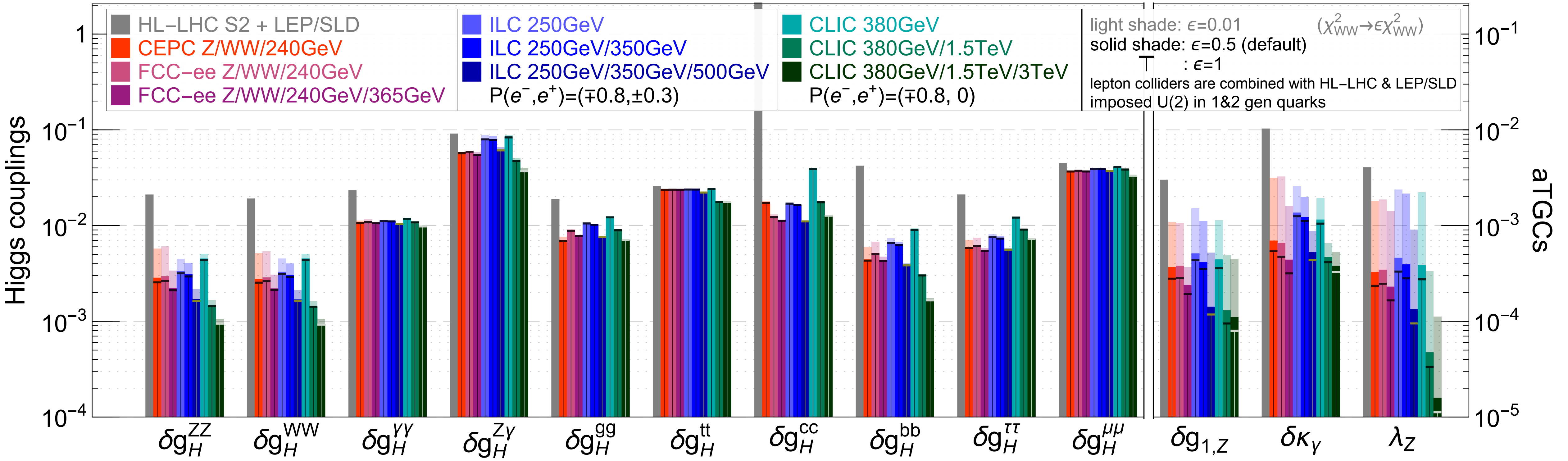
Impact of Diboson Systematics

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

precision reach of aTGCs at CEPC 240GeV



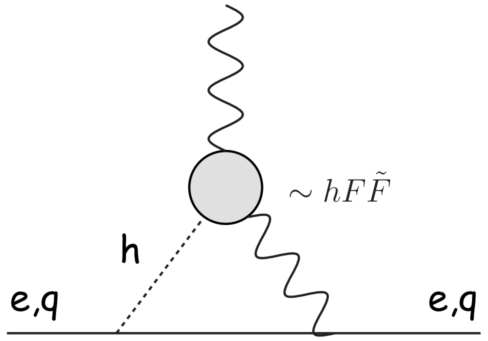
precision reach with different assumptions on $e^+e^-\to WW$ measurements



CP Violation in Higgs Sector

Is CP a good symmetry of Nature? 2 CP-violating couplings in the SM$_4$.
SM$_6$ has many more CPV couplings: 1149 CPV couplings (incl. 1014 Four-Fermi ones)
LHC is getting sensitive to them ($|\theta_{thh}| < 43^\circ \,\&\, \theta_{\tau\tau} = (4 \pm 17)^\circ$), but not competitive with EDM

operators with γ:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12

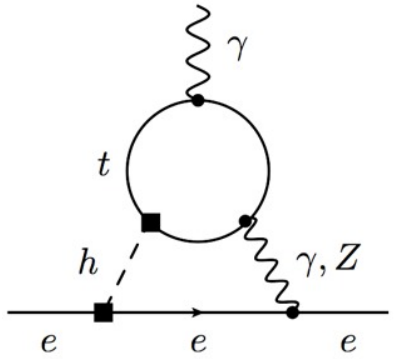


$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

$\Lambda_{\rm CPV}$ > 25 TeV

operators with top:
already severely constrained
by e and q EDMs

Brod, Haisch, Zupan '13



$$\delta\tilde{g}_{htt} \leq 0.01$$

$\Lambda_{\rm CPV}$ > 2.5 TeV

Caveats: h couplings to light particles can be significantly reduced

Not mature topic yet: next step is e.g. to develop STXS that are CP-odd

often need double differential distributions because of non-interference with SM

CP Violation in Higgs Sector

Is CP a good symmetry of Nature? 2 CP-violating couplings in the SM_4.

