Recent Progress on Theory/Physics

(‘WHY?’ and ‘HOW?’)

2022 CEPC Workshop
Oct. 28, 2022

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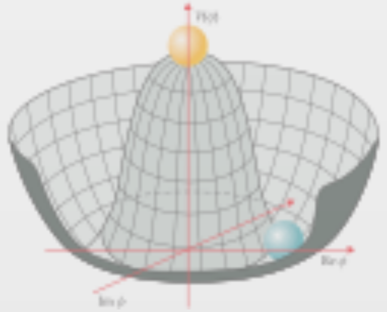
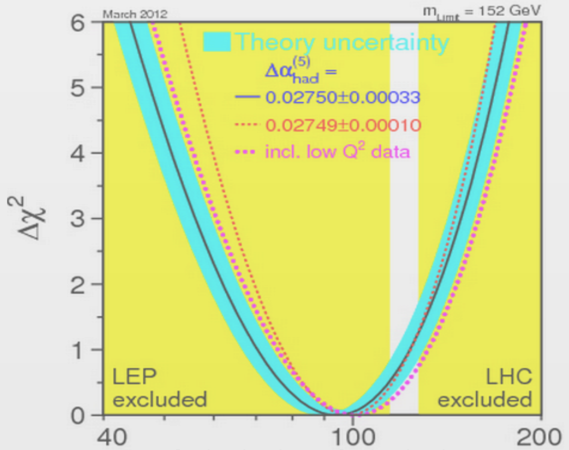
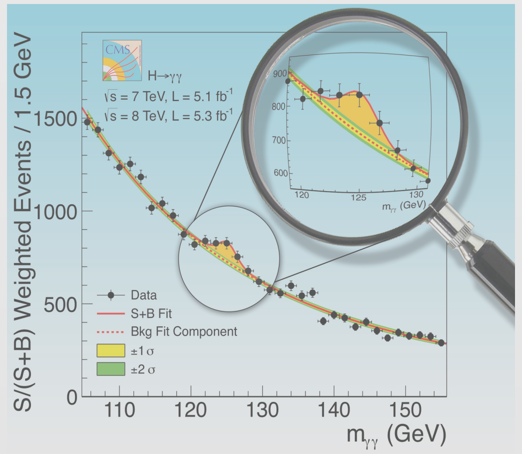


1964

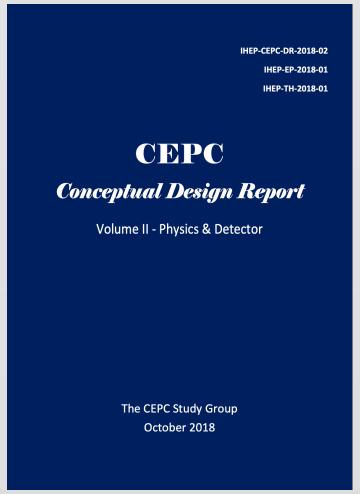


1992-1999

2010



2012

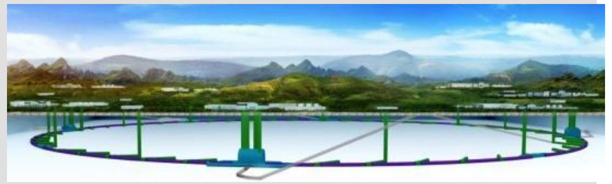


IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC
Conceptual Design Report
Volume II - Physics & Detector

The CEPC Study Group
October 2018

2018



203X/204X?

Theory/Physics and CEPC

O(50) talks in 5 parallel sessions BSM, QCD, EW-top, Flavour, Higgs

— What does CEPC need theory/physics for? —

* **WHY?** Sharpen the physics case and convince the world (politicians, funding agencies, scientists in general, linear collider colleagues…) that CEPC is worth building
* **HOW?** Exploit the wealth of data that will be collected

— What can CEPC do for theory/physics? —

* Better knowledge of SM
* Exploration of BSM scenarios

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- Exploration of BSM scenarios

> We are not shooting in the dark.
>
> Let's move away from "The SM is incomplete" and "we need to search everywhere"
>
> Instead, we might say
>
> We have made the following discoveries, which will enlarge our model of the Universe once we figure out how it fits into what we already know.
>
> Highlights and Messages from the Snowmass Summer Study. Prisca Cushman

CEPC/FCC-ee
has a unique opportunity
to refine
our "model" of the Universe

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)

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

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

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

"Weak Scale Triggers"

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"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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"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.

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This makes CEPC valuable on its own and not only through the synergy with SppC.

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/CEPC
(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

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m_W, m_Z ↔ Higgs couplings ✓

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lifetime of stars
(why $t_{\rm Sun} \sim t_{\rm life\ evolution}$?)

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size of atoms ↗ (m_e)
nuclei stability ↖ (m_u, m_d)

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?

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

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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

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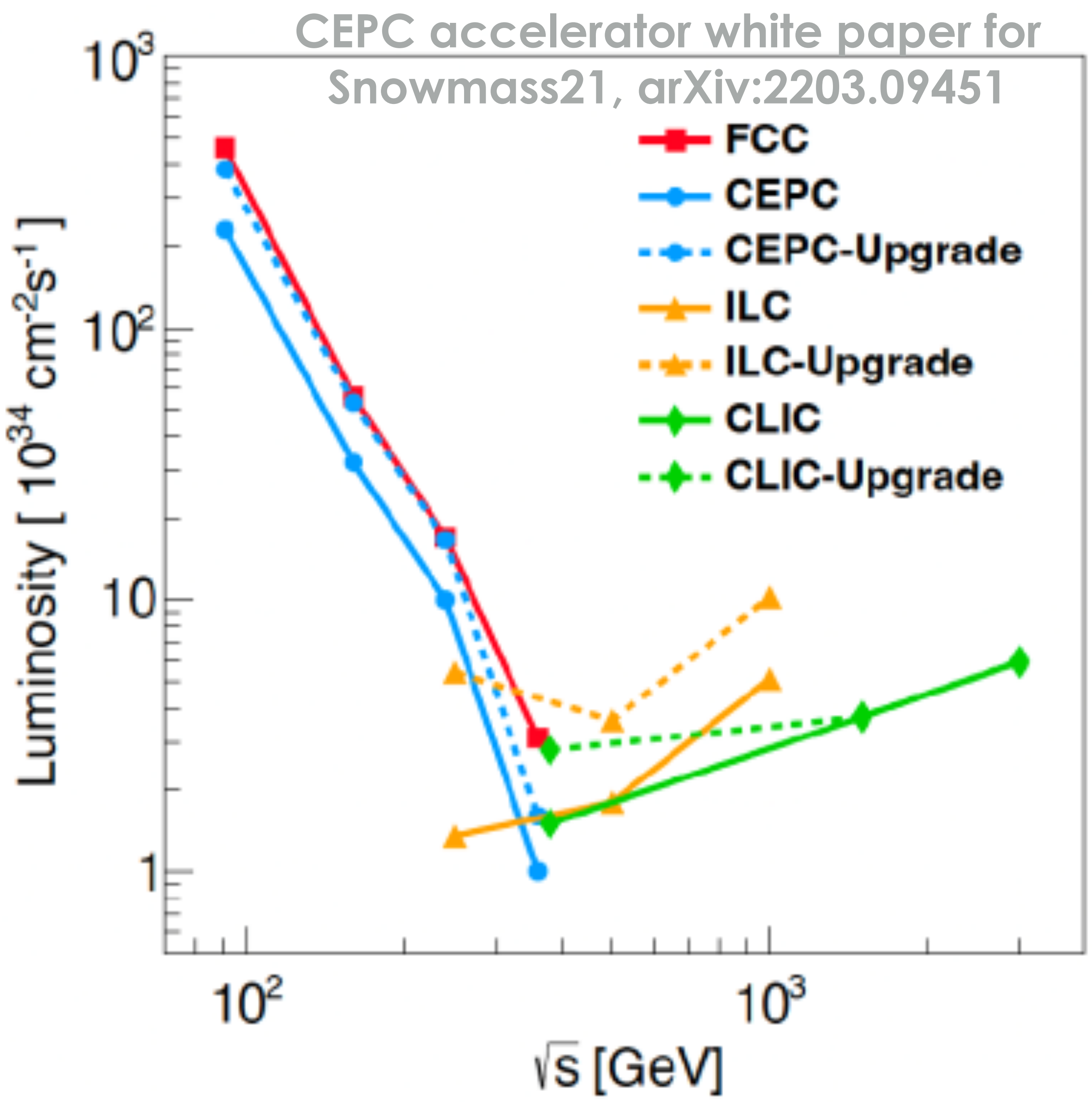
Precision physics exp. (EDMs, g-2…) usually constrains one operator.
Need a collider to have access to several of them and
then understand the underlying structure.

ee Higgs Factory Luminosity

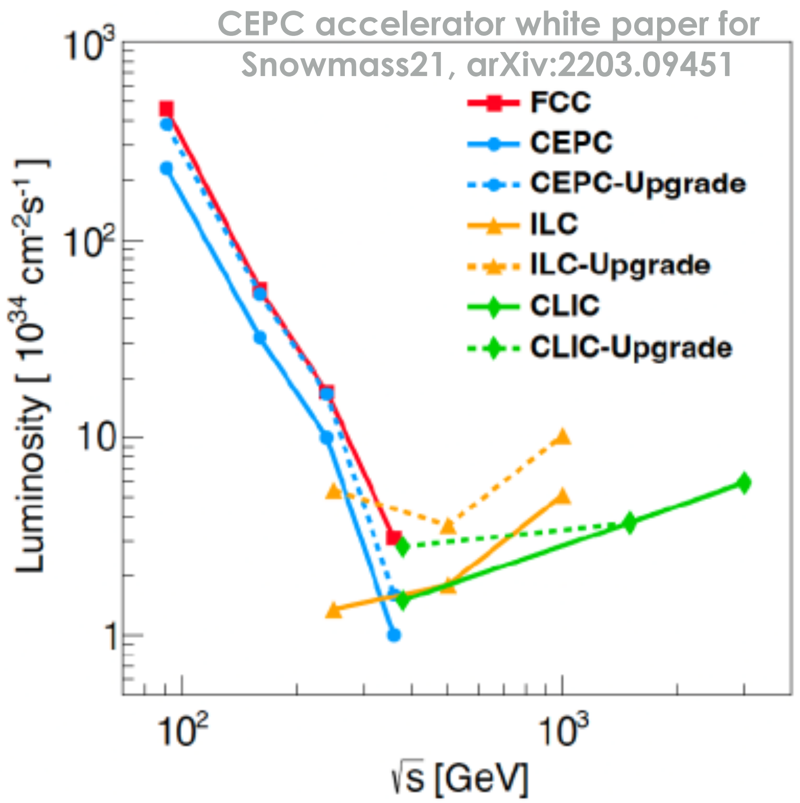


Linear collider can achieve Z-pole programme (10^6 Z) via radiative return or dedicated low luminosity run (10^9 Z).
Circular collider can collect 10^{12} Z in only a few years.

CEPC 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)



CEPC accelerator white paper for Snowmass21, arXiv:2203.09451

CEPC Operation mode		ZH	Z	W^+W^-	ttbar
		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	***L* / IP [$\times 10^{34}$ cm^{-2}s^{-1}]**	3	32	10	-
	[ab^{-1}, 2 IPs]	5.6	16	2.6	-
	Event yields [2 IPs]	**1×10^6**	**7×10^{11}**	**2×10^7**	-
Run time [years]		10	2	1	5
Latest (50MW)	***L* / IP [$\times 10^{34}$ cm^{-2}s^{-1}]**	8.3	192	27	0.83
	[ab^{-1}, 2 IPs]	20	96	7	1
	Event yields [2 IPs]	**4×10^6**	**4×10^{12}**	**5×10^7**	**5×10^5**

João Guimarães @ CEPC22

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

— Superb statistics achieved in only 18 years —

CEPC Physics Programme

FCC-ee
CEPC

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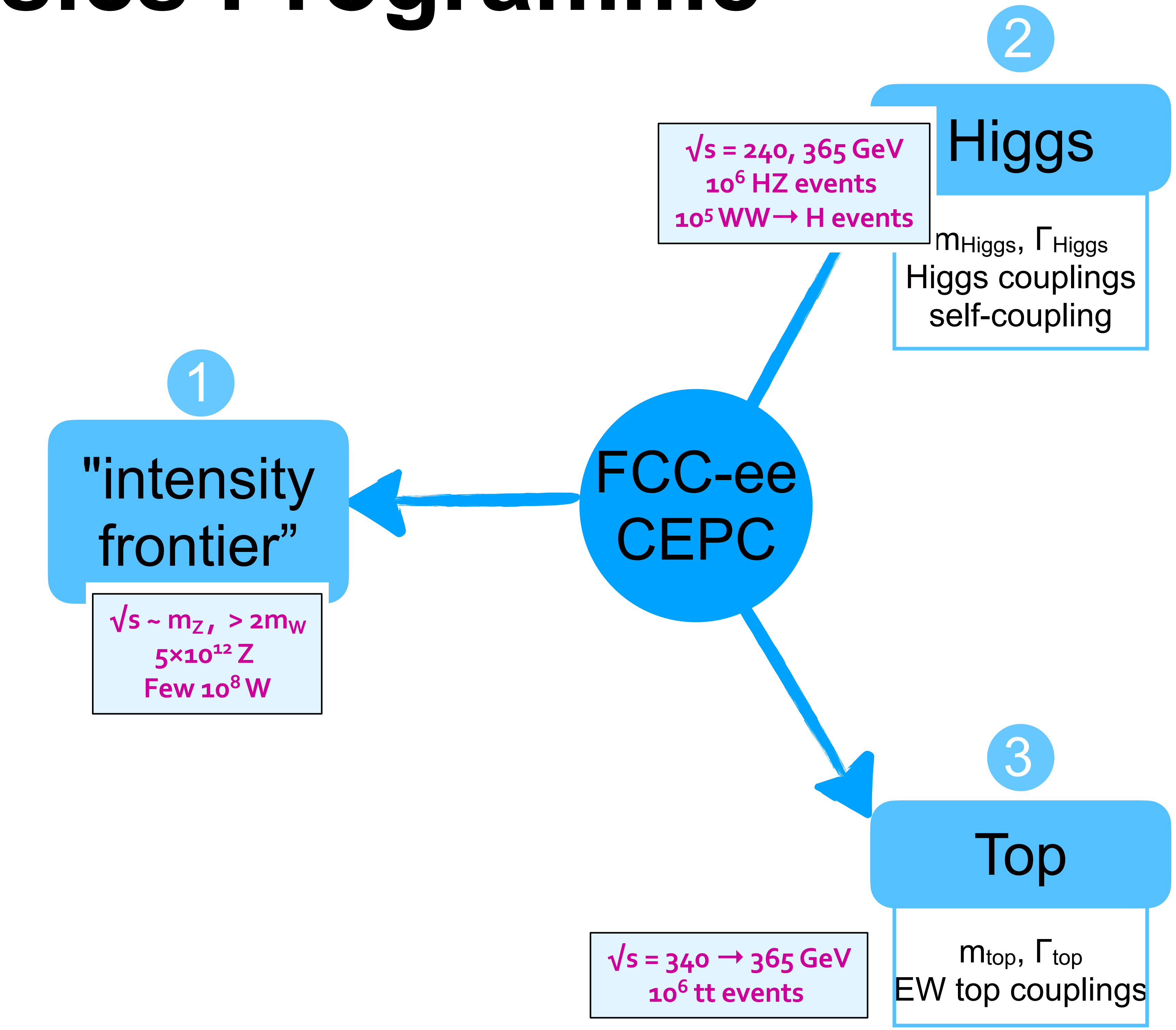


FCC-ee
CEPC

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

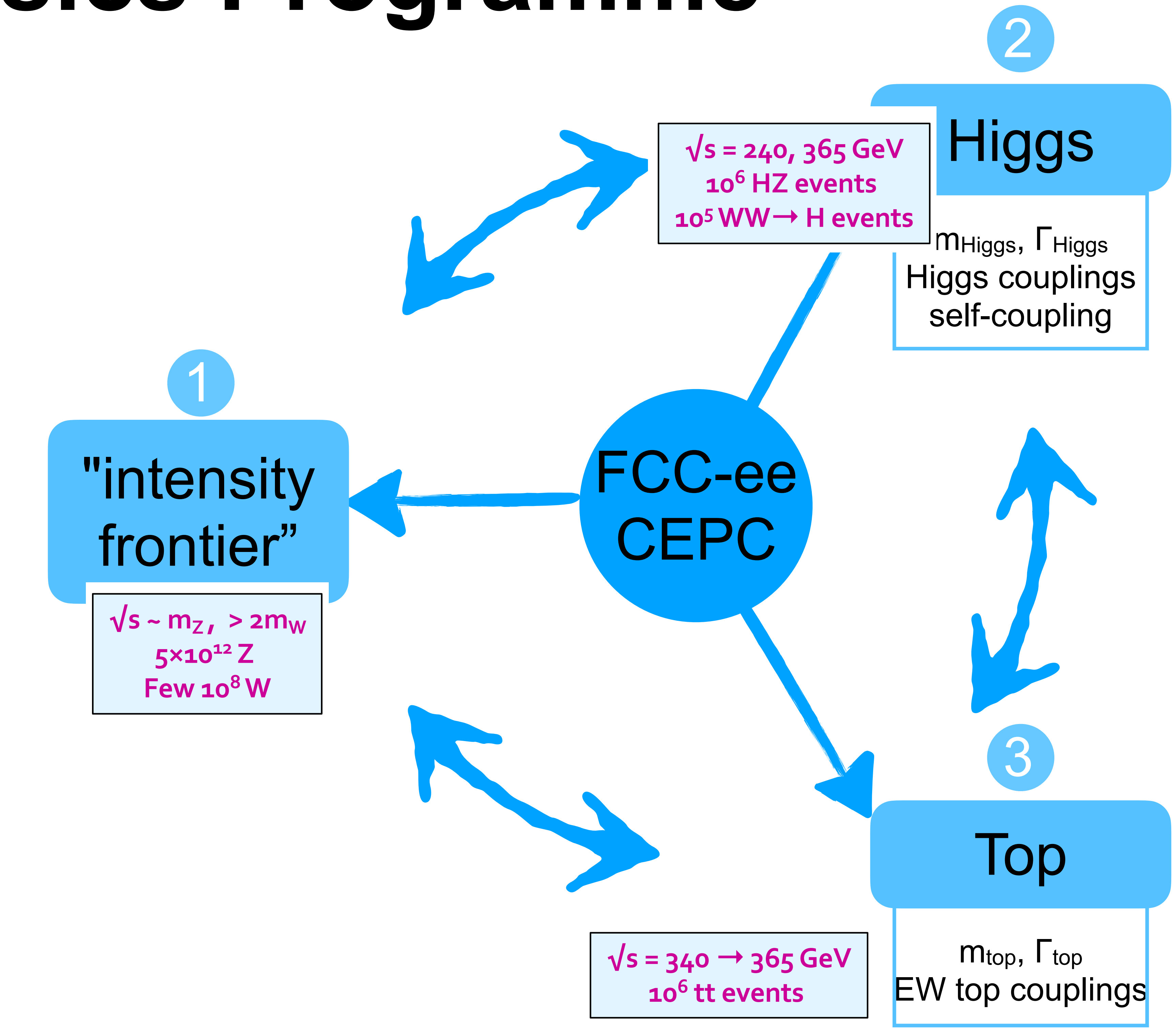
m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

3
Top

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

m_{top}, Γ_{top}
EW top couplings

CEPC Physics Programme



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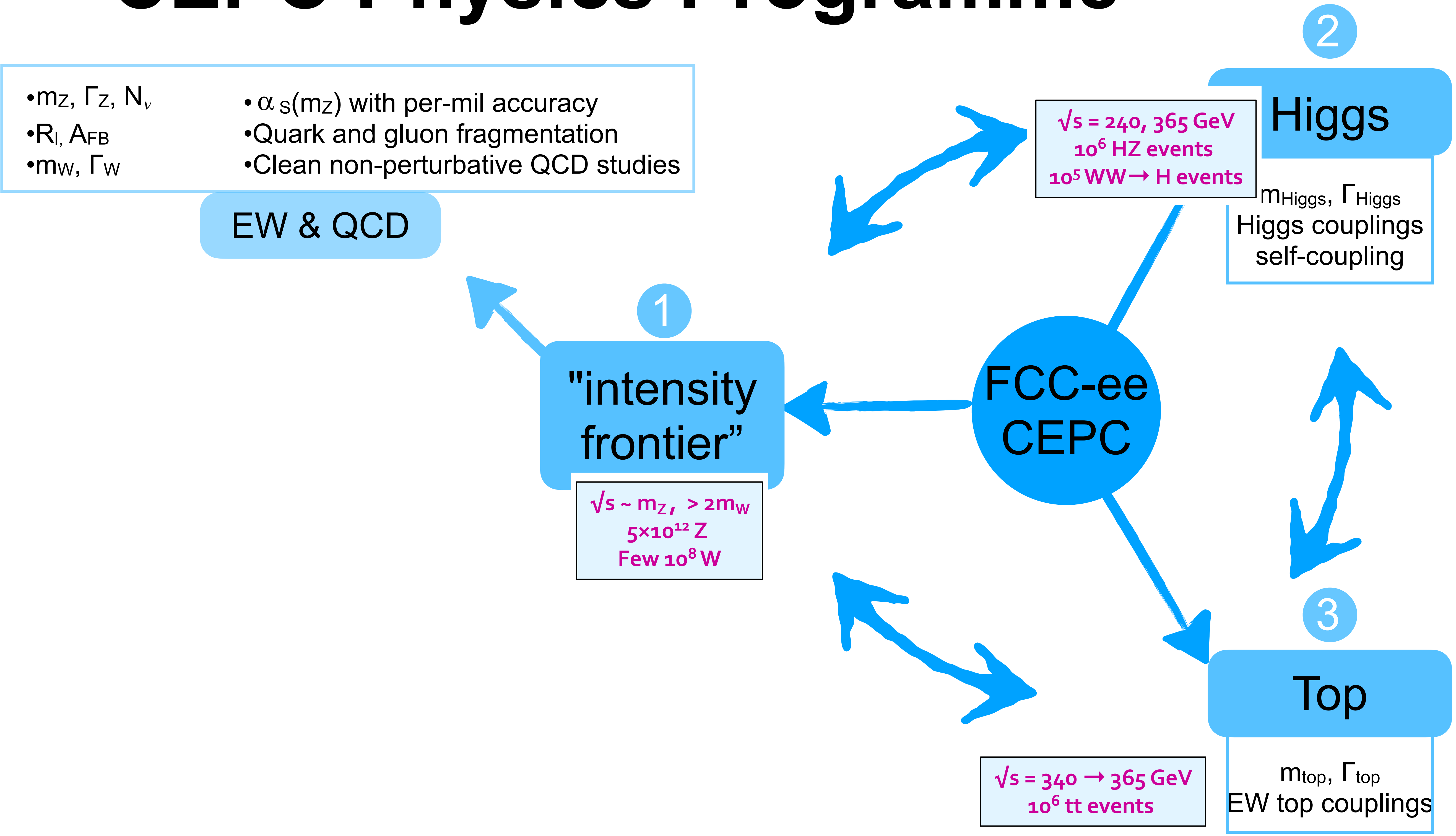

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W

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

EW & QCD

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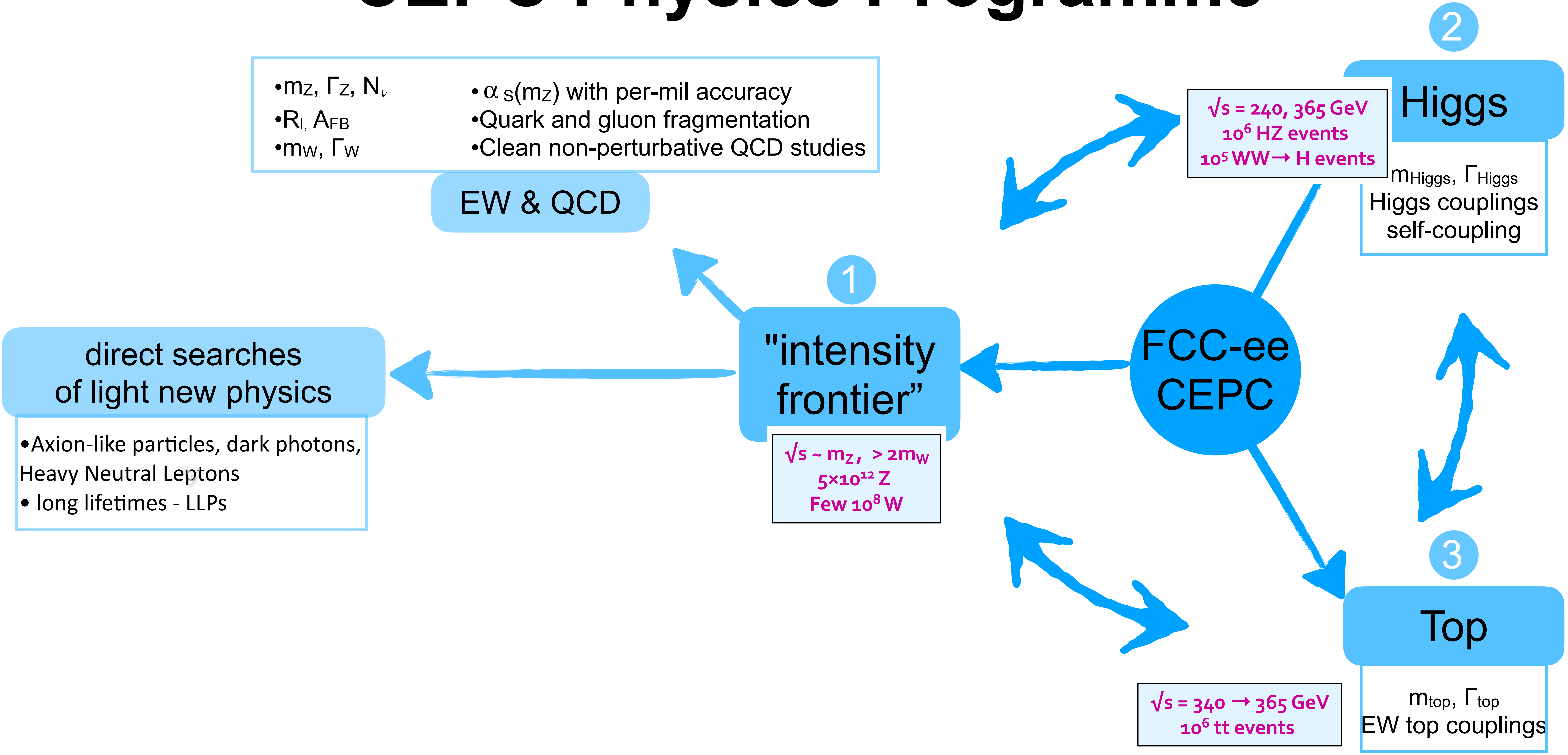

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direct searches
of light new physics

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

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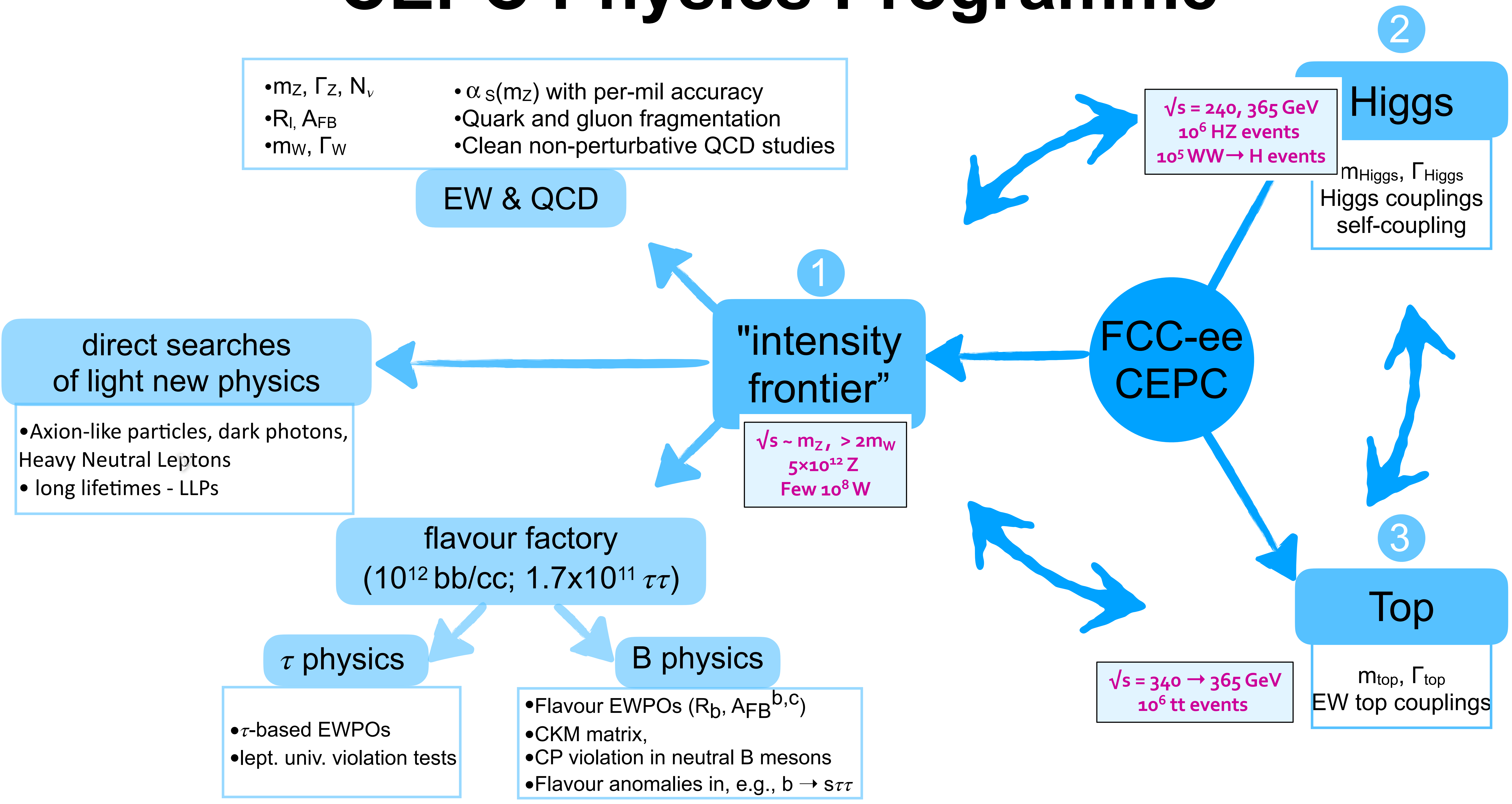

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flavour factory
(10^{12} bb/cc; $1.7\text{x}10^{11}$ $\tau\tau$)

τ physics

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

B physics

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

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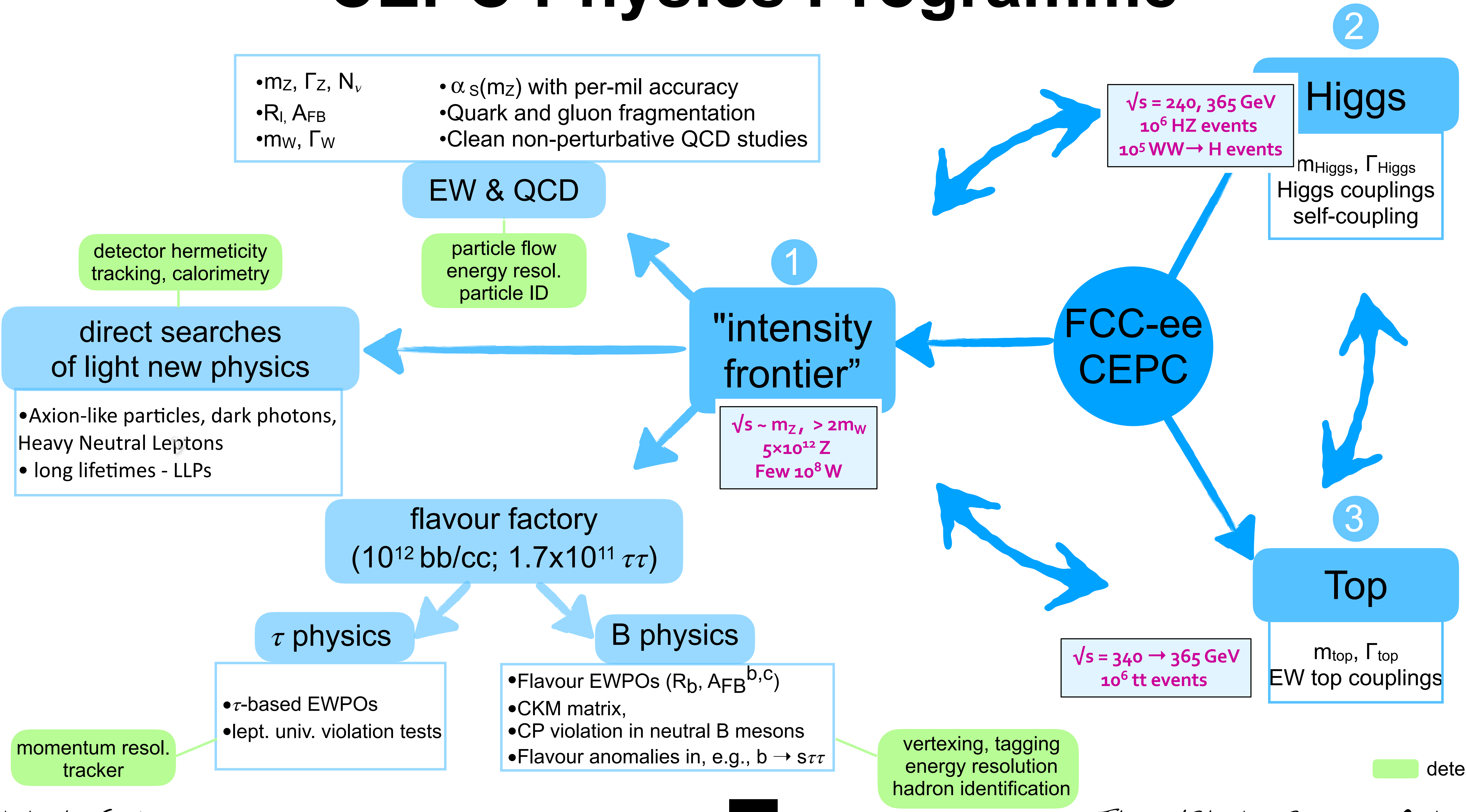

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EW & QCD

particle flow
energy resol.
particle ID

detector hermeticity
tracking, calorimetry

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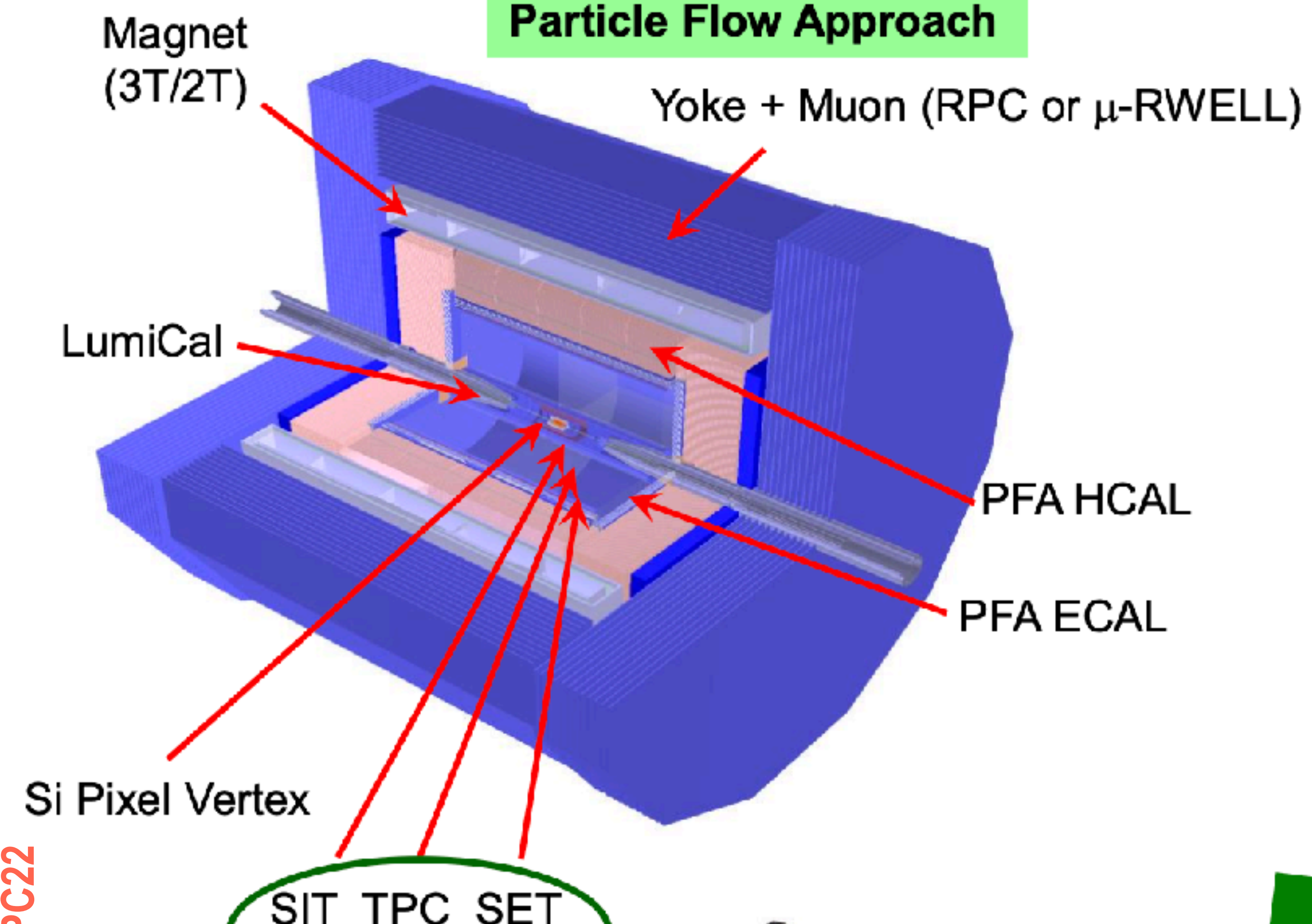
vertexing, tagging
energy resolution
hadron identification

🟩 detector req.

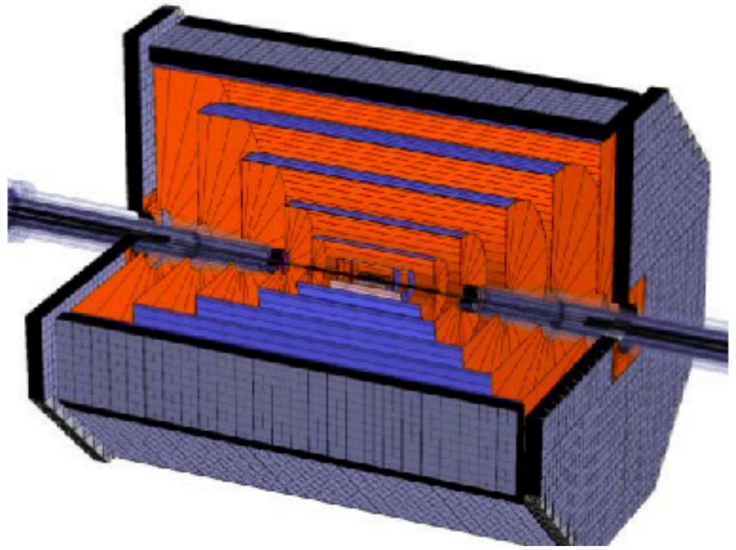
CEPC Physics Programme

CDR

(Baseline Design)
Particle Flow Approach

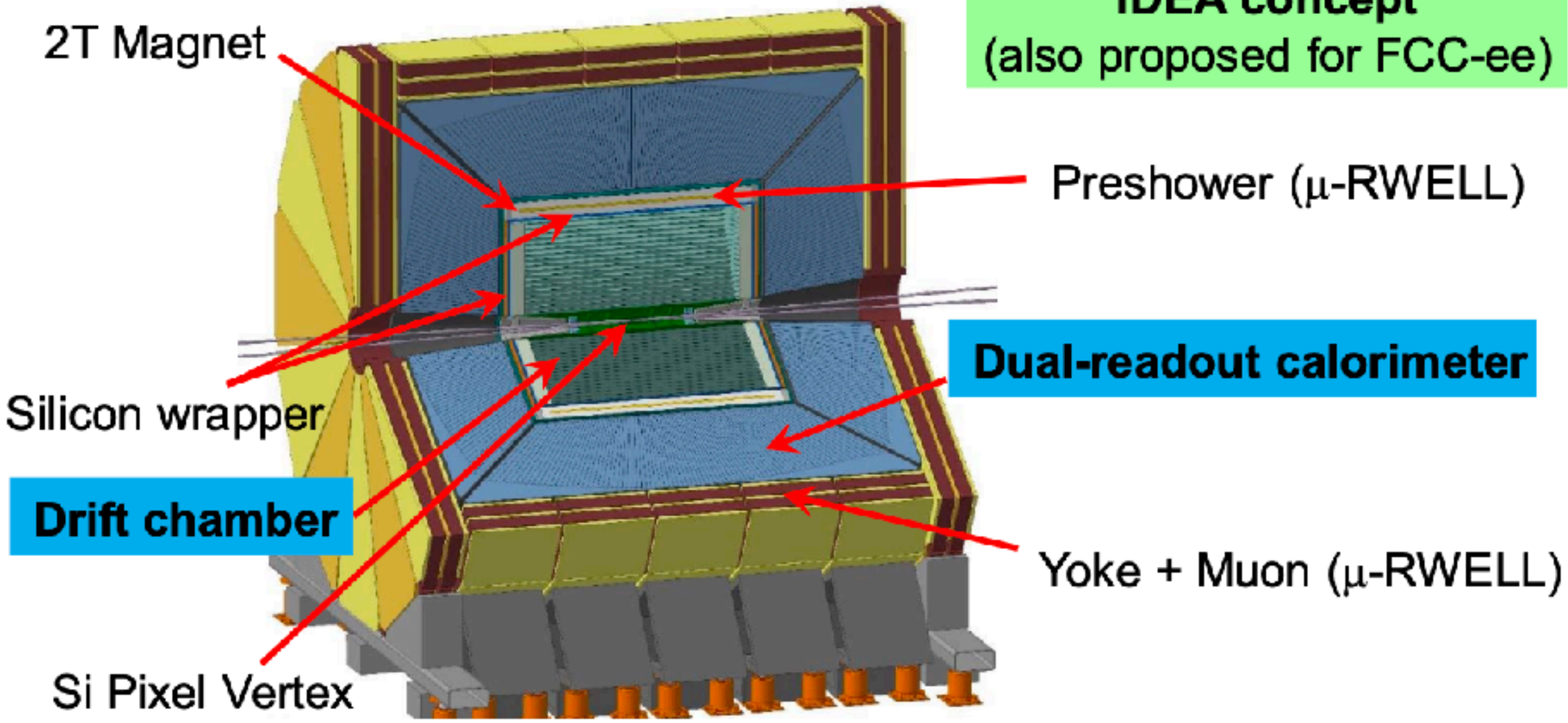


SIT TPC SET
FTD ETD



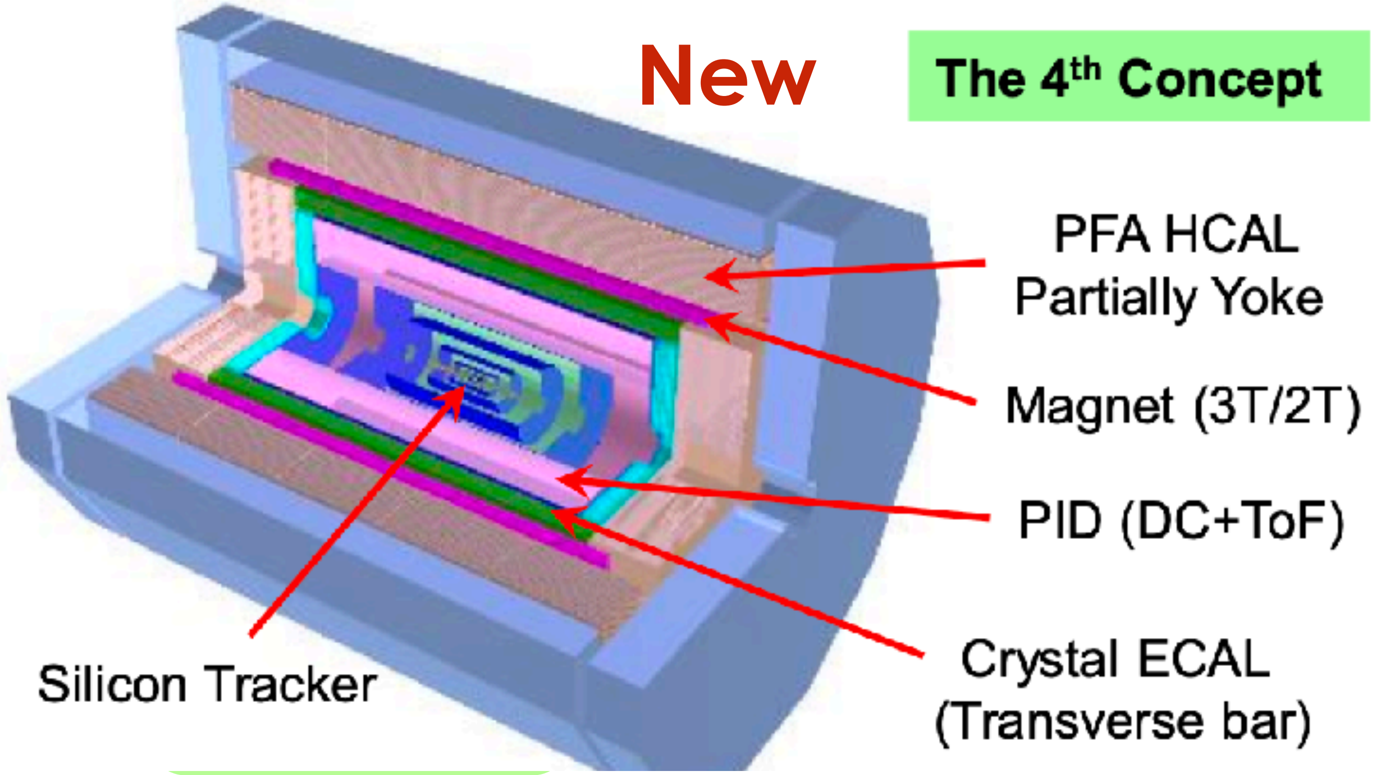
FST concept
(Full Silicon Tracker)

IDEA concept
(also proposed for FCC-ee)



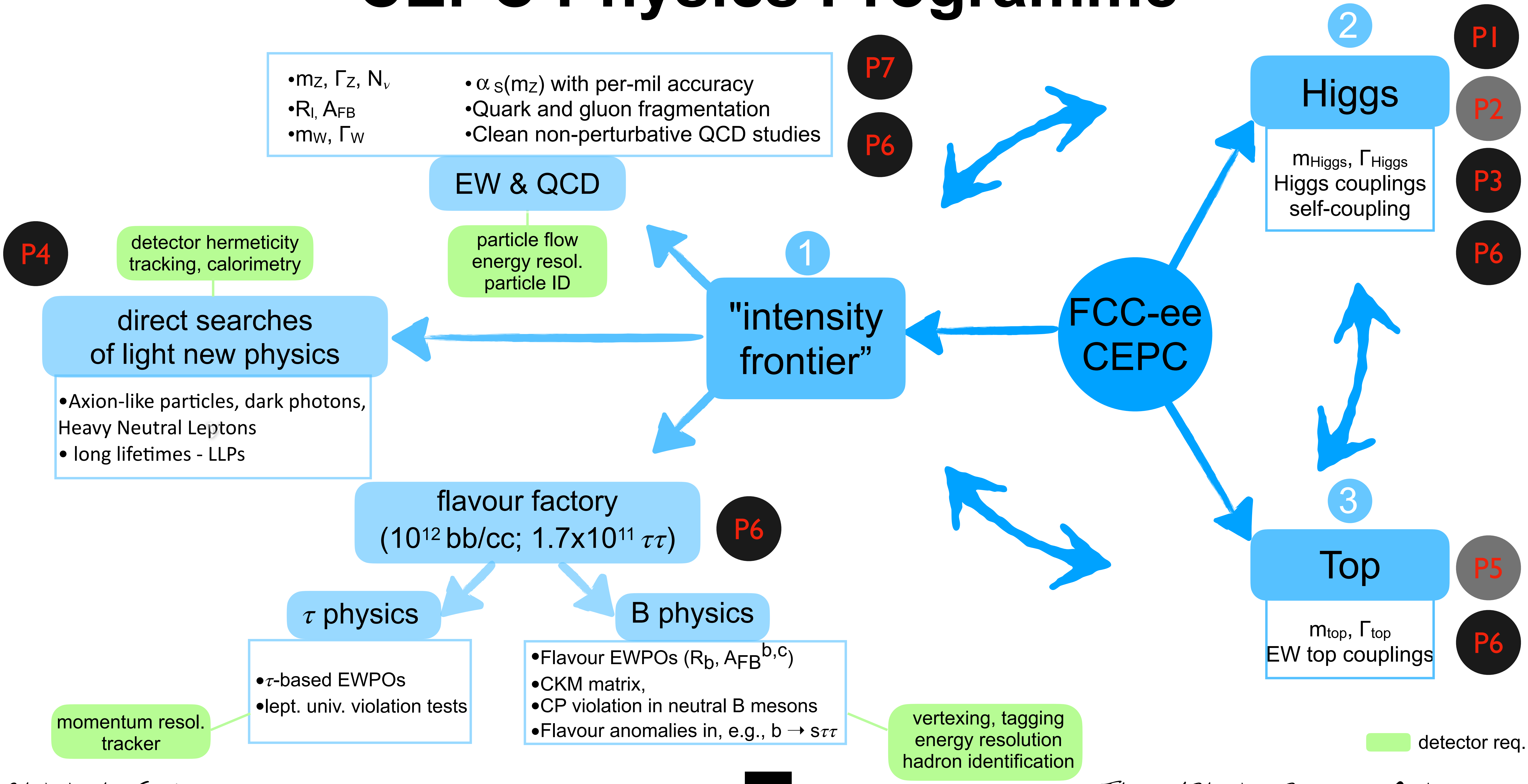
New

The 4th Concept



João Guimarães @ CEPC22

CEPC 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

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
CEPC

2

Higgs

P1

P2

P3

P6

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

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

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

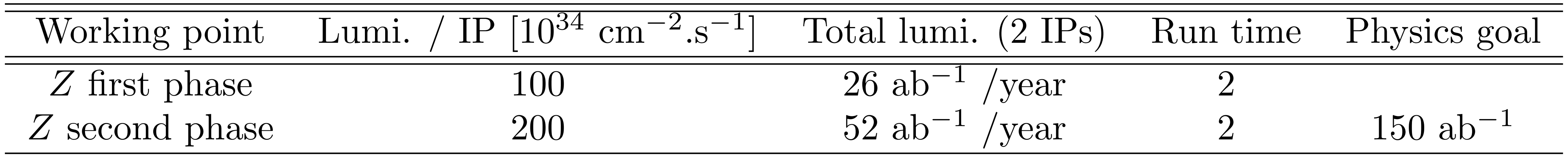
T8	T9	T10	T11	T12-T13	T14-T15	T16
Stability and calibration of collision energy	Beam stability and luminosity calibration	Ability to control beam-related backgrounds	Ability to provide independent confirmation of new discoveries	Ability to provide polarised electrons/ positrons	Possibility to reconfigure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

T17
Need for, and scientific utility of, technology demonstrators

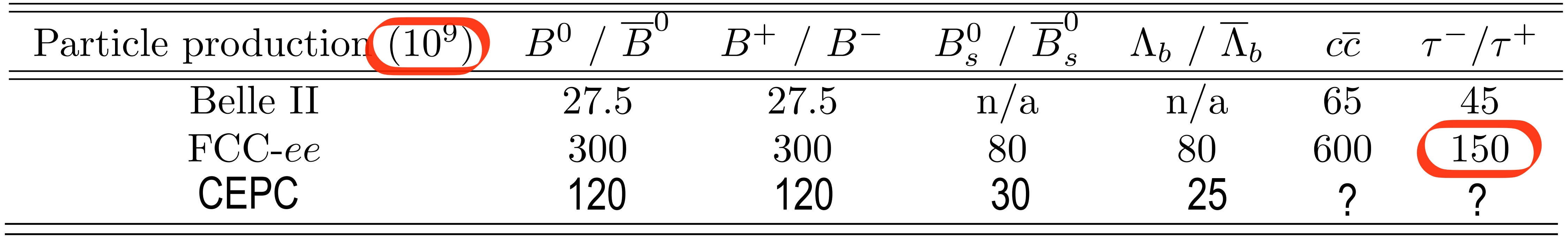
Z-Factories are great Flavour Factories

S. Monteil, Flavour@FCC '22

T. H. Kwok CEPC'22

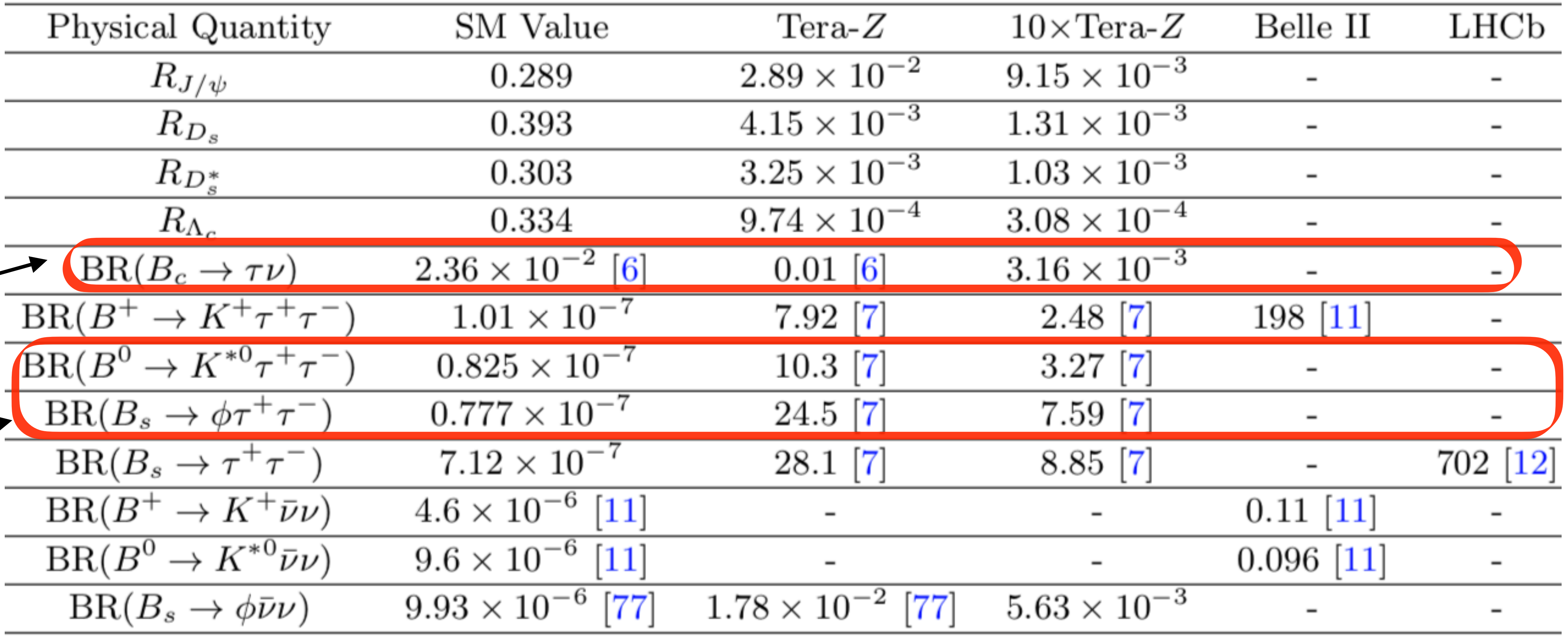


Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}



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
CEPC	120	120	30	25	?	?

large rates
clean envrmt



Physical Quantity	SM Value	Tera-Z	10×Tera-Z	Belle II	LHCb
$R_{J/\psi}$	0.289	2.89×10^{-2}	9.15×10^{-3}	-	-
R_{D_s}	0.393	4.15×10^{-3}	1.31×10^{-3}	-	-
$R_{D_s^*}$	0.303	3.25×10^{-3}	1.03×10^{-3}	-	-
R_{Λ_c}	0.334	9.74×10^{-4}	3.08×10^{-4}	-	-
BR($B_c \to \tau\nu$)	2.36×10^{-2} [6]	0.01 [6]	3.16×10^{-3}	-	-
BR($B^+ \to K^+\tau^+\tau^-$)	1.01×10^{-7}	7.92 [7]	2.48 [7]	198 [11]	-
BR($B^0 \to K^{*0}\tau^+\tau^-$)	0.825×10^{-7}	10.3 [7]	3.27 [7]	-	-
BR($B_s \to \phi\tau^+\tau^-$)	0.777×10^{-7}	24.5 [7]	7.59 [7]	-	-
BR($B_s \to \tau^+\tau^-$)	7.12×10^{-7}	28.1 [7]	8.85 [7]	-	702 [12]
BR($B^+ \to K^+\bar{\nu}\nu$)	4.6×10^{-6} [11]	-	-	0.11 [11]	-
BR($B^0 \to K^{*0}\bar{\nu}\nu$)	9.6×10^{-6} [11]	-	-	0.096 [11]	-
BR($B_s \to \phi\bar{\nu}\nu$)	9.93×10^{-6} [77]	1.78×10^{-2} [77]	5.63×10^{-3}	-	-

out of reach
at LHCb/Belle

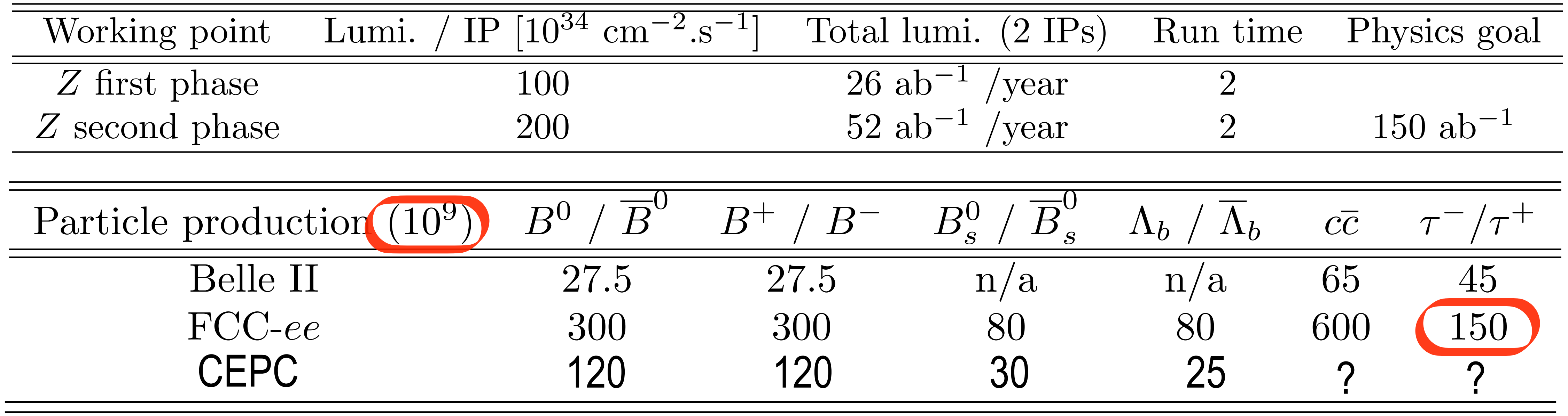
boosted b's/τ's
at Z-factory

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

Z-Factories are great Flavour Factories

S. Monteil, Flavour@FCC '22

T. H. Kwok CEPC'22



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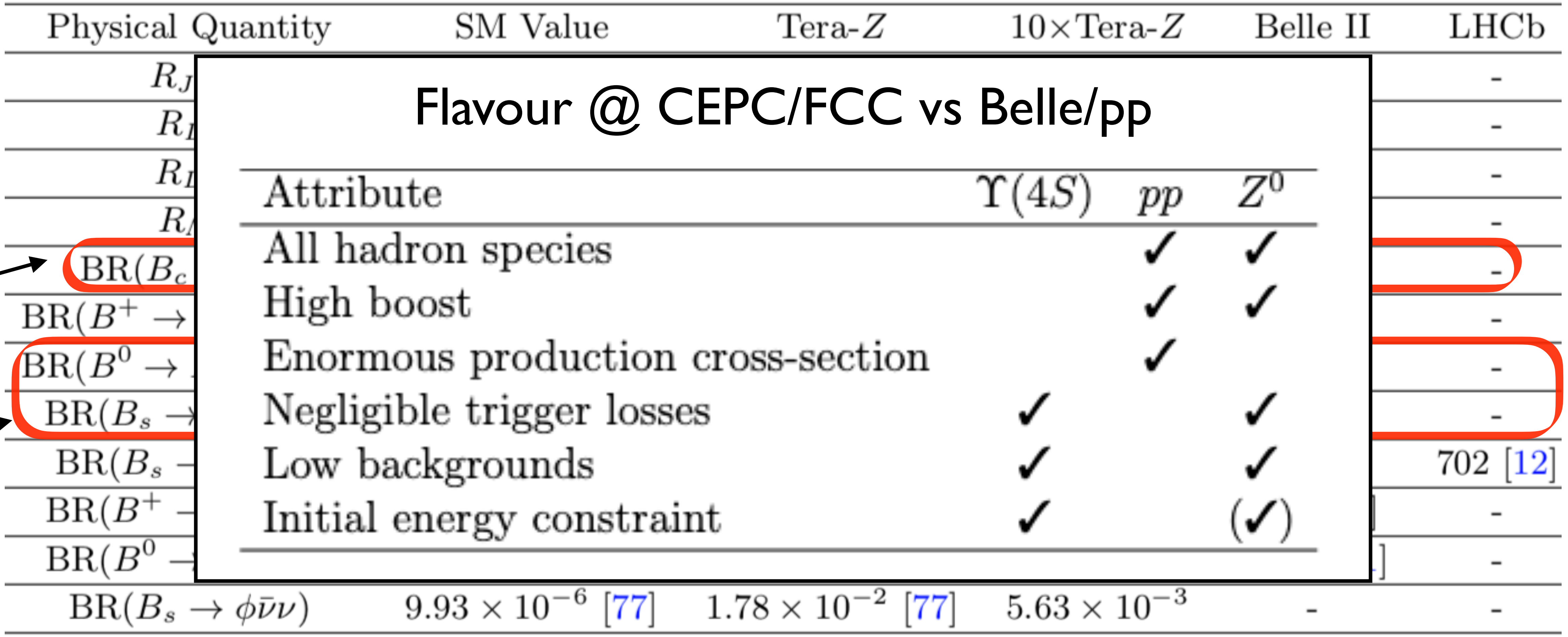