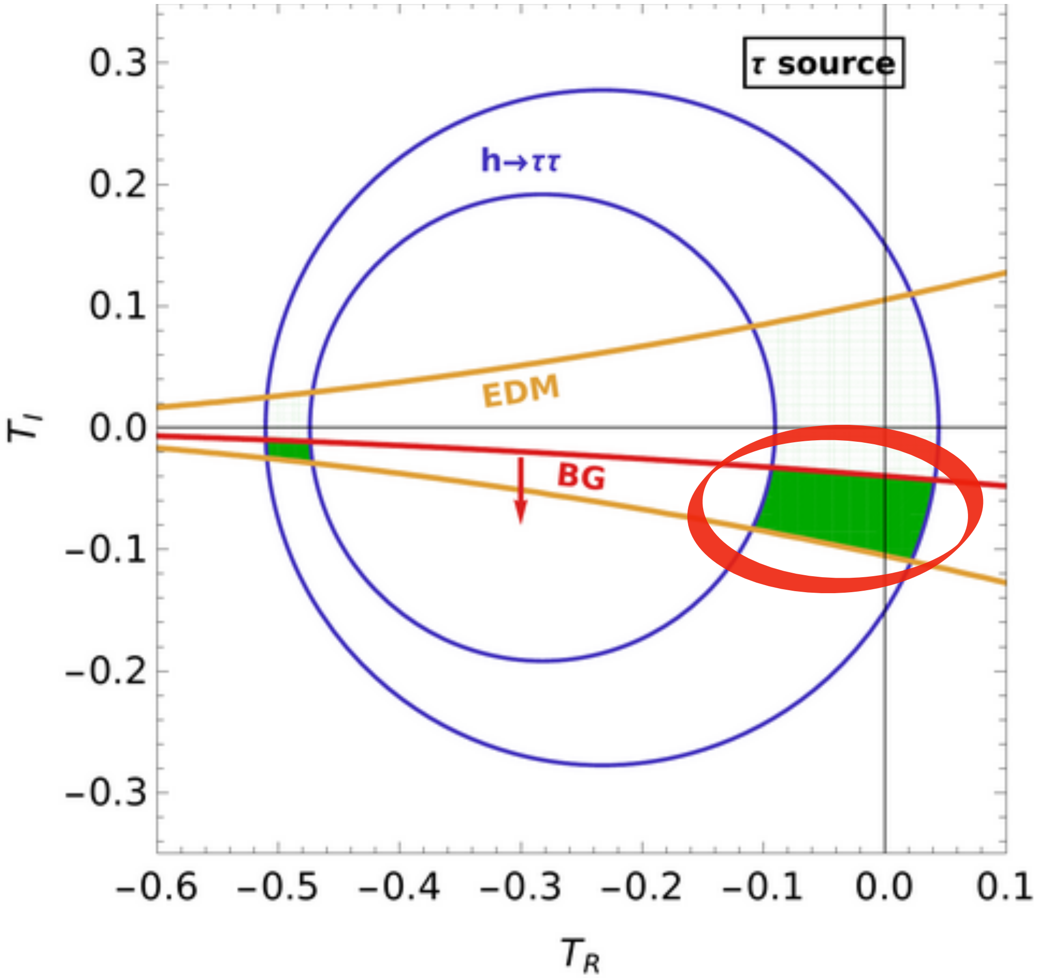
SM_6 has many more CPV couplings: 1149 CPV couplings (incl. 1014 Four-Fermi ones)

LHC is getting sensitive to them ($|\theta_{thh}| < 43^\circ \;\&\; \theta_{\tau\tau} = (4 \pm 17)^\circ$), but not competitive with EDM

Despite tighter and tighter constraints, CPV Yukawa could still be the source of EW baryogenesis

Fuchs et al. '20

see also
de Vries et al. '17



sufficient baryon asymmetry within LHC & EDM limits?

τ: yes

t, b, μ: no

EDM

μ(h→ μμ)<1.7

EFT Cut-off scales $\Lambda/\sqrt{X_{R,I}}$

Minimal scales maximally allowed T (collider, EDM)

τ, b: 1 - 3 TeV; t: 1 TeV (LHC), 9 TeV (EDM)

μ: 10 – 12 TeV

Maximal scales minimally required T_I (EWBG)

$\Lambda/\sqrt{X_I^\tau} \lesssim 18\ \mathrm{TeV}\ (0.01/T_I^\tau)^{1/2}$

— continue the exploration, especially in the tau sector —

CP Violation in Higgs Sector

Searching for source of CPV that can trigger matter-antimatter imbalance
SM: only 1 CPV invariant (Jarlskog)
BSM: 707 new sources of CPV at leading order

CPV is a Collective effect: CPV is accidentally small in the SM

SM:

$$J_4 = \mathrm{Im}\mathrm{Tr}\left([Y_u Y_u^\dagger, Y_d Y_d^\dagger]^3\right) \sim \lambda^{36} \sim 10^{-24}$$

BSM:
(dim.6 Yukawa)

$$L_1^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger\right] \quad L_2^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger X_u\right] \quad L_3^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger X_d\right]$$

$$L_4^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger X_u X_d\right] \quad L_5^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger X_d X_u\right] \quad L_6^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger X_u^2 X_d^2\right]$$

$$L_7^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger X_d^2 X_u^2\right] \quad L_8^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger X_u X_d^2 X_u^2\right] \quad L_9^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH}Y_u^\dagger X_d X_u^2 X_d^2\right]$$