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R_J					-
R_I					-
R_I					-
R_I					-
BR(B_c					-
BR($B^+ \to$					-
BR($B^0 \to$					-
BR($B_s \to$					-
BR(B_s –					702 [12]
BR(B^+ –					-
BR(B^0 –					-
BR($B_s \to \phi\bar{\nu}\nu$)	9.93×10^{-6} [77]	1.78×10^{-2} [77]	5.63×10^{-3}	-	-

Flavour @ CEPC/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	✓		(✓)

out of reach
at LHCb/Belle

boosted b's/τ's
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Makes possible
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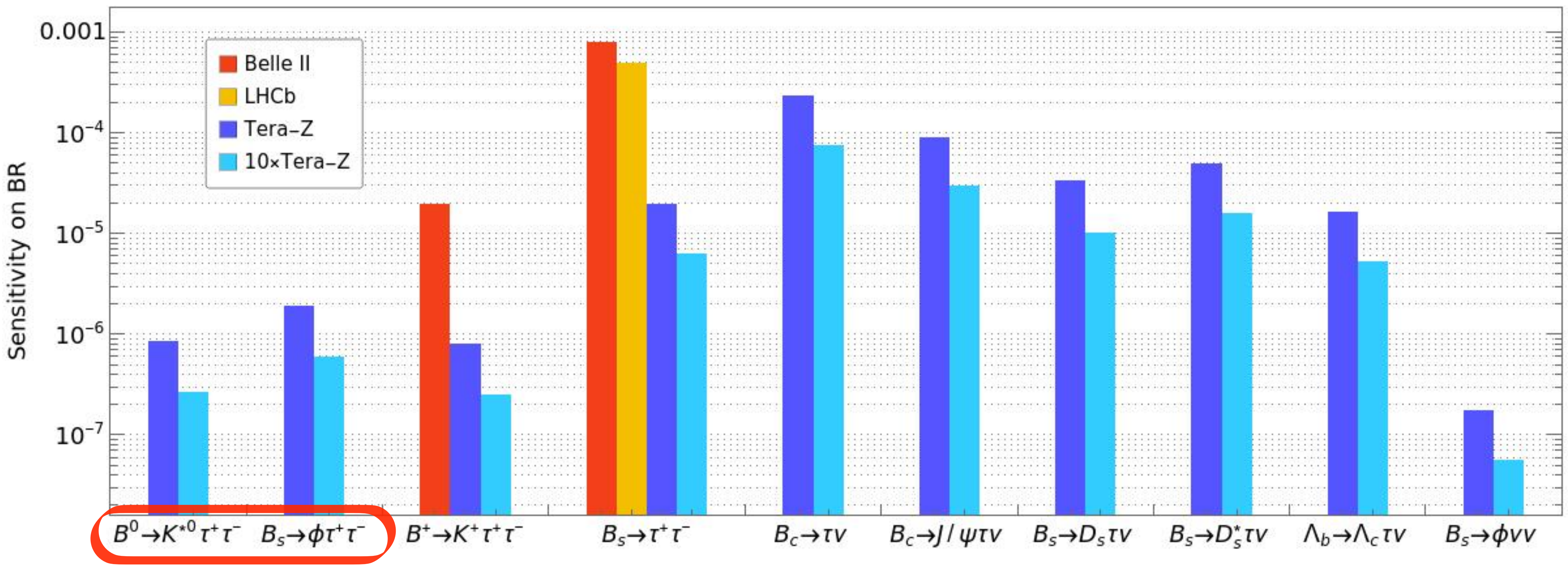
w/ miss. energy

Lepton Flavour Universality Tests



out of reach at LHCb/Belle

b→s$\tau\tau$

best probes of models addressing R_{K^*} LHCb anomalies

W. Altmannshofer CEPC'22

T. H. Kwok CEPC'22

X. Jiang CEPC'22

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FCCC

b→c

$$R_{J/\psi} = \frac{\mathrm{Br}\,(B_c \to J/\psi\tau\nu)}{\mathrm{Br}\,(B_c \to J/\psi\mu\nu)}$$

$$R_{D_s^{(*)}} = \frac{\mathrm{Br}\,(B_s \to D_s^{(*)}\tau\nu)}{\mathrm{Br}\,(B_s \to D_s^{(*)}\mu\nu)}$$

$$R_{\Lambda_c} = \frac{\mathrm{Br}\,(\Lambda_b \to \Lambda_c\tau\nu)}{\mathrm{Br}\,(\Lambda_b \to \Lambda_c\mu\nu)}$$

Lepton Flavour Universality Tests

T. H. Kwok CEPC'22

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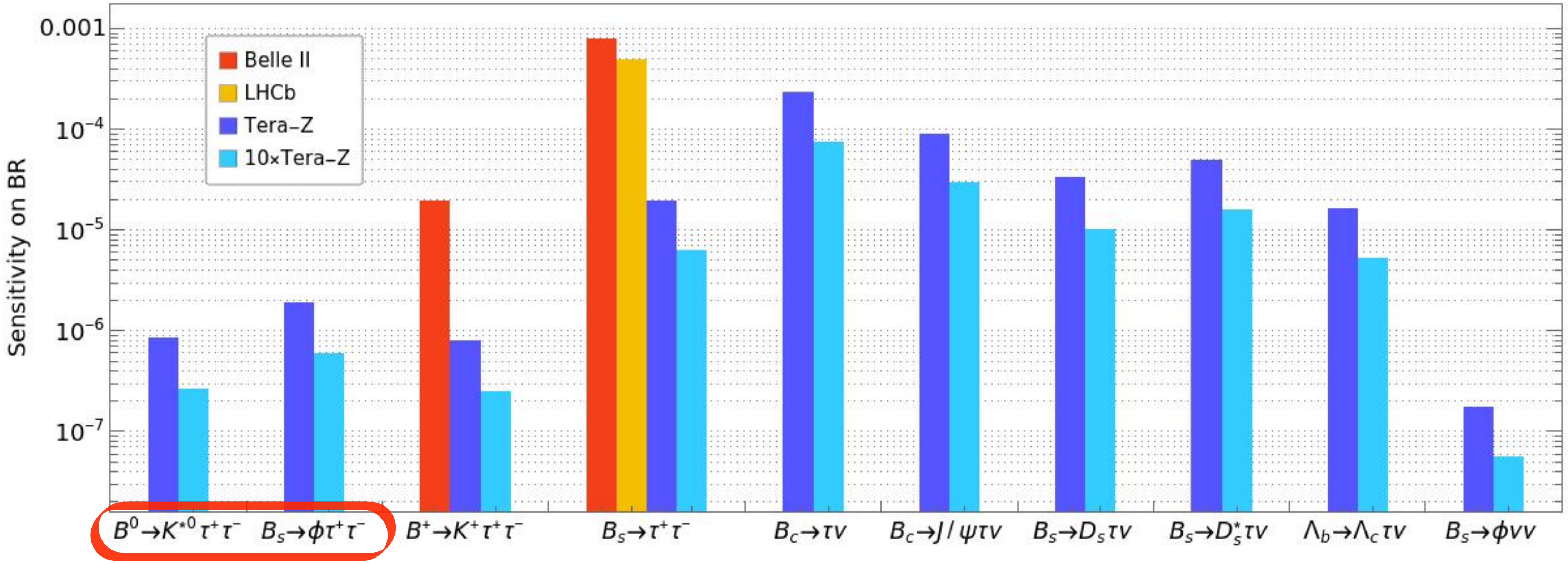

out of reach at LHCb/Belle

b→s$\tau\tau$

best probes of models addressing R_{K^*} LHCb anomalies

W. Altmannshofer CEPC'22

New proposal: time-dependent analysis to probe CP-violation in interference in mixing and decay

S. Decotes-Genon CEPC'22

FCCC b→c

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$$R_{J/\psi}=\frac{\mathrm{Br}\,(B_c\to J/\psi\tau\nu)}{\mathrm{Br}\,(B_c\to J/\psi\mu\nu)}$$

$$R_{D_s^{(*)}}=\frac{\mathrm{Br}\,(B_s\to D_s^{(*)}\tau\nu)}{\mathrm{Br}\,(B_s\to D_s^{(*)}\mu\nu)}$$

$$R_{\Lambda_c}=\frac{\mathrm{Br}\,(\Lambda_b\to\Lambda_c\tau\nu)}{\mathrm{Br}\,(\Lambda_b\to\Lambda_c\mu\nu)}$$

τ Physics

"3 more tau's than at Belle II"

Z factory produces $\sim \mathcal{O}(10^{10})$ $\tau^+\tau^-$ pairs from $Z \to \tau^+\tau^-$

- Measuring BR($\tau \to \ell\nu\bar{\nu}$)

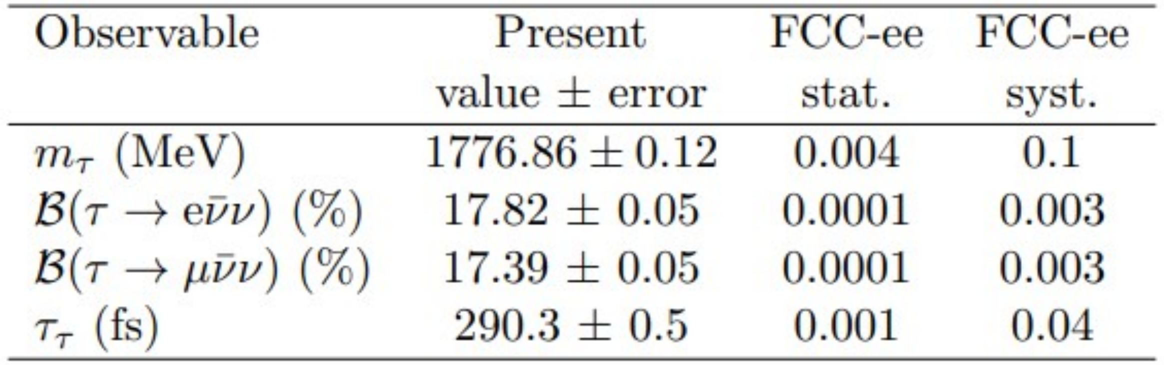
  Improvement: $\sim \mathcal{O}(10^2)$

- Measuring τ lifetime

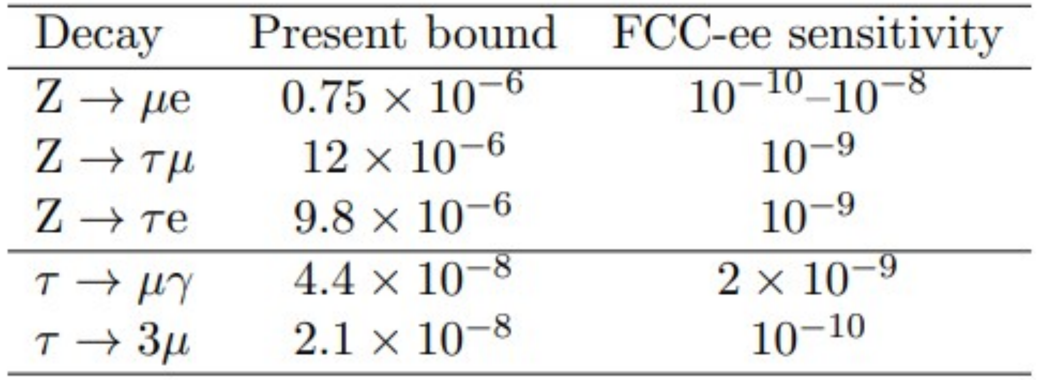
  Improvement: $\sim \mathcal{O}(10^3)$

- Measuring BR($\tau \to 3\mu$) and BR($\tau \to \mu\gamma$)

  Improvement: $\sim \mathcal{O}(10 - 10^2)$



Observable	Present value $\pm$ error	FCC-ee stat.	FCC-ee syst.
m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
$\mathcal{B}(\tau \to e\bar{\nu}\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
$\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

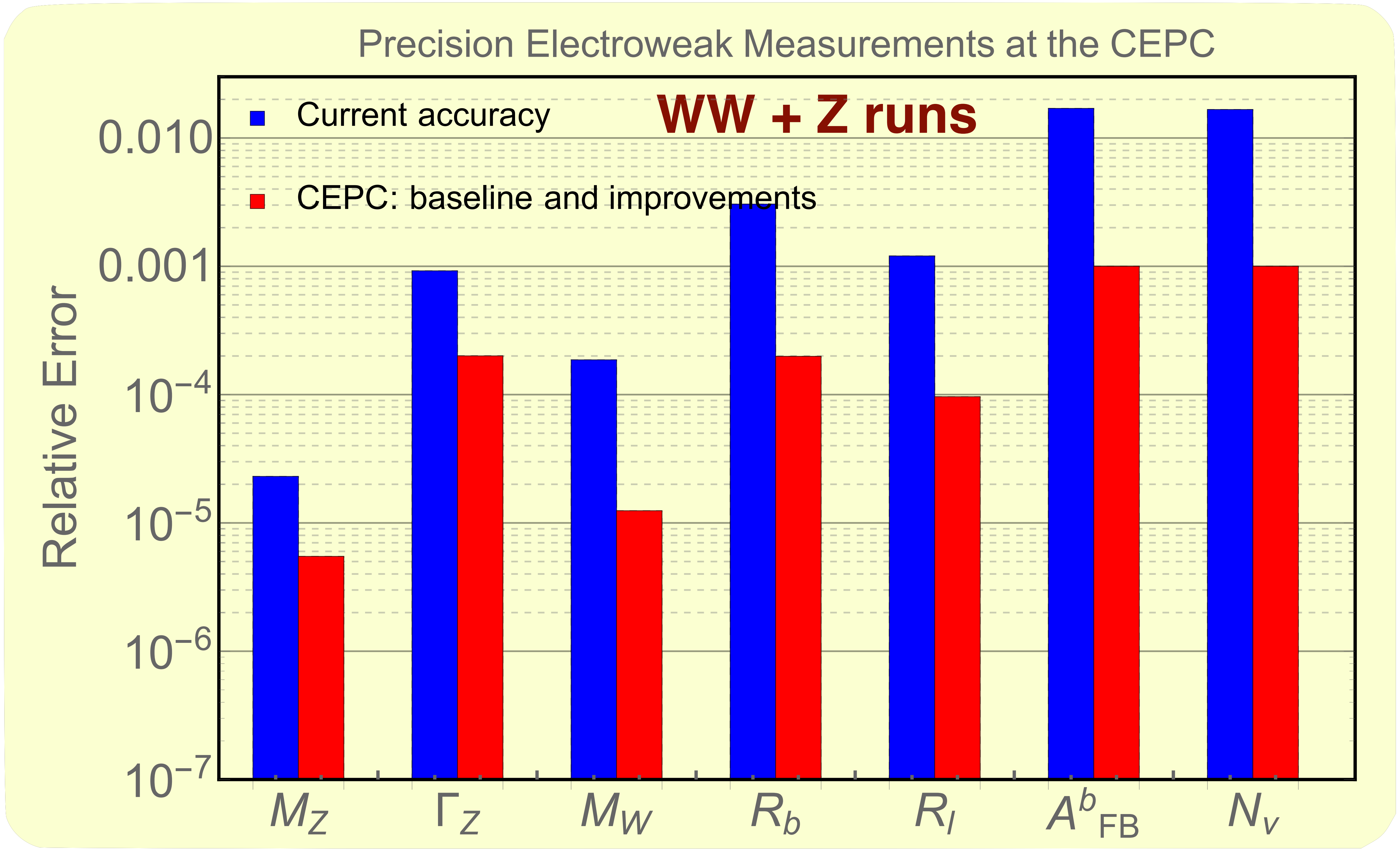


Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

Strong bounds on LFV

T. H. Kwok CEPC'22

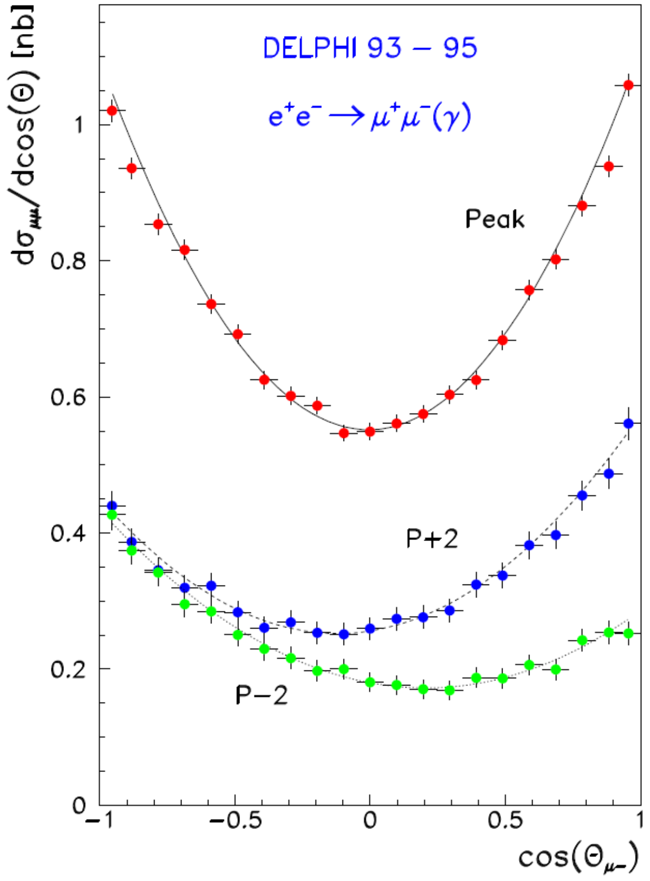
EW measurements @ Tera Z



João Guimarães @ CEPC22

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 ←

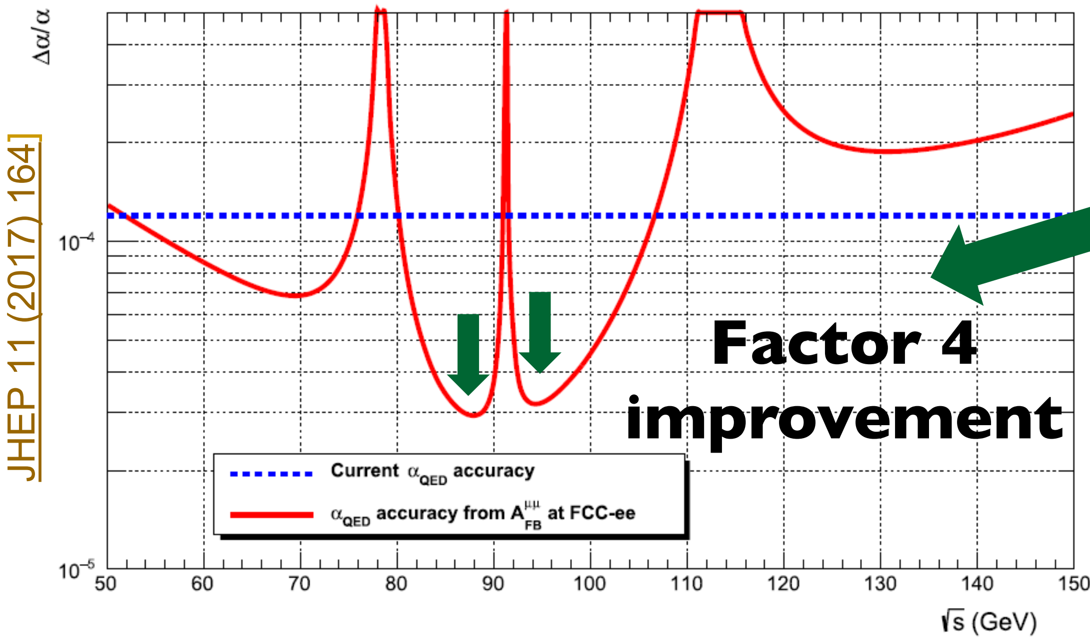
direct measurement of $\alpha_{QED}(s)$ at √s != m_Z ←

measure $\sin^2\theta_W$ to high precision ←

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

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 3x10^{-5} rel. precision (currently 1.1x10^{-4}) 80/ab

→ 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

— theory improvements needed —

→ $\delta(\Delta\alpha_{\text{had}}) \sim 3 \times 10^{-5}$ for $\mathcal{L}_{\text{int}} = 85\ \text{ab}^{-1}$

→ Requires 2/3-loop corrections for $e^+e^- \to \mu^+\mu^-$

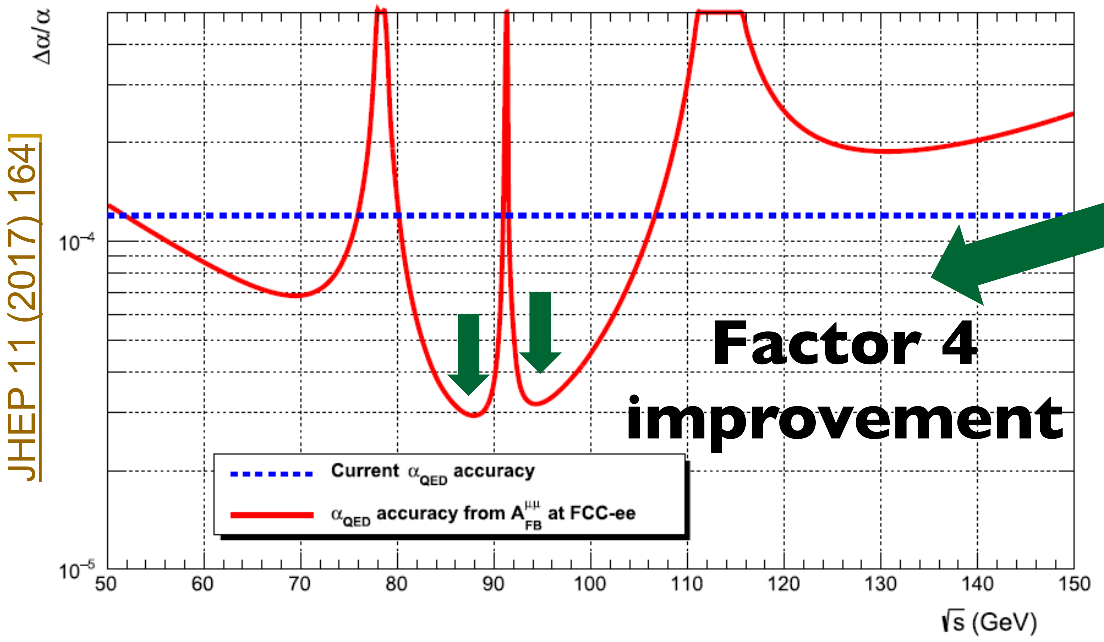
A. Freitas @ CEPC'22

G. Wilkinson @ FCC week 2021

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

P.Janot '16

[JHEP 02 (2016) 053.
JHEP 11 (2017) 164]



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

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

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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 $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ events:

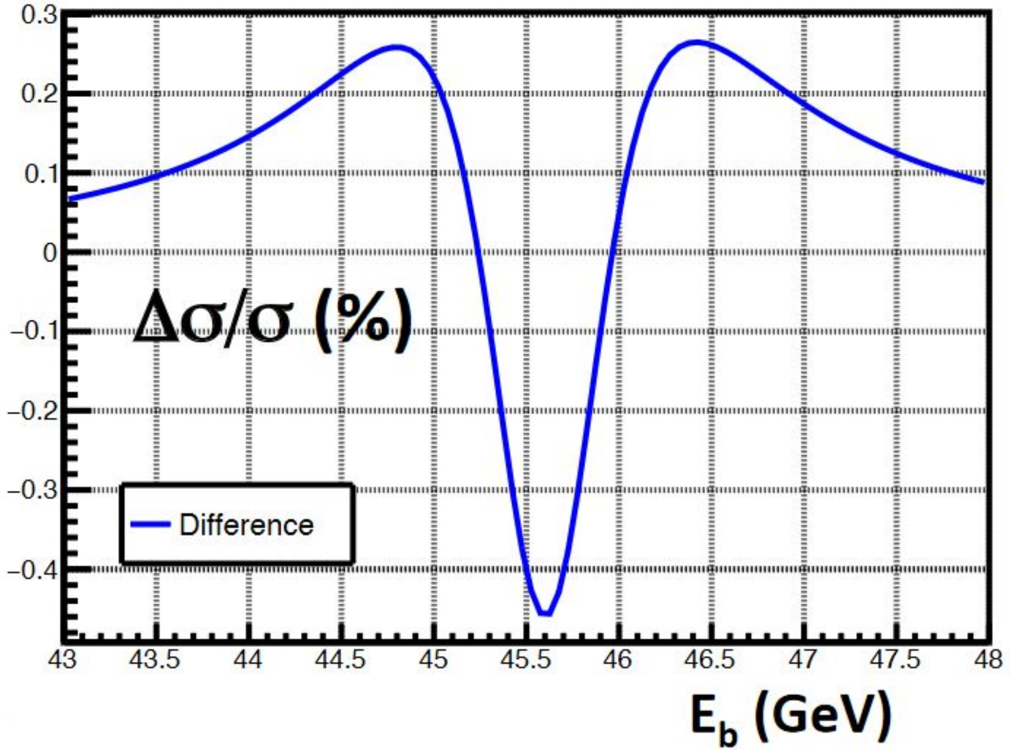
      → Constrain BES uncertainty to per-mille level
      → Taking into account asymmetric beam optics (x-angle α 30 mrad) and γ-ISR
      → Muon angular resolution ~ 0.1 mrad required

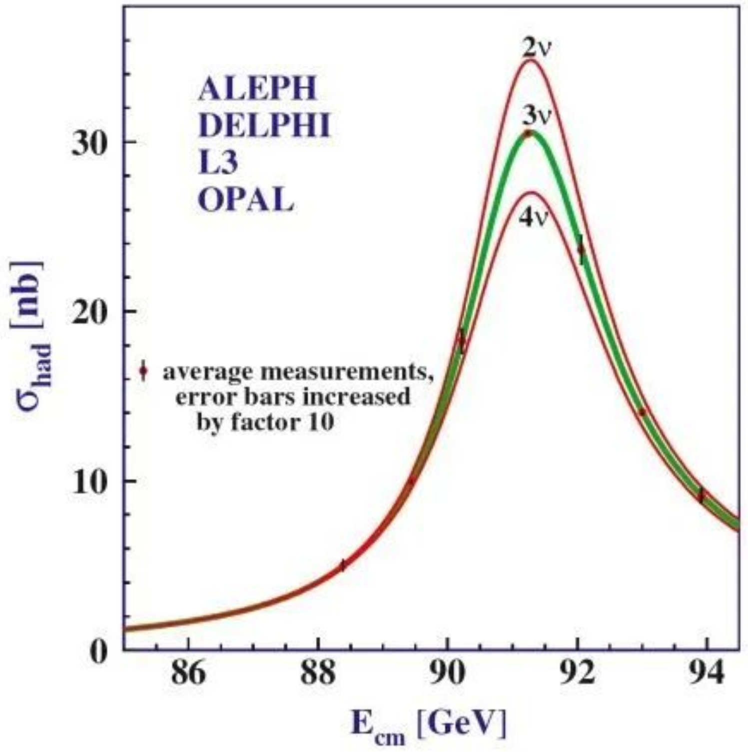
→ **Hadronic cross-section** σ^0_{had}: ± 4 pb [LEP 37 pb]

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

- 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 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

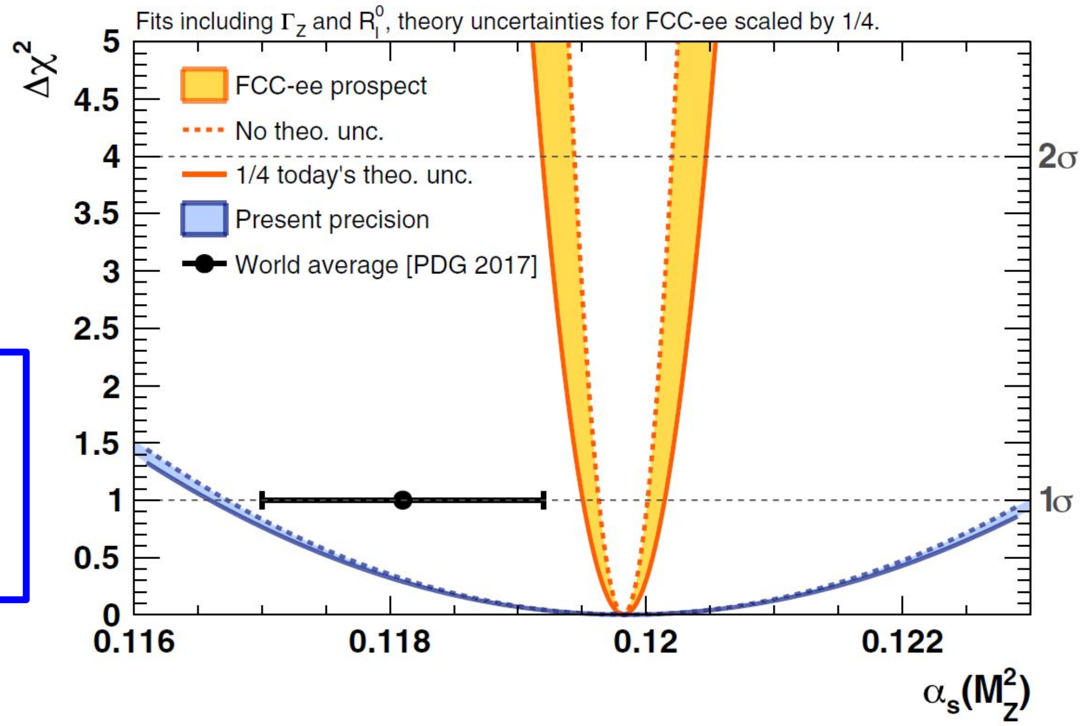
Relative unc. on couplings

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)

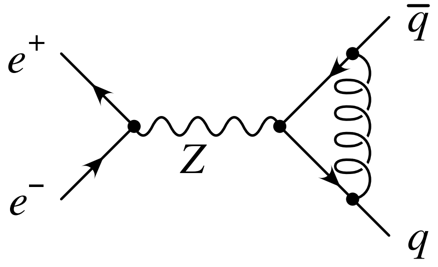


J. Eysermans @ EPS2021

Example of EW measurements @ Tera Z

— theory improvements needed —

→ No (negligible) non-perturbative QCD effects



Theory input: N^{3}LO EW corr. + leading N^{4}LO
to keep $\delta_{\rm th} R_\ell \lesssim \delta_{\rm exp} R_\ell$

A. Freitas @ CEPC'22

J. Eysermans @ EPS2021

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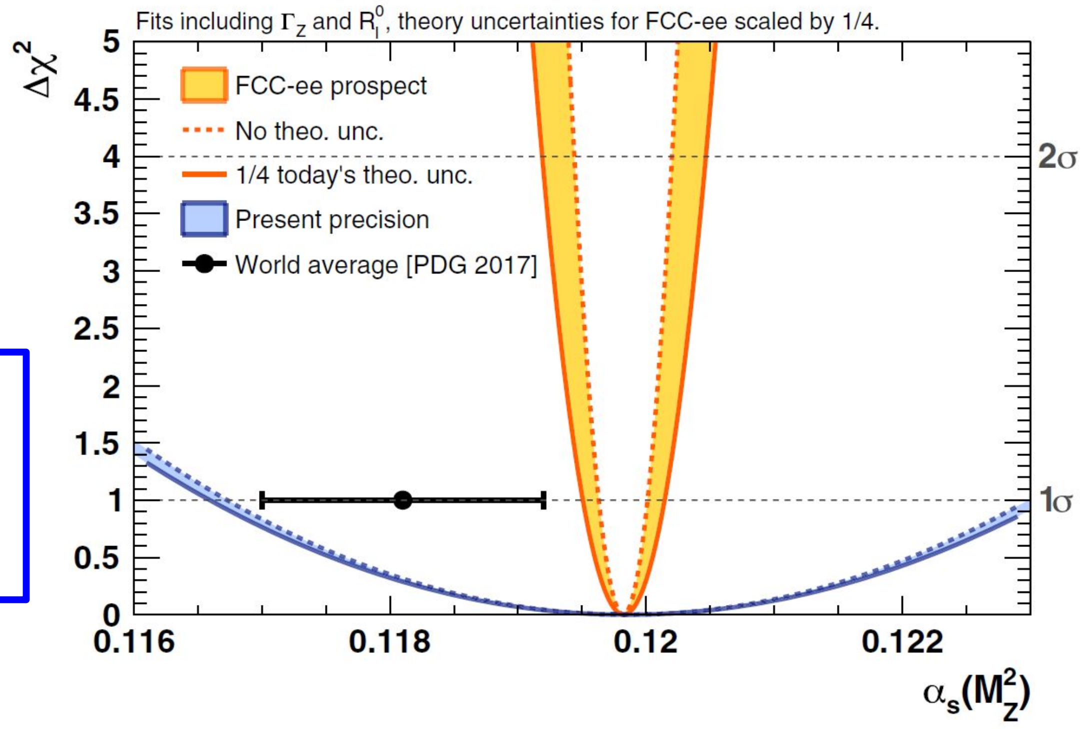

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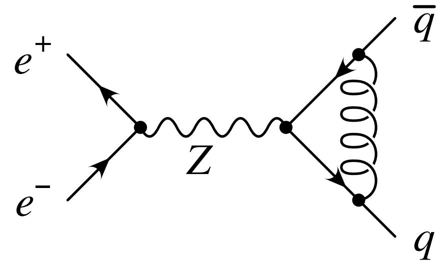

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A. Freitas @ CEPC'22

— other determination methods of α_s —

energy-energy correlators in collinear limit

S. Xu @ CEPC'22

see also S.Q. Wang @ CEPC'22

see also P. Nason @ CEPC'22 for a assessment of non-perturbative effects

Sensitivity on EW couplings

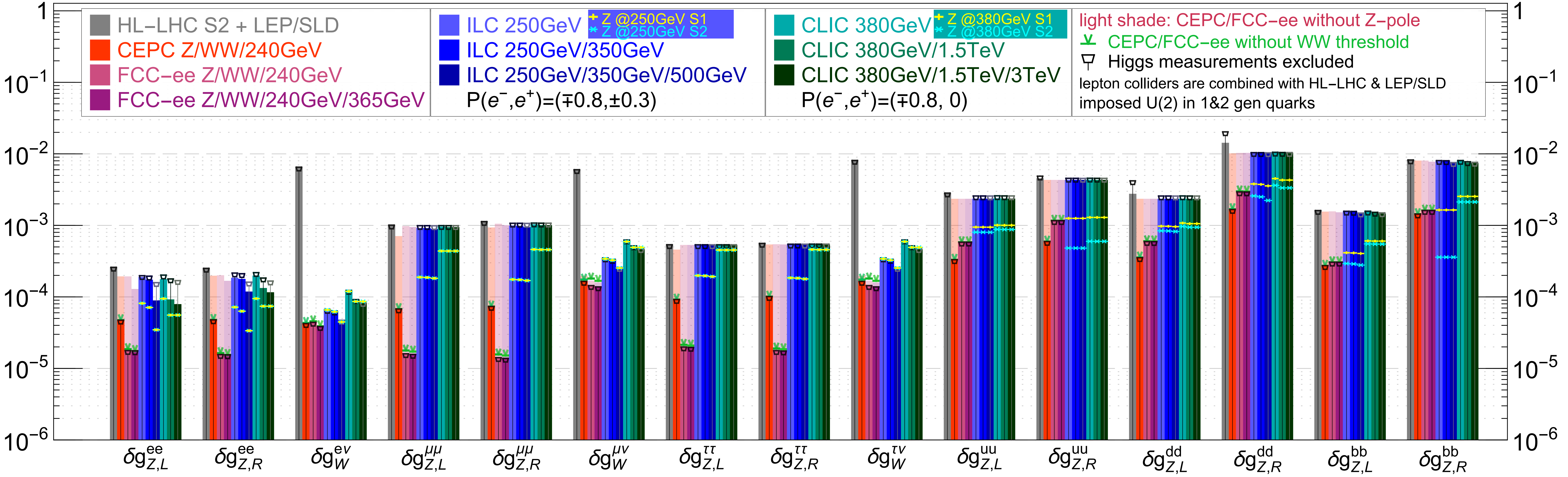
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

Showmass update: J. De Blas + 2206.08326

For possible improvements in WW analysis thanks to ML techniques, see S. Chiai @ CEPC'ee

see also J. Gu @ CEPC'22

and Y. Du @ CEPC'22



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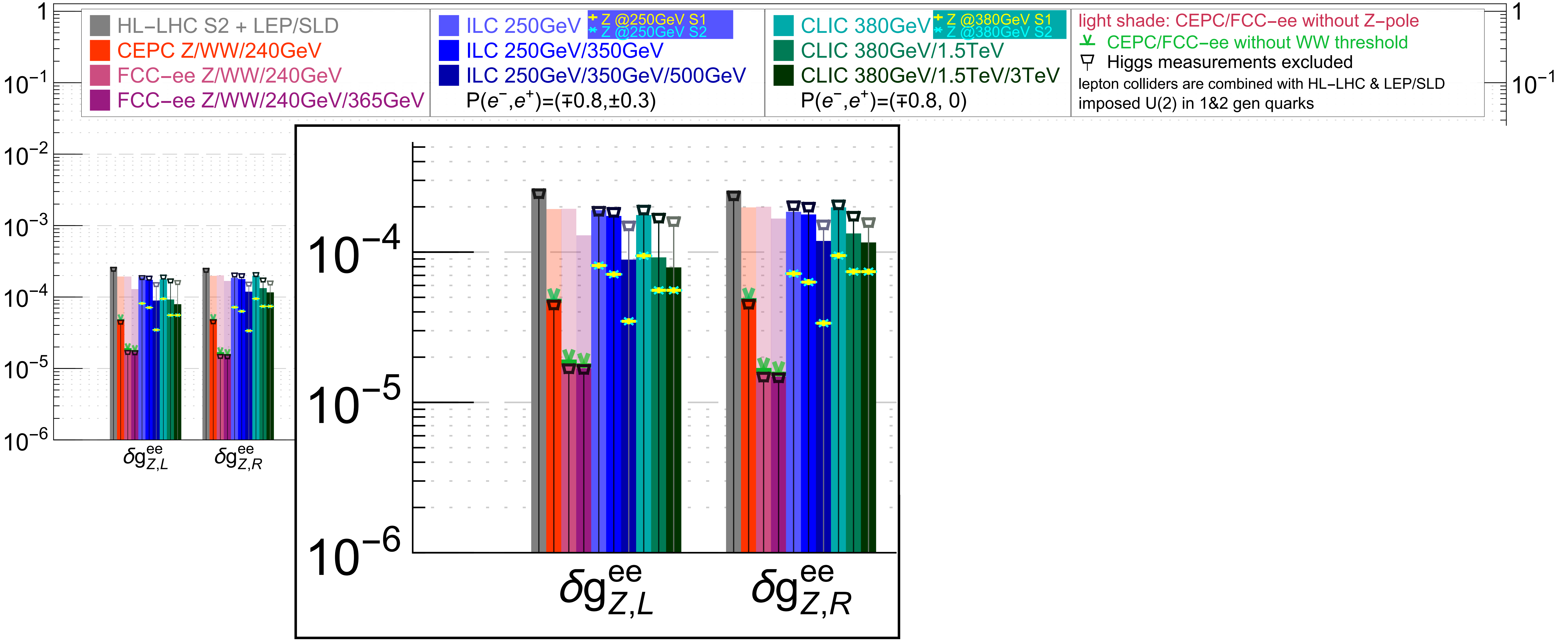

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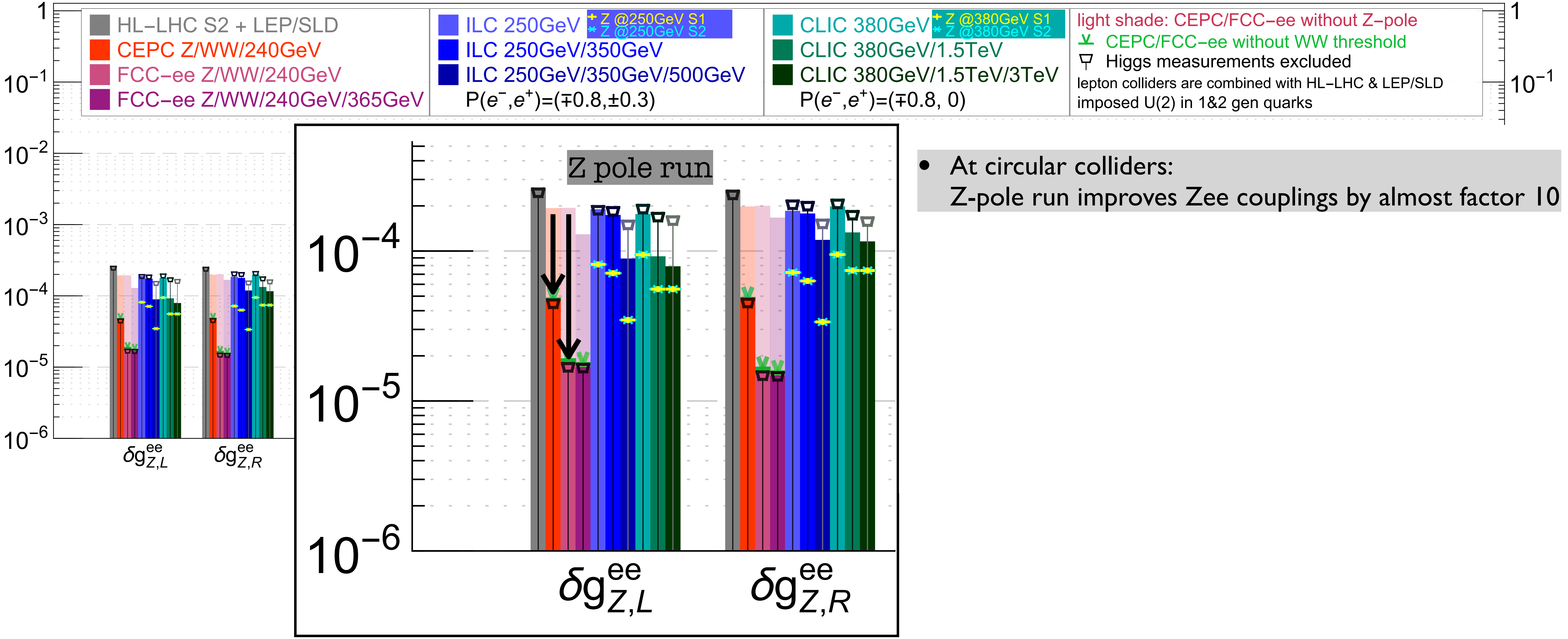


- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10

Sensitivity on EW couplings

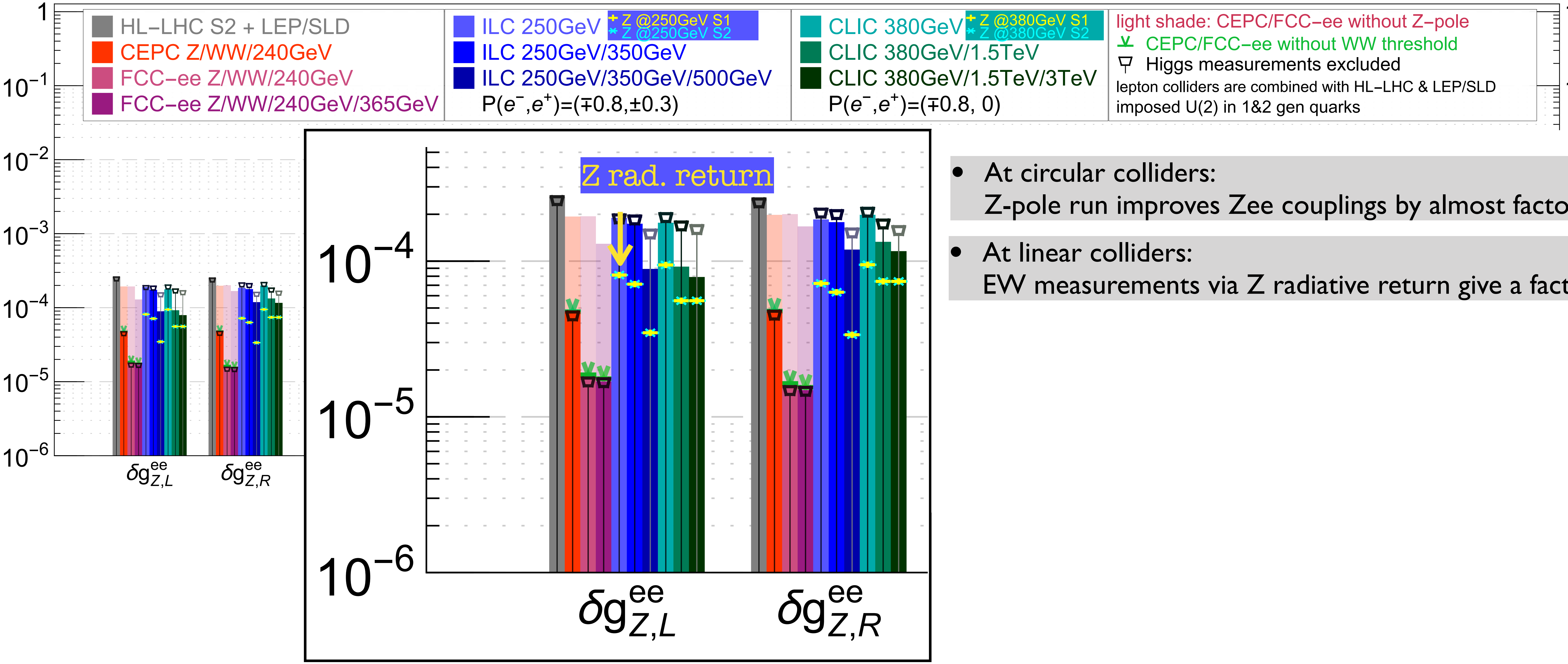
see also J. Gu @ CEPC'22

and Y. Du @ CEPC'22

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

Showmass update: J. De Blas + 2206.08326

For possible improvements in WW analysis thanks to ML techniques, see S. Chiai @ CEPC'ee



- 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

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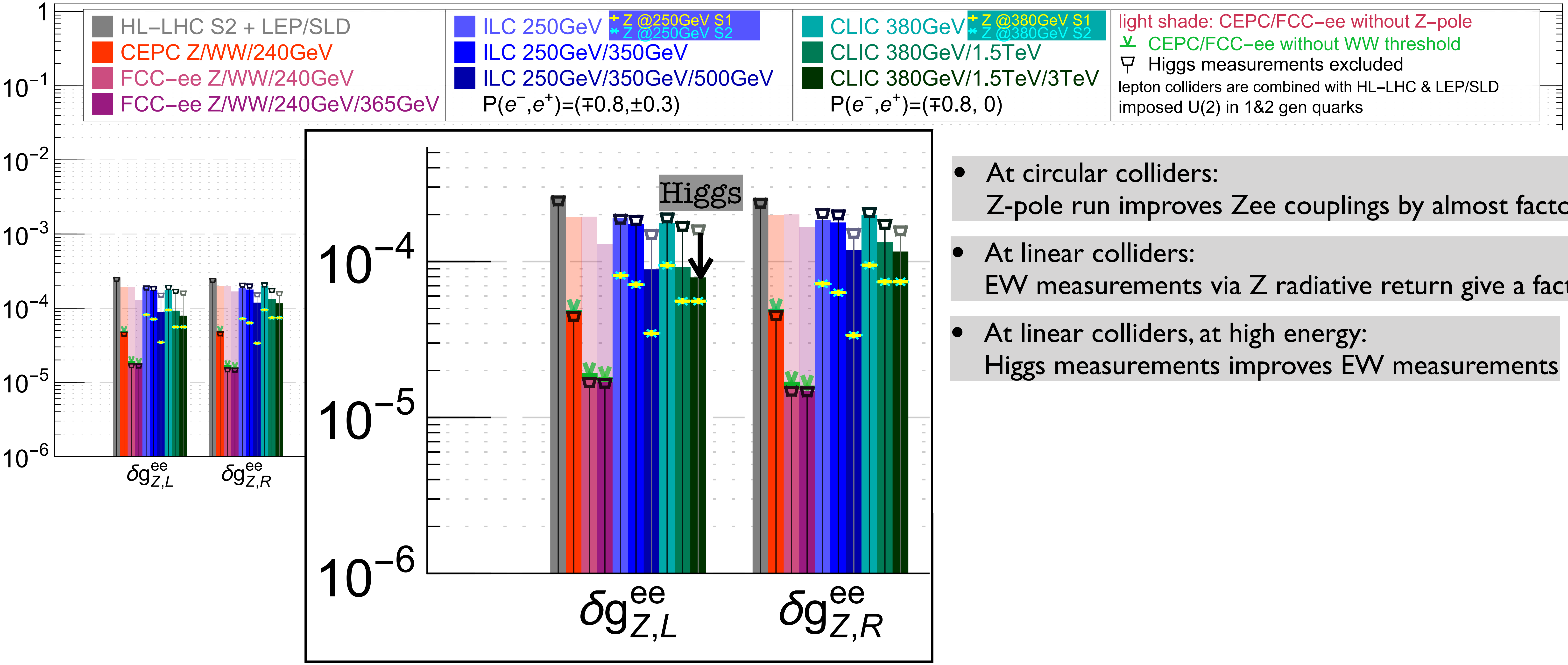

- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings

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and Y. Du @ CEPC'22

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

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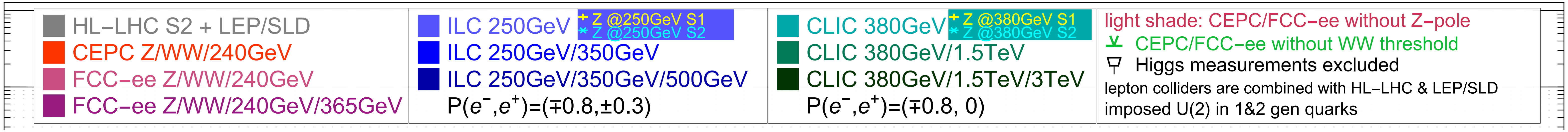
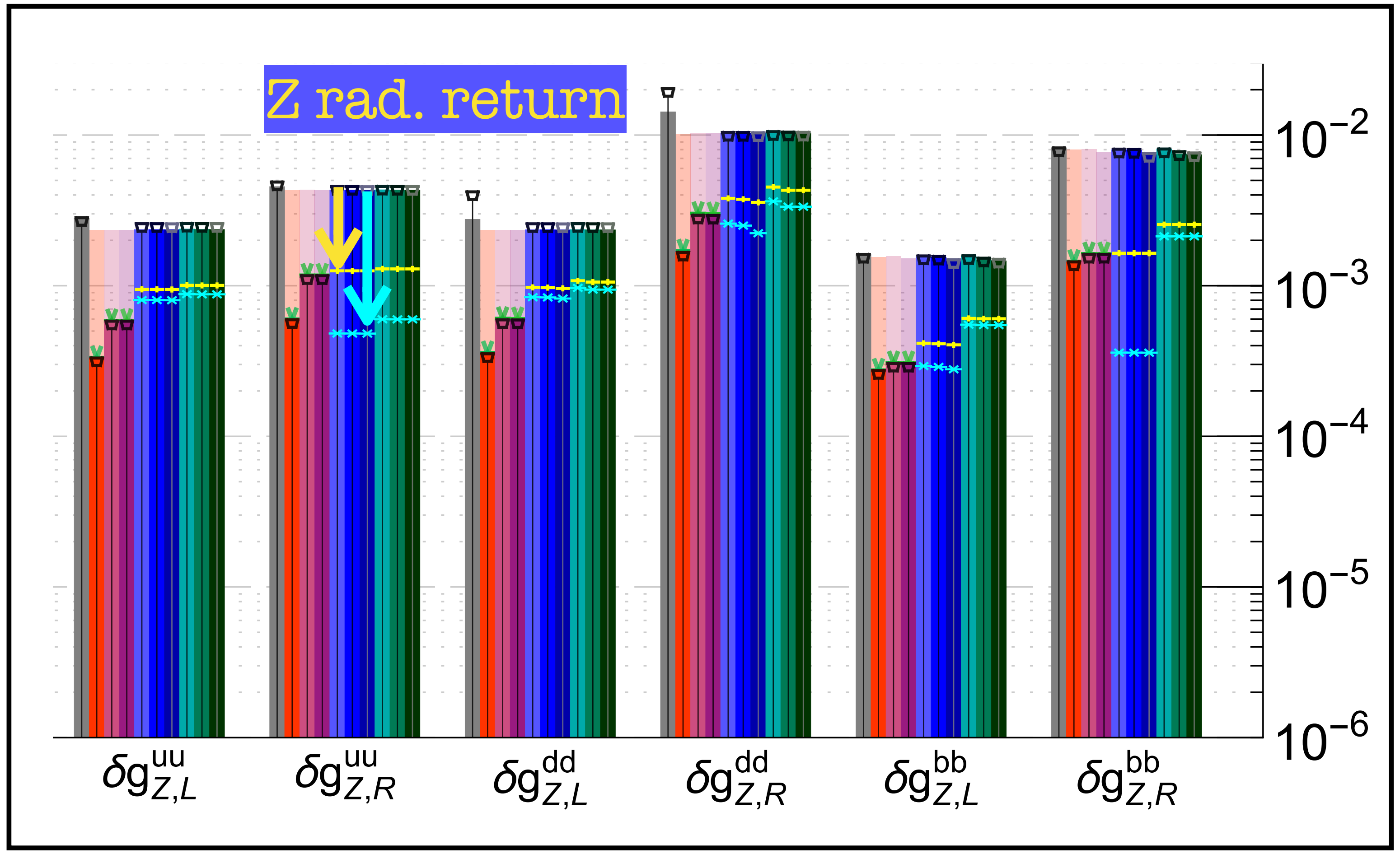
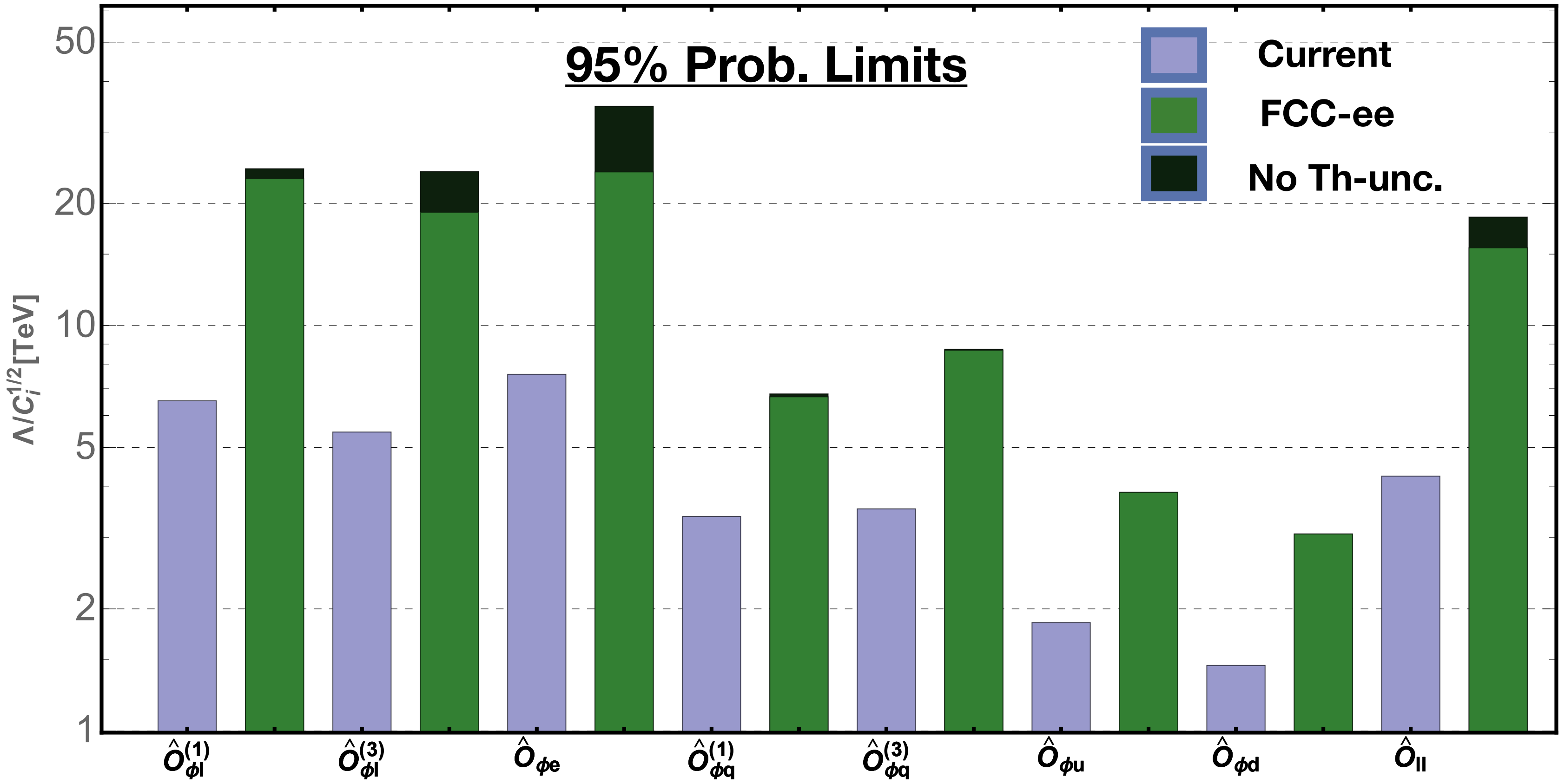


- At linear colliders, at high energy:
EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
    Yellow: LEP/SLD systematics / 2
    Blue: small EXP and TH systematics



Impact of TH uncertainties

J. de Blas, FCC CDR overview ‘19

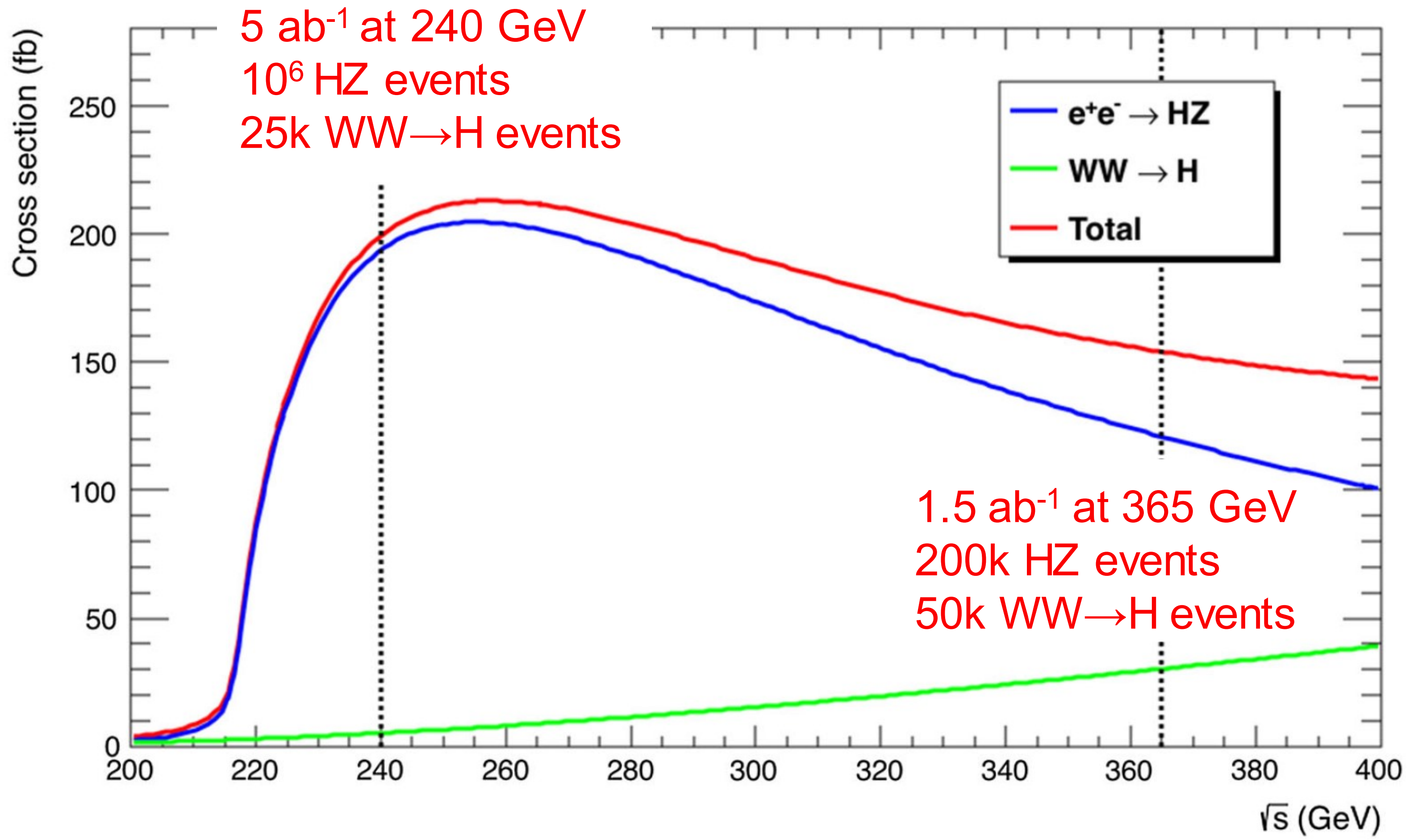


	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
δM_W [MeV]	±15	±8	±1	$\pm0.6/\pm1$	±1
$\delta\Gamma_Z$ [MeV]	±2.3	±0.73	±0.1	±0.1	±0.2
$\delta\mathcal{A}_\ell\,[\times10^{-5}]$	±210	±93	±2.1	$\pm8/\pm14$	±11.8
$\delta R_b^0\,[\times10^{-5}]$	±66	±3	±6	±0.3	$\pm$ 5

Higgs @ FCC-ee

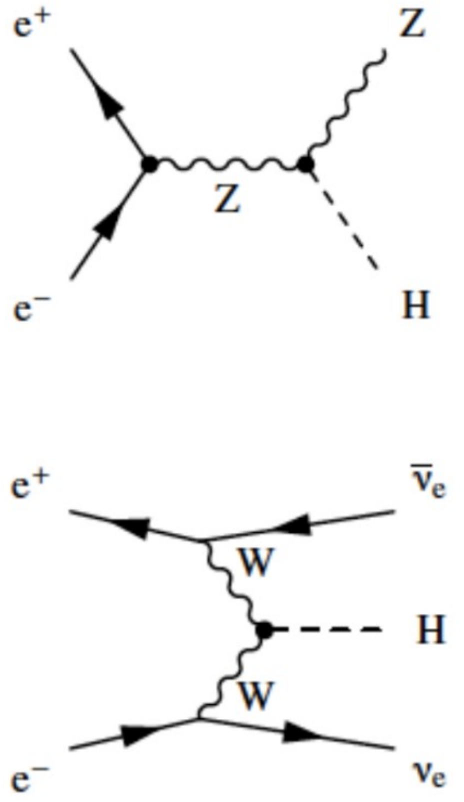
K. Zhang @ CEPC'22

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.