	Generic	MFV
Rank 1	$\mathcal{O}(\lambda^0)$	$\mathcal{O}(\lambda^0)$
Rank 2	$\mathcal{O}(\lambda^4)$	$\mathcal{O}(\lambda 8)$
Rank 3	$\mathcal{O}(\lambda^8)$	$\mathcal{O}(\lambda^{12})$

all suppressed by v^2/(New Physics scale)^2 but no big collective suppression

sizes of CPV sources depend on flavour symmetry of BSM interactions

Bonnefoy et al: arXiv:2112.03889

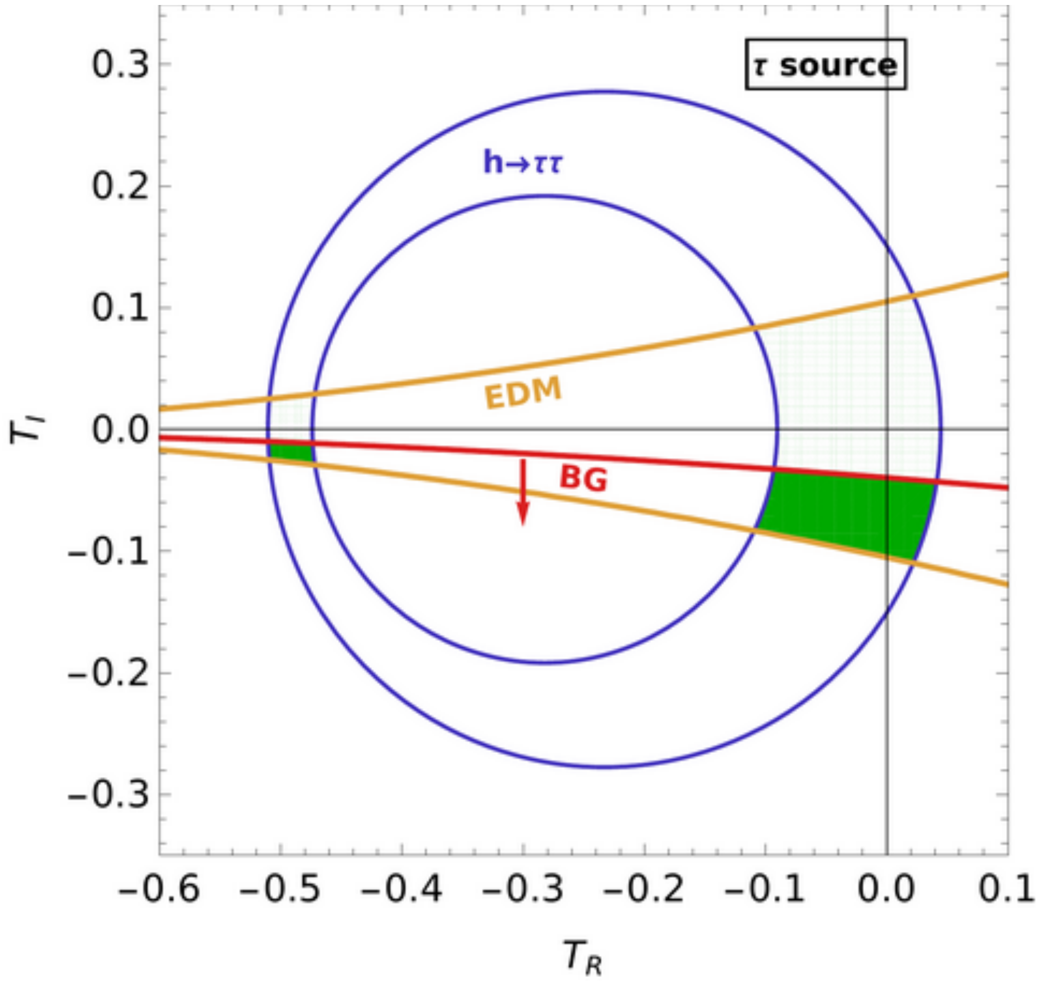
CP Violation in Higgs Sector

Searching for source of CPV that can trigger matter-antimatter imbalance
SM: only 1 CPV invariant (Jarlskog)
BSM: 707 new sources of CPV at leading order

CPV Yukawa could still be the source of EW baryogenesis

Fuchs et al. '20

see also
de Vries et al. '17



sufficient baryon asymmetry within LHC & EDM limits?

τ: yes

t, b, μ: no

EDM   μ(h→ μμ)<1.7

EFT Cut-off scales $\Lambda/\sqrt{X_{R,I}}$

Minimal scales   maximally allowed T (collider, EDM)

τ, b: 1 - 3 TeV; t: 1 TeV (LHC), 9 TeV (EDM)

μ: 10 – 12 TeV

Maximal scales   minimally required T_I (EWBG)

$$\Lambda/\sqrt{X_I^\tau} \lesssim 18\ \text{TeV}\ (0.01/T_I^\tau)^{1/2}$$

— continue the exploration, especially in the tau sector —