For the (indirect) sensitivity on Higgs self-coupling, see J. Gu @ CEPC'22

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

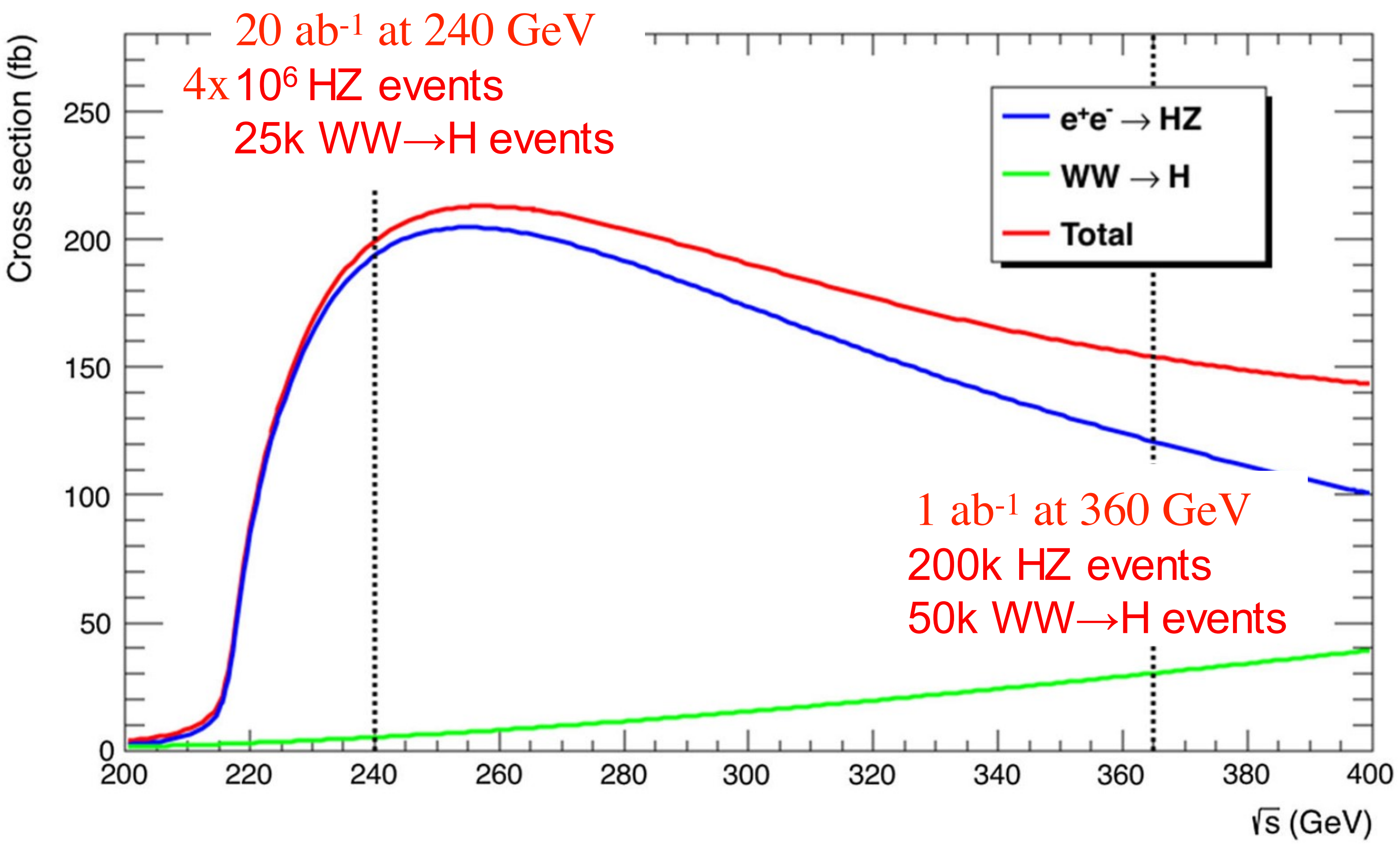
Collider	ILC_{250}	CLIC_{380}	FCC-ee_{240}
Cost (Euros/Higgs)	7,000 to 12,000	2,000	255

1906.02693

Higgs @ CEPC

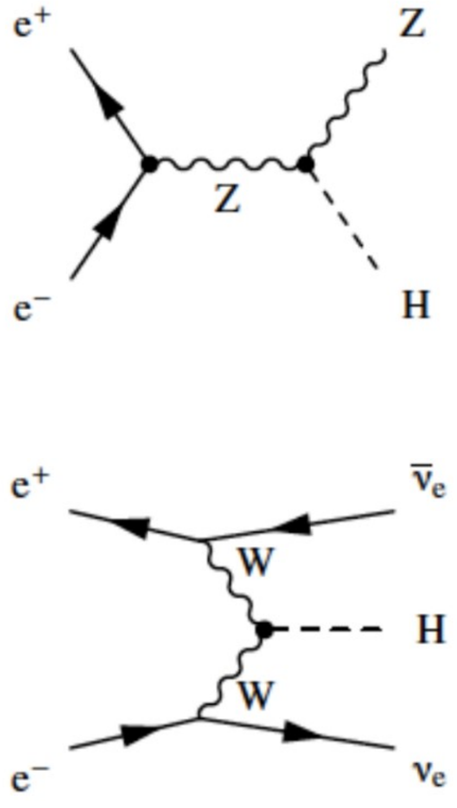
CEPC CDR: arXiv:1811.10545
White Paper: arXiv:1810.09037
CEPC Snowmass 2021(Latest):
arXiv:2205.08553

K. Zhang @ CEPC'22
G. Wilkinson, FCC Physics WS '22



20 ab^{-1} at 240 GeV
4x 10^6 HZ events
25k WW→H events

1 ab^{-1} at 360 GeV
200k HZ events
50k WW→H events



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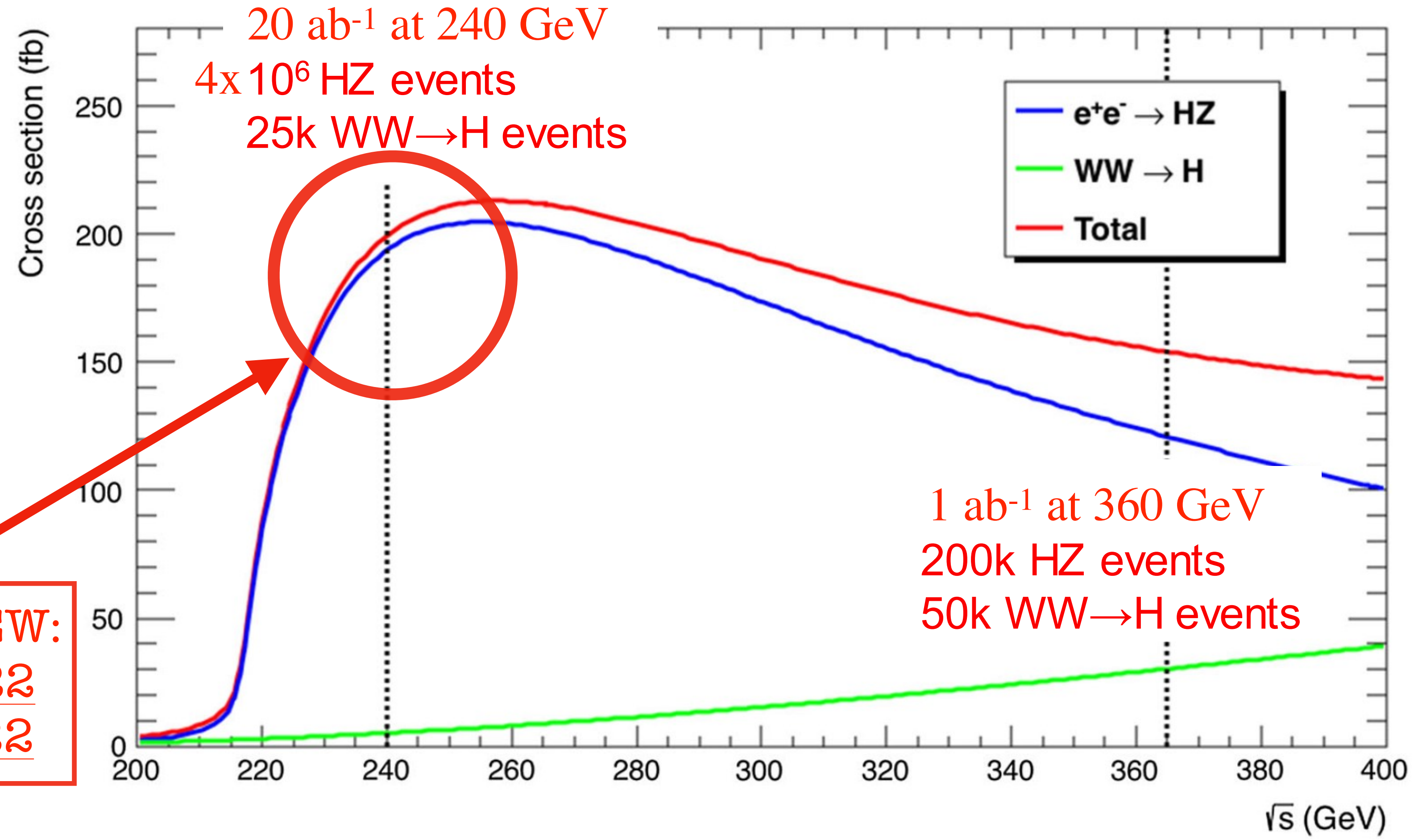

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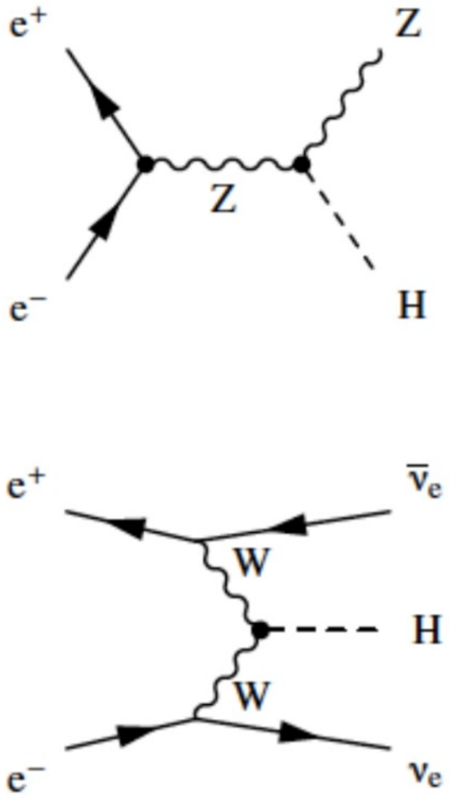
Complete 2-loop EW:
X. Guan@CEPC'22
Q. Song@ CEPC'22



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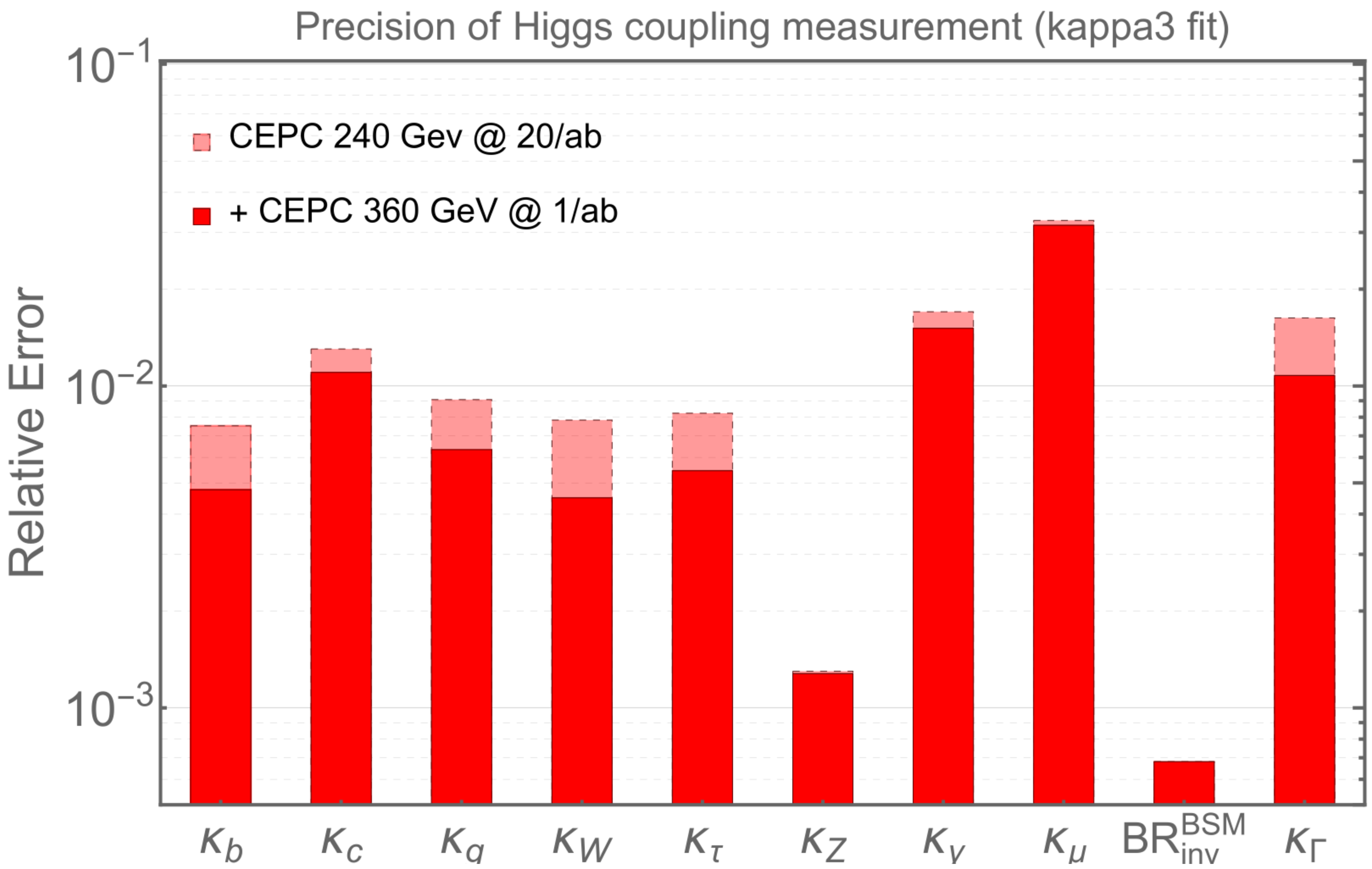
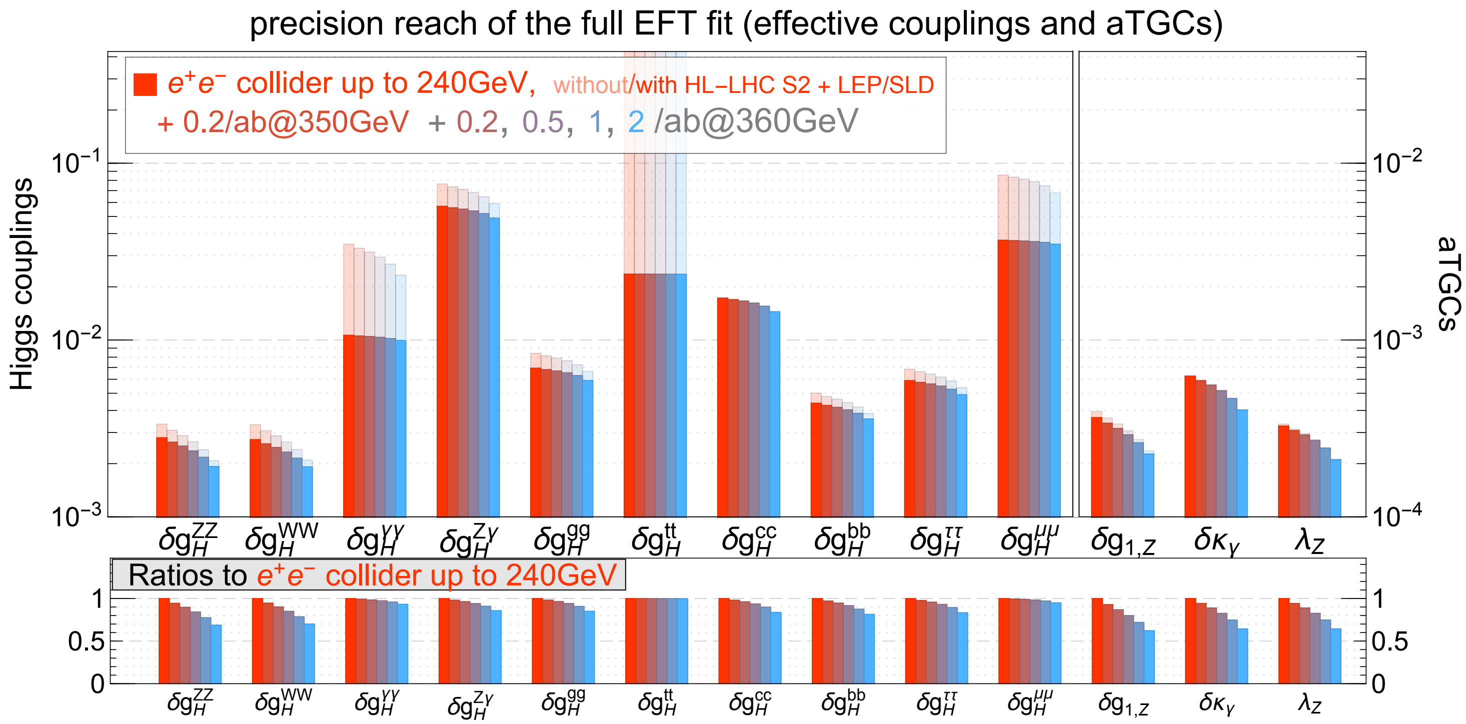
1906.02693

Higgs @ CEPC: Complementarity of 240/360 GeV

K. Zhang @ CEPC'22

J. Gu @ CEPC'22





Higgs @ CEPC: Complementarity with HL-LHC

ECFA Higgs study group '19

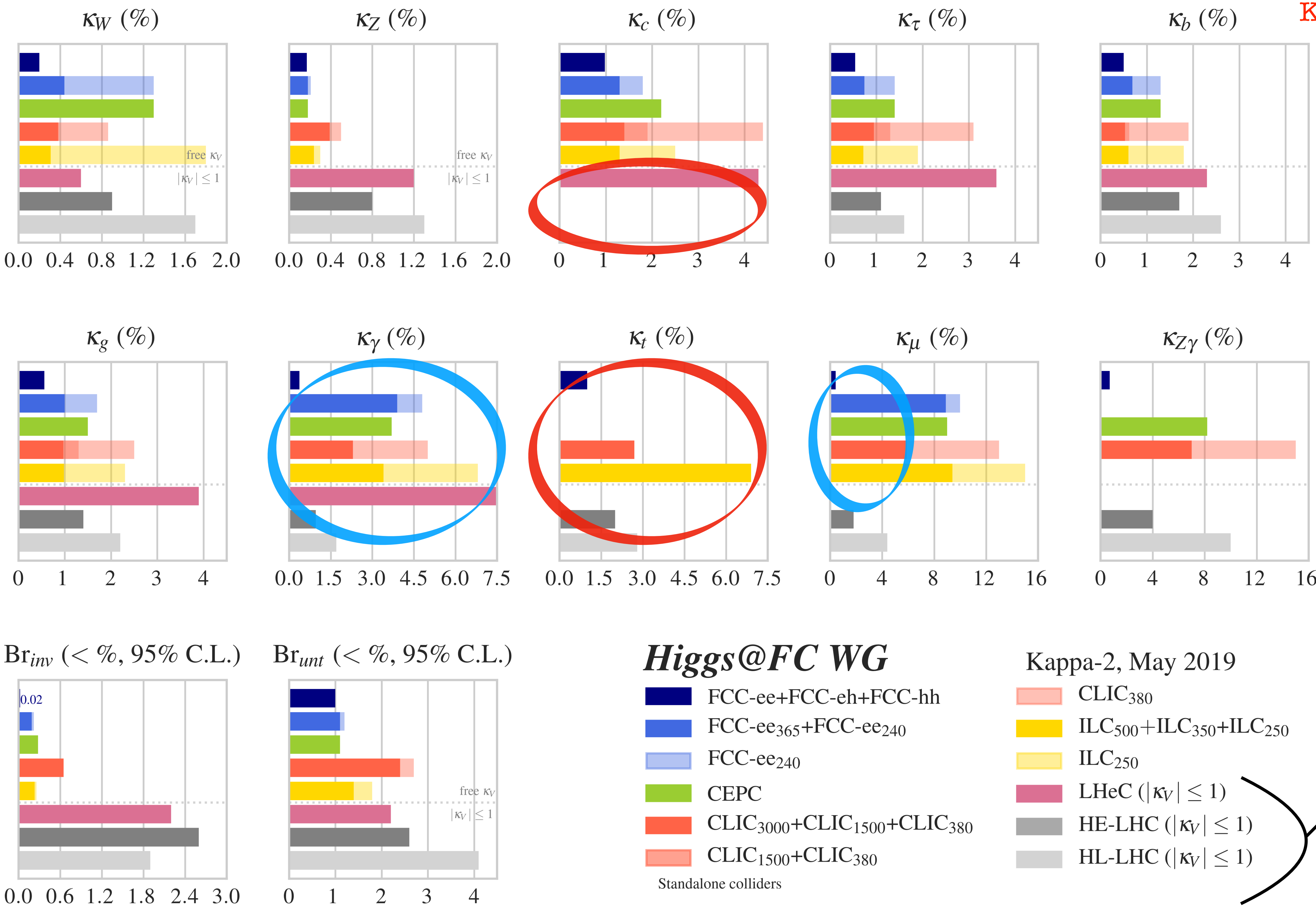
K. Zhang @ CEPC'22

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

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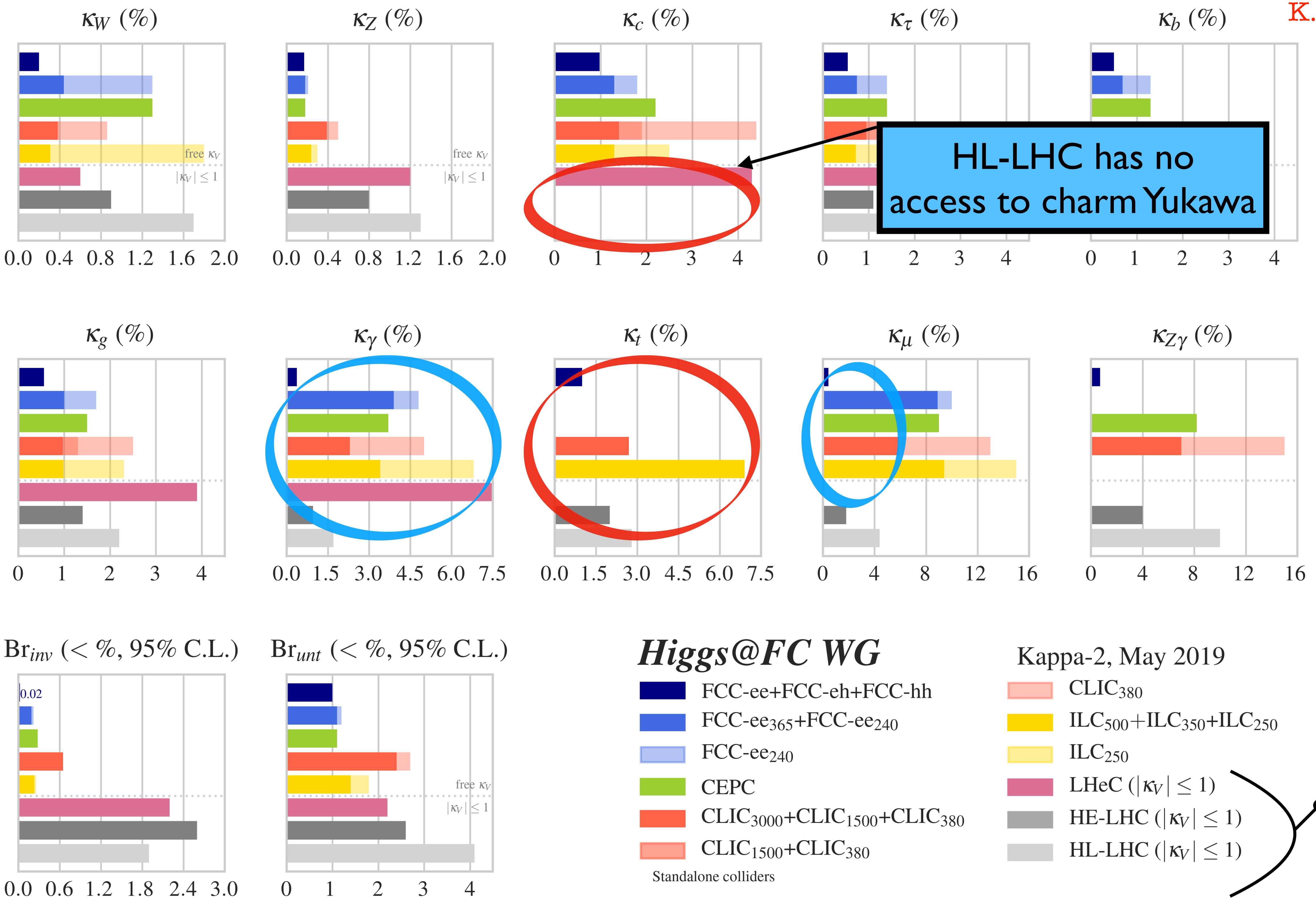


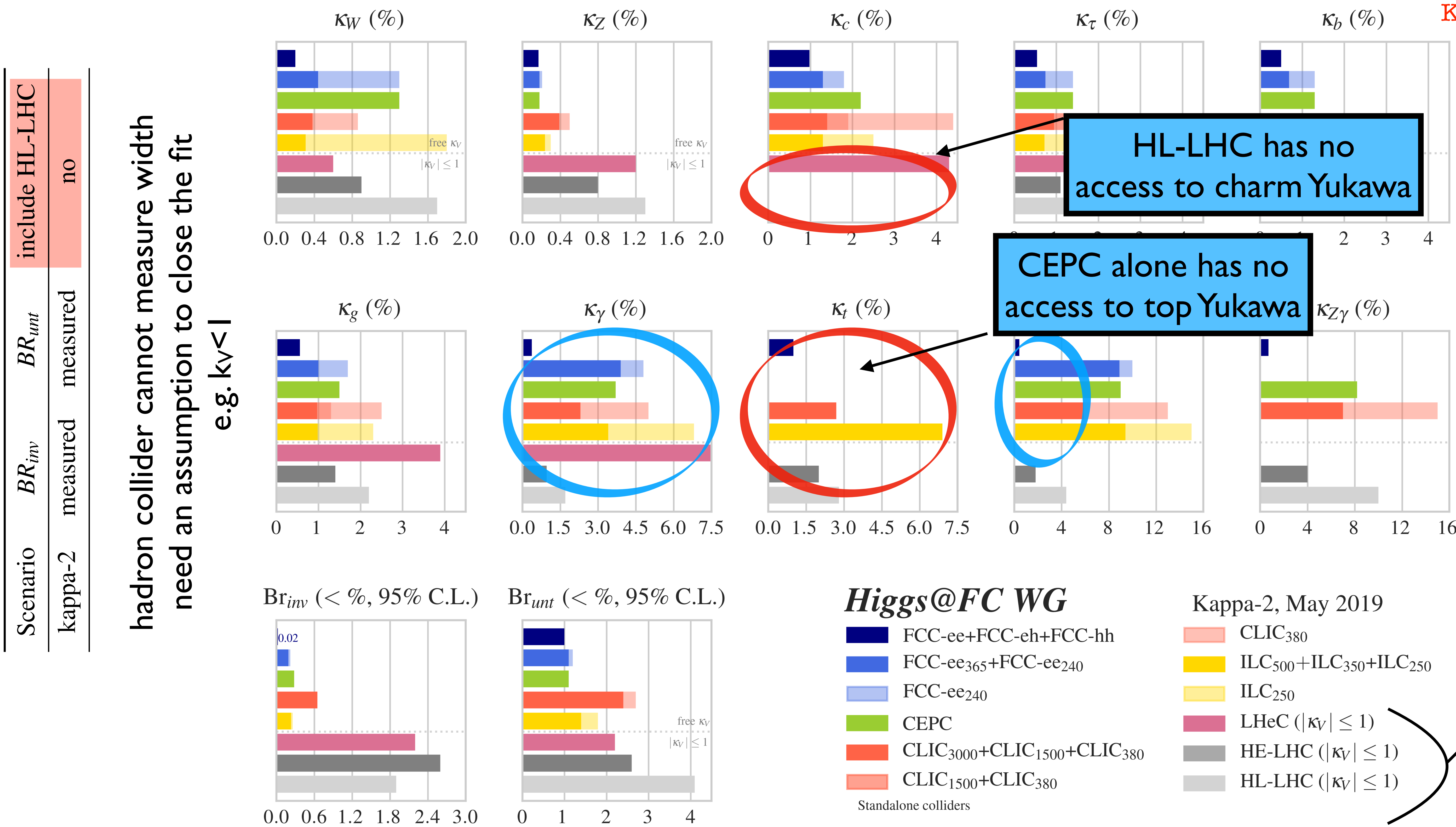
HL-LHC has no access to charm Yukawa

assumption needed for the fit to close at hadron machines

Higgs @ CEPC: Complementarity with HL-LHC

ECFA Higgs study group '19

K. Zhang @ CEPC'22



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need an assumption to close the fit
e.g. κ_V<1

HL-LHC has no access to charm Yukawa

CEPC alone has no access to top Yukawa

assumption needed for the fit to close at hadron machines

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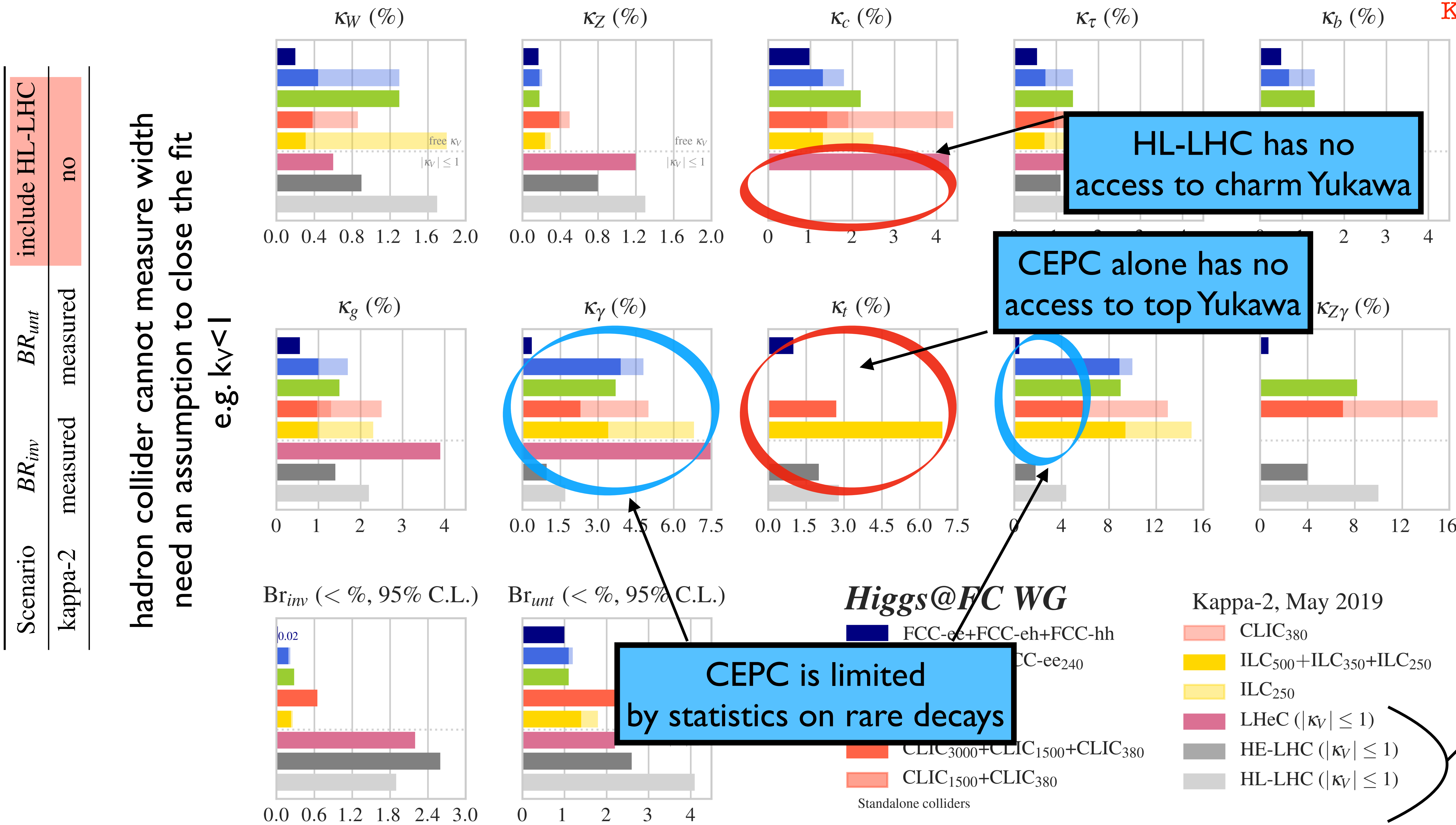


HL-LHC has no access to charm Yukawa

CEPC alone has no access to top Yukawa

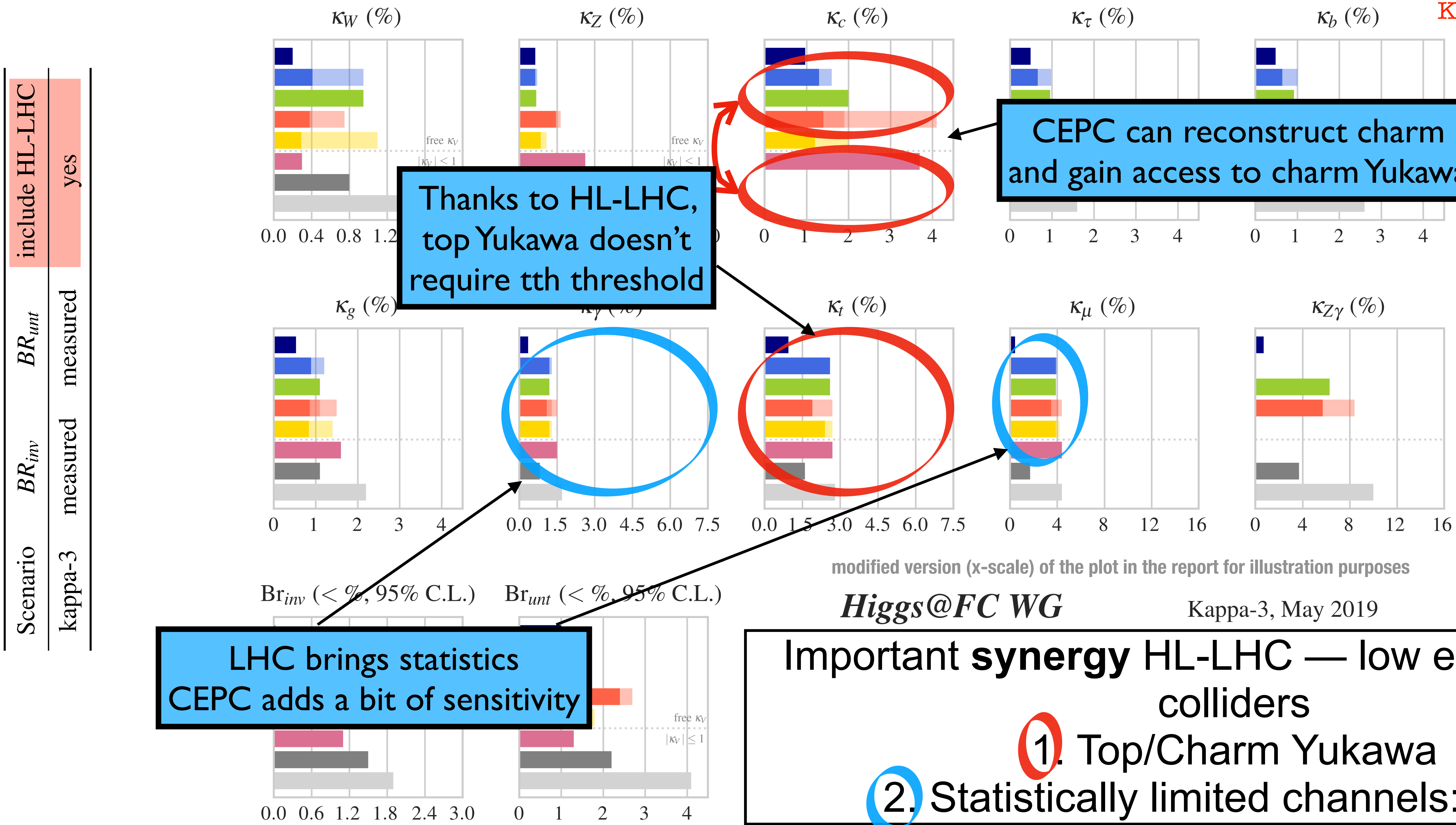
CEPC is limited by statistics on rare decays

assumption needed for the fit to close at hadron machines

Higgs @ CEPC: Complementarity with HL-LHC

ECFA Higgs study group '19

K. Zhang @ CEPC'22



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

CEPC can reconstruct charm and gain access to charm Yukawa

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

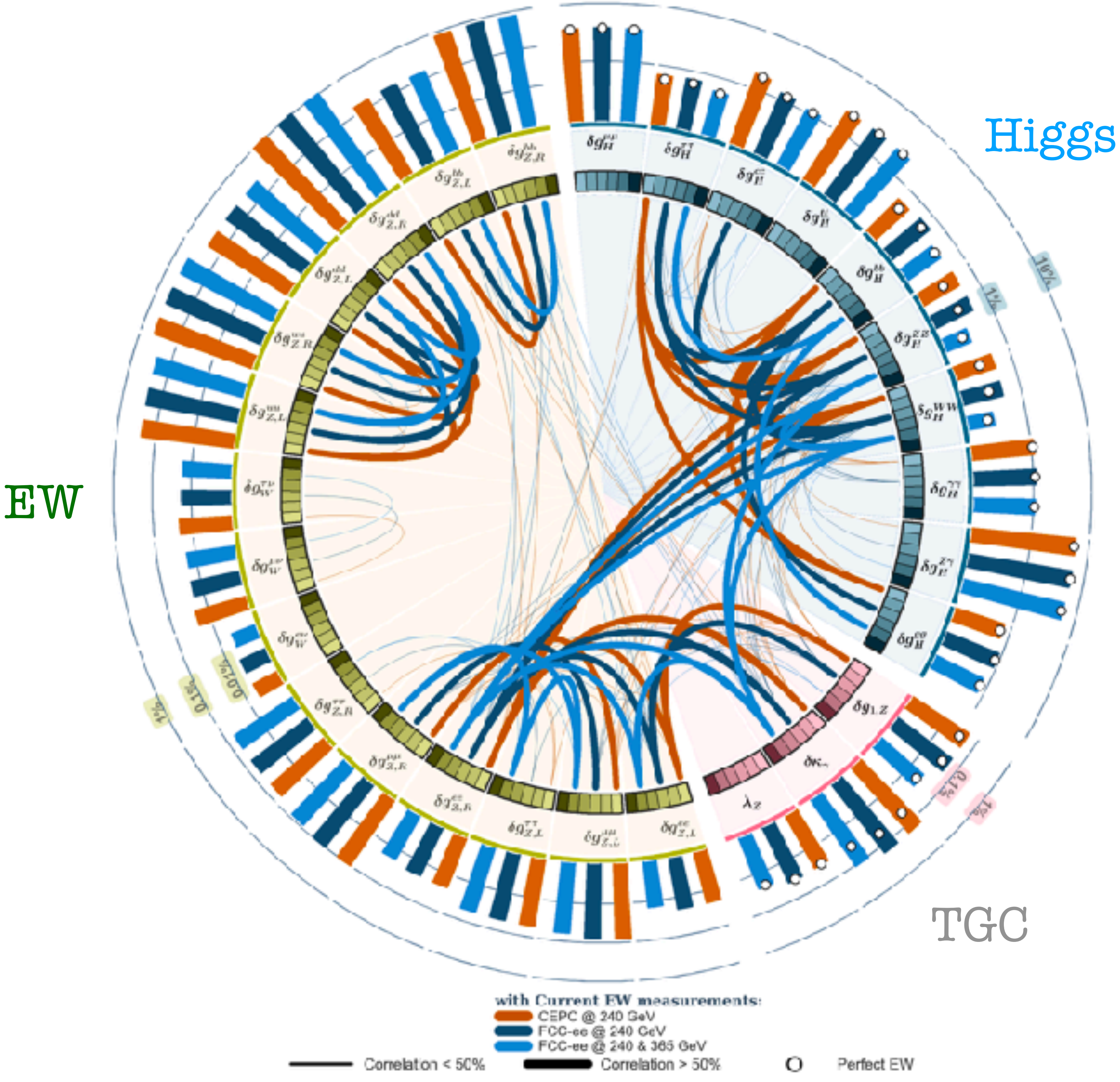
LHC brings statistics
CEPC adds a bit of sensitivity

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

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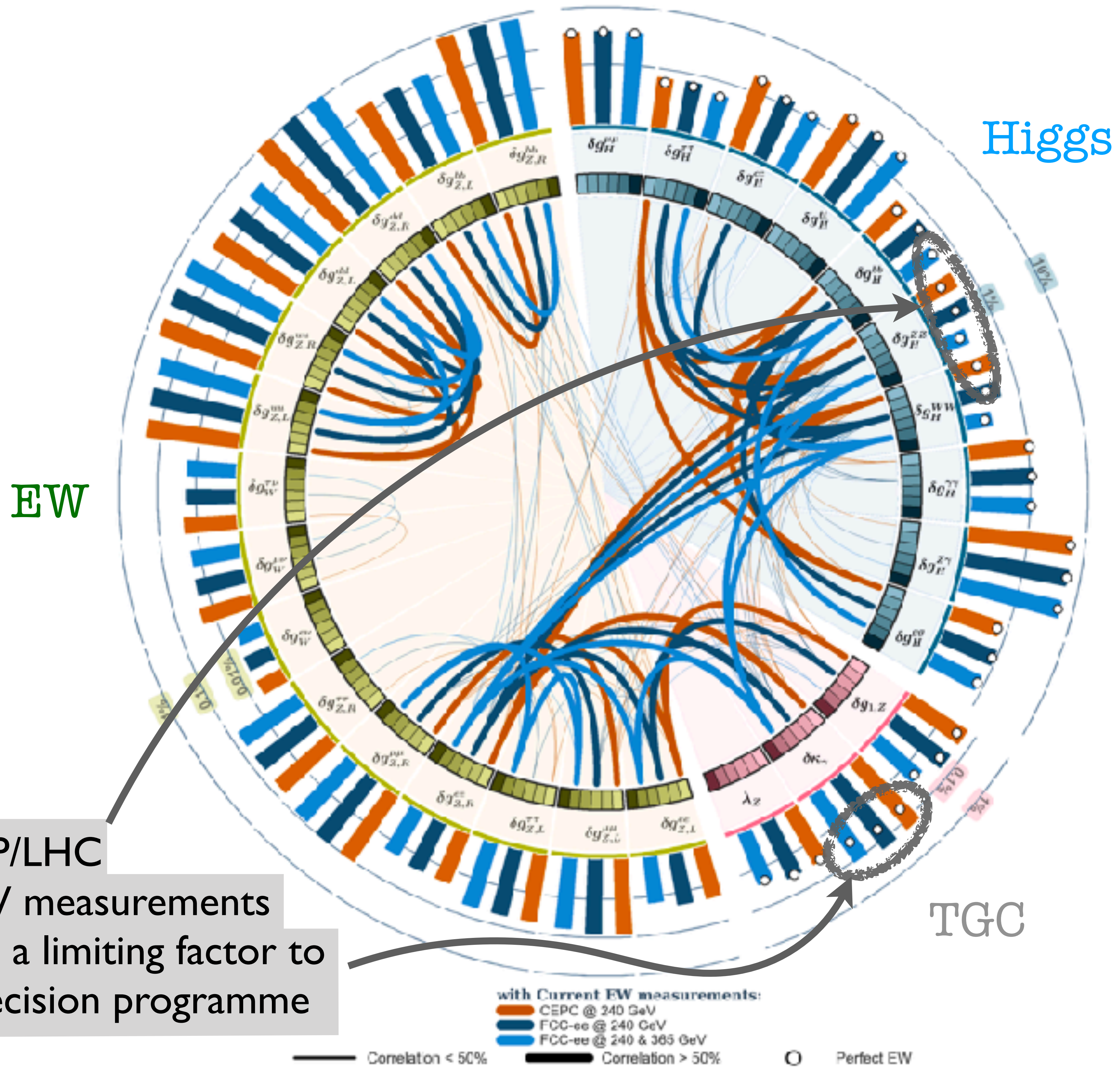

LEP/LHC
EW measurements
are a limiting factor to
precision programme

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

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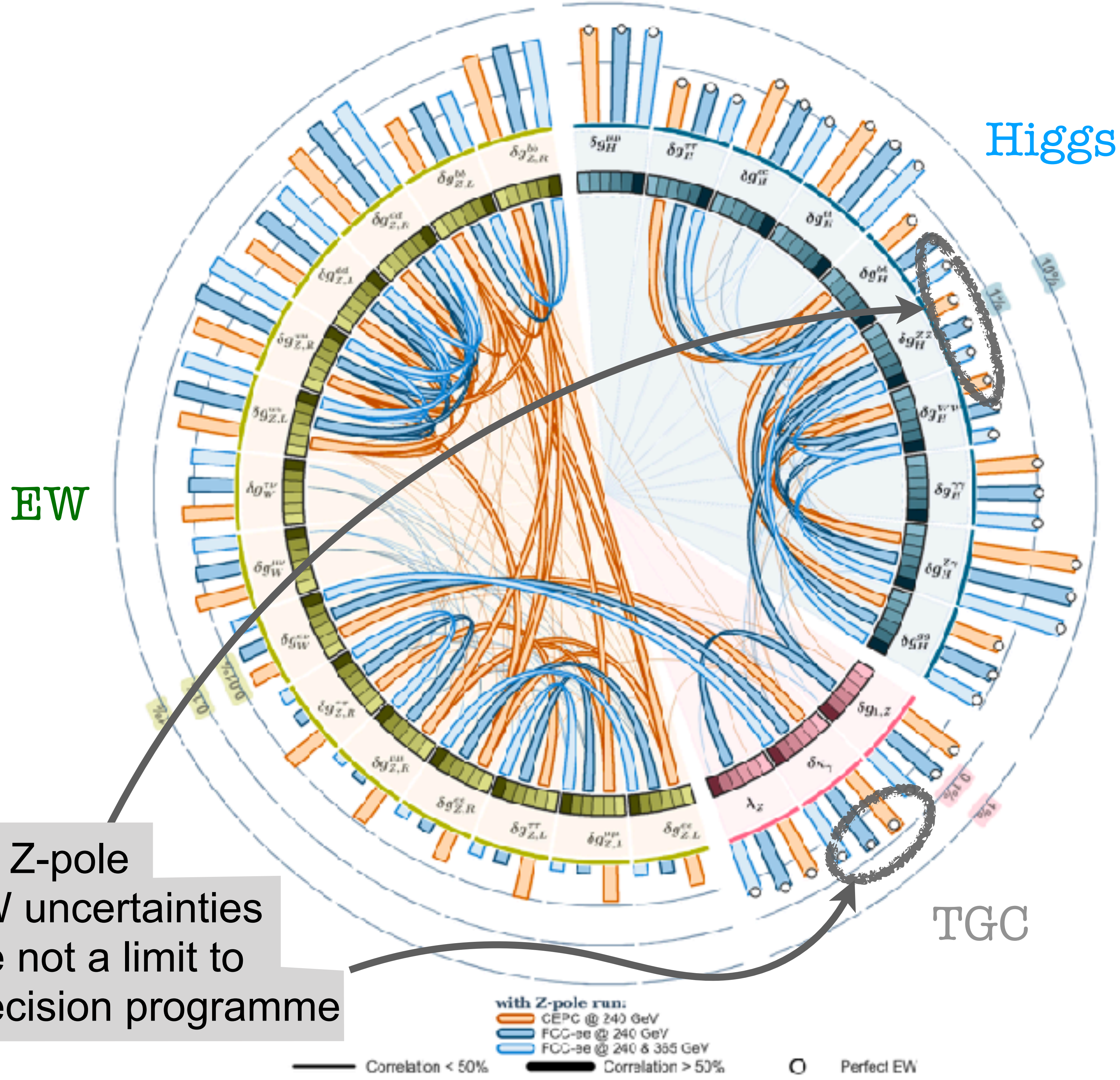


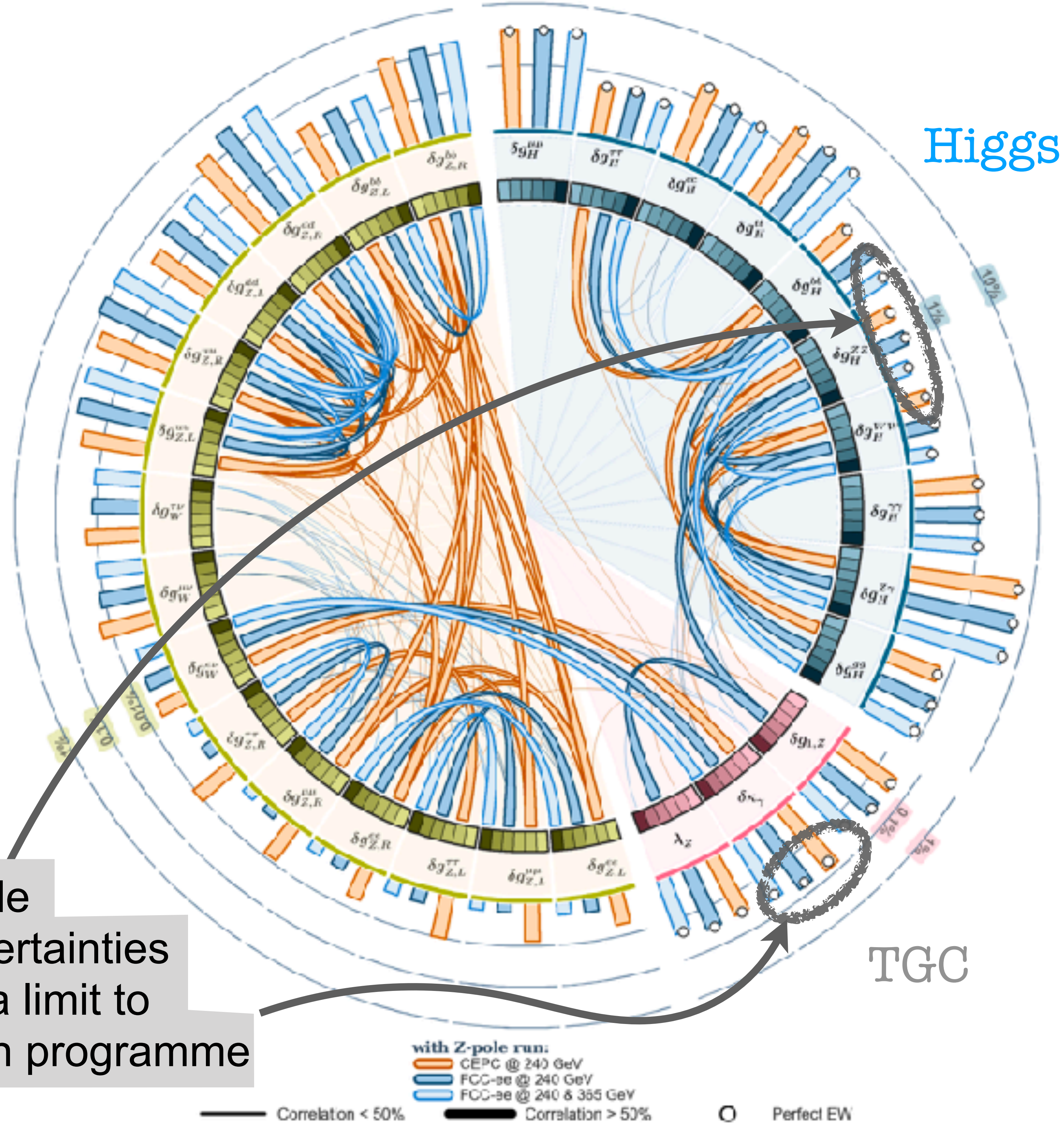
Contamination EW/TGC/Higgs can be understood by looking at correlations

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

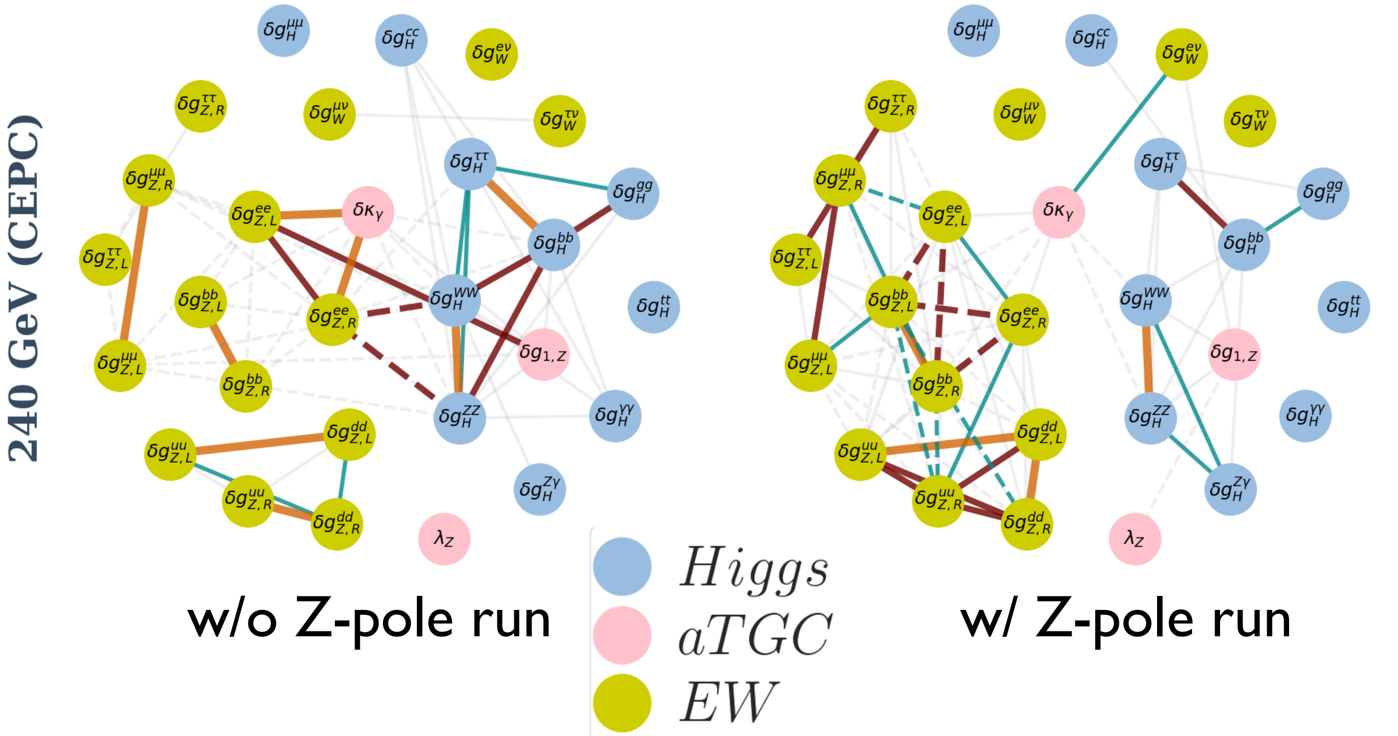
J. De Blas et al. 1907.04311



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

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

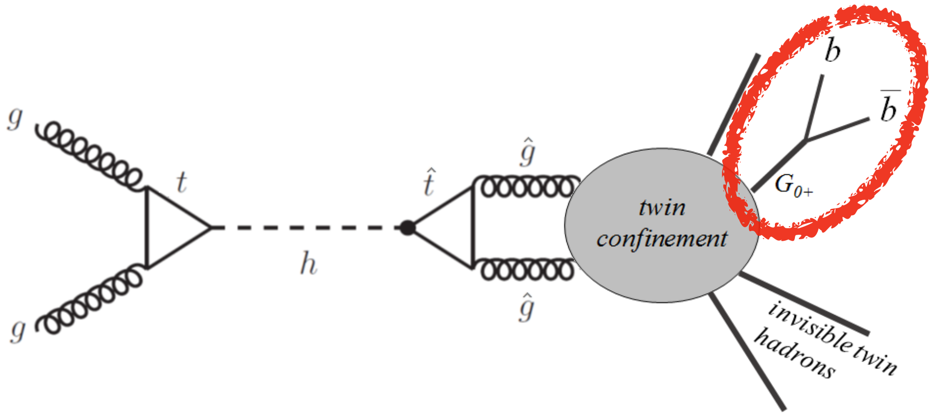
Z-pole runs at circular colliders isolate EW and Higgs sectors from each others



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

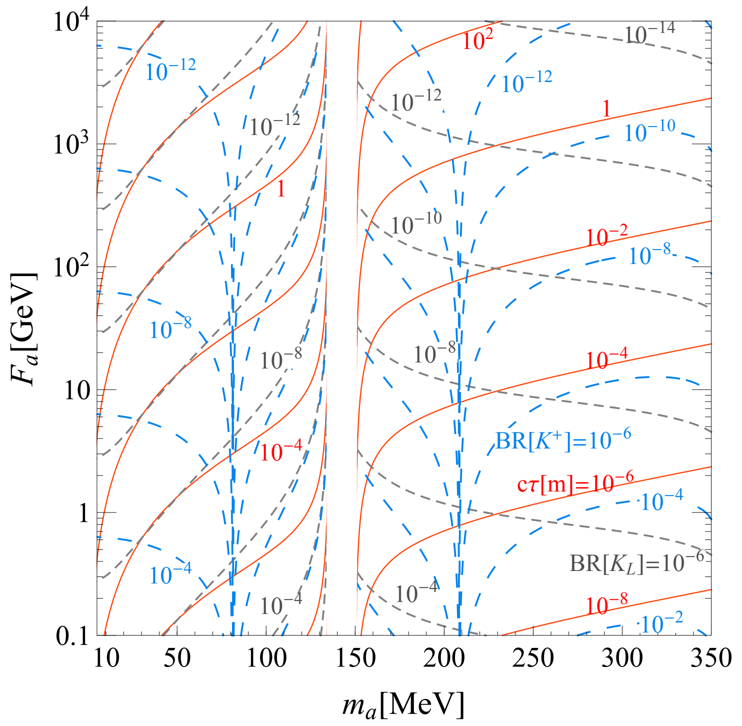
Craig et al, arXiv:1501.05310



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

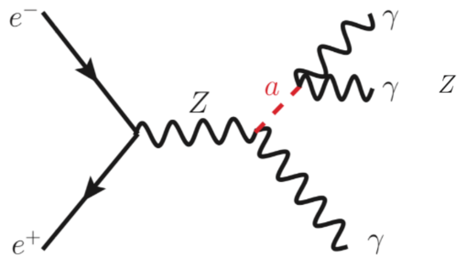
$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \text{ (KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \text{ (NA62)}$$

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

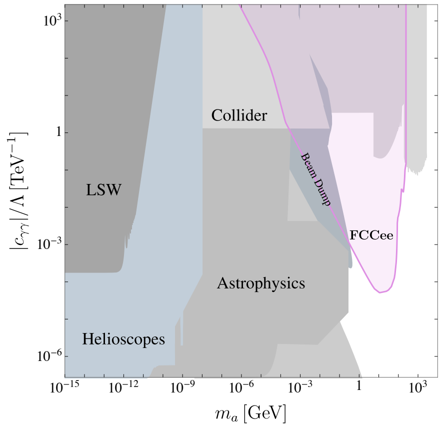


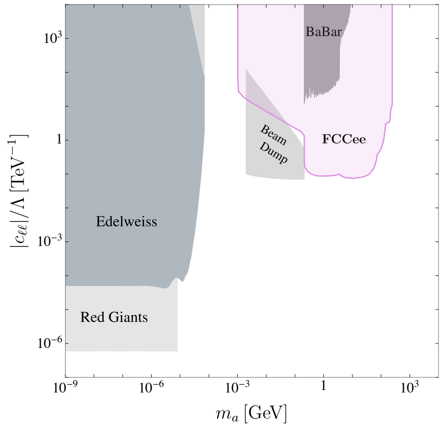
- **ALPs@ colliders**
  e.g. $e^+e^- \to \gamma a$

  $e^+e^- \to h a$



Knapen, Thamm arXiv:2108.08949



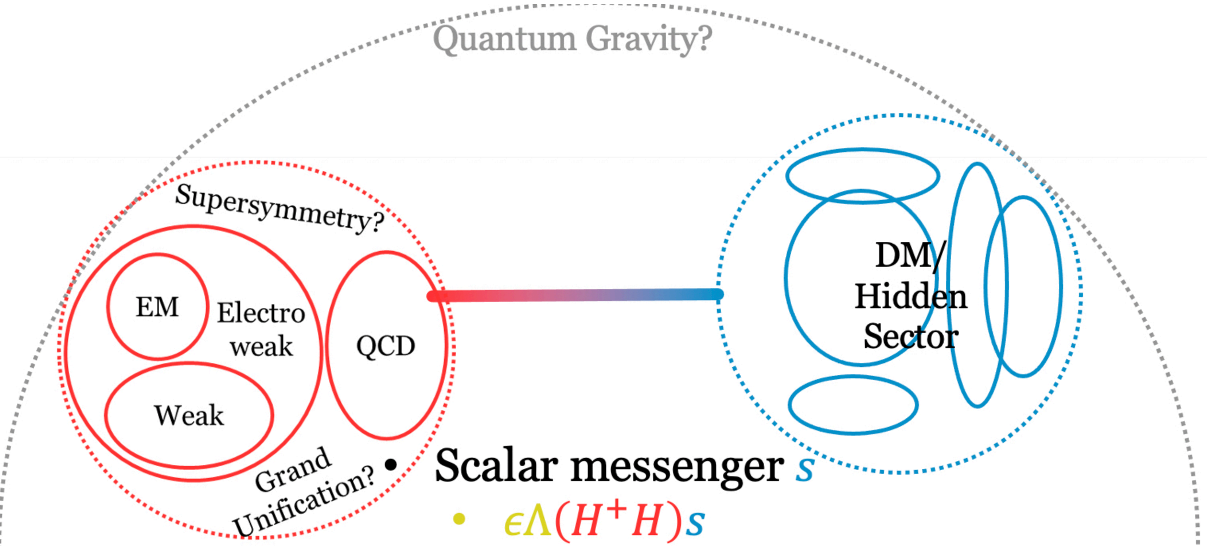


Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

ALP & Flavor
see J. Zupan @ CEPC'22

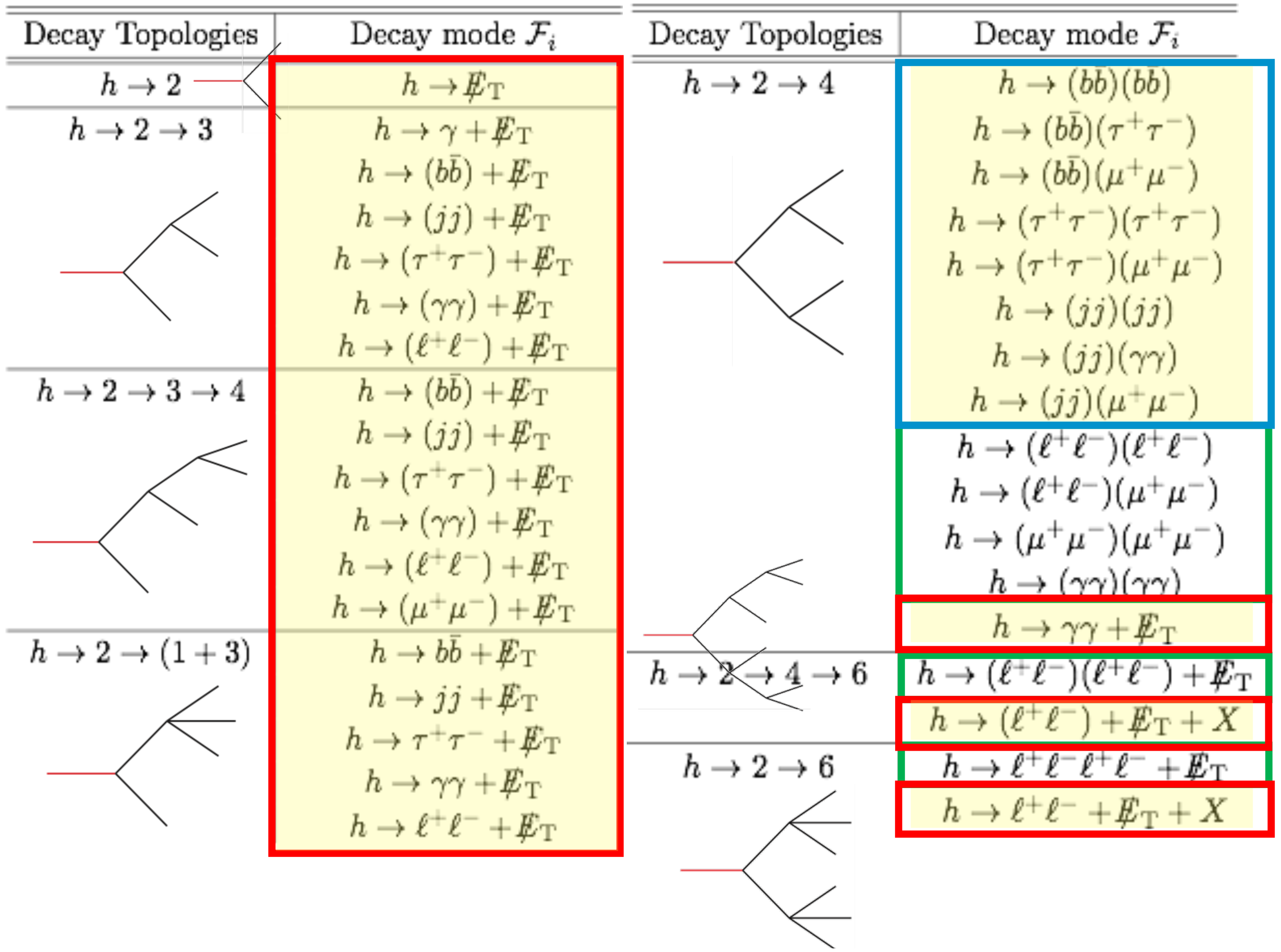
Exotics/Long Lived Particles

Z. Liu @ CEPC 2020



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

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



Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

LHC's strength

Hard at LHC due to missing energy

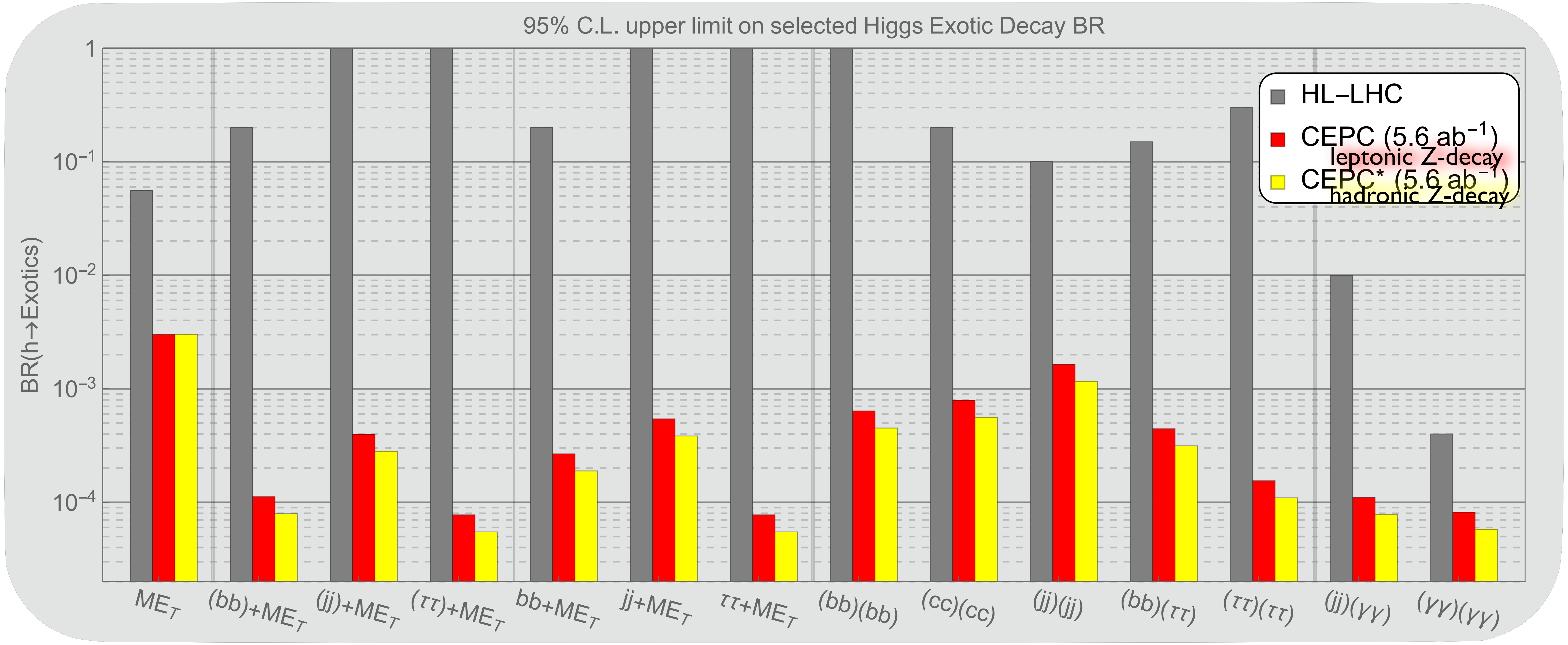
Hard at LHC due to hadronic background

Lepton colliders' strength

Exotics/Long Lived Particles

Z. Liu @ CEPC 2020

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



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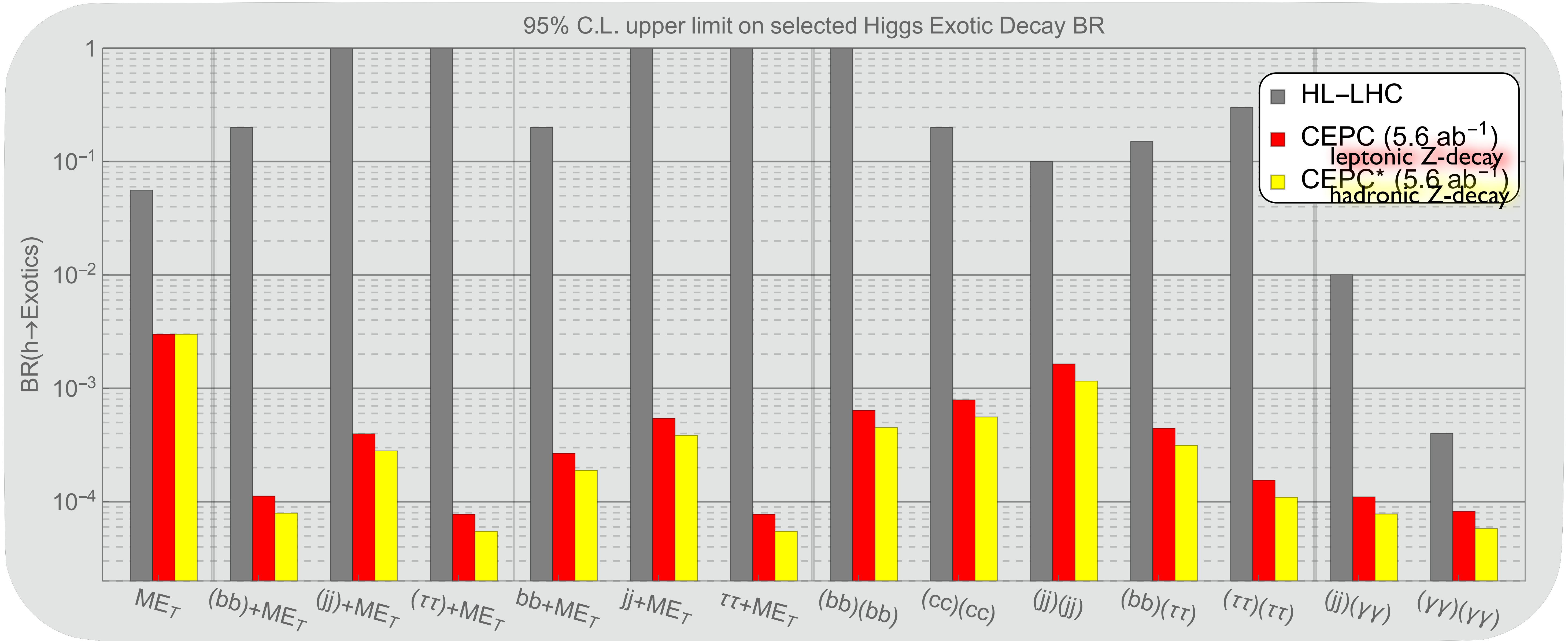

How to improve?
> Dedicated detectors, see e.g. talk by R. Gonzalez Suarez @ FCC week 2021

Conclusions

A **circular "Higgs factory"** like CEPC has a rich potential:

- Direct and indirect sensitivity to New Physics.
- Establish new organising principles of Nature (LEP→ gauge symmetries, Z/H factory→??).
- 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/CEPC are an essential part of an **integrated** programme to probe New Physics.

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FCC-ee/CEPC are an essential part of an **integrated** programme to probe New Physics.

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

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	-

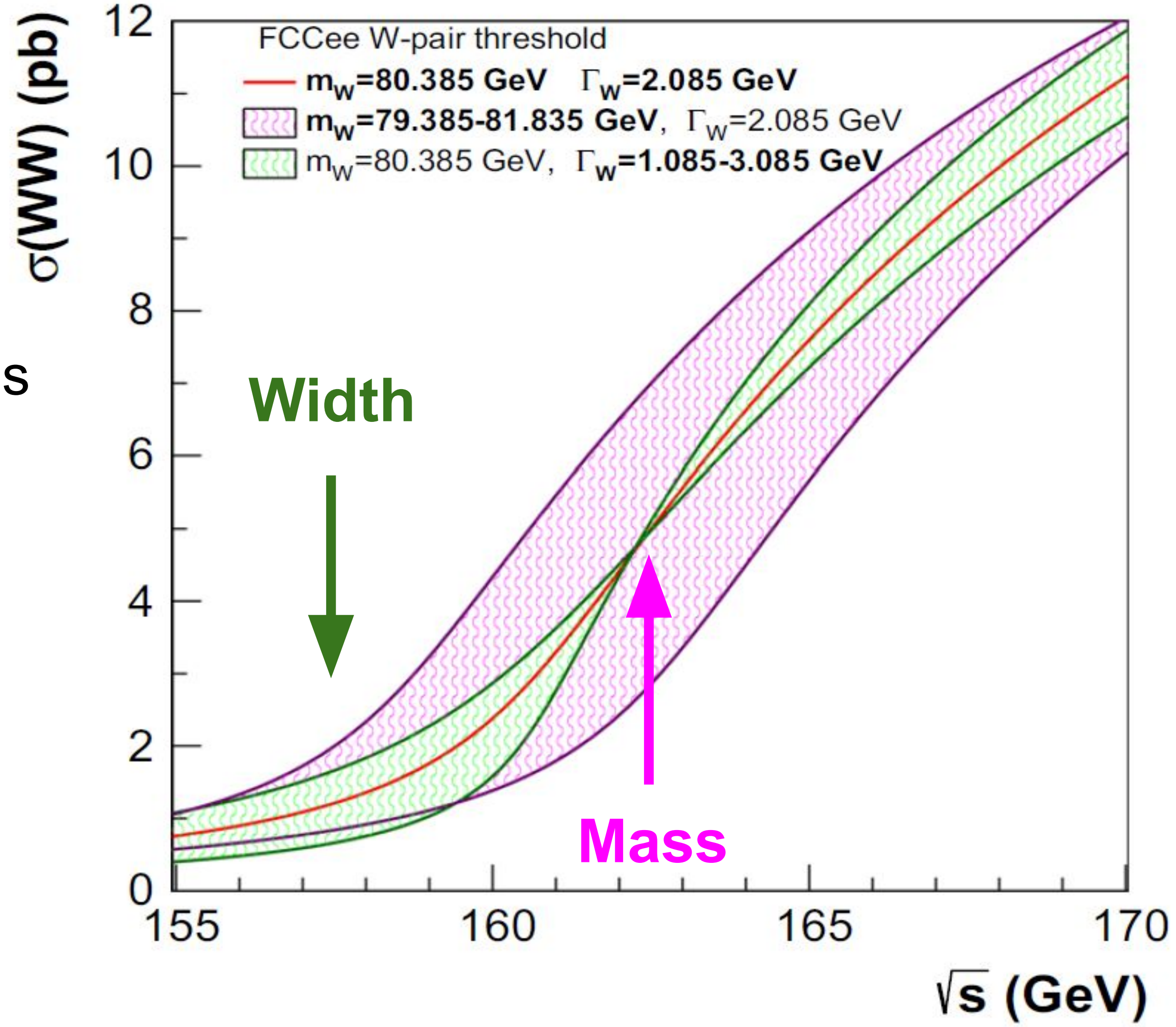
Example of measurements @ WW threshold

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

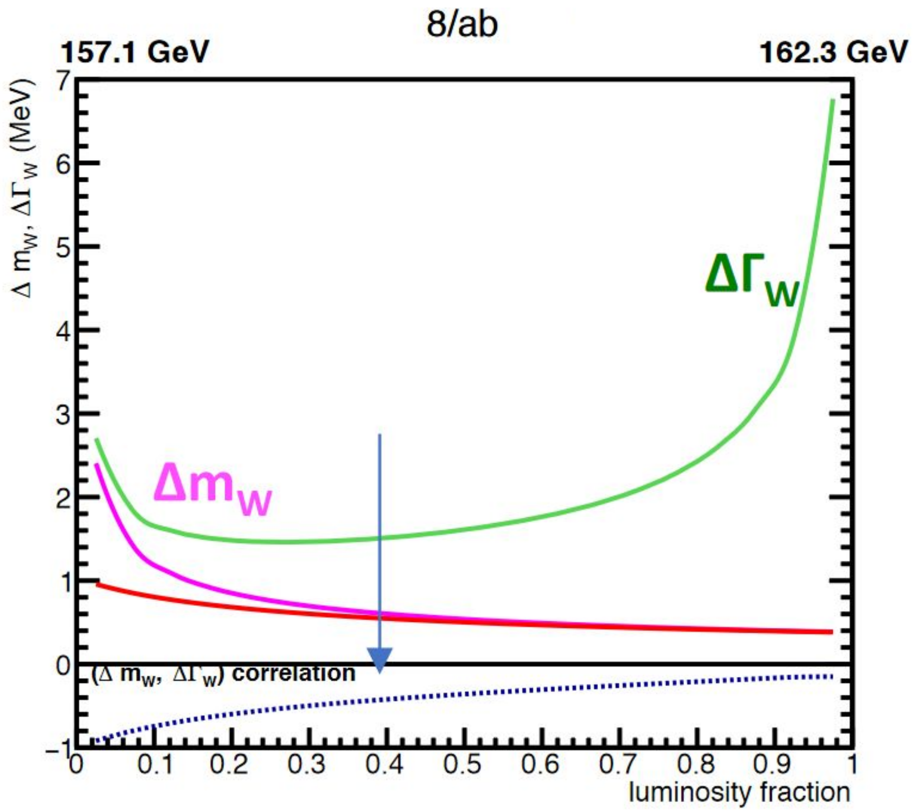
2 energy points determined from Δm_W and $\Delta\Gamma_W$ sensitivities on WW xsec:

→ **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



J. Eysermans @ EPS2021

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)

Example of measurements @ WW threshold

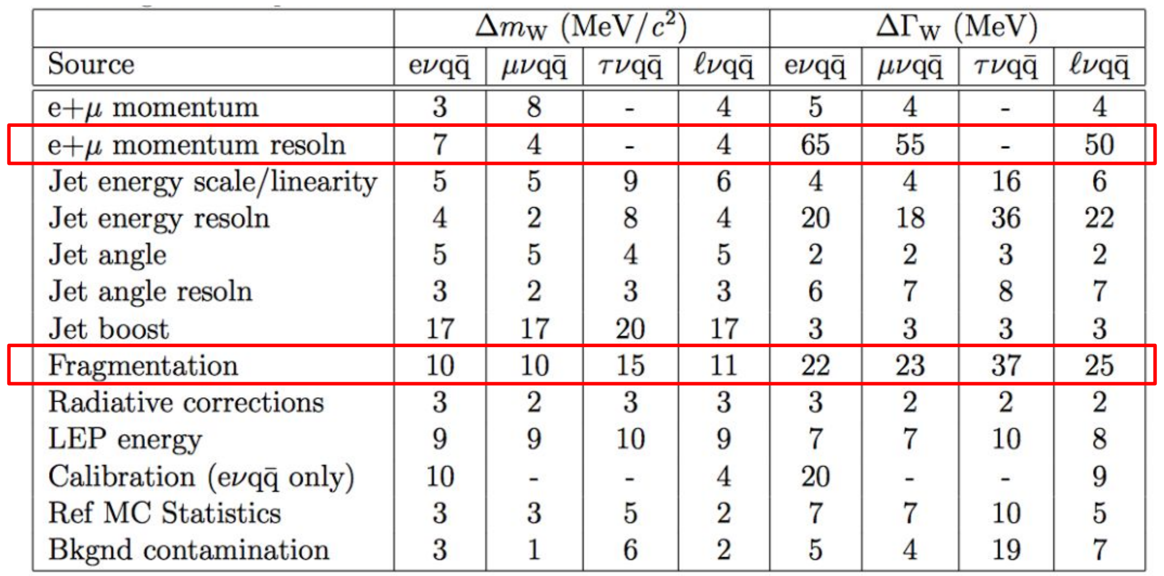
Independent analysis on W mass and width using kinematic reconstruction techniques in WW → qqlv events

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

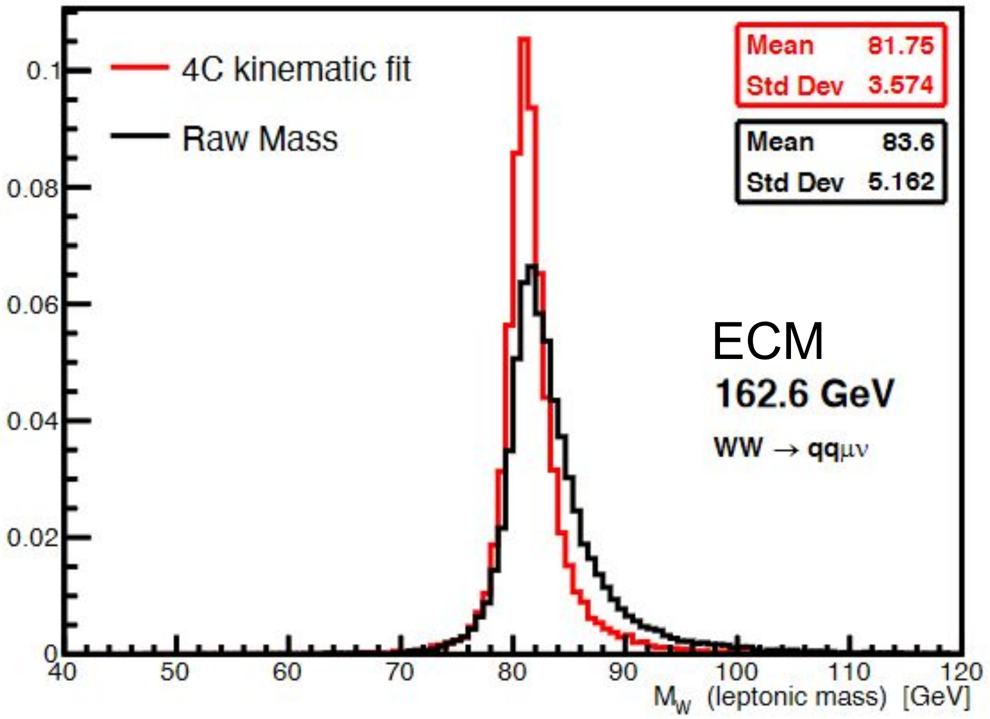
Δm_W (stat) ~ 250 keV → similar as xsec measurement

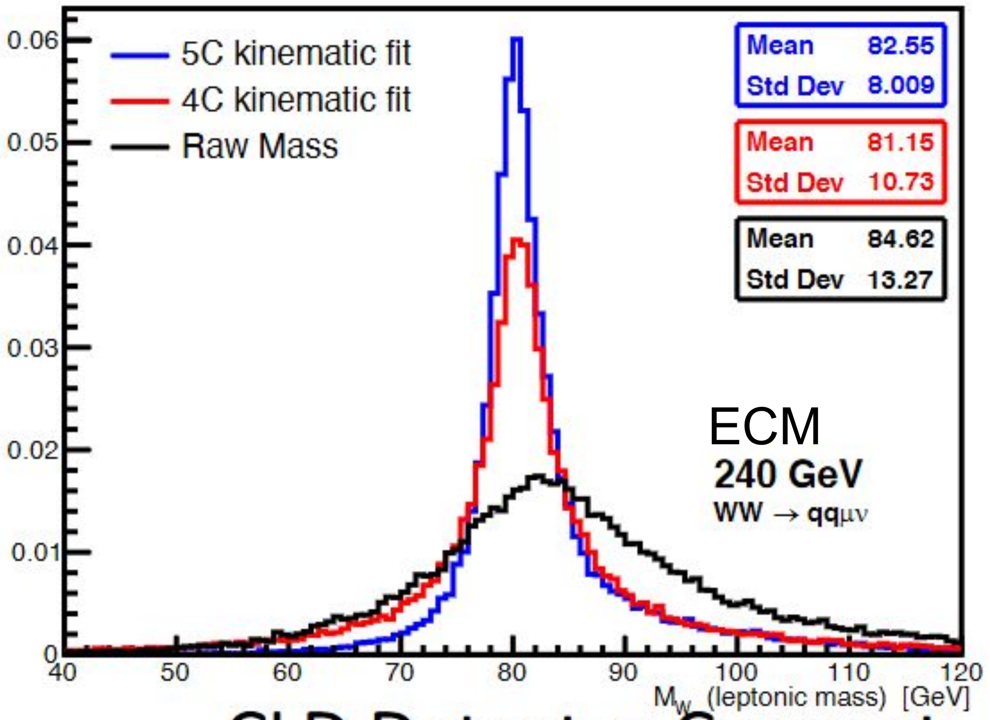
$\Delta\Gamma_W$ (stat) ~ 350 keV → reduction factor 2-3

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

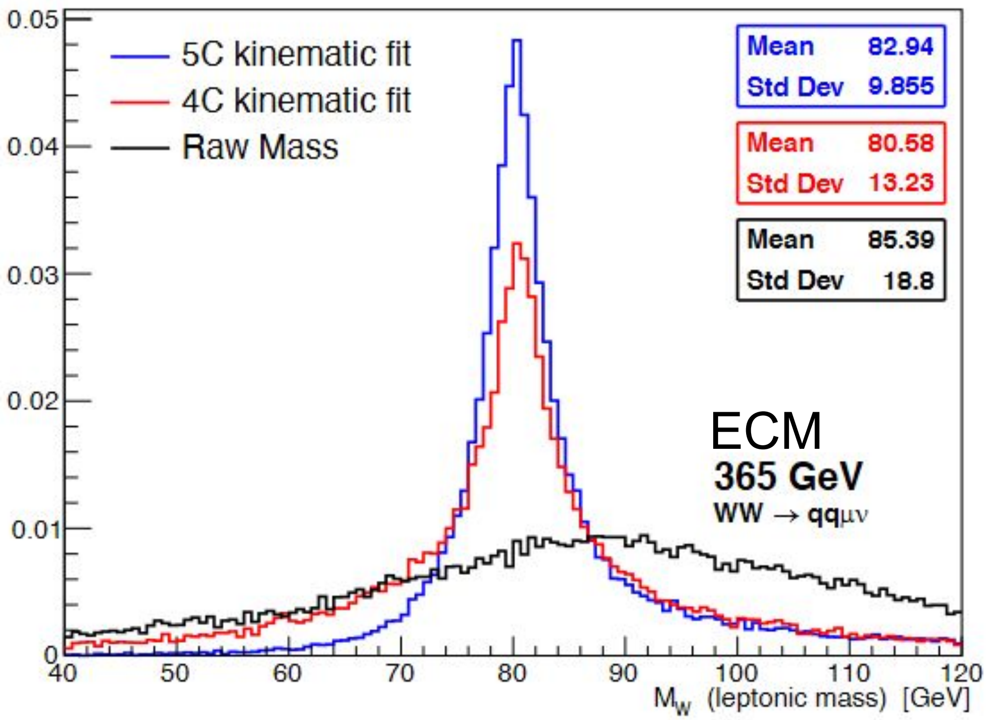


	Δm_W (MeV/c^2)				$\Delta\Gamma_W$ (MeV)			
Source	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$
e+μ momentum	3	8	-	4	5	4	-	4
e+μ momentum resoln	7	4	-	4	65	55	-	50
Jet energy scale/linearity	5	5	9	6	4	4	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





CLD Detector Concept



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

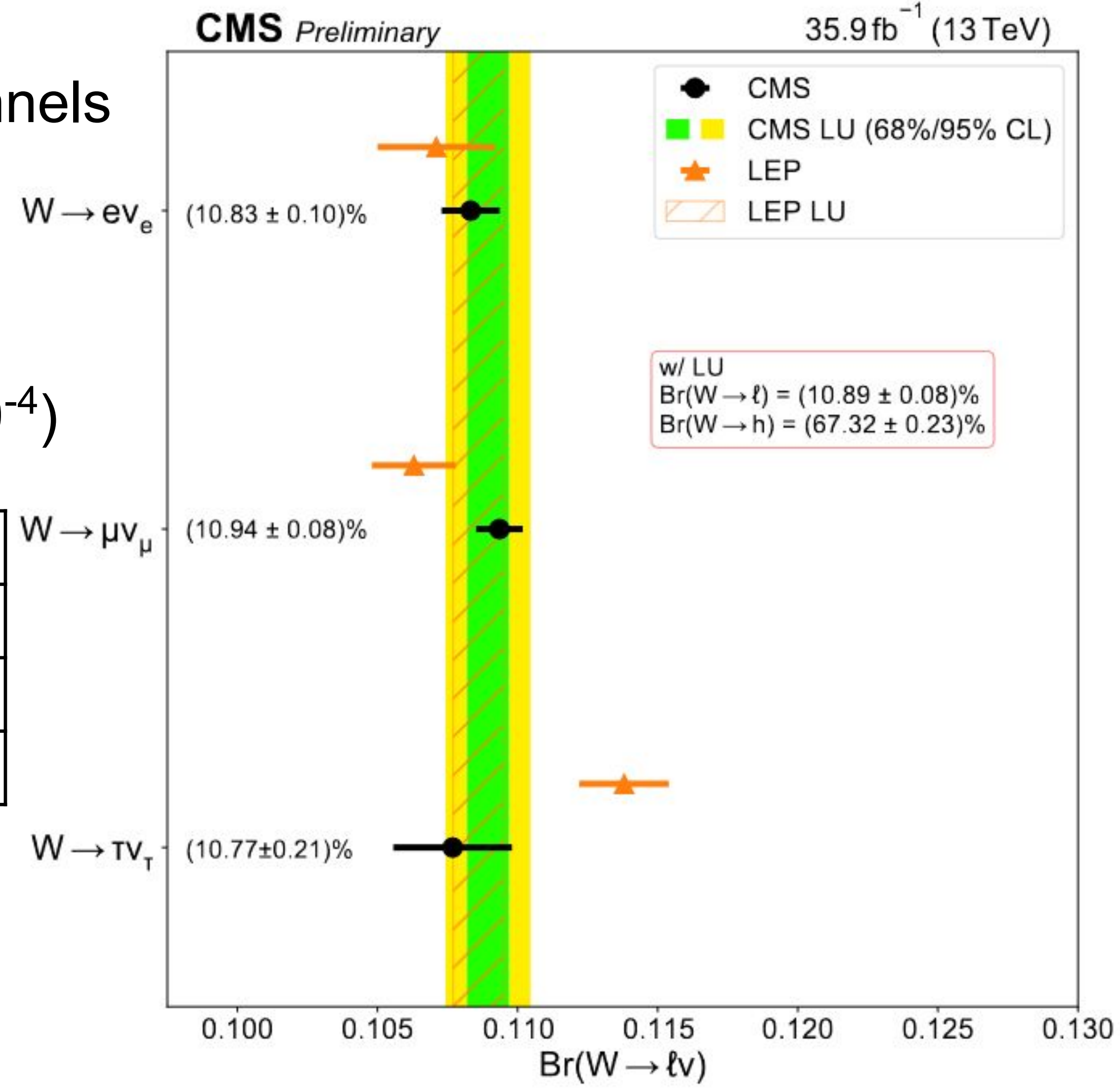
Example of measurements @ WW threshold

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

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

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

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Example of measurements @ tt threshold

Top mass and width measurements similar as WW line-shape

Though more energy points needed:

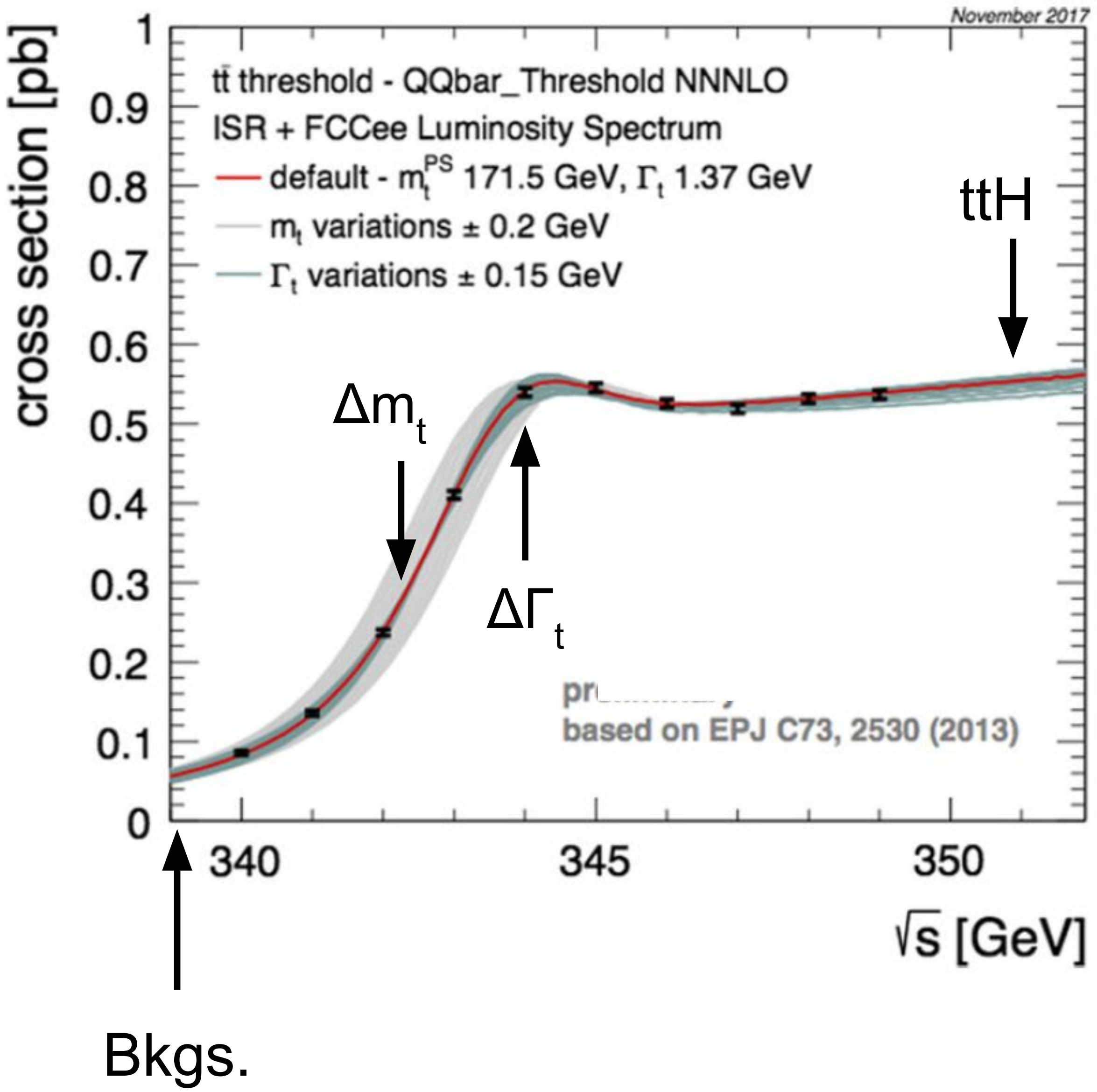
- Relative large uncertainty on top mass (+/- 0.5 GeV)
- Need to constrain shape in optimal way
- Possible to constrain backgrounds (below) and ttH (above)

→ 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



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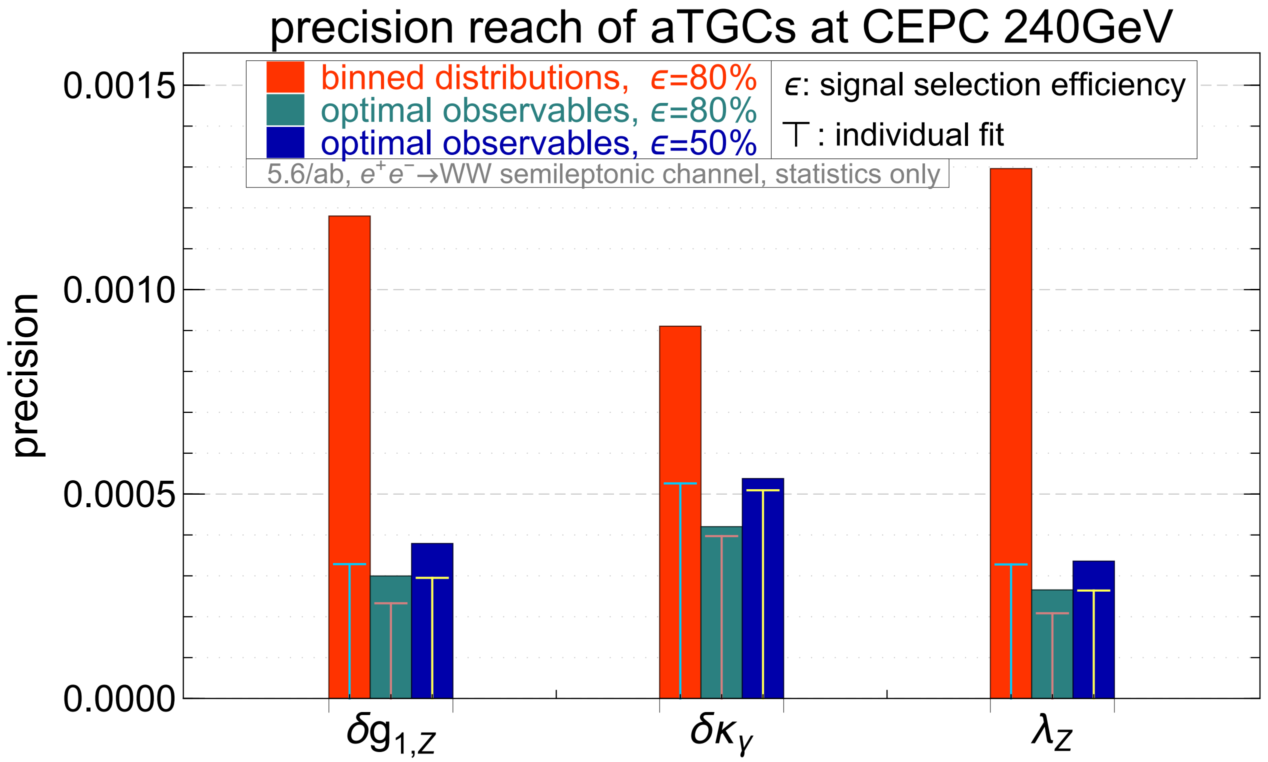
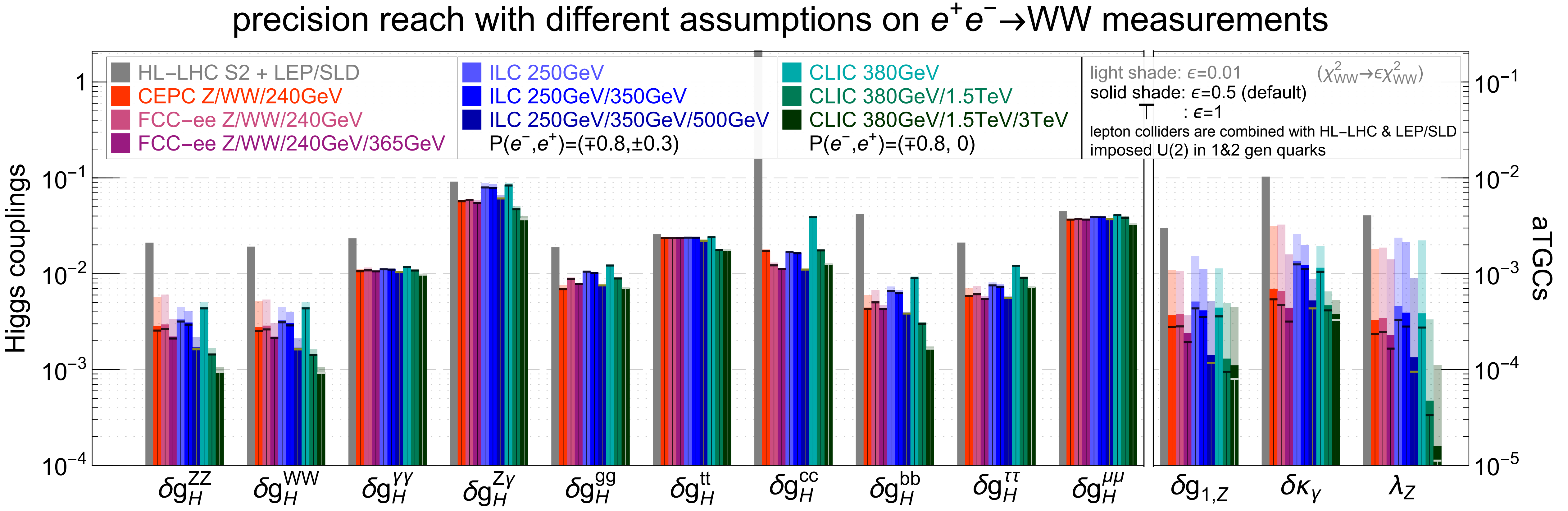
Impact of Diboson Systematics

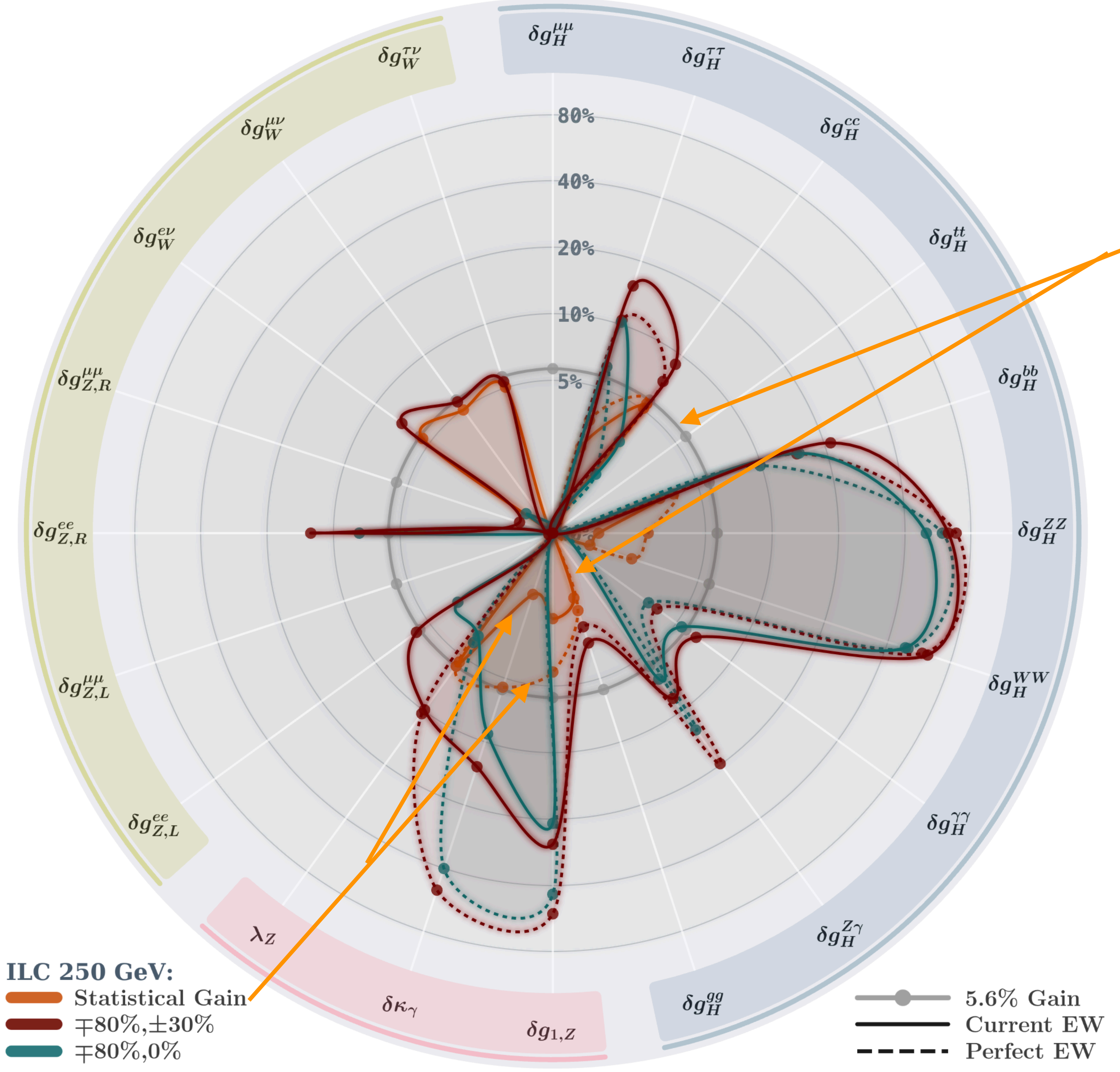
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311





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)

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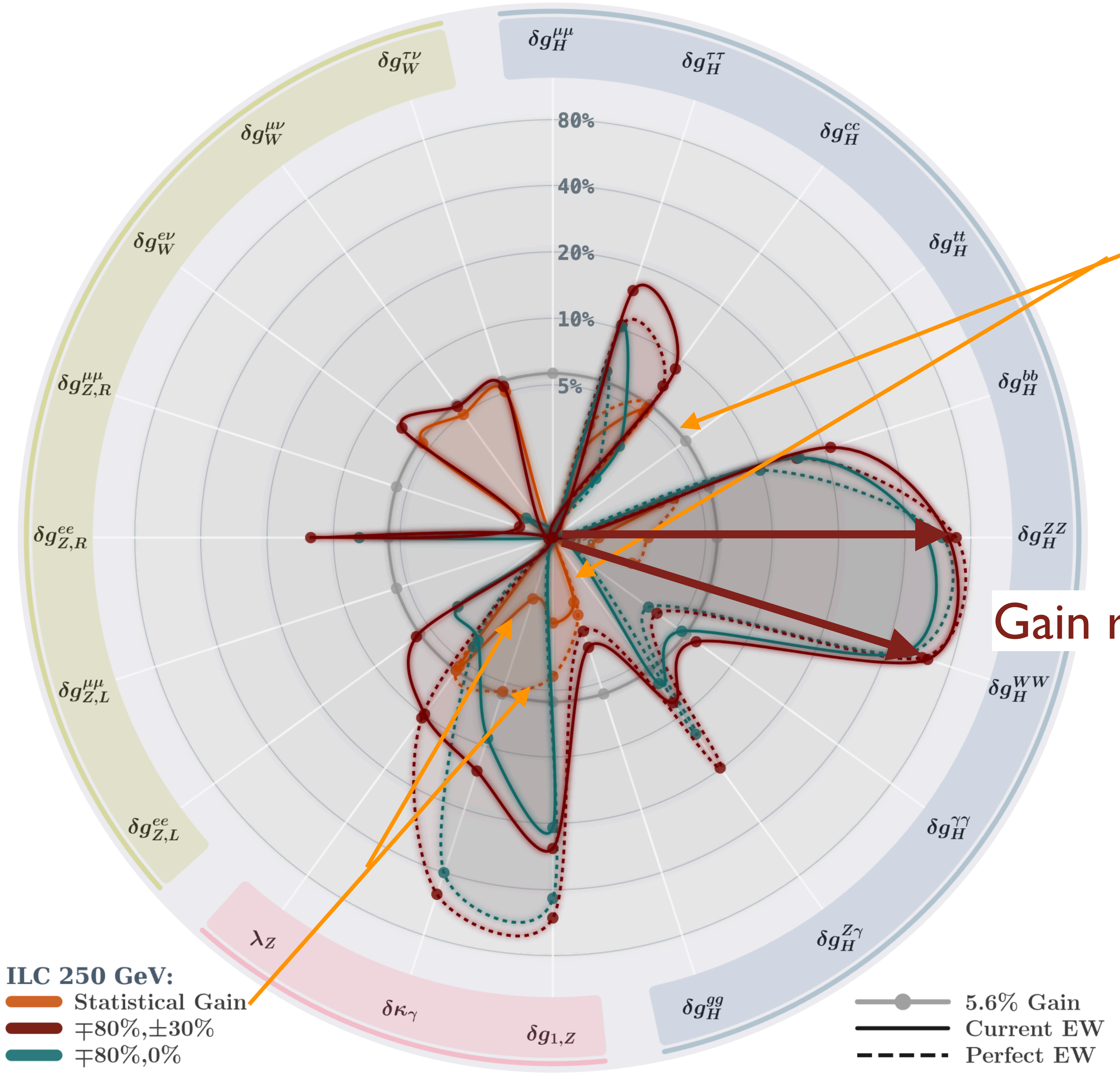

Gain reaches 80%

Statistical gain from increased rates

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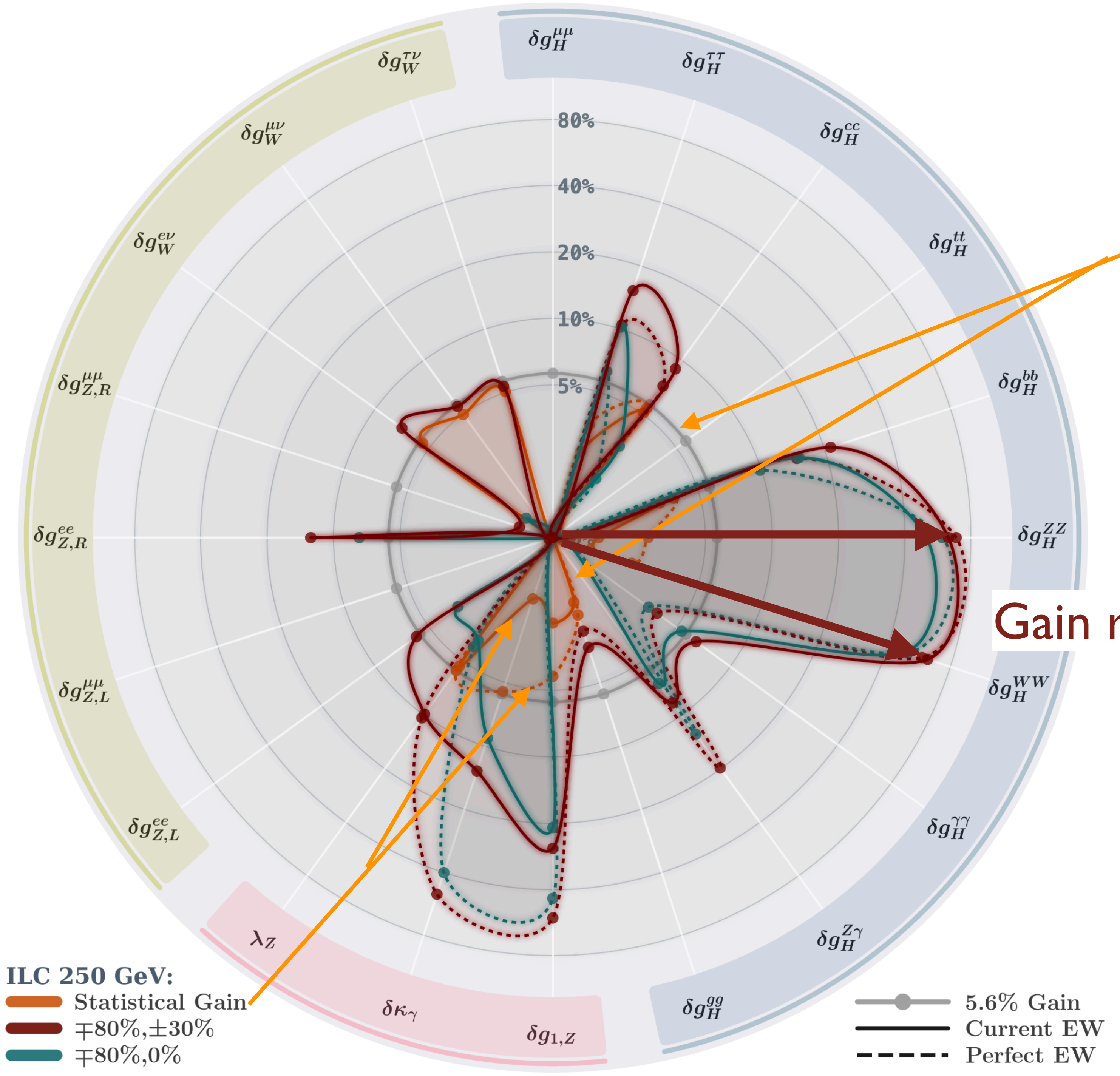

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O(6%) increased coupling sensitivity

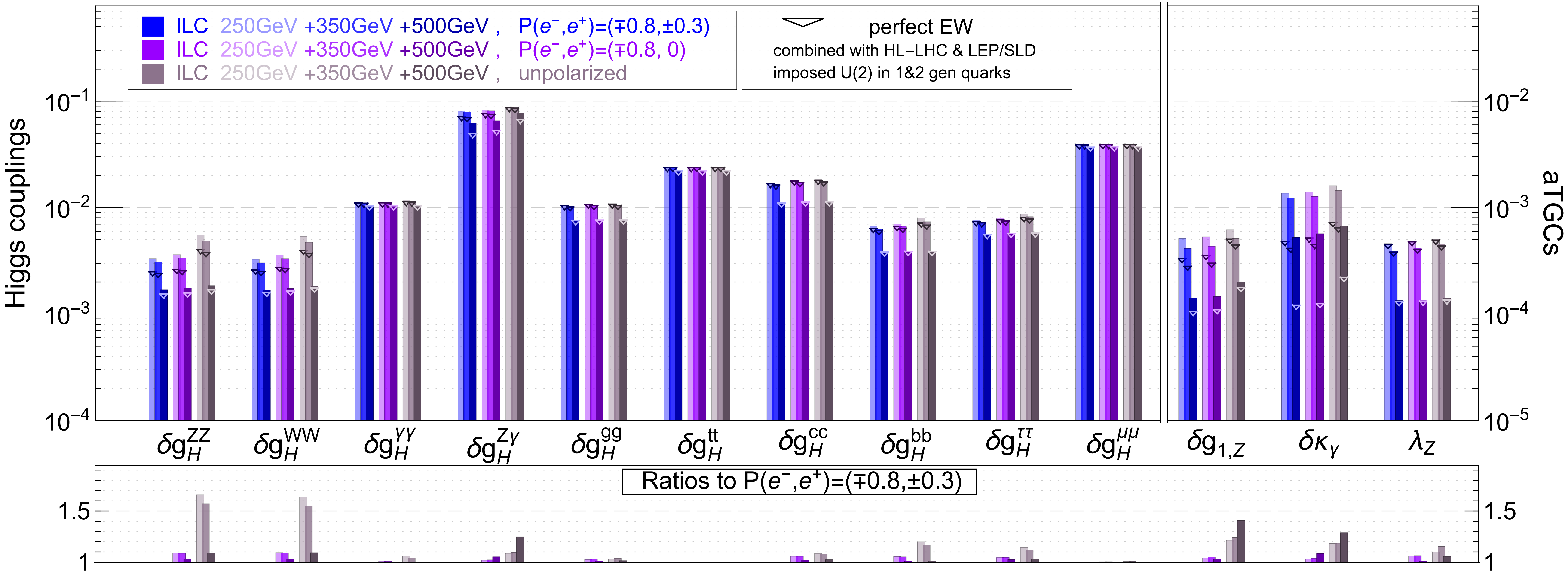
Gain is much higher in global EFT fit since polarisation removes degeneracies among operators

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

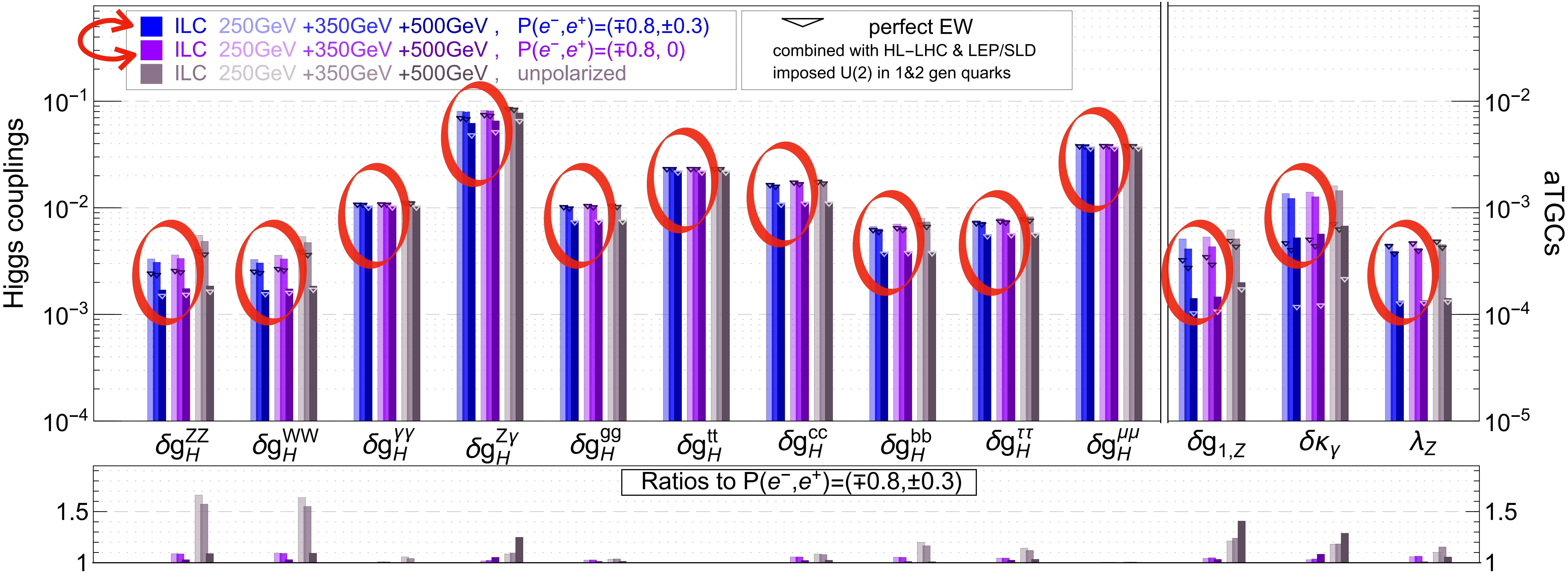
Impact of Beam Polarisation

J. De Blas et al. 1907.04311



Impact of Beam Polarisation

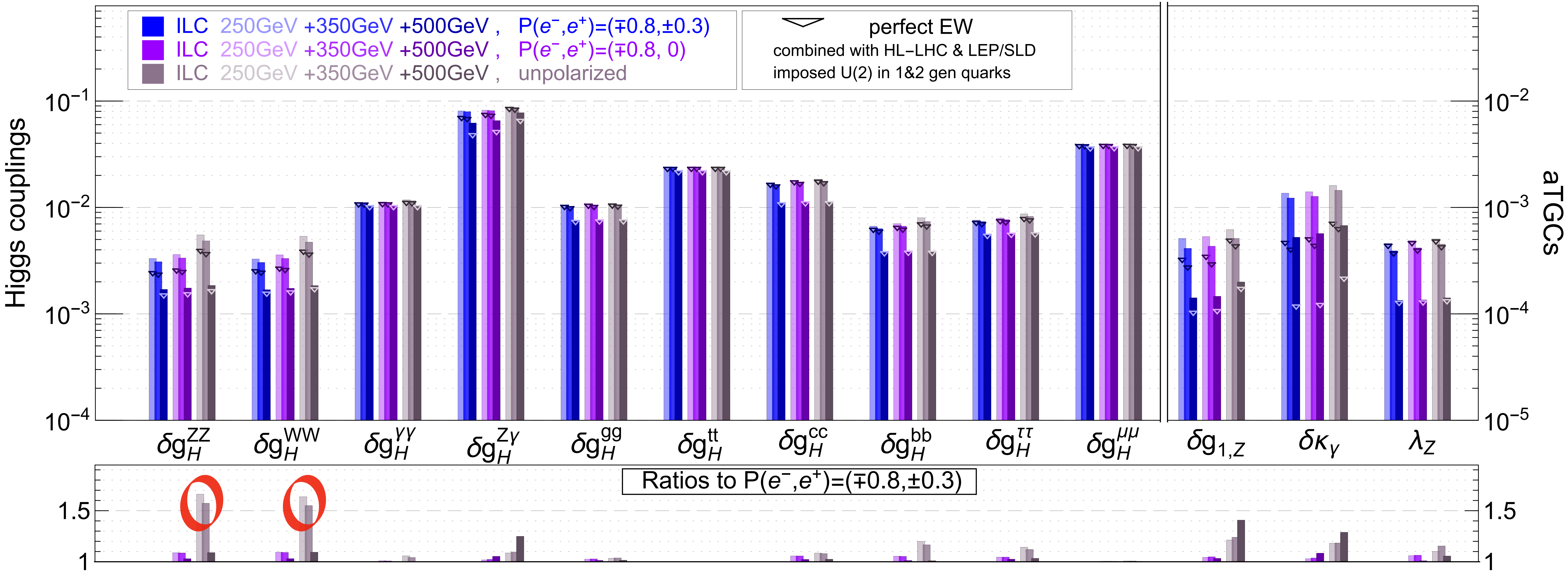
J. De Blas et al. 1907.04311



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

Impact of Beam Polarisation

J. De Blas et al. 1907.04311



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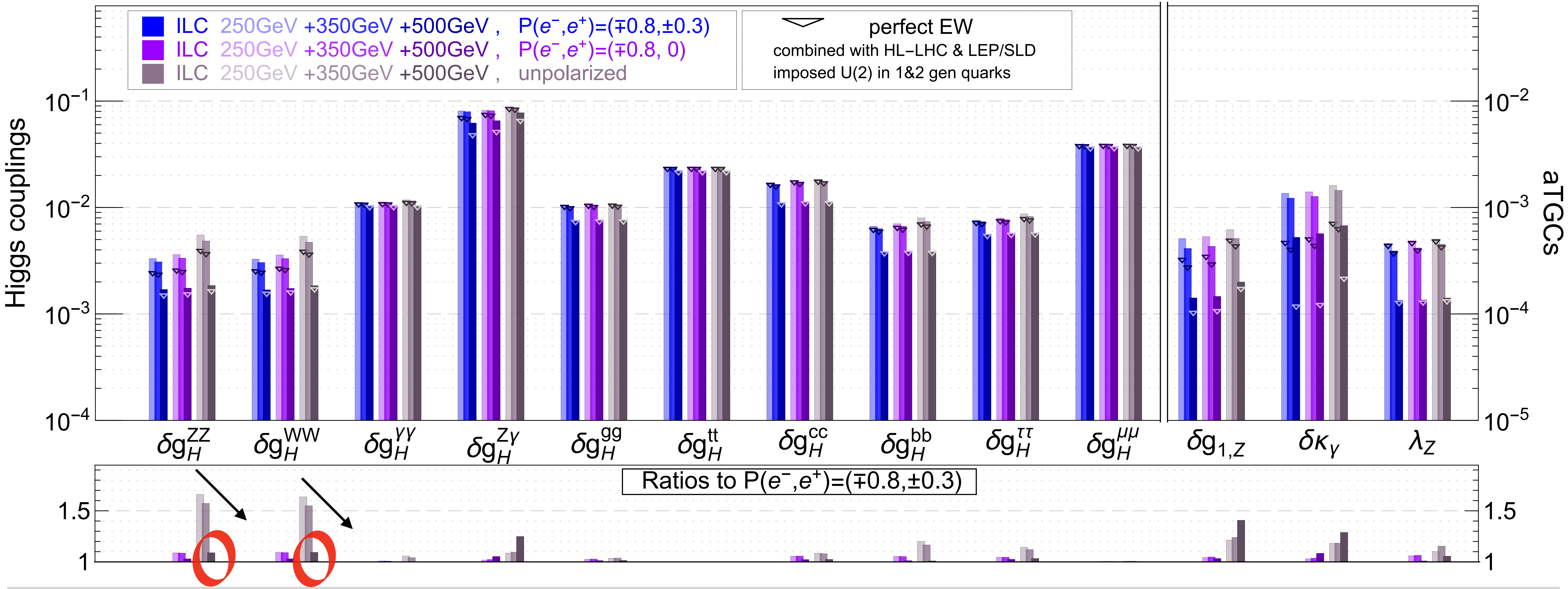
Impact of Beam Polarisation

